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# Axion quality from the symmetric of SU($N$)

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based on M. Ardu, L. Di Luzio, A. Strumia, D. Teresi and J. Wang, JHEP 11 (2020) 090

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HIDDeν Hunting Invisibles: Dark sectors, Dark matter and Neutrinos
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# Outline

- The Peccei-Quinn (PQ) solution to the Strong CP problem is problematic
- Simple axion models are not able to solve the Strong CP problem
- New gauge symmetries can solve the issue

# The Strong CP problem

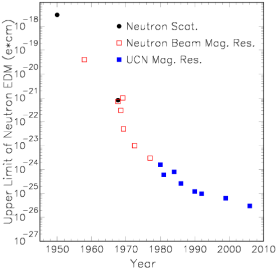
CP violation in QCD

$$\mathcal{L}_{\text{QCD}} \supset \bar{\theta}\frac{\alpha_s}{8\pi} G^a_{\mu\nu}\widetilde{G}^{\mu\nu}_a$$

- gauge invariant
- renormalizable

➡ *natural expectation* $\rightarrow \bar{\theta} \sim \mathcal{O}(1)$

*Prediction:* non-zero neutron eletric dipole moment $d_n \approx 10^{-16}|\bar{\theta}|e{\cdot}\text{cm}$




➡ $|\bar{\theta}| \lesssim 10^{-10}$

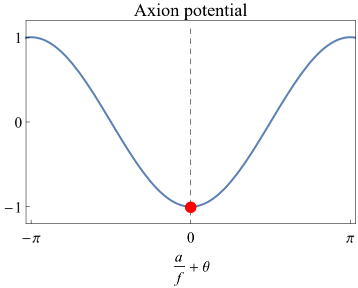
*Why so small?*

# Peccei-Quinn mechanism

A new global *chiral* $\mathrm{U}(1)_{\mathrm{PQ}}$ symmetry

1. spontaneously broken
   $\longrightarrow$ a new *Goldstone* boson: the *axion*
2. QCD anomalous $\approx$ generates the axion-gluon coupling

$$\mathcal{L}_{\mathrm{QCD}}^{\mathrm{PQ}} \supset \left(\bar{\theta} - \frac{a(x)}{f_a}\right) \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a \equiv \theta_{\mathrm{eff}}(x) \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a$$




$\langle \theta_{\mathrm{eff}} \rangle = 0$

CP-conserving minimum!

# The modern point of view on global symmetries

Global symmetries (as $\mathrm{U}(1)_{\mathrm{PQ}}$) arise *accidentally* at low-energy scales

$$\mathcal{L} = \mathcal{L}^{(4)}$$

They are broken by UV physics (non-renormalizable operators)

$$\Delta\mathcal{L}_{\mathrm{UV}} \sim \frac{1}{\Lambda_{\mathrm{UV}}^{d-4}}\mathcal{O}^{[d]}, \qquad d > 4$$

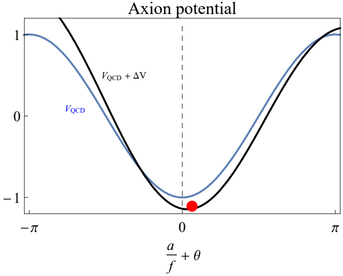
Quantum gravity conjectures: $\mathrm{U}(1)_{\mathrm{PQ}}$ broken at $\Lambda_{\mathrm{UV}} = M_{\mathrm{Pl}}$

New contributions to the potential from $\mathrm{U}(1)_{\mathrm{PQ}}$-breaking operators

$$\mathcal{O}^{[d]}_{\not{\mathrm{PQ}}} \longrightarrow \qquad \Delta V_{\mathrm{UV}}(\theta_{\mathrm{eff}}) \propto \Lambda_{\mathrm{UV}}^4 \left(\frac{f_a}{\Lambda_{\mathrm{UV}}}\right)^d$$

# PQ quality problem

The minimum of the $V(\theta_{\text{eff}})$ potential is shifted




Generic *CP-violating* minimum $\langle\theta_{\text{eff}}\rangle \neq 0$. We need $\theta_{\text{eff}} < 10^{-10}$

$$\left(\frac{f_a}{\Lambda_{\text{UV}}}\right)^{d-4} f_a^4 \lesssim 10^{-10}\Lambda_{\text{QCD}}^4$$

$\text{U}(1)_{\text{PQ}}$ *must be preserved up to operators of dimension* $d \gtrsim 12$

**Very good symmetry of UV physics! (High-quality)**

# The symmetric model

- Gauge group $G = G_{\rm SM} \times \mathrm{SU}(N)$ with $\mathcal{S}$ in the symmetric

| Field name | Lorentz spin | Gauge symmetries $\mathrm{U}(1)_Y$ | $\mathrm{SU}(2)_L$ | $\mathrm{SU}(3)_c$ | $\mathrm{SU}(N)$ | Global accidental symmetries $\mathrm{U}(1)_{\rm PQ}$ | $\mathrm{U}(1)_{\mathcal{Q}}$ | $\mathrm{U}(1)_{\mathcal{L}}$ |
|---|---|---|---|---|---|---|---|---|
| $\mathcal{S}$ | 0 | 0 | 1 | 1 | $NN$ | $+1$ | 0 | 0 |
| $\mathcal{Q}_L$ | $1/2$ | $+Y_{\mathcal{Q}}$ | 1 | 3 | $N$ | $+1/2$ | $+1$ | 0 |
| $\mathcal{Q}_R$ | $1/2$ | $-Y_{\mathcal{Q}}$ | 1 | $\bar{3}$ | $N$ | $+1/2$ | $-1$ | 0 |
| $\mathcal{L}_L^{1,2,3}$ | $1/2$ | $+Y_{\mathcal{L}}$ | 1 | 1 | $\bar{N}$ | $-1/2$ | 0 | $+1$ |
| $\mathcal{L}_R^{1,2,3}$ | $1/2$ | $-Y_{\mathcal{L}}$ | 1 | 1 | $\bar{N}$ | $-1/2$ | 0 | $-1$ |

- accidental $\mathrm{U}(1)_{\rm PQ}$ at the renormalizable level
- $\langle \mathcal{S} \rangle \sim f_a$ breaks $\mathrm{SU}(N) \otimes \mathrm{U}(1)_{\rm PQ} \to \mathrm{SO}(N)$
- 2 scales: $f_a$ and confinement scale $\Lambda_{\rm SO} \ll f_a$

# Solving the axion quality problem

**PQ charges**

$q_{\mathrm{PQ}}(\mathcal{S}_{IJ}) = 1 \qquad q_{\mathrm{PQ}}(\mathcal{Q}_I) = 1/2 \qquad q_{\mathrm{PQ}}(\mathcal{L}^I) = -1/2$

- *Dangerous operators*

  (1) *gauge-invariant*
  (2) $\mathrm{U}(1)_{\mathrm{PQ}}$-breaking

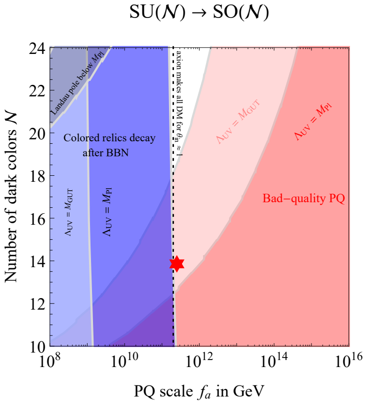
- Lowest-dimensional $\mathrm{U}(1)_{\mathrm{PQ}}$-breaking operator arises at dimension $N$

- If $N$ is large enough $\to$ quality problem solved! ($N \gtrsim 12$ for $\Lambda_{\mathrm{UV}} = M_{\mathrm{Pl}}$)

**Message:** gauge-invariance forbids $\mathrm{U}(1)_{\mathrm{PQ}}$-breaking below dimension $N$ and allows for *arbitrary* high protection

# Parameter space

- Constraints
  - PQ quality
  - Colored relics ($\mathcal{Q}$ bound states) must decay before BBN
  - No Landau Poles below $\Lambda_{\rm UV}$



# Dark Matter

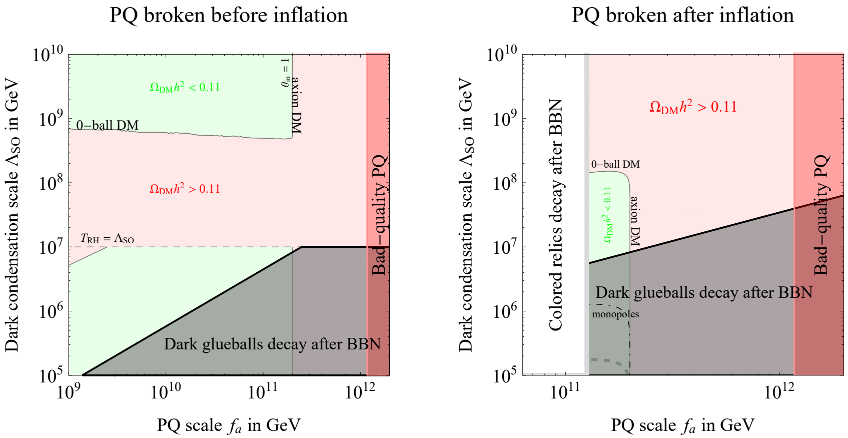
- axions

# Dark Matter

- axions
- composite SO($N$) bound states
  - they form after gauge confinement at $\Lambda_{\text{SO}} \ll f_a$
  - stabilized by an *accidental* $Z_2$ symmetry
  - thermal production (freeze-out or freeze-in)

# Dark Matter

- axions
- composite $SO(N)$ bound states



# Conclusions

- The Peccei-Quinn mechanism has a *UV-sensitivity* problem
- *Gauge dynamics* provides a consistent implementation...
- ...and can explain the *Dark Matter* abundance of the Universe!