Peccei-Quinn mechanism and the quality problem Based on 1703.01112

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Outline

1. Strong CP Problem and the Peccei-Quinn symmetry
2. Big Challenge in the PQ symmetry - Quality problem
3. Our study
    3.1 “Gauged” axion

Strong CP Problem and the Solutions

Strong CP Problem

- Yang-Mills theory in 4D has θ vacua, which can be written in Lagrangian: $\Delta\mathcal{L} \sim \theta F\tilde{F}$ *(see Seiberg 10)*
- Non-zero θ breaks CP symmetry: $|\theta_{QCD}| \lesssim 10^{-10}$
- θ_{QCD} consists of two parts, θ_{YM} and $\arg(\det(Y_u Y_d))$
  - We expect the latter is around $J \sim 10^{-5}$, at least
  - No reason to cancel
- Why is θ_{QCD} so small? - *Strong CP Problem*
- Anthoropic principle cannot be used *see Ubaldi 08, for instance*

Peccei-Quinn Mechanism

- In a nutshell, "if a symmetry were anomalous in QCD, θ would be unphysical"
- The anomaly never disappear (e.g. Anomaly Matching)
- That anomaly must have low-energy consequence!
  - Massless *colored* Fermion - massless up
    - (For historical reason, this is usually not referred as PQ)
    - Inconsistent with lattice?
  - Pseudo NGB with $\Delta\mathcal{L} \sim \frac{a}{f_a} G\tilde{G}$
    - Peccei and Quinn 1977, Weinberg 1978, Wilczek 1978

Axion and the Mass

- The pseudo NGB is called axion
- U$(1)_{\text{PQ}}$ is not exact - the axion, a, has mass
- From the chiral condensation,

$$m_a{}^2 \sim \frac{m_q \Lambda_{QCD}{}^3}{f_a{}^2} \sim \left(1\,\text{meV}\,\frac{10^9\,\text{GeV}}{f_a}\right)^2$$

- f_a: axion decay constant, $\sim \langle\phi\rangle$

Big Challenge in the PQ symmetry - Quality problem

Big Obstacle for the Peccei-Quinn Mechanism

- U$(1)_{PQ}$ must be an **extremely** good "symmetry"

$$\Delta\mathcal{L} = c\frac{\phi^5}{M_{\mathrm{Pl}}} \Rightarrow \mathcal{L}_a = -\frac{{m_a}^2}{2}a^2 + c\frac{{f_a}^4}{M_{\mathrm{Pl}}}a$$

  Since $\theta_{\mathrm{eff}} = \langle a\rangle/f_a$, $c \lesssim 10^{-60}$ for $\theta \lesssim 10^{-10}$!
- *Quality problem*
- So, *where does the U$(1)_{PQ}$ come?*
  - U$(1)_{PQ}$ is *by definition* not a symmetry
  - Even an exact global symmetry should be broken in Quantum Gravity
  - No anthoropic argument!
    - Accidental or/and "anthoropic-izing" solution

How Can We Solve It? (using field theory)

- Imposing discrete (gauge) symmetries
  - Discrete symmetries may emerge from gauge symmetry
    - e.g. Abelian Higgs with charge $+2$
  - For $\Delta\mathcal{L} \sim \mathcal{O}(1)\frac{\phi^n}{{M_{\mathrm{Pl}}}^{n-4}}$, $n \gtrsim 11$!
- Imposing continuous gauge symmetries
- Heavy QCD Axion

Our Study

Our Study

- We show two different models as examples
  - "Gauged" axion *HF, Ibe, Suzuki, Yanagida 1703.01112*
  - Heavy axion *Chiang, HF, Harigaya, Ibe, Yanagida 1504.06084, 1602.07909, 1702.00227*

“Gauged” Axion

“Gauged” Axion

- Needless to say, $\mathrm{U}(1)_{PQ}$ cannot be gauged
- However, gauge symmetry may protect $\mathrm{U}(1)_{PQ}$ *Georgi, Hall, Wise 81*

Gauged U(1) Symmetries and Anomalies

- Chiral U(1) symmetries generally have anomalies
- How about U$(1)_Y$?
  - There, anomalies from *lepton* and *quark* sectors are cancelled!
  - Conversely, "U$(1)_Y$" in each sector are anomalous
    - Of course, due to Higgs, both sector are connected
    - However, what if we have 2HDM? - Weinberg-Wilczek model
    - $B - L$, B and L? R-parity?
- Generally, multiple "U(1)" are assembled into one gauged U(1)
- Hence, if a gauged U(1) exists, anomalous U(1)s may well exist

Example of Models *Barr, Seckel 92, HF, Ibe, Suzuki, Yanagida 17*

	SU$(3)_{QCD}$	U$(1)_g$	(U$(1)_{PQ}$)
ϕ_1	1	1	1
$\psi_{L1,10}$	3	-1	-1
$\bar{\psi}_{R1,10}$	$\bar{3}$	0	0
ϕ_2	1	-10	0
ψ_{L2}	3	10	0
$\bar{\psi}_{R2}$	$\bar{3}$	0	0

With interaction: $\Delta\mathcal{L} \sim \phi_1\bar{\psi}_{R1,10}\psi_{L1,10} + \phi_2\bar{\psi}_{R2}\psi_{L2}$

- Breaking Operator: $\mathcal{L}_{\cancel{PQ}} = \frac{1}{M_{\rm PL}^7}\phi_1^{10}\phi_2^\dagger +$ H.c.

How to Build Models?

- Building models are really easy
- Introducing two PQ sector, gauging the diagonal group
    - Always, one linear combination of two PQ currents are anomaly-free in QCD
- The problem is how we can suppress cross-terms
- How “realistic” can the model be? - Future work
- What is the cosmological evolution? - Future work

Summary

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- The Peccei-Quinn mechanism is probably the most successful solution to the Strong CP problem
- However, its quality is puzzling
- We have proposed two different way to realize good quality
    - “Gauged” axion
        - Gauge symmetry may protect PQ
        - How realistic does it look? - Future work
        - Cosmological evolution - Future work

Heavy Axion

Heavy Axion

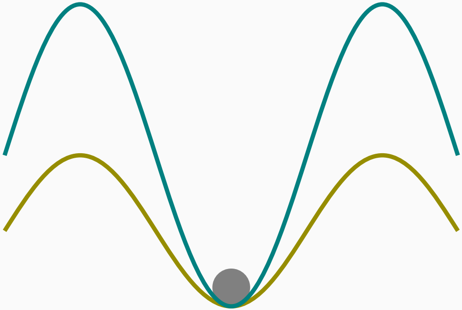
- As I mentioned, m_a is written in terms of f_a, $m_a \sim \sqrt{m_q \Lambda^3}/f_a$
- Okay, let us forget it temporarily
- With PQ-breaking operator $\Delta\mathcal{L} = c\phi^5/M_{\mathsf{Pl}}$,

$$\mathcal{L}_a \sim -\frac{{m_a}^2}{2}a^2 + c\frac{{f_a}^4}{M_{\mathsf{Pl}}}a$$

- Thus, if m_a were bigger, we could ignore $\Delta\mathcal{L}$!

How to Make it Heavier?

- Another gauge theory with the same θ is needed



What is the Other Gauge Theory?

- Two way is known
- Use of larger group SU$(N+3) \supset$ SU$(3)_{QCD} \times$ SU(N) *Dimopoulos 79*
  - Recently Shifman *et al.* 16, used this
  - However, we believe this is almost dead
- Use of a copy of the standard model *Rubakov 94*
  - This is only the possibility

Use of the Copy SM *1504.06084, 1602.07909, 1702.00227*

- The axion mass is now $m_a \sim \sqrt{m'_q \Lambda'^3}/f_a$
- If the axion is heavier than $\mathcal{O}(1\text{-}10) GeV$, we have no constraint for the axion
  - Cosmology like BBN,...
  - Meson Invisible Decay
  - Astrophysics like SN1978A,...
- We may make v' and Λ' large using $\mathbb{Z}_2$ breaking
- Since we have introduced a copy, many particles are stable
  - We have found that one of them may be the dark matter
    - How to detect it? - Future work