How should we tackle the strong CP problem?

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Outline

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    3.2 Heavy 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*

The Solutions

- As far as I know, there are roughly two ways
- Spontaneous CP Breaking (e.g. Nelson-Barr Mechanism)
    - Complicated and not so easy *Dine and Draper. 15 for detail*
- Use of anomaly

Anomaly and θ

- Chiral (non-vectorial) U(1) symmetries in 4D generally have anomalies

$$\partial J \sim F\tilde{F}$$

- The chiral rotation only moves θ - θ becomes unphysical!
- This is why we do not have "Weak CP Problem"...

$$\partial J_L \sim W\tilde{W} + F\tilde{F} \quad \therefore \bar{e}_R \to e^{-i\theta_w/3}\bar{e}_R, L_L \to e^{i\theta_w/3}L_L, \theta_w \to 0$$

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
        - (For historical reason, this is usually not referred as PQ)
    - Pseudo NGB with $\Delta\mathcal{L} \sim \frac{a}{f_a} G\tilde{G}$
        - Peccei and Quinn 1977, Weinberg 1978, Wilczek 1978

With Massless Colored Fermion

- No additional massless Fermion is allowed in SM
- May *up* be massless? - So called *“massless up” solution*
- Inconsistent with chiral perturbation?
    - Still instanton may save it? *Georgi and McArthur 81*
- (Un)fortunately, lattice people finally concluded it is inconsistent

Axion, the Main Topic!

- Among many ways, the simplest is KSVZ axion

	SU$(3)_{QCD}$	U$(1)_{PQ}$
ϕ	1	1
ψ_L	3	-1
$\bar{\psi}_R$	$\bar{3}$	0

- The Lagrangian is $\Delta\mathcal{L} \sim \phi\bar{\psi}_R\psi_L - V(\phi)$
- With the "wine-bottle" $V(\phi)$, U$(1)_{PQ}$ is spontaneously broken and axion appears, with $\Delta\mathcal{L} \sim \frac{a}{f_a}G\tilde{G}$

Axion Mass

- $\mathrm{U}(1)_{\mathrm{PQ}}$ 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, $\sim \langle \phi \rangle$

Rich Phenomenology of Axion

- Axion couples with baryons, photons (and leptons)
- Many experiments/observations constrain axions
  - Star lifetime, axion helioscopes, reactors, *etc.*
  - $f_a(\sim \langle\phi\rangle) \gtrsim 10^9$ GeV
- Axion coherent oscilation may be the dark matter
  - $\ddot{a}(t) + 3H\dot{a}(t) - {m_a}^2 a(t) = 0 \Rightarrow \rho_a(t) R(t)^3$ = const.
  - The initial amplitude of oscilation is $\mathcal{O}(1) f_a$
  - For $\Omega h^2 \sim 0.1$, $f_a \sim 10^{12}$ GeV

Summary So Far

- The Standard Model has the Strong CP problem
- The most plausible ($\simeq$ consistent with other observations) solution is the Peccei-Quinn mechanism and axion
- Rich phenomenology, many things to do!

Challenge for the origin of Peccei-Quinn symmetry

Big Obstacle for the Peccei-Quinn Mechanism

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

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

Since $\theta_{\mathsf{eff}} = \langle a\rangle/f_a$, $c \lesssim 10^{-60}$ 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?

- Expecting something in some unknown theory
  - Brane separation, *etc*.
- Using modulies in String Theory
  - Many modulies, many “light” mode
    - Most of them get mass
  - Some of them might be really light
  - The decay constant should be around string / Planck scale
    - Too large for DM, but anthoropic arguments may be used
  - This will be confirmed / excluded by BH superradiance

How Can We Solve It? (cont.)

- Imposing discrete (gauge) symmetries
  - Discrete symmetries may emerge from gauge symmetry
    - e.g. Abelian Higgs with charge $+2$
  - For $\Delta\mathcal{L} \sim \mathcal{O}(1)\frac{\phi^n}{{M_{\mathsf{Pl}}}^{n-4}}$, $n \gtrsim 11$!
- 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, U$(1)_{PQ}$ cannot be gauged
- However, gauge symmetry may protect U$(1)_{PQ}$ *Georgi, Hall, Wise 81*

Gauged $\mathrm{U}(1)$ Symmetries and Anomalies

- Chiral $\mathrm{U}(1)$ symmetries generally have anomalies
- How about $\mathrm{U}(1)_Y$?
    - There, anomalies from *lepton* and *quark* sectors are cancelled!
    - Conversely, "$\mathrm{U}(1)_Y$" 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 "$\mathrm{U}(1)$" are assembled into one gauged $\mathrm{U}(1)$
- Hence, if a gauged $\mathrm{U}(1)$ exists, anomalous $\mathrm{U}(1)$s may well exist

Gauged U(1) and Protection of U$(1)_{PQ}$

- No operators breaking gauged U(1) is allowed
- The problem is the connection between two sector
  - Depending on the charge assignment, PQ breaking operators are suppressed

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

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

Heavy Axion

Heavy Axion

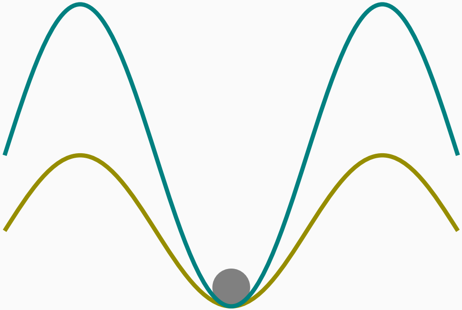
- As I mentioned, m_a is written in terms of f_a, $m_a \sim \sqrt{m_q \Lambda^3}/f_a$
- Okay, let us forget it temporarily
- With PQ-breaking operator $\Delta\mathcal{L} = c\phi^5/M_{\mathsf{Pl}}$,

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

- 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

Summary

Summary

- 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
    - If axion were heavy, quality becomes better
    - Many phenomenology - Future work