Cosmological Phase Transition of Composite Higgs Confinement

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Introduction

- Composite Higgs models are well motivated as they can generate the large hierarchies observed.
- Higgs can be a confined composite state of strong dynamics at or above the TeV scale.
- Early universe 1^{st} order phase transitions (PT):
  - *Stochastic gravitational wave background from the PT can be observed.*
  - *PT affects baryon and dark matter genesis.*
- Confinement-deconfinement PT
- *Strongly coupled, non-perturbative!*

How to analyze the confinement PT?

Composite Higgs models: nearly conformal, large N

Holography (5D)

- 4D strong coupling → weakly coupled 5D Gravity $(G_N^{5D} \sim \frac{1}{N^2})$
- PT dynamics in 5D EFT control Agashe, Du, M.E., Kumar, Sundrum 2020

Spontaneous confinement (4D)

- Deconfined theory approximately scale invariant
- Confinement breaks scale invariance, but spontaneously
- Corresponding pNGB is dilaton
- Dynamics of dilaton dominates the PT in some regime

Spontaneous Confinement- Dilaton EFT

$$\mathcal{L}(\Lambda_{UV}) = \mathcal{L}_{CFT} + \frac{1}{\Lambda_{UV}^{\epsilon}}\mathcal{O}$$

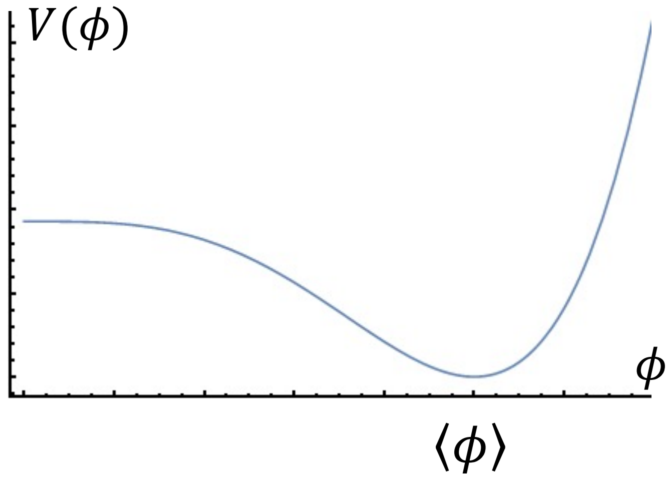
Deform the CFT
$[\mathcal{O}] = 4 + \epsilon$

Dilaton Lagrangian:

$$\mathcal{L}_{dilaton} = \frac{N^2}{16\pi^2}\left((\partial\phi)^2 - \lambda\phi^4\left(1 - \omega\left(\frac{\phi}{\Lambda_{\rm UV}}\right)^{\epsilon}\right)\right)$$

- ϵ parameterizes explicit breaking of scale invariance and sets the hierarchy

$$\ln\frac{M_{\rm Pl}}{\rm TeV} \sim \ln\frac{\Lambda_{\rm UV}}{\langle\phi\rangle} \sim \frac{1}{\epsilon} \sim 30$$



Bubble nucleation rate

- Probability of bubble nucleation per unit 4-volume:

$$\Gamma \sim T^4 e^{-S_{\text{bounce}}}$$

- PT completes if $\Gamma \gtrsim H^4$ $\left(H \sim \frac{T_C^2}{M_{Pl}}\right)$

$$S_{\text{bounce}} \lesssim 4 \ln \frac{M_{Pl}}{T_C} \approx 140$$

- For T close to T_C (thin-wall):

$$S_{\text{bounce}} \gtrsim 40 \frac{N^2}{(\lambda\epsilon)^{3/4}}$$

- Action enhanced by large N and small ϵ

Creminelli, Nicolis & Rattazzi 2002

- PT does not complete near T_C

Beyond the minimal model

- *Is it possible to have a prompt/faster phase transition?*
- In the minimal model the parameter ϵ that is setting the hierarchy (and hence H) suppresses the rate:

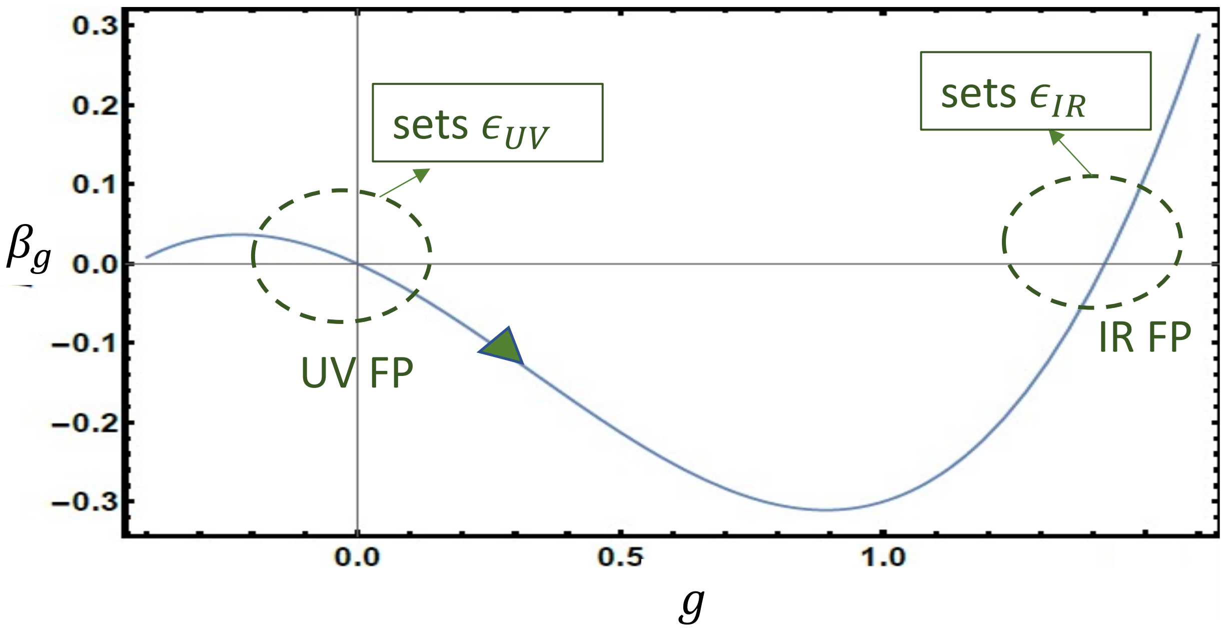
$$S_{\text{bounce}} \sim 40\,\frac{N^2}{\epsilon^{3/4}} > 4\,\ln\frac{M_{Pl}}{\text{TeV}} \sim \frac{4}{\epsilon}$$

- Have a small ϵ in the UV, which becomes (effectively) larger in the IR?

$$S_{\text{bounce}} \sim 40\,\frac{N^2}{\epsilon_{IR}^{3/4}} \overset{?}{<} 4\,\ln\frac{M_{Pl}}{\text{TeV}} \sim \frac{4}{\epsilon_{UV}}$$

Separate fixed points- Faster PT

- RGE with UV and IR fixed points
- ϵ_{UV} and ϵ_{IR} are the anomalous dimensions corresponding to the UV and the IR fixed points.
- Holographic dual: Self-interacting Goldberger-Wise



Agashe, Du, M.E., Kumar, Sundrum 2019

Nucleation rate enhanced if ϵ_{IR} not too small.

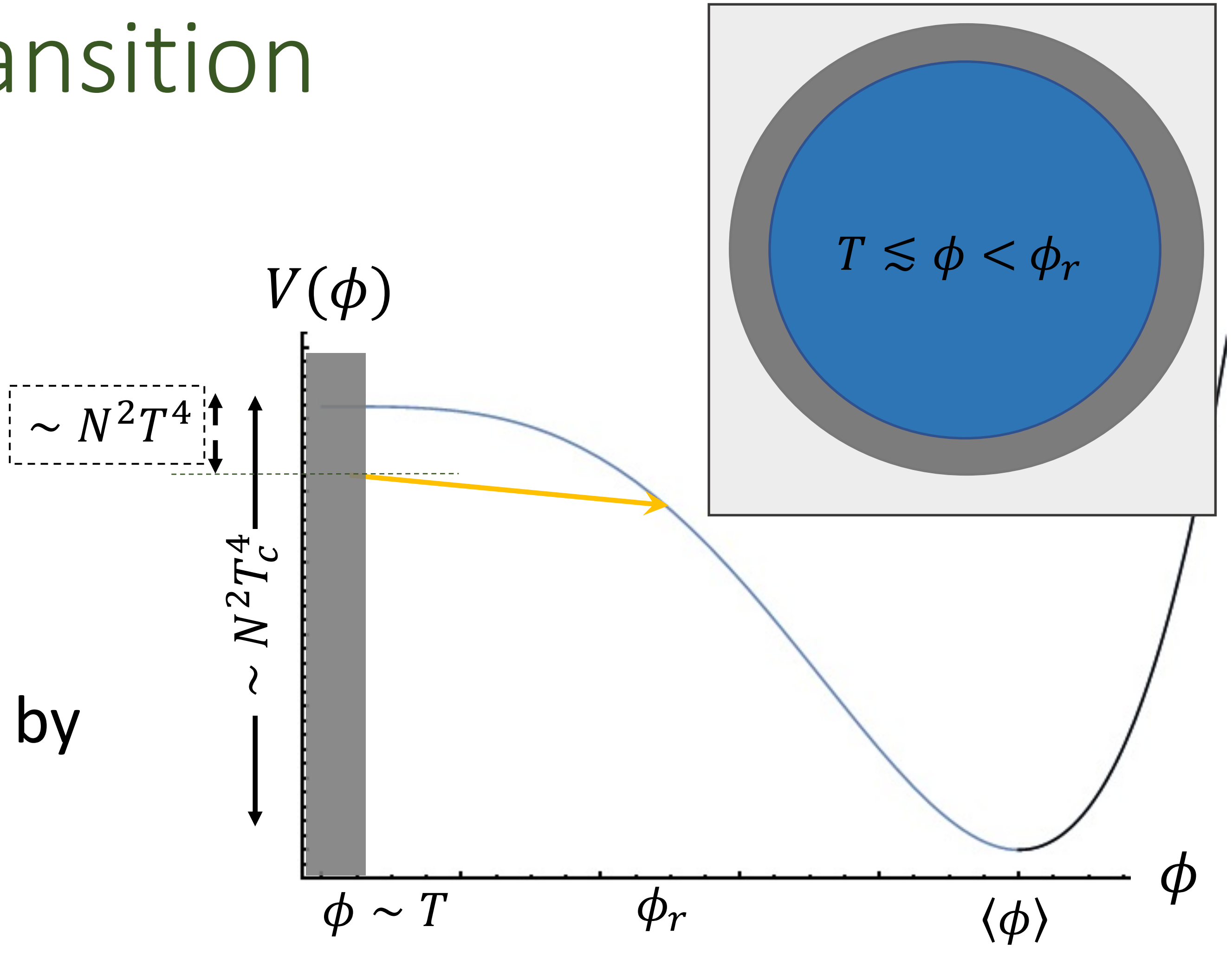
Supercooled phase transition

- For small T/T_C:

$$\left(\ln\frac{T_c}{T} \gtrsim \frac{1}{\epsilon_{IR}}\right) \qquad S_{\text{bounce}} \sim \frac{N^2}{\lambda^{\frac{3}{4}}}$$

No enhancement by small ϵ_{IR}

- A period of inflation: dilution of baryon and DM number densities by a factor of $\sim \left(\frac{T}{T_c}\right)^3$
- Larger $\epsilon_{IR} \rightarrow$ less supercooling.

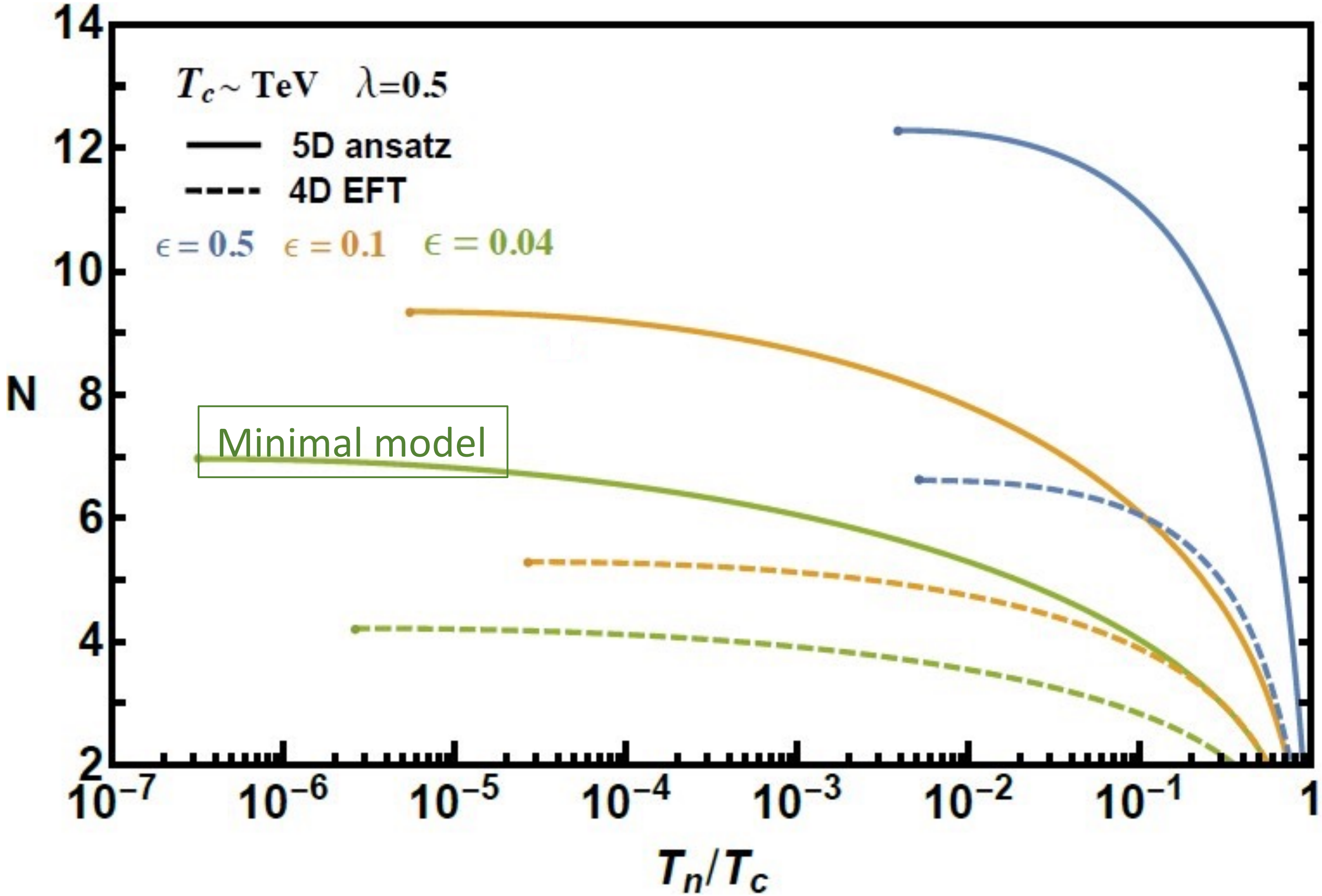


Randall & Servant 2006
Konstandin & Servant 2011

Results

Larger ϵ_{IR}:

- ✓ Less supercooling
- ✓ Less dilution of preexisting matter
- ✓ Larger N allowed to complete the PT



Summary

- Confinement PT of composite Higgs models can be studied using holography (RS) and/or in the scenario of spontaneous confinement .
- Slow PT in the minimal model, leading to empty universe or large supercooling and dilution of (dark) matter.
- Two fixed point model: Separate critical exponents controlling the hierarchies (ϵ_{UV}) and PT dynamics (ϵ_{IR})
- PT can complete without large supercooling, compatible with preexisting baryon asymmetry, and within theoretical control.
- Gravitational wave signal and dilaton mass sensitive to critical exponents.

Thank you!

Extra Slides

Gravitational waves

- Strength and the frequency of gravitational waves from PT depend on a parameter β.
- $1/\beta$ is the duration of the PT: $\frac{\beta}{H} = -\frac{T}{\Gamma}\frac{d\Gamma}{dT}|_{T_n}$

Turner, Weinberg & Widrow 1992
Kosowsky & Turner 1992
Kosowsky, Turner & Watkins 1992

For composite Higgs models:

- S_{b} independent of T in the supercooled limit (result of 4D scale invariance):

$$\frac{\beta}{H} \approx -4 + 3\,\epsilon_{IR}\left(\frac{T_n}{\lambda^{\frac{1}{4}}\langle\phi\rangle}\right)^{\epsilon_{IR}} \ln\left(\frac{M_P}{T_C}\right)$$

Agashe, Du, M.E., Kumar, Sundrum 2019

- Small β_{GW}, for small ϵ_{IR}

Konstandin & Servant 2011

- Strong GW signal

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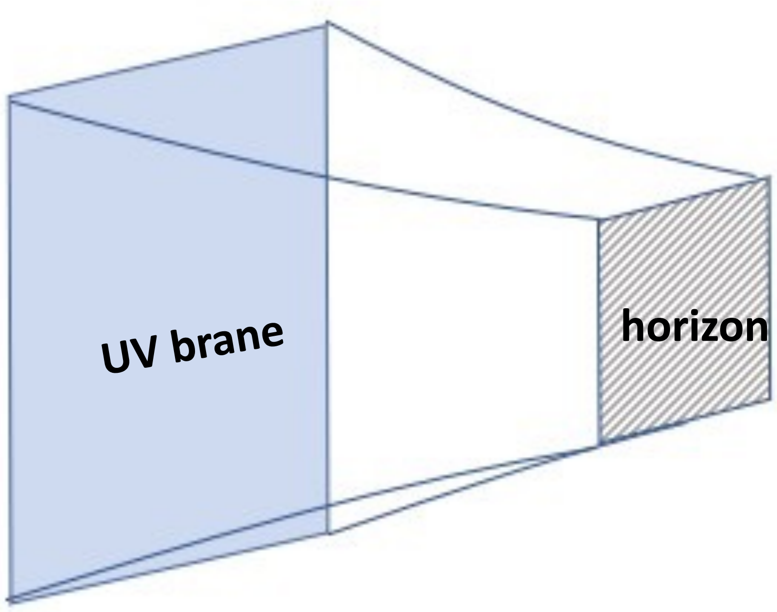
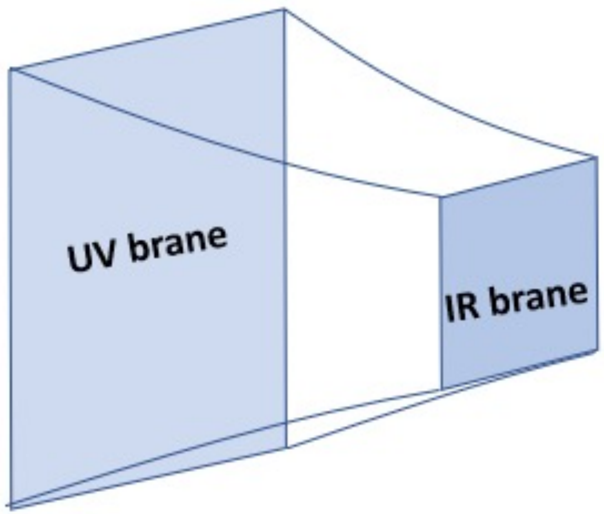
Creminelli, Nicolis & Rattazzi 2002

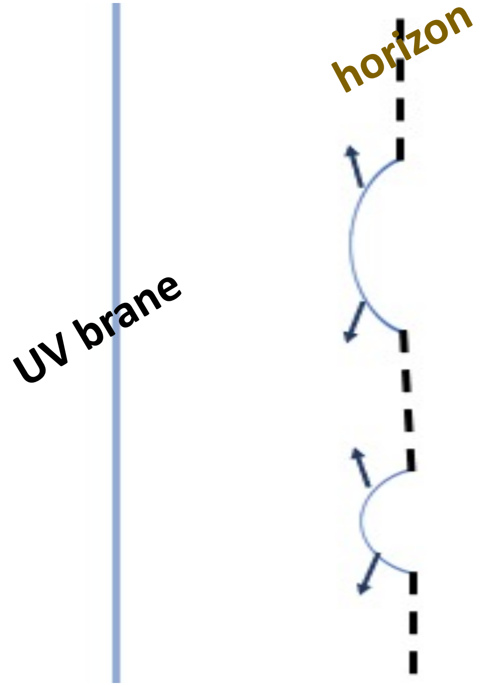
Holography

Black-brane phase → RS1



Tunneling





IR brane emerges from the horizon

(Non-perturbative)
Tunneling rate:

$$\Gamma \sim e^{-1/G_N^{(5D)}} \sim e^{-N^2}$$

Outline

- PT in the minimal model

  (Slow, resulting in empty universe or large supercooling and dilution)

- Faster transition rate? A two fixed point model
- Phenomenology
- Summary

How to analyze the confinement PT?

Composite Higgs models: nearly conformal, large N

Holography (5D)

- Gravity weakly coupled
- PT dynamics in 5D EFT control   Agashe, Du, M.E., Kumar, Sundrum 2020

Spontaneous confinement (4D)

Focus of this talk

- Deconfined theory approximately scale invariant
- Confinement breaks scale invariance, but spontaneously
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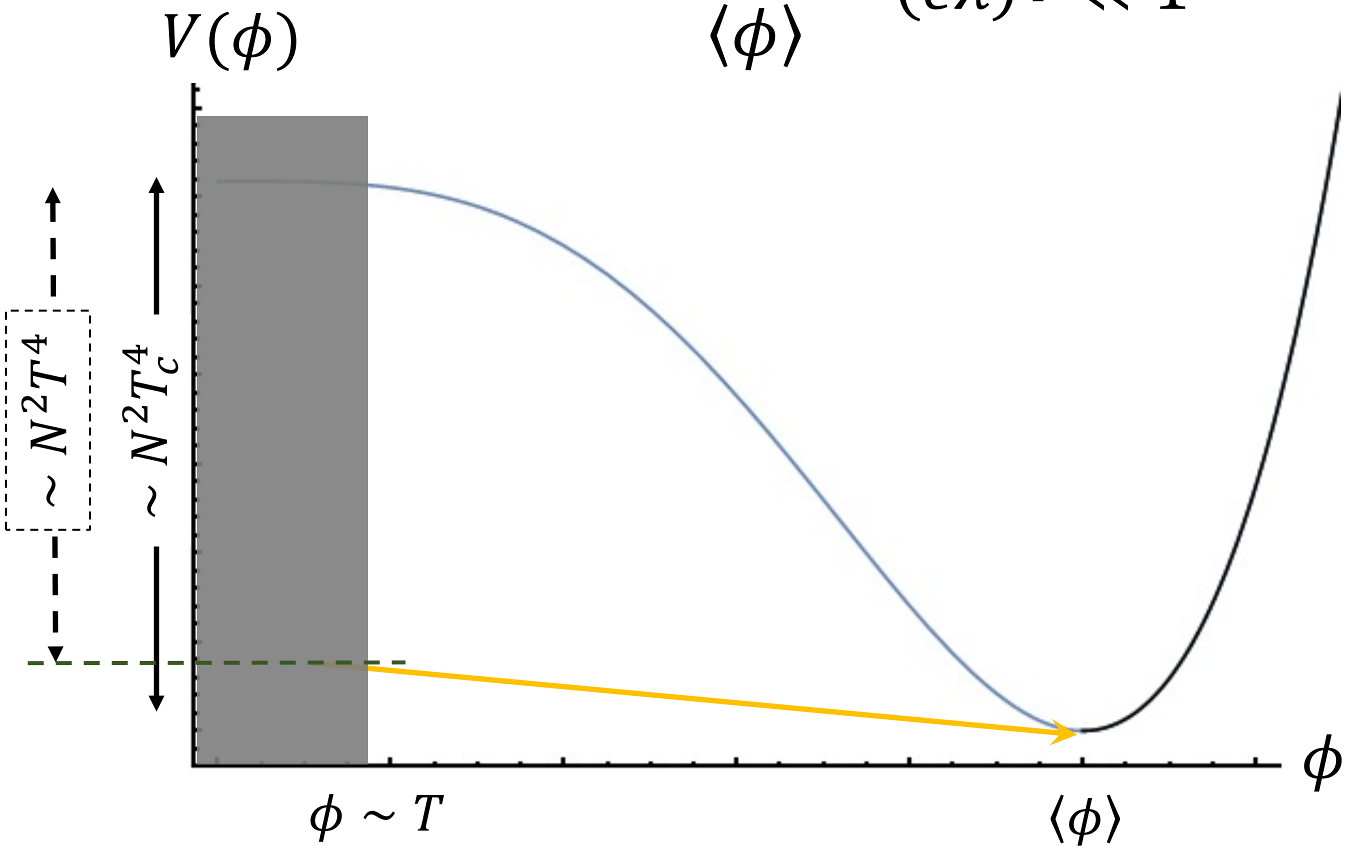
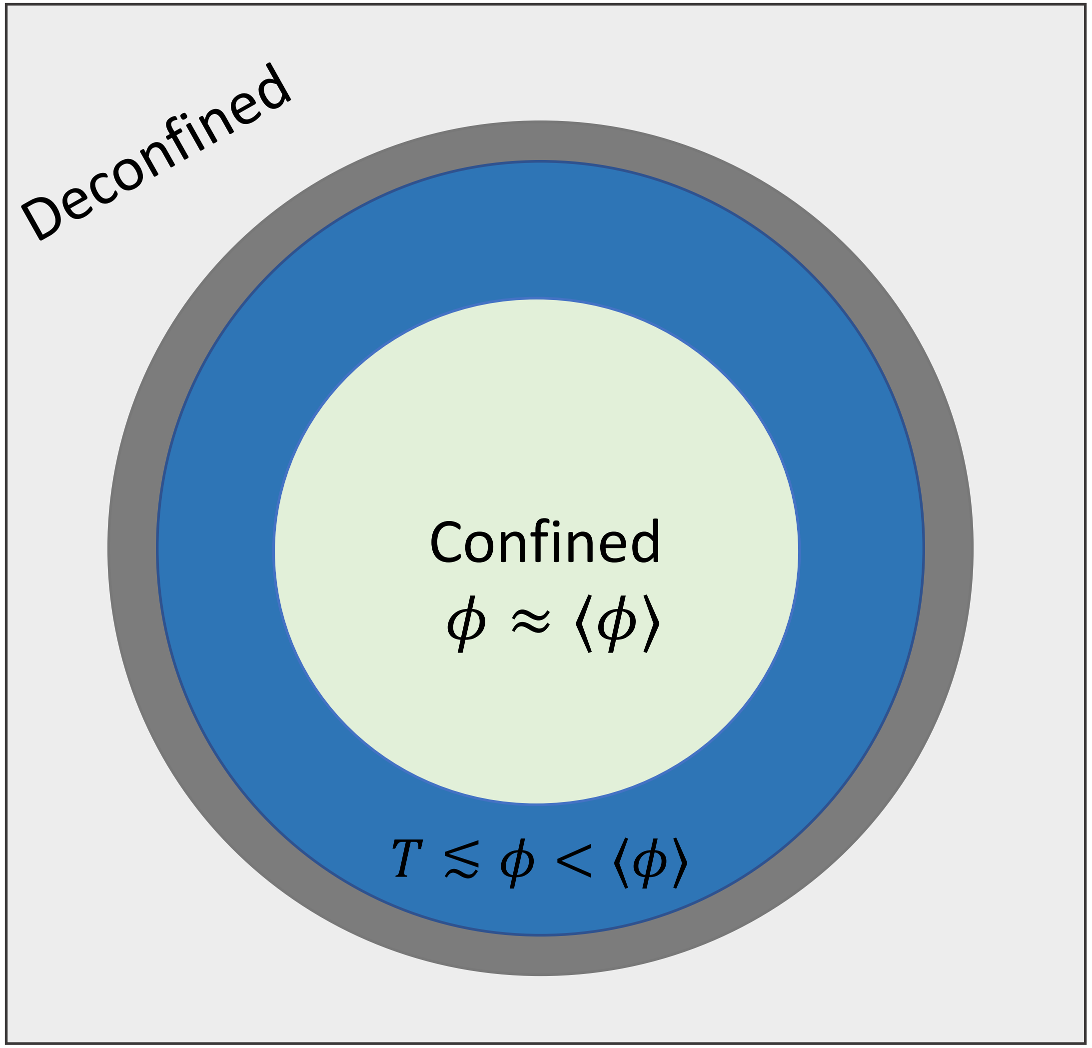
- Dynamics of dilaton dominates the PT in some regime

Bubble Nucleation

$$\frac{T_C}{\langle\phi\rangle} \sim (\epsilon\lambda)^{\frac{1}{4}} \ll 1$$





The (de)confinement PT

- Critical Temperature: $\frac{T_C}{\langle\phi\rangle} \sim (\epsilon\lambda)^{\frac{1}{4}} \ll 1$

Justifies dilaton EFT

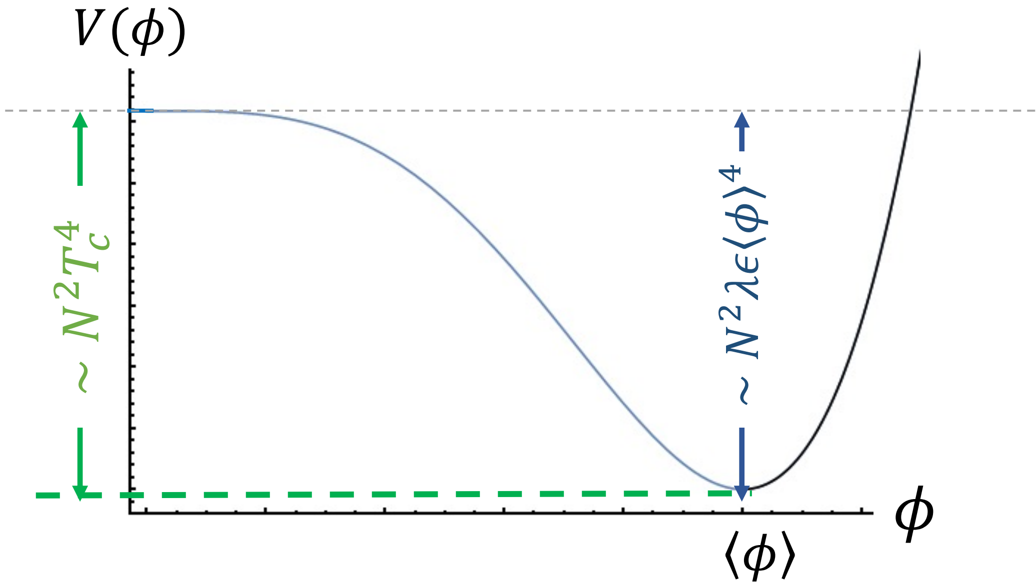
- Typical composites not excited

$$m_{\text{comp}} \sim \langle\phi\rangle \gg T$$

- PT is first order, for small ϵ or λ.

1st order $\Longrightarrow$ bubble nucleation

$$F_{\text{deconfined}} - V(0) \sim -N^2T^4$$



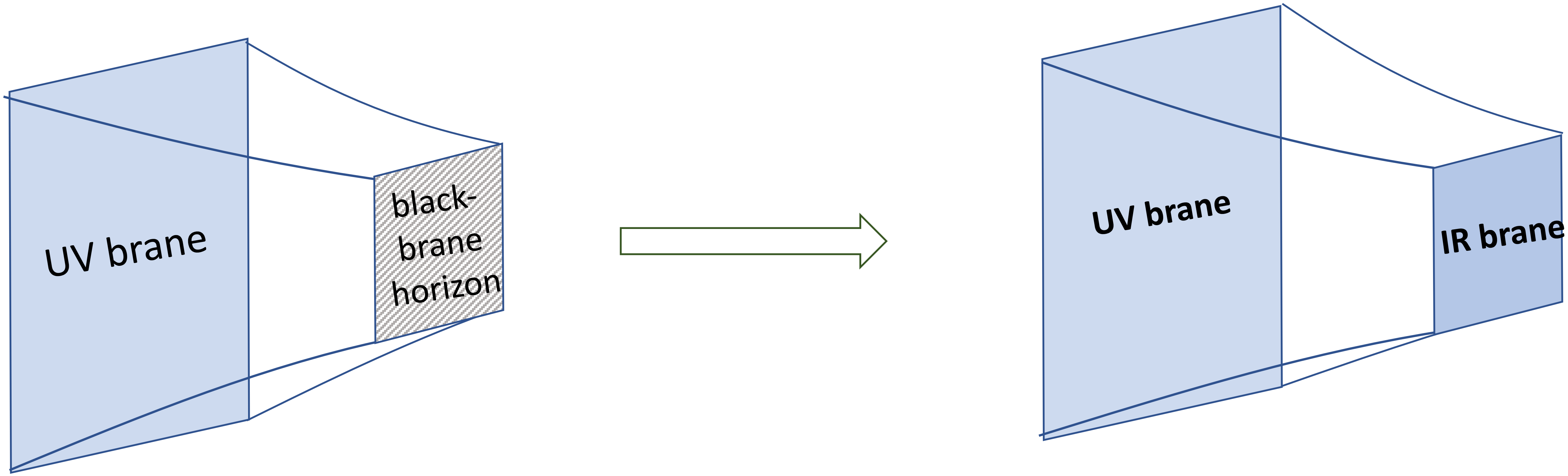
Creminelli, Nicolis & Rattazzi 2002

Holographic dual

Creminelli, Nicolis & Rattazzi 2002

Black-brane phase → RS1

Control parameter: large N, $\frac{N^2}{16\pi^2} = \left(\frac{M_5}{k}\right)^3$

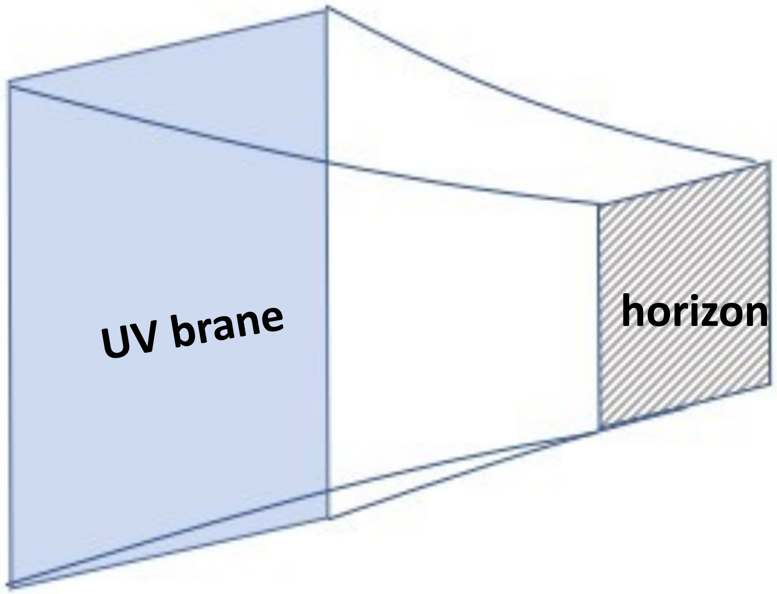


Dual of the deconfined phase

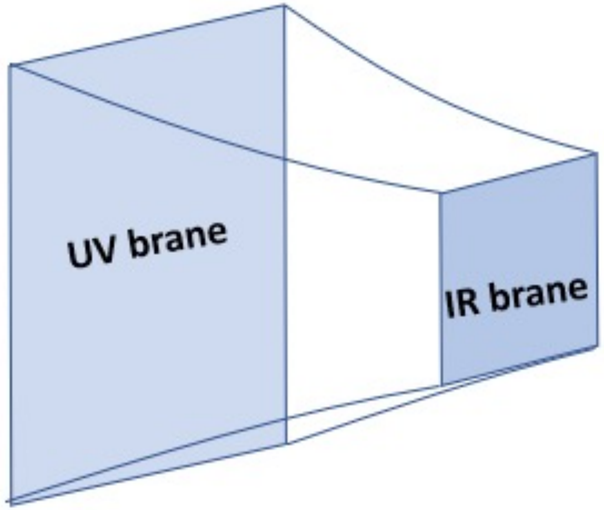
Dual of the confined phase

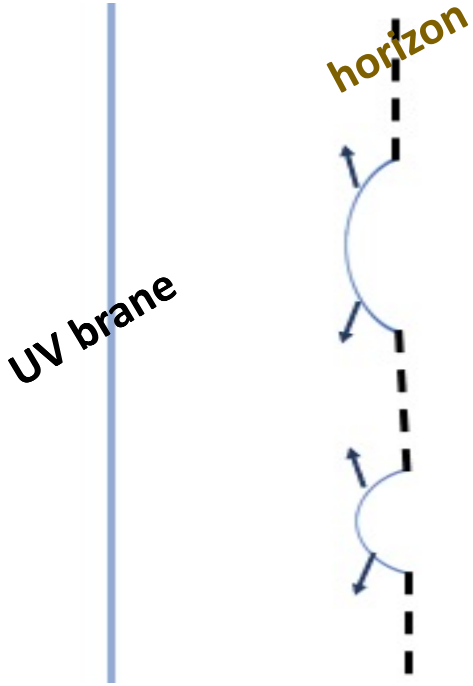
Creminelli, Nicolis & Rattazzi 2002

Holography
Black-brane phase → RS1



Tunneling





IR brane emerges from the horizon

(Non-perturbative)
Tunneling rate:

$$\Gamma \sim e^{-1/G_N^{(5D)}} \sim e^{-N^2}$$

Spontaneous Confinement- Dilaton EFT

A large N CFT: $\mathcal{L} = \mathcal{L}_{CFT}$

Dilaton Lagrangian:

$$\mathcal{L}_{dilaton} = \frac{N^2}{16\pi^2}\left((\partial\phi)^2 - \lambda\phi^4\right)$$

- Large N and small $\lambda \lesssim 1$
- Spontaneous confinement, $\langle\phi\rangle \neq 0$, not stable

Review of RS-I

Randall & Sundrum 1999

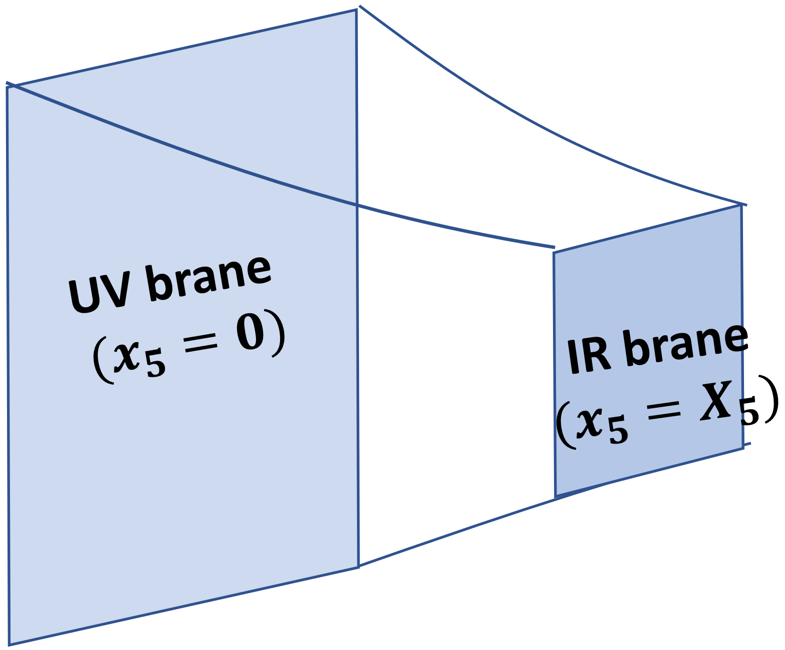
- Planck/weak hierarchy is related to the position of the IR brane:

$$\frac{\text{TeV}}{M_{Pl}} \sim e^{-kX_5}$$

- IR brane stabilized using a bulk scalar (Goldberger-Wise) field

$$V_{GW}(\Phi) = \frac{1}{2}m^2\Phi^2$$

- Generate a potential for the radion, $\varphi = ke^{-kX_5}$, the field corresponding to the position of the IR brane.
- Hierarchy controlled mainly by $\epsilon \approx \frac{m^2}{4k^2}$: $\ln\frac{M_{Pl}}{\text{TeV}} \sim \frac{1}{\epsilon}$



Goldberger & Wise 1999

Separate fixed points- Faster PT

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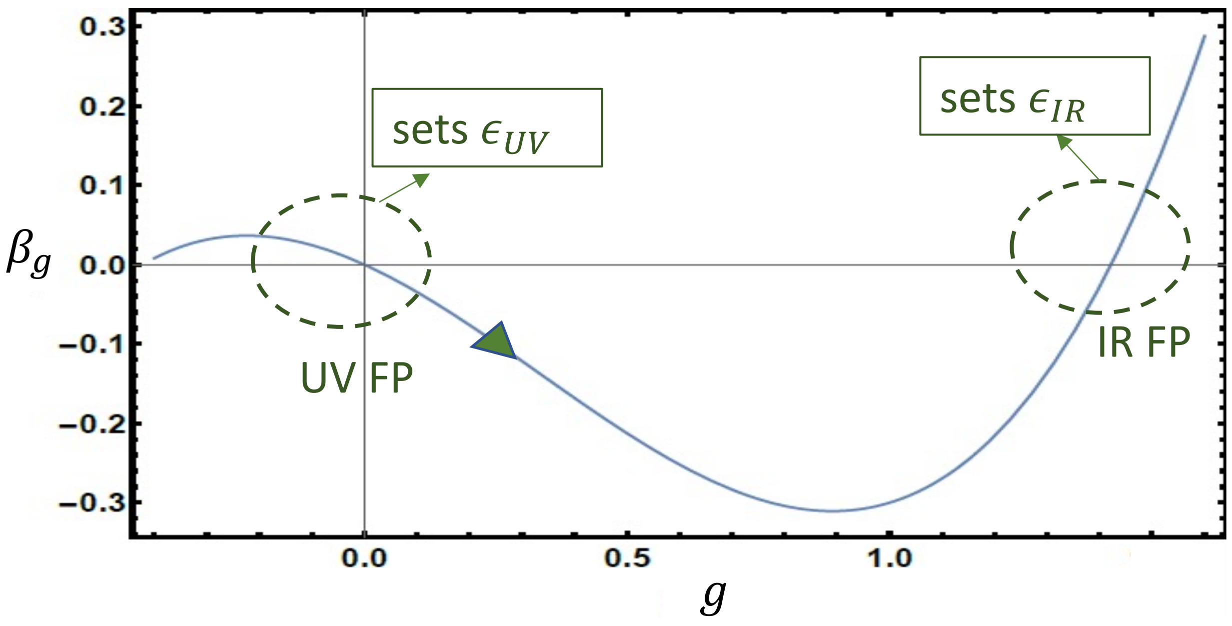

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Beyond the minimal model

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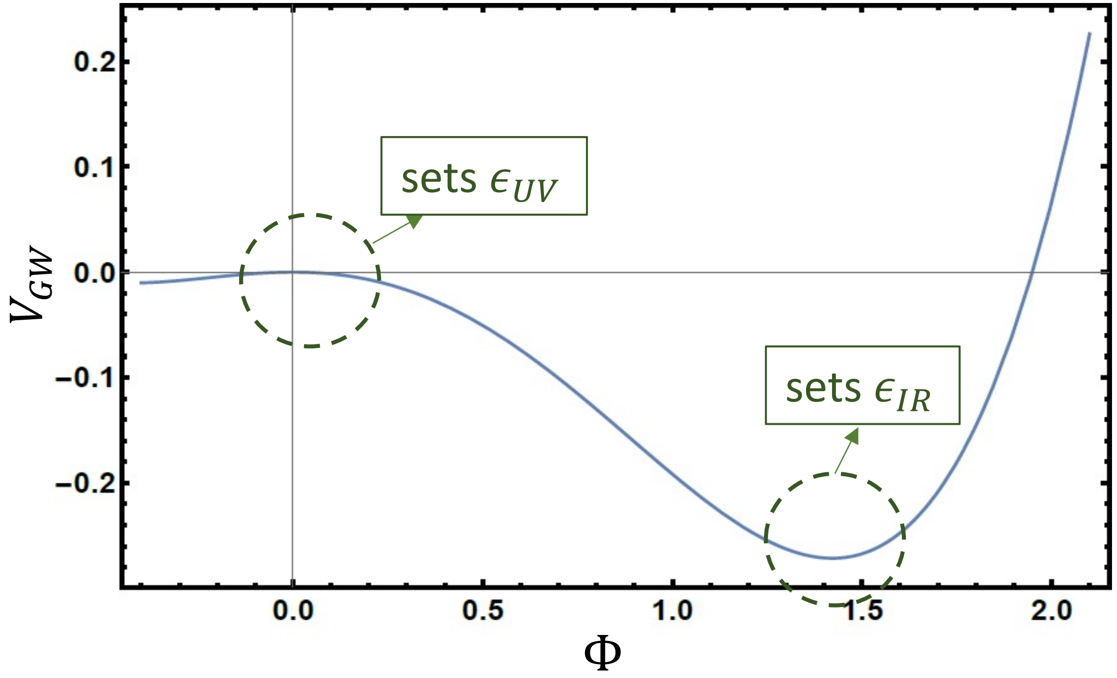
- Goldberger-Wise field with self- interactions:

$$V_{GW}(\Phi) = \frac{1}{2}m^2\Phi^2 + \frac{1}{3!}\eta\Phi^3 + \frac{1}{4!}\kappa\Phi^4$$

- Effective mass: $m_{eff}^2 \sim V''_{GW}(\Phi)$



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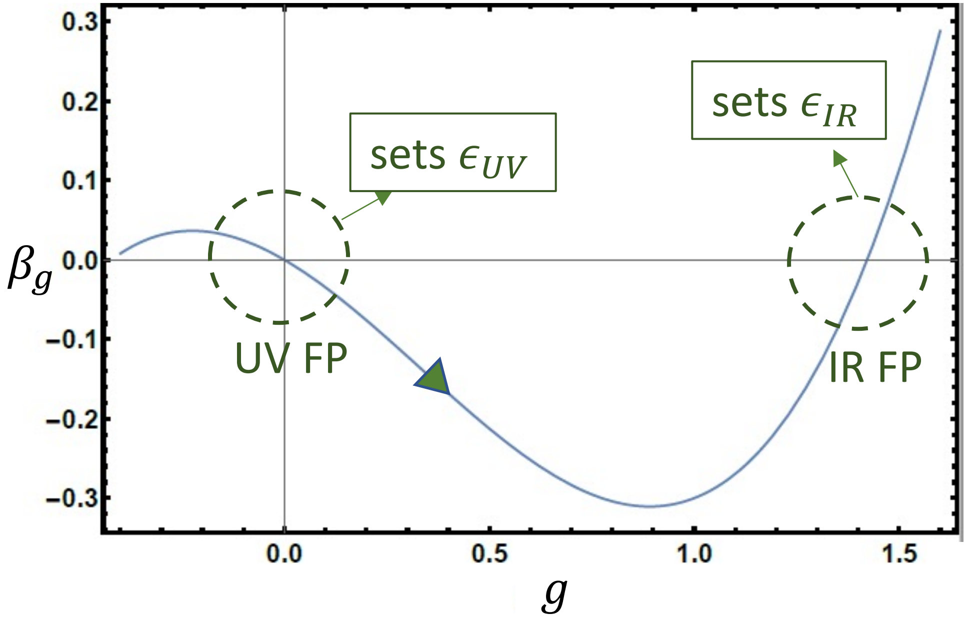


Questions to answer about the PT

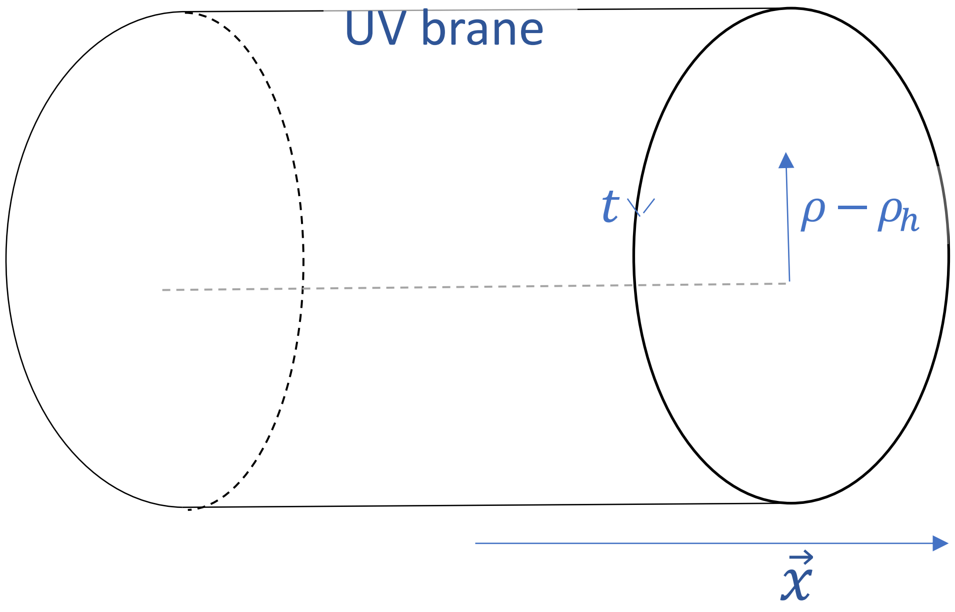
- Is it 1st order, 2nd order, cross over?
- What is the critical/transition temperature?

PT Dynamics

- What is the rate of bubble nucleation?
- Does the PT complete? If yes, at what temperature? Is it prompt or supercooled?
- How do the bubbles/bounce solutions look like?
- What are the features of the gravitational waves generated by the PT?

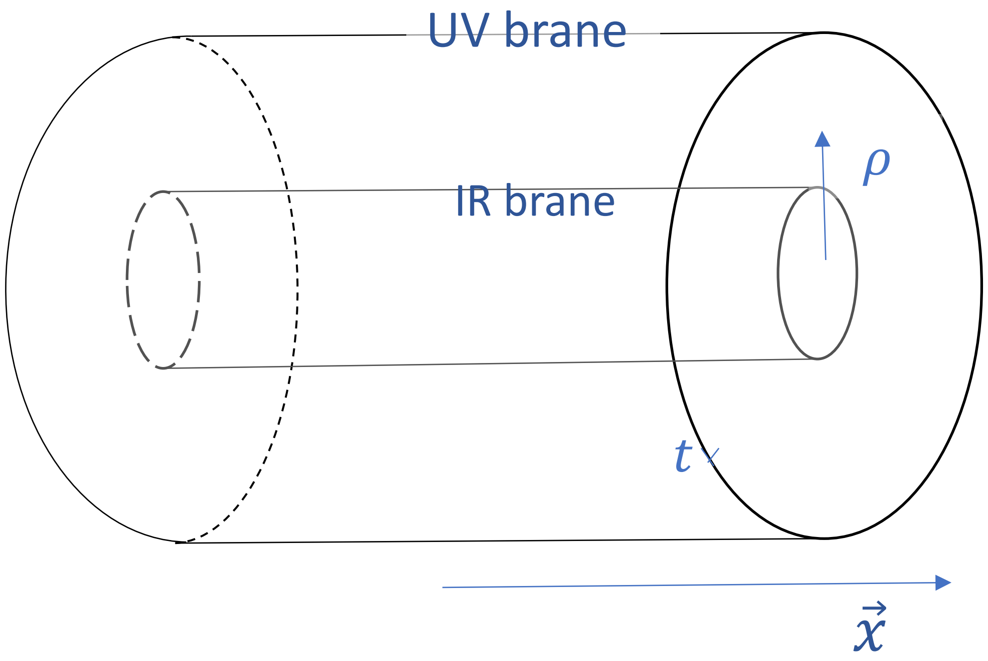
The 5D bounce

AdS-Schwarzschild



$$ds^2 = \left(\rho^2 - \frac{\rho_h^4}{\rho^2}\right) dt^2 + \frac{d\rho^2}{\left(\rho^2 - \frac{\rho_h^4}{\rho^2}\right)} + \rho^2 \sum_i dx_i^2$$

RS 1

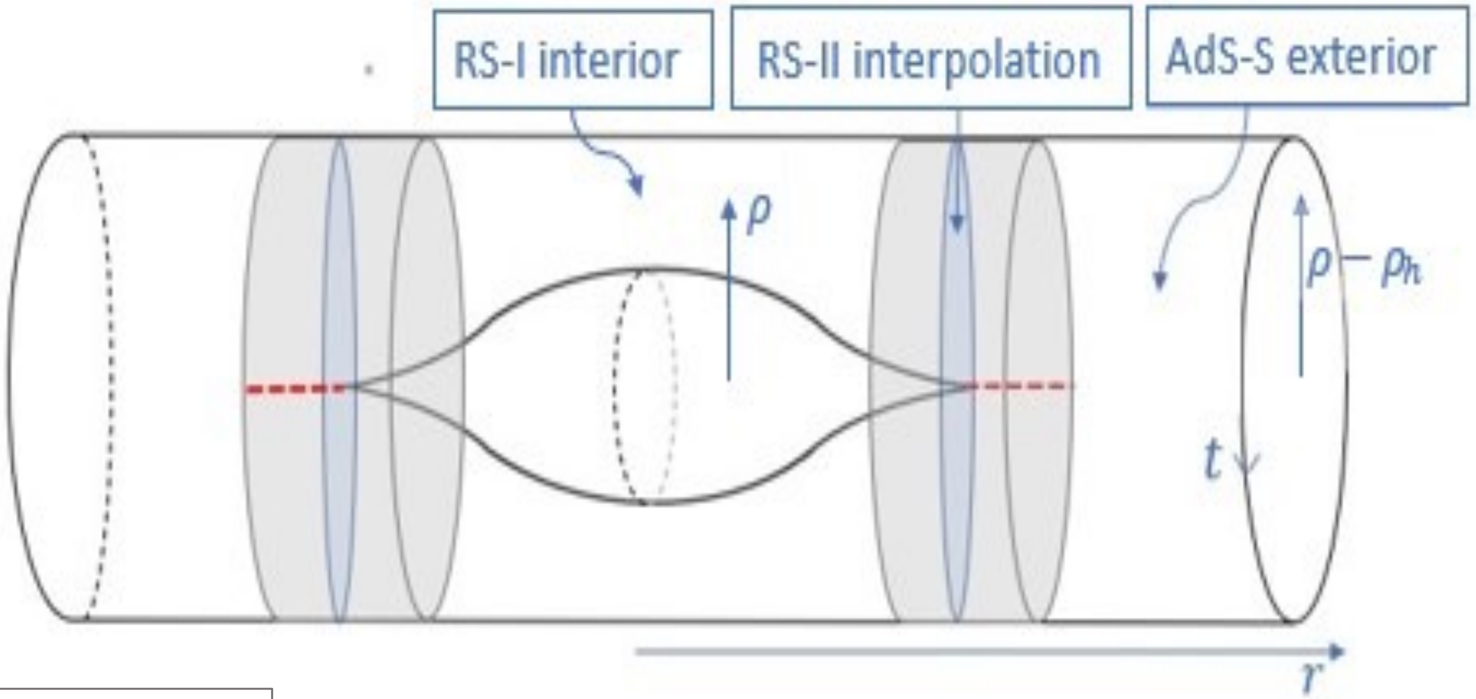


$$ds^2 = \rho^2 dt^2 + \frac{d\rho^2}{\rho^2} + \rho^2 \sum_i dx_i^2$$

$$(\rho_{IR} < \rho < \rho_{UV})$$

The 5D bounce

- Connect the two phases through their common RS-II limits?



AdS-S: $ds^2 = \left(\rho^2 - \frac{\rho_h^4}{\rho^2}\right) dt^2 + \frac{d\rho^2}{\left(\rho^2 - \frac{\rho_h^4}{\rho^2}\right)} + \rho^2 \sum_i dx_i^2$

RS1: $ds^2 = \rho^2 dt^2 + \frac{d\rho^2}{\rho^2} + \rho^2 \sum_i dx_i^2$
$(\rho_{IR} < \rho < \rho_{UV})$

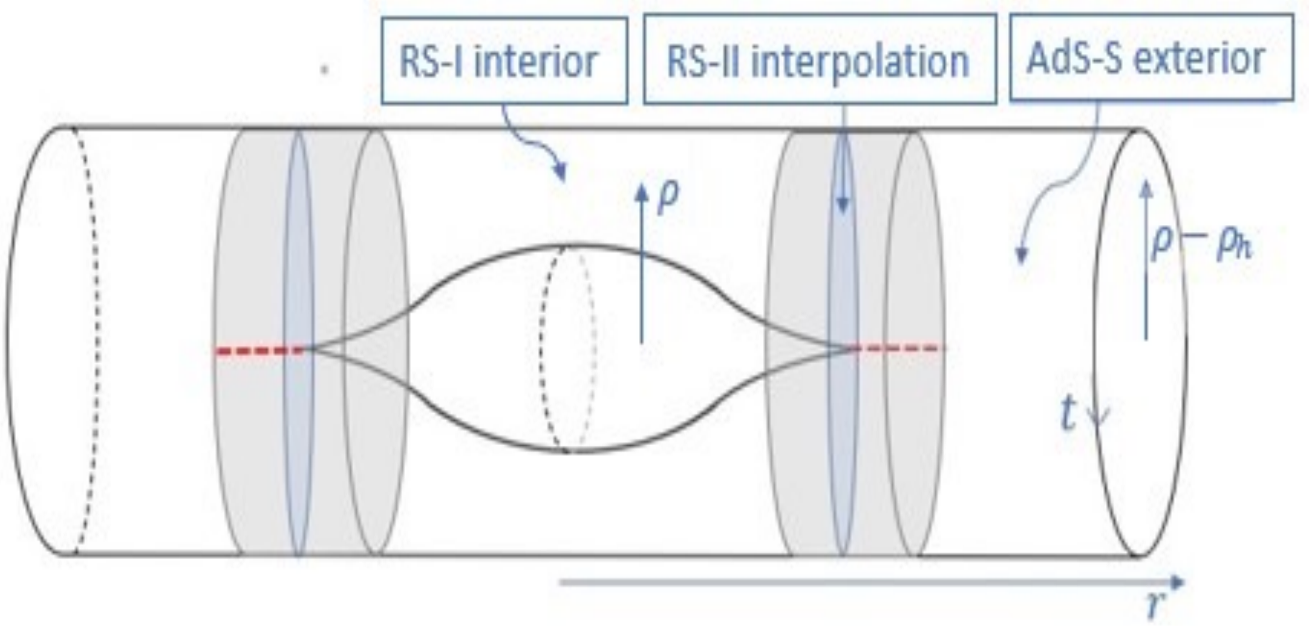
RS2 limit: $ds^2 = \rho^2 dt^2 + \frac{d\rho^2}{\rho^2} + \rho^2 \sum_i dx_i^2$
$(\rho < \rho_{UV})$

Creminelli, Nicolis & Rattazzi 2002

The 5D bounce

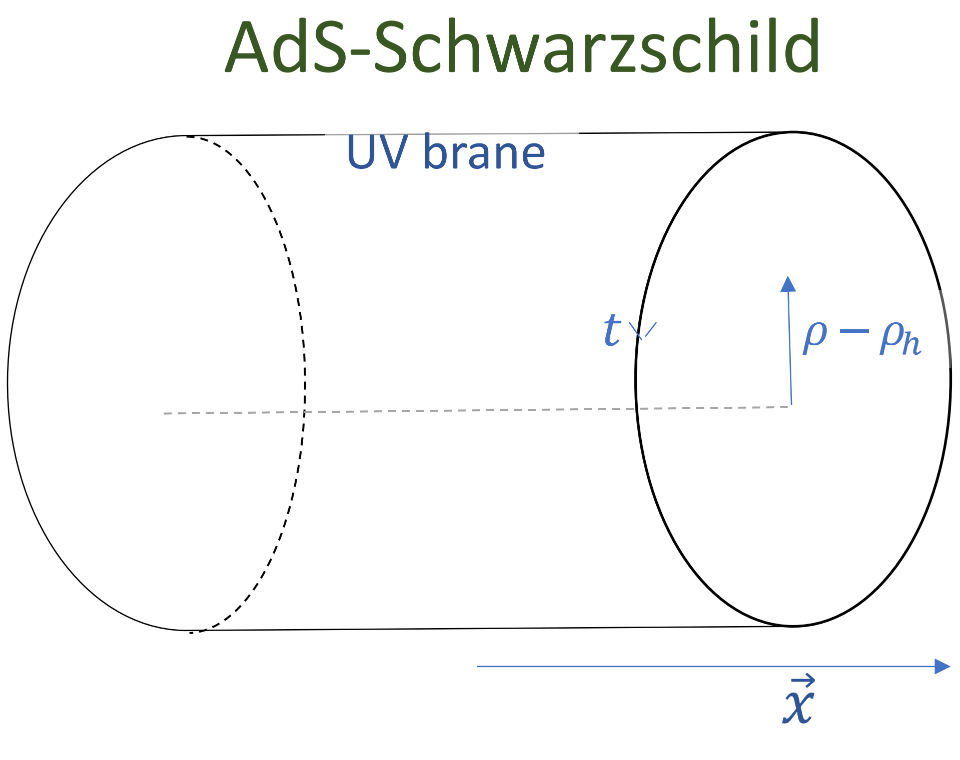
- Connect the two phases through their common RS-II limits?

Not fully in 5D EFT control

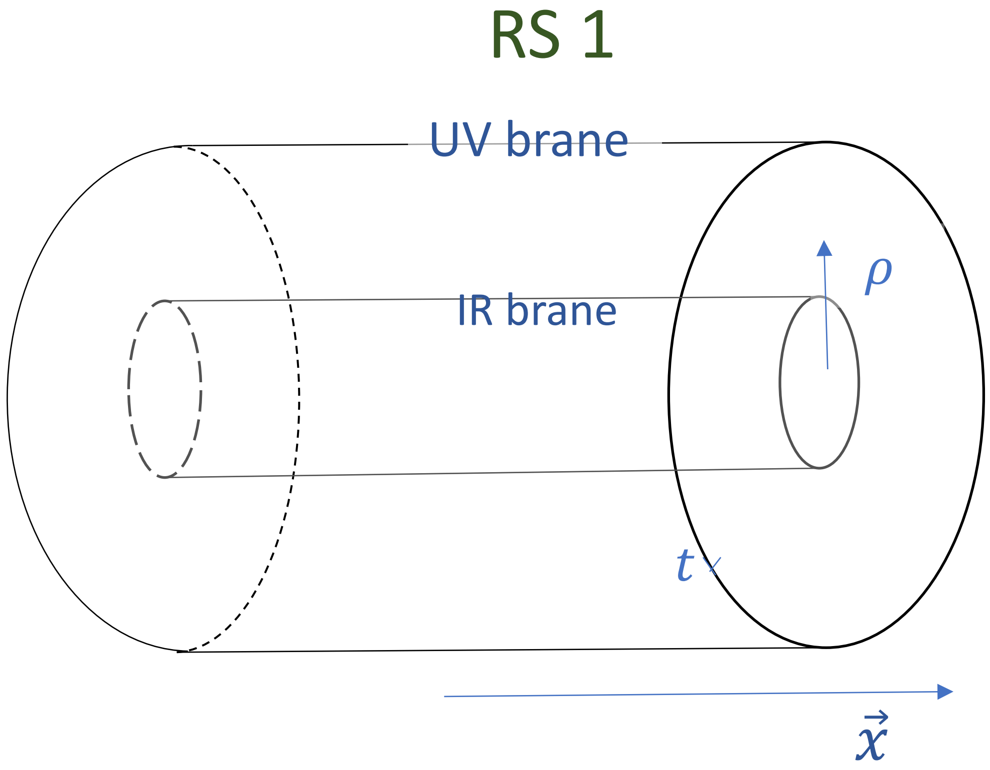


Creminelli, Nicolis & Rattazzi 2002

Is there a smooth bounce configuration?



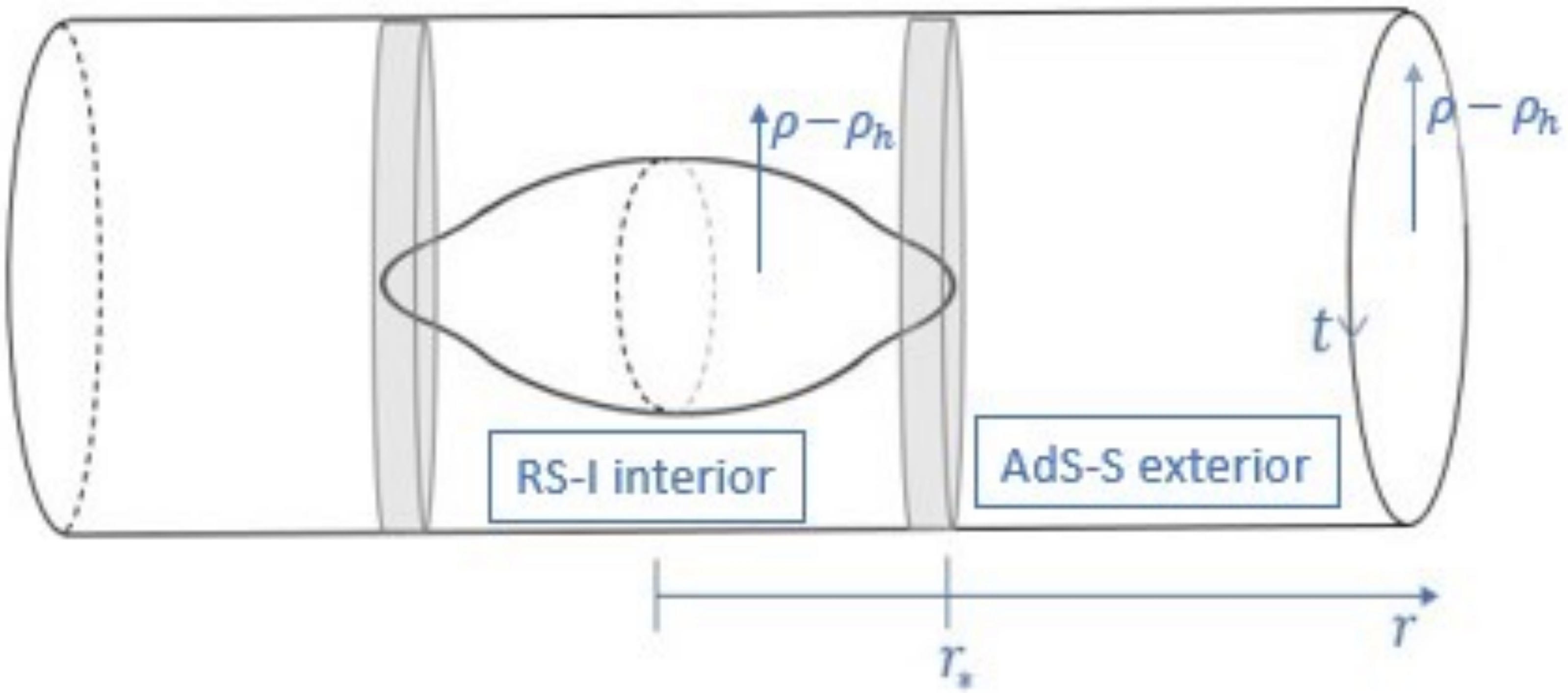
$$ds^2 = \left(\rho^2 - \frac{\rho_h^4}{\rho^2}\right) dt^2 + \frac{d\rho^2}{\left(\rho^2 - \frac{\rho_h^4}{\rho^2}\right)} + \rho^2 \sum_i dx_i^2$$



$$ds^2 = \rho^2 dt^2 + \frac{d\rho^2}{\rho^2} + \rho^2 \sum_i dx_i^2$$

$$(\rho_{IR} < \rho < \rho_{UV})$$

The 5D bounce- smoothness



✓ IR-brane can be smoothly sealed at the horizon

✓Smooth, finite curvature, and can be described in 5D EFT

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