Finanziato dall'Unione europea NextGenerationEU | Ministero dell'Università e della Ricerca | Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA | INFN Istituto Nazionale di Fisica Nucleare

Imperfect Axions

59th Rencontres de Moriond (EW)
23-30 March 2025

Luca Di Luzio

INFN PADOVA

Work supported by the European Union - Next Generation EU and by the Italian Ministry of University and Research (MUR) via the PRIN 2022 project n. 2022K4B58X - AxionOrigins

Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
INFN Istituto Nazionale di Fisica Nucleare

Outline

1. Imperfect axions: CP violation & PQ breaking

2. CP-violating axions and new macroscopic forces

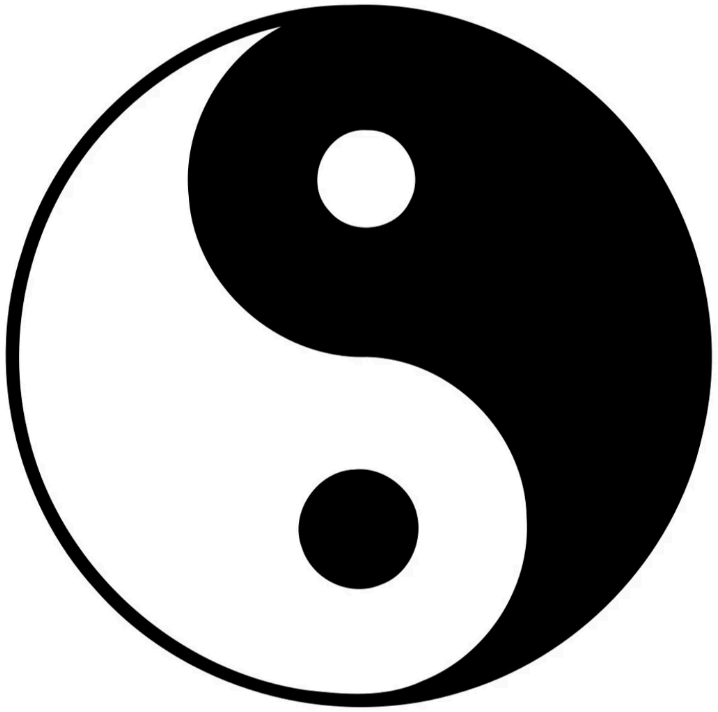
[Bertolini, LDL, Nesti 2006.12508 PRL
LDL, Gisbert, Nesti, Sørensen 2407.15928 PRD]

3. PQ quality from the interplay of vertical/horizontal gauge symmetries

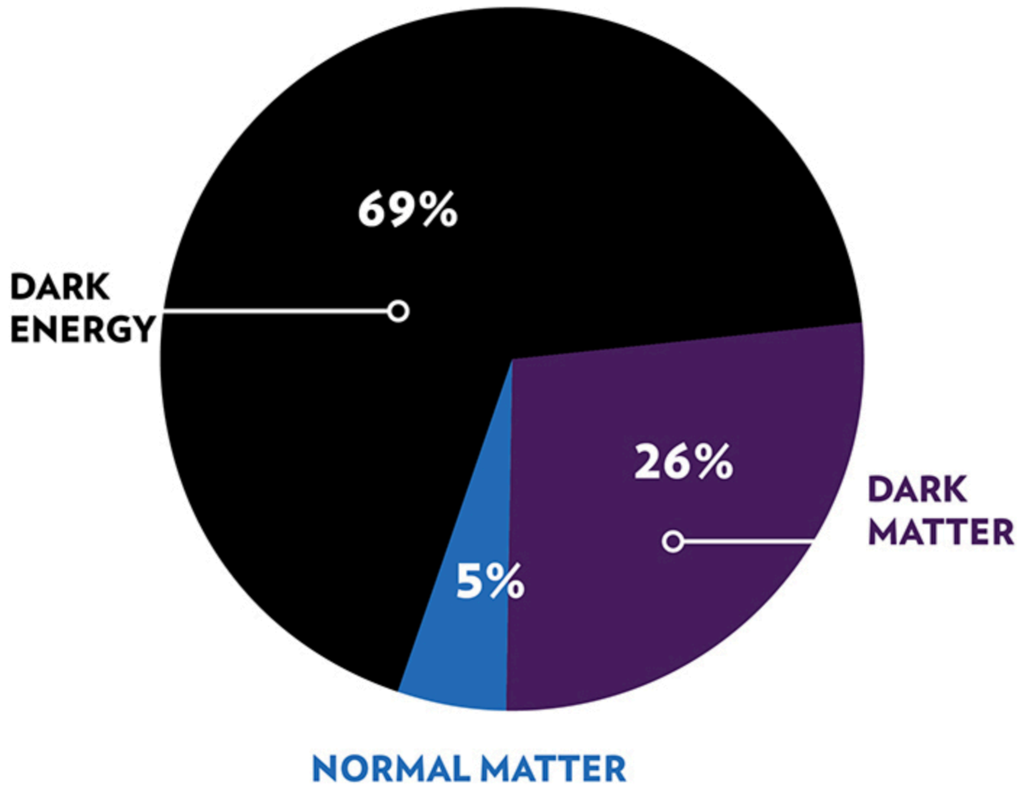
[LDL 2008.09119 JHEP
[LDL, Landini, Mescia, Susič 2503.16648]

The QCD axion

Strong CP problem



Dark Matter



The QCD axion

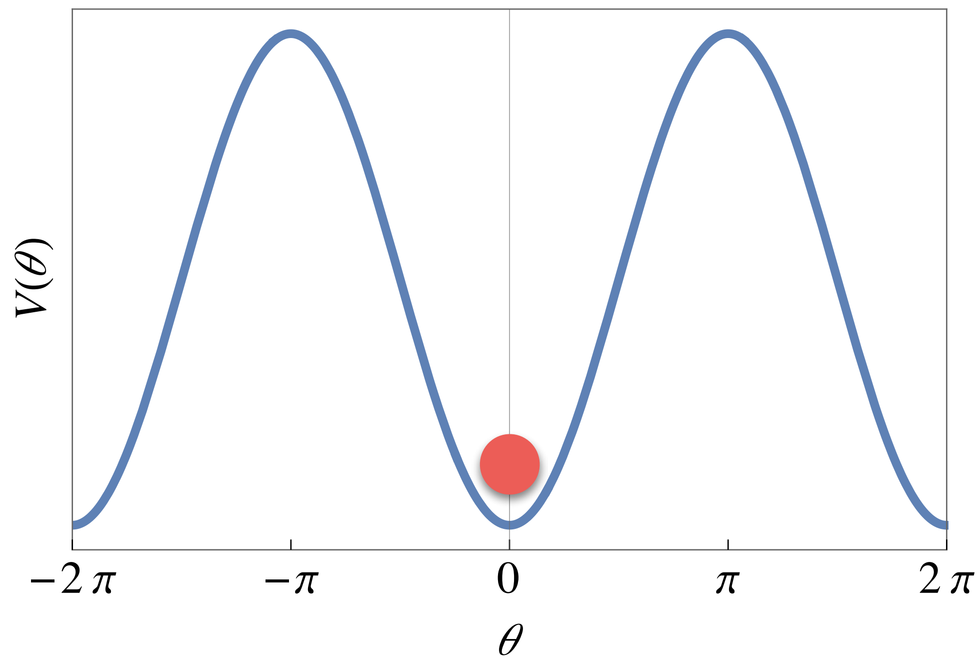
Strong CP problem

$$\delta \mathcal{L}_{\rm QCD} = \theta \frac{g_s^2}{32\pi^2} G\tilde{G} \qquad |\theta| \lesssim 10^{-10}$$

promote θ to a dynamical field (axion) which relaxes to zero

$$\theta \to \frac{a}{f_a} \quad \textit{with} \quad \langle a \rangle = 0$$

[Peccei, Quinn '77, Weinberg '78, Wilczek '78]



Dark Matter

$\Omega_{\rm DM}$ (non-thermal production)

i) misalignment mechanism (axion oscillations)

ii) topological defects: strings & domain walls

[Preskill, Wise, Wilczek '83
Abbott, Sikivie '83
Dine, Fischler '83,
Davies '86,
Harari, Sikivie '87, …]

PQ mechanism

- New spin-0 boson with a pseudo-shift symmetry $a \to a + \kappa f_a$

broken by $\frac{a}{f_a} \frac{g_s^2}{32\pi^2} G\tilde{G}$ → $E(0) \leq E(\langle a \rangle)$ [Vafa, Witten PRL 53 (1984)]

PQ mechanism

- New spin-0 boson with a pseudo-shift symmetry $a \to a + \kappa f_a$

broken by $\frac{a}{f_a}\frac{g_s^2}{32\pi^2}G\tilde{G}$ → $E(0) \leq E(\langle a \rangle)$ [Vafa, Witten PRL 53 (1984)]

$$\theta_{\text{eff}} = \frac{\langle a \rangle}{f_a}$$

$$\begin{aligned} e^{-V_4 E(\theta_{\text{eff}})} &= \int \mathcal{D}\varphi \, e^{-S_0 + i\theta_{\text{eff}} \int G\tilde{G}} \\ &= \left| \int \mathcal{D}\varphi \, e^{-S_0 + i\theta_{\text{eff}} \int G\tilde{G}} \right| \\ &\leq \int \mathcal{D}\varphi \left| e^{-S_0 + i\theta_{\text{eff}} \int G\tilde{G}} \right| = e^{-V_4 E(0)} \end{aligned}$$

(path-integral measure positive definite for a vector-like theory, e.g. QCD)

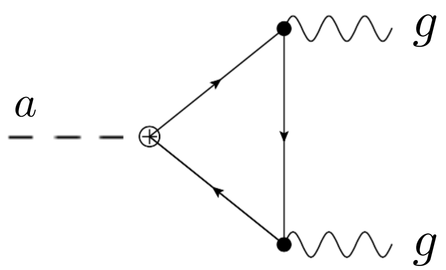
PQ mechanism

- New spin-0 boson with a pseudo-shift symmetry $a \to a + \kappa f_a$

broken by $\frac{a}{f_a}\frac{g_s^2}{32\pi^2}G\tilde{G}$ → $E(0) \leq E(\langle a \rangle)$ [Vafa, Witten PRL 53 (1984)]

- its origin* can be traced back to a global $U(1)_{PQ}$ [Peccei, Quinn '77, Weinberg '78, Wilczek '78]

1. spontaneously broken (the axion is the associated pNGB)
2. QCD anomalous



$$\partial^\mu J_\mu^{PQ} = \frac{N\alpha_s}{4\pi}G \cdot \tilde{G}$$

*axions can also arise as zero modes from string theory compactification [Witten PLB 149 (1984), ...]

Imperfect axions

- Does the axion really relax to zero ?

  - PQ mechanism is imperfect already in the SM (due to CKM)

$$\theta_{\rm eff} = \frac{\langle a \rangle}{f_a} \sim G_F^2 f_\pi^4 j_{\rm CKM} \approx 10^{-18}$$

[Georgi, Randall, NPB276 (1986)]

Imperfect axions

- Does the axion really relax to zero ?

  - PQ mechanism is imperfect already in the SM (due to CKM)

  - $U(1)_{PQ}$ is not expected to be exact (being a global symmetry)

$$\theta_{\rm eff} \equiv \frac{\langle a \rangle}{f_a} \lesssim 10^{-10}$$

$$\mathcal{O}_{\rm PQ-break} = \frac{\phi^d}{\Lambda_{\rm UV}^{d-4}} \quad \longrightarrow \quad \left(\frac{f_a}{\Lambda_{\rm UV}}\right)^{d-4} f_a^4 \lesssim 10^{-10} \Lambda^4_{\rm QCD}$$

$$\phi \sim f_a e^{i\frac{a}{f_a}}$$

$\longrightarrow$ $d \gtrsim 9$ (for $\Lambda_{\rm UV} \sim M_{\rm Pl}$ and $f_a \sim 10^9$ GeV)

PQ-quality problem

[Barr, Seckel PRD 46 (1992)
Kamionkowski, March-Russell PLB 282 (1992)
Holman+ PLB 282 (1992), …]

CP-violating axions

- $\mathscr{L} \supset g^P_{aN} a \overline{N} i \gamma_5 N + g^S_{aN} a \overline{N} N$

$$g^S_{aN} \sim \frac{f_\pi}{f_a} \theta_{\text{eff}}$$

← from UV sources of CP-violation or PQ breaking

[Moody, Wilczek PRD 30 (1984)
Barbieri, Romanino, Strumia hep-ph/9605368
Pospelov hep-ph/9707431
Bertolini, LDL, Nesti 2006.12508
Okawa, Pospelov, Ritz, 2111.08040
Dekens, de Vries, Shain, 2203.11230]

CP-violating axions

- $\mathscr{L} \supset g^P_{aN} a \overline{N} i\gamma_5 N + g^S_{aN} a \overline{N} N$ $g^S_{aN} \sim \frac{f_\pi}{f_a}\theta_{\rm eff}$ ← from UV sources of CP-violation or PQ breaking

[Moody, Wilczek PRD 30 (1984)
Barbieri, Romanino, Strumia hep-ph/9605368
Pospelov hep-ph/9707431
Bertolini, LDL, Nesti 2006.12508
Okawa, Pospelov, Ritz, 2111.08040
Dekens, de Vries, Shain, 2203.11230]

- From LO bary-meson chiral Lagrangian

[Bertolini, LDL, Nesti 2006.12508
PRL126 (2021)]

$$g^S_{an,\,p} \simeq \frac{4B_0\, m_u m_d}{f_a(m_u+m_d)}\left[\pm\,(b_D+b_F)\frac{\langle\pi^0\rangle}{F_\pi} + \frac{b_D-3b_F}{\sqrt{3}}\frac{\langle\eta_8\rangle}{F_\pi} - \sqrt{\frac{2}{3}}(3b_0+2b_D)\frac{\langle\eta_0\rangle}{F_\pi} - \left(b_0+(b_D+b_F)\frac{m_{u,d}}{m_d+m_u}\right)\theta_{\rm eff}\right]$$

- *meson tadpoles (absent if origin of CPV is due to PQ breaking)*

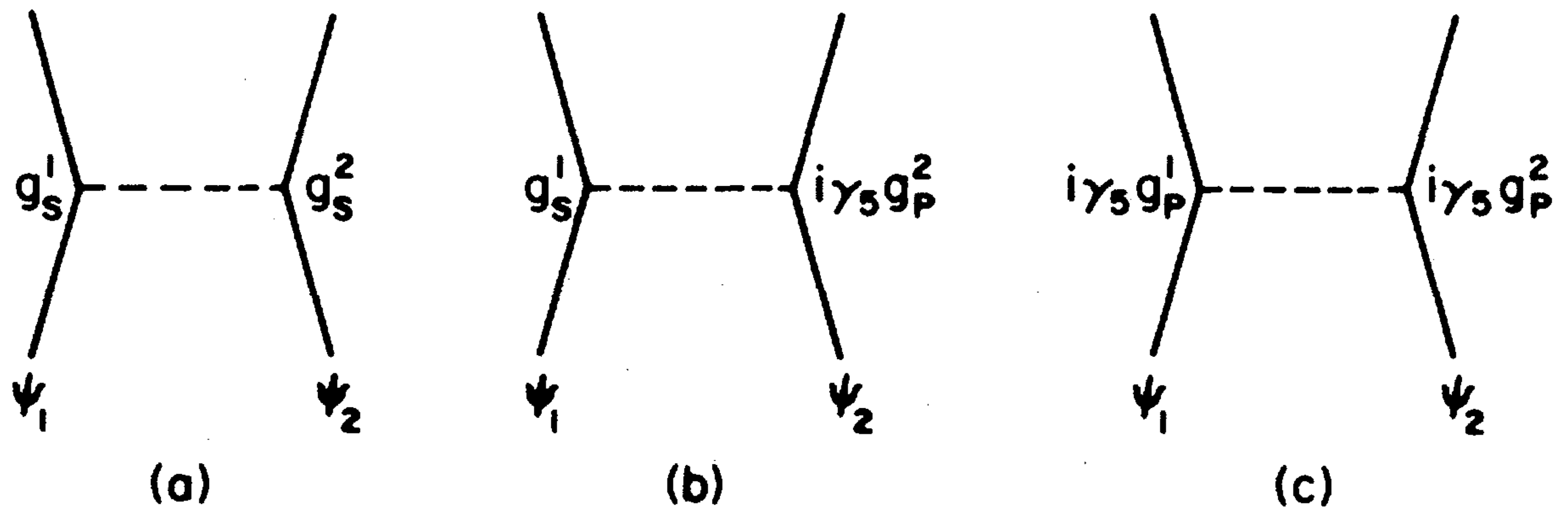
- *iso-spin breaking*

- *MW missed a factor 1/2*

CP-violating axions

- $\mathscr{L} \supset g^P_{aN} a \overline{N} i\gamma_5 N + g^S_{aN} a \overline{N} N$ $\qquad g^S_{aN} \sim \frac{f_\pi}{f_a}\theta_{\text{eff}}$ ← from UV sources of CP-violation or PQ breaking

New macroscopic forces from non-relativistic potentials [Moody, Wilczek PRD 30 (1984)]



monopole-monopole | monopole-dipole | dipole-dipole

$$V(r) = \frac{-g_S^1 g_S^2 e^{-m_\varphi r}}{4\pi r}$$

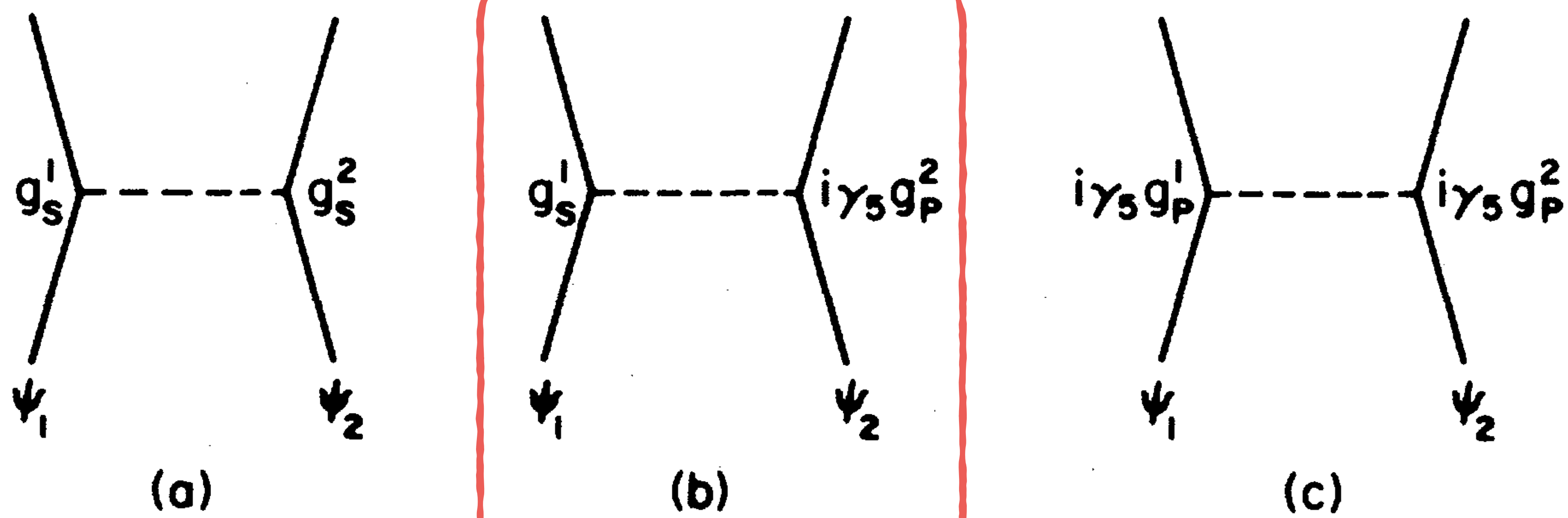
$$V(r) = (g_S^1 g_P^2)\frac{\hat{\sigma}_2 \cdot \hat{r}}{8\pi M_2}\left[\frac{m_\varphi}{r} + \frac{1}{r^2}\right] e^{-m_\varphi r}$$

. . .

CP-violating axions

- $\mathscr{L} \supset g^P_{aN} a \overline{N} i\gamma_5 N + g^S_{aN} a \overline{N} N$ $\qquad g^S_{aN} \sim \frac{f_\pi}{f_a}\theta_{\rm eff}$ ← from UV sources of CP-violation or PQ breaking

New macroscopic forces from non-relativistic potentials [Moody, Wilczek PRD 30 (1984)]



monopole-monopole	monopole-dipole	dipole-dipole
double $\theta_{\rm eff}$ suppression	ARIADNE, QUAX-gpgs, …	*spin suppression + bkgd from ordinary magnetic forces*

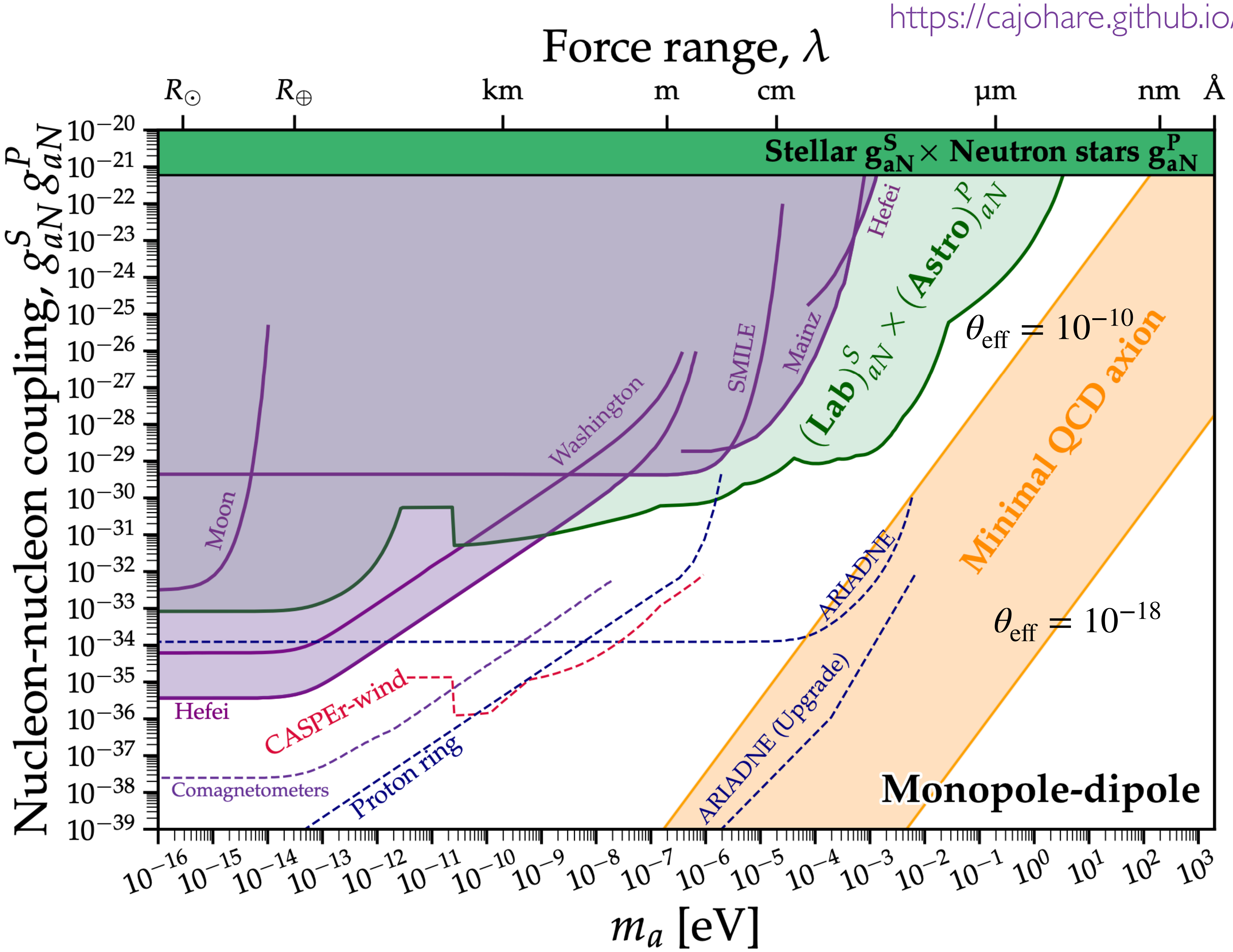
CP-violating axions

- $\mathscr{L} \supset g^P_{aN} a \overline{N} i \gamma_5 N + g^S_{aN} a \overline{N} N$

$$g^S_{aN} \sim \frac{f_\pi}{f_a} \theta_{\text{eff}}$$

from UV sources of CP-violation or PQ breaking

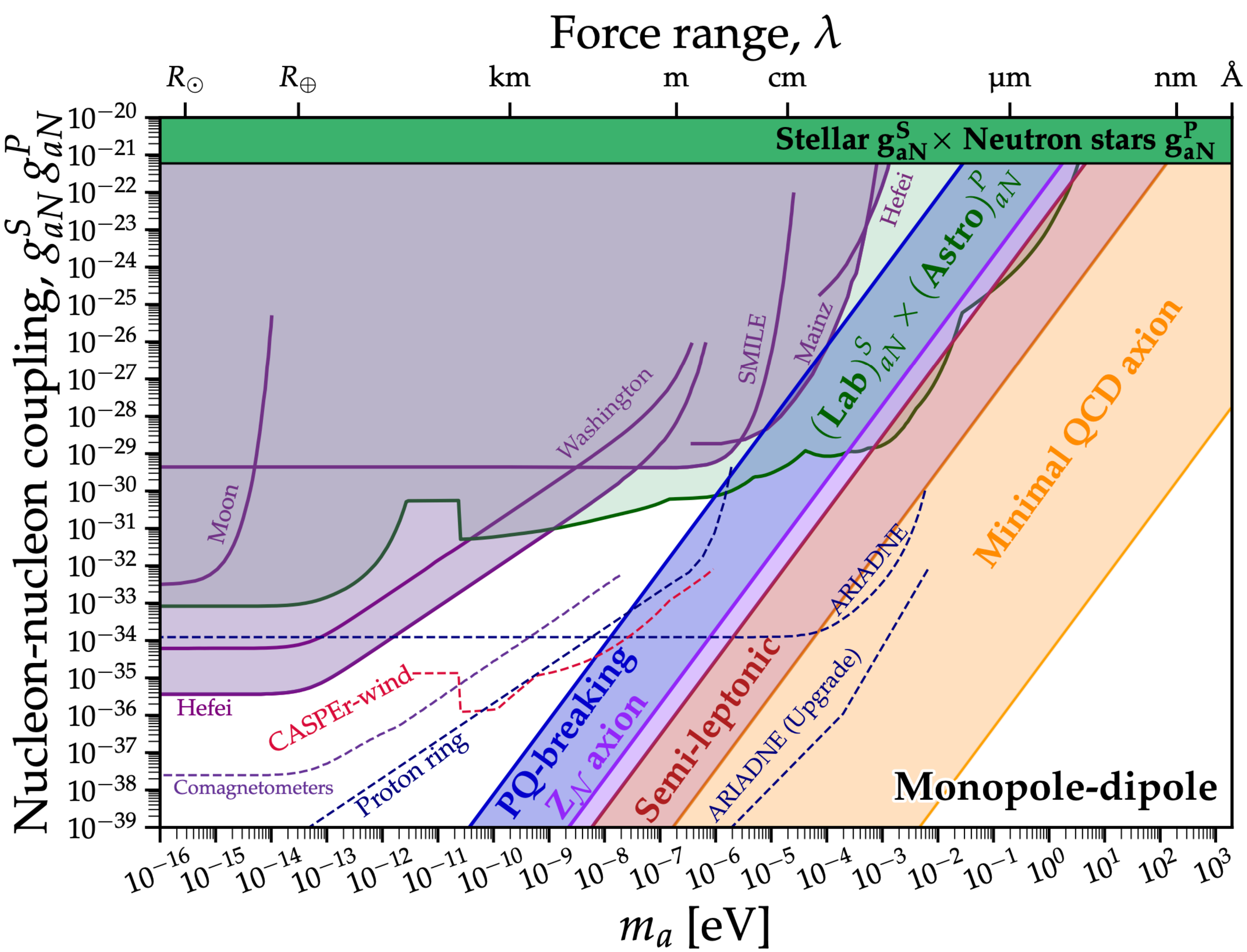
[O'Hare, Vitagliano 2010.03889 https://cajohare.github.io/AxionLimits]



CP-violating axions

- $\mathscr{L} \supset g^P_{aN} a\bar{N} i\gamma_5 N + g^S_{aN} a\bar{N}N$ $g^S_{aN} \sim \frac{f_\pi}{f_a}\theta_{\text{eff}}$ ← from UV sources of CP-violation or PQ breaking

[LDL, Gisbert, Nesti, Sørensen 2407.15928]



The need for a “PQ theory”

- $U(1)_{PQ}$ often imposed ‘by hand’, while a proper PQ theory should:

1. realise the PQ as an accidental symmetry
2. protect the $U(1)_{PQ}$ against UV sources of PQ breaking (PQ-quality problem)

The need for a “PQ theory”

- $U(1)_{PQ}$ often imposed ‘by hand’, while a proper PQ theory should:

  1. realise the PQ as an accidental symmetry

  2. protect the $U(1)_{PQ}$ against UV sources of PQ breaking (PQ-quality problem)

- Many attempts based on extra discrete/continuous gauge symmetries

  - ad-hoc gauge symmetries (e.g. $\mathbf{Z}_9$ symmetry acting on ϕ allows only ϕ^9 terms and higher)

  - solution to PQ-quality problem hidden in the UV

Accidental SO(10) axion

- Automatic $U(1)_{PQ}$ in SO(10), upon gauging the flavour group $SU(3)_f$ [LDL 2008.09119]

[See also Chang, Senjanovic PLB 188 (1987)]

$$\psi_{16}^i = \begin{pmatrix} u_L^1 & u_L^2 & u_L^3 & \nu_L & u_R^{1c} & u_R^{2c} & u_R^{3c} & \nu_R^c \\ d_L^1 & d_L^2 & d_L^3 & e_L & d_R^{1c} & d_R^{2c} & d_R^{3c} & e_R^c \end{pmatrix}^i \qquad i = 1, 2, 3$$

→ $\mathrm{U}(3) = \mathrm{U}(1)_{\mathrm{PQ}} \times \mathrm{SU}(3)_f$

Accidental SO(10) axion

- Automatic $U(1)_{PQ}$ in SO(10), upon gauging the flavour group $SU(3)_f$ [LDL 2008.09119]

[See also Chang, Senjanovic PLB 188 (1987)]

$$\psi^i_{16} = \begin{pmatrix} u^1_L & u^2_L & u^3_L & \nu_L & u^{1c}_R & u^{2c}_R & u^{3c}_R & \nu^c_R \\ d^1_L & d^2_L & d^3_L & e_L & d^{1c}_R & d^{2c}_R & d^{3c}_R & e^c_R \end{pmatrix}^i \qquad i = 1, 2, 3$$

→ $$\mathrm{U}(3) = \mathrm{U}(1)_{\mathrm{PQ}} \times \mathrm{SU}(3)_f$$

$\psi_{16} \to e^{i\alpha} \psi_{16}$ *born as a PQ symmetry, due to chiral SO(10) embedding*

Accidental SO(10) axion

- Automatic $U(1)_{PQ}$ in SO(10), upon gauging the flavour group $SU(3)_f$ [LDL 2008.09119]

[See also Chang, Senjanovic PLB 188 (1987)]

Field	Lorentz	SO(10)	$\mathbb{Z}_4$	$SU(3)_f$	$\mathbb{Z}_3$	$U(1)_{PQ}$
ψ_{16}	$(1/2,0)$	16	i	$\mathbf{3}$	$e^{i2\pi/3}$	1
$\psi_1^{1,\dots,16}$	$(1/2,0)$	1	1	$\overline{\mathbf{3}}$	$e^{i4\pi/3}$	0
ϕ_{10}	$(0,0)$	10	-1	$\overline{\mathbf{6}}$	$e^{i2\pi/3}$	-2
ϕ_{16}	$(0,0)$	16	i	$\overline{\mathbf{3}}$	$e^{i4\pi/3}$	-1
$\phi_{\overline{126}}$	$(0,0)$	$\overline{126}$	-1	$\overline{\mathbf{6}}$	$e^{i2\pi/3}$	-2
ϕ_{45}	$(0,0)$	45	1	$\mathbf{1}$	1	0

- $U(1)_{PQ}$ arises accidentally in the renormalizable Lagrangian

$$\mathscr{L}_Y = y_{10}\,\psi_{16}\psi_{16}\phi_{10} + y_{\overline{126}}\,\psi_{16}\psi_{16}\phi_{\overline{126}} + \text{h.c.}$$

$$\mathcal{V}_2 = |\phi_{10}|^2 + |\phi_{\overline{126}}|^2 + \phi_{45}^2 + |\phi_{16}|^2\,,$$

$$\mathcal{V}_3 = \phi_{16}^2\phi_{10}^\star + \text{h.c.}\,,$$

$$\mathcal{V}_4 = \mathcal{V}_2^2\text{-terms} + \phi_{10}^2\phi_{\overline{126}}^{\star 2} + \phi_{10}\phi_{\overline{126}}\phi_{\overline{126}}^{\star 2} + \phi_{16}^2\phi_{10}^\star\phi_{45} + \text{h.c.}$$

Accidental SO(10) axion

- Automatic $U(1)_{PQ}$ in SO(10), upon gauging the flavour group $SU(3)_f$ [LDL 2008.09119]

Field	Lorentz	SO(10)	$\mathbb{Z}_4$	$SU(3)_f$	$\mathbb{Z}_3$	$U(1)_{PQ}$
ψ_{16}	$(1/2, 0)$	16	i	$\mathbf{3}$	$e^{i2\pi/3}$	1
$\psi_1^{1,\ldots,16}$	$(1/2, 0)$	1	1	$\overline{\mathbf{3}}$	$e^{i4\pi/3}$	0
ϕ_{10}	$(0, 0)$	10	-1	$\overline{\mathbf{6}}$	$e^{i2\pi/3}$	-2
ϕ_{16}	$(0, 0)$	16	i	$\overline{\mathbf{3}}$	$e^{i4\pi/3}$	-1
$\phi_{\overline{126}}$	$(0, 0)$	$\overline{126}$	-1	$\overline{\mathbf{6}}$	$e^{i2\pi/3}$	-2
ϕ_{45}	$(0, 0)$	45	1	$\mathbf{1}$	1	0

- $U(1)_{PQ}$ arises accidentally in the renormalizable Lagrangian

→ Leading PQ-breaking operator is $\phi_{16}^6 \phi_{\overline{126}}^3$ (d=9)

(protection neatly understood in terms of Z_4 x Z_3 center)

Accidental SO(10) axion

- Automatic $U(1)_{PQ}$ in SO(10), upon gauging the flavour group $SU(3)_f$ [LDL 2008.09119]

Field	Lorentz	SO(10)	$\mathbb{Z}_4$	$SU(3)_f$	$\mathbb{Z}_3$	$U(1)_{PQ}$
ψ_{16}	$(1/2,0)$	16	i	$\mathbf{3}$	$e^{i2\pi/3}$	1
$\psi_1^{1,\ldots,16}$	$(1/2,0)$	1	1	$\overline{\mathbf{3}}$	$e^{i4\pi/3}$	0
ϕ_{10}	$(0,0)$	10	-1	$\overline{\mathbf{6}}$	$e^{i2\pi/3}$	-2
ϕ_{16}	$(0,0)$	16	i	$\overline{\mathbf{3}}$	$e^{i4\pi/3}$	-1
$\phi_{\overline{126}}$	$(0,0)$	$\overline{126}$	-1	$\overline{\mathbf{6}}$	$e^{i2\pi/3}$	-2
ϕ_{45}	$(0,0)$	45	1	$\mathbf{1}$	1	0

- Axion in a linear combination of 16 and 126 phases

$$f_a = \frac{V_{\overline{126}} V_{16}}{3\sqrt{V_{16}^2 + 4V_{\overline{126}}^2}}$$

$$\begin{aligned} SO(10)\times U(1)_{PQ} &\xrightarrow{\langle\phi_{45}\rangle_{B-L}} SU(3)_c\times SU(2)_L\times SU(2)_R\times U(1)_{B-L}\times U(1)_{PQ} \\ &\xrightarrow{V_{\overline{126}}} SU(3)_c\times SU(2)_L\times U(1)_Y\times U(1)'_{PQ} \\ &\xrightarrow{V_{16}} SU(3)_c\times SU(2)_L\times U(1)_Y \end{aligned}$$

Accidental SO(10) axion

- Automatic $U(1)_{PQ}$ in SO(10), upon gauging the flavour group $SU(3)_f$ [LDL 2008.09119]

Field	Lorentz	SO(10)	$\mathbb{Z}_4$	$SU(3)_f$	$\mathbb{Z}_3$	$U(1)_{PQ}$
ψ_{16}	$(1/2,0)$	16	i	$\mathbf{3}$	$e^{i2\pi/3}$	1
$\psi_1^{1,\ldots,16}$	$(1/2,0)$	1	1	$\overline{\mathbf{3}}$	$e^{i4\pi/3}$	0
ϕ_{10}	$(0,0)$	10	-1	$\overline{\mathbf{6}}$	$e^{i2\pi/3}$	-2
ϕ_{16}	$(0,0)$	16	i	$\overline{\mathbf{3}}$	$e^{i4\pi/3}$	-1
$\phi_{\overline{126}}$	$(0,0)$	$\overline{126}$	-1	$\overline{\mathbf{6}}$	$e^{i2\pi/3}$	-2
ϕ_{45}	$(0,0)$	45	1	$\mathbf{1}$	1	0

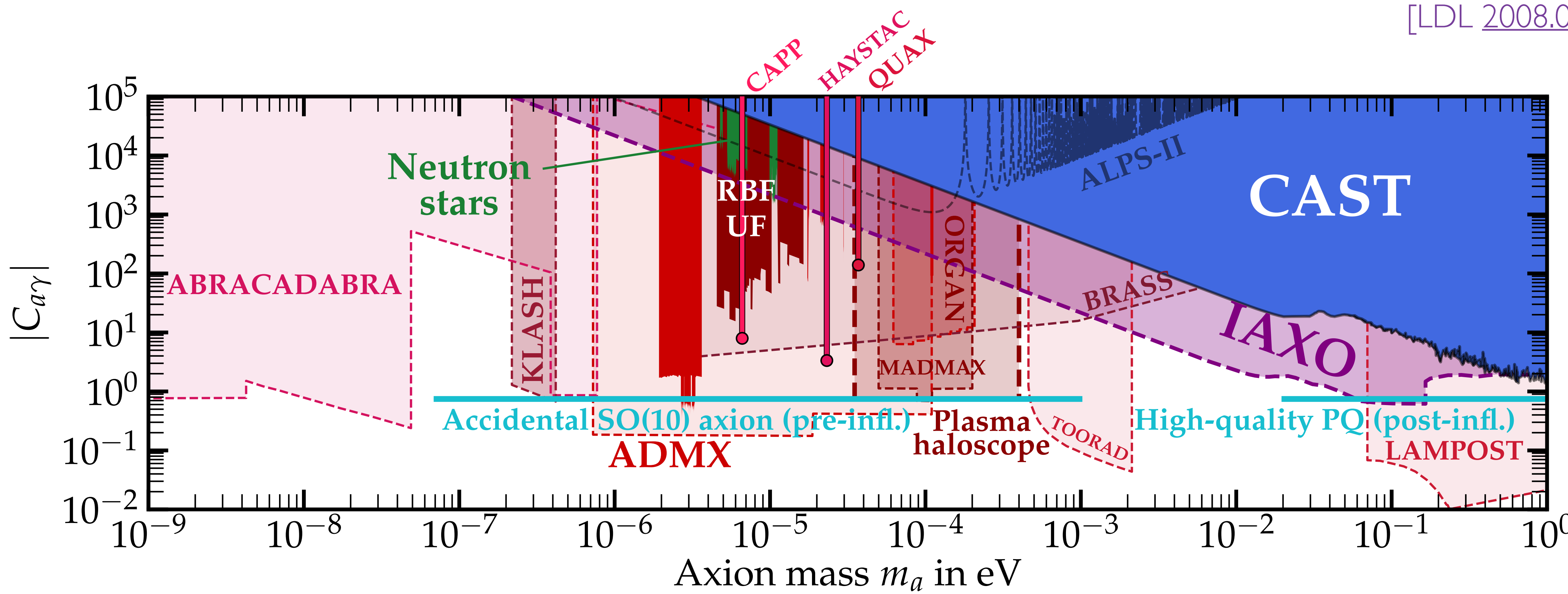
- Anomalons (cancel $SU(3)_f$ gauge anomalies)

massless at the renormalizable level ⟷ related to the emergence of $U(1)_{PQ}$

parametrically light, zero mass lifted by effective operators, e.g. $\frac{1}{M_{\rm Pl}^2}\psi_1\psi_1\phi_{16}^2\phi_{\overline{126}}$

Accidental SO(10) axion

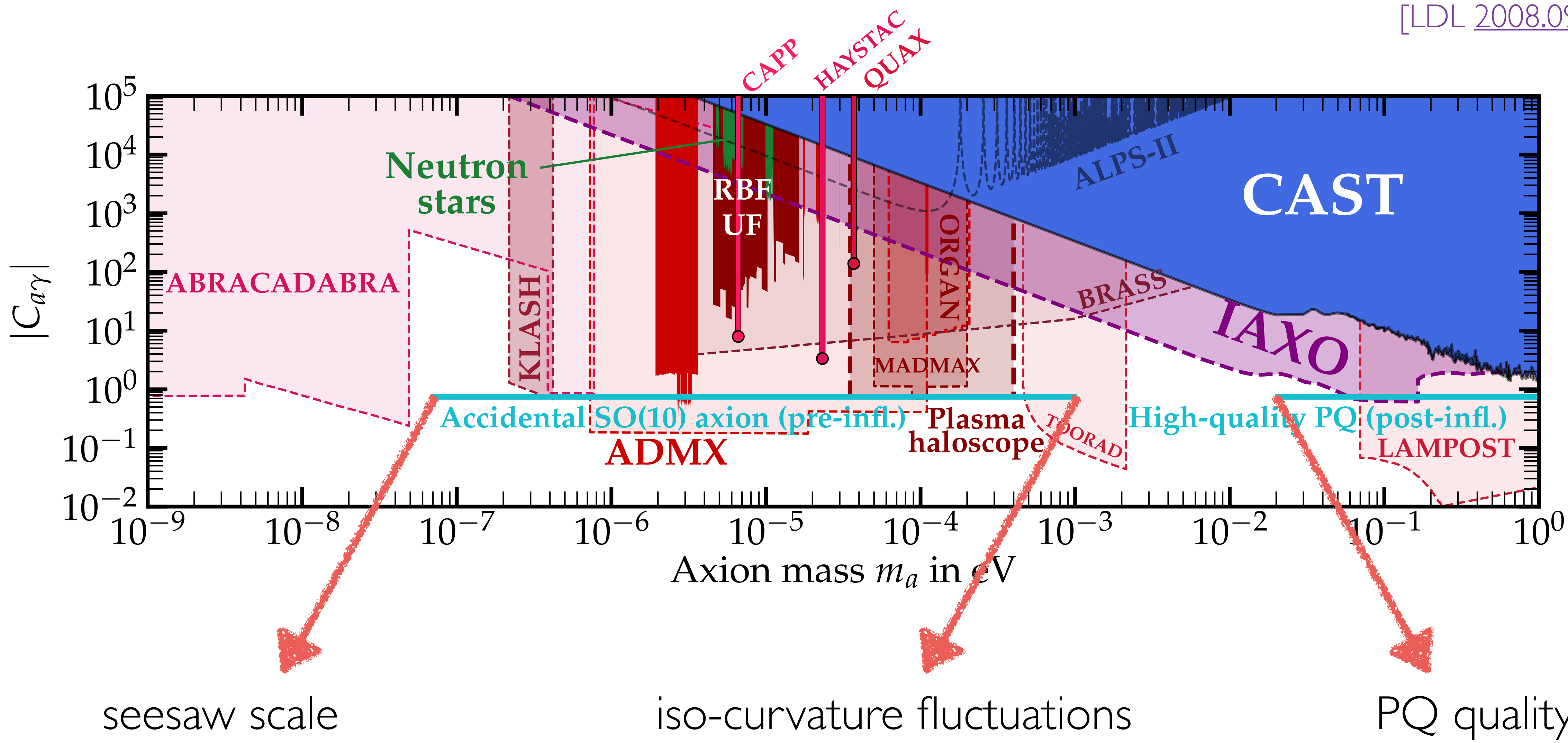
[LDL 2008.09119]



→ *a PQ theory could tell us where to search in an otherwise huge param. space !*

Accidental SO(10) axion

[LDL 2008.09119]



a PQ theory could tell us where to search in an otherwise huge param. space !

Accidental Pati-Salam axion

- We recently studied a simpler version of the theory [LDL, Landini, Mescia, Susič 2503.16648]

Field	Lorentz	Pati-Salam	$\mathbb{Z}_4$	$SU(3)_{f_R}$	$\mathbb{Z}_3$	Generations	$U(1)_{PQ}$
Q_L	$(1/2, 0)$	$(4, 2, 1)$	$+i$	$\mathbf{1}$	$+1$	3	$+3$
Q_R	$(0, 1/2)$	$(4, 1, 2)$	$+i$	$\mathbf{3}$	$e^{i2\pi/3}$	1	$+1$
Ψ_R	$(0, 1/2)$	$(1, 1, 1)$	$+1$	$\overline{\mathbf{3}}$	$e^{i4\pi/3}$	8	$+2$
Φ	$(0, 0)$	$(1, 2, 2)$	$+1$	$\overline{\mathbf{3}}$	$e^{i4\pi/3}$	$N_\Phi \geq 1$	$+2$
Σ	$(0, 0)$	$(15, 2, 2)$	$+1$	$\overline{\mathbf{3}}$	$e^{i4\pi/3}$	$N_\Sigma \geq 2$	$+2$
Δ	$(0, 0)$	$(10, 1, 3)$	-1	$\mathbf{6}$	$e^{i4\pi/3}$	1	$+2$
χ	$(0, 0)$	$(4, 1, 2)$	$+i$	$\overline{\mathbf{3}}$	$e^{i4\pi/3}$	1	-1
ξ	$(0, 0)$	$(15, 1, 3)$	$+1$	$\mathbf{1}$	$+1$	1	0

Table 1: Field content of the Pati-Salam model and relative transformation properties under the Lorentz group, $SU(4)_{PS} \times SU(2)_L \times SU(2)_R \times SU(3)_{f_R}$, its $\mathbb{Z}_4 \times \mathbb{Z}_3$ center, and the accidental $U(1)_{PQ}$. Exotic fermions, which ensure $SU(3)_{f_R}$ anomaly cancellation, are highlighted in light gray. Note that the $U(1)_{PQ}$ charge of Ψ_R is fixed by non-renormalizable operators, while ξ is not charged under $U(1)_{PQ}$ being a real scalar field.

Accidental Pati-Salam axion

- We recently studied a simpler version of the theory [LDL, Landini, Mescia, Susič 2503.16648]

✔ SM flavor structure

✔ anomalon-neutrino spectrum → high-quality PQ predicts sub-eV anomalons

✔ anomalon contribution to $\Delta N_{\rm eff}$

✔ axion phenomenology (degenerate with SO(10) model)

✘ Landau pole emerges one order of magnitude above f_a

Conclusions

- Axion imperfections lead to interesting phenomenology
- PQ breaking and/or CP violation → axion-mediated forces

  - low-energy portal to new sources of CP violation beyond CKM ?

Conclusions

- Axion imperfections lead to interesting phenomenology
- PQ breaking and/or CP violation → axion-mediated forces

  - low-energy portal to new sources of CP violation beyond CKM ?

- New solution to PQ quality problem based on vertical/horizontal gauge symmetries

  - predicts a somewhat heavy axion $m_a \gtrsim 0.01$ eV

  - anomalons as low-energy remnants of UV mechanism responsible for PQ quality

Backup slides

PQ breaking & monopole-dipole

- Axion scalar coupling to atomic system ${}^A_Z X$

[LDL, Gisbert, Nesti, Sørensen 2407.15928
See also Zhang 2209.09429]

$$g^S_{aX} \equiv \frac{A-Z}{A} g^S_{an} + \frac{Z}{A} g^S_{ap} + \frac{Z}{A} g^S_{ae}$$

- leverage PQ-breaking in the electron Yukawa sector

$$\mathcal{L}_{\not{PQ}} \supset -e^{i\delta} \left(\frac{\phi}{\Lambda}\right)^n \frac{\sqrt{2} m_e}{v} \overline{L}_L H e_R + \text{h.c.}$$

→

$$g^S_{ae} = n \left(\frac{f_a}{\sqrt{2}\Lambda}\right)^n \frac{m_e}{f_a} \sin\delta$$

$$\theta_{\text{eff}} \simeq \frac{n}{2\pi^2} \left(\frac{f_a}{\sqrt{2}\Lambda}\right)^n \frac{m_e^4}{\chi_{\text{QCD}}} \sin\delta \, \ln\left(\frac{v}{1\,\text{GeV}}\right)$$

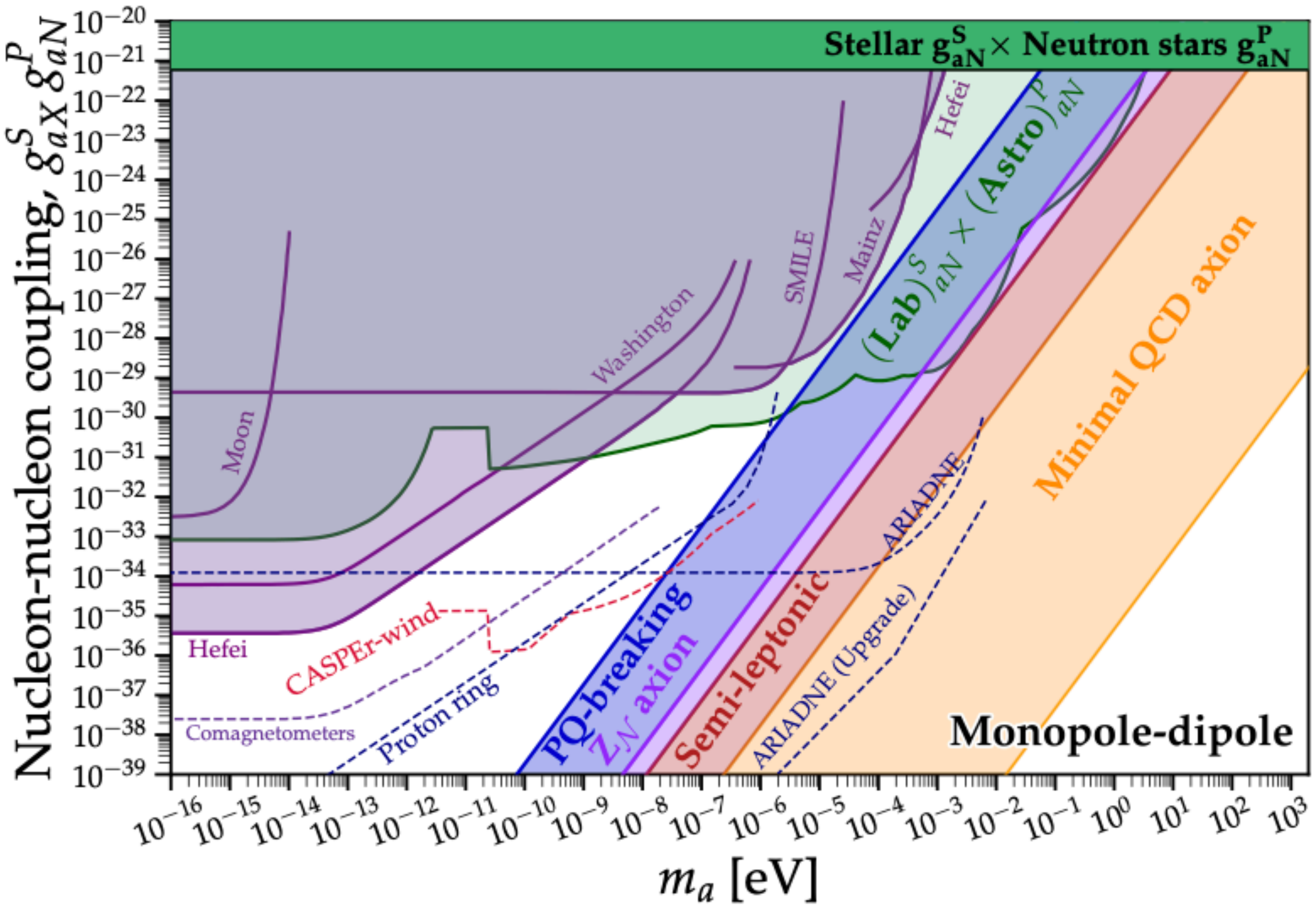
- nEDM bound relaxed due to loop and chirality suppression

PQ breaking & monopole-dipole

- Axion scalar coupling to atomic system ${}^{A}_{Z}X$

[LDL, Gisbert, Nesti, Sørensen 2407.15928
See also Zhang 2209.09429]

$$g^S_{aX} \equiv \frac{A-Z}{A}\, g^S_{an} + \frac{Z}{A}\, g^S_{ap} + \frac{Z}{A}\, g^S_{ae}$$



- nEDM bound relaxed due to loop and chirality suppression

PQ quality in Pati-Salam model

- PQ-breaking operators

[LDL, Landini, Mescia, Susič 2503.16648]

$$\Delta^4 \Delta^* \chi^{*6}\,, \qquad \Phi^{2-k} \Sigma^k \Delta^2 \chi^{*4}\,, \qquad \Phi^{4-k} \Sigma^k \Delta \chi^{*2}\,, \qquad \Phi^{4-k} \Sigma^k \Sigma^2\,,$$

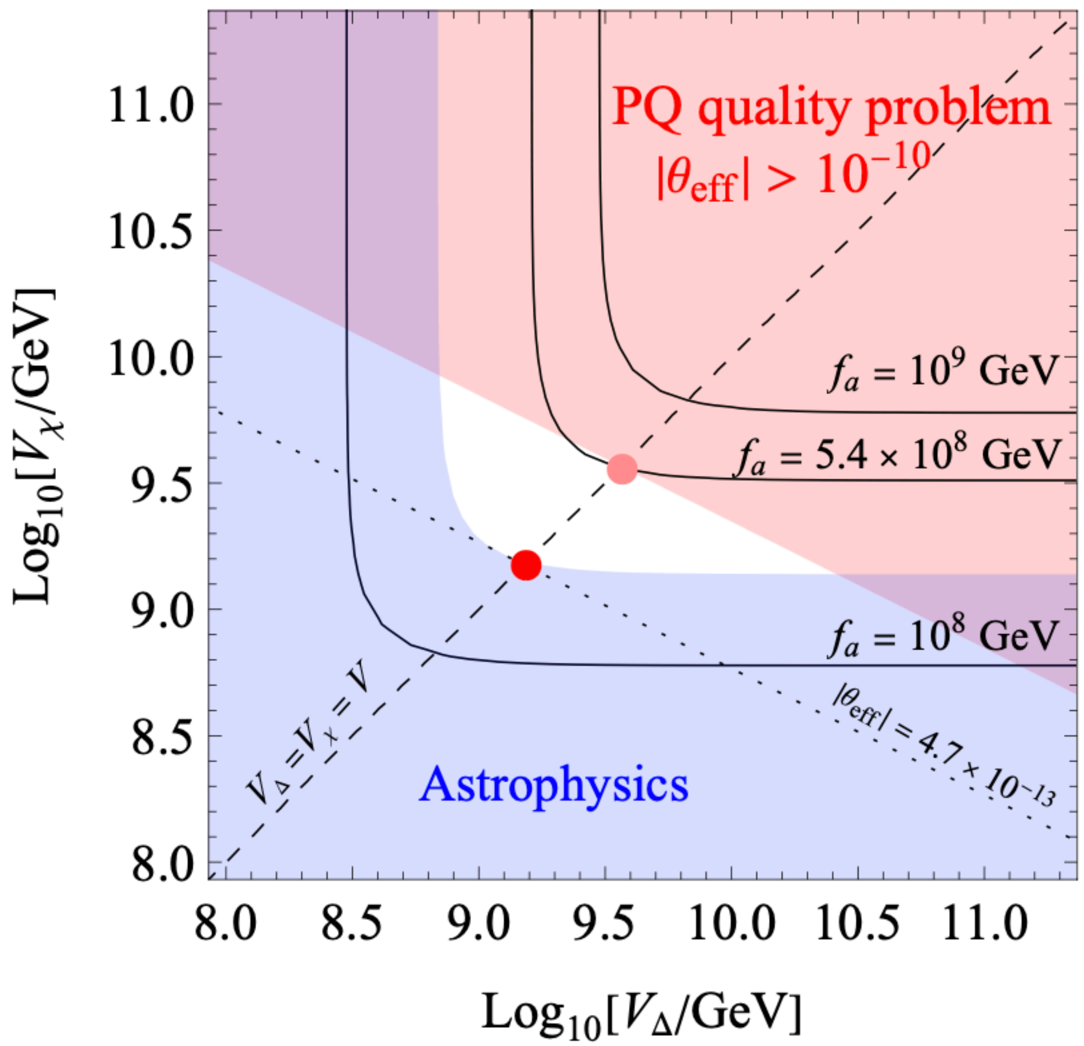
$$\xrightarrow{V_\chi \sim V_\Delta \sim V} \qquad \frac{V^{11}}{\Lambda_{\rm UV}^7}\,, \qquad \frac{v^2 V^6}{\Lambda_{\rm UV}^4}\,, \qquad \frac{v^4 V^3}{\Lambda_{\rm UV}^3}\,, \qquad \frac{v^6}{\Lambda_{\rm UV}^2}\,,$$

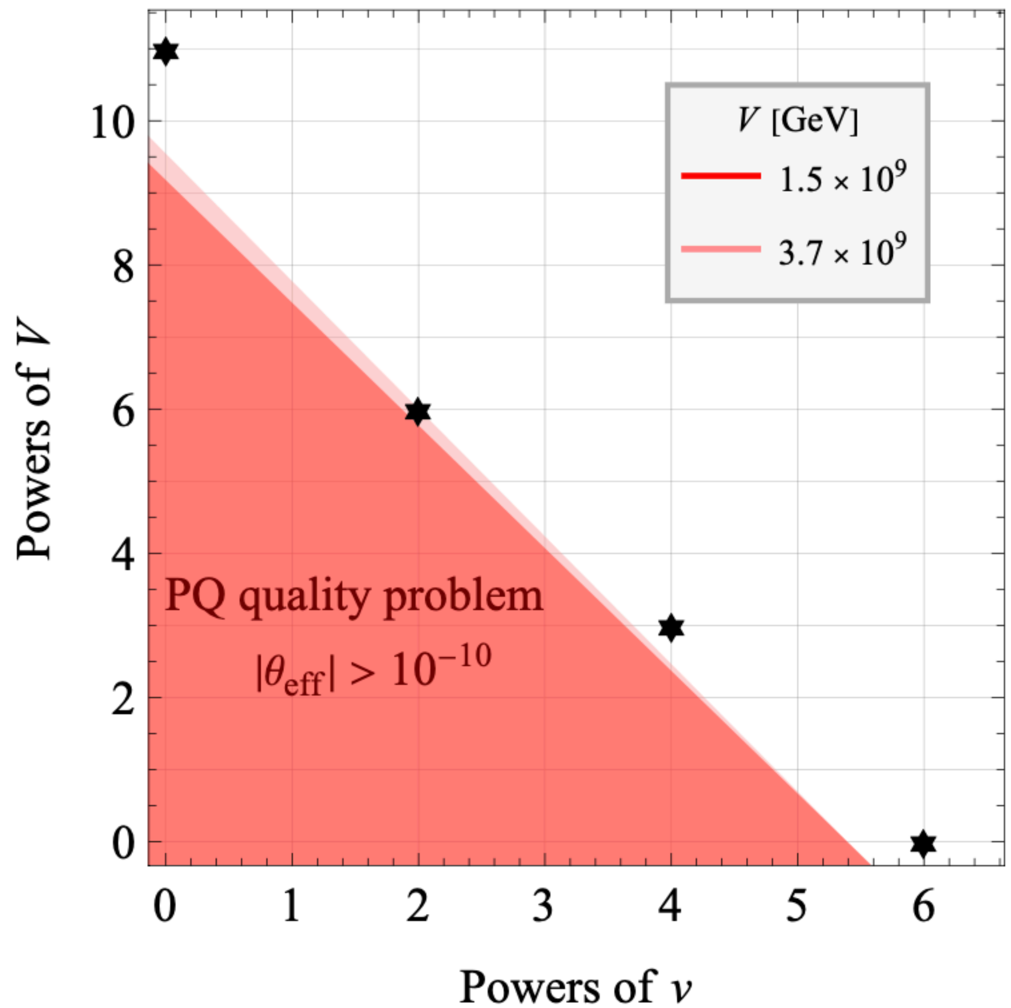
$$f_a = \frac{V_\chi V_\Delta}{3\sqrt{V_\chi^2 + 4 V_\Delta^2}} \qquad \Lambda_{\rm UV} \sim M_{\rm Pl} = 1.22 \times 10^{19}\,{\rm GeV}$$

PQ quality in Pati-Salam model

- PQ quality condition $\frac{v^m V^n}{\Lambda_{\rm UV}^{n+m-4}} \lesssim 10^{-10} \chi_{\rm QCD}^4$

[LDL, Landini, Mescia, Susič 2503.16648]





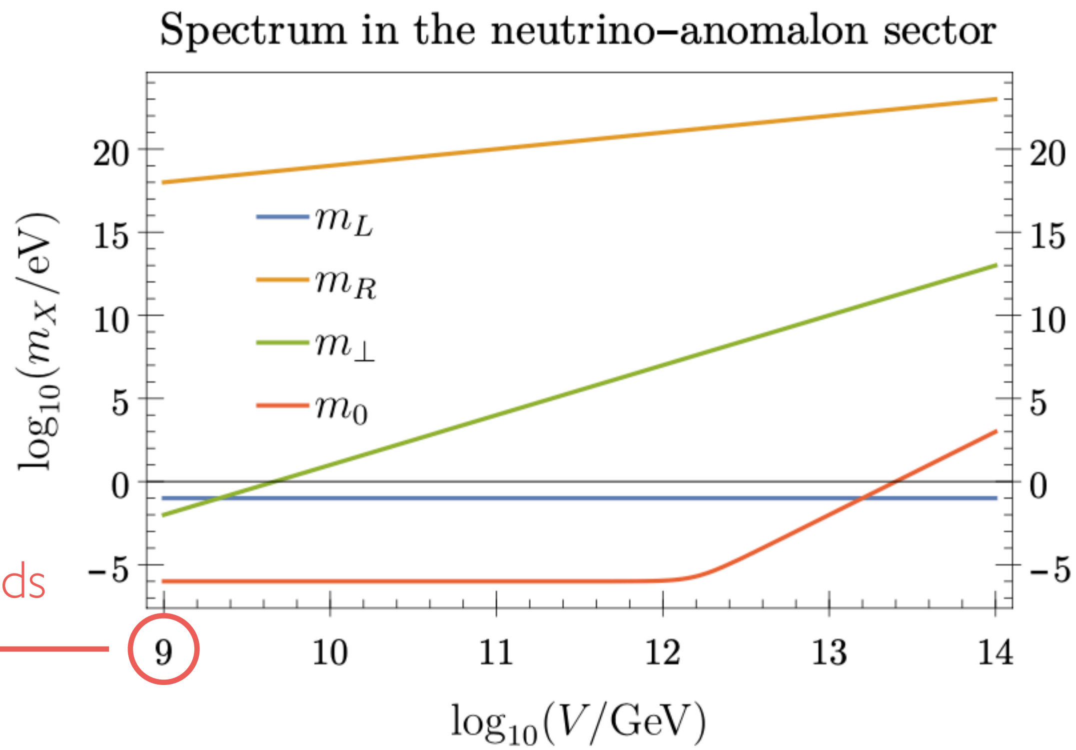
$$f_a = \frac{V_\chi V_\Delta}{3\sqrt{V_\chi^2 + 4V_\Delta^2}}$$

$$\Lambda_{\rm UV} \sim M_{\rm Pl} = 1.22 \times 10^{19}\,\mathrm{GeV}$$

Anomalon spectrum

- $L \oplus R \oplus \Psi_\perp \oplus \Psi_0$ basis (3+3+16+8) [LDL, Landini, Mescia, Susič 2503.16648]

$$\begin{pmatrix} M_{LL} & M_{LR} & M_{L\Psi_\perp} & M_{L\Psi_0} \\ M_{RL} & M_{RR} & M_{R\Psi_\perp} & M_{R\Psi_0} \\ M_{\Psi_\perp L} & M_{\Psi_\perp R} & M_{\Psi_\perp \Psi_\perp} & M_{\Psi_\perp \Psi_0} \\ M_{\Psi_0 L} & M_{\Psi_0 R} & M_{\Psi_0 \Psi_\perp} & M_{\Psi_0 \Psi_0} \end{pmatrix} \sim \begin{pmatrix} \frac{v^2 V}{\Lambda_{UV}^2} & yv & l\,\frac{vV}{\Lambda_{UV}} & \tilde{l}\,\frac{vV^2}{\Lambda_{UV}^2} \\ .. & V & r\,\frac{V^2}{\Lambda_{UV}} & \tilde{r}\,\frac{V^4}{\Lambda_{UV}^3} \\ .. & .. & \frac{V^3}{\Lambda_{UV}^2} & \frac{v^2}{\Lambda_{UV}} + \frac{V^5}{\Lambda_{UV}^4} \\ .. & .. & .. & \frac{v^2}{\Lambda_{UV}} + \frac{V^5}{\Lambda_{UV}^4} \end{pmatrix}$$



High-quality PQ scenario corresponds to sub-eV anomalons

Anomalons & $\Delta N_{\rm eff}$

- Production channels:

[LDL, Landini, Mescia, Susič 2503.16648]

1. Flavor interactions

$$\Delta N_{\rm eff} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{\rho_\Psi}{\rho_\gamma} \simeq 1.13\,\frac{N_\Psi}{24}\left(\frac{106.75}{g_s(T_{\rm dec})}\right)^{4/3}$$

→ too large if thermally produced

- to avoid thermalization: small gauge coupling or low reheating temperature

$$g_{f_R} \ll 10^{-9}\left(\frac{V}{10^9\,{\rm GeV}}\right)\left(\frac{g_*(m_{W_{f_R}})}{106.75}\right)^{1/2}$$

$$T_{\rm RH} \ll V\left(\frac{g_*^{1/2}(T_{\rm RH})V}{M_{\rm Pl}}\right)^{1/3} \simeq 10^6\,{\rm GeV}\left(\frac{V}{10^9\,{\rm GeV}}\right)^{4/3}\left(\frac{g_*(T_{\rm RH})}{106.75}\right)^{1/6}$$

- freeze-in production generically below present & future sensitivity on $\Delta N_{\rm eff}$

Anomalons & $\Delta N_{\rm eff}$

- Production channels: [LDL, Landini, Mescia, Susič 2503.16648]

1. Flavor interactions

2. Neutrino-anomalon conversion: $e^+e^- \to \bar{\nu}_L \nu_L \to \bar{\nu}_L \Psi_m$

- non-resonant scenario $m_\Psi \gtrsim m_\nu$

$$Y_\Psi^{\nu-\rm mix}\Big|_{m_\Psi \gg m_\nu} \sim 2.5 \times 10^4 \left(\frac{10.75}{g_{\rm SM}}\right)^{3/2} \sum_{m=1}^{N_\Psi} \left(|\theta_{\nu\Psi_m}|^2 \frac{m_{\Psi_m}}{\rm keV}\right)$$

- resonant scenario $m_\Psi \lesssim m_\nu$

→ expect larger contribution to $\Delta N_{\rm eff}$ / stronger constraints on mixing angles

Axion phenomenology

- Pati-Salam and SO(10) models yield same predictions [LDL, Landini, Mescia, Susič 2503.16648]