Title: Firewalls vs. Scrambling

Speakers: Beni Yoshida

Collection: Quantum Matter: Emergence & Entanglement 3

Date: April 23, 2019 - 11:30 AM

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Abstract: Recently we pointed out that the black hole interior operators can be reconstructed by using the Hayden-Preskill recovery protocols. Building on this observation, we propose a resolution of the firewall problem by presenting a state-independent reconstruction of interior operators. Our construction avoids the non-locality problem which plagued the "A=RB" or "ER=EPR" proposals. We show that the gravitational backreaction by the infalling observer, who simply falls into a black hole, disentangles the outgoing mode from the early radiation. The infalling observer crosses the horizon smoothly and sees quantum entanglement between the outgoing mode and the interior mode which is distinct from the originally entangled qubit. Namely, any quantum operation on the early radiation cannot influence the experience of the infalling observer as description of the interior mode does not involve the early radiation at all. We also argue that verification of entanglement by the outside observer does not create a firewall. Instead it will perform the Hayden-Preskill recovery which saves an infalling observer from crossing the horizon.

Taming Quantum Entanglement

Perimeter Institute 4/23/19

MPA Fisher

- Classical system: Entropy always increases (2nd law of thermo)
- Isolated Quantum system: Entanglement entropy (= thermal entropy)
- Entanglement entropy always grows

  "Disorder always reigns"

How to control (entanglement) entropy growth?

Via Measurements – disentangle

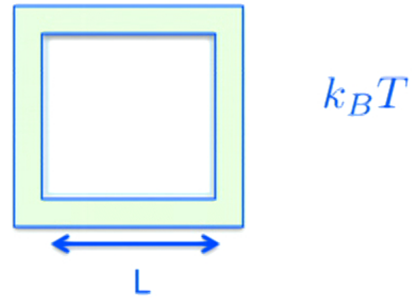
Measurement driven entanglement transition

Entropy: Thermal “versus” entanglement

Thermal entropy:

Number of states,
extensive for T>0

$$S_{th} = -Tr[\hat{\rho}_{th} \ln \hat{\rho}_{th}] \sim L^d$$

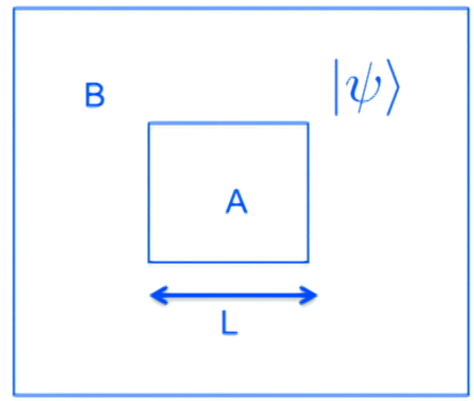


Entanglement Entropy: Single eigenstate

$$\hat{\mathcal{H}}|\psi\rangle = E|\psi\rangle$$
$$\hat{\rho} = |\psi\rangle\langle\psi|$$
$$\hat{\rho}_A = Tr_B(\hat{\rho})$$

Entanglement entropy:

$$S_A(L) = -Tr_A(\hat{\rho}_A \ln \hat{\rho}_A)$$



ETH: Equivalence of Thermal and entanglement entropies

$$S_A/L^d = S_{th}/L^d; \quad L \to \infty$$

Thermal entropy is state counting, entanglement entropy
depends on the properties of the states!

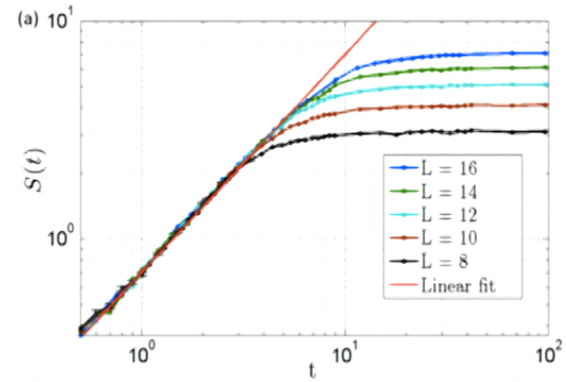
Entanglement Dynamics (i.e. Growth)

1) Quantum Quench

Evolve unentangled initial state w/ Hamiltonian

$$H = \sum_{i=1}^{L} \left(g\sigma_i^x + h\sigma_i^z + J\sigma_i^z\sigma_{i+1}^z \right)$$

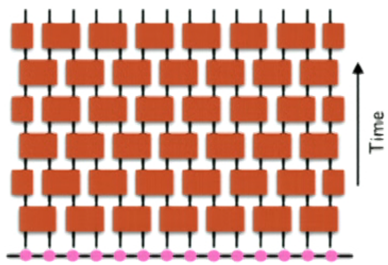
Entanglement spreads ballistically, even though energy diffuses

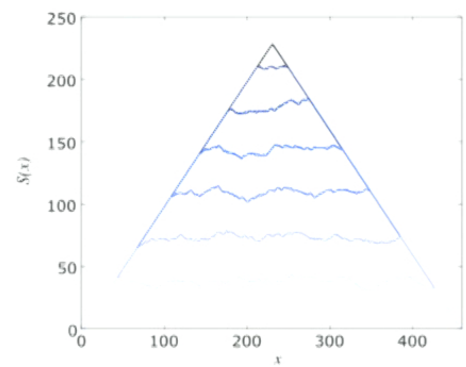


Half-cut entanglement entropy   Kim + Huse (2013)

2) Unitary Dynamics with no energy conservation

Quantum circuit: evolve Qubits w/ (random) unitary gates
Initial state: unentangled product state
Entanglement spreads ballistically, into maximal entropy state

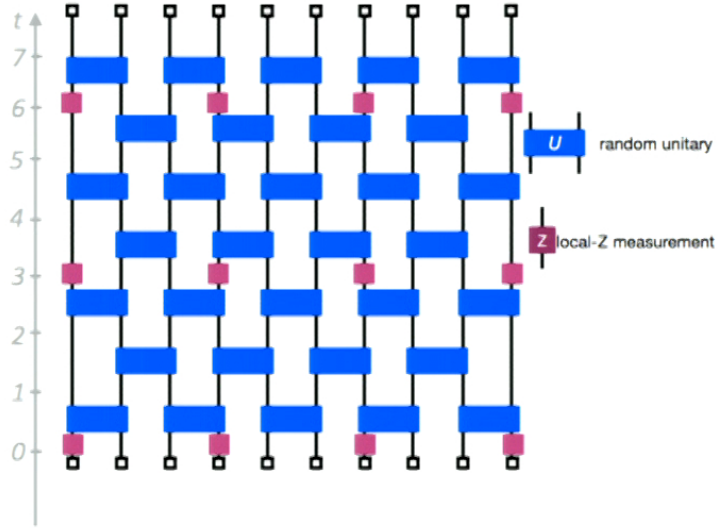




Nahum, Ruhman, Vijay, Haah (2017)

How to control (entanglement) entropy growth?

Via Measurements

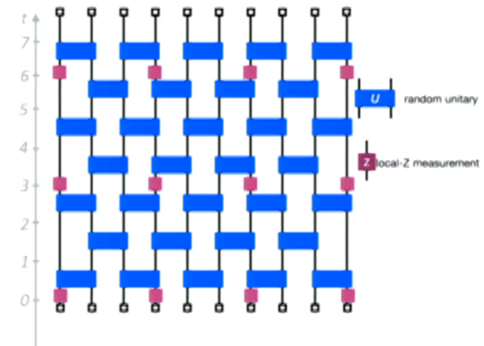


Measurement driven entanglement transition

Taming entanglement w/ ***measurements***

"Hybrid Quantum Circuit" w/ both unitary and measurement gates

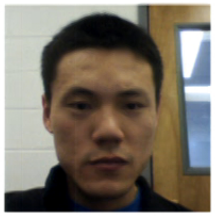
- Unitary evolution induces entanglement growth
- Measurements induce disentanglement



Explore competition between unitary evolution and measurements

- Li, Chen, MPAF (2018/2019)
- Skinner, Ruhman, Nahum (2018)
- Chan, Nandkishore, Pretko, Smith (2018)

Yaodong Li



Xiao Chen

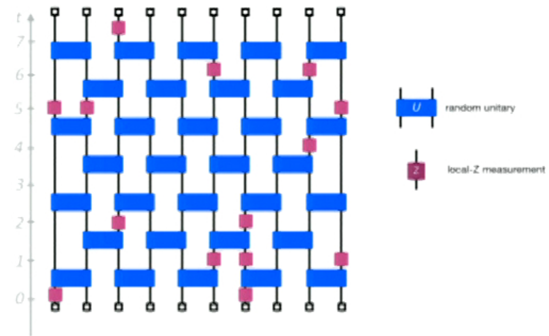
“Hybrid” Quantum Circuit

Quantum circuit w/ unitary gates and projective measurements

2-Qubit Unitaries:

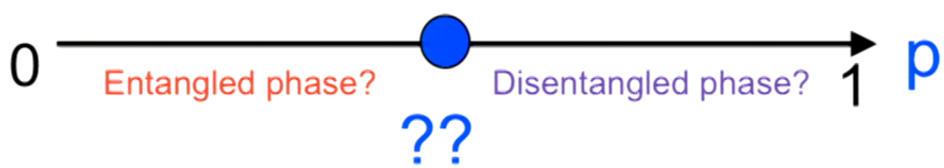
1-Qubit Measurements

Make measurements with probability, p

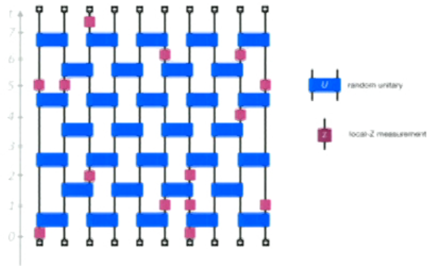


Phase Diagram??

- p=0; No measurement, Volume law entanglement
- p=1; Measure every Qubit, no entanglement (area law)
- Transition at $p=p_c$??



Numerics on Hybrid Circuits?



Direct simulation very challenging for large L
(since the Hilbert space grows as 2^{L})

Employ Quantum information "technology":

- **"Stabilizers"** to encode special **"codeword"** quantum states
- Evolve stabilizers with **Clifford unitaries**
- Measurements of Z-component of spin

Gottesman-Knill Theorem: Such quantum circuits can be efficiently simulated on a classical computer (accessing >500 Qubits, say)

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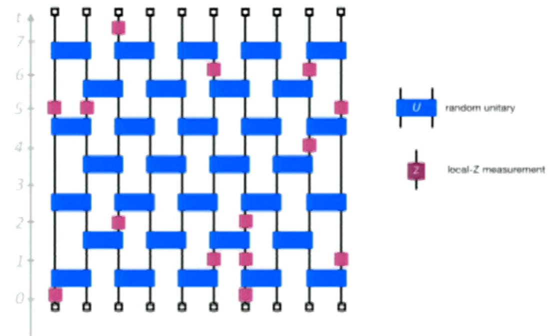

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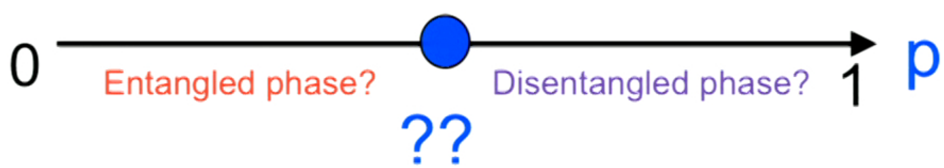

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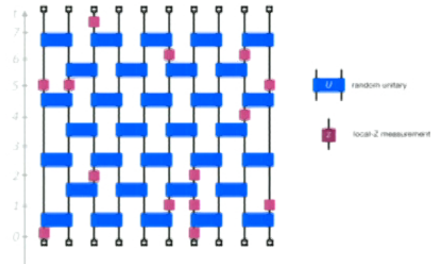

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Pauli Strings, Stabilizers and Codewords

Pauli operators for a single Qubit $\{1, \sigma_x, \sigma_y, \sigma_z\} \rightarrow \{1, X, Y, Z\}$

Pauli String Operators for L Qubits: $g = 1_1 Y_2 X_3 I_4 X_5 \ldots Z_L$

g

Stabilizers and "codewords":

$|\psi\rangle$ is a "codeword" state if "stabilized" by L independent, commuting Pauli string operators $g_j|\psi\rangle = |\psi\rangle$

Example 1: $|\psi\rangle = |00,\ldots 0\rangle$ is stabilized by $g_j = Z_j$

Example 2: $|\psi\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$ is stabilized by $g_1 = Z_1 Z_2$

$g_2 = X_1 X_2$

Clifford Unitaries/Dynamics

Clifford unitaries take Pauli string operators
into other Pauli string operators

$$\hat{U}\hat{g}U^{\dagger} = \hat{g}'$$

Unitary evolution of a "codeword" state: follow the dynamics of the L stabilizers:

If $|\psi\rangle$ stabilized by g_j then $|\psi'\rangle = U|\psi\rangle$ stabilized by $g_j' = U g_j U^{\dagger}$

Measurements and Stabilizers

Consider a projective measurement of a codeword $g_j|\psi\rangle = |\psi\rangle$

$$|\psi\rangle \rightarrow P_{\pm}|\psi\rangle \qquad P_{\pm} = (1 \pm Z_j)/2$$

Measuring Z-component of j^{th} qubit

If Z_j anticommutes with g_1 and commutes with $g_2,...,g_L$ (say) the stabilizers are modified under the measurement as:

$$\{g_1, g_2, ..., g_L\} \rightarrow \{\pm Z_j, g_2, ..., g_L\}$$

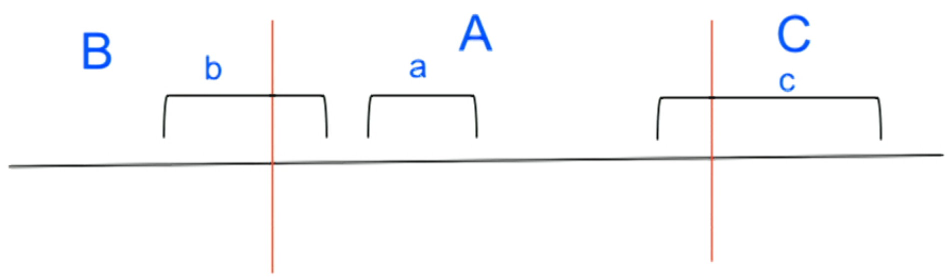
when the result of the measurement is ± 1

Entanglement and Stabilizers

Stabilizer length length=6

$$g = 1_1 1_2 X_3 1_4 Z_5 Y_6 1_7 Z_8 1_9 1_{10}$$

Entanglement entropy S_A



Denote number of stabilizers starting in A and ending in A,B,C as n_a, n_b, n_c

Entanglement: $$S_A = \frac{(n_b + n_c)}{2} \log(2)$$

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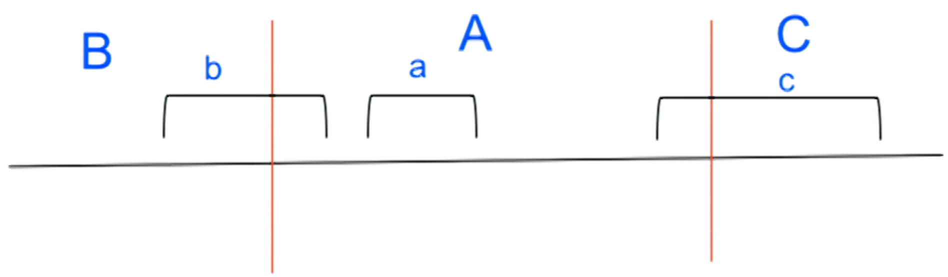

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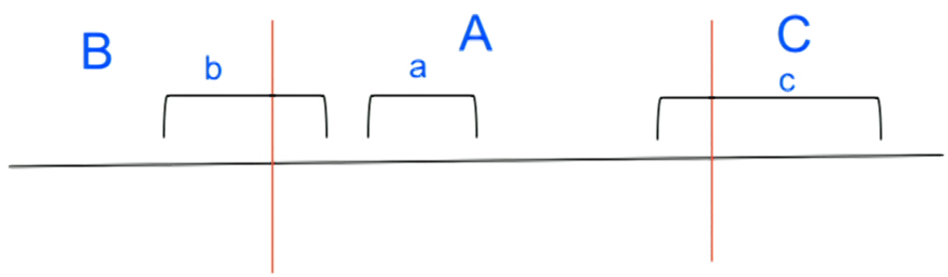

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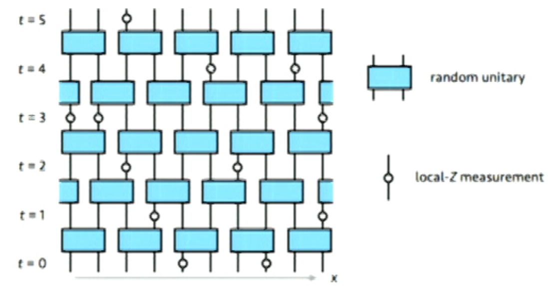
Clifford Circuit: Simulable

All 2-Qubit unitaries taken from the Clifford group:

$$|\psi_t\rangle \rightarrow |\psi_{t+1}\rangle = U|\psi_t\rangle$$



All single Qubit measurements taken from Pauli group

$$|\psi\rangle \rightarrow \frac{P_\pm|\psi\rangle}{\sqrt{p_\pm}} \qquad P_\pm = \tfrac{1}{2}(1 \pm Z)$$

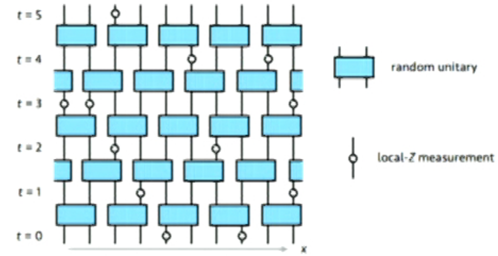
Make measurements with probability p

Simulate Clifford quantum circuits on classical computer (accessing >500 Qubits)

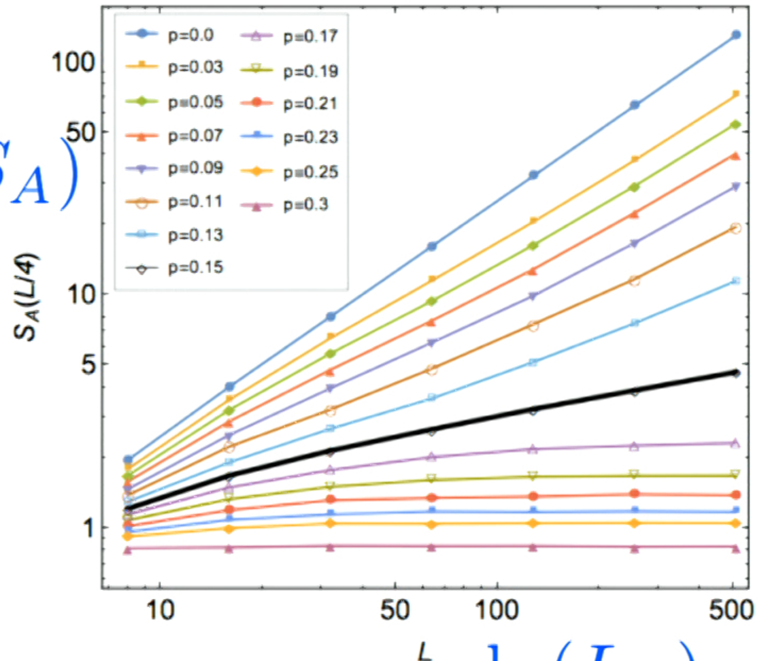
(Comment: For Clifford circuits, all Renyi entropies are equal)

Entanglement Entropy

Long-time steady-state of Clifford circuit



$\ln(S_A)$



$\ln(L_A)$

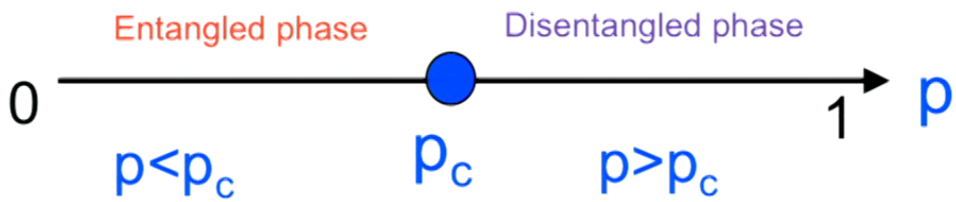
Volume law entanglement

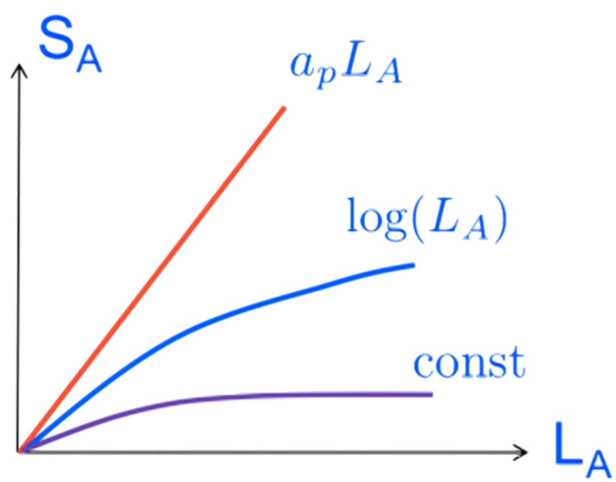
Increasing measurement rate

Area law entanglement

Entanglement Transition

Li, Chen, MPAF (2018)

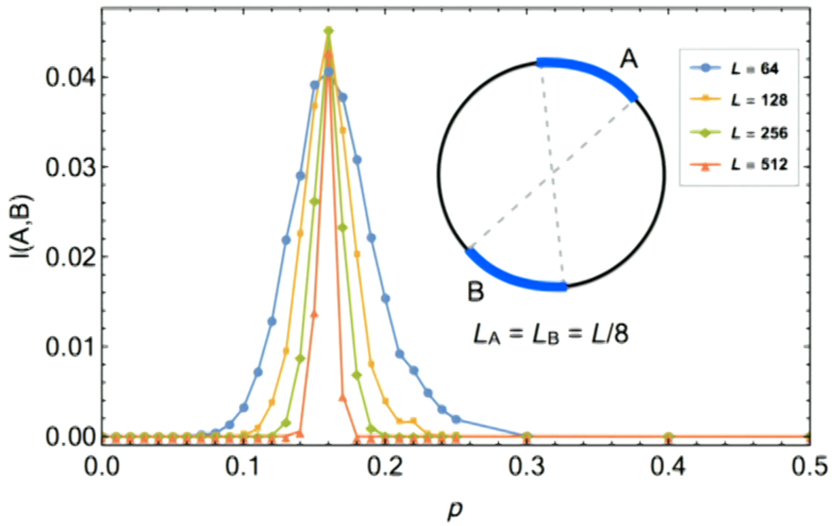




$$S_A(L_A) \sim \begin{cases} a_p L_A; & p < p_c \\ \log(L_A); & p = p_c \\ \text{const}; & p > p_c \end{cases}$$

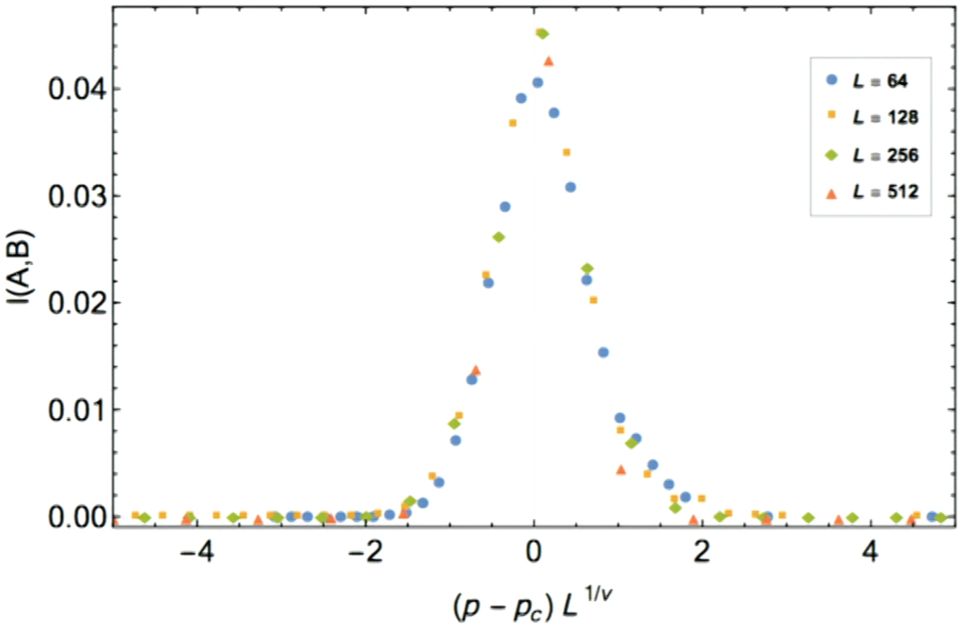
Mutual Information: Locates transition

$$\mathcal{I}_{AB} = S_A + S_B - S_{AB}$$



$$\mathcal{I}_{AB}(L \to \infty) = \begin{cases} 0; & p \neq p_c \\ \text{const}; & p = p_c \end{cases}$$

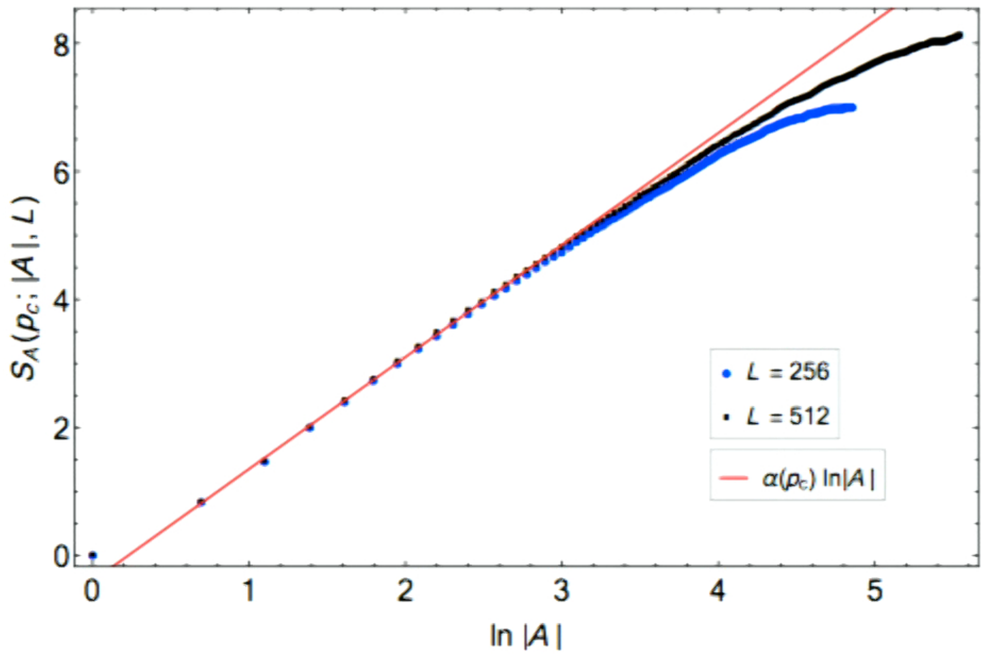
Data Collapse: Mutual Information



$$\nu \approx 1.4$$

Log Scaling at Criticality (p=p$_c$)

$$S_A(L_A) = \alpha_c \log(L_A) \qquad \alpha_c \approx 1.6$$

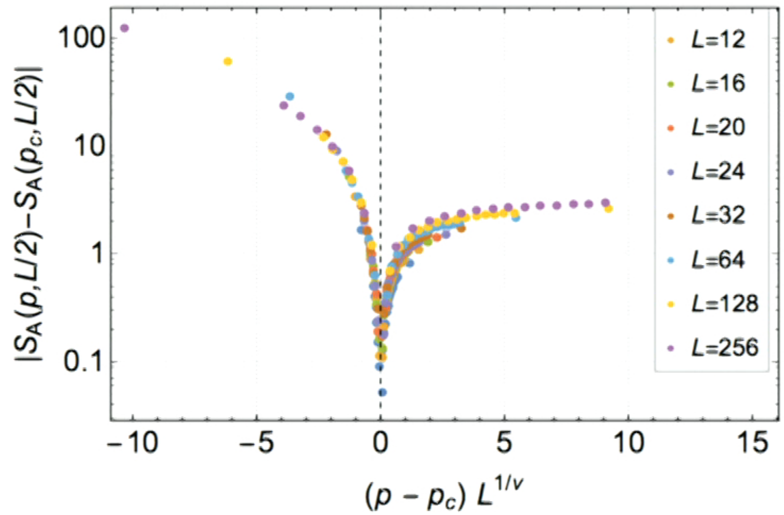


"Log" Scaling Collapse

$$S_A(p, L_A) = A \log L_A + G(L_A/\xi)$$

$$\xi \sim |p - p_c|^{-\nu} \qquad \nu \approx 1.4$$

$$S_A(p, L_A) - S_A(p_c, L_A) = \tilde{G}(L_A/\xi)$$



Conformal Symmetry at criticality (p=p$_c$)

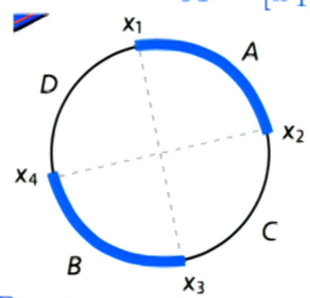
If have underlying conformal field theory, then mutual information depends only on the cross ratio

$$I_{AB} = f(\eta)$$

$$\eta \equiv \frac{x_{12}x_{34}}{x_{13}x_{24}}$$

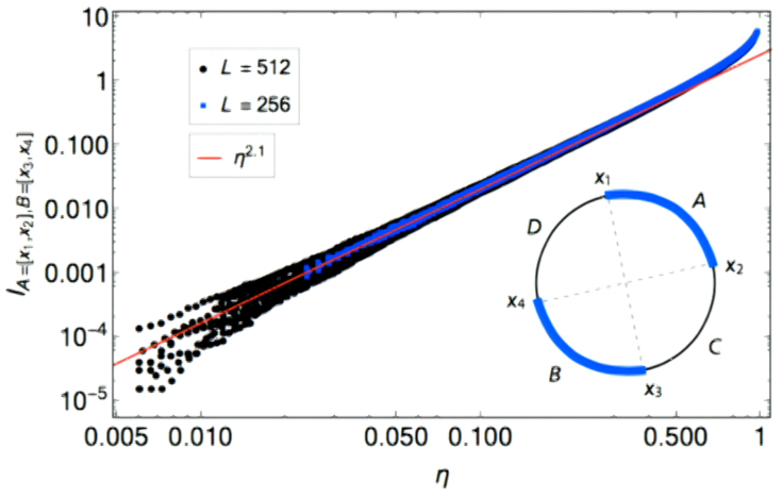
$$x_{ij} = \frac{L}{\pi}\sin\left(\frac{\pi}{L}|x_i - x_j|\right)$$

$A = [x_1, x_2]$



$B = [x_3, x_4]$

I_{AB}



η

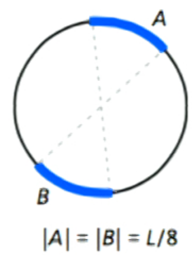
Correlation functions

Mutual information upper bound for all correlation functions
$$I_{AB} \geq \frac{1}{2}\frac{|\langle \mathcal{O}_A \mathcal{O}_B \rangle_c|^2}{||\mathcal{O}_A||^2||\mathcal{O}_B||^2}$$

Averaged squared correlation function (not equal to expectation value of any operator)
$$\overline{|\langle \mathcal{O}_A \mathcal{O}_B \rangle_c|^2} \neq Tr\big(\rho \mathcal{O}_{A\cup B}\big)$$

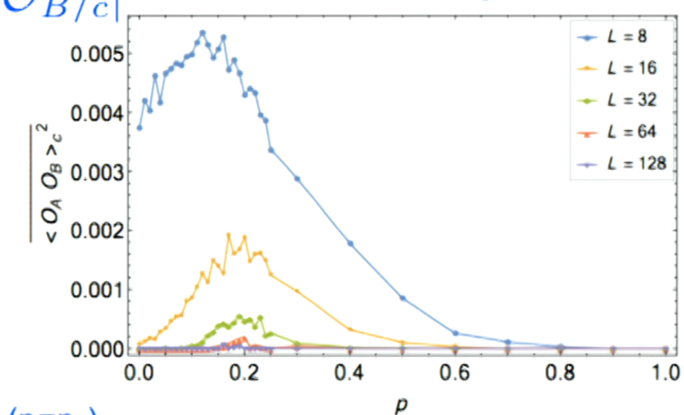
$$\mathcal{O}_A = \sum_{x\in A} Z_x$$

$$\mathcal{O}_B = \sum_{x\in B} Z_x$$



$$\overline{|\langle \mathcal{O}_A \mathcal{O}_B \rangle_c|^2}$$

Peak at p=p$_c$



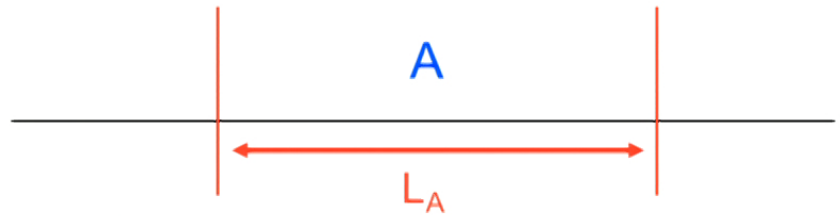
p

Consistent w/ power law decay at criticality (p=p$_c$)

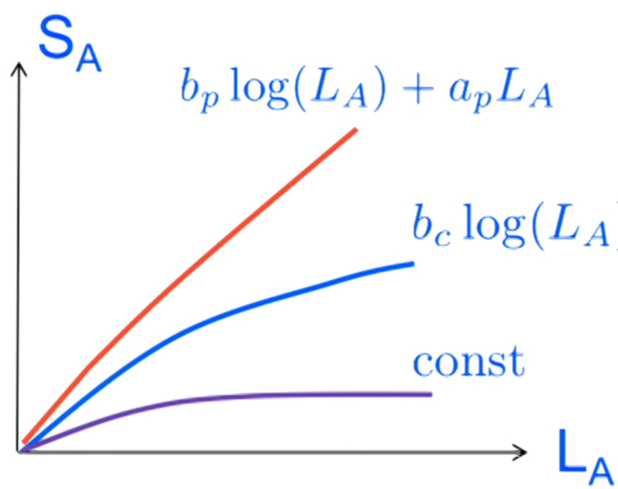
$$\overline{|\langle \mathcal{O}_A \mathcal{O}_B \rangle_c|^2} \sim |x_A - x_B|^{-\gamma}$$

“Hidden” log inside volume-law phase

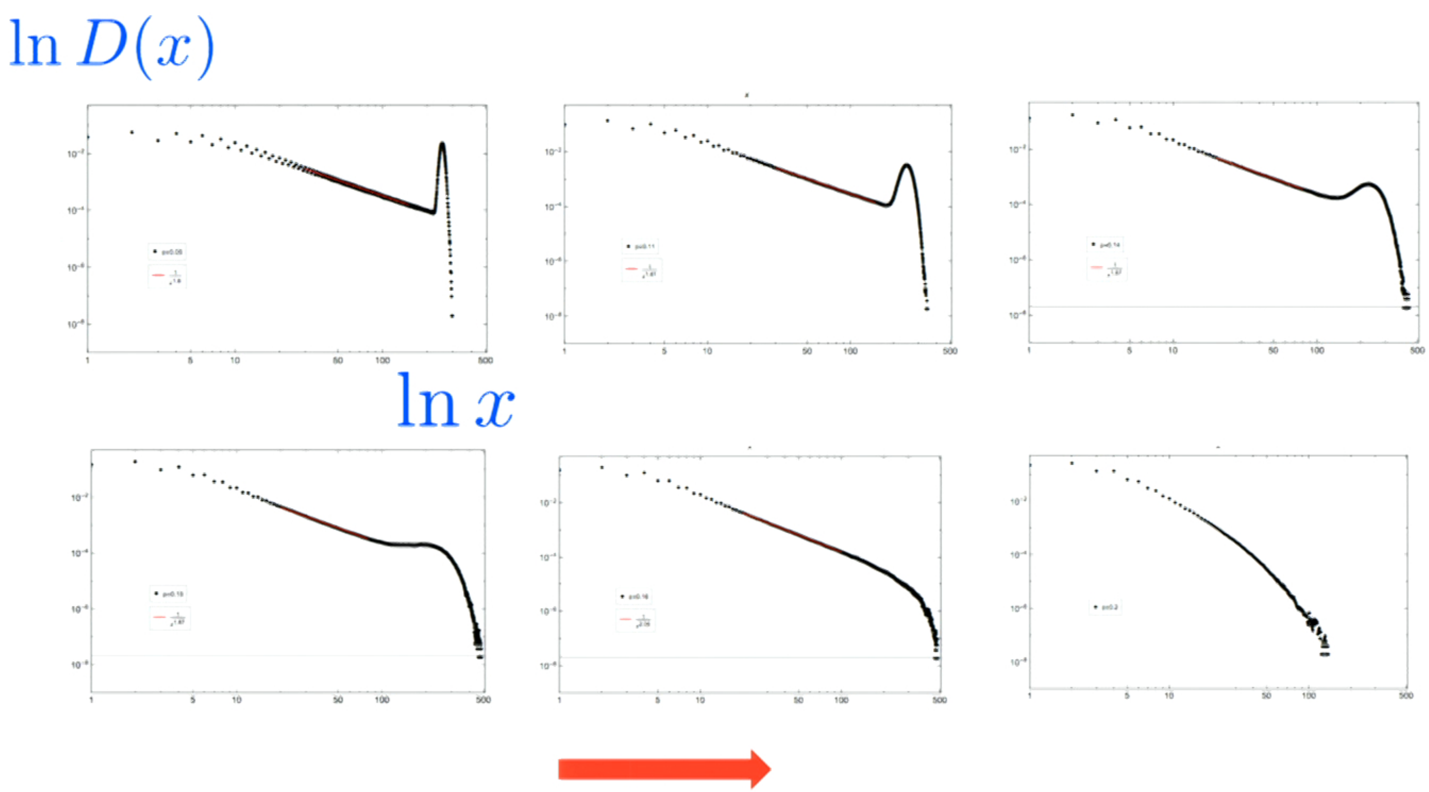
Entanglement entropy:



$$S_A(L_A) \approx \begin{cases} b_p \log(L_A) + a_p L_A; & p < p_c \\ b_c \log(L_A); & p = p_c \\ \log(\xi); & p > p_c \end{cases}$$



“Hidden log” inside volume law phase: Stabilizer length distribution function



Increasing measurement rate

Stabilizer length distribution function

$$D(x,L) \approx \begin{cases} \frac{b_p}{x^2} + a_p \delta(x - L/2); & p < p_c \\ \frac{b_c}{x^2}; & p = p_c \\ \frac{e^{-x/\xi}}{x^2}; & p > p_c \end{cases}$$

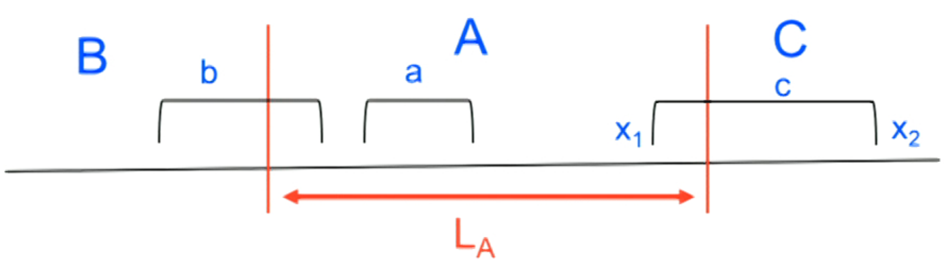
Long stabilizers + power law

Power law

Short stabilizers

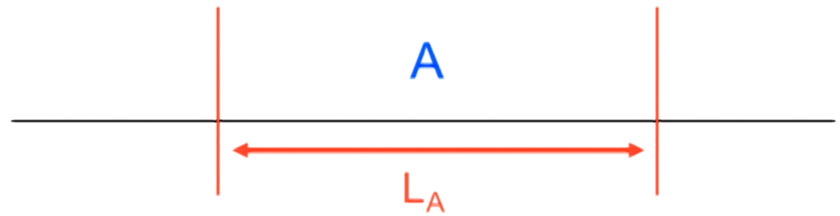
Entanglement entropy follows: $S_A = \frac{(n_b + n_c)}{2} \log(2)$

$$S_A(L_A) \approx \int_0^{L_A} dx_1 \int_{L_A}^{L} dx_2 D(x_1 - x_2, L)$$



“Hidden” log inside volume-law phase

Entanglement entropy:



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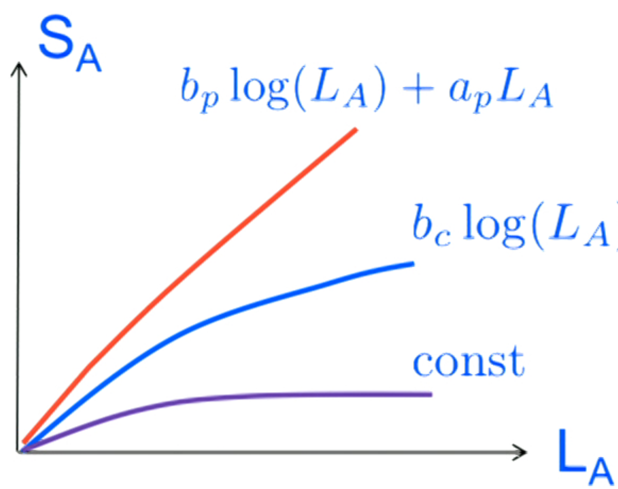
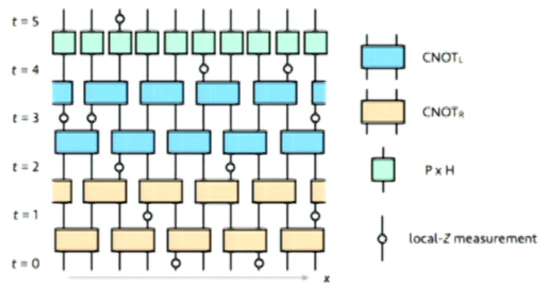
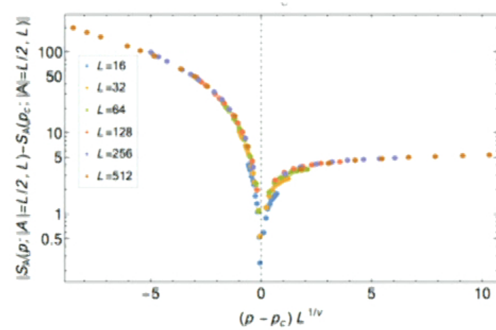


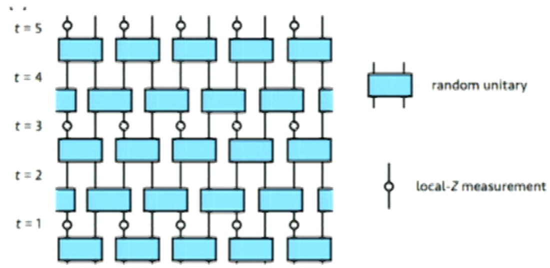
Circuits with (Translational) Symmetry

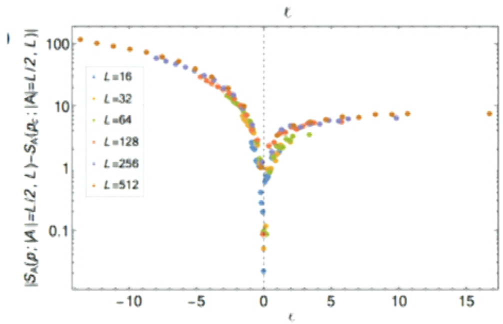
Floquet-Clifford Circuit



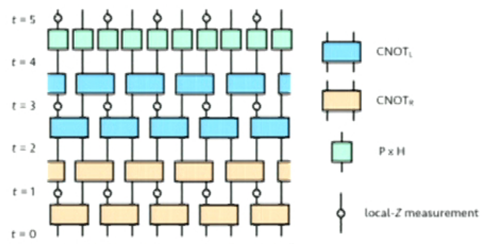


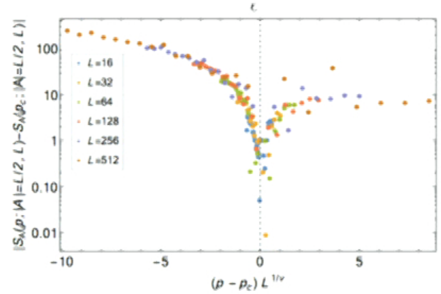
Circuit with (quasi-) periodic measurement locations





Floquet w/ periodic measurements (no randomness)





All exponents the same!!

Beyond Clifford: Haar random Unitaries

Haar random unitaries with
single qubit projective measurements

Skinner, Ruhman, Nahum (2018)

Mapped Zeroth Renyi entropy (n=0)
to (first passage) percolation, with

$$p_c^{n=0} = 1/2$$

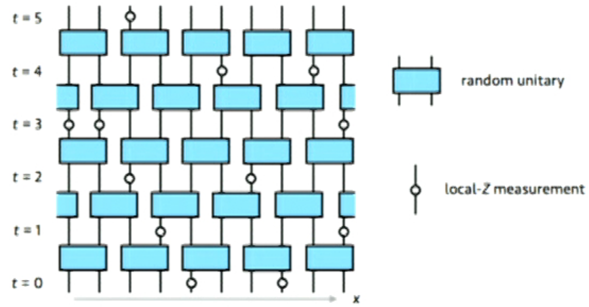
Numerics for n-th Renyi entropy;
“Different transition”, $p_c < 1/2$

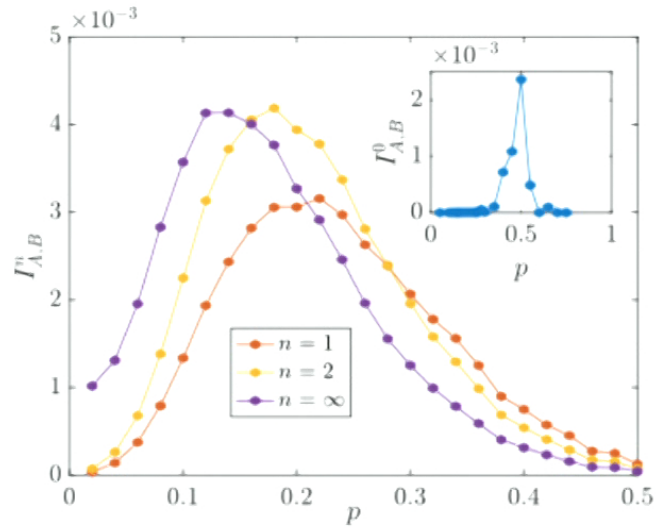
Li, Chen, MPAF (2019)

Mutual Information, varying Renyi index, n

$$I_{AB}^n = S_A^n + S_B^n - S_{AB}^n$$

$$p_c^{n\geq 1} \approx 0.2$$

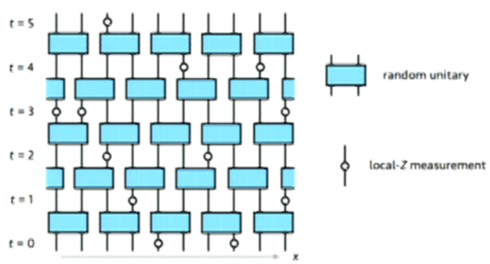




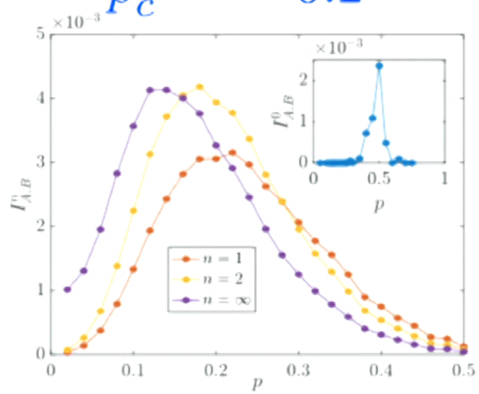
Random Haar w/ Generalized measurements

Projective measurements

$$P_{\pm} = \frac{1 \pm Z}{2}$$



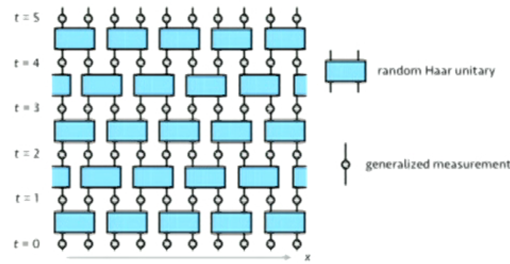
$$p_c^{n \geq 1} \approx 0.2$$



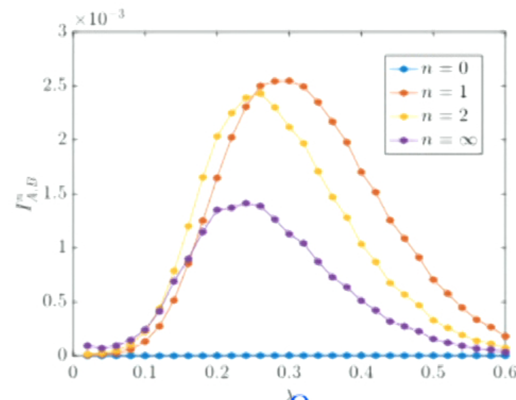
$$p_c^{n=0} = 1/2$$

Generalized measurements

$$M_{\pm} = \frac{1 \pm \lambda Z}{\sqrt{2(1+\lambda^2)}} \qquad \lambda \in [0,1]$$



$$\lambda_c^{n \geq 1} \approx 0.3$$

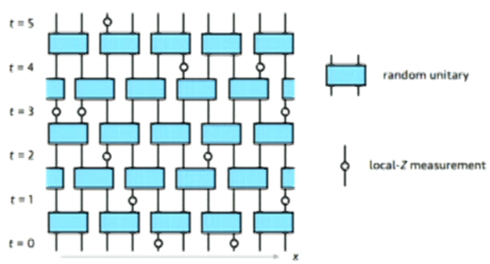


$$\lambda_c^{n=0} = 1$$

Random Haar w/ Generalized measurements

Projective measurements

$$P_{\pm} = \frac{1 \pm Z}{2}$$



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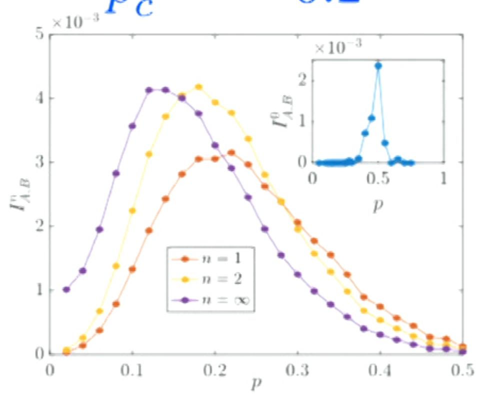

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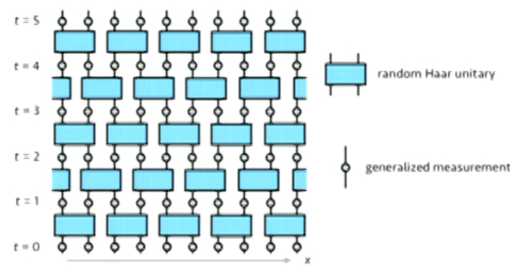

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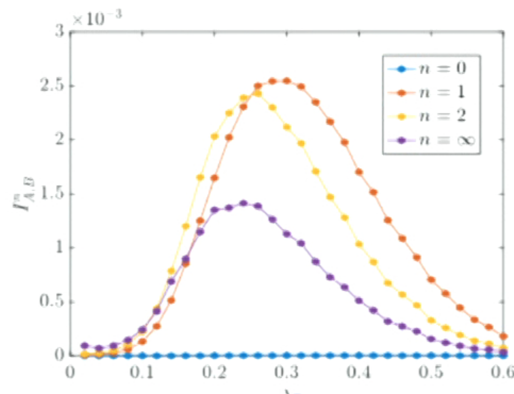


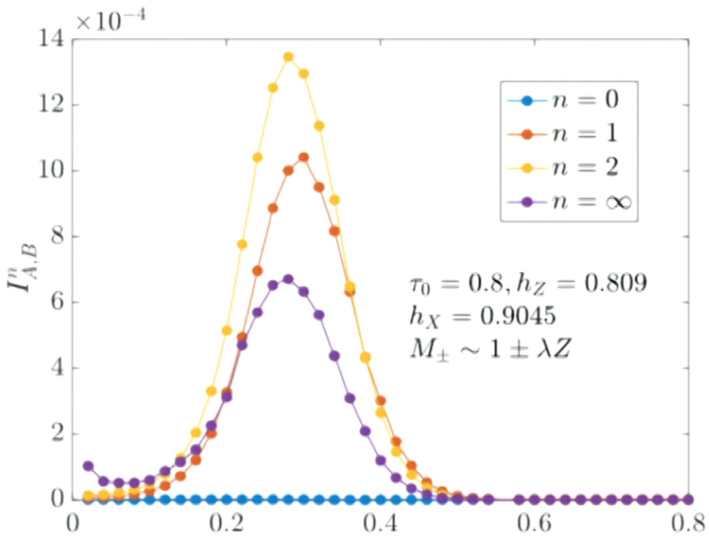
$$\lambda_c^{n=0} = 1$$

Beyond Clifford: Ising Floquet Unitaries

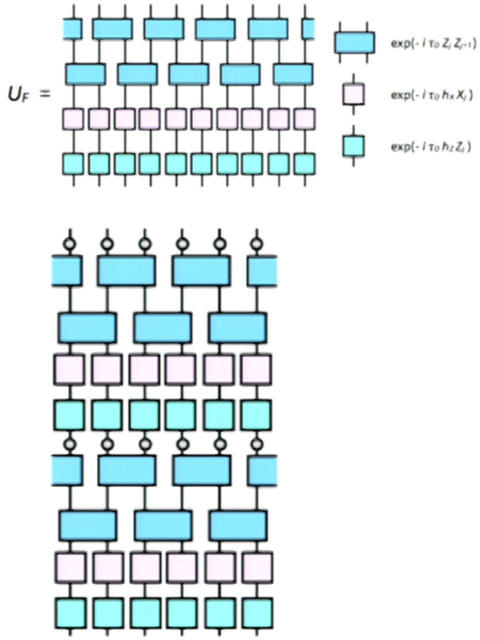
With generalized measurements:
No randomness

$$I^n_{AB} = S^n_A + S^n_B - S^n_{AB}$$

$$\lambda_c^{n\geq 1} \approx 0.25$$

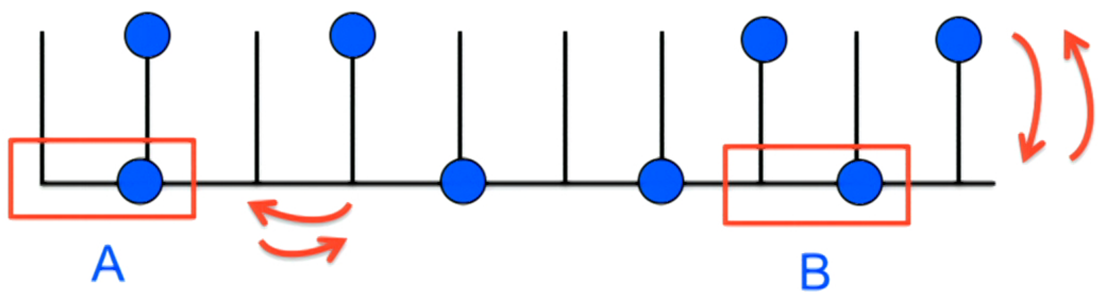


$$\lambda_c^{n=0} = 1$$



Measurable in Cold Atoms/Ions?

"Comb" Lattice



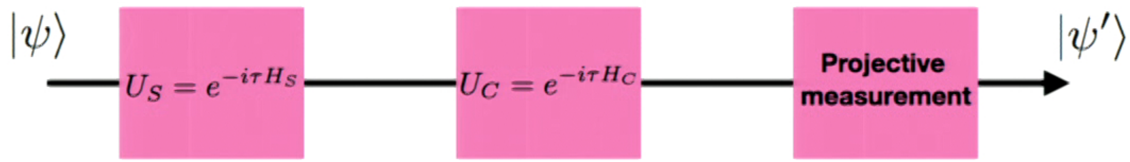
Set-up

- Bosons hopping on a "comb" lattice
- Make projective measurements on "top" of "teeth"
- Compute (and measure?) averaged-squared number fluctuation correlation function
- Expect power law decay at criticality

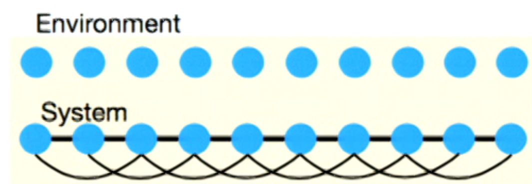
$$\overline{|\langle \delta \mathcal{N}_A \delta N_B \rangle_c|^2} \sim |x_A - x_B|^{-\gamma}$$

Cold atoms set-up

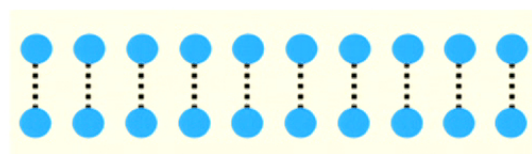
Three steps:



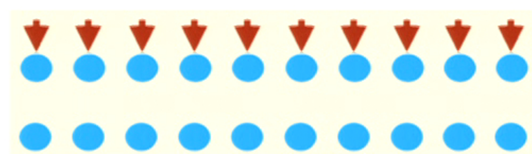
$$H_S = \sum_i X_i^S X_{i+1}^S + Y_i^S Y_{i+1}^S + J_1^z Z_i^S Z_{i+1}^S + J_2^z Z_i^S Z_{i+2}^S$$



$$H_C = \kappa \sum_i X_i^S X_i^E + Y_i^S Y_i^E$$

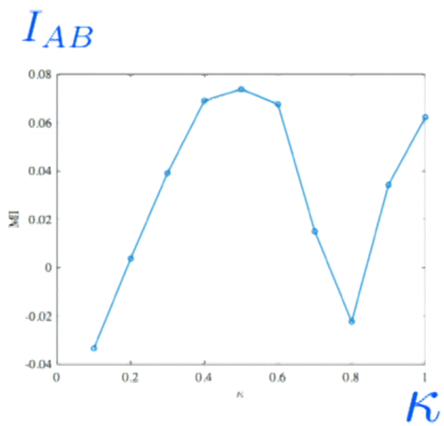


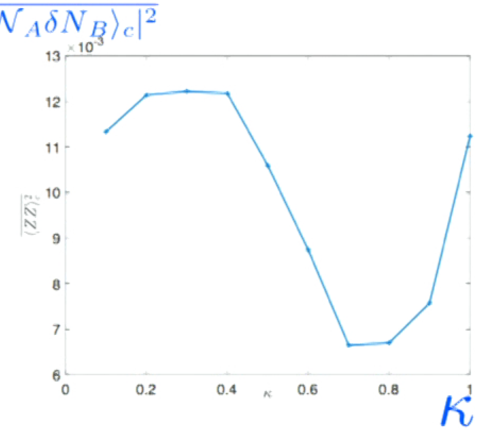
Projective measurement



Transition accessible in principle

See a peak for L=20, L_A=1, L_B =1, $x_A - x_B$ = 10





But in practice? Might be hard to measure from ensemble of (different) pure states

$$\langle \psi | \delta\mathcal{N}_A \delta N_B | \psi \rangle$$

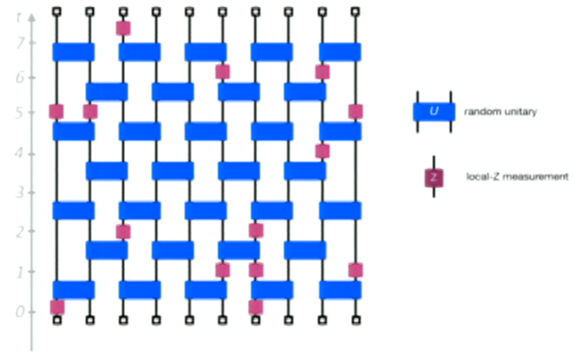
Why?

- Cannot measure expectation value in a one-shot measurement (exploit self-averaging?)
- Making multiple copies of each pure state will be hard

Summary: Taming Entanglement

Quantum Entanglement Transition:

Competition between unitary induced entanglement and measurement induced disentanglement



Open/future:

- Genericity of Clifford transition?
- Analytic access to 1+1 transition?
- Transitions in d>1?
- Dual gravity description? Black hole information paradox?
- Experimental access?? Quantum computer or cold atoms/ions?

Firewall vs. Scrambling

1 Review of Firewall argument

2 Review of Hayden-Preskill

3 Interior operator from HP recovery

4 State-independent interior operators

5 Effect of infalling observer

6 Resolution of the puzzle

7 Discussions

Beni Yoshida (Perimeter Institute)

Firewall vs. Scrambling

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Proposals (for impatient listeners)

• I will construct the interior operator in a “state-independent” manner without involving the distant radiation ever. It “avoids” previous no-go results.

• I will show that the infalling observer leaves non-trivial gravitational backreaction and disentangles the outgoing mode from the early radiation, no matter how she falls.

(Each phrase will be defined more precisely later)

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• I will construct the interior operator in a "state-independent" manner without involving the distant radiation ever. It "avoids" previous no-go results.

• I will show that the infalling observer leaves non-trivial gravitational backreaction and disentangles the outgoing mode from the early radiation, no matter how she falls.

• I will argue that the infalling observer sees a smooth horizon. Her infalling experience cannot be influenced by any operation on the early radiation.

(Each phrase will be defined more precisely later)

Firewall vs. Scrambling

Beni Yoshida (Perimeter Institute)

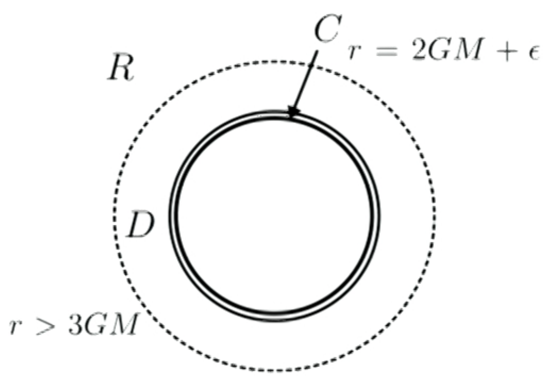
Firewall puzzle(s), brief summary

From the outside (Bob)

C : Remaining black hole

D : Outgoing mode

R : Early radiation



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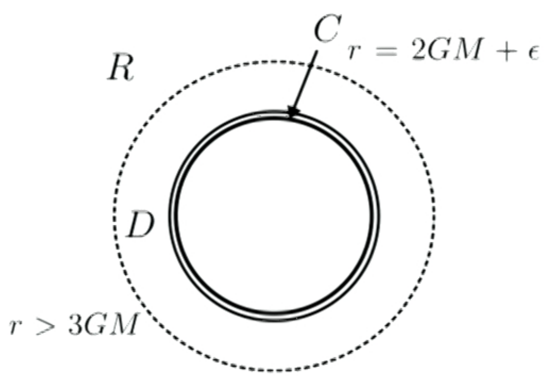
"old" black hole

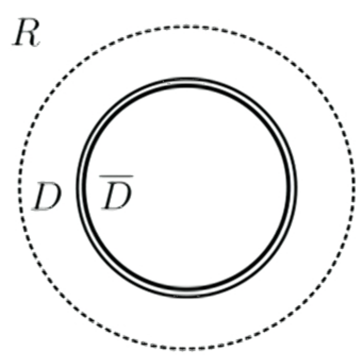
$I(D,R) \approx \max \qquad I(C,D) \approx 0$

From the inside (Alice)

$D\bar{D}$: Rindler modes

$I(D,\bar{D}) \approx \max$





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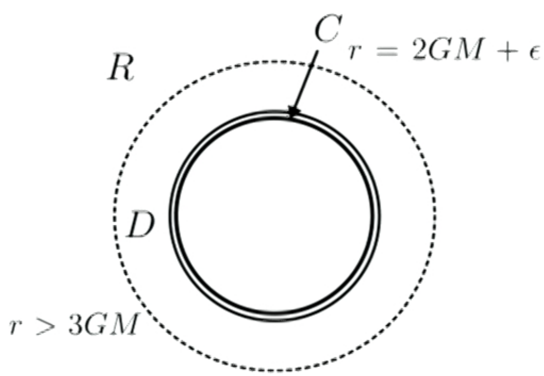

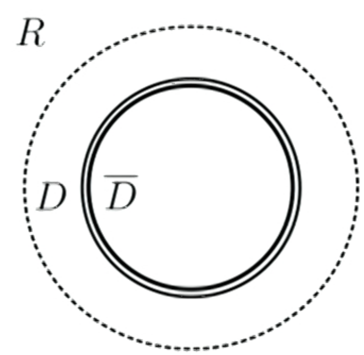

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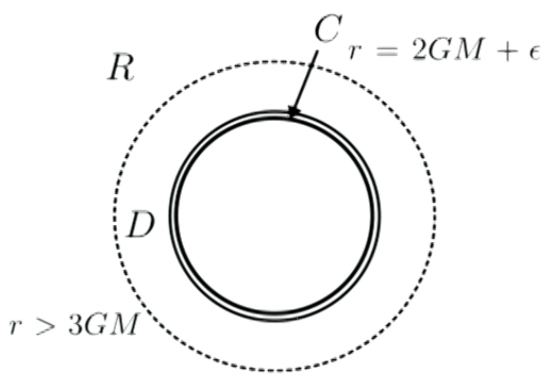
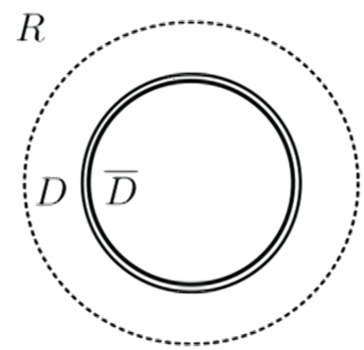
$I(D,R) \approx \max$ $\quad I(C,D) \approx 0$ $\longrightarrow$ $I(D,\bar{D}) \approx 0$ firewall?

From the inside (Alice)

$D\bar{D}$: Rindler modes

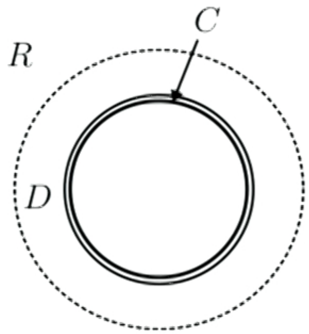
$I(D,\bar{D}) \approx \max$





Interior operators

- In outside description, $\bar{D}$ is supported on CR not on C (remaining BH)

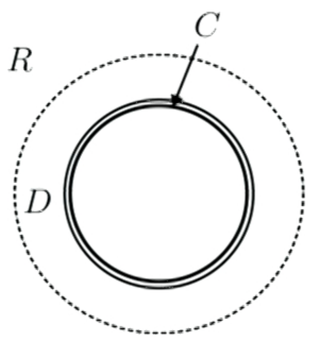


Interior operators

- In outside description, $\bar{D}$ is supported on CR not on C (remaining BH)
- Non-locality problem

Place R at a far distant universe.

"A = RB" approach, "ER = EPR" approach (This is how quantum gravity works?)



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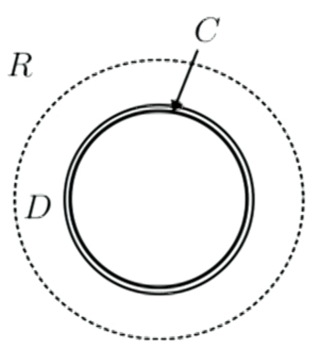

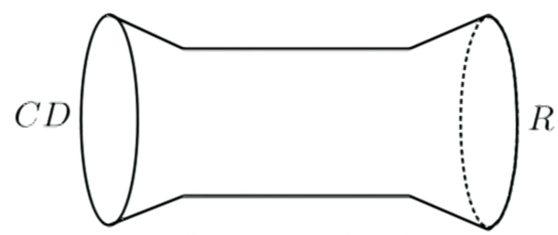

"long throat" AdS

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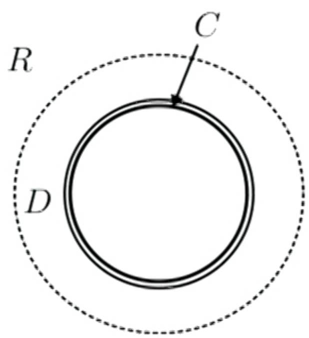
- Non-locality problem

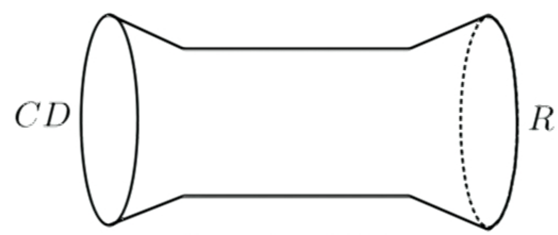
  Place R at a far distant universe.

  "A = RB" approach, "ER = EPR" approach (This is how quantum gravity works?)

- State-dependence problem

  - Interior operators depend on the state, namely R.
  - Violation of Born rule, Frozen vacuum, …
  - Papadodimas-Raju proposal for state-dependence, …





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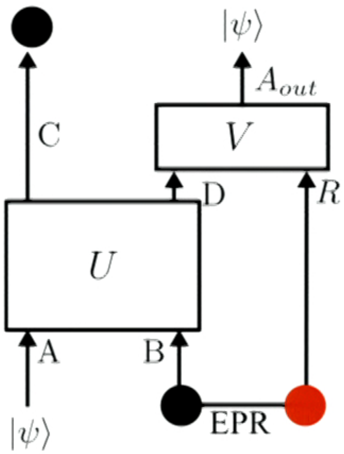
Hayden-Preskill, brief summary

• Alice throws a quantum state into an old black hole. Bob collects the Hawking radiation and reconstruct the original state.

C : Remaining BH

D : Late radiation

R : Early radiation



Hayden-Preskill, brief summary

• Alice throws a quantum state into an old black hole. Bob collects the Hawking radiation and reconstruct the original state.

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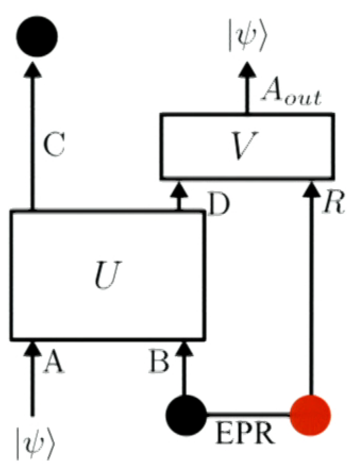
- Bob needs to collect just a few qubits from D.

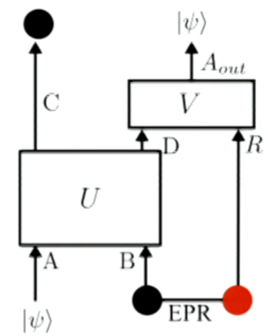


"Black hole as mirrors" (Hayden-Preskill)

V : recovery unitary

Out-of-time order correlation

- Hayden-Preskill : Haar random U. Existence proof of decoder V.



A : input
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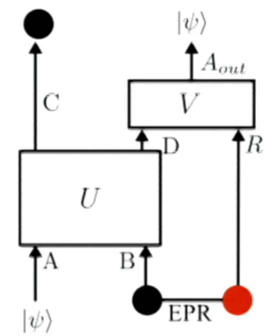
- Hosur-Qi-Roberts-BY : decay of out-of-time order correlator (OTOC) implies existence of V. (2015)

$$\langle O_A(0) O_D(t) O_A^\dagger(0) O_D^\dagger(t) \rangle \equiv \frac{1}{d} \mathrm{Tr} \left(O_A U^\dagger O_D U O_A^\dagger U^\dagger O_D^\dagger U \right)$$



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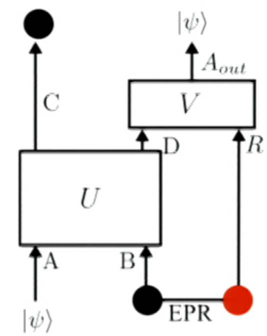
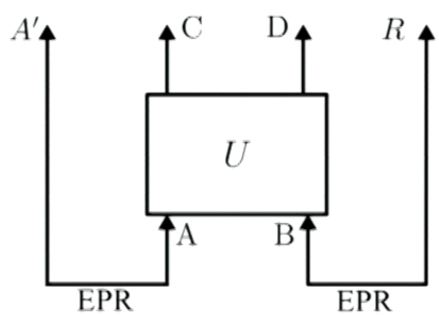
$$\longrightarrow \quad 2^{-\boxed{I^{(2)}(A',RD)}} = \int dO_A dO_D \ \langle O_A(0)O_D(t)O_A^\dagger(0)O_D^\dagger(t)\rangle$$





"state representation" of U

A : input
C : remaining BH
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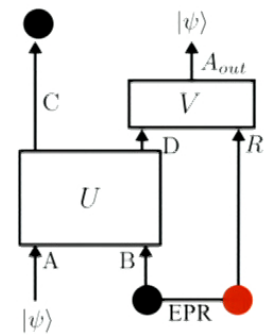
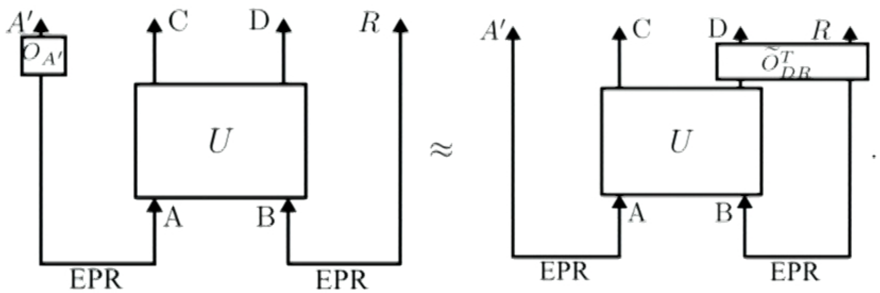


"partner operator"



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Decoding protocol

- Kitaev-BY : decay of OTOC implies "simple" recovery protocols. (2017)

Decoding protocol

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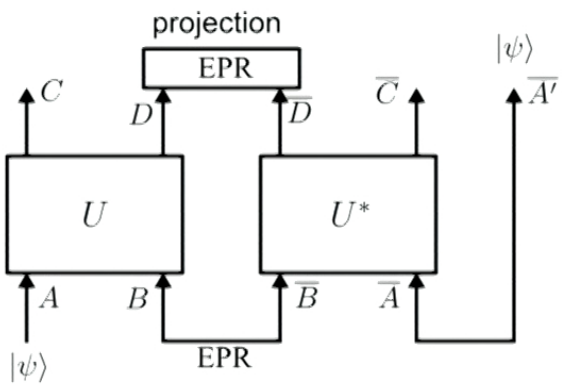
- Project $D\bar{D}$ onto the EPR pair. (probabilistic)



"Decoding protocol"

Decoding protocol

- Kitaev-BY : decay of OTOC implies "simple" recovery protocols. (2017)
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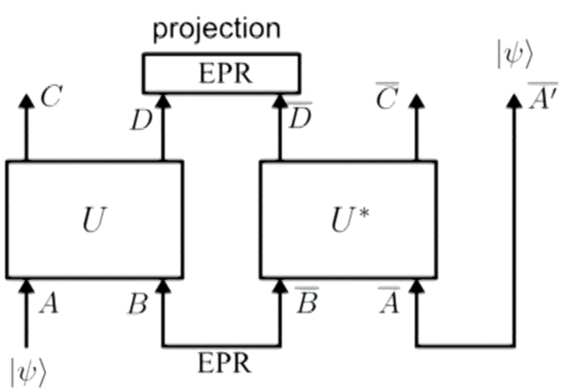

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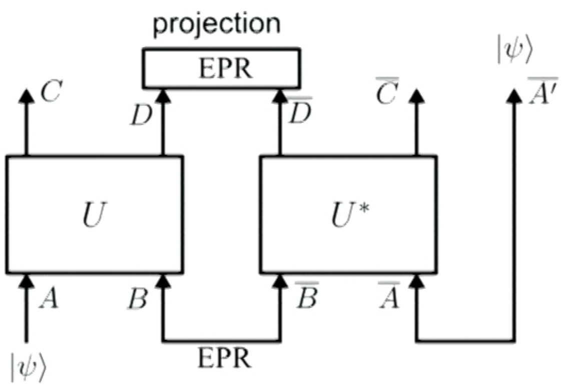
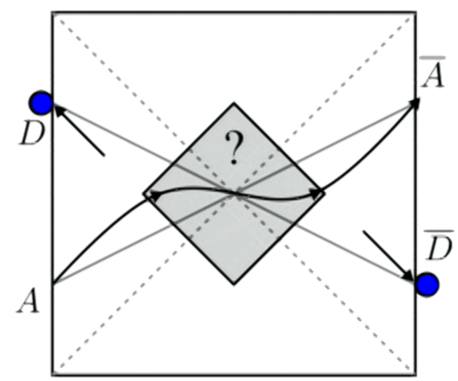


"Decoding protocol"



"Traversable wormhole"

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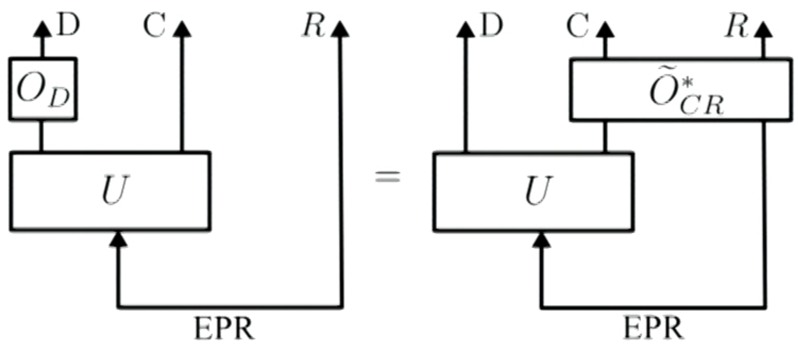
Interior operators

- and the AMPS problem…

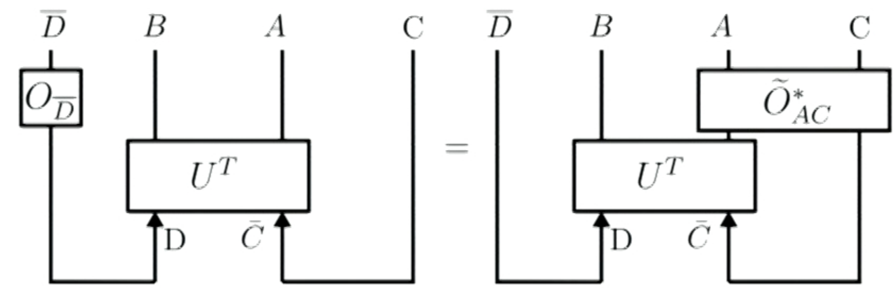


C : Remaining BH
D : Outgoing mode
R : Radiation

Split R into AB, and rotate the diagram.

Interior operators

- Interior partner in A (a few qubits in R) and C (remaining BH)



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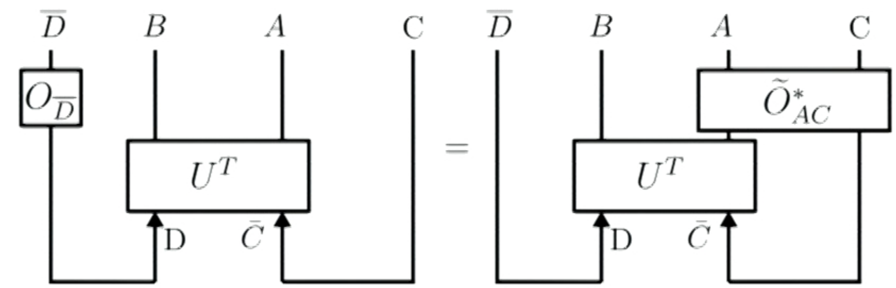


C : Remaining BH

D : Outgoing mode

R : Radiation

AMPS Reconstruct D (outgoing) from C (remaining BH) and A (early mode)

HP Reconstruct A (early mode) from B (initial BH) and D (outgoing)

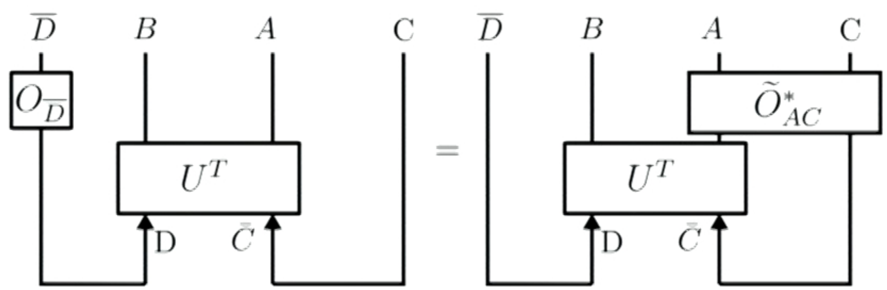
Interior operators

- Properties
  - You can choose any subsystem A from R to reconstruct $\bar{D}$
  - Construction of $\bar{D}$ is naturally fault-tolerant.
  - $\bar{D}$ is "almost" inside C with a few extra qubits from R.

C : Remaining BH

D : The zone

R : Radiation



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  - Construction of $\bar{D}$ is naturally fault-tolerant.
  - $\bar{D}$ is "almost" inside C with a few extra qubits from R.
- Problems …
  - Construction is state-dependent. $(I \otimes K)|\mathrm{EPR}\rangle$
  - Non-locality problem (use of A)

C : Remaining BH

D : The zone

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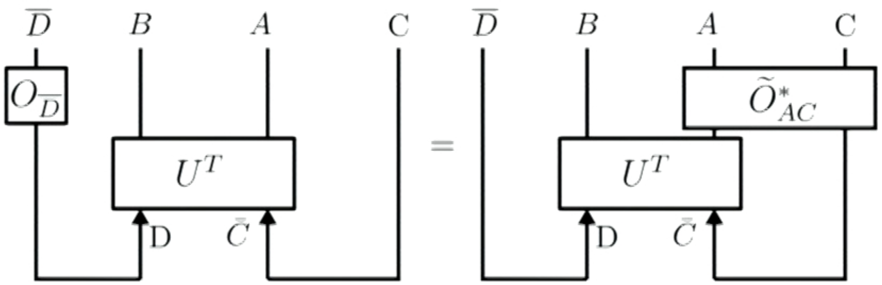
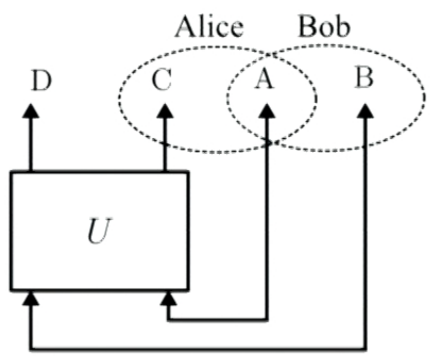


Some lessons

- Reconstruction of interior operators

If Alice takes A, then Alice possesses the EPR pair

If Alice didn't take A, then Bob possesses the EPR pair



AB : Radiation (R)

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Some lessons

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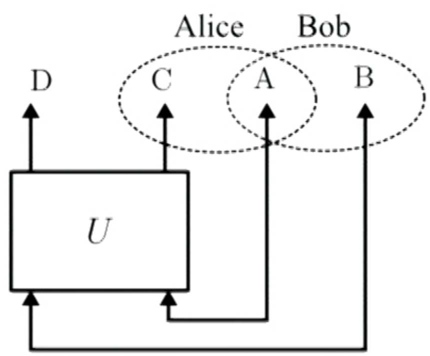


AB : Radiation (R)

C : remaining black hole

D : outgoing mode

• We can choose A to be any small subsystem !

Firewall vs. Scrambling

1 Review of Firewall argument

2 Review of Hayden-Preskill

3 Interior operator from HP recovery (BY 2018)

4 **State-independent interior operators (BY 2019)**

5 Effect of infalling observer

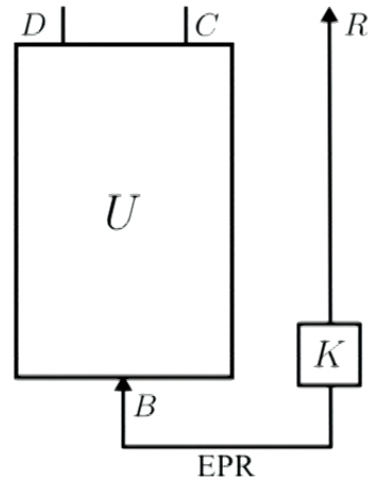
6 Resolution of the puzzle

7 Discussions

Beni Yoshida (Perimeter Institute)

“Long-throat” “AdS” black hole

- Very complex AdS BH $(I \otimes K)|\mathrm{EPR}\rangle$



Long-throat AdS = K is arbitrary, BH not evaporating

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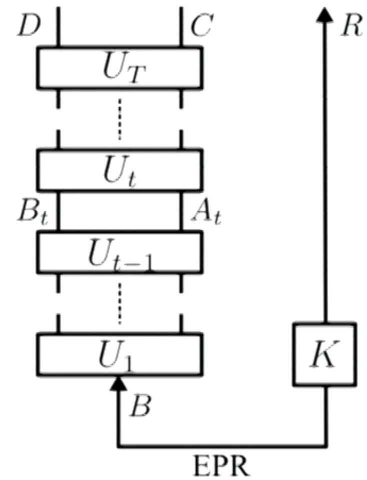

A_t : boundary modes

B_t : other modes

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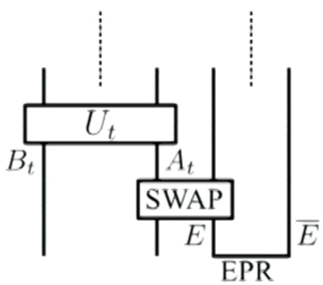
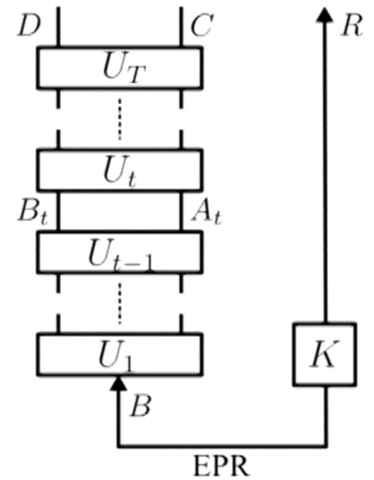
Prepare ancillary EPR and apply SWAP





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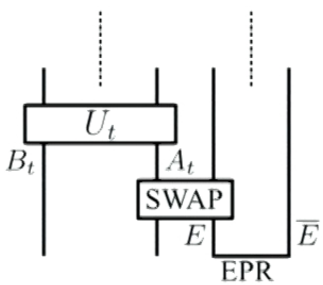

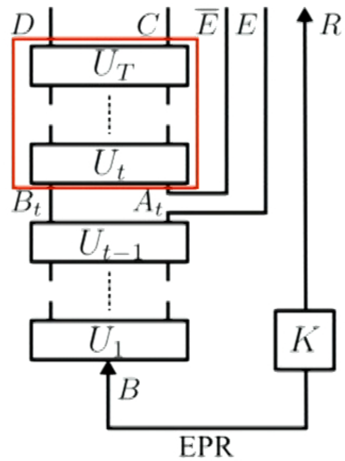

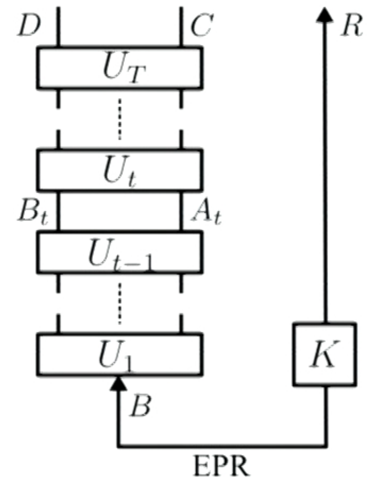

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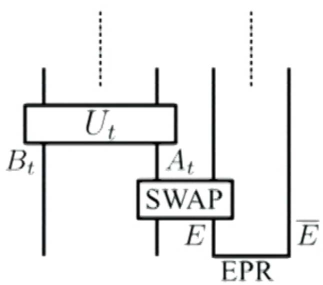

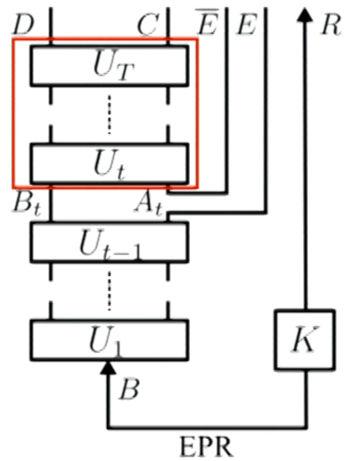

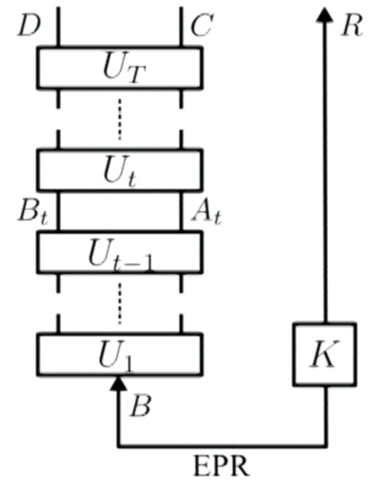

A_t : boundary modes

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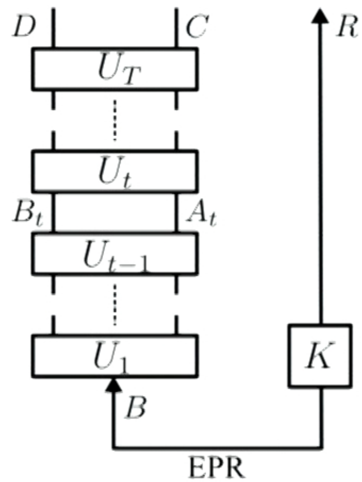
- $\bar{D}$ can be reconstructed on C and A_t

without ever accessing R

Long-throat AdS = K is arbitrary, BH not evaporating

State-independence



State-independence

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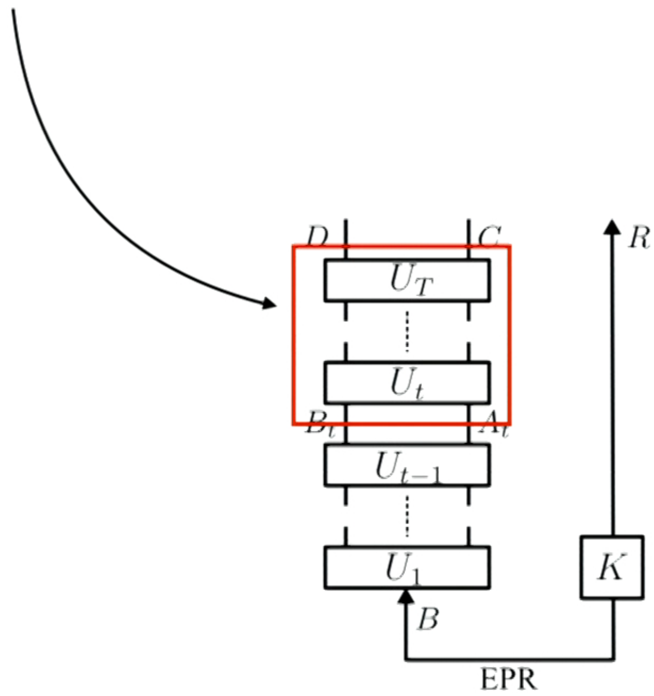
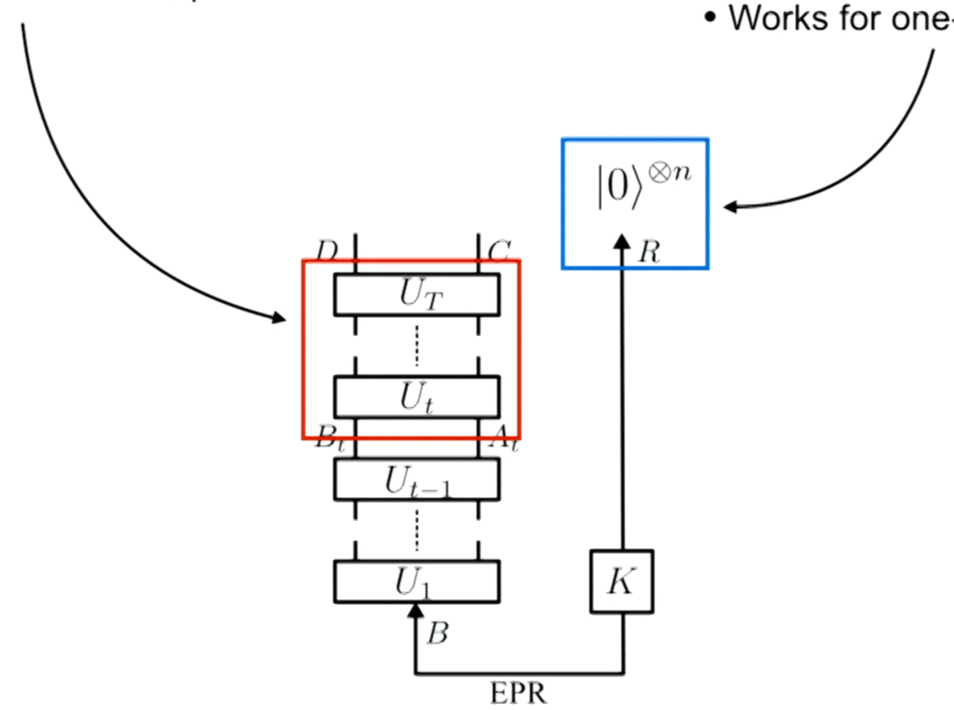


State-independence

- Construction does not depend on K
- Works for one-sided BH too.

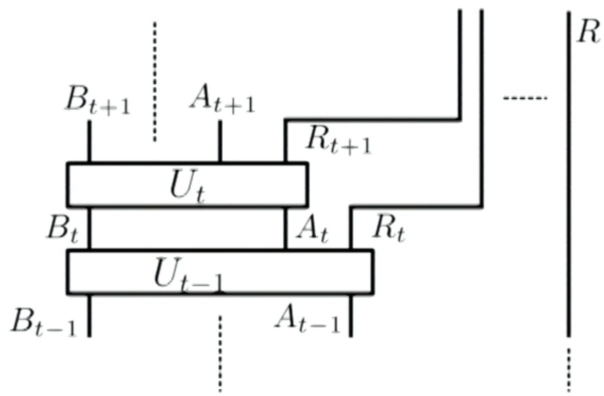


Evaporating black hole

R_t : high-energy radiation

A_t : modes on the zone

B_t : modes at stretched horizon



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2. Review of Hayden-Preskill
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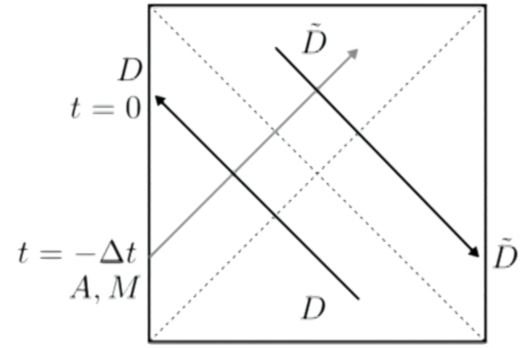
Beni Yoshida (Perimeter Institute)

Including Alice

- Consider the eternal AdS. Bob's can verify entanglement on $D\tilde{D}$ from the boundary.



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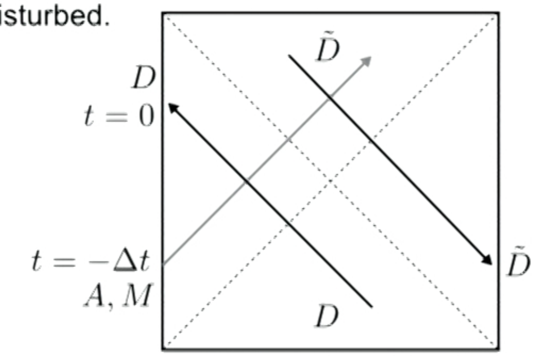
- Consider the eternal AdS. Bob's can verify entanglement on $D\tilde{D}$ from the boundary.
- Add an apparatus M which travels along with A.

M becomes gravitational shockwave. Bob's entanglement is disturbed.

Due to decay of OTOCs.



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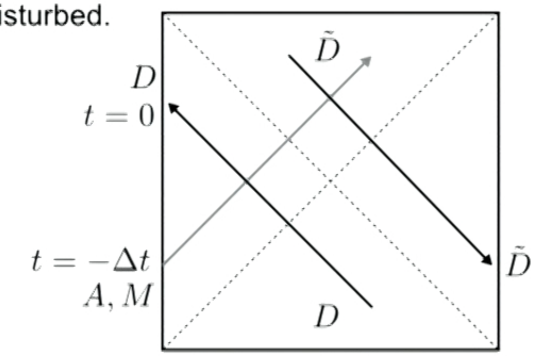

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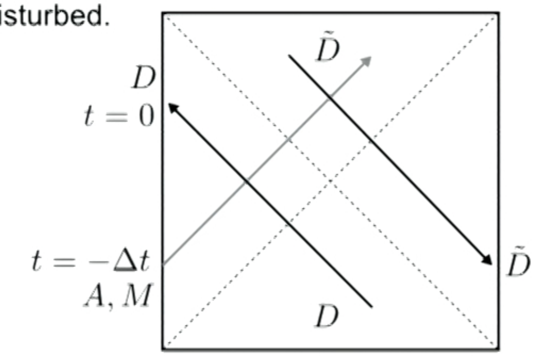

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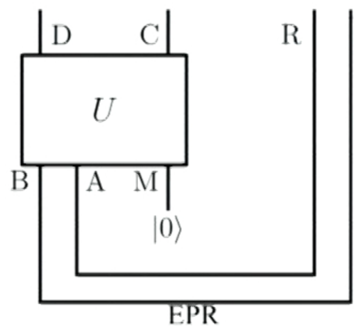
"Proof"



Small OTOC → $I(C, D) \approx \max$

→ D is not entangled with R

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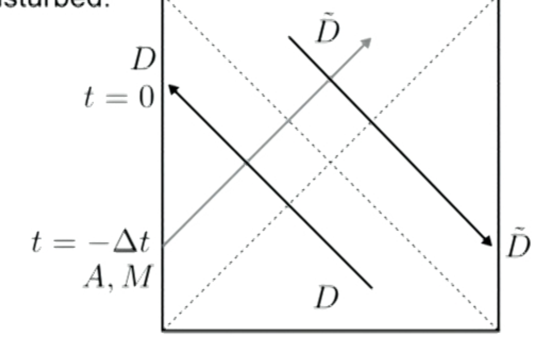

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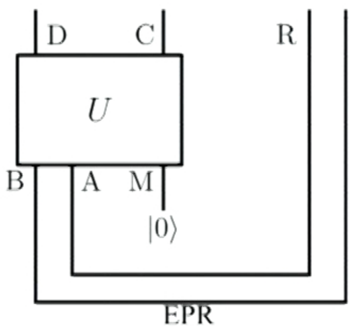

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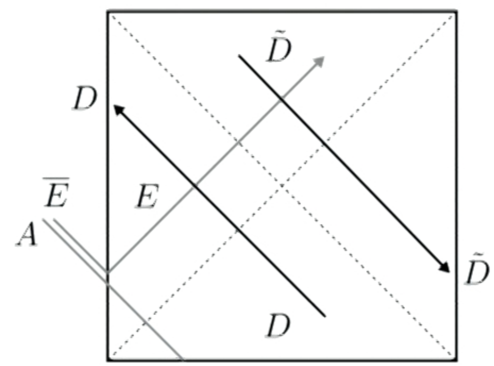
- Works for black holes on flat space. (Follows from QM and OTOC decay).

Sending probes

- Shoot a probe mode into the BH (mimics the reconstruction protocol)



Sending probes

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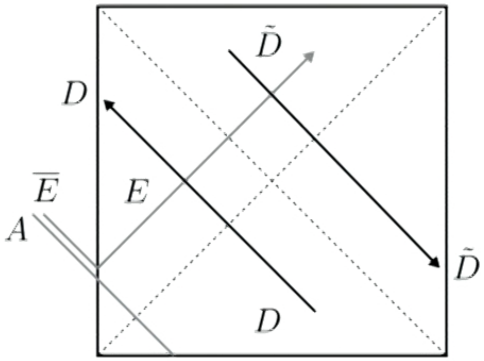
- OTOC decay implies $I^{(2)}(D, \overline{E}C) \approx \max$, so D is not entangled with R.

- Outgoing mode is disentangled from early radiation no matter how Alice falls in !
    - Decay of OTOC is universal gravitational phenomena.
    - Interior operator does not depend on R, but depends on the observer.



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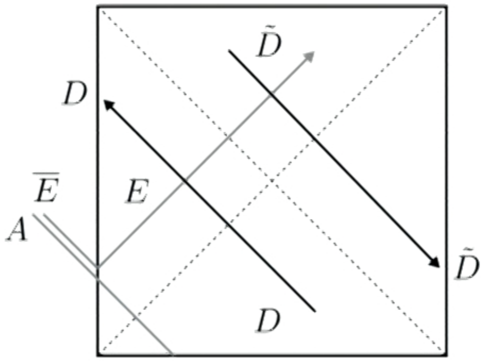
- Some caveats

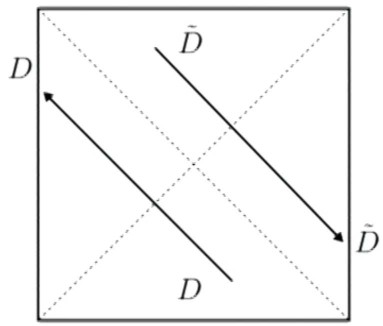
    - This requires scrambling time separation.

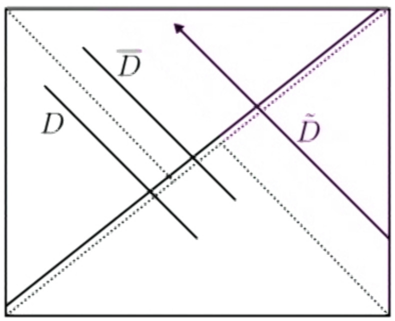
    - A (or E) needs to be as large as D.



Bulk interpretations

- Treat Alice as a shockwave





without Alice D —— $\tilde{D}$

with Alice D —— $\overline{D}$

Bulk interpretations

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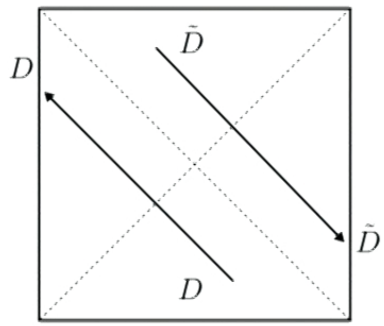

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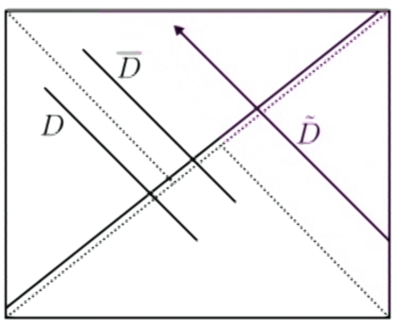

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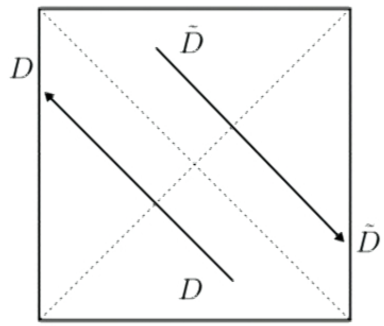

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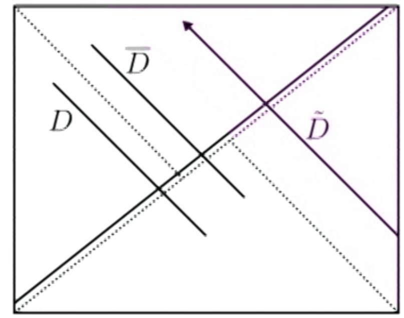

with Alice D —— $\overline{D}$

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Resolution of non-locality problem

• Alice sees a "phantom" of $\tilde{D}$. Non-locality problem can be resolved.

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AMPS thought experiment

- Original argument

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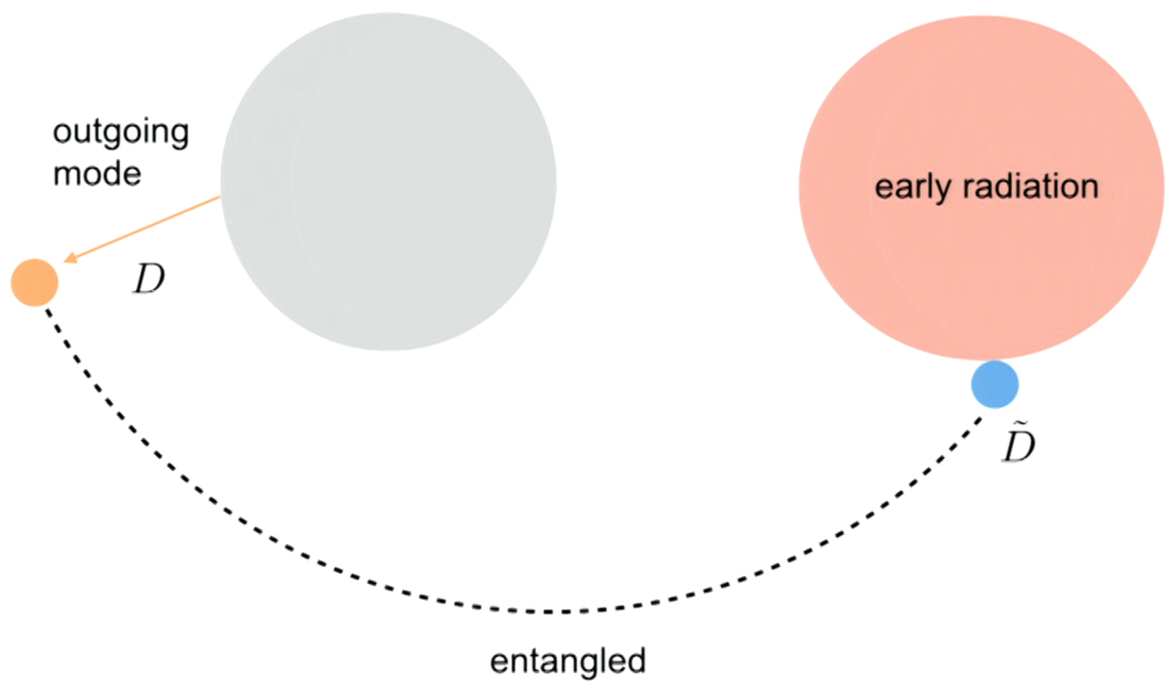

AMPS thought experiment

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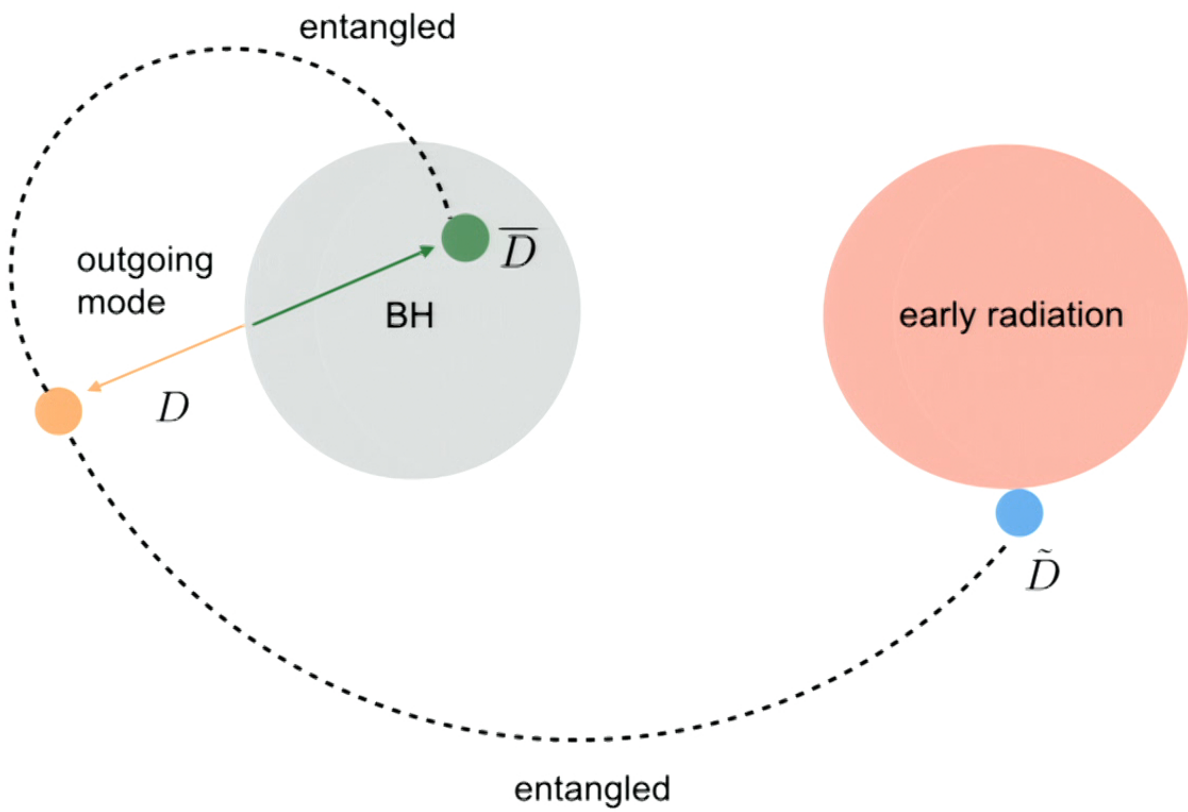

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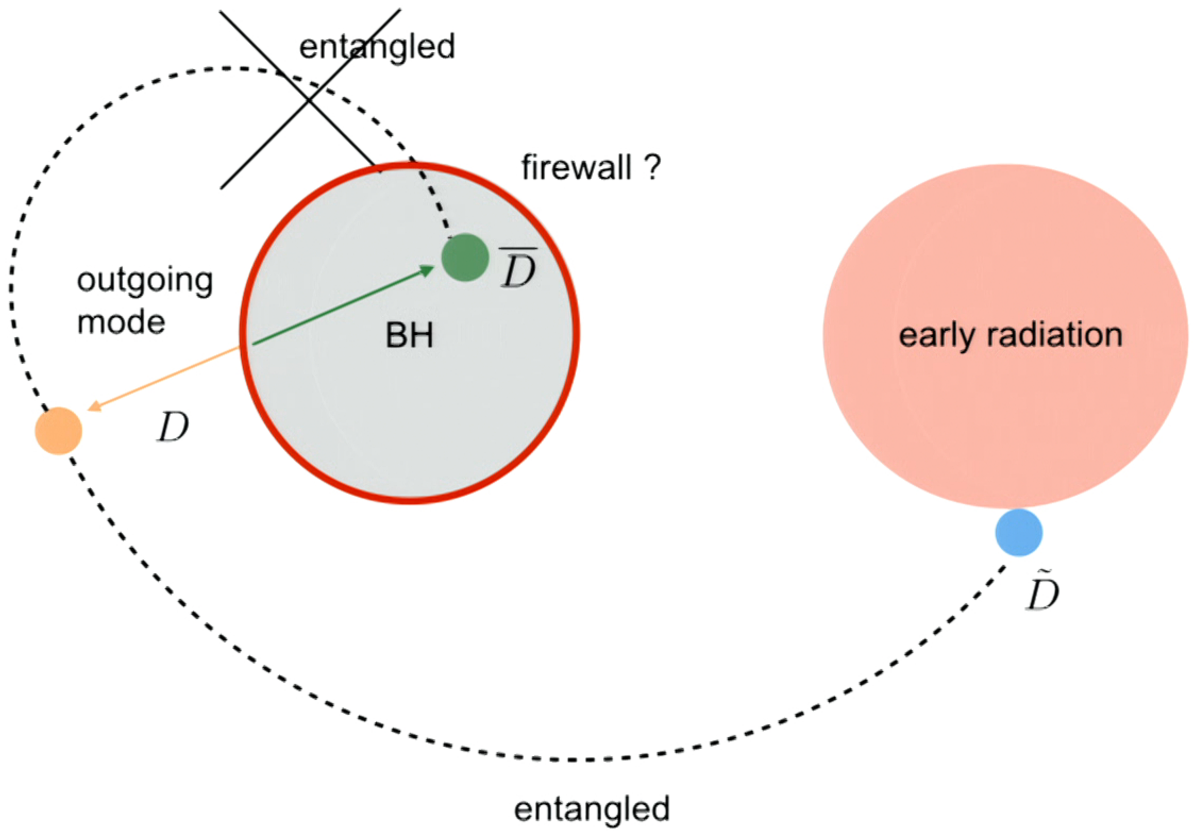

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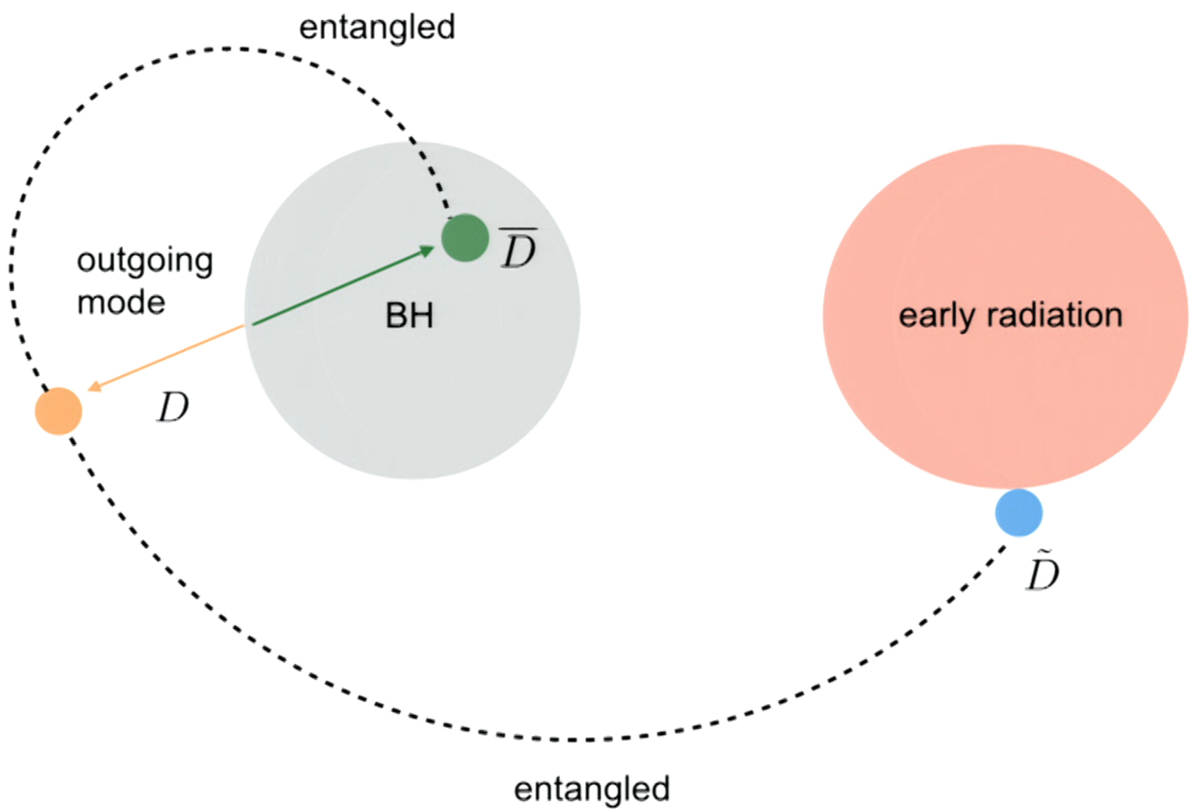

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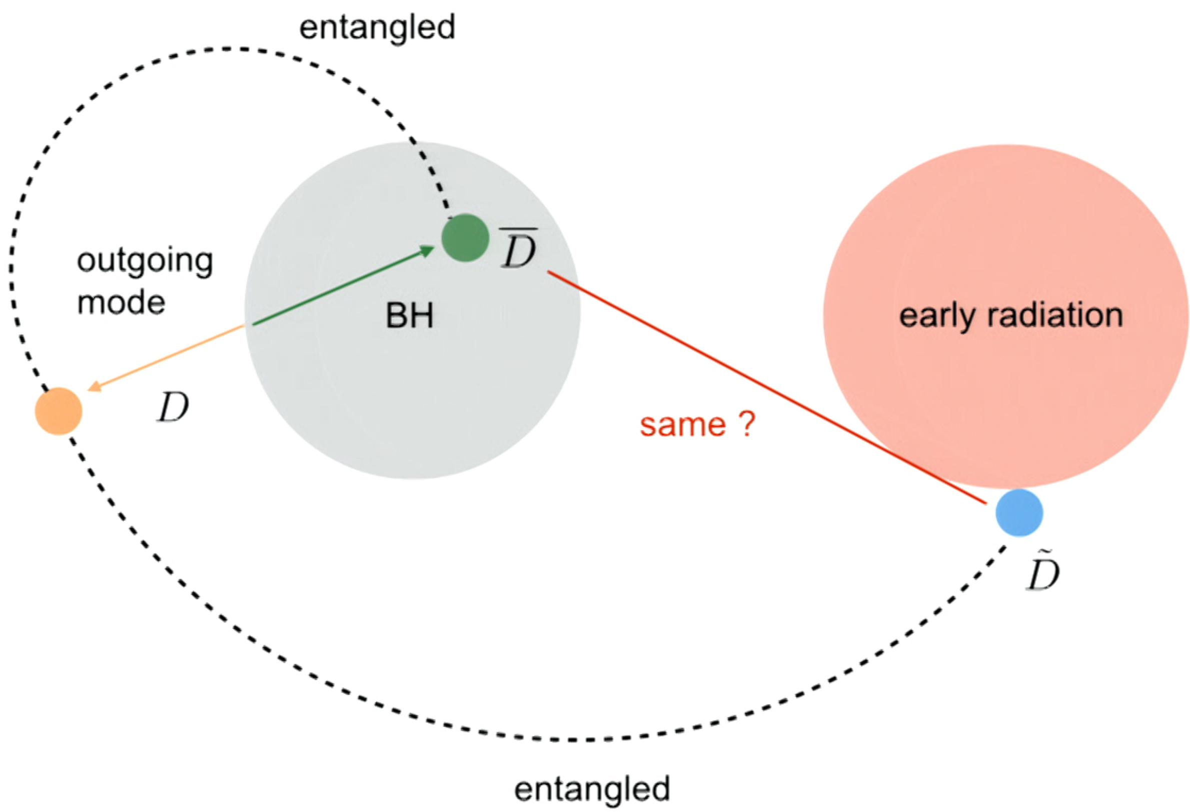

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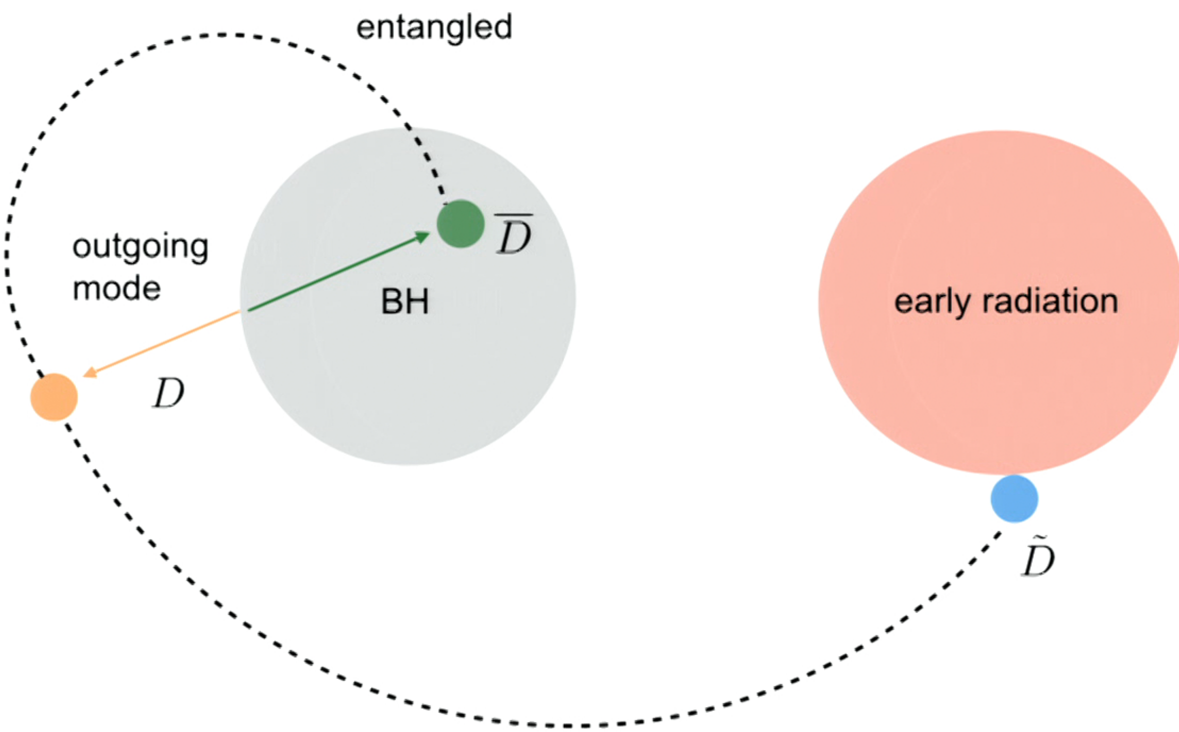
- Our proposal



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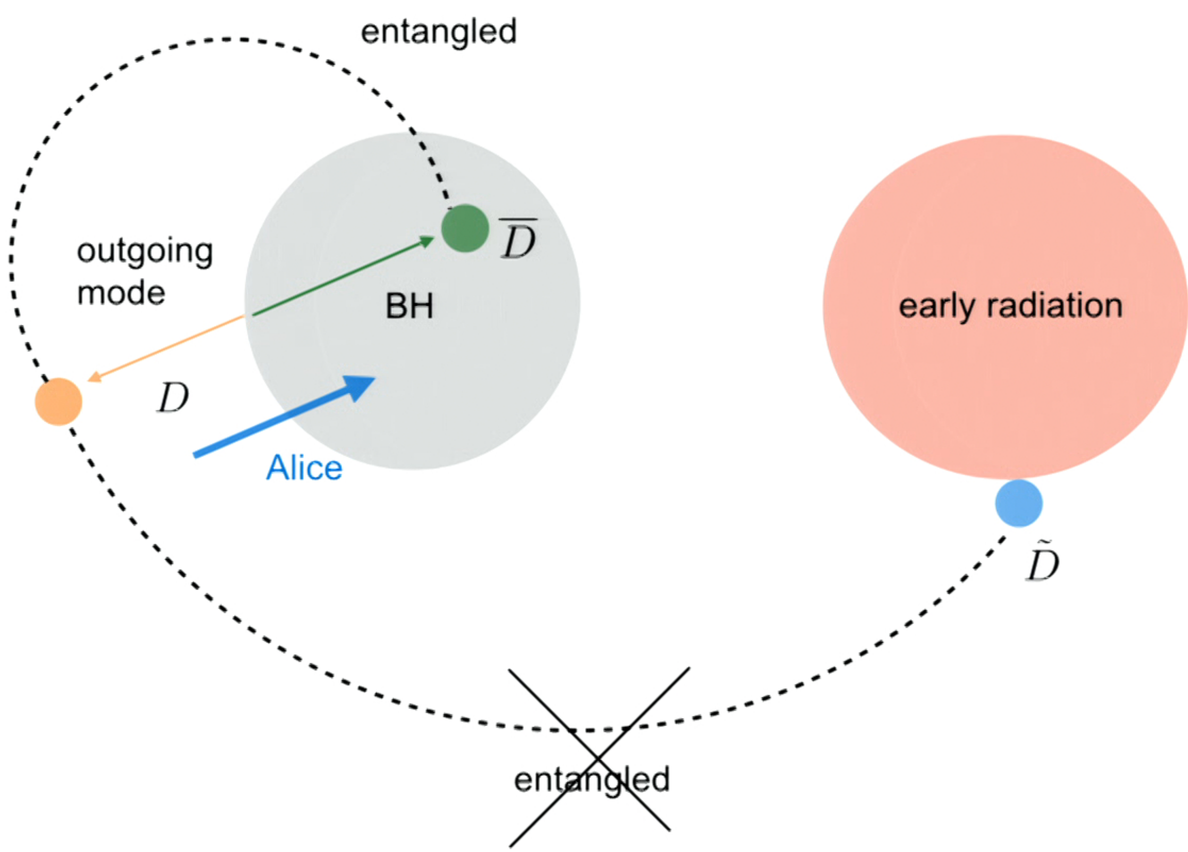

Opposite limit of monogamy relation

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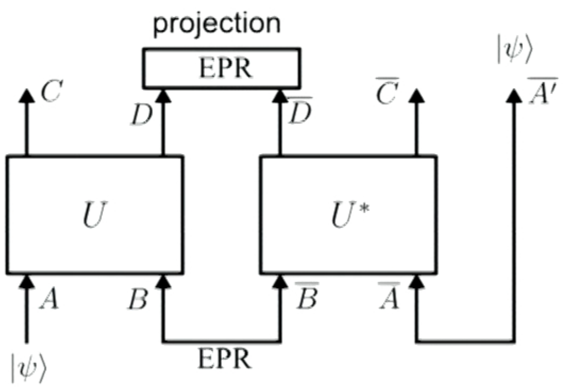
- Recall the recovery protocol by BY and Kitaev… Verification of $D\bar{D}$ entanglement.



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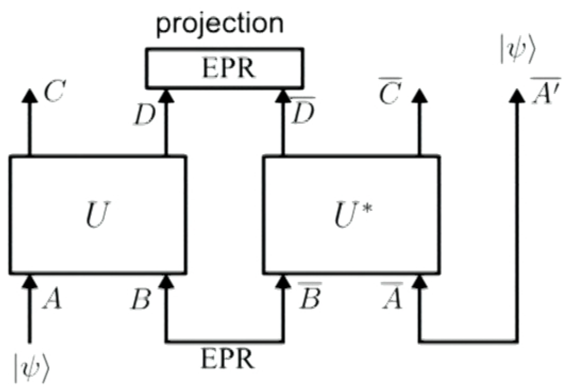

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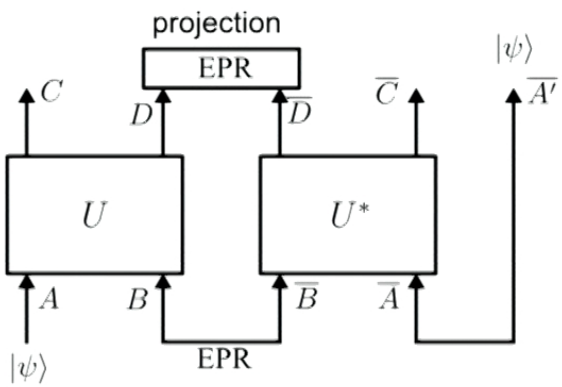
- Since Alice does not cross the horizon, she will not see the EPR pair.



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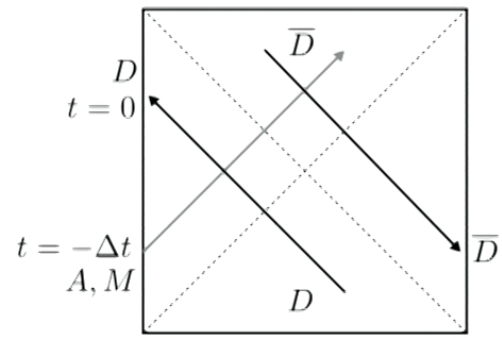

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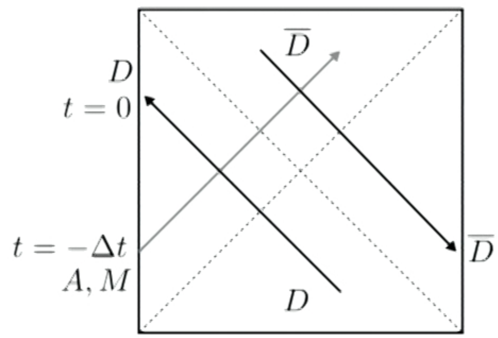
Alice see $\overline{D}$ very close to the singularity.



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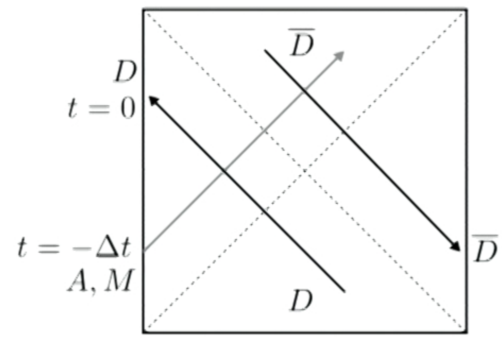
Alice see $\overline{D}$ very close to the singularity.

- Scenario 2

The quality of the EPR pair becomes bad ? $T = \frac{1}{2\pi\rho}$

To have small ρ , we need $\Delta t \gtrapprox r_S \log r_S$



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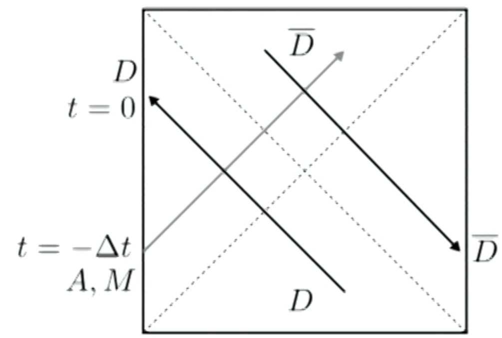
Alice see $\overline{D}$ very close to the singularity.

- Scenario 2



The quality of the EPR pair becomes bad ? $T = \frac{1}{2\pi\rho}$

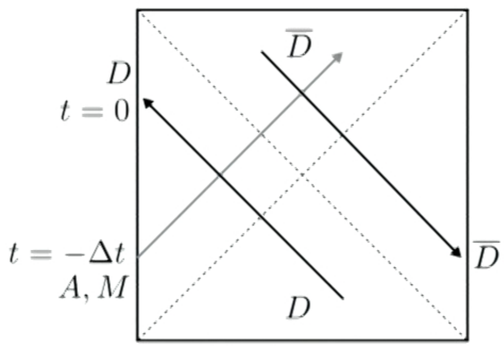
To have small ρ , we need $\Delta t \gtrapprox r_S \log r_S$

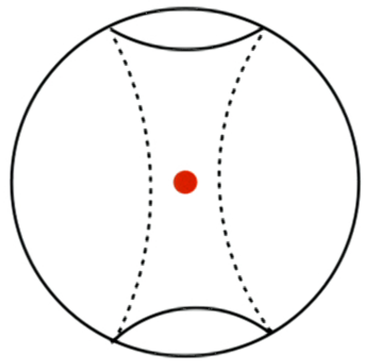
- Scenario 3

Even if they are not entangled, it won't create a firewall ?

Entanglement wedge reconstruction

- Can we use the Hayden-Preskill recovery to construct the state-independent interior operator in the entanglement wedge?





Firewall vs. Scrambling

1 Review of Firewall argument

2 Review of Hayden-Preskill

3 Interior operator from HP recovery

4 State-independent interior operators

5 Effect of infalling observer

6 Resolution of the puzzle

7 Discussions

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