Possibility of the Heavy QCD Axion

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Strong CP Problem

- QCD should break CP symmetry

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

- However, the violation looks very small

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

Peccei-Quinn mechanism Peccei and Quinn, 1977

U$(1)_{\text{PQ}}$ Symmetry

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

- U$(1)_{\text{PQ}}$ 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 $\mathrm{U}(1)_{\mathrm{PQ}}$ 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?

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

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

even for the WW axion

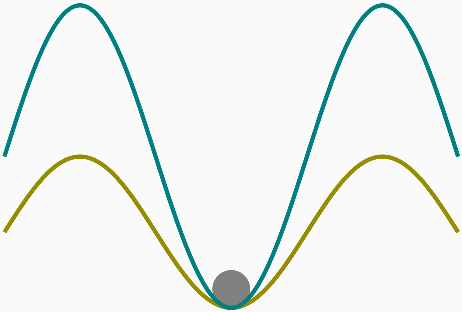
Realizing a Heavy Axion

- (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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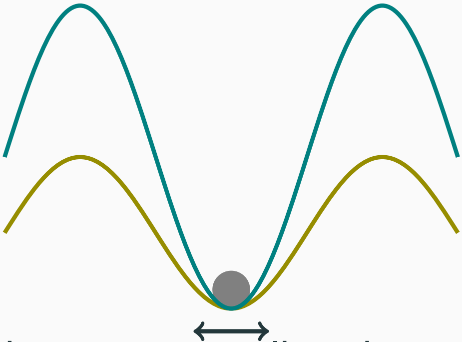


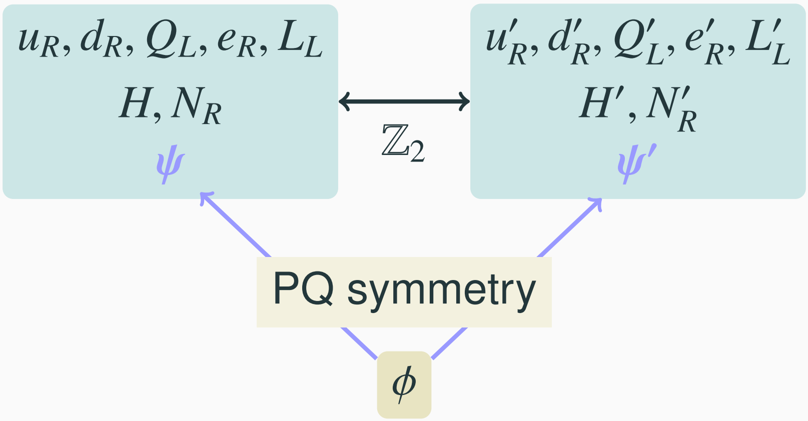
Then how can we align the two θs?

Copy of SM

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

- 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


u_R, d_R, Q_L, e_R, L_L
H, N_R
ψ
$\mathbb{Z}_2$
$u'_R, d'_R, Q'_L, e'_R, L'_L$
H', N'_R
ψ'
PQ symmetry
ϕ

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'	$\pi^{\pm\prime}$	(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

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

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Dilaton s

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

Effective Lagrangian

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

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

Dilaton Decay

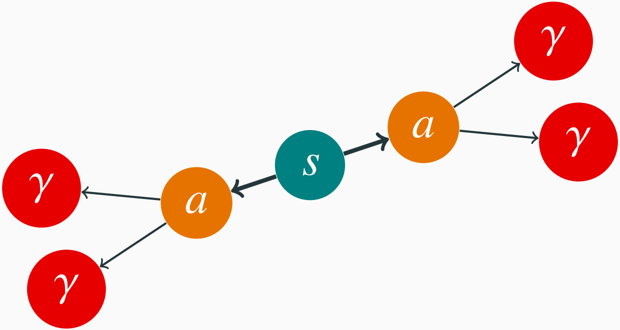
- Obviously, $\frac{s}{f_a}\partial a \partial a$ is the strongest
- Almost no $s \to 2\gamma^{(\prime)}$ decay
- Does it fail?

Dilaton Decay

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

Photons and Photon Jets

- ECAL can't count the number of γ
  - Use "$s \to 2a$, $a \to 2$ collinear γ" 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
  - BR$(s \to 4\gamma)$ = BR$(a \to 2\gamma)^2$
- a-G-G coupling looks too strong

Is Large BR Possible?

Two possibility

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

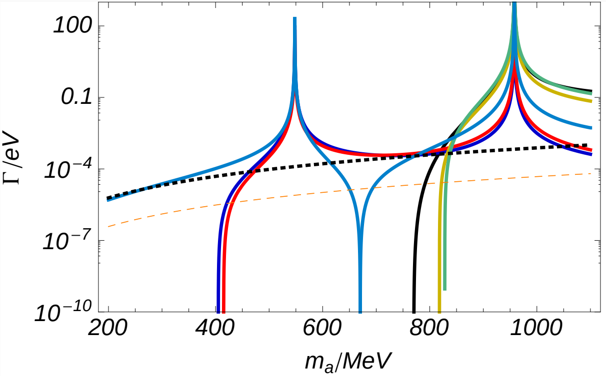
$m_a < 3m_\pi$

- An axion lives too longer
- Typically,

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

Mixings with Mesons

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



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