Realistic axion model with ``Gauged'' PQ mechanism

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I. Introduction

Standard Model (SM) is now complete

Unsettled issues

- Nature of dark matter
- Finiteness of neutrino mass
- Asymmetry of matter and anti-matter
- Naturalness problem of physical constant

Novel models e.g.

- Dark matter + Baryogenesis
- Dark matter + Strong CP problem
- Dark matter + Hierarchy problem

Challenge

Unified framework

Model at low energy scale

My approach

Implications from physics at Planck scale

All global symmetries are accidental ones

e.g. Axion model

II. Accidental PQ symmetry

Strong CP problem

QCD has its own CP- and P- violating parameter: θ

$$S_{QCD} = \int d^4x \left(-\frac{1}{4g^2} G^a_{\mu\nu} G^{a\mu\nu} + \frac{\theta}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu} + \mathcal{L}_q \right)$$

(positive quark masses)

θ-term is constrained experimentally

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

by measurement of neutron electric dipole moment (nEDM)

hep-ex/0602020

Strong CP problem

Why θ so small ?

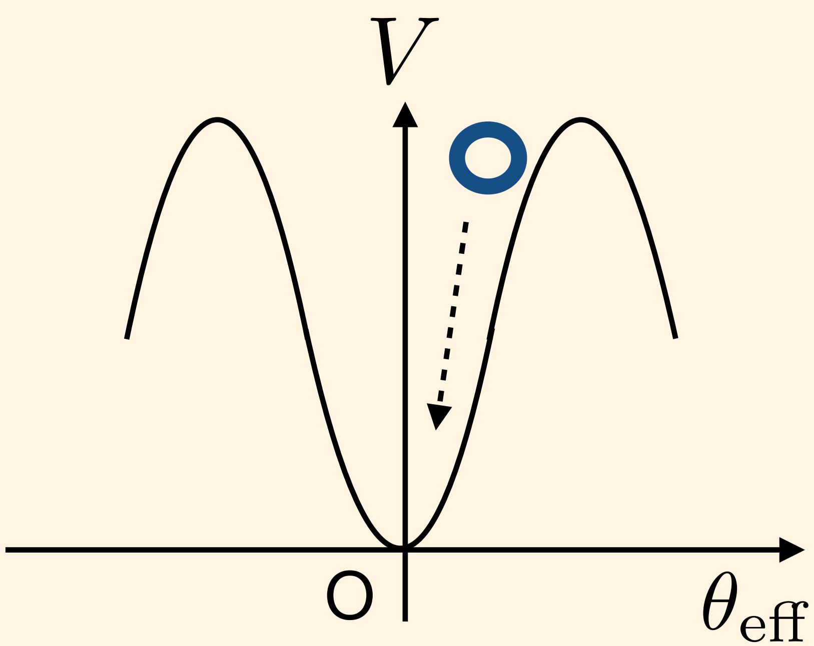
Peccei-Quinn mechanism '77 Peccei, Quinn

Peccei-Quinn (PQ) symmetry: color anomaly

Axion: pseudo Nambu-Goldstone boson from PQ symmetry breaking

Axion cancels θ-parameter dynamically

'78 Weinberg, '78 Wilczek



Peccei-Quinn mechanism can solve Strong CP problem

Implication

PQ symmetry is broken by quantum gravity effect

'88 Giddings and Strominger
'88 Coleman
'89 Abbott and Wise
'89 Coleman and Lee
'95 Kallosh, Linde, Linde, Susskind
'10 Banks and Seiberg
et,al,

Gravity may break PQ symmetry badly

e.g. KSVZ model '79 Kim, '80 Shifman, Vainshtein, Zakharov

$$\mathcal{L} \ni \Phi q_L \bar{q}_R$$

(extra quarks)

Spontaneous PQ breaking scalar field

$$\Phi \ni \frac{1}{\sqrt{2}} f_a e^{i\frac{a}{f_a}}$$

a: axion field

f_a: axion decay constant

If physics at Planck scale breaks PQ symmetry

$$\mathcal{L} \ni \sum_{k=1,2,\ldots} \left(\lambda_k \frac{\Phi^{k+4}}{M_{\rm pl}} + \tilde{\lambda}_k \frac{|\Phi^{2k}|\Phi}{M_{\rm pl}} + h.c. + \ldots \right)$$

$\lambda_k, \ \tilde{\lambda}_k$: dimensionless couplings

Axion potential is affected by Planck mass suppressed term

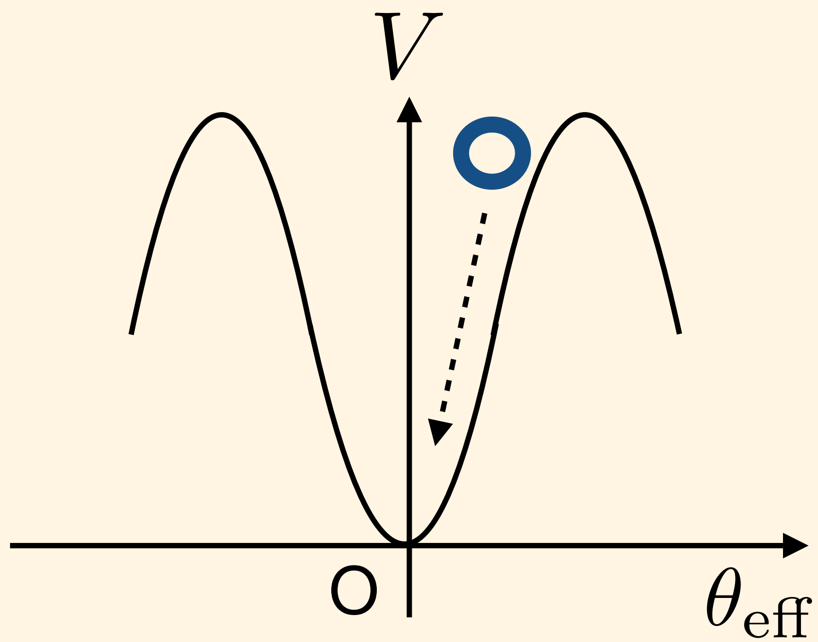
$$V \sim -m_a^2 f_a^2 \cos\left(\frac{a}{f_a}\right) + \left(\lambda_1 \frac{(f_a/\sqrt{2})^5}{M_{\rm pl}} e^{i5a/f_a} + h.c. \right) + \ldots$$

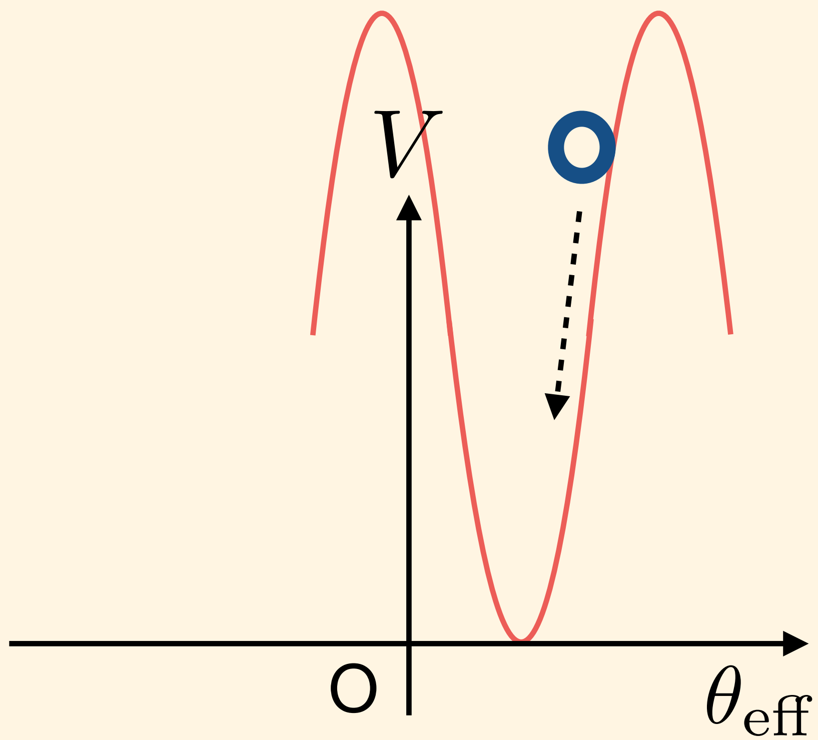
m_a: axion mass

Gravity may break PQ symmetry badly

Axion potential

$$V \sim -m_a^2 f_a^2 \cos\left(\frac{a}{f_a}\right) + \left(\lambda_1 \frac{(f_a/\sqrt{2})^5}{M_{\rm pl}} e^{i5a/f_a} + h.c.\right) + \dots$$





Gravity distorts axion potential !

Vacuum at θ ≠ 0 !

Gravity may break PQ symmetry badly

More quantitatively,
Shift of axion VEV should be smaller than 10^{-10}

$$V(a) \sim m_a^2 a^2 + |\lambda_1| \frac{f_a^5}{\sqrt{2}^5 M_{\rm pl}} \left(\left(\frac{5a}{f_a}\right)^2 + \frac{5a}{f_a}\delta \right) + \dots$$

$$\sim \quad \Lambda_{QCD}^4 \frac{a^2}{f_a^2} + |\lambda_1| \frac{f_a^4}{\sqrt{2}^5 M_{\rm pl}} \frac{5a}{f_a}\delta$$

$$\sim \quad \Lambda_{QCD}^4 \left(\frac{a}{f_a} + |\lambda_1| \frac{f_a^4}{\sqrt{2}^5 M_{\rm pl} \Lambda_{QCD}^4} \frac{5}{2}\delta \right)^2$$

$$|\Delta\theta| = |\left\langle \frac{a}{f_a} \right\rangle| = |\lambda_1| \frac{f_a^5}{\sqrt{2}^5 M_{\rm pl} \Lambda_{QCD}^4} \frac{5}{2}\delta < 10^{-10}$$

Couplings must be extremely tiny

$$|\lambda_1| < 10^{-56} \left(\frac{10^{12}\ GeV}{f_a} \right)^5 \left(\frac{\Lambda_{QCD}}{0.1\ GeV} \right)^4 \quad \text{for } \delta = O(1)$$

Strong CP problem again !!

How to solve ``remained'' Strong CP problem?

One approach

Gauge symmetry

Gauge symmetry protecting PQ symmetry

Introducing new discrete gauge symmetry ``by hand''

e.g. $\Phi(+1)$: charged by discrete gauge Z_{11}, Z_{12}, ...

Gauge symmetry can protect PQ symmetry

$$\mathcal{L} \ni \frac{\Phi^5}{M_{pl}} \quad \longrightarrow \quad \mathcal{L} \ni \frac{\Phi^{11}}{M_{\rm pl}^7}, \ \frac{\Phi^{12}}{M_{\rm pl}^8}, \cdots$$

Higher gauge symmetry Z_N ($N \geq 11$), smaller shift of axion VEV

✓ $\Delta\theta < 10^{-10}$

Higher discrete gauge symmetry seems to be artificial

Gauge symmetry protecting PQ symmetry

Another example: Barr-Seckel model (extension of KSVZ model)

'92 Barr and Seckel

Using abelian gauge symmetry $U(1)_{BS}$

Introduce **two complex scalar fields charged by $U(1)_{BS}$**

$$\phi_1(10),\ \ \phi_2(-1)$$

Introduce **two kinds of KSVZ quarks**, $Q_1, \bar{Q}_1$, and Q_2, $\bar{Q}_2$

$$\mathcal{L} = y_1\phi_1 Q_1 \bar{Q}_1 + y_2 \phi_2 Q_2 \bar{Q}_2$$

$Q_1, \bar{Q}_1$: N_1 flavors

$Q_2, \bar{Q}_2$: N_2 flavors

KSVZ quarks obtain their mass from VEV of scalar fields

Barr-Seckel model
'92 Barr and Seckel

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$Q_2, \bar{Q}_2$: N_2 flavors

Flavors determined by quantum anomaly cancellation, $U(1)_{BS}$-SU(3)c-SU(3)c

$$(N_1, N_2) = (1, 10)$$

Barr-Seckel model

Introduce two complex scalar fields charged by U(1)$_{BS}$

$$\phi_1(10),\ \ \phi_2(-1)$$

KSVZ quarks obtain their mass from VEV of scalar fields

$$\mathcal{L} = y_1\phi_1 Q_1\bar{Q}_1 + y_2\phi_2 Q_2\bar{Q}_2$$

$Q_1, \bar{Q}_1$: 1 flavors

$Q_2, \bar{Q}_2$: 10 flavors

Where is axion?

Two NG bosons after scalar fields obtain VEVs

One: eaten by U(1)$_{BS}$

Another One: Axion !

Barr-Seckel model

Explicit PQ breaking term

$$\mathcal{L} \simeq \frac{\phi_1 \phi_2^{10}}{M_{\rm pl}^7}$$

Sufficiently suppressed shift of axion VEV

What is essential point of Barr-Seckel model?

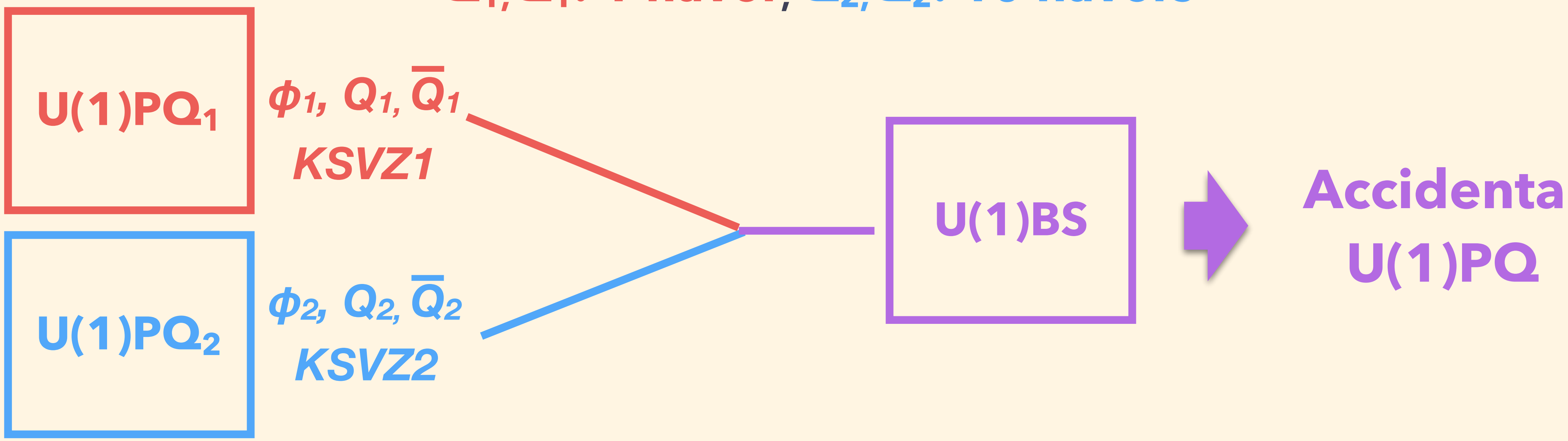
Essential point of Barr-Seckel model

Apparent two sectors and apparent two PQ symmetries

$$L = y_1 \varphi_1 Q_1 \overline{Q}_1 + y_2 \varphi_2 Q_2 \overline{Q}_2$$

φ_1 (10), φ_2 (-1)

$Q_1, \overline{Q}_1$: 1 flavor, $Q_2, \overline{Q}_2$: 10 flavors



Gauging anomaly free combination of two PQ symmetries

$$U(1)_{PQ_1} \times U(1)_{PQ_2} \longrightarrow U(1)_{BS} \times U(1)_{PQ}$$

$U(1)_{BS}$ can work to provide accidental PQ symmetry

$$L = M_{PL}^{4-(\dim O_1 + \dim O_2)} O_1 O_2 \quad (\dim O_1 + \dim O_2) \geq 11$$

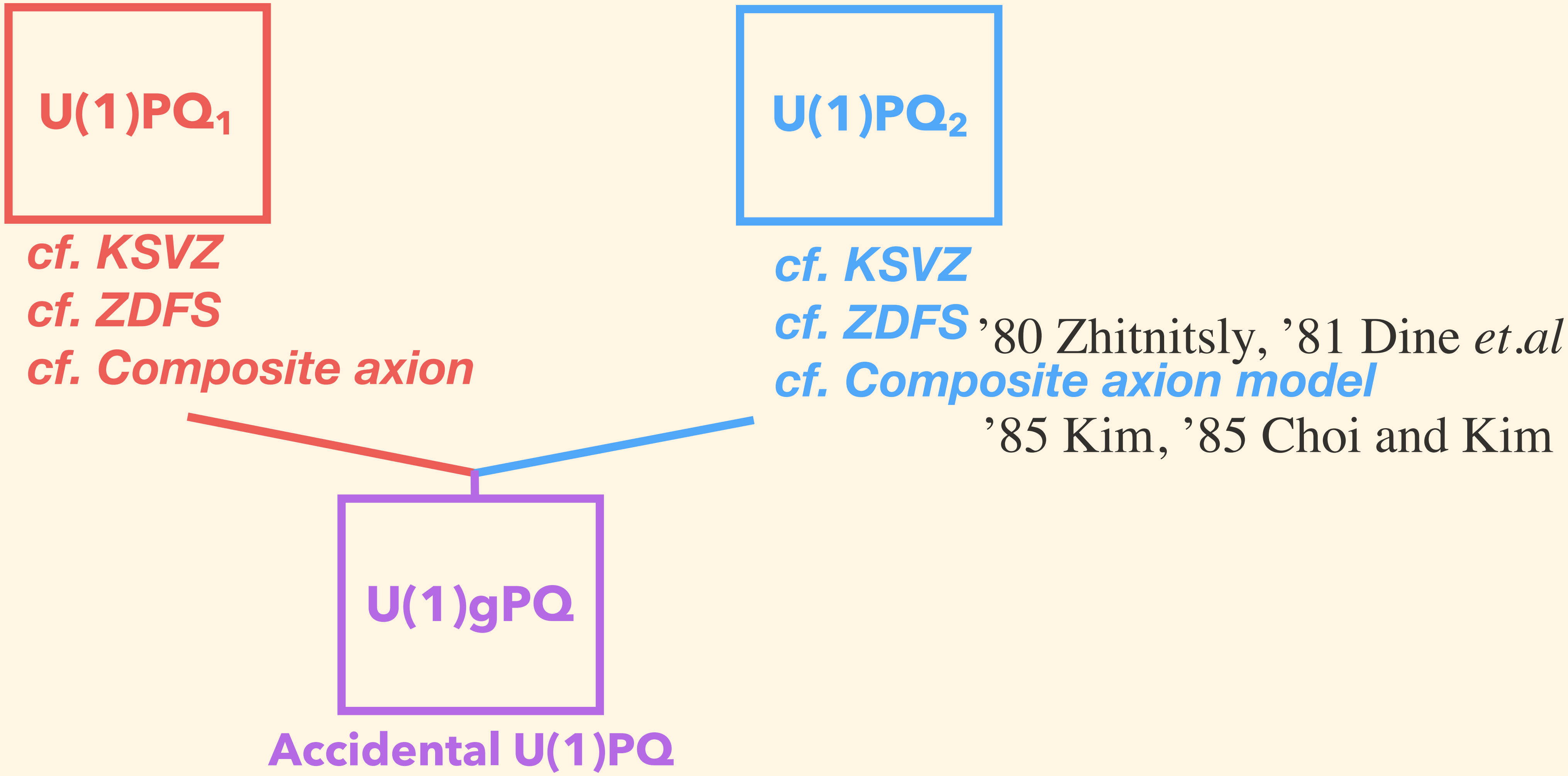
$$\mathcal{L} \simeq \frac{\phi_1 \phi_2^{10}}{M_{\rm pl}^7}$$

III. Our works
-general protection mechanism-

Our work: Gauged PQ mechanism

H. Fukuda, M. Ibe, M. S, and T. T. Yanagida, Phys. Lett. B771, 327 (2017).

General protection mechanism



$$U(1)PQ_1 \times U(1)PQ_2 \longrightarrow U(1)_{gPQ} \times U(1)_{PQ}$$

Protection gauge symmetry = Gauged PQ symmetry

Our work: application to SUSY model

H. Fukuda, M. Ibe, M. S, and T. T. Yanagida, JHEP1807, 128 (2018).

Higgs mass 125 GeV → High scale SUSY

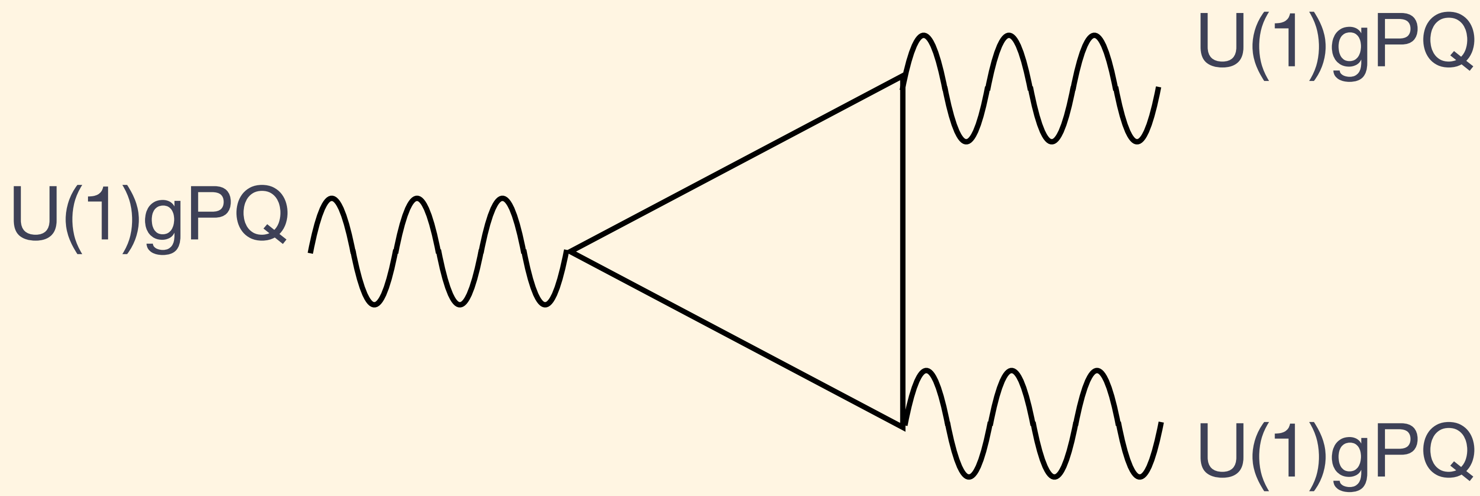
SUSY breaking scale $\simeq$ PQ breaking scale

'13 Feldstein and Yanagida

Model where PQ is broken with dynamical SUSY breaking

Cosmological Problem

To cancel triangle anomaly, adding extra SM singlets (fermions)



Extra ones tend to be light and behave as dark radiation

→ **Unacceptably large number of effective neutrino spieces**

Realistic model

Gauged PQ symmetry with no extra ones

Standard Model (SM) is now complete

Unsettled issues

- Nature of dark matter
- Finiteness of neutrino mass
- Asymmetry of matter and anti-matter
- Naturalness problem of physical constant

Gauged PQ symmetry = B-L gauge symmetry?

Standard Model (SM) is now complete

Unsettled issues

- Nature of dark matter
  axion
- Finiteness of neutrino mass
  seesaw
- Asymmetry of matter and anti-matter
  thermal leptogenesis
- Naturalness problem of physical constant
  axion solves Strong CP problem

Unified picture

Gauged PQ symmetry = B-L gauge symmetry?

Let us find model

B-L = Gauged PQ without un-wanted singlets

B-L gauge symmetry = gauged PQ symmetry

M. Ibe, M. S, and T. T. Yanagida, JHEP 1808, 049 (2018).

Set up

In SU(5) GUT, B-L is achieved as U(1) fiveness=5(B-L)-4Y

$$\mathbf{10}_{SM}\,(+1),\ \bar{\mathbf{5}}_{SM}\,(-3),\ \bar{N}_R\,(+5)$$

B-L is anomaly free in SM + three right-handed neutrinos

Seesaw mechanism by introducing complex scalar φ(-10)

$$L = y_N\, \varphi\, \bar{N}_R \bar{N}_R$$

$$\rightarrow M_R = y_N \langle \varphi \rangle$$

B-L = gauged PQ symmetry

Gauged PQ mechanism

Set two PQ sectors

U(1)PQ1 sector

Introduce KSVZ quarks coupling with **φ(-10)**

$$\mathcal{L} = y_1 \phi^* \mathbf{5}_1 \bar{\mathbf{5}}_1 + h.c.$$

$\mathbf{5}_1, \bar{\mathbf{5}}_1$: N_1 flavors of KSVZ quarks

U(1)PQ2 sector

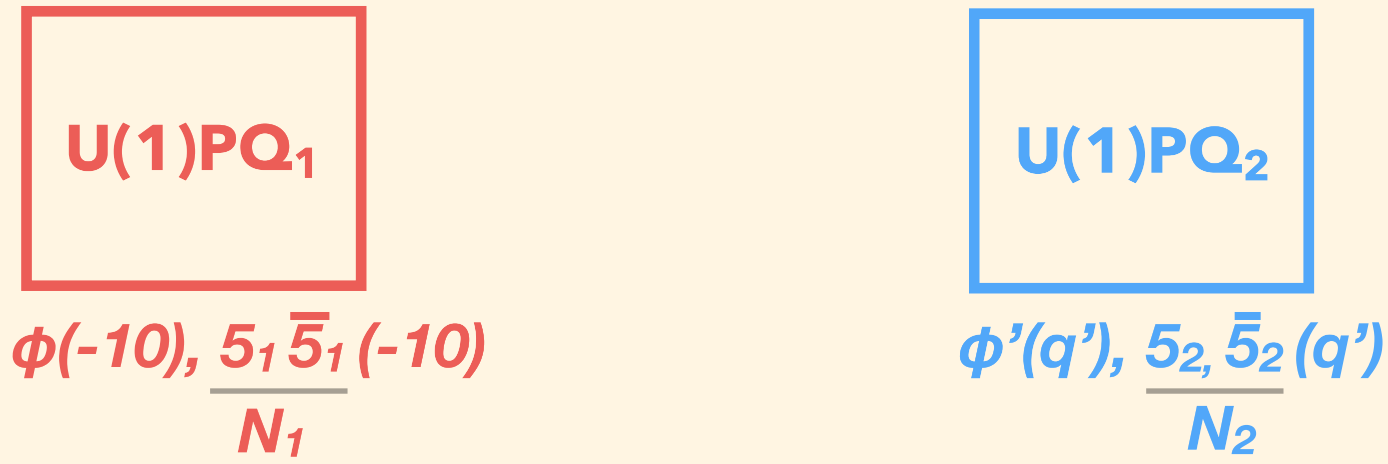
Introduce another sector : KSVZ quarks +**φ'(q')**

$$\mathcal{L} = y_2 \phi'^* \mathbf{5}_2 \bar{\mathbf{5}}_2 + h.c.$$

$\mathbf{5}_2, \bar{\mathbf{5}}_2$: N_2 flavors of KSVZ quarks

B-L = gauged PQ symmetry

Schematic picture



Assumption

$\bar{5}_{SM}(-3)$, $\bar{5}_1(-3)$, $\bar{5}_2(-3)$

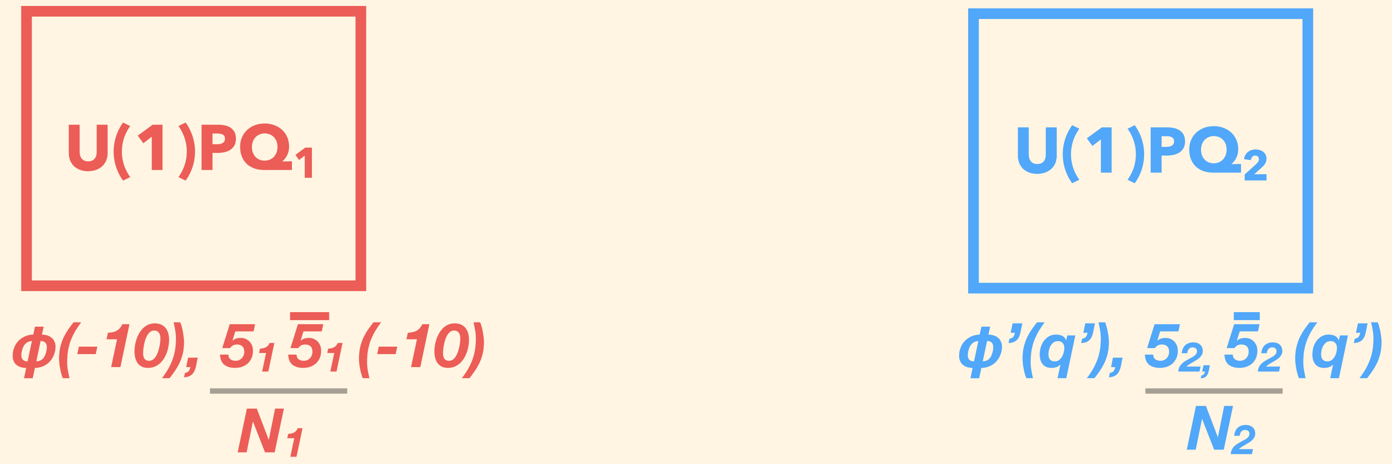
All KSVZ quarks decay into SM particles

Nontrivial anomaly free conditions

$$[U(1)_{B-L}-SU(5)-SU(5)],\ [U(1)_{B-L}]^3$$

B-L = gauged PQ symmetry

Schematic picture



Assumption

$\bar{\mathbf{5}}_{SM}(-3), \bar{\mathbf{5}}_1(-3), \bar{\mathbf{5}}_2(-3)$

All KSVZ quarks decay into SM particles

Nontrivial anomaly free conditions

$$[U(1)_{B-L} - SU(5) - SU(5)],\ [U(1)_{B-L}]^3$$

We find **only ``one'' solution** for $N_1 + N_2 < 22$

$$\phi(-10),\ \phi'(+1),\ \mathbf{5}_1(-7),\ \bar{\mathbf{5}}_1(-3),\ \mathbf{5}_2(+4),\ \bar{\mathbf{5}}_2(-3)$$

B-L = gauged PQ symmetry

We find only ``one'' solution for $N_1 + N_2 < 22$

$$\phi(-10),\ \ \phi'(+1),\ \ \mathbf{5}_1(-7),\ \ \bar{\mathbf{5}}_1(-3),\ \ \mathbf{5}_2(+4),\ \ \bar{\mathbf{5}}_2(-3)$$

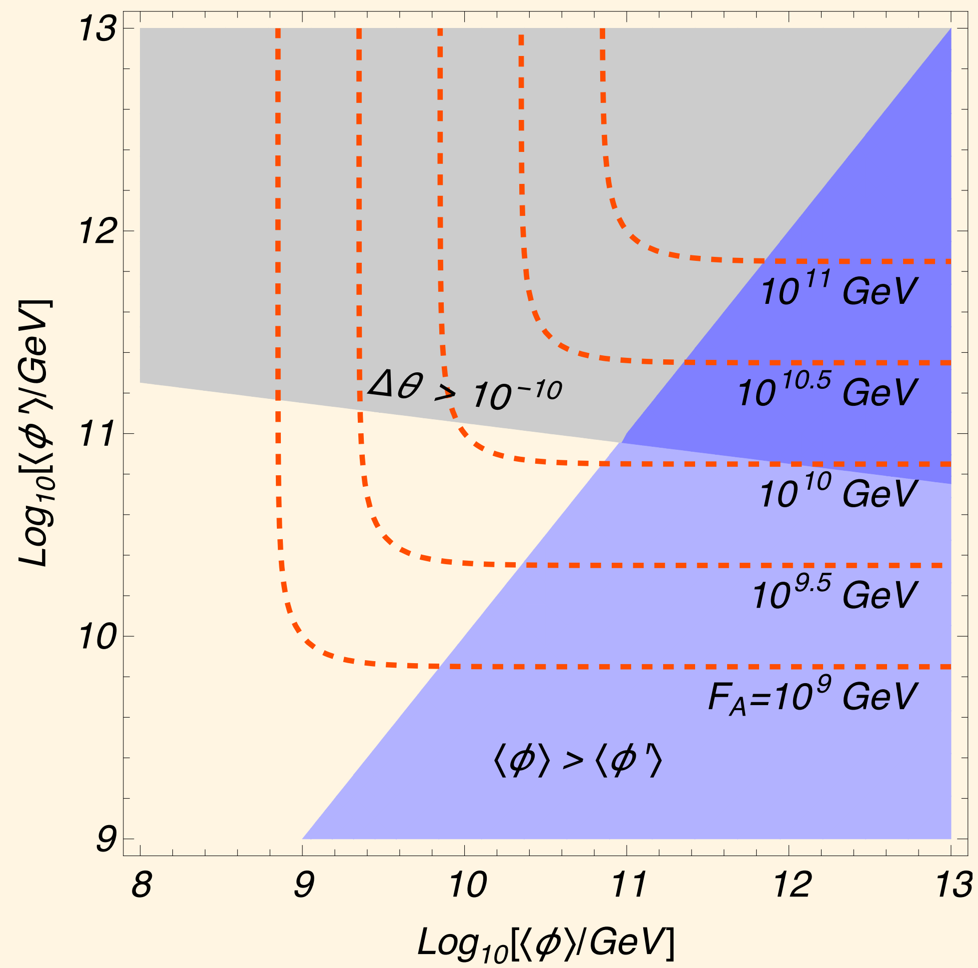
Explicit PQ breaking?

$$\mathcal{L} \sim \frac{1}{10!}\frac{\phi\phi'^{10}}{M_{\rm pl}^7} + h.c.$$

Fortunately,
B-L protects PQ symmetry well !!

B-L = gauged PQ symmetry

Quantitatively



$$F_A = \sqrt{2}\frac{\langle\phi\rangle\langle\phi'\rangle}{\sqrt{(-10)^2\langle\phi\rangle^2 + (+1)^2\langle\phi'\rangle^2}}$$

If φ′ obtains VEV during inflation and only φ obtains VEV after inflation

✔ N_{dom}=1 domain wall scenario

$U(1)PQ_1$

ϕ(-10), $5_1\,\bar{5}_1$ (-10)

1

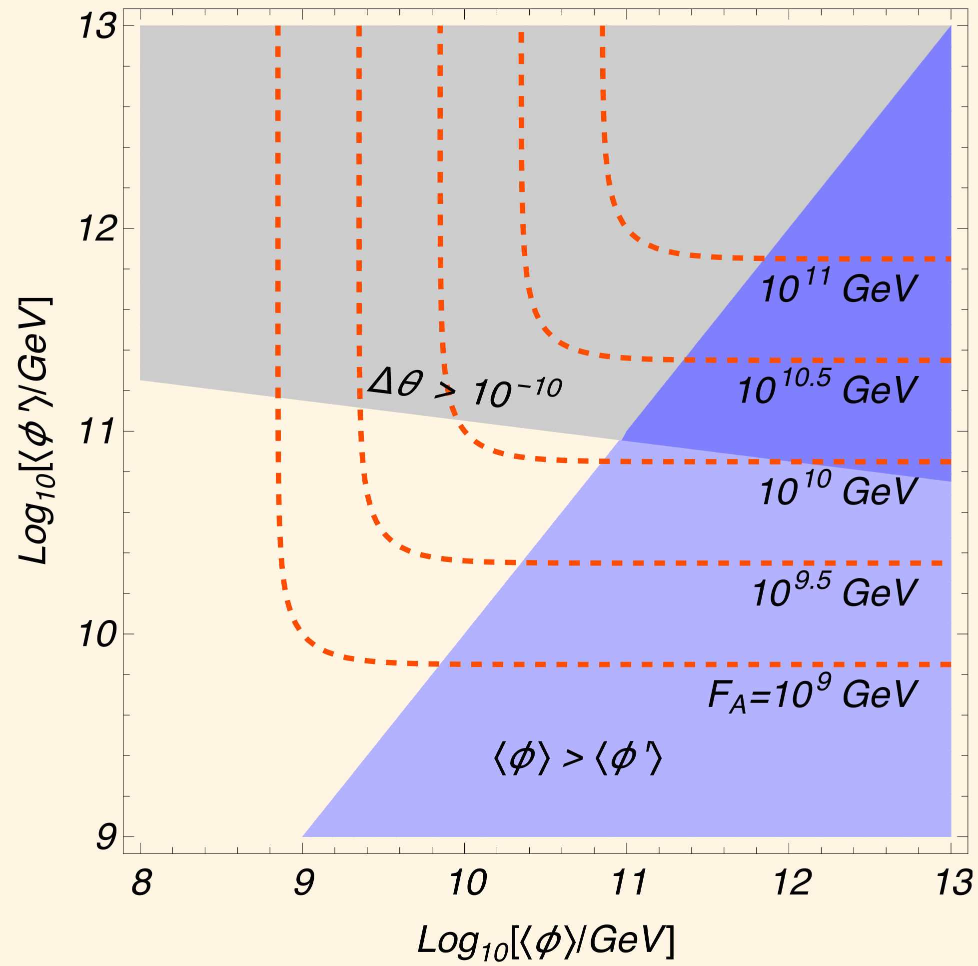
$U(1)PQ_2$

ϕ'(q'), $5_{2,}\,\bar{5}_2$ (q')

10

B-L = gauged PQ symmetry

Quantitatively



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If φ′ obtains VEV during inflation and only φ obtains VEV after inflation

✔ N_{dom}=1 domain wall scenario

✔ **Axion dark matter for F_A~10^{10} GeV**

'12 Hiramatsu *et.al*.

Conclusion

B-L = Gauged PQ symmetry

without extra singlets

- Nature of dark matter

  axion

- Finiteness of neutrino mass

  seesaw

- Asymmetry of matter and anti-matter

  thermal leptogenesis

- Naturalness problem of physical constant

  axion solves Strong CP problem

  SUSY solves hierarchy problem (SUSY version)

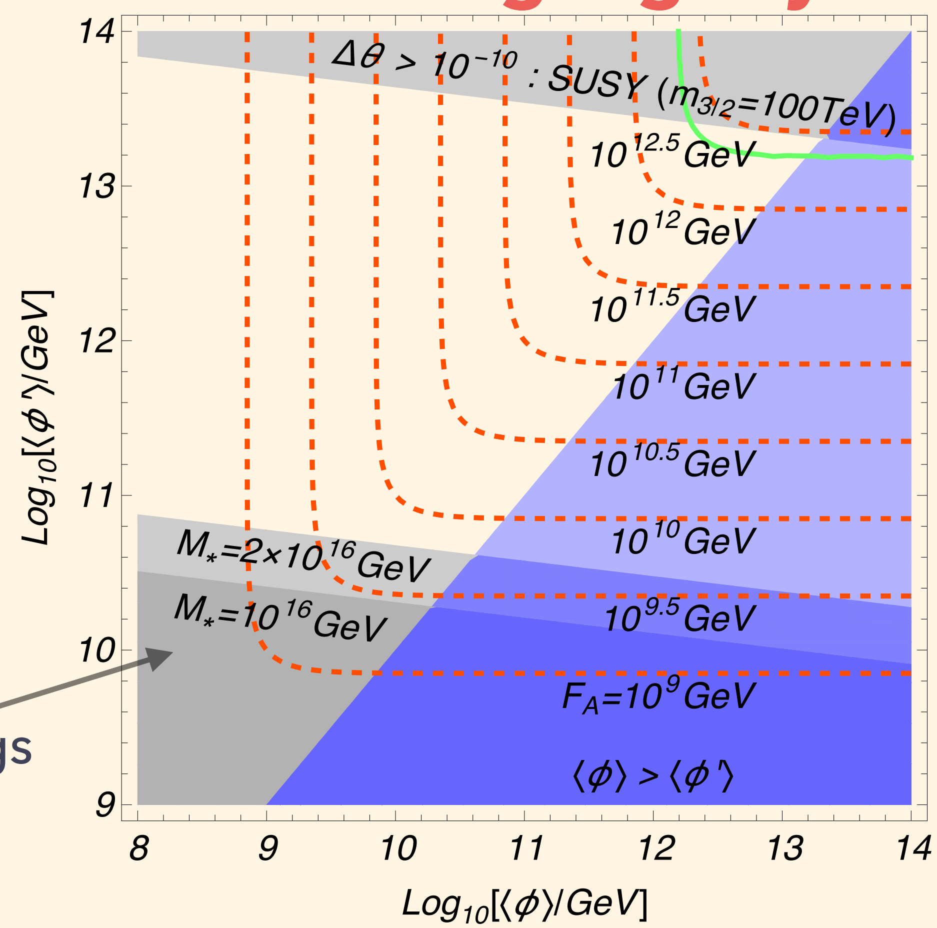
Future work

Further unified picture? GUT?

Non-trivial cosmology when $U(1)_{gPQ} \times U(1)_{PQ}$ broken after inflation end

B-L = gauged PQ symmetry

SUSY version with discrete Z4R gauge symmetry



Blow-up of SM gauge couplings

Axion dark matter

✓ Misalignment mechanism or N_{dom}=1 domain wall scenario