9th Crete Regional Meeting in String Theory 2017

Self-Tuning Of The Cosmological Constant And Holographic RG Flows

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with Jewel Kumar Ghosh, Elias Kiritsis & Francesco Nitti

Motivation

Braneworlds offer a possible solution to the
Cosmological Constant (CC) problem:

- Possible to reconcile a **flat** or **weakly curved** 4d space-time despite a large 4d vacuum energy Λ_4.

- Vacuum energy Λ_4 curves the higher dimensional bulk, while the 4d brane world volume may be flat or weakly curved.

- The setup allows for **self-tuning**: a flat or weakly curved brane world volume may emerge for generic values of Λ_4.

Motivation

Braneworlds offer a possible solution to the
Cosmological Constant (CC) problem:

- **Previous work:**

  [Arkani-Hamed, Dimopoulos, Kaloper and Sundrum '00]
  [Kachru, Schulz, Silverstein '00]
  [Csaki, Erlich, Grojean, Hollowood '00]

- **Here:**

  Work with a semi-holographic model by Kiritsis, Nitti.

  The model has been discussed in the **talk by Francesco Nitti**.

  Self-tuning has been explored in [Charmousis, Kiritsis, Nitti '17]

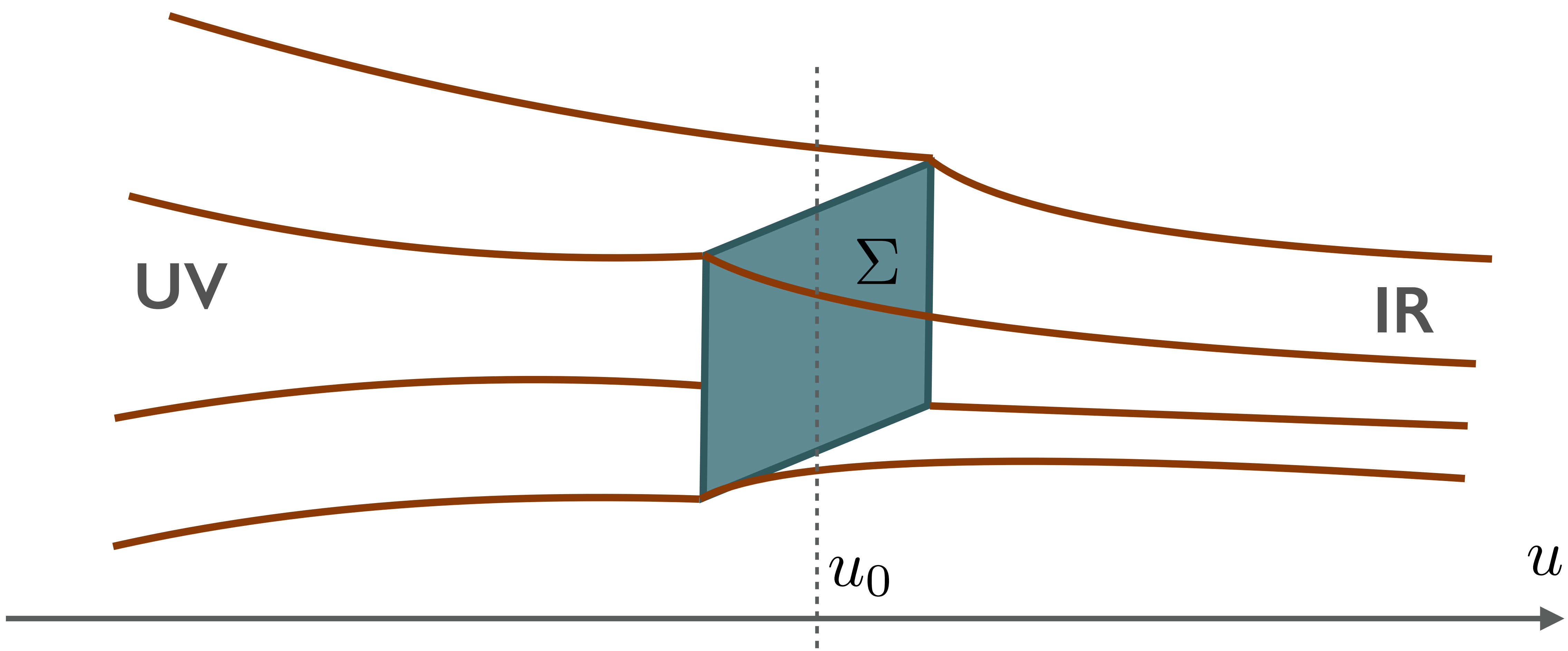
Motivation

5d gravity theory with a bulk scalar

$$S = M^3 \int du \int d^4x \sqrt{-g} \left[R - \frac{1}{2} g^{ab}\partial_a\varphi\partial_b\varphi - V(\varphi)\right] + S_{GH}$$

$$+M^3 \int_\Sigma d^4\sigma \sqrt{-\gamma} \left[-W_B(\varphi) - \frac{1}{2} Z(\varphi)\gamma^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi + U(\varphi)R^{(\gamma)} + \mathcal{L}_{\rm SM}\right]$$

4d QFT on a brane including SM



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Address self-tuning in **increasingly realistic** setups:

1.) Establish self-tuning for a **flat** brane.

2.) Reinstate Higgs sector and study **EW symmetry breaking.**

3.) Establish self tuning for a **curved** brane.

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Address self-tuning in increasingly realistic setups:

1.) Establish self-tuning for a flat brane. ✓

See [Charmousis, Kiritsis, Nitti arXiv:1704.05075] and **talk** by Francesco Nitti

2.) Reinstate Higgs sector and st
EW symmetry breaki

Work in progress

3.) Establish ing for a curved brane.

Outline

1.) Recap:

Review of the setup and self-tuning for a flat brane

2.) Self-tuning of the CC and EW symmetry breaking:

Reinstate the Higgs sector

3.) Self-tuning for a curved brane:

- Allow brane worldvolume to be maximally symmetric curved spacetime (dS, AdS)
- Finding bulk solutions equivalent to studying holographic RG flows for QFTs on curved spacetime.

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Self-tuning: Flat Brane

5d gravity dual of 4d CFT

$$S = M^3 \int du \int d^4x \sqrt{-g} \left[R - \frac{1}{2} g^{ab} \partial_a \varphi \partial_b \varphi - V(\varphi) \right] + S_{GH}$$

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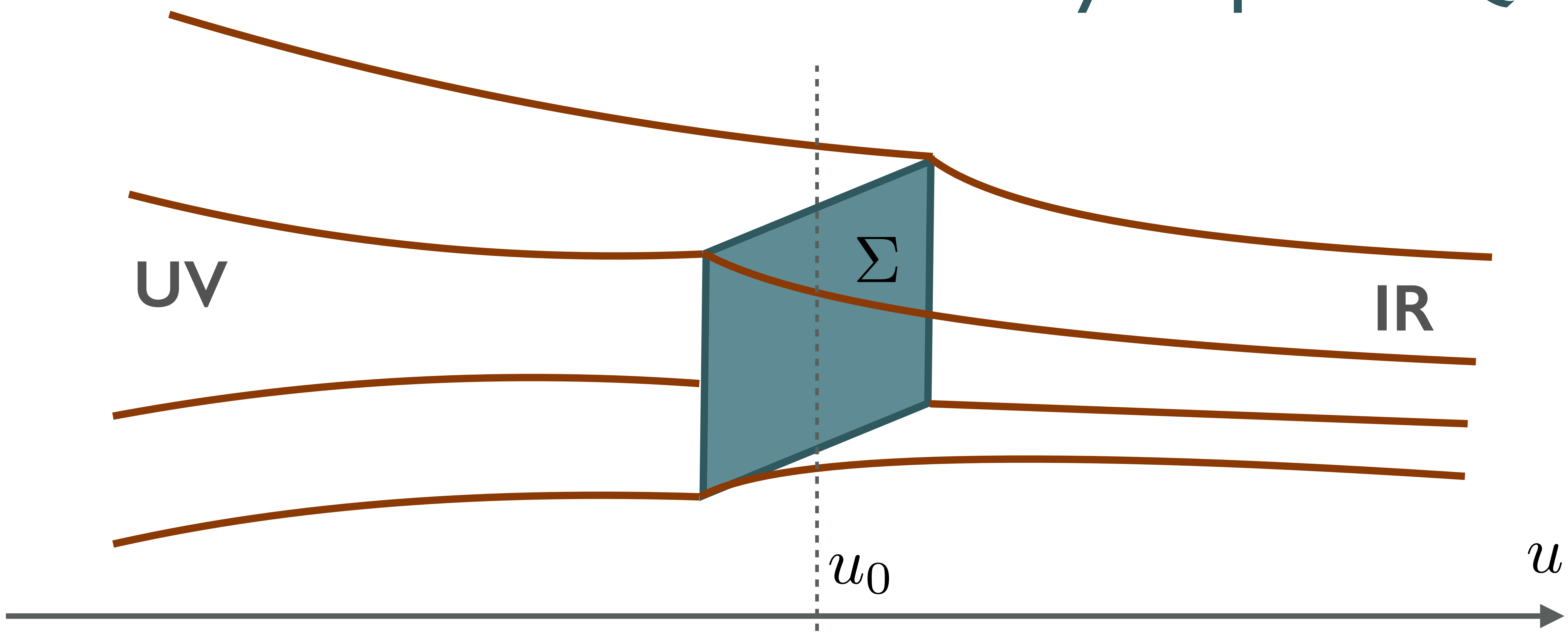
Weakly coupled 4d QFT



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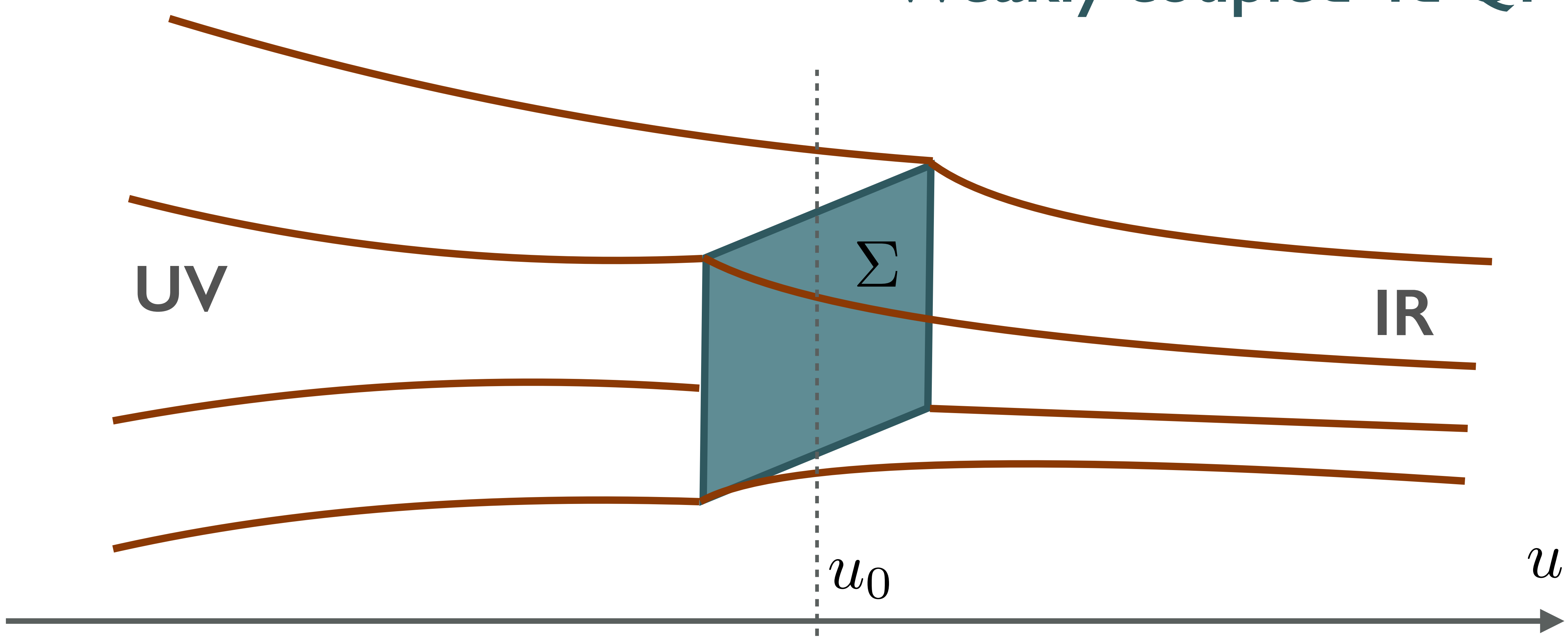

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Ansatz for a flat brane:

- Domain wall metric with flat slices:

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

- Bulk scalar: $\varphi = \varphi(u)$.

The brane is located at a fixed u_0 which corresponds to a fixed $\varphi_0 = \varphi(u_0)$.

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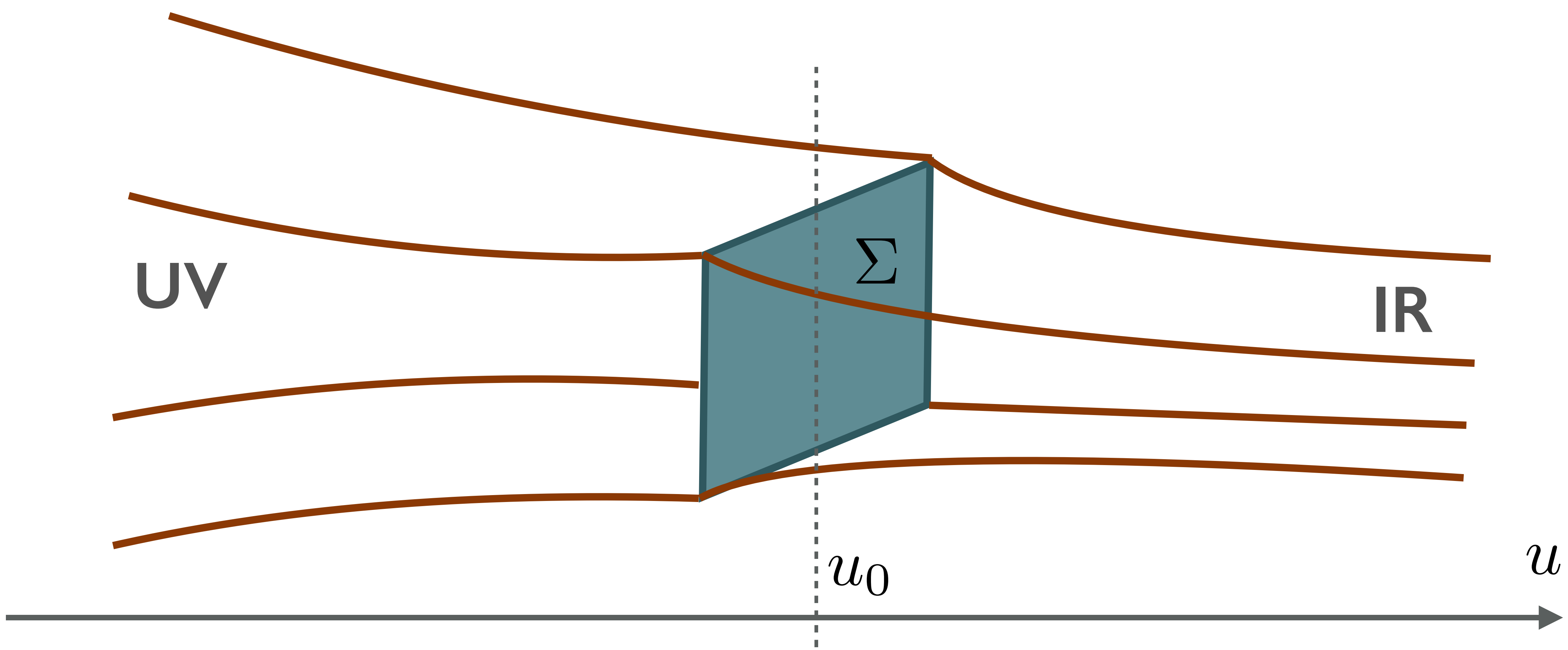
Q: Is there are solution despite $W_B \neq 0$?

Self-tuning: Flat Brane

Strategy:

- Solve for scale factor and bulk scalar in **UV** region.
- Solve for scale factor and bulk scalar in **IR** region.
- Match solutions at brane position via **Israel junction conditions**.



Self-tuning: Flat Brane

Strategy:

- Convenient to define a new variable: the superpotential $W(\varphi)$.

$$W(\varphi(u)) = -2(d-1)\frac{dA}{du}\,,$$

$$\frac{dW}{d\varphi}(\varphi(u)) = \frac{d\varphi}{du}\,.$$

Convention: Bulk spacetime $(d+1)$-dimensional.

Self-tuning: Flat Brane

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$$\frac{dW}{d\varphi}(\varphi(u)) = \frac{d\varphi}{du}\,.$$

- Einstein equations: above definitions together with eq. below:

$$-\frac{d}{4(d-1)}W^2 + \frac{1}{2}\left(\frac{dW}{d\varphi}\right)^2 = V\,.$$

Convention: Bulk spacetime $(d+1)$-dimensional.

Self-tuning: Flat Brane

Self-tuning solution:

- Solve for W_{IR} in IR region. Regularity fixes solution uniquely.
- Solve for W_{UV} in UV region up to an integration constant C_{UV}.
- Apply junction conditions:

$$W_{UV}(\varphi_0) - W_{IR}(\varphi_0) = -W_B(\varphi_0)\,,$$

$$\frac{dW_{UV}}{d\varphi}(\varphi_0) - \frac{dW_{IR}}{d\varphi}(\varphi_0) = -\frac{dW_B}{d\varphi}(\varphi_0)\,.$$

Solving these fixes C_{UV} and the brane position φ_0.

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Self-tuning: both C_{UV} and φ_0 adjust to allow for a **flat brane solution** despite $W_B \neq 0$.

Self-tuning:

Flat Brane + Higgs Sector

Self-tuning: Flat Brane + Higgs Sector

5d gravity dual of 4d CFT

$$S = M^3 \int du \int d^4x \sqrt{-g} \left[R - \frac{1}{2} g^{ab} \partial_a \varphi \partial_b \varphi - V(\varphi) \right] + S_{GH}$$

$$+ M^3 \int_\Sigma d^4\sigma \sqrt{-\gamma}\, \mathcal{L}(\gamma_{\mu\nu}, \varphi, \text{SM fields})$$

Weakly coupled 4d QFT

Let H be the Higgs doublet.

Write down the Higgs sector explicitly.

Self-tuning: Flat Brane + Higgs Sector

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$$\left. - X(\varphi)|H|^2 - Y(\varphi)|H|^4 + P(\varphi) R^{(\gamma)} |H|^2 + \ldots \right]$$

Let H be the Higgs doublet.

Write down the Higgs sector explicitly.

Study how this impacts the self-tuning solution.

Self-tuning: Flat Brane + Higgs Sector

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$$- X(\varphi)|H|^2 - Y(\varphi)|H|^4 + P(\varphi) R^{(\gamma)} |H|^2 + \ldots \Big]$$

The brane action can be written more compactly as:

$$S_b = M^3 \int_\Sigma d^4\sigma \sqrt{-\gamma} \left[-\hat{W}_B(\varphi, |H|) - \frac{1}{2} Z(\varphi) \gamma^{\mu\nu} \partial_\mu \varphi \partial_\nu \varphi + \hat{U}(\varphi, |H|) R^{(\gamma)} + \mathcal{L}_{\rm SM} \right],$$

with $\quad \hat{W}_B(\varphi, |H|) = W_B(\varphi) + X(\varphi)|H|^2 + Y(\varphi)|H|^4 \,,$

and $\quad \hat{U}(\varphi, |H|) = U(\varphi) + P(\varphi)|H|^2 \,.$

Self-tuning: Flat Brane + Higgs Sector

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Again, use ansatz for a flat brane:

- Domain wall metric with flat slices:

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

- Bulk scalar: $\varphi = \varphi(u) \, .$

Self-tuning: Flat Brane + Higgs Sector

Solution:

- Solve for W_{IR} and W_{UV} in the bulk as before.

- The junction conditions now become:

$$W_{UV}(\varphi_0) - W_{IR}(\varphi_0) = -\hat{W}_B(\varphi_0, |H|)\,,$$

$$\frac{dW_{UV}}{d\varphi}(\varphi_0) - \frac{dW_{IR}}{d\varphi}(\varphi_0) = -\frac{d\hat{W}_B}{d\varphi}(\varphi_0, |H|)\,.$$

- In addition, varying w.r.t. the Higgs gives:

$$\left[X(\varphi_0) + 2Y(\varphi_0)|H|^2\right] H = 0\,.$$

Self-tuning: Flat Brane + Higgs Sector

EW symmetry breaking:

- Solve for C_{UV}, φ_0, $|H|$.
- Have successful EW symmetry breaking if $X(\varphi_0) < 0$:

$$\Rightarrow |H|^2 = -\frac{X(\varphi_0)}{2Y(\varphi_0)} \, .$$

- The self-tuning mechanism neutralises any contribution to the vacuum energy due to the Higgs sector.
- Interestingly, in this setup the physics of EW symmetry breaking and the self-tuning of the CC are intertwined.

Self-tuning: Flat Brane + Higgs Sector

Open questions:

- For EW symmetry breaking it is important that $X(\varphi)$ can become negative. Need to understand the microscopic origin of $X(\varphi)$ to check whether this can occur.

- What about the EW hierarchy problem?
  Can the solution reproduce the observed value of the Higgs vev? I.e. does this setup generate a hierarchy between the Higgs vev and the Planck scale and / or the cutoff?

$$|H|^2 = -\frac{X(\varphi_0)}{2Y(\varphi_0)} \, .$$

Self-tuning:

Curved Brane

&

Holographic RG Flows

Self-tuning: Curved Brane

So far: only considered metric ansatz with **flat slicing**:

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

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So far: only considered metric ansatz with **flat slicing**:

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Now: allow for **curved slices** with **maximal symmetry**:

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

i.e. $\zeta_{\mu\nu}$ describes a d-dimensional maximally symmetric spacetime:

$$R^{(\zeta)}_{\mu\nu} = \kappa \zeta_{\mu\nu} \, , \quad R^{(\zeta)} = d\kappa \, , \quad \text{and} \quad \kappa = \begin{cases} \frac{(d-1)}{\alpha^2} & \text{dS}_\text{d} \\ 0 & \text{Minkowski} \\ -\frac{(d-1)}{\alpha^2} & \text{AdS}_\text{d} \end{cases}$$

Self-tuning: Curved Slicing

Strategy as before:

- Solve the bulk e.o.m. in the UV and the IR.
- Apply matching conditions at brane locus.

However:

- Note that the bulk e.o.m. are modified compared to the case with flat slicing
- **Ignore** the presence of the **brane** at first and study solutions to the bulk e.o.m. first.

Self-tuning: Curved Slicing

$$S = \quad M^3 \int du \int d^dx \sqrt{-g} \left[R - \frac{1}{2} g^{ab} \partial_a \varphi \partial_b \varphi - V(\varphi) \right] + S_{GH} \, ,$$

subject to $\quad \varphi = \varphi(u) \quad$ and $\quad ds^2 = du^2 + e^{2A(u)} \zeta_{\mu\nu} dx^\mu dx^\nu \, ,$

Closely related to study of Holographic RG flows for field theories on **curved manifolds.**

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Closely related to study of Holographic RG flows for field theories on **curved manifolds.**

- The bulk scalar φ will be dual to a scalar operator $\mathcal{O}$.
- The solution $\varphi(u)$ is interpreted as the running coupling.
- Given a solution $A(u), \varphi(u)$ the beta function is: $\beta = \dfrac{d\varphi}{dA}$.
- The space of solutions to $A(u), \varphi(u)$ will be in one-to-one correspondence with the space of possible RG-flows.

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Closely related to study of Holographic RG flows for field theories on **curved manifolds.**

Here:

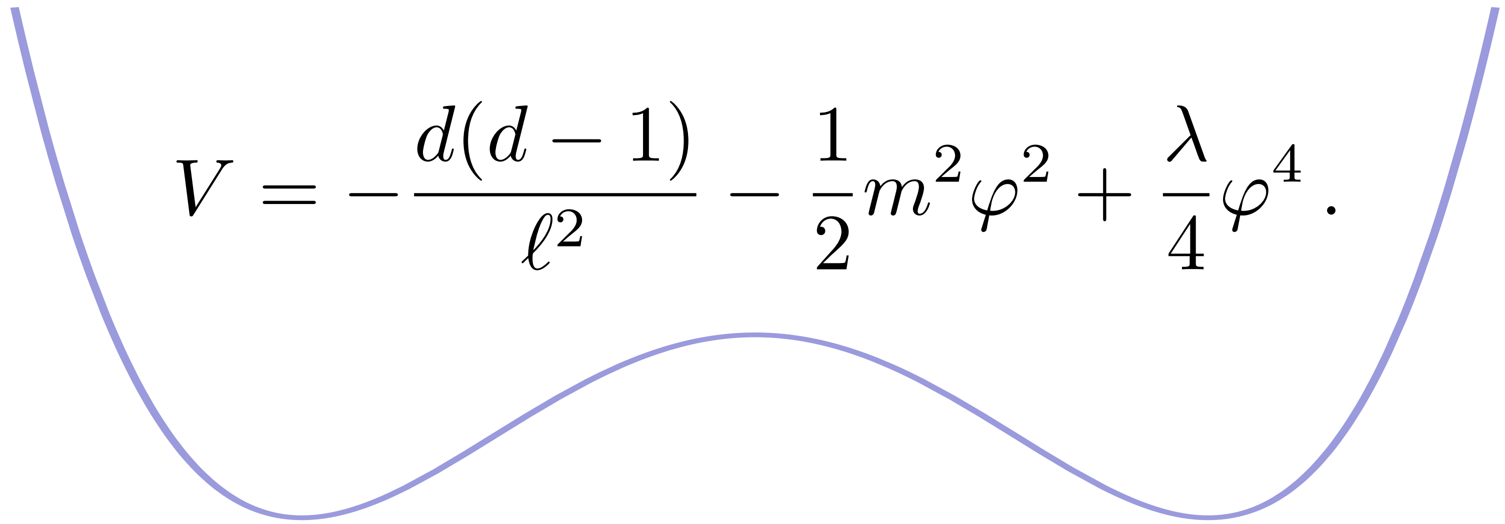
- Consider negative potentials only $V < 0$.
- We will consider asymptotically $AdS_{(d+1)}$ solutions.
- Hence we will study RG flows for CFTs deformed by a relevant operator, defined on a maximally symmetric curved manifold.

Holographic RG Flows

Use an example to illustrate our results:

- Let

$$V = -\frac{d(d-1)}{\ell^2} - \frac{1}{2}m^2\varphi^2 + \frac{\lambda}{4}\varphi^4\,.$$



- Restrict focus on **dS$_d$ slicings only**, i.e. $\zeta_{\mu\nu}$ is a metric on dS$_d$.

- WLOG we choose u to increase along a flow.
  Can also choose $A(u)$ to be monotonically decreasing along the flow.

Holographic RG Flows

To make contact with literature on holographic RG flows rewrite the e.o.m. as coupled 1st order differential equations:

- Define "superpotentials":

$$W(\varphi(u)) = -2(d-1)\dot{A}(u)\,,$$
$$S(\varphi(u)) = \dot{\varphi}(u)\,,$$
$$T(\varphi(u)) = R^{\zeta} e^{-2A(u)}\,.$$

$$\dot{} \equiv \frac{d}{du}\,, \qquad {}' \equiv \frac{d}{d\varphi}\,.$$

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\end{aligned}
$$

- E.o.m.:

$$
\begin{aligned}
2(d-1)\ddot{A} + \dot{\varphi}^2 + \frac{2}{d} e^{-2A} R^{(\zeta)} &= 0\,, \\
d(d-1)\dot{A}^2 - \frac{1}{2}\dot{\varphi}^2 + V - e^{-2A} R^{(\zeta)} &= 0\,, \\
\ddot{\varphi} + d\dot{A}\dot{\varphi} - V' &= 0\,.
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- E.o.m.:

$$S^2 - SW' + \frac{2}{d}T = 0\,,$$
$$\frac{d}{2(d-1)}W^2 - S^2 - 2T + 2V = 0\,,$$
$$S' - \frac{d}{2(d-1)}SW - V' = 0\,.$$

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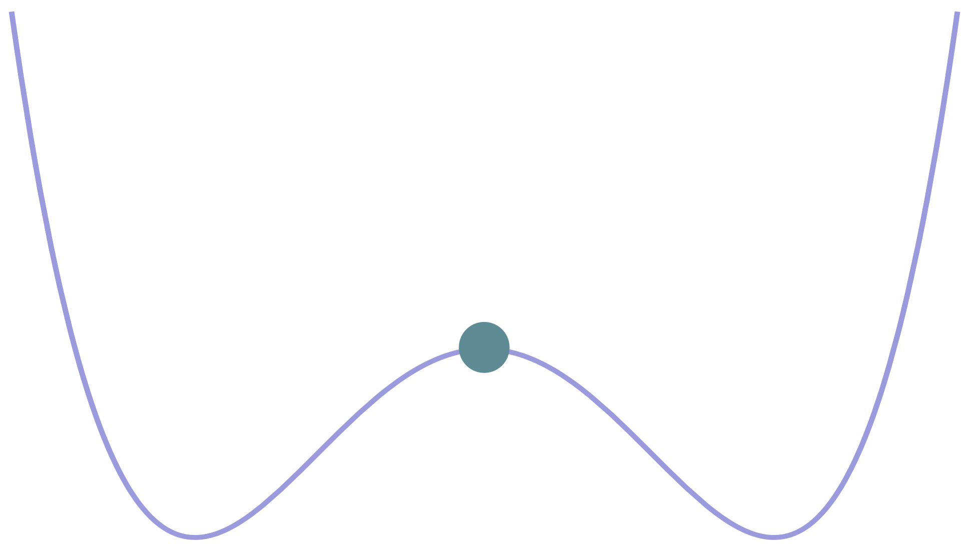
Holographic RG Flows

Extrema of the potential: **Maxima**



- **Maxima** will correspond to **UV fixed** points.
- Scale factor $e^{A(u)}$ diverges there.
- The bulk geometry will asymptote to **AdS$_{(d+1)}$**.
- Each maximum allows for a family of solutions, parameterised by two constants C and $\mathcal{R}$.

Holographic RG Flows

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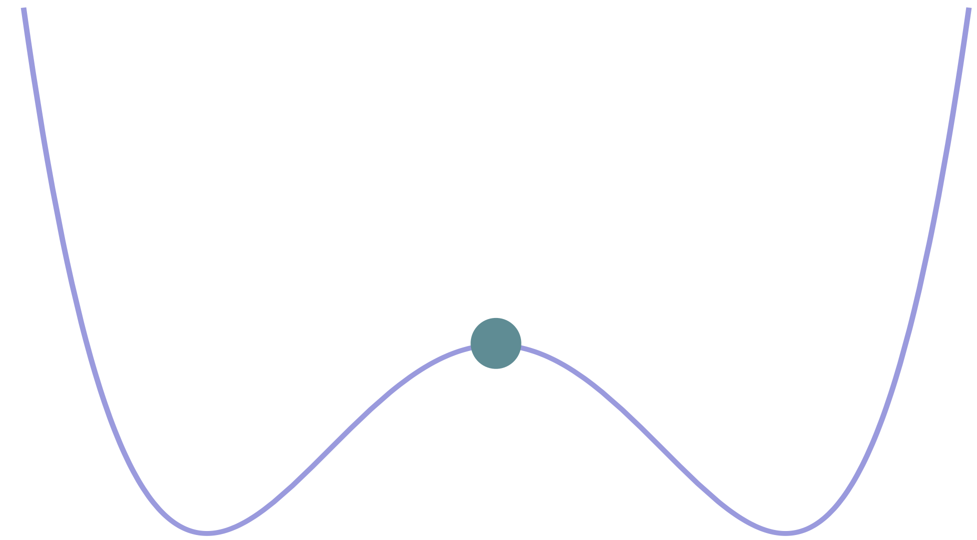

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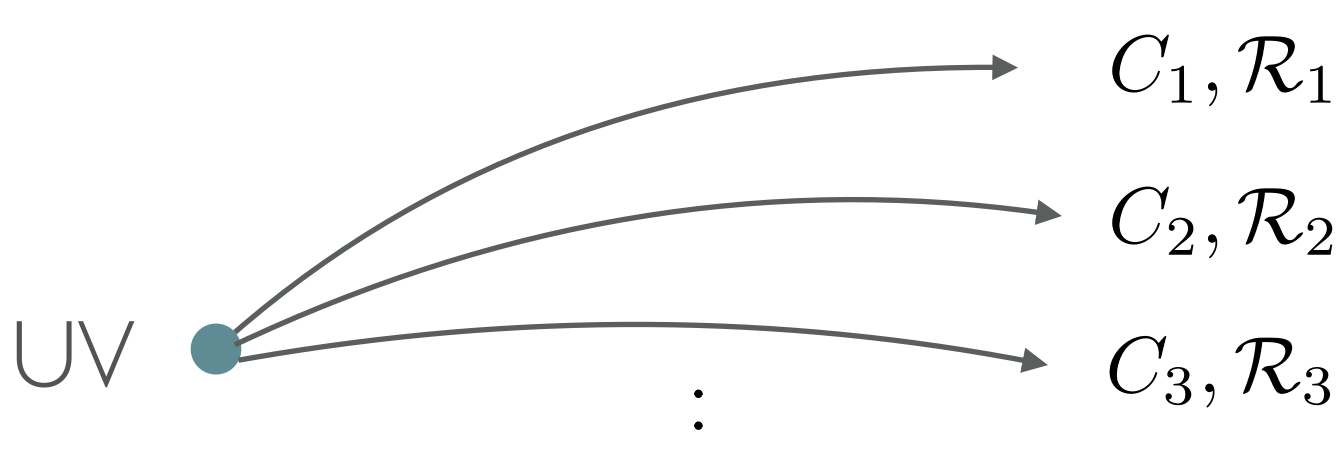


Holographic RG Flows

Extrema of the potential: **Maxima**

$$\Delta_\pm = \frac{d}{2} \pm \sqrt{\frac{d^2}{4} - m^2\ell^2}$$

- In the vicinity of the UV fixed point $u \to -\infty$ the solutions for $\varphi(u)$ and the metric become:

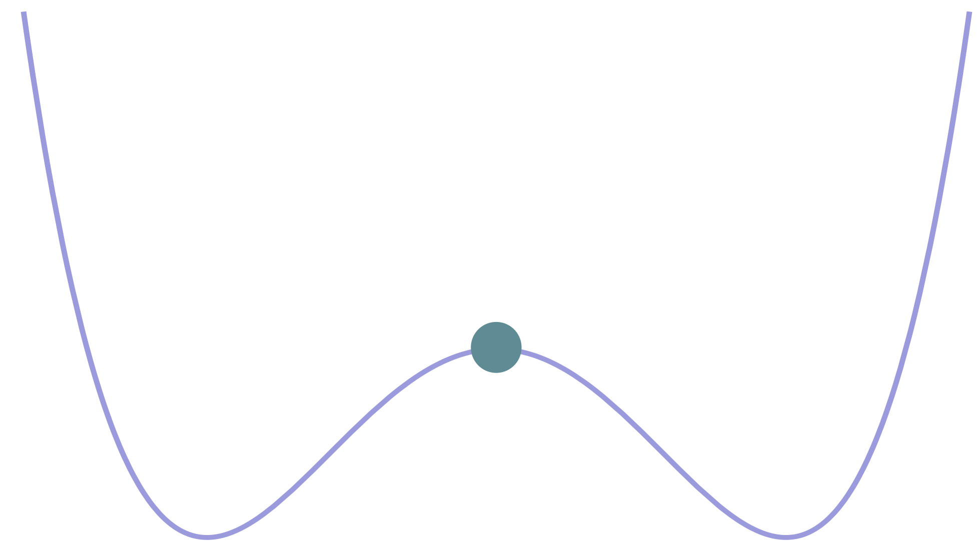
$$\varphi(u) \underset{u\to-\infty}{=} \varphi_- e^{\Delta_- u/\ell} + \frac{\langle \mathcal{O} \rangle}{2\Delta_+ - d} e^{\Delta_+ u/\ell},$$

$$ds^2 \underset{u\to-\infty}{=} du^2 + e^{-2u/\ell}\tilde{\gamma}_{\mu\nu} dx^\mu dx^\nu \; .$$

- Given a source φ_-:

VEV: $\langle \mathcal{O} \rangle = \frac{C d\ell}{\Delta_-} \varphi_-^{\Delta_+/\Delta_-}$ Boundary curvature: $R^{\tilde{\gamma}} = \mathcal{R} \varphi_-^{2/\Delta_-}$

Holographic RG Flows



Maxima = UV fixed points

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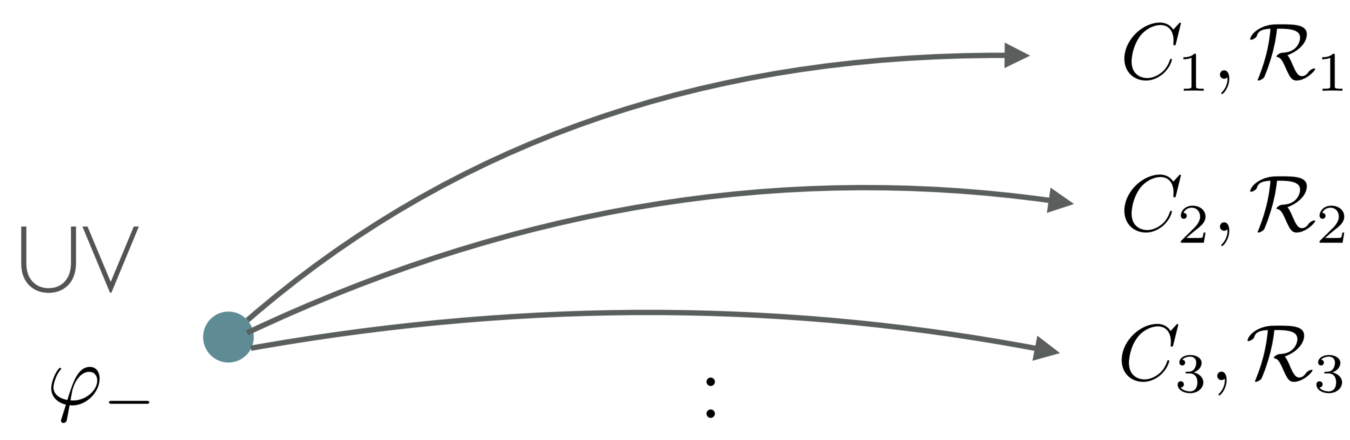

Holographic RG Flows

Where do flows end? What is the IR?

- IR: the scale factor $e^{A(u)}$ vanishes and the flow stops: $\dot{\varphi} = 0$.

1.) Flat slicing: $R^{(\zeta)} = 0$

IR fixed points = minima of the potential.

(Flows to infinity are also allowed if sufficiently well-behaved.)

Only have a finite number of solutions at most.

Holographic RG Flows

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IR fixed points = minima of the potential.

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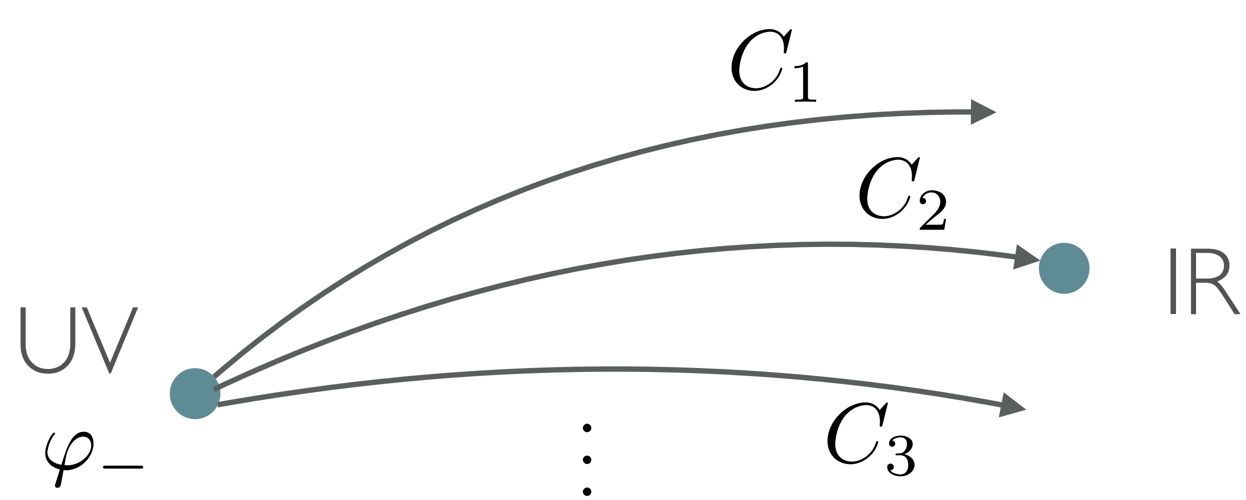
Have a unique solution in IR.



Holographic RG Flows

Where do flows end? What is the IR?

- IR: the scale factor $e^{A(u)}$ vanishes and the flow stops: $\dot{\varphi} = 0$.

1.) Curved slicing: $R^{(\zeta)} \neq 0$

A solution with $e^{A} \to 0$, $\dot{\varphi} \to 0$ exists for every value of φ, as long as $V' \neq 0$ there. Every point φ except extrema of the potential can be an IR.

At an IR point at some $\varphi_\star$ the bulk geometry asymptotes to $AdS_{(d+1)}$ with AdS length ℓ_{IR} given by $V(\varphi_\star) = -\frac{d(d-1)}{\ell_{IR}^2}$.

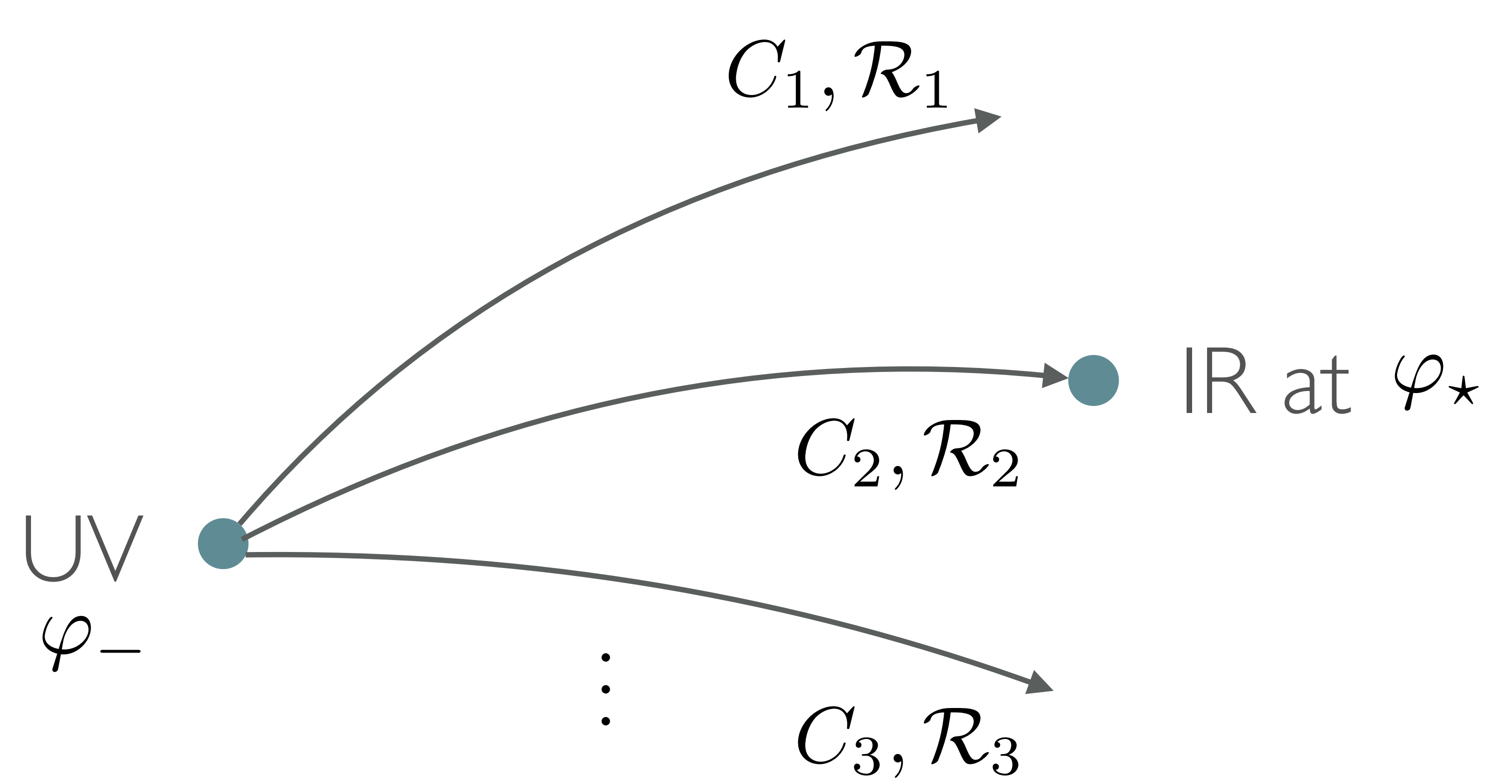
Holographic RG Flows

Where do flows end? What is the IR?

- IR: the scale factor $e^{A(u)}$ vanishes and the flow stops: $\dot{\varphi} = 0$.

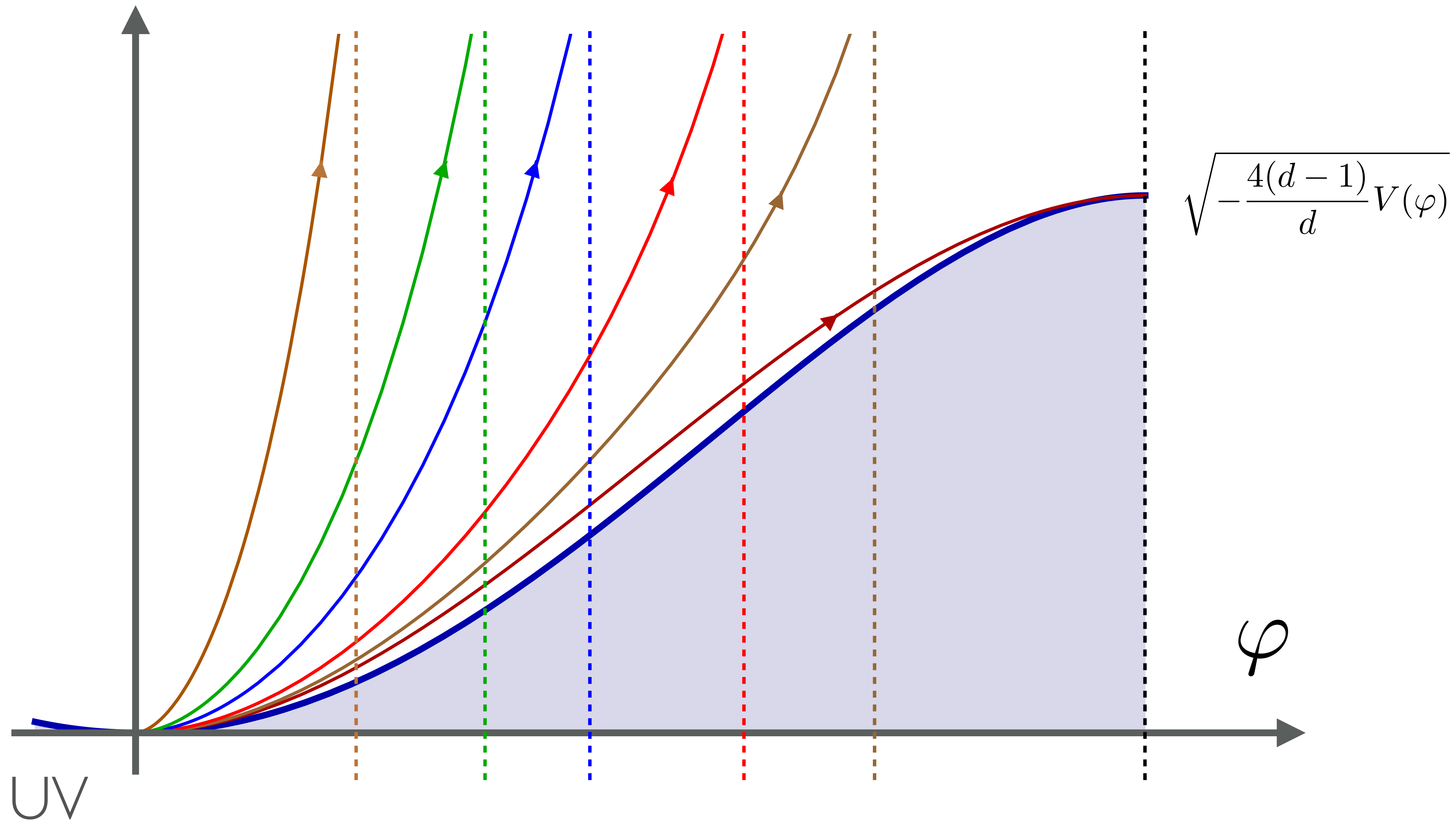
I.) Curved slicing: $R^{(\zeta)} \neq 0$

Again, find a unique solutions per IR.



Holographic RG Flows

Summary: plot $W(\phi)$ vs. φ for various IR points $\varphi_\star$.



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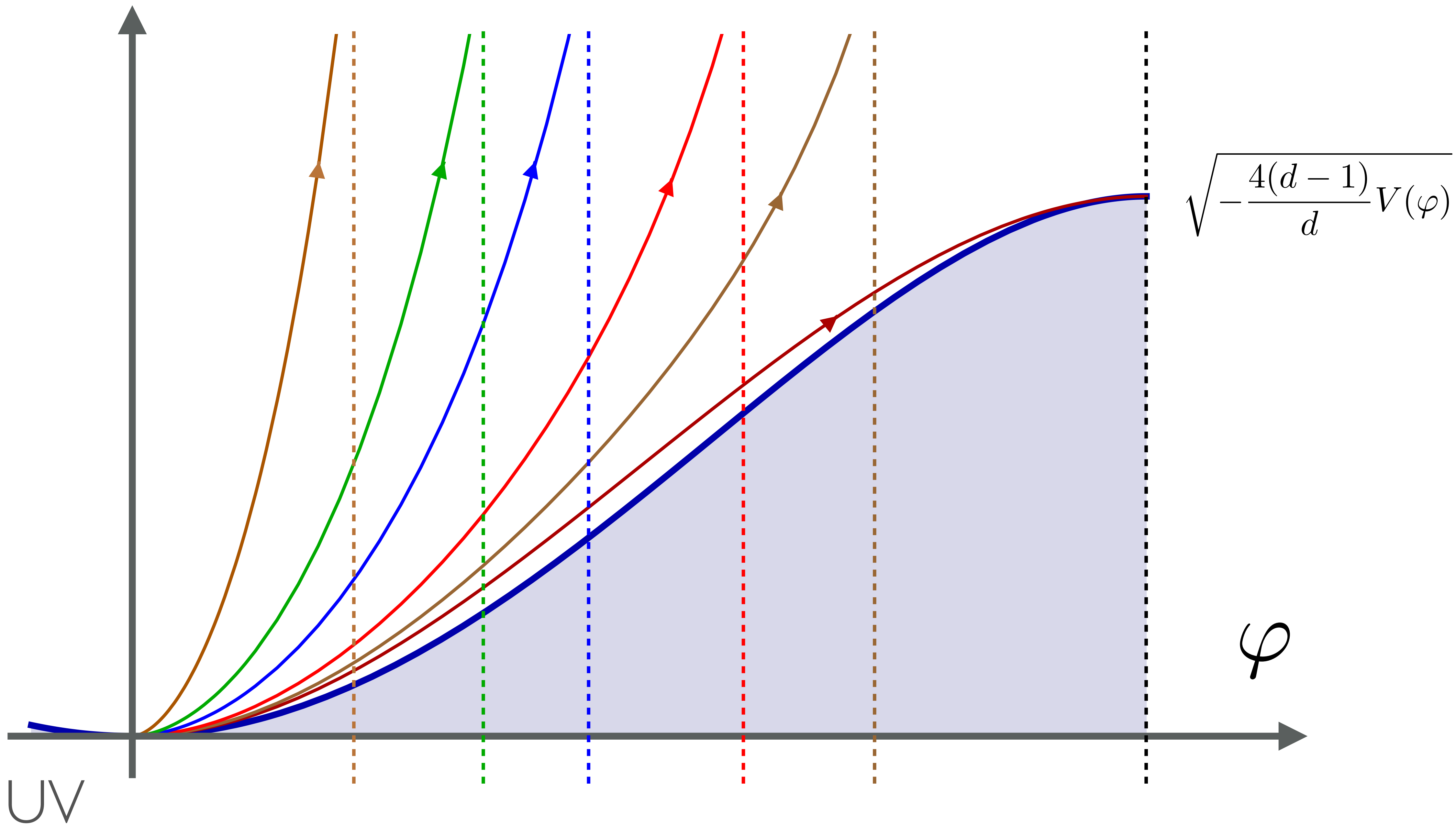

Given: $\varphi_\star$ Solution selects $C, \mathcal{R}$

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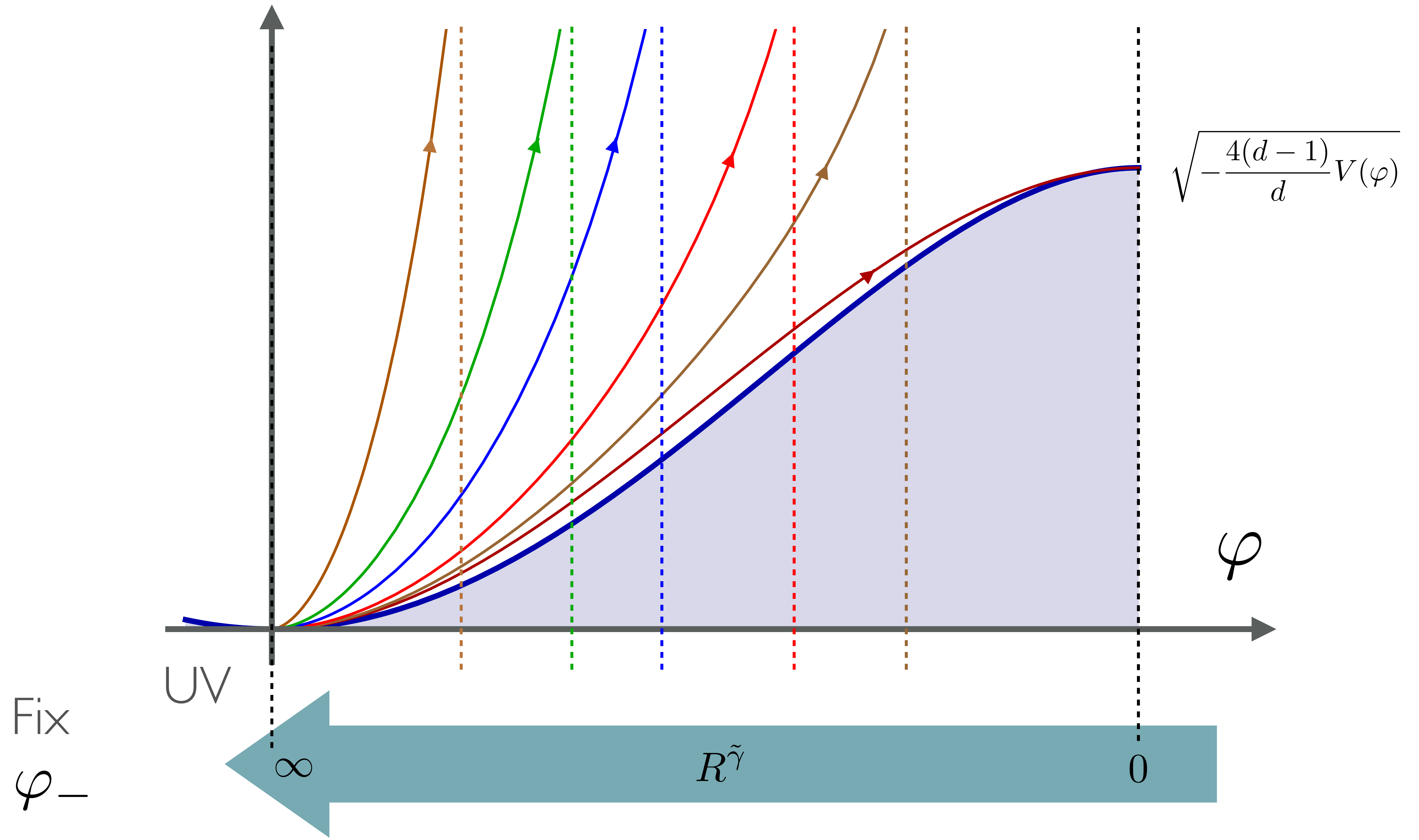

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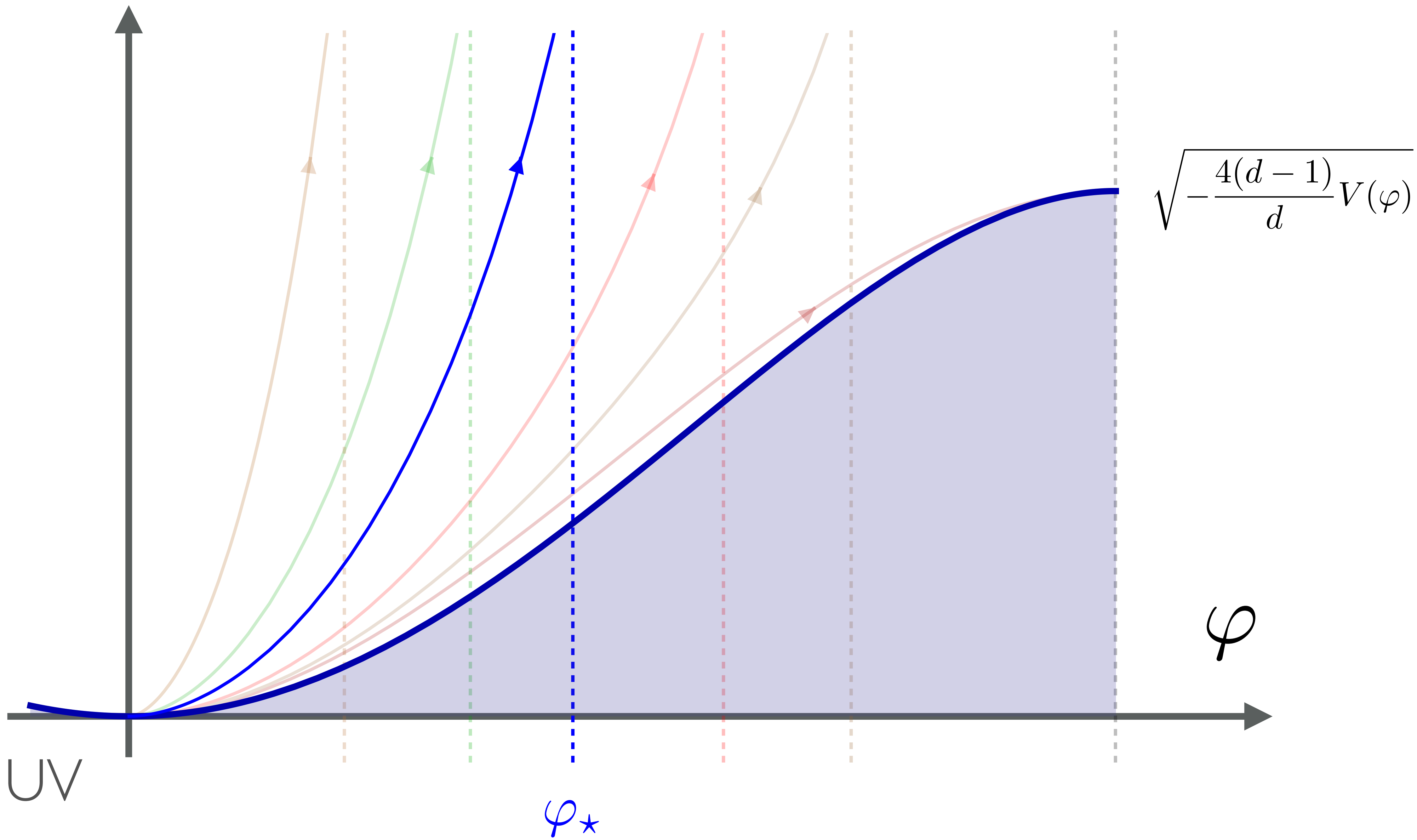

Fix φ_- and $R^{\tilde{\gamma}}$

Solution selects C .

Outlook

Holographic RG flows can exhibit **exotic** phenomena:

→ **Talk by Leandro Silva Pimenta**

- Fixed points can be skipped
- φ can change direction along the flow can reverse (bounce)

These phenomena persist at finite curvature.

→ **Talk by Jewel Kumar Ghosh**

The **F-theorem** is concerned with the change of an appropriately defined function along the RG flow for QFTs on a sphere in d=3.

Test the F-theorem in a holographic setup.

[c.f. M.Taylor, W.Woodhead 2016]

Many Thanks!

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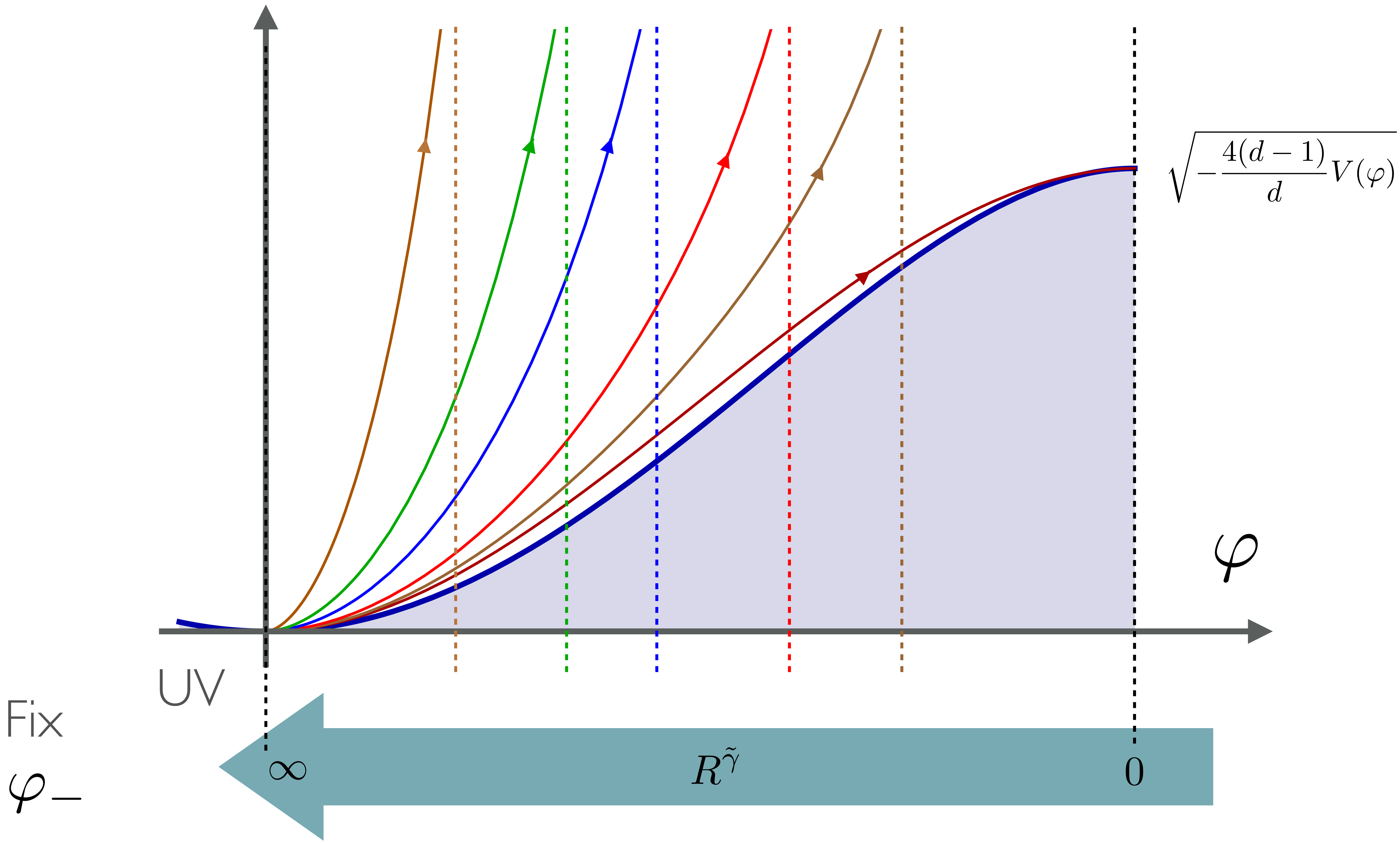

Back-Up: Setup

The model:

Consider a model with a **UV conformal fixed point** including

- a strongly coupled large-*N* CFT, deformed by a relevant operator,
- the weakly coupled Standard Model fields, and
- some heavy messengers with mass scale Λ, coupling the first two.

Integrating out the messengers leaves as an EFT the (broken) CFT coupled to the SM, with some effective couplings set by Λ.

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Semi-holographic description:

Strongly coupled large-*N* CFT ⟷ 5d gravity with metric g_{ab} and bulk scalars φ_i

Weakly coupled SM degrees of freedom have a standard field theoretical description, occupying the worldvolume of a 4d defect (brane).

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