A Model of Visible Axion

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CP conservation in QCD

- CP should be broken in QCD

$$|\theta\rangle = \sum e^{in\theta}|n\rangle$$

$$\det(\text{Yukawa matrices})$$

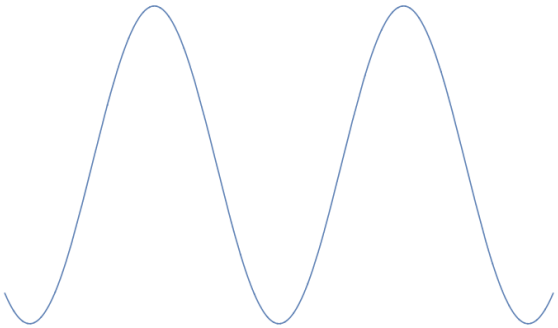
but measured CPV is quite small

QCD Axion

- An axion is usually introduced

$$\theta \to \theta + a/f, \langle a \rangle / f = -\theta$$

- The condensation gives potential



Better models are needed!

- Experimentally, PQ scale f should be grater than about 10^9 GeV
- Fine-tuning for fine-tuning?

$$\Delta\theta \sim f/M_{\rm Pl}$$

- Smaller f is preferred

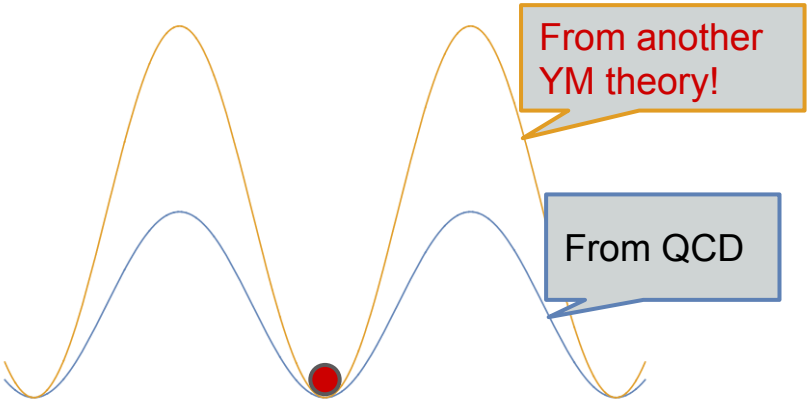
Requirement

- The smaller f is, the easier it is to detect axions, basically
- Axions must not be created!
  - They must be heavy enough
- How can we make it heavy?

$$m_a \simeq m_q {\Lambda_{\mathrm{QCD}}}^3 / f^2$$

Heavy axion

- Another gauge theory can make an axion heavier



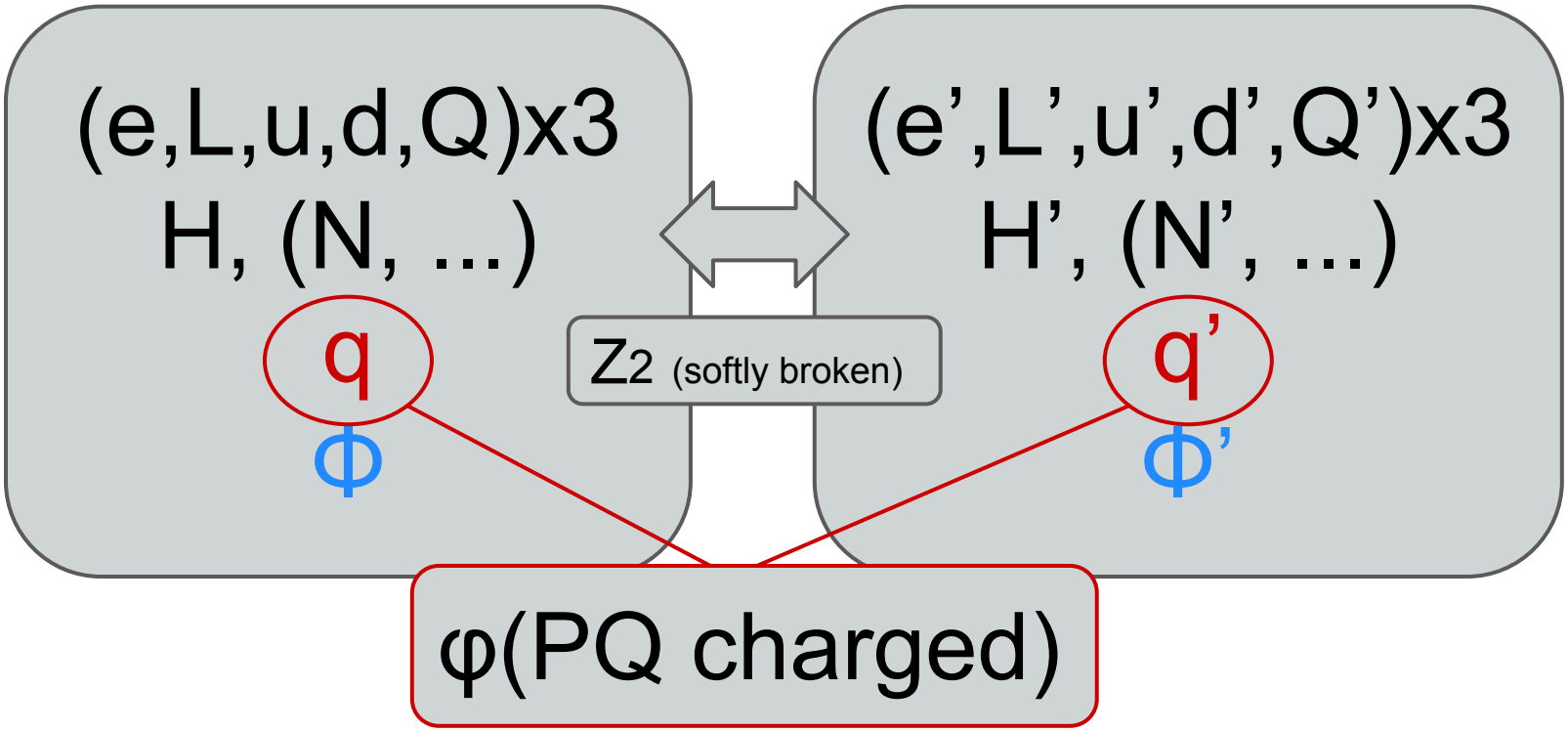
- We must align the effective theta
  - Use a $\mathbf{Z}_2$ symmetry (mirror sector)

[Rubakov 1997]

[Berezhiani, Gianfagna and Giannotti 2000, Hook 2014, HF, Harigaya, Ibe and Yanagida 2015]

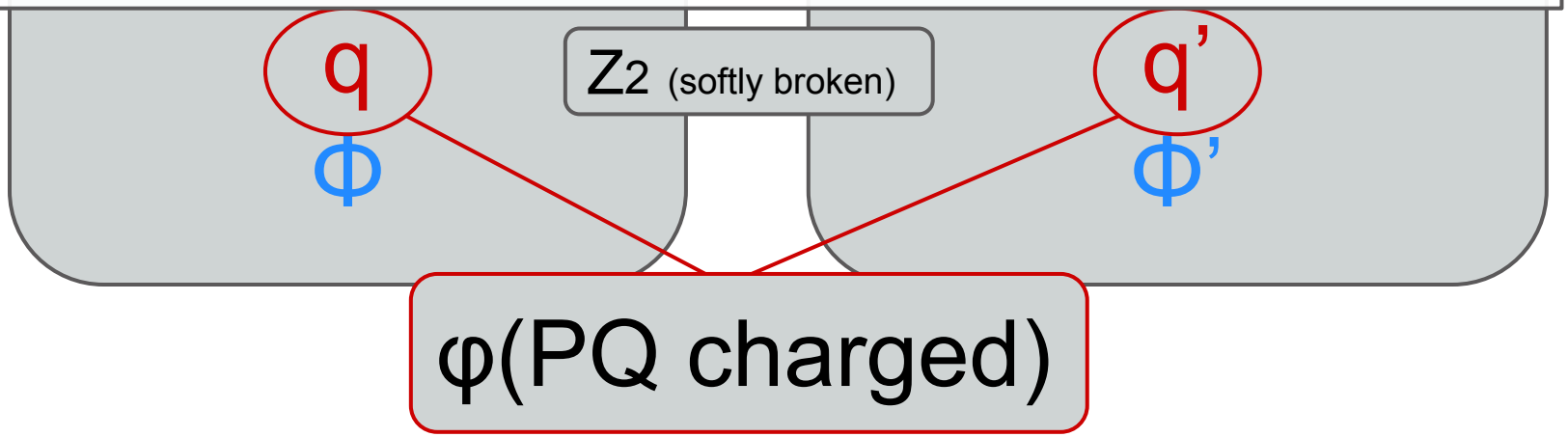
Set up

- q and Φ are color-charged



Set up

- $m_a^2 \propto v' \Lambda^3 \Rightarrow$ larger v', g_{QCD}'
- Using a spurion σ, we vary $-m_H^2$
- We also change the masses of Φ
- Seesaw' must not happen

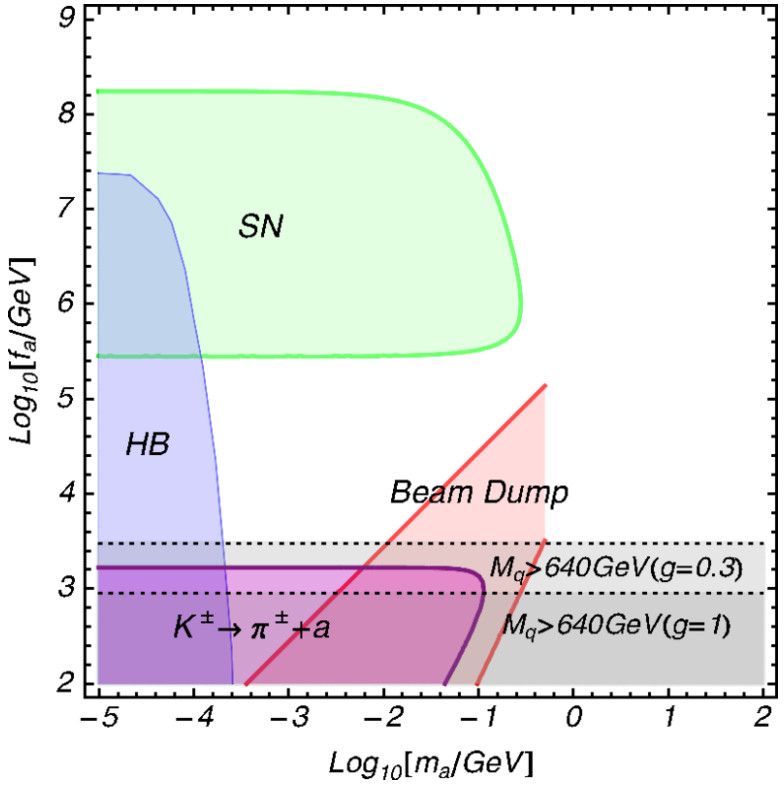


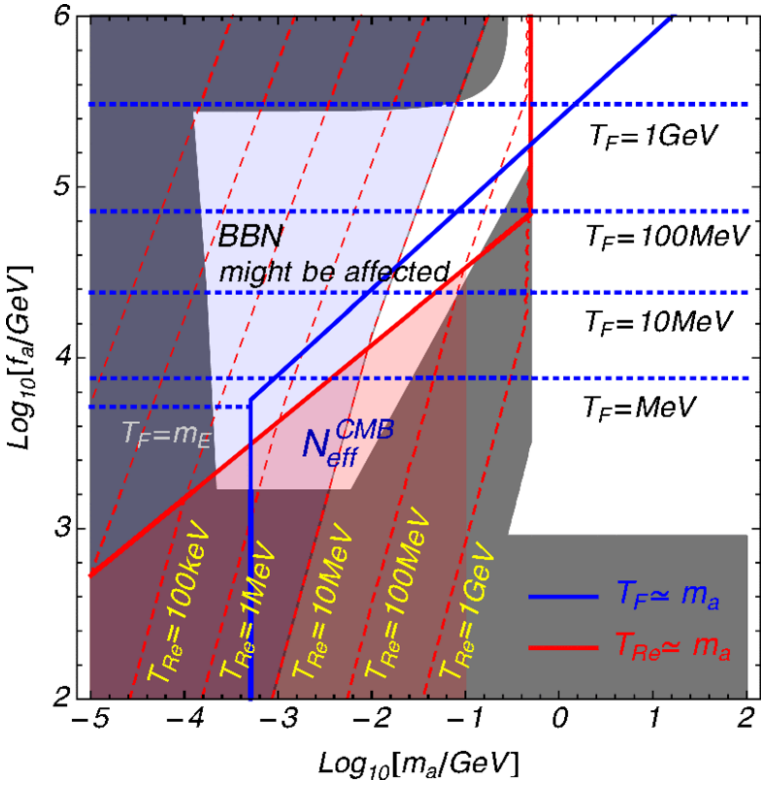
Corrections to θ

- From the higher dim. operators
  - $\Delta\theta \sim \sigma/M_{PL}$
    - Once *B-L* is gauged, only M_N^2s appear
- From radiative corrections
  - Weak and Yukawa couplings and CKM angles are involved
  - small enough

Parameter space

- Now m_a and f become independent.





How is our model verified?

- We have two ways.
  - Finding axion
  - Finding other particles (m ~ f, Λ')
- Beam dump exp. for the former
- LHC may be useful for the both!
  - What if Λ' ~ 1 TeV theory exists?
  - e.g. the diboson anomaly

[1507.02483 Chiang, HF, Harigaya, Ibe, Yanagida]

Summary

- We can introduce a very heavy QCD axion, once we assume mirror Z_2
- Not only experimental constraints, but also cosmological constraints are important
- We may see some hints of mirrored sector at LHC soon!

Typical values

- $m_a > O(100)$ MeV
- $f_a > 1$ TeV
- If we don't want η' like axion, $m' \sim O(100)$ MeV
- Then, $\Lambda' \sim 0.1 - 1$ TeV