Title: Inside the Hologram: The bulk observer's experience

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Series: Quantum Fields and Strings

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Abstract: I will present a holographic framework for reconstructing the experience of bulk observers in AdS/CFT. In particular, I will show how to recover the proper time and energy distribution measured along bulk worldlines, directly in the CFT via a universal, background-independent prescription. For an observer falling into an eternal AdS black hole, the proposal resolves a conceptual puzzle raised by Marolf and Wall. Notably, the prescription does not rely on an external dynamical Hamiltonian or the AdS boundary conditions and is, therefore, outlining a general framework for the emergence of time.

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INSIDE THE HOLOGRAM

Lampros Lamprou w/ Daniel Jafferis

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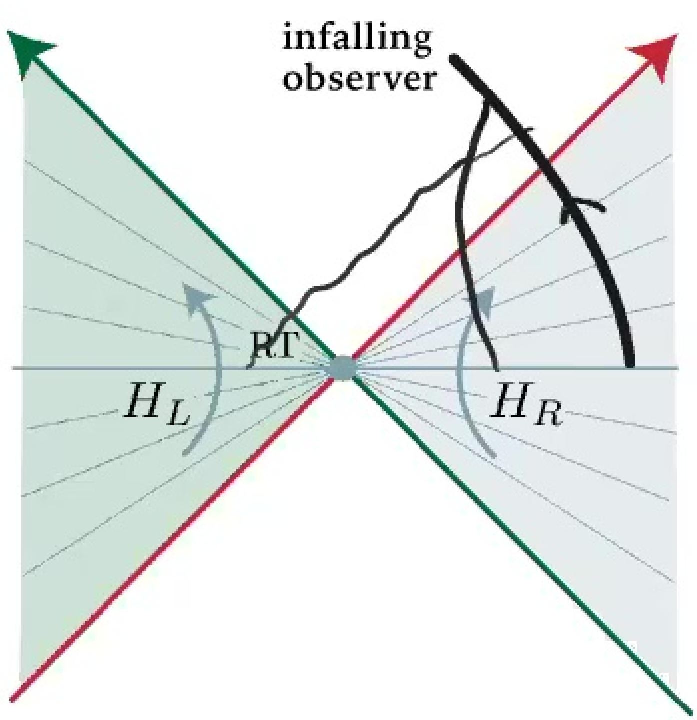

THE QUESTION

- **What does the infalling observer experience after crossing the horizon?**
- Can we answer in the dual CFT:
  - A. How much proper time till they hit the singularity?
  - B. How many times their Geiger counter "clicked"?
  - C. What CFT operators can they excite or measure?

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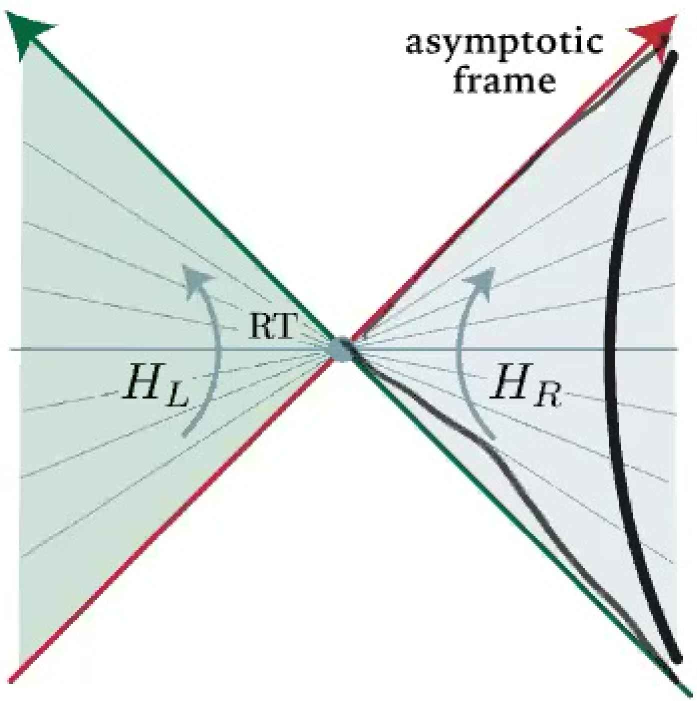
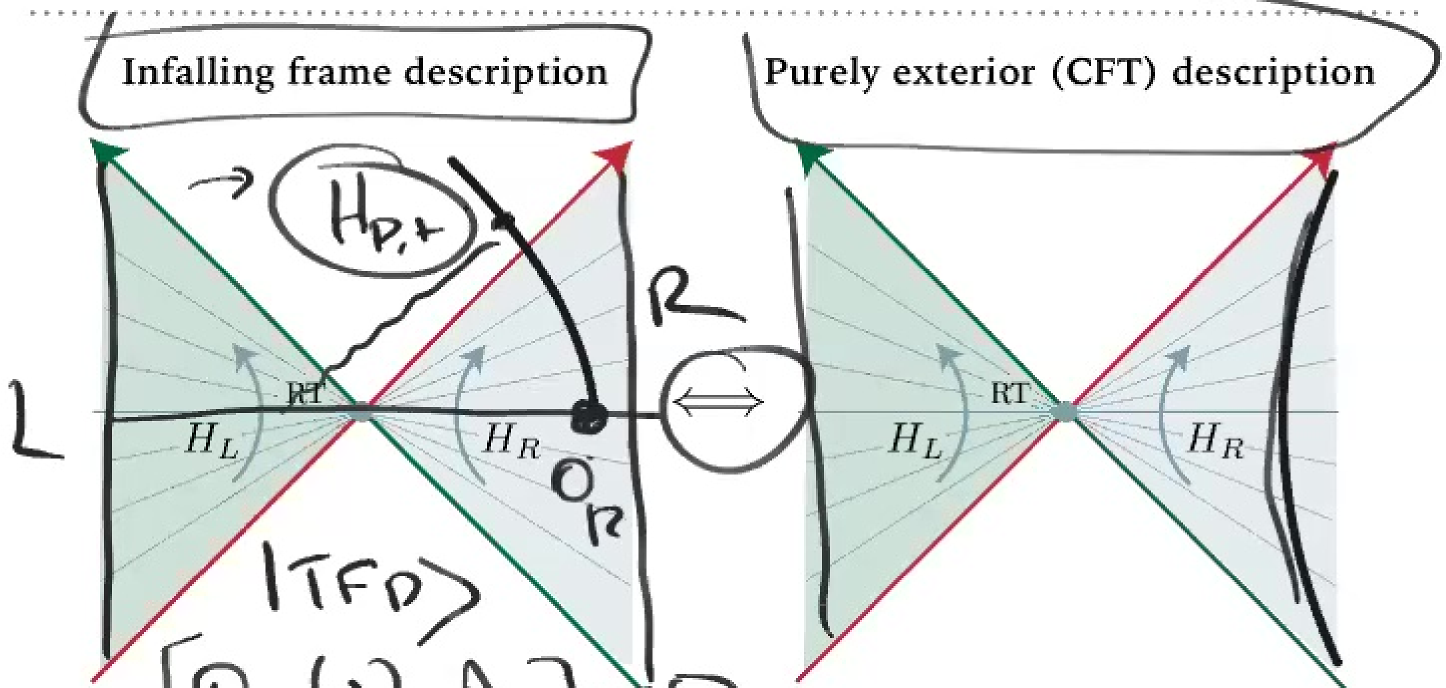


WHAT DOES ADS/CFT SAY?

- CFT describes the Black Hole from an **asymptotic frame**.
- From this point of view it is an **ordinary thermal quantum system** with:
  - A. Finite entropy.
  - B. Fast scrambling dynamics.
  - C. Unitary evolution.
- Interior is **"in the future"** of the Schwarzschild evolution.

COMPLEMENTARITY



$[O_R(t), A_L] = 0$

Puzzle: *If observer is made out of quarks and gluons of* ***Right CFT*** *and the two CFTs are* ***decoupled****, how can they* ***receive signals*** *from the* ***Left CFT****?*

$[O_R(t), A_L] \neq 0$

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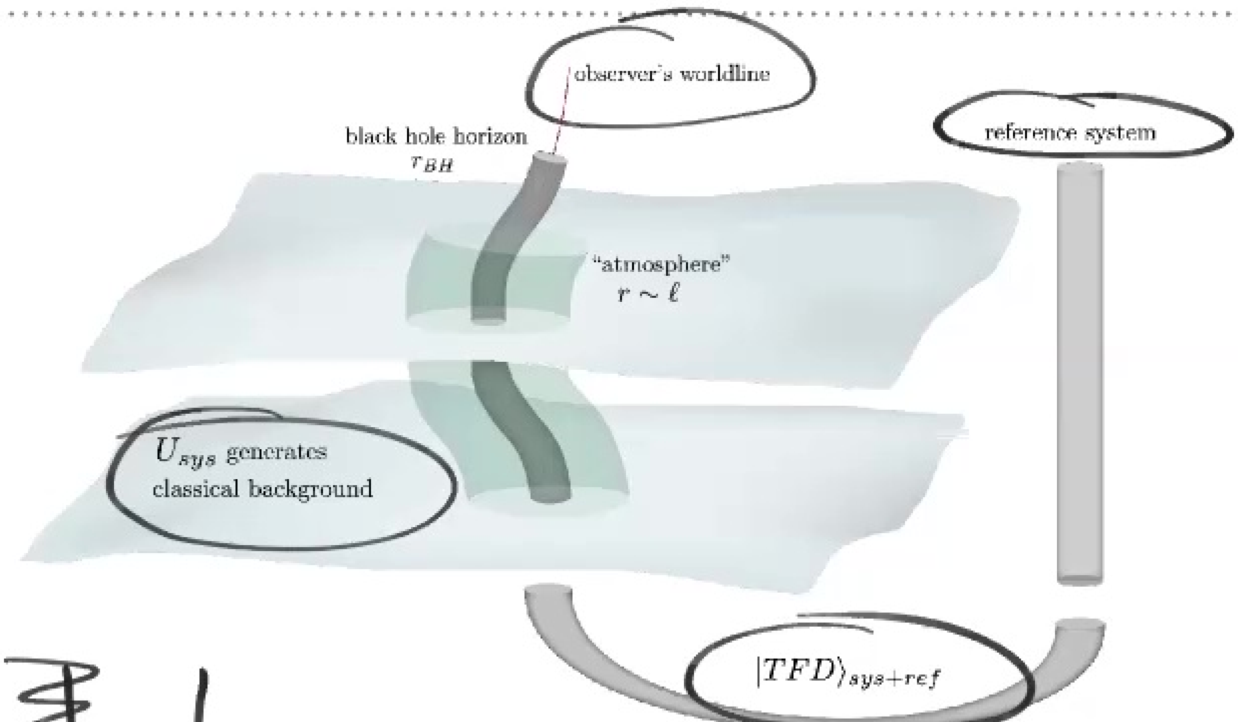
"UNIVERSAL" BULK RECONSTRUCTION

- Closely related puzzle for ordinary bulk reconstruction (no black holes)
- HKLL, modular flow reconstruction, Petz map, all require as input the bulk background solution.
- **Q: Is there a universal prescription formulated directly in the boundary CFT?**

PROBE BLACK HOLE AS A HOLOGRAPHIC "OBSERVER"

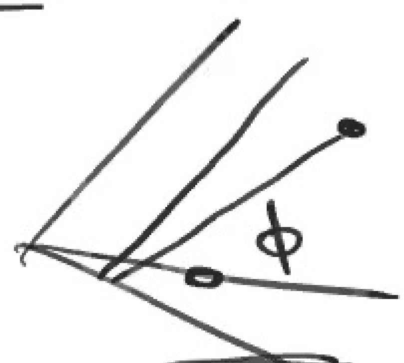


$t=0 \quad |\psi\rangle_t = e^{iHt} U_{sys} |TFD\rangle$

BASIC CONCEPTS I

- At t_i and t_f we have access to CFT duals of the algebra of **atmosphere operators**

$$S_t \equiv \{\phi_i(x_i), \phi_j(x_j)\phi_l(x_l), \partial\phi_k(x_k), \ldots \,|\, x_i \in \Sigma_t \text{ and } |x_i - x_H| \leq \ell\}$$



- The **unitary** $\boxed{V(t_i, t_f)}$ that relates S_{t_i} and S_{t_f} is, by definition, the **proper time evolution** operator.

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BASIC CONCEPTS II

- Tracing out the reference, gives us a **modular Hamiltonian** for the system:

$$\boxed{K(t) = e^{-iHt} U_{sys} H U_{sys}^{\dagger} e^{iHt}}$$

$$\underline{|\psi\rangle} \longrightarrow \rho_{sys} \longrightarrow K = -\log \rho_{sys}$$

THE CASE OF NO INFALLING PARTICLES

- The initial and final (Heisenberg) atmosphere operators:

$$\phi^t_H(x) = V_H(0,t)\,\phi^0_H(x)\,V^\dagger_H(0,t)$$

- Geometry=approximately Schwarzschild, atmosphere state=approximately thermal and no infalling energy:

$$\langle\Psi|\,\phi^t_{H,1}\ldots\phi^t_{H,n}\,|\Psi\rangle = \langle\Psi|\,\phi^0_{H,1}\ldots\phi^0_{H,n}\,|\Psi\rangle$$

- Unitary must be a **modular symmetry***:

$$V_H(0,t) = \exp\left[-i\frac{\tau(t)}{2\pi}\,K(0) - i\sum_a d_a(t)Q'_a\right]$$

$$[Q_a, P_{code}K(0)P_{code}] = 0, \text{ where: } \mathcal{H}_{code} = \{O|\Psi\rangle, \forall\, O \in S_0\}$$

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proper time

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THE MAIN CLAIM

$$[K, G_\lambda] = \lambda G_\lambda$$

proper

$$i \log V_H(0,t) = \frac{\tau(t)}{2\pi} \int d\Omega_{d-2}\, f(\Omega)\, G_{2\pi}(\Omega) + \frac{\tau(t)}{2\pi} K$$

energy distribution

$$+\text{other zero-modes} + O(e^{-\tau}, N^{-1})$$

$$\lambda = i\kappa^2$$

$$\kappa^2 \leq 2\pi$$

scrambling modes

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A GEOMETRIC ARGUMENT I

- The modular Hamiltonian is defined as the **KMS operator**:

$$\langle\Psi|\phi_1^\dagger e^{-K}\,\phi_2|\Psi\rangle = \langle\Psi|\phi_2\,\phi_1^\dagger|\Psi\rangle$$

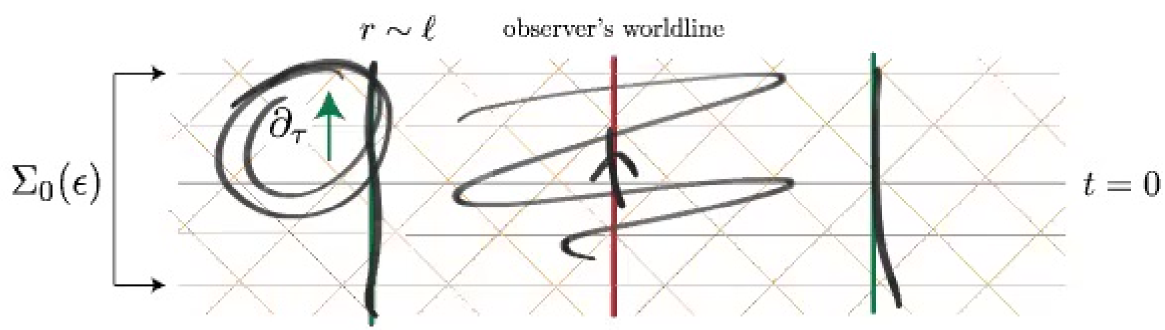
  for the atmosphere operators $\phi_i \in S_t$

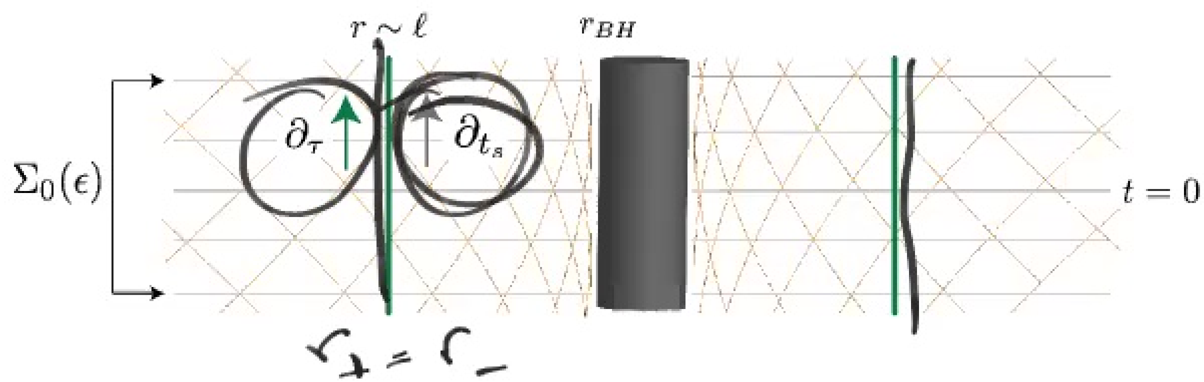
- Atmosphere is in local **thermal equilibrium.** Thermal circle is the Wick rotation of the **local timelike killing vector**

$$\langle\Psi|\phi_2\,\phi_1^\dagger|\Psi\rangle \approx \langle\Psi|\phi_1^\dagger e^{-2\pi P_{\xi_s}}\,\phi_2|\Psi\rangle$$

- Therefore $K \approx \partial_\tau$ when acting in region $r \sim \ell$

A GEOMETRIC ARGUMENT II





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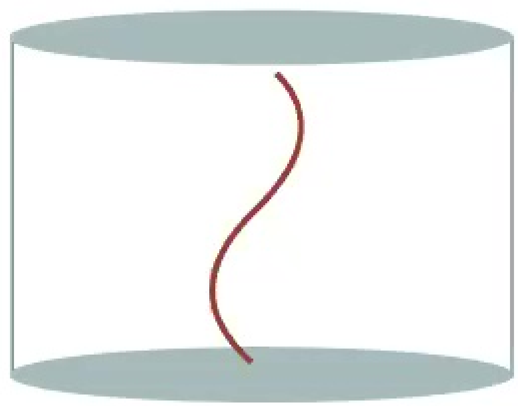
EXAMPLE I: INERTIAL MOTION IN PURE ADS

➤ Consider **boosted AdS black hole** entangled with reference:

$$|\Psi\rangle = e^{-iB\eta}|TFD\rangle$$



$$x(t) = \tanh^{-1}\left(\tanh\eta(0)\,\sin t\right)$$
$$\eta(t) = \sinh^{-1}\left(\sinh\eta(0)\cos t\right)$$

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EXAMPLE I: PURE ADS

- For a **static BH** an operator at a specific location relative to the horizon is given by the **HKLL construction**.

$$\phi^{static}$$

- For the **moving black hole**, they read:

$$\phi^0(r,\Omega) = e^{-iB\eta}\phi^{\text{static}}(r,\Omega)\, e^{iB\eta}$$

$$\phi^t(r,\Omega) = e^{-iPx(t)}e^{-iB\eta(t)}\phi^{\text{static}}(r,\Omega)\, e^{iB\eta(t)}e^{iPx(t)}$$

EXAMPLE I: PURE ADS

- Extract the CFT unitary $V_H(0,t)$

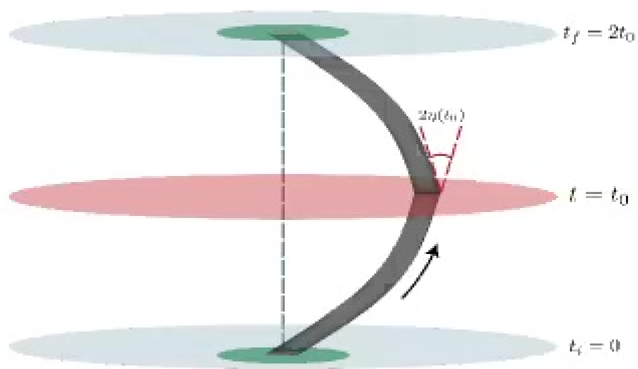
$$\phi^t_H(x) = V_H(0,t)\,\phi^0_H(x)\,V^\dagger_H(0,t)$$

- Decompose into eigen-operators of K

$$V_H(0,t) = \exp\left[-i(2\pi)^{-1}\tanh^{-1}\frac{tant}{\cosh\eta(0)}K(0)\right]$$

EXAMPLE II: WEAKLY CURVED ADS

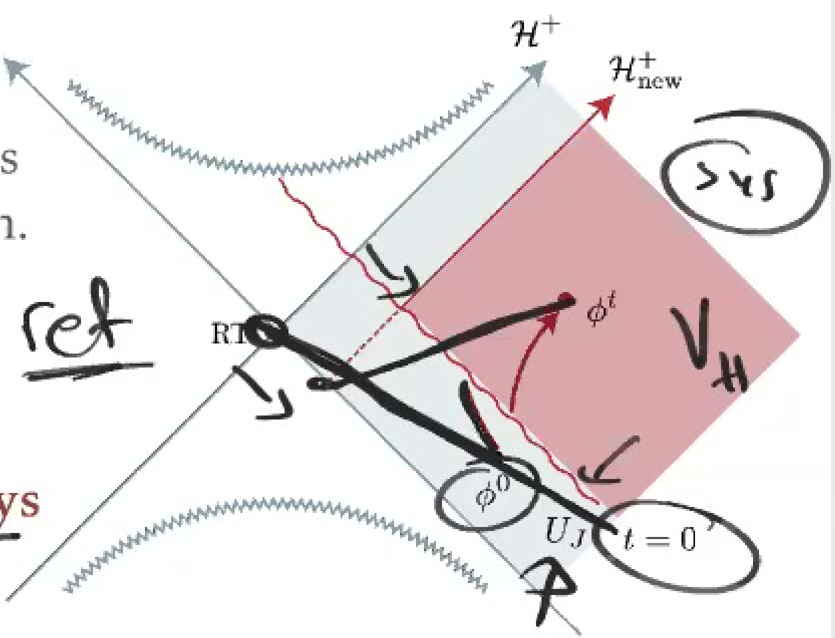
- Prescription works if we kick the black hole.



- By a dense sequence of kicks we can construct arbitrary accelerated trajectories.
- In the Newtonian approximation, this extends our prescription to weakly curved AdS spacetimes.

DETECTING INFALLING PARTICLES

- Our probe black hole also acts as a **particle detector**.
- When initial state contains infalling particles: **final event horizon** is **shifted** relative to the **initial**.
- **Proper time** flow preserves distance from **local** horizon.
- **Energy distribution** gets imprinted in **Shapiro delays** of the atmosphere fields.

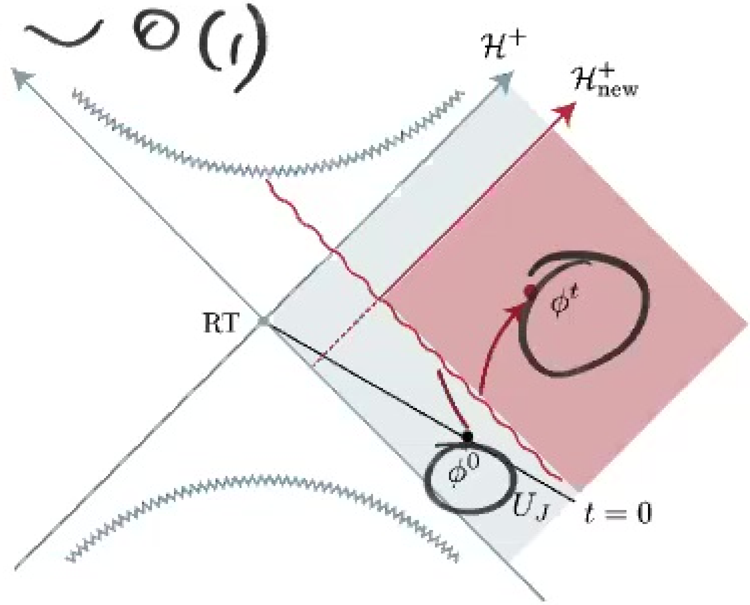


MODULAR VS PROPER TIME FLOW

- Modular flow of the initial atmosphere fields in a state with infalling particles reads:

$$\phi_K(t) = e^{iK_J t}\phi^0 e^{-iK_J t} = U_J e^{iHt}\phi^0 e^{-iHt}U_J^\dagger$$

- $\left(\phi_K(t)U_J|TFD\rangle, \phi_H^t U_J|TFD\rangle\right) \sim O(1)$



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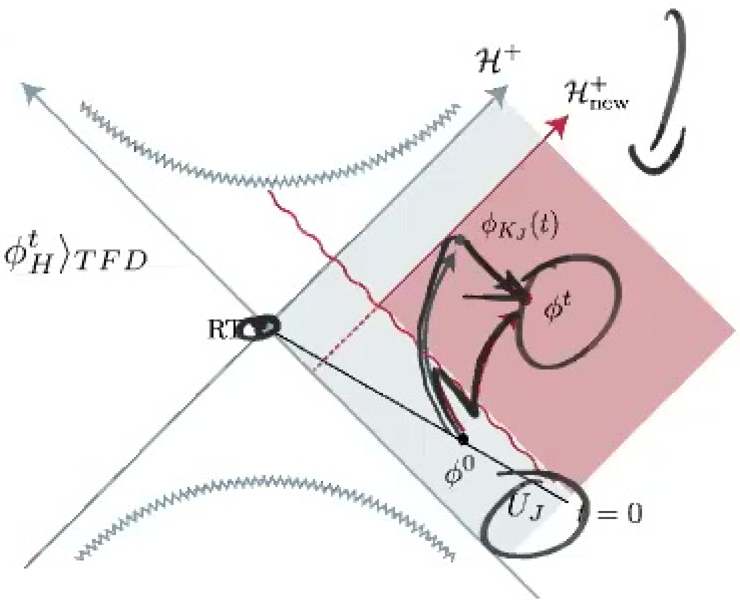
- $\left(\phi_K(t)U_J|TFD\rangle,\ \phi_H^t U_J|TFD\rangle\right)$

$$= \langle U_J^\dagger \phi_H^t U_J \phi_H^t\rangle_{TFD} \longrightarrow 0$$

$$\approx \langle \phi_H^t \exp\left[-i\int d\Omega\, \Delta x^-(t,\Omega)P_-(\Omega)\right]\phi_H^t\rangle_{TFD}$$



- **Shapiro delay:**

$$\Delta x^- = e^t \int_{\Omega'} f(\Omega,\Omega')\delta E_0^+(\Omega')$$

MODULAR CHAOS BOUND

- Proper time flow = Modular flow + Scrambling mode flow

$$V_H(0,t) \approx \exp\left[\frac{i}{2\pi}\int \delta E^0_+(\Omega')\, f(\Omega,\Omega')\, G_{2\pi}(\Omega)\, t + \frac{i}{2\pi}K_J\, t + O\left(e^{-t}, N^{-1}\right)\right]$$

- Difference of proper time and modular Hamiltonians saturates modular chaos bound

$$\langle\phi_1|e^{iKs}\,(H_{p.t.} - K_J)\, e^{-iKs}|\phi_2\rangle \lesssim e^{2\pi s}\, G_{2\pi}$$

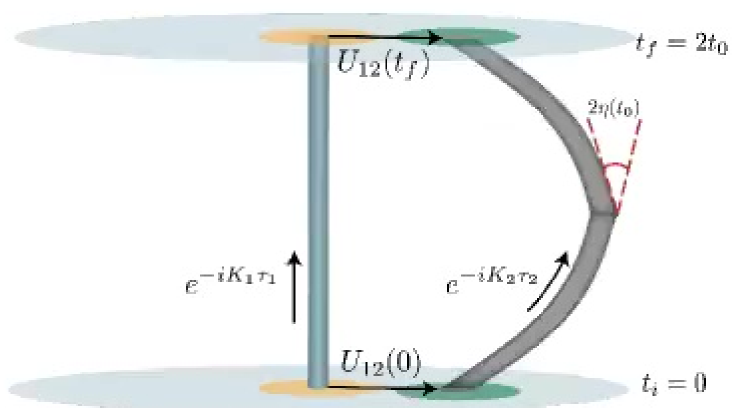
THE MAIN CLAIM

$$i \log V_H(0,t) = \frac{\tau(t)}{2\pi} \int d\Omega_{d-2}\, f(\Omega)\, G_{2\pi}(\Omega) + \frac{\tau(t)}{2\pi} K$$

$$+\text{other zero-modes} + O(e^{-\tau}, N^{-1})$$

TIME DILATION

- Consider a pair of black hole observers

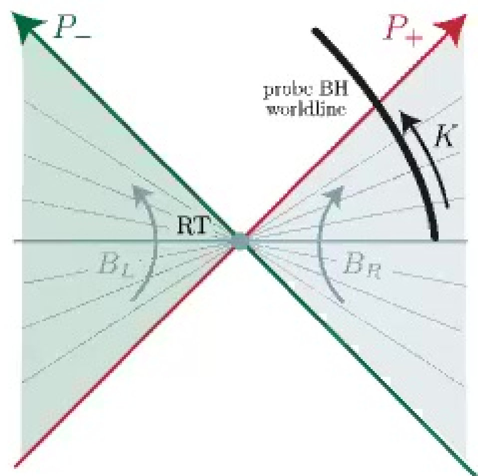


- Proper time is computed by the amount of modular flow in:

$$U_{12}^{\dagger}(0)V_H^{(2)}U_{12}(0)V_H^{(1)\dagger}$$

RESOLUTION OF THE MAROLF-WALL PUZZLE

- Introduce a **right** bulk observer in the eternal AdS black hole.
- In our formalism: Entangle $\mathrm{CFT_R}$ subsystem with a reference.

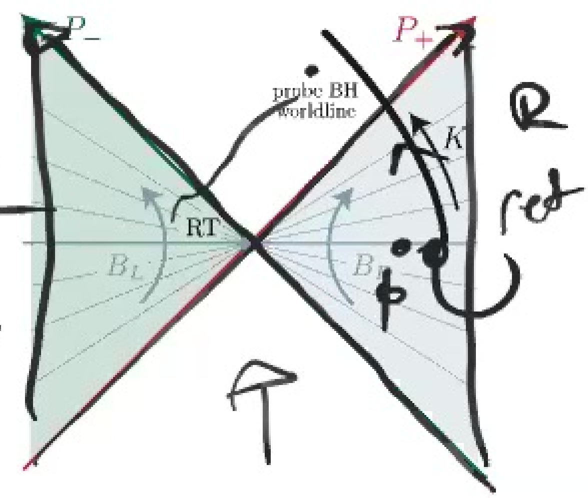


- Proper time evolution=Modular flow
- Due to entanglement, observer's modular flow **couples** Left and Right.
- Coupling $\approx$ Horizon symmetry generators (explicit in SYK)

RESOLUTION OF THE MAROLF-WALL PUZZLE

- Introduce a right bulk observer in the eternal AdS black hole.
- In our formalism: Entangle CFT_R subsystem with a reference.

$$e^{iO_R O_{ref}} |TFD\rangle_{LR} |0\rangle_{ref}$$



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- Due to entanglement, observer's modular flow couples Left and Right.
- Coupling ≈ Horizon symmetry generators (explicit in SYK)

$V \supset$ site Q: - Streicher

PROBING SUB-ADS SCALES

- The "canonical" TFD can only describe BH larger than L_{AdS} due to the Hawking-Page transition.
- Small BH entropically dominate the **microcanonical** ensemble for **parametrically smaller** horizon radii

$$\frac{R_H}{L_{AdS}} \sim \left(\frac{L_{AdS}}{\ell_{pl}}\right)^{\frac{1-d}{2d-1}}$$

- We can introduce **sub-AdS scale observers** by starting from the **"microcanonical" TFD**:

$$|TFD\rangle_{micro} = \mathcal{Z}^{-1/2} \sum_n e^{-bE_n} f(E_n) |E_n\rangle_{sys} |E_n\rangle_{ref}$$

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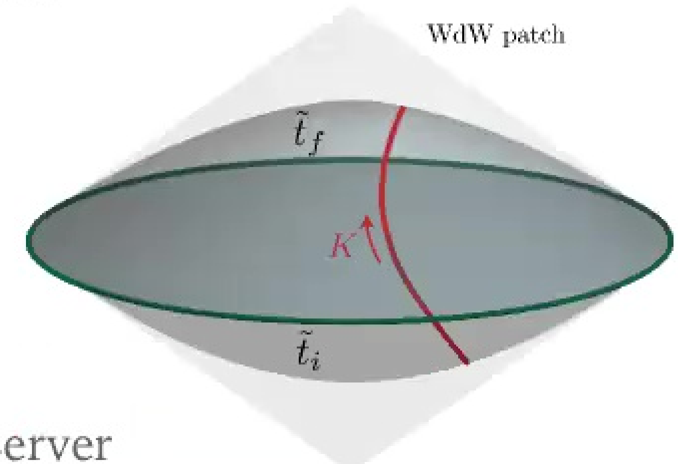
EMERGENT TIME

- Prescription does not require an external dynamical Hamiltonian or AdS asymptotics.



- Can be applied to two slices inside a WdW patch.
- Proper time emerges from observer -environment entanglement.
- Can be applied to Matrix Theory, Cosmological models, etc.