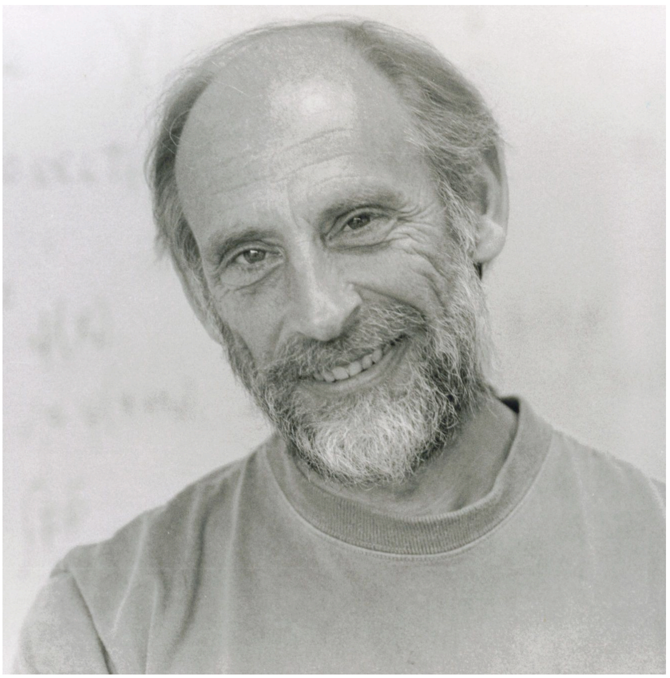
Wormholes and and entangled states

Juan Maldacena

Strings 2013, Korea

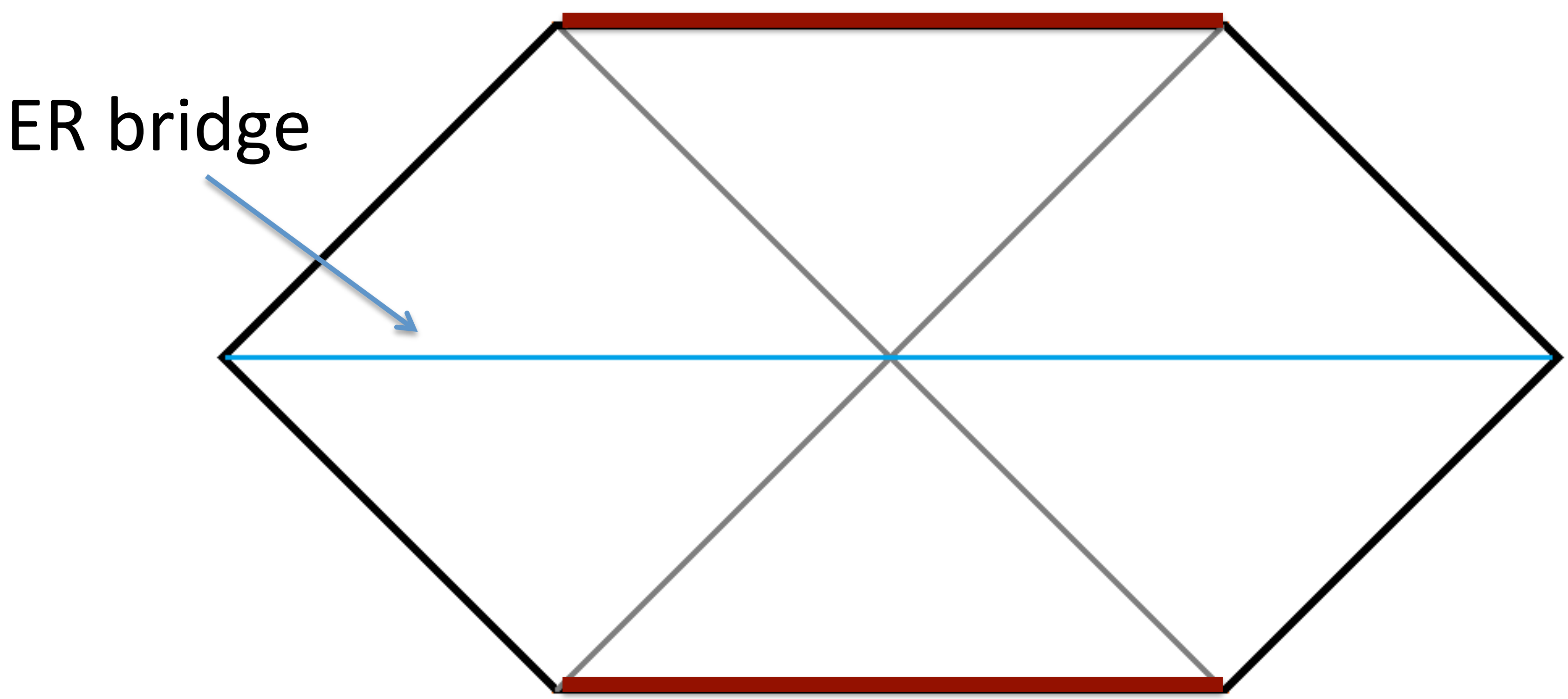
Collaborators



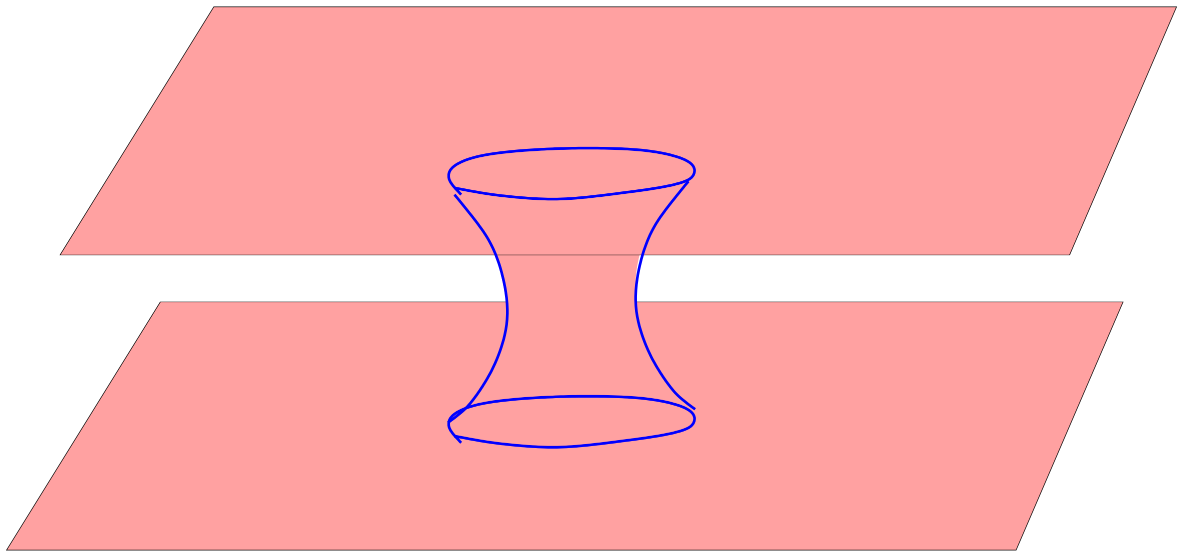
L. Susskind

T. Hartman

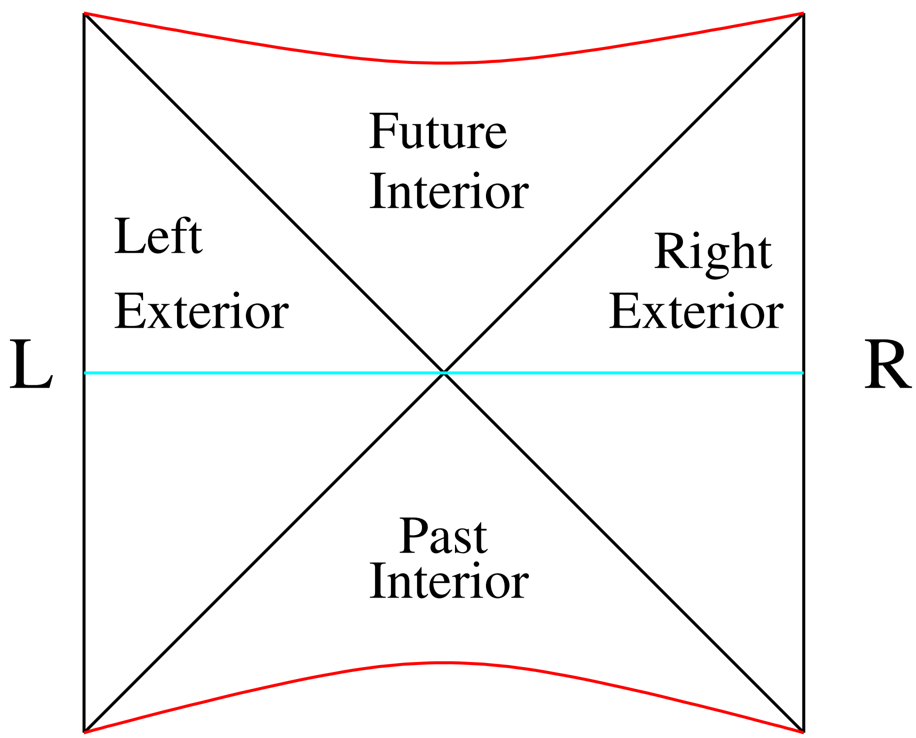
Eternal black hole



Einstein-Rosen bridge



Eternal AdS black hole

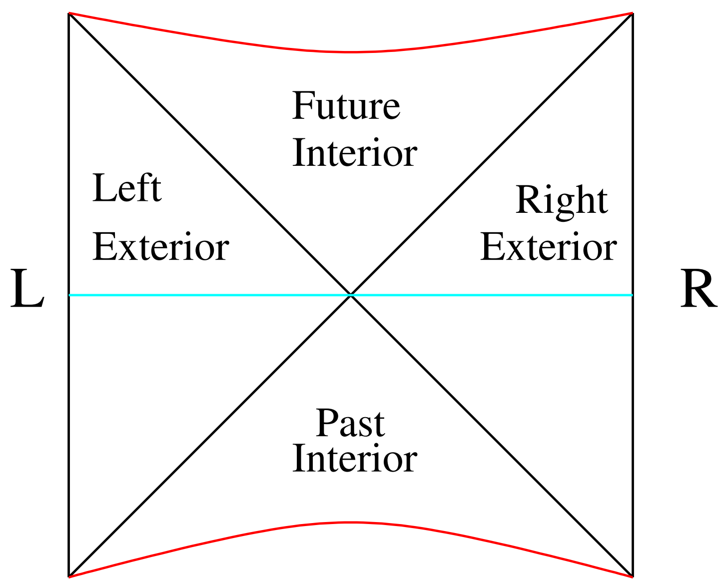


Entangled state in two non-interacting CFT's.

Israel
JM

$$|\Psi\rangle = \sum_n e^{-\beta E_n/2} |E_n\rangle_L^{CPT} \times |E_n\rangle_R$$

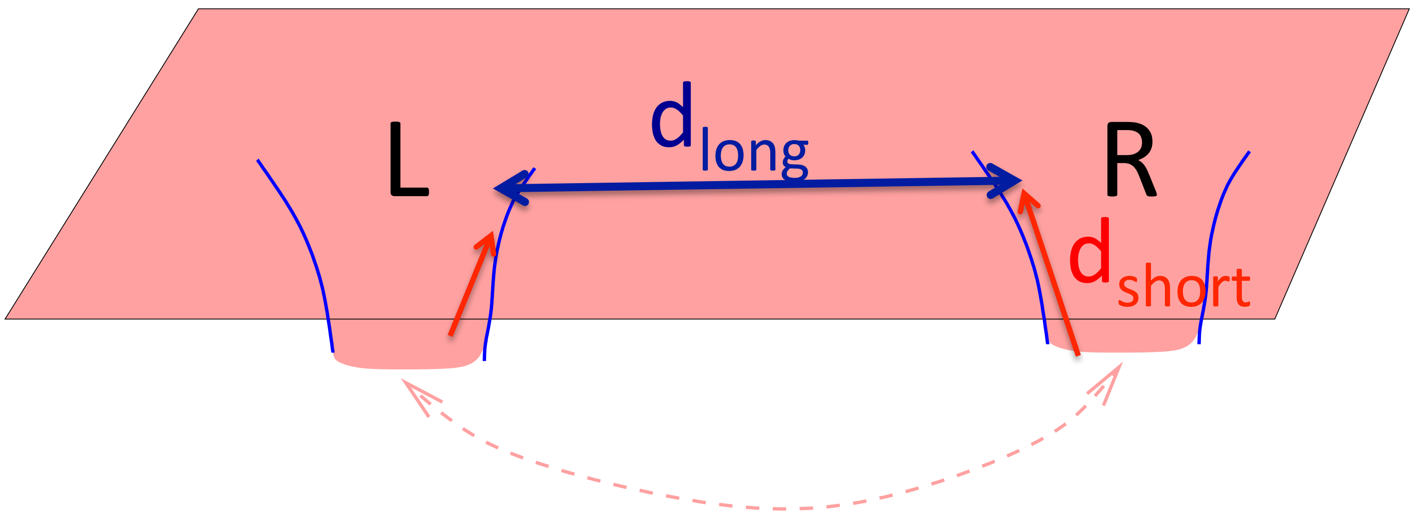
Eternal AdS black hole



$$\frac{\text{Area}}{4G_N} = \text{Entanglement entropy}$$

$$|\Psi\rangle = \sum_n e^{-\beta E_n/2} |E_n\rangle_L^{CPT} \times |E_n\rangle_R$$

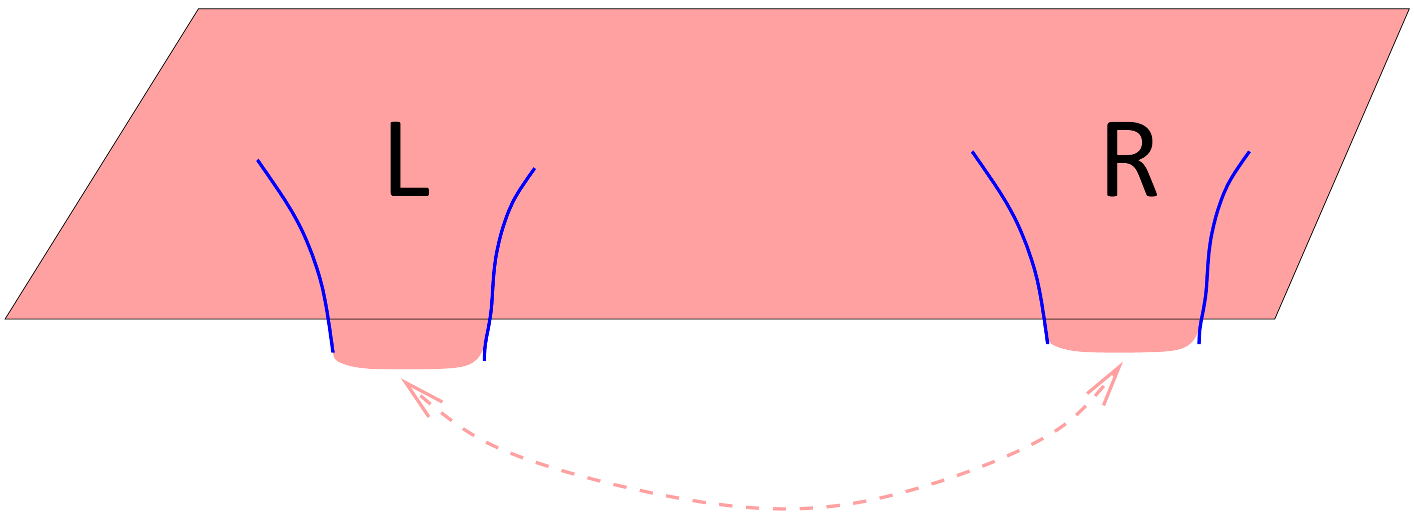
Wormhole interpretation.

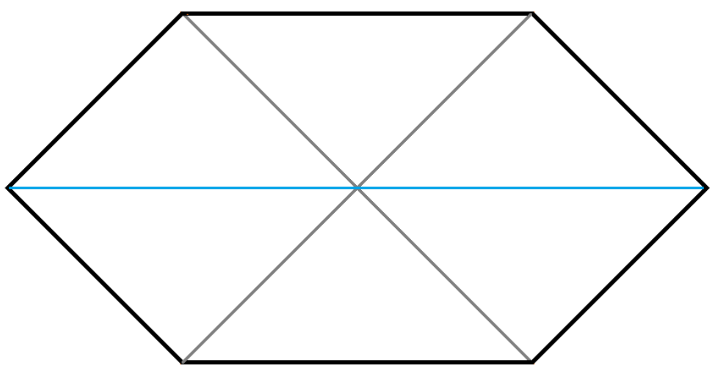


$$\langle \phi\phi \rangle = \frac{1}{d^2_{short}}$$

Fuller, Wheeler, Friedman, Schleich, Witt, Galloway, Wooglar

Wormhole interpretation.





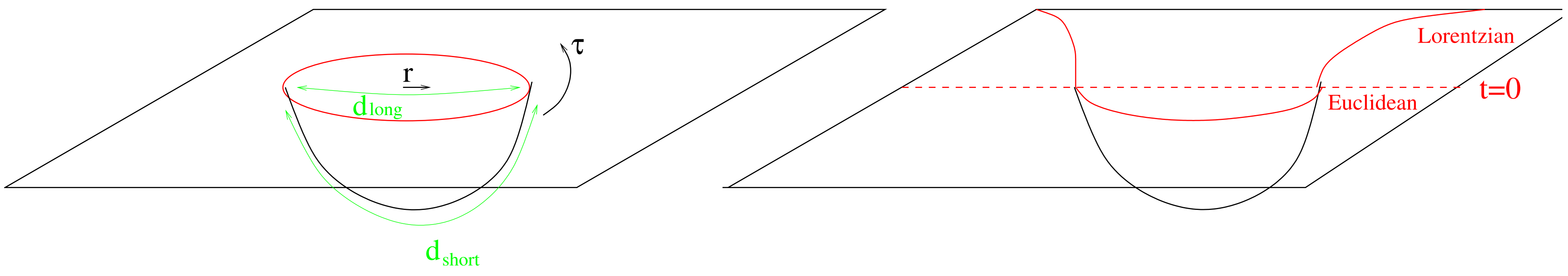
Non travesable

No signals

No causality violation

Fuller, Wheeler, Friedman, Schleich, Witt, Galloway, Wooglar

“Natural” production in a magnetic field



Garfinkle Giddings Strominger

ER = EPR

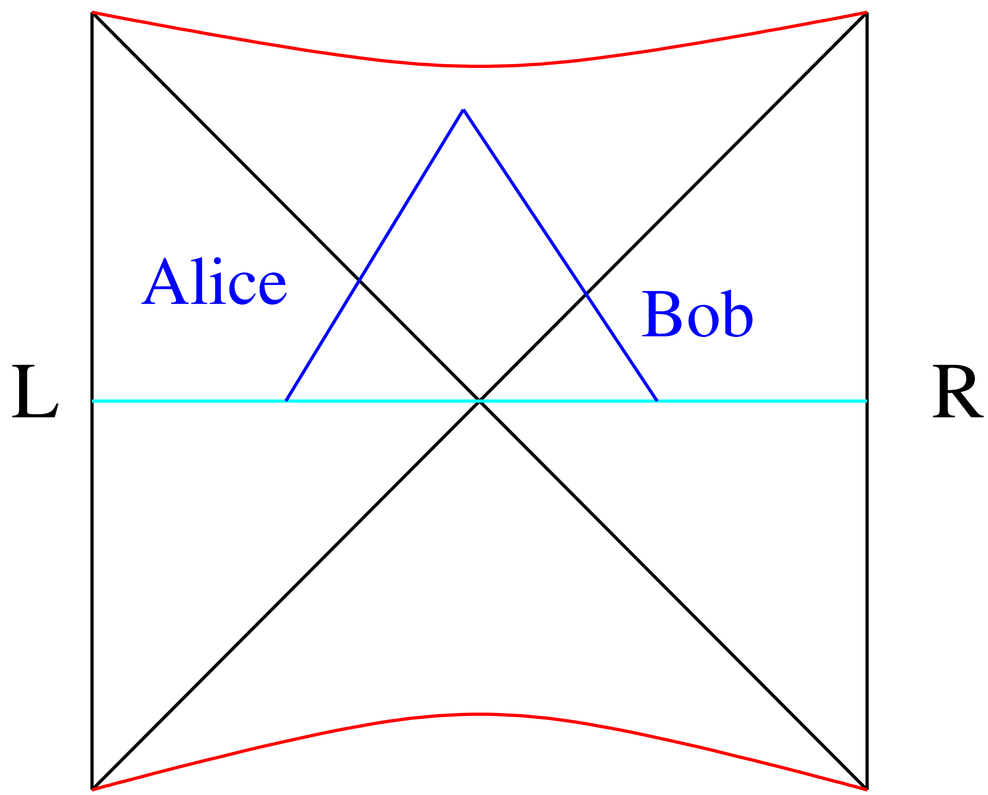
- Wormhole = EPR pair of two black holes in a particular entangled state.

- Large amounts of entanglement <u>can</u> give rise to a geometric connection.

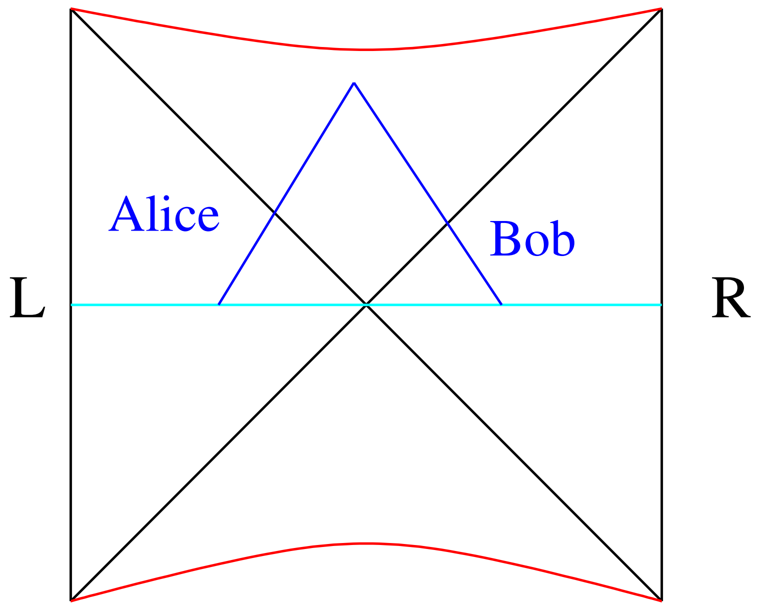
- If one accepts very ``quantum geometries" then even the spin ½ entangled states could be connected by a tiny quantum wormhole in some sense.

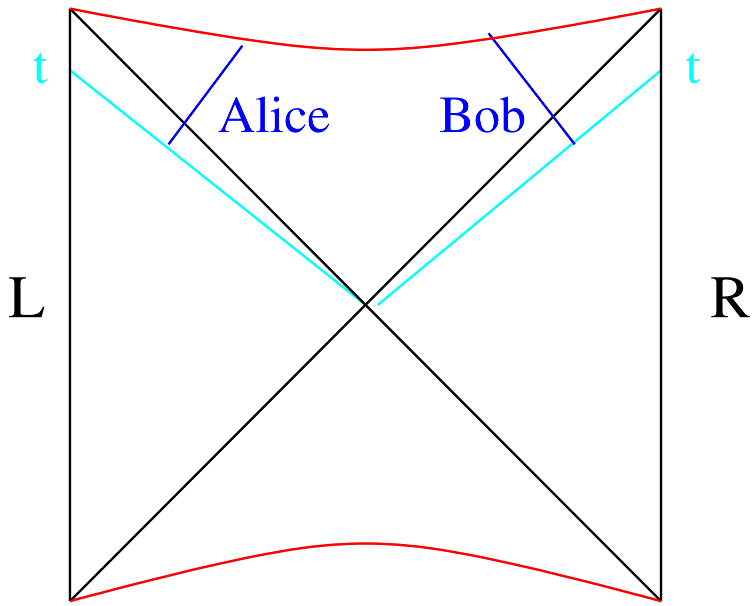
Neither can be used to send signals.

Can be used for a quick (and fatal) meeting.

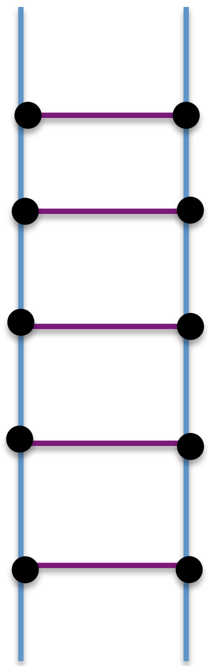


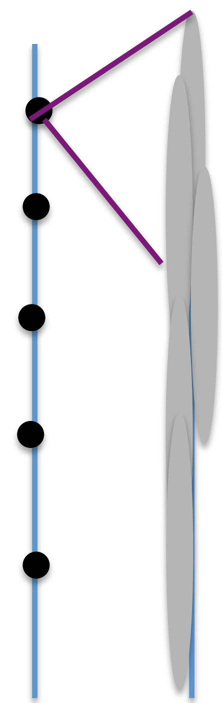
Time dependence





Spread of entanglement

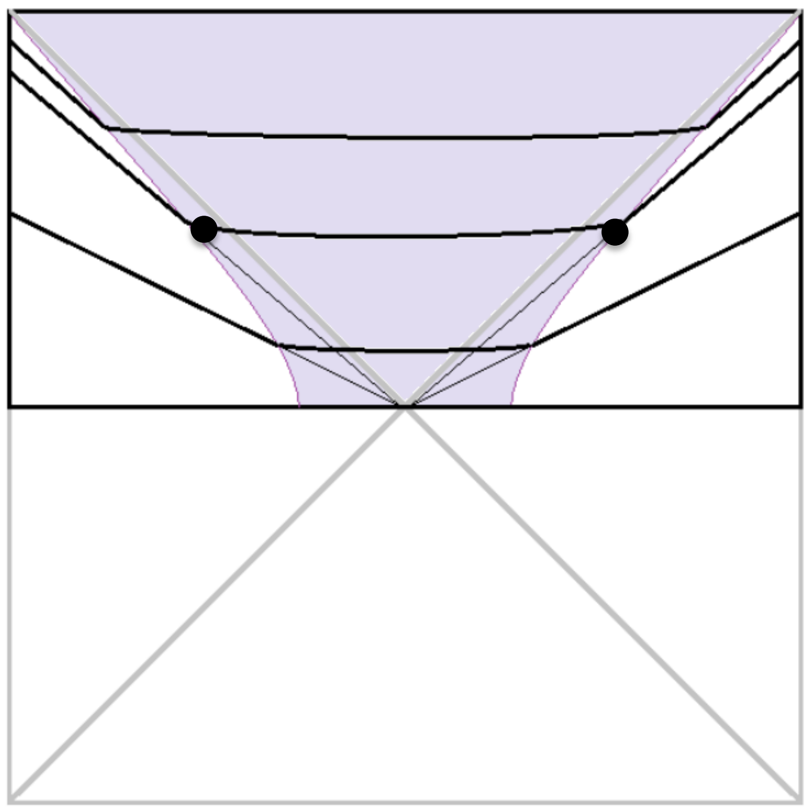




Van Raamsdonk
Hartman, JM
...

Local entanglement across the horizon at t=0

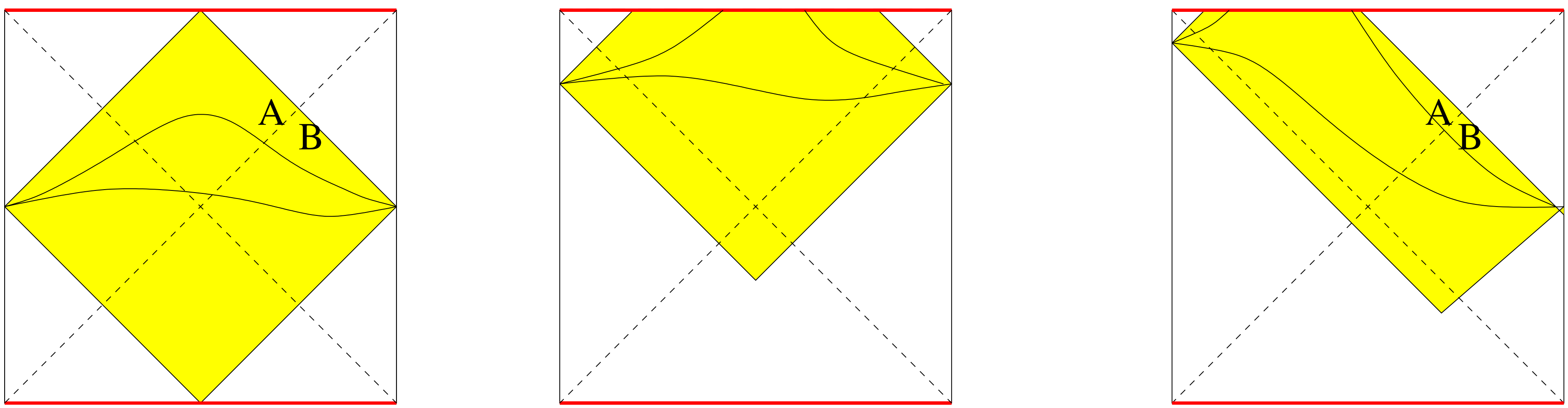
The entanglement becomes more non local as time increases. Due to the motion of the particles in each copy of the field theory.



Changing the entangled state

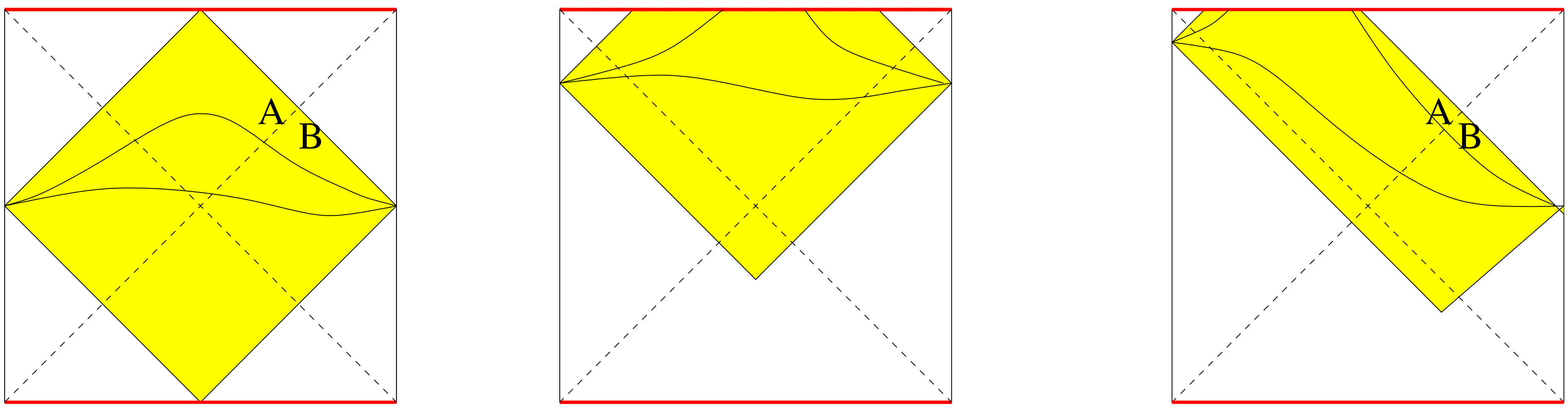
- Time evolution → Different slicings→ phases

$$|\Psi\rangle = \sum_n e^{-2iE_n t} e^{-\beta E_n/2} |E_n\rangle_L^{CPT} \times |E_n\rangle_R$$

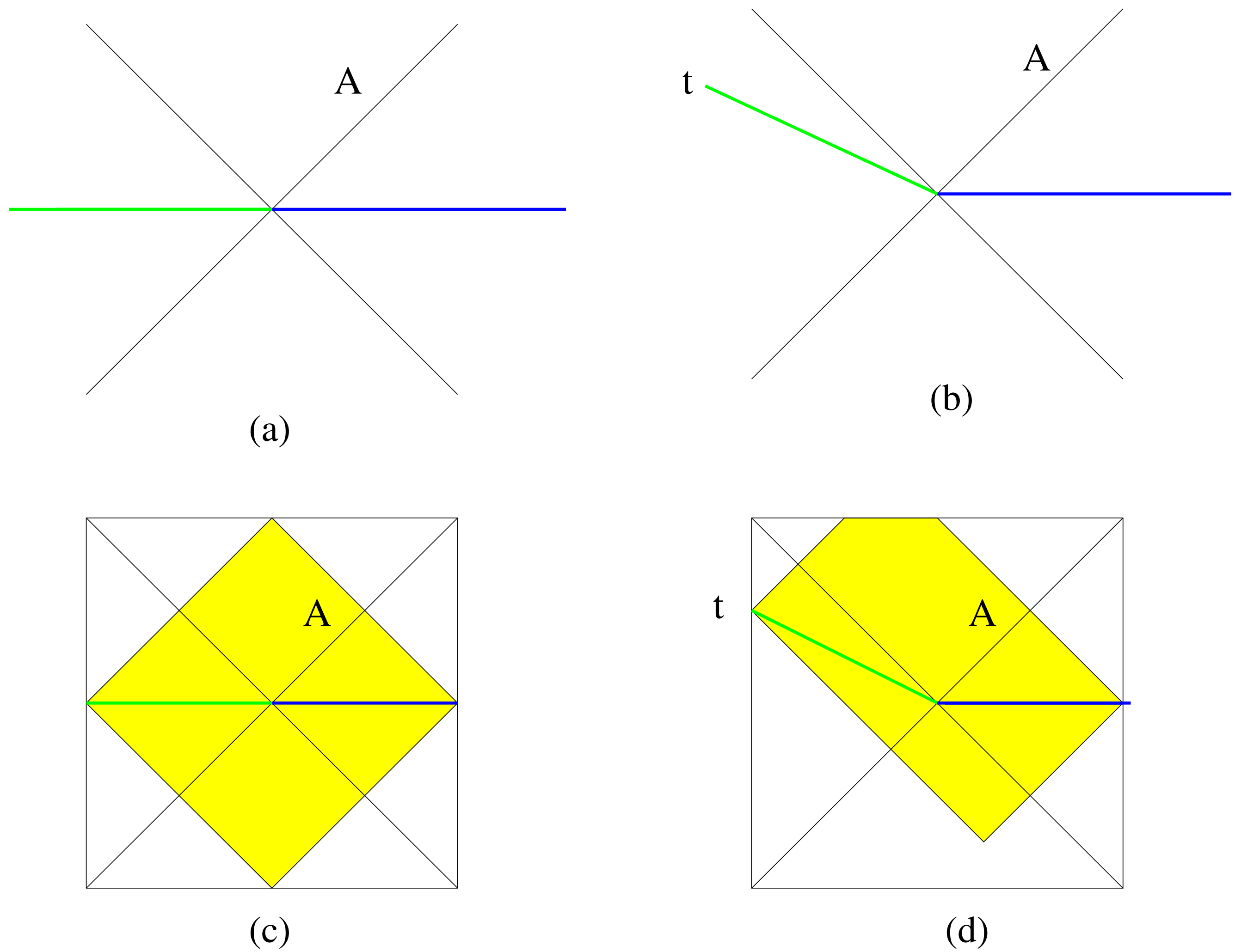


Each time: Whole yellow region, slices related by the Wheeler de Wit equation.

Heemskerk, Marolf, Polchinski, Sully



Note that region A is common to more than one state.

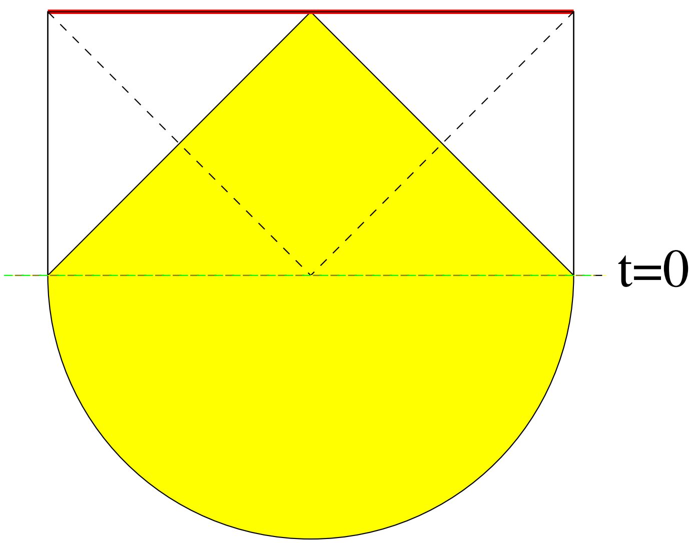


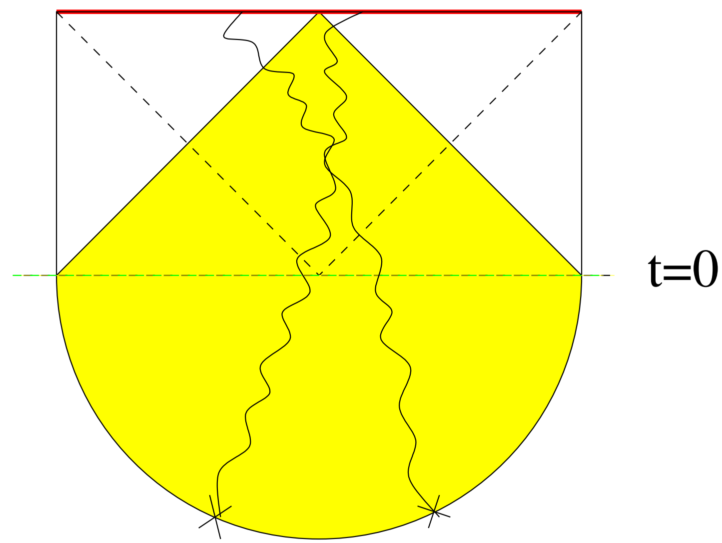
$$U_\theta|0\rangle_M = \exp\left\{\int d\omega e^{-\beta\omega/2} e^{-i\omega t} b^\dagger_{L,\omega} b^\dagger_{R,\omega}\right\}|0\rangle_R$$ → Singular in flat space QFT

$$|\Psi\rangle = \sum_n e^{-iE_n t} e^{-\beta E_n/2} |E_n\rangle_L^{CPT} \times |E_n\rangle_R$$ → Non-singular in gravity

Other states

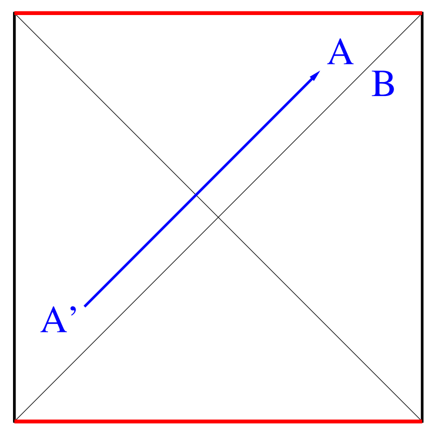
Adding particles to the Hartle-Hawking state.
Precise translation between states in the CFT and states in the bulk.



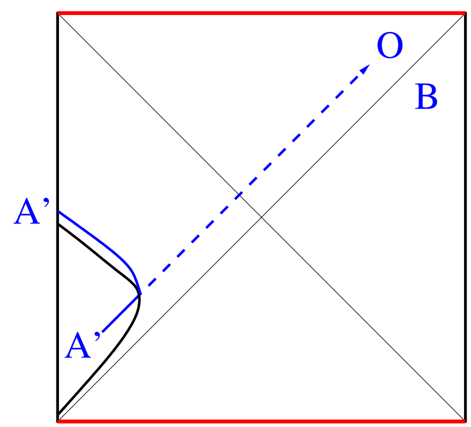


- Entangled states can be connected by a smooth geometry.
- Each entangled state corresponds to a whole region of the bulk, with slices related by the WdW equation.
- Different entangled states correspond to different geometries, or the same geometry plus extra particles.
- We did not make a statement about the generic entangled state.

Version of the AMPS paradox.

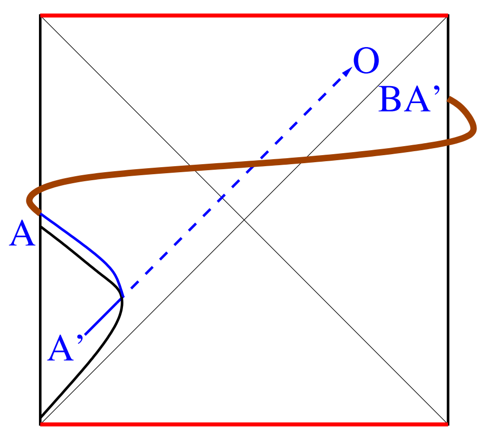


(a)



(b)

Hawking,
Mathur,
Giddings,Shi, Braunstein,
Almheri, Marolf, Pochinski, Sully



(c)

Two CFT's in the lab in the entangled state.
We distill the qubit entangled with B and give it to a bulk observer on the right.
In the process we replace A by an uncorrelated qubit.

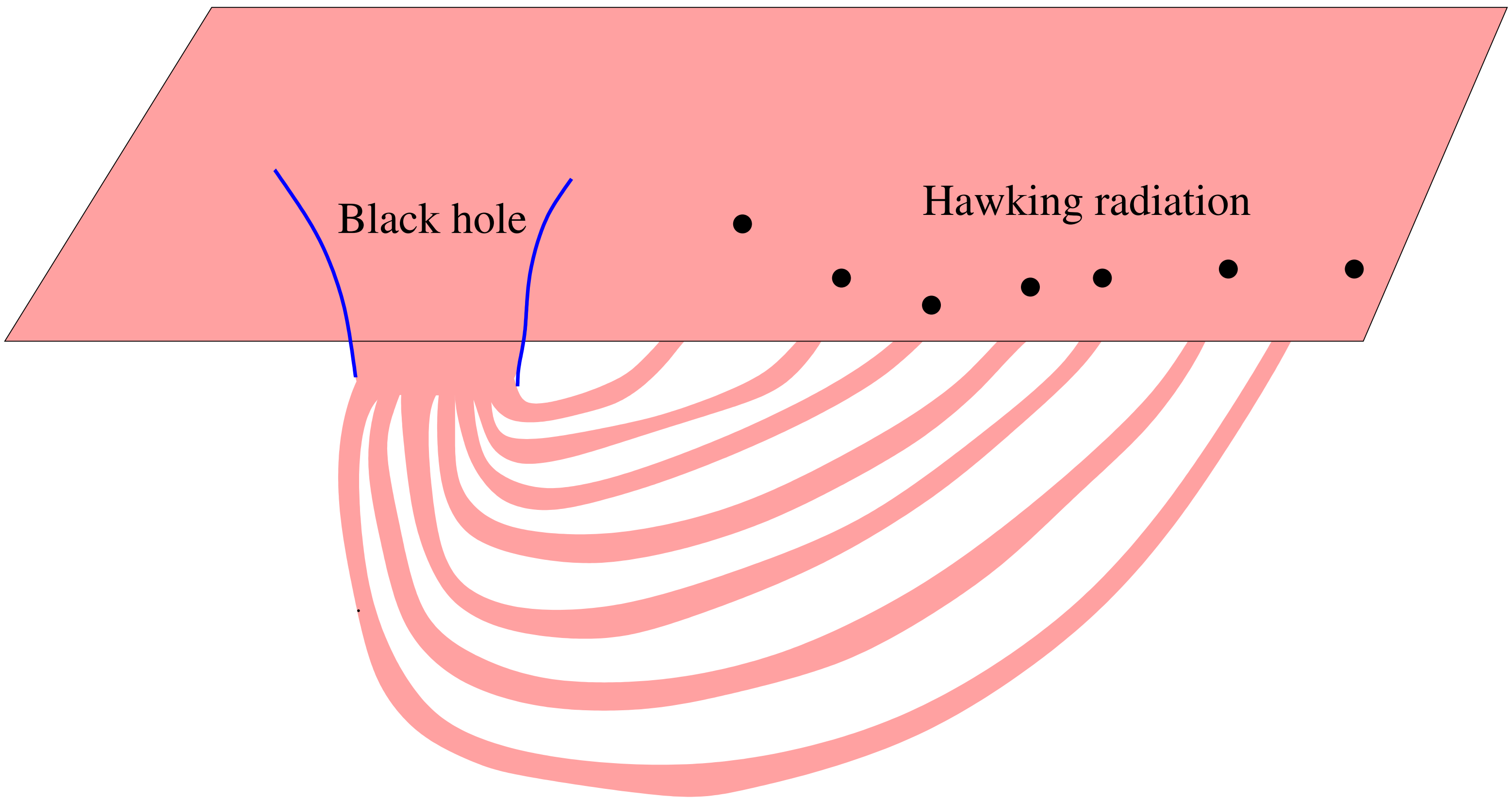
Similar points: Papadodimas, Raju, Verlinde^2

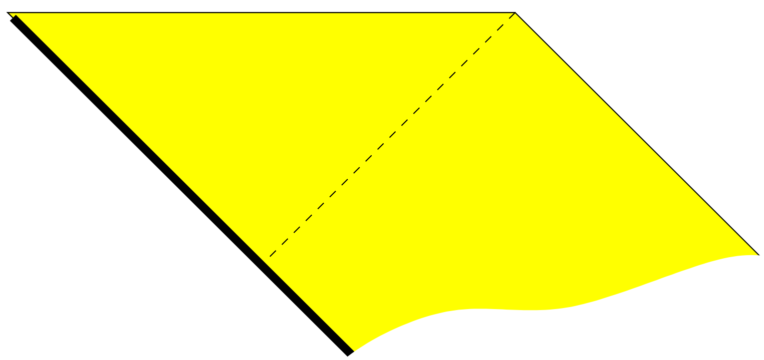
- We can view the left side as ``processed'' radiation.
- What we do to the radiation matters for what an infalling observer sees.
- The AMPS paradox is real (if we ignore computational constraints).

Harlow Hayden

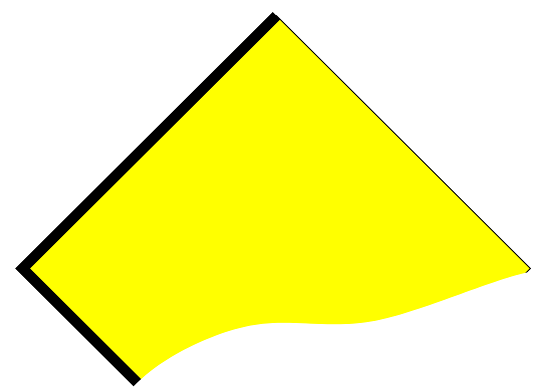
- Some states are not smooth.
- What happens if we do nothing ?. What is the particular entangled state produced by the ``natural'' evolution of an evaporating black hole ?

Black hole + radiation ?





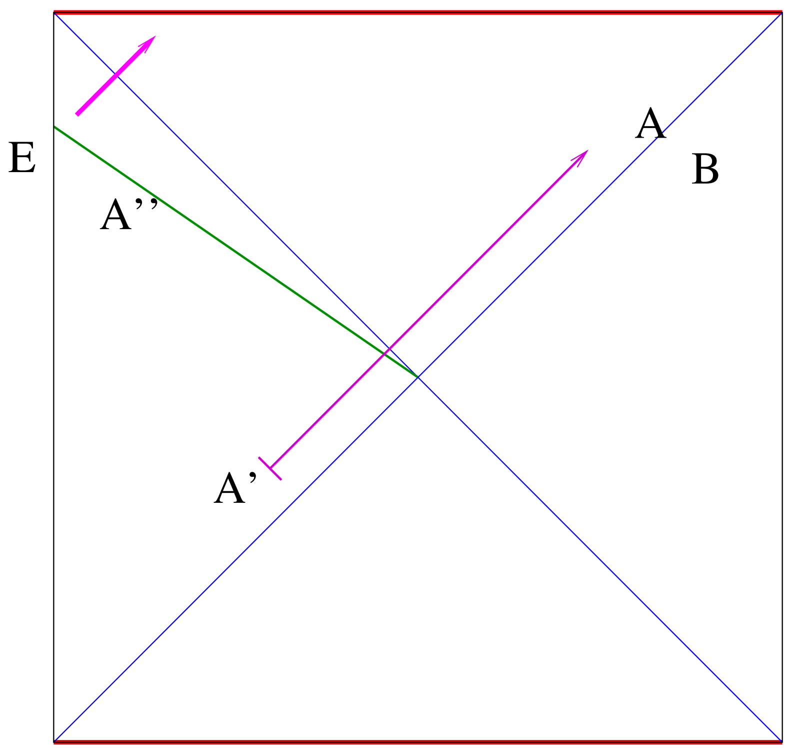
or



Smooth horizon

Firewall

Easy measurements

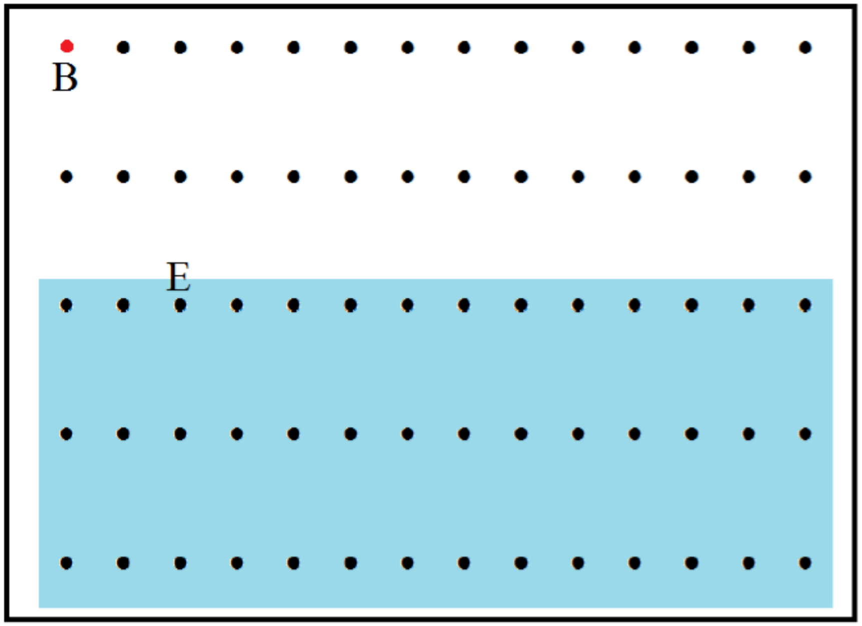


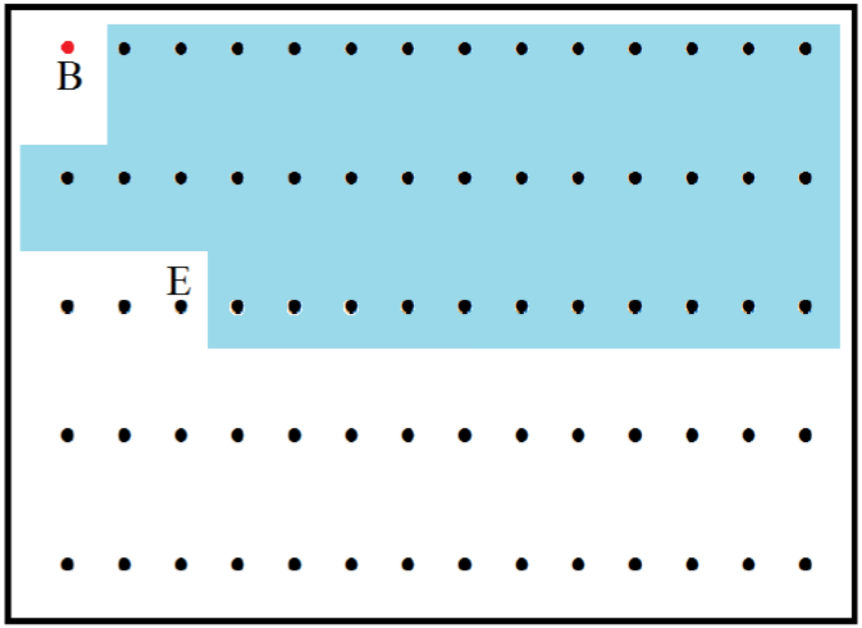
According to the bulk
E does not modify A.
But we expect that A'' and E not to commute.

We can create a large disruption
by measuring E in the past

Shenker, Stanford

Measuring E does not destroy the qubit entangled with B





Measuring E does destroy the entanglement of B with the rest of the system.

Similar to the story of quantum error correction. (This argument can only fix less than S/4 random measurements)

Crucial difference with measuring A' (or R_B , which is the qubit entangled with B)

Comments

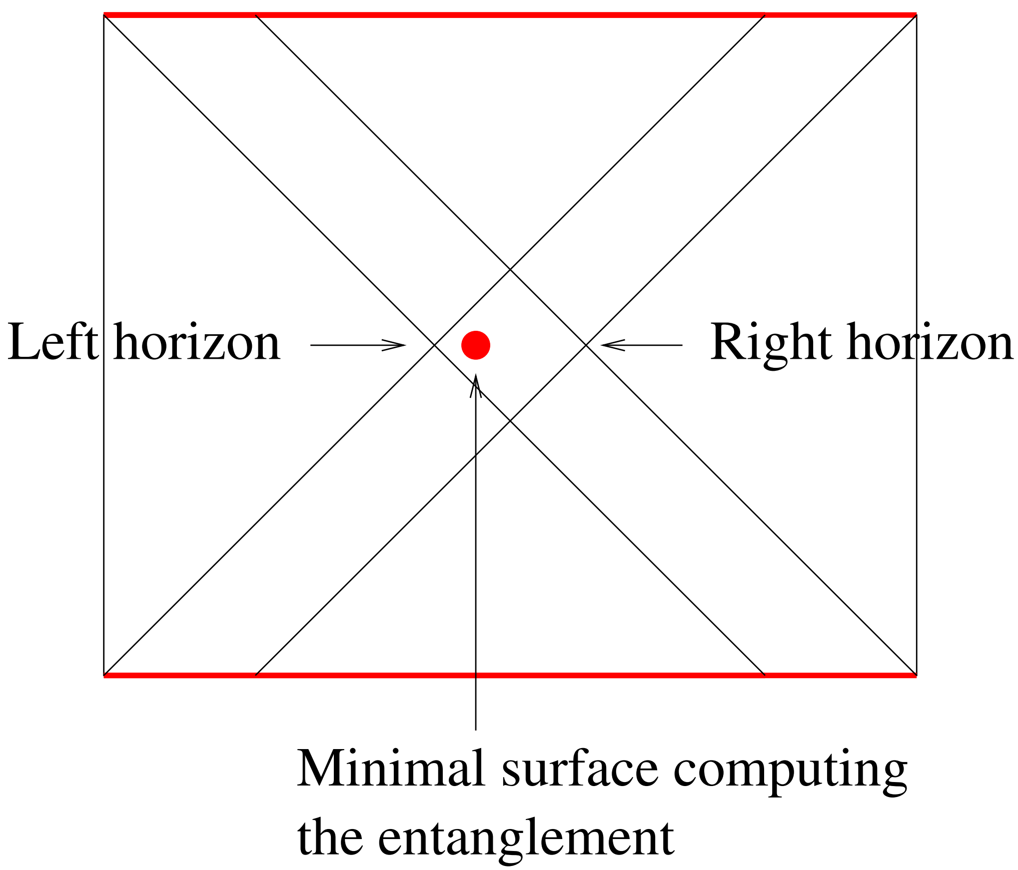
- In the gauge gravity duality, bulk locality within an AdS radius is a strong coupling phenomenon.
- AdS black holes are such that the proper time an observer spends in the interior is less than an AdS radius.
- To distinguish a putative firewall at the horizon from the expected one at the singularity we need to understand this bulk locality.
- I think that a proper understanding of the interior will probably need a proper understanding of bulk locality (within an AdS radius).

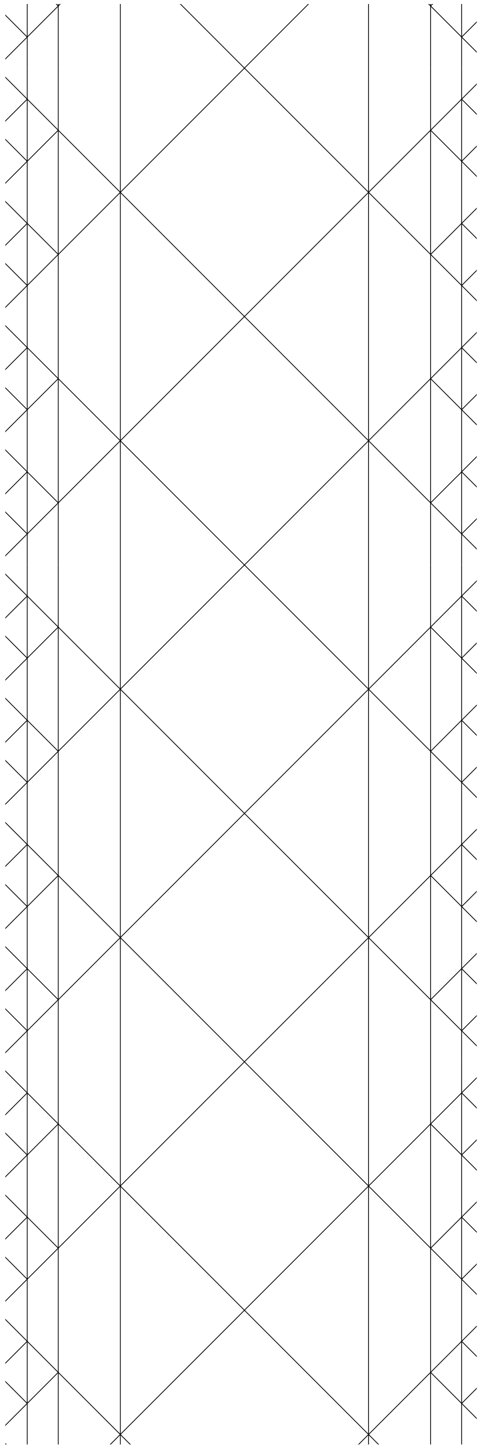
Conclusions

- We gave an EPR interpretation to the ER bridge.
- The topology of space can be modified by massive amounts of entanglement.
- A black hole entangled with radiation could produce a similar geometric bridge. Its interior could depend on what we do with the radiation.
- We discussed the AMPS paradox and saw that in this case, it is resolved by noticing that the interior is made both the black hole microstates and the states entangled with them.

Backup slides

Less than maximal entanglement





Entanglement pattern
across the horizon

A small region of one horizon
is entangled with the corresponding
small region on the other.

(Using tensor networks)

Abajo-Arrastia, Aparicio, Lopez, Albash, Johnson
Balasubramanian, Bernamonti, de Boer, Copland,
Craps, Keski-Vakkuri, Muller, Schafer, Galli, Takayanagi,
Ugajin, Asplund, Avery,Basu, Das, Nishioka, Buchel,
Lehner, Myers, Van Niekerk, Nozaki, Numasawa, Allais,
Tonni, Hartman, JM, Liu, Li