Addressing the Axion Quality Problem

K.S. Babu

Oklahoma State University

DPF-Pheno 2024

University of Pittsburgh/Carnegie Mellon University

May 13-17, 2024

Credits

Talk based on work done in collaboration with:

Bhaskar Dutta and Rabi Mohapatra (to appear)

Supported by the US Department of Energy

Axion Solution to Strong CP Problem

- Strong interactions allow a CP violating term in the Lagrangian,

$$\mathcal{L} = \left(\frac{g_s^2}{32\pi^2}\right)\overline{\theta}\, G_{\mu\nu}\tilde{G}^{\mu\nu}$$

- In its presence, neutron acquires a nonzero electric dipole moment, $d_n \simeq \overline{\theta} \times (10^{-16})$ e-cm. Current limit on d_n, $|d_n| \leq 1.1 \times 10^{-26}$ e-cm, sets a limit $\overline{\theta} < 10^{-10}$.

- A lack of understanding of the extreme smallness of $\overline{\theta}$ within the Standard Model is the strong CP problem

- In presence of a light pseudoscalar particle, the axion (a), this problem can be solved by the Peceei-Quinn (PQ) mechanism

- The PQ mechanism assumes a global $U(1)$ symmetry that has a QCD anomaly. This $U(1)$ is spontaneously broken by a Higgs scalar, and also explictly by the QCD anomaly term

Axion and the PQ Mechanism

- The Lagrangian for a PQ symmetric theory contains the terms

$$\mathcal{L} = \left(\frac{g_s^2}{32\pi^2}\right)\frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu} - \lambda(|\Phi|^2 - f_a^2)^2 - \Lambda^4 \cos\left(\frac{Na}{f_a}\right),$$

- Note that $\overline{\theta}$ has been absorbed into the dynamical axion field a which is the phase of Φ: $\Phi = \frac{(\rho+f_a)}{\sqrt{2}} e^{i\frac{a}{f_a}}$
- Here Λ is the QCD scale, N is an integer ≥ 1 related to the QCD anomaly coefficient, and f_a is the axion decay constant.
- Minimizing the potentail leads to $a = 0$, which thus solves the strong CP problem
- Quantum gravity is expected to break all global symmetries, including $U(1)_{PQ}$. This gives rise to the axion quality problem
- For example, a gravity-induced term in the Higgs potential,

$$V_{gravity} = \frac{\kappa}{M_{\rm Pl}}|\Phi|^4(e^{i\delta}\Phi + h.c.)$$

would shift the vacuum value $a = 0$ to unacceptably large values

Axion Quality Problem

- Minimizing the potential in presence of the quantum gravity correction one has

$$\bar{\theta} \simeq \frac{\kappa \sin\delta}{2\sqrt{2}} \frac{f_a^5}{\Lambda^4 M_{\rm Pl} N^2}$$

- For currently favored values of $f_a = (10^9 - 10^{12})$ GeV, with $\Lambda \simeq 200$ MeV and $M_{\rm Pl} = 1.22 \times 10^{19}$ GeV, one finds the limits

$$\kappa \sin\delta \leq \{10^{-38} - 10^{-53}\}$$

- This is rather severe, much worse than the strong CP problem itself!
  Holman et. al. (1992); Kamionkowski, March-Russell (1992); Barr, Seckel (1992); Ghigna, Lusignoli, Roncadelli (1992)

- Attempts to solve the axion quality problem have used gauge symmetries with an accidental global $U(1)$, composite axion, and discrete gauge symmetries

- Realizing accidental PQ symmetry from a gauge symmetry is nontrivial, since PQ symmetry should have a QCD anomaly, but the original gauge symmetry has no anomaly

- In the rest of the talk I shall present our attempts to construct such models and discuss briefly phenomenology of successful models

Accidental PQ From Gauged U(1)

- Standard Model is extended with a gauged $U(1)_a$. All SM particles are neutral under this $U(1)_a$. Vectorlike fermions are added which carry $U(1)_a$ charges:

Field	$SU(3).SU(2)_L.U(1)_Y$	$U(1)_a$
Fermions		
$(Q_{1L},\ Q_{2L},\ Q_{3L})$	$(3,1,y)$	$(1,\ 1,\ -2)$
$(Q_{1R},\ Q_{2R},\ Q_{3R})$	$(3,1,y)$	$-(1,\ 1,\ -2)$
$(N_{1R},\ N_{2R},\ N_{3R})$	$(1,1,0)$	$(1,3,-4)$
Scalars		
$(S,\ T)$	$(1,1,0)$	$(\frac{2}{n},\ 4)$

- All anomalies cancel, including $[U(1)_a]^3$ via the singlet fermions
- n is an integer with $n \geq 5$
- Yukawa interactions of S and T generate vectorlike quark masses:

$$-\mathcal{L}_{\rm Yuk} = Y_3\, \overline{Q}_{3L} Q_{3R}\, T^* + Y_{1,2}\, \overline{Q}_{1,2,L} Q_{1,2,R}\, \frac{S^n}{(M_*)^{(n-1)}} + h.c.$$

- Model has two global $U(1)$s, one acting on (Q_3, T) and another acting on $(Q_{1,2}, S)$. Each has a QCD anomaly
- Thus there are two Goldstone bosons, one eaten up by the $U(1)_a$ gauge boson, with the other identified as the axion

High Quality Axion

- Axion is orthogonal to Goldstone:

$$G = \frac{\left(\frac{2}{n} f_S \eta_S + 4 f_T \eta_T\right)}{\sqrt{(4f_T)^2 + (\frac{2}{n} f_S)^2}}, \quad a = \frac{\left(4 f_T \eta_S - \frac{2}{n} f_S \eta_T\right)}{\sqrt{(4f_T)^2 + (\frac{2}{n} f_S)^2}}$$

Here $S = \frac{(\rho_S + f_S)}{\sqrt{2}} e^{\eta_S / f_S}$ and $T = \frac{(\rho_T + f_T)}{\sqrt{2}} e^{i\eta_T / f_T}$ are used

- Axion decay constant f_a can be worked out to be

$$f_a = \frac{f_T f_S}{\sqrt{4 f_T^2 n^2 + f_S^2}}$$

- This is a KSVZ type axion model, but with high quality axion
- The leading quantum gravity correction that can destabilize the axion potential is

$$V_{\rm gravity} = \frac{\kappa e^{i\delta} S^{2n} T^*}{M_{\rm Pl}^{2n-3}} + h.c.$$

- The induced $\overline{\theta}$ is

$$\overline{\theta} \simeq \frac{\kappa \sin\delta}{(\sqrt{2})^{(2n-1)}} \frac{f_S^{2n} f_T}{\Lambda^4 M_{\rm Pl}^{2n-3}}$$

- For $f_S = f_T = f_a \sqrt{1 + 4n^2}$, and with $n = 5$, $f_a = 10^{10}$ GeV, one has $\overline{\theta} \sim 7 \times 10^{-12}$. If $f_a = 10^{12}$ GeV is used, $n = 7$ gives $\overline{\theta} \sim 10^{-12}$, showing the high quality, all for $\kappa \sin\delta = 1$

Generalization to a Family of Models

- A family of models can be found as extensions of the model. $m+1$ vectorlike quarks are used:

Field	$SU(3).SU(2)_L.U(1)_Y$	$U(1)_a$
Fermions		
$(Q_{1L},\ Q_{2L}, \dots Q_{m+1,L})$	$(3,1,y)$	$(1,\ 1, \dots, 1,\ -m)$
$(Q_{1R},\ Q_{2R}, \dots Q_{m+1,R})$	$(3,1,y)$	$-(1,\ 1, ..1,\ -m)$
$(N_{1R},\ N_{2R},\ N_{3R})$	$(1,1,0)$	$(m-1, m+1, -2m)$
Scalars		
$(S,\ T)$	$(1,1,0)$	$(\frac{2}{n},\ 2m)$

- All anomalies cancel, with the previous model being $m=2$ case
- Axion field is given as

$$a = \frac{\left(2mf_T\eta_S - \frac{2}{n}f_S\eta_T\right)}{\sqrt{(2mf_T)^2 + (\frac{2}{n}f_S)^2}}, \quad f_a = \frac{f_T f_S}{\sqrt{f_T^2 m^2 n^2 + f_S^2}}$$

- This leads to a high quality KSVZ type axion. For $m \geq 9$, $n=1$ can be chosen, whence all quarks acquire mass at renormalizable level
- Couplings of axion to nucleon and electron are same as KSVZ
- Domain wall number $N_{DW} = 1$, which is harmless in cosmology
  Sikivie (1982)

$$N_{\rm DW} = \text{minimum integer} \left\{ \frac{1}{f_a} \sum_i n_i\, c_i\, v_i\ , \quad n_i \in \mathcal{Z} \right\}, \quad a = \sum_i c_i a_i$$

Ernst, Ringwald, Tamarit (2018)

SO(10) Model with Gauged U(1) and Axion

- Unified $SO(10) \times U(1)$ can lead to high quality axion
- The attractive features of $SO(10)$ GUT are preserved, including coupling unification and predictive fermion spectrum
- The fermion content and transformation under $SO(10) \times U(1)$:

$$\{3 \times 16_1 + 1 \times 10_{-6} + 1 \times 1_{12}\} + \{2 \times 1_{-4} + 1 \times 1_8\}$$

- All gauge anomalies cancel. Some resemblance to E_6 charges
- Higgs sector contains the usual $SO(10)$ fields and two singlets:

$$\{10_H(-2) + \overline{126}_H(-2) + 45_H(0) \textit{ or } 54_H(0) + T(1_{+1}) + S(1_{12})\}$$

- Yukawa couplings:

$$\begin{aligned} \mathcal{L}_{\rm Yuk} &= Y_{10} 16\, 16\, 10_H + Y_{126} 16\, 16\, \overline{126}_H + y_{10} 10_{-6} 10_{-6} S_{12} \\ &+ y'_{10} 10_{-6} 1_8\, 10_H + 1_{12} 1_{12} \frac{(S^*)^2}{M_{\rm Pl}} + ...h.c. \end{aligned}$$

- Realistic fermion masses are induced, including exotics

High Quality SO(10) Axion

- Model has two decoupled sectors, one with 16-fermions, and one with 10-fermion. This results in accidental PQ symmetry
- Leading correction to PQ symmetry from gravity is

$$V \supset \frac{T^{12} S^*}{M_{\rm Pl}^9}$$

- Resulting shift in $\overline{\theta}$ is highly suppressed. $f_a < 2 \times 10^{11}$ GeV is required for quality. Domain wall number $N_{DW} = 1$ in the model
- Axion field is orthogonal to pseudoscalars and Goldstones

$a \simeq 1/\sqrt{1 + \frac{144 v_S^2 v^2}{X}} \left(\eta_S - 12 v_T v_S v^2 \eta_T / X\right) + \ldots, \quad f_a = v_S / \sqrt{1 + \frac{144 v_S^2 v^2}{X}},$
$X = v_T^2 v^2 + 4\tilde{v}^2 (v_u^{02} + v_d^{02}) + 16 v_u^{02} v_d^{02}$

- Axion coupling to fermions are modified compared to DFSZ or KSVZ models:

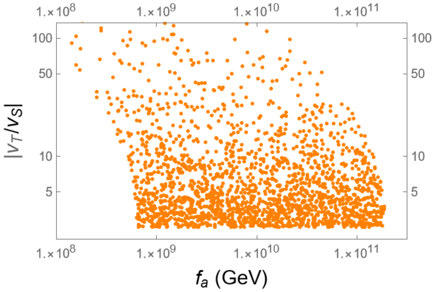
$$\mathcal{L}(f, a) = i \frac{m_u}{f_a} \left[\frac{24 v_S^2 (2 v_d^{02} + \tilde{v}^2)}{X + 144 v_S^2 v^2}\right] \bar{u}\gamma_5 u a + i \frac{m_d}{f_a} \left[\frac{24 v_S^2 (2 v_u^{02} + \tilde{v}^2)}{X + 144 v_S^2 v^2}\right] \bar{d}\gamma_5 d a + i \frac{m_e}{f_a} \left[\frac{24 v_S^2 (2 v_u^{02} + \tilde{v}^2)}{X + 144 v_S^2 v^2}\right] \bar{e}\gamma_5 e a$$

An upper limit on f_a in SO(10) model

- The induced $\overline{\theta}$ from quantum gravity is

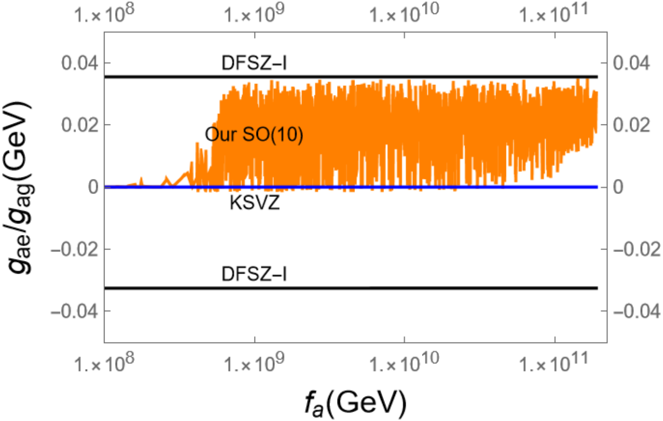
$$\overline{\theta} \simeq \frac{\kappa \sin\delta}{2^{(11/2)}} \sqrt{1 + \frac{144 v_S^2}{v_T^2}} \frac{v_T^{12} f_a}{\Lambda^4 M_{\rm Pl}^9}$$

- This sets a limit $f_a < 2 \times 10^{11}$ GeV

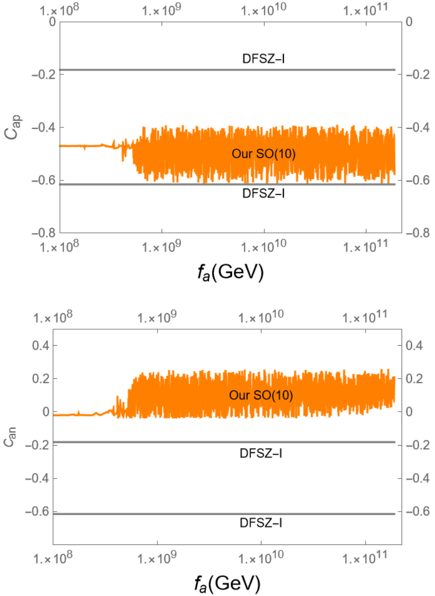


Axion couplings to electron in SO(10) model

Ratio of electron coupling of axion versus gluon coupling:



Axion couplings to proton and neutron in SO(10)



Conclusions

- Two classes of models presented which have an accidental PQ symmetry
- In one class, SM $\times U(1)$ resulted in high quality axion which is similar to KSVZ model
- $N_{DW} = 1$ in these models for domain wall number, causing no cosmological issues
- A second class in within the framework of $SO(10)$ unification. It leads to a hybrid KSVZ-DFSZ axion with high quality
- $N_{DW} = 1$ in these models without cosmological problems
- Axion couplings to fermions can potentially distinguish these models from standard benchmarks
- In all cases there is room for the axion to be the entire dark matter content of the universe