A heavy axion from a Grand Color

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Outline

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The Strong CP problem

Colored sector of the SM

$$\mathcal{L}_{\mathrm{C}}^{\mathrm{SM}} = \mathcal{L}_{\mathrm{kin}} + \frac{g_{\mathrm{C}}^2}{32\pi^2}\theta\, G_{\mu\nu}^a \widetilde{G}^{a\,\mu\nu} - Y_u\, qHu - Y_d\, qH^* d$$

$$\text{Irreducible } \not{C}\!P : \begin{cases} \delta_{\,\mathrm{CKM}} \subset V_{\mathrm{CKM}} \\ \bar{\theta} = \theta + \arg\det Y_u Y_d \end{cases}$$

$\boldsymbol{\delta_{\,\mathrm{CKM}} \approx 1.2}$

PDG (2021)

$\boldsymbol{\bar{\theta} \lesssim 10^{-10}}$

C. Abel et al. (2020)

The Strong CP problem:

Why is CP violation in flavor-conserving processes so suppressed?
A naturalness question

Axion solution

The axion solution:

1. promote $\bar{\theta} \longrightarrow \bar{a}(x)/f_a$
2. assume a PQ symmetry $\bar{a} \to \bar{a} + f_a \times \text{const}$, broken only non-perturbatively:

$$\mathcal{L} \supset \frac{g_C^2}{32\pi^2} \frac{\bar{a}(x)}{f_a} G^a_{\mu\nu} \widetilde{G}^{a\,\mu\nu}$$

$$\Big\downarrow \ \langle \bar{q}_L q_R \rangle \sim 4\pi f_\pi^3$$

$$V_C(a) \simeq -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{\bar{a}}{2f_a}\right)}$$

Minimum:

$$\boldsymbol{\langle \bar{a}/f_a \rangle = \bar{\theta} = 0}, \qquad \boldsymbol{m_{a,C}^2 \simeq m_\pi^2 f_\pi^2 / f_a^2}$$

Strong CP problem dynamically solved, with a light scalar. Or is it?

The quality problem

The PQ symmetry is assumed to be broken *only* non-perturbatively. How restrictive is this?

For $\bar{a}(x)$ as NGB of a spontaneously broken anomalous $U(1)_{\text{PQ}}$,

$$\Phi = \left(\frac{f_a + \rho}{\sqrt{2}}\right) e^{i\bar{a}/f_a}, \qquad \mathcal{L}_{\text{UV}} \supset \frac{\lambda_*}{f_{\text{UV}}^{n-4}} \Phi^n \to \delta V \sim \frac{\lambda_* f_a^n}{f_{\text{UV}}^{n-4}}$$

$$\text{Strong CP}: \frac{\delta V}{V_{\text{C}}} \lesssim 10^{-10} \quad \longrightarrow \quad n - 4 > \frac{\log\left(10^{10}\,\lambda_* f_a^2/m_{a,\text{C}}^2\right)}{\log\left(f_{\text{UV}}/f_a\right)}$$

$\to f_a \sim 10^{10}$ GeV and $f_{\text{UV}} = M_P$, $\boldsymbol{n > 10}$:
the PQ symmetry must be of an extremely *high quality* to avoid reintroducing a fine-tuning. How to ensure this?

Outline

Adding C$'$

Two ways to obtain $\delta V / V_{\rm C} \lesssim 10^{-10}$:

1. reduce δV increasing $n \to$ next talk by G. Landini
2. enhance $V_{\rm C}$. How? Idea: **additional C$'$** confining at $f \gg f_\pi$

$$\mathcal{L} \supset \frac{g_{\rm C}^2}{32\pi^2}\left(\bar{\theta}_{\rm C} + \frac{a}{f_a}\right) G^a_{\mu\nu}\widetilde{G}^{a\,\mu\nu} + \frac{g_{\rm C'}^2}{32\pi^2}\left(\bar{\theta}_{\rm C'} + \frac{a}{f_a}\right) G'^a_{\mu\nu}\widetilde{G}'^{a\,\mu\nu}$$

with the **fundamental condition**

$$\boldsymbol{\bar{\theta}_{\rm C} = \bar{\theta}_{\rm C'}}.$$

If $V_{\rm C'}$ is such that $\langle \bar{a} \rangle / f_a \equiv \bar{\theta}_{\rm C} + \langle a \rangle / f_a = 0$, as in QCD, the quality problem may be sizebly ameliorated!

The Grand Color group

Minimal way to obtain $\bar{\theta}_{\mathrm{C}} = \bar{\theta}_{\mathrm{C}'}$: embed

$$\boldsymbol{SU(3)_{\mathrm{C}} \times \mathrm{C}' \supset SU(N)_{\mathrm{GC}}}\ \textbf{Grand Color group}$$

Dimopoulos (1979)

However C′-quarks confinement may break $SU(2)_{\mathrm{L}} \times U(1)_Y$.
To avoid, take

$$\mathrm{C}' = USp(N-3), \qquad N-3 \in 2\mathbb{N}$$

$$SU(N)_{\mathrm{GC}} \xrightarrow{f_{\mathrm{GC}}} SU(3)_{\mathrm{C}} \times USp(N-3)$$

Alternatively, generate mass for quarks partners and integrate them out
Gherghetta, Nagata, Shifman (2016)
Gaillard, Gavela, Houtz, Quilez, Del Rey (2018)
But $\bar{\theta}_{\mathrm{C}} = \bar{\theta}_{\mathrm{C}'}$ up to 10^{-10}?

A concrete model

	$SU(N)_{\rm GC}$	$SU(2)_{\rm L}$	$U(1)_{\rm Y'}$
Q	$\mathbf{N}$	$\mathbf{2}$	$+\frac{1}{2N}$
U	$\overline{\mathbf{N}}$	$\mathbf{1}$	$-\frac{1}{2}-\frac{1}{2N}$
D	$\overline{\mathbf{N}}$	$\mathbf{1}$	$+\frac{1}{2}-\frac{1}{2N}$
ℓ	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$
e	$\mathbf{1}$	$\mathbf{1}$	$+1$
H	$\mathbf{1}$	$\mathbf{2}$	$+\frac{1}{2}$
Φ	$\mathbf{Adj}$	$\mathbf{1}$	0
Ξ	$\mathbf{N}\otimes_A\mathbf{N}$	$\mathbf{1}$	$+\frac{1}{N}$

Breaking through $\langle\Phi\rangle\sim\langle\Xi\rangle\sim f_{\rm GC}$:

$$\begin{aligned} & SU(N)_{\rm GC}\times SU(2)_{\rm L}\times U(1)_{\rm Y'} \\ \xrightarrow{\langle\Phi\rangle} & SU(3)_{\rm C}\times SU(N-3)\times U(1)_{\rm GC}\times SU(2)_{\rm L}\times U(1)_{\rm Y'} \\ \xrightarrow{\langle\Xi\rangle} & SU(3)_{\rm C}\times USp(N-3)\times SU(2)_{\rm L}\times U(1)_{\rm Y} \end{aligned}$$

A concrete model

Quarks decomposition:

	$SU(3)_C$	$USp(N-3)$	$U(1)_Y$
$Q = \begin{pmatrix} q \\ \psi_q \end{pmatrix}$	$\mathbf{3}$	$\mathbf{1}$	$+\frac{1}{6}$
	$\mathbf{1}$	$\mathbf{N-3}$	0
$U = \begin{pmatrix} u \\ \psi_u \end{pmatrix}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-\frac{2}{3}$
	$\mathbf{1}$	$\mathbf{N-3}$	$-\frac{1}{2}$
$D = \begin{pmatrix} d \\ \psi_d \end{pmatrix}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$+\frac{1}{3}$
	$\mathbf{1}$	$\mathbf{N-3}$	$+\frac{1}{2}$

Flavor structure of C′ sector identical to SM one

$$\begin{aligned} \mathcal{L}_{\text{Yuk}} &= Y_u\, QHU + Y_d\, QH^* D \\ &\to Y_u\, qHu + Y_d\, qH^* d + Y_u\, \psi_q H \psi_u + Y_d\, \psi_q H^* \psi_d \end{aligned}$$

Crucial: implies $\bar{\theta}_C = \bar{\theta}_{C'}$ up to SM $\bar{\theta}$ renormalization $\ll 10^{-10}$

Coset structure

$USp(N-3)$ confinement at $\sim f$:

- $N \geq 7$ for $f > f_\pi$ (but $N \lesssim 17$ to avoid Landau poles)
- chiral condensates: Peskin (1980), Preskill (1981)

$$\langle \psi_{q_u} \psi_{q_d} \rangle = - \langle \psi_{q_d} \psi_{q_u} \rangle = \langle \psi_u \psi_d \rangle \sim 4\pi f^3 / \sqrt{N}$$

break $SU(12) \to USp(12) \supset SU(2)_\mathrm{L} \times U(1)_\mathrm{Y}$: **no EWSB**

- coset structure $SU(12)/USp(12)$: $65 = 51 + 14$ NGBs.
  51 charged ones heavy and irrelevant for $V_{\mathrm{C}'}(a)$. Effective coset:

$$\left.\begin{array}{l} \Sigma_L \in SU(3)_q / SO(3)_q \\ \Sigma_R \in SU(3)_u \times SU(3)_d / SU(3)_{u-d} \\ \eta_\mathrm{B} \in U(1)_\mathrm{B} \end{array}\right\} \quad \begin{array}{l} SO(3)_q \times SU(3)_{u-d} \\ \subset USp(12) \end{array}$$

Axion potential

Axion and NGBs' potential due to Yukawas:

1. rotate $\psi_u \to e^{i\bar{a}/3f_a}\psi_u$

$$\mathcal{L}_{\text{Yuk}} = Y_u e^{i\bar{a}/3f_a}\,\psi_q H \psi_u + Y_d\,\psi_q H^* \psi_d$$

2. expand the coset lagrangian in $Y_{u,d}$

$$\begin{aligned} V_{C'} &= \frac{c_{ud}}{N} f^4 \text{tr}\left[Y_u \Sigma_R Y_d^t \Sigma_L\right]\, e^{i\bar{a}/3f_a} + \text{hc} + \mathcal{O}(Y_{u,d}^4) \\ \to V_{C'}^{\text{LO}} &= \frac{c_{ud}}{N} f^4 \text{tr}\left[\widehat{Y}_u \Sigma_R \widehat{Y}_d V_{\text{CKM}}^\dagger \Sigma_L\right]\, e^{i\bar{a}/3f_a} + \text{hc} \end{aligned}$$

3. η_{B} exactly flat: no explicit $U(1)_{\text{B}}$ breaking operators
   Not a problem, but in case can be gauged away via (B-L)

Axion potential

$$V_{C'}^{\rm LO} = \frac{c_{ud}}{N} f^4 {\rm tr}\left[\widehat{Y}_u \Sigma_R \widehat{Y}_d V_{\rm CKM}^\dagger \Sigma_L\right] e^{i\bar{a}/3f_a} + {\rm hc}$$

Analytical considerations & numerical minimization:

$$\frac{\langle \bar{a} \rangle}{f_a} = \begin{cases} 0 & \text{if } c_{ud} < 0 \\ \pi & \text{if } c_{ud} > 0 \end{cases}$$

$$m_a^2 \simeq \frac{|c_{ud}|}{N} y_u y_d \frac{f^4}{f_a^2} \approx 10^{-10} \times \frac{|c_{ud}|}{N} \frac{f^4}{f_a^2}$$

- $c_{ud} < 0$ crucial: incalculable, but qualitative arguments favor this
- $m_a \gtrsim m_{a,{\rm C}}$ for $f \gtrsim 10^2 f_\pi \approx 10$ GeV: axion always heavier
- $m_{\Pi_{0,i}} \simeq \{10, 10^4\} \times m_a \times (f_a/f)$: tower of massive ALPs

Subleading corrections and heavy axion quality

1. renormalizable $\not{C}\not{P}$ due entirely to the SM Jarlskog: small, NLO correction to $V_{C'}$ do not destabilize $\langle \bar{a} \rangle = 0$
2. non-renormalizable $\not{C}\not{P}$: upper bounds on f due to $\delta V_{C'}$

$$\frac{\bar{c}_{ijkl}}{f_{\rm UV}^2} Q_i Q_j U_k D_l, \quad \frac{\bar{c}_{ijkl}}{f_{\rm UV}^2} (\Psi_i \Psi_j)^\dagger (\Psi_k \Psi_l), \quad \frac{\bar{c}_W}{(4\pi f_{\rm UV}^2)} \frac{g_{\rm GC}^2}{16\pi^2} G_{\rm GC} G_{\rm GC} \widetilde{G}_{\rm GC}$$

$\delta V_{C'}/V_{C'} \lesssim 10^{-10} \to f \lesssim 10^{-7} f_{\rm UV}$. For $f = M_P$, $f \lesssim 10^{11}$ GeV.

Novel sensitivity to UV sources of $\not{C}\not{P}$.

Gherghetta, Pospelov, Bedi (2022)

3. **quality problem always improved:**

$$(n-4) > (n-4)_{\rm C} - \frac{\log(m_a^2/m_{a,\rm C}^2)}{\log(f_{\rm UV}/f_a)}$$

For $f_{\rm UV} = M_P, f_a = 10^{10}$ GeV and $f = 10^8$ GeV, $n > 7$ ($n_{\rm C} > 10$)

Outline

Phenomenology

Qualitative assessment:

- charged NGBs, hadrons: decay in $H/W^{\pm}/Z + \Pi_{0,i}$.
  Set roughly $f \gtrsim$ TeV (direct searches)
- axion:

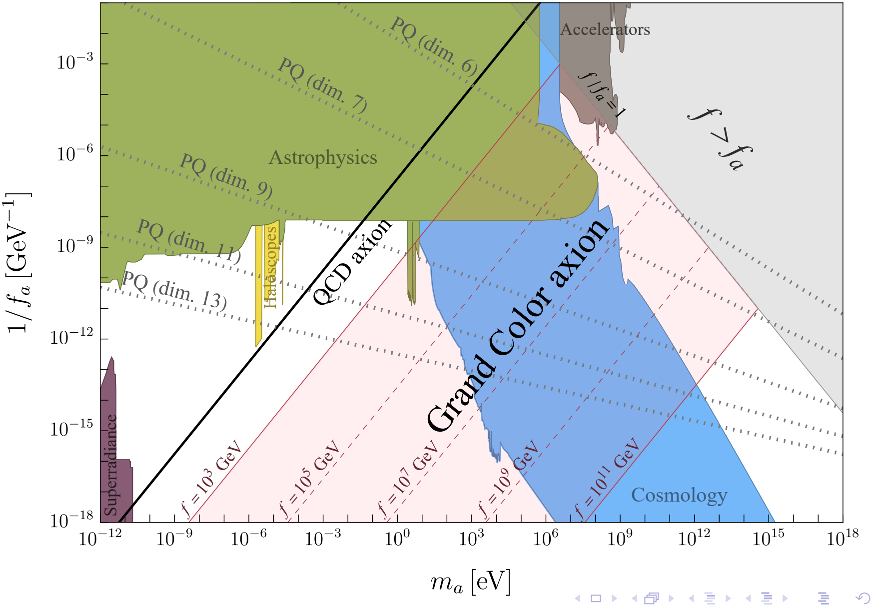
$$10^{-9}\text{eV} \lesssim m_a \lesssim 100\ \text{TeV}, \qquad \Delta(E/N) = -\frac{1}{2}(N-3)\left(1 - \frac{1}{3N}\right)$$

  Interplay of astrophysics, cosmology and accelerators bounds
- neutral NGBs $\Pi_{0,i}$: decay to SM vectors due to mixing with axion

$$\Gamma(\Pi_{0,i} \to gg) \gtrsim \Gamma(\bar{a} \to gg) \times \frac{f_a}{f}$$

- η_B: massless but photophobic, $f \gtrsim 300$ TeV Craig, Hook, Kasko (2018)

Axion bounds



Outline

Conclusions

- The QCD axion hides an extreme sensitivity to UV physics due to the smallness of the QCD potential (PQ quality problem)
- Address by enhancing the size of the potential: additional C' with $f \gg f_\pi$, embedded with C in a *Grand Color* group $SU(N)_{\mathrm{GC}}$. Crucially, $\bar{\theta}_{\mathrm{C}'} = \bar{\theta}_{\mathrm{C}}$ and no additional $\not{C}\not{P}$ introduced
- $\mathrm{C}' = USp(N-3)$ guarantees no high-scale EWSB and $\langle \bar{a} \rangle = 0$:

Strong CP problem robustly solved with a heaxy axion and improved quality problem

- Rich phenomenology: heavy axion (m_a up to ~ 100 TeV), heavier ALPs and exotic charged states

Thank you for your attention!

Backup slides

Minimization of the axion potential

$$V_{C'}^{\text{LO}} = \frac{c_{ud}}{N} f^4 \text{tr}\left[\widehat{Y}_u \Sigma_R \widehat{Y}_d V_{\text{CKM}}^\dagger \Sigma_L\right] e^{i\bar{a}/3f_a} + \text{hc}$$
$$\equiv V_0(\mathbf{\Pi_0}/f) e^{i\bar{a}/N_g f_a} + hc$$

$$V_0 = \frac{c_{ud}}{N} f^4 \, [\widehat{Y}_u]_i \, [A]_{ii}, \qquad A = \Sigma_R \widehat{Y}_d V_{\text{CKM}}^\dagger \Sigma_L$$

Minimum of $V_{C'}$ by maximizing $|V_0|$, with

$$\frac{\langle \bar{a} \rangle}{f_a} = N_g(\pi - \phi), \qquad \phi = \arg[V_0].$$

Minimization of the axion potential

Maximum of $|V_0|$ for A aligned with $\widehat{Y}_u$ (Schwarz inequality). Not possible exactly for $N_g = 3$, but results in ($\det A = \Pi_i [\widehat{Y}_d]_i$)

$$\frac{\langle \bar{a} \rangle}{f_a} = N_g(\pi + \arg c_{ud} + 2\pi n/N_g) = N_g(\pi + \arg c_{ud})$$

For odd N_g, $c_{ud} < 0$ crucial.
Analytical examples:

- $N_g = 1$: no neutral NGBs, and

$$V_{C'} = \frac{c_{ud}}{N} f^4 \, y_u y_d \cos\left(\frac{\bar{a}}{f_a}\right)$$

$$\frac{\langle \bar{a} \rangle}{f_a} = \begin{cases} 0 & \text{mod } 2\pi \text{ if } c_{ud} < 0 \\ \pi & \text{mod } 2\pi \text{ if } c_{ud} > 0 \end{cases} , \qquad m_a^2 = \frac{|c_{ud}|}{N} y_u y_d \frac{f^4}{f_a^2}$$

Minimization of the axion potential

- $N_g = 2$: 5 neutral NGBs, integrating them out results in

$$V_{C'}^{\text{eff}} = -\frac{|c_{ud}|}{N} f^4 \, \text{tr}[\widehat{Y}_u \widehat{Y}_d] \sqrt{1 - \frac{\det \widehat{Y}_u \widehat{Y}_d}{\text{tr}([\widehat{Y}_u \widehat{Y}_d])^2} \sin^2\left(\frac{\bar{a}}{2f_a}\right)}$$

$$\frac{\langle \bar{a} \rangle}{f_a} = 0 \mod 2\pi, \qquad m_a^2 = \frac{|c_{ud}|}{N} \frac{\det \widehat{[Y_u \widehat{Y}_d]}}{\text{tr}[\widehat{Y}_u \widehat{Y}_d]} \frac{f^4}{f_a^2} \approx \frac{|c_{ud}|}{N} y_u y_d \frac{f^4}{f_a^2}$$

Scaling $m_a^2 \propto y_u y_d$ is expected: if a Yukawa is null, PQ is exact and $\bar{a}(x)$ is flat $\to m_a$ controlled by smallest Yukawas.