Entanglement and Connectivity

in de Sitter holography

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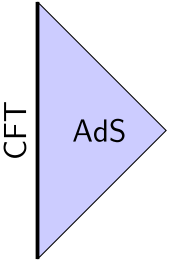
Based on:
Arxiv:2305.12861 (JHEP) with H. Partouche, F. Rondeau, and N. Toumbas.

Eurostrings, Southampton, 2024

Introduction

Holography:

Gravity on $\mathcal{B} \leftrightarrow$ QFT on $\partial\mathcal{B}$



A very useful tool: Connection between geometry and entanglement:

- Subregion-subregion duality [Dong, Harlow, Wall '16]
- Black hole information paradox [Penington '20, Almheiri et al. '20]
- ...
- **Emergence of spacetime** [Maldacena '03, Van Raamsdonk '10]

Entanglement builds bridges [Van Raamsdonk '10]

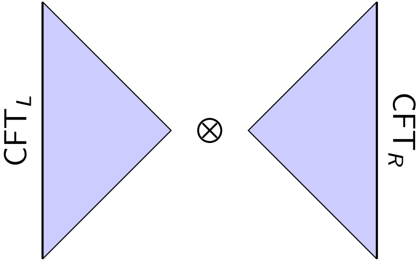
What happens if we entangle two identical CFT dual to AdS?

Eigenstates $|\Psi_i\rangle$ of energy E_i

$$|\Psi\rangle = |\Psi\rangle_L \otimes |\Psi\rangle_R$$

$$|\Psi\rangle = \sum_i e^{-\frac{\beta E_i}{2}} |\Psi_i\rangle_L \otimes |\Psi_i\rangle_R$$

("Thermofield-double state")



Two copies of AdS spacetime

?

Entanglement builds bridges [Van Raamsdonk '10]

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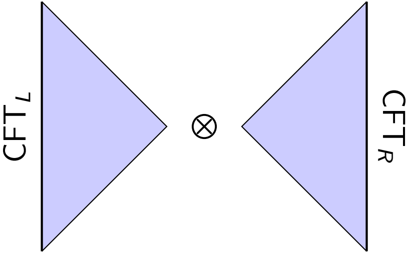
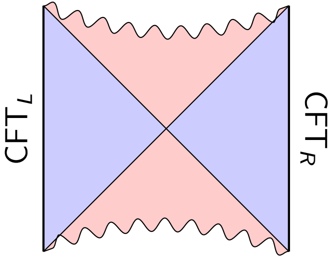
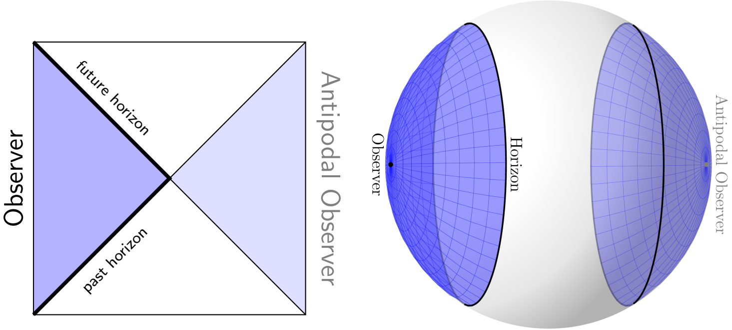


Two copies of AdS spacetime



AdS Black Hole

de Sitter space



- An observer cannot observe the full spacetime
  → **cosmological horizons**
- 2 **observers** at the poles have disconnected causal patches

Holographic description of de Sitter?

There is no spatial boundary → 3 interpretations

1. **No holographic principle** in dS

   ⟶ Unsatisfactory, what about the covariant entropy bound?...

2. **dS/CFT**: hologram located at null infinity $\mathcal{I}^+$ [Strominger '01]

3. **There are no dynamical degrees of freedom**

   ⟶ Consistent with path integral computations, and the island formula [Almheiri et al.'20]

Static patch holography

- Physically meaningful observables should be measured by an **observer**
- Explicitly including such observer is necessary to get a consistent theory! [Chandrasekaran et al. '22, Witten '23]
- Including an observer implicitly selects a static patch
- Static patch of the observer has an effective boundary

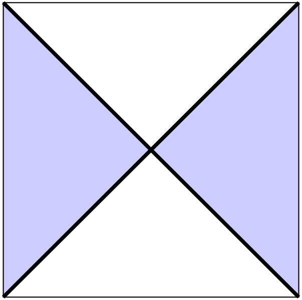
  $\Rightarrow$ Holographic d.o.f. located on the cosmological horizon

Static patch holography

- Natural interpretation of Bekenstein-Hawking formula

$$S_{BH} = \frac{\mathrm{Area(Horizon)}}{4G\hbar}$$

- Consistent with the covariant entropy bound [Bousso '99]



The state of the causal patch of an observer in de Sitter space is described by a quantum system defined on the cosmological horizon of the observer.

[Susskind '21]

A question

How can a closed and connected de Sitter spacetime emerge from a holographic theory that describes only open and finite regions of space-time?

A covariant entropy prescription in dS

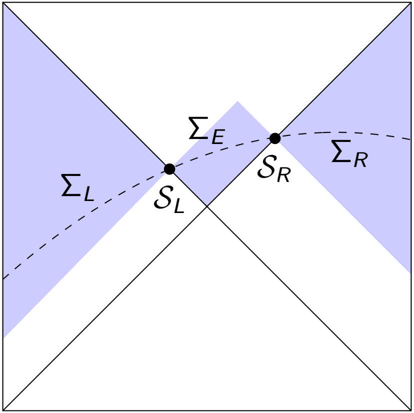
- In AdS/CFT, RT formula : **Geometry** $\leftrightarrow$ **Entanglement**
  [Hubeny, Rangamani, Takayanagi '07]

- The monolayer and bilayer proposals offer a modification of RT for the time-symmetric slice of dS [Susskind, Shaghoulian '21,'22] .

- We define a **covariant** holographic entropy prescription, taking into account quantum corrections
  [V.F., Partouche, Rondeau, Toumbas (FPRT) '23]

A covariant entropy prescription in dS

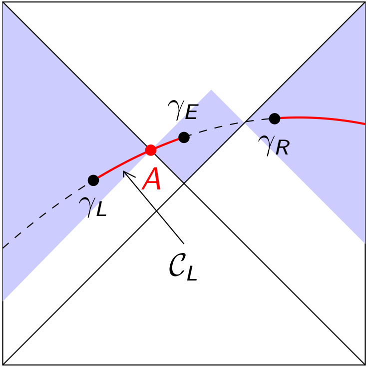
- Consider spatial slice of the screens
- Horizons define three bulk regions
- Entropy prescription ~ 3 coupled HRT prescriptions in 3 regions



A covariant entropy prescription in dS

Subsystem A of the screens $\mathcal{S}_L \cup \mathcal{S}_R$

- In each region R_i, look for the minimal quantum **extremal** surface **homologous** to A
- Homology: $\partial \mathcal{C}_i = \chi_i \cup (A \cap R_i)$

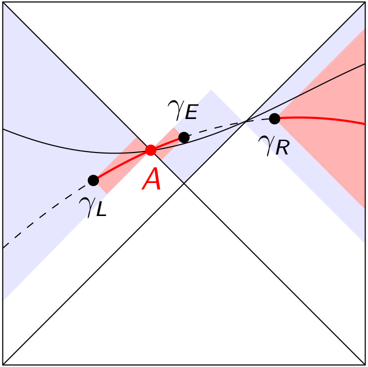


$$S(A) = \sum_i \frac{\mathrm{Area}(\chi_i)}{4G\hbar} + S_{\mathrm{semicl}}\Big(\bigcup_j \mathcal{C}_j\Big)$$

Entanglement wedges

Assuming **entanglement wedge** (EW) reconstruction [Wall '14] ,

- The union of the three causal diamonds of $\mathcal{C}_L$, $\mathcal{C}_E$, $\mathcal{C}_R$ is completely reconstructible from the subsystem A of the quantum theory



“Bridging the static patches”

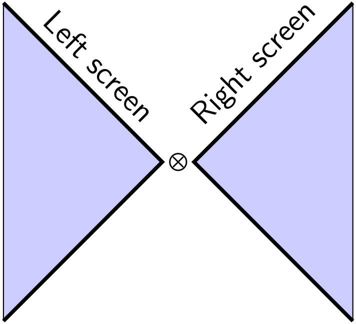
Consider $A = \mathcal{S}_L \cup \mathcal{S}_R$

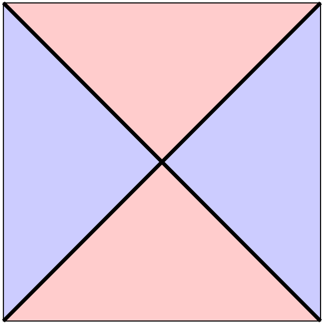
- $\varnothing \cup \mathcal{S}_i = \Sigma_i \quad \Rightarrow \varnothing$ is homologous
- $S(\mathcal{S}_{\rm L} \cup \mathcal{S}_{\rm R}) = 0 \quad \Rightarrow$ **Pure state**
- $\mathcal{W}(\mathcal{S}_{\rm L} \cup \mathcal{S}_{\rm R})$ covers complete Cauchy slices
- Conjecture [Shaghoulian 21’, FPRT ’23] : **The full de Sitter spacetime can be described holographically by a theory living on the two (stretched) horizons of antipodal observers.**

"Bridging the static patches"

Reminiscent of the double sided black hole in AdS

- Static patch: $\rho = e^{\beta H}$ $(\beta \to 0)$
- Thermofield-double state: $|\Psi_{\rm BD}\rangle = \frac{1}{\sqrt{Z}} \sum e^{-\frac{1}{2}\beta E_i} |\Psi_i\rangle_{\rm L} \otimes |\Psi_i\rangle_{\rm R}\,,$
- Entanglement between the screens $\leftrightarrow$ Exterior region





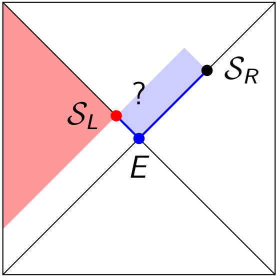
Entropy of an horizon

- At the classical level [Shaghoulian, Susskind '22],

$$S(\mathcal{S}_L) = \frac{\mathrm{Area}(\mathcal{S}_\mathrm{L})}{4G\hbar} + \mathcal{O}\left((G\hbar)^0\right)$$

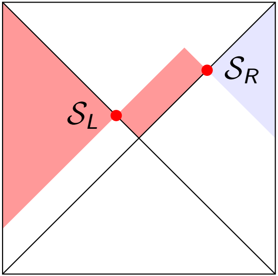
  → Entropy of the de Sitter horizon [Gibbons, Hawking '77]

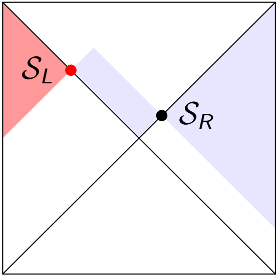
- γ_E is **degenerate** → EW not determined at the classical level



A phase transition for the entanglement wedges

- First order quantum corrections produce a **phase transition**
- Two competing quantum extremal surfaces: $\mathcal{S}_L$ and $\mathcal{S}_R$
- One of the screens always encodes the exterior
- Transfer of a type III compex factor from $\mathcal{W}(\mathcal{S}_L)$ to $\mathcal{W}(\mathcal{S}_R)$?
  [Engelhardt, Liu '23]





Conclusion

1. Defined a covariant prescriptions to compute holographic entanglement entropies in de Sitter space
2. Extension of static patch holography where the whole spacetime is encoded
3. Spatial connection between the static patches emerges from entanglement
4. Exchange of dominance between quantum extremal surfaces $\leftrightarrow$ Transfer of entanglement wedge between the screens

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