Title: Black hole microstate cosmology

Speakers: Mark Van Raamsdonk

Series: Quantum Fields and Strings

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Abstract: In this talk we study a special class of high-energy states in holographic CFTs defined via Euclidean evolution from conformal boundary states. We argue that these are dual to black hole microstates with a geometrical behind-the-horizon region. We study the time-dependent physics of this behind-the-horizon region, whose ETW boundary geometry takes the form of a closed FRW spacetime. We show that in many cases, this behind-the-horizon physics can be probed directly by looking at the time dependence of entanglement entropy for sufficiently large spatial CFT subsystems. A fascinating possibility is that for certain states, we might have gravity localized to the ETW brane as in the Randall-Sundrum II scenario for cosmology. In this case, the effective description of physics beyond the horizon could be a big bang/big crunch cosmology of the same dimensionality as the CFT. In this case, the d-dimensional CFT describing the black hole microstate would give a precise, microscopic description of the d-dimensional cosmological physics.

BLACK HOLE MICROSTATE COSMOLOGY

Mark Van Raamsdonk, UBC

based on: 1810.10601 with S. Cooper, M. Rozali, B. Swingle, C. Waddell, D. Wakeham

Talking:

Big questions for quantum gravity:

- physics of black holes
- big bang / cosmology (incl. dark energy)

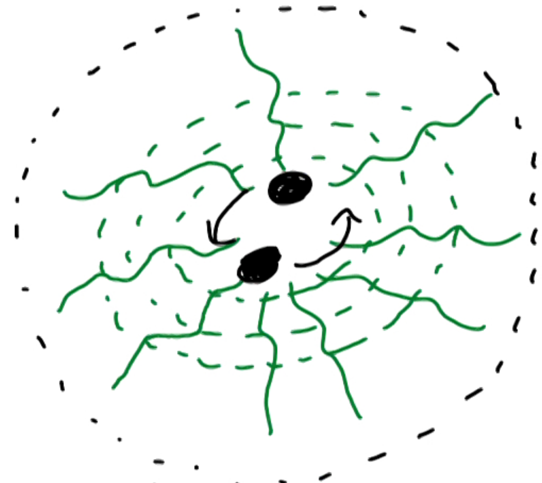
Use AdS/CFT correspondence as a fundamental definition

Talking: Mark

THE AdS/CFT correspondence

CFT on S^d

$\Longleftrightarrow$

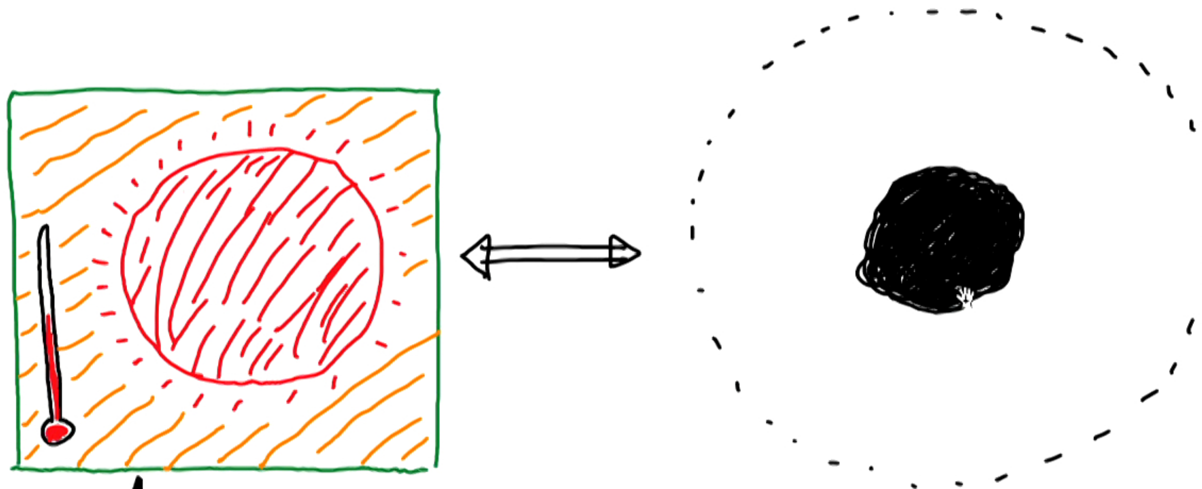


$$i\hbar \frac{d|\Psi\rangle}{dt} = H|\Psi\rangle$$

$\mathcal{M}_{|\Psi\rangle}$

asymptotic to global AdS_{d+1}

Black holes in AdS/CFT



$T > \frac{1}{R}$

Thermal state of CFT $\Longleftrightarrow$ Black hole in AdS

Witten

Talking: Mark

Black holes in AdS/CFT: what is the physics behind the horizon?

Thermal state

= mixed state of CFT

subsystem of larger system

(CFT + heat bath)

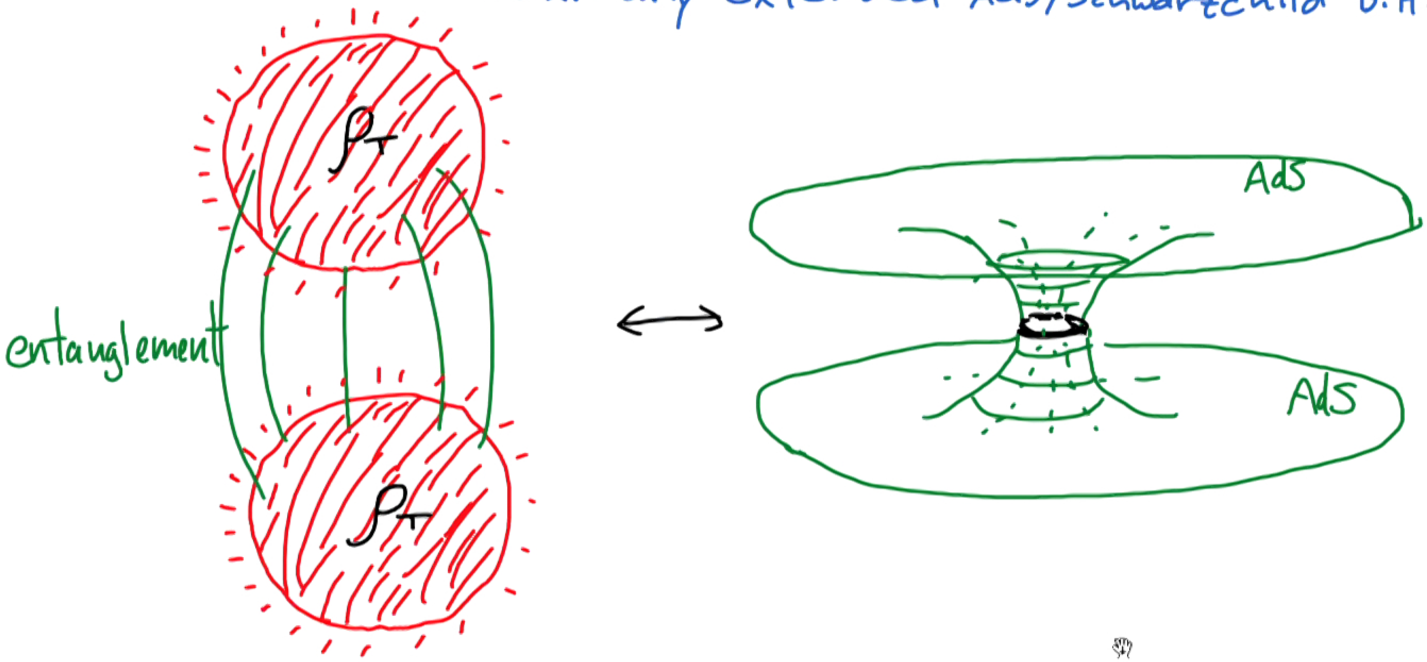
OR

ensemble of pure states

"

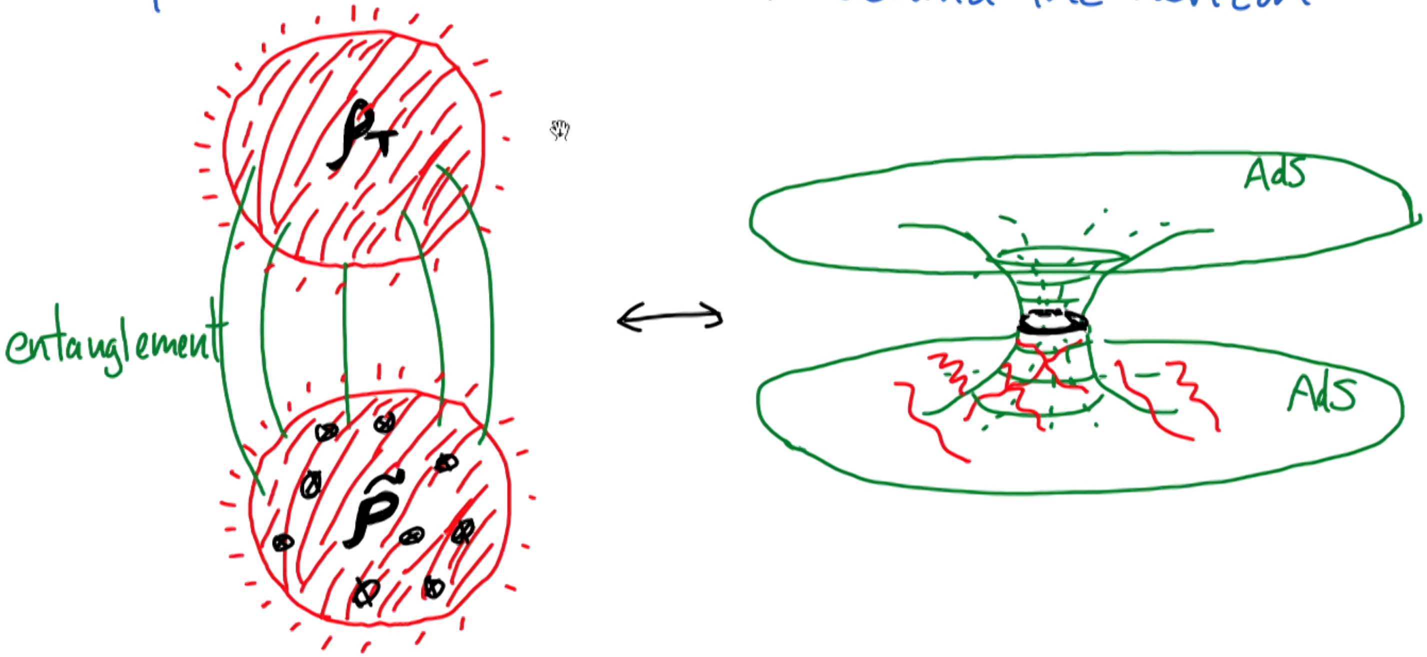
black hole microstates

Maldacena: "Thermofield double" purification corresponds to maximally extended AdS/Schwarzchild B.H.



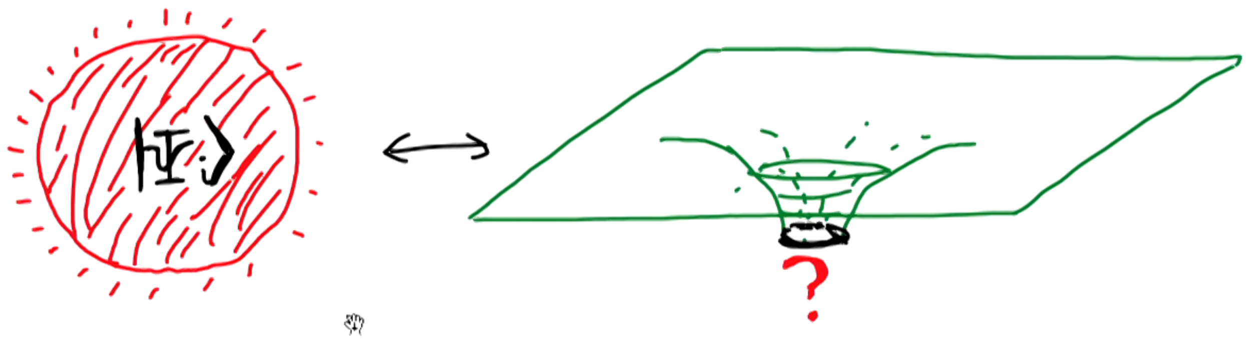
$$|\Psi\rangle = \sum_i e^{-\beta E_i/2} \, |E_i\rangle \otimes |E_i\rangle$$

But other purifications correspond to extended spacetimes with "stuff" behind the horizon



$$|\Psi\rangle = \sum_i e^{-\beta E_i/2} |E_i\rangle \otimes \left(\underbrace{\mathcal{U}}_{\text{unitary}} |E_i\rangle\right)$$

What about black hole microstates?



$$|\Psi_i\rangle \in \rho_T$$

significant controversy e.g. firewall debate 2013+

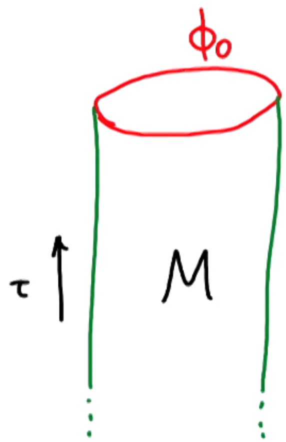
We will describe a class of CFT excited states whose behind-the-horizon geometries can be understood explicitly.

(motivated by Kourkoulou + Maldacena SYK discussion)

Talking: Mark

CFT states from path integrals:

vacuum state wavefunction for CFT on S^d:

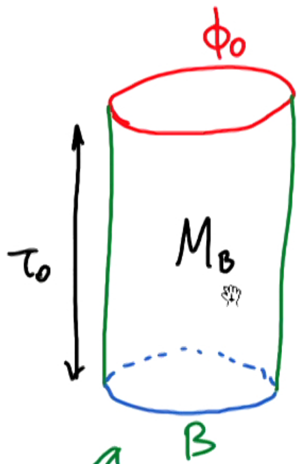


$$\Psi_{vac}[\phi_0] = \int_M^{\phi(\tau=0)=\phi_0} [d\phi]\, e^{-S_{Euc}}$$

from: $|vac\rangle \sim \lim_{\beta\to\infty} e^{-\beta H}|\Psi_0\rangle$

Black hole microstates from "boundary states":

(Maldacena, Kourkoulou)



$$\Psi_{B,\tau_0}[\phi_0] = \int_{M_B}^{\phi(\tau=0)=\phi_0} [d\phi]\, e^{-S_{Euc}}$$

$$|\Psi\rangle = e^{-\tau_0 H}\,|B\rangle$$

"boundary state"

add boundary with some boundary condition for CFT

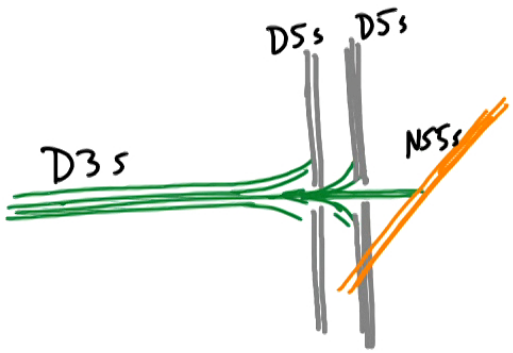
INTERLUDE: CFTs with boundary and their gravity duals

Given a CFT, have various consistent boundary conditions

e.g: Neumann/Dirichlet for free scalar

Some preserve scale/conformal invariance

$SO(d,2) \to SO(d-1,2)$

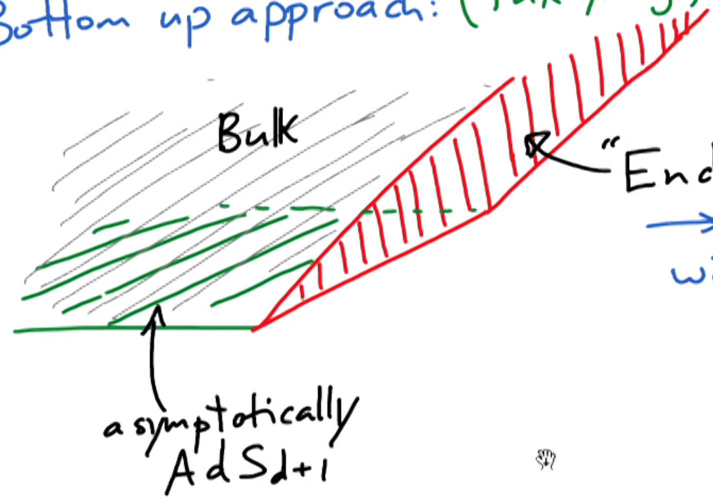


e.g. $\frac{1}{2}$ susy b.c.'s for $\mathcal{N}=4$ SYM

Gaiotto Witten

Gravity duals of BCFTs:

① Bottom up approach: (Takayanagi; Karch Randall)



→ model via boundary action with tension, couplings to bulk fields

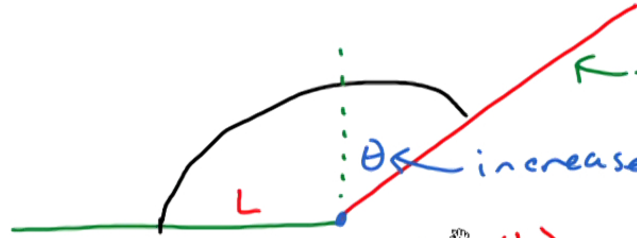
* we will use this *

② Top down approach: full 10D solutions

- no explicit brane

e.g. Aharony et. al. solutions dual to $\mathcal{N}=4$ w. $\frac{1}{2}$ susy b.c.'s

Brane tension vs boundary entropy



← tension $\propto T$

θ ← increases w. increasing T

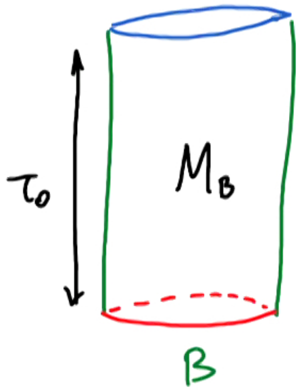
$$S = \frac{c}{6}\ln\left(\frac{L}{\varepsilon}\right) + \operatorname{arctanh}(T)$$

$$S = \frac{c}{6}\ln\left(\frac{L}{\varepsilon}\right) + \ln(g)$$

← measure of
\# of boundary d.o.f.

* Currently exploring which values of T are possible in holographic theories by computing boundary entropy for SUSY cases with explicit dual solutions w. Chris Waddell

Back to our CFT states



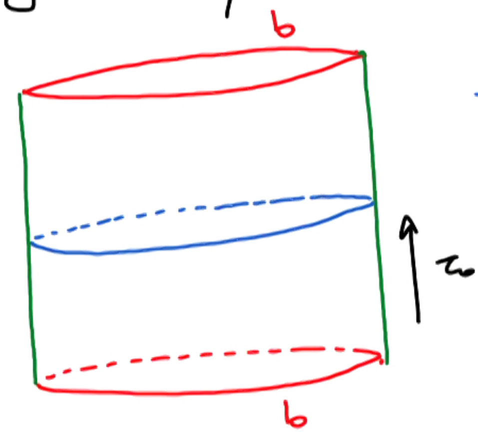
$$\Psi_{B,\tau_0}[\phi_0] = \int_{M_B}^{\phi(\tau=0)=\phi_0} [d\phi]\, e^{-S_{Euc}}$$

* Defines excited state for CFT on S^{d-1} *

* CFT boundary appears only in Euclidean past *

What is the dual geometry?

Follow AdS/CFT recipe to find dual black hole geometry:



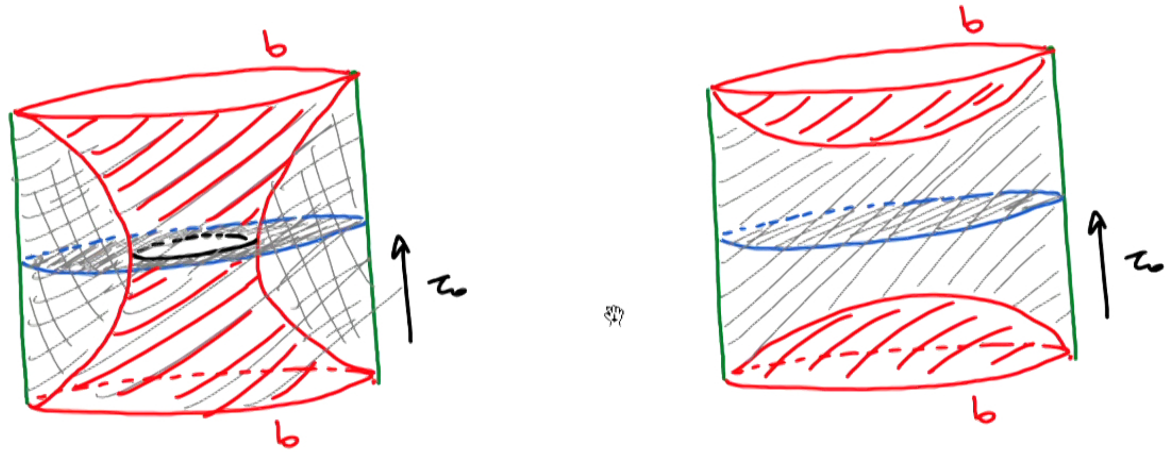
$\longrightarrow$ CFT path integral on this space used to compute observables e.g.

$$\langle \Psi_{b,\tau_0} | \mathcal{O}_1 \ldots \mathcal{O}_n | \Psi_{b,\tau_0} \rangle$$

Dual gravity calculation: First, find Euclidean asympt. AdS spacetime with this boundary geometry.

Dual geometry (using bottom-up approach)

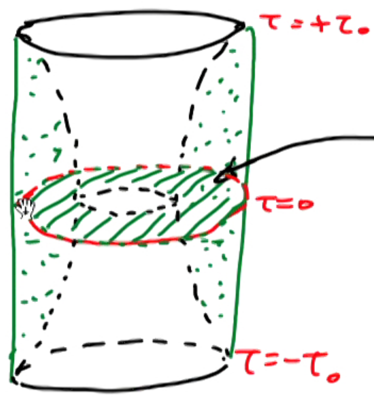
2 possible topologies:



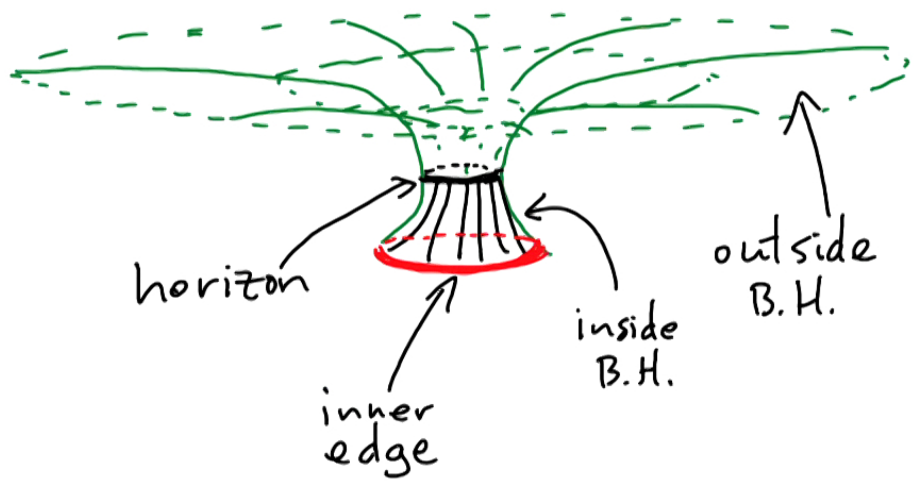
this has lower action for small τ_0

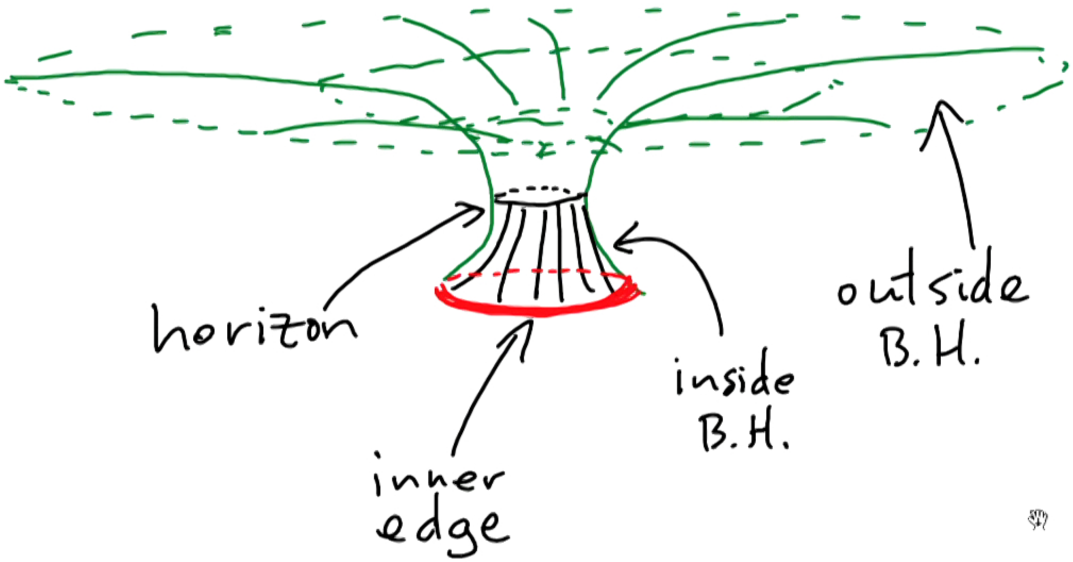
– black hole phase

Dual Lorentzian spacetime: (for ETW brane tension $T>0$)



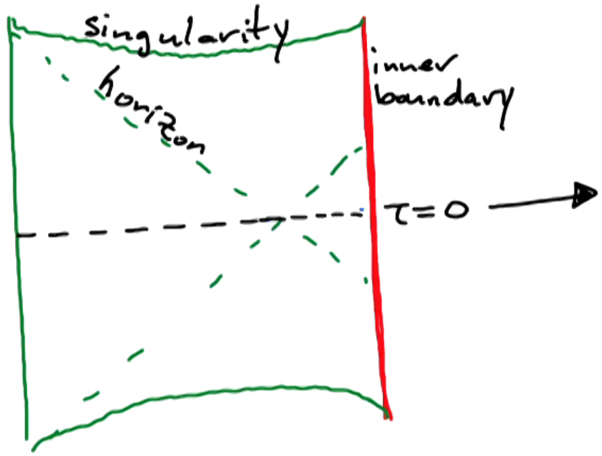
initial data for Lorentzian spacetime dual to B.H. state





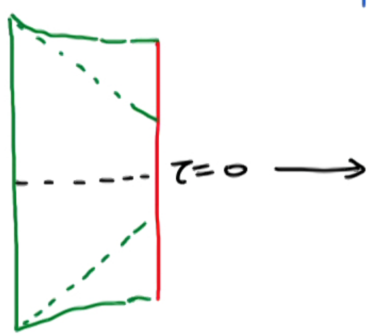
detailed properties of this inner boundary depend on boundary condition chosen to define state.

Spacetime picture:



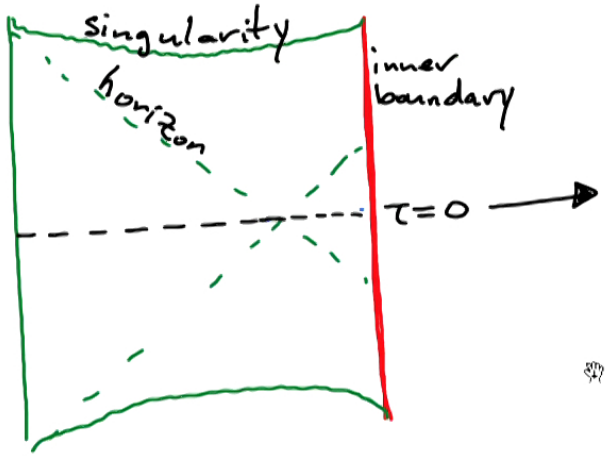
$T > 0$ case:

$T < 0$ case:



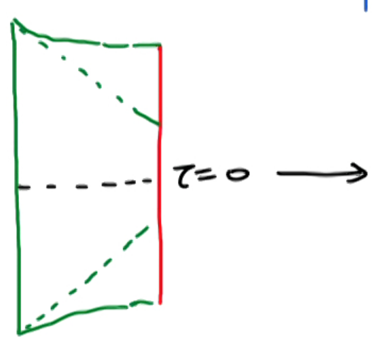
How can we probe behind the horizon via the CFT state?

Spacetime picture:



$T > 0$ case:

$T < 0$ case:

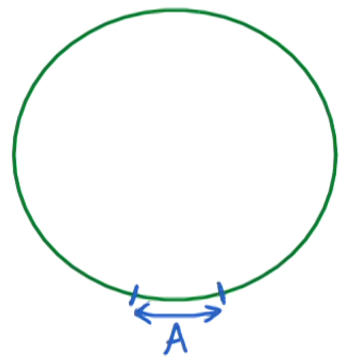


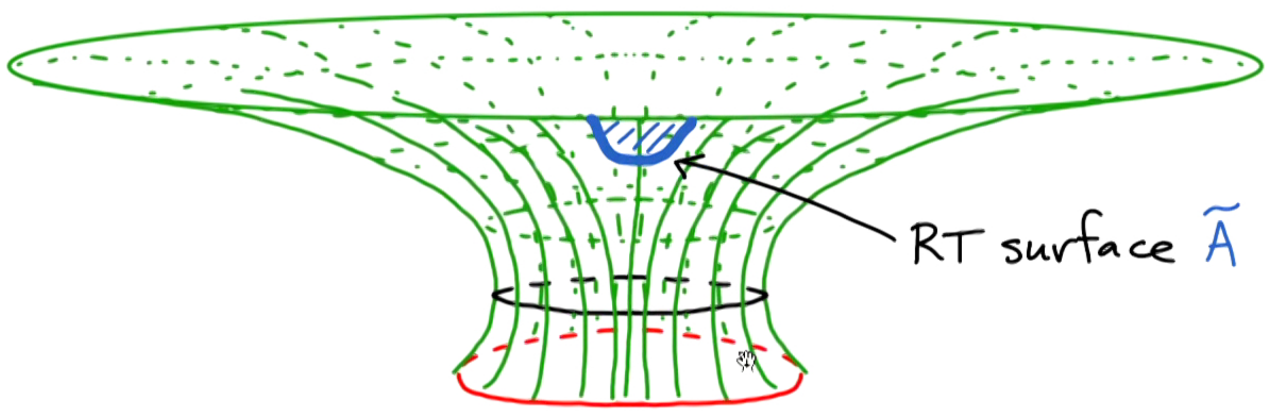
How can we probe behind the horizon via the CFT state?

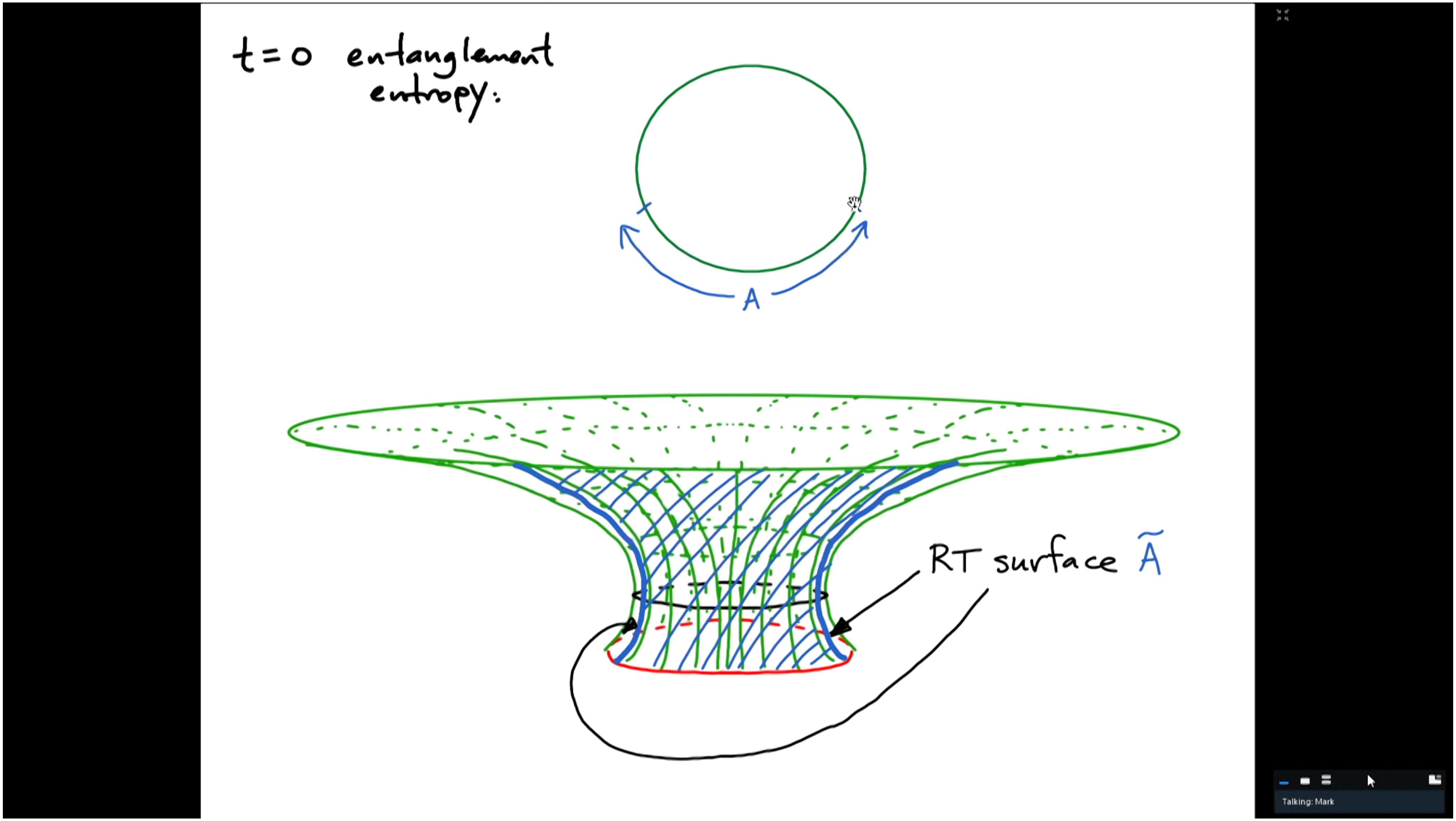
Entanglement entropy!

Talking: Mark

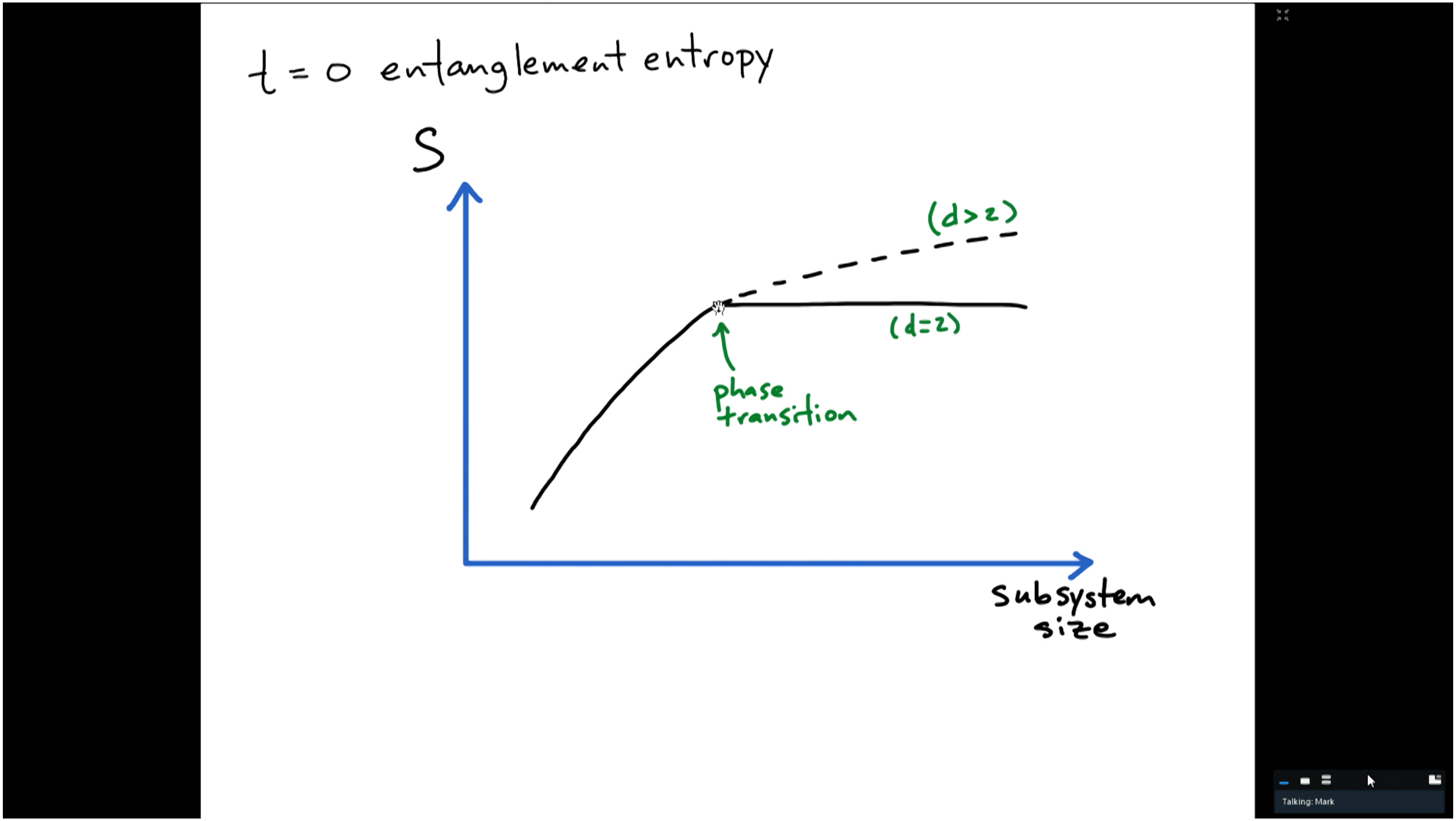
$t=0$ entanglement entropy:



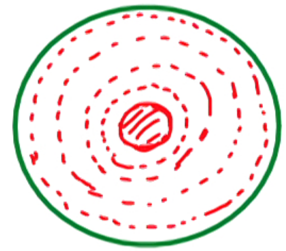


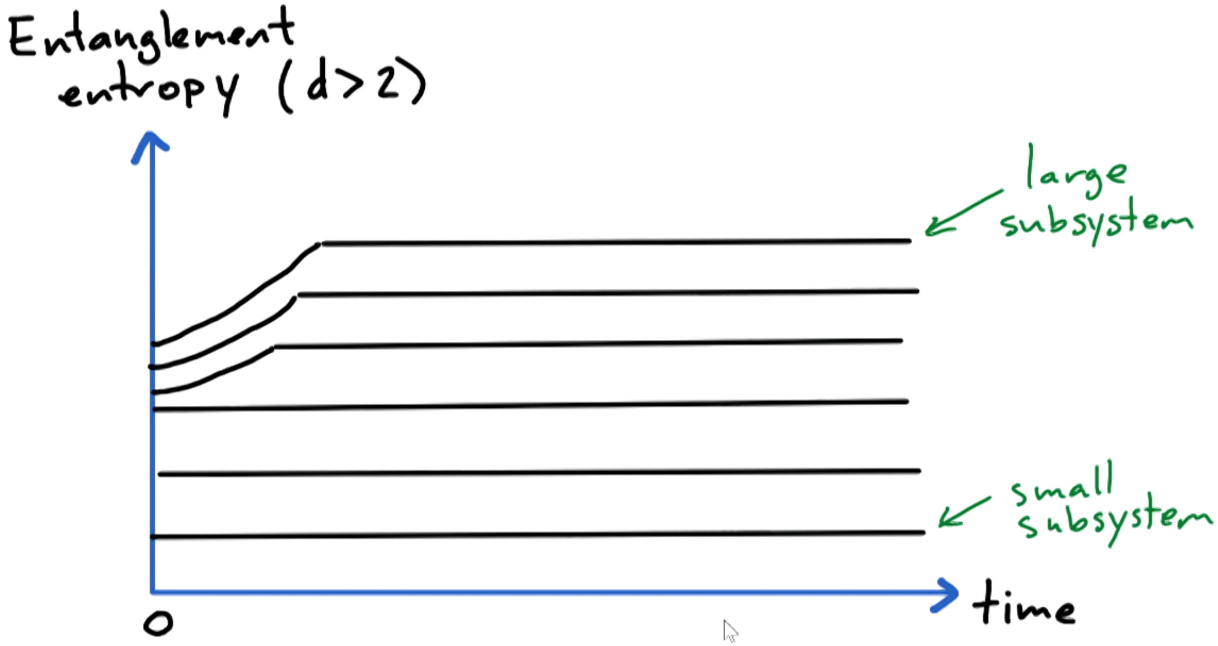


t=0 entanglement entropy:
A
RT surface $\tilde{A}$
Talking: Mark


t = 0 entanglement entropy
S
(d>2)
(d=2)
phase transition
subsystem size
Talking: Mark

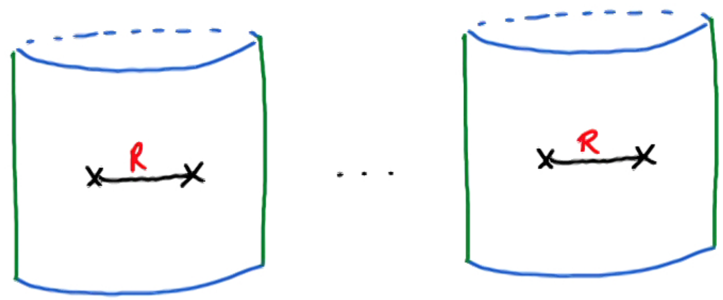
Time-dependent entanglement entropies:





Direct CFT calculation:

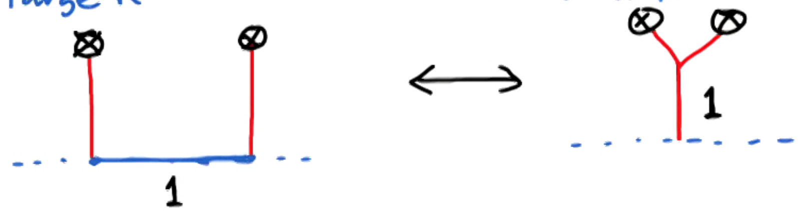
$$S = \lim_{n \to 1} \frac{1}{1-n} \frac{Z_n}{Z_1^n}$$



$= Z_n$

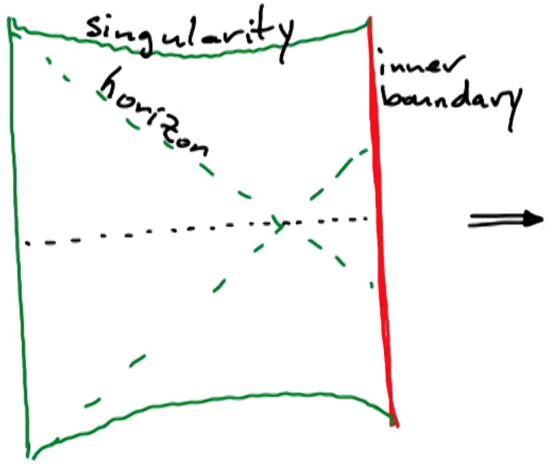
Transition + detailed results reproduced by assuming identity block dominance in some channel

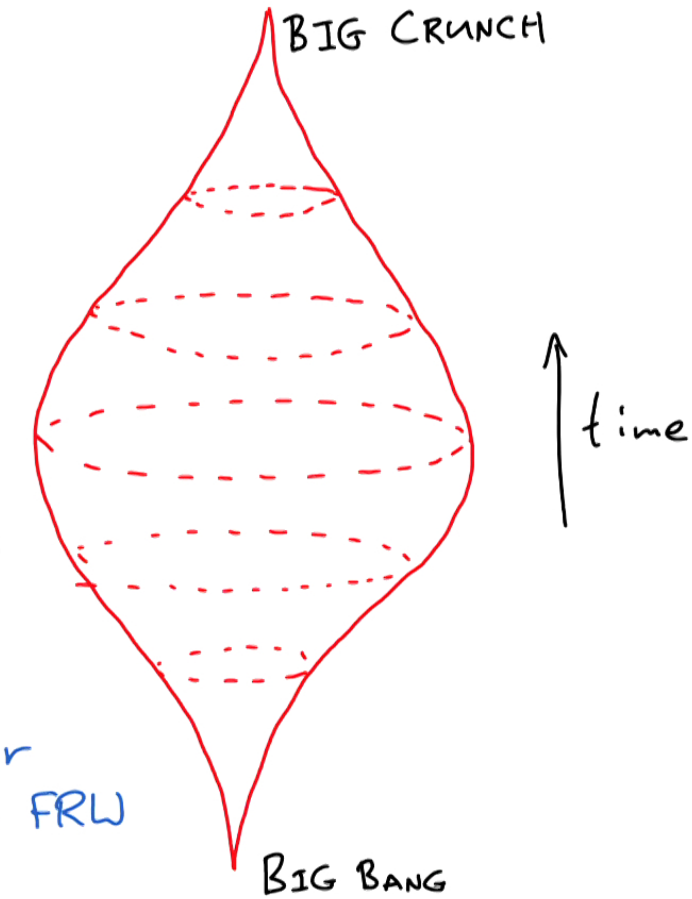
large R: small R:



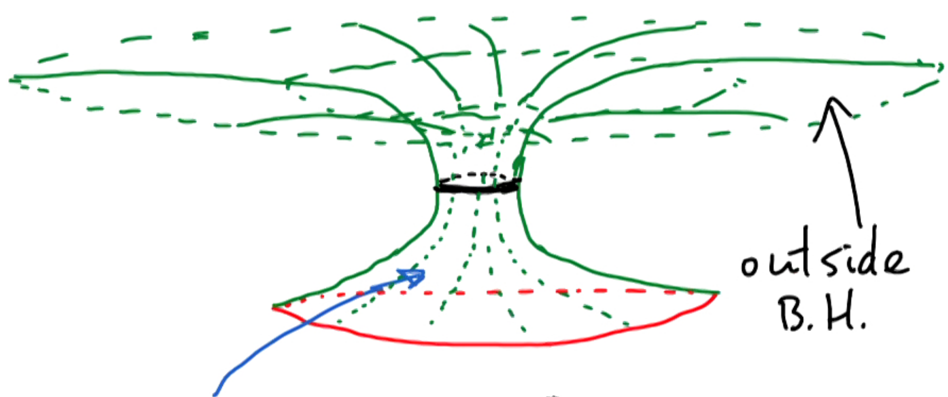
David Wakeham, MVR in progress

A connection to cosmology?

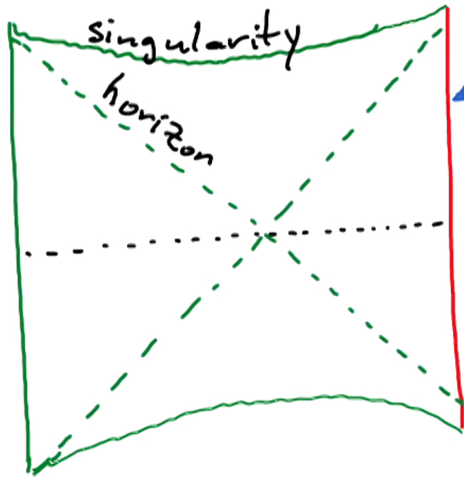




- spacetime geometry of inner boundary looks like closed FRW cosmology



If inner region is large enough, gravity can "localize" on the inner boundary.

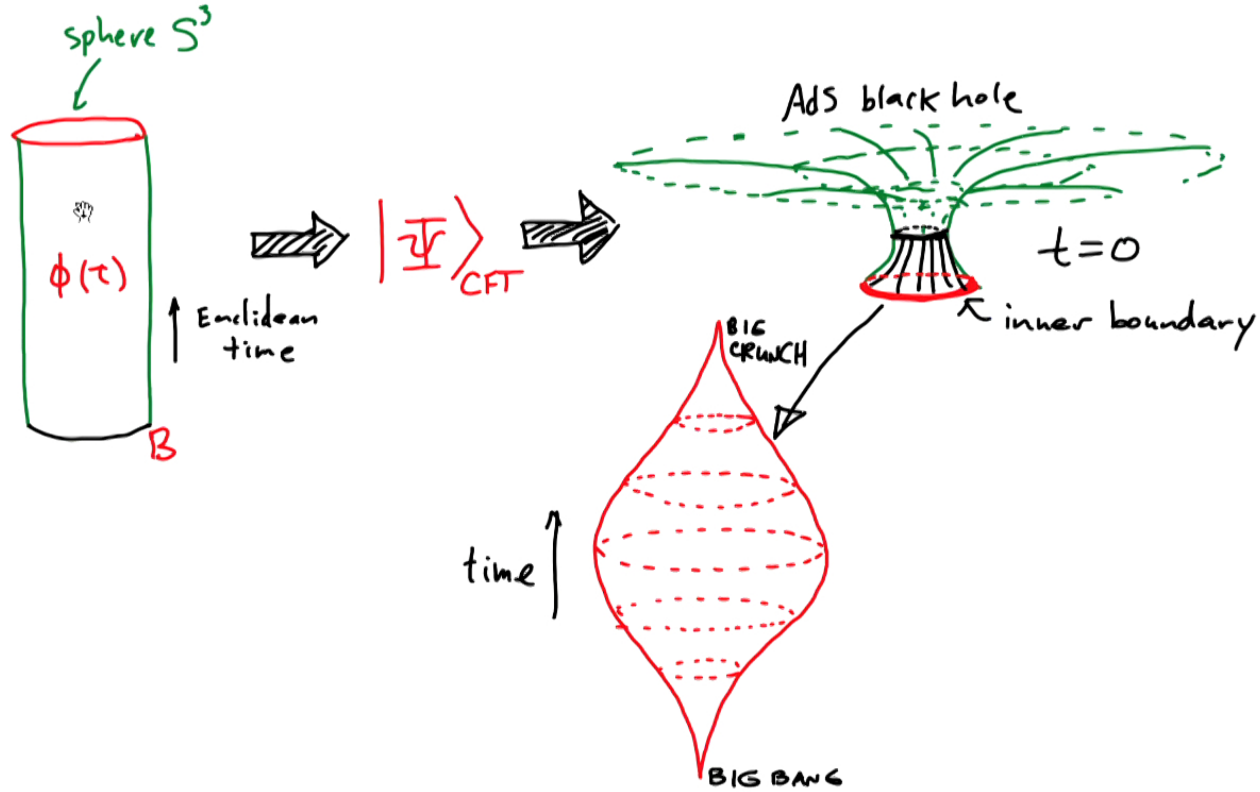


"UV brane"

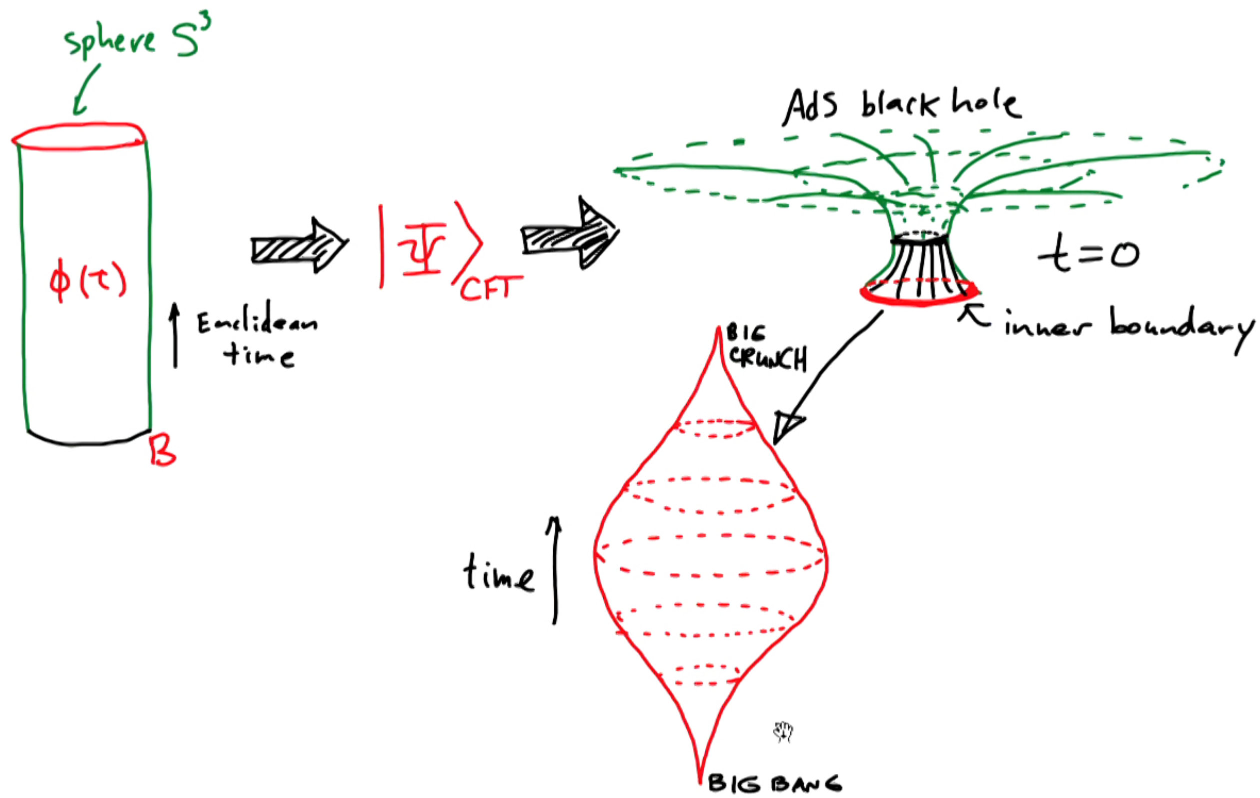
Randall - Sundrum II

Cosmology

Punch line: Certain high-energy states of a CFT on S^3 may provide a microscopic description of big bang cosmology



Punch line: Certain high-energy states of a CFT on S^3 may provide a microscopic description of big bang cosmology



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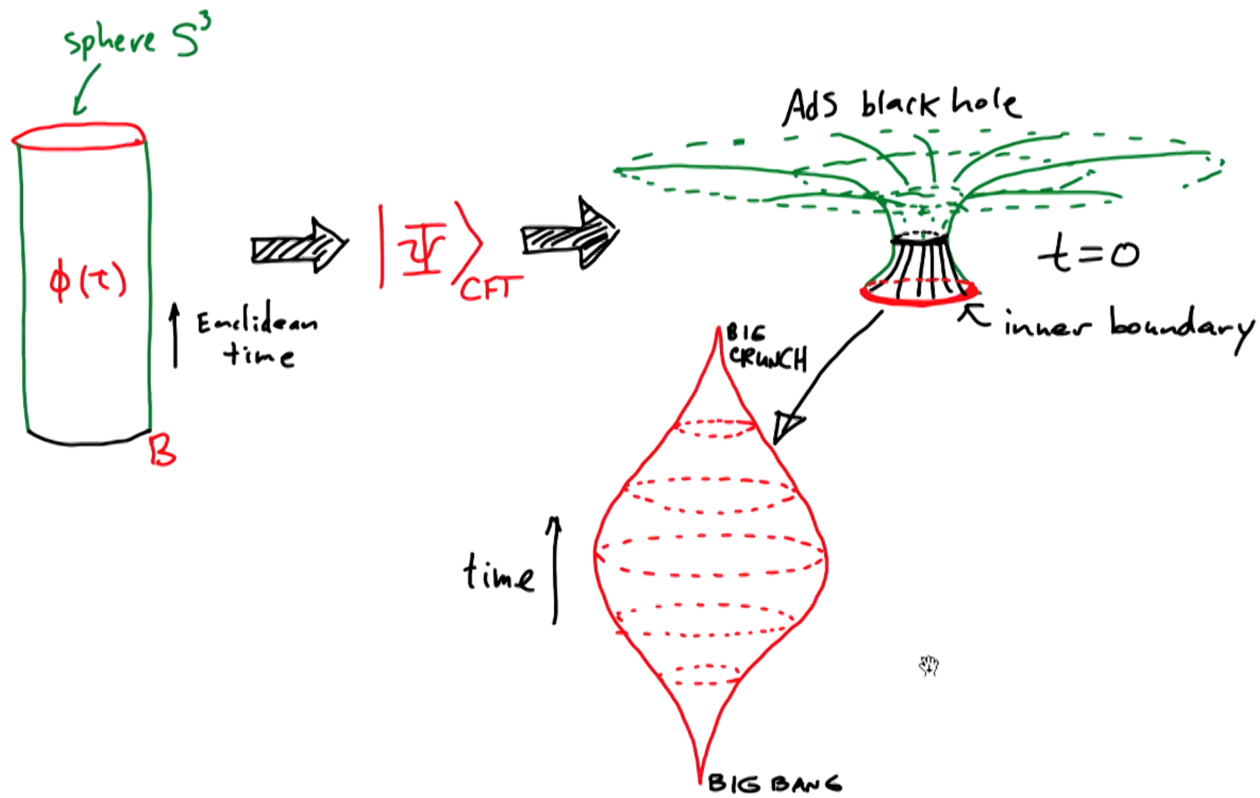

Talking: Mark

Very interesting even if can't be made realistic

* currently no complete quantum gravity theory for cosmological spacetimes*

Key question: how is the detailed cosmological physics encoded in the CFT?

- need to understand description of local behind-the-horizon operators (hard!)

Talking: Mark