True axions beyond the canonical band.

Patras 2021 Workshop - June 14th 2021

Pablo Quílez Lasanta - *pablo.quilez@desy.de*

The QCD axion

- ➔ Solves the Strong CP problem
- ➔ Excellent Dark Matter candidate

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

[Abbot+Sikivie, 83]
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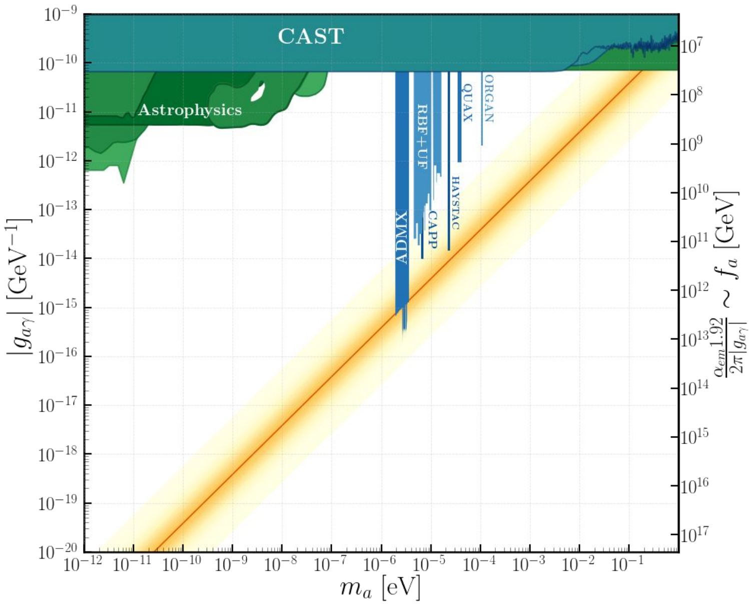

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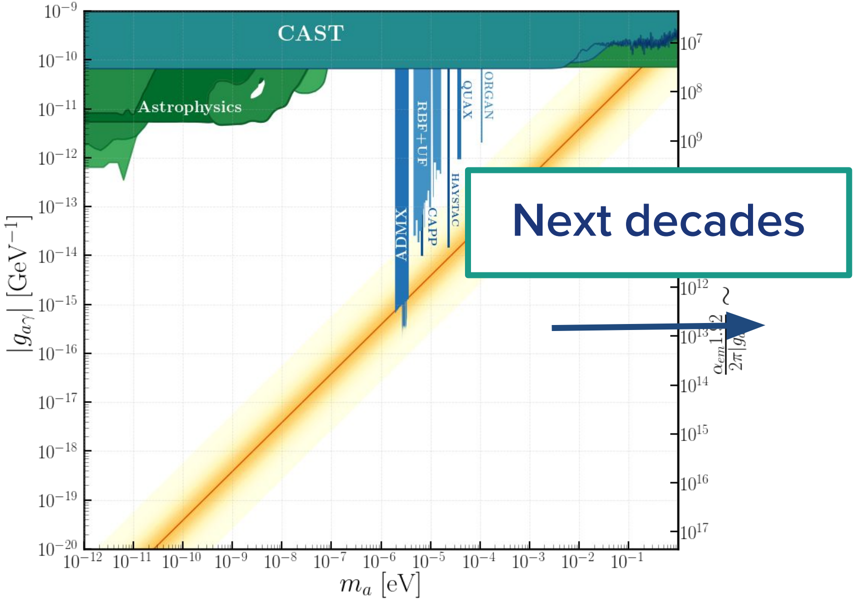

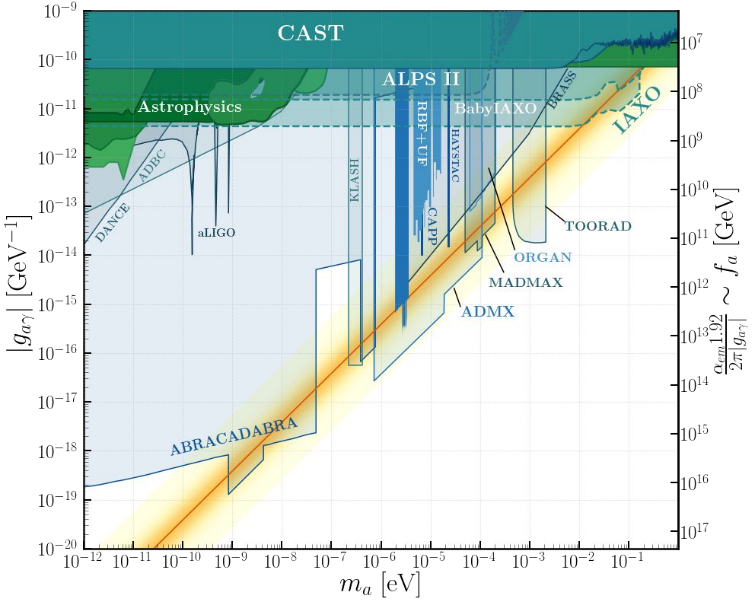

https://github.com/cajohare/AxionLimits

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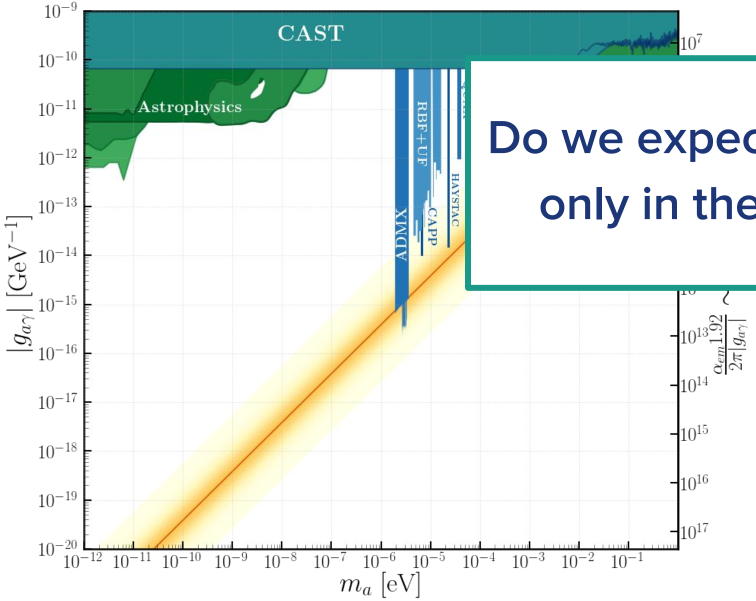
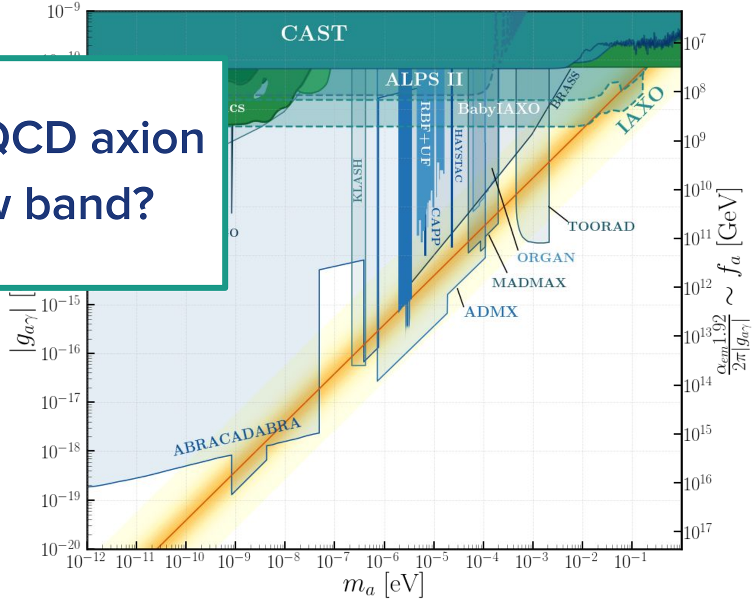


Do we expect the QCD axion only in the yellow band?



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True axion = QCD axion = axion that solves the strong CP problem

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Canonical axion = Vanilla axion = Original invisibles axions KSVZ, DFSZ, Composite

Outline

1. The QCD axion
    a. Canonical axion mass
    b. Canonical axion coupling to photons
2. Beyond the canonical band
    a. Photophilic/photophobic axions
        i. Single scalar: Playing with fermionic representations
        ii. Multiple scalars: Alignment in field space
    b. Heavy/even lighter axions
3. How to disentangle them?
    a. Other couplings
    b. DM

The axion solution

[Peccei+Quinn 77]

- ➔ Strong CP problem $\mathcal{L} \supset \bar{\theta}_{\rm QCD} \frac{\alpha_s}{8\pi} G\tilde{G}$

Neutron EDM
(Electric Dipole Moment)

Why is it so small?

$$\bar{\theta} \lesssim 10^{-10}$$

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Neutron EDM
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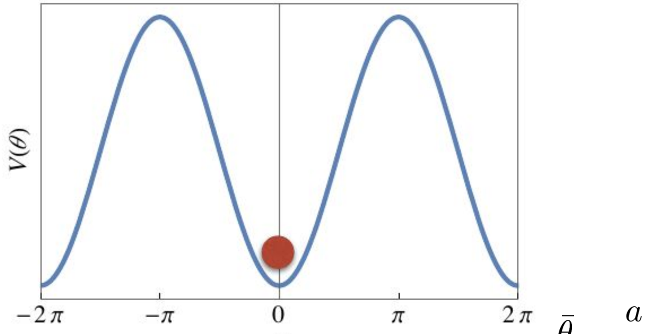
Why is it so small?

$$\bar{\theta} \lesssim 10^{-10}$$

- ➔ If $\bar{\theta}$ were a scalar field, its vev would be zero

[Vafa+Witten, 84]

$$\bar{\theta} \frac{\alpha_s}{8\pi} G\tilde{G} \longrightarrow \left(\bar{\theta} - \frac{a}{f_a}\right) \frac{\alpha_s}{8\pi} G\tilde{G}$$



$$\bar{\theta}_{\rm eff} = \langle \bar{\theta} - \frac{a}{f_a} \rangle = 0$$

The PQ mechanism

➔ Introduce a $U(1)_{PQ}$ symmetry (classically exact): [Peccei+Quinn 77]

- Spontaneously broken
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INVISIBLE AXIONS

KSVZ

- Complex scalar singlet
- Exotic quarks

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

DFSZ

- Complex scalar singlet
- 2HDM
- SM quarks generate anom.

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

Composite axion

- Massless exotic quarks
- New confining sector

[Kim, 85]
[Kim, Choi, 85]

Axion: pseudo-Goldstone boson of $U(1)_{PQ}$

- ➔ Axion properties follow from its pGB nature: derivative and anomalous couplings
- ➔ Axion EFT can be computed from the PQ current

$$j^\mu_{PQ} = f_{PQ}\partial^\mu a + \sum_i \chi_i \bar{\psi}_i \gamma^\mu \psi_i + \dots$$

$$\mathcal{L}_a = \frac{\partial_\mu a}{f_{PQ}} \times j^\mu_{PQ} + \frac{a}{f_{PQ}} \times \partial_\mu j^\mu_{PQ}$$

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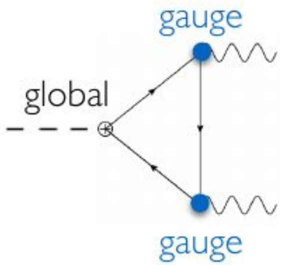
- At quantum level: $\partial^\mu J^{PQ}_\mu = \frac{N\alpha_s}{4\pi} G\cdot\tilde{G} + \frac{E\alpha}{4\pi} F\cdot\tilde{F}$

$$N = \sum_Q (\mathcal{X}_L - \mathcal{X}_R)\, T(\mathcal{C}_Q)$$

$$E = \sum_Q (\mathcal{X}_L - \mathcal{X}_R)\, \mathcal{Q}_Q^2$$

Anomaly coefficients



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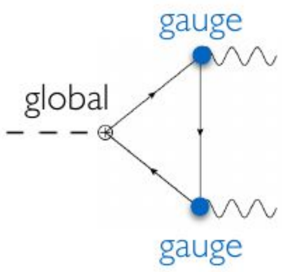

[Di Luzio]

$$\mathcal{L}_a \supset E\frac{\alpha_{em}}{4\pi}\frac{a}{f_{\rm PQ}} F_{\mu\nu}\tilde{F}^{\mu\nu} + N\frac{\alpha_s}{4\pi}\frac{a}{f_{\rm PQ}} G_{\mu\nu}\tilde{G}^{\mu\nu}$$

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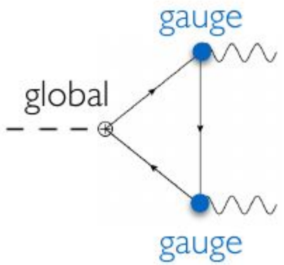

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$$f_a \equiv \frac{f_{\rm PQ}}{N}$$

$$\mathcal{L}_a \supset \frac{E}{N}\frac{\alpha_{em}}{4\pi}\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{\alpha_s}{4\pi}\frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu}$$

Canonical axion parameter space $\{g_{a\gamma}, m_a\}$

$g_{a\gamma}$

$$\mathcal{L}_a = \frac{1}{4} g_{a\gamma\gamma} a F \tilde{F}$$

$$g_{a\gamma\gamma} = -\frac{1}{2\pi f_a}\alpha_{\rm em}\left(\frac{E}{N} - 1.92(4)\right)$$

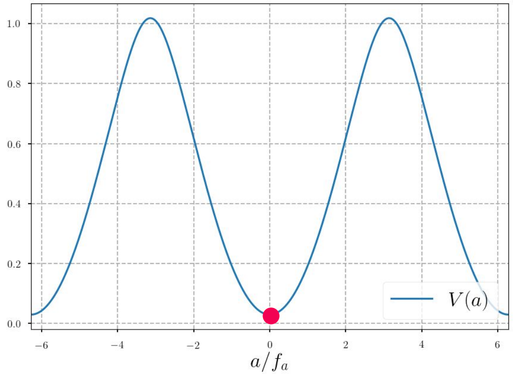
Model dependent

Model independent

m_a

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

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



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[Di Vecchia +Veneziano,80]
[Leutwyler+Smilga, 92]
[di Cortona et al, 15]

Canonical axion

$g_{a\gamma}$

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$$g_{a\gamma\gamma} = -\frac{1}{2\pi f_a}\alpha_{\rm em}\left(\frac{E}{N} - 1.92(4)\right)$$

Model dependent

M
indep

Usual Benchmarks:

- **Original KSVZ E/N=0**
- **DFSZ/GUT E/N=8/3**

$$|E/N - 1.92| \in [0.07, 7]$$

m_a

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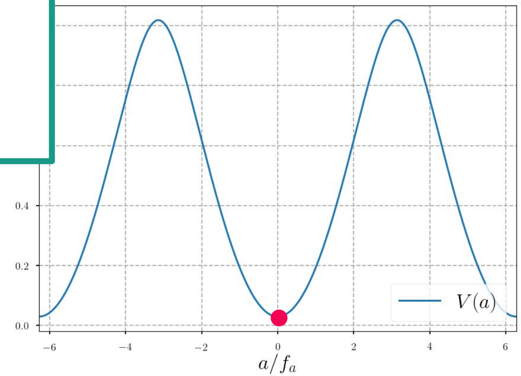

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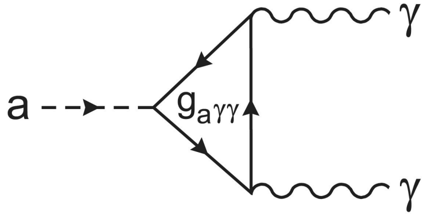
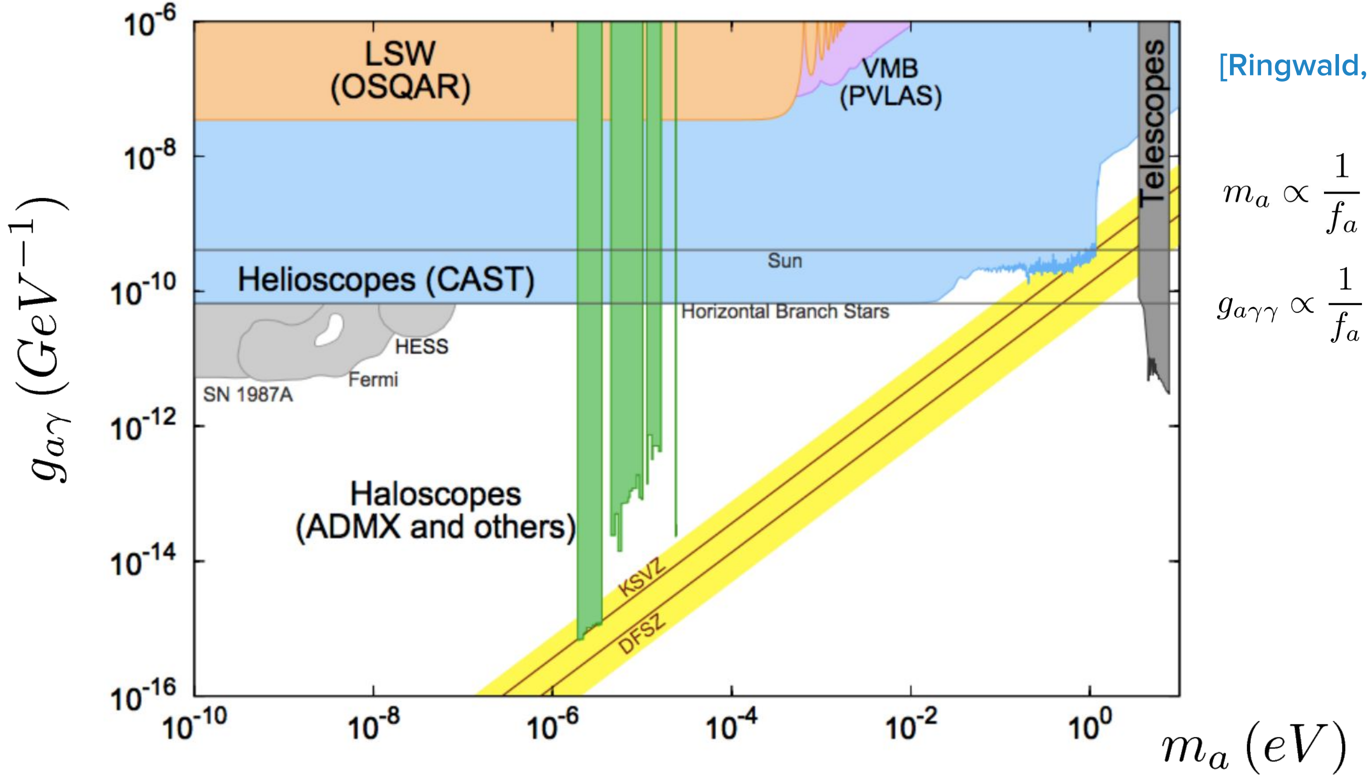
Invisible axion parameter space





[Ringwald, PDG 17]

$$m_a \propto \frac{1}{f_a}$$

$$g_{a\gamma\gamma} \propto \frac{1}{f_a}$$

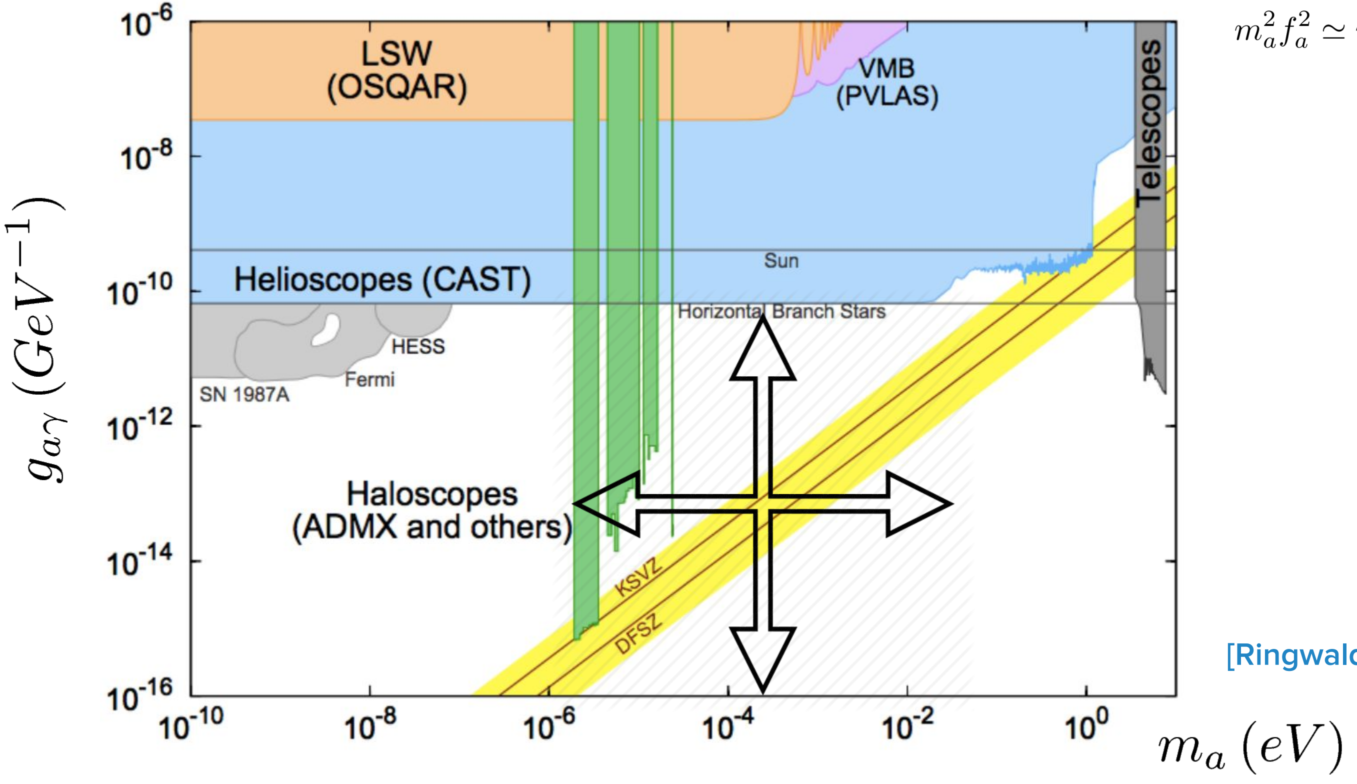
$$\Longrightarrow \quad g_{a\gamma\gamma} \propto m_a$$

Are there other possibilities?

$$g_{a\gamma\gamma} = -\frac{1}{2\pi f_a}\alpha_{\rm em}\left(\frac{E}{N} - 1.92(4)\right)$$

$\mathcal{VS}$

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



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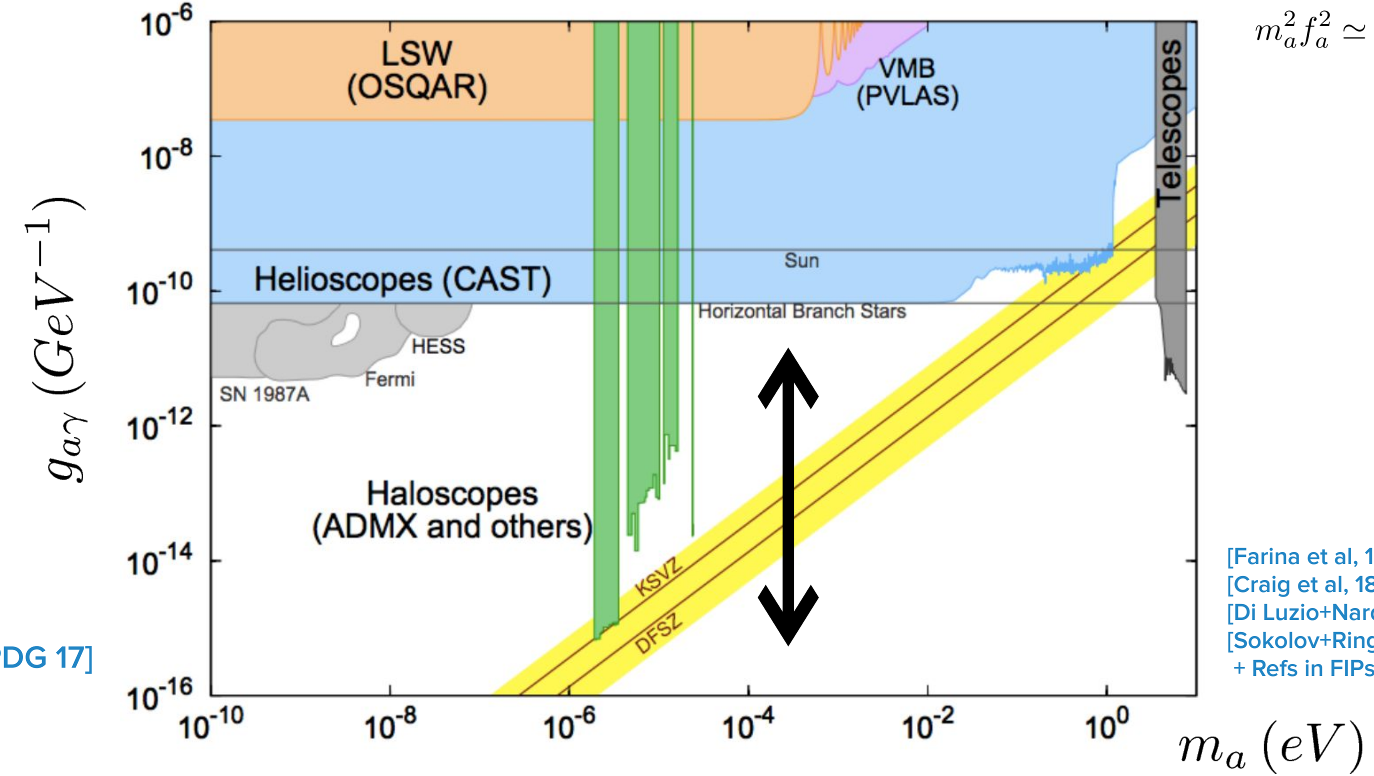
Photophilic/photophobic

$$\boxed{g_{a\gamma\gamma} = -\frac{1}{2\pi f_a}\alpha_{\rm em}\left(\frac{E}{N} - 1.92(4)\right)}$$

vs

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



[Ringwald, PDG 17]

[Farina et al, 17]
[Craig et al, 18]
[Di Luzio+Nardi et al, 17]
[Sokolov+Ringwald, 21] ...
+ Refs in FIPs report [2102.12143]

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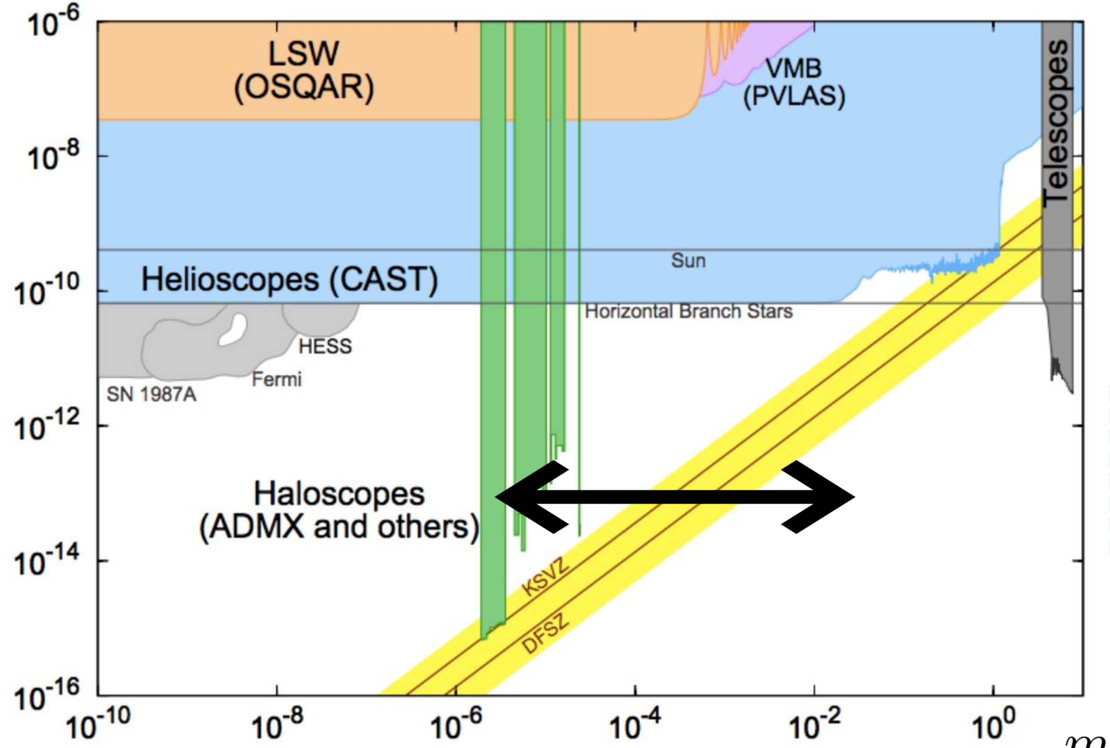
Heavier/lighter axion

$$g_{a\gamma\gamma} = -\frac{1}{2\pi f_a}\alpha_{\rm em}\left(\frac{E}{N} - 1.92(4)\right)$$

vs

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



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[Rubakov, 97]
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Beyond the canonical band

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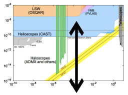

A) Photophilic/photophobic axions

1. Single scalar: Playing with fermionic representations

"Preferred axion window"

[Di Luzio, Mescia, Nardi, 16]
[Di Luzio, Mescia, Nardi, 18]

"Axion from monopoles"

[Sokolov, Ringwald, 21]

2. Multiple scalars: Alignment in field space

"Clockwork axion"

[Farina et al, 17]
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[Kaplan et al 16]
[Giudice et al 16]

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[Di Luzio, Giannotti, Nardi, Visinelli, 16]
[Darmé, Di Luzio, Giannotti, Nardi, 20]

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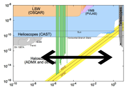

B) Heavy/even lighter axions

1. Heavy axions: extra instantons

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2. Even lighter QCD axion

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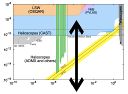
Why bother?

- Test the robustness of our theoretical predictions
- Widen the parameter space of axions solving the Strong CP
- Solution to invisible axion shortcomings:
  - Peccei-Quinn quality problem
  - DM axion postinflationary: Domain Wall problem
  - DM axion preinflationary: isocurvature perturbations

See talk of E. Nardi on Friday

Beyond the canonical band

$g_{a\gamma}$



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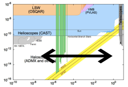

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vs

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- Two criteria:
  1) KSVZ fermions decay fast enough
  2) Absence of Landau poles below m_{pl}

(Assuming KSVZ post-inflationary scenario)

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- Result: Only 15 representations survive

$$|E/N - 1.92| \in [44/3, 5/3]$$

R_Q	$\mathcal{O}_{Qq}$	$\Lambda^{R_Q}_{LP}$[GeV]	E/N	N_{DW}
R_1: $(3,1,-\frac{1}{3})$	$\overline{Q}_L d_R$	$9.3\cdot 10^{38}(g_1)$	$2/3$	1
R_2: $(3,1,+\frac{2}{3})$	$\overline{Q}_L u_R$	$5.4\cdot 10^{34}(g_1)$	$8/3$	1
R_3: $(3,2,+\frac{1}{6})$	$\overline{Q}_R q_L$	$6.5\cdot 10^{39}(g_1)$	$5/3$	2
R_4: $(3,2,-\frac{5}{6})$	$\overline{Q}_L d_R H^\dagger$	$4.3\cdot 10^{27}(g_1)$	$17/3$	2
R_5: $(3,2,+\frac{7}{6})$	$\overline{Q}_L u_R H$	$5.6\cdot 10^{22}(g_1)$	$29/3$	2
R_6: $(3,3,-\frac{1}{3})$	$\overline{Q}_R q_L H^\dagger$	$5.1\cdot 10^{30}(g_2)$	$14/3$	3
R_7: $(3,3,+\frac{2}{3})$	$\overline{Q}_R q_L H$	$6.6\cdot 10^{27}(g_2)$	$20/3$	3
R_8: $(3,3,-\frac{4}{3})$	$\overline{Q}_L d_R H^{\dagger 2}$	$3.5\cdot 10^{18}(g_1)$	$44/3$	3
R_9: $(\overline{6},1,-\frac{1}{3})$	$\overline{Q}_L \sigma d_R \cdot G$	$2.3\cdot 10^{37}(g_1)$	$4/15$	5
R_{10}: $(\overline{6},1,+\frac{2}{3})$	$\overline{Q}_L \sigma u_R \cdot G$	$5.1\cdot 10^{30}(g_1)$	$16/15$	5
R_{11}: $(\overline{6},2,+\frac{1}{6})$	$\overline{Q}_R \sigma q_L \cdot G$	$7.3\cdot 10^{38}(g_1)$	$2/3$	10
R_{12}: $(8,1,-1)$	$\overline{Q}_L \sigma e_R \cdot G$	$7.6\cdot 10^{22}(g_1)$	$8/3$	6
R_{13}: $(8,2,-\frac{1}{2})$	$\overline{Q}_R \sigma \ell_L \cdot G$	$6.7\cdot 10^{27}(g_1)$	$4/3$	12
R_{14}: $(15,1,-\frac{1}{3})$	$\overline{Q}_L \sigma d_R \cdot G$	$8.3\cdot 10^{21}(g_3)$	$1/6$	20
R_{15}: $(15,1,+\frac{2}{3})$	$\overline{Q}_L \sigma u_R \cdot G$	$7.6\cdot 10^{21}(g_3)$	$2/3$	20

Preferred axion window: 1 quark

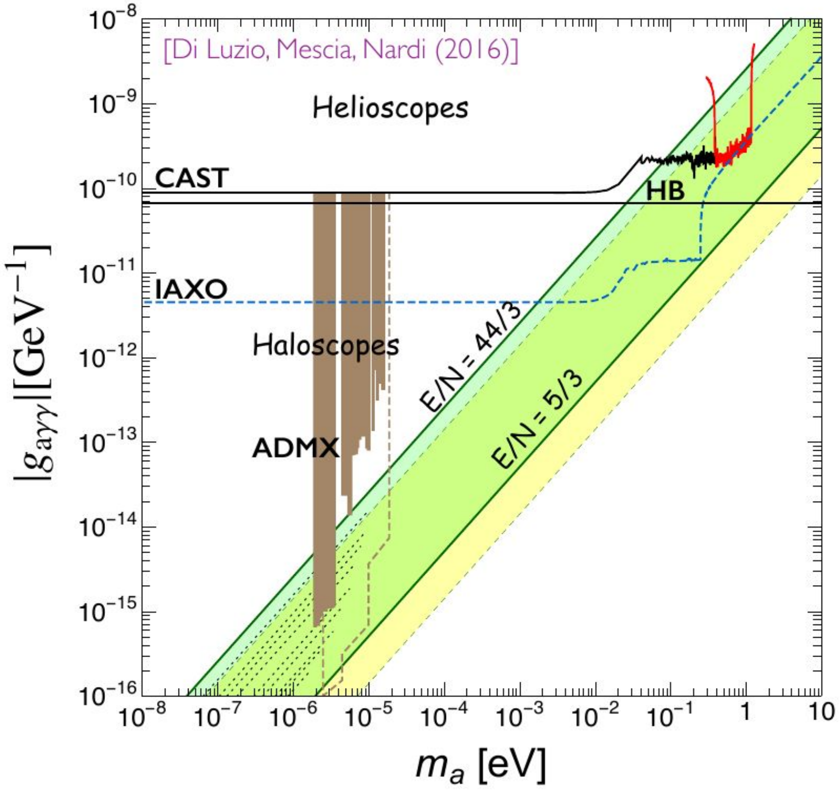
$$g_{a\gamma\gamma} = -\frac{1}{2\pi f_a}\alpha_{\rm em}\left(\boxed{\frac{E}{N}} - 1.92(4)\right)$$

vs

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

[Di Luzio, Mescia, Nardi, 16]
[Di Luzio, Mescia, Nardi, 18]

$$|E/N - 1.92| \in [44/3, 5/3]$$



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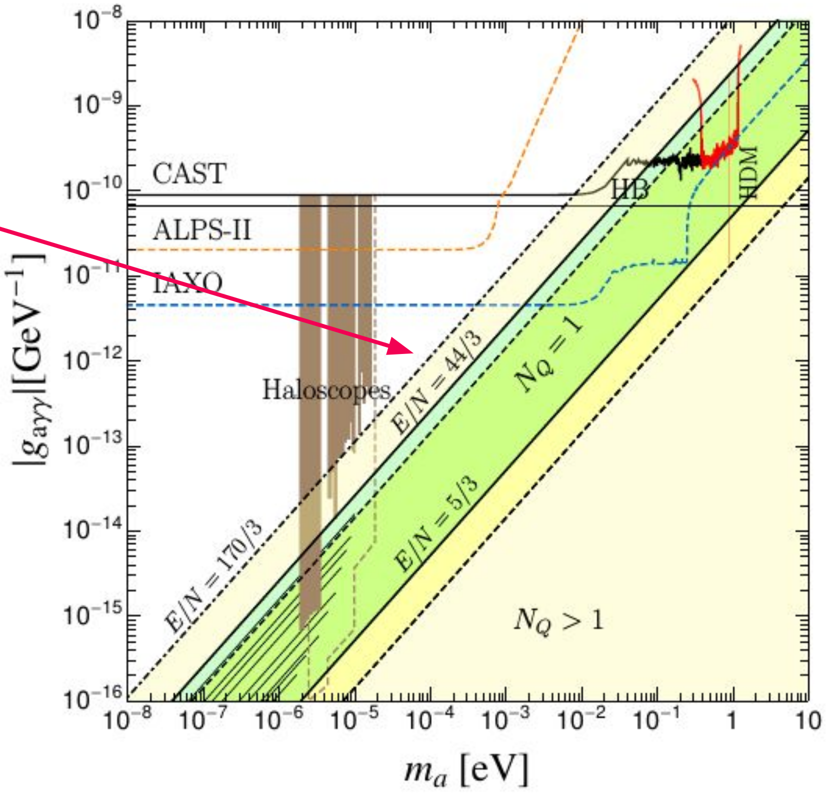
➔ Maximum coupling:

$$E/N = 170/3$$



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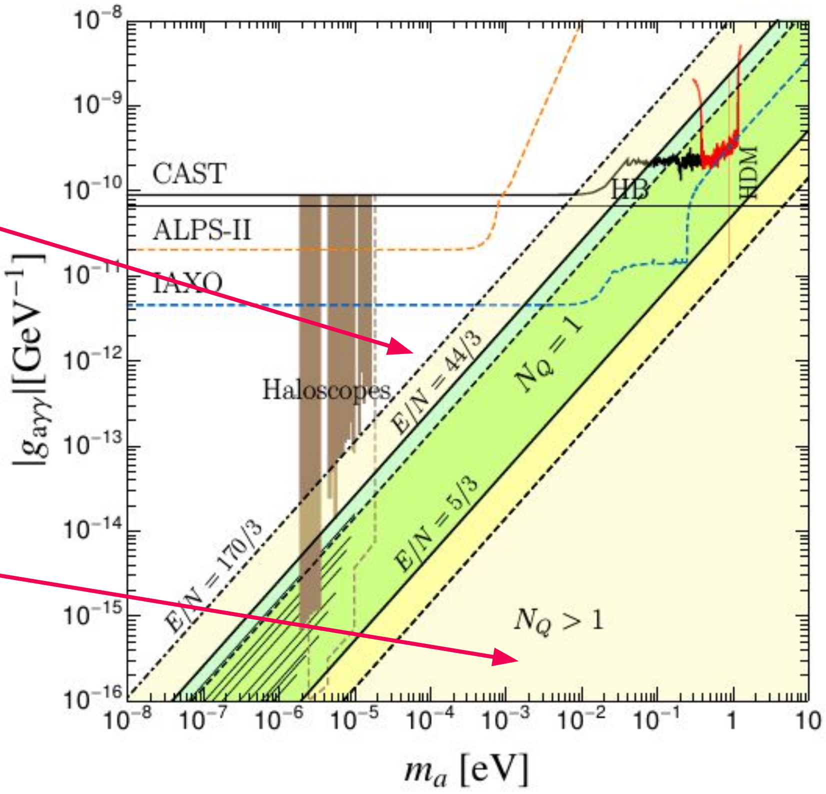
➔ Maximum coupling:

$$E/N = 170/3$$

➔ Minimum coupling:

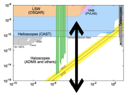
$$E/N \simeq (1.92, 1.94, 1.95)$$

Even completely photophobic (within th. errors)



Beyond the canonical band

$g_{a\gamma}$



A) Photophilic/photophobic axions

1. Single scalar: Playing with fermionic representations

"Preferred axion window"

[Di Luzio, Mescia, Nardi, 16]
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"Axion from monopoles"

[Sokolov, Ringwald, 21]

2. Multiple scalars: Alignment in field space

"Clockwork axion"

[Farina et al, 17]
[Coy, Frigerio, 17]
[Kim et al, 04]
[Choi et al, 14 and 16]
[Kaplan et al 16]
[Giudice et al 16]

"KNP alignment"

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+ Refs in FIPs report [2102.12143]

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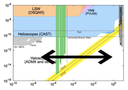
[Di Luzio, Mescia, Nardi, 17]
[Di Luzio, Giannotti, Nardi, Visinelli, 16]
[Darmé, Di Luzio, Giannotti, Nardi, 20]

m_a



B) Heavy/even lighter axions

1. Heavy axions: extra instantons

[Rubakov, 97]
[Berezhiani et al ,01]
[Fukuda et al, 01]
[Hsu et al, 04]
[Gianotti, 05]
[Hook et al, 14]
[Chiang et al, 16]
[Khobadize et al,]
[Dimopoulos et al, 16]
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[Fuentes-Martin et al, 19]
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2. Even lighter QCD axion

[Hook, 18]
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Axion from monopoles

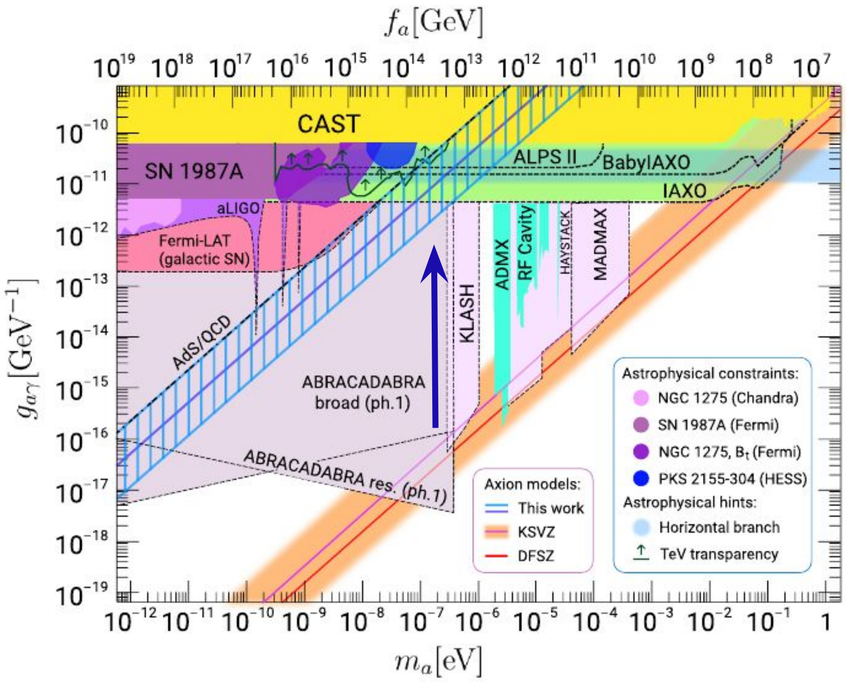
See talk of Anton Sokolov on Friday

$$g_{a\gamma\gamma} = -\frac{1}{2\pi f_a}\boxed{\alpha_{\rm em}}\left(\frac{E}{N} - 1.92(4)\right)$$

vs

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

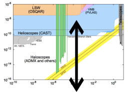
[Sokolov, Ringwald, 21]



$$\mathcal{L}_{\rm eff} \supset \frac{y}{\sqrt{2}} aJ_a = \frac{a}{16\pi^2 v_a} \times \begin{cases} -\frac{3}{4\alpha^2} e^2 F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{8\alpha_s^2} g_s^2 G^a_{(d)\mu\nu}\tilde{G}^{a\,\mu\nu}_{(d)}, \\ -\frac{27}{4\alpha^2} e^2 F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2} g_s^2 G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu}, \end{cases}$$

Beyond the canonical band

$g_{a\gamma}$



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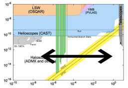

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$$m_a^2 f_a^2 \simeq m_\pi^2 f_\pi^2 \frac{m_u m_d}{(m_u + m_d)^2}$$

- ➔ Clockwork, KNP, Multi-higgs... share the key mechanism: hierarchical charges are obtained because the axion is an admixture of several axions with a particular alignment.
- ➔ Toy example with two scalars that take vevs: $\phi_1 = \frac{1}{\sqrt{2}}(v + \rho_1)\, e^{i\frac{a_1}{v}}$ $\quad \phi_2 = \frac{1}{\sqrt{2}}(v + \rho_2)\, e^{i\frac{a_2}{v}}$

$$\mathcal{L} = \phi_1 \bar{\psi}\psi + \phi_2 \bar{\chi}\chi$$

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$$\mathcal{L} = \phi_1 \bar\psi\psi \;+\; \phi_2\bar\chi\chi$$

- ➔ There are 2 U(1)'s and therefore two conserved currents:

$$j_1^\mu = v\,\partial^\mu a_1 + \bar\psi\gamma^\mu\gamma^5\psi + \dots$$
$$j_2^\mu = v\,\partial^\mu a_2 + \bar\chi\gamma^\mu\gamma^5\chi + \dots$$

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$$\mathcal{L} = \phi_1 \bar\psi\psi + \phi_2 \bar\chi\chi + \frac{c}{\lambda^{M-3}}\phi_1^*\phi_2^M$$

- ➔ The 2 U(1)'s are now broken to $U(1)_1 x U(1)_2 \rightarrow U(1)_{PQ}$

$$j_1^\mu = v\,\partial^\mu a_1 + \bar\psi\gamma^\mu\gamma^5\psi + \dots$$
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$$j_h^\mu = -j_1^\mu + M\, j_2^\mu$$
$$j_{PQ}^\mu = M j_1^\mu + j_2^\mu$$

+Scalars: Alignment in field space

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$$\mathcal{L} = \phi_1 \bar\psi\psi \,+\, \phi_2\bar\chi\chi \,+\, \frac{c}{\lambda^{M-3}}\phi_1^*\phi_2^M$$

- ➔ The PQ current reads:

$$j^\mu_{PQ} = v\,\partial^\mu(M a_1 + a_2) + M\bar\psi\gamma^\mu\gamma^5\psi + \bar\chi\gamma^\mu\gamma^5\chi\dots$$

+Scalars: Alignment in field space

$$g_{a\gamma\gamma} = -\frac{1}{2\pi f_a}\alpha_{\rm em}\left(\boxed{\frac{E}{N}} - 1.92(4)\right)$$

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- If ψ is electromagnetically charged Q_{EM}=1 and χ is QCD triplet:

$$\frac{E}{N} = M \gg 1$$

Photophilic axion!

Photophilic clockwork axion

$$g_{a\gamma\gamma} = -\frac{1}{2\pi f_a}\alpha_{\text{em}}\left(\boxed{\frac{E}{N}} - 1.92(4)\right)$$

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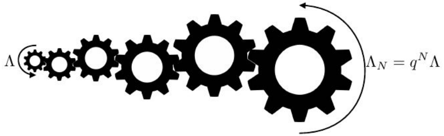
[Farina et al, 17]

➔ Let us consider N+1 scalar fields with next neighbour interactions:

$$\sum_{n=0}^{N-1}\left(\kappa_n \phi_n^\dagger \phi_{n+1}^3 + \text{h.c.}\right)$$



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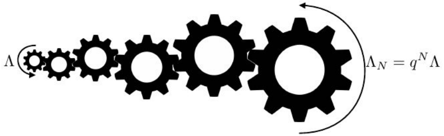

➔ These terms break $[U(1)]^{N+1} \rightarrow U(1)_{PQ}$ and the PQ axion is a specific combination

$$a = C\left(\pi_0 + \frac{1}{3}\pi_1 + \ldots + \frac{1}{3^M}\pi_M + \ldots + \frac{1}{3^N}\pi_N\right)$$

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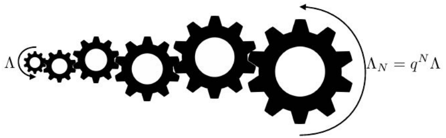

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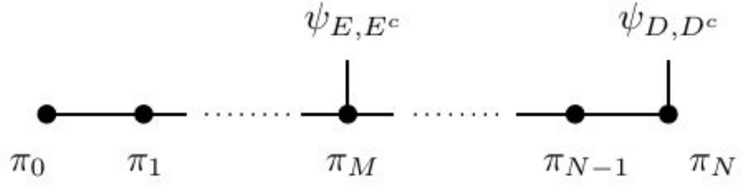

Exponentially large!

$$\frac{E}{N} = 3^{N-M}$$

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[Farina et al, 17]

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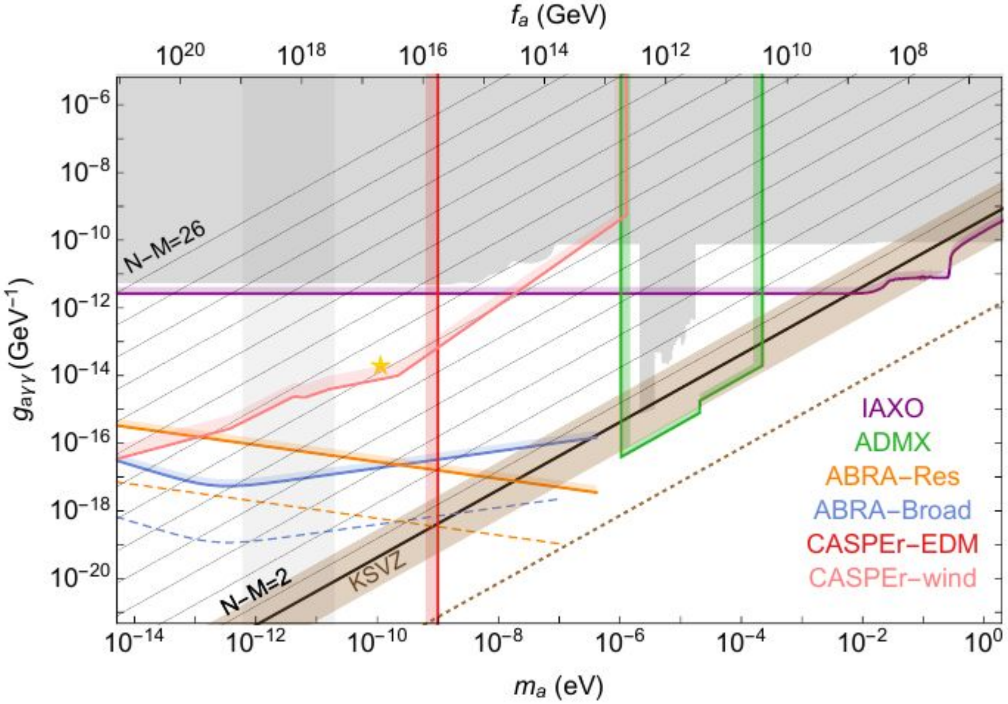

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➔ Similarly to toy example. A hidden group is responsible for the alignment

$$\mathcal{L} = -\frac{1}{4}(H_{\mu\nu}H^{\mu\nu} + G_{\mu\nu}G^{\mu\nu} + F_{\mu\nu}F^{\mu\nu}) + \frac{\alpha_h}{8\pi F_0}(a + M^\alpha b)H_{\mu\nu}\widetilde{H}^{\mu\nu} + \frac{\alpha_s}{8\pi F_0} bG_{\mu\nu}\widetilde{G}^{\mu\nu} + \frac{\alpha_{\rm em}}{8\pi F_0} M^\beta a F_{\mu\nu}\widetilde{F}^{\mu\nu}$$

$$\frac{E}{N} = M^{\alpha+\beta}$$

➔ With several axions and hiddens sectors one can also implement clockwork.

➔ Alternative scenario: kinetic mixing with an extra light axion.

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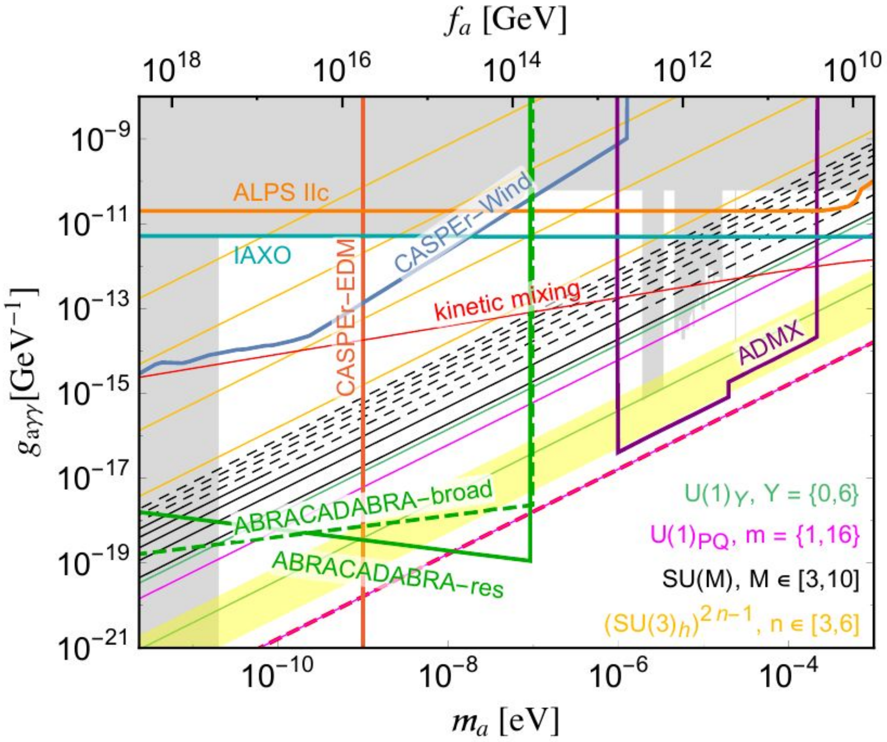

Multiple-Higgs doublet models

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➔ DFSZ with 3+N Higgs doublets and PQ scalar:

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

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

- ➔ The photon coupling is enhanced by enlarging the electron PQ charge

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

[Di Luzio, Mescia, Nardi, 17]
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Multiple-Higgs doublet models

$$g_{a\gamma\gamma} = -\frac{1}{2\pi f_a}\alpha_{\rm em}\left(\boxed{\frac{E}{N}} - 1.92(4)\right)$$

vs

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

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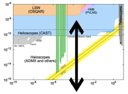
➔ And it can be done similarly a la clockwork with the N extra doblets

$$\frac{E}{N} \propto 2^N$$

➔ Interesting interplay with nucleophobic/electrophobic models.

Beyond the canonical band

$g_{a\gamma}$



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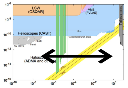

B) Heavy/even lighter axions

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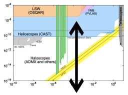

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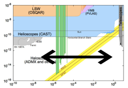

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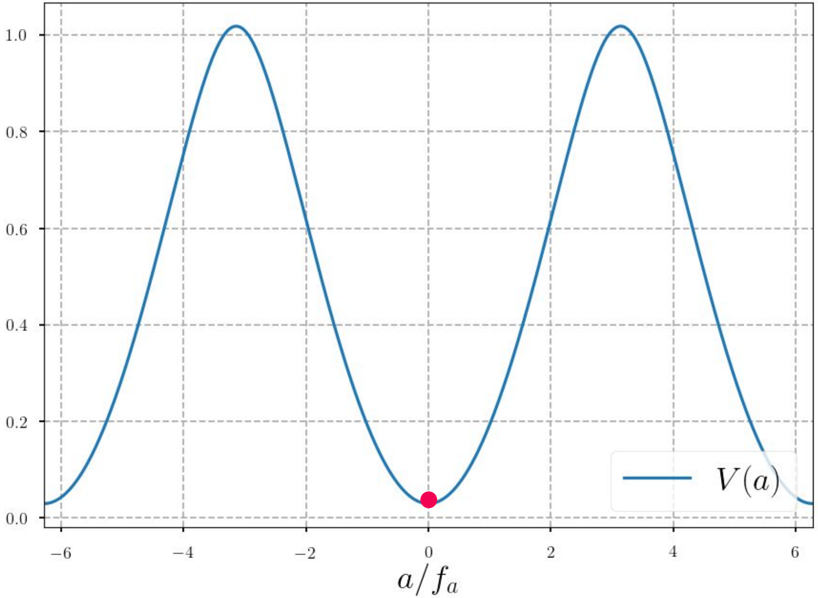
Modifying the axion mass

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

[Di Vecchia +Veneziano,80]
[Leutwyler+Smilga, 92]
[di Cortona et al, 15]



$$\bar{\theta}_{\rm eff} = \langle \bar{\theta} - \frac{a}{f_a} \rangle = 0$$

The Z2 case: Mirror world

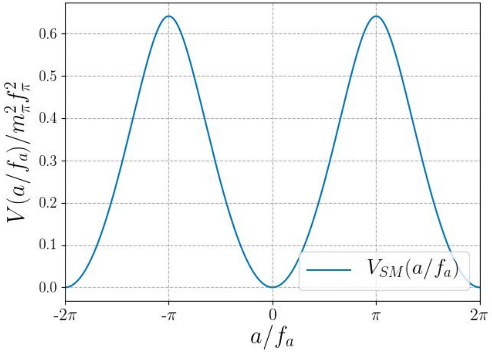
$$Z_2: \quad \mathrm{SM} \longrightarrow \mathrm{SM}'$$

$$a \longrightarrow a + \pi f_a$$

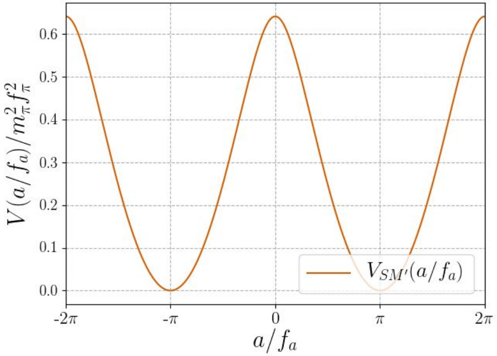
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{SM}'} + \frac{\alpha_s}{8\pi}\left(\frac{a}{f_a} - \theta\right) \underbrace{G\widetilde{G}}_{\text{QCD}} + \frac{\alpha_s}{8\pi}\left(\frac{a}{f_a} - \theta + \pi\right) \underbrace{G'\widetilde{G}'}_{\text{QCD'}}$$

What about lighter axions?

SM



SM'



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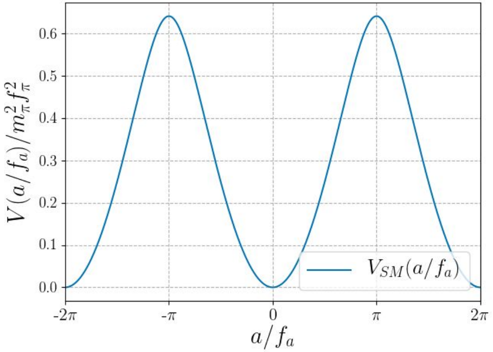

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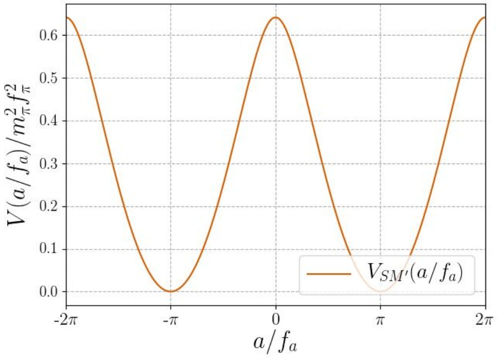

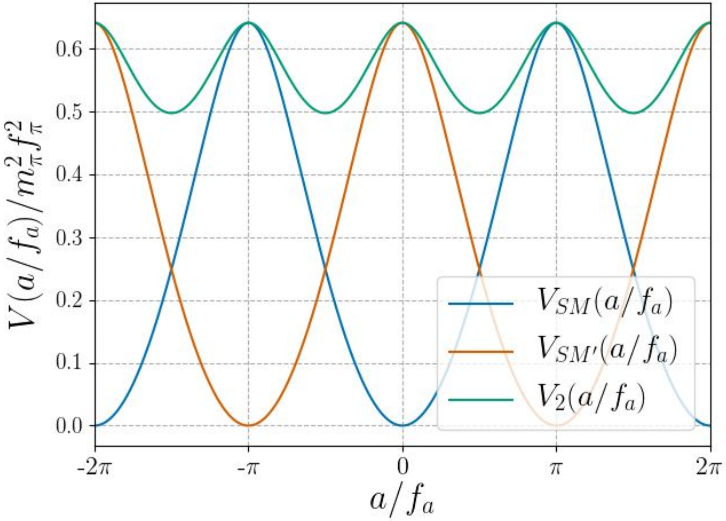

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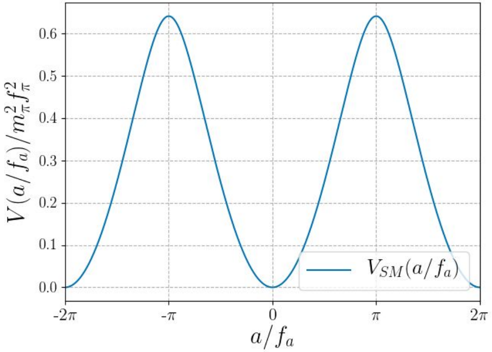

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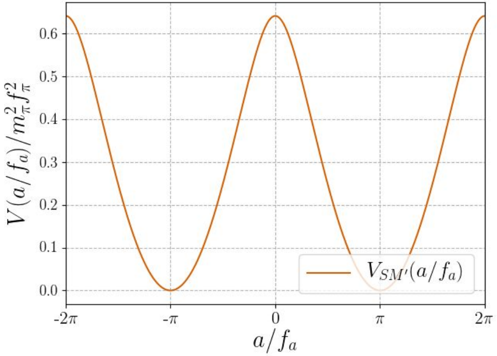
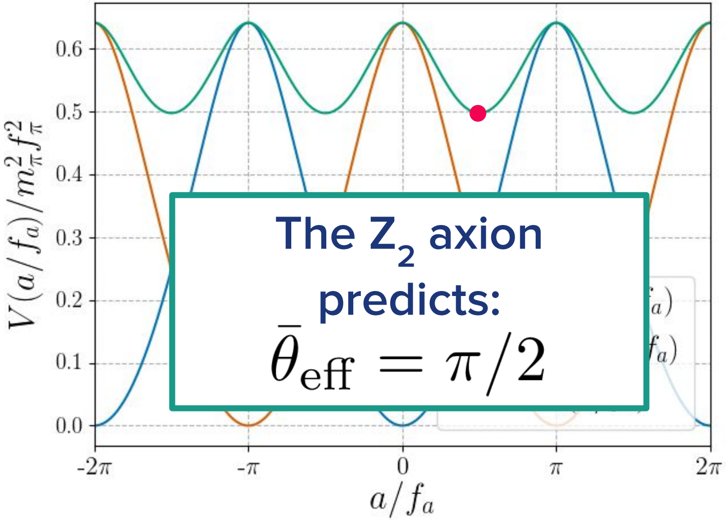




The Z_2 axion predicts:

$$\bar{\theta}_{\text{eff}} = \pi/2$$

$$g_{a\gamma\gamma} = -\frac{1}{2\pi f_a}\alpha_{\rm em}\left(\frac{E}{N} - 1.92(4)\right)$$

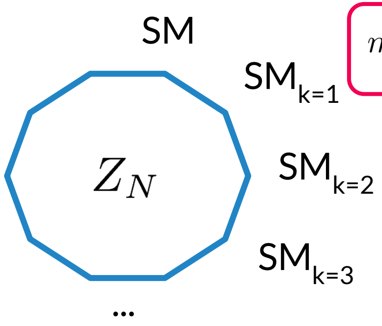
vs

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

Z_N axion: N-mirror worlds

$$Z_N: \quad \mathrm{SM} \longrightarrow \mathrm{SM}^k$$

$$a \longrightarrow a + \frac{2\pi k}{N} f_a$$



- ➔ The axion realizes the Z_N non-linearly.
- ➔ N degenerate worlds with the same couplings as in the SM except for the theta parameter

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

[Hook, 18]
[Luzio, Gavela, PQ, Ringwald, 21]
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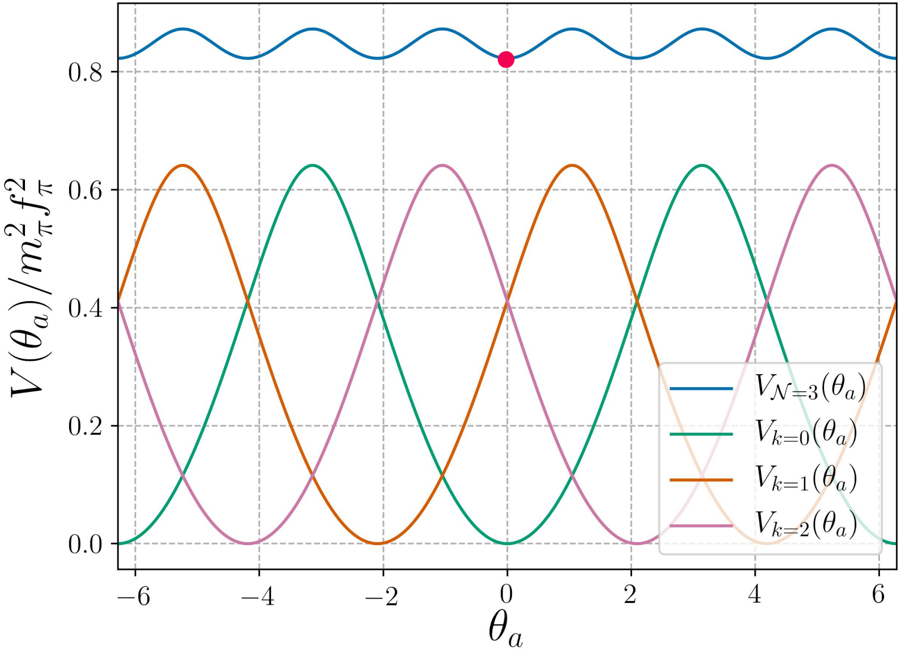
Z_N axion: N-mirror worlds

$$g_{a\gamma\gamma} = -\frac{1}{2\pi f_a}\alpha_{\rm em}\left(\frac{E}{N} - 1.92(4)\right)$$

$\mathcal{VS}$

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

➔ N needs to be odd. Example: Z_3



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

$$z = m_u/m_d$$

[Hook, 18]
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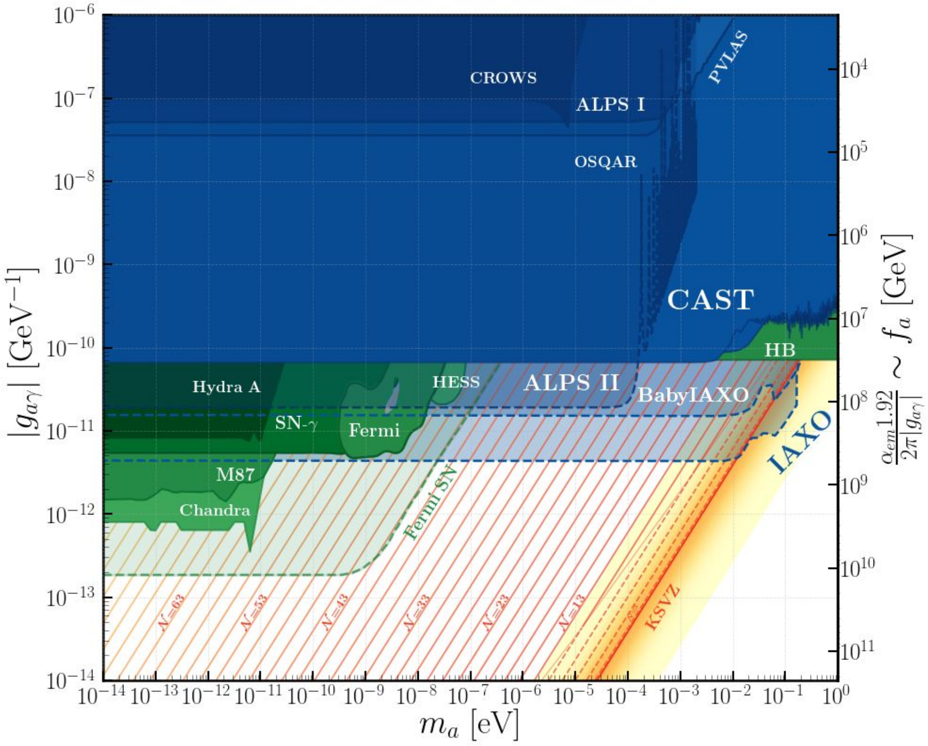
Even lighter Z_N axion

$$g_{a\gamma\gamma} = -\frac{1}{2\pi f_a}\alpha_{\rm em}\left(\frac{E}{N} - 1.92(4)\right)$$

vs

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



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

$$m_a^2 f_a^2 \propto (m_u/m_d)^N \sim 2^{-N}$$

[Hook, 18]
[Luzio, Gavela, PQ, Ringwald, 21]
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How can we disentangle the different scenarios?

Disentangling different scenarios

$$g_{a\gamma\gamma} = -\frac{1}{2\pi f_a}\alpha_{\rm em}\left(\frac{E}{N} - 1.92(4)\right)$$

vs

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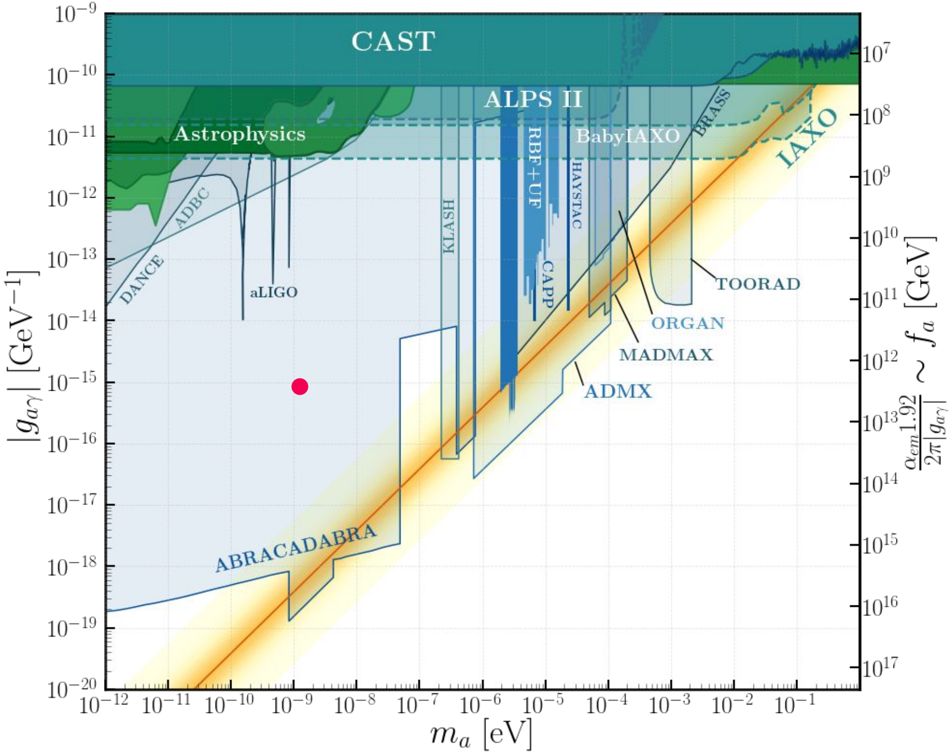

$$m_a\,(eV)$$

Disentangling different scenarios

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VS

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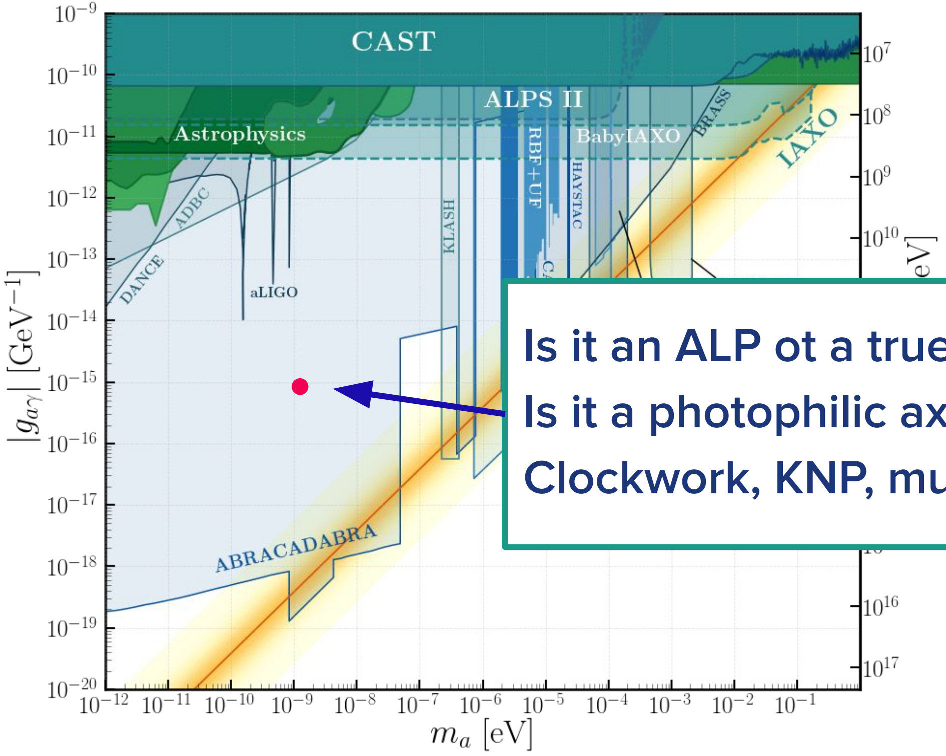


Is it an ALP ot a true QCD axion?

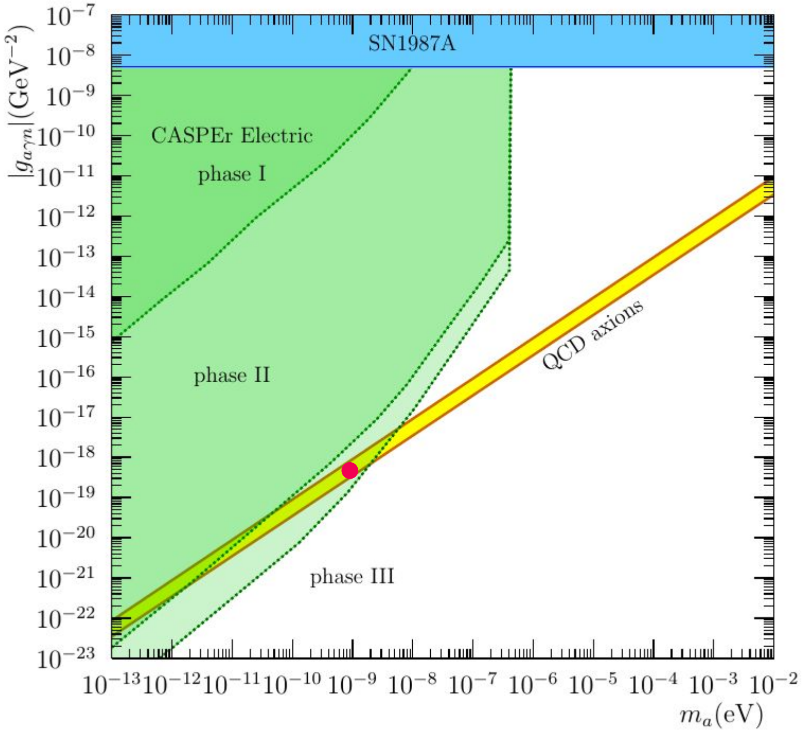
Is it a photophilic axion or a light axion?

Clockwork, KNP, multihiggs, Z_N,…?

$$m_a\,(eV)$$

CASPEr Electric

$g_{a\gamma n}$



[Irastorza+Redondo, 18]

➔ Every true DM axion generates a signal in CASPEr

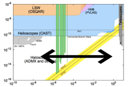
$$\mathcal{L} \supset \frac{a}{f_a}\frac{\alpha_s}{8\pi}G\tilde{G} \longleftrightarrow \delta\mathcal{L} \equiv -\frac{i}{2}\frac{0.011\, e}{m_n}\frac{a}{f_a}\bar{n}\sigma_{\mu\nu}\gamma_5 n F^{\mu\nu}$$

Coupling to the nEDM

$\equiv g_{a\gamma n}$

For the nEDM one can only go beyond the QCD band horizontally

m_a

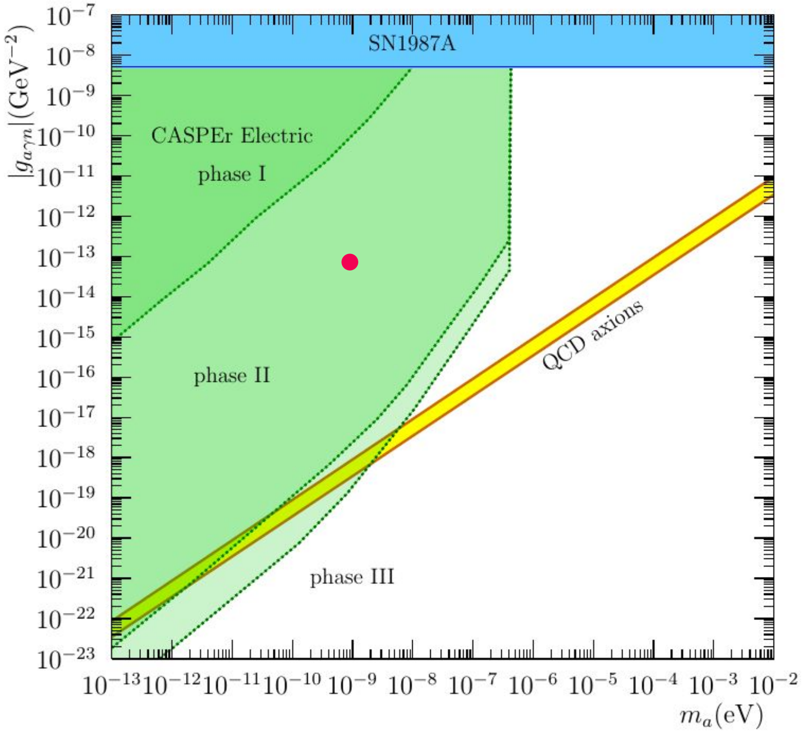


➔ If it lies in the yellow band ⇔ photophilic

$m_a\,(eV)$

CASPEr Electric

$g_{a\gamma n}$



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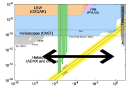


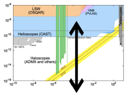
➔ If it lies in the yellow band ⇔ photophilic/fobic

➔ If it lies outside the band ⇔ even lighter axion

$m_a\,(eV)$

Beyond the canonical band: DM prediction

$g_{a\gamma}$



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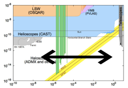

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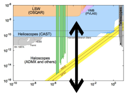

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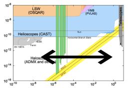

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Unaffected

Modified

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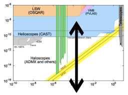

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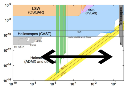

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[Khobadize et al,]

[Dimopoulos et al, 16]
[Gherghetta et al, 16]
[Agrawal et al, 17]
[Gaillard, Gavela, Houtz, Rey PQ, 18]
[Fuentes-Martin et al, 19]
[Csaki et al, 19]
[Gherghetta et al, 20]

2. Even lighter QCD axion

[Hook, 18]
[Luzio, Gavela, PQ, Ringwald, 21]
[Luzio, Gavela, PQ, Ringwald, 21]

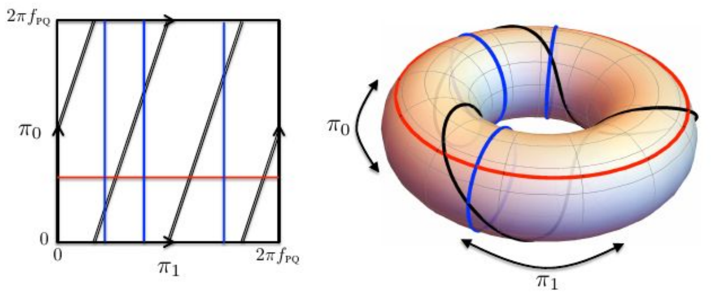
Unaffected

Modified

Clockwork axion dark matter

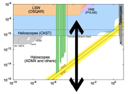
[Long et al, 18]

- ➔ Usual misalignment is unaffected
- ➔ Axions from decays of topological defects drastically modified:
  - ◆ Since $f_{PQ} \ll f_a$ there is more room for the post inflationary scenario
  - ◆ Rich structure of the string/domain wall network from all the extra scalars => SUPPRESSED DM axion production
  - ◆ Production of relativistic axions => Dark radiation that can be constrained with $N_{eff.}$

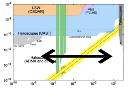


Beyond the canonical band: DM prediction

$g_{a\gamma}$



m_a



A) Photophilic/photophobic axions

1. Single scalar: Playing with fermionic representations

"Preferred axion window"

[Di Luzio, Mescia, Nardi, 16]
[Di Luzio, Mescia, Nardi, 18]

"Axion from monopoles"

[Sokolov, Ringwald, 21]

2. Multiple scalars: Alignment in field space

"Clockwork axion"

[Farina et al, 17]
[Coy, Frigerio, 17]
[Kim et al, 04]
[Choi et al, 14 and 16]
[Kaplan et al 16]
[Giudice et al 16]

"KNP alignment"

[Agrawal et al 17]
[Kim et al, 04]
+ Refs in FIPs report
[2102.12143]

"Multi-higgs models"

[Di Luzio, Mescia, Nardi, 17]
[Di Luzio, Giannotti, Nardi, Visinelli, 16]
[Darmé, Di Luzio, Giannotti, Nardi, 20]

B) Heavy/even lighter axions

1. Heavy axions: extra instantons

[Rubakov, 97]
[Berezhiani et al ,01]
[Fukuda et al, 01]
[Hsu et al, 04]
[Gianotti, 05]
[Hook et al, 14]
[Chiang et al, 16]
[Khobadize et al,]

[Dimopoulos et al, 16]
[Gherghetta et al, 16]
[Agrawal et al, 17]
[Gaillard, Gavela, Houtz, Rey PQ, 18]
[Fuentes-Martin et al, 19]
[Csaki et al, 19]
[Gherghetta et al, 20]

2. Even lighter QCD axion

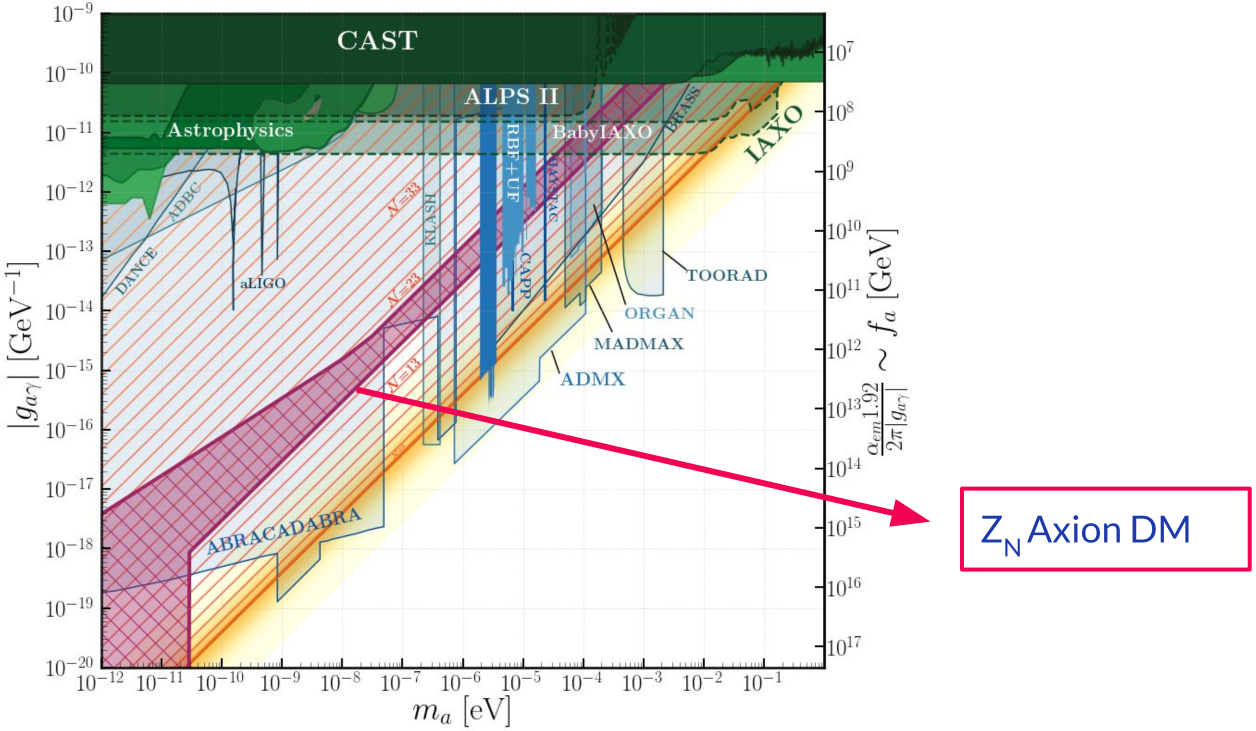
[Hook, 18]
[Luzio, Gavela, PQ, Ringwald, 21]
[Luzio, Gavela, PQ, Ringwald, 21]

Unaffected

Modified

Dark matter from even lighter Z_N axion

➔ Novel production mechanism: trapped misalignment that enhances the relic density.



[Hook, 18]
[Luzio, Gavela, PQ, Ringwald, 21]
[Luzio, Gavela, PQ, Ringwald, 21]

Conclusions

- ➔ The parameter space of true axions may be much wider.
- ➔ The QCD axion might already be in the reach of your experiment!
- ➔ Experiments should explore further down than the E/N=0 benchmark
- ➔ Much needs to be done to disentangle the axion model parameters from possible signals in multiple experiments.

  See talk of S. Hoof on Wednesday

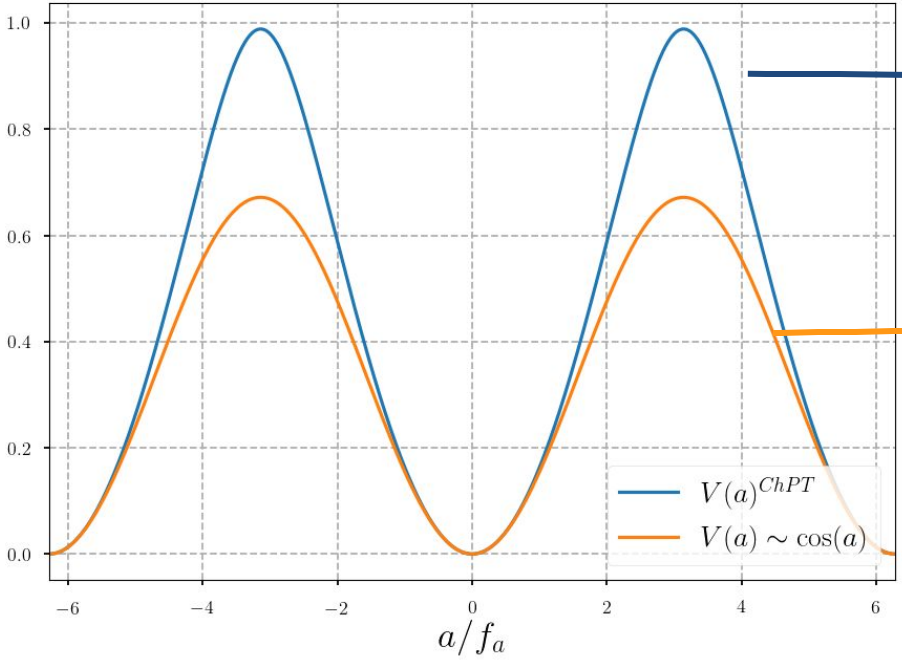
- ➔ Much progress has also been made in extending the ALP DM arena (kinetic mis., trapped mis., axion fragmentation...)

  See talks of P. Sørensen and C. Eröncel on Tuesday.

Thank you

Backup slides

True axion potential



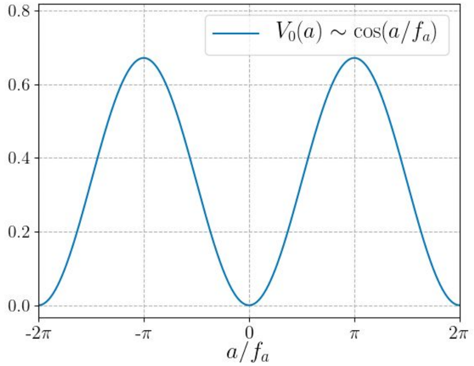
$$V(a) = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{a}{2 f_a}\right)}$$

[Di Vecchia +Veneziano,80]
[Leutwyler+Smilga, 92]
[di Cortona et al, 15]

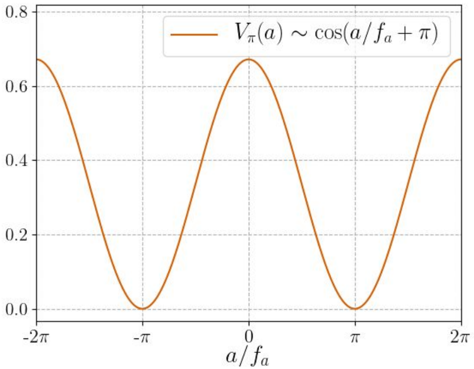
$$V(a) \sim -m_a^2 f_a^2 \cos(a/f_a)$$

What about lighter axions?

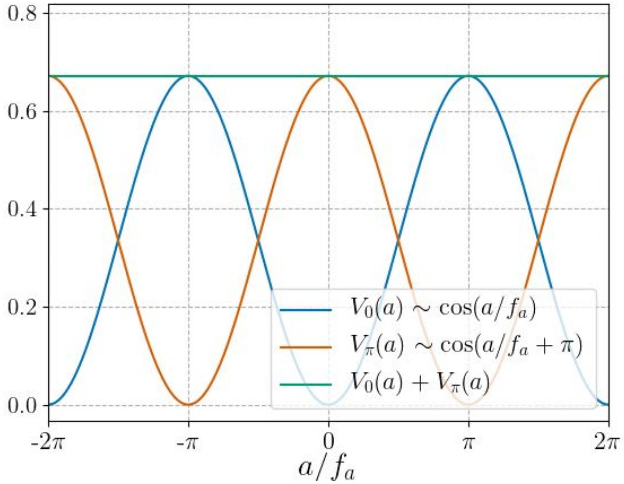
SM



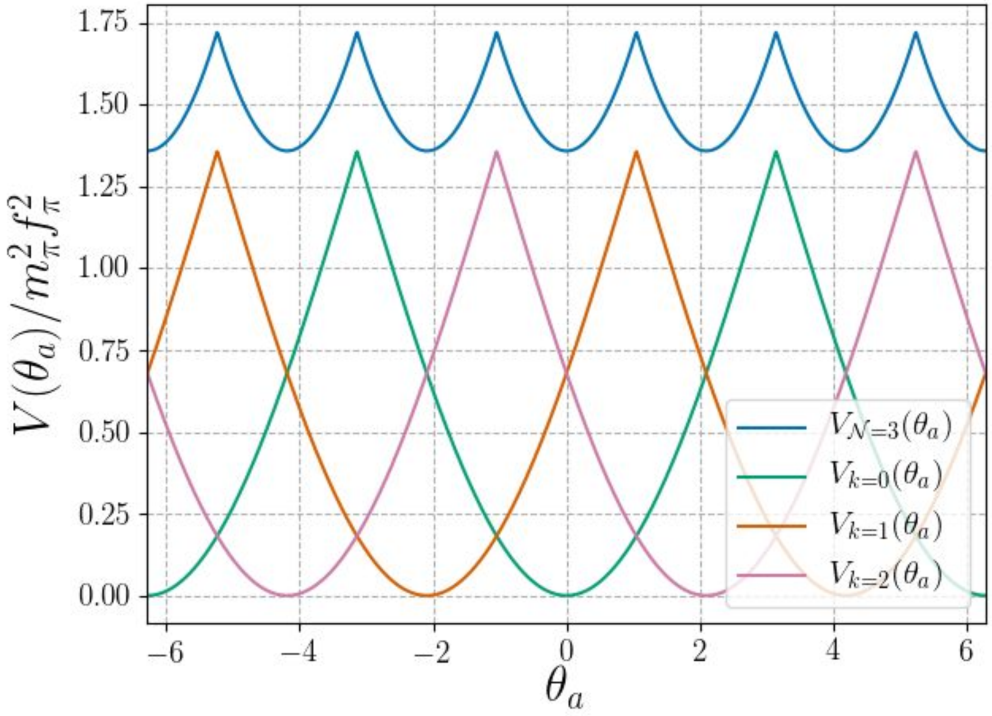
SM'



Completely massless axion?



Potential for N=3, z=1



The axion mass matrix

There are two pseudoscalars that couple to the anomaly: the axion and the η':

$$\frac{\alpha}{8\pi}\left(2\frac{\eta_0}{f_\pi}+\frac{a}{f_a}\right)\tilde{G}G \longrightarrow \frac{1}{2}\Lambda^4_{QCD}\left(2\frac{\eta_0}{f_\pi}+\frac{a}{f_a}\right)^2$$

$$M^2_{\{\pi_3,\,\eta_0,a\}}=4\begin{pmatrix} B_0\,(m_u+m_d) & B_0\,(m_u-m_d) & 0 \\ B_0\,(m_u-m_d) & 4K/f_\pi+B_0(m_u+m_d) & 2K/(f_\pi f_a) \\ 0 & 2K/(f_\pi f_a) & K/f_a^2 \end{pmatrix}$$

The physical axion is a (model-independent) combination of the pion and the eta':

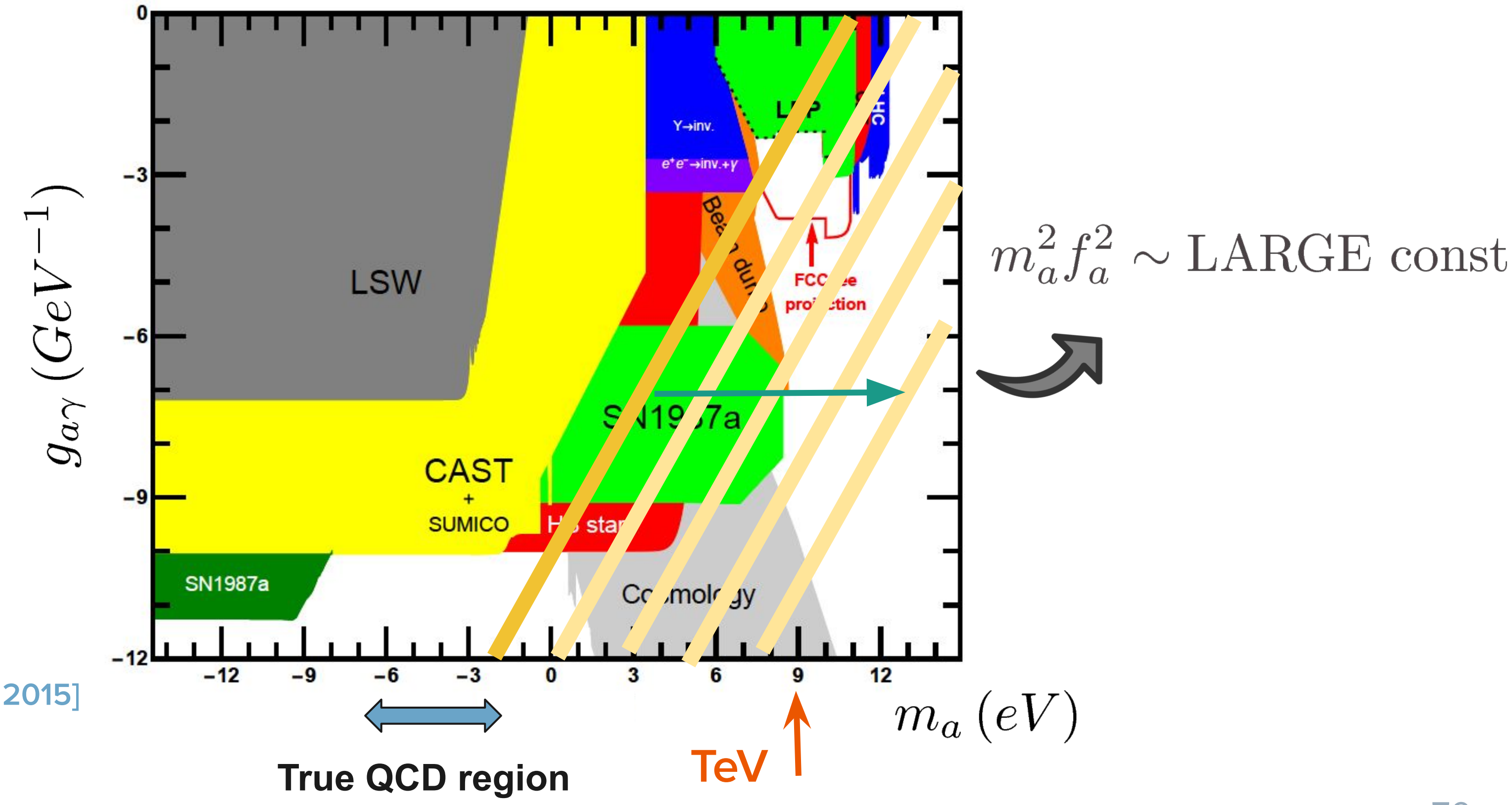
$$\boxed{a_{phys}\simeq \hat{a}-\frac{f_\pi}{2f_a}\frac{m_d-m_u}{m_u+m_d}\pi_3-\frac{f_\pi}{2f_a}\eta_0}$$

$$\boxed{g_{aXX}=g^0_{aXX}+\theta_{a\pi}\,g_{\pi XX}+\theta_{a\eta'}\,g_{\eta' XX}}$$

$$g_{a\gamma\gamma}=-\frac{1}{2\pi f_a}\alpha_{\rm em}\left(\frac{E}{N}-\underbrace{\boxed{\frac{2}{3}\frac{m_u+4m_d}{m_u+m_d}}}_{\sim 1.92}\right),$$

arXiv:1811.05466

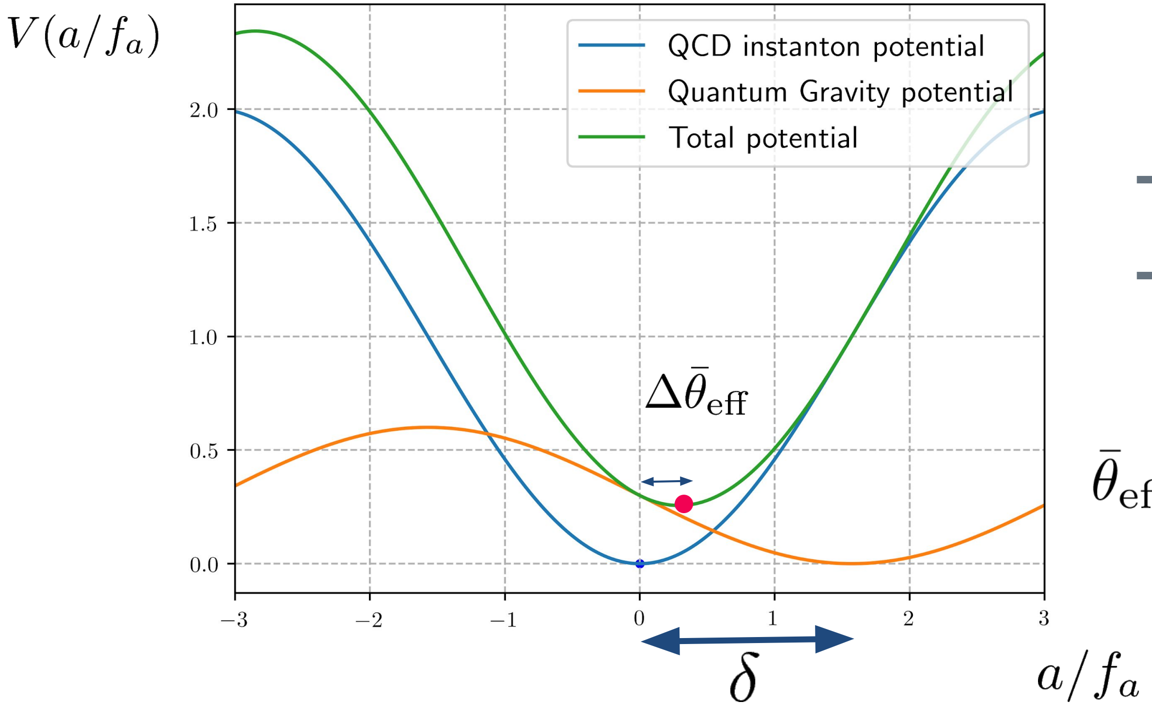
Heavy axion models



[Jaeckel+ Spannowsky 2015]

Axion potential

$$\mathcal{L} \supset \frac{a}{f_a}\frac{\alpha_s}{8\pi} G\tilde{G} \longrightarrow V(a/f_a) \sim m_\pi^2 f_\pi^2 \frac{m_u\, m_d}{(m_u+m_d)^2}\cos(a/f_a)$$



- ➔ Alignment
- ➔ Cancelation

$$\bar{\theta}_{\rm eff} = \langle \bar{\theta} - \frac{a}{f_a} \rangle \neq 0$$