# Entanglement, gravity and tensor networks

Review talk

Juan Maldacena

Strings 2016
Beijing

# Motivation

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→ Follow the qubit !

# Outline

- Ancient concepts → quantum entropy

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- Quantum entropy in QFT.

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- Wormholes
- Tensor networks

# Quantum entropy

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- Quantum entropy: $$S = -Tr[\rho \log \rho]$$

- Modular Hamiltonian.

$$K = -\log \rho \ , \qquad \rho = e^{-K}$$

Makes the density matrix look ``thermal''

- Relative entropy

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Measure of the distinguishability of states

- Positivity $S(\rho|\sigma) \geq 0$

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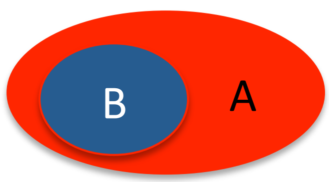
Measure of the distinguishability of states

- Positivity $S(\rho|\sigma) \geq 0$
- Monotonicity



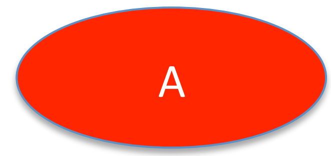

$$B \subset A \longrightarrow \quad S(\rho_B|\sigma_B) \leq S(\rho_A|\sigma_A)$$

Looking at less, we can distinguish less

# In quantum field theory

# Entropy in QFT

- Quantum entropy of subregions.



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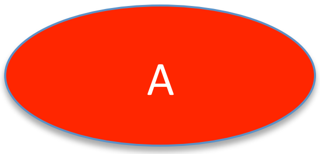


- Divergent

$$S(A) = \frac{\text{Area}}{\epsilon^2} + \cdots + \text{Finite}$$

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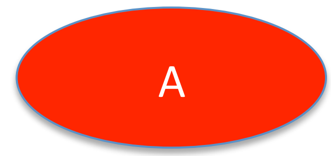


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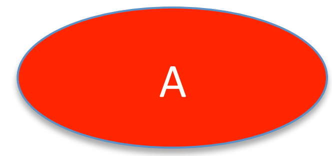



- Quantum entropy of subregions.

- Divergent

$$S(A) = \frac{\text{Area}}{\epsilon^2} + \cdots + \text{Finite}$$

- Interesting: Finite results.

- Recall the QFT is a ``target’’ for what we should approximately get in the bulk.

# Half space in relativistic QFT

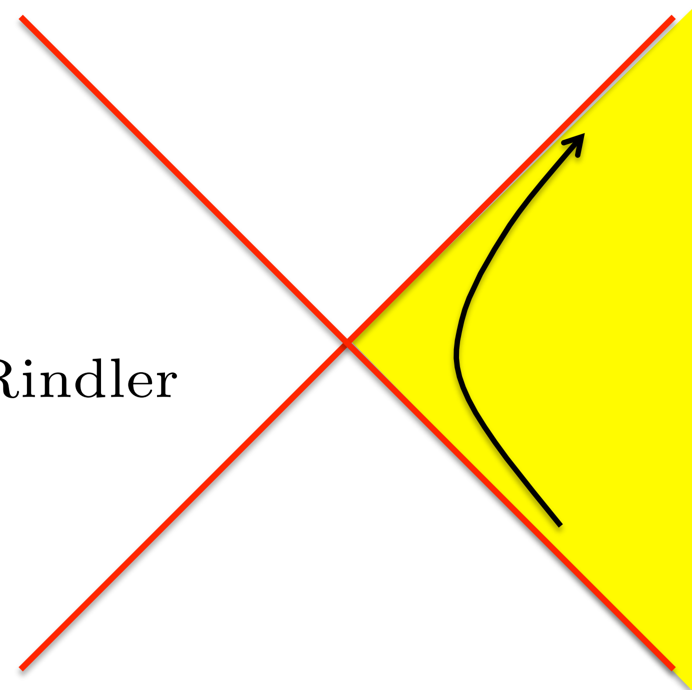
Bisognano Wichmann, Unruh

- Half space → Thermal in Rindler space
- Consequence of the Lorentz symmetry

$$\rho = e^{-2\pi B}$$

$$B = \int_0^\infty d^{D-2}y dx x T_{00} = E_{\rm Rindler}$$

Local
Energy for accelerating observer



# Entanglement → useful results in QFT

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- Bekenstein-Casini bound :

Sorkin
Marolf, Minic Ross
Casini

$$S(\rho|\rho_v) \geq 0 \longrightarrow \Delta S \leq 2\pi\langle \Delta B\rangle = 2\pi\langle \Delta E_R\rangle$$

Relative entropy is UV finite

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- c and f theorems (in 1+1 and <u>2+1</u> dimensions)

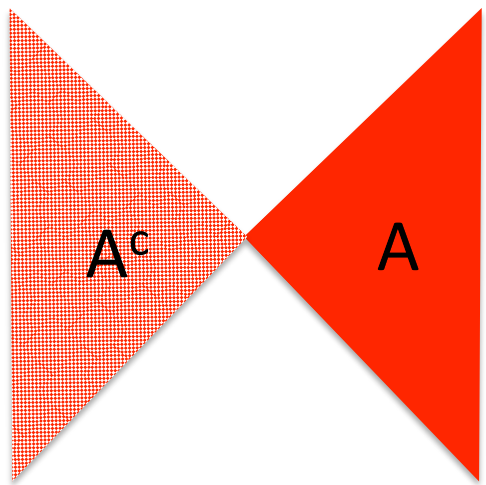
Casini Huerta

- Integrated null energy condition (integrated along a null line)

$$\langle \int dx^- T_{--}(x^-, x^+, \vec{y}) \rangle \geq 0$$

Faulkner, Leigh, Parrikar, Wang

# Idea of the argument



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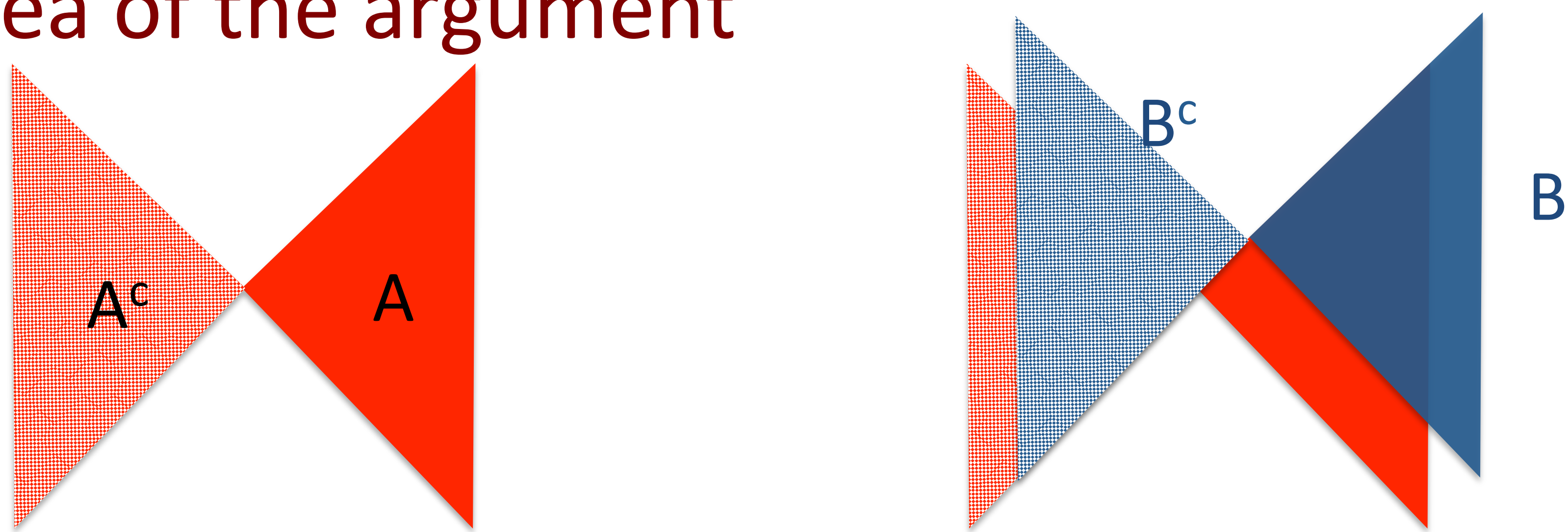

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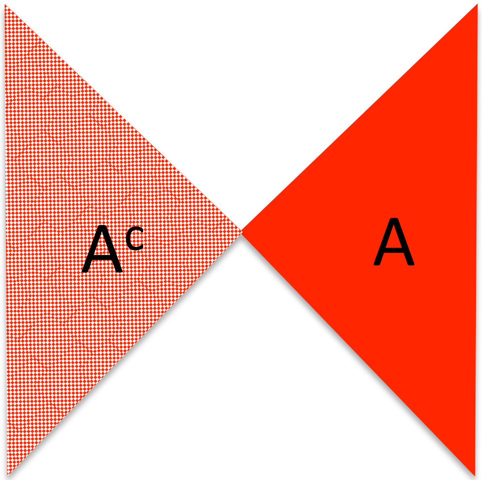


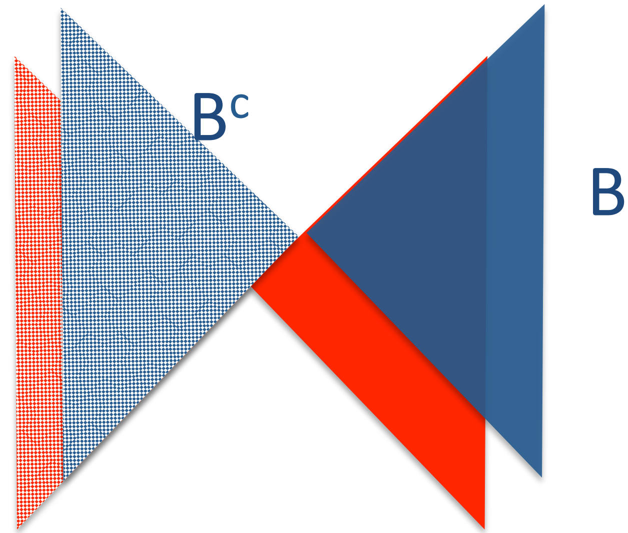


$$B \subset A$$
$$A^c \subset B^c$$

$\longrightarrow$

$$S(\rho_B, \sigma_B) \leq S(\rho_A, \sigma_A)$$
$$S(\rho_{A^c} | \sigma_{A^c}) \leq S(\rho_{B^c} | \sigma_{B^c})$$

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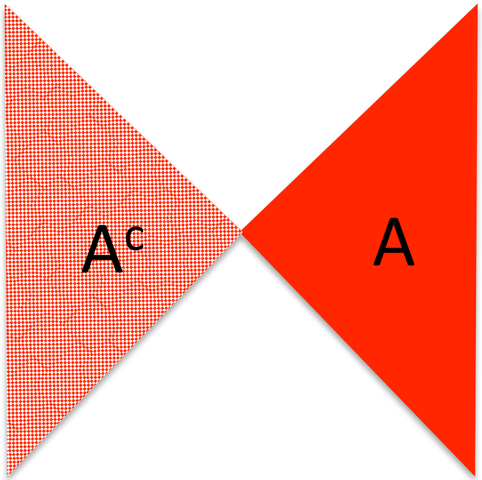


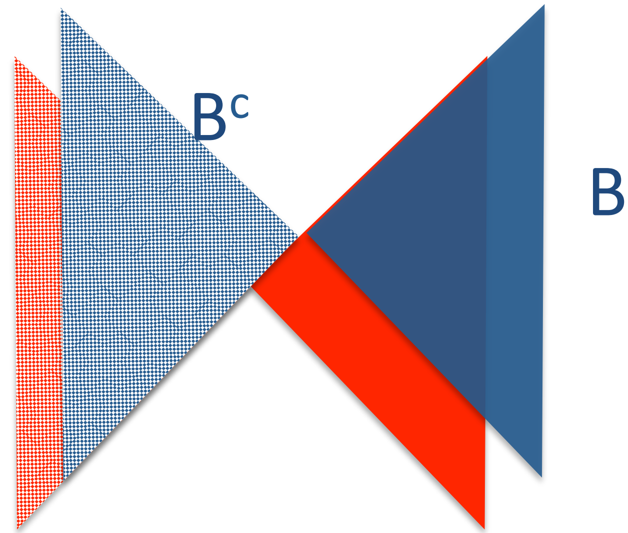


$$B \subset A \qquad\qquad S(\rho_B, \sigma_B) \leq S(\rho_A, \sigma_A)$$

$$A^c \subset B^c \longrightarrow S(\rho_{A^c}|\sigma_{A^c}) \leq S(\rho_{B^c}|\sigma_{B^c})$$

$$\longrightarrow \quad \langle K_B \rangle - \langle K_{B^c} \rangle \leq \langle K_A \rangle - \langle K_{A^c} \rangle$$

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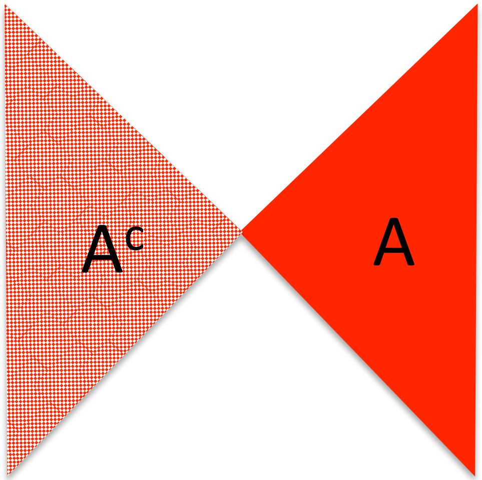


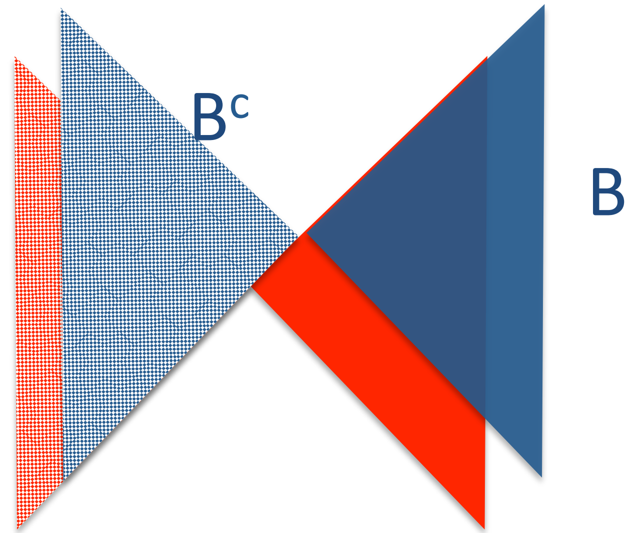


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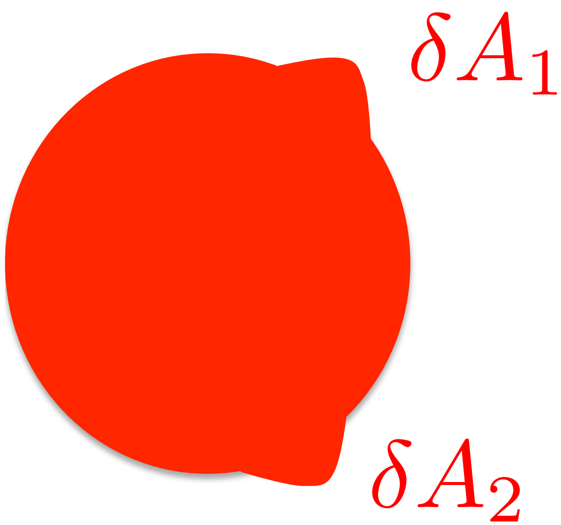
$$\longrightarrow \quad \langle K_B \rangle - \langle K_{B^c} \rangle \leq \langle K_A \rangle - \langle K_{A^c} \rangle$$

$$\longrightarrow \quad 0 \leq \langle B_A \rangle - \langle B_B \rangle = -\langle P_+ \rangle \Delta X^+$$

# Real arguments uses…

# Shape dependence of the entropy




Small deformation from a spherical surface.

Leading quadratic dependence on the deformation:

Faulkner, Leigh, Parrikar

Nozaki, Numasawa, Prudenziati, Takayanagi, Miao, Witczak-Krempa, Bueno, Myers, Rosenhaus, Smolkin, Mezei, Allais, Bianchi, Meineri, Balakrishnan, Dutta, Carmi, Lewkowycz, Perlmutter, Lee, Mcgough, Safdi, Dowker, Chapman, Bianchi, Galante, Bhattacharya, Hubeny, Rangamani, Czech, Lamprou McCandish, Sully, Klebanov, Pufu, Nishioka, Elvang, Hadjiantonis, Fonda, Seminara, Tonni…

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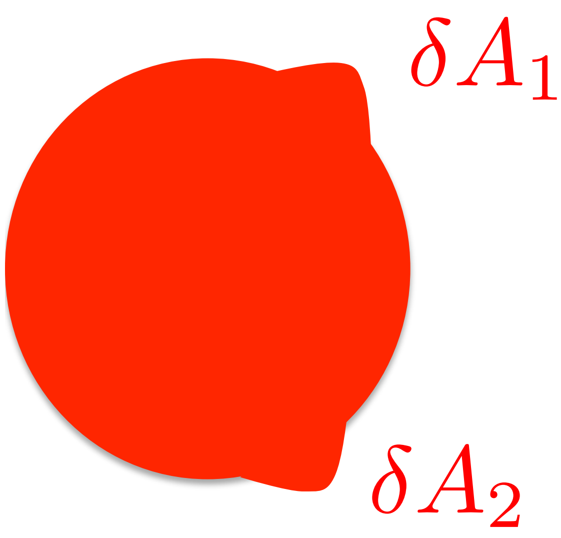


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Leading quadratic dependence on the deformation:

Fixed by conformal symmetry and $C_T$ , the vacuum two point function of the stress tensor.

Idea: Changing shape → changing metric → insertions of stress tensor

Faulkner, Leigh, Parrikar

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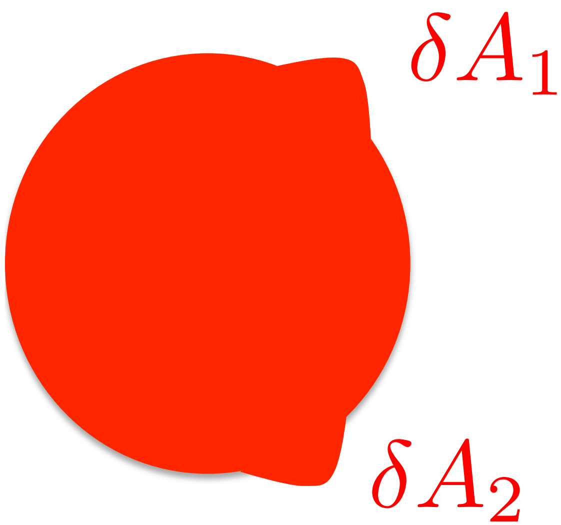


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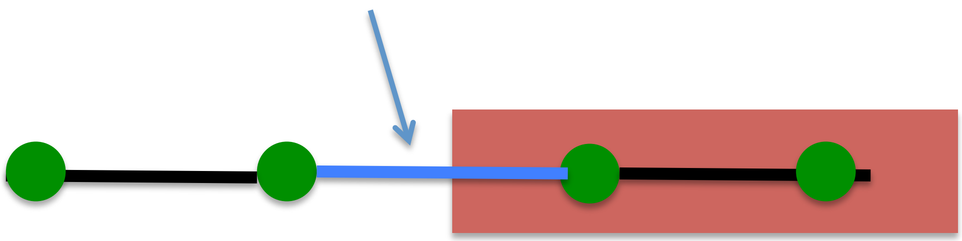
Faulkner, Leigh, Parrikar

Universality of corner entropy.

Nozaki, Numasawa, Prudenziati, Takayanagi, Miao, Witczak-Krempa, Bueno, Myers, Rosenhaus, Smolkin, Mezei, Allais, Bianchi, Meineri, Balakrishnan, Dutta, Carmi, Lewkowycz, Perlmutter, Lee, Mcgough, Safdi, Dowker, Chapman, Bianchi, Galante, Bhattacharya, Hubeny, Rangamani, Czech, Lamprou McCandish, Sully, Klebanov, Pufu, Nishioka, Elvang, Hadjiantonis, Fonda, Seminara, Tonni…

# Gauge fields and Edge Modes

Center variables = Electric field on the separating surface.



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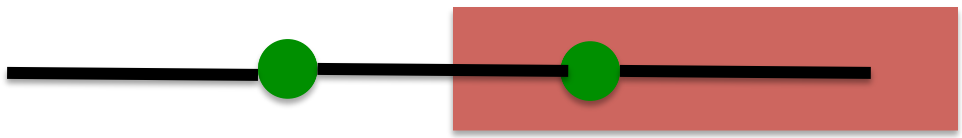

Donelly Wall Radicevic
Casini Huerta Rosabal
Hawking, Strominger, Perry
Harlow

$$H = \sum_q H_L^q \times H_R^{-q}$$

Splitting of Hilbert space in each charge sector.

Shannon term

$$\rho \to p_q, \rho_q \quad , \qquad S = \sum_q -p_q Tr[\rho_q \log \rho_q] - p_q \log p_q$$

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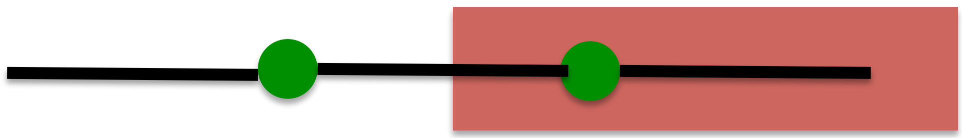

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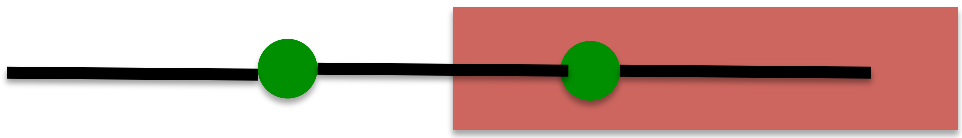
Donelly Freidel

Expect a similar story for gravity: Electric field → geometry of the surface

# Gauge fields and Edge Modes



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Consequences of this for UV finite quantities remain to be seen…

# Quantum entropy in semiclassical gravity

# Results in semiclassical gravity

- QFT in a gravitational background.

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See eg. Sen et al

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$$S_{gen} = \frac{\text{Area}}{4G_N} + S_{ent}$$

Bombelli, Koul, Lee, Sorkin
Srednicki
Callan Wilzcek Larsen Holzey
Susskind Uglum
Solodhukin, Frolov, Fursaev …

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UV finite

- Second law of thermodynamics, S increases
  (monotonicity of relative entropy)

Hawking, Wall

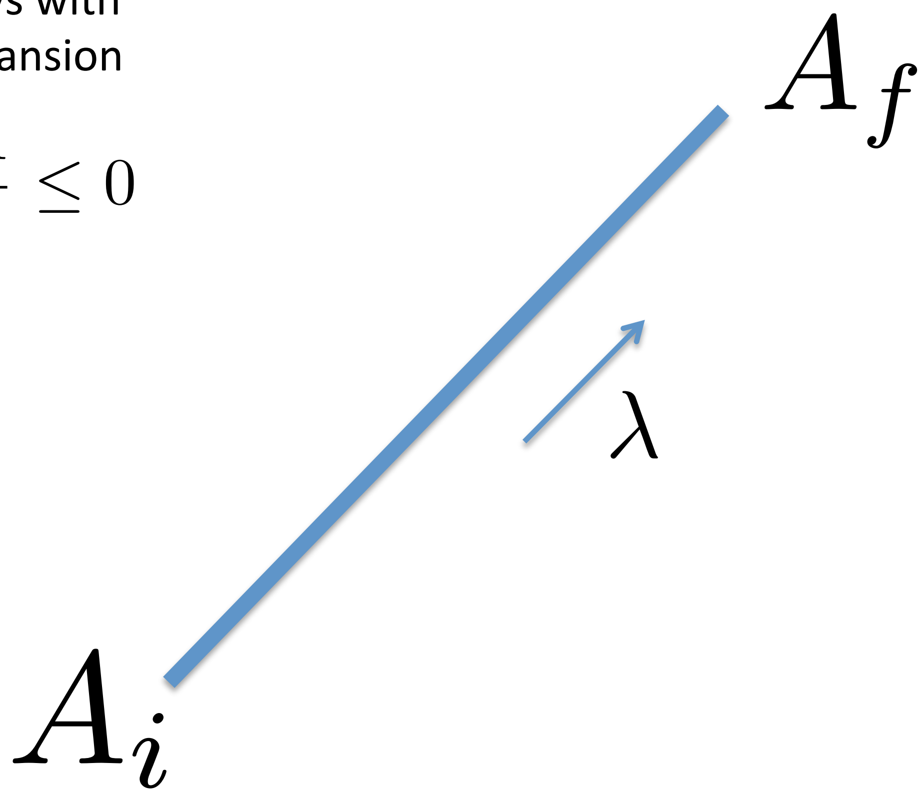
# Results in semiclassical gravity

- Better understanding of the quantum Bousso bound.

# Classical Bousso bound

Set of null rays with negative expansion

$$\theta = \frac{1}{A}\frac{dA}{d\lambda} \leq 0$$



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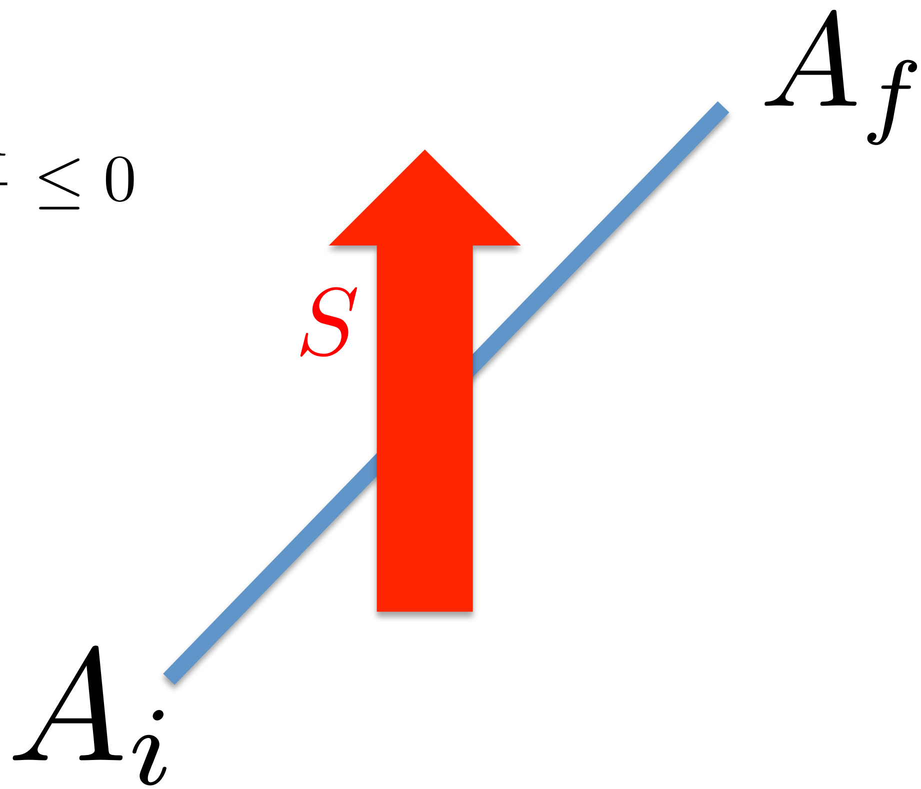



$$S \leq \frac{A_i - A_f}{4G_N}$$

Bousso
Flanagan, Marolf, Wald

# Quantum Bousso Bound

- 2 versions

1) Bousso, Casini, Fischer, JM

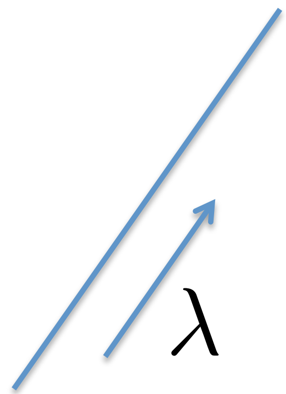
2) Strominger, Thompson
   Bousso, Fischer, Leichenauer,
   Wall + Koeller

# Quantum Bousso Bound

- Quantum focusing conjecture

Strominger, Thompson
Bousso, Fischer, Leichenauer,
Wall + Koeller

- Classical focusing theorem




$$\theta \equiv \frac{1}{A}\frac{dA}{d\lambda}$$

$$\frac{d\theta}{d\lambda} \leq 0 \ , \qquad \text{since} \quad T_{\lambda\lambda} \geq 0$$

# Quantum Focusing conjecture

- Define the ``quantum expansion''

$$\Theta \equiv \frac{1}{A}\frac{dS_{gen}}{d\lambda}$$

Bousso, Fischer, Leichenauer, Wall + Koeller

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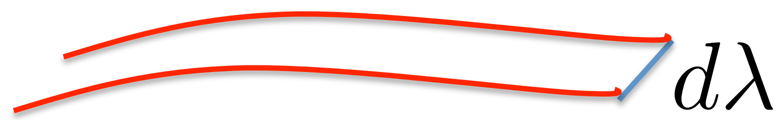
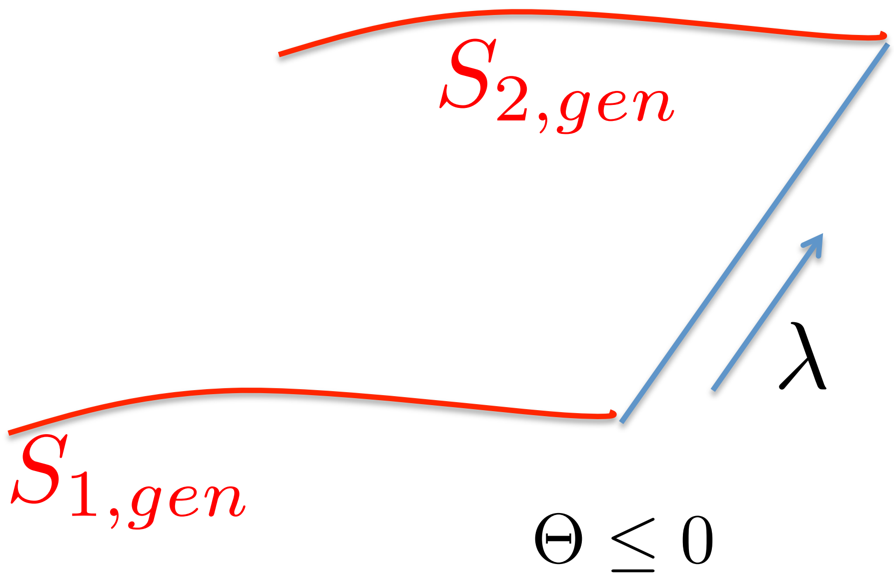



- Conjecture

$$\boxed{\frac{d\Theta}{d\lambda} \leq 0}$$

# Quantum Focusing conjecture

Bousso, Fischer, Leichenauer, Wall + Koeller

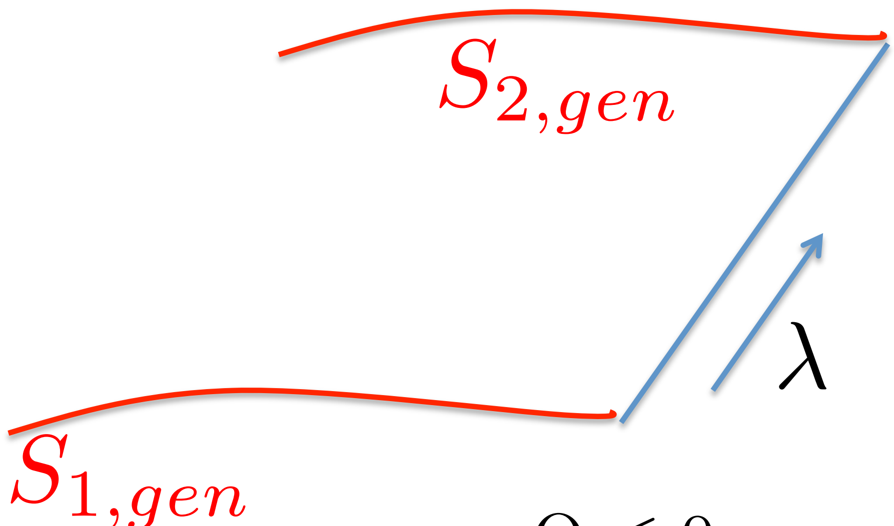



$$\Longrightarrow \Delta S \leq \frac{\Delta A}{4G_N}$$

Classical Bousso bound

# Quantum Focusing conjecture

Bousso, Fischer, Leichenauer, Wall + Koeller




$$\Theta \leq 0$$

$$\Longrightarrow \Delta S \leq \frac{\Delta A}{4G_N}$$

Classical Bousso bound

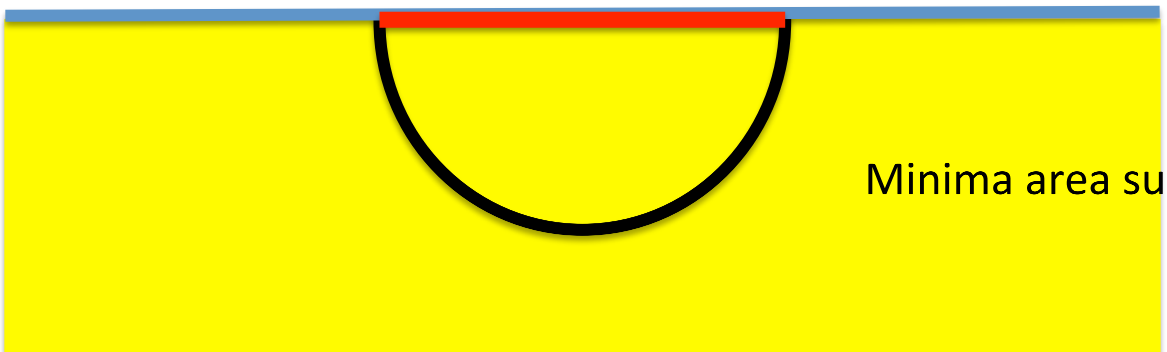
Weak gravity:

$$\langle T_{--} \rangle \geq \frac{1}{2\pi} \lim_{A \to 0} \frac{S''_{out}}{A}$$

Quantum null energy condition. Proven in some cases.

# Entanglement and holography

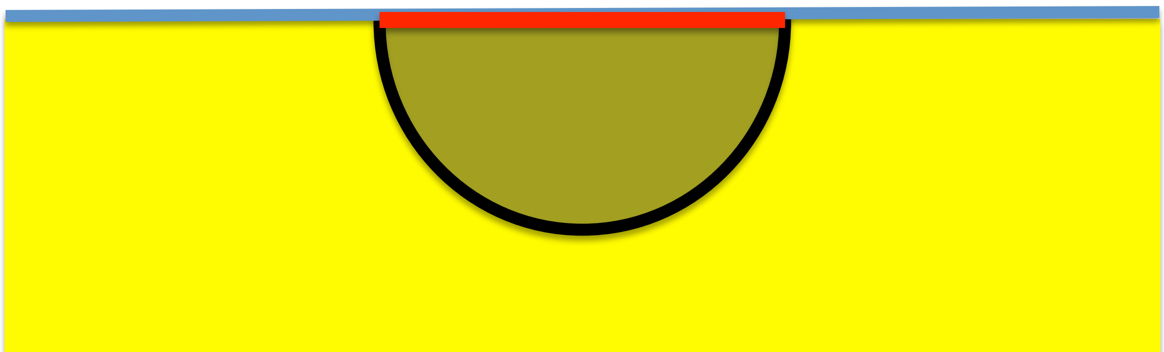
# Entanglement in theories with gravity duals




$$S = \frac{(\text{Area})_{\text{min}}}{4G_N}$$

Ryu Takayanagi
Hubeny, Rangamani, Takayangi

# Entanglement in theories with gravity duals



$$S = \frac{(\text{Area})_{\min} + \alpha'(\text{curvature}) + \cdots}{4G_N} + S_{\text{bulk}} + o(G_N)$$

Wald, Myers, Jacobson, … ,Dong

Faulkner, Lewkowicz, JM
Barrella, Dong, Hartnoll, Martin

# Relative entropy

Lashkari, Van Raamsdonk
Jafferis, Lewkowycz, JM, Suh

$$S(\rho, \sigma) = S_{\text{bulk}}(\rho, \sigma)$$

$$K = \frac{A}{4G_N} + K_{\text{bulk}}$$

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Lashkari, Van Raamsdonk
Jafferis, Lewkowycz, JM, Suh

$$S(\rho, \sigma) = S_{\text{bulk}}(\rho, \sigma)$$

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Two points of view:

1- Only holds for restricted semiclassical states…

2 -All dof are visible in the bulk (cutoff independent indication that all of black hole entropy comes from the atmosphere)

# Qualitative idea for black hole entropy

$$S_{gen} = \frac{\text{Area}}{4G_N} + S_{ent}$$

As ε → 0 , area term goes to zero and all entropy is entanglement.

Is all of black hole entropy just bulk entanglement entropy, with a suitable cutoff ?

This happens in ``induced gravity theories'' (not well defined)…

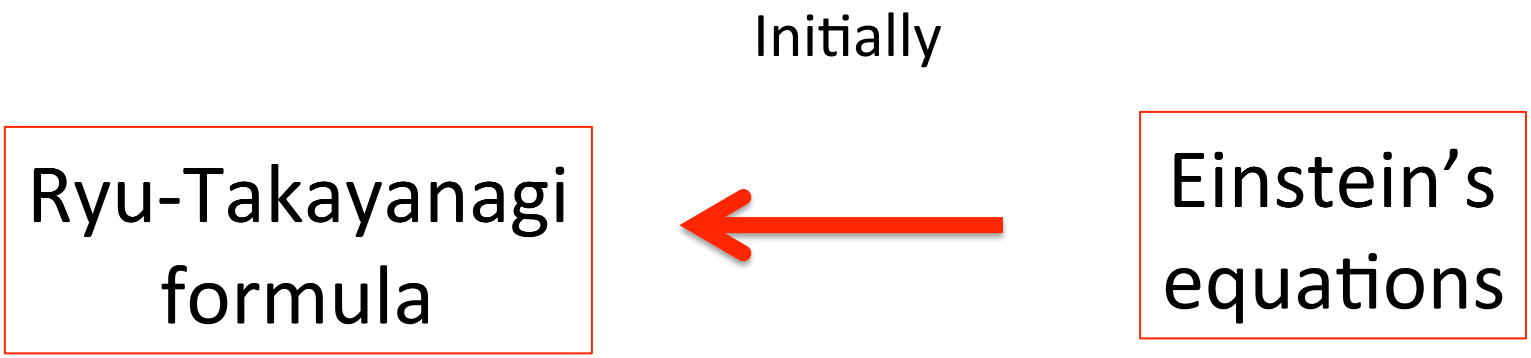
Conservative : do not mix the leading order with the subleading order…

Dreamer: figure out in what sense this is true….

$$S(\rho, \sigma) = S_{\rm bulk}(\rho, \sigma)$$

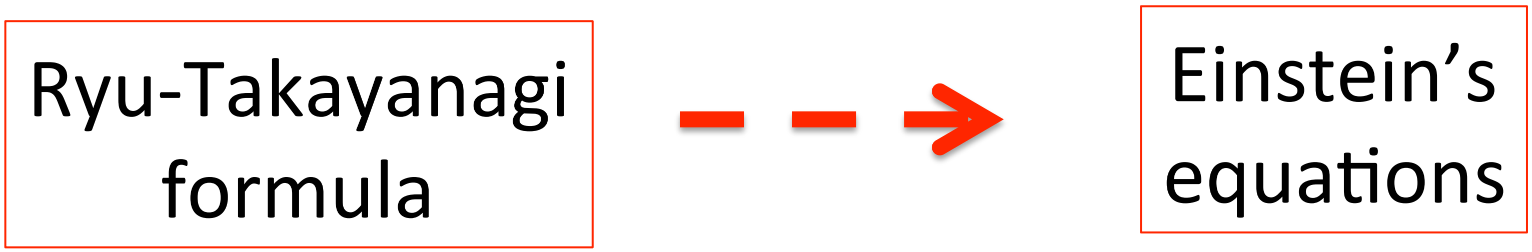
Is a cutoff independent indication of this.

# Einstein equations from the entanglement formula



# Einstein equations from the entanglement formula

Can go in the other direction

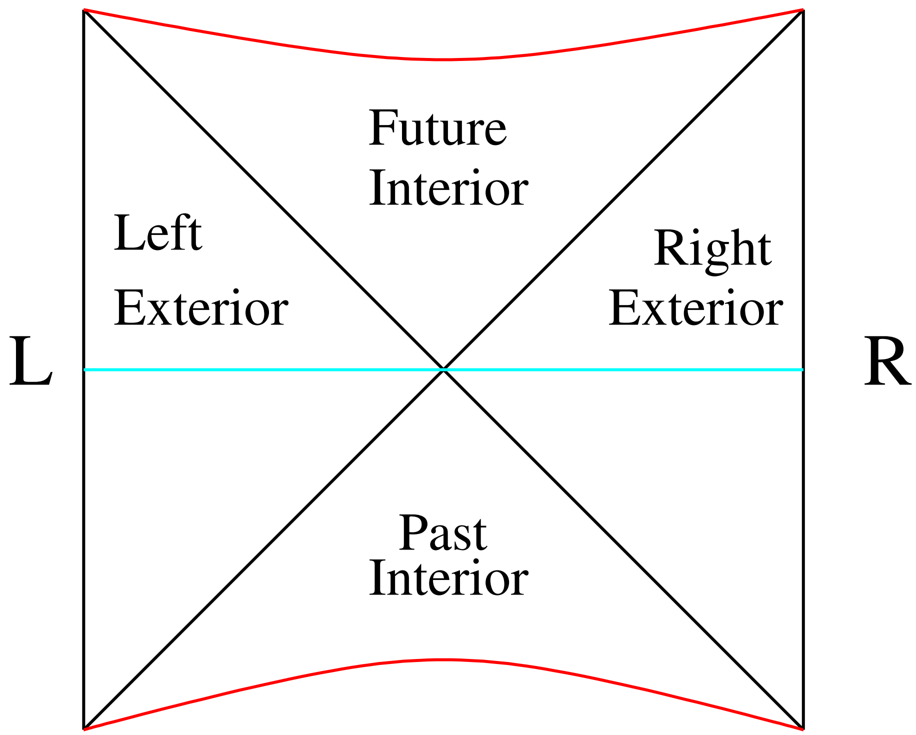



Lashkari, McDermott, Van Raamsdonk, Faulkner, Guica, Hartman, Myers, Swingle
Jacobson

(not in full generality yet…)

# Wormholes

# Wormholes and entangled states




Full Schwarzschild-AdS Geometry

=

Entangled state in two non-interacting CFT's.

Israel
JM

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

# Wormhole physics

- Integrated null energy condition → no signal propagation. (recall recent entanglement based proof)

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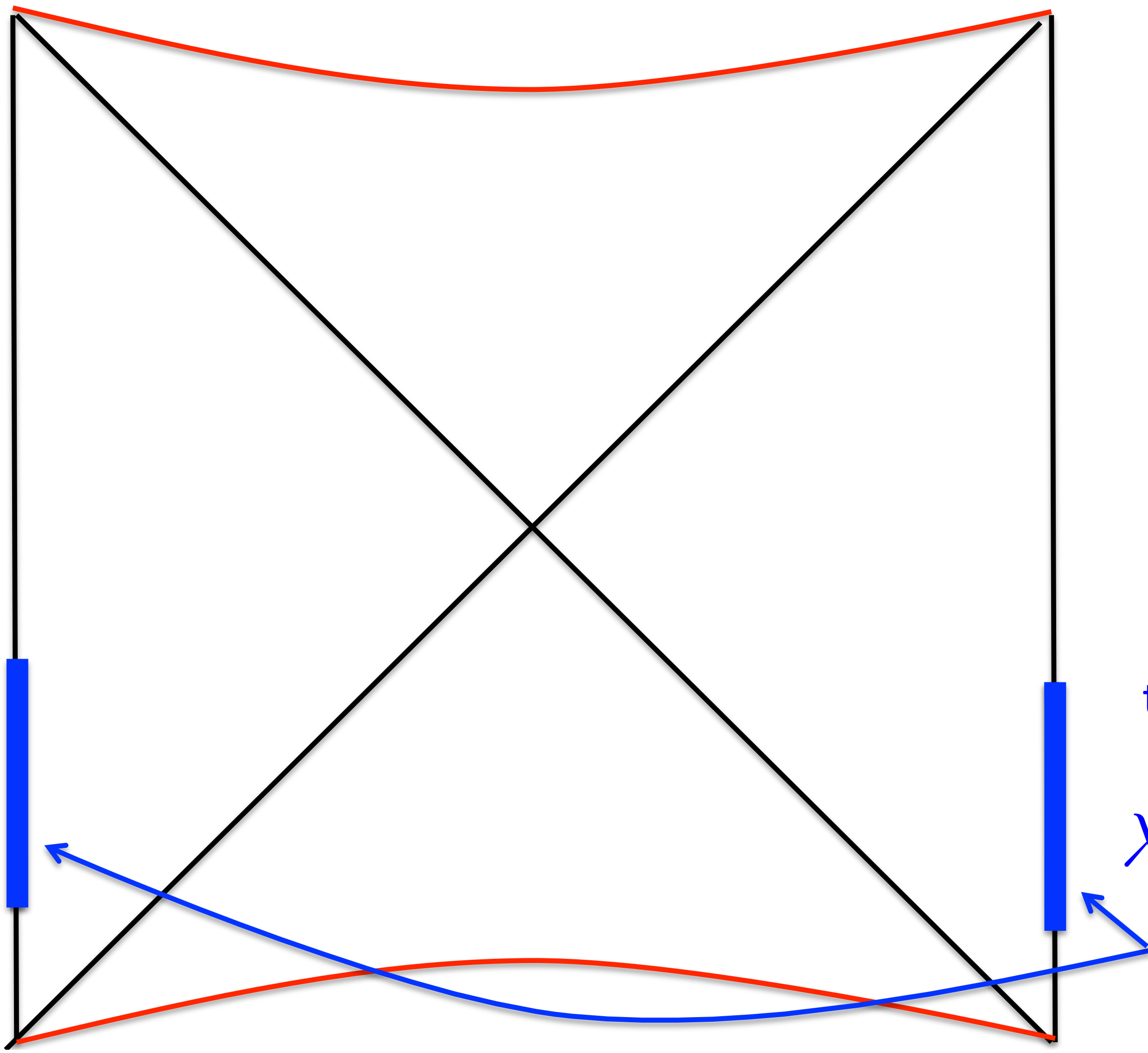
- Allowing interactions between the two sides → can have negative energy → can get signal propagation.

Gao Jafferis Wall

# Wormholes and entangled states

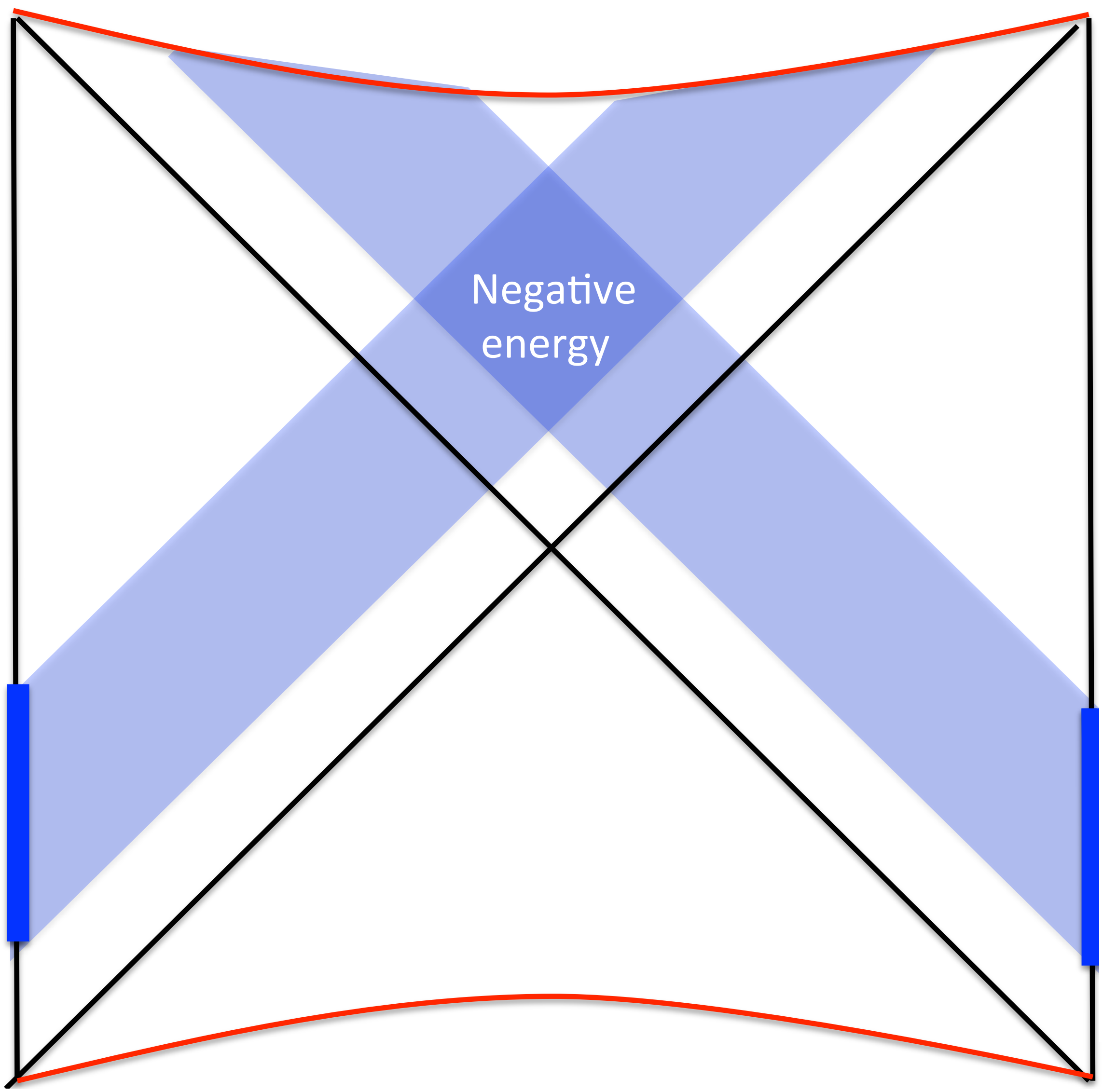
Gao Jafferis Wall



Interaction between the two sides for some time.

$$\lambda \int dt O_L(t) O_R(t)$$

# Wormholes and entangled states




Gao Jafferis Wall

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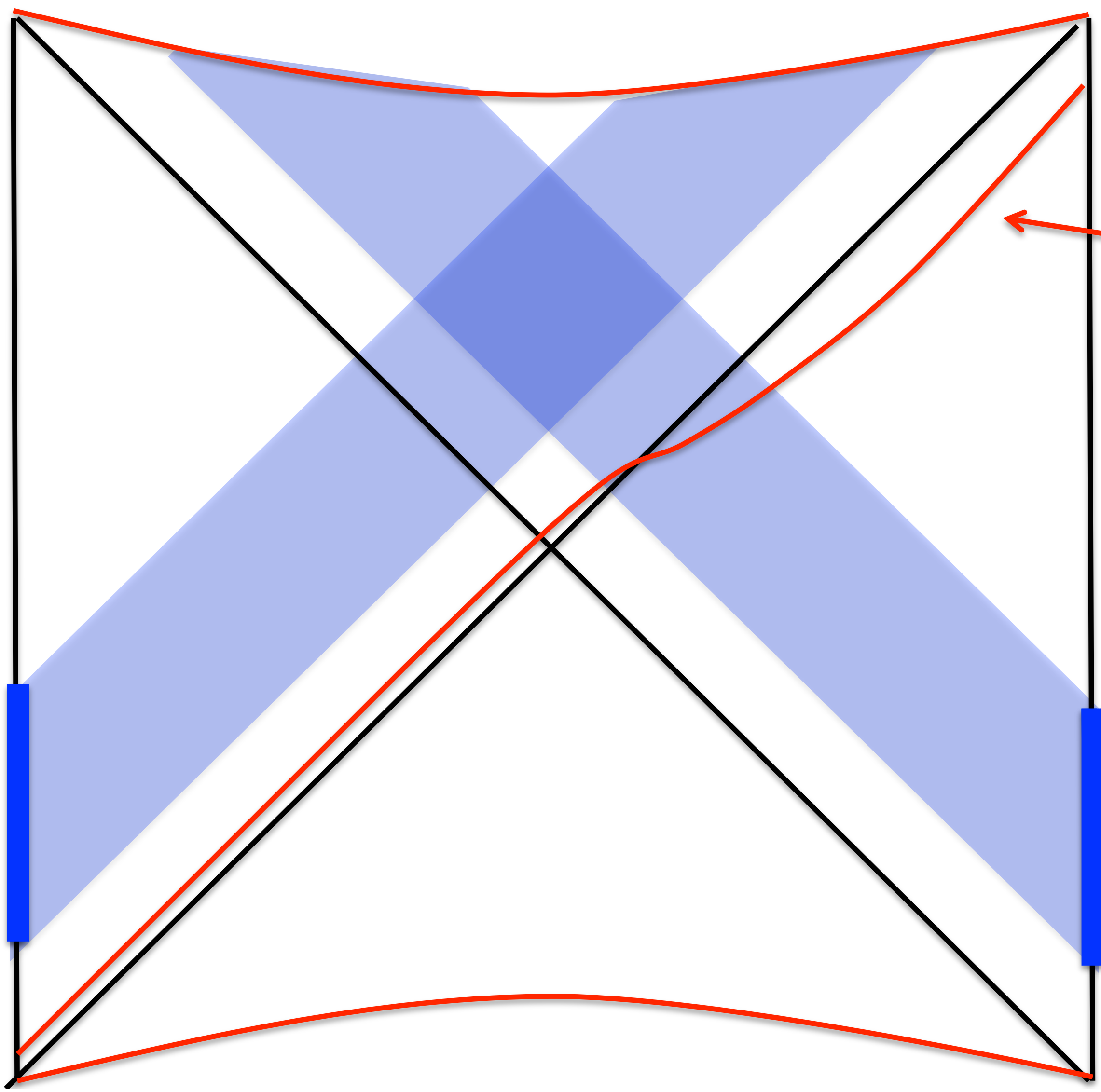


Gao Jafferis

Signal through the wormhole

Interaction between the two sides for some time.

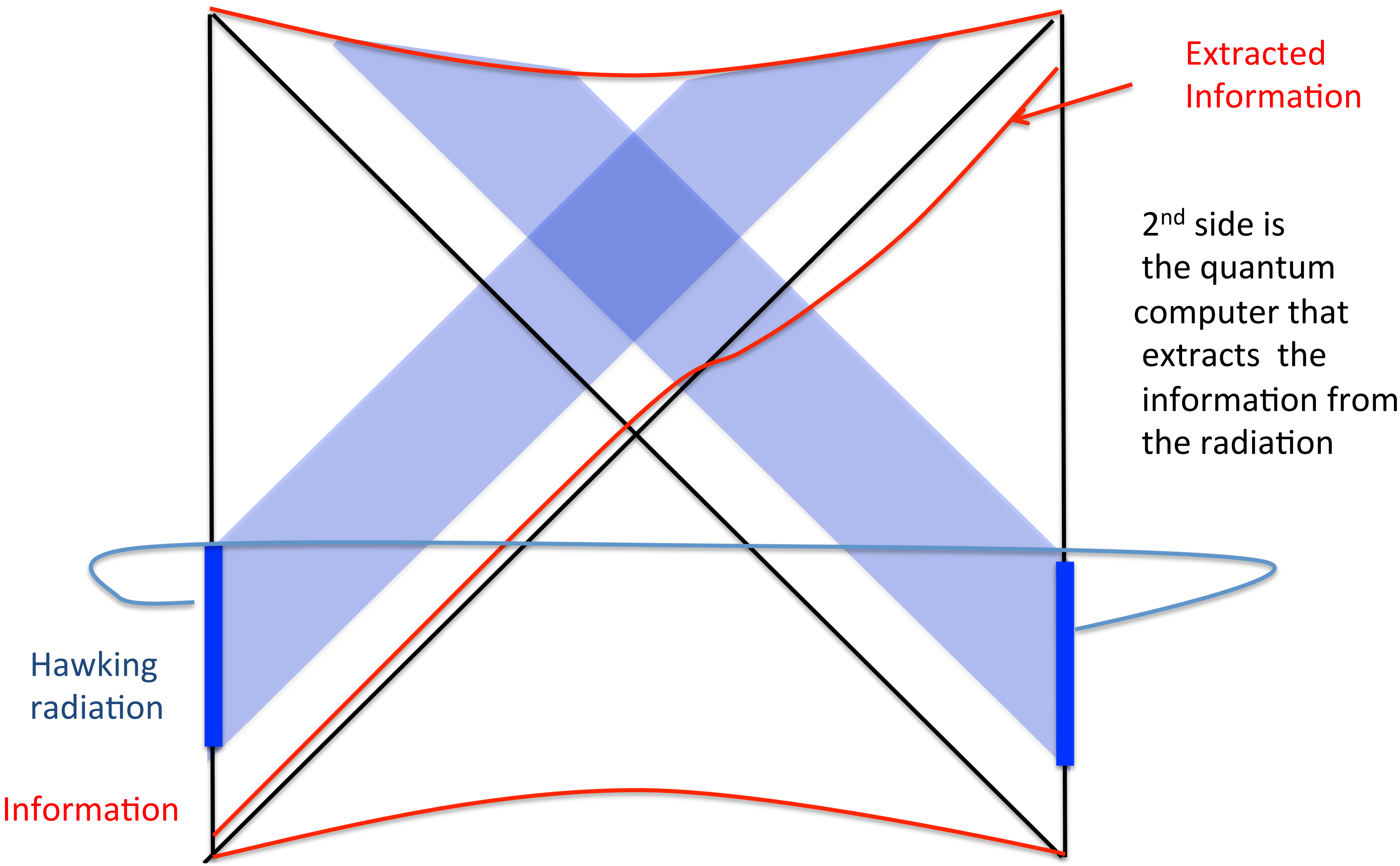
$$\lambda \int dt O_L(t) O_R(t)$$

- Connected with “black holes as mirrors”

Hayden Preskill

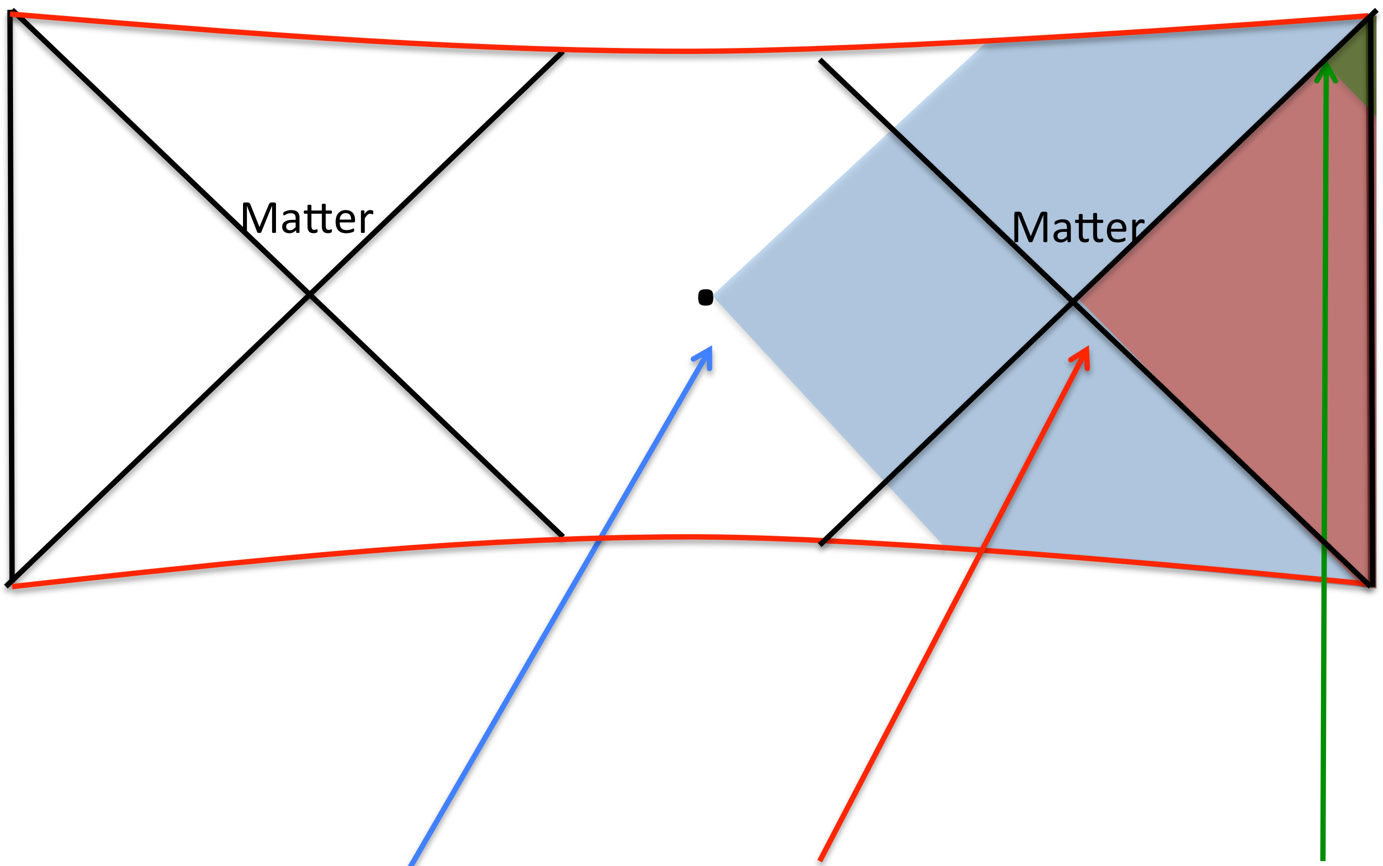
- If one has access to a state that is maximally entangled with a black hole, then information that is sent into the black hole can be recovered by looking at a small amount of Hawking radiation.

# Wormholes and entangled states



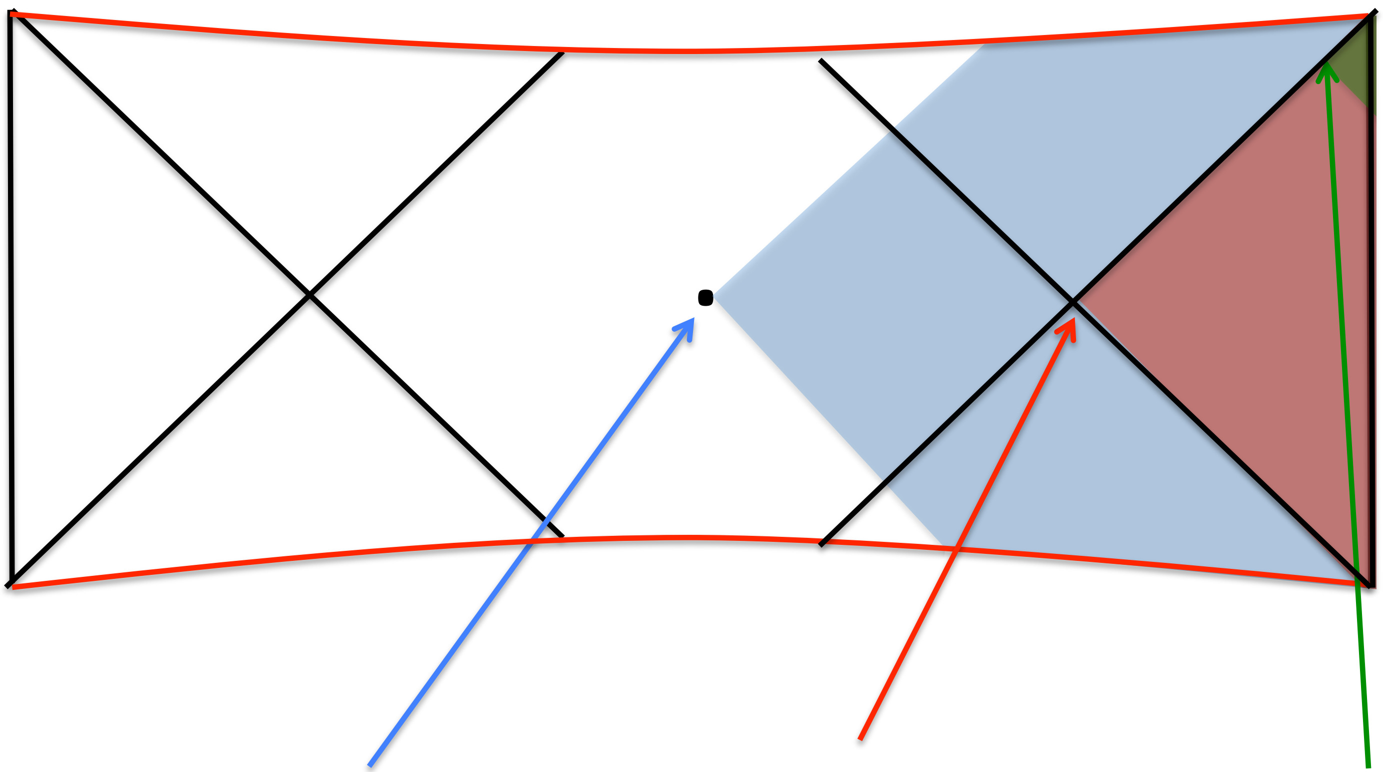
Not just entanglement entropy…

# Entanglement wedge vs. causal wedge




$$\frac{A_{RT}}{4G_N} \leq \frac{A_{\text{Causal wedge}}}{4G_N} \leq \frac{A_{\text{final}}}{4G_N}$$

# Entanglement wedge vs. causal wedge



$$\frac{A_{RT}}{4G_N} + S_{bulk} \le \frac{A_{\text{Causal wedge}}}{4G_N} + S_{bulk} \le \frac{A_{\text{final}}}{4G_N} + S_{bulk}$$

2nd Law

# Different notions of entropy

$$\frac{A_{RT}}{4G_N} + S_{bulk} \leq \frac{A_{\text{Causal wedge}}}{4G_N} + S_{bulk} \leq \frac{A_{\text{final}}}{4G_N} + S_{bulk}$$

Fine grained entropy

These should be coarse grained entropies

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Fine grained entropy

These should be coarse grained entropies

Restrict the algebra of observables to gravity fields. Simple operators acting within a scrambling time

Entropy of the maximal entropy state compatible with the density matrix of the simple algebra…

Kelly, Wall, Papadodimas, Raju,….

# Tensor Networks

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- Wavefuction constructed out of simpler objects, out of simpler tensors.
- Originated as a numerical method.
- They embody the renormalization group.
- There are some qualitative similarities with gravity.

# Examples

- Matrix product states.

white

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

$$T_{s_i} = (T_{s_i})_l^k \qquad D \times D \quad \text{matrix}$$

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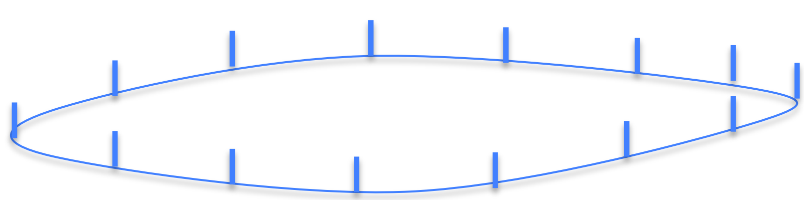
$$2D^2 \; , \qquad \text{or} \qquad 2ND^2 \qquad \ll \qquad 2^N$$

Subspace of the Hilbert space !

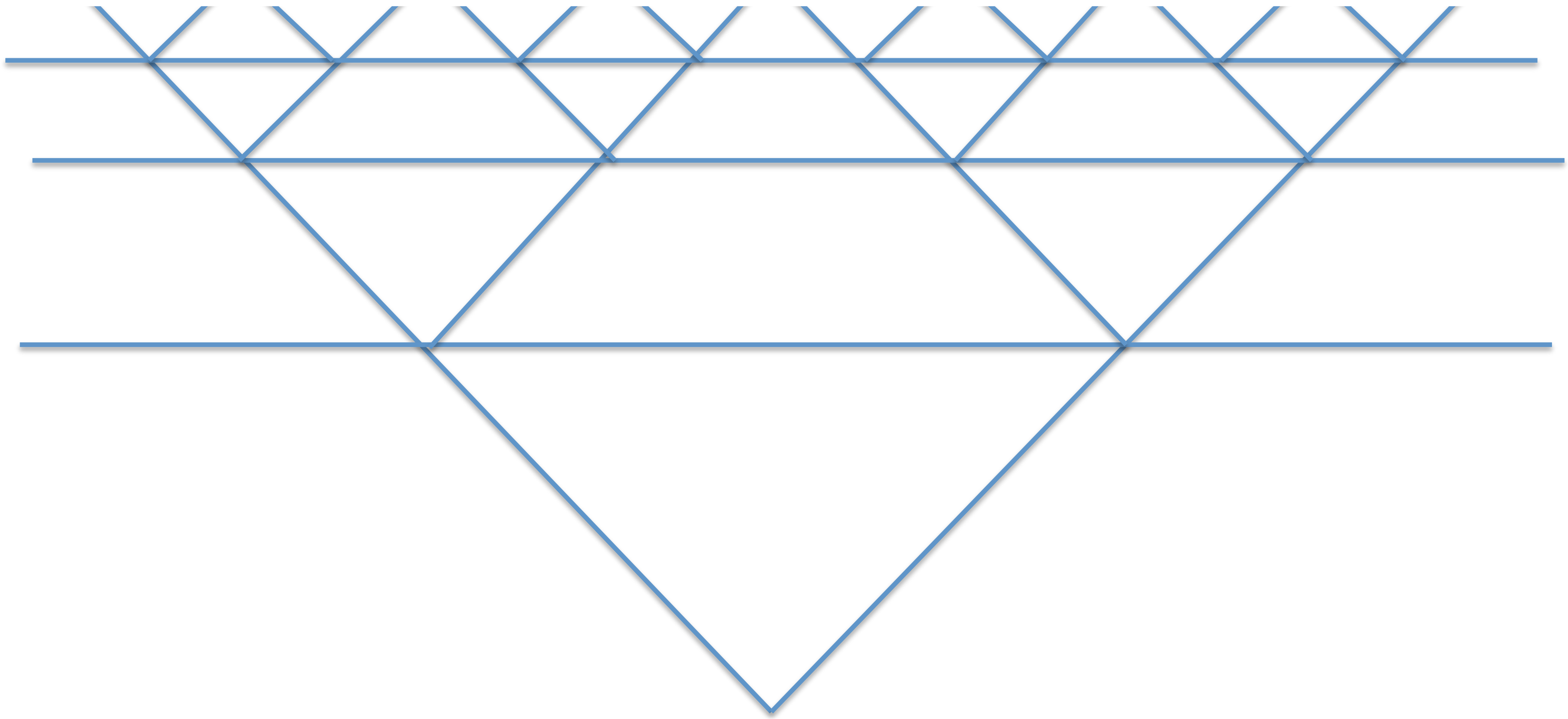
Works for states with finite Amount of long range entanglement



Vertex = tensor
Open line = open index
Link = contracted index

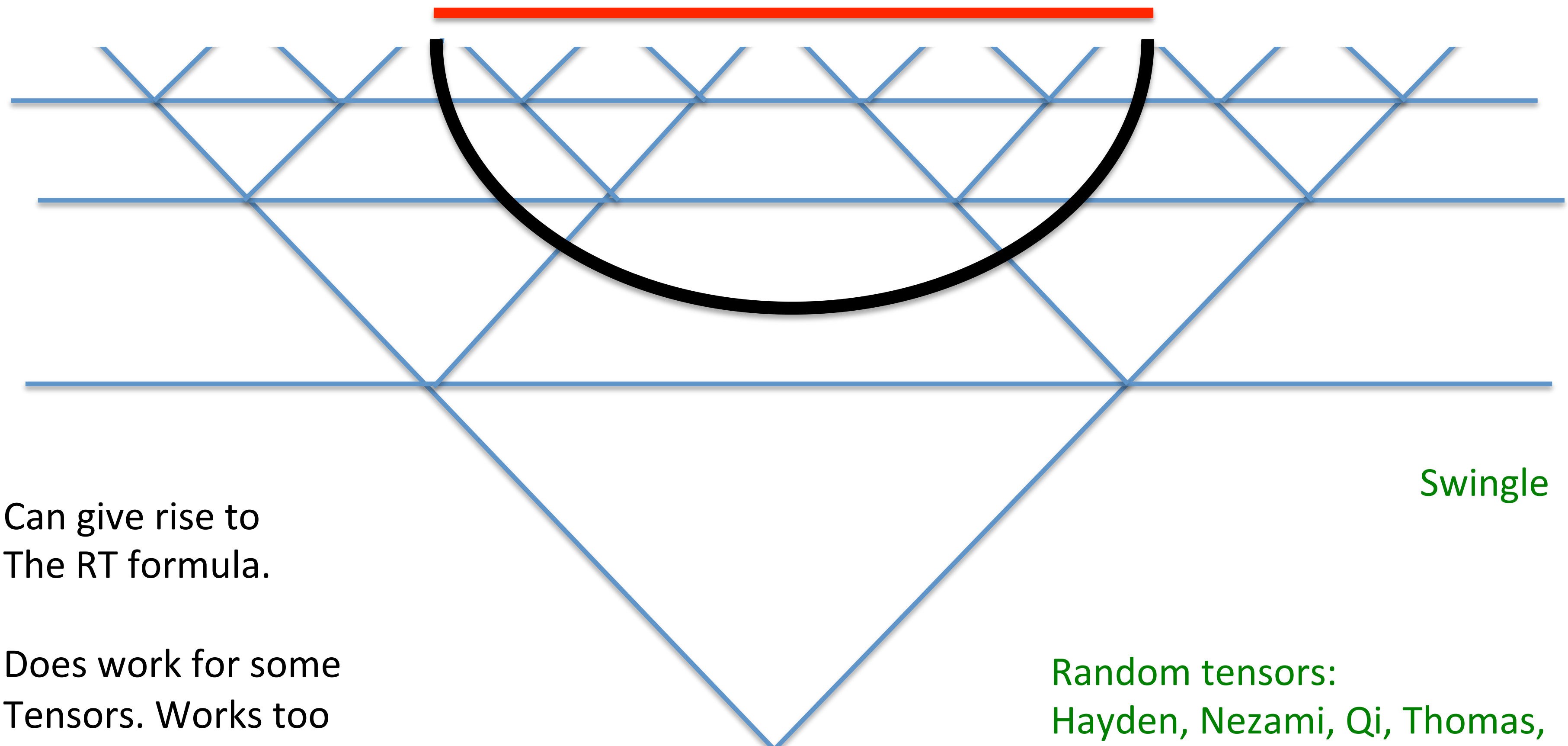
# Scale invariant wavefunctions

Vidal



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

# Scale invariant wavefunctions



Swingle

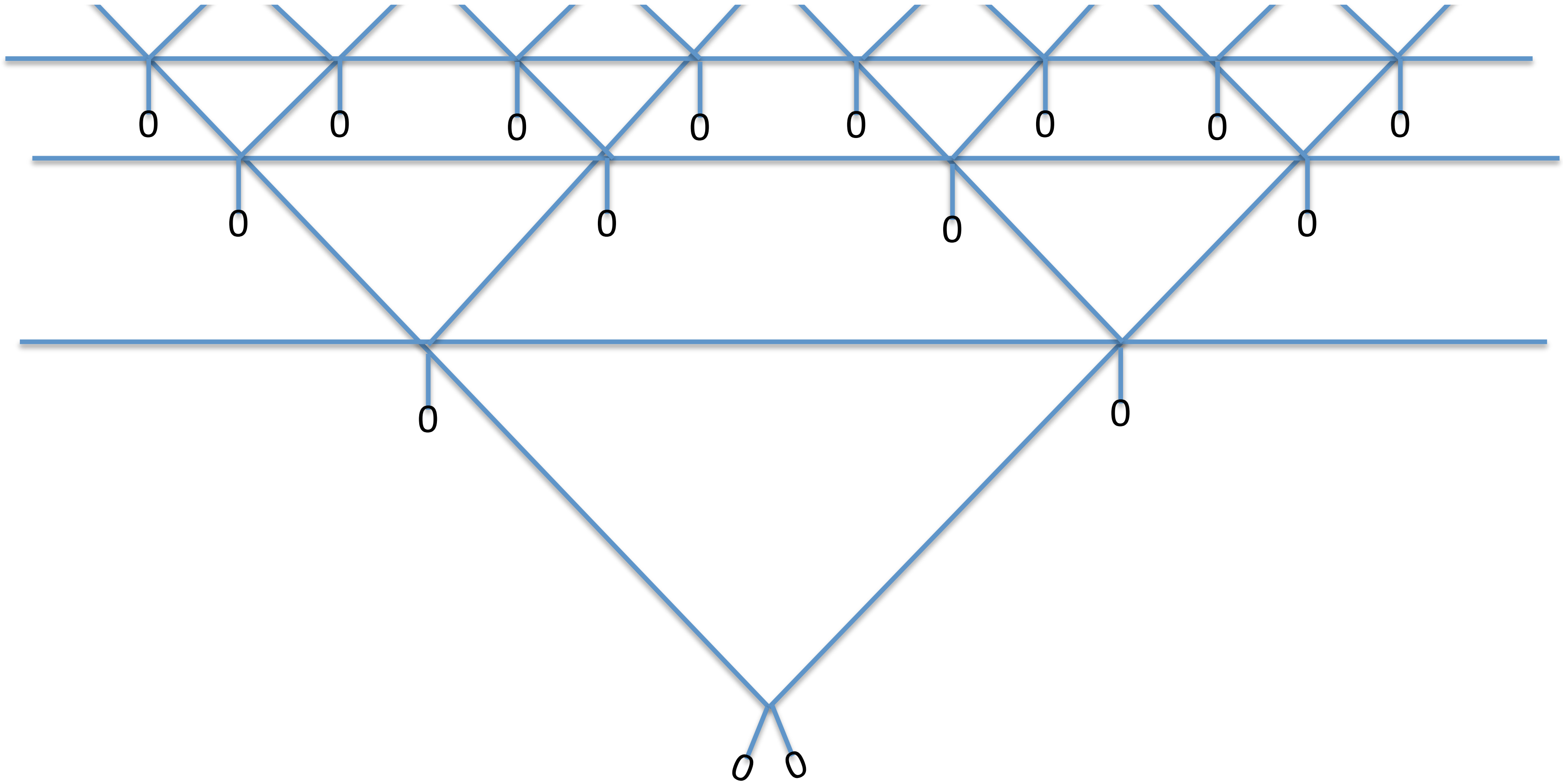
Can give rise to
The RT formula.

Does work for some
Tensors. Works too
well → all Renyi entropies

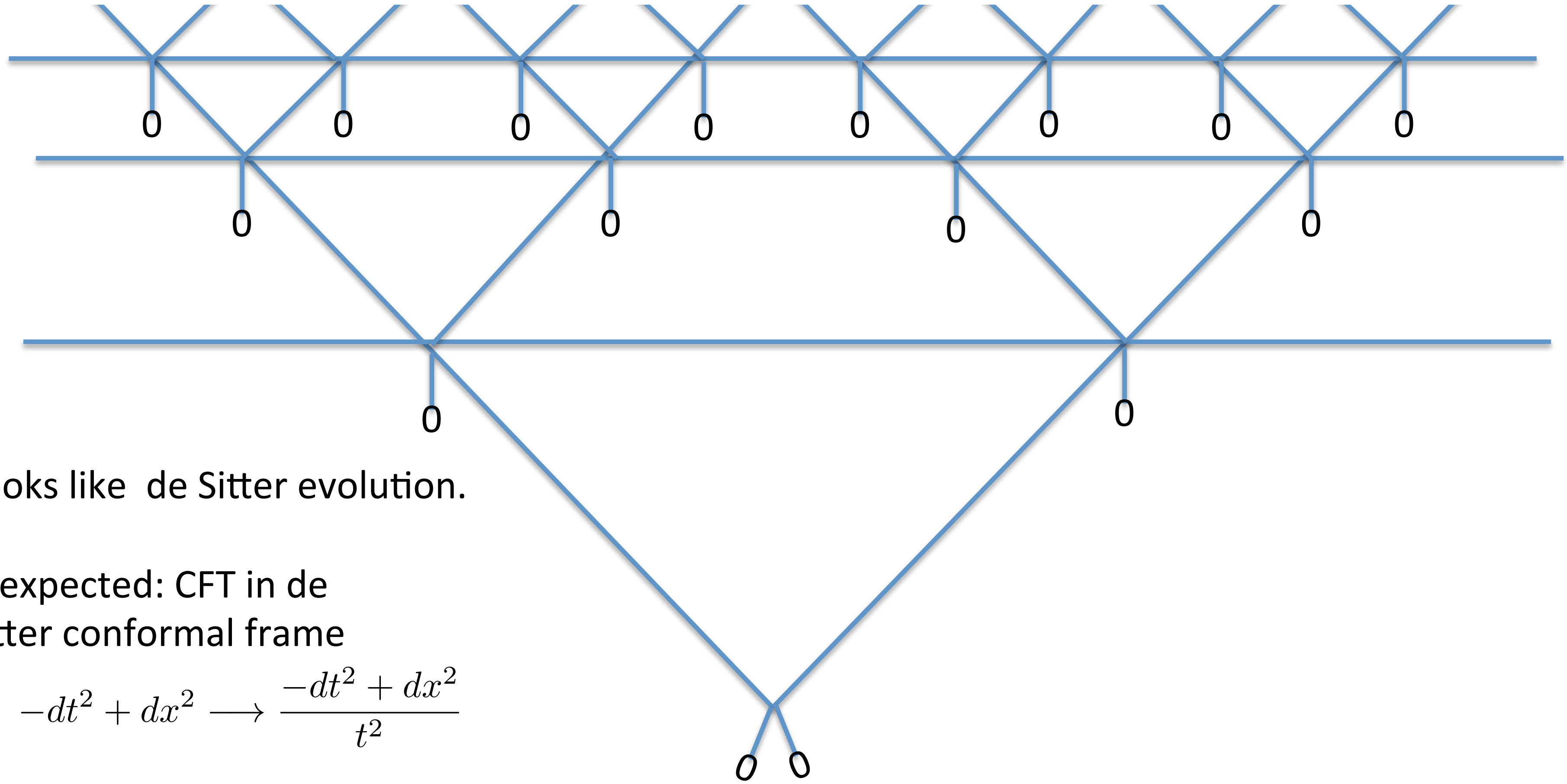
Random tensors:
Hayden, Nezami, Qi, Thomas,
Walter, Yang

Qualitatively similar to the bulk in AdS/CFT

# As a unitary transformation



# As a unitary transformation




Looks like de Sitter evolution.

Is expected: CFT in de Sitter conformal frame

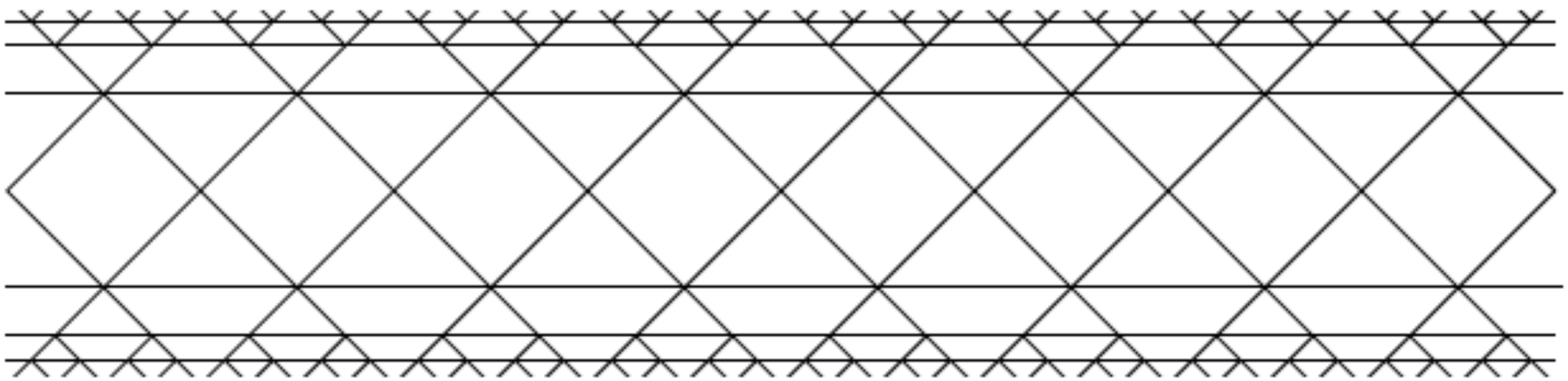
$$-dt^2 + dx^2 \longrightarrow \frac{-dt^2 + dx^2}{t^2}$$

Connection to ``kinematic space'' (space of pairs of points) Czech, Lamprou, McCandish, Sully

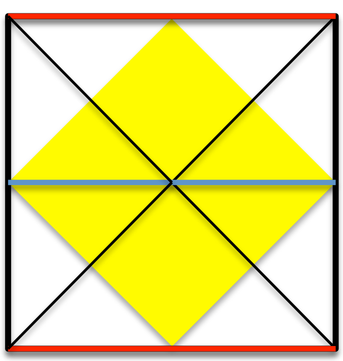
Could also use it as a representation of the cosmological wavefunction…

# Peeking into the interior

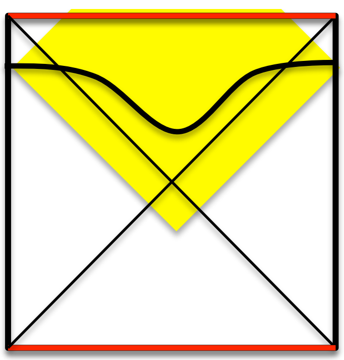
# Thermal states

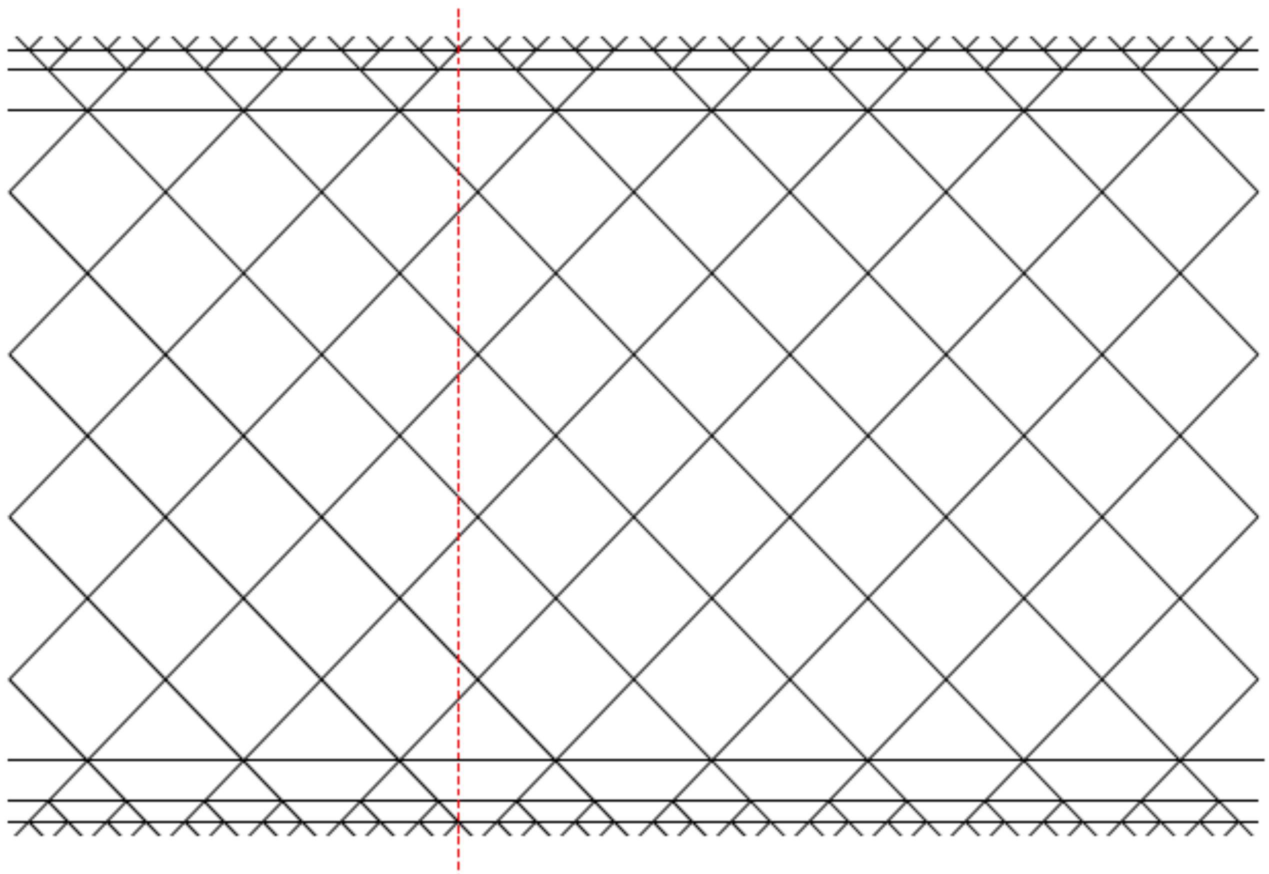


Spatial direction along horizon



# Time evolution of thermofield double





Similar to the stretching of the geometry behind the horizon.

Hartman JM

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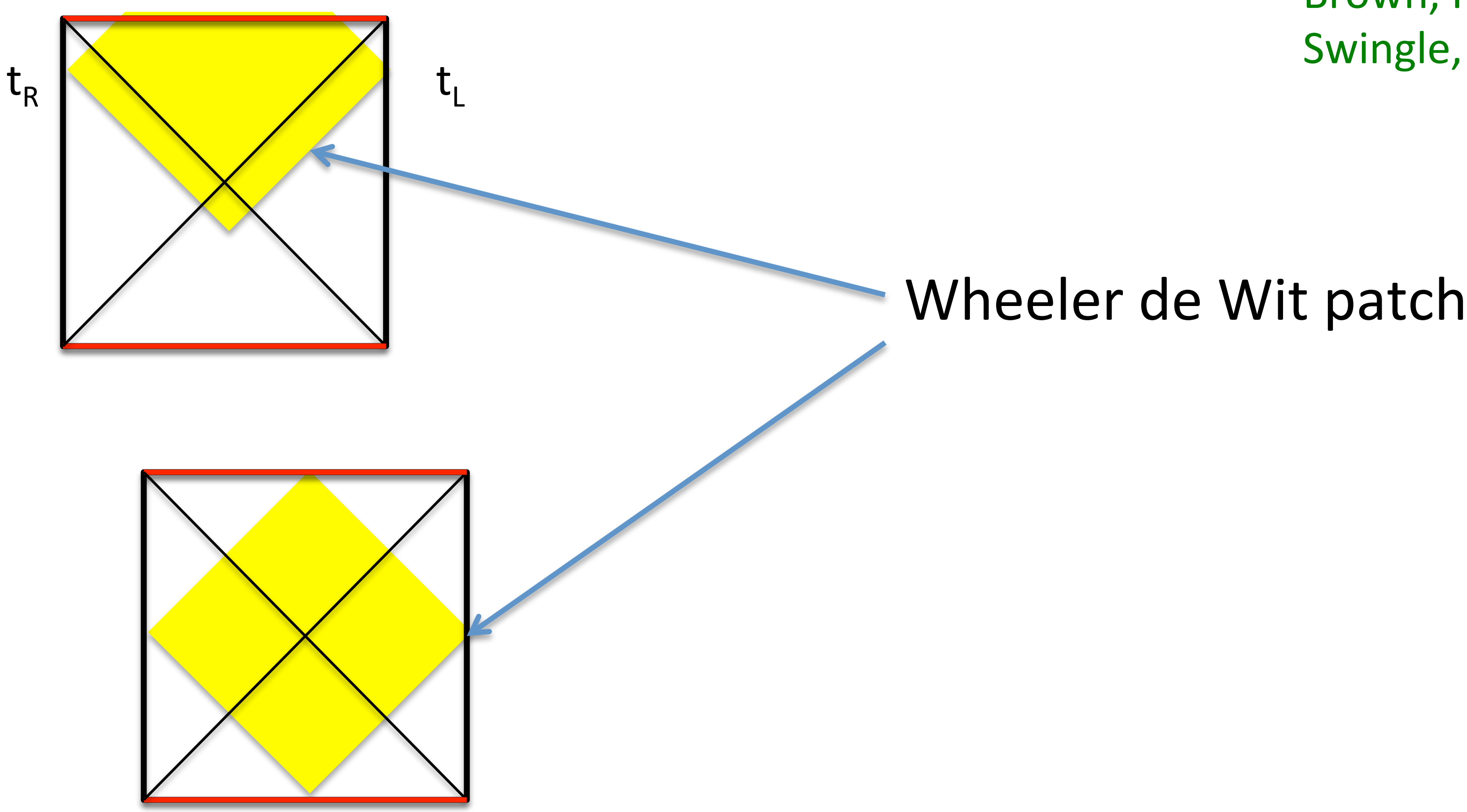
- <u>Complexity</u> = number of simple gates

# Complexity = Action ?

- Complexity = action of the WdW patch ?

Brown, Roberts, Susskind, Swingle, Zhao



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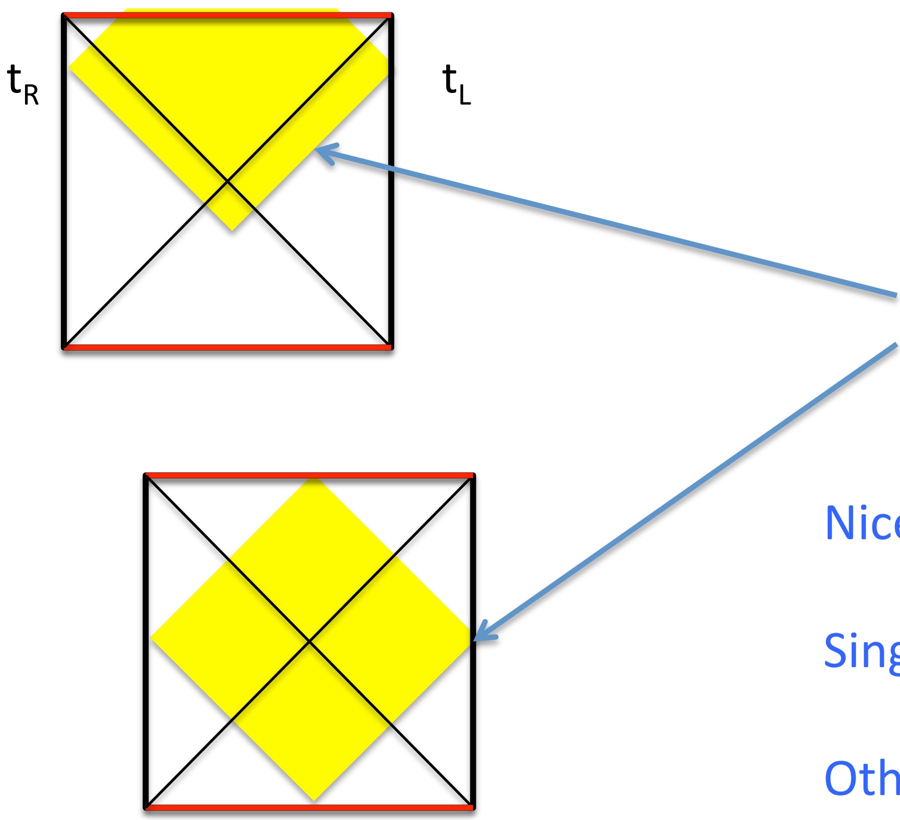


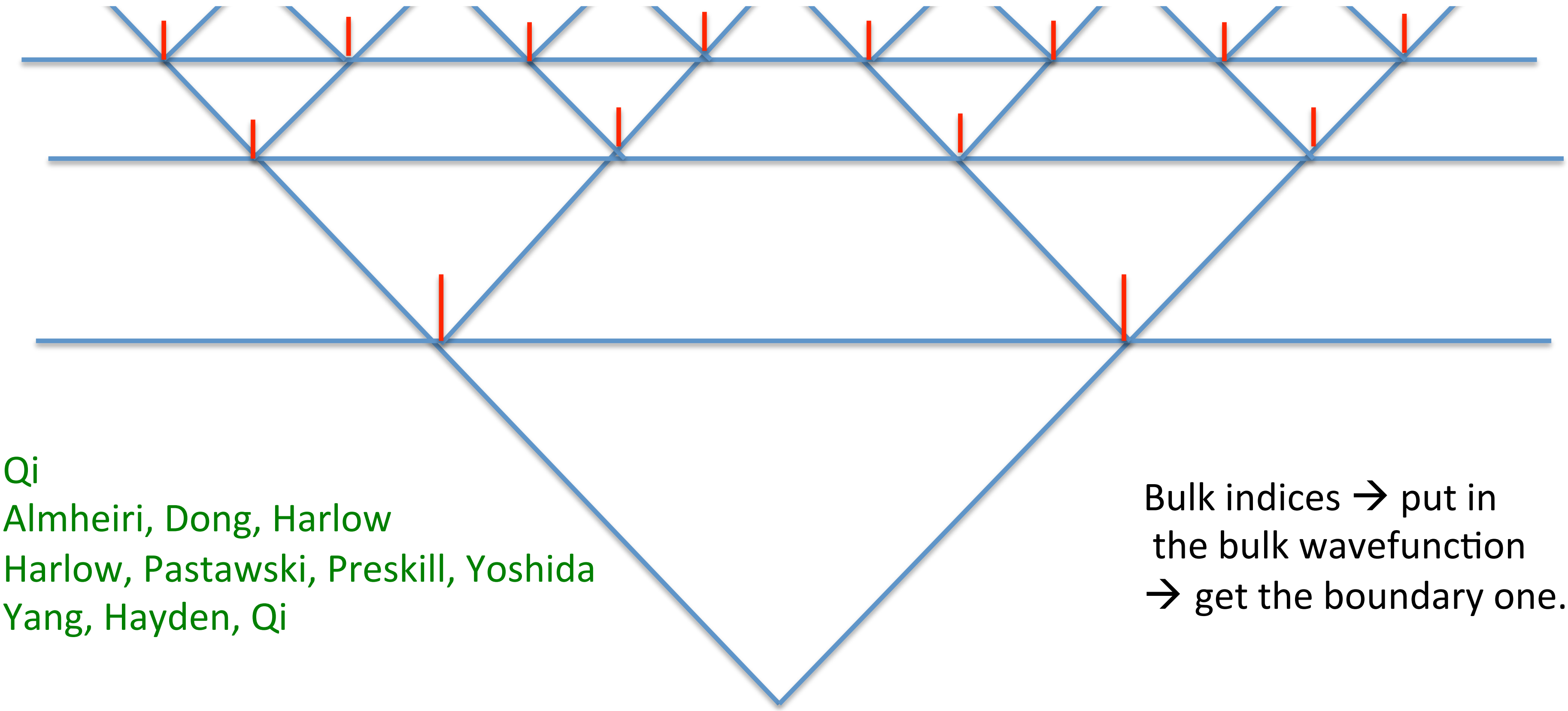

Wheeler de Wit patch

Nice qualitative agreement → time dependence

Singularity ?

Other physical interpretation ?

# Tensor networks and the holographic encoding



Qi
Almheiri, Dong, Harlow
Harlow, Pastawski, Preskill, Yoshida
Yang, Hayden, Qi

Bulk indices → put in the bulk wavefunction → get the boundary one.

Tensor network is an encoding of the bulk into the boundary

$$\mathcal{H}_{\rm Bulk} \longrightarrow \mathcal{H}_{\rm Boundary}$$

- Capture many qualitative features!

- Local lorentz invariance in the bulk ?

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- Gravity + QFT → interesting entropy statements, which are being proved. $2^{nd}$ Law. Bousso bound. Holographic entanglement formulas…
- Weird wormholes → help constrain how spacetime emerges.
- Tensor networks capture interesting properties of black hole geometries. (But not local bulk lorentz invariance, so far…)

End