Wormholes and entangled states

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Two descriptions of black holes

- Unitary: From infinity, microstates
- Local: Infalling observer, general covariance, interior.
- → we should make them consistent!

It will probably require all of your ideas…

- Does gravity emerge as a result of an approximation?

- Why does this approximation sacrifice unitarity ?

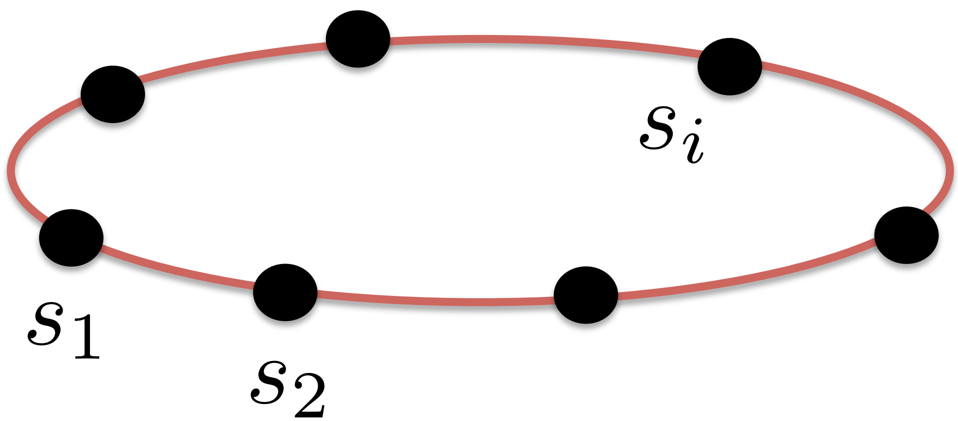
Emergence of spacetime

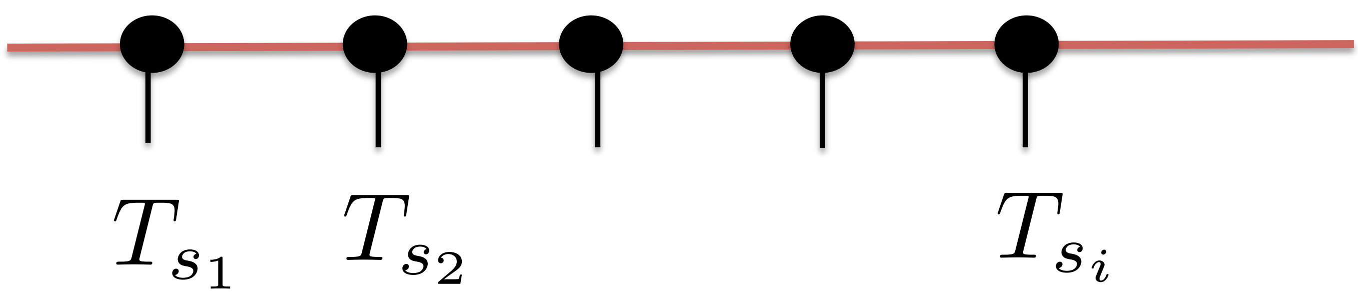
- New properties of matter due to collective behavior.
- Wilson → Universality.

Geometry for the ground state of field theories

- Wilson → Usual RG picture.
- Condensed matter theorists found a convenient quantum mechanical, real time description of the states→ Tensor networks.

$$\Psi(s_1, \cdots, s_n) = Tr[T_{1,s_1} T_{2,s_2} \cdots T_{n,s_n}]$$





This representation works well for states with a mass gap. If we choose

$$Log(D) \gg S_{\rm ent}$$

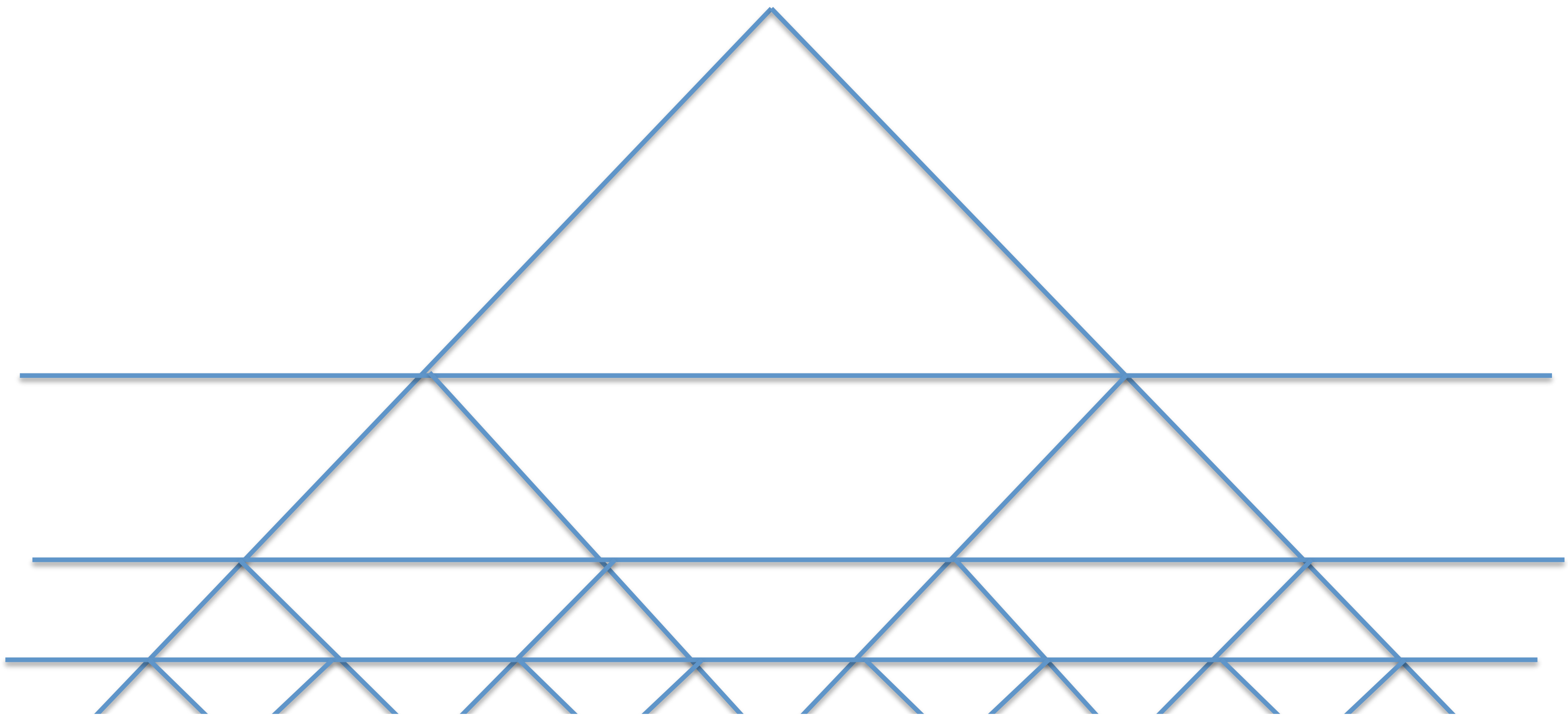
Special wavefunctions. L sites.

$$\dim(H) = 2^L$$
$$\dim(\text{Space of Tensors}) = LD^2$$

Of course, if we do arbitrary superpositions of tensor networks, we get a much bigger space:

$$\dim(\text{Superposition of Tensors}) = 2^{LD^2}$$

Scale invariant wavefunctions



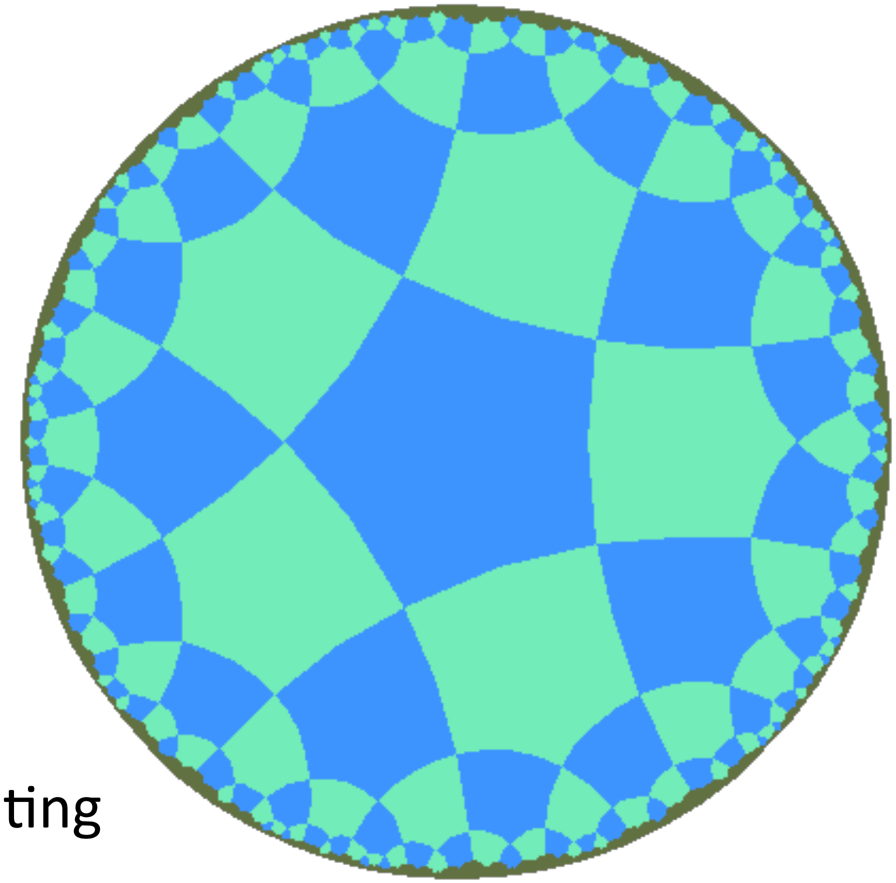
Each vertex is a five index tensor. Each line is an index contraction.

Indices → not ``real'' states.

Vidal

This is similar to the geometry of AdS

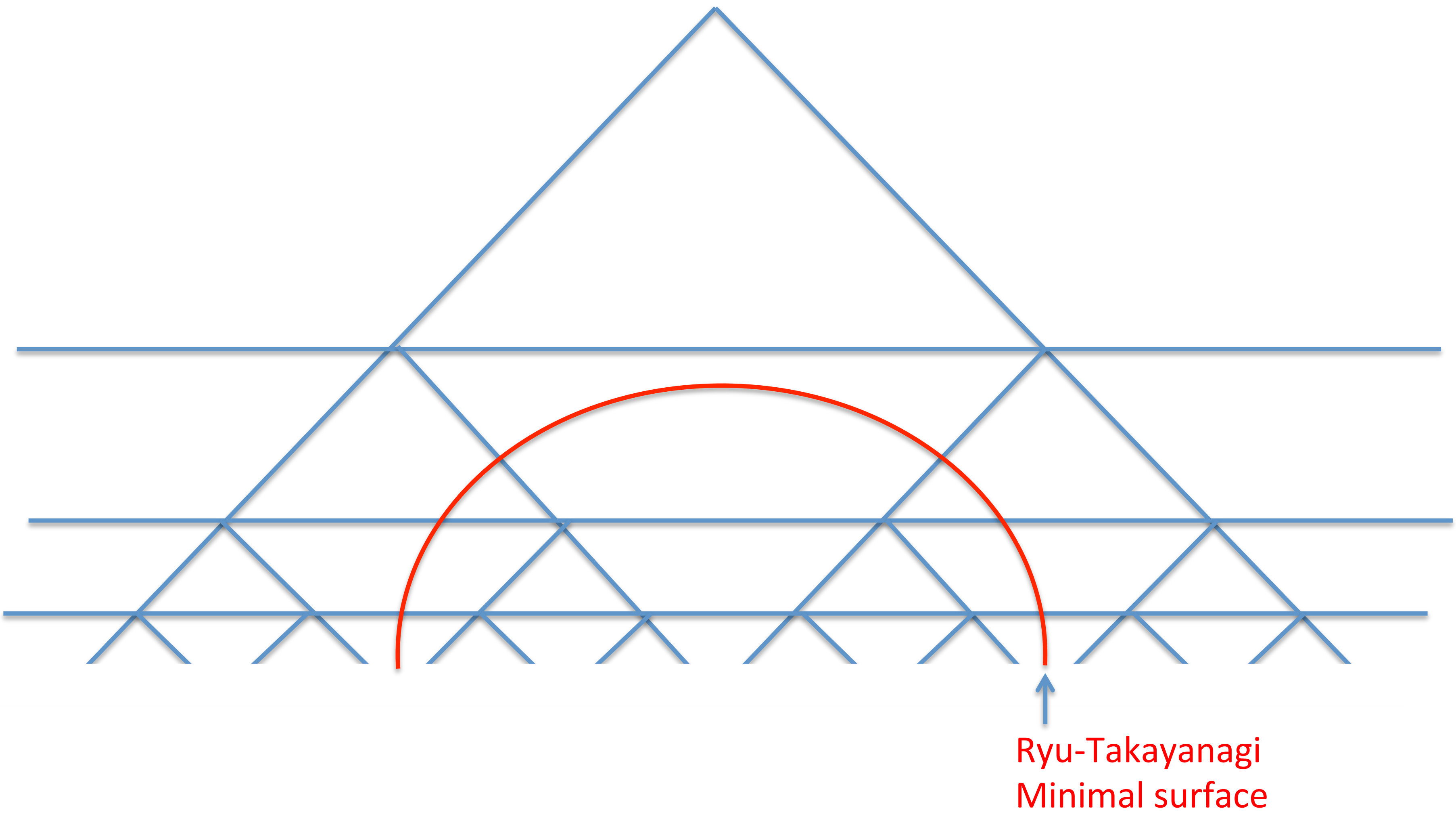
Swingle



Think of the tensors as representing
 the AdS vacuum wavefunction.

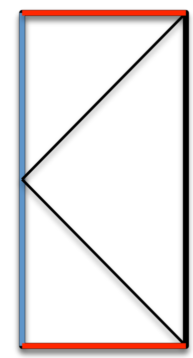
Tensor index contractions → entanglement

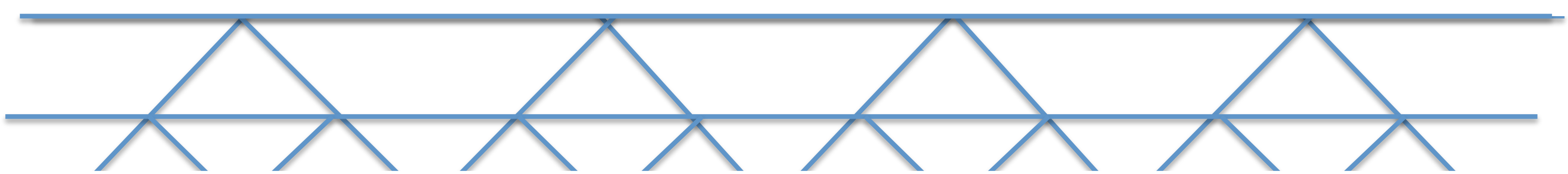
Entanglement & structure of space



Conformal invariant system in a state with a mass gap.

eg: AdS space with an end of the world brane in the IR





Bulk effective field theory

Start with a wavefunction given by a tensor network.

This is the bulk vacuum.

Find new states as ``small'' deformations of the tensors.
These are particles on top of the bulk vacuum.

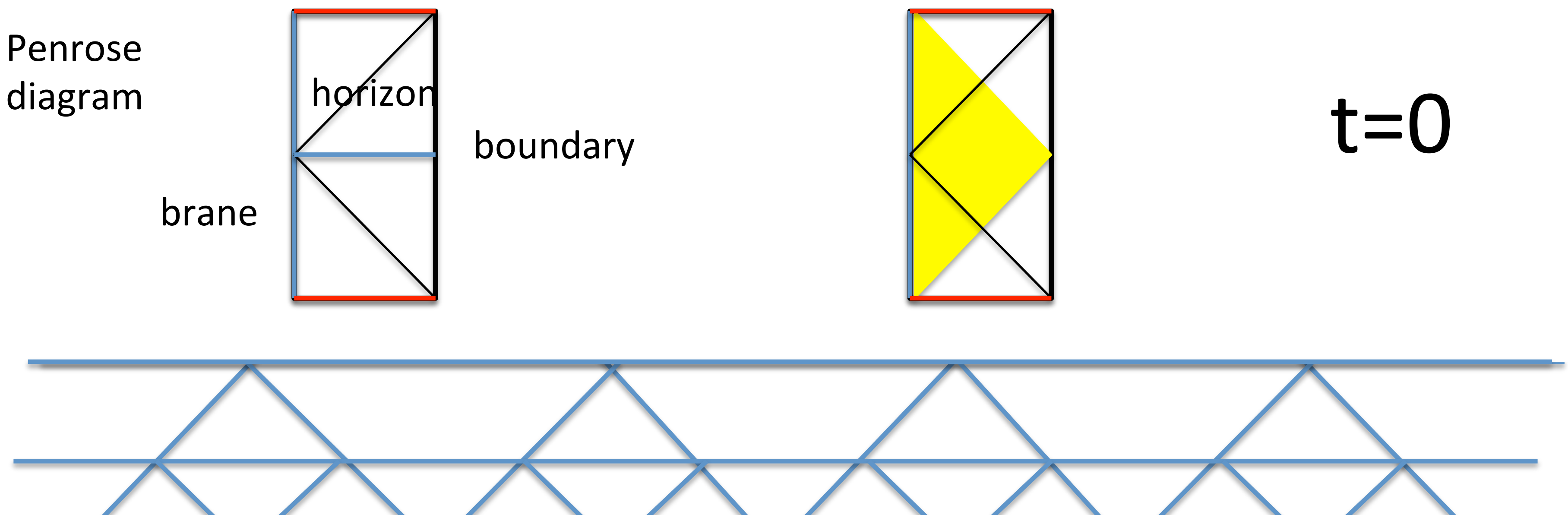
$$TT\delta TTT; \qquad TT\delta TTT\delta TT..$$

Local degrees of freedom $\rightarrow$ indices of the tensor..

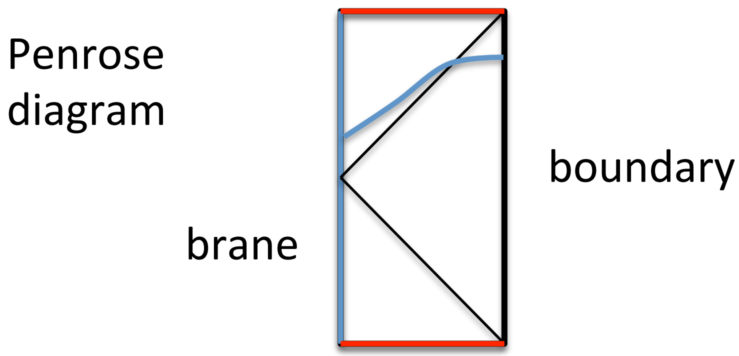
- If we consider superpositions of these networks we get a ``semiclassical’’ fock space.
- It is an overcomplete space. The projection on to the correct space is obtained by evaluating the wavefunction from the network.

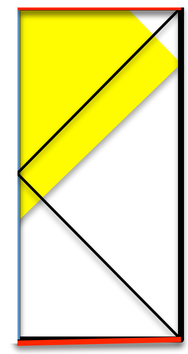
Time dependence

Start with a state with a gap and evolve it.
Eg. Brane in Ads that falls into a black hole

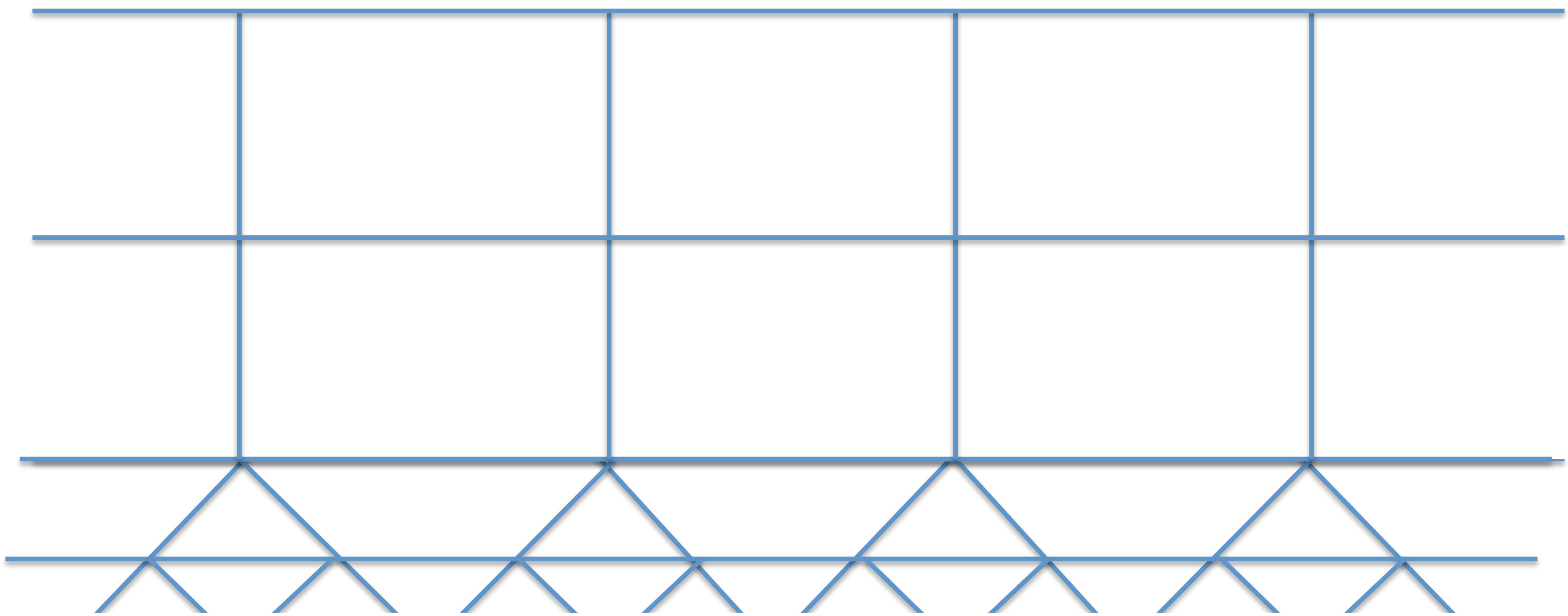


Hartman & JM

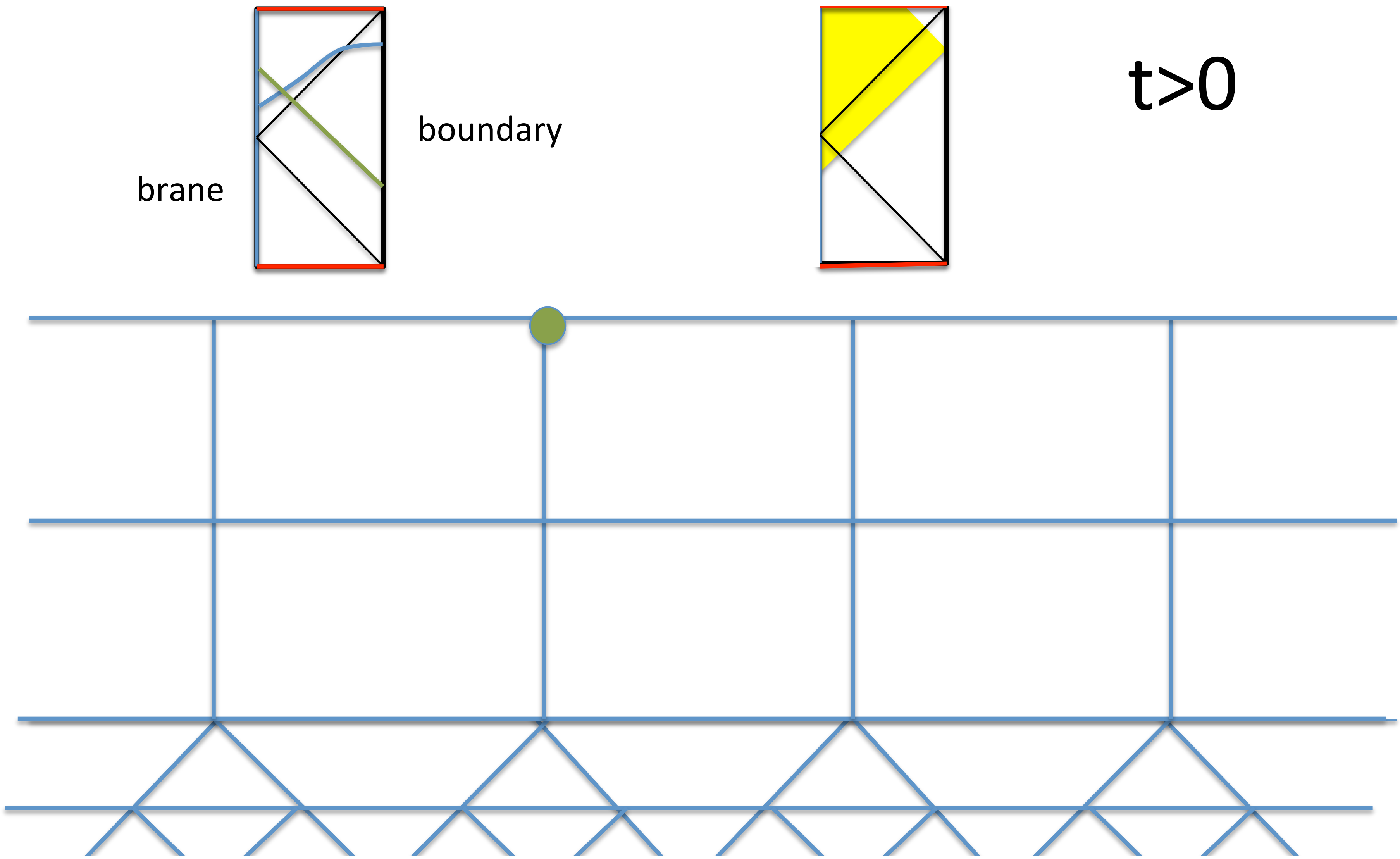




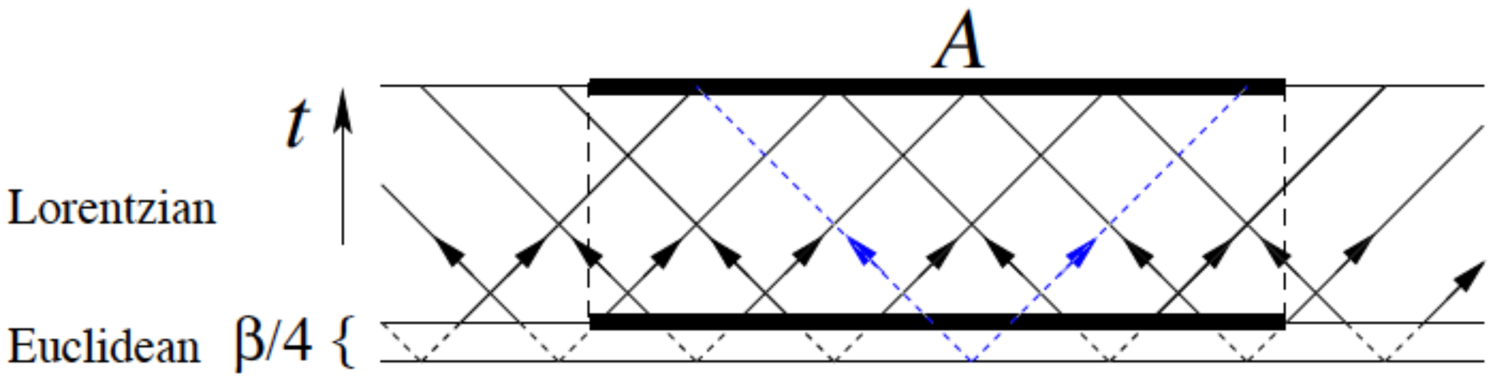
t>0



Time evolution produces a wavefunction that can be represented as a geometry which
Is simply longer.


brane
boundary
t>0

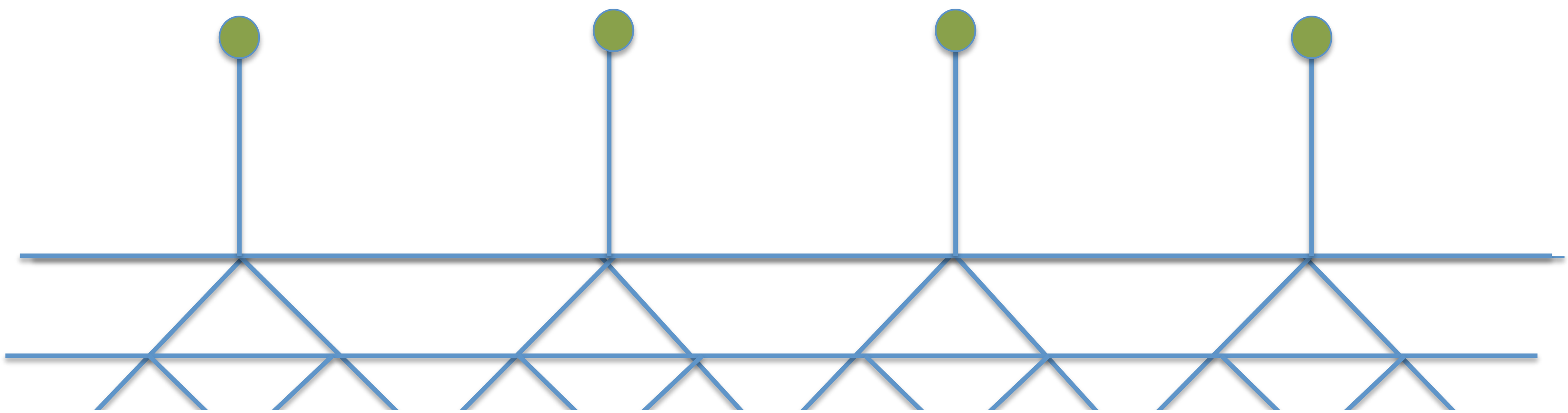
Field theory picture. (focus on IR)



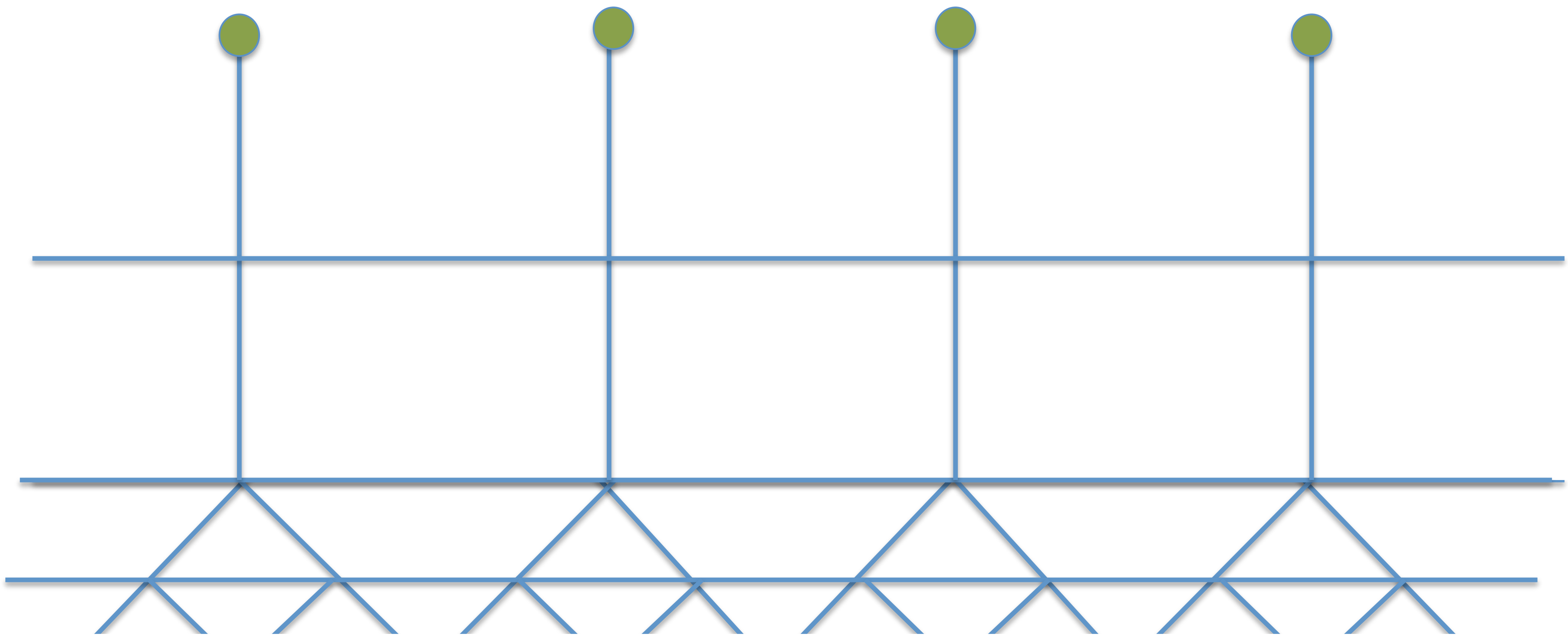
Network = history of the state.

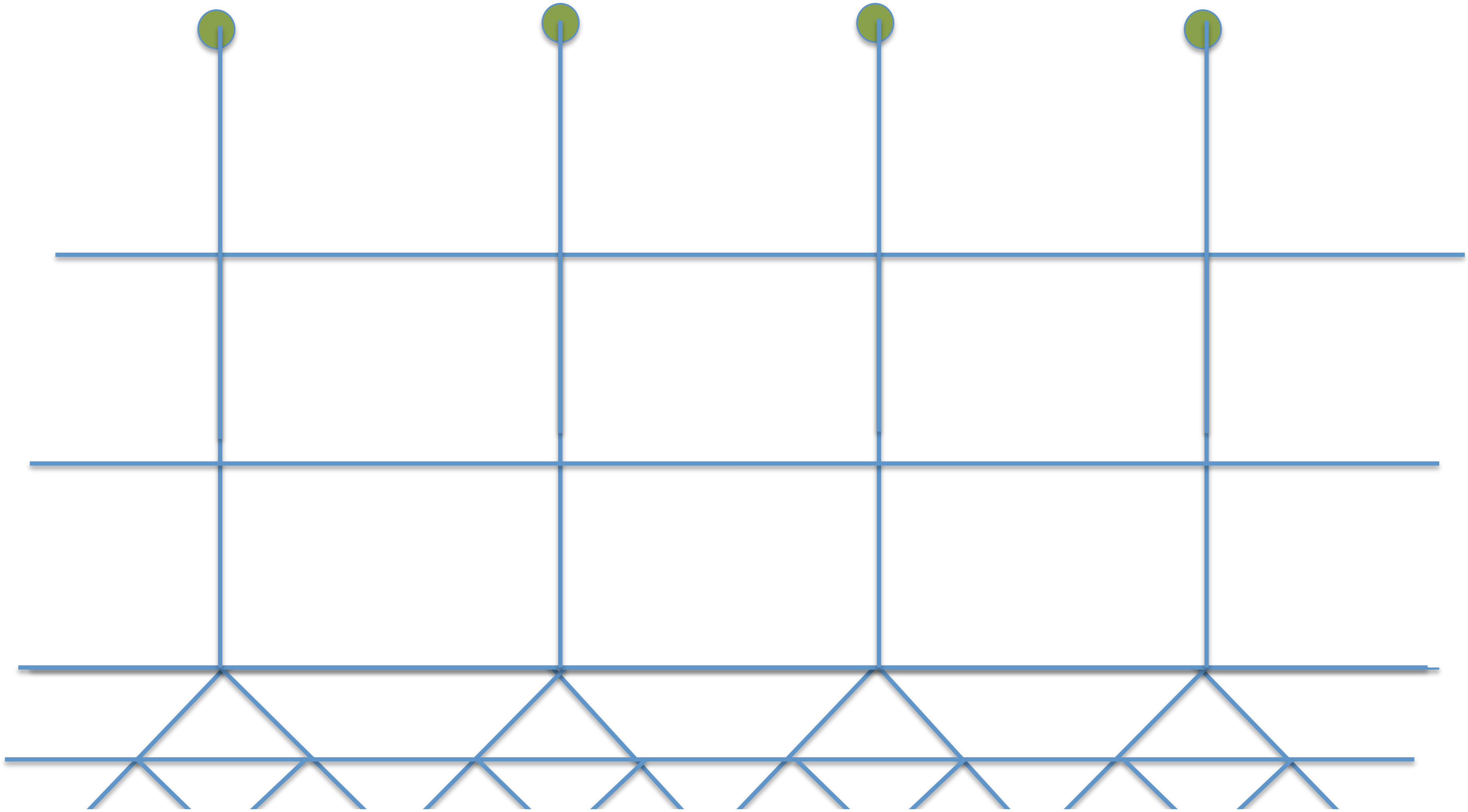
→ geometry captures the history ?

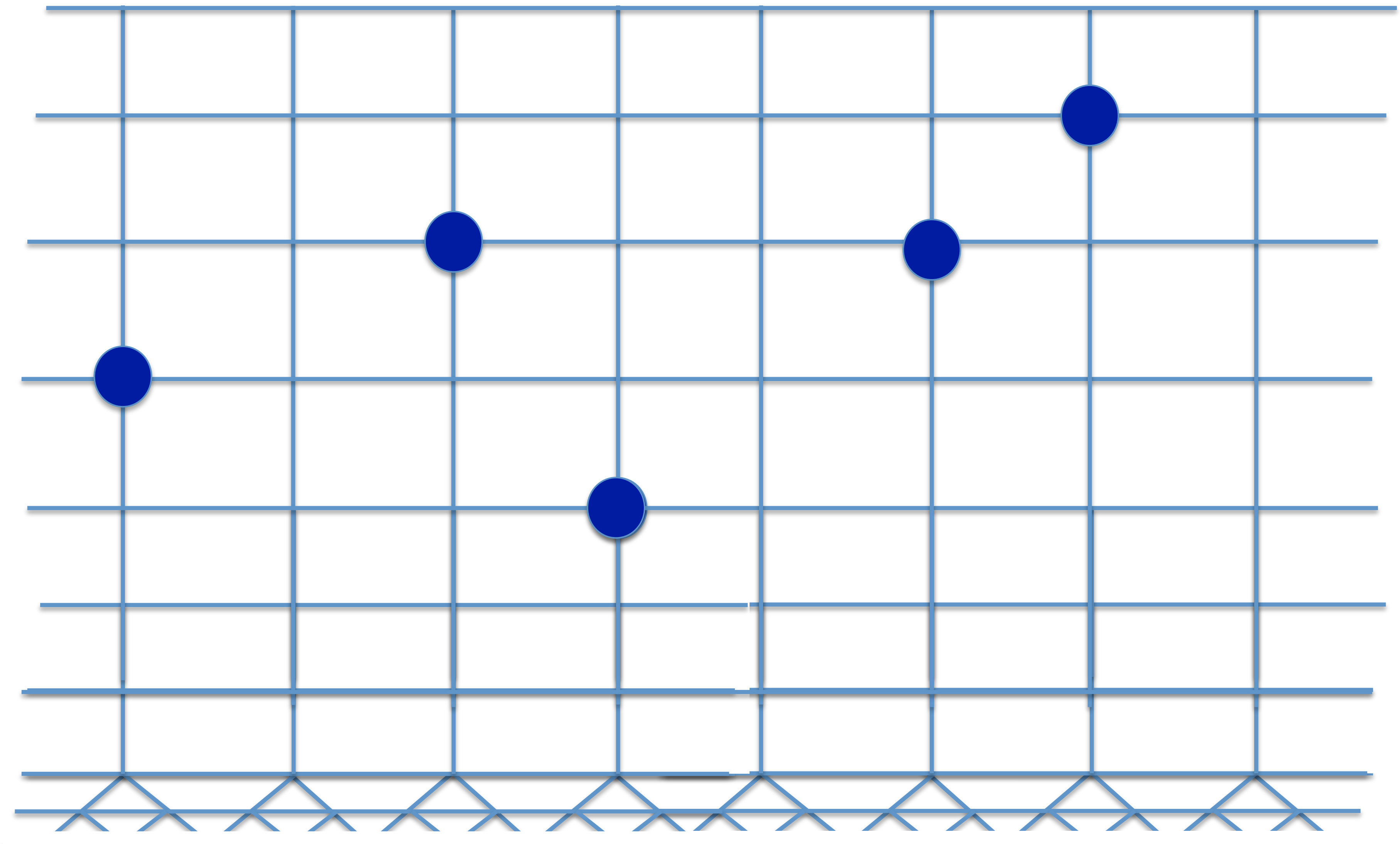
Start with basis of localized, unentangled states
Is a complete basis.



Each member evolves as:







Producing a more generic state

Over complete set of states in the interior. Many changes produce same boundary state.

Tensor networks for generic states ?

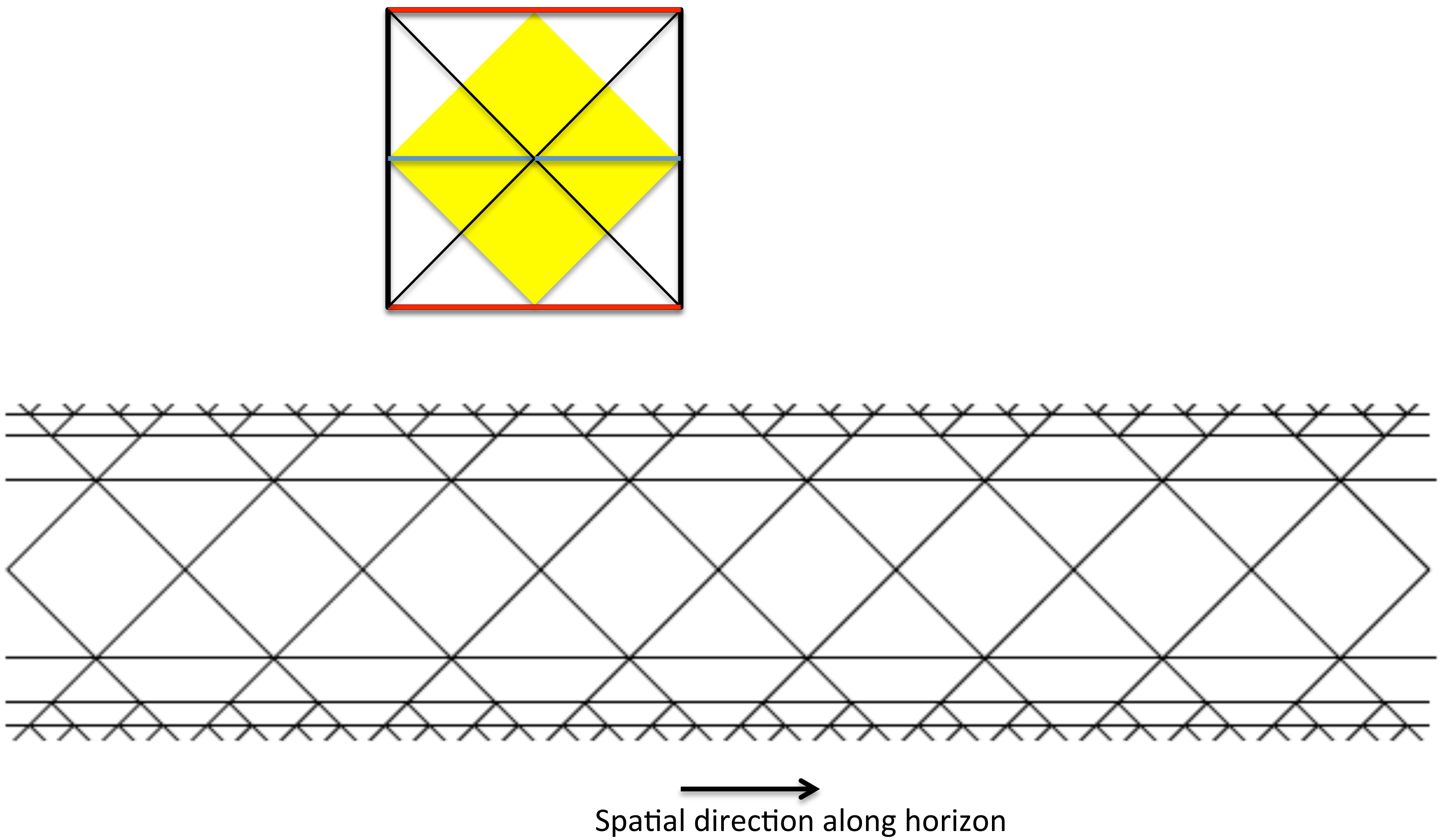
Produce a generic state for the first system by considering a

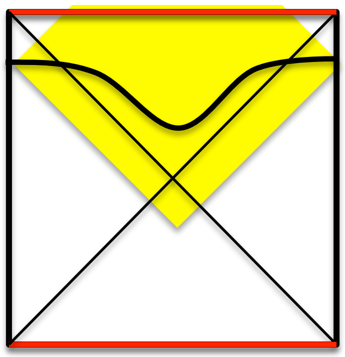
state entangled with a second system.

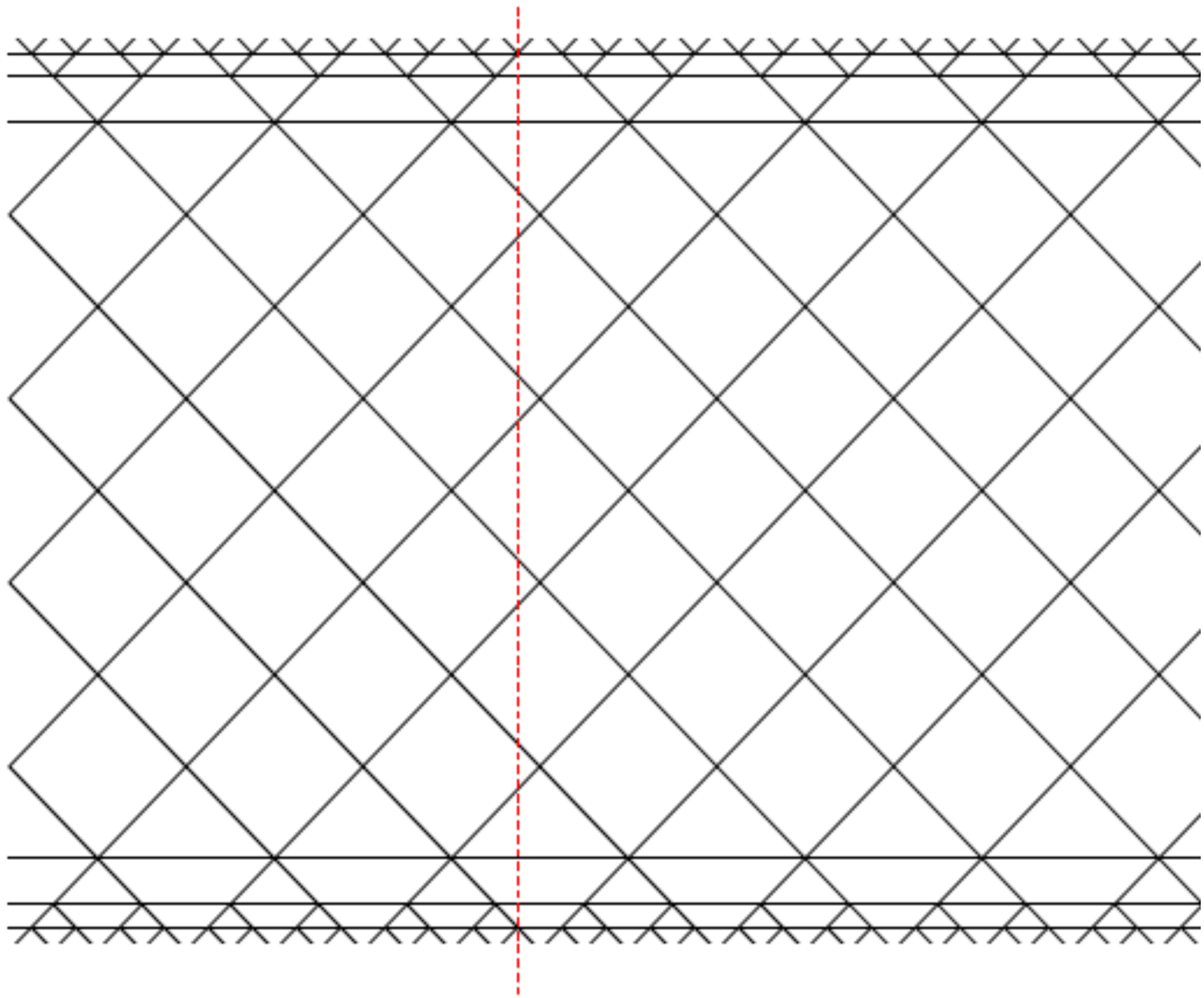
$$|\Psi\rangle = \sum_n e^{-\beta E_n/2} |\bar{n}\rangle |n\rangle$$

Israel, JM,...

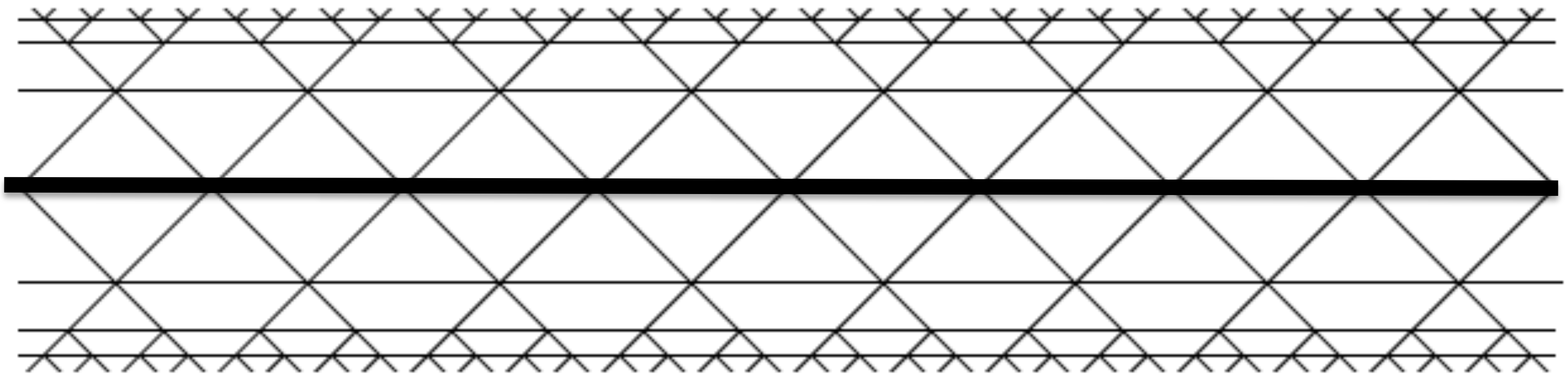
We find a smooth geometry !

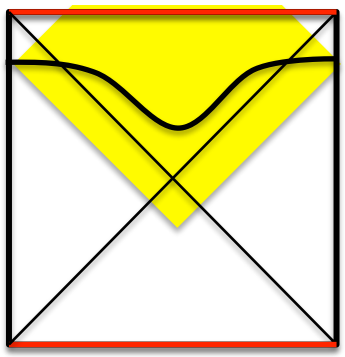

Spatial direction along horizon

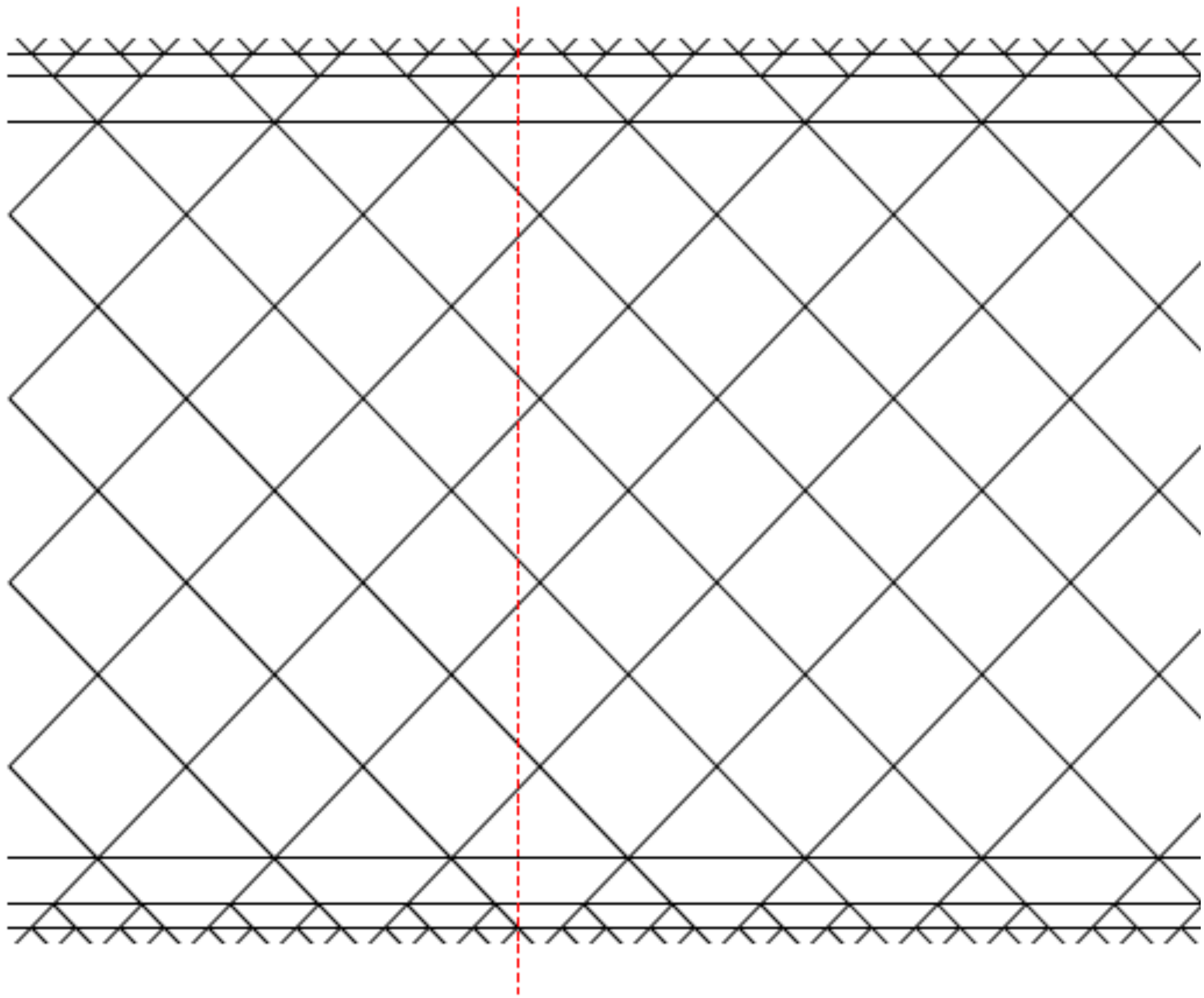




We could also have represented it in this way…

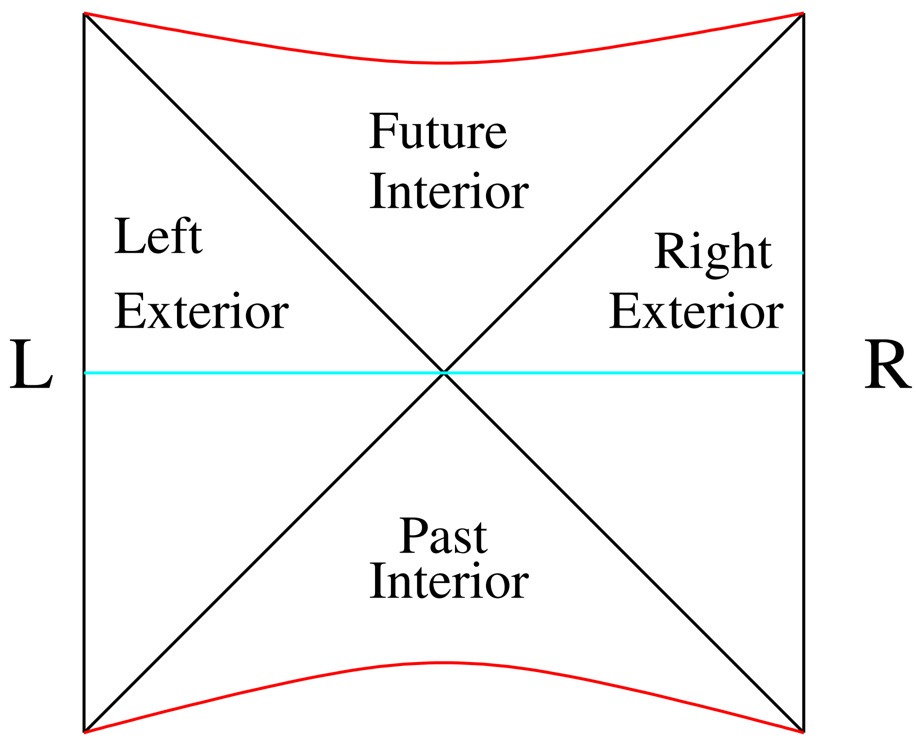






Captures better the entanglement patern.
Seems more similar to the ``nice slices'', which expand. The two horizons moving away…

Eternal AdS black hole



Entangled state in two non-interacting CFT's.

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

ER = EPR

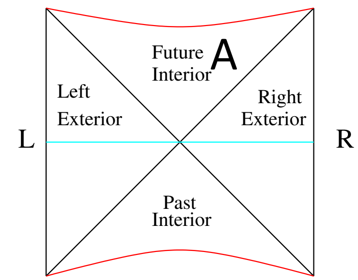
- Wormhole = EPR pair of two black holes in a particular entangled state.

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

- Geometry is a way to codify, or generate the entanglement between the two systems.

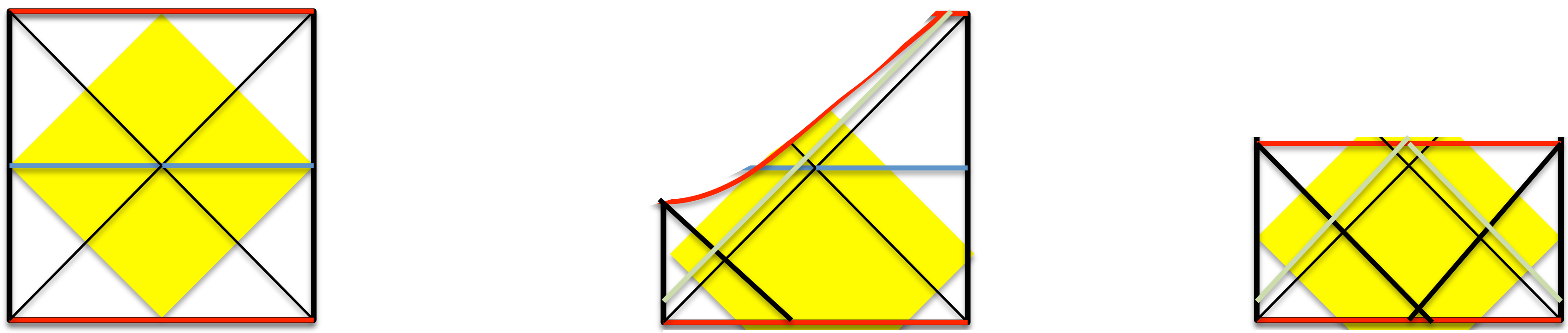
Some Lessons

- Do not confuse left exterior with interior.
- To describe this interior the microstates of one black hole is not enough. One CFT is not enough, we need the second.
- This is not A $=R_B$. We are <u>not</u> identifying the interior with the left exterior.
- The interior is constructed in a subtle way from both the left and right exterior its structure depends on the pattern of entanglement.
- The observer in the interior can receive signals from both, but cannot send arbitrary signals to either of the two exteriors.
- We cannot say that A is some operator in the left Hilbert space. If there were so, an infalling Right-person could send a signal to a Left-person by changing A.



Should the left and right horizons touch ?

- Only for special states.



Shenker Stanford

Not all entangled states have a smooth geometry

$$|\Psi\rangle = \sum_n e^{-\beta E_n/2} |n\rangle|n\rangle|n\rangle|n\rangle$$

GHZ –like state:

$$I = S(A \cup B \cup C) - S(A \cup B) - S(A \cup C) - S(B \cup C) + S(A) + S(B) + S(C) \leq 0$$

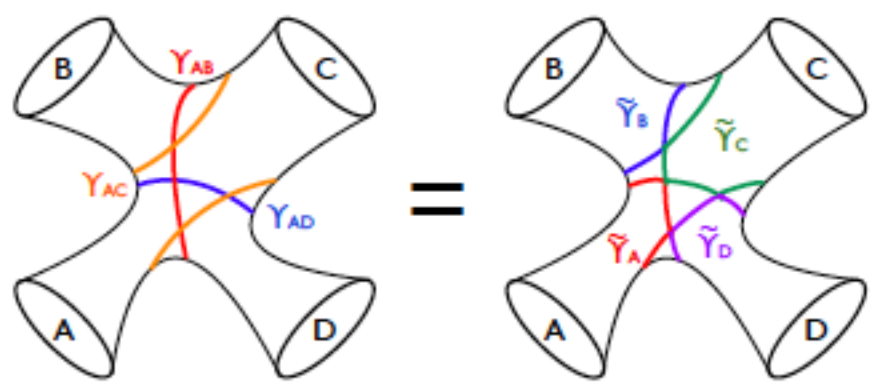
States connected by a smooth geometry obey the following inequality for the triple mutual Information

$$S(A) = S(A \cup B) = S(A \cup B \cup C)$$

Here we have:

$$I > 0$$

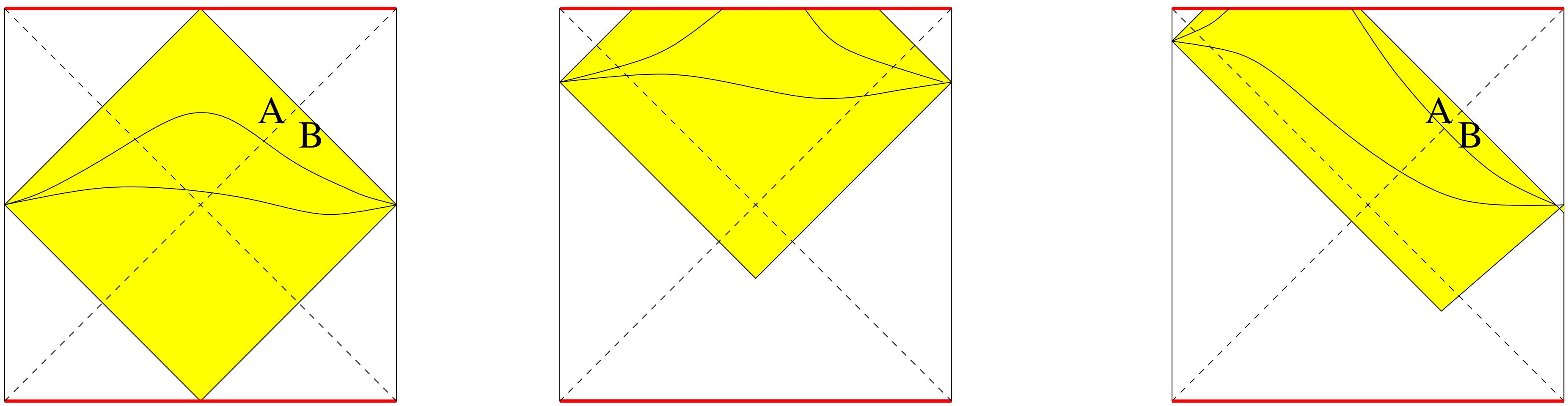
(Hayden, Maloney)
Gharibyan, Penna



Changing the entangled state

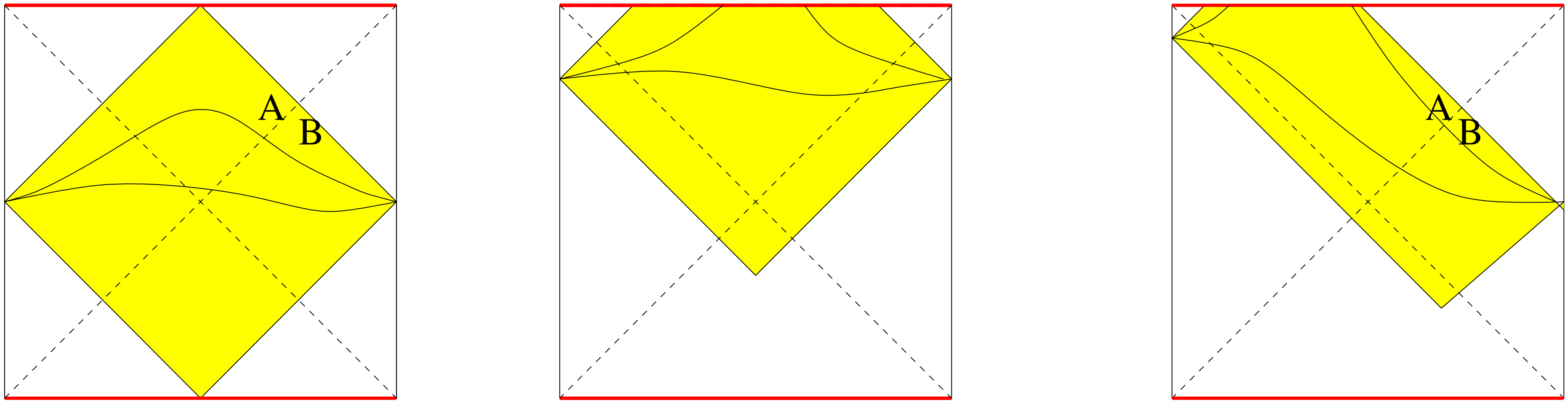
- Time evolution → Different slicings → phases

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

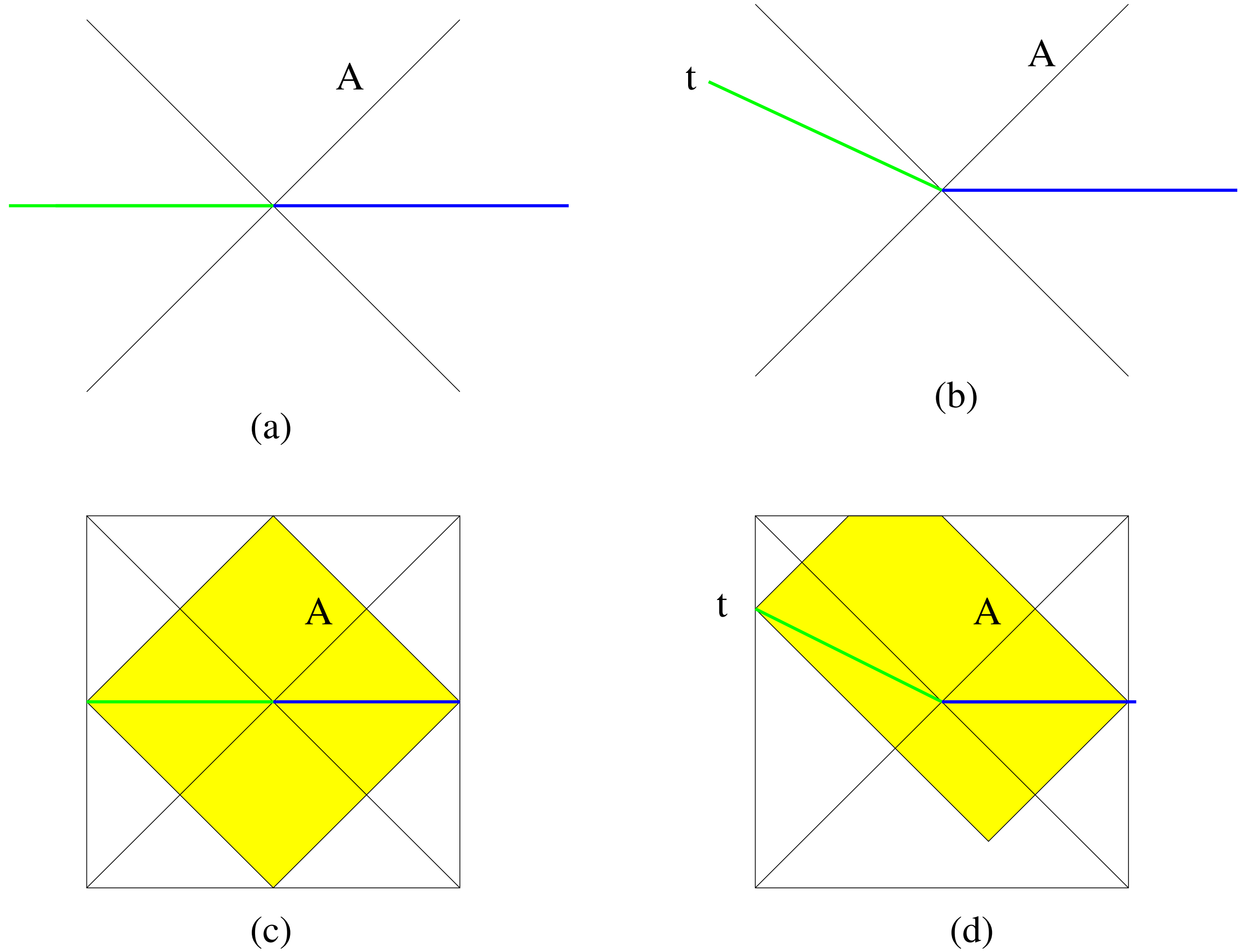


Each time: Whole yellow region, slices related by the Wheeler de Wit equation.

Heemskerk, Marolf, Polchinski, Sully



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

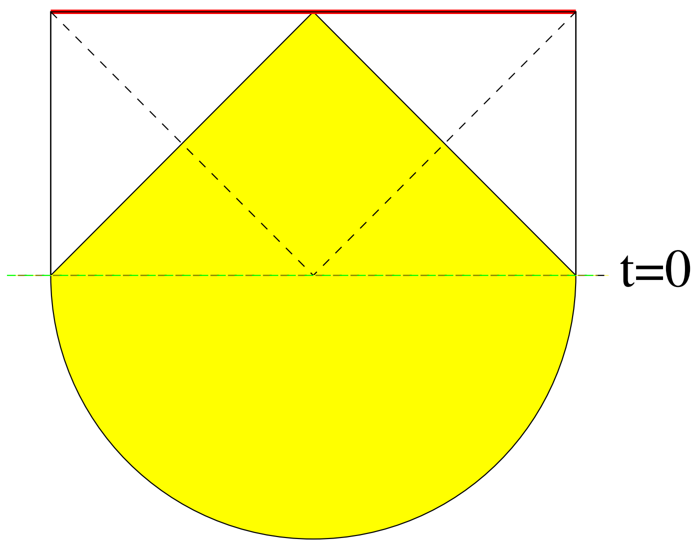


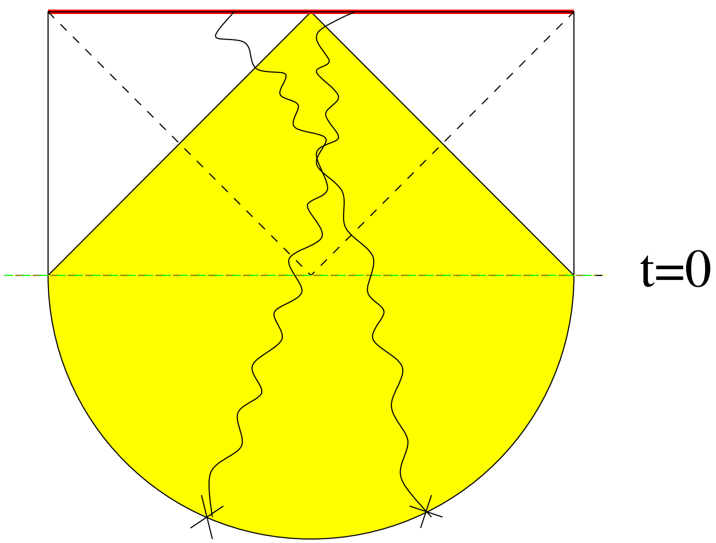
$$U_\theta|0\rangle_M = \exp\left\{\int d\omega e^{-\beta\omega/2} e^{-i\omega t} b^\dagger_{L,\omega} b^\dagger_{R,\omega}\right\}|0\rangle_R \longrightarrow$$ Singular in flat space QFT

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





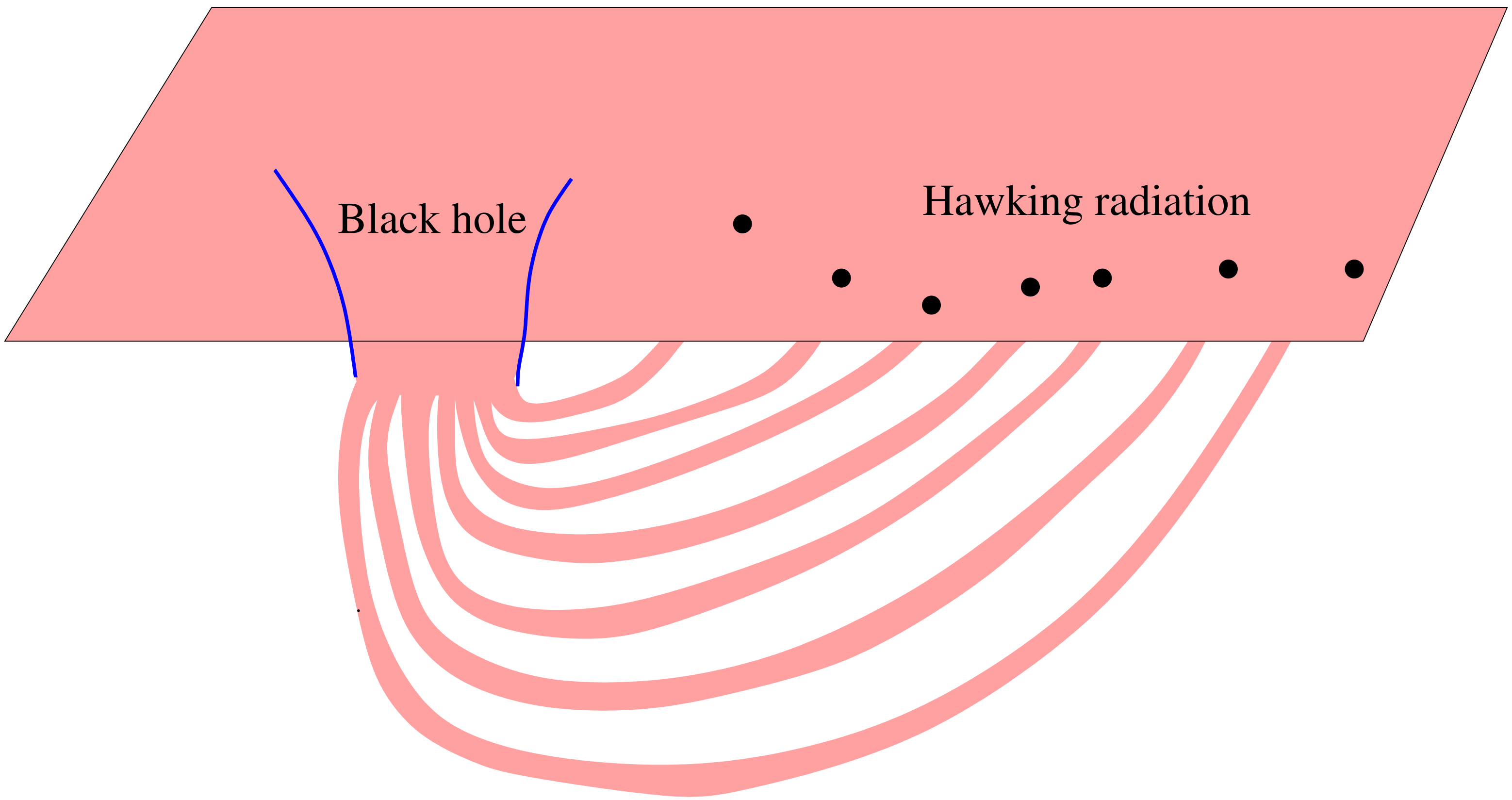
Comments

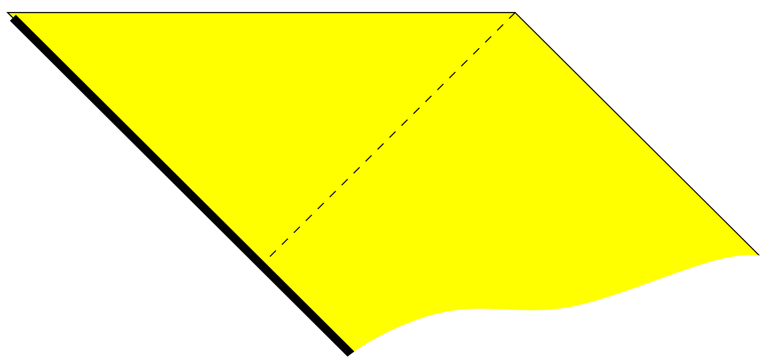
- Entangled states can be connected by a smooth geometry.
- Each entangled state corresponds to a whole region of the bulk, with slices related by the WdW equation.
- Different entangled states correspond to different geometries, or the same geometry plus extra particles.
- We did not make a statement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

- 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).
- 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 ?

Harlow Hayden

Black hole + radiation ?





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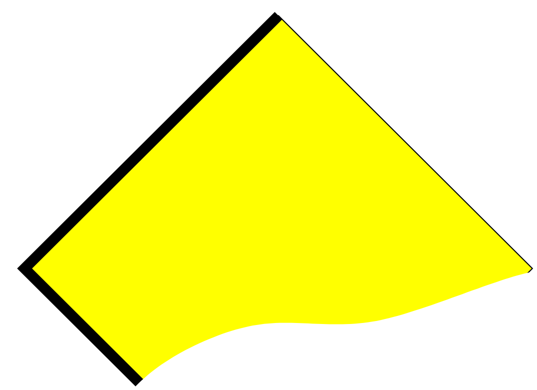

Smooth horizon

Firewall

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 <u>could</u> produce a similar geometric bridge. Its interior could depend on what we do with the radiation.
- We discussed some qualitative similarities between the tensor network description of quantum states and the spacetime description.