Cosmology as a Holographic Wormhole

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Holotube Seminar, Nov 22, 2022

It from Qubit
Simons Collaboration on
Quantum Fields, Gravity and Information

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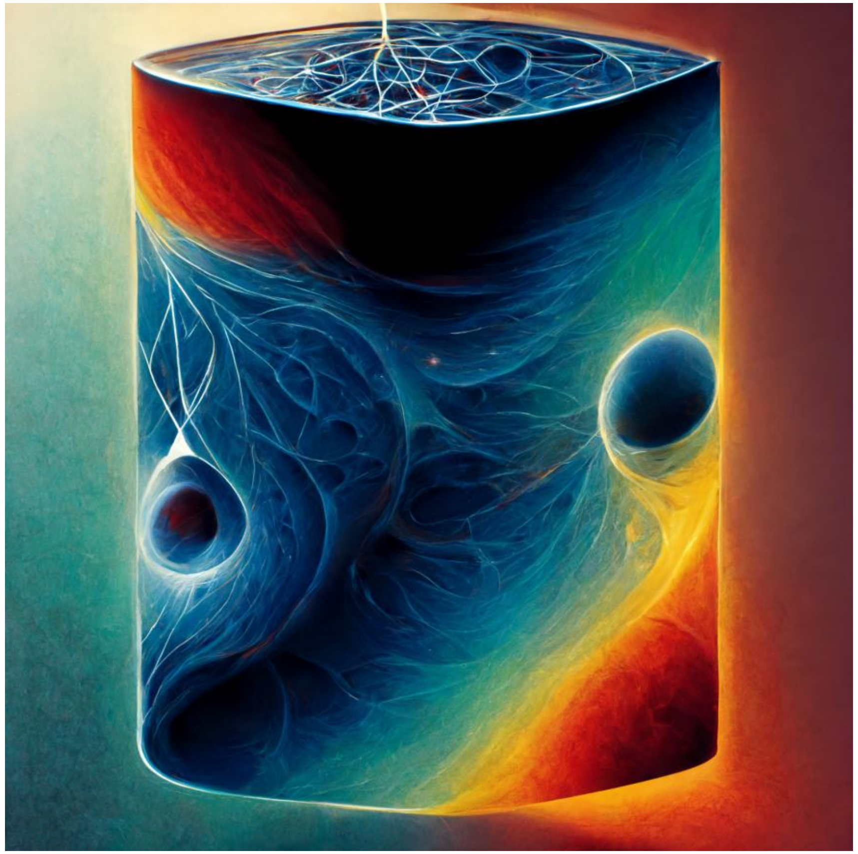
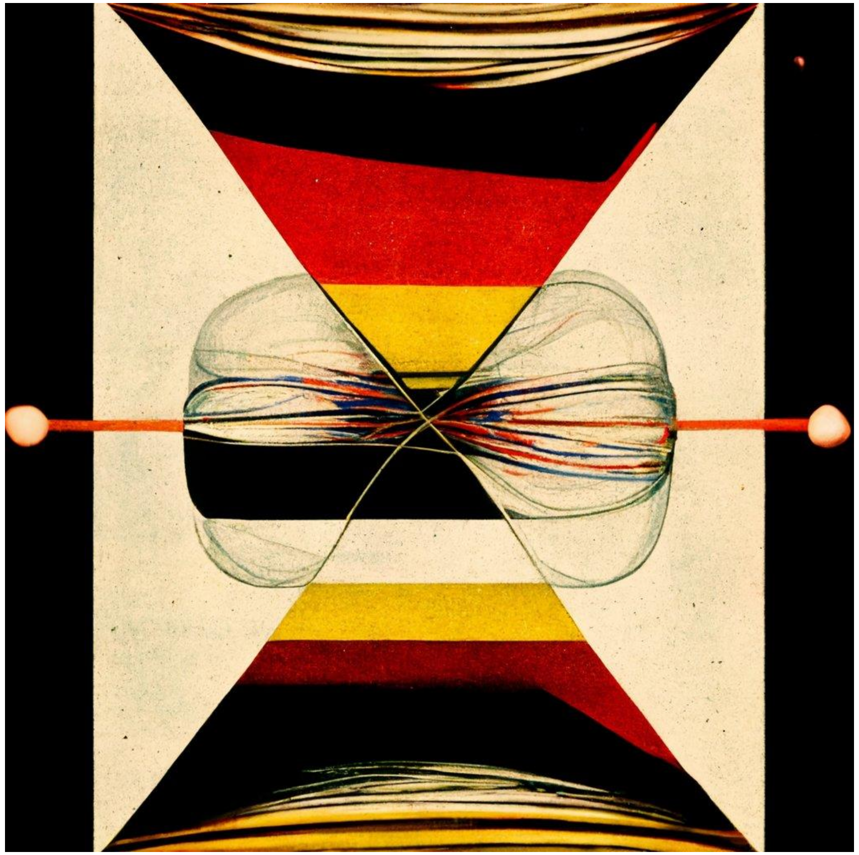
Quantum Gravity



Quantum Matter



- Fruitful models of quantum gravitational physics (from AdS/CFT and string theory) and wonderful connections with models of quantum matter
- However, it remains a significant open problem to find a quantum gravitational description of the physics of cosmologies like our own universe

This talk

- An optimistic scenario for understanding the large-scale structure of the universe in which:
  - There is a non-perturbative microscopic theory
  - There is a preferred state
- Based on 2203.11220, 2206.14821, 2207.02225 with Stefano Antonini, Petar Simidzija, and Mark Van Raamsdonk; WIP with all + Chris Waddell
- Prior works include Cooper-…-Waddell-Van Raamsdonk-S 1810.10601, Van Raamsdonk 2008.02259 and 2102.050057, Antonini-S 1907.06667
- Related ideas include McFadden-Skenderis 0907.5542, Boyle-Finn-Turok 1803.08928, islands/cosmology Hartman-Jiang-Shaghoulian 2008.01022, …

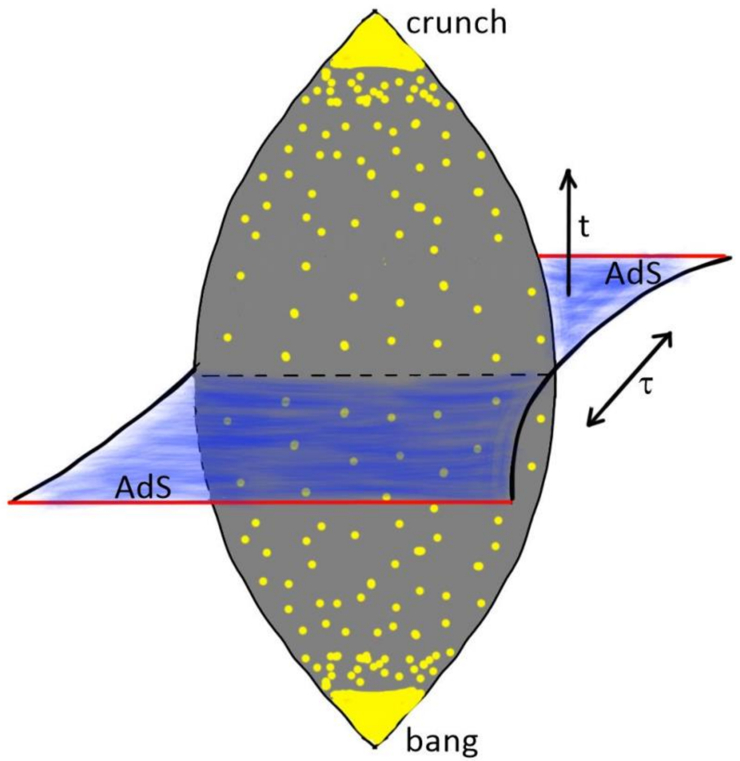
Cosmology with negative CC?

- Data show that the universe is experiencing a period of accelerating expansion; one explanation is a positive cosmological constant (CC)
- However, accelerating expansion can also be explained with a negative CC and time-dependent scalar fields
    - Time-dependent scalars respect the same symmetries as an FRW universe
    - Negative CC is much better understood theoretically and offers the prospect of a holographic description
- But “holographic” cosmology is still challenging because we don’t have any asymptotic AdS regions in the cosmological picture

Example: flat + radiation + negative CC

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{\rho + \Lambda}{3} \qquad \frac{\ddot{a}}{a} = \frac{-\rho + \Lambda}{3}$$

$$a(t) = a(0)\sqrt{\cos\left(2\sqrt{\frac{|\Lambda|}{3}}\,t\right)}$$



- Time-symmetric big bang/crunch cosmology
- Complexified geometry has asymptotically AdS regions

(NO accelerated expansion … yet)

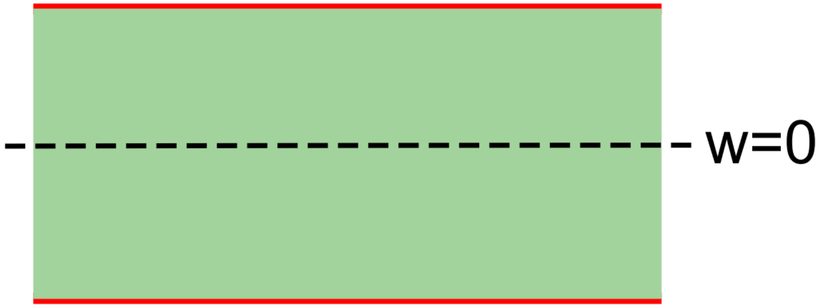
Cosmology from the Vacuum

- Two copies of holographic 3D CFTs on $\mathbb{R}^3$
- 4D (non) holographic CFT on $\mathbb{R}^3 \times I$, $c_{4D} \ll c_{3D}$
- Couple the 3D CFTs at the ends of the interval I by relevant perturbation

Slicing duality

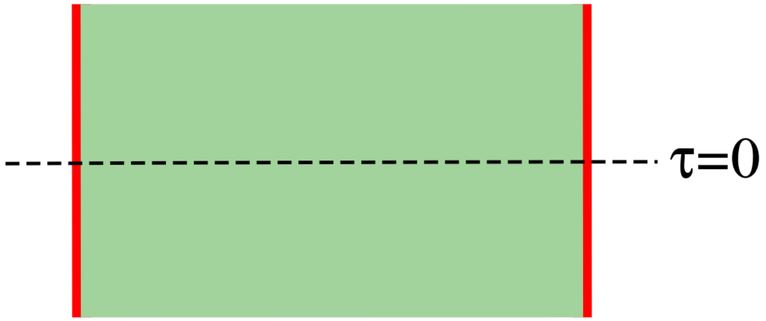
Slicing 1

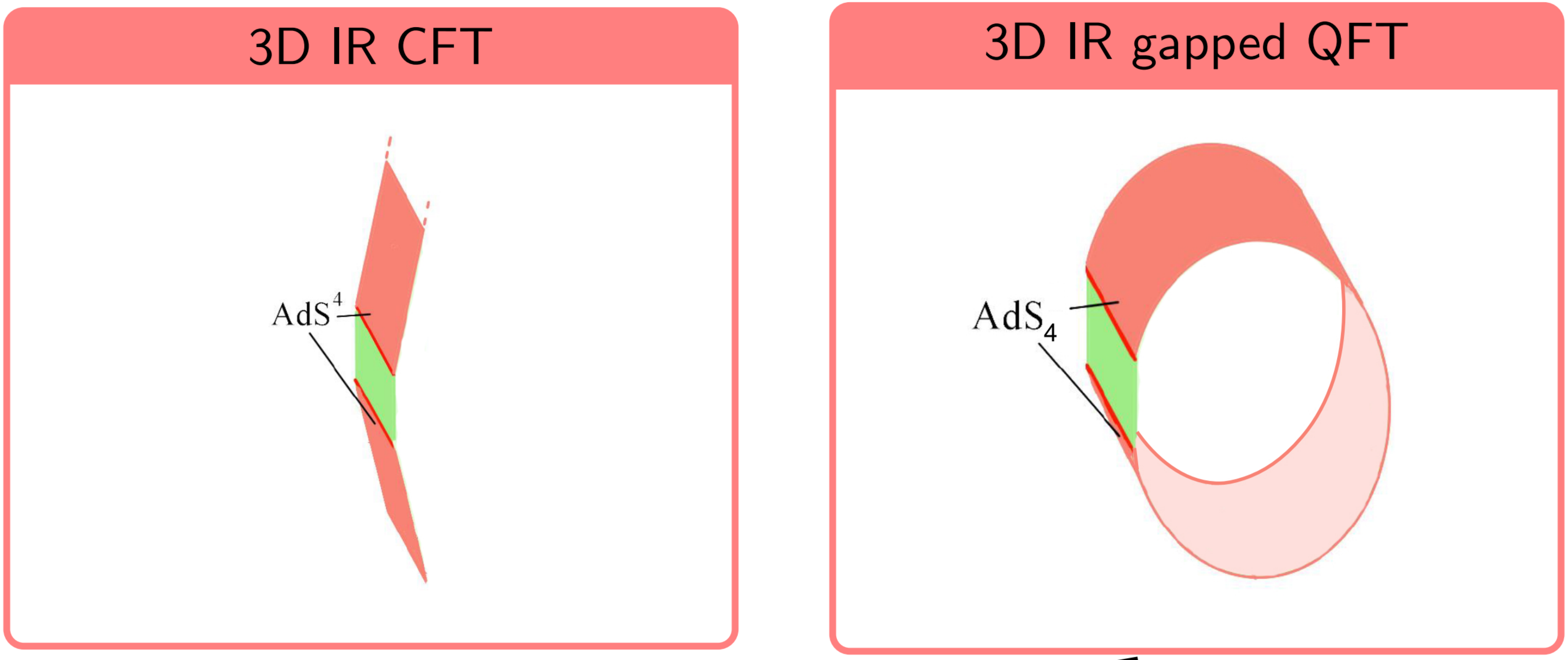
- Divide l in half
- Excited state of 4D CFT
- No 3D DOF in Lorentzian theory



Slicing 2

- Divide τ direction in half
- Vacuum of 3D-4D-3D (gapped) theory
- 3D and 4D DOF in Lorentzian theory

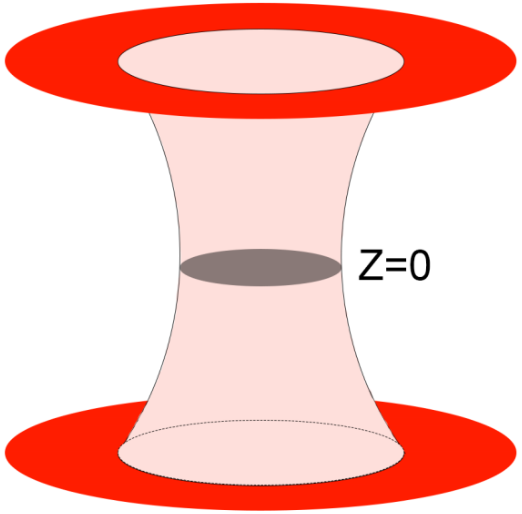




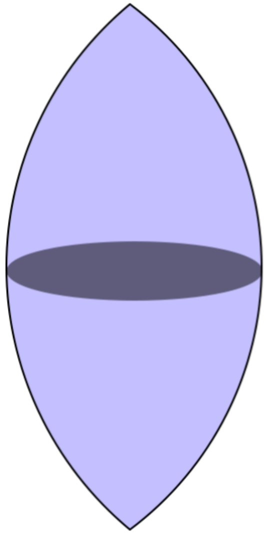
$$ds^2 = a(z)\left(dz^2 + d\tau^2 + dx^2 + dy^2\right), \qquad a(z) \sim \frac{c}{(z - z_0)(z + z_0)} + \ldots$$

4D CFT excited state (even non-holographic!)	$\Leftrightarrow$	Symmetric Big Bang - Big Crunch FLRW cosmology

- Field theory slicing corresponds to bulk path integral slicing:



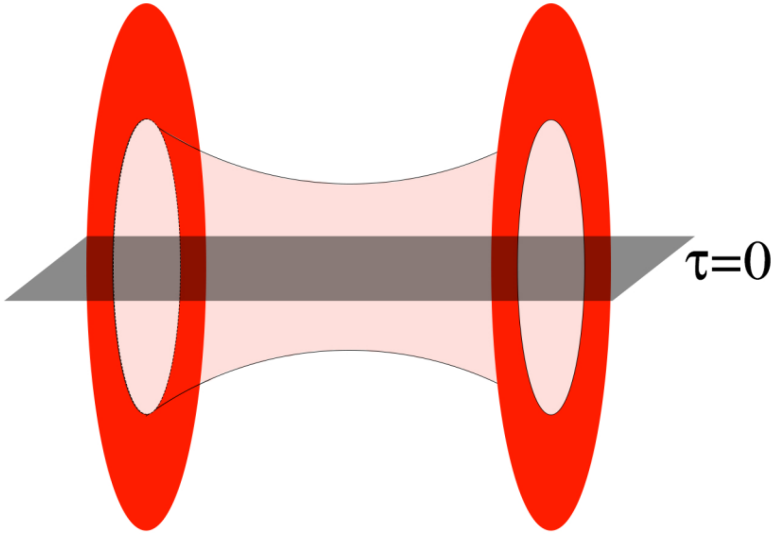
$\Rightarrow$



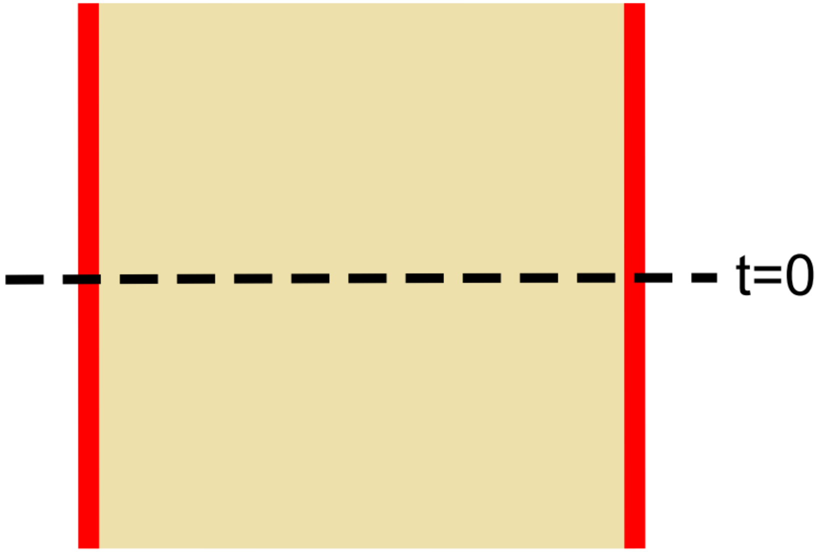
$$ds^2 = a^2(\zeta)\left(-d\zeta^2 + d\tau^2 + dx^2 + dy^2\right) \qquad (\zeta^2 = -z^2)$$

Vacuum state of 3D-4D-3D (gapped) Lorentzian sandwich theory	$\Leftrightarrow$	Static AdS planar traversable wormhole

- Field theory slicing corresponds to bulk path integral slicing:

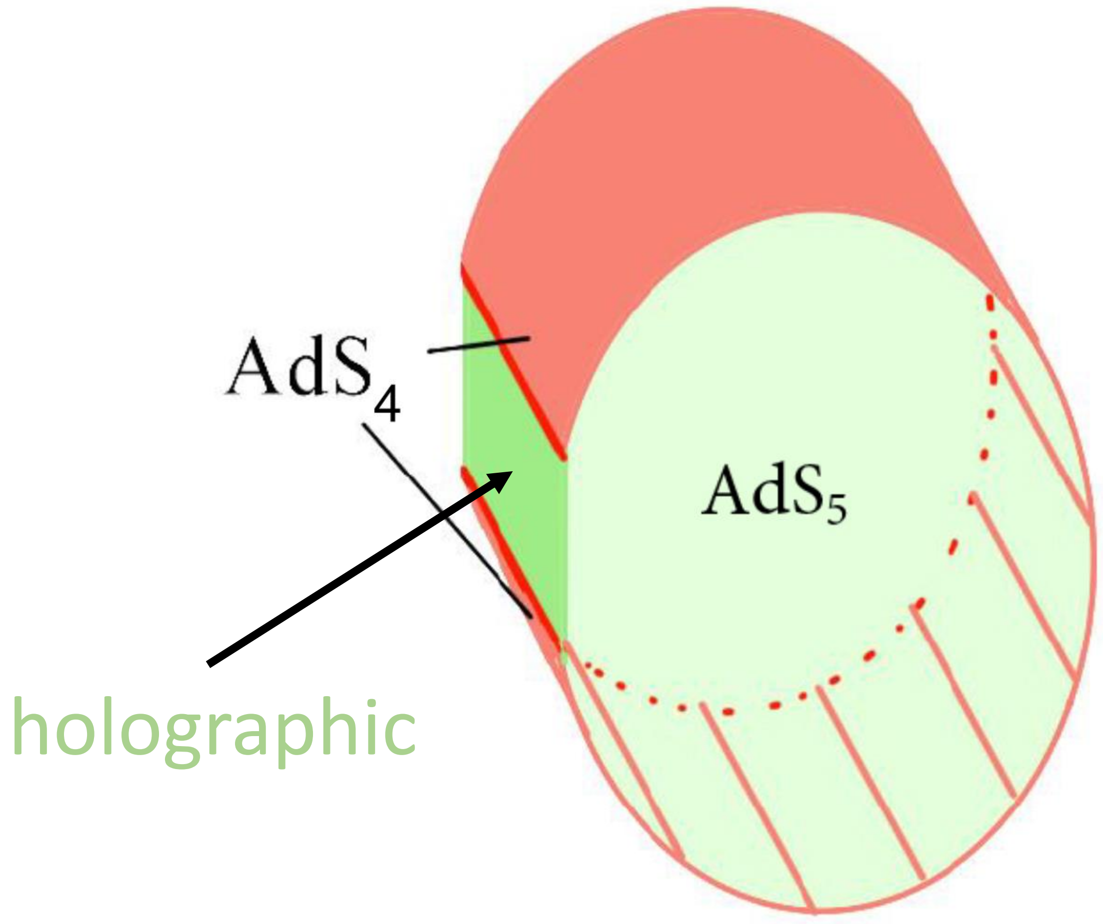


$\Rightarrow$



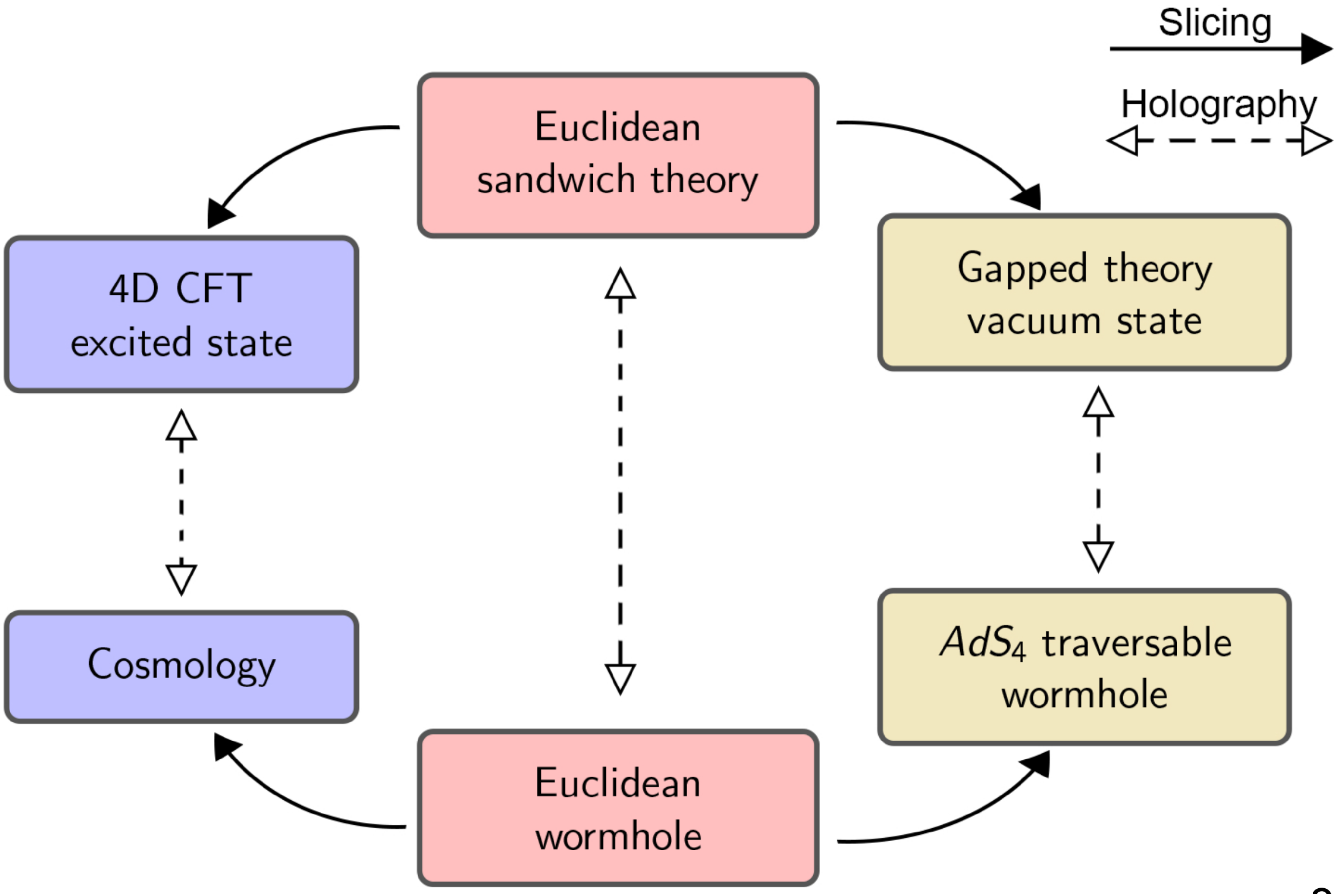
$$ds^2 = a^2(z)\left(dz^2 - dt^2 + dx^2 + dy^2\right) \qquad (t^2 = -\tau^2)$$

Special case: holographic 4D theory

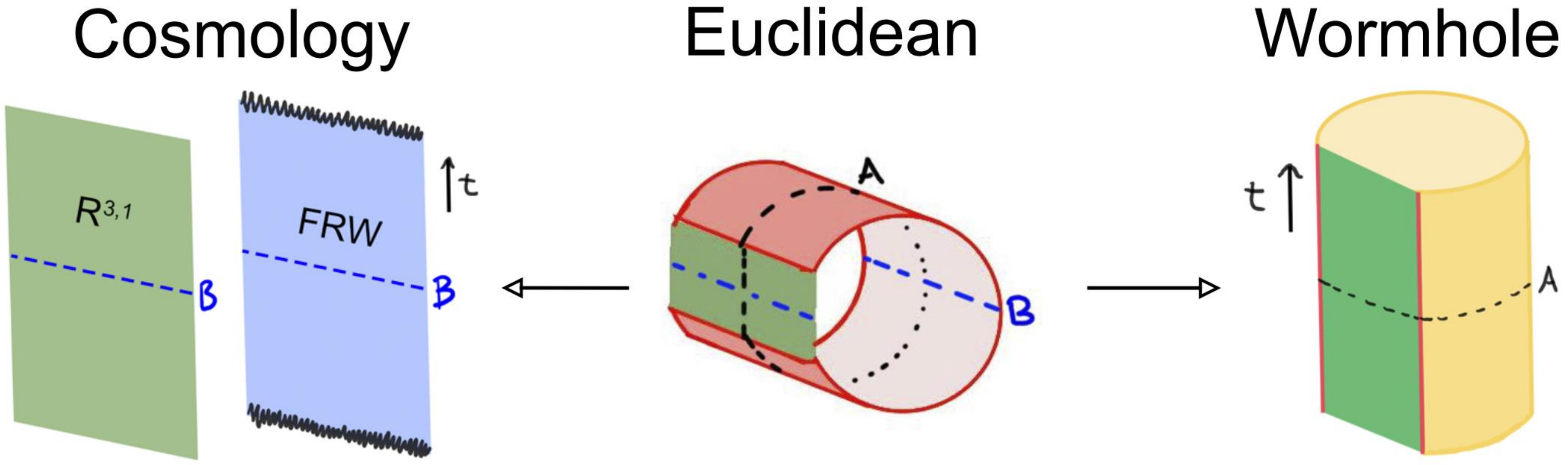


- In the cosmology picture, the excited state of the 4D theory has a black hole in the bulk (microstate)
- End-of-the-world brane behind the horizon hosts the cosmology
- Seemingly very difficult to probe the cosmology, literally behind a horizon

[idea: Cooper-…-S 1810.10601, adding charge: Antonini-S 1907.06667, …]


Slicing
Holography
Euclidean sandwich theory
4D CFT excited state
Gapped theory vacuum state
Cosmology
AdS_4 traversable wormhole
Euclidean wormhole

- Slicing open the EFT path integral gives bulk + auxiliary (non-gravitational) system:

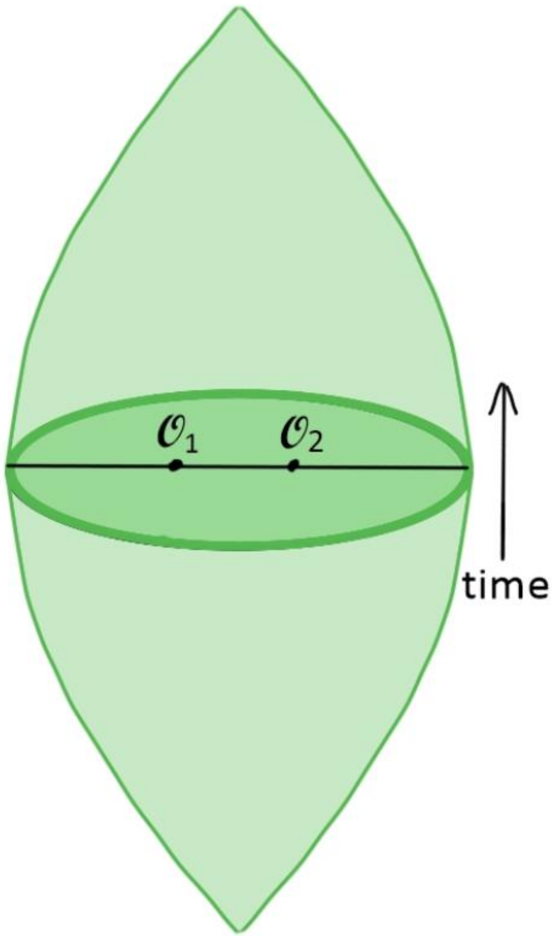


- Cosmology picture: disconnected entangled "bath"
- Wormhole picture: auxiliary system coupling the two boundaries

Special state for cosmology

- The Euclidean path integral naturally defines a state for cosmology at the turning point of the universe, far from the singularities
- We can then try to understand earlier times by evolving backward from the turning point without ever referencing the singularity
- Interesting features include:
  - Flatness is built in as a symmetry
  - Cosmic coincidence: CC and matter/radiation are equal at the turning point
  - Horizon problem: massless modes of IR theory yield long-distance correlations at the turning point (ground state → infinite imaginary time); can these match data at earlier times?

Cosmology from the vacuum



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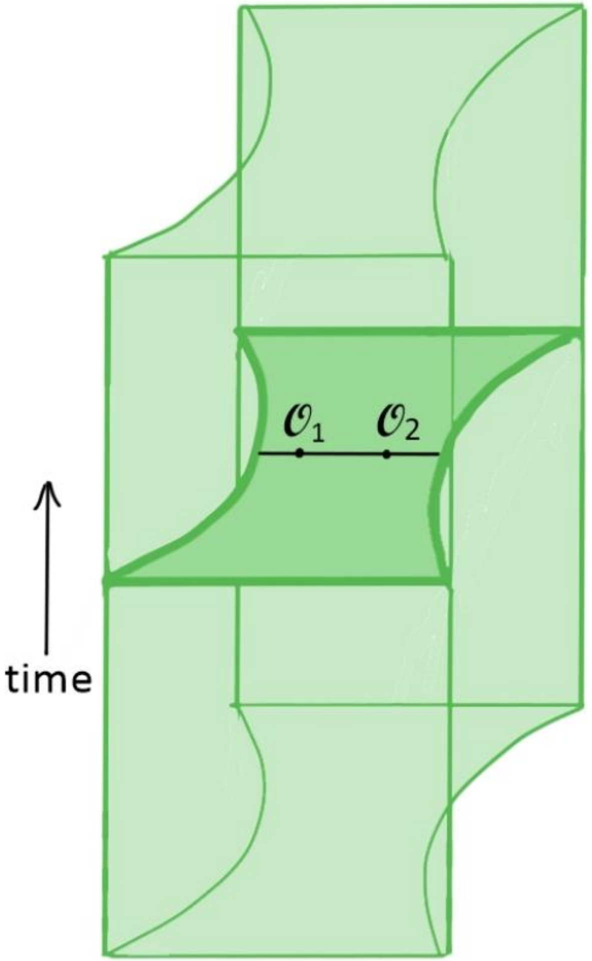


Accelerated Expansion

Bulk effective field theory

- Let's look for solutions for the scale factor and a time-dependent scalar field moving in a potential
- These solutions should be symmetric and exhibit a period of accelerating expansion
- We expect the relevant nature of the coupling in the 3D-4D-3D sandwich theory will be important

Cosmology	Wormhole
$ds^2 = -dt^2 + a^2(t)(\delta_{ij} dx^i dx^j)$	$ds^2 = d\tau^2 + a^2(\tau)(\eta_{ij} dx^i dx^j)$

Equations of motion

Cosmology

$$\begin{cases} H^2 = \frac{1}{3}\left[\Lambda + \frac{F}{a^4} + \frac{1}{2}\dot{\varphi}^2 + V(\varphi)\right] \\ \ddot{\varphi} + 3H\dot{\varphi} + \frac{\partial V}{\partial \varphi} = 0 \end{cases} \qquad H = \frac{\dot{a}(t)}{a(t)}$$

Wormhole

$$\begin{cases} H_E^2 = -\frac{1}{3}\left[\Lambda + \frac{F}{a^4} - \frac{1}{2}(\varphi')^2 + V(\varphi)\right] \\ \varphi'' + 3H_E\varphi' \boxed{- \frac{\partial V}{\partial \varphi}} = 0 \end{cases} \qquad H_E = \frac{a'(\tau)}{a(\tau)}$$

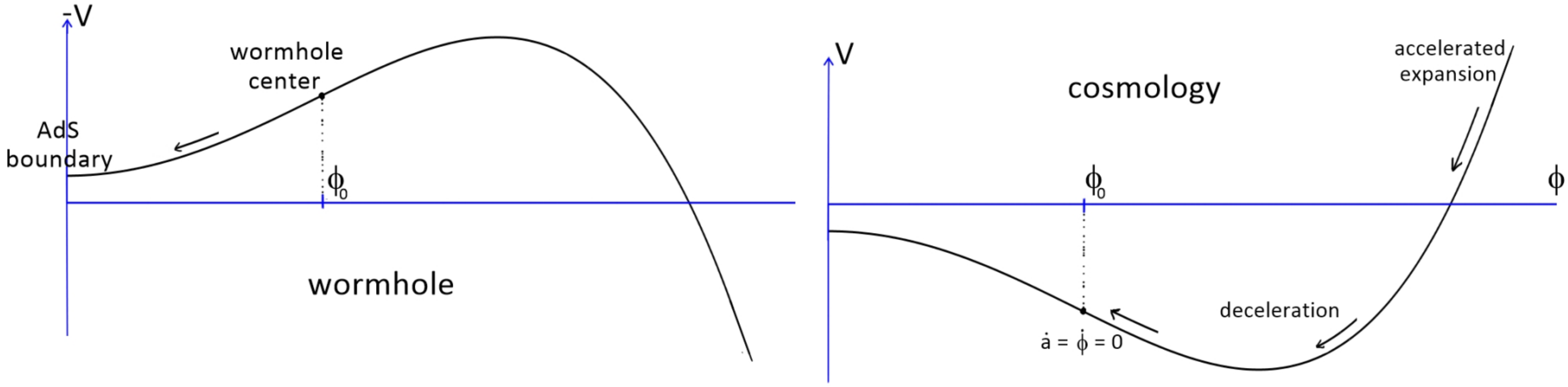
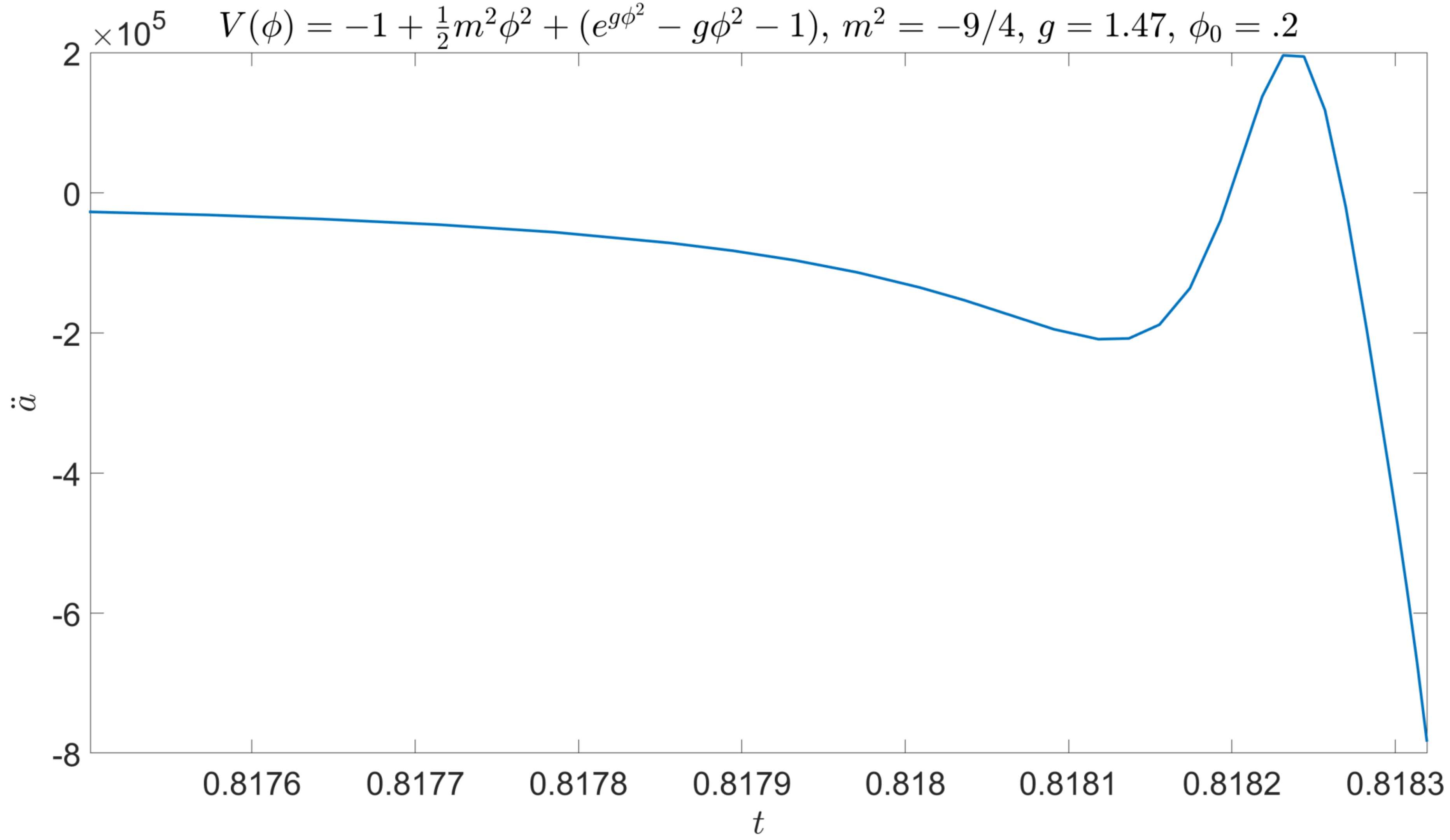
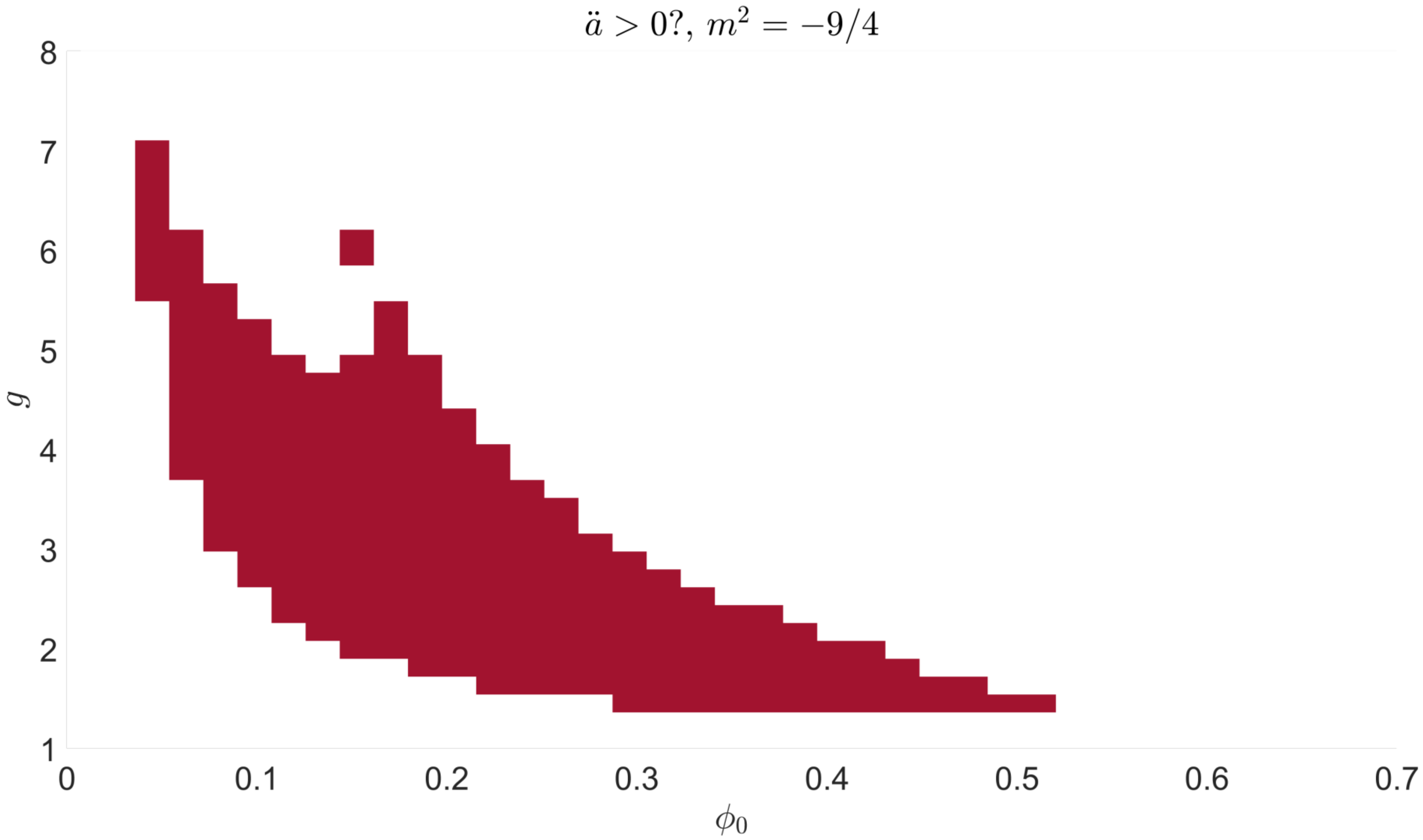


Figure 7. Left: evolution of the scalar from the wormhole center to the asymptotically AdS region corresponds to damped motion in the inverted potential $-V$ with damping "constant" $3a_E'/a_E$. The evolution of the scalar is dual to the RG flow induced by perturbing the dual CFT by a relevant operator. Right: Evolution of the scalar field in the cosmology from early times to the time-reversal symmetric point corresponds to damped motion in the potential V with damping constant $3\dot{a}/a$. The initial positive values of the potential typically give rise to a phase of accelerated expansion before deceleration and collapse.

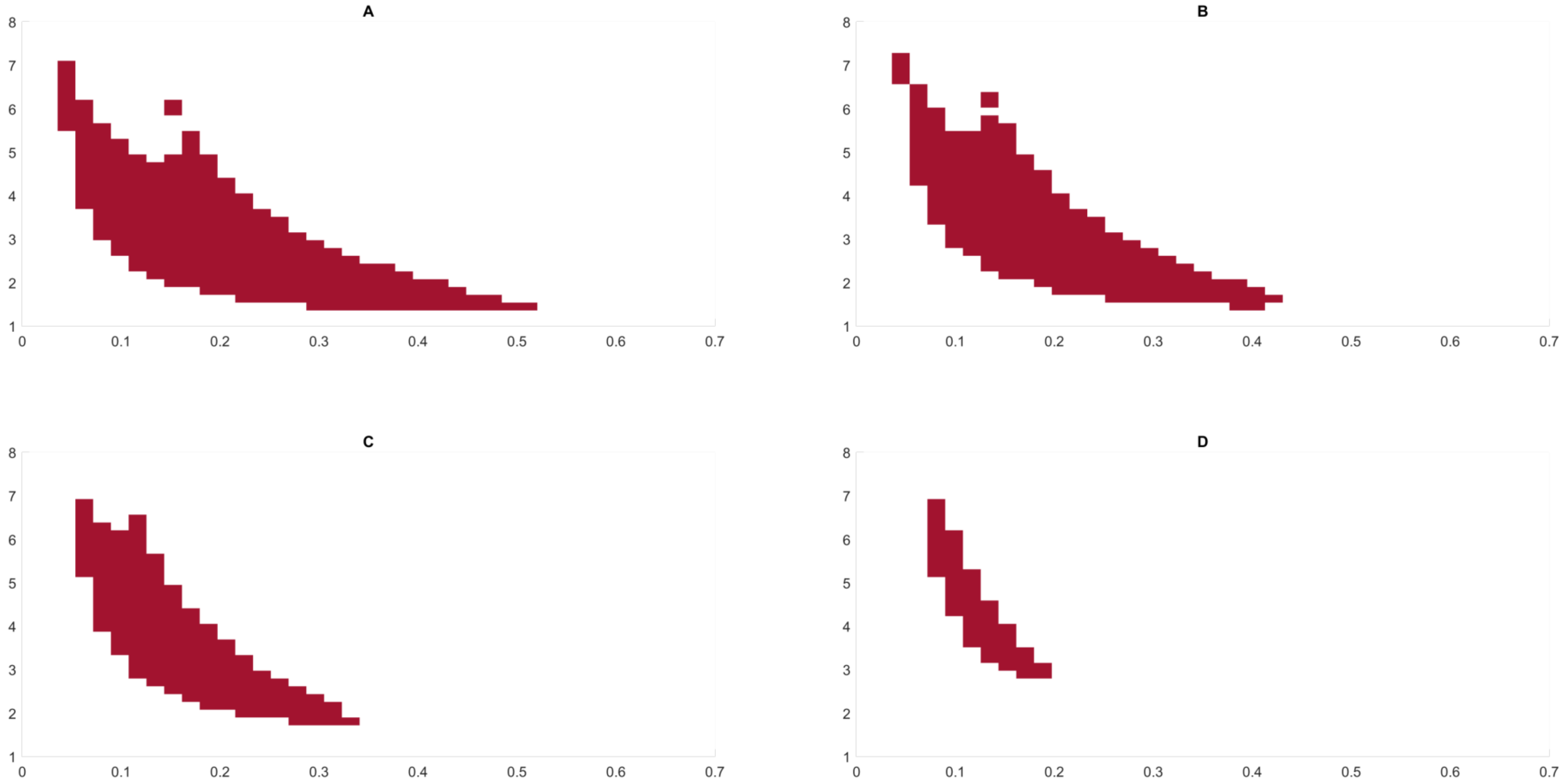
Small period of acceleration



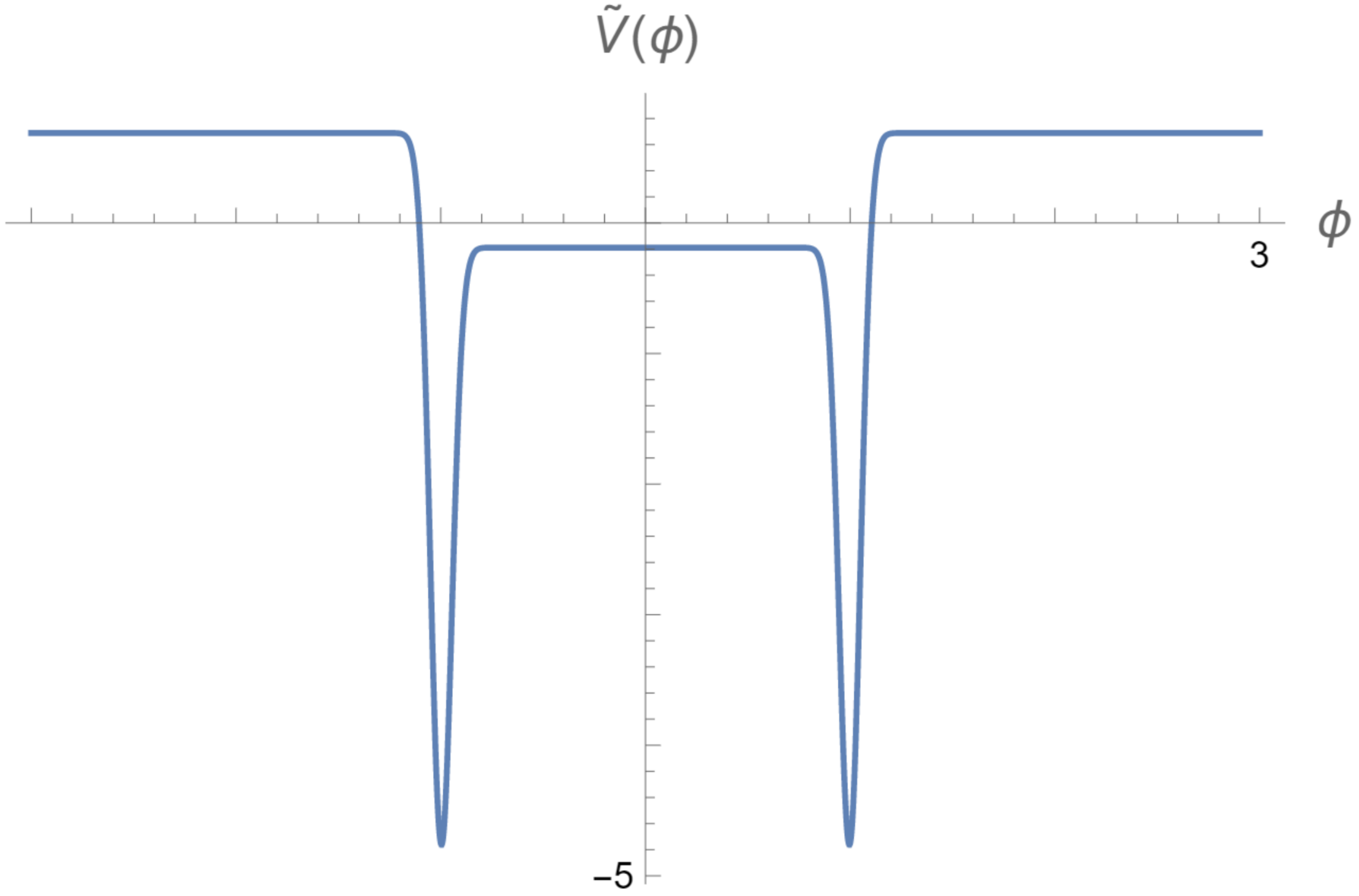
Codimension zero in parameter space

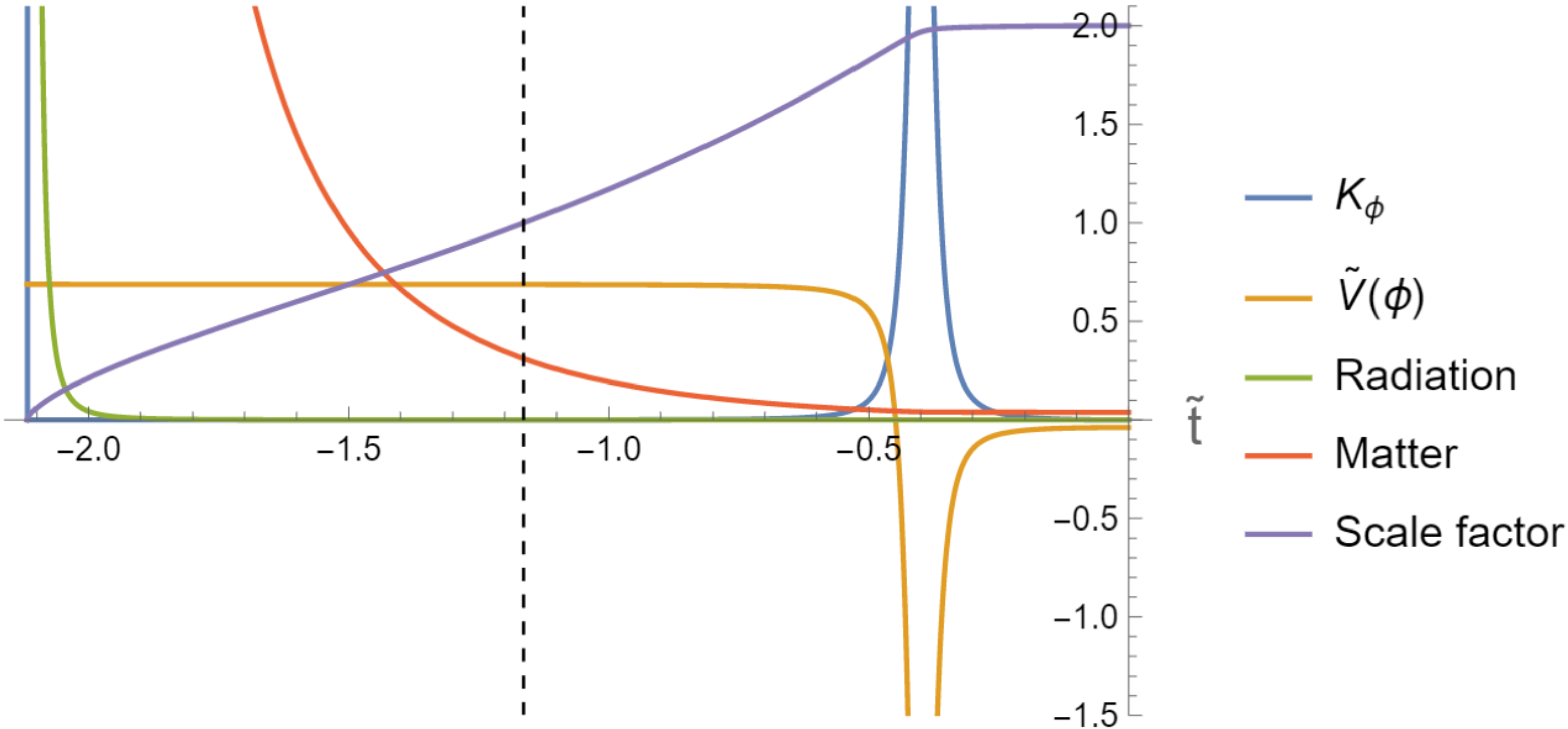


But still fragile …

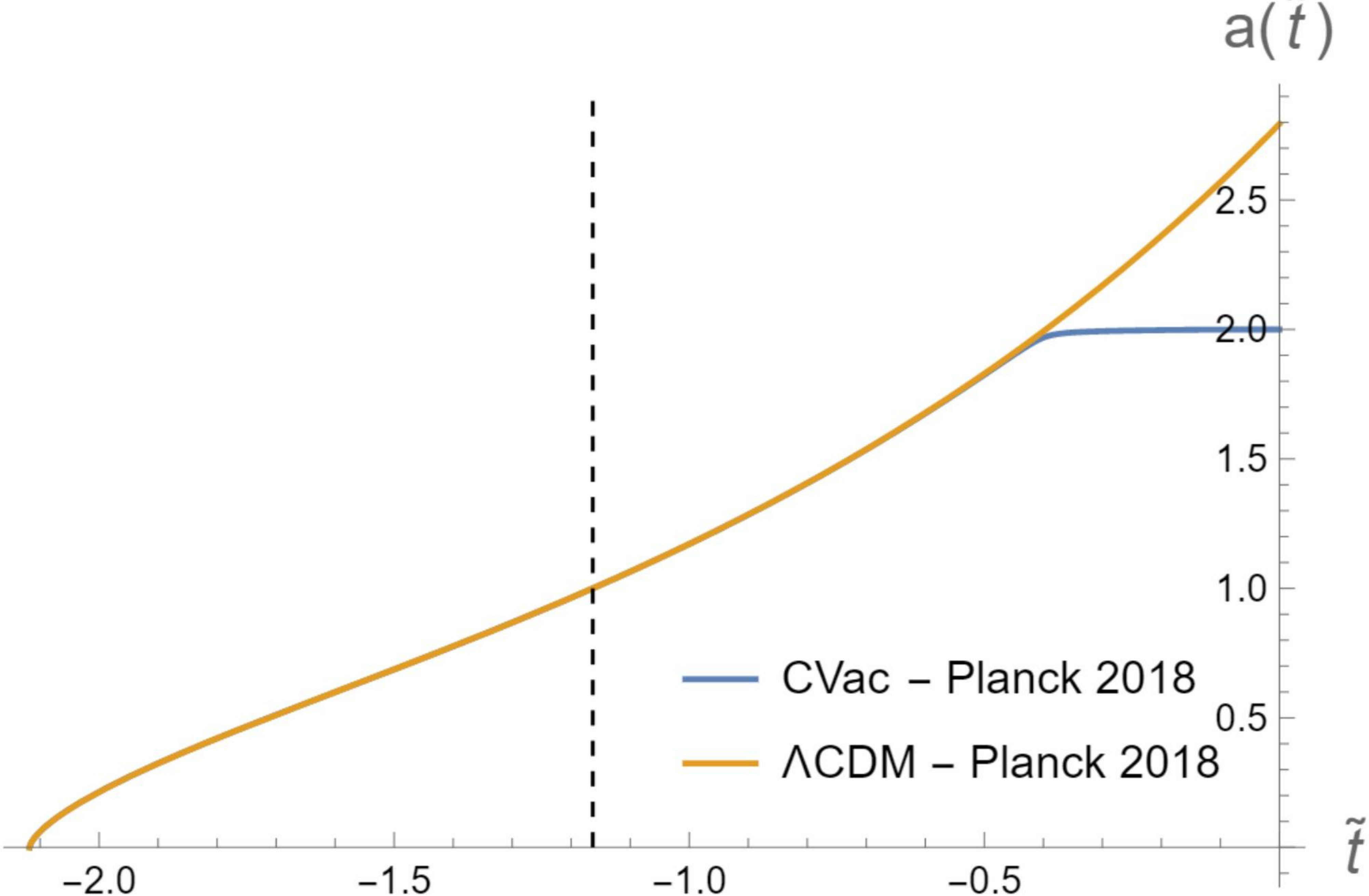


Now let's do more fine-tuning





2.0
1.5
1.0
0.5
−0.5
−1.0
−1.5
−2.0
−1.5
−1.0
−0.5
$\tilde{t}$
K_ϕ
$\tilde{V}(\phi)$
Radiation
Matter
Scale factor



a($\tilde{t}$)
2.5
2.0
1.5
1.0
0.5
$\tilde{t}$
−2.0
−1.5
−1.0
−0.5
CVac – Planck 2018
ΛCDM – Planck 2018

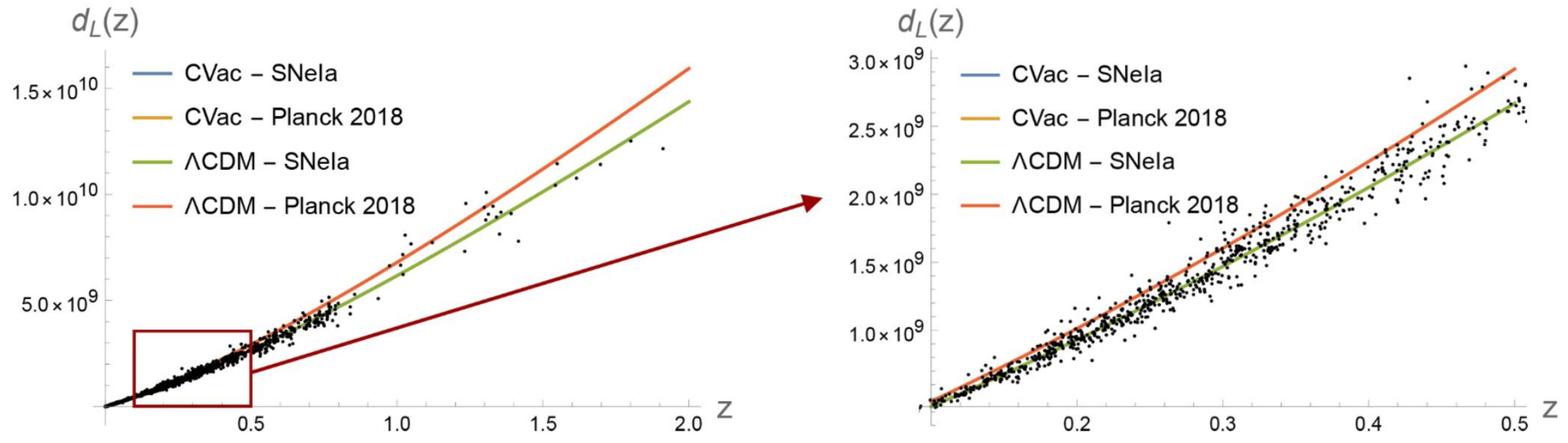


Figure 10: Luminosity distance $d_L(z)$ computed for two solutions involving rolling scalars (denoted by "CVac") and their corresponding ΛCDM solutions. For the *Planck* 2018 solution, the cosmological parameters are given in equation (3.15), the potential parameters in equation (3.16), and we used $H_0^{planck} = 67.66$ km s^{-1} Mpc^{-1} [24]. For the SNeIa solution, the cosmological parameters are given by[15] $\Omega_R = 9.96 \times 10^{-5}$, $\Omega_M = 0.338$, $\Omega_\Lambda = 0.662$, $H_0^{SN} = 73.4$ km s^{-1} Mpc^{-1} [22], and the potential parameters are $A = 0.662$, $B = -0.03$, $C = -5$, $X = 1$, $\Delta = 0.0716914850735$; this yields $\phi_0 = 0.824448$. The Pantheon+SH0ES experimental data is also depicted [32]. Our cosmological solutions and their corresponding ΛCDM solutions are indistinguishable, meaning that our model matches supernovae data as well as the ΛCDM model. Notice that the solutions generated using *Planck* 2018 cosmological parameters are in tension with data, while the ones generated using cosmological parameters derived from supernovae observations agree with data: this is a manifestation of the Hubble tension.

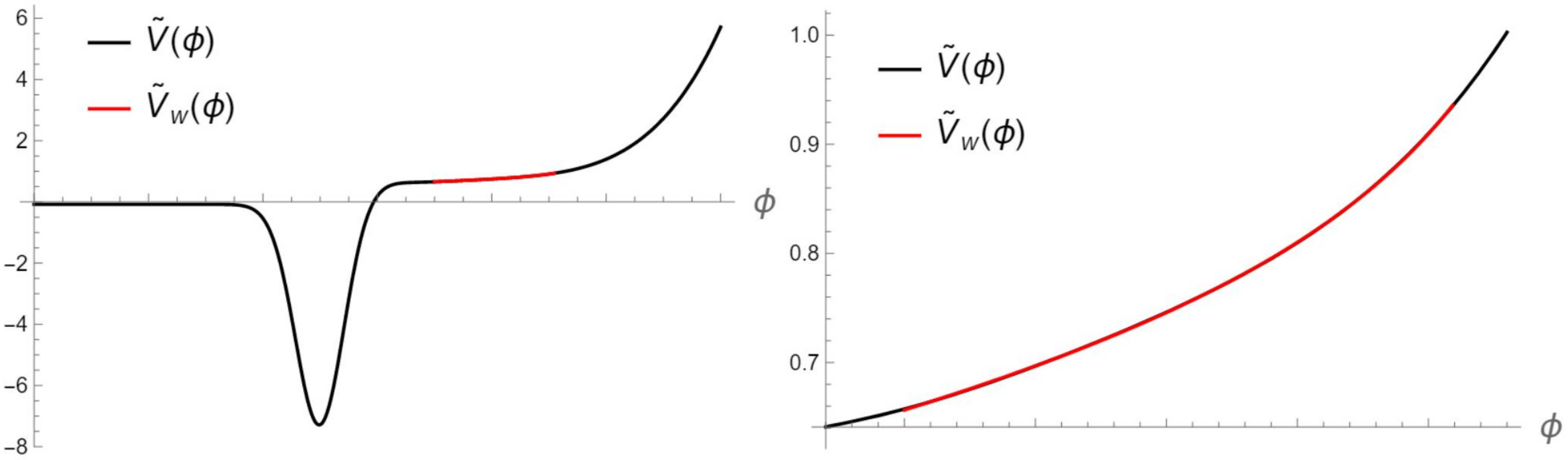


Figure 12: Rescaled potentials for the model $V(\phi)$ and reconstruction $V_w(\phi)$, where the region of the latter probed by the scalar field in the range $z \in (z_{\rm min}, z_{\rm max})$ is shown. The righthand plot is a close-up on this region. The precise form of the model $V(\phi)$ can be found in Appendix A.2.

Outlook

- Full cosmological history is encoded in a complex quantum state of a 4D QFT (not necessarily holographic or large N)
- Suggests the possibility of different solutions to cosmological problems, e.g. flatness, coincidence, horizon, etc.

Many questions:

- Spectrum of perturbations vs data? Role for primordial inflation?
- Large negative energy to stabilize the wormhole? Role of supersymmetry?
- Arrow of time? Spontaneous breaking of time reversal?
- Hubble tension? Predictions from the scalar sector?