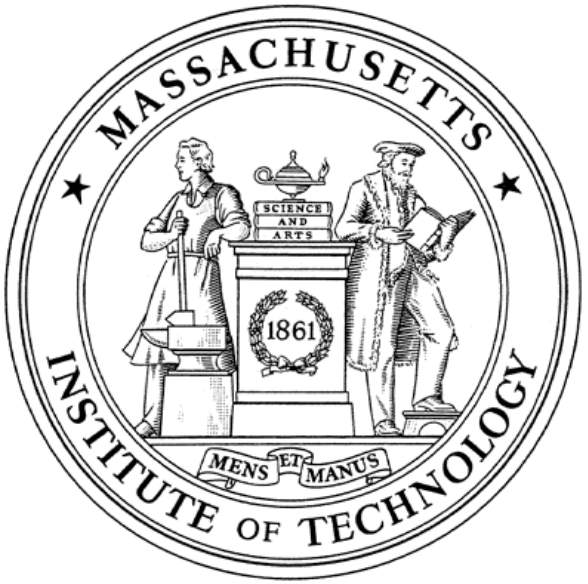
Emergence of space and time in holography

Hong Liu



Strings 2022, Vienna

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based on work with Samuel Leutheusser

arXiv: 2110.05497, 2112.12156 and to appear

Emergence of space and time in holography

An outstanding question in holography:

how bulk space, time and the associated geometric (including causal) structures arise in its boundary description.

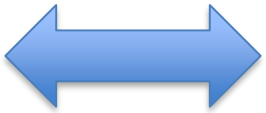
Geometric notions such as local spacetime regions, horizons, are sharply defined only in the $G_N \to 0$ limit

which translates into the $N \to \infty$ limit in the boundary theory.

Can we pinpoint the precise mathematical structure that is responsible for the emergence of various geometric notions?

In this talk,

Bulk spacetime is a geometrization
of emergent boundary type III_1 algebras

Emergent type III_1 von Neumann algebras  bulk spacetime regions

Properties of such emergent type III algebras  Geometric notions such as horizons, times, causal structure, …..

1. Emergence of horizon and Kruskal-like times in an AdS eternal BH and the associated causal structure

2. Emergent error correcting properties and RT surface without entropy

3. More general formulation of subregion duality

entanglement wedges without RT surface

Large N limit

Consider, e.g. $\mathcal{N}$=4 super-Yang-Mills with gauge group SU(N)

Many states and operators do not have a well-defined large N limit

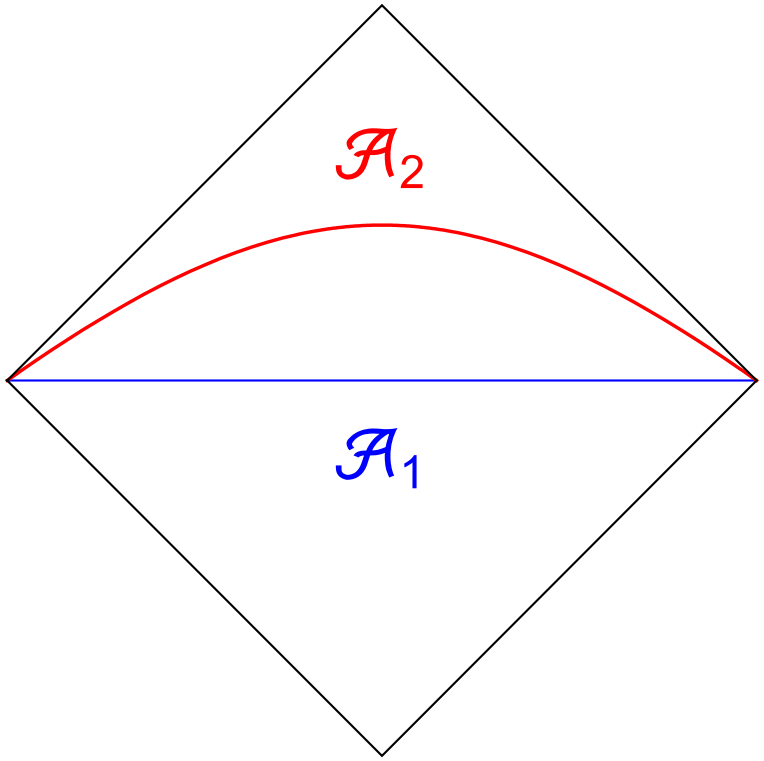
the structures of Hilbert space and operator algebras undergo dramatic changes in the large N limit

- The full Hilbert space splits into disconnected GNS Hilbert spaces around semi-classical states (e.g. vacuum or thermal field double).

- Operator algebras generated by single-trace operators
  - Single-trace operators at different times are independent
  - Structure of an operator algebra can become state-dependent
  - Ubiquitous emergence of type III_1 von Neumann algebras

In a general QFT: O(t) can be expressed in terms of operators at t=0.

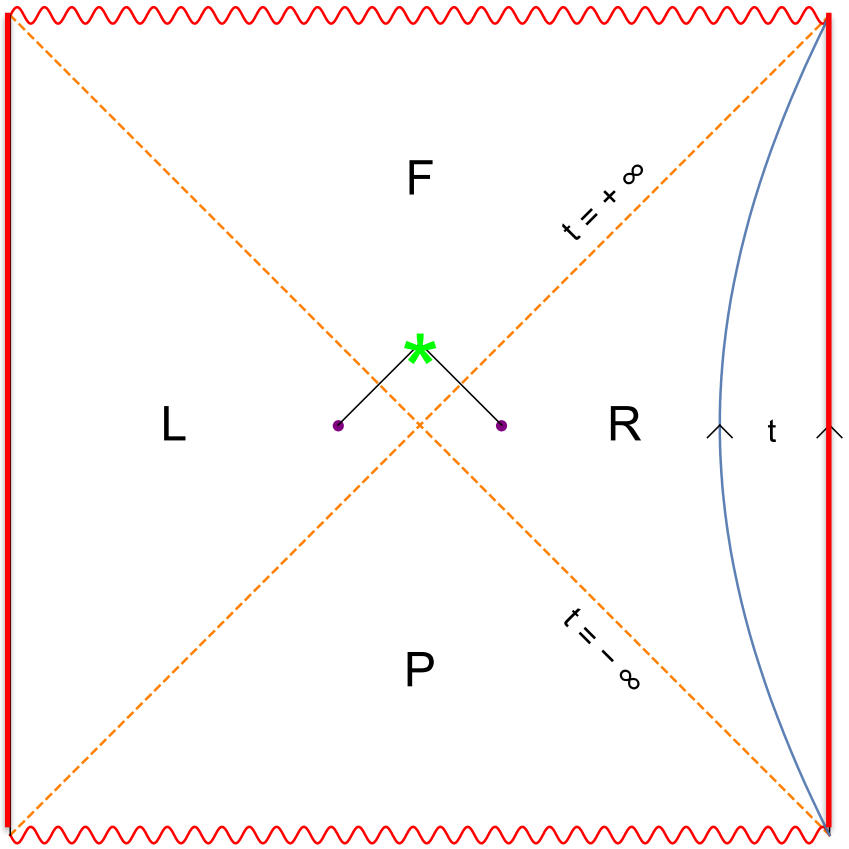
But a single-trace operator O(t) can not be expressed in terms of single-trace operators at t=0.



In a QFT, $\mathcal{A}_1 = \mathcal{A}_2$

For algebras of single-trace operator, $\mathcal{A}_1 \neq \mathcal{A}_2$

Eternal black hole in AdS



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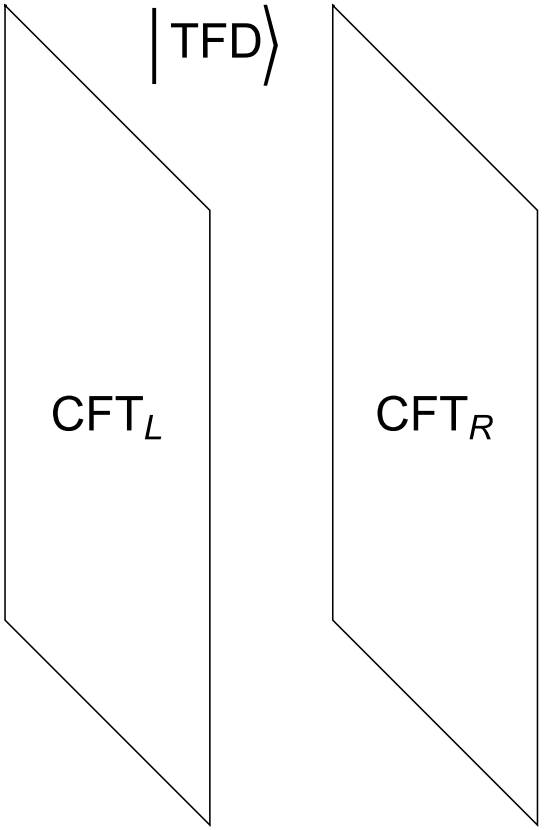


Maldacena, 2001

Boundary description of F and P regions? Kruskal-like time?

Boundary description of horizons and associated causal structure ?

Emergent type III_1 vN algebras

BH is described by CFT_R x CFT_L in the thermal field double (TFD) state
(for $T > T_{\text{Hawking-Page}}$)

At finite N, the (bounded) operator algebra of CFT_R or CFT_L is a type I von Neumann (vN) algebra (not relevant for large N)

In the large N limit,

$\mathcal{A}_R$: algebra generated by single-trace operators of CFT_R

Action of $\mathcal{A}_R$ on the TFD state form a Hilbert space: $\mathcal{H}_{\mathrm{TFD}}$

$\mathcal{M}_R$: representation of $\mathcal{A}_R$ in $\mathcal{H}_{\mathrm{TFD}}$ (state dependent)

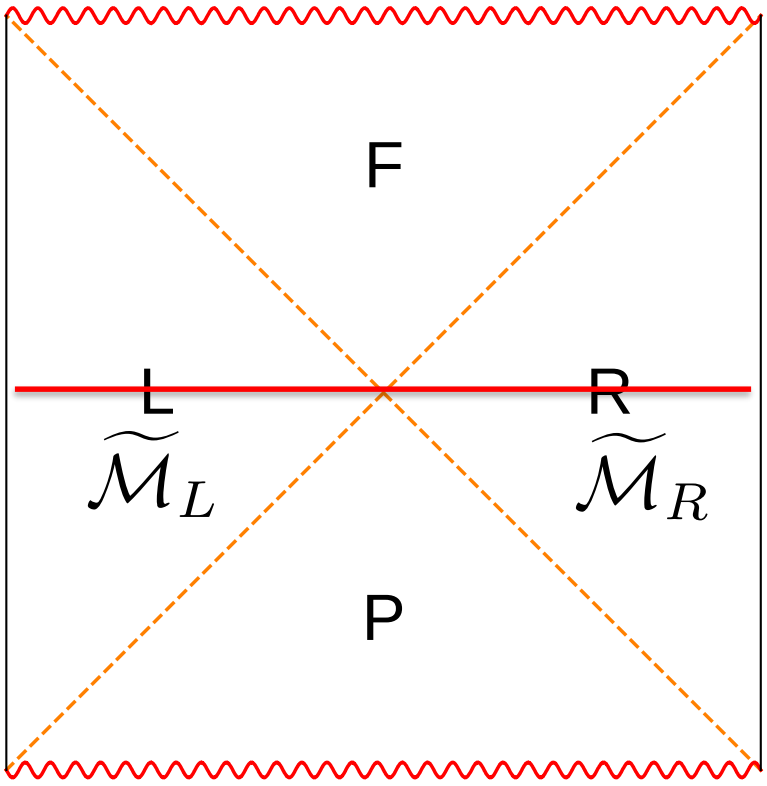
$T < T_{\text{Hawking-Page}}$: $\mathcal{M}_R$ is type I vN algebra

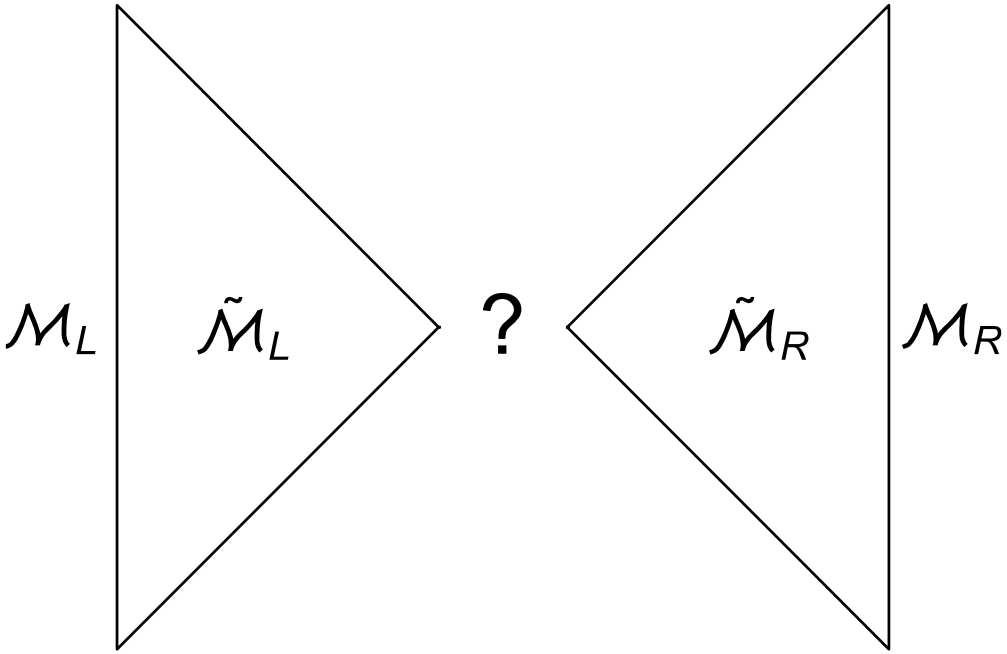
$T > T_{\text{Hawking-Page}}$: $\mathcal{M}_R$ becomes type III_1 vN algebra

Identification of algebras

Duality: $\mathcal{M}_R = \widetilde{\mathcal{M}}_R, \quad \mathcal{M}_L = \widetilde{\mathcal{M}}_L$

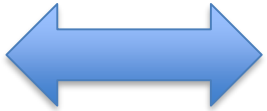
$\widetilde{\mathcal{M}}_R, \widetilde{\mathcal{M}}_L$: bulk operator algebras in the R and L regions





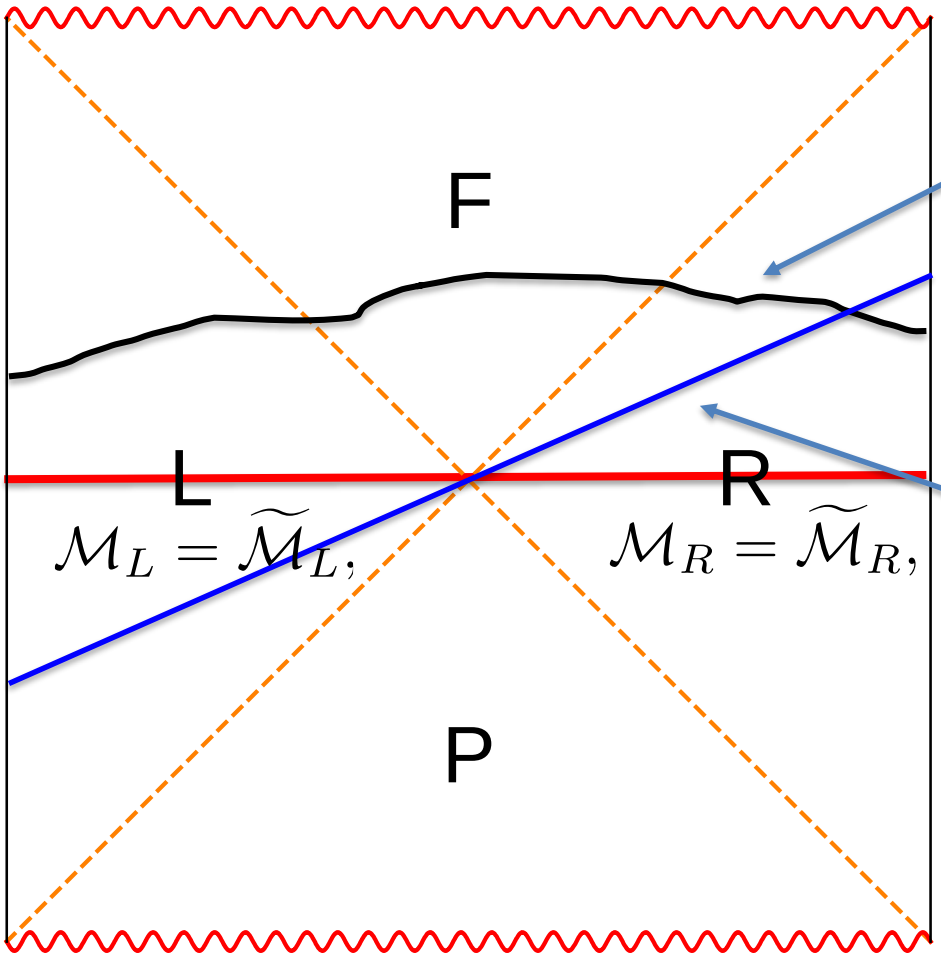
Times in the bulk gravity ?

Bulk time evolutions



Boundary automorphisms of

$$\mathcal{M}_R \vee \mathcal{M}_L$$

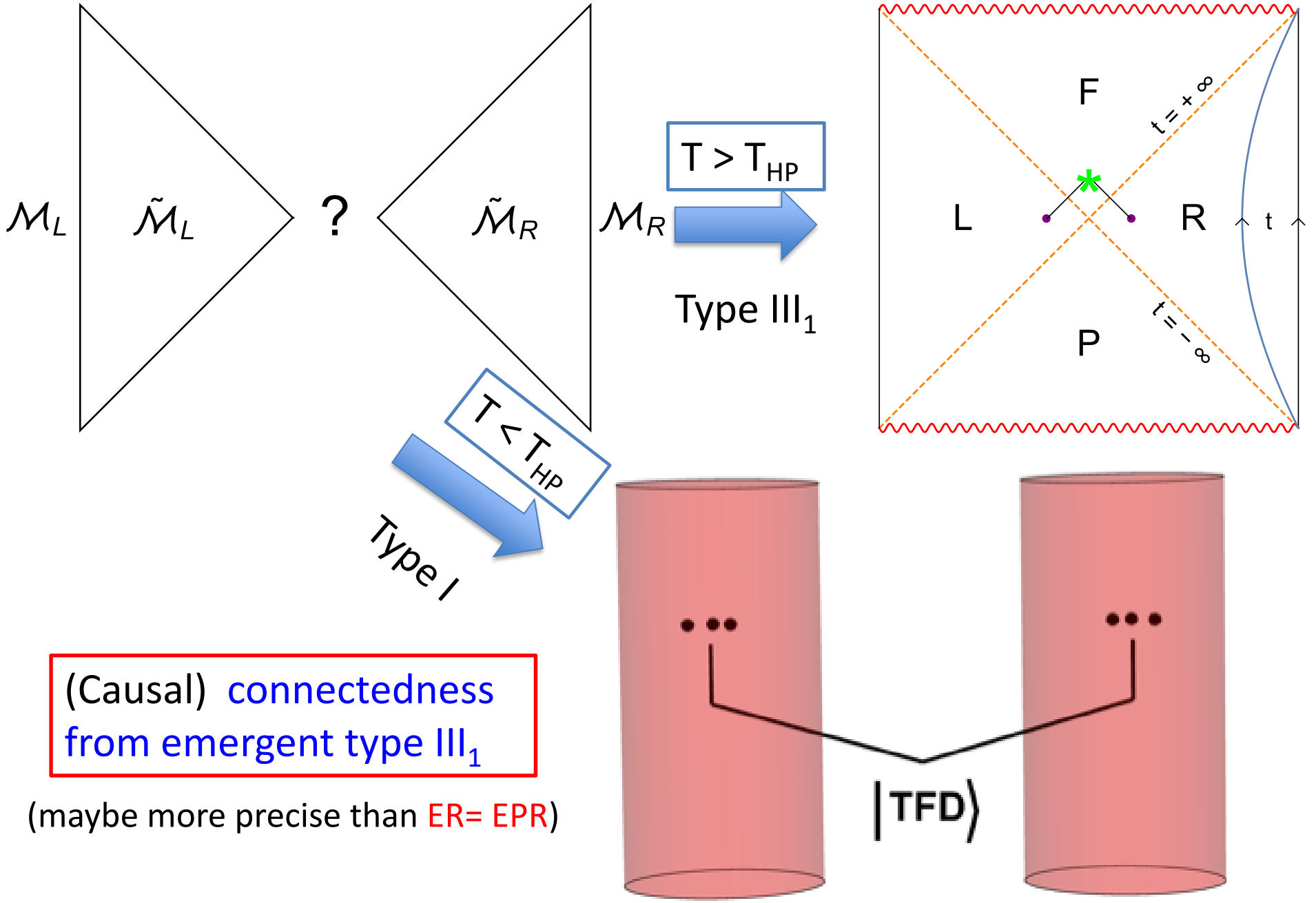


If $\mathcal{M}_L, \mathcal{M}_R$ are type III_1, half-sided modular times (specific to type III_1)

generate F and regions (sharp boundary signature of horizon)

Time generated by H_R-H_L

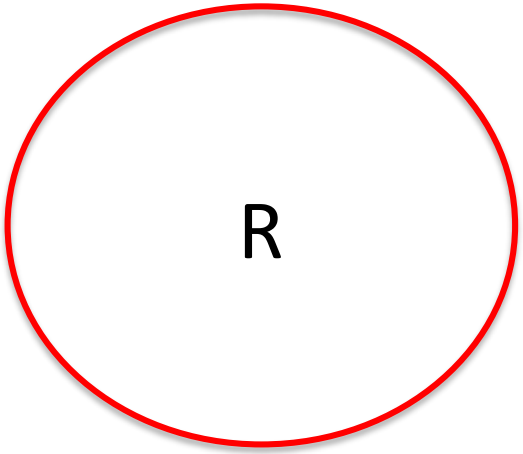
- regardless of types of algebra of $\mathcal{M}_L, \mathcal{M}_R$
- Evolution by $H_R + H_L$ does not have a sensible large N limit



(Causal) connectedness from emergent type III_1

(maybe more precise than ER= EPR)

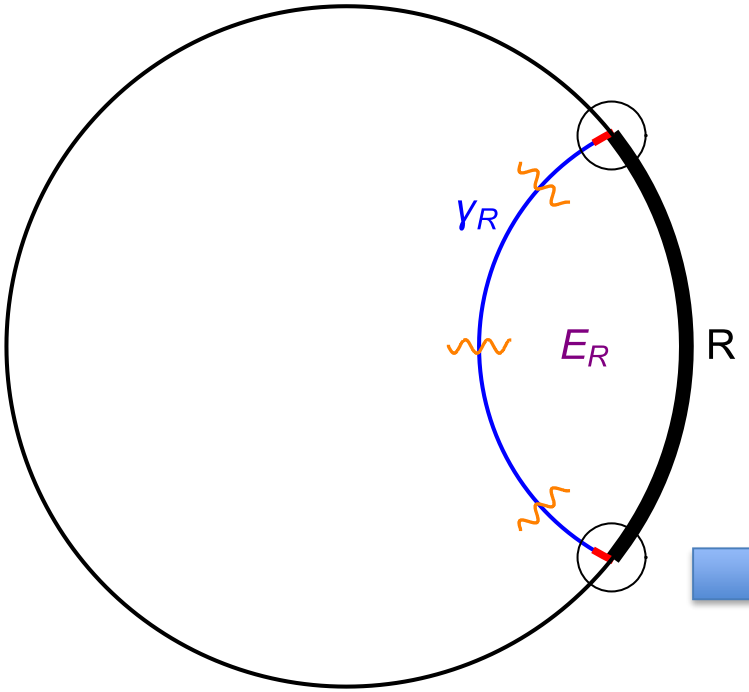
Entanglement wedge without entropy



Consider the boundary CFT in the vacuum state and a region R

At finite N full operator algebra in R is type III_1
(not relevant at large N limit)

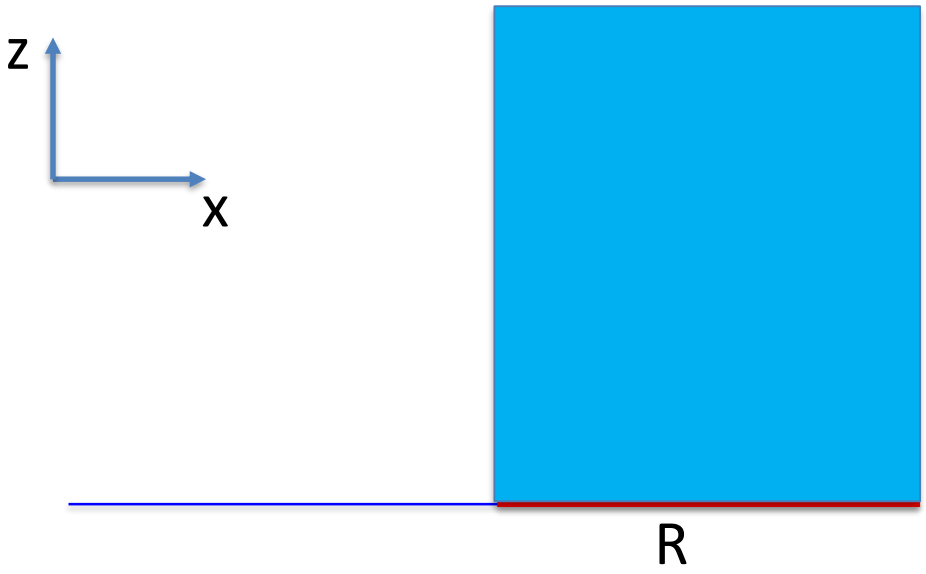
In the large N limit, the completion of single-trace operator algebra $\mathcal{A}_R$ in causal completion of R is an emergent type III_1 (state dependent)

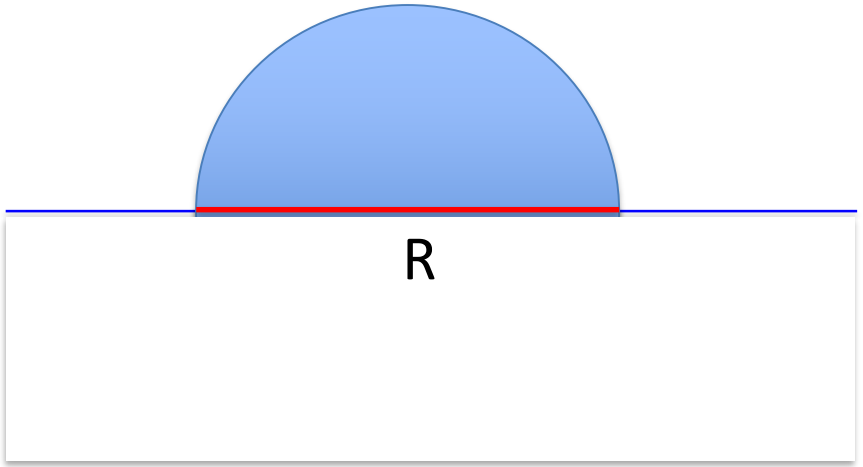


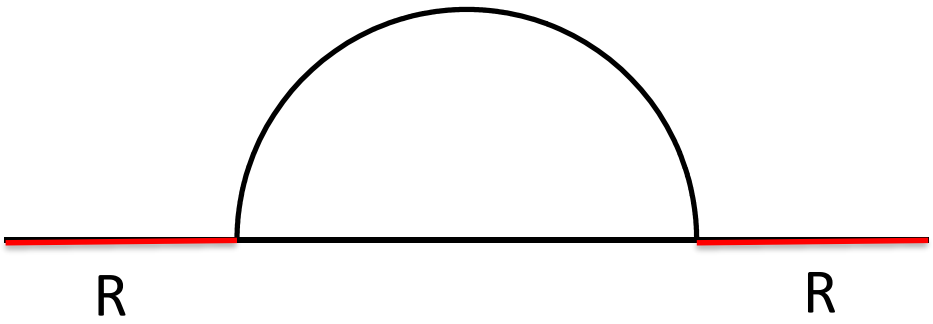
Entanglement wedge: bulk spacetime region whose operator algebra is identified with $\mathcal{A}_R$.

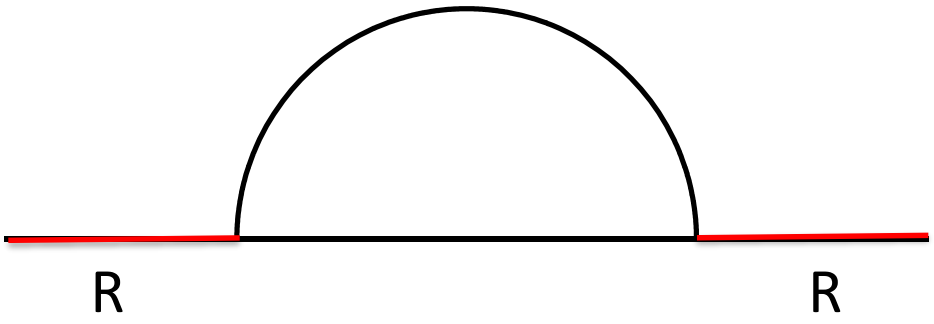
Ryu-Takayanagi surface without using minimal surface

RT surface from emergent type III_1



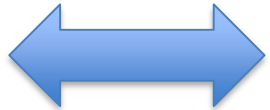




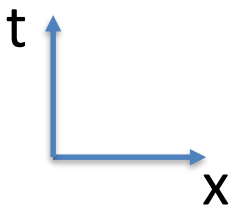


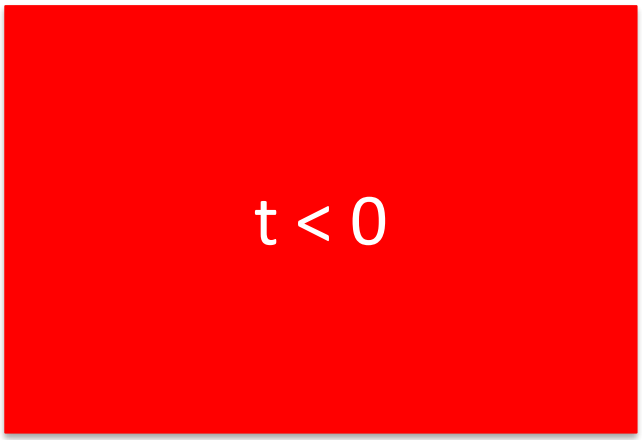
Subregion duality beyond RT

An emergent type III_1 von Neumann algebra

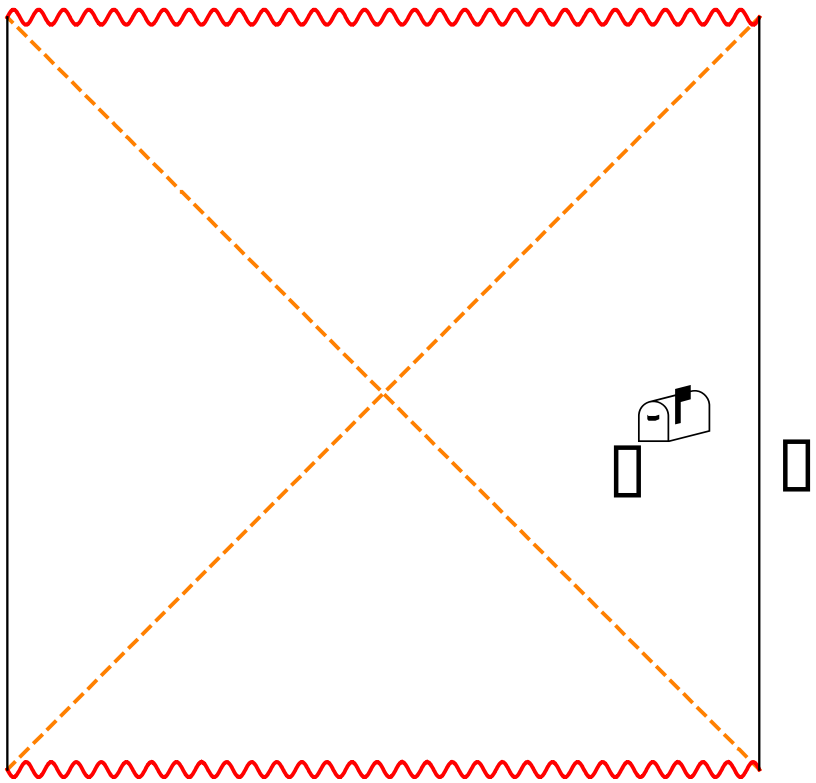


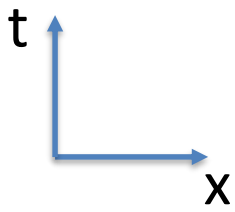
bulk operator algebra in some spacetime region

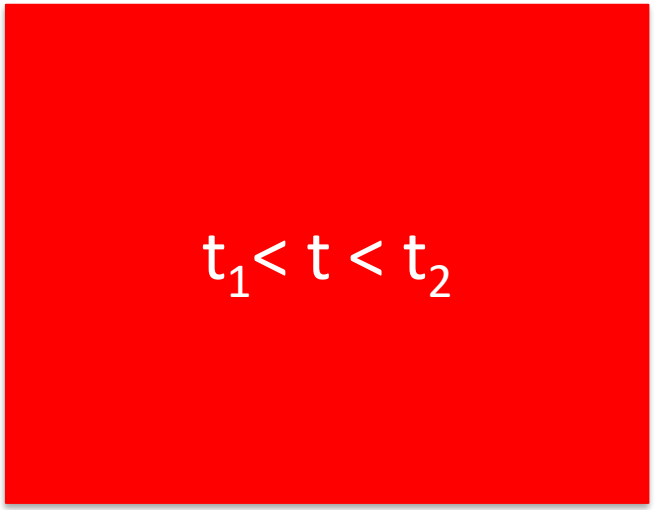




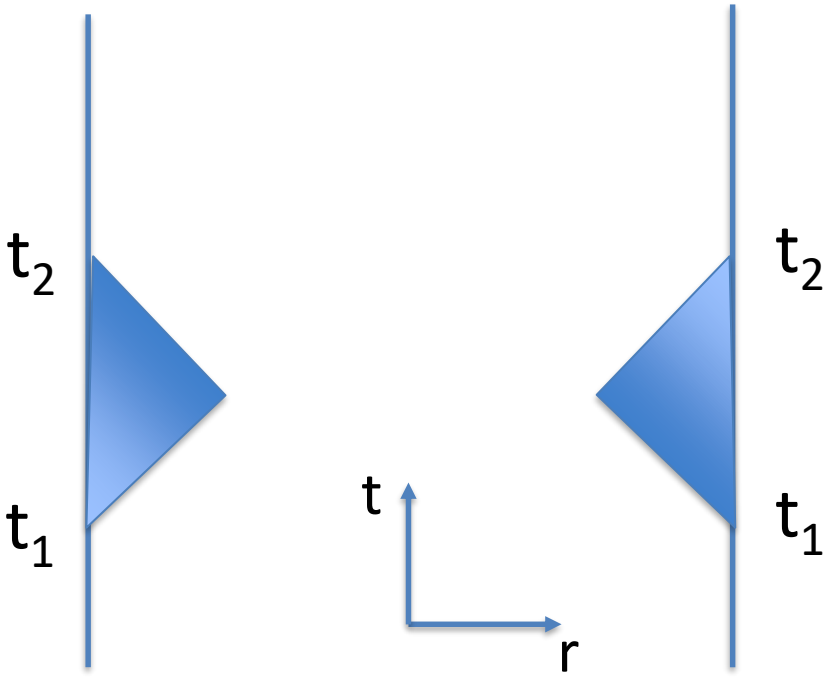
CFT_R in TFD

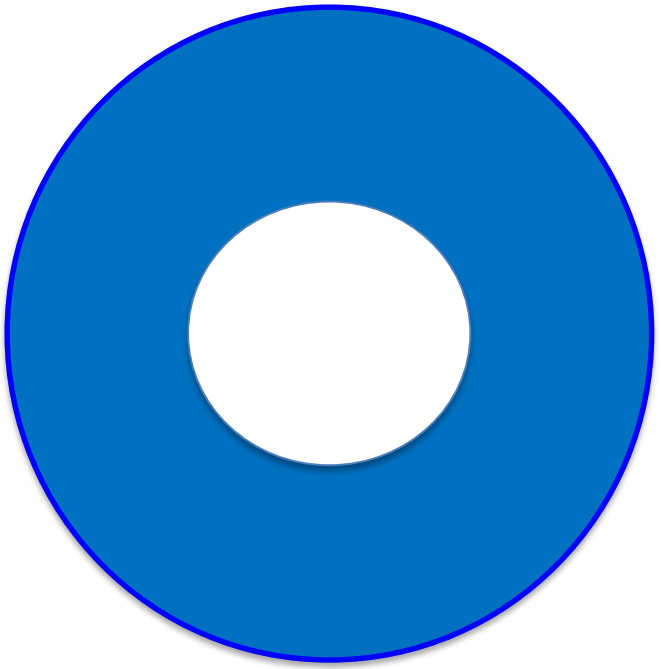




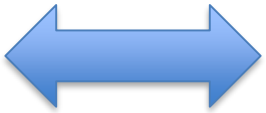


CFT_2 in the vacuum



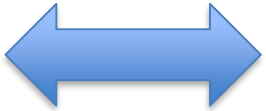


An emergent type III_1
von Neumann algebra



bulk operator algebra
in some spacetime region

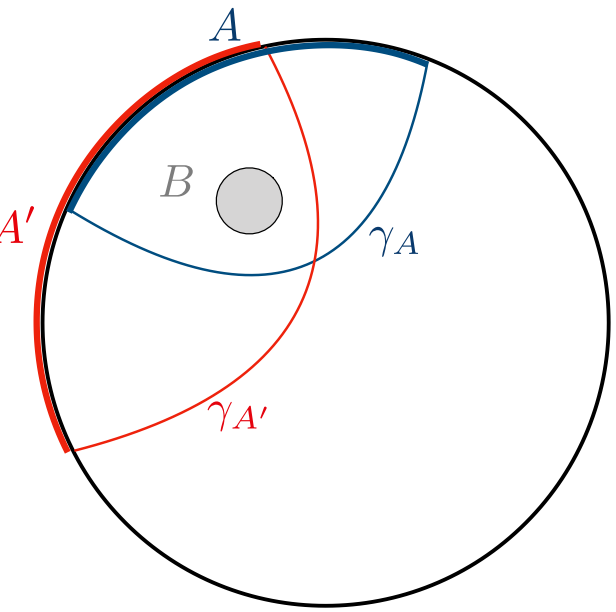
Emergent type III_1
von Neumann algebras



bulk spacetime regions

Bulk spacetime is a geometrization
of emergent of type III_1 algebras

Emergent quantum error correction properties



subregion reconstruction → bulk description is highly redundant

This has been given a beautiful interpretation in terms of quantum error corrections Almheiri, Dong, and Harlow

Providing a guiding principle for building many toy models of holography using finite-dimensional Hilbert spaces (or type I algebras)

1. the physical origin of quantum error correcting properties remains unclear.

2. In real holographic systems, should be intrinsic properties of the large N limit

Can indeed be understood as consequences of emergent type III_1 structure (works very differently from models based on type I)

Future perspectives

- connections with finite N

Eternal BH: Type III_1: (perturbative in 1/N to any finite order)

Type II: (1/N corrections to all orders) Witten (arXiv:2112:12828)

Type I: (finite N)

- Implications for holography in flat and cosmological spacetimes

Witten's talk

- New perspectives on single-sided or evaporating BHs, Derivation of "island''

- Entropy associated with general bulk surfaces

……

Thank you!