A natural model of spontaneous CP violation

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High energy theory
(unified theory)

Development in physics including gravity
Development in mathematics
Constructing a new model
Studying more on existing model

Low energy theory

High energy theory
(unified theory)

✅ **Development in physics including gravity**
Development in mathematics
✅ Constructing a new model
Studying more on existing model

New model to solve Strong CP problem,
Hierarchy problem

Low energy theory

Strong CP problem

- QCD action:

$$S_{\mathrm{QCD}} = \int d^4x \left[\mathcal{L}_{quarks} - \theta \frac{g^2}{32\pi^2} G^{a\mu\nu} \tilde{G}^a_{\mu\nu} \right]$$

- QCD vacuum angle:

$$\bar{\theta} = \theta - \arg(\det M_u \cdot \det M_d)$$

- Experimental upper bound on the angle:

$$\bar{\theta} \lesssim 10^{-10}$$ '06 Baker *et.al.*

How to explain the smallness?

Strong CP problem

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

- CP symmetry is maximally broken by CKM phase:

$$\delta_{\mathrm{CKM}} \sim 1$$

- The challenge for model building:

O(1) CP phase quark mass matrices

$\downarrow$

$$|\arg(\det M_u \cdot \det M_d)| \sim 1$$

$\downarrow$

$$\bar{\theta} \gg 10^{-10}$$ **Some mechanism needs!**

Solution to Strong CP problem
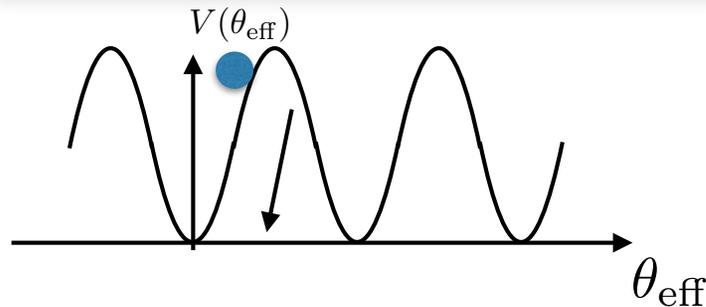
Axion: a dynamical solution to Strong CP problem

- θ-parameter becomes a dynamical field θeff

$$\boxed{\theta \to \theta_{\text{eff}}} \text{ (axion field)}$$

$$\mathcal{L}_\theta = -\theta \frac{g^2}{32\pi^2} G^{a\mu\nu} \tilde{G}^a_{\mu\nu} \quad \to \quad \mathcal{L} = -\theta_{\text{eff}} \frac{g^2}{32\pi^2} G^{a\mu\nu} \tilde{G}^a_{\mu\nu}$$

- Axion obtains potential by non-perturbative QCD effect

$$\boxed{V(\theta_{\text{eff}}) = -\Lambda^4_{\text{QCD}} \cos(\theta_{\text{eff}})}$$
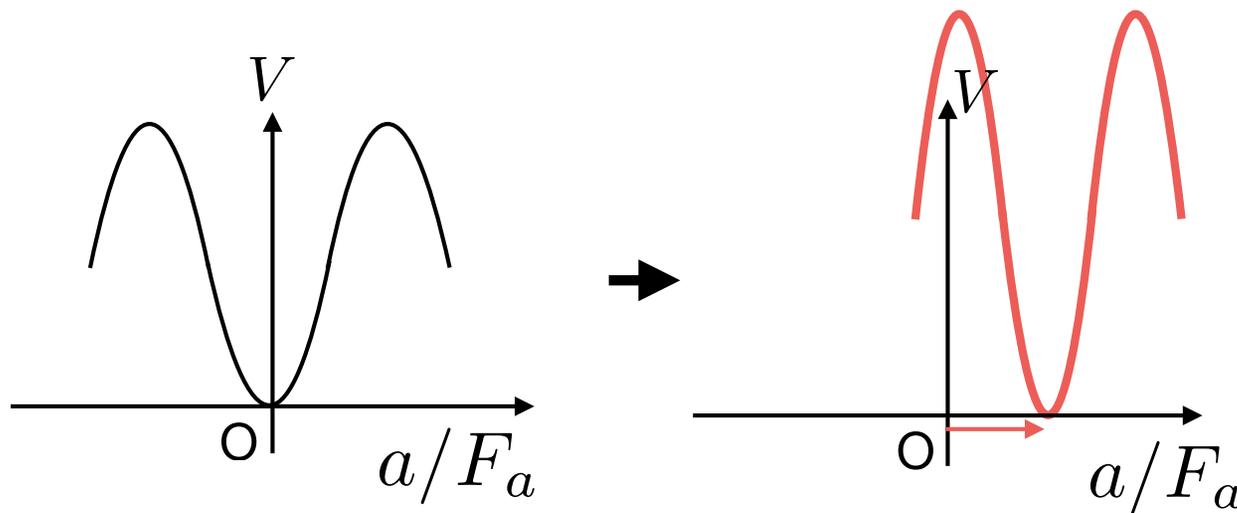

- At the potential minimum, Strong CP problem is solved!

$$\boxed{\langle \bar{\theta} \rangle = 0}$$

- Global symmetry does not protect axion potential

$$V(\theta_{\text{eff}}) = -\Lambda_{\text{QCD}}^4 \cos(a/F_a) + V_{\text{gravity}}$$

$$V_{\text{gravity}} \sim \lambda \frac{F_a^5}{M_P} \cos(\theta_{eff} + \delta)$$

$\langle \bar{\theta} \rangle \sim 1$ without very very tiny parameters

Solutions to axion quality problem

- Extra dimension model (5D axion model)
- Introduction of additional gauge symmetries
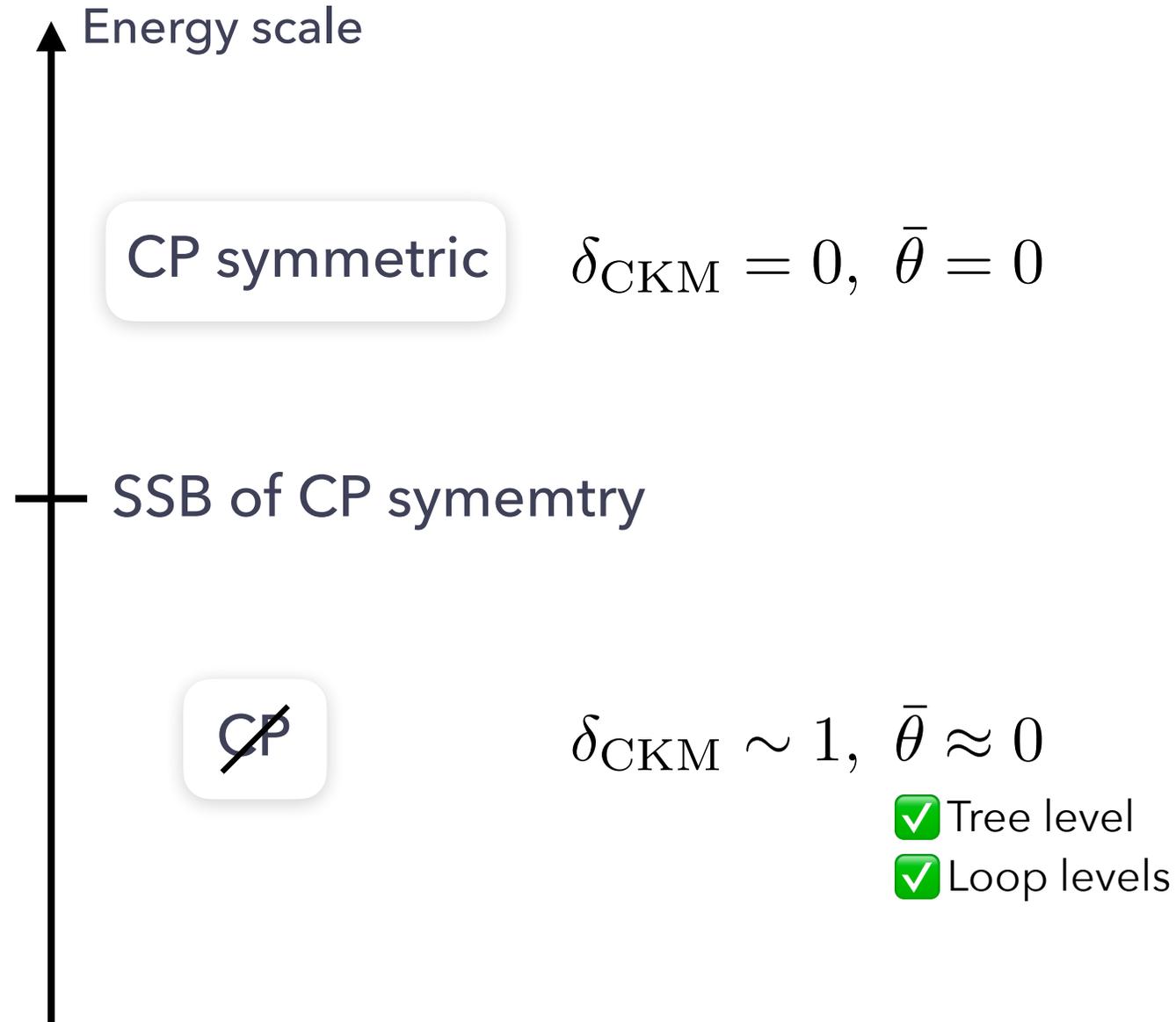- Conformal symmetry etc.

Alternatice solution to Strong CP problem?

Spontaneous CP violation model

'84 Nelson, '84 Barr

Spontaneous CP violation model

Energy scale

CP symmetric $\delta_{\mathrm{CKM}} = 0,\ \bar{\theta} = 0$

SSB of CP symemtry

C̸P̸ $\delta_{\mathrm{CKM}} \sim 1,\ \bar{\theta} \approx 0$

✅ Tree level
✅ Loop levels

A concrete model

SM quark sector

$$Q_f, \ \bar{u}_f, \ \bar{d}_f$$

$$\eta_a$$
$$\arg\langle\eta_a\rangle \neq 0$$

vector-like quarks

$$q, \ \bar{q}$$

$$\mathcal{L} \supset \ +\sum_{f,f'} Y^d_{f,f'} H Q_f \bar{d}_{f'} \quad +\sum_{a,f} a^d_{af} \eta_a q \bar{d}_f \quad +\mu q \bar{q}$$

$$\hat{M}_d = \begin{pmatrix} \mu & \sum_a a^d_{a,f}\langle\eta_a\rangle \\ 0 & Y^d_{ff'}\langle H\rangle \end{pmatrix}$$

$$\arg\det\hat{M}_d = 0 \ \text{at tree level}$$

The angle is zero: $\bar{\theta} = \theta - \arg(\det\hat{M}_u \cdot \det\hat{M}_d) = 0$ **at tree level**

A concrete model

SM quark sector	η_a	vector-like quarks
$Q_f,\ \bar{u}_f,\ \bar{d}_f$	$\arg\langle\eta_a\rangle \neq 0$	$q,\ \bar{q}$

$$\mathcal{L} \supset +\sum_{f,f'} Y^d_{f,f'} H Q_f \bar{d}_{f'} + \sum_{a,f} a^d_{af} \eta_a q \bar{d}_f + \mu q \bar{q}$$

- **Coincidence of scales is needed for CKM phase:**

$$a^d_{af}\langle\eta_a\rangle \sim \mu$$

$$\downarrow$$

$$\delta_{CKM} \sim 1$$

$$\mathcal{L} \supset +\sum_{f,f'} Y^d_{f,f'} HQ_f \bar{d}_{f'} + \sum_{a,f} a^d_{af} \eta_a q \bar{d}_f + \mu q \bar{q}$$

$$\hat{M}_d = \begin{pmatrix} \mu & \sum_a a^d_{a,f} \langle \eta_a \rangle \\ 0 & Y^d_{ff'} \langle H \rangle \end{pmatrix}$$

- **Dangetous terms:** $+\sum_f HQ_f \bar{q} + \sum_a \eta_a q \bar{q}$

$$\downarrow$$

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

- **Forbiding dangerous terms by introducing a symmetry:**

$$\mathbb{Z}_N : q \rightarrow e^{2\pi i/N} q, \ \bar{q} \rightarrow e^{-2\pi i/N} \bar{q}, \ \eta_a \rightarrow e^{-2\pi i/N} \eta_a$$

Dangerous terms II

- **Dangetous terms that cannot be forbidden by the ZN:**

$$\frac{\eta_b^*}{\Lambda} \eta_a q \bar{q} + \frac{\eta_a^*}{\Lambda} H Q \bar{q}$$

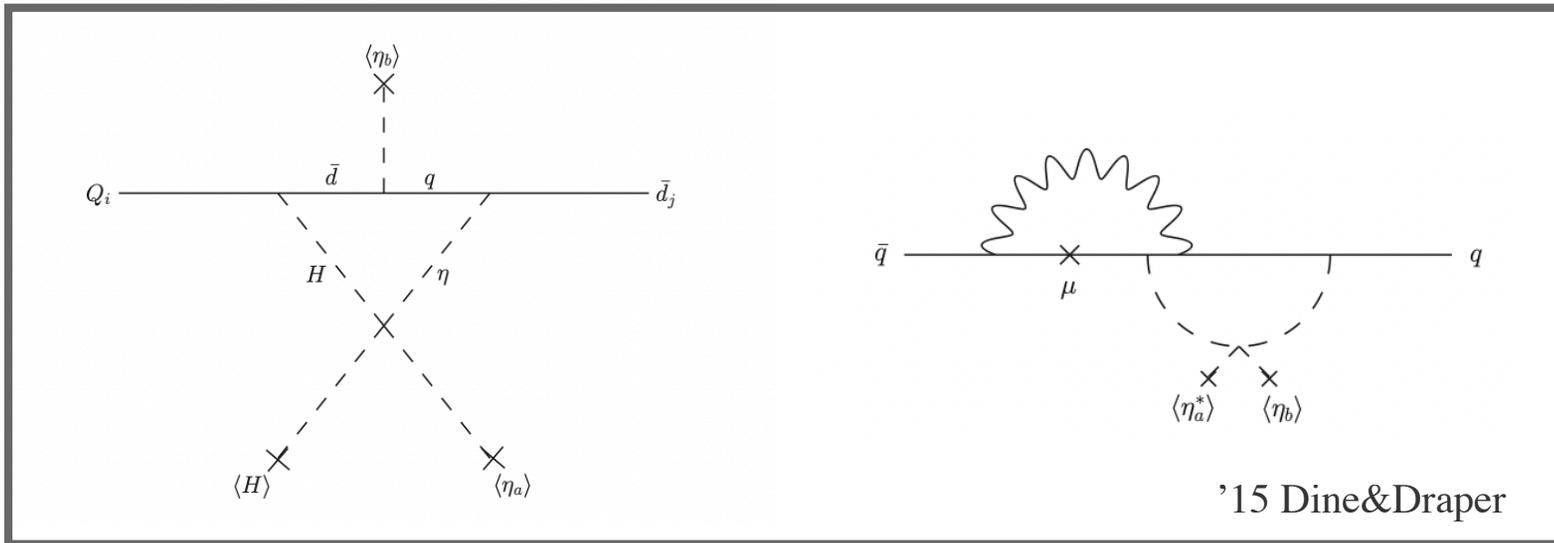$$\downarrow$$

$$|\langle \eta_a \rangle| / M_P < 10^{-10}$$

$$\downarrow$$

Energy scale

CP symmetric

SSB of CP symemtry $\lesssim 10^8 \,\mathrm{GeV}$

$\cancel{CP}$

Radiative corrections

$$\mathcal{L} \supset \gamma_{ab}\eta_a^*\eta_b H^\dagger H + \gamma_{abcd}\eta_a\eta_b\eta_c^*\eta_d^* + \text{h.c.}$$

'15 Dine&Draper

$$\delta\bar{\theta} \sim \left| \frac{\gamma_{bc} a_{af}^d a_{bf}^d \eta_a \eta_c^*}{16\pi^2 M_{\text{CP}}^2} \right| \;,\; \delta\bar{\theta} \sim \left| \frac{g^2 \gamma_{abcd} a_{af}^d a_{cf}^d \eta_b^* \eta_d}{(16\pi^2)^2 M_{\text{CP}}^2} \right|$$

Small coupling is required: $a_{af}^d \lesssim 10^{-3}$ for $|\delta\bar{\theta}| < 10^{-10}$
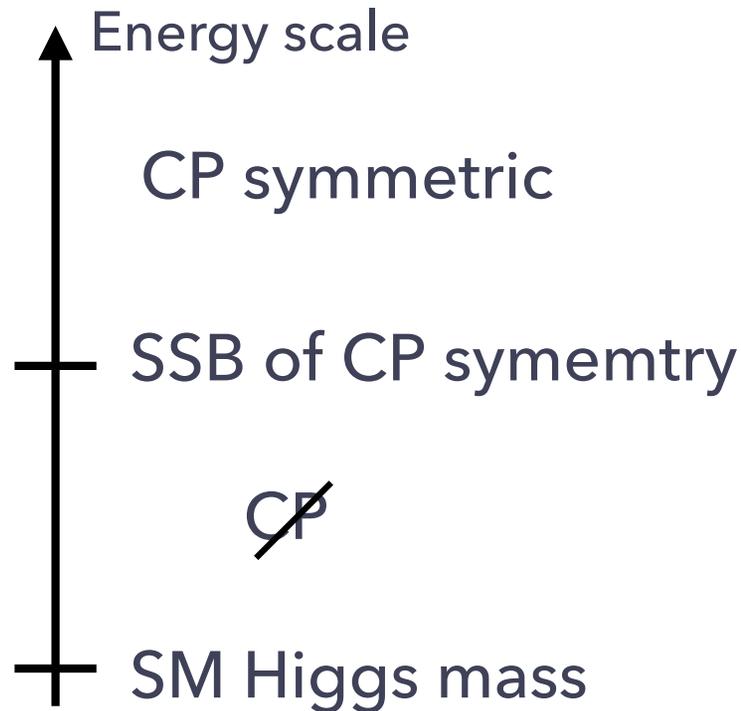
$$c.f. \, \mathcal{L} \supset \sum_{a,f} a_{af}^d \eta_a q \bar{d}_f$$

Our goal: natural models

'07 C. Cheung et.al., '14 L. Vecchi, etc.

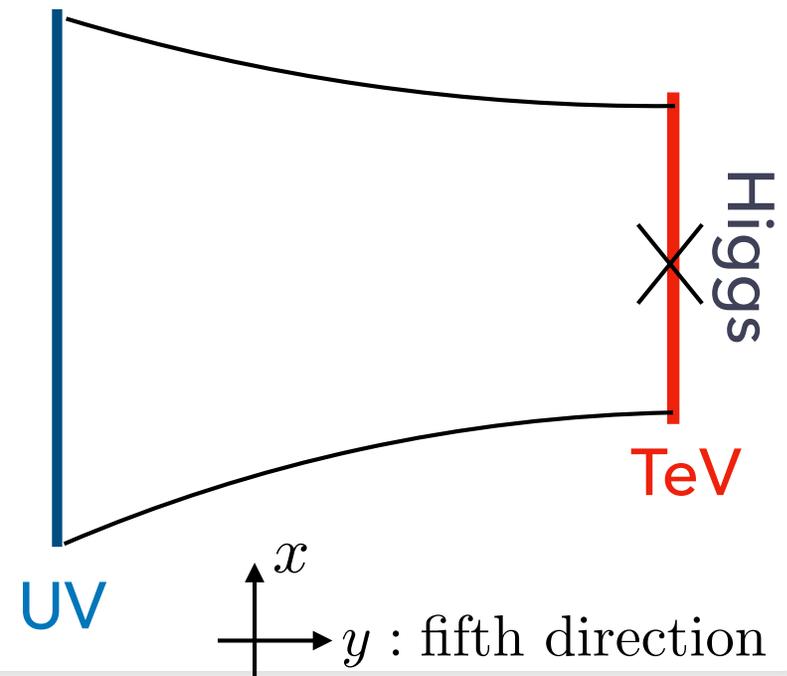✅Strong CP problem
✅Hierarchy problem

Spontaneous CP violation

Energy scale

CP symmetric
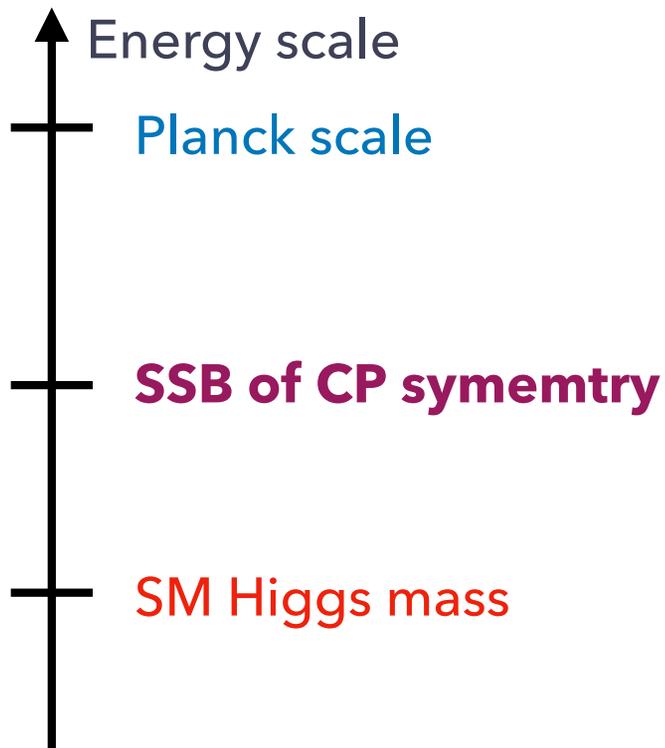
SSB of CP symemtry

C̸P̸

SM Higgs mass

+

Warped extra dimension

Higgs

TeV

UV

x

y : fifth direction

Our work

'22 S. Girmohanta, S. J. Lee, Y. Nakai, M.S.

Spontaneous CP violation

Simple NB-type model (BBP)

Energy scale

Planck scale

SSB of CP symemtry

SM Higgs mass

+

Warped extra dimension

Three branes

Intermediate brane

Higgs

TeV

UV

x

y : fifth direction

Radion stabilization in three brane

Two brane case

Three brane case

Λ_1 Λ_2

UV TeV

UV Intermediate TeV

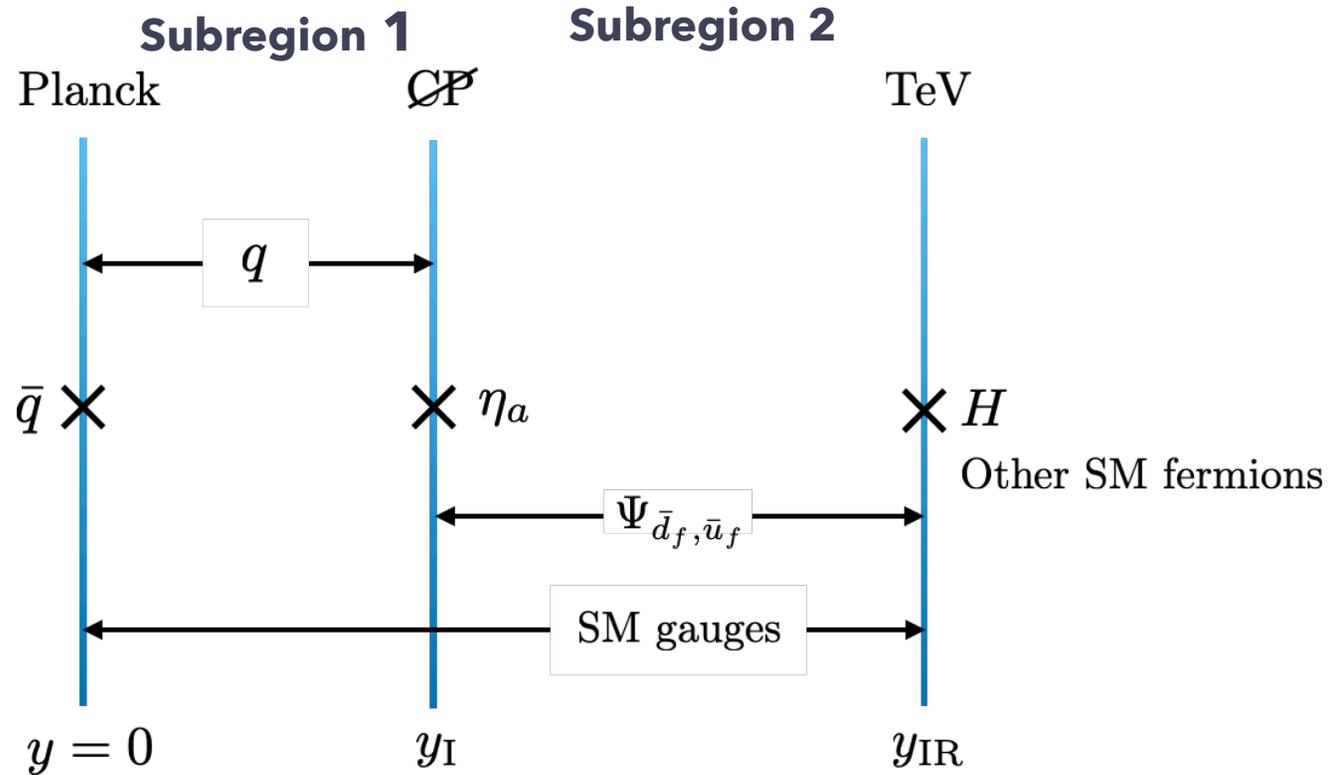- There is one radion

- The radion is stabilized by Goldberger-Wise mechamism

- There are two radions

- The radion is stabilized by Goldberger-Wise mechamism

- $|\Lambda_2| > |\Lambda_1|$

A natural model

'22 S. Girmohanta, S. J. Lee, Y. Nakai, M.S.

Subregion 1   **Subregion 2**

Planck $\cancel{CP}$ TeV

$\xleftarrow{\quad q \quad}\!\!\longrightarrow$

$\bar{q}$ ✗   ✗ η_a ✗ H

Other SM fermions

$\xleftarrow{\quad \Psi_{\bar{d}_f,\bar{u}_f} \quad}\!\!\longrightarrow$

$\xleftarrow{\qquad\qquad \text{SM gauges} \qquad\qquad}\!\!\longrightarrow$

$y = 0$ y_{I} y_{IR}

Higgs (SM fields) : IR brane
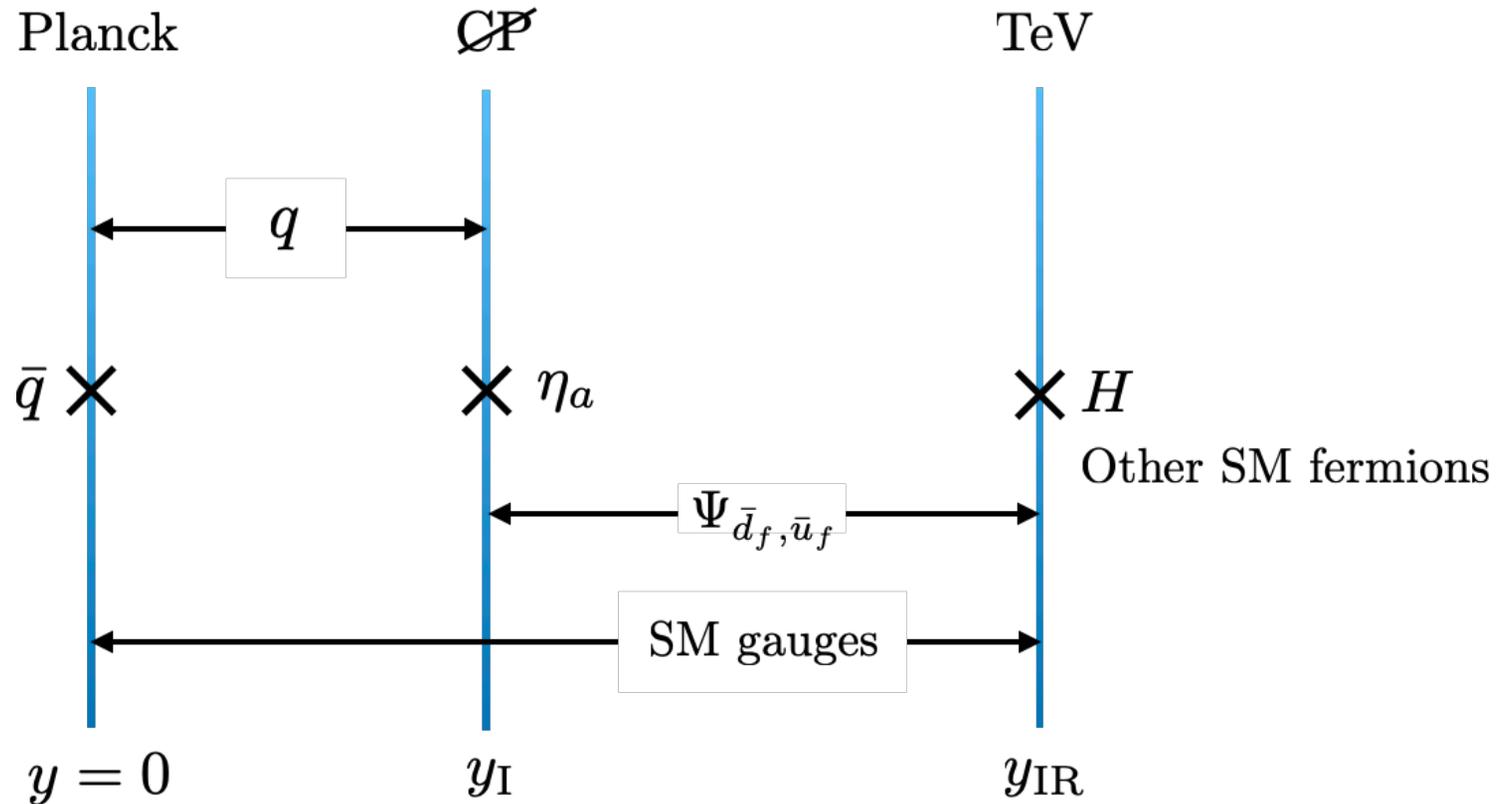
$\bar{u}$ and $\bar{d}$: subregion 2

η: intermediate brane

q: subregion 1

$\bar{q}$: UV brane

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A natural model

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Planck $\cancel{CP}$ TeV

q

$\bar{q}$ ✕   ✕ η_a ✕ H

Other SM fermions

$\Psi_{\bar{d}_f, \bar{u}_f}$

SM gauges

$y = 0$ y_{I} y_{IR}

Down-type: $\quad \mathcal{L} \supset \mu_d q_d \bar{q}_d \qquad a^d_{af} \eta_a q \bar{d}_f \qquad Y^d_{f,f'} H Q_f \bar{d}_{f'}$

Up-type: $\quad \mathcal{L} \supset \mu_u q_u \bar{q}_u \qquad a^u_{af} \eta_a q_u \bar{u}_f \qquad Y^d_{f,f'} H^\dagger Q_f \bar{u}_{f'}$

A natural model

Subregion 1   **Subregion 2**

Planck $\cancel{CP}$ TeV

q

$\bar{q}$ ✗   ✗ η_a ✗ H

Other SM fermions

$\Psi_{\bar{d}_f, \bar{u}_f}$

SM gauges

$y = 0$ y_{I} y_{IR}

● Because H, η, $\bar{\mathrm{q}}$ live in defferent branes, we do not have

$$\gamma_{ab}\eta_a^*\eta_b H^\dagger H \qquad \frac{\eta_b^*}{\Lambda}\eta_a q\bar{q} \qquad \frac{\eta_a^*}{\Lambda}HQ\bar{q}$$
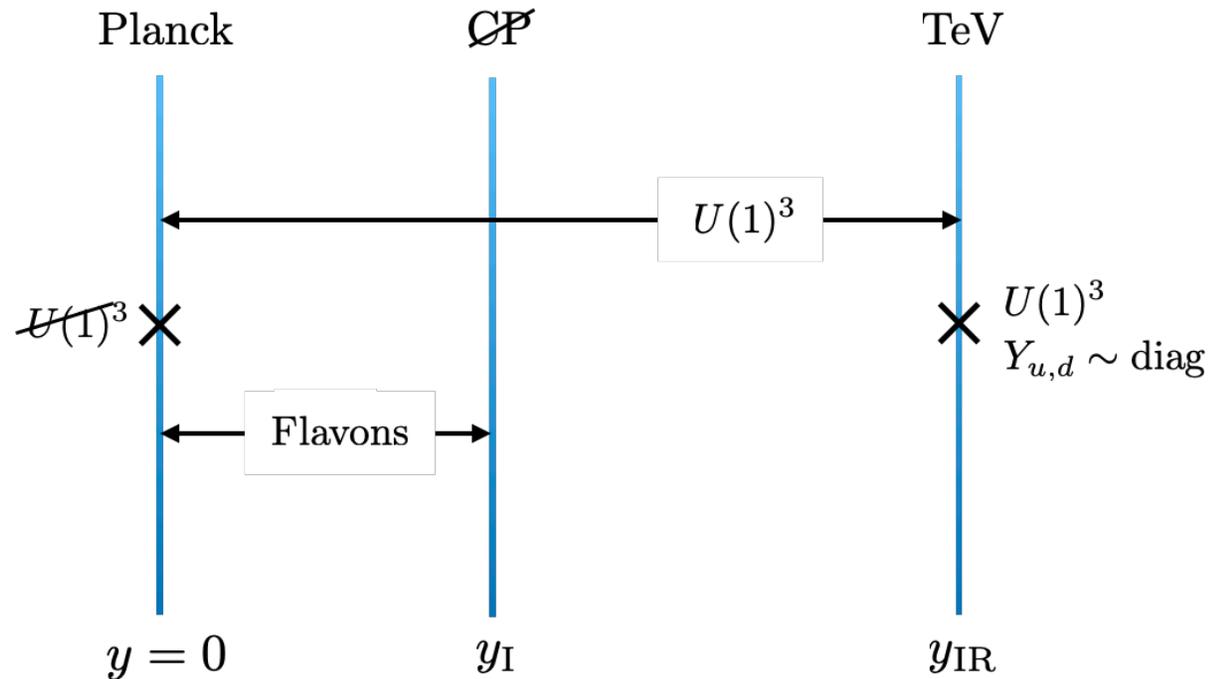
● Dangerous $\gamma_{abcd}\eta_a\eta_b\eta_c^*\eta_d^*$ is not suppressed

$$a_{af}^d \lesssim 10^{-3} \ \text{ for } |\delta\bar{\theta}| < 10^{-10}$$

$$a_{af}^d \eta_a q\bar{d}_f$$

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A natural model

'22 S. Girmohanta, S. J. Lee, Y. Nakai, M.S.

- Qf, $\bar{\text{d}}$f, $\bar{\text{u}}$f are charge under flavor symmetries

$$\downarrow$$

Suppression of $a^d_{af}\eta_a q \bar{d}_f$

- Diagonal Yu, Yd is good to suppress radiative corrections

- CKM matrix is obtained in 4D effective theory
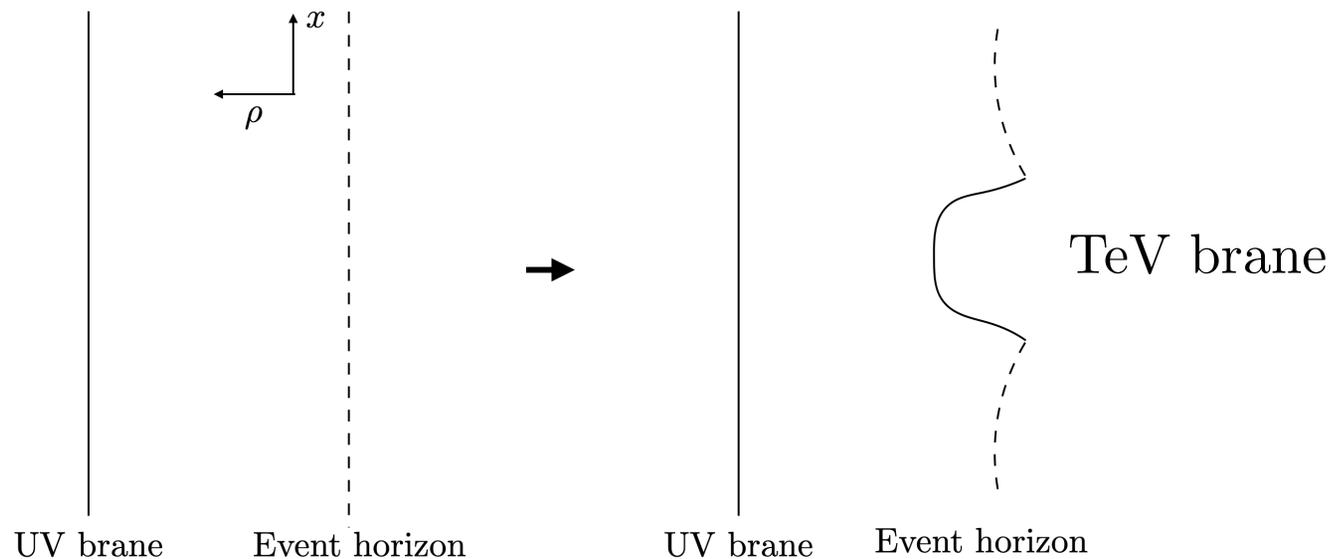(flavor symmetry violation in intermediate brane)

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Cosmological signal

- First order phase transition in two brane case:

AdS-S (high T) $\rightarrow$ **RS (low T)**

$\updownarrow$ dual

Deconfinement $\rightarrow$ **Confinement**

P. Creminelli, A. Nicolis, and R. Rattazzi (2002)
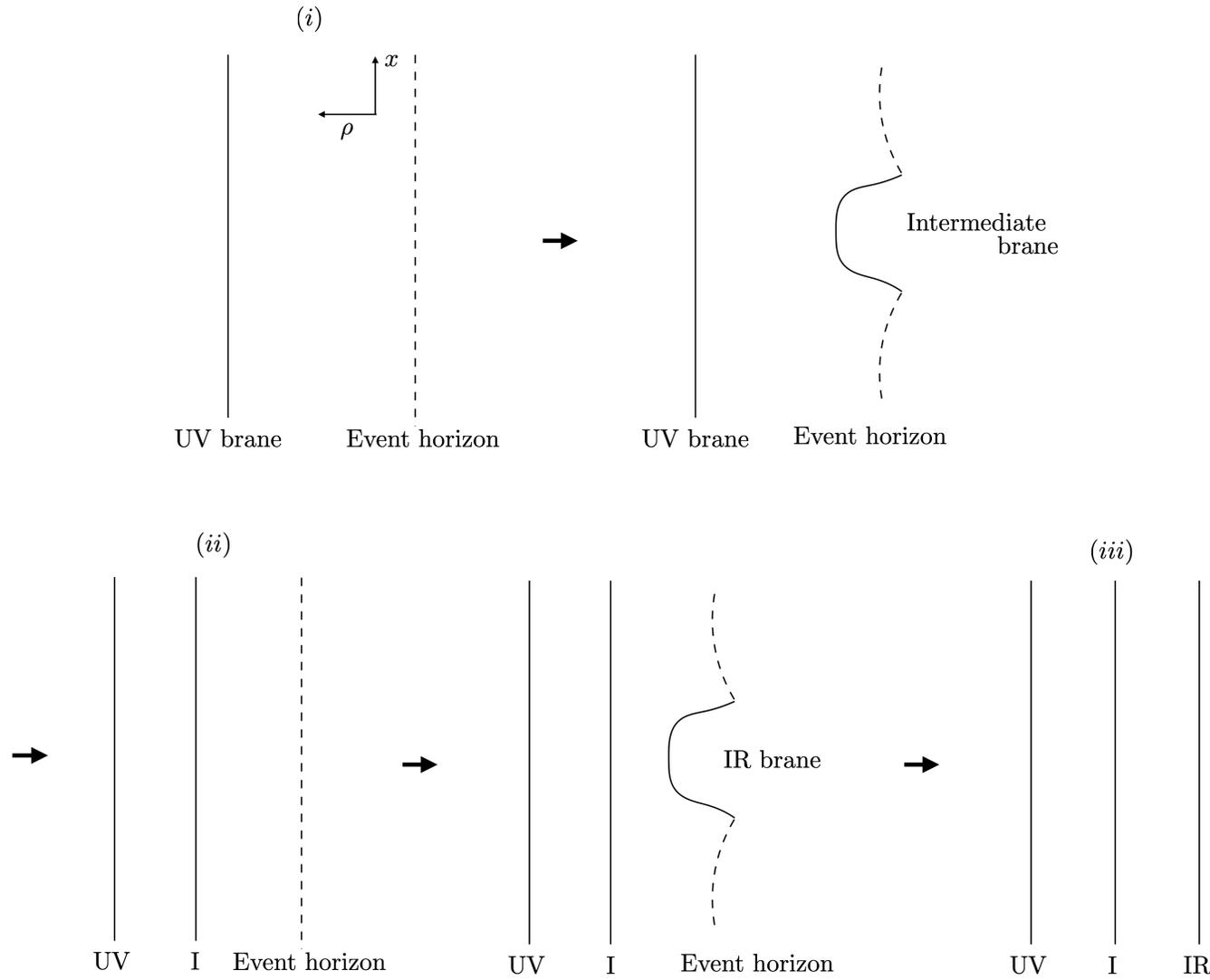

UV brane   Event horizon   UV brane   Event horizon

TeV brane

Gravitational waves!!

'23 S. Girmohanta, S. J. Lee, Y. Nakai, M.S.

- **In three branes, we have first order phase transitions twice**

(i)

x

ρ

Intermediate brane

UV brane   Event horizon   UV brane   Event horizon

(ii) (iii)

IR brane

UV   I   Event horizon   UV   I   Event horizon   UV   I   IR

Gravitational waves!!

Summary & outlook

- We have explored a doubly composite dynamics via a holographic warped extra dimension model with three 3-branes that realizes the NB mechanism to address the strong CP problem.

- In the three brane setup, we expect two times of the first order phase transition. The gravitational waves produced at different times may be detected in future.

Thank you!!

'22 S. Girmohanta, S. J. Lee, Y. Nakai, M.S.