Axion Mass from Small Instantons?

Takafumi Aoki

ICRR, the University of Tokyo

This work is in progress with Masahiro Ibe, Satoshi Shirai and Keiichi Watanabe.

Solution to Strong CP Problem

- **Massless quark**: QCD θ-angle is absorbed by chiral rotations. → A solution to the strong CP problem.

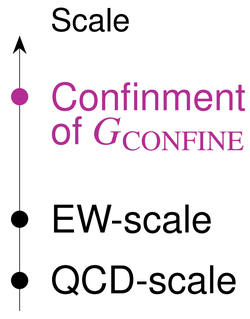
Can we solve the strong CP problem, with **massless fermions** in UV?

1. Massless fermions must not remain in low energy.
   → confinement of hidden gauge dynamics in UV.
2. Axion appears as a "pion" of hidden gauge dynamics (**"composite axion models."**)
   → Peccei-Quinn (PQ) mechanism.
3. Such models overcome "axion quality problem."

Does the axion mass increase by hidden dynamics?

→It affects the search strategy of QCD axion.

Models with Hidden Confinment



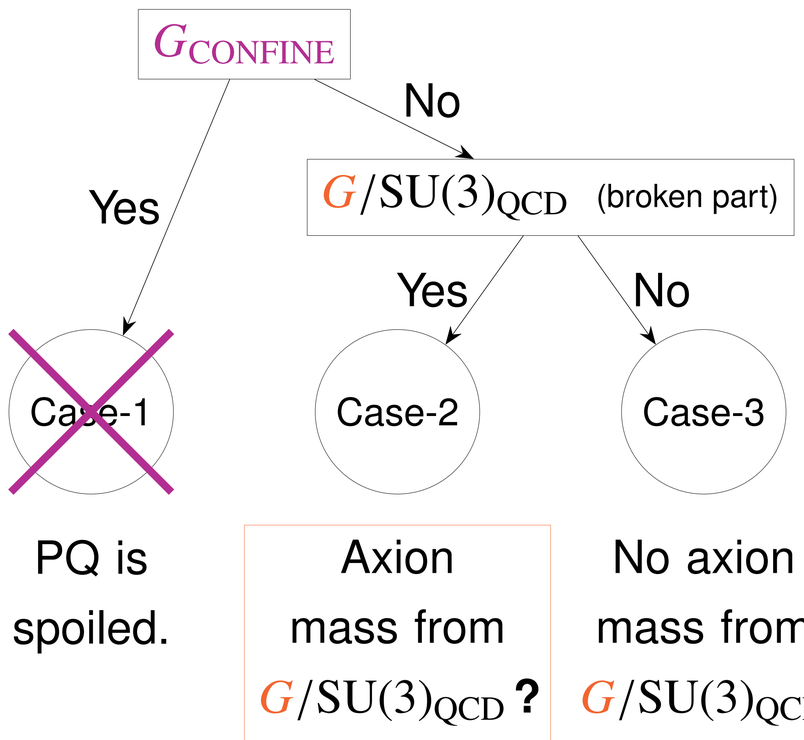
Symmetry breaking by $G_{\rm CONFINE}$:

- GAUGE: $G \supset \mathrm{SU}(3)_{\rm QCD}$
- GLOBAL: PQ (→ Axion)

G depends on models.

Dynamical scales: $\Lambda_{\rm CONFINE} \gg \Lambda_G$

Q. Is PQ symmetry **anomalous under**...?



An example of "Case-2" by Redi & Sato (2016):

$$G = \mathrm{SU}(3) \times \mathrm{SU}(4) \times \cdots \times \mathrm{SU}(4) \supset \mathrm{SU}(3)_{\rm QCD}$$

Small Instantons

Situation: Axion couples to instantons of $G/\mathrm{SU}(3)_{\rm QCD}$ (i.e. broken, non-QCD part of G).

Question: Instantons with a size $\lesssim \Lambda_{\rm CONFINE}^{-1}$ exists. Such "**small instantons**" contribute to the axion mass?

Axion Mass and Fermion Zero Modes

Q. Axion mass from small instantons?

Fermion zero modes are crucial.

1. **What are "zero modes"?**
   Oscillations along them do not change the action S.
2. **When fermion zero modes are present:**
$$\int \mathcal{D}\psi \exp(iS)\mathcal{O} \propto \int \mathrm{d}\xi^{(0)}\,(\text{const.}) = \mathbf{0}\,,$$
   (except for $\mathcal{O}$ including all the zero modes.)
3. **When interactions are added:**
   S "respond" to oscillations along zero modes.
   → Non-zero path integral.
   (example: QCD instanton effects $\propto$ quark Yukawa couplings.)

What we found (in a model by Redi & Sato (2016)):

Fermion zero modes around small instantons do not interact in a way generating the axion mass.

→ **No axion mass from small instantons.**

∗ Strictly speaking, some appropriate pairs of small instantons contribute. ← Effectively QCD instantons with a small size $\sim \Lambda_{\rm CONFINE}^{-1}$.

Summary

1. With Hidden gauge dynamics, massless fermions in UV can solve the strong CP problem.
   small instantons might enhance the axion mass.
2. However, close look at **fermion zero modes** is needed. We found that **axion mass is not enhanced** in a model by Redi and Sato (2016).
3. **Future prospect**: A generalization of our result, to be applied to other models.

For more detail, please turn over this poster.