The self-tuning of the cosmological constant and the holographic relaxion

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1905.03663 and work in progress,

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Fine tuning problems

- Cosmological constant problem:

  The natural value of the cosmological constant is $(\text{SUSY breaking})^4 \gg (\text{meV})^4$.

- Gauge hierarchy problem:

  The natural value of the Higgs mass is $(\text{SUSY breaking})^2 \gg (125\text{GeV})^2$.

Our project: Try to solve these problems in the context of the brane world inspired by holography.

Fine tuning problems

- Cosmological constant problem:

  The natural value of the cosmological constant is (SUSY breaking)^4 >> (meV)^4.

  (Holographic) self tuning

- Gauge hierarchy problem:

  The natural value of the Higgs mass is (SUSY breaking)^2 >> (125GeV)^2.

  relaxion

Our project: Try to solve these problems in the context of the brane world inspired by holography.

Self-tuning of cc

- In the brane world setup, the solution of EoM with flat brane exists for generic brane cosmological constant. The 4d flat universe is realized on the brane.

[Arkani Hamed-Dimopoulos-Kaloper-Sundrum '00] [Kachru-Schulz-Silverstein '00]

- Problems: For generic choice of integration constant of EoM, the bad bulk singularity exists, whose interpretation is unclear.

- Holographic self-tuning: If fundamental theory is 4d QFT, dual to brane world setup, we must choose integration constant in such a way that holography makes sense (no bad bulk singularity).

[Charmousis-Kiritsis-Nitti, '17]

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Holographic Self Tuning

- 5d Einstein-Dilaton theory with brane.

$$S_{bulk} = M_5^3 \int d^5x\sqrt{-g}\left[R - \frac{1}{2}g^{ab}\partial_a\varphi\partial_b\varphi - V(\varphi)\right] + S_{GHY}$$

φ: dilaton

5d Planck mass

5d Ricci scalar

Boundary term

- $$S_{brane} = M_5^3 \int d^4x\sqrt{-\gamma}\left[-W_B(\varphi) + \cdots\right]$$

Brane cosmological constant

- Ansatz: flat metric on the brane.

$$ds^2 = du^2 + e^{2A(u)}\eta_{\mu\nu}dx^\mu dx^\nu, \qquad \varphi = \varphi(u)$$

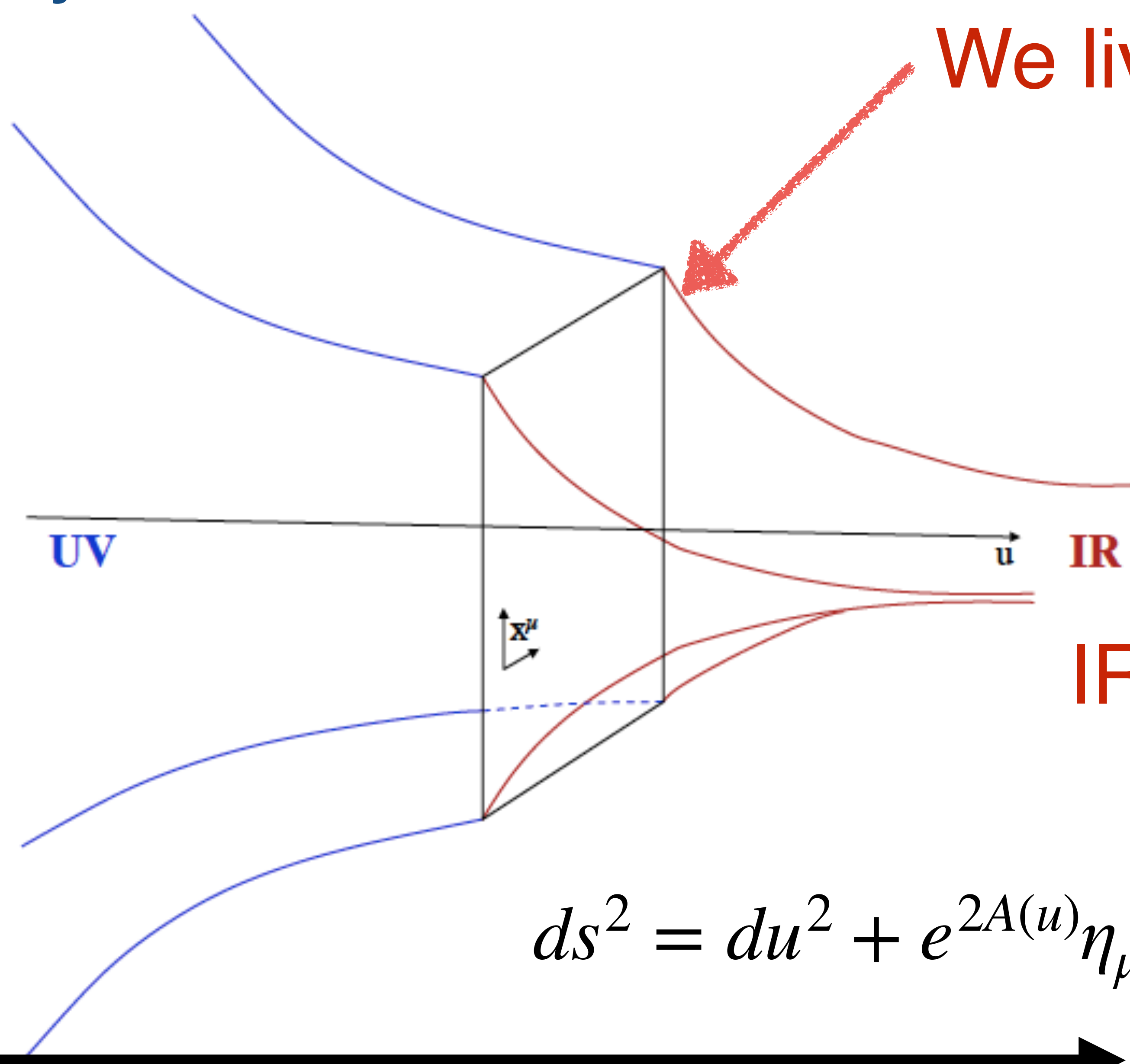
- For generic choice of $W_B(\varphi)$, flat brane solution exists.

[Charmousis-Kiritsis-Nitti, '17]

Setup of holographic self-tuning

UV region:
Asymptotically AdS

Brane at $u=u_0$
We live here.



IR region

$$ds^2 = du^2 + e^{2A(u)}\eta_{\mu\nu}dx^\mu dx^\nu, \qquad \varphi = \varphi(u)$$

Holographic coordinate u

[Graham-Kaplan-Rajendran, '15]

Relaxion

- The smallness of Higgs mass is explained by
  - Many vacua, one of which realizes the small Higgs mass.
  - Mechanism to relax into desired vacuum through cosmological evolution.

[Graham-Kaplan-Rajendran, '15]

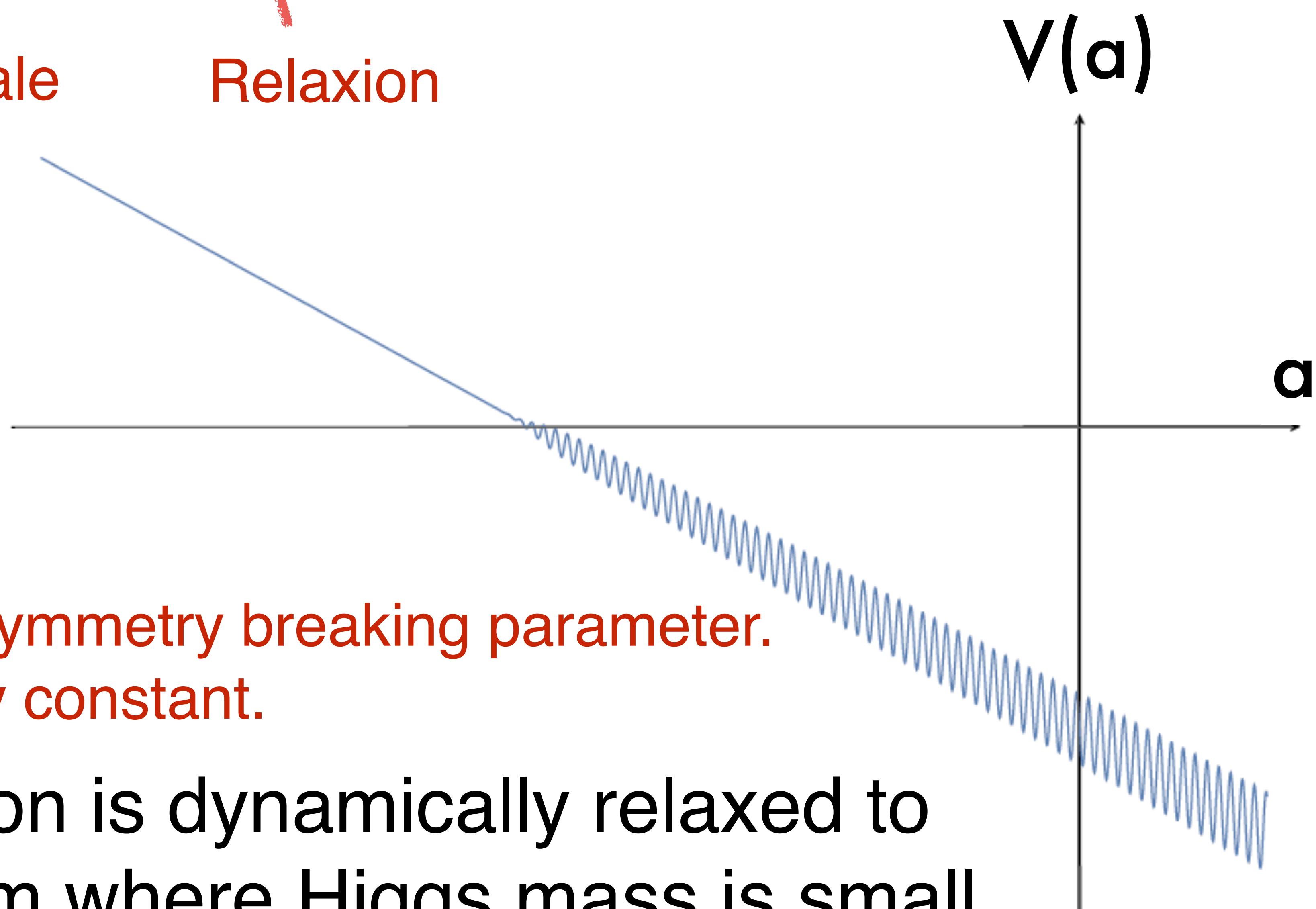
Relaxion potential

$$V(a) = (M^2 - ga)|H|^2 - (gM^2a + g^2a^2 + \cdots) + \Lambda^4 \cos(a/f_a)$$

Cutoff scale

Relaxion

Instanton potential



g: small shift symmetry breaking parameter.

f_a: axion decay constant.

The relaxion is dynamically relaxed to the vacuum where Higgs mass is small.

[YH-Kiritsis-Nitti-Witkowski, 1905.03663 & work in progress]

Our Setup

- We use the idea of relaxion in the holographic self tuning setup.

- We work in Einstein-Axion-Dilaton theory with brane where SM lives. φ: dilaton, a: axion, H: Higgs.

Bulk $S_{bulk} = M_5^3 \int d^5x \sqrt{-g} \left[R - \frac{1}{2} g^{ab} \partial_a \varphi \partial_b \varphi - \underbrace{\frac{1}{2} Y(\varphi) g^{ab} \partial_a a \partial_b a}_{\text{Axion kinetic term}} - V(\varphi) \right] + S_{GHY}$

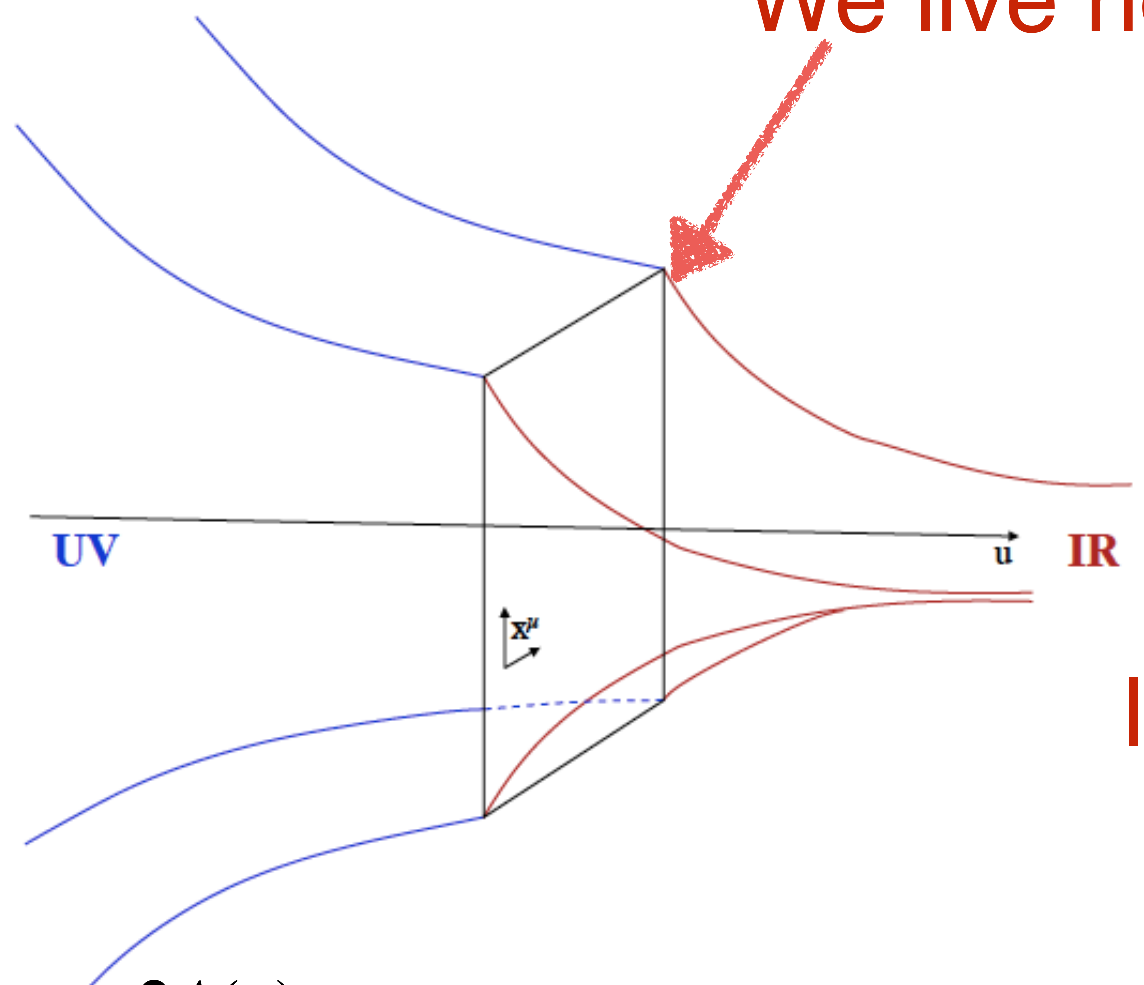
Brane $S_{brane} = M_5^3 \int d^4x \sqrt{-\gamma} \left[-W_B(\varphi, a) - \underbrace{X_H(\varphi, a) |H|^2}_{\text{Higgs mass}} - \underbrace{S_H(\varphi, a) |H|^4}_{\text{Higgs coupling}} + \cdots \right]$

[YH-Kiritsis-Nitti-Witkowski, 1905.03663 & work in progress]

Our Setup

UV region:
Asymptotically AdS

SM Brane at u=u0
We live here.



IR region

$$ds^2 = du^2 + e^{2A(u)}\eta_{\mu\nu}dx^\mu dx^\nu, \qquad \varphi = \varphi(u), \qquad \underline{a = a(u)}$$

Holographic coordinate u

Monodromy

- Our setup realizes the many vacua in bulk theory.

- a_{UV} : source of axion (field value in the UV).

  θ_{UV} : θ angle in dual QFT.

  Holographic dictionary is

$$\theta_{UV} + 2\pi k = N_c a_{UV}, \quad k \in \mathbb{Z}, \quad 0 \leq \theta_{UV} < 2\pi$$

- For large N_c,

One θ_{UV} ⟺ many a_{UV} $\quad k = 0, \pm 1, \pm 2, \cdots$

$$a_{UV} = \frac{\theta_{UV} + 2\pi k}{N_c}$$

Monodromy

- There are many saddle point (vacua) parametrized by integer k.

$$a_{UV} = \frac{\theta_{UV} + 2\pi k}{N_c} \qquad k = 0, \pm 1, \pm 2, \cdots$$

- The small Higgs mass can be realized in one of the vacua.

Numerics

- We numerically check the existence of vacuum where Higgs mass is small.
- Choose the form of bulk & brane potentials. (please see our paper for detail).
- Solve the equation of motion w/ ansatz

$$ds^2 = du^2 + e^{2A(u)}\eta_{\mu\nu}dx^\mu dx^\nu, \qquad \varphi = \varphi(u), \qquad a = a(u)$$

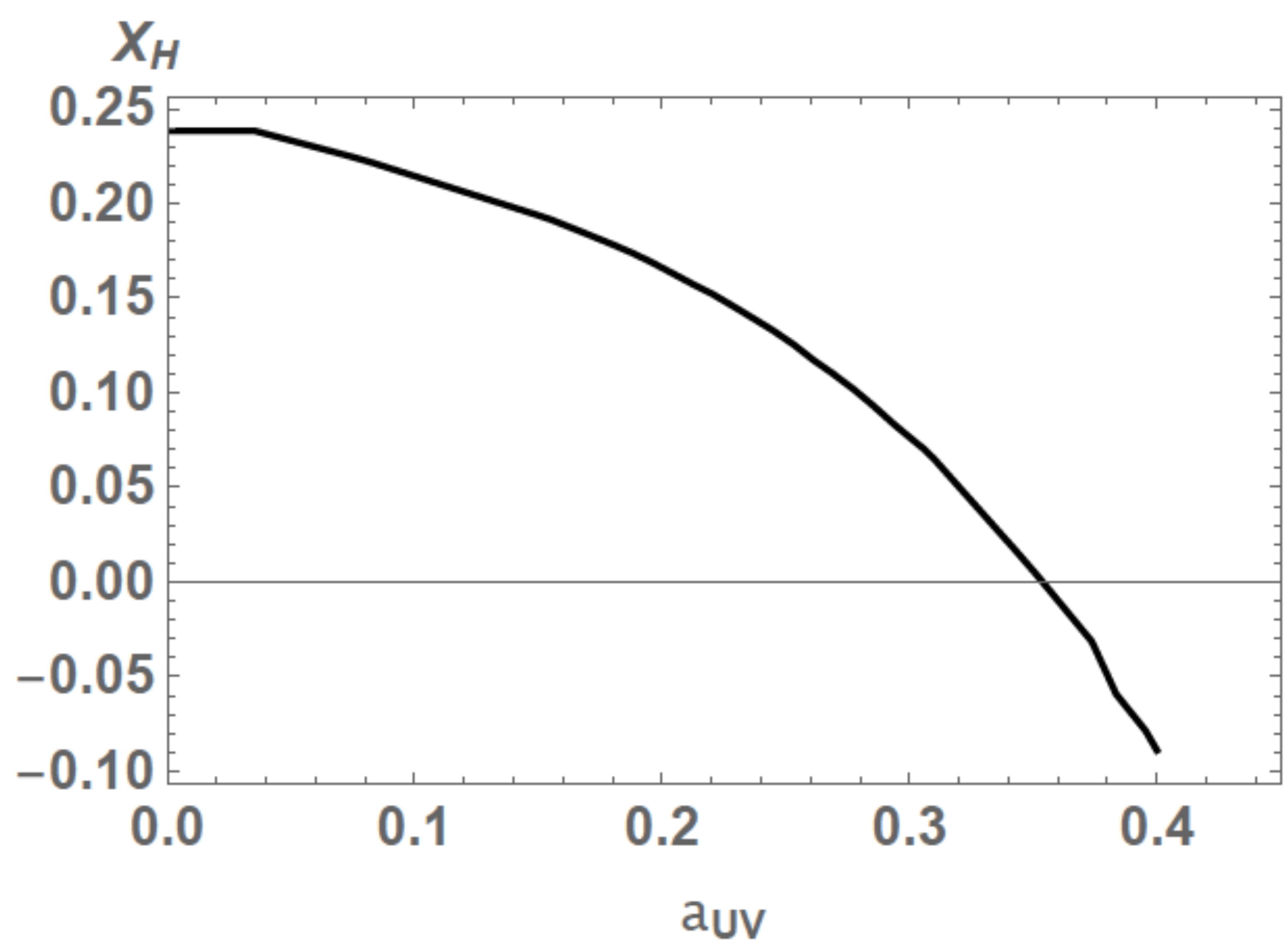
- Israel junction condition at brane position. Regularity condition at IR.
- Only free integration constant is axion source.

[YH-Kiritsis-Nitti-Witkowski, preliminary result]

Numerics

(Higgs mass)²

$$a_{UV} = \frac{\theta_{UV} + 2\pi k}{N_c}$$



Axion source

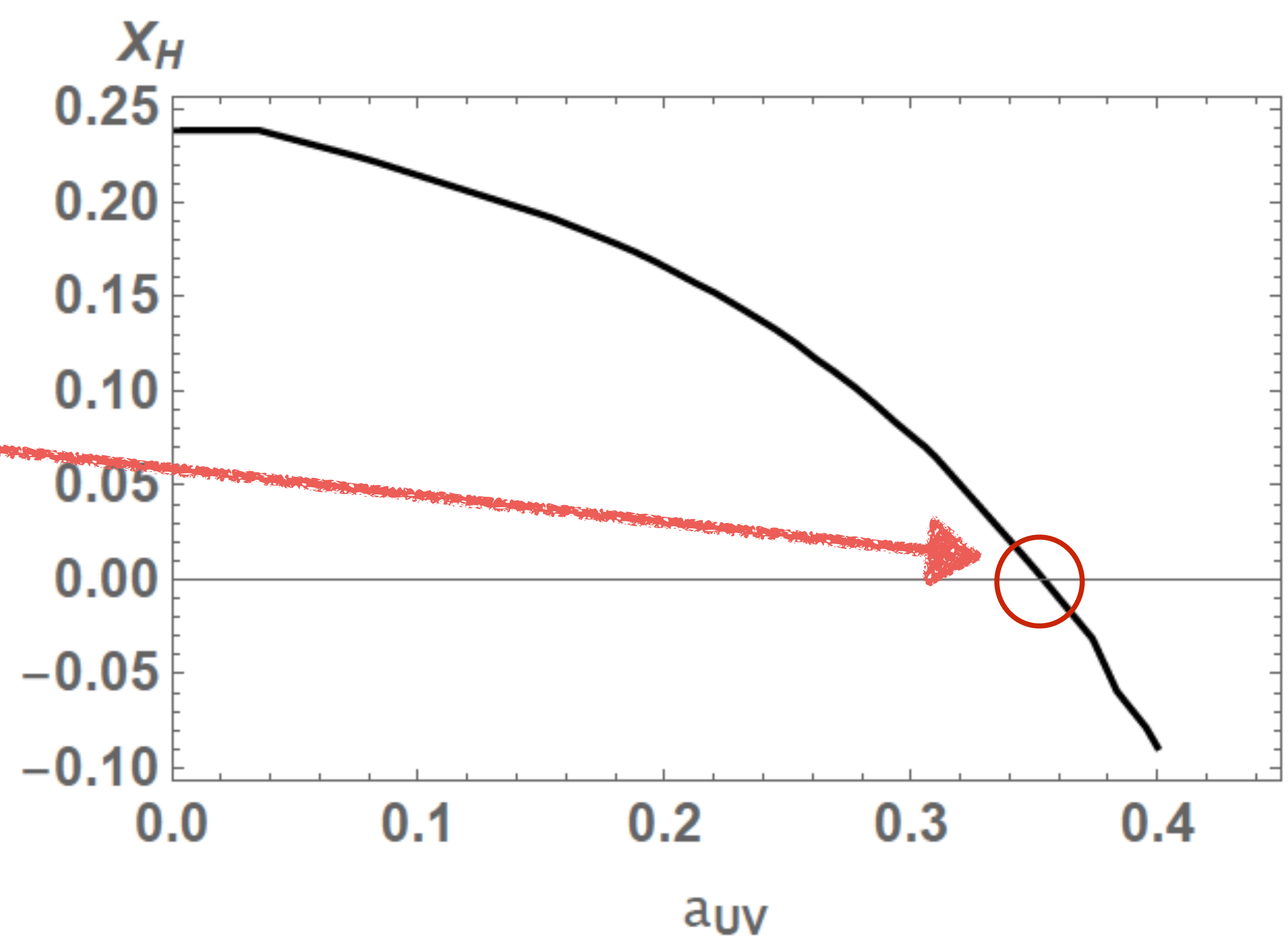
[YH-Kiritsis-Nitti-Witkowski, preliminary result]

Numerics

(Higgs mass)²

$$a_{UV} = \frac{\theta_{UV} + 2\pi k}{N_c}$$

Existence of zero



Axion source

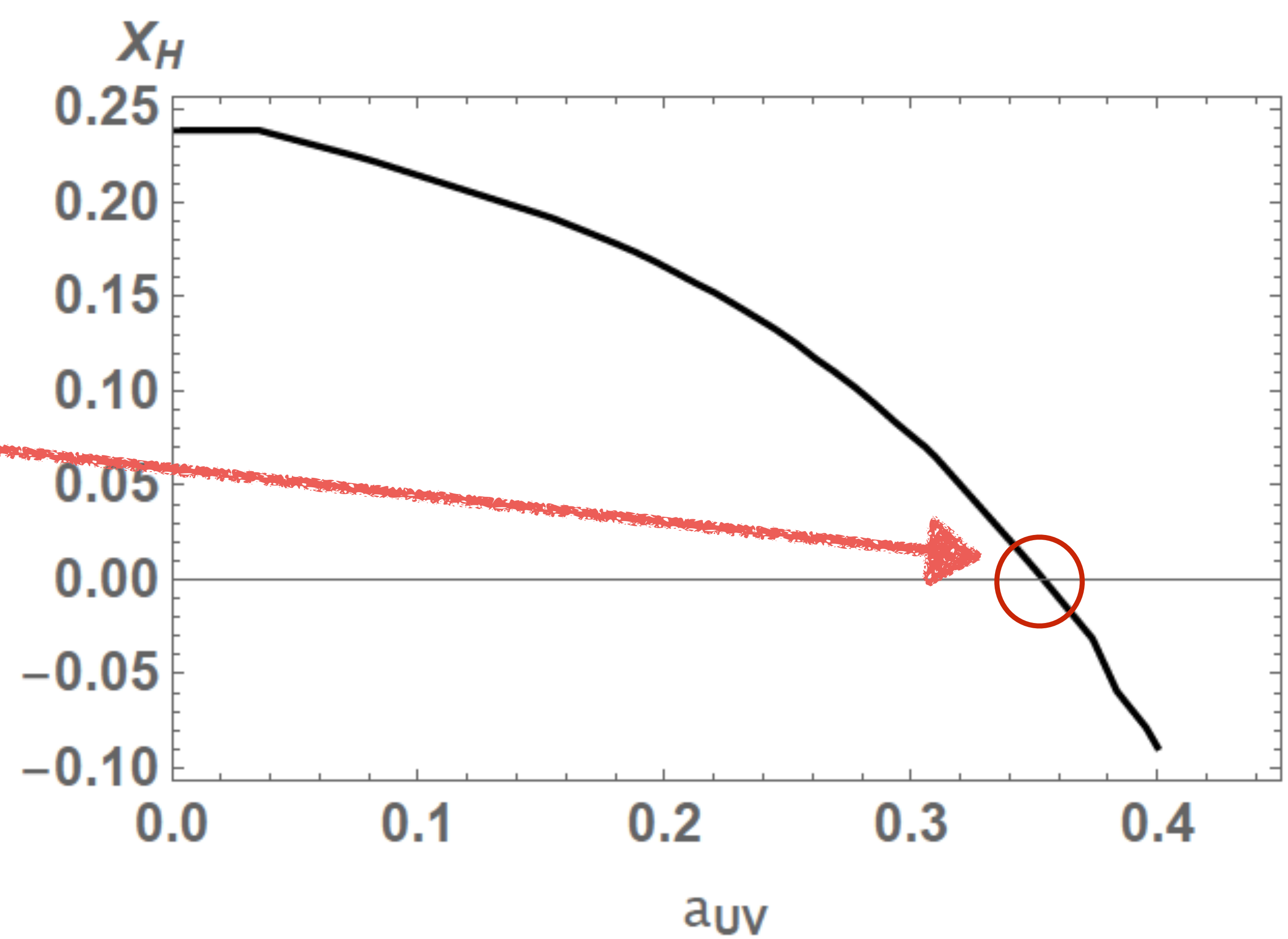
[YH-Kiritsis-Nitti-Witkowski, preliminary result]

Numerics

(Higgs mass)^2

$$a_{UV} = \frac{\theta_{UV} + 2\pi k}{N_c}$$

Existence of zero



Axion source

For given θ_{UV} and large N_c,
we can find the branch k
which realizes the small Higgs mass.

Possibilities

- How the system evolves into the desired vacuum?
- If small Higgs mass saddle is lowest free energy, it is stable vacuum.
- If not, small Higgs mass is realized in metastable vacuum.
  - Cosmological evolution like relaxion case
  - Anthropic principle

Summary

- We investigate fine tuning problems in the brane world setup motivated by holography.
- The solution where the brane is flat exists.
- For fixed θ angle in dual QFT, there are many saddle points in bulk, one of which realizes the small Higgs mass.

Backup

Functions

- Bulk&Brane functions are chosen as

$$S = M_p^{d-1} \int d^{d+1}x\sqrt{-g}\left[R - \frac{1}{2}g^{ab}\partial_a\varphi\partial_b\varphi - \frac{1}{2}Y(\varphi)g^{ab}\partial_a a\partial_b a - V(\varphi)\right] + S_{GHY}$$

$$S_{brane} = M_p^{d-1} \int d^d x\sqrt{-\gamma}\Big[-W_B(\varphi, a) - X_H(\varphi, a)|H|^2 - S_H(\varphi, a)|H|^4 + \cdots\Big]$$

$$W_B = \Lambda^4(-1 - \varphi + e^{\varphi/s}), \quad X_H = \Lambda^2 - \Lambda_a^2 a, \quad S_H = 1$$

$$V = -\frac{1}{\ell^2}\left[d(d-1) + \left(\frac{1}{2}(d - \Delta_-)\Delta_- - b^2 V_\infty\right)\varphi^2 + 4V_\infty \sinh^2\left(\frac{b\varphi}{2}\right)\right], \quad Y = Y_\infty e^{\gamma\varphi}$$

$$\Delta_- = 1.2, \quad d = 4, \quad b = 1.3, \quad \gamma = 1.5, \quad V_\infty = 1,$$
$$Y_\infty = 1, \quad s = 5, \quad \Lambda = 1, \quad \Lambda_a = 1.7$$