Black Holes, AdS, & CFTs
or
What does AdS/CFT really teach us about about unitarity and black holes?

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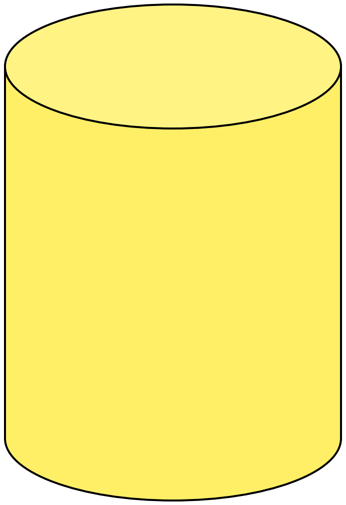
Take-home messages

1. AdS/CFT describes a unitary theory with $\sim e^{S_{BH}(E,J)}$ states.
2. Info in these states is fully encoded in bulk observables near the boundary.
3. Black hole evaporation is unitary.

#2 (and thus #3) are natural consequences of bulk gravitational physics.

The mystery is #1!!

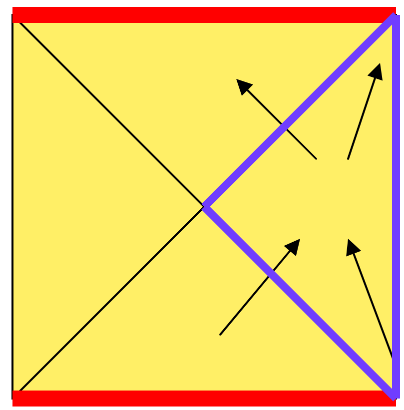


Outline

- Black Hole Unitarity?
- AdS/CFT implies unitarity
- Unitarity and bulk physics
- Mysteries and open issues

Unitarity & Black Holes (AdS)

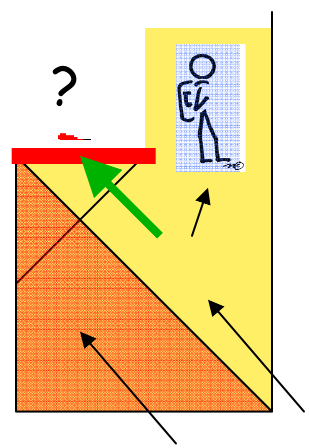
QFT on a fixed black hole background



"Non-unitary evolution"

though system conserves information, so long as one includes all degrees of freedom

Evaporating black hole?



What happens to the green information?

Is it accessible to a (somehwat) late-time external observer (blue)?

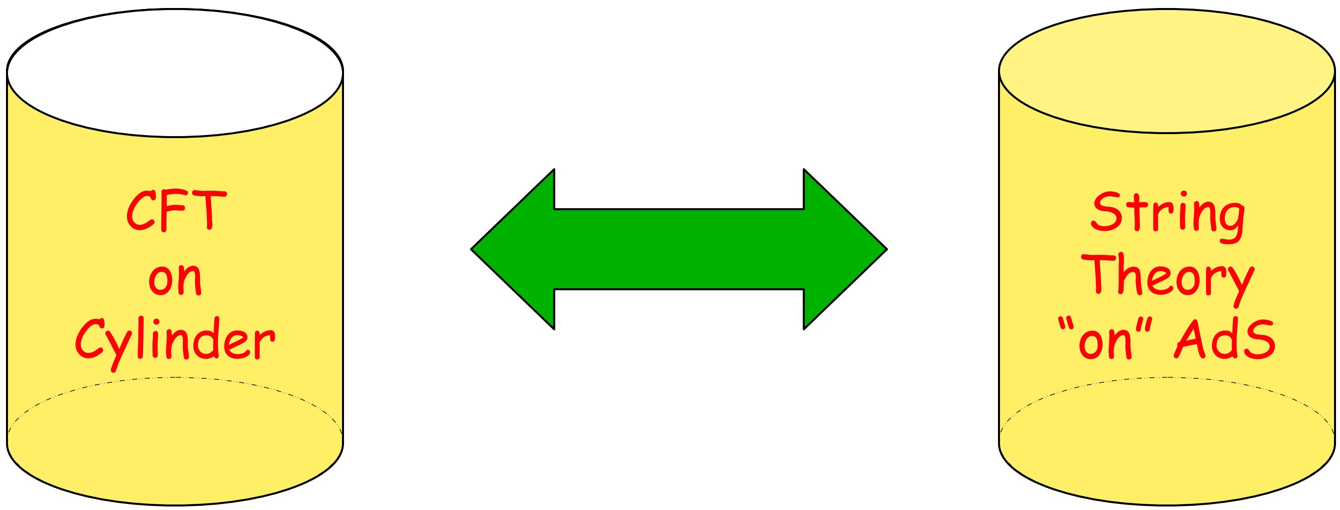
Or, do other states carry it away? (for a long time)

Recall AdS/CFT

From Maldacena:

Certain families of local Field Theories.

String (or M-) theory with (families of) asymptotically AdS x K boundary conditions.



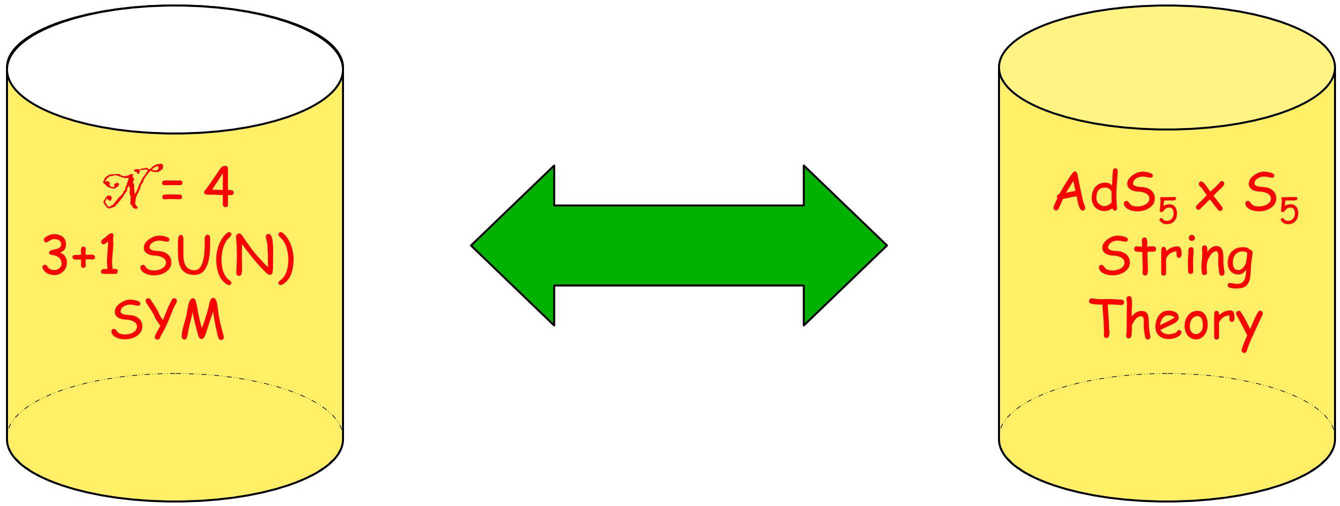
N^p ~ # of fields

Classical gravity recovered at large N (& strong CFT coupling)

We will assume this conjecture to be is correct and that it can be made precise.

Example #1

From Maldacena:



N^2 ~ # of fields

g_{YM} ~ coupling constant

λ = 't Hooft coupling = $g^2_{YM} N$

$\ell_s/\ell_{AdS} \sim \lambda^{-1/4}$

5d: $\ell_{planck}/\ell_{AdS} \sim N^{-2/3}$

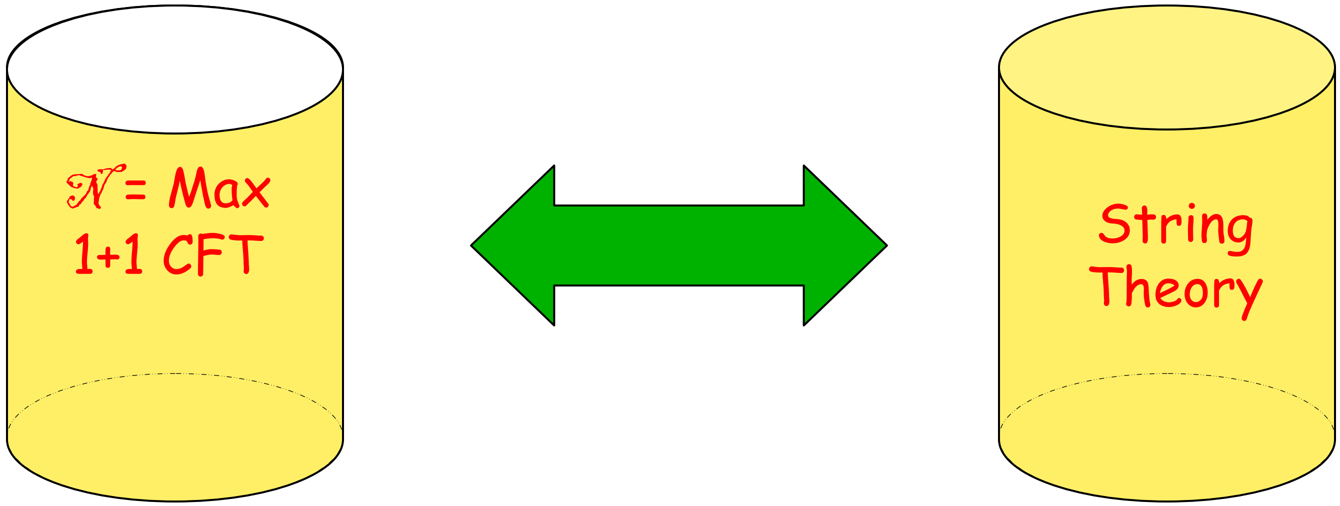
Classical gravity recovered at large N & large λ.

Background Fields ⟷ Boundary Conditions

Example #2 (D1-D5 system)

From Maldacena:

$AdS_3 \times S^3 \times T^4$



$SU(N_1) \times SU(N_5)$ symmetry

3d: $G_3/\ell_{AdS} = \ell_{planck}/\ell_{AdS} = 3c/2$

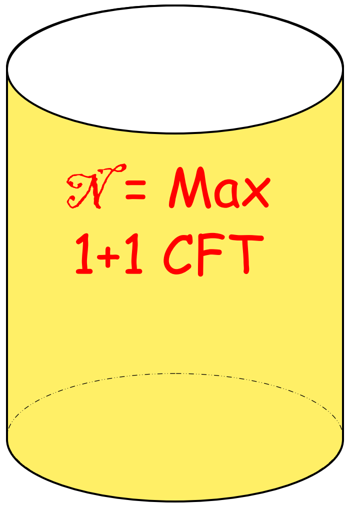
central charge: $c=6N_1N_5$

Classical gravity recovered at large N1, N5.

We will focus on this case due to the power of 1+1 CFTs.

Background Fields ⟷ Boundary Conditions

D1-D5 CFT facts



$SU(N_1) \times SU(N_5)$ gauge symmetry

central charge: $c=6N_1N_5$

Moments of the stress tensor give the Virasoro algebra

$$[L_m, L_n] = (m-n)\, L_{m+n} + (c/12)\,(m^3-m)\,\delta_{m+n,0}$$

$$[\bar{L}_m, \bar{L}_n] = (m-n)\, \bar{L}_{m+n} + (c/12)\,(m^3-m)\,\delta_{m+n,0}$$

$$[L_m, \bar{L}_n] = 0$$

$$J = L_0 - \bar{L}_0$$

$$E \sim L_0 + \bar{L}_0$$

Representation theory & Modular invariance

Cardy's Formula

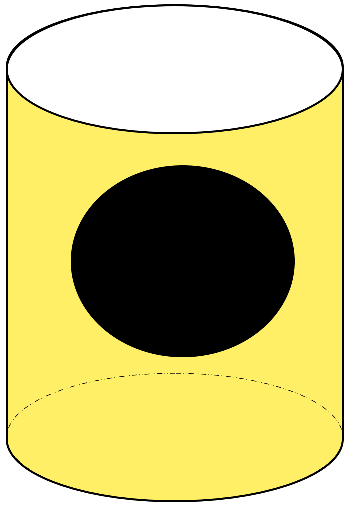
# of states ~ e^S with

$$S(E,J) = 2\pi\sqrt{cL_0/6} + 2\pi\sqrt{c\bar{L}_0/6}$$

at large level #s

In general, finite density of states.

AdS_3 & BTZ facts (Brown & Henneaux)



Asymptotic symmetries give the Virasoro algebra

$$[L_m, L_n] = (m-n)\, L_{m+n} + (c/12)\,(m^3-m)\,\delta_{m+n,0}$$

$$[\bar{L}_m, \bar{L}_n] = (m-n)\, \bar{L}_{m+n} + (c/12)\,(m^3-m)\,\delta_{m+n,0}$$

$$[L_m, \bar{L}_n] = 0$$

$$J = L_0 - L_0$$

$$E \sim L_0 + L_0$$

central charge:
$c = 3\ell_{AsS}/2\ell_{planck}$

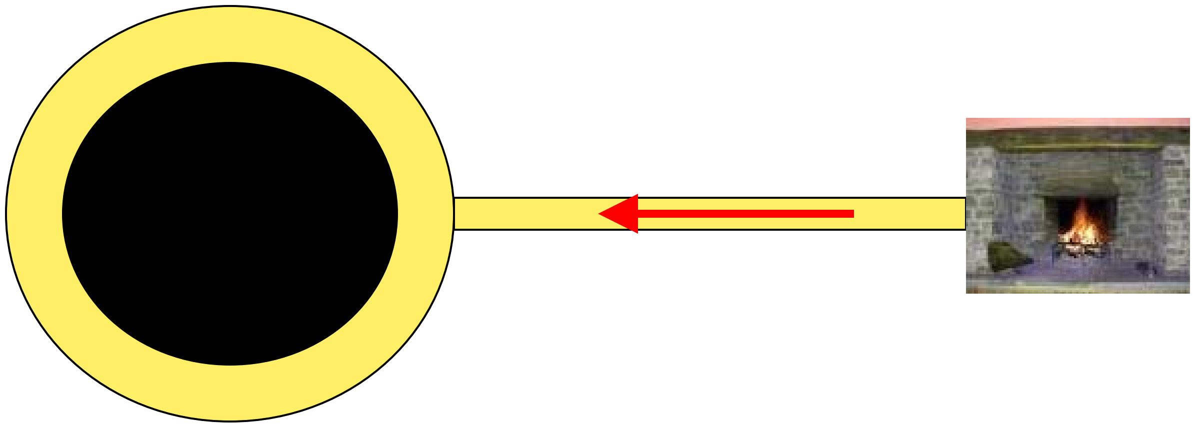
(Strominger:) BTZ black holes have

$$S(E,J) = 2\pi\sqrt{cL_0/6} + 2\pi\sqrt{c\bar{L}_0/6} = S_{Cardy}$$

at large level #s

Observe: Almost all highly excited states of the dual CFT are needed to describe BTZ black holes. There are few "extra" states for baby universes.

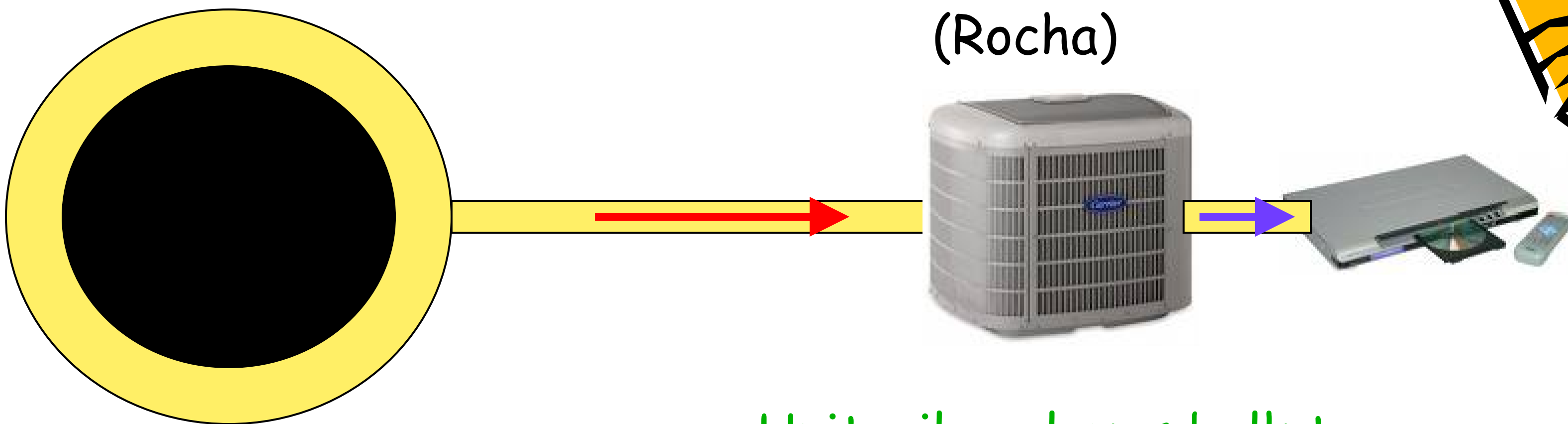
Does this imply unitarity?



BH at time t in 2+1 AdS

Does this imply unitarity?

(Rocha)



BH at time t in 2+1 AdS

Unitarily relaxes bulk to empty AdS.

Few (if any) baby universes → (Almost) all info can be extracted via observables near the boundary.

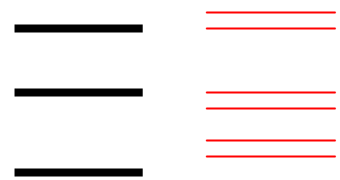
Black Hole "Unitarity"

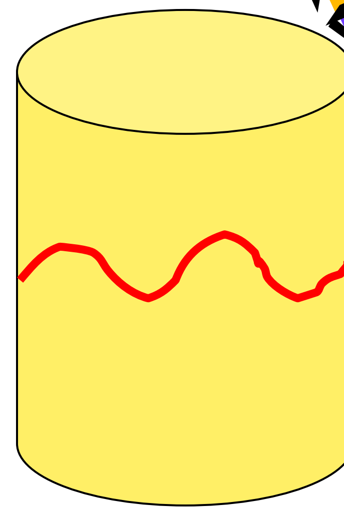
Bulk interpretation?

(V. Balasubramanian, M. Rozali, D.M.)

Lesson from CFT: Energy spectrum is discrete

Strongly interacting CFT:





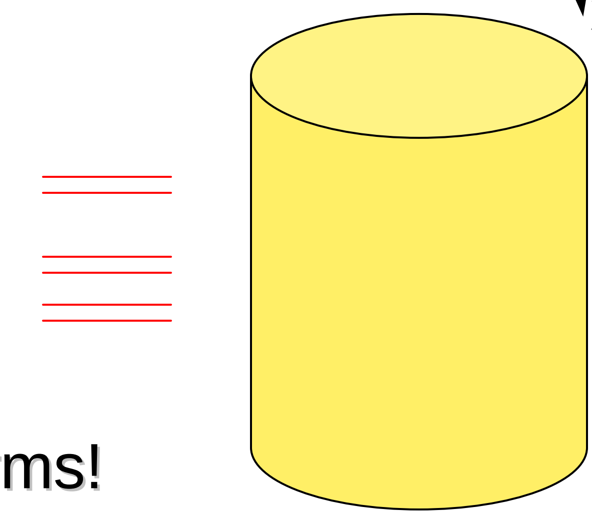
- *Expect* spectrum of H to be non-degenerate up to symmetries.
- Only symmetries are rotations (J) (& SUSY)
- Expect a unique state for (most*) given eigenvalues of H, "J" , Q.

* Exceptions may occur for states invariant under some SUSY.

Bulk interpretation?

(V. Balasubramanian, M. Rozali, D.M.)

Expect that H, J, Q are good quantum numbers.



But H, J, Q given by ADM boundary terms!

*All** info about state is encoded in grav. field at the boundary.

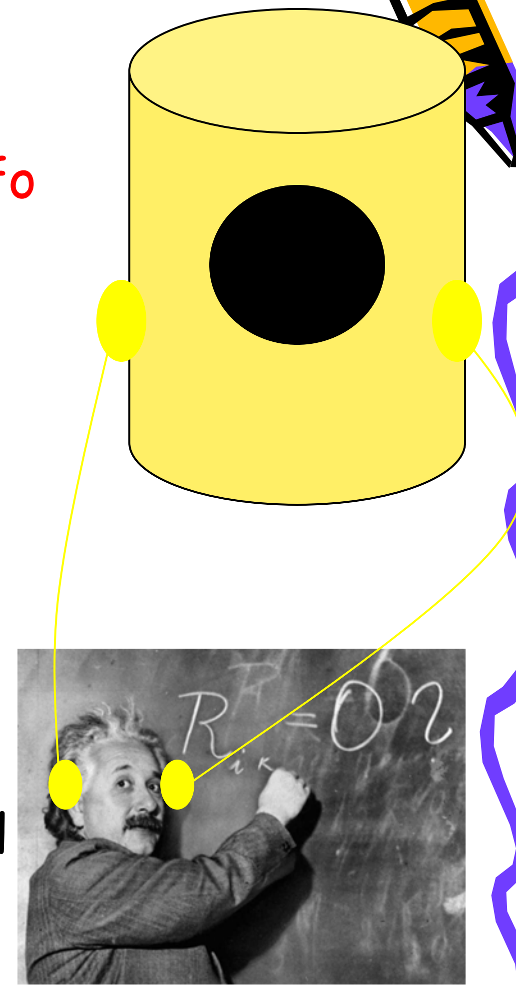
* $|\Psi\rangle = \Sigma_n c_n |\psi_i\rangle$
"Measuring" probabilities of given H,J give $|c_n|^2$.
Must "measure" something else (e.g., R, ϕ @ bdny) to get phases.

Information extraction

Info transferred to Hawking rad
by Energy Conservation

Couple to outside observer to extract info

$$\Delta E \sim dE/dN \sim e^{-S_{BH}}$$



Switch coupling on *very* slowly
$\Delta t >> 1/\Delta E \sim e^{S_{BH}}$

Note: On this time scale,
black hole will *explode* in rare
fluctuation!

Observables "inside" *do* have causal
contact w/ boundary;
expect commutators ~ $e^{-S_{BH}}$

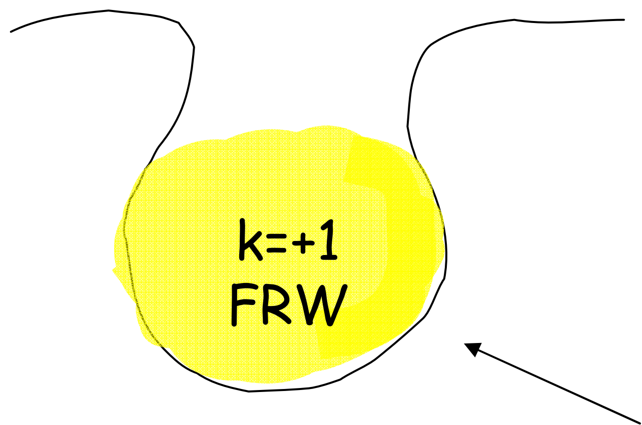
Unitary evolution is natural given finite # of states.

Mysteries & open issues

Why aren't there higher entropy states?

E.g. Wheeler's time-symmetric
"Bags of Gold"

Schwarzschild Exterior
of mass M



dS interior:
Freivogel, Hubeny, Maloney,
Myers, Rangamani, Shenker

Can be arbitrarily large
(w/ large S) for fixed
M.

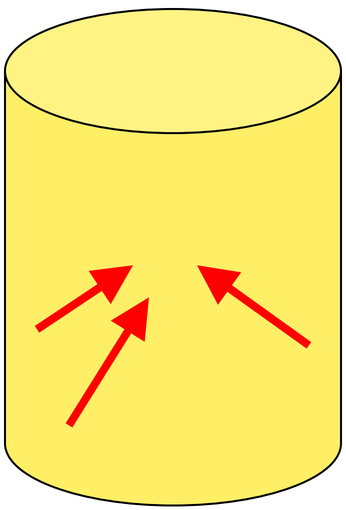
No big ones in AdS_3/CFT_2.

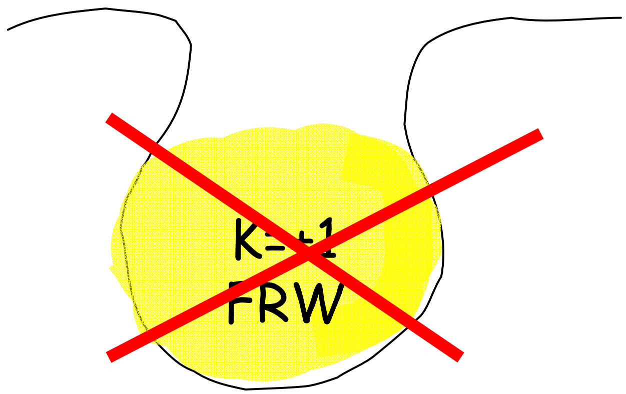
Inconsistent at QM level or superselected

Superselection?

Maybe: • (Probably) Can't make these classically by throwing in stuff from infinity.

• Not created by (known) smooth instantons.





But continuously connected to such via "Monsters" (Hsu & Reeb)

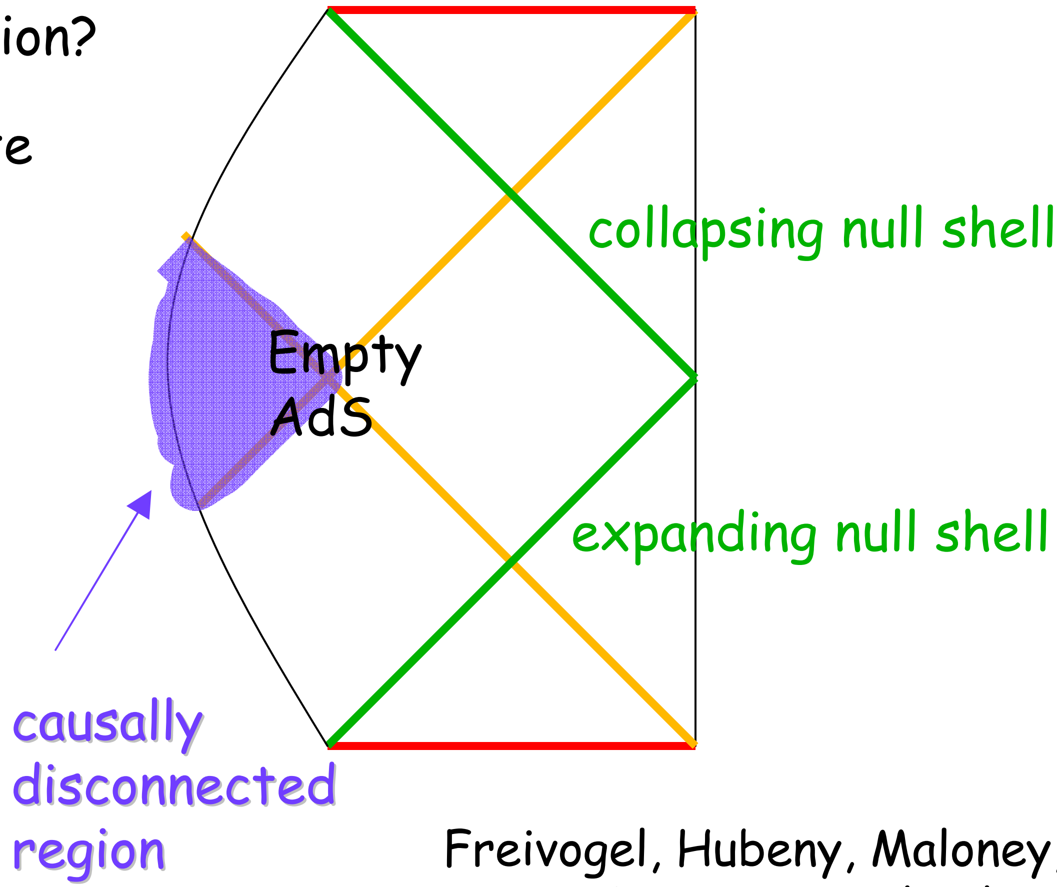
What prevents quantum tunneling into this region of phase space?

Where does one draw the line?

Where to draw the line?

Causal disconnection?

Allowed state



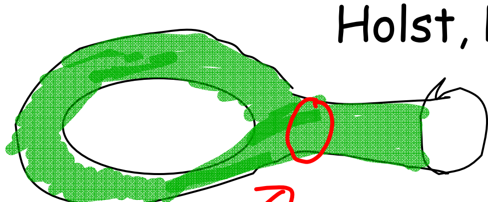
Freivogel, Hubeny, Maloney,
Myers, Rangamani, Shenker

Where to draw the line?

BTZ = AdS/$\mathbb{Z}$

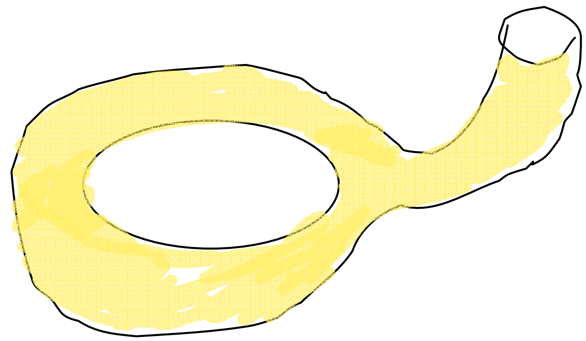
Geon = AdS/Γ

Aminneborg, Bengtsson, Brill, Holst, Peldan



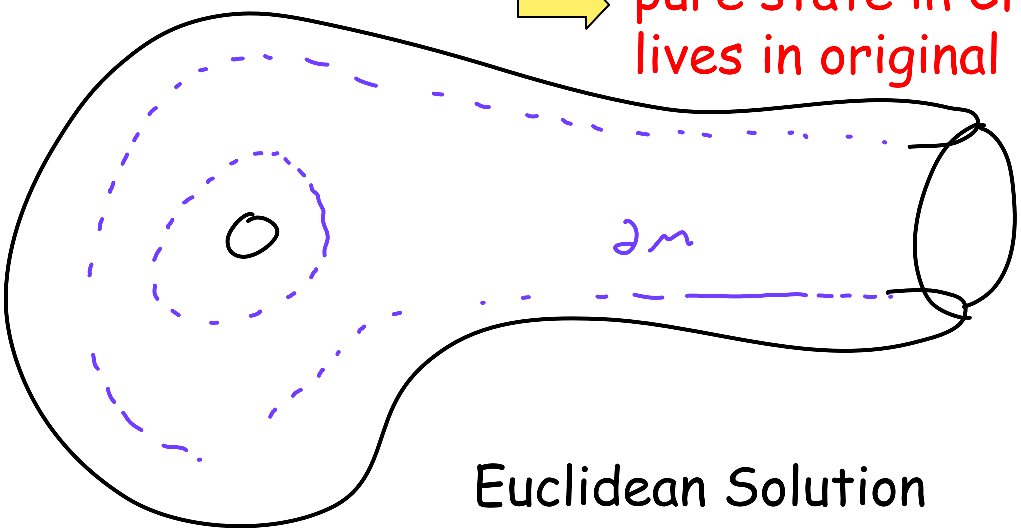
K_{ij} = 0 slice

Apparent horizon



Euclidean boundary

⇨ pure state in CFT, lives in original Hilbert space



Euclidean Solution

Louko & DM, Maldacena, FHMMRS

Summary

- 1. AdS/CFT describes a unitary theory with ~$e^{S_{BH}(E,J)}$ states. But which bulk states?
- 2. Info in these states is encoded in bulk observables near the boundary.
- 3. Black hole evaporation is unitary.

#2 (and thus #3) are natural consequences of bulk gravitational physics.
(E,J,Q are boundary integrals, rare fluctuations destroy horizons)

The mystery is #1!!