Theory overview: the QCD axion

Kick-off Meeting COSMIC WISPers
@ LNF - 24.02.2023

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STARS @ UNIPD
SUPPORTING TALENT IN RESEARCH @UNIVERSITY OF PADOVA

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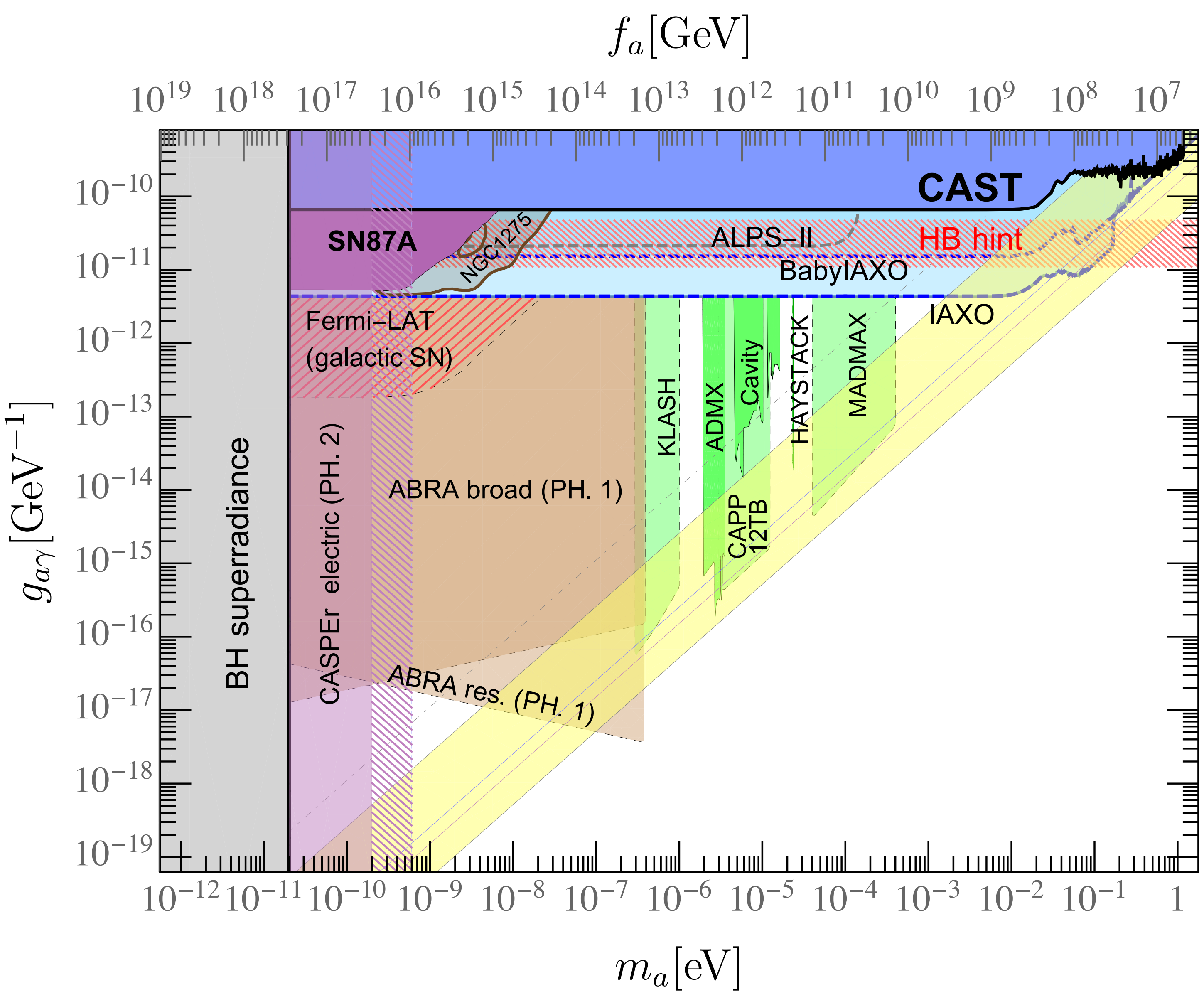
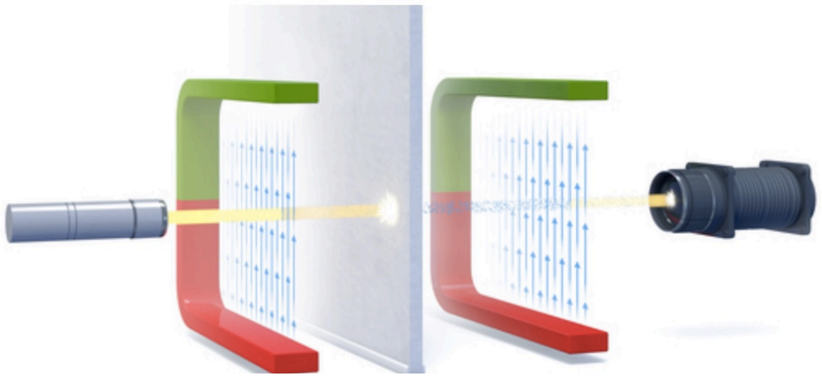
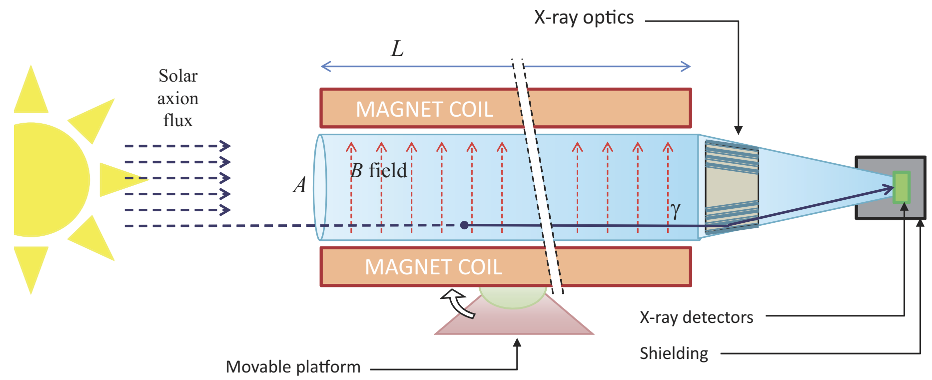
UNIVERSITÀ DEGLI STUDI DI PADOVA

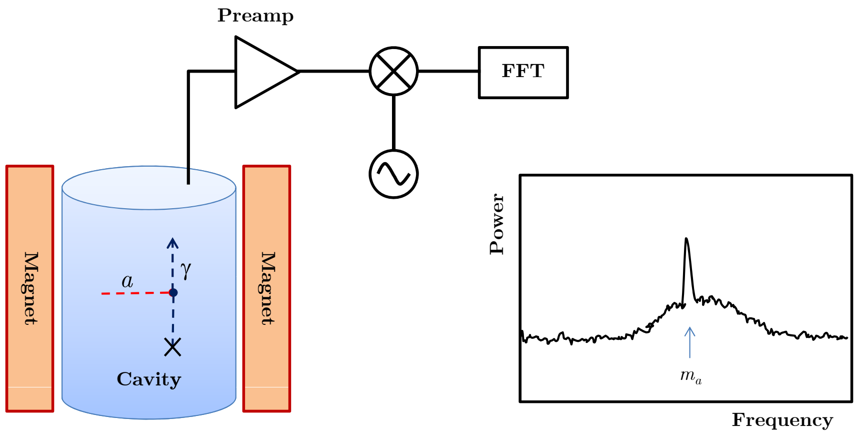
Dipartimento di Fisica e Astronomia "Galileo Galilei"

An experimental opportunity



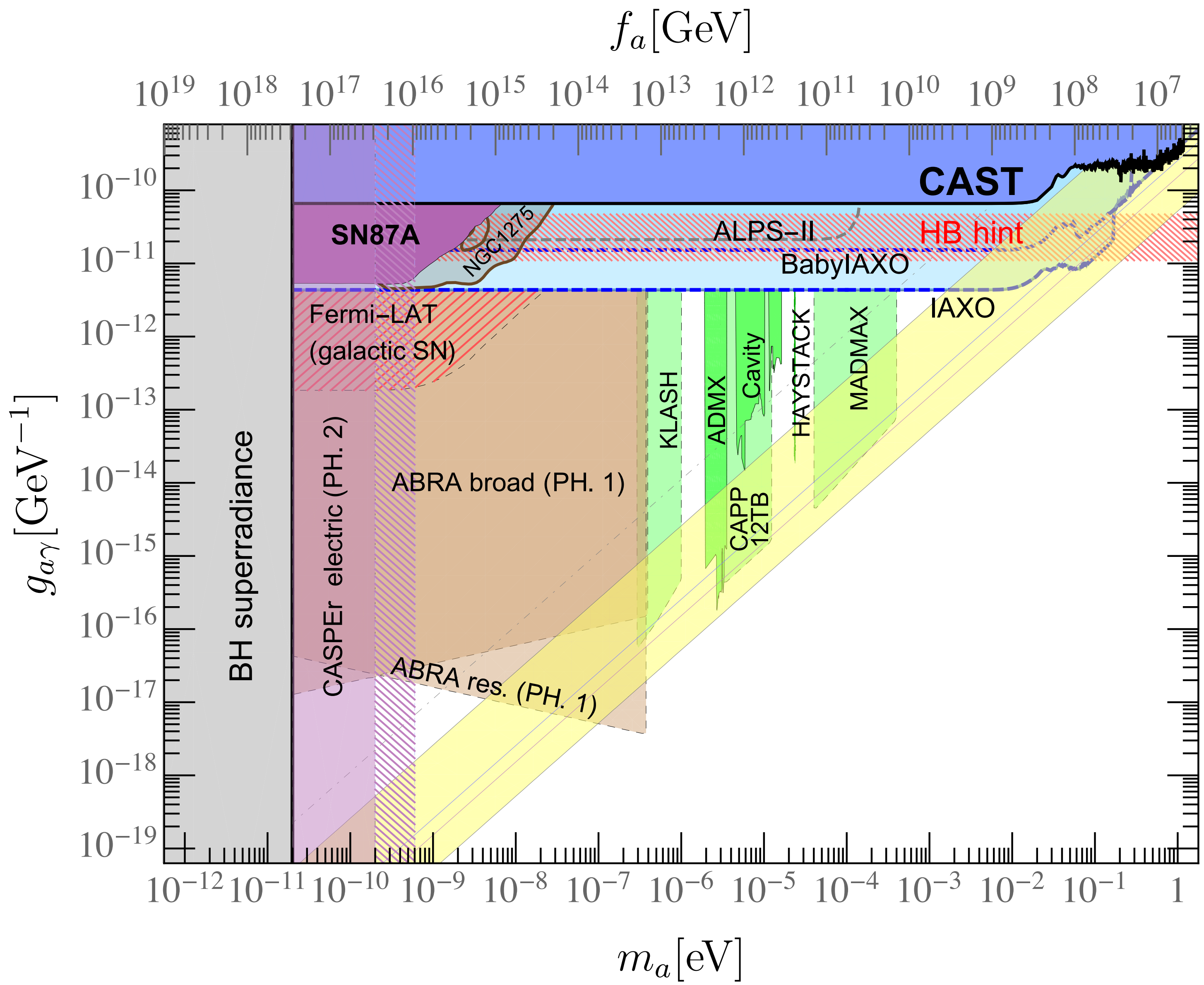






[Irastorza, Redondo 1801.08127 (Prog. Part. Nucl. Phys.)
LDL, Giannotti, Nardi, Visinelli 2003.01100 (Phys. Rept.)]

An experimental opportunity



★ Time now to rethink the QCD axion

1. PQ mechanism
2. Axion couplings
   [from EFTs to UV models]
3. QCD axions beyond standard benchmarks

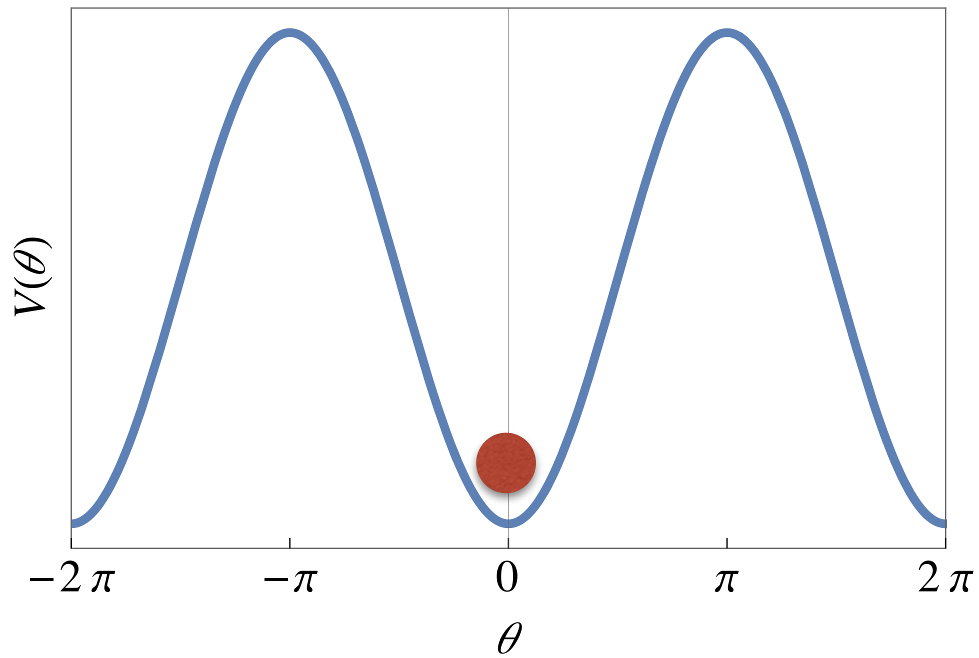
[Irastorza, Redondo 1801.08127 (Prog. Part. Nucl. Phys.)
LDL, Giannotti, Nardi, Visinelli 2003.01100 (Phys. Rept.)]

QCD axion

Strong CP problem

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

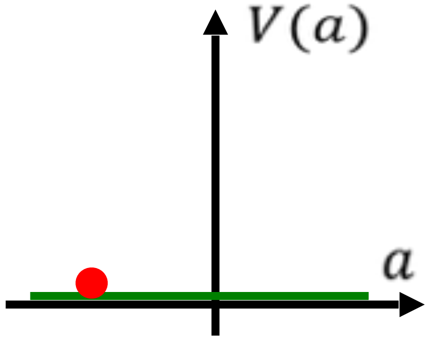
promote θ to a dynamical field, which washes-out CP violation in QCD



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

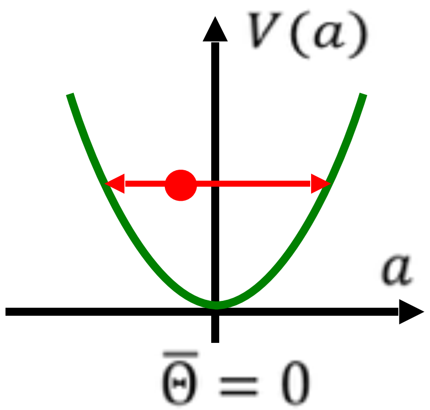
Dark Matter

misalignment + topological defects



$T \gg 1$ GeV

[Raffelt]



$T \sim 1$ GeV

$$w_a = p_a/\rho_a \simeq 0$$

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

PQ mechanism

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

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)]

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

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

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- Does the axion really relax to zero ?

$\mathcal{D}\varphi \equiv dA^a_\mu \det(\not{D} + M)$ → *path-integral measure positive definite only for a vector-like theory (e.g. QCD)*

does not apply to the SM !

PQ mechanism

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

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)]

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

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

- Does the axion really relax to zero ?

→ $\theta_{\rm eff} \sim G_F^2 f_\pi^4 j_{\rm CKM} \approx 10^{-18}$ [Georgi Randall, NPB276 (1986) Okawa, Pospelov, Ritz, 2111.08040]

PQ mechanism works accidentally in the SM $j_{\rm CKM} = {\rm Im}\, V_{ud} V_{cd}^* V_{cs} V_{us}^* \approx 10^{-5}$

PQ mechanism

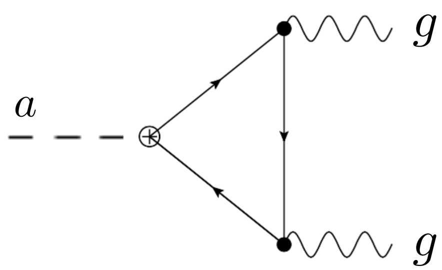
- Assume a new spin-0 boson with a pseudo-shift symmetry $a \to a + \alpha\, f_a$

broken by $\frac{a}{f_a} \frac{g_s^2}{32\pi^2} G\tilde{G}$ → $E(0) \leq E(\langle a \rangle)$

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

1. spontaneously broken (axion is the associated pNGB)

2. QCD anomalous



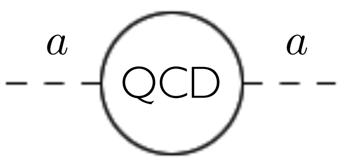
$$\partial^\mu J_\mu^{PQ} = \frac{N\alpha_s}{4\pi} G \cdot \tilde{G}$$

[see talk by Alexander Westphal for string theory axions]

Axion properties [model-indep.]

- Consequences of $\frac{a}{f_a}\frac{g_s^2}{32\pi^2}G\tilde{G}$

1. axion mass



$\sim \frac{\Lambda^4_{\rm QCD}}{f_a^2}$ → $m_a \sim \Lambda^2_{\rm QCD}/f_a$

$$m_a = 5.691(51)\,\mu\text{eV}\,\frac{10^{12}\ \text{GeV}}{f_a}$$

[Gorghetto, Villadoro, 1812.01008 (NNLO chiPT)
Bonati et al, 1512.06746 (lattice)
Borsanyi et al, 1606.07494 (lattice)]

Axion properties [model-indep.]

- Consequences of $\frac{a}{f_a}\frac{g_s^2}{32\pi^2}G\tilde{G}$

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

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

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

[Grilli di Cortona, Hardy, Vega, Villadoro, 1511.02867
Lu, Du, Guo, Meißner, Vonk, 2003.01625
Choi, Im, Kim, Seong, 2106.05816]

Axion properties [model-indep.]

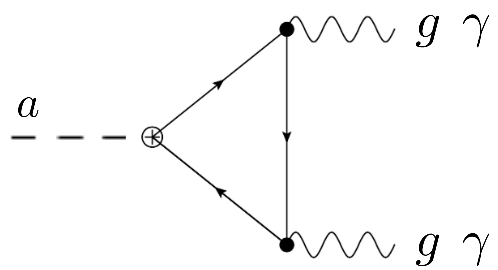
- Consequences of $\frac{a}{f_a}\frac{g_s^2}{32\pi^2}G\tilde{G}$

3. 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



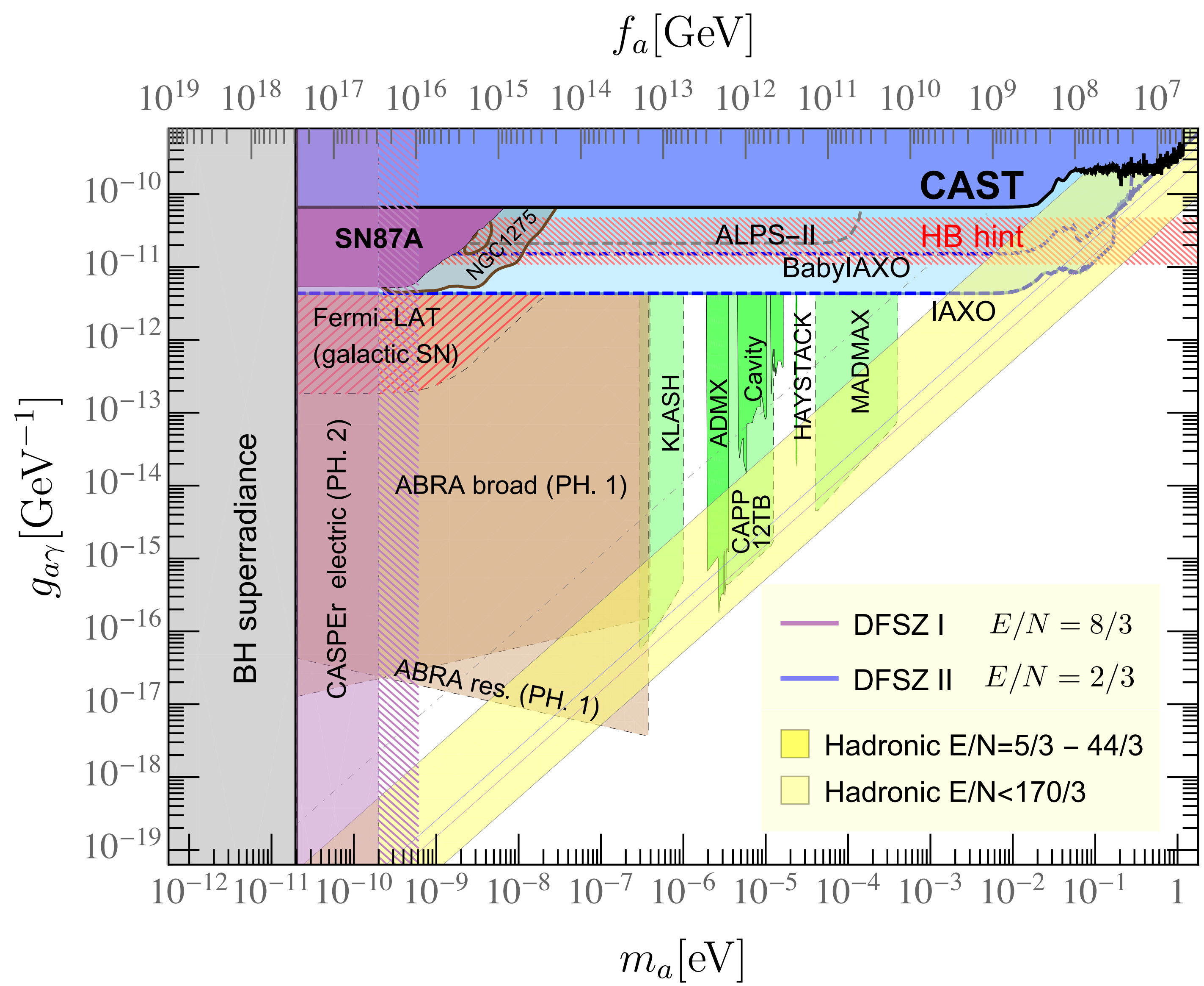
$$\partial^\mu J^{PQ}_\mu = \frac{N\alpha_s}{4\pi} G\cdot\tilde{G} + \frac{E\alpha}{4\pi} F\cdot\tilde{F}$$

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

model-independent

depends on UV completion

enhance/suppress C_γ

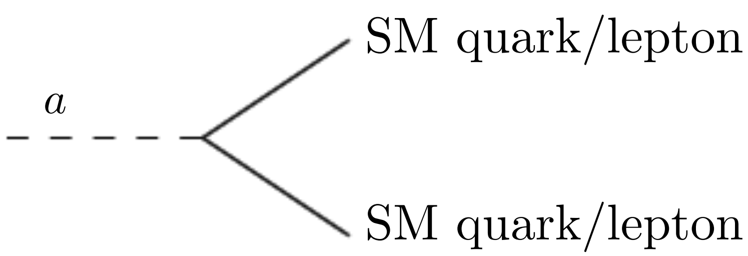


[LDL, Giannotti, Nardi, Visinelli 2003.01100 (Phys. Rept.)]

Axion properties [model-dep.]

2. Axion-SM fermions

[LDL, Mescia, Nardi, Panci, Ziegler, 1712.04940 + 1907.06575 "Astrophobic Axions"]



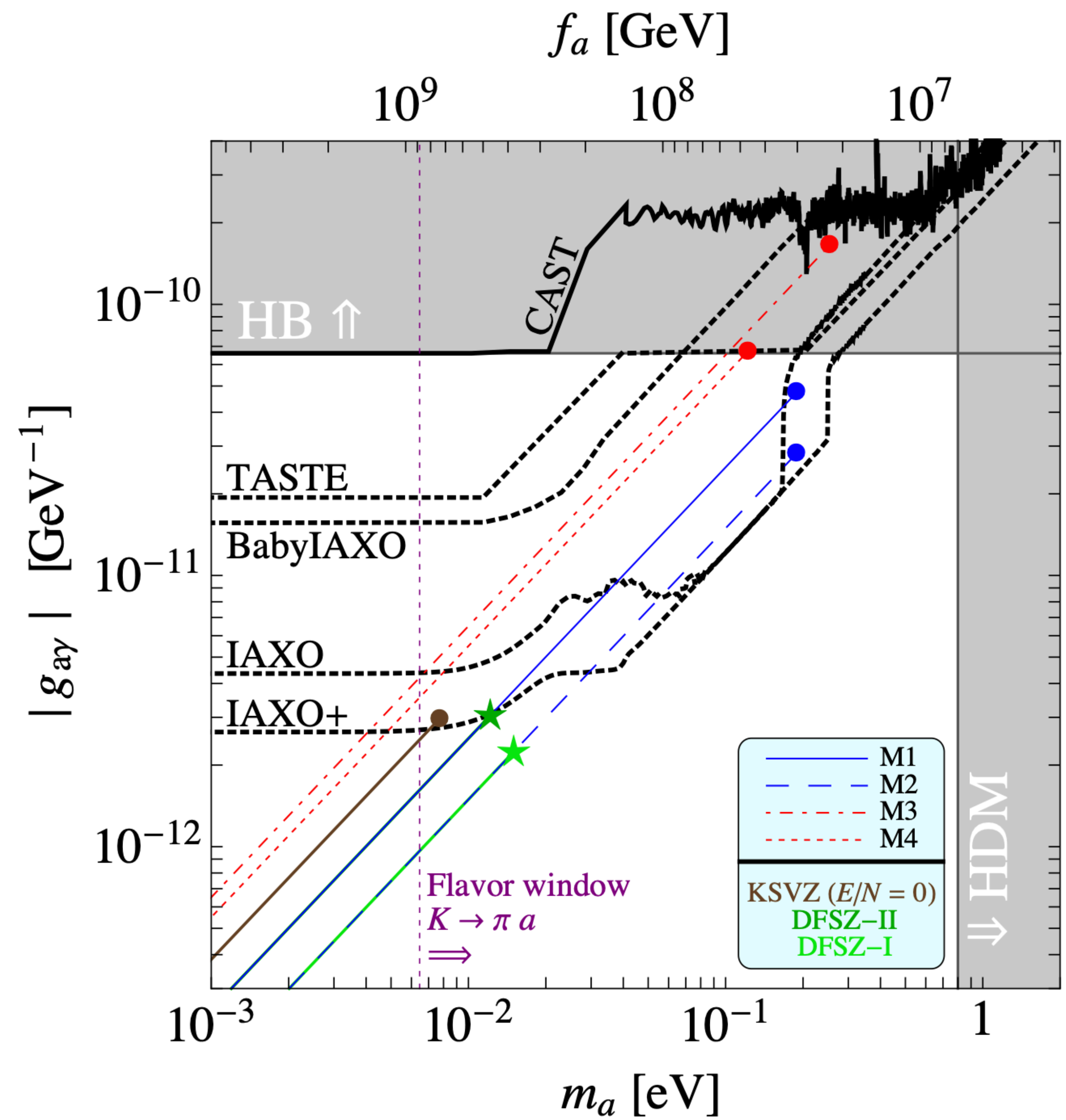
$$\frac{\partial_\mu a}{2f_a}\overline{\psi}_i\gamma^\mu(C^V_{ij}+C^A_{ij}\gamma_5)\psi_j$$

$$\downarrow$$

$$J^\mu_{\rm PQ}$$

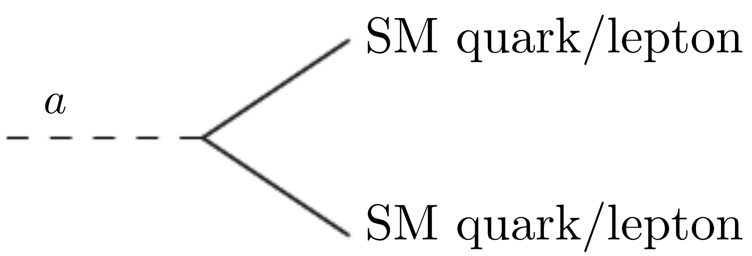
enhance/suppress $C_{p,n,e}$

flavour-violating axion coupling



Axion properties [model-dep.]

2. Axion-SM fermions



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

$J^\mu_{\rm PQ}$

$C^{V,A}_{i \neq j} \propto (V^\dagger_\psi \, \mathrm{PQ}_\psi V_\psi)_{i \neq j} \neq 0$ if PQ_ψ non-universal

→ PQ as a flavour symmetry ?

[Ema, Hamaguchi, Moroi, Nakayama 1612.05492
Calibbi, Goertz, Redigolo, Ziegler, Zupan 1612.08040
Björkeroth, LDL, Mescia, Nardi 1811.09637]

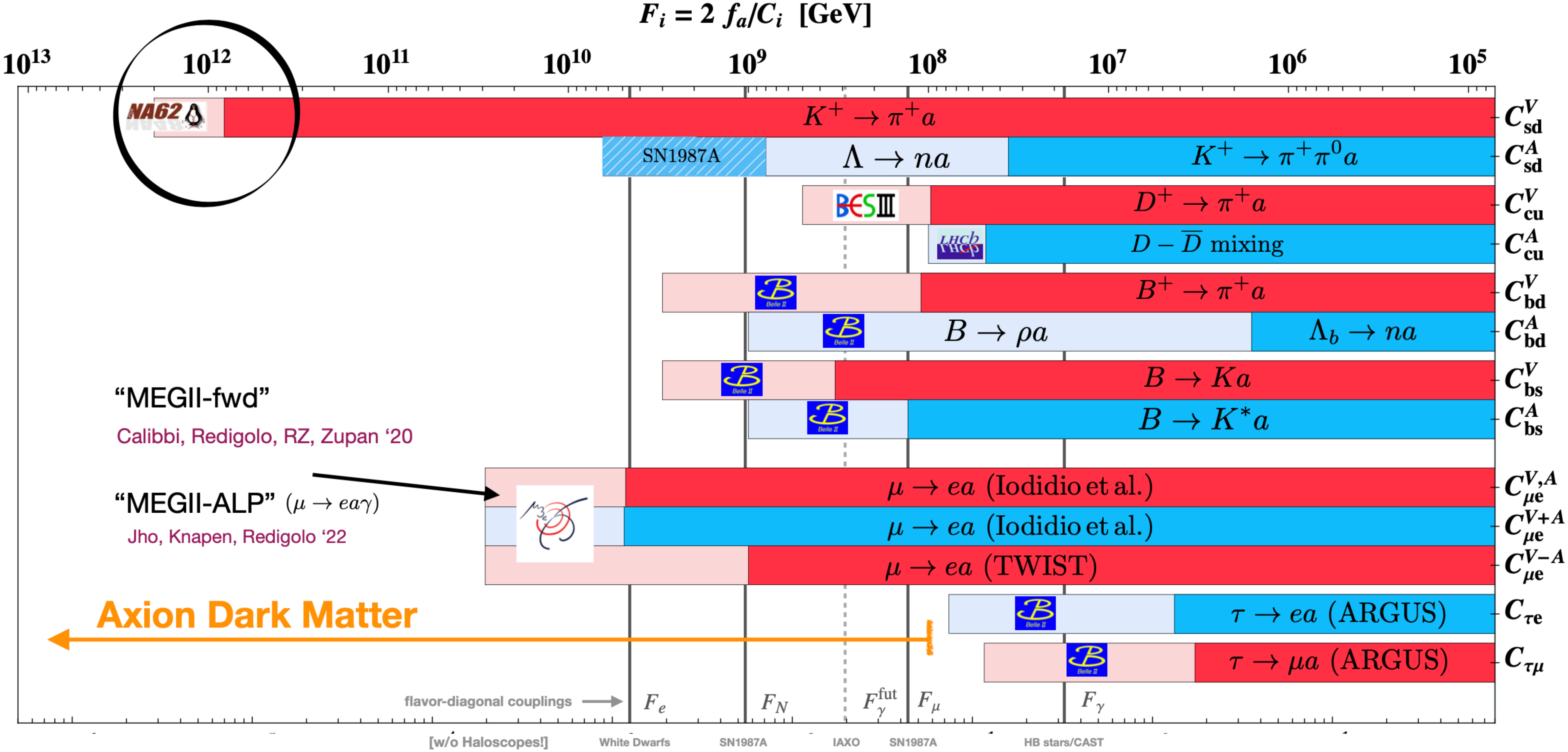
enhance/suppress $C_{p,n,e}$

flavour-violating axion coupling

Axion properties [model-dep.]

2. Axion-SM fermions

[Robert Ziegler, Padua22]



for $C_i = \{C_\gamma, C_e, C_N, C_{sd}, C_{bs}, C_{bd}, C_{\mu e}\} = 1$ *flavour beats astrophysics !*

Axion properties [model-dep.]

3. CP-violating axions [Moody, Wilczek PRD30 (1984)]

$$\mathcal{L} \supset g^S_{aN} a \overline{N} N + g^P_{af} a \overline{f} i \gamma_5 f \qquad g^S_{aN} \sim \frac{f_\pi}{f_a} \theta_{\rm eff}$$

← from UV sources of CP-violation
e.g. $\mathcal{O}_{\rm CPV} = (\overline{u} u)(\overline{d} i \gamma_5 d)$

[Barbieri, Romanino, Strumia hep-ph/9605368
Pospelov hep-ph/9707431
Bigazzi, Cotrone, Jarvinen, Kiritsis 1906.12132
Bertolini, LDL, Nesti 2006.12508
Okawa, Pospelov, Ritz, 2111.08040
Dekens, de Vries, Shain, 2203.11230]

$$V(a) \simeq \frac{1}{2}\frac{a^2}{f_a^2} \underbrace{\left\langle G\tilde{G}, G\tilde{G} \right\rangle}_{\chi} + \frac{a}{f_a} \underbrace{\left\langle G\tilde{G}, \mathcal{O}_{\rm CPV} \right\rangle}_{\chi'} \quad \longrightarrow \quad \theta_{\rm eff} \equiv \frac{\langle a \rangle}{f_a} = -\frac{\chi'}{\chi}$$

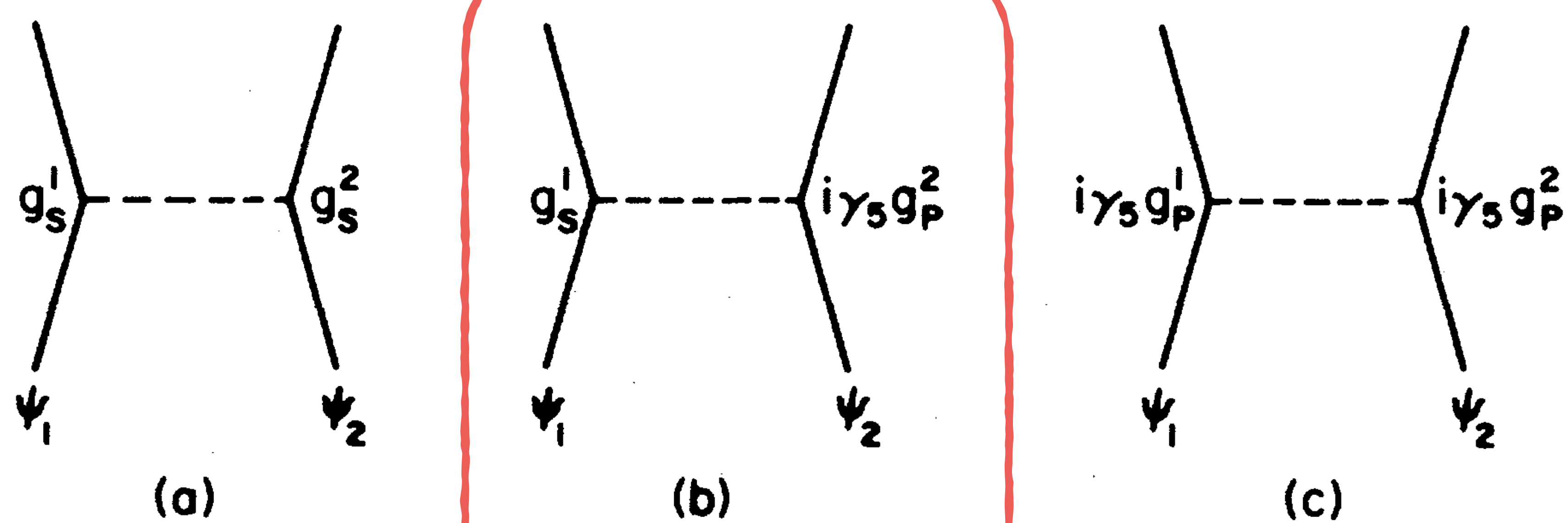
Axion properties [model-dep.]

3. CP-violating axions [Moody, Wilczek PRD30 (1984)]

$$\mathcal{L} \supset g^S_{aN} a \overline{N} N + g^P_{af} a \overline{f} i \gamma_5 f \qquad g^S_{aN} \sim \frac{f_\pi}{f_a} \theta_{\rm eff}$$

← from UV sources of CP-violation

New macroscopic forces from non-relativistic potentials (axion doesn't need to be DM)



monopole-monopole | monopole-dipole | dipole-dipole

double $\theta_{\rm eff}$ suppression

ARIADNE, QUAX-gpgs, …
NMR enhancement

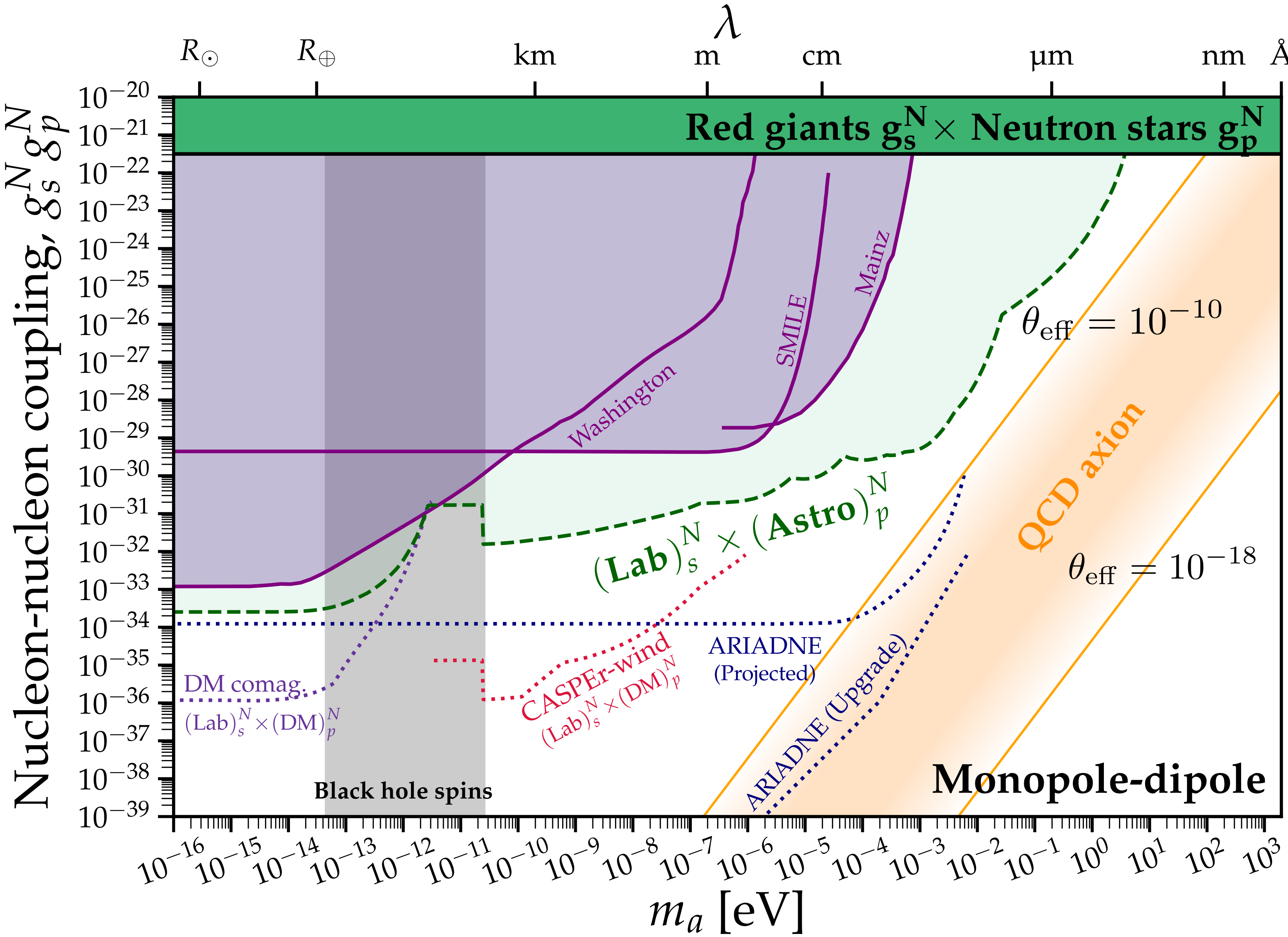
spin suppression + bkgd from ordinary magnetic forces

Axion properties [model-dep.]

3. CP-violating axions [Moody, Wilczek PRD30 (1984)]

$$\mathcal{L} \supset g^S_{aN} a \overline{N} N + g^P_{af} a \overline{f} i \gamma_5 f \qquad g^S_{aN} \sim \frac{f_\pi}{f_a} \theta_{\rm eff}$$

from UV sources of CP-violation



[O'Hare, Vitagliano 2010.03889 Raffelt 1205.1776]

BSM (optimistic)

SM (pessimistic)

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 | 2Higgs+Singlet | Higgs+Singlet

PQWW | DFSZ | KSVZ

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

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

[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)$_{\rm PQ}$ (*QCD anomalous* + *spontaneously broken*)

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

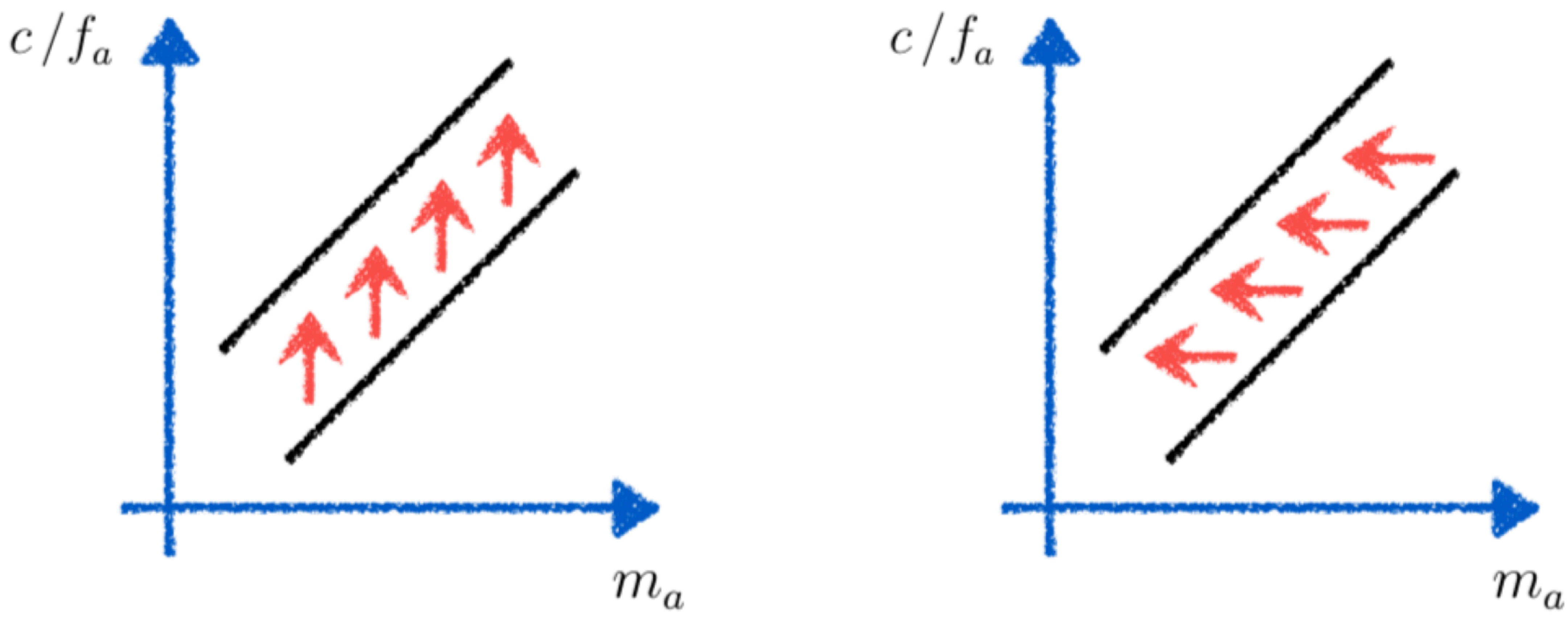
SM fermions → 2Higgs+Singlet — **DFSZ**

BSM fermions → Higgs+Singlet — **KSVZ**

	DFSZ	KSVZ
$C_\gamma = E/N - 1.92(4)$	$E/N = 8/3$	$E/N = 0$
	$C_{p,n,e}(\beta) \sim \mathcal{O}(1)$	$C_p \simeq -0.5$
		$C_{n,e} \simeq 0$

(also no flavour and CP-violating effects)

Axions beyond benchmarks



enhance Wilson coefficient for fixed m_a

[LDL, Mescia, Nardi 1610.07593 + 1705.05370
Farina, Pappadopulo, Rompineve, Tesi 1611.09855
Agrawal, Fan, Reece, Wang 1709.06085
Darme', LDL, Giannotti, Nardi 2010.15846
Ringwald, Sokolov 2104.02574]

suppress axion mass for fixed f_a

[Hook 1802.10093,
LDL, Gavela, Quilez, Ringwald 2102.00012
+ 2102.01082]

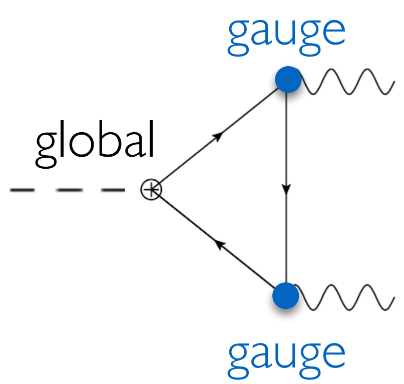
→ *QCD axion parameter space <u>much larger</u> than what traditionally thought*

Enhancing $g_{a\gamma}$

$$g_{a\gamma} = \frac{\alpha}{2\pi}\frac{C_{a\gamma}}{f_a}$$

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

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



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$$\boxed{C_{a\gamma} = E/N - 1.92(4)}$$

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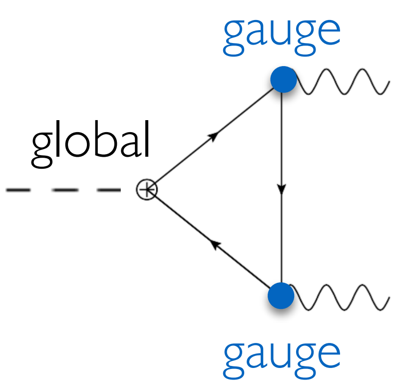


	R_Q	$\mathcal{O}_{Qq}$	$\Lambda^{2-\text{loop}}_{\text{Landau}}$[GeV]	E/N
	$(3,1,-1/3)$	$\overline{Q}_L d_R$	$9.3\cdot 10^{38}(g_1)$	$2/3$
	$(3,1,2/3)$	$\overline{Q}_L u_R$	$5.4\cdot 10^{34}(g_1)$	$8/3$
R_Q^w	$(3,2,1/6)$	$\overline{Q}_R q_L$	$6.5\cdot 10^{39}(g_1)$	$5/3$
	$(3,2,-5/6)$	$\overline{Q}_L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

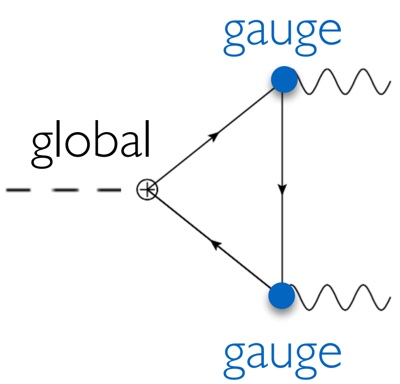
- Pheno preferred hadronic axions
  1. *Q-fermions short lived (no coloured relics)*
  2. *No Landau poles below Planck*

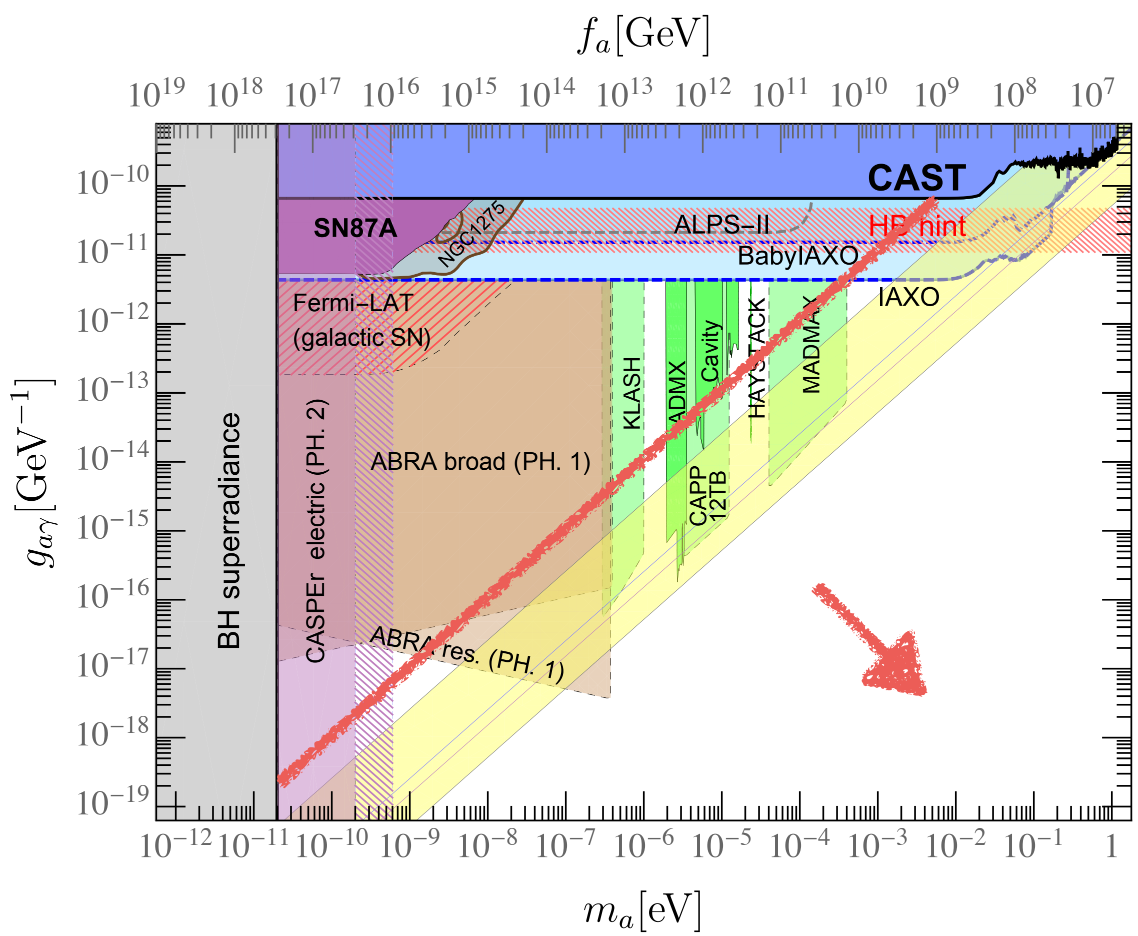
→ $E/N \in [5/3, 44/3]$

[LDL, Mescia, Nardi 1610.07593]

Enhancing $g_{a\gamma}$

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





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

- More Q's ? [LDL, Mescia, Nardi 1705.05370 Plakkot, Hoof 2107.12378]

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

  $g_{a\gamma} \to 0$

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

- Going <u>above</u> E/N = 170/3 ?

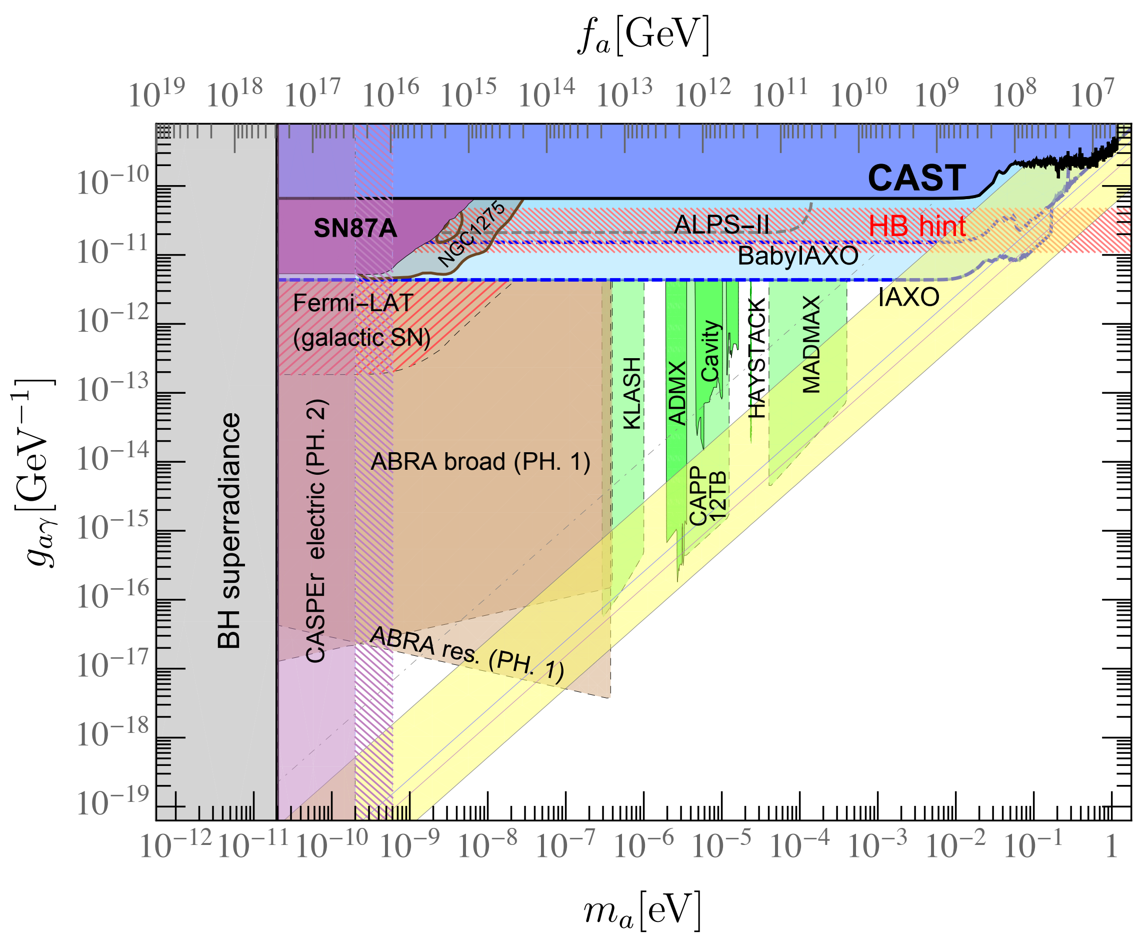
  - *boost global charge (clockwork)* → backup slides

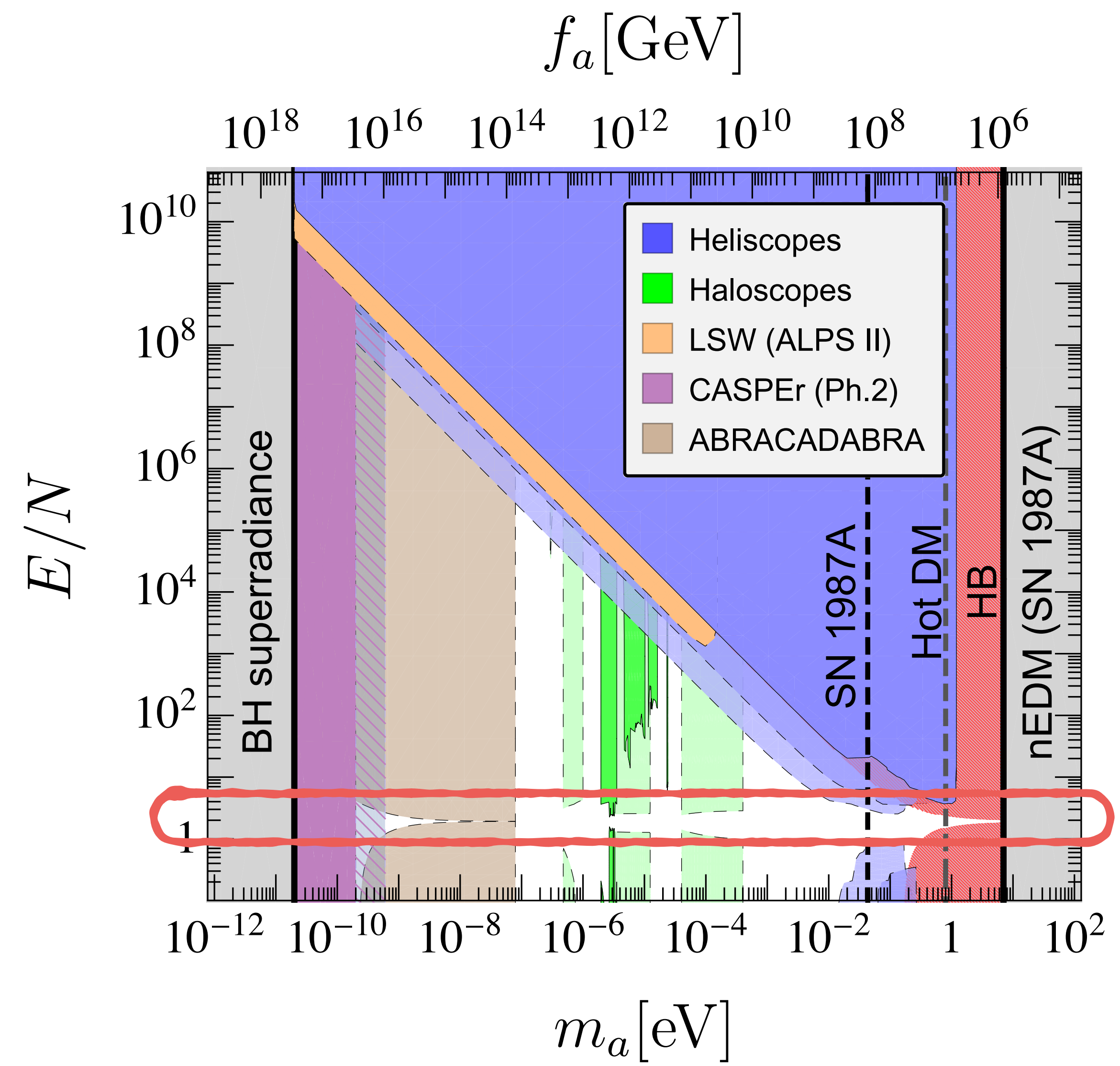
  - *be agnostic, E/N is a free parameter*

Enhancing $g_{a\gamma}$

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

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



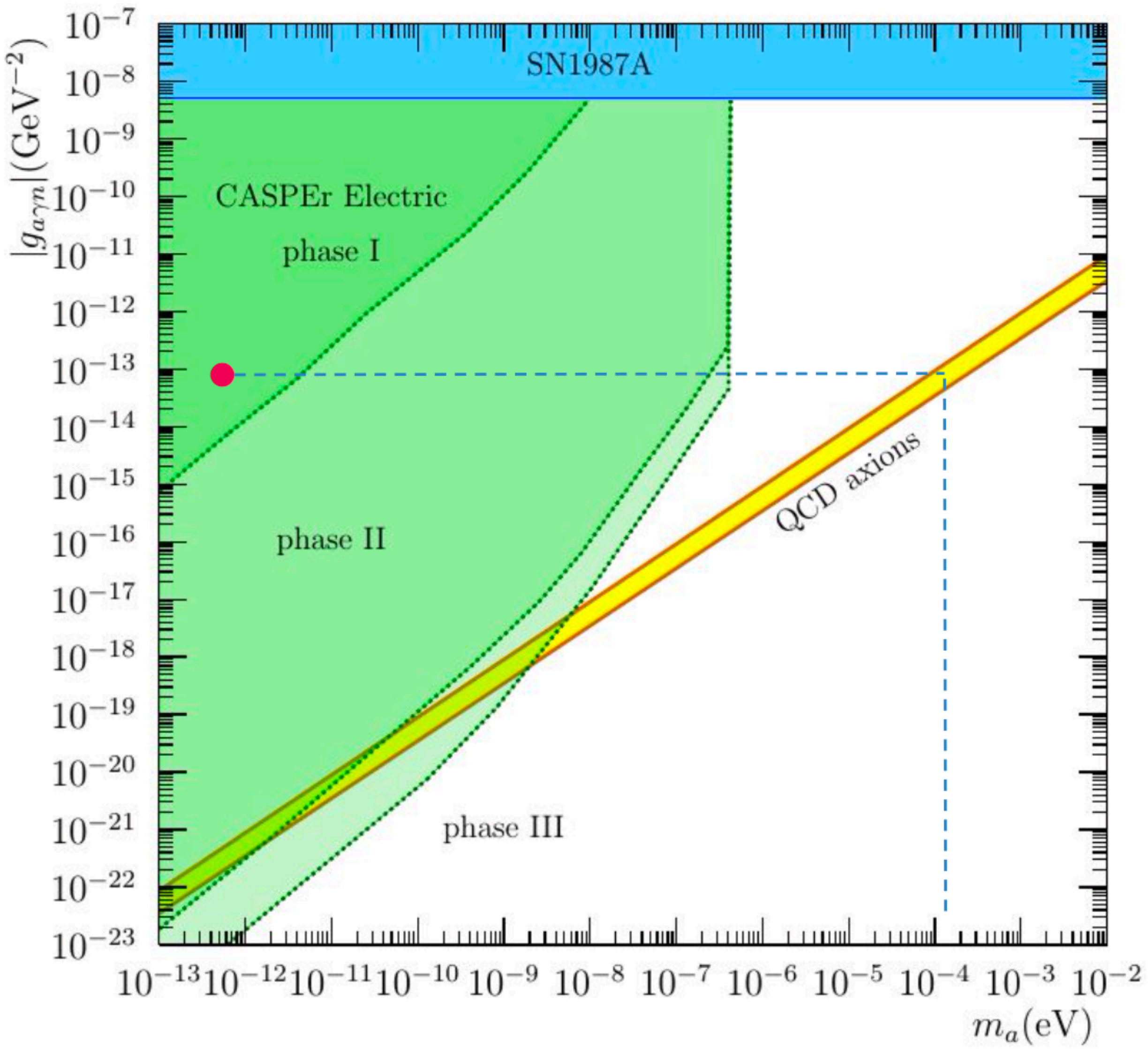


1. *exp.s have just started to constrain E/N from above*
2. *E/N ~ 1.92 appears as a tuned region in theory space*

An even lighter QCD axion ?

- Two questions:

  1. Can CASPEr-Electric Phase I detect a QCD axion ?



$$\mathcal{L} \supset \frac{a}{f_a}\frac{\alpha_s}{8\pi}G\tilde{G}$$

$$\delta\mathcal{L} \equiv -\frac{i}{2}\frac{0.011\,e}{m_n}\frac{a}{f_a}\bar{n}\sigma_{\mu\nu}\gamma_5 n F^{\mu\nu}$$

$$\equiv g_{a\gamma n}$$

Coupling to the nEDM

$$m_a^2 f_a^2 \simeq m_\pi^2 f_\pi^2 \frac{m_u\, m_d}{(m_u+m_d)^2}$$

Axion mass

Axion DM field induces an oscillating nEDM

$$d_n(t) = g_d \frac{\sqrt{2\rho_{\mathrm{DM}}}}{m_a}\cos(m_a t)$$

An even lighter QCD axion ?

- Two questions:

  1. *Can CASPEr-Electric Phase I detect a QCD axion ?*
  2. *Can a QCD axion be ultra-light / fuzzy DM ?*

$$\mathcal{L} \supset \frac{a}{f_a} \frac{\alpha_s}{8\pi} G\tilde{G}$$

$$m_a^2 f_a^2 \simeq m_\pi^2 f_\pi^2 \frac{m_u m_d}{(m_u + m_d)^2}$$

Axion mass

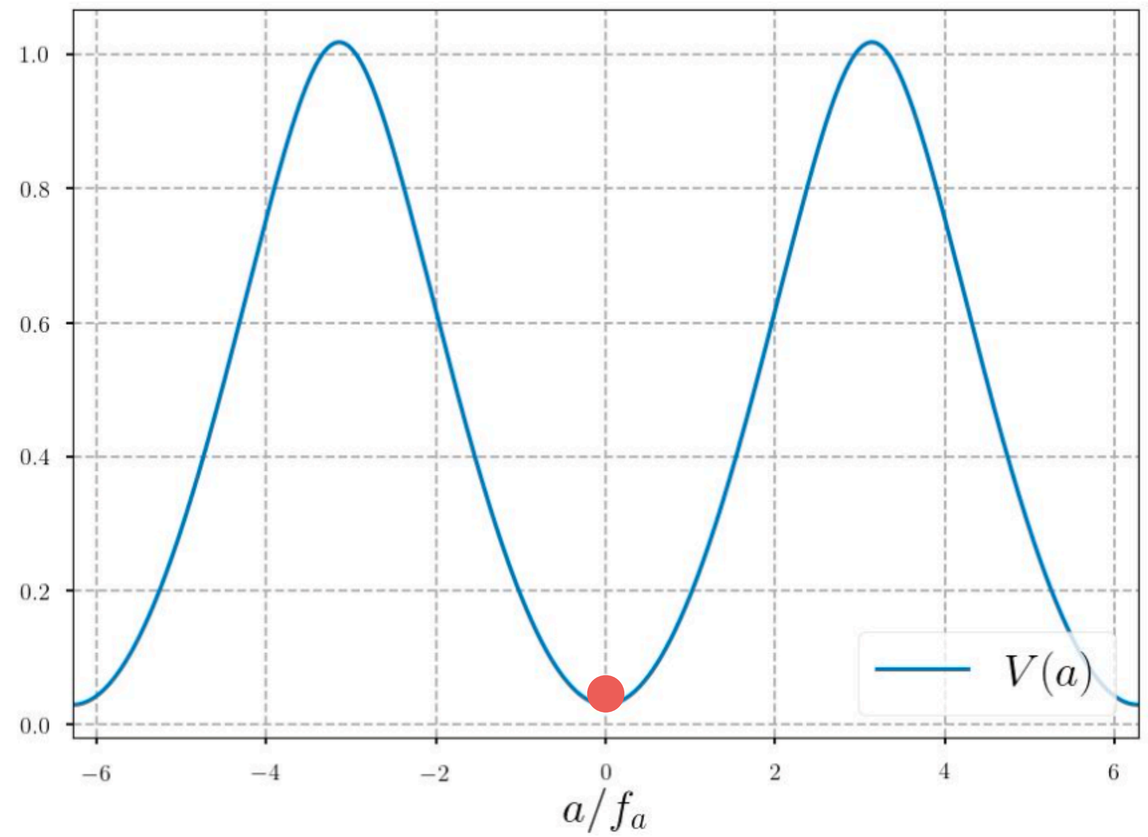
$m_a \sim 10^{-22}\,\mathrm{eV}$ → $f_a \sim 10^{28}\,\mathrm{GeV} \gg M_{\mathrm{Pl}}$

Suppressing m_a

- Standard QCD axion

[Di Vecchia, Veneziano, NPB171 (1980)
Grilli di Cortona, Hardy, Vega, Villadoro, 1511.02867]

$$\frac{a}{f_a}\frac{\alpha_s}{8\pi}G\tilde{G} \quad \longrightarrow \quad V(a) = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4m_u m_d}{(m_u+m_d)^2}\sin^2\left(\frac{a}{2f_a}\right)}$$

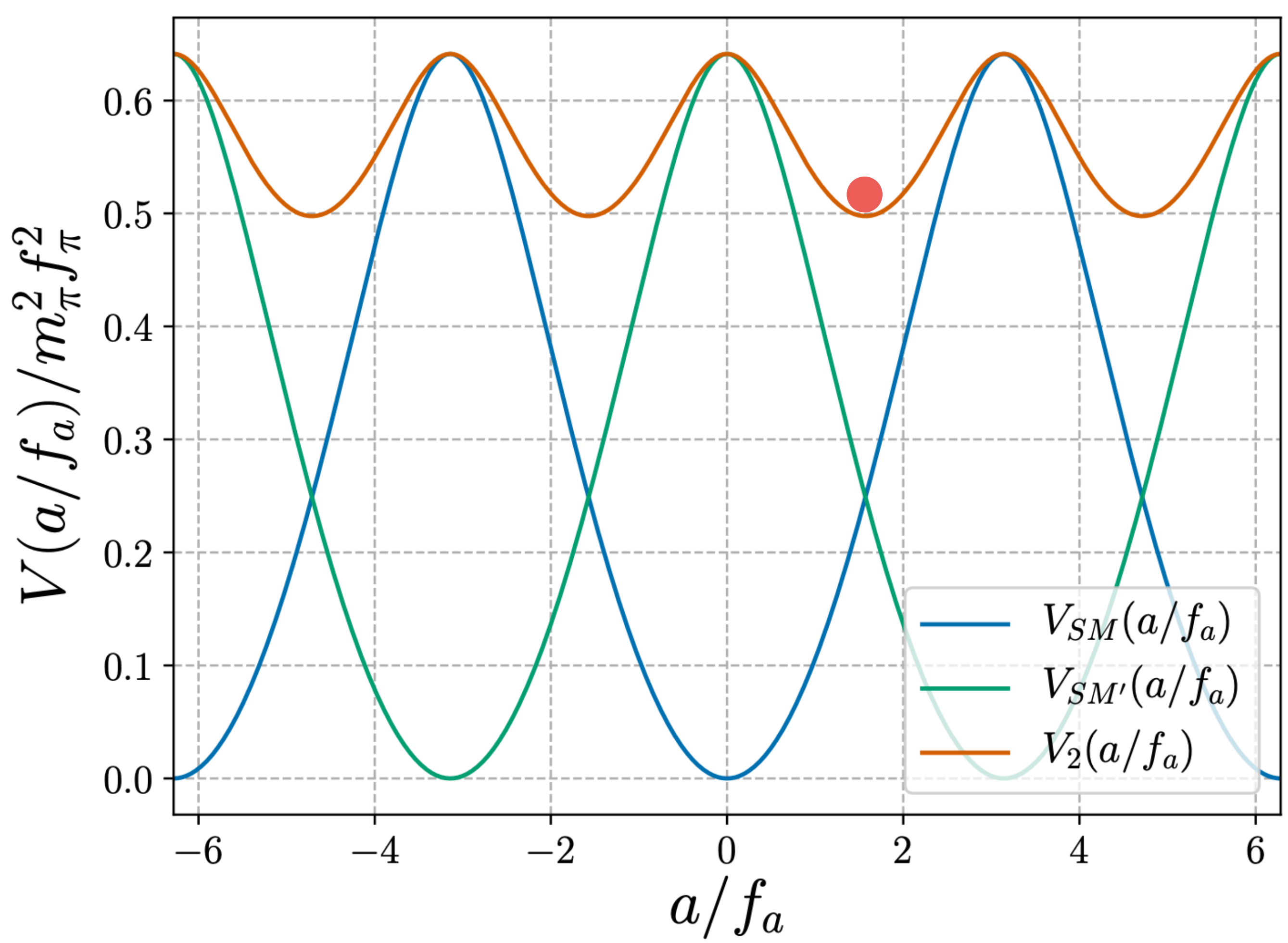


Suppressing m_a

- Z_2 axion: mirror world

$$\mathrm{SM} \longleftrightarrow \mathrm{SM}'$$
$$a \longrightarrow a + \pi f_a$$

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{SM}'} + \frac{\alpha_s}{8\pi}\left(\frac{a}{f_a} - \theta\right)G\widetilde{G} + \frac{\alpha_s}{8\pi}\left(\frac{a}{f_a} - \theta + \pi\right)G'\widetilde{G}'$$

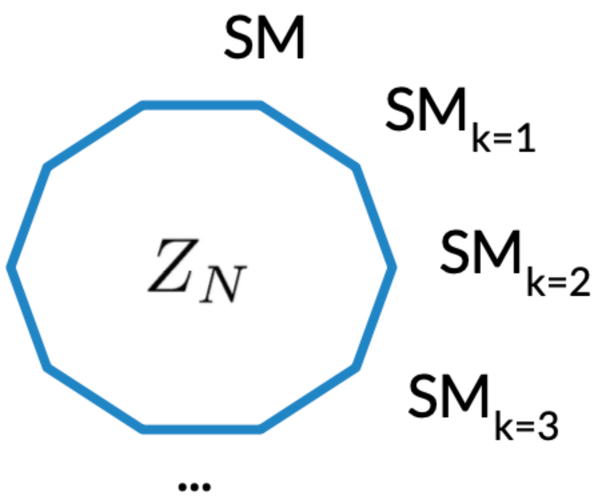


→ *axion mass is suppressed but minimum in* $\pi/2$

Suppressing m_a

- Z_N axion: N mirror worlds [Hook 1802.10093]

$$\mathrm{SM}_k \longrightarrow \mathrm{SM}_{k+1\,(\mathrm{mod}\,\mathcal{N})}$$
$$a \longrightarrow a + \frac{2\pi k}{\mathcal{N}} f_a \,,$$



the axion ($\theta_a \equiv a/f_a$) realizes the Z_N symmetry non-linearly

$$\mathcal{L} = \sum_{k=0}^{\mathcal{N}-1} \left[\mathcal{L}_{\mathrm{SM}_k} + \frac{\alpha_s}{8\pi} \left(\theta_a + \frac{2\pi k}{\mathcal{N}} \right) G_k \widetilde{G}_k \right]$$

[LDL, Gavela, Quilez, Ringwald 2102.00012]

$$\longrightarrow \quad V_{\mathcal{N}}(\theta_a) = -m_\pi^2 f_\pi^2 \sum_{k=0}^{\mathcal{N}-1} \sqrt{1 - \frac{4z}{(1+z)^2} \sin^2\left(\frac{\theta_a}{2} + \frac{\pi k}{\mathcal{N}} \right)}$$

$$z \equiv \frac{m_u}{m_d} \sim 1/2$$

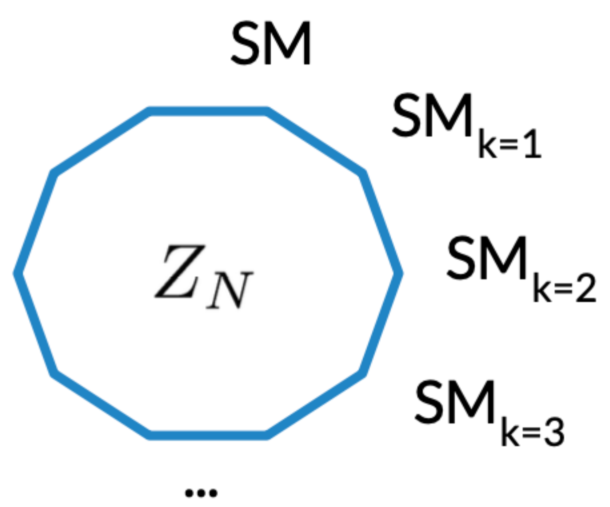
$$\simeq \frac{m_\pi^2 f_\pi^2}{\sqrt{\pi}} \sqrt{\frac{1-z}{1+z}} \mathcal{N}^{-1/2} (-1)^{\mathcal{N}} z^{\mathcal{N}} \cos(\mathcal{N}\theta_a)$$

axion potential exponentially suppressed at large N

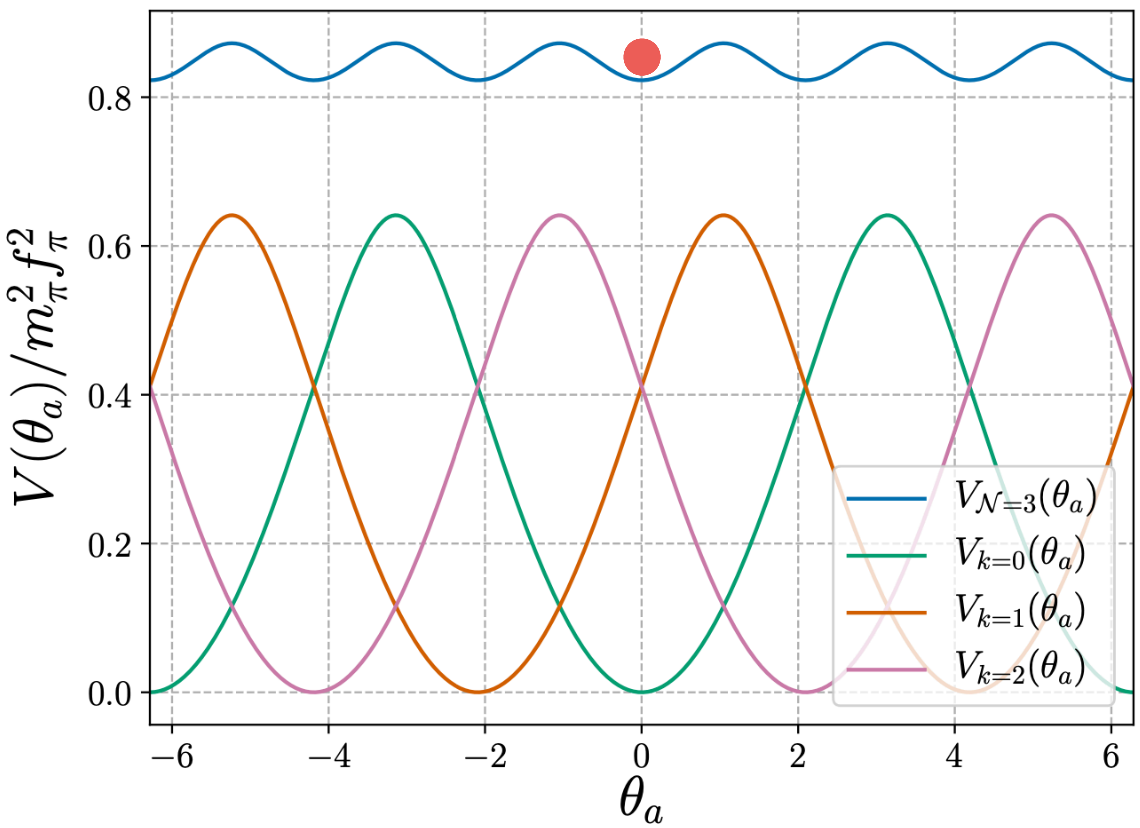
Suppressing m_a

- Z_N axion: N mirror worlds [Hook 1802.10093]

$$\mathrm{SM}_k \longrightarrow \mathrm{SM}_{k+1\,(\mathrm{mod}\,\mathcal{N})}$$
$$a \longrightarrow a + \frac{2\pi k}{\mathcal{N}} f_a \,,$$



e.g. Z_3 axion



[LDL, Gavela, Quilez, Ringwald 2102.00012]

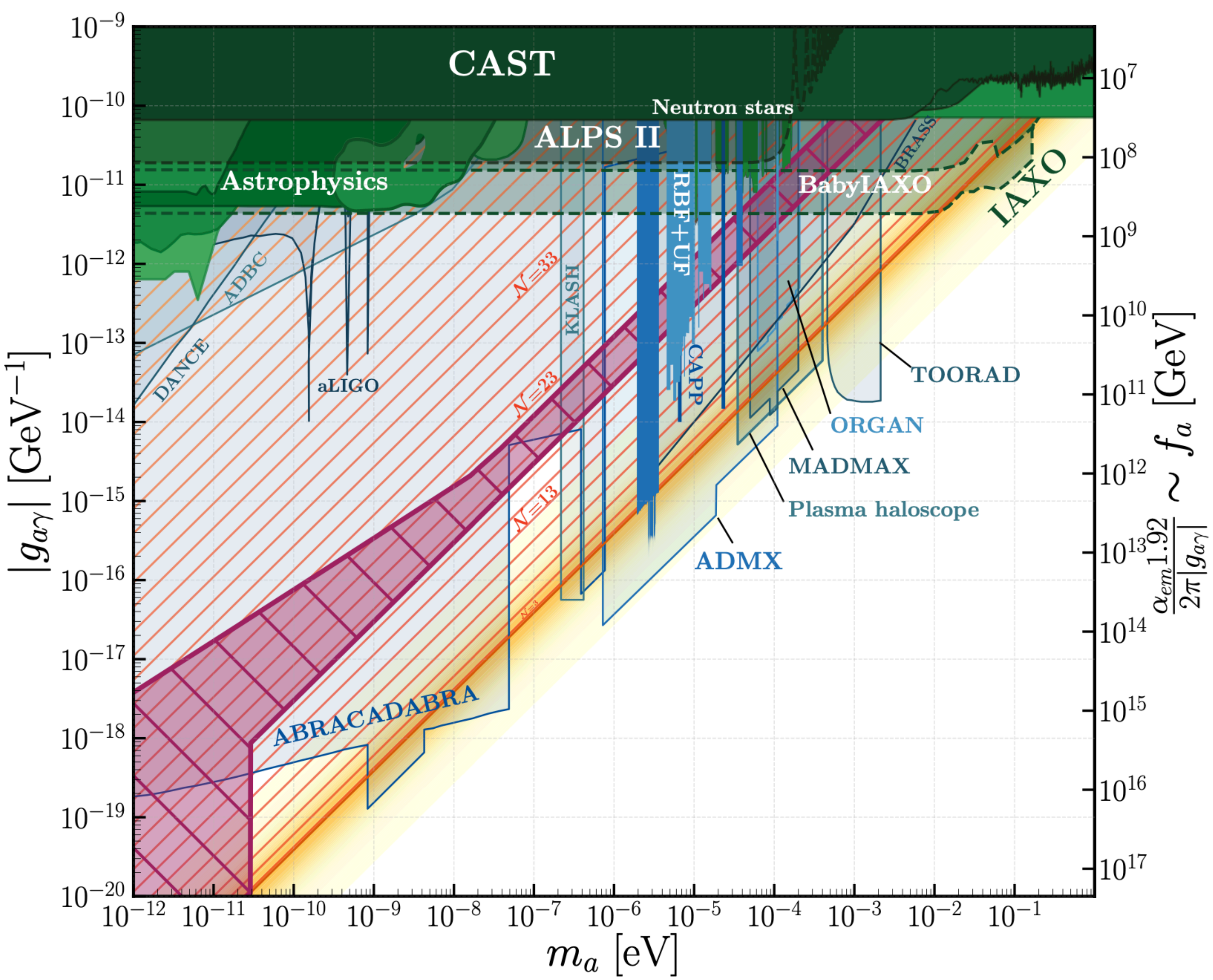
N needs to be odd in order to have a minimum in zero

(strong CP problem is solved with 1/N probability)

Suppressing m_a

- Z_N axion: N mirror worlds

[LDL, Gavela, Quilez, Ringwald 2102.00012 + 2102.01082]



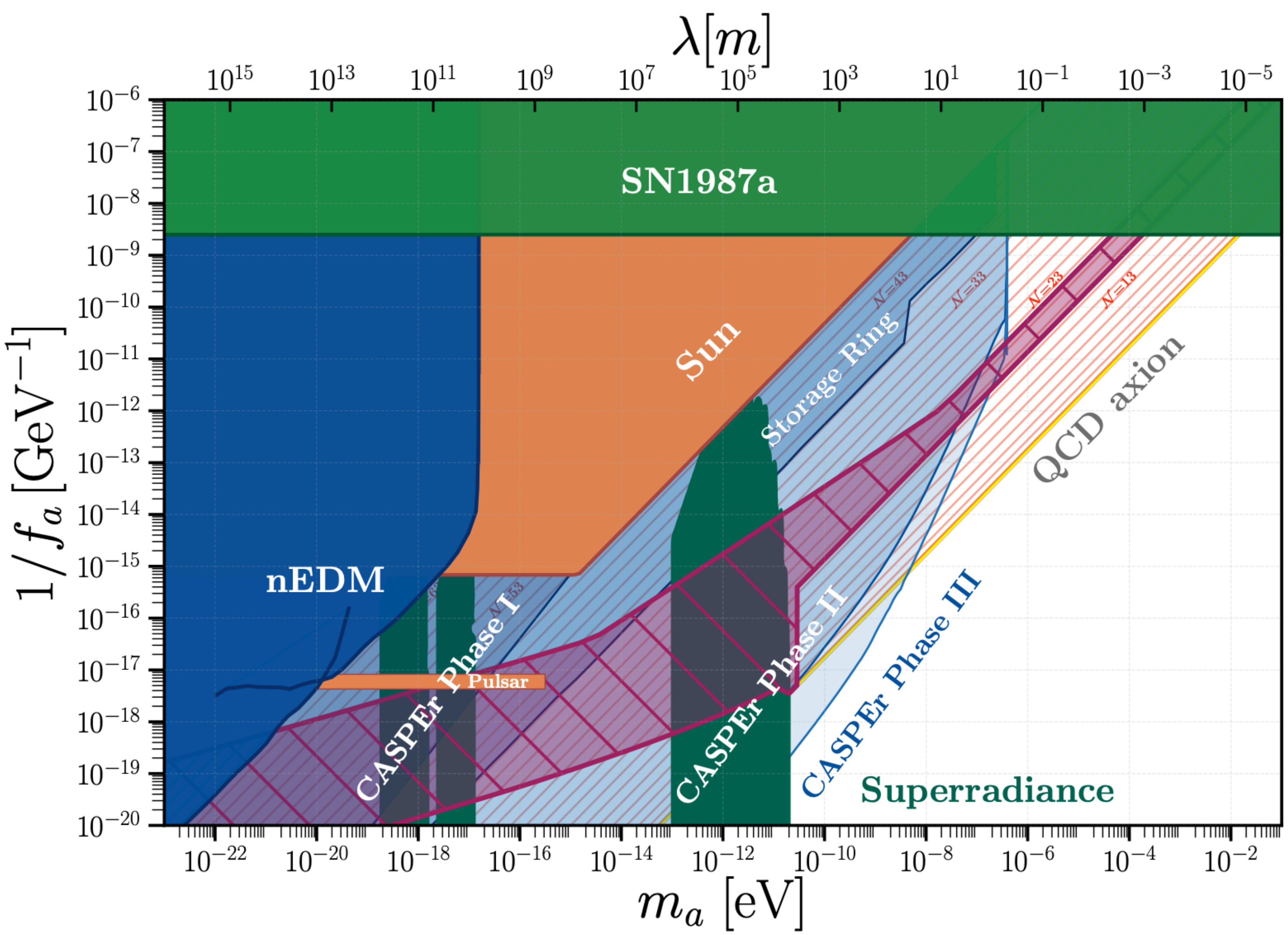
$$m_a^2 \simeq \frac{m_\pi^2 f_\pi^2}{f_a^2} \frac{1}{\sqrt{\pi}} \sqrt{\frac{1-z}{1+z}}\, \mathcal{N}^{3/2} z^{\mathcal{N}}$$

universal enhancement of all axion couplings w.r.t. standard QCD axion

Suppressing m_a

- Z_N axion: N mirror worlds

[LDL, Gavela, Quilez, Ringwald 2102.00012 + 2102.01082]



$$m_a^2 \simeq \frac{m_\pi^2 f_\pi^2}{f_a^2} \frac{1}{\sqrt{\pi}} \sqrt{\frac{1-z}{1+z}}\, \mathcal{N}^{3/2} z^{\mathcal{N}}$$

universal enhancement of all axion couplings w.r.t. standard QCD axion

CASPEr-Electric could disentangle enhanced coupling vs. suppressed mass mechanism

Conclusions

- Take home message

axion properties are UV dependent

1. enhanced/suppressed axion couplings
2. modified m_a - f_a relation
3. flavour violating axions
4. CP-violating axions

if an "axion-like particle" will be ever discovered away from the canonical QCD window, it might still have something to do with strong CP violation

Backup slides

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

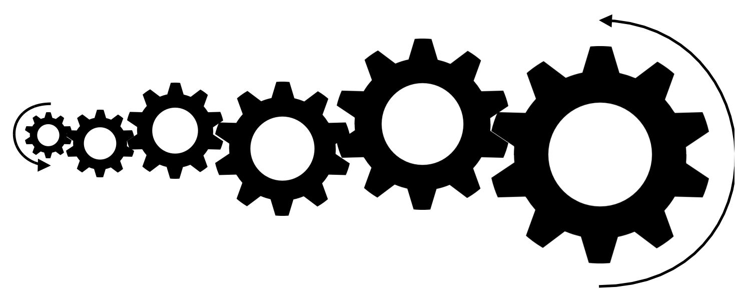
clockwork-like scenarios allow to consistently boost E/N [LDL, Mescia, Nardi 1705.05370]

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

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

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

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



[Giudice, McCullough]

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

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

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