Axions in a highly protected gauge symmetry model

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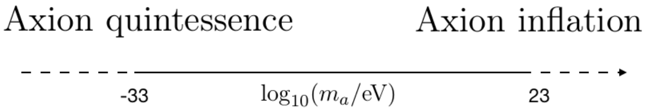
based on arXiv:1804.01112
in collaboration with E. Dudas and S. Pokorski

Centre de Physique Théorique - École Polytechnique

Workshop "The strong CP puzzle and axions"
May 15th, 2018

Phenomenology of axion models: caracterized by **axion mass**



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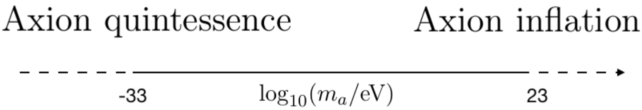

and **couplings to SM fields**

$$\mathcal{L} \supset \frac{g_{a\gamma\gamma}}{f_a} a F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{i g_{a,\text{EDM}}}{f_a} a \overline{N}\gamma_{\mu\nu}\gamma^5 N F^{\mu\nu} + \frac{g_{aNN}}{f_a}\partial_\mu a \overline{N}\gamma^\mu\gamma^5 N + \frac{g_{aee}}{f_a}\partial_\mu a \bar{e}\gamma^\mu\gamma^5 e$$

(Very) **light axions** useful for model building. Ex:

- QCD axion ($m_a \sim 10^{-12} - 10^{-3}$ eV)
- dark matter candidates ($m_a \gtrsim 10^{-22}$ eV)
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How to make such small masses consistent with a UV-complete theory?

Why such a question in the first place?

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Constraint on the mass → **need for a controled breaking**

However: global symmetries expected to be **broken by quantum gravity effects**

Hawking (1987), Giddings & Strominger (1988), Banks & Seiberg (2010)

Effects of the **gravity breaking?** Example of a Peccei-Quinn symmetry:

Peccei-Quinn symmetry:

Explains why the $\not{CP}$ "θ-term" $\mathcal{L}_{\mathrm{QCD}} \supset \frac{\theta_{\mathrm{QCD}}}{32\pi^2}\epsilon^{\mu\nu\rho\sigma}F_{\mu\nu}F_{\rho\sigma}$ verifies $\theta_{\mathrm{QCD}} < 10^{-10}$

Postulates a global symmetry with a $SU(3)^2 \times U(1)_{PQ}$ anomaly $\rightarrow$ makes θ_{QCD} dynamical (axion) and stabilizes it at $\theta_{\mathrm{QCD}} = 0$

PQ symmetry: Global symmetry with a $SU(3)^2 \times U(1)_{PQ}$ anomaly + axion→ $\theta_{\rm QCD} = 0$

Specific realization: **KSVZ model** with

$\mathcal{L}_{PQ} \supset \phi\overline{Q_L}Q_R + h.c. - V(|\phi|^2)$, $\phi \xrightarrow{U(1)_{PQ}} e^{i\alpha}\phi$ and $\phi = \frac{f+r}{\sqrt{2}}e^{i\frac{a}{f}}$

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Then:

$$\text{QCD anom. + instantons} \rightarrow \mathcal{L} \supset m_\pi^2 f_\pi^2 \frac{\sqrt{m_u m_d}}{m_u + m_d} \cos\left(\frac{a}{f} - \theta_{\rm QCD}\right)$$

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$$\frac{\phi^n}{M_P^{n-4}} \text{ term} \rightarrow \mathcal{L} \supset \left(\frac{f}{\sqrt{2} M_P}\right)^n M_P^4 \cos\left(\frac{na}{f}\right)$$

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Fields	ϕ_1	ϕ_2	$Q_L^{i=1\ldots q}$	$\widetilde{Q}_L^{i=1\ldots p}$	$Q_R^{i=1\ldots p+q}$
$SU(3)$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$
$U(1)$	p	q	p	$-q$	0
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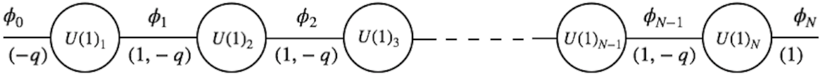
$$\mathcal{L} \supset \underbrace{\phi_1 \overline{Q_L} Y Q_R + \phi_2^* \overline{\widetilde{Q}_L} \widetilde{Y} Q_R}_{\mathcal{L}_{PQ}} + \underbrace{\frac{\phi_1^q \phi_2^{*p}}{M_P^{p+q-4}}}_{\mathcal{L}_{\not{PQ}}} + h.c.$$

Outline

A gauge theory with a pGB

A gauge theory:



$$\mathcal{L} = -\frac{1}{4}\sum_{i=1}^{N} F_{\mu\nu,i}F_i^{\mu\nu} - \sum_{k=0}^{N} |D_\mu \phi_k|^2 - V(|\phi_0|^2, |\phi_1|^2, \ldots)$$

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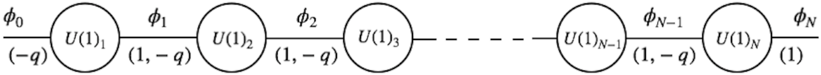

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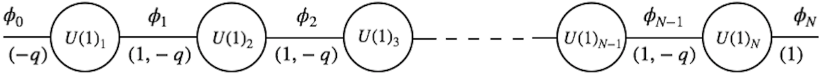
Ahmed & Dillon (2017), Coy Frigerio & Ibe (2017), Choi Im & Shin (2017), within discussions about the **clockwork mechanism**: Choi & Im (2016), Kaplan & Rattazzi (2016), Giudice & McCullough (2017)

Inspiration from 5-dimensional models: **axionic shift symmetry inherited from a 5d gauge invariance**

Clockwork models: warped fifth dimension (linear dilaton)



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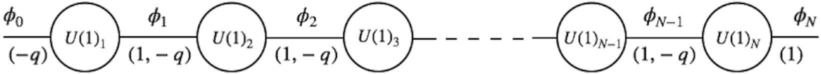
with one global accidental $U(1)$: $\phi_k \to e^{iq^k\alpha}\phi_k$



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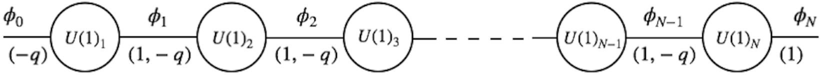
In the spectrum for a complete spontaneous breaking:

- massive scalars and vectors
- **Goldstone boson** a
  $a \sim \frac{1}{q^N f_0}\theta_0 + \frac{1}{q^{N-1} f_1}\theta_1 + \dots + \frac{1}{f_N}\theta_N$



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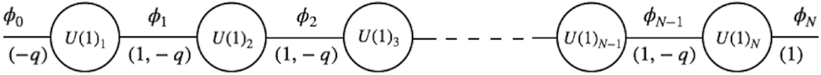

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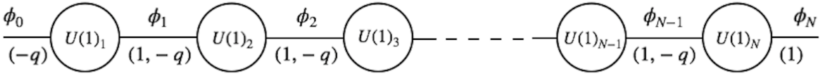
How much approximate? Gauge invariant operators:

$$|\phi_k|^2 \text{ and } \phi_0\phi_1^q...\phi_N^{q^N}$$

→ **exponential increase of the order of the breaking operators** with q and N



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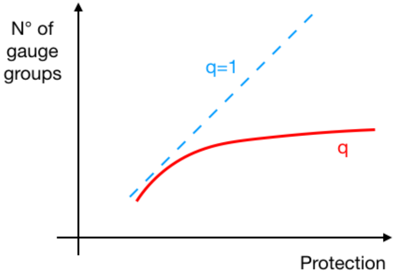

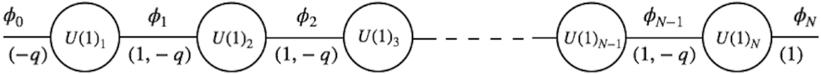

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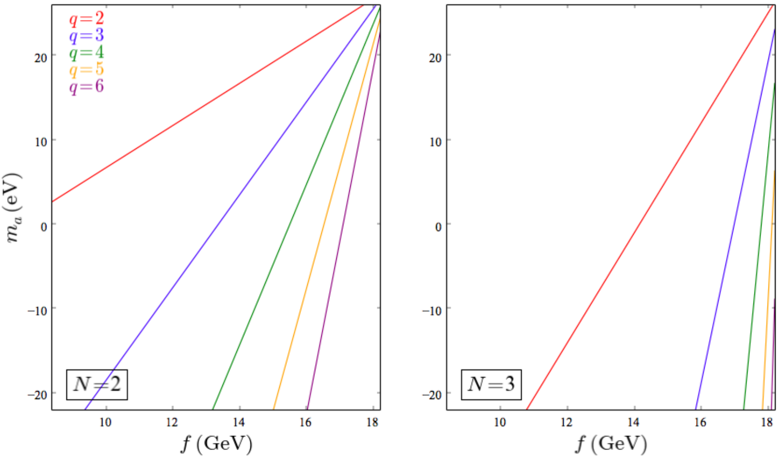
Gravitational breaking under control:

$$\mathcal{L} \supset \frac{\phi_0 \phi_1^q \ldots \phi_N^{q^N}}{M_P^{1+\ldots-4}} \to \boxed{m_a^{(\text{grav})} = \left(\frac{f}{\sqrt{2}M_P}\right)^{\frac{q+\ldots+q^N-1}{2}} \sqrt{1+q^2+\ldots+q^{2N}}\, M_P}$$

Mass suppression with **few additional gauge groups**:



Applications (I)

For a QCD axion:

Protection efficient if $m_a^{(\text{grav})} < 10^{-5}\left(m_a^{(\text{QCD})} \sim \frac{m_\pi f_\pi}{2 f_a}\right)$

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$f_a = f$ for the KSVZ model. **What about f_a in our setup?**

In the KSVZ model ($\mathcal{L}_{PQ} \supset \phi \overline{Q_L} Q_R + h.c.$): axionic coupling to gluons

$$\mathcal{L} \supset i \log\left(\frac{\phi}{f}\right) G\tilde{G} = -\frac{a}{f} G\tilde{G}$$

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Not gauge-invariant now. Only possibility:

$$\mathcal{L} \supset i \log\left(\frac{\phi_0 \phi_1^q \ldots \phi_N^{q^N}}{f^{1+q+\ldots}}\right) G\tilde{G} = -\frac{\sqrt{1+q^2+\ldots q^{2N}}}{f} aG\tilde{G}$$

$$\rightarrow f_a = \frac{f}{\sqrt{1+q^2+\ldots q^{2N}}}$$

$\theta_{\rm QCD} < 10^{-10}$ if:

$$\left[m_a^{(\rm QCD)} \sim \frac{m_\pi f_\pi}{2 f_a}\right] > 10^5 \left[m_a^{(\rm grav)} \sim \left(\frac{f}{M_P}\right)^{\frac{q+\ldots+q^N-1}{2}} \frac{f}{f_a} M_P\right]$$

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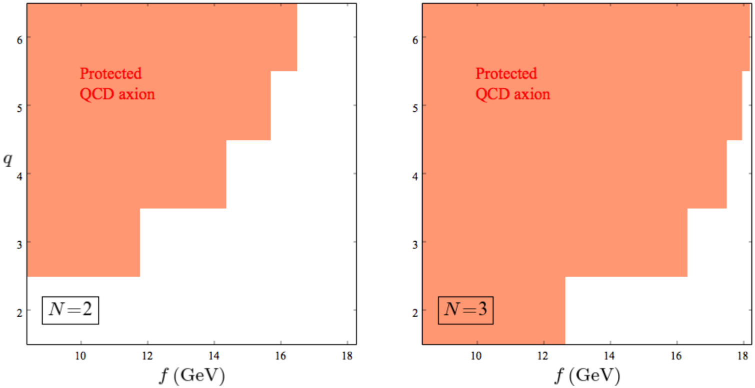

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However: coupling $aG\tilde{G}$ via fermion loops: non-minimal sector due to the protection

SM couplings

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	Sym-violating	Sym-preserving
Decay to photons	$\frac{a}{f_a}F\tilde{F}$	$\frac{\Box aF\tilde{F}, \partial_\mu aF_{\nu\eta}\partial^\eta\tilde{F}^{\mu\nu}}{f_a\Lambda^2}$
Couplings to matter	$\frac{a}{f_a}\overline{N}\gamma_{\mu\nu}\gamma^5 NF^{\mu\nu}$	$\frac{\partial_\mu a}{f_a}\overline{N}\gamma^\mu\gamma^5 N$

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In the effective theory:

$$\log\left(\phi_0 \phi_1^q \ldots \phi_N^{q^N}\right) F\tilde{F} \qquad \frac{\phi_i^* D_\mu \phi_i}{f^2}\overline{N}\gamma^\mu\gamma^5 N$$

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In the effective theory:

Site-dependence $\quad \frac{\phi_i^* D_\mu \phi_i}{f^2}\overline{N}\gamma^\mu\gamma^5 N$

Applications (II)

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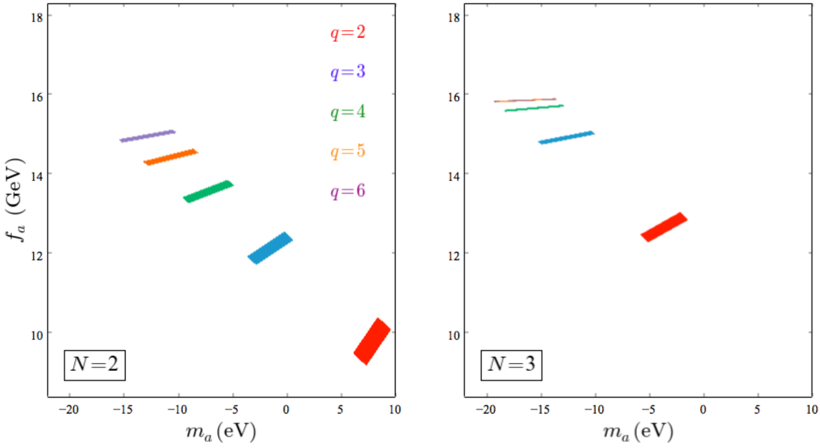
Focus here on **gravitational origin** and on **misalignment mechanism** (with pre-inflationnary breaking):

$$V = -\frac{\phi_0 \phi_1^q \ldots \phi_N^{q^N}}{M_P^{1+q+\ldots+q^N-4}} \supset -\left(\frac{f}{M_P}\right)^{1+q+\ldots q^N} M_P^4 \cos\left(\frac{a}{f_a}\right)$$

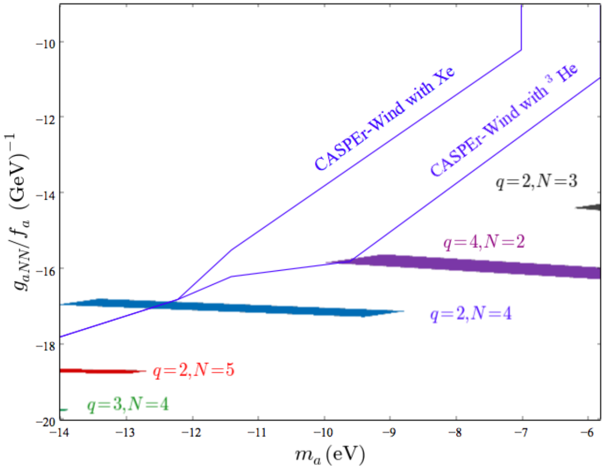
and

$$< a_{\rm init} >= \text{random}$$

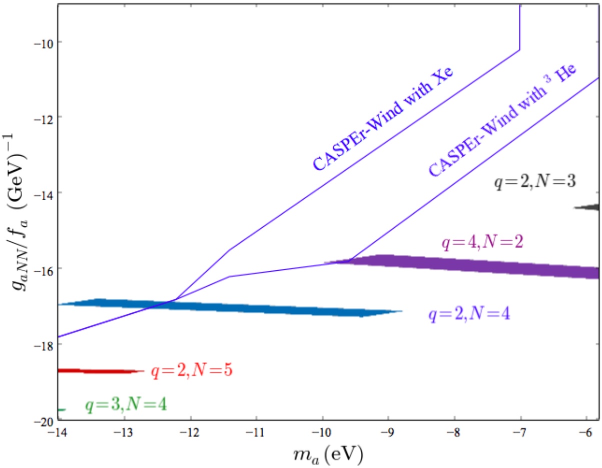
$\Omega_a h^2 = 0.12$ when:



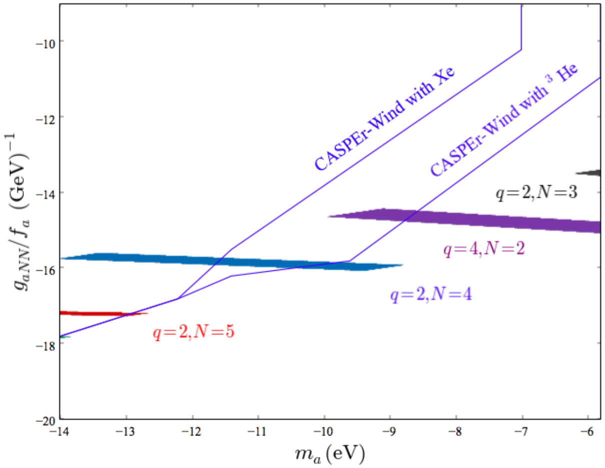
Detection with NMR (with $\frac{\partial_\mu a}{f_a}\overline{N}\gamma^\mu\gamma^5 N$):



Detection with NMR (with $\frac{\partial_\mu a}{f_a}\overline{N}\gamma^\mu\gamma^5 N$): Coupled at site 0



Detection with NMR (with $\frac{\partial_\mu a}{f_a}\overline{N}\gamma^\mu\gamma^5 N$): Coupled at site N



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Conclusions

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In the minimal setup, the (unavoidable) **gravity contribution is sufficient to provide the correct DM density**.
NMR-based searches can then detect such a particle.

Thank you!

Backups

Origin of the log for the QCD axion?

KSVZ model: anomalous set of fermions

$$\mathcal{L} \supset \phi \overline{Q_L} Q_R + h.c. \xrightarrow{Q\text{ loop}} \log\left(\frac{\phi}{f}\right) G\tilde{G}$$

Gauge-anomalous now. **Need more fermions**:

$$\mathcal{L} \supset \phi_0 \overline{Q_{L,0}} Q_{R,0} + h.c.$$

$$\xrightarrow{U(1)_1\text{ anom.}} \mathcal{L} \supset \phi_0 \overline{Q_{L,0}} Q_{R,0} + \sum_{i=1}^{q} \phi_1 \overline{Q^i_{L,1}} Q^i_{R,1} + h.c.$$

$$\xrightarrow{U(1)_2\text{ anom.}} \mathcal{L} \supset \phi_0 \overline{Q_{L,0}} Q_{R,0} + \sum_{i=1}^{q} \phi_1 \overline{Q^i_{L,1}} Q^i_{R,1} + \sum_{i=1}^{q^2} \phi_2 \overline{Q^i_{L,2}} Q^i_{R,2} + h.c.$$

$$\xrightarrow{U(1)_3\text{ anom.}} \dots$$

Origin of the log for the QCD axion?

KSVZ model: anomalous set of fermions

$$\mathcal{L} \supset \phi \overline{Q_L} Q_R + h.c. \xrightarrow{Q \text{ loop}} \log\left(\frac{\phi}{f}\right) G\tilde{G}$$

Gauge-anomalous now. **Need more fermions**:

$$\mathcal{L} \supset \phi_0 \overline{Q_{L,0}} Q_{R,0} + h.c.$$

$$\xrightarrow{U(1)_1 \text{ anom.}} \mathcal{L} \supset \phi_0 \overline{Q_{L,0}} Q_{R,0} + \sum_{i=1}^{q} \phi_1 \overline{Q^i_{L,1}} Q^i_{R,1} + h.c.$$

$$\xrightarrow{U(1)_2 \text{ anom.}} \dots$$

$$\rightarrow i \log\left(\frac{\phi_0 \phi_1^q \dots \phi_N^{q^N}}{f^{1+q+\dots}}\right) G\tilde{G}$$

$\boldsymbol{q = 3, N = 2}$ $\rightarrow$ 13 additional colored Dirac fermions (+13 additional singlet Dirac fermions)

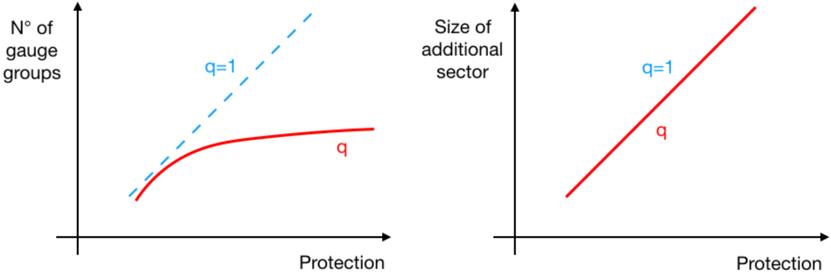
Number of fermions $\sim q^N$: growing with protection quality

General feature:

$$\mathcal{L} \supset -\sum_i (\mathcal{O}_i \overline{\psi_{i,L}} \psi_{i,R}) \xrightarrow{\text{triangles}} \frac{i}{32\pi^2} \log\left(\prod_i \mathcal{O}_i\right) G\tilde{G}$$

General feature:

$$\mathcal{L} \supset -\sum_i (\mathcal{O}_i \overline{\psi_{i,L}} \psi_{i,R}) \xrightarrow{\text{triangles}} \frac{i}{32\pi^2} \log\left(\prod_i \mathcal{O}_i\right) G\tilde{G}$$



Stability of the DM ALP's?

No anomaly: **no ALP-photon conversion** via usual $\mathcal{L} \supset \frac{a}{f_a} F\tilde{F}$

Instead: **derivative interactions** + tiny mass → **long lifetime**

Example: coupling to a heavy anomaly-free set of electrically charged fermions:

$$\mathcal{L} \supset y_1 \phi_i \overline{\psi_{R,1}} \psi_{L,1} + y_2 \phi_i \overline{\psi_{L,2}} \psi_{R,2} + h.c. \ .$$

$$\xrightarrow{\text{fermions integr.}} \mathcal{L}_{eff} \supset \frac{e^2}{48\pi^2 q^i f}\left(\frac{1}{m_1^2} - \frac{1}{m_2^2}\right)(\Box a F\tilde{F} - \frac{1}{2}\partial_\mu a F_{\nu\eta}\partial^\eta \tilde{F}^{\mu\nu})$$

Lifetimes for the FDM: $\sim 10^{300}$s

Detection of these ALP's?

No anomaly: **no ALP-photon conversion** via usual $\mathcal{L} \supset \frac{a}{f_a} F\tilde{F}$

But **possible ALP-spin couplings:**

$$\mathcal{L} \supset \frac{g_{aee}}{f_a}\partial_\mu a \; \overline{e}\gamma^\mu\gamma_5 e + \frac{g_{aNN}}{f_a}\partial_\mu a \; \overline{N}\gamma^\mu\gamma_5 N$$

Example: coupling to the first SM generation

$$\mathcal{L} \supset \; -\frac{1}{M_P}\Big(\overline{u_R} H\phi_i Y_u Q_L + \overline{d_R}(H\phi_i)^* Y_d Q_L + \overline{e_R}(H\phi_i)^* Y_e L_L\Big) + h.c.$$

$$\xrightarrow{\text{chiral redef.}} \mathcal{L} \supset \; \frac{-iq^i \partial_\mu a}{2\sqrt{1+...+q^{2N}}f}(\overline{u}\gamma_5\gamma^\mu u + \overline{d}\gamma_5\gamma^\mu d + \overline{e}\gamma_5\gamma^\mu e)$$