Title: Gravity As An Oracle (Vision Talk)

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Subject: Quantum Gravity, Quantum Information

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Abstract:

Our search for a quantum theory of gravity is aided by a unique and perplexing feature of the classical theory: General Relativity "knows" about its own quantum states (the entropy of a black hole), and about those of all matter (via the Quantum Focusing Conjecture). The results we are able to extract from classical gravity are inherently non-perturbative and increasingly sophisticated. Recent breakthroughs include a derivation of the entropy of Hawking radiation, a computation of the exact integer number of states of some black holes, a proof of the QFC, and the construction of gravitational holograms in general spacetimes. The nature of the oracle, and its full power, remain unknown.

A. Gravity As an Oracle
B. Holograms in General Spacetimes

Raphael Bousso, UC Berkeley

I. Gravity knows about its own quantum states

Hawking (1974): black holes radiate. This shocked people, because classically black holes cannot emit anything. But classically, ordinary matter cannot radiate either.

The real surprise is that Hawking was able to compute exactly how a black hole radiates: thermally, at a particular temperature. From this, he could deduce the number of quantum states of a black hole, $\exp(A/4G)$, where A is the area of the horizon.

This is outrageous, because Hawking made no assumptions about the microscopic structure of a black hole; nor did he have a black hole in his lab that he could heat up. Classical gravity appears to know about its own quantum states.

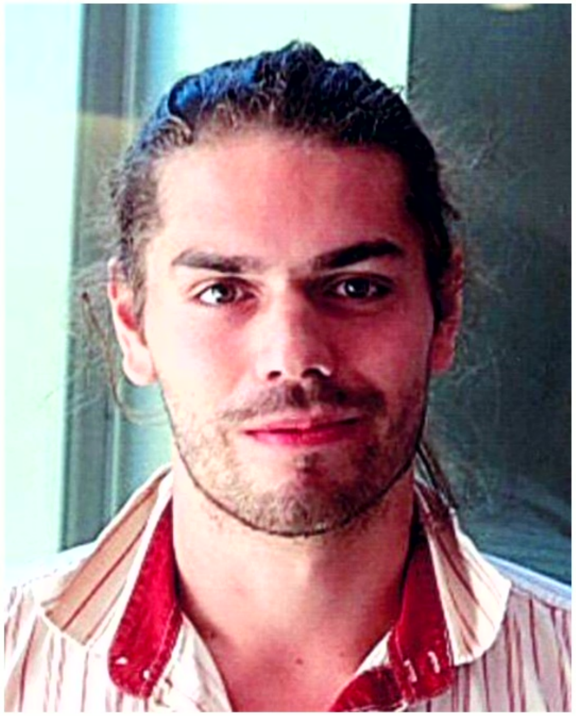
I. Gravity knows about its own quantum states

Recent development:

Iliesiu, Murthy, and Turiaci (2022) were able to compute the exact integer number of states of a black hole using only gravity.

The gravitational path integral receives an infinite number of contributions from geometries allowed by general relativity, none of which are integers.

But the terms coincide with the Hardy-Ramanujan-Rademacher expansion developed in analytic number theory for integer partitions. It sums up to an integer.



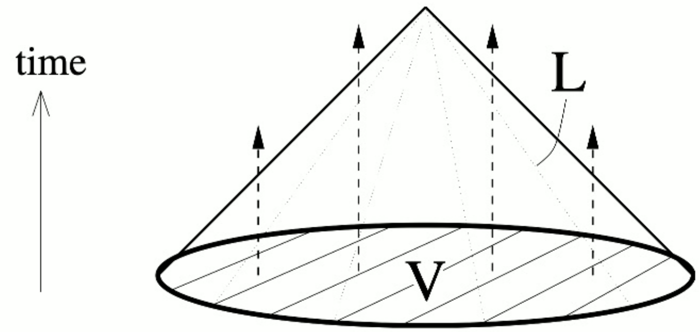
II. Gravity knows about the quantum states of matter

Generalized Second Law (Bekenstein 1972):

$$\delta A > -\delta S$$

$\Longleftarrow$ Covariant Entropy Bound (RB 1999):

$$S_{\text{matter}}(L) \leq \frac{A}{4G\hbar}$$



$\Longleftarrow$ Quantum Focusing Conjecture (RB, Fisher, Leichenauer, Wall 2015):

$$\Theta' \leq 0 \, .$$

II. Gravity knows about the quantum states of matter

The Quantum Focusing Conjecture has an immediate, highly nontrivial implication for Quantum Field Theory without gravity.

Quantum Null Energy Condition (RB, Fisher, Leichenauer, Wall 2015):

$$T_{kk} \geq \frac{\hbar}{2\pi} S''$$

Proven (laboriously) in QFT (Ceyhan, Faulkner 2018).

General Relativity has become a precise, quantitative discovery tool for the quantum description of matter.

III. Gravity knows about the entropy of the quantum gravity theory

What is the entropy of the CFT quantum state reduced to a portion B of the boundary?

Classical gravity can answer this question (Ryu-Takayanagi 2006, Hubeny et al. 2007): the area of the minimal stationary bulk surface γ homologous to B.

$$S(B) = \frac{A[\gamma]}{4G}$$

GR performs the replica trick: it computes all integer Renyi entropies and performs an analytic contination to the von Neumann entropy ($n = 1$). Lewkowycz, Maldacena 2013

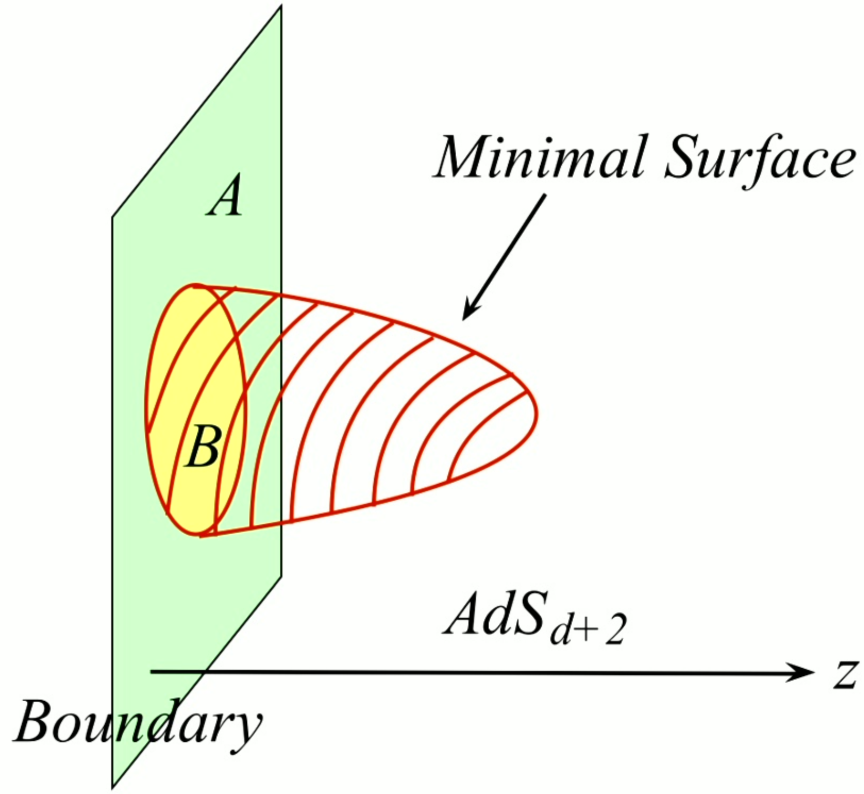


Figure: Nishioka et al. 2009

III. Gravity knows about the entropy of the quantum gravity theory

This can be used to prove the Quantum Focusing Conjecture!

Shahbazi-Moghaddam 2022

More precisely, Arvin proved a slightly weaker form of the conjecture, which nevertheless suffices for all known applications (covariant bound, GSL, singularity theorems, causal wedge is inside entanglement wedge, SSA of EW, etc.)

In fact the conjecture can be stripped down further: “Discrete Max Focusing”

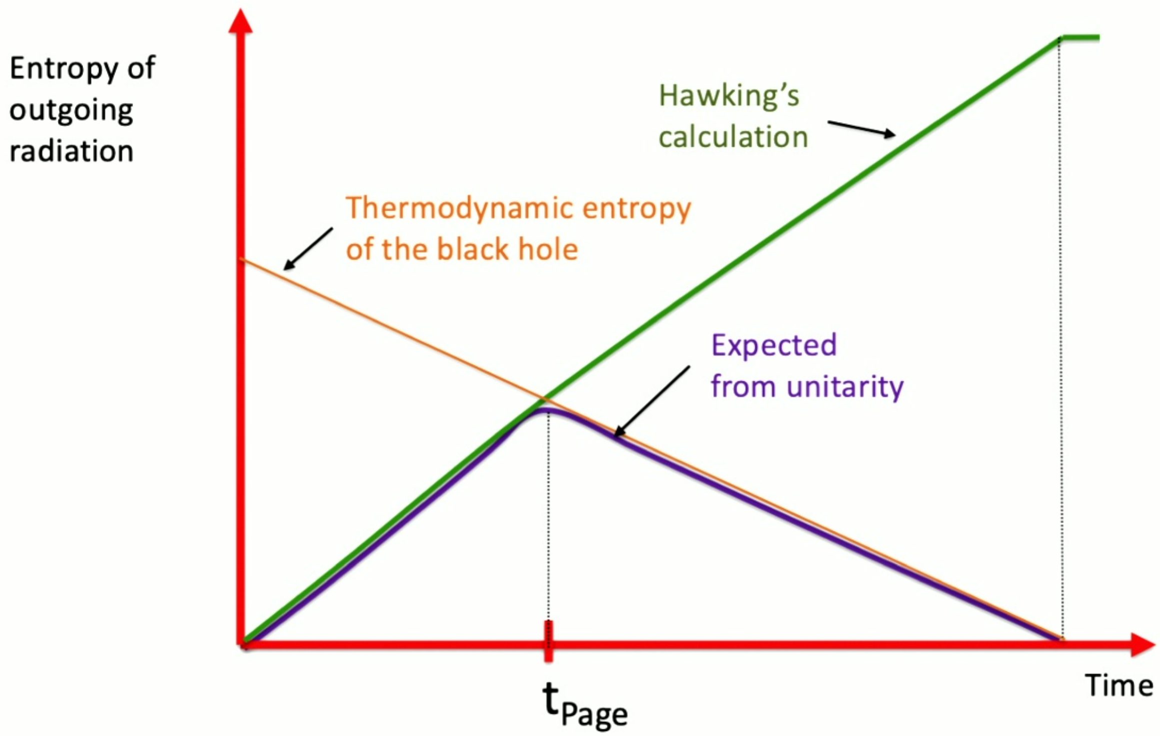
RB, Tabor 2024

III. Gravity knows about the entropy of the quantum gravity theory

This prescription for the entanglement wedge has been refined over the years: Ryu, Takayanagi (2006); Hubeny et al. (2007), Faulkner et al. (2013).

The Quantum Extremal Surface prescription (Engelhardt, Wall 2014) is essential for the Page curve result (see later).

IV. Gravity knows that quantum information is ~~lost~~ preserved



Hawking (1976) found that information about the initial quantum state is lost when a black hole evaporates: the entropy of the Hawking radiation grows monotonically.

IV. Gravity knows that quantum information is ~~lost~~ preserved

The Quantum Extremal Surface prescription computes the entropy of the radiation directly, without first computing ρ.
Penington 2019
Almheiri, Engelhardt, Marolf, Maxfield 2019

Recall that GR performs the replica trick: it computes all integer Renyi entropies and performs an analytic contination to the von Neumann entropy ($n = 1$).
Lewkowycz, Maldacena 2013
Penington et al. 2019
Almheiri et al. 2019

IV. Gravity knows that quantum information is ~~lost~~ preserved

Contradiction?

Suppose that the gravitational path integral computes some kind of average. Then it is consistent that $\overline{S(\rho)} \neq S(\overline{\rho})$.

What is this average, in general? More broadly, how does the oracle work?

RB, Tomasevic 2019

RB, Wildenhain 2020

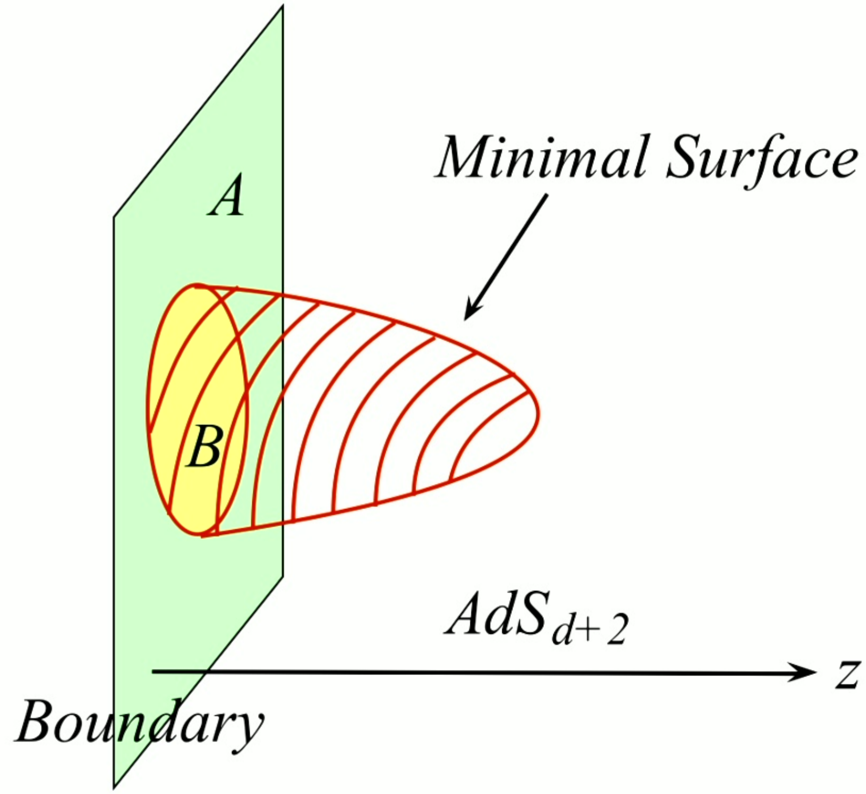
V. Gravity knows the reach of quantum gravity

What portion of the AdS bulk is determined by the CFT quantum state reduced to a portion *B* of the boundary?

Classical gravity can answer this question (Wall 2014): the homology region enclosed by the minimal stationary bulk surface.

The reconstructible region is called the entanglement wedge of the boundary region *B*.

Figure: Nishioka et al. 2009

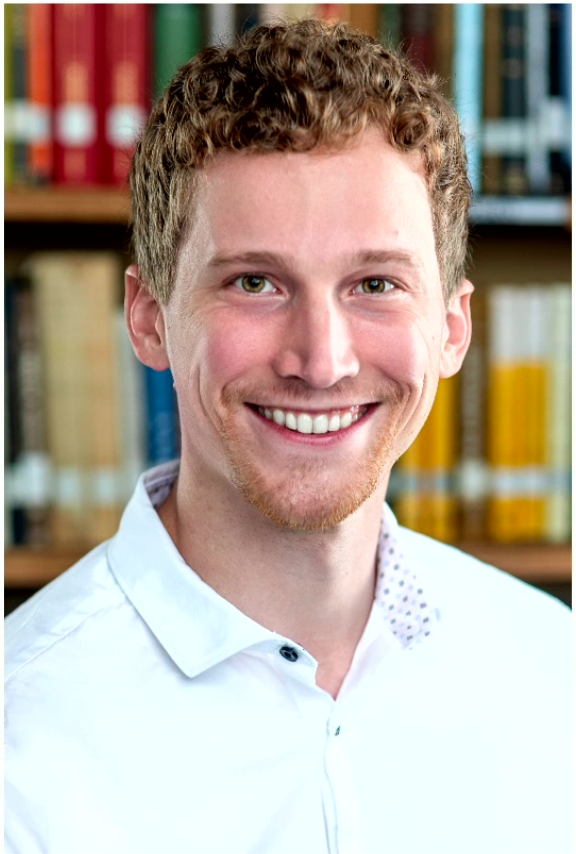


V. Gravity knows the reach of quantum gravity

Recent refinement: to determine the size of the entanglement wedge, gravity treats the areas of surfaces as a resource for a specific single-shot communication task.
Akers, Penington 2020

The max-entanglement wedge, e_{max}, is the largest region such that quantum state merging across across any intermediate homology surface can be performed using its area as a resource.

The min-entanglement wedge, $e_{\text{min}} \supset e_{\text{max}}$, is defined in terms of a weaker reconstruction task. It obeys complementarity: if $\bar{B}$ is the boundary complement of B, then $e_{\text{min}}(B)$ is the bulk complement of $e_{\text{max}}(\bar{B})$.



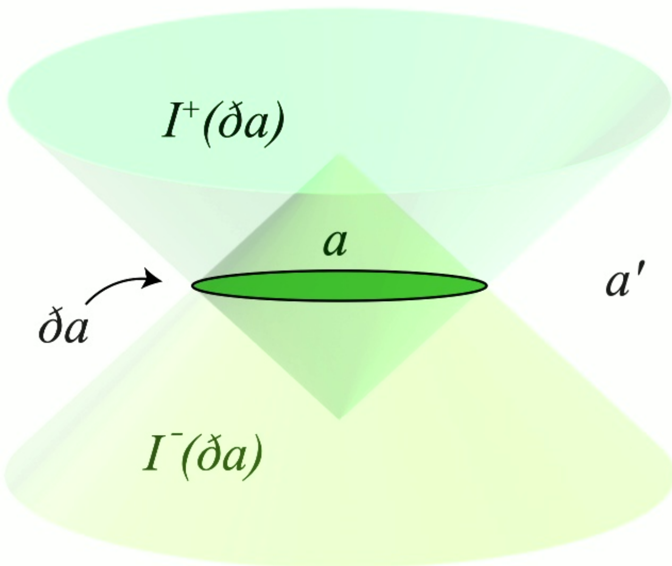
V. Gravity knows the reach of quantum gravity

If not for the vagaries of its discovery, the entanglement wedge of an AdS boundary region B would simply be called the hologram of B.

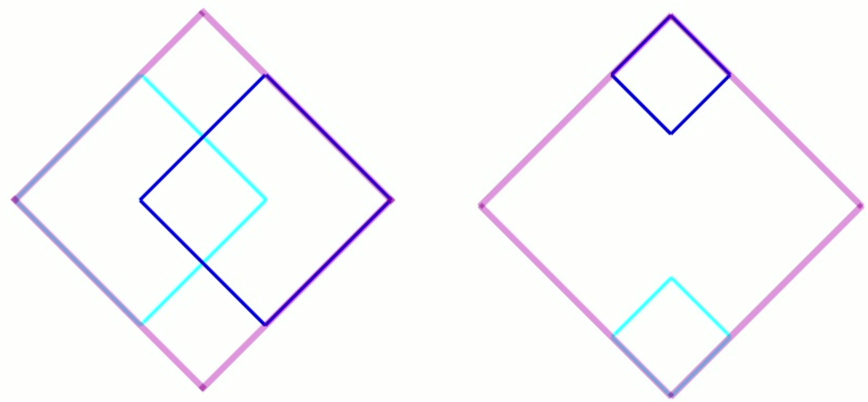
Its construction is entirely (semi-)classical and unrelated to the AdS setting.

Therefore, the gravitational construction of holograms should generalize beyond AdS!

Basic Idea



The fundamental causal unit in the bulk is a wedge, a set that is equal to its double spacelike complement: $a = a''$. Unions of wedges are always double-complemented.



Basic Idea

The hologram is a map from an “input” bulk wedge *a* to an equal or larger bulk wedge *e*(*a*). RB, Penington (2021, 2022)

The homology condition of AdS/CFT becomes two requirements. First, *e*(*a*) must contain the input wedge *a*. This is analogous to requiring that the asymptotic boundary of EW(*B*) in AdS contain the CFT region *B*.

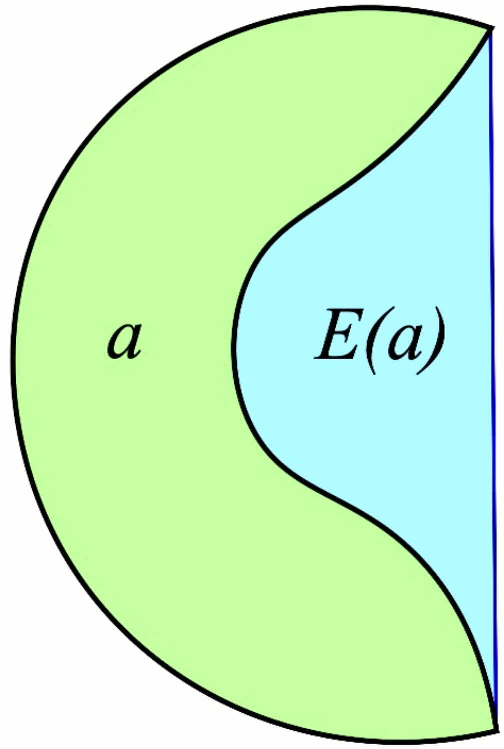


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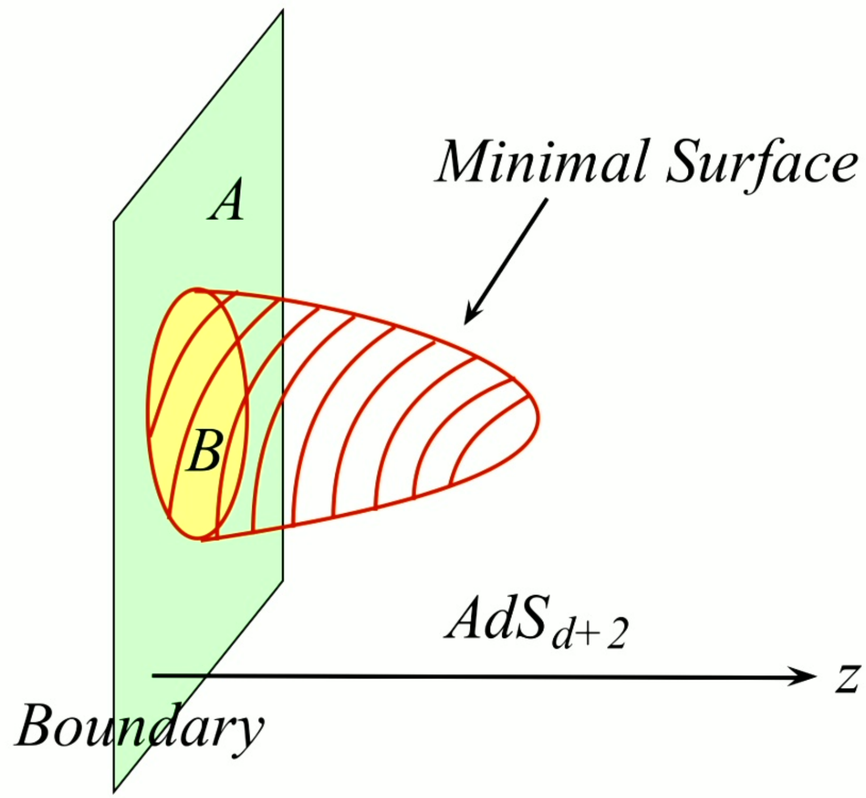
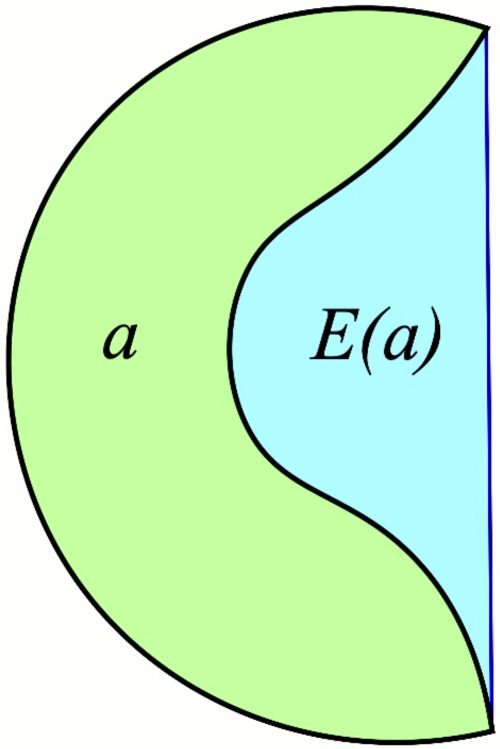
Figure: Nishioka et al. 2009



Basic Idea

The hologram is a map from an "input" bulk wedge a to an equal or larger bulk wedge $e(a)$. RB, Penington (2021, 2022)

The homology condition of AdS/CFT becomes two requirements. First, $e(a)$ must contain the input wedge a. This is analogous to requiring that the asymptotic boundary of EW(B) in AdS contain the CFT region B.



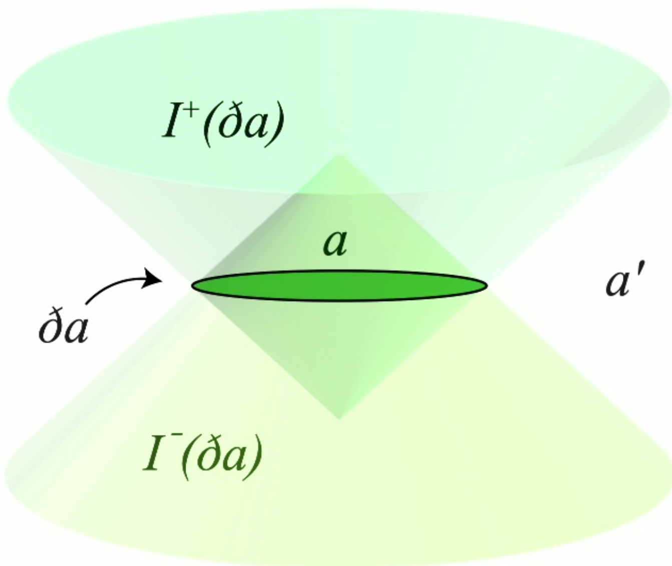
Basic Idea

Second, $e(a)$ must be spacelike to $\tilde{a}$, the "fundamental complement" of a. This is analogous to requiring that the asymptotic boundary of $\mathrm{EW}(B)$ must not overlap with $\bar{B}$.

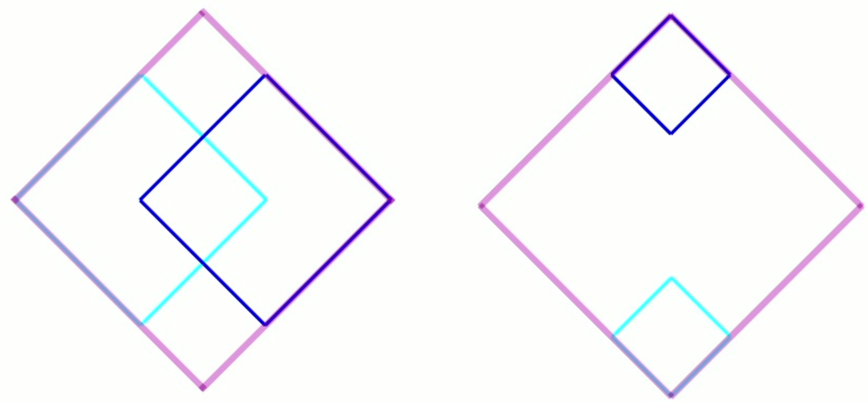
$\tilde{a}$ is the wedge spanned by doubly-infinite-length timelike curves that stay within the spacelike complement a'.

RB, Kaya 2025

Basic Idea



The fundamental causal unit in the bulk is a wedge, a set that is equal to its double spacelike complement: $a = a''$. Unions of wedges are always double-complemented.

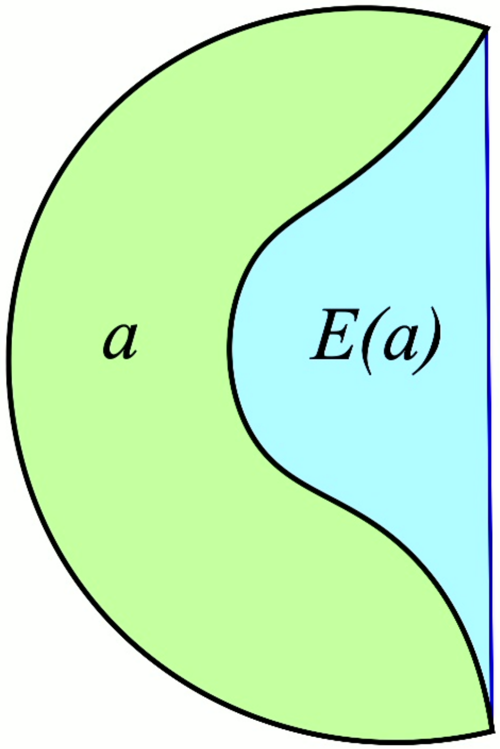


Hologram of a Bulk Region *a*

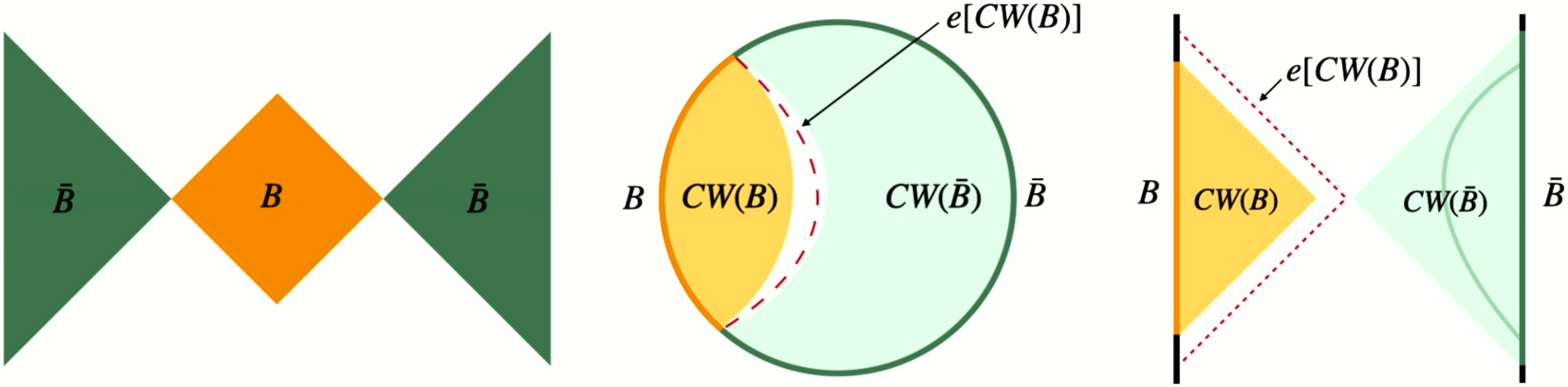
Among all wedges that contain *a* and are contained in $\tilde{a}'$,

and which are quantum extremal except on the edge of *a*,

e(*a*) is the wedge with smallest generalized entropy.



Evidence for Holograms of Bulk Regions



The AdS prescription can be recovered as a special case:

$$\mathrm{maxEW}(B) = e_{\mathrm{max}}[\mathrm{CW}(B)]$$

Evidence for Holograms of Bulk Regions

Nesting, no-cloning, and min- and max-strong subadditivity: For *a*, *b*, *c* mutually spacelike wedges satisfying

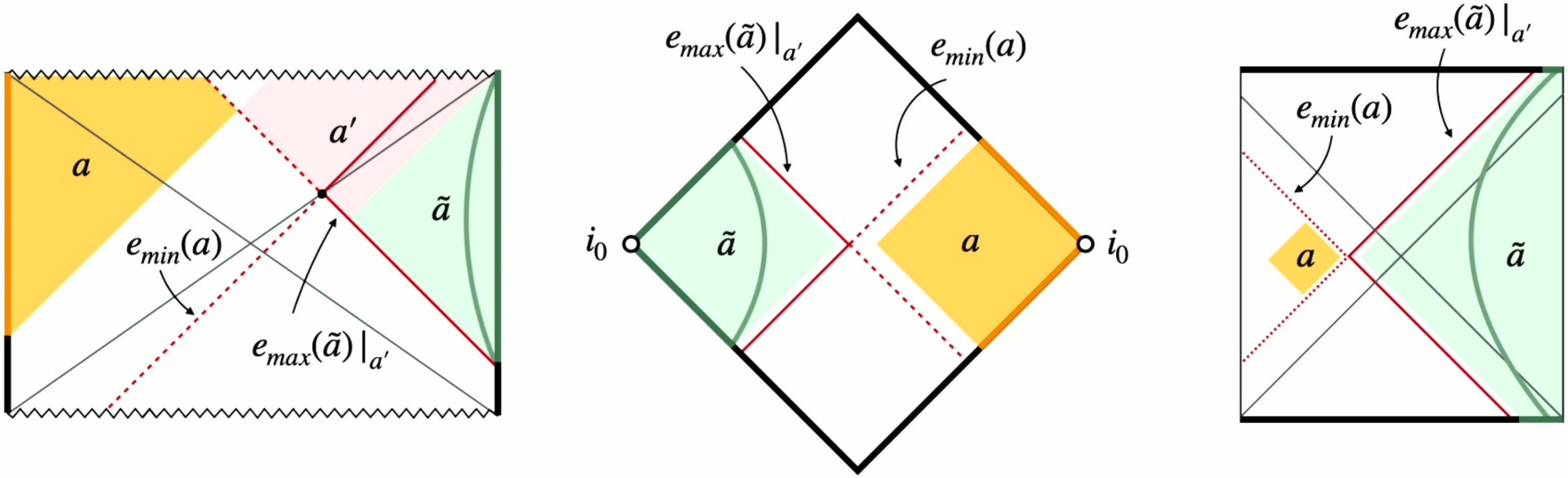
$$e_{\min}(ab) = e_{\max}(ab)\ ,\ e_{\min}(bc) = e_{\max}(bc)\ ,$$
$$e_{\min}(b) = e_{\max}(b)\ ,\ \text{and } e_{\min}(abc) = e_{\max}(abc)\ ,$$

$e = e_{\min} = e_{\max}$ satisfies

$$H_{\max,\text{gen}}[e(bc)|e(b)] \geq H_{\max,\text{gen}}[e(abc)|e(ab)]\ ;$$
$$H_{\min,\text{gen}}[e(bc)|e(b)] \geq H_{\min,\text{gen}}[e(abc)|e(ab)]\ .$$

RB, Penington (2023)
RB, Tabor (2024)

New Evidence: Complementarity Theorem



$$e_{\min}(a)' = e_{\max}(\tilde{a})|_{a'}$$

Kaya

Towards Gravity/Gravity Duality

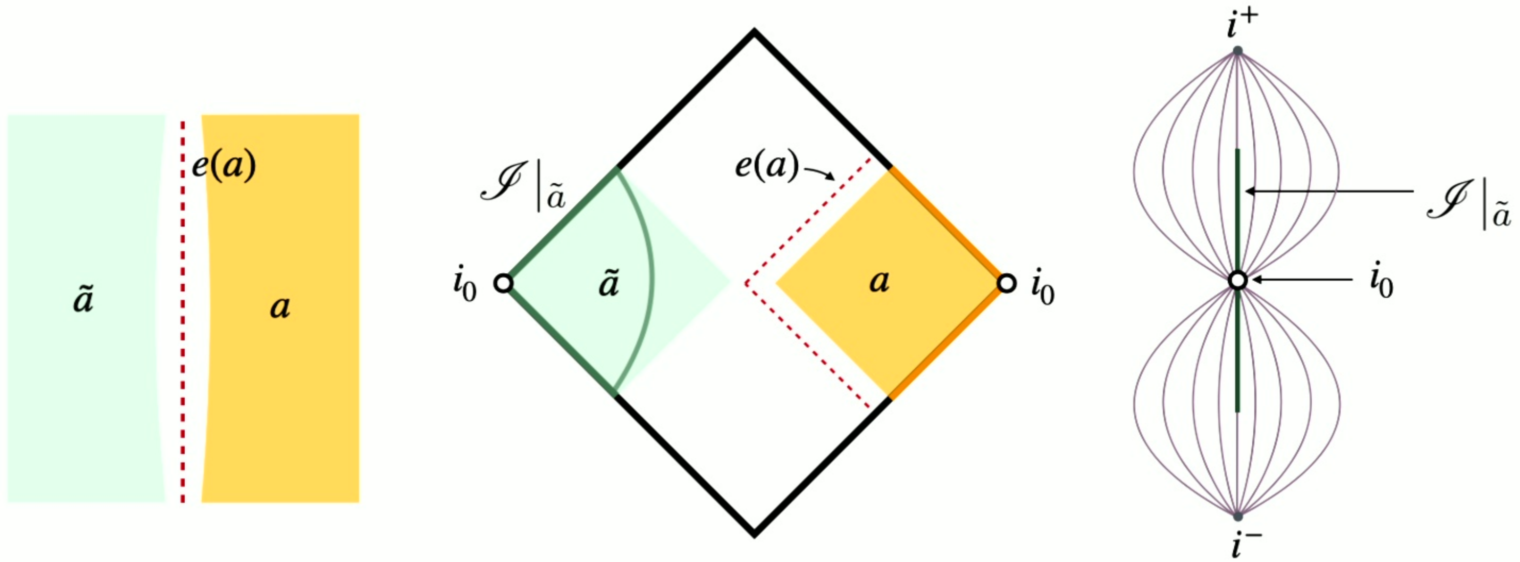
These properties support the interpretation of $e(a)$ as an algebra in the fundamental theory. They suggest that it is possible to reconstruct holographically from gravitating (bulk) regions.

The precise meaning of this statement is not yet clear.

A possible interpretation is that the semiclassical operators in the input region a generate the full algebra of the fundamental theory pertaining to $e(a)$.

An example where we can make this precise is if a is an asymptotic bulk region in AdS. The quasi-local bulk operators in a are local CFT operators, and those can generate the full CFT algebra.

Further examples



Rindler wedge in asymptotically flat spacetime with generic matter content. The matter focuses the Rindler horizons, causing the gaps between the edges of $\tilde{a}$, $e(a)$, and a. *Left:* Portion of a Cauchy slice containing all edges. *Middle:* Penrose diagram. *Right:* Conformal infinity.

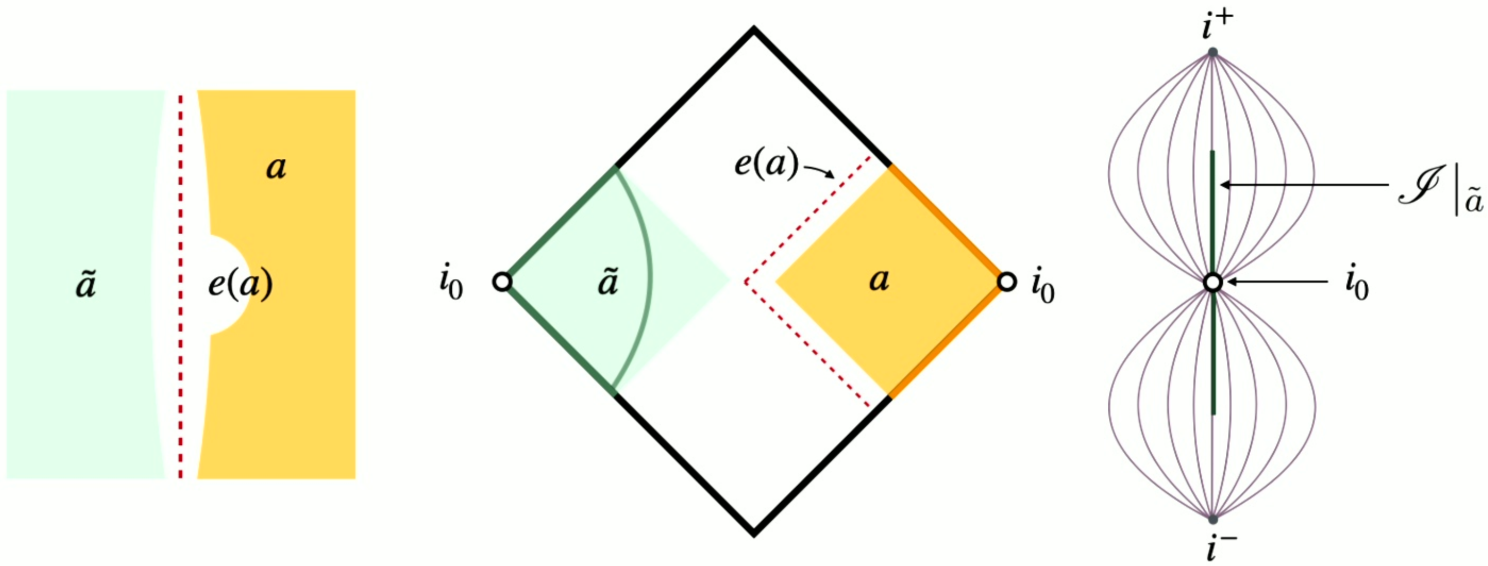
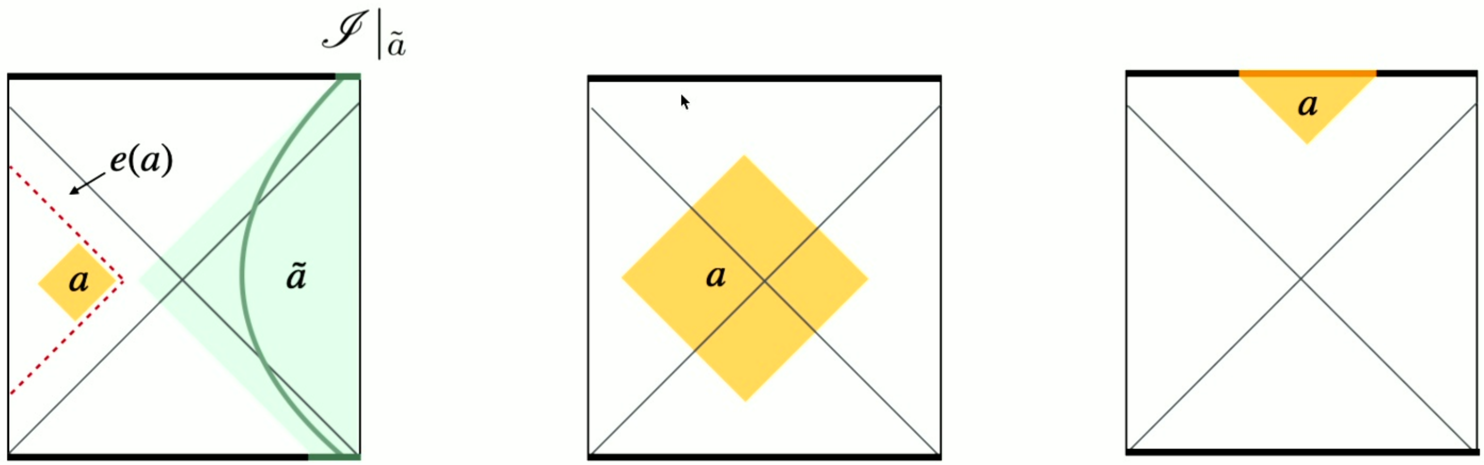
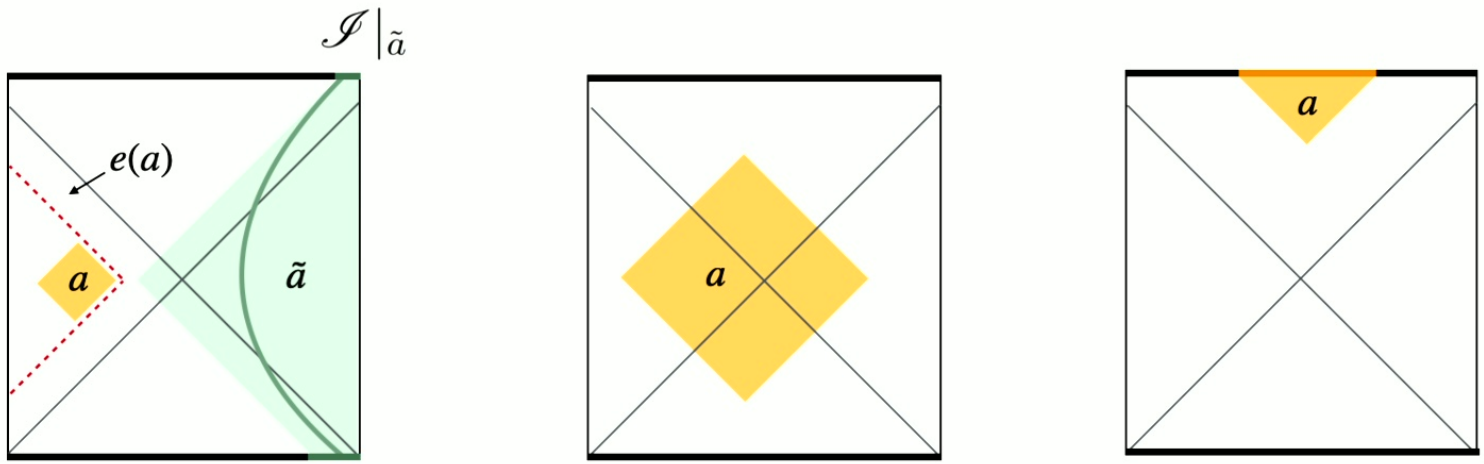


Figure: Here a is a Rindler wedge with a notch (a spacelike inward deformation. Again the gaps are generic, but $e(a)$ always fills in the notch. In exact Minkowski, $\tilde{a}' = e(a)$ would be an undeformed Rindler wedge. (The Penrose diagram does not show the notch.)



Left: Shell contained in a single static patch of de Sitter space. The fundamental complement $\tilde{a}$ prevents $e(a)$ from including the entire universe. *Middle and Right:* If the past and future of a includes past or future infinity, then $\tilde{a} = \varnothing$ and $e(a) = M$.



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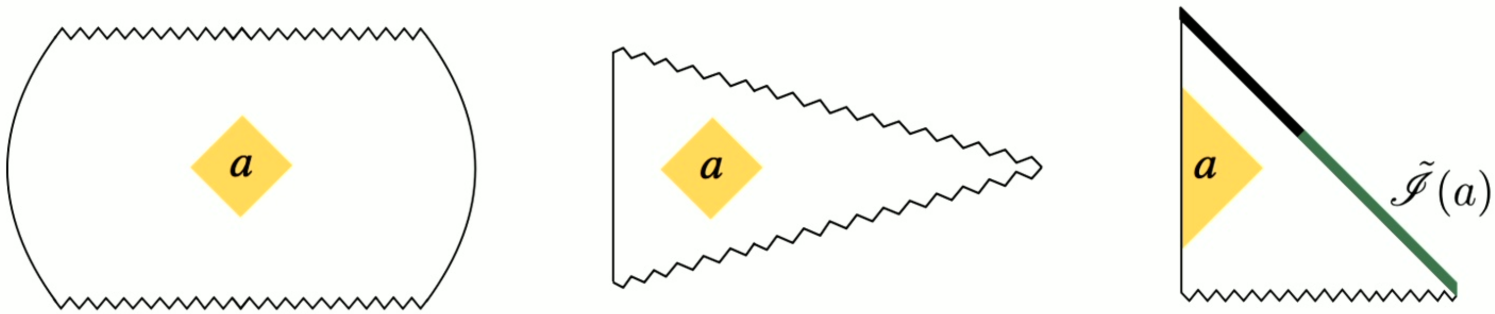

Trivial reconstructibility of *M* (one-dimensional Hilbert space) is associated with the absence of future or past infinity, *not* with closed spatial topology.