

Possibility of the Heavy QCD Axion

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Strong CP Problem

- QCD should break CP symmetry

$$\theta = \theta_{\text{YM}} + \arg \det(Y_u Y_d)$$

- However, the violation looks very small

$$|\theta| \lesssim 10^{-10}$$

Peccei-Quinn mechanism Peccei and Quinn, 1977

$U(1)_{PQ}$ Symmetry

$$q_L \rightarrow e^{i\alpha} q_L, \quad \theta \rightarrow \theta + 2T(R)\alpha$$

- $U(1)_{PQ}$ must be broken at f_a and a pseudo NG Boson a appears

Weinberg 1978, Wilczek 1978

Their Original Model

- The VEVs of 2HDM break EW gauge group and $U(1)_{PQ}$ simultaneously
- It's simple and minimal, but experimentally excluded

Which Direction?

- There are roughly two ways to achieve the PQ mechanism
 - Larger f_a , *invisible axion*
 - Heavier m_a , *heavy axion*

Axion Mass and Decay Constant

Axion Mass

$$m_a^2 \simeq \frac{m_q \Lambda^3}{f_a^2}$$

- Heavier m_a with sufficiently large f_a is hence difficult

Larger f_a isn't Easy, Either

- Why does no higher dim. op. exist?

$$\Delta\mathcal{L} = c \frac{\phi^5}{M_{\text{Pl}}}$$

$$\Rightarrow \Delta\theta \simeq c \frac{f_a^3}{M_{\text{Pl}} m_a^2} \gg 10^{-10},$$

even for the WW axion

Realizing a Heavy Axion

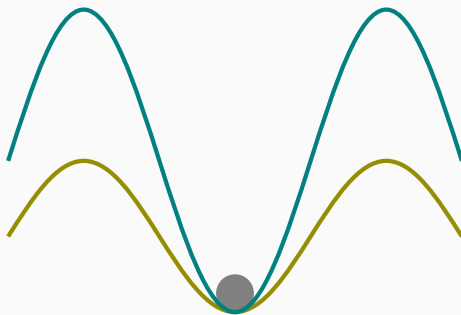
- (Rubakov, 1997) suggested a *consistent way* to achieve a heavy axion

Rubakov 1997; Berezhiani, Gianfagna and Giannotti 2000

Hook 2014, HF, Harigaya, Ibe and Yanagida 2015, Albaid, Dine and Draper 2015

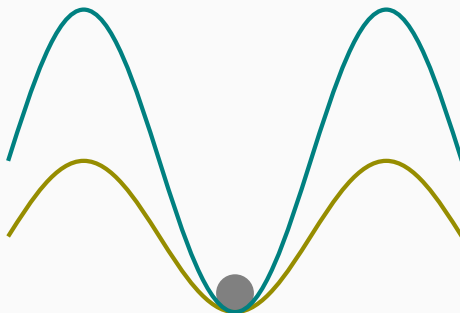
How to Make an Axion Heavier?

- Another gauge theory is needed



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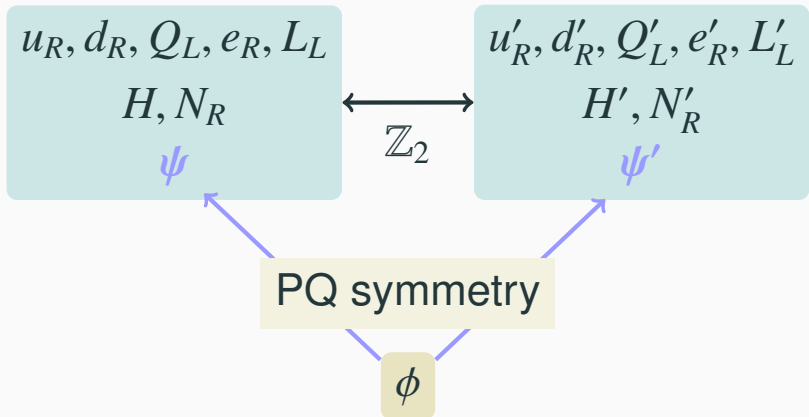
Then how can we align the two θ s?

Copy of SM

$$\theta = \theta_{\text{YM}} + \arg \det(Y_u Y_d)$$

- θ' must also have Yukawa sector
- Thus, we need a complete copy of SM
 - We assume \mathbb{Z}_2 parity, which is spontaneously broken

Our Model



Use of spontaneous \mathbb{Z}_2 breaking

- Recall

$$m_a^2 \simeq \frac{m'_q \Lambda'^3}{f_a^2}$$

- We have to increase $m'_q \propto v'$ and Λ'
 - For Λ' , we introduce color charged particles and change their masses.

Cosmological Properties

- γ' is massless
 - The axion must decouple before QCD PT
- Seesaw mechanism in ν' is forbidden
 - ν' s have large Dirac mass
 - No fine-tuning: $\sigma_{\mathbb{Z}_2} = \sigma_{B'-L'}^2 / M_{\text{Pl}}$

Stable Particle

- Two of the followings are stable

	e'	ν'	$\pi^{\pm'}$	(p')
$B' - L'$	-1	-1	0	+1
Q'	-1	0	± 1	+1

- ν' must be unstable

Low Energy Spectrum

Axion a

$$m_a \gtrsim 400 \text{ MeV}$$

Vector like quark ψ, ψ'

$$m_\psi = \frac{1}{\sqrt{2}} g f_a \gtrsim 900 \text{ GeV}$$

Dilaton s

$$m_s = \sqrt{2\lambda} f_a \gtrsim O(100) \text{ GeV}$$

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$$m_s = \sqrt{2\lambda} f_a \simeq 750 \text{ GeV??}$$

Effective Lagrangian

$$\begin{aligned}\mathcal{L} = & \frac{s}{f_a} \partial a \partial a + N_1 \frac{\alpha_s}{8\pi} \frac{s}{f_a} G G + N_2 \frac{\alpha}{8\pi} \frac{s}{f_a} F^{(\prime)} F^{(\prime)} \\ & + N_1 \frac{\alpha_s}{8\pi} \frac{a}{f_a} G \tilde{G} + N_2 \frac{\alpha}{8\pi} \frac{a}{f_a} F^{(\prime)} \tilde{F}^{(\prime)}\end{aligned}$$

- Since higher dim. op.s destroy domain walls, $N_1 \neq 1$ is allowed

Dilaton Decay

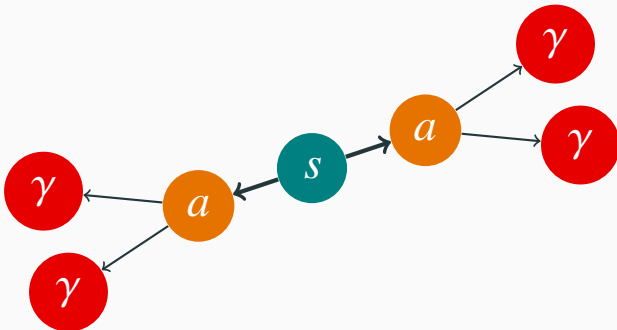
- Obviously, $\frac{s}{f_a} \partial a \partial a$ is the strongest
- Almost no $s \rightarrow 2\gamma^{(\prime)}$ decay
- Is it failed?

Dilaton Decay

- Obviously, $\frac{s}{f_a} \partial a \partial a$ is the strongest
- Almost no $s \rightarrow 2\gamma^{(\prime)}$ decay
- Is it failed? - **No!**

Photons and Photon Jets

- ECAL can't count the number of γ
 - Use “ $s \rightarrow 2a, a \rightarrow 2 \text{ collinear } \gamma$ ” mode



How to Distinguish the Jet

- Some fraction of photons is converted into e^+e^- in the detectors
- Several properties are different
 - The conversion rate
 - The acceptance...

Draper *et al.* 2012, Ellis *et al.* 2013, ... ;
Dasgupta *et al.* 2016, HF, Ibe, Nojiri in preparation

Axion Decay

Lagrangian

$$\mathcal{L}_a = N_1 \frac{\alpha_s}{8\pi} \frac{a}{f_a} G^{(\prime)} \tilde{G}^{(\prime)} + N_2 \frac{\alpha}{8\pi} \frac{a}{f_a} F^{(\prime)} \tilde{F}^{(\prime)}$$

- We need large BR
 - $\text{BR}(s \rightarrow 4\gamma) = \text{BR}(a \rightarrow 2\gamma)^2$
- a - G - G coupling looks too strong

Is Large BR Possible?

Two possibility

- $m_a < 3m_\pi$, the threshold of $a \rightarrow 2g$
- Use the mixings with mesons

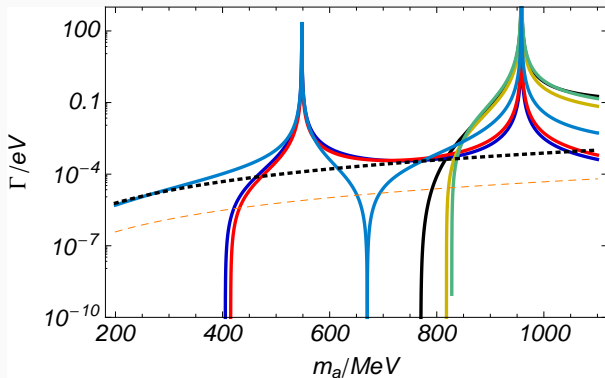
$$m_a < 3m_\pi$$

- An axion lives too longer
- Typically,

$$\gamma\Gamma^{-1} \sim \frac{100 \text{ GeV}}{m_a} \left(\frac{4\pi}{\alpha} \right)^2 \frac{f_a^2}{m_a^3} \gtrsim O(1) \text{ m}$$

Mixings with Mesons

- The phase space suppresses $a \rightarrow 3\pi$



Summary

- The heavy axion is possible
- We need a complete copy of SM
- The diphoton excess can be explained as the dilaton using our model