Title: Accelerating cosmology from Î› < 0 gravitational effective field theory

Speakers: Chris Waddell

Series: Perimeter Institute Quantum Discussions

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Abstract: A large class of ? < 0 cosmologies have big-bang / big crunch spacetimes with time-symmetric backgrounds and asymptotically AdS Euclidean continuations suggesting a possible holographic realization. We argue that these models generically have time-dependent scalar fields, and these can lead to realistic cosmologies at the level of the homogeneous background geometry, with an accelerating phase prior to the turnaround and crunch. We first demonstrate via explicit effective field theory examples that models with an asymptotically AdS Euclidean continuation can also exhibit a period of accelerated expansion without fine tuning. We then show that certain significantly more tuned examples can give predictions arbitrarily close to a ?CDM model. Finally, we demonstrate via an explicit construction that the potentials of interest can arise from a superpotential, thus suggesting that these solutions may be compatible with an underlying supersymmetric theory.

This talk is based on 2212.00050.

Zoom link: https://pitp.zoom.us/j/93499736007?pwd=Qmw5cmZERUN3UmtwTzdKcEdXejJ5UT09

# Accelerating Cosmology from $\Lambda < 0$ Gravitational Effective Field Theory

Chris Waddell

UBC

December 12, 2022
Perimeter Institute

Based on arXiv:2212.00050 (w/ Antonini, Simidzija, Swingle, Van Raamsdonk)

# An Important Clarification

Observations (e.g. type Ia supernovae)

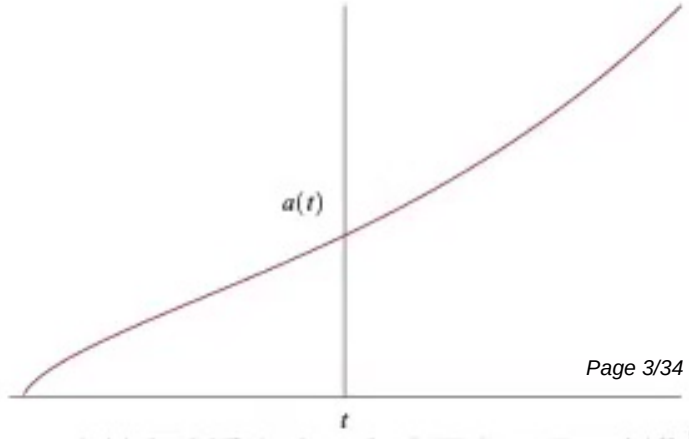
$+$

$\Lambda$CDM model ($\mathbf{\Lambda}$ and **C**old **D**ark **M**atter)

$\Downarrow$

$\Lambda > 0$

- Current energy density:
  - 70% cosmological constant
  - 30% matter (25% dark, 5% baryonic)
- Without $\Lambda > 0$, no acceleration
  - Matter domination: $a(t) \sim t^{2/3}$
  - Negative c.c. causes *deceleration*



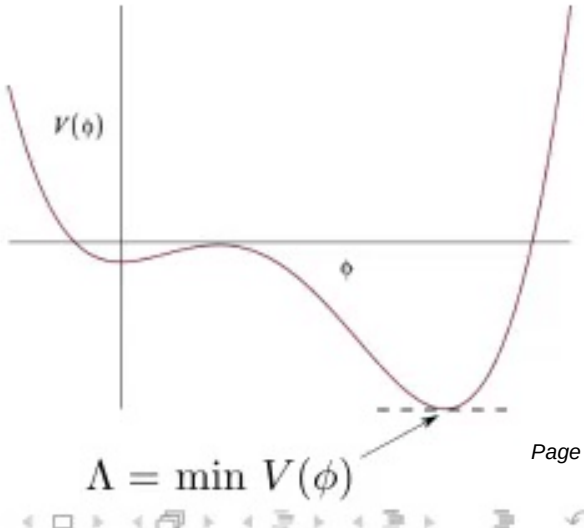
# An Important Clarification

Observations (e.g. type Ia supernovae)

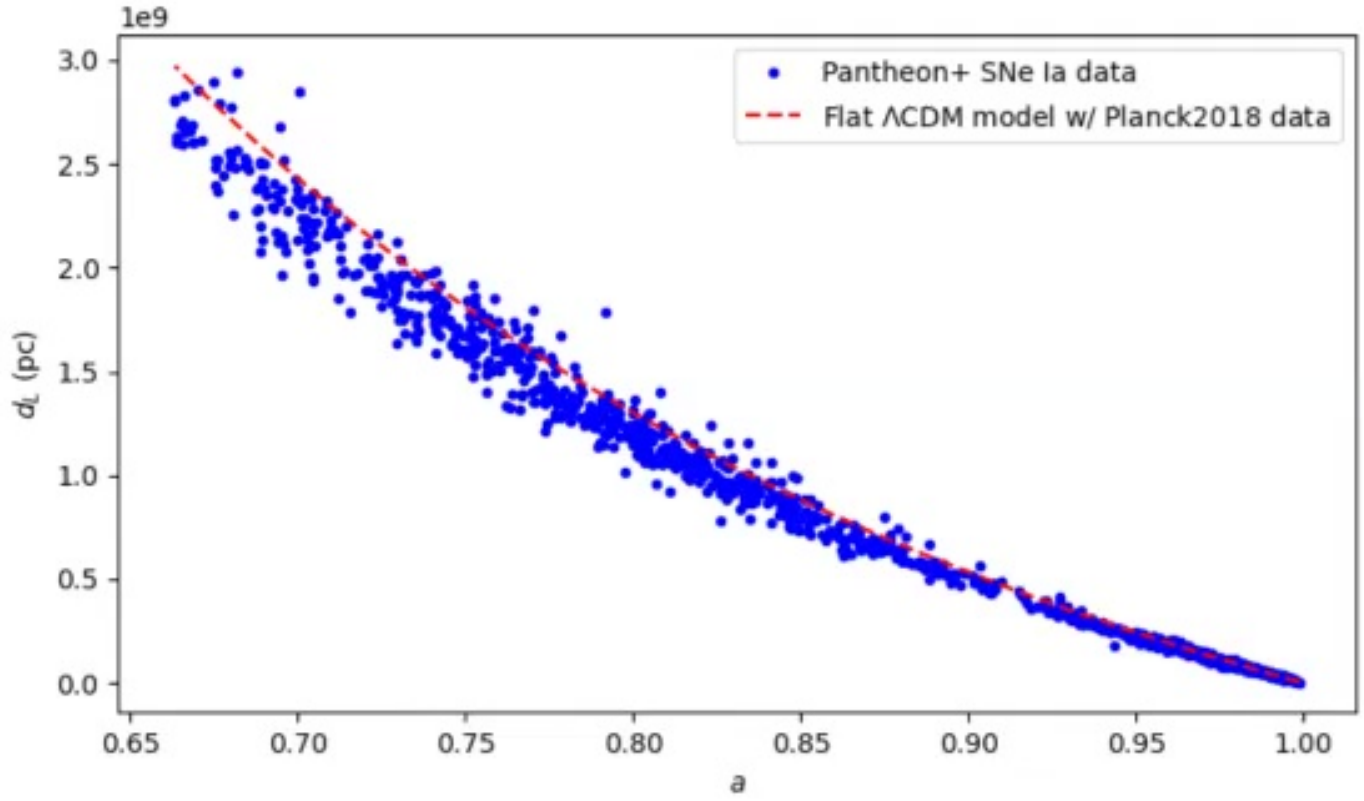
$\Downarrow$

$\dot{a} > 0$, $\ddot{a} > 0$, other mild constraints on $a(t)$

- Most general possibility consistent with symmetry: $t$-dependent **dark energy**
- Can model as scalar field $\phi$ ("quintessence")
  - $\ddot{a} > 0 \implies V(\phi) > 0$ *currently*
  - $\Lambda$ can be $> 0$, $< 0$, $= 0$



# What Do Observations Prefer?




N.B. (apparent luminosity) $= \frac{\text{(source luminosity)}}{4\pi d_L^2}$

# What Does Theory Prefer?

Difficult to say without complete understanding of non-perturbative quantum gravity, but...

- String Theory:
  - Compactifications typically result in light scalar fields
  - Various proposals for metastable dS vacua [Kachru, Kallosh, Linde, Trivedi], though no completely controlled microscopic examples (and *de Sitter conjecture*) [Danielsson, Van Riet], [Obied, Ooguri, Spodyneiko, Vafa], ...
- AdS/CFT:
  - Non-perturbative formulation of quantum gravity on $\Lambda < 0$ backgrounds
  - By analogy to holographic RG flows, having scalars that vary on cosmological time scales "generic" [Van Raamsdonk]

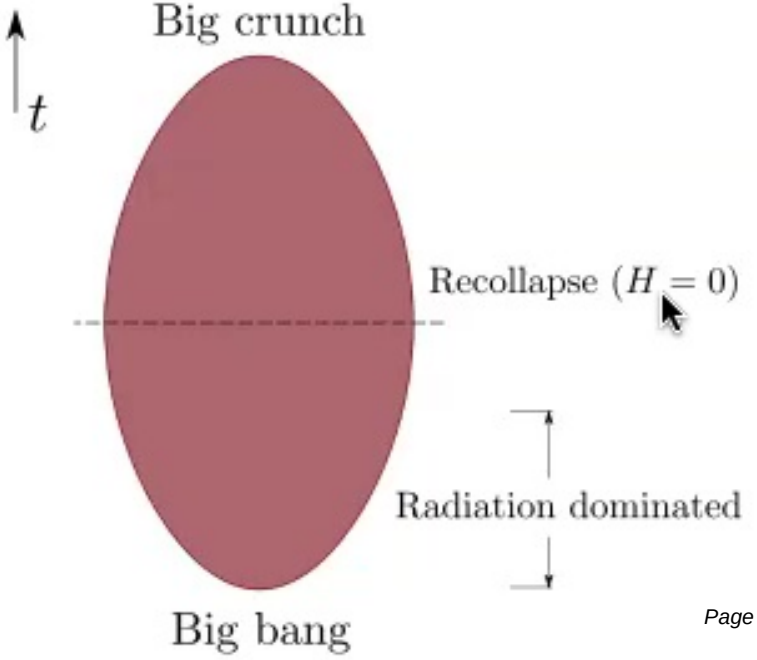
# Input from Holography

Want $\Lambda < 0$ cosmologies with a **holographic** description.
Conditions on effective theories/solutions?

Negative $\Lambda$ not sufficient!

Ex: Constant $\Lambda < 0$ & radiation, spatially flat

- $H^2 = \frac{\rho_R}{a^4} + \Lambda \quad (H = \frac{\dot{a}}{a})$
- Spatial slices are $\mathbb{R}^3$
- **No AdS boundaries!** Where could CFT live?



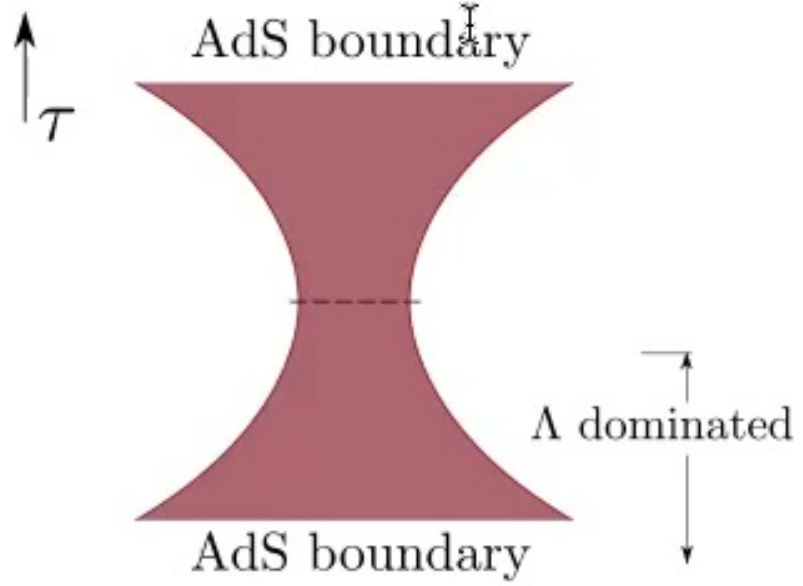
# Input from Holography

Solution: Analytic continuation!

- $t \to i\tau \quad (\dot{a}^2 \to -(a')^2)$
- Time reflection symmetry $\implies$ real Euclidean geometry

Ex: Constant $\Lambda < 0$ & radiation, spatially flat

- $(\frac{a'}{a})^2 = -\frac{\rho_R}{a^4} - \Lambda$
- **AdS boundaries** in Euclidean past/future!




[Maldacena, Maoz]
[Cooper, Rozali, Swingle, Van Raamsdonk, CW, Wakeham]; [Van Raamsdonk]; [Antonini, Simidzija, Swingle, Van Raamsdonk]

## Input from Holography

We will henceforth work with gravity + scalar theory

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{|g|}R + \int d^4x\sqrt{|g|}\left(-\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi)\right)$$

with additional radiation ($p = \frac{1}{3}\rho$) and/or matter ($p = 0$)

Not every $\Lambda < 0$ potential $V(\phi)$ permits Euclidean AdS wormholes!

Geometry of the Euclidean wormhole:

- Spatially flat cosmology $\implies$ planar symmetry

$$ds^2_{\text{4D}} = d\tau^2 + a(\tau)^2 dx_i dx^i$$

## Input from Holography

(Euclidean) scalar field equation with this wormhole ansatz:

$$\phi'' + 3\frac{a'}{a}\phi' - V'(\phi) = 0$$

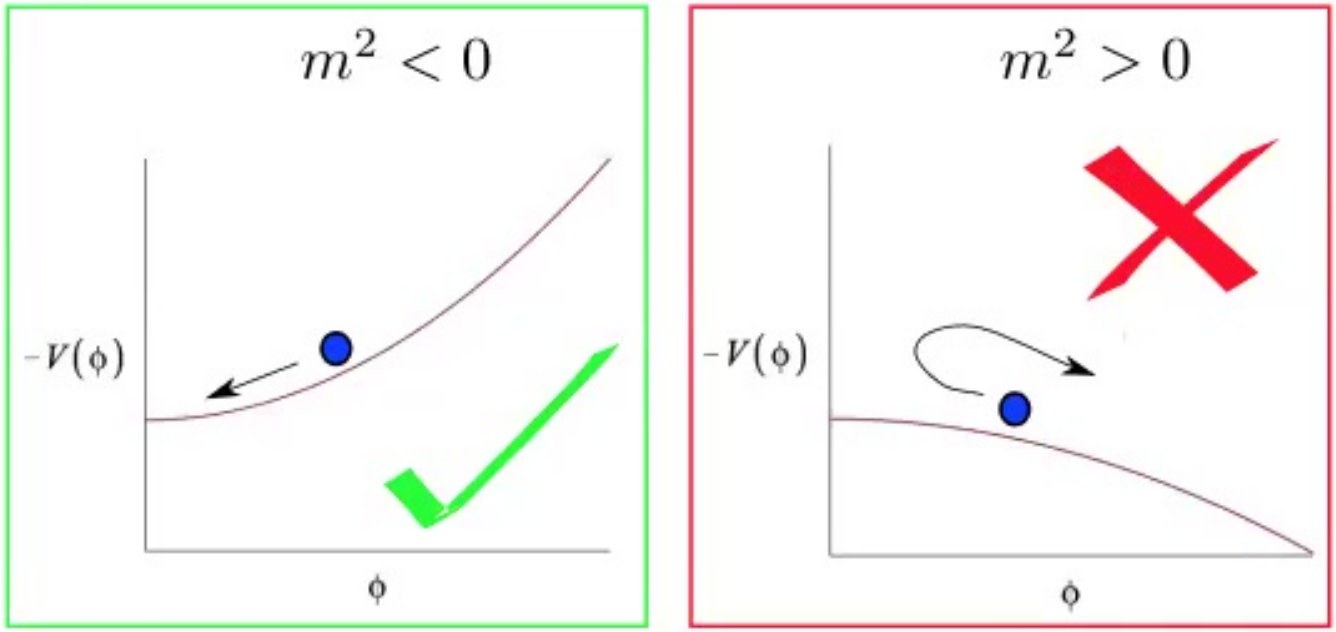
Particle in inverted potential $-V(\phi)$ with (anti)friction!

- $\frac{a'}{a} > 0$: Damped
- $\frac{a'}{a} < 0$: Anti-damped

Need $\phi$ to approach constant (we take $\phi = 0$) in AdS regions

# Input from Holography

Need $\phi$ to approach constant (we take $\phi = 0$) in AdS regions




Require $\boxed{V'(0) = 0}$ and $\boxed{m^2 \equiv V''(0) < 0}$

## Input from Holography

Additional constraint on $V''(0)$ in any holographic theory:
**Breitenlohner-Freedman (BF) bound**

- In 4d bulk: $-\frac{9}{4} \leq \frac{V''(0)}{|V(0)|} \equiv m^2 L^2_{\text{AdS}}$
- In AdS/CFT (4d bulk)

$$m^2 L^2_{\text{AdS}} = \Delta(\Delta - 3) \implies \Delta = \frac{3}{2} \pm \sqrt{\frac{9}{4} + m^2 L^2}$$

so BF bound is basic consequence of e.g. unitarity in CFT

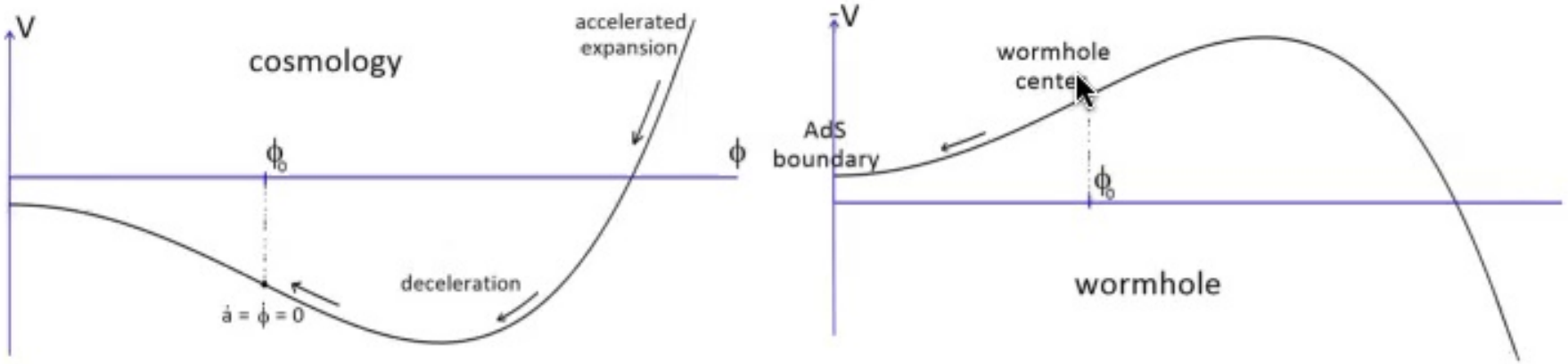
# Input from Holography

Recap of holographic constraints on theories/solutions:

- Negative $\Lambda$: $V(0) < 0$
- Euclidean continuation to real, asymptotically AdS wormhole:
  - $V'(0) = 0$
  - $V''(0) < 0$
  - Time-symmetric solution
- Stability of quantum theory: BF bound $-\frac{9}{4} \leq \frac{V''(0)}{|V(0)|}$

# Input from Holography

Recap of holographic constraints on theories/solutions:




So much for holography. What about **cosmology**?

# Accelerating Holographic Cosmologies

**Q:** Can we obtain realistic (e.g. *accelerating*) cosmological backgrounds?

- Lorentzian (cosmology) equations of motion

$$\ddot{\phi} + 3H\dot{\phi} + V'(0) = 0 \qquad \text{(scalar)}$$

$$H^2 = \frac{1}{2}\dot{\phi}^2 + V(\phi) + \frac{\rho_M}{a^3} + \frac{\rho_R}{a^4} \qquad \text{(Friedmann)}$$

# Accelerating Holographic Cosmologies

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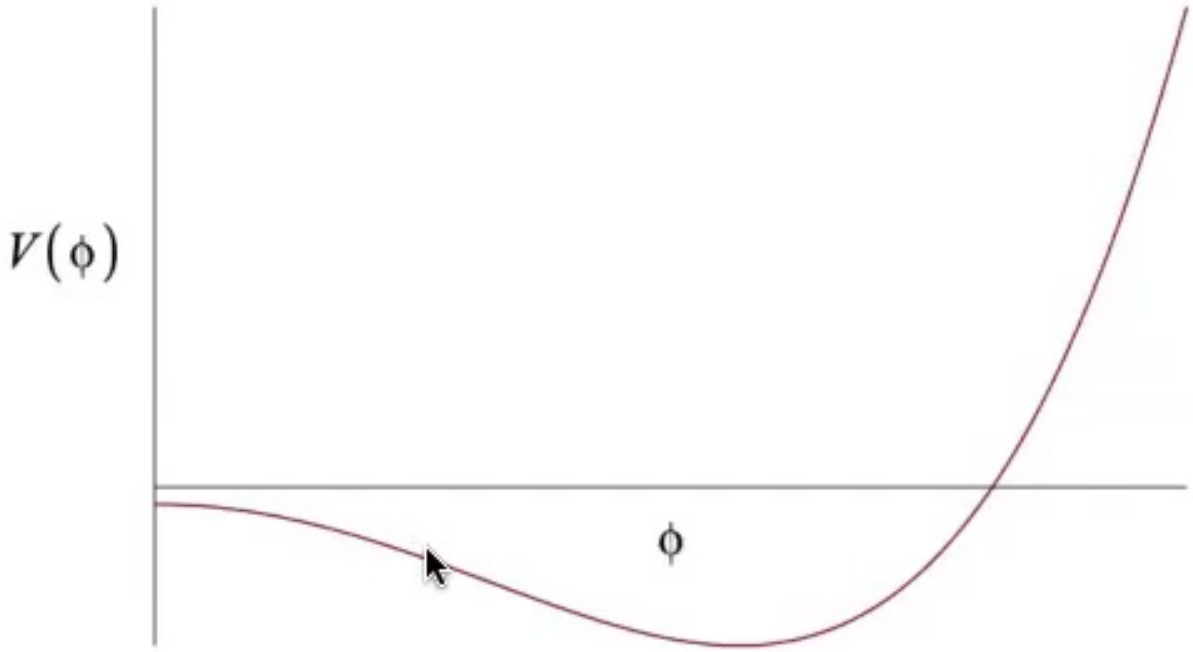
- Together, imply acceleration equation

$$\frac{\ddot{a}}{a} = -\dot{\phi}^2 + V(\phi) - \frac{1}{2}\frac{\rho_M}{a^3} - \frac{\rho_R}{a^4}$$

- Immediate consequence: $\ddot{a} > 0 \implies V(\phi) > 0$

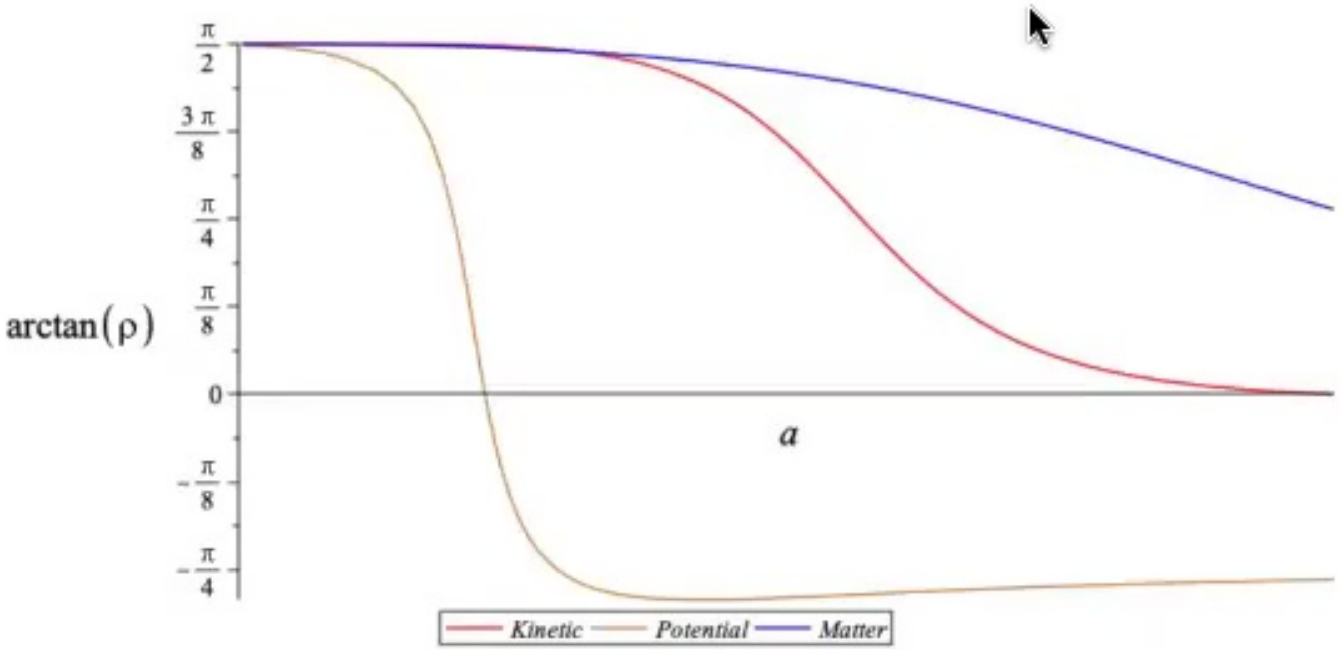
# Accelerating Holographic Cosmologies




**Q:** Are we done?

**A:** No! We have time-symmetric initial conditions $H(0) = \dot{\phi}(0) = 0$.
Solving backward in time, the potential may never dominate.

# Accelerating Holographic Cosmologies



# Accelerating Holographic Cosmologies

We will argue that obtaining acceleration doesn't require significant fine-tuning of parameters *or* initial conditions.

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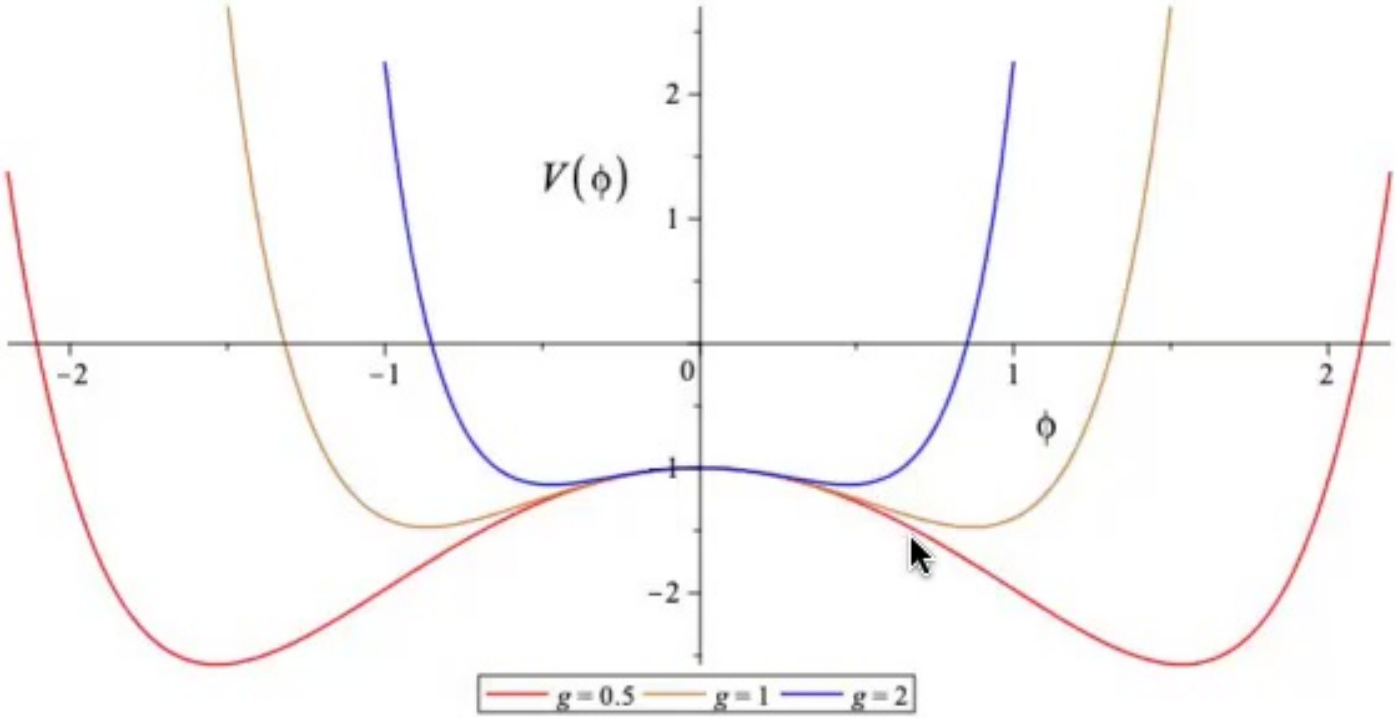
Ex: Consider the potential

$$V(\phi) = -1 - \frac{9}{8}\phi^2 + V_{\text{int}}(\phi)$$

$$V_{\text{int}}(\phi) = e^{g\phi^2} - g\phi^2 - 1$$

# Accelerating Holographic Cosmologies



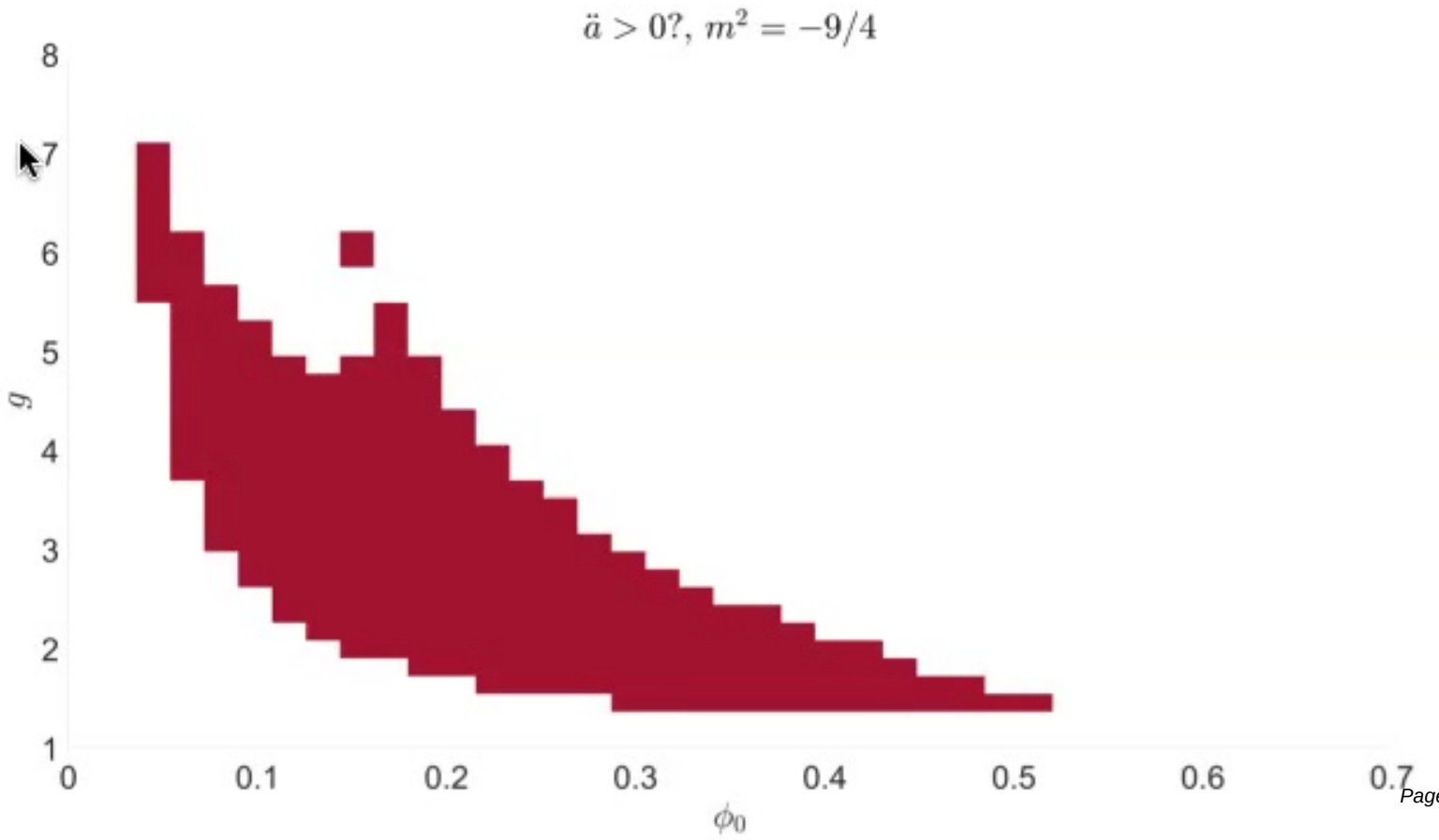
# Accelerating Holographic Cosmologies

Ex: Consider the potential

$$V(\phi) = -1 - \frac{9}{8}\phi^2 + V_{\text{int}}(\phi)$$
$$V_{\text{int}}(\phi) = e^{g\phi^2} - g\phi^2 - 1$$

In the theory with scalar + radiation, time-symmetric solutions parametrized by $\phi(0) = \phi_0$ (up to rescaling of $a(t)$)

# Accelerating Holographic Cosmologies



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# Realistic Holographic Cosmologies

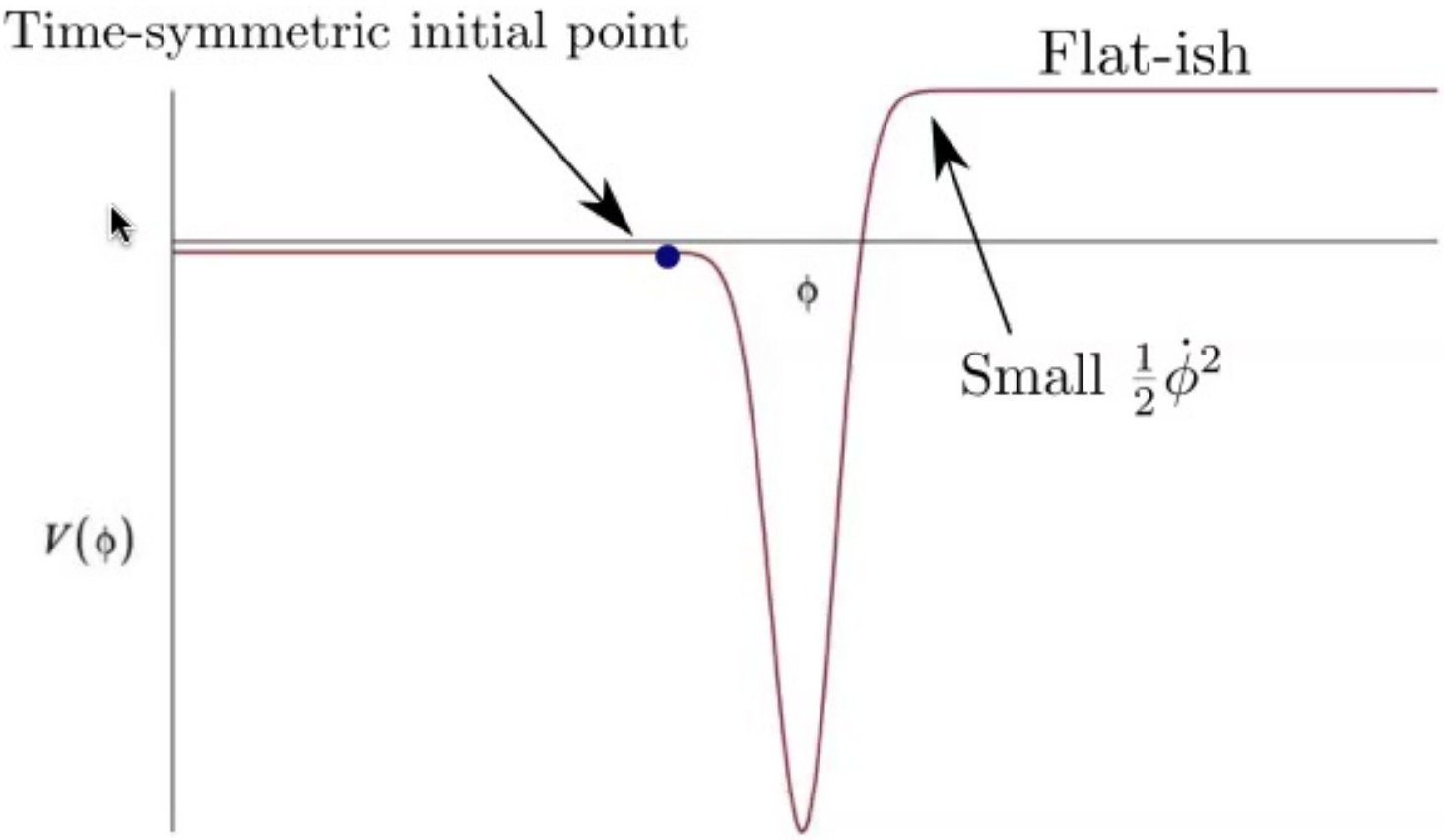
Basic holographic constraints on theories/solutions do not prevent accelerating cosmologies

**Q:** What about more realistic cosmology solutions?
**A:** Also fine!

- From the perspective of the effective theory, there is a trade-off between obtaining a desired $a(t)$ and fine-tuning
- However, observational constraints on $a(t)$ consistent with broad range of potentials [Antonini, Simidzija, Swingle, Van Raamsdonk, CW] (to appear)

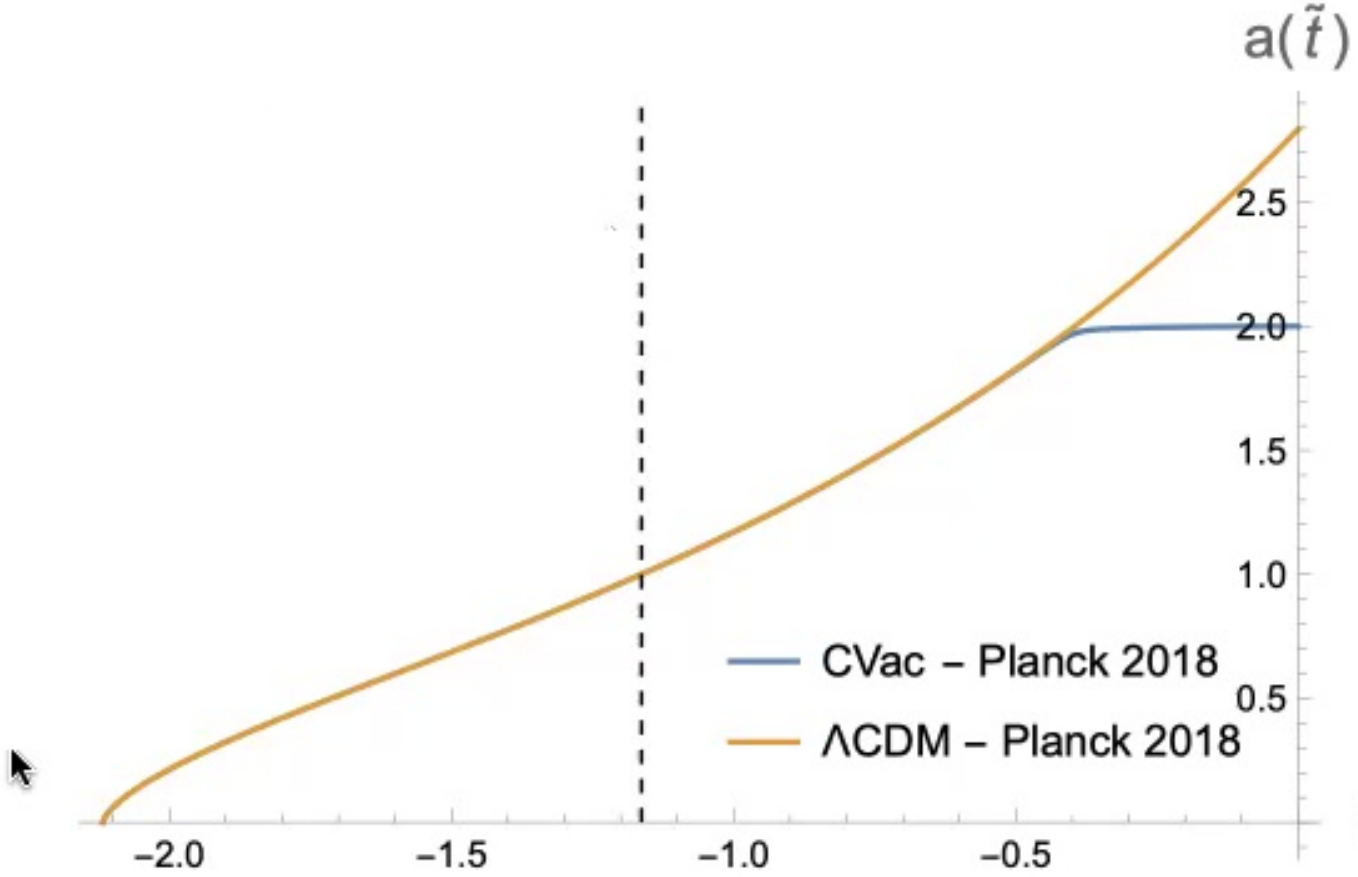
# Realistic Holographic Cosmologies

Ex: ΛCDM



# Realistic Holographic Cosmologies

Ex: ΛCDM



# Realistic Holographic Cosmologies

We tuned the potential to be flat to precisely match $\Lambda$CDM.
In reality, we should match observations, not $\Lambda$CDM!
This allows much more freedom in $V(\phi)$.

Ex: Type Ia supernovae probe scale factor in range $\frac{a(t)}{a(t_{\text{present}})} \in (0.27, 1)$

It is possible to have $\Delta V/V = O(1)$ in this range and still agree with these observations!

# Realistic Holographic Cosmologies

Ex: $w$CDM model

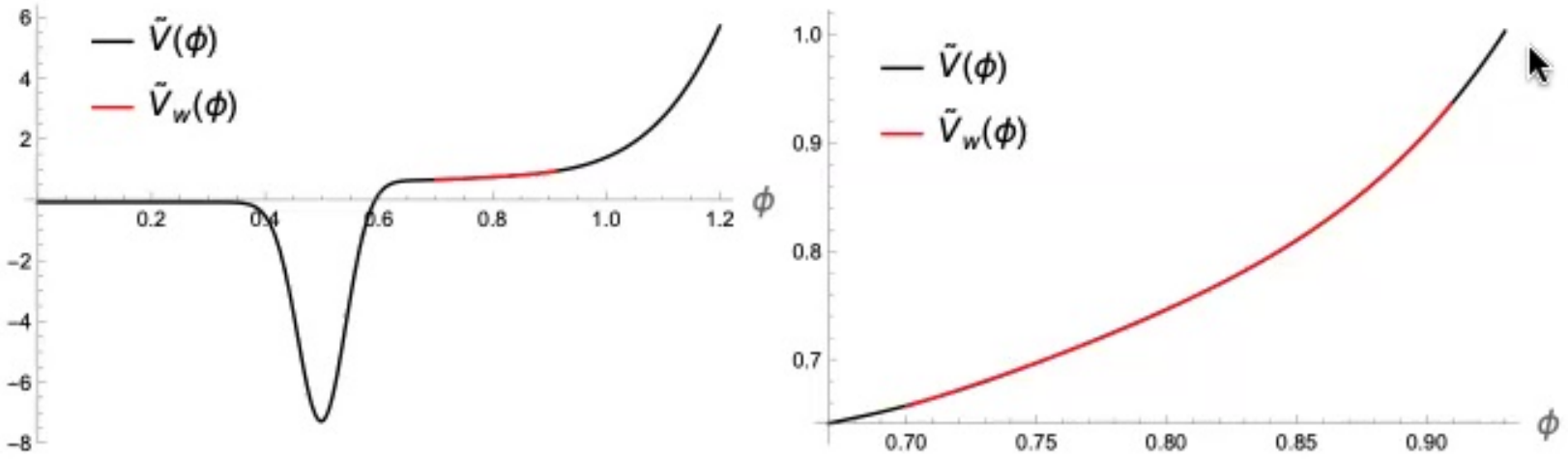
- Dark energy is a perfect fluid with equation of state $p = w\rho$, with constant $w$
- $\Lambda$ is special case $w = -1$
- This equation of state can be realized by time-evolving scalar field:

$$w = \frac{\frac{1}{2}\dot{\phi}^2 - V}{\frac{1}{2}\dot{\phi}^2 + V}$$

- Constraint from type Ia supernovae in $\frac{a(t)}{a(t_{\text{present}})} \in (0.27, 1)$: $w = -0.90 \pm 0.14$ [Pantheon+]

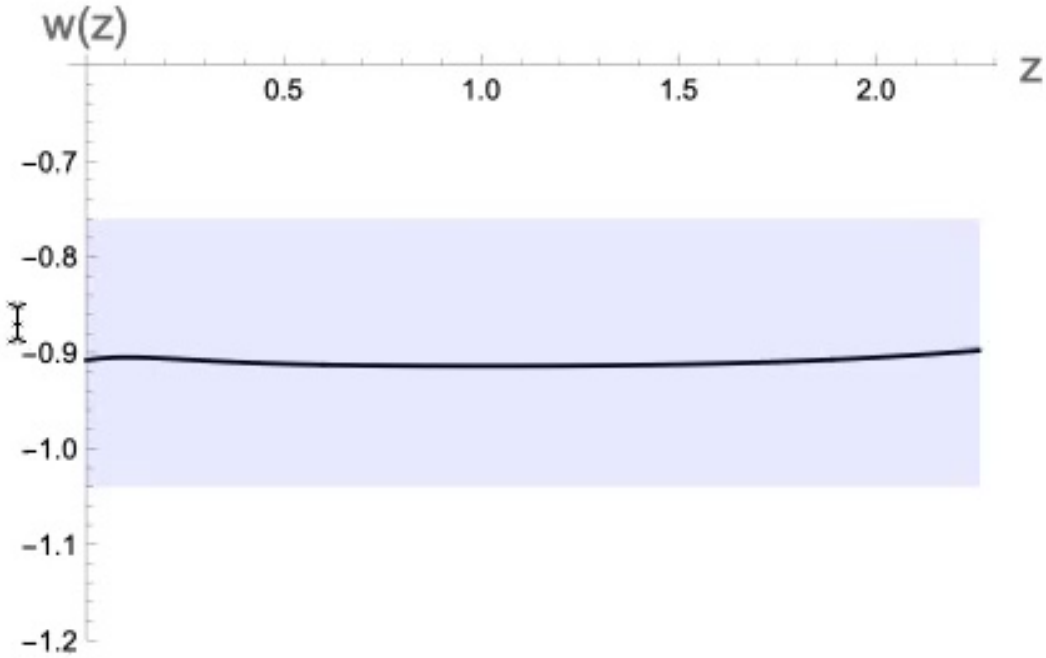
# Realistic Holographic Cosmologies

Ex: $w$CDM model



# Realistic Holographic Cosmologies

Ex: $w$CDM model




N.B. $1 + z = \frac{1}{a(t)}$

## Summary

- Cosmology with $\Lambda < 0$ and time-dependent dark energy observationally consistent and theoretically well-motivated
- Formulated conditions on $\Lambda < 0$ EFT admitting AdS/CFT description
  - $V(0) < 0$ and $V'(0) = 0$ and $-\frac{9}{4}|V(0)| \leq V''(0) < 0$
  - Time-symmetric solutions
- Acceleration generic (for some families of EFTs)
- Possible to obtain realistic cosmological background for arbitrarily long time (with tuning)
- Also in 2212.00050: Possible for EFT to be *supersymmetric*

What next?

# Outlook

- **Direct reconstruction** of $V(\phi)$ from supernova observations:
  - Obviates the need for fine-tuning?
  - See upcoming [Antonini, Simidzija, Swingle, Van Raamsdonk, CW]
- Can we explain **structure**?
  - Can we reproduce the CMB power spectrum?
  - Do we require inflation?
- Moving from effective field theory to a **microscopic theory**
  - Candidate microscopic description: supersymmetric 3D-4D-3D CFTs [Van Raamsdonk]
  - Can we understand the physics of these theories better (either in CFT, 10D supergravity, or 4D effective theory)?

# Thanks!