Title: Holographic models of big bang cosmology (Vision Talk)

Speakers: Mark Van Raamsdonk

Collection/Series: QIQG 2025

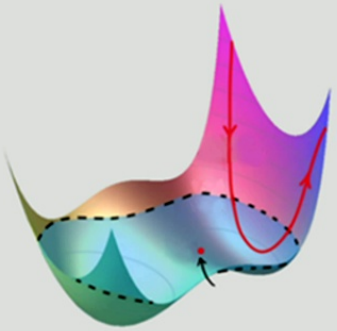
Subject: Quantum Gravity, Quantum Information

Date: June 25, 2025 - 10:00 AM

URL: https://pirsa.org/25060014

Abstract:

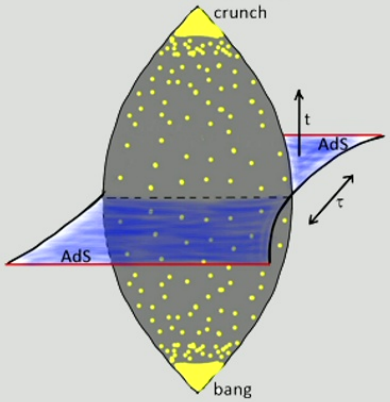
I will describe various constructions of cosmological spacetimes with big bangs using the tools of holography. I will point out features that appear to be common to holographic models of cosmology and discuss general questions that these models might be used to understand.

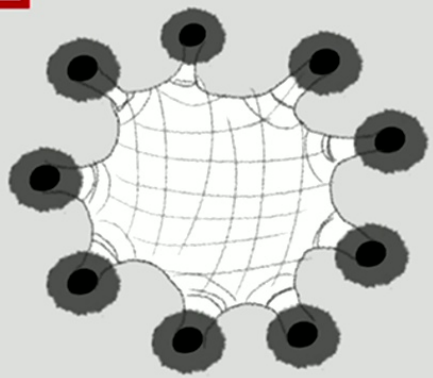


HOLOGRAPHIC MODELS OF BIG BANG COSMOLOGY

Mark Van Raamsdonk (UBC)

QIQG 2025, Perimeter





Can we come up with complete
quantum gravity models of big bang cosmology?

Can we come up with complete quantum gravity models of big bang cosmology?

what comes out of a big bang?

which gravitational EFTs are possible?

My approach (2018-present w Antonini Swingle, Simidzija, Waddell, Wakeham, Maloney, Merulia, Sahu, Leung, Zibakhsh)

- AdS/CFT is our best model of quantum gravity
- $\Lambda < 0$ gravitational EFTs dual to CFTs have cosmological solutions
- Try to describe these microscopically via CFT physics

My approach (2018-present w Antonini Swingle, Simidzija, Waddell, Wakeham, Maloney, Merulia, Sahu, Leung, Zibakhsh)

- AdS/CFT is our best model of quantum gravity
- $\Lambda < 0$ gravitational EFTs dual to CFTs have cosmological solutions
- Try to describe these microscopically via CFT physics

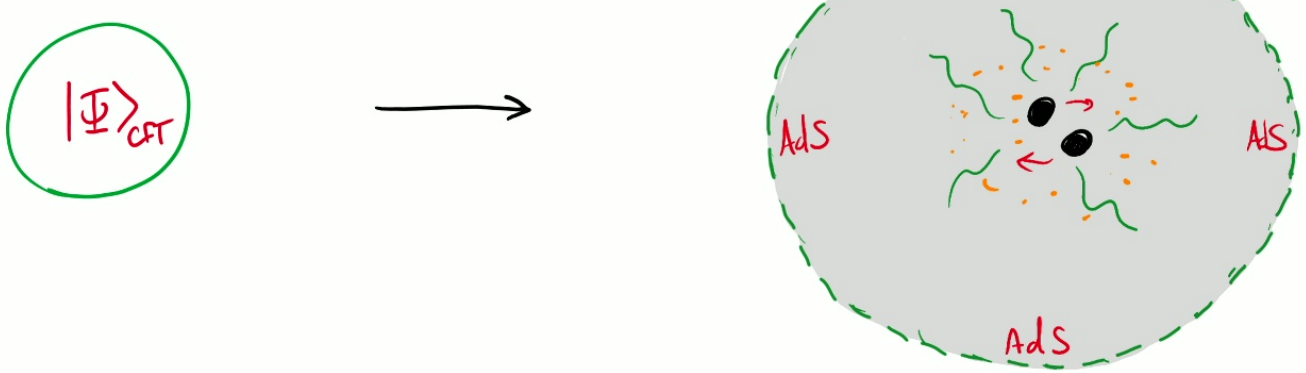
very useful for black holes (general lessons)

sign of Λ irrelevant for early universe & much of history

real world could be $\Lambda < 0$ w. evolving scalars

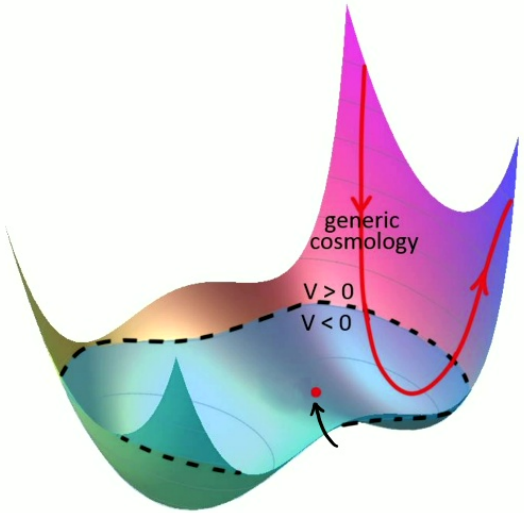
Starting point: pick your favorite holographic CFT

- This is associated with some gravitational EFT with $\Lambda < 0$
- Finite energy states are dual to spacetimes that are asymptotically empty and static.



BUT: The same $\Lambda < 0$ EFT has cosmological solutions, with arbitrary spatial curvature

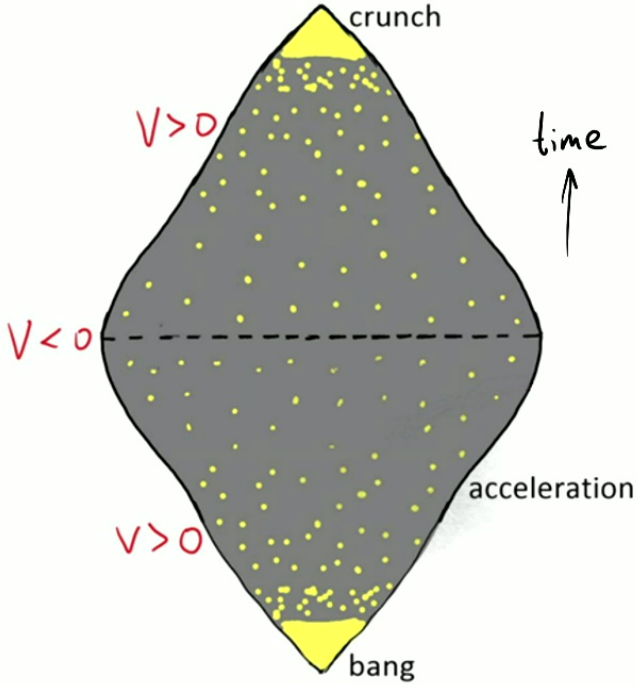
generic solutions: matter + radiation + scalar $\varphi_i(t)$



scalar evolution

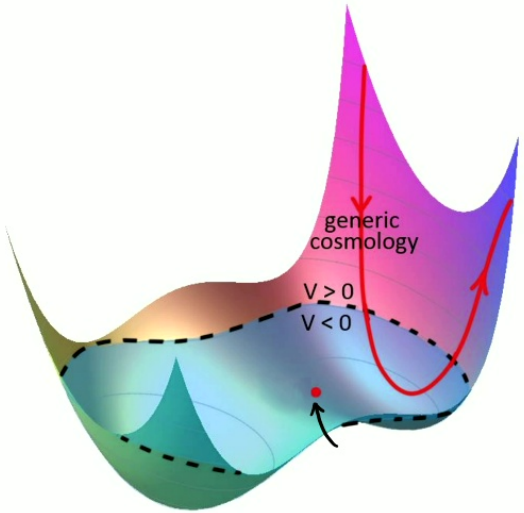
FRW ansatz

$$ds^2 = -dt^2 + a^2(t)\, d\Sigma^2$$



BUT: The same $\Lambda < 0$ EFT has cosmological solutions, with arbitrary spatial curvature

generic solutions: matter + radiation + scalar $\varphi_i(t)$

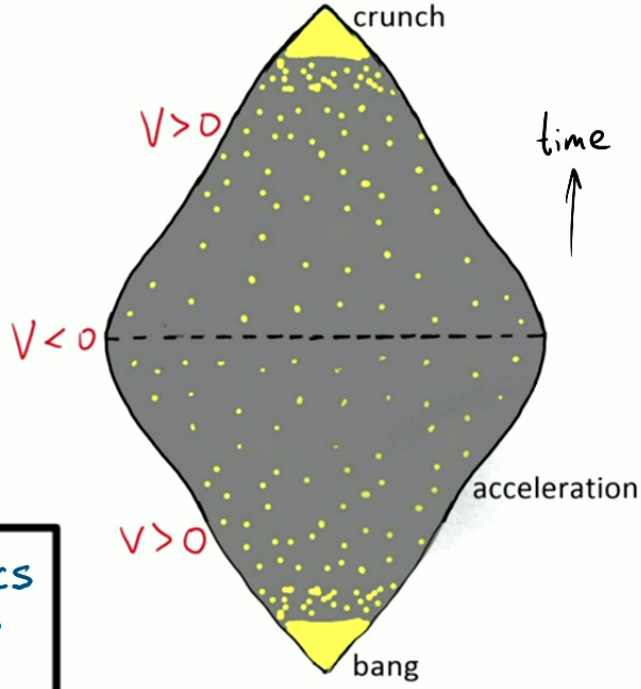


scalar evolution

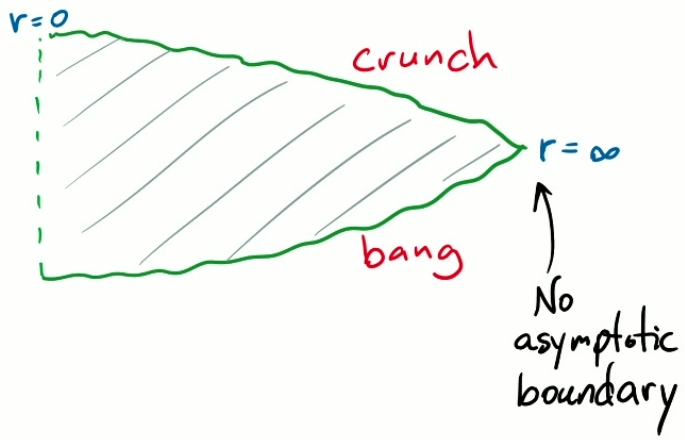
FRW ansatz

$$ds^2 = -dt^2 + a^2(t)\, d\Sigma^2$$

Can we relate physics of this cosmology to CFT physics?



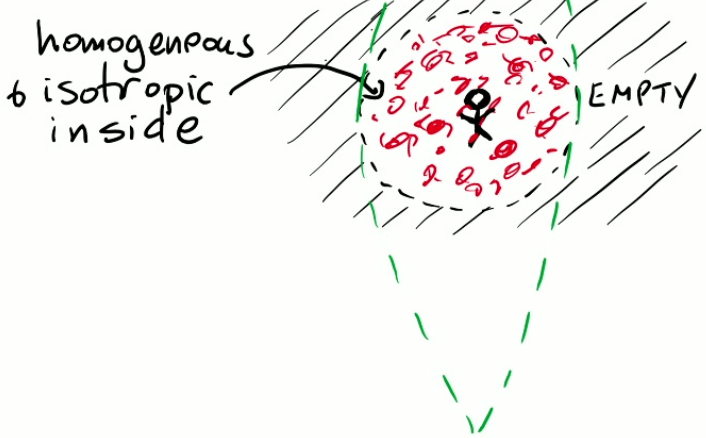
Challenge: $\Lambda < 0$ big-bang/big crunch spacetimes are not asymptotically AdS.



Lorentzian Constructions

Construction #1 (Sahu, Simidzija, MVR 2023)

c.f. Oppenheimer, Snyder 1939



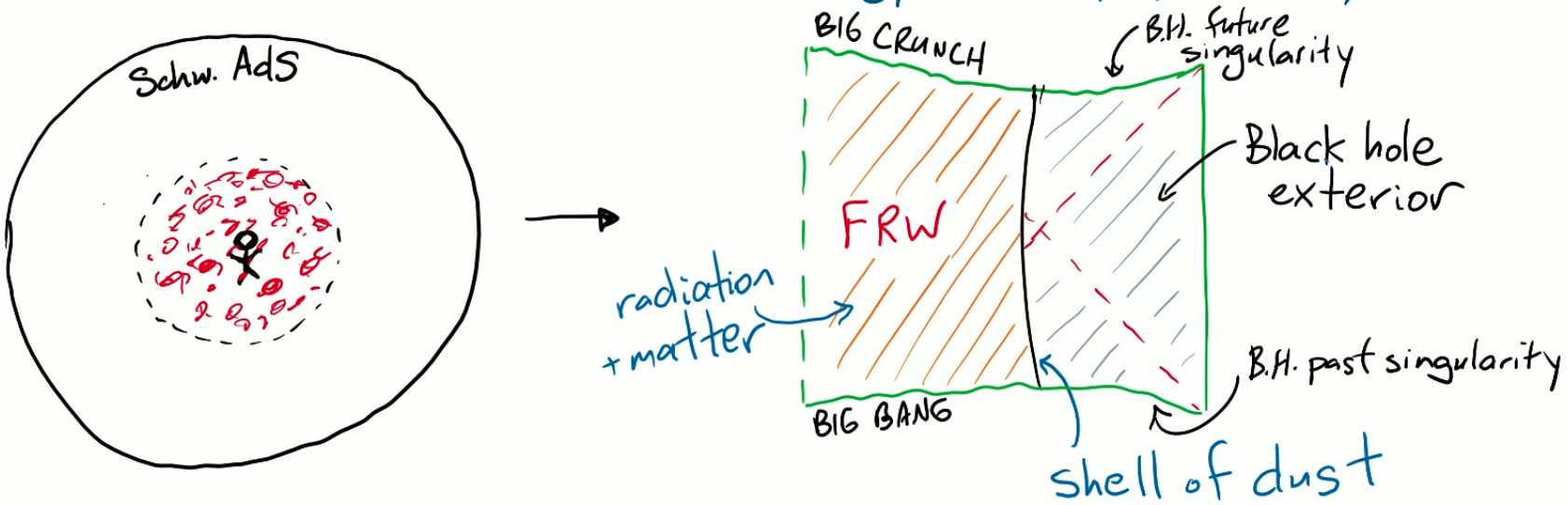
- Collapse of uniform ball of matter appears as FRW cosmology from inside.

→ embed in AdS

MVR + Sahu + Simidzija '23

Construction #1:

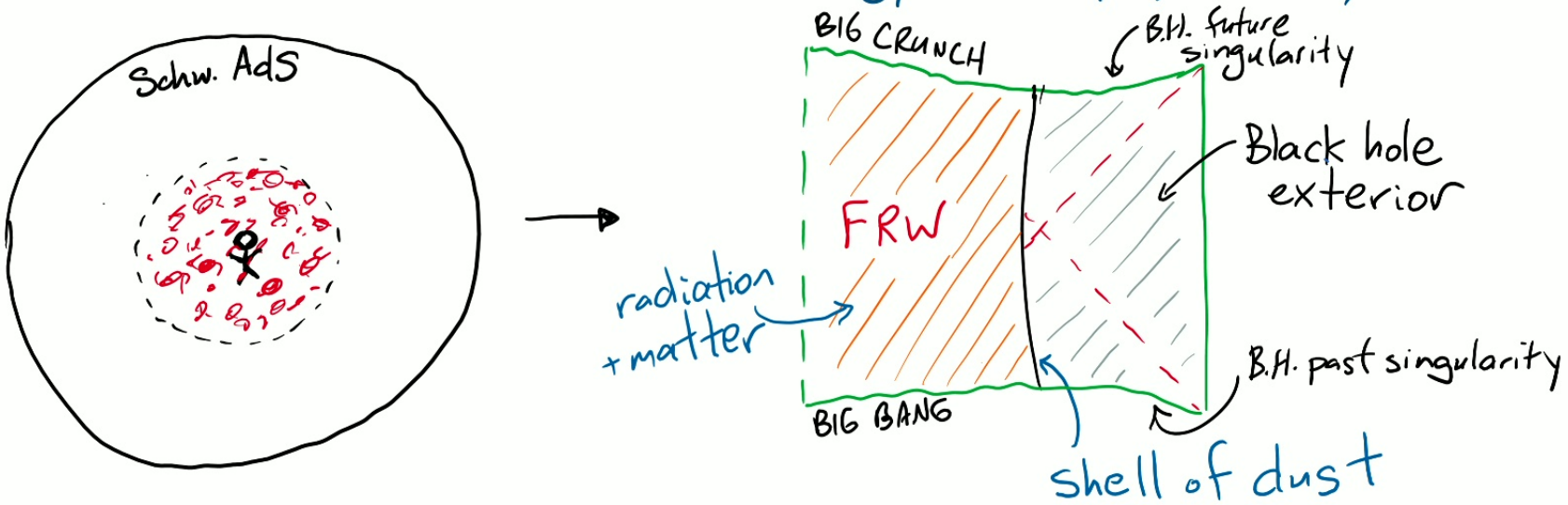
- embed finite BUBBLE of cosmology into asymptotically AdS



MVR + Sahu + Simidzija '23

Construction #1:

- embed finite BUBBLE of cosmology into asymptotically AdS

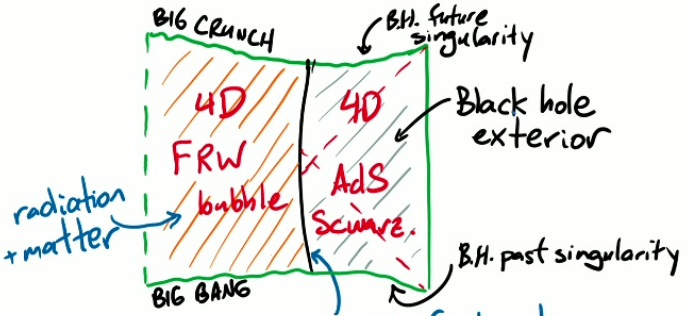


→ Dual to special high-energy state of CFT.

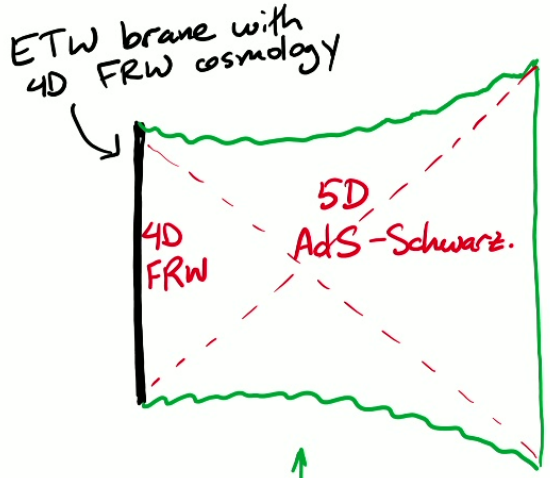
→ Can embed region of cosmology with all physics accessible to observer

Construction #2 → embed cosmology on ETW brane inside 5D black hole

previous:



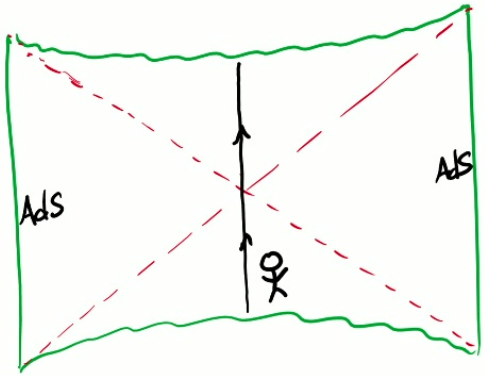
$|\Psi\rangle_{3D\ CFT}$

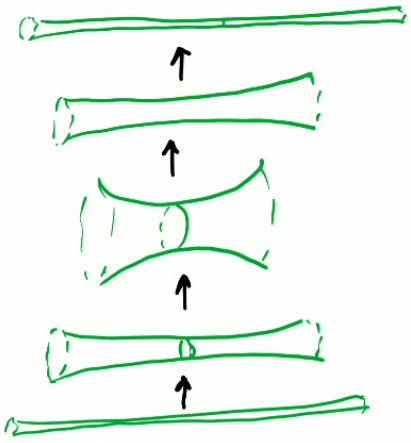


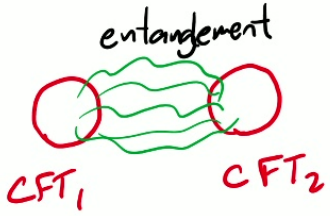
$|\Psi\rangle_{4D\ CFT}$

w. Cooper, Rozali, Swingle, Waddell, Wakeham 2018

Construction #3 : an anisotropic cosmology



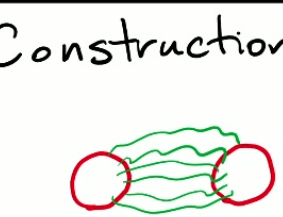


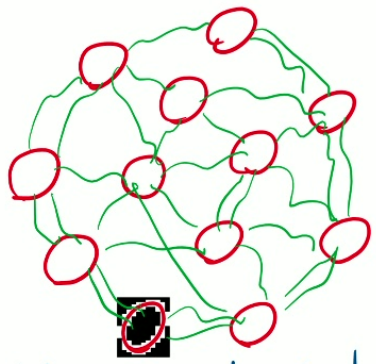


$$|\Psi\rangle = \sum |E_i\rangle_1 \otimes |\bar{E}_i\rangle_2 \, e^{-\beta E_i/2}$$

Maldacena 2001

Construction #3 : a more isotropic multiboundary generalization



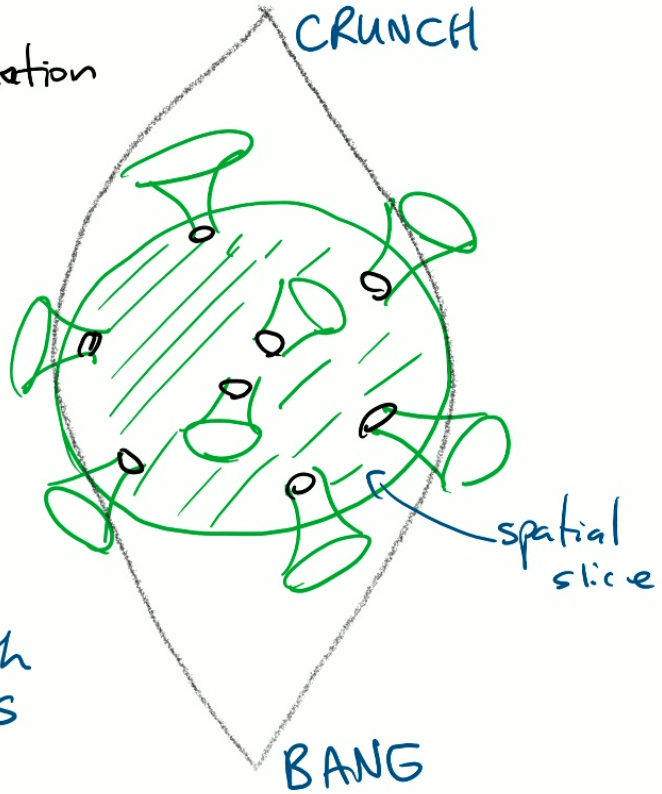


Many entangled CFTs (high E)

$\longleftrightarrow$

Multiboundary wormhole

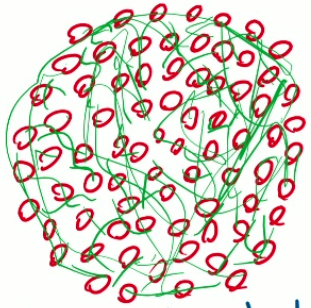
→ interior is closed FRW universe with black holes

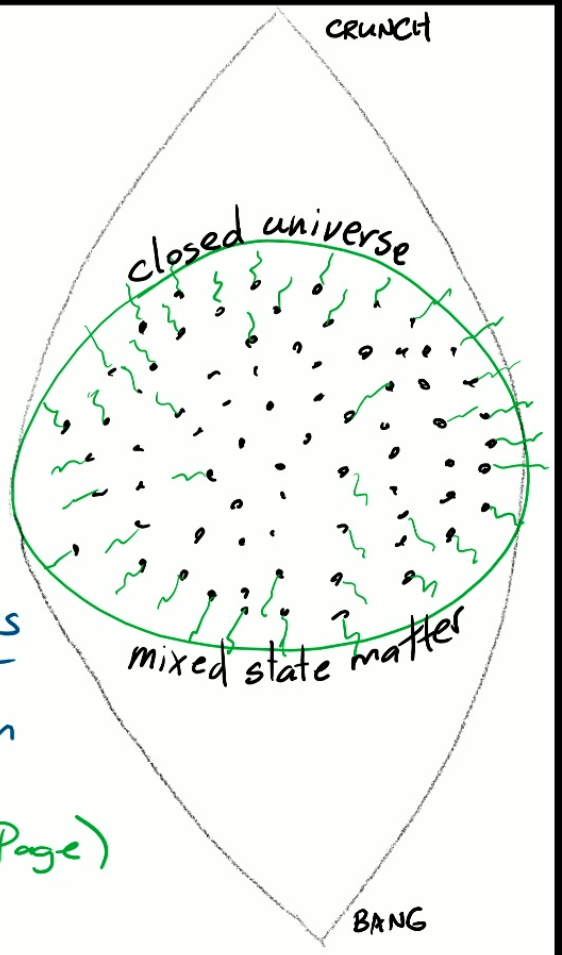


Sahu + MVR 2024

Construction #3: generalization

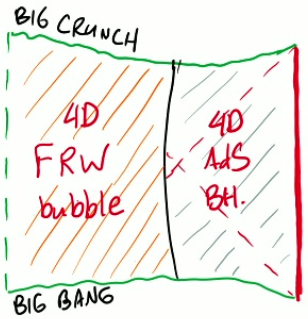
→ replace smaller number of large black holes w. larger number of small black holes or lighter objects.



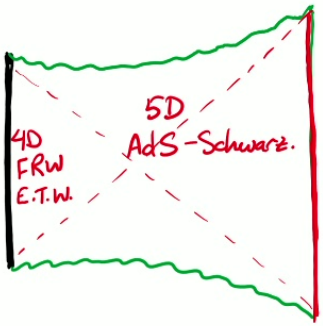


- entangled state of very many CFTs (or other auxiliary degrees of freedom)

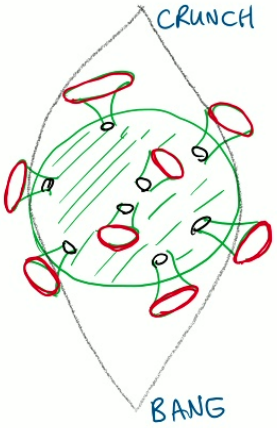
- cosmology becomes subdominant part of wavefunction in this case (like low T Hawking-Page)



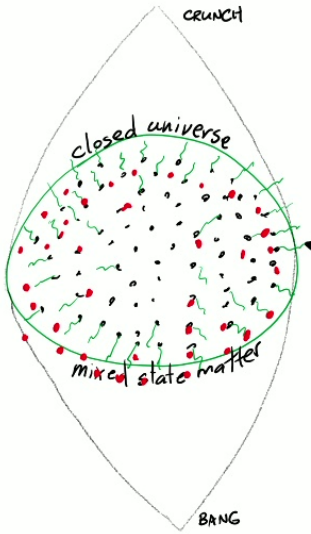
$\longleftrightarrow |\Psi\rangle_{3D\,CFT}$



$\longleftrightarrow |\Psi\rangle_{4D\,CFT}$



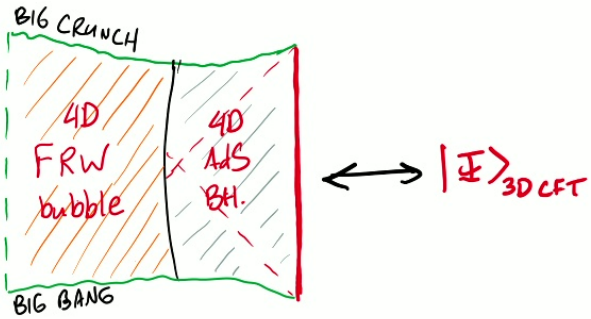
$\longleftrightarrow |\Psi\rangle_{N\ CFTs}$



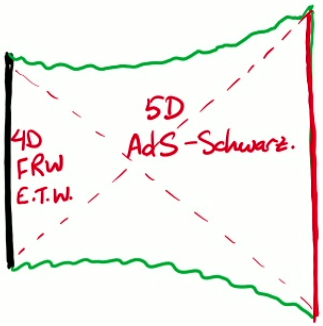
$\longleftrightarrow |\Psi\rangle_{many\ CFTs}$ or general multipart auxiliary system

General Lessons:

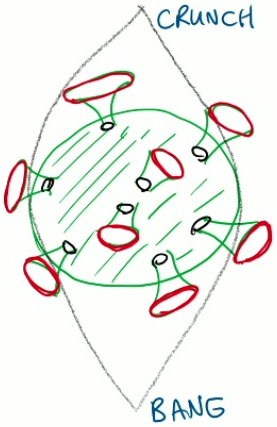
- The cosmology is always a mixed state
- Hilbert space for cosmological state always associated w. some auxiliary part of construction
- Big bang singularity is a special case of black hole singularity
- Cosmological observables may be difficult to access from underlying state. Easier if there is is a Euclidean construction



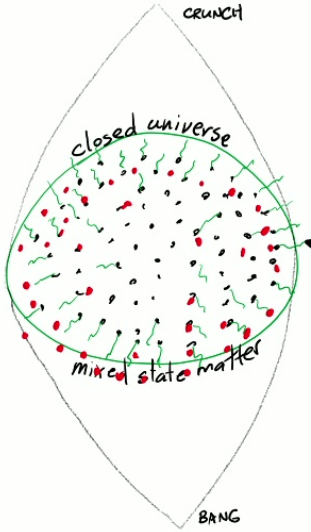
$\longleftrightarrow |\Psi\rangle_{3D\,CFT}$



$\longleftrightarrow |\Psi\rangle_{4D\,CFT}$



$\longleftrightarrow |\Psi\rangle_{N\ CFTs}$



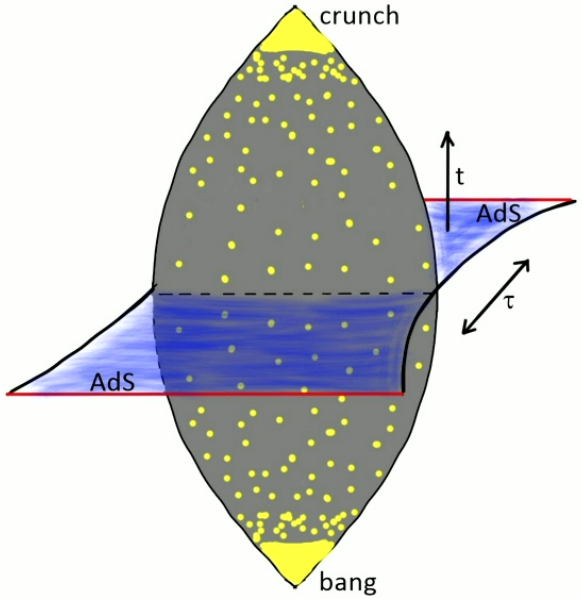
$\longleftrightarrow |\Psi\rangle_{many\ CFTs}$ or general multipart auxiliary system

Euclidean Constructions

Euclidean Constructions:

Start with observation: analytic continuation $t \to i\tau$ of $\Lambda<0$ cosmology gives an asymptotically AdS Euclidean wormhole

(c.f. Maldacena - Maoz)



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

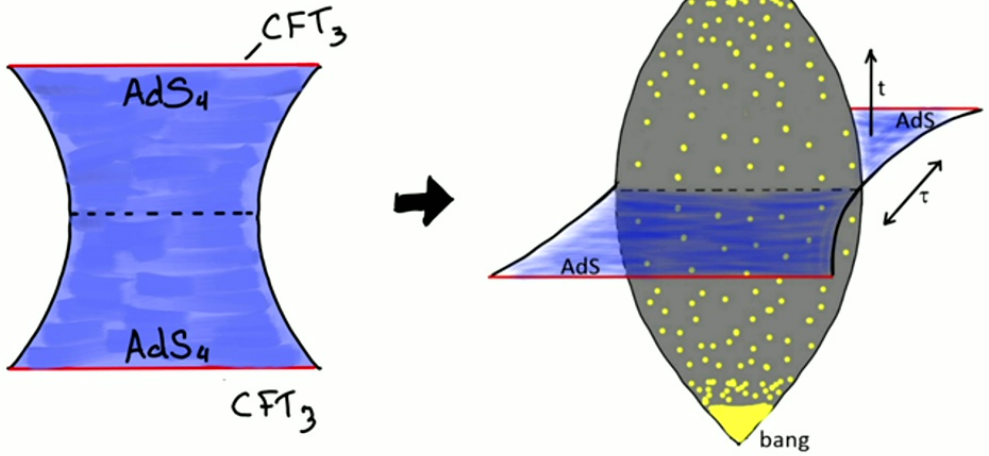
e.g.

$$ds^2 = -dt^2 + \cos\left(\frac{t}{L}\right) d\vec{x}^2$$

IDEA:

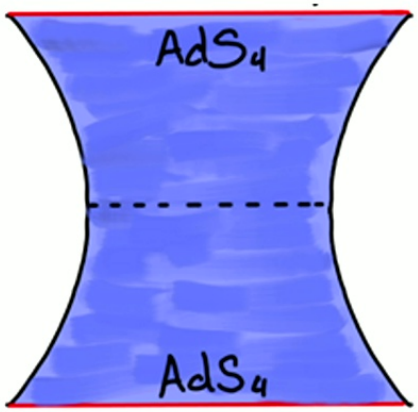
① find holographic construction of Euclidean wormhole:

② use this to prepare state for cosmology (like Hartle-Hawking)



cosmological observables via analytic continuation from Euclidean picture

How do we holographically describe the wormhole?



- 2 AdS_4 boundaries suggest pair of 3D Euclidean CFTs

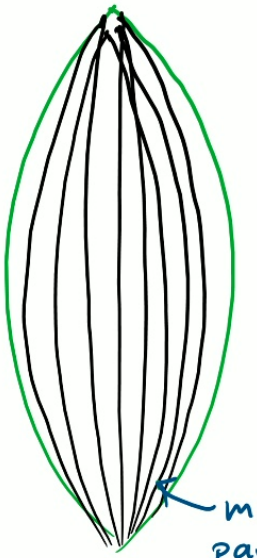
But: these would be dual to disconnected pair of AdS spacetimes.

Need ENSEMBLE or INTERACTION to introduce correlation between CFTs

EXAMPLE #1: heavy particle cosmology

(w. Maloney & Meruliya 2025)

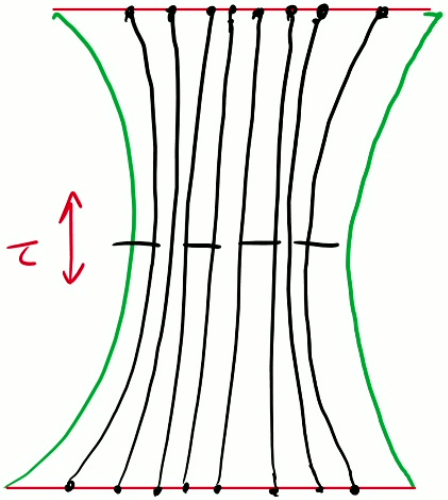
Cosmology



$\uparrow t$

$t = i\tau$

Wormhole



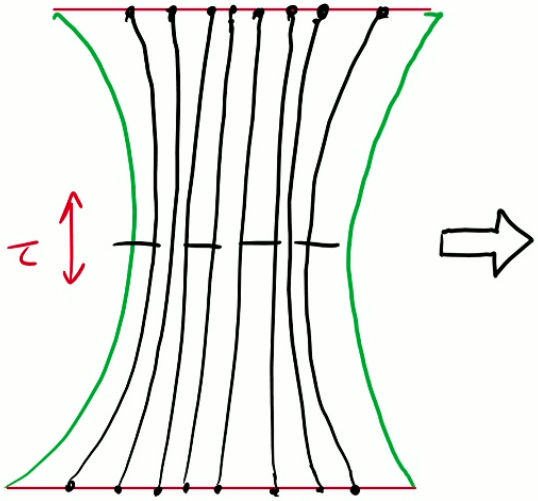
τ

massive particles

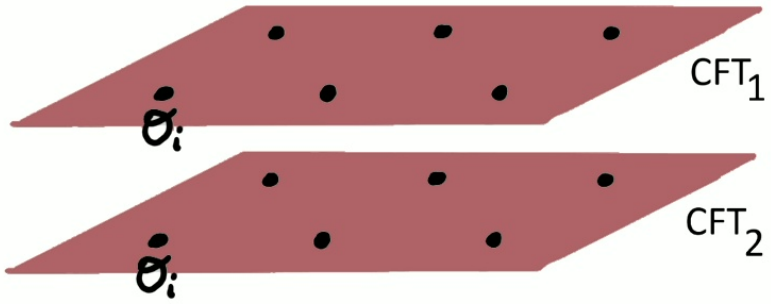
exact solutions in 3D gravity

EXAMPLE #1: heavy particle cosmology

Wormhole



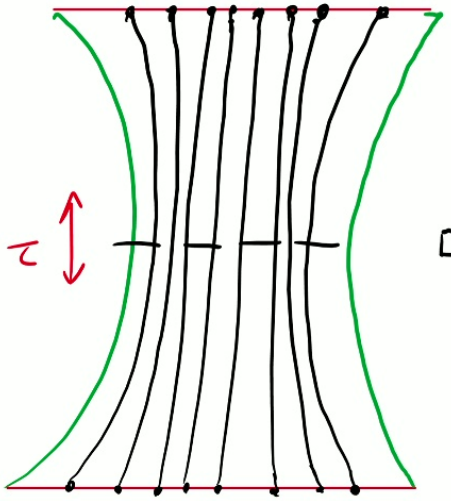
CFT picture: heavy particle geodesics imply operator insertions

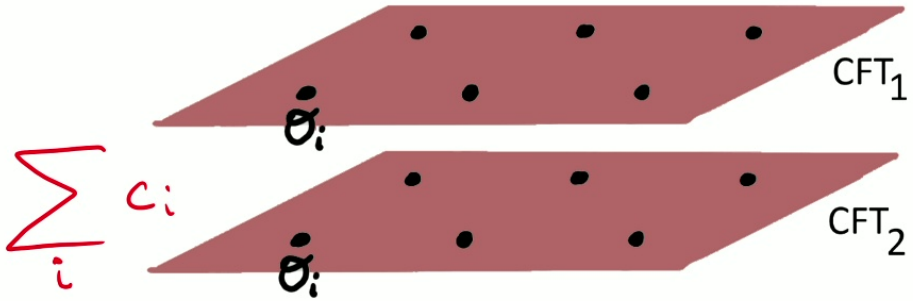


EXAMPLE #1: heavy particle cosmology

CFT picture: heavy particle geodesics imply operator insertions

Wormhole





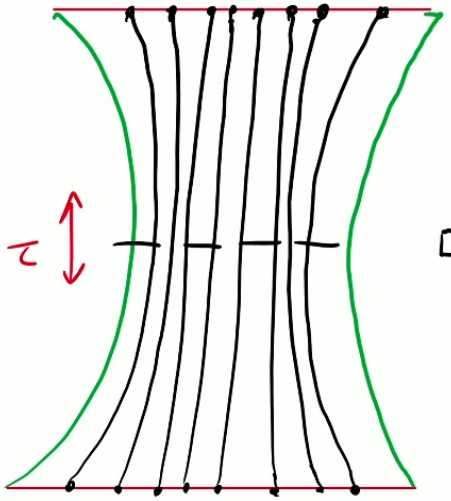
one way to get ensemble: sum over insertions for each pair of operators → MIXED STATE COSMOLOGY

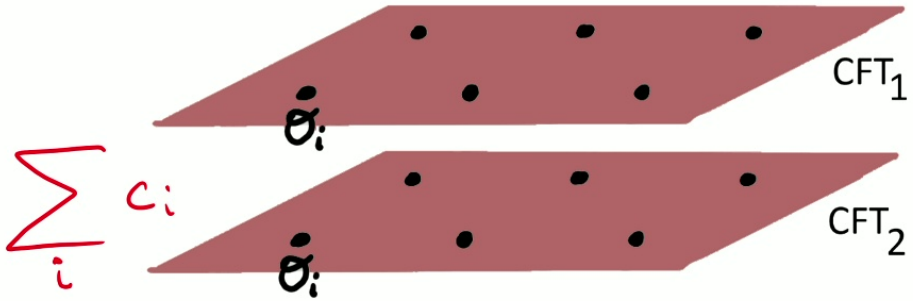
We need a lot of entropy for cosmological spacetime to be dominant saddle.

EXAMPLE #1: heavy particle cosmology

CFT picture: heavy particle geodesics imply operator insertions

Wormhole



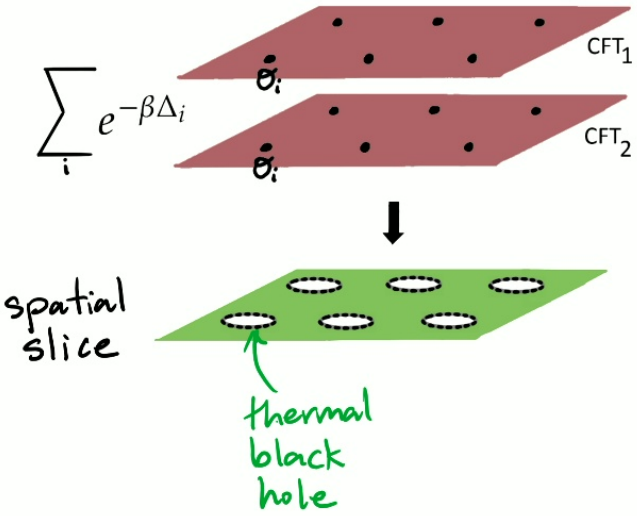


one way to get ensemble: sum over insertions for each pair of operators → MIXED STATE COSMOLOGY

Example #2: Black hole cosmology

MVR + Sahu 2024

- consider "canonical ensemble" of operator insertions with small β $\rightsquigarrow$ dominated by heavy operators



Example #2: Black hole cosmology

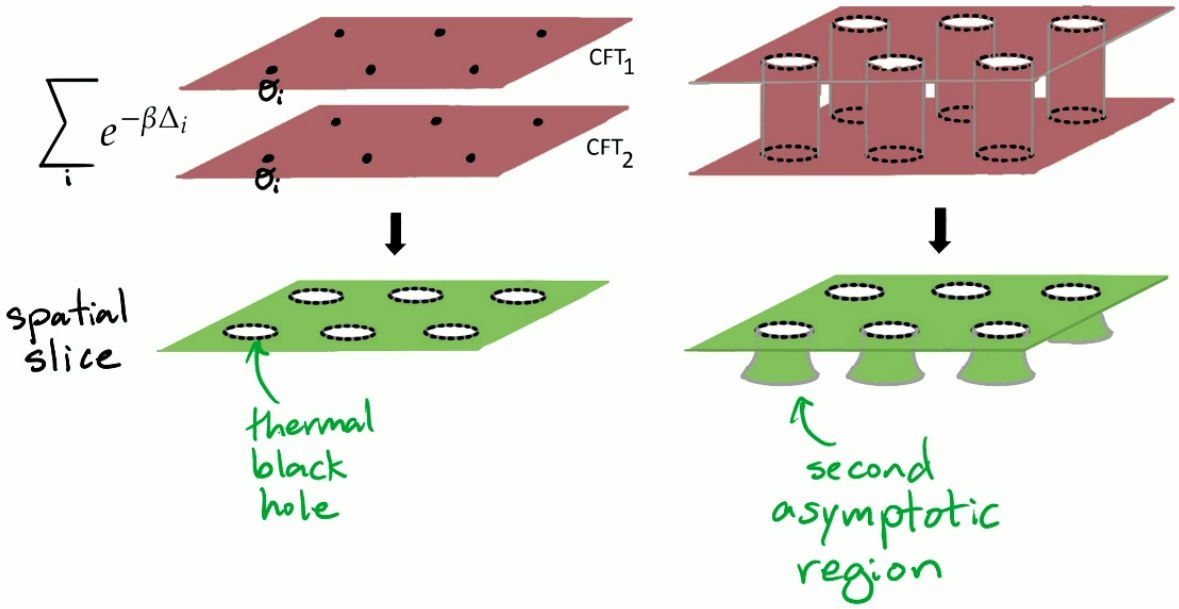
MVR + Sahu 2024

purify by integrating in CFT tubes.

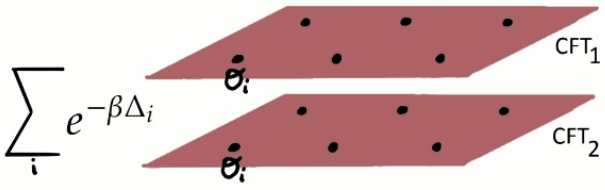
ensemble

↓

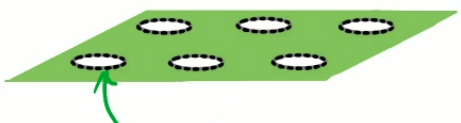
interaction



Example #2: Black hole cosmology

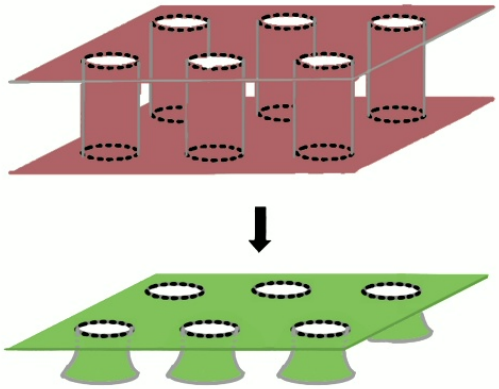


spatial slice



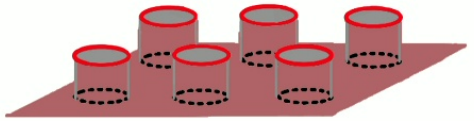
thermal black hole

purify by integrating in CFT tubes.



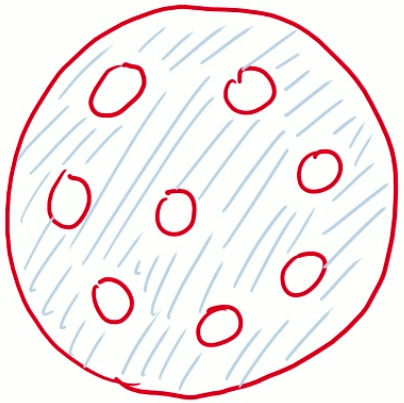
second asymptotic region

this path integral constructs a pure entangled state of many CFTs

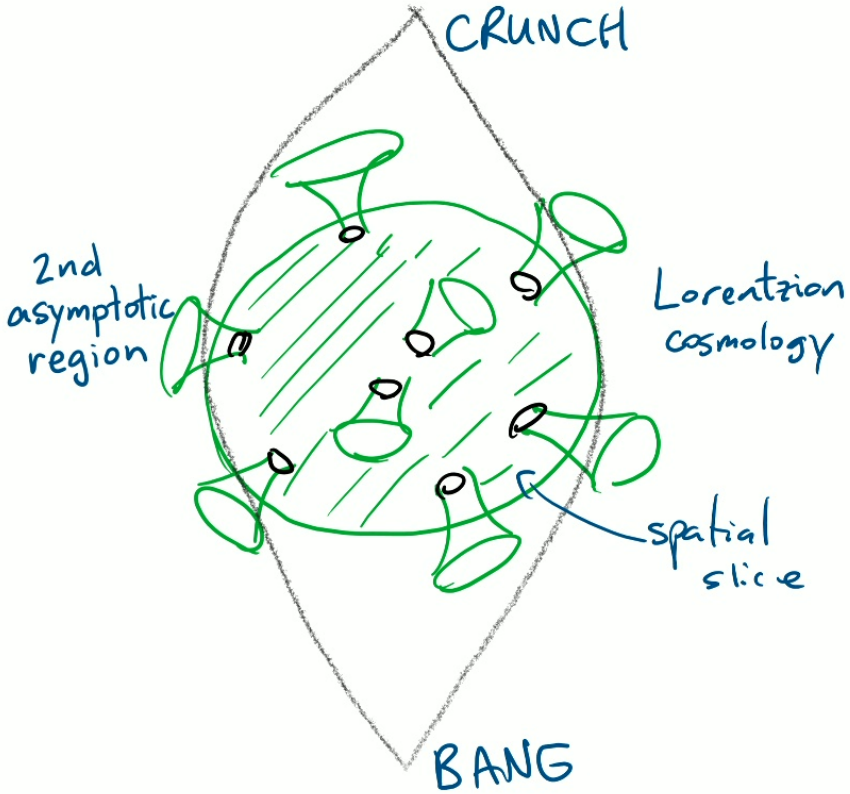


dual to black hole cosmology w. 2nd asymptotic regions

EXAMPLE #2: Black hole cosmology (sphere version)

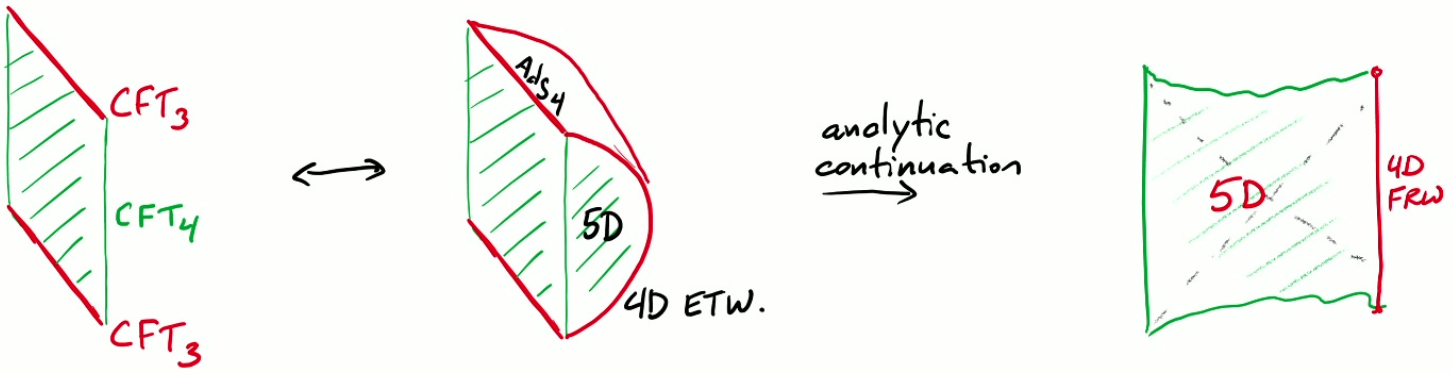


Entangled state of N CFTs on S^1



EXAMPLE #3: correlate CFTs via interaction w. auxiliary system.

(Cooper, Rozali, Swingle, Waddell, Wakeham, MURI 2018



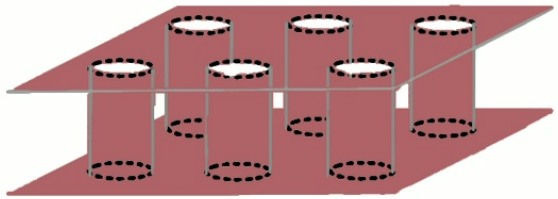
(may have only 4D cosmology part if CFT_4 not holographic)

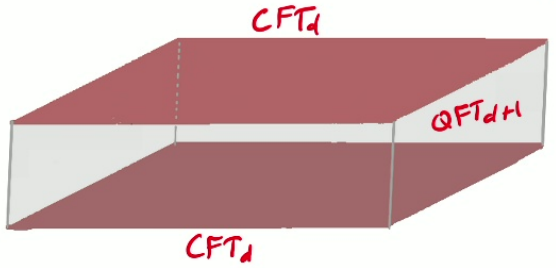
The global approach: Lessons

→ Wormhole from ensemble ⟶ mixed state cosmologies.

→ Purify by adding auxiliary d.o.f. that couple 2 CFTs

→ These auxiliary d.o.f. provide a Hilbert space for the cosmology. ⇝ sounds similar to recent "observers" story

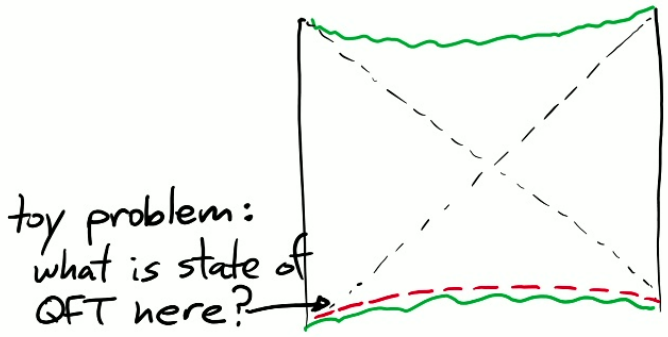




What can we do with these constructions?

Key goal for quantum gravity cosmology models:

- predict what comes out of the big bang
- what are perturbations + correlations when EFT becomes valid?



- Can we understand why arrow of time points away from big bang?
- Can a big bang singularity do the same as inflation?

Thanks!

- Thanks to collaborators

Stefano Antonini,
Brian Swingle,
Moshe Rozali,
Petar Simidzija,
Alex Maloney,
Viraj Merulia,
Sean Cooper,
Pompey Leung
Rana Zibakhsh

+

Abhisek Sahu
(graduating student)

Chris Waddell