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

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Firewall puzzle(s), brief summary

From the outside (Bob)

C : Remaining black hole

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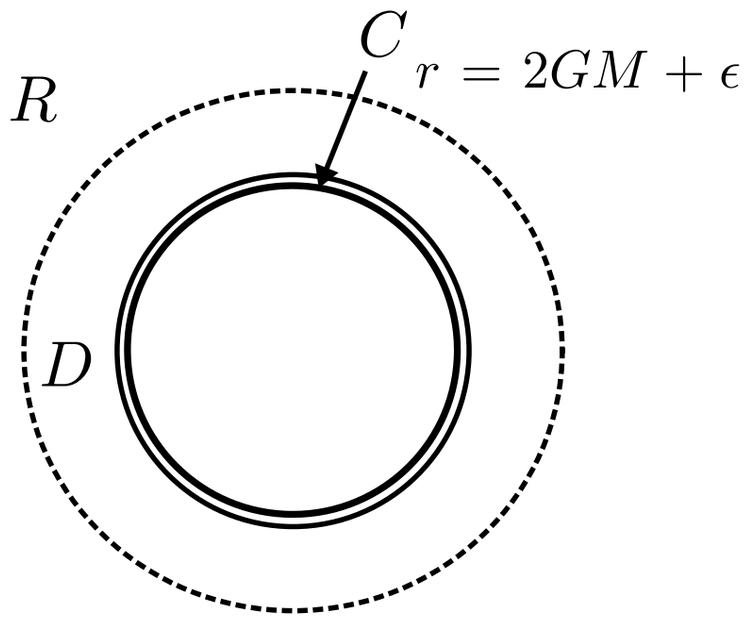

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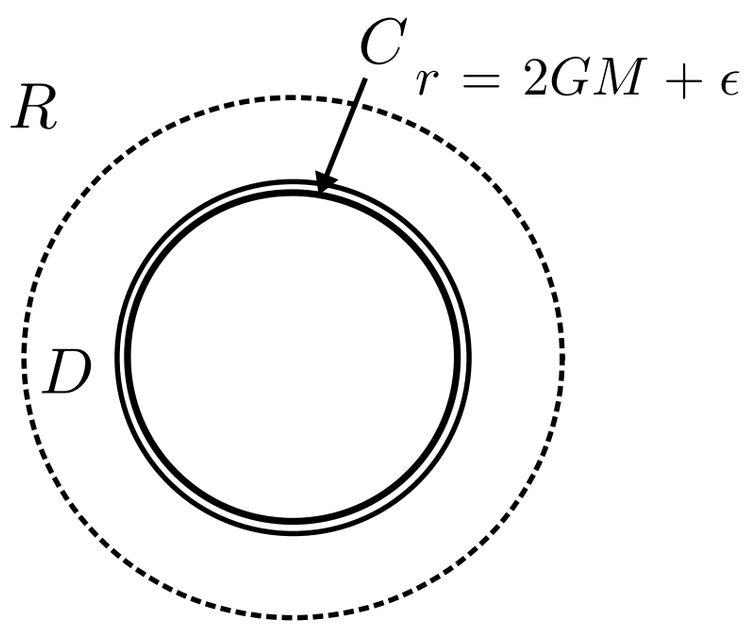
“old” black hole

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



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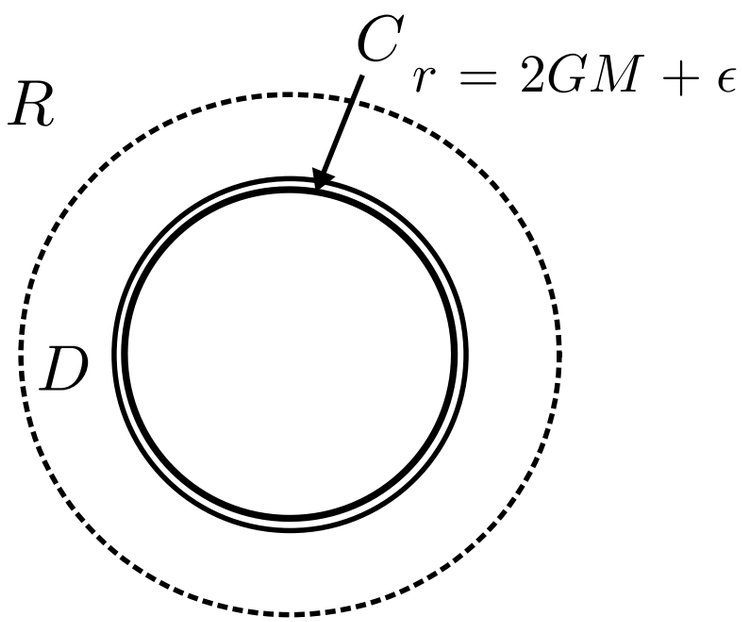

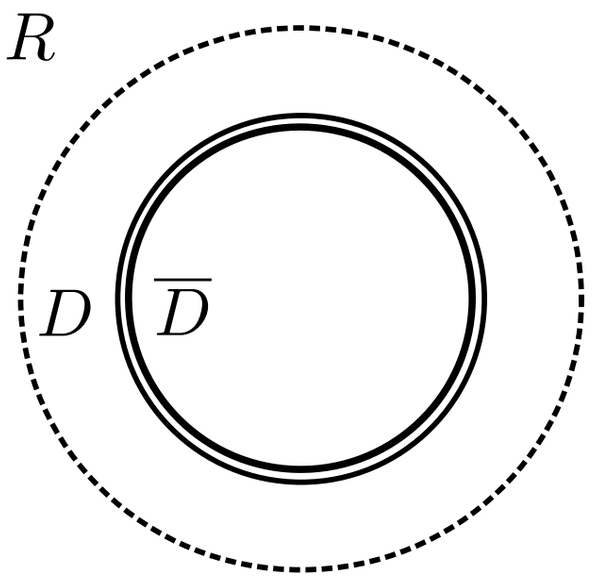

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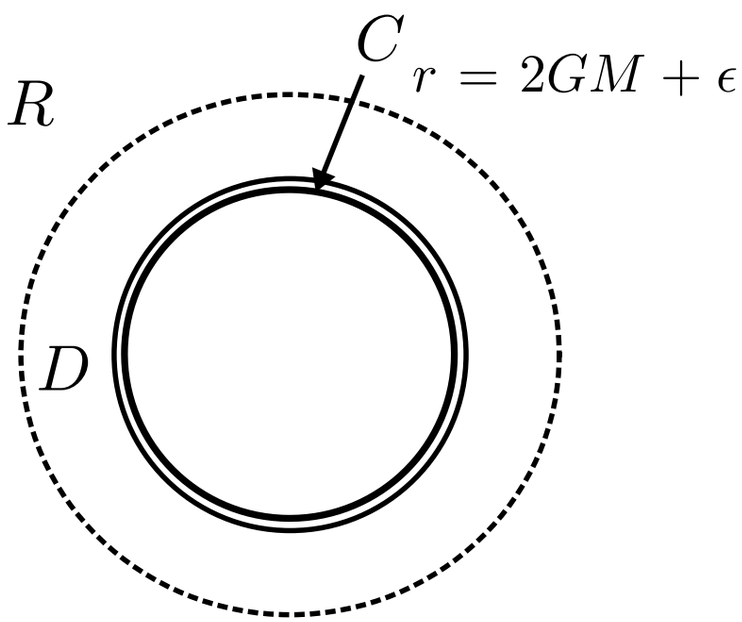

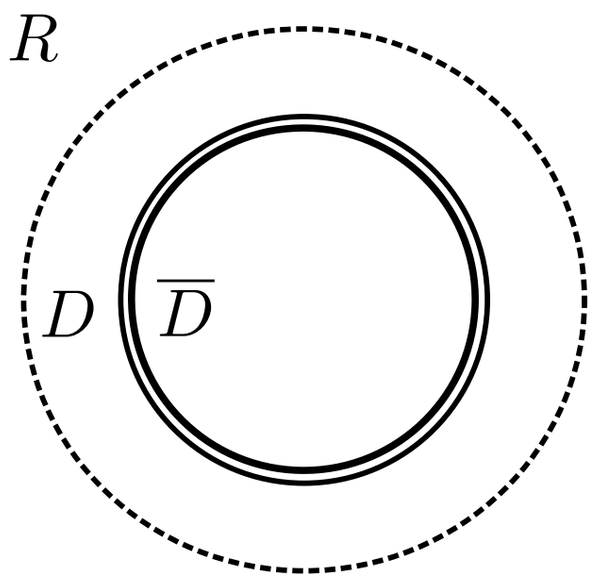

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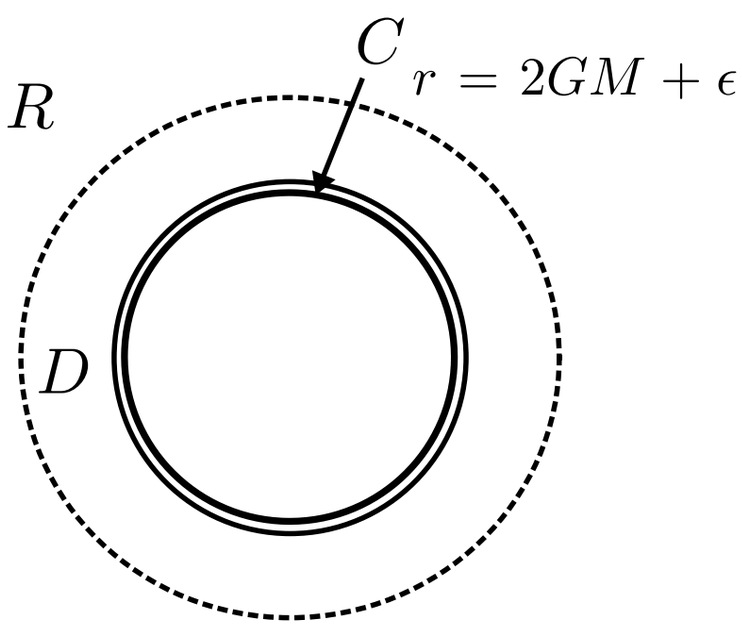

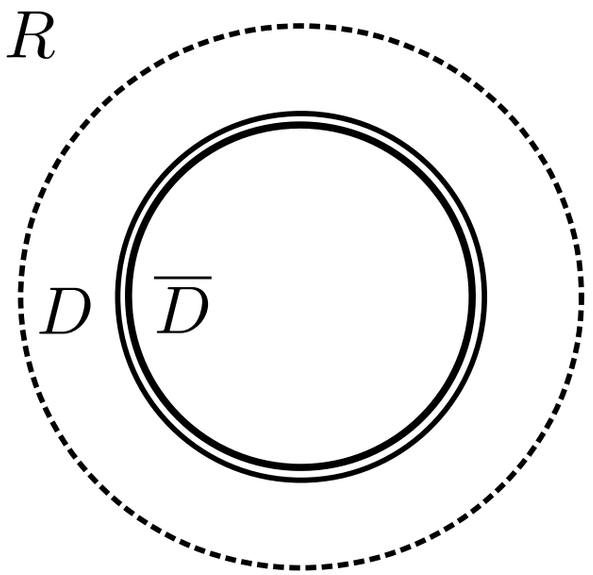

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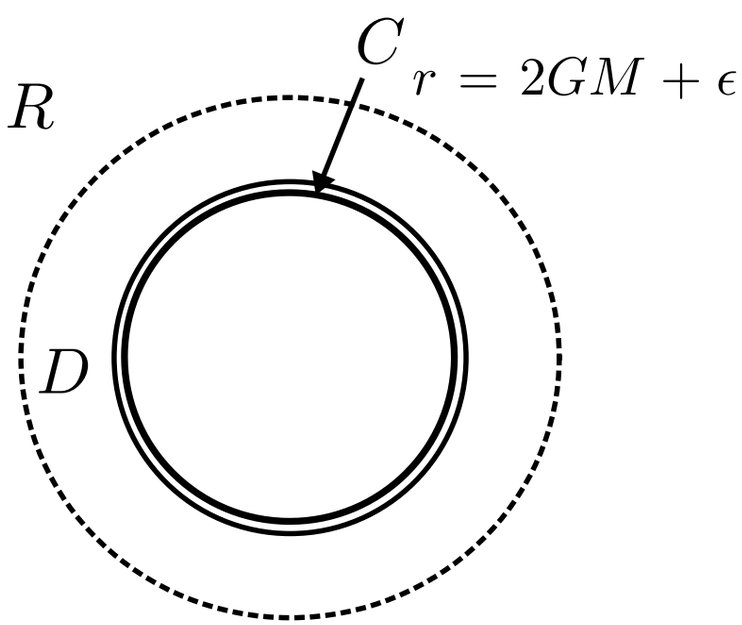
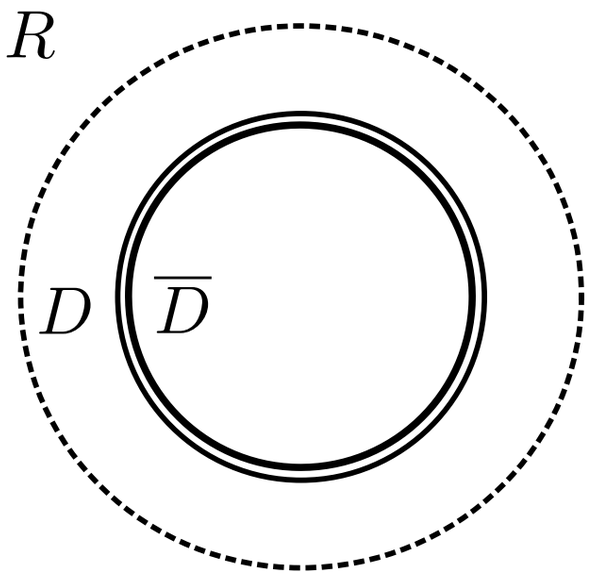
$\longrightarrow$

$I(D, \bar{D}) \approx 0$ firewall?





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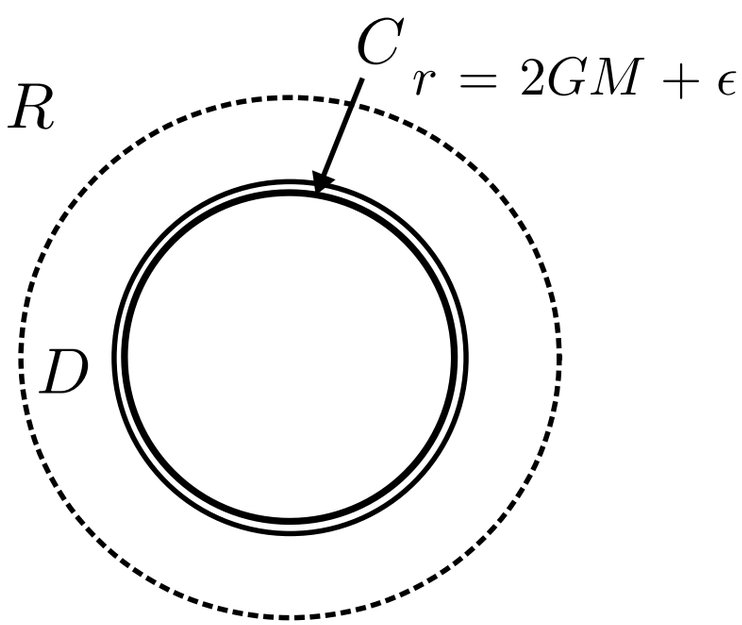
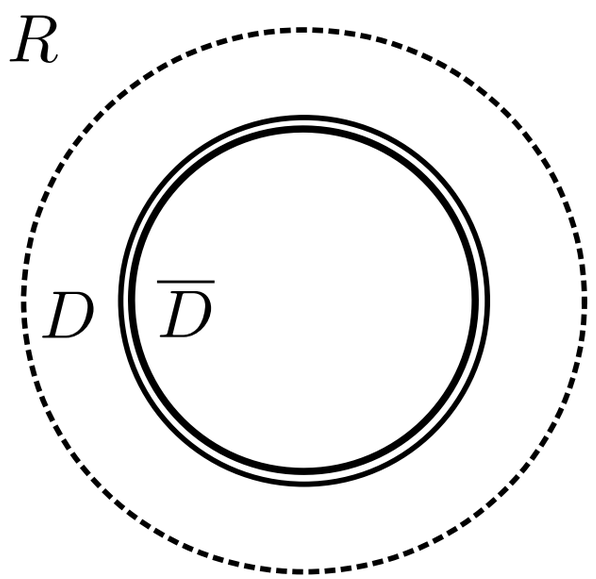
Monogamy of entanglement

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





Interior operators

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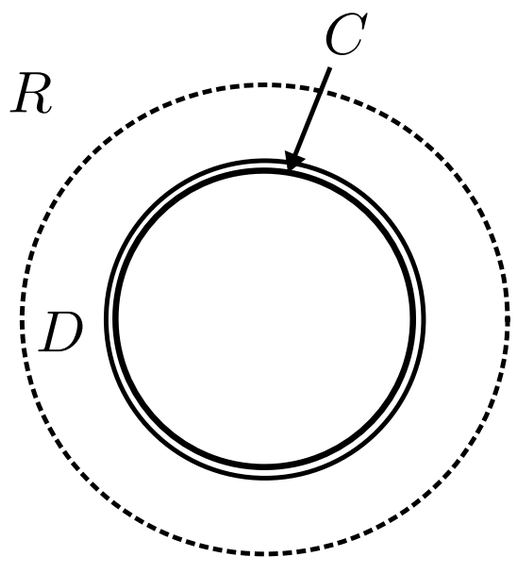

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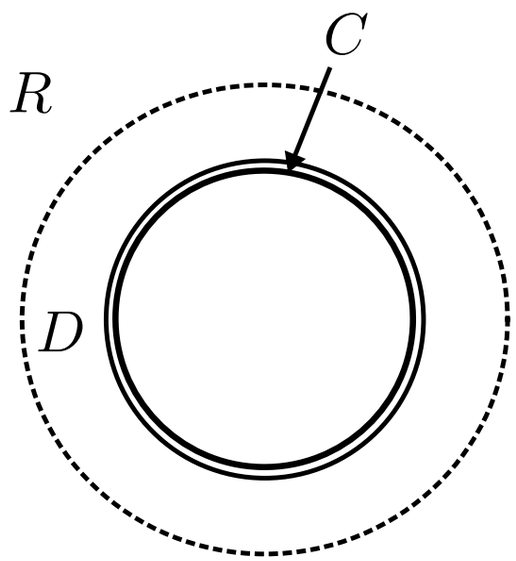
  Place R at a far distant universe.

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



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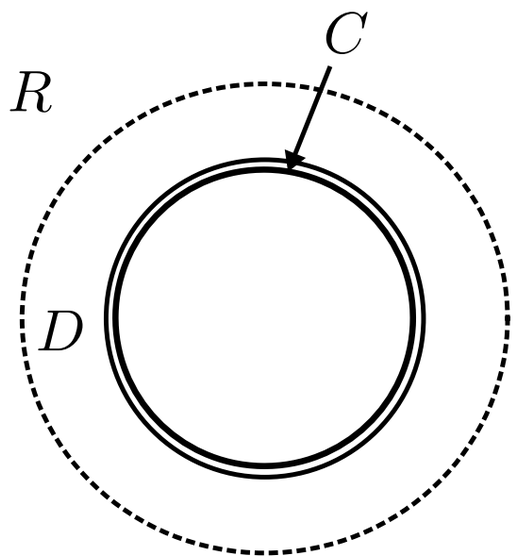

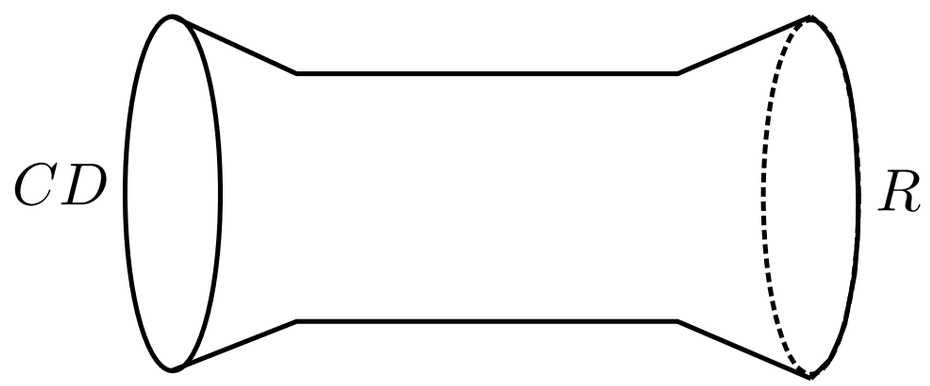

Two-sided AdS black hole

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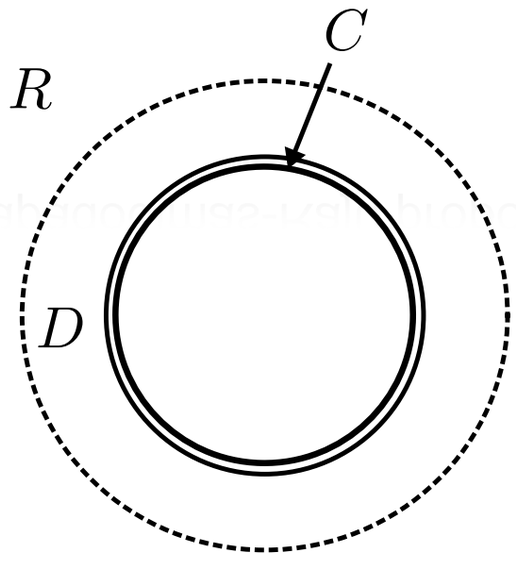
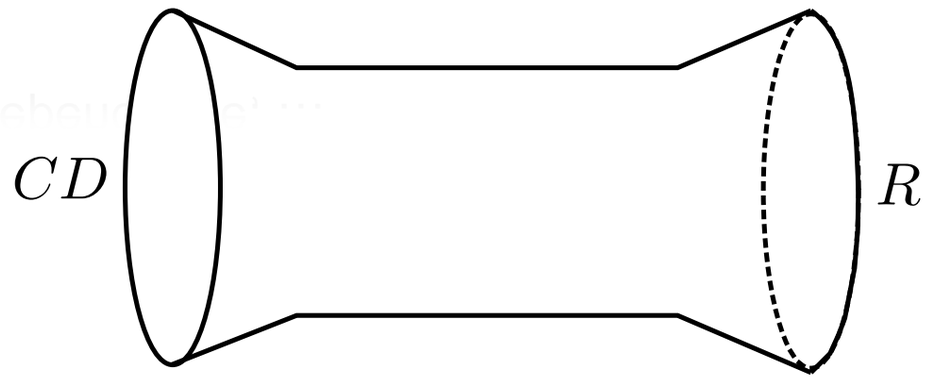
- State-dependence problem
  - Interior operators depend on the state, namely R.
  - Violation of Born rule, Frozen vacuum, …
  - Papadodimas-Raju proposal for state-dependence, …





Two-sided AdS black hole

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IFQ lecture (4th week)

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

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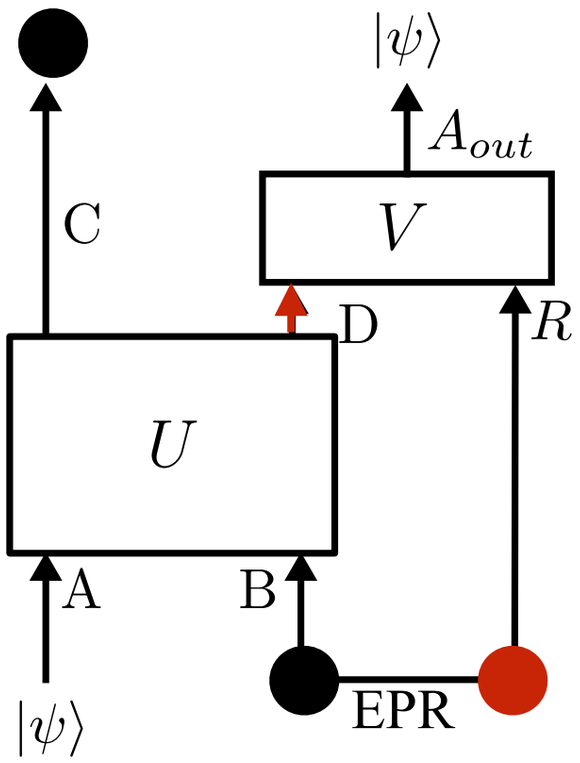

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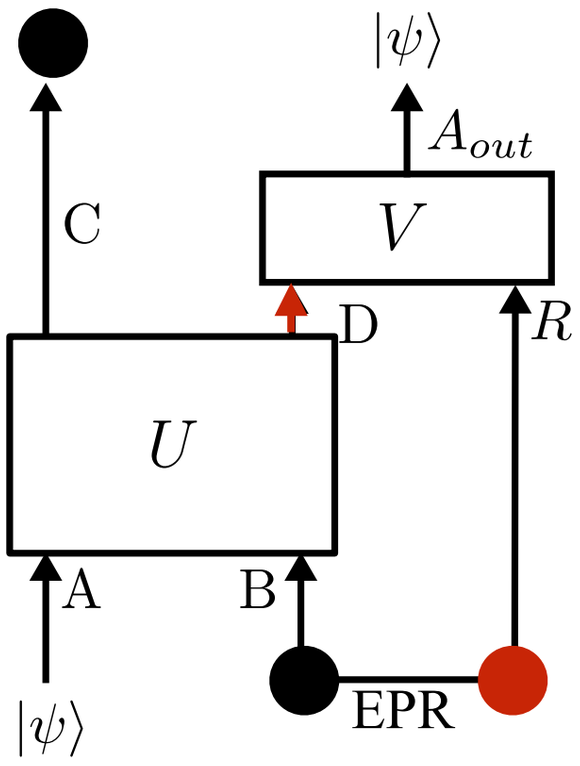
- Bob needs to collect just a few qubits from D.

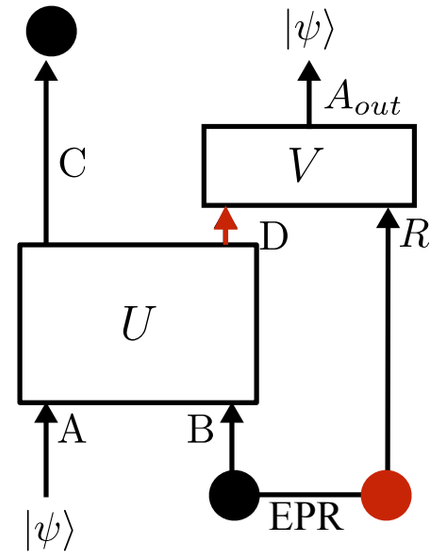


"Black hole as mirrors" (Hayden-Preskill)

V : recovery unitary

Out-of-time order correlation

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



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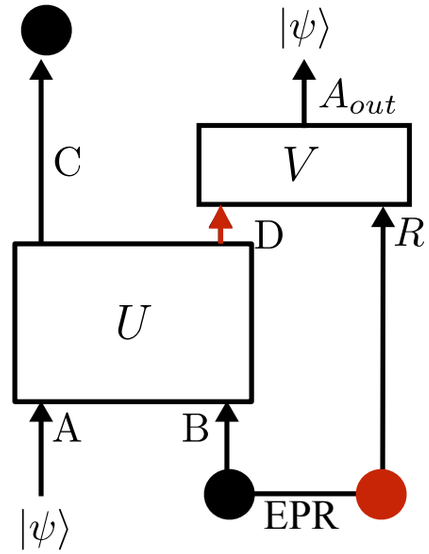
$$\langle O_A(0) O_D(t) O_A^\dagger(0) O_D^\dagger(t) \rangle \equiv \frac{1}{d} \mathrm{Tr} \left(O_A U^\dagger O_D U O_A^\dagger U^\dagger O_D^\dagger U \right)$$



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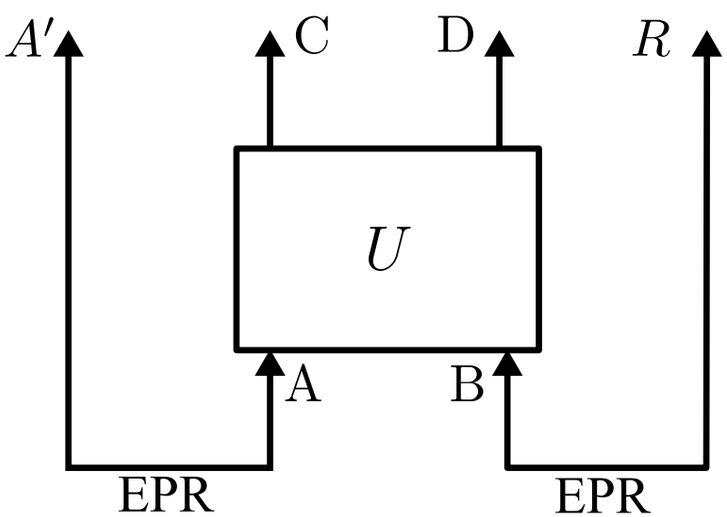
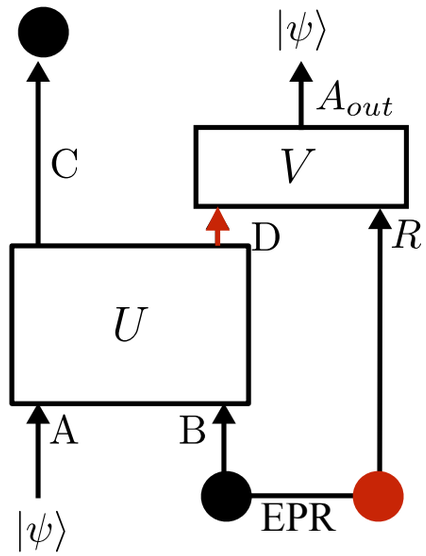


"state representation" of U



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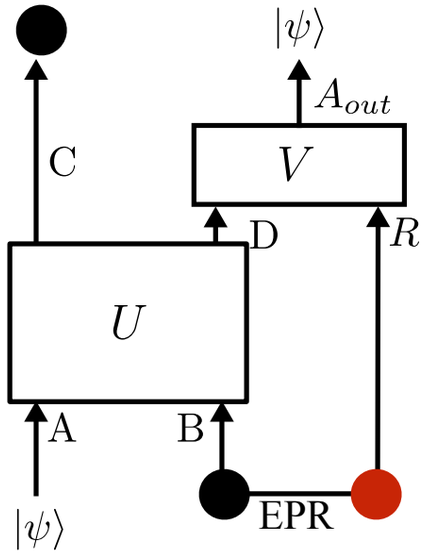
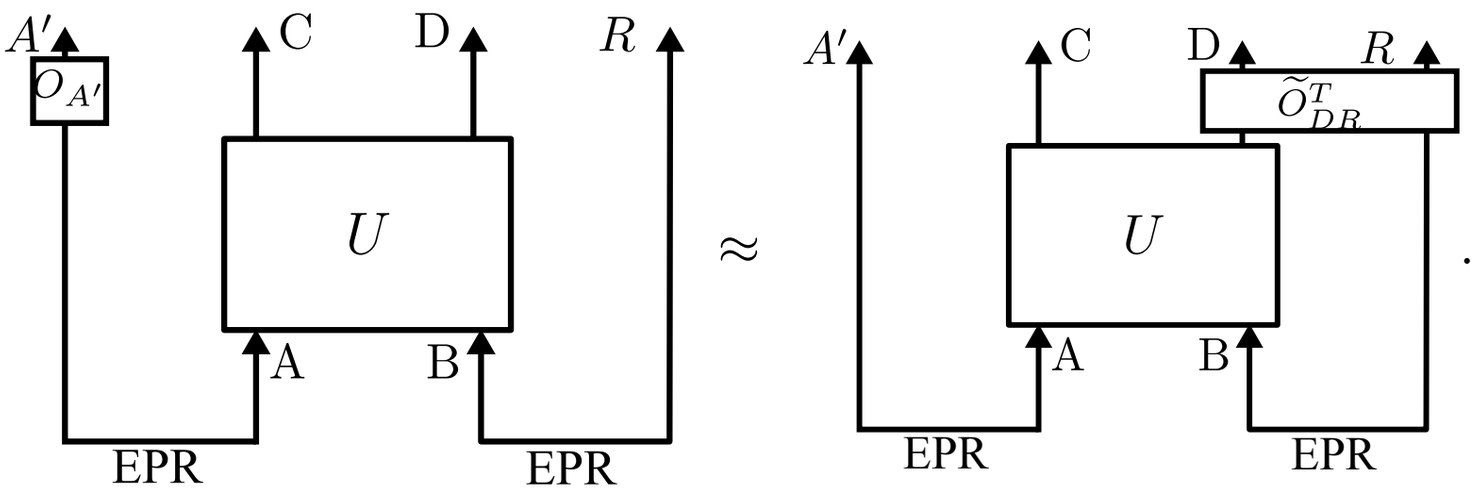


"partner operator"



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

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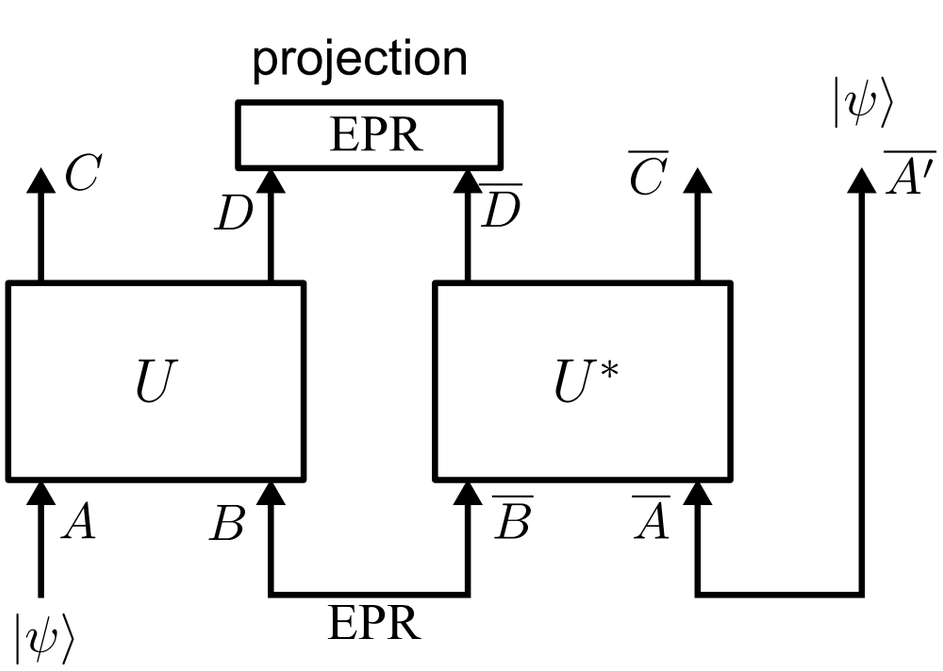

“Decoding protocol”

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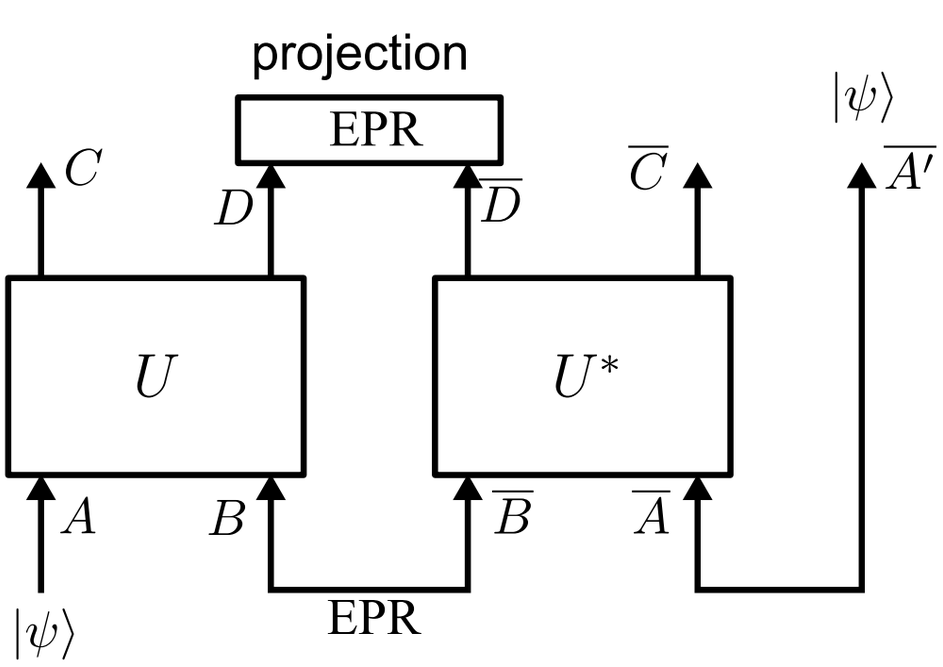

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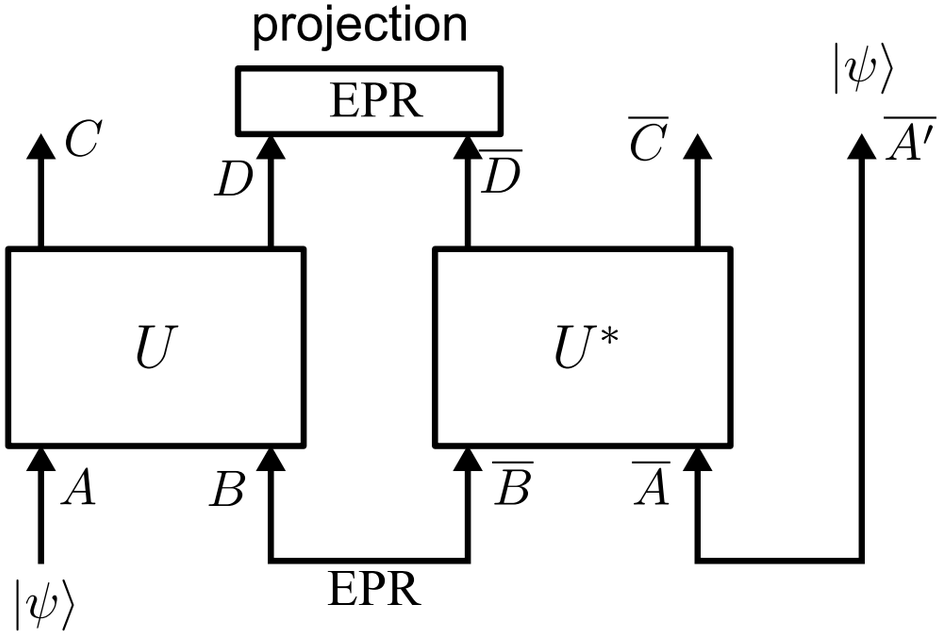

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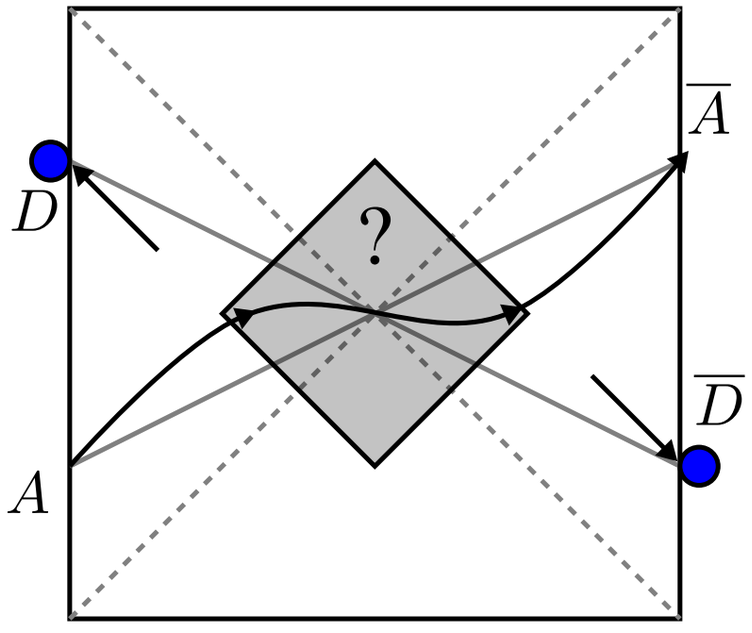

“Traversable wormhole”

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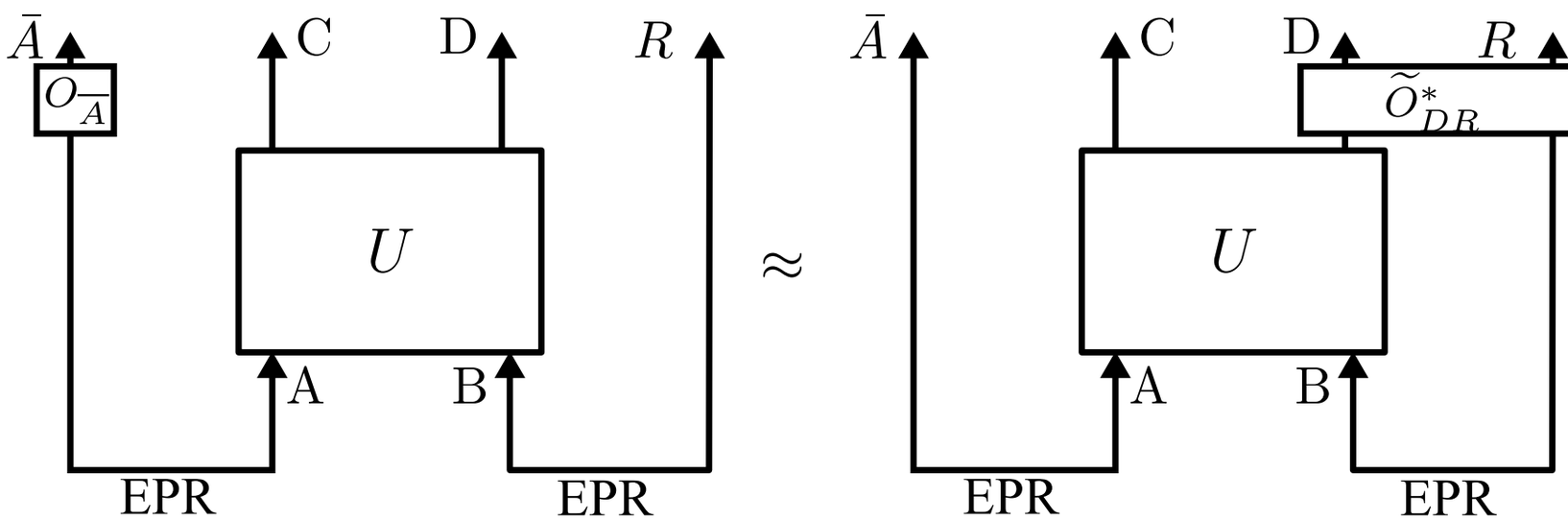
Interior operators

- Recall the Hayden-Preskill recovery



Interior operators

- and the AMPS problem…

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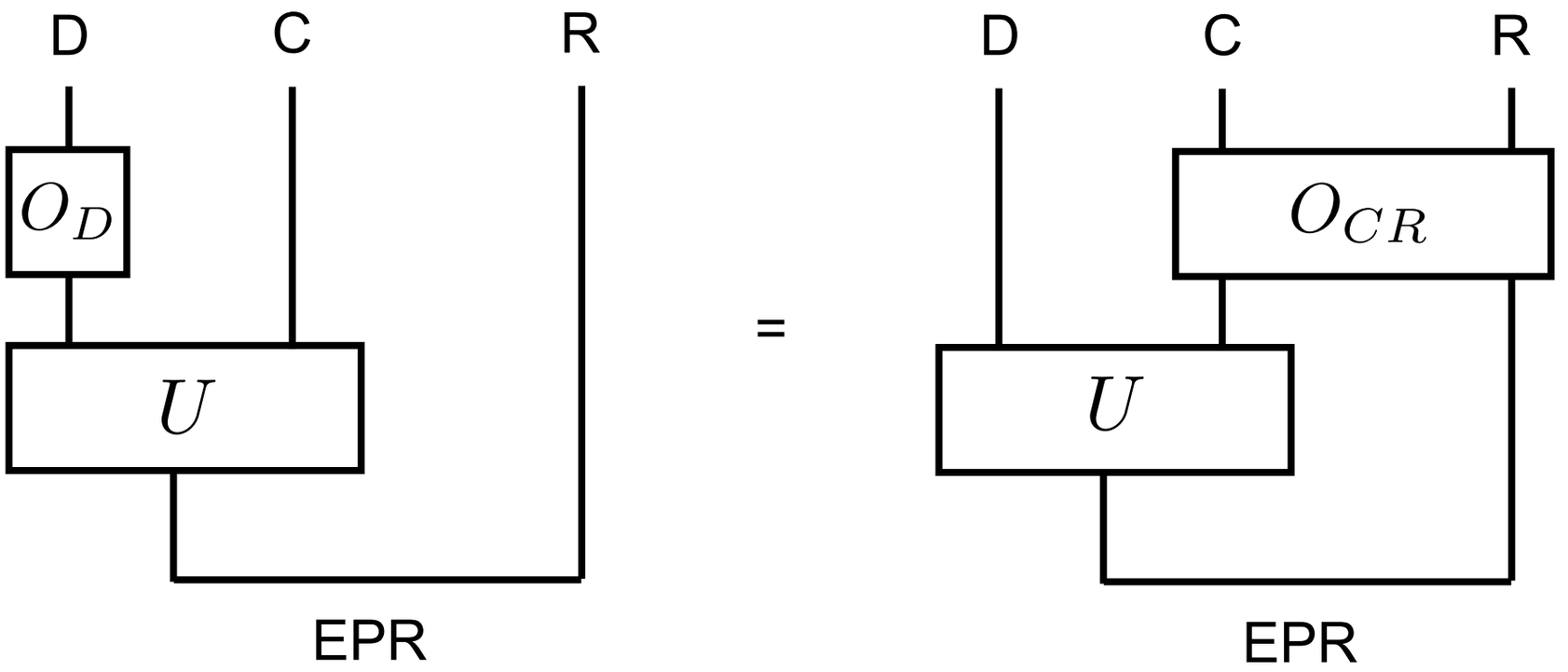

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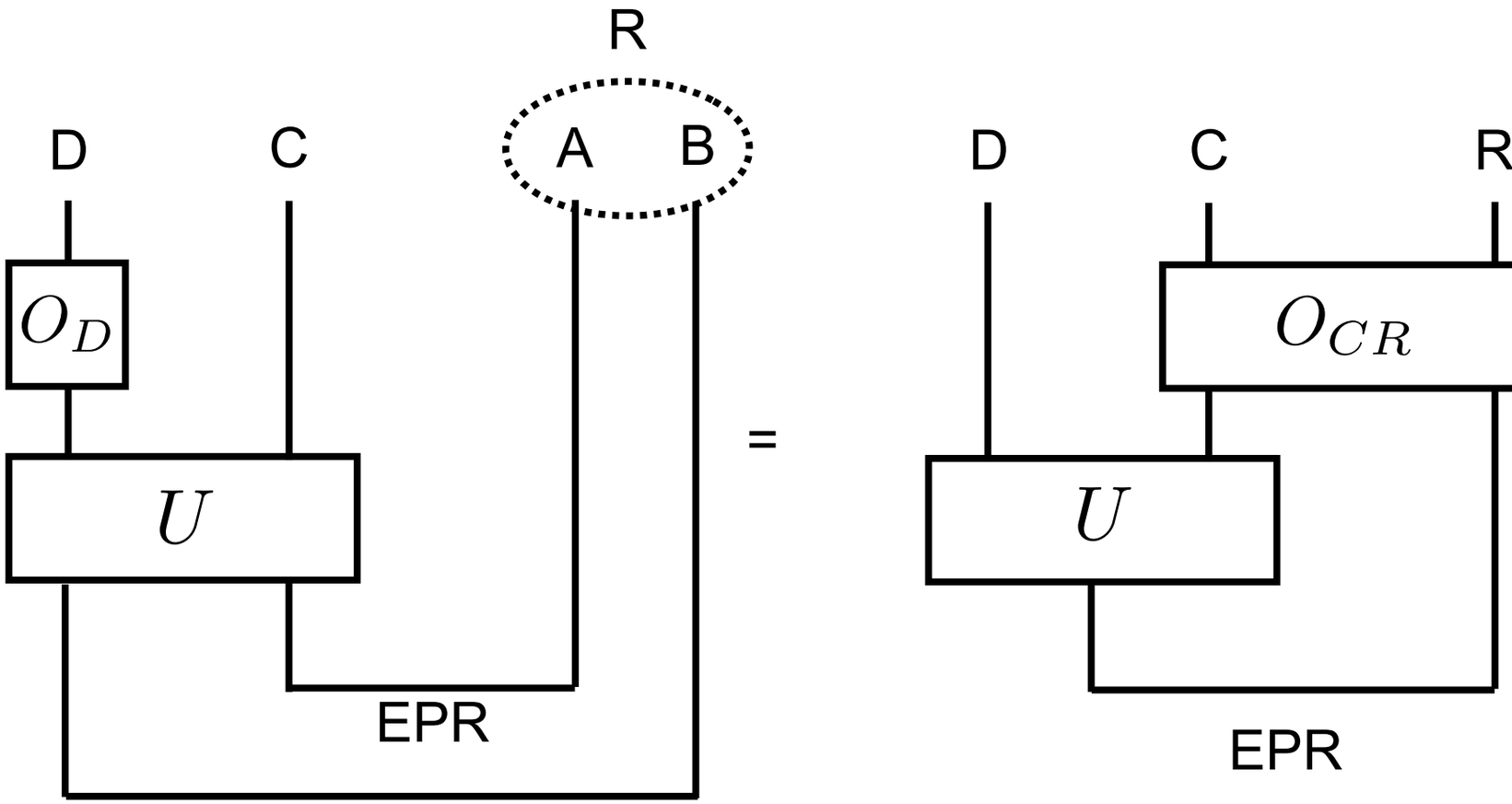

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Split R into AB

Interior operators

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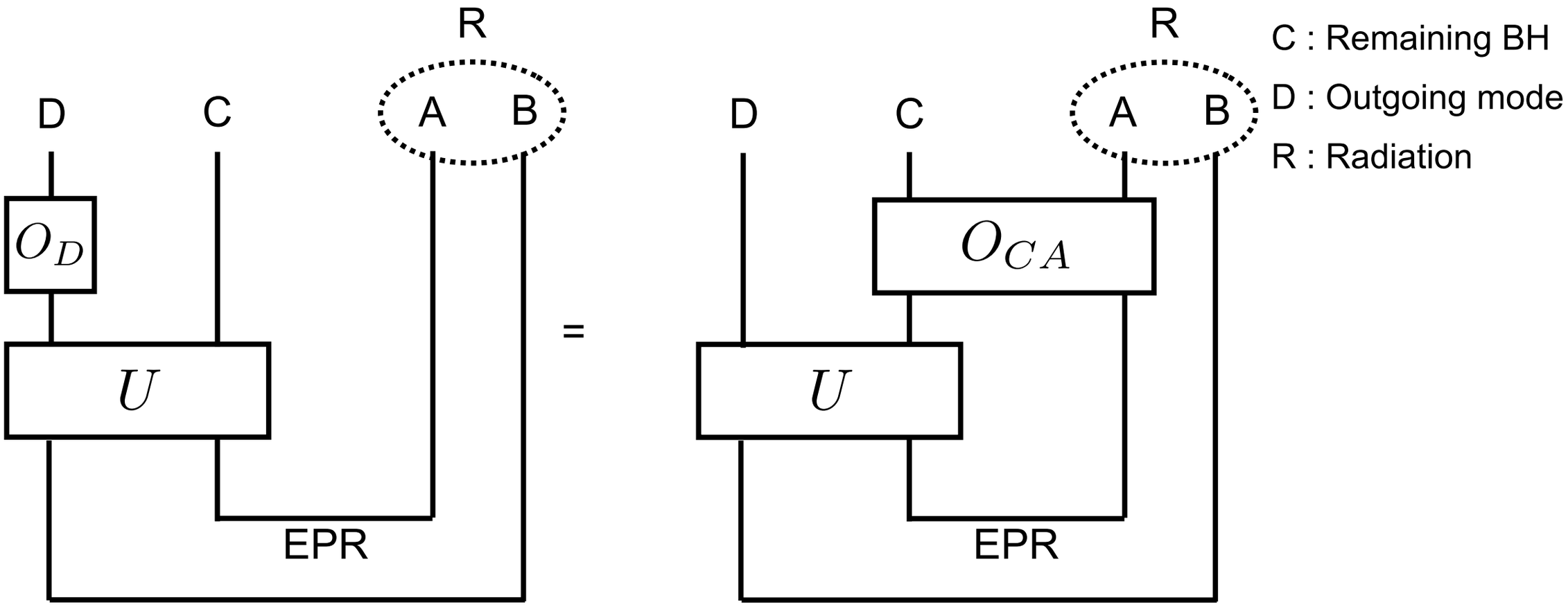

Split R into AB

Reconstruct on CA.

Interior operators

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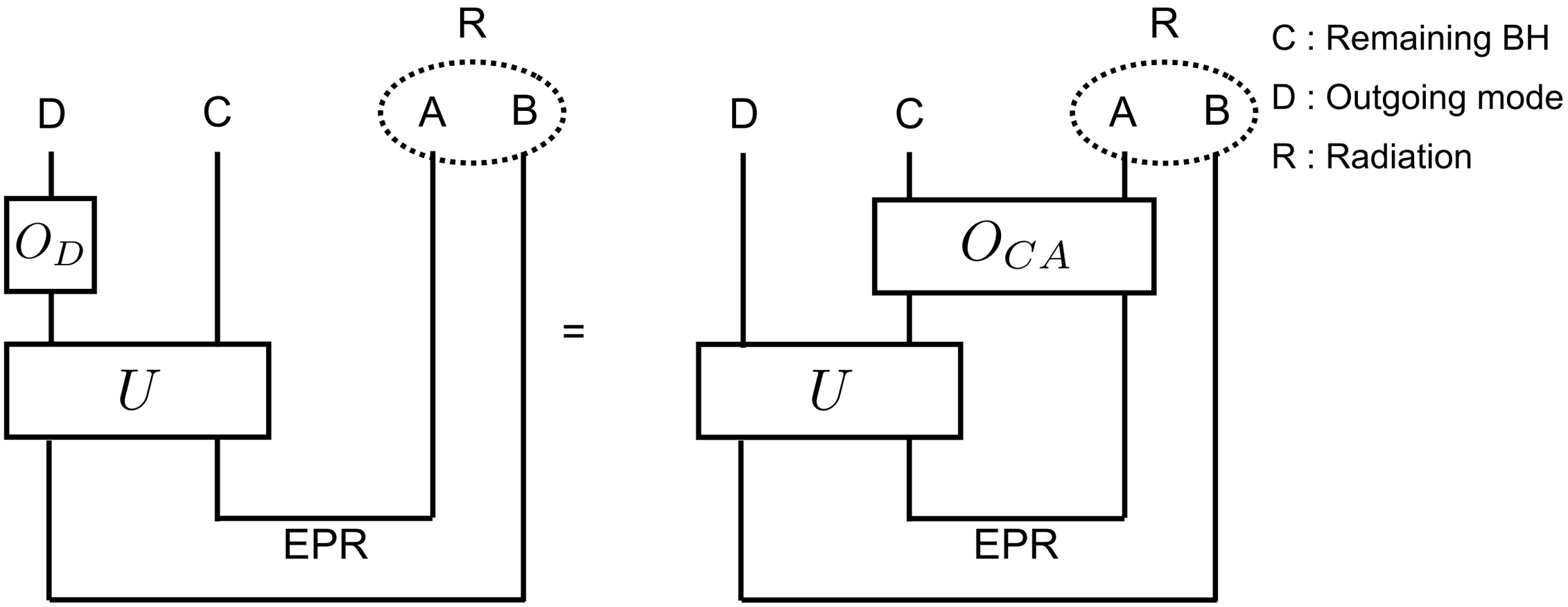

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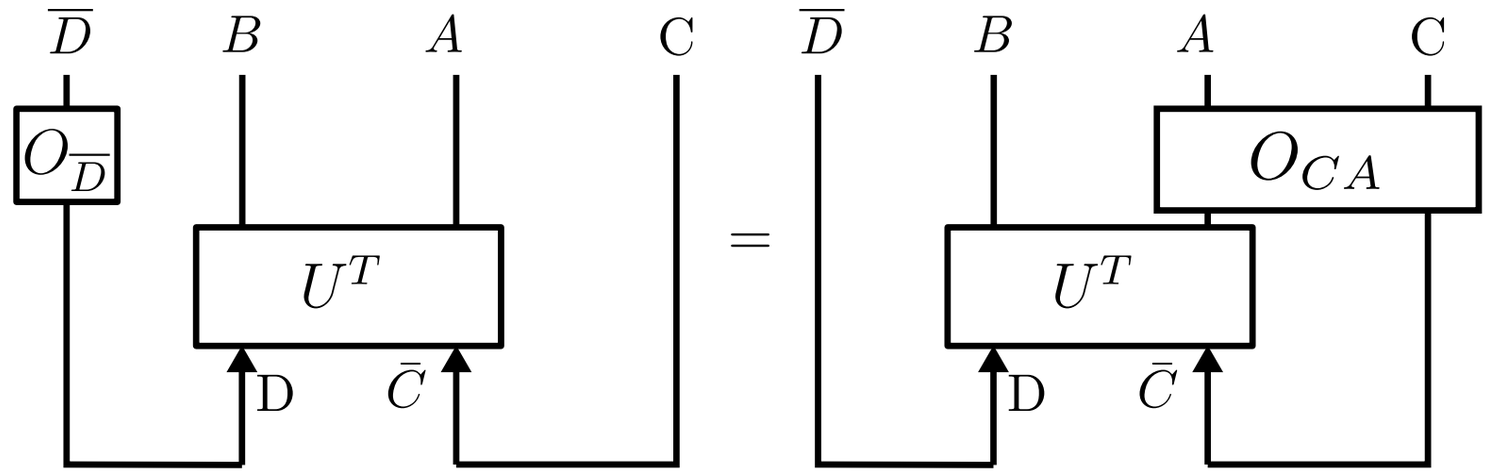
Rotate the figure…

Interior operators

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



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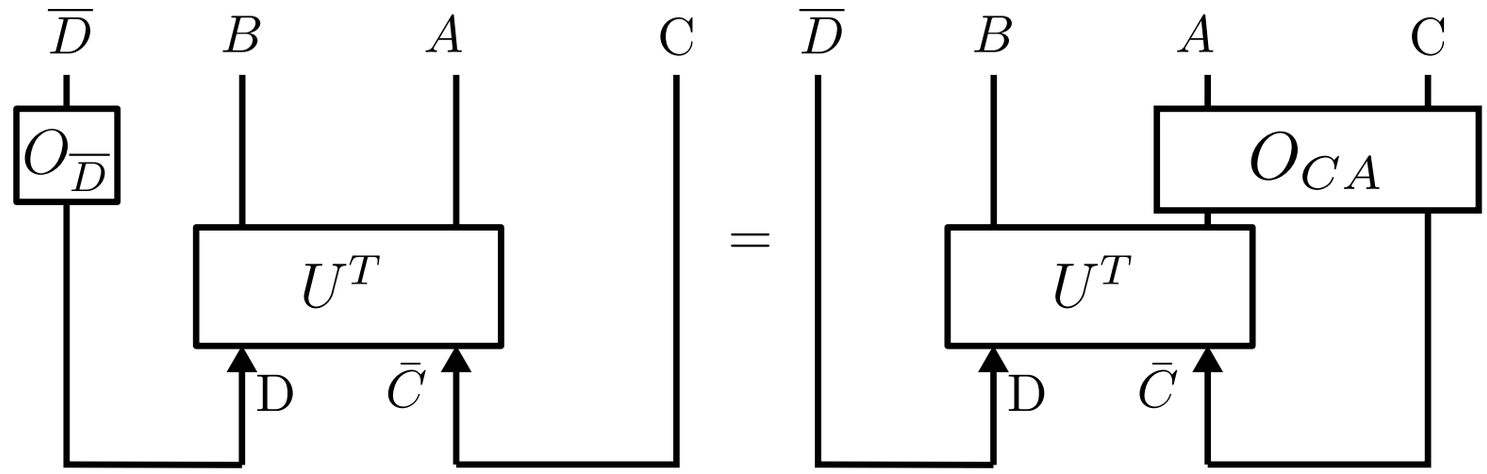

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AMPS Reconstruct D (outgoing) from C (remaining BH) and A (early mode)

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

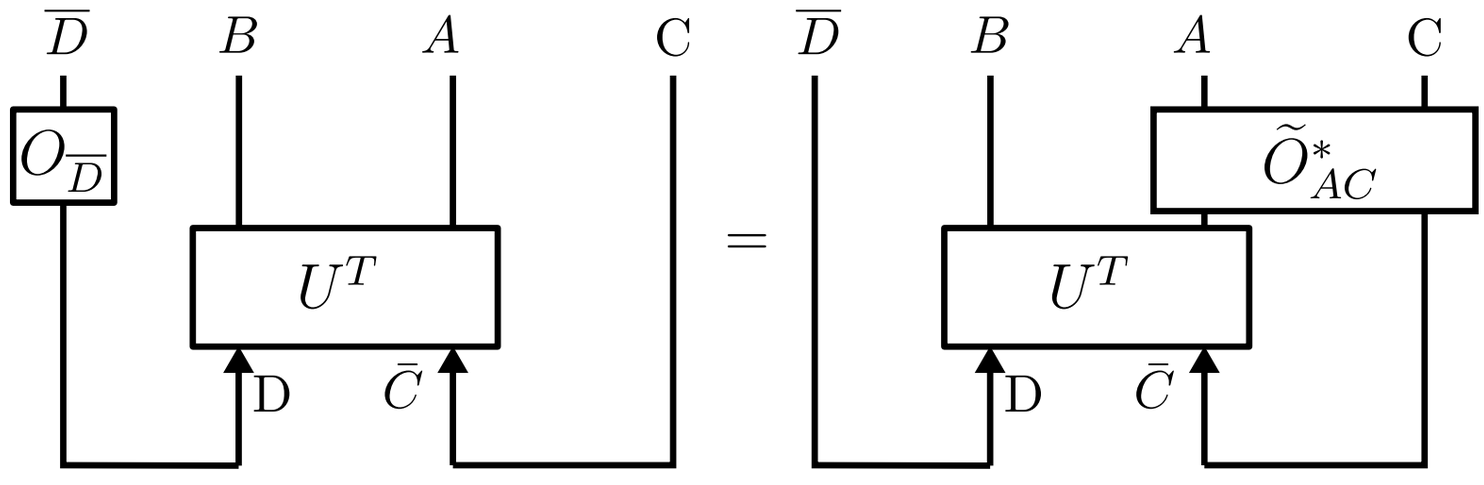
Interior operators

- 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



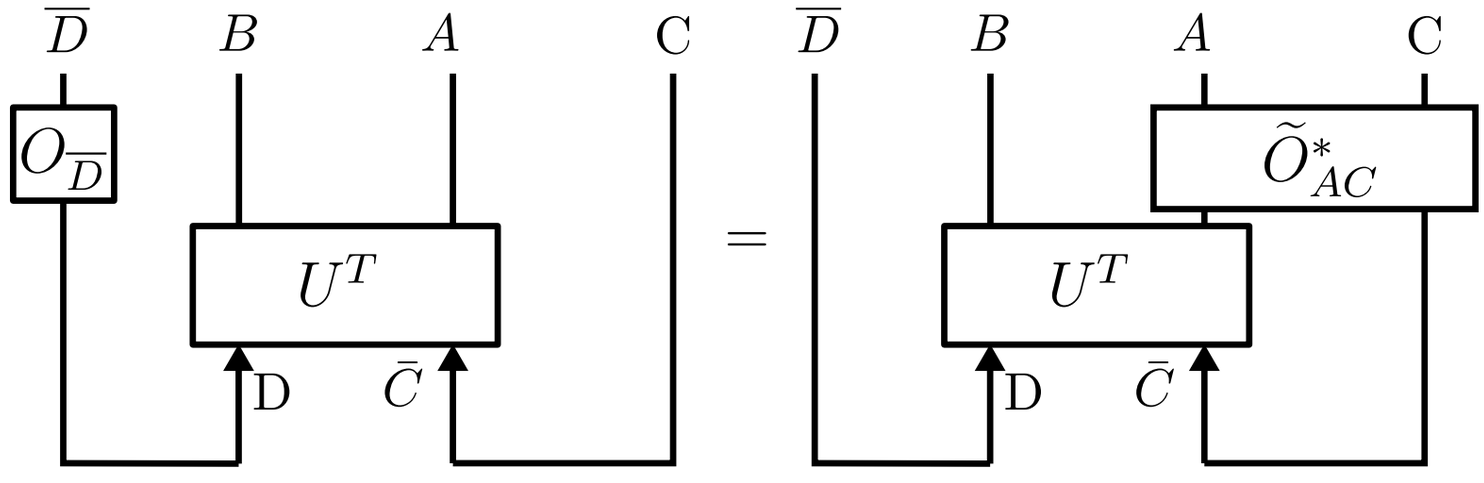
Interior operators

- 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.
- Problems …
  - Construction is state-dependent. $(I \otimes K)|\mathrm{EPR}\rangle$
  - Non-locality problem (use of A)

C : Remaining BH

D : The zone

R : Radiation



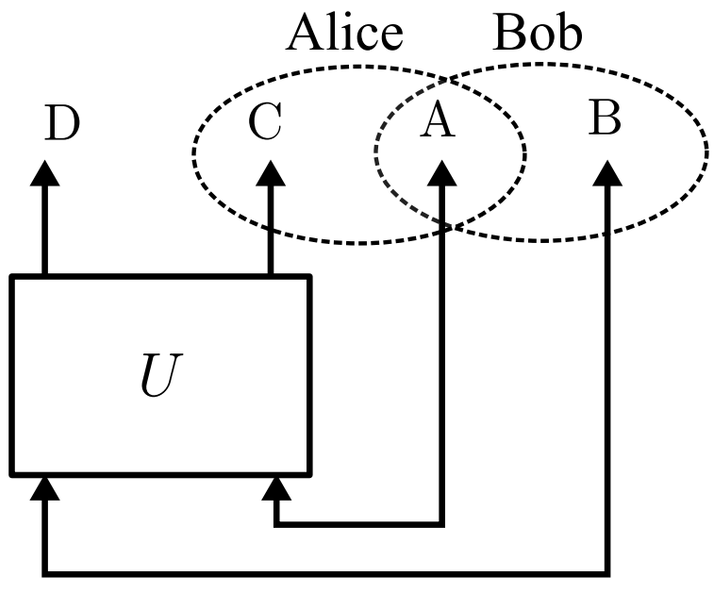
Some lesson

Some lesson

- 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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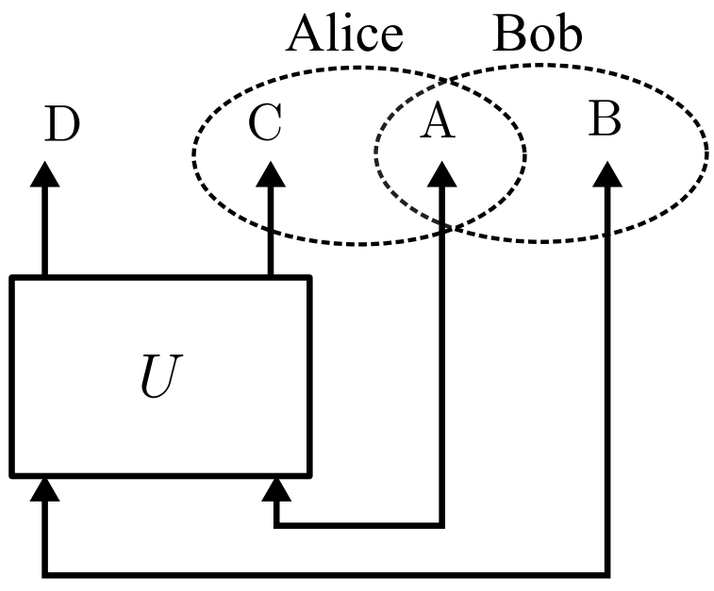

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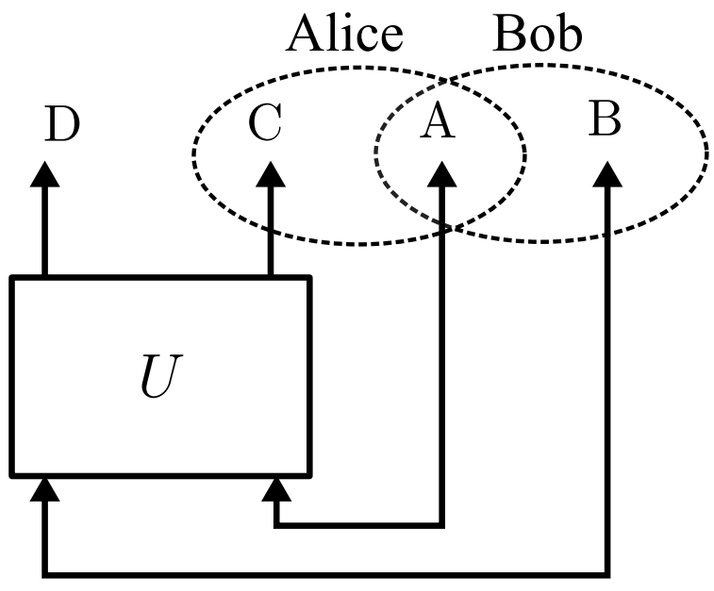

AB : Radiation (R)

C : remaining black hole

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- We can choose A to be any small subsystem !

- Alice does not need to take A. She simply needs to fall into a black hole.

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

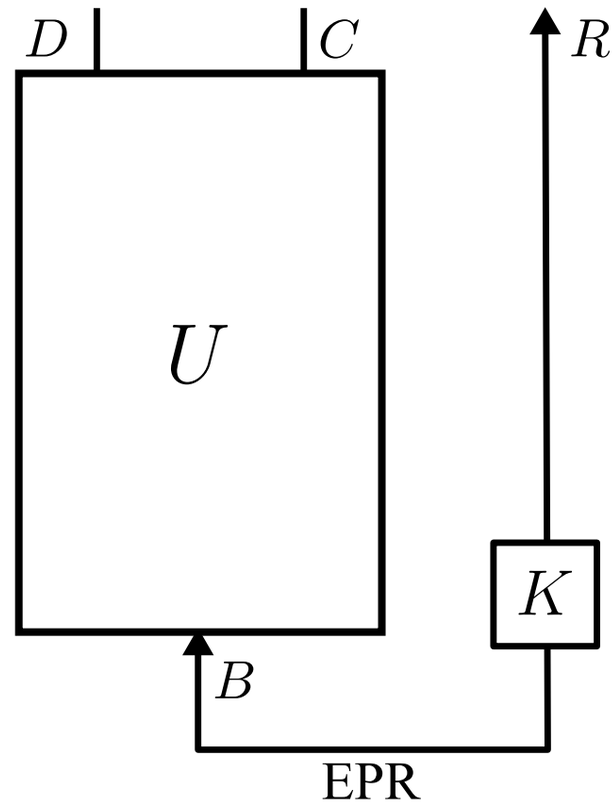
6 Resolution of the puzzle

7 Discussions

Beni Yoshida (Perimeter Institute)

“Generic” two-sided “AdS” black hole

- Generic two-sided AdS BH $(I \otimes K)|\mathrm{EPR}\rangle$



Generic two-sided AdS = K is arbitrary, BH not evaporating

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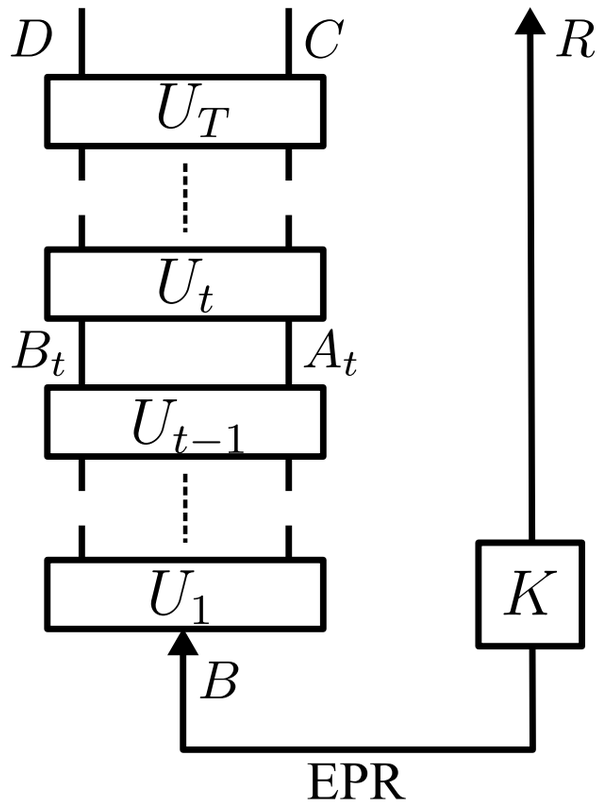

A_t : boundary modes

B_t : other modes

Generic two-sided AdS = K is arbitrary, BH not evaporating

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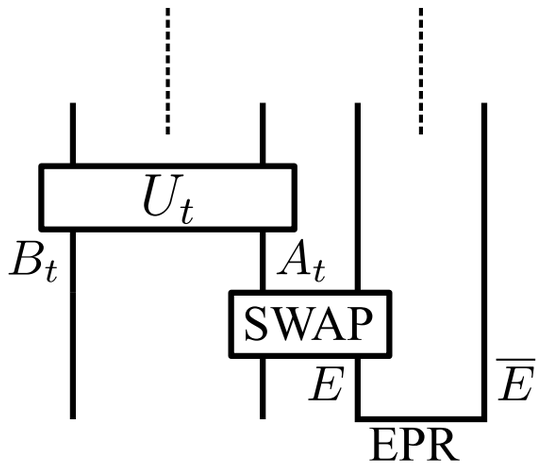
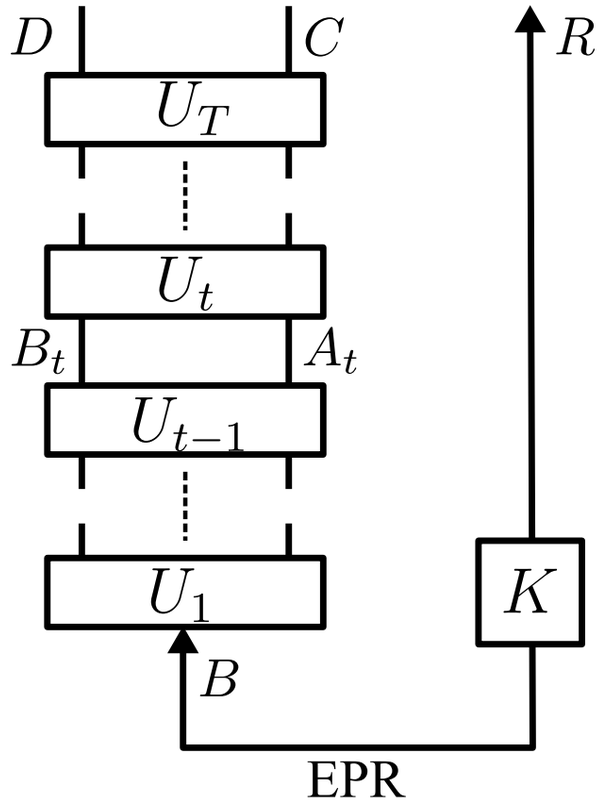
Prepare ancillary EPR and apply SWAP





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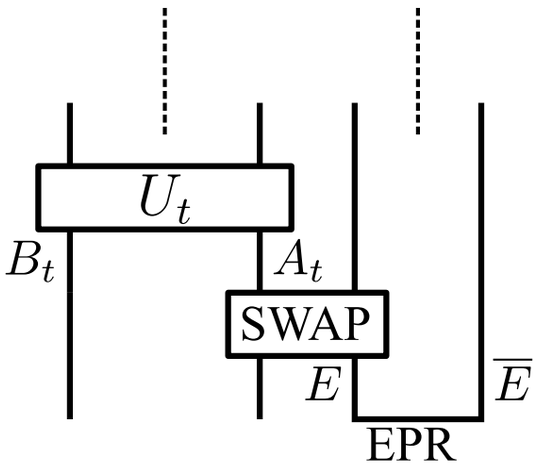

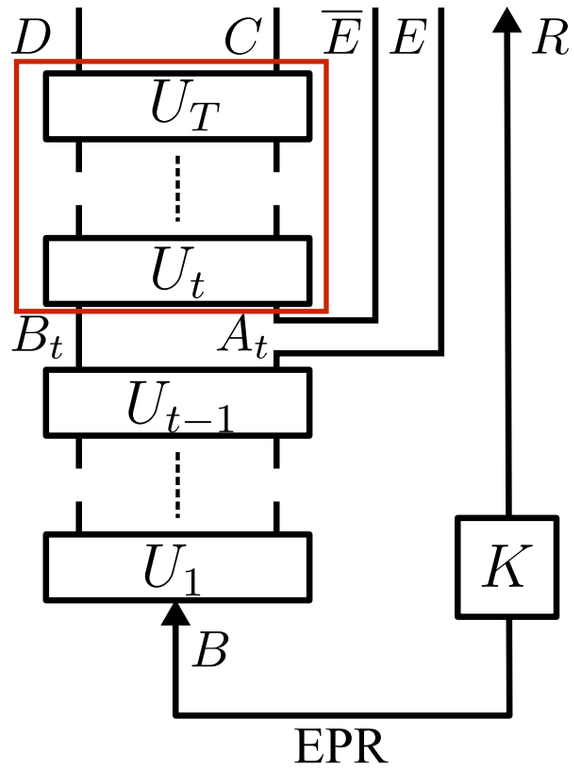

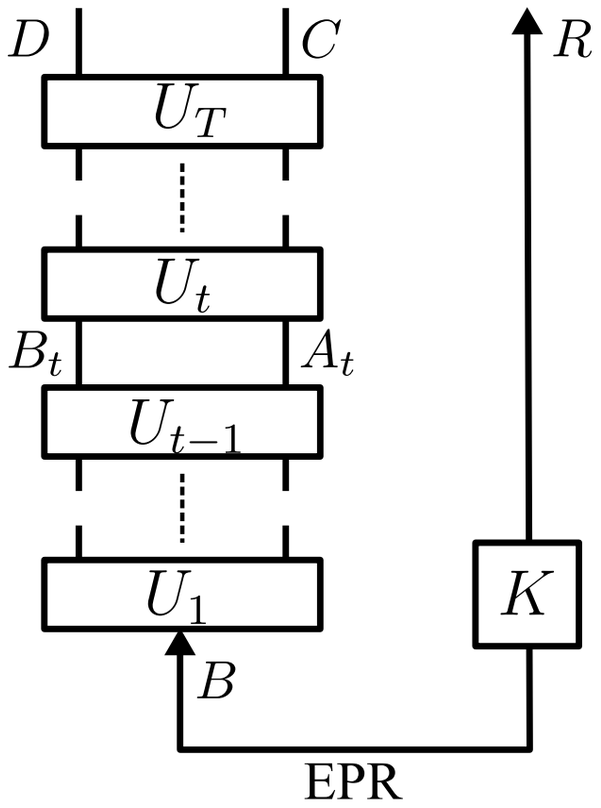

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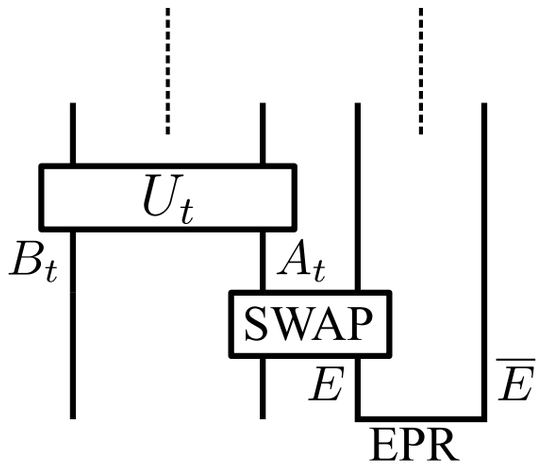

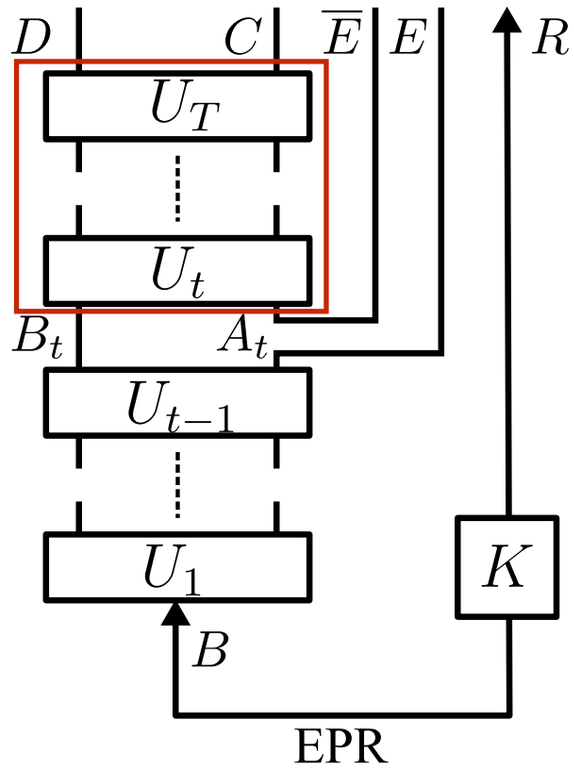

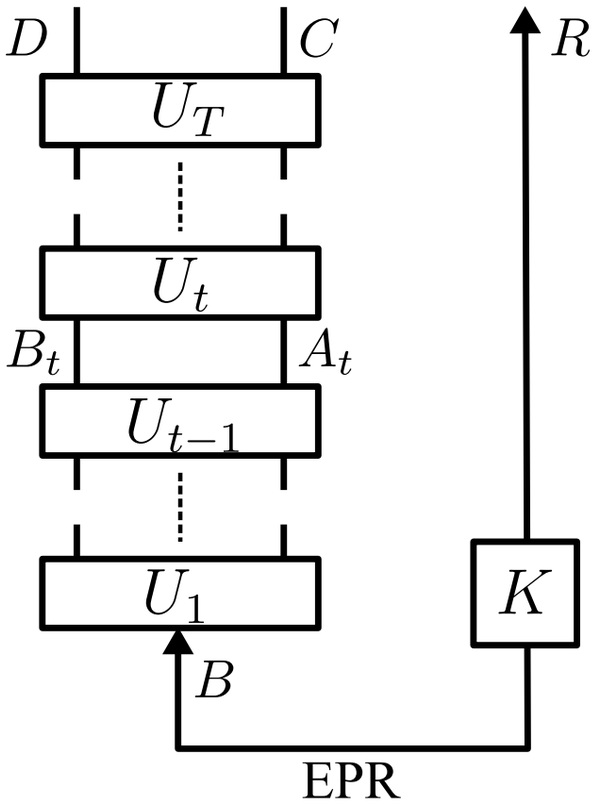

A_t : boundary modes

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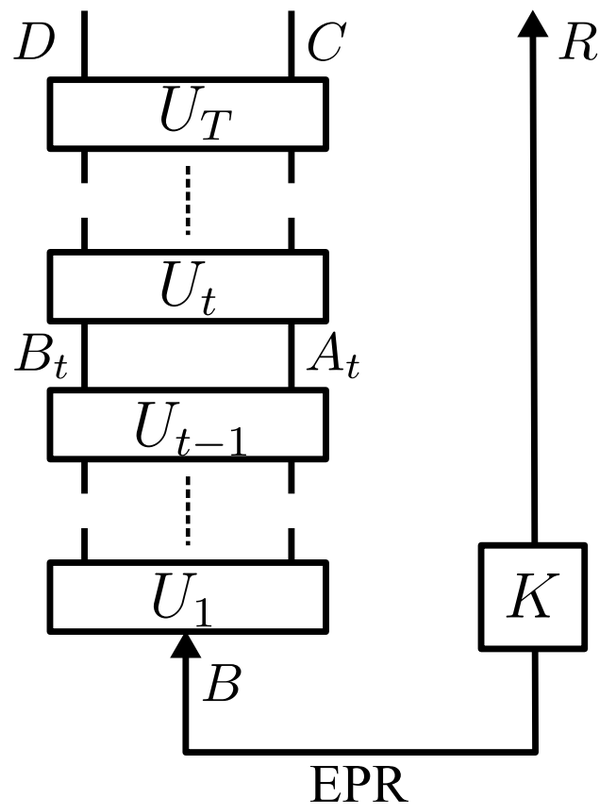
- $\bar{D}$ can be reconstructed on C and A_t

without ever accessing R

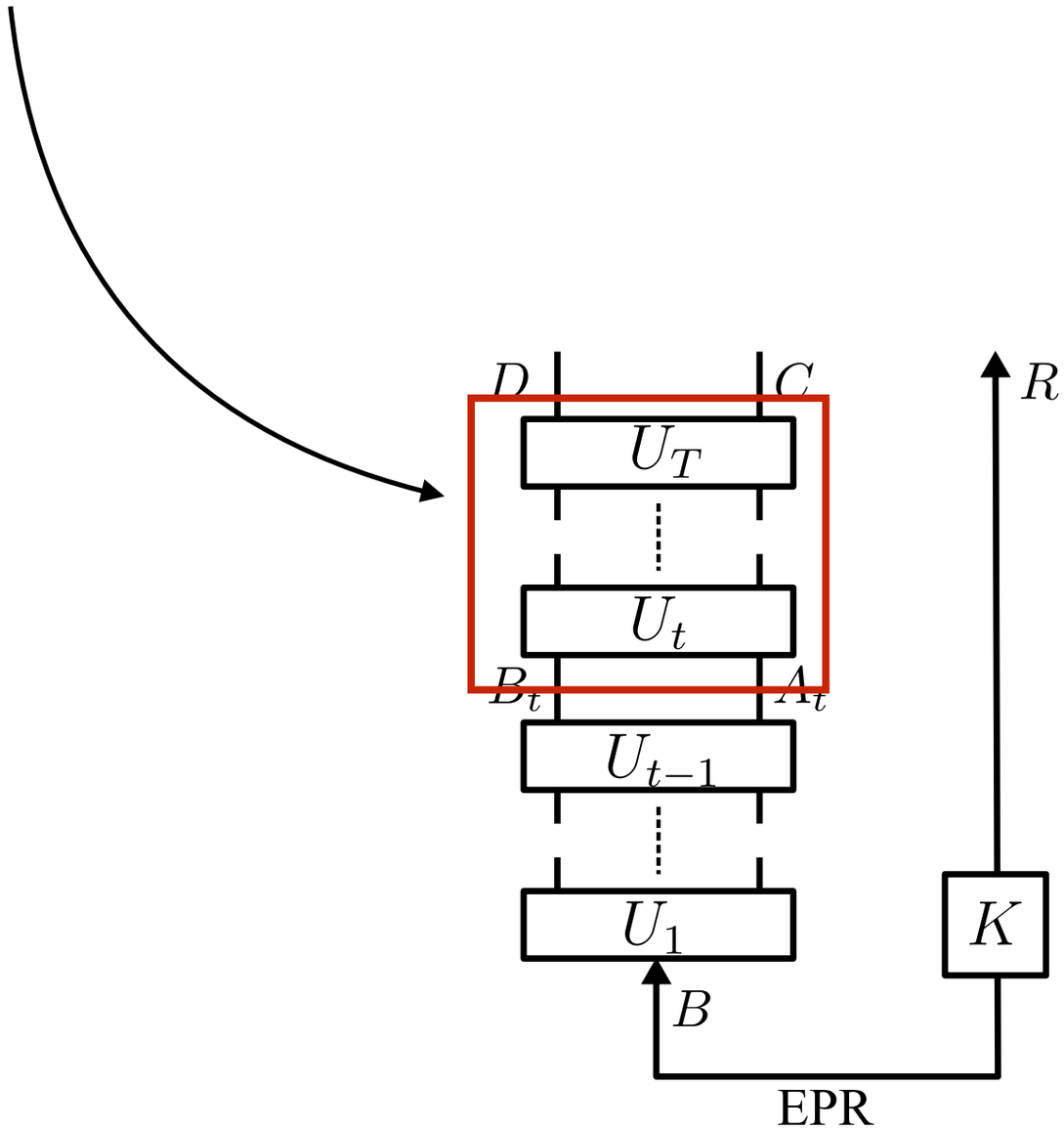
Generic two-sided AdS = K is arbitrary, BH not evaporating

State-independence



State-independence

- Construction does not depend on K



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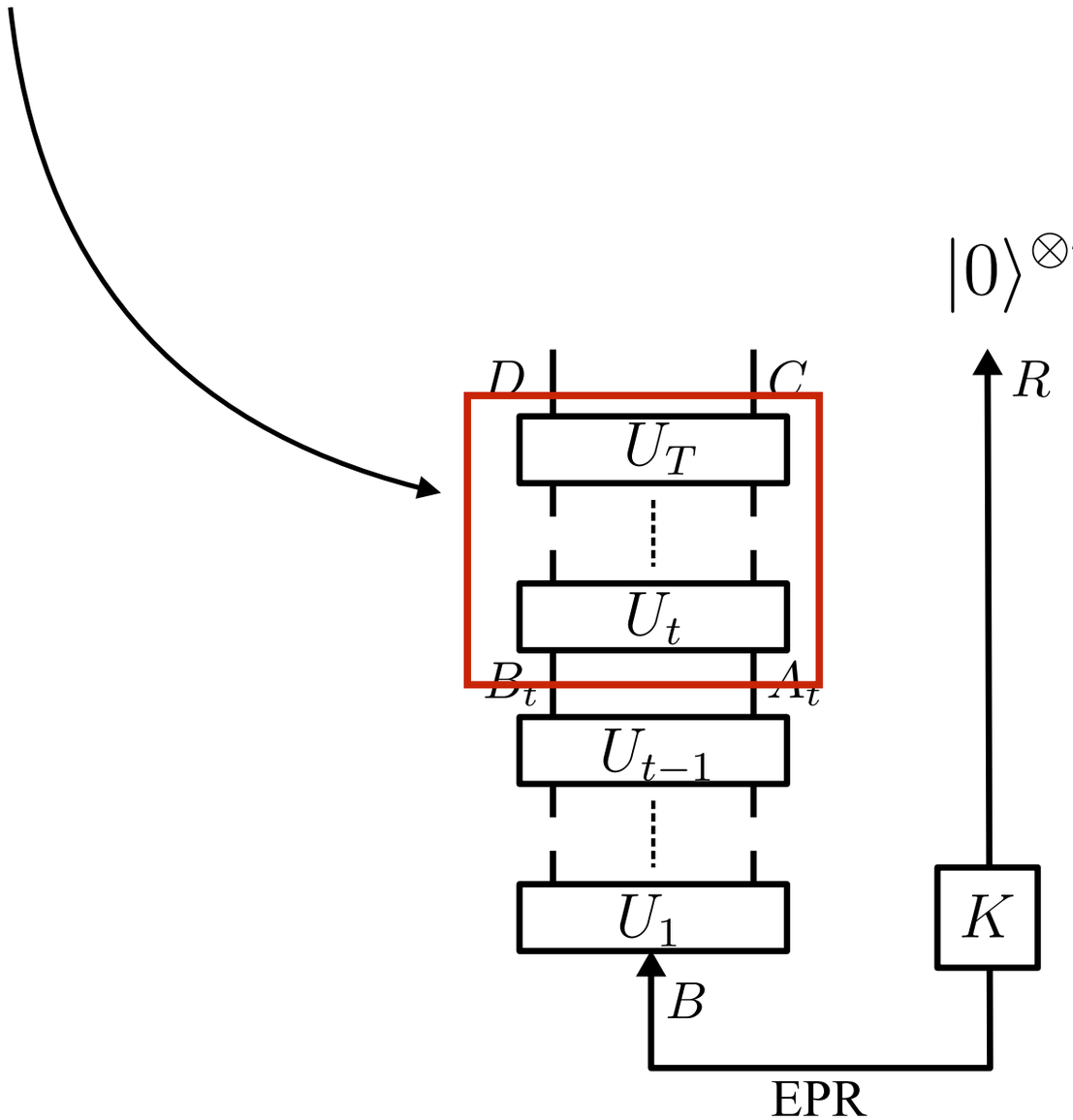
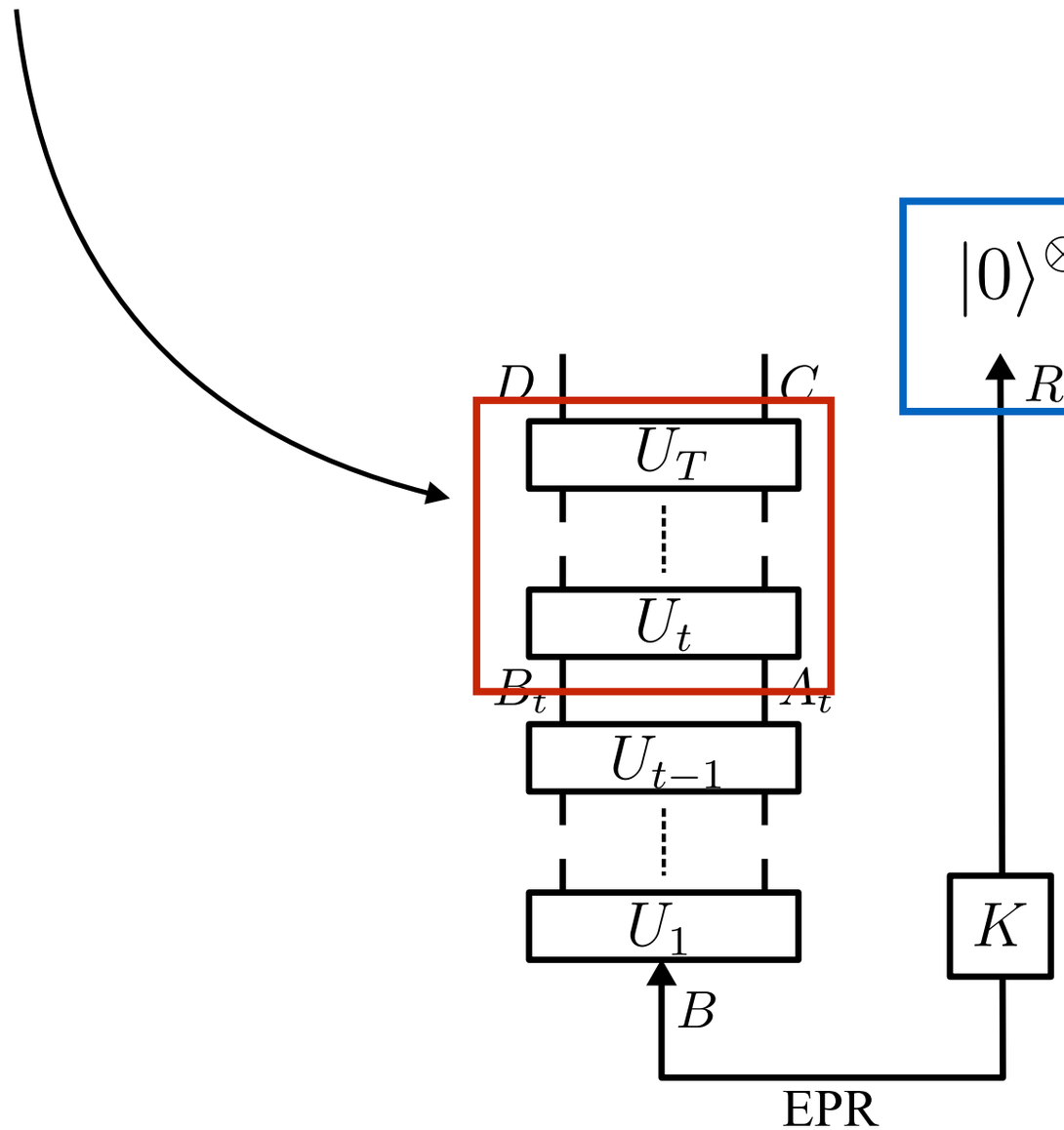


State-independence

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

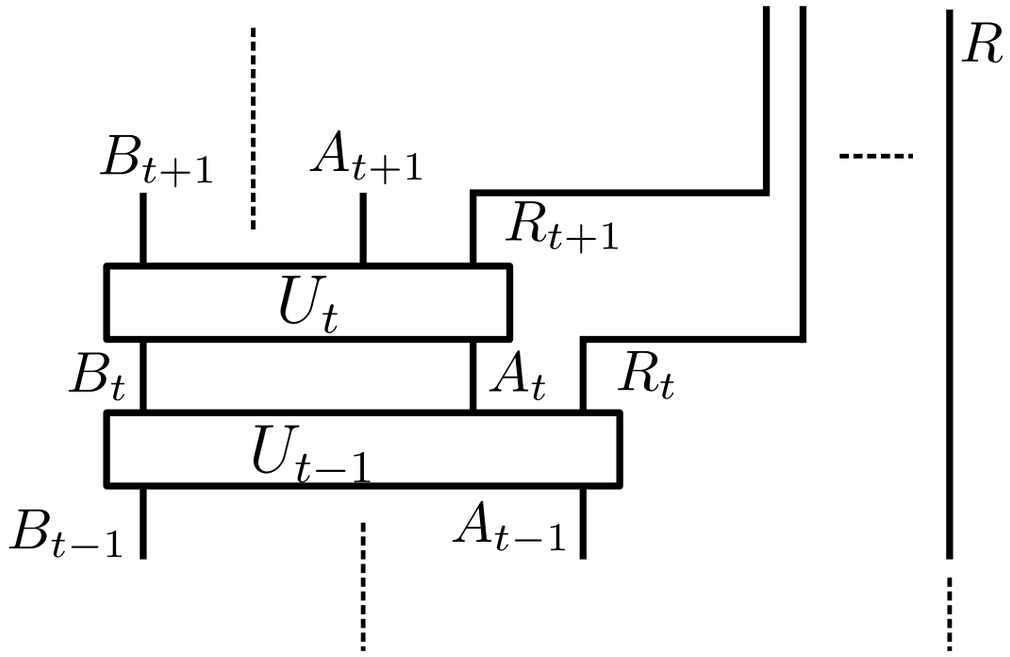


Evaporating black hole

R_t : high-energy radiation

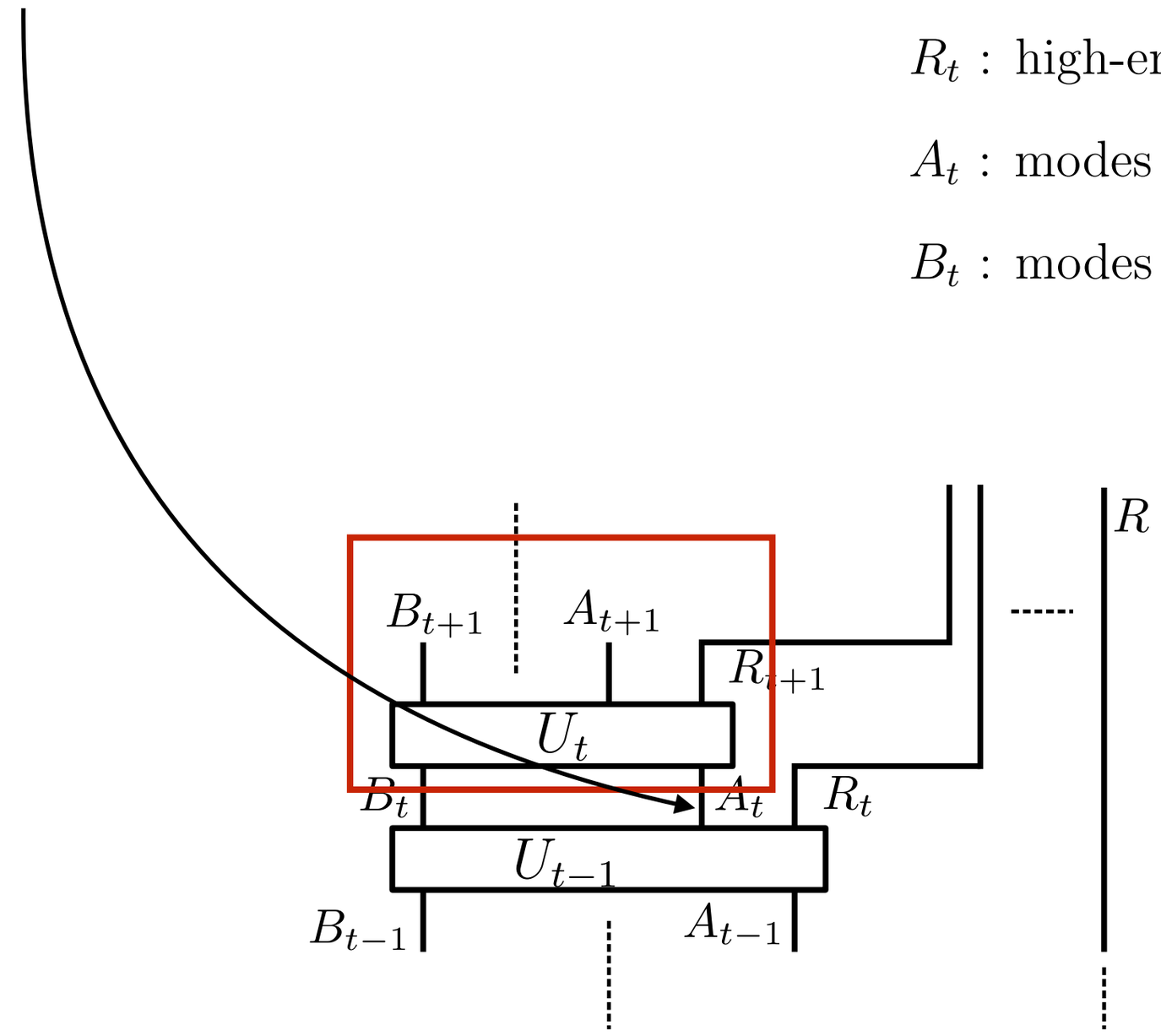
A_t : modes on the zone

B_t : modes at stretched horizon



Evaporating black hole

- Use A_t not R



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Codeword subspaces

- State-independence inside codeword subspace

  “S-qubit” toy model

  Coarse-grained Hilbert space $\mathcal{H}_{\rm code} \approx 2^{S_{\rm BH}}\text{-dimensional}$, determined by M, J, Q…

  $\mathcal{H}_{\rm code}$: wavefunctions with the same classical geometry

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- Eigenstate Thermalization Hypothesis (ETH)

- Claim: state-independence for black holes initially in thermal equilibrium.

$\approx r_S$	$\approx r_S \log r_S$
thermalization time	scrambling time

Firewall vs. Scrambling

1 Review of Firewall argument

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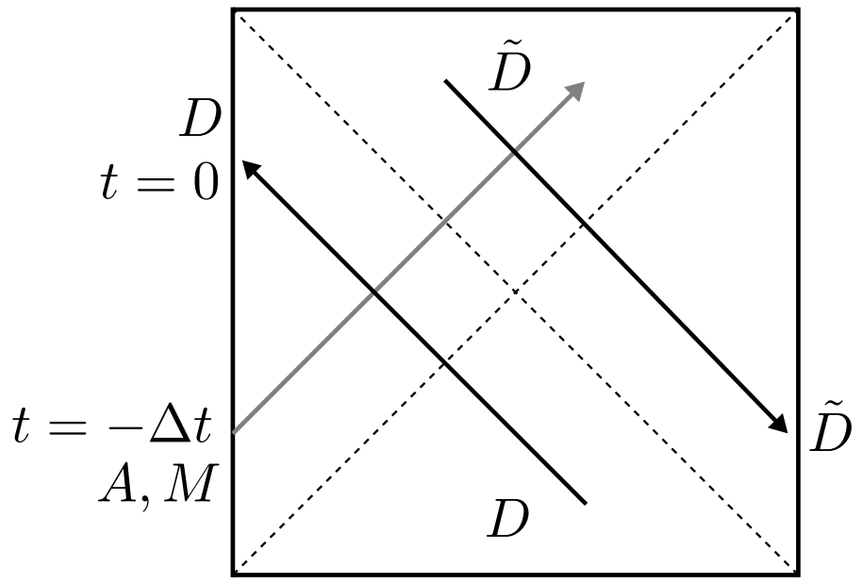
Beni Yoshida (Perimeter Institute)

Including Alice

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



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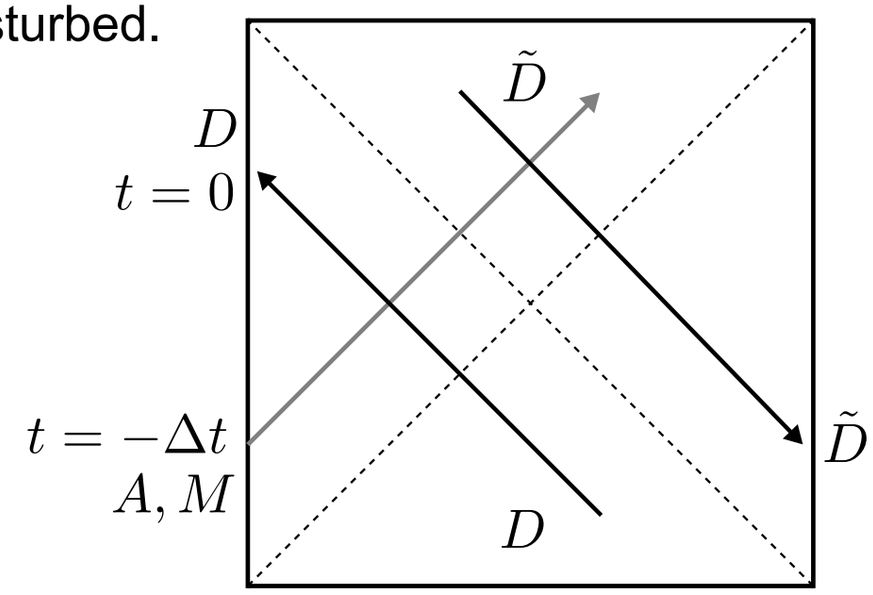
- Add an apparatus M which travels along with A.

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

  Due to decay of OTOCs.



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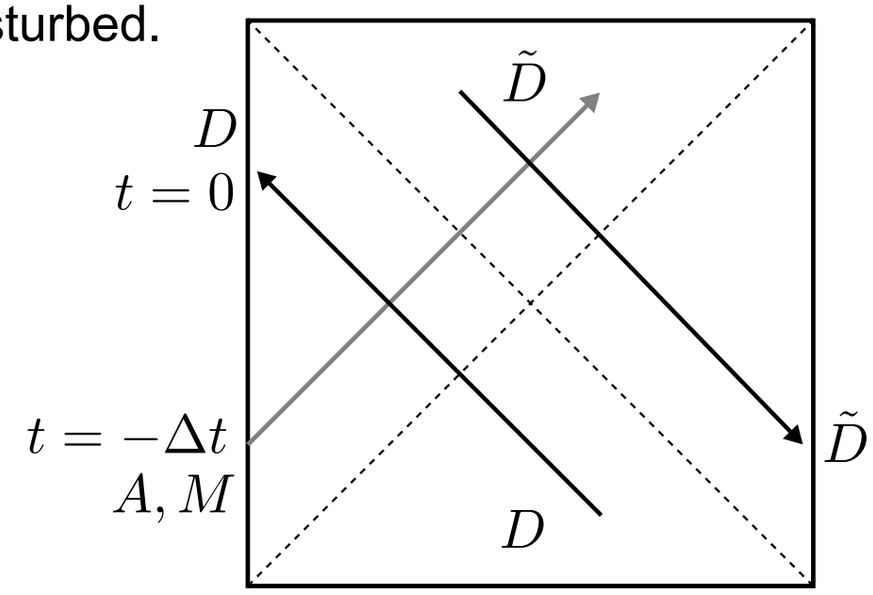

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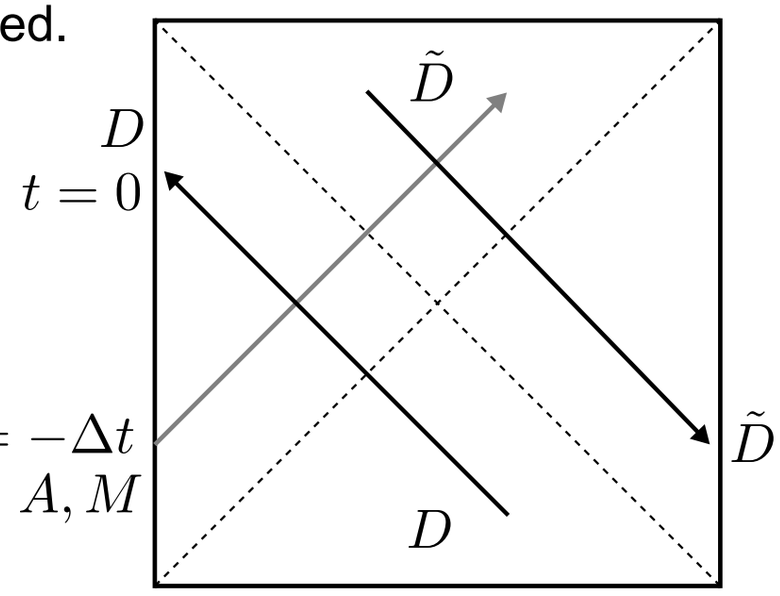

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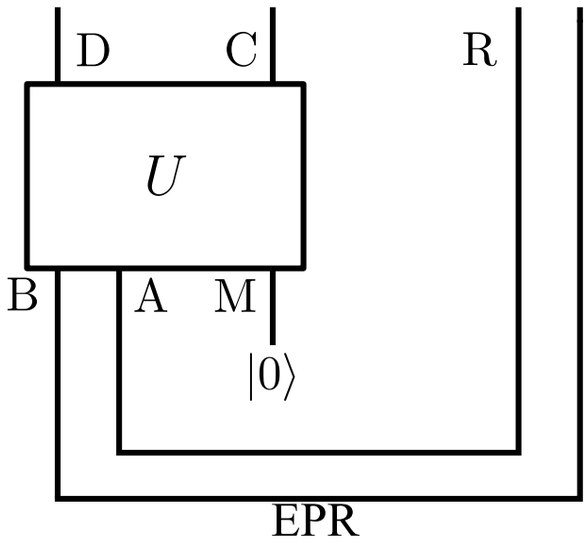
"Proof"



Small OTOC $\longrightarrow$ $I(C, D) \approx \max$

$\longrightarrow$ D is not entangled with R

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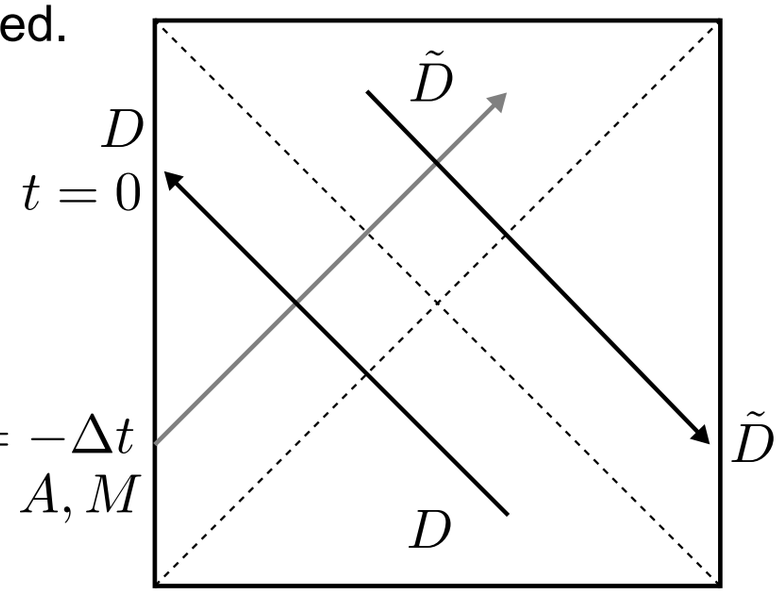

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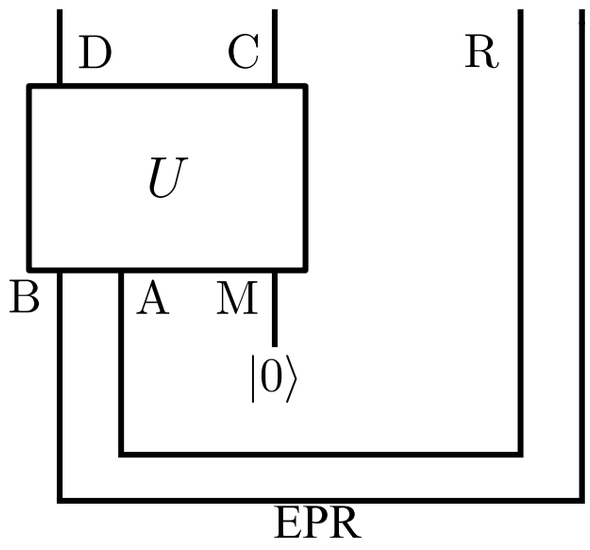

Small OTOC $\longrightarrow$ $I(C, D) \approx \max$

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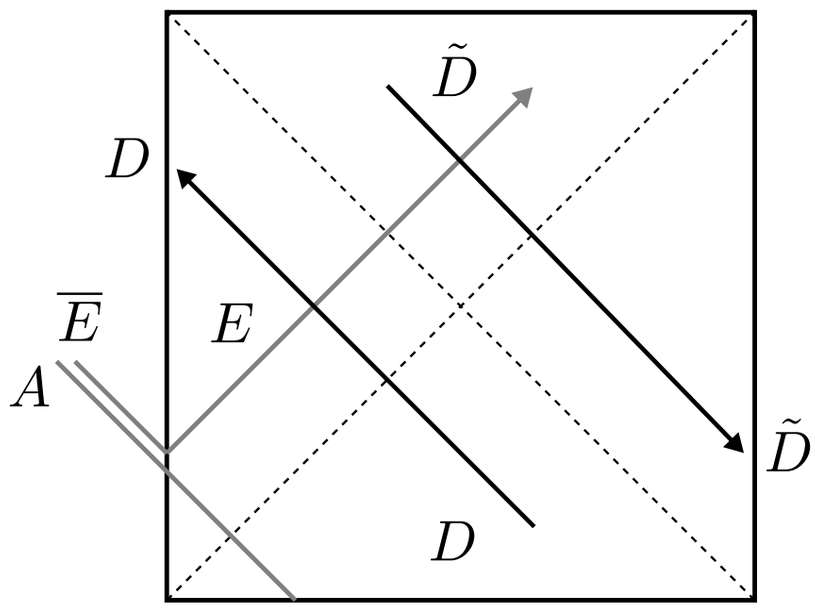
- Works for black holes on flat space. (Follows from QM and OTOC decay).

Sending probes

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



Sending probes

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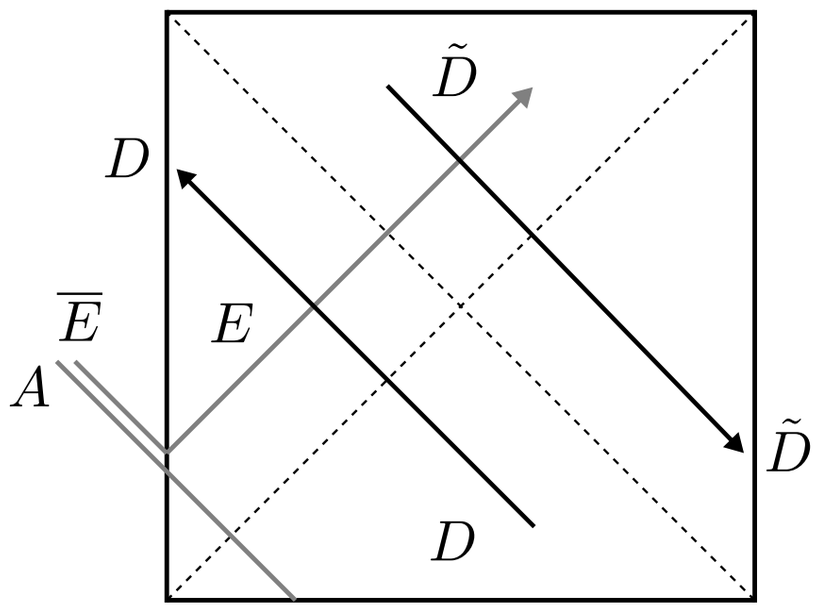

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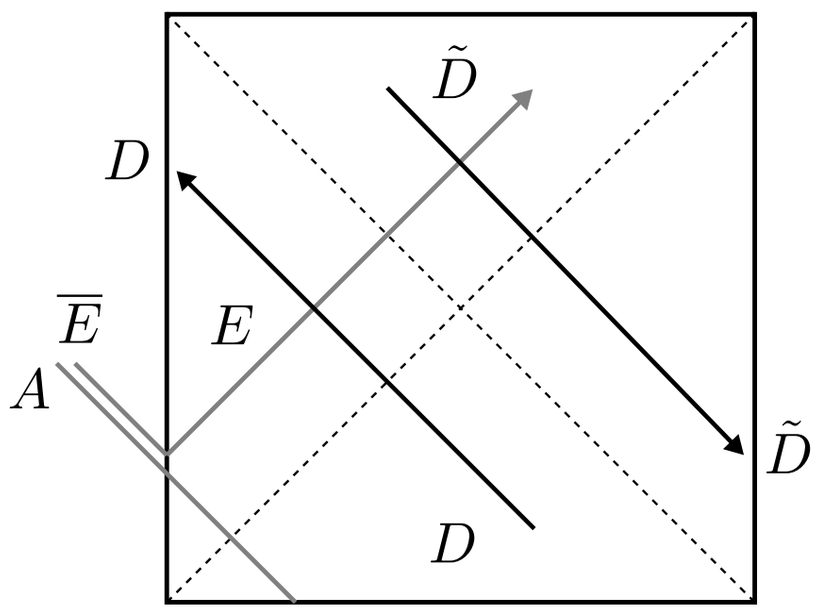
  - Decay of OTOC is universal gravitational phenomena.

  - Interior operator does not depend on R, but depends on the observer.



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    - Decay of OTOC is universal gravitational phenomena.
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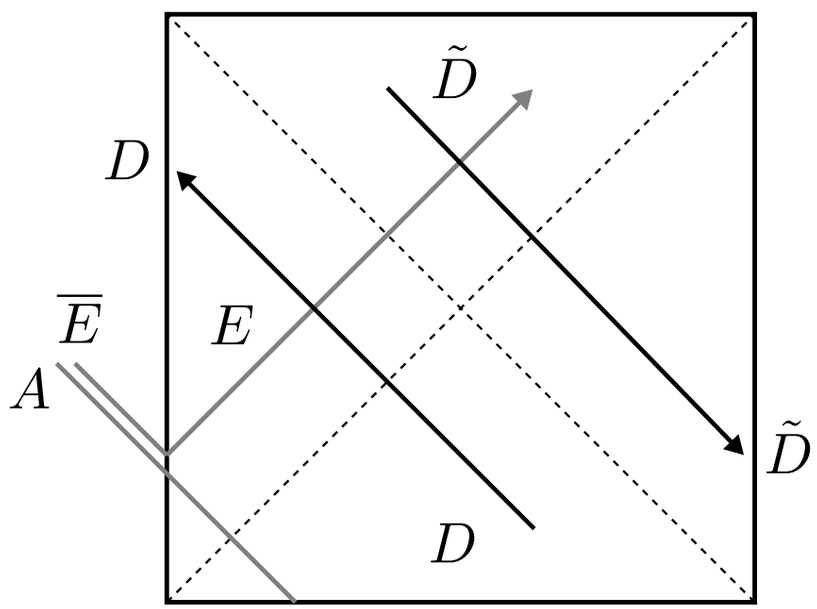
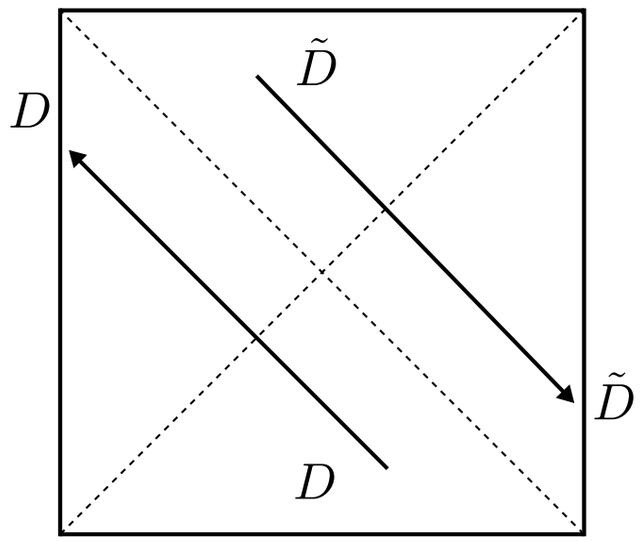
- Some caveats
    - This requires scrambling time separation.
    - A (or E) needs to be as large as D.



Bulk interpretations

- Treat Alice as a shockwave



without Alice D —— $\tilde{D}$

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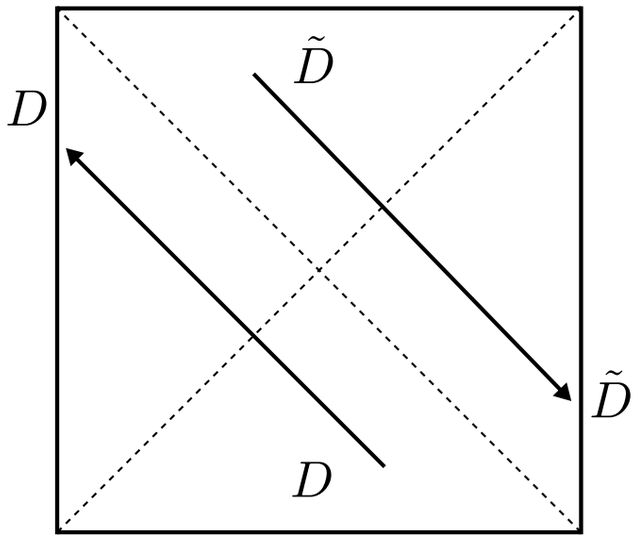

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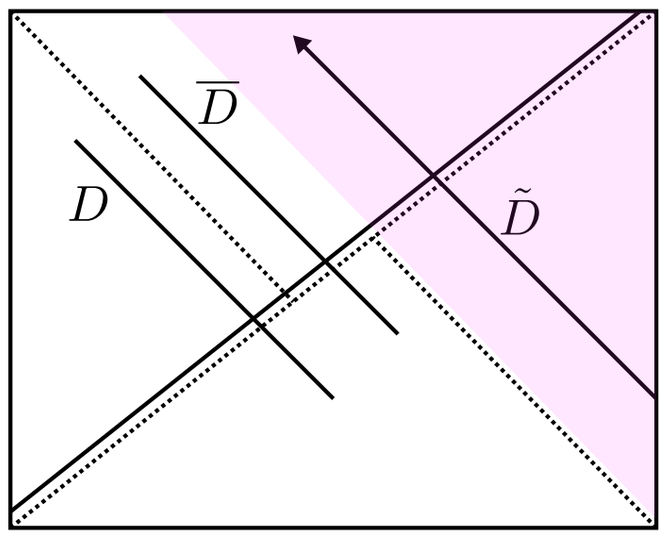

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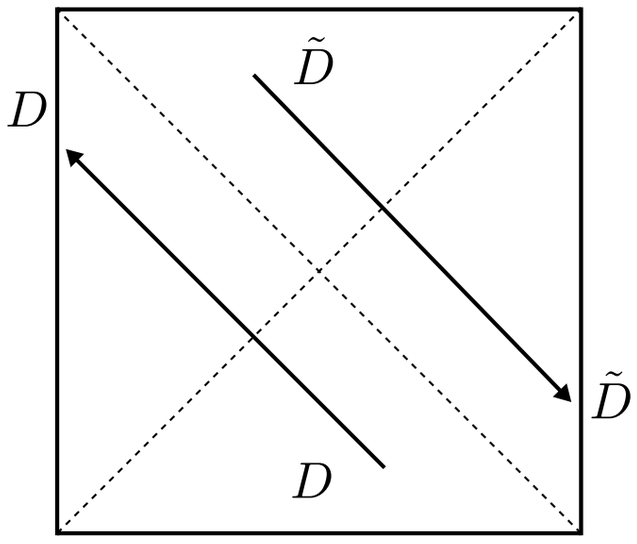

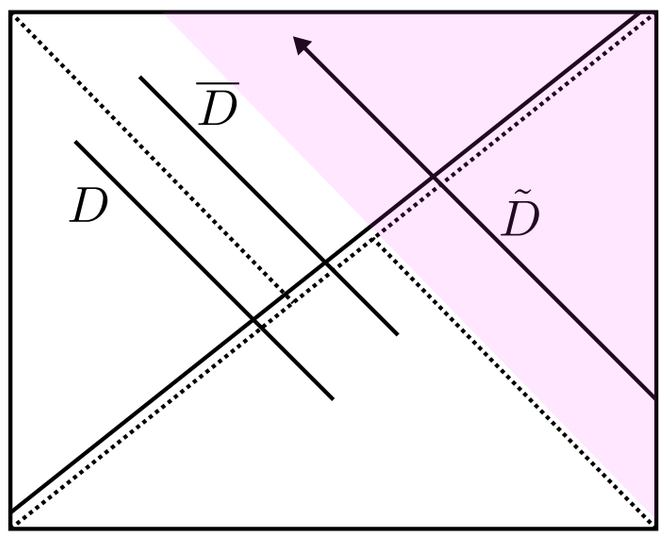

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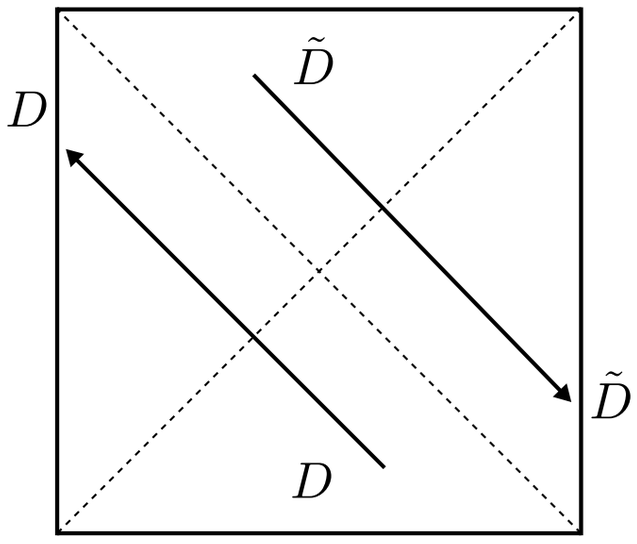

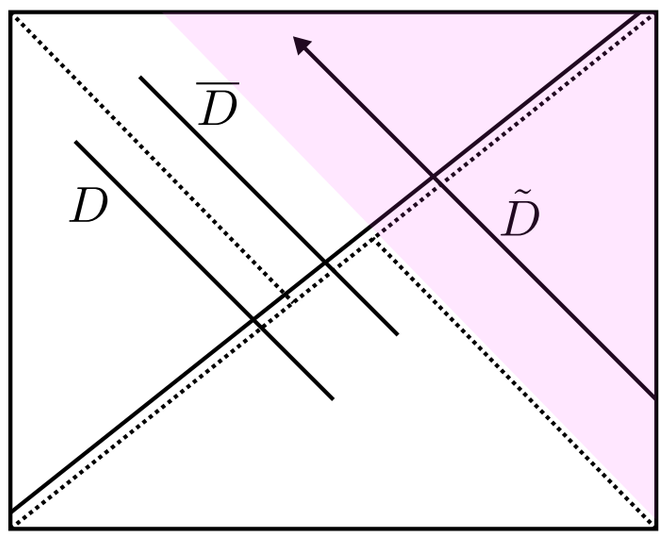

without Alice D —— $\tilde{D}$

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Resolution of non-locality problem

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

Firewall vs. Scrambling

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AMPS thought experiment

- Original argument

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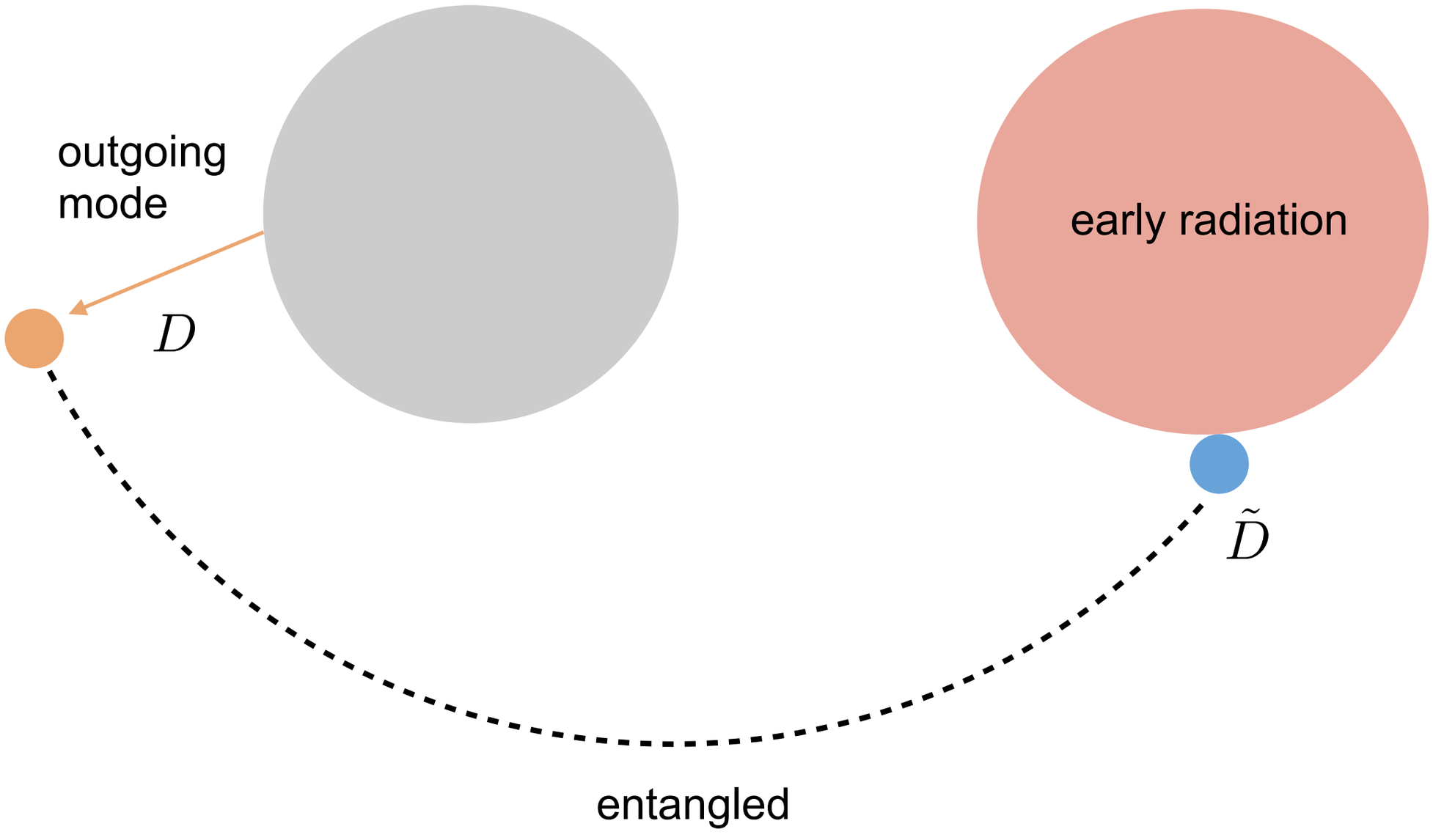

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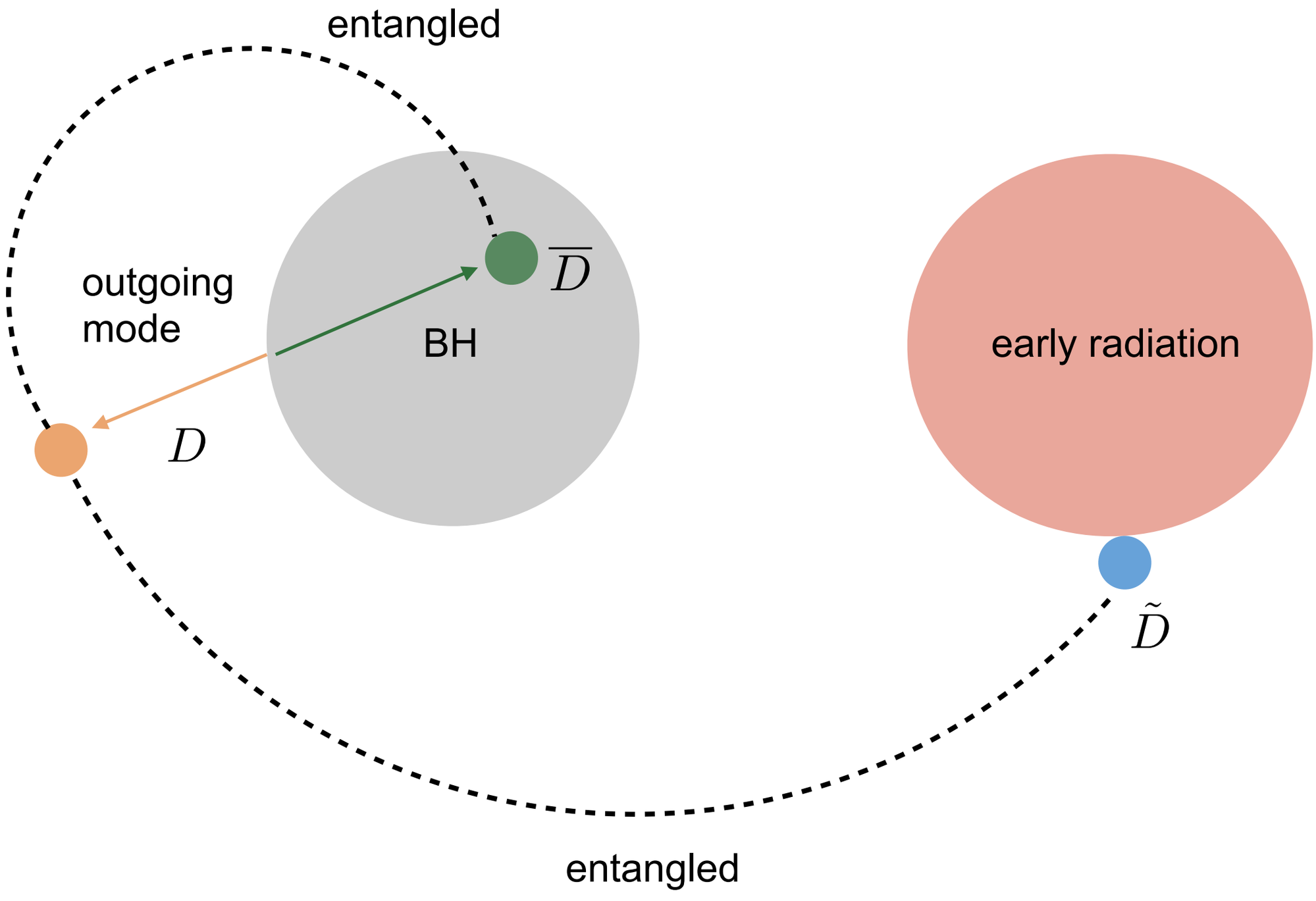

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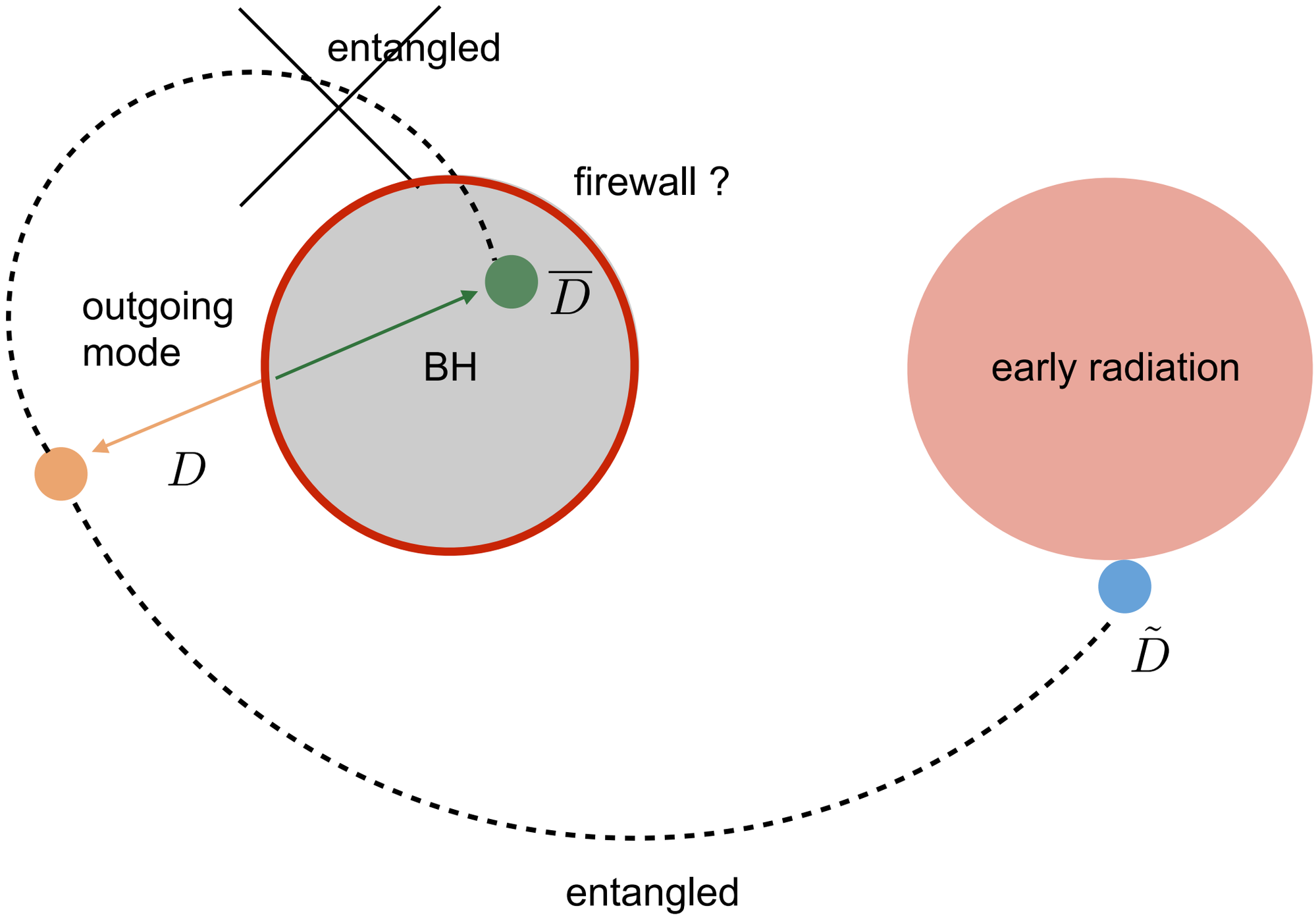
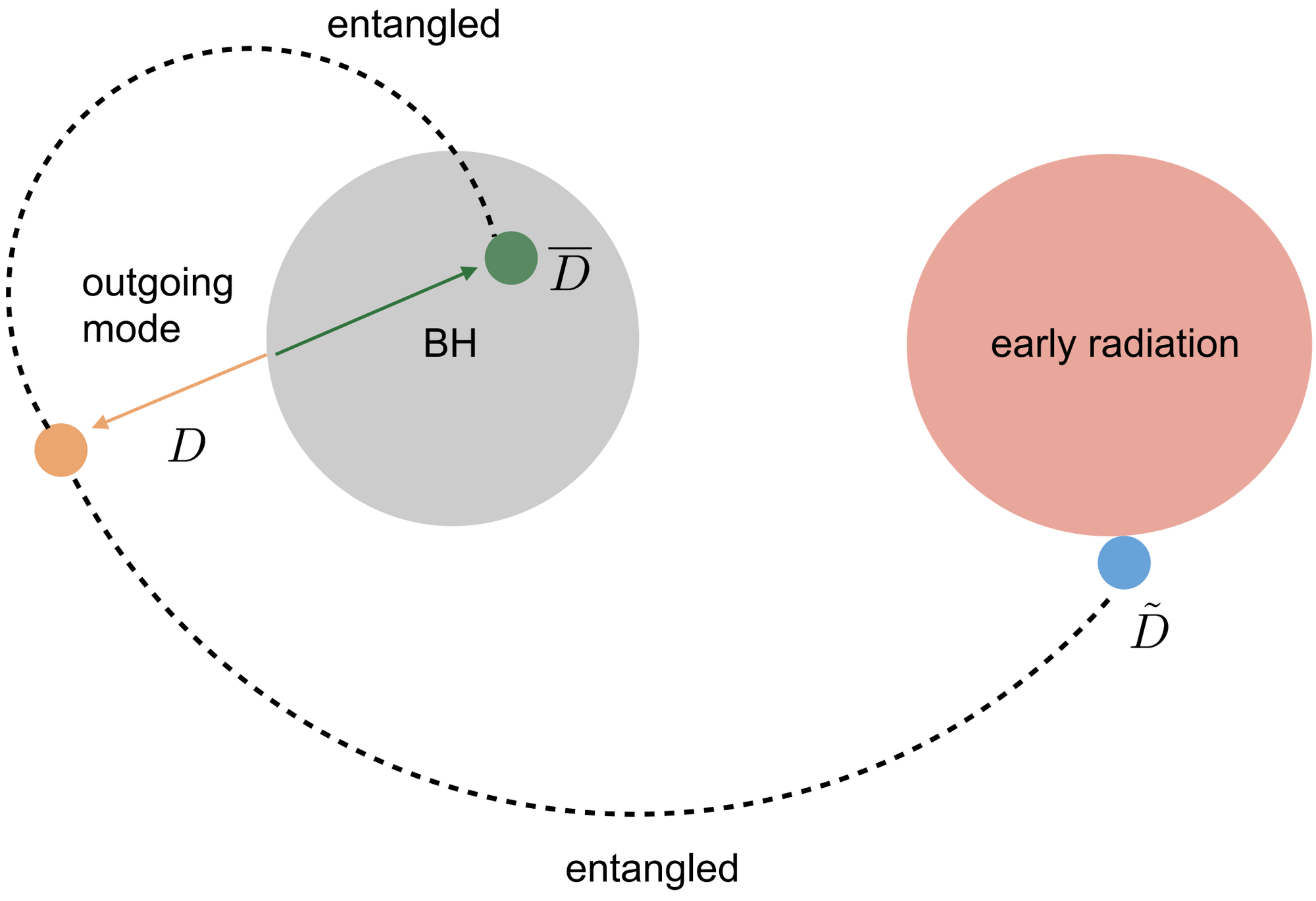


AMPS thought experiment

- Some previous proposals…



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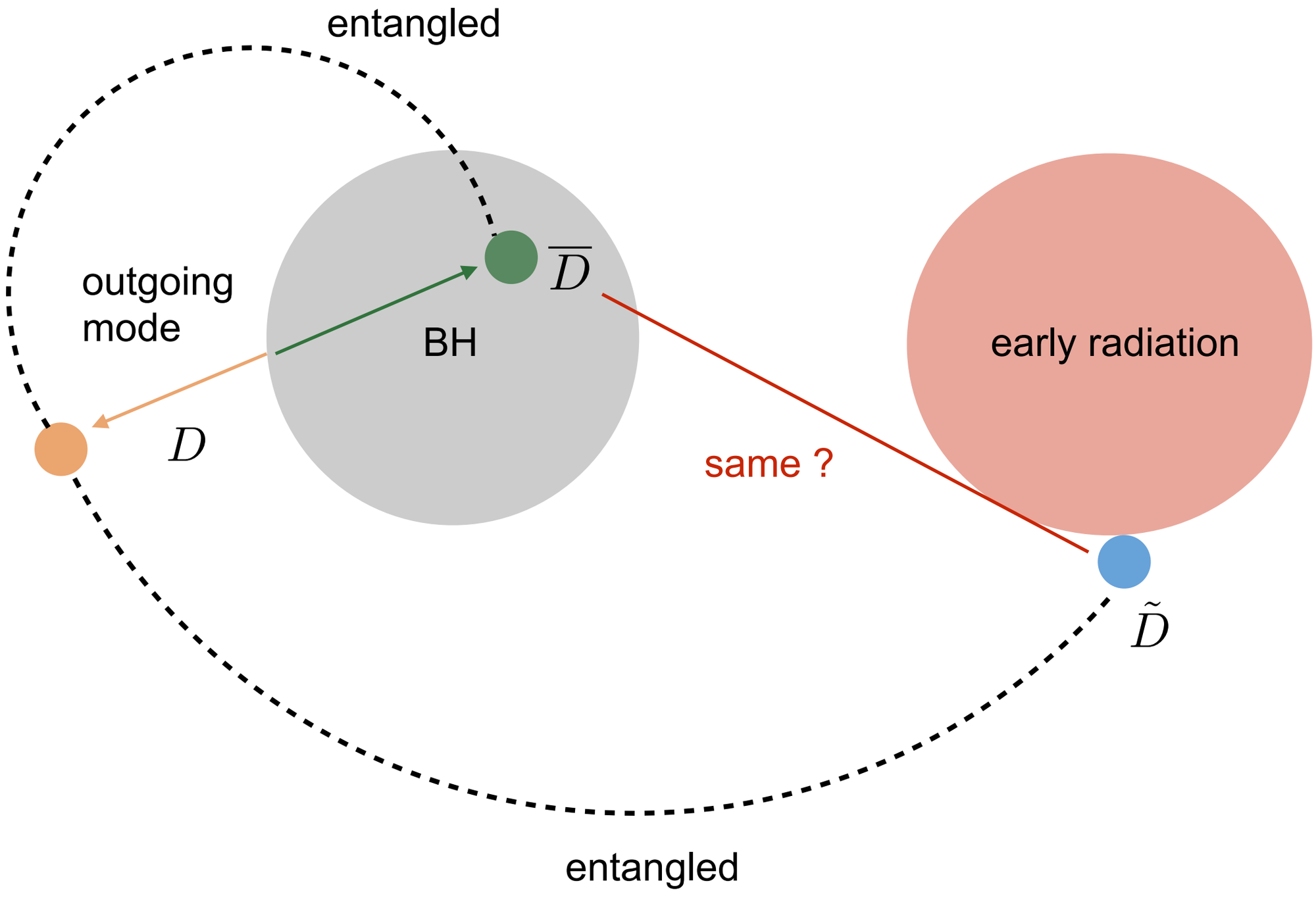

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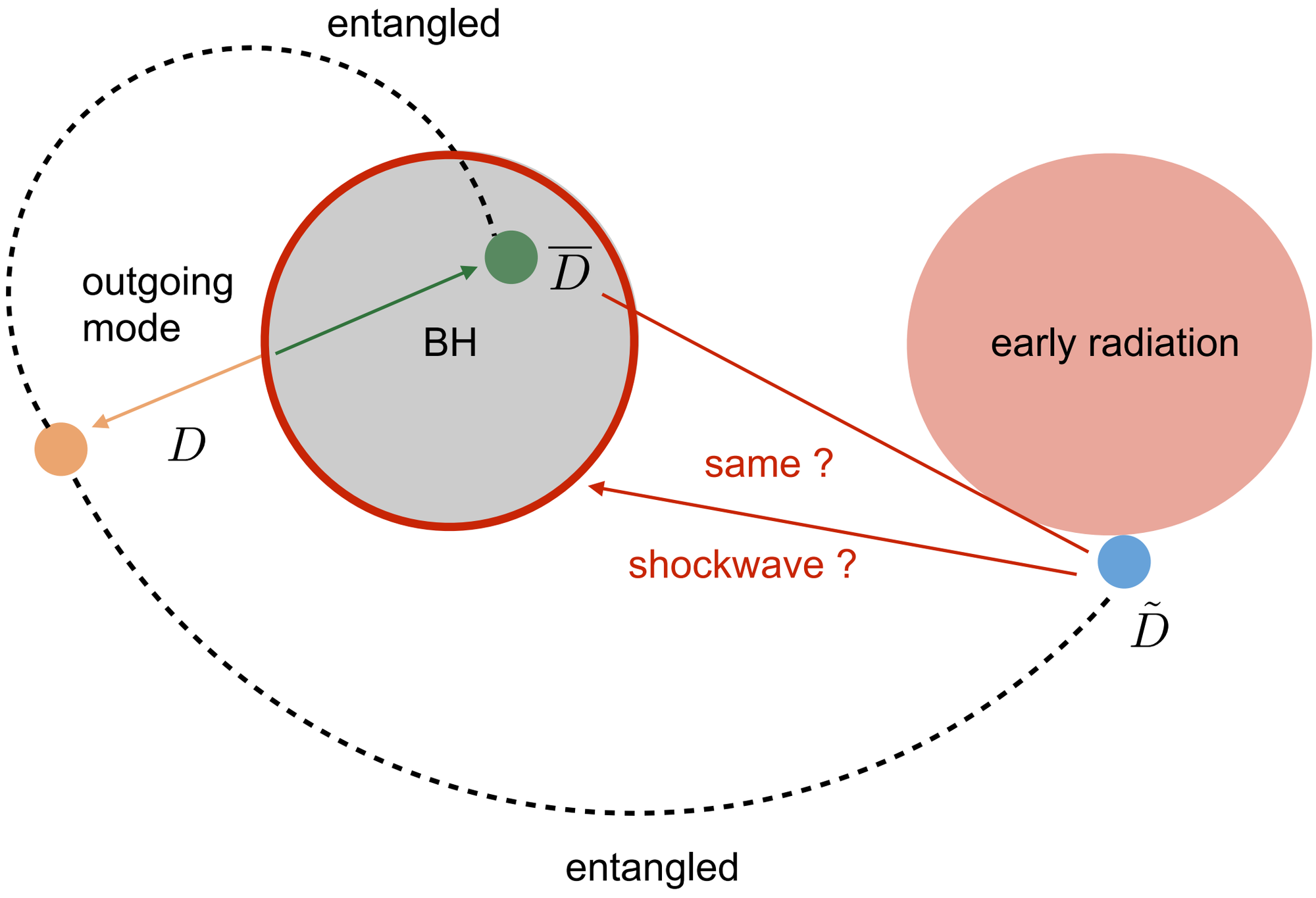
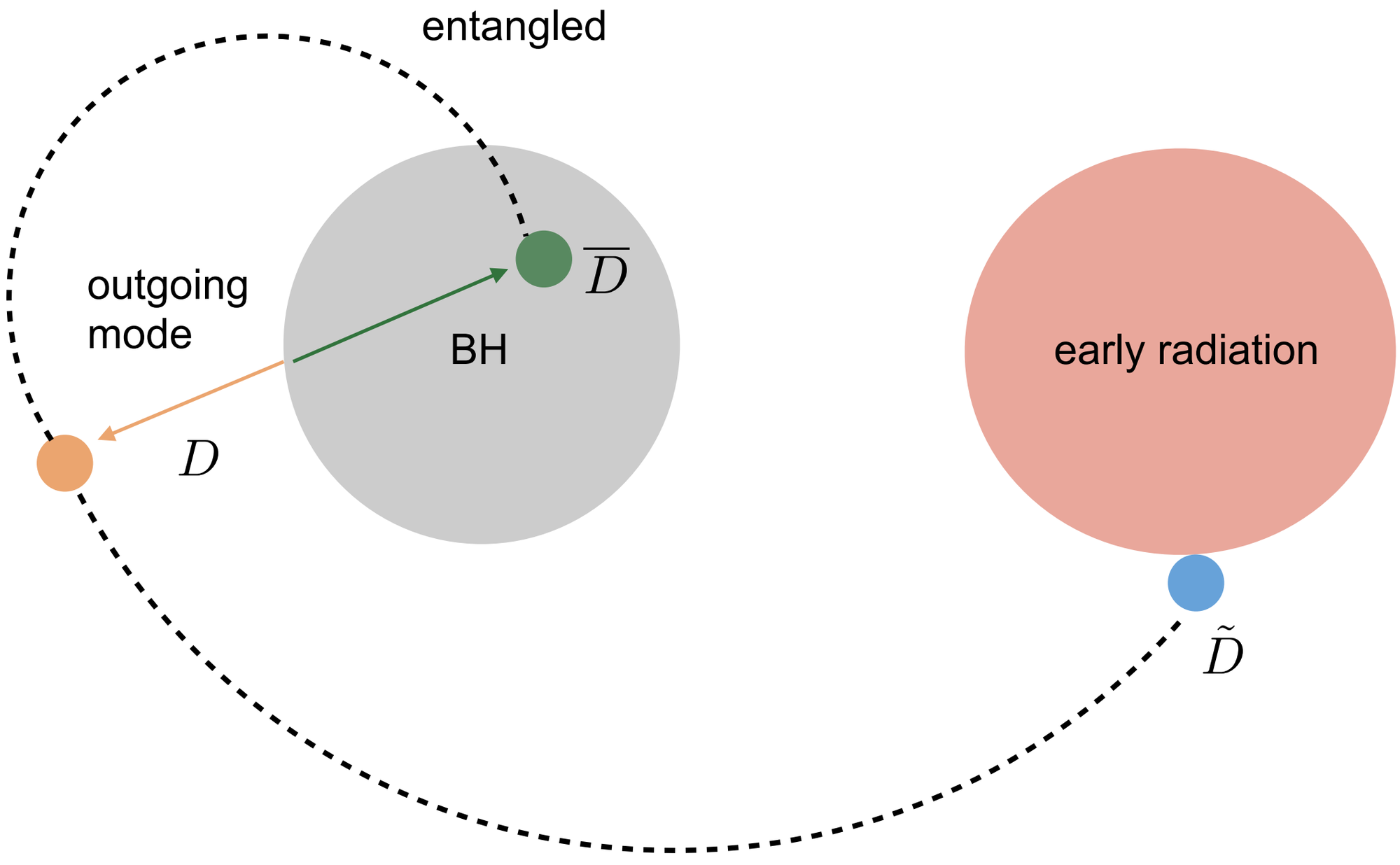


AMPS thought experiment

- Our proposal



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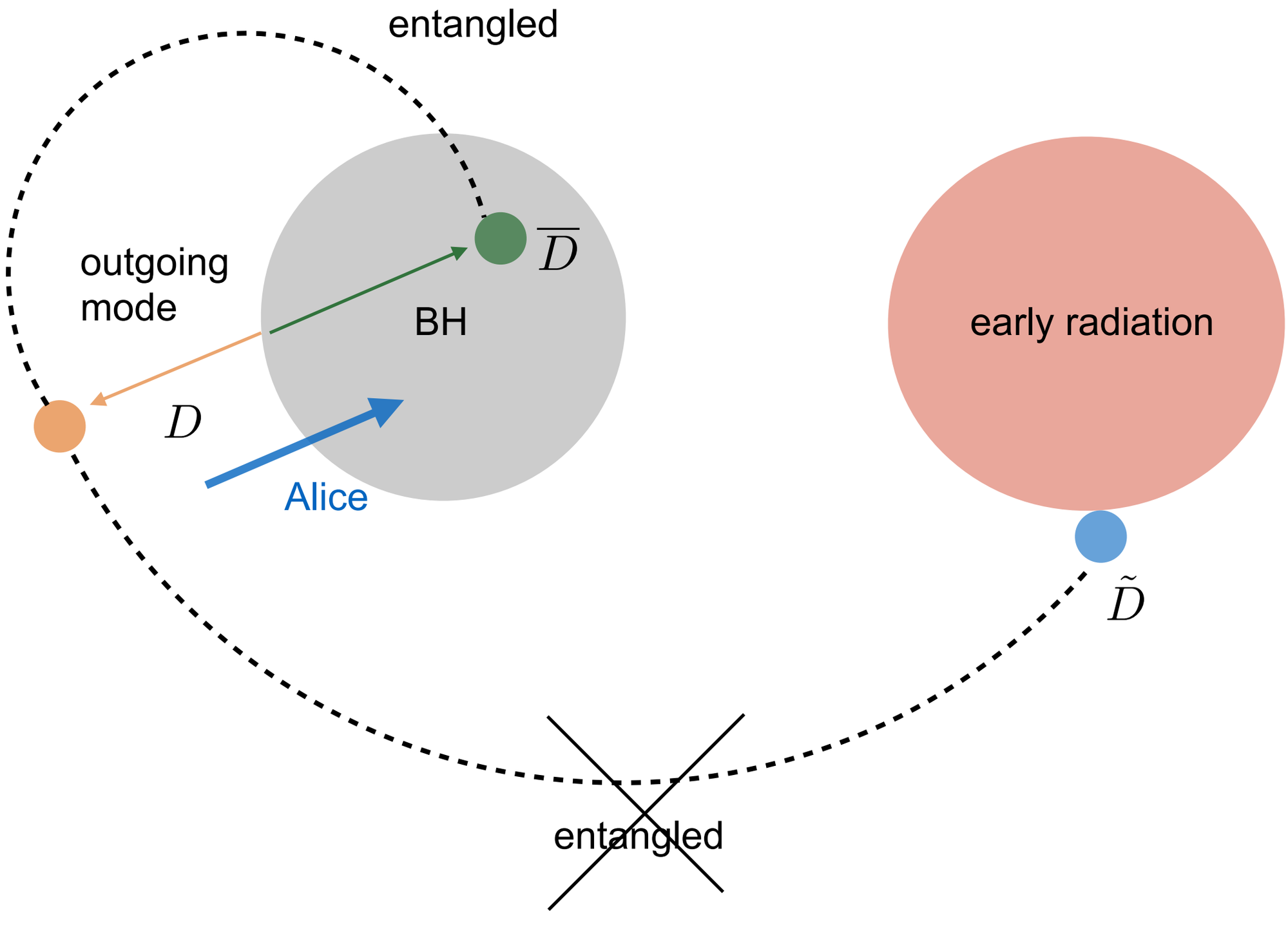

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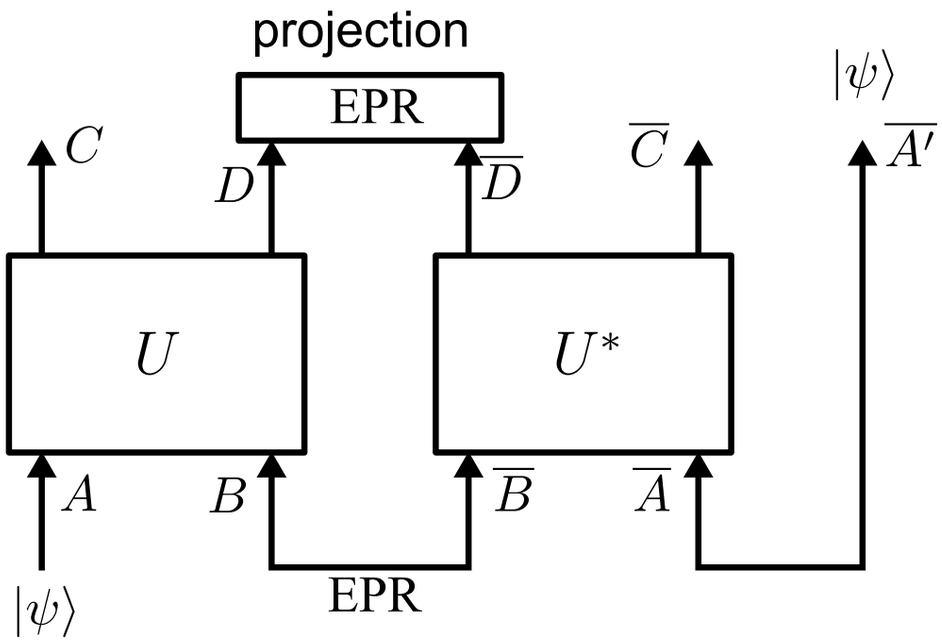

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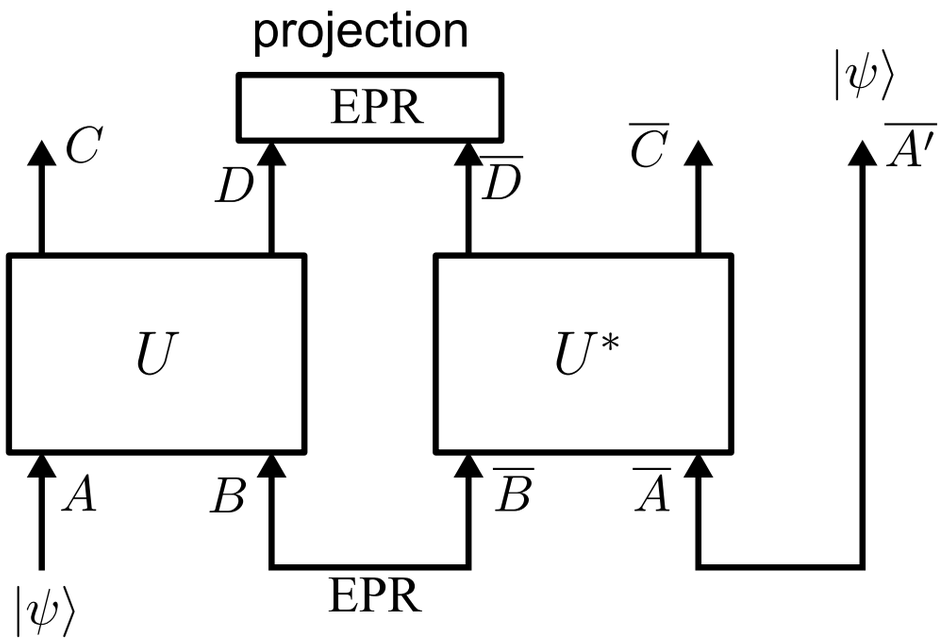

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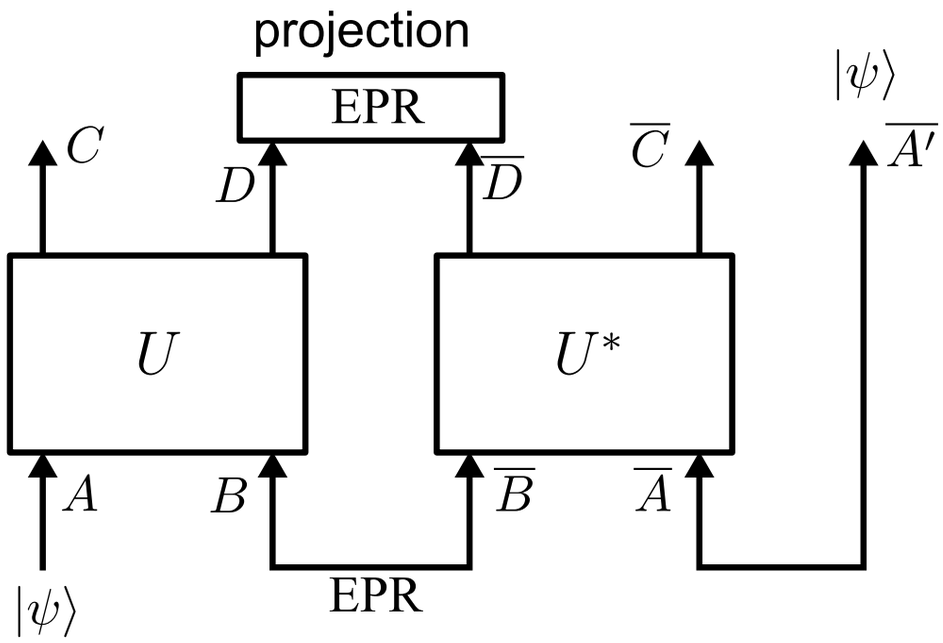

Firewall (Hayden-Preskill) in a laboratory

- In a sense, Hayden-Preskill recovery is a firewall although it actually saves Alice.

Experiment of HP recovery protocol

LETTER

Nature 567 (7746), 61

https://doi.org/10.1038/s41586-019-0952-6

Verified quantum information scrambling

K. A. Landsman[1]*, C. Figgatt[1,6], T. Schuster[2], N. M. Linke[1], B. Yoshida[3], N. Y. Yao[2,4] & C. Monroe[1,5]

Quantum scrambling is the dispersal of local information into many-body quantum entanglements and correlations distributed throughout an entire system. This concept accompanies the dynamics of thermalization in closed quantum systems, and has recently emerged as a powerful tool for characterizing chaos in black holes[1–4]. However, the direct experimental measurement of quantum scrambling is difficult, owing to the exponential complexity of ergodic many-body entangled states. One way to characterize quantum scrambling is to measure an out-of-time-ordered correlation function (OTOC); however, because scrambling leads to their decay, OTOCs do not generally discriminate between quantum scrambling and ordinary decoherence. Here we implement a quantum circuit that provides a positive test for the scrambling features of a given unitary process[5,6]. This approach conditionally teleports a quantum state through the circuit, providing an unambiguous test for whether scrambling has occurred, while simultaneously measuring an OTOC. We engineer quantum scrambling processes through a tunable three-qubit unitary operation as part of a seven-qubit circuit on an ion trap quantum computer. Measured teleportation fidelities are typically about 80 per cent, and enable us to experimentally bound the scrambling-induced decay of the corresponding OTOC measurement.

For example, non-unitary time-evolution arising from depolarization or classical noise processes naturally lead the OTOC to decay, even in the absence of quantum scrambling. A similar decay can also originate from even slight mismatches between the purported forward and backwards time-evolution of $\hat{W}(t)$ (refs [6,16] and [24]). Although full quantum tomography can in principle distinguish scrambling from decoherence and experimental noise, this requires a number of measurements that scales exponentially with system size and is thus impractical.

In this work, we overcome this challenge and implement a quantum teleporation protocol that robustly distinguishes information scrambling from both decoherence and experimental noise[5,6]. Using this protocol, we demonstrate verifiable information scrambling in a family of unitary circuits and provide a quantitative bound on the amount of scrambling observed in the experiments.

The intuition behind our approach lies in a re-interpretation of the black-hole information paradox[9,10], under the assumption that the dynamics of the black hole can be modelled as a random unitary operation $\hat{U}$ (Fig. 1). Schematically, an observer (Alice) throws a secret quantum state into a black hole, while an outside observer (Bob) attempts to reconstruct this state by collecting the Hawking radiation emitted at a later time[1,10].

An explicit decoding protocol has been recently proposed[5,6], which

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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)

Before scrambling time

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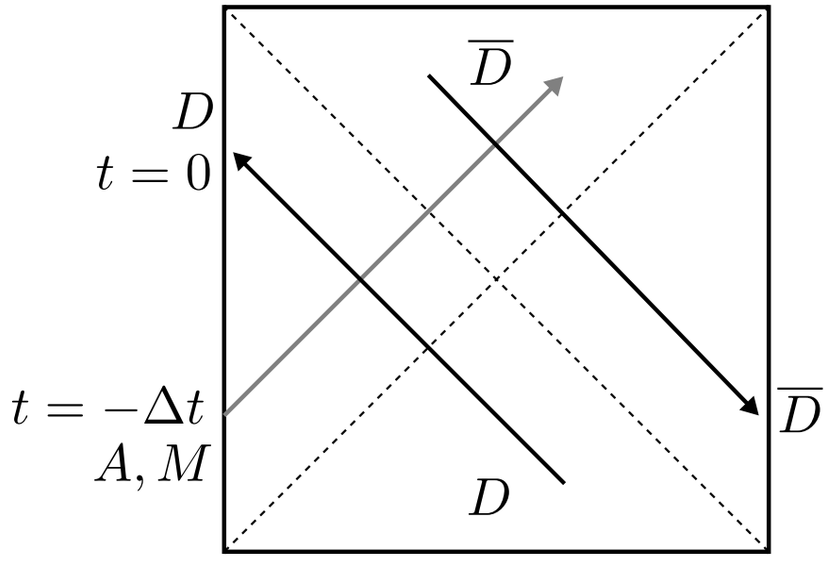

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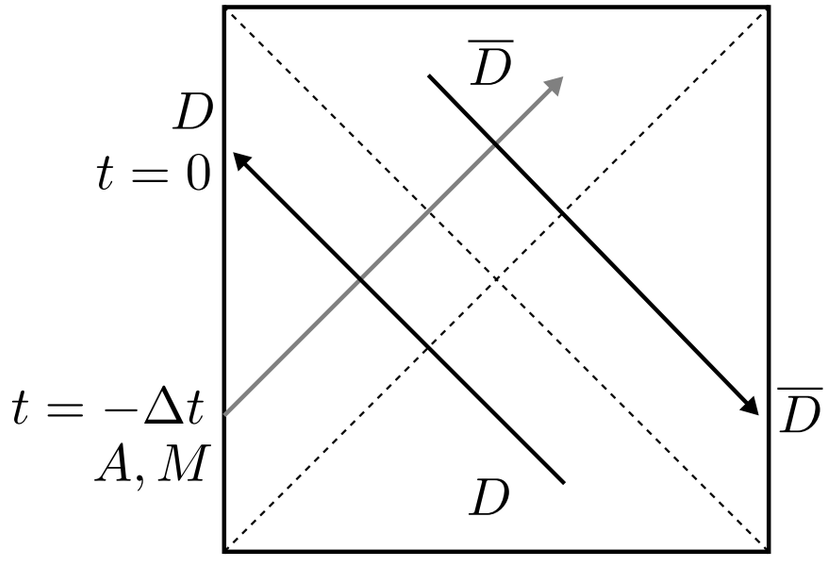

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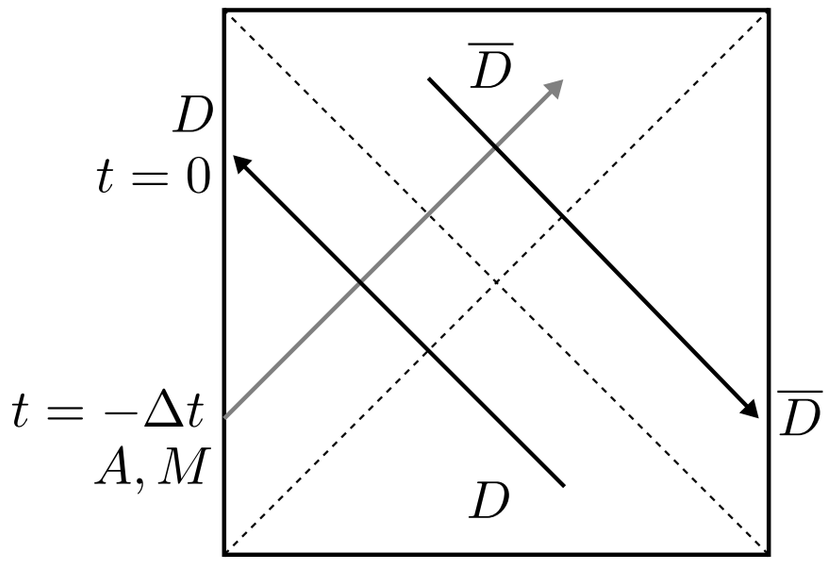
To have small ρ , we need $\Delta t \gtrapprox r_S \log r_S$



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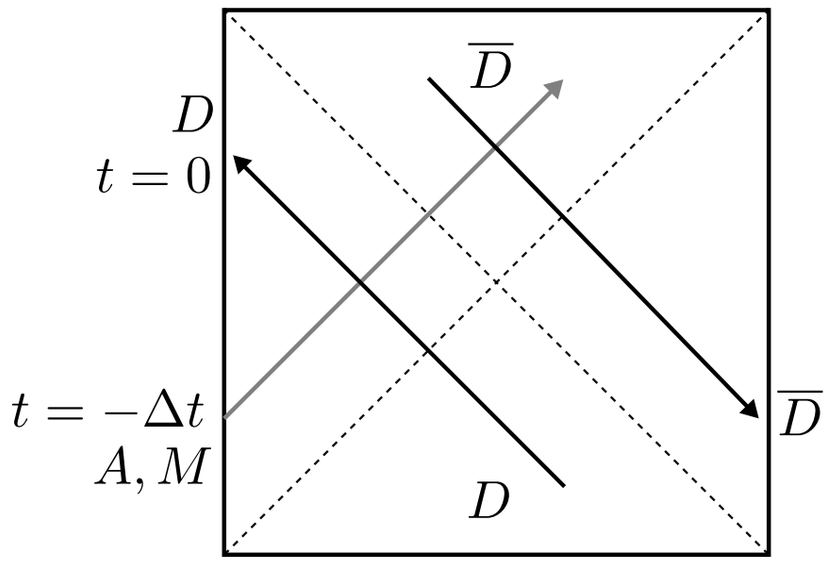
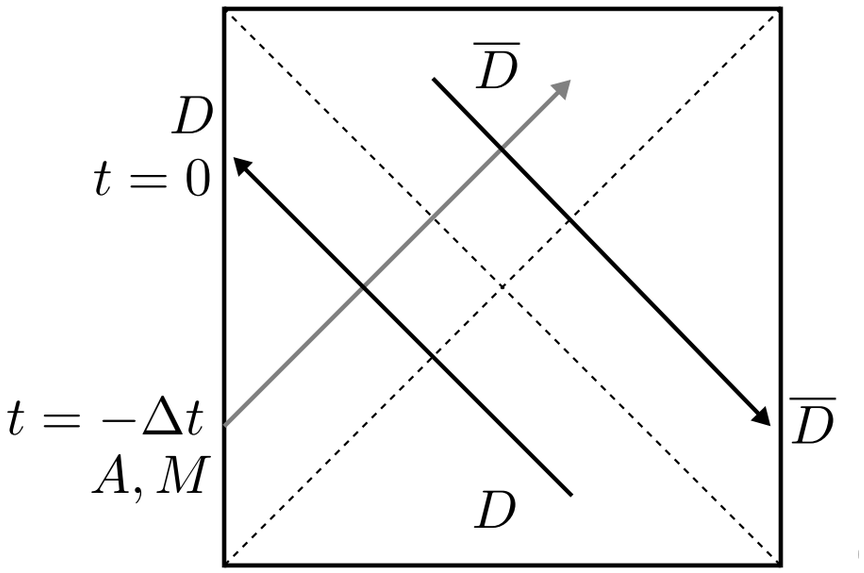


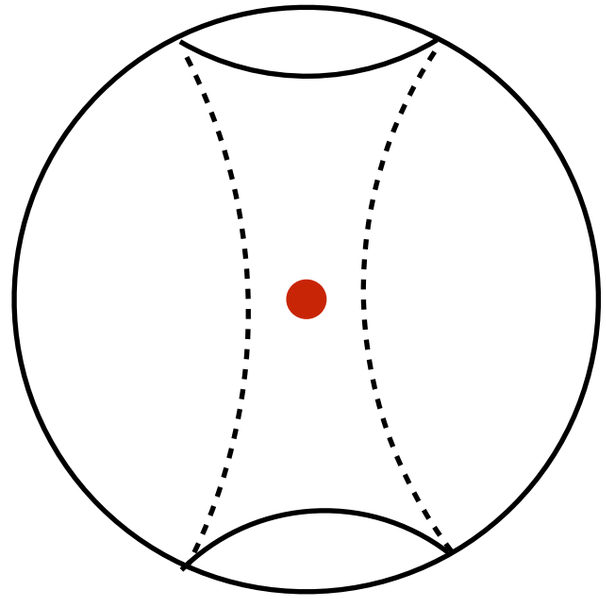
• Scenario 3

Even if they are not entangled, it won't create a firewall (low energy)?

Entanglement wedge reconstruction

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





Firewall in de Sitter Horizon ?

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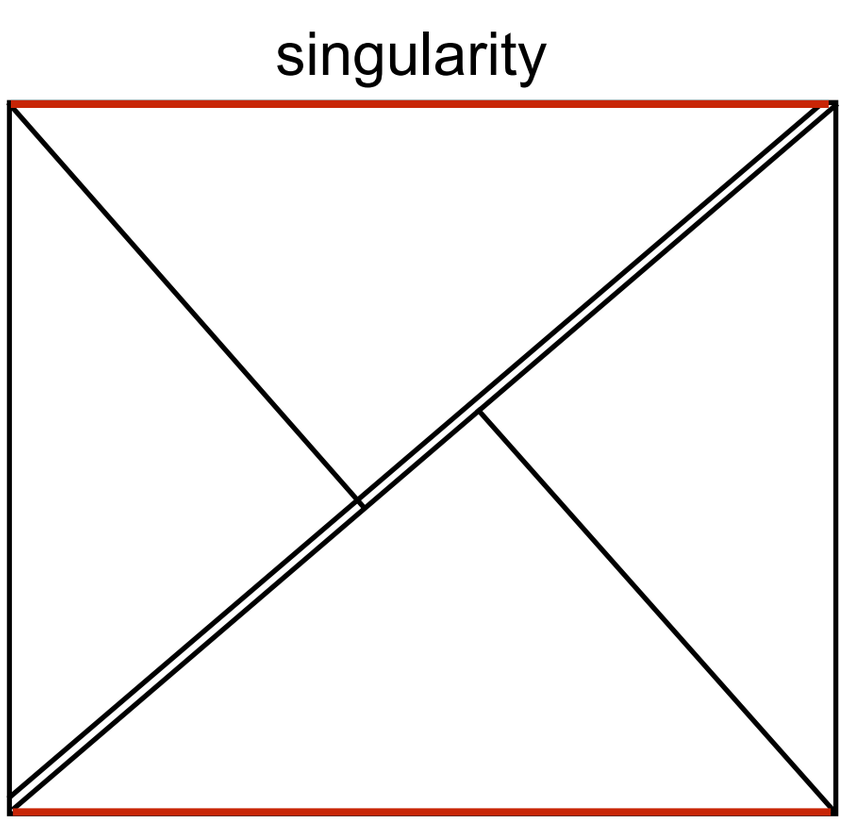
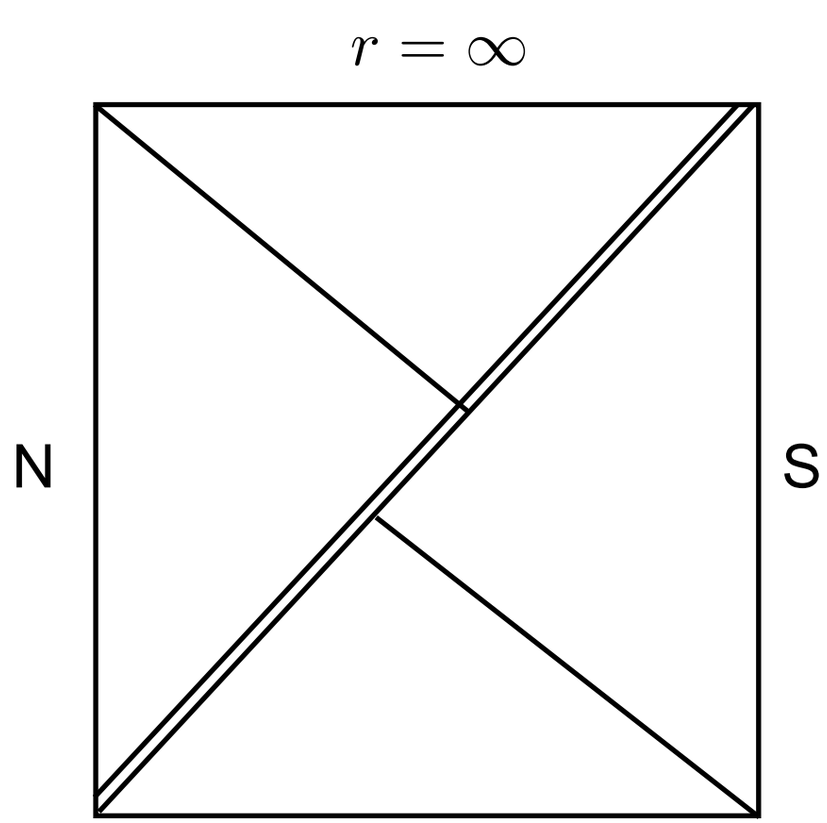


black hole horizon



cosmological horizon

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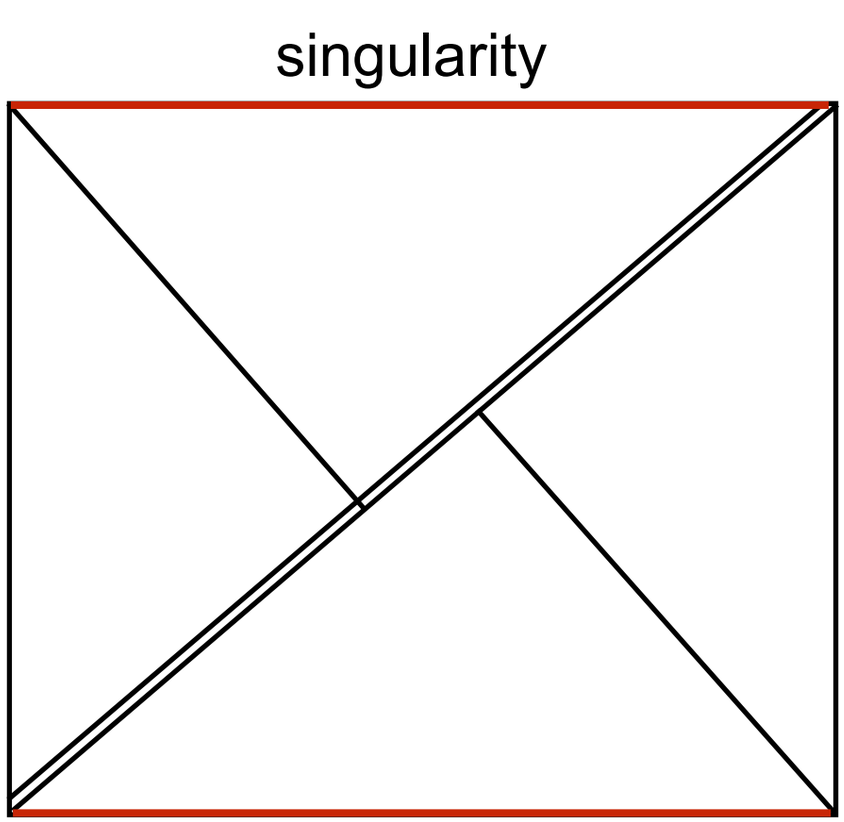
⟶ Alice cannot really cross the de Sitter horizon?



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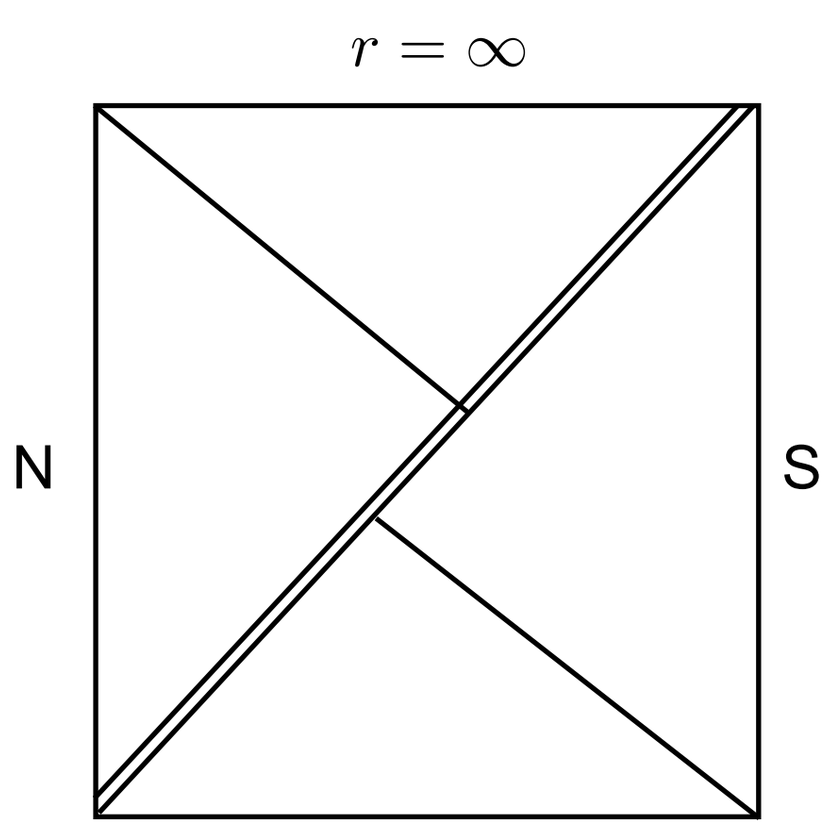

cosmological horizon

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2015 Chaos in quantum channel Hosur, Qi, Roberts, BY

2015 Chaos and complexity by design Roberts, BY

2017 Efficient decoding for Hayden-Preskill protocol Kitaev, BY

2018 Verified quantum information scrambling Landsman, BY et al

2018 Soft mode and interior operators in Hayden-Preskill thought experiment, BY

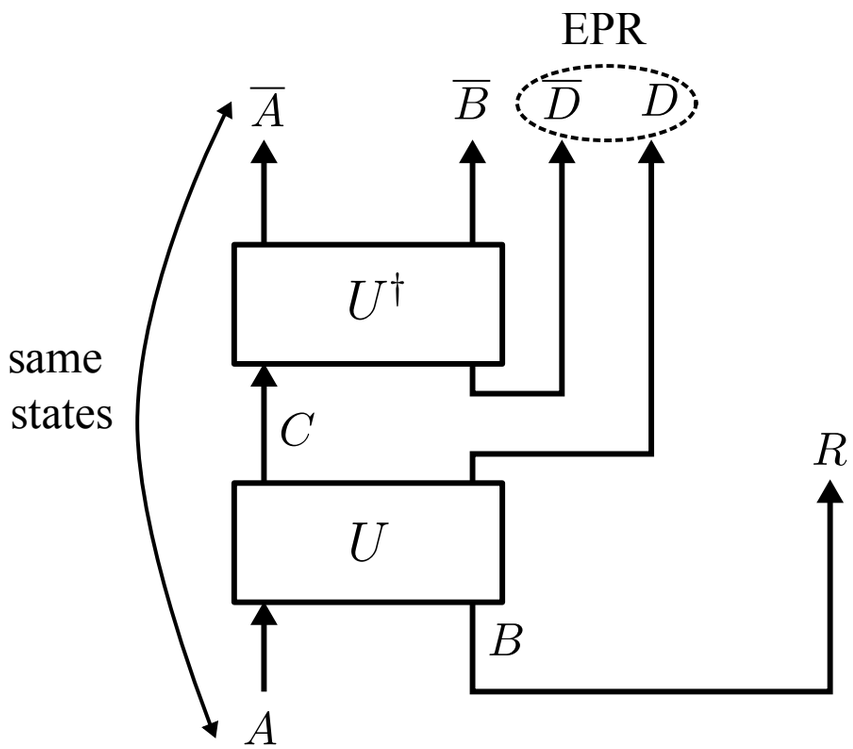
2019 Firewalls vs. scrambling, BY

Relevant work

2012 Black hole entanglement and quantum error-correction, Verlinde-Verlinde

“One-sided” traversable wormhole

- Physical interpretation of the protocol to reconstruct the interior operator?



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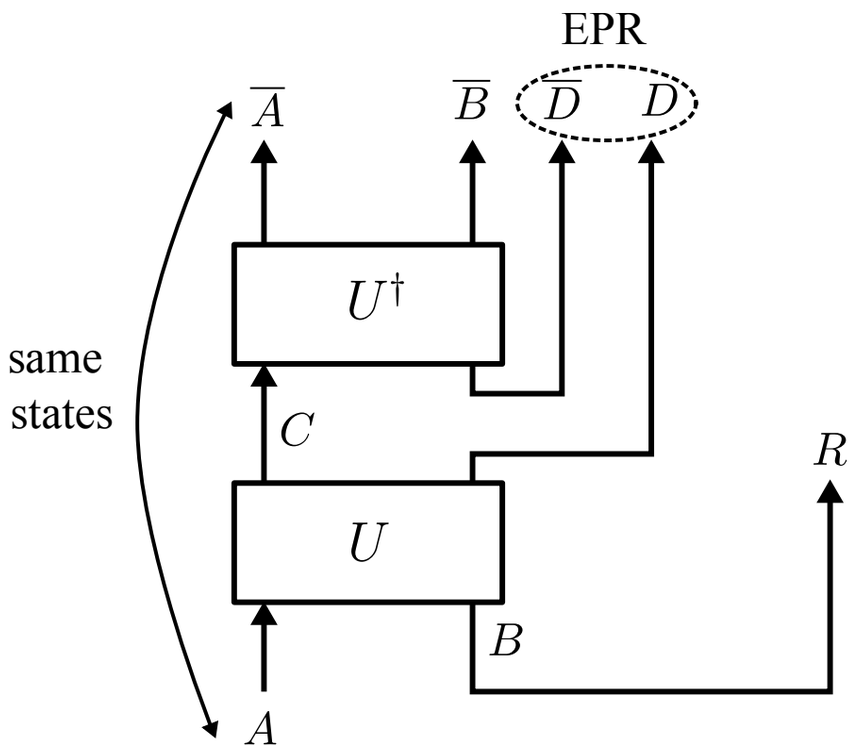

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