Title: Emergent time and reconstruction of the black hole interior

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Series: Perimeter Institute Quantum Discussions

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Abstract: I will present a general bulk reconstruction technique in AdS/CFT suitable for addressing a facet of the black hole information problem: How to unambiguously predict the results of measurements performed by an infalling observer in the black hole interior.

I will explicitly apply the method in the AdS_2/SYK correspondence. My proposal provides an internal notion of time for quantum gravitational systems that may be useful for cosmology.

EMERGENT TIME AND THE BLACK HOLE INTERIOR

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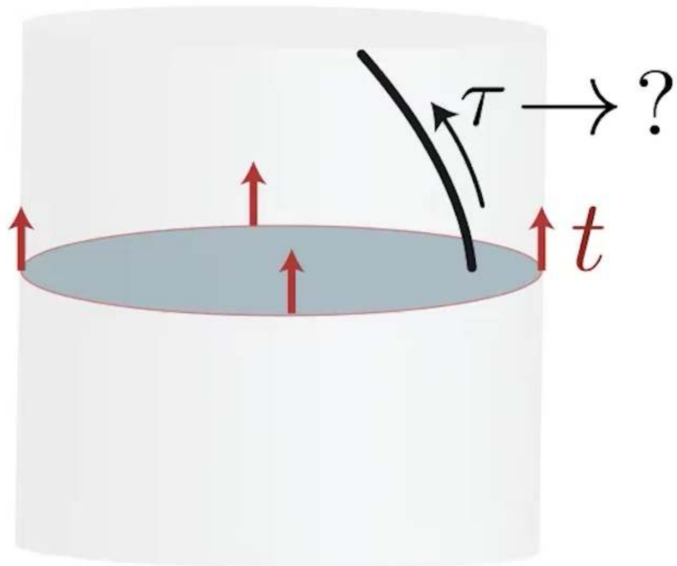
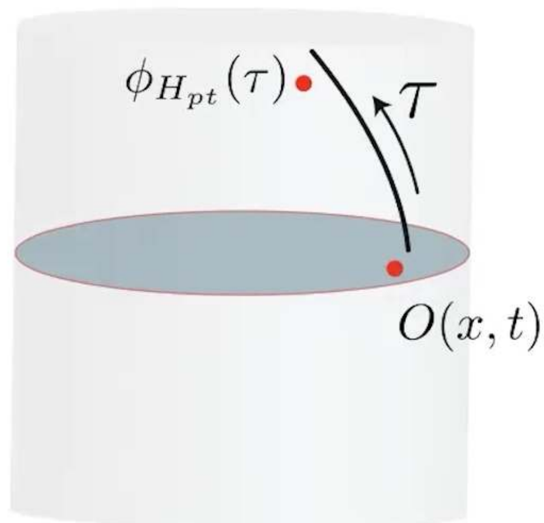
More phenomenologically relevant notion:

Proper time of an observer

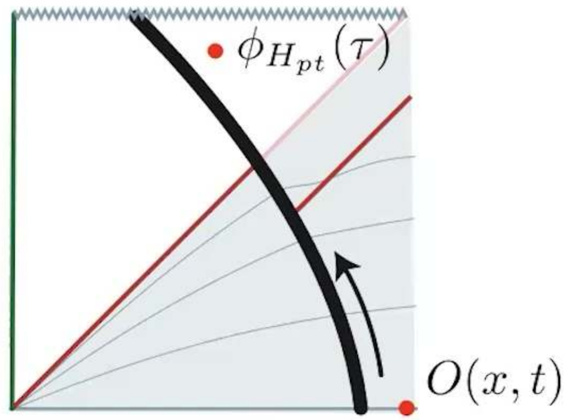


Time experienced by observers is "emergent"!

1) Bulk reconstruction (from first principles)



2) Black hole interiors: Singularity signatures, typicality of firewalls, etc



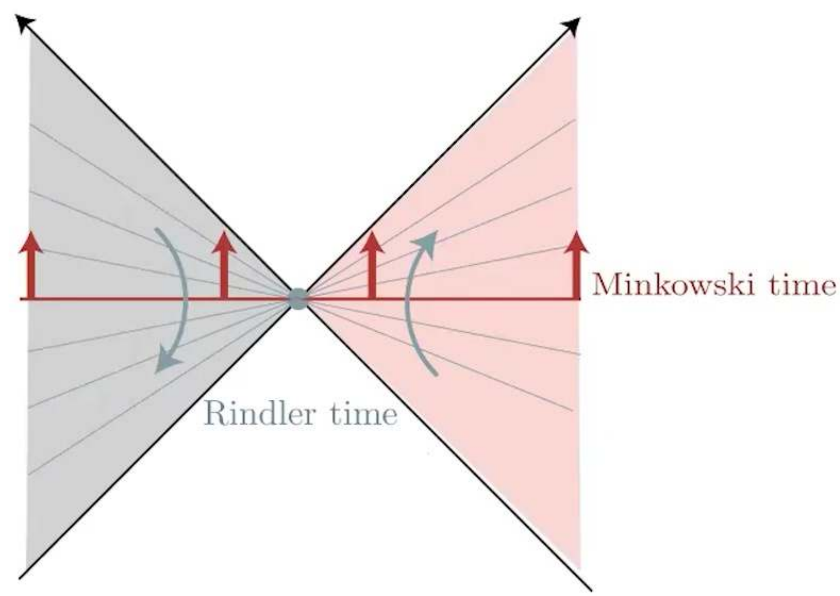
3) Cosmology: No asymptotic clock

(a) How to select a subsystem as a frame of reference.

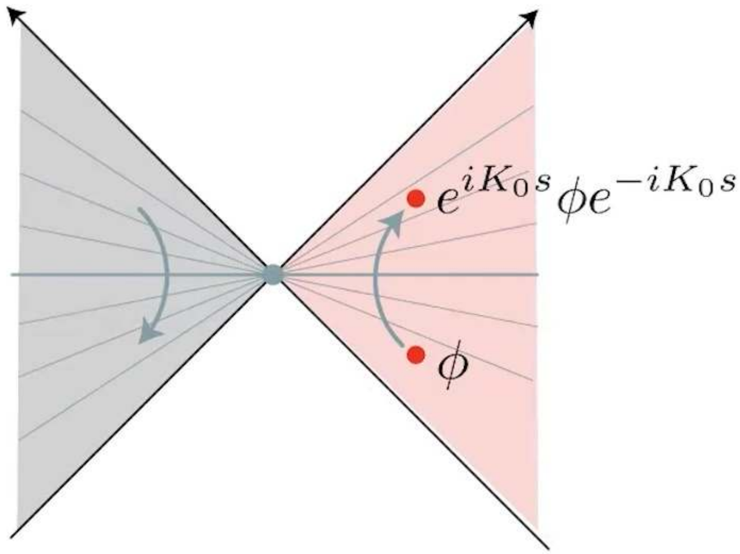
(b) Understand how to evolve the Universe relative to it.

(c) Follow an infalling observer into a black hole!

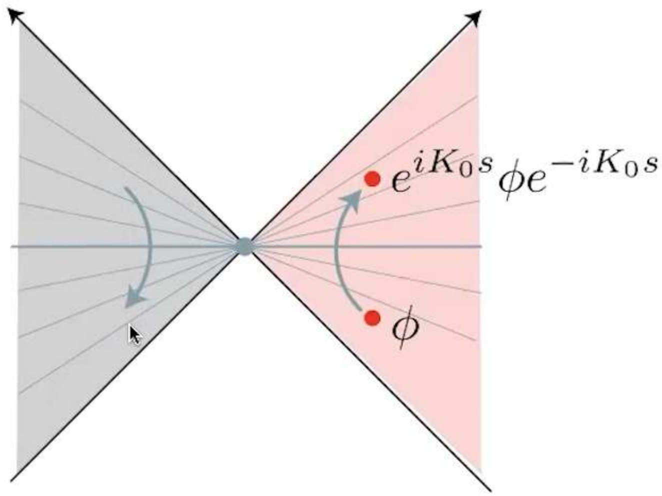
Toy example: Global Minkowski vs Rindler time



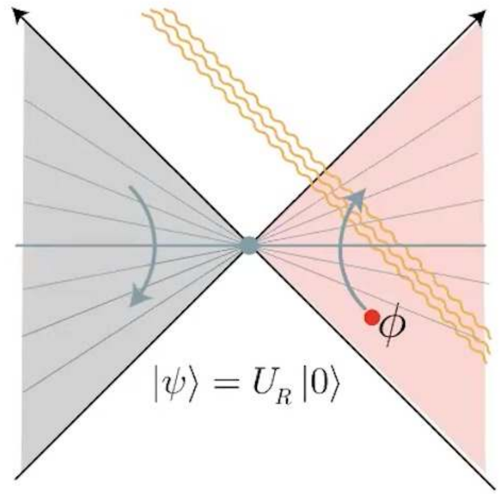
A quantum notion of internal time



$|0\rangle,\ \mathcal{A}_R \to\ K_0$ modular operator



$|0\rangle$, $\mathcal{A}_R \to \ K_0$ modular operator

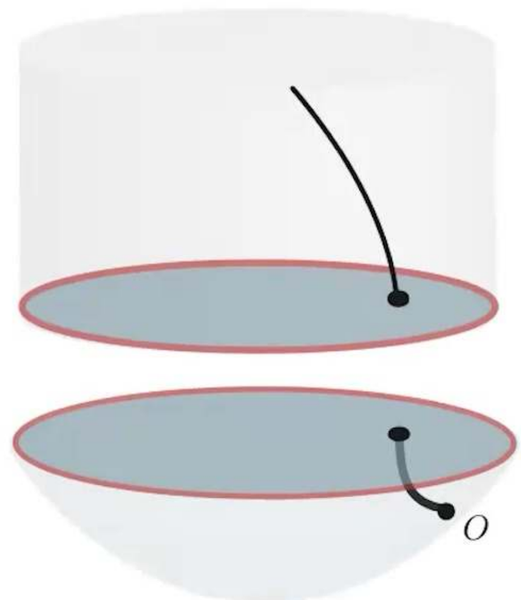


$$e^{iK_\psi s}\phi e^{-iK_\psi s} = U_R \phi_{K_0}(s) U_R^\dagger$$

Lorentz boosts are generated by the modular Hamiltonian K

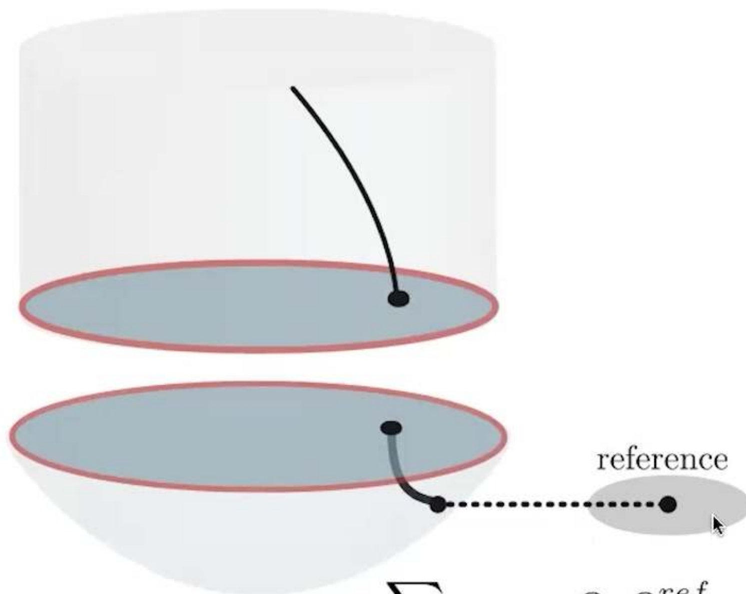
of the state $|0\rangle = U|\psi\rangle$ that minimizes $\langle H_{global}\rangle$

An observer in AdS/CFT



An observer in AdS/CFT

“Micro-canonical”
black hole
probe



$$\sum_{\Delta_i \in [E, E+\Delta E]} c_i \, O_i \, O_i^{ref}$$

An observer in AdS/CFT

“Micro-canonical”
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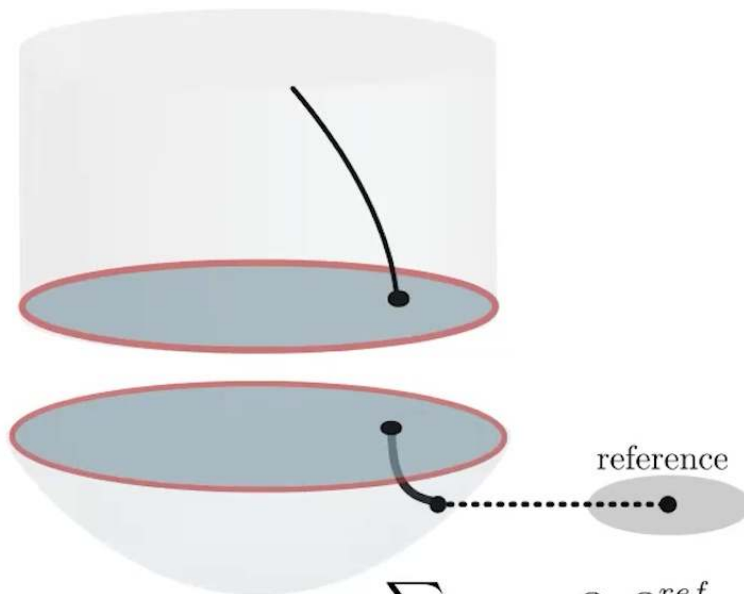


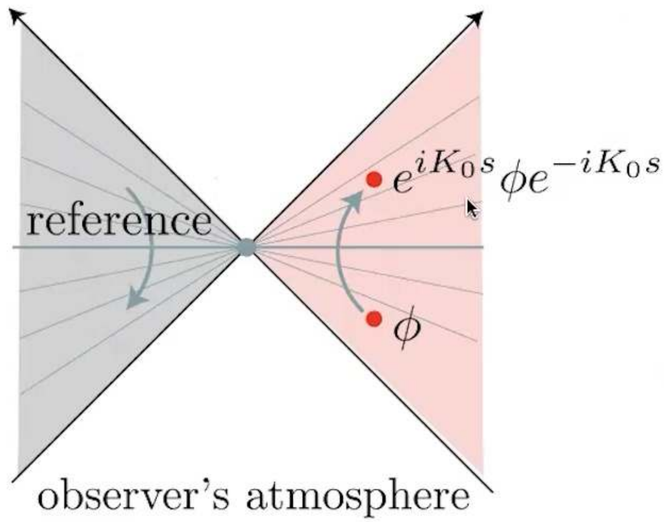
Double scaling

$$\frac{\beta}{L_{ads}} \to 0$$

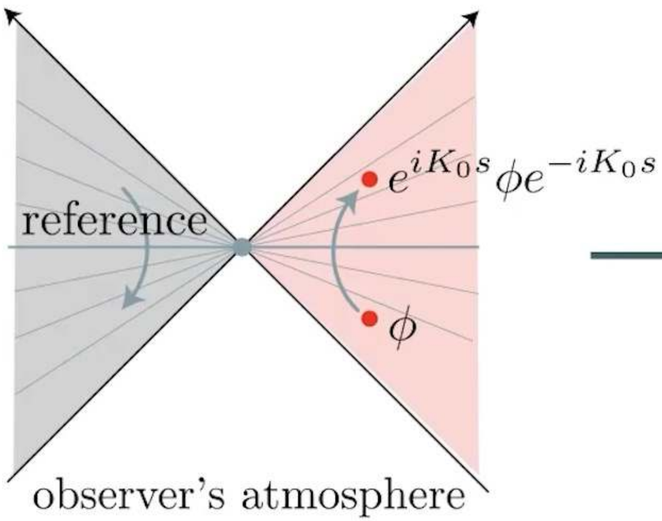
$$\frac{t_{scr}}{L_{ads}} = \frac{\beta}{L_{ads}} \log S = \text{fixed}$$

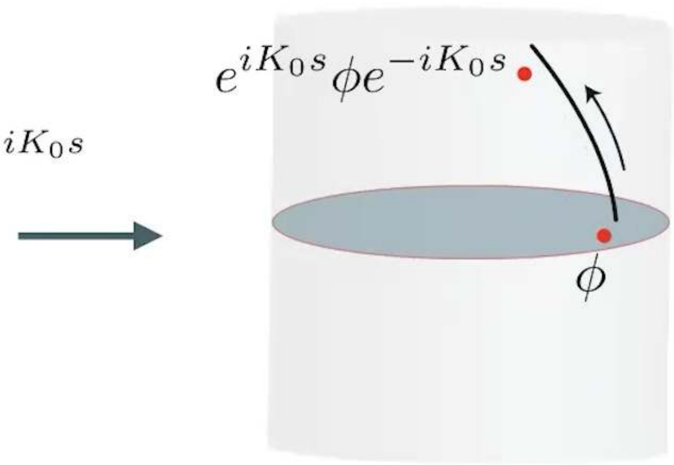
$$\sum_{\Delta_i \in [E, E+\Delta E]} c_i \, O_i \, O_i^{ref}$$

Modular flow = Proper time evolution



Modular flow = Proper time evolution





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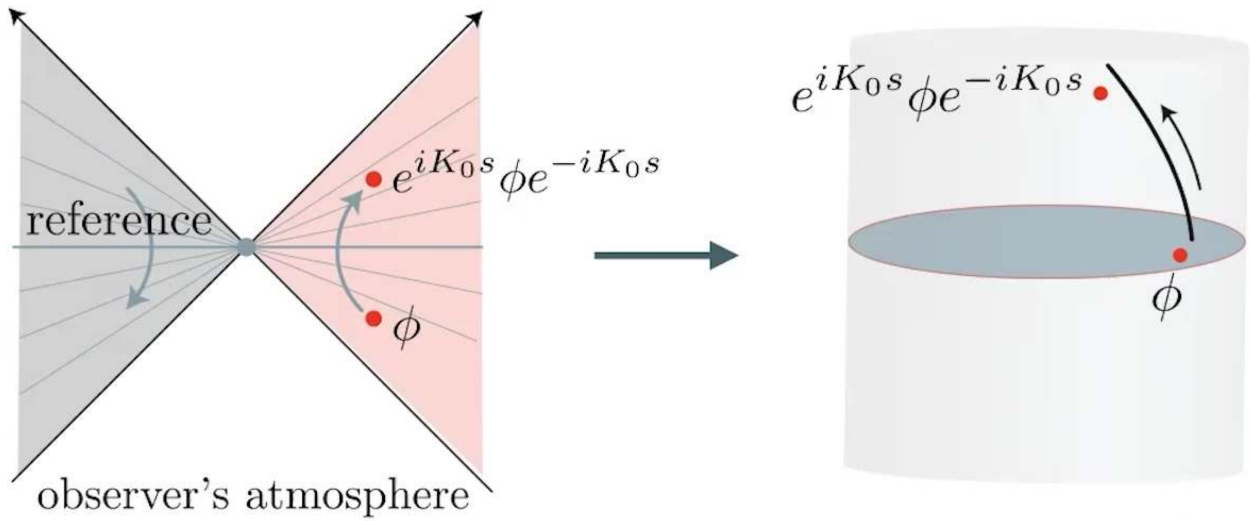


How to choose the "vacuum state"?

"Local equilibrium" states

So far we are given: $|\psi\rangle \rightarrow K_{\psi}$

Build a "code" subspace: $\mathcal{H}_{code} \equiv \{O_i|\psi\rangle \mid O_i \in \mathcal{A}^{cft}_{simple}\}$

Local equilibrium state: $|\psi_{eq}\rangle = U_{eq}|\psi\rangle \quad U_{eq}: \mathcal{H}_{code} \rightarrow \mathcal{H}_{code}$

"Local equilibrium" states

Local equilibrium state: $|\psi_{eq}\rangle = U_{eq}|\psi\rangle \quad U_{eq} : \mathcal{H}_{code} \to \mathcal{H}_{code}$

- Consider operator ϕ and its modular flow

$$\phi_{K_U}(s) = e^{iK_U s} \phi e^{-iK_U s} \qquad U \text{ : arbitrary}$$

- Define the *complexity* of the excitation as

$$C_\phi(s|U) = C\left[\phi_{K_U}(s)|\psi\rangle\right] - C\left[|\psi\rangle\right]$$

- U_{eq} minimizes $C_\phi(s = \log S|U) \ \forall \phi$

Taking stock

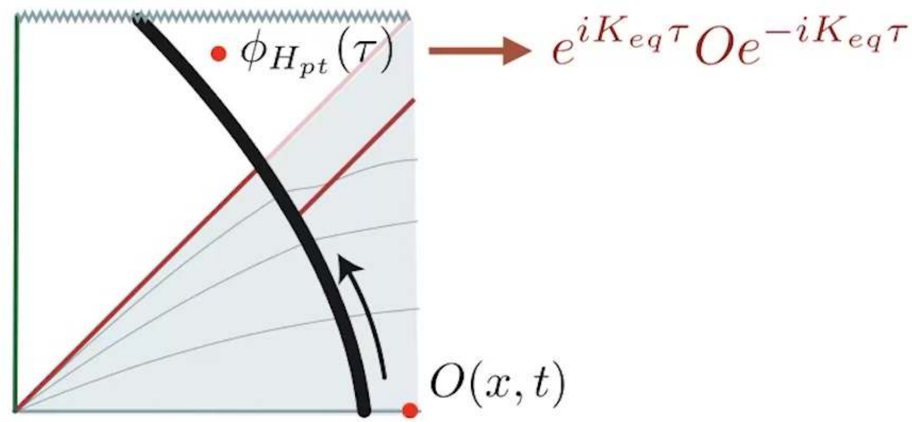
Given a "code" subspace → $|\psi_{eq}\rangle,\ K_{eq}$

↓ Hilbert space about a geometric background

↓ proper time generator along a wordline

Well-defined in the black hole interior!

What can we learn from it?



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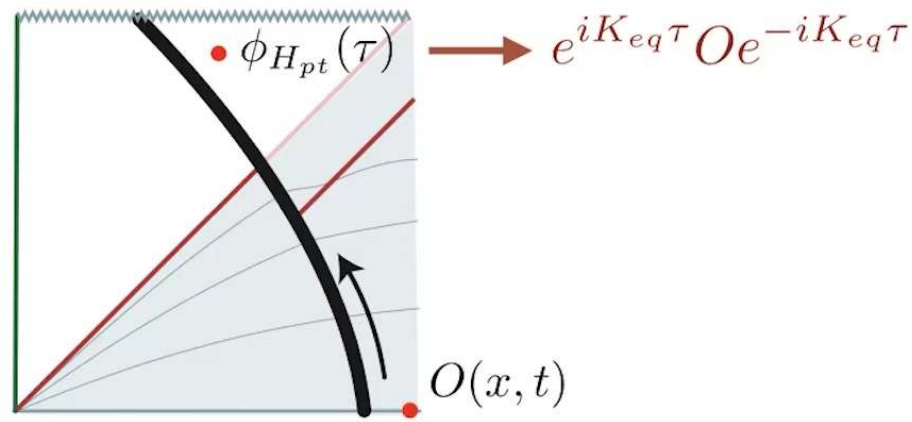

1) Singularity: $\langle \phi_{K_{eq}}(\tau_d) O \rangle \to \log r(\tau_d)$ divergence at $N = \infty$

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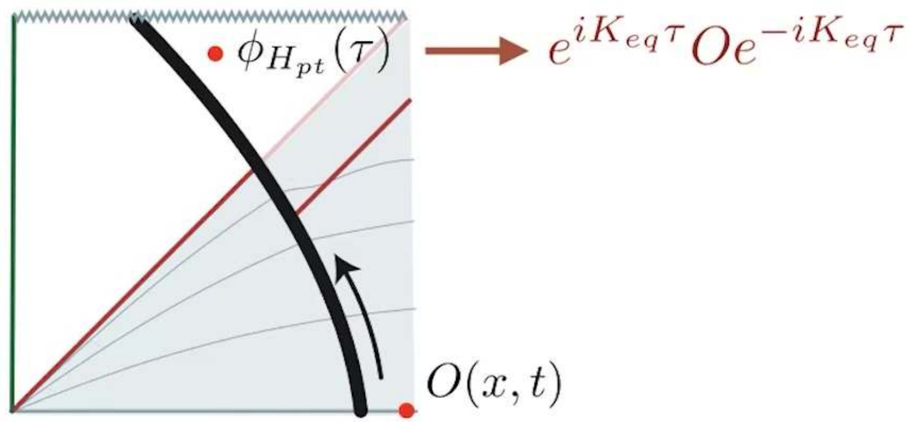

1) Singularity: $\langle \phi_{K_{eq}}(\tau_d) O \rangle \to \log r(\tau_d)$ divergence at $N = \infty$

2) Firewalls: $\tau_d \doteq$ size of interior $\longrightarrow$ $\mathbb{E}[\tau_d], \mathrm{Var}[\tau_d] = ?$

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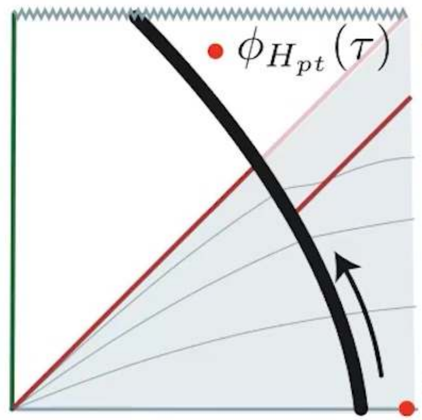

1) Singularity: $\langle \phi_{K_{eq}}(\tau_d) O \rangle \to \log r(\tau_d)$ divergence at $N = \infty$

2) Firewalls: $\tau_d =$ size of interior $\longrightarrow$ $\mathbb{E}[\tau_d], \mathrm{Var}[\tau_d] =?$

3) Structure of microstate interior: $\langle \psi_{bh} | \, \phi_{K_{eq}}(\tau) \, | \psi_{bh} \rangle =?$

arXiv: 2111.14010