Black Hole Scrambling and Spacetime Locality

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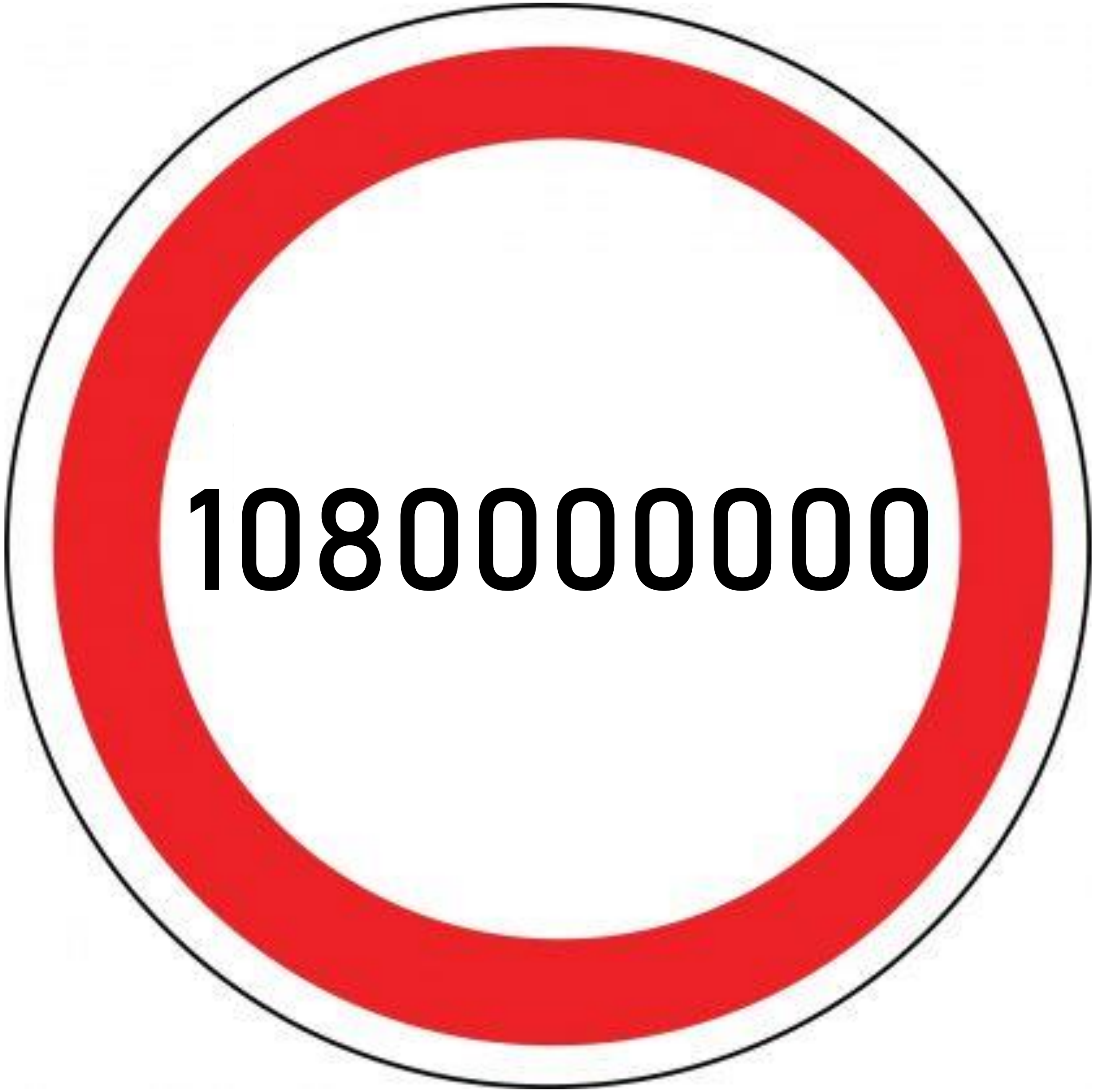
Gravity, Information, and Fundamental Symmetries - MPQ

November 6, 2019

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

Many-body physics and fundamental physics

- Charting the world of complex entangled states is a rich and exciting grand challenge in its own right
- But also many ties to traditional fundamental physics, examples:
  - Jun Ye talk: using many-body systems for precision metrology
  - Symmetries/anomalies related to symmetry protected phases of matter
  - Origins of spacetime: gravity emerging from strong correlations e.g. AdS/CFT
- Today: a glimpse of the grand challenge to understand how spacetime, locality, and gravity emerge from non-geometric stuff
- Why now? Revolutionary new language and experimental tools from quantum information, including prospect of simulating quantum gravity in the lab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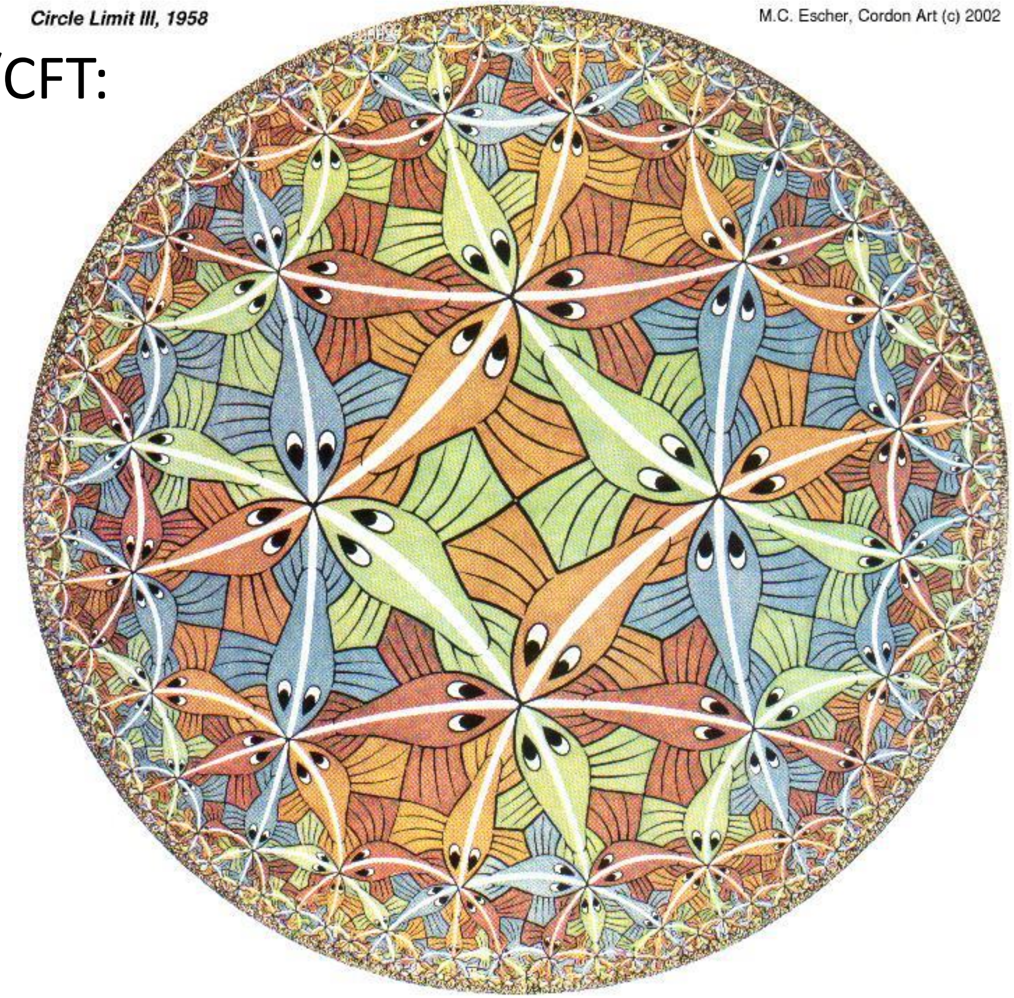
SPEED LIMIT
ENFORCED BY
AIRCRAFT

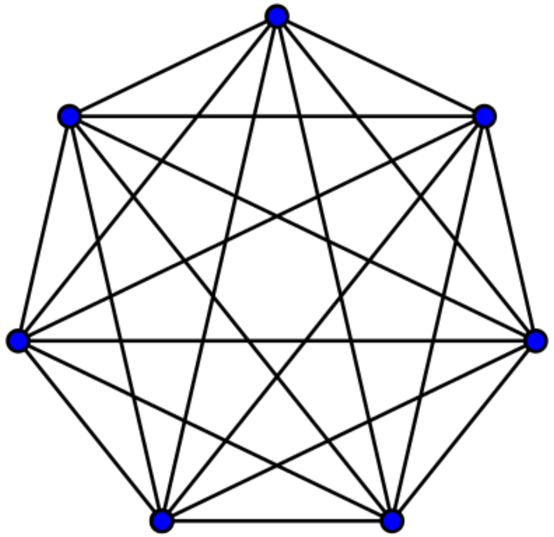
Why is there something to understand?

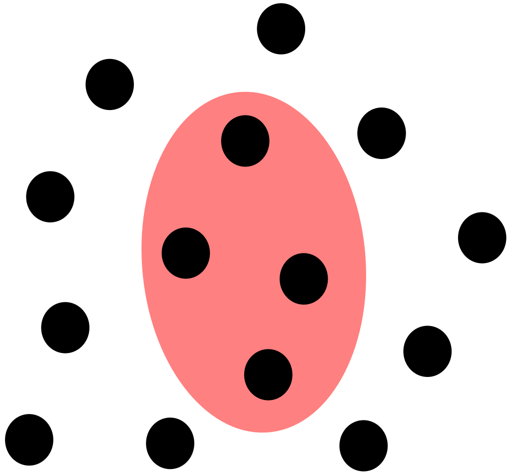
AdS/CFT:



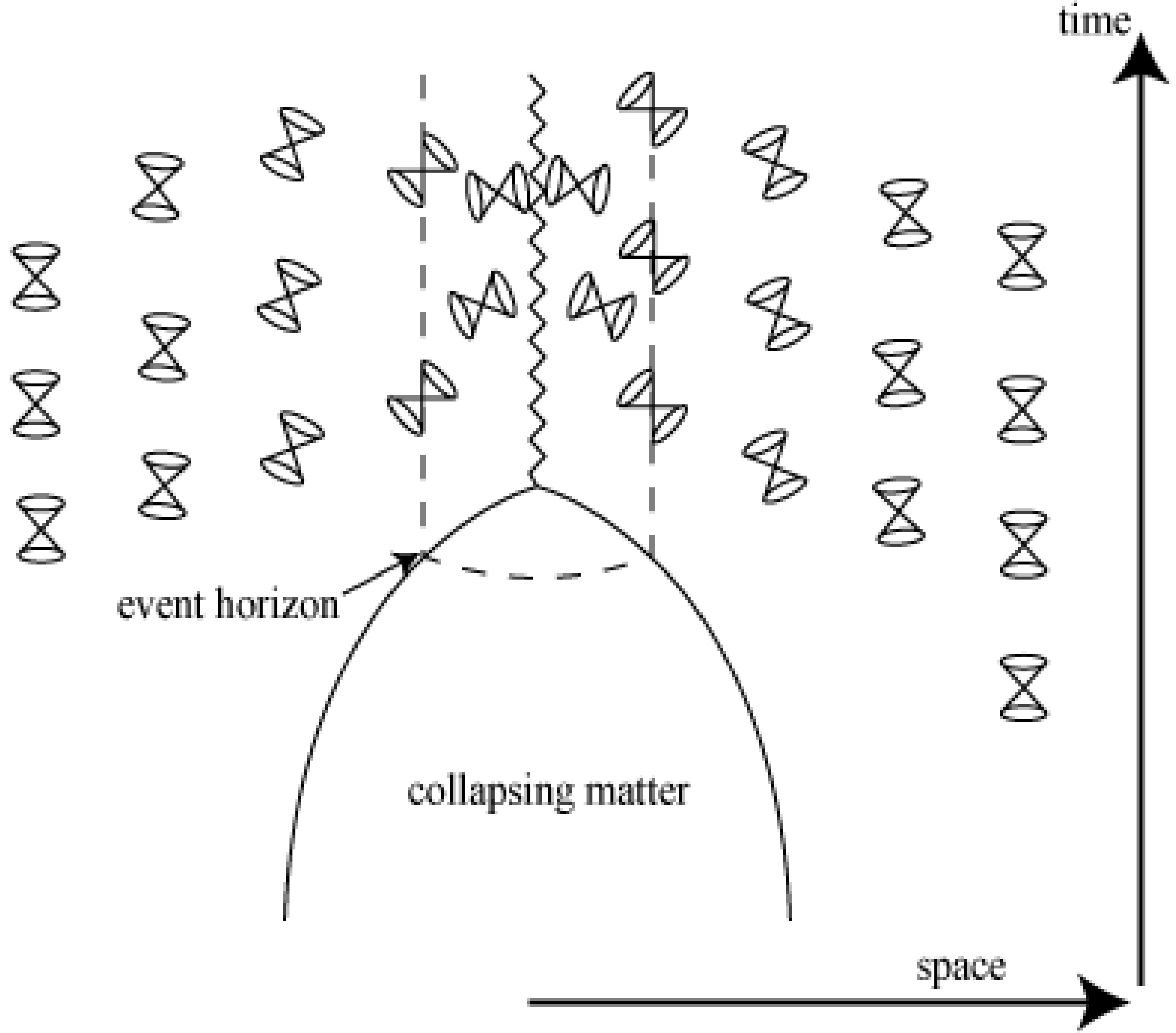
Sachdev-Ye-Kitaev model:

$$H = \frac{1}{4!}\sum_{abcd} J_{abcd}\chi_a\chi_b\chi_c\chi_d$$

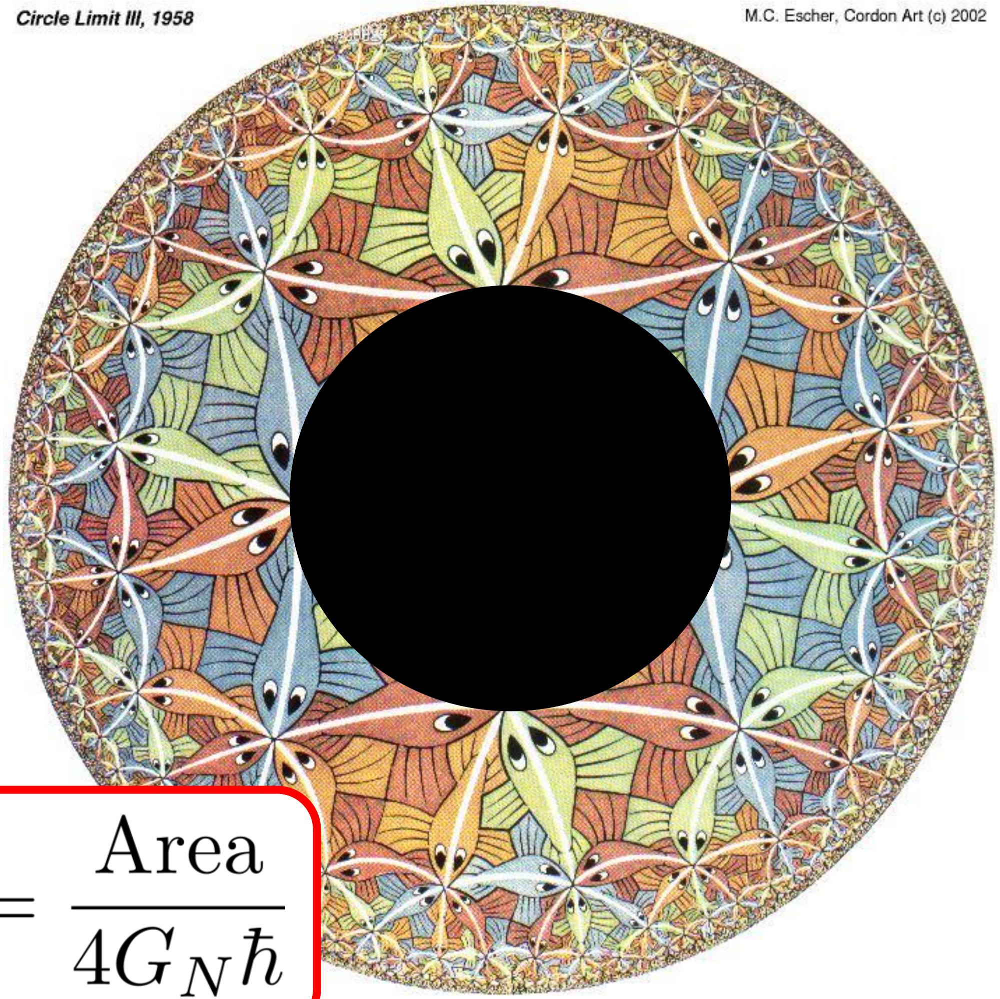




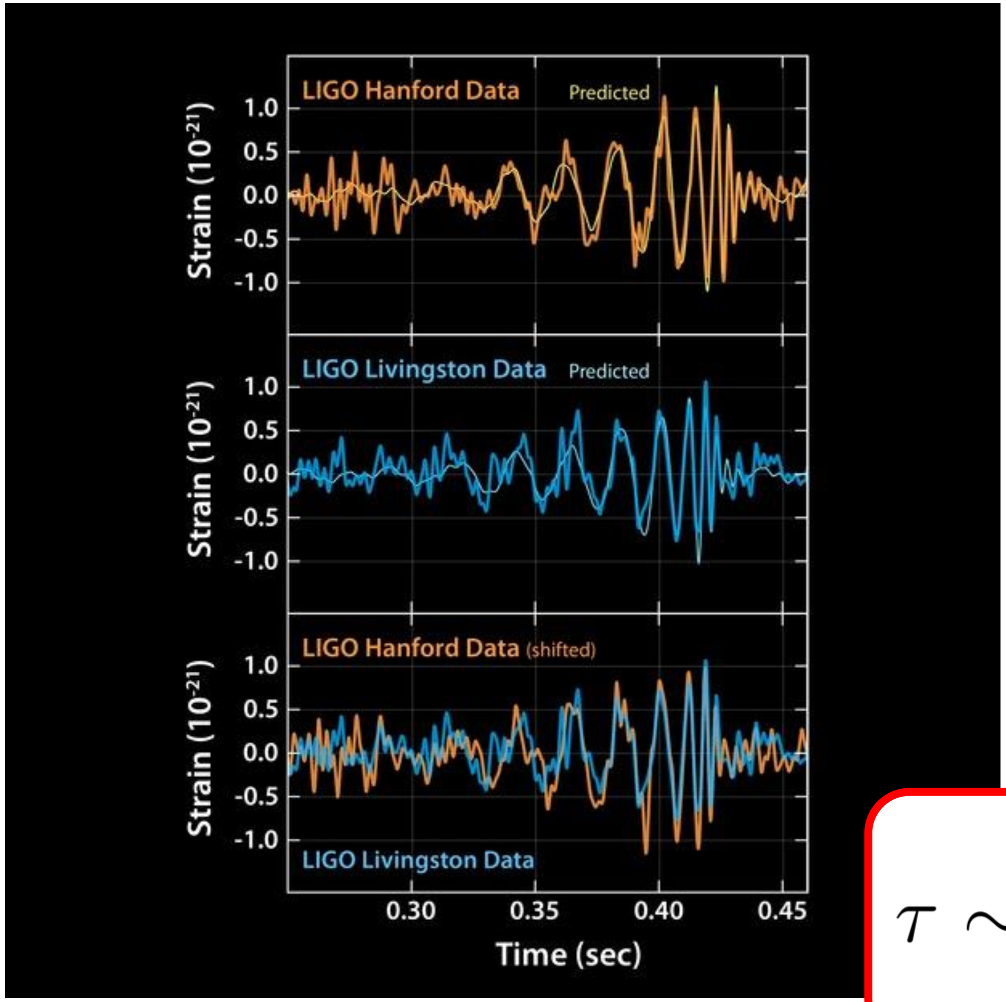
Later, we will discuss a sharp puzzle …


time
event horizon
collapsing matter
space

Central hypothesis: black holes as quantum chaotic systems



$$S = \frac{\text{Area}}{4 G_N \hbar}$$

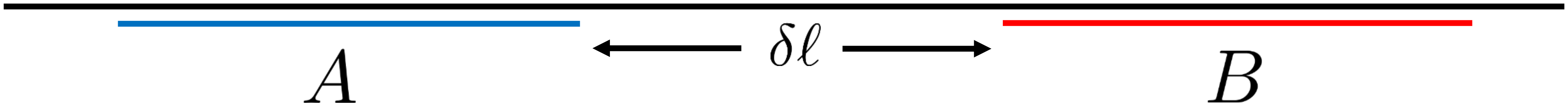


$$\tau \sim \frac{\hbar}{T}$$

Motion of Quantum Information

A simple communication protocol

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



$X_a,\ a = 0, 1$

$X_a^\dagger X_a = 1$

$Y_b,\ b = 0, 1$

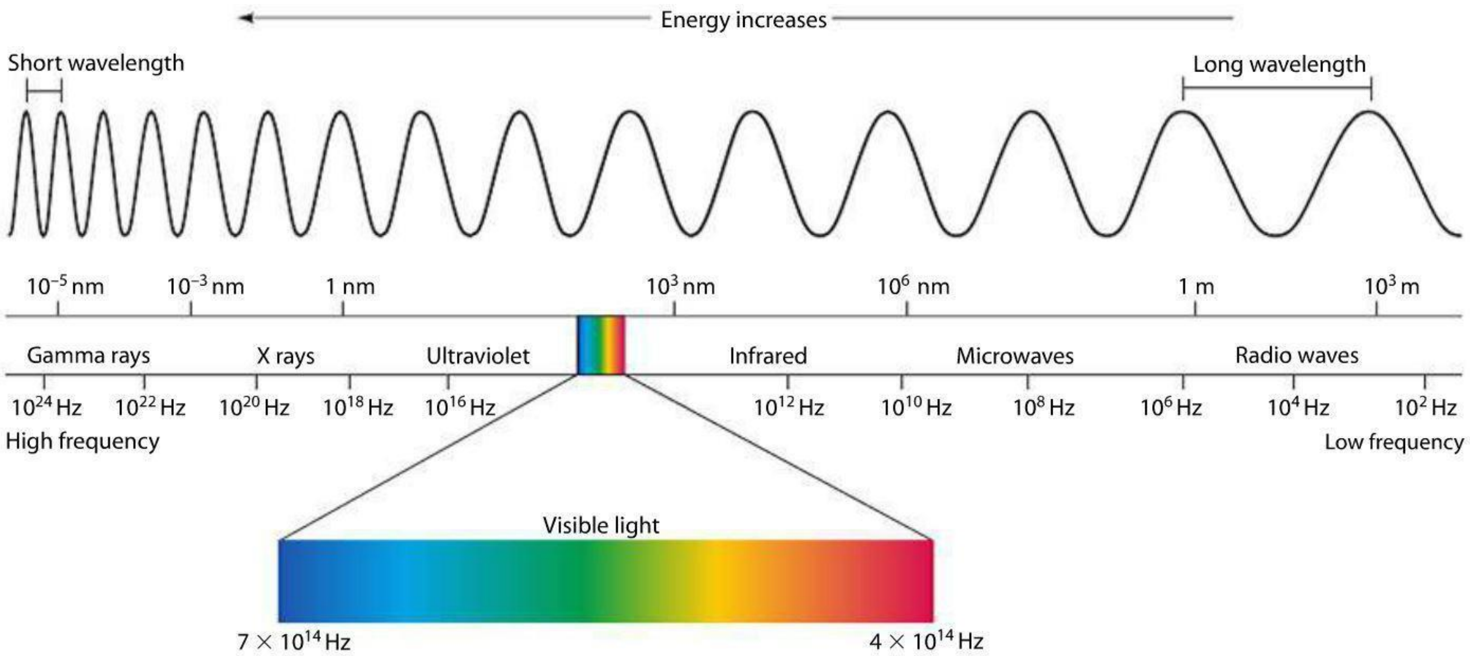
$\sum_b Y_b = 1$

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

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

Weakly interacting stuff

- 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

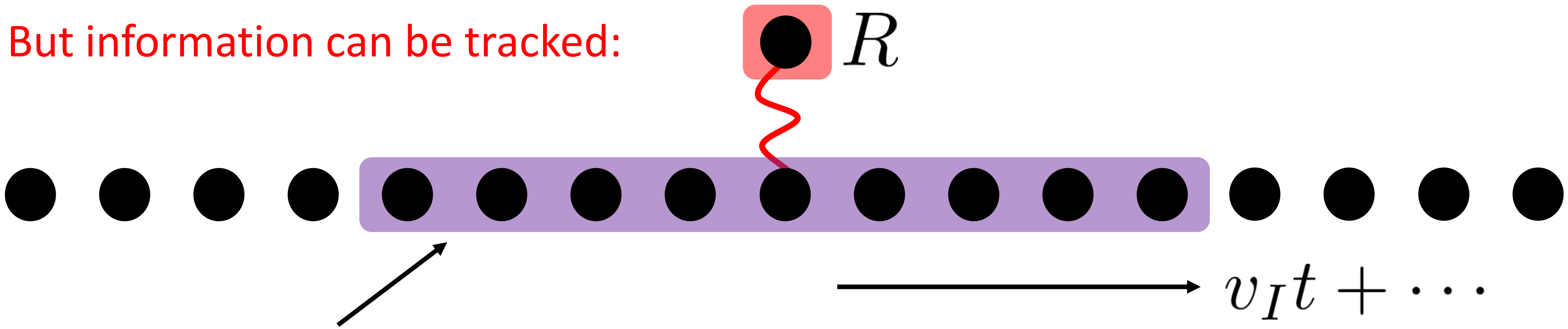


Strongly interacting stuff

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

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

But information can be tracked:



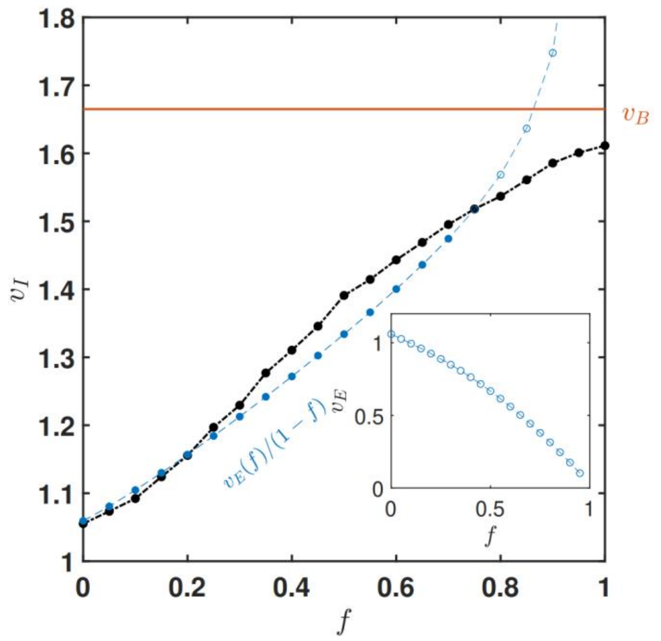
Minimal region needed to recover the entanglement

Velocity from quantum information argument

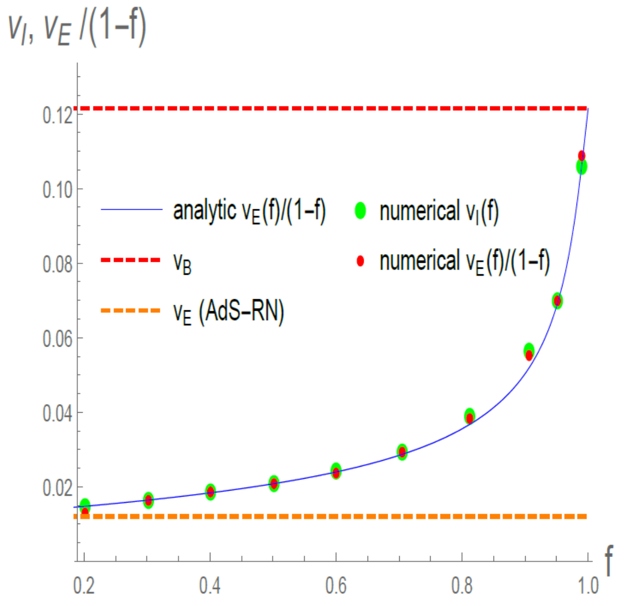
- Initial state; energy density ε; entanglement fraction f:
- Result: information velocity $v_I = \min\left\{ \frac{v_E(f)}{1-f}, v_B \right\}$

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

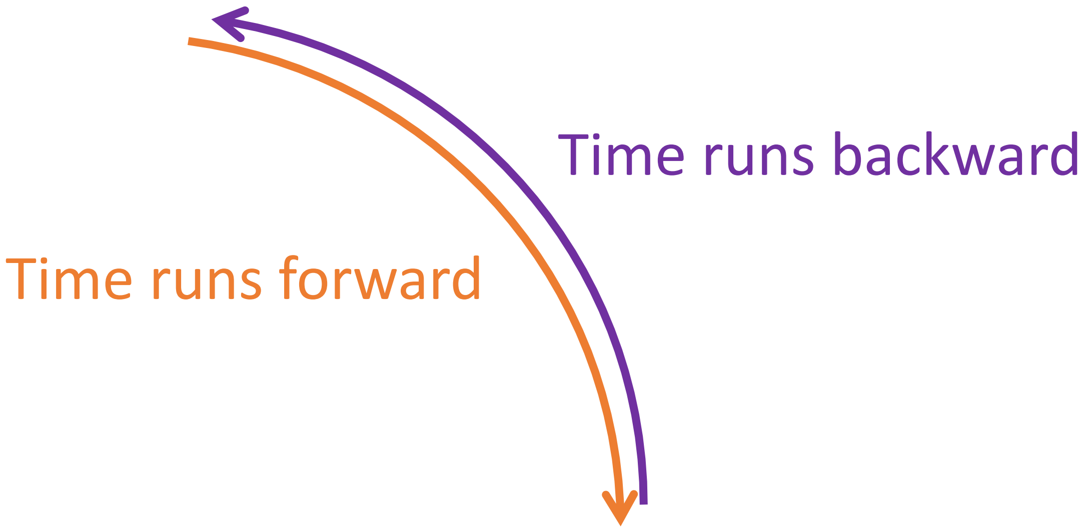
Spin chain:

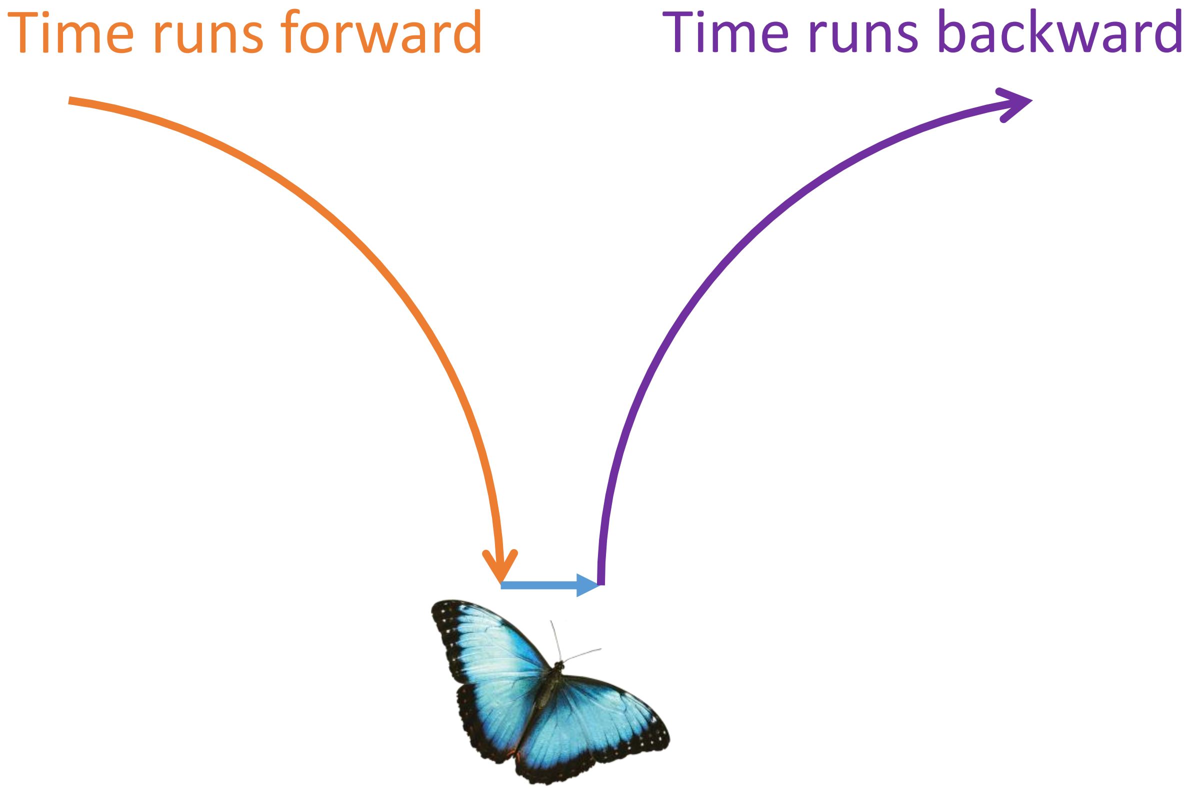


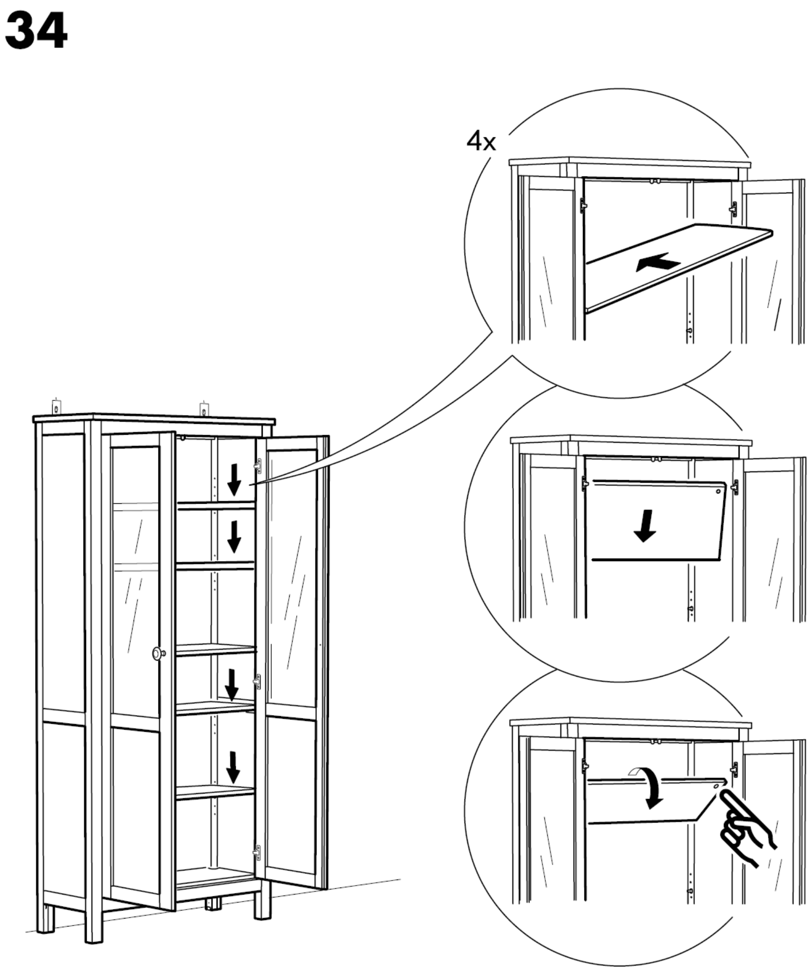
AdS/CFT:



Quantum butterfly effect thought experiment





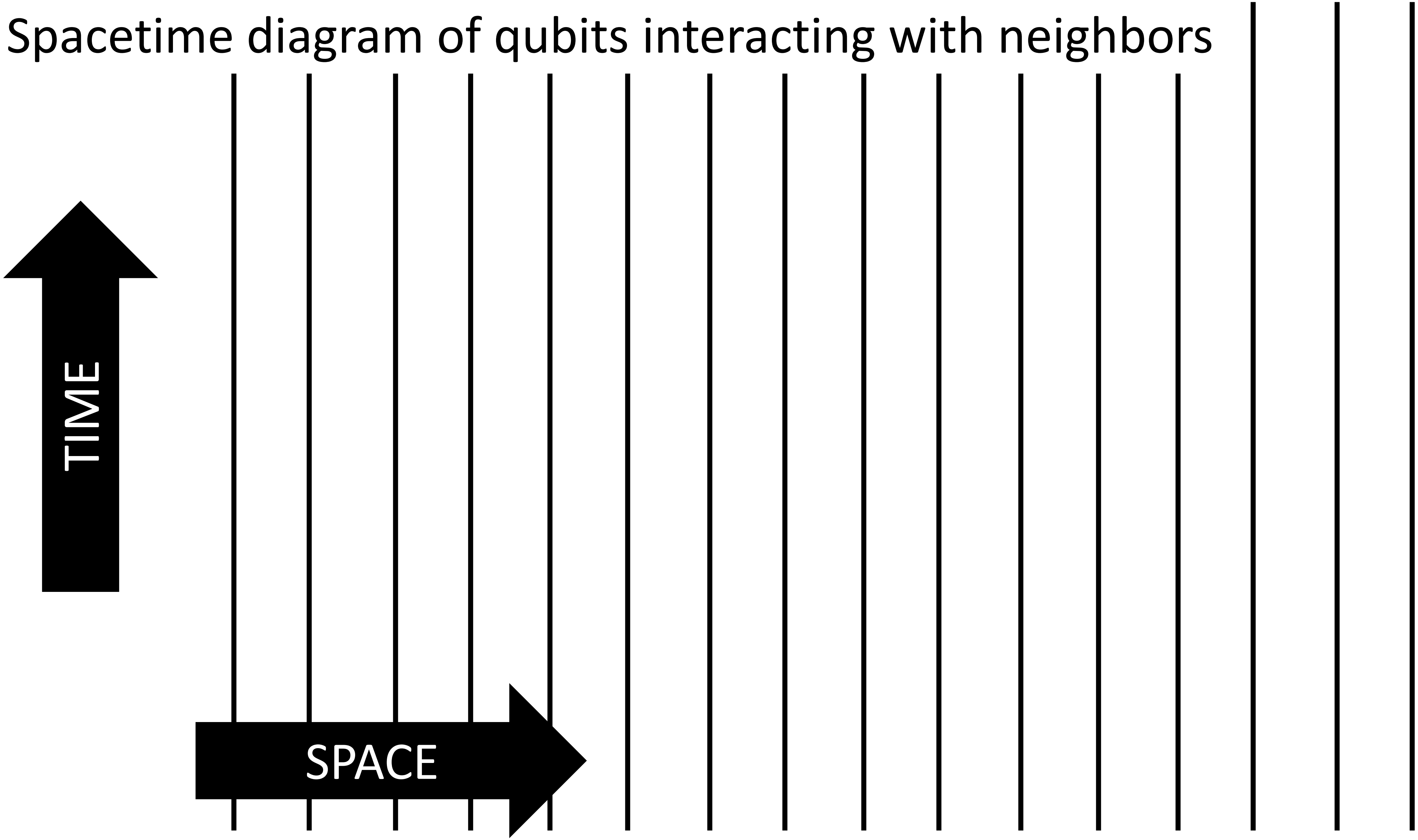


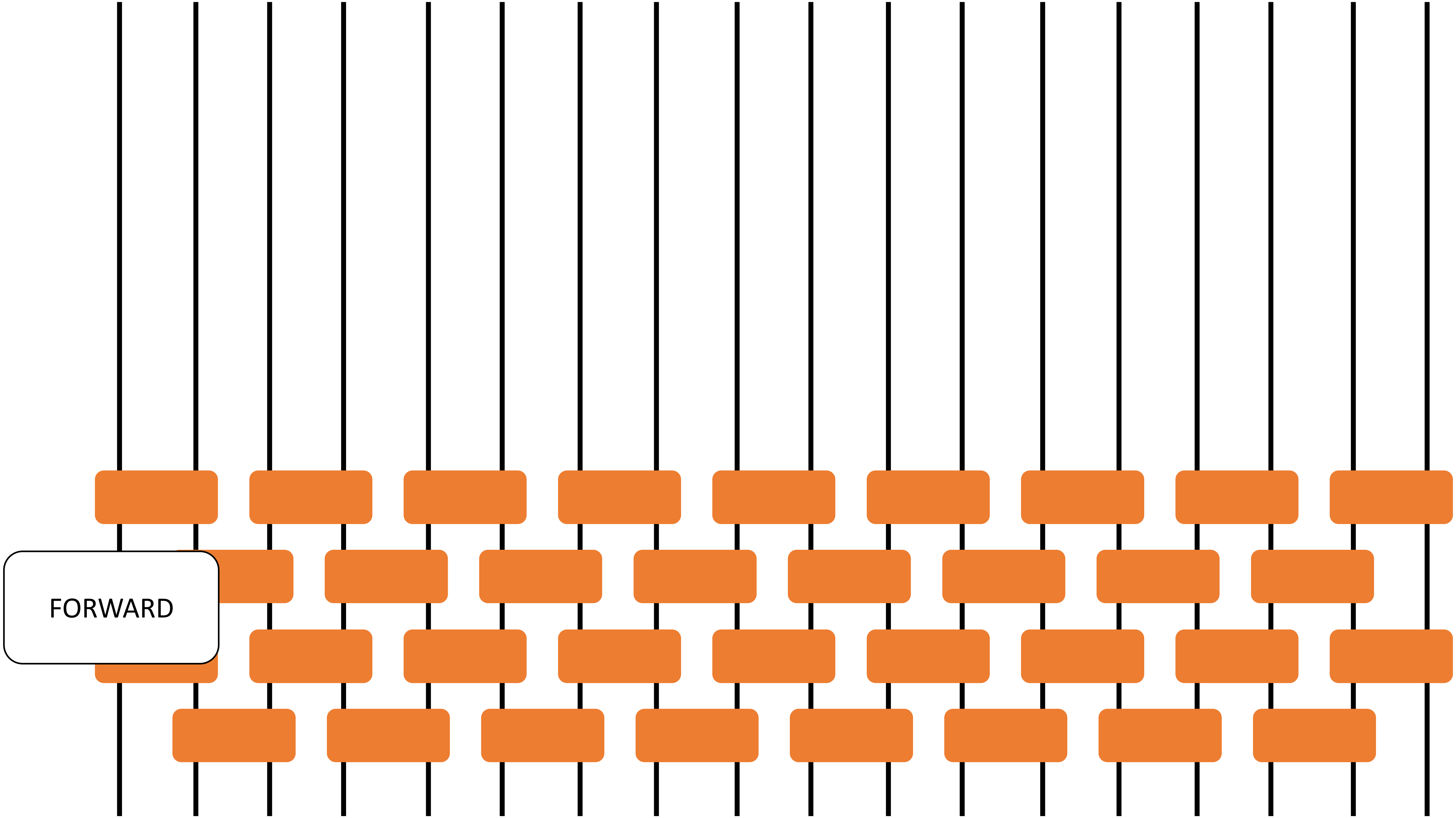
???

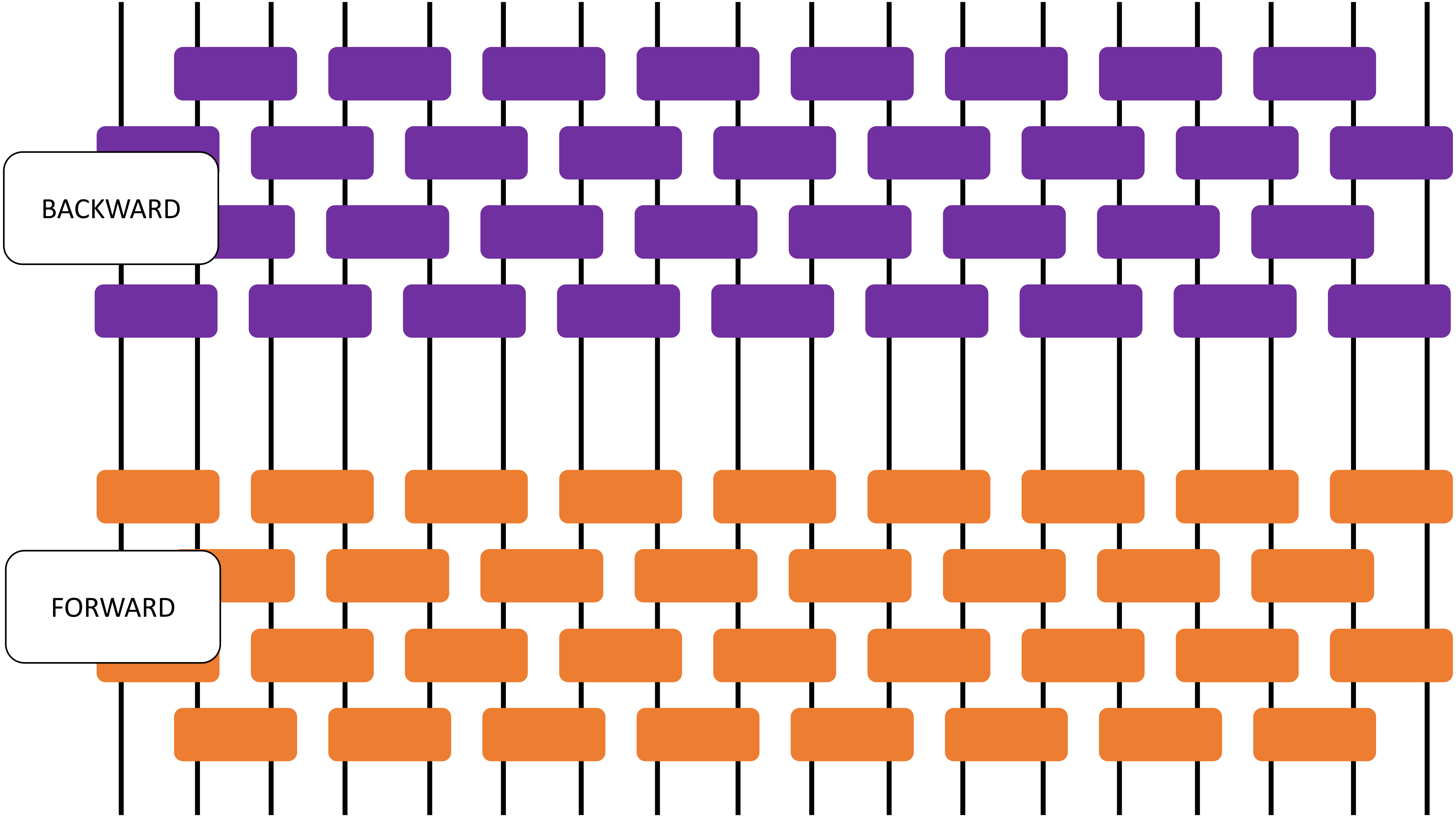
Missed a screw in step 2!

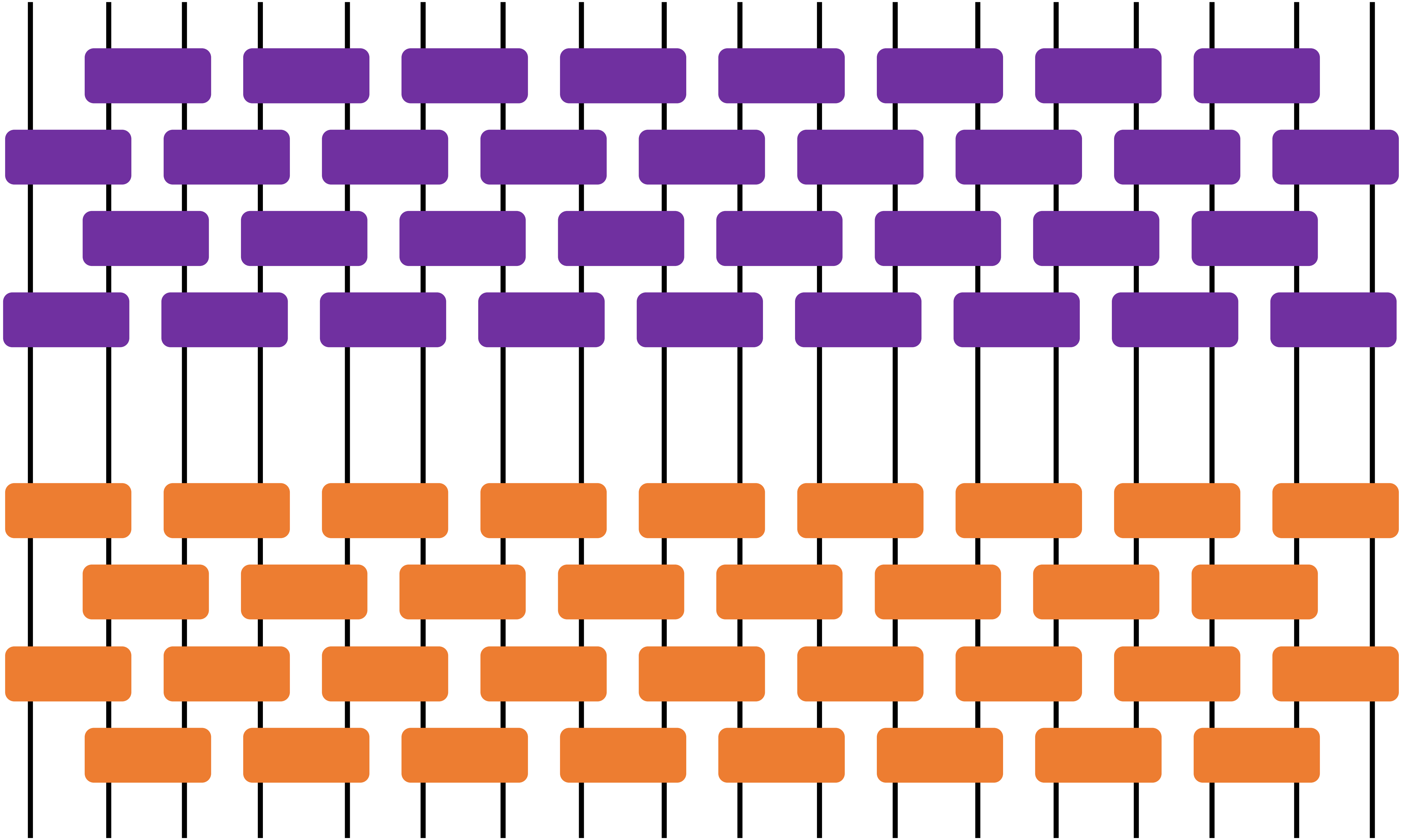
Fix: deconstruct back to step 2, add screw, rebuild

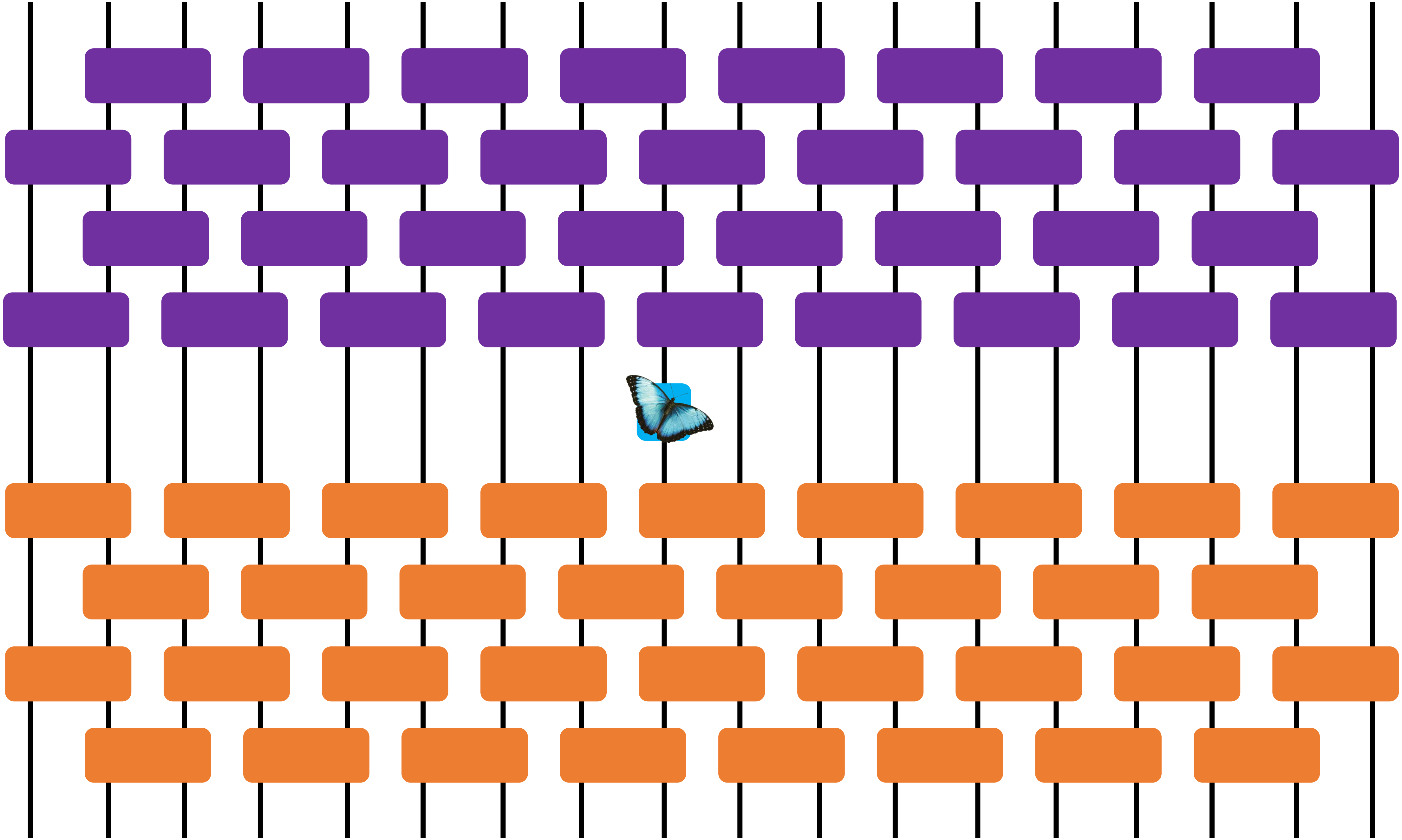
Spacetime diagram of qubits interacting with neighbors




FORWARD

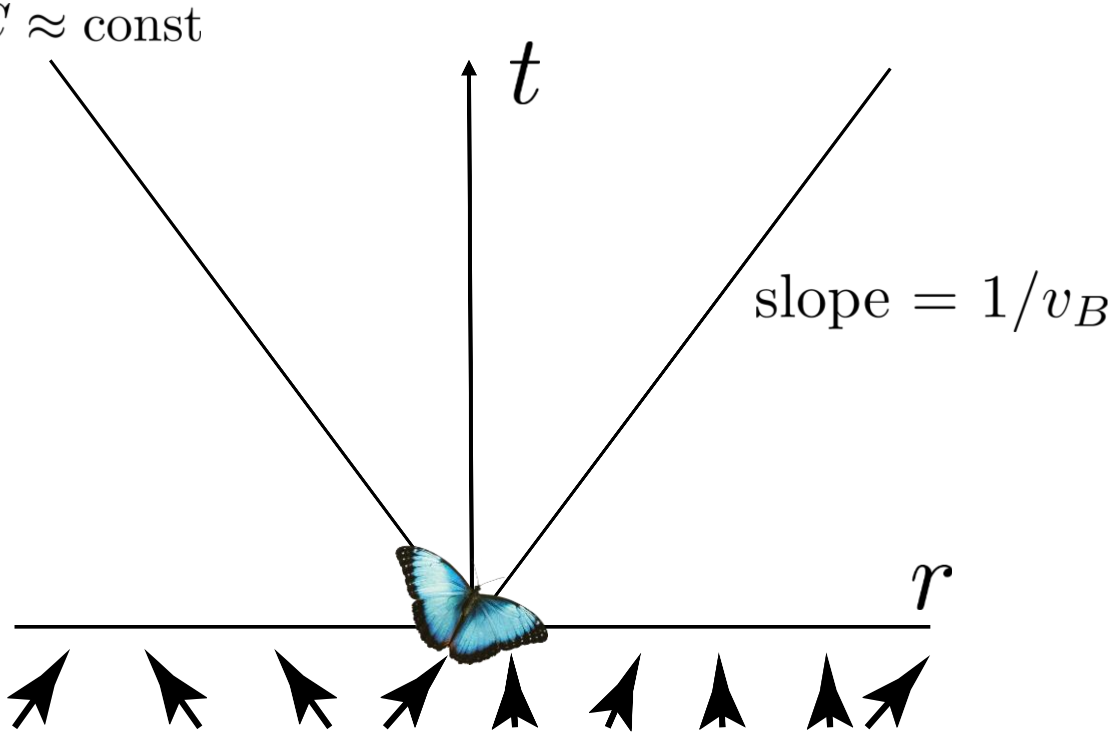

BACKWARD
FORWARD





$$C(r,t) = \langle [W(t), V]^\dagger [W(t), V] \rangle$$

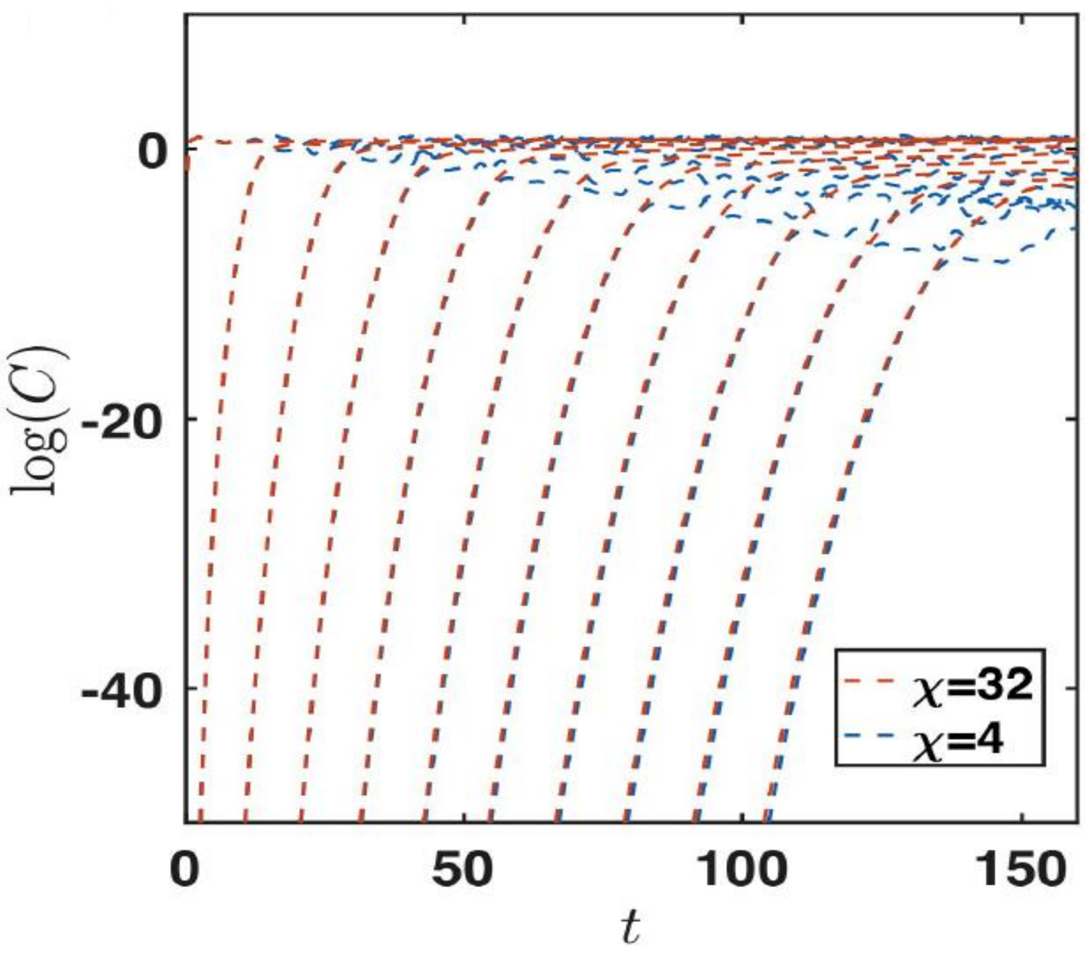
$W =$  $\quad \mathrm{dist}(W, V) = r$

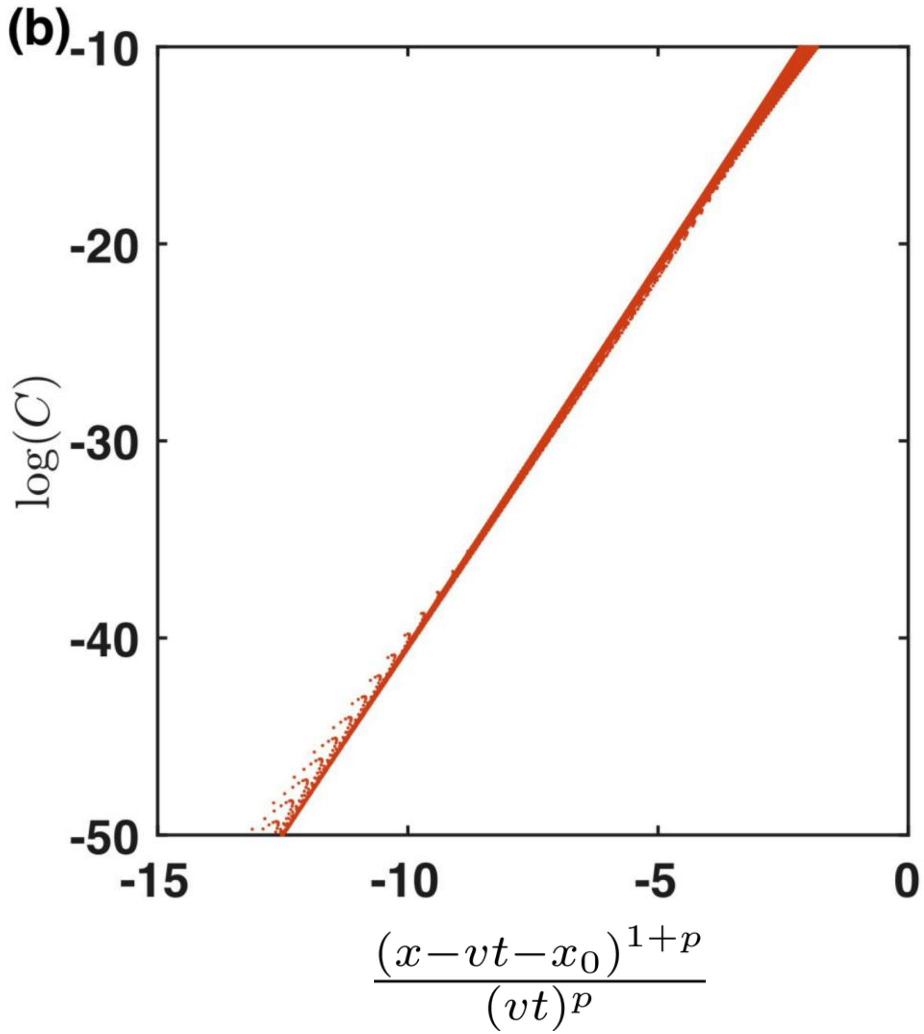


Conjectured universal form of operator growth:

Spin chain – tensor networks

$$C(x,t) = \exp\left(-\lambda \frac{(x-vt)^{1+p}}{v(vt)^p}\right)$$

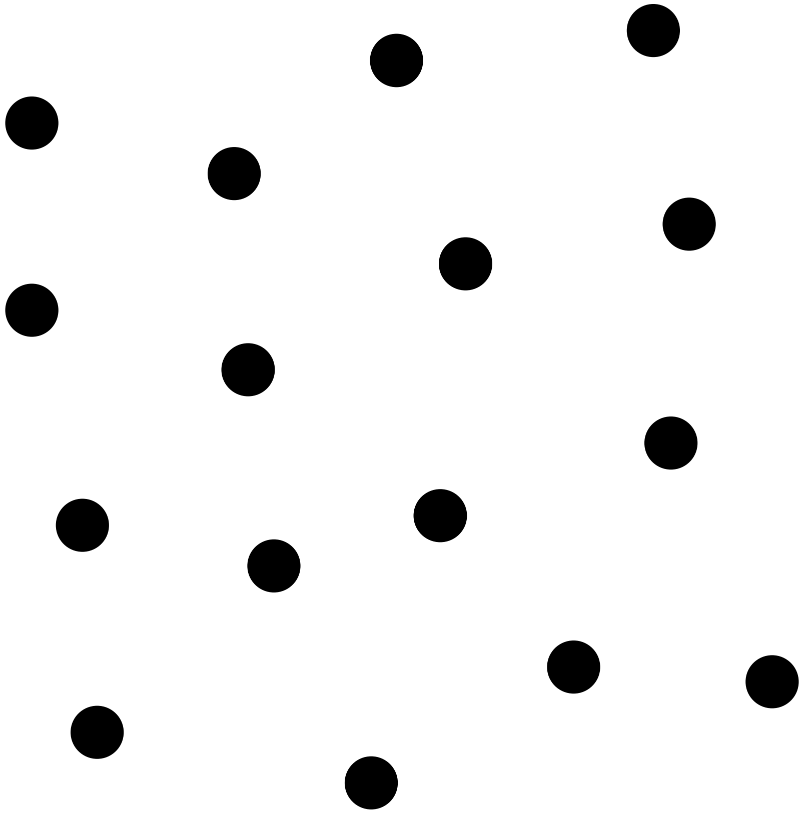


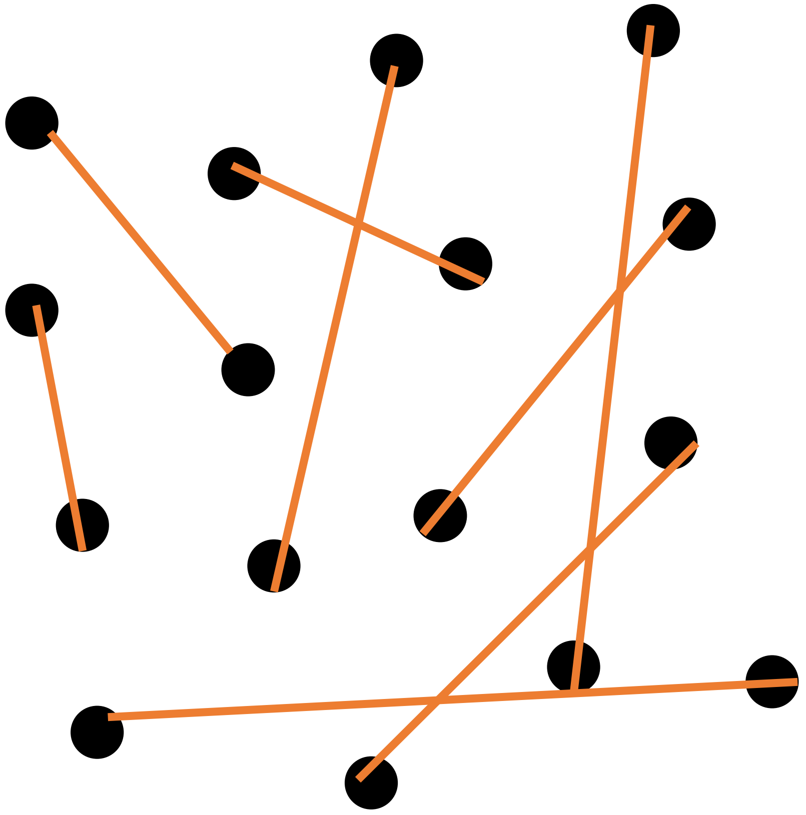


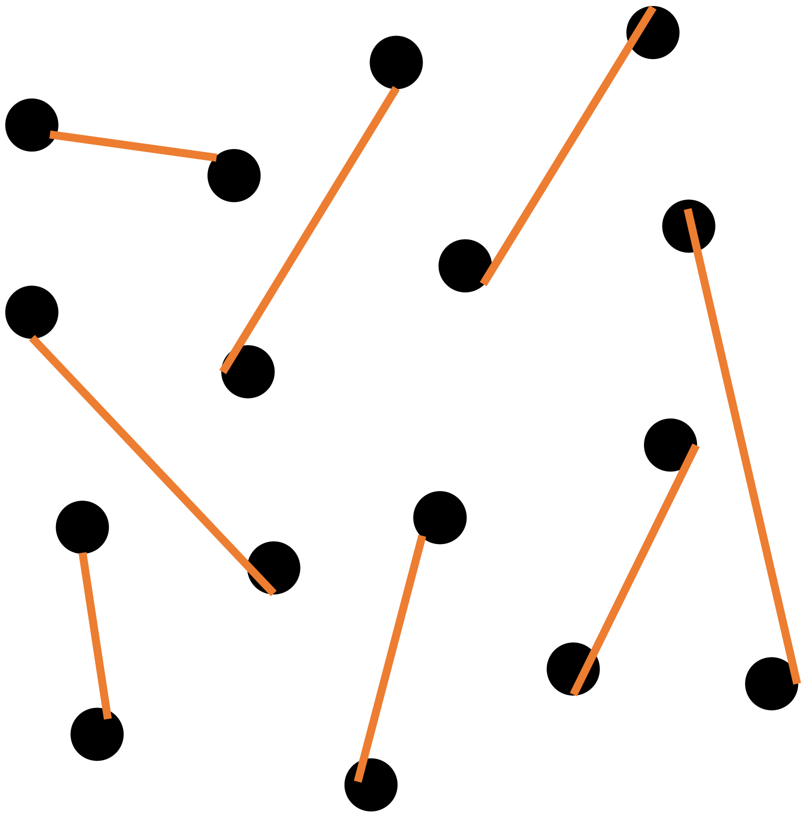
$L = 201$ rapid convergence with bond dimension

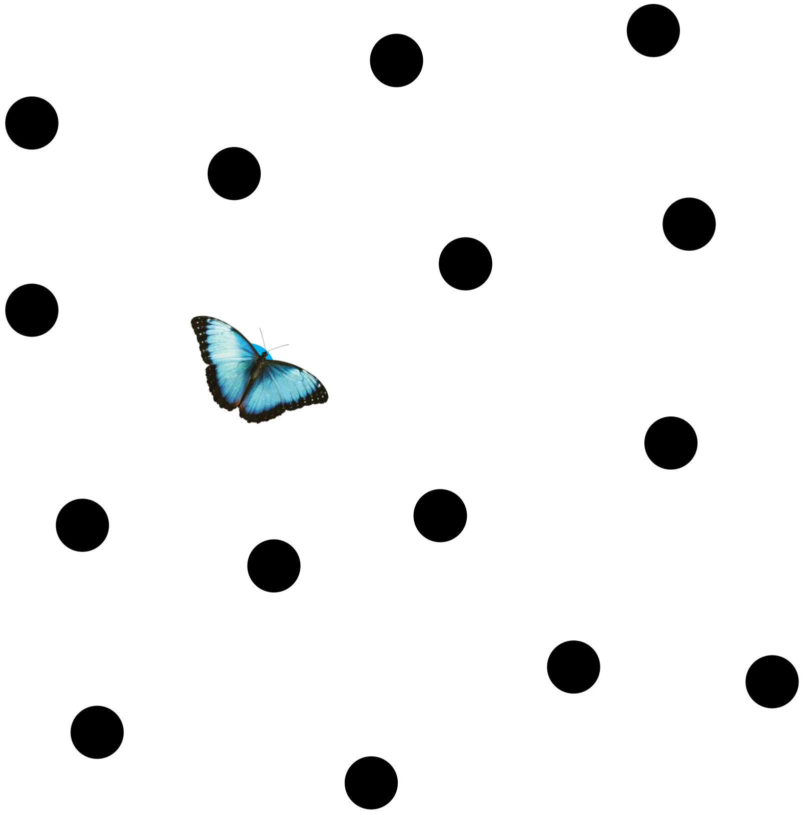
[Xu/S arXiv:1802.00801]

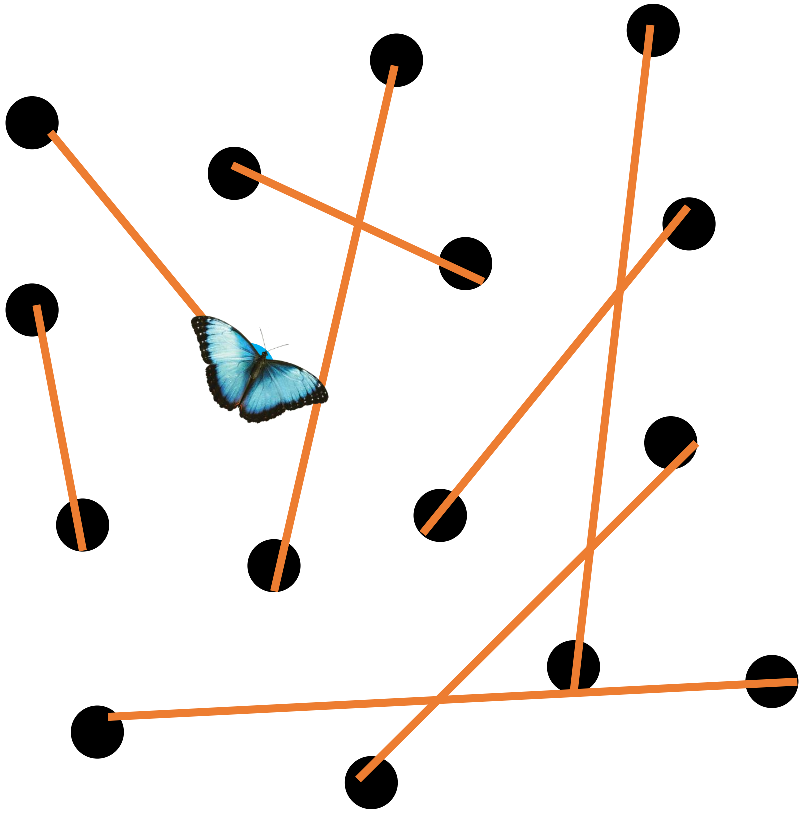
Snapshots of qubits with all-to-all interactions

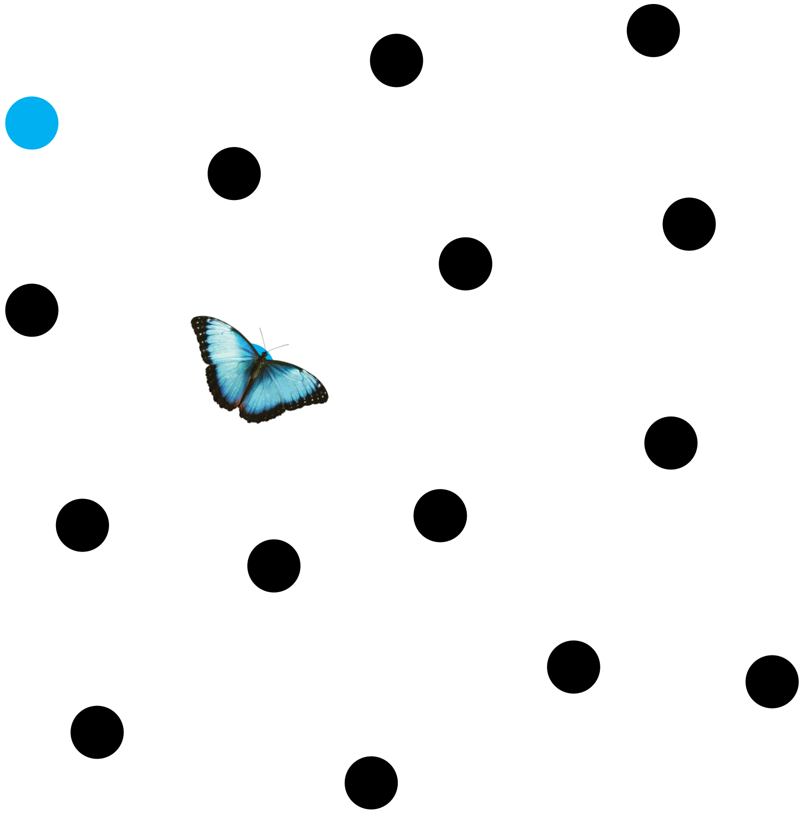


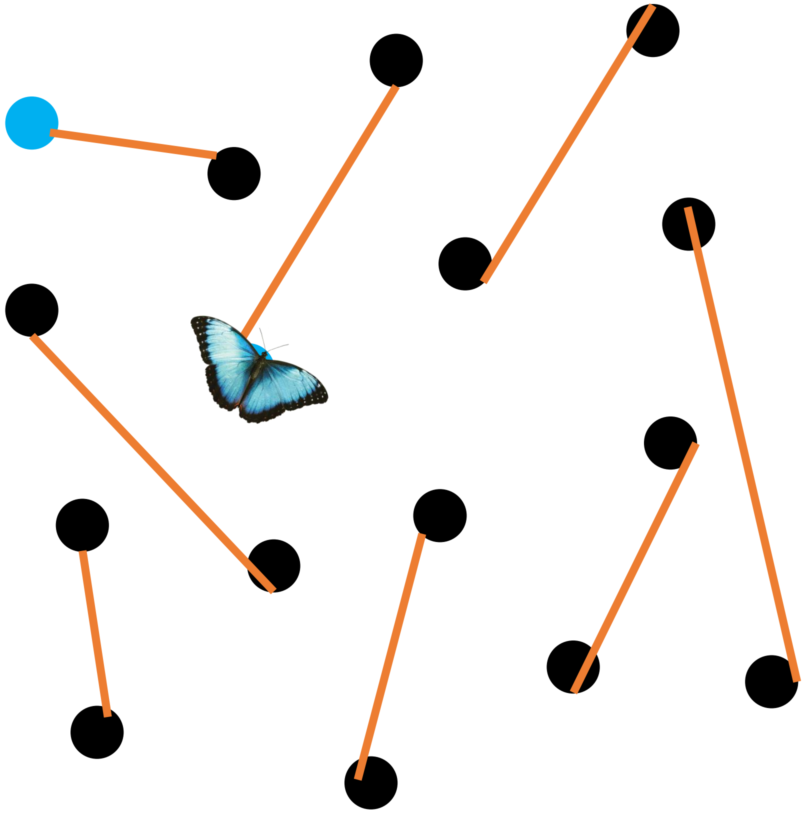


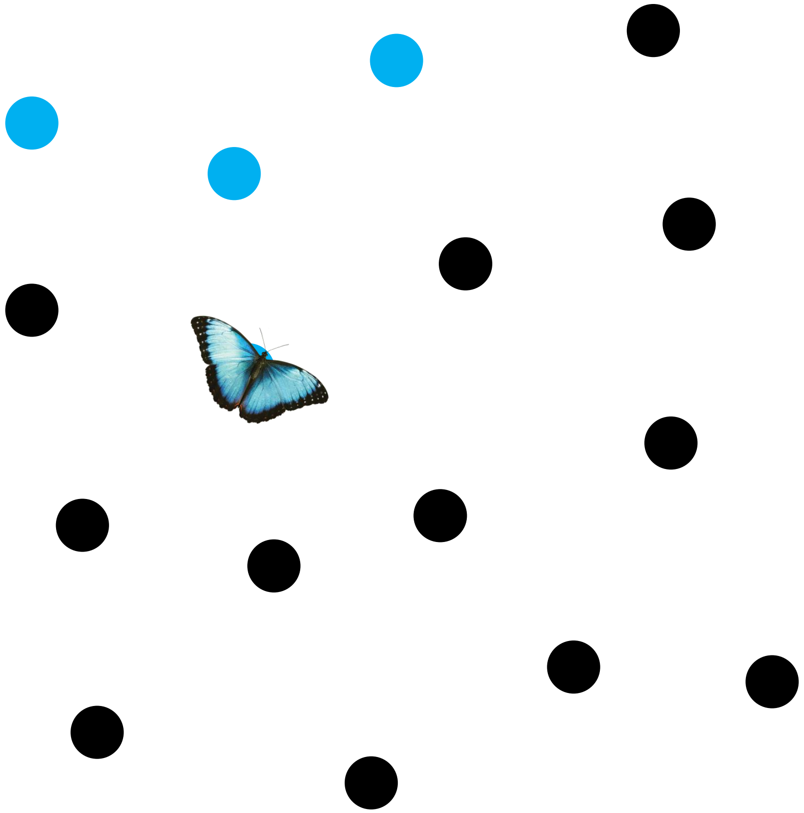


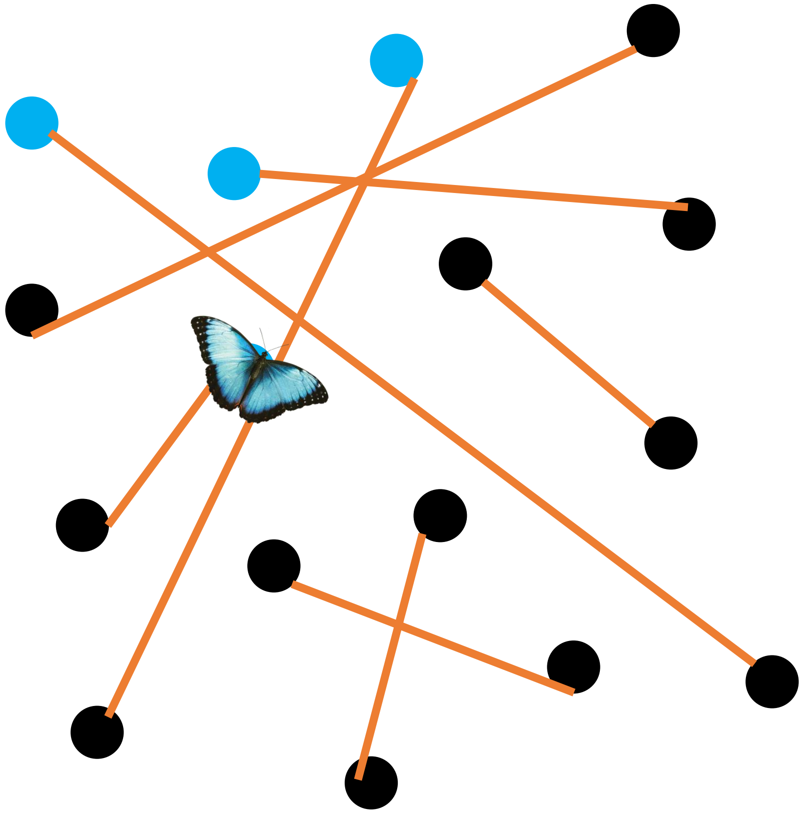


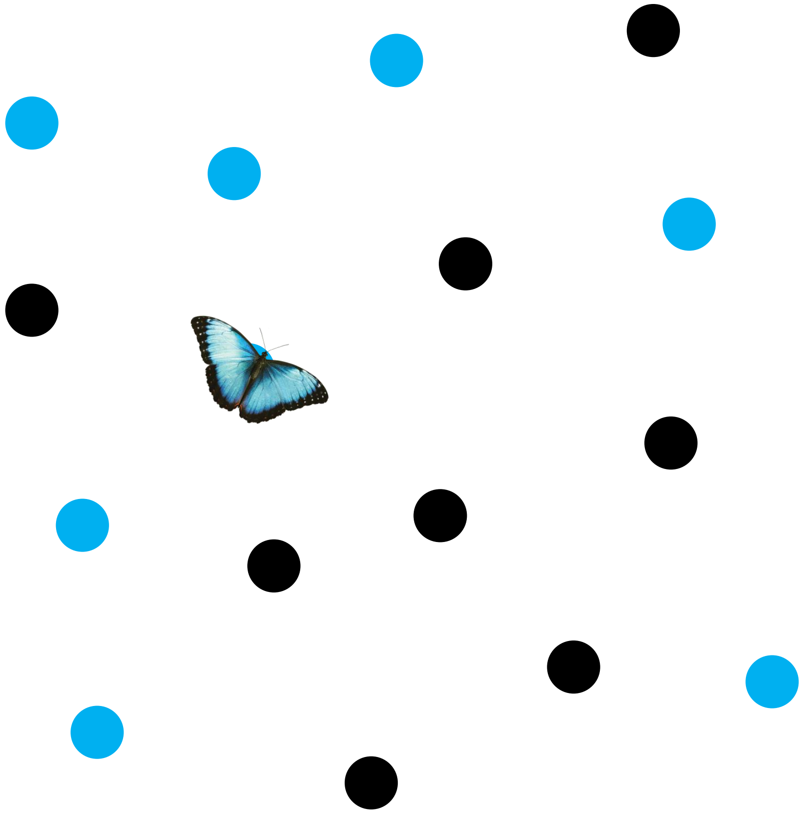












Affected region doubles every time step …

Commutators, chaos, and black holes

- Semiclassical limit $V = e^{iq/a},\ W = e^{ip/b}$

$$\langle [q_t, p] \rangle \approx i\hbar \{q_t, p\}_{\mathrm{PB}} = i\hbar \frac{\partial q_t}{\partial q} = i\hbar e^{\lambda_L t}$$

[Larkin-Ovchinnikov 1968]

- Black hole chaos (AdS/CFT)

$$C \sim c_1 \frac{e^{2\pi T t}}{S} + c_2 \frac{e^{4\pi T t}}{S^2} + \cdots$$

early time, saturation later

[Shenker-Stanford ’13, Kitaev ’14, Maldacena-Shenker-Stanford]

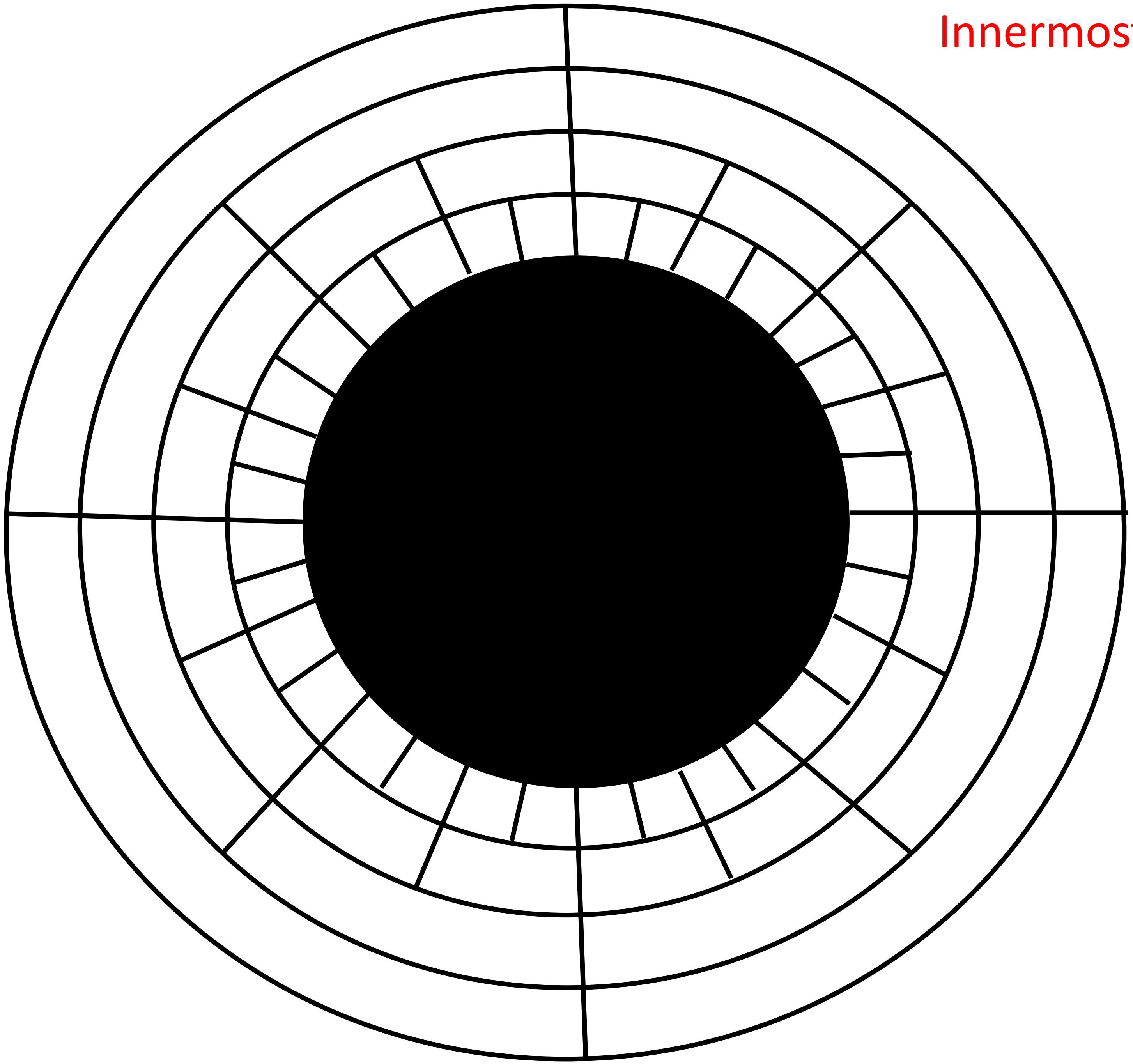
Black holes and fundamental speed limits

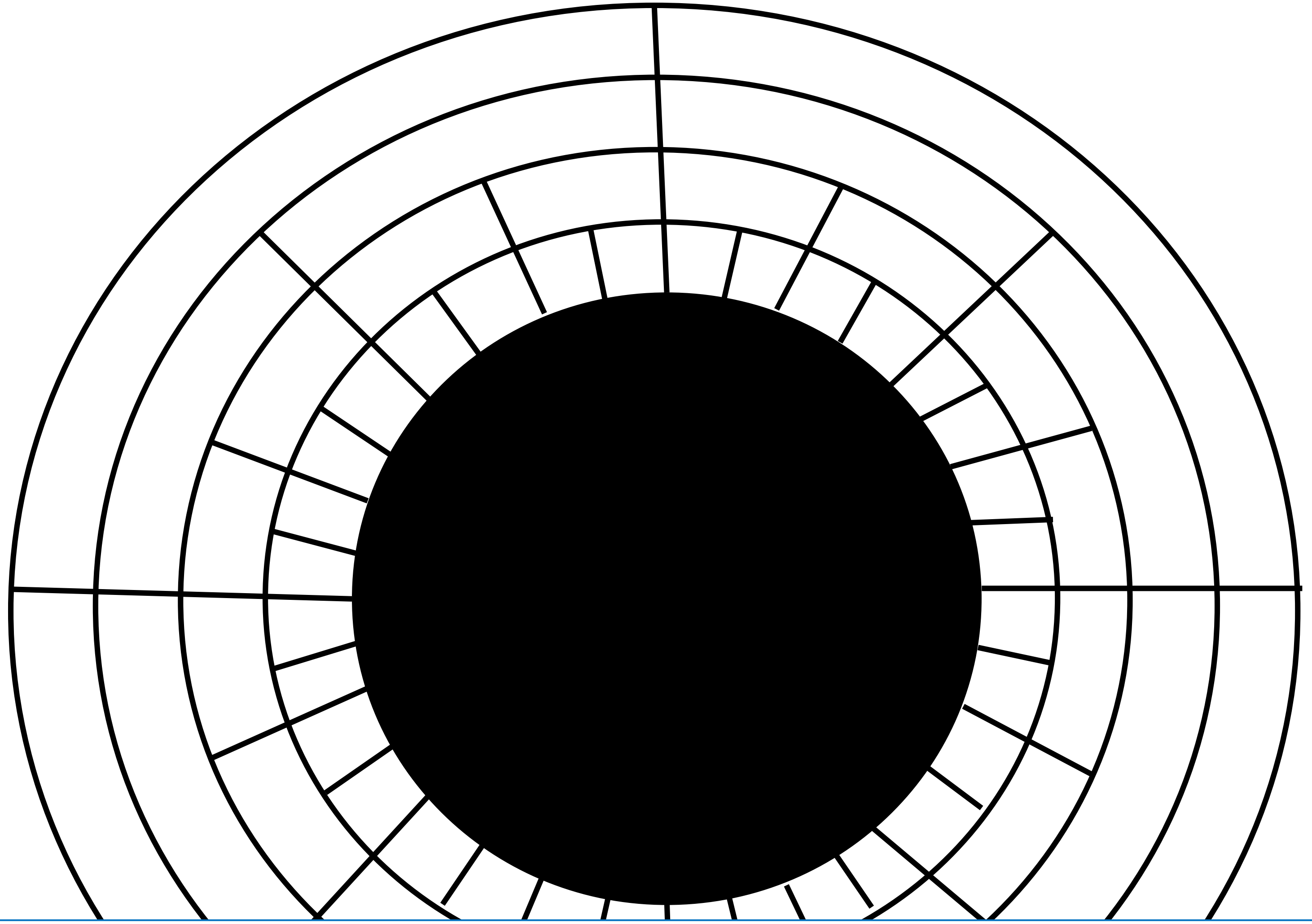
Toy model of external dynamics of black hole

- 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

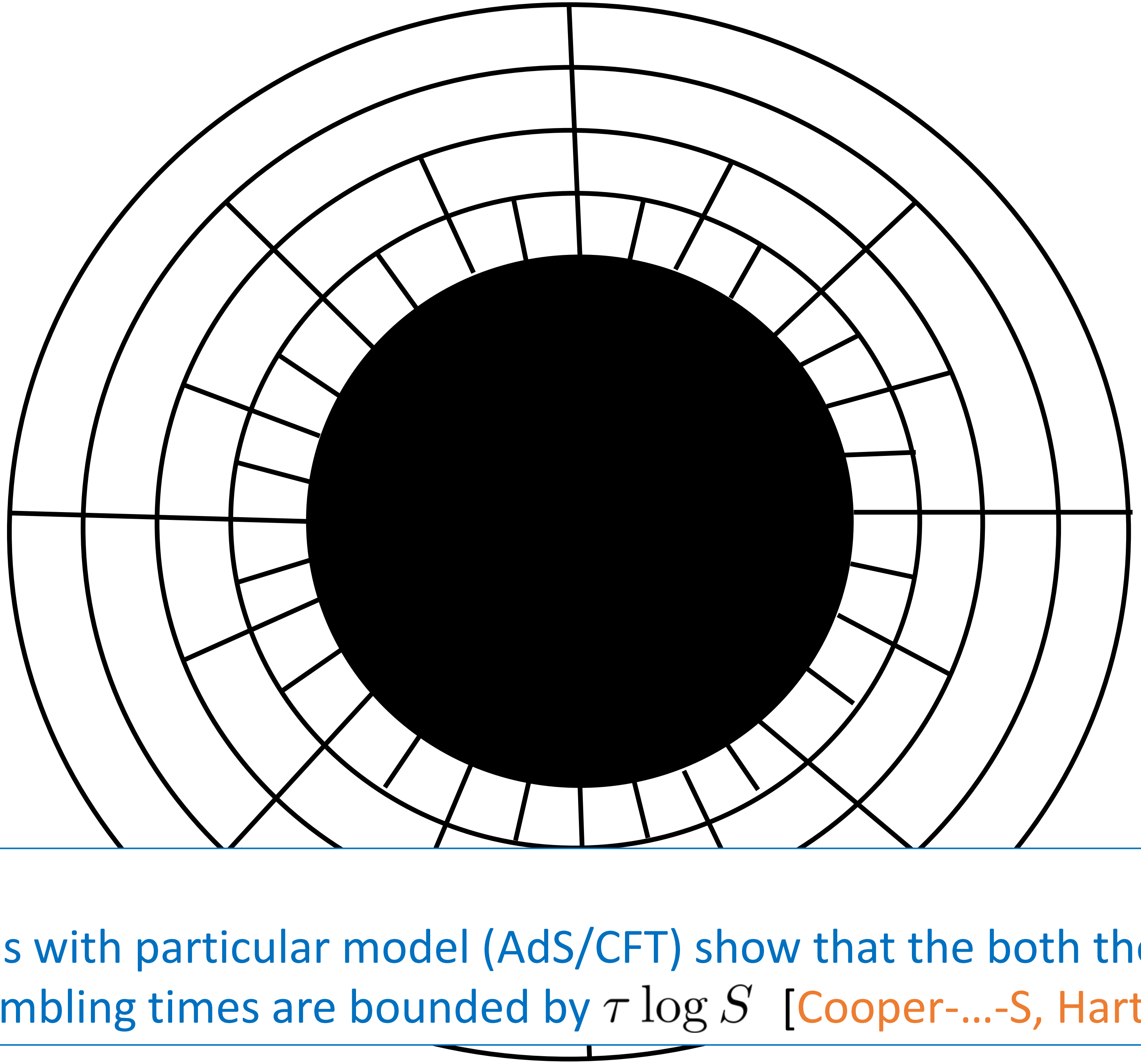
Innermost layer has O(S) cells





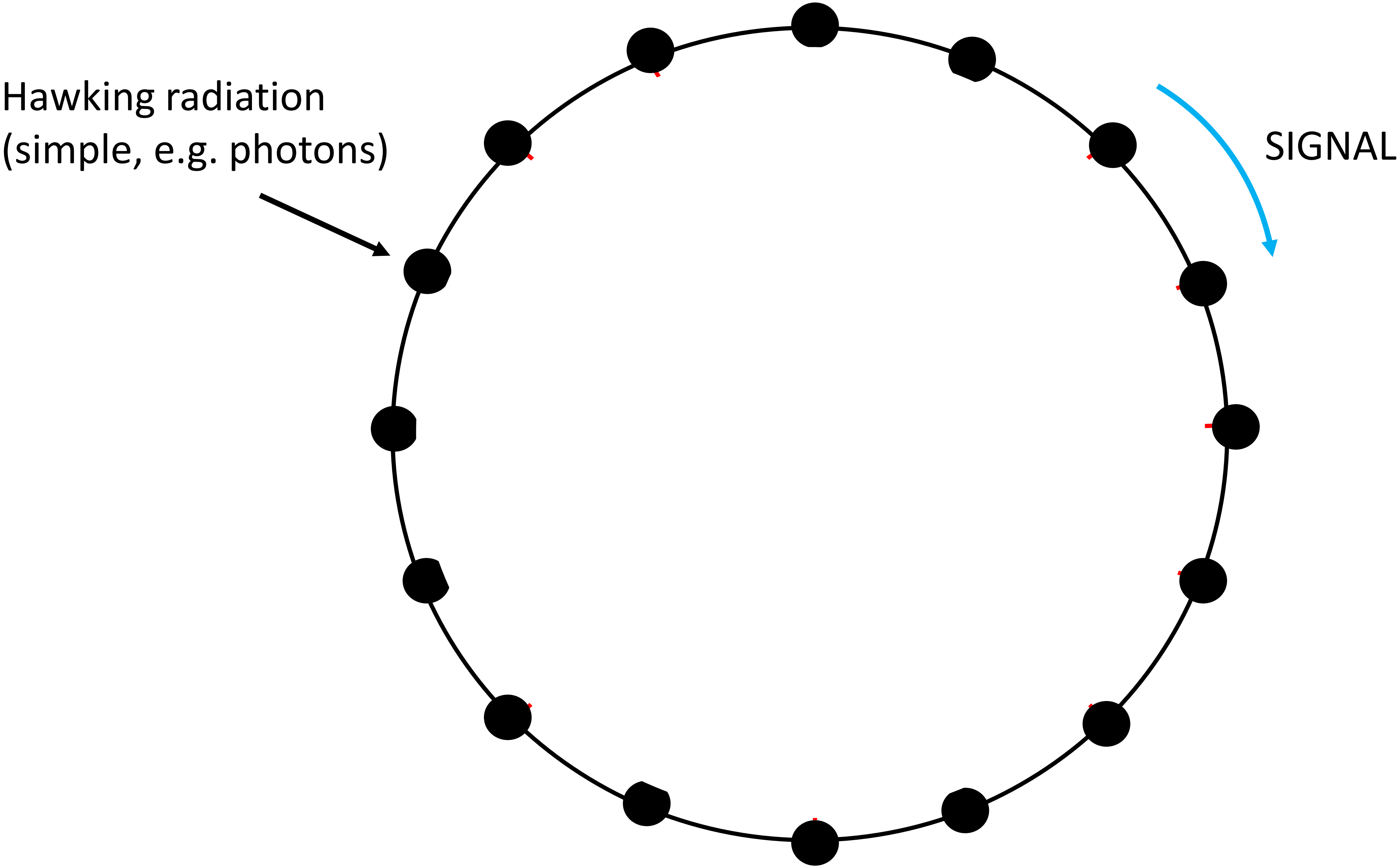
Bounds (Shor):

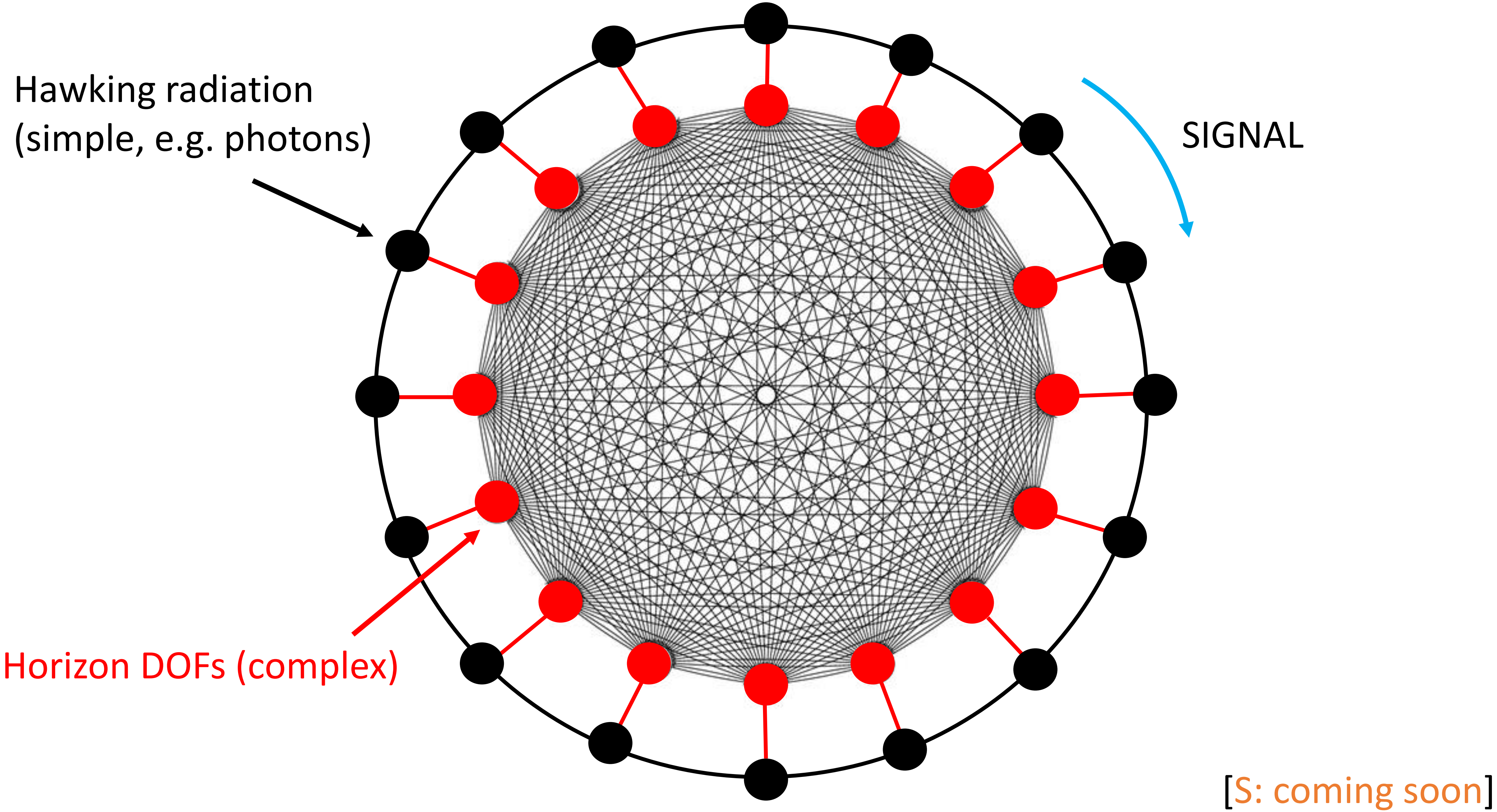
- Weak scrambling (= mixing O(1) qubits) is possible in time $\tau \log S$
- Strong scrambling (= generating nearly maximal entanglement) takes at least time τS $(\text{or } \tau S^{\#})$



Challenge:

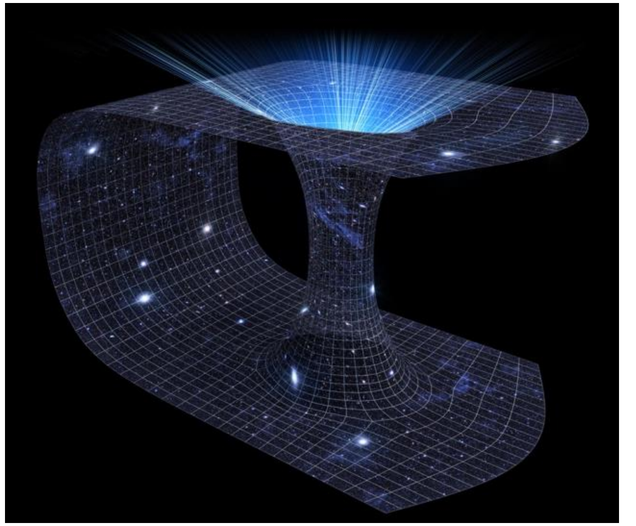
- Calculations with particular model (AdS/CFT) show that the both the weak and strong scrambling times are bounded by $\tau \log S$ [Cooper-…-S, Hartman-Maldacena]

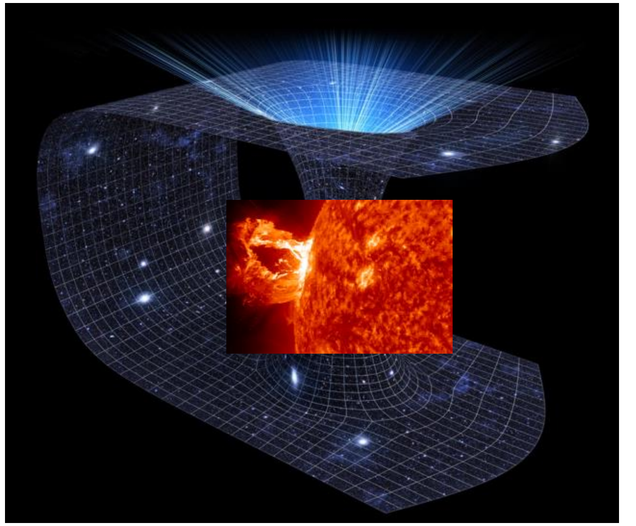

Hawking radiation
(simple, e.g. photons)
SIGNAL


Hawking radiation
(simple, e.g. photons)
SIGNAL
Horizon DOFs (complex)
[S: coming soon]

What is spacetime geometry?

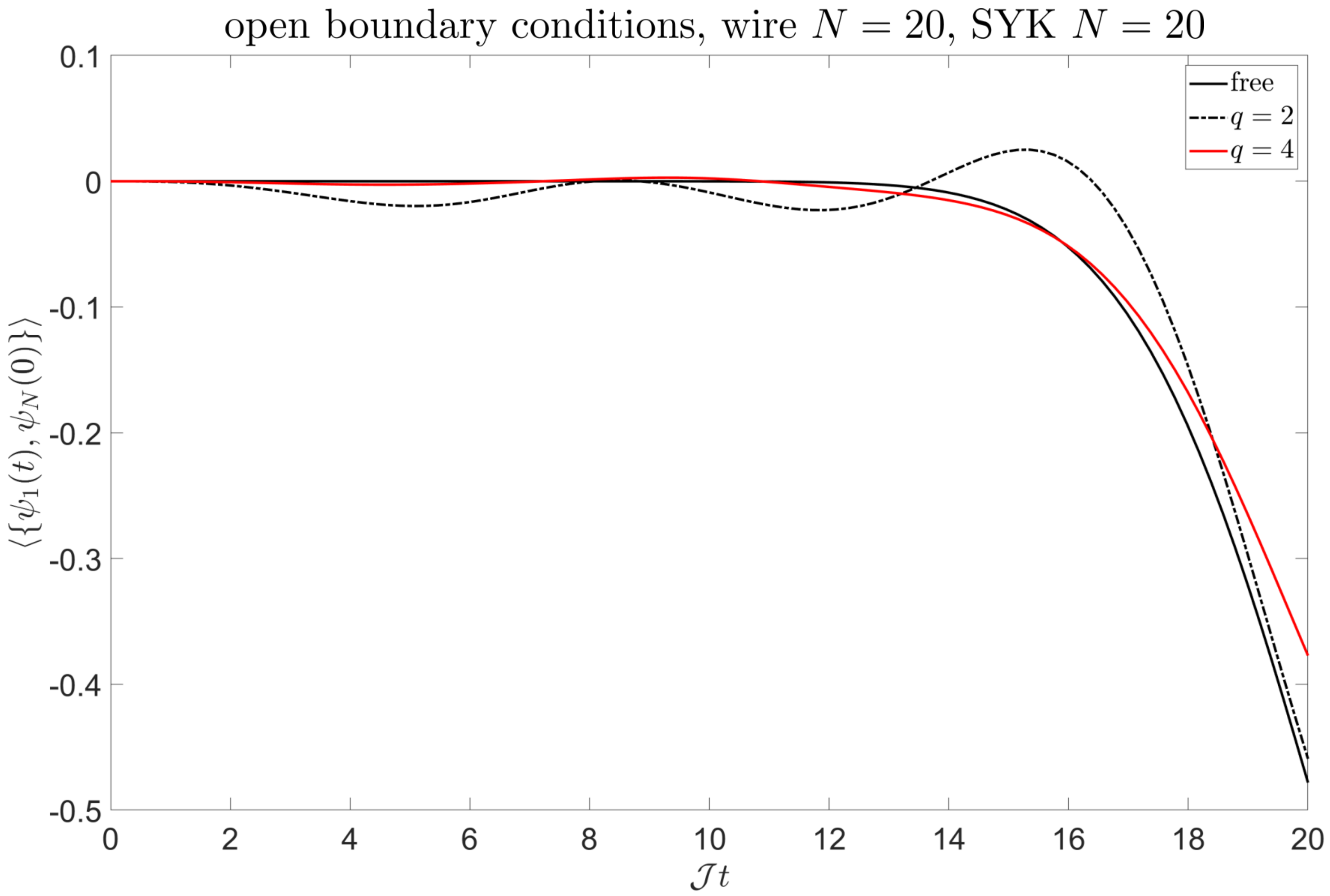
- It should be *operationally defined* in terms of the motion of simple signals → Einstein's rods and clocks!
- In the model, simple signals continue to respect the local structure, up to entropy-suppressed corrections
- A super-observer with access to multiple copies of the universe, or who can run 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





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

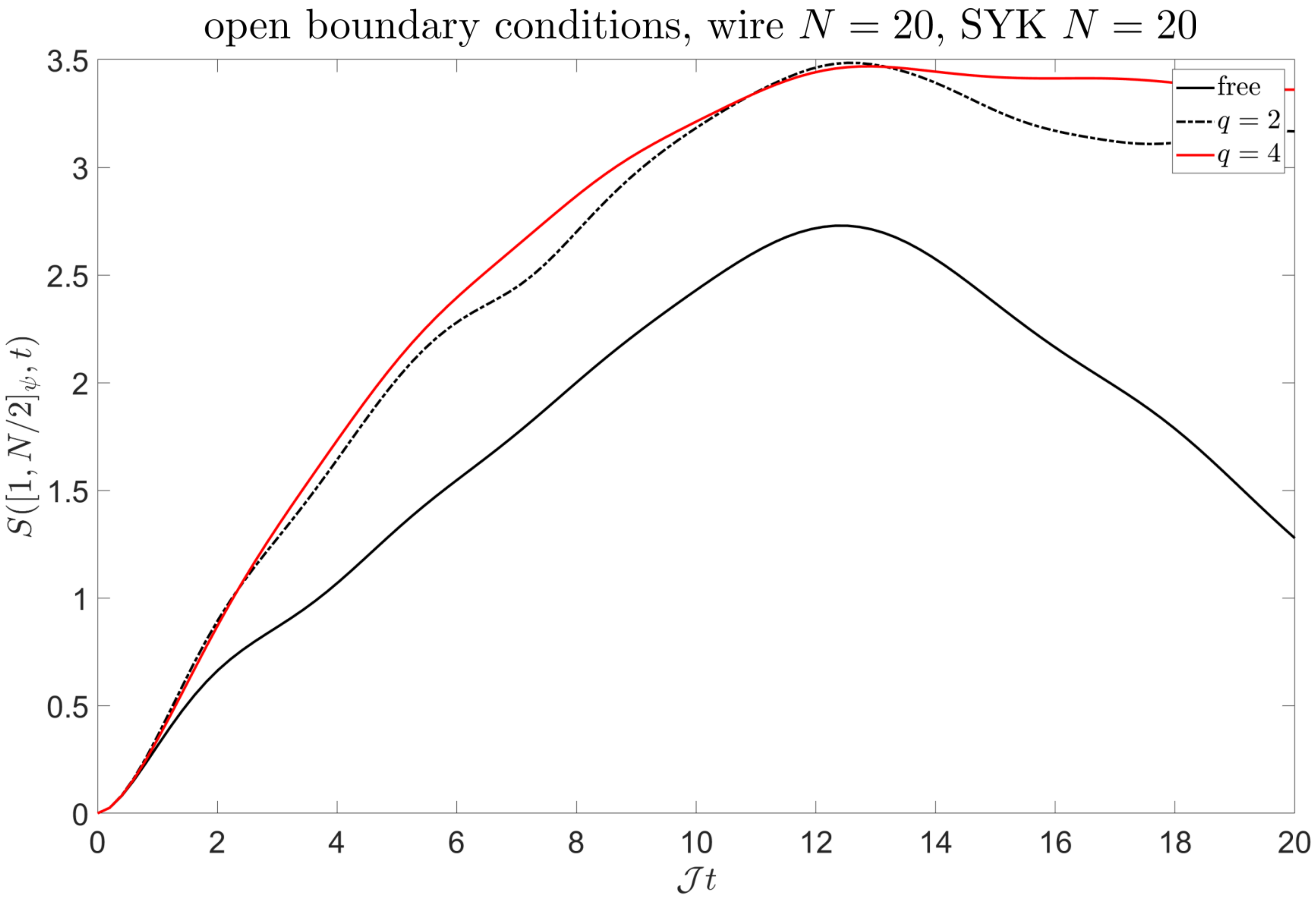
Response



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]

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
- New perspective on the information dynamics of black holes, possibly addressing tension between fast dynamics and spacetime locality
- Just the beginning: a large number of directions to think about, including the particularly exciting direction of simulating quantum gravity in the lab, e.g. via the SYK model or N=4 SYM or …

ASPEN CENTER FOR PHYSICS

2020 WINTER CONFERENCE

QUANTUM INFORMATION AND SYSTEMS FOR FUNDAMENTAL PHYSICS

February 17 through 22, 2020
Monday evening welcome reception
Meetings Tuesday through Saturday evening

The last decade has seen wonderful progress on fundamental physics, including both the discovery of the Higgs boson by the LHC and the direct detection of gravitational waves and black holes by LIGO. These successes increasingly highlight other fundamental challenges in physics ranging from understanding the nature of dark matter to unraveling the quantum physics of spacetime itself. At the same time, there have been dramatic improvements in our ability to manipulate complex quantum systems and a concomitant explosion in our theoretical understanding of the nature of information in a quantum universe. An exciting possibility raised by these two parallel developments is that quantum information and systems could provide a powerful new approach to questions in fundamental physics. Nevertheless, efforts in this direction are still nascent.

One set of ideas revolves around using engineered quantum systems to make ultra-precise measurements to directly detect faint dark matter signatures. Another set of ideas attempts to decode the way spacetime emerges from microscopic degrees of freedom using the language of entanglement, complexity, and computation. Given these and other early developments, the time is ripe for a meeting across communities to share ideas and look forward. This Aspen Winter Conference will bring these communities together in a focused meeting to identify common goals and look for new opportunities. Such a meeting should be more productive than previously possible thanks to the new common language of quantum information and a new set of experimental tools of broad interest. The meeting will include invited plenary talks and a poster sessions, and limited travel support may be available to junior participants.

Application deadline is November 30, 2019

Please complete your application at:
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Conference Website: https://indico.physics.lbl.gov/indico/event/939/

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