Quantum Information in Gravity

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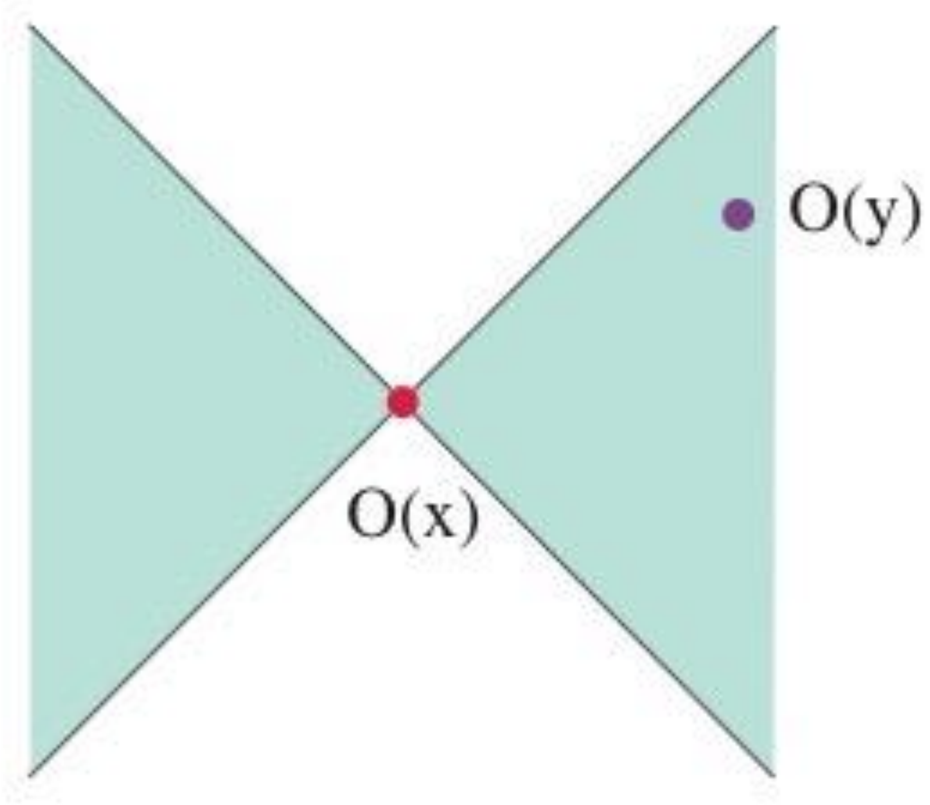
Quantum Field Theory



Fixed spacetime manifold

Microcausality: spacelike separated operators commute (events that cannot communicate should not affect each other):

$$[O_1(x), O_2(y)] = 0 \;\; \forall \; d(x, y) > 0$$

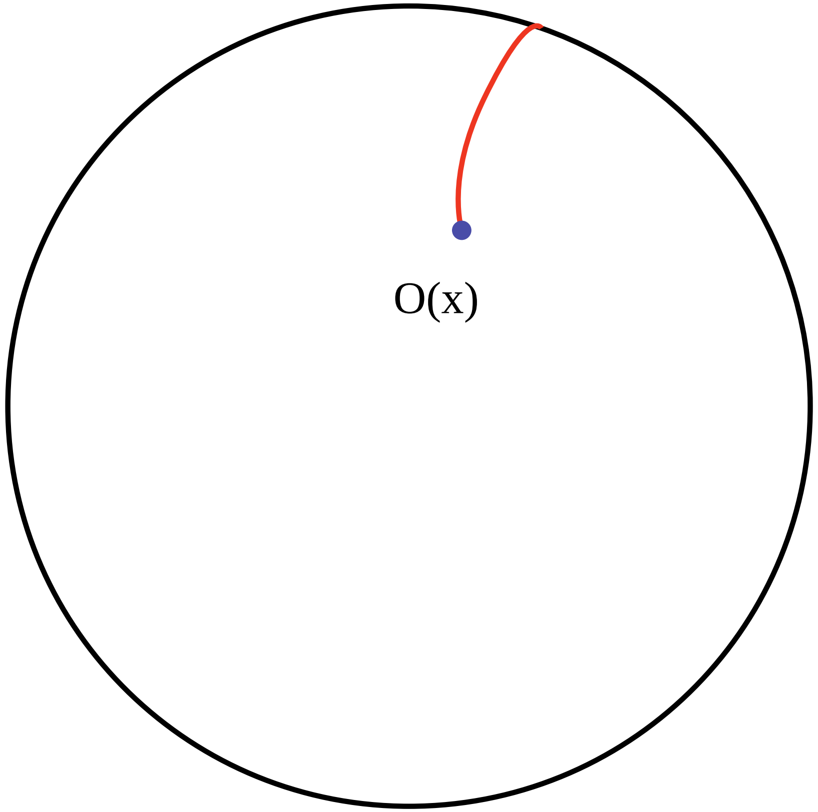
Gravity

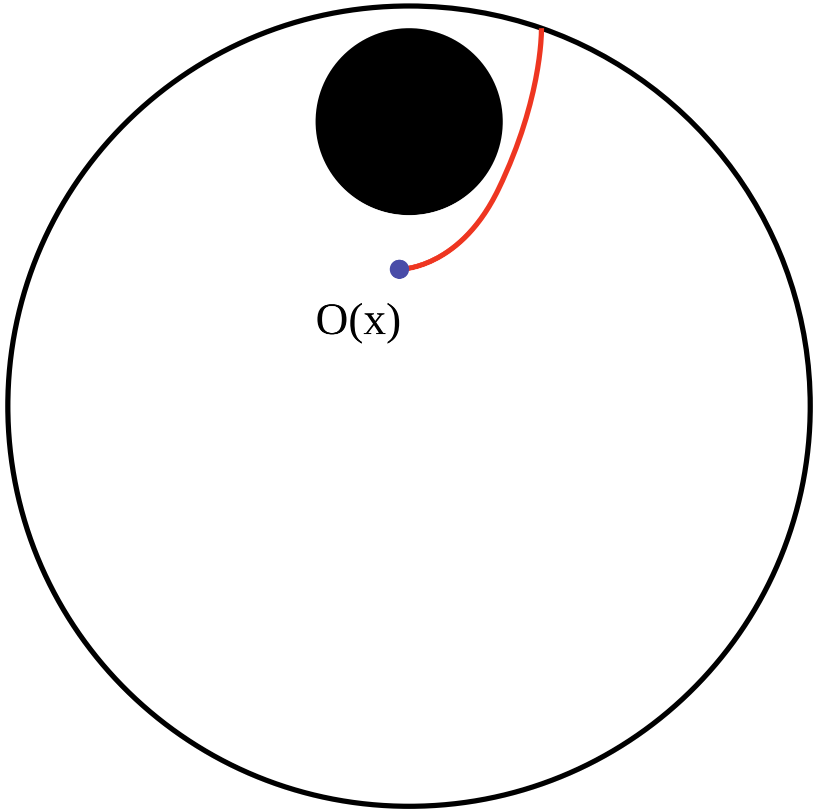
Spacetime is dynamical

The naively defined local operator $O(x)$ is not gauge invariant (this means there are many different mathematical descriptions of the same physical object)

Gravity is inherently nonlocal

Gravity





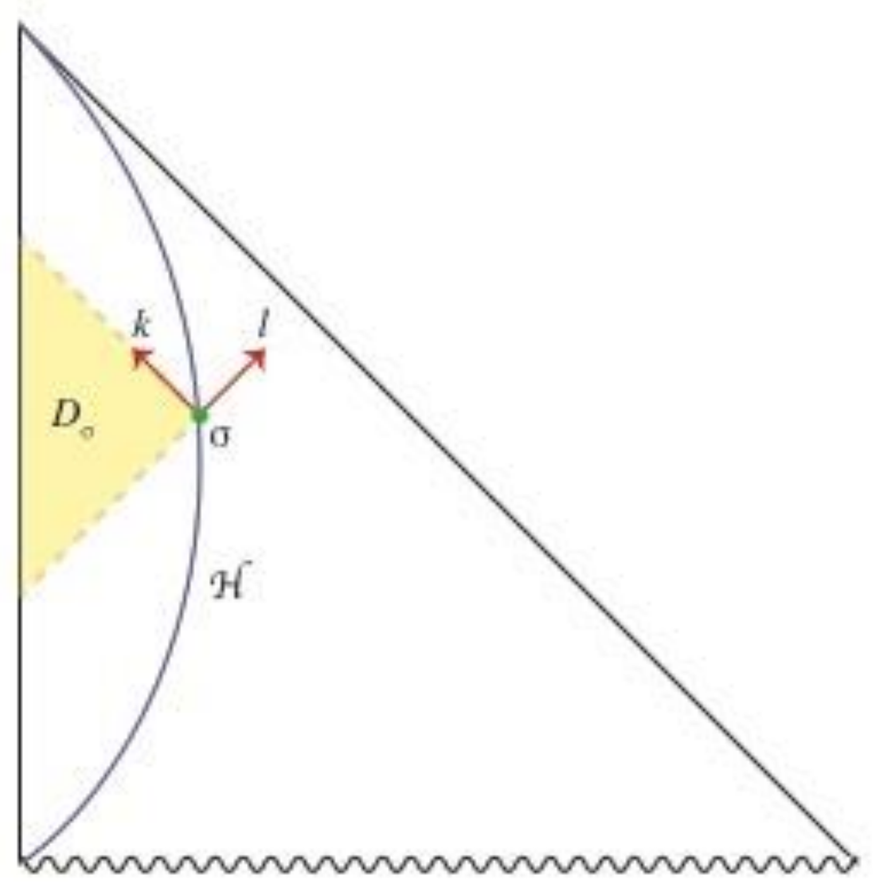
Holography

Nonlocality naively goes beyond defining operators that are gauge invariant

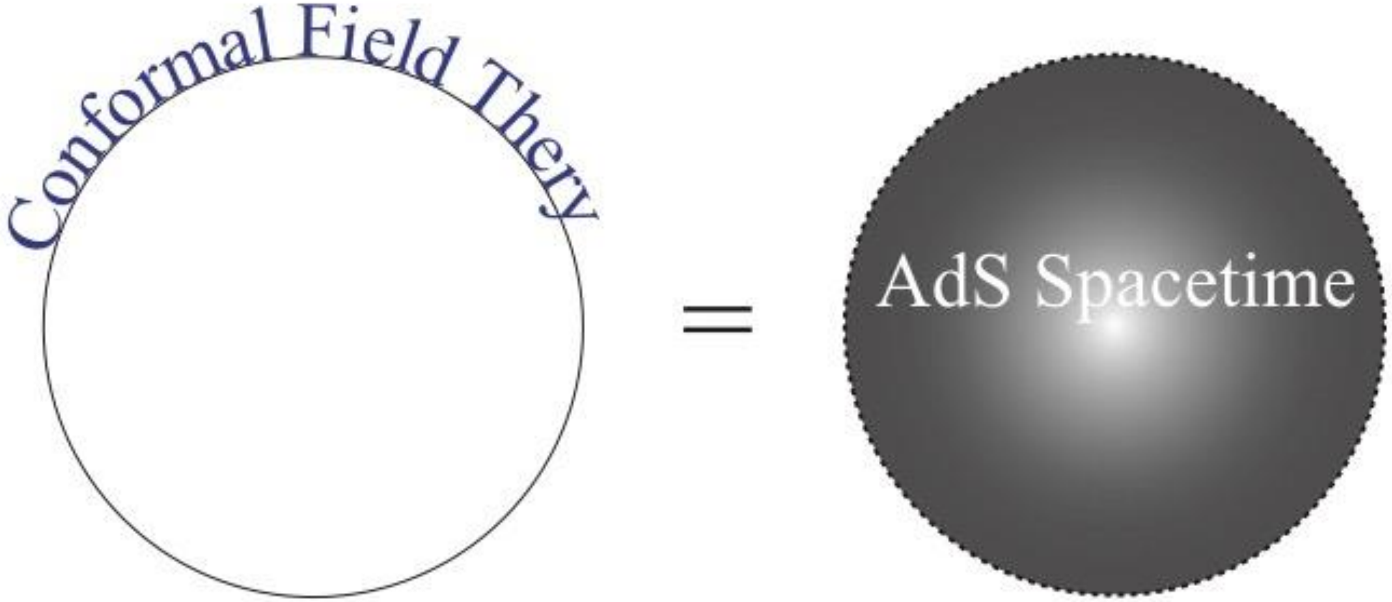
Black holes entropy scales by its area,

$$S_{BH} = \frac{A}{4}$$

Gravitational degrees of freedom are better thought of as living on one dimension lower than the spacetime they describe.



AdS/CFT



20 years of research

1. **The Large N limit of superconformal field theories and supergravity**
(13033) Juan Martin Maldacena (Harvard U.). Nov 1997. 21 pp.
Published in **Int.J.Theor.Phys. 38 (1999) 1113-1133, Adv.Theor.Math.Phys. 2 (1998) 231-252**
HUTP-97-A097, HUTP-98-A097
DOI: 10.1023/A:1026654312961
e-Print: **hep-th/9711200** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; AMS MathSciNet; OSTI Information Bridge Server
Detailed record - Cited by 13033 records 1000+

still no complete dictionary between the two theories, i.e. operator mapping

‘Reconstructing’ operators

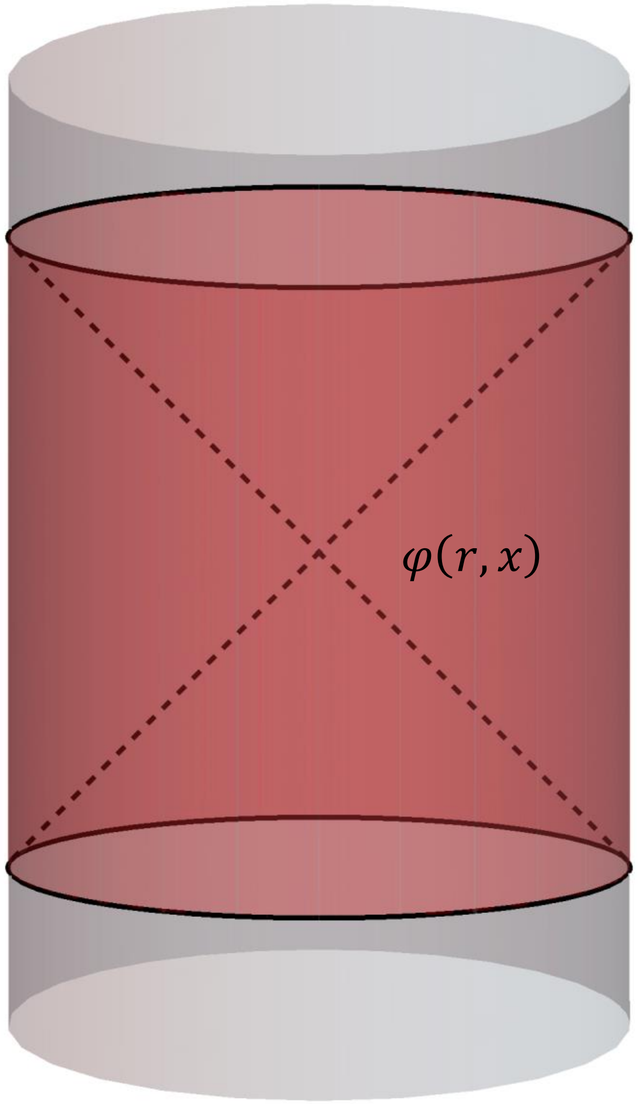
Extrapolate dictionary

$$\lim_{r\to\infty} r^{\Delta}\varphi(x) = O(x)$$

Global reconstruction

$$\varphi(r,x) = \int_{\partial M} K(r,x;x')\,O(x')dx'$$

∂M integral taken over the spacelike portion

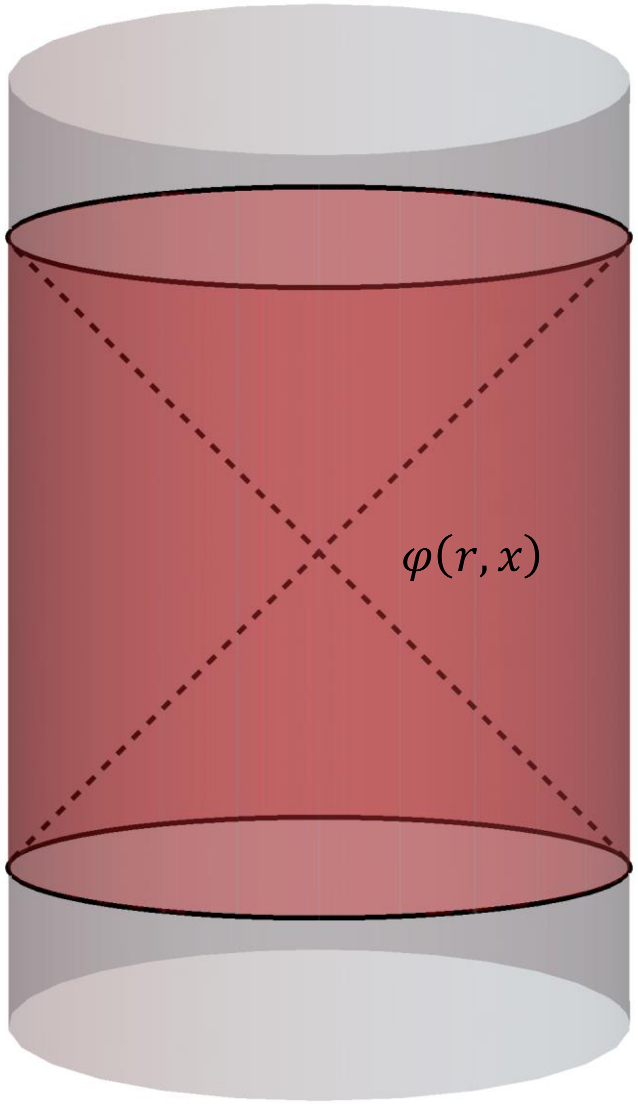


‘Reconstructing’ operators

Without equations:

- We know how to translate between the bulk and the boundary if the operator is very close to the boundary

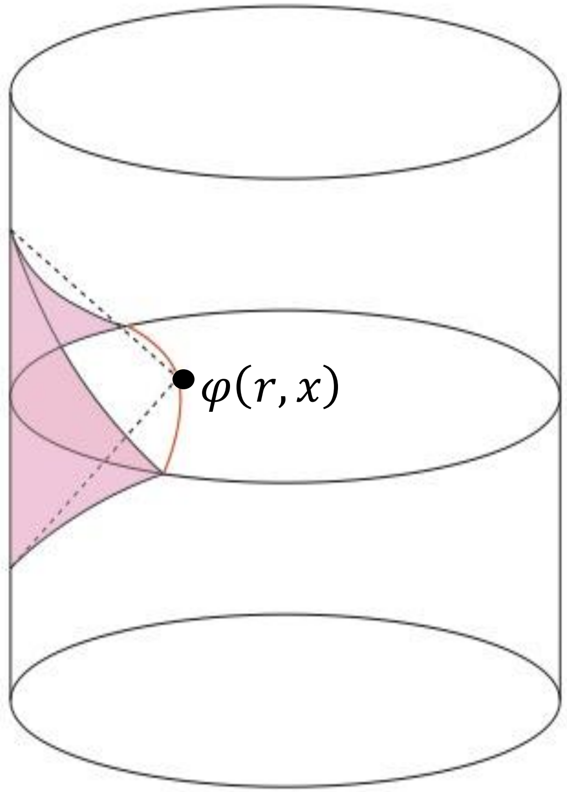
- With a lot of effort we can rewrite a bulk operator at a bulk point as a complicated superposition of operators spread throughout the entire boundary.



‘Reconstructing’ operators

HKLL – Rindler reconstruction – for $\phi \subset \mathrm{CW}(R)$

$$\phi(r,x) = \int_{D[R]} K(r,x;x')O(x')dx'$$



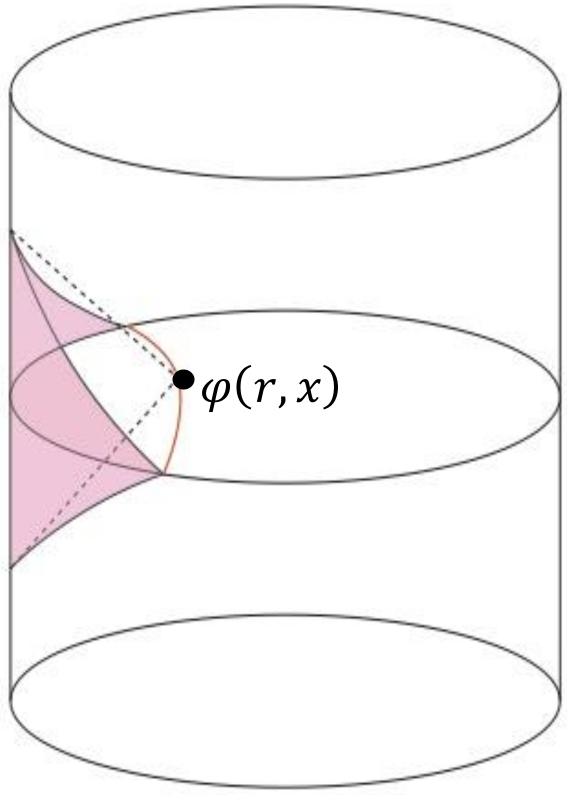
D$[R]$ is the domain of dependence of subregion R and $\phi(r,x)$ should be inside the causal wedge $\phi(r,x) \subset \mathrm{CW}[R] = J^+[\mathrm{D}[R]] \cap J^-[\mathrm{D}[R]]$

‘Reconstructing’ operators

It turns out that writing bulk operators as an integral over the entire boundary is slightly too verbose.

HKLL discovered that there is a much more efficient way to express a bulk object in terms of boundary quantities.

To achieve this, we use the notion of causality (use boundary objects located at regions that can reach the bulk point we are interested in).



‘Reconstruction’

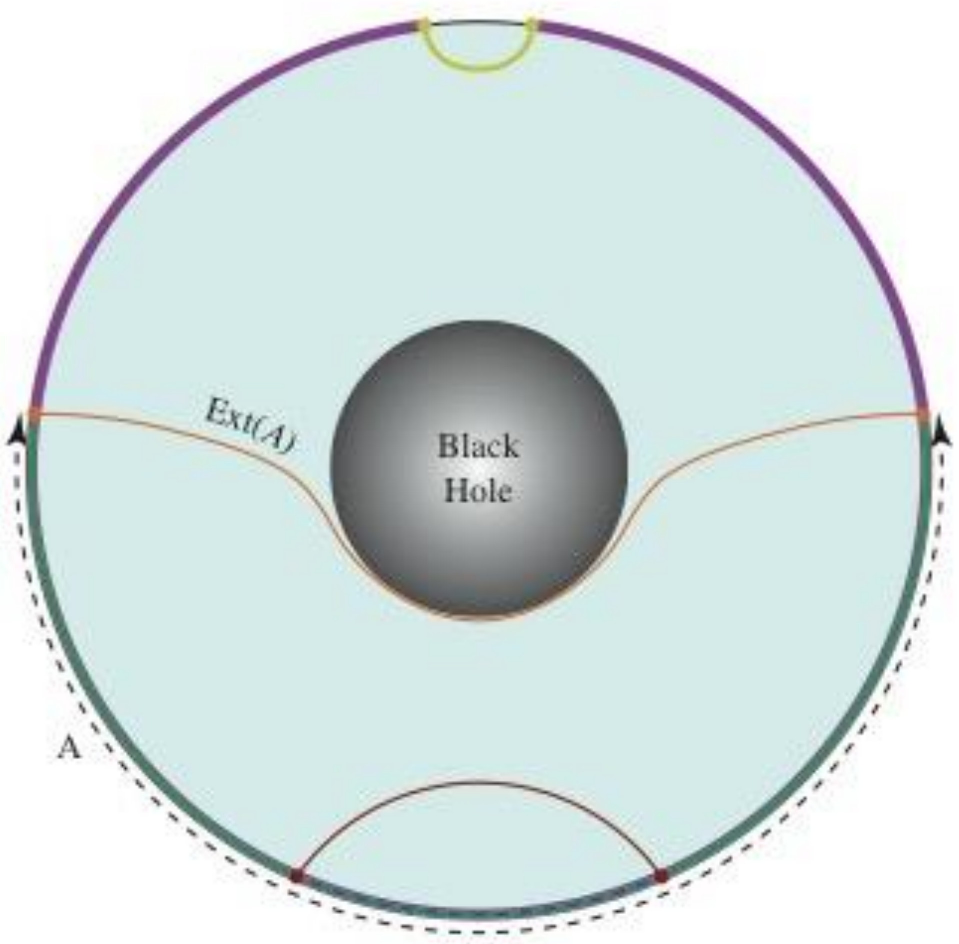
$$\phi(r,x) = \int_{D[R]} K(r,x;x')O(x')dx'$$

requires prior knowledge of bulk metric

$$K^{g}(r,x;x')$$

- This means we can only go through this procedure if we assume we already knew the spacetime geometry.
- This is problematic since we do not know how to obtain the bulk metric from boundary information

Holographic entanglement



$$S_{ent} \stackrel{\text{def}}{=} -\mathrm{Tr}\,[\rho_A \log \rho_A] = \frac{\|\mathrm{ext}(A)\|}{4 l_p^2}$$

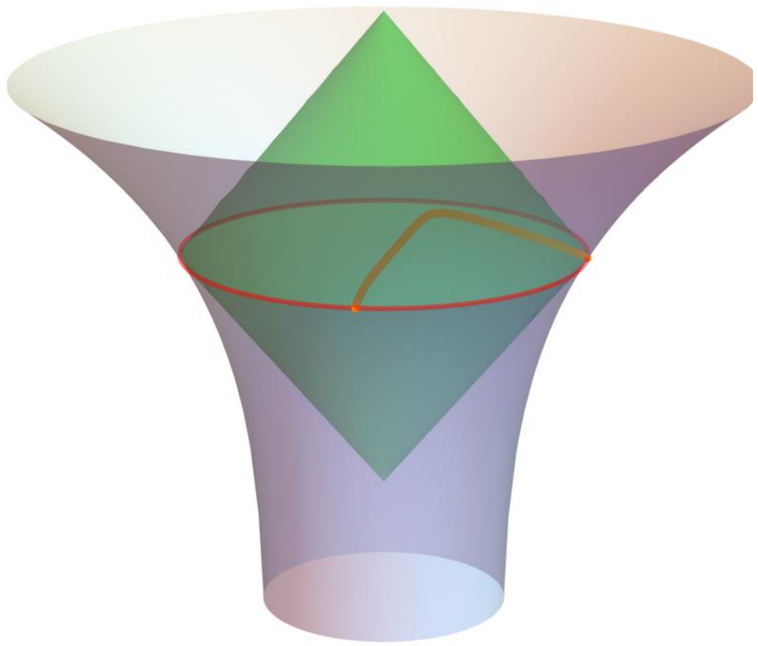
von Neumann entropy of a boundary subregion is equal, to first order, to the area of the codimension 2 stationary surface anchored with

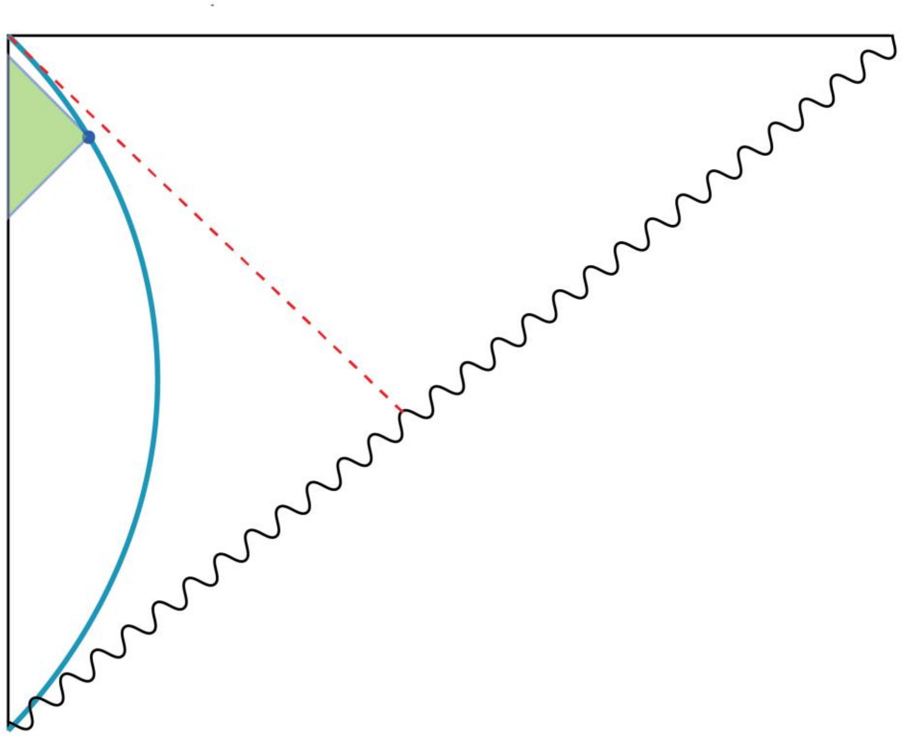
$$\partial A = \partial \mathrm{ext}(A)$$

[Hubeny, Rangamani, Ryu, Takayanagi]

- **Relationship between entanglement and geometry!**

Beyond AdS





The holographic entanglement proposal can be extended to spacetimes that are not asymptotically AdS [FS, S. Weinberg]

Hilbert space properties of such theories [Y. Nomura, N. Salzetta, FS, S. Weinberg]

A puzzle with reconstruction

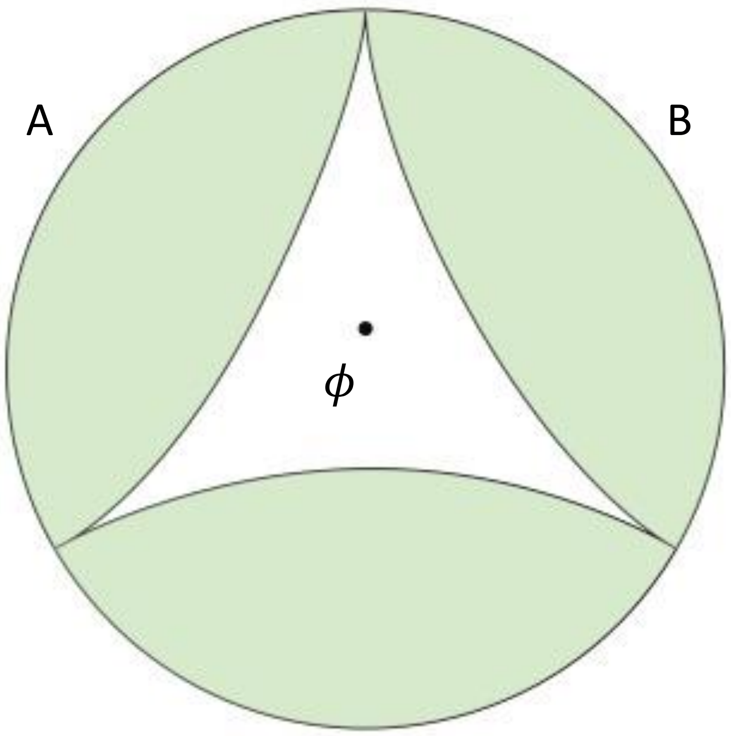
The possible reconstruction of ϕ are operators in the algebras of

$$A \cup B, \qquad A \cup C, \qquad B \cup C$$

then,

$$[\phi_{AB}, O_C] = 0$$
$$[\phi_{AC}, O_B] = 0$$
$$[\phi_{BC}, O_A] = 0$$

Does this mean $\phi = \mathbb{I}$?



Quantum error correction

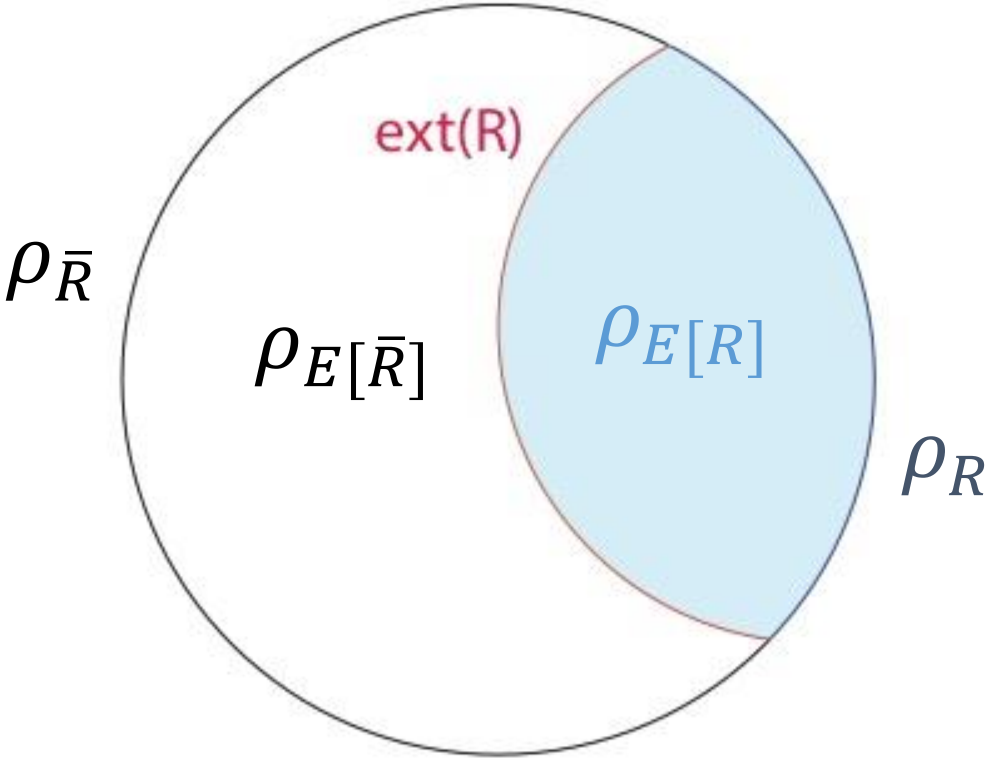
$$
\begin{aligned}
|\tilde{0}\rangle &= |000\rangle + |111\rangle + |222\rangle \\
|\tilde{1}\rangle &= |012\rangle + |120\rangle + |201\rangle \\
|\tilde{2}\rangle &= |021\rangle + |102\rangle + |210\rangle
\end{aligned}
$$

3 dimensional **code subsubace** G out of a 27 dimensional hilbert space.

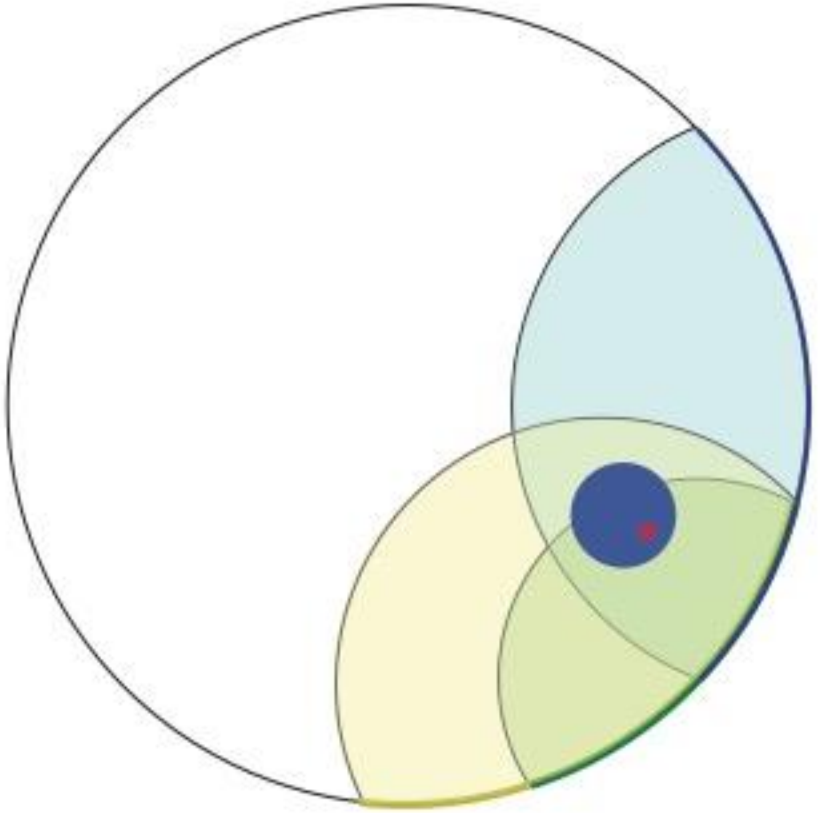
The action of any operator on stated in the code subspace can be achieved by an operator on any 2 qutrits.

True reconstruction

Any bulk operator with support in the entanglement wedge $\mathbf{E}[R]$ can be reconstructed with operators in the algebra of the region R.
[Almheiri, Dong, Harlow, Wall]

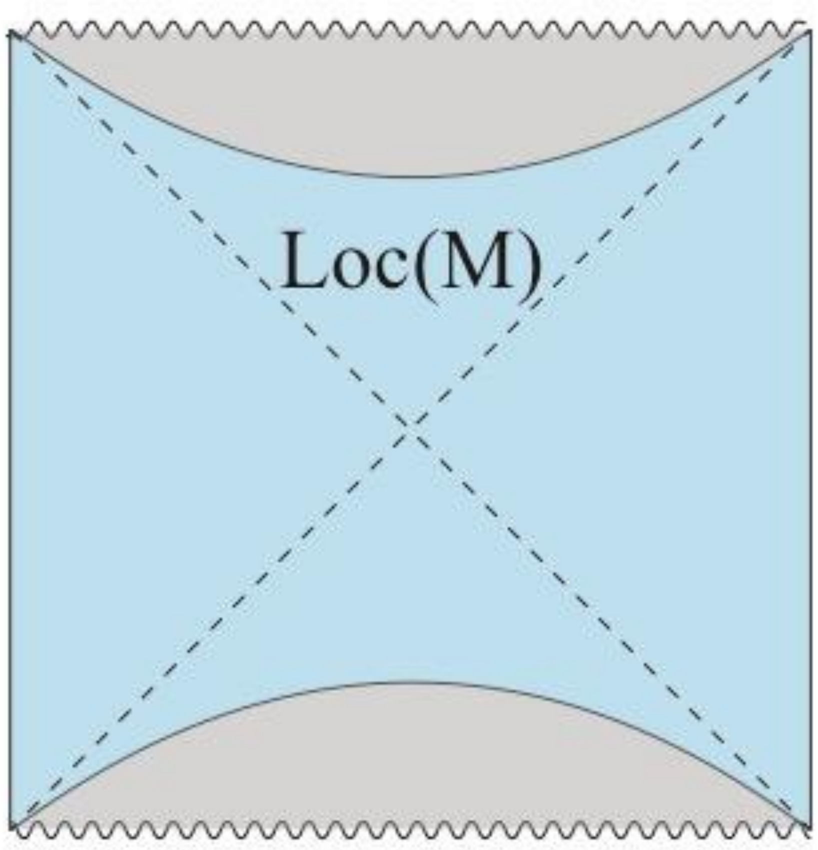


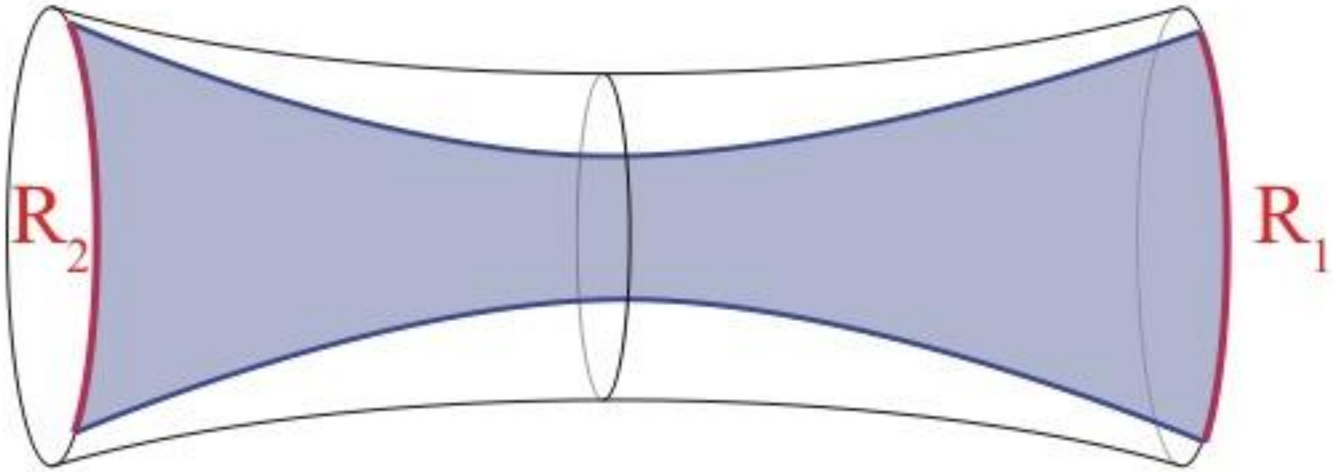
Identifying local operators from the CFT



The quantum error correcting view can be used to identify local operators from the CFT without prior knowledge of the bulk [FS, S. Weinberg]

True reconstruction of bulk manifold





Emergence of locality

- Gravity is holographic

- Locality in the quantum field theory emerges when gravity is weak

What is the fundamental mechanism that is responsible for the emergence of the bulk?

At the same time, how does approximate locality work if the boundary description is highly nonlocal?

Quantum error correction/redundancy in the bulk to boundary map is critical to holography and suggestive of a relationship to how locality emerges in gravity [FS, S. Weinberg]