Spacetime Locality and the Motion of Quantum Information

Brian Swingle (UMD)

Jan 17, 2020

Geometry from the Quantum, KITP

It from Qubit
Simons Collaboration on
Quantum Fields, Gravity and Information

Plan

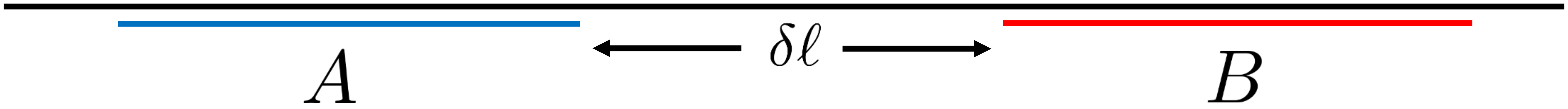
- Discuss motion of quantum information in chaotic many-body systems (focuses on quasi-1d situations, but general criterion given)
  - Work with Josiah Couch, Stefan Eccles, Phuc Nguyen, and Shenglong Xu
  - arXiv:1908.06993
- Discuss a puzzle raised by Shor and a toy model displaying a phenomenon of “chaos-protected locality”
- In another universe … a mostly unrelated result giving a no-go result for realizing SYK-like physics in bosonic models
  - Work with Chris Baldwin
  - arXiv:1911.11865

$$H = \sum_{\alpha, a} J^{\alpha_1 \cdots \alpha_p}_{a_1 \cdots a_p} \sigma^{\alpha_1}_{a_1} \cdots \sigma^{\alpha_p}_{a_p}$$

$Z[J]$ fails to self-average at low temperature (roughly)

A simple communication protocol

$$|\psi\rangle,\, U = e^{-iHt}$$



$$X_a,\ a = 0, 1 \qquad X_a^\dagger X_a = 1$$

$$Y_b,\ b = 0, 1 \qquad \sum_b Y_b = 1$$

1. A signals at time 0
2. B measures at time t

$$P(b|a) - P(b|\emptyset) = \langle\psi|X_a^\dagger[Y_b(t), X_a]|\psi\rangle$$

Weak vs non-weak interaction...

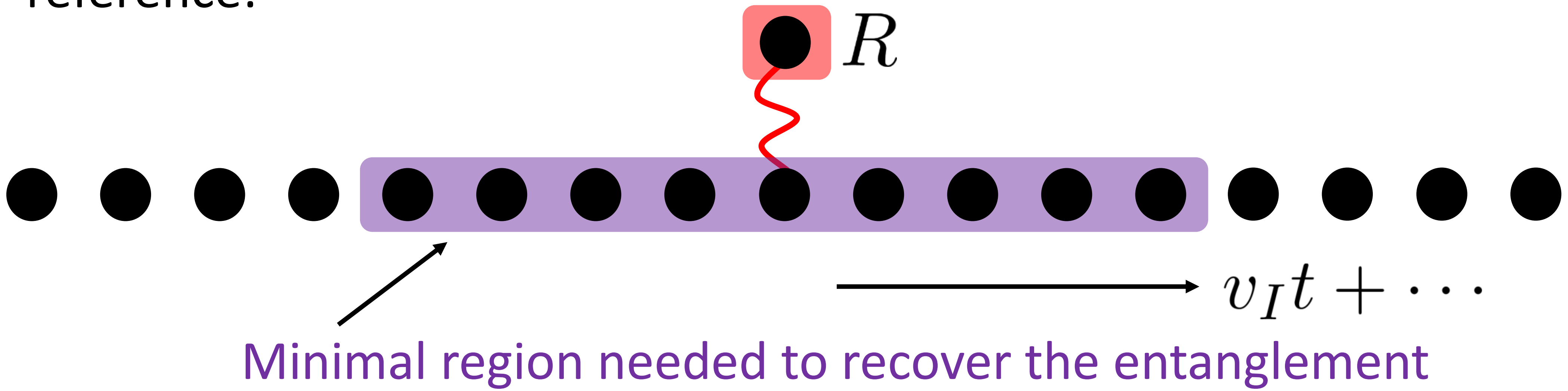
- Nearly free particles or waves:
  - Excite localized wavepacket carrying information, e.g. electromagnetic wave
  - Wavepacket moves at group velocity
  - Commutator related to free particle propagator, can be large at late time

- Interacting, chaotic system
  - Can inject energy, but typically no long-lived coherent excitations
  - Commutator decays rapidly in time, distant observers see only noise

$$P(b|a) - P(b|\emptyset) = \langle\psi|X_a^\dagger[Y_b(t), X_a]|\psi\rangle \approx 0$$

Communication vs information spreading

- Weakly coupled degrees of freedom can be used to transmit information in a locally accessible way, e.g. electromagnetic wave
- Strongly coupled degrees of freedom typically do not transmit information in locally accessible form
- Information spread can be measured by tracking entanglement with a reference:



Quantum info toy model (quasi-1d = strips)

- Initial state; energy density $\mathcal{E}$; entanglement fraction f :
- Entanglement growth: $S(A) = \min\{fs|A| + sv_E(f)|\partial A|t, s|A|\}$
- Operator spreading: v_B

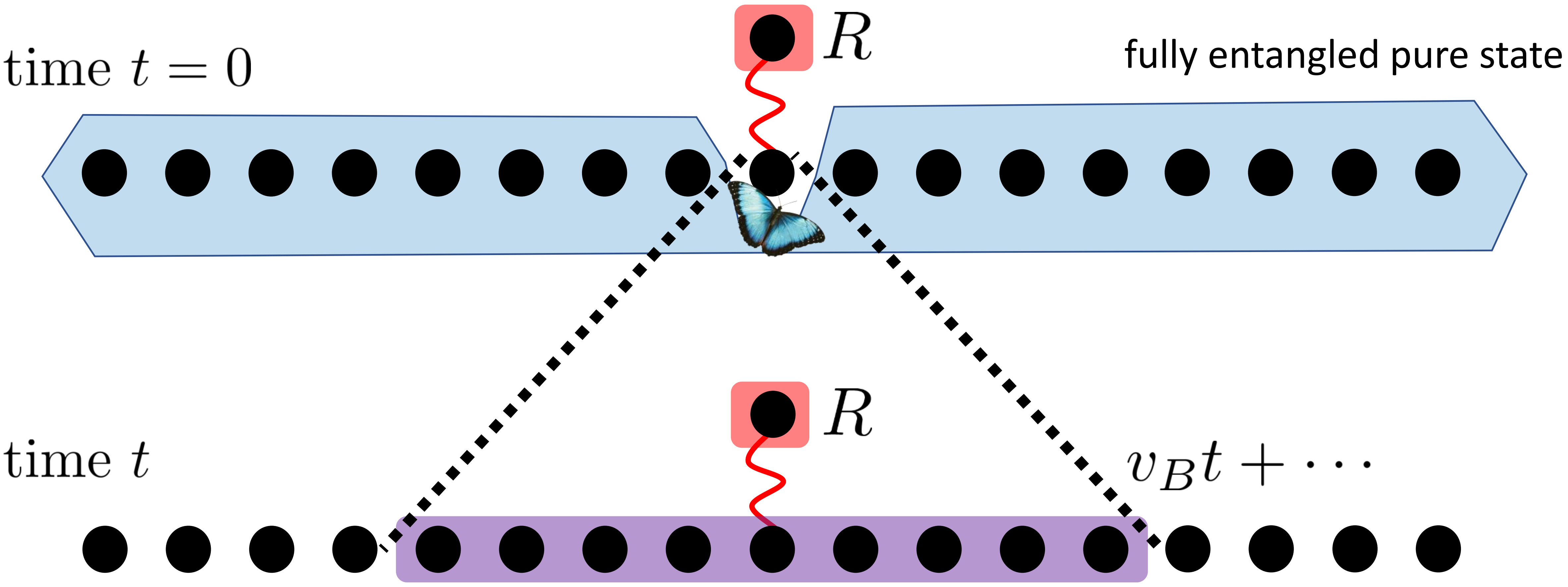
[Suh-Liu, …, f-dependent rate discussed by Nahum et al.]

- Result: information velocity $v_I = \min\left\{\frac{v_E(f)}{1-f}, v_B\right\}$

[Eccles-Couch-Nguyen-S-Xu 1908.06993]

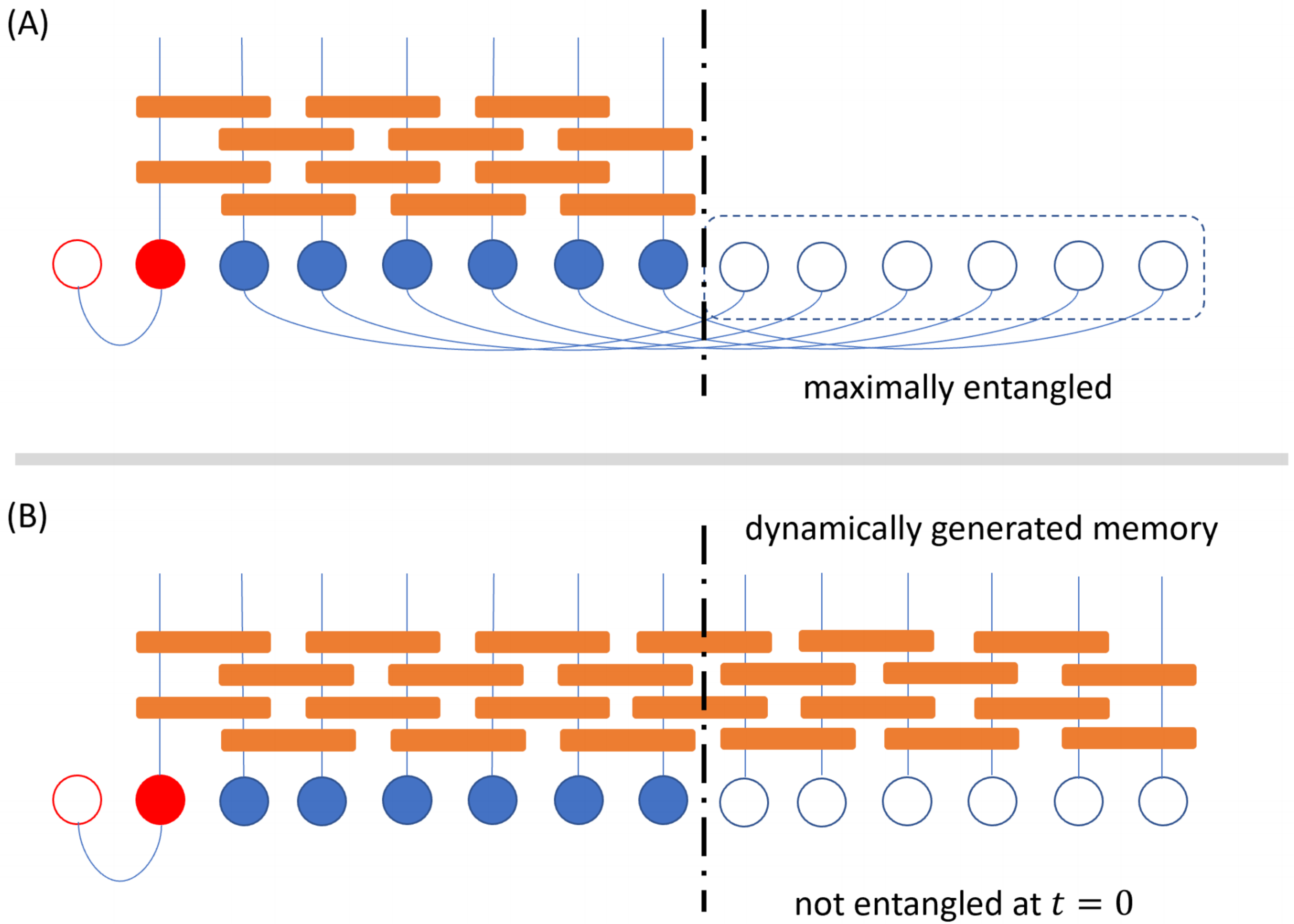
- Argument: minimal region that can recover the entanglement roughly equivalent to maximal complementary region that cannot recover the entanglement → generalization of [Hayden-Preskill] for complement

Example: f=1



If purple region smaller than butterfly cone, then complement can recover entanglement (HP: maximal entanglement and access to scrambled output)

$$v_I = v_B$$


(A)
maximally entangled
(B)
dynamically generated memory
not entangled at $t = 0$

Quantum information argument

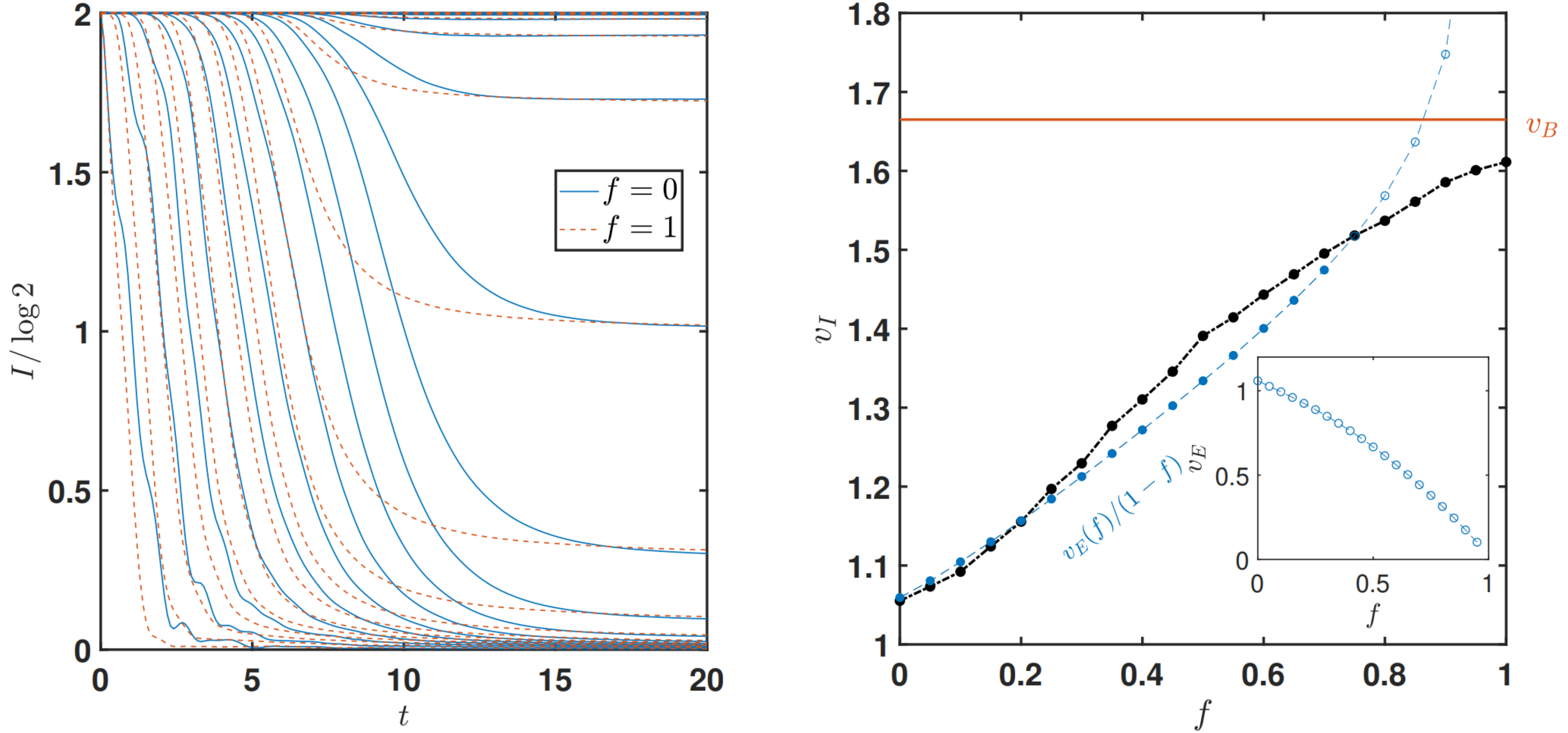
- Assume $v_E(f) \leq v_B(1-f)$ (we have an argument that is a modification of [Afkhami-Jeddi-Hartman]); this implies that operator spreading is not the rate-limiting step, except when f=1
- Then we need to track the effective size of system + memory for HP
- Key point: let A_{sat} be the region whose entropy has just saturated, then the effective size of system + memory is twice the size of A_{sat}
- Thus, if $A > A_{sat}$, recovery is possible, and if $A < A_{sat}$, recovery is not possible (because recovery is possible in the complement of A):

$$t_{sat} = \frac{R(1-f)}{v_E(f)} + \cdots \qquad v_I = \lim_{t\to\infty} \frac{R}{t_{sat}} = \frac{v_E(f)}{1-f}$$

Spin chain evidence (1d)

$$H = -\left(J \sum_{r=1}^{L-1} Z_r Z_{r+1} + h_z \sum_{r=1}^{L} Z_r + h_x \sum_{r=1}^{L} X_r \right)$$

L=22 spins, Krylov method



Holographic evidence (focus on quasi-1d)

- We can construct a general class of states with a given energy density and entanglement fraction by beginning with a thermofield double state of some lower energy density and adding energy:

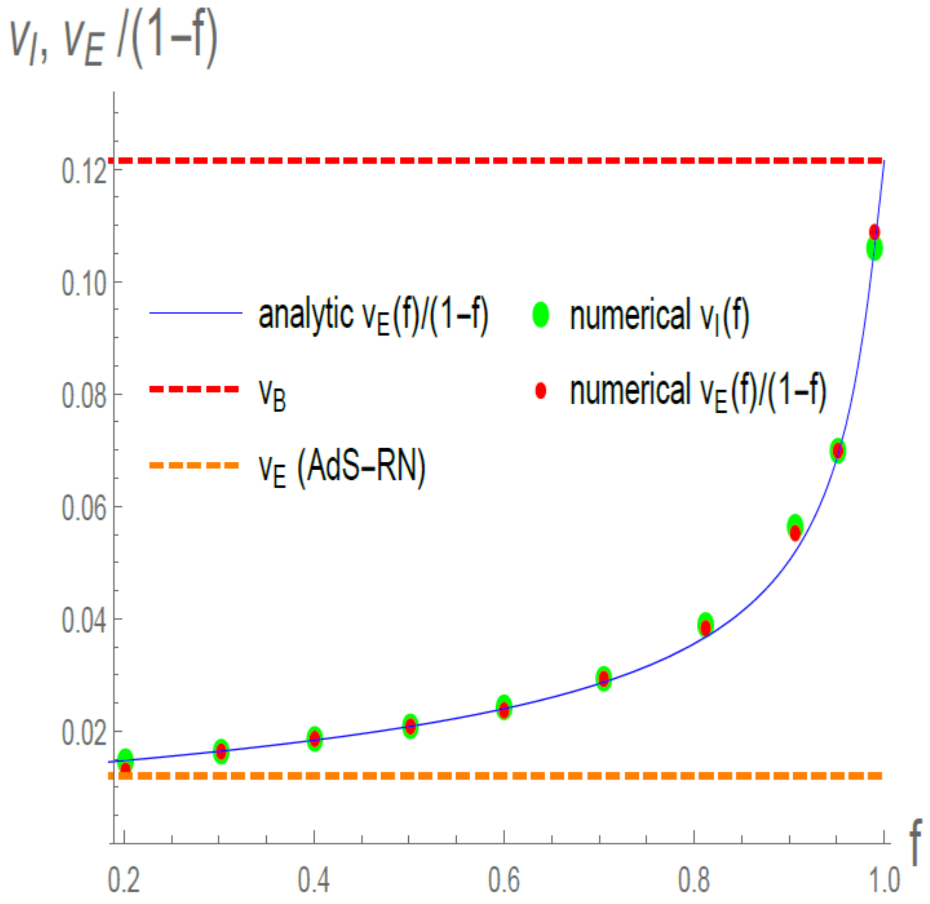
$$f = \frac{s(\varepsilon_0)}{s(\varepsilon)}$$

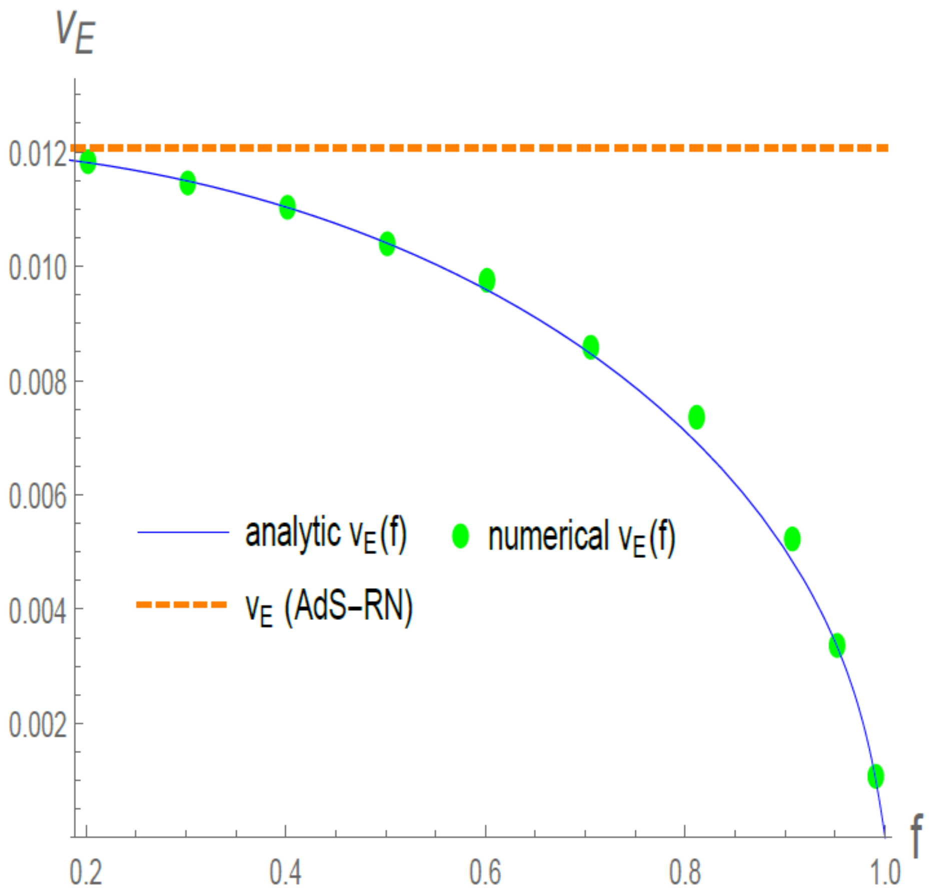
- Add entanglement by injecting a particle entangled with a reference
- Rule: any region whose entanglement wedge includes the infalling particle can recover the entanglement
- Goal: find the smallest such region, as a function of time

(generalizes [Mezei-Stanford])

General case (quasi-1d)

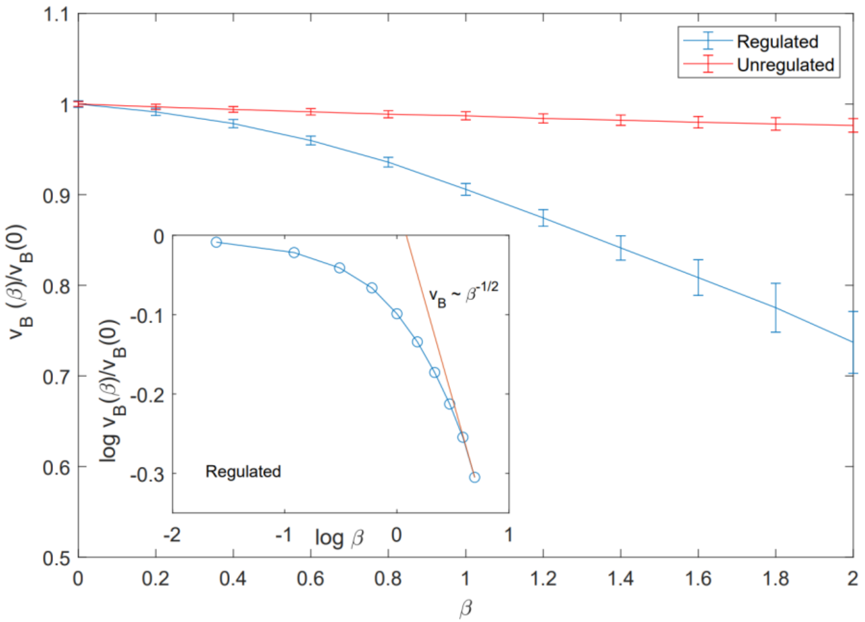
$$v_E = \frac{z_{f,+}^{d-1}}{z_{i,+}^{d-1}} \sqrt{-h_f(z_m)\left(\frac{z_{i,+}^{2(d-1)}}{z_m^{2(d-1)}} - 1\right)}$$





Comments

- Interesting story about shape dependence in higher dim (in progress)
- Can see explicitly that the output is scrambled using geometry, nice setting where many aspects of recent BH info discussion appear
- Open questions at finite temperature, e.g. which butterfly speed?



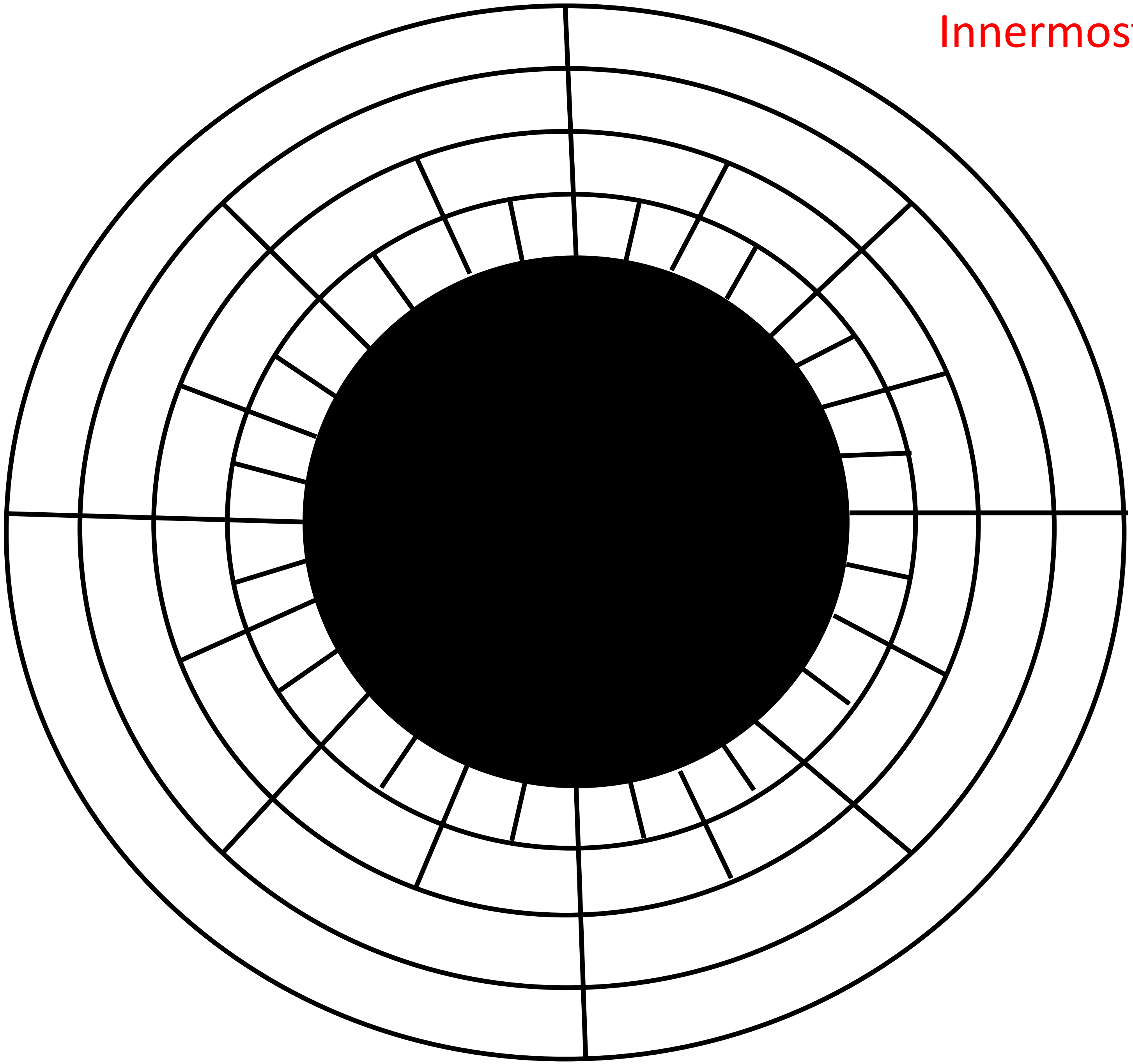
[in progress Sahu-S, Liao-Galitski, Romero-Bermudez et al.]

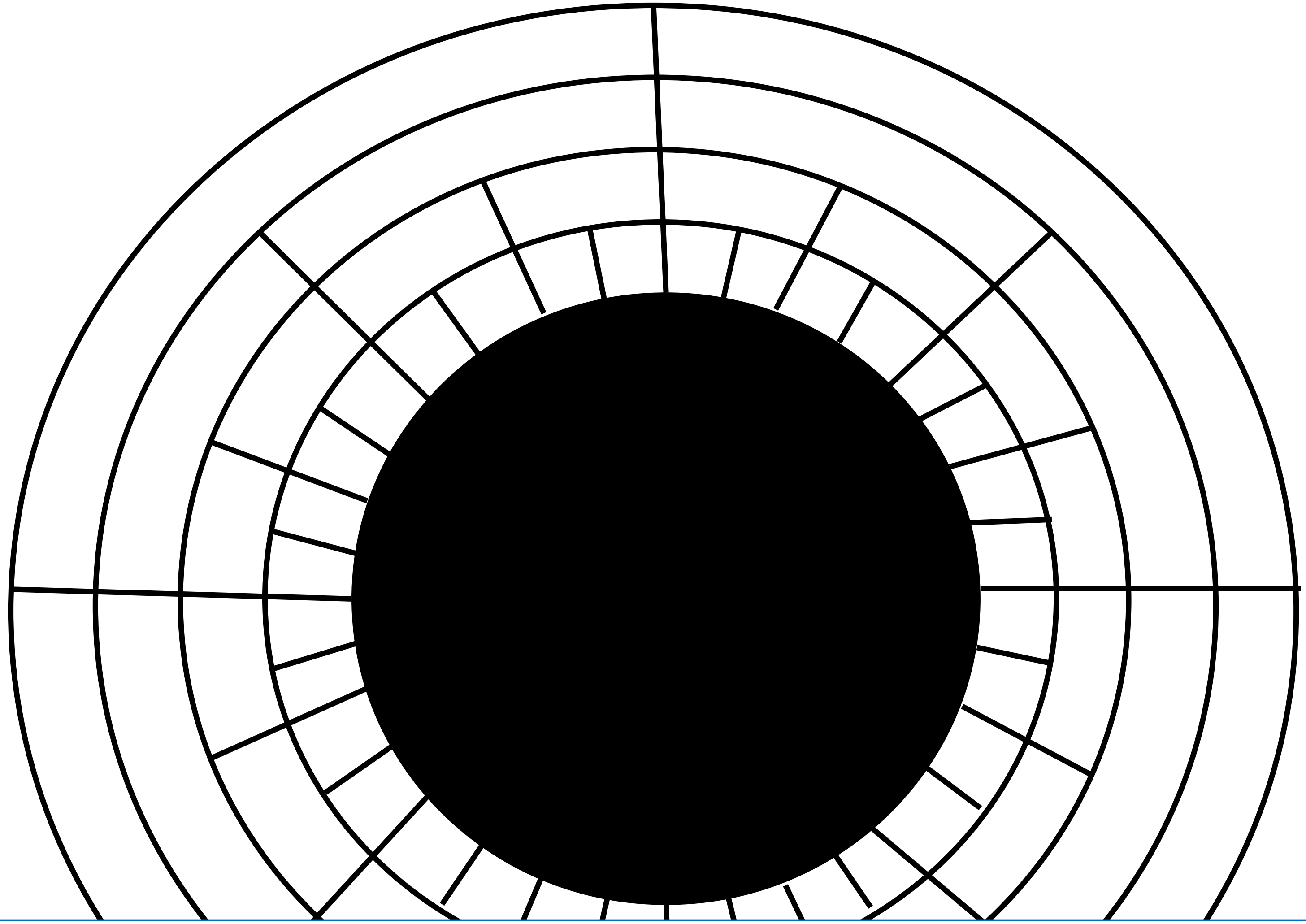
Toy model of external dynamics of black hole

- Setup a computational toy model of the outside dynamics of a black hole (Shor's model of Schwarzschild BH; S: think of AdS-sized BH)
- Black hole has a characteristic time $\mathcal{T}$ and coarse-grained entropy S
- Rules:
  - Break the spacetime up into cells defined by requiring the time (Schwarzschild time) for light to cross the cell is order $\mathcal{T}$
  - A calculation shows that each cell holds O(1) bits (or qubits) of entropy arising from thermal excitations; outside only view of the physics
  - We declare ignorance about the quantum gravity dynamics of the black hole except that they are bounded by the motion of light in black hole spacetime

NOT TO SCALE

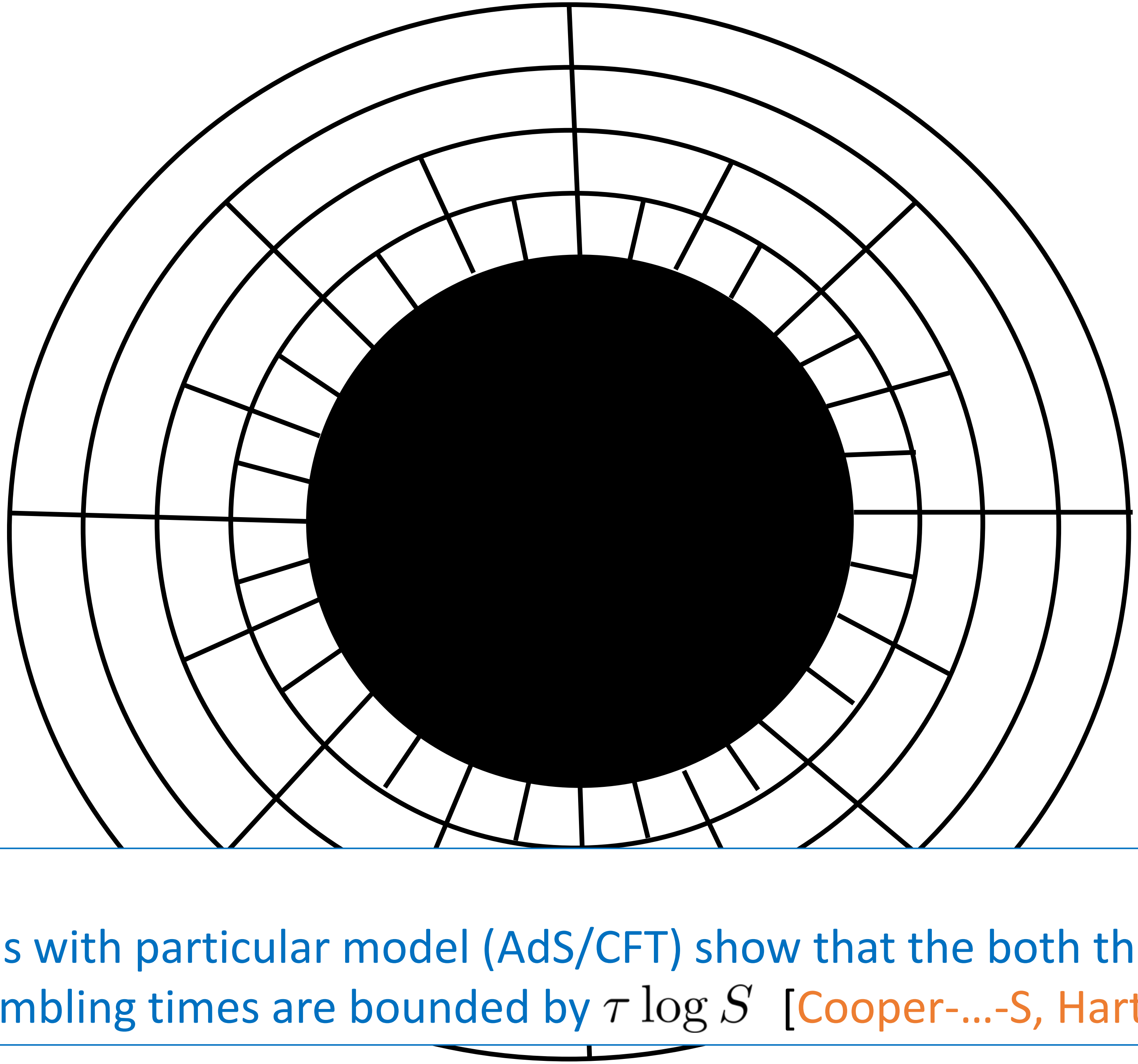
Innermost layer has O(S) cells





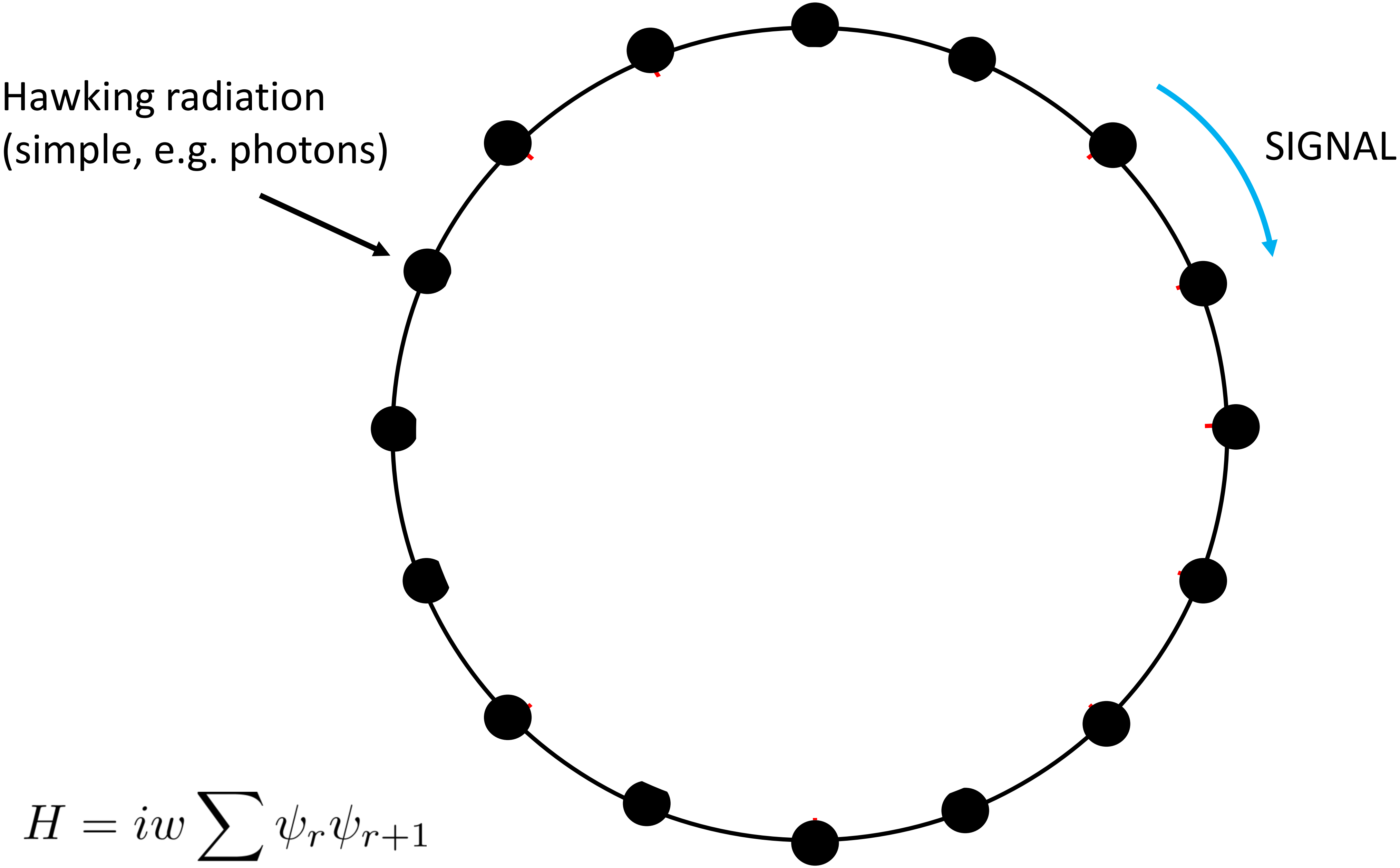
Bounds (Shor):

- Weak scrambling (= mixing O(1) qubits) is possible in time $\tau \log S$
- Strong scrambling (= generating nearly maximal entanglement) takes at least time τS (or $\tau S^{\#}$)

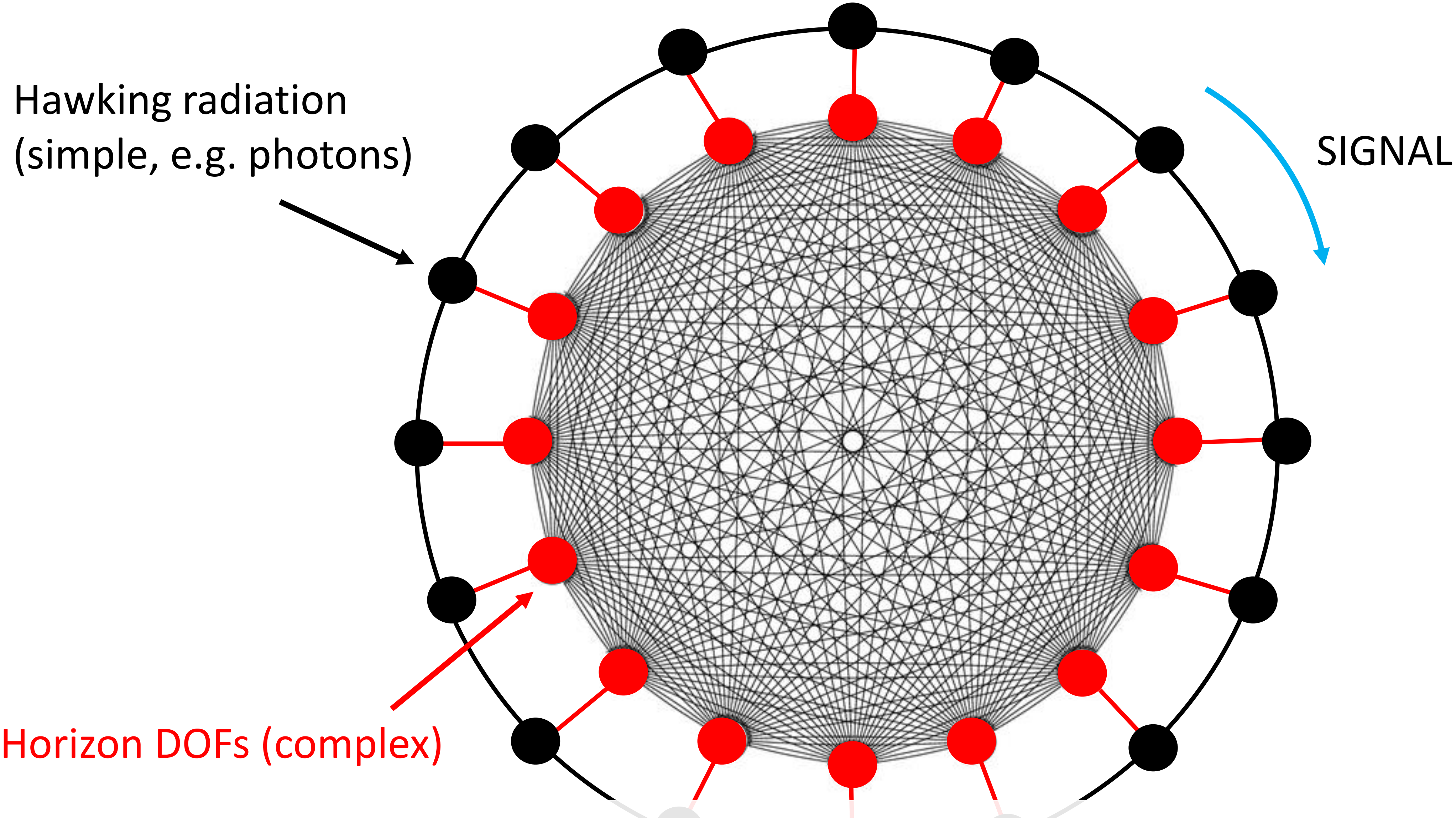


Challenge:

- Calculations with particular model (AdS/CFT) show that the both the weak and strong scrambling times are bounded by $\tau \log S$ [Cooper-…-S, Hartman-Maldacena]



$$H = iw \sum_r \psi_r \psi_{r+1}$$

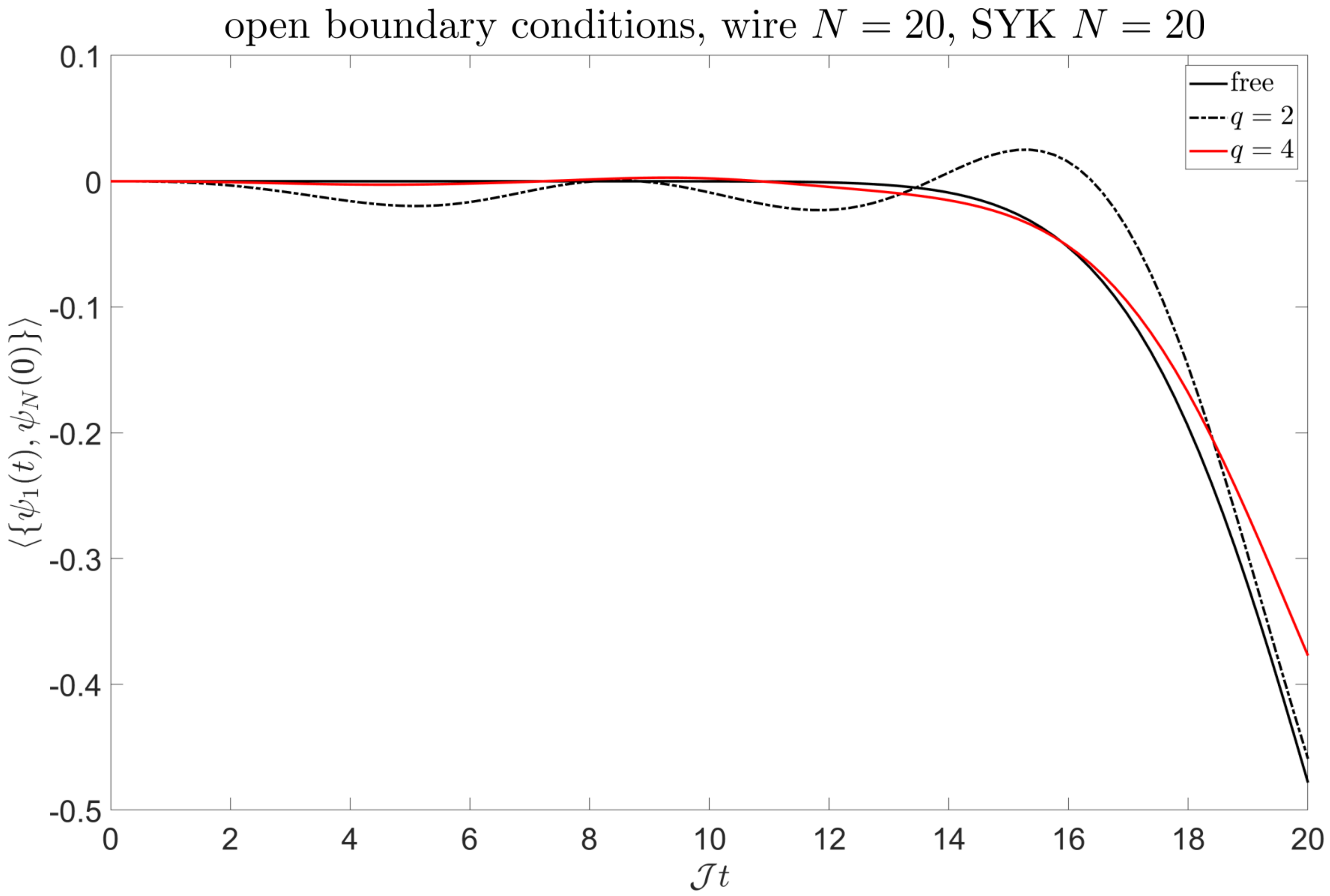


$$H = iw \sum_r \psi_r \psi_{r+1} + g \sum_{ra} K_{ra} \psi_r \chi_{a_1} \cdots \chi_{a_p} + \sum_b J_b \chi_{b_1} \cdots \chi_{b_q}$$

[S: coming soon]

Black: only simple part; Red: chaotic inner part; Black dot-dashed: non-chaotic inner part

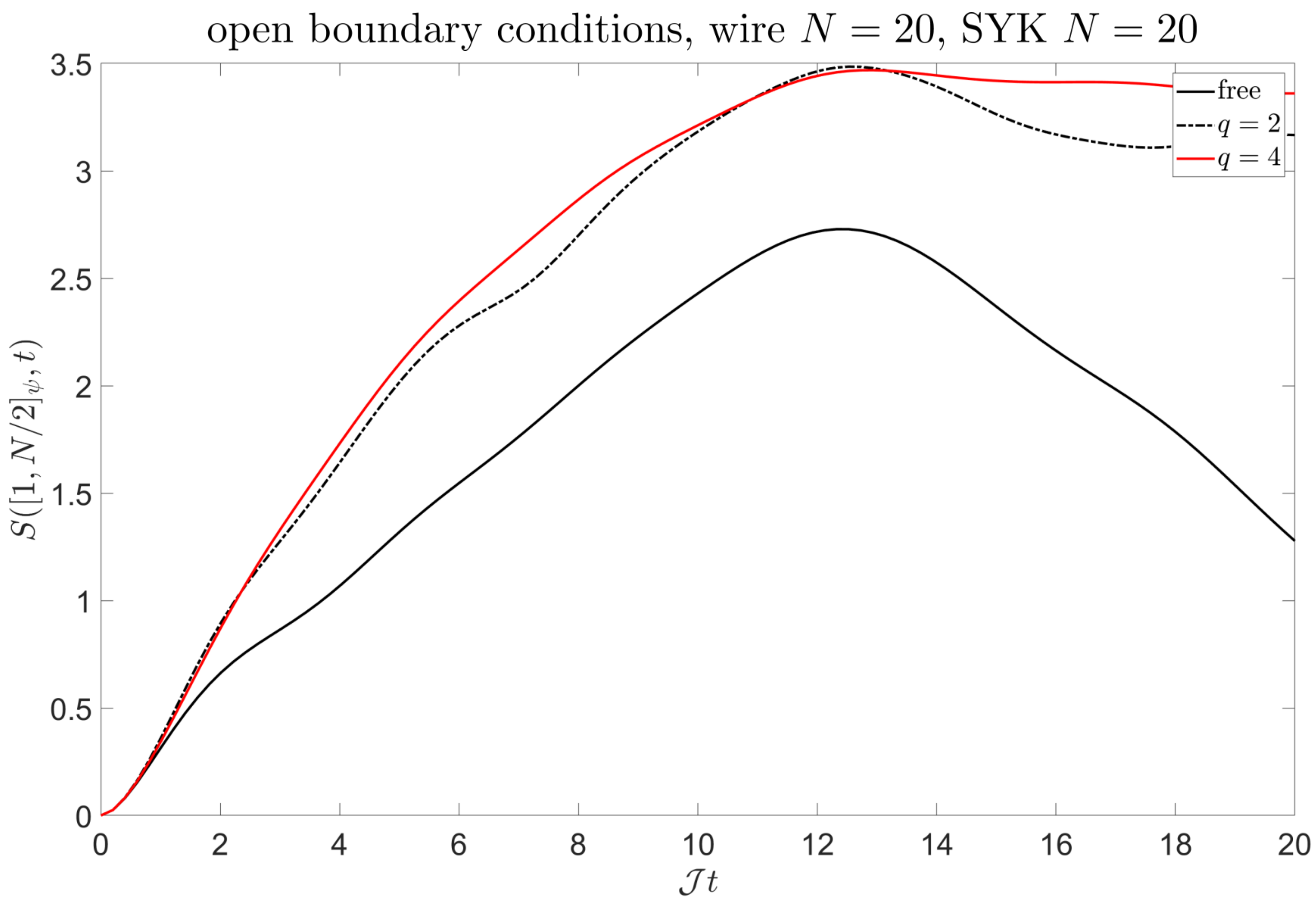
Response



Sachdev-Ye-Kitaev model: violations of locality are suppressed by system size [S: coming soon]

Black: only simple part; Red: chaotic inner part; Black dot-dashed: non-chaotic inner part

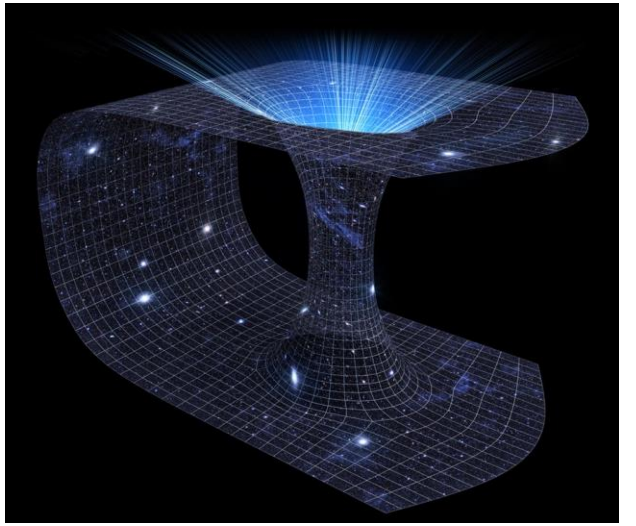
Entanglement

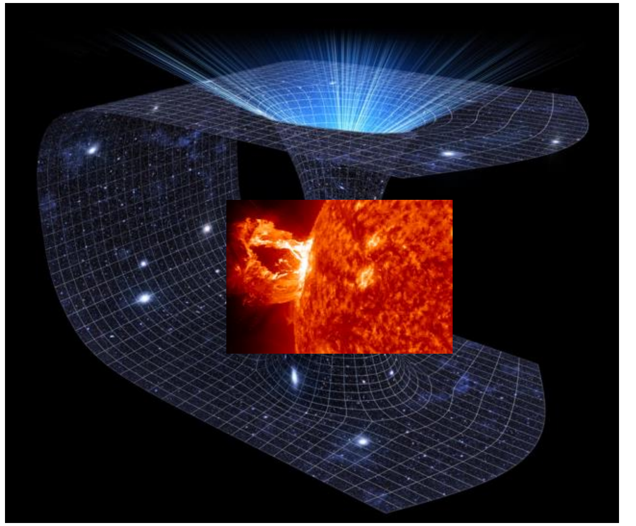


Sachdev-Ye-Kitaev model: violations of locality are suppressed by system size [S: coming soon]

What is spacetime geometry?

- It should be *operationally defined* in terms of the motion of simple signals → Einstein's rods and clocks!
- In the model, simple signals continue to respect the local structure, up to entropy-suppressed corrections
- A super-observer with access to multiple copies of the universe, or who can run time backwards, or process the whole system in a quantum computer, could in principle detect the anomalously fast entanglement spreading – but this could be OK, we've never tested it





Summary

- Quantum information can move coherently or spread chaotically; its motion obeys various kinds of speed limits
- We are building a set of concepts and tools to help us understand and calculate the motion of quantum information; new physics includes universal patterns of chaos spreading and emergent slow speed limits
- Possible application to black holes: "chaos-protected locality" defuses tension between fast information dynamics and spacetime locality