Heavy Axion Solution to the Strong CP Problem

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The strong CP problem

- QCD instanton induced CP violation

$$\mathcal{L}_{\text{QCD}} = \sum_f \bar{q}_f \left(i\gamma^\mu D_\mu - m_f\right) q_f - \frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} + \mathcal{L}_{\not{CP}}$$

$$\mathcal{L}_{\not{CP}} = \bar{\theta} \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}, \quad \tilde{G}^{a\mu\nu} = \frac{1}{2} \epsilon^{\mu\nu\rho\sigma} G^a_{\rho\sigma}$$

- Contribution to the neutron EDM

$$d_n \sim e\bar{\theta} \frac{m_q}{M_n} \Rightarrow \bar{\theta} \lesssim 10^{-10}$$

Solutions to the strong CP problem

i. No instanton, no problem - e.g., high-dimensional models with quasi-localized gluons (Chaichian & AK '01)

ii. Spontaneous CP violation - $\bar{\theta} = 0$ at tree level, must be induced at 2 (or higher) loops.

However, CKM is a good description of CP violation in the Standard Model, contrived models (Nelson, Barr '84)

Solutions to the strong CP problem

iii. Additional chiral (anomalous) $U_A(1)$ removes $\bar{\theta}$

- $m_u=0$ (inconsistent with lattice calculations)

- Spontaneously broken $U_A(1)$ $\Rightarrow$ axion

(Peccei & Quinn '77, Weinberg '78, Wilczek '78)

PQ mechanism

$$U_A(1) \xrightarrow{f_a e^{\frac{ia(x)}{f_a}}} \mathbb{I} \qquad J^{\mu}_{\mathrm{PQ}} = \frac{1}{f_a}\partial_\mu a + ...$$

$$\partial_\mu J^{\mu}_{\mathrm{PQ}} = \xi \frac{\alpha_s}{8\pi} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$ (colour anomaly)

$$\Box a = \frac{\xi}{f_a}\frac{\alpha_s}{8\pi} G^a_{\mu\nu}\tilde{G}^{a\mu\nu} + ...$$

$$\mathcal{L} \supset \mathcal{L}_{\mathrm{SM}} + \frac{1}{2}\left(\partial_\mu a\right)^2 + \frac{\xi}{f_a}\frac{\alpha_s}{8\pi} a G^a_{\mu\nu}\tilde{G}^{a\mu\nu} + \bar{\theta}\frac{\alpha_s}{8\pi} G^a_{\mu\nu}\tilde{G}^{a\mu\nu} + ...$$

$$\boxed{\langle a\rangle = -\frac{f_a}{\xi}\bar{\theta}, \quad [\langle G^a_{\mu\nu}\tilde{G}^{a\mu\nu}\rangle \neq 0]}$$

$\bar{\theta}$ is cancelled out in the vacuum!

PQ mechanism

- Axion mass $$m_a^2 = \langle \frac{\partial^2 V_{eff}}{\partial a^2} \rangle = -\frac{\xi}{f_a}\frac{\alpha_s}{8\pi}\frac{\partial}{\partial a}\langle G^a_{\mu\ni}\tilde{G}^{a\mu\nu}\rangle$$ $$\simeq \frac{m_\pi^2 f_\pi^2}{f_a^2}\frac{m_u m_d}{(m_u+m_d)^2}$$

- Couplings to SM fields $\sim 1/f_a$

- PQWW axion $f_a \sim v_{\rm EW} \simeq 246$ Gev, $m_a \approx 25$ KeV

Excluded:

$K^+ \to \pi^+ a,\ K^+ \to \pi^+ + \text{nothing};\ f_a \gtrsim 10^9$ GeV (star cooling)

Invisible axion

(Kim ‘79, Shifman, Vainstein & Zakharov ‘80; Zhitnitsky ‘80, Dine, Fischler, Srednicki ‘81)

$$f_a \gtrsim 10^9 \text{ GeV } (10^9 \text{ GeV} \lesssim f_a \lesssim 10^{12} \text{ GeV})$$

$$m_a \sim 10^{-6} - 10^{-3} \text{ eV}$$

- Note, for $m_a \gtrsim 100 \text{ KeV}$ no astrophysical constraints. Can the axion be made ‘visible’ ?
- New contribution to mass

$$m_a \sim c\Lambda_{\text{QCD}} + c'\Lambda_{\text{QCD}'}$$

e.g., enlarged colour group (Rubakov ‘97, Berezhiani, Gianfagna & Giannotti ’01)

Super economical (simple) model:

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- Add to the SM a vector-like quark Q in R-representation of the ordinary colour $SU(3)_C$, $d(R)>3$.

- Can carry hypercharge, y_Q, $e_Q = y_Q/2$

- Mass term $m_Q\bar{Q}Q$ - must be generated spontaneously, e.g.,

$$\alpha_Q(\bar{Q}Q)^2 \to m_Q = \alpha_Q\langle\bar{Q}Q\rangle <<< \left(\langle\bar{Q}Q\rangle\right)^{1/3}$$

or, if explicit, must be sufficiently small

Super economical (simple) model:

- Q-sector global symmetry:

$$U_V(1) \times U_A(1)$$

Exact, Q-quark is stable

Anomalous, spontaneously broken -> Composite axion

$$\langle \bar{Q} Q \rangle = -c_Q f_a^3 \, \mathrm{e}^{i \frac{a(x)}{f_a}}$$

$$a(x) \sim \bar{Q} \gamma_5 Q$$

Composite axion

- The PQ mechanism is in place. At low energies $< f_a$

$$\mathcal{L} \supset \frac{T(R)\alpha_s}{4\pi f_a} a G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

$$\langle a \rangle = -\frac{f_a}{4T(R)}\bar{\theta}$$ - strong CP phase is cancelled out

- Dynkin index $$T(R) = \frac{1}{8} C_2(R) d(R)$$

Composite axion

$$J^\mu_A = \bar{Q}\gamma^\mu\gamma_5 Q$$

$$\partial_\mu J^\mu_A = 2im_Q Q\gamma_5 Q + \frac{T(R)\alpha_s}{4\pi} G^a_{\mu\nu}\tilde{G}_{a\mu\nu} + \frac{d(R)y_Q^2\alpha_1}{4\pi} B_{\mu\nu}\tilde{B}_{\mu\nu}$$

- Axion mass eigenstate couples to an QCD anomaly-free current

$$\tilde{J}^\mu_A = J^\mu_A - T(R)\left(j^\mu_A + \kappa j^\mu_3\right)$$

$$j^\mu_A = \bar{q}\gamma^\mu\gamma_5 q,\ \ j^\mu_3 = \bar{q}\sigma^3\gamma^\mu\gamma_5 q$$

$$q = (u,d)^{\mathrm{T}},\ \ \kappa = \frac{m_d - m_u}{m_d + m_u}$$

- QCD instantons preserve the charge:

$$\tilde{Q}^\mu_5 = \int d^3x\ \tilde{J}^0_A$$

Composite axion

- Use Dashen's formula:

$$m_a^2 = -\frac{1}{f_a}\langle\left[\tilde{Q}_5, \partial_\mu \tilde{J}_A^\mu\right]\rangle$$

$$= \underbrace{4c_Q m_Q f_a}_{Q-\text{sector}} + \underbrace{4T^2(R)\frac{m_\pi^2 f_\pi^2}{f_a^2}\frac{m_u m_d}{m_u + m_d}}_{q-\text{sector}}$$

- Axion interactions:

$$\mathcal{L} \supseteq C_B a B_{\mu\nu}\tilde{B}_{\alpha\beta},\ C_B = \frac{\alpha_1}{4\pi}\frac{1}{f_a}\left(d(R)y_Q^2 - \frac{2T(R)}{3}\frac{4m_d + m_u}{m_d + m_u}\right)$$

$$\mathcal{L} \supseteq \frac{2ia}{f_a}\left(m_Q\bar{Q}\gamma_5 Q + T(R)\frac{m_u m_d}{m_u + m_d}\bar{q}\gamma_5 q\right)$$

Composite axion

- Estimate f_a (Marciano '80):

$$C_2(3)\alpha_3(\Lambda_q) = C_2(R)\alpha_3(\Lambda_Q), \;\; f_a/f_\pi \approx \Lambda_Q/\Lambda_q$$

$$f_a \approx f_\pi \exp\left[\frac{2\pi}{7\alpha_3(\Lambda_q)}\left(\frac{3}{4}\mathrm{C}_2(\mathcal{R}) - 1\right)\right]$$

Repr.	$\mathrm{C}_2(R)$	$\mathrm{T}(R)$	f_a, GeV
$\mathrm{d}(R)$=6	10/3	5/2	2.0 – 12.0
$\mathrm{d}(R)$=8	3	3	1.0 – 6.0
$\mathrm{d}(R)$=10	6	15/2	75.0 – 4590.0
$\mathrm{d}(R)$=15	28/3	35/2	$(0.007 - 8.0)\cdot 10^6$
$\mathrm{d}(R)$=21	40/3	35	$(10^{-4} - 5.0)\cdot 10^{11}$

Table 1: Estimates of f_a for various high-colour representations according to Eq. (10). The strong coupling is assumed in the range $\alpha_3(\Lambda_q) = 0.3 - 0.5$.

Composite axion

- Assume m_Q=0 (strong CP phase is rotated away, just like in the m_u=0 case)

$$m_a|_{m_Q=0} \simeq 2T(R) m_\pi \frac{f_\pi}{f_a} \frac{\sqrt{m_u m_d}}{m_u + m_d} = \begin{cases} 123.0 \left(\frac{f_a}{1\ \mathrm{TeV}}\right)^{-1}\ \mathrm{KeV}, & \text{for } d(R) = 10 \\ 29.0 \left(\frac{f_a}{10\ \mathrm{TeV}}\right)^{-1}\ \mathrm{KeV}, & \text{for } d(R) = 15 \\ 6.0 \left(\frac{f_a}{10^8\ \mathrm{TeV}}\right)^{-1}\ \mathrm{meV}, & \text{for } d(R) = 21 \end{cases}$$

- $m_Q \neq 0$

$$m_a \simeq 2 c_Q^{1/2} \sqrt{m_Q f_a}$$

E.g., $f_a \sim 3$ TeV, $m_Q \sim 47$ GeV $\Rightarrow m_a \simeq 750$ GeV

750 GeV diphoton excess(?)

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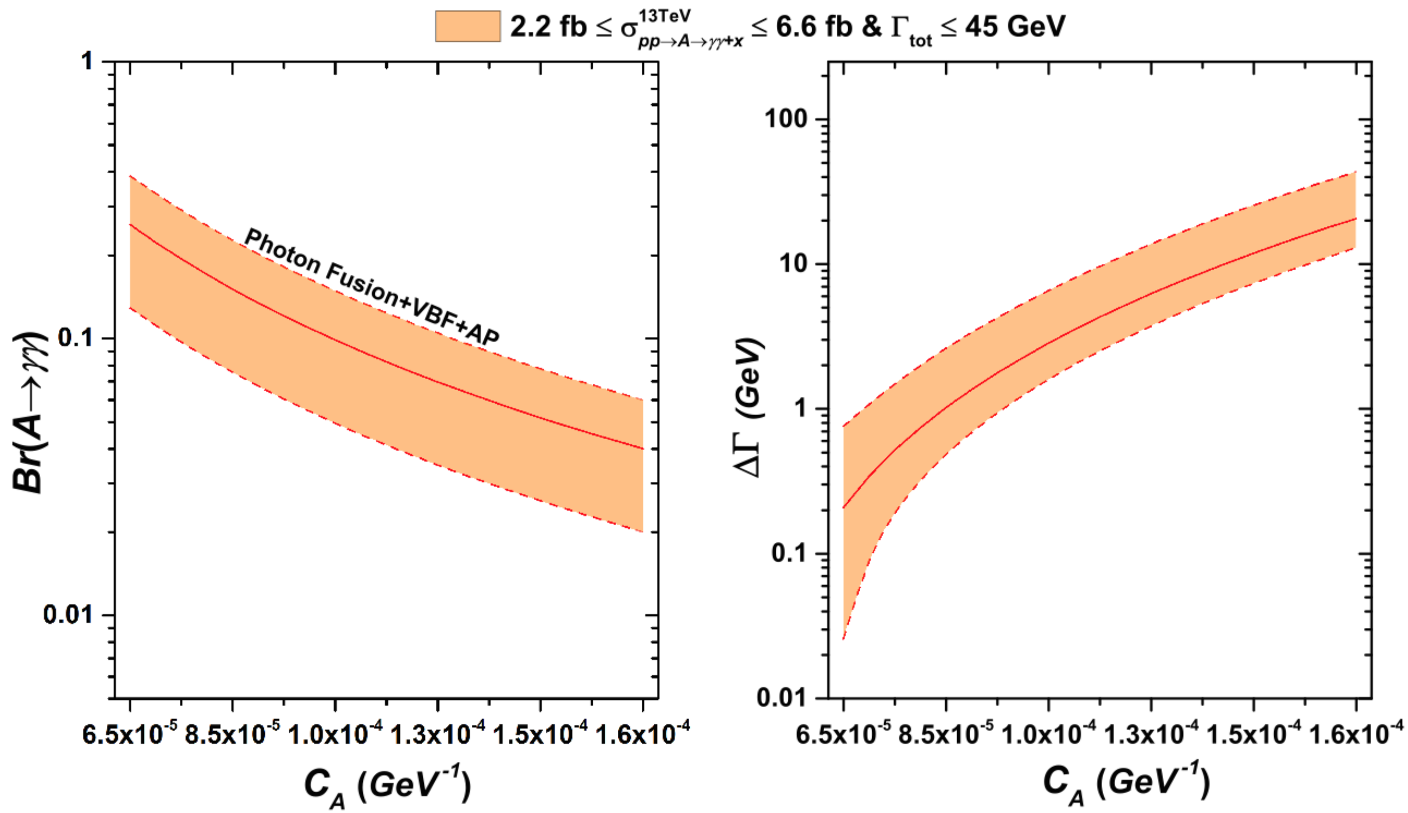

d(R)=10 or d(R)=15 with y_Q~ 3.

Potential problems:

- CHAMP abundance constraint:

$$n_{\rm CHAMP} \lesssim \left(10^{-20} - 10^{-15}\right) n_p$$

  - Can be neutral, $y_Q=0$
  - High confinement scale f_a may reduce abundance of dangerous Q-champs
  - $T_r \ll f_a$ (solves also axion domain wall problem)

Conclusion

- Heavy composite axion model is proposed within a very simple scenario with hypothetical high-colour quarks
- Composite axion is potentially accessible at LHC
- May play important role in the electroweak phase transition -> baryogenesis, magnetogenesis, gravitational waves