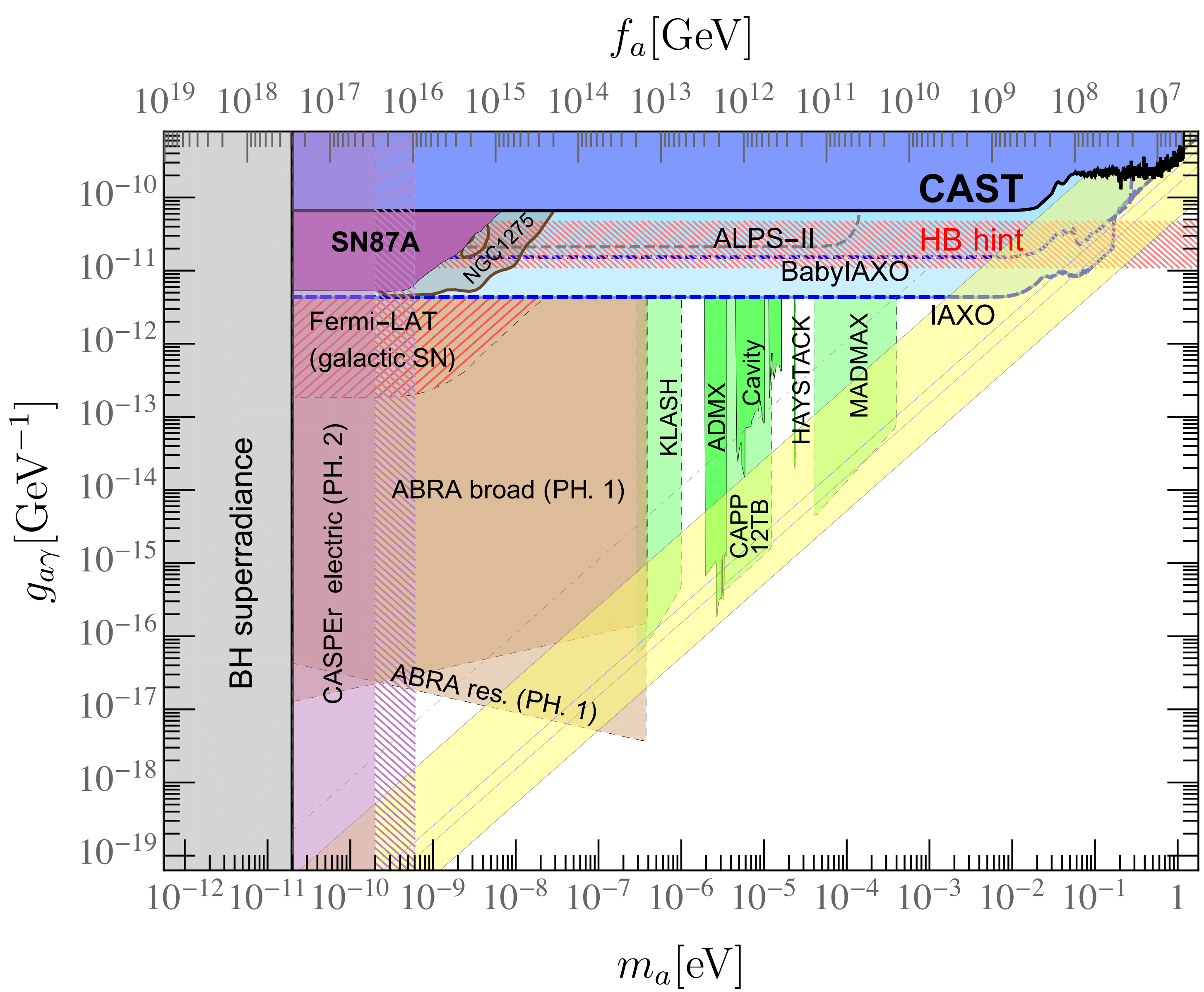
The quest for the QCD axion: status & perspectives

Theoretical Particle Physics Seminar
Zürich - 26.10.20

Luca Di Luzio

In 10 years from now ?



[LDL, Giannotti, Nardi, Visinelli 2003.01100 (Phys. Rept.)]

- An experimental opportunity

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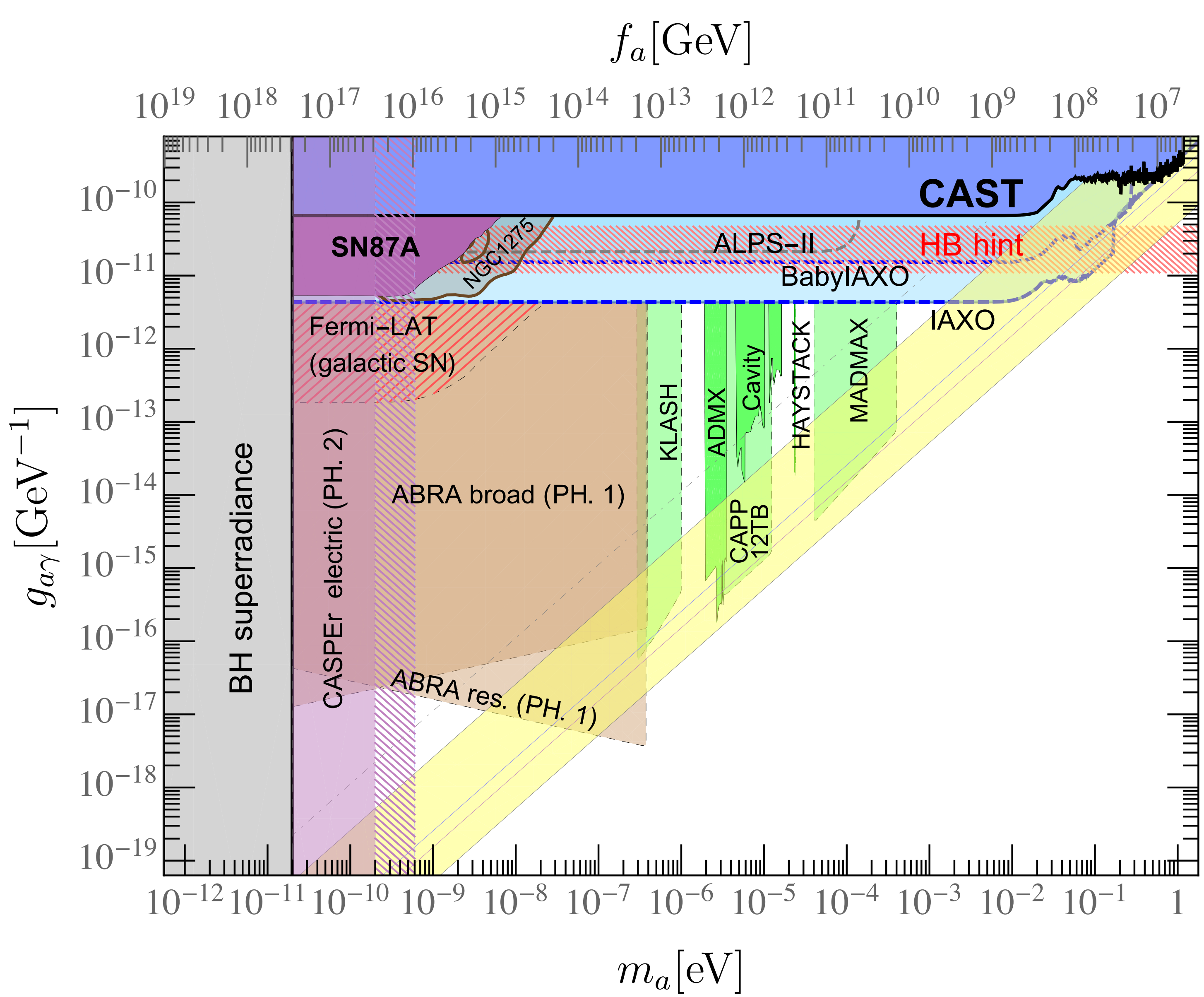

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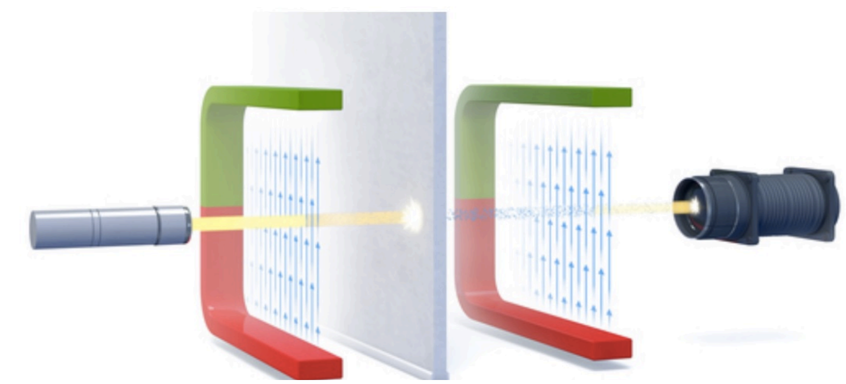

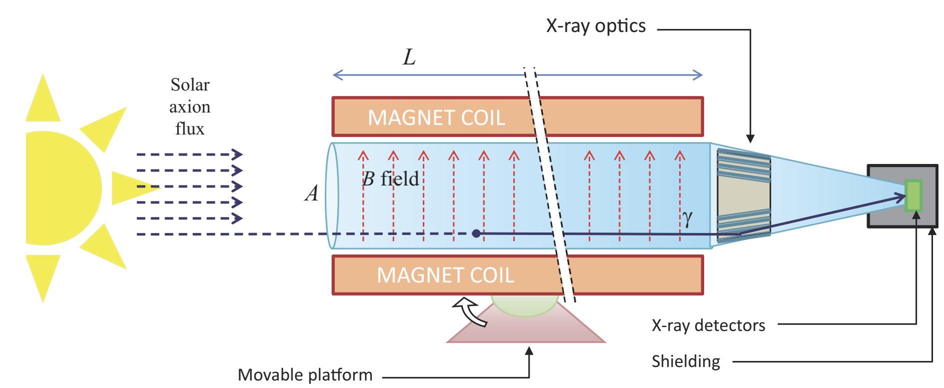

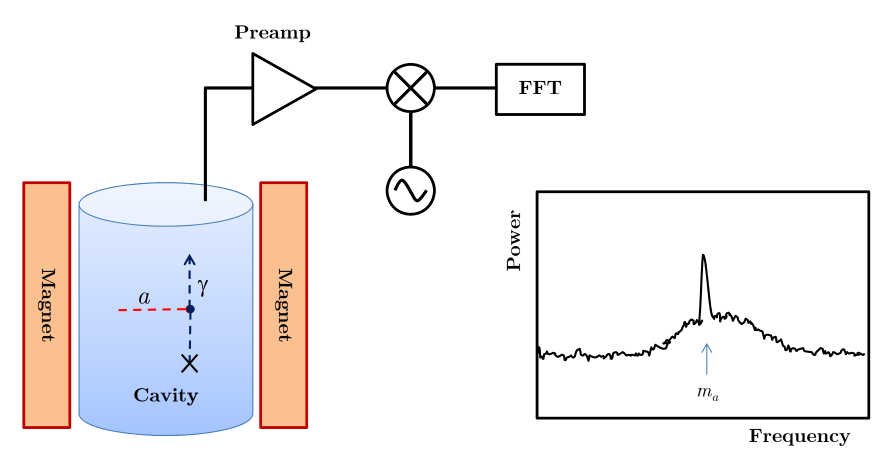

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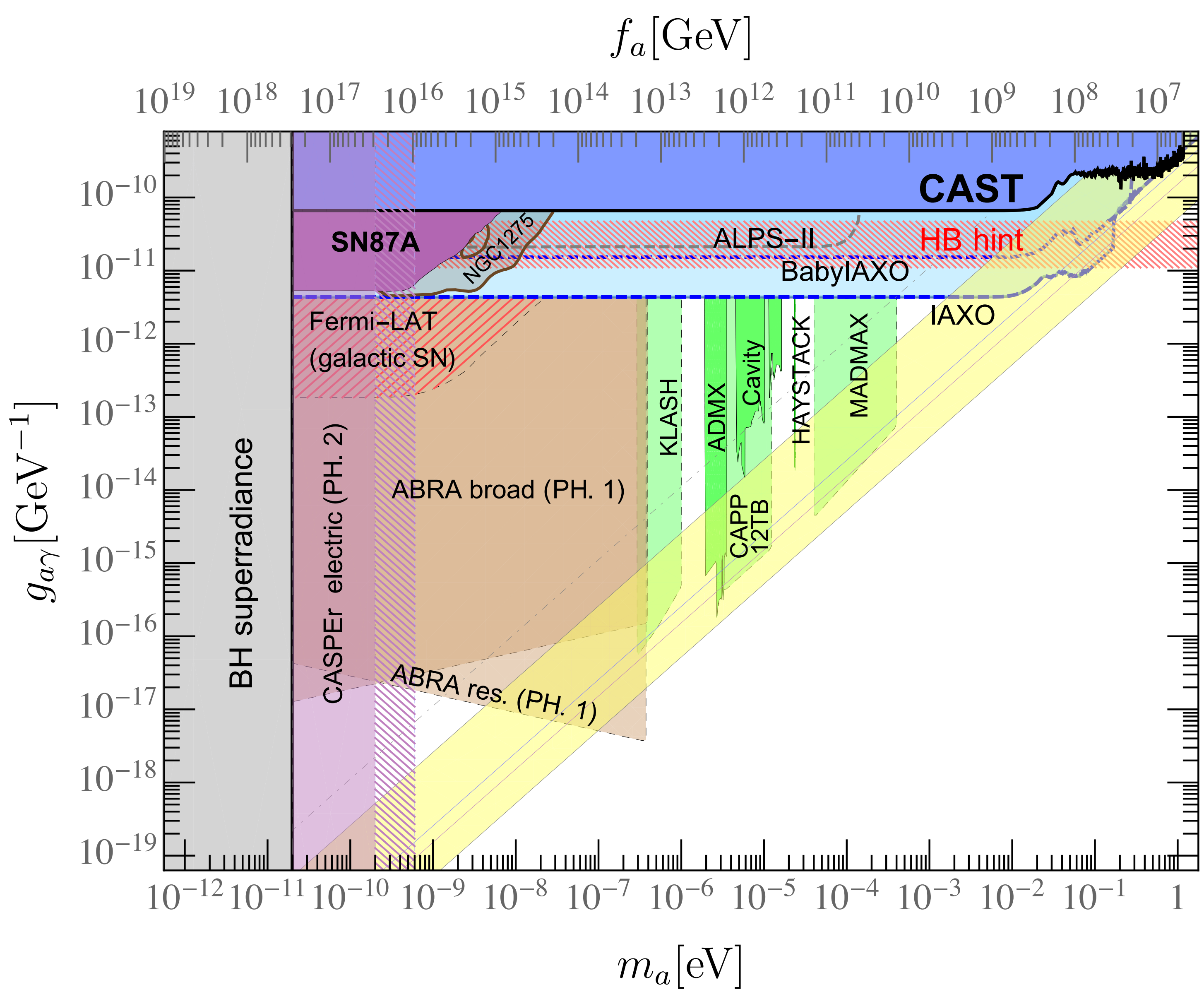

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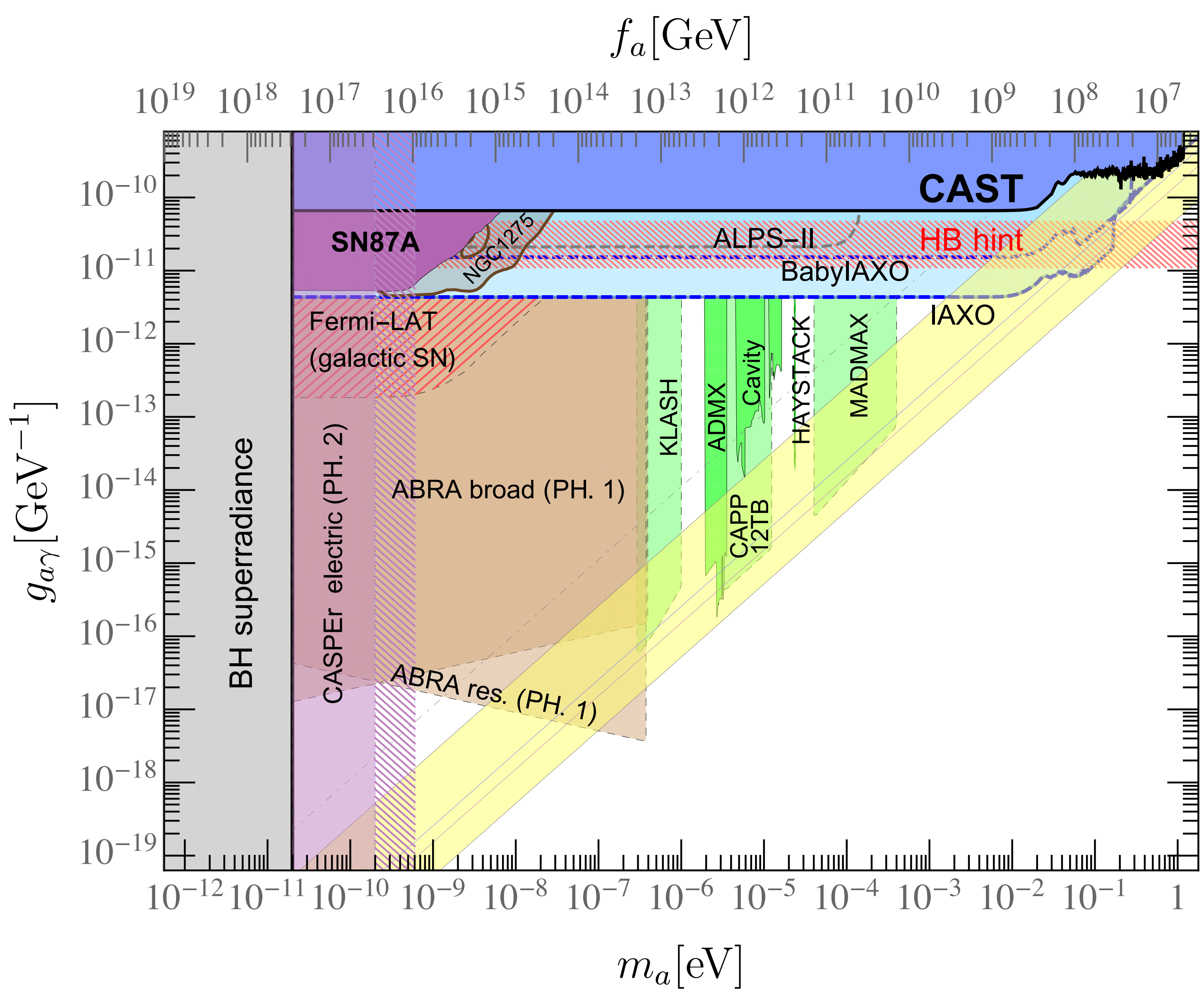
✤ An experimental opportunity

★ Time now to rethink the QCD axion

1. Strong CP and QCD Axion
2. Axion couplings
   [from EFT to UV models]
3. Redefining the QCD axion parameter space
4. Towards a PQ theory

In 10 years from now ?



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Strong CP (I)

- P and CP were believed to be symmetries of QCD until ~1975

[Belavin, Polyakov, Schwarz, Tyupkin PLB59 (1975),
Jackiw, Rebbi PRL37 (1976)
Callan, Dashen, Gross PLB63 (1976) …]

→ *discovery of YM instantons & QCD vacuum structure*

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$\longrightarrow$ *discovery of YM instantons & QCD vacuum structure*

$$\Delta\,\mathcal{L}_\theta \equiv \frac{\theta}{32\,\pi^2}\,G^a_{\mu\nu}\,\tilde{G}^a_{\mu\nu} \qquad \left(\tilde{G}^a_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma}G^{a,\rho\sigma}\right)$$

dim=4 operator, violates P and T (and hence CP)

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→ *discovery of YM instantons & QCD vacuum structure*

$$\Delta \mathcal{L}_\theta \equiv \frac{\theta}{32\,\pi^2} G^a_{\mu\nu} \tilde{G}^a_{\mu\nu} = \theta\, \partial_\mu K_\mu \qquad K_\mu = \frac{1}{16\,\pi^2} \varepsilon_{\mu\nu\alpha\beta} \left(A^a_\nu \partial_\alpha A^a_\beta + \frac{1}{3} f_{abc} A^a_\nu A^b_\alpha A^c_\beta \right)$$

despite being a total derivative, it contributes to the action via instanton configurations

$$Z[A] = \int \mathcal{D}A\, e^{-\frac{1}{4}\int d^4x\, GG + i\theta \frac{g_s^2}{32\pi^2} \int d^4x\, G\tilde{G}} \sim e^{-\frac{8\pi^2}{g_s^2}} e^{i\theta}$$

Strong CP (2)

- Non-trivial role of quark masses

$$\mathcal{L}_{\text{QCD}} = \sum_q \overline{q} \left(i\not{D} - m_q e^{i\theta_q} \right) q - \frac{1}{4} G_a^{\mu\nu} G^a_{\mu\nu} - \theta \frac{\alpha_s}{8\pi} G_a^{\mu\nu} \tilde{G}^a_{\mu\nu}$$

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$$q \to e^{i\gamma_5 \alpha} q \quad \longrightarrow \quad \begin{cases} \theta_q \to \theta_q + 2\alpha \\ \theta \to \theta + 2\alpha \end{cases}$$

from non-invariance of path integral measure (chiral anomaly)

[Fujikawa, PRL 42 (1979)]

$$\mathcal{D}q\mathcal{D}\overline{q} \to \exp\left(-i\alpha \int d^4x \, \frac{\alpha_s}{4\pi} G_a^{\mu\nu} \tilde{G}^a_{\mu\nu} \right) \mathcal{D}q\mathcal{D}\overline{q}$$

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$$q \to e^{i\gamma_5 \alpha} q \quad \Longrightarrow \quad \begin{cases} \theta_q \to \theta_q + 2\alpha \\ \theta \to \theta + 2\alpha \end{cases}$$

$\Longrightarrow$ $\overline{\theta} = \theta - \theta_q$ <u>invariant</u>

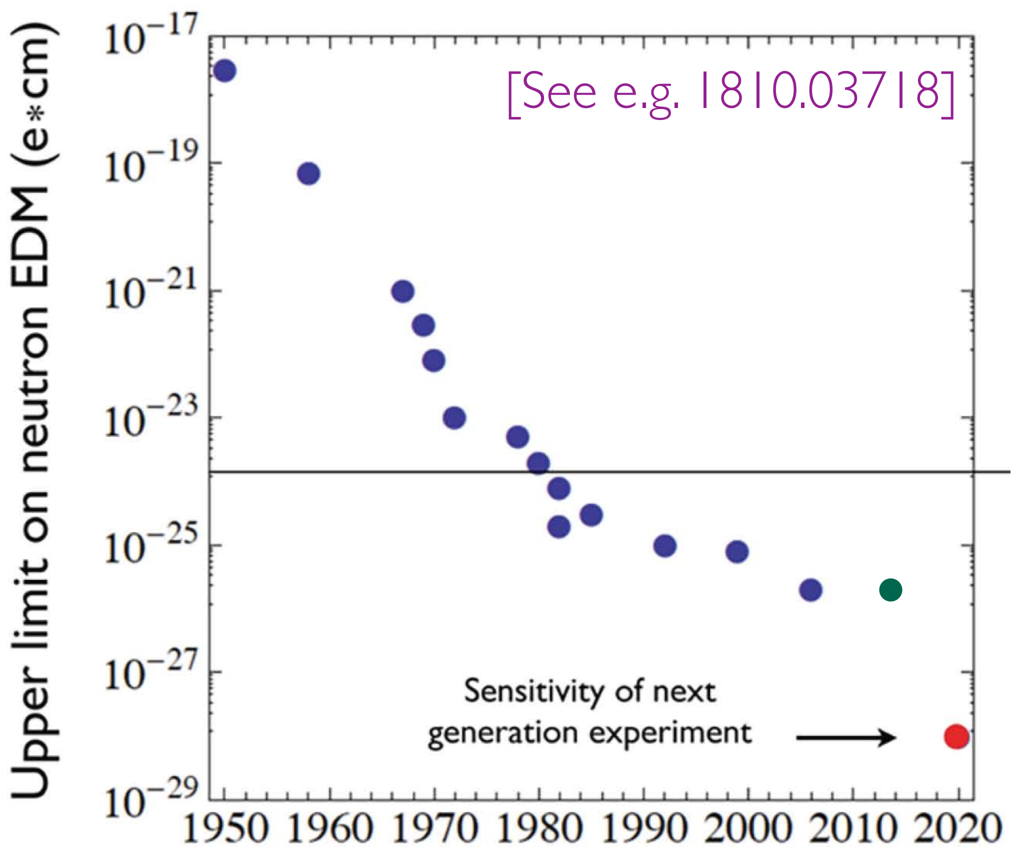
$= \theta - \arg\det\left(Y_u Y_d\right)$ *(generalization to an arbitrary chiral transf. in the EW theory)*

Strong CP (3)

- CP violation: neutron EDM

[Baluni PRD 19 (1979), Crewther et al, PLB 88 (1979), …]

$$d_n^{\text{exp}} < 2.9 \cdot 10^{-26}\ e\ \text{cm} = 1.5 \cdot 10^{-12}\ e\ \text{GeV}^{-1}$$



[B. Fillipone]

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$$H = -d_n \, \mathbf{E} \cdot \hat{\mathbf{S}} \qquad \Longleftrightarrow \qquad \mathcal{L} = -d_n \, \frac{i}{2} \overline{n} \sigma^{\mu\nu} \gamma_5 n F_{\mu\nu}$$

$$\left(1 - c \frac{m_q}{2 m_n} e^{i\overline{\theta}}\right) \frac{e}{m_n} \overline{n} \sigma^{\mu\nu} \gamma_5 n F_{\mu\nu} + \text{h.c.} \quad \longrightarrow \quad d_n = c \frac{m_q}{m_n} \frac{e}{m_n} \overline{\theta}$$

an NDA estimate

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an NDA estimate $\qquad 10^{-2} \quad e\ {\rm GeV}^{-1}$

$\longrightarrow \quad |\overline{\theta}| \lesssim 10^{-10}$ *why so small ?*

Strong CP (4)

- Is the strong CP problem a problem ?

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1. theta is radiatively stable in the SM

[Ellis, Gaillard NPB 150 (1979), Khriplovich, Vainshtein NPB 414 (1994)]

$$\longrightarrow \qquad \bar{\theta} \sim \frac{1}{(4\pi)^{14}} g'^2 \left[Y^2(u_R) - Y^2(d_R) \right] J_{\rm CKM} \log \Lambda_{\rm UV}$$

divergence expected to arise at 7-loops

Fig. 9. Generic topology of a class of divergent *CP* violating 14th-order diagrams in the Kobayashi-Maskawa model [21,22].

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$$\to \quad \bar{\theta} \sim \frac{1}{(4\pi)^{14}} g'^2 \left[Y^2(u_R) - Y^2(d_R) \right] J_{\rm CKM} \log \Lambda_{\rm UV} \sim 10^{-46} \log \Lambda_{\rm UV}$$

$$\mathrm{Im}\,\mathrm{Det}\left[Y_U Y_U^\dagger, Y_D Y_D^\dagger \right] \approx 10^{-29}$$

<u>OK even with a Planckian cut-off</u> - to be compared instead with EW hierarchy problem

$$m_H^2 \sim \text{loop} \times \Lambda_{\rm UV}^2$$

(radiative instability of theta might be more severe in theories beyond the SM)

Strong CP (4)

- Is the strong CP problem a problem ?

1. *theta is radiatively stable <u>in the SM</u>*

2. *it evades enviromental/anthropic explanations*

→ nuclear physics and BBN practically unaffected for $\bar{\theta} \lesssim 10^{-2}$

[See e.g. Ubaldi, 0811.1599]

(*unlike* $\Lambda_{\rm c.c.}$ *and* $y_{e,u,d} \sim 10^{-6} \div 10^{-5}$)

Strong CP (4)

- Is the strong CP problem a problem ?

1. *theta is radiatively stable <u>in the SM</u>*

2. *it evades enviromental/anthropic explanations*

3. *more than a small value problem ?*

$$|\theta - \arg\det(Y_u Y_d)| < 10^{-10}$$

QCD vacuum

$$|\theta\rangle = \sum_{n=-\infty}^{+\infty} e^{in\theta}|n\rangle$$

flavour

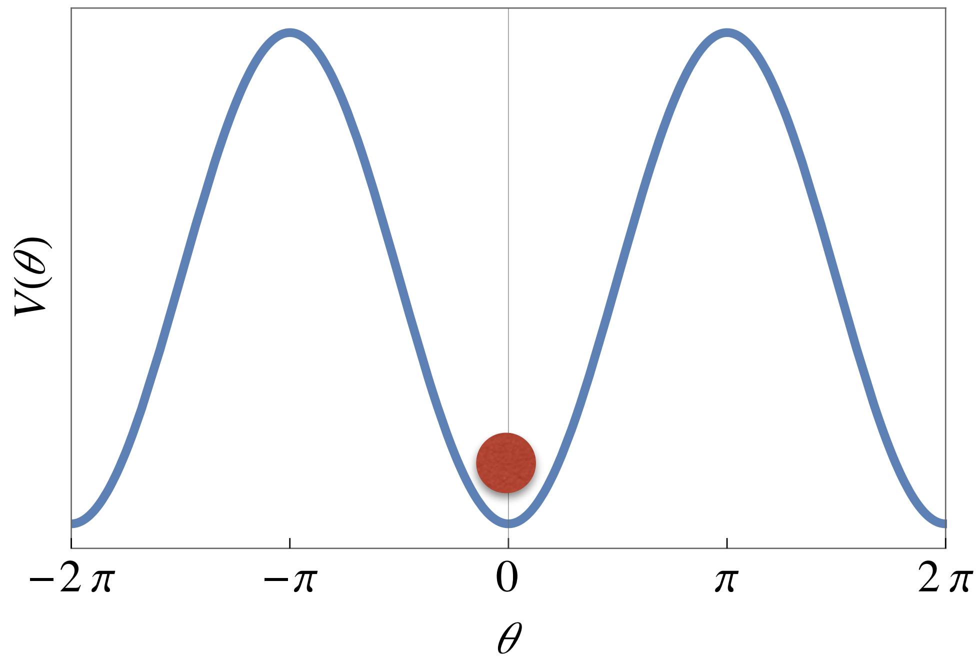
(imagine a theory of flavour generating Yukawas: would expect O(1) phases like CKM)

QCD axion

Strong CP problem

$$\delta\mathcal{L}_{\rm QCD} = \theta\,\frac{\alpha_s}{8\pi} G\tilde{G} \qquad |\theta| \lesssim 10^{-10}$$

promote θ *to a dynamical field,*
which relaxes to zero via QCD dynamics



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

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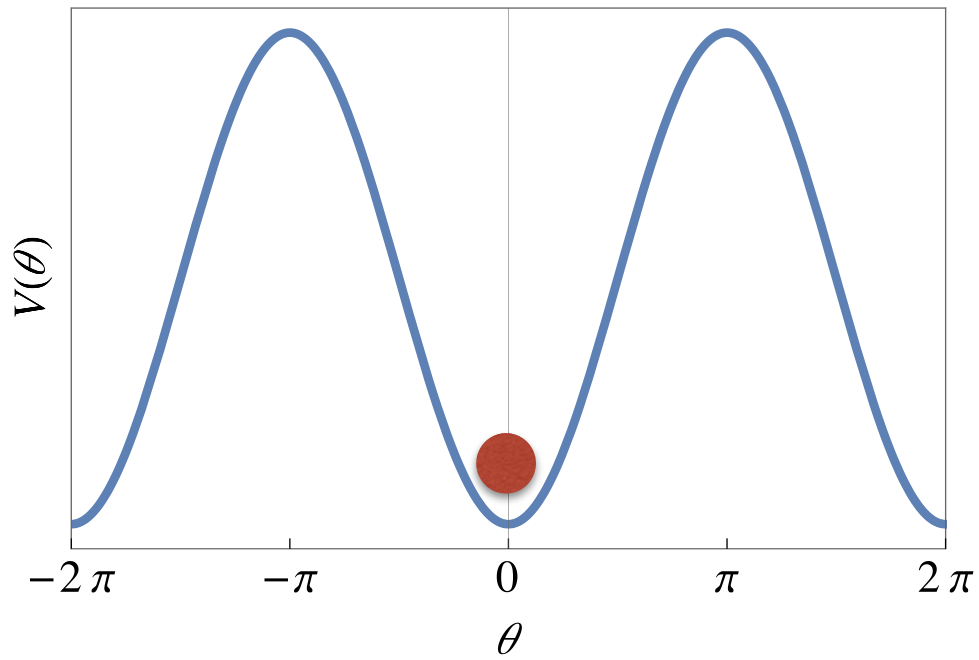

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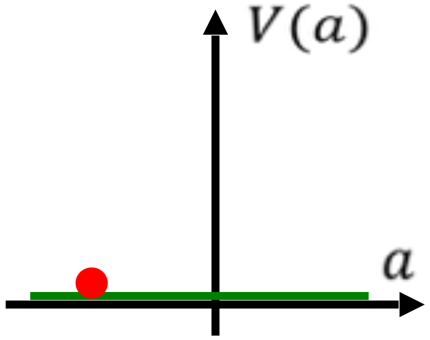
Dark Matter

vacuum re-alignment mechanism:



[Raffelt]

$T \gg 1$ GeV

$$\ddot{a} + 3H\dot{a} + \cancel{m_a^2(T) f_a} \sin\left(\frac{a}{f_a}\right) = 0$$

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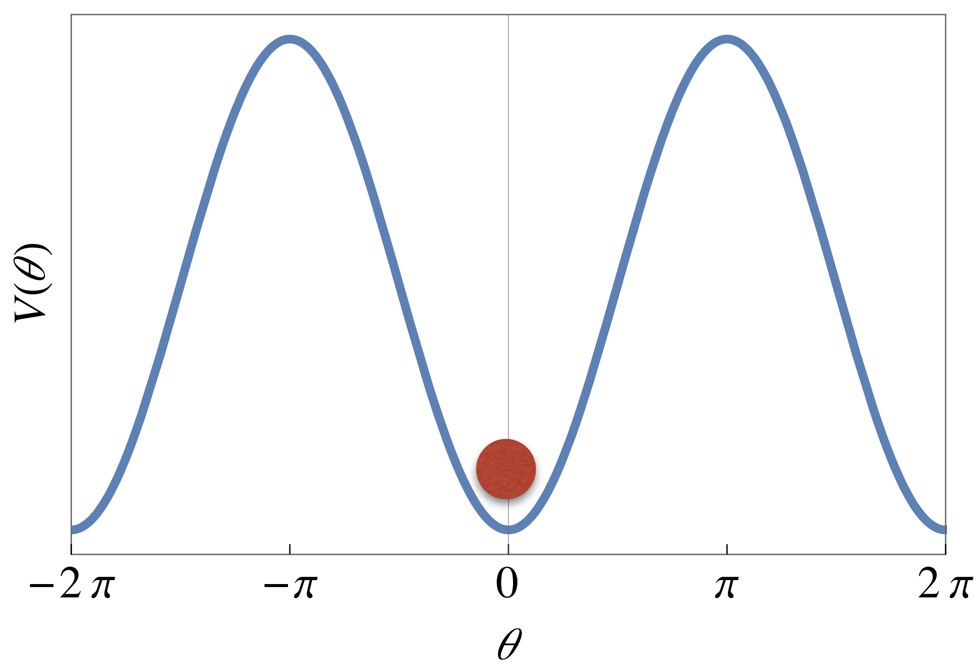

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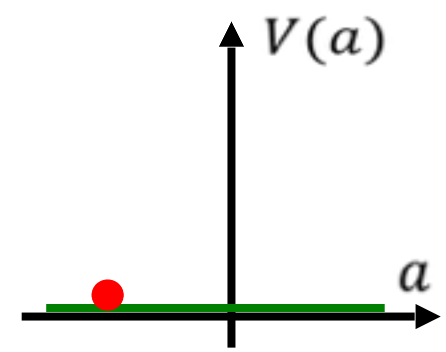

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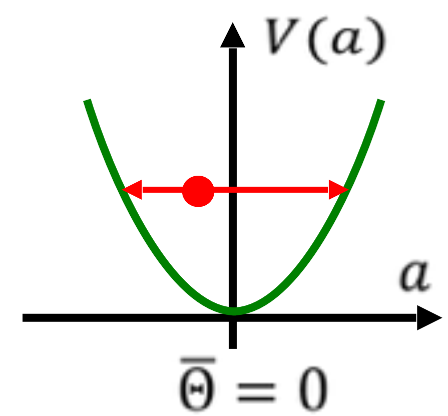

$T \sim 1\ \mathrm{GeV}$

$w_a = p_a/\rho_a \simeq 0$

$$\ddot{a} + \cancel{3H}\dot{a} + m_a^2(T) f_a \sin\left(\frac{a}{f_a}\right) = 0$$

PQ solution

- Assume a new spin-0 boson with a pseudo-shift symmetry $a \to a + \alpha\, f_a$

broken by $\frac{a}{f_a}\frac{\alpha_s}{8\pi}G_a^{\mu\nu}\tilde{G}^a_{\mu\nu}$ $\longrightarrow$ $E(0) \leq E(\langle a \rangle)$ [Vafa-Witten, PRL 53 (1984)]

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

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**Proof fails for a chiral theory (as in the SM)*

$$\theta_{\text{eff}} \sim G_F^2 f_\pi^4 j_{\text{CKM}} \approx 10^{-18}$$ [Georgi Randall, NPB276 (1986)]

PQ solution relies also on SM flavour structure $j_{\text{CKM}} = \text{Im}\, V_{ud} V^*_{cd} V_{cs} V^*_{us} \approx 10^{-5}$

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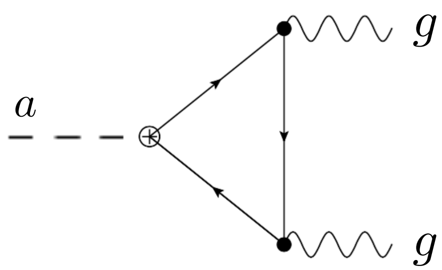
- its origin can be traced back into a global $U(1)_{PQ}$ [Peccei, Quinn '77, Weinberg '78, Wilczek '78]

1. spontaneously broken (axion is the associated pNGB)

2. QCD anomalous

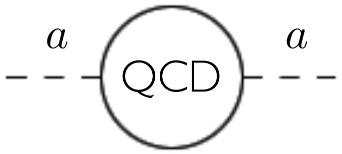


$$\partial^\mu J_\mu^{PQ} = \frac{N\alpha_s}{4\pi} G \cdot \tilde{G}$$

Axion properties [model-indep.]

- Consequences of $\frac{a}{f_a}\frac{\alpha_s}{8\pi}G^{\mu\nu}_a\tilde{G}^a_{\mu\nu}$

1. axion mass



$\sim \frac{\Lambda^4_{\text{QCD}}}{f_a^2} \quad \longrightarrow \quad m_a \sim \Lambda^2_{\text{QCD}}/f_a \simeq 0.1 \text{ eV}\left(\frac{10^8 \text{ GeV}}{f_a}\right)$

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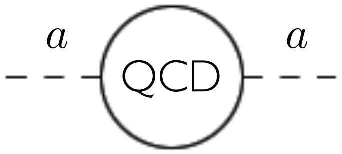

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$$f_a \gtrsim 10^8 \text{ GeV} \quad \longrightarrow \quad m_a \lesssim 0.1 \text{ eV}$$

(astrophysics)

experimentally, more useful to think about the axion as a wave (rather than a particle)

$$\lambda_a = \frac{h}{m_a c} \sim 20 \text{ cm} \frac{\mu\text{eV}}{m_a}$$

Axion properties [model-indep.]

- Consequences of $\frac{a}{f_a}\frac{\alpha_s}{8\pi}G_a^{\mu\nu}\tilde{G}^a_{\mu\nu}$

1. axion mass

2. 'model-independent' axion couplings to photons, nucleons, electrons, …

$C_\gamma = -1.92(4)$ $\quad C_p = -0.47(3)$ $\quad C_n = -0.02(3)$ $\quad C_e = -7.8(2)\times 10^{-6}\log\left(\frac{f_a}{m_e}\right)$

$$\mathcal{L}_a \supset \frac{\alpha}{8\pi}\frac{C_\gamma}{f_a}aF_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{C_f}{2f_a}\partial_\mu a\bar{f}\gamma^\mu\gamma_5 f \qquad (f = p, n, e)$$

[Grilli di Cortona, Hardy, Vega, Villadoro, 1511.02867]

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- Consequences of $\frac{a}{f_a}\frac{\alpha_s}{8\pi}G_a^{\mu\nu}\tilde{G}^a_{\mu\nu}$

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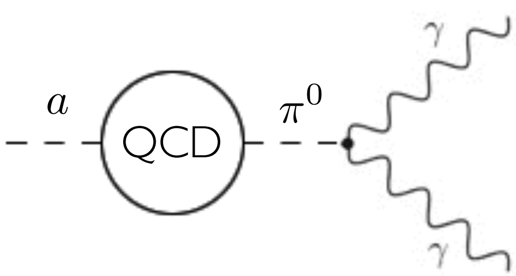

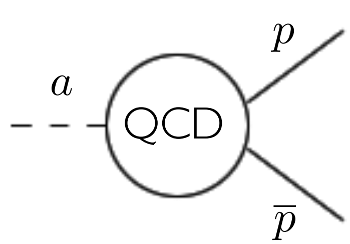

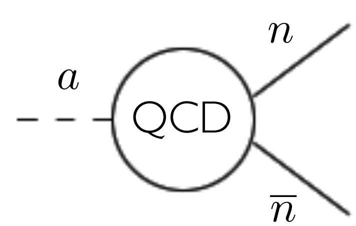

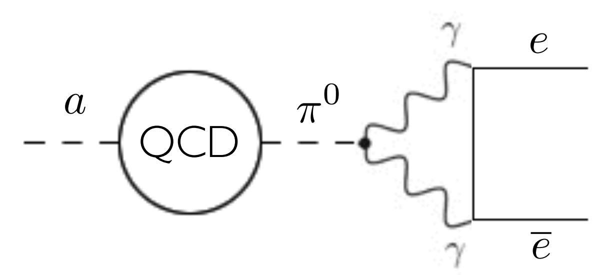

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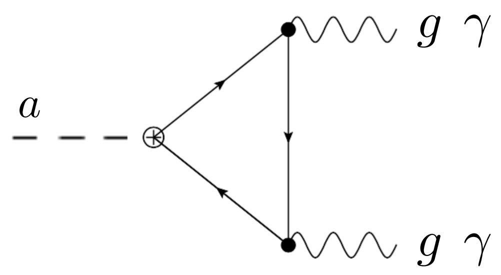
- EFT breaks down at energies of order f_a → *UV completion can drastically affect low-energy axion properties*

Axion properties [model-dep.]

1. Axion-photon



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

$$C_\gamma = E/N - 1.92(4)$$

model independent

depends on UV completion

enhance/suppress C_γ

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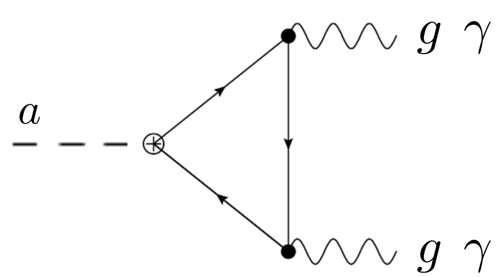

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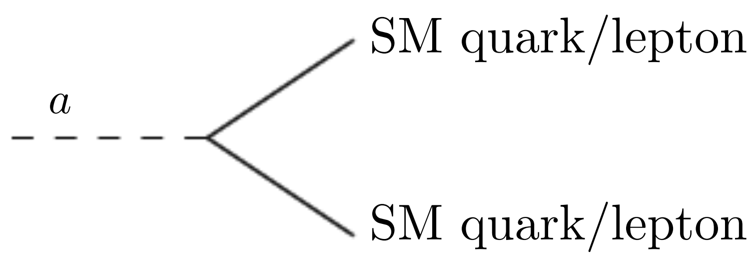
2. Axion-SM fermion current



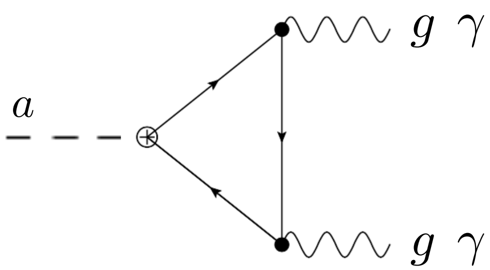
$$\frac{\partial_\mu a}{2 f_a} \underbrace{\overline{\psi}_i \gamma^\mu (C_{ij}^V + C_{ij}^A \gamma_5) \psi_j}_{J^\mu_{\mathrm{PQ}}}$$

enhance/suppress $C_{p,n,e}$

<u>flavour-violating</u> axion coupl.

Axion properties [model-dep.]

1. Axion-photon



$$\partial^\mu J^{PQ}_\mu = \frac{N\alpha_s}{4\pi} G\cdot\tilde{G} + \frac{E\alpha}{4\pi} F\cdot\tilde{F}$$

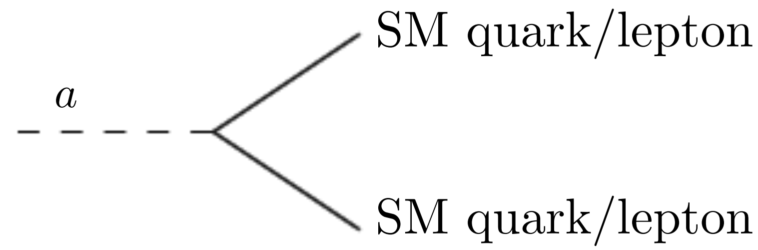
$$C_\gamma = E/N - 1.92(4)$$

model independent

depends on UV completion

enhance/suppress C_γ

2. Axion-SM fermion current



$$\frac{\partial_\mu a}{2f_a}\underbrace{\overline{\psi}_i\gamma^\mu(C^V_{ij}+C^A_{ij}\gamma_5)\psi_j}_{J^\mu_{\rm PQ}}$$

enhance/suppress $C_{p,n,e}$

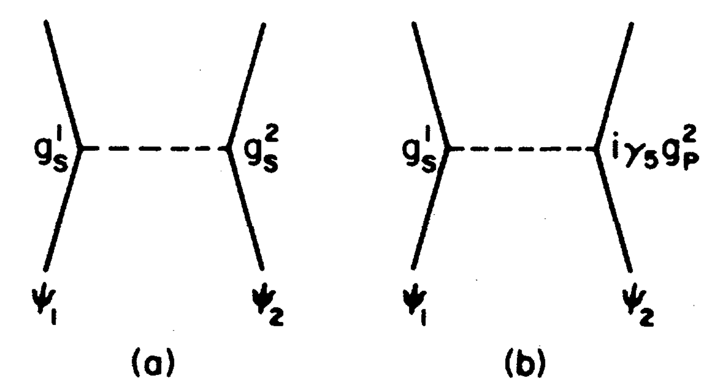
<u>flavour-violating</u> axion coupl.

3. CP-violating axion

$$\frac{f_\pi}{2}\frac{a^2}{f_a^2}\overline{N}N \longrightarrow g^S_{aN}a\overline{N}N$$

$$g^S_{aN} \sim \frac{f_\pi}{f_a}\theta_{\rm eff} \quad \left(\theta_{\rm eff} = \frac{\langle a\rangle}{f_a}\right)$$

scalar axion coupling leads to *long range forced*



monopole-monopole monopole-dipole

Benchmark axion models

- global U(1)$_{\rm PQ}$ (*QCD anomalous* + *spontaneously broken*)

$$U(1)_{\rm PQ} \times SU(3)_c^2$$

SM fermions

BSM fermions

2Higgs

PQWW

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

2Higgs+Singlet

DFSZ

[Zhitnitsky '80,
Dine, Fischler, Srednicki '81]

Higgs+Singlet

KSVZ

[Kim '79,
Shifman, Vainshtein, Zakharov '80]

$f_a \sim v$ ruled out

$f_a \gg v$ "Invisible" axion (phase of singlet field)

Benchmark axion models

- global $U(1)_{PQ}$ (*QCD anomalous* + *spontaneously broken*)

$$U(1)_{\rm PQ} \times SU(3)_c^2$$

SM fermions | BSM fermions

2Higgs+Singlet | Higgs+Singlet

DFSZ | KSVZ

$$C_\gamma = E/N - 1.92(4)$$

	DFSZ	KSVZ
	$E/N = 8/3$	$E/N = 0$
	$C_{p,n,e}(\beta) \sim \mathcal{O}(1)$	$C_p \simeq -0.5$

Axions beyond benchmarks

- Some examples:

- enhance/suppress C_γ [LDL, Mescia, Nardi 1810.07593 + 1705.05370]

- suppress $C_{p,n}$ (and C_e) [LDL, Mescia, Nardi, Panci, Ziegler 1712.04940 Björkeroth, LDL, Mescia, Nardi, Panci, Ziegler 1907.06575]

- enhance C_e [LDL, Mescia, Nardi 1705.05370 LDL, Giannotti, Nardi, Visinelli 2003.01100]

- enhance $C_{p,n}$ [LDL, Giannotti, Nardi, Visinelli 2003.01100 Darme', LDL, Giannotti, Nardi, to appear]

- Flavour violating axions [Bjorkeroth, LDL, Mescia, Nardi 1811.09637]

- CP violating axions [Bertolini, LDL, Nesti 2006.12508]

→ *QCD axion parameter space <u>much larger</u> than what traditionally thought*

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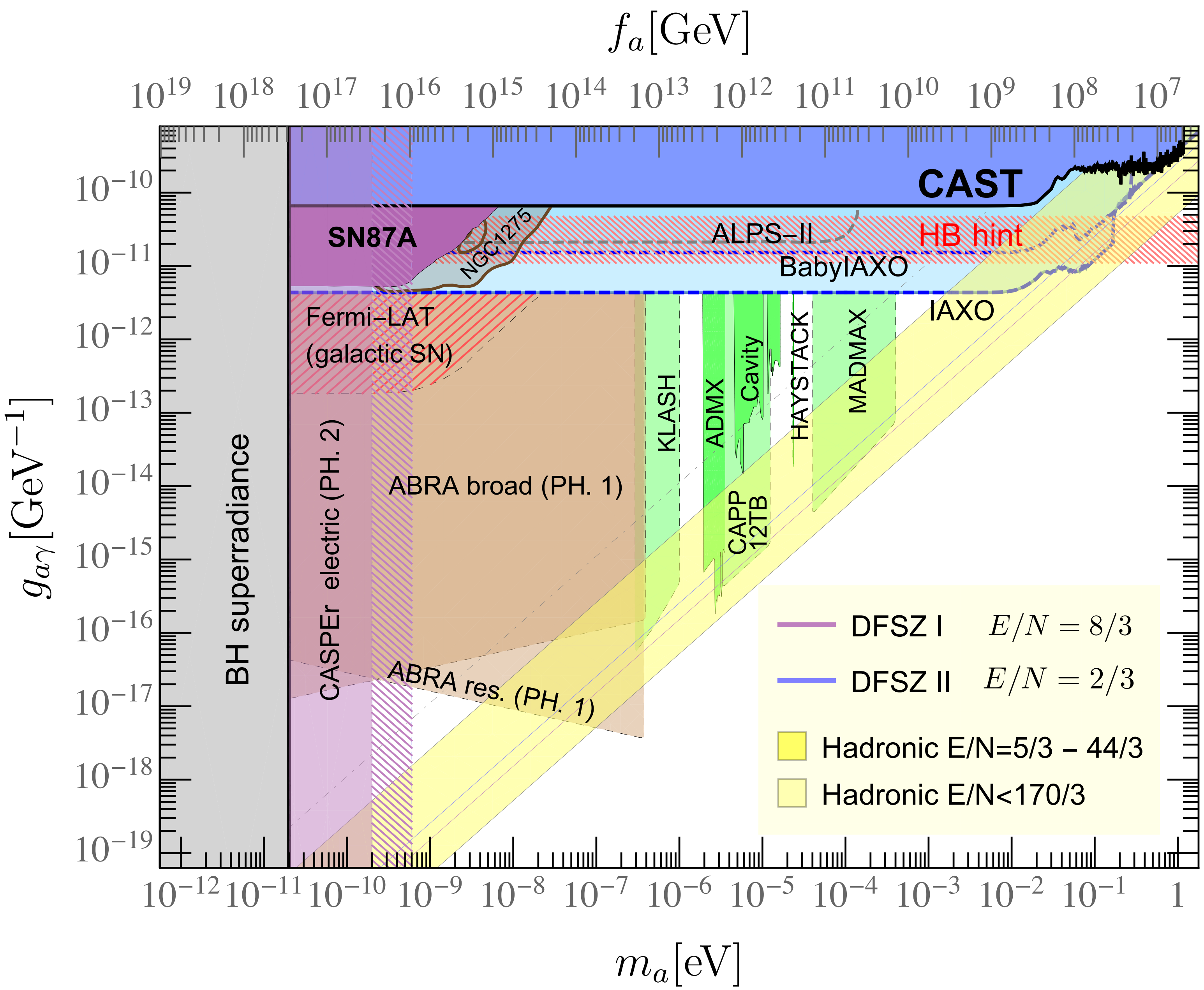
→ *QCD axion parameter space <u>much larger</u> than what traditionally thought*

Axion-Photon

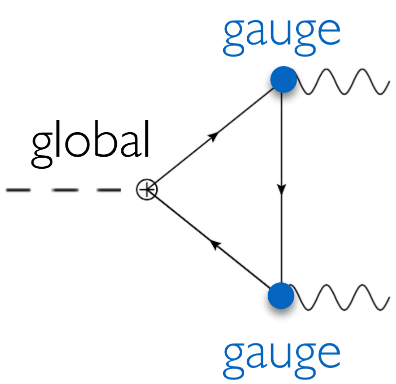
EXP	STATUS
CAST (CERN)	finished
ADMX (Seattle)	running
HAYSTAC (New Haven)	running
ALPs-II (DESY)	construction
CAPP (South Korea)	construction
ORGAN (Perth)	prototype
ABRACADABRA (MIT)	prototype
(Baby)IAXO (DESY)	preparation
MADMAX (DESY)	preparation
ACTION (South Korea)	proposed
KLASH (Frascati)	CDR
QUAX-aɣ (Legnaro)	running
…	…



[LDL, Giannotti, Nardi, Visinelli 2003.01100 (Phys. Rept.)]

Axion-Photon

$$g_{a\gamma} = \frac{\alpha}{2\pi}\frac{C_{a\gamma}}{f_a} \qquad \boxed{C_{a\gamma} = E/N - 1.92(4)} \qquad \partial^\mu J_\mu^{PQ} = \frac{N\alpha_s}{4\pi} G\cdot\tilde{G} + \frac{E\alpha}{4\pi} F\cdot\tilde{F}$$



	R_Q	$\mathcal{O}_{Qq}$	$\Lambda^{2-\text{loop}}_{\text{Landau}}[\text{GeV}]$	E/N
	$(3,1,-1/3)$	$\overline{Q}_L d_R$	$9.3\cdot 10^{38}(g_1)$	$2/3$
	$(3,1,2/3)$	$\overline{Q}_L u_R$	$5.4\cdot 10^{34}(g_1)$	$8/3$
R_Q^w	$(3,2,1/6)$	$\overline{Q}_R q_L$	$6.5\cdot 10^{39}(g_1)$	$5/3$
	$(3,2,-5/6)$	$\overline{Q}_L d_R H^\dagger$	$4.3\cdot 10^{27}(g_1)$	$17/3$
	$(3,2,7/6)$	$\overline{Q}_L u_R H$	$5.6\cdot 10^{22}(g_1)$	$29/3$
	$(3,3,-1/3)$	$\overline{Q}_R q_L H^\dagger$	$5.1\cdot 10^{30}(g_2)$	$14/3$
	$(3,3,2/3)$	$\overline{Q}_R q_L H$	$6.6\cdot 10^{27}(g_2)$	$20/3$
R_Q^s	$(3,3,-4/3)$	$\overline{Q}_L d_R H^{\dagger 2}$	$3.5\cdot 10^{18}(g_1)$	$44/3$
	$(\overline{6},1,-1/3)$	$\overline{Q}_L \sigma_{\mu\nu} d_R G^{\mu\nu}$	$2.3\cdot 10^{37}(g_1)$	$4/15$
	$(\overline{6},1,2/3)$	$\overline{Q}_L \sigma_{\mu\nu} u_R G^{\mu\nu}$	$5.1\cdot 10^{30}(g_1)$	$16/15$
	$(\overline{6},2,1/6)$	$\overline{Q}_R \sigma_{\mu\nu} q_L G^{\mu\nu}$	$7.3\cdot 10^{38}(g_1)$	$2/3$
	$(8,1,-1)$	$\overline{Q}_L \sigma_{\mu\nu} e_R G^{\mu\nu}$	$7.6\cdot 10^{22}(g_1)$	$8/3$
	$(8,2,-1/2)$	$\overline{Q}_R \sigma_{\mu\nu} \ell_L G^{\mu\nu}$	$6.7\cdot 10^{27}(g_1)$	$4/3$
	$(15,1,-1/3)$	$\overline{Q}_L \sigma_{\mu\nu} d_R G^{\mu\nu}$	$8.3\cdot 10^{21}(g_3)$	$1/6$
	$(15,1,2/3)$	$\overline{Q}_L \sigma_{\mu\nu} u_R G^{\mu\nu}$	$7.6\cdot 10^{21}(g_3)$	$2/3$

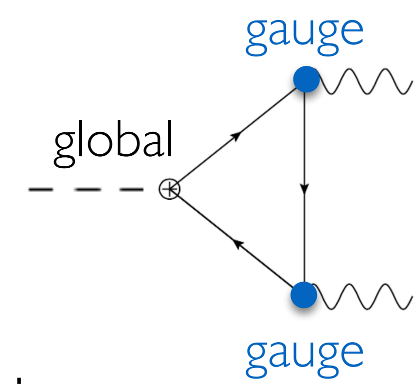
- Pheno preferred hadronic axions
  1. *Q-short lived (no coloured relics)*
  2. *No Landau poles below Planck*

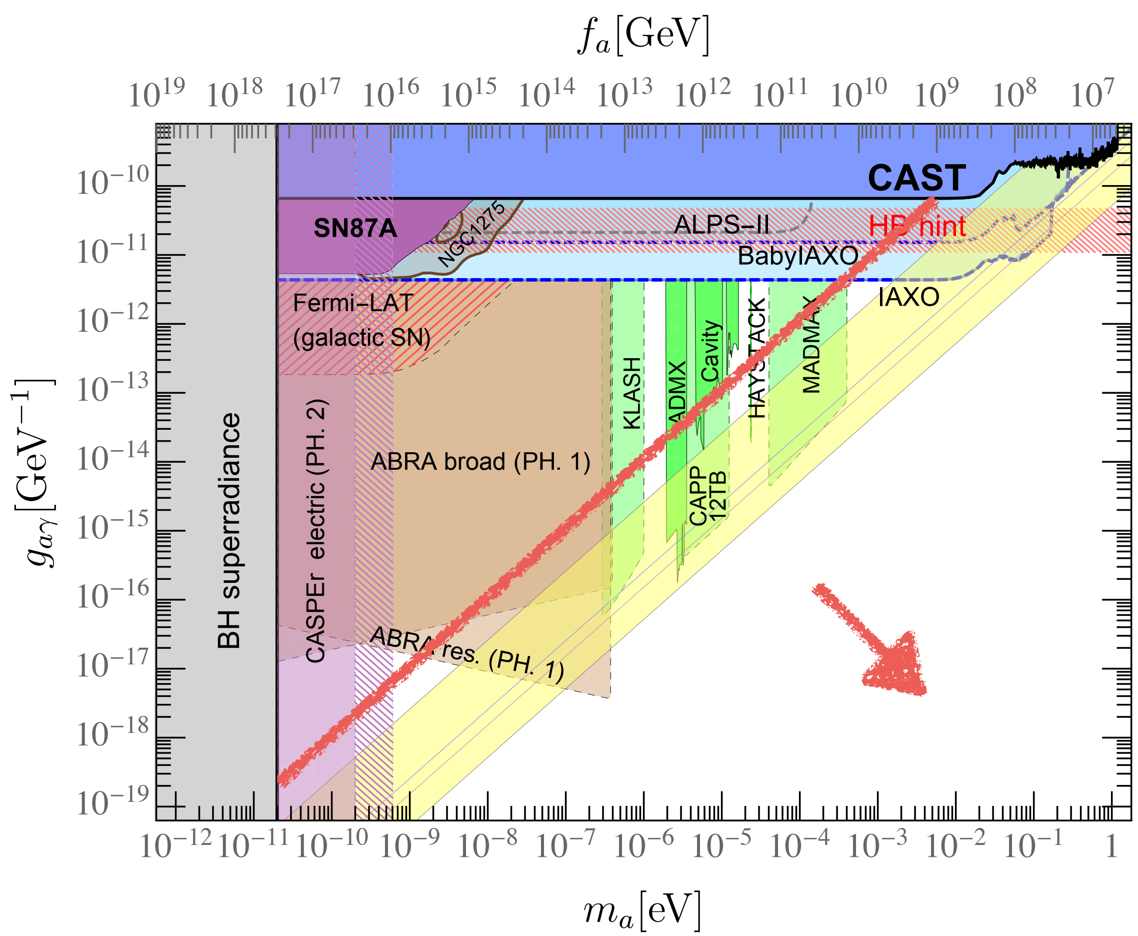
$\longrightarrow \quad E/N \in [5/3, 44/3]$

[LDL, Mescia, Nardi 1810.07593]

Axion-Photon

$$g_{a\gamma} = \frac{\alpha}{2\pi}\frac{C_{a\gamma}}{f_a} \qquad \boxed{C_{a\gamma} = E/N - 1.92(4)} \qquad \partial^\mu J^{PQ}_\mu = \frac{N\alpha_s}{4\pi} G\cdot\tilde{G} + \frac{E\alpha}{4\pi} F\cdot\tilde{F}$$





- Pheno preferred <u>hadronic axions</u>

- More Q's ? [LDL, Mescia, Nardi 1705.05370]

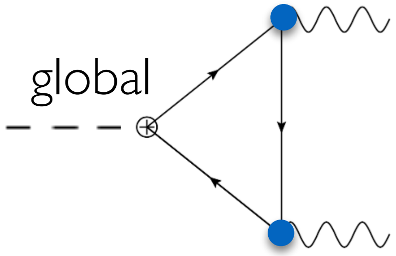
$E/N < 170/3$ *(perturbativity)*

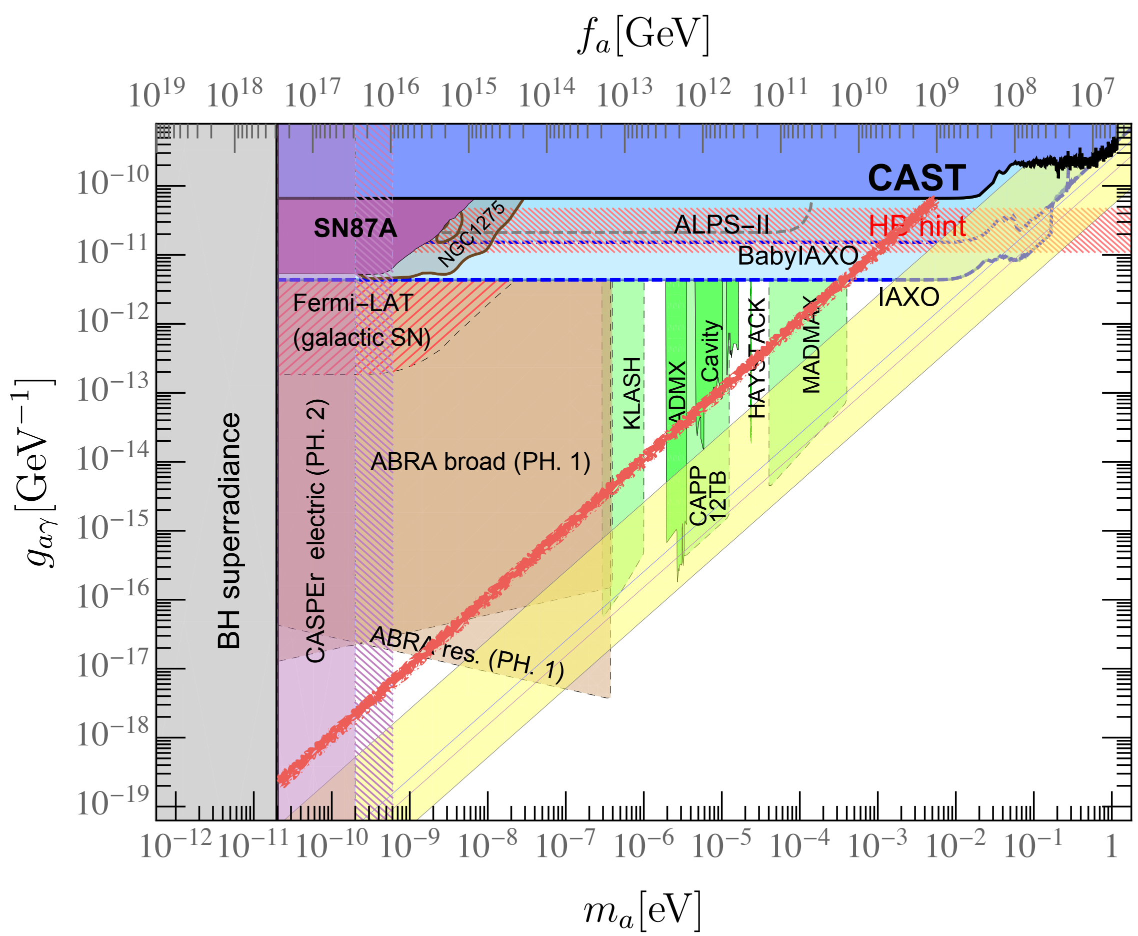
$g_{a\gamma} \to 0$

[*"such a cancellation is immoral, but not unnatural"*, D. B. Kaplan, NPB260 (1985)]

Axion-Photon

$$g_{a\gamma} = \frac{\alpha}{2\pi}\frac{C_{a\gamma}}{f_a} \qquad \boxed{C_{a\gamma} = E/N - 1.92(4)} \qquad \partial^\mu J_\mu^{PQ} = \frac{N\alpha_s}{4\pi} G\cdot\tilde{G} + \frac{E\alpha}{4\pi} F\cdot\tilde{F}$$





- Pheno preferred hadronic axions
- More Q's ? [LDL, Mescia, Nardi 1705.05370]

  $E/N < 170/3$ *(perturbativity)*

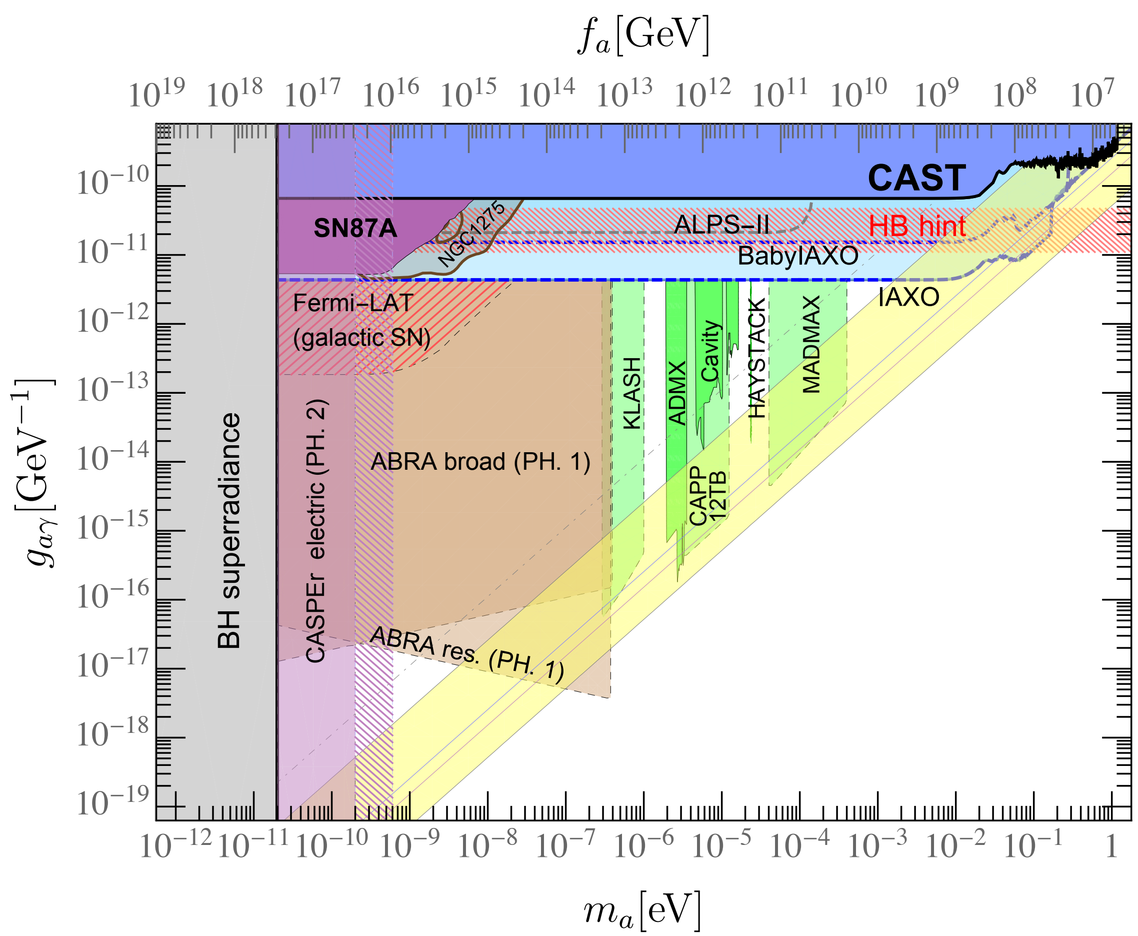
- Going above 170/3 ?

  - *boost global charge (clockwork-like)*
  - *be agnostic, E/N is a free parameter*

A change of perspective

$$g_{a\gamma} = \frac{\alpha}{2\pi}\frac{C_{a\gamma}}{f_a} \qquad \boxed{C_{a\gamma} = E/N - 1.92(4)}$$

[LDL, Giannotti, Nardi, Visinelli 2003.01100 (Phys. Rept.)]



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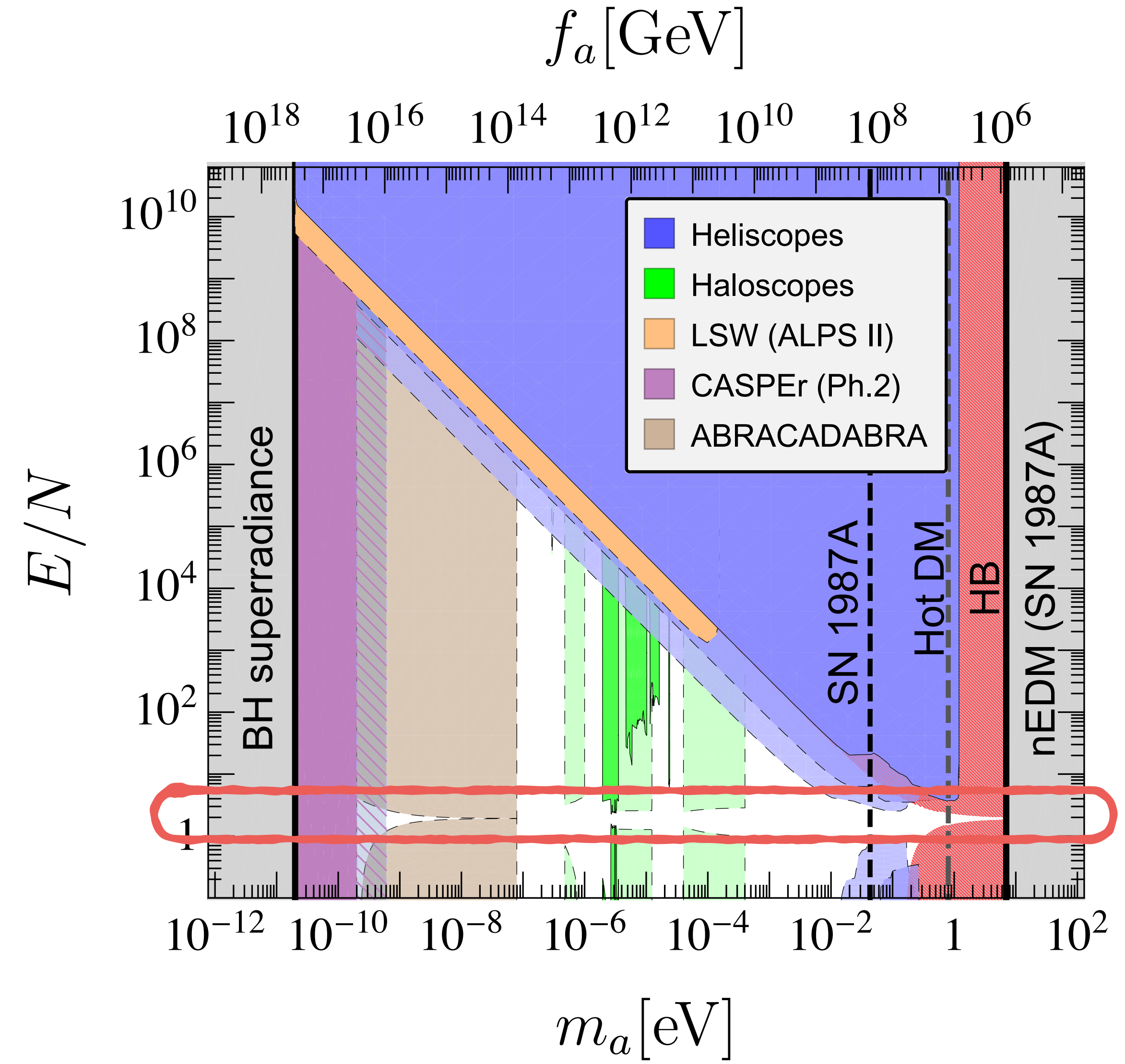

1. <u>They are all QCD axions</u>, *exp.s have just started to constrain E/N from above*

2. *E/N ~ 1.92 appears as a tuned region in theory space*

CPV axion & long-range forces

- New CP violation in the UV can source a *scalar* axion-nucleon coupling

$$\frac{f_\pi}{2}\frac{a^2}{f_a^2}\overline{N}N \longrightarrow \overline{g}_{aN} a\overline{N}N \qquad \overline{g}_{aN} \sim \frac{f_\pi}{f_a}\theta_{\rm eff} \qquad \left(\theta_{\rm eff} = \frac{\langle a \rangle}{f_a} \neq 0\right)$$

[Moody, Wilczek PRD30 (1984)]

$$\frac{1}{2}\frac{a^2}{f_a^2}\underbrace{\left\langle G\tilde{G}, G\tilde{G}\right\rangle}_{\chi} + \frac{a}{f_a}\underbrace{\left\langle G\tilde{G}, \mathcal{O}_{\rm CPV}\right\rangle}_{\chi'} \longrightarrow \frac{\langle a \rangle}{f_a} = -\frac{\chi'}{\chi}$$

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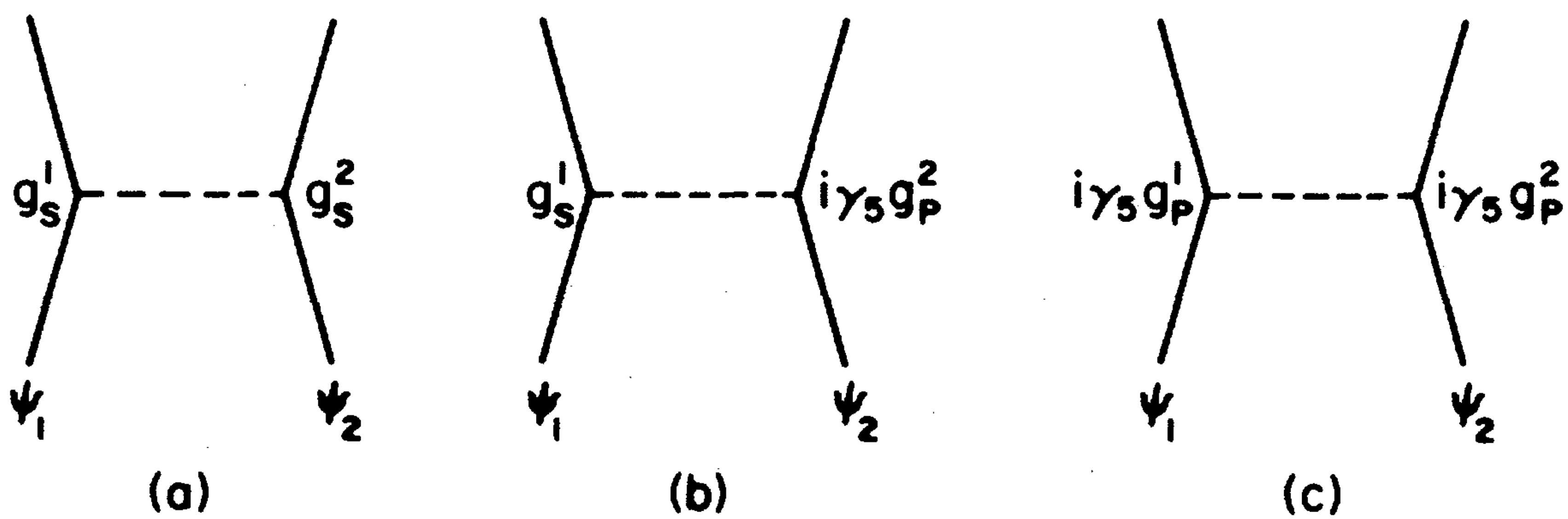

monopole-monopole monopole-dipole dipole-dipole

$$V(r) = \frac{-g_S^1 g_S^2 e^{-m_\varphi r}}{4\pi r} \qquad V(r) = (g_S^1 g_P^2)\frac{\hat{\sigma}_2 \cdot \hat{r}}{8\pi M_2}\left[\frac{m_\varphi}{r} + \frac{1}{r^2}\right]e^{-m_\varphi r}$$

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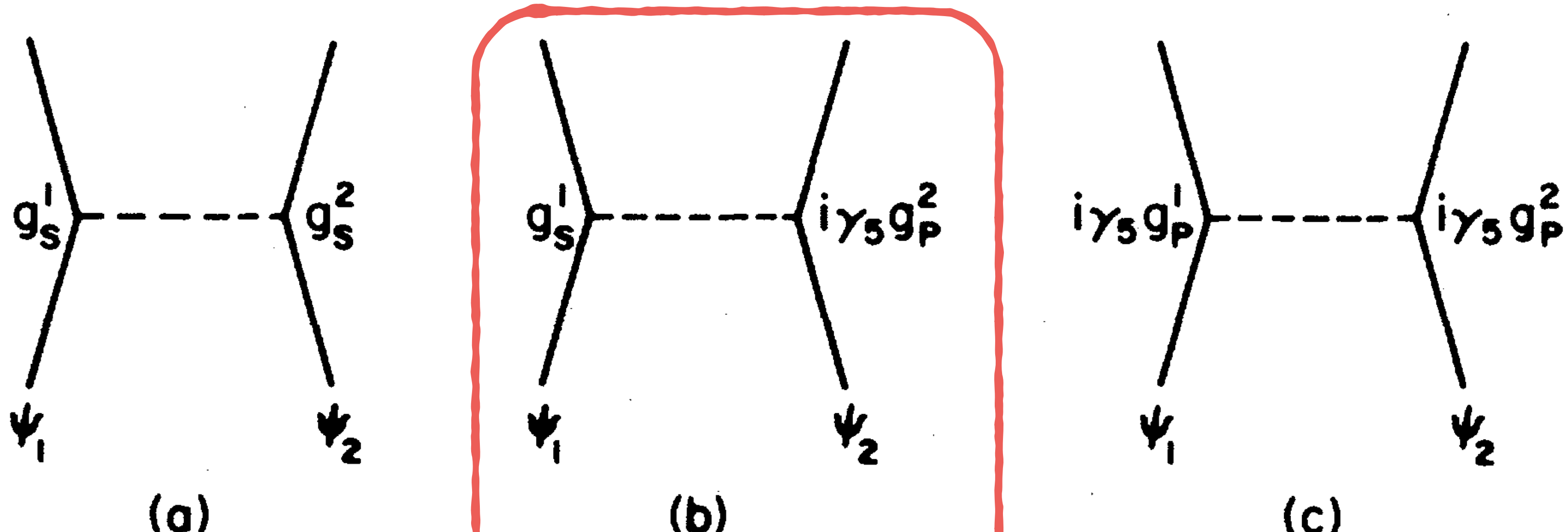

monopole-monopole | monopole-dipole | dipole-dipole

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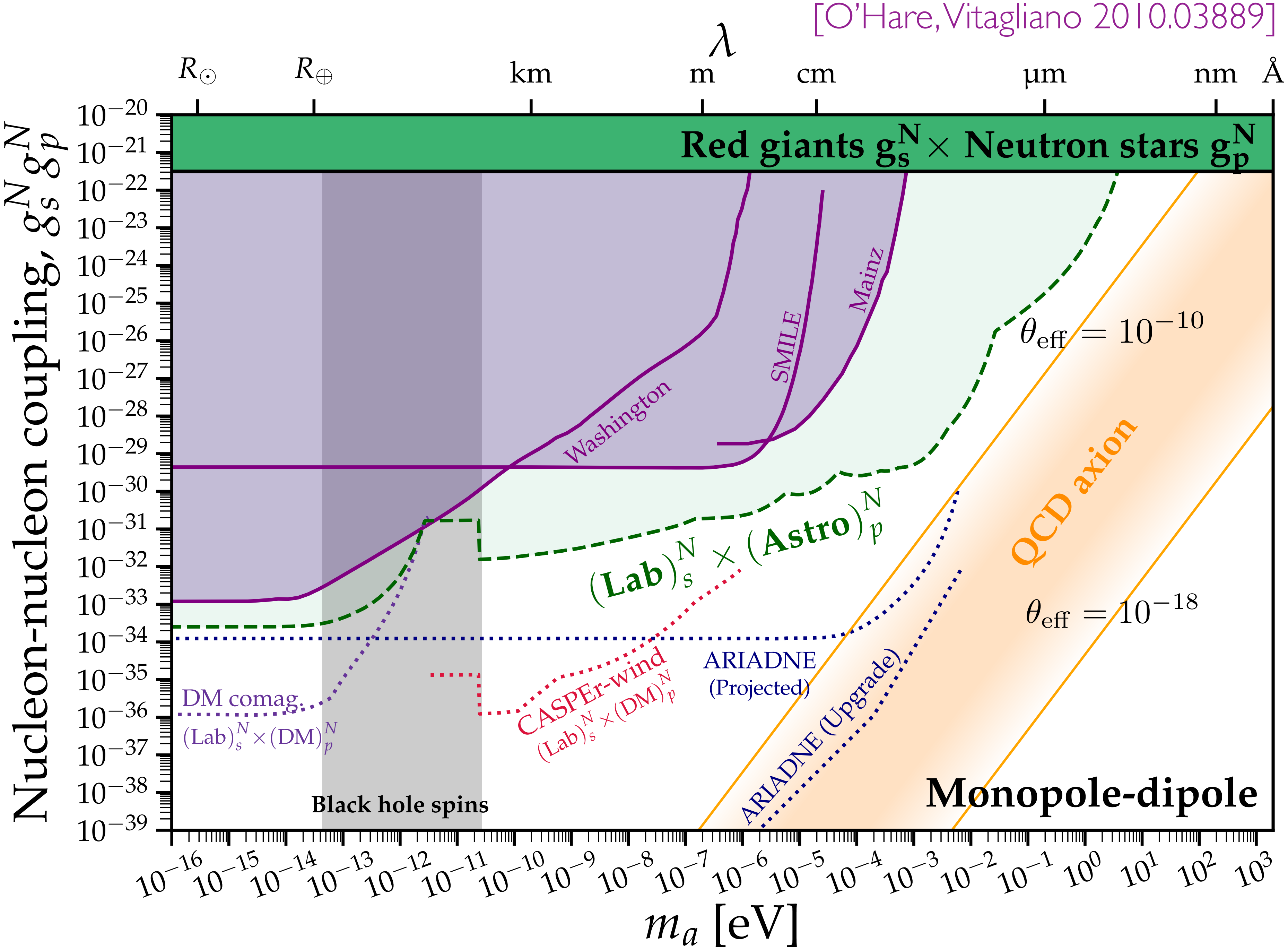
[O'Hare, Vitagliano 2010.03889]



A new master formula

- Moody-Wilczek formula [Moody, Wilczek PRD30 (1984)]

$$\bar{g}_{aN} = \frac{\bar{\theta}_{\rm eff}}{f_a} \frac{m_u m_d}{m_u + m_d} \langle N | \bar{u}u + \bar{d}d | N \rangle \simeq \bar{\theta}_{\rm eff} \left(\frac{17 \text{ MeV}}{f_a} \right)$$

- From LO bary-meson chiral Lagrangian [Bertolini, LDL, Nesti 2006.12508]

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

meson tadpoles

iso-spin breaking

MW missed a factor 1/2

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- Moody-Wilczek formula [Moody, Wilczek PRD30 (1984)]

$$\bar{g}_{aN} = \frac{1}{2}\frac{\overline{\theta}_{\rm eff}}{f_a}\frac{m_u m_d}{m_u + m_d}\langle N|\overline{u}u + \overline{d}d|N\rangle \simeq \frac{1}{2}\overline{\theta}_{\rm eff}\left(\frac{17\ \text{MeV}}{f_a}\right)$$

- From LO bary-meson chiral Lagrangian [Bertolini, LDL, Nesti 2006.12508]

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

meson tadpoles

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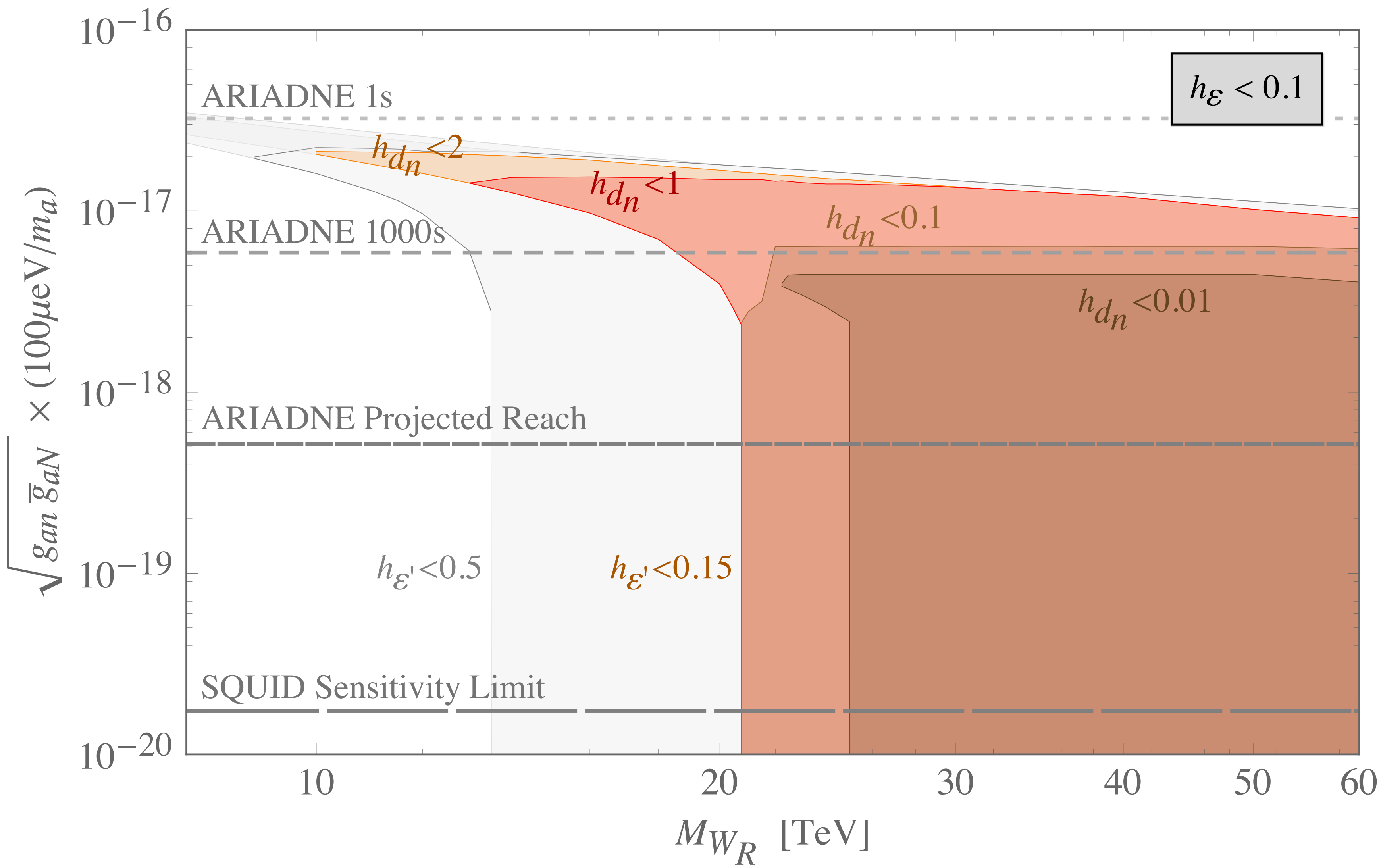
A new master formula

- Predictions from low-scale PQ-LR with P-parity [Bertolini, LDL, Nesti 2006.12508]

4 CPV observables $(\varepsilon,\ \varepsilon',\ d_n,\ \overline{g}_{aN})$ *function of a single phase* $\boldsymbol{\alpha}$ $\langle\Phi\rangle = \mathrm{diag}\{v_1, e^{i\alpha}v_2\}$



$$h_{\mathcal{O}} \equiv \frac{\mathcal{O}^{\mathrm{th}}}{\mathcal{O}^{\mathrm{exp}}}$$

Towards 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)

Towards a PQ theory

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1. realise the PQ as an accidental symmetry

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

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

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

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

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

Accidental SO(10) axion

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

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

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

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

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

Accidental SO(10) axion

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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 renorm. Lagrangian

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

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

Accidental SO(10) axion

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ϕ_{45}	$(0, 0)$	45	1	$\mathbf{1}$	1	0

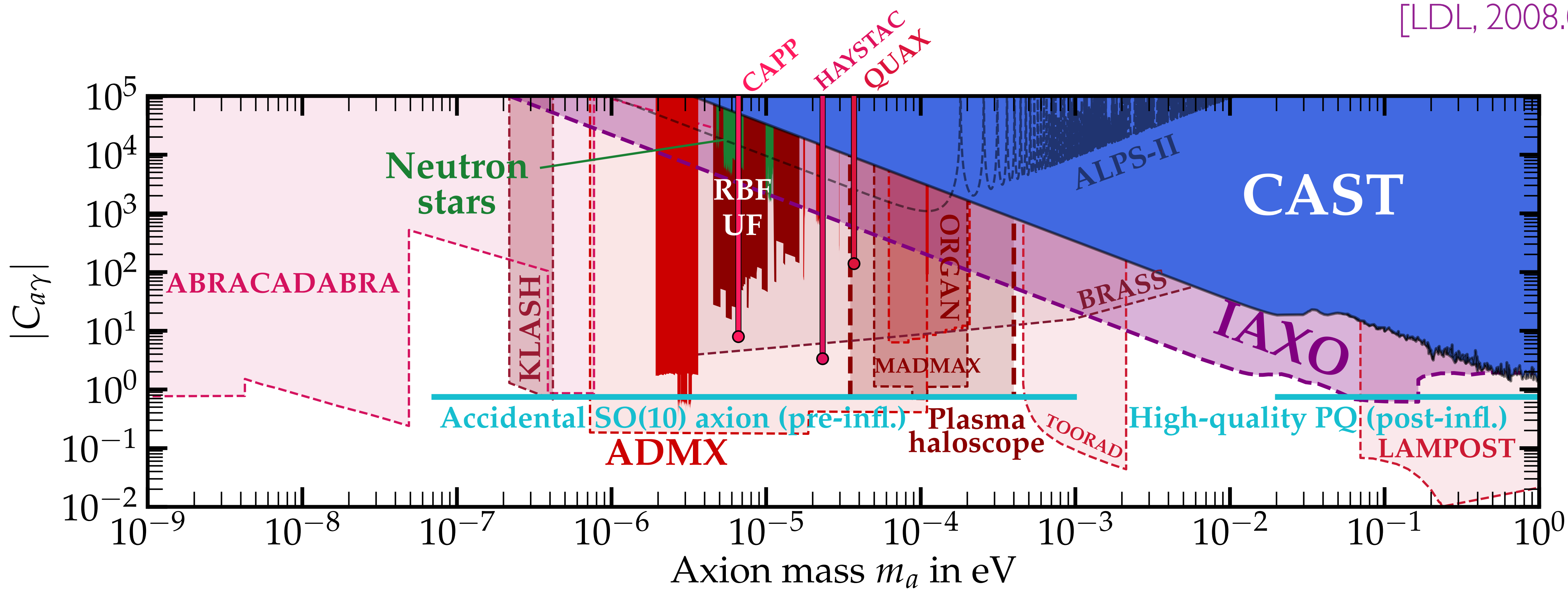
→ Axion in a linear combination of 16 and 126 phases

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

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

Accidental SO(10) axion

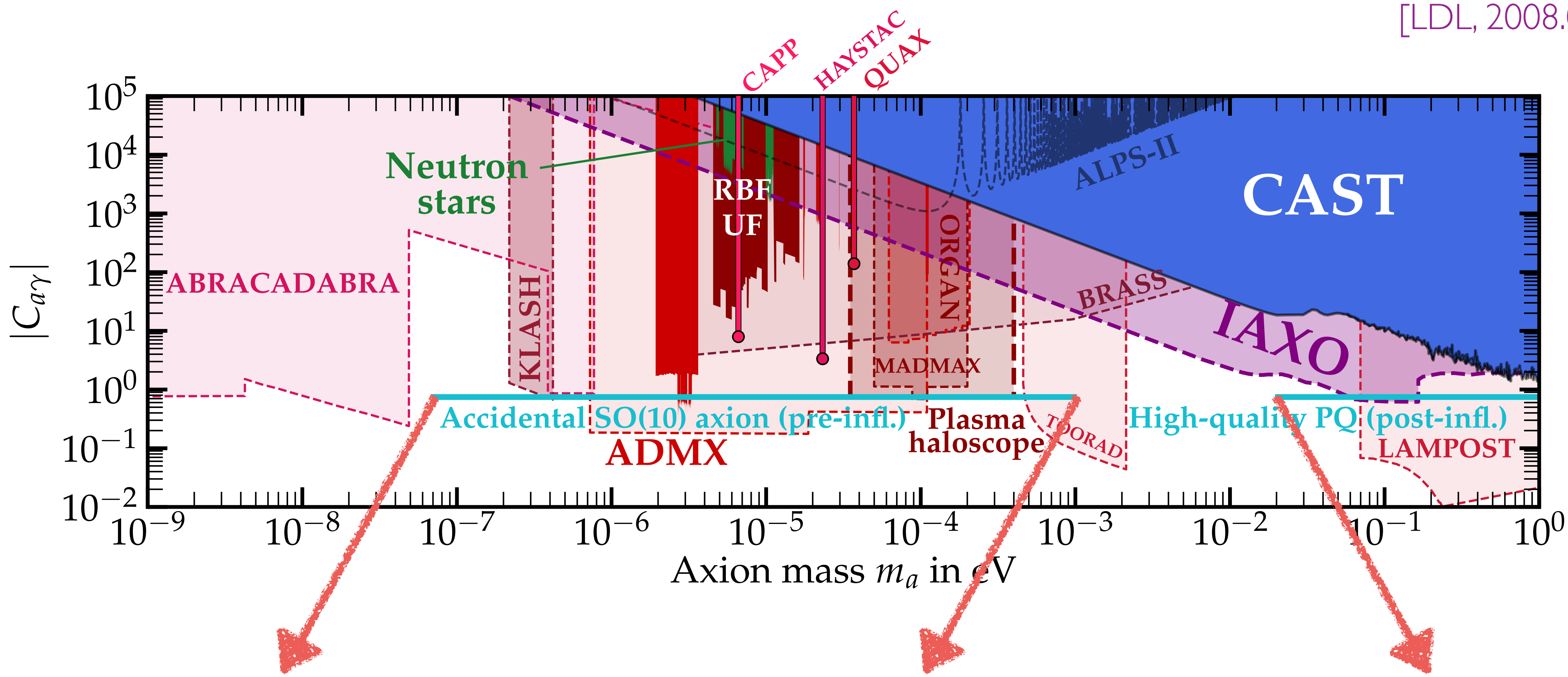
[LDL, 2008.09119]



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

Accidental SO(10) axion

[LDL, 2008.09119]



seesaw scale

iso-curvature fluctuations

PQ quality

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

Conclusions

- QCD axion: 2 birds with 1 stone

  1. Strong CP problem

  2. Dark Matter

- Experimentally driven phase

  we are entering <u>now</u> the preferred window for the QCD axion

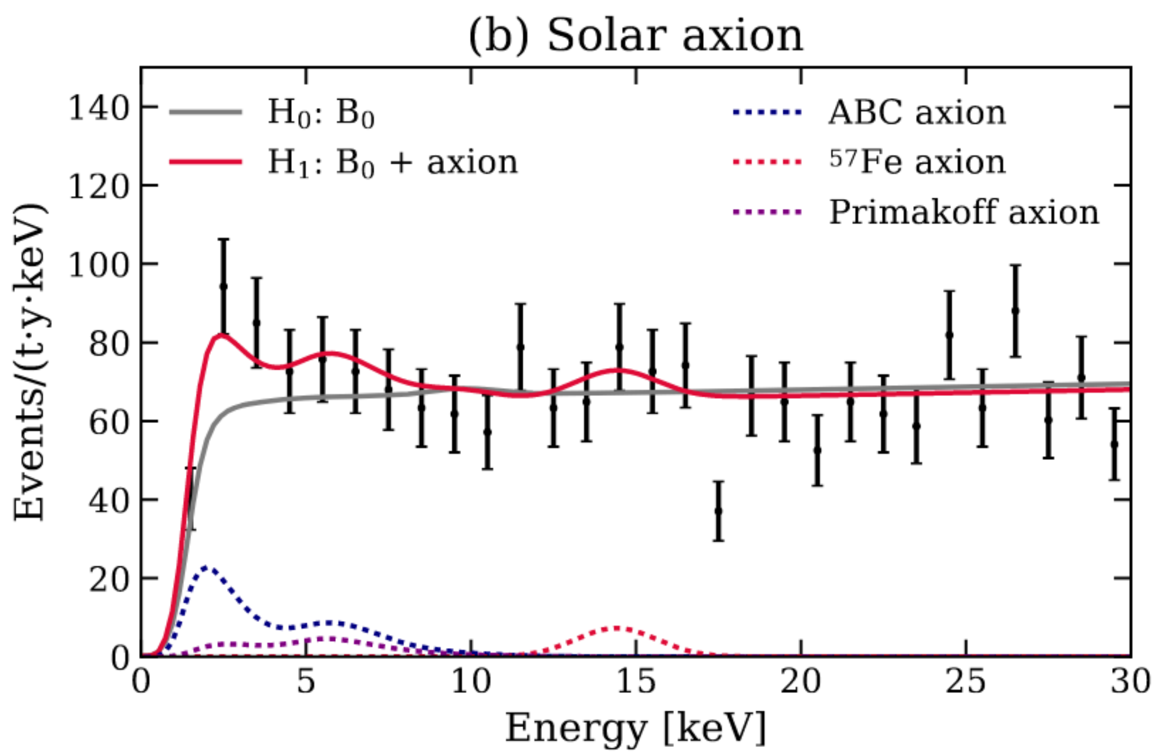
- Take home message

  axion couplings are <u>UV dependent</u> (enhanced couplings, flavour, CPV, etc.)

  if an "axion-like particle" will be ever discovered,
  it would be tempting to think that it had something to do with the strong CP problem

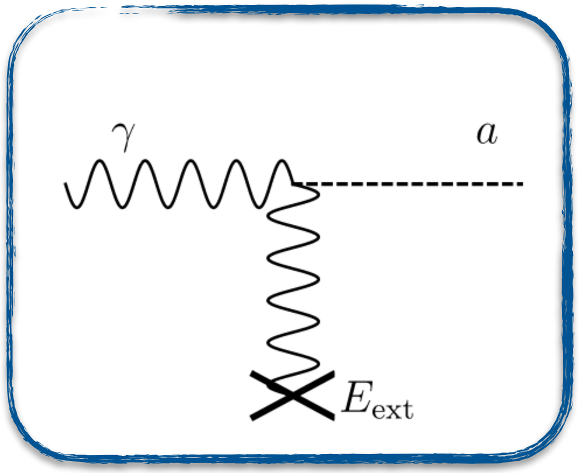
Backup slides

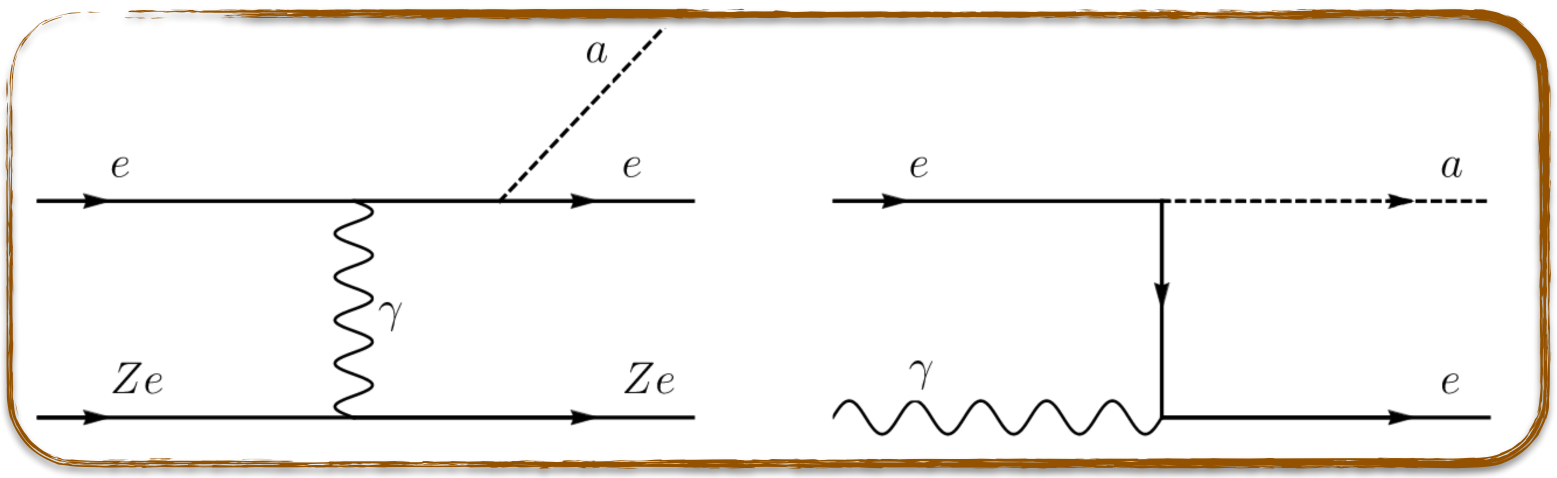
XENON1T



Solar axion hypoth. favoured at 3.5σ

$$\mathcal{L}_{\rm int} = \frac{1}{4} g_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} + g_{ae} \frac{\partial_\mu a}{2 m_e} \bar{e} \gamma^\mu \gamma_5 e$$





Primakoff

Bremsstrahlung

Compton

XENON1T

[LDL, Fedele, Giannotti, Mescia, Nardi 2006.12487 (Phys. Rev. Lett.)]

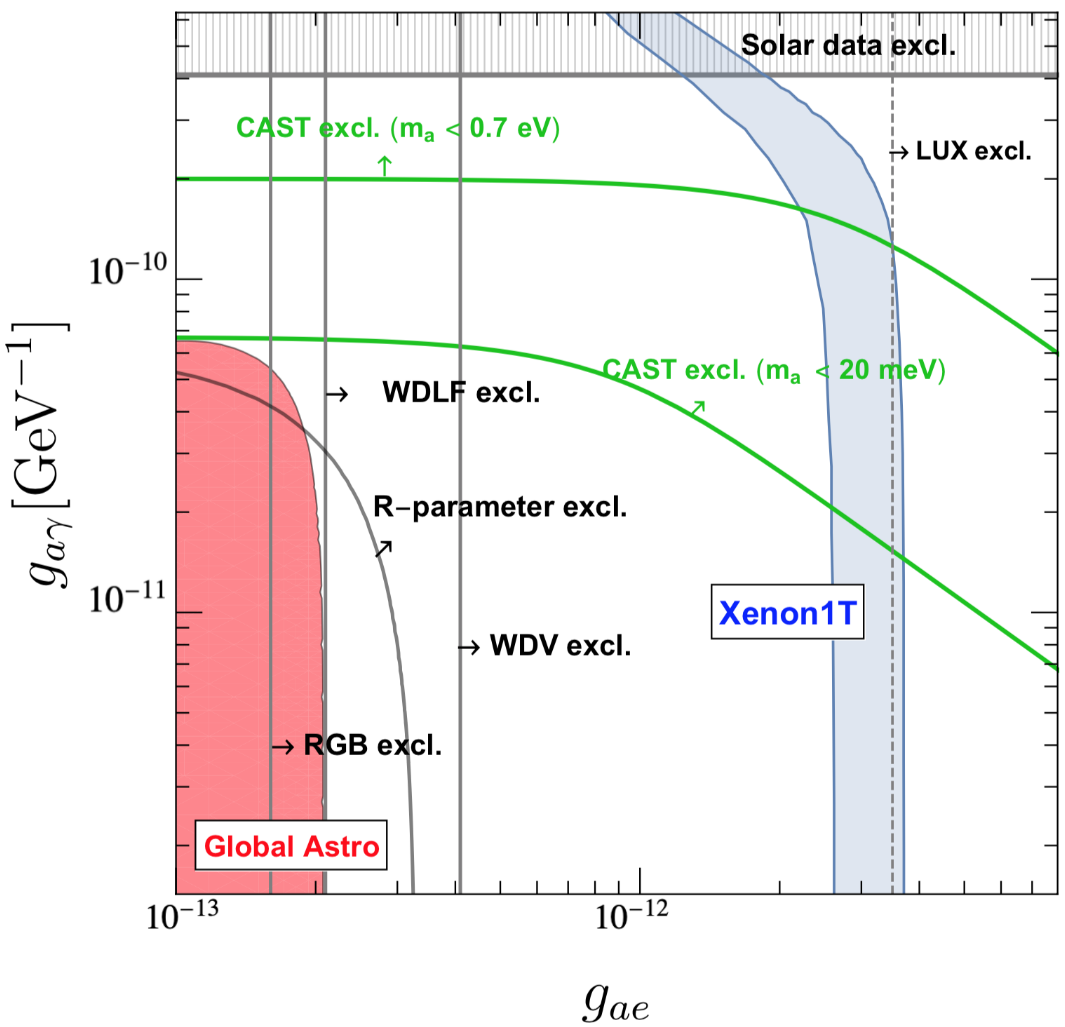


FIG. 2. XENON1T 90% C.L. fit (blue region). 3σ exclusion limit from solar data (grey hatched region). 2σ LUX limit (grey dashed line) and CAST limits for $m_a < 20\,\mathrm{meV}$ and $m_a < 0.7\,\mathrm{eV}$ (green lines). Individual 2σ limits from R-parameter, TRGB, WDLF, WDVs (grey lines) and 2σ global bound from astrophysics (red region).

*Solar axion hypoth. favoured at 3.5***σ**

Untenable, when confronted with astrophysics !

Observable	Measured	Expected	Tension
R-parameter	1.39 ± 0.03	$\leq 0.83\ (g_{e13} = 9)$	$19\sigma^\star$
$M^{\mathrm{LMC}}_{I,\mathrm{TRGB}}$ [mag]	-4.047 ± 0.045	$\leq -4.92\ (g_{e13} = 9)$	$19\sigma^\star$
g^{WDLF}_{e13}	$\leq 2.8\ (3\sigma)$	29.7 ± 4.8	5.6σ
$\dot{\Pi}^{(113)}_{\mathrm{L19-2}}$	3.0 ± 0.6	57 ± 16	3.4σ
$\dot{\Pi}^{(192)}_{\mathrm{L19-2}}$	3.0 ± 0.6	95 ± 27	3.4σ
$\dot{\Pi}_{\mathrm{PG1351+489}}$	200 ± 90	19620 ± 5730	3.4σ
$\dot{\Pi}_{\mathrm{G117-B15A}}$	4.2 ± 0.7	113 ± 33	3.3σ
$\dot{\Pi}_{\mathrm{R548}}$	3.3 ± 1.1	87 ± 25	3.3σ

TABLE I. Measured values of astrophysic observables and expected ranges, for g_{ae}, $g_{a\gamma}$ falling within the 1σ region of the XENON1T fit ($\bar{g}_{e13} \in [28, 35]$). $\dot{\Pi}_{\mathrm{WD_i}}$ are in units of

XENON1T

[LDL, Fedele, Giannotti, Mescia, Nardi 2006.12487 (Phys. Rev. Lett.)]

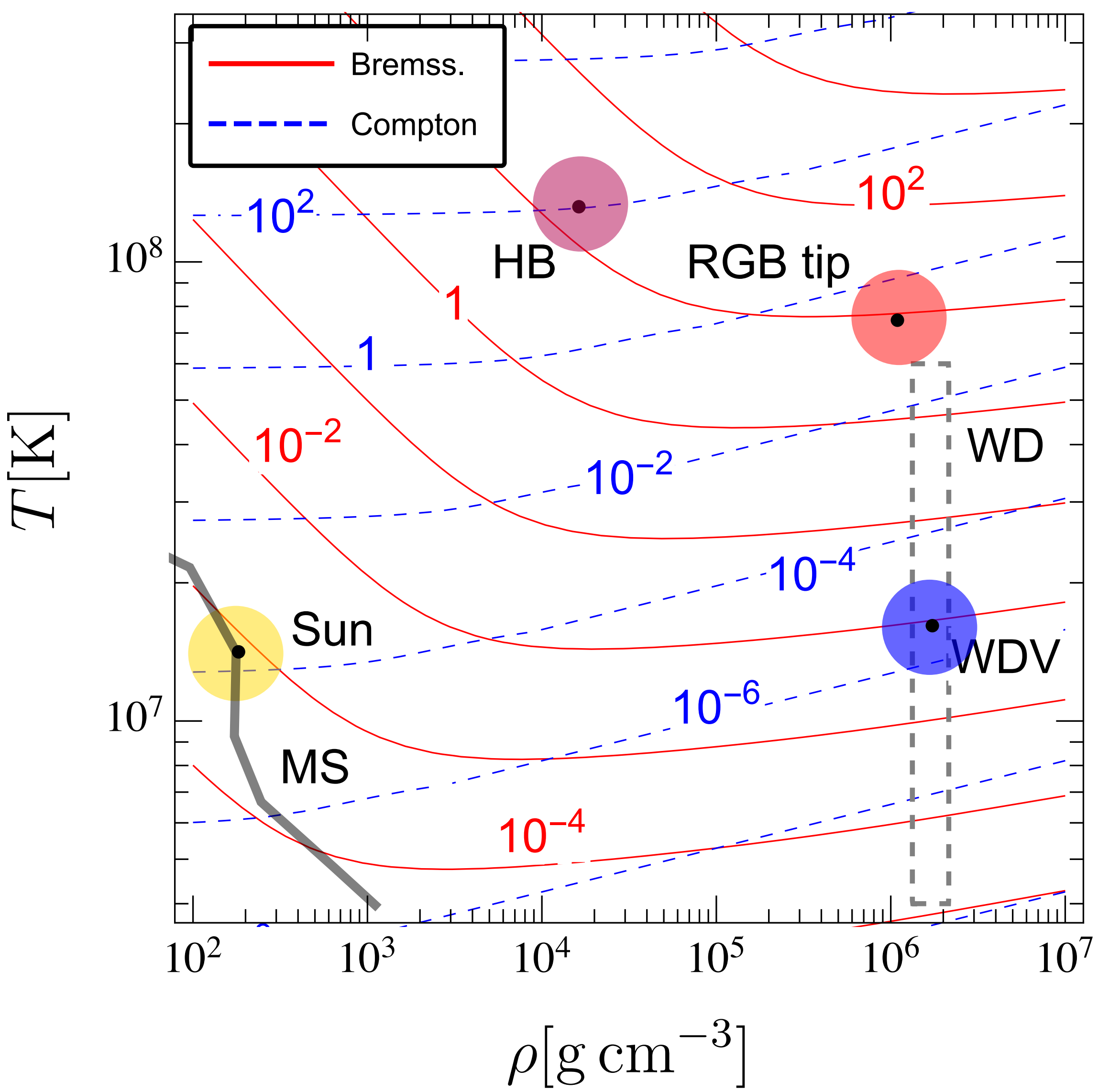


FIG. 1. Contours of the axion energy-loss rates per unit mass, in $\mathrm{erg\,g^{-1}s^{-1}}$, for a pure He plasma and $g_{e13} = 4.3$.

*Solar axion hypoth. favoured at 3.5***σ**

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KSVZ axions

- Field content

Field	Spin	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{PQ}$
Q_L	$1/2$	$\mathcal{C}_Q$	$\mathcal{I}_Q$	$\mathcal{Y}_Q$	$\mathcal{X}_L$
Q_R	$1/2$	$\mathcal{C}_Q$	$\mathcal{I}_Q$	$\mathcal{Y}_Q$	$\mathcal{X}_R$
Φ	0	1	1	0	1

[Kim '79,
Shifman, Vainshtein, Zakharov '80]

PQ charges carried by a vector-like quark $Q = Q_L + Q_R$

[original KSVZ model assumes Q ~ (3,1,0)]

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

$$\left.\begin{aligned} N &= \sum_Q (\mathcal{X}_L - \mathcal{X}_R)\ T(\mathcal{C}_Q) \\ E &= \sum_Q (\mathcal{X}_L - \mathcal{X}_R)\ \mathcal{Q}_Q^2 \end{aligned}\right\}\ \text{anomaly coeff.}$$

and a SM singlet **Φ** containing the "invisible" axion ($f_a \gg v$)

$$\Phi(x) = \frac{1}{\sqrt{2}}\left[\rho(x) + f_a\right] e^{ia(x)/f_a}$$

KSVZ axions

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Φ	0	1	1	0	1

[Kim '79,
Shifman, Vainshtein, Zakharov '80]

- Lagrangian

$$\mathcal{L}_a = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm PQ} - V_{H\Phi} + \mathcal{L}_{Qq}$$

$$|\mathcal{X}_L - \mathcal{X}_R| = 1$$

- $\mathcal{L}_{\rm PQ} = |\partial_\mu \Phi|^2 + \overline{Q} i \not{D} Q - (y_Q \, \overline{Q}_L Q_R \Phi + \text{H.c.})$ $\rightarrow$ $m_Q = y_Q f_a / \sqrt{2}$
- $V_{H\Phi} = -\mu_\Phi^2 |\Phi|^2 + \lambda_\Phi |\Phi|^4 + \lambda_{H\Phi} |H|^2 |\Phi|^2$ $\rightarrow$ $m_\rho \sim f_a$
- $\mathcal{L}_{Qq}$ d $\leq$ 4 mixing with SM quarks (depends in Q-gauge quantum numbers)

Q stability

- Symmetry of the kinetic term

$$U(1)_{Q_L} \times U(1)_{Q_R} \times U(1)_\Phi \xrightarrow{y_Q \neq 0} U(1)_{\rm PQ} \times U(1)_{\rm Q}$$

$$\mathcal{L}_{\rm PQ} = |\partial_\mu \Phi|^2 + \overline{Q} i \not{D} Q - (y_Q \overline{Q}_L Q_R \Phi + \text{H.c.})$$

- $U(1)_{\rm Q}$ is the Q-baryon number: <u>if exact, Q would be stable</u>

$\downarrow$

cosmological issue if thermally produced
in the early universe !

Q stability

- Symmetry of the kinetic term

$$U(1)_{Q_L} \times U(1)_{Q_R} \times U(1)_{\Phi} \xrightarrow{y_Q \neq 0} U(1)_{\rm PQ} \times U(1)_{\rm Q}$$

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- $U(1)_{\rm Q}$ is the Q-baryon number: <u>if exact, Q would be stable</u>

- if $\mathcal{L}_{Qq} \neq 0$ $U(1)_{\rm Q}$ is further broken and Q-decay is possible [Ringwald, Saikawa, 1512.06436]

- decay also possible via d>4 operators (e.g. Planck-induced)

→ stability depends on Q representations

Selection criteria

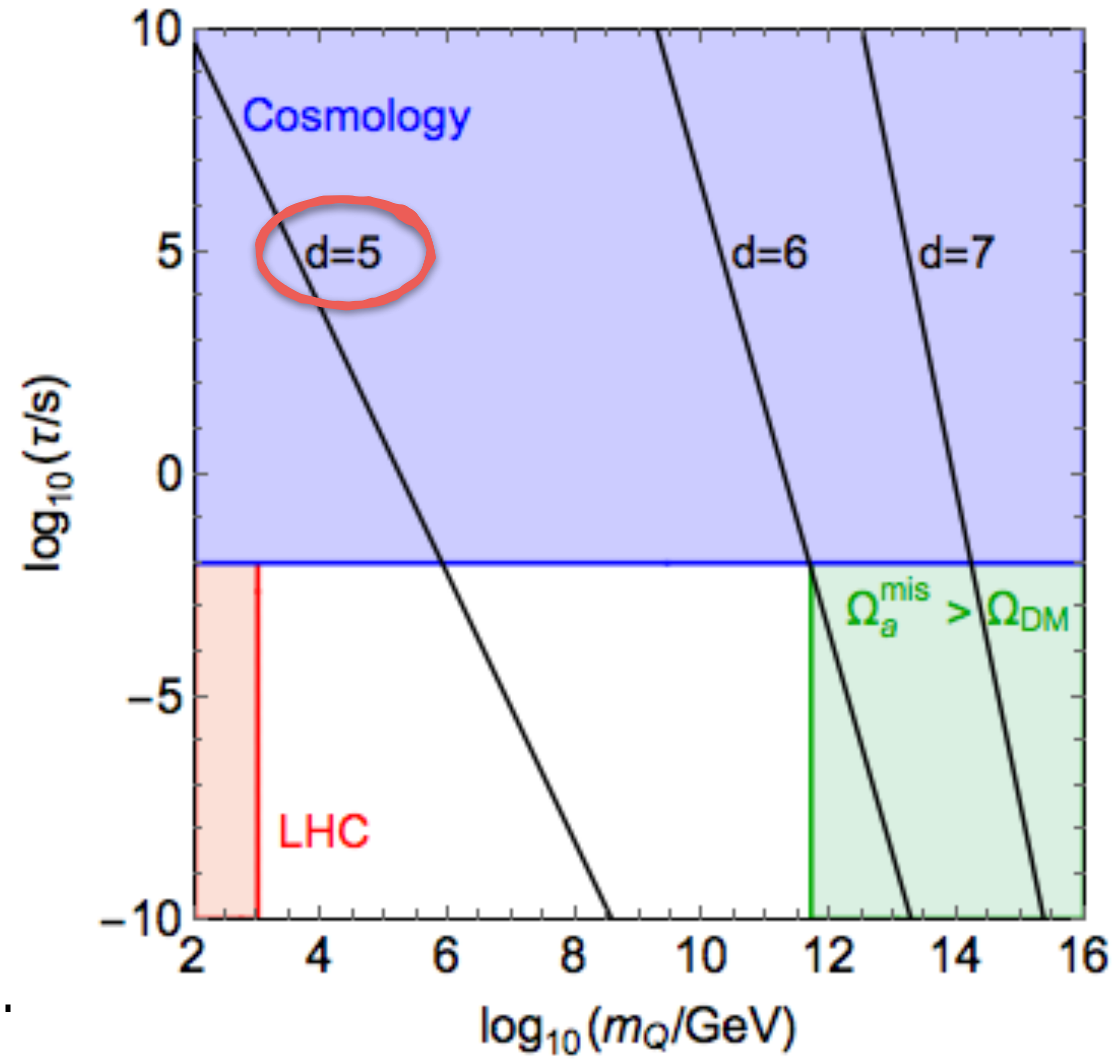
- We require: [for $T_{\rm reheating} > m_Q \sim f_a$ (post-inflat. PQ breaking)]

1. Q sufficiently short lived $\tau_Q \lesssim 10^{-2}$ s

   - decays via d=4 operators are fast enough
   - decays via effective operators

$$\mathcal{L}^{d>4}_{Qq} = \frac{1}{M^{(d-4)}_{\rm Planck}} \mathcal{O}^{d>4}_{Qq} + \text{h.c.}$$

$$\Gamma_{\rm NDA} = \frac{1}{4(4\pi)^{2n_f-3}(n_f-1)!(n_f-2)!} \frac{m_Q^{2d-7}}{M^{2(d-4)}_{\rm Planck}}$$



→ "safe" Q must allow for d=4 or 5 decay op.

Selection criteria

- We require: [for $T_{reheating} > m_Q \sim f_a$ (post-inflat. PQ breaking)]

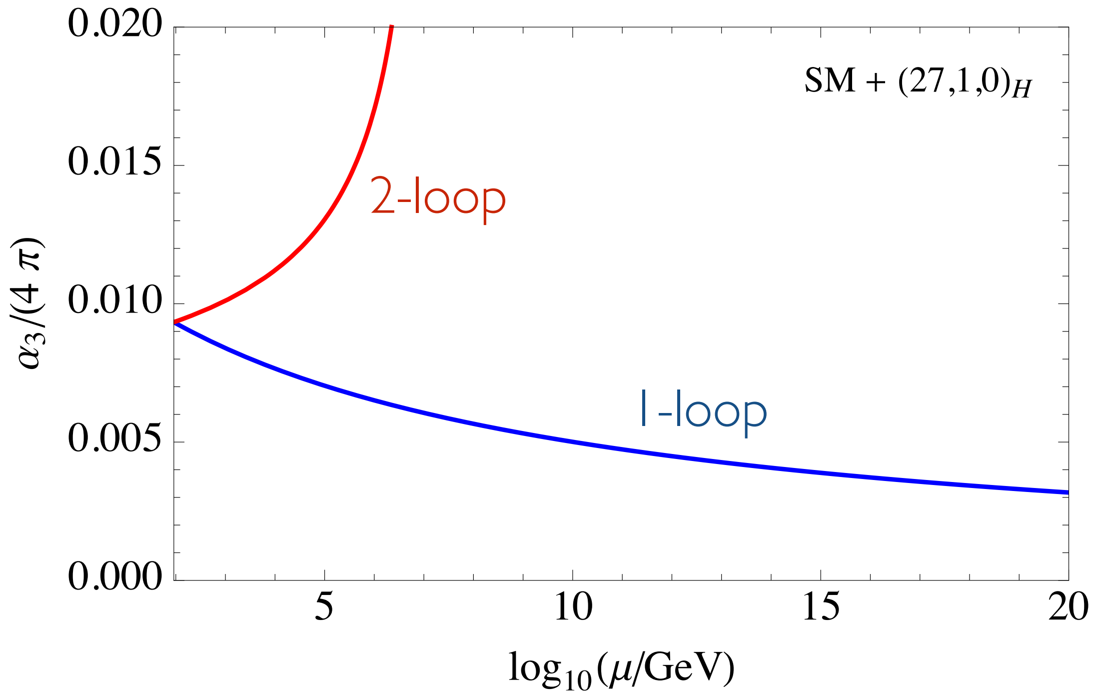
1. Q sufficiently short lived $\tau_Q \lesssim 10^{-2}$ s
2. No Landau poles below 10^{18} GeV

- bound on Q multiplet dimensionality

$$\mu \frac{d}{d\mu} g_i = -b_i \, g_i^3 \qquad b_i = \text{gauge -matter}$$

N.B. two-loop effects crucial if 1-loop b.f. is accidentally small

[LDL, Gröber, Kamenik, Nardecchia, 1504.00359]



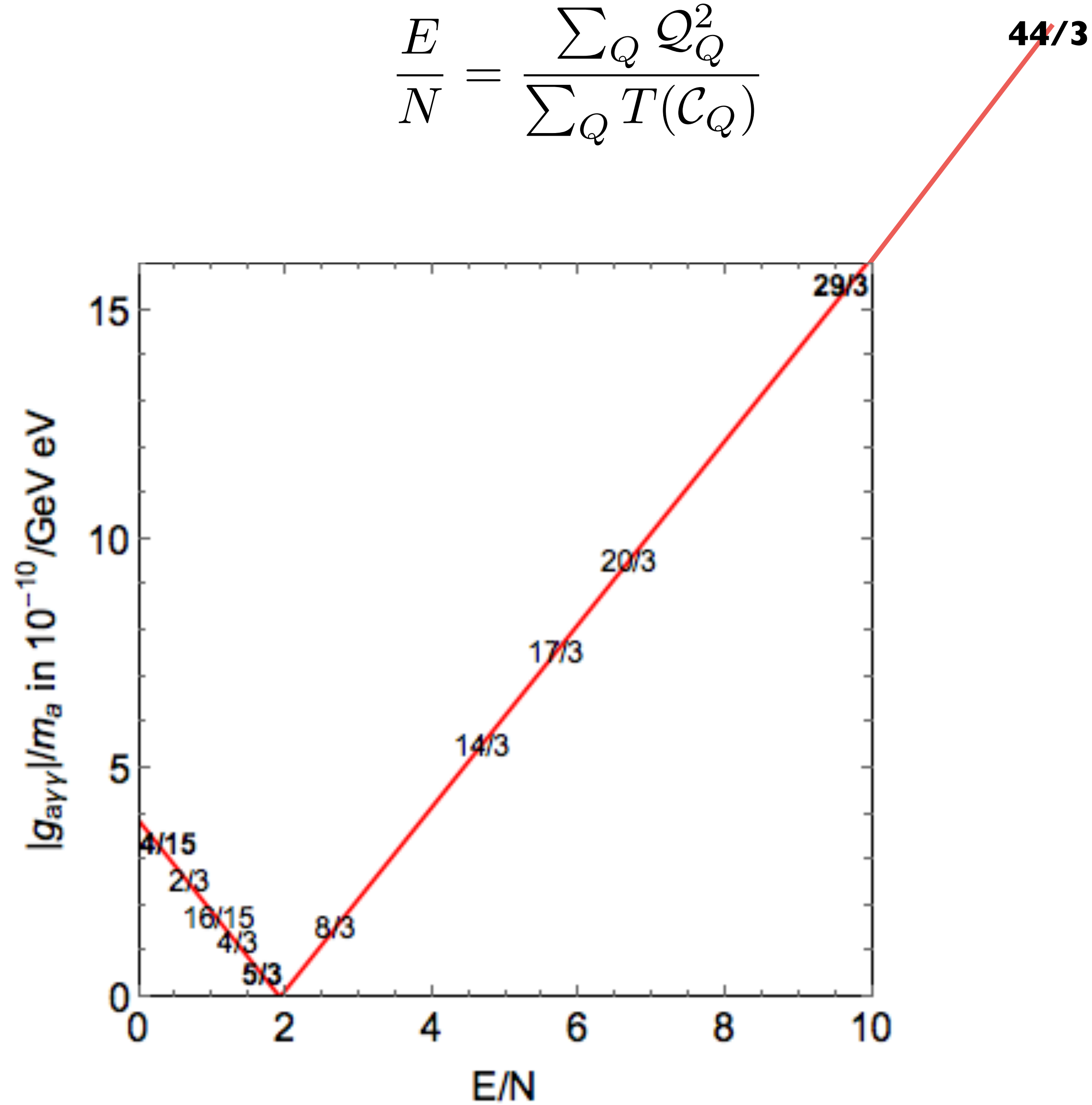
Pheno preferred KSVZ fermions

- Q short lived + no Landau poles < Planck

$$g_{a\gamma\gamma} = \frac{m_a}{\text{eV}} \, \frac{2.0}{10^{10}\ \text{GeV}} \left(\frac{E}{N} - 1.92(4) \right)$$

$$\frac{E}{N} = \frac{\sum_Q \mathcal{Q}_Q^2}{\sum_Q T(\mathcal{C}_Q)}$$

R_Q	$\mathcal{O}_{Qq}$	$\Lambda^{2-\text{loop}}_{\text{Landau}}[\text{GeV}]$	E/N
$(3, 1, -1/3)$	$\overline{Q}_L d_R$	$9.3 \cdot 10^{38}(g_1)$	$2/3$
$(3, 1, 2/3)$	$\overline{Q}_L u_R$	$5.4 \cdot 10^{34}(g_1)$	$8/3$
$(3, 2, 1/6)$	$\overline{Q}_R q_L$	$6.5 \cdot 10^{39}(g_1)$	$5/3$
$(3, 2, -5/6)$	$\overline{Q}_L d_R H^\dagger$	$4.3 \cdot 10^{27}(g_1)$	$17/3$
$(3, 2, 7/6)$	$\overline{Q}_L u_R H$	$5.6 \cdot 10^{22}(g_1)$	$29/3$
$(3, 3, -1/3)$	$\overline{Q}_R q_L H^\dagger$	$5.1 \cdot 10^{30}(g_2)$	$14/3$
$(3, 3, 2/3)$	$\overline{Q}_R q_L H$	$6.6 \cdot 10^{27}(g_2)$	$20/3$
$(3, 3, -4/3)$	$\overline{Q}_L d_R H^{\dagger 2}$	$3.5 \cdot 10^{18}(g_1)$	$44/3$
$(\overline{6}, 1, -1/3)$	$\overline{Q}_L \sigma_{\mu\nu} d_R G^{\mu\nu}$	$2.3 \cdot 10^{37}(g_1)$	$4/15$
$(\overline{6}, 1, 2/3)$	$\overline{Q}_L \sigma_{\mu\nu} u_R G^{\mu\nu}$	$5.1 \cdot 10^{30}(g_1)$	$16/15$
$(\overline{6}, 2, 1/6)$	$\overline{Q}_R \sigma_{\mu\nu} q_L G^{\mu\nu}$	$7.3 \cdot 10^{38}(g_1)$	$2/3$
$(8, 1, -1)$	$\overline{Q}_L \sigma_{\mu\nu} e_R G^{\mu\nu}$	$7.6 \cdot 10^{22}(g_1)$	$8/3$
$(8, 2, -1/2)$	$\overline{Q}_R \sigma_{\mu\nu} \ell_L G^{\mu\nu}$	$6.7 \cdot 10^{27}(g_1)$	$4/3$
$(15, 1, -1/3)$	$\overline{Q}_L \sigma_{\mu\nu} d_R G^{\mu\nu}$	$8.3 \cdot 10^{21}(g_3)$	$1/6$
$(15, 1, 2/3)$	$\overline{Q}_L \sigma_{\mu\nu} u_R G^{\mu\nu}$	$7.6 \cdot 10^{21}(g_3)$	$2/3$



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R_Q^w	$(3,2,1/6)$	$\overline{Q}_R q_L$	$6.5 \cdot 10^{39}(g_1)$	$5/3$
	$(3,2,-5/6)$	$\overline{Q}_L d_R H^\dagger$	$4.3 \cdot 10^{27}(g_1)$	$17/3$
	$(3,2,7/6)$	$\overline{Q}_L u_R H$	$5.6 \cdot 10^{22}(g_1)$	$29/3$
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R_Q^s	$(3,3,-4/3)$	$\overline{Q}_L d_R H^{\dagger 2}$	$3.5 \cdot 10^{18}(g_1)$	$44/3$
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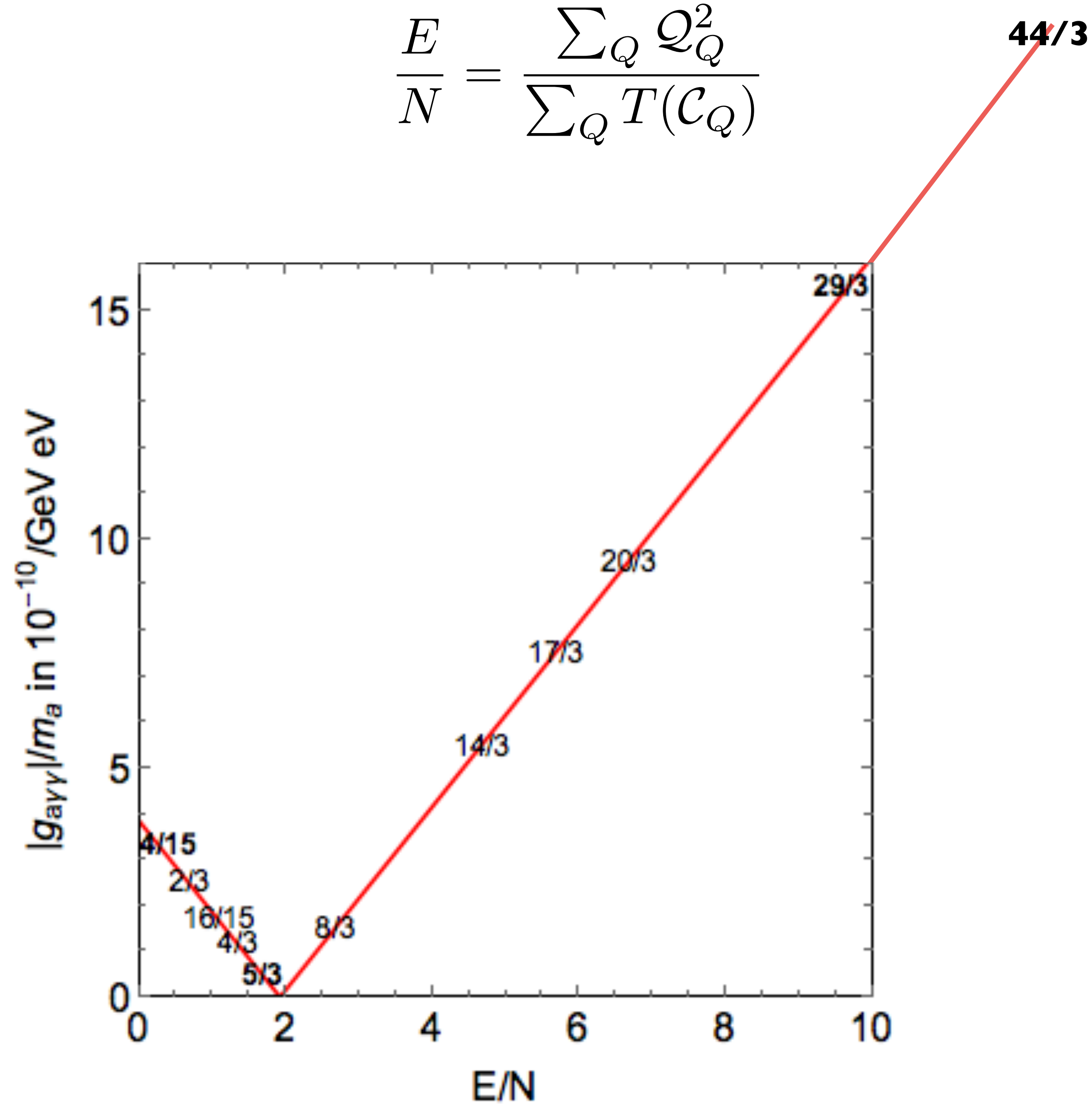
	$(8,1,-1)$	$\overline{Q}_L \sigma_{\mu\nu} e_R G^{\mu\nu}$	$7.6 \cdot 10^{22}(g_1)$	$8/3$
	$(8,2,-1/2)$	$\overline{Q}_R \sigma_{\mu\nu} \ell_L G^{\mu\nu}$	$6.7 \cdot 10^{27}(g_1)$	$4/3$
	$(15,1,-1/3)$	$\overline{Q}_L \sigma_{\mu\nu} d_R G^{\mu\nu}$	$8.3 \cdot 10^{21}(g_3)$	$1/6$
	$(15,1,2/3)$	$\overline{Q}_L \sigma_{\mu\nu} u_R G^{\mu\nu}$	$7.6 \cdot 10^{21}(g_3)$	$2/3$



Astrophobia

- *Is it possible to decouple the axion both from nucleons and electrons ?*

→ nucleophobia + electrophobia = astrophobia

- *Why interested in such constructions ?*

[LDL, Mescia, Nardi, Panci, Ziegler 1712.04940
Bjorkeroth, LDL, Mescia, Nardi 1811.09637
Björkeroth, LDL, Mescia, Nardi, Panci, Ziegler 1907.06575]

1. not possible in standard KSVZ/DFSZ
2. relax the upper bound on axion mass by ~ 1 order of magnitude
3. improve visibility at IAXO (axion-photon)
4. improve fit to stellar cooling anomalies (axion-electron) [Giannotti et al. 1708.02111]
5. requires <u>flavour violating</u> axion couplings

[more in backup slides…]

Relic abundance

post-inflationary PQ breaking	*pre-inflationary PQ breaking*
$f_a < \max\{H_I, T_R\}$	$f_a > \max\{H_I, T_R\}$
averaged over several Universe patches	θ_0 arbitrary
$\langle\theta_0\rangle = \pi/\sqrt{3}$ $\Omega_a^{\rm mis} < \Omega_{\rm DM} \longrightarrow f_a \lesssim 5 \cdot 10^{11}\ \text{GeV}$	misalignment contribution unique, but depends on initial conditions
+ contribution from topological defects	$f_a \gg 10^{12}\ \text{GeV}$ only for $\theta_0 \ll 1$

[See e.g. Ringwald, Saikawa 1512.06436
Gorghetto, Hardy, Villadoro 1806.04677]

A photo- and electro-philic Axion ?

- Consider a DFSZ-like construction with 2 + n Higgs doublets + a SM singlet Φ

$$\mathcal{L}_Y = Y_u \overline{Q}_L u_R H_u + Y_d \overline{Q}_L d_R H_d + Y_e \overline{L}_L e_R H_e$$

$$\frac{E}{N} = \frac{\frac{4}{3}\mathcal{X}(H_u) + \frac{1}{3}\mathcal{X}(H_d) + \mathcal{X}(H_e)}{\frac{1}{2}\mathcal{X}(H_u) + \frac{1}{2}\mathcal{X}(H_d)} \qquad g_{ae} = \frac{\mathcal{X}(H_e)}{2N}\frac{m_e}{f_a}$$

naively, a large PQ charge for H_e would make the job… but, enhanced global symmetry

$$U(1)^{n+3} \to U(1)_{\rm PQ} \times U(1)_Y$$

must be explicitly broken in the scalar potential via non-trivial invariants (e.g. $H_u H_d \Phi^2$)

→ *non-trivial constraints on PQ charges*

A photo- and electro-philic Axion ?

- Consider a DFSZ-like construction with 2 + n Higgs doublets + a SM singlet Φ

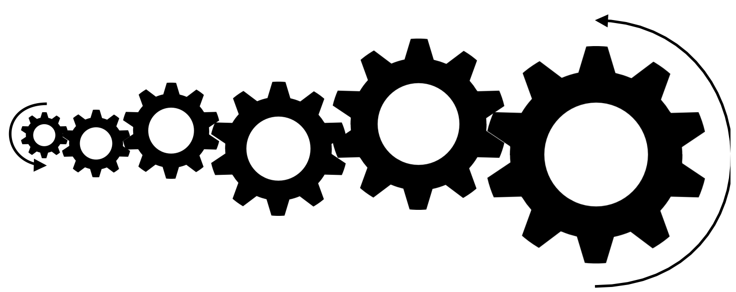
clockwork-like scenarios allow to consistently boost E/N [LDL, Mescia, Nardi 1705.05370]

$$\frac{E}{N} = \frac{\frac{4}{3}\mathcal{X}(H_u) + \frac{1}{3}\mathcal{X}(H_d) + \mathcal{X}(H_e)}{\frac{1}{2}\mathcal{X}(H_u) + \frac{1}{2}\mathcal{X}(H_d)} \qquad g_{ae} = \frac{\mathcal{X}(H_e)}{2N}\frac{m_e}{f_a}$$

$$(H_u H_d \Phi^2)$$

$$(H_k H^*_{k-1})(H^*_{k-1} H^*_d)$$

$$(H_e H_n)(H_n H_d)$$



[Giudice, McCullough]

$$\longrightarrow \quad E/N \sim 2^{n+1}$$

[See also Farina et al. 1611.09855, for KSVZ clockwork]

$$\mathcal{X}(H_e) = 2^{n+1}\left(1 - \frac{v_e^2}{v^2}\right) - \sum_{k=2}^{n} 2^k \frac{v_k^2}{v^2}$$