The landscape of QCD axion models

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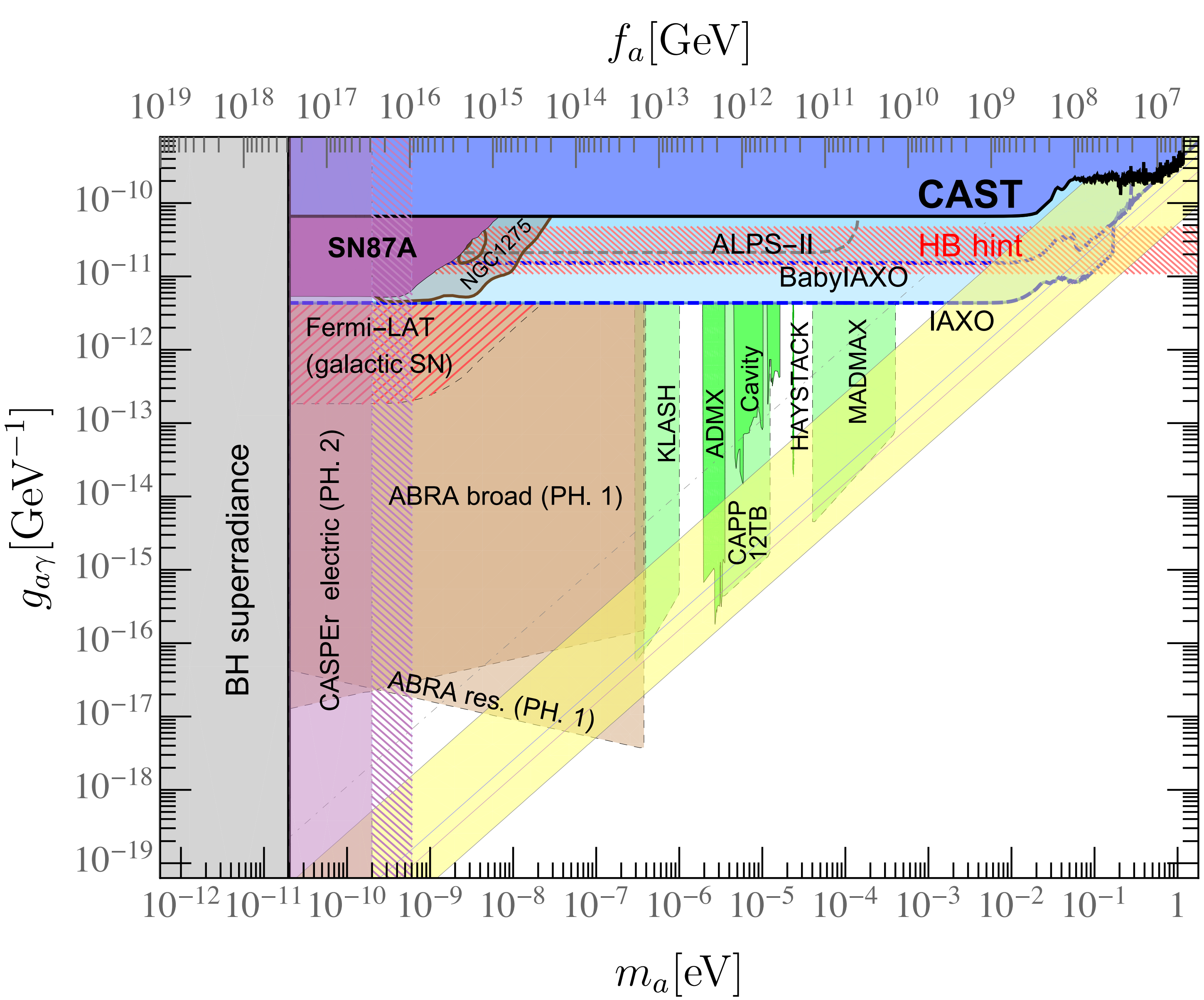
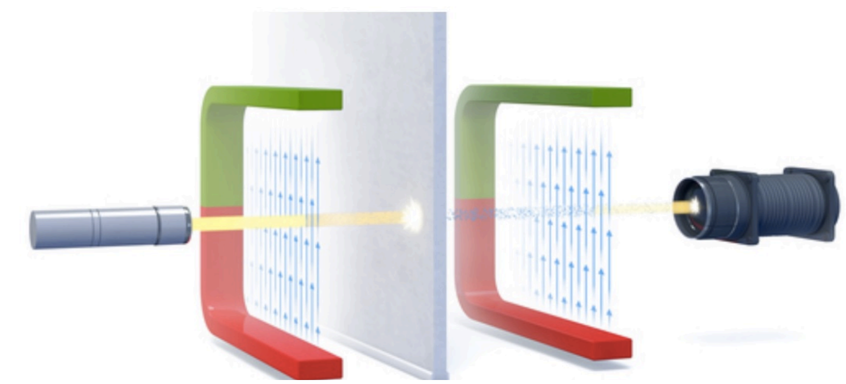
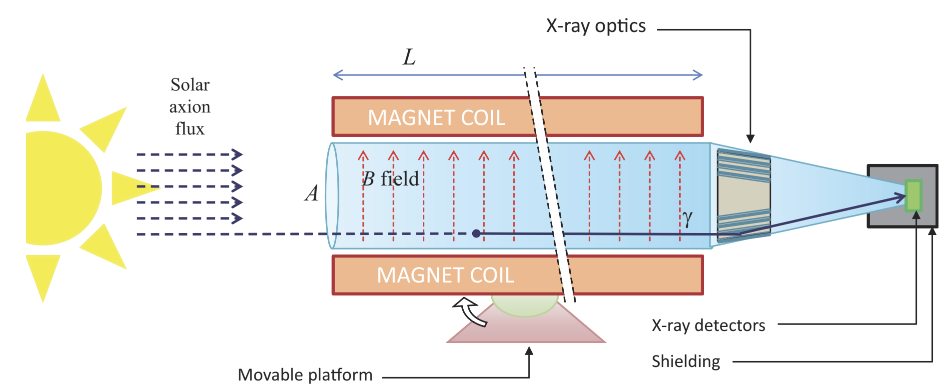
In 10 years from now ?

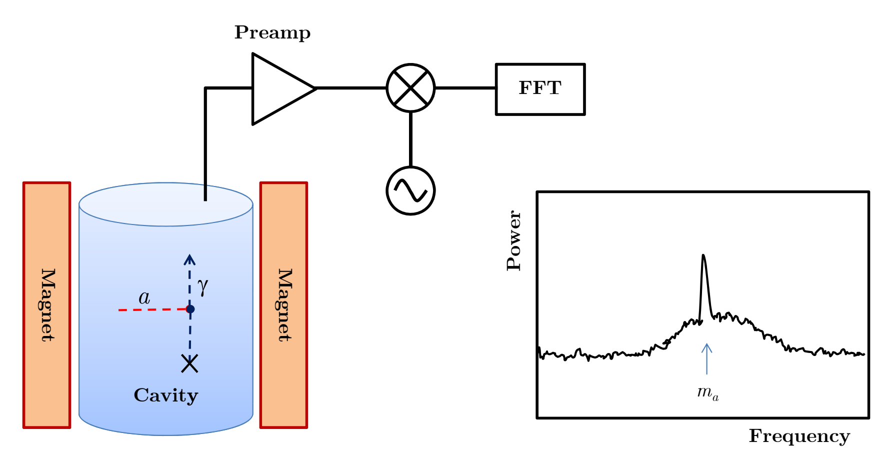


[LDL, Giannotti, Nardi, Visinelli 2003.01100 (Phys. Rept.)]

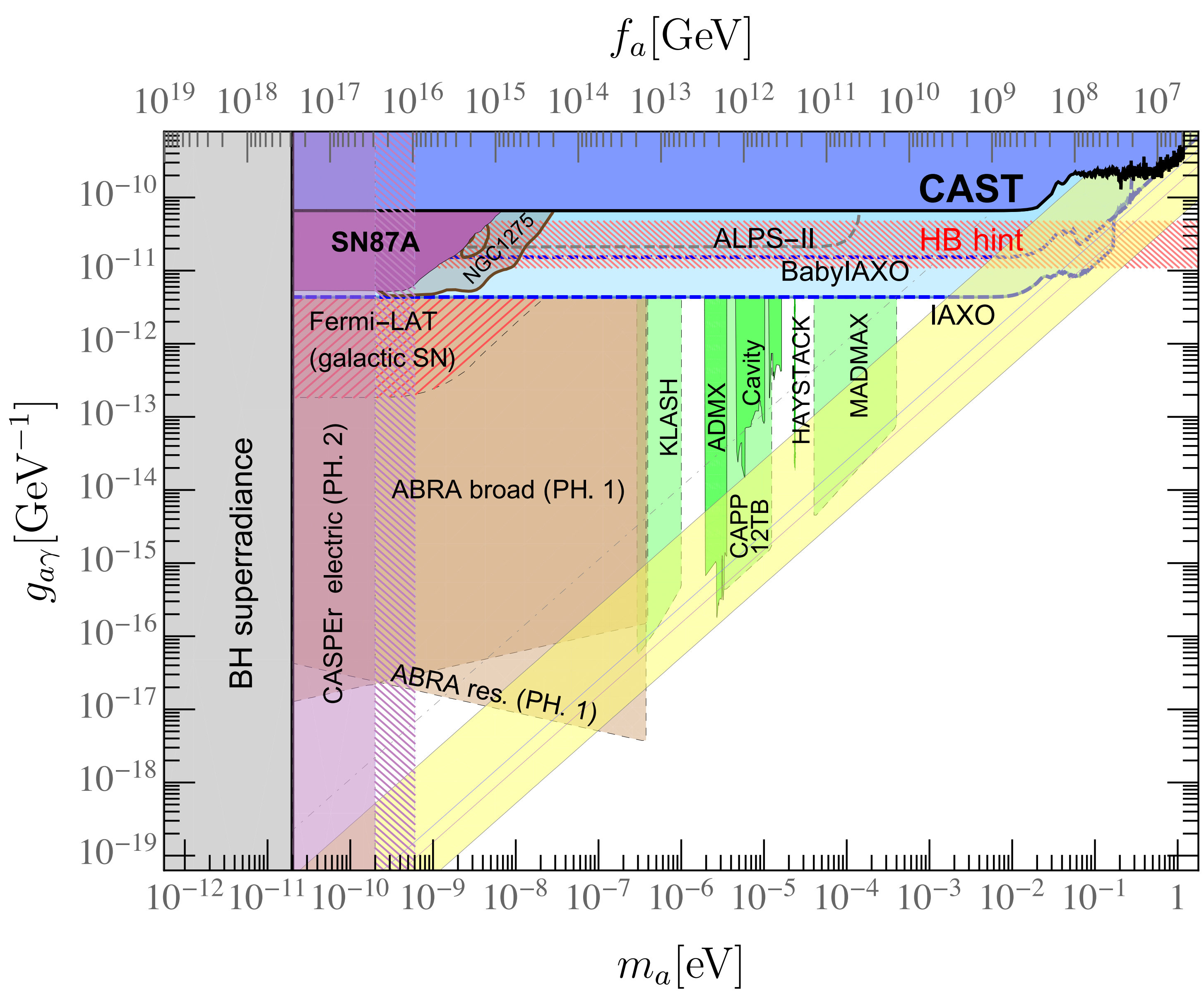
✤ An experimental opportunity







In 10 years from now ?



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

✤ An experimental opportunity

★ Time now to rethink the QCD axion

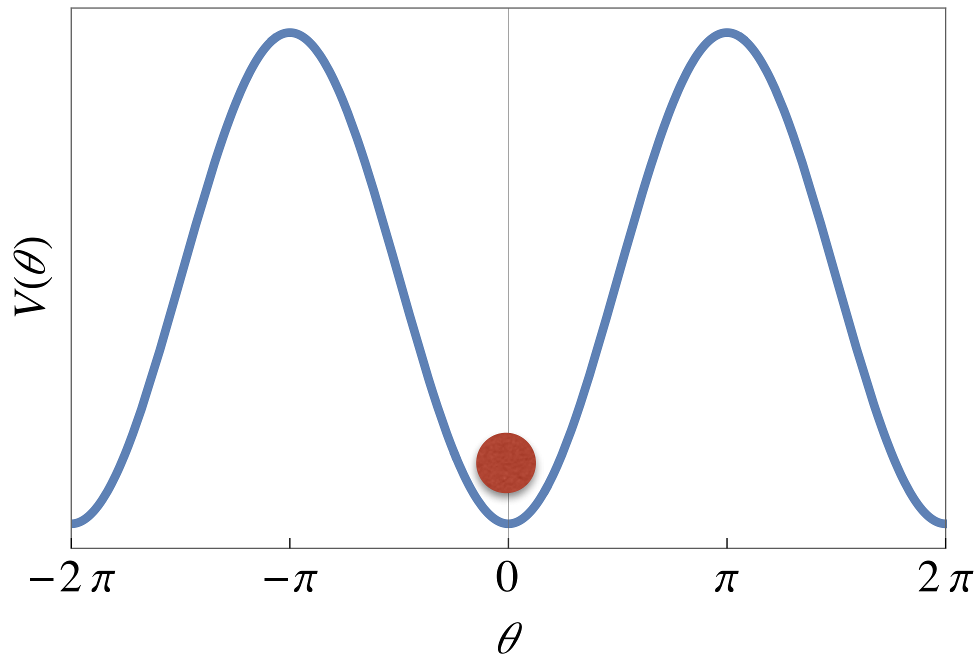
1. PQ mechanism
2. Axion couplings
   [from EFTs to UV models]
3. QCD axions beyond standard benchmarks

QCD axion

Strong CP problem

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

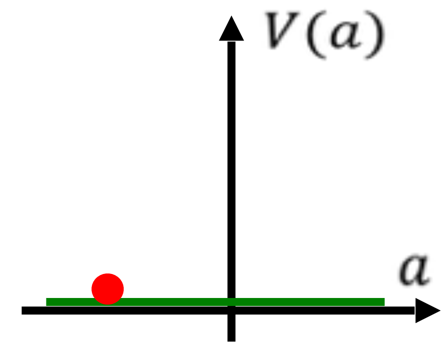
promote θ to a dynamical field, which washes-out CP violation in QCD



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

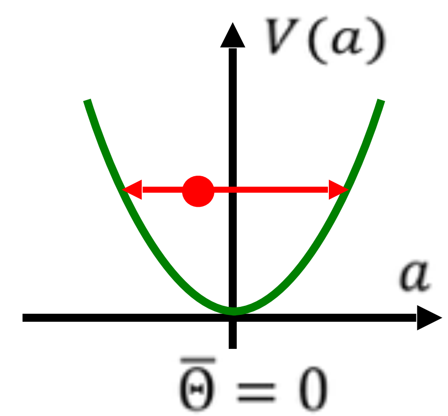
Dark Matter

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)]

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

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

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- Does the axion really relax to zero ?

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

does not apply to the SM !

PQ mechanism

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- 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

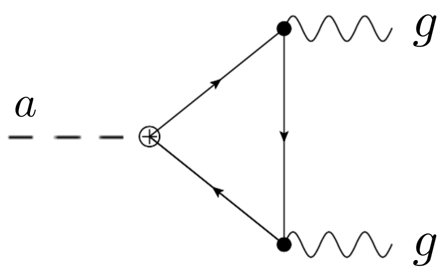
- Assume a new spin-0 boson with a pseudo-shift symmetry $a \to a + \alpha f_a$

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

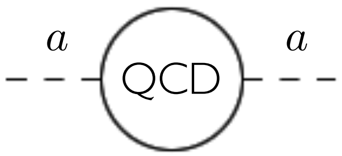


$$\partial^\mu J_\mu^{PQ} = \frac{N\alpha_s}{4\pi} G \cdot \tilde{G}$$

Axion properties [model-indep.]

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

1. axion mass



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

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

[Gorghetto, Villadoro, 1812.01008 (NNLO chiPT)
Bonati, D'Elia, Mariti, Martinelli, Mesiti, Negro, Sanfilippo, Villadoro, 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, …

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

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

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

[see talk by G. Piazza for axion-pion coupling]

Axion properties [model-indep.]

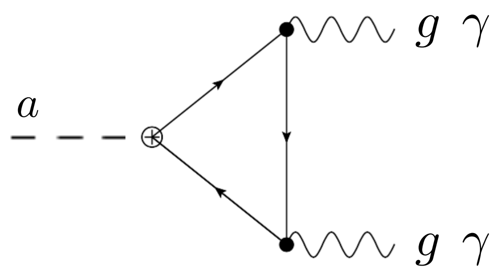
- Consequences of $\frac{a}{f_a}\frac{g_s^2}{32\pi^2}G\tilde{G}$

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



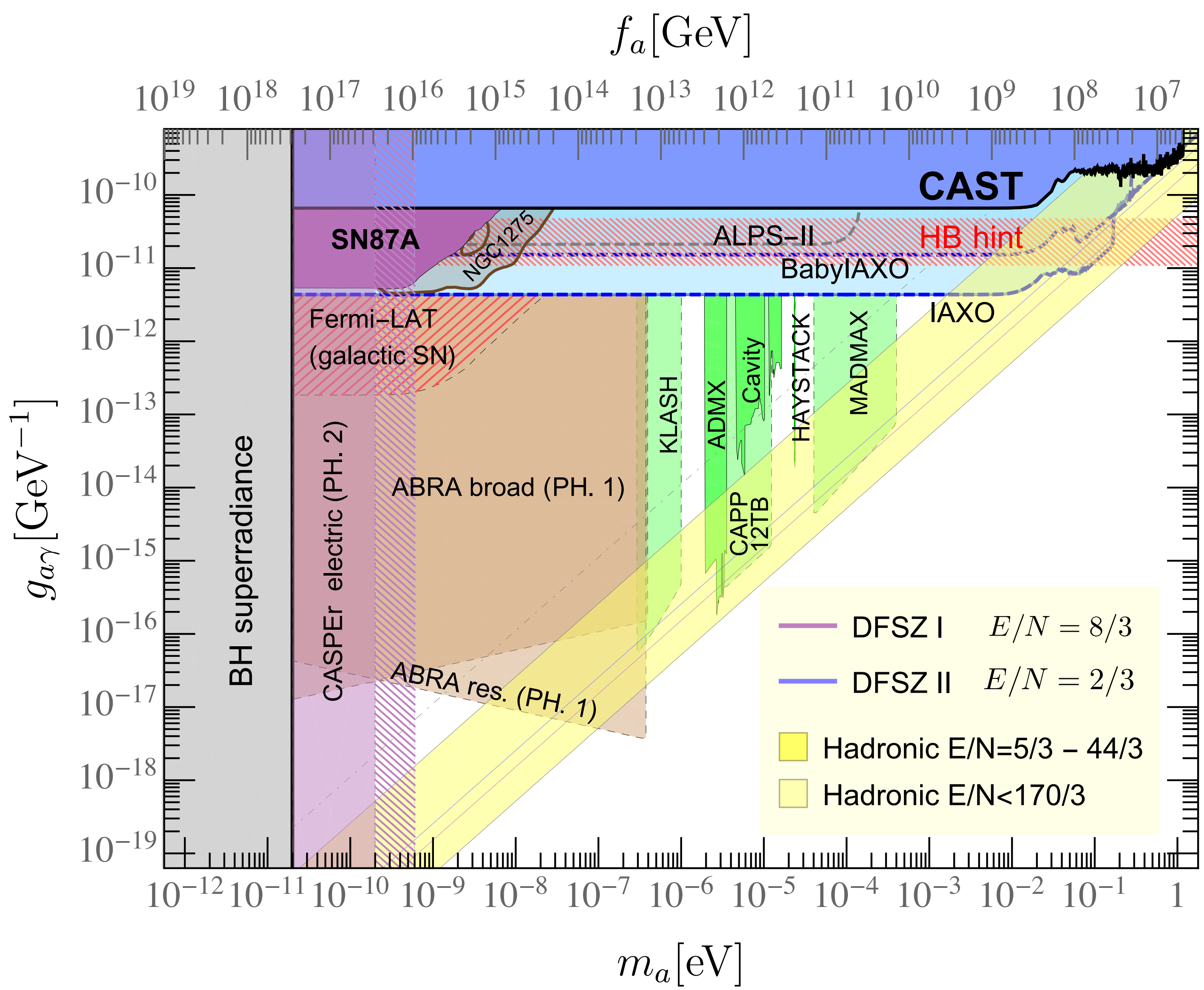
$$\partial^\mu J^{PQ}_\mu = \frac{N\alpha_s}{4\pi} G\cdot\tilde{G} + \frac{E\alpha}{4\pi} F\cdot\tilde{F}$$

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

model-independent

depends on UV completion

enhance/suppress C_γ

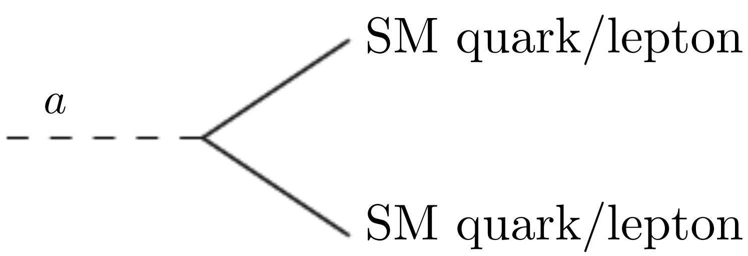


[LDL, Giannotti, Nardi, Visinelli 2003.01100 (Phys. Rept.)]

Axion properties [model-dep.]

2. Axion-SM fermions

[Robert Ziegler, La Thuile'19]



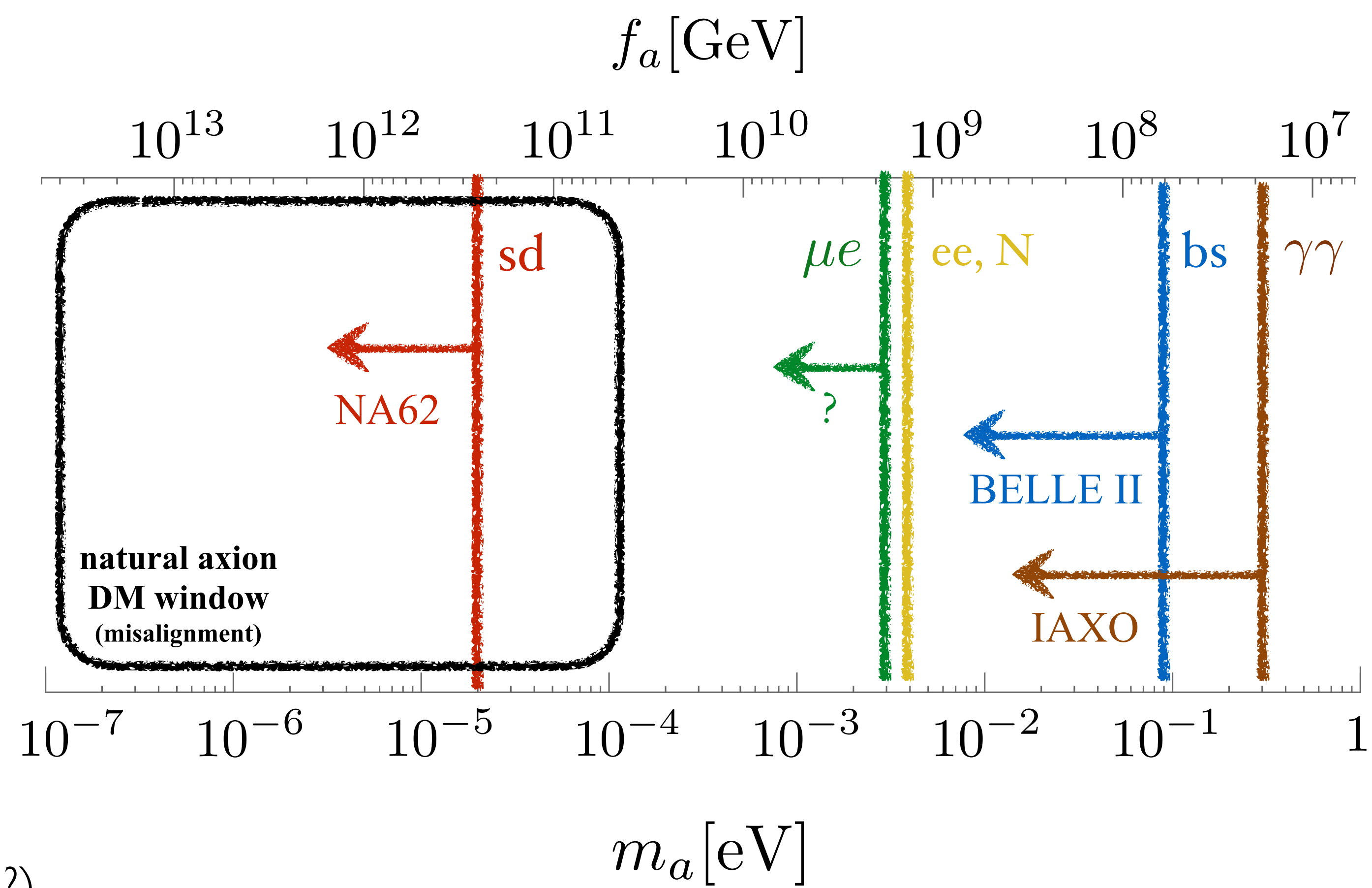
$$\frac{\partial_\mu a}{2 f_a} \overline{\psi}_i \gamma^\mu (C^V_{ij} + C^A_{ij} \gamma_5) \psi_j$$

$\downarrow$ J^μ_{PQ}

$C^{V,A}_{ij} \propto (V^\dagger_\psi \, \mathrm{PQ}_\psi V_\psi)_{ij}$ (PQ as a flavour symmetry ?)

flavour-violating axion coupling

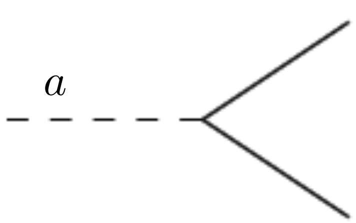
enhance/suppress $C_{p,n,e}$



for $C_i = \{C_\gamma, C_e, C_N, C^V_{sd}, C^V_{bs}\} = 1$
flavour beats astrophysics !

Axion properties [model-dep.]

2. Axion-SM fermions



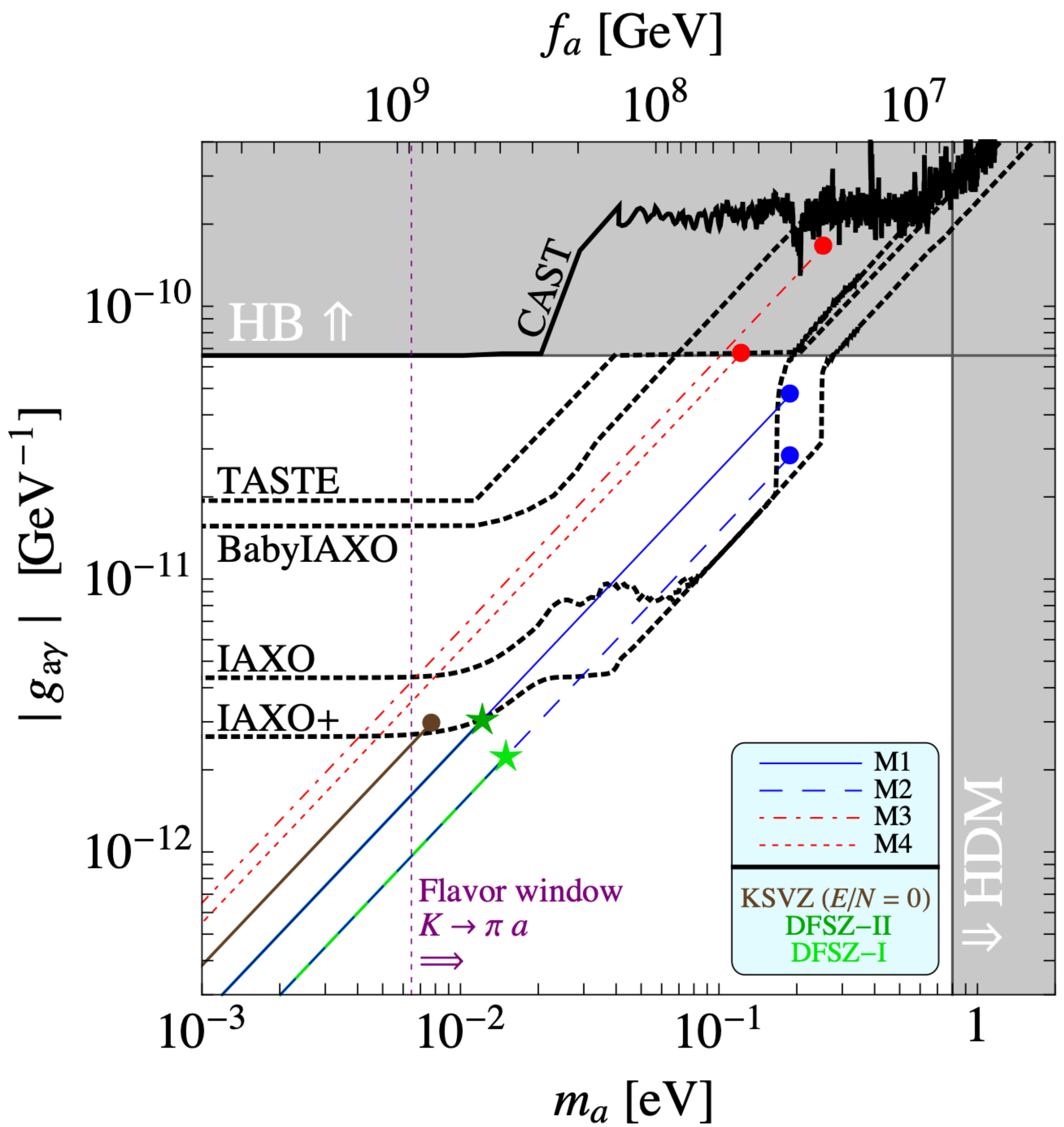
$$\frac{\partial_\mu a}{2f_a}\overline{\psi}_i\gamma^\mu(C^V_{ij}+C^A_{ij}\gamma_5)\psi_j$$

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

flavour-violating axion coupling

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

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



Axion properties [model-dep.]

3. CP-violating axions

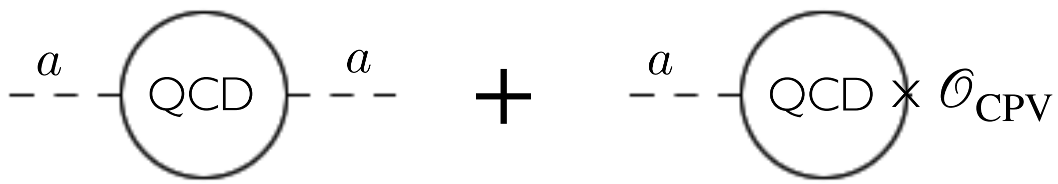
[Moody, Wilczek PRD30 (1984)]

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

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

[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]

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



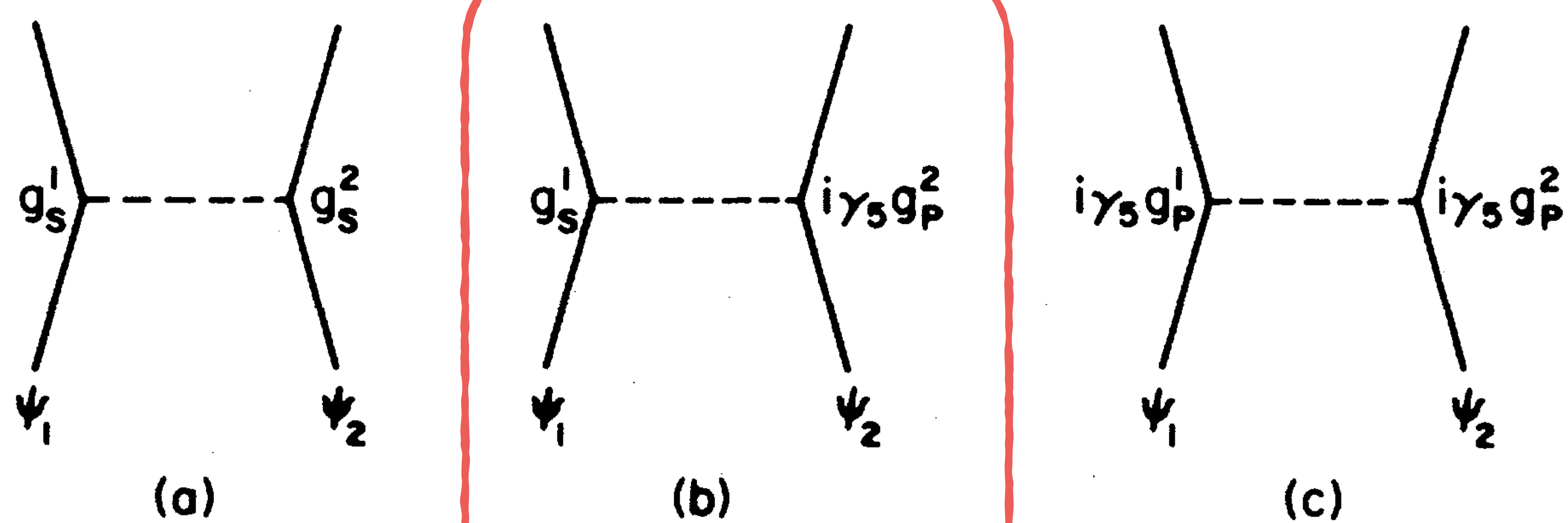
Axion properties [model-dep.]

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



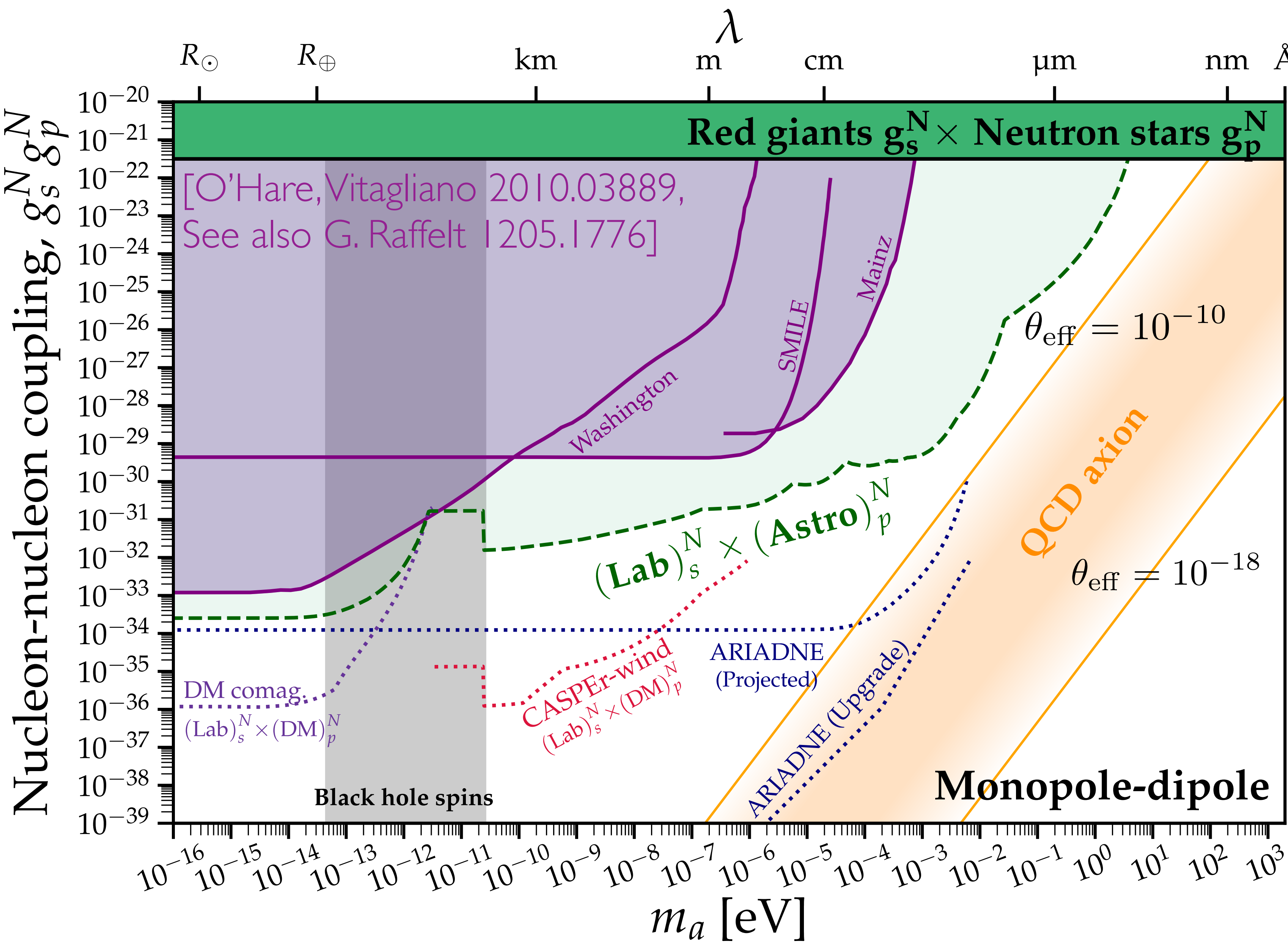
monopole-monopole	monopole-dipole	dipole-dipole
double $\theta_{\rm eff}$ suppression	ARIADNE, QUAX-gpgs, … NMR enhancement	*spin suppression + bkgd from ordinary magnetic forces*

Axion properties [model-dep.]

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

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

from UV sources of CP-violation



BSM (optimistic)

SM (pessimistic)

Benchmark axion models

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

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

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

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

SM fermions | BSM fermions

2Higgs+Singlet | Higgs+Singlet

DFSZ | KSVZ

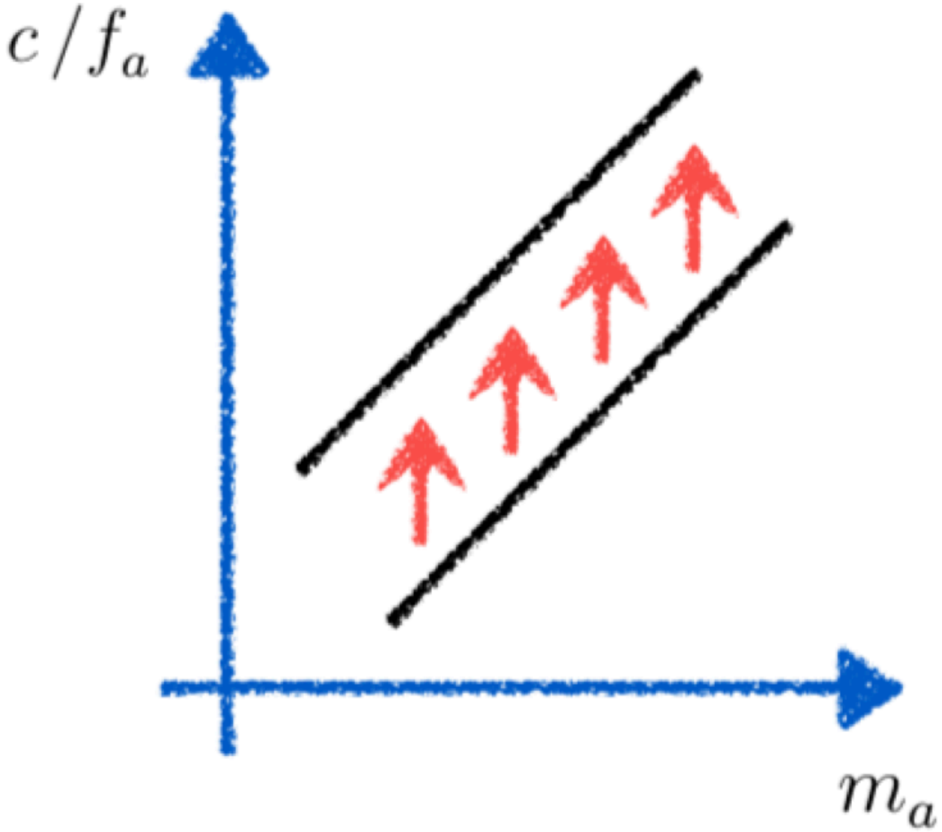
$C_\gamma = E/N - 1.92(4)$

DFSZ: $E/N = 8/3$, $C_{p,n,e}(\beta) \sim \mathcal{O}(1)$

KSVZ: $E/N = 0$, $C_p \simeq -0.5$, $C_{n,e} \simeq 0$

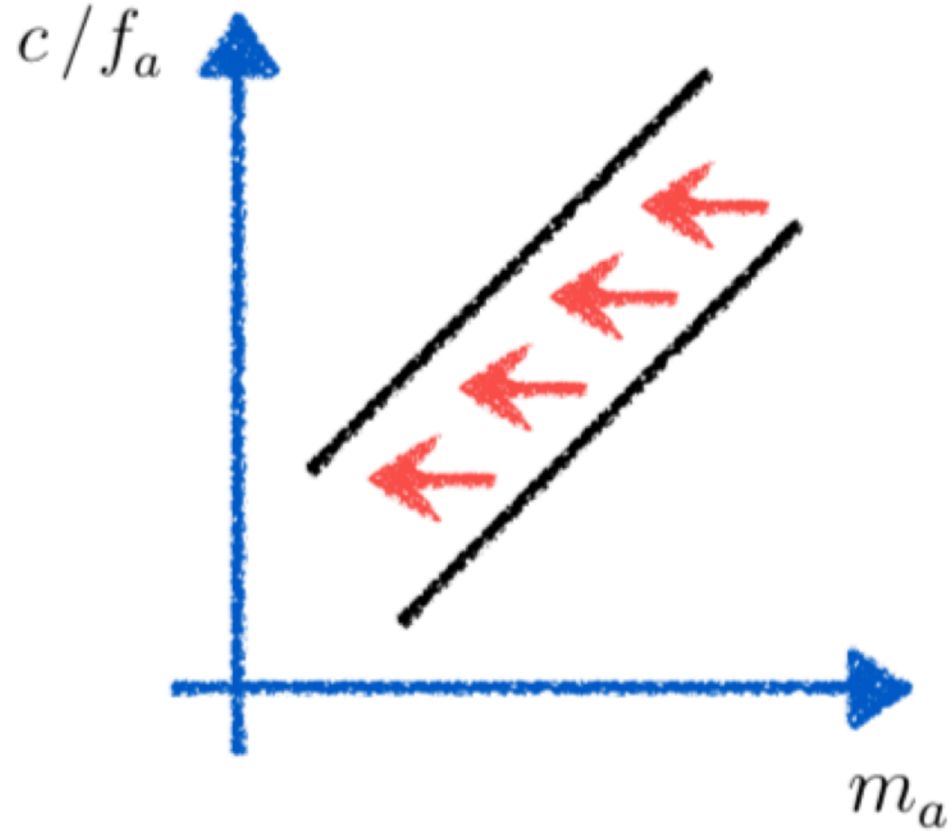
(also no flavour and CP-violating effects)

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]



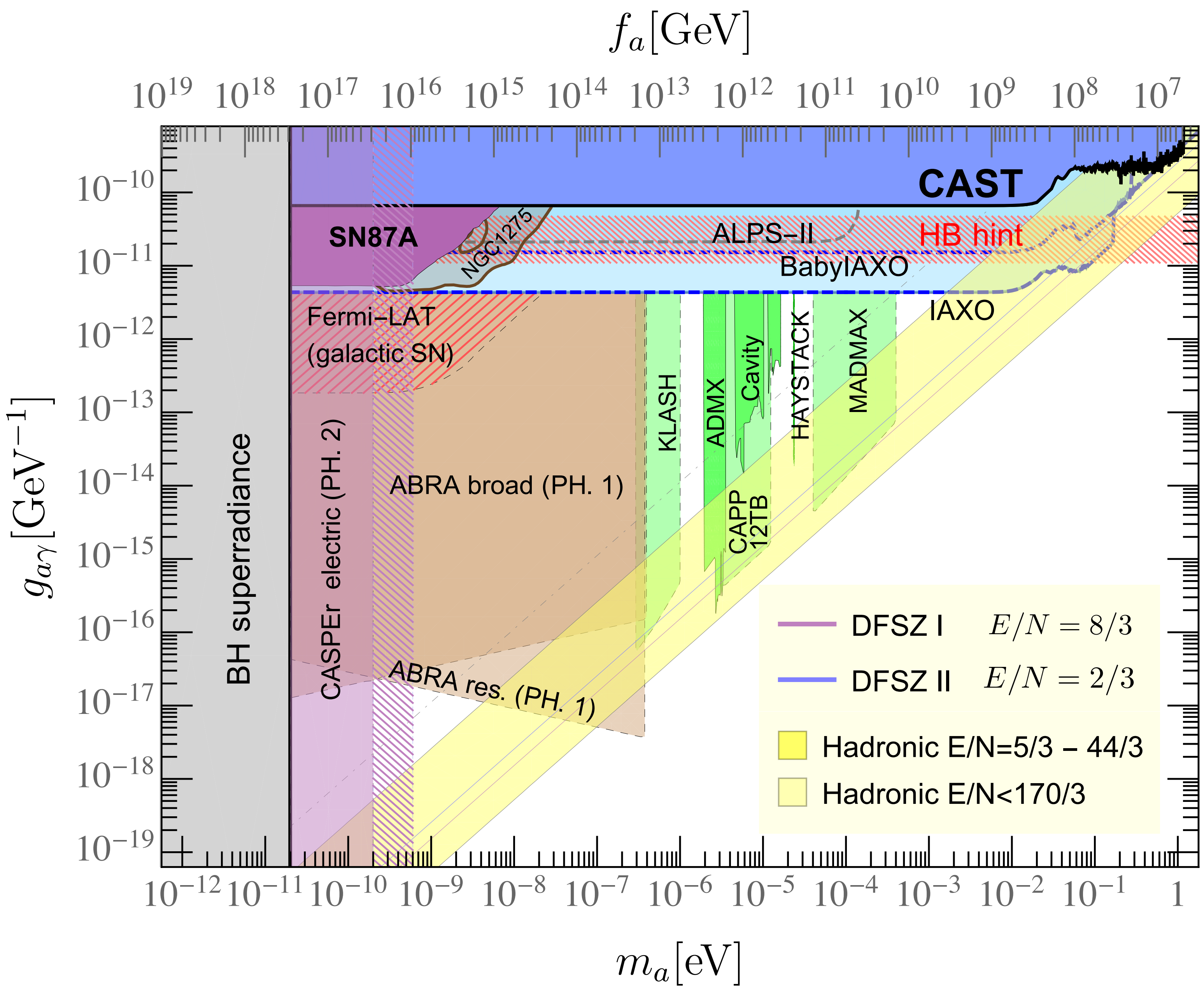
suppress axion mass for fixed f_a

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

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

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
FLASH (Frascati)	CDR
QUAX-aγ (Legnaro)	running
…	…



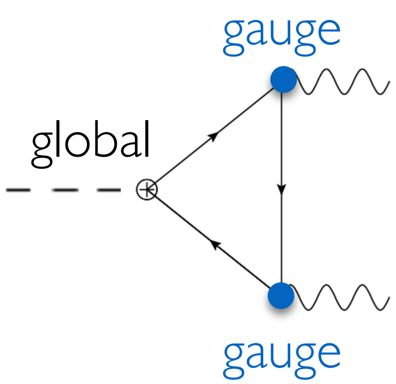
[LDL, Giannotti, Nardi, Visinelli 2003.01100 (Phys. Rept.)]

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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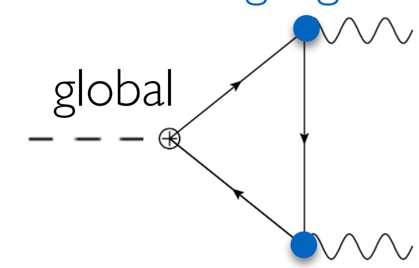


	R_Q	$\mathcal{O}_{Qq}$	$\Lambda^{2-\text{loop}}_{\text{Landau}}[\text{GeV}]$	E/N
	$(3,1,-1/3)$	$\overline{Q}_L d_R$	$9.3\cdot 10^{38}(g_1)$	$2/3$
	$(3,1,2/3)$	$\overline{Q}_L u_R$	$5.4\cdot 10^{34}(g_1)$	$8/3$
R^w_Q	$(3,2,1/6)$	$\overline{Q}_R q_L$	$6.5\cdot 10^{39}(g_1)$	$5/3$
	$(3,2,-5/6)$	$\overline{Q}_L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

- Pheno preferred hadronic axions

  1. Q-fermions short lived (no coloured relics)

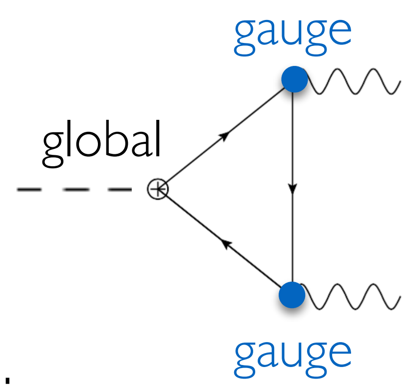
  2. No Landau poles below Planck

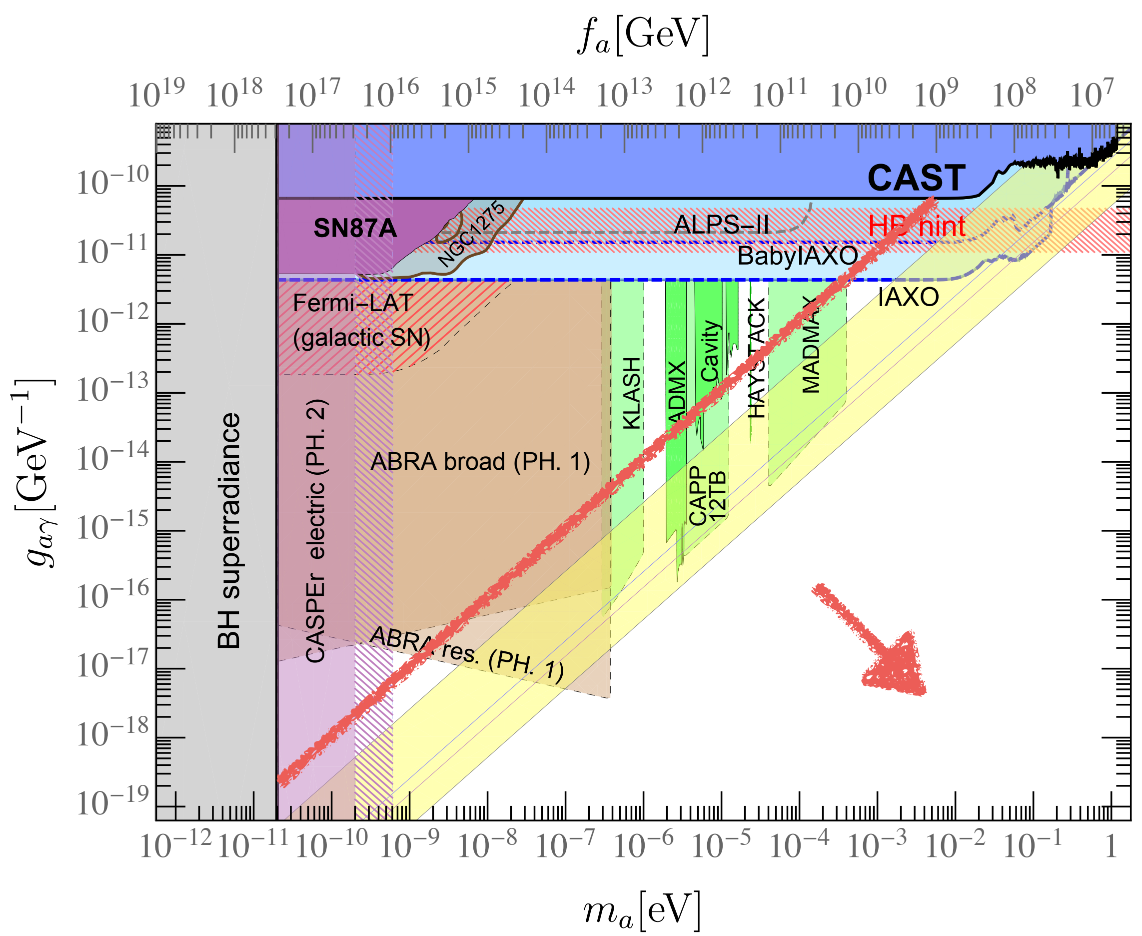
→ $E/N \in [5/3, 44/3]$

[LDL, Mescia, Nardi 1610.07593]

Enhancing $g_{a\gamma}$

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





- 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)]

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

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

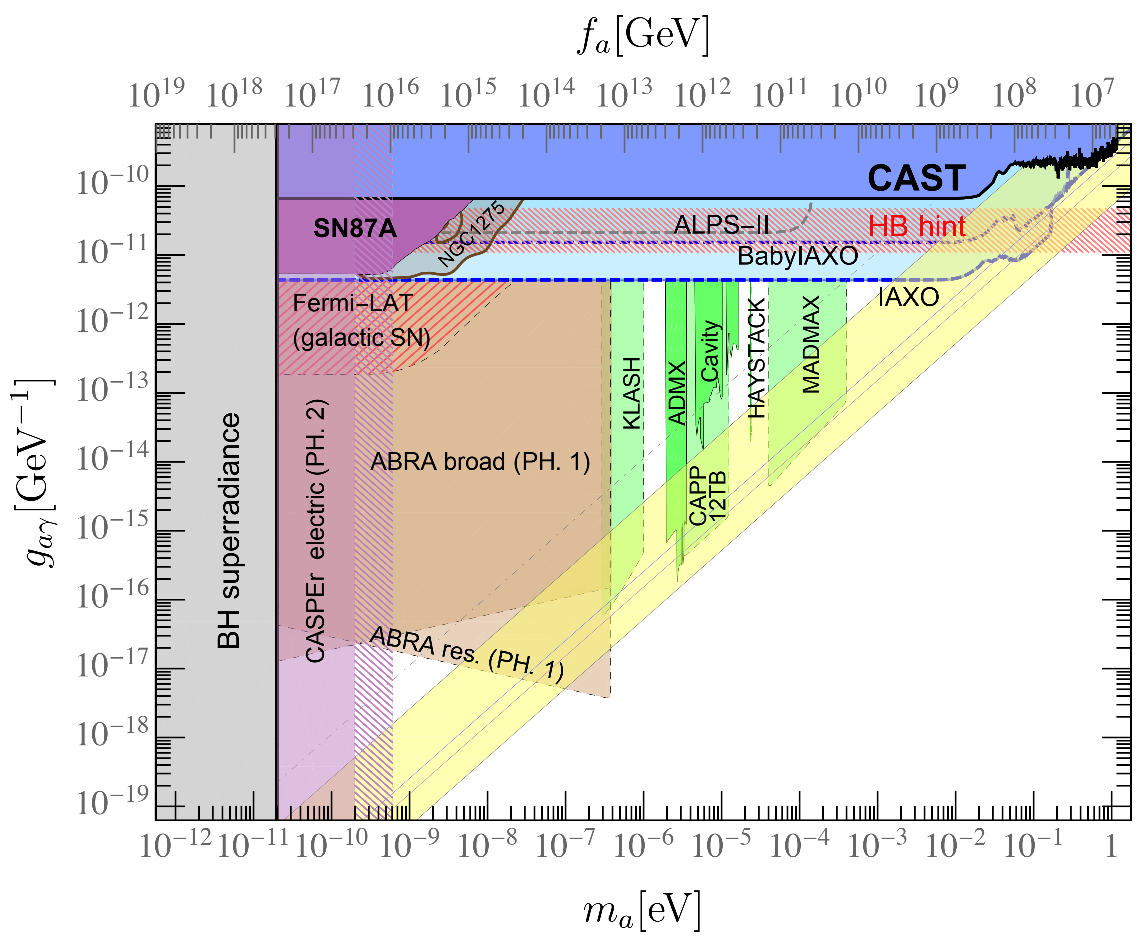
  - *be agnostic, E/N is a free parameter*

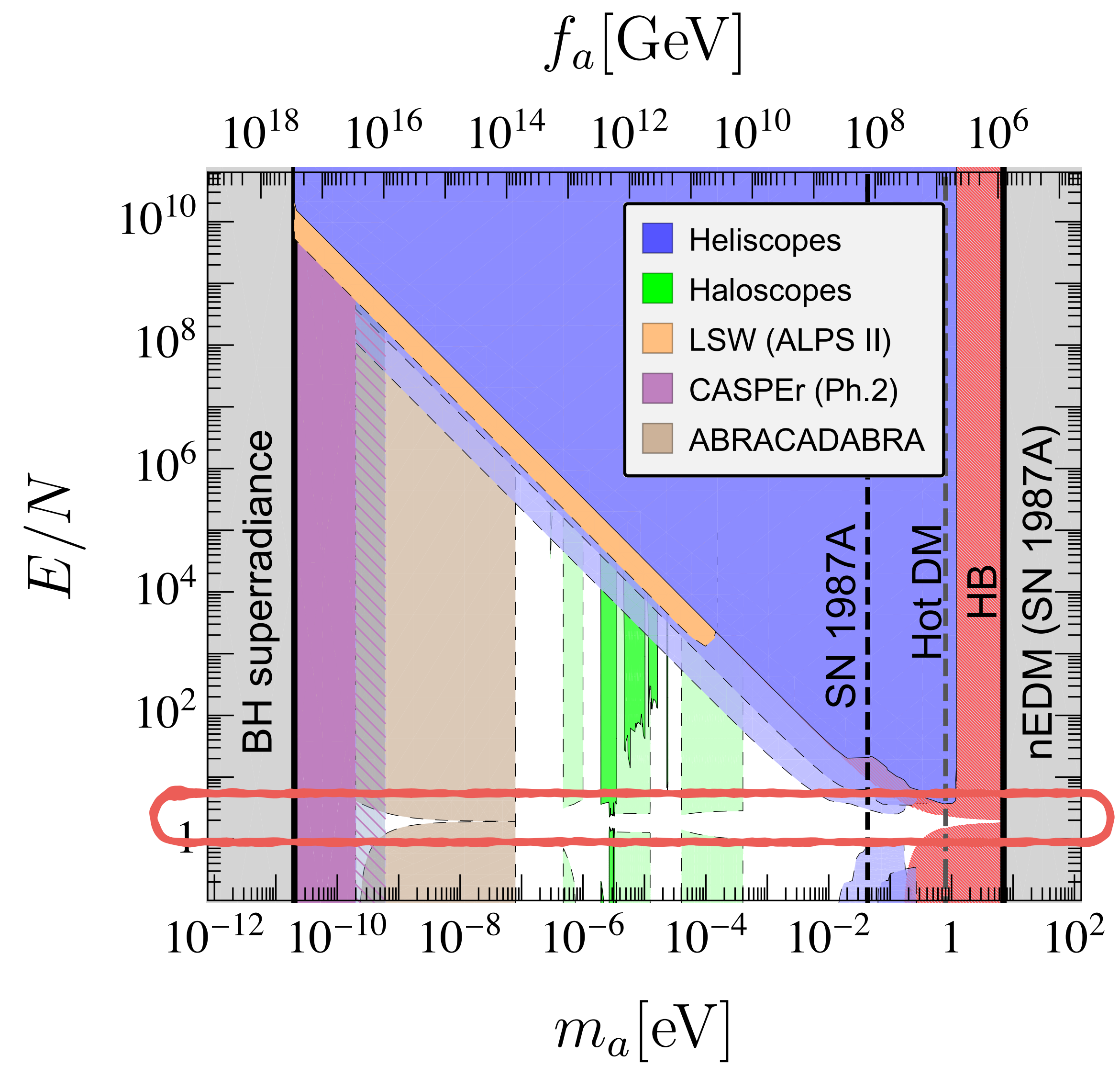
Enhancing $g_{a\gamma}$

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

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

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





1. *exp.s have just started to constrain E/N from above*

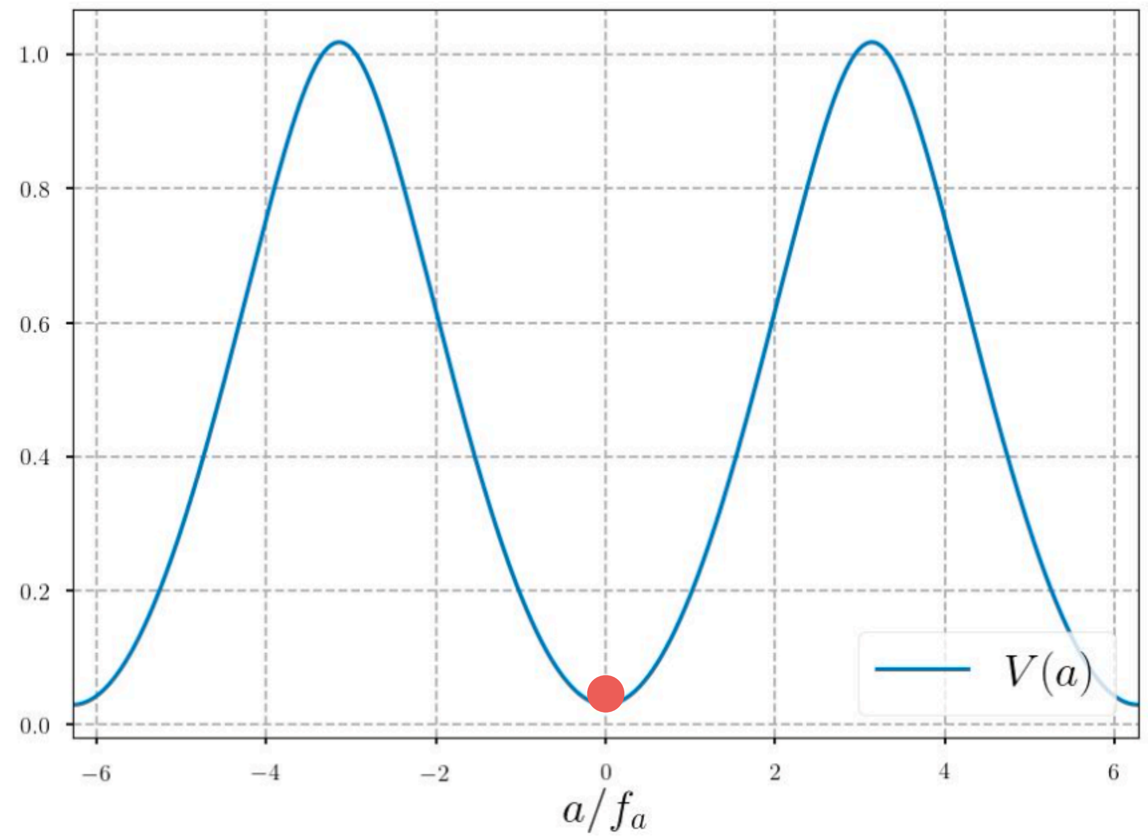
2. *E/N ~ 1.92 appears as a tuned region in theory space*

Suppressing m_a

- Standard QCD axion

[Di Vecchia, Veneziano, NPB171 (1980)
Leutwyler, Smilga, PRD46 (1992)
Grilli di Cortona, Hardy, Vega, Villadoro, 1511.02867]

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

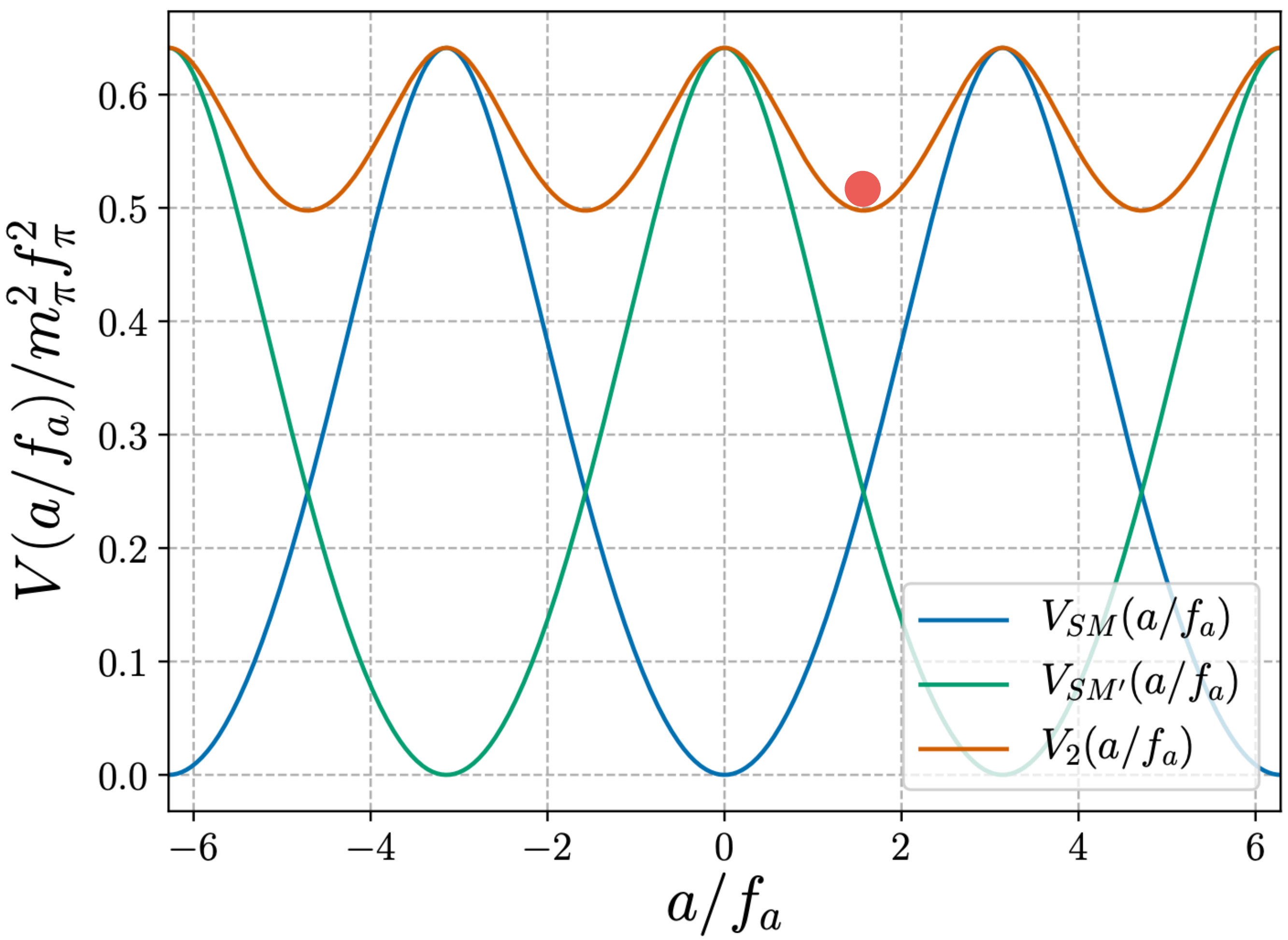


Suppressing m_a

- Z_2 axion: mirror world

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

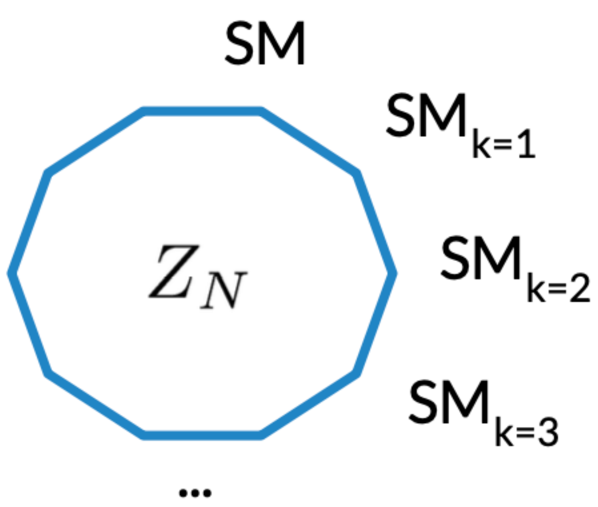
$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{SM}'} + \frac{\alpha_s}{8\pi}\left(\frac{a}{f_a} - \theta\right) G\widetilde{G} + \frac{\alpha_s}{8\pi}\left(\frac{a}{f_a} - \theta + \pi\right) G'\widetilde{G}'$$



→ *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]

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

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

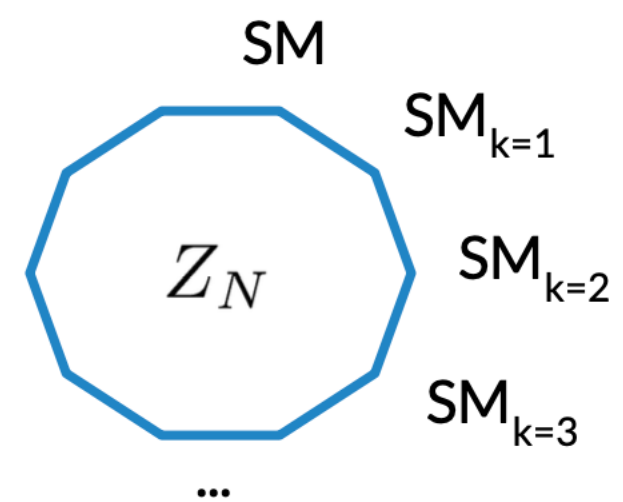
$$\simeq \frac{m_\pi^2 f_\pi^2}{\sqrt{\pi}} \sqrt{\frac{1-z}{1+z}} \mathcal{N}^{-1/2} (-1)^{\mathcal{N}} z^{\mathcal{N}} \cos(\mathcal{N}\theta_a)$$

axion potential exponentially suppressed at large N

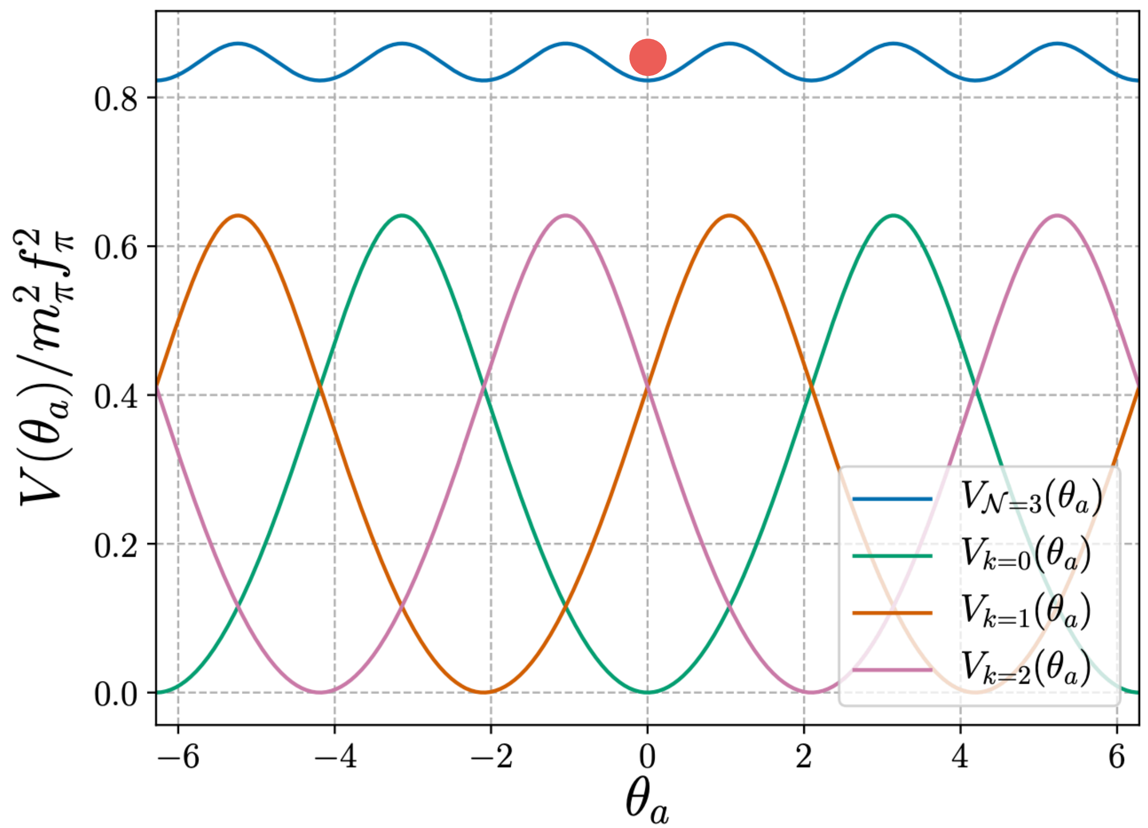
Suppressing m_a

- 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]

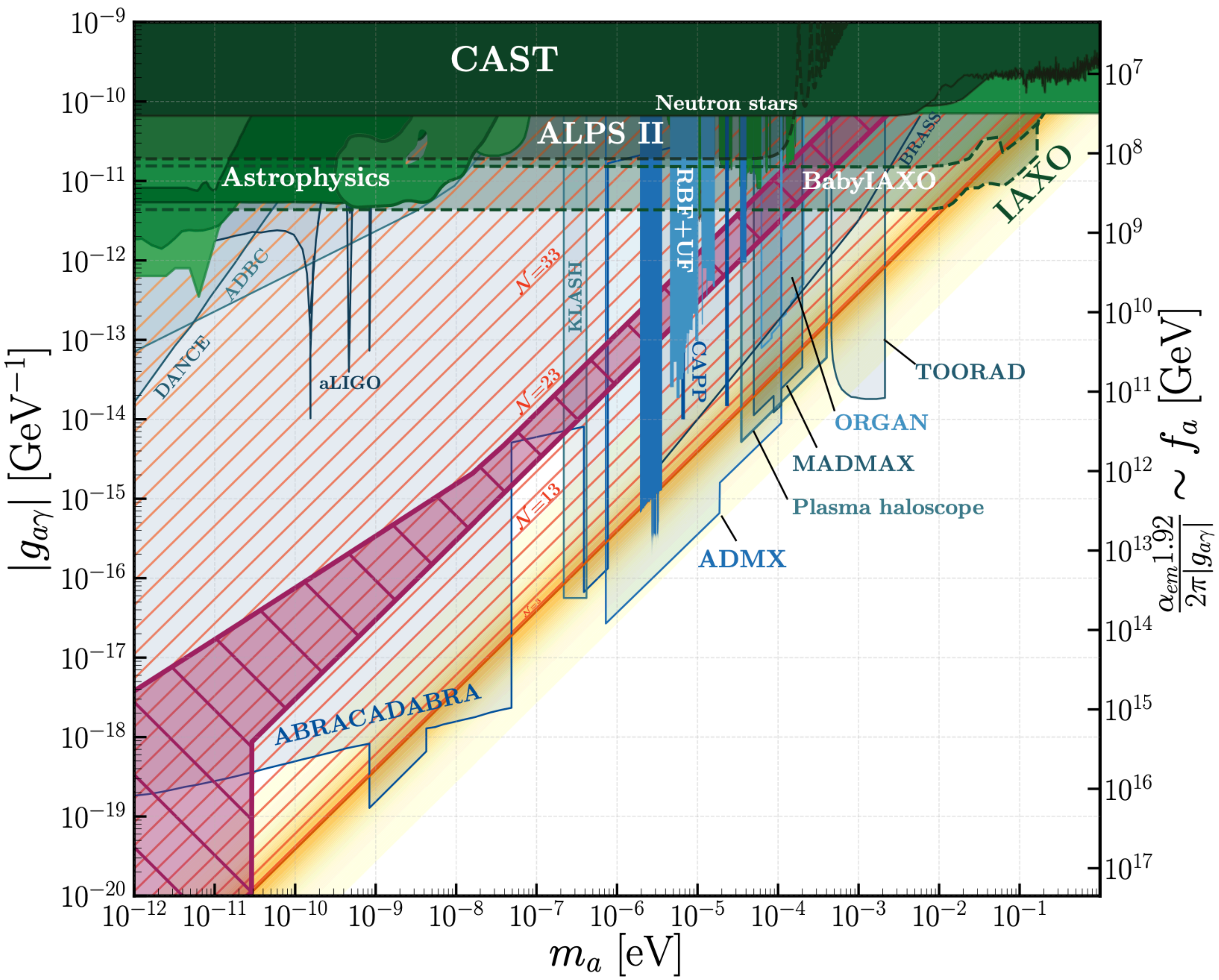
N needs to be odd in order to have a minimum in zero

(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

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

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

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

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

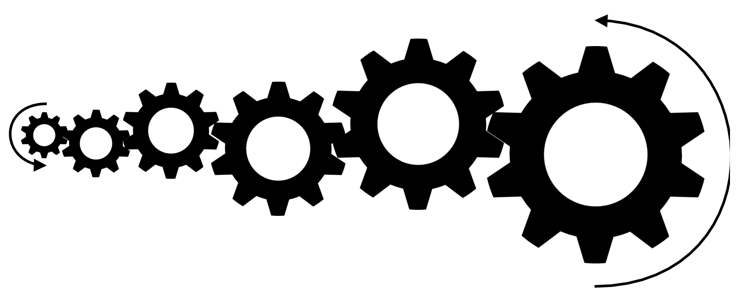
clockwork-like scenarios allow to consistently boost E/N [LDL, Mescia, Nardi 1705.05370]

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

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

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

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



[Giudice, McCullough]

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

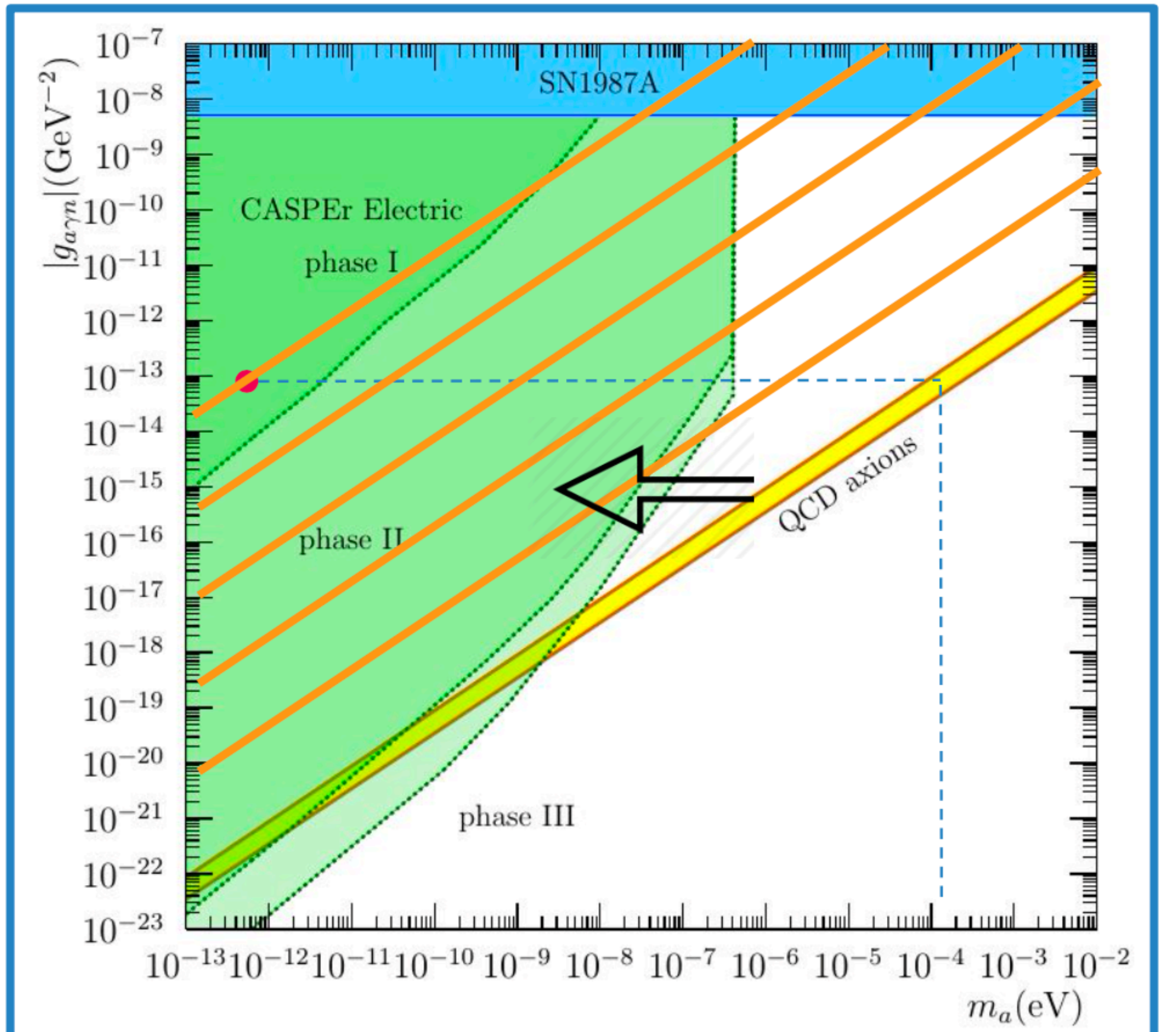
[See also Farina et al. 1611.09855, for KSVZ clockwork]

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

How to tell which mechanism ?

→ *CASPEr-Electric could disentangle enhanced coupling vs. suppressed mass*

$g_{a\gamma n}$ [Pablo Quilez]



[Irastorza+Redondo, 18]

Based on **2102.00012** and **2102.01082**

$m_a\,(eV)$

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

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

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

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

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

Coupling to the nEDM

Axion mass

CASPEr-Electric

- Cosmic Axion Spin Precession Experiment

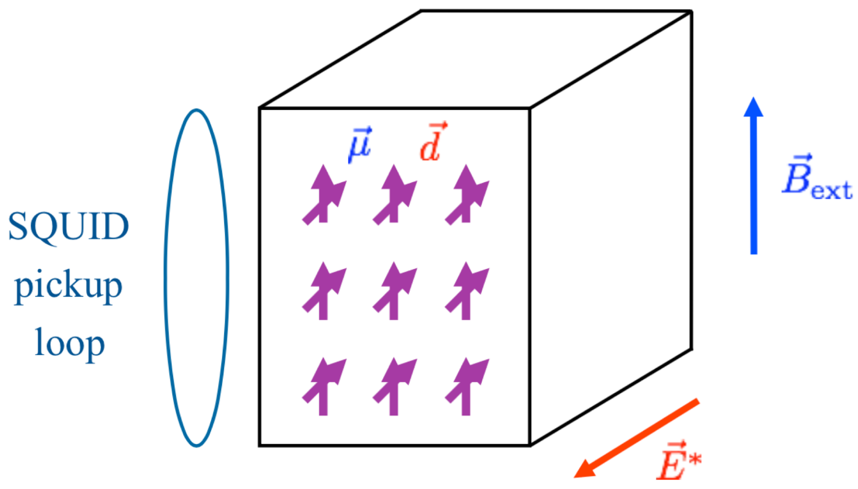
[Graham, Rajendran 1306.6088, Budker+ 1306.6089, Jackson Kimball+ 1711.08999]

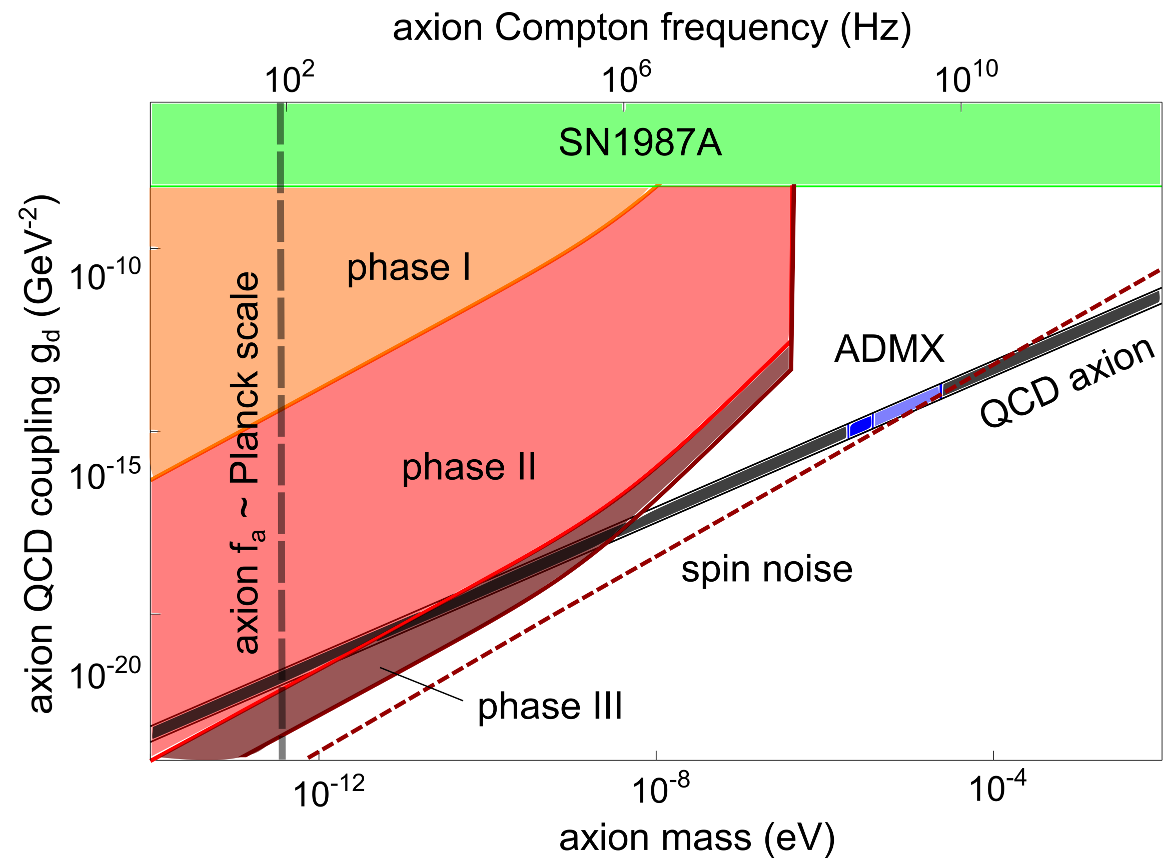
Axion DM field induces an oscillating nEDM

$$\mathcal{L} \supset -\frac{i}{2} \underbrace{g_d a}_{} \, \overline{n} \sigma_{\mu\nu} \gamma_5 n F^{\mu\nu}$$

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

…which is detected via NMR techniques





CPV axion & long-range forces

- New <u>CP violation</u> in the UV can source a *scalar* axion-nucleon coupling

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

[Moody, Wilczek PRD30 (1984)]

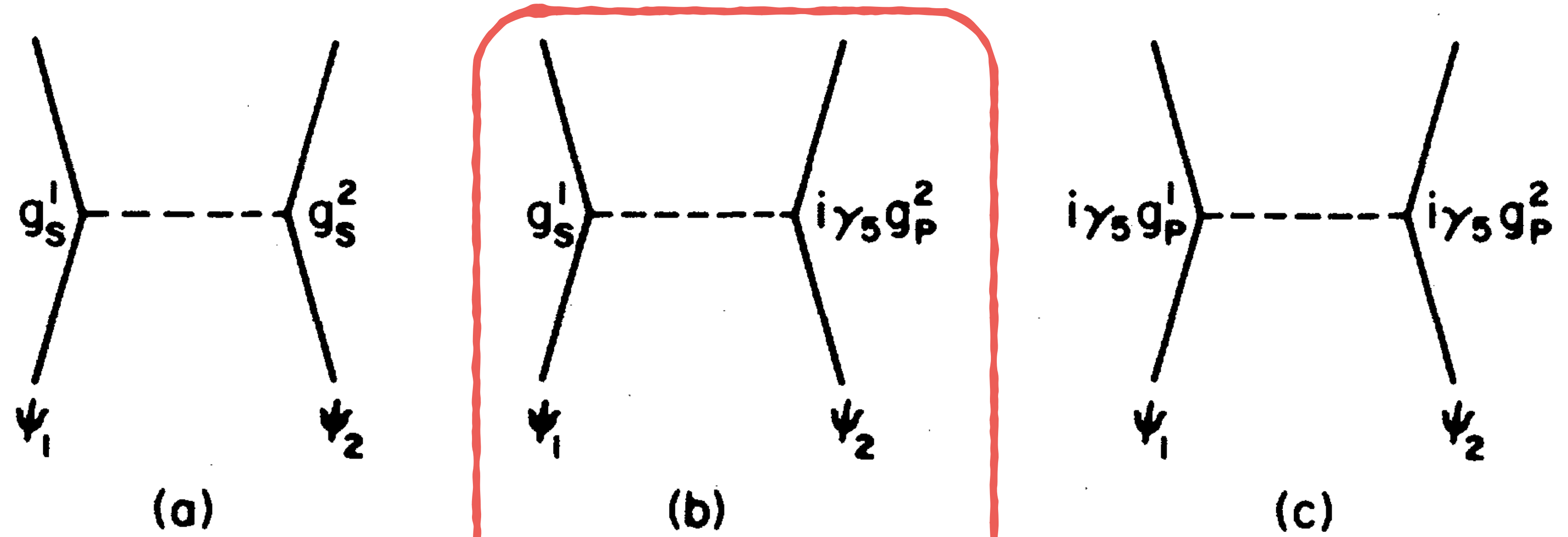
$$\frac{1}{2}\frac{a^2}{f_a^2}\underbrace{\left\langle G\tilde{G}, G\tilde{G}\right\rangle}_{\chi} + \frac{a}{f_a}\underbrace{\left\langle G\tilde{G}, \mathcal{O}_{\text{CPV}}\right\rangle}_{\chi'} \longrightarrow \frac{\langle a \rangle}{f_a} = -\frac{\chi'}{\chi}$$

CPV axion & long-range forces

- New <u>CP violation</u> in the UV can source a *scalar* axion-nucleon coupling

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

[Moody, Wilczek PRD30 (1984)]



monopole-monopole | monopole-dipole | dipole-dipole

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

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

A new master formula

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

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

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

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

meson tadpoles

iso-spin breaking

MW missed a factor 1/2

An application: Left-Right

- Low-scale (PQ)Left-Right with P-parity

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

4-quark op. from W_R *exchange*

chiral representation

$$\mathcal{O}_1^{ud} = (\overline{u}u)(\overline{d}i\gamma_5 d) \longrightarrow c_3(U^\dagger_{11}U_{22} - U_{11}U^\dagger_{22})$$

$$U = \exp\left[\frac{2i}{\sqrt{6}F_0}\eta_0 I + \frac{2i}{F_\pi}\Pi\right]$$

$$\frac{\langle\pi^0\rangle}{F_\pi} \simeq \frac{G_F}{\sqrt{2}}\mathcal{C}_1^{[ud]}\frac{c_3}{B_0F_\pi^2}\frac{m_u+m_d+4m_s}{m_um_d+m_dm_s+m_sm_u}$$

$$\frac{\langle\eta_8\rangle}{F_\pi} \simeq \frac{G_F}{\sqrt{2}}\mathcal{C}_1^{[ud]}\frac{\sqrt{3}c_3}{B_0F_\pi^2}\frac{m_d-m_u}{m_um_d+m_dm_s+m_sm_u}$$

$$\theta_{\rm eff} \simeq \frac{G_F}{\sqrt{2}}\mathcal{C}_1^{[ud]}\frac{2c_3}{B_0F_\pi^2}\frac{m_d-m_u}{m_um_d}$$

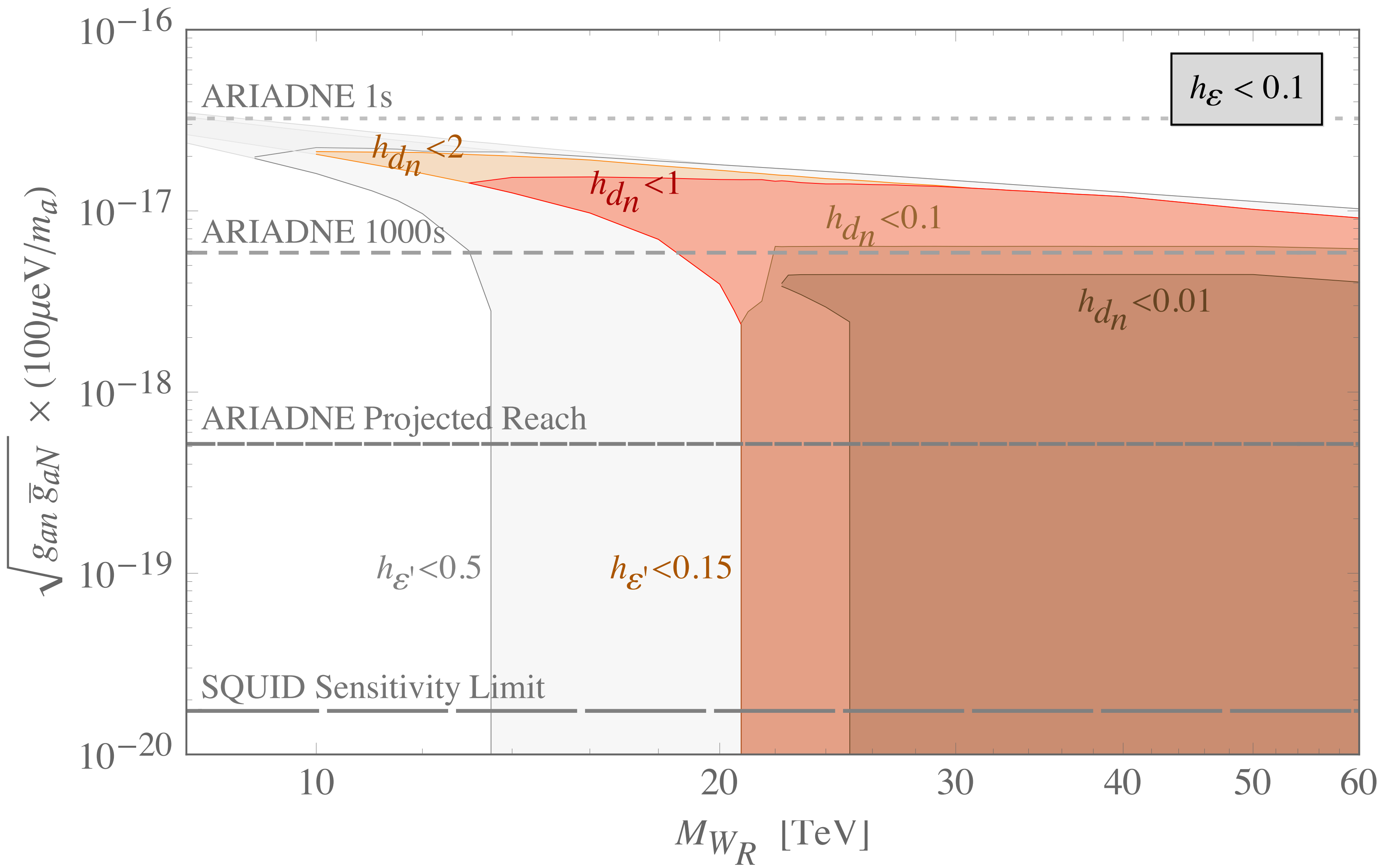
An application: Left-Right

- Low-scale (PQ)Left-Right with P-parity

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

4 CPV observables $(\varepsilon,\ \varepsilon',\ d_n,\ \overline{g}_{aN})$ *function of a single phase* $\boldsymbol{\alpha}$

$$\langle \Phi \rangle = \mathrm{diag}\left\{v_1, e^{i\alpha} v_2\right\}$$



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

CP-violating axions

- Rethinking the axion as a portal to UV sources of CP-violation

Fundamental origin of CP violation
Baryogenesis ?

$\Lambda_{\rm CPV}$

$\mathcal{O}_{\rm CPV}$

$\Lambda_{\rm QCD}$

$\left\langle G\tilde{G}, \mathcal{O}_{\rm CPV} \right\rangle \neq 0$ → $\theta_{\rm eff} \equiv \frac{\langle a \rangle}{f_a}$ *nEDM (bound)*

→ g^S_{aN} *new macroscopic forces*

strong CP problem or strong CP opportunity ?