# Opening the QCD Axion Window

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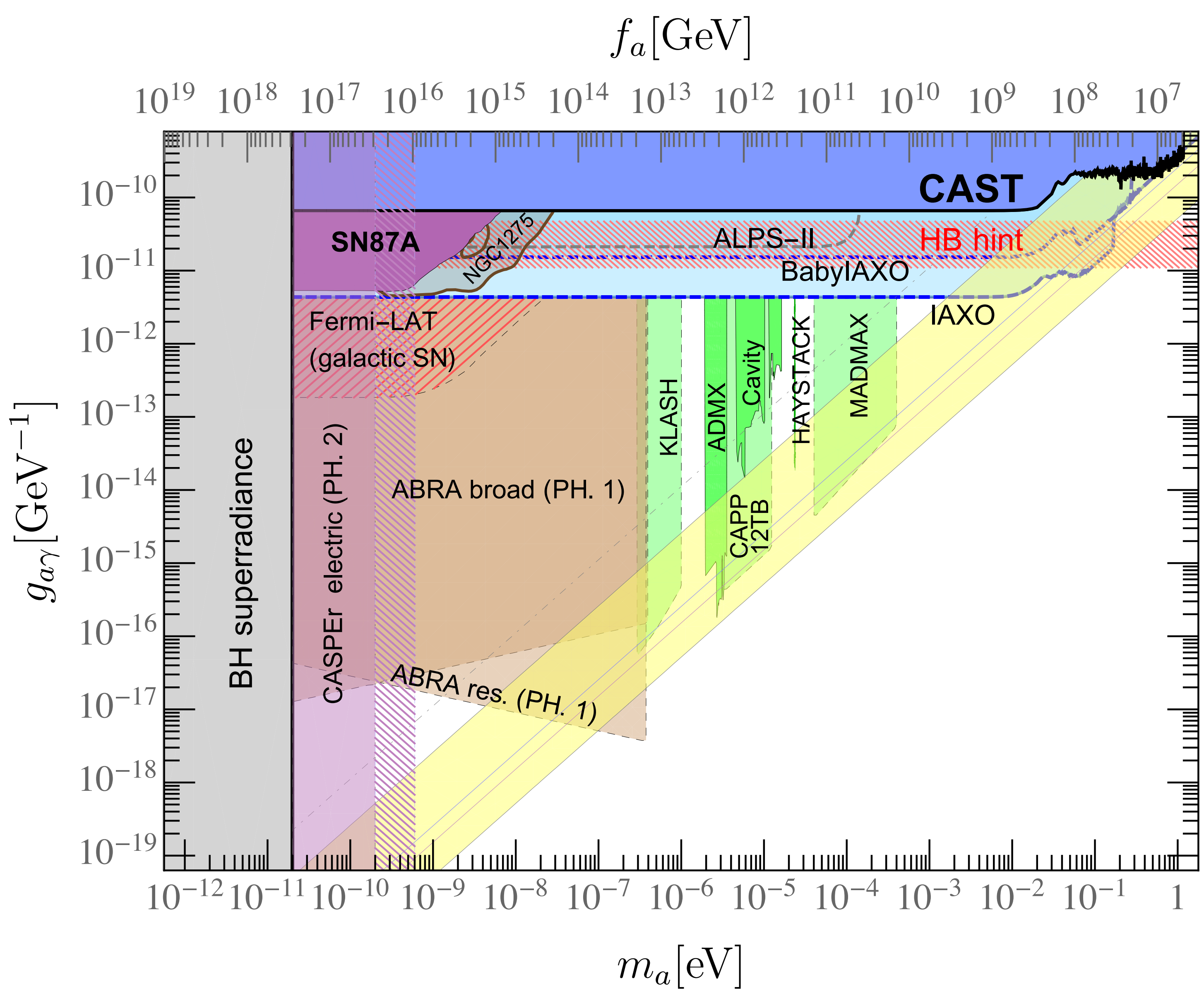
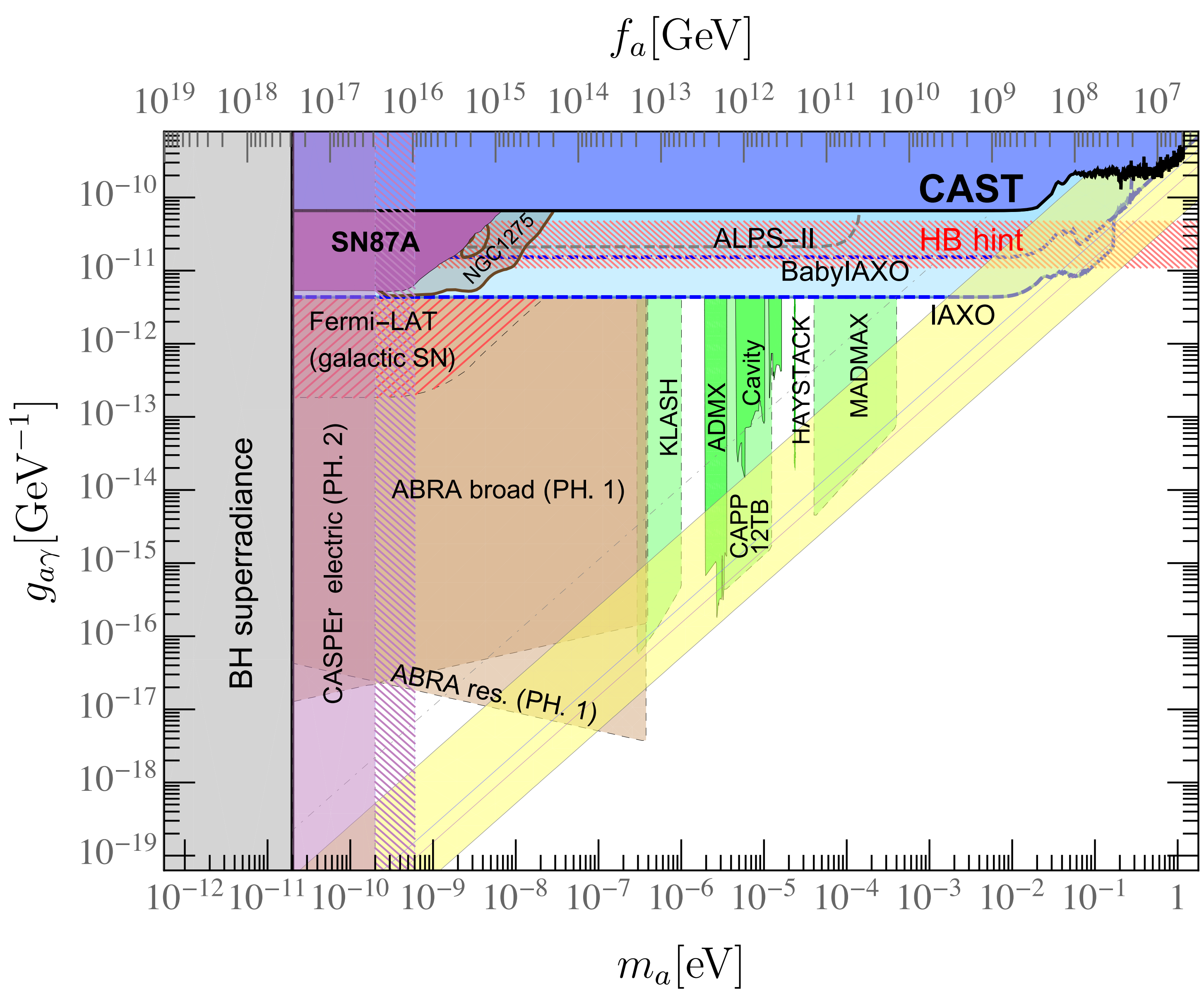
# In 10 years from now ?




[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

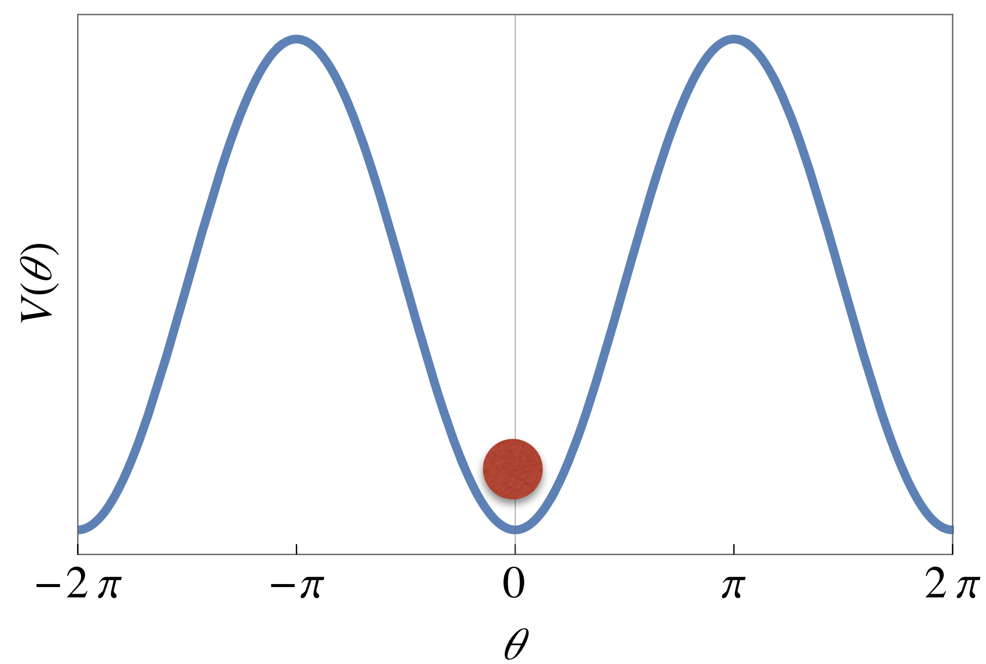
1. PQ mechanism
2. Axion couplings
   [from EFTs to UV models]
3. QCD axions beyond standard benchmarks

# QCD axion

Strong CP problem

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

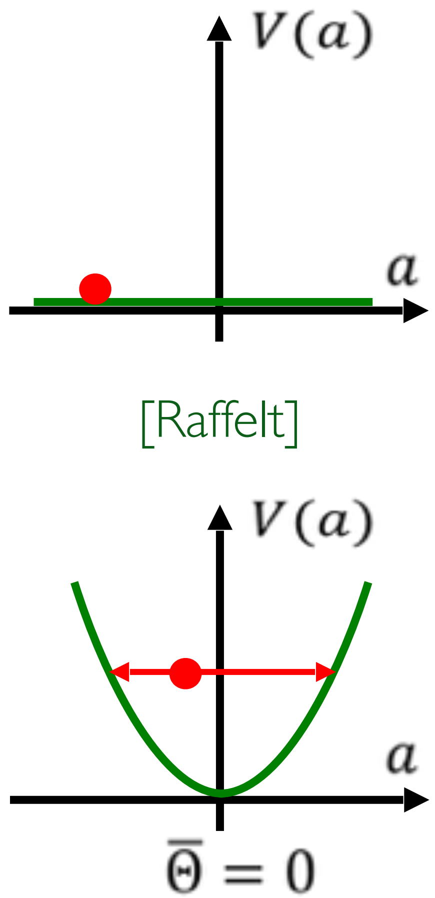
*promote* $\theta$ *to a dynamical field,*
*which relaxes to zero via QCD dynamics*




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

Dark Matter

*vacuum re-alignment mechanism:*




[Raffelt]

$T \gg 1$ GeV

$T \sim 1$ 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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$$\theta_{\text{eff}} = \frac{\langle a \rangle}{f_a}$$

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

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

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

*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

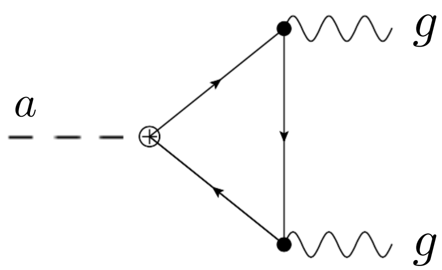
- Assume a new spin-0 boson with a pseudo-shift symmetry $a \to a + \alpha\, f_a$

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

- 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*

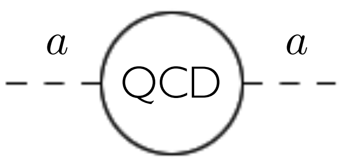



$$\partial^\mu J_\mu^{PQ} = \frac{N\alpha_s}{4\pi} G \cdot \tilde{G}$$

# Axion properties [model-indep.]

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

1. axion mass




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

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

# 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, …


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

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

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

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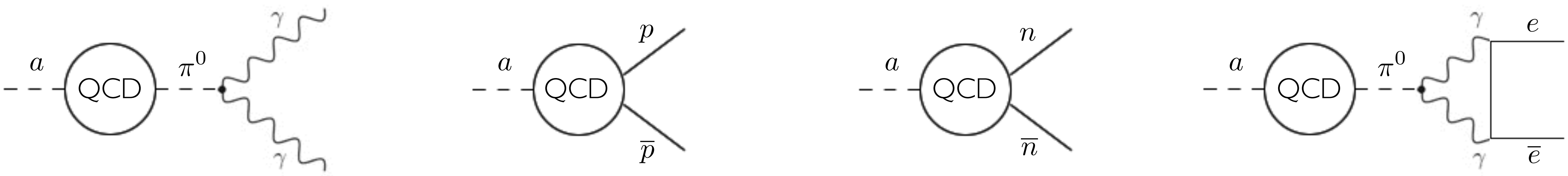


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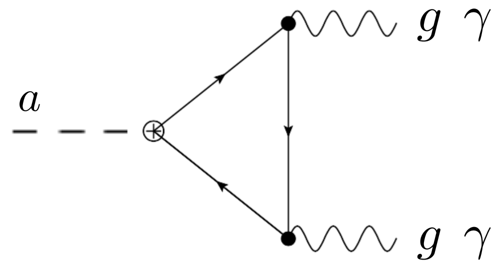
- EFT breaks down at energies of order $f_a$ → *UV completion can drastically affect low-energy axion properties*

# 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 $C_\gamma$

# Axion properties [model-dep.]

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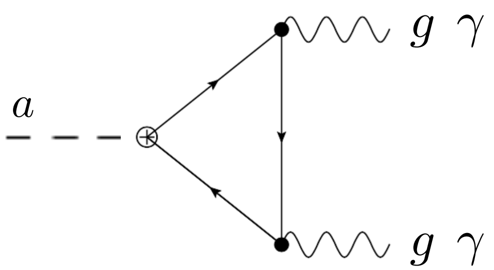


$$\partial^\mu J^{PQ}_\mu = \frac{N\alpha_s}{4\pi} G\cdot\tilde{G} + \frac{E\alpha}{4\pi} F\cdot\tilde{F}$$

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*model independent*

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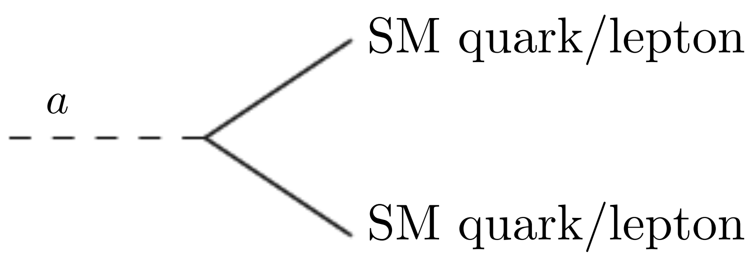
## 2. Axion-SM fermion current




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

$\to J^\mu_{\mathrm{PQ}}$

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

<u>flavour-violating</u> axion coupling

# Axion properties [model-dep.]

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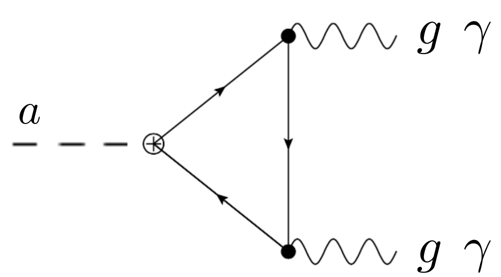


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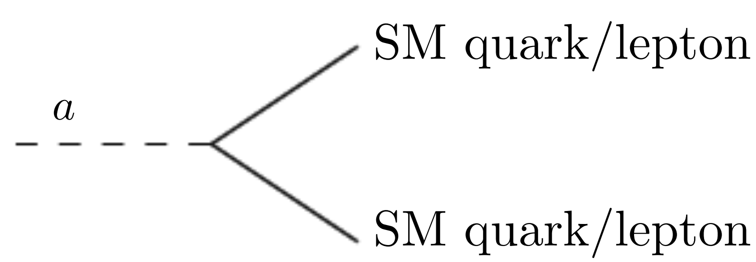



$$\frac{\partial_\mu a}{2f_a}\overline{\psi}_i\gamma^\mu (C^V_{ij} + C^A_{ij}\gamma_5)\psi_j$$

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

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

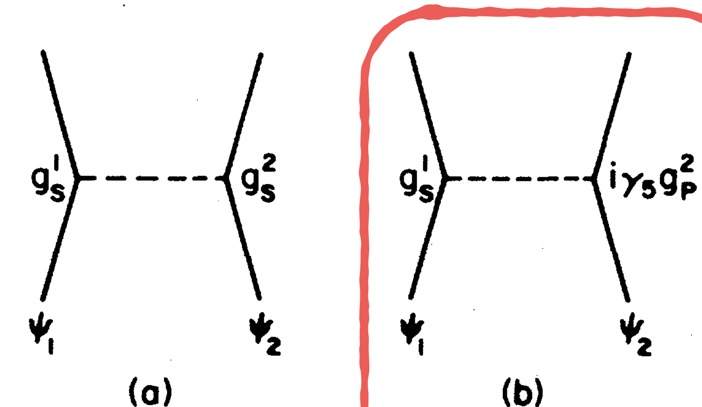
flavour-violating axion coupling

## 3. CP-violating axions

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

$$g^S_{aN} \sim \frac{f_\pi}{f_a}\theta_{\rm eff} \qquad \theta_{\rm eff} = \frac{\langle a\rangle}{f_a}$$

scalar axion coupling leads to *long-range forces*




monopole-monopole

monopole-dipole

ARIADNE
QUAX-gpgs

# 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*)

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

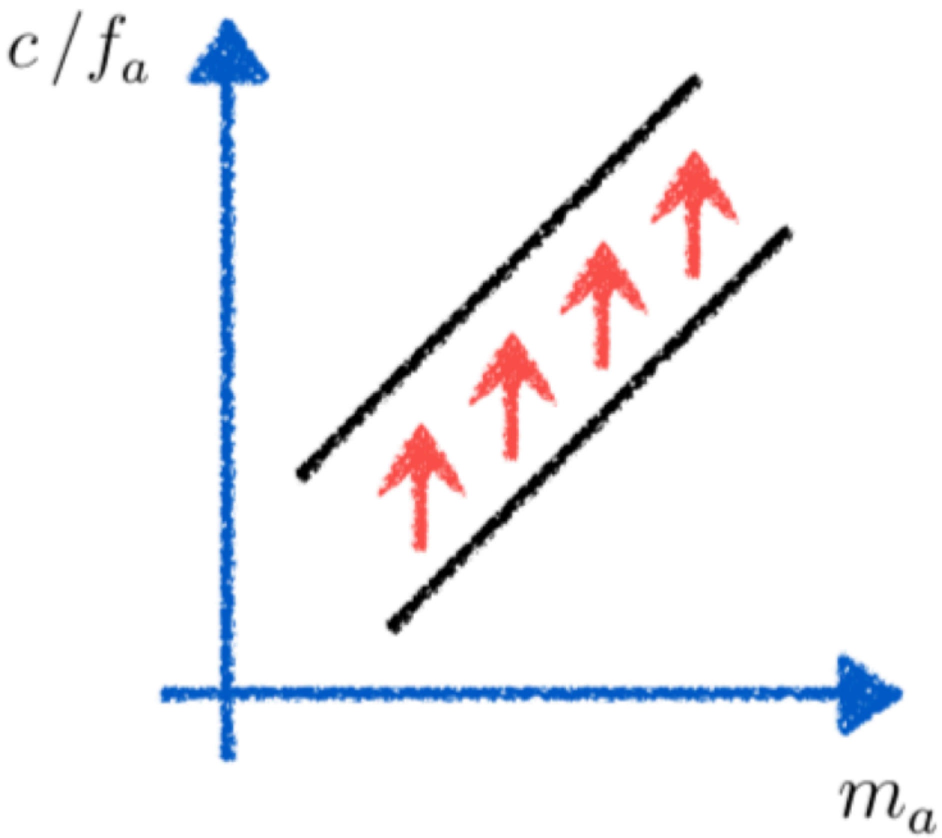
SM fermions → 2Higgs+Singlet — DFSZ

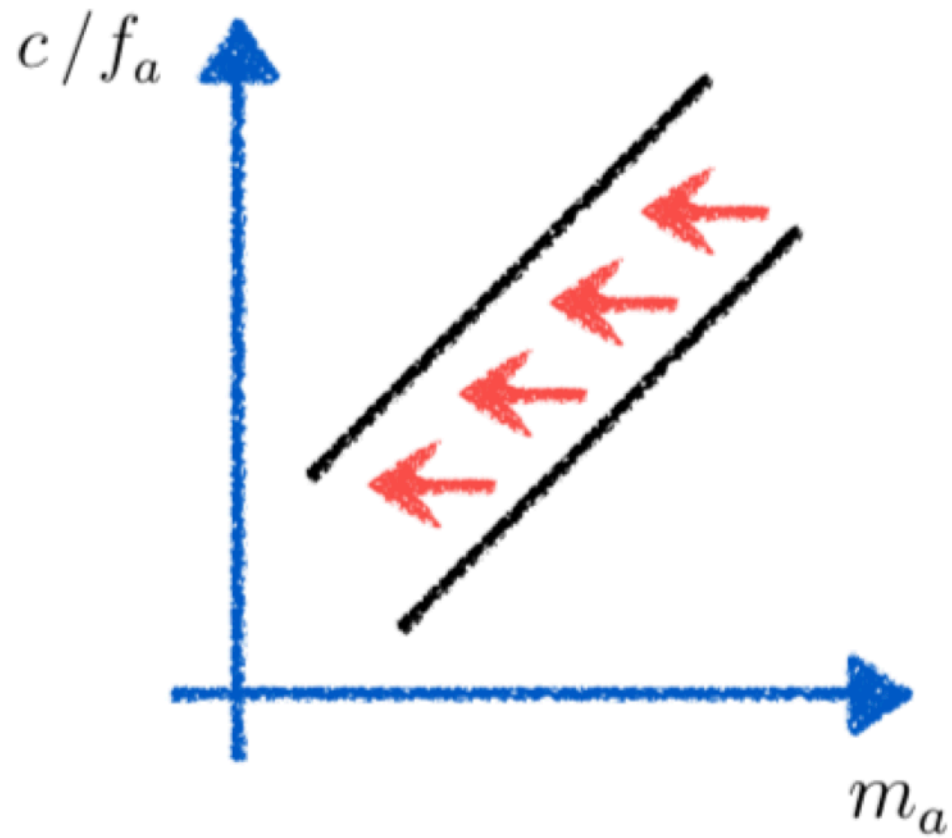
BSM fermions → Higgs+Singlet — KSVZ

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

| | 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




*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]

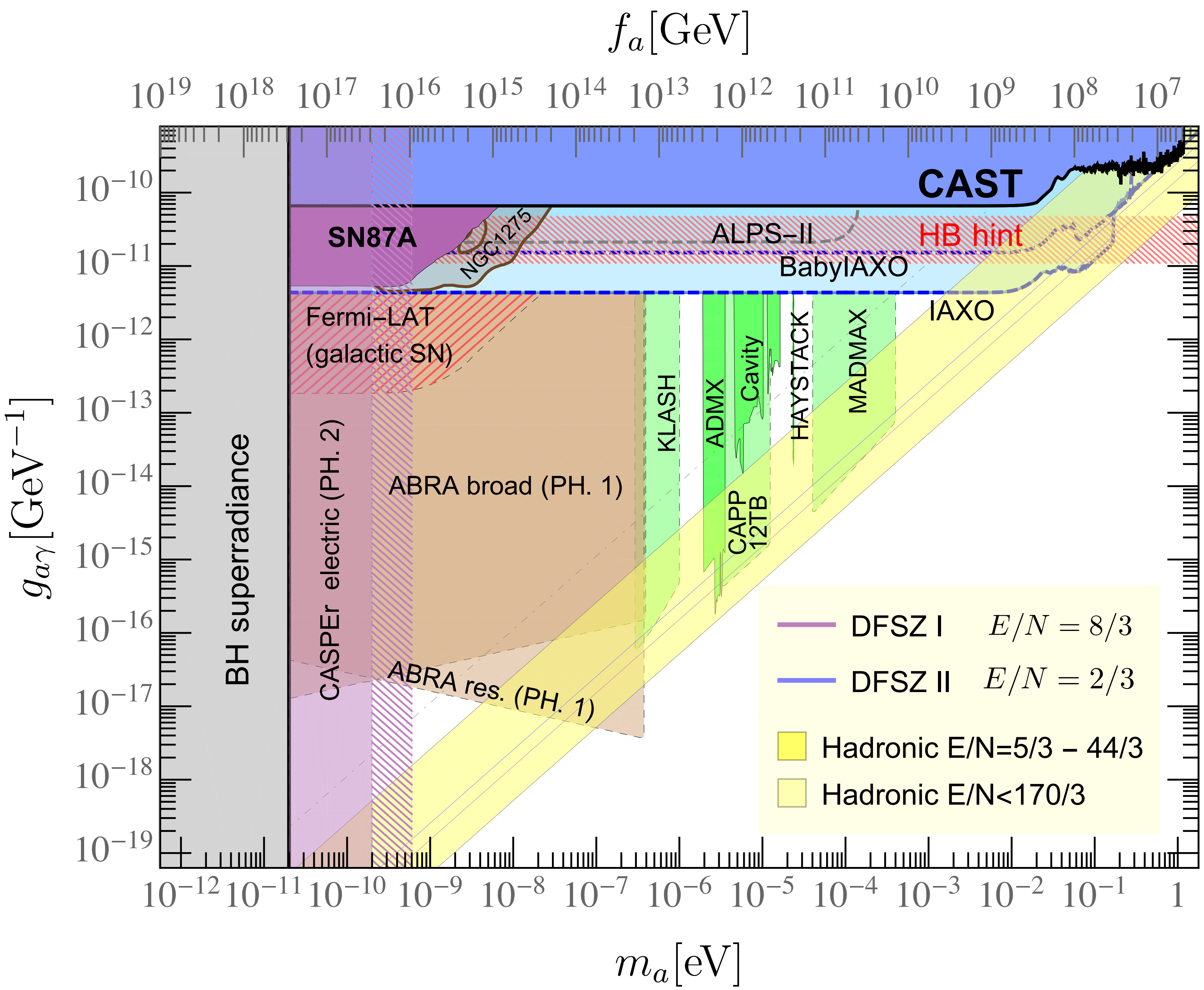
*suppress axion mass for fixed* $f_a$

[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 |
| … | … |



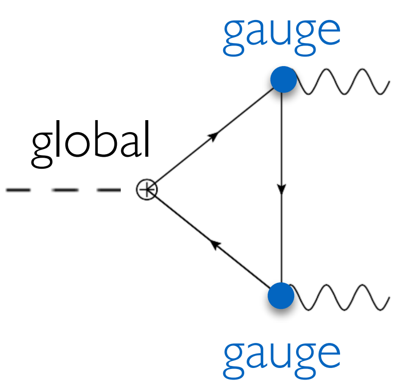

[LDL, Giannotti, Nardi, Visinelli 2003.01100 (Phys. Rept.)]

# 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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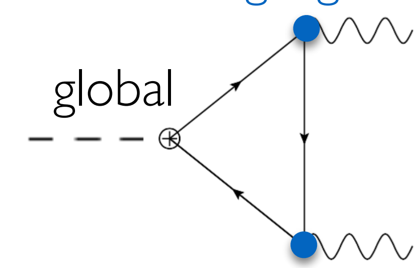


| | $R_Q$ | $\mathcal{O}_{Qq}$ | $\Lambda^{2-\text{loop}}_{\text{Landau}}[\text{GeV}]$ | $E/N$ |
|---|---|---|---|---|
| | $(3,1,-1/3)$ | $\overline{Q}_L d_R$ | $9.3\cdot 10^{38}(g_1)$ | $2/3$ |
| | $(3,1,2/3)$ | $\overline{Q}_L u_R$ | $5.4\cdot 10^{34}(g_1)$ | $8/3$ |
| $R_Q^w$ | $(3,2,1/6)$ | $\overline{Q}_R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

- Pheno preferred <u>hadronic axions</u>
  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 $g_{a\gamma}$

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

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

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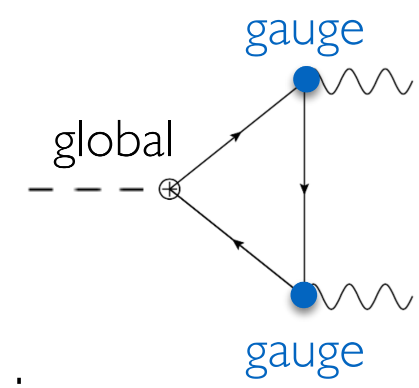
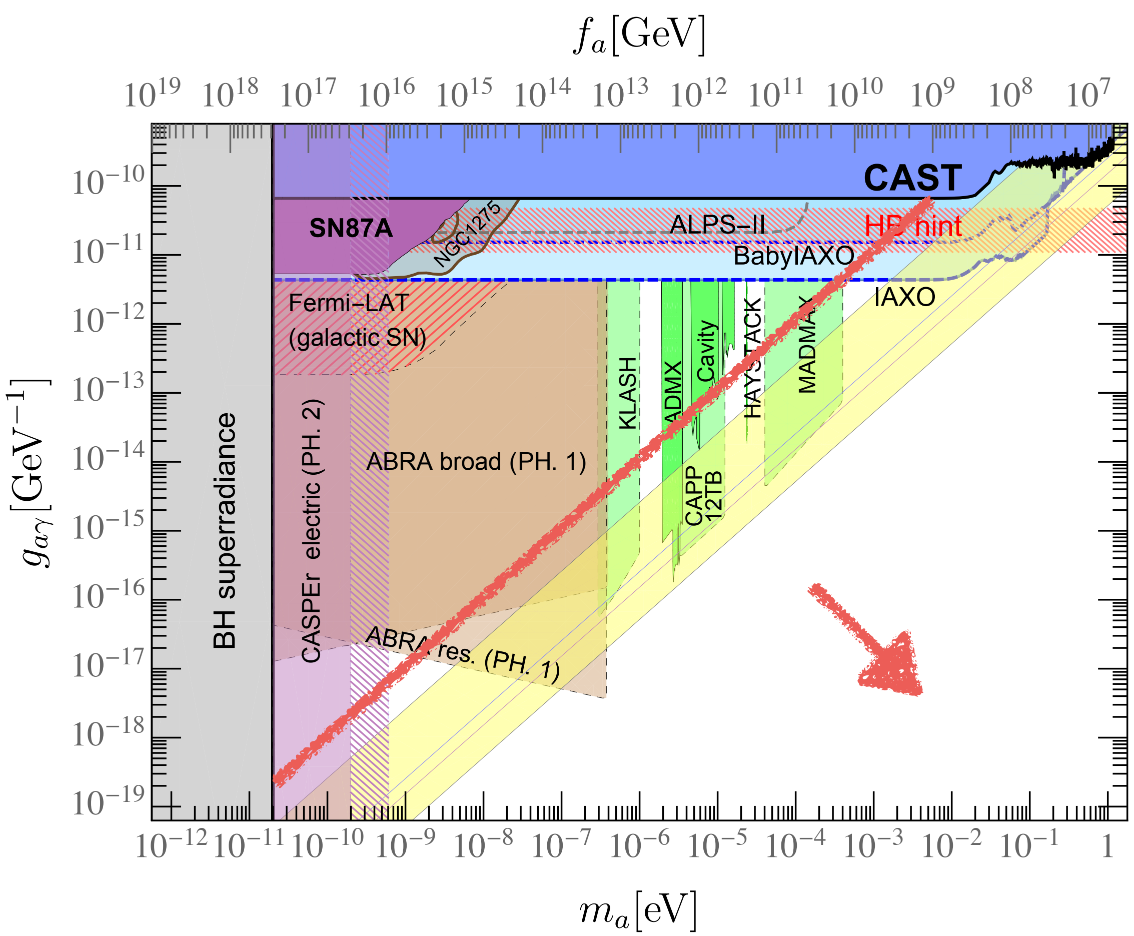



- Pheno preferred <u>hadronic axions</u>

- 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 ?

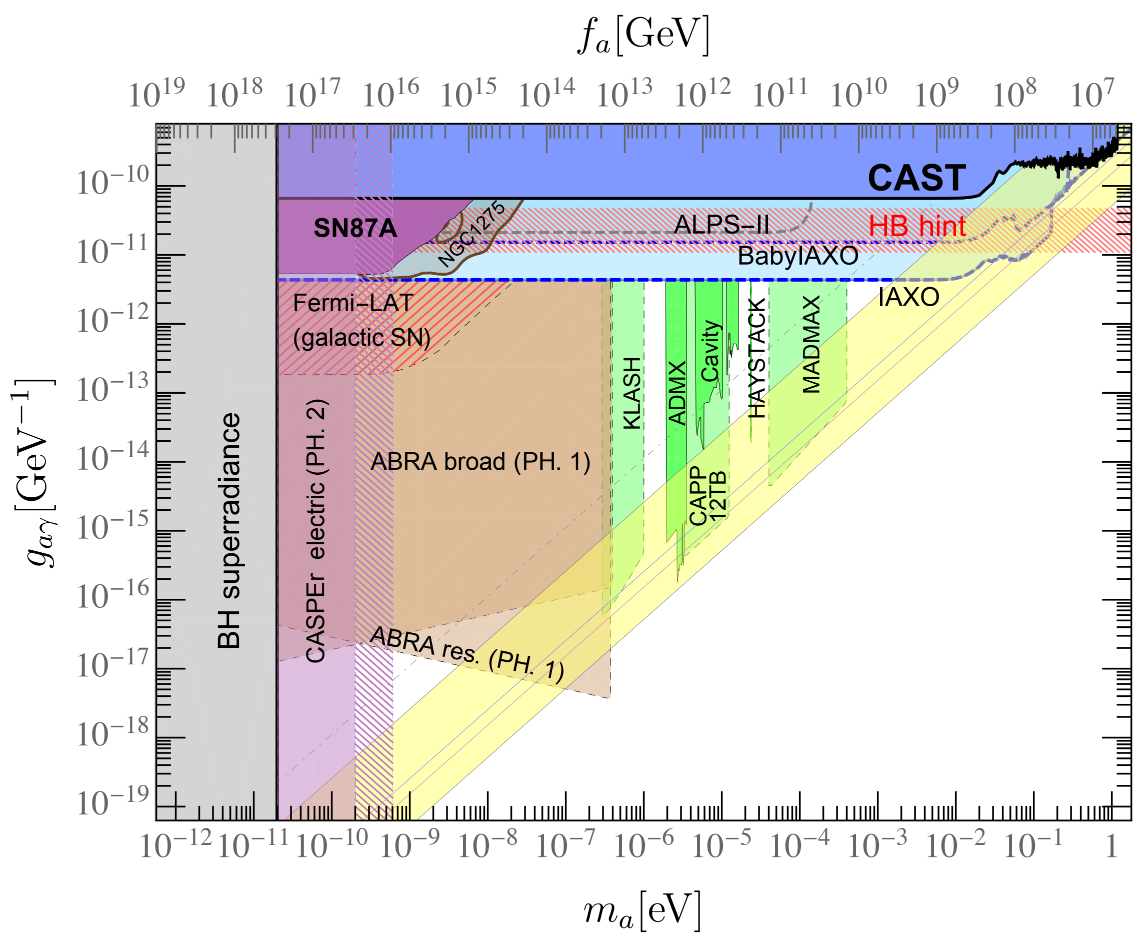
  - *boost global charge (clockwork)* → backup slides

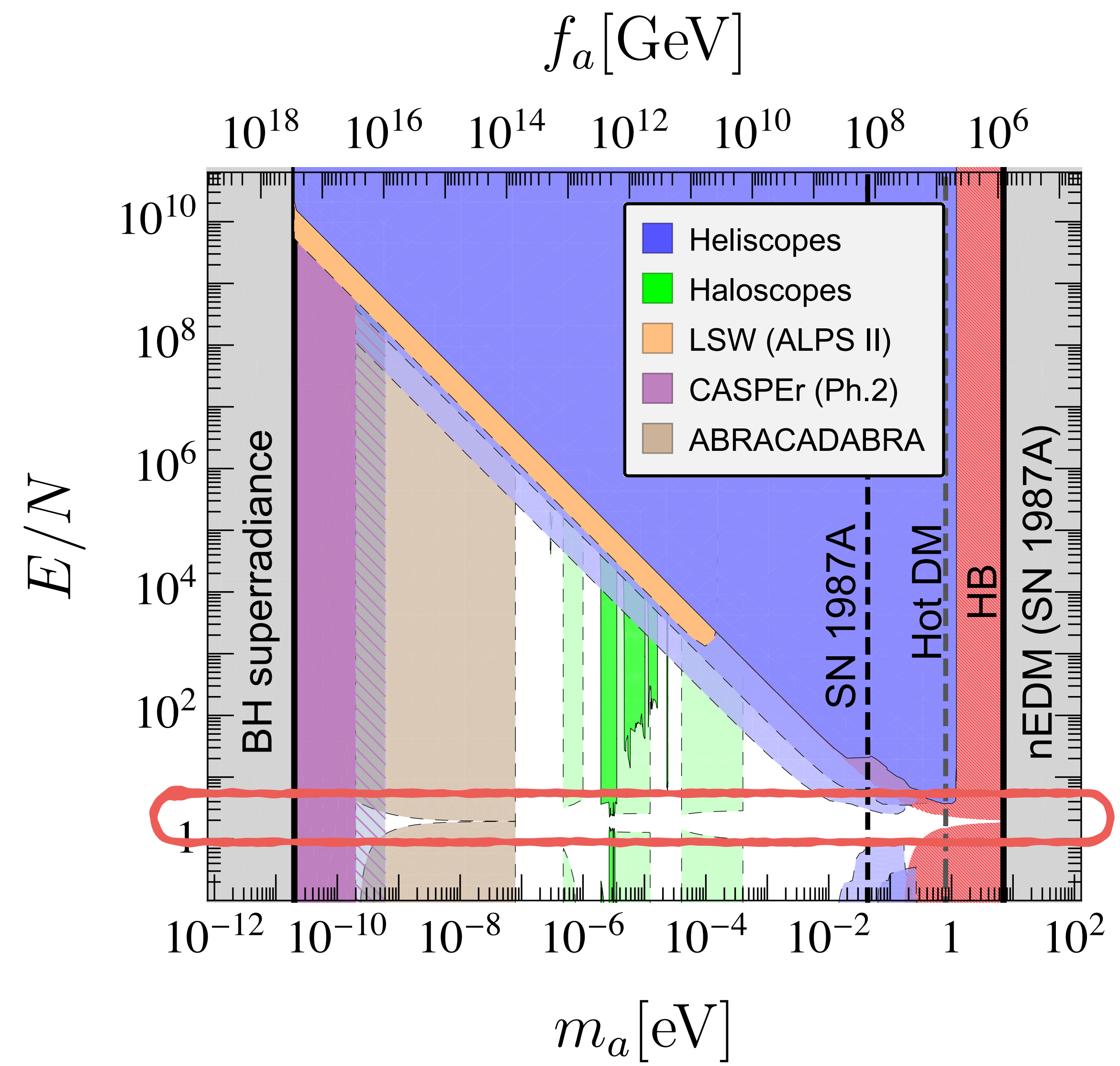
  - *be agnostic, E/N is a free parameter*

# Enhancing $g_{a\gamma}$

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

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




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

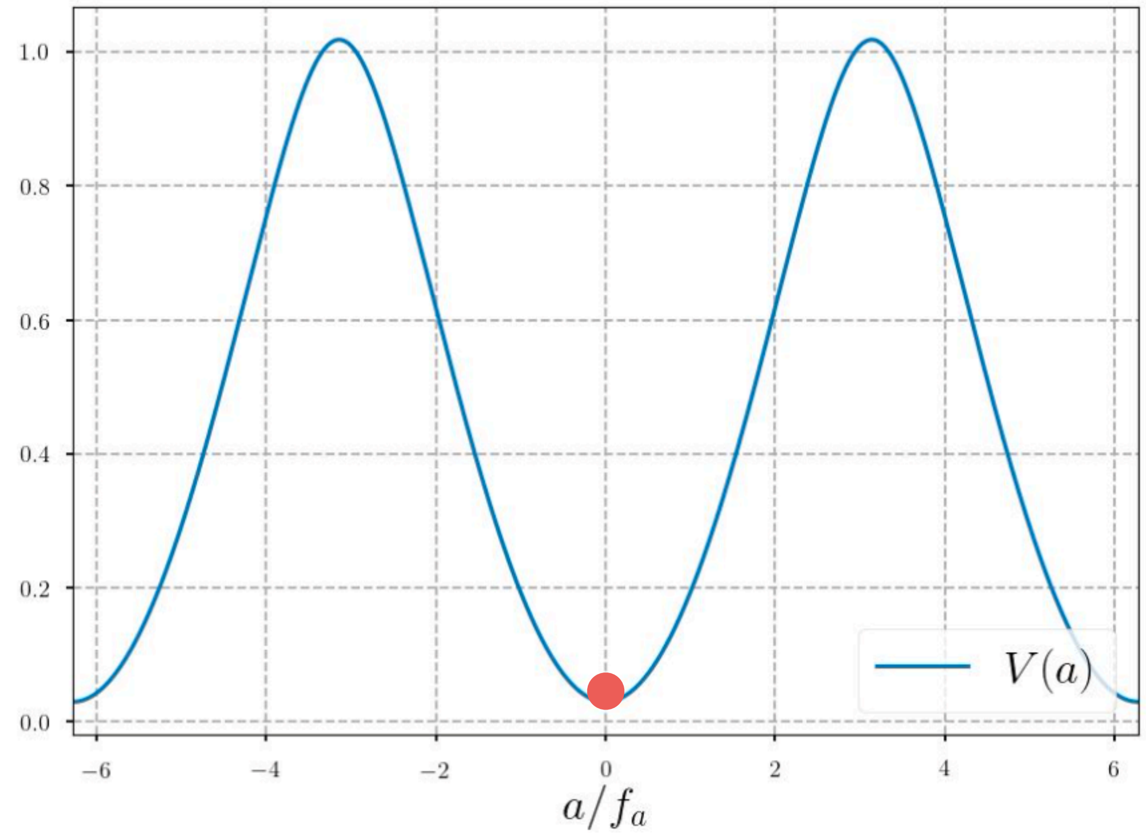
2. *E/N ~ 1.92 appears as a tuned region in theory space*

# Suppressing $m_a$

- Standard QCD axion

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

[Di Vecchia, Veneziano NPB171 (1980)]

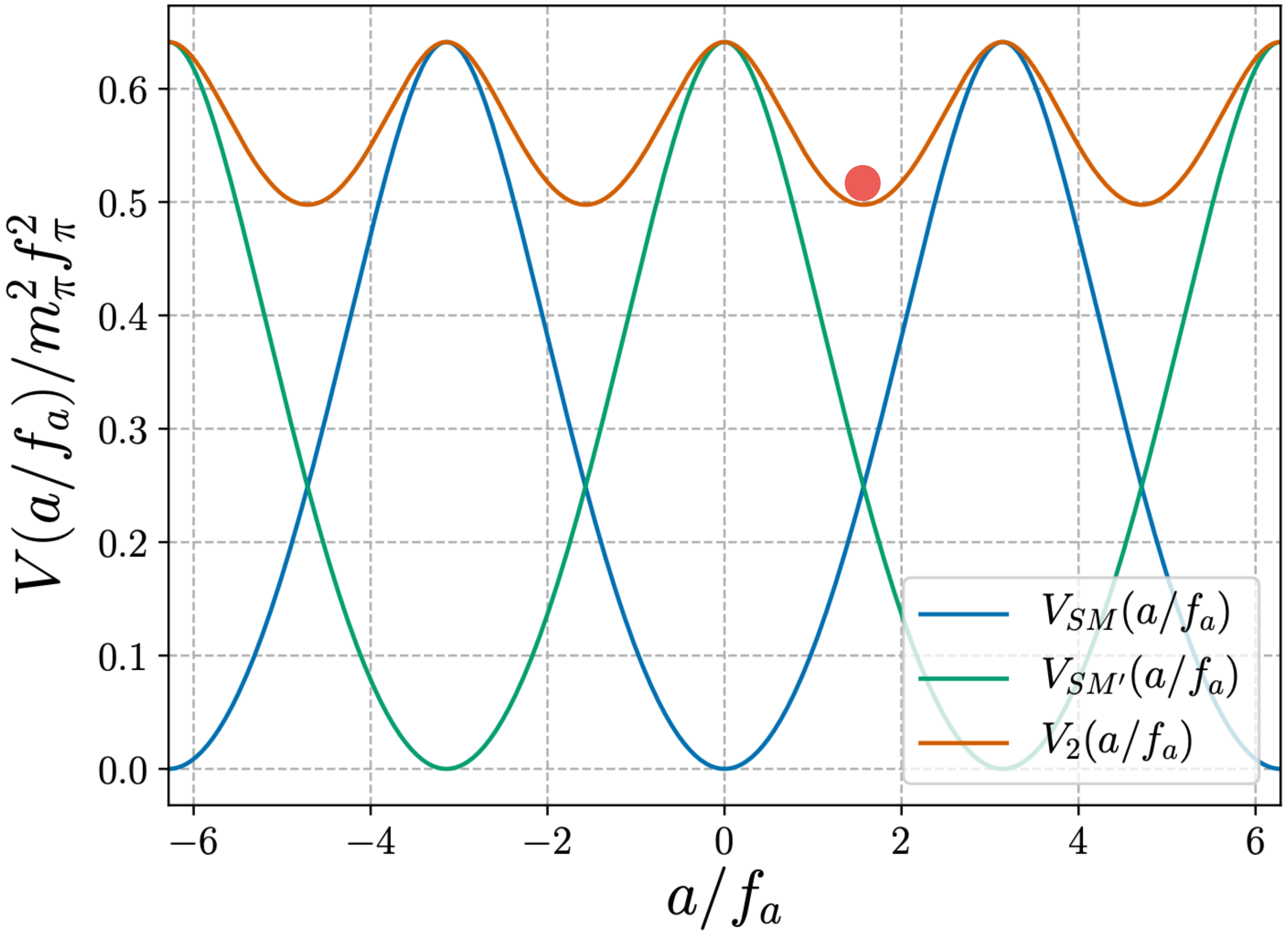


# Suppressing $m_a$

- $Z_2$ axion: mirror world

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

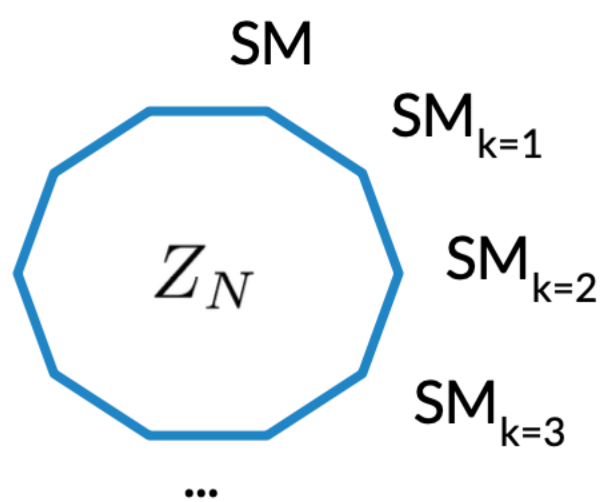
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{SM}'} + \frac{\alpha_s}{8\pi}\left(\frac{a}{f_a} - \theta\right) G\widetilde{G} + \frac{\alpha_s}{8\pi}\left(\frac{a}{f_a} - \theta + \pi\right) G'\widetilde{G}'$$




→ *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]

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

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

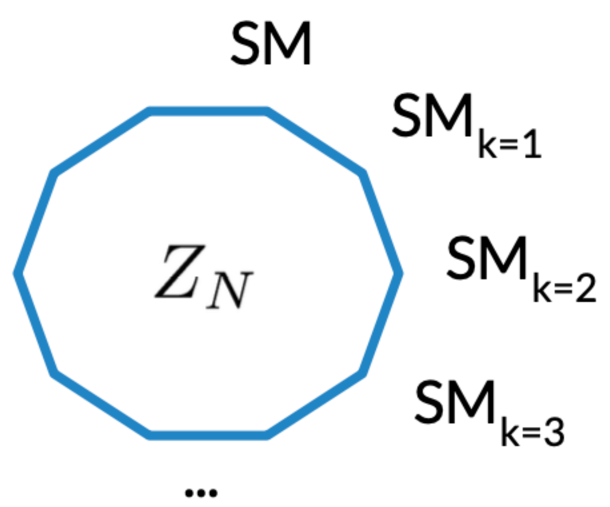
$$\simeq \frac{m_\pi^2 f_\pi^2}{\sqrt{\pi}} \sqrt{\frac{1-z}{1+z}} \mathcal{N}^{-1/2} (-1)^{\mathcal{N}} z^{\mathcal{N}} \cos(\mathcal{N}\theta_a)$$

*axion potential exponentially suppressed at large N*

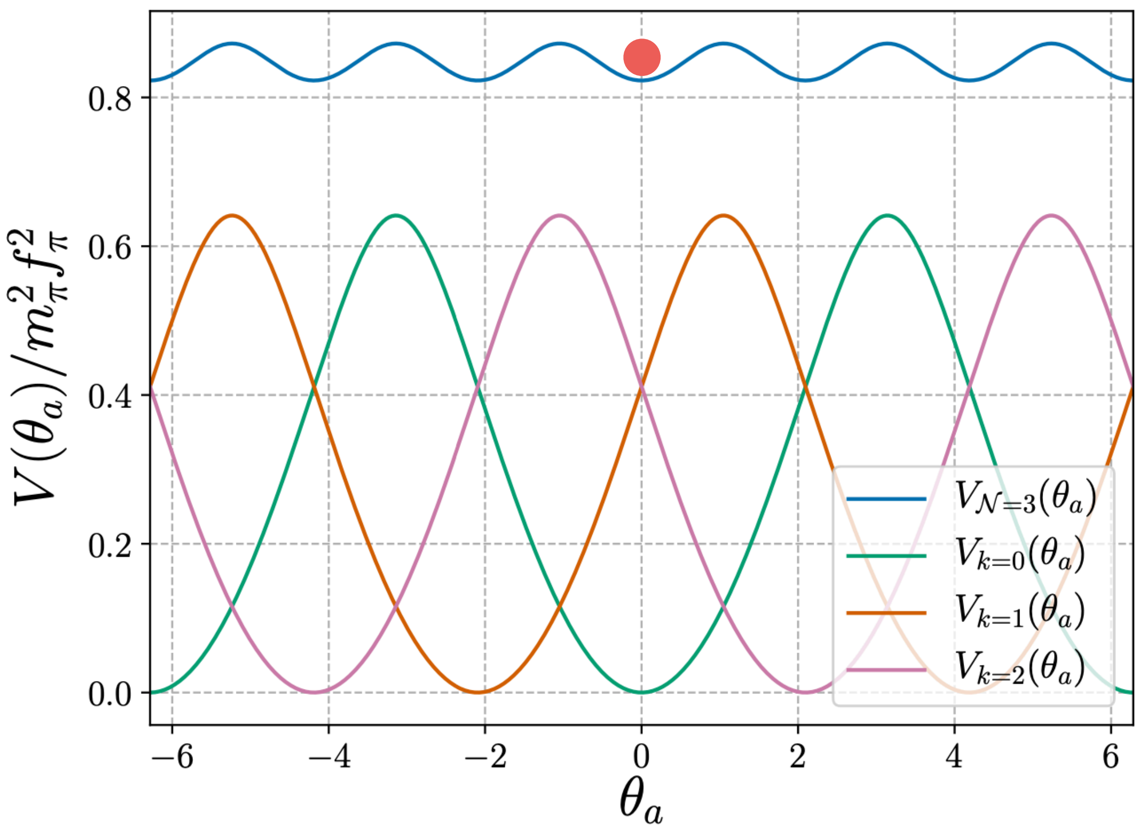
# Suppressing $m_a$

- $Z_N$ 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]

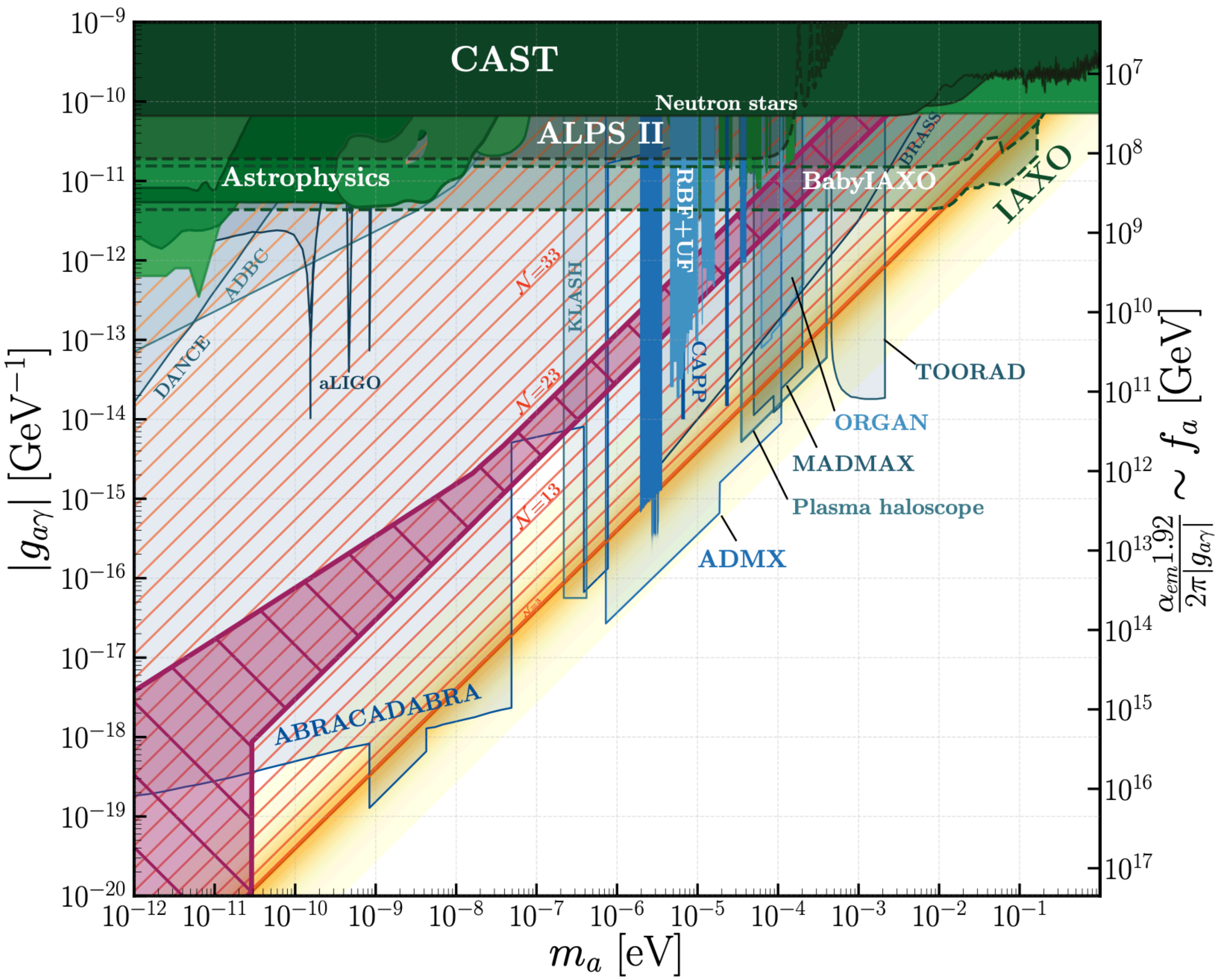
*N needs to be odd in order to have a minimum in zero*

*(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

- QCD axion: 2 birds with 1 stone

  1. Strong CP problem

  2. Dark Matter

- Experimentally driven phase

  we are entering now the preferred window for the QCD axion

- Take home message

  axion couplings are UV dependent (enhanced/suppressed couplings, flavour, CPV, etc.)

  *if an "axion-like particle" will be ever discovered away from the canonical QCD window, it will be still tempting to think that it had something to do with the strong CP problem*

# Backup slides

# A photo- and electro-philic Axion ?

- Consider a DFSZ-like construction with 2 + n Higgs doublets + a SM singlet $\Phi$

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

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

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 $\Phi$

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

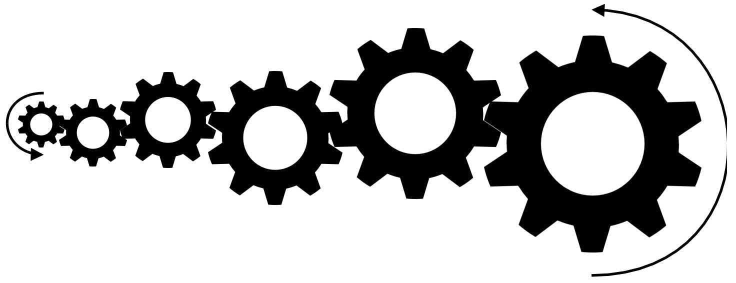
$$\frac{E}{N} = \frac{\frac{4}{3}\mathcal{X}(H_u) + \frac{1}{3}\mathcal{X}(H_d) + \mathcal{X}(H_e)}{\frac{1}{2}\mathcal{X}(H_u) + \frac{1}{2}\mathcal{X}(H_d)}$$

$$g_{ae} = \frac{\mathcal{X}(H_e)}{2N}\frac{m_e}{f_a}$$

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

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

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



[Giudice, McCullough]

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

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

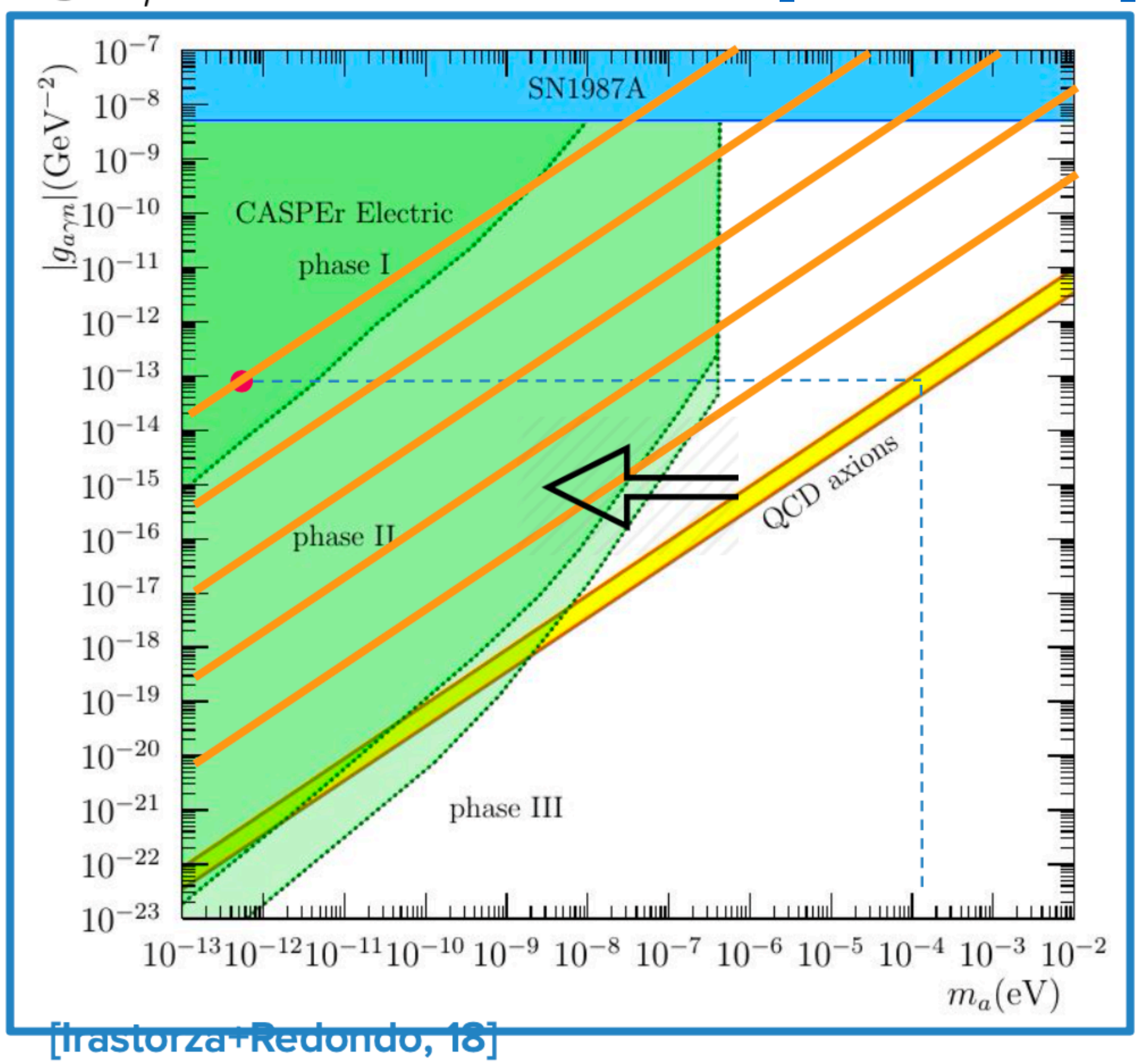
$$\mathcal{X}(H_e) = 2^{n+1}\left(1 - \frac{v_e^2}{v^2}\right) - \sum_{k=2}^{n} 2^k \frac{v_k^2}{v^2}$$

# How to tell which mechanism ?

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

$g_{a\gamma n}$

[Pablo Quilez]




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

$m_a\ (eV)$

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

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

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

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

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

**Coupling to the nEDM**

**Axion mass**

# CASPEr-Electric

- Cosmic Axion Spin Precession Experiment

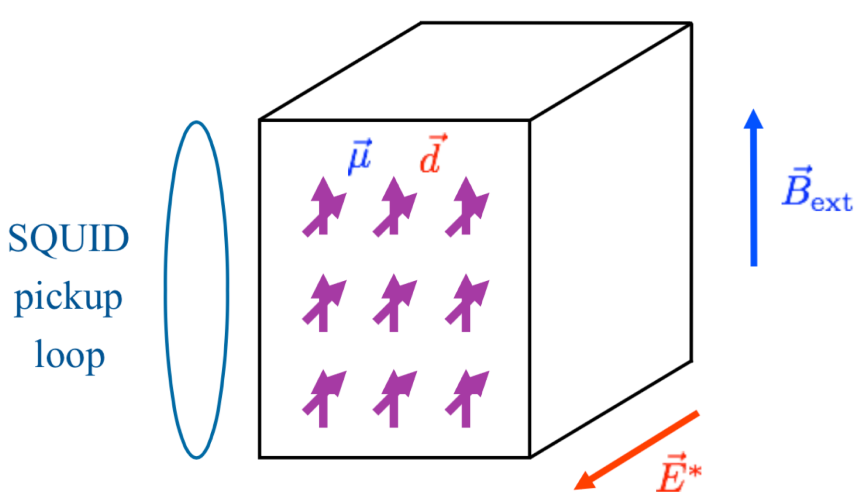
[Graham, Rajendran 1306.6088, Budker+ 1306.6089, Jackson Kimball+ 1711.08999]

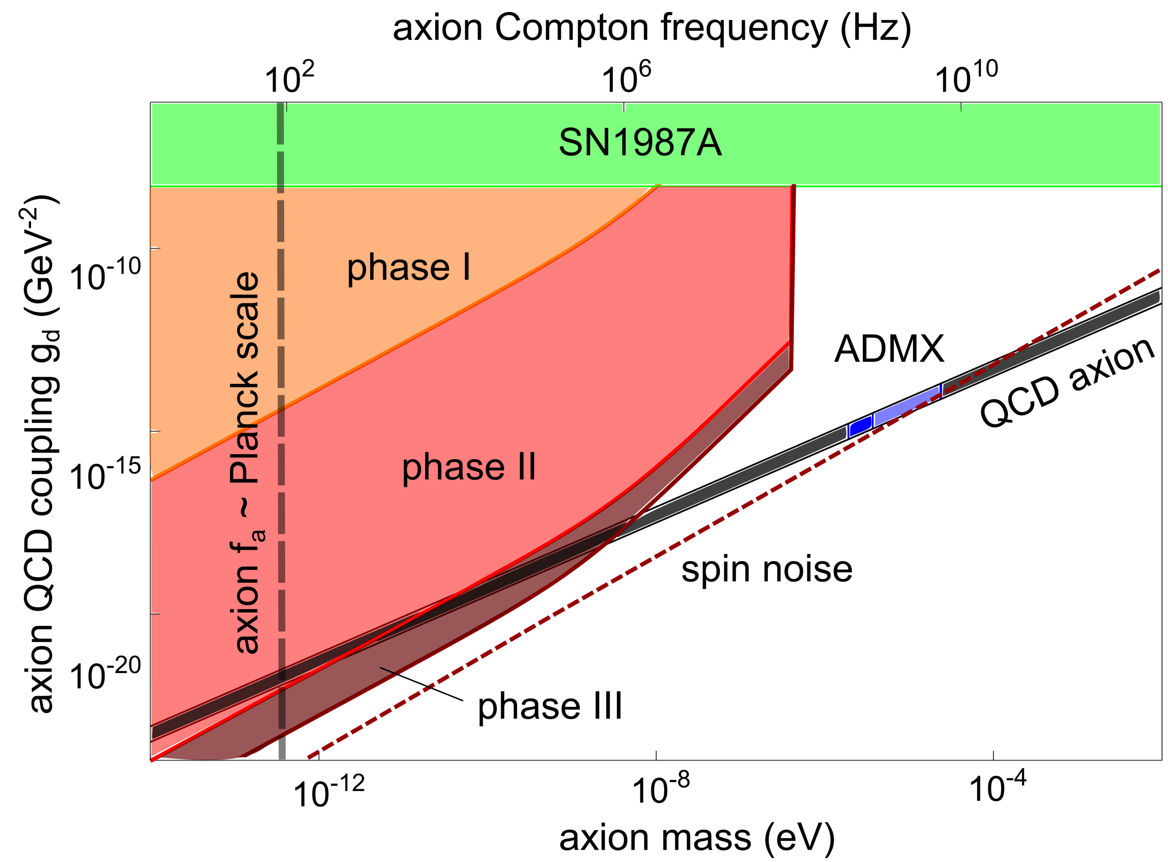
Axion DM field induces an oscillating nEDM

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

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

…which is detected via NMR techniques



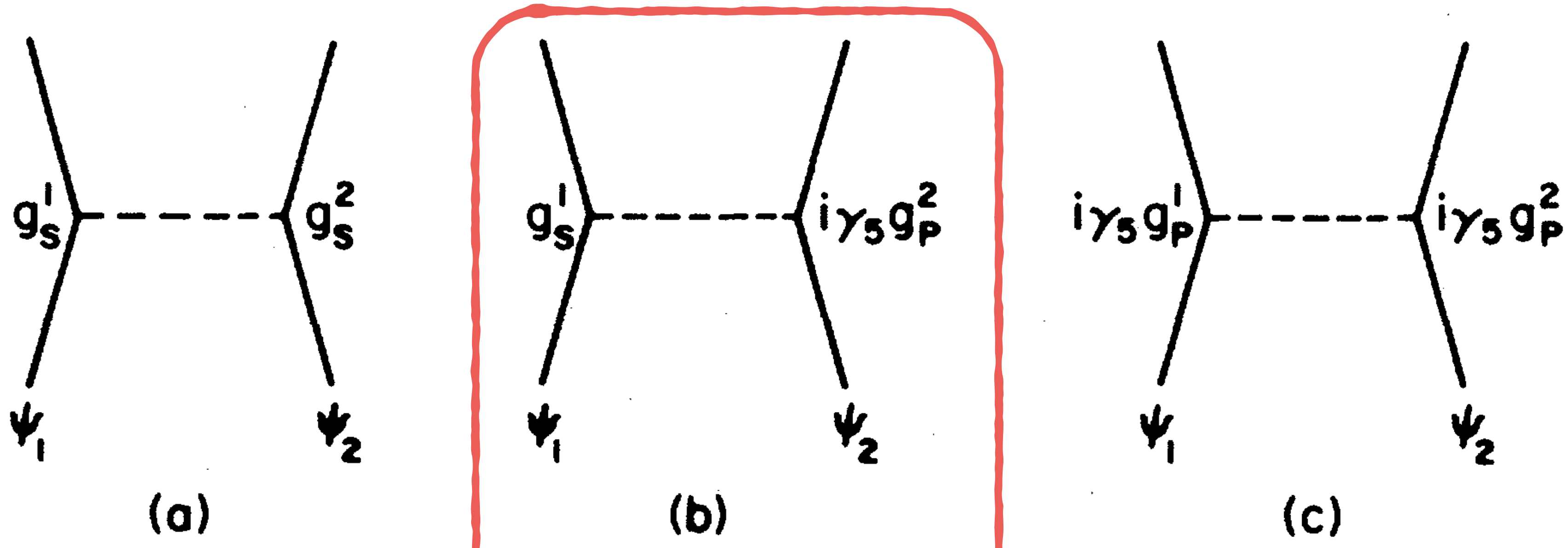



# CPV axion & long-range forces

- New 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)]




monopole-monopole | monopole-dipole | dipole-dipole

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

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

# CPV axion & long-range forces

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

[O'Hare, Vitagliano 2010.03889]