

BLACK HOLE MICROSTATE COSMOLOGY

Mark Van Raamsdonk, UBC

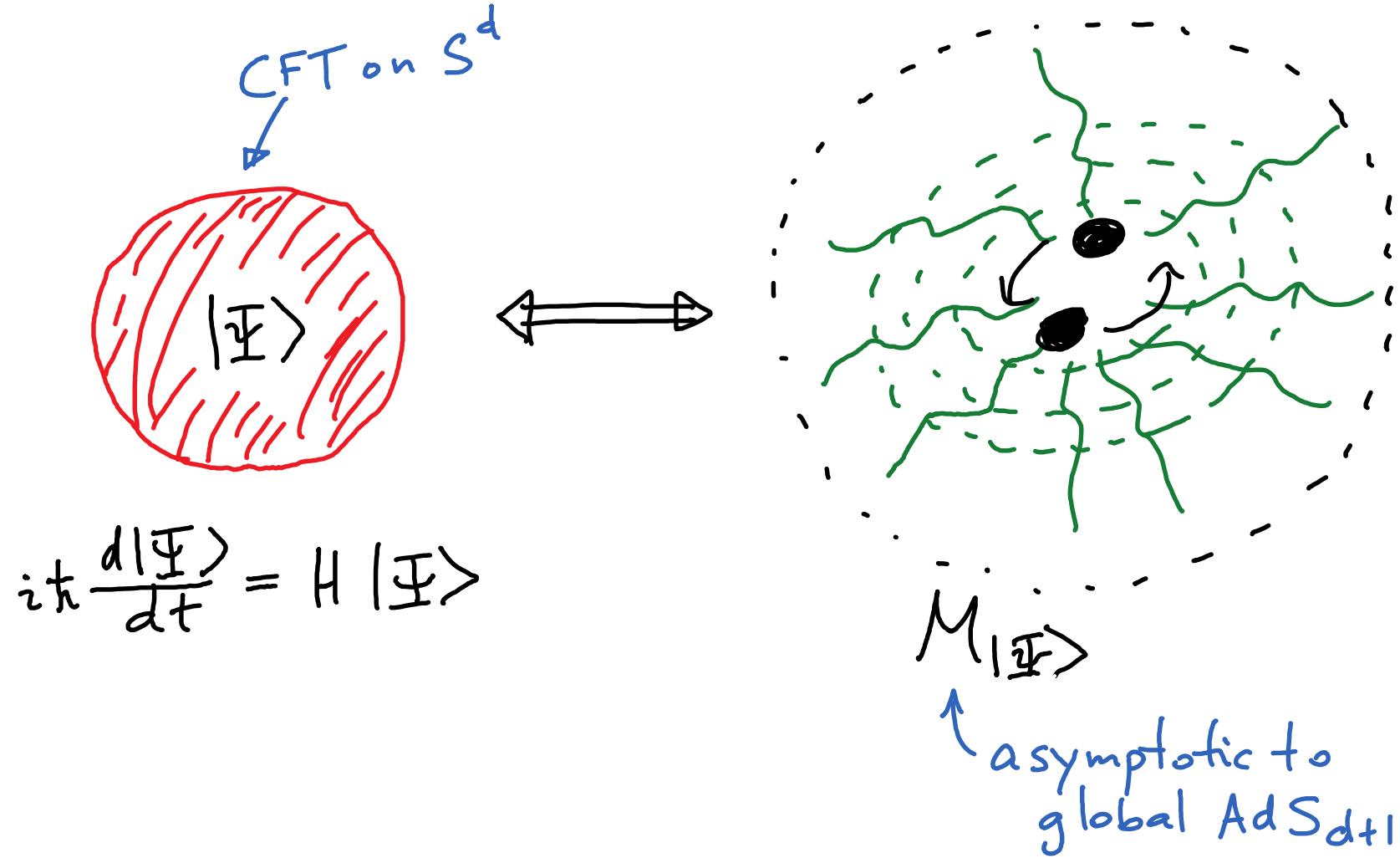
based on: 1810.10601 with S.Cooper, M.Rozali, B.Swingle
C.Waddell, D.Wakeham

Big questions for quantum gravity:

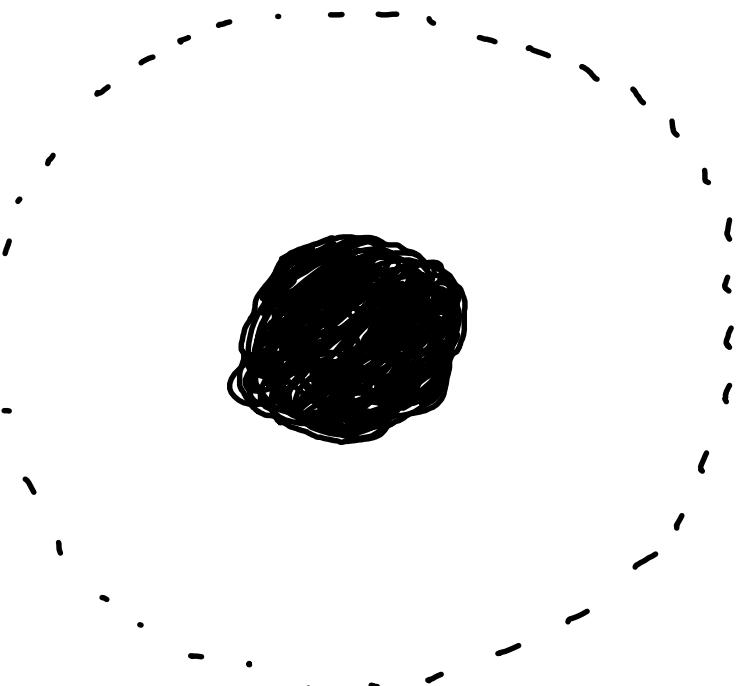
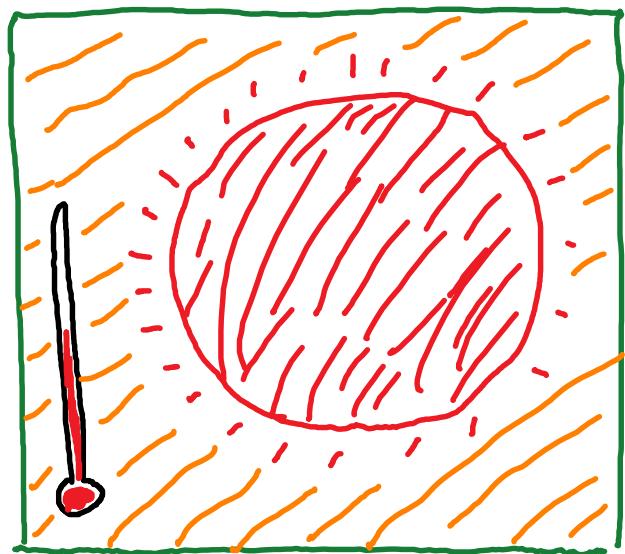
- physics of black holes
- big bang/cosmology
(incl. dark energy)

Use AdS/CFT correspondence as a fundamental definition

THE AdS/CFT correspondence



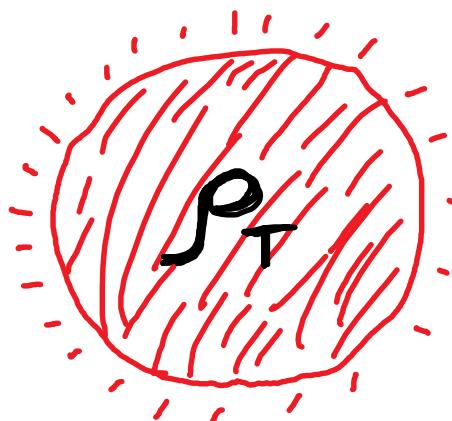
Black holes in AdS/CFT



Thermal state of CFT \iff Black hole in AdS

Witten

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



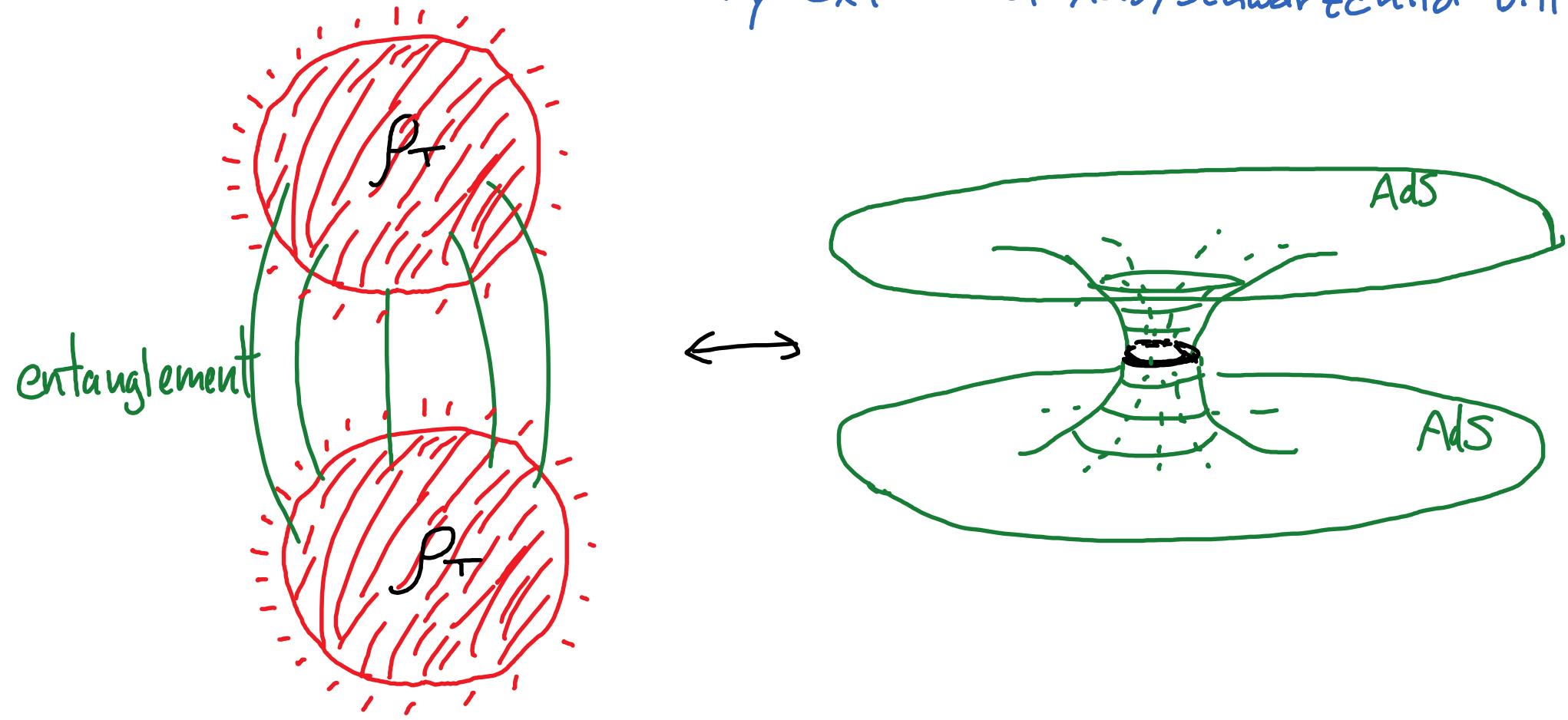
Thermal state
= mixed state of CFT

subsystem
of larger system
(CFT + heat bath)

OR

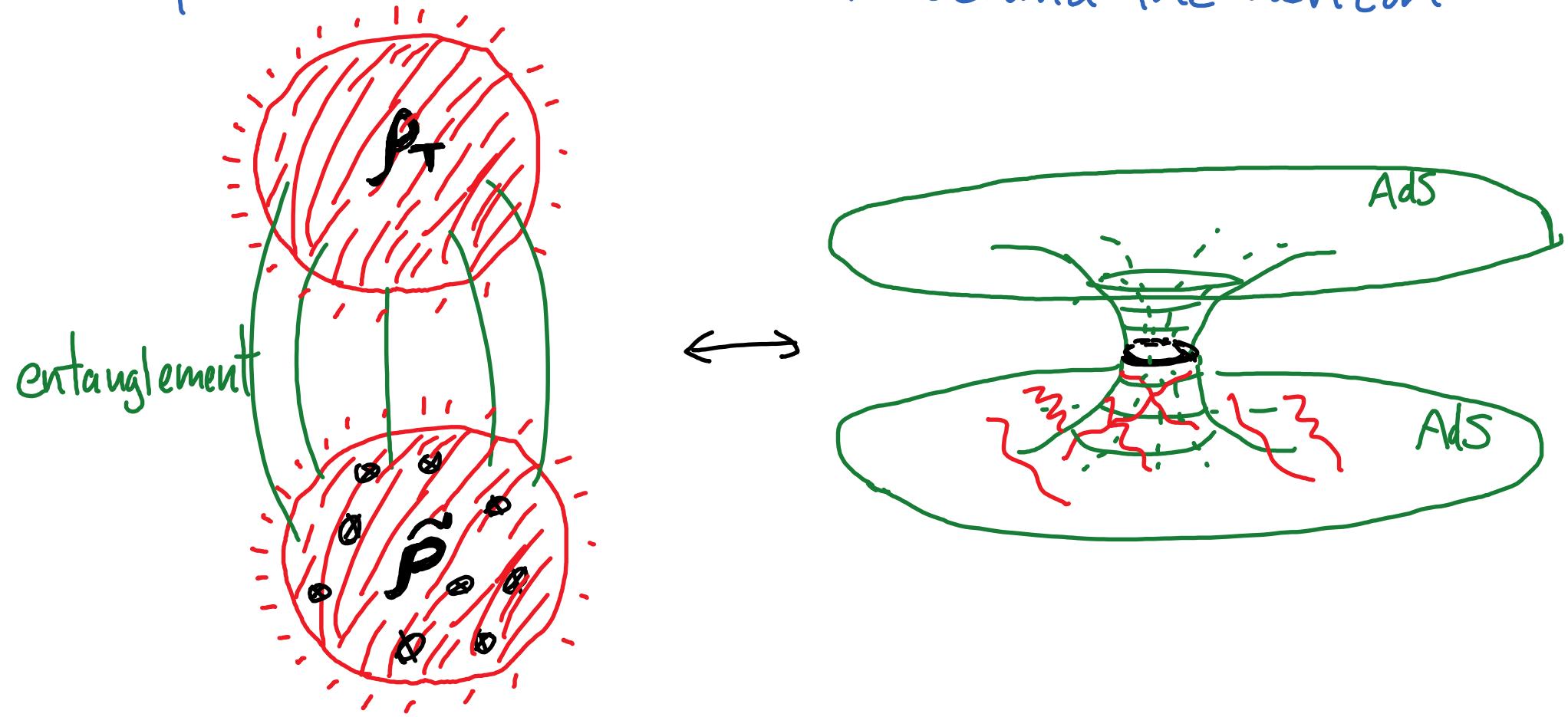
ensemble
of pure states
"black hole
microstates"

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



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

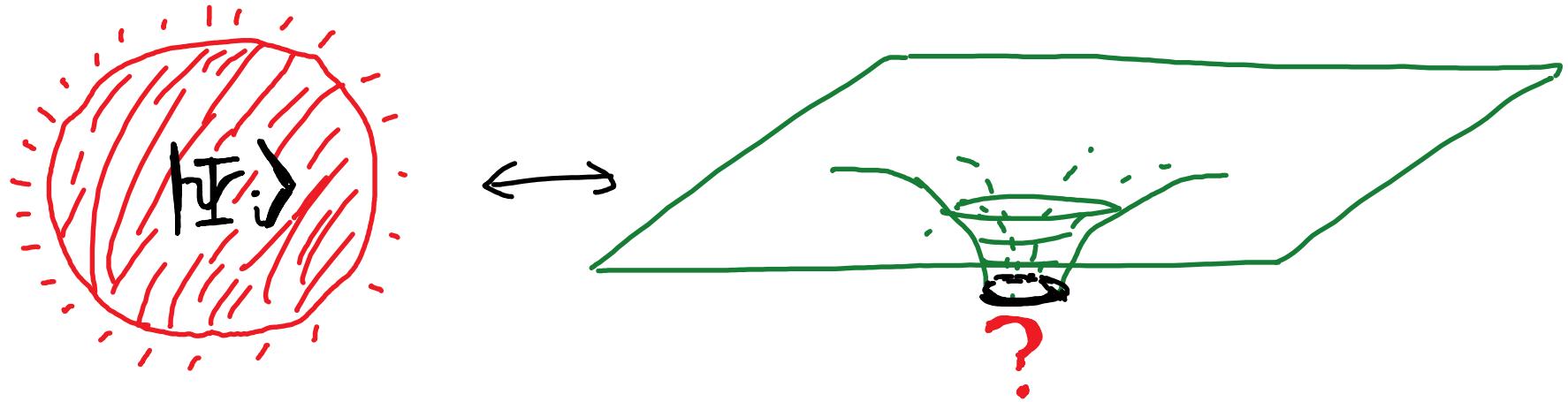
But other purifications correspond to extended spacetimes with "stuff" behind the horizon



$$|\Psi\rangle = \sum_i e^{-\beta E_i/z} |\bar{E}_i\rangle \otimes (\mathcal{U} |\bar{E}_i\rangle)$$

unitary

What about black hole microstates?



$$| \Psi \rangle \in \mathcal{P}_+$$

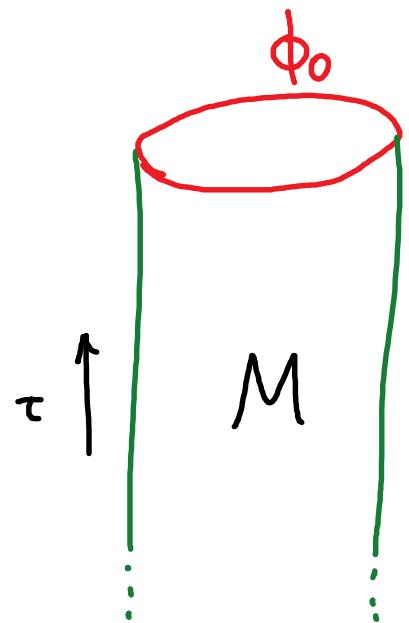
significant controversy e.g. firewall debate 2013+

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

(motivated by Kourkousis Maldacena
SYK discussion)

CFT states from path integrals:

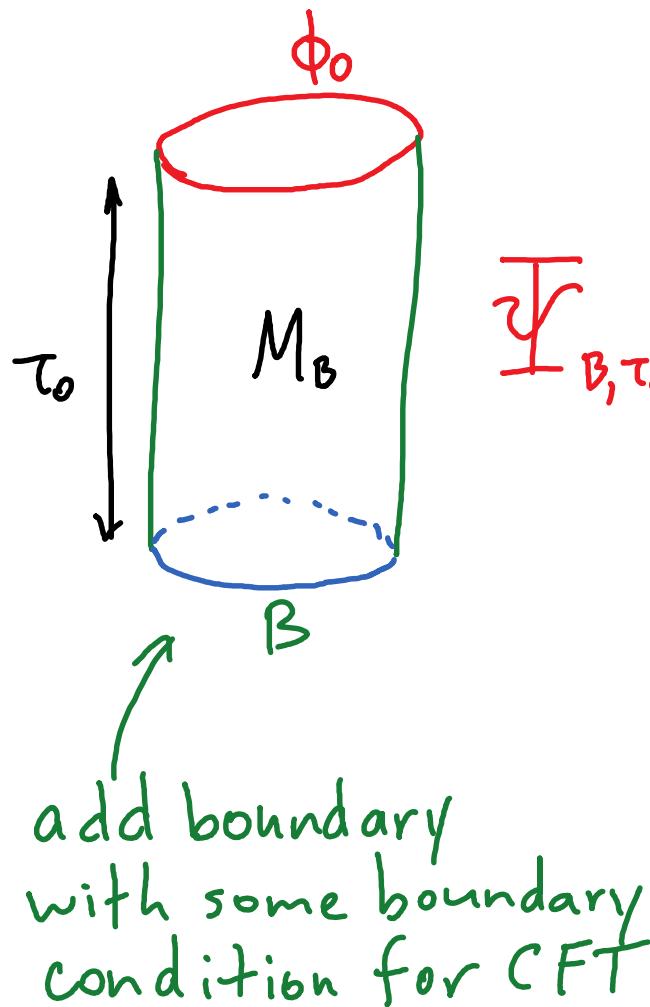
vacuum state wavefunction for CFT on S^d :



$$\Psi_{\text{vac}}[\phi_0] = \int_M [d\phi] e^{-S_{\text{Euc}}} \quad \begin{matrix} \phi(\tau=0) = \phi_0 \\ \end{matrix}$$

from: $|\text{vac}\rangle \sim \lim_{\beta \rightarrow \infty} e^{-\beta H} |\pm\rangle$

Black hole microstates from "boundary states": (Maldacena, Kourkoulou)



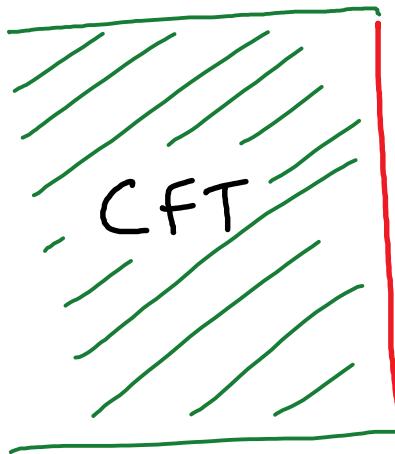
$$\Psi_{B, \tau_0}[\phi_0] = \int_{M_B} [d\phi] e^{-S_{\text{Euc}}}$$

$\phi(\tau=0) = \phi_0$

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

“boundary
state”

INTERLUDE: CFTs with boundary and their gravity duals



Given a CFT, have various consistent boundary conditions

e.g.: Neumann/Dirichlet for free scalar

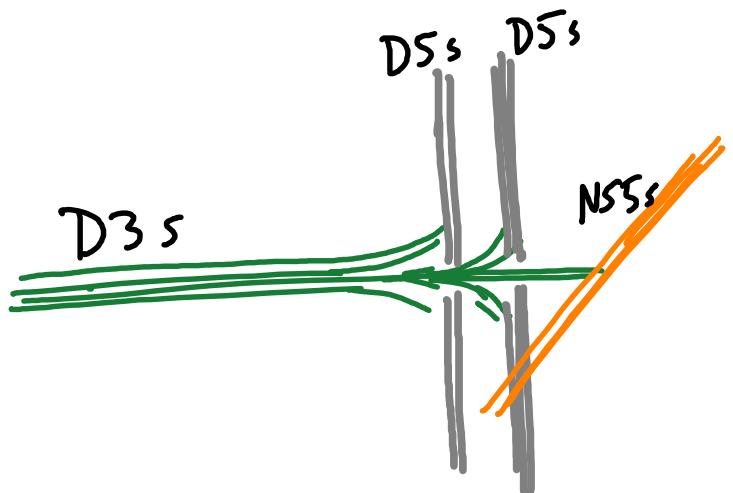
Some preserve scale/conformal invariance
 $SO(d, z) \rightarrow SO(d-1, z)$

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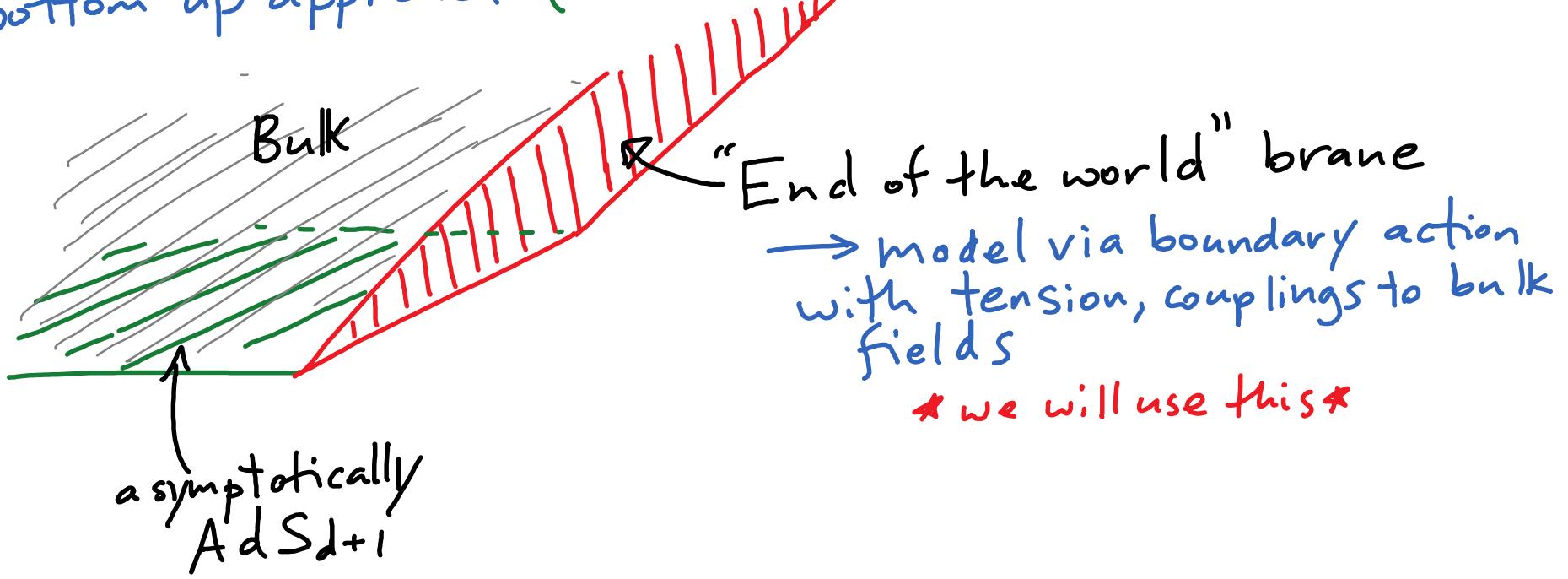


e.g. $\frac{1}{2}$ SUSY b.c.'s for $N=4$ SYM

Gaiotto & Witten

Gravity duals of BCFTs:

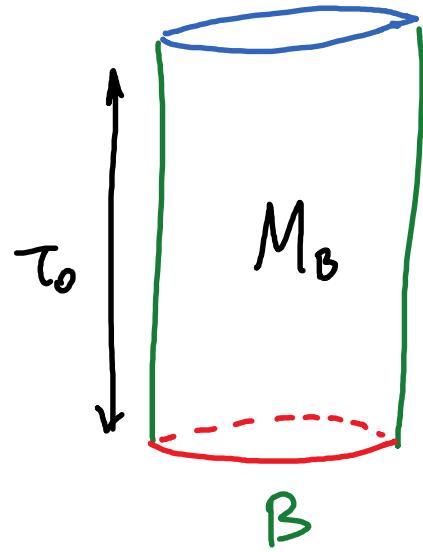
- ① Bottom up approach: (Takayanagi; Karch Randall)



- ② Top down approach: full 10D solutions
- no explicit brane

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

Back to our CFT states



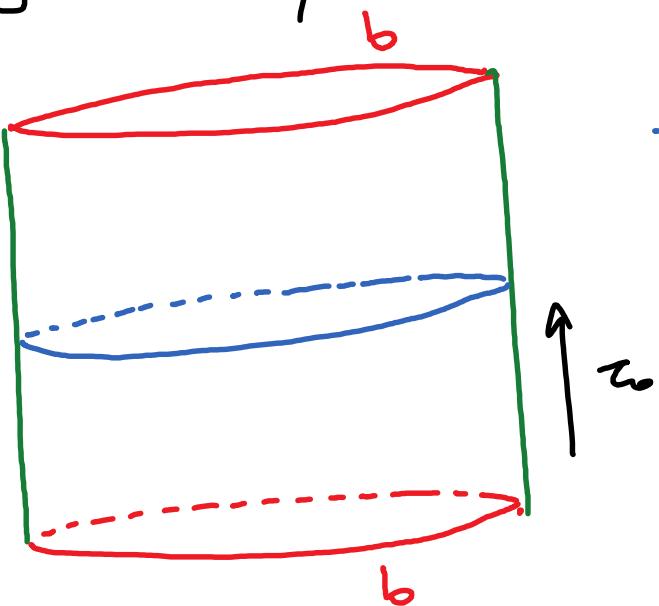
$$\Psi_{B, \tau_0}[\phi_0] = \int_{M_B}^{[\phi(\tau=0) = \phi_0]} e^{-S_{\text{Euc}}} [d\phi]$$

* 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:



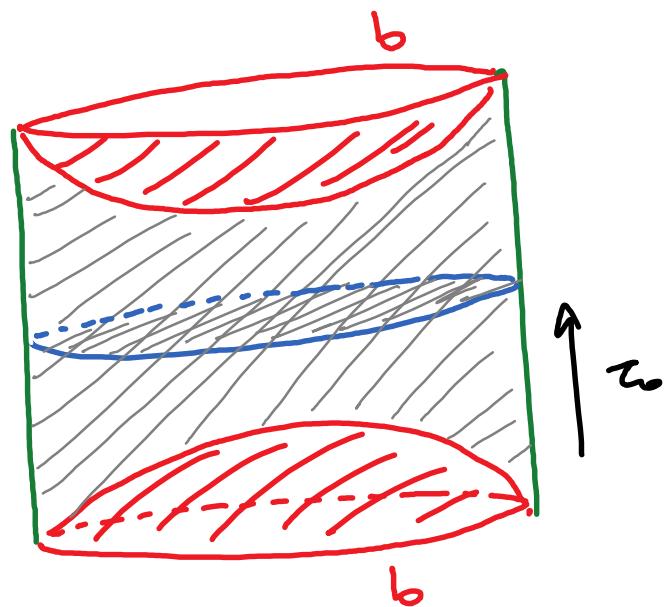
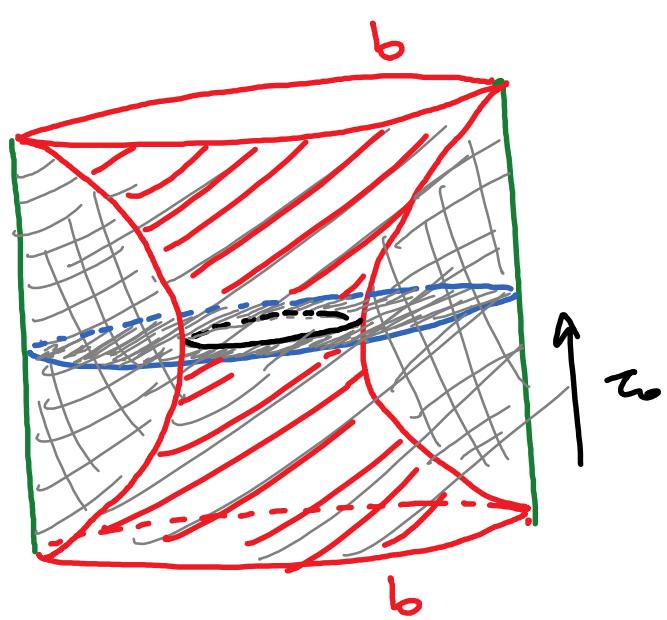
→ CFT path integral on this space used to compute observables e.g.

$$\langle \Xi_{b,z_0} | \theta, \dots \theta_n | \Xi_{b,z_0} \rangle$$

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

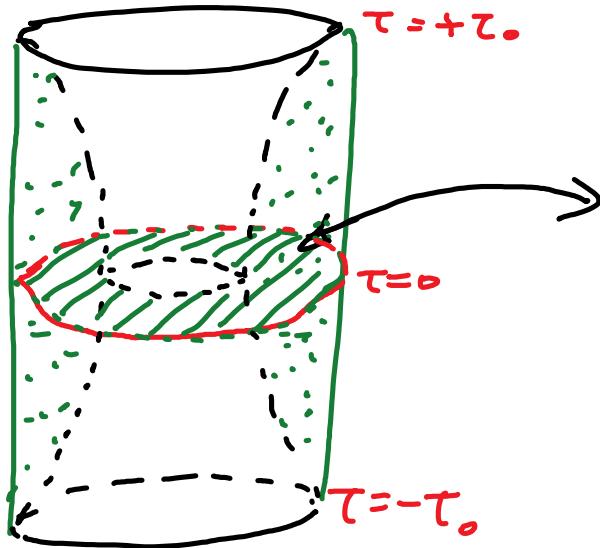
Dual geometry (using bottom-up approach)

2 possible topologies:

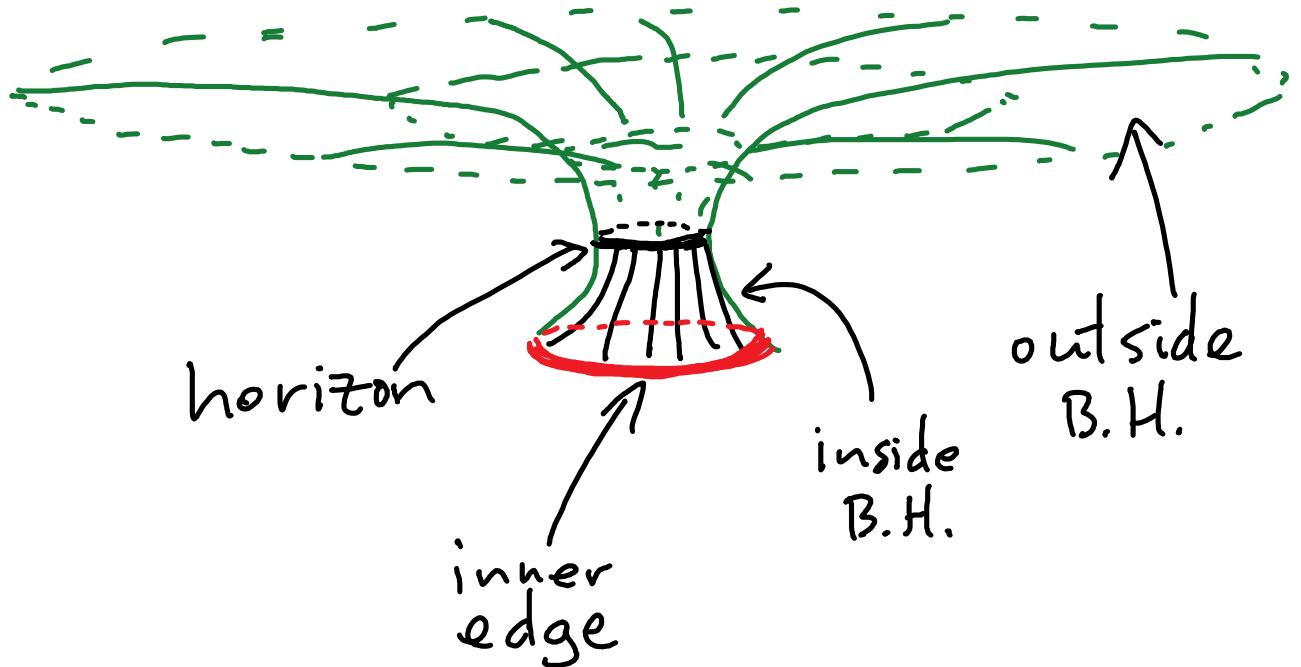


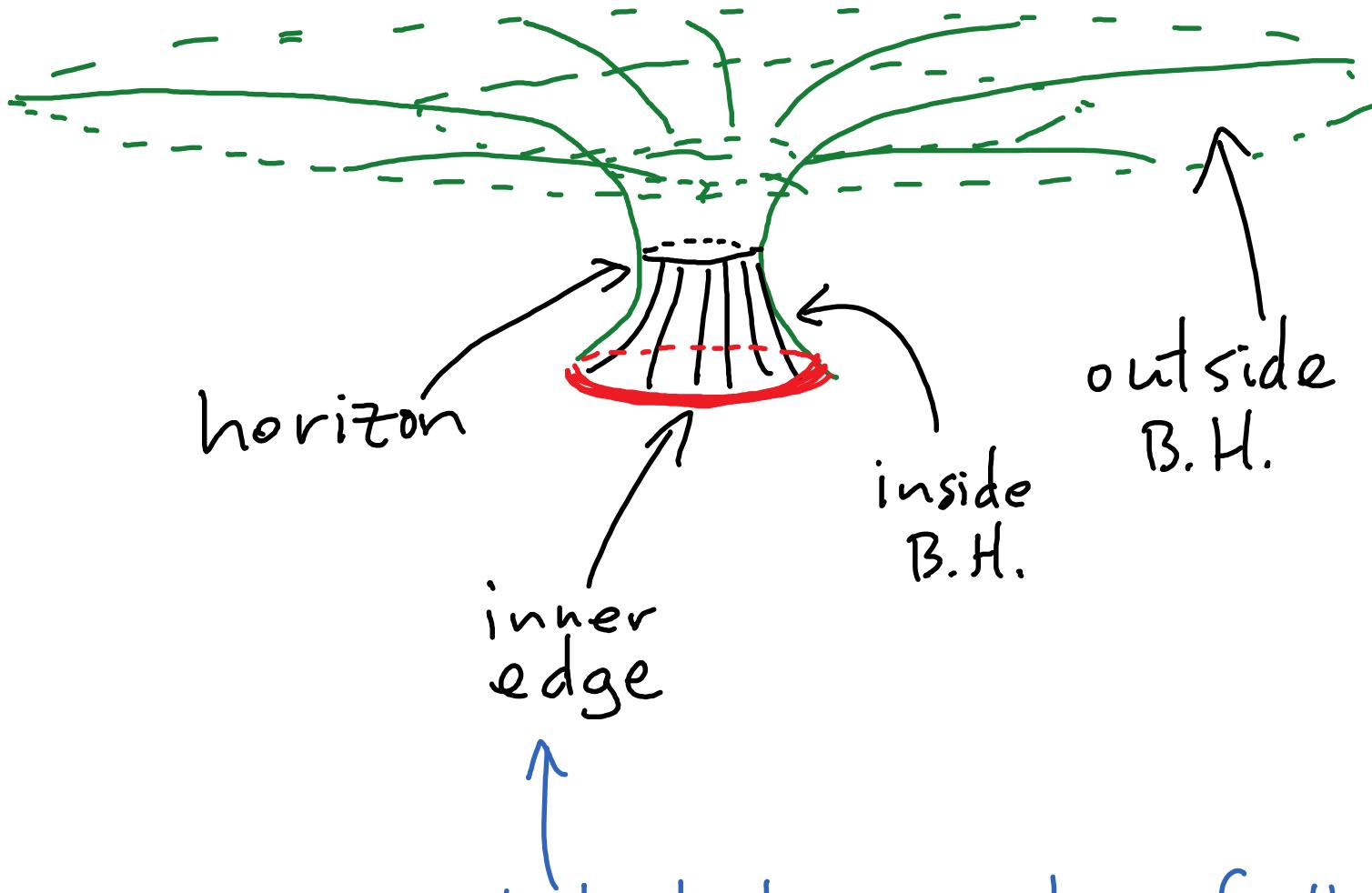
↑
this has lower action for small T_0
- black hole phase

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



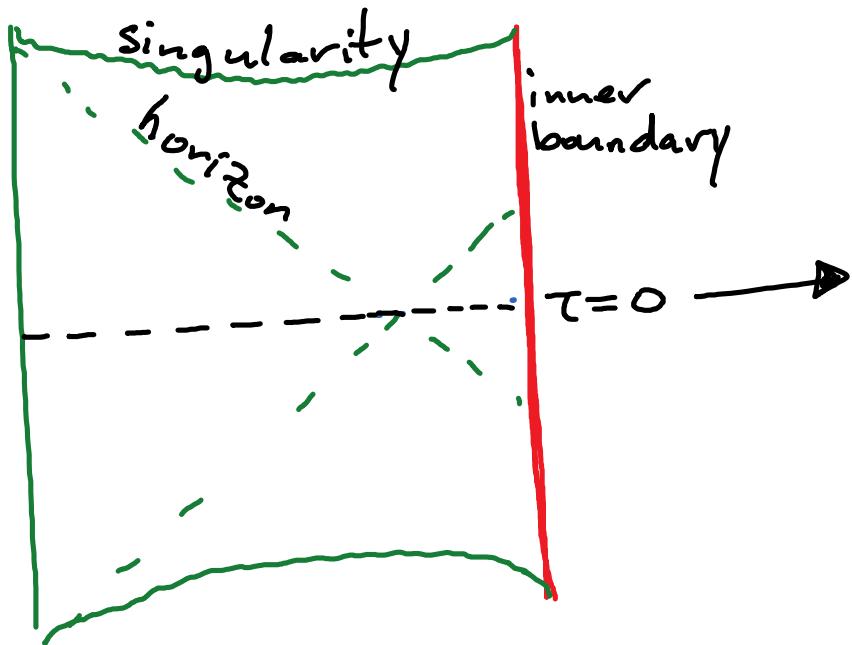
initial
data
for Lorentzian
spacetime
dual to B.H.
state



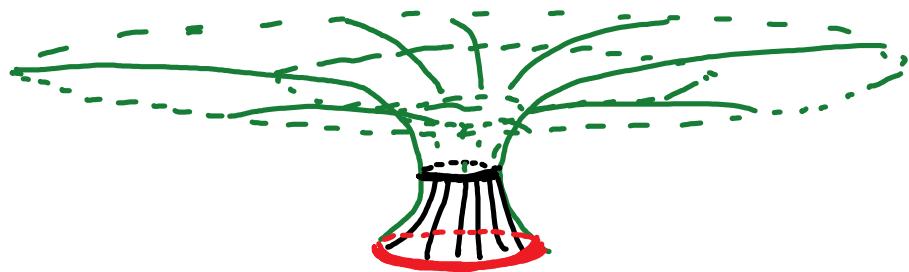


↑
detailed properties of this inner
boundary depend on boundary
condition chosen to define state.

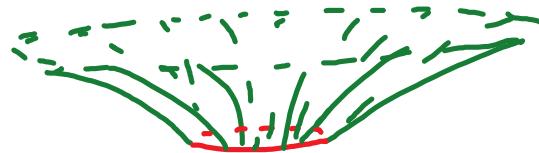
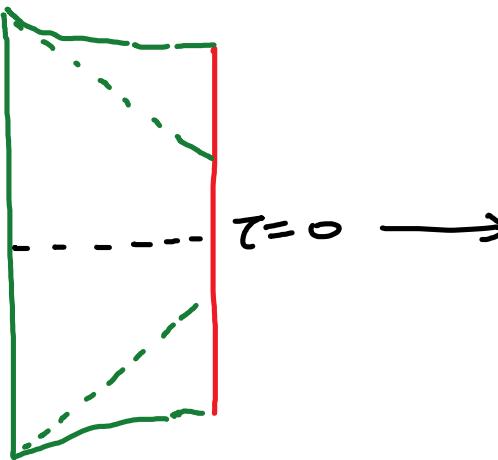
Spacetime picture:



$T > 0$ case:



$T < 0$ case:

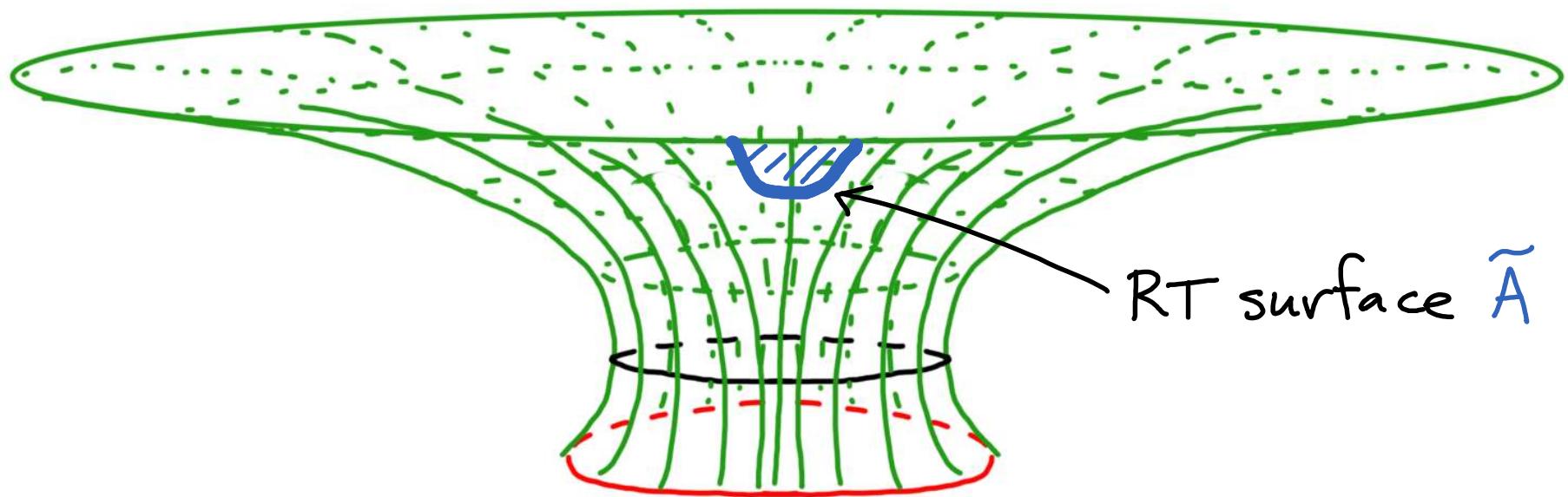
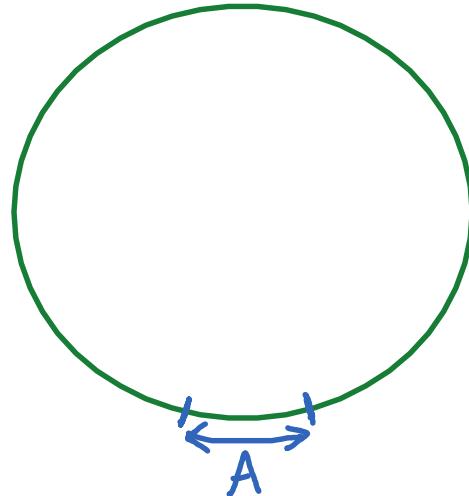


How can we probe behind the horizon via the CFT state?

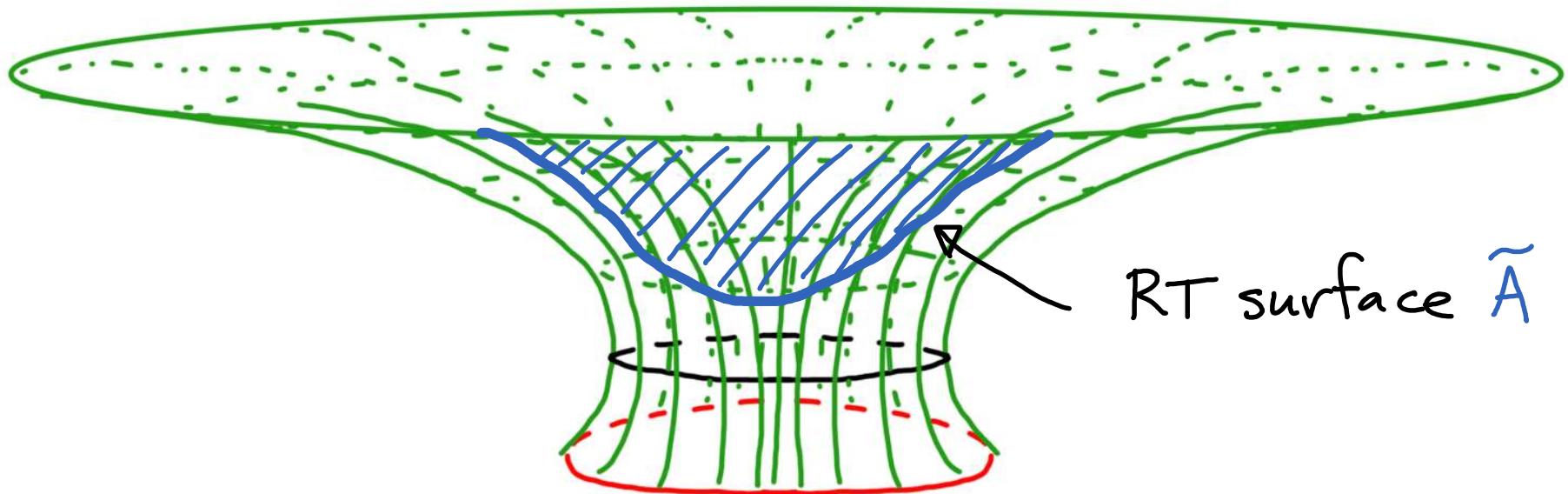
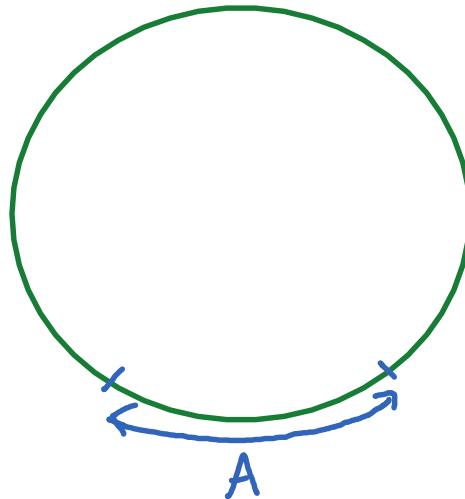
How can we probe behind the horizon via the CFT state?

Entanglement entropy!

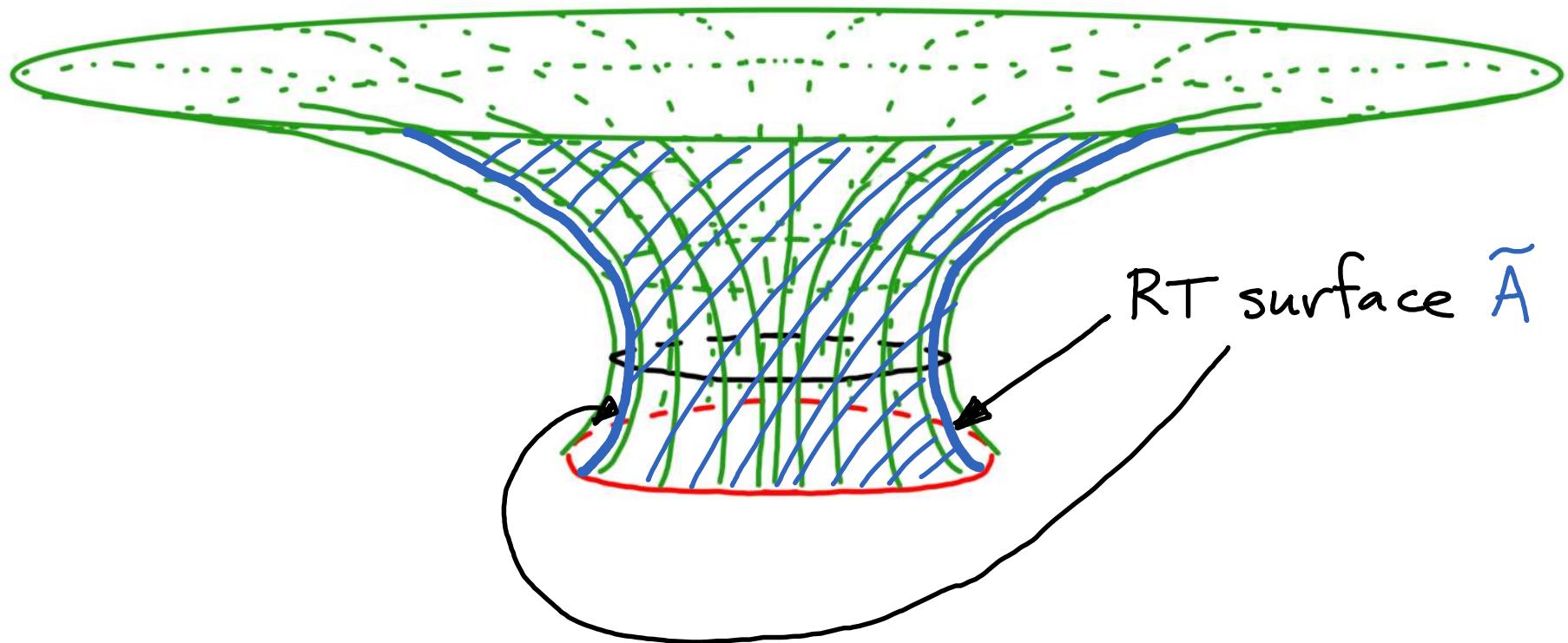
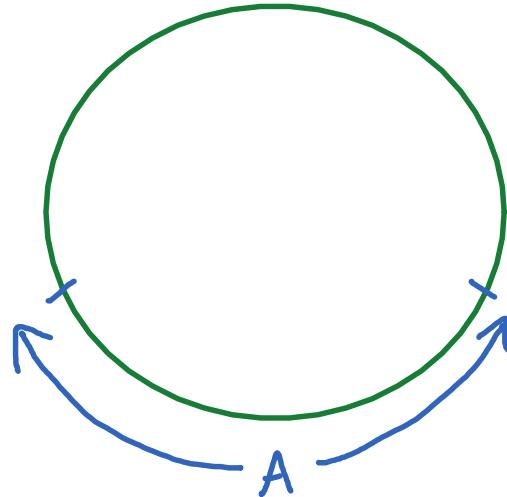
$t=0$ entanglement entropy:



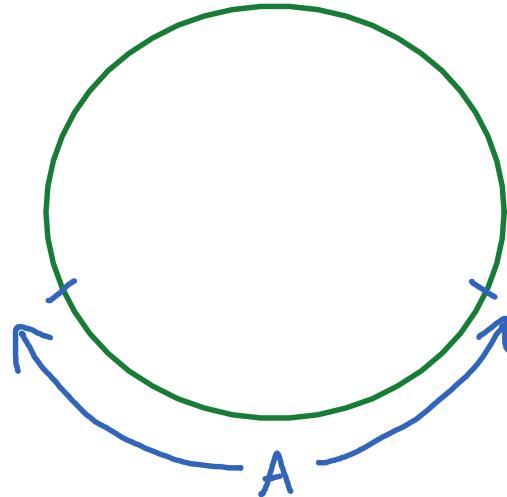
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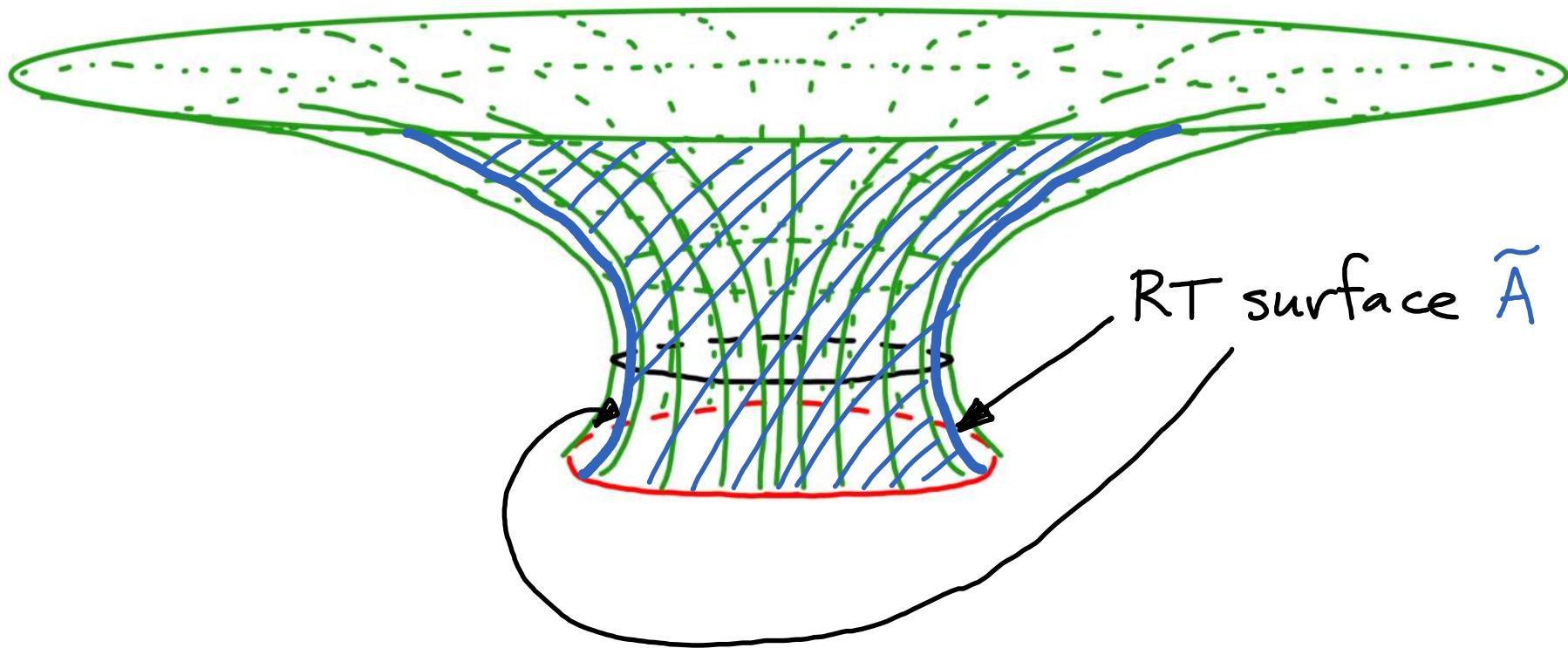
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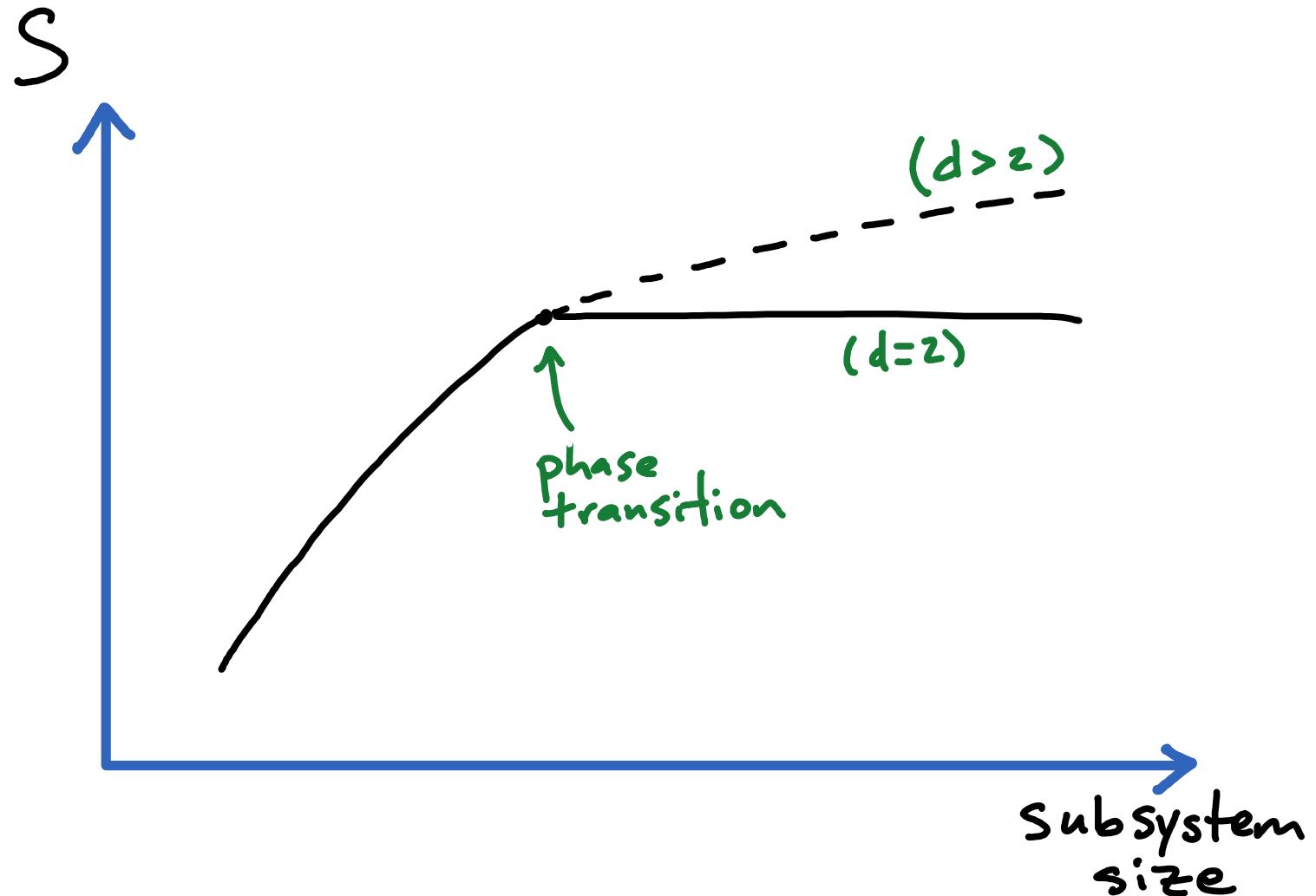
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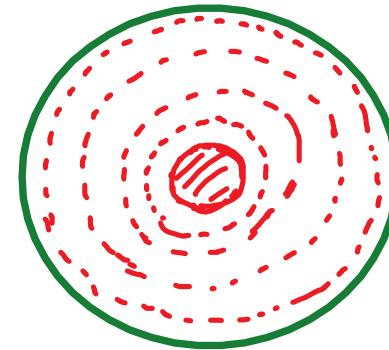
* Entanglement entropies for sufficiently large subsystems can probe behind-the-horizon physics *



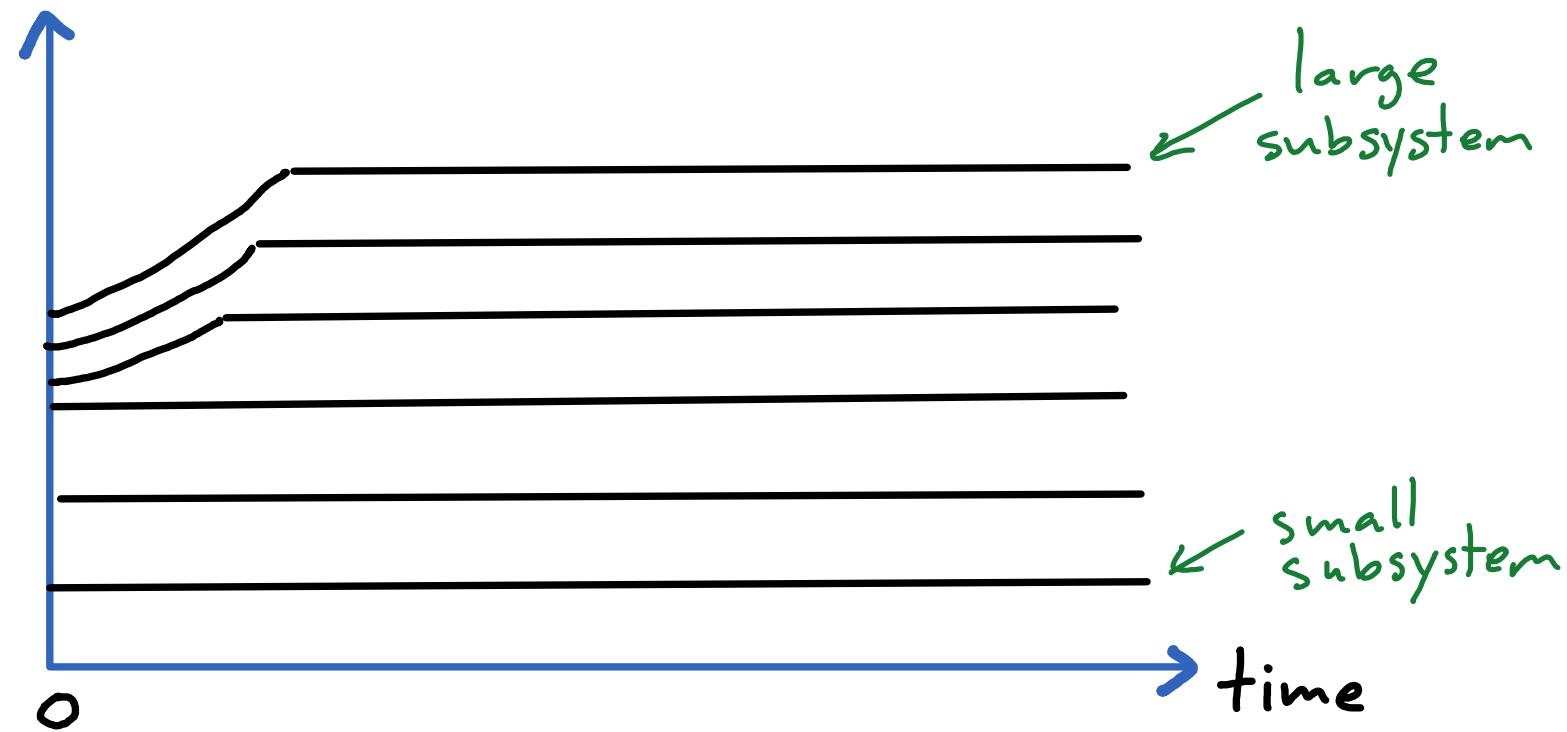
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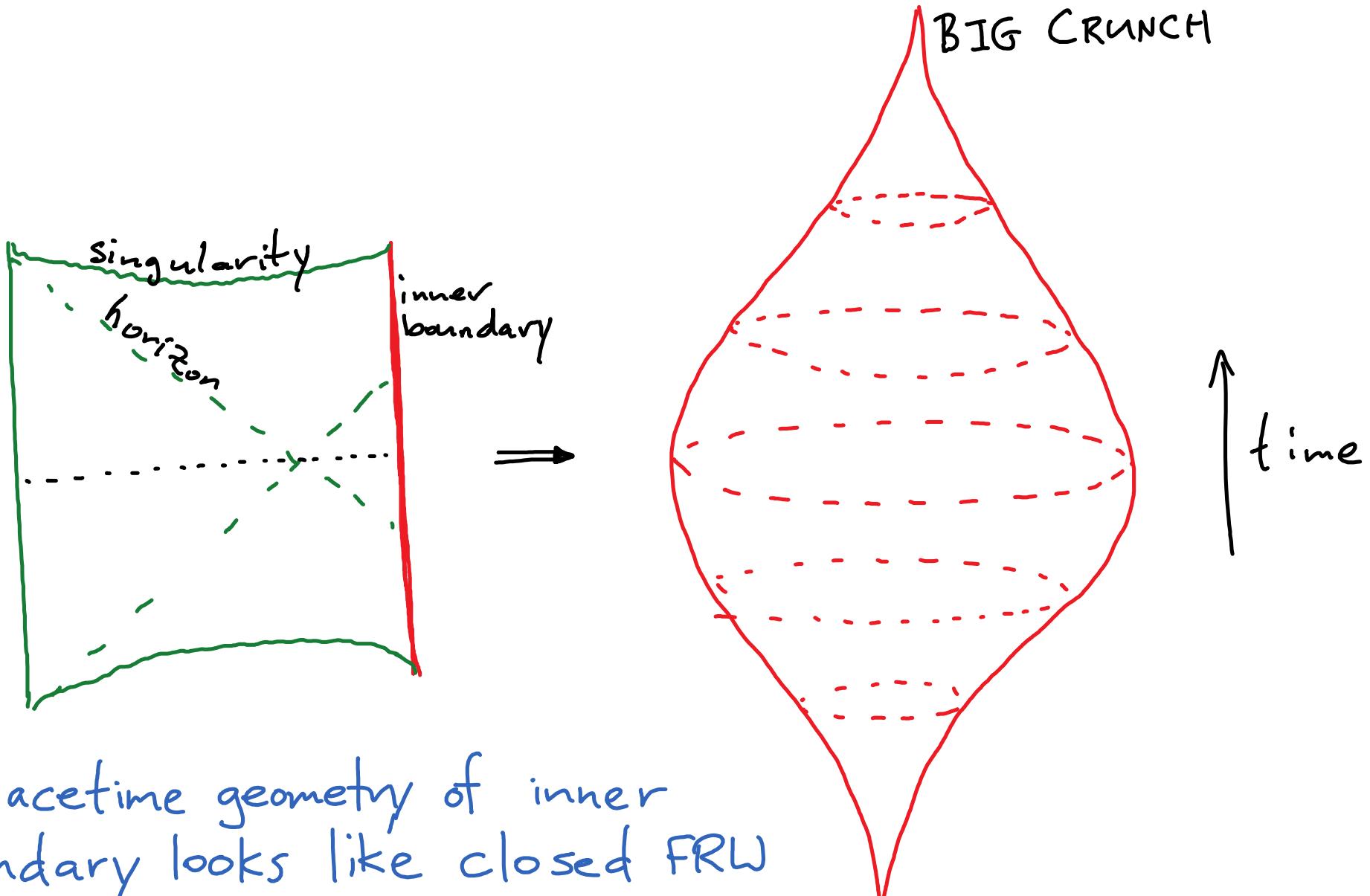
Time-dependent entanglement entropies:



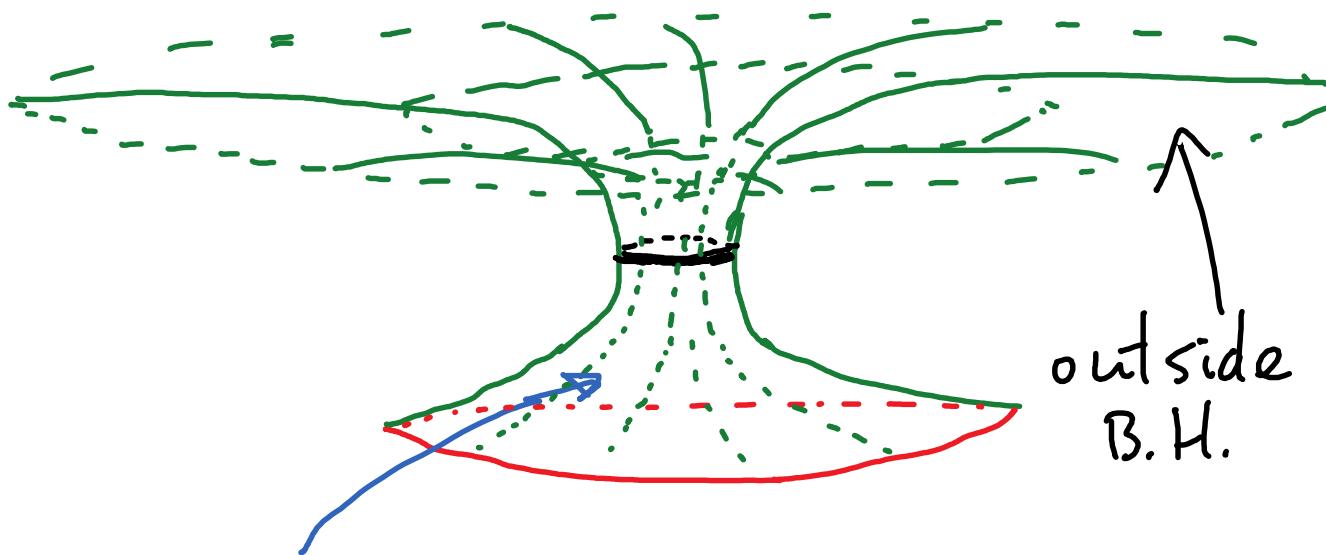
Entanglement
entropy ($d > 2$)



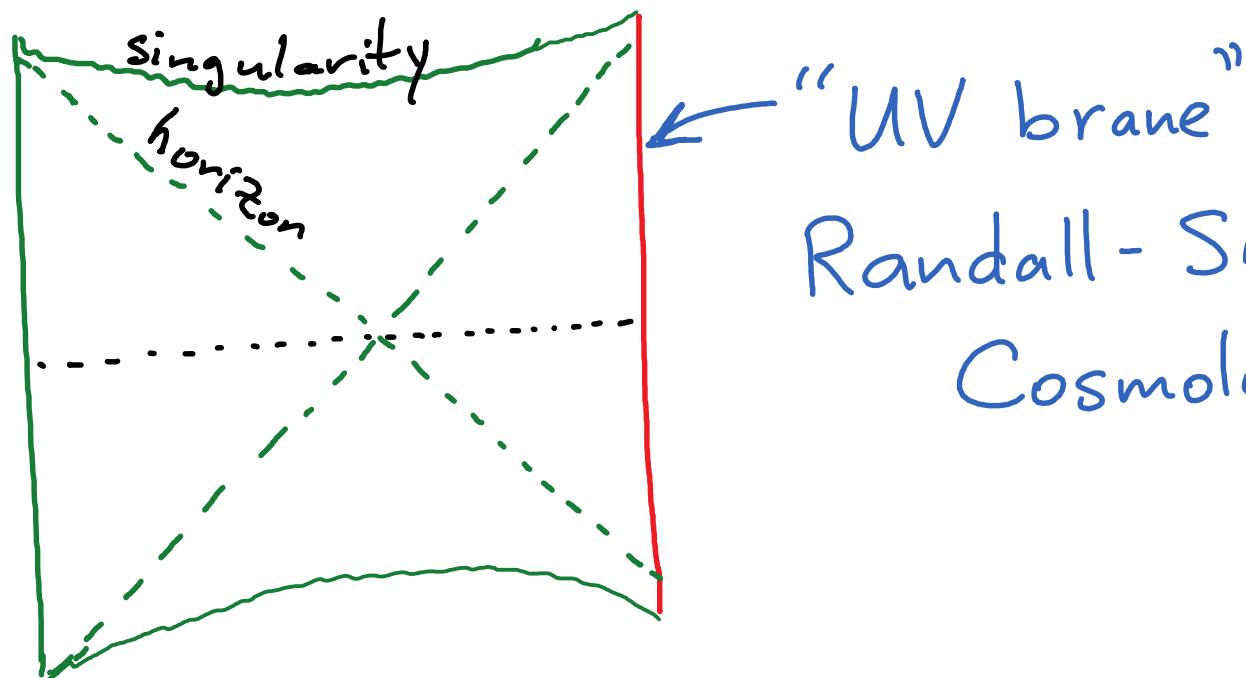
A connection to cosmology?



- spacetime geometry of inner boundary looks like closed FRW cosmology

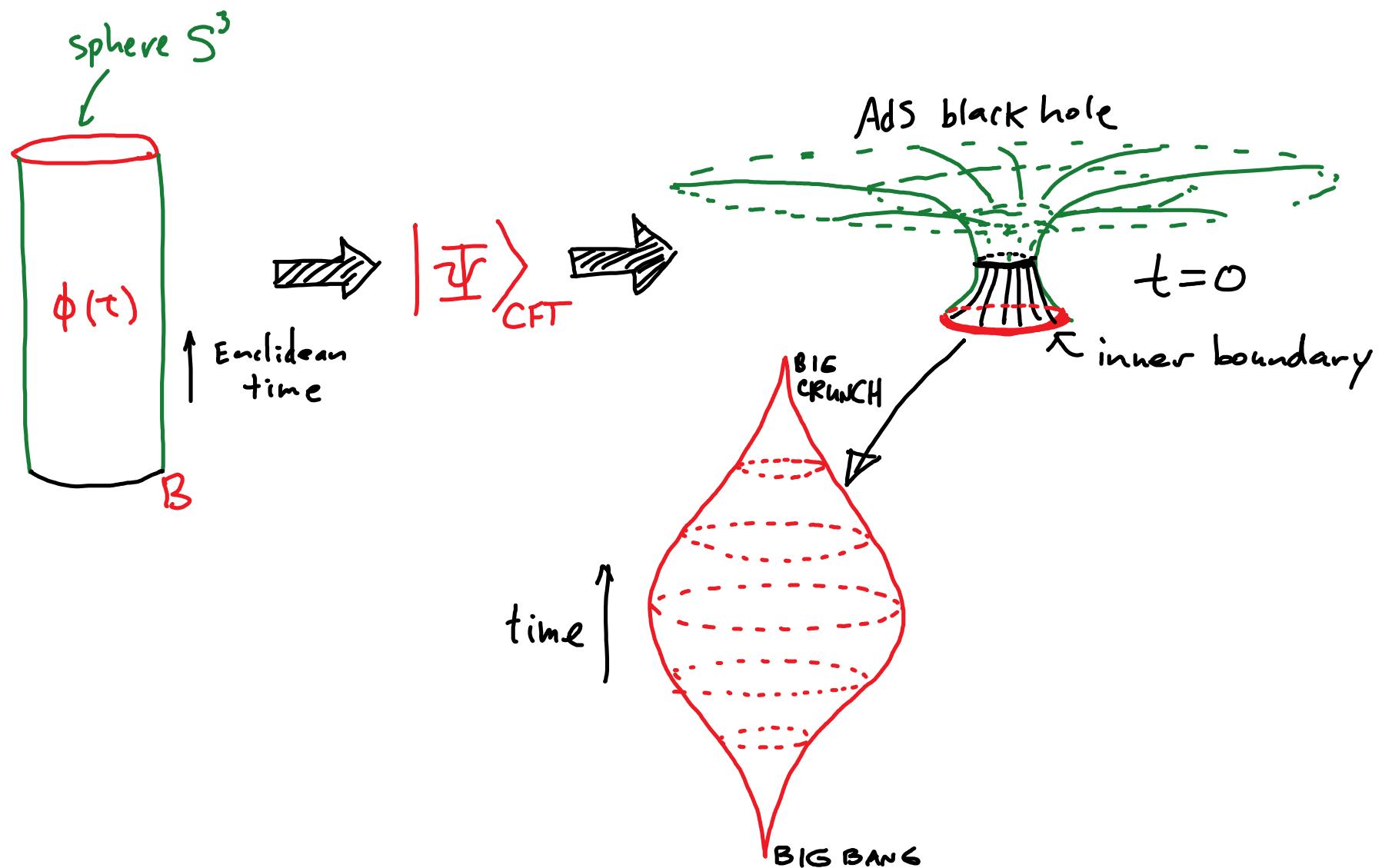


If inner region is large enough, gravity can "localize" on the inner boundary.



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



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!)