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Axion framework with colour-mediated Dirac neutrino masses

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Motivation

Although the Standard Model (SM) is highly successful in terms of producing experimental predictions, it cannot explain:

- **Neutrino flavour oscillations** which imply non-zero neutrino masses
- Observed **Dark Matter** abundance
- **Strong CP problem**: Lack of a theoretical explanation for the non-observation of the neutron electric dipole moment which indicates that strong interactions preserve CP symmetry.

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The unique dimension-five **Weinberg operator** leads to Majorana neutrino masses,

$$-\mathcal{L}^{d=5}_{\text{Maj.}} = \frac{\boldsymbol{\kappa}_{\text{Maj.}}}{\Lambda} \left(\bar{L}^c \tilde{\Phi}^*\right)\left(\tilde{\Phi}^\dagger L\right) + \text{H.c.}$$

The existence of **right-handed neutrinos** and the **absence of the Weinberg operator** leads to Dirac neutrino masses,

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

The Strong CP problem and axions

Strong CP problem

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

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

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Axion

Peccei,Quinn (1977),
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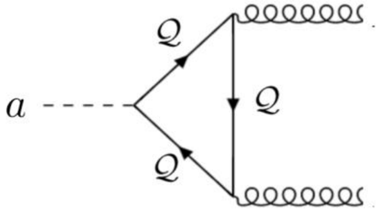
$$\mathrm{U}(1)_{\rm PQ}$$

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



KSVZ (1979, 1980)

Vector-like quarks

$$\Psi_{L,R}$$

$$\mathcal{L}_{\rm eff} \supset \frac{\alpha_s}{8\pi} \frac{a}{f_a} G^a_{\mu\nu} \tilde{G}^{a\,\mu\nu}$$

$$a(x) + \overline{\theta}\, f_a \to a(x)$$

$$\overline{\theta}_{\rm eff} = \overline{\theta} + \left\langle \frac{a}{f_a} \right\rangle = 0$$

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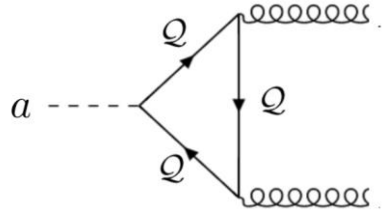

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Our approach:

New framework where **Dirac 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 Dirac neutrino masses

Fields	$\mathrm{SU}(3)_c \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$	$\mathrm{U}(1)_{\mathrm{PQ}}$
ℓ_L	$(\mathbf{1}, \mathbf{2}, -1/2)$	$1/6$
e_R	$(\mathbf{1}, \mathbf{1}, -1)$	$1/6$
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$\Psi_{1,2L}; \Psi_{1,2R}$	$(\mathbf{3}, \mathbf{n}_\Psi, y_\Psi)$	$\mathcal{Q}_{\mathrm{PQ}}; \mathcal{Q}_{\mathrm{PQ}} - 1/2$
Φ	$(\mathbf{1}, \mathbf{2}, 1/2)$	0
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Scalar Potential: $$V \supset \kappa \, (\eta^\dagger \Phi) \chi + \text{H.c.}$$

Axion dark matter and cosmology

Due to their **weak interactions** with ordinary matter, **cosmological stability**, and **light mass**, axions are viable dark matter candidates. They can also be nonthermally produced in the early Universe via the **misalignment mechanism**.

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Relic abundance in the pre-inflationary scenario:

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

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

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The initial misalignment angle is not a free variable in the post-inflationary scenario and by performing a statistical average,

$$\langle \theta_0^2 \rangle \simeq 2.15^2 \Longrightarrow f_a \lesssim 2 \times 10^{11} \ \mathrm{GeV}$$

Axion paradigm with colour-mediated Dirac neutrino masses

Mixing between the heavy VLQs and the ordinary SM quarks leads to the **decay of baryonic relics**.

$\mathbf{n}_\Psi$	y_Ψ	$\mathcal{Q}_{PQ}$	$\mathbf{n}_\eta$	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		$\overline{\Psi_L} u_R$	-
$\mathbf{2}$	$1/6$	$1/2$	$\mathbf{1,3}$	$\overline{q_L}\Psi_R$	$\overline{\ell_L}\chi^* d_R$
		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	$\mathbf{2}$	$\overline{q_L}\Phi\Psi_R$	$\overline{\ell_L}\tilde{\eta} d_R$
			$\mathbf{4}$		-
	$2/3$		$\mathbf{2}$	$\overline{q_L}\tilde{\Phi}\Psi_R$	$\overline{\ell_L}\tilde{\eta} u_R, \overline{q_L}\eta e_R$
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There is a **residual $\mathcal{Z}_3$ symmetry** under which,

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

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This **forbids** all **Majorana** type operators,

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

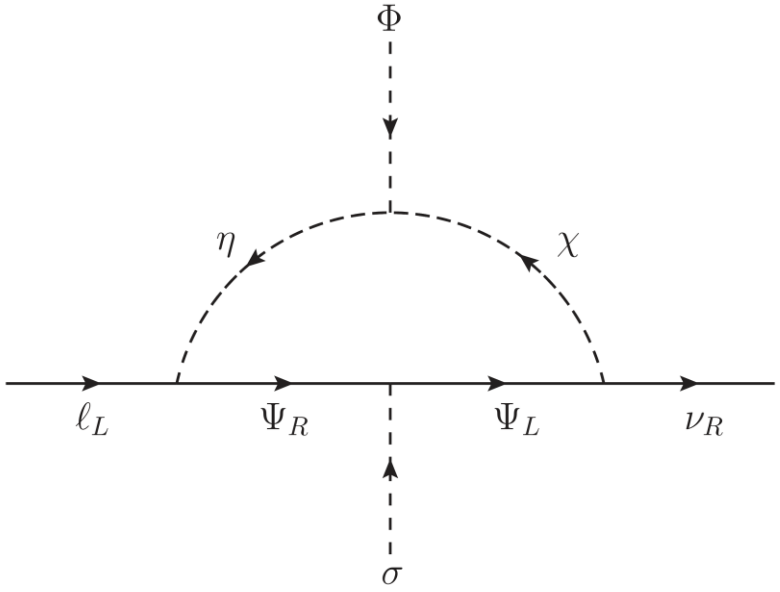
However, there is an **accidental baryon number symmetry** under which the SM quark fields and the new colored ones are equally charged **forbids dangerous proton decay** operators such as the dimension 6,

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

Axion paradigm with colour-mediated neutrino masses

Neutrino mass generation

One-loop colour-mediated Dirac neutrino masses



Axion paradigm with colour-mediated neutrino masses

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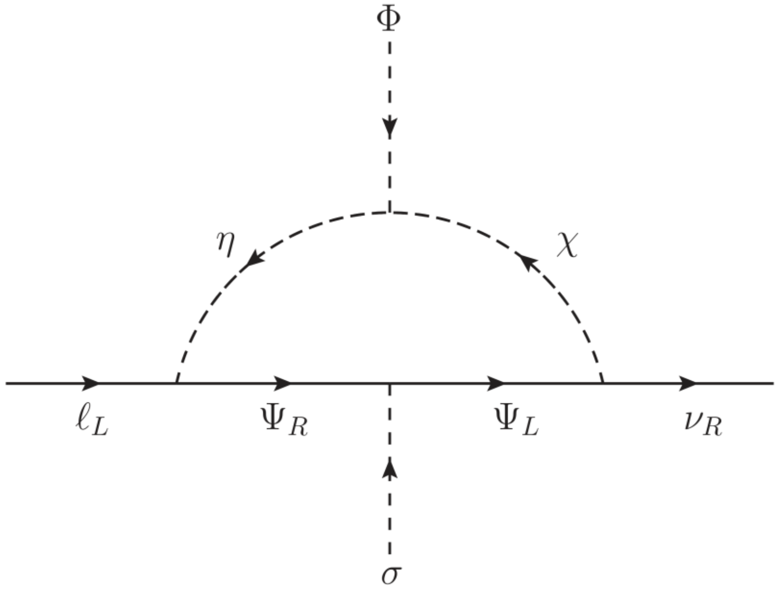

$$(M_\nu)_{\alpha\beta} \sim 0.1\text{eV} \left(\frac{(\tilde{Y}_\eta)_{\alpha j}(\tilde{Y}_\chi)_{j\beta}}{10^{-2}}\right)\left(\frac{\kappa}{10^2\ \text{GeV}}\right)\left(\frac{\tilde{M}_{\Psi j}}{10^{12}\ \text{GeV}}\right)\left(\frac{10^{10}\ \text{GeV}}{m_{\zeta_k}}\right)^2$$

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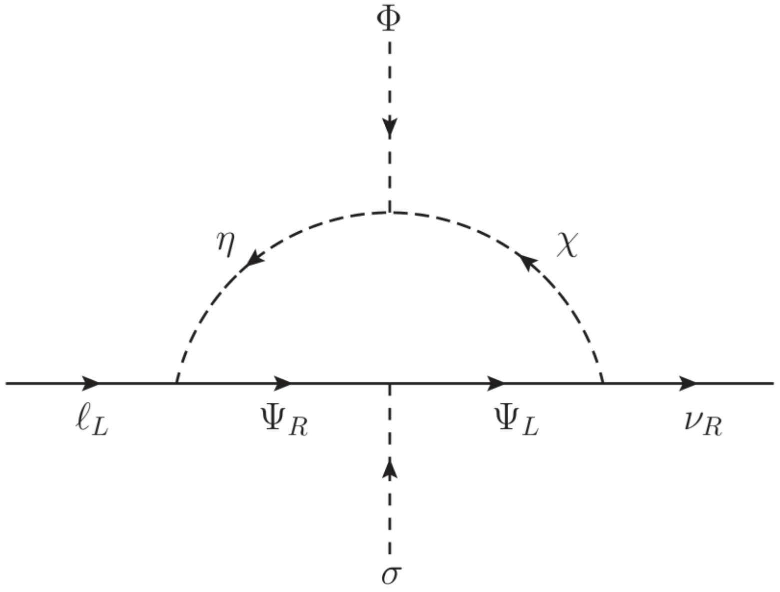

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Strong CP problem

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

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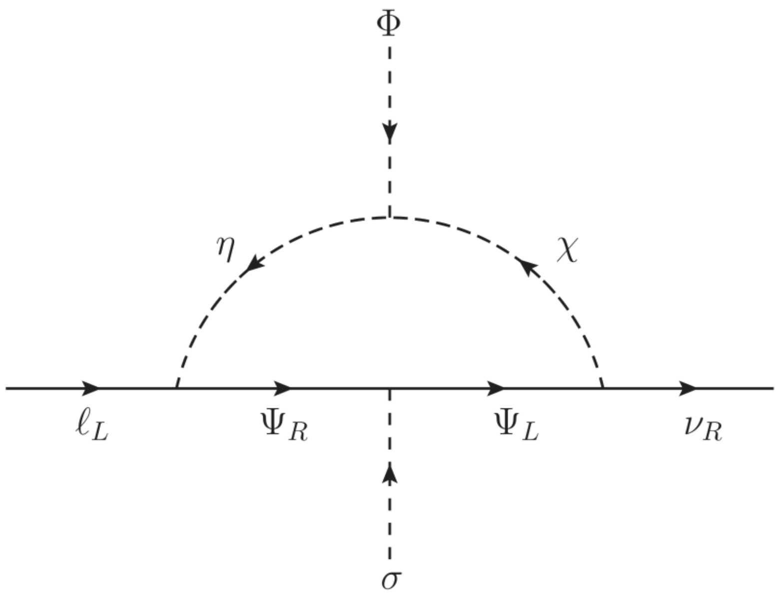

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Axion decay constant

$$f_a = \frac{f_{\text{PQ}}}{N} = \frac{v_\sigma}{\sqrt{2}N}$$

QCD axion mass relation

$$m_a = 5.70(7)\left(\frac{10^{12}\ \text{GeV}}{f_a}\right)\ \mu\text{eV}$$

Cortona et al.(2016)

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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Model dependent contribution to the electromagnetic and colour anomaly factors:

$$E = 2 \sum_f \left(\omega_L^f - \omega_R^f \right) q_f^2$$

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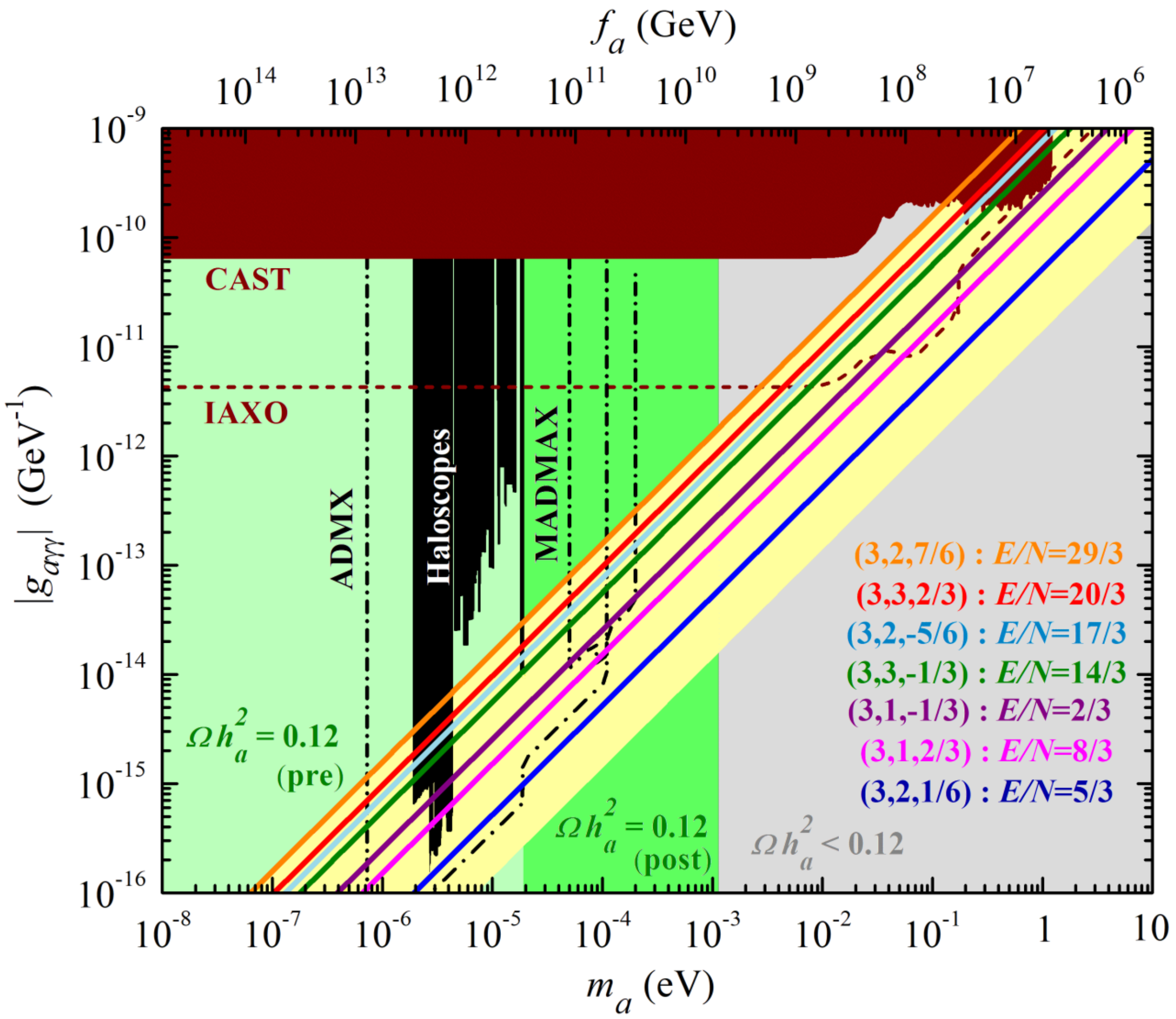

The different models can be probed through the **axion-to-photon coupling** at **helioscope** and **haloscope** experiments.

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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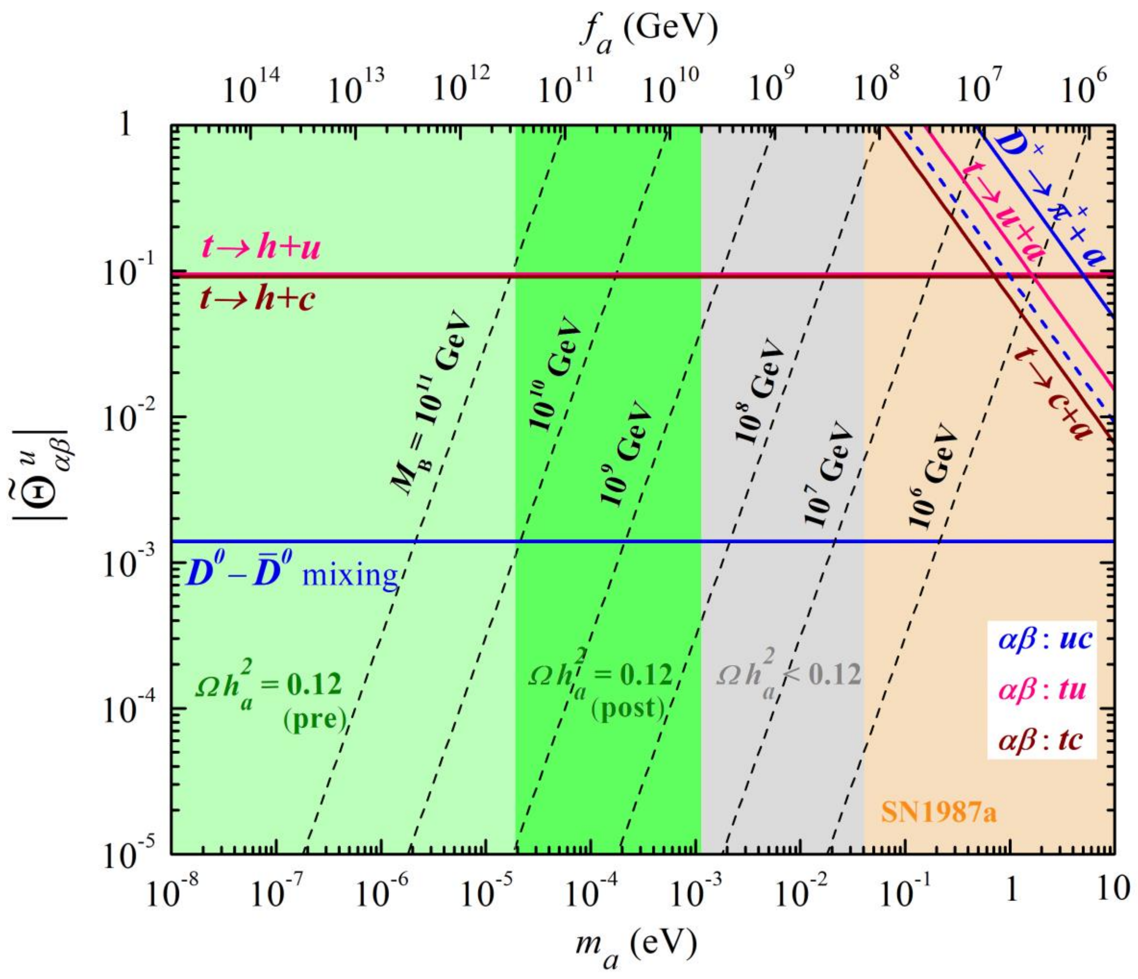
$\mathbf{n}_\Psi$	y_Ψ	$\mathcal{Q}_{\rm PQ}$	Heavy-light quark mixing terms	$\mathbf{\Theta}^q_X$ mixing parameter
1	$-1/3$	0	$\mathbf{M}_{\Psi d}\overline{\Psi_L} d_R$	$\boxed{\Theta^d_R \sim M_{\Psi d}/M_\psi}$, $\Theta^d_L \sim (v/M_\Psi) Y_d \Theta^d_R$
	$2/3$		$\mathbf{M}_{\Psi u}\overline{\Psi_L} u_R$	$\boxed{\Theta^u_R \sim M_{\Psi u}/M_\psi}$, $\Theta^u_L \sim (v/M_\Psi) Y_u \Theta^u_R$
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	$\mathbf{Y}_{q\Psi}\overline{q_L}\Phi\Psi_R$	$\Theta^d_R \sim (v/M_\psi) Y_{q\Psi}$, $\Theta^d_L \sim (v/M_\Psi) Y_d \Theta^d_R$
	$2/3$		$\mathbf{Y}_{q\Psi}\overline{q_L}\tilde{\Phi}\Psi_R$	$\Theta^u_R \sim (v/M_\psi) Y_{q\Psi}$, $\Theta^u_L \sim (v/M_\Psi) Y_u \Theta^u_R$

Flavour-violating axion couplings

Up sector



Down sector

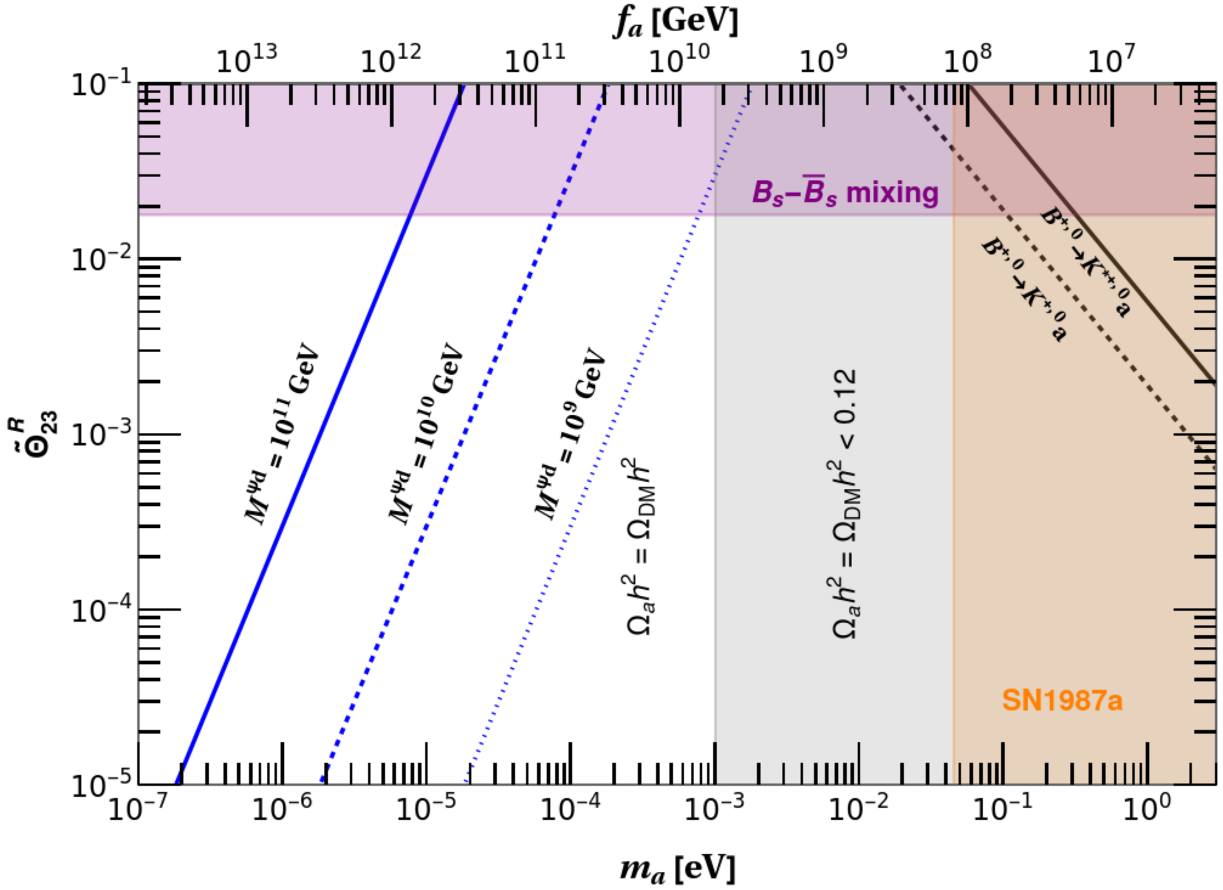


Figure taken from C. Hati et al., arXiv:2408.00060 [hep-ph]

Concluding remarks

- We have proposed a theoretical framework addressing three open problems of the SM: **neutrino masses, dark matter, and the strong CP problem**.

- A **Peccei-Quinn symmetry** under which exotic fermions are chirally charged leads to a **KSVZ-type axion**, solving the strong CP problem. Neutrino masses are generated at the one-loop level by the **exchange of colored particles**. The PQ symmetry ensures the **Dirac nature of light neutrinos** and **forbids proton decay**.

- We examined all possible scenarios resulting in **heavy-light quark mixing**. These enable us to consider the more predictive **post-inflationary axion DM** picture.

- Our various models can be scrutinized through their distinctive **axion-to-photon coupling** predictions at future **haloscope and helioscope experiments**. Due to the heavy-light quark mixing, some of our models allow for complementary phenomenological features associated to sizable **axion-to-quark flavor-violating couplings**.

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Thank you!