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Dark linear seesaw mechanism

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Motivation

The Standard Model cannot explain:

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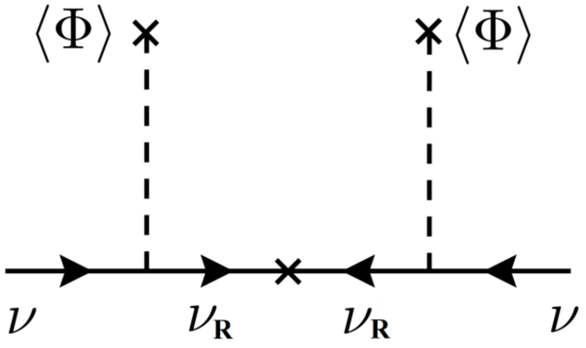
Straightforward and elegant solution for neutrino masses:

Type-I Seesaw Model



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

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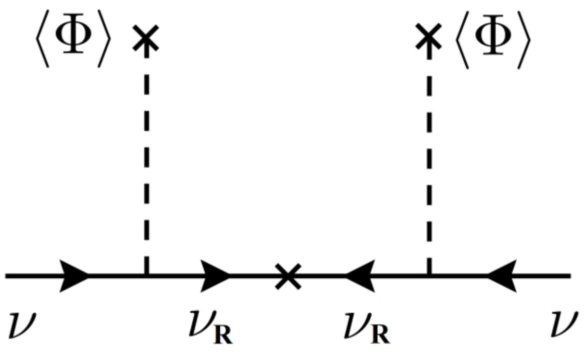

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$$-\mathcal{L} = \mathbf{Y}_\nu \overline{\ell_L}\tilde{\Phi}\nu_R + \mathbf{M}_R \overline{\nu_R^c}\nu_R + \mathrm{H.c.}$$

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & \mathbf{M}_D \\ \mathbf{M}_D^T & \mathbf{M}_R \end{pmatrix} \, , \quad \mathbf{M}_D = \frac{v_\Phi \mathbf{Y}_\nu}{\sqrt{2}}$$

$\mathbf{M}_D \ll \mathbf{M}_R$

$$\mathbf{M}_\nu \simeq -\mathbf{M}_D \mathbf{M}_R^{-1} \mathbf{M}_D^T \sim \frac{v_\Phi^2}{\mathbf{M}_R}$$

- The **Type-I Seesaw** is by far the **simplest solution** to the neutrino mass problem.
- A major drawback of this model is the **large mass scale** of the right-handed neutrinos, far away from the reach of current experiments.

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Low-scale solutions, such as the **inverse and linear seesaws**, despite being more complicated offer more testability prospects at ongoing experiments.

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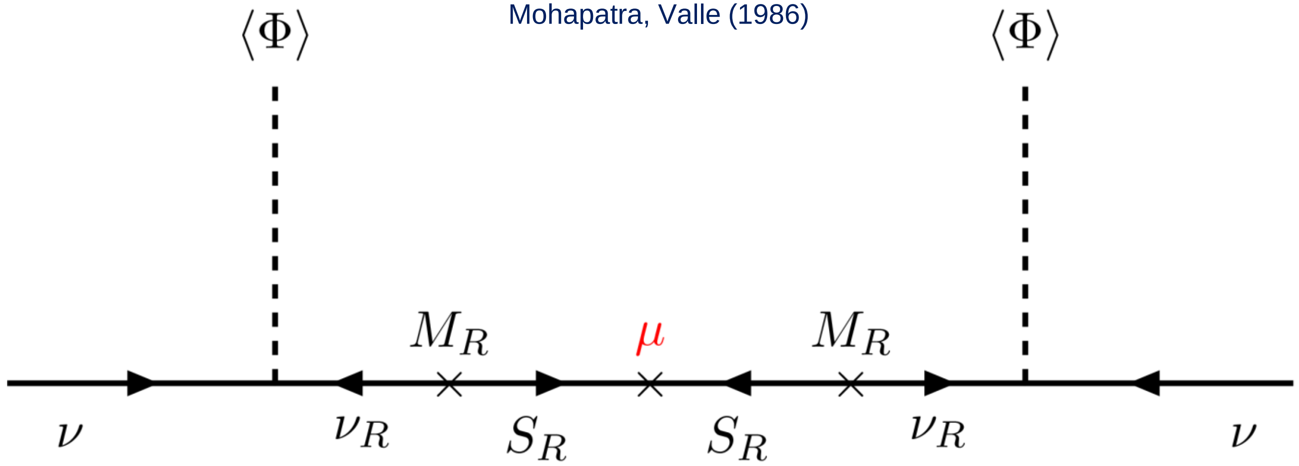

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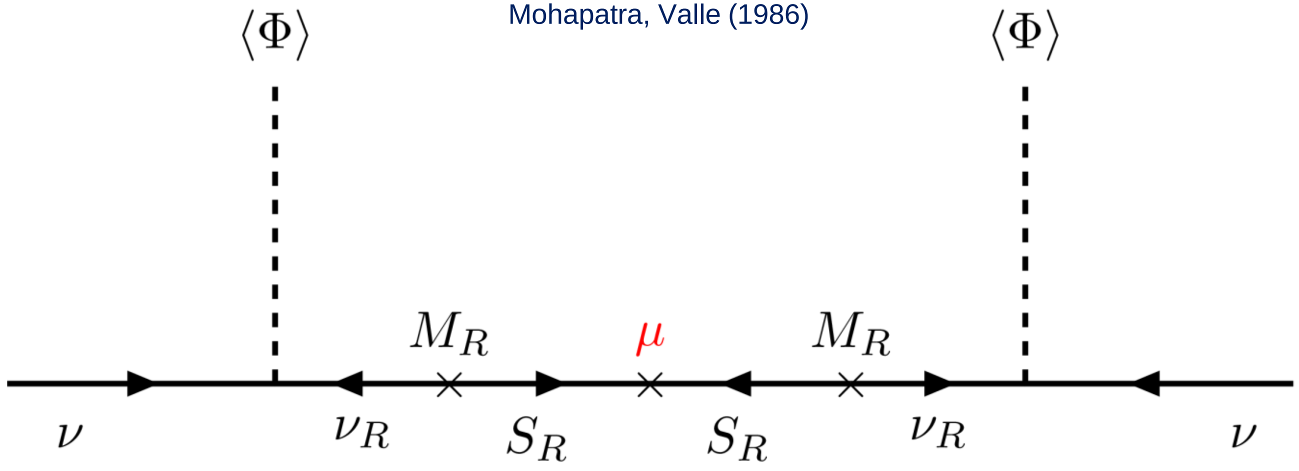

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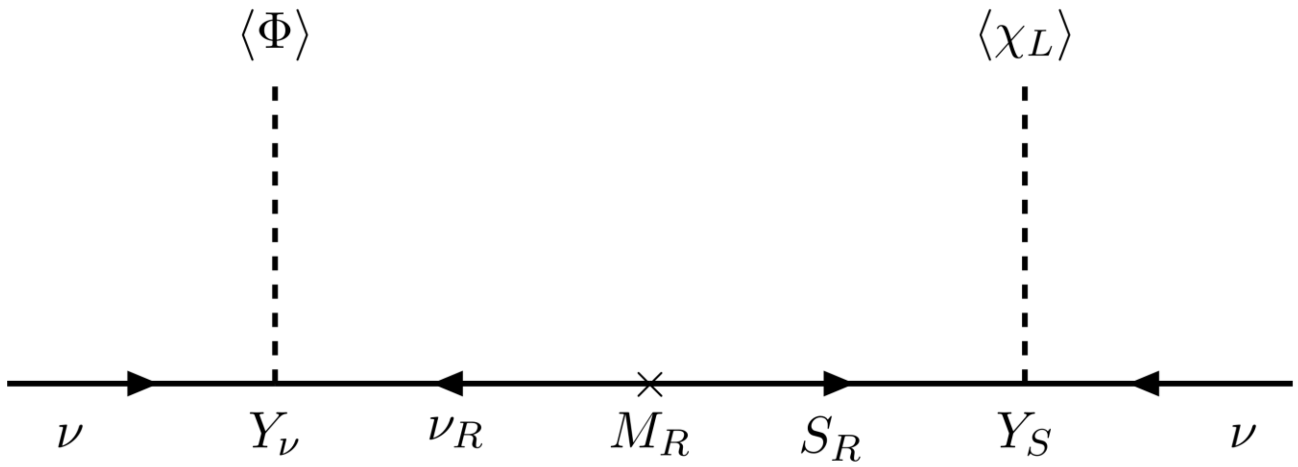
in the (ν_L, ν_R^c, S_R^c) basis, $$\mathcal{M}_\nu = \begin{pmatrix} 0 & \mathbf{M}_D & 0 \\ \mathbf{M}_D^T & 0 & \mathbf{M}_R \\ \mathbf{m}_S^T & \mathbf{M}_R & \mu \end{pmatrix} \longrightarrow m_\nu \sim \frac{v_\Phi^2}{M_R^2}\mu$$

μ violates lepton number and can be naturally small in the t'Hooft sense. Hence, neutrino masses are suppressed and extremely heavy mediators like in the Type-I seesaw are not required.

Linear Seesaw Model

Akhmedov *et al.* (1996), Malinsky *et al.* (2005)



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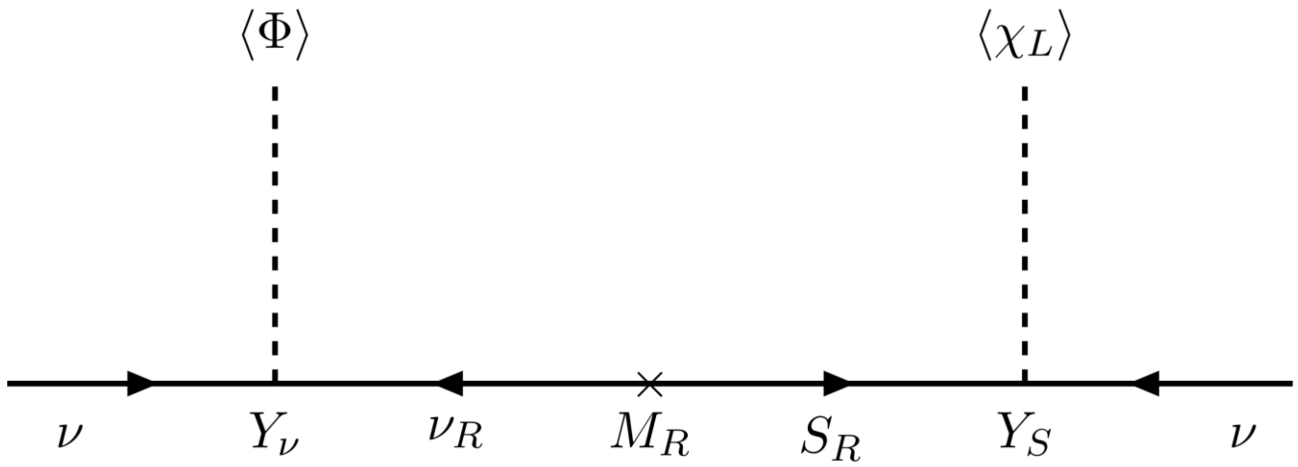

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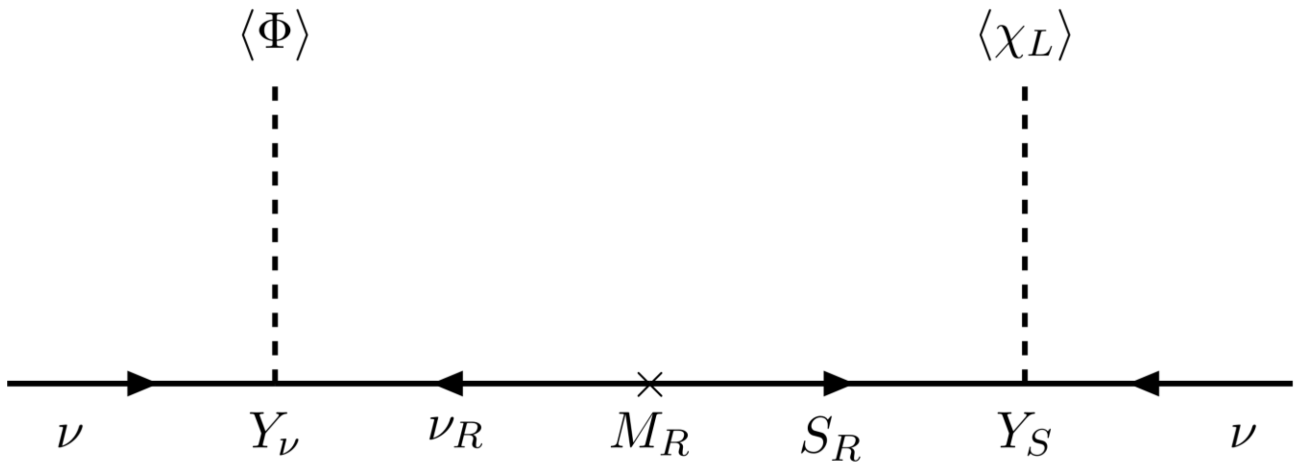

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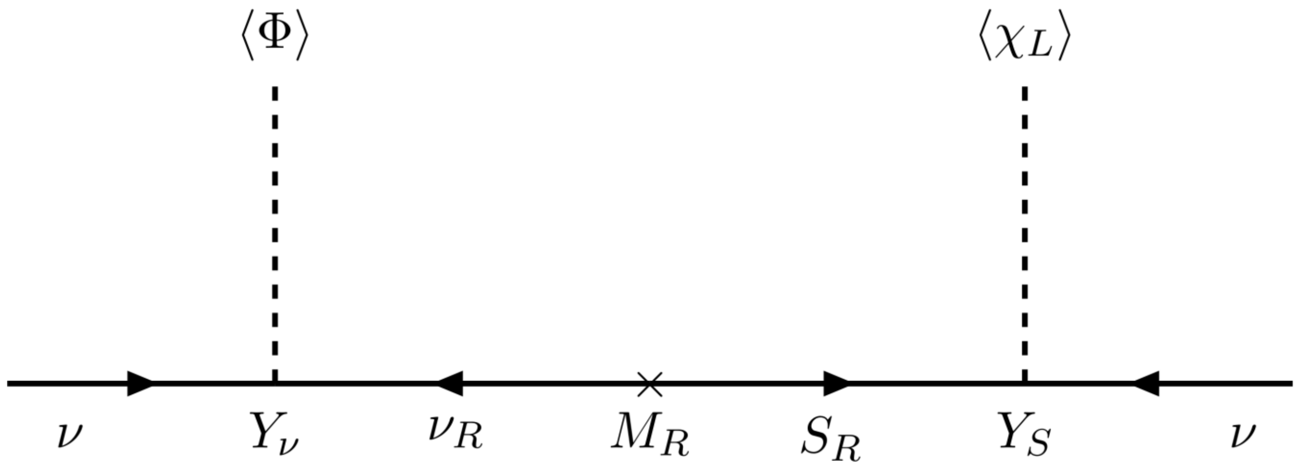

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Is there a way to incorporate **dark matter** into these models?

Dark matter seeded neutrino mass

In **radiative neutrino mass models**, small neutrino masses are induced at the quantum level. Particles entering the loops may also be **viable DM candidates** stabilized by some symmetry as a simple $\mathcal{Z}_2$.

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L	$(1, 2, -\frac{1}{2})$	$+1$
ℓ	$(1, 1, -1)$	$+1$
Φ	$(1, 2, \frac{1}{2})$	$+1$
N	$(1, 1, 0)$	-1
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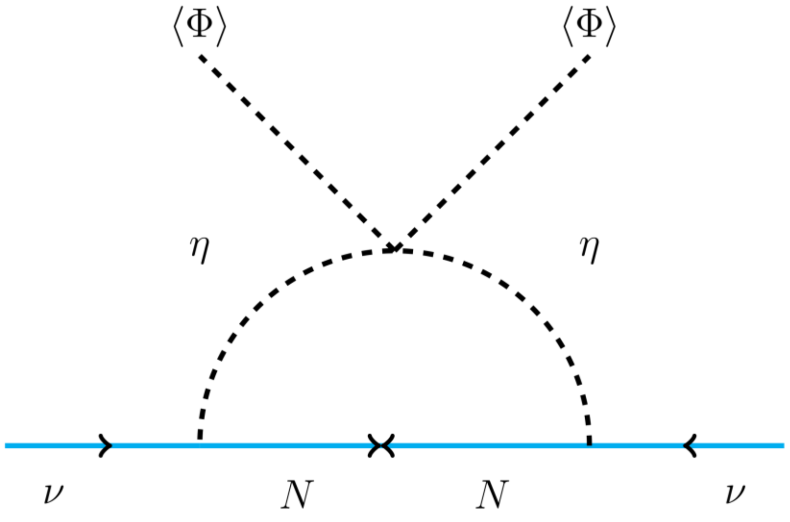

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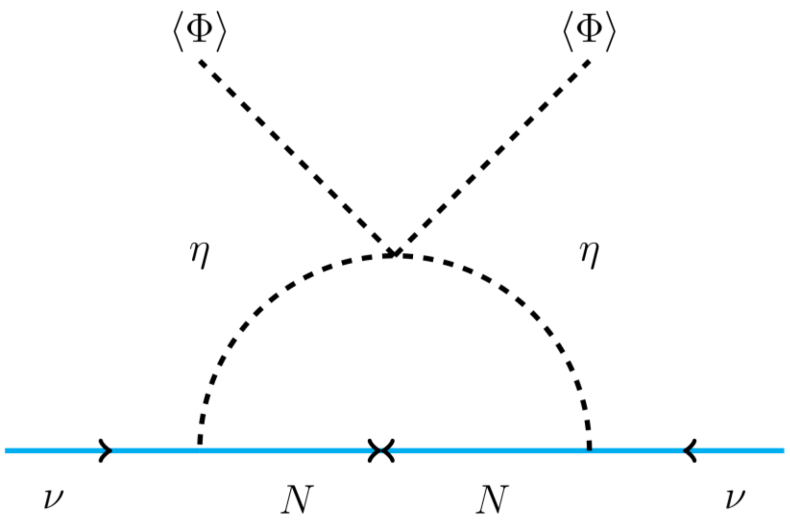

Dark Inverse Seesaw Model

Mandal *et al.* (2021)

Fields	$SU(2)_L \otimes U(1)_Y$	$U(1)_L$	$\mathcal{Z}_2$
ℓ_L	$(\mathbf{2}, -1)$	-1	$+$
e_R	$(\mathbf{1}, 2)$	1	$+$
ν_R	$(\mathbf{1}, 0)$	1	$+$
S	$(\mathbf{1}, 0)$	-1	$+$
f	$(\mathbf{1}, 0)$	0	$-$
Φ	$(\mathbf{2}, 1)$	0	$+$
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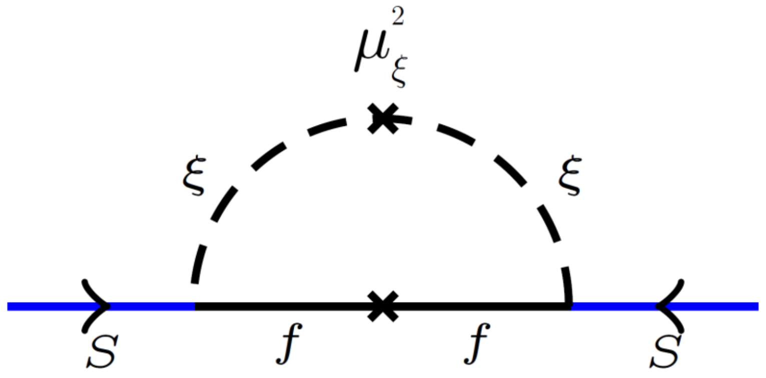

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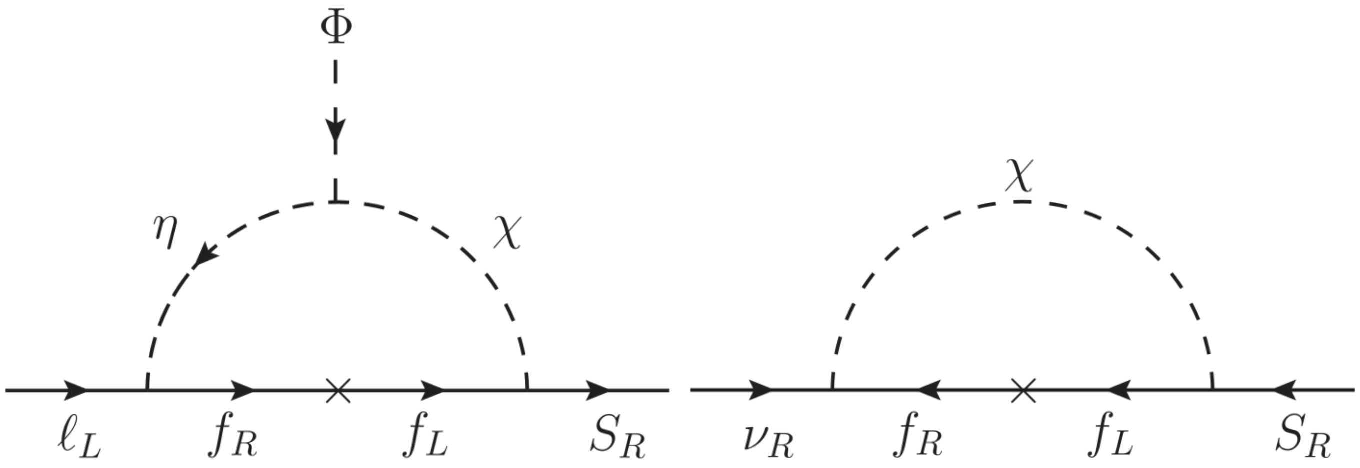

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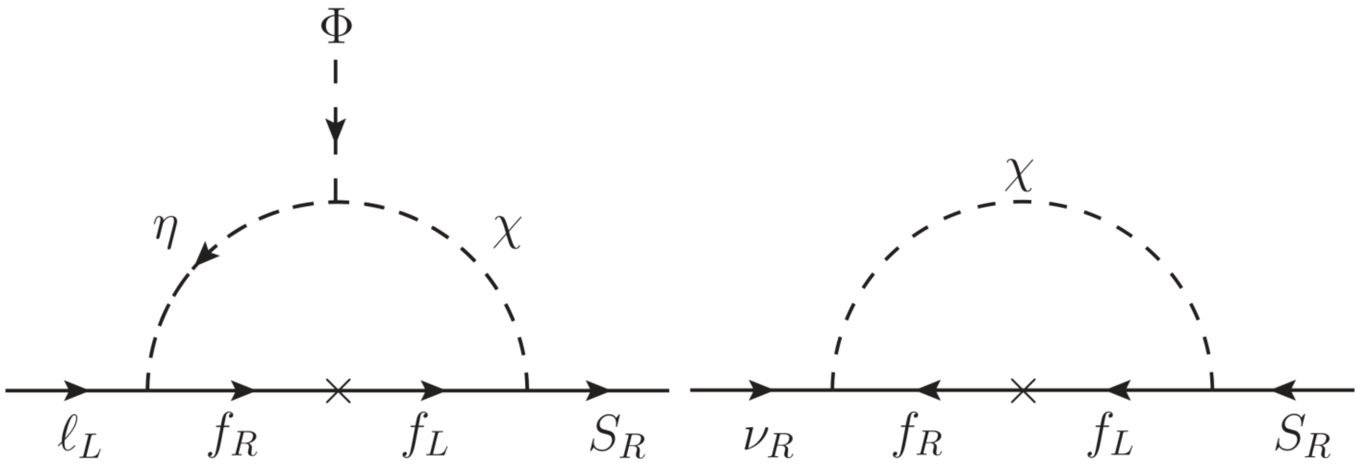

$$-\mathcal{L} = \mathbf{Y}_e \overline{\ell_L}\Phi e_R + \mathbf{Y}_D \overline{\ell_L}\tilde{\Phi}\nu_R + \mathbf{Y}_f \overline{\ell_L}\tilde{\eta} f_R + Y_S \overline{f_L} S_R \chi + Y_R \overline{f_R^c}\nu_R \chi + M_B \overline{\nu_R^c} S_R + M_f \overline{f_L} f_R + \text{H.c.}$$

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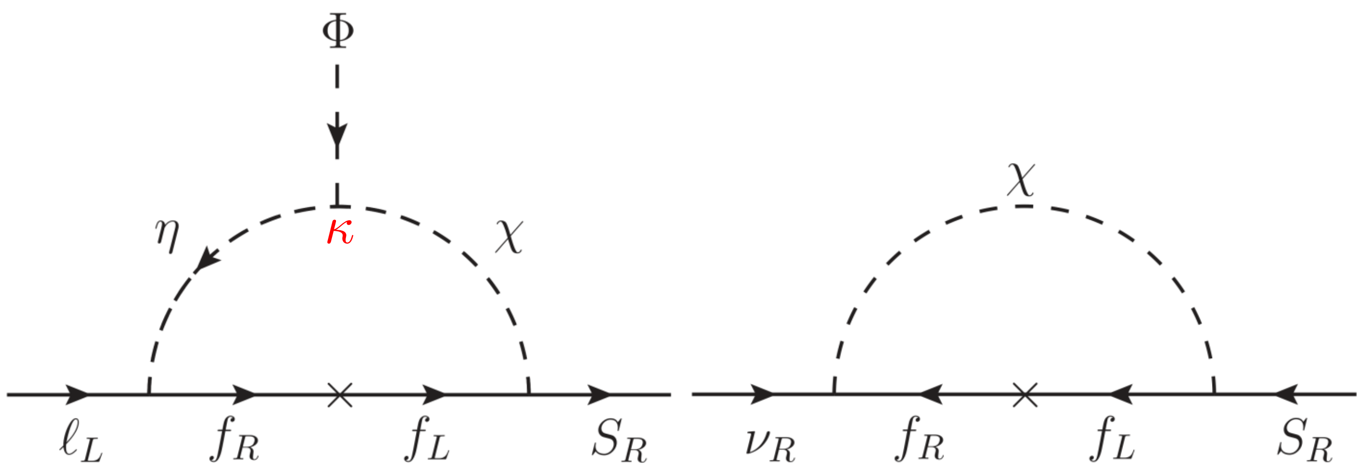

$$-\mathcal{L} = \mathbf{Y}_e \overline{\ell_L} \Phi e_R + \mathbf{Y}_D \overline{\ell_L} \tilde{\Phi} \nu_R + \mathbf{Y}_f \overline{\ell_L} \tilde{\eta} f_R + Y_S \overline{f_L} S_R \chi + Y_R \overline{f_R^c} \nu_R \chi + M_B \overline{\nu_R^c} S_R + M_f \overline{f_L} f_R + \mathrm{H.c.}$$

The **lepton number symmetry** is violated by the scalar potential term:

$$V_{\mathrm{soft}} = \kappa \left(\eta^\dagger \Phi\right) \chi + \mathrm{H.c.}$$

Numerical scan

We performed a complete numerical study to test our framework.

Sector	Parameters	Scan range
Fermion	M_f	$[10, 10^4]$ (GeV)
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	Y_S, Y_R	$[10^{-3}, 1]$
Scalar	m_η^2, m_χ^2	$[10^2, 10^8]$ (GeV^2)
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We also applied the following experimental constraints:

- LEP: $m_{\zeta_i} > m_Z/2$, $m_{\zeta_i} + m_{\zeta_j} > m_Z$ and $m_{\zeta^+} > 70$ GeV
- LHC Higgs data: $\mathrm{BR}(h \to \mathrm{inv}) \leq 0.19$ and $R_{\gamma\gamma} = \dfrac{\mathrm{BR}(h \to \gamma\gamma)}{\mathrm{BR}(h \to \gamma\gamma)_{\mathrm{SM}}} = 0.99^{+0.15}_{-0.14}$
- cLFV: $\mathrm{BR}(\mu \to e\gamma) < 4.2 \times 10^{-13}$ [MEG]

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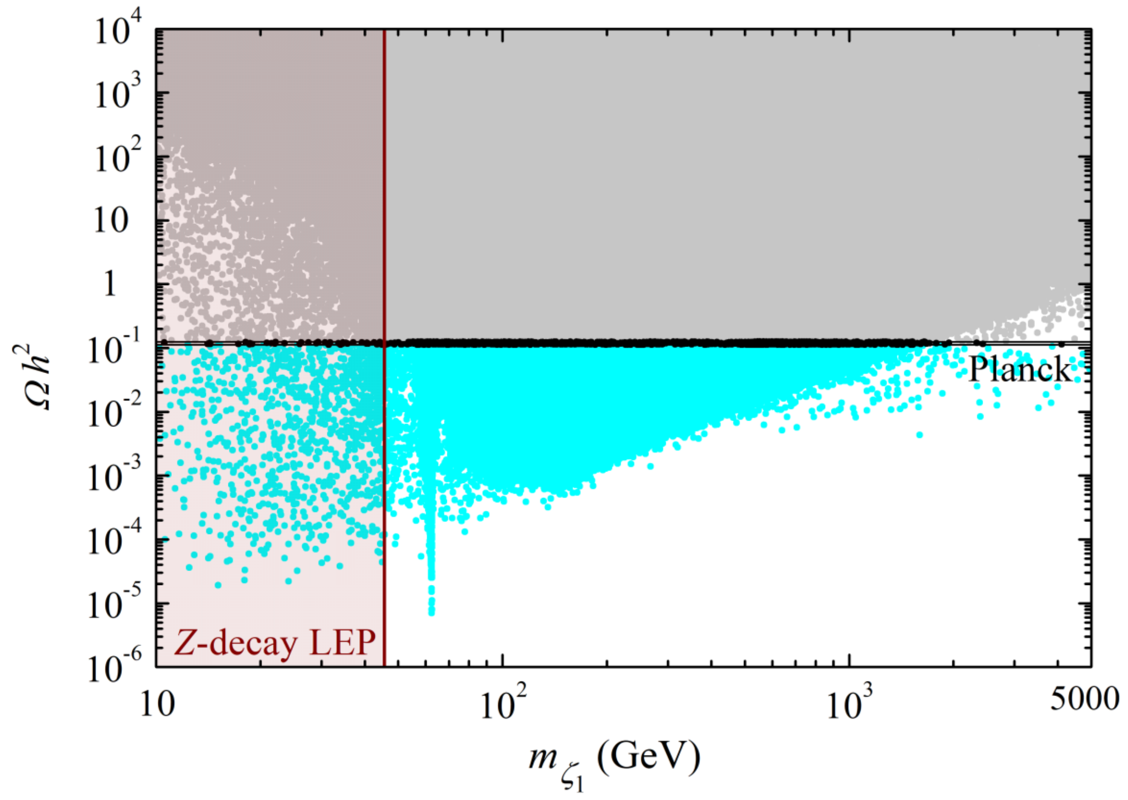
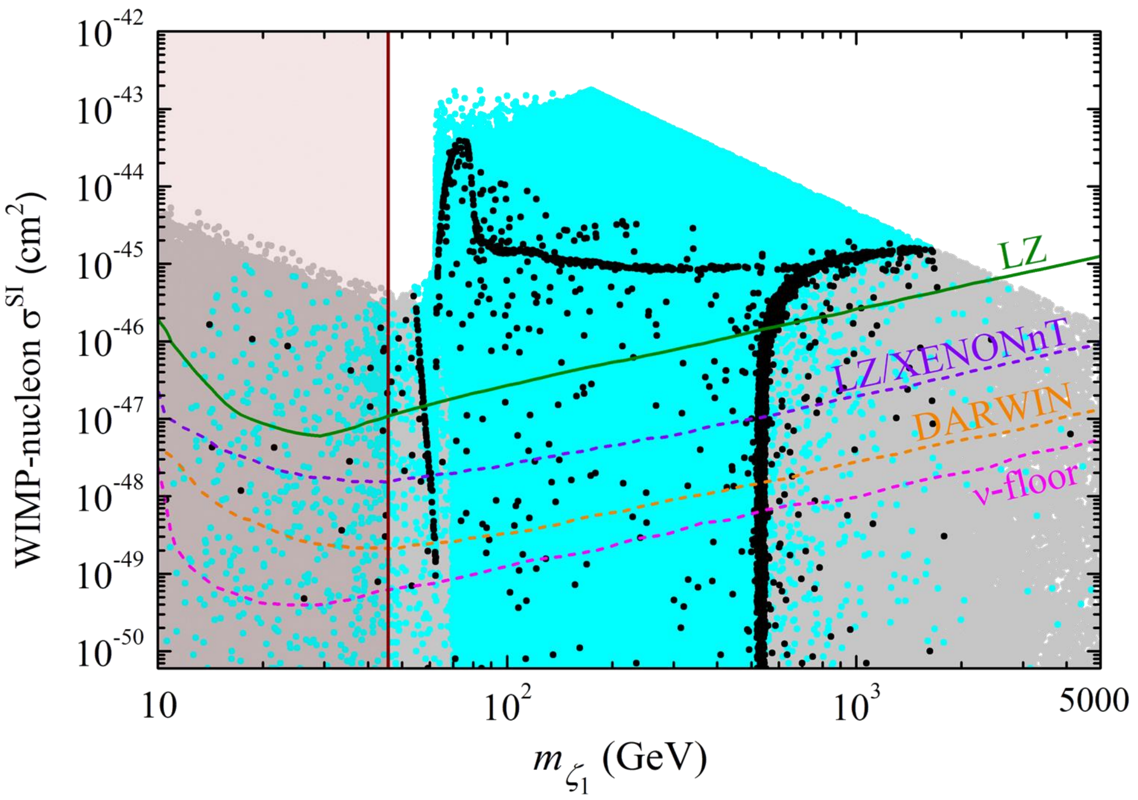


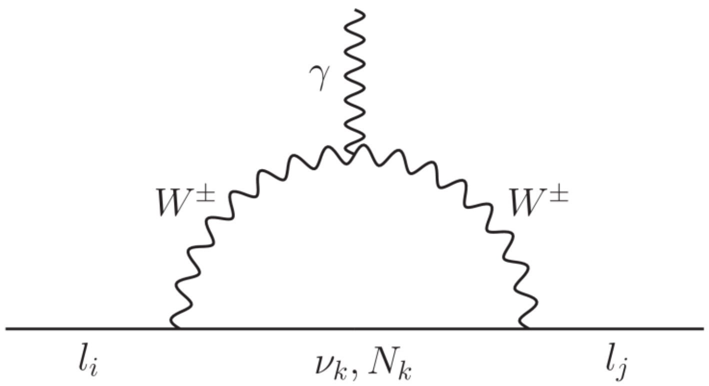
Direct detection

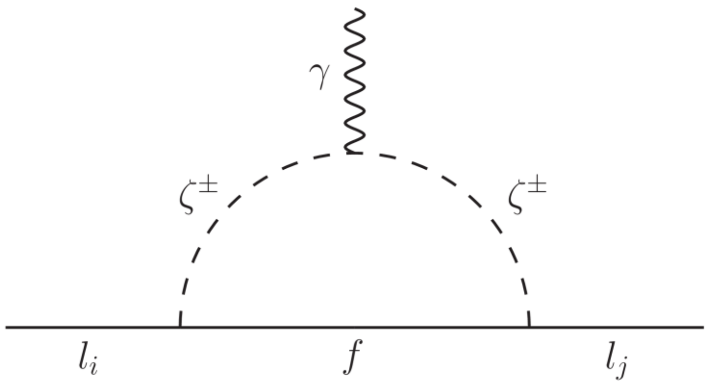


Direct detection is mediated by the SM Higgs boson and the Z-boson.

Charged lepton flavour violation

The new particles can mediate **charged lepton flavour violating decays** with sizable branching ratios.





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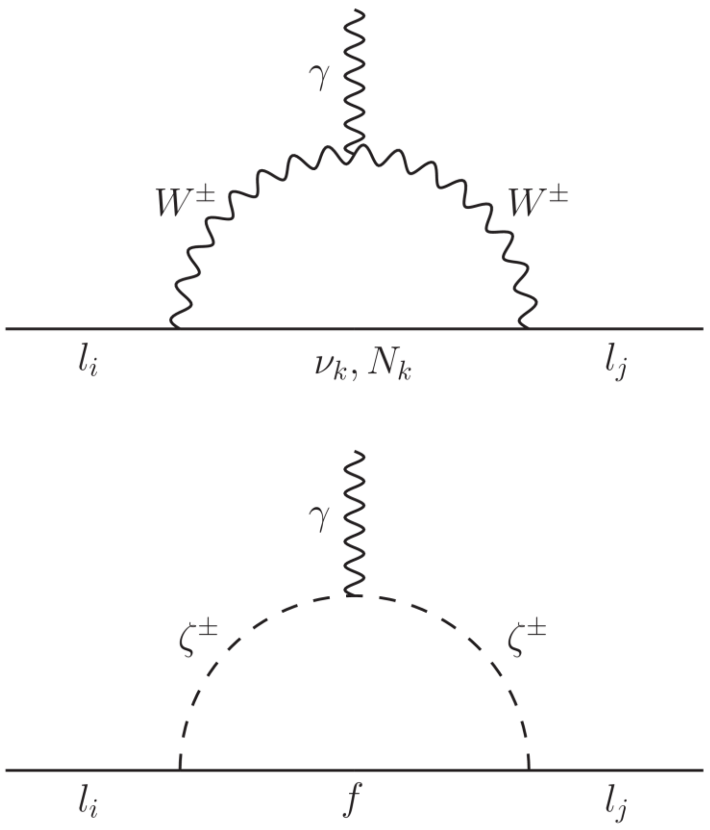
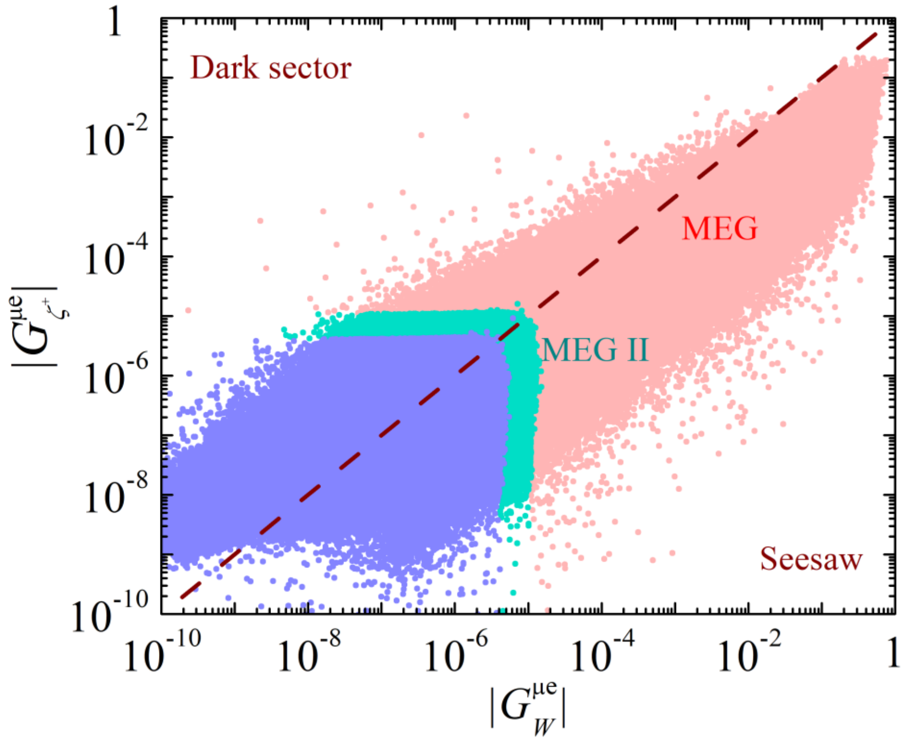


$$\frac{\mathrm{BR}(\ell_\alpha \to \ell_\beta \gamma)}{\mathrm{BR}\left(\ell_\alpha \to \ell_\beta \nu_\alpha \overline{\nu_\beta}\right)} = \frac{3\alpha_e}{2\pi} \left| G_W^{\alpha\beta} + G_{\zeta+}^{\alpha\beta} \right|^2$$



Therefore, our model can be probed through these processes at various current and upcoming experiments.

Concluding remarks

- The **Type-I Seesaw** is by far the **simplest solution** to the neutrino mass problem. However, the large mass scale of the right-handed neutrinos makes it far away from the reach of current experiments.

- **Low-scale solutions**, such as the **inverse and linear seesaws**, despite being more complicated offer more testability prospects at ongoing experiments.

- Small neutrino masses can also be induced at the quantum level in **radiative neutrino mass models.** Particles entering the loops may also be **viable DM candidates** stabilized by some symmetry as a simple $\mathcal{Z}_2$.

- The **dark linear seesaw** is the simplest framework in which a dark-sector induces the small lepton number violating parameter that generates neutrino masses via the linear seesaw mechanism, without contributing to any other mass term which could generate light neutrino masses through another mechanism.

- This model offers both the testability of low-scale seesaws through experiments that search for **charged lepton flavour violating decays** as well as **viable DM candidates** that can be directly detected at various current and upcoming experiments.

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