Possibility of the Heavy QCD Axion

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Strong CP Problem

- CP symmetry in QCD should be broken

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

- However, the violation looks very small

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

Peccei-Quinn mechanism Peccei and Quinn, 1977

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

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

- $\mathrm{U}(1)_{\mathrm{PQ}}$ 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, weaker interactions
  - Heavier m_a, evading astro constraints

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?

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

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

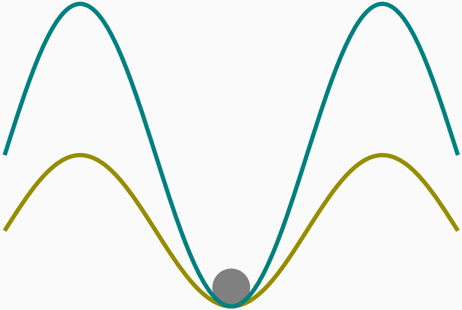
even for the WW axion

Realizing a Heavy Axion

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

How to Make an Axion Heavier?

- Another gauge theory is needed



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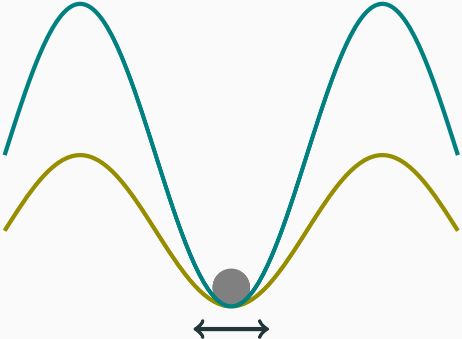

Then how can we align the two θs?

θ and θ'

- As was shown, θ comes from two parts:

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

- Aligning each parts looks easy

Copy of SM

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

- θ' must have Yukawa sector
- Thus, we need a complete copy of SM
  - We call it as a "mirrored" copy

Our Model

u_R, d_R, Q_L, e_R, L_L

H, N_R

ψ

$\xleftrightarrow[\mathbb{Z}_2]{}$

$u'_R, d'_R, Q'_L, e'_R, L'_L$

H', N'_R

ψ'

PQ symmetry

ϕ

Breakdown of $\mathbb{Z}_2$

- $\mathbb{Z}_2$ must be spontaneously broken
  - Otherwise the axion couldn't be heavy
- Which parameters do we change using spurion σ?

Heavy Axion Mass

- 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, Φ, Φ', 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

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

$$m_a \gtrsim 400\,\mathrm{MeV}$$

Vector like quark ψ, ψ'

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

Dilaton s

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

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

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 f_a is low and 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
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- Is it failed?

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- Is it failed? - **No!**

Photons and Photon Jets

- ECAL can't count the number of γ
  - Use "$s \to 2a$, $a \to 2$ collimated γ" mode

Photons and Photon Jets

- ECAL can't count the number of γ
  - Use "$s \to 2a$, $a \to 2$ collimated γ" mode
  - TRT, a tracker just before ECAL, is able to count converted photons, although 4γ seems still allowed

Axion Decay

Lagrangian

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

- We need large BR
  - $\mathrm{BR}(s \to 4\gamma) = \mathrm{BR}(a \to 2\gamma)^2$
- 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

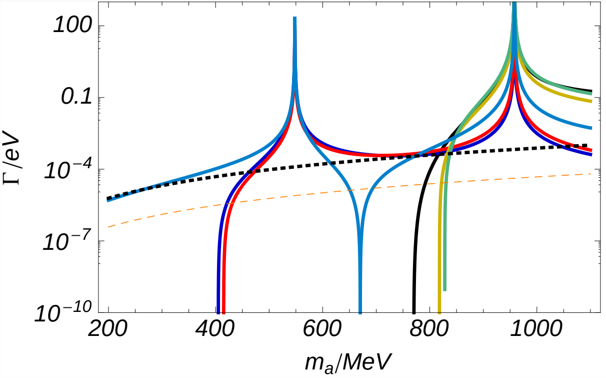
$m_a < 3m_\pi$

- 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

- $a \to 3\pi$ is suppressed by the phase factor



Summary

- The heavy axion is possible
- The diphoton excess can be explained as the dilaton
    - Photon jets may be interesting