

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.

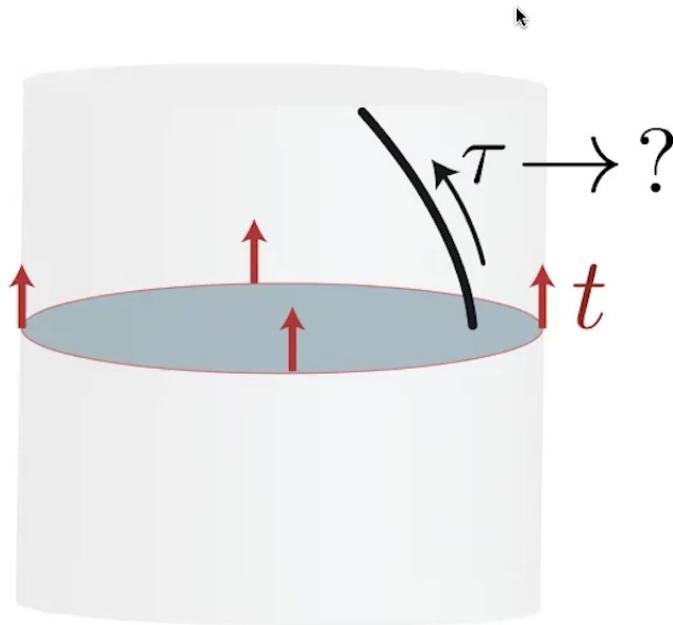
I will explicitly apply the method in the AdS₂/SYK correspondence. My proposal provides an internal notion of time for quantum gravitational systems that may be useful for cosmology.



EMERGENT TIME AND THE BLACK HOLE INTERIOR

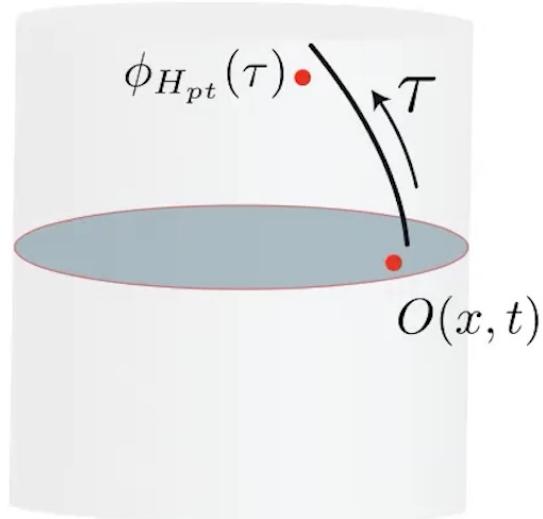
Lampros Lamprou
University of British Columbia

More phenomenologically relevant notion:
Proper time of an observer

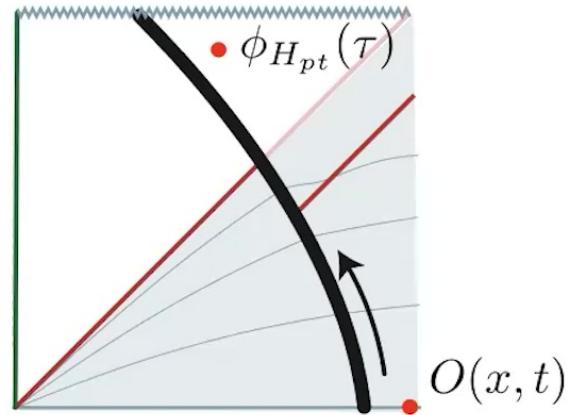


Time experienced by observers is “emergent”!

1) Bulk reconstruction (from first principles)



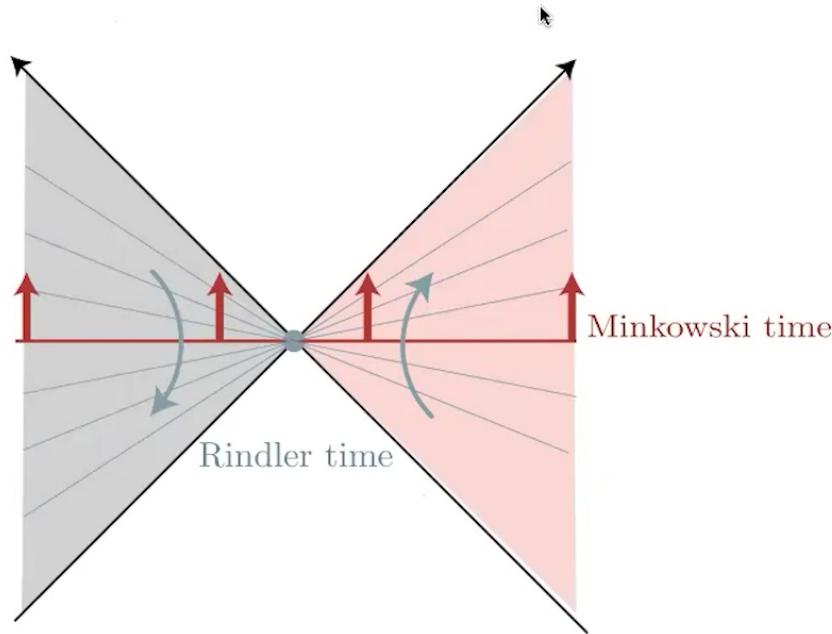
- 2) Black hole interiors: Singularity signatures,
typicality of firewalls, etc



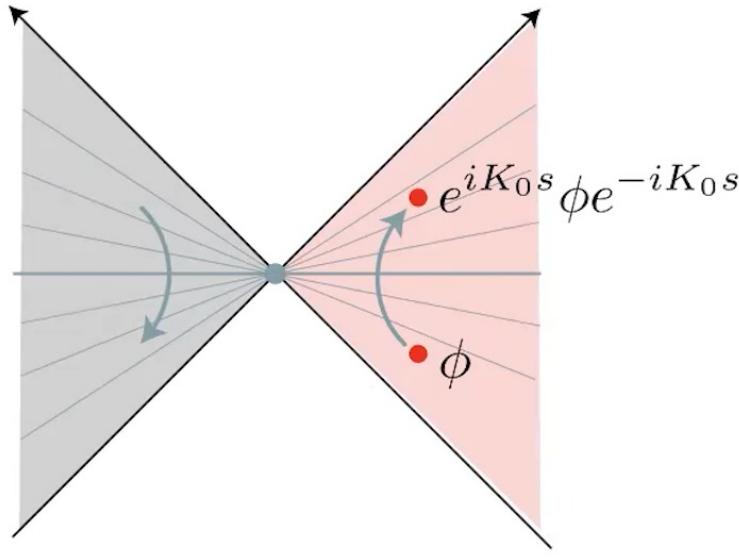
- 3) Cosmology: No asymptotic clock

- (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!

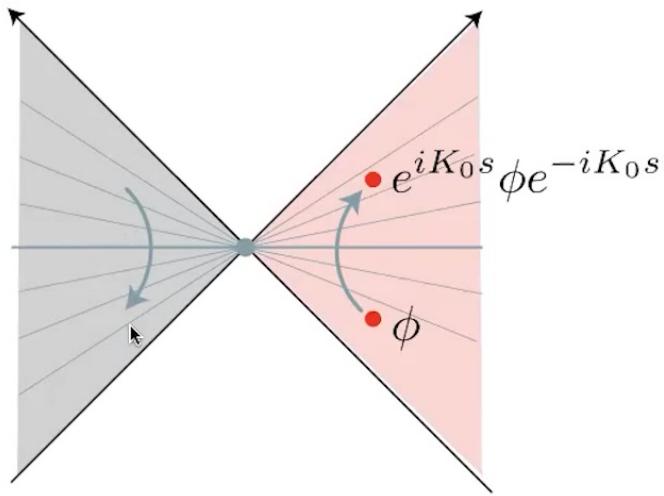
Toy example: Global Minkowski vs Rindler time



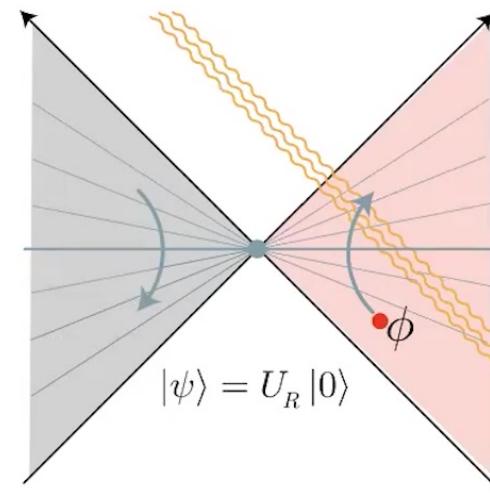
A quantum notion of internal time



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



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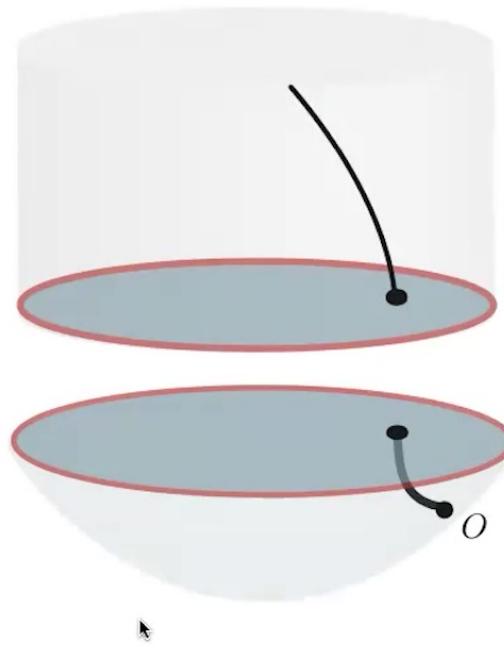


$$e^{iK_\psi s} \phi e^{-iK_\psi s} = U_R \phi_{K_0}(s) U_R^\dagger$$

Lorentz boosts are generated by the modular Hamiltonian K

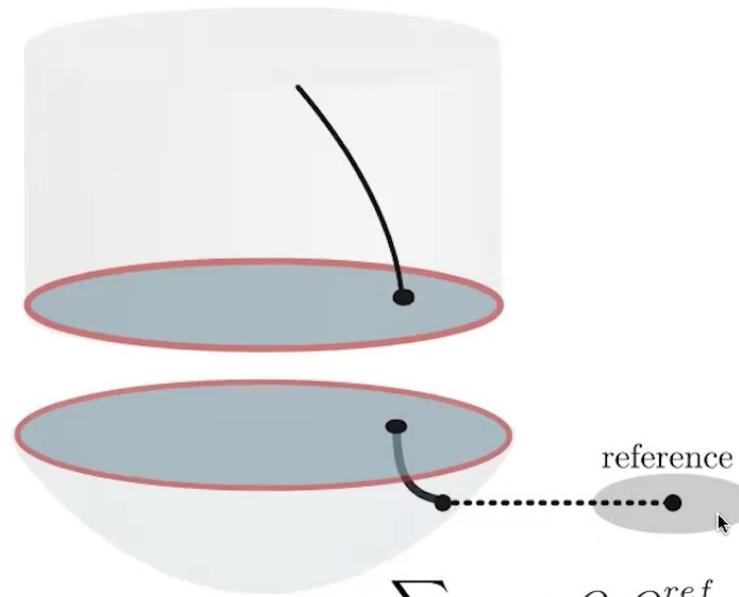
of the state $|0\rangle = U|\psi\rangle$ that minimizes $\langle H_{global} \rangle$

An observer in AdS/CFT



An observer in AdS/CFT

“Micro-canonical”
black hole
probe



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

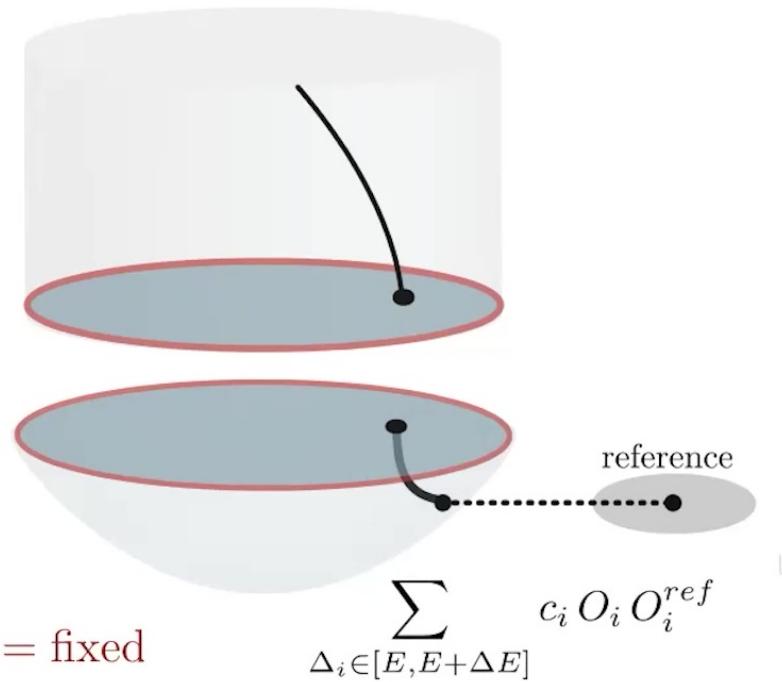
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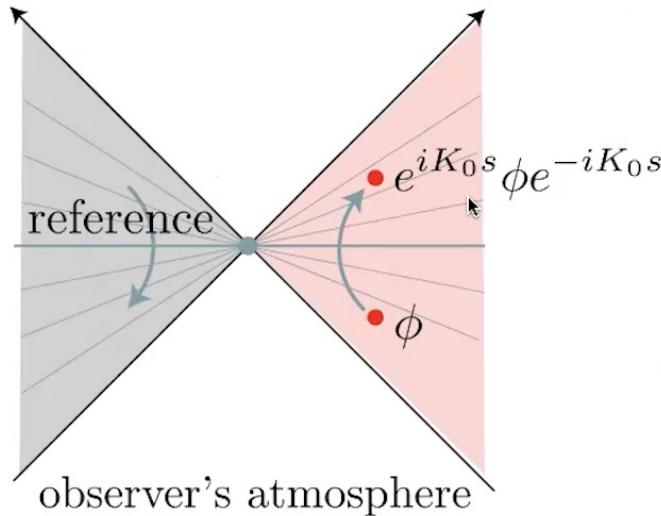
Double scaling

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

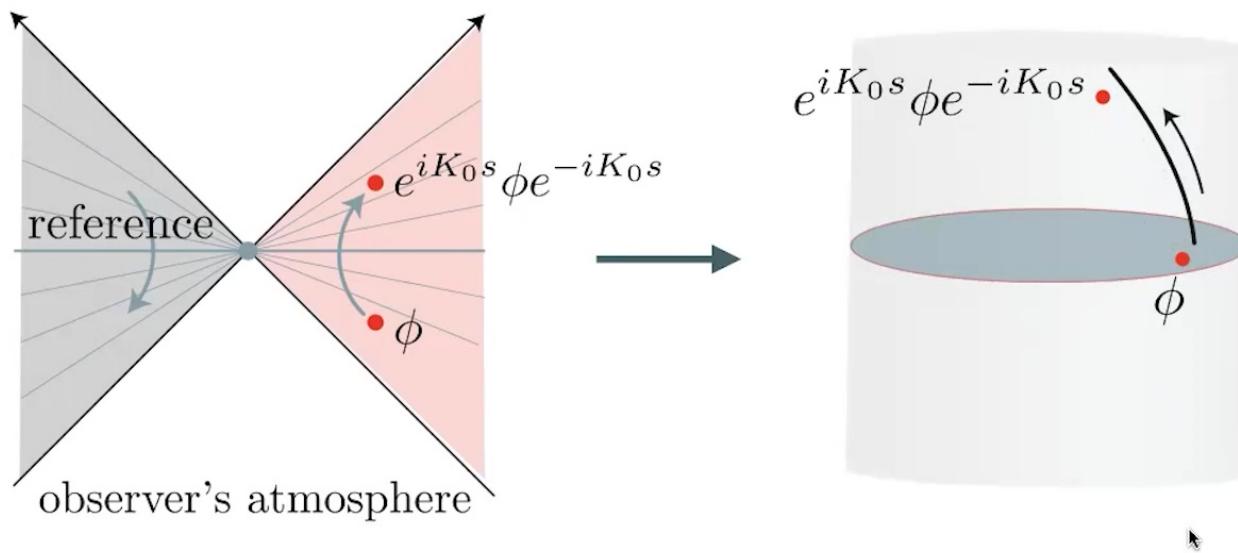
$$\frac{t_{scr}}{L_{ads}} = \frac{\beta}{L_{ads}} \log S = \text{fixed}$$



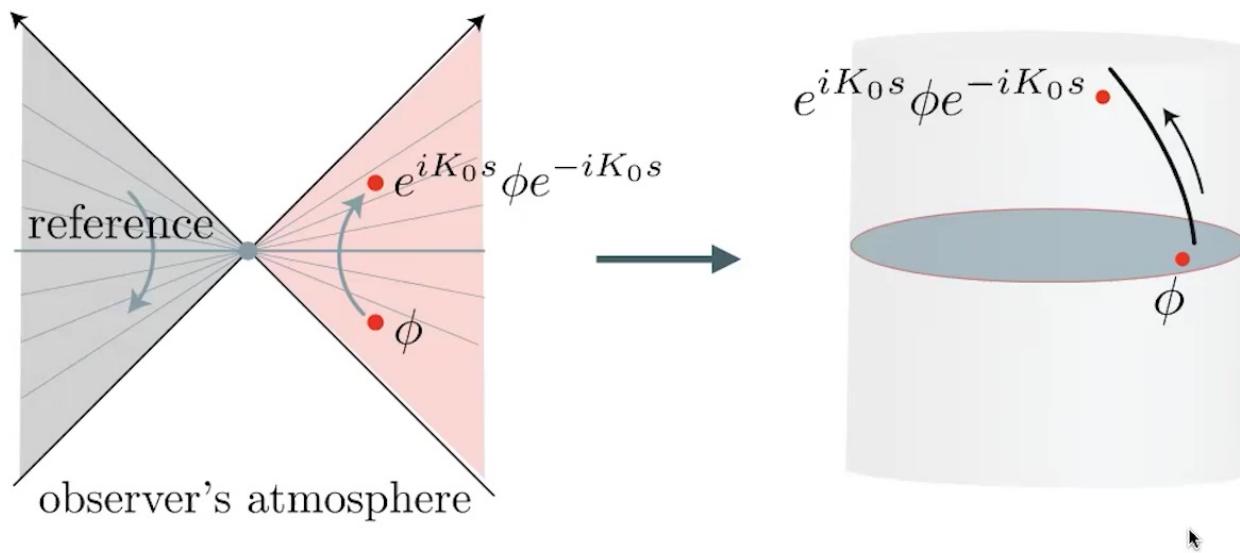
Modular flow = Proper time evolution



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

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

“Local equilibrium” states

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

- Consider operator ϕ and its modular flow

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

- Define the *complexity* of the excitation as

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

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

Taking stock

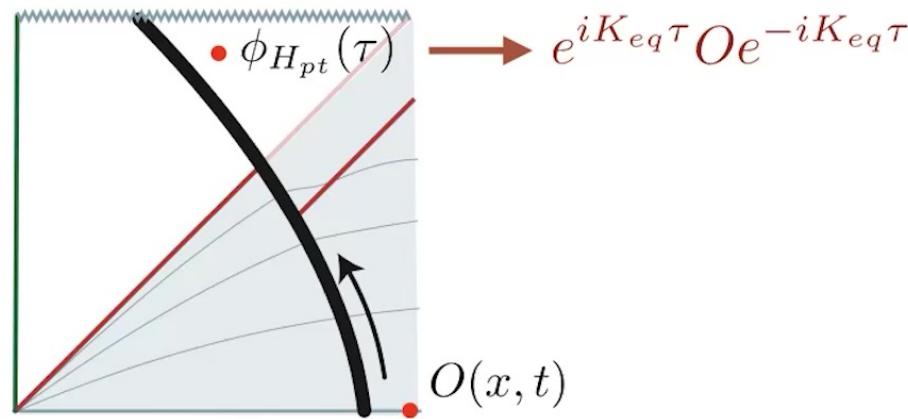
Given a “code” subspace $\rightarrow |\psi_{eq}\rangle, K_{eq}$

Hilbert space about a geometric background

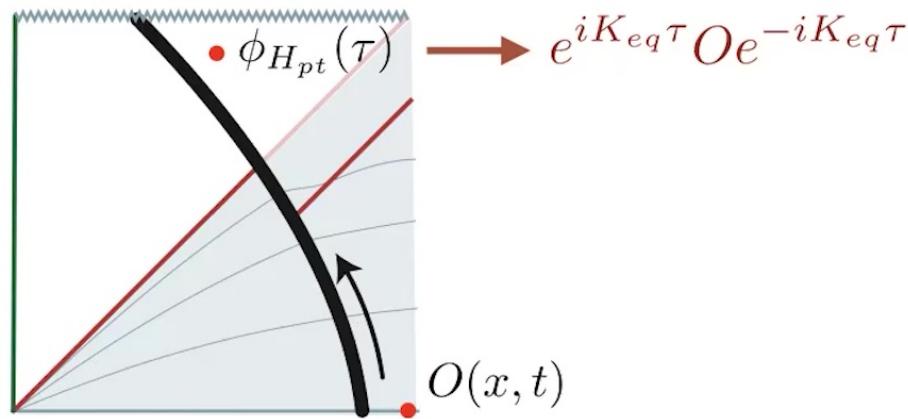
proper time generator along a wordline

Well-defined in the black hole interior!

What can we learn from it?

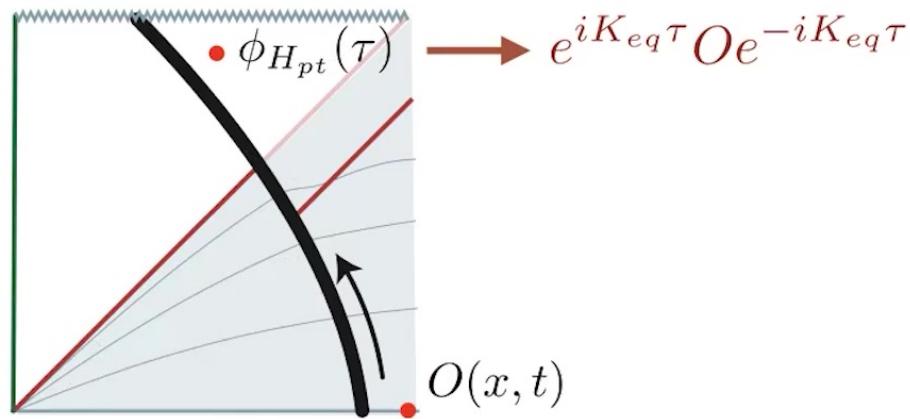


What can we learn from it?



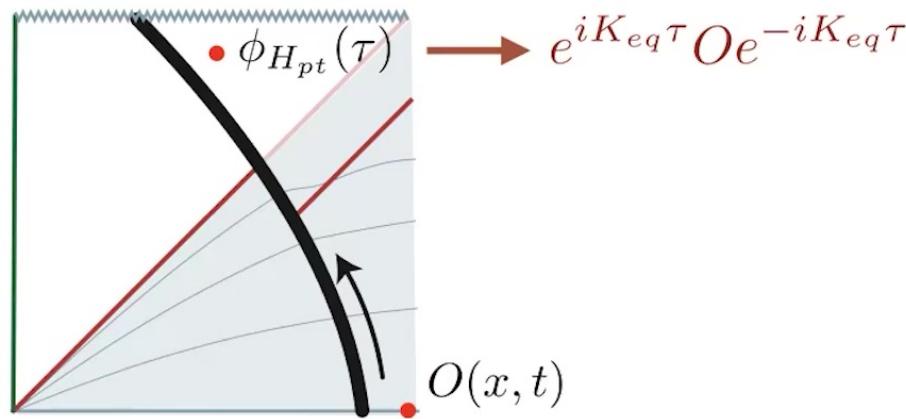
- 1) Singularity: $\langle \phi_{K_{eq}}(\tau_d) O \rangle \rightarrow \log r(\tau_d)$ divergence at $N = \infty$

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

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- 1) Singularity: $\langle \phi_{K_{eq}}(\tau_d) O \rangle \rightarrow \log r(\tau_d)$ divergence at $N = \infty$
- 2) Firewalls: $\tau_d =$ size of interior $\rightarrow \mathbb{E}[\tau_d], \text{Var}[\tau_d] = ?$
- 3) Structure of microstate interior: $\langle \psi_{bh} | \phi_{K_{eq}}(\tau) | \psi_{bh} \rangle = ?$

arXiv: 2111.14010