The Neutrino Dark Matter connection

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List of papers

- A. Batra, P. Bharadwaj, S. Mandal, R. Srivastava, and J. W. F. Valle, “*Phenomenology of the simplest linear seesaw mechanism*”, ***JHEP* 07 (2023) 221**, arXiv:2305.00994 [hep-ph].

- A. Batra, P. Bharadwaj, S. Mandal, R. Srivastava, and J. W. F. Valle, “*Large lepton number violation at colliders: Predictions from the minimal linear seesaw mechanism*”, ***Phys.Lett.B* 860 (2025) 139204**, arXiv:2304.06080 [hep-ph].

- A. Batra, H. B. Câmara, and F. R. Joaquim, “*Dark linear seesaw mechanism*”, ***Phys.Lett.B* 843 (2023) 138012**, arXiv:2305.01687 [hep-ph].

- A. Batra, H. B. Câmara, F. R. Joaquim, R. Srivastava, and J. W. F. Valle, “*Axion Paradigm with Color-Mediated Neutrino Masses*”, ***Phys.Rev.Lett.* 132 (2024) 5, 051801**, arXiv:2309.06473 [hep-ph].

- A. Batra, H. B. Câmara, F. R. Joaquim, N. Nath, R. Srivastava, and J. W. F. Valle, “*Axion framework with color-mediated Dirac neutrino masses*”, arXiv: 2501.13156 [hep-ph].

Motivation

The Standard Model (SM) of particle physics is a theory that describes electromagnetic, weak and strong interactions using symmetry groups $\mathrm{SU}(3)_\mathrm{c} \otimes \mathrm{SU}(2)_\mathrm{L} \otimes \mathrm{U}(1)_\mathrm{Y}$. It also classifies all known fundamental particles with specific charges under these groups.

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$$\mathcal{L}^{d=5}_{\mathrm{Maj.}} = \frac{\boldsymbol{\kappa}_{\mathrm{Maj.}}}{\Lambda}(\bar{L}^c\tilde{\Phi}^*)(\tilde{\Phi}^\dagger L) + \mathrm{H.c.} \qquad (1)$$

Neutrino masses

The unique lowest-dimensional effective operator that can be added to the SM is the dimension-five **Weinberg operator**.

This operator leads to **Majorana masses** for neutrinos after electroweak symmetry breaking.

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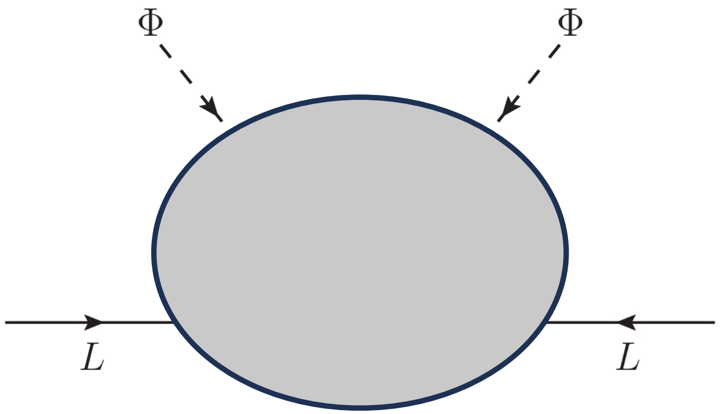

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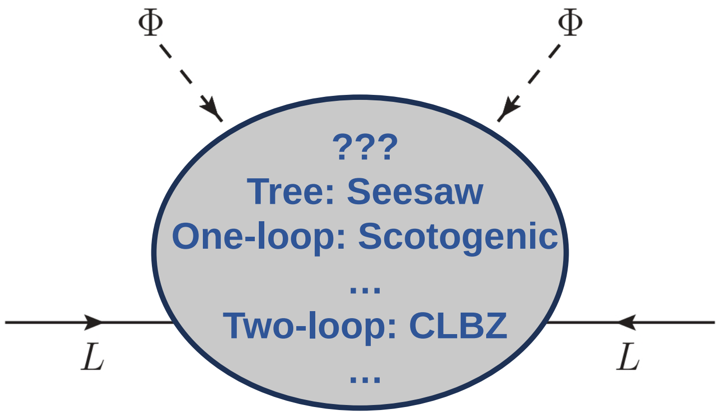

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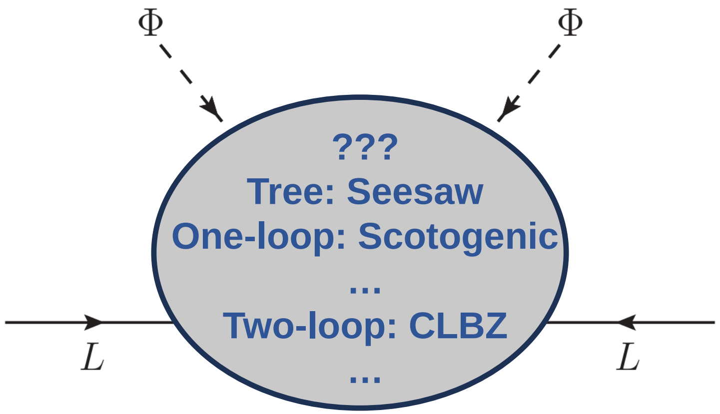


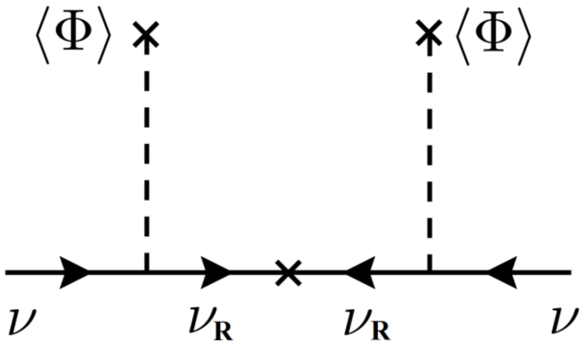
Alternatively, neutrinos could be **Dirac particles**. This scenario requires the existence of **right-handed neutrino** counterparts and the absence of the Weinberg operator, thereby forbidding Majorana mass terms.

$$-\mathcal{L}^{d=4}_{\text{Dirac}} = \boldsymbol{\kappa}_{\text{Dirac}} \, (\bar{L} \tilde{\Phi} \nu_R) + \text{H.c.}$$

The Seesaw mechanism

A straightforward and elegant solution for neutrino masses:

Type-I Seesaw Model



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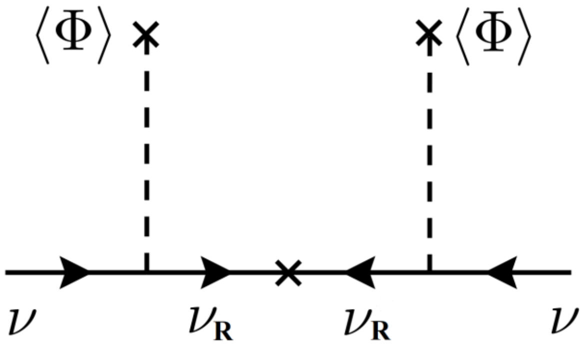

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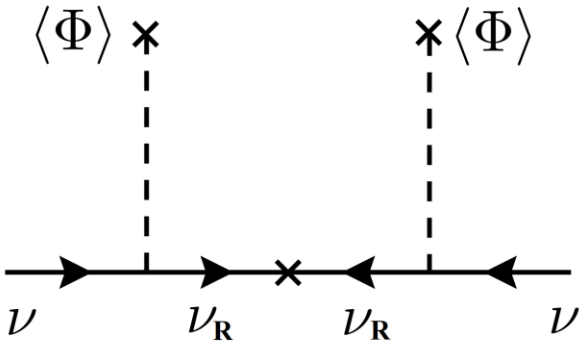

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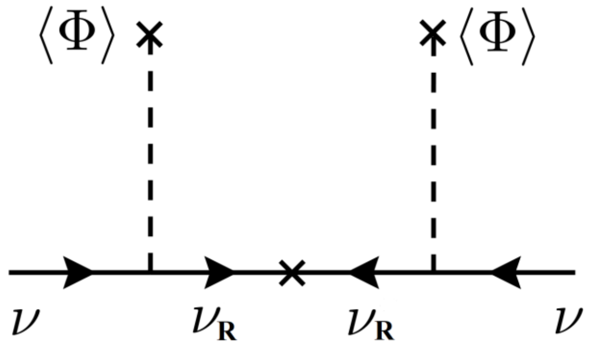

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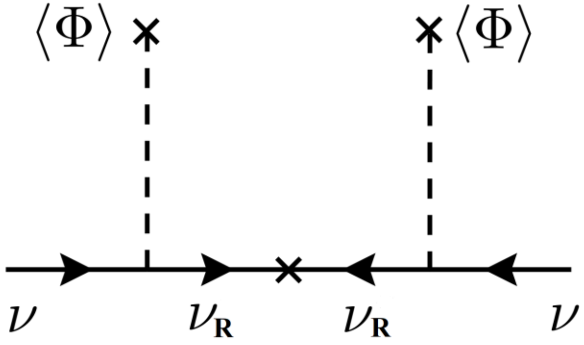

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- The **Type-I Seesaw** is by far the **simplest solution** to the neutrino mass problem.
- However, a major drawback of this model is the **large mass scale** of the right-handed neutrinos, far away from the reach of current experiments.

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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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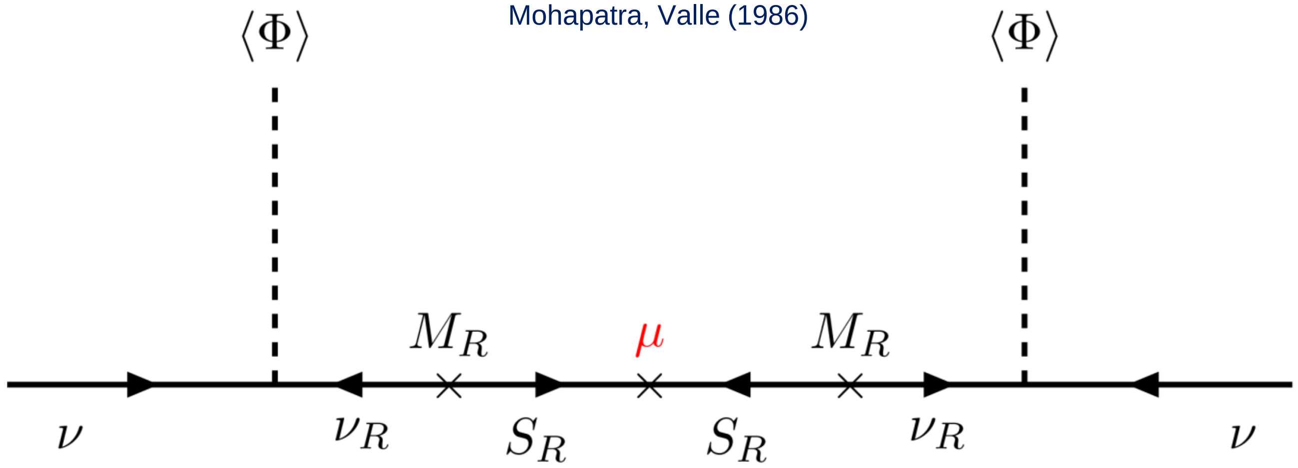
Inverse Seesaw Model

Mohapatra, Valle (1986)



Fields	$\mathrm{SU(2)_L \otimes U(1)_Y}$	$\mathrm{U(1)}_L$
ℓ_L	$(\mathbf{2}, -1)$	1
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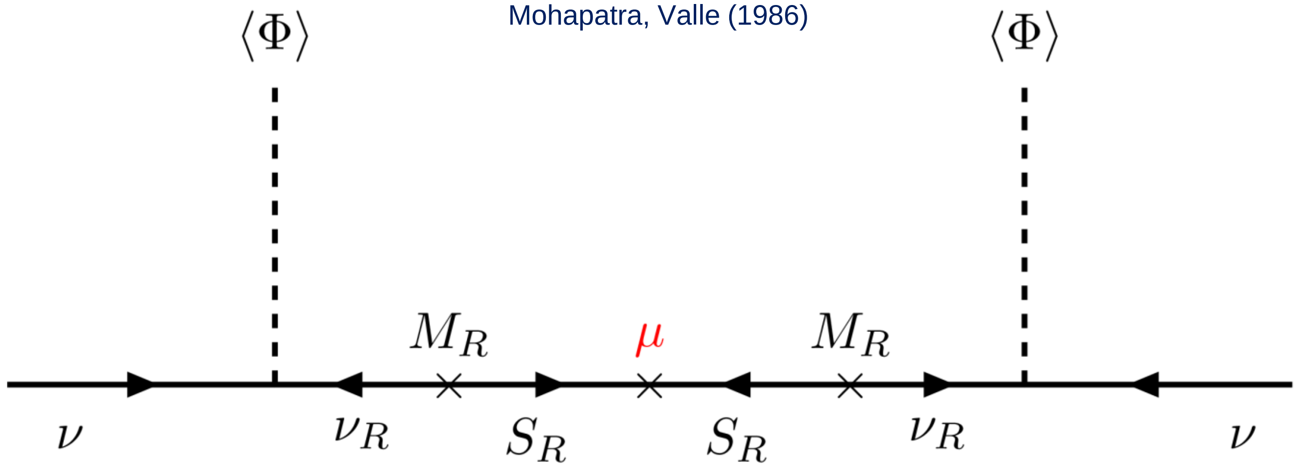

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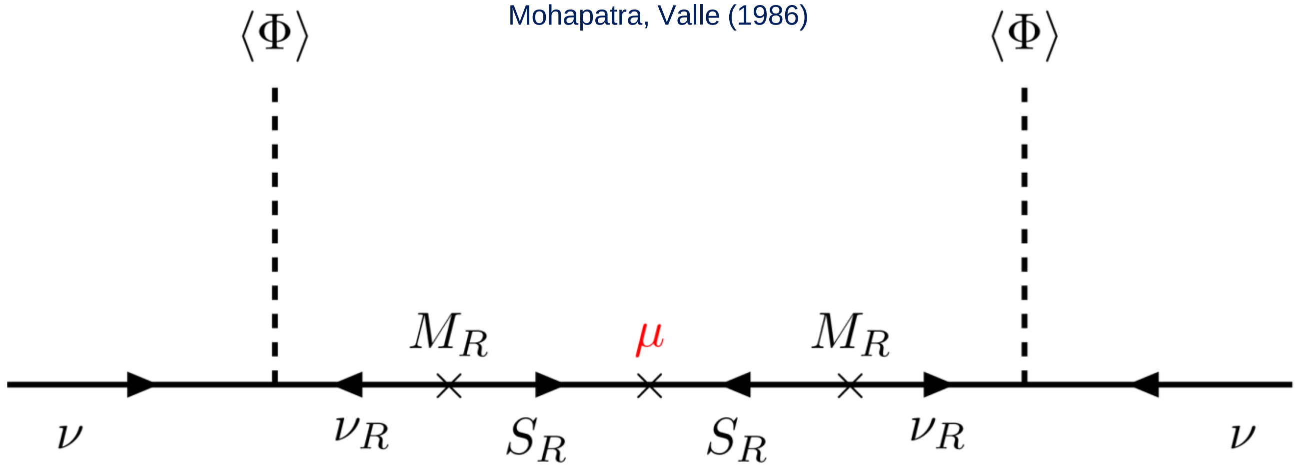

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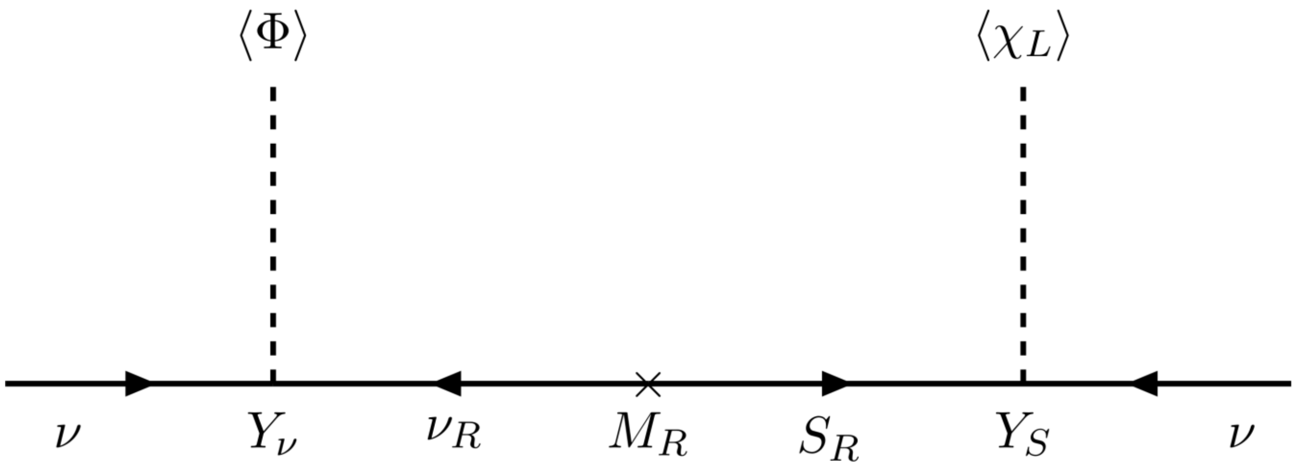
μ violates lepton number and can be naturally small in the t'Hooft sense. Hence, neutrino masses are suppressed and extremely heavy mediators like in the Type-I seesaw are not required.

Linear Seesaw Model

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



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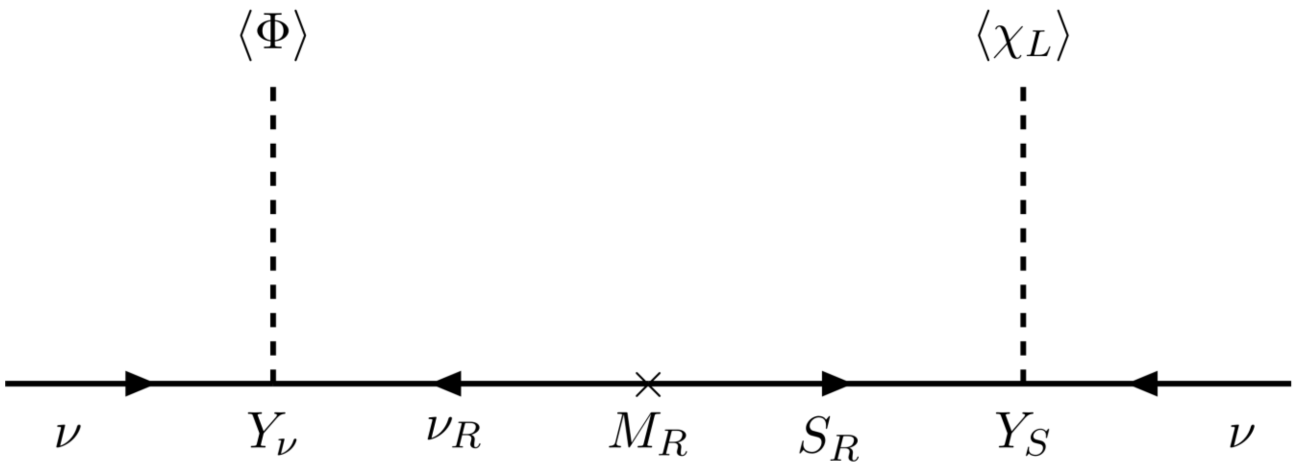

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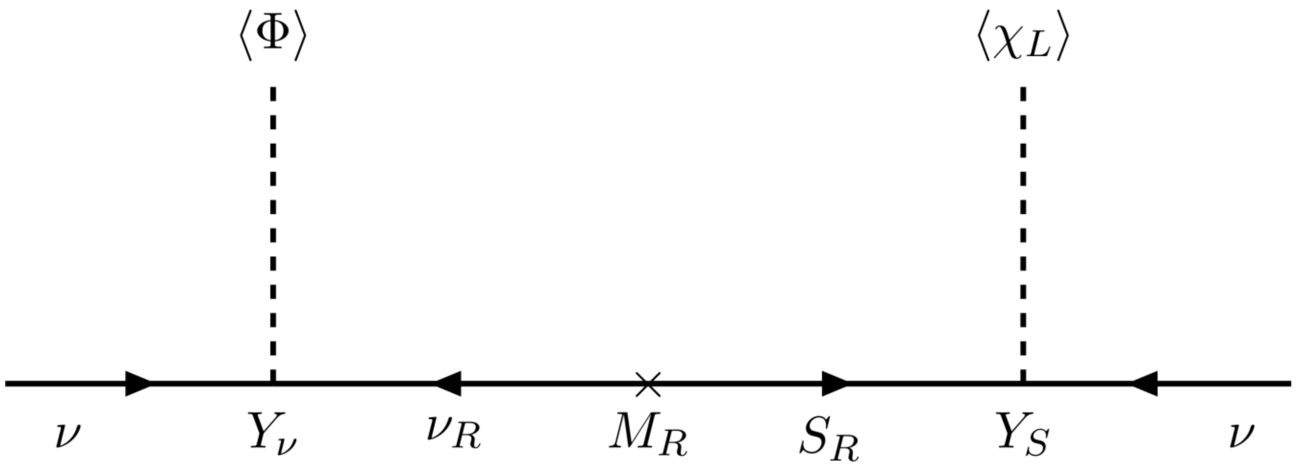

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v_χ is induced through the mixing term $\mu\Phi^\dagger\chi_L$ in the scalar potential which violates lepton number and hence can be naturally small. Again, the mediators can be at the TeV scale within the reach of current experiments.

Dark matter

Particle dark matter candidates must be:

- **Electromagnetically Neutral** and **Non-Baryonic**: constraints from searches in terrestrial, lunar, and meteoritic materials
- **Non-Relativistic**: to allow structure formation in the early Universe
- **Cosmologically Stable** or **Long-Lived**: to account for the observed dark matter density, $\Omega_{\mathrm{CDM}} h^2 = 0.1200 \pm 0.0012$

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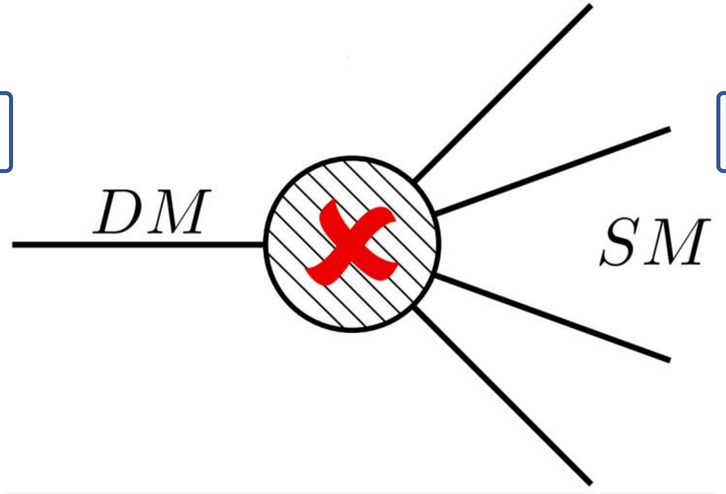

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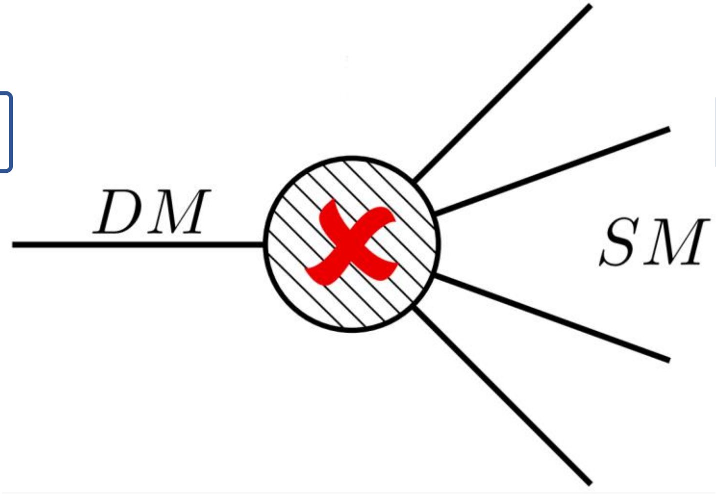

Even under $\mathcal{Z}_{\mathbf{2}}$

Is there a way to incorporate **dark matter** into neutrino mass 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 symmetry.

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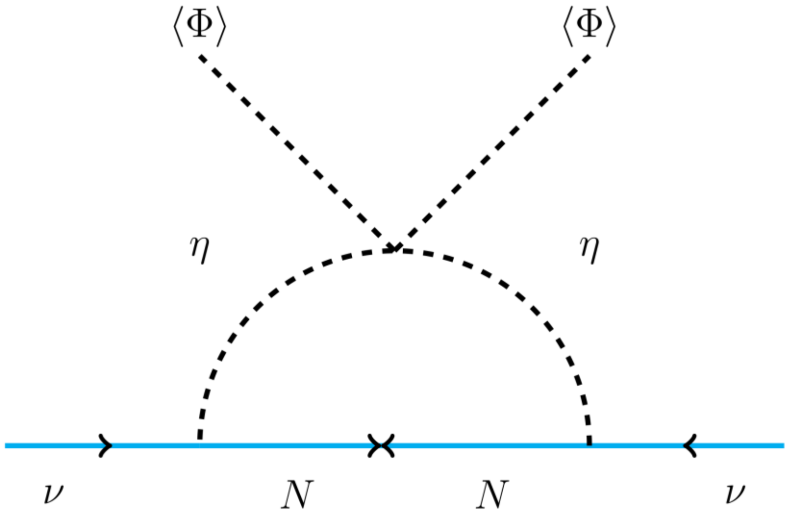

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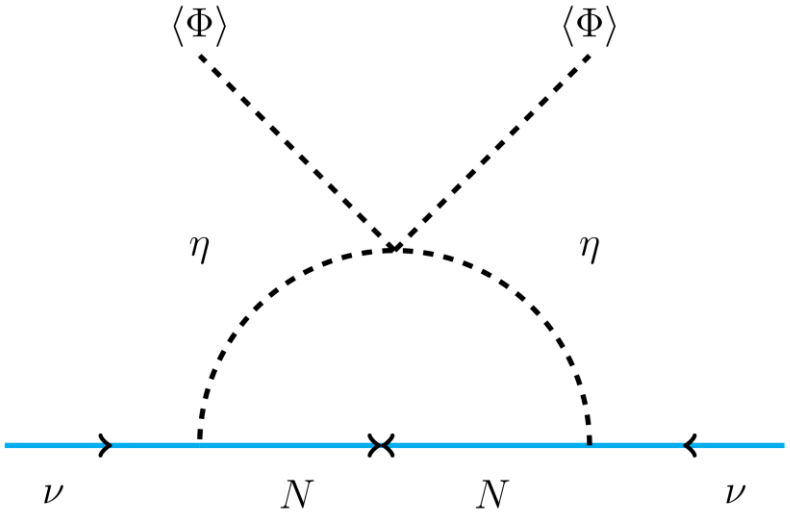

Dark Inverse Seesaw Model

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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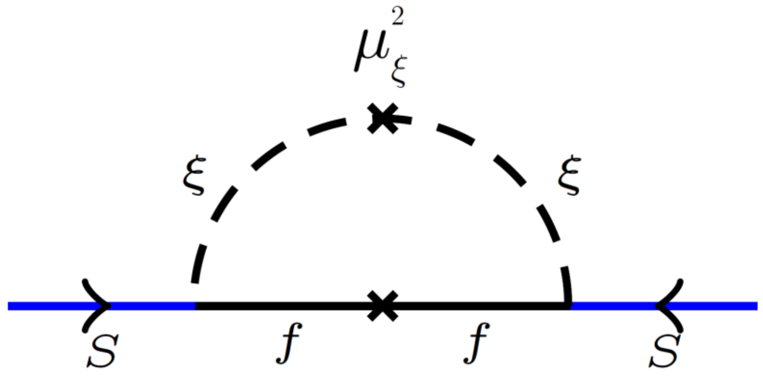

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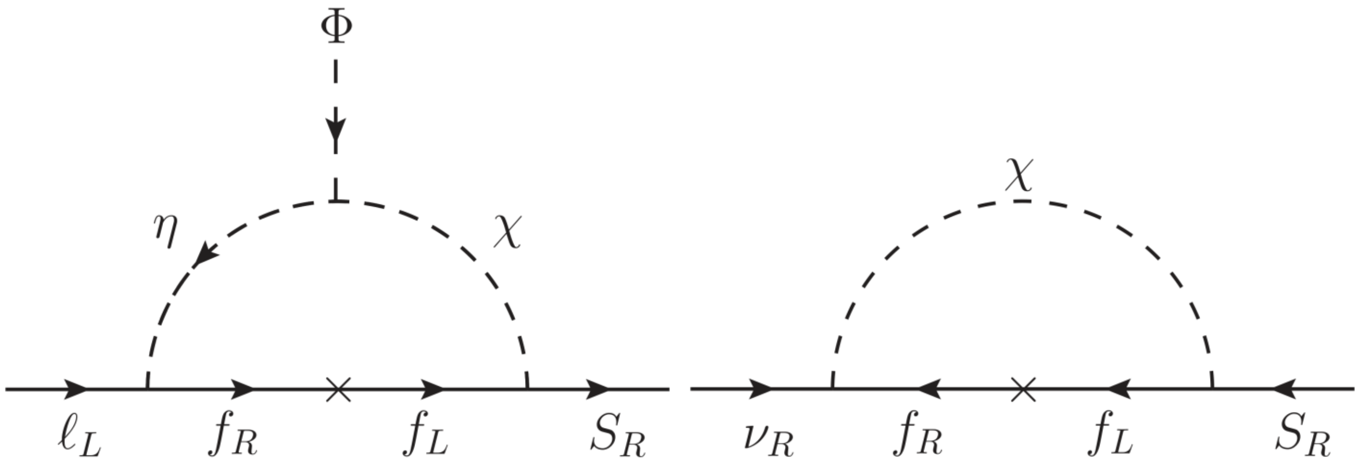
Fermions	ℓ_L	$(\mathbf{2}, -1)$	1	$+$
	e_R	$(\mathbf{1}, 2)$	1	$+$
	ν_R	$(\mathbf{1}, 0)$	1	$+$
	S_R	$(\mathbf{1}, 0)$	-1	$+$
	$f_{L,R}$	$(\mathbf{1}, 0)$	-1	$-$
Scalars	Φ	$(\mathbf{2}, 1)$	0	$+$
	η	$(\mathbf{2}, 1)$	-2	$-$
	χ	$(\mathbf{1}, 0)$	0	$-$



The dark linear seesaw

We propose a model where the **low-scale linear seesaw** neutrino mass generation mechanism is seeded by cosmologically stable dark matter particles accounting for both **neutrino flavour oscillations** and the observed **dark matter** abundance.

	Fields	$\mathrm{SU(2)_L \otimes U(1)_Y}$	$\mathrm{U}(1)_L$	$\mathcal{Z}_2$
Fermions	ℓ_L	$(\mathbf{2}, -1)$	1	$+$
	e_R	$(\mathbf{1}, 2)$	1	$+$
	ν_R	$(\mathbf{1}, 0)$	1	$+$
	S_R	$(\mathbf{1}, 0)$	-1	$+$
	$f_{L,R}$	$(\mathbf{1}, 0)$	-1	$-$
Scalars	Φ	$(\mathbf{2}, 1)$	0	$+$
	η	$(\mathbf{2}, 1)$	-2	$-$
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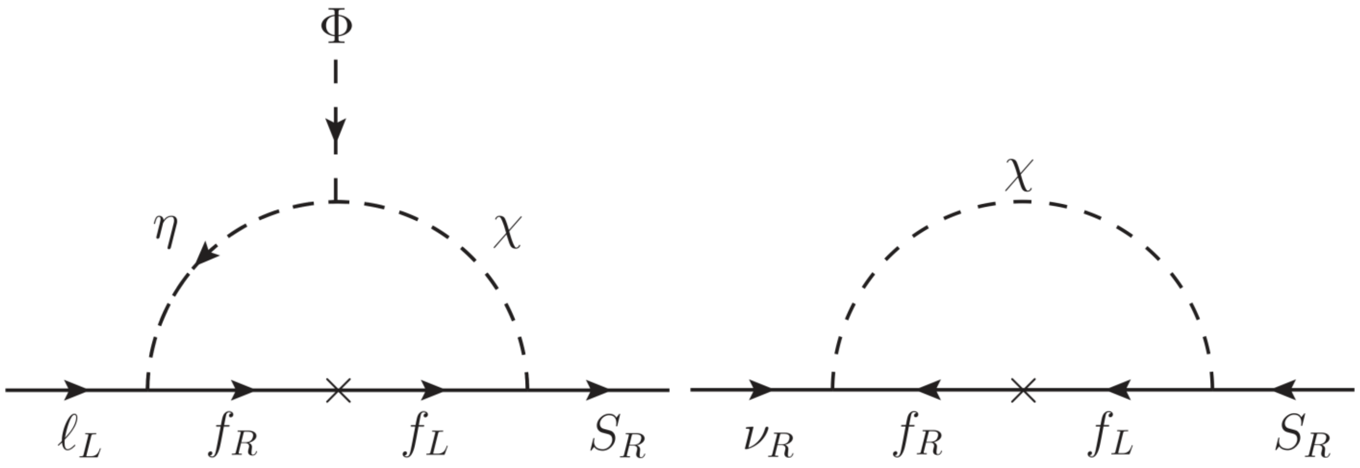

$$-\mathcal{L} = \mathbf{Y}_e \ell_L \Phi e_R + \mathbf{Y}_D \ell_L \tilde{\Phi} \nu_R + \mathbf{Y}_f \ell_L \tilde{\eta} f_R + Y_S f_L S_R \chi + Y_R f_R^c \nu_R \chi + M_B \nu_R^c S_R + M_f f_L f_R + \mathrm{H.c.}$$

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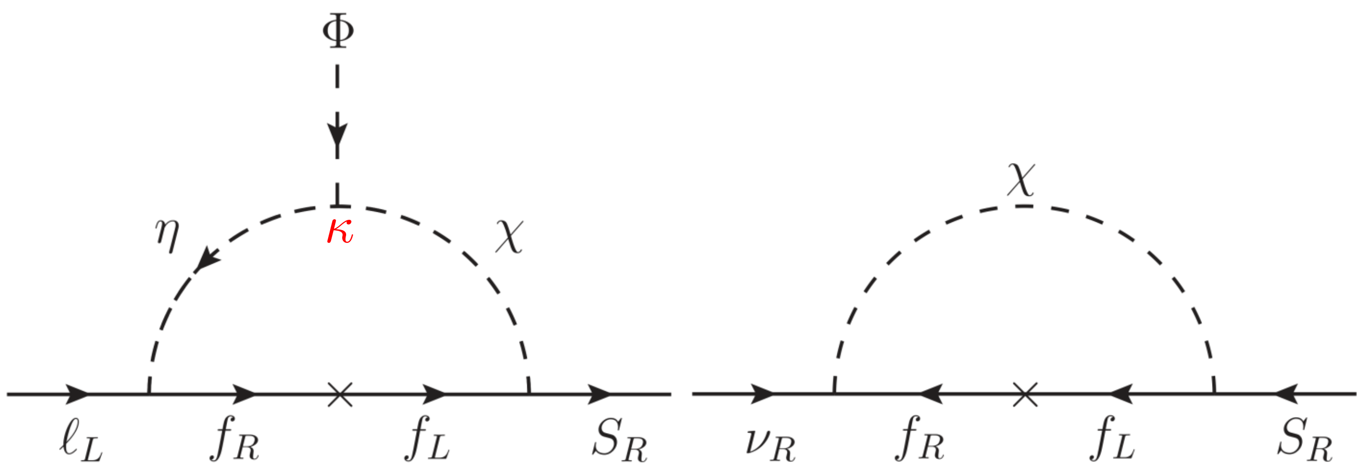

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The **lepton number symmetry** is violated by the scalar potential term:

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

Dark matter

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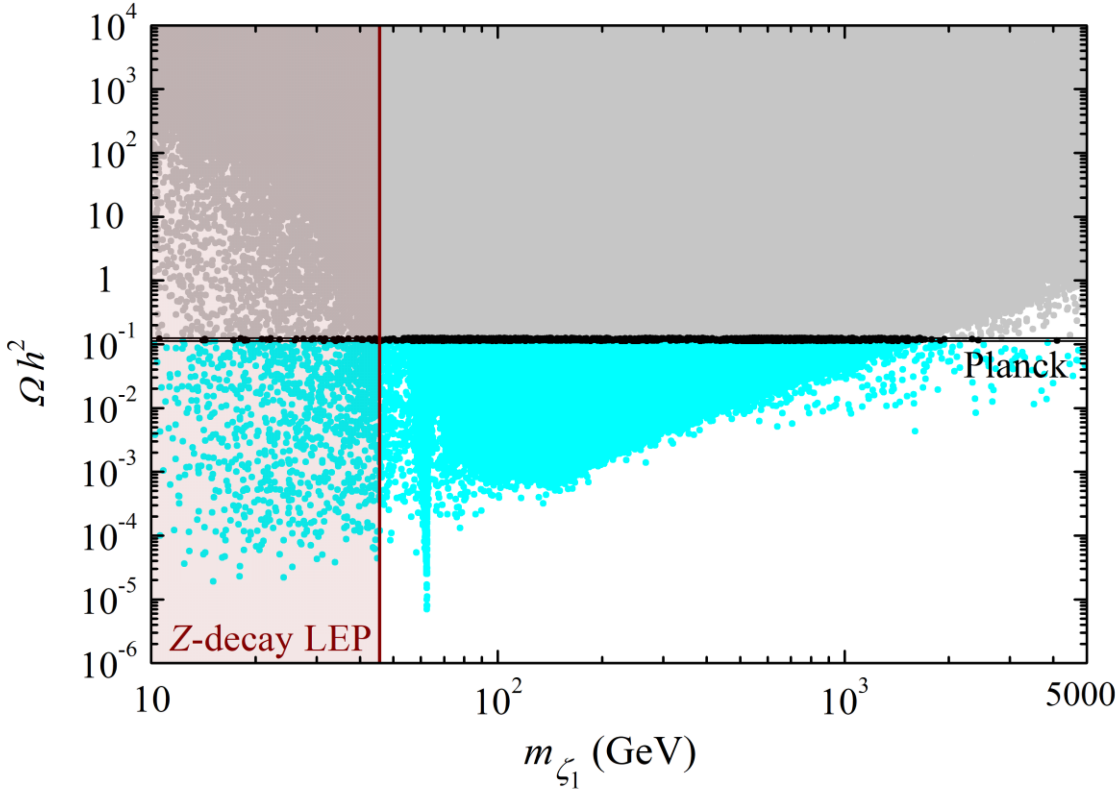
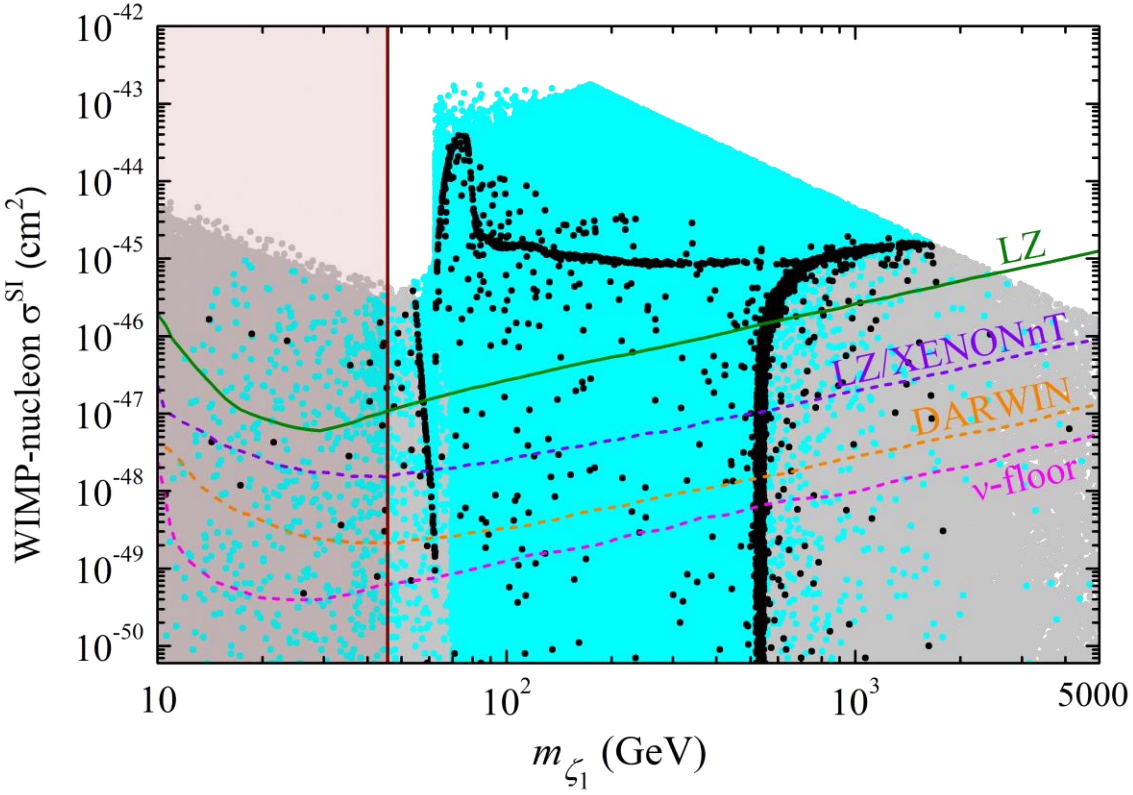
Relic abundance



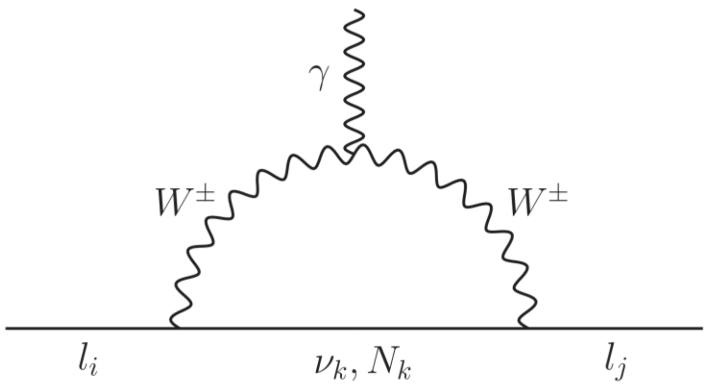
Direct detection

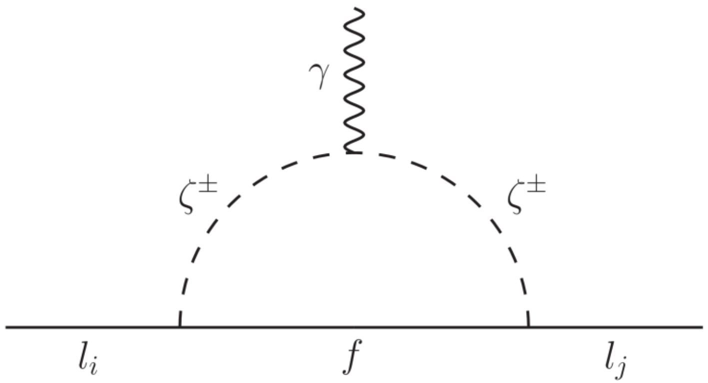


Direct detection is mediated by the SM Higgs boson and the Z-boson.

Charged lepton flavour violation

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





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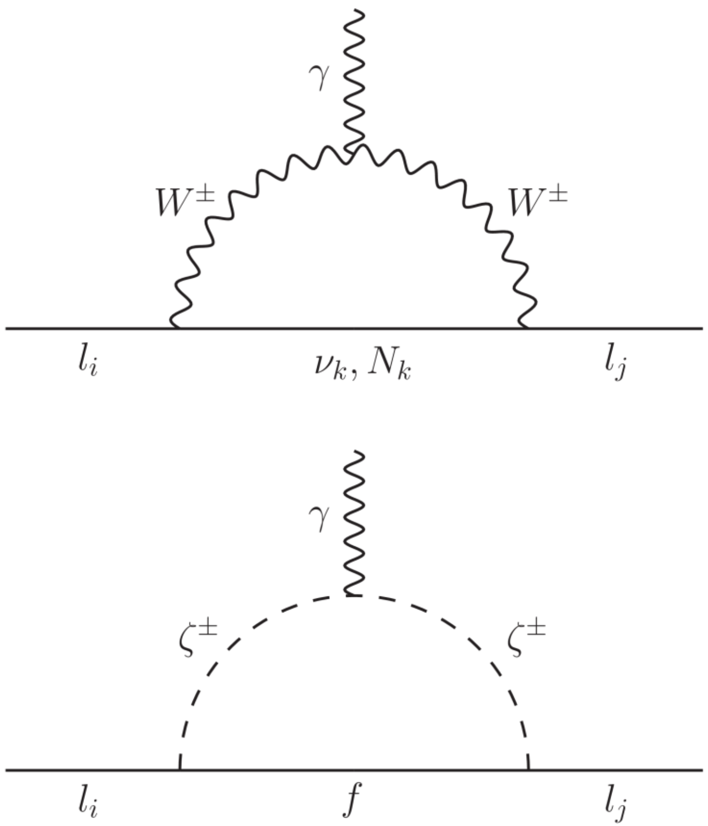
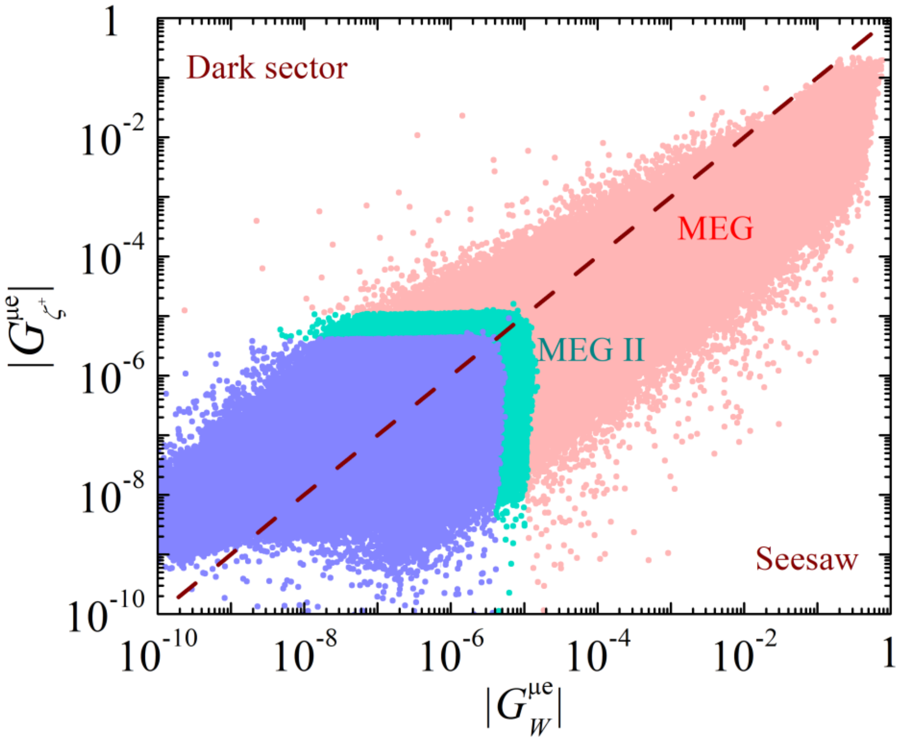


$$\frac{\mathrm{BR}(\ell_\alpha \to \ell_\beta \gamma)}{\mathrm{BR}\left(\ell_\alpha \to \ell_\beta \nu_\alpha \overline{\nu_\beta}\right)} = \frac{3\alpha_e}{2\pi}\left|G_W^{\alpha\beta} + G_{\zeta^+}^{\alpha\beta}\right|^2$$



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

The Strong CP problem and axions

Strong CP problem

$$\mathcal{L}_{\mathrm{QCD}} \supset \overline{\theta}\, \frac{\alpha_s}{8\pi} G^b_{\mu\nu} \tilde{G}^{b,\mu\nu}$$

$$|\bar{\theta}| < 10^{-10}$$

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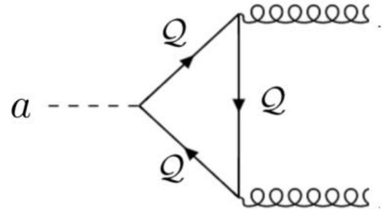
$$\sigma = \frac{v_\sigma + \rho}{\sqrt{2}} e^{i a_\sigma / v_\sigma}$$



KSVZ (1979, 1980)

Vector-like quarks

$$\Psi_{L,R}$$

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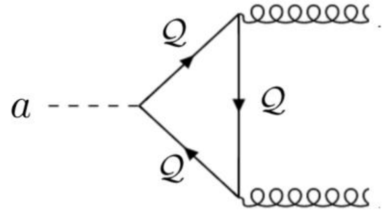

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Our approach:

New class of models where **neutrino masses** are **radiatively generated by coloured particles** which **simultaneously** solve through the PQ mechanism the **strong CP problem**. The predicted **axion** particle accounts for **dark matter**.

Axion paradigm with colour-mediated neutrino masses

Fields	$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$	$U(1)_{PQ}$	Multiplicity
Ψ_L	$((p,q), 2n \pm 1, 0)$	ω	n_Ψ
Ψ_R	$((p,q), 2n \pm 1, 0)$	0	n_Ψ
σ	$(\mathbf{1}, \mathbf{1}, 0)$	ω	1
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$$-\mathcal{L}_{\text{Yuk.}} \supset \mathbf{Y}_\Psi \overline{\Psi_L} \Psi_R \sigma + \frac{1}{2} \mathbf{Y}_{\chi_j} \Psi_R^T C \chi_j \Psi_R + \mathbf{Y}_i \bar{L} \eta_i^* \Psi_R + \text{H.c.}$$

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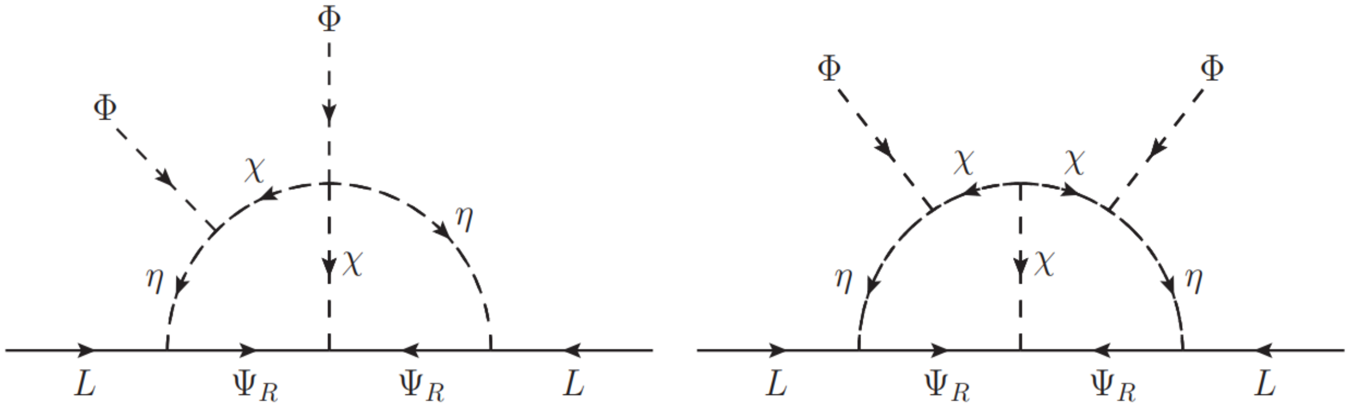
Scalar Potential:

$$V \supset \mu_{ijk} \chi_i \chi_j \chi_k + \kappa_{ij} \eta_i^\dagger \Phi \chi_j + \lambda_{ijk} \Phi^\dagger \eta_i \chi_j \chi_k + \text{H.c.}$$

Axion paradigm with colour-mediated neutrino masses

Neutrino mass generation

Two-loop colour-mediated Majorana neutrino masses



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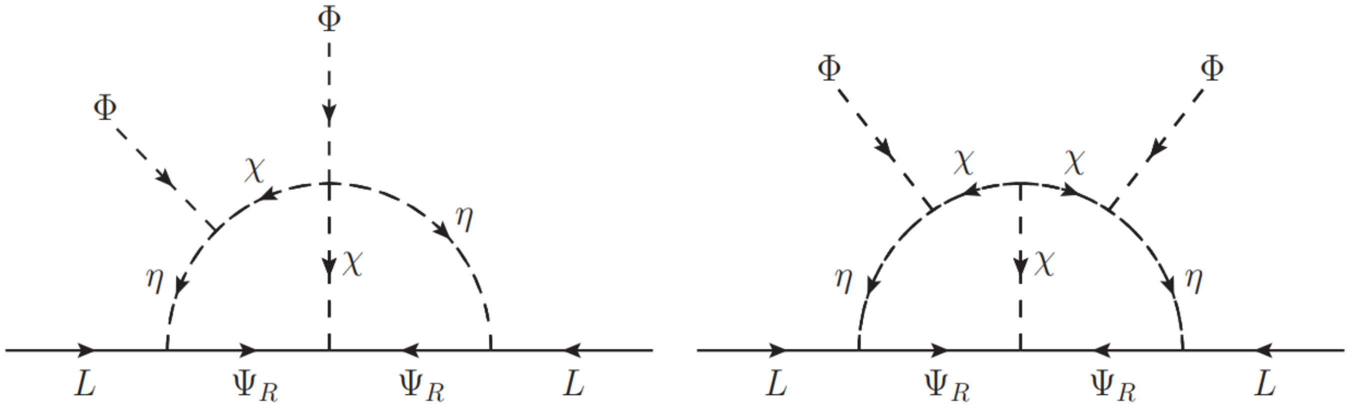

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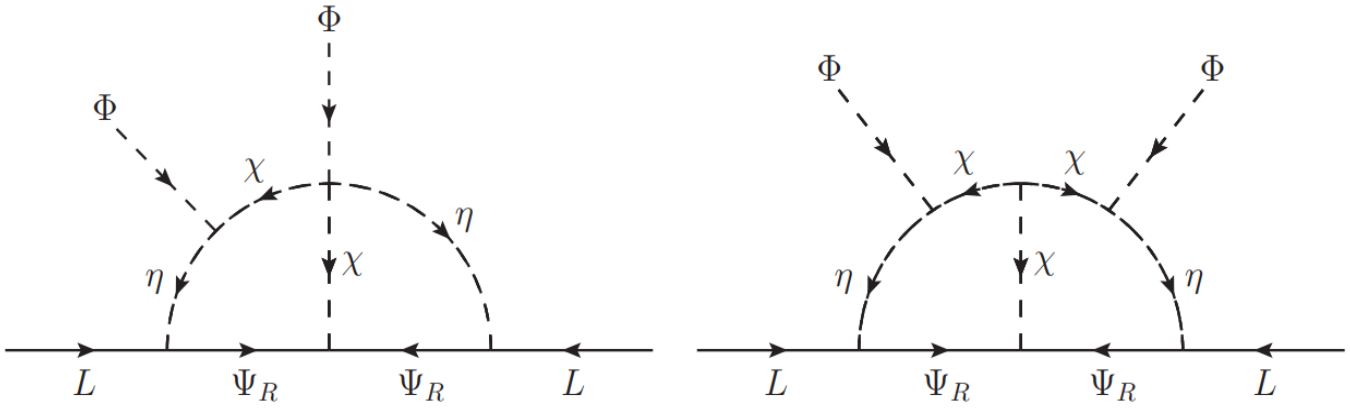

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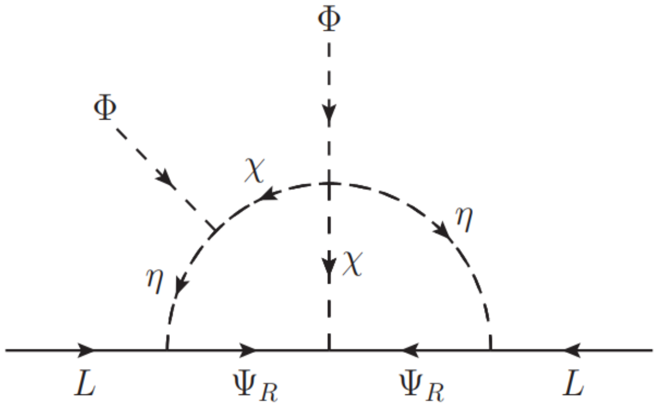

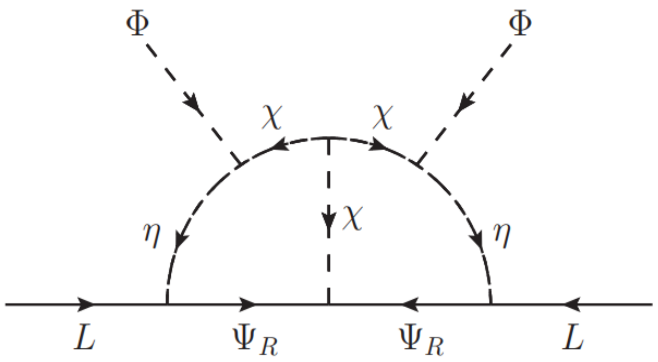

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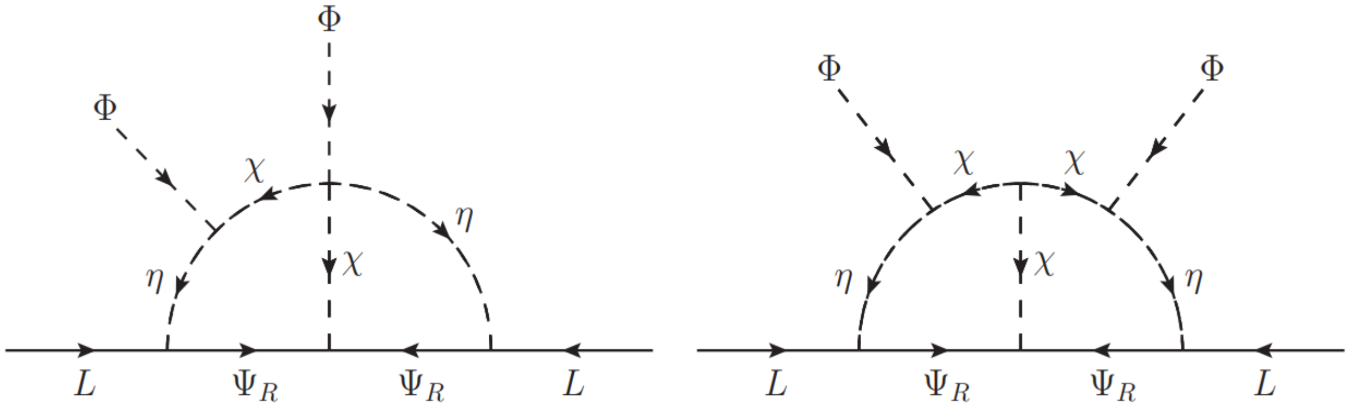

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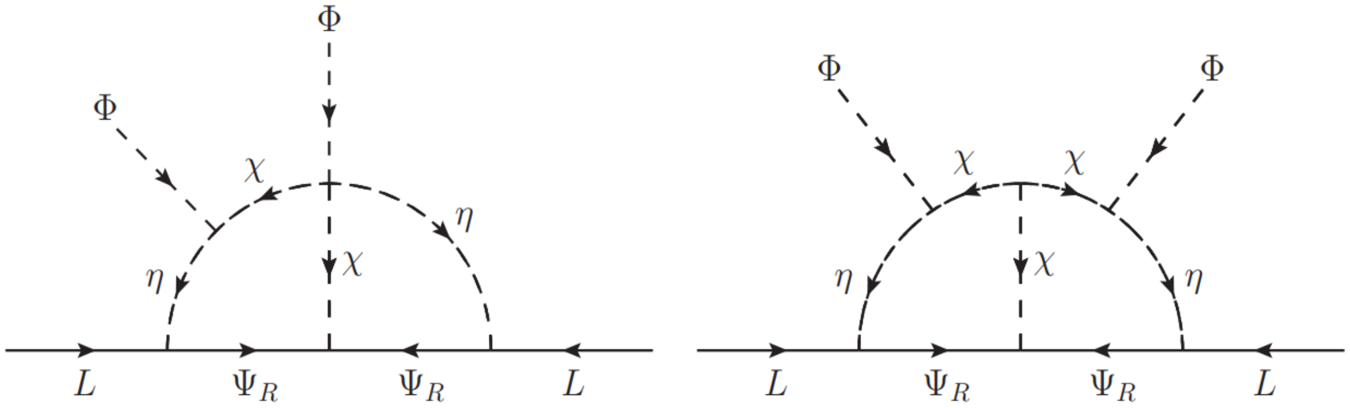

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Colour-anomaly factor

$$N = 2n_\Psi\omega(2n \pm 1)T(p, q)$$

Probing the axion-to-photon coupling

Axion-to-photon coupling:

$$g_{a\gamma\gamma} = \frac{\alpha_e}{2\pi f_a}\left[\frac{E}{N} - 1.92(4)\right]$$

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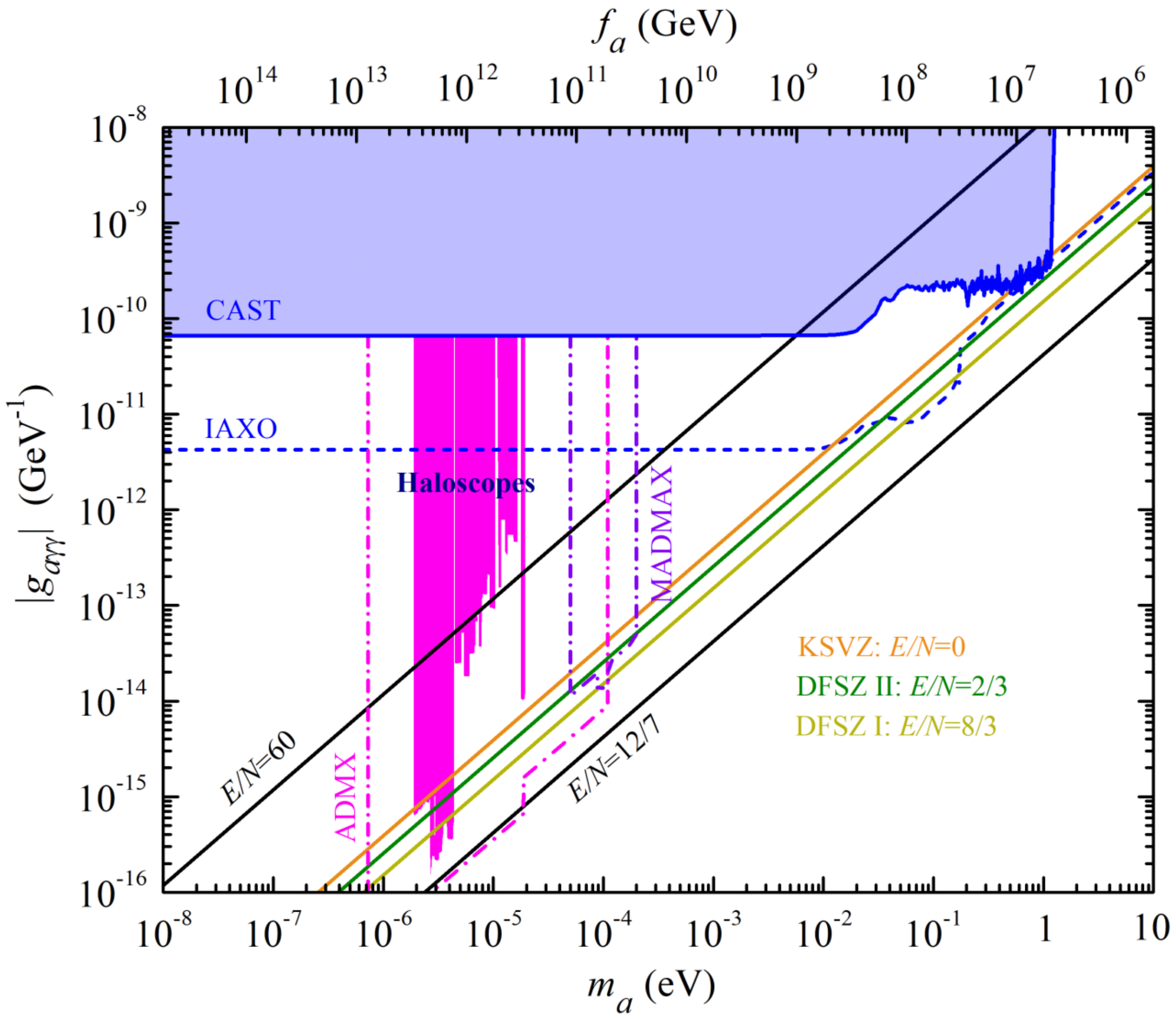
$\longrightarrow$

E/N		$SU(2)_L$				
		3	**5**	**7**	**9**	**11**
$SU(3)_c$	**3**	4	12	24	40	60
	6	8/5	24/5	48/5	16	24
	10	8/9	8/3	16/3	80/9	40/3
	15	1	3	6	10	15
	15′	4/7	12/7	24/7	40/7	60/7

Probing the axion-to-photon coupling

The different models can be probed through the **axion-to-photon coupling** at **helioscope** and **haloscope** experiments.



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$$\Omega_a h^2 \simeq \Omega_{\mathrm{CDM}} h^2 \, \frac{\theta_0^2}{2.15^2} \left(\frac{f_a}{2 \times 10^{11} \ \mathrm{GeV}} \right)^{\frac{7}{6}}$$

Callan et al. (1978); Gross et al. (1981); Dimopoulos et al. (2008)

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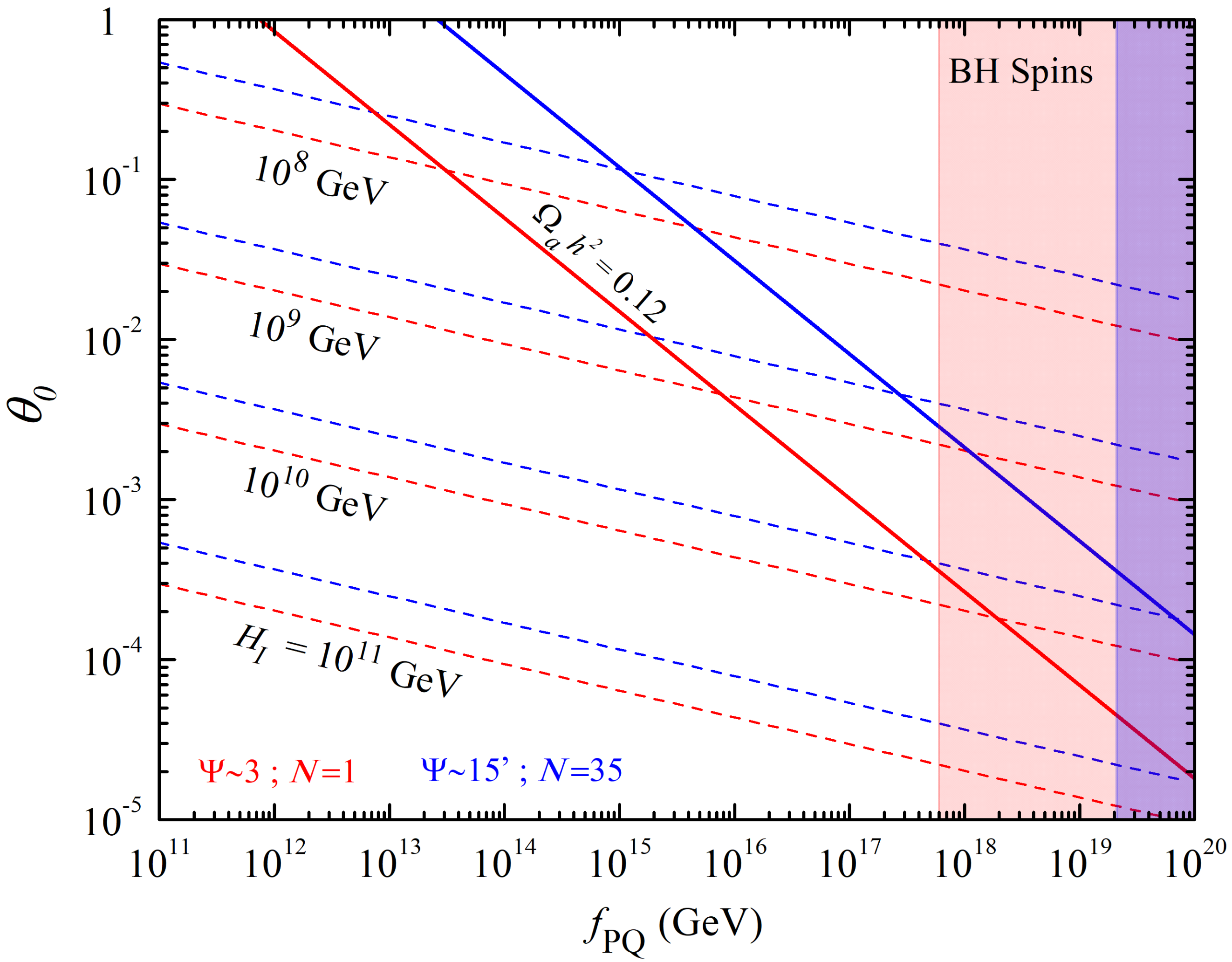
Callan et al. (1978); Gross et al. (1981); Dimopoulos et al. (2008)

Isocurvature fluctuations are constrained by CMB data setting a bound on the inflationary scale:

$$H_I \lesssim \frac{0.9 \times 10^7}{\Omega_a h^2 / \Omega_{\mathrm{CDM}} h^2} \left(\frac{\theta_0}{\pi} \frac{f_a}{10^{11}\ \mathrm{GeV}} \right) \mathrm{GeV}$$

Di Luzio et al. (2017)

Axion dark matter and cosmology



For $\theta_0 \sim \mathcal{O}(1)$ axions can account for the **full CDM budget**, provided $f_a \sim 5 \times 10^{11}$ GeV, a region currently under scrutiny at **haloscopes**.

Axion paradigm with colour-mediated Dirac neutrino masses

	Fields	$\mathrm{SU}(3)_c \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$	$\mathrm{U}(1)_{\mathrm{PQ}}$
Leptons	ℓ_L	$(\mathbf{1}, \mathbf{2}, -1/2)$	$1/6$
	e_R	$(\mathbf{1}, \mathbf{1}, -1)$	$1/6$
	ν_R	$(\mathbf{1}, \mathbf{1}, 0)$	$4/6$
Vector-like quarks	$\Psi_{1,2L}; \Psi_{1,2R}$	$(\mathbf{3}, \mathbf{n}_\Psi, y_\Psi)$	$\mathcal{Q}_{\mathrm{PQ}}; \mathcal{Q}_{\mathrm{PQ}} - 1/2$
Scalars	Φ	$(\mathbf{1}, \mathbf{2}, 1/2)$	0
	σ	$(\mathbf{1}, \mathbf{1}, 0)$	$1/2$
Scalar Leptoquarks	η	$(\mathbf{3}, \mathbf{n}_\eta \equiv \mathbf{n}_\Psi \pm \mathbf{1}, y_\Psi + 1/2)$	$\mathcal{Q}_{\mathrm{PQ}} - 4/6$
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$$-\mathcal{L}^{\nu}_{\mathrm{Yuk.}} = \mathbf{Y}_\eta \ell_L\, \tilde{\eta} \Psi_R + \mathbf{Y}_\chi \Psi_L \chi \nu_R + \mathbf{Y}_\Psi \Psi_L \Psi_R \sigma + \mathrm{H.c.}$$

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$\mathbf{n}_\Psi$	y_Ψ	$\mathcal{Q}_{\mathrm{PQ}}$	$\mathbf{n}_\eta$	Heavy-light quark mixing terms	Other decay terms
$\mathbf{1}$	$-1/3$	$1/2$	$\mathbf{2}$	$\overline{q_L}\Phi\Psi_R, \overline{\Psi_L}\sigma d_R$	$\overline{\ell_L}\tilde{\eta} d_R$
		0		$\overline{\Psi_L} d_R$	$\overline{q_L}\eta\nu_R$
	$2/3$	$1/2$		$\overline{q_L}\tilde{\Phi}\Psi_R, \overline{\Psi_L}\sigma u_R$	$\overline{\ell_L}\tilde{\eta} u_R, \overline{q_L}\eta e_R$
		0		$\overline{\Psi_L} u_R$	-
$\mathbf{2}$	$1/6$	$1/2$	$\mathbf{1}, \mathbf{3}$	$\overline{q_L}\Psi_R$	$\overline{\ell_L}\chi^* d_R$
		0		$\overline{q_L}\sigma\Psi_R, \overline{\Psi_L}\Phi d_R, \overline{\Psi_L}\tilde{\Phi} u_R$	-
	$-5/6$	0		$\overline{\Psi_L}\tilde{\Phi} d_R$	-
	$7/6$			$\overline{\Psi_L}\Phi u_R$	-
$\mathbf{3}$	$-1/3$	0	$\mathbf{2}$	$\overline{q_L}\Phi\Psi_R$	$\overline{\ell_L}\tilde{\eta} d_R$
			$\mathbf{4}$		-
	$2/3$		$\mathbf{2}$	$\overline{q_L}\tilde{\Phi}\Psi_R$	$\overline{\ell_L}\tilde{\eta} u_R, \overline{q_L}\eta e_R$
			$\mathbf{4}$		-

Axion paradigm with colour-mediated Dirac neutrino masses

There is a **residual $\mathcal{Z}_3$ symmetry** under which,

$$(\ell_L, e_R, \nu_R) \rightarrow \omega(\ell_L, e_R, \nu_R)$$

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The scalar leptoquarks η and χ lead to lepton-quark interaction terms.

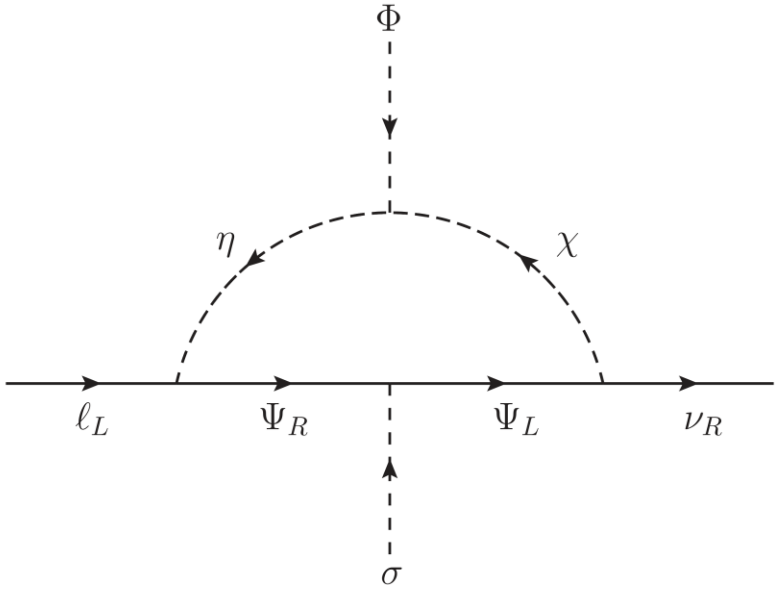
However, there is an **accidental baryon number symmetry** under which the SM quark fields and the new colored ones are equally charged **forbids dangerous proton decay** operators such as the dimension 6,

$$d^c u^c u^c e^c/\Lambda^2, \; \bar{e^c}\bar{u^c} qq/\Lambda^2, \; \bar{d^c}\bar{u^c} q\ell/\Lambda^2, \; qqql/\Lambda^2$$

Axion paradigm with colour-mediated Dirac neutrino masses

Neutrino mass generation

One-loop colour-mediated Dirac neutrino masses



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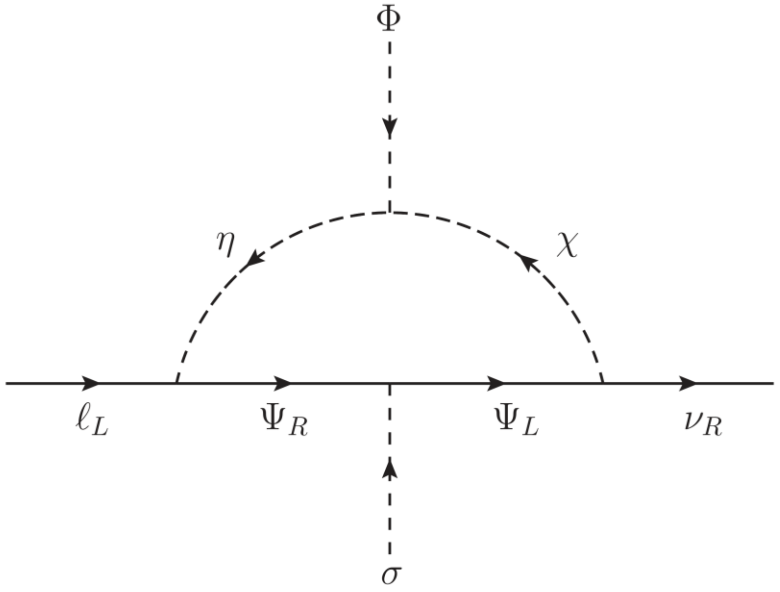

$$(M_\nu)_{\alpha\beta} \sim 0.1\text{eV}\left(\frac{(\tilde{Y}_\eta)_{\alpha j}(\tilde{Y}_\chi)_{j\beta}}{10^{-2}}\right)\left(\frac{\kappa}{10^2\ \text{GeV}}\right)\left(\frac{\tilde{M}_{\Psi j}}{10^{12}\ \text{GeV}}\right)\left(\frac{10^{10}\ \text{GeV}}{m_{\zeta_k}}\right)^2$$

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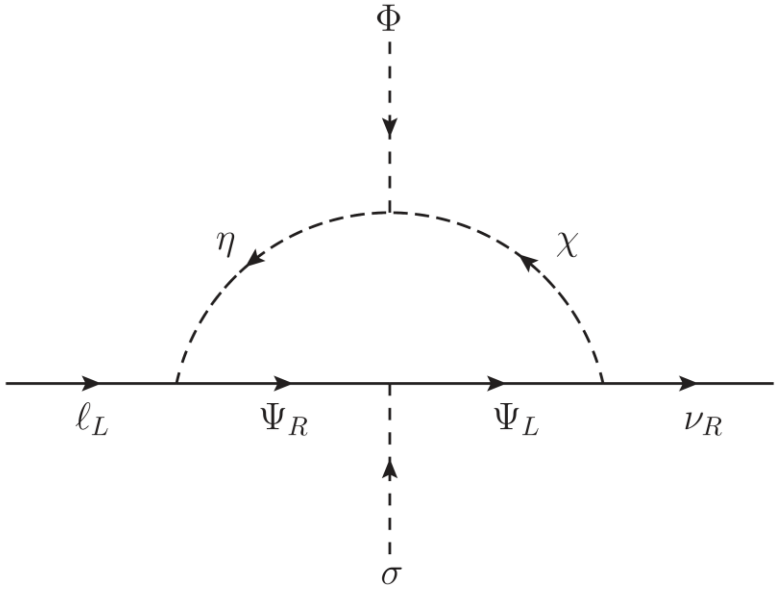

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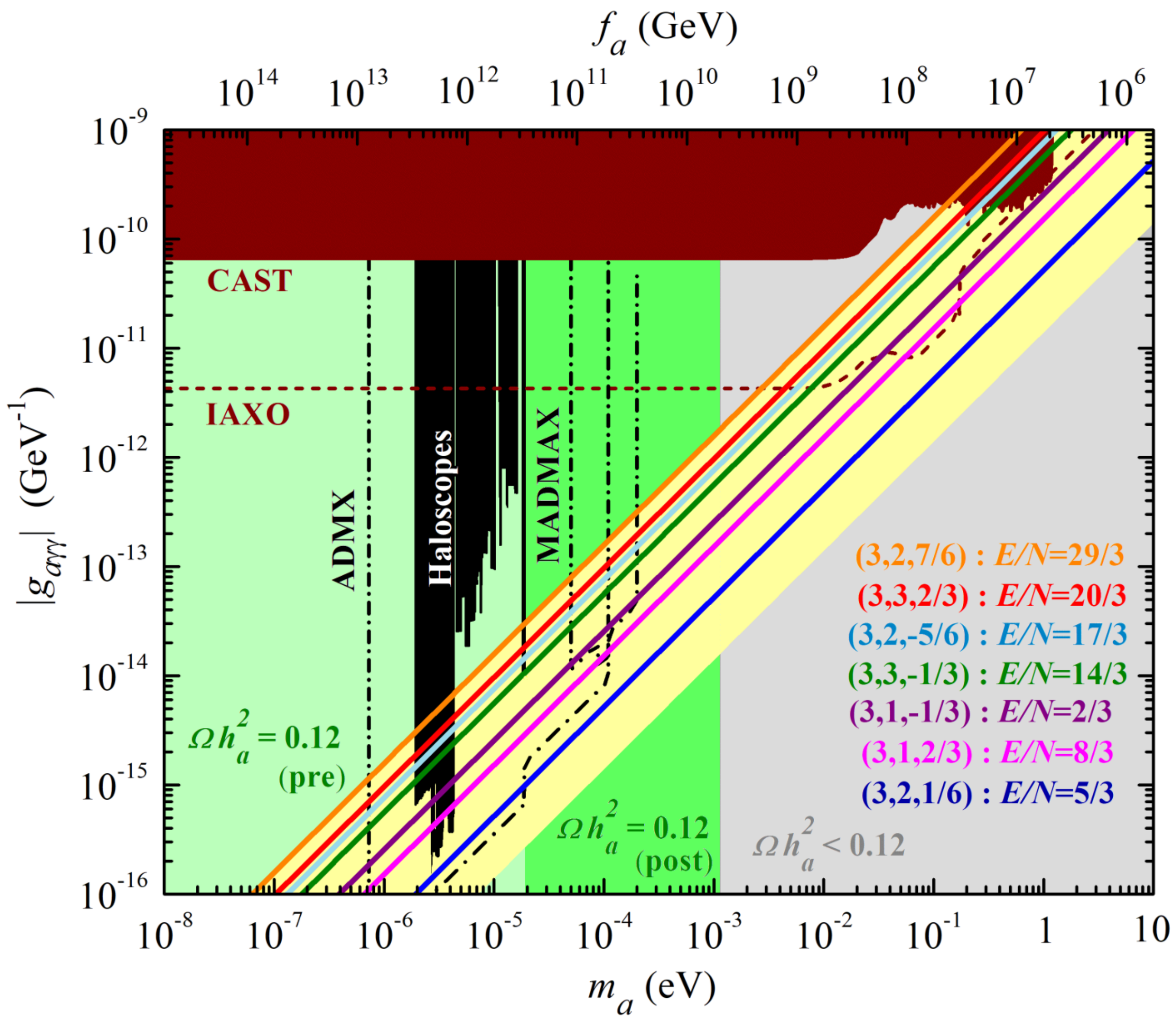
Axion dark matter

The initial misalignment angle is no longer a free variable in the post-inflationary scenario and by performing a statistical average one obtains, $\langle\theta_0^2\rangle \simeq 2.15^2 \implies f_a \lesssim 2\times 10^{11}\ \text{GeV}$

Probing the axion-to-photon coupling



Flavour-violating axion couplings

Mixing between the heavy VLQs and the ordinary SM quarks induces flavor-violating axion-quark couplings:

$$\mathcal{L}^{a}_{\mathrm{FV}} = \frac{\partial_\mu a}{v_\sigma} \overline{q_{\alpha X}} \, \gamma^\mu \, \mathcal{Q}_X (\tilde{\mathbf{\Theta}}^q_X)_{\alpha\beta} \, q_{\beta X}$$

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1	$-1/3$	0	$\mathbf{M}_{\Psi d} \overline{\Psi_L} d_R$	$\boxed{\Theta^d_R \sim M_{\Psi d}/M_\psi}$, $\Theta^d_L \sim (v/M_\Psi) Y_d \Theta^d_R$
	$2/3$		$\mathbf{M}_{\Psi u} \overline{\Psi_L} u_R$	$\boxed{\Theta^u_R \sim M_{\Psi u}/M_\psi}$, $\Theta^u_L \sim (v/M_\Psi) Y_u \Theta^u_R$
2	$1/6$	$1/2$	$\mathbf{M}_{q\Psi} \overline{q_L} \Psi_R$	$\boxed{\Theta^{d,u}_L \sim M_{q\Psi}/M_\psi}$, $\Theta^{d,u}_R \sim (v/M_\Psi) Y_{d,u} \Theta^{d,u}_L$
	$-5/6$	0	$\mathbf{Y}_{\Psi d} \overline{\Psi_L} \tilde{\Phi} d_R$	$\Theta^d_R \sim (v/M_\psi) Y_{\Psi d}$, $\Theta^d_L \sim (v/M_\Psi) Y_d \Theta^d_R$
	$7/6$		$\mathbf{Y}_{\Psi u} \overline{\Psi_L} \Phi u_R$	$\Theta^u_R \sim (v/M_\psi) Y_{\Psi u}$, $\Theta^u_L \sim (v/M_\Psi) Y_u \Theta^u_R$
3	$-1/3$	0	$\mathbf{Y}_{q\Psi} \overline{q_L} \Phi \Psi_R$	$\Theta^d_R \sim (v/M_\psi) Y_{q\Psi}$, $\Theta^d_L \sim (v/M_\Psi) Y_d \Theta^d_R$
	$2/3$		$\mathbf{Y}_{q\Psi} \overline{q_L} \tilde{\Phi} \Psi_R$	$\Theta^u_R \sim (v/M_\psi) Y_{q\Psi}$, $\Theta^u_L \sim (v/M_\Psi) Y_u \Theta^u_R$

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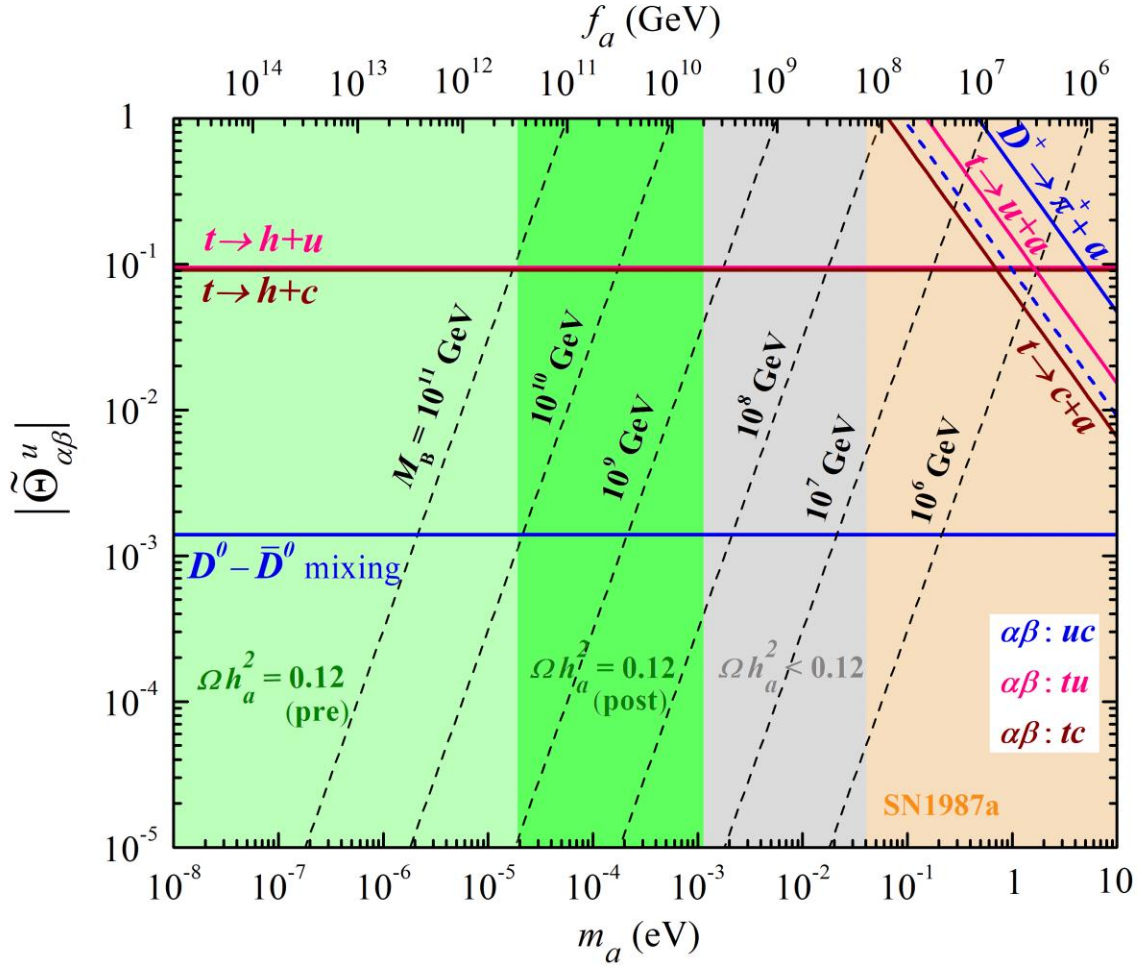

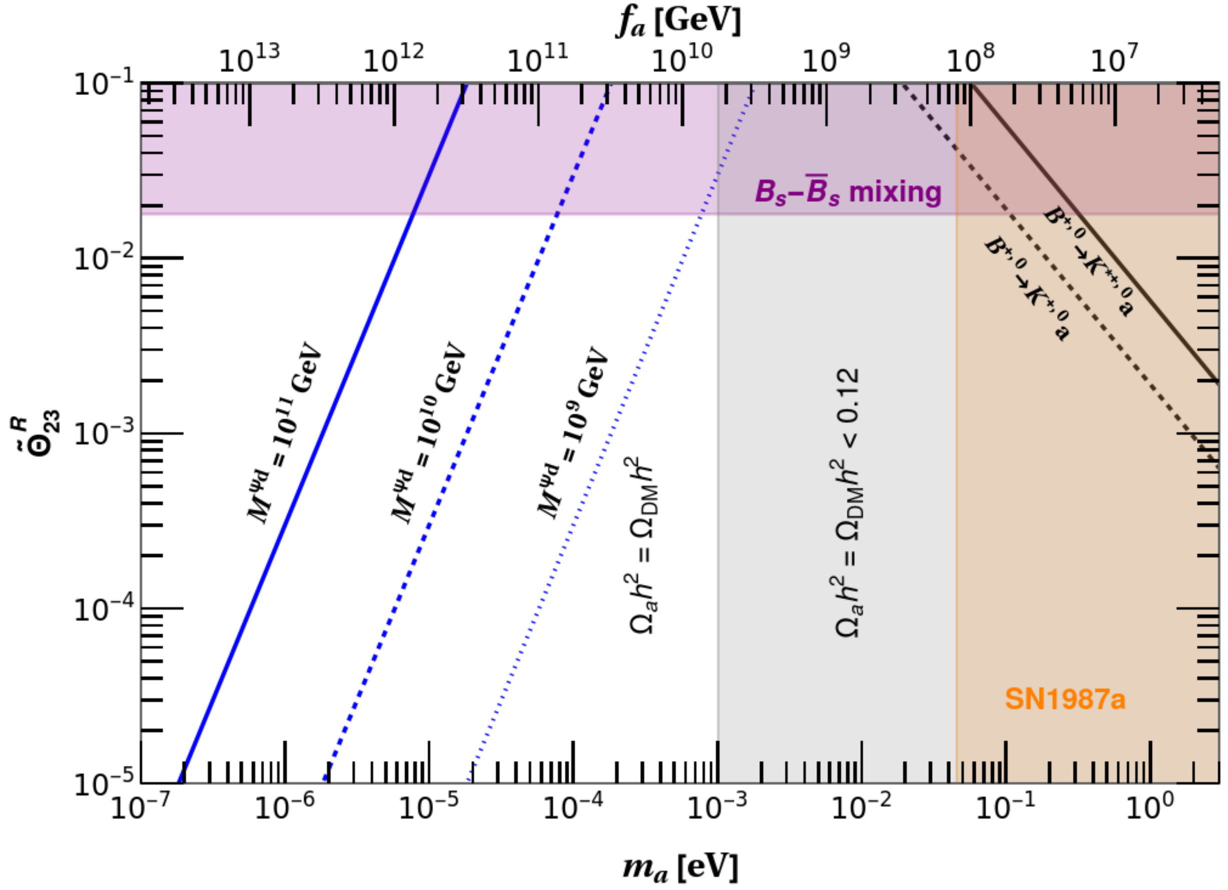

Concluding remarks

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