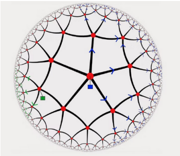
The central dogma and horizons in quantum cosmology

Edgar Shaghoulian
University of California Santa Cruz

Quantum de Sitter workshop

April 21, 2023



Quantum black hole

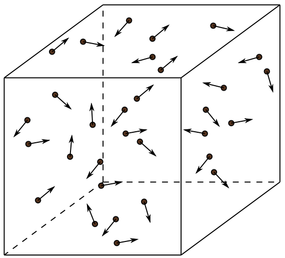
Like a gas in a box, black holes have a **temperature** and an **entropy**:

$$T = \frac{1}{8\pi G M}$$

$$S = \frac{\text{Area}}{4G}$$

Quantum black hole

Boltzmann provided atomic description for gas:



Black hole central dogma: from the outside, a black hole can be described in terms of a quantum system with $\log \dim(\mathcal{H}_{\rm BH}) = \frac{\rm Area}{4G}$, which evolves unitarily. [Bekenstein, Hawking, 't Hooft, Susskind,...]

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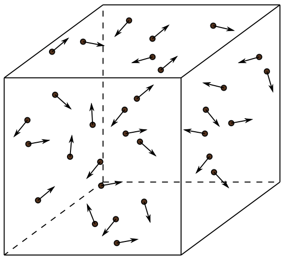

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Region beyond event horizon can be accessed from outside. [Penington] [Almheiri, Engelhardt, Marolf, Maxfield] [Penington, Shenker, Stanford, Yang] [Almheiri, Hartman, Maldacena, ES, Tajdini]

Cosmic central dogma

Cosmological horizons have an entropy $\text{Area}/4G$ [Gibbons, Hawking]. They radiate and have a temperature. Do they obey a central dogma?

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Cosmic central dogma

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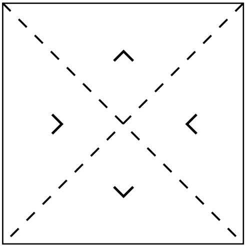
Will focus on de Sitter spacetime in this talk:

$$ds^2 = -\left(1 - r^2/\ell^2\right) dt^2 + \frac{dr^2}{1 - r^2/\ell^2} + r^2 d\Omega^2_{d-1}$$

$$T = \frac{1}{2\pi\ell}\,, \qquad S = \frac{\ell^{d-1}\,\mathrm{Area}(S^{d-1})}{4G}$$

Holography for de Sitter



Holographic dual located near $\mathcal{I}^{\pm}$ (dS/CFT). [Strominger] [Maldacena] [Anninos, Hartman, Strominger]

Holographic dual located near static patch observer. [Anninos, Hartnoll, Hofman]

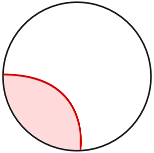
Holographic dual located near cosmic horizon. [Banks, Fischler] [Alishahiha, Karch, Silverstein, Tong]

Entanglement entropy in AdS/CFT

Entanglement entropy of dual CFT computed by extremizing [Ryu, Takayanagi] [Hubeny, Rangamani, Takayanagi] [Faulkner, Lewkowycz, Maldacena] [Engelhardt, Wall]

$$-\mathrm{Tr}(\rho_{\mathrm{CFT}} \log \rho_{\mathrm{CFT}}) \equiv S_{\mathrm{CFT}} = \mathrm{ext}\ S_{\mathrm{gen}} = \mathrm{ext} \left(\frac{\mathrm{Area}}{4G} + S_{\mathrm{matter}} \right)$$

with respect to red surface:



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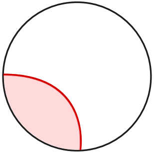

Entanglement wedge reconstruction: data within pink region is reconstructable from CFT data on boundary $\cap$ pink. [Czech, Karczmarek, Nogueira, Van Raamsdonk] [Jafferis, Lewkowycz, Maldacena, Suh] [Dong, Harlow, Wall]

Entanglement wedge nesting: pink region should grow as CFT region grows.

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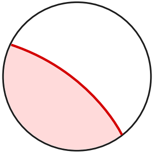

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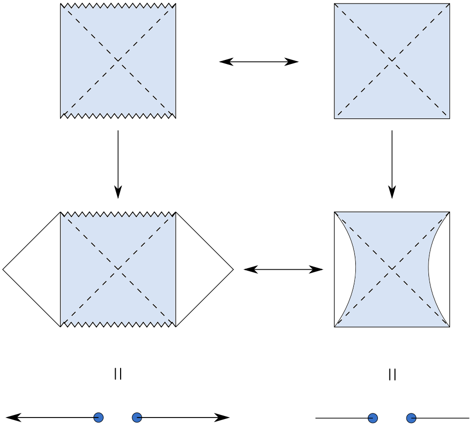
Holographic dual near static patch observers



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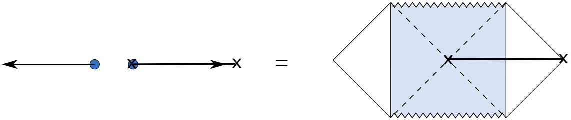
Black hole entropy interpreted as entanglement between two sides:



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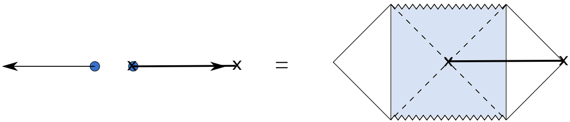
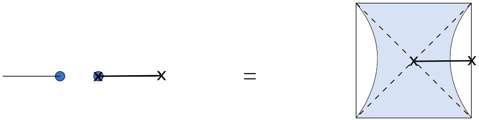
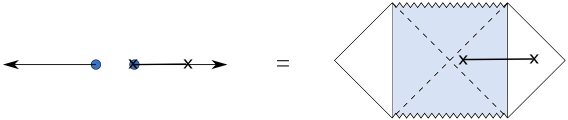




de Sitter horizon entropy seems to have similar interpretation!

Holographic dual near static patch observers

Encoded region for black hole shrinks as region in boundary shrinks:



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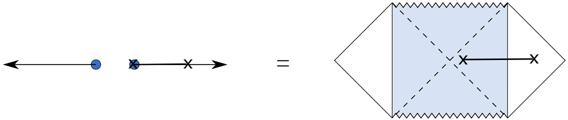

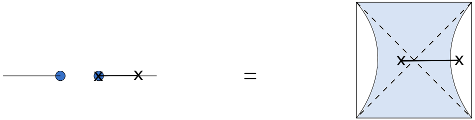

de Sitter case violates entanglement wedge nesting! Strong subadditivity locates endpoint in left wedge; calculable in 2d.

Use of dS bifurcate horizon to compute entropy seems prohibited; **minimax vs maximin surface.**

Holographic dual on horizon

Place holographic dual theory on dS horizon. Which side is encoded?

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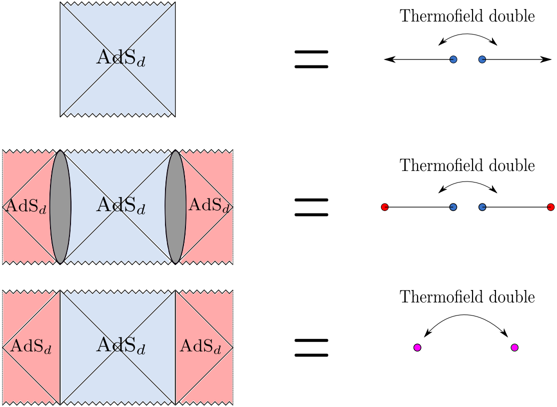
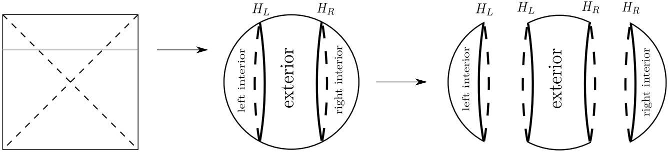


Prescription is to find extremal surface on *both* sides of AdS boundary.

Holographic dual on horizon

Microscopic theory lives on pair of horizons on global slice:



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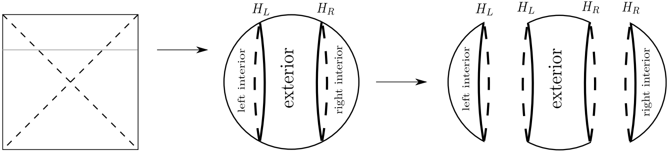
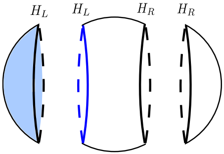


Extremize on both sides of horizon – bilayer proposal [ES].

Extremize in between horizons – monolayer proposal [Susskind; Dong, Silverstein, Torroba].

Extremal surfaces: pure de Sitter



$S(H_L) = A/4G$; EW = interior. Horizon is now maximin!

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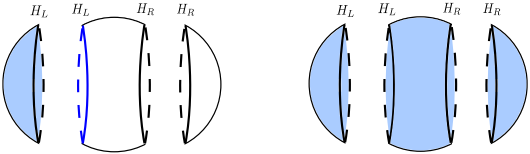

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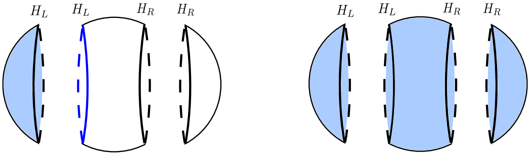

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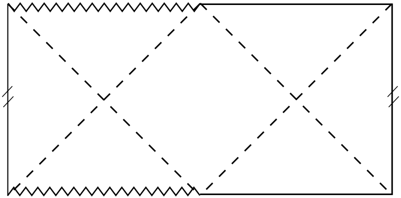
Monolayer theory gives same answer for entropies.

Extremal surfaces: Schwarzschild-de Sitter

Schwarzschild black hole in de Sitter:

$$ds^2 = -(1 - 2m/r^{d-2} - r^2/\ell^2)dt^2 + \frac{dr^2}{1 - 2m/r^{d-2} - r^2/\ell^2} + r^2 d\Omega_{d-1}^2$$



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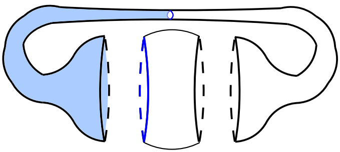

$S(H_L) = A_{\rm CH}/4G + A_{\rm BH}/4G$; EW = region between BH and CH.

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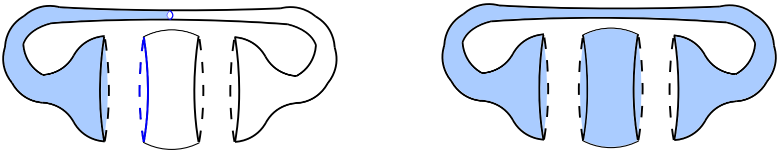

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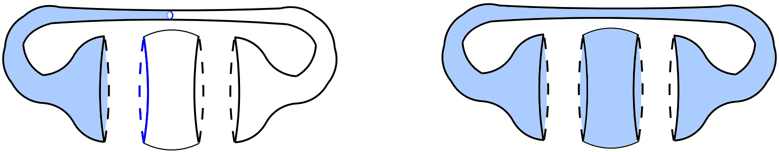

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Monolayer theory gives same answer upon extremizing between BH horizons as well.

Anchor to horizon: subregions on one horizon

Unclear if dividing a horizon makes sense, similar to chopping up internal space in AdS/CFT.

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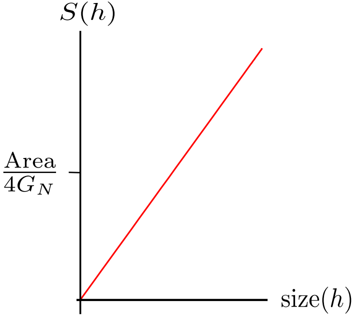

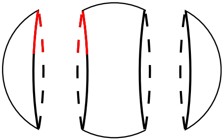

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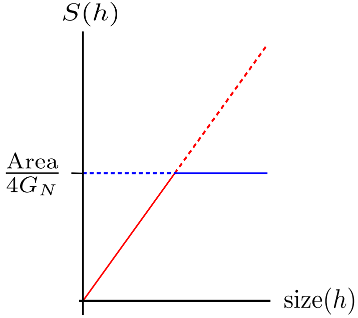

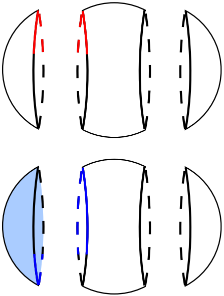

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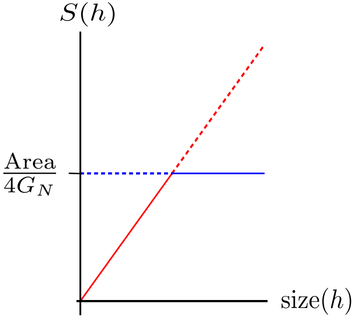

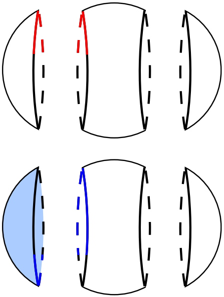

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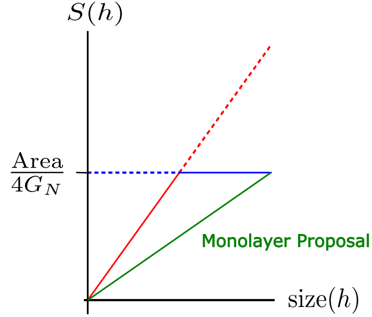

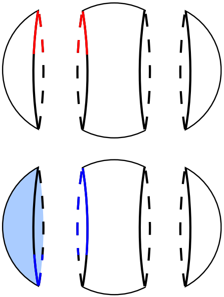

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Large-N thermodynamics

Large-N limit not the same as thermodynamic (large volume) limit!

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Pattern of higher form symmetry breaking in holographic CFTs, through Eguchi-Kawai mechanism, makes them very similar sometimes [ES '16, '20]

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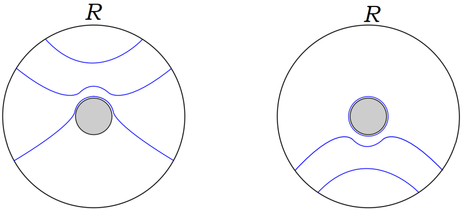


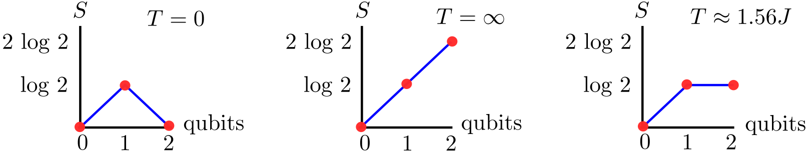
BH entropy saturated at $O(1)$ fraction of system size.

Model

Model with finite dim $\mathcal{H}$: Heisenberg antiferromagnet for two qubits

$$H = J\sigma \cdot \tau$$

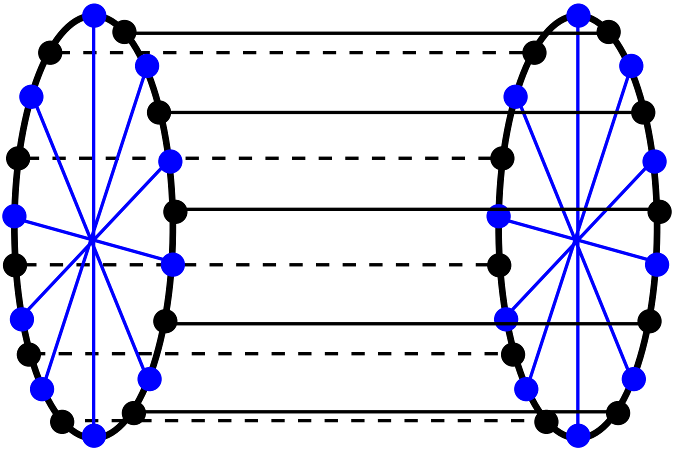
Entropy for thermal state:



spin singlet

maximally mixed

Qubit representation



Let's switch gears.

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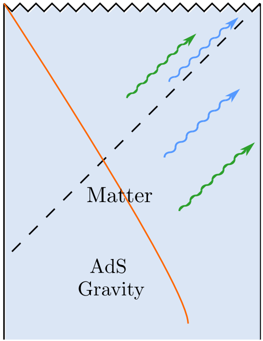
Can we encode beyond horizon?

Use gravity path integral; don't assume holography (Orwellian; see [Harlow, ES])

[Penington]

[Almheiri, Engelhardt, Marolf, Maxfield]



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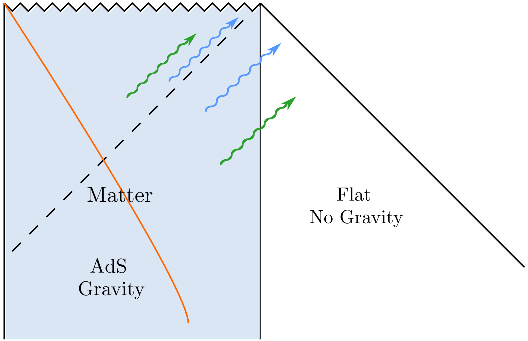

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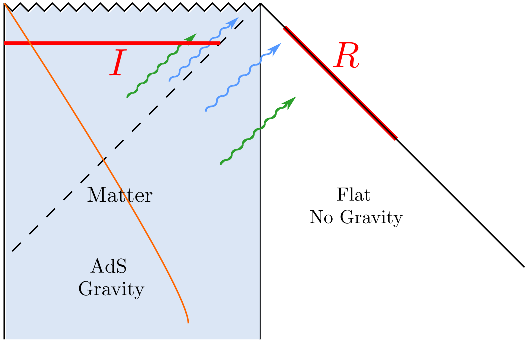

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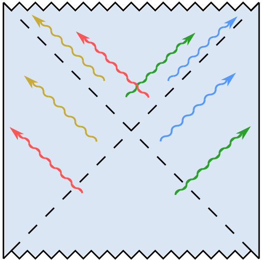

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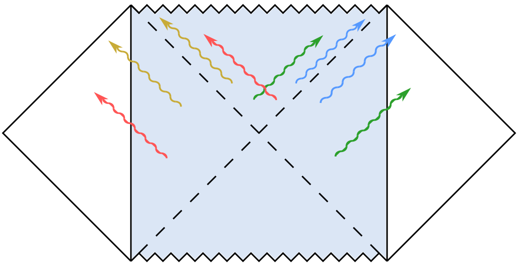

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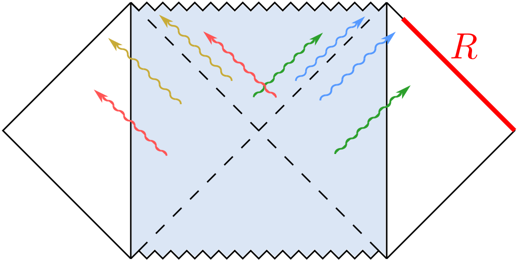

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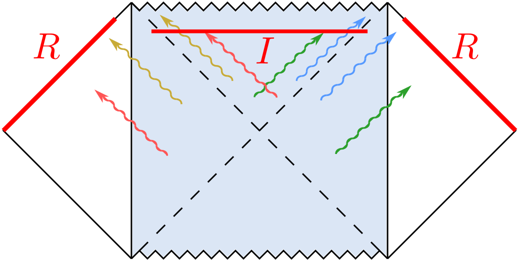
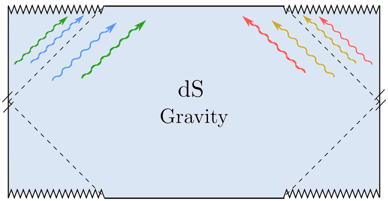


[Hartman, Jiang, ES]

[Chen, Gorbenko, Maldacena]



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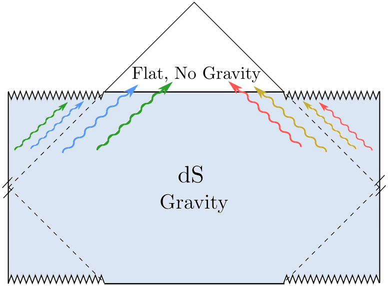

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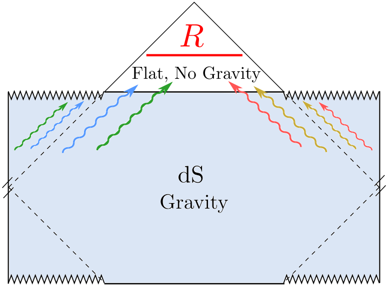

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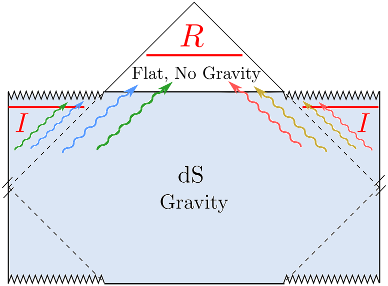

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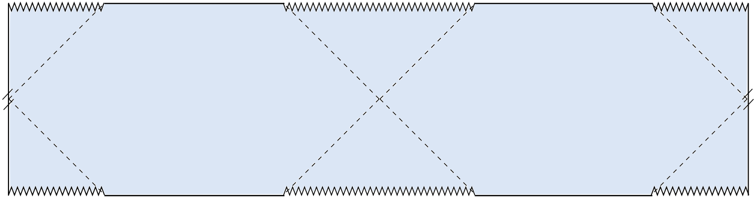

See also [Aguilar-Gutierrez, Chatwin-Davies, Hertog, Pinzani-Fokeeva, Robinson]

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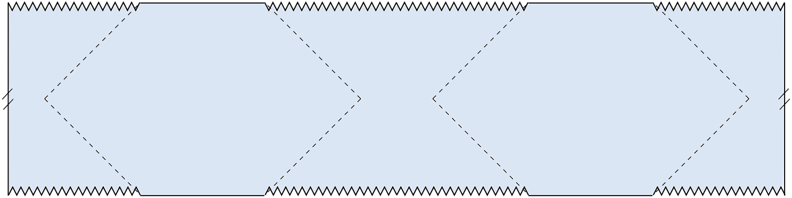

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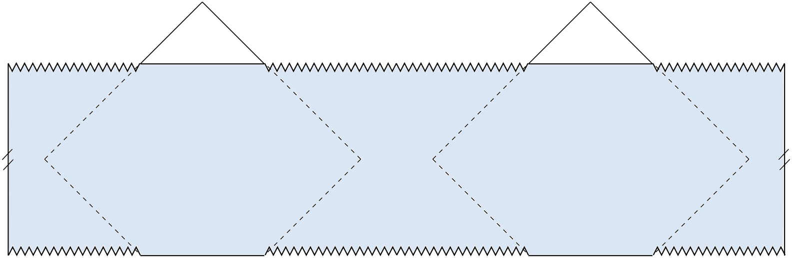

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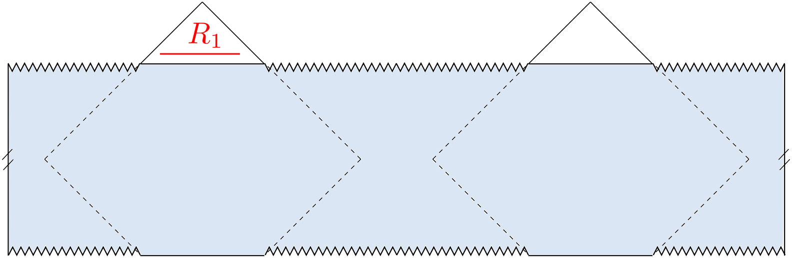

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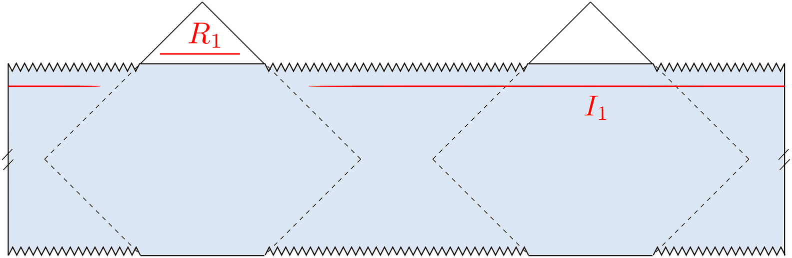

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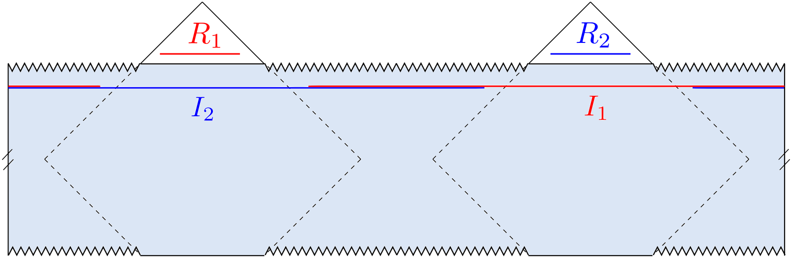

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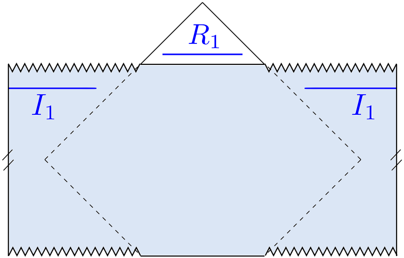

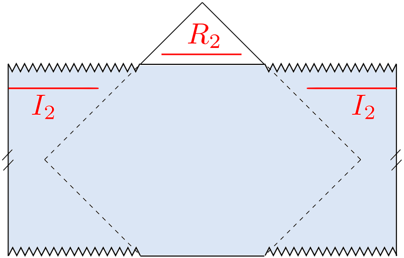

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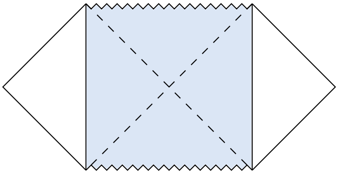

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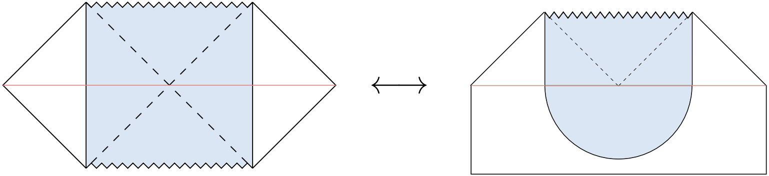

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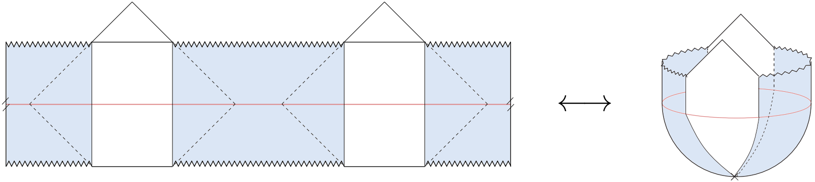

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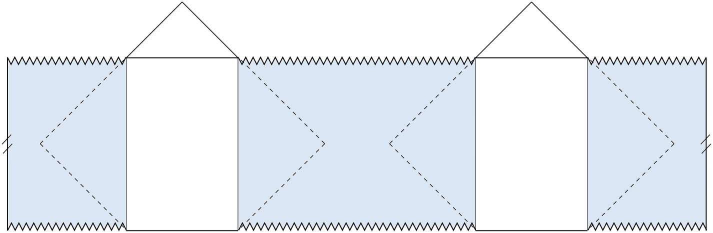

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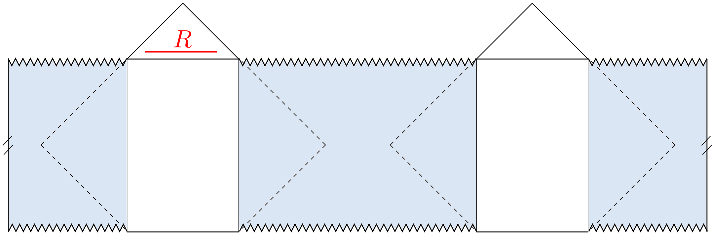

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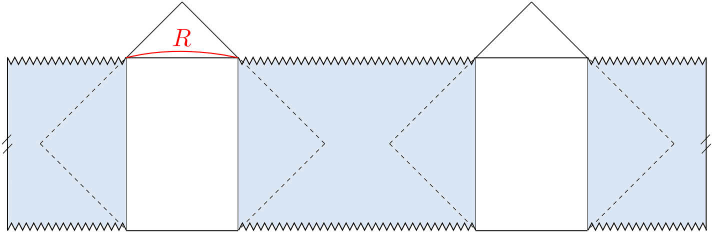

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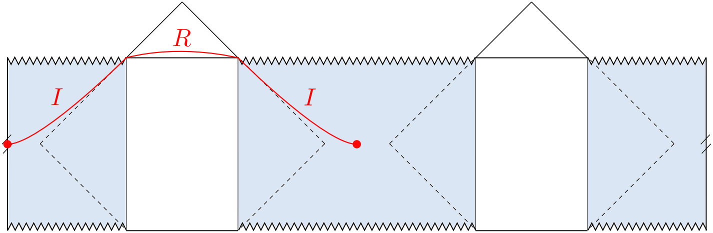

Summary + Future

Cosmological horizon very different than black hole horizon (minimax vs maximin), does not naively work as a quantum extremal surface.

Anchoring to horizon allows you to use the horizon and its associated entropy without violating entanglement wedge nesting.

Gravity path integral smart enough to avoid potential paradox due to observer-dependence of horizon!

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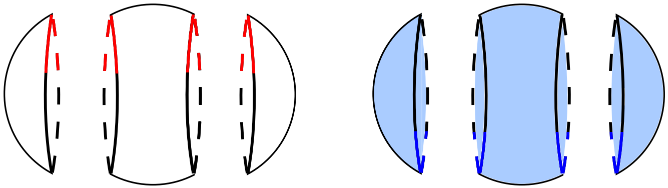
Anchor to horizon: subregions on both horizons

Pick same interval on both horizons in dS_3. Four possible saddles:



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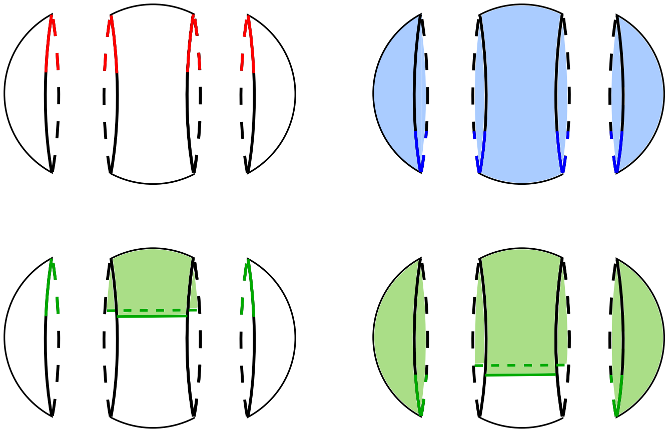
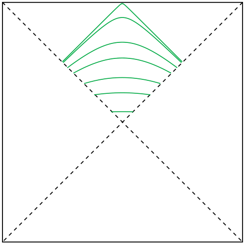


Anchor to horizon: subregions on both horizons

Geodesics are pieces of infinite family of degenerate length-π geodesics connecting static patch origin $r = 0$ at $t = 0$ to its antipodal point



Connected surface dominates at early times, grows to maximum length 2π and disappears; transition to disconnected surface occurs before it disappears. Analog of Hartman-Maldacena transition for dS.

Area of connected surface grows without bound for $\mathrm{dS}_{d>3}$.