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Addressing the Strong CP problem in Composite Higgs/ RS model

in collaboration with
Y. Nakai, M. Suzuki *JHEP* 02 (2022) 050
Y. Nakai, M. Suzuki *JHEP* 03 (2022) 038
S. Girmohanta, Y. Nakai, M. Suzuki *JHEP* 12 (2022) 024

Strong CP problem

- The SM Strong CP

$$\mathcal{L} \supset -\theta \frac{g_s^2}{32\pi^2} G^a_{\mu\nu} \widetilde{G}^{a\mu\nu}$$

strong CP angle: $\bar{\theta} = \theta + \arg\det M = \theta + \arg\det[Y_u Y_d]$

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Observable effect:

Neutron electric dipole moment $d_N \simeq (5 \times 10^{-16} e \cdot \mathrm{cm})\bar{\theta}$

$$|d_N| \lesssim 3 \times 10^{-26} e \cdot \mathrm{cm} \quad \Rightarrow \quad \bar{\theta} \lesssim 10^{-10}$$

Strong CP problem

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small

strong CP angle: $\bar{\theta} = \theta + \arg\det M = \theta + \arg\det[Y_u Y_d]$

CKM phase: $\arg\det[Y_u Y_d - Y_d Y_u]$ large

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Strong CP problem in the SM

- Is this a problem? Not necessarily: different spurions at tree level they are orthogonal, as exploited in Nelson-Barr type of models (cf. total effective CP becomes zero for axion)

- <u>RG running of $\bar{\theta}$</u>: if we set it to be zero -> no symmetry emerges (like higgs mass) => fine-tuning problem like Higgs mass?
  at 7-loops the EDM receives log-divergent contributions but it is tiny, and the finite contribution predicts $\bar{\theta} \sim 10^{-16}$

J. Ellis and M.K. Gaillard (1979)

E.P. Shabalin (1979)

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more like a Dirac fine tuning, like flavor puzzle

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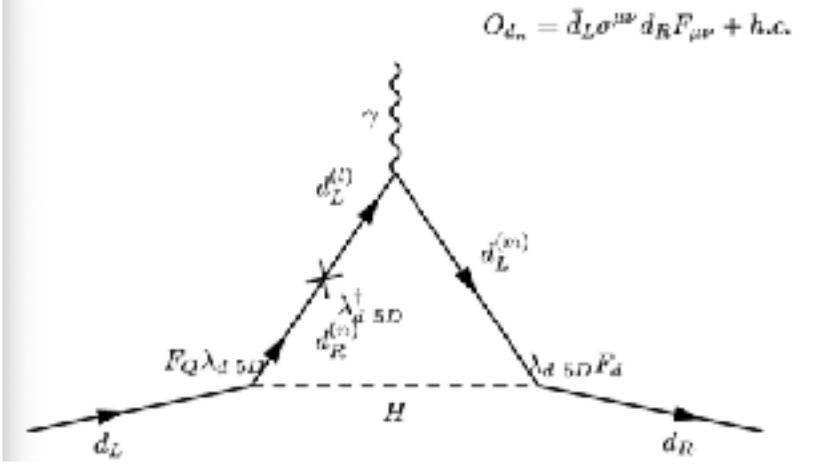
But, the situation is different, if BSM is considered:

e.g. in SUSY, 1-loop RG running from the gluino mass phase is large, or in composite Higgs, 1-loop with KK quarks and Higgs is large



Adressing Strong CP problem

- Addressing the problem by Spurious symmetries of $\mathcal{L}_{\text{QCD}}$

  - anomalous $U(1) : \bar{\theta} \to \bar{\theta} + \alpha$
    - -) linear: massless up quark $\to$ ruled out
    - -) non-linear: $U(1)_{PQ} \to$ axion

  - P: $\bar{\theta} \to -\bar{\theta}$. Mirror world, . . .

  - CP: $\bar{\theta} \to -\bar{\theta}$. **Nelson-Barr models**

$\Big\}$ "good" UV symmetries: gauged in extra dimensions

Dine, Leigh, MacIntire (1992)
Choi, Kaplan, Nelson (1993)

Outline of the lest of talk

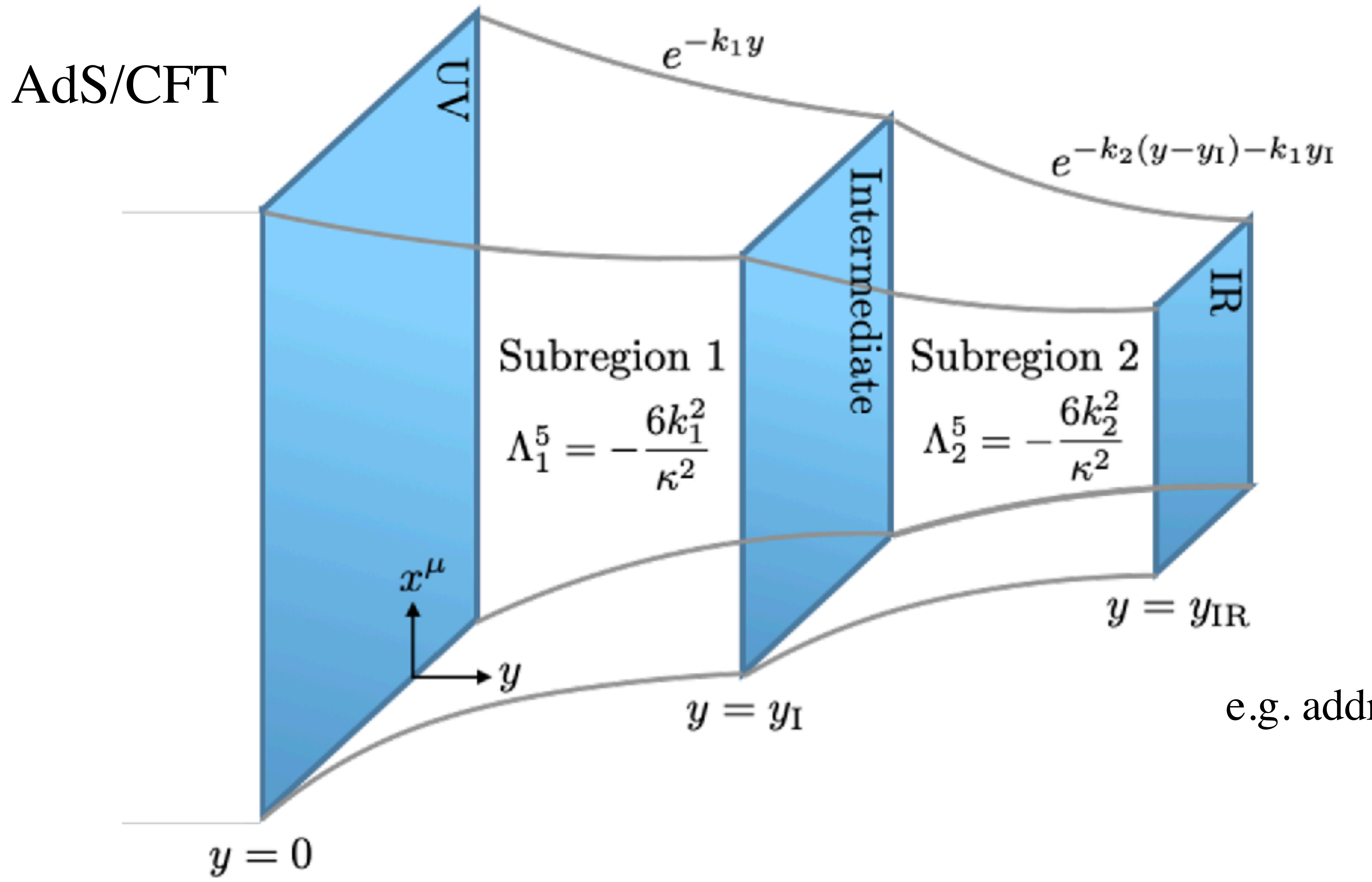
We assume there is a BSM physics, which makes the strong CP problem serious. (in our case BSM is Composite Higgs/RS model)

- Doubly Composite Higgs / Three-brane RS model
- Nelson-Barr models in Composite Higgs / RS model
- High Quality Axion in Composite Higgs / RS model
- Summary

Doubly Composite Higgs / Three-brane RS model

- If you have more than two scales in the theory, i.e. 3 different scales, it furnishes a useful framework (basically framework for this talk!)

CFT I → **CFT II**



the presence of the intermediate brane can be understood as spontaneous breaking of a conformal symmetry, but the resulting 4D dual theory flows into a new conformal fixed point

e.g. addressing flavor: Agashe, Du, Hong and Sundrum (2017)

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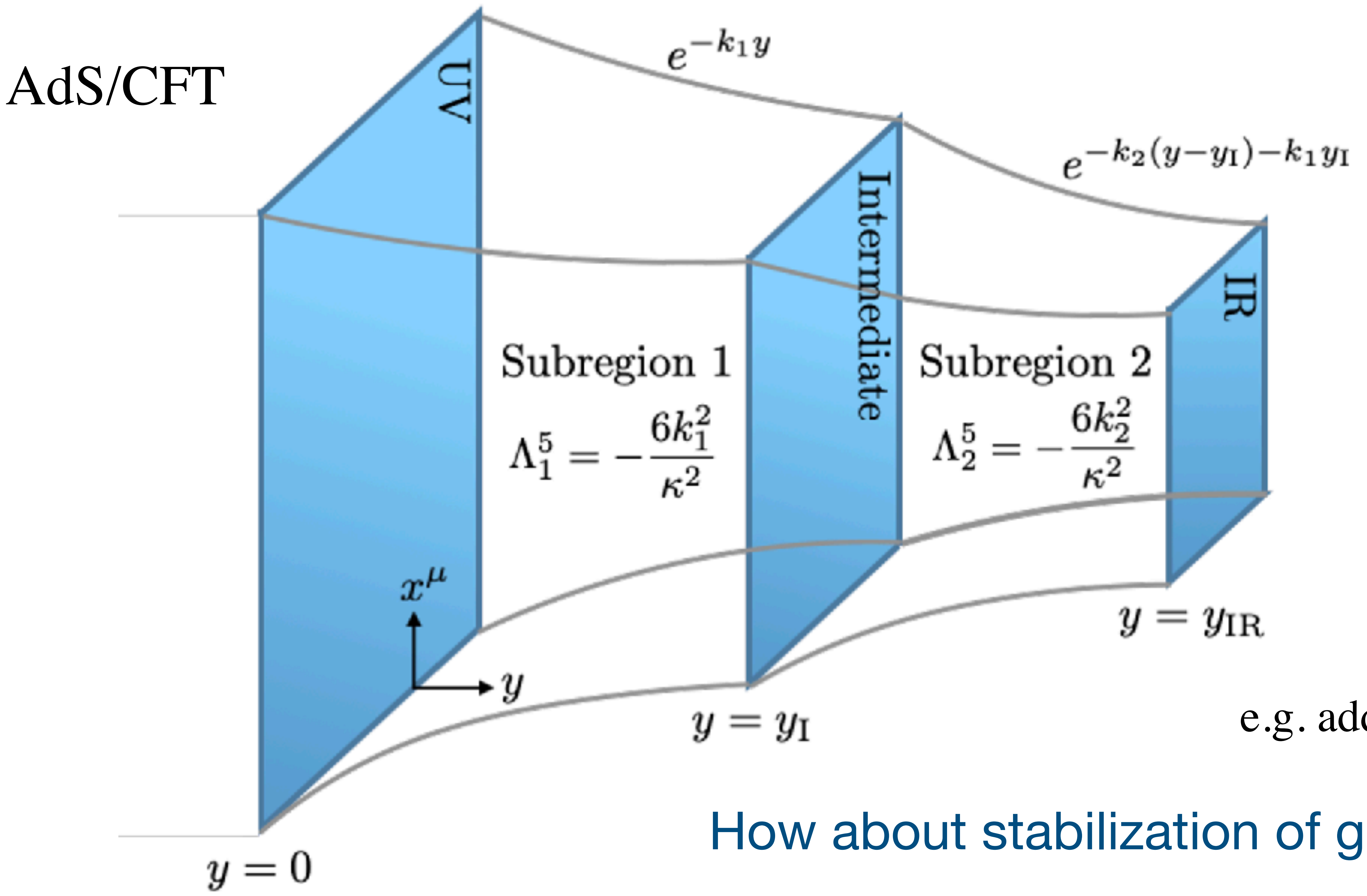

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e.g. addressing flavor: Agashe, Du, Hong and Sundrum (2017)

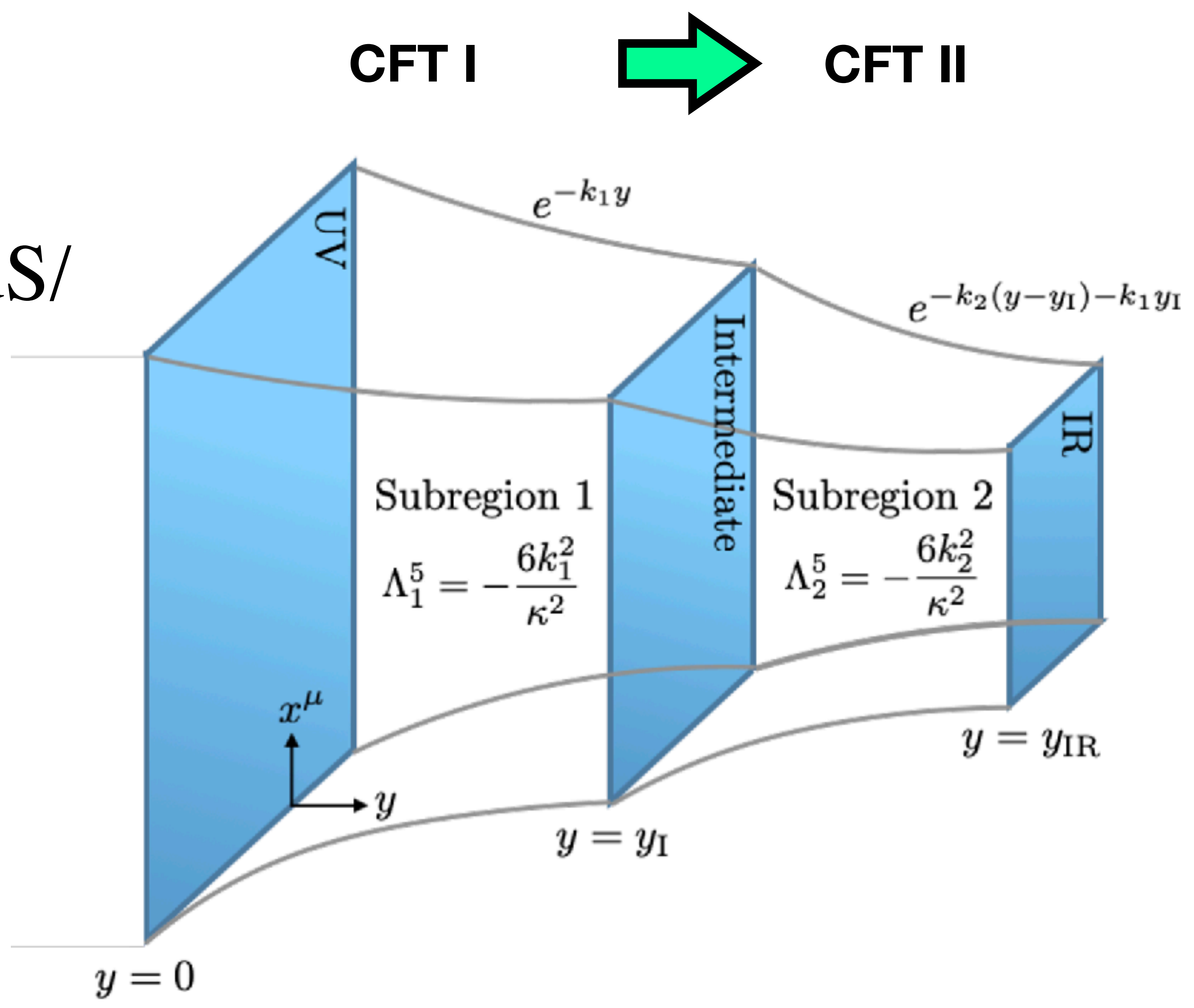
How about stabilization of geometry? SL, Y. Nakai, M. Suzuki (2022)

Doubly Composite Higgs / Three-brane RS model

"Warped" dimension is dual to 4D strong dynamics

- What's the advantage?

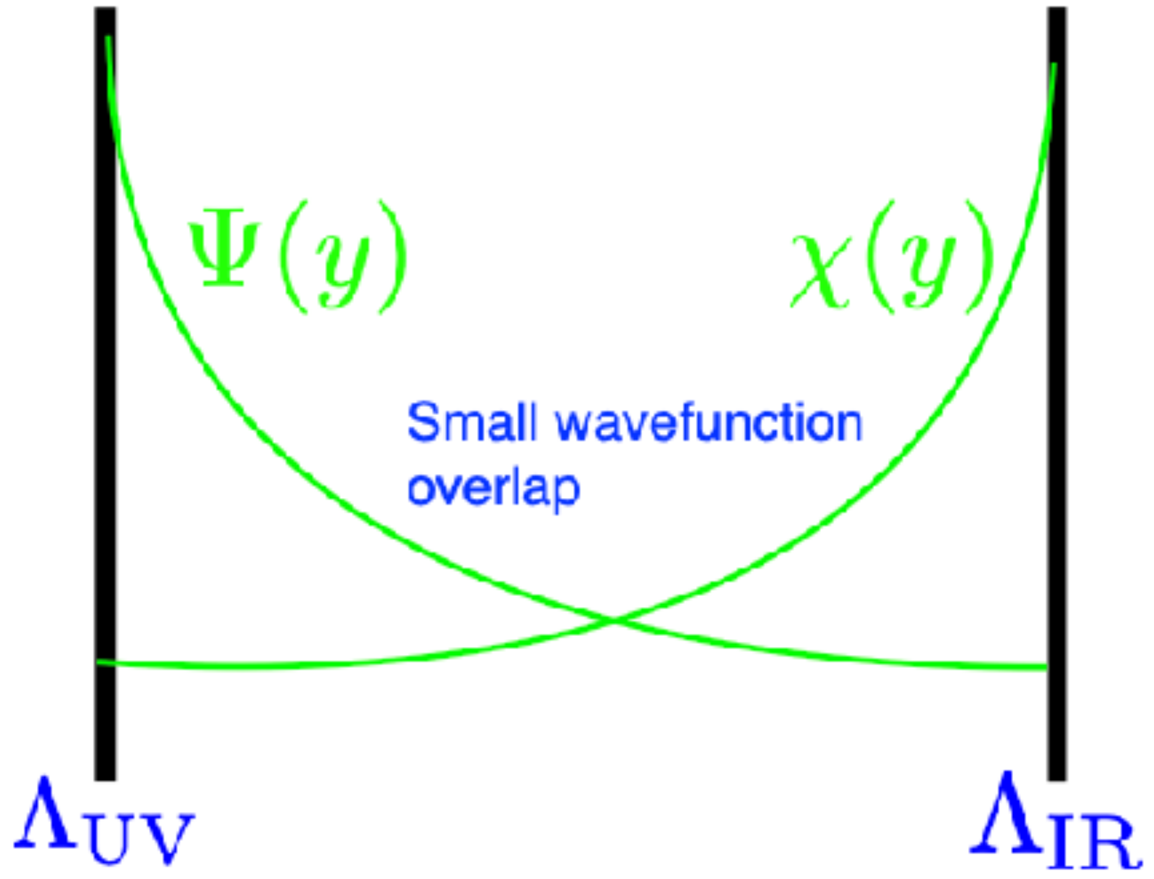
AdS/



- Can generate a hierarchy of scales dynamically

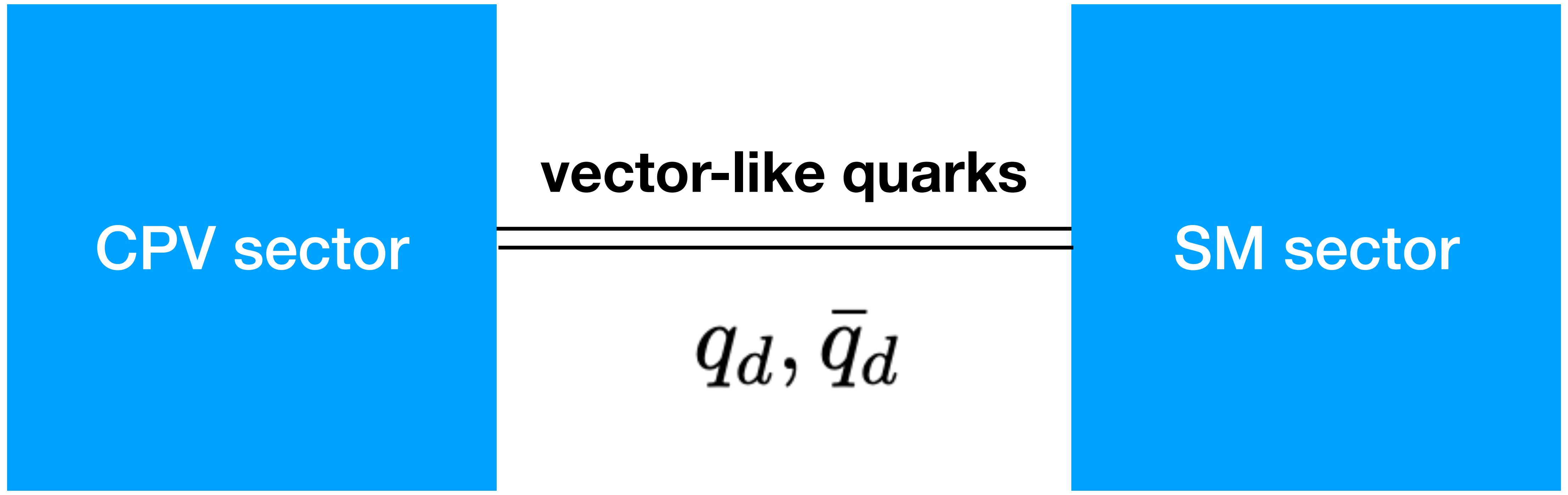
$$\Lambda_{IR} = \Lambda_{UV}\, e^{-ky}$$

- Can generate small couplings
(partial compositeness via different 5D profile)



Nelson-Barr models in Composite Higgs / RS model

- Basic idea of Nelson Barr:



$$\mathcal{L}_{\rm NB} = \mu_d q_d \bar{q}_d + \sum_{a,f} a^d_{af} \eta_a q_d \bar{d}_f + \sum_{f,f'} Y^d_{ff'} H Q_f \bar{d}_{f'}$$

- UV: CP is a symmetry (Nelson-Barr class: $\bar{\theta} = 0$)
- IR: Spontaneous CPV: complex scalar get a vev, $\langle \eta_a \rangle$

Question (not so easy):

can we keep $\bar{\theta} < 10^{-10}$, including loop and UV effects? i.e. radiative contribution should be under control

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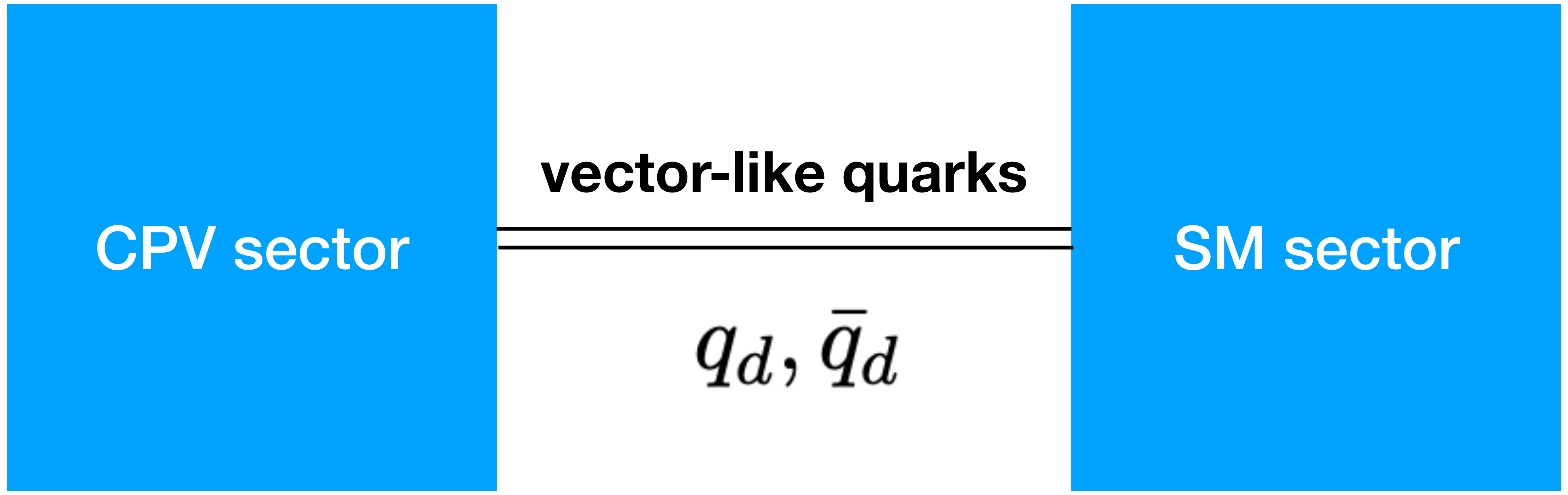

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real

SM singlet complex scalar

ordinary Yukawa

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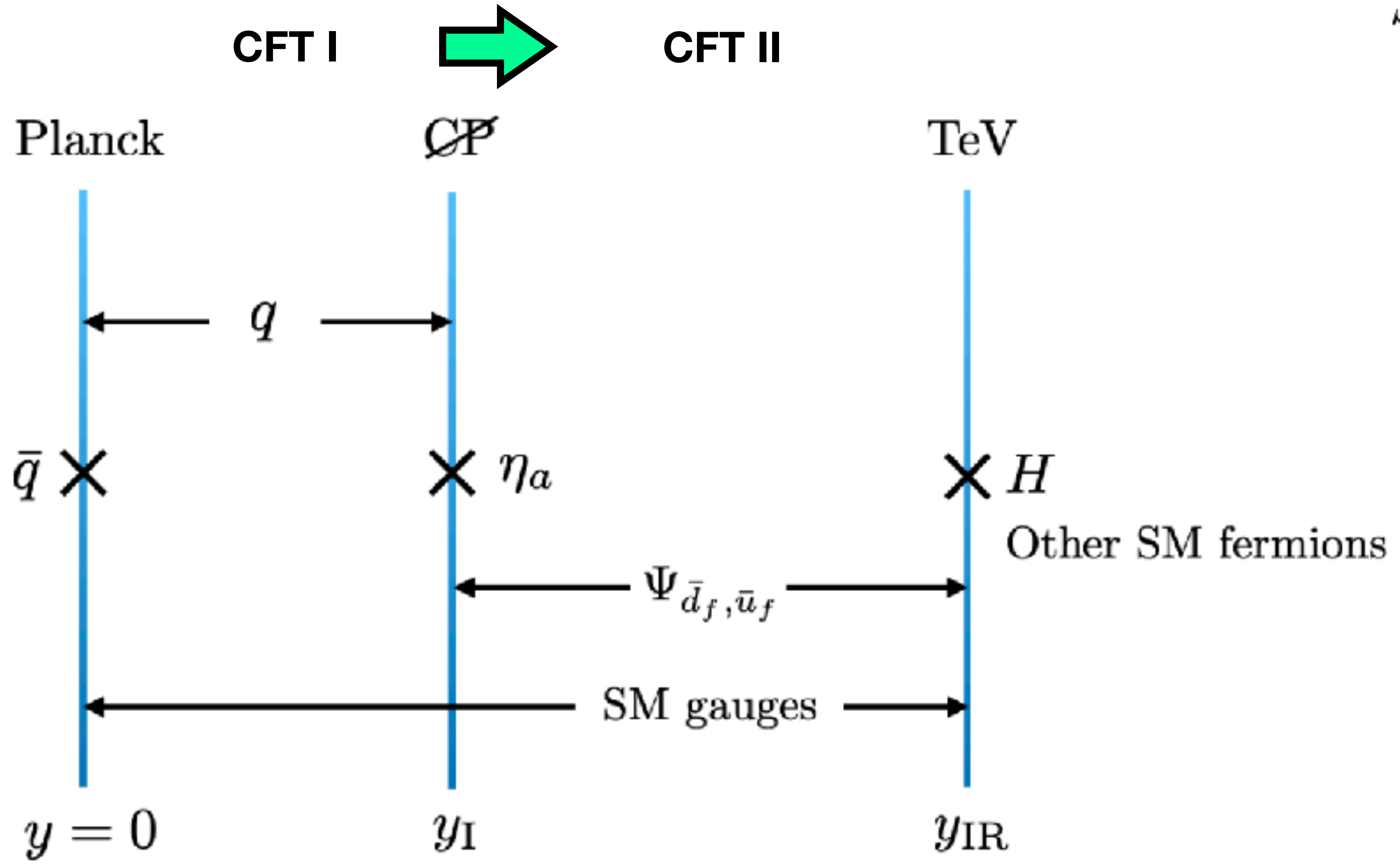
Nelson-Barr models in Composite Higgs / RS model

S. Girmohanta, SL, Y. Nakai, M. Suzuki (2022)

- Our toy model (solve gauge hierarchy problem as usual):

◆ spontaneous CPV at intermediate scale



$$S \supset \int d^4x \sqrt{|g_{\rm in}|}\, \hat{\mu}_d \psi_{q_d} \bar{q}_d + \text{h.c.} \Big|_{y=0}$$
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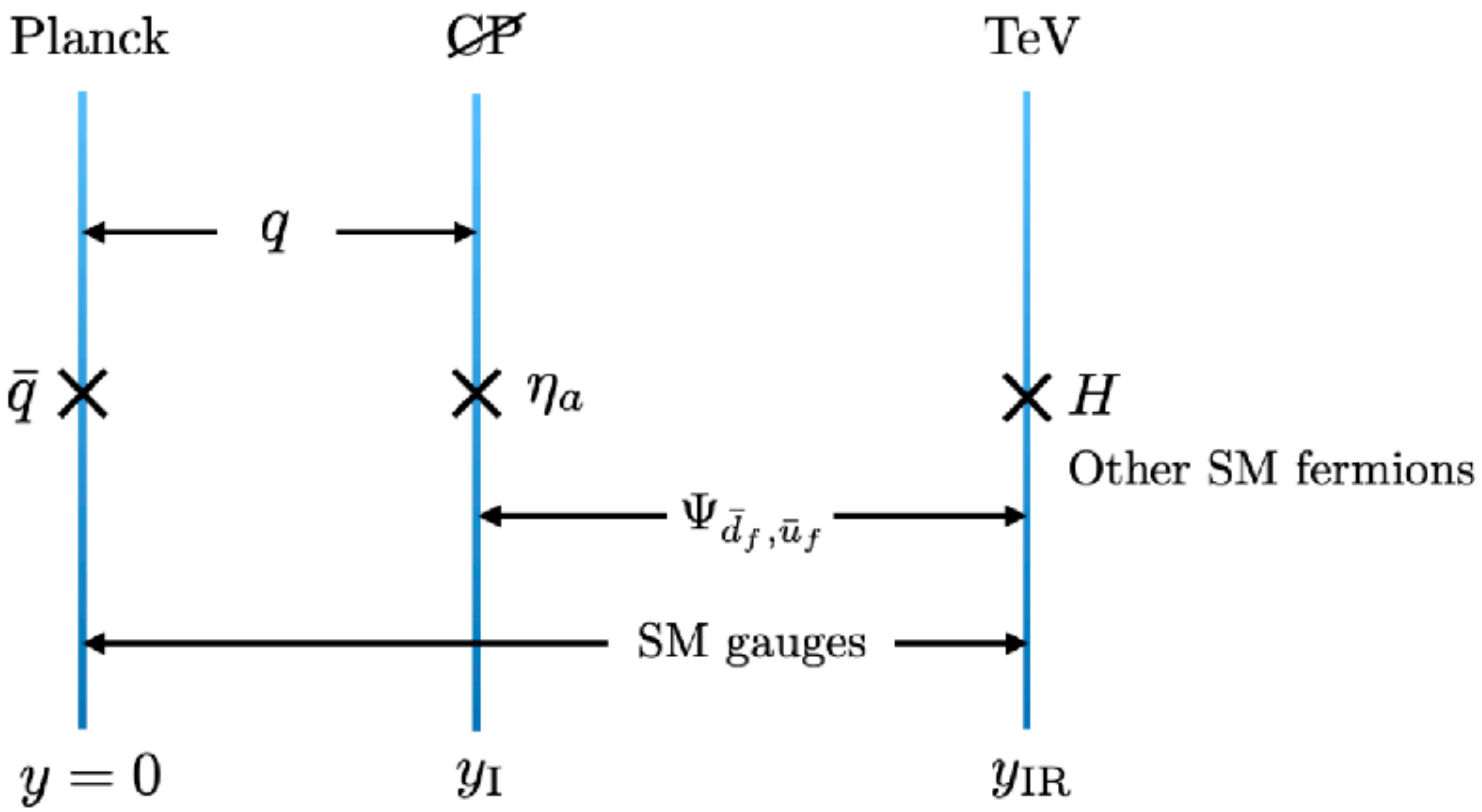
Nelson-Barr models in Composite Higgs / RS model

S. Girmohanta, SL, Y. Nakai, M. Suzuki (2022)



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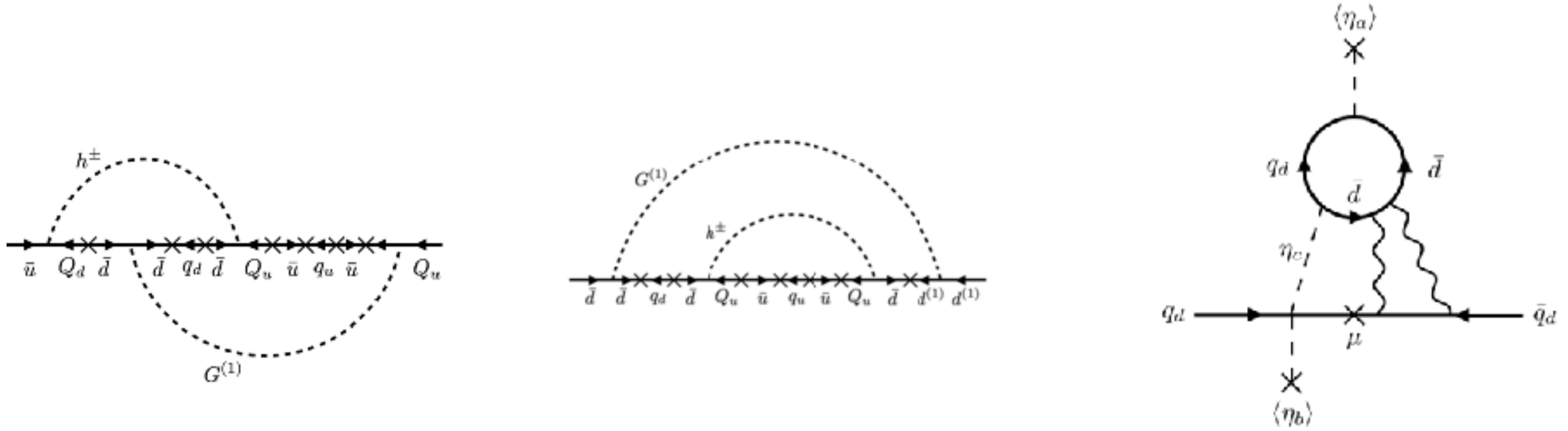
- Reproduces the SM, and satisfies constraints
- Radiative corrections are under control:

  no 1-loop contribution

  three branes are essential to forbid dangerous operators leading to a large corrections



- Flavor symetries are needed!

Nelson-Barr models in Composite Higgs / RS model

S. Girmohanta, SL, Y. Nakai, M. Suzuki (2022)

- Our toy model (solve gauge hierarchy problem as usual):

Yukawa terms and bulk masses and brane kinetic terms are flavor diagonal owing to the flavor symmetries for each flavor

On the intermediate brane, there are flavor violation effects on mixing terms with the vector-like quarks, brane kinetic terms.

However, the flavor violation effects of the latter brane kinetic terms are suppressed well by the flavor symmetries and small VEVs of the flavons.

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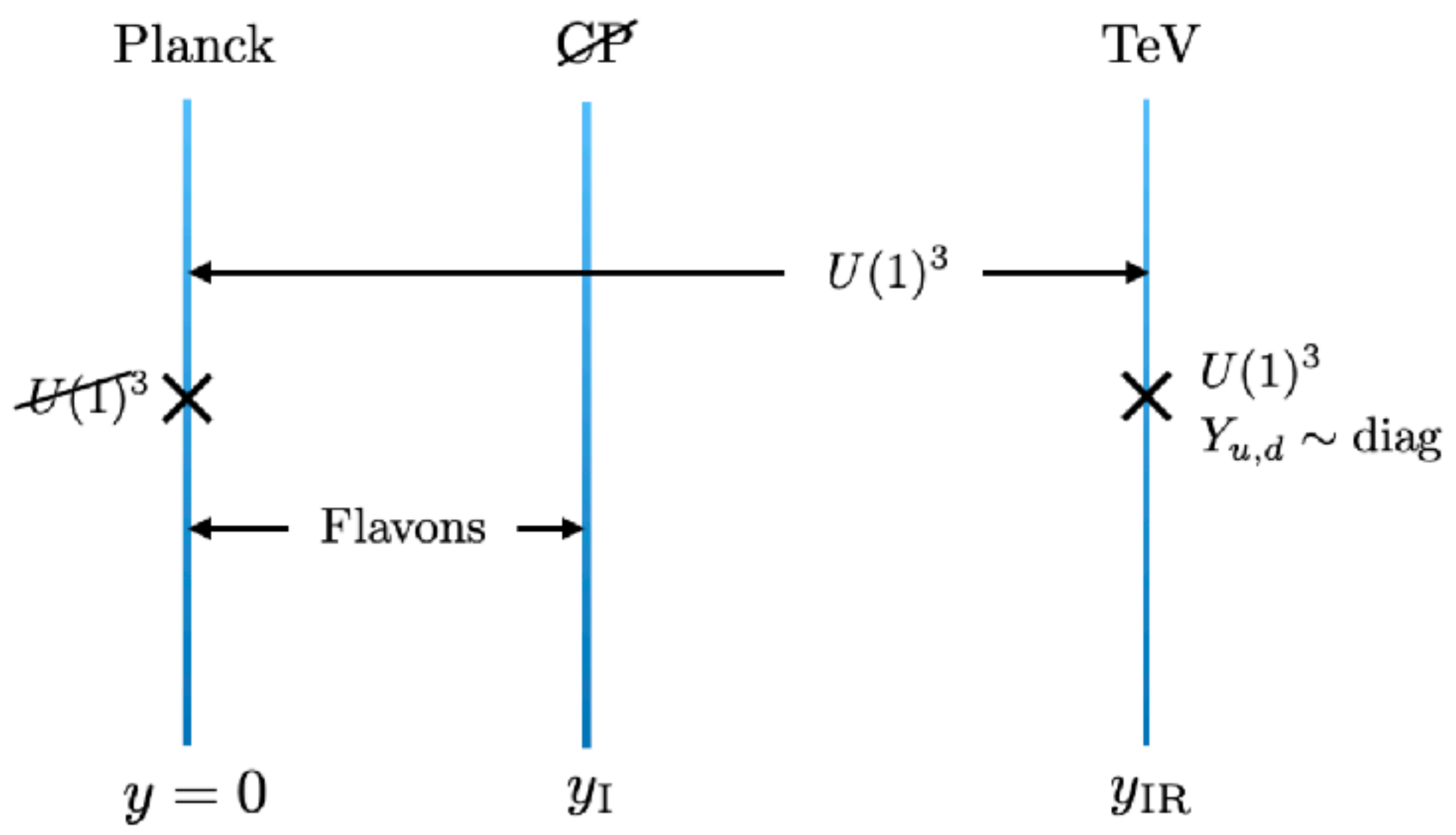
- require flavor symmetries



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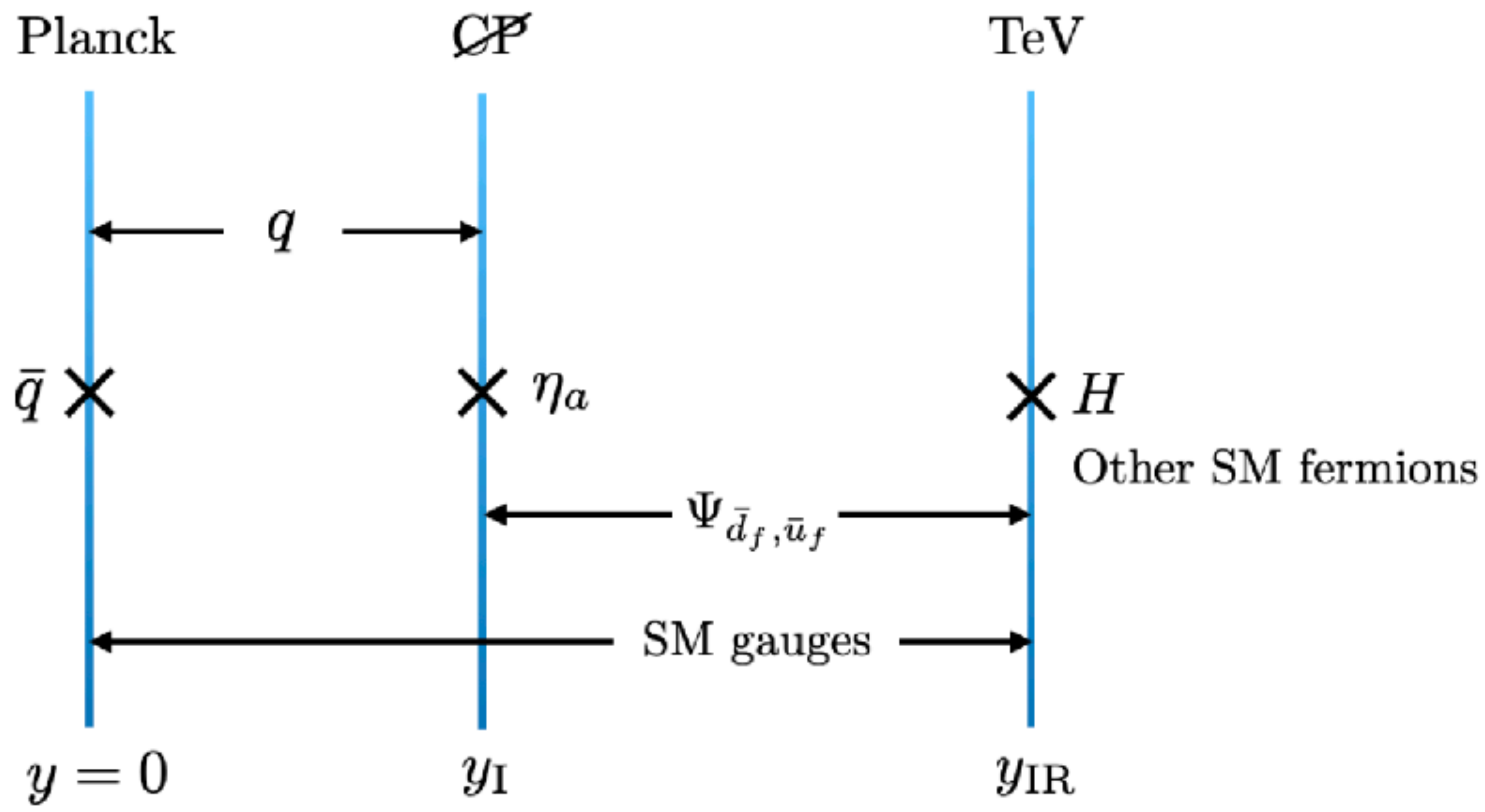

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◆ Bonus: addressing coincidence problem

naively uncorrelated mass scales, namely μ and $a_{af}\langle\eta\rangle$

1) intermediate brane naturally provides the mass scale of $\langle\eta\rangle$

2) overlap of the UV brane-localized $\bar{q}$ and (quasi-) intermediate brane-localized q determines μ, which is controlled by the intermediate brane mass scale for $c_q = O(1)$.

3) dual 4D description, $\bar{q}$ is elementary whereas q is (mostly) composite. Hence, the prescription to the coincidence problem is similar in nature to the solution for the hierarchy problem in warped extra dimension models.

High Quality Axion in Composite Higgs / RS model

SL, Y. Nakai, M. Suzuki (2022)

- Axion Quality Problem
  - Axion EFT

$$\mathcal{L} \supset \left(\frac{a}{f_a} + \theta\right) \frac{1}{32\pi^2} G\tilde{G}.$$

- anomalous symmetry associated with axion coupling: $a \to a + \alpha f_a, \qquad \theta \to \theta - \alpha,$

- but, there is no symmetry associated with it!

1. Because axion has no symmetry properties, there is no way to form axion coupling in the above EFT Lagrangian, without also including a host of other couplings (EFT should allow every couplings not forbidden by symmetry)

2. Quantum gravity breaks un-gauged symmetries. => even if one imposes the anomalous symmetry, gravitational effects will break it and the axion will obtain a separate mass term that is not centered around a zero neutron EDM, which reintroduces the problem.

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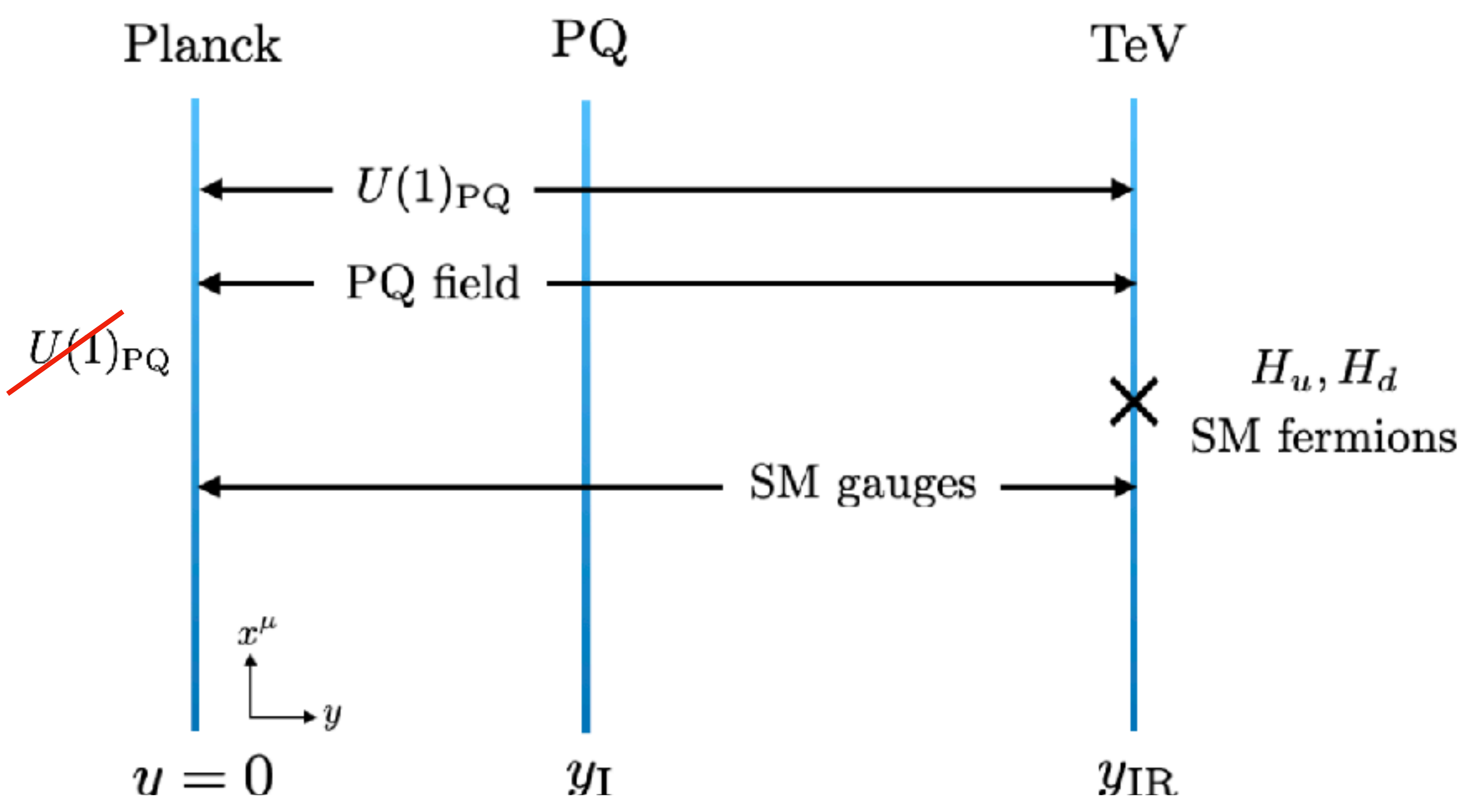
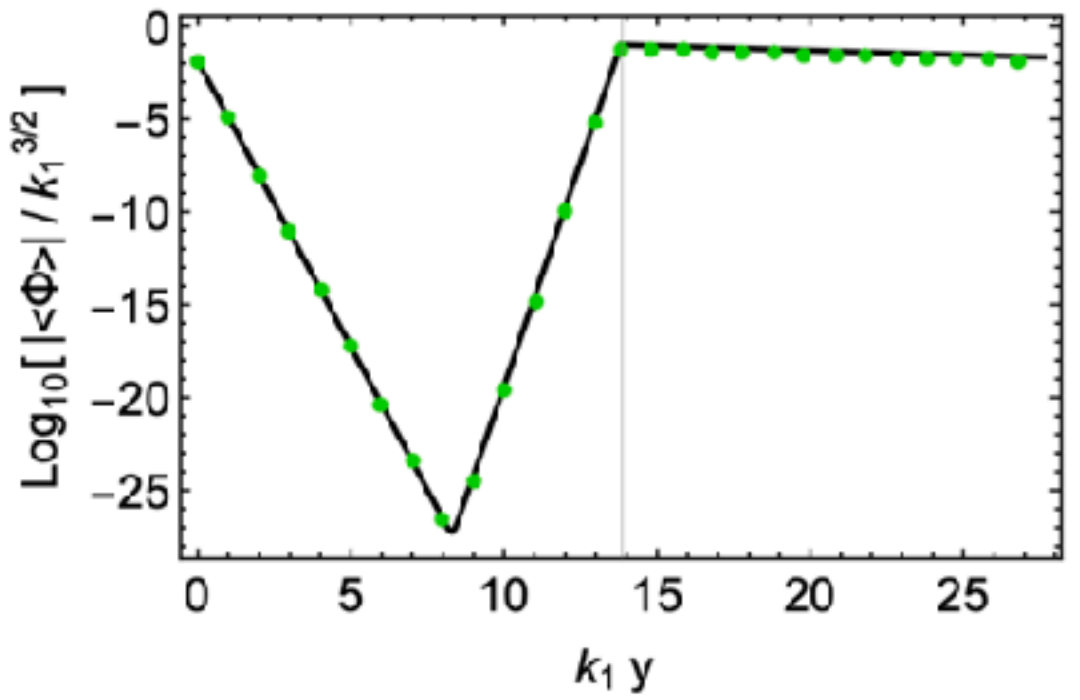
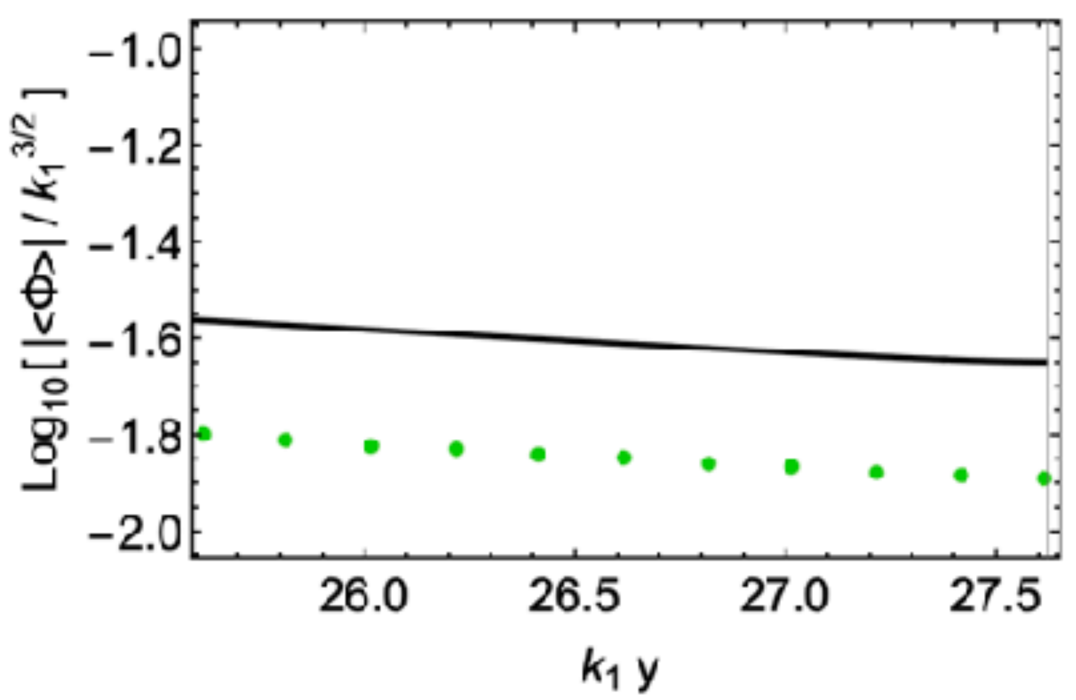
- Our toy model (solve gauge hierarchy problem as usual): use DFSZ model

extension of work by Cox, Gherghetta , Nguyen (2019)







PQ symmetry is realized as a gauge symmetry in the bulk of the extra dimension to solve the axion quality problem

Choi (2003), Flacke, Gripaios, March-Russell, Maybury (2006)

$$\Phi \equiv (\langle\Phi\rangle + \eta)\, e^{ia}$$

PQ symmetry breaking → "Bulk VEV"

$$-\,\partial_5(e^{-4\sigma}\partial_5\langle\Phi\rangle) + m_p^2\, e^{-4\sigma}\langle\Phi\rangle = 0$$

$$m_{1,2}^2 \equiv \Delta_{1,2}\,(\Delta_{1,2}-4)\,k_{1,2}^2$$ "Bulk mass"

$$\langle\Phi_1\rangle = k_1^{3/2}\left[c_a\, e^{k_1 y(4-\Delta_1)} + c_b\, e^{k_1 y \Delta_1}\right] \quad \text{(subregion 1)}$$

$$\langle\Phi_2\rangle = k_2^{3/2}\left[c_c\, e^{k_2 y(4-\Delta_2)} + c_d\, e^{k_2 y \Delta_2}\right] \quad \text{(subregion 2)}$$

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- Our toy model (solve gauge hierarchy problem as usual): use DFSZ model

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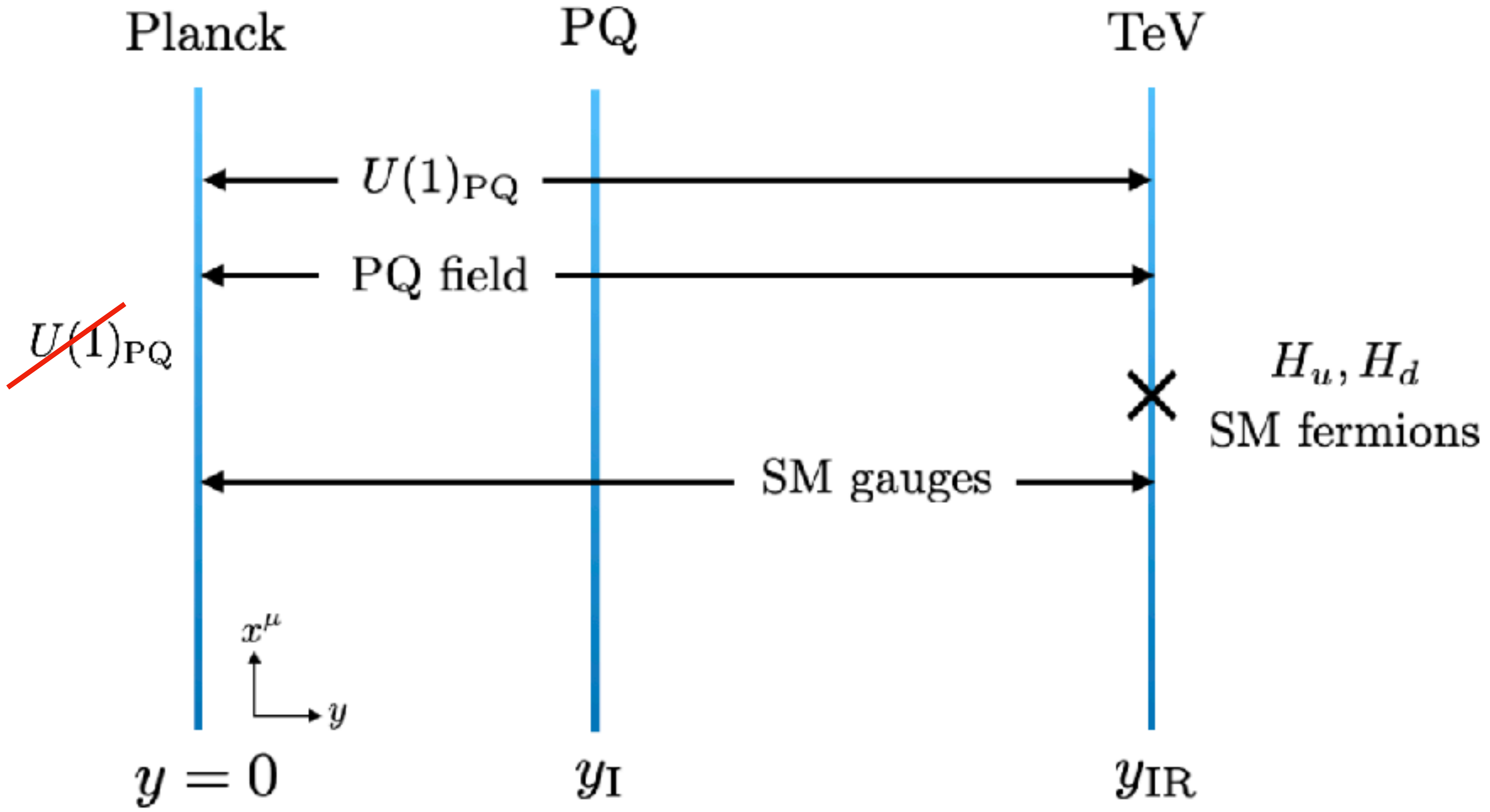

$$|\langle\Phi\rangle|^2 m_a^2 f_a + e^{2\sigma}\partial_5\left\{e^{-4\sigma}|\langle\Phi\rangle|^2(\partial_5 f_a)\right\} = 0$$

$$f_{a,1} = \frac{e^{k_1 y(2-\Delta_1)}\left(J_{\Delta_1-2}\left(\frac{e^{k_1 y}m_a}{k_1}\right)C_{a1} + Y_{\Delta_1-2}\left(\frac{e^{k_1 y}m_a}{k_1}\right)C_{a2}\right)}{c_a e^{2k_1 y(2-\Delta_1)} + c_b},$$

$$f_{a,2} = \frac{e^{k_2 y(2-\Delta_2)}\left(J_{\Delta_2-2}\left(\frac{e^{k_2 y + y_{\rm I}(k_1-k_2)}m_a}{k_2}\right)C_{a3} + Y_{\Delta_2-2}\left(\frac{e^{k_2 y + y_{\rm I}(k_1-k_2)}m_a}{k_2}\right)C_{a4}\right)}{c_c e^{2k_2 y(2-\Delta_2)} + c_d}$$

◆ UV PQ-breaking

$$S \supset 2\int_{y_{\rm UV}}^{y_{\rm IR}} d^5x\sqrt{g}\left(\frac{1}{2}\langle\Phi\rangle^2 a\Box a + \frac{1}{2g_5^2}A_5\Box A_5\right)$$

$$\Box A_5 - g_5^2|\langle\Phi\rangle|^2 e^{-2\sigma}\left(\partial_5 a - A_5\right) + \xi\,\partial_5\left\{\partial_5(e^{-2\sigma}A_5) - g_5^2 e^{-2\sigma}|\langle\Phi\rangle|^2 a\right\} = 0\,,$$

$$|\langle\Phi\rangle|^2\Box a - e^{2\sigma}\partial_5\left\{e^{-4\sigma}|\langle\Phi\rangle|^2\left(\partial_5 a - A_5\right)\right\} + \xi|\langle\Phi\rangle|^2\left\{\partial_5(e^{-2\sigma}A_5) - g_5^2|\langle\Phi\rangle|^2 e^{-2\sigma}a\right\} = 0$$

$$a(x,y) = \sum_n f_a^{(n)}(y)\, a^{(n)}(x)$$

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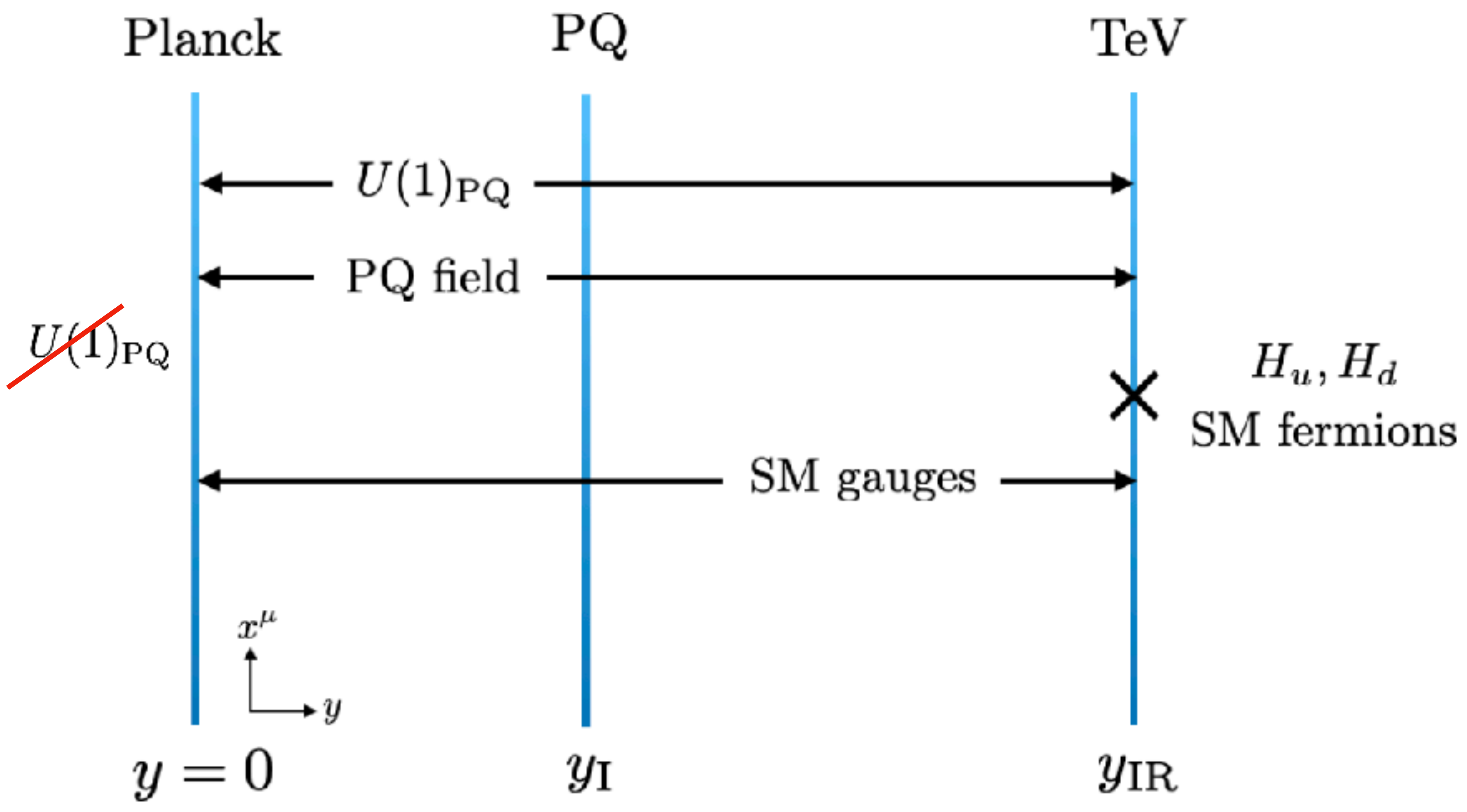

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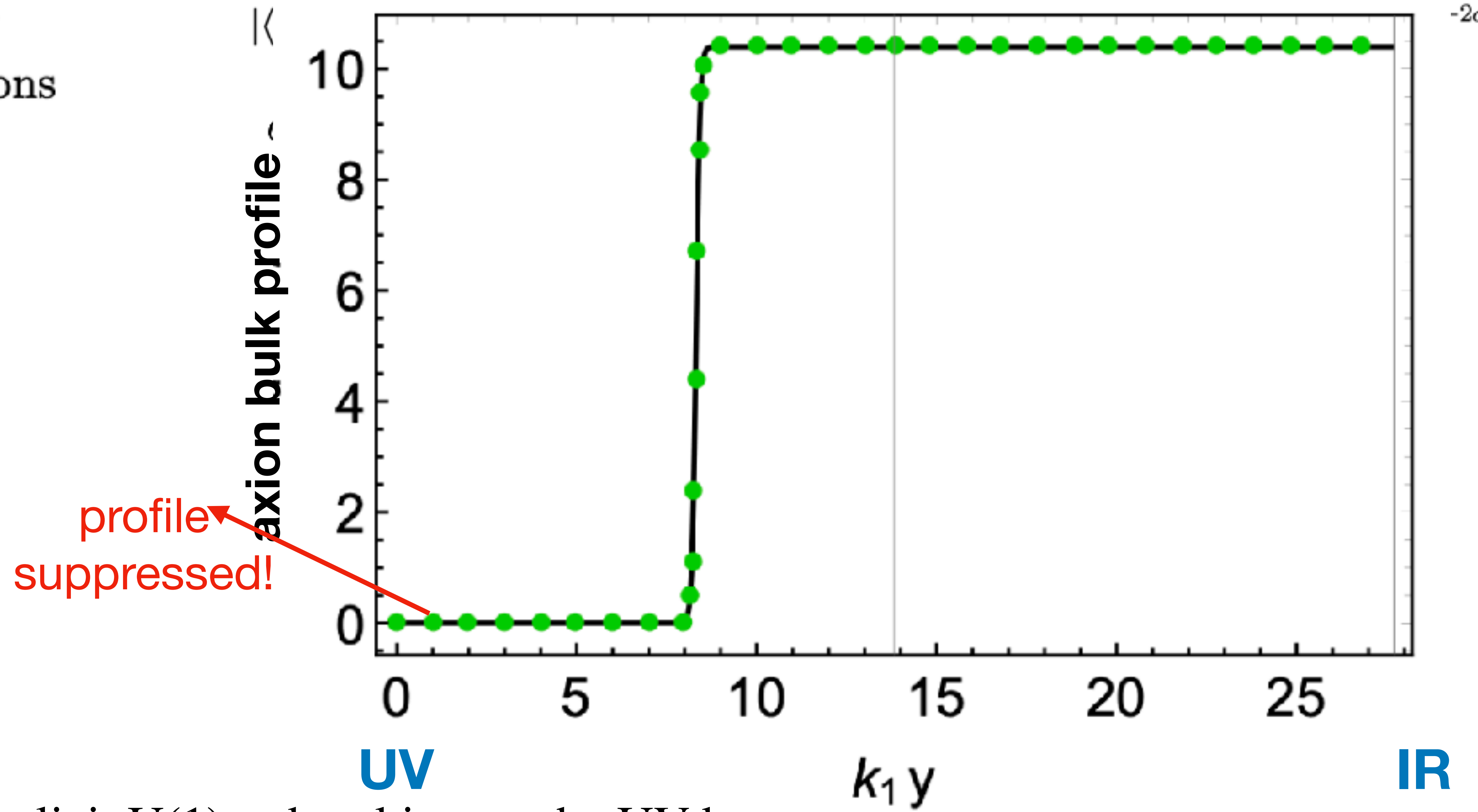

explicit $U(1)_{\rm PQ}$ breaking on the UV brane

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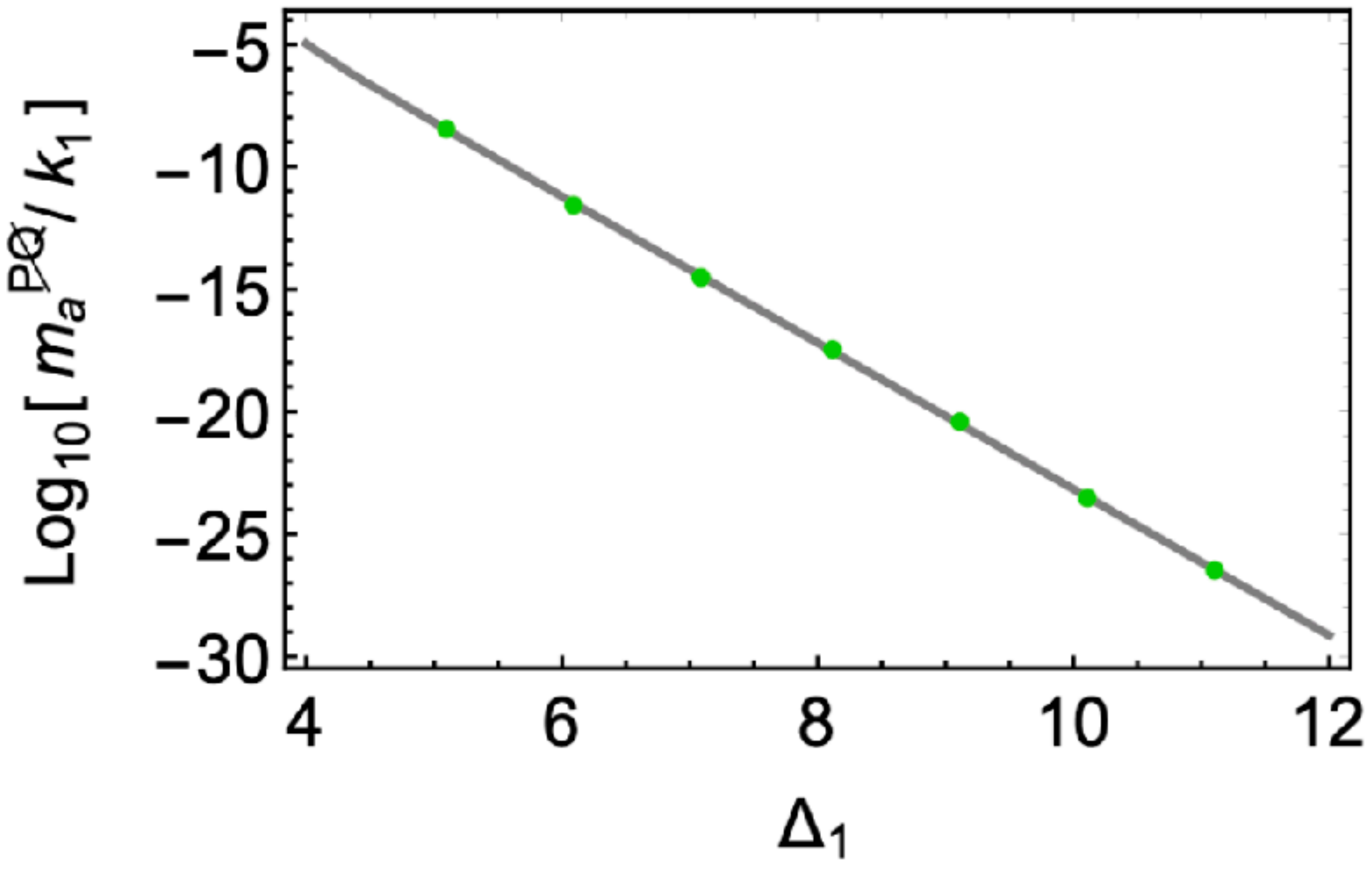

◆ UV axion mass

$$\Box A_5 - g_5^2|\langle\Phi\rangle|^2 e^{-2\sigma}\left(\partial_5 a - A_5\right) + \xi\,\partial_5\left\{\partial_5(e^{-2\sigma}A_5) - g_5^2 e^{-2\sigma}|\langle\Phi\rangle|^2 a\right\} = 0\,,$$

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$$a(x,y) = \sum_n f_a^{(n)}(y)\, a^{(n)}(x)$$

$$|\langle\Phi\rangle|^2 m_a^2 f_a + e^{2\sigma}\partial_5\left\{e^{-4\sigma}|\langle\Phi\rangle|^2(\partial_5 f_a)\right\} = 0$$

$$m_a^{\cancel{\mathrm{PQ}}} \approx 2k_1 e^{-k_1 y_1(\Delta_1-2)/2}\sqrt{\frac{l_{\mathrm{UV}}}{\sigma_0}\frac{2-3\Delta_1+\Delta_1^2}{b_{\mathrm{UV}}+\Delta_1-4}}$$

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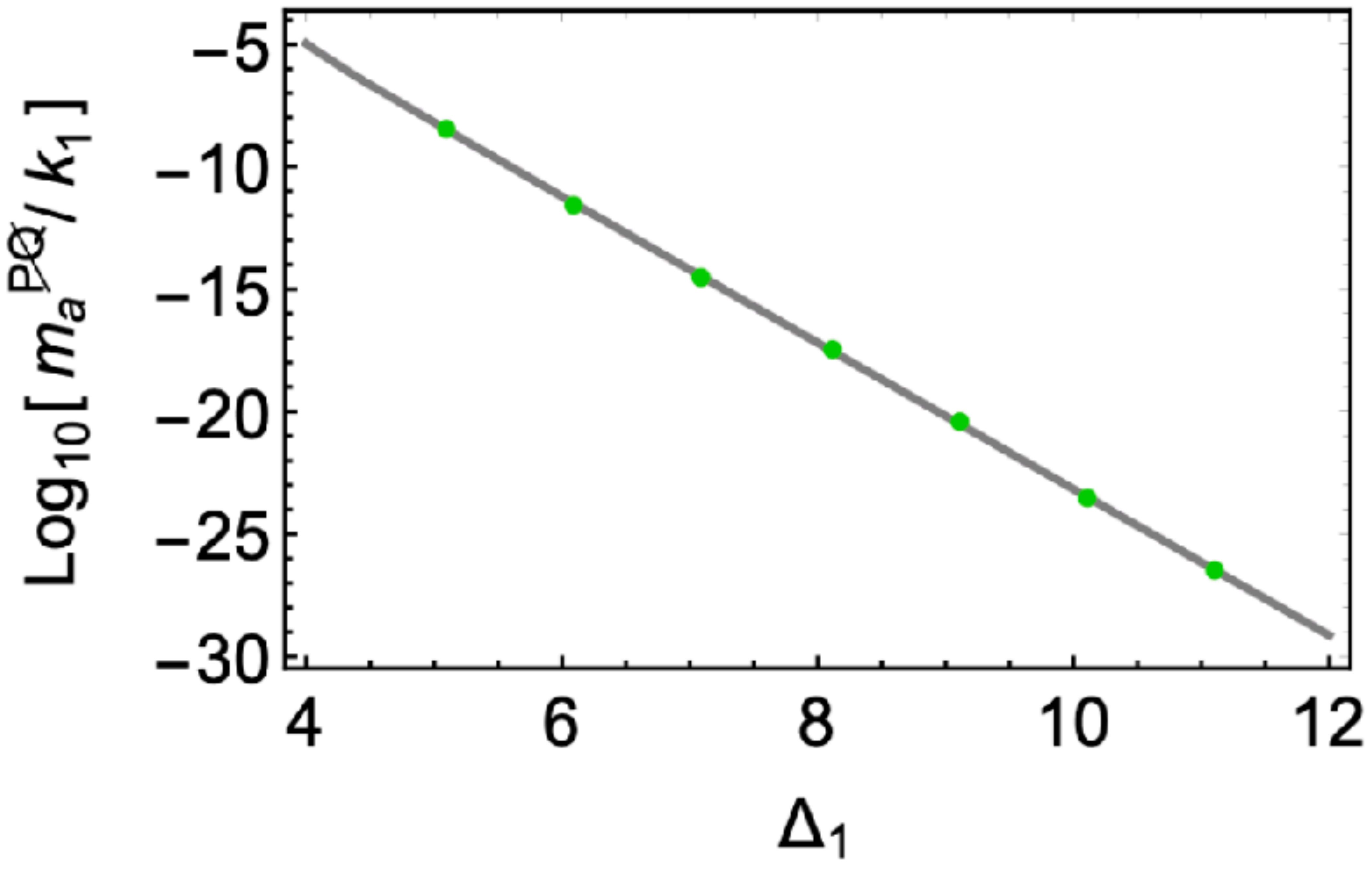


◆ UV axion mass

$$\Box A_5 - g_5^2 |\langle\Phi\rangle|^2 e^{-2\sigma} (\partial_5 a - A_5) + \xi\, \partial_5 \left\{ \partial_5 (e^{-2\sigma} A_5) - g_5^2 e^{-2\sigma} |\langle\Phi\rangle|^2 a \right\} = 0\,,$$

$$|\langle\Phi\rangle|^2 \Box a - e^{2\sigma} \partial_5 \left\{ e^{-4\sigma} |\langle\Phi\rangle|^2 (\partial_5 a - A_5) \right\} + \xi |\langle\Phi\rangle|^2 \left\{ \partial_5 (e^{-2\sigma} A_5) - g_5^2 |\langle\Phi\rangle|^2 e^{-2\sigma} a \right\} = 0$$

$$a(x,y) = \sum_n f_a^{(n)}(y)\, a^{(n)}(x)$$

$$|\langle\Phi\rangle|^2 m_a^2 f_a + e^{2\sigma} \partial_5 \left\{ e^{-4\sigma} |\langle\Phi\rangle|^2 (\partial_5 f_a) \right\} = 0$$

$$m_a^{\mathrm{PQ}\!\!\!/} \approx 2 k_1 e^{-k_1 y_1 (\Delta_1 - 2)/2} \sqrt{\frac{l_{\mathrm{UV}}}{\sigma_0} \frac{2 - 3\Delta_1 + \Delta_1^2}{b_{\mathrm{UV}} + \Delta_1 - 4}}$$

$\Rightarrow$ UV axion mass suppressed for large Δ

High Quality Axion in Composite Higgs / RS model

SL, Y. Nakai, M. Suzuki (2022)

- Axion High Quality Problem in our model:

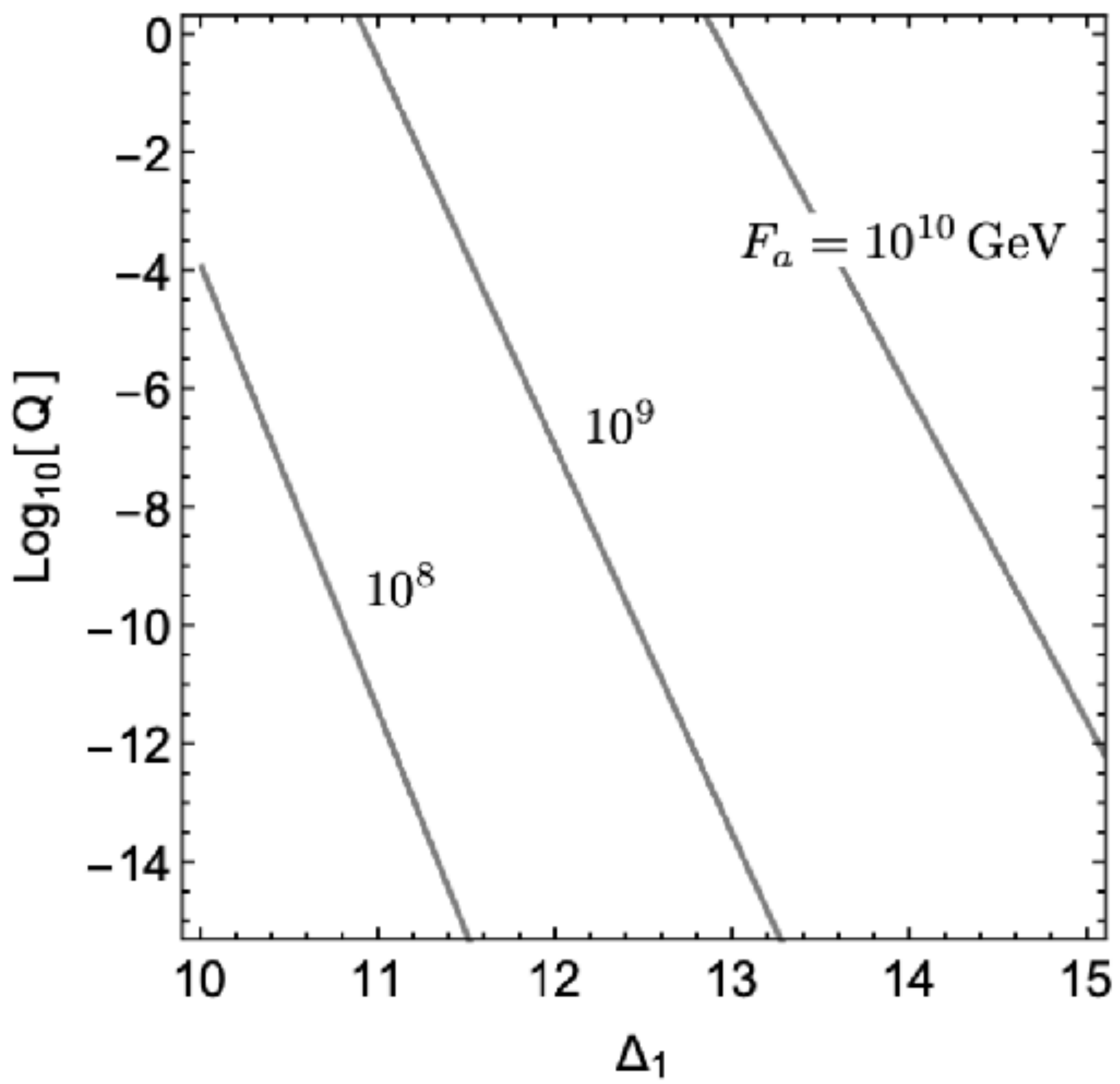
◆ axion mass: generated from non-perturbative QCD effects

$$m_a^{\rm QCD} = \frac{\sqrt{z}}{1+z}\frac{m_\pi F_\pi}{F_a}$$

$$z \equiv m_u/m_d \simeq 0.56$$

◆ Quality factor

$$\mathcal{Q} \equiv (m_a^{\cancel{\rm PQ}}/m_a^{\rm QCD})^2$$



The strong CP problem is correctly solved with $Q \leq 10^{-10}$
Q is significantly suppressed as Δ_1 increases and the axion quality problem is solved for $\Delta_1 \sim 10$

High Quality Axion in Composite Higgs / RS model

- Prediction

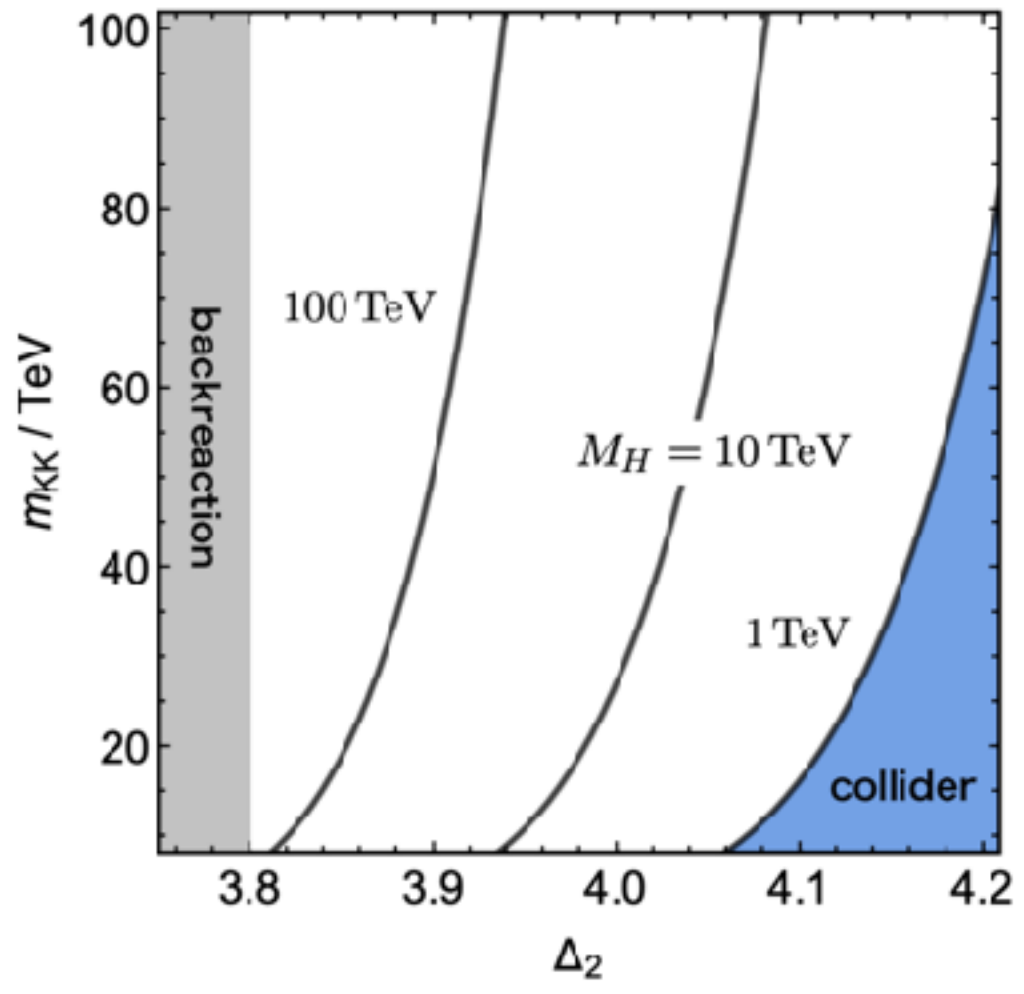
SL, Y. Nakai, M. Suzuki (2022)

◆ TeV scale KK axions

$$S_{\text{eff}} \supset \int d^4x \, \frac{1}{32\pi^2 F_{a^{(1)}_{KK}}} a^{(1)}(x) G^{a(0)}_{\mu\nu} \widetilde{G}^{a(0)\mu\nu} \,, \qquad \frac{1}{F_{a^{(1)}_{KK}}} \equiv A_{\text{QCD}} \, f^{(1)}_a(y_{\text{IR}})$$

◆ TeV scale KK excitation of η and gauge $U(1)_Q$

◆ Extra Higgs boson



$$M_H^2 \approx \frac{2\, e^{-2k_2 y_{\text{IR}} - 2(k_1 - k_2) y_{\text{I}}} \, \kappa_{ud} \, \langle \Phi(y_{\text{IR}}) \rangle^2}{\sin(2\beta) M_5}$$

◆ GW with multiple peak frequencies

(multiple confinement-deconfinement phase transitions in the early Universe)

Summary

- Strong CP is a serious problem for extension of the SM model
- We show how to address it with doubly composite Higgs model / RS with three branes:
  - Nelson-Barr models in Composite Higgs / RS model
  - High Quality Axion in Composite Higgs / RS model
- our model also address the naturalness problem for EWSB