A highly protected global symmetry from quiver gauge symmetries

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Global symmetry explicitly but weakly broken: **nearly massless pseudo-Nambu-Goldstone boson** (pGB) in the spectrum

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Expected to be **broken by quantum gravity effects**

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

Peccei-Quinn symmetry:

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

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

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Possible correction: $\mathcal{L}_{\not{PQ}} \supset \frac{\phi^n}{M_P^{n-4}}$ → **destabilizes $\boldsymbol{\theta < 10^{-10}}$ if $\boldsymbol{n < 10}$**

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Examples:

- B, L in the renormalizable standard model lagrangian
- Known examples for Peccei-Quinn symmetry (Barr and Seckel (1992), etc)

Outline

A quiver gauge theory and a pGB

Protected Goldstone bosons from 5D: **fifth component of a gauge field**

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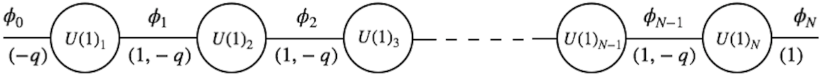
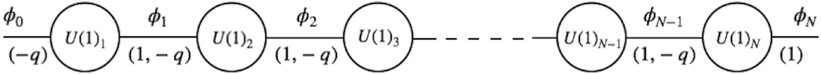
With a 5d **linear dilaton geometry**:



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

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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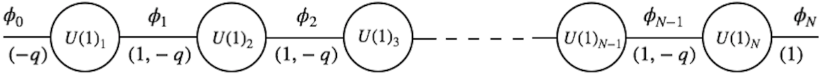

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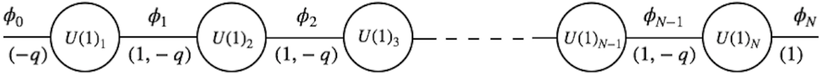
How much approximate? Gauge invariant operators:

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

$\rightarrow$ **exponential increase of the order of the breaking operators** with q and N



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In the spectrum:

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

QCD axion

KSVZ model ($\mathcal{L}_{PQ} \supset \phi\overline{Q_L}Q_R$): axionic coupling to gluons

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Not gauge-invariant now. Only possibility:

$$\mathcal{L} \supset \log\left(\frac{\phi_0 \phi_1^q \ldots \phi_N^{q^N}}{f^{1+q+\ldots}}\right) G\tilde{G} \sim \frac{q^N a}{f} G\tilde{G}$$

Results into:

$$\mathcal{L} \supset m_\pi^2 f_\pi^2 \cos\left(\frac{a}{f_a} + \theta_{\text{QCD}}\right), \text{ with } f_a = \frac{f}{\sqrt{1 + q^2 + ... + q^{2N}}}$$

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Explicit breaking term:

$$\frac{\phi_0 \phi_1^q ... \phi_N^{q^N}}{M_P^{1+q+...+q^N-4}}$$

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

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

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Origin of the log?

KSVZ model: anomalous set of fermions

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

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

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

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

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

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General feature:

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

Sum-up:

- **protected QCD axion**
- **need for an appropriate, non-minimal new sector**

ALP's in cosmology

Pseudo-Goldstone bosons in cosmology

Consistent DM candidates

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Focus on **misalignment mechanism**
Initial conditions $< a >_{\text{init}}$=random

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

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- **DM with correct relic density possible**
- **Small masses with few gauge groups**
  Ex: FDM for $f \approx 0.2 M_P, q = 3$ and $N = 4$

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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

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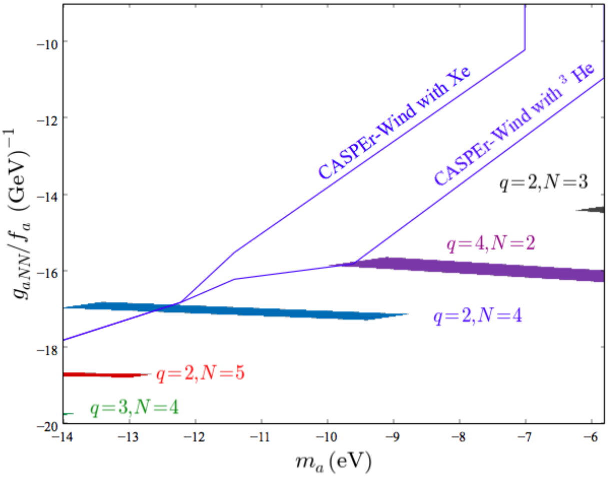
Example: coupling to the first SM generation

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

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

Detection with NMR:



Sum-up:

- **realization of small masses with few gauge groups**
- **gravitational contributions sufficient to recover the DM relic density**
- **non-anomalous couplings**

Conclusions

We considered a **pGB protected against (gravitational) breaking effects**. Its mass is easily very small.

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It can be a **consistent QCD axion**, but the protection comes with a price.

If there is no anomaly, the (unavoidable) **gravity contribution is sufficient to provide the correct DM density**. Then, however, only NMR-based searches can detect such a particle.

Thank you!