QCD axion from chiral gauge theories

Shonosuke Takeshita Hiroshima University

Working in progress w/ Ryosuke Sato (U. of Osaka)

Theoretical Particle and Hadron Physics Group

Graduate School of Advanced Science and Engineering
Hiroshima University

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QCD axion

CP violation in quark sector

1.The phase in CKM matrix:$\delta = O(1)$ PDG2024

$$V_{\mathrm{CKM}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

2.QCD θ term: $|\bar{\theta}| \lesssim 10^{-10}$ C. Abel et al., Phys. Rev. Lett. **124** no.8, 081803 (2020)

$$\mathcal{L}_\theta = \theta \frac{g_s^2}{32\pi^2} G^{a\mu\nu}\tilde{G}^a_{\mu\nu} + \sum_q \left[m_q e^{i\theta_q}\bar{q}_L q_R + \mathrm{h.c.}\right]$$

$$\bar{\theta} = \theta + \sum_q \theta_q$$ Ex). R. Jackiw and C. Rebbi (1976)

Why $|\bar{\theta}|$ is too small? ⟶ Strong CP problem

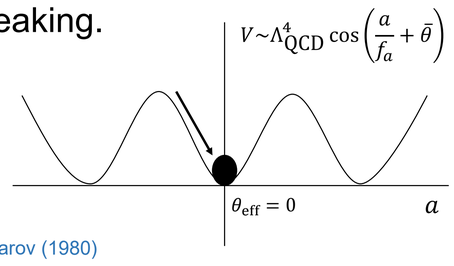
Peccei-Quinn(PQ)mechanism: introducing new global symmetry

R. D. Peccei and H. R. Quinn (1977)

PQ symmetry

- NG boson appears with PQ symmetry breaking.

Axion S. Weinberg (1978); F. Wilczek (1978)



Axion cancels θ parameter dynamically.

QCD axion model

J.E. Kim (1979)
M.A. Shifman, A.I. Vainshtein and V.I. Zakharov (1980)

QCD axion model	PQ symmetry breaking
KSVZ model、DFSZ model	VEV of PQ scalar fields
Composite axion model	New strong dynamics

M. Dine, W. Fischler and M. Srednicki (1981)
A.R. Zhitnitsky (1980)

Easy to analyze!

The most of models utilize strong dynamics of QCD-like gauge theories.

Ex). K. Choi and J. E. Kim (1985)
L. Randall (1992)
M. Redi and R. Sato (2016)

Q. How about chiral gauge theories?

A. Discussion of model based on chiral gauge theories is quite limited.

The analysis is too difficult.

- t' Hooft anomaly matching
- tumbling

M. B. Gavela et al. (2019)
P. Cox et al. (2023)

Our study

We propose QCD axion model based on SUSY chiral gauge theories.

Point

Thanks to SUSY, non-perturbative dynamics of chiral gauge theories can be solved in analytic expressions.

Our model

We introduce $\mathrm{SU}(2N+4)_1 \times \mathrm{SU}(N)_2$ gauge symmetry and chiral multiples $\bar{F}_q$, $\bar{F}_{\bar{q}}$, and A.

	$\mathrm{SU}(2N+4)_1$	$\mathrm{SU}(N)_2$	$\mathrm{U}(1)_{\mathrm{PQ}}$	$\mathrm{U}(1)_q$	$\mathrm{U}(1)_R$	$\mathrm{SU}(2N)_{\bar{F}}$
$\bar{F}_q$	$\overline{\square}$	$\square$	$N+1$	1	0	$\square$
$\bar{F}_{\bar{q}}$	$\overline{\square}$	$\overline{\square}$	$N+1$	-1	0	
A	$\begin{smallmatrix}\square\square\\\square\end{smallmatrix}$	$\mathbf{1}$	$-N$	0	$-3/(N+1)$	$\mathbf{1}$

$\mathrm{SU}(2N+4)_1 \supset \mathrm{SU}(N)_1 \times \mathrm{Sp}(4)_1$
$\mathrm{SU}(N)_1 \times \mathrm{SU}(N)_2 \longrightarrow \mathrm{SU}(N)_d$
$\mathrm{U}(1)_1 \times \mathrm{U}(1)_q \longrightarrow \mathrm{U}(1)_d$

Symmetry breaking

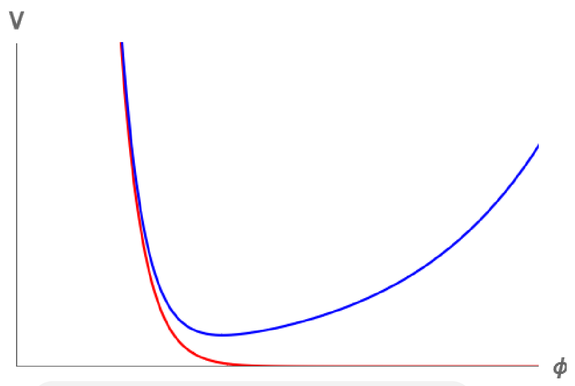
D-flat condition: Affleck, Dine, and Seiberg (1985)

$$D^a = \varphi^{\dagger l} T_l^{ak} \varphi_k = 0 \longrightarrow 2A^\dagger A - \bar{F}_q \bar{F}_q^\dagger - \bar{F}_{\bar{q}} \bar{F}_{\bar{q}}^\dagger \propto I_{2N},\ \bar{F}_q^\dagger \bar{F}_q - \bar{F}_{\bar{q}}^T \bar{F}_{\bar{q}}^* \propto I_N$$

$$\longrightarrow A = \begin{pmatrix} 0_{N\times N} & -icI_N & & \\ icI_N & 0_{N\times N} & & \\ & & 0_{2\times 2} & -ic' I_2 \\ & & ic' I_2 & 0_{2\times 2} \end{pmatrix},\quad \bar{F}_q = \phi \begin{pmatrix} I_N \\ 0_{N\times N} \\ 0_{N\times 4} \end{pmatrix},\quad \bar{F}_{\bar{q}} = \phi \begin{pmatrix} 0_{N\times N} \\ I_N \\ 0_{N\times 4} \end{pmatrix}$$

$$[\mathrm{SU}(2N+4)_1 \times \mathrm{SU}(N)_2] \times \mathrm{U}(1)_{\mathrm{PQ}} \times \mathrm{U}(1)_q \times \mathrm{U}(1)_R \longrightarrow [\mathrm{Sp}(4)_1 \times \mathrm{SU}(N)_d] \times \mathrm{U}(1)_d$$

Potential analysis



Red: $V = \sum_{X=A,\bar{F}_q,\bar{F}_{\bar{q}}} \left|\frac{\partial W}{\partial X}\right|^2$

Blue: $V = \sum_{X=A,\bar{F}_q,\bar{F}_{\bar{q}}} \left|\frac{\partial W}{\partial X}\right|^2 + V_{\mathrm{soft}}$

Dynamical superpotential induced by Sp(4) gaugino condensation:

$$W = 3 \cdot 2^{-\frac{1+N}{3}} \left(\frac{\Lambda_{2N+4}^{4N+11}}{(\mathrm{Pf}\, A\bar{F}\bar{F})(\mathrm{Pf}\, A)}\right)^{1/3}$$

Soft SUSY breaking terms:

$$V_{\mathrm{soft}} = m^2 \left|\bar{F}_q\right|^2 + m^2 \left|\bar{F}_{\bar{q}}\right|^2 + m^2 |A|^2$$

D-flat direction is stabilized by SUSY breaking.

Potential minimum

$$\phi = x_N \Lambda_{2N+4} \left(\frac{\Lambda_{2N+4}}{m}\right)^{3/(4N+8)}$$

$$c = y_N \Lambda_{2N+4} \left(\frac{\Lambda_{2N+4}}{m}\right)^{3/(4N+8)}$$

$\phi, c \gg \Lambda_{2N+4}$ for $\Lambda_{2N+4} \gg m$ ⟶ We can justify the weakly coupled analysis.

C. Csaki, H. Murayama, and O. Telem (2021)

Axion decay constant

$$f_a = \frac{\sqrt{4N(N+1)^2\phi^2 + 4c^2N^3 + 8c'^2N^2}}{N_{\mathrm{anom}}} = w_N \Lambda_{2N+4} \left(\frac{\Lambda_{2N+4}}{m}\right)^{3/(4N+8)}$$

QCD anomaly factor: $N_{\mathrm{anom}} = 4(N+1)(N+2)$

Domain-wall number: $N_{\mathrm{DW}} = \frac{N_{\mathrm{anom}}}{N+2} = 4(N+1)$

GUT-motivated QCD axion model

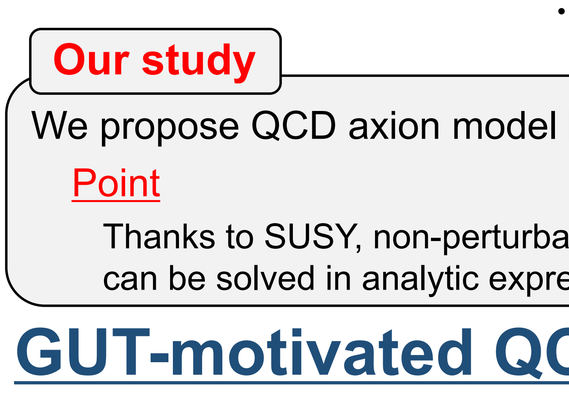
	$\mathrm{SU}(14)_1$	$\mathrm{SU}(5)_2$	$\mathrm{U}(1)_{\mathrm{PQ}}$	$\mathrm{U}(1)_q$	$\mathrm{SU}(10)_{\bar{F}}$
$\bar{F}_q$	$\overline{\square}$	$\square$	6	1	$\square$
$\bar{F}_{\bar{q}}$	$\overline{\square}$	$\overline{\square}$	6	-1	
A	$\begin{smallmatrix}\square\square\\\square\end{smallmatrix}$	$\mathbf{1}$	-5	0	$\mathbf{1}$
$\Phi = (\bar{D} \oplus L)$	$\mathbf{1}$	$\overline{\square}$	0	0	$\mathbf{1}$
$\Psi = (Q \oplus \bar{U} \oplus \bar{E})$	$\mathbf{1}$	$\begin{smallmatrix}\square\square\\\square\end{smallmatrix}$	0	0	$\mathbf{1}$
H	$\mathbf{1}$	$\square$	0	0	$\mathbf{1}$
$\bar{H}$	$\mathbf{1}$	$\overline{\square}$	0	0	$\mathbf{1}$
Σ	$\mathbf{1}$	$\mathbf{adj}$	0	0	$\mathbf{1}$

➢MSSM chiral multiplets are charged under $\mathrm{SU}(5)_2$.

➢The SU(5) gauge symmetry is broken by introducing a chiral multiplet Σ (1, **adj**).

Constraints from Landau pole

Sato and ST in preparation



$f_a \gtrsim 3.4 \times 10^{15}$ GeV
$(\Lambda_{14} \gtrsim 1.3 \times 10^{15}$ GeV)

⟶ $M_{\mathrm{GUT}} > M_{\mathrm{PQ}}$ case is excluded.

Symmetry breaking patterns

- $M_{\mathrm{GUT}} > M_{\mathrm{PQ}}$

$[\mathrm{SU}(14)_1 \times \mathrm{SU}(5)_2] \times \mathrm{U}(1)_{\mathrm{PQ}} \times \mathrm{U}(1)_q \times \mathrm{U}(1)_R$
$\longrightarrow [\mathrm{SU}(14)_1 \times \mathrm{SU}(3)_2 \times \mathrm{SU}(2)_2 \times \mathrm{U}(1)_2] \times \mathrm{U}(1)_{\mathrm{PQ}} \times \mathrm{U}(1)_q \times \mathrm{U}(1)_R$
$\longrightarrow [\mathrm{Sp}(4)_1 \times \mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y] \times \mathrm{U}(1)_d$

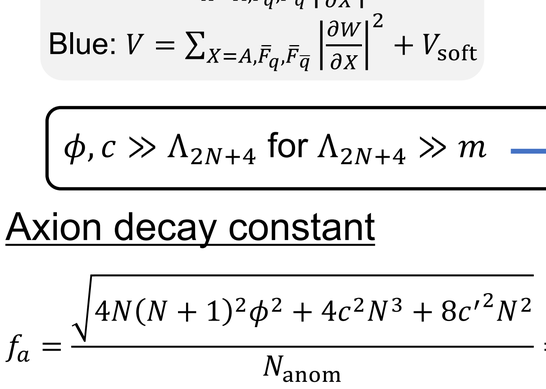
- $M_{\mathrm{GUT}} < M_{\mathrm{PQ}}$

$[\mathrm{SU}(14)_1 \times \mathrm{SU}(5)_2] \times \mathrm{U}(1)_{\mathrm{PQ}} \times \mathrm{U}(1)_q \times \mathrm{U}(1)_R$
$\longrightarrow [\mathrm{Sp}(4)_1 \times \mathrm{SU}(5)_{\mathrm{GUT}}] \times \mathrm{U}(1)_d$
$\longrightarrow [\mathrm{Sp}(4)_1 \times \mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y] \times \mathrm{U}(1)_d$

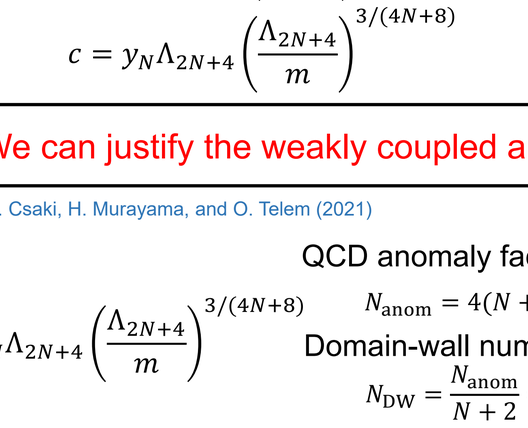
We assume high-scale SUSY scenario with anomaly mediation.
$M_2 = 3$ TeV, $M_3/M_2 = 9$
$M_S = 100$ TeV, $\tan\beta = 3$

L. Randall and R. Sundrum (1998)
G. F. Giudice, M. A. Luty, H. Murayama, and R. Rattazzi (1998)

Successful unification



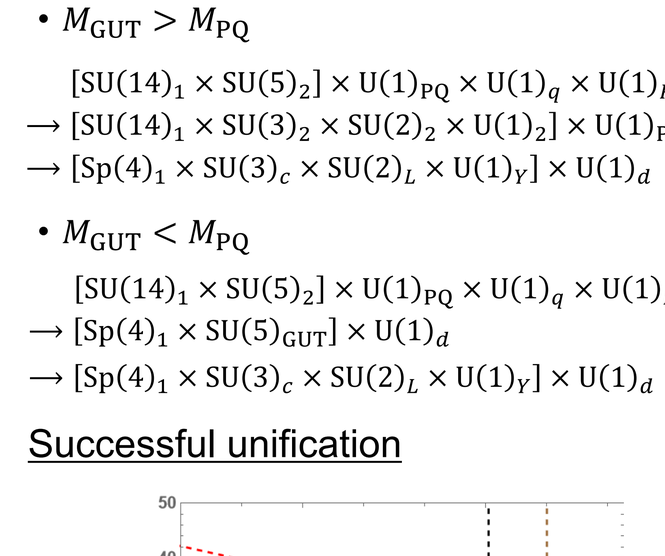
$M_{\mathrm{GUT}} > M_{\mathrm{PQ}}$ $(\Lambda_{14} = 10^{14}\mathrm{GeV})$



$M_{\mathrm{GUT}} < M_{\mathrm{PQ}}$ $(\Lambda_{14} = 10^{16}\mathrm{GeV})$

Proton decay

Sato and ST in preparation



Red: $\alpha_1(M_{\mathrm{GUT}}) = \alpha_2(M_{\mathrm{GUT}})$
Blue: $\alpha_2(M_{\mathrm{GUT}}) = \alpha_3(M_{\mathrm{GUT}})$
Green: $\alpha_1(M_{\mathrm{GUT}}) = \alpha_3(M_{\mathrm{GUT}})$

➢$M_{\mathrm{GUT}} > M_{\mathrm{PQ}}$

The unified gauge coupling becomes larger than minimal SU(5) GUT.

⟶ The proton lifetime become shorter for lower f_a.

➢ $M_{\mathrm{GUT}} < M_{\mathrm{PQ}}$

The unified gauge coupling is same with minimal SU(5) GUT.

⟶ The proton lifetime is independent on f_a.

SK: $\tau_p(p \to \pi^0 e^+) > 2.4 \times 10^{34}$ years
A. Takenaka et al., (2020)
HK: $\tau_p(p \to \pi^0 e^+) = 7.8 \times 10^{34}$ years
K. Abe et al., (2018)

Summary

- We propose QCD axion model based on SUSY chiral gauge theories.
- PQ symmetry is broken by non-perturbative dynamics and it can be analyzed thanks to SUSY.
- We apply this model to SU(5) GUT and high scale f_a is preferred to avoid the Landau pole below the Planck scale.