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# Axions in a highly protected gauge symmetry model

#### Quentin Bonnefoy

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

Centre de Physique Théorique - École Polytechnique

Planck 2018 Bonn, May 23rd 2018 Motivation and modelCouplings and scales in the EFTApplication: ALP DM detectionConclusions0000000000000000

# Outline

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## Motivation and model

Couplings and scales in the EFT

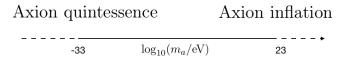
Application: ALP DM detection

Conclusions

# Motivation and model

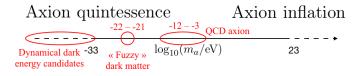
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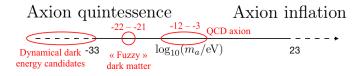
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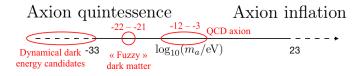
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Small masses: need for a controlled explicit breaking

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Small masses: need for a controlled explicit breaking

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

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

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# Protection of global symmetries: make them accidental.

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### Protection of global symmetries: make them accidental.

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• B, L in the renormalizable standard model lagrangian

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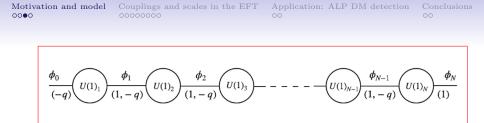
#### Protection of global symmetries: make them accidental.

- B, L in the renormalizable standard model lagrangian
- this talk:

$$\frac{\phi_{0}}{(-q)} \underbrace{U(1)_{1}}_{(1,-q)} \underbrace{\psi_{1}}_{(1,-q)} \underbrace{\psi_{2}}_{(1,-q)} \underbrace{U(1)_{3}}_{(1,-q)} - - - \underbrace{U(1)_{N-1}}_{(1,-q)} \underbrace{\psi_{N-1}}_{(1,-q)} \underbrace{U(1)_{N}}_{(1)} \underbrace{\phi_{N}}_{(1)} \\
\mathcal{L} = -\frac{1}{4} \sum_{i=1}^{N} F_{\mu\nu,i} F_{i}^{\mu\nu} - \sum_{k=0}^{N} |D_{\mu}\phi_{k}|^{2} - V(|\phi_{0}|^{2}, |\phi_{1}|^{2}, ...)$$

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)

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

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

$$\frac{\phi_{0}}{(-q)} \underbrace{U(1)_{1}}_{(1,-q)} \underbrace{\phi_{1}}_{(1,-q)} \underbrace{U(1)_{2}}_{(1,-q)} \underbrace{\phi_{2}}_{(1,-q)} \underbrace{U(1)_{3}}_{(1,-q)} - - - \underbrace{U(1)_{N-1}}_{(1,-q)} \underbrace{\phi_{N-1}}_{(1,-q)} \underbrace{U(1)_{N}}_{(1)} \underbrace{\phi_{N}}_{(1)} \\
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- A global accidental  $U(1): \phi_k \to e^{iq^k\alpha}\phi_k$
- A Goldstone boson:  $a \sim \frac{1}{q^N f_0} \theta_0 + \frac{1}{q^{N-1} f_1} \theta_1 + ... + \frac{1}{f_N} \theta_N$

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$$\begin{split} & \underbrace{\phi_0}_{(-q)} \underbrace{U(1)_1}_{(1,-q)} \underbrace{\phi_1}_{(1,-q)} \underbrace{\phi_2}_{(1,-q)} \underbrace{U(1)_3}_{(1,-q)} & - - - - \underbrace{U(1)_{N-1}}_{(1,-q)} \underbrace{\phi_{N-1}}_{(1,-q)} \underbrace{U(1)_N}_{(1)} \underbrace{\phi_N}_{(1)} \\ & \mathcal{L} = -\frac{1}{4} \sum_{i=1}^N F_{\mu\nu,i} F_i^{\mu\nu} - \sum_{k=0}^N |D_\mu \phi_k|^2 - V(|\phi_0|^2, |\phi_1|^2, \dots) \end{split}$$

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• High dimension breaking operators:  $\frac{\phi_0\phi_1^q...\phi_N^{q^N}}{M_{-1}^{1+q+...+q^N-4}}$ 

$$\begin{split} & \underbrace{\phi_0}_{(-q)} \underbrace{U(1)_1}_{(1,-q)} \underbrace{\phi_1}_{(1,-q)} \underbrace{\psi_2}_{(1,-q)} \underbrace{U(1)_3}_{(1,-q)} - - - \underbrace{U(1)_{N-1}}_{(1,-q)} \underbrace{\phi_{N-1}}_{(1,-q)} \underbrace{U(1)_N}_{(1)} \underbrace{\phi_N}_{(1)} \\ & \mathcal{L} = -\frac{1}{4} \sum_{i=1}^N F_{\mu\nu,i} F_i^{\mu\nu} - \sum_{k=0}^N |D_\mu \phi_k|^2 - V(|\phi_0|^2, |\phi_1|^2, \dots) \end{split}$$

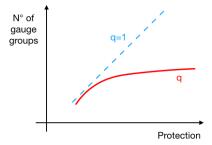
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- High dimension breaking operators:  $\frac{\phi_0\phi_1^q...\phi_N^{qN}}{M_P^{1+q+...+q^N-4}}$ 

Can protect a QCD axion or explain very-low DM masses

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$$\frac{\phi_{0}}{(-q)} \underbrace{U(1)_{1}}_{(1,-q)} \underbrace{\psi_{1}}_{(1,-q)} \underbrace{U(1)_{2}}_{(1,-q)} \underbrace{U(1)_{3}}_{(1,-q)} - - - \underbrace{U(1)_{N-1}}_{(1,-q)} \underbrace{\psi_{N-1}}_{(1,-q)} \underbrace{U(1)_{N}}_{(1)} \underbrace{\phi_{N}}_{(1)} \underbrace{\psi_{N}}_{(1)} \underbrace{\psi_{$$



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# Couplings and scales in the EFT

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#### Phenomenology of axion models: characterized by axion mass

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#### Phenomenology of axion models: characterized by axion mass

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### and couplings to SM fields $% \left( {{{\mathbf{N}}_{\mathrm{S}}}} \right)$

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

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$$\mathcal{L} \supset \frac{g_{a\gamma\gamma}}{f_a} a F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{g_{aNN}}{f_a} \partial_\mu a \overline{N} \gamma^\mu \gamma^5 N + \dots$$

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$$\mathcal{L} \supset \frac{g_{a\gamma\gamma}}{f_a} a F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{g_{aNN}}{f_a} \partial_\mu a \overline{N} \gamma^\mu \gamma^5 N + \dots$$

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Axion field 
$$a = \frac{\theta_0 + q\theta_1 + \dots + q^N \theta_N}{\sqrt{1 + q^2 + \dots + q^{2N}}}$$

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KSVZ model of invisible QCD axion: anomalous set of fermions

$$\mathcal{L} \supset \phi \overline{Q_L} Q_R + h.c. \xrightarrow{Q \text{ triangle loop}} \frac{a}{f} F \tilde{F}$$

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Gauge-anomalous now. Need more fermions:

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

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

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$$\mathcal{L} \supset \frac{g_{a\gamma\gamma}}{f_a} a F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{g_{aNN}}{f_a} \partial_\mu a \overline{N} \gamma^\mu \gamma^5 N + \dots$$

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 $U(1)_2$  anom.

$$\xrightarrow{\text{triangle loops}} \frac{\sqrt{1+q^2+\ldots+q^{2N}}}{f} a F \tilde{F}$$

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$$\mathcal{L} \supset \frac{g_{a\gamma\gamma}}{f_a} a F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{g_{aNN}}{f_a} \partial_{\mu} a \overline{N} \gamma^{\mu} \gamma^5 N + \dots$$

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

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$$\mathcal{L} \supset \frac{g_{a\gamma\gamma}}{f_a} a F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{g_{aNN}}{f_a} \partial_\mu a \overline{N} \gamma^\mu \gamma^5 N + \dots$$

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

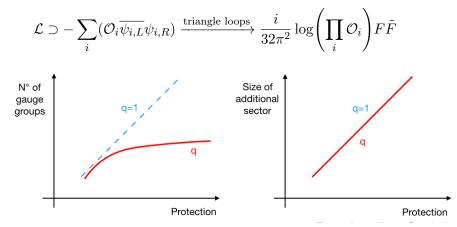
$$\mathcal{L} \supset -\sum_{i} (\mathcal{O}_{i} \overline{\psi_{i,L}} \psi_{i,R}) \xrightarrow{\text{triangle loops}} \frac{i}{32\pi^{2}} \log \left(\prod_{i} \mathcal{O}_{i}\right) F \tilde{F}$$

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$$\mathcal{L} \supset \frac{g_{a\gamma\gamma}}{f_a} a F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{g_{aNN}}{f_a} \partial_\mu a \overline{N} \gamma^\mu \gamma^5 N + \dots$$

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Example: coupling to the first SM generation

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

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$$\mathcal{L} \supset \frac{g_{a\gamma\gamma}}{f_a} a F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{g_{aNN}}{f_a} \partial_\mu a \overline{N} \gamma^\mu \gamma^5 N + \dots$$

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

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$$\mathcal{L} \supset \frac{g_{a\gamma\gamma}}{f_a} a F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{g_{aNN}}{f_a} \partial_\mu a \overline{N} \gamma^\mu \gamma^5 N + \dots$$

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Site-dependent coupling to the spins derived in minimal setup

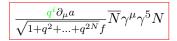
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Axion field 
$$a = \frac{\theta_0 + q\theta_1 + \dots + q^N \theta_N}{\sqrt{1 + q^2 + \dots + q^{2N}}}$$

In the effective theory:

$$\frac{\sqrt{1+q^2+\ldots+q^{2N}}}{f}aF\tilde{F}$$



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$$\mathcal{L} \supset \frac{g_{a\gamma\gamma}}{f_a} a F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{g_{aNN}}{f_a} \partial_\mu a \overline{N} \gamma^\mu \gamma^5 N + \dots$$

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$$\frac{\sqrt{1+q^2+\ldots+q^{2N}}}{f}aF\tilde{F} \qquad \frac{q^i\partial_\mu a}{\sqrt{1+q^2+\ldots+q^{2N}}f}\overline{N}\gamma^\mu\gamma^5N$$
Scales:  $f \quad \frac{f_a}{g_{a\gamma\gamma}} = \frac{f}{\sqrt{1+q^2+\ldots+q^{2N}}} \qquad \frac{f_a}{g_{aee}} = \frac{\sqrt{1+q^2+\ldots+q^{2N}}f}{q^i}$ 

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$$a = \frac{\theta_0 + q\theta_1 + \dots + q^N \theta_N}{\sqrt{1 + q^2 + \dots + q^{2N}}}$$

In the effective theory:

$$\begin{array}{ccc} \log\left(\phi_{0}\phi_{1}^{q}...\phi_{N}^{q^{N}}\right)F\tilde{F} & & \frac{\phi_{i}^{*}D_{\mu}\phi_{i}}{f^{2}}\overline{N}\gamma^{\mu}\gamma^{5}N \\ & \downarrow & & \downarrow \\ \hline \sqrt{1+q^{2}+...+q^{2N}}aF\tilde{F} & & \frac{q^{i}\partial_{\mu}a}{\sqrt{1+q^{2}+...+q^{2N}f}}\overline{N}\gamma^{\mu}\gamma^{5}N \\ \end{array}$$
Scales: 
$$f \quad \frac{f_{a}}{g_{a\gamma\gamma}} = \frac{f}{\sqrt{1+q^{2}+...+q^{2N}}} & & \frac{f_{a}}{g_{aee}} = \frac{\sqrt{1+q^{2}+...+q^{2N}f}}{q^{i}} \end{array}$$

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$$\begin{array}{c} \begin{array}{c} \mbox{Motivation and model} & \mbox{Couplings and scales in the EFT} & \mbox{Application: ALP DM detection} & \mbox{Conclusions} & \mbox{oo} \end{array} \\ \\ \mbox{$\mathcal{L}$} \supset & \begin{array}{c} \mbox{$\frac{g_{a\gamma\gamma}}{f_a}aF_{\mu\nu}\tilde{F}^{\mu\nu}$} \\ \end{array} \\ + \begin{array}{c} \mbox{$\frac{g_{aNN}}{f_a}\partial_{\mu}a\overline{N}\gamma^{\mu}\gamma^5N$} \\ \end{array} \\ + \dots \end{array} \end{array}$$

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$$\begin{array}{c} \begin{array}{c} \mbox{Motivation and model} & \mbox{Couplings and scales in the EFT} & \mbox{Application: ALP DM detection} & \mbox{Conclusions} & \mbox{oo} & \mbox{$$

Anomalous symmetry:

• needs a non-minimal setup (specific matter at each site) due to the protection

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$$\begin{array}{c} \begin{array}{c} \mbox{Motivation and model} & \mbox{Couplings and scales in the EFT} & \mbox{Application: ALP DM detection} & \mbox{Conclusions} & \mbox{oo} \end{array} \\ \\ \mbox{$\mathcal{L} \supset \left[ \frac{g_{a\gamma\gamma}}{f_a} a F_{\mu\nu} \tilde{F}^{\mu\nu} \right] + \left[ \frac{g_{aNN}}{f_a} \partial_{\mu} a \overline{N} \gamma^{\mu} \gamma^5 N \right] + \dots } \end{array} \right.$$

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Symmetry-preserving operators:

• can be present in minimal setups

$$\mathcal{L} \supset \frac{g_a \gamma \gamma}{f_a} a F_{\mu\nu} F^{\mu\nu} + \frac{g_a N N}{f_a} \partial_\mu a N \gamma^\mu \gamma^5 N + \dots$$

Anomalous symmetry:

- needs a non-minimal setup (specific matter at each site) due to the protection
- implies a reduced decay constant due to the number of particles contributing to the anomaly

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Symmetry-preserving operators:

• can be present in minimal setups

Motivation and model Couplings and scales in the EFT Application: ALP DM detection Conclusions on 
$$\int \frac{g_{a\gamma\gamma}}{\sqrt{2\pi}} aF = \tilde{F}^{\mu\nu} + \frac{g_{aNN}}{\sqrt{2\pi}} a\overline{N} \sqrt{\mu} \sqrt{5} N + \frac{g_{a\gamma\gamma}}{\sqrt{2\pi}} aF = \tilde{F}^{\mu\nu}$$

$$\mathcal{L} \supset \frac{g_{a\gamma\gamma}}{f_a} a F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{g_{aNN}}{f_a} \partial_\mu a \overline{N} \gamma^\mu \gamma^5 N + \dots$$

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Symmetry-preserving operators:

- can be present in minimal setups
- are site-localized and display clockwork properties of the theory

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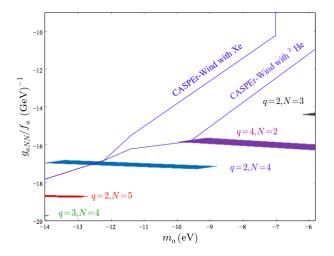
### Application: ALP DM detection

Couplings and scales in the EFT Application: ALP DM detection Conclusions .

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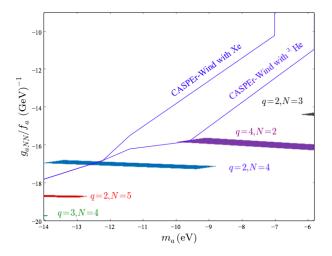
### **Detection with NMR** (with $\frac{\partial_{\mu}a}{f_a}\overline{N}\gamma^{\mu}\gamma^5 N$ obtained in minimal setup):

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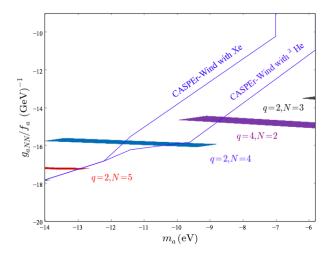
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# **Detection with NMR** (with $\frac{\partial_{\mu}a}{f_a}\overline{N}\gamma^{\mu}\gamma^5 N$ obtained in minimal setup): Coupled at site 0



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## **Detection with NMR** (with $\frac{\partial_{\mu}a}{f_a}\overline{N}\gamma^{\mu}\gamma^5 N$ obtained in minimal setup): Coupled at site N



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### Conclusions

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Motivation and model<br/>0000Couplings and scales in the EFT<br/>00000000Application: ALP DM detection<br/>00Conclusions<br/>•0

We considered a **pGB protected against (gravitational) breaking effects**. Its mass is easily very small, even with few additional gauge groups.

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#### All usual axion couplings can be generated.

Symmetry-preserving couplings are generated in minimal setups and display site-dependence, whereas anomalous couplings (such as those of a QCD axion) require the use of an extended fermion sector populating every site of the quiver.

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Symmetry-preserving couplings are generated in minimal setups and display site-dependence, whereas anomalous couplings (such as those of a QCD axion) require the use of an extended fermion sector populating every site of the quiver.

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

Application: ALP DM detection Conclusions

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### Thank you!

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### Backups

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### KSVZ model with:

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

Then:

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

Possible correction:

$$\mathcal{L}_{PQ} \supset \frac{\phi^n}{M_P^{n-4}} + h.c.$$

 $\rightarrow$  destabilizes  $\theta < 10^{-10}$  if n < 10 (if  $f \gtrsim 10^9$  GeV). Indeed:

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

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### $U(1)_{PQ}$ protection: Barr and Seckel (1992)

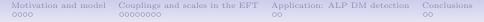
	Fields	$\phi_1$	$\phi_2$	$Q_L^{i=1\dots q}$	$\widetilde{Q}_L^{i=1\dots p}$	$Q_R^{i=1\dots p+q}$
	SU(3)	1	1	3	3	3
	U(1)	p	q	p	-q	0
	$U(1)_{PQ}$	q	-p	q	p	0
where $gcd(p,q) = 1$ and $p + q \ge 10$						
$\mathcal{L} \supset \underbrace{\phi_1 \overline{Q_L} Y Q_R + \phi_2^* \overline{\widetilde{Q}_L} \widetilde{Y} Q_R}_{\mathcal{L}_{PQ}} + \underbrace{\frac{\phi_1^q \phi_2^{*p}}{M_P^{p+q-4}}}_{\mathcal{L}_{\mathcal{PQ}}} + h.c.$						

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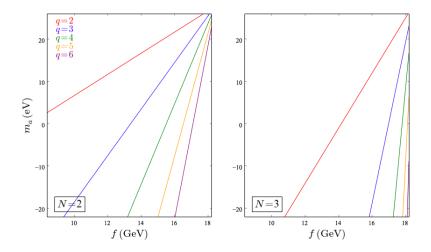
$$\frac{\phi_{0}}{(-q)} \underbrace{U(1)_{1}}_{(1,-q)} \underbrace{\psi_{1}}_{(1,-q)} \underbrace{\psi_{2}}_{(1,-q)} \underbrace{U(1)_{3}}_{(1,-q)} - - - \underbrace{U(1)_{N-1}}_{(1,-q)} \underbrace{\phi_{N-1}}_{(1,-q)} \underbrace{U(1)_{N}}_{(1)} \underbrace{\phi_{N}}_{(1)} \underbrace{\psi_{N}}_{(1)} \underbrace{\psi_{N}}$$

Gravitational breaking:

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



### Mass suppression with few additional gauge groups:

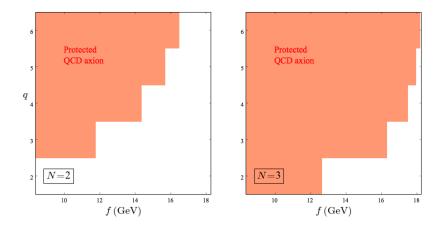


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### Application to QCD axion: $\theta_{\rm QCD} < 10^{-10}$ if $m_a^{\rm (QCD)} > 10^5 m_a^{\rm (grav)}$



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### For an ALP dark matter candidate:

#### Masses can be perturbative or non-perturbative

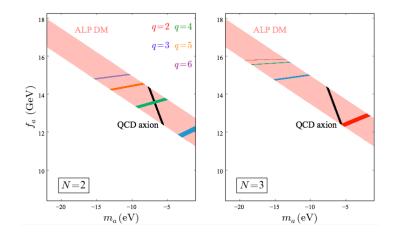
Focus here on gravitational origin and on misalignment mechanism (with pre-inflationnary breaking):

$$V = -\frac{\phi_0 \phi_1^q \dots \phi_N^{q^N}}{M_P^{1+q+\dots+q^N-4}} \supset -\left(\frac{f}{M_P}\right)^{1+q+\dots q^N} M_P^4 \cos\left(\frac{a}{f_a}\right)$$
  
and  
$$< a_{\text{init}} \ge \text{random}$$

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 $\Omega_a h^2 = 0.12$  when:



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### 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 $\rightarrow$ long lifetime

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

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

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

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

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