Automatic Peccei-Quinn symmetry

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The axion solution

- ➔ Strong CP: Why is $\bar{\theta}$ so small? $\bar{\theta} \lesssim 10^{-10}$
- ➔ If $\bar{\theta}$ were a scalar field, its vev would be zero [Vafa+Witten, 84]

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

- ➔ Introduce a $U(1)_{PQ}$ symmetry (classically exact): [Peccei+Quinn 77]
  - ◆ Spontaneously broken $\longrightarrow$ pGoldstone Boson: AXION
  - ◆ Anomalous: explicitly broken by QCD instantons $\longrightarrow$ massive

Massless quarks: Dynamical Axion

[Choi+Kim 85]

- Under a axial rotation: $U(1)_A: \quad q \to e^{\frac{\alpha}{2} i\gamma_5} q$

$$\mathcal{L} \supset -m_q \bar{q} q - \theta \frac{\alpha_s}{8\pi} G\tilde{G} \longrightarrow -m_q \bar{q} e^{i\alpha\gamma_5} q - (\theta - \alpha)\frac{\alpha_s}{8\pi} G\tilde{G}$$

Massless quarks: Dynamical Axion

[Choi+Kim 85]

- ➔ Under a axial rotation: $U(1)_A : \quad q \to e^{\frac{\alpha}{2} i\gamma_5} q$

$$\mathcal{L} \supset \cancel{-m_q \bar{q} q} - \theta \frac{\alpha_s}{8\pi} G\tilde{G} \longrightarrow \cancel{-m_q \bar{q} e^{i\alpha\gamma_5}} q - (\theta - \alpha) \frac{\alpha_s}{8\pi} G\tilde{G}$$

- ➔ New confining group $\tilde{\Lambda} \gg \Lambda_{QCD}$
- ➔ Two massless quarks ⇔ two $\theta' s$

	$SU(3)_c$	$SU(\tilde{N})$
ψ	$\square$	$\square$
χ	1	$\square$

- ➔ $SU(\tilde{N})$ Confines + Chiral Symmetry Breaking: $U(4)_L \times U(4)_R \xrightarrow[\langle\bar{\chi}\chi\rangle]{\langle\bar{\psi}\psi\rangle} U(4)_V$

pseudo-Goldstone Bosons (pGB): $16 = 8 + 3 + \bar{3} + 1 + 1$

The η' becomes the dynamical axion

Massless quarks: Dynamical Axion

[Choi+Kim 85]

- Under a axial rotation: $U(1)_A: \quad q \rightarrow e^{\frac{\alpha}{2} i\gamma_5} q$

$\mathcal{L} \supset$

- New

- Two

- $SU($

pseud

$SU(\tilde{N})$

$\square$

$\square$

$\xrightarrow[\langle\bar{\chi}\chi\rangle]{\langle\bar{\psi}\psi\rangle} U(4)_V$

Just another UV completion of the invisible axion...

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

... but composite

The η' becomes the dynamical axion

Invisible Axion drawbacks

➔ The $U(1)_{PQ}$ symmetry is imposed

$$\mathcal{L} \supset -m\cancel{\bar{\psi}}\psi - m\cancel{\bar{\chi}}\chi$$

➔ PQ quality: Quantum gravity operators

$$g_5 \frac{|\Phi|^4 (\Phi + \Phi^*)}{M_{\text{Planck}}}$$

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➔ Possible solution: Accidental axions

[Randall 92]
[Dobrescu 97]
[Butter+Gaillard 05]
[Redi+Sato 16]
[Fukuda et al 17]
[Ibe et al 18]
[Lillard+Tait 18]
[Gavela+Ibe+PQ+Yanagida 18]

Automatic Peccei-Quinn Symmetry

M.B. Gavela, M. Ibe, P.Q, T. T. Yanagida

Dynamical axion with automatic and protected PQ due to chiral SU(5)

Automatic PQ

		$SU(5)$	$SU(3)_c$
LH	$\psi_{\bar{5}}$	$\bar{\mathbf{5}}$	$\mathbf{R}$
	ψ_{10}	$\mathbf{10}$	$\mathbf{R}$

- ➔ Free from gauge anomalies
  - Analogous to usual SU(5) GUT: **5*** + **10**
  - **R** is a pseudoreal representation

Automatic PQ

	$SU(5)$	$SU(3)_c$	$U(1)_{PQ}$
$\psi_{\bar{5}}$	$\bar{\mathbf{5}}$	$\mathbf{8}$	-3
ψ_{10}	$\mathbf{10}$	$\mathbf{8}$	$+1$

➔ Free from gauge anomalies

- Analogous to usual SU(5) GUT: **5*** + **10**
- **8** is a pseudoreal representation

➔ Automatically we get a $U(1)_{PQ}$:

- Mass terms are automatically forbidden!
- Analogous to usual B-L in SU(5) GUT

Automatic PQ: Global chiral symmetry

➔ SU(5) confines at a high scale $\Lambda_5 \gg \Lambda_{QCD}$

$\psi_{\bar{5}}$

ψ_{10}

Are chiral symmetries spontaneously broken after confinement?

See Poster for interesting discussion

➔ The global chiral symmetry at high energies:

$$SU(8)_{5^*} \times SU(8)_{10} \times U(1)_{5^*} \times U(1)_{10} \rightarrow \boxed{SU(8)_{5^*} \times SU(8)_{10} \times U(1)_{PQ=B-L} \,.}$$

Automatic PQ: Global chiral symmetry

➔ SU

$\psi_{\bar{5}}$

ψ_{10}

➔ T

$SU(8)_5$ … $Q{=}B{-}L$ ·

When $U(1)_{PQ}$ is spontaneously broken

=> composite axion

$$\langle \bar{\mathbf{5}}\,\bar{\mathbf{5}}\,\mathbf{10}\,\bar{\mathbf{5}}\,\bar{\mathbf{5}}\,\mathbf{10}\rangle \sim \Lambda_5^9\,,$$

$$\bar{\mathbf{5}}\,\bar{\mathbf{5}}\,\mathbf{10}\,\bar{\mathbf{5}}\,\bar{\mathbf{5}}\,\mathbf{10} \sim \Lambda_5^9\, e^{-i\,10\,a/f_{\rm PQ}}\,;$$

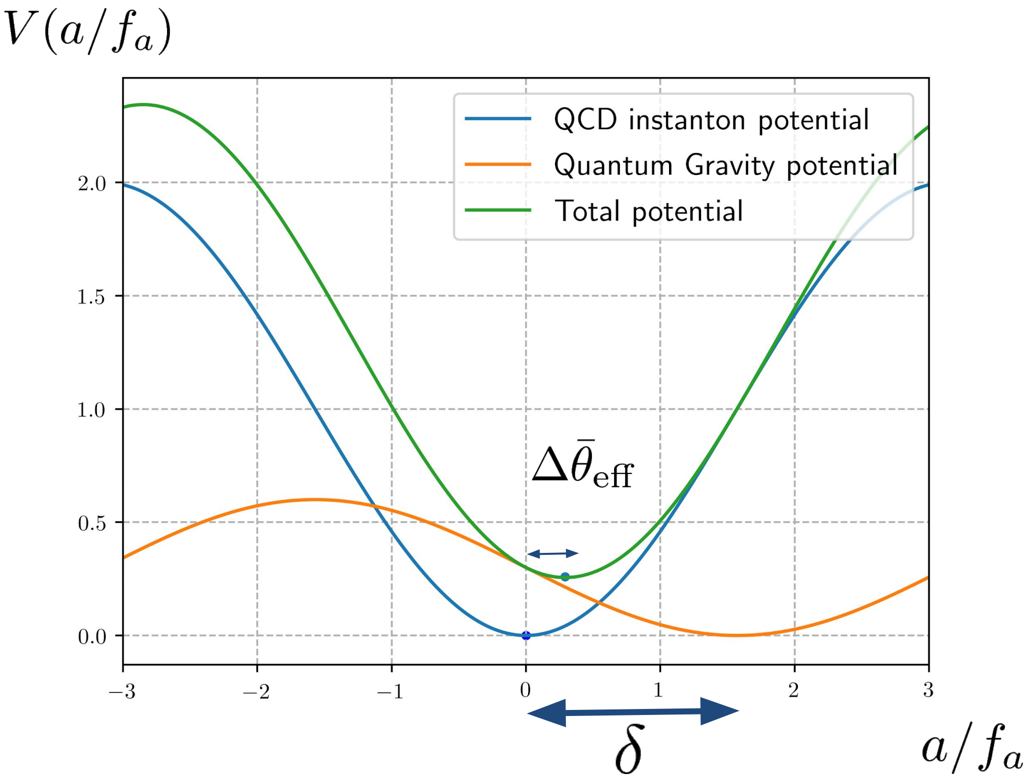
… but automatic and protected.

PQ quality

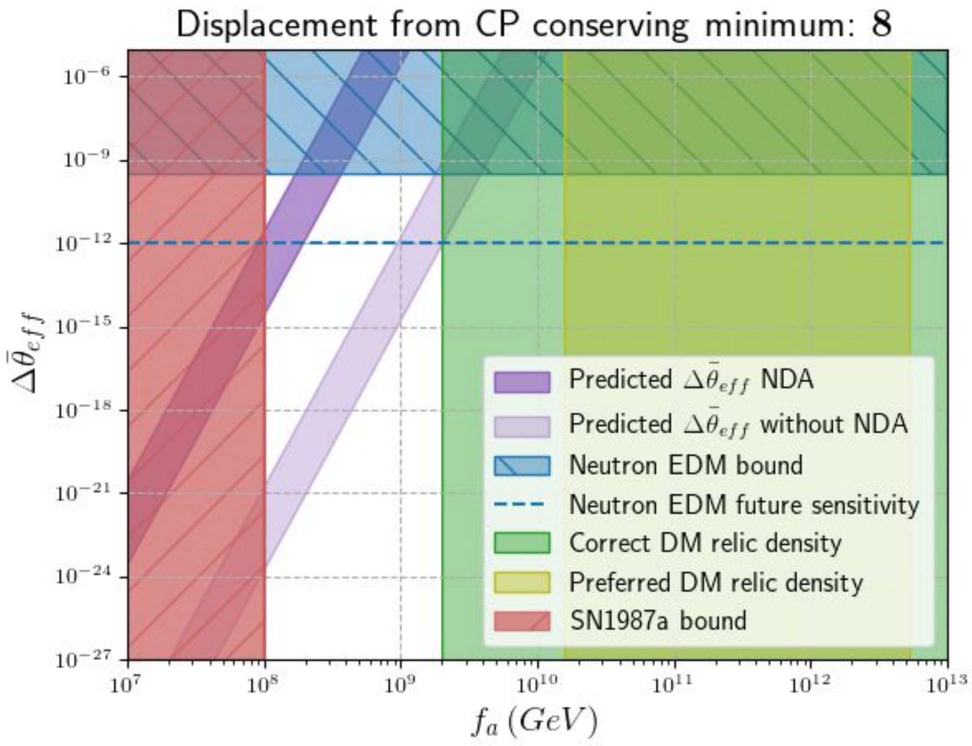
➔ Lowest dim PQV operator has d=9:

$$\mathcal{L}_{\cancel{PQ}} = c\,\frac{1}{4\pi}\,\frac{1}{M_{\rm Pl}^5}\,\frac{1}{2!\,4!}\,\bar{\mathbf{5}}\,\bar{\mathbf{5}}\,\mathbf{10}\,\bar{\mathbf{5}}\,\bar{\mathbf{5}}\,\mathbf{10}$$

$$|\Delta\bar{\theta}_{eff}| = |c\sin(\delta)|\,\frac{2\,(4\pi)^2}{4!}\left(\frac{N}{5}\right)^8\frac{f_a^9}{M_{Pl}^5\,\Lambda_{\rm QCD}^4}$$



Automatic PQ



Conclusions

- ➔ A simple dynamical (composite) axion model where the PQ symmetry arises **automatically** is constructed.
- ➔ Based on a confining group **SU(5) with chiral fermions** in pseudoreal representations of colour.
- ➔ Presents an **inherent protection** from dangerous quantum non-perturbative gravitational effects.

Thank you!

Strong CP problem

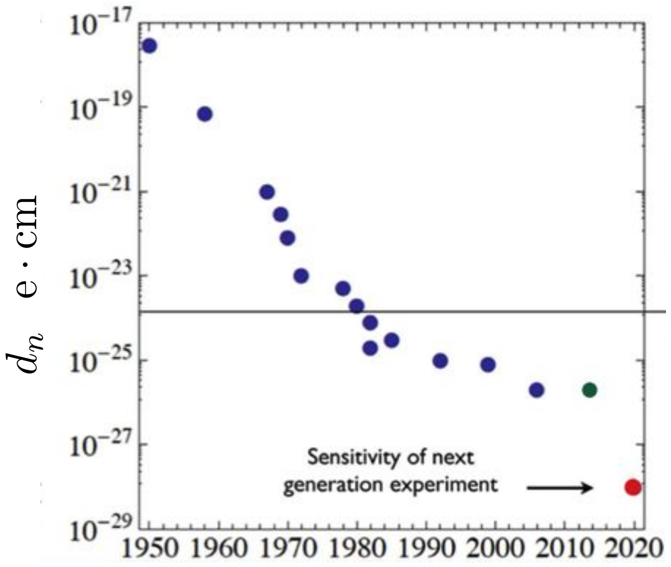
$$\mathcal{L}_{QCD} \supset \mathcal{L}_{\cancel{CP}} = -\bar{q} m e^{i\beta} q + \theta_{QCD} \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

One physical CPV phase: $\bar{\theta} = \theta_{QCD} + \arg\det M$

$$d_n \approx 10^{-16} |\bar{\theta}| \mathrm{e}\cdot\mathrm{cm} \qquad \bar{\theta} \lesssim 10^{-10}$$

Why is it so small?

Neutron EDM (Electric Dipole Moment)



[B.Fillipone via diLuzio]

Invisible Axion drawbacks

- ➔ The $U(1)_{PQ}$ symmetry is imposed

$$\mathcal{L} \supset -\cancel{m\bar{\psi}}\psi - \cancel{m\bar{\chi}}\chi$$

- ➔ PQ quality: Quantum gravity operators

$$g_5 \frac{|\Phi|^4 (\Phi + \Phi^*)}{M_{\text{Planck}}}$$

Although g_5 could be arguably small, see [Alonso+Urbano 17]

Confinement VS Chiral symmetry breaking

➔ There are two options:

- Global symmetries are spontaneously broken ⇒ (pseudo)- **Goldstone bosons** arise.
- Global symmetries remain unbroken ⇒ **massless baryons** arise, and

  ‘t Hooft anomaly matching conditions are fulfilled.

$$SU(8)_{5^*} \times SU(8)_{10} \times U(1)_{PQ=B-L}$$

Confinement VS Chiral symmetry breaking

➔ Global anomalies at high energies in terms of quarks

$$
\begin{aligned}
[SU(8)_{\bar{5}}]^3 : &\qquad 5 \times A(\Box) = 5\,, \\
[SU(8)_{10}]^3 : &\qquad 10 \times A(\Box) = 10\,, \\
U(1)_{PQ} \times [SU(8)_{\bar{5}}]^2 : &\qquad 5 \times 2\,T(\Box) Q_{\bar{5}} = -15\,, \\
U(1)_{PQ} \times [SU(8)_{10}]^2 : &\qquad 10 \times 2\,T(\Box) Q_{10} = 10\,, \\
[U(1)_{PQ}]^3 : &\qquad 8\left(5\,(Q_{\bar{5}})^3 + 10\,(Q_{10})^3\right) = -1000\,.
\end{aligned}
$$

➔ Global anomalies at low energies in terms of bound states:

$$
\begin{aligned}
[SU(8)_{\bar{5}}]^3 : &\qquad 8\,(n_{28}\,A(\mathbf{28}) + n_{36}\,A(\mathbf{36})) = 32(n_{28} + 3n_{36})\,, \\
[SU(8)_{10}]^3 : &\qquad 28\,n_{28}\,A(\mathbf{8}) + 36\,n_{36}\,A(\mathbf{8}) = 4(7\,n_{28} + 9\,n_{36})\,, \\
U(1)_{PQ} \times [SU(8)_{\bar{5}}]^2 : &\qquad 8\,PQ(\chi)\,(n_{28}\,2\,T(\mathbf{28}) + n_{36}\,2\,T(\mathbf{36})) = -80(3\,n_{28} + 5n_{36})\,, \\
U(1)_{PQ} \times [SU(8)_{10}]^2 : &\qquad PQ(\chi)\,(28\,n_{28}\,2\,T(\mathbf{8}) + 36\,n_{36}\,2\,T(\mathbf{8})) = -20(7n_{28} + 9n_{36})\,, \\
[U(1)_{PQ}]^3 : &\qquad 8\,(28n_{28} + 36n_{36})\,(PQ(\chi))^3 = -4000\,(7n_{28} + 9n_{36})\,.
\end{aligned}
$$

Confinement VS Chiral symmetry breaking

$$\boxed{SU(8)_{5^*} \times SU(8)_{10}} \times U(1)_{PQ=B-L}$$

Impossible to match anomalies:
It has to be spontaneously broken

$$\langle \mathbf{10\,10\,10\,\bar{5}} \rangle \sim \Lambda_5^6 \quad \Longrightarrow \quad SU(n)_{\bar{5}} \times SU(n)_{10} \longrightarrow G \supset SU(3)_c \,.$$

Confinement VS Chiral symmetry breaking

$$SU(8)_{5^*} \times SU(8)_{10} \times \boxed{U(1)_{PQ=B-L}}$$

Possible to match anomalies. Two options:

1. No chiral SB $\Rightarrow$ Massless coloured baryon phenomenologically excluded χ = 10 5* 5*
2. Chiral SB $\Rightarrow$ pGB, **AXION**

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A simple UV completion of the invisible axion model

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