The central dogma and cosmological horizons

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University of Pennsylvania

IPMU Seminar
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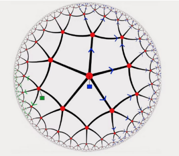
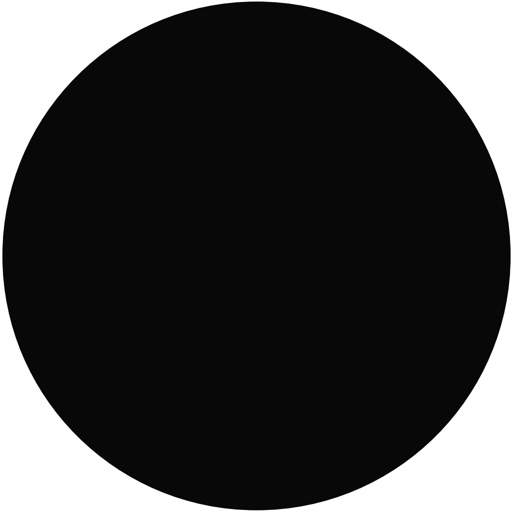
[ES 2110.13210]

[ES, Susskind 2201.03603]

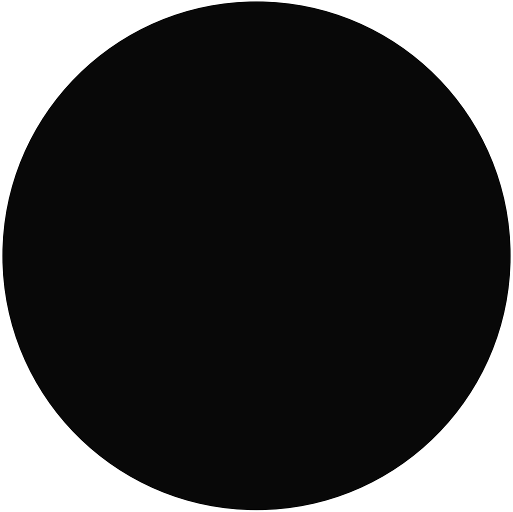


Classical black hole [Schwarzschild 1916]



“The war treated me kindly enough, in spite of the heavy gunfire, to allow me to get away from it all and take this walk in the land of your ideas.”

Quantum black hole [Hawking 1975]



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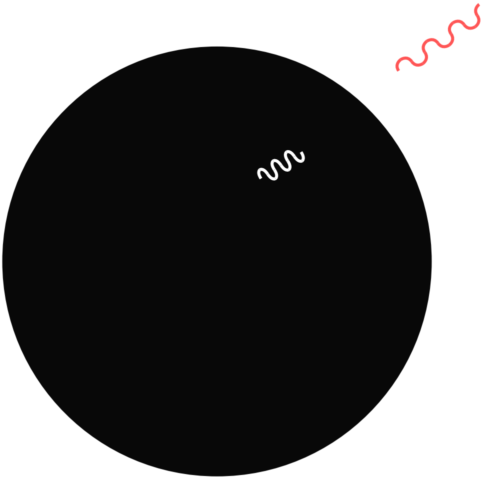

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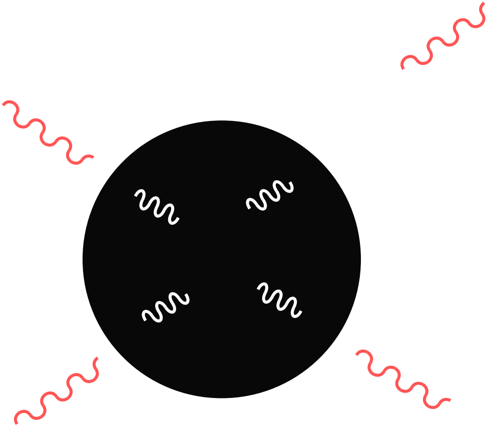

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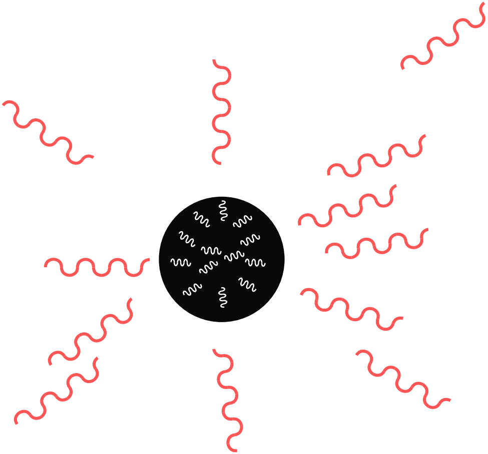

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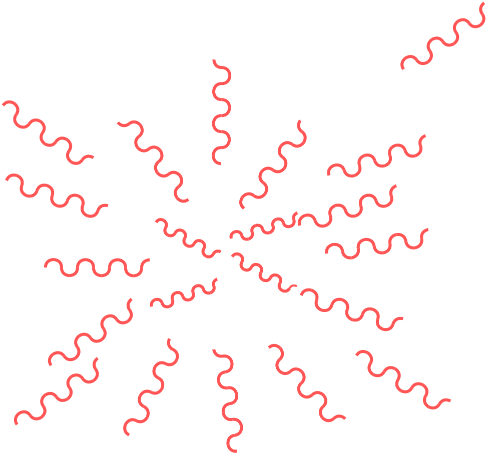

Quantum black hole [Hawking 1975]

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

$$S = \frac{k_B c^3}{\hbar} \frac{\text{Area}}{4G}$$

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

relativity

thermodynamics

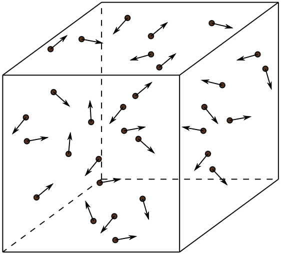
$$S = \frac{k_B c^3}{\hbar} \, \frac{\text{Area}}{4G}$$

quantum mechanics

gravity

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 $\dim(\mathcal{H}_{\mathrm{BH}}) = \frac{\text{Area}}{4G_N}$, which evolves unitarily. [Bekenstein, Hawking, 't Hooft, Susskind,...]

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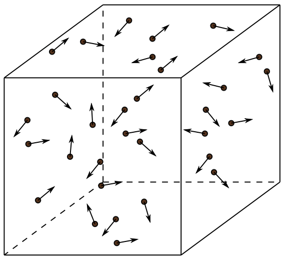

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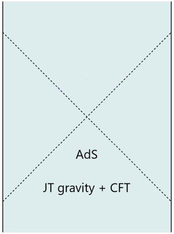
Computations of the Page curve are evidence for central dogma.

[Penington] [Almheiri, Engelhardt, Marolf, Maxfield] [Penington, Shenker, Stanford, Yang] [Almheiri, Hartman, Maldacena, ES, Tajdini]

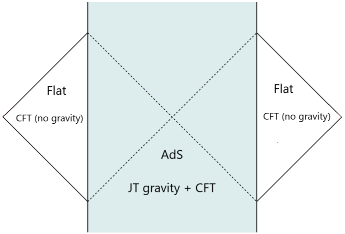
JT gravity coupled to CFT with wings



Take JT gravity coupled to a CFT:

$$I = I_{grav}[\phi, g] + I_{CFT}[g, \psi_i]$$

JT gravity coupled to CFT with wings



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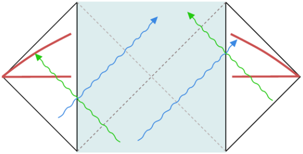
CFT has transparent boundary conditions at AdS_2 boundary.

$$\mathcal{H} = \mathcal{H}_{\mathrm{BH}} \otimes \mathcal{H}_{\mathrm{flat}}$$

Page curve and island rule

Entropy of Hawking radiation unbounded for eternal black hole:



Threatens central dogma! Entropy bounded by $\dim(\mathcal{H}_{\mathrm{BH}})$.

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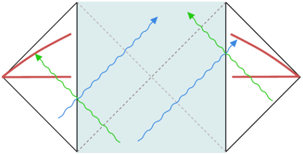

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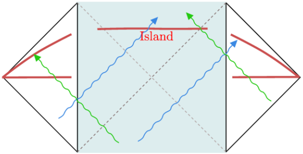
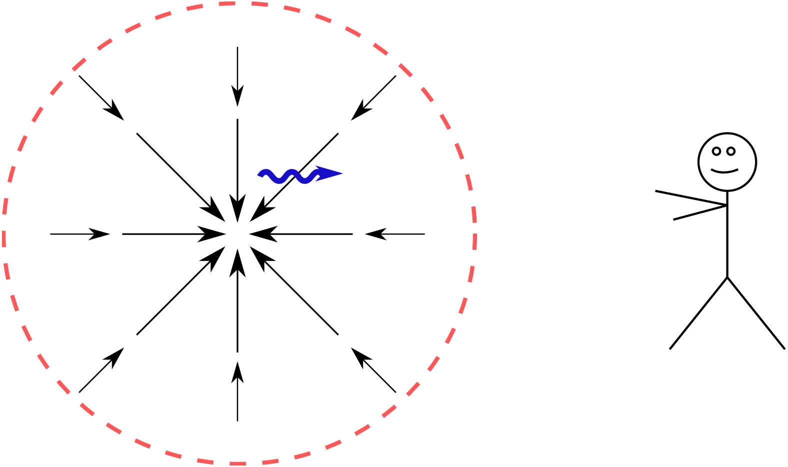
Island rule is extension of Ryu-Takayanagi formula in AdS/CFT:

$$S_R = \min_I \operatorname*{ext}_I \left[S_{\mathrm{matter}}(R \cup I) + S_{\mathrm{grav}}(I)\right]$$

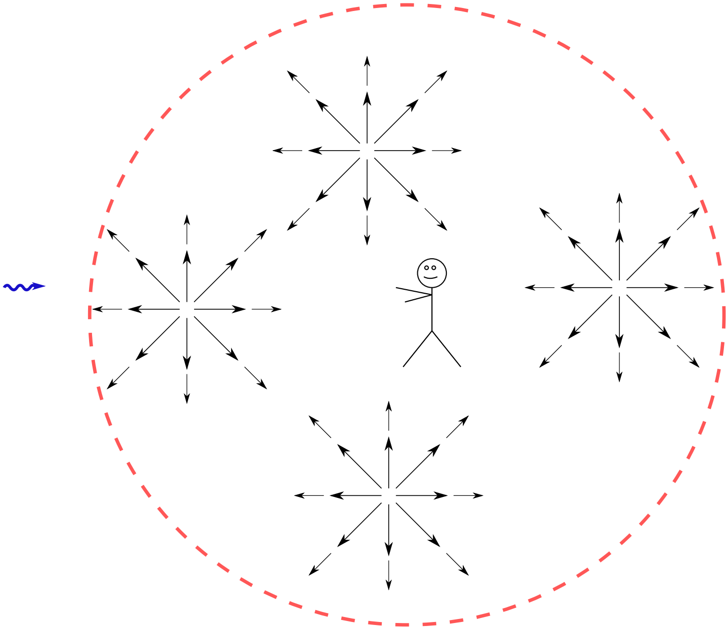


Island "encoded" in exterior.

Black hole event horizon



Cosmological event horizon



Cosmic central dogma

Cosmological horizons have a horizon with Gibbons-Hawking entropy Area/$4G_N$. Do they obey a central dogma? [Bousso; Banks; Fischler]

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Will focus on de Sitter spacetime in this talk:

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

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

CAUTION!

Little microscopic support for Gibbons-Hawking entropy.

Zero-point entropy difficult to interpret.

Black hole horizon encodes interior; which side does cosmological horizon encode?

Cosmological horizon both more universal and more observer-dependent than BH horizon.

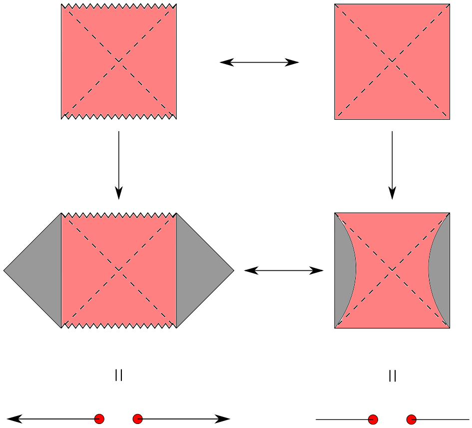
No asymptotic region (at fixed time) with weak gravity, backreaction on system important.

Overlapping islands.

...

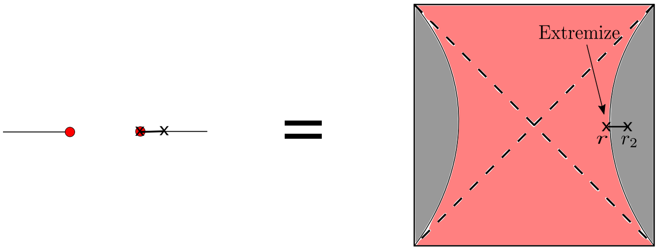
BREAK

Naive analogy



Can gray region in dS_d probe beyond horizon?

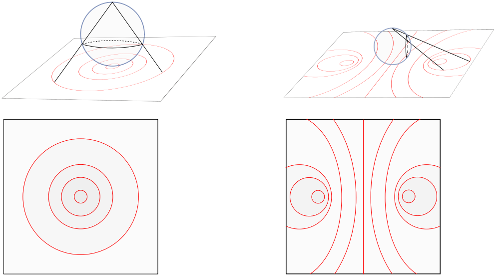
Naive analogy



Entropy of region in microscopic description given by extremizing generalized entropy $S_{\text{matter}} + S_{\text{grav}}$ with respect to left endpoint.

Need entropy for region at $t = 0$ in dS_d in Hartle-Hawking state.

Naive analogy

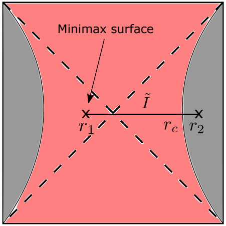


Region at $t = 0$ maps to annulus in plane, use strong subadditivity [Hirata, Takayanagi]:

$$S_0'(R) \geq 0\,, \qquad S_0''(R) \leq 0$$

$$S_0(R \to 1) \sim -\frac{1}{(R-1)^{d-2}}\,, \qquad S_0(R \to \infty) \approx -2F$$

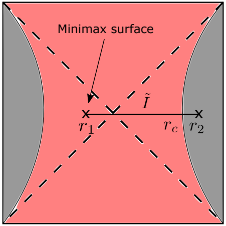
Naive analogy



Strong subadditivity can be used to locate r_1 in the left wedge.

Can explicitly solve for r_1 in dS_2 JT gravity.

Naive analogy



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Can explicitly solve for r_1 in dS_2 JT gravity.

As r_2 moves rightward, r_1 also moves rightward; violation of entanglement wedge nesting!

Use of dS bifurcate horizon to compute entropy seems prohibited; **very different than black hole bifurcate horizon.**

(True QES lives right at cutoff r_c.)

Anchor to horizon – AdS analogy

Let's anchor to horizon [Sanches, Weinberg; Nomura, Rath, Salzetta; Susskind]. Which side is encoded?

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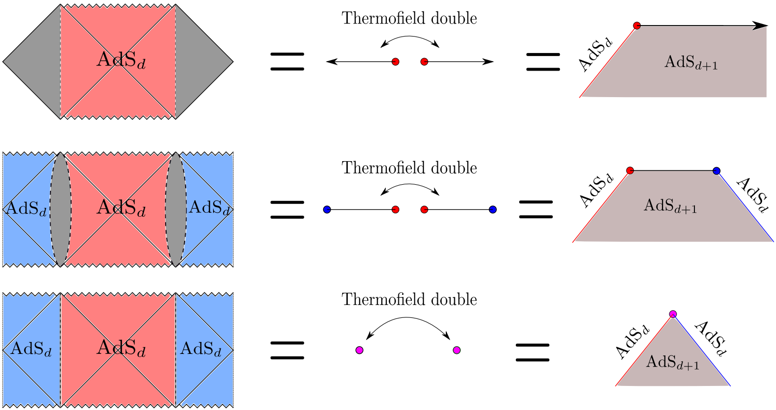
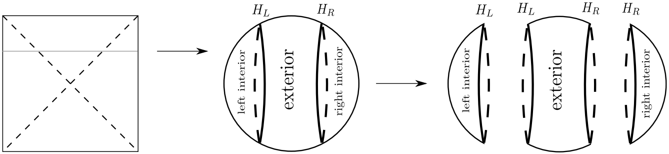


Prescription is to find extremal surface on *both* sides of AdS boundary.

Anchor to horizon: de Sitter proposal

Microscopic theory lives on pair of horizons on global slice:



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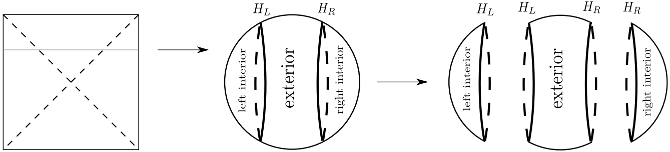

Extremize on both sides of horizon – bilayer proposal [Shaghoulian].

Extremize in between horizons – monolayer proposal [Susskind].

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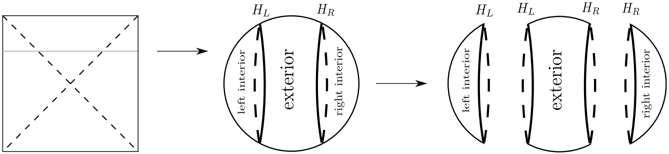

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Entanglement wedge in bilayer proposal

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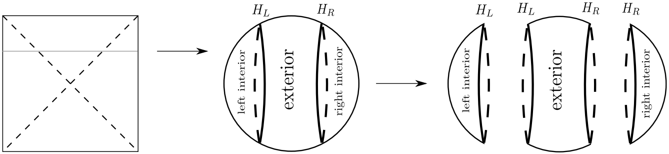

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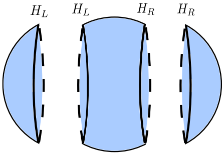
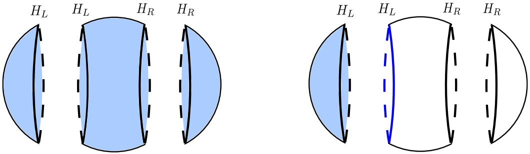
Entanglement wedge in bilayer proposal $\implies$ QES extension.

Anchor to horizon: pure de Sitter



$S(H_L \cup H_R) = 0$; EW = entire spacetime.

Anchor to horizon: pure de Sitter



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

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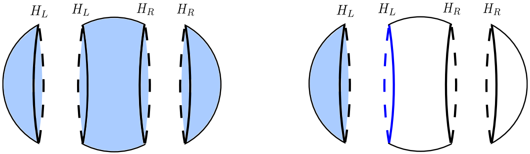

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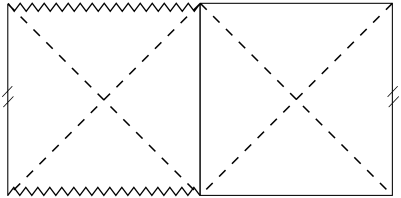
Monolayer theory gives same answer for entropies.

Anchor to horizon: 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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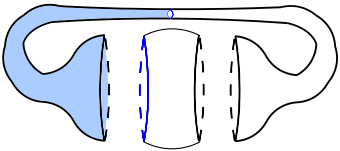

$S(H_L) = A_{\mathrm{CH}}/4G + A_{\mathrm{BH}}/4G$; EW = region between BH and CH.

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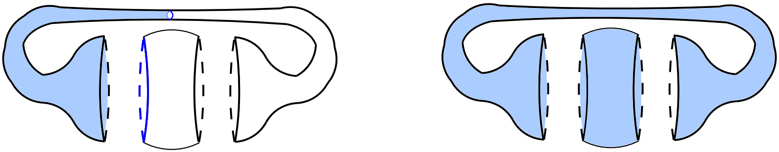

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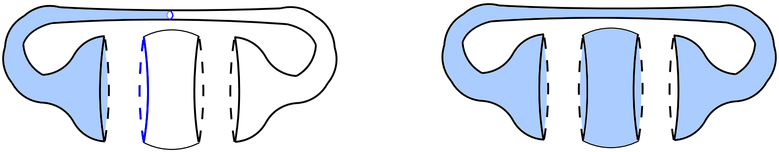

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Unclear if dividing a horizon makes sense, similar to chopping up internal space in AdS/CFT.

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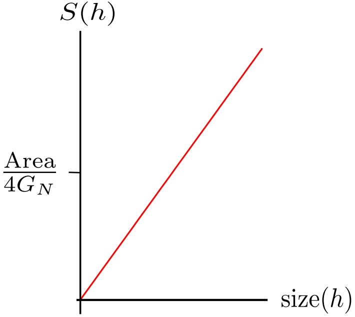

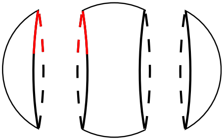

Central dogma threatened.

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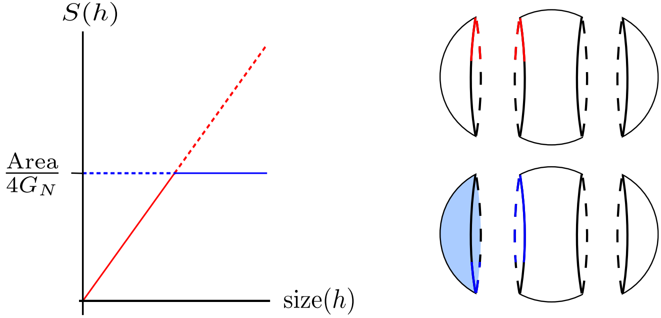

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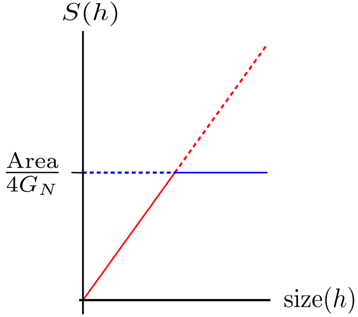

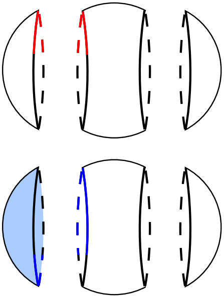

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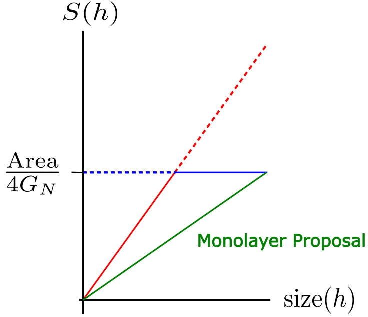

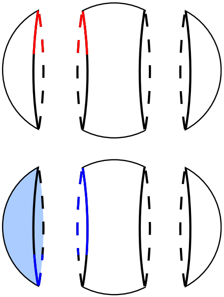

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Large-N thermodynamics

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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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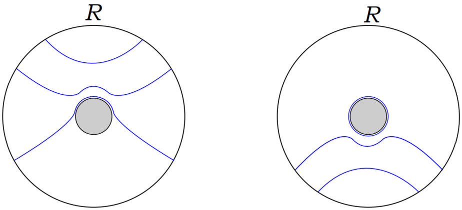
but not all the time

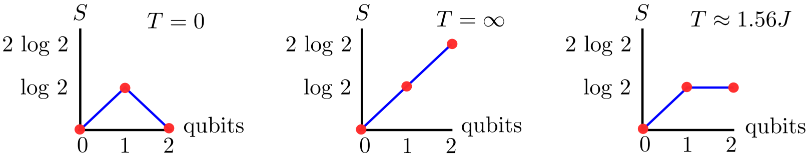


Model

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

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

Entropy for thermal state:

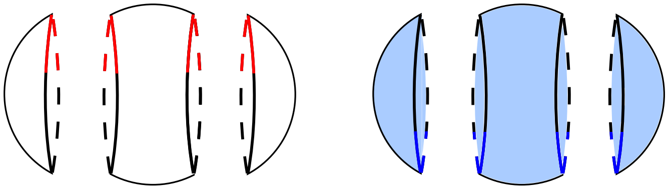


spin singlet

maximally mixed

Anchor to horizon: subregions on both horizons

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



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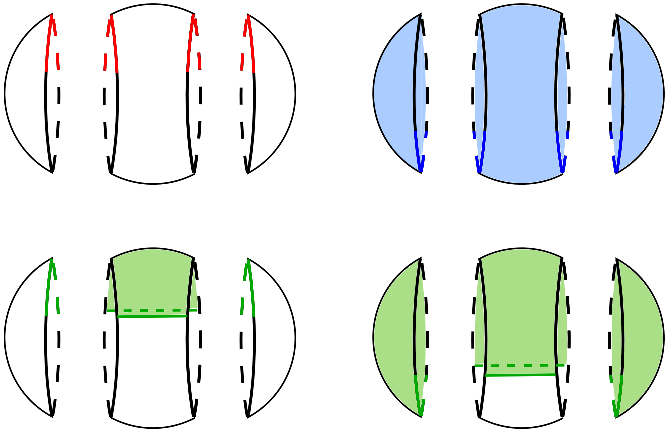
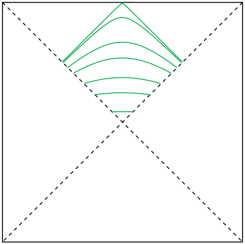


Anchor to horizon: subregions on both horizons

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 $\mathrm{dS}_{d>3}$.

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.

Does anchoring to a black hole event horizon make sense? Probe in AdS/CFT.

More general cosmologies cannot be encoded by pair of horizons; how should encoding work?

Microscopic model matching these features.