Confinement, Wormholes, and Cosmology

Mark Van Raamsdonk, UBC

Island Hopping, Nov. 2020

1810.10601 w Cooper, Rozali, Swingle, Waddell, Wakeham

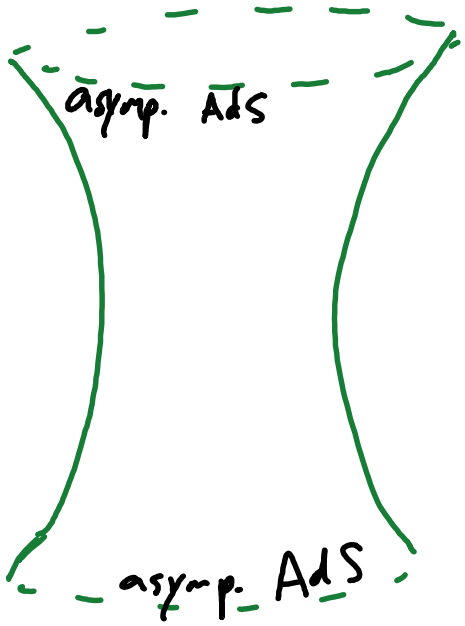
1910.12836 w. Rozali, Sully, Waddell, Wakeham

2008.02259

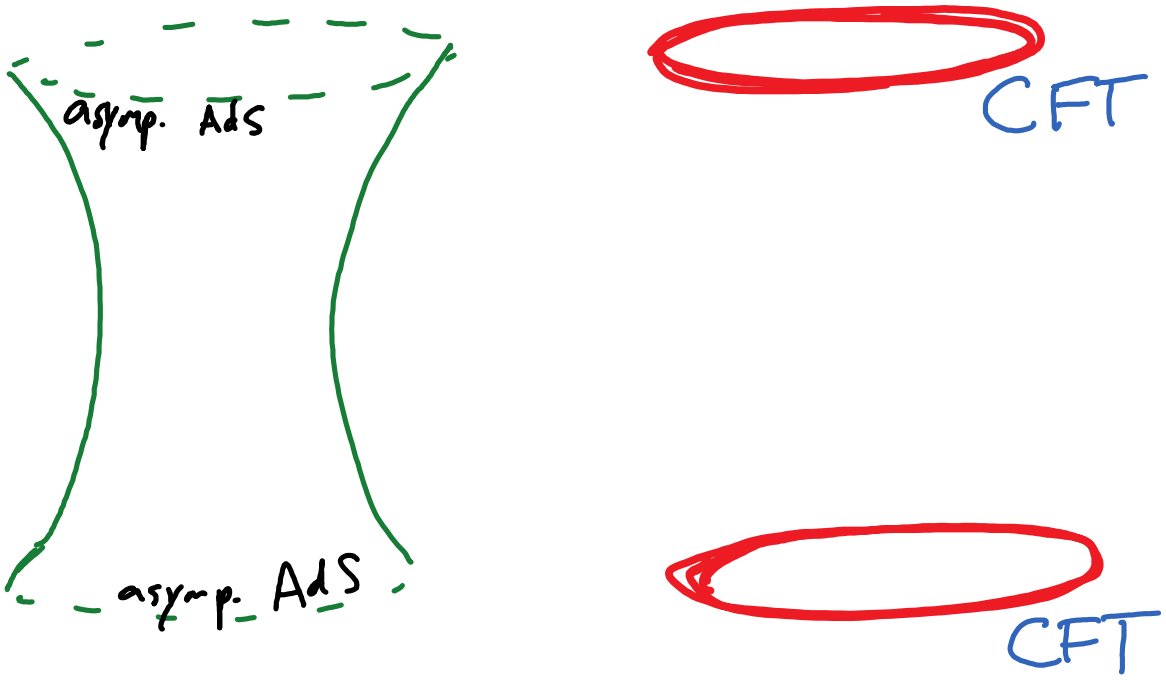
+ work in progress

asymptotically AdS, Euclidean

How do we build a wormhole?



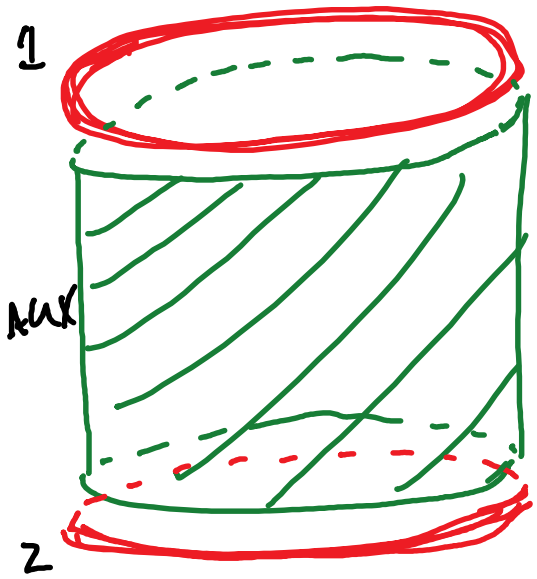
How do we build a asymptotically AdS, Euclidean wormhole?



2 asympt. AdS regions ⟹ involves 2 CFTs

non-factorization of correlators

- ensemble? e.g. Maldacena-Maoz, Saad Shenker Stanford
- soft interactions? e.g Betzios, Kiritsis, Papadoulaki



Another idea: couple via some auxiliary degrees of freedom

gives "soft" interactions

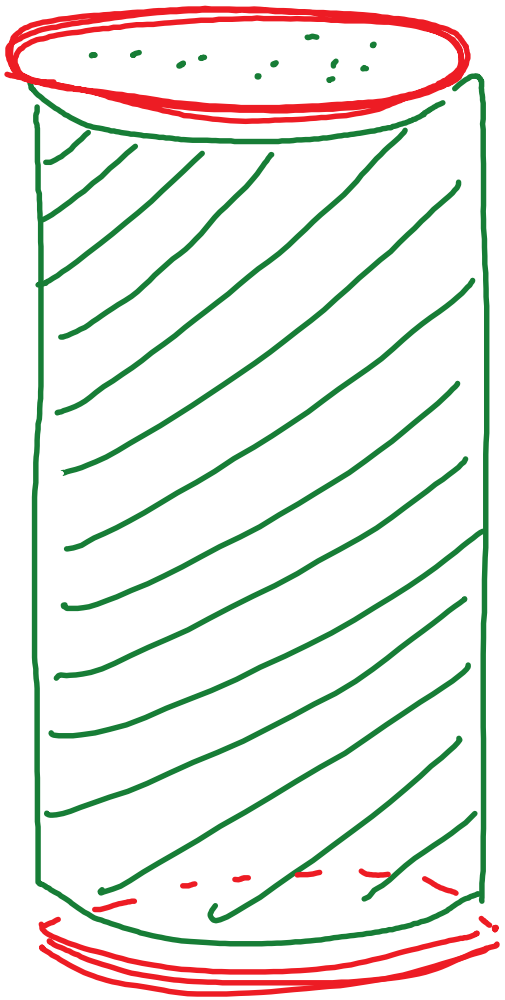
Z_{full} is equivalent to ensemble avg

$$\left\langle Z_1[J_1]\, Z_2[J_2] \right\rangle_{P[J_1,J_2]}$$

sources built from auxiliary fields

generated by path int. for aux. fields

Auxiliary d.o.f. spread over extra dimension:

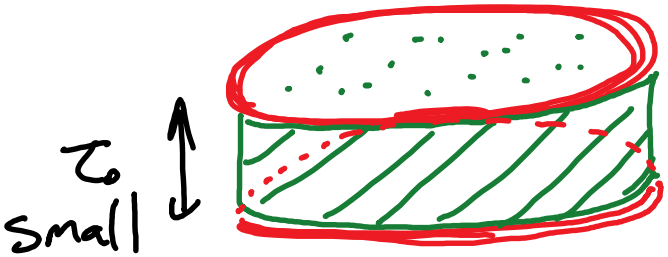


to large

sources weakly correlated

↓

no wormhole



to small

strongly correlated sources (more like ensemble avg.)

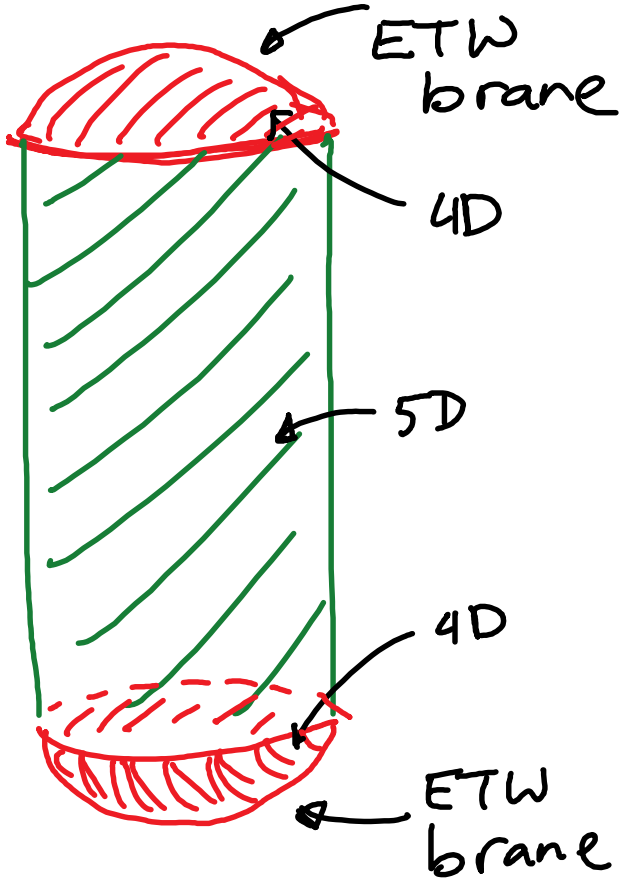
↓

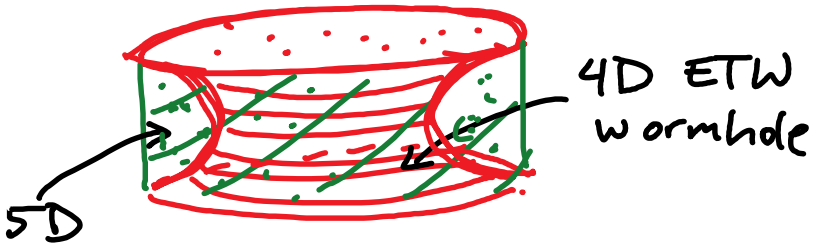
wormhole?

Example: holographic auxiliary d.o.f.

dual gravity solutions:

(see Takayanagi; Almheiri; Cooper, Rozali, Swingle, MVR Waddell, Wakeham)



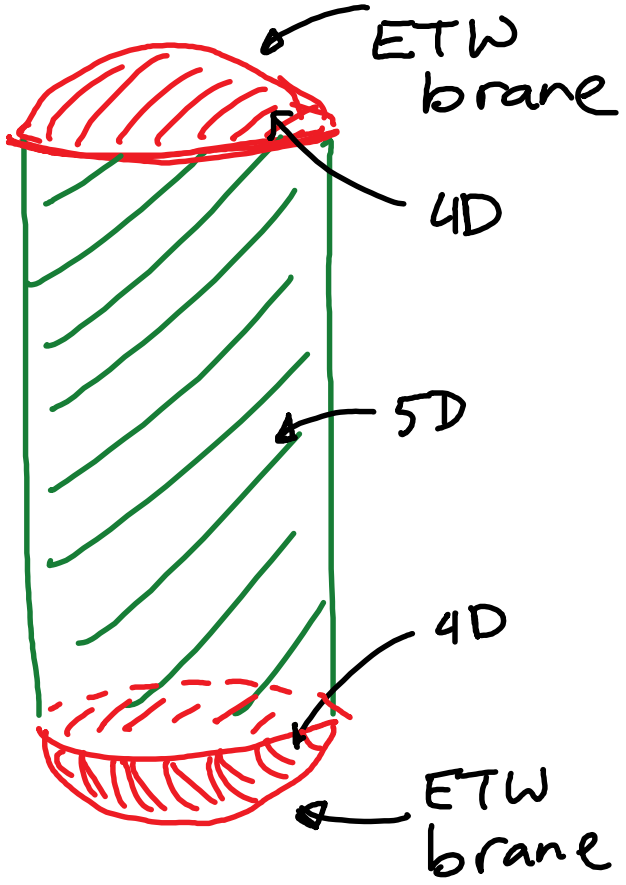


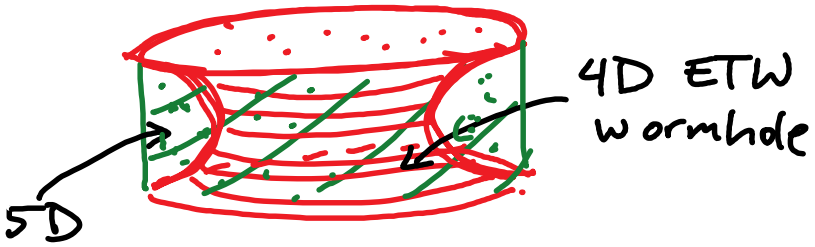
lower action solution for small T_0?

Example: holographic auxiliary d.o.f.

dual gravity solutions:

(see Takayanagi; Almheiri; Cooper, Rozali, Swingle, MVR Waddell, Wakeham)



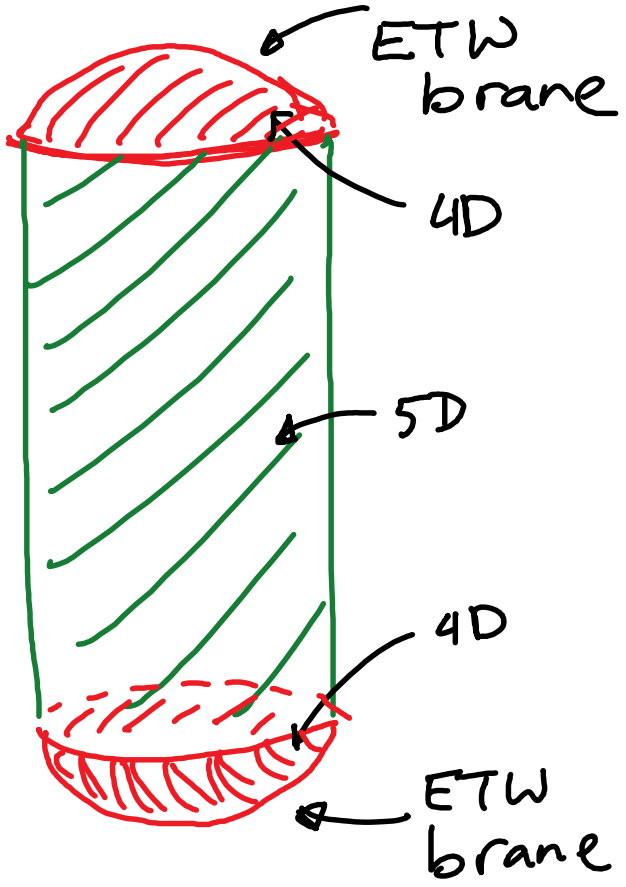


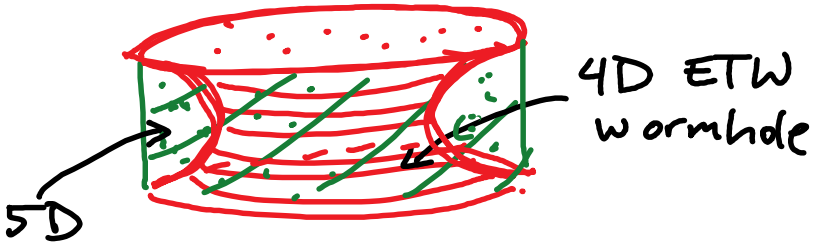
lower action solution for small T_0?

Is this cheating?

Example: holographic auxiliary d.o.f.

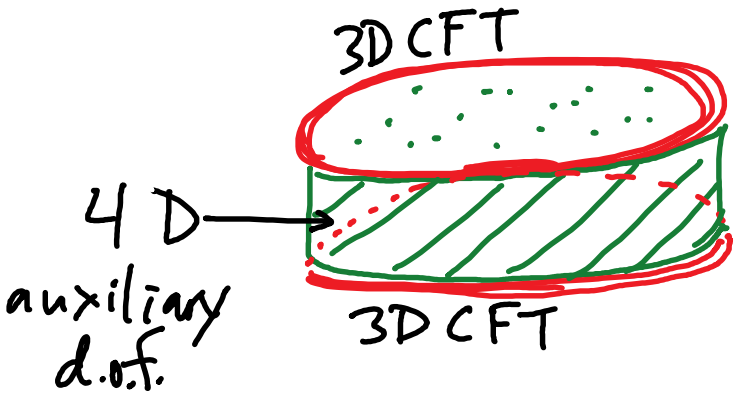
dual gravity solutions:





lower action solution for small T_0?

Will argue: if $C_{3D} \gg C_{4D}$, gravity can be localized to ETW brane + effective theory is 4D

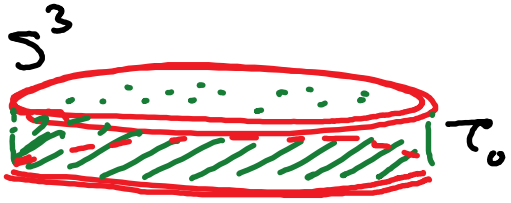


To get wormhole with 4D effective description:

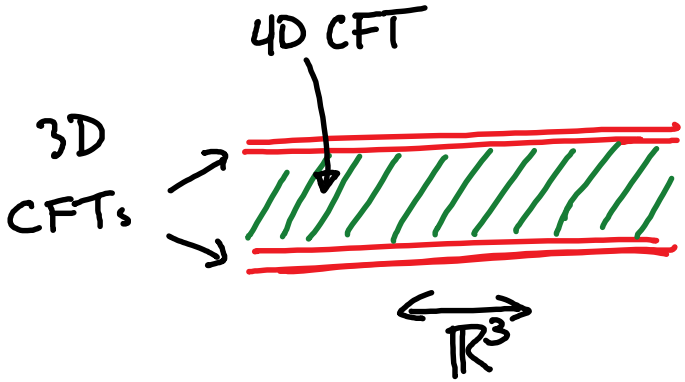
- want relatively few auxiliary d.o.f. so dual description is approximately 4D

- BUT need strong enough interactions to connect the two sides

Do we get a wormhole for $\tau_0 \to 0$?

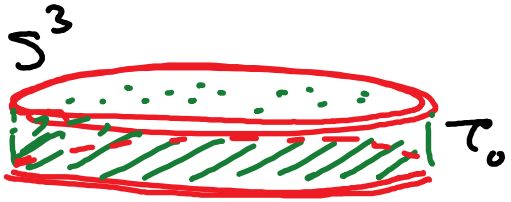


Controlled by planar limit:

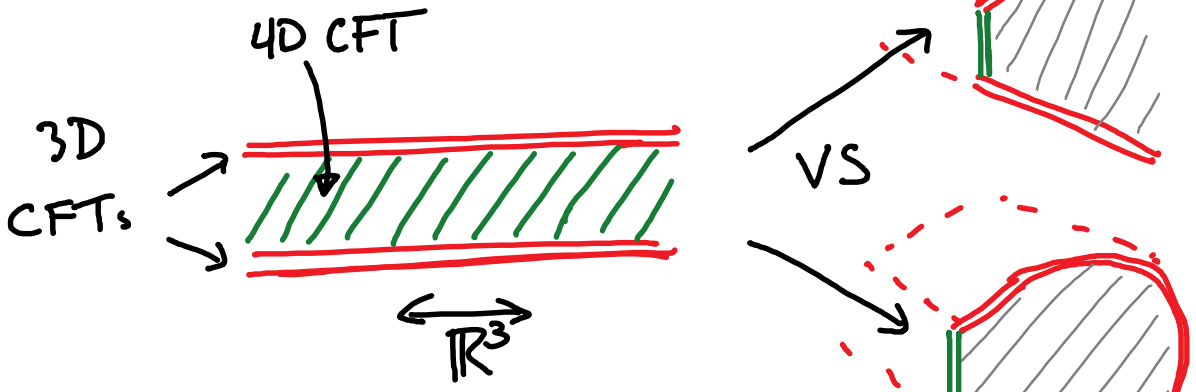


What is IR physics?

Do we get a wormhole for $\tau_0 \to 0$?



Controlled by planar limit:



VS

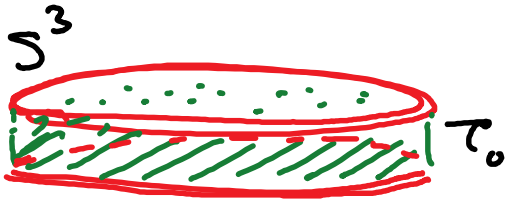
3D CFT in IR

IR 3D theory is gapped

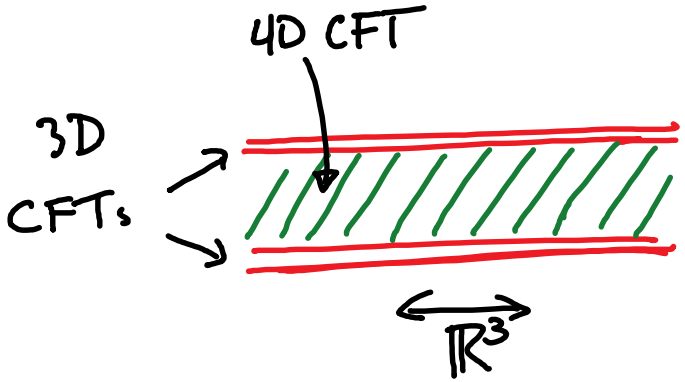
generic?

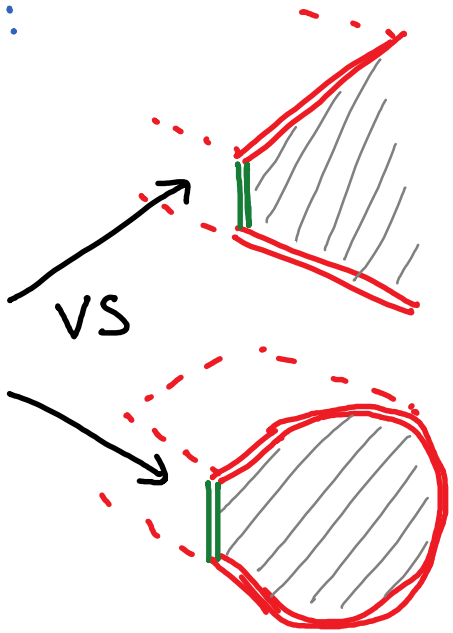
gravity picture

Do we get a wormhole for $\tau_0 \to 0$?



Controlled by planar limit:



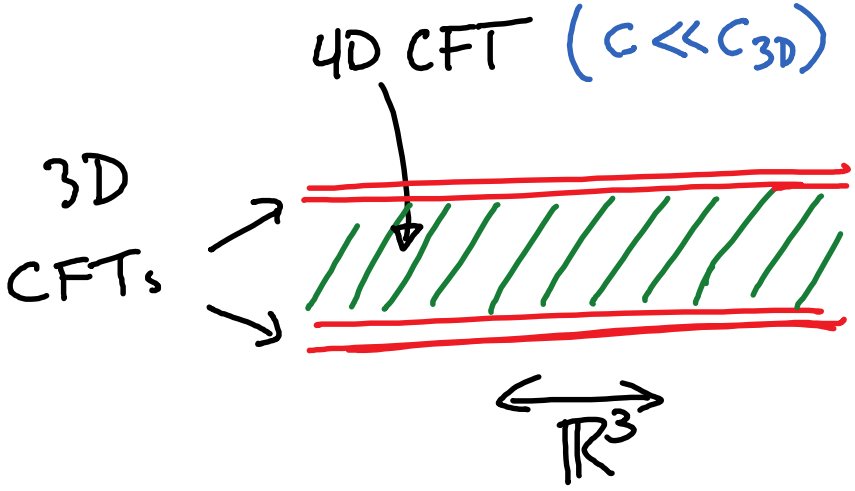


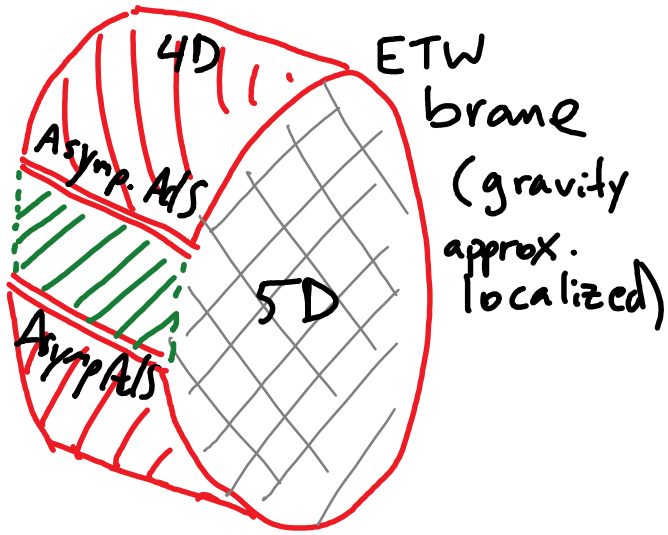
3D CFT in IR

IR 3D theory is gapped / confining

Can we find example w. $C_{3D} \gg C_{4D}$ that is gapped in IR?

Summary so far:



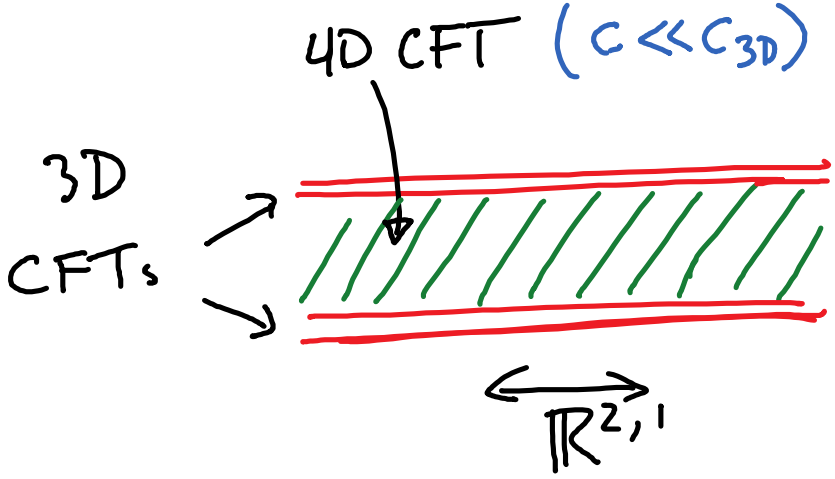


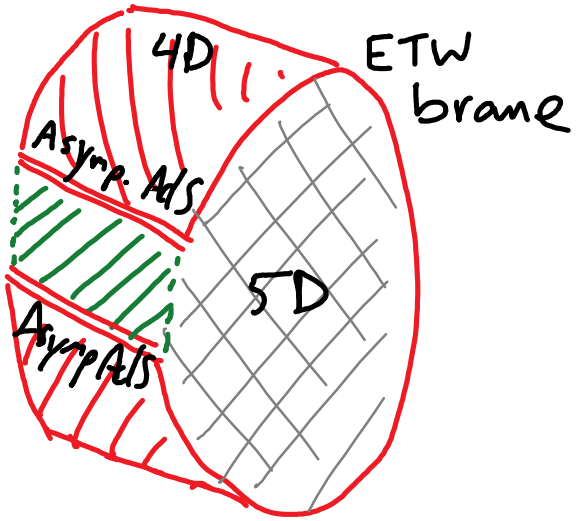
- Start w. pair of holographic 3D CFTs.
- Add auxiliary 4D d.o.f. so that IR physics is gapped
- Conjecture: if $c_{4D} \ll c_{3D}$, effective description can be 4D Euclidean asympt. AdS wormhole

effective description or non-holographic case

Application: an eternally traversable Lorentzian wormhole?

Analytically continue one non-compact direction





- Integrating out 4D CFT gives infinite number of terms $\int d^2x_1 \int d^2x_2 \, O_1(x_1) O_2(x_2)$

  c.f. Gao-Jafferis-Wall

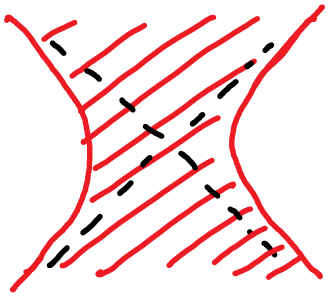
  Maldacena-Qi

- Wormhole is clearly traversable based on CFT picture – information takes a long time to go from one side to other for small c_{4D}/c_{3D} ⟶ can we interpret as long wormhole in 4D gravity picture?

From TFD to ETW

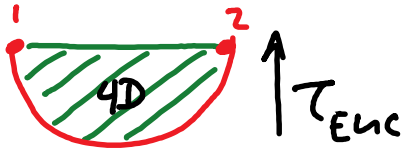
TFD state of $CFT_1^{3D} + CFT_2^{3D}$

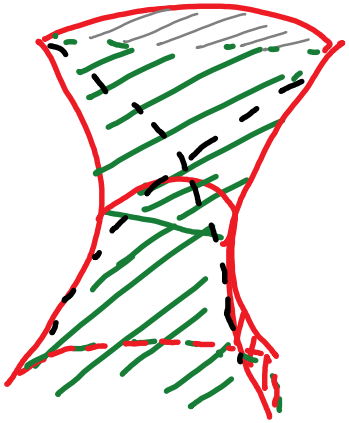
dual to



2-sided 4D planar B.H.

couple via 4D d.o.f. (few)

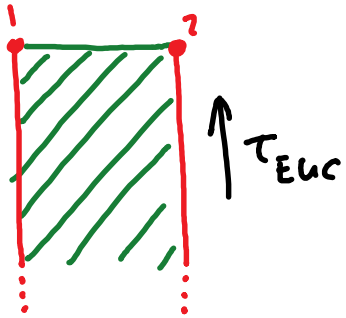


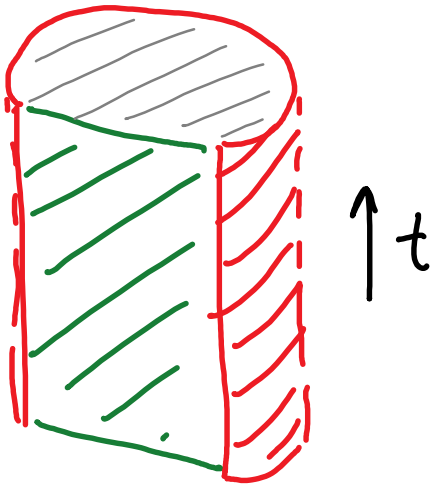


perturbed by adding radial direction to AdS^5 asymptotic region (time-dep)

deform P.I. geometry

Vacuum state of $CFT_1^{3D} + CFT_2^{3D}$ + aux^{4D}

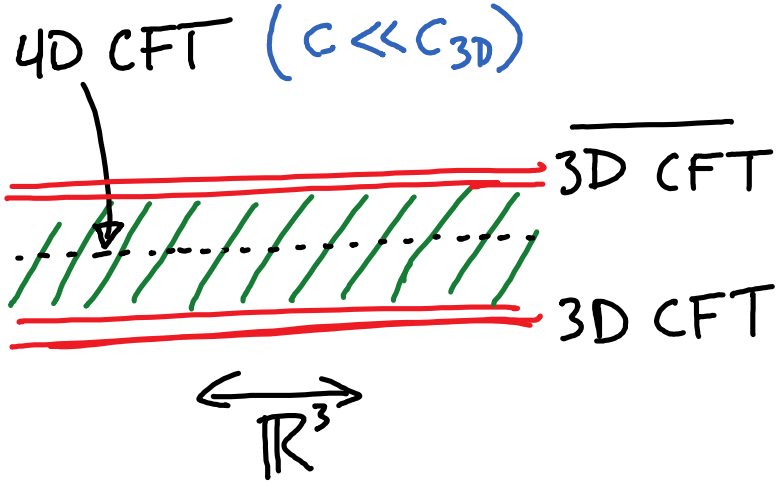


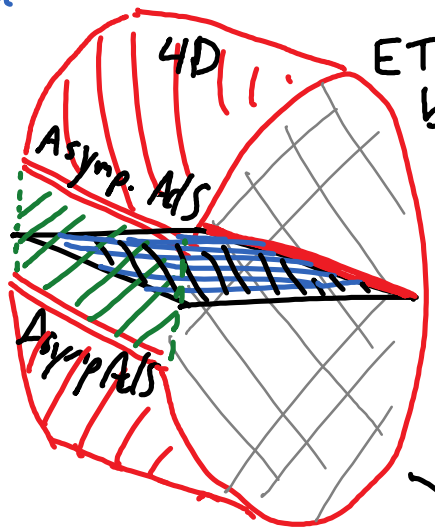


static geometry

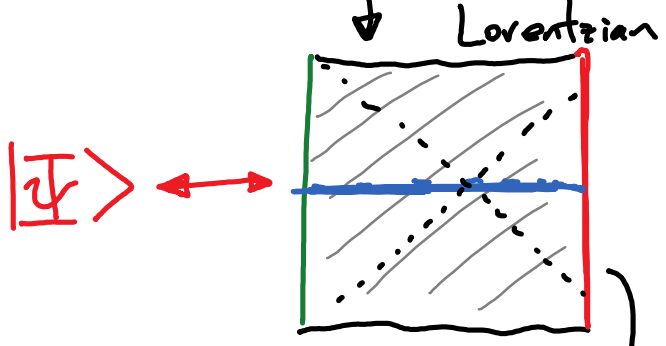
Application: Cosmology (via Maldacena - Maoz)

Analytically continue direction along interval



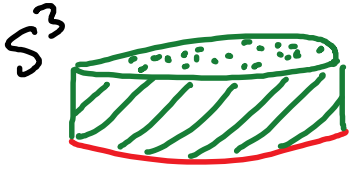


"bra-ket wormhole"



- Interpret path integral as constructing state of 4D CFT on $\mathbb{R}^3$ or S^3
- Initial data for time-symmetric dual Lorentzian geometry is time-symmetric slice of Euclidean geometry

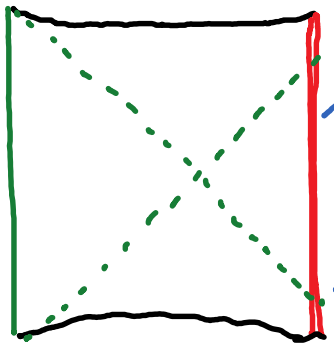
S^3 version:



$|\Psi\rangle_{CFT}$

↑ high-energy state of CFT on S^3

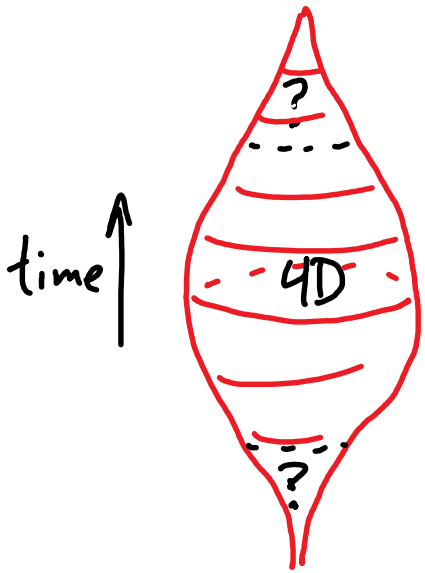
dual to



end of the world (ETW) brane = inner boundary of black hole

= Planck brane for 2nd asympt. region

ETW brane geometry is FRW big bang/big crunch



gravity approximately localized via Randall-Sundrum mechanism

"Black Hole Microstate Cosmology" - Cooper, Rozali, Swingle, MVR, Wakeham, Waddell
- Antonini, Swingle

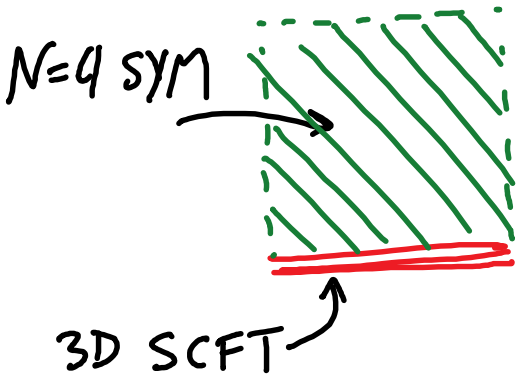
lower D versions: Chen, Gorbenko, Maldacena; Penington, Shenker, Stanford, Yang

Question: can we actually realize these things in some microscopic example?

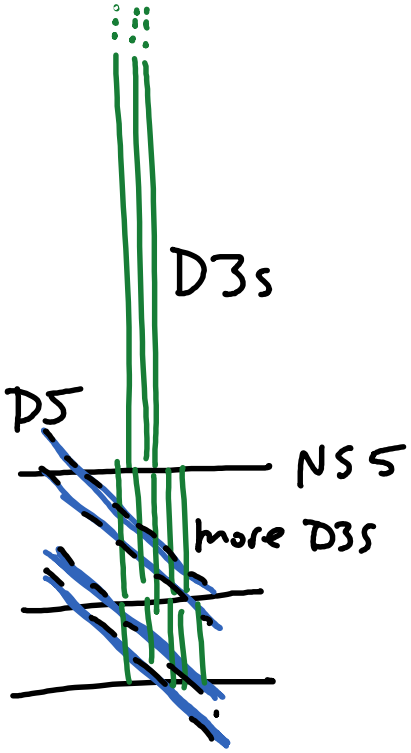
Microscopic Example

Start w. $\mathcal{N}=4$ SYM theory.

Can introduce boundary w. 3D SCFT
Gaiotto, Witten



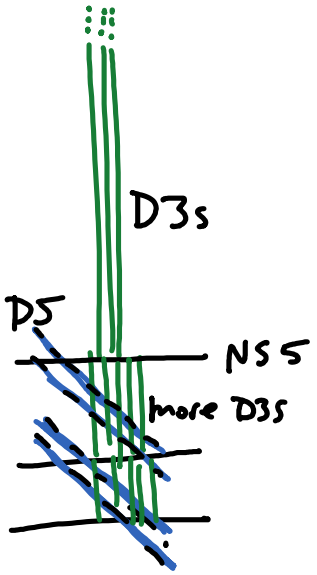
from



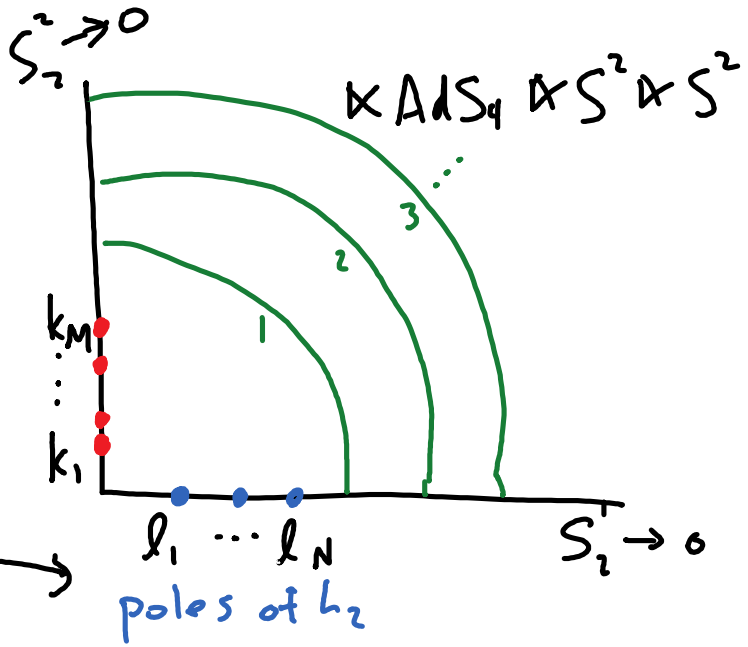
Preserves $\frac{1}{2}$ SUSY, can have arbitrarily large $\frac{C_{bdy}}{C_{bulk}}$

IIB supergravity solutions known explicitly.
Estes, d'Hoker, Gutperle
Aharony et. al.
Bachas et. al.

Gravity duals for $\mathcal{N}=4$ SYM with single ½ susy boundary

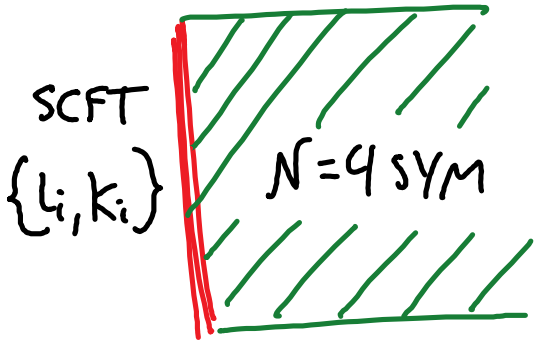


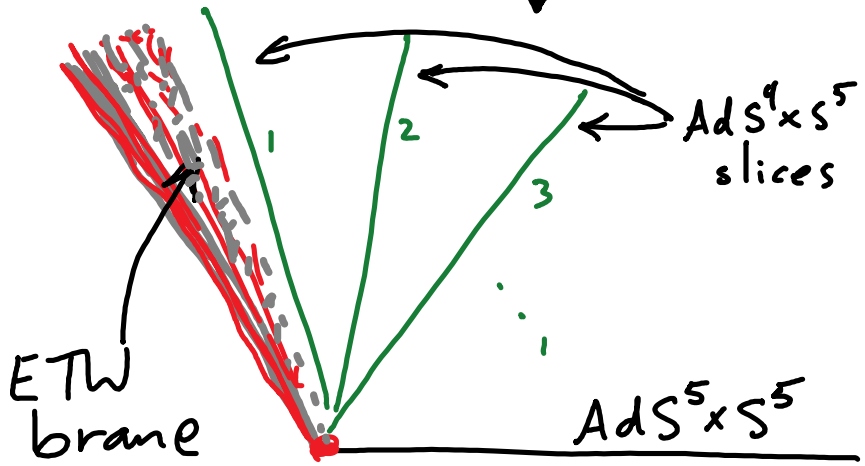
brane data



IIB solutions determined by harmonic functions h_1, h_2 on quadrant of $\mathbb{R}^2$

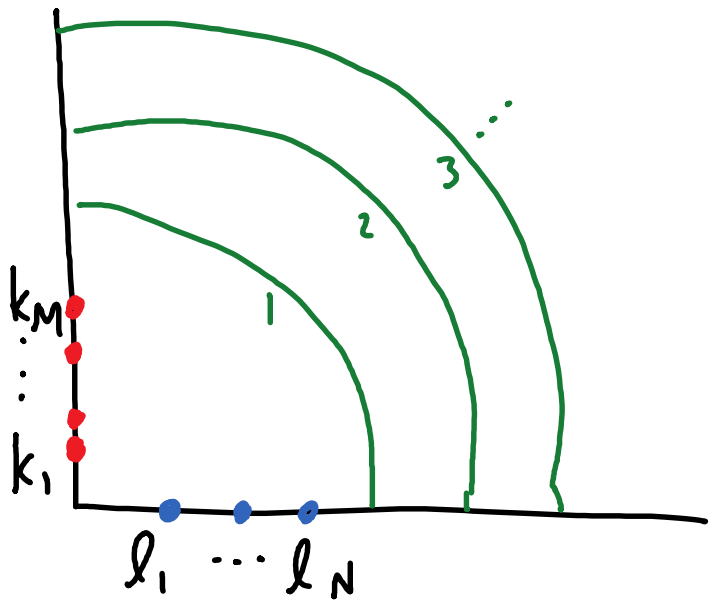
decoupling limit

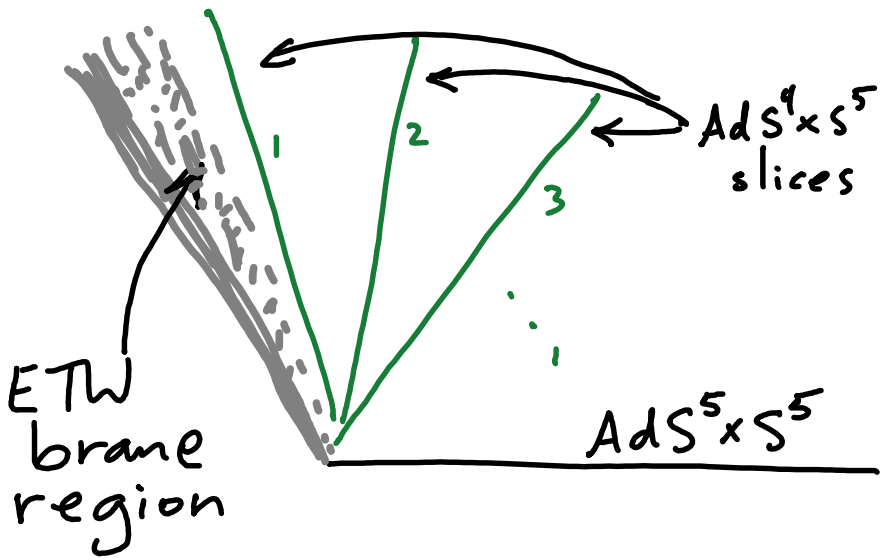




(see MVR, Waddell)

Gravity duals for $N=4$ SYM with single $\frac{1}{2}$ susy boundary

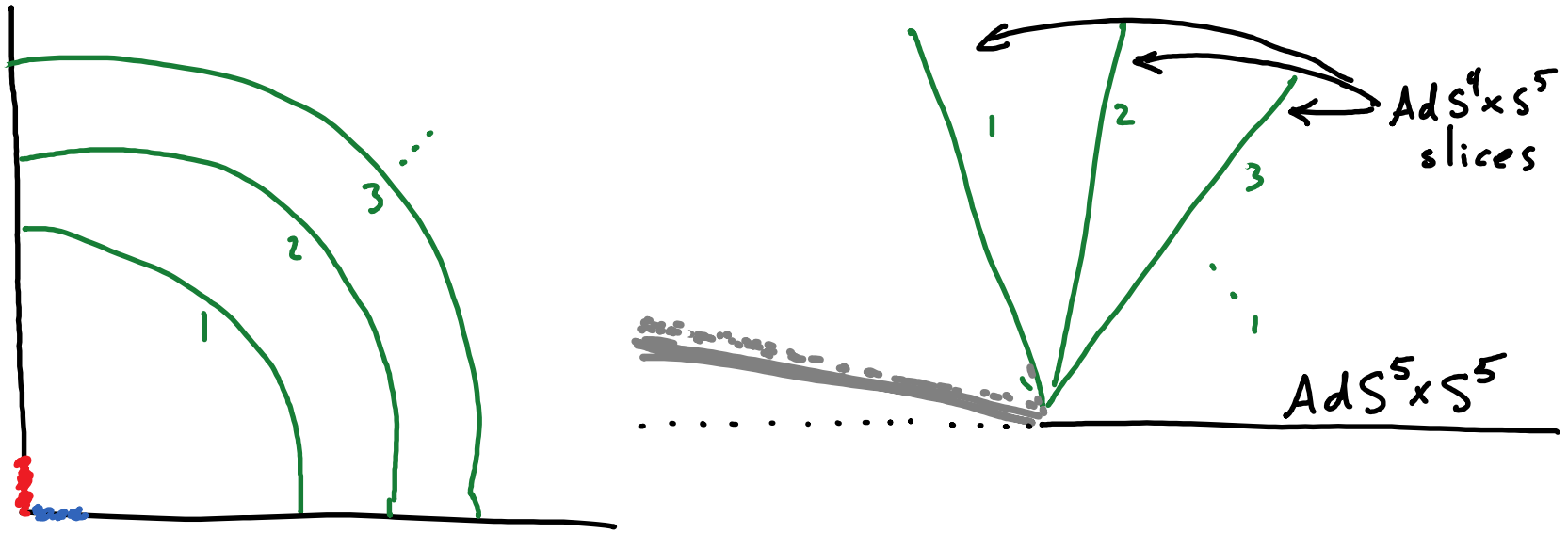




AdS radius determined by $N = \sum_{i=1}^{M} k_i + \sum_{j=1}^{N} \ell_j$

★ With fixed N in limit of large number of poles, ETW brane approaches "missing" boundary and we recover $AdS^5 \times S^5$! ★

Gravity duals for $N=4$ SYM with single ½ susy boundary



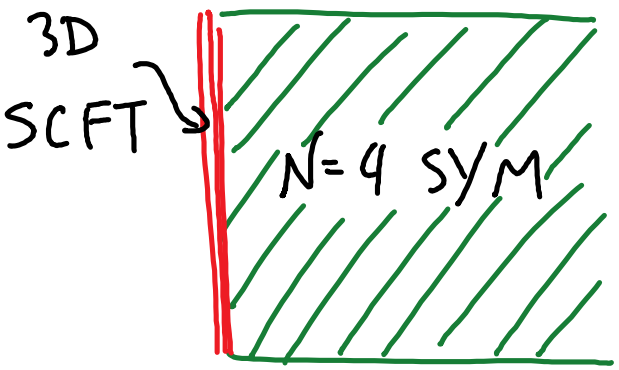
AdS radius determined by $N = \sum_{i=1}^{M} k_i + \sum_{j=1}^{N} l_j$

★ With fixed N in limit of large number of poles, ETW brane approaches "missing" boundary and we recover $AdS^5 \times S^5$! ★

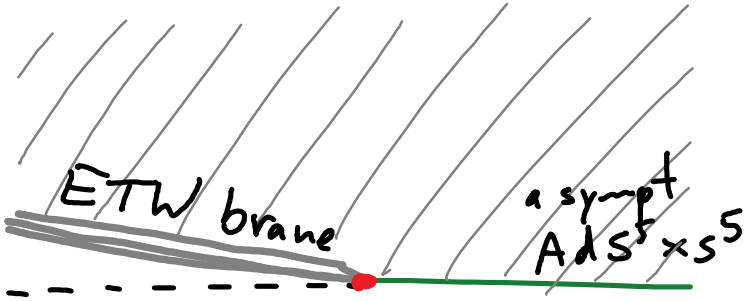
ETW brane becomes a Planck brane w. localized gravity! (large # boundary d.o.f. in this case)

3 descriptions

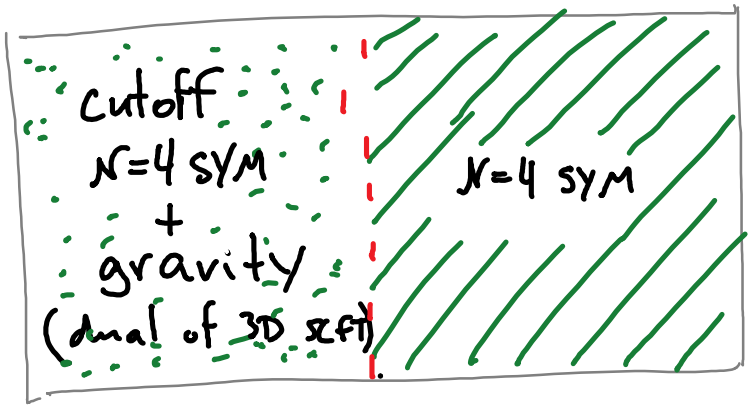
like doubly holographic models
(Almheiri, Mahajan, Maldacena)



Microscopic picture

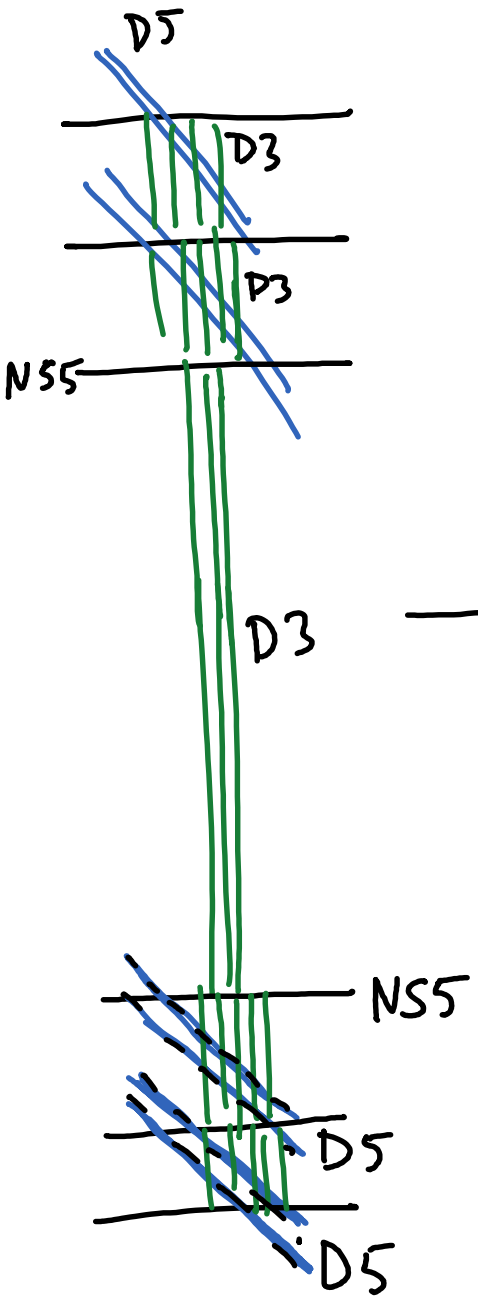


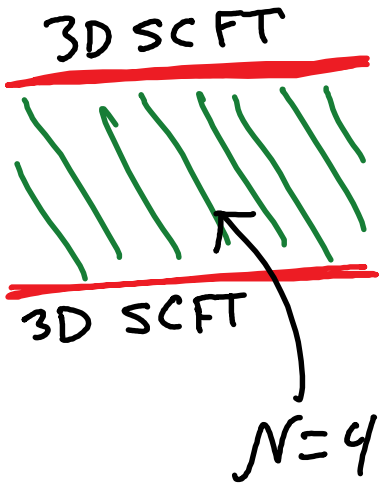
Dual gravity picture



Effective description

Now add 2nd boundary:



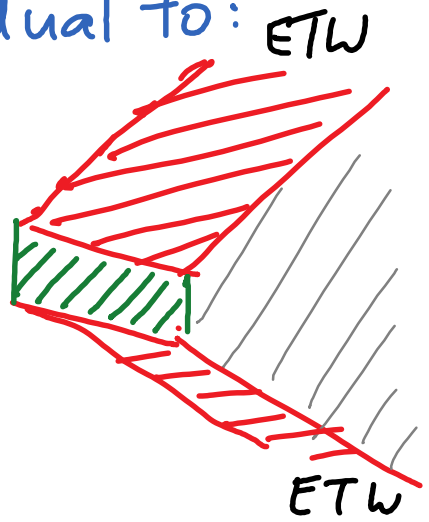


preserves SUSY → flows to 3D SCFT in IR

3D dual of wedge of $AdS^5 \times S^5$!

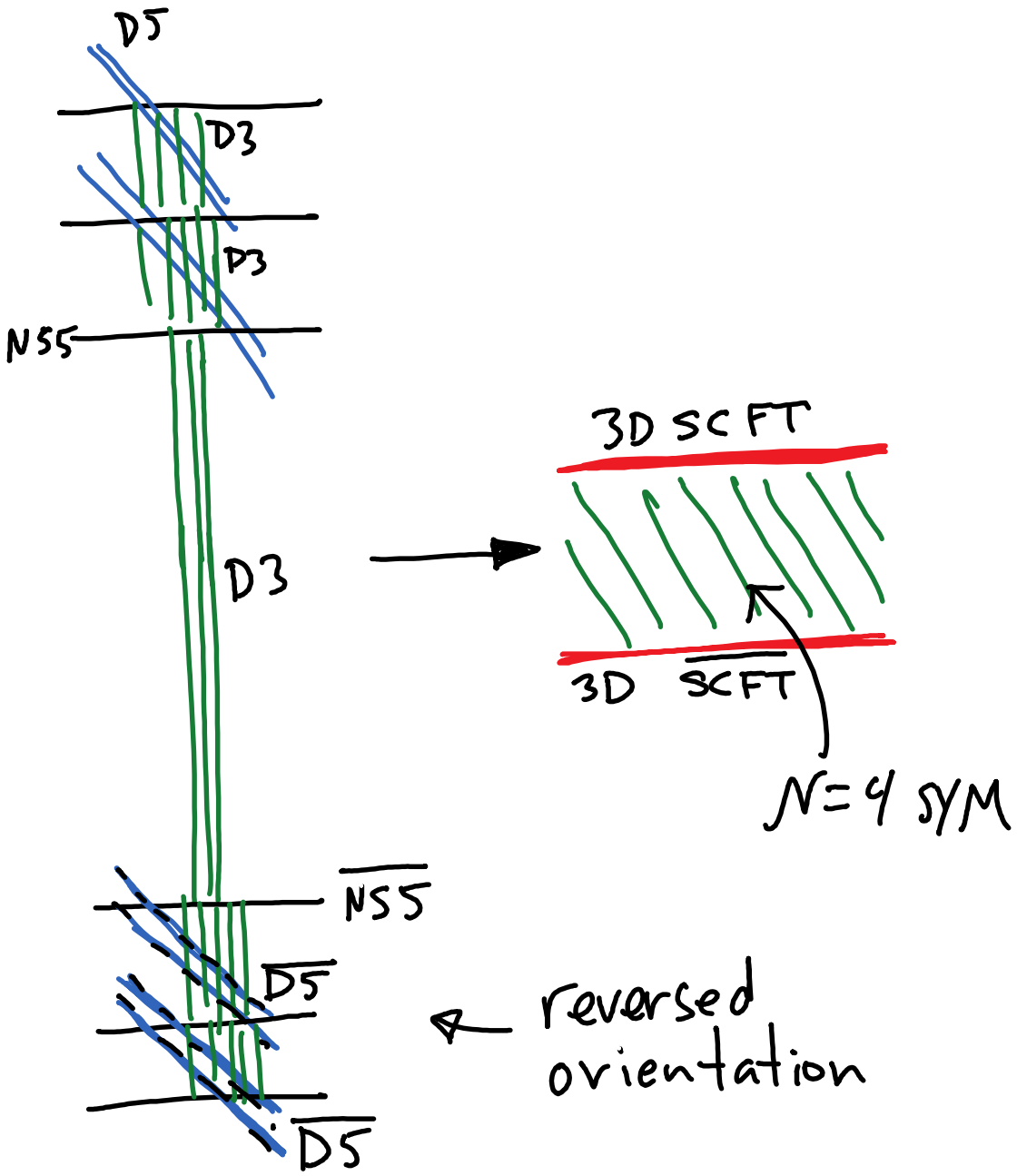
(c.f. Bachas & Lavdas; Akal, Kusuki, Takayanagi, Wei)

dual to:



NOT WHAT WE WANT

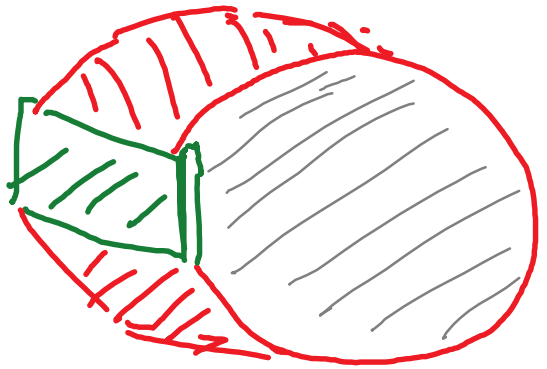
Now add 2nd boundary:



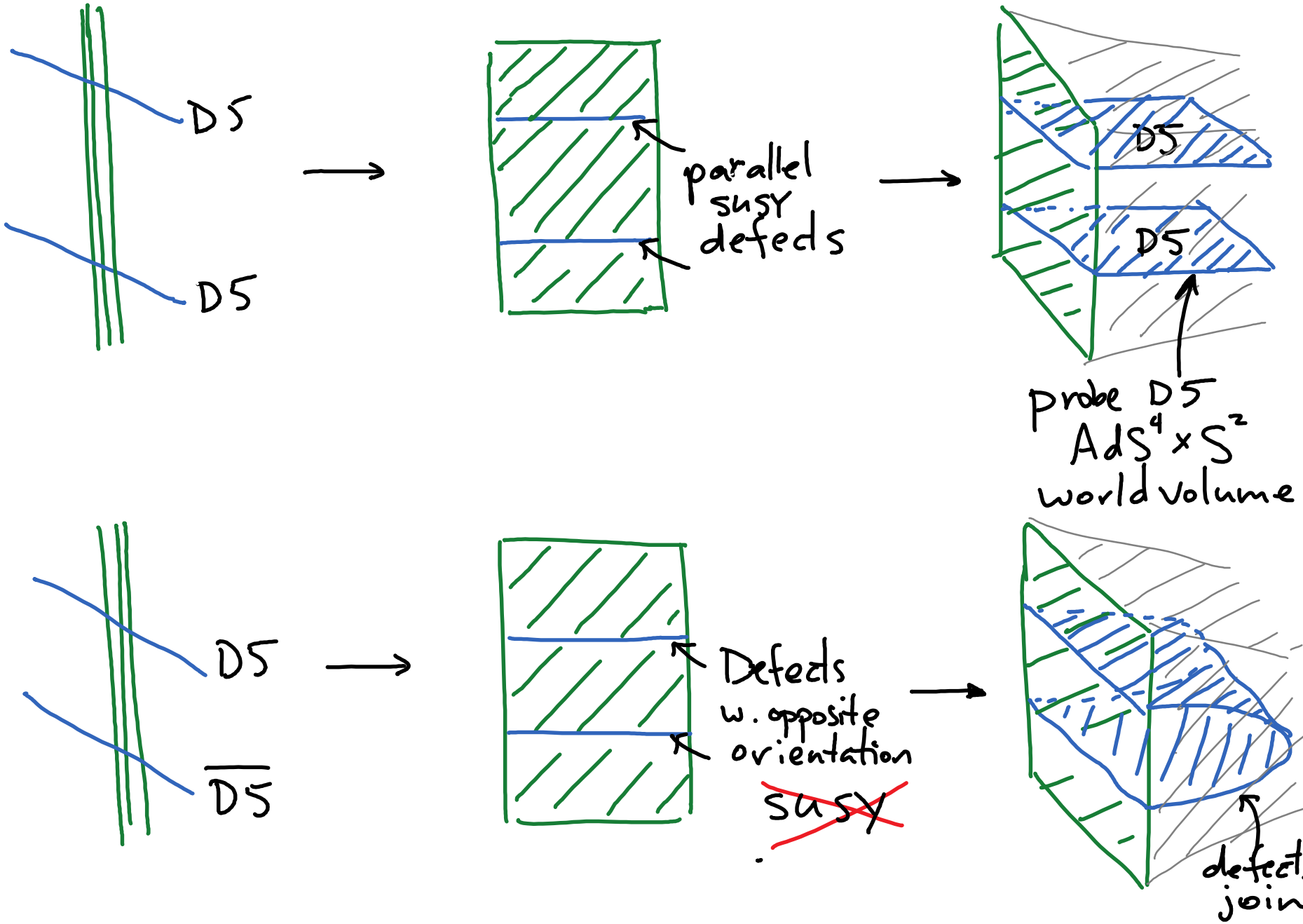
breaks all SUSY

conjecture:

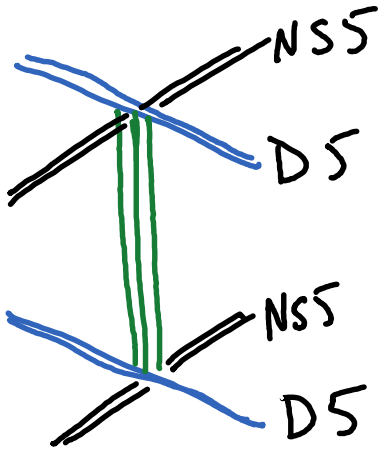
this will lead to gapped theory in IR and connected ETW brane:

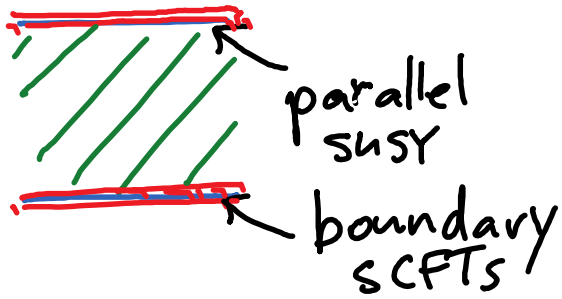


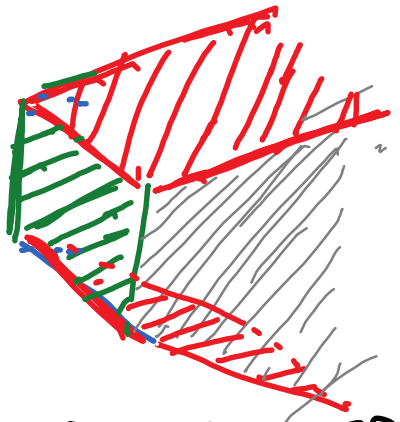
Probe analogue: (Antonyan, Harvey, Kutasov)



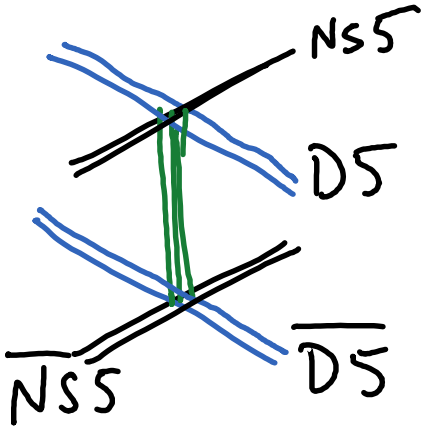
Boundary case:

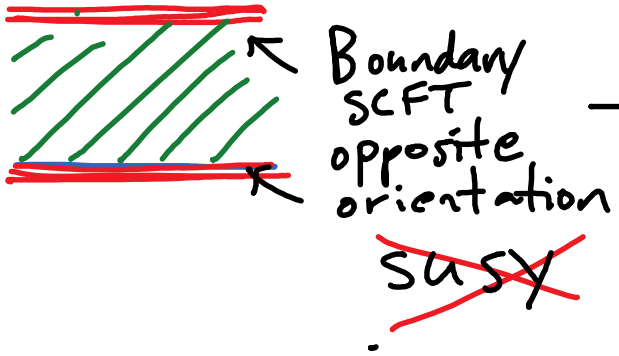




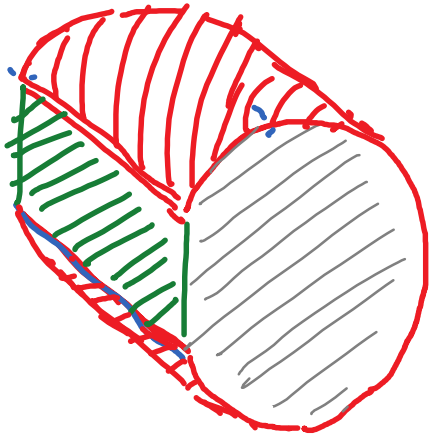


3D SCFT in IR





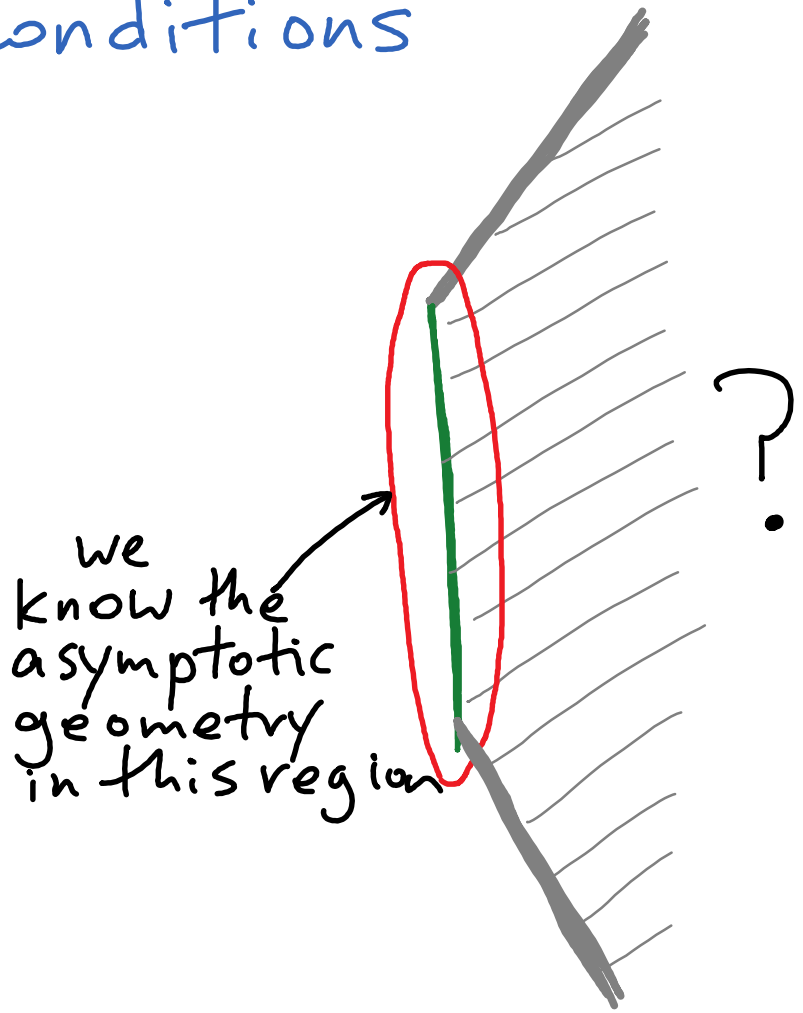
gapped in IR?



like Witten's model of confinement

How can we tell for sure?

Analyze type IIB supergravity equations with asymptotic behavior corresponding to chosen boundary conditions



probe example suggests that geometry will be $\mathbb{R}^3 \times S^2 \times S^2$ fibered over 3D space, so fields depend non-trivially on 3 coordinates.

Questions:

Is there a connected solution?

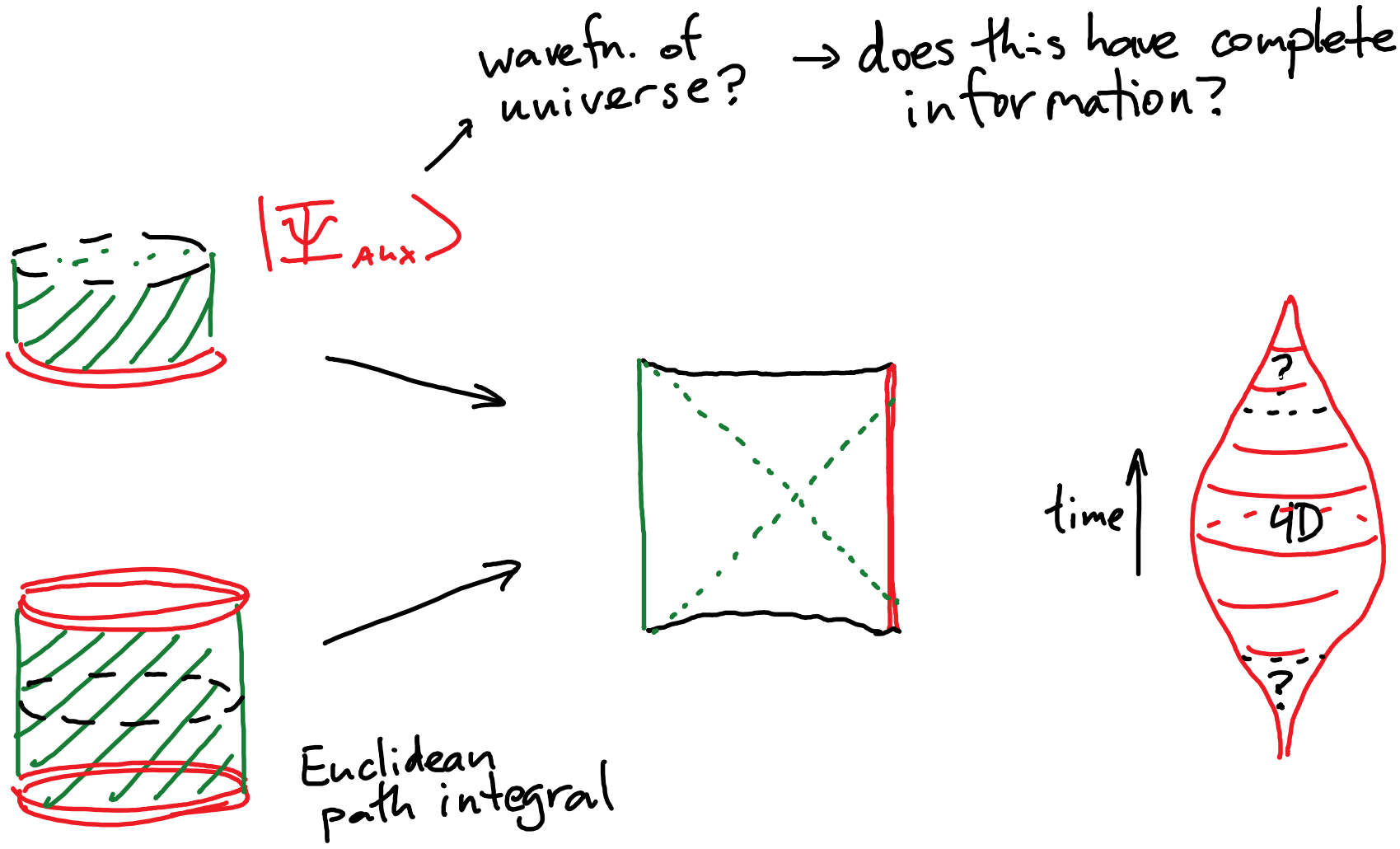
Is this the least action solution?

Does gravity localize?

What is the 4D effective description of the physics? (Lin + Maldacena)

see: Antonini, Swingle

How do we compute cosmological observables?



Interesting to study 2D versions

Thanks!