DISCRETE 2022

Baden-Baden, Germany, 7-11 November, 2022

Hybrid scoto/seesaw: flavour and dark matter

Henrique Brito Câmara

henrique.b.camara@tecnico.ulisboa.pt

CFTP/IST, U. Lisbon

In collaboration with: D. M. Barreiros and F. R. Joaquim

arXiv: **2204.13605** [hep-ph]

JHEP 08 (2022) 030

Motivation

The Standard Model cannot explain:

- **Neutrino flavour oscillations** which imply massive neutrinos and lepton mixing
- Observed **dark matter** abundance

Motivation

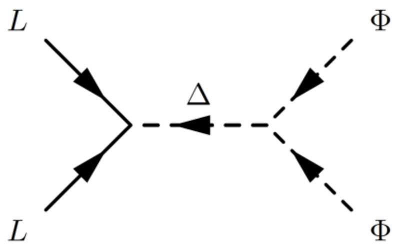
The Standard Model cannot explain:

- **Neutrino flavour oscillations** which imply massive neutrinos and lepton mixing
- Observed **dark matter** abundance

Straightforward and **elegant** solutions:

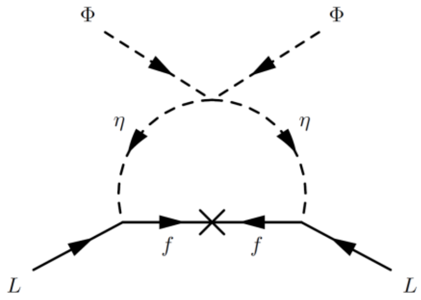
Type II Seesaw Model

Konetschny *et al.* (1977), Cheng *et al.* (1980), Lazarides *et al.* (1981), Valle *et al.* (1980), Magg *et al.* (1980), Mohapatra *et al.* (1981)



Scotogenic Model

Ma (2006)



Motivation

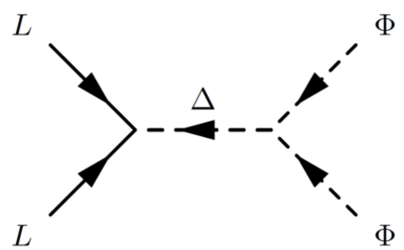
The Standard Model cannot explain:

- **Neutrino flavour oscillations** which imply massive neutrinos and lepton mixing
- Observed **dark matter** abundance

Straightforward and **elegant** solutions:

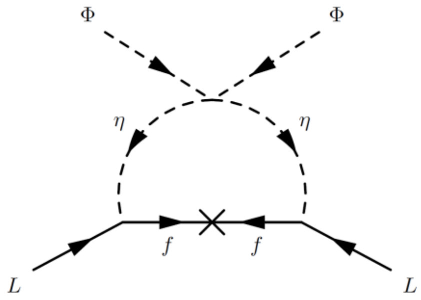
Type II Seesaw Model

Konetschny *et al.* (1977), Cheng *et al.* (1980), Lazarides *et al.* (1981), Valle *et al.* (1980), Magg *et al.* (1980), Mohapatra *et al.* (1981)



Scotogenic Model

Ma (2006)



Our approach:

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

Scoto/type-II seesaw model

	Fields	$\mathrm{SU}(2)_\mathrm{L} \otimes \mathrm{U}(1)_\mathrm{Y}$	$\mathcal{Z}_8^{e-\mu *} \to \mathcal{Z}_2$
Fermions	ℓ_{eL}, e_R	$(\mathbf{2}, -1/2), (\mathbf{1}, -1)$	$1 \to +$
	$\ell_{\mu L}, \mu_R$	$(\mathbf{2}, -1/2), (\mathbf{1}, -1)$	$\omega^6 \to +$
	$\ell_{\tau L}, \tau_R$	$(\mathbf{2}, -1/2), (\mathbf{1}, -1)$	$\omega^2 \to +$
	f	$(\mathbf{1}, 0)$	$\omega^3 \to -$
Scalars	Φ	$(\mathbf{2}, 1/2)$	$1 \to +$
	Δ	$(\mathbf{3}, 1)$	$1 \to +$
	σ	$(\mathbf{1}, 0)$	$\omega^2 \to +$
	η_1	$(\mathbf{2}, 1/2)$	$\omega^3 \to -$
	η_2	$(\mathbf{2}, 1/2)$	$\omega^5 \to -$

* $\mathcal{Z}_8^{e-\tau}$ and $\mathcal{Z}_8^{\mu-\tau}$ are other possible charge assignments

Scoto/type-II seesaw model

	Fields	$\mathrm{SU(2)_L} \otimes \mathrm{U(1)_Y}$	$\mathcal{Z}_8^{e-\mu *} \to \mathcal{Z}_2$
Fermions	ℓ_{eL}, e_R	$(\mathbf{2}, -1/2), (\mathbf{1}, -1)$	$1 \to +$
	$\ell_{\mu L}, \mu_R$	$(\mathbf{2}, -1/2), (\mathbf{1}, -1)$	$\omega^6 \to +$
	$\ell_{\tau L}, \tau_R$	$(\mathbf{2}, -1/2), (\mathbf{1}, -1)$	$\omega^2 \to +$
	f	$(\mathbf{1}, 0)$	$\omega^3 \to -$
Scalars	Φ	$(\mathbf{2}, 1/2)$	$1 \to +$
	Δ	$(\mathbf{3}, 1)$	$1 \to +$
	σ	$(\mathbf{1}, 0)$	$\omega^2 \to +$
	η_1	$(\mathbf{2}, 1/2)$	$\omega^3 \to -$
	η_2	$(\mathbf{2}, 1/2)$	$\omega^5 \to -$

* $\mathcal{Z}_8^{e-\tau}$ and $\mathcal{Z}_8^{\mu-\tau}$ are other possible charge assignments

Z_8 discrete symmetry

- New Z_8 symmetry reduces number of parameters in the Lagrangian
- Leads to **low-energy predictions** for neutrino mass and mixing parameters
- Presence of **dark particles** (odd under remnant Z_2 after SSB): **fermion f** and **scalars $\eta_{1,2}$**

Scoto/type-II seesaw model

	Fields	$\mathrm{SU}(2)_\mathrm{L} \otimes \mathrm{U}(1)_\mathrm{Y}$	$\mathcal{Z}_8^{e-\mu *} \to \mathcal{Z}_2$
Fermions	ℓ_{eL}, e_R	$(\mathbf{2}, -1/2), (\mathbf{1}, -1)$	$1 \to +$
	$\ell_{\mu L}, \mu_R$	$(\mathbf{2}, -1/2), (\mathbf{1}, -1)$	$\omega^6 \to +$
	$\ell_{\tau L}, \tau_R$	$(\mathbf{2}, -1/2), (\mathbf{1}, -1)$	$\omega^2 \to +$
	f	$(\mathbf{1}, 0)$	$\omega^3 \to -$
Scalars	Φ	$(\mathbf{2}, 1/2)$	$1 \to +$
	Δ	$(\mathbf{3}, 1)$	$1 \to +$
	σ	$(\mathbf{1}, 0)$	$\omega^2 \to +$
	η_1	$(\mathbf{2}, 1/2)$	$\omega^3 \to -$
	η_2	$(\mathbf{2}, 1/2)$	$\omega^5 \to -$

* $\mathcal{Z}_8^{e-\tau}$ and $\mathcal{Z}_8^{\mu-\tau}$ are other possible charge assignments

Z_8 discrete symmetry

- New Z_8 symmetry reduces number of parameters in the Lagrangian
- Leads to **low-energy predictions** for neutrino mass and mixing parameters
- Presence of **dark particles** (odd under remnant Z_2 after SSB): **fermion f** and **scalars $\eta_{1,2}$**

CP symmetry

- Lagrangian is required to be CP invariant which makes all couplings real
- CP is **spontaneously broken** by the **complex VEV** of σ and is **successfully** transmitted to the leptonic sector

Scoto/type-II seesaw model

	Fields	$\mathrm{SU}(2)_\mathrm{L} \otimes \mathrm{U}(1)_\mathrm{Y}$	$\mathcal{Z}_8^{e-\mu *} \to \mathcal{Z}_2$
Fermions	ℓ_{eL}, e_R	$(\mathbf{2}, -1/2), (\mathbf{1}, -1)$	$1 \to +$
	$\ell_{\mu L}, \mu_R$	$(\mathbf{2}, -1/2), (\mathbf{1}, -1)$	$\omega^6 \to +$
	$\ell_{\tau L}, \tau_R$	$(\mathbf{2}, -1/2), (\mathbf{1}, -1)$	$\omega^2 \to +$
	f	$(\mathbf{1}, 0)$	$\omega^3 \to -$
Scalars	Φ	$(\mathbf{2}, 1/2)$	$1 \to +$
	Δ	$(\mathbf{3}, 1)$	$1 \to +$
	σ	$(\mathbf{1}, 0)$	$\omega^2 \to +$
	η_1	$(\mathbf{2}, 1/2)$	$\omega^3 \to -$
	η_2	$(\mathbf{2}, 1/2)$	$\omega^5 \to -$

* $\mathcal{Z}_8^{e-\tau}$ and $\mathcal{Z}_8^{\mu-\tau}$ are other possible charge assignments

Z_8 discrete symmetry

- New Z_8 symmetry reduces number of parameters in the Lagrangian
- Leads to **low-energy predictions** for neutrino mass and mixing parameters
- Presence of **dark particles** (odd under remnant Z_2 after SSB): **fermion f** and **scalars $\eta_{1,2}$**

CP symmetry

- Lagrangian is required to be CP invariant which makes all couplings real
- CP is **spontaneously broken** by the **complex VEV** of σ and is **successfully** transmitted to the leptonic sector

Vacuum configuration

$$\langle \phi^0 \rangle = \frac{v}{\sqrt{2}} \, , \; \langle \eta^0_{1,2} \rangle = 0 \, , \; \langle \Delta^0 \rangle = \frac{w}{\sqrt{2}} \, , \; \langle \sigma \rangle = \frac{u \, e^{i\theta}}{\sqrt{2}}$$

Scalar sector and spontaneous CP violation

Scalar potential contains:

$$V_\sigma = m_\sigma^2 \left|\sigma\right|^2 + \frac{\lambda_\sigma}{2} \left|\sigma\right|^4 + m_\sigma'^2 \left(\sigma^2 + \sigma^{*2}\right) + \frac{\lambda_\sigma'}{2} \left(\sigma^4 + \sigma^{*4}\right)$$

Scalar sector and spontaneous CP violation

Scalar potential contains:

$$V_\sigma = m_\sigma^2 \left|\sigma\right|^2 + \frac{\lambda_\sigma}{2} \left|\sigma\right|^4 + m_\sigma'^2 \left(\sigma^2 + \sigma^{*2}\right) + \frac{\lambda'_\sigma}{2} \left(\sigma^4 + \sigma^{*4}\right)$$

CPV solution to the minimisation conditions

$$\langle \phi^0 \rangle = \frac{v}{\sqrt{2}} \, , \, \langle \eta^0_{1,2} \rangle = 0 \, , \, \langle \Delta^0 \rangle = \frac{w}{\sqrt{2}} \, , \langle \sigma \rangle = \frac{u \, e^{i\theta}}{\sqrt{2}}$$

⬇

$$\cos(2\theta) = -\frac{m_\sigma'^2}{2u^2 \lambda'_\sigma}$$

Scalar sector and spontaneous CP violation

Scalar potential contains:

$$V_\sigma = m_\sigma^2 |\sigma|^2 + \frac{\lambda_\sigma}{2} |\sigma|^4 + m_\sigma'^2 \left(\sigma^2 + \sigma^{*2}\right) + \frac{\lambda'_\sigma}{2} \left(\sigma^4 + \sigma^{*4}\right)$$

CPV solution to the minimisation conditions

$$\langle \phi^0 \rangle = \frac{v}{\sqrt{2}}\,,\ \langle \eta^0_{1,2} \rangle = 0\,,\ \langle \Delta^0 \rangle = \frac{w}{\sqrt{2}}\,, \langle \sigma \rangle = \frac{u\, e^{i\theta}}{\sqrt{2}}$$

⬇

$$\cos(2\theta) = -\frac{m_\sigma'^{\,2}}{2u^2 \lambda'_\sigma}$$

Higgs triplet, doublet and singlet

$$V \supset \ \mu_\Delta \left(\Phi^\dagger \Delta i\tau_2 \Phi^* + \mathrm{H.c.}\right)$$

$$w \simeq -\frac{\sqrt{2}\mu_\Delta v^2}{v^2 \lambda_{\Delta 3} + u^2 \lambda_{\Delta\sigma} + 2m_\Delta^2}$$

Naturally small triplet VEV

$$\begin{pmatrix} \phi^0_{\mathrm{R}} \\ \sigma_{\mathrm{R}} \\ \sigma_{\mathrm{I}} \end{pmatrix} = \mathbf{K} \begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix}$$

We consider triplet decoupled from remaining states

Scalar sector and spontaneous CP violation

Scalar potential contains:

$$V_\sigma = m_\sigma^2 |\sigma|^2 + \frac{\lambda_\sigma}{2} |\sigma|^4 + m_\sigma'^2 \left(\sigma^2 + \sigma^{*2}\right) + \frac{\lambda'_\sigma}{2} \left(\sigma^4 + \sigma^{*4}\right)$$

CPV solution to the minimisation conditions

$$\langle \phi^0 \rangle = \frac{v}{\sqrt{2}} \, , \; \langle \eta^0_{1,2} \rangle = 0 \, , \; \langle \Delta^0 \rangle = \frac{w}{\sqrt{2}} \, , \langle \sigma \rangle = \frac{u\, e^{i\theta}}{\sqrt{2}}$$

$$\cos(2\theta) = -\frac{m_\sigma'^2}{2u^2 \lambda'_\sigma}$$

Higgs triplet, doublet and singlet

$$V \supset \; \mu_\Delta \left(\Phi^\dagger \Delta i \tau_2 \Phi^* + \text{H.c.}\right)$$

$$w \simeq -\frac{\sqrt{2}\mu_\Delta v^2}{v^2 \lambda_{\Delta 3} + u^2 \lambda_{\Delta\sigma} + 2m_\Delta^2}$$

Naturally small triplet VEV

$$\begin{pmatrix} \phi^0_R \\ \sigma_R \\ \sigma_I \end{pmatrix} = \mathbf{K} \begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix}$$

We consider triplet decoupled from remaining states

Dark sector: two inert doublets

$$\begin{pmatrix} \eta_1^+ \\ \eta_2^+ \end{pmatrix} = \mathbf{R} \begin{pmatrix} S_1^+ \\ S_2^+ \end{pmatrix}$$

Charged lepton flavour violation

$$\begin{pmatrix} \eta^0_{R1} \\ \eta^0_{R2} \\ \eta^0_{I1} \\ \eta^0_{I2} \end{pmatrix} = \mathbf{V} \begin{pmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \end{pmatrix}$$

Neutrino mass generation and dark matter

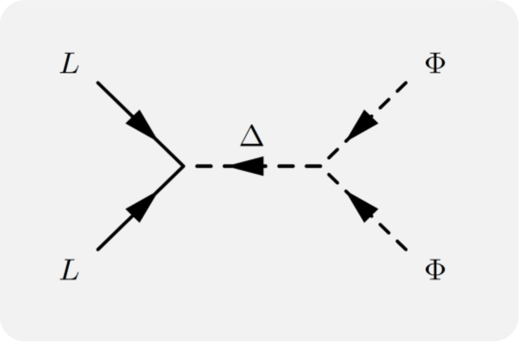
Neutrino mass generation

$$-\mathcal{L}_{\text{Yuk.}} = \overline{\ell_L}\mathbf{Y}_\ell\,\Phi\,e_R + \overline{\ell_L^c}\mathbf{Y}_\Delta i\tau_2\Delta\ell_L + \overline{\ell_L}\mathbf{Y}_f^1\tilde{\eta}_1 f + \overline{\ell_L}\mathbf{Y}_f^2\tilde{\eta}_2 f + \frac{1}{2}y_f\,\sigma\overline{f^c}f + \text{H.c.}$$

Neutrino mass generation

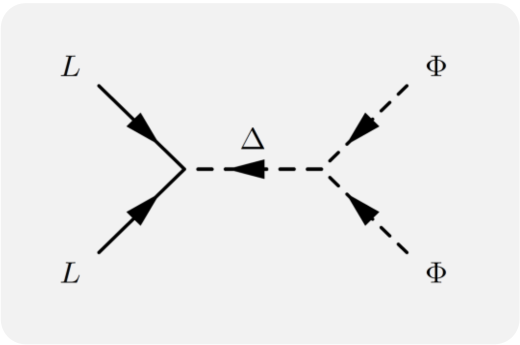
$$-\mathcal{L}_{\text{Yuk.}} = \overline{\ell_L}\mathbf{Y}_\ell\,\Phi\,e_R + \overline{\ell^c_L}\mathbf{Y}_\Delta i\tau_2\Delta\ell_L + \overline{\ell_L}\mathbf{Y}^1_f\tilde{\eta}_1 f + \overline{\ell_L}\mathbf{Y}^2_f\tilde{\eta}_2 f + \frac{1}{2}y_f\,\sigma\overline{f^c}f + \text{H.c.}$$

Type-II seesaw

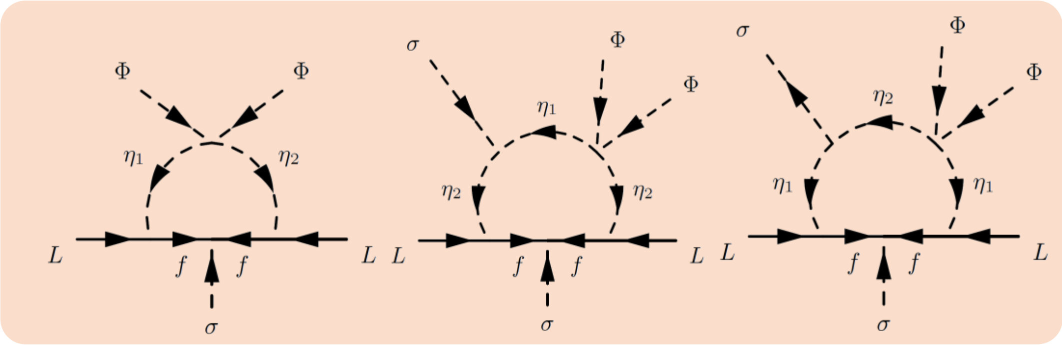


$$-\mathcal{L}_{\text{Yuk.}} = \overline{\ell_L}\mathbf{Y}_\ell\,\Phi\,e_R + \overline{\ell_L^c}\mathbf{Y}_\Delta i\tau_2\Delta\ell_L + \overline{\ell_L}\mathbf{Y}_f^1\tilde{\eta}_1 f + \overline{\ell_L}\mathbf{Y}_f^2\tilde{\eta}_2 f + \frac{1}{2}y_f\,\sigma\overline{f^c}f + \text{H.c.}$$

Type-II seesaw



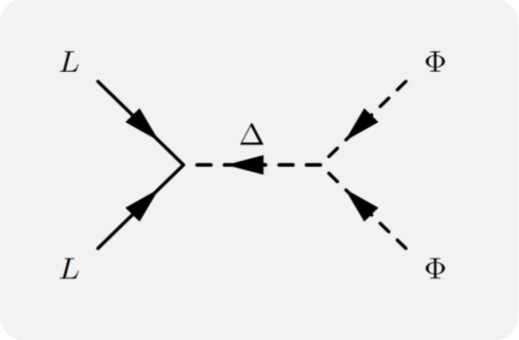
Scotogenic



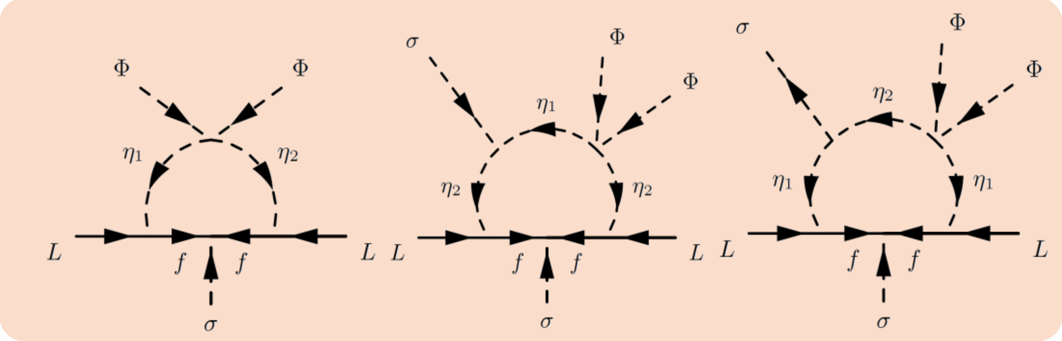
Neutrino mass generation

$$-\mathcal{L}_{\text{Yuk.}} = \overline{\ell_L}\mathbf{Y}_\ell\,\Phi\,e_R + \overline{\ell_L^c}\mathbf{Y}_\Delta i\tau_2\Delta\ell_L + \overline{\ell_L}\mathbf{Y}_f^1\tilde{\eta}_1 f + \overline{\ell_L}\mathbf{Y}_f^2\tilde{\eta}_2 f + \frac{1}{2}y_f\,\sigma\overline{f^c}f + \text{H.c.}$$

Type-II seesaw



Scotogenic

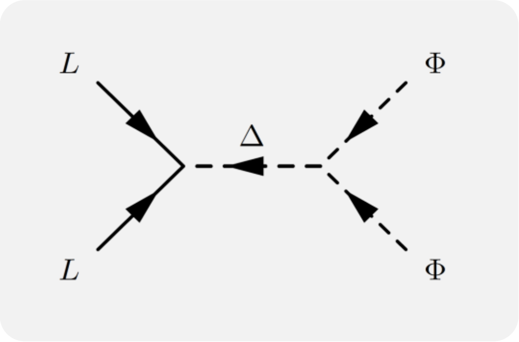


$$\mathbf{Y}_\ell = \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & \times \end{pmatrix}$$

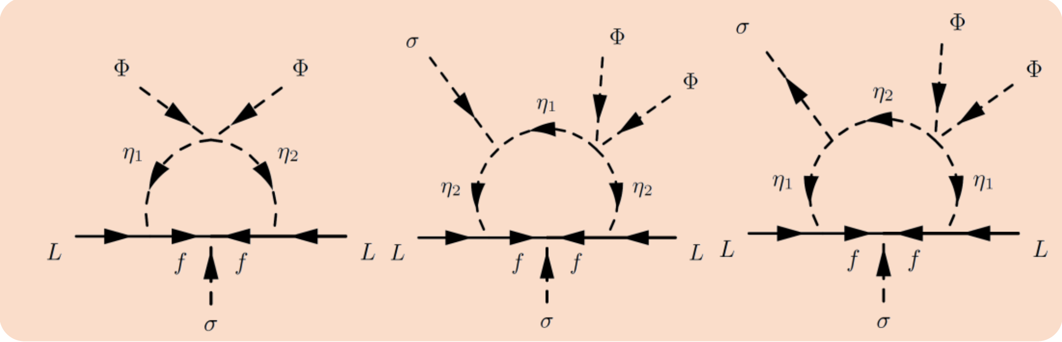
Neutrino mass generation

$$-\mathcal{L}_{\text{Yuk.}} = \overline{\ell_L}\mathbf{Y}_\ell\,\Phi\,e_R + \overline{\ell_L^c}\mathbf{Y}_\Delta i\tau_2\Delta\ell_L + \overline{\ell_L}\mathbf{Y}_f^1\tilde{\eta}_1 f + \overline{\ell_L}\mathbf{Y}_f^2\tilde{\eta}_2 f + \frac{1}{2}y_f\,\sigma\overline{f^c}f + \text{H.c.}$$

Type-II seesaw



Scotogenic



$\mathcal{Z}_8^{e-\mu}$

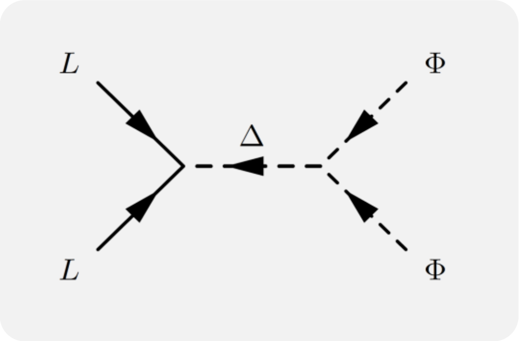
$$\mathbf{Y}_\ell = \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & \times \end{pmatrix}$$

$$\mathbf{Y}_f^1 = \begin{pmatrix} y_e \\ 0 \\ 0 \end{pmatrix} \; \mathbf{Y}_f^2 = \begin{pmatrix} 0 \\ y_\mu \\ 0 \end{pmatrix} \; \mathbf{Y}_\Delta = \begin{pmatrix} y_1 & 0 & 0 \\ 0 & 0 & y_2 \\ 0 & y_2 & 0 \end{pmatrix} e^{-i\theta}$$

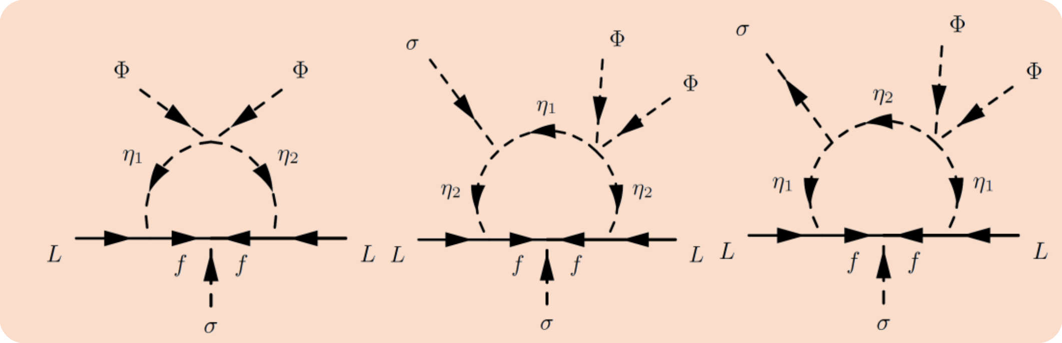
Neutrino mass generation

$$-\mathcal{L}_{\text{Yuk.}} = \overline{\ell_L}\mathbf{Y}_\ell\,\Phi\, e_R + \overline{\ell_L^c}\mathbf{Y}_\Delta i\tau_2\Delta\ell_L + \overline{\ell_L}\mathbf{Y}_f^1\tilde{\eta}_1 f + \overline{\ell_L}\mathbf{Y}_f^2\tilde{\eta}_2 f + \frac{1}{2}y_f\,\sigma\overline{f^c}f + \text{H.c.}$$

Type-II seesaw



Scotogenic



$$\mathcal{Z}_8^{e-\mu}$$

$$\mathbf{Y}_\ell = \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & \times \end{pmatrix}$$

$$\mathbf{Y}_f^1 = \begin{pmatrix} y_e \\ 0 \\ 0 \end{pmatrix} \quad \mathbf{Y}_f^2 = \begin{pmatrix} 0 \\ y_\mu \\ 0 \end{pmatrix} \quad \mathbf{Y}_\Delta = \begin{pmatrix} y_1 & 0 & 0 \\ 0 & 0 & y_2 \\ 0 & y_2 & 0 \end{pmatrix} e^{-i\theta}$$

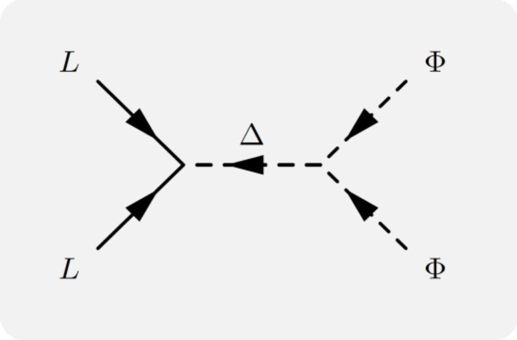
$$\mathbf{M}_\nu = \begin{pmatrix} \mathcal{F}_{11}M_f\,y_e^2 + \sqrt{2}w\,y_1\,e^{-i\theta} & \mathcal{F}_{12}M_f\,y_e y_\mu & 0 \\ \cdot & \mathcal{F}_{22}M_f\,y_\mu^2 & \sqrt{2}w\,y_2 e^{-i\theta} \\ \cdot & \cdot & 0 \end{pmatrix}$$

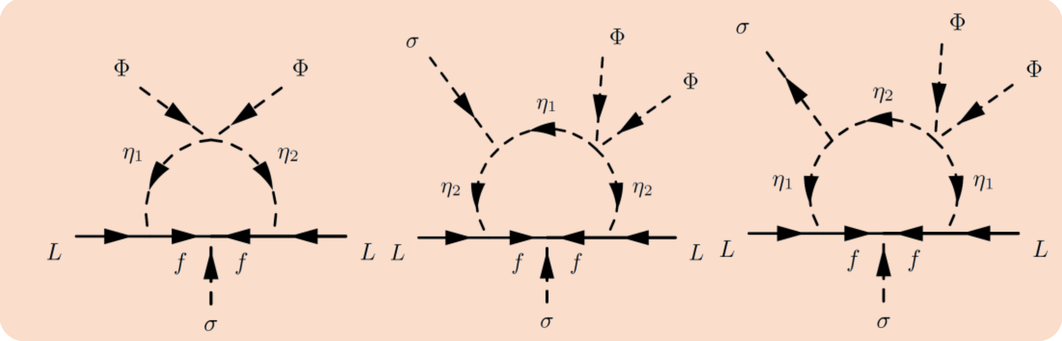
Effective neutrino mass matrix

$$-\mathcal{L}_{\text{Yuk.}} = \overline{\ell_L}\mathbf{Y}_\ell\,\Phi\,e_R + \overline{\ell_L^c}\mathbf{Y}_\Delta i\tau_2\Delta\ell_L + \overline{\ell_L}\mathbf{Y}_f^1\tilde{\eta}_1 f + \overline{\ell_L}\mathbf{Y}_f^2\tilde{\eta}_2 f + \frac{1}{2}y_f\,\sigma\overline{f^c}f + \text{H.c.}$$

Type-II seesaw

Scotogenic





$\mathcal{Z}_8^{e-\mu}$

$$\mathbf{Y}_\ell = \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & \times \end{pmatrix} \quad \mathbf{Y}_f^1 = \begin{pmatrix} y_e \\ 0 \\ 0 \end{pmatrix} \quad \mathbf{Y}_f^2 = \begin{pmatrix} 0 \\ y_\mu \\ 0 \end{pmatrix} \quad \mathbf{Y}_\Delta = \begin{pmatrix} y_1 & 0 & 0 \\ 0 & 0 & y_2 \\ 0 & y_2 & 0 \end{pmatrix} \; e^{-i\theta}$$

Spontaneous origin for leptonic CP violation

$$\langle\sigma\rangle = \frac{u\,e^{i\theta}}{\sqrt{2}}$$

$$\mathbf{M}_\nu = \begin{pmatrix} \mathcal{F}_{11}M_f\,y_e^2 + \sqrt{2}w\,y_1\,e^{-i\theta} & \mathcal{F}_{12}M_f\,y_e y_\mu & 0 \\ \cdot & \mathcal{F}_{22}M_f\,y_\mu^2 & \sqrt{2}w\,y_2 e^{-i\theta} \\ \cdot & \cdot & 0 \end{pmatrix}$$

Effective neutrino mass matrix

Compatibility with neutrino data

$$\mathbf{M}_\nu = \begin{pmatrix} \mathcal{F}_{11} M_f\, y_e^2 + \sqrt{2} w\, y_1\, e^{-i\theta} & \mathcal{F}_{12} M_f\, y_e y_\mu & 0 \\ \cdot & \mathcal{F}_{22} M_f\, y_\mu^2 & \sqrt{2} w\, y_2 e^{-i\theta} \\ \cdot & \cdot & 0 \end{pmatrix}$$

High-energy parameters

Compatibility with neutrino data

$$\mathbf{M}_\nu = \begin{pmatrix} \mathcal{F}_{11} M_f\, y_e^2 + \sqrt{2} w\, y_1\, e^{-i\theta} & \mathcal{F}_{12} M_f\, y_e y_\mu & 0 \\ \cdot & \mathcal{F}_{22} M_f\, y_\mu^2 & \sqrt{2} w\, y_2 e^{-i\theta} \\ \cdot & \cdot & 0 \end{pmatrix}$$

Matching

$$\widehat{\mathbf{M}}_\nu = \mathbf{U}^*\, \mathrm{diag}(m_1, m_2, m_3)\, \mathbf{U}^\dagger$$

High-energy parameters

Low-energy parameters

Global fit of neutrino oscillation data

Salas *et al.* (2020), Esteban *et al.* (2020), Capozzi *et al.* (2021)

Parameter	Best Fit $\pm 1\sigma$	3σ range
$\theta_{12}(^\circ)$	34.3 ± 1.0	$31.4 \to 37.4$
$\theta_{23}(^\circ)$[NO]	49.26 ± 0.79	$41.20 \to 51.33$
$\theta_{23}(^\circ)$[IO]	$49.46^{+0.60}_{-0.97}$	$41.16 \to 51.25$
$\theta_{13}(^\circ)$[NO]	$8.53^{+0.13}_{-0.12}$	$8.13 \to 8.92$
$\theta_{13}(^\circ)$[IO]	$8.58^{+0.12}_{-0.14}$	$8.17 \to 8.96$
$\delta(^\circ)$[NO]	194^{+24}_{-22}	$128 \to 359$
$\delta(^\circ)$[IO]	284^{+26}_{-28}	$200 \to 353$
$\Delta m^2_{21}\left(\times 10^{-5}\,\mathrm{eV}^2\right)$	$7.50^{+0.22}_{-0.20}$	$6.94 \to 8.14$
$\lvert\Delta m^2_{31}\rvert\left(\times 10^{-3}\,\mathrm{eV}^2\right)$ [NO]	$2.55^{+0.02}_{-0.03}$	$2.47 \to 2.63$
$\lvert\Delta m^2_{31}\rvert\left(\times 10^{-3}\,\mathrm{eV}^2\right)$ [IO]	$2.45^{+0.02}_{-0.03}$	$2.37 \to 2.53$

Compatibility with neutrino data

$$\mathbf{M}_\nu = \begin{pmatrix} \mathcal{F}_{11} M_f\, y_e^2 + \sqrt{2} w\, y_1\, e^{-i\theta} & \mathcal{F}_{12} M_f\, y_e y_\mu & 0 \\ \cdot & \mathcal{F}_{22} M_f\, y_\mu^2 & \sqrt{2} w\, y_2 e^{-i\theta} \\ \cdot & \cdot & 0 \end{pmatrix}$$

Matching

$$\widehat{\mathbf{M}}_\nu = \mathbf{U}^*\, \mathrm{diag}(m_1, m_2, m_3)\, \mathbf{U}^\dagger$$

High-energy parameters

Low-energy parameters

The presence of **two texture zeros in the neutrino mass matrix** leads to **testable low-energy constraints**

$$\mathcal{Z}_8^{e-\mu} \rightarrow \mathrm{B}_4 : \begin{pmatrix} \times & \times & 0 \\ \cdot & \times & \times \\ \cdot & \cdot & 0 \end{pmatrix},$$

$$\mathcal{Z}_8^{e-\tau} \rightarrow \mathrm{B}_3 : \begin{pmatrix} \times & 0 & \times \\ \cdot & 0 & \times \\ \cdot & \cdot & \times \end{pmatrix},$$

$$\mathcal{Z}_8^{\mu-\tau} \rightarrow \mathrm{A}_1 : \begin{pmatrix} 0 & 0 & \times \\ \cdot & \times & \times \\ \cdot & \cdot & \times \end{pmatrix}$$

Alcaide, Salvado, Santamaria (2018)

Global fit of neutrino oscillation data

Salas *et al.* (2020), Esteban *et al.* (2020), Capozzi *et al.* (2021)

Parameter	Best Fit $\pm 1\sigma$	3σ range
$\theta_{12}(^\circ)$	34.3 ± 1.0	$31.4 \rightarrow 37.4$
$\theta_{23}(^\circ)$[NO]	49.26 ± 0.79	$41.20 \rightarrow 51.33$
$\theta_{23}(^\circ)$[IO]	$49.46^{+0.60}_{-0.97}$	$41.16 \rightarrow 51.25$
$\theta_{13}(^\circ)$[NO]	$8.53^{+0.13}_{-0.12}$	$8.13 \rightarrow 8.92$
$\theta_{13}(^\circ)$[IO]	$8.58^{+0.12}_{-0.14}$	$8.17 \rightarrow 8.96$
$\delta(^\circ)$[NO]	194^{+24}_{-22}	$128 \rightarrow 359$
$\delta(^\circ)$[IO]	284^{+26}_{-28}	$200 \rightarrow 353$
$\Delta m^2_{21}\ (\times 10^{-5}\ \mathrm{eV}^2)$	$7.50^{+0.22}_{-0.20}$	$6.94 \rightarrow 8.14$
$\lvert\Delta m^2_{31}\rvert\ (\times 10^{-3}\ \mathrm{eV}^2)$ [NO]	$2.55^{+0.02}_{-0.03}$	$2.47 \rightarrow 2.63$
$\lvert\Delta m^2_{31}\rvert\ (\times 10^{-3}\ \mathrm{eV}^2)$ [IO]	$2.45^{+0.02}_{-0.03}$	$2.37 \rightarrow 2.53$

Compatibility with neutrino data

$$\mathbf{M}_\nu = \begin{pmatrix} \mathcal{F}_{11} M_f\, y_e^2 + \sqrt{2} w\, y_1\, e^{-i\theta} & \mathcal{F}_{12} M_f\, y_e y_\mu & 0 \\ \cdot & \mathcal{F}_{22} M_f\, y_\mu^2 & \sqrt{2} w\, y_2 e^{-i\theta} \\ \cdot & \cdot & 0 \end{pmatrix}$$

Matching ⟷

$$\widehat{\mathbf{M}}_\nu = \mathbf{U}^* \,\mathrm{diag}(m_1, m_2, m_3)\, \mathbf{U}^\dagger$$

High-energy parameters

Low-energy parameters

The presence of **two texture zeros in the neutrino mass matrix** leads to **testable low-energy constraints**

$$\mathcal{Z}_8^{e-\mu} \to \mathrm{B}_4 : \begin{pmatrix} \times & \times & 0 \\ \cdot & \times & \times \\ \cdot & \cdot & 0 \end{pmatrix},$$

$$\mathcal{Z}_8^{e-\tau} \to \mathrm{B}_3 : \begin{pmatrix} \times & 0 & \times \\ \cdot & 0 & \times \\ \cdot & \cdot & \times \end{pmatrix},$$

$$\mathcal{Z}_8^{\mu-\tau} \to \mathrm{A}_1 : \begin{pmatrix} 0 & 0 & \times \\ \cdot & \times & \times \\ \cdot & \cdot & \times \end{pmatrix}$$

Alcaide, Salvado, Santamaria (2018)

Global fit of neutrino oscillation data

Salas *et al.* (2020), Esteban *et al.* (2020), Capozzi *et al.* (2021)

Parameter	Best Fit $\pm 1\sigma$	3σ range
$\theta_{12}(^\circ)$	34.3 ± 1.0	$31.4 \to 37.4$
$\theta_{23}(^\circ)$[NO]	49.26 ± 0.79	$41.20 \to 51.33$
$\theta_{23}(^\circ)$[IO]	$49.46^{+0.60}_{-0.97}$	$41.16 \to 51.25$
$\theta_{13}(^\circ)$[NO]	$8.53^{+0.13}_{-0.12}$	$8.13 \to 8.92$
$\theta_{13}(^\circ)$[IO]	$8.58^{+0.12}_{-0.14}$	$8.17 \to 8.96$
$\delta(^\circ)$[NO]	194^{+24}_{-22}	$128 \to 359$
$\delta(^\circ)$[IO]	284^{+26}_{-28}	$200 \to 353$
$\Delta m^2_{21}\ (\times 10^{-5}\,\mathrm{eV}^2)$	$7.50^{+0.22}_{-0.20}$	$6.94 \to 8.14$
$\lvert\Delta m^2_{31}\rvert\ (\times 10^{-3}\,\mathrm{eV}^2)$ [NO]	$2.55^{+0.02}_{-0.03}$	$2.47 \to 2.63$
$\lvert\Delta m^2_{31}\rvert\ (\times 10^{-3}\,\mathrm{eV}^2)$ [IO]	$2.45^{+0.02}_{-0.03}$	$2.37 \to 2.53$

Predictions for **lightest neutrino mass** and **effective Majorana mass**

Normal Ordering (NO): $m_1 = m_{\text{lightest}},\ m_2 = \sqrt{m^2_{\text{lightest}} + \Delta m^2_{21}},\ m_3 = \sqrt{m^2_{\text{lightest}} + \Delta m^2_{31}}$

$$m_{\beta\beta} = \left| c_{12}^2 c_{13}^2\, m_1 + s_{12}^2 c_{13}^2\, m_2\, e^{-i\alpha_{21}} + s_{13}^2\, m_3\, e^{-i\alpha_{31}} \right|$$

Neutrino sector predictions

Neutrino sector predictions

Case $Z_8^{e-\mu}$ NO

$$\mathcal{Z}_8^{e-\mu} \to \mathrm{B}_4 : \begin{pmatrix} \times & \times & 0 \\ \cdot & \times & \times \\ \cdot & \cdot & 0 \end{pmatrix}$$

$$(\mathbf{M}_\nu)_{13} = (\mathbf{M}_\nu)_{33} = 0$$

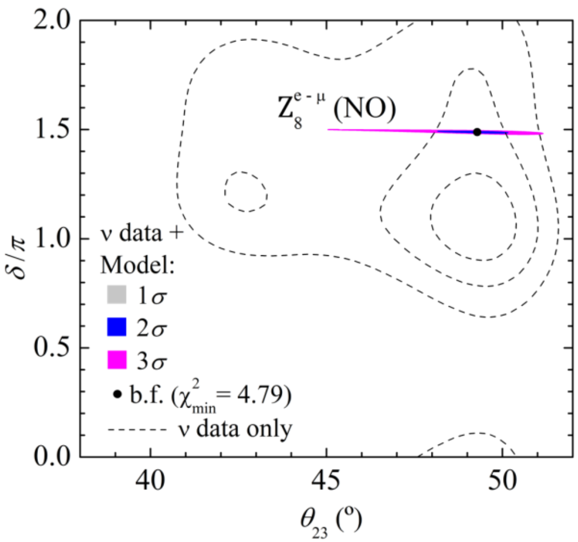
Neutrino sector predictions

Case $Z_8^{e-\mu}$ NO

$$\mathcal{Z}_8^{e-\mu} \to \mathrm{B}_4 : \begin{pmatrix} \times & \times & 0 \\ \cdot & \times & \times \\ \cdot & \cdot & 0 \end{pmatrix}$$

$$(\mathbf{M}_\nu)_{13} = (\mathbf{M}_\nu)_{33} = 0$$

δ and θ_{23}



- Sharply predicts $\delta \sim 3\pi/2$ and selects **second octant for θ_{23}**

Neutrino sector predictions

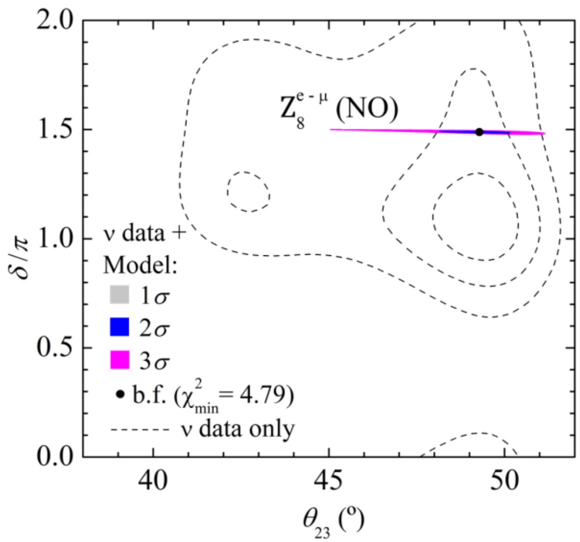
Case $Z_8^{e-\mu}$ NO

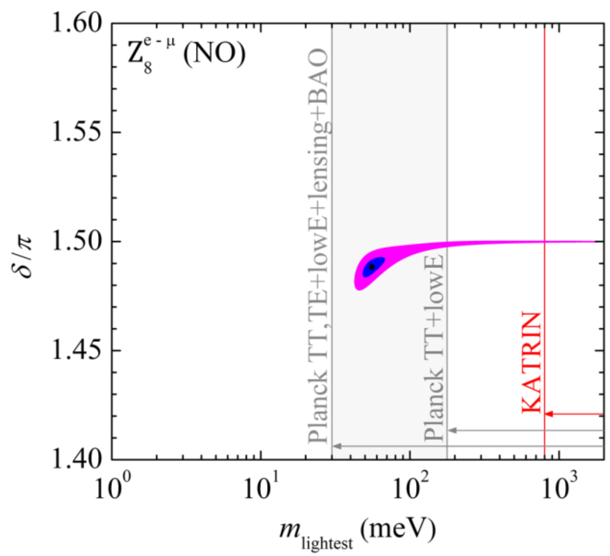
$$\mathcal{Z}_8^{e-\mu} \to \mathrm{B}_4 : \begin{pmatrix} \times & \times & 0 \\ \cdot & \times & \times \\ \cdot & \cdot & 0 \end{pmatrix}$$

$$(\mathbf{M}_\nu)_{13} = (\mathbf{M}_\nu)_{33} = 0$$

δ and θ_{23}

Lightest neutrino mass





- Sharply predicts $\boldsymbol{\delta \sim 3\pi/2}$ and selects **second octant for $\boldsymbol{\theta_{23}}$**

- Lower limit ~ 40 meV ($3\,\sigma$) **now being probed by cosmology**
- Upper limit ~ 60 meV ($2\,\sigma$)

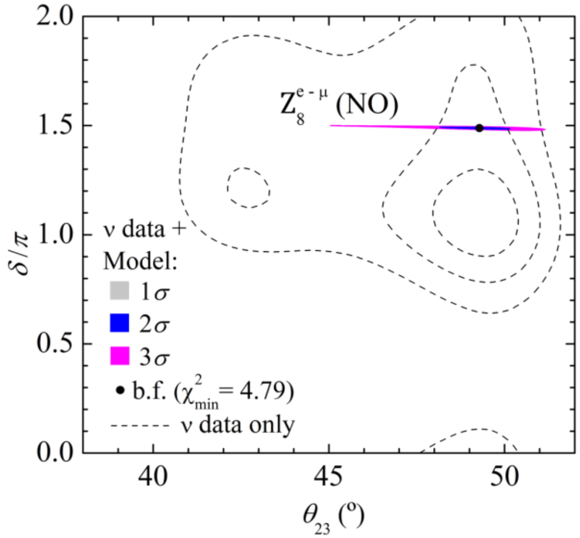
Neutrino sector predictions

Case $Z_8^{e-\mu}$ NO

$$\mathcal{Z}_8^{e-\mu} \to \mathrm{B}_4 : \begin{pmatrix} \times & \times & 0 \\ \cdot & \times & \times \\ \cdot & \cdot & 0 \end{pmatrix}$$

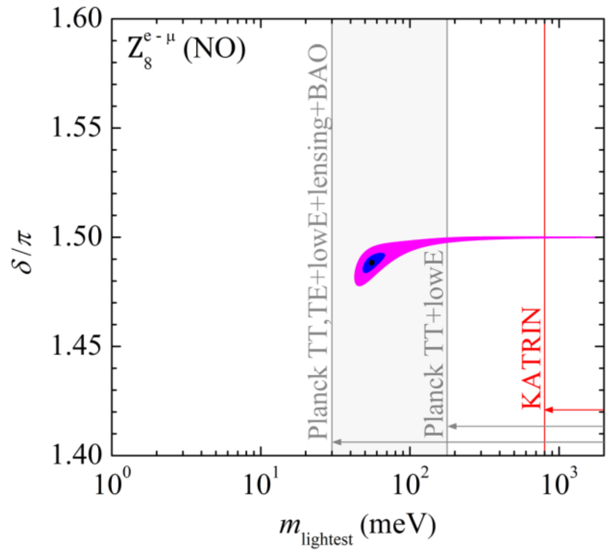
$$(\mathbf{M}_\nu)_{13} = (\mathbf{M}_\nu)_{33} = 0$$

δ and θ_{23}



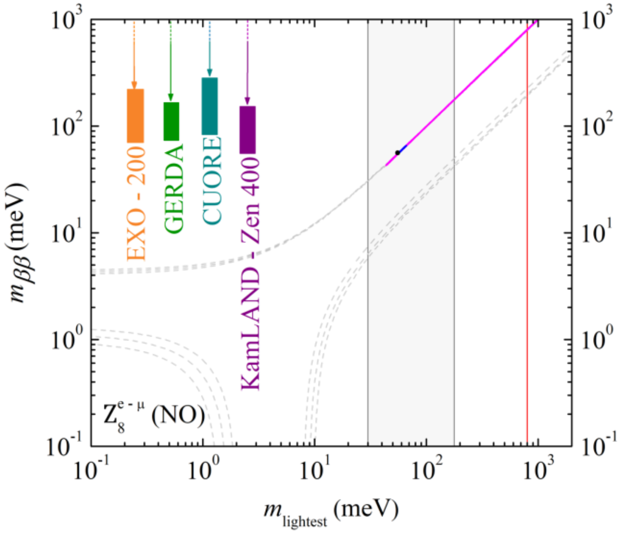
- Sharply predicts $\delta \sim 3\pi/2$ and selects **second octant for θ_{23}**

Lightest neutrino mass



- Lower limit ~ 40 meV (3 σ) **now being probed by cosmology**
- Upper limit ~ 60 meV (2 σ)

$m_{\beta\beta}$



- Current KamLAND-Zen 400 almost excludes this case, will be **tested by near-future $0\nu\beta\beta$ experiments**

Charged-lepton flavour violation

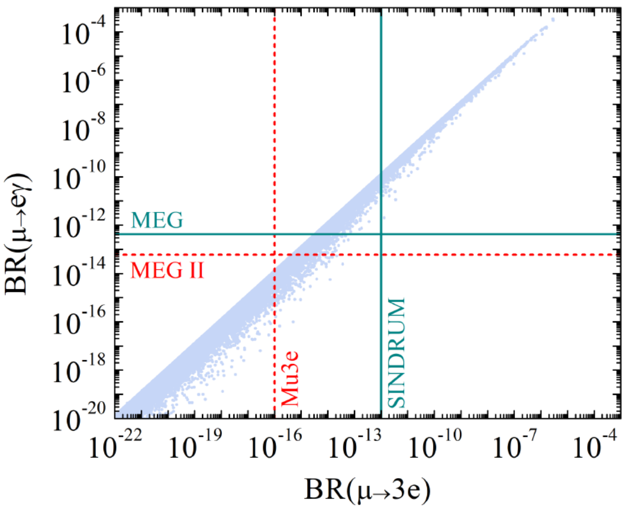
Charged-lepton flavour violation

Cases		Type-II seesaw	Scotogenic
$\mathcal{Z}_8^{e-\mu}$	(B_4)	$\tau^- \to \mu^+ e^- e^-$	$\mu \to e\gamma,\ \mu \to 3e,\ \mu - e$ conversion
$\mathcal{Z}_8^{e-\tau}$	(B_3)	$\tau^- \to \mu^+ e^- e^-$	$\tau \to e\gamma,\ \tau \to 3e$
$\mathcal{Z}_8^{\mu-\tau}$	(A_1)	$\tau^- \to e^+ \mu^- \mu^-$	$\tau \to \mu\gamma,\ \tau \to 3\mu$

Charged-lepton flavour violation

Cases		Type-II seesaw	Scotogenic
$\mathcal{Z}_8^{e-\mu}$	(B_4)	$\tau^- \to \mu^+ e^- e^-$	$\mu \to e\gamma,\ \mu \to 3e,\ \mu - e$ conversion
$\mathcal{Z}_8^{e-\tau}$	(B_3)	$\tau^- \to \mu^+ e^- e^-$	$\tau \to e\gamma,\ \tau \to 3e$
$\mathcal{Z}_8^{\mu-\tau}$	(A_1)	$\tau^- \to e^+ \mu^- \mu^-$	$\tau \to \mu\gamma,\ \tau \to 3\mu$

Parameters	Scan range
M_f	$[10, 1000]$ (GeV)
$m^2_{\eta_1}, m^2_{\eta_2}$	$[10^2, 1000^2]$ (GeV^2)
$\lvert\mu_{12}\rvert$	$[10^{-6}, 10^3]$ (GeV)
$\lvert\lambda_3\rvert,\ \lvert\lambda_4\rvert,\ \lvert\lambda'_3\rvert,\ \lvert\lambda'_4\rvert$	$[10^{-5}, 1]$
$\lvert\lambda_5\rvert$	$[10^{-12}, 1]$

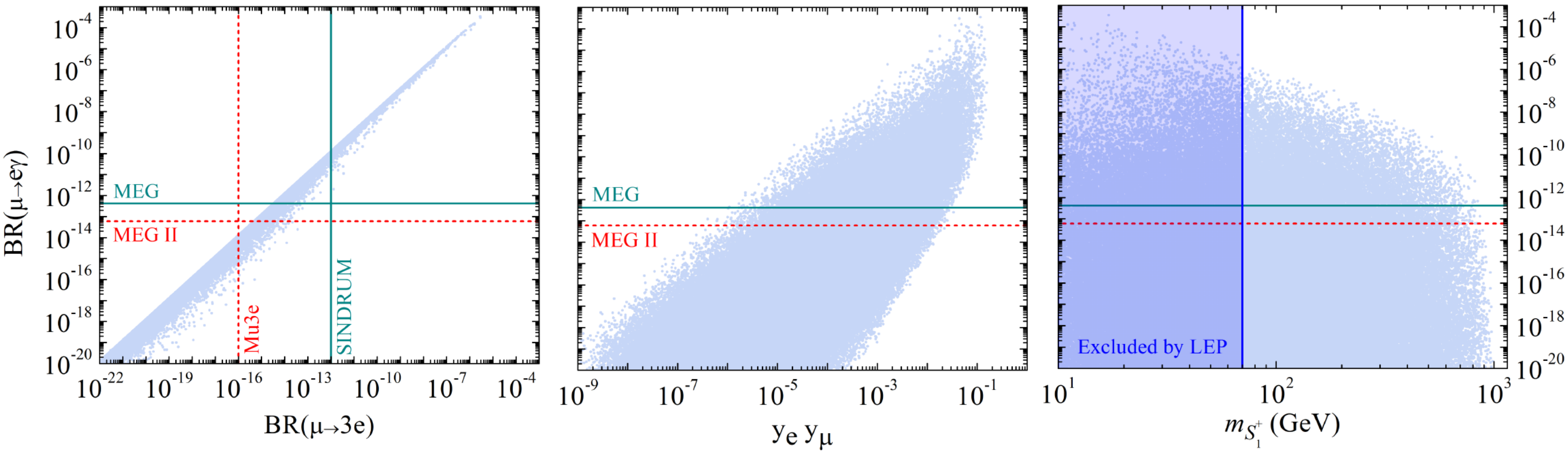


- Large fraction of **parameter space is excluded by current cLFV constraints**

Charged-lepton flavour violation

Cases		Type-II seesaw	Scotogenic
$\mathcal{Z}_8^{e-\mu}$	(B$_4$)	$\tau^- \to \mu^+ e^- e^-$	$\mu \to e\gamma,\ \mu \to 3e,\ \mu - e$ conversion
$\mathcal{Z}_8^{e-\tau}$	(B$_3$)	$\tau^- \to \mu^+ e^- e^-$	$\tau \to e\gamma,\ \tau \to 3e$
$\mathcal{Z}_8^{\mu-\tau}$	(A$_1$)	$\tau^- \to e^+ \mu^- \mu^-$	$\tau \to \mu\gamma,\ \tau \to 3\mu$

Parameters	Scan range
M_f	$[10, 1000]$ (GeV)
$m^2_{\eta_1}, m^2_{\eta_2}$	$[10^2, 1000^2]$ (GeV^2)
$\lvert\mu_{12}\rvert$	$[10^{-6}, 10^3]$ (GeV)
$\lvert\lambda_3\rvert,\ \lvert\lambda_4\rvert,\ \lvert\lambda'_3\rvert,\ \lvert\lambda'_4\rvert$	$[10^{-5}, 1]$
$\lvert\lambda_5\rvert$	$[10^{-12}, 1]$



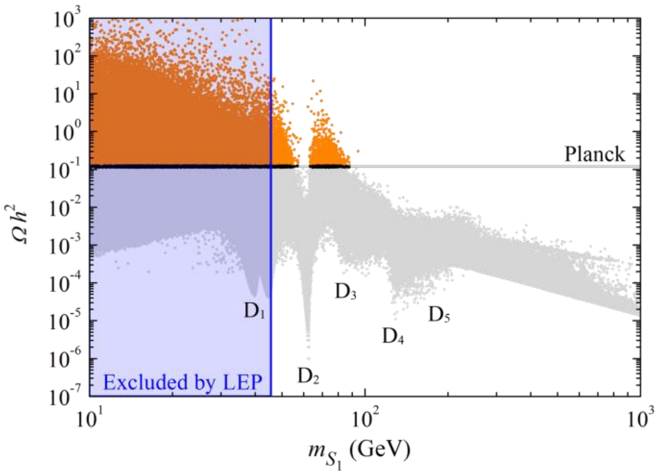
- Large fraction of **parameter space is excluded by current cLFV constraints**
- Scotogenic cLFV processes are **mediated at loop level by dark charged scalars**

$$\frac{\mathrm{BR}(\mu \to e\gamma)}{4.2 \times 10^{-13}} \approx 1.98 \times 10^{10} \left(\frac{70\ \mathrm{GeV}}{m_{S_1^+}}\right)^4 \sin^2(2\varphi) y_e^2 y_\mu^2 \left| g\left(\frac{M_f^2}{m^2_{S_1^+}}\right) - \frac{m^2_{S_1^+}}{m^2_{S_2^+}} g\left(\frac{M_f^2}{m^2_{S_2^+}}\right)\right|^2$$

Scalar Dark Matter

Scalar Dark Matter

Relic density

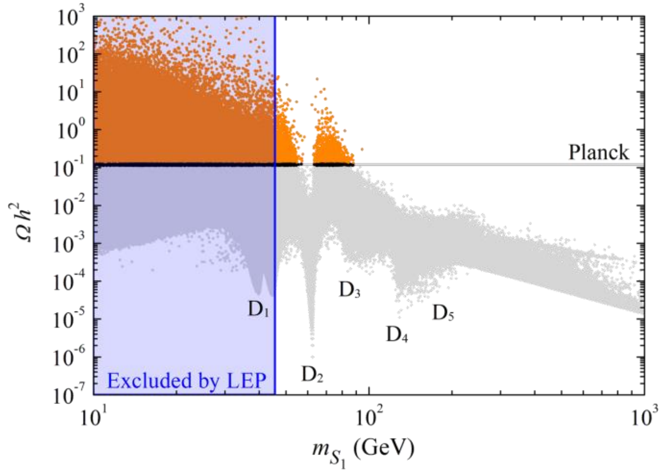


The case of **scalar DM:**

lightest neutral scalar S_1

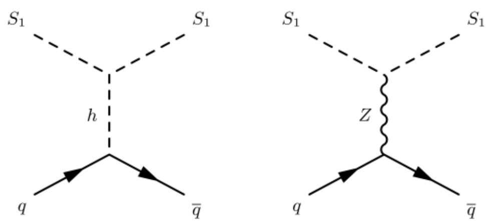
Scalar Dark Matter

Relic density

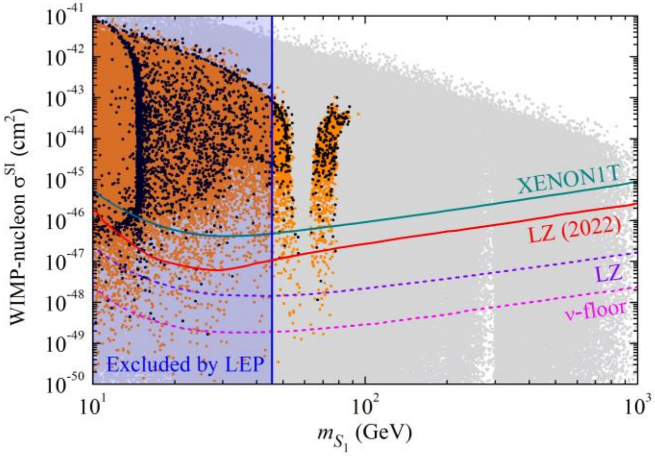


The case of **scalar DM:**

lightest neutral scalar S_1

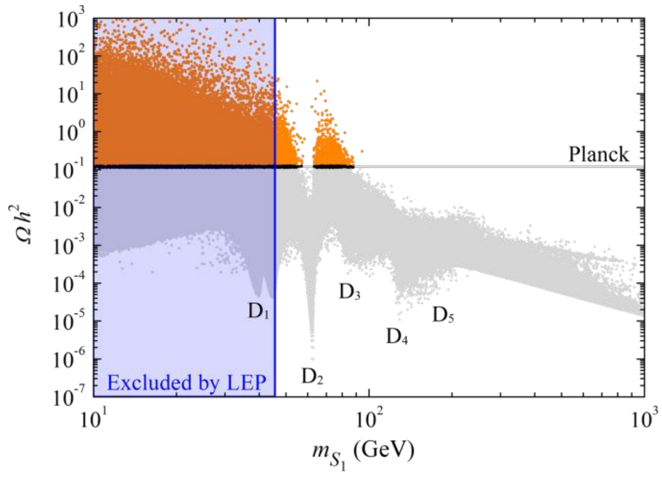


WIMP-nucleon SI elastic cross-section



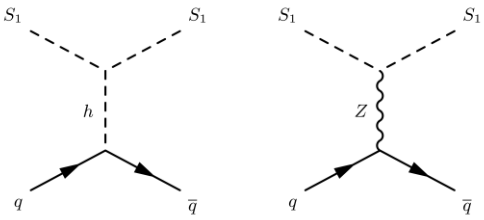
Scalar Dark Matter

Relic density



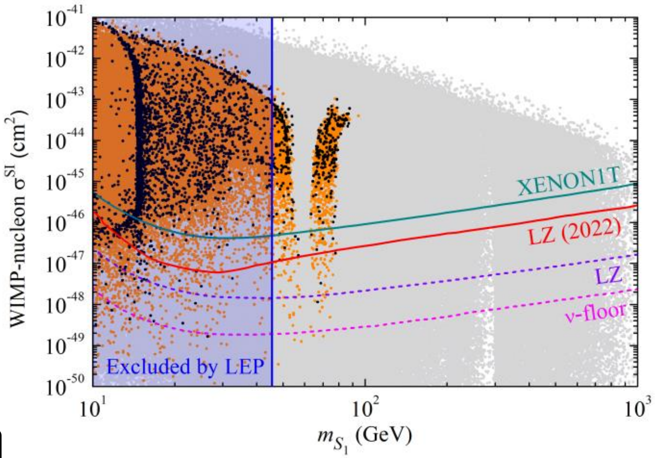
The case of **scalar DM:**

lightest neutral scalar S_1



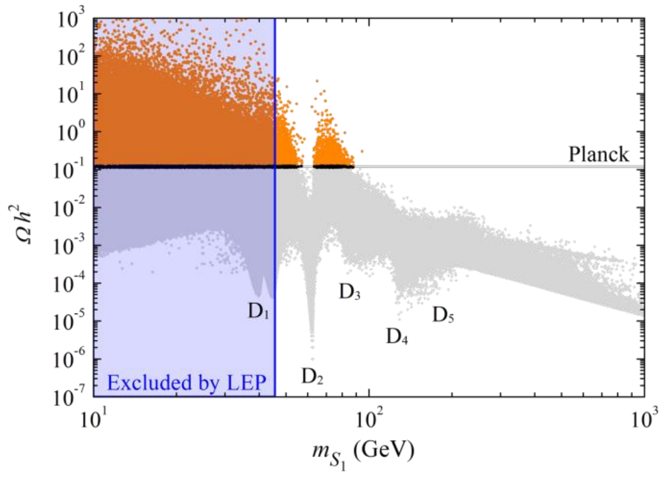
Direct Detection + LHC Higgs data

WIMP-nucleon SI elastic cross-section

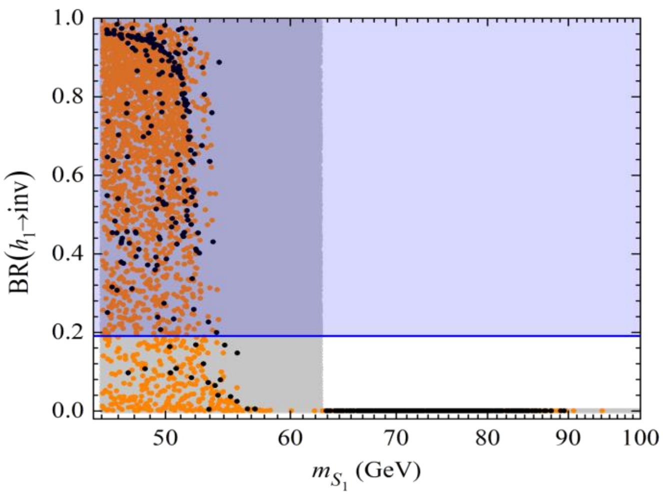


Scalar Dark Matter

Relic density

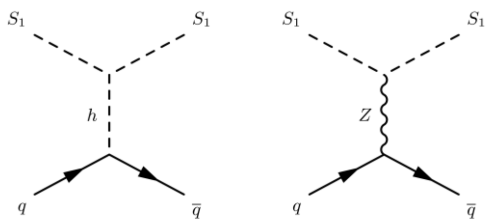


Higgs invisible decay



The case of **scalar DM:**

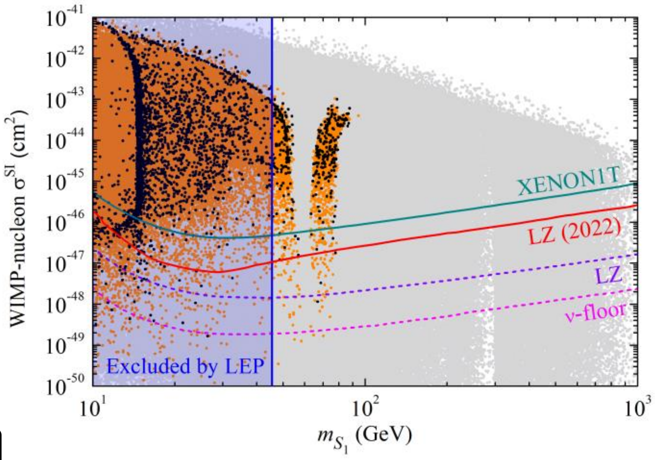
lightest neutral scalar S_1



Direct Detection + LHC Higgs data

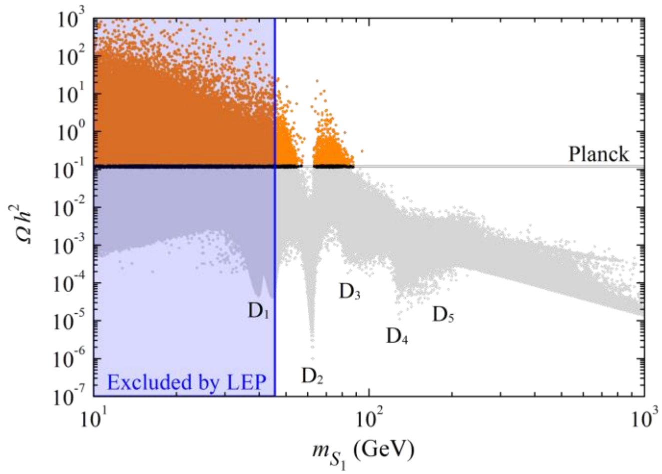
$$\mathrm{BR}(h_1 \to \mathrm{inv}) \leq 0.19$$

WIMP-nucleon SI elastic cross-section



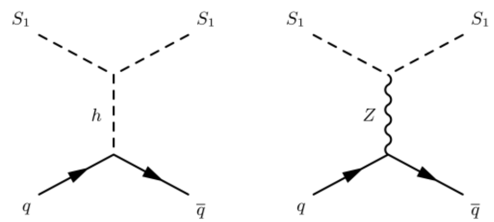
Scalar Dark Matter

Relic density

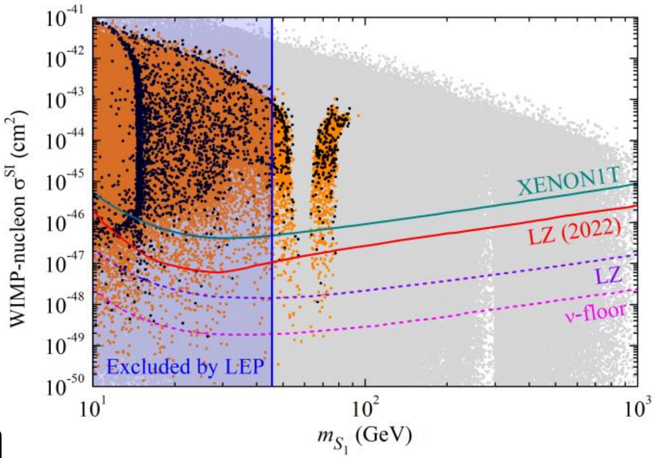


The case of **scalar DM:**

lightest neutral scalar S_1

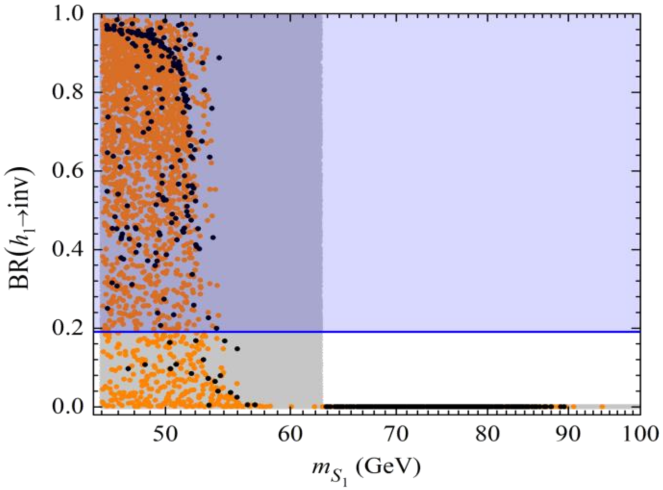


WIMP-nucleon SI elastic cross-section



Direct Detection + LHC Higgs data

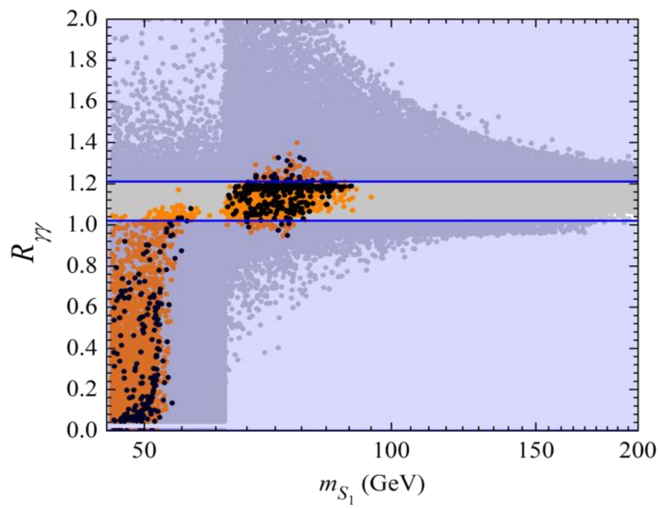
Higgs invisible decay



$$\mathrm{BR}(h_1 \to \mathrm{inv}) \leq 0.19$$

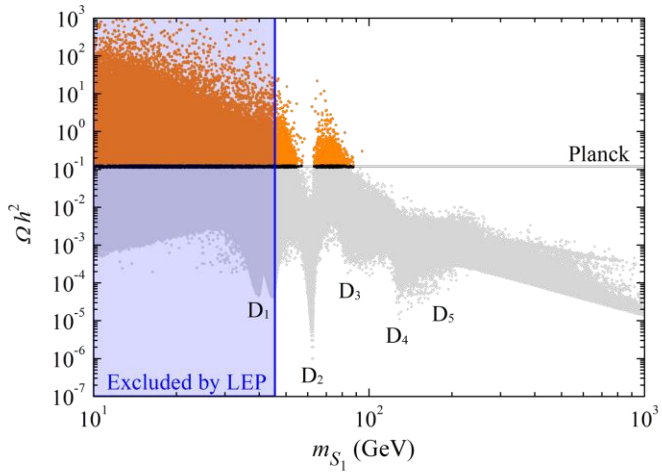
$$R_{\gamma\gamma} = 1.11^{+0.10}_{-0.09}$$

Higgs to photon-photon



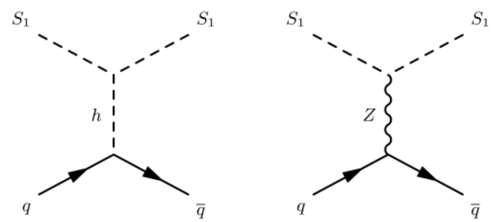
Scalar Dark Matter

Relic density

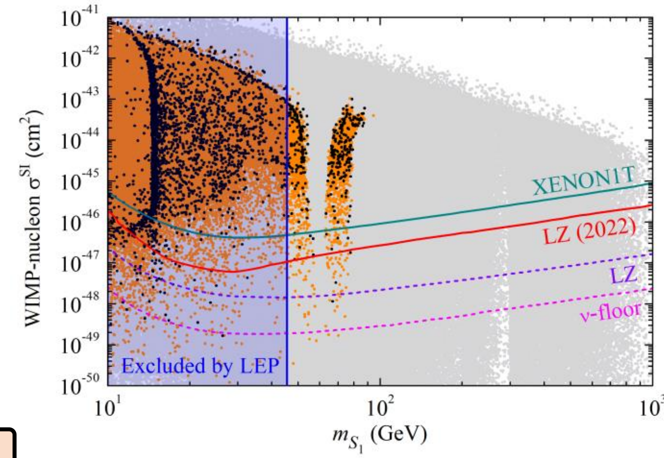


The case of **scalar DM:**

lightest neutral scalar S_1

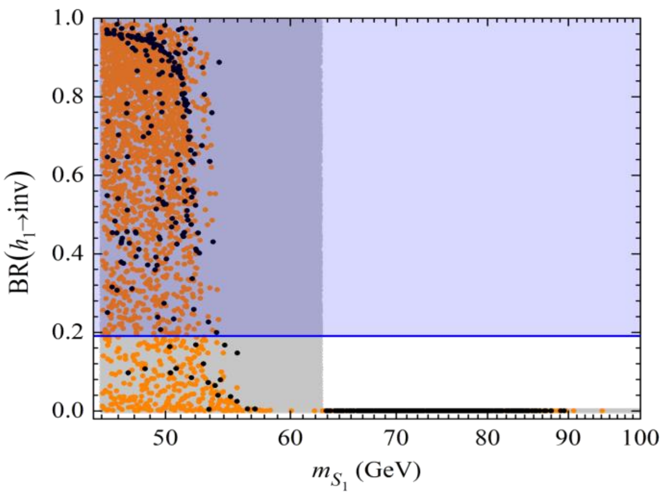


WIMP-nucleon SI elastic cross-section



Direct Detection + LHC Higgs data

Higgs invisible decay



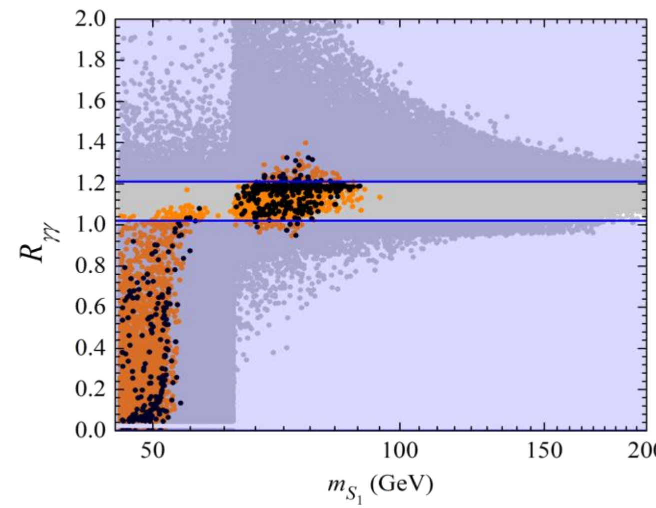
$$\mathrm{BR}(h_1 \to \mathrm{inv}) \leq 0.19$$

$$R_{\gamma\gamma} = 1.11^{+0.10}_{-0.09}$$

Allowed mass region:

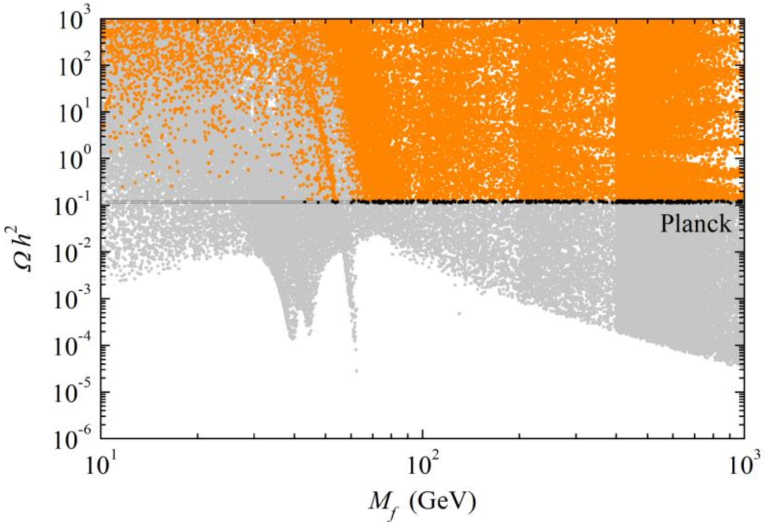
68 to 90 GeV

Higgs to photon-photon



Fermion Dark Matter

Relic density



The case of **fermionic DM:**

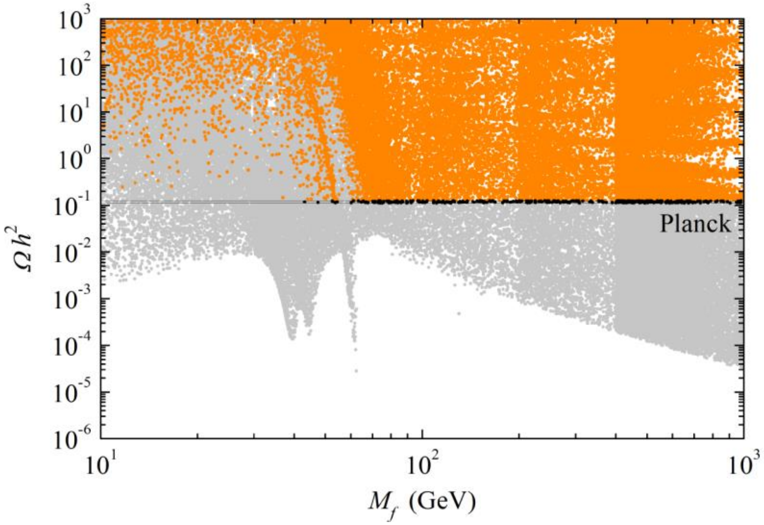
fermion f

Allowed mass region:

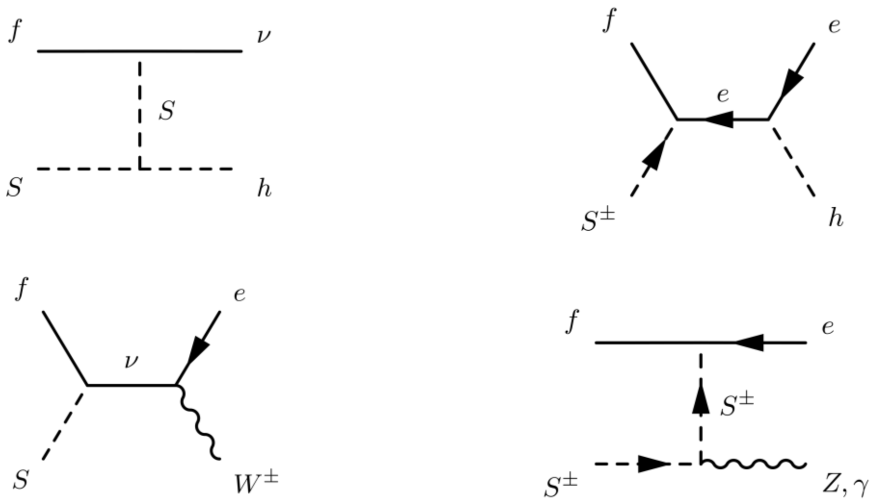
above 45 GeV

Fermion Dark Matter

Relic density



Co-annihilation channels, e.g. :



The case of **fermionic DM:**

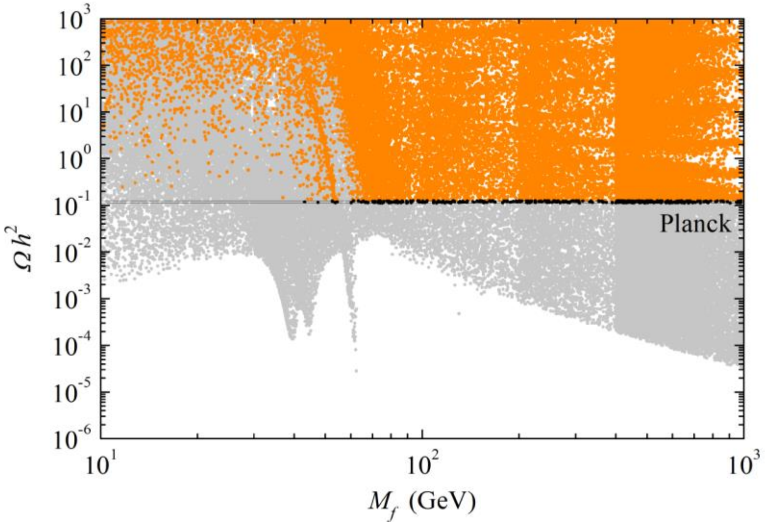
fermion f

Allowed mass region:

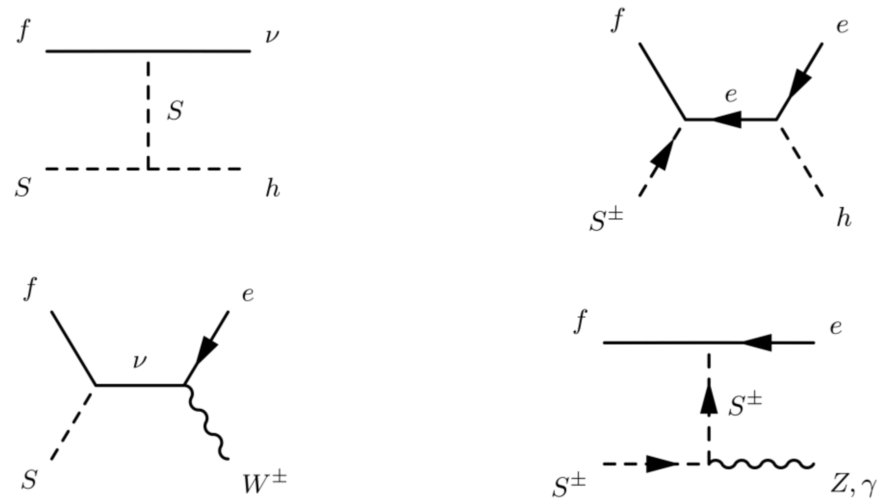
above 45 GeV

Fermion Dark Matter

Relic density



Co-annihilation channels, e.g. :

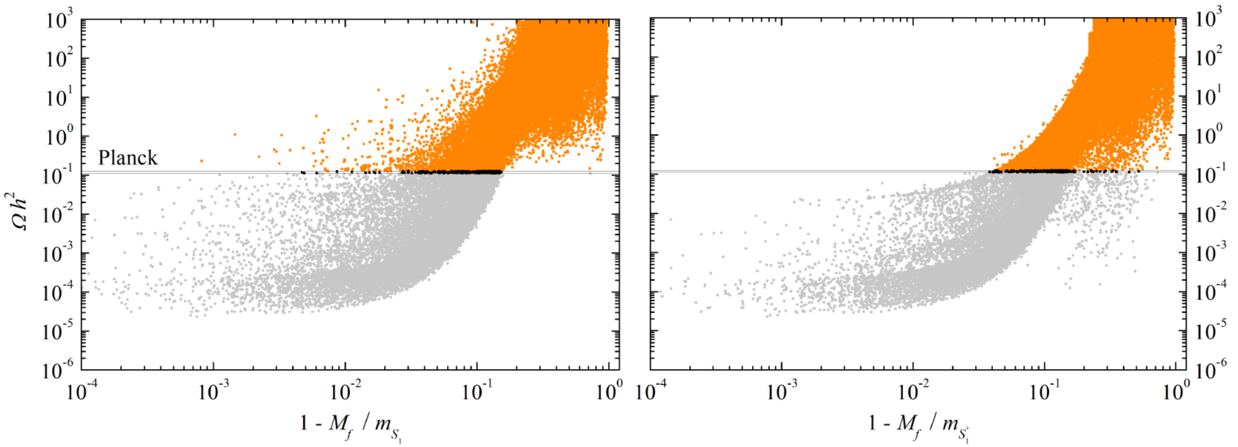


The case of **fermionic DM:**

fermion f

Allowed mass region:

above 45 GeV



Conclusion

Conclusion

- Neutrino masses are generated via the **interplay** between **type-II seesaw** and **scotogenic** mechanisms

Conclusion

- Neutrino masses are generated via the **interplay** between **type-II seesaw** and **scotogenic** mechanisms

- A single $\boldsymbol{Z_8}$ **symmetry is broken down to a dark** $\boldsymbol{Z_2}$ by the **complex VEV of a scalar singlet**, leading to **observable CP-violating effects** in the lepton sector and **low-energy constraints,** resulting in **two-texture zero patterns in the effective neutrino mass matrix**

Conclusion

- Neutrino masses are generated via the **interplay** between **type-II seesaw** and **scotogenic** mechanisms

- A single $\boldsymbol{Z_8}$ **symmetry is broken down to a dark** $\boldsymbol{Z_2}$ by the **complex VEV of a scalar singlet**, leading to **observable CP-violating effects** in the lepton sector and **low-energy constraints,** resulting in **two-texture zero patterns in the effective neutrino mass matrix**

- For most cases the **model selects one** $\boldsymbol{\theta_{23}}$ **octant with** $\boldsymbol{\delta \sim 3\pi/2}$, predictions for the lightest neutrino mass are in the range probed by **cosmology** and will be tested by near future $\boldsymbol{0\nu\beta\beta}$**-decay** experiments

Conclusion

- Neutrino masses are generated via the **interplay** between **type-II seesaw** and **scotogenic** mechanisms
- A single $\boldsymbol{Z_8}$ **symmetry is broken down to a dark** $\boldsymbol{Z_2}$ by the **complex VEV of a scalar singlet**, leading to **observable CP-violating effects** in the lepton sector and **low-energy constraints,** resulting in **two-texture zero patterns in the effective neutrino mass matrix**
- For most cases the **model selects one** $\boldsymbol{\theta_{23}}$ **octant with** $\boldsymbol{\delta \sim 3\pi/2}$, predictions for the lightest neutrino mass are in the range probed by **cosmology** and will be tested by near future $\boldsymbol{0\nu\beta\beta}$**-decay** experiments
- A large fraction of **our model's parameter space is excluded by current cLFV constraints** while other regions will be probed by future experiments

Conclusion

- Neutrino masses are generated via the **interplay** between **type-II seesaw** and **scotogenic** mechanisms

- A single Z_8 **symmetry is broken down to a dark** Z_2 by the **complex VEV of a scalar singlet**, leading to **observable CP-violating effects** in the lepton sector and **low-energy constraints,** resulting in **two-texture zero patterns in the effective neutrino mass matrix**

- For most cases the **model selects one** θ_{23} **octant with** $\delta \sim 3\pi/2$, predictions for the lightest neutrino mass are in the range probed by **cosmology** and will be tested by near future $0\nu\beta\beta$**-decay** experiments

- A large fraction of **our model's parameter space is excluded by current cLFV constraints** while other regions will be probed by future experiments

- **Scalar DM:** one viable mass region **between 68 GeV and 90 GeV** is compatible with the observed **DM relic density, current DD constraints and collider bounds** (LEP and Higgs data), this region will be **probed by future DD searches**

Conclusion

- Neutrino masses are generated via the **interplay** between **type-II seesaw** and **scotogenic** mechanisms
- A single $\boldsymbol{Z_8}$ **symmetry is broken down to a dark** $\boldsymbol{Z_2}$ by the **complex VEV of a scalar singlet**, leading to **observable CP-violating effects** in the lepton sector and **low-energy constraints,** resulting in **two-texture zero patterns in the effective neutrino mass matrix**
- For most cases the **model selects one** $\boldsymbol{\theta_{23}}$ **octant with** $\boldsymbol{\delta \sim 3\pi/2}$, predictions for the lightest neutrino mass are in the range probed by **cosmology** and will be tested by near future $\boldsymbol{0\nu\beta\beta}$**-decay** experiments
- A large fraction of **our model's parameter space is excluded by current cLFV constraints** while other regions will be probed by future experiments
- **Scalar DM:** one viable mass region **between 68 GeV and 90 GeV** is compatible with the observed **DM relic density, current DD constraints and collider bounds** (LEP and Higgs data), this region will be **probed by future DD searches**
- **Fermion DM:** masses **above 45 GeV** are compatible with observed **relic density**

Conclusion

- Neutrino masses are generated via the **interplay** between **type-II seesaw** and **scotogenic** mechanisms
- A single Z_8 **symmetry is broken down to a dark** Z_2 by the **complex VEV of a scalar singlet**, leading to **observable CP-violating effects** in the lepton sector and **low-energy constraints,** resulting in **two-texture zero patterns in the effective neutrino mass matrix**
- For most cases the **model selects one** θ_{23} **octant with** $\delta \sim 3\pi/2$, predictions for the lightest neutrino mass are in the range probed by **cosmology** and will be tested by near future $0\nu\beta\beta$**-decay** experiments
- A large fraction of **our model's parameter space is excluded by current cLFV constraints** while other regions will be probed by future experiments
- **Scalar DM:** one viable mass region **between 68 GeV and 90 GeV** is compatible with the observed **DM relic density, current DD constraints and collider bounds** (LEP and Higgs data), this region will be **probed by future DD searches**
- **Fermion DM:** masses **above 45 GeV** are compatible with observed **relic density**

Thank you !