Chiral spin model:
geometry, chaos
& quantum teleportation

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UNIVERSITY OF LEEDS

Who and what

M. Horner, A. Hallam & JKP, PRL

E. Forbes, M. Horner, A. Hallam, J. Barker, JKP, PRB

A. Deger, M. Horner & JKP, PRB

A. Daniel, A. Hallam, M. Horner & JKP, Sci. Reports

A. Benhemou, G. Nixon, A. Deger, U. Schneider, JKP, 2312.14058

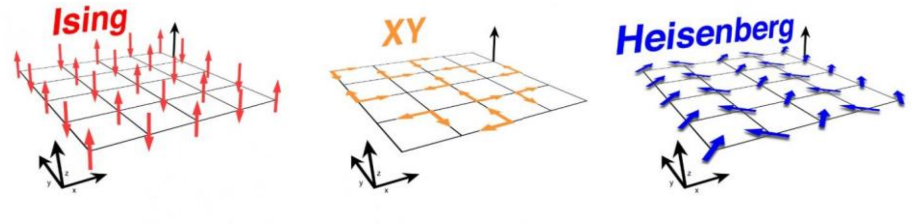
A. Daniel, T. Bhore, JKP, C. Liu, A. Hallam, 2503.10761

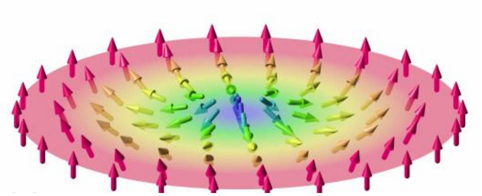
I. Sofos, A. Hallam, JKP, 2509.22774

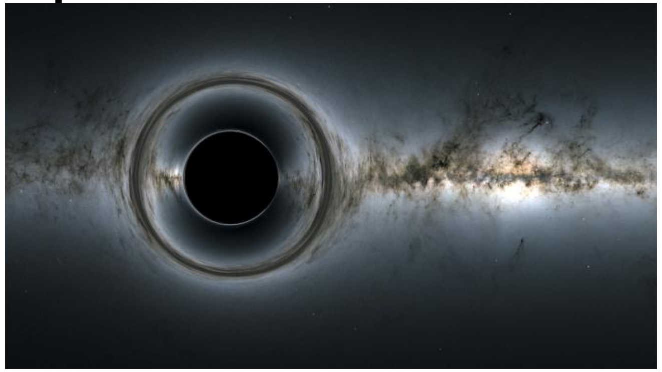
R. Smith, E. Forbes, A. Hallam, JKP (to appear)

Outline & motivation

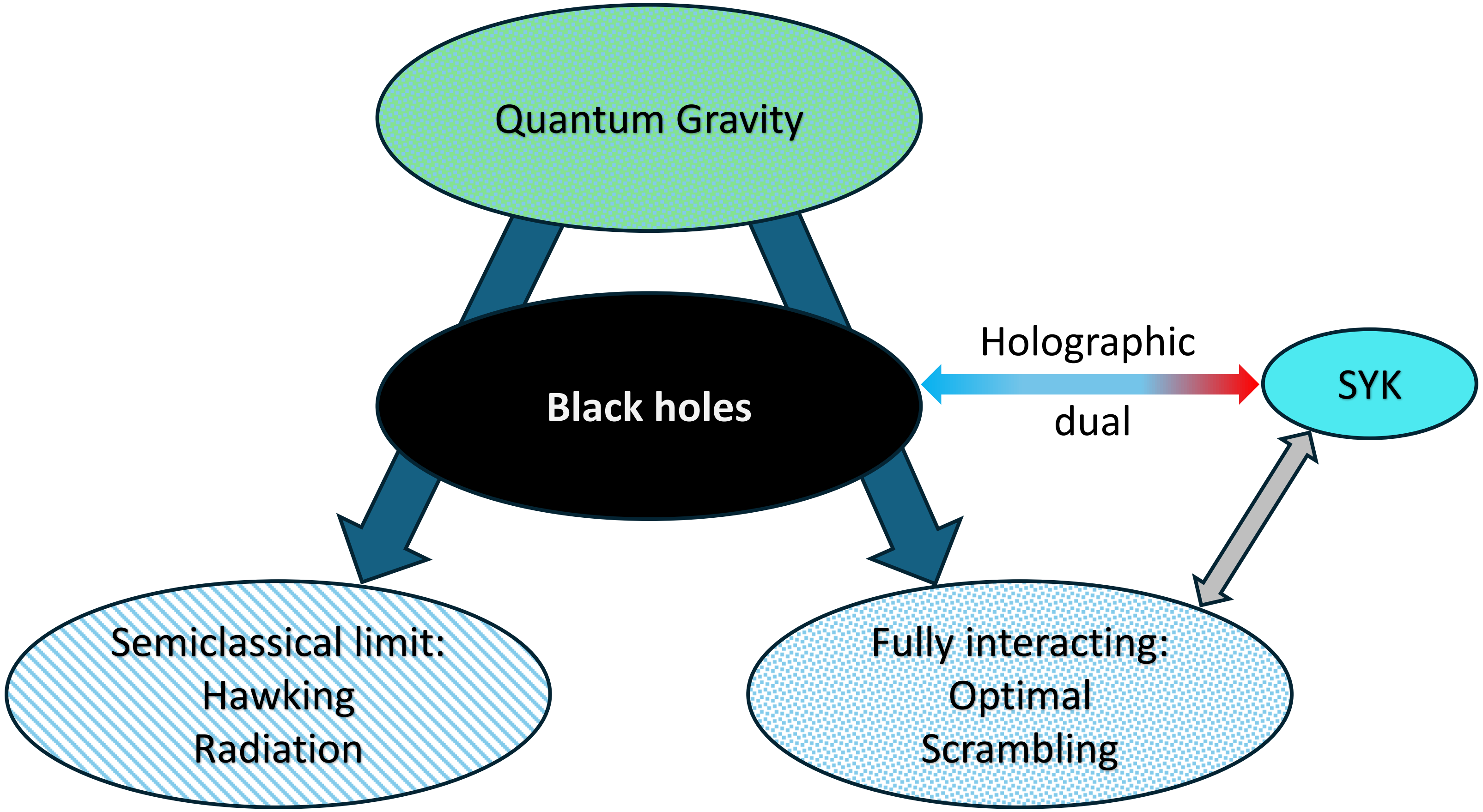
- Quantum properties of black holes are fascinating: Hawking radiation and optimal scrambling
- Chiral spin model:
  - Emergent QFT in curved space: **Hawking radiation**
  - Chaotic behaviour: **Optimal scrambling**
- Application: Black hole quantum teleportation







Quantum, gravity, black holes

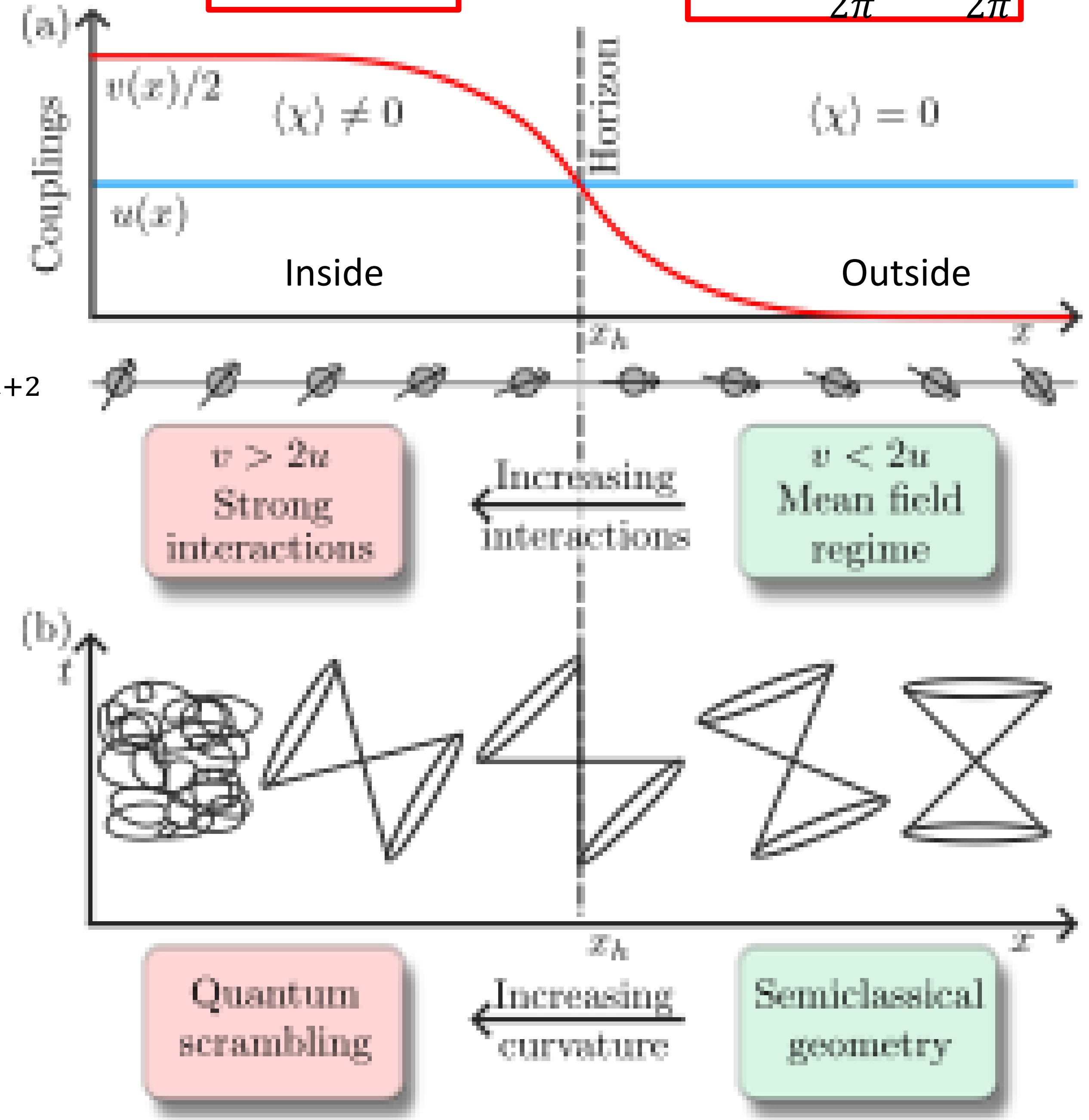


The full picture

$$\lambda = 2\pi T \cdot J$$

$$T_H = \frac{v'(x_h)}{2\pi} = \frac{\alpha\beta}{2\pi}$$

$$H = -\frac{u}{2}\sum_n \left(S_n^x S_{n+1}^x + S_n^y S_{n+1}^y\right) + \frac{v}{4}\sum_n S_n \cdot S_{n+1} \times S_{n+2}$$



A simple chiral spin-chain model unifies two important quantum aspects of black holes

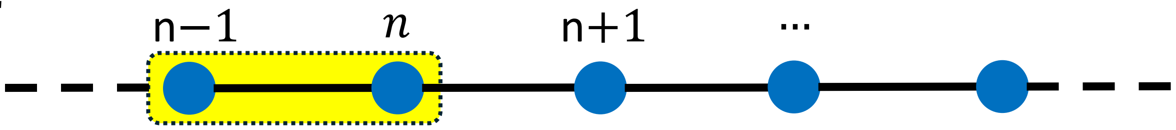
A controllable toy model that can be tested in the lab

Emergent relativity

1D XY model:

$$S_n^a = \frac{\sigma_n^a}{2}$$

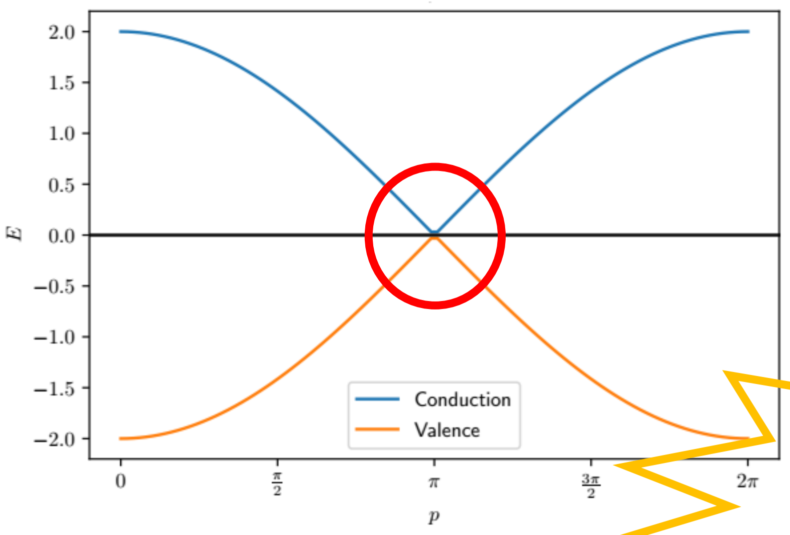
$$H = -\frac{u}{2}\sum_n \left(S_n^x S_{n+1}^x + S_n^y S_{n+1}^y\right)$$



Emergent relativity?
-> Jordan-Wigner transformation:

$$H = -\frac{u}{4}\sum_n c_n^\dagger c_{n+1} + h.c. = \sum_p E(p) c_p^\dagger c_p$$

Fourier transform



$E(p) = \pm v_F p$
Relativistic!

Fermionic modes:

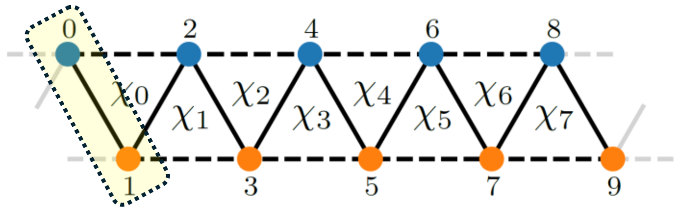
$$\{c_n, c_m^\dagger\} = \delta_{nm},$$
$$\{c_n, c_m\} = \{c_n^\dagger, c_m^\dagger\} = 0$$

Chiral Spin chain model

Modify the XY model

New piece

$$H = -\frac{u}{2}\sum_n \left(S_n^x S_{n+1}^x + S_n^y S_{n+1}^y\right) + \frac{v}{4}\sum_n S_n \cdot S_{n+1} \times S_{n+2}$$



$$\chi_n = S_n \cdot S_{n+1} \times S_{n+2}$$

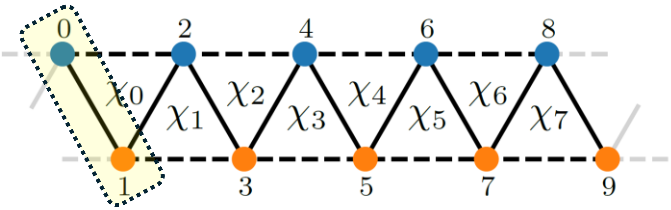
Spin chirality:
classically, measures solid angle

$$\|\chi\| = \sqrt{tr(\chi^\dagger \chi)} = 2.121\ldots$$

Jordan-Wigner transformation: **interacting model**
(not quadratic in fermions) ☹

$$H = \frac{1}{4}\sum_n \left[-u c_n^\dagger c_{n+1} - \frac{iv}{4} c_n^\dagger c_{n+2} + \frac{iv}{4}\left(c_n^\dagger c_{n+1}\sigma_{n+2}^z + c_{n+1}^\dagger c_{n+2}\sigma_n^z\right)\right] + h.c.$$

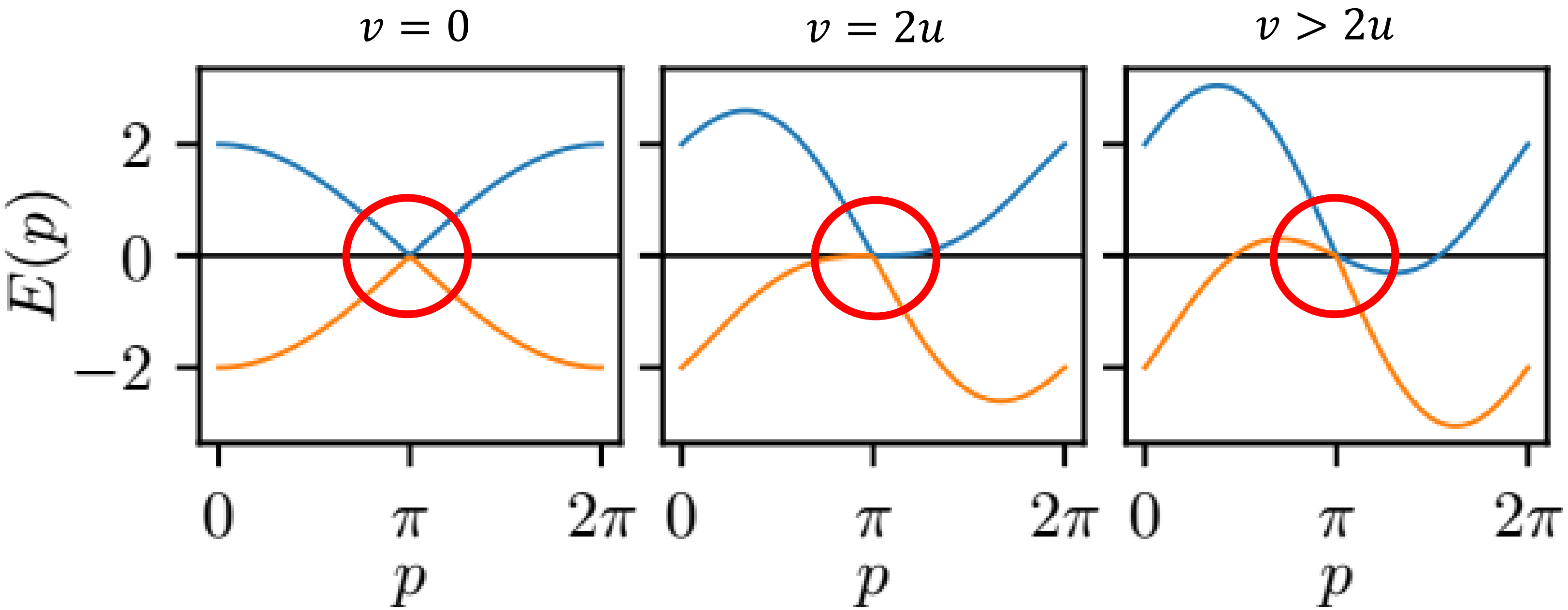
Chiral Spin chain model



Mean field theory

$$H_{MF} = \frac{1}{4}\sum_n \left(-u c_n^\dagger c_{n+1} - \frac{iv}{4} c_n^\dagger c_{n+2} \right) + h.c.$$

Quadratic (exactly solvable)
Gives rise to tilting Dirac cones



Is this a black hole?

Effective curved spacetime

$$H_{MF} = \frac{1}{4}\sum_n \left(-u c_n^\dagger c_{n+1} - \frac{iv}{4} c_n^\dagger c_{n+2}\right) + h.c.$$

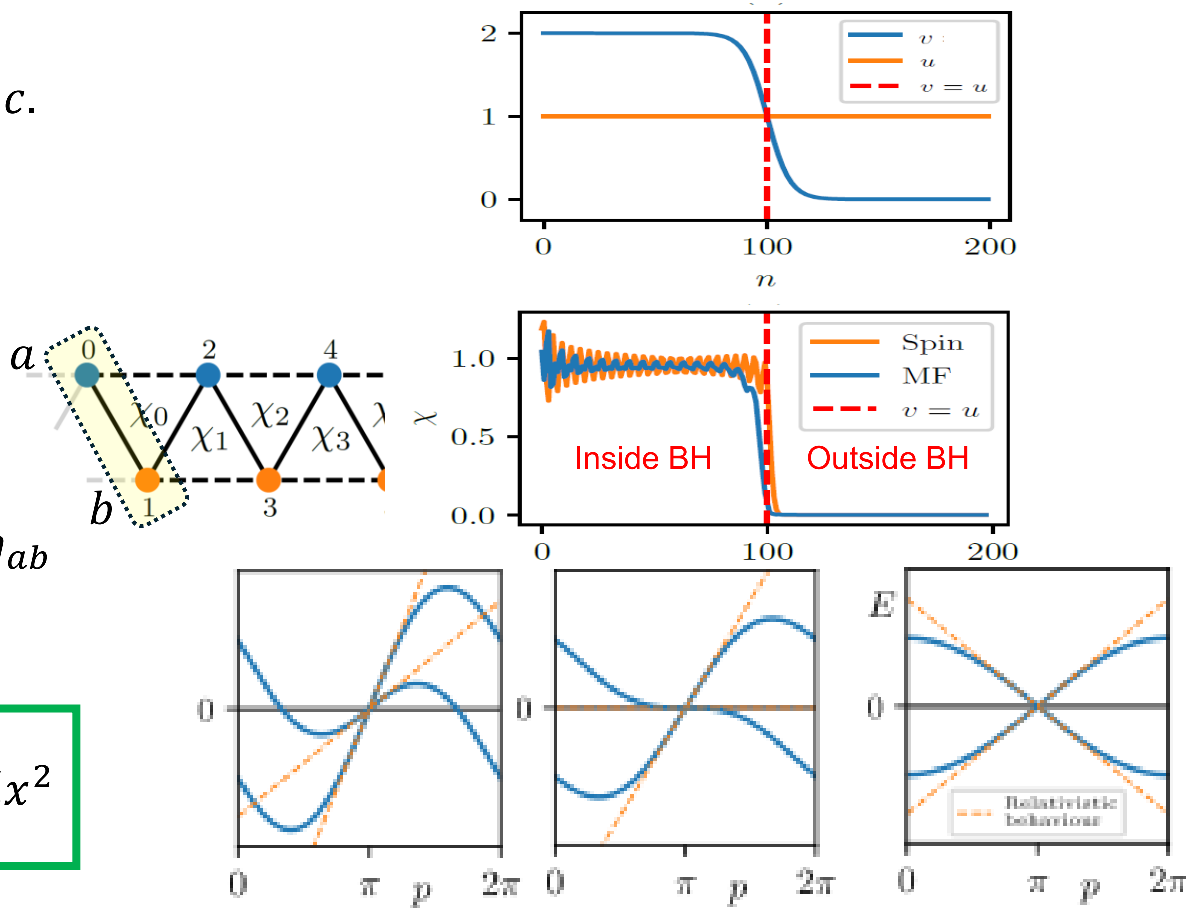
Take the continuum limit to get a Dirac equation on a curved spacetime with metric

$$H = \int \psi^\dagger \, h(p) \, \psi \, dp \qquad \psi = \binom{a}{b}$$

$$h(p) = e_a^\mu \alpha^a p_\mu \qquad g_{\mu\nu} = e_\mu^a e_\nu^b \eta_{ab}$$

Gullstrand–Painlevé metric

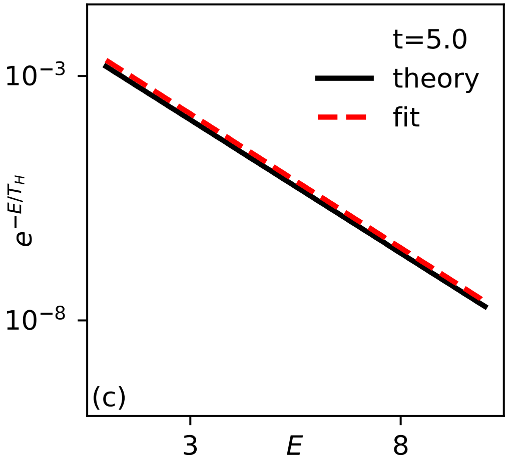
$$ds^2 = \left(1 - \frac{v^2}{4u^2}\right) dt^2 + \frac{4v}{u^2} dt dx - \frac{16}{u^2} dx^2$$



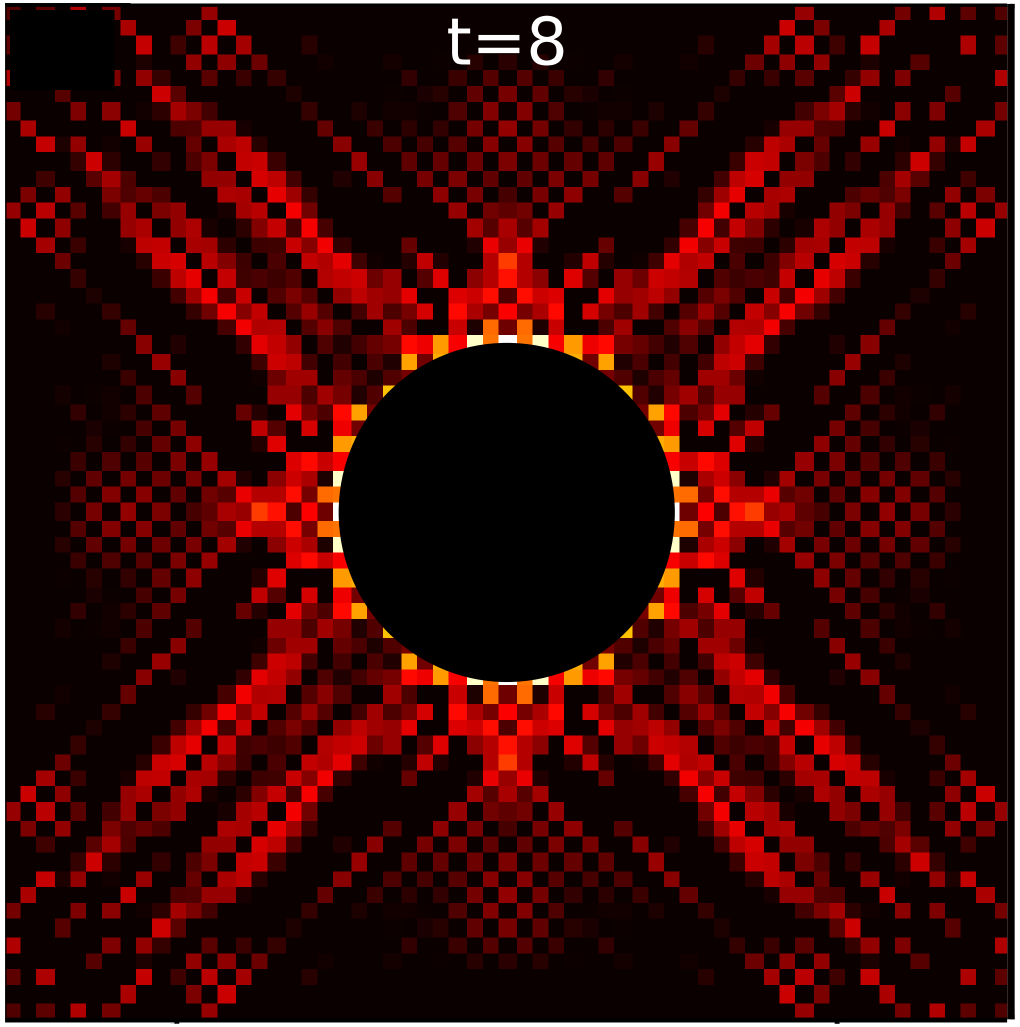
Chiral interface = event horizon

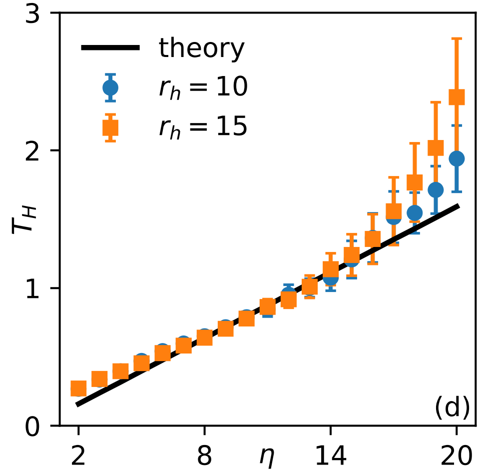
Can predict quench dynamics and thermalisation properties.

Hawking radiation

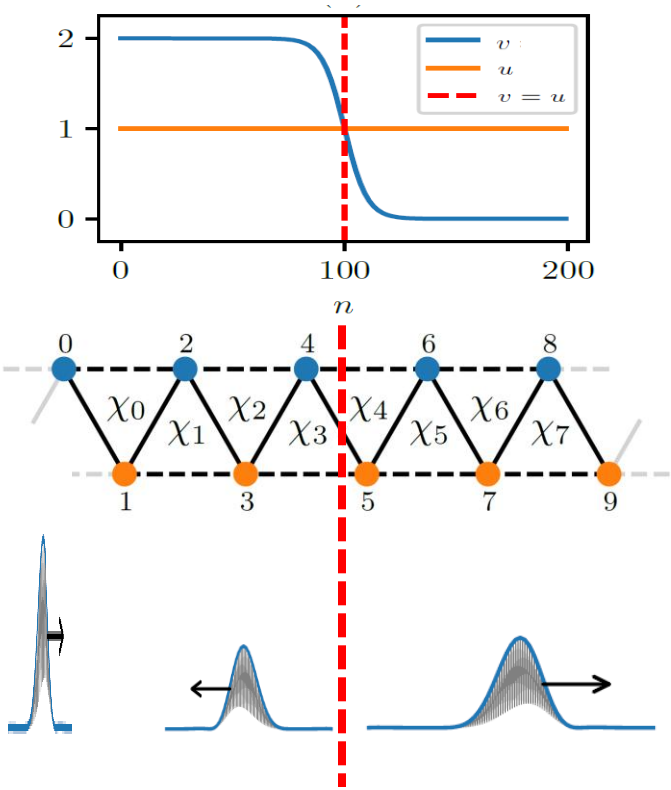


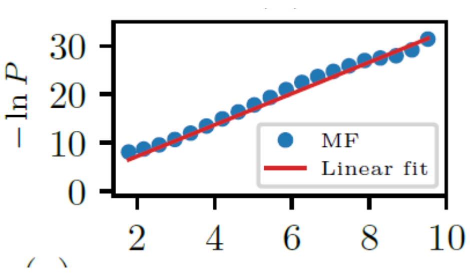
Quantum
(semiclassical limit)

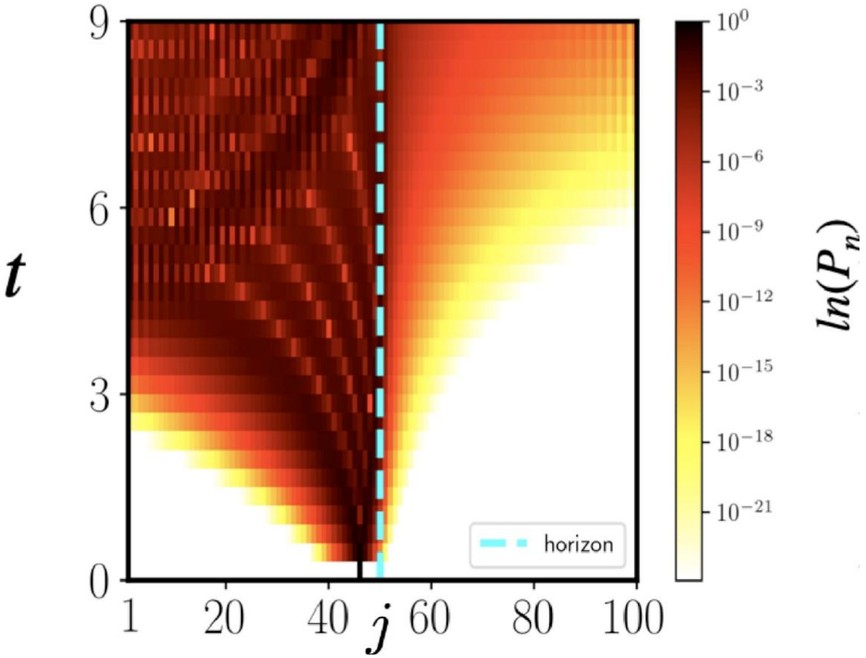


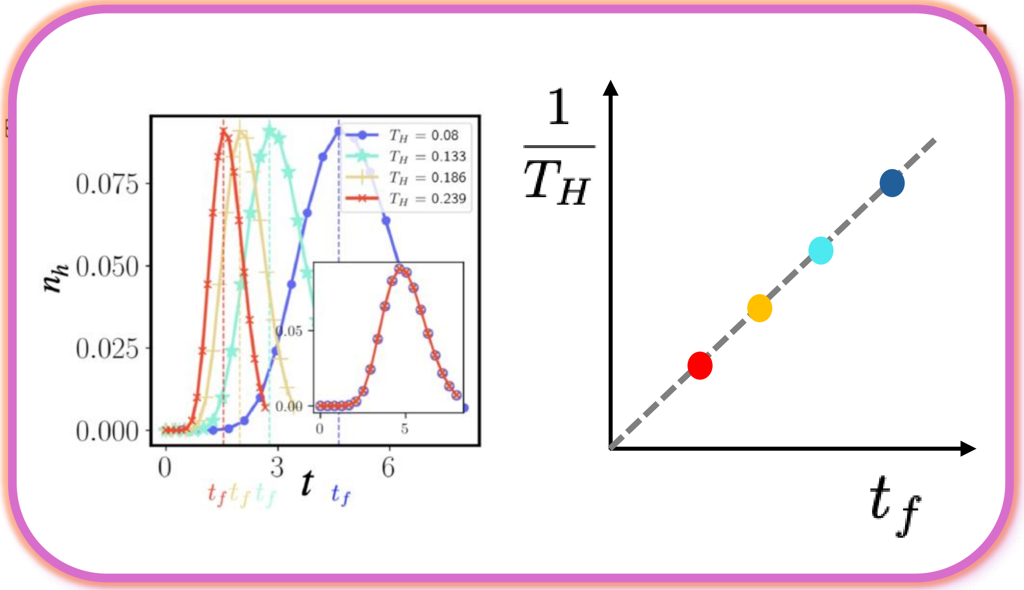


Hawking radiation









$$p(E) = |\langle E|\psi(t)\rangle|^2 \propto e^{-\frac{E}{T_H}}$$

We expect

$$T_H = \frac{v'(x_h)}{2\pi} = \frac{\alpha\beta}{2\pi}$$

Hawking temperature

Quantum Chaos

$$H = -\frac{u}{2}\sum_n \left(S_n^x S_{n+1}^x + S_n^y S_{n+1}^y\right) + \frac{v}{4}\sum_n S_n \cdot S_{n+1} \times S_{n+2}$$

Quantum Chaos: *Energy level statistics*

Poisson or Wigner-Dyson

Inside the black hole, i.e. $\frac{v}{2} > u$

$$H|\Psi_n\rangle = E_n|\Psi_n\rangle$$

Resolve symmetries: Translation, U(1), global spin flip

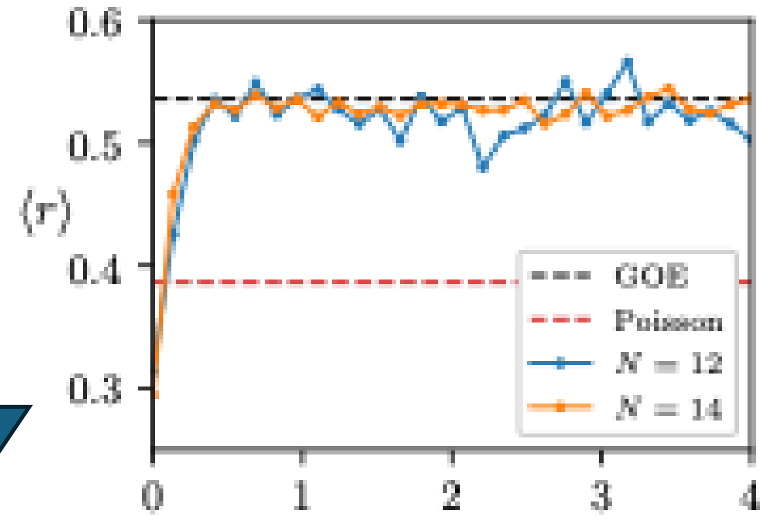
$k = 0 \qquad z = 0 \qquad x = +1$

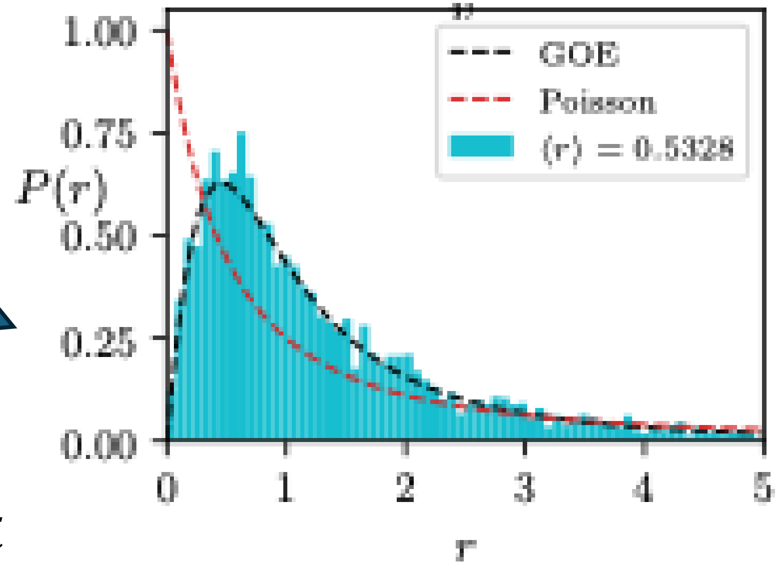
$$s_n = E_n - E_{n-1} \qquad r_n = \frac{\min\{s_n, s_{n-1}\}}{\max\{s_n, s_{n-1}\}}$$

$\Rightarrow$ GOE vs GUE: Hence system is chaotic.

But **is it maximally chaotic**?

…as promised for black holes.

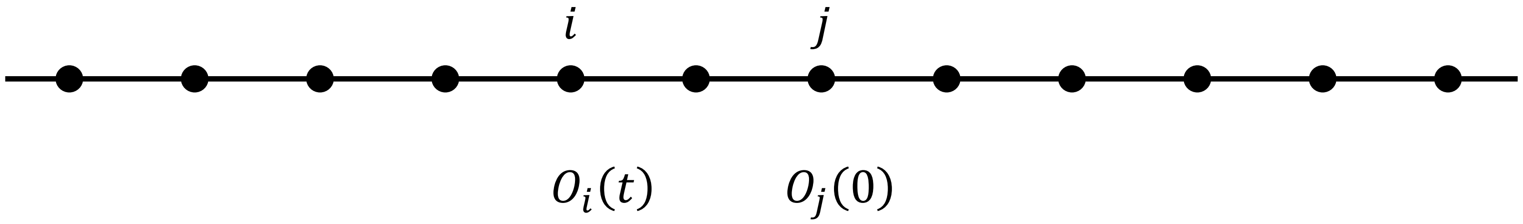




$$H = MH^TM$$
$$M: i \rightarrow N - i$$

Quantum Chaos

Quantum Chaos: **Out-of-time-order correlations** (OTOCs) of **Hamiltonian H**



$$\rho = \frac{e^{-H/T}}{Z}$$

Regularised OTOC

$$C(t) = tr(O_i(t)\rho^{1/4} O_j(0)\rho^{1/4}\, O_i(t)\rho^{1/4}\, O_j(0)\rho^{1/4})$$

Scaled to $C(0) = 1$

For 1+1 D dilaton grav. BHs: [1606.01857]

$$C(t) = U\left(\frac{1}{2}, 1, N\, e^{-\lambda t}\right)\sqrt{N} e^{-\lambda t/2}$$

U: Kummer's confluent hyperbolic function

- Scrambling: $\lambda \leq 2\pi T \cdot J \quad (/\hbar)$

[Maldacena, Shenker, Stanford, JHEP (2016)]

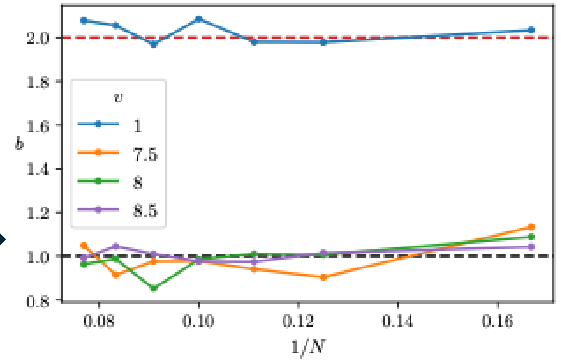
- Black holes saturate this bound $\lambda = 2\pi T \cdot J$

[Shenker, Stanford, JHEP (2015)]

Black hole optimal scrambling

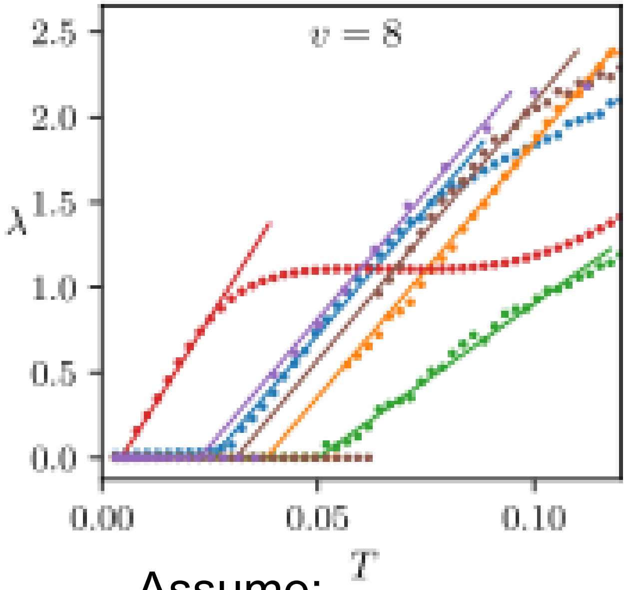
Black holes are optimal scramblers: $\lambda = 2\pi T \cdot J$

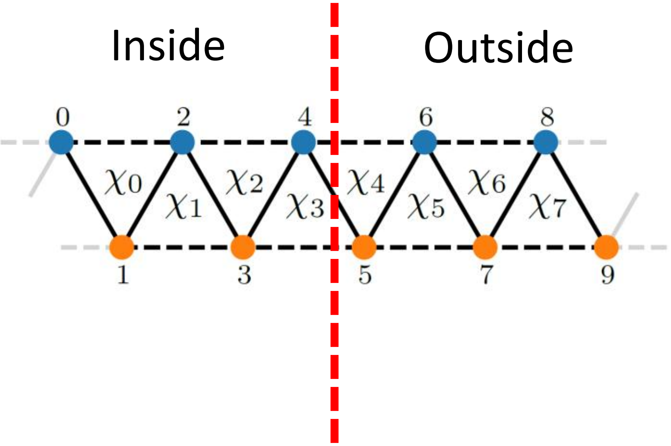
Determine *T*-dependence: $\lambda = a(T^b - c)$

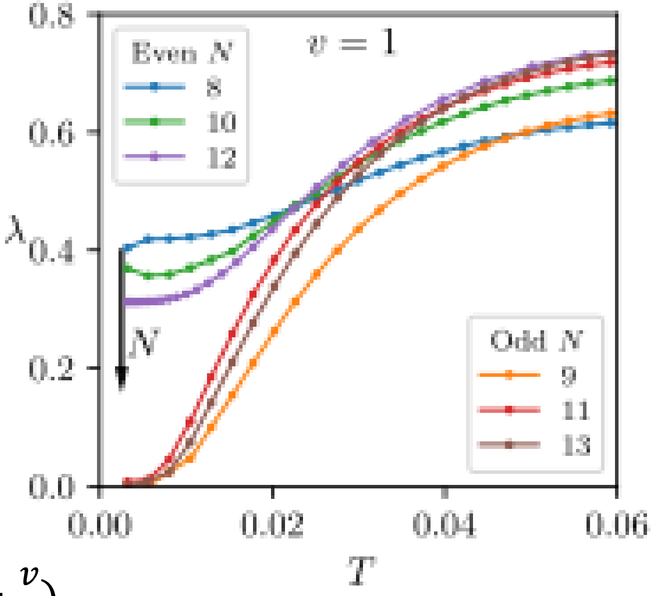


Small v

Large v

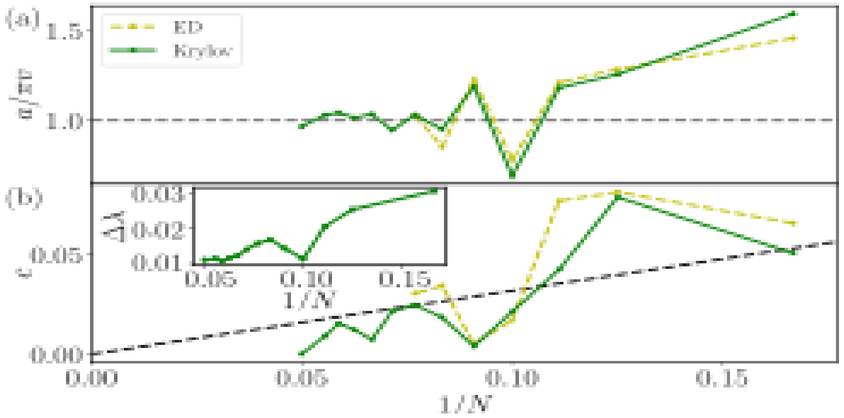






Assume:

$\lambda = a(T - c)$



$a = 2\pi J \ (J = \frac{v}{2})$

Quantum simulation

So far: theory + phenomenology

→ Now: simulate BH directly on quantum hardware

It is possible to simulate algorithmically time evolution of a BH.

- Dispersion relation
- Hawking radiation
- Chaotic evolutions

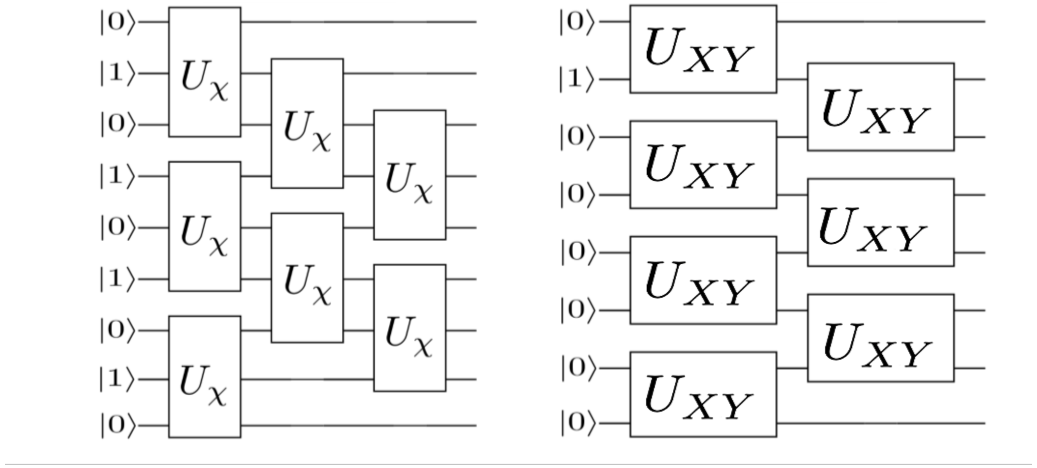
Black hole:

- XY model: Rindler coordinates -> already implemented
- Chiral model: GP coordinates ->numerics + near-term circuits

Quantum simulation

Decomposition:

$$U(t) \sim e^{-iuH_{XY}t} e^{-ivH_{\chi}t}$$

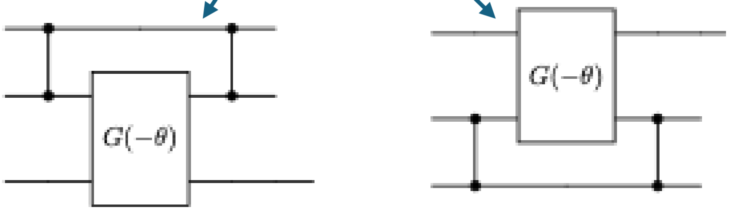


2-qubit gates (q-IBM native, easy)

$$e^{-iuH_{XY}t} = U_{XY}(\theta_u)$$

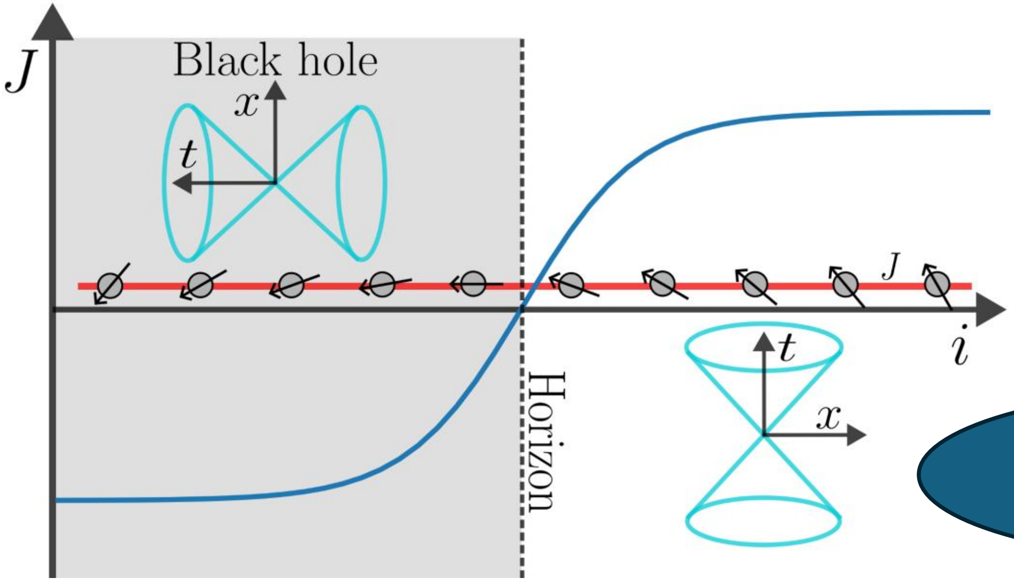
3-qubit gates (more complex)

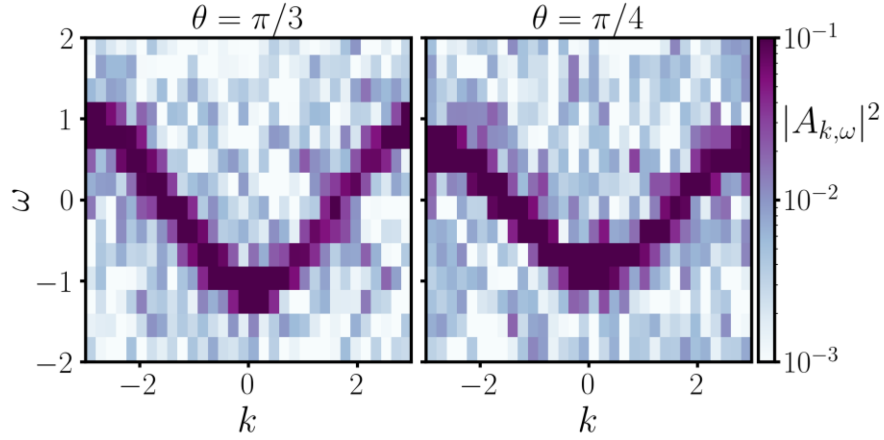
$$e^{-ivH_{\chi}t} = U^{(1)}U^{(3)} = U_{\chi}(\theta_v)$$



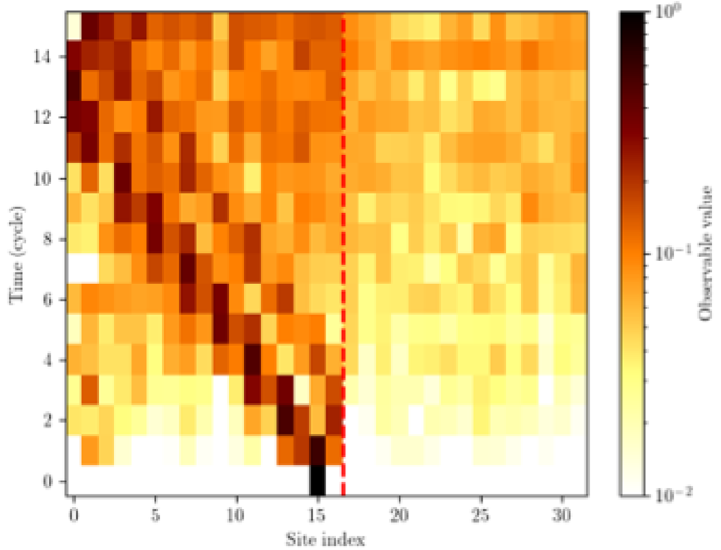
Quantum simulation

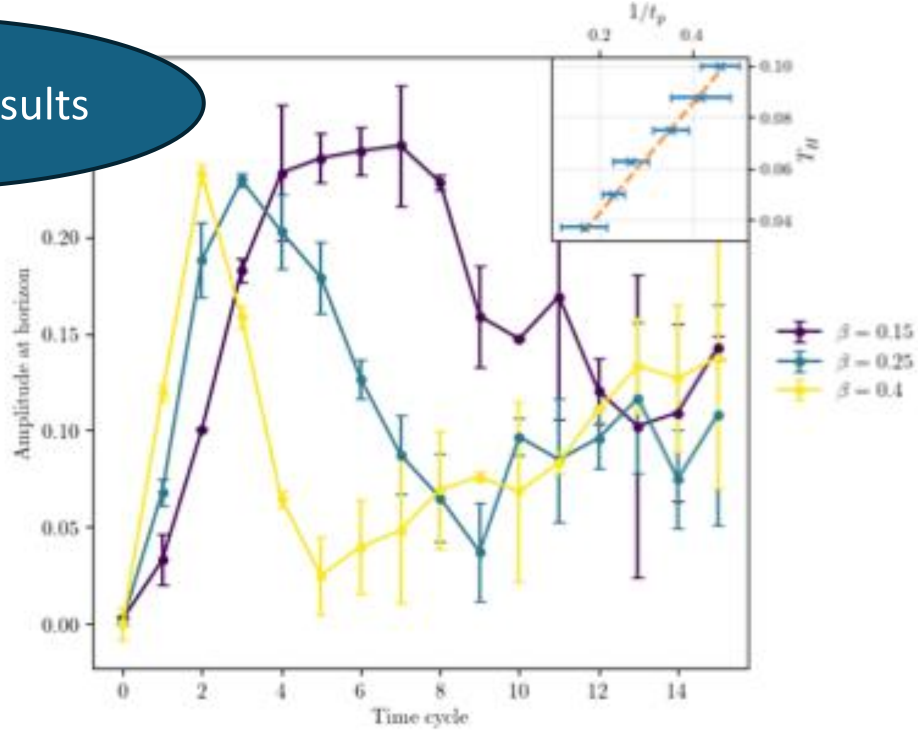
"XY" Black Hole





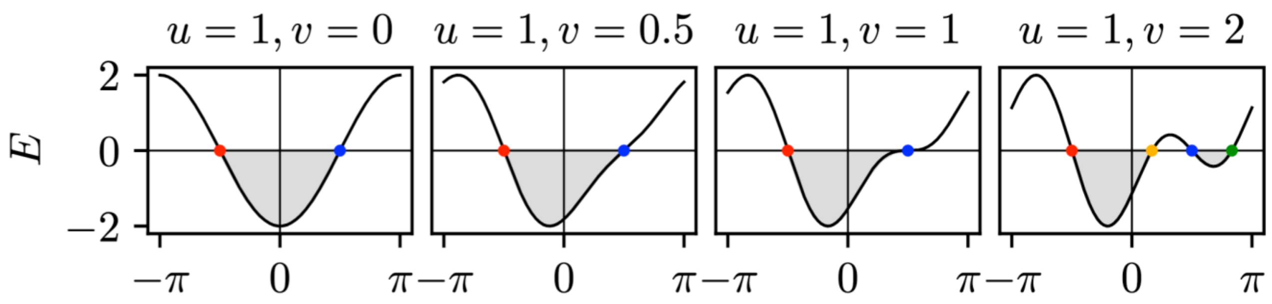
Experimental results





Quantum simulation

“Chiral” Black Hole



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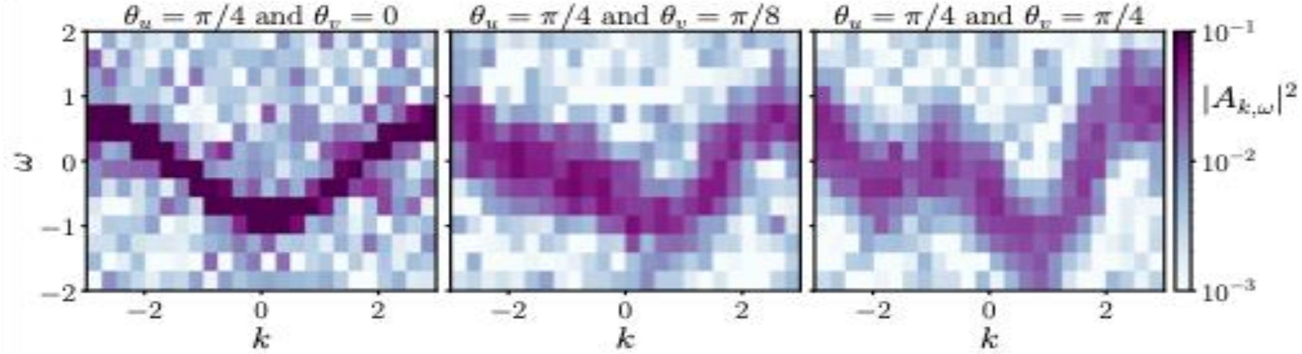
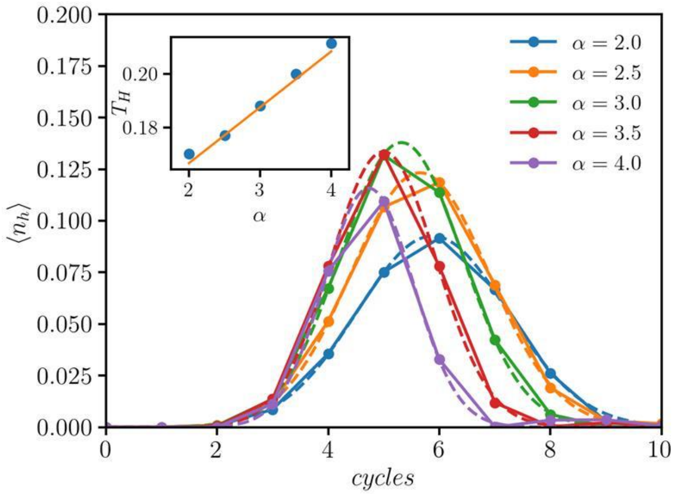
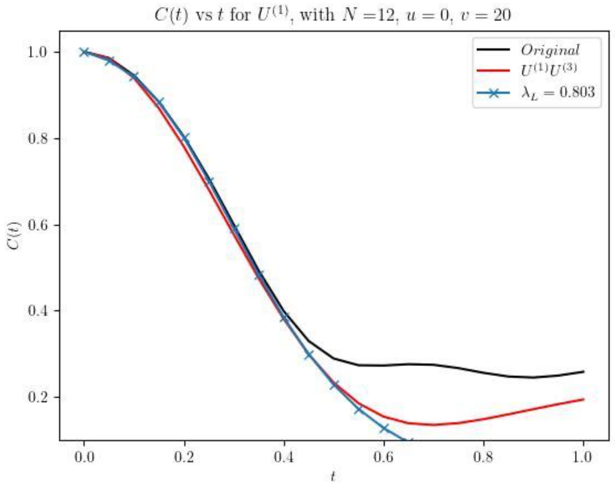


Numerical results





The full picture

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$$T_H = \frac{v'(x_h)}{2\pi} = \frac{\alpha\beta}{2\pi}$$

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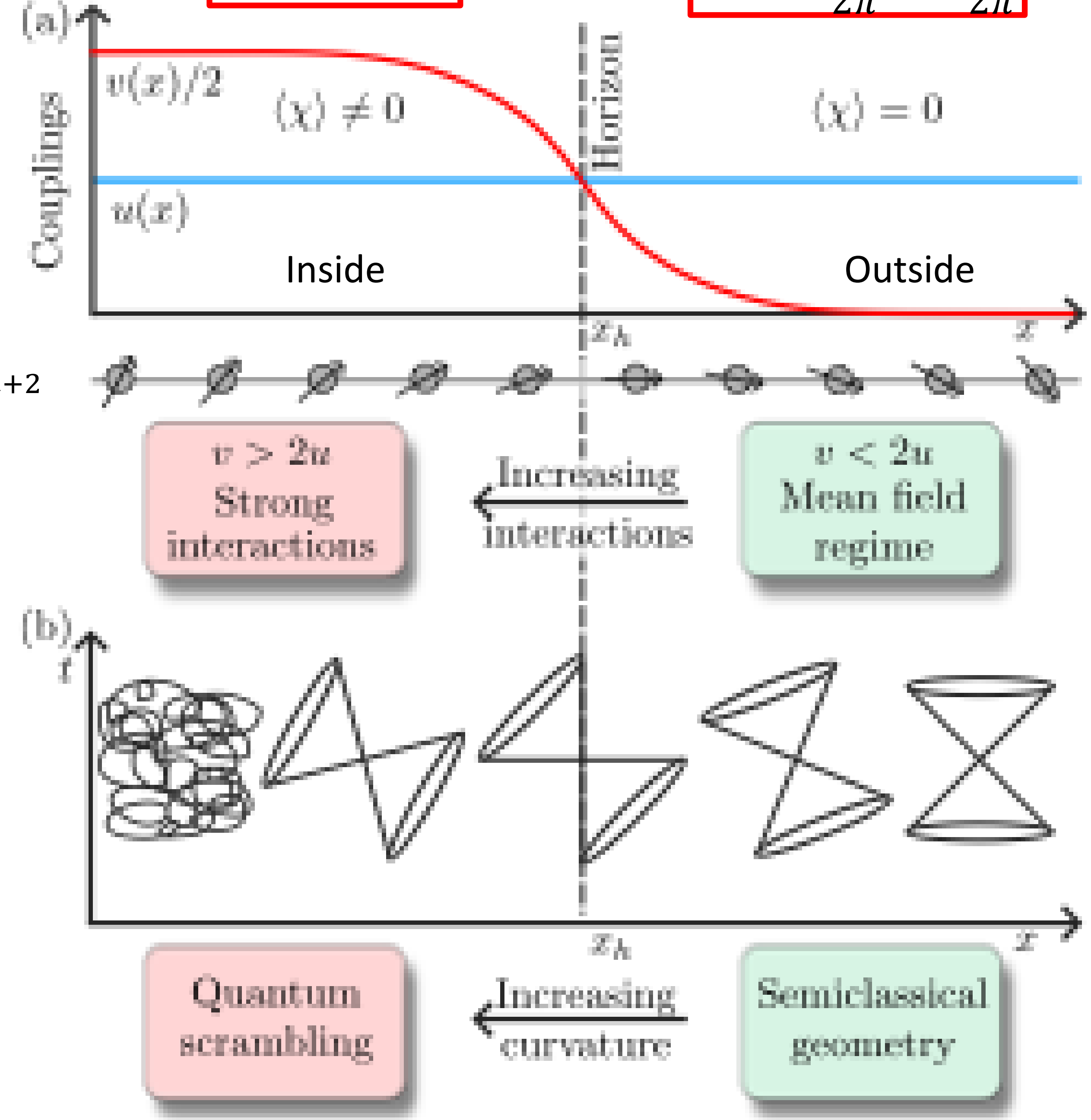
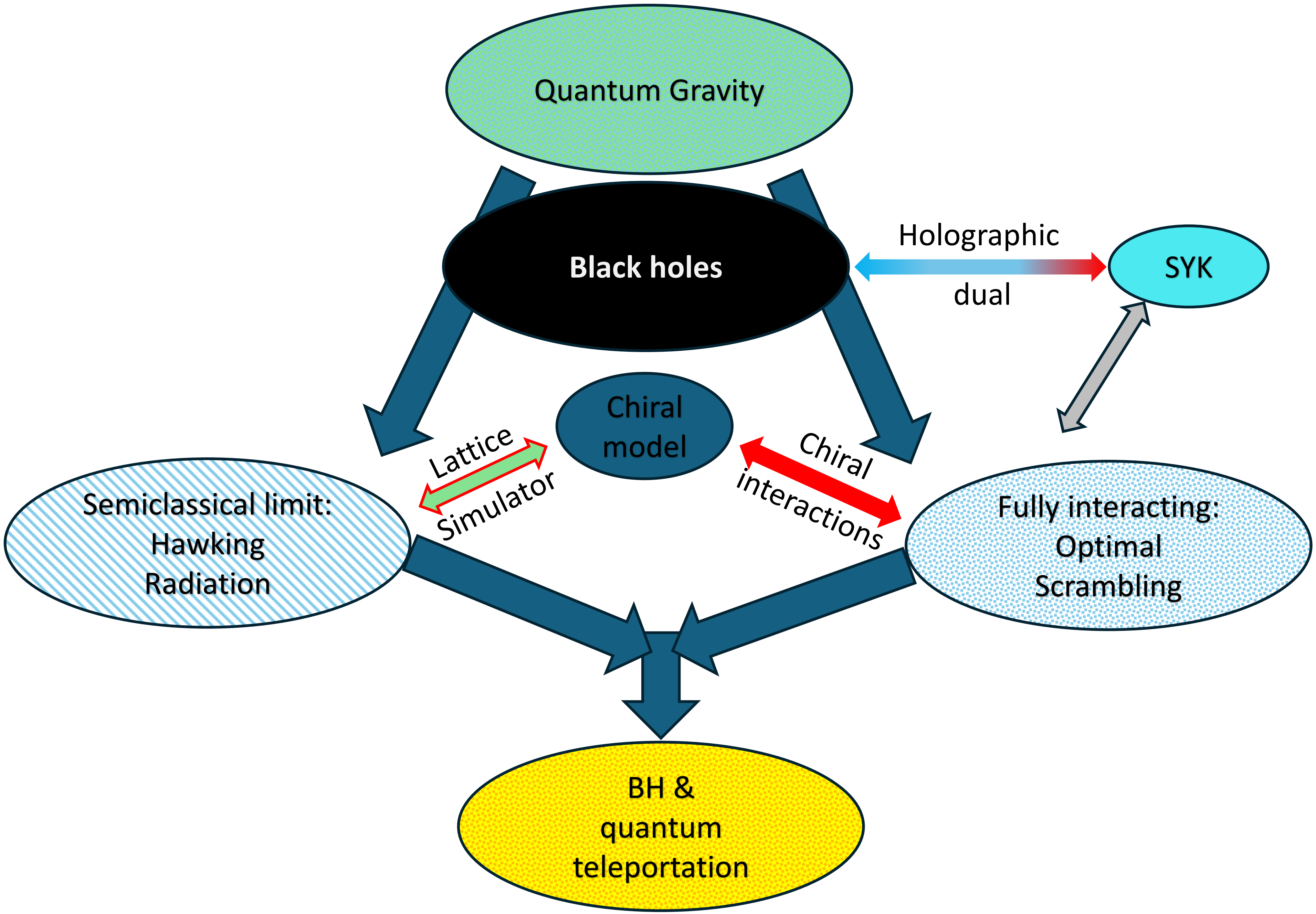


A simple chiral spin-chain model unifies two important quantum aspects of black holes

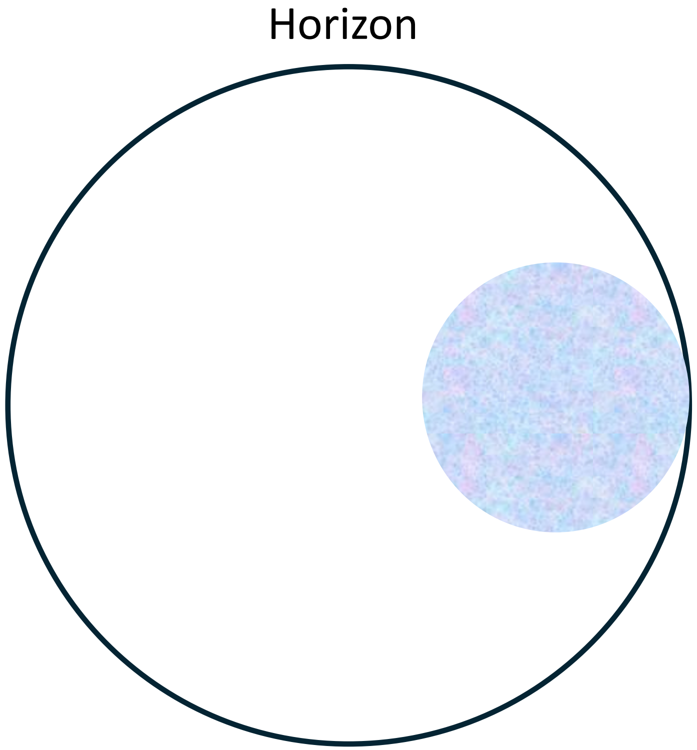
Toy model that can be test in the lab



Quantum Gravity
Black holes
Holographic
dual
SYK
Chiral
model
Lattice
Simulator
Chiral
interactions
Semiclassical limit:
Hawking
Radiation
Fully interacting:
Optimal
Scrambling
BH &
quantum
teleportation

Information, radiation and Bob

During black hole evaporation quantum information escapes through the horizon.



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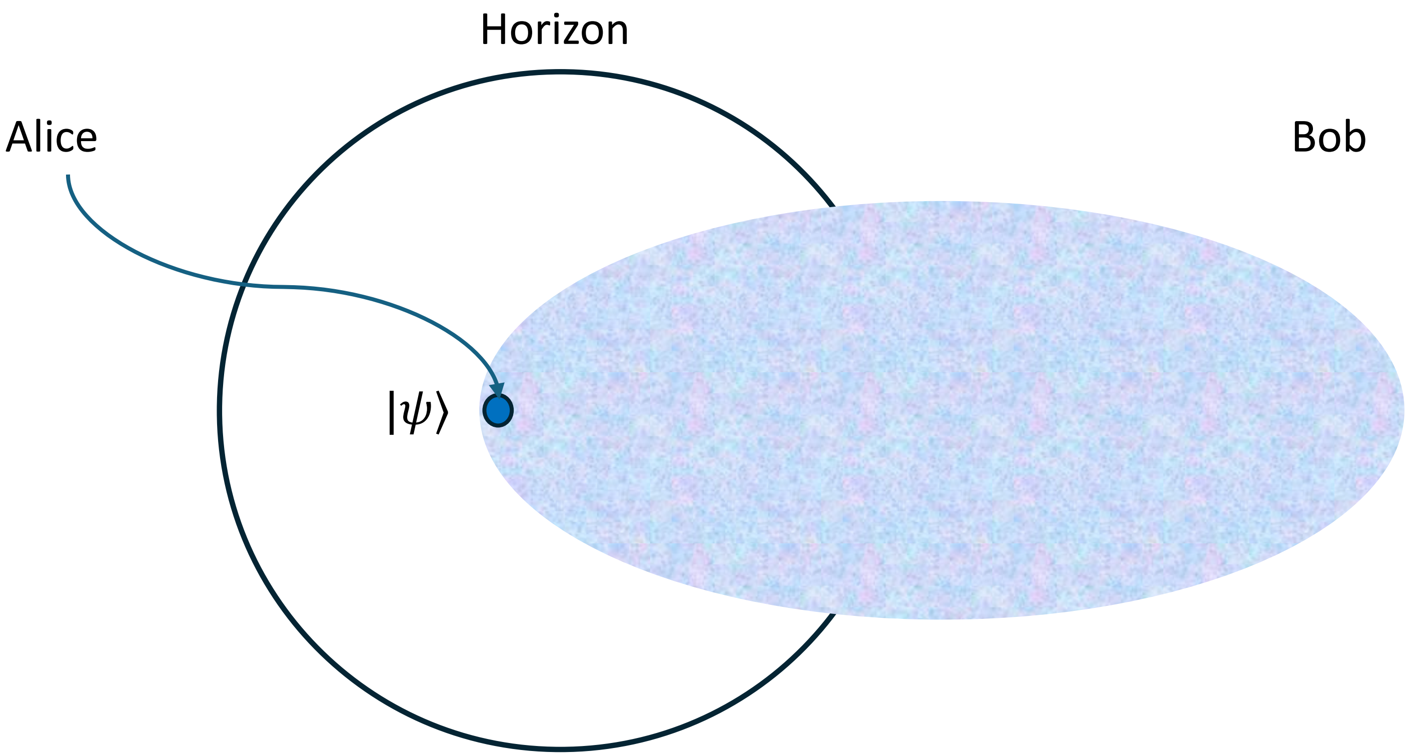

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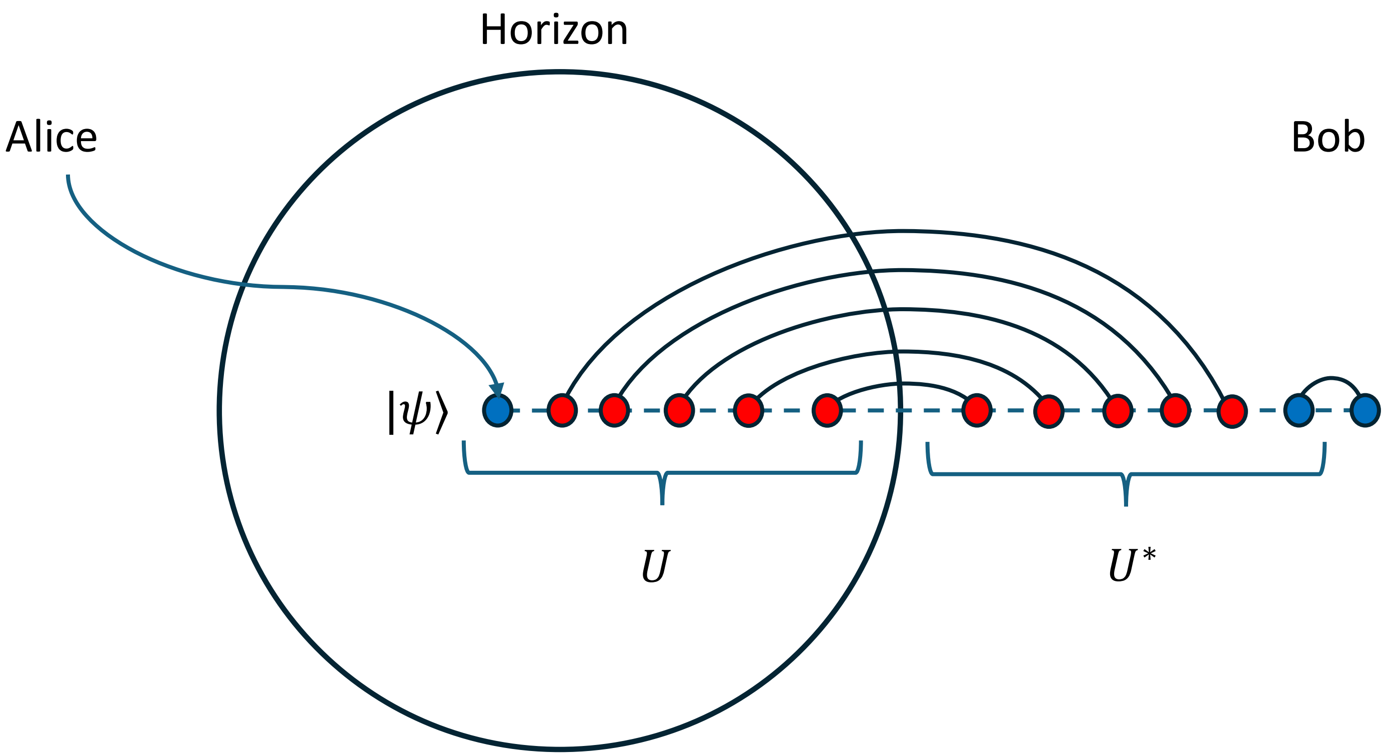

Information, radiation and Bob

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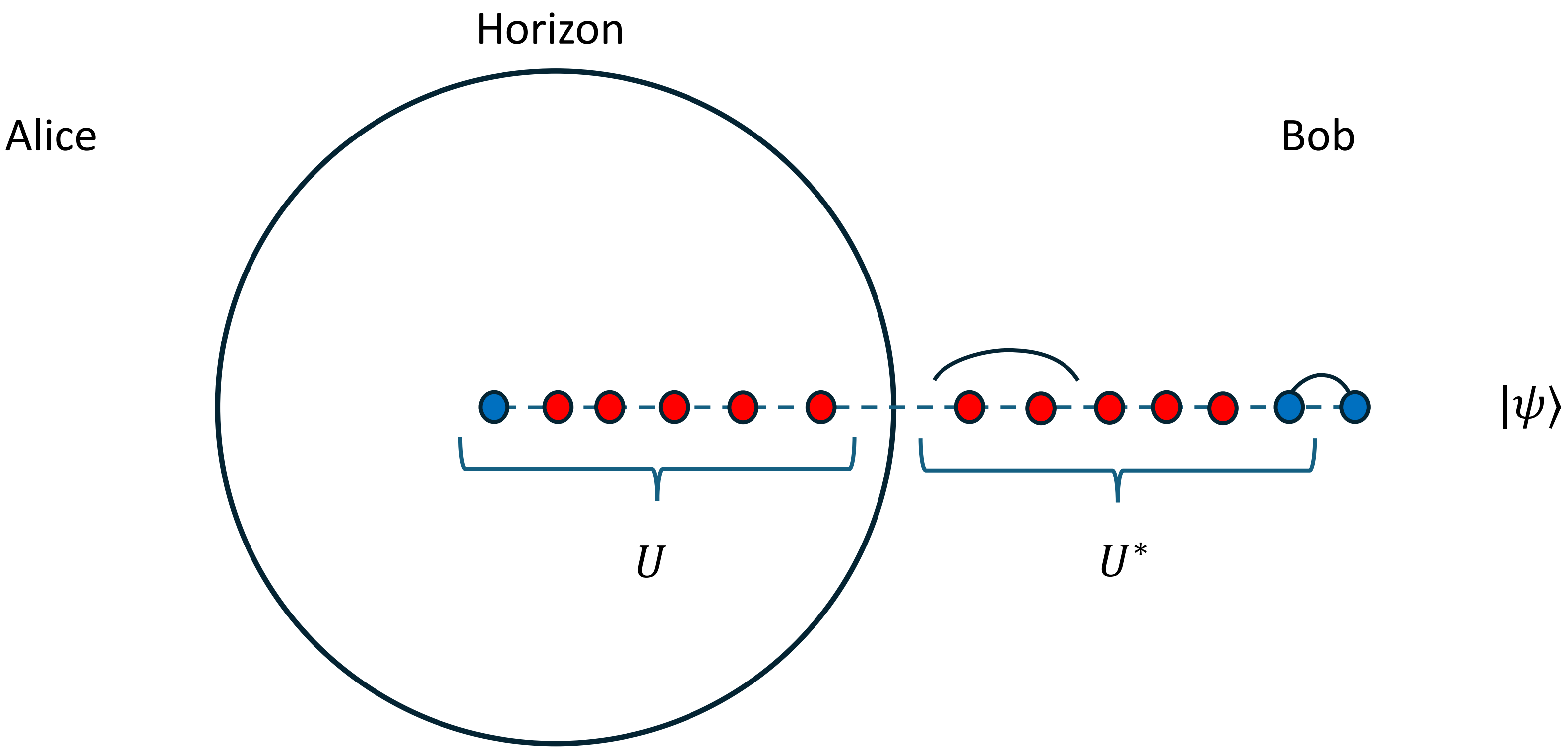
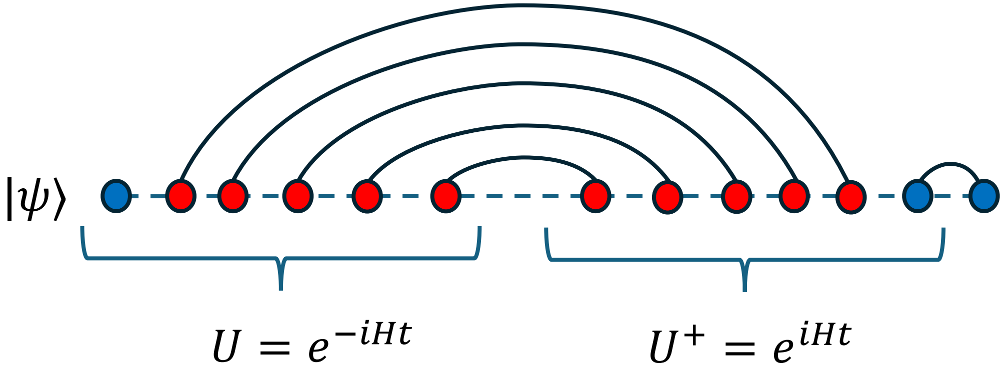
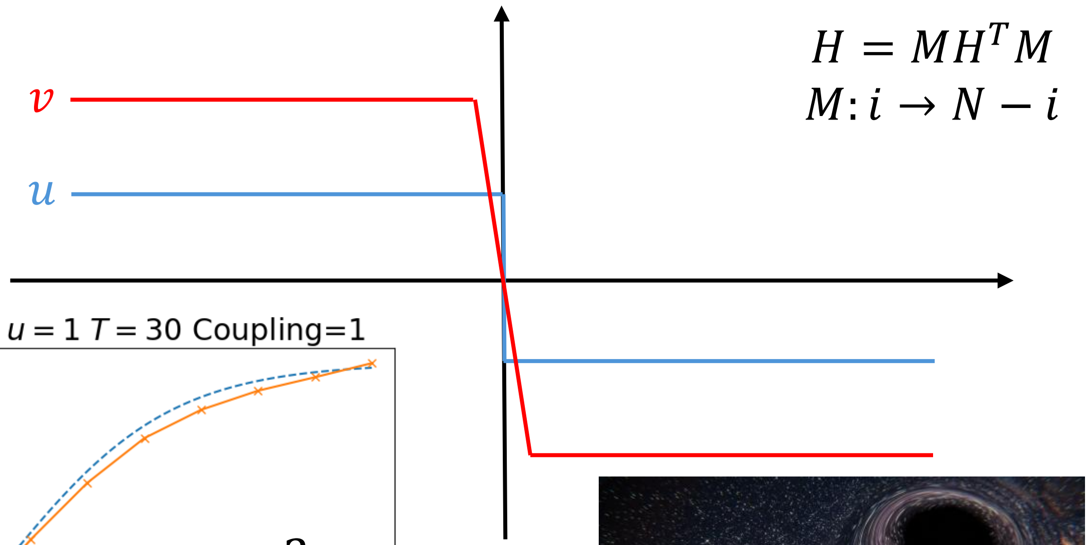


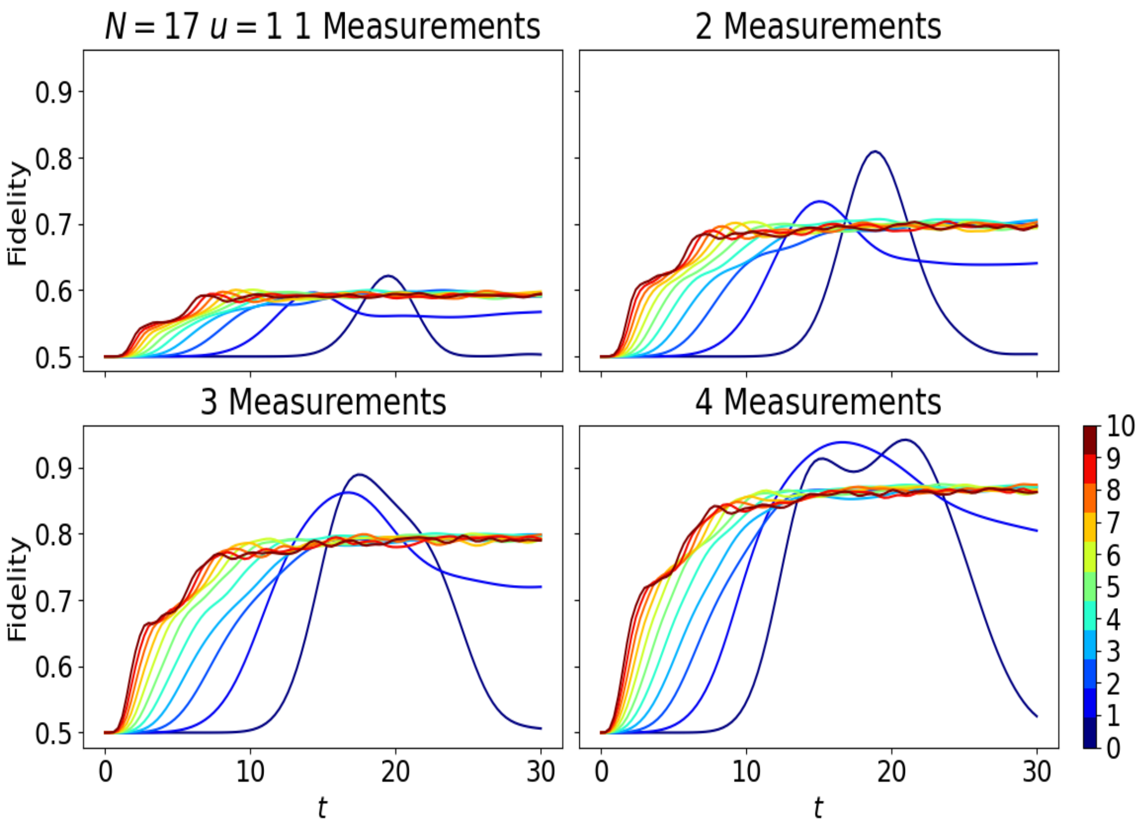
Information, radiation and Bob

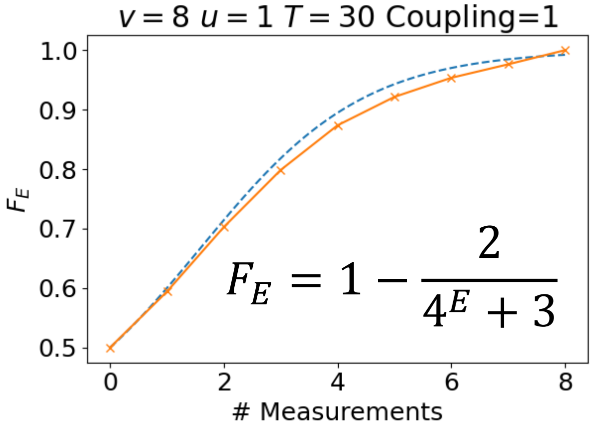
Chiral spin chain modelling of Hayden-Preskill Protocol.

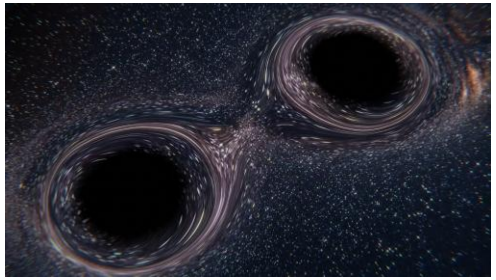
$$H = -\frac{u}{2}\sum_n \left(S_n^x S_{n+1}^x + S_n^y S_{n+1}^y\right) + \frac{v}{4}\sum_n S_n \cdot S_{n+1} \times S_{n+2}$$











Conclusions & Outlook

Chiral spin-chain modelling:

- A controllable model that captures two key quantum black hole features in one platform:

  Hawking-like radiation & strong quantum information scrambling

- Hayden-Preskill protocol
- Single model simulating **fundamental** quantum black hole and its **semiclassical** limit.

Future:

- Compare fundamental and semiclassical (theory of islands, information loss etc)
- Model black hole evaporation
- Encode/decode quantum information with deterministic optimal scrambling