

Title: Cosmology from the vacuum

Speakers: Mark Van Raamsdonk

Series: Quantum Fields and Strings

Date: April 26, 2022 - 2:00 PM

URL: <https://pirsa.org/22040128>

Abstract: We suggest a framework for cosmology based on gravitational effective field theories with a negative fundamental cosmological constant, which may exhibit accelerated expansion due to the positive potential energy of rolling scalar fields. The framework postulates an exact time-reversal symmetry of the quantum state (with a time-symmetric big bang / big crunch background cosmology) and an analyticity property that relates cosmological observables to observables in a Euclidean gravitational theory defined with a pair of asymptotically AdS planar boundaries. The latter can be given a microscopic definition using holography, so the model is UV complete. While it is not yet clear whether the framework can give realistic predictions, it has the potential to resolve various naturalness puzzles without the need for inflation.

Zoom Link: <https://pitp.zoom.us/j/95099004342?pwd=OWZoanJJMHNzMXF4S3VYM2Vxcklodz09>



# COSMOLOGY FROM THE VACUUM

Perimeter Institute, Apr 2022

Mark Van Raamsdonk (UBC)

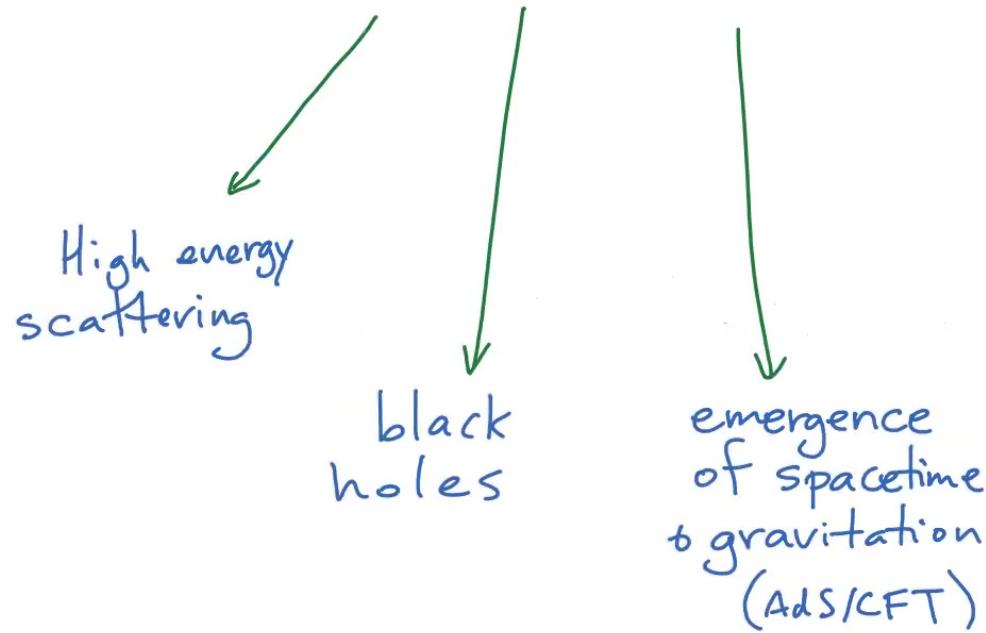


1810.10601 w Cooper, Rozali, Swingle, Waddell, Wakeham

2008.02259 , 2102.05057 , in progress w. Swingle  
Simidzija  
Antonini



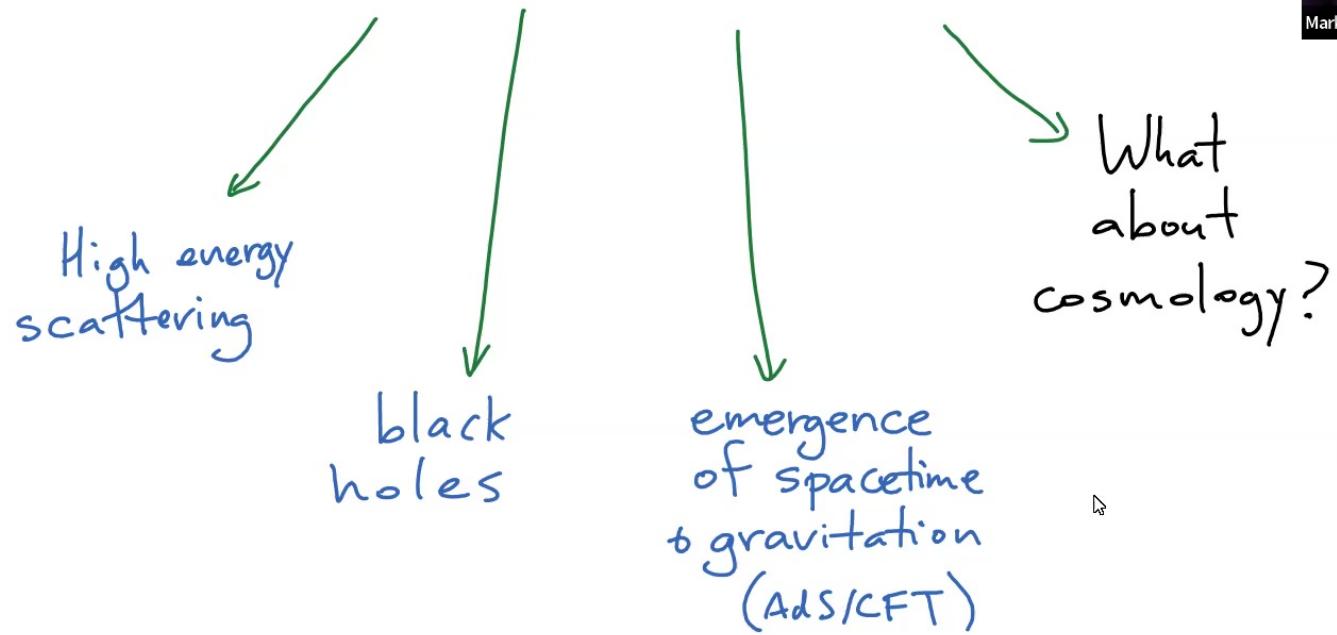
## Quantum gravity from string theory





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## Quantum gravity from string theory





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Possible misconception:

Hard to come up with non-perturbative  
description of cosmology because AdS/CFT  
works for  $\Lambda < 0$  and our universe has  $\Lambda > 0$





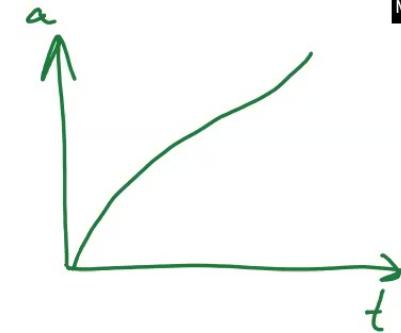
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Observations:

$$ds^2 = -dt^2 + a^2(t) d\vec{x}^2$$

$$\dot{a}(t) > 0$$

$$\ddot{a} > 0 \quad \text{presently}$$



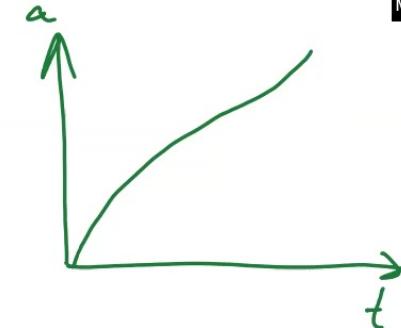


Observations:

$$ds^2 = -dt^2 + \dot{a}^2(t)d\vec{x}^2$$

$$\dot{a}(t) > 0$$

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Einstein's equations:

$$\ddot{a} > 0 \implies 3p + \rho < 0$$

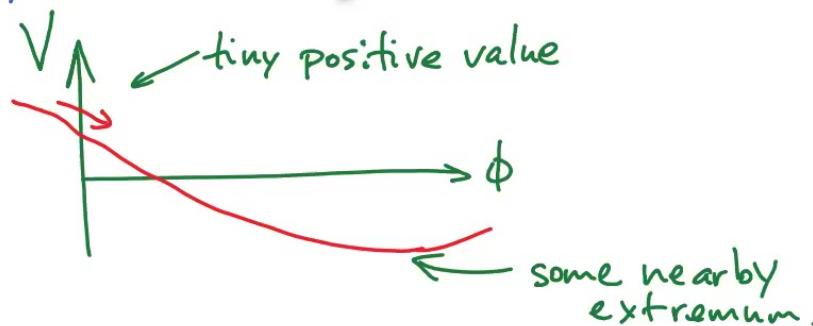
Could be from ①  $\Lambda > 0$

② time dep. scalar with  
 $V(\vec{\phi}) > 0$



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- \* most general background consistent with symmetries of cosmology has time-dep. scalars
- \* if  $\ddot{a} > 0$  is due to  $V(\phi)$  for time-dep. scalars, it is natural to have  $\Lambda < 0$



$$\textcircled{1} \quad \Lambda > 0$$

$$\textcircled{2} \quad V(\vec{\varphi}) > 0 \quad \begin{array}{l} \nearrow \Lambda > 0 \\ \rightarrow \Lambda = 0 \\ \searrow \Lambda < 0 \end{array}$$



What does string theory prefer?





$$\textcircled{1} \quad \Lambda > 0$$

$$\textcircled{2} \quad V(\vec{\varphi}) > 0 \quad \begin{array}{l} \rightarrow \Lambda > 0 \\ \rightarrow \Lambda = 0 \\ \rightarrow \Lambda < 0 \end{array}$$

What does string theory prefer?

→ plenty of scalars in effective field theory descriptions



→ beautiful microscopic understanding of  
 $\Lambda < 0$  physics using holography



$$\textcircled{1} \quad \Lambda > 0$$

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What does string theory prefer?

→ plenty of scalars in effective field theory descriptions

→ beautiful microscopic understanding of  $\Lambda < 0$  physics using holography

- String theory discussions of cosmology focused on  $\Lambda > 0$

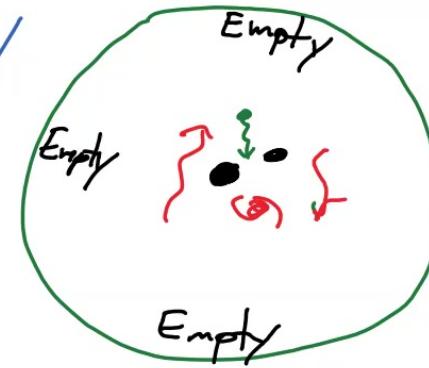
-  $\Lambda < 0$  cosmology seems like better target!



Main challenge with describing  $\Lambda < 0$  cosmology  
holographically:



- Cosmology has homogeneous + isotropic matter
- AdS/CFT describes spacetimes that are asymptotically EMPTY



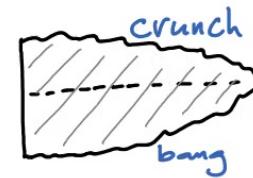
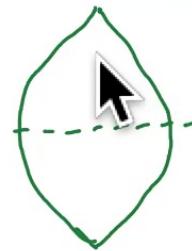


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Alternatively:  $\Lambda < 0$  cosmological spacetimes  
are typically big-bang/big crunch spacetimes  
with no asymptotically AdS regions

e.g.  $\Lambda < 0$  + radiation flat cosmology

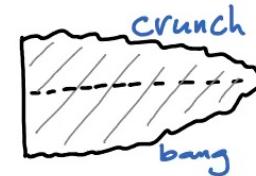
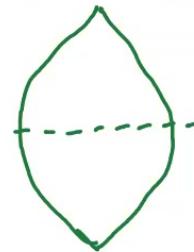
$$ds^2 = -dt^2 + L^2 \cos(Ht) d\vec{x}^2$$





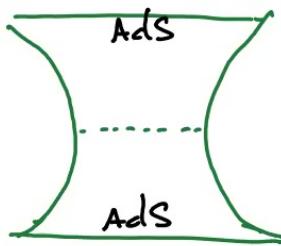
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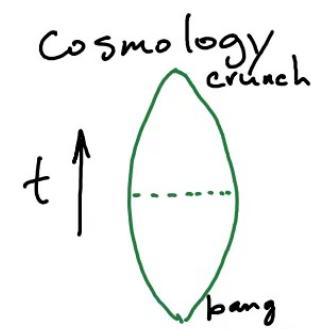
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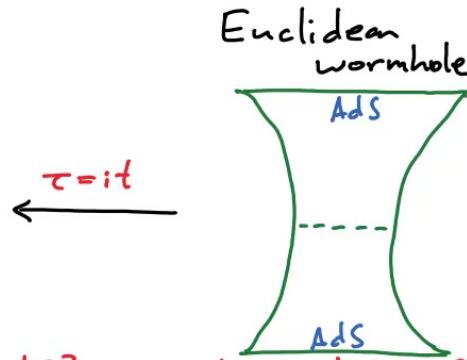
BUT: this has asymptotically AdS regions in analytic continuation!

$$ds^2 = d\tau^2 + L^2 \cosh(H\tau) d\vec{x}^2$$

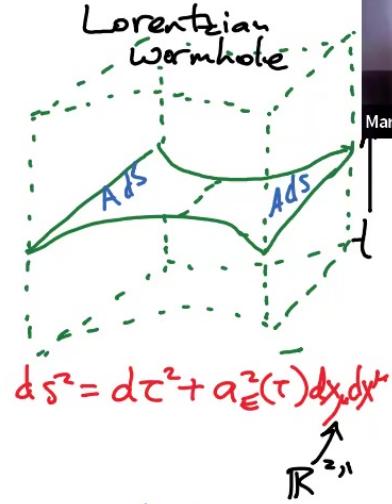




$$ds^2 = -dt^2 + a^2(t)d\vec{x}^2$$



$$ds^2 = d\tau^2 + a_E^2(\tau)d\vec{x}^2$$

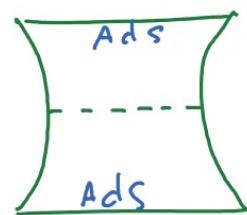


$$ds^2 = d\tau^2 + a_E^2(\tau)dx^i dx^i$$



- Another analytic continuation gives a static Lorentzian planar wormhole.
- Start by understanding holographic description of this.





2 asymptotically  
AdS regions

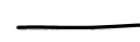


2 3D holographic  
CFTs

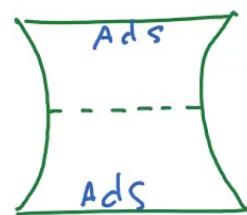


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traversable



CFTs must  
interact somehow,  
but not locally



2 asymptotically  
AdS regions

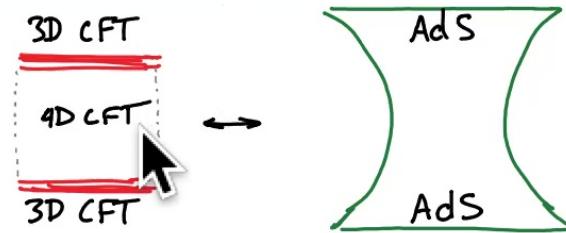
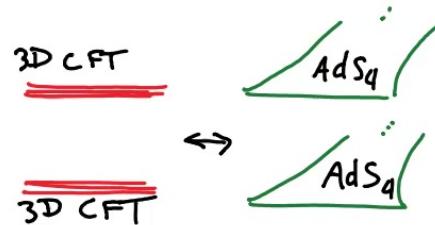


2 3D holograph  
CFTs



traversable → CFTs must  
interact somehow,  
but not locally

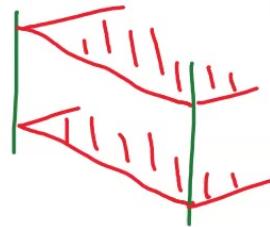
IDEA:



- couple 2 CFTs by small  $N$  4D CFT



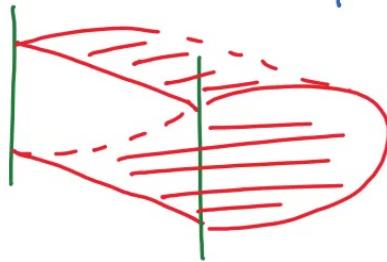
String theory motivation:



Defects = branes in dual gravity  
description

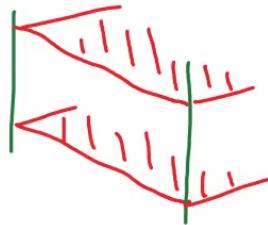
Choose defects to correspond to brane-antibrane pair.

→ parallel branes unstable + connect up in bulk





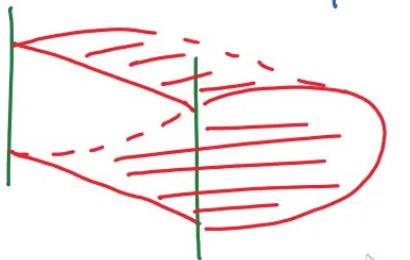
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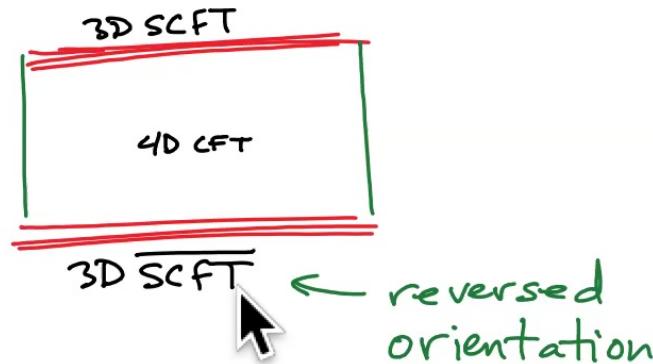
→ parallel branes unstable to connect up in bulk



\* we want mostly 4D gravity, so no holographic defect/boundary theories coupled by non-holographic theory.

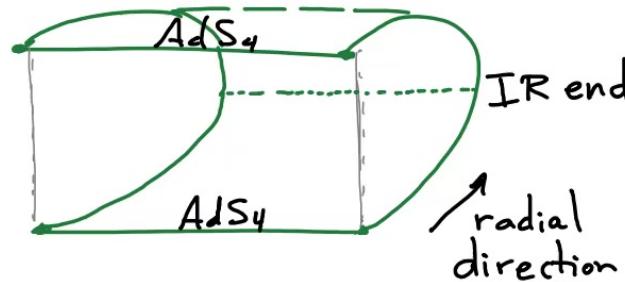


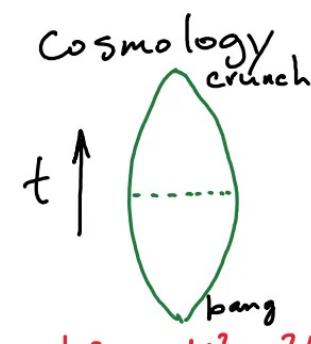
# Field theory description of brane-antibrane physics:



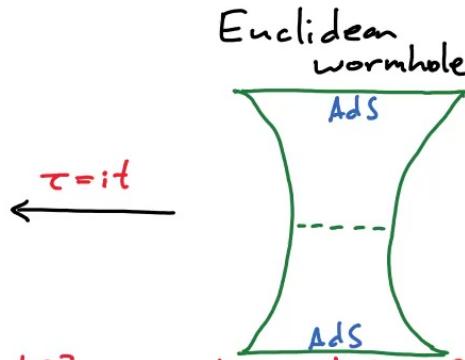
3D Lorentz-invariant  
QFT with  
confinement in  
IR and symmetry  
breaking

$$G \times G \rightarrow G$$

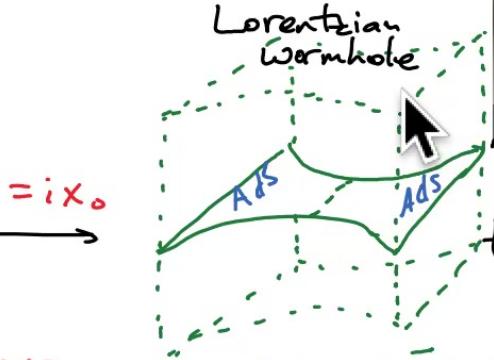




$$ds^2 = -dt^2 + a^2(t)d\vec{x}^2$$



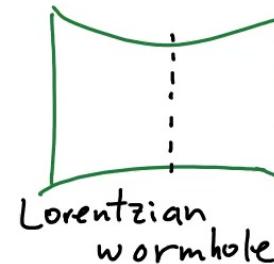
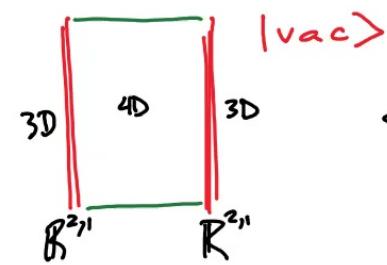
$$ds^2 = d\tau^2 + a_E^2(\tau)d\vec{x}^2$$



$$ds^2 = d\tau^2 + a_E^2(\tau)dx^0 dx^1$$

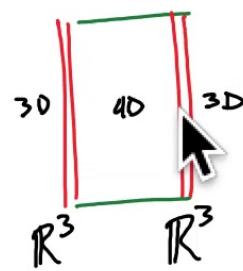
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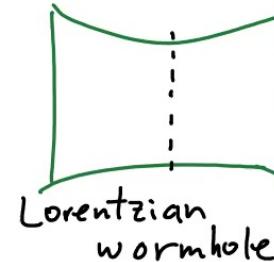
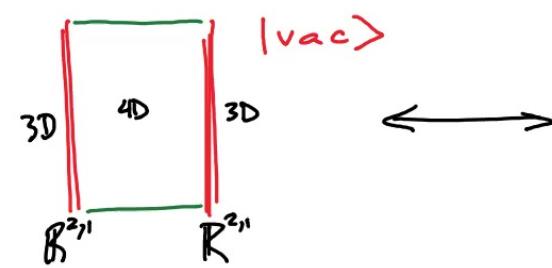


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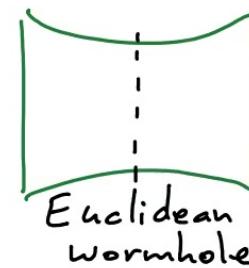
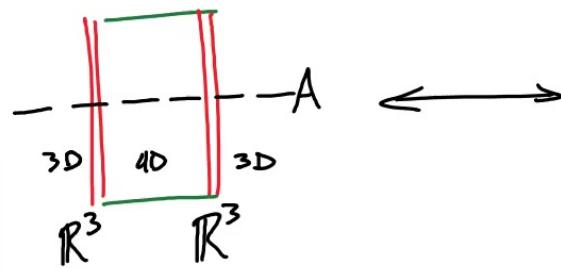


$$ds^2 = d\tau^2 + \tilde{a}_E^2(\tau) d\vec{x}^2$$



$$ds^2 = d\tau^2 + a_E^2(\tau) d\vec{x}^2$$

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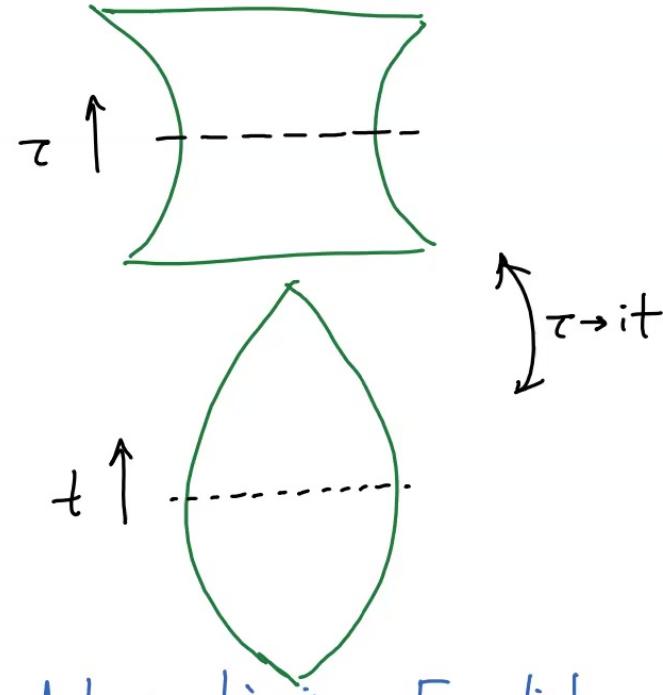
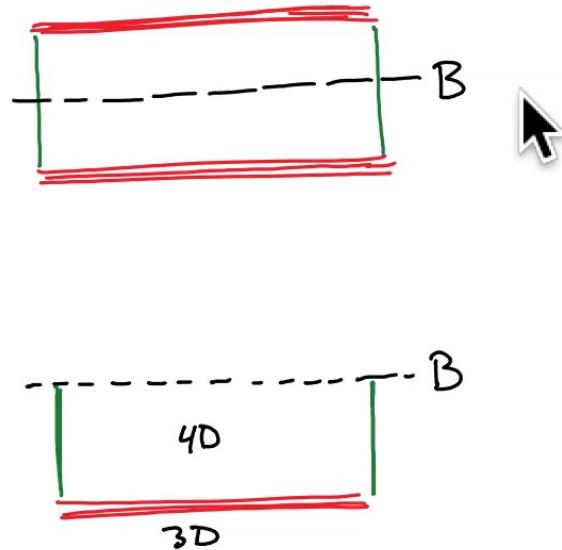
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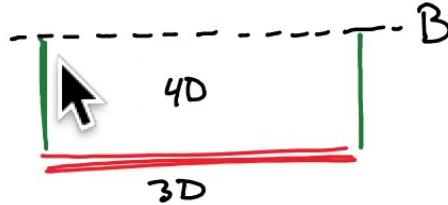
State of Lorentzian theory defined by slicing  
 Euclidean path integral:  $\mathcal{I}_A[\phi_0] = \int [d\phi] e^{-S_E}$



## Holographic description of cosmology:



State for cosmology defined by slicing Euclidean path integral in perp. direction:  $\Psi_B[\phi_0] = \int_{\{\phi=0\}}^{[\phi(B)=\phi_0]} [d\phi] e^{-S_E}$

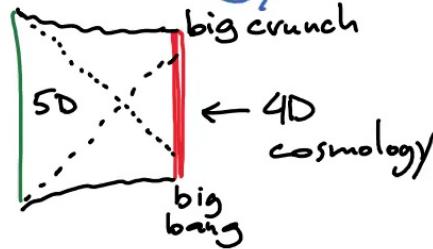


$$\mathcal{I}_{4D}[\phi] = \int [d\phi_{3D}] [d\phi_{4D}] e^{-S_E} \quad \phi_{4D}[B] = \phi_0$$

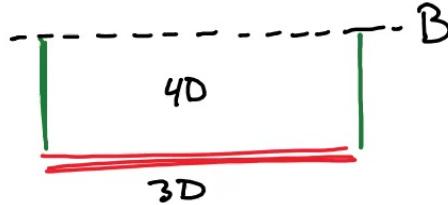


Complex high-energy state of 4D CFT  
 ↙ generally  
 non-holographic

Holographic case: dual to black hole microstate,  
 cosmology is behind horizon!



$$ds^2 = -dt^2 + a^2(t) d\vec{x}^2$$



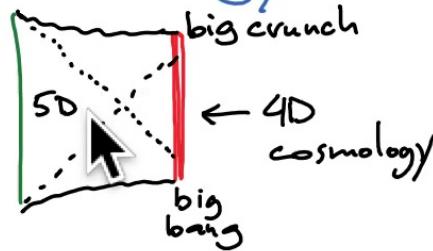
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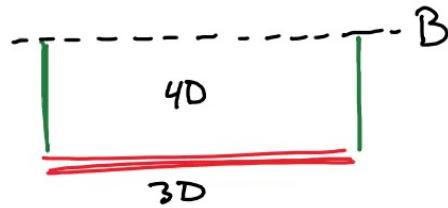


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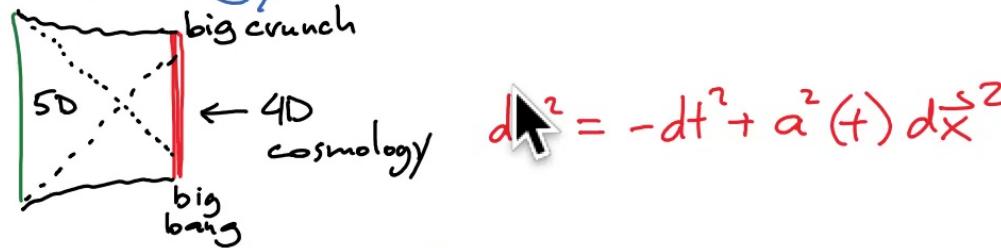


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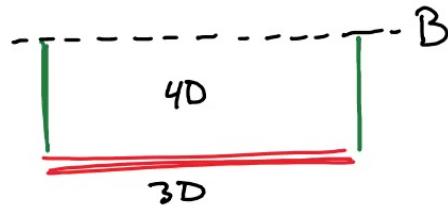
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$$ds^2 = -dt^2 + a^2(t) d\vec{x}^2$$

General case: only cosmology has geometrical description,  
 encoded in deep IR physics of QFT state.

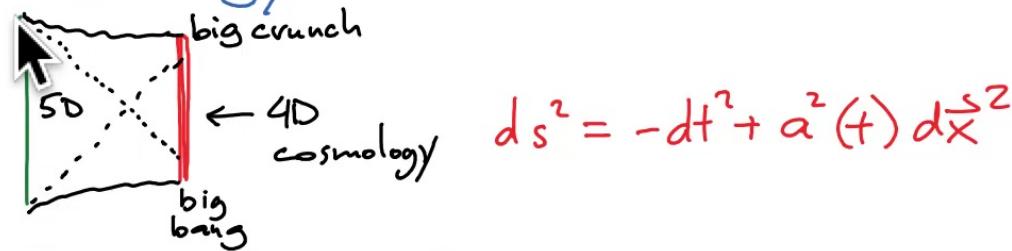


$$\mathcal{W}_{4D}[\phi] = \int [d\phi_{3D}] [d\phi_{4D}] e^{-S_E}$$

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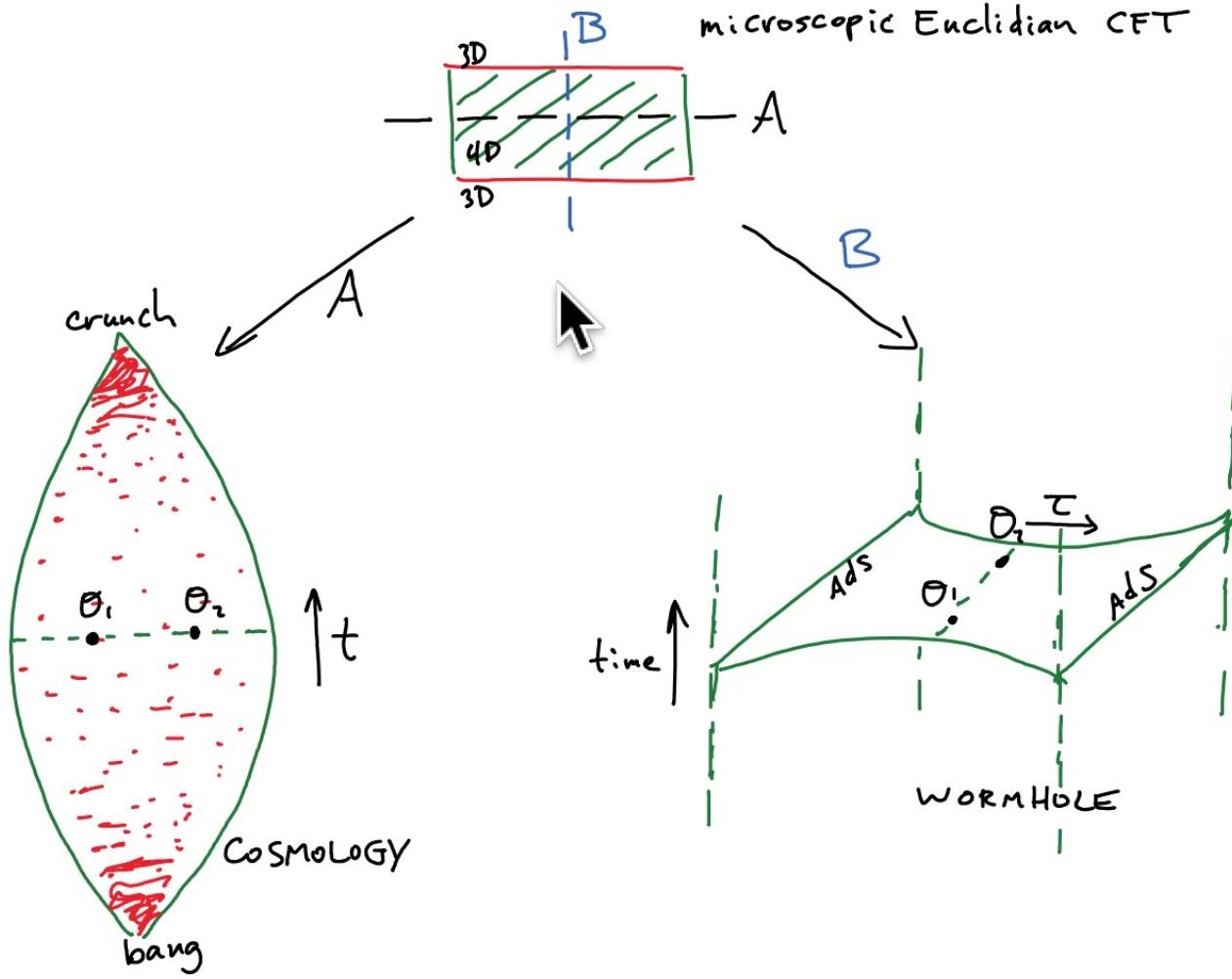
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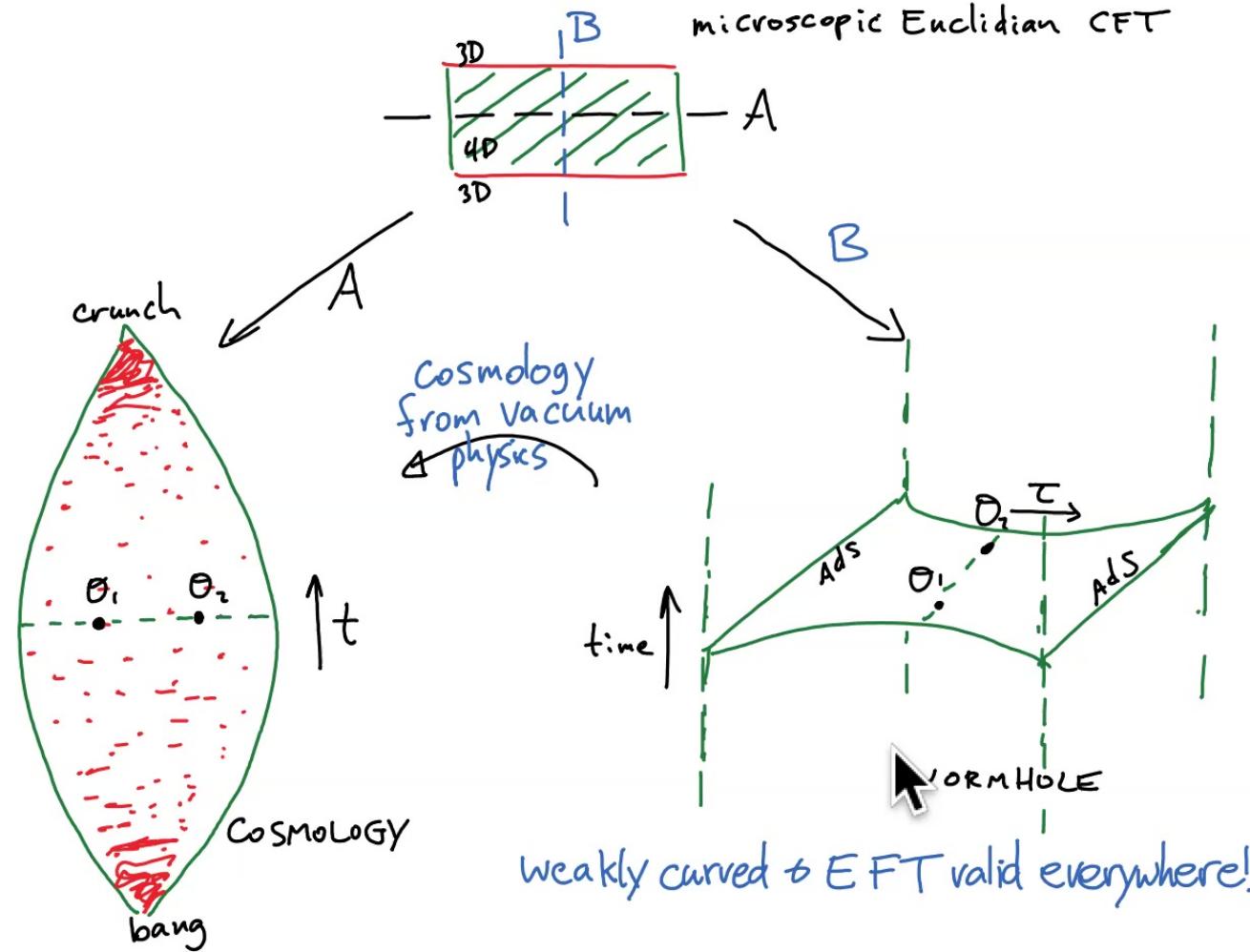
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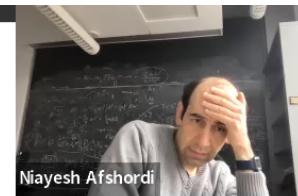
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Mark Van Raamsdonk





Niayesh Afshordi

Predictions of this framework:

- \* homogeneous, isotropic, flat cosmology  
( $\mathbb{R}^3$  symmetry broken only in individual classical branches)
  - ↳ no horizon/flatness problem
- \* correlations at all scales (since equivalent to vacuum correlators in wormhole)  
→ don't need inflation to explain this
- \* crunching time-symmetric background



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→ don't need inflation to explain this
- \* crunching time-symmetric background
- \* time-dependent dark energy is GENERIC,  $\ddot{\alpha} > 0$  possible

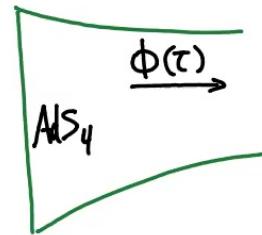


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$CFT_3$



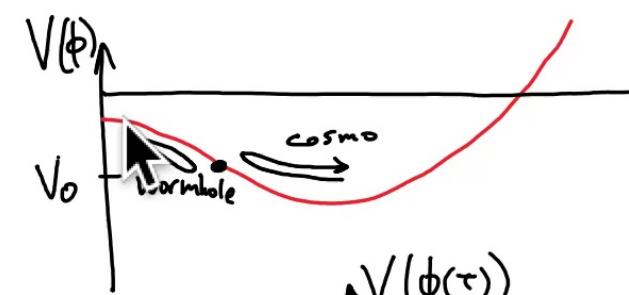
$CFT_3$   
+  $\lambda \mathcal{O}$



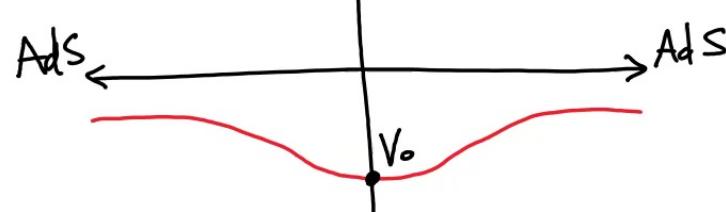
Typical effective F.T.  
dual to CFT has scalars  
related to light scalar  
operators in CFT.

scalar mass  $\longleftrightarrow$  operator dimension

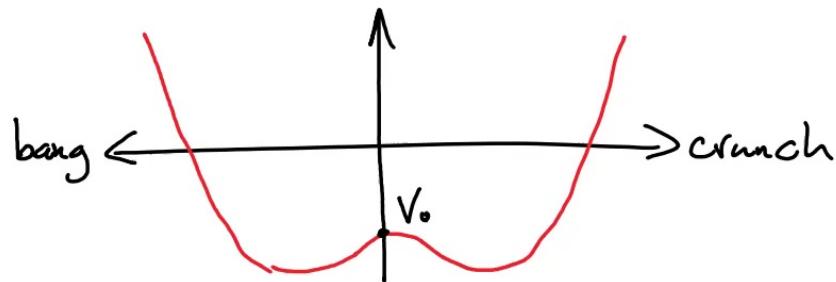
More generic solutions  
of EFT have spatially  
varying scalars:  
well-behaved solutions  
correspond to perturbation  
by relevant operators in  
CFT.



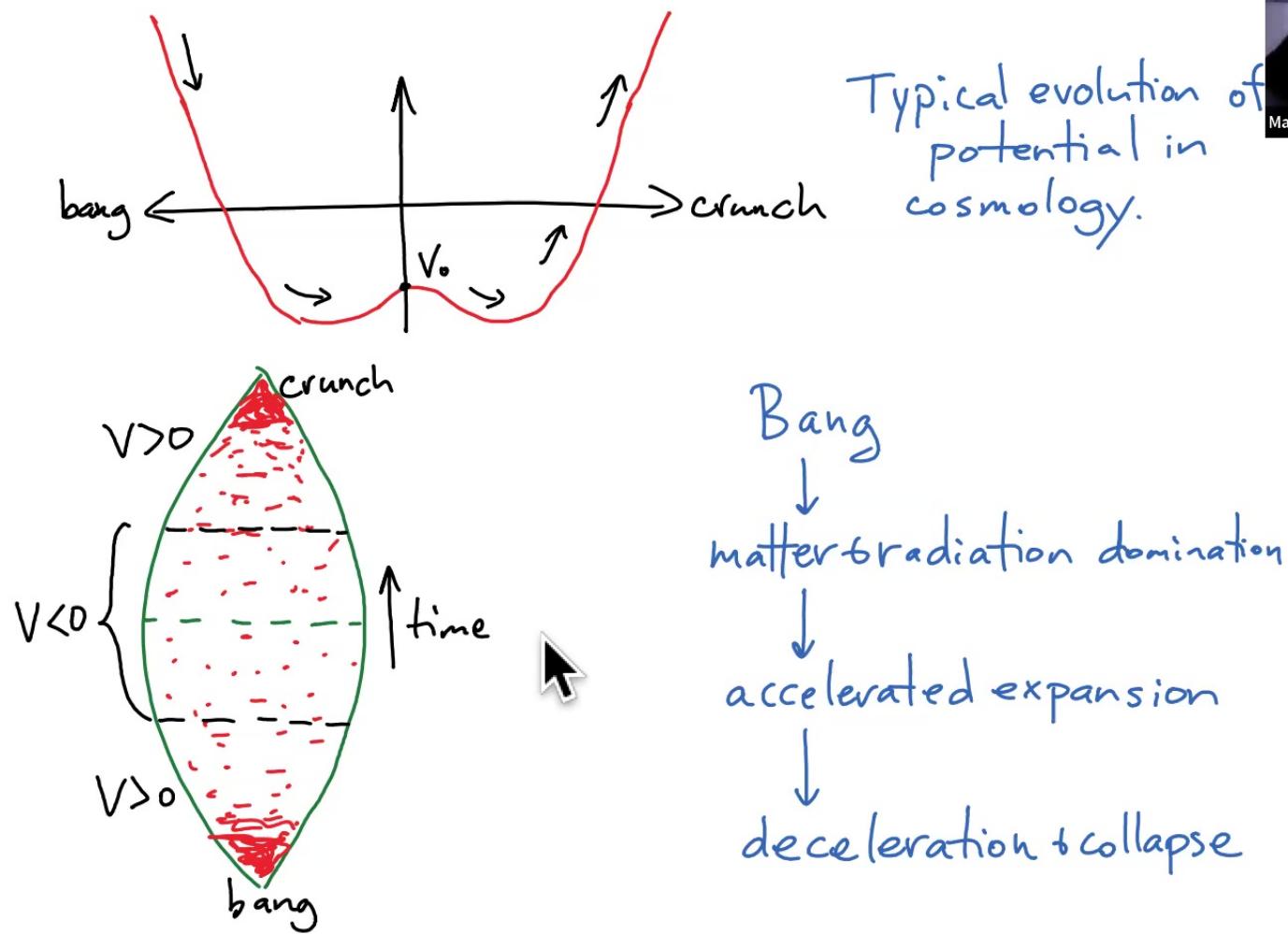
Typical potential  
for scalar field  
corresponding to  
relevant operator.



Typical evolution of  
potential in wormhole  
picture.



Typical evolution of  
potential in  
cosmology.



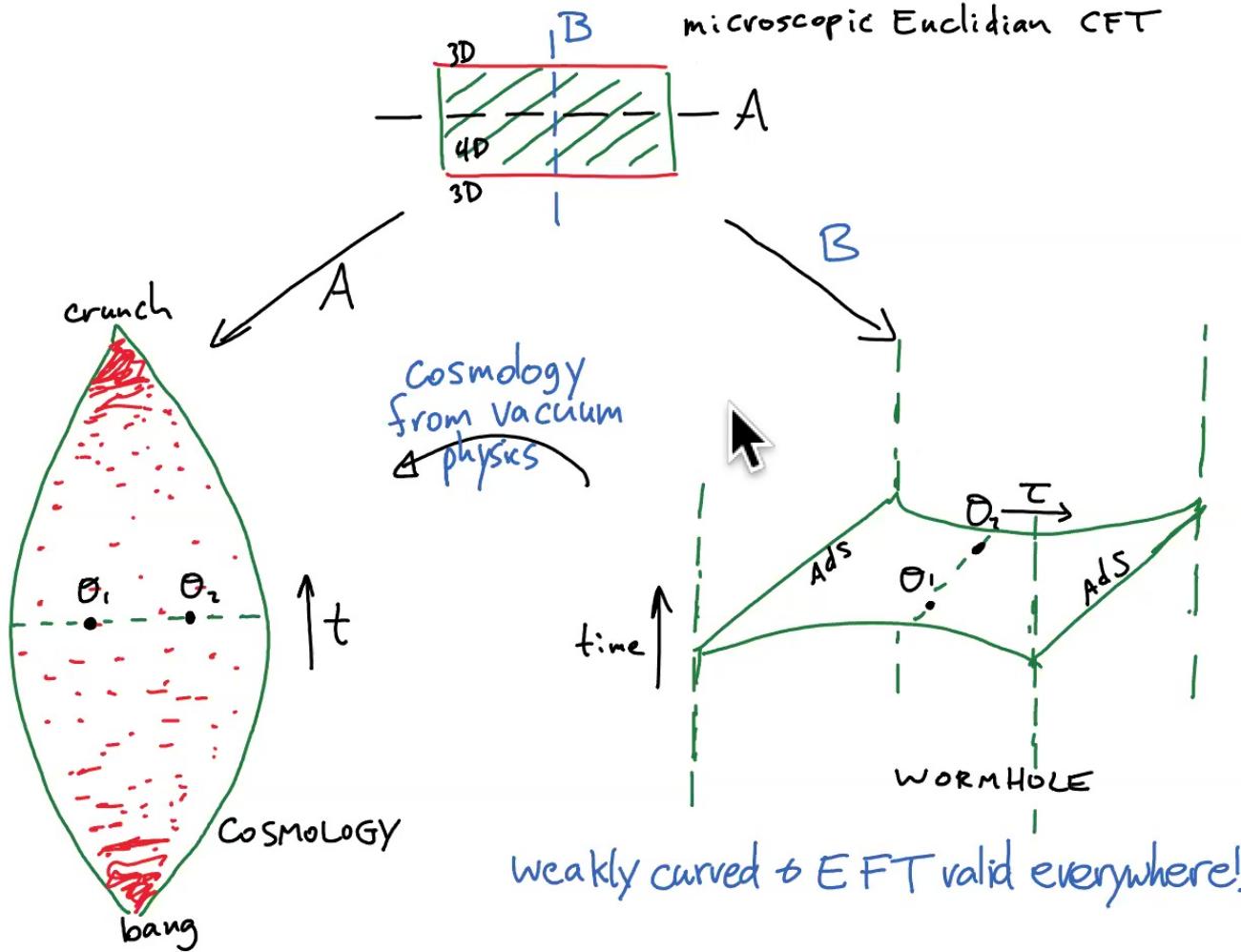


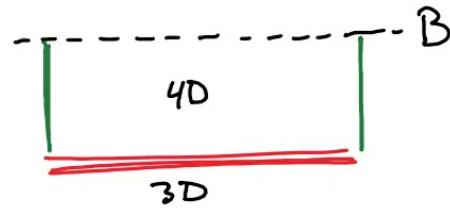
## Summary:

- Making progress on understanding microscopic models of cosmology using string theory suggests focusing on  $\Lambda < 0$  
- Can describe  $\Lambda < 0$  models using standard tools of cosmology
- These give special state for cosmology → "dual" description of cosmological observables in terms of vacuum physics on wormhole geometry
- Models can have a phase of accelerated expansion at late times → may alleviate need for inflation.



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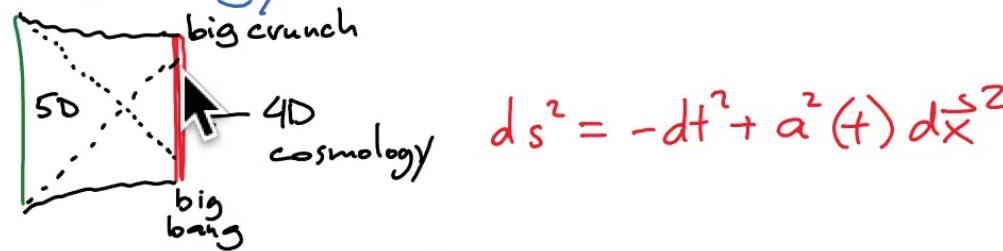




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 ↪ generally non-holographic

Holographic case: dual to black hole microstate,  
 cosmology is behind horizon!



$$ds^2 = -dt^2 + a^2(t) d\vec{x}^2$$

General case: only cosmology has geometrical description,  
 encoded in deep IR physics of QFT state.