Title: Baby Universes and Holography II: Observer Complementarity

Speakers: Elliott Gesteau

Collection/Series: QIQG 2025

Subject: Quantum Gravity, Quantum Information

Date: June 27, 2025 - 12:00 PM

URL: https://pirsa.org/25060026

Abstract:

The notion of complementarity, first introduced in the context of the information paradox, posits that the experiences of two observers who cannot communicate need not match in quantum gravity. In the context of the previous talk, I will argue that the recent proposals for explicitly taking observers into account provide a way to describe semiclassical closed universes in holography, at the expense of a resort to complementarity. I will then discuss an analogous setup in the case of an evaporating black hole, and propose a set of general principles for black hole complementarity.

This talk is based on an ongoing collaboration with Netta Engelhardt and Daniel Harlow.

BABY UNIVERSES AND HOLOGRAPHY

II - OBSERVER COMPLEMENTARITY

Elliott Gesteau (Caltech/KITP)

2507:xxxxx with Netta Engelhardt and Daniel Harlow

PUZZLE FROM NETTA'S TALK

- Netta's talk: **violations of the extrapolate dictionary** if we try to encode a more than one-dimensional baby universe into the CFT. [Engelhardt, EG '25]
- Puzzling: seems to **forbid closed cosmologies** altogether in AdS/CFT!

A CAVEAT

- Let's be careful about the **Heisenberg cut!**
- In traditional AdS/CFT, the observer looks at the system **from outside** (manipulates the CFT in their lab).
- They are **not gravitating** in the bulk.
- Daniel's talk: taking the observer into account **enlarges the Hilbert space** in closed universes. [Harlow, Usatyuk, Zhao '25][Abdalla, Antonini, Iliesiu, Levine '25]
- Can we do the same here?

OBSERVER COMPLEMENTARITY

- We can do this, but a **price to pay**: the experience of the observer in the closed universe **will not match** the one of the observer outside.

- This is a form of **complementarity**: the two observers live in different connected components of spacetime and **will never communicate.** [Susskind, Thorlacius, Uglum '93]

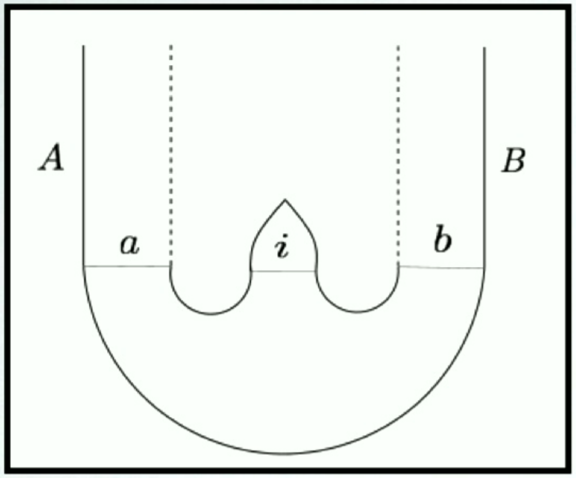
- **Complementarity:** very popular pre-AMPS, mostly evaded in islands/nonisometric codes… But here it **strikes back!**

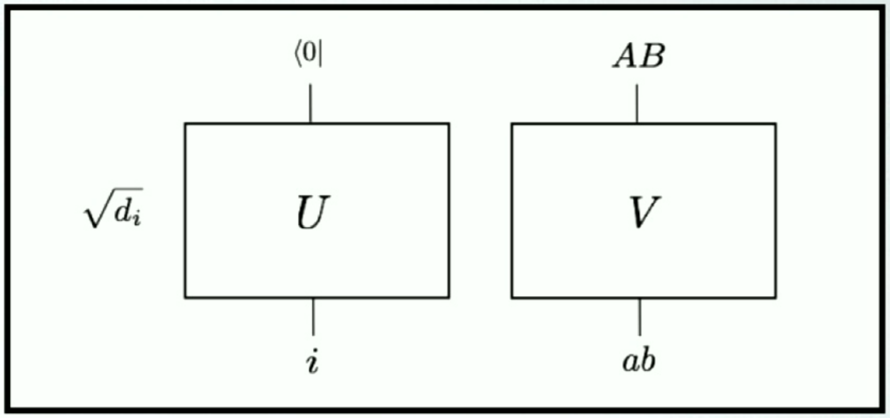
OUTLINE

- **I - Observers in Antonini—Rath**
- **II - Observers in evaporating black holes**
- **III - Principles for black hole complementarity**

I - Observers in Antonini—Rath

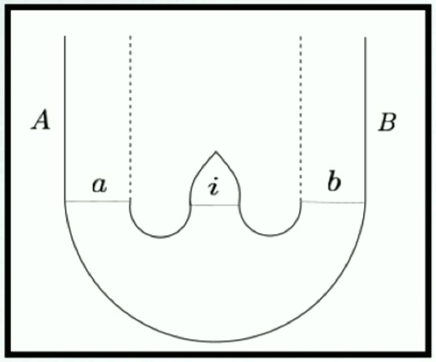
A CODE MODEL

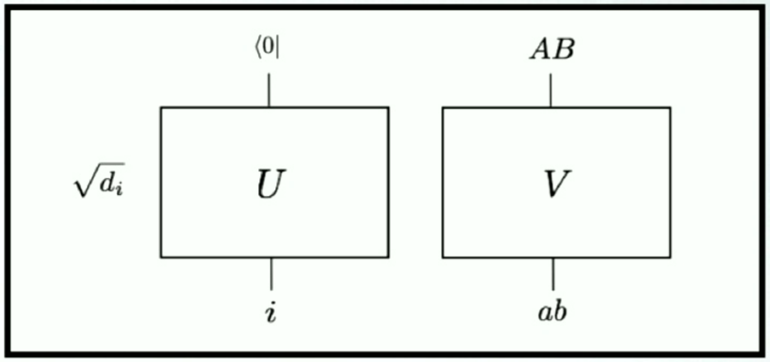




- U random unitary, V HKLL isometry.

OBSERVER OUTSIDE THE SYSTEM



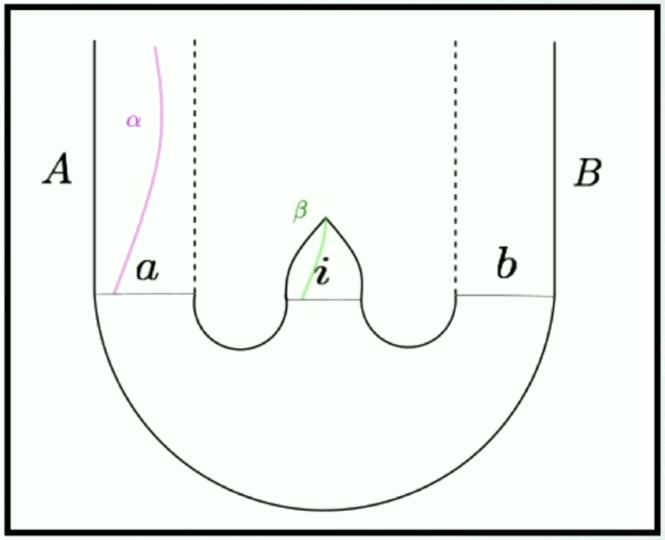


- This case (usual AdS/CFT) was treated during Netta's talk. [Engelhardt, EG '25]

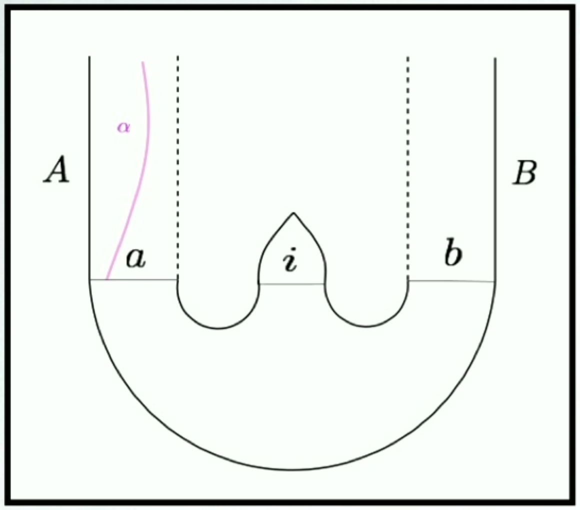
- We find that the code violates the extrapolate dictionary: $\langle \mathcal{S} \rangle \sim e^{-S\left(\phi_i^{(1)}\right)}$. $\langle \mathcal{S}_\partial \rangle = \langle V \mathcal{S} V^\dagger \rangle = 1.$

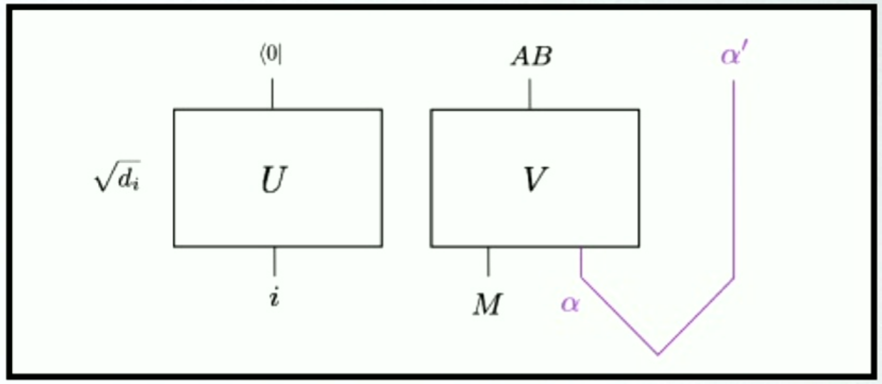
POSSIBLE OBSERVERS

- In usual AdS/CFT, **outside** the system.
- α in the **causal wedge**.
- β in the **baby universe**.
- What happens if we apply the **observer rule** [Harlow, Usatyuk, Zhao '25] to them?



OBSERVER IN THE CAUSAL WEDGE

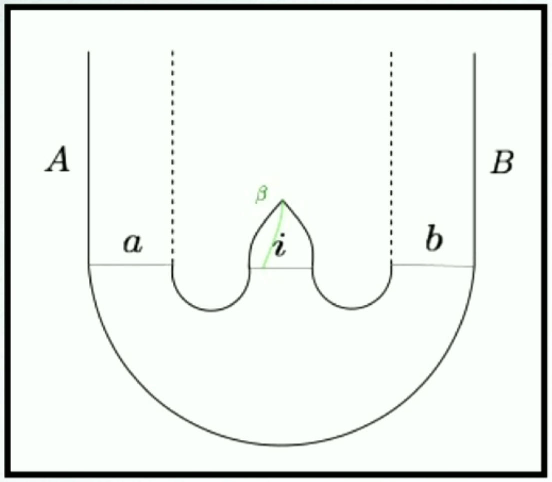


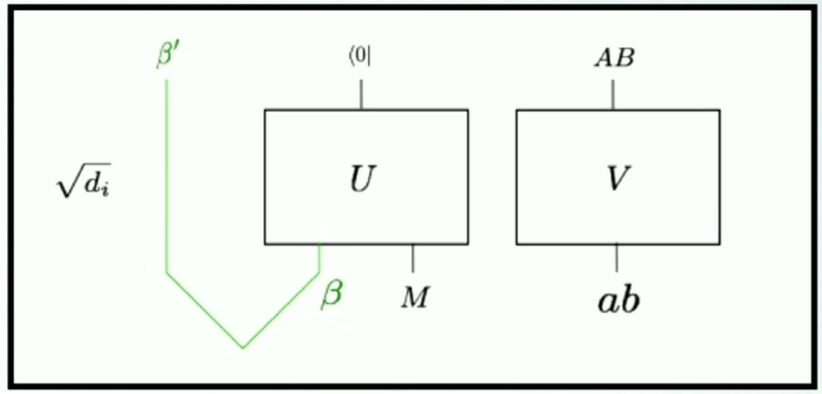


- If we **swap** the matter, we still obtain:

$$\langle \mathcal{S}^M \rangle \sim e^{-S\left(\phi_i^{(1)}\right)}. \qquad \langle \mathcal{S}_\partial^M \rangle = 1.$$

OBSERVER IN THE BABY UNIVERSE





- If we **swap** the causal wedge, we now obtain

$$\langle \mathcal{S} \rangle \sim e^{-S\left(\phi_i^{(1)}\right)}. \qquad \langle \mathcal{S}_\partial \rangle \sim \max\left\{ e^{-S\left(\phi_i^{(1)}\right)}, e^{-S_\beta} \right\}.$$

- The extrapolate dictionary is **fixed**! (Up to e^{-S_β}.)

II - Observers in evaporating black holes

COMPLEMENTARITY

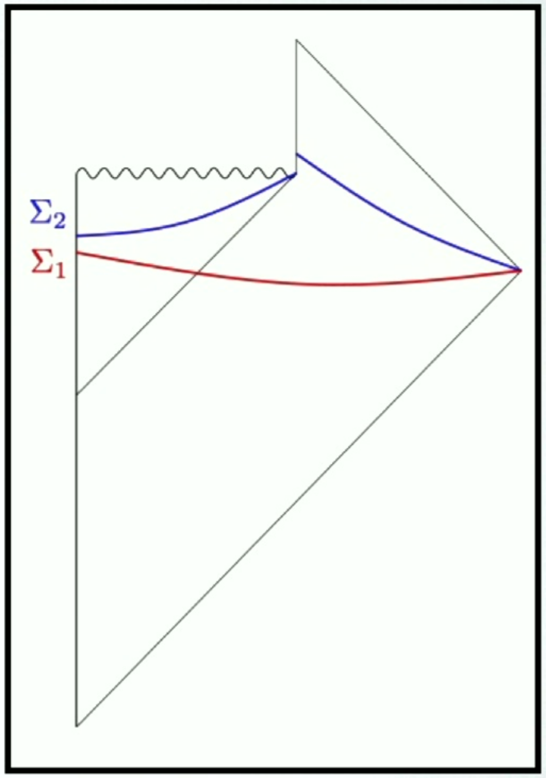
- The expectation values of the HKLL reconstruct S_∂ of the swap operator are **not the same** in the fundamental descriptions of α and β !

- α finds an expectation value of **one**: predicts a vanishing baby universe.

- β finds a **small** expectation value, consistent with a semiclassical baby universe.

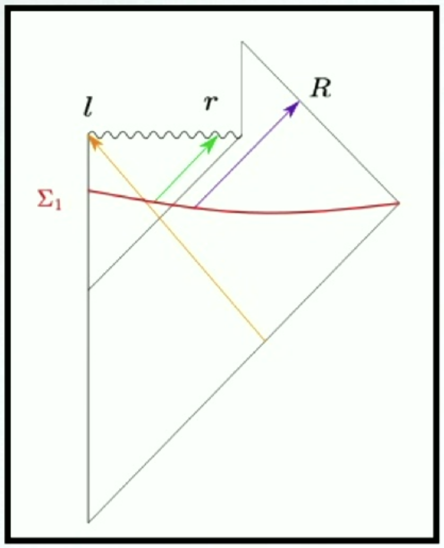
EVAPORATING BLACK HOLES

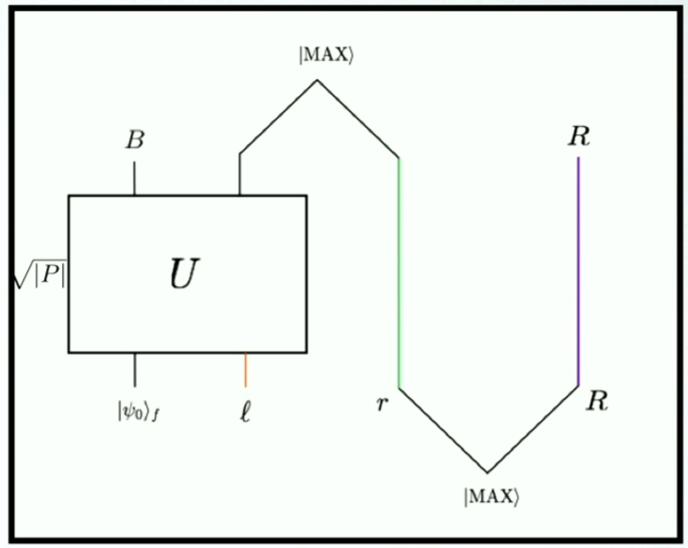
- On slice Σ_1 the black hole is **after the Page time** but its horizon is still macroscopically large.
- On slice Σ_2 the black hole is **fully evaporated**. Interior: **baby universe** disconnected at the singularity.



THE CODE ON THE FIRST SLICE

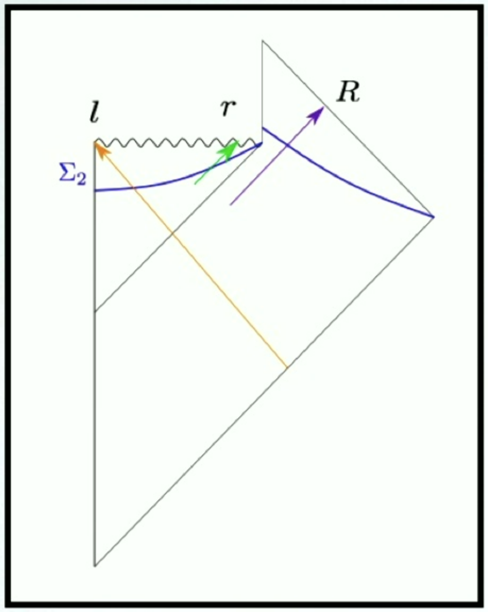
[Akers, Engelhardt, Harlow, Penington, Vardhan '22]

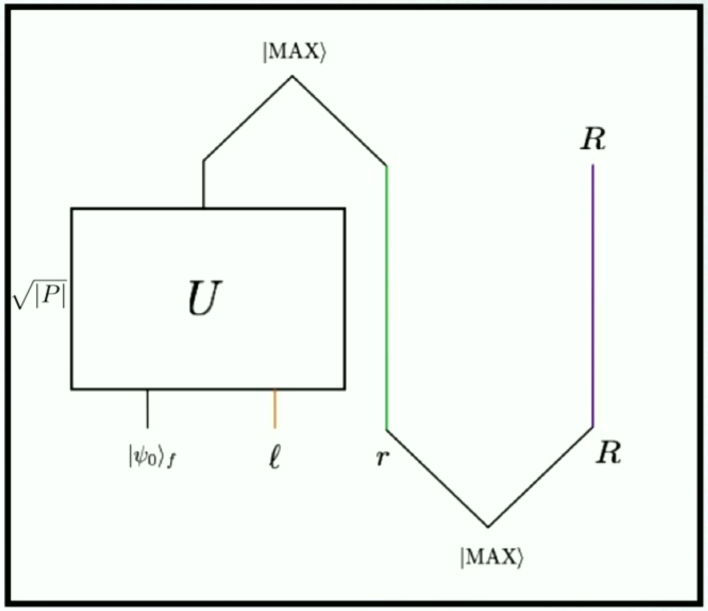




- **Nonisometric code:** inner product preserved for low complexity observables up to $\mathcal{O}\left(\frac{1}{|B|}\right)$.
- This allows to describe **subexponentially complex** interior physics very well, from the point of view of both observers.

THE CODE ON THE SECOND SLICE





- Now there is a **rank one projection** on the interior!
- Can think of it as a **baby universe.**

SWAP TEST ON RADIATION

- For α,

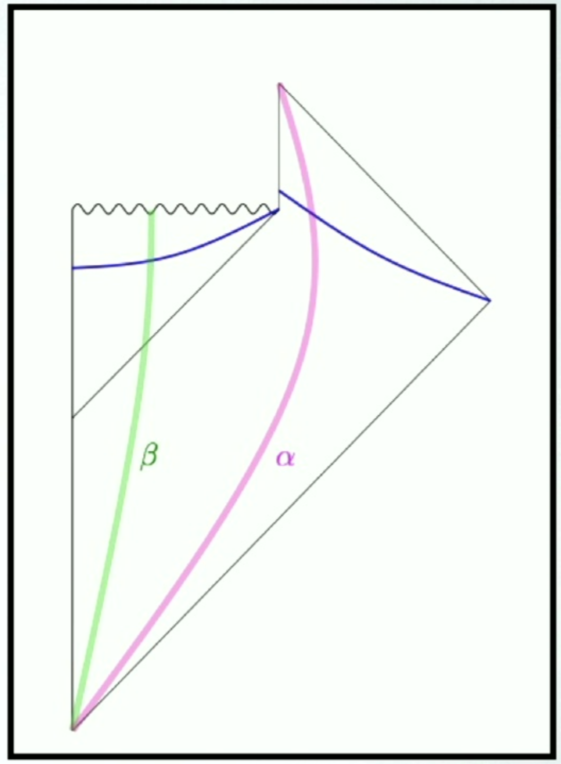
  $\langle \mathcal{S} \rangle \sim e^{-S_{\rm rad}^{\rm fin}}.$

  $\langle \mathcal{S}_\partial \rangle = 1.$

- For β,

  $\langle \mathcal{S} \rangle \sim e^{-S_{\rm rad}^{\rm fin}}.$

  $\langle \mathcal{S}_\partial \rangle \sim \max\left\{ e^{-S_{\rm rad}^{\rm fin}}, e^{-S_\beta} \right\}.$

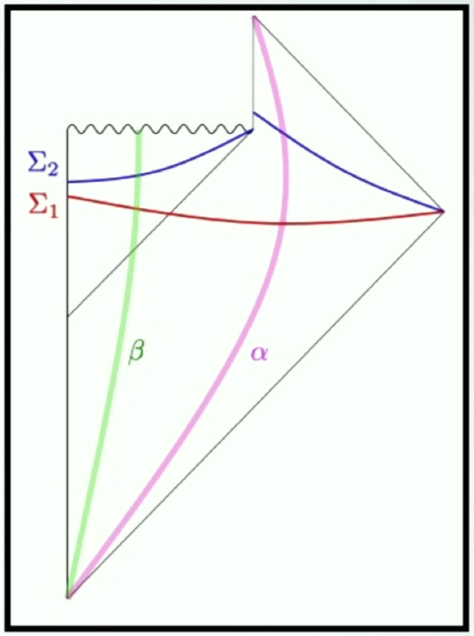


III - Principles for black hole complementarity

SUMMARIZING THE DATA

Σ_1	$\langle S_\partial \rangle$
α	$1/(\dim \mathcal{H}_{BH}^{\text{fund}})$
β	$\lesssim e^{-S_\beta}$
Hawking	$1/(\dim \mathcal{H}_{\text{rad}}^{\text{eff}})$

Σ_2	$\langle S_\partial \rangle$
α	1
β	$\lesssim e^{-S_\beta}$
Hawking	$e^{-S_{\text{rad}}^{\text{fin}}}$



- α finds results consistent with the unitarity of black hole evaporation.
- β agrees with **Hawking** up to exponentially small errors in their entropy.
- Also works for more questions like **complexity of reconstruction** (being careful about the singularity).

PRINCIPLES FOR COMPLEMENTARITY

- **Principle 1:** Observer α finds results consistent with **unitarity** of black hole evaporation.

- **Principle 2:** Observer β finds results consistent with **Hawking's calculation** up to exponentially small errors in their own entropy for every **subexponentially complex** operation in their entropy (within the semiclassical picture).

- **Principle 3:** Observers α and β must agree up to exponentially small errors in their own entropy when they perform operations within effective field theory that can be **causally communicated** between them.