# B-L as a Gauged Peccei-Quinn symmetry

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**Motoo Suzuki**

*Institute for Cosmic Ray Research (ICRR)*
*The University of Tokyo*

arXiv : 1805.10029 and

Phys. Lett. B771, 327 (2017) , arXiv.:1703.01112

**In collaboration with Hajime Fukuda, Masahiro Ibe and Tsutomu. T. Yanagida**

# Strong CP problem

<u>One of the long-standing problem in the Standard Model</u>

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

$$\mathcal{L}_\theta \sim \frac{g^2}{32\pi^2}\bar{\theta}G\tilde{G}$$

θ parameter is observable

Neutron electric dipole moment constrains the θ

$$\bar{\theta} < 10^{-10}$$

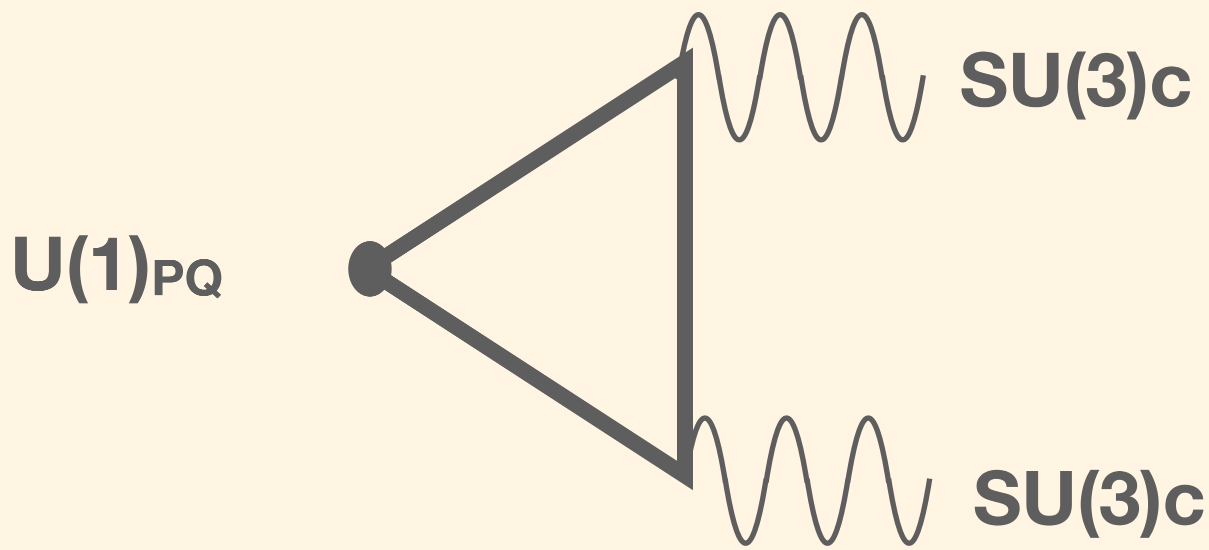
'06 Baker et al.

**Why is the theta value so small ??**

# Peccei-Quinn mechanism

QCD anomalous symmetry: Peccei-Quinn (PQ) symmetry

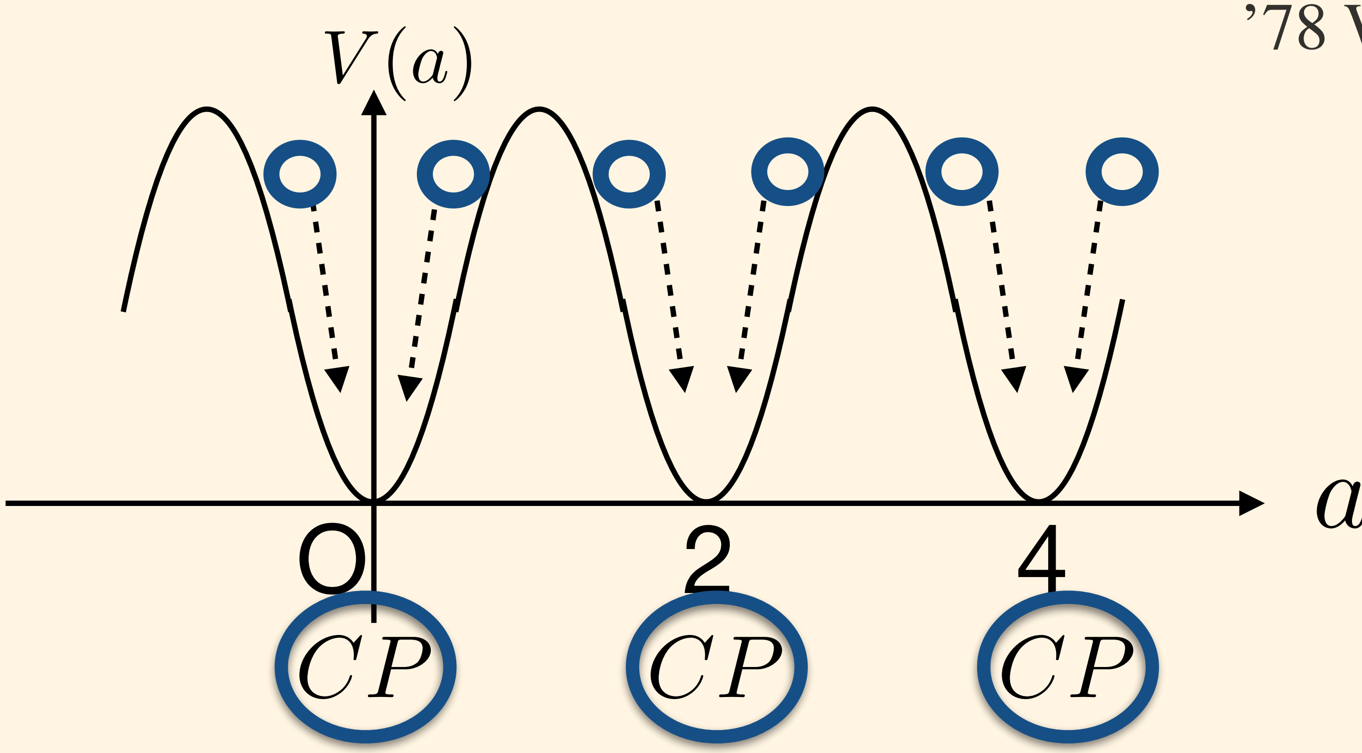
’77 Peccei and Quinn




$\neq 0$

Axion (U(1)PQ NG boson) dynamically cancel theta-term

’78 Weinberg, ’78 Wilczek




**Peccei-Quinn mechanism can solve the Strong CP problem !!**

# Gravity badly and explicitly breaks PQ symmetry

Spontaneous PQ breaking scalar field (Global PQ charge : +1)

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

$a$ ***: axion***

If physics at Planck scale breaks PQ symmetry

$$\mathcal{L} \ni \frac{\Phi^5}{M_{\rm pl}} + h.c....$$

which distorts axion potential

$$V(a) \sim -m_a^2 f_a^2 \cos\left(\frac{a}{f_a}\right) + \left(\lambda_1 \frac{f_a^5}{\sqrt{2}M_{\rm pl}} e^{i5\frac{a}{f_a}} + h.c.\right) + ...$$

Naively, the large theta angle is expected

$$\bar{\theta} \sim \mathcal{O}(1) \gg 10^{-10}$$

**Gravity disturbs the axion potential !!**

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If phys… …ck scale breaks PQ symmetry

$$\cdots \frac{\Phi^5}{\cdots} + h.c. \ldots$$

**Strong CP problem again !!**

which distorts axion potential

$$V(a) \sim -m_a^2 f_a^2 \cos\left(\frac{a}{f_a}\right) + \left( \cdots \frac{a}{\cdots} + h.c. \right) + \ldots$$

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If phys … ck scale breaks PQ symmetry

**Stron …**

**How to protect the axion potential??**

**… em again !!**

$$\ldots \frac{a}{f_a} \Big) + \Big( \lambda_1 \ldots \frac{a}{\ldots} + h.c. \Big) + \ldots$$

Na …, the large theta angle is expected

$$\bar{\theta} \sim \mathcal{O}(1) \gg 10^{-10}$$

**Gravity disturbs the axion potential !!**

# Gauge symmetry to overcome gravity effect

To prohibit the axion potential term induced by gravity

$$\mathcal{L} \ni \frac{\Phi^5}{M_{pl}}$$

One answer : Gauge symmetry '89 Krauss and Wilczek, '95 Intriligator and Seiberg

$\Phi(+1)$ : charged under Z12, 13… or U(1)X gauge symmetry

$$\mathcal{L} \ni \cancel{\frac{\Phi^5}{M_{pl}}} \longrightarrow \mathcal{L} \ni \frac{\Phi^{12}}{M_{pl}^8}, \frac{\Phi^{13}}{M_{pl}^9} \cdots$$

Higher discrete gauge symmetry, smaller the shift of theta

✔ $\Delta\bar{\theta} \ll 10^{-10}$

**What is the origin of the gauge symmetry e.g. Z12??**

# Gauged PQ mechanism (Our proposal)

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

Two or more PQ symmetries make a gauge symmetry U(1)gPQ protecting anomalous global symmetry

e.g. One linear combination of two anomalous symmetry can be anomaly free

$\boxed{U(1)PQ1}$

*cf.ZDFS model*
*cf. Composite axion model*
*cf. KSVZ model*

$\boxed{U(1)PQ2}$

*cf.ZDFS model*
*cf. Composite axion model*
*cf. KSVZ model*

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

***Let seek the possibility***

***B-L symmetry = U(1)gPQ symmetry***
***( fiveness )***

M. Ibe, M. S, and T. T. Yanagida, arXiv:1805.10029.

# B-L (fiveness) gauge symmetry

Let us consider SU(5) GUT with right-handed neutrinos

Fiveness (B-L) charges c.f. $5(B-L)-4Y$

For matter fields $\mathbf{10}_{\rm SM}=(q_L,\bar{u}_R,\bar{e}_R),\ \bar{\mathbf{5}}_{\rm SM}=(\bar{d}_R,l_L)$

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

The higgs doublet has the fiveness charge (B-L=0)

$$h(+2)$$

**The colored Higgs assumed to have GUT scale mass*

Right handed neutrinos

$$\bar{N}_R(+5)$$

Yukawa potential is

$$\mathcal{L}=\mathbf{10}_{\rm SM}\mathbf{10}_{\rm SM}h^*+\mathbf{10}_{\rm SM}\bar{5}_{\rm SM}h+\bar{5}_{\rm SM}\bar{N}_Rh^*+h.c.$$

**B-L gauge symmetry is the plausible addition as a extension of SM**

# B-L (fiveness) gauge symmetry

For the seesaw mechanism,
Introduce a SM singlet scalar

$$\phi(+10)$$

which spontaneously breaks the fiveness symmetry

$$\langle\phi\rangle \neq 0$$

Thus, the potential is

$$\mathcal{L} = -\frac{1}{2} y_N \phi \bar{N}_R \bar{N}_R + \mathbf{10}_{\rm SM} \mathbf{10}_{\rm SM} h^* + \mathbf{10}_{\rm SM} \bar{5}_{\rm SM} h + \bar{5}_{\rm SM} \bar{N}_R h^* + h.c.$$

Where the marinara masses

$$M_N = y_N \langle\phi\rangle$$

**SU(5)×fiveness model as a possible extension of SM**

# B-L (fiveness) = Gauged PQ symmetry U(1)gPQ?

Let us identify the gauged PQ symmetry as fiveness

As in KSVZ model,
We add the extra vector-like multiplet (one flavor)

$$\mathbf{5}_K,\ \bar{\mathbf{5}}_K$$

Which obtain the mass from a coupling with the singlet

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

**We comment about the reason that we choose this mass term later*

In this stage, the fiveness is an anomalous symmetry

$$\partial j_g|_{\mathrm{SM+N+K}} = -10 \frac{g^2}{32\pi^2} F\tilde{F}$$

**In gauged PQ mechanism, this anomaly is canceled by another sector**

# B-L (fiveness) = Gauged PQ symmetry U(1)gPQ?

To cancel the fiveness anomaly ( with SU(5) ),

Let us introduce the ten flavor of extra multiplet

$$\mathbf{5}'_K,\ \bar{\mathbf{5}}'_K\ \times 10$$

which obtain the mass from an extra singlet complex scalar field with fiveness charge "+1"

$$\phi'(+1),\ \langle\phi'\rangle \neq 0$$

Therefore,

$$\mathcal{L} = y'_K \phi'^{*} \mathbf{5}'_K \bar{\mathbf{5}}'_K$$

With these choice, the anomaly of fiveness are canceled

$$\partial j_5|_{\mathrm{SM+N+K+K'}} = 0$$

# B-L (fiveness) = Gauged PQ symmetry U(1)gPQ?

To obtain the gauged PQ symmetry (B-L symmetry),

[U(1)gPQ]^3 and gravitational anomaly must be canceled

$$[U(1)_{\mathrm{gPQ}}]^3 \propto ((-10-\bar{q}_K)^3+(\bar{q}_K)^3)+10((1-\bar{q}'_K)^3+(\bar{q}'_K)^3)$$

$$[\mathrm{gravitational}] \propto ((-10-\bar{q}_K)+(\bar{q}_K))+10((1-\bar{q}'_K)+(\bar{q}'_K))$$

where the charges are assigned by

$$\mathbf{5}_K(-10-\bar{q}_K),\ \bar{\mathbf{5}}_K(\bar{q}_K)$$

$$\mathbf{5}'_K(1-\bar{q}'_K),\ \bar{\mathbf{5}}'_K(q'_K) \qquad \times 10$$

The answer is

$$\mathbf{5}_K(-7),\ \bar{\mathbf{5}}_K(-3),\ \bar{\mathbf{5}}'_K(+4),\ \bar{\mathbf{5}}'_K(-3)$$

No additional singlet fermions

**B-L = U(1)gPQ**

# The quality under gauged PQ symmetry

The global PQ symmetry is broken by some gauge invariant term

The lowest one is

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

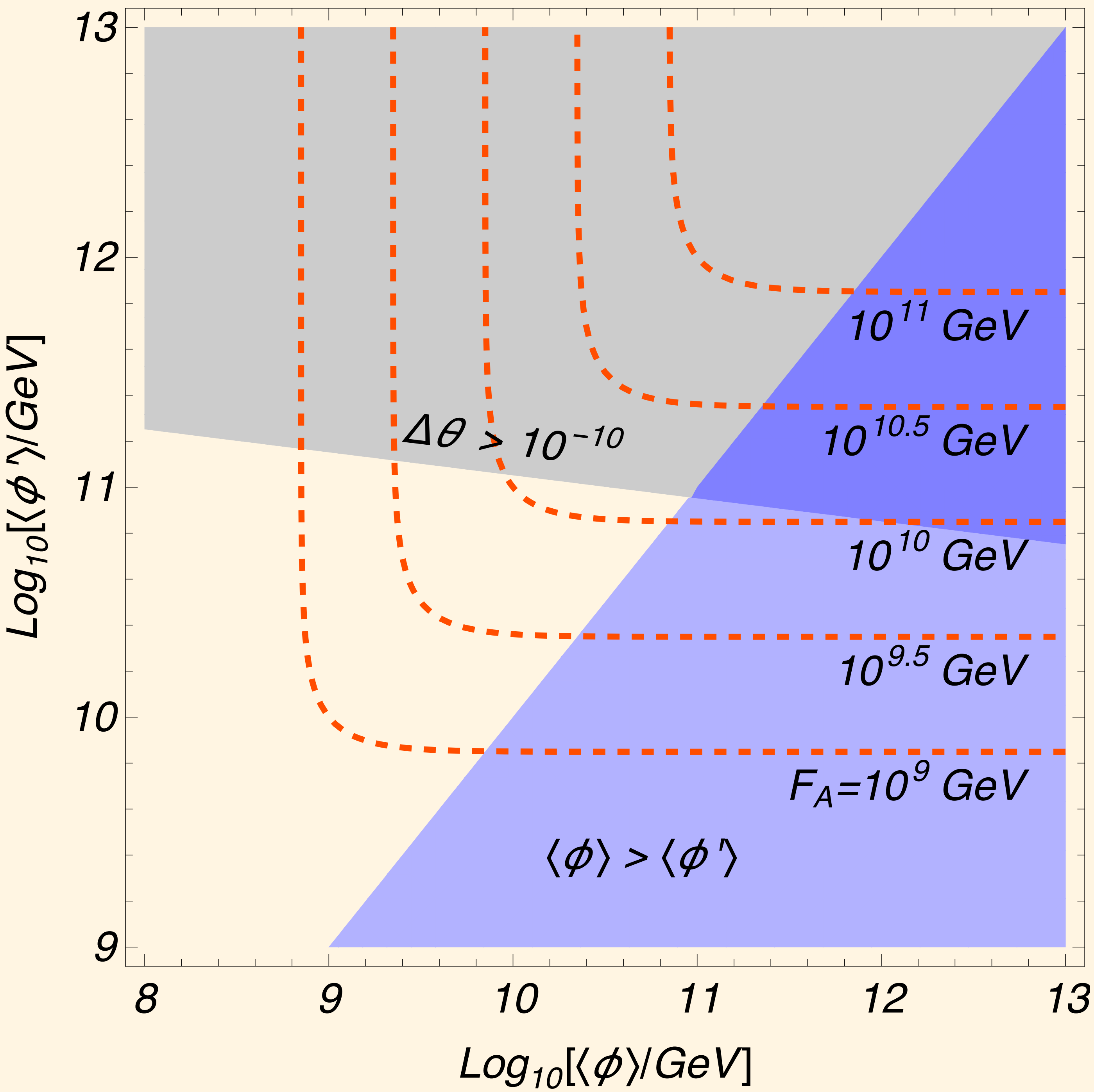
The quality of global PQ symmetry is

$$\Delta\theta \sim 2 \frac{1}{10!} \frac{\langle\phi\rangle\langle\phi'\rangle^{10}}{M_{\rm PL}^7 m_a^2 F_A^2} \sim 3 \times 10^{-11} \left(\frac{\langle\phi\rangle}{10^{10}\mathrm{GeV}}\right) \left(\frac{\langle\phi'\rangle}{10^{11}\mathrm{GeV}}\right)^{10}$$

**Consistent with the current experimental bound**

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

# Summary of constraints on PQ (gPQ) breaking scale




The axion decay constant

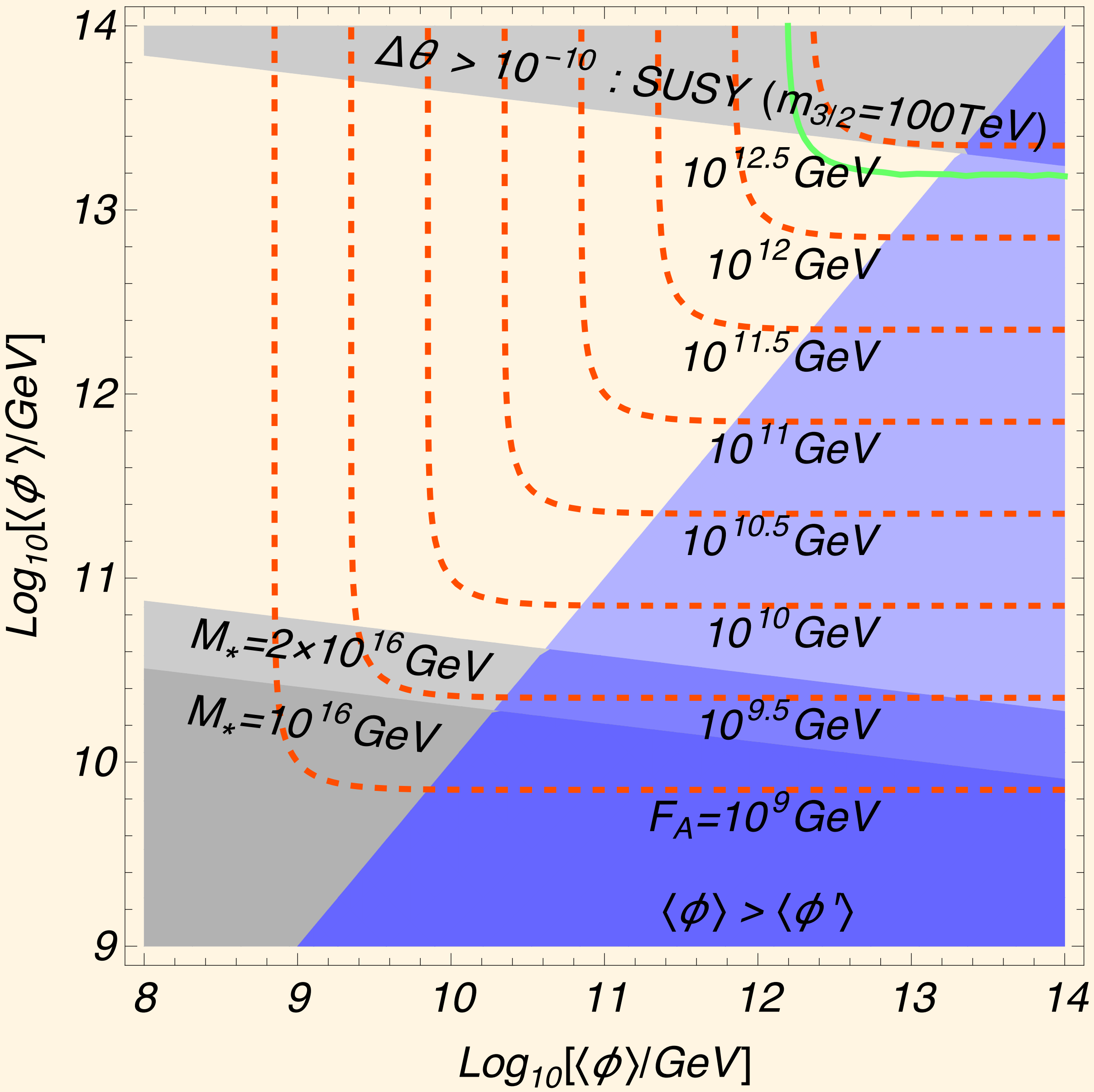
$$F_A = \frac{\sqrt{2}\langle\phi\rangle\langle\phi'\rangle}{\sqrt{\langle\phi\rangle^2 + 10^2\langle\phi'\rangle^2}}$$

Mass of right-handed neutrino

✔ Thermal leptogenesis $M_N = y_N\langle\phi\rangle \gtrsim 10^9\mathrm{GeV}$

✔ Astrophysical constraint $F_A \gtrsim 10^9\mathrm{GeV}$

# The summary of constraints on PQ (gPQ) scale (SUSY)




The axion decay constant

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The axion production
by the misalignment mechanism

$$\Omega_a h^2 \simeq 0.18\theta_a^2 \left(\frac{F_A}{10^{12}\mathrm{GeV}}\right)^{1.19}$$

'92 Lyth

✔ Thermal leptogenesis $M_N = y_N\langle\phi\rangle \gtrsim 10^9\mathrm{GeV}$

✔ Astrophysical constraint $F_A \gtrsim 10^9\mathrm{GeV}$

## *Uniqueness of fiveness charges*

M. Ibe, M. S, and T. T. Yanagida, arXiv:1805.10029.

# Uniqueness of the Fiveness Charge

Introduce n+3 flavor of $\bar{\mathbf{5}}$

$$\bar{\mathbf{5}} \times (n+3) \quad \text{( with same charge )}$$

For **n=0,**

Adding

$$\mathbf{10}_{\mathrm{SM}} \text{ and } \bar{N}_R \quad \times 3$$

The fiveness charge assignments

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

The anomaly free fiveness and SU(5) symmetries

# Uniqueness of the Fiveness Charge

**For n>0**,
The anomaly free condition require more fermions

Given the fact that the SM consists of 3 flavors,
it is simple to add n-flavors of $\mathbf{5}$ fermions

In the seesaw mechanism
The order parameter with fiveness charge -10

$$\phi(-10),\ \langle\phi\rangle \neq 0$$

However, another scalar field is needed to obtain anomaly free fiveness

$$\phi'(q_{\phi'}),\ \langle\phi'\rangle \neq 0$$

In the presence of these scalar fields,
the mass terms of are generated from

$$\mathcal{L} = \phi\mathbf{5}\bar{\mathbf{5}} + \phi^*\mathbf{5}'\bar{\mathbf{5}} + \phi'\mathbf{5}^{''}\bar{\mathbf{5}} + \phi^{'*}\mathbf{5}^{'''}\bar{\mathbf{5}}$$

# Uniqueness of the Fiveness Charge

Find the anomaly free condition under the following charge assignemts

All of $\bar{\mathbf{5}}$ are assumed to have same charges

$$\bar{\mathbf{5}}(-3)$$

Each $\mathbf{5}$ has the fiveness charges

$$\mathbf{5}(+13),\ \mathbf{5}'(-7),\ \mathbf{5}^{''}(-q_{\phi'}+3),\ \mathbf{5}^{'''}(q_{\phi'}+3)$$

With flavors to

$$N_5,\ N_5',\ N_5^{''},\ N_5^{'''}$$ respectively

**The self and gravity anomaly free conditions**

$$13^3 N_5 - 7^3 N_5' + (q_{\phi'}+3)^3 N_5^{''} + (-q_{\phi'}+3)^3 N_5^{'''} - 3^3 n = 0$$

$$13 N_5 - 7 N_5' + (q_{\phi'}+3) N_5^{''} + (-q_{\phi'}+3) N_5^{'''} - 3n = 0$$

$$n = N_5 + N_5^{'} + N_5^{''} + N_5^{'''}$$

# Uniqueness of the Fiveness Charge

For n<22 $n = N_5 + N_5^{'} + N_5^{''} + N_5^{'''}$

Only two sets of solution exists

$$N_5 = 0,\ N_5' = 10,\ N_5^{''} = 0,\ N_5^{'''} = 1,\ q_{\phi'} = 1$$

Or

$$N_5 = 7,\ N_5' = 1,\ N_5^{''} = 3,\ N_5^{'''} = 0,\ q_{\phi'} = 20$$

To solve the remaining Strong CP problem

**Only one candidate is**

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This is our choice in the model

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## Summary

We construct the model

$$U(1)B\text{-}L = \text{Gauged PQ symmetry}$$

M. Ibe, M. S, and T. T. Yanagida, arXiv:1805.10029

This model is only one possibility
Once we allow the principle

$$\text{N flavor of } \bar{\mathbf{5}}$$

Any deeper insights?

# Back up

# Where is the axion?

**Axial component**

$$\phi_1 = \frac{1}{\sqrt{2}} f_1 e^{i\tilde{a}/f_1}, \;\; \phi_2 = \frac{1}{\sqrt{2}} f_2 e^{i\tilde{b}/f_2}$$

**One combination eaten by U(1)gPQ gauge boson**

$$\begin{aligned}
\mathcal{L} &= |D_\mu \phi_1|^2 + |D_\mu \phi_2|^2 \\
&= \frac{1}{2}(\partial \tilde{a})^2 + \frac{1}{2}(\partial \tilde{b})^2 - g_{gPQ} A_\mu (q_1 f_a \partial^\mu \tilde{a} + q_2 f_a \partial^\mu \tilde{b}) \\
&+ \frac{g_{gPQ}^2}{2}(q_1^2 f_1^2 + q_2^2 f_2^2) A^\mu A_\mu \\
&= \boxed{\frac{1}{2}(\partial a)^2} + \frac{1}{2} m_A^2 \left( A_\mu - \boxed{\frac{1}{m_A}\partial_\mu b)^2} \right)
\end{aligned}$$

$$(m_A^2 = g^2(q_1^2 f_1^2 + q_2^2 f_2^2))$$

Axion

$$\begin{pmatrix} \boxed{a} \\ \boxed{b} \end{pmatrix} = \frac{1}{\sqrt{q^2 f_1^2 + q_2^2 f_2^2}} \begin{pmatrix} q_2 f_2 & -q_1 f_1 \\ q_1 f_1 & q_2 f_2 \end{pmatrix} \begin{pmatrix} \tilde{a} \\ \tilde{b} \end{pmatrix}$$

Eaten