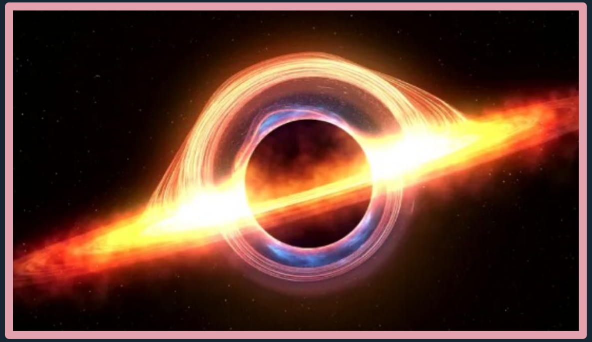
Quantum Commitments and Black Hole Radiation Decoding

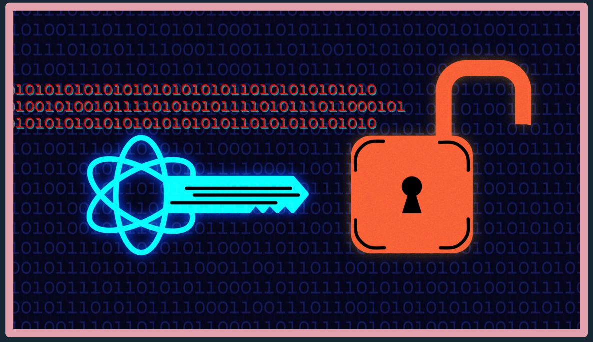
Fermi Ma

(Simons and Berkeley)

Based on discussions with Sam Gunn (Berkeley) and Alex Lombardi (Berkeley → Princeton)

Question: What does black hole radiation decoding have to do with quantum cryptography?





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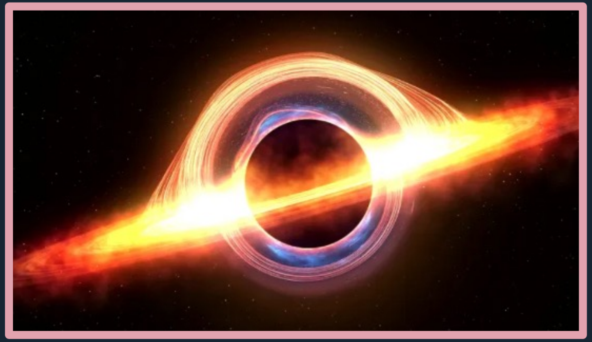

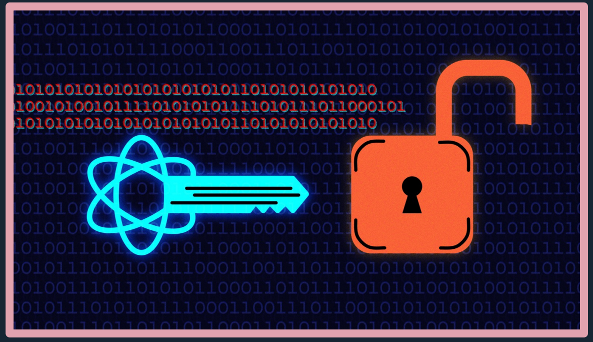

Answer:

Black-Hole Radiation Decoding is Quantum Cryptography

Zvika Brakerski*

Abstract

We propose to study equivalence relations between phenomena in high-energy physics and the existence of standard cryptographic primitives, and show the first example where such an

(building on [Harlow-Hayden13, Aaronson16])

You might be wondering…

“Black-Hole Radiation Decoding is Quantum Cryptography.”

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Goal: understand the title of Zvika's paper

Plan for this talk

(1) Background on black holes

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(2) Radiation decoding problem [Harlow-Hayden13]

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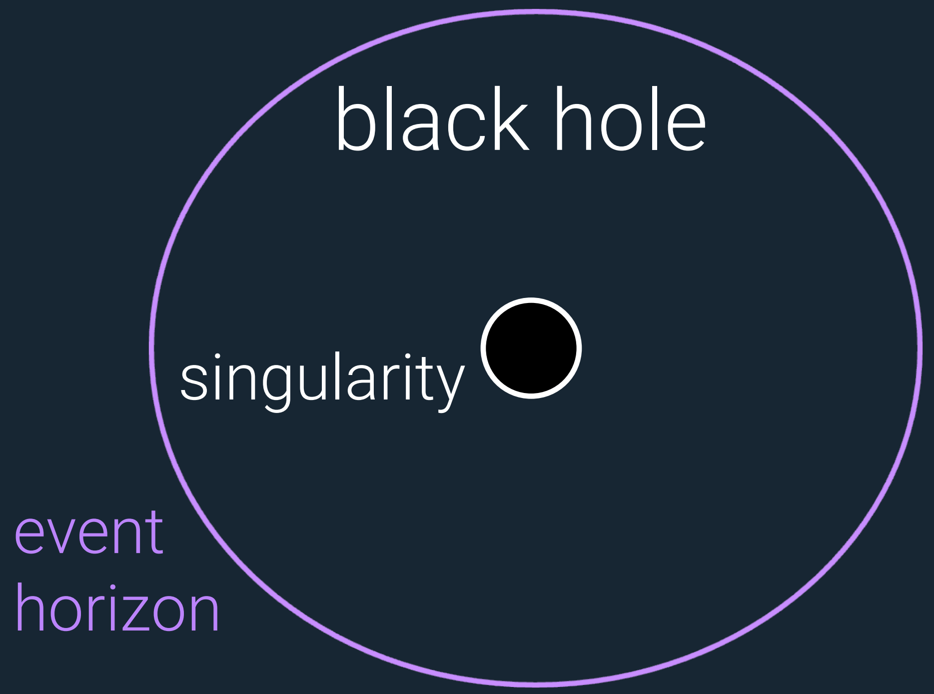
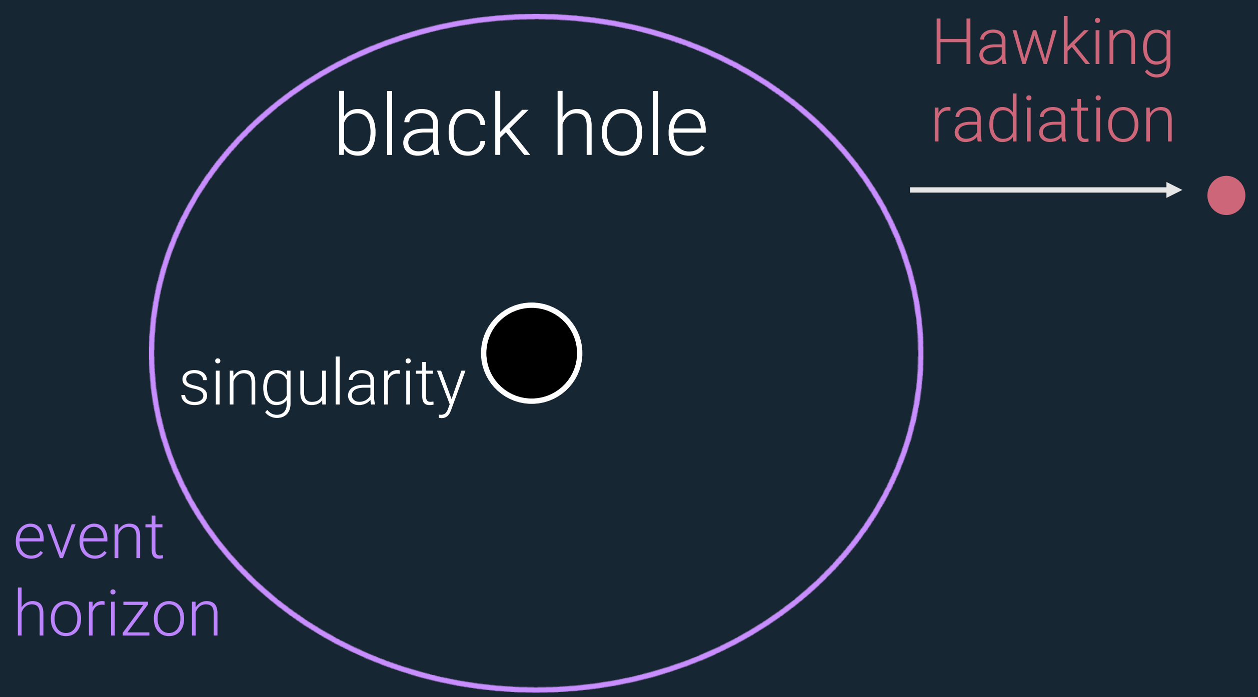
Everything I'm about to say about black hole physics is from Scott Aaronson's Barbados lecture notes (any mistakes are my own).

Black Hole Radiation



Black Hole Radiation

- Black holes emit qubits of Hawking radiation.



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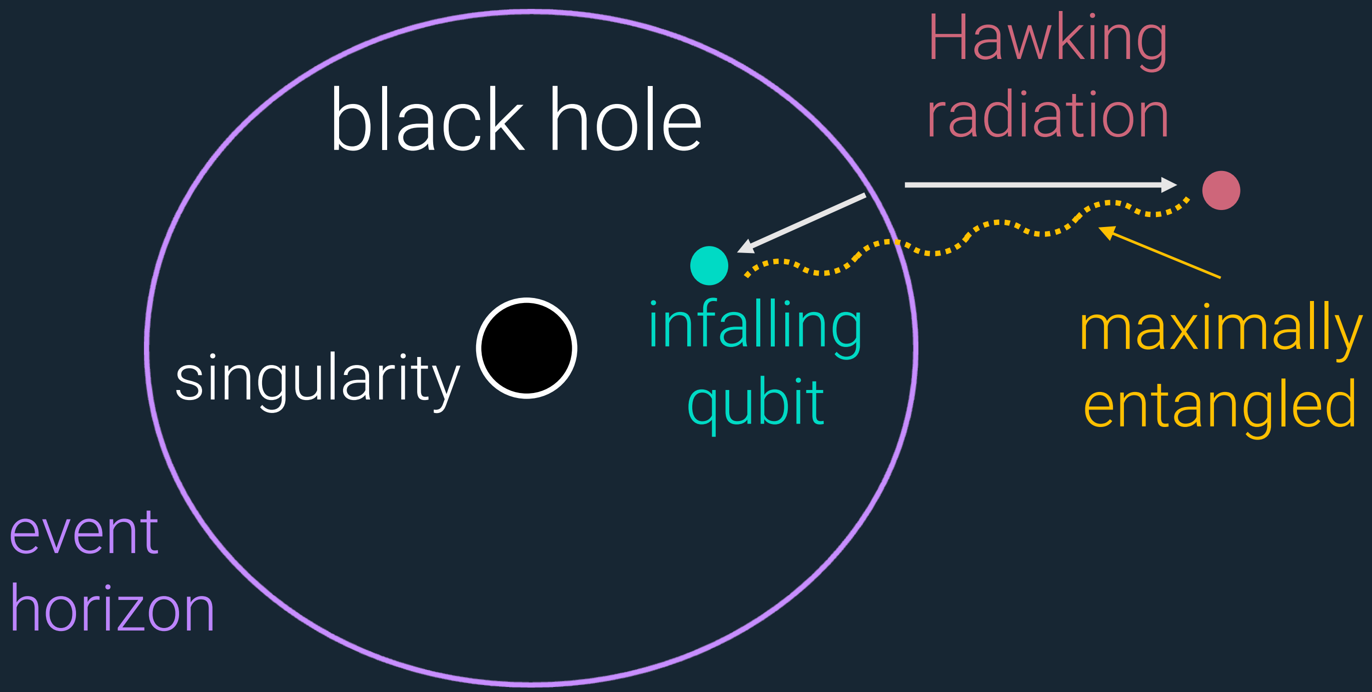
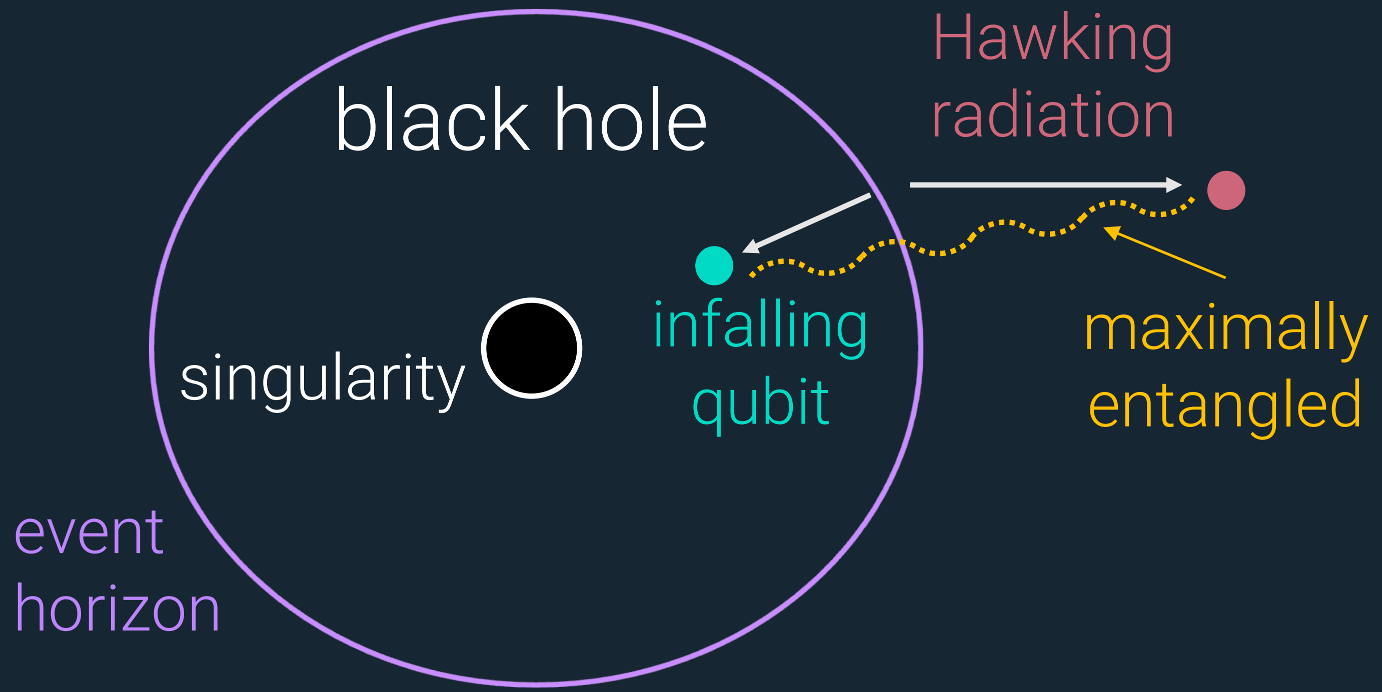
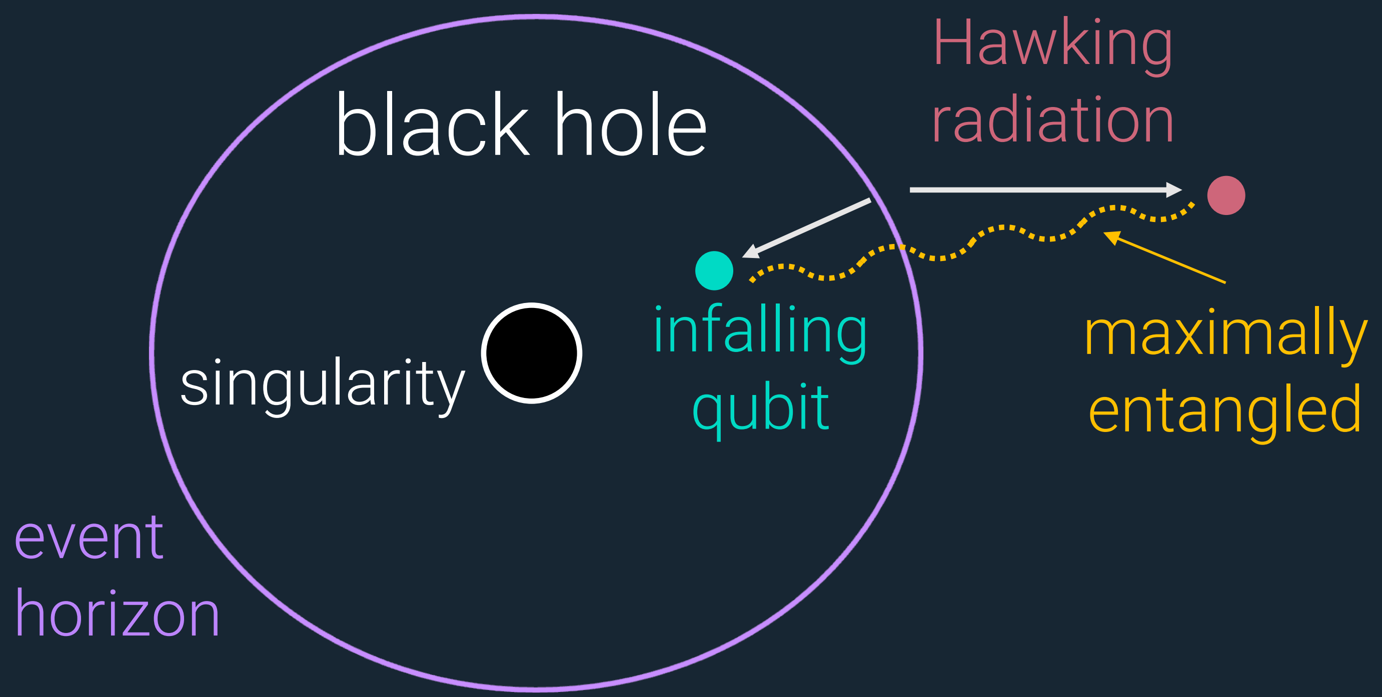


Black Hole Radiation

- Black holes emit qubits of Hawking radiation.
- Each outgoing qubit is maximally entangled with an infalling qubit.
- After long enough, black hole evaporates completely.



Emitted radiation comes out "scrambled."



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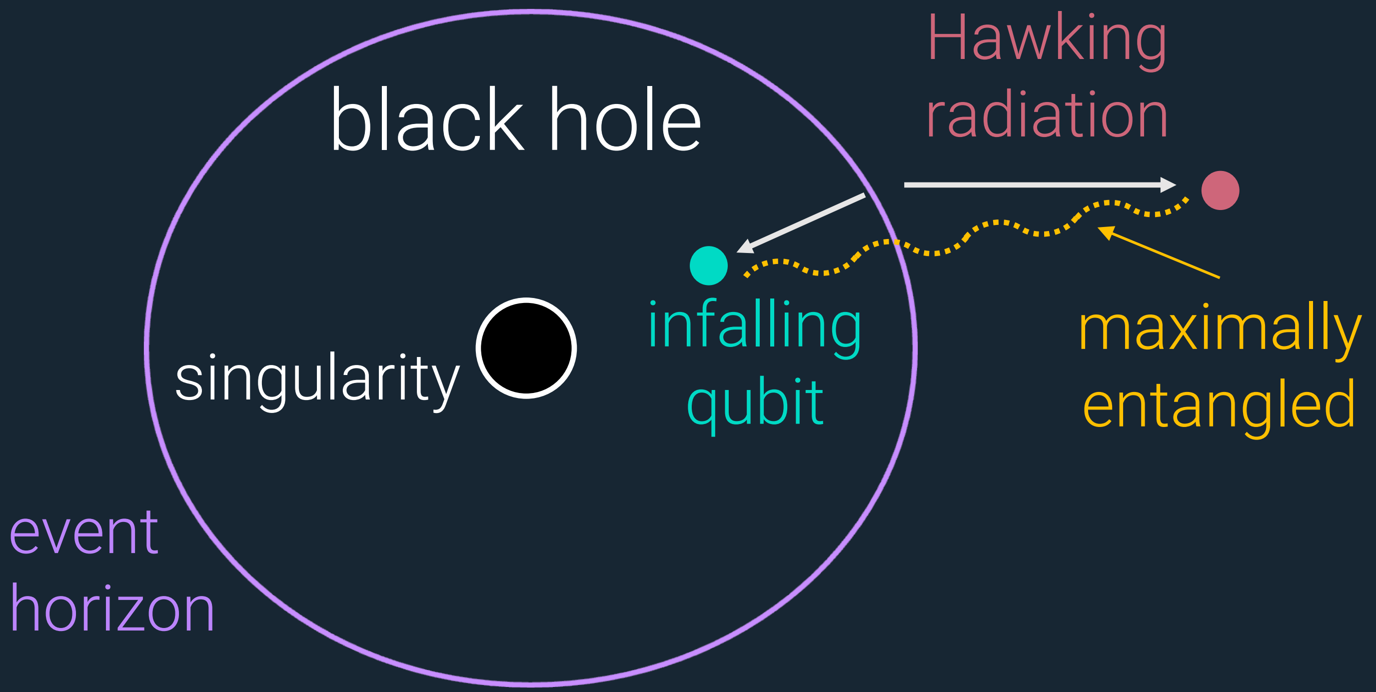

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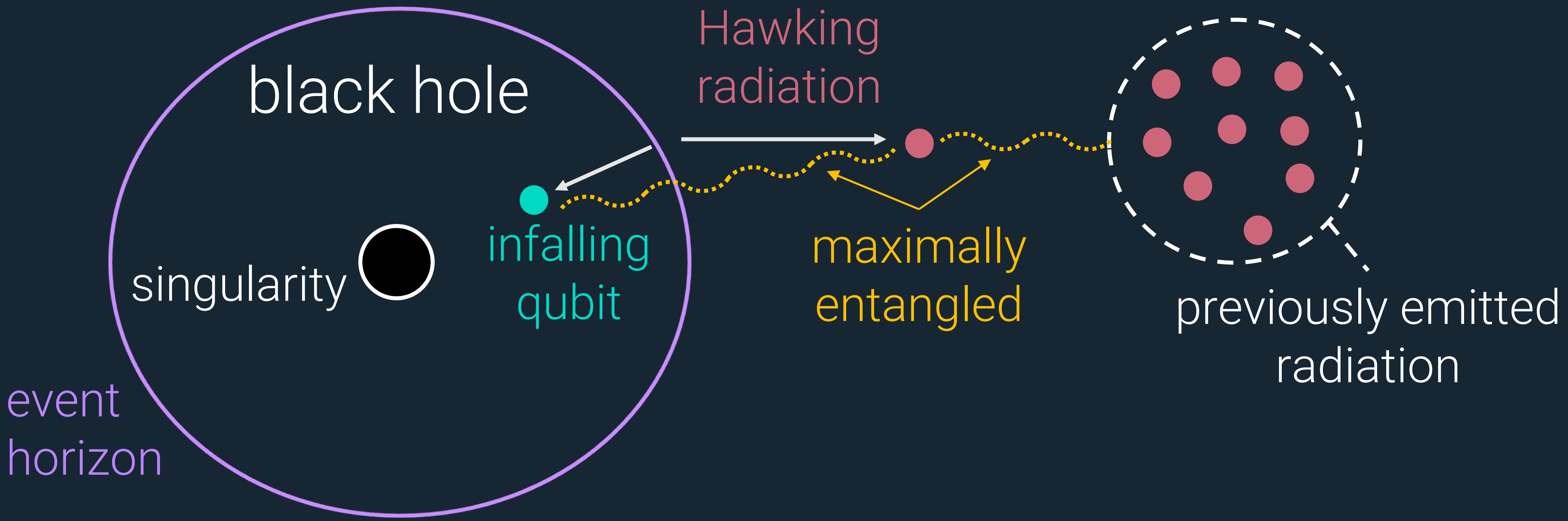

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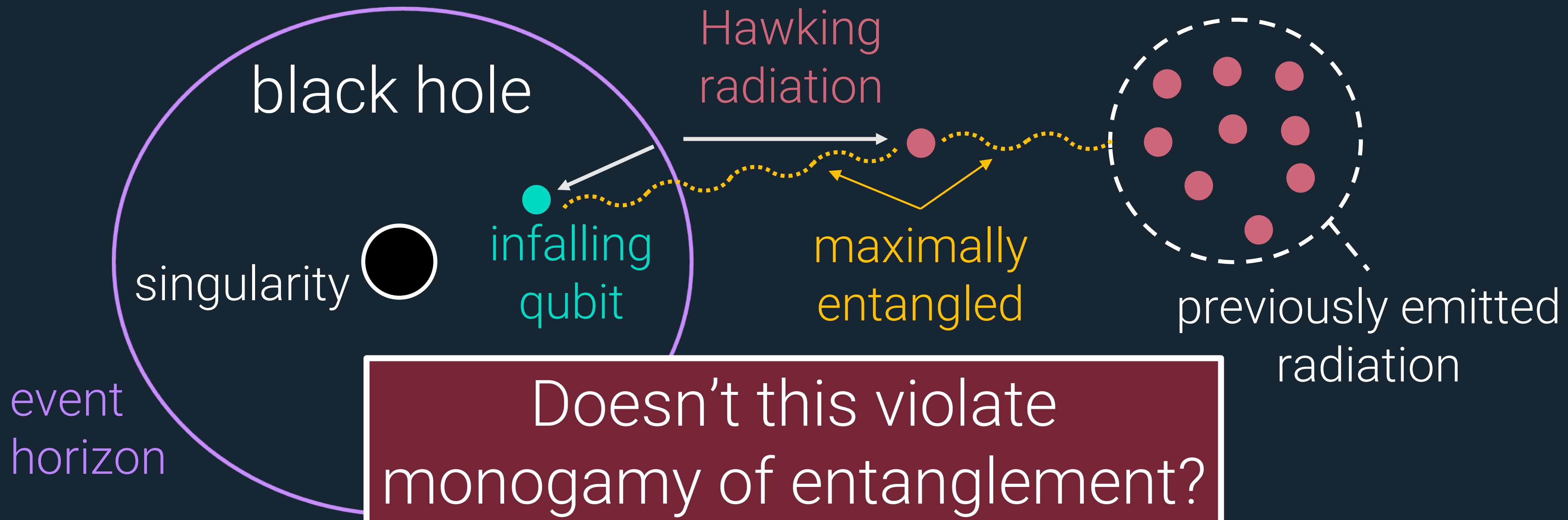
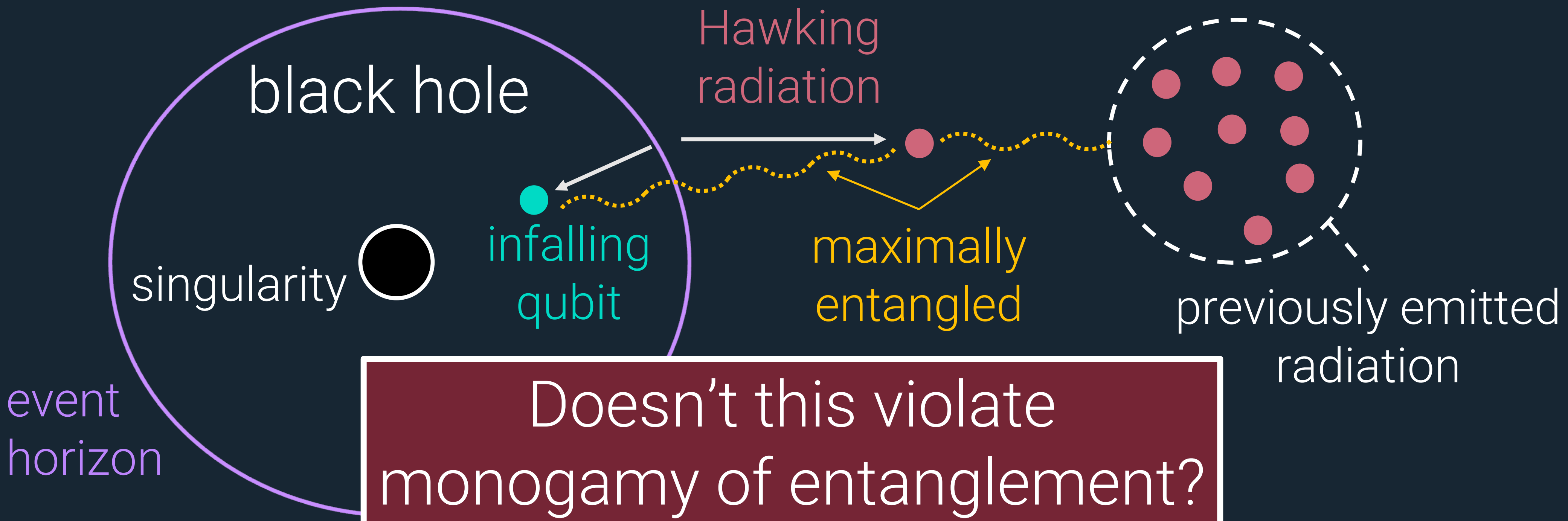


Doesn't this violate monogamy of entanglement?

Black hole complementarity [Susskind-'t Hooft, 90s]

If radiation is maximally entangled with two systems, they're the ***same system***.



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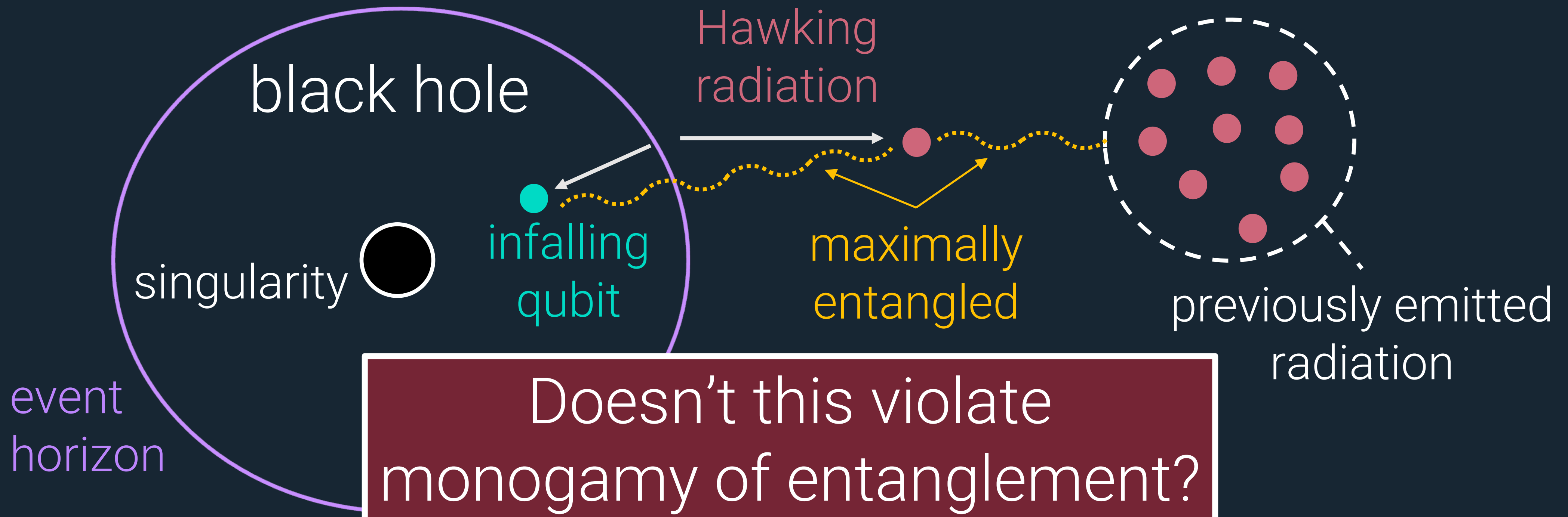
Firewall paradox [Almheiri-Marolf-Polchinski-Sully, 11]

Thought experiment in which an observer ***detects*** the monogamy violation.



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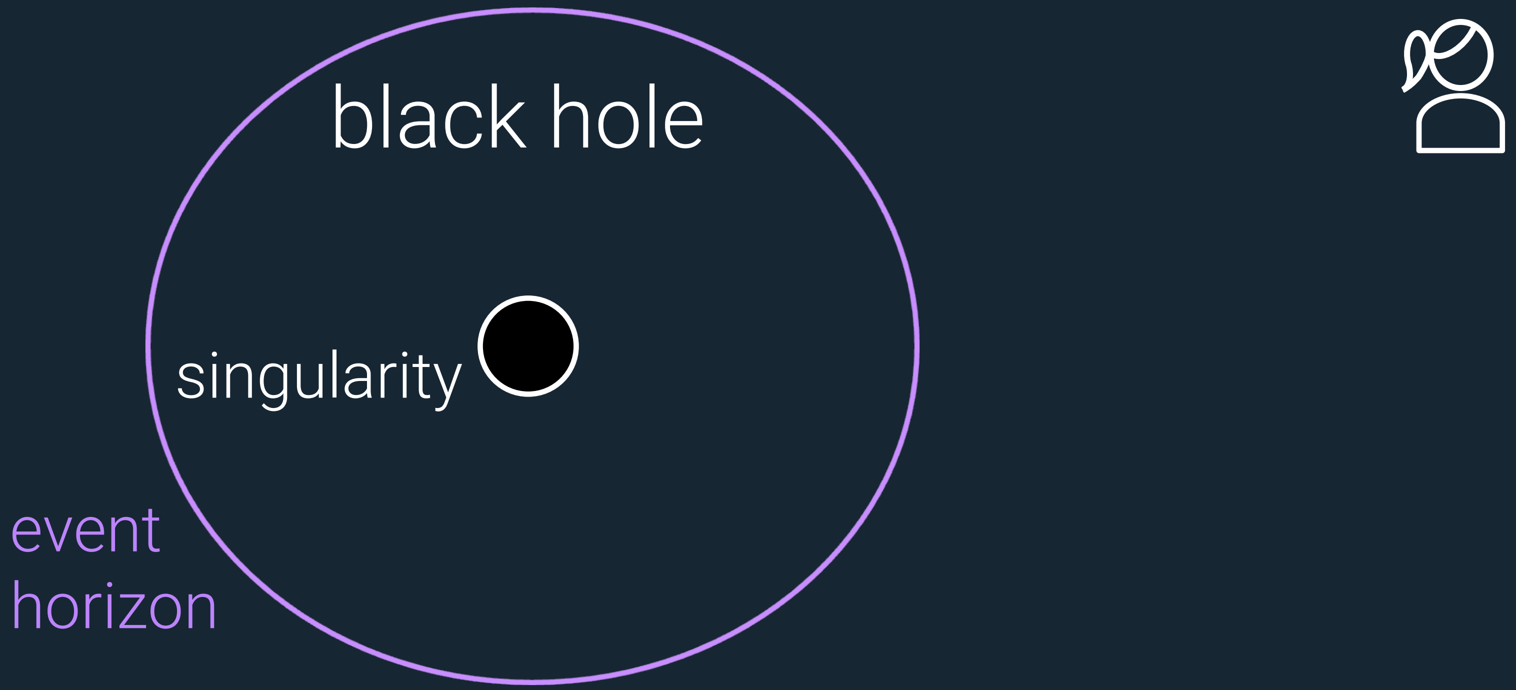

[AMPS11] experiment:

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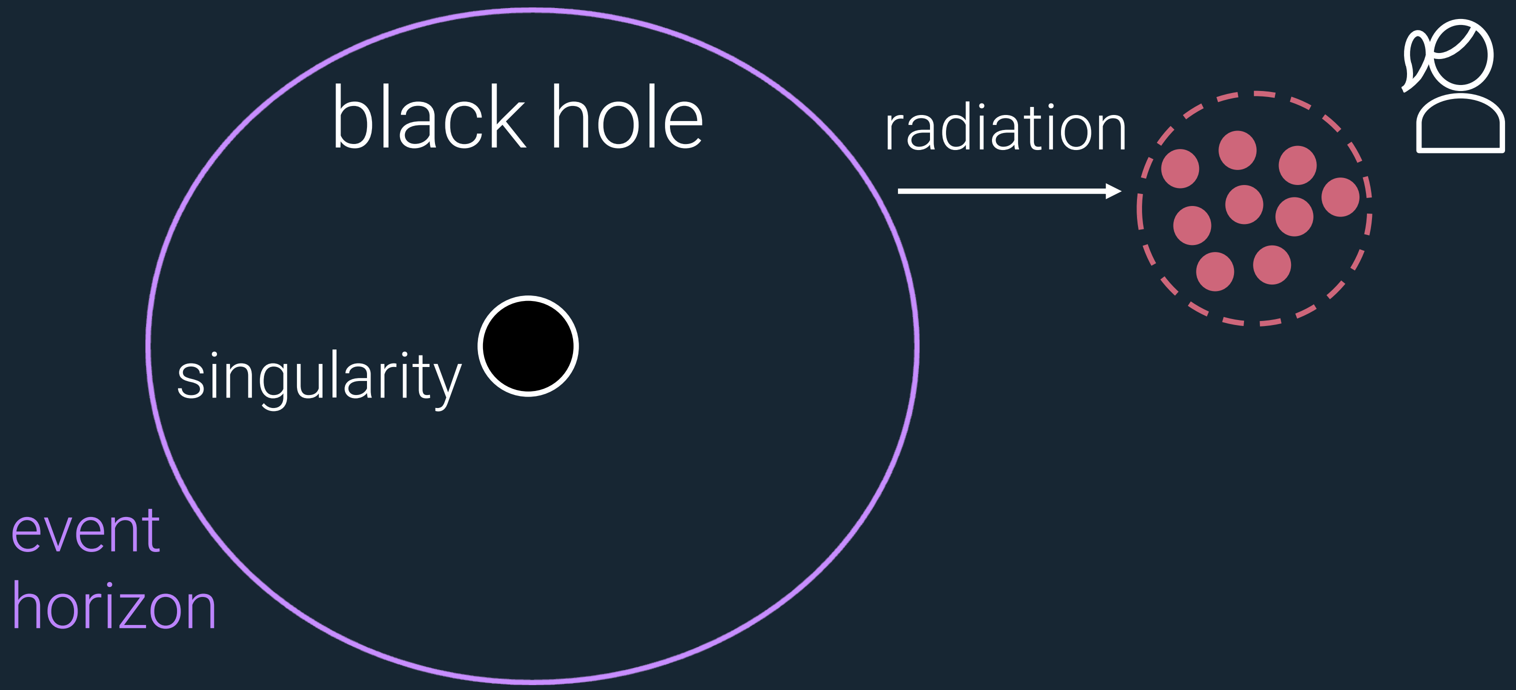

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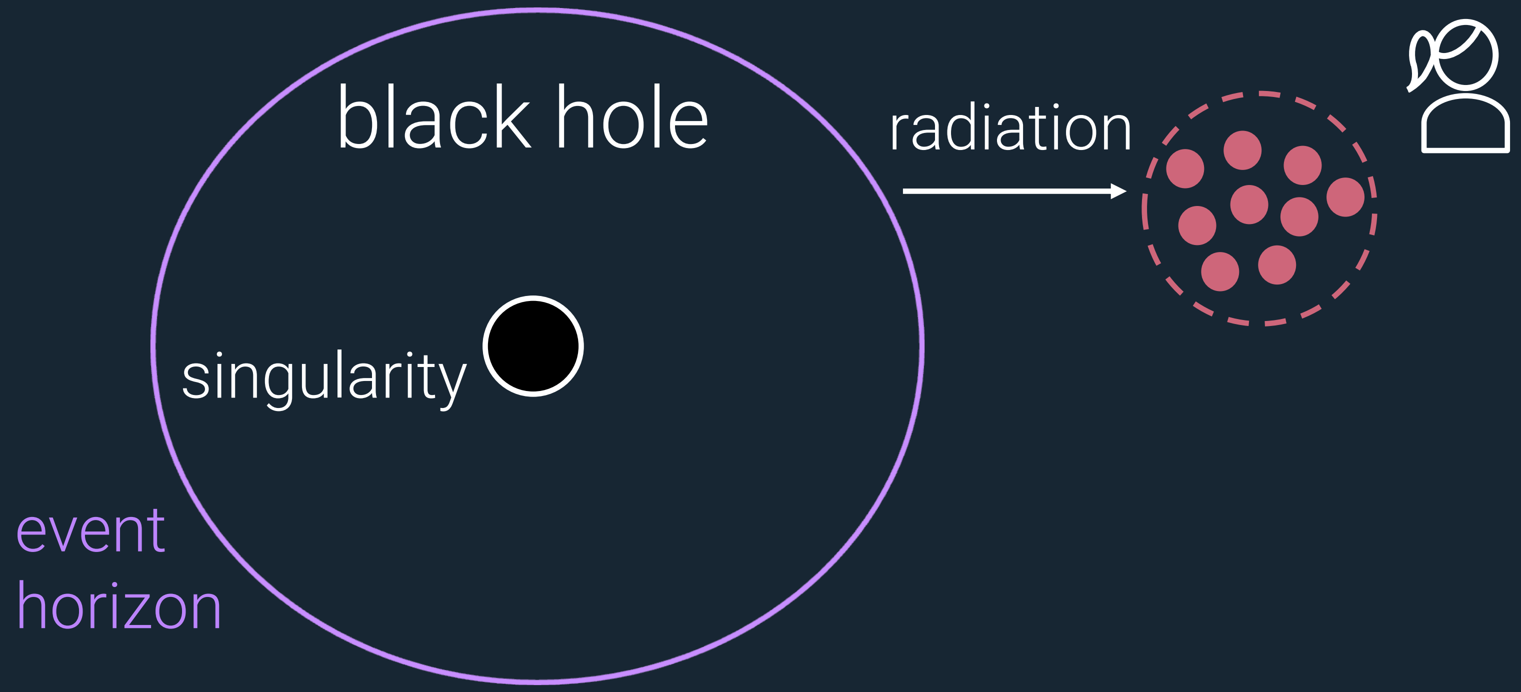

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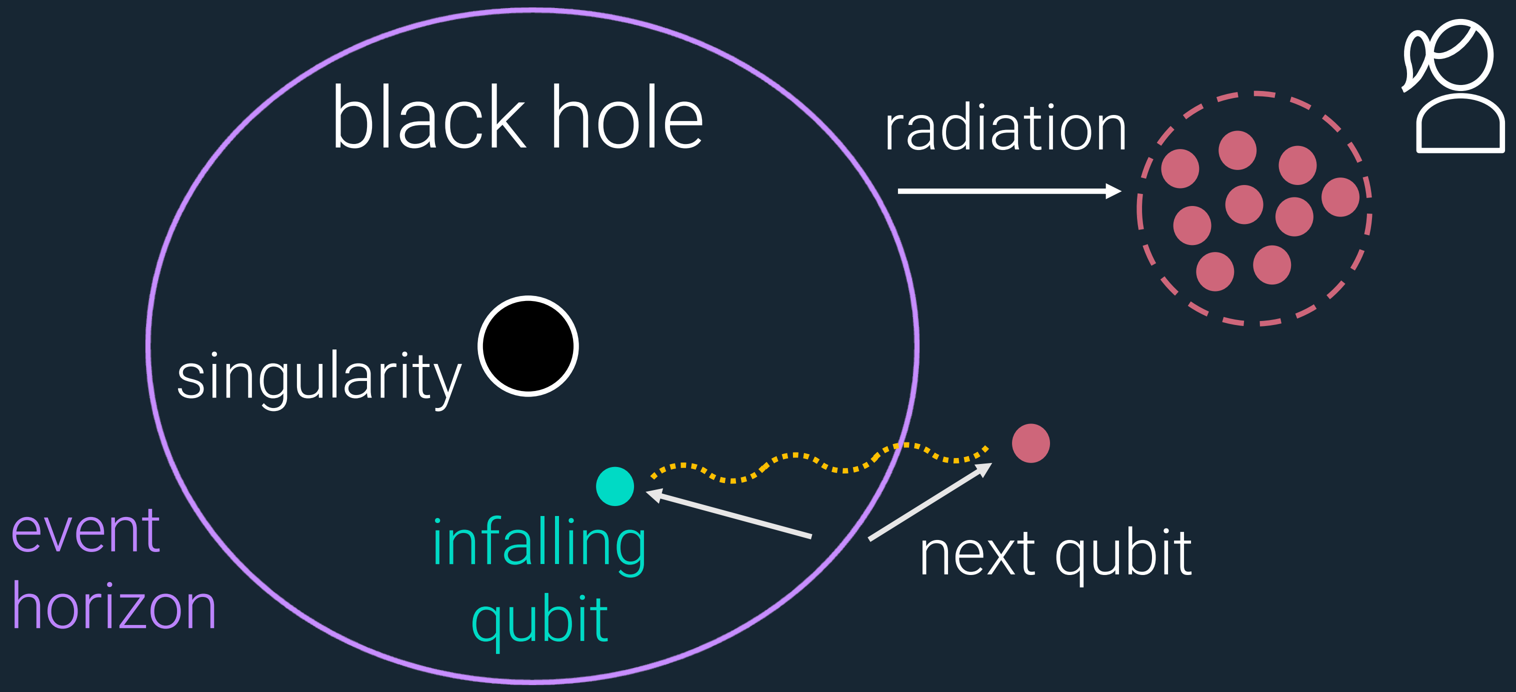

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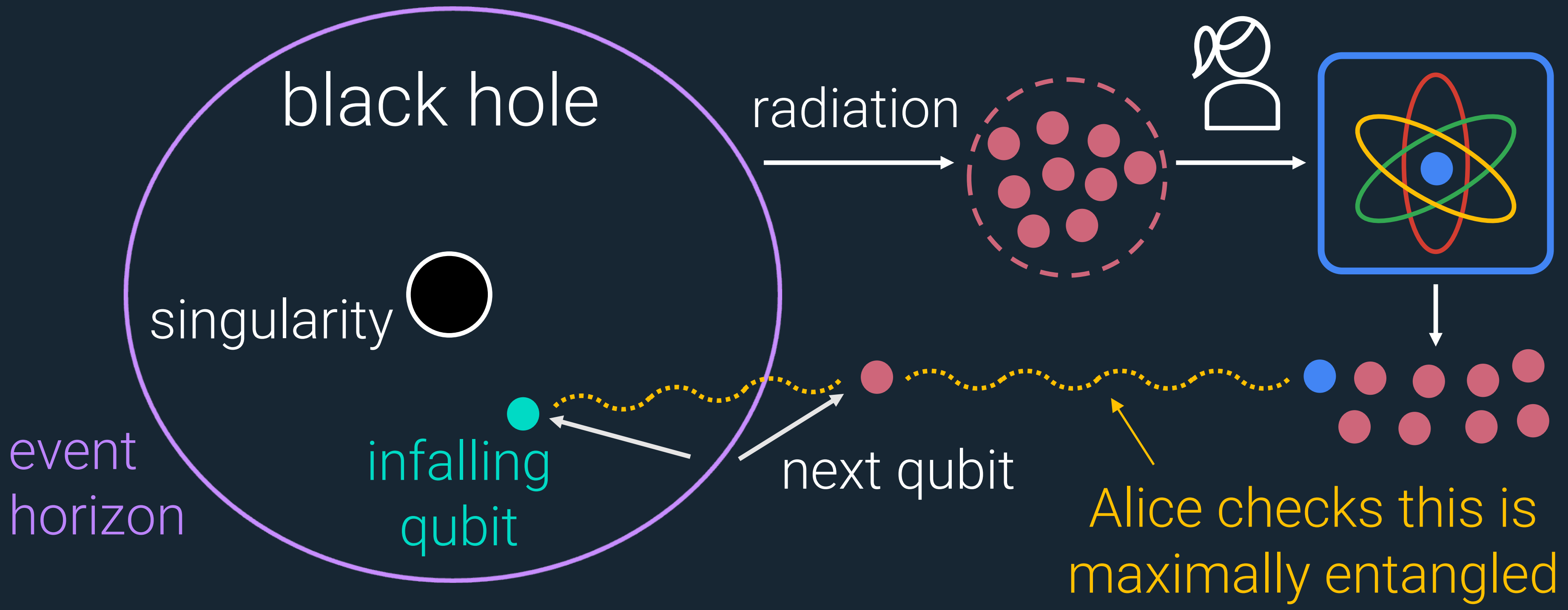

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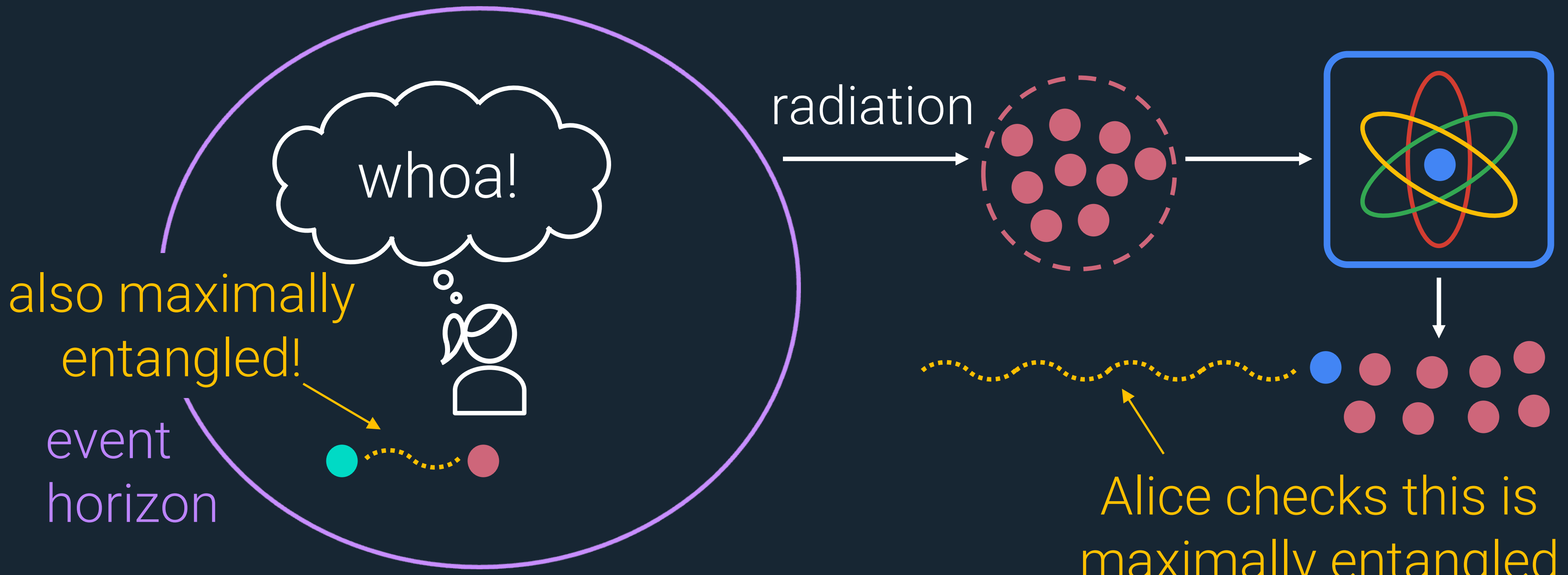
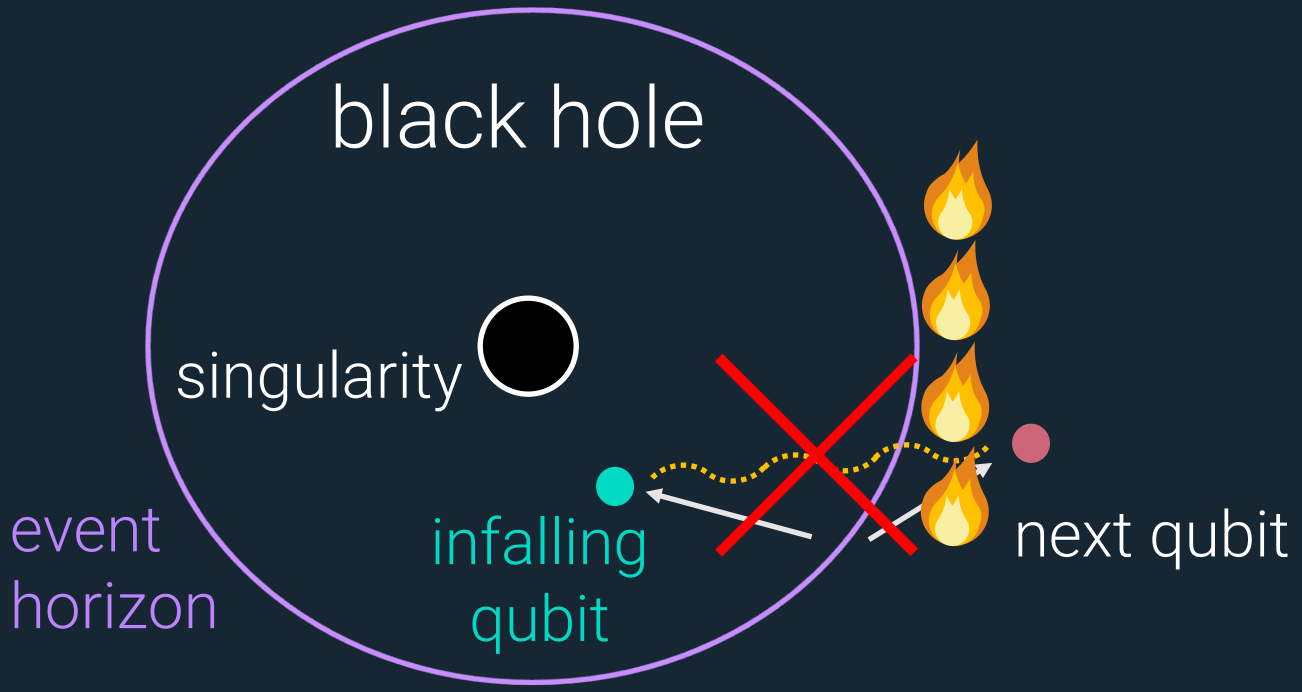


AMPS11 proposed resolution:

"Firewall" outside event horizon (breaking entanglement)



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Very cool and surprising!!

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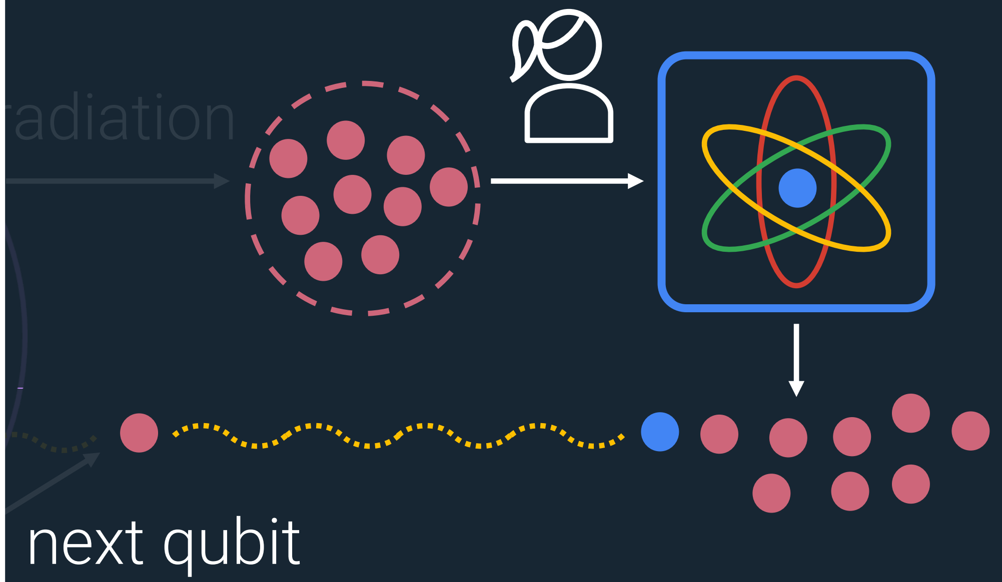
[Harlow-Hayden 2013]

Under certain cryptographic assumptions, this step can require ***exponential*** time.



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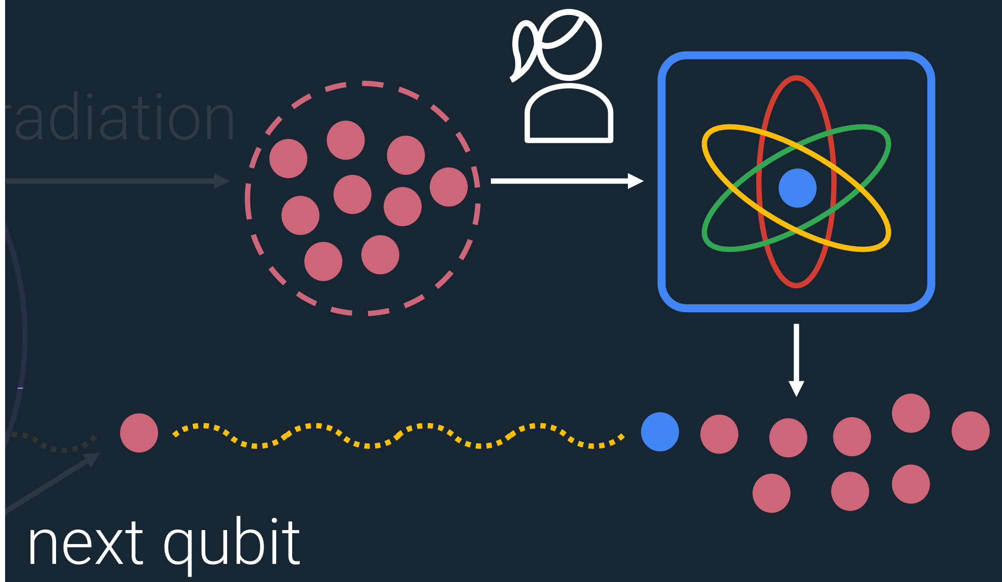
> By the time she's done decoding, the black hole will have evaporated!



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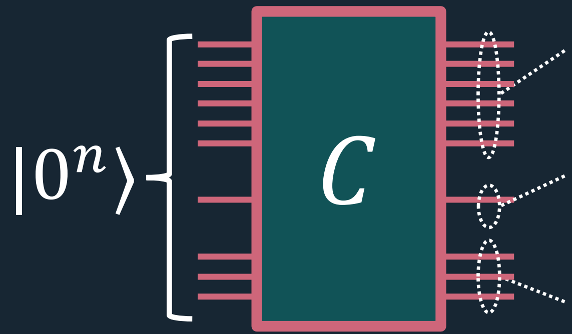

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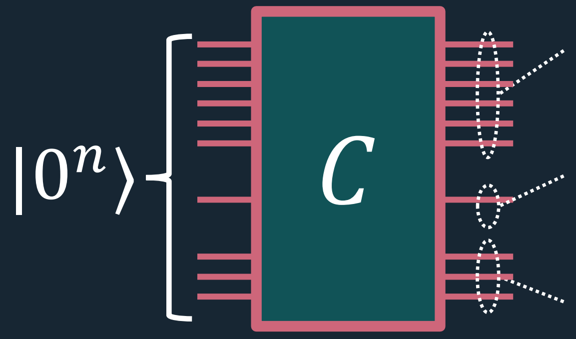

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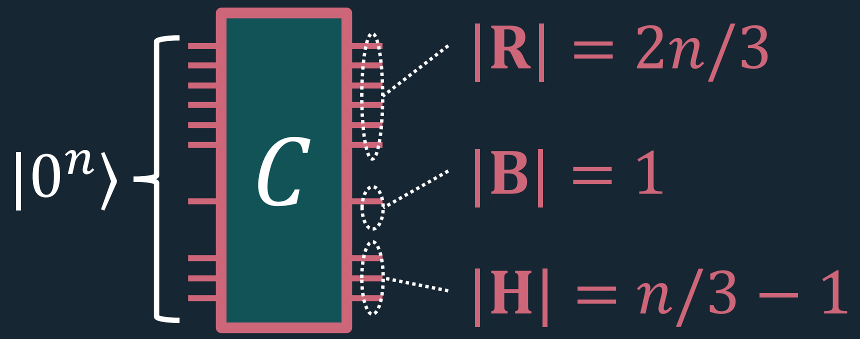
Task: Given $\mathbf{R}$ register of $|\psi\rangle_{\mathbf{RBH}} = C|0^n\rangle$, output a single qubit $\mathbf{A}$ such that $(\mathbf{A}, \mathbf{B})$ is the EPR state $|00\rangle + |11\rangle$.

(promised that $\mathbf{R}$ and $\mathbf{B}$ are maximally entangled)



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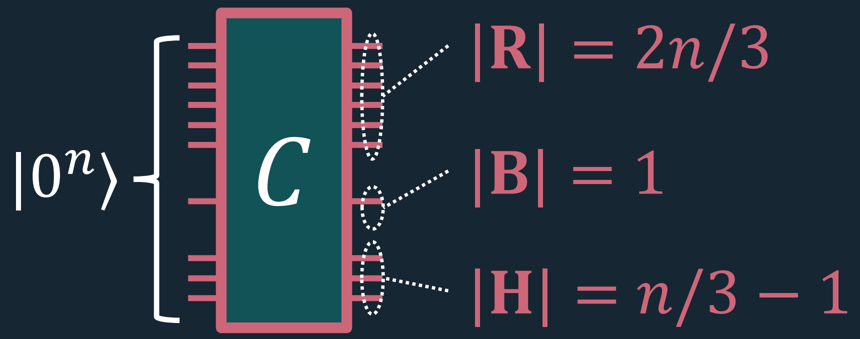

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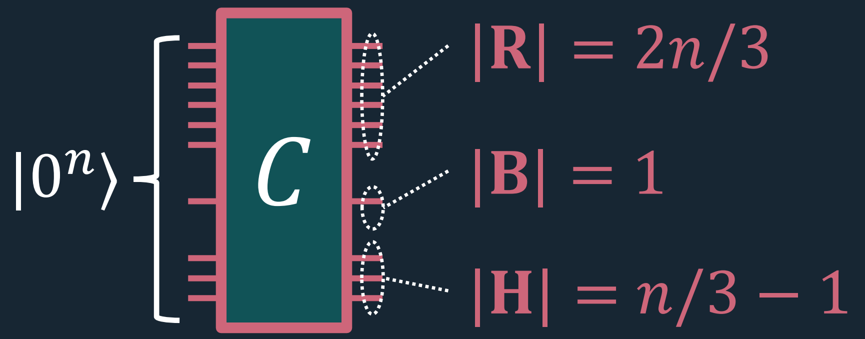

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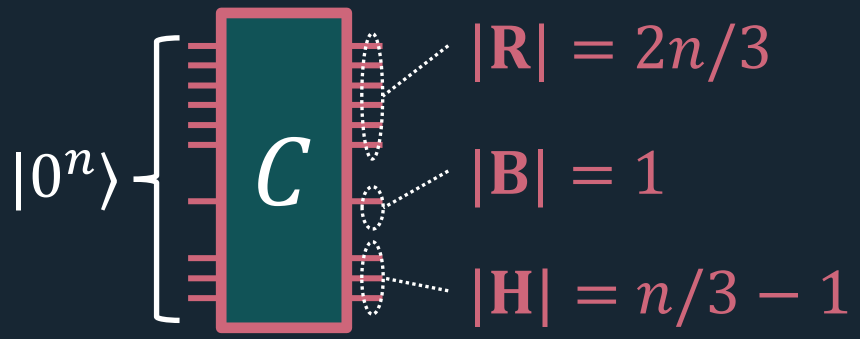
"Hard" means no QPT adversary can win with probability $\geq \frac{1}{4} + \mathbf{negl}(n)$ (formalized by [Brakerski23])



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Later works *weakened* the assumptions needed:

- [Aaronson16]: quantum-secure one-way functions
- [Brakerski23]: quantum bit commitment

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Why cryptographers care: quantum commitments imply many important primitives, e.g., quantum oblivious transfer, multi-party computation, and zero knowledge.

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Why cryptographers care: quantum commitments imply many important primitives, e.g., quantum oblivious transfer, multi-party computation, and zero knowledge.

"This can be viewed (with proper disclaimers, as we discuss) as providing a physical justification for the existence of secure cryptography" – [Brakerski23]

Rest of today: new perspective on Brakerski's result/proof.

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(2) Radiation decoding problem [Harlow-Hayden13]

(3) Radiation *distinguishing* problem

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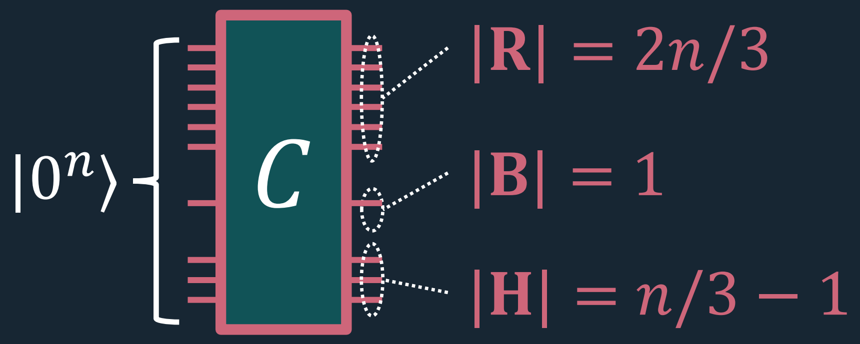
Instead of studying the [HH13] radiation **decoding** problem, we'll define a new radiation **distinguishing** problem.



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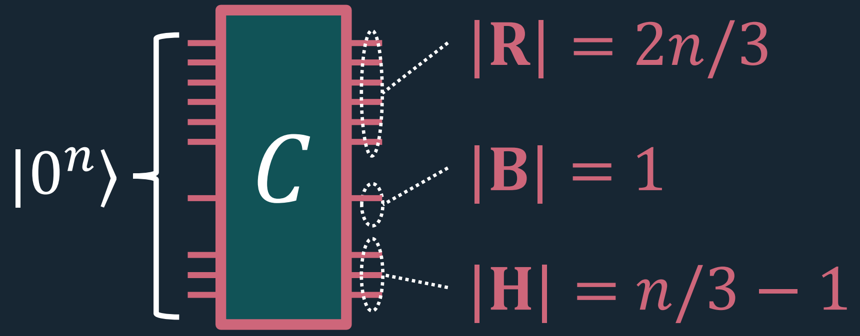

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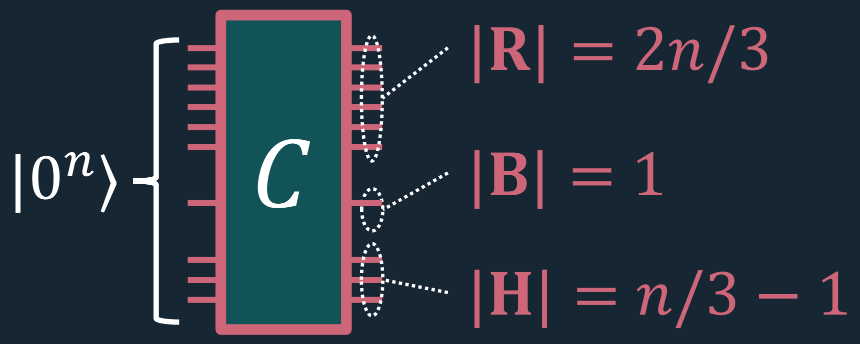
The point:

$\mathbf{R}$ and $\mathbf{B}$ are maximally entangled, but this entanglement isn't efficiently detectable.



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Distinguish $(\mathbf{R}, \mathbf{B})$ from $(\mathbf{R}, \mathbf{B}')$ where $\mathbf{B}'$ is an unentangled, maximally mixed qubit.

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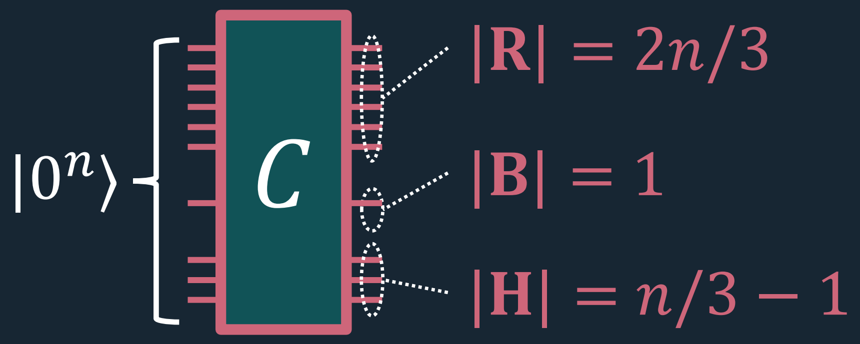

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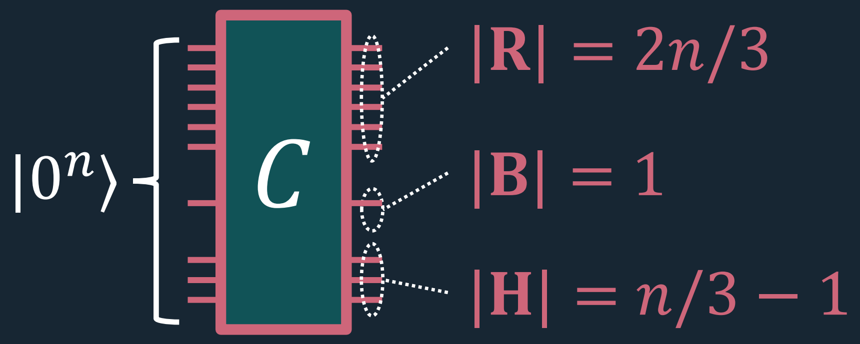

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Claim 2: Distinguishing should still be hard.

If Alice can't trigger a firewall, then she shouldn't be able to detect entanglement between $\mathbf{B}$ and $\mathbf{R}$ in the AMPS experiment.

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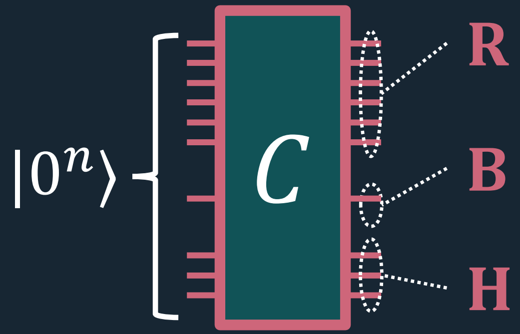

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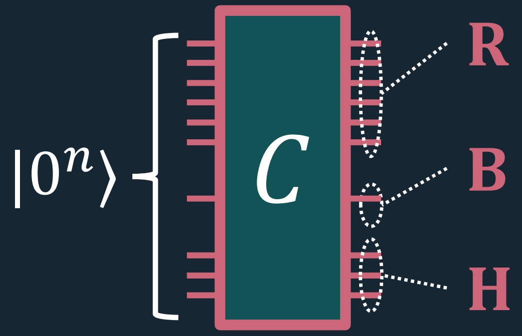

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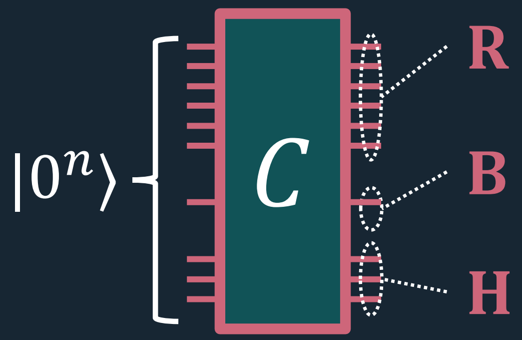

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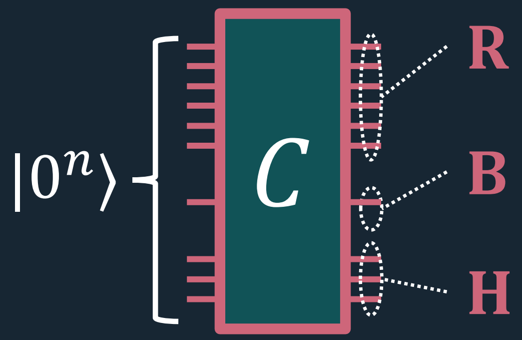

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Up next: define commitments to quantum states

Quantum State Commitments

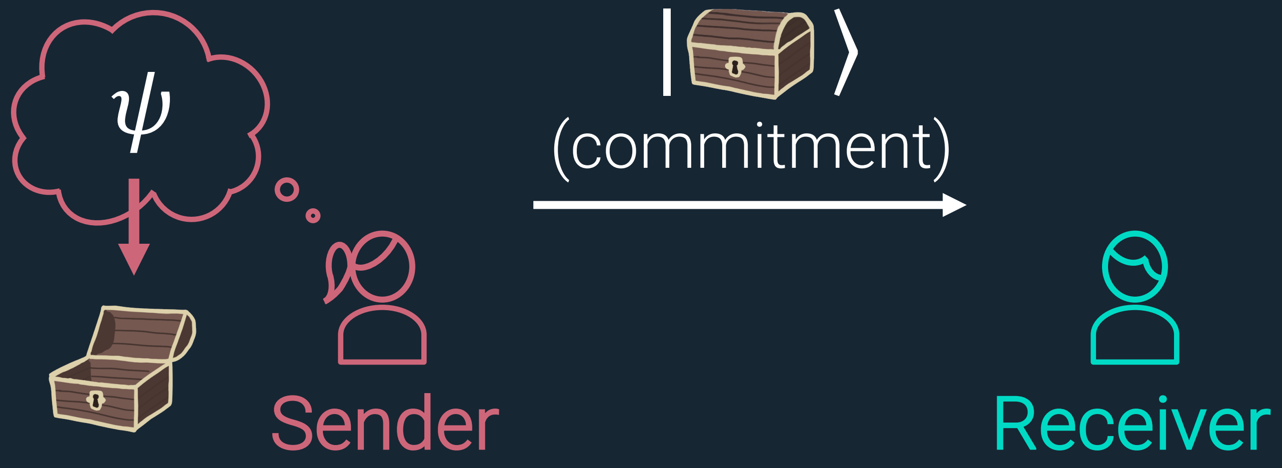
[Gunn-Ju-M-Zhandry23]

Protocol that lets a sender commit to a (possibly entangled) quantum state ψ, with the ability to reveal ψ later.

Quantum State Commitments

[Gunn-Ju-M-Zhandry23]

Protocol that lets a sender commit to a (possibly entangled) quantum state ψ, with the ability to reveal ψ later.



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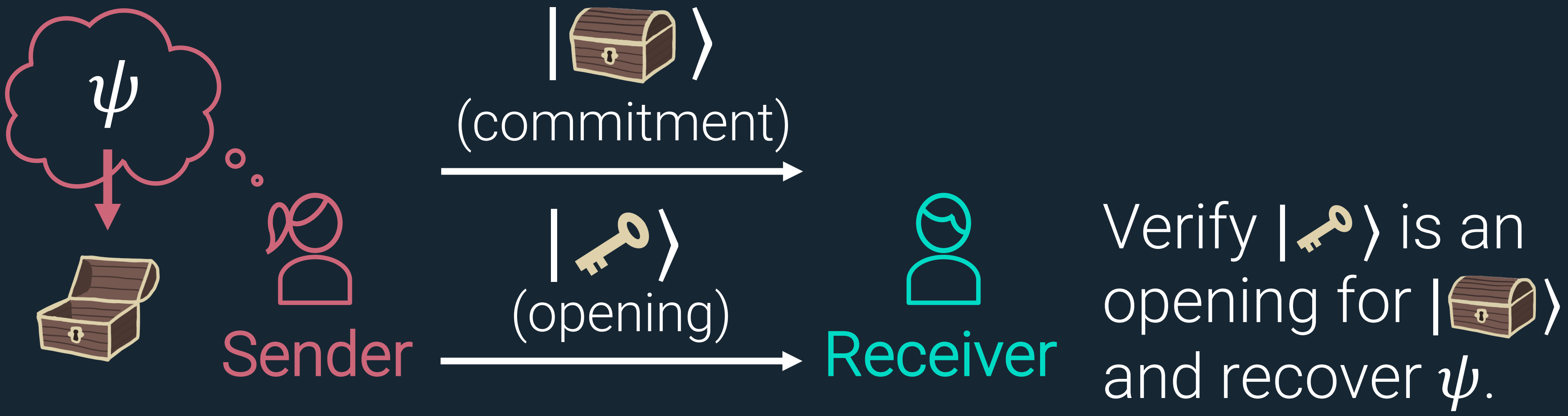

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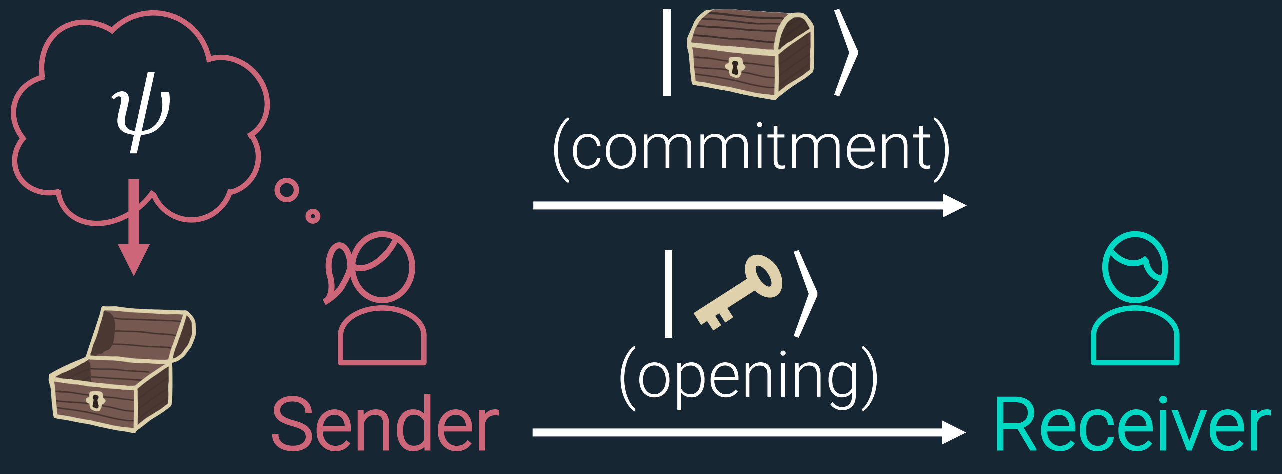

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Hiding: |🧰⟩ hides message from receiver.

Binding: after sending |🧰⟩, sender can't change ψ.

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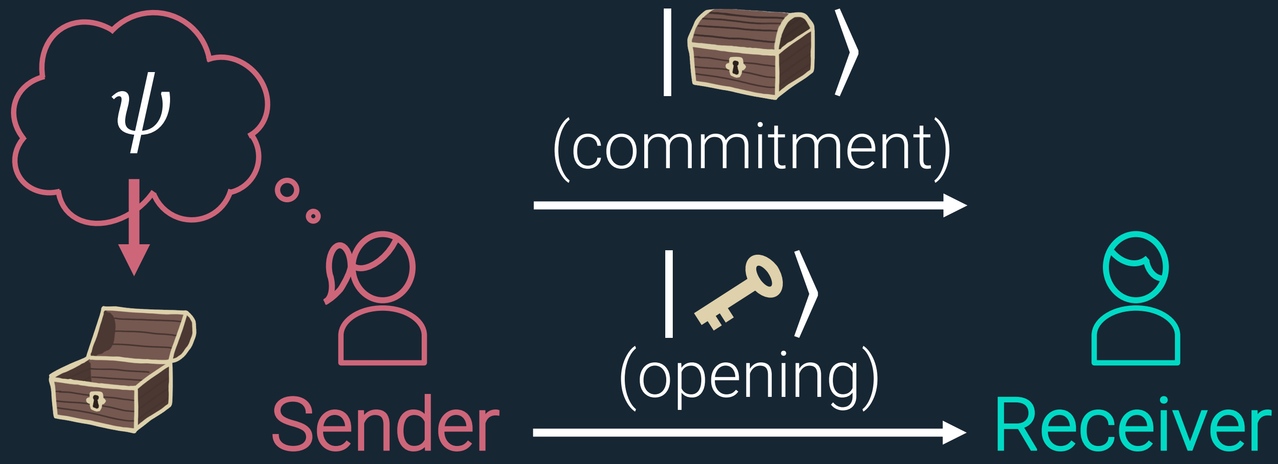

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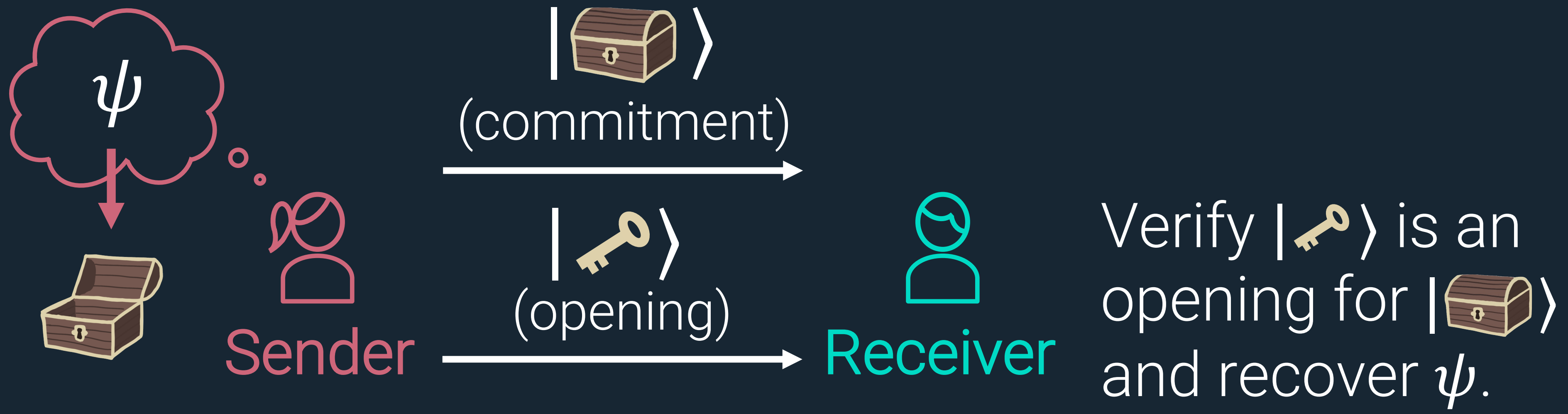

- Requires computational assumptions [M96, LC96].
- Exist if and only if quantum bit commitments exist.

Commitment Syntax

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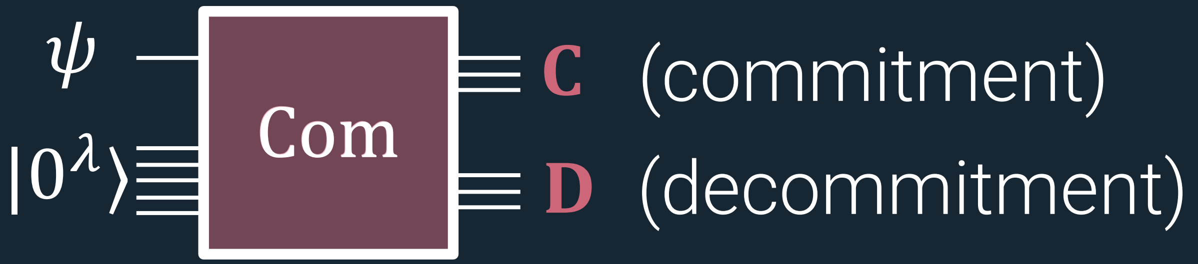

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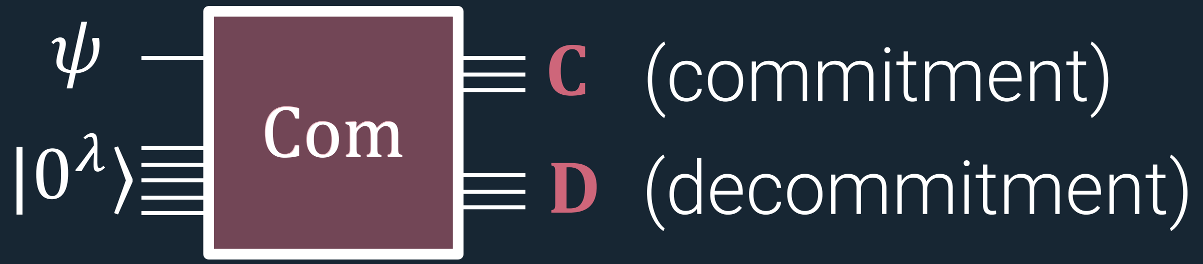

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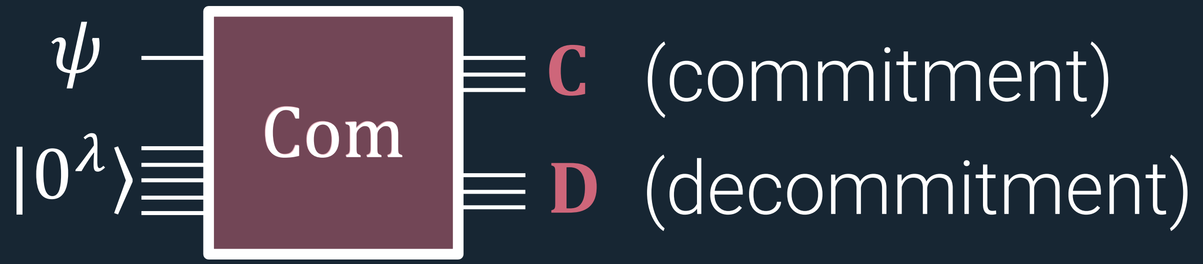

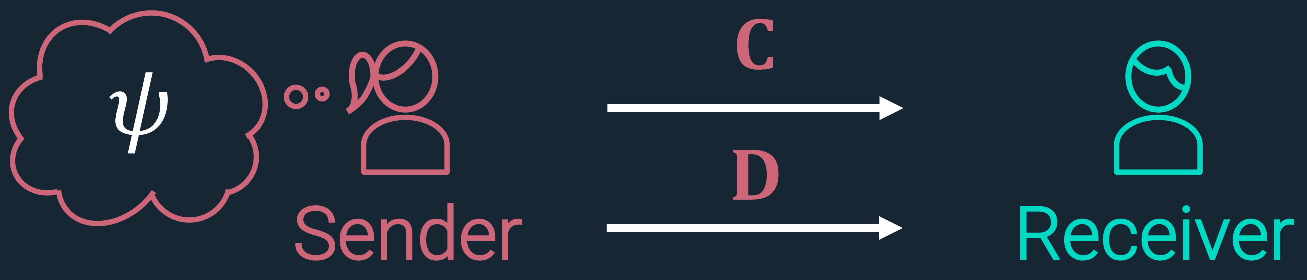

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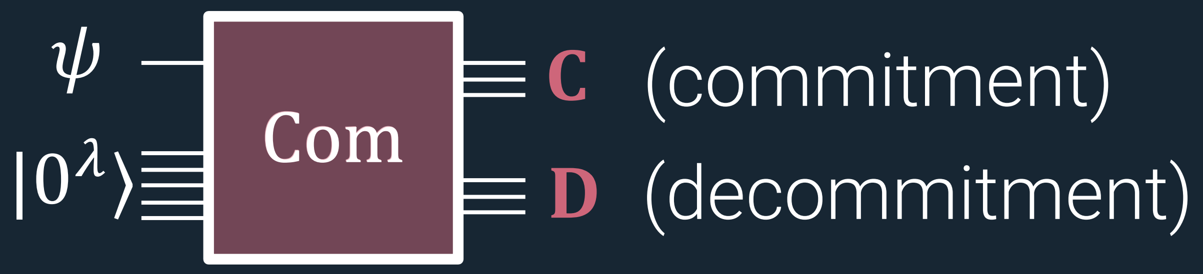
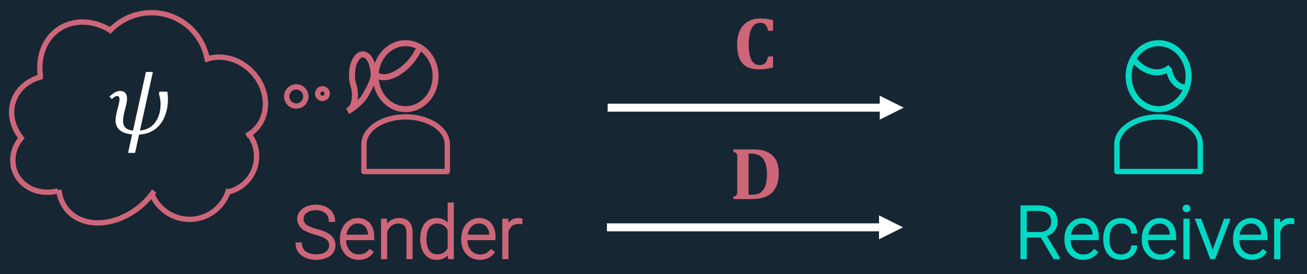
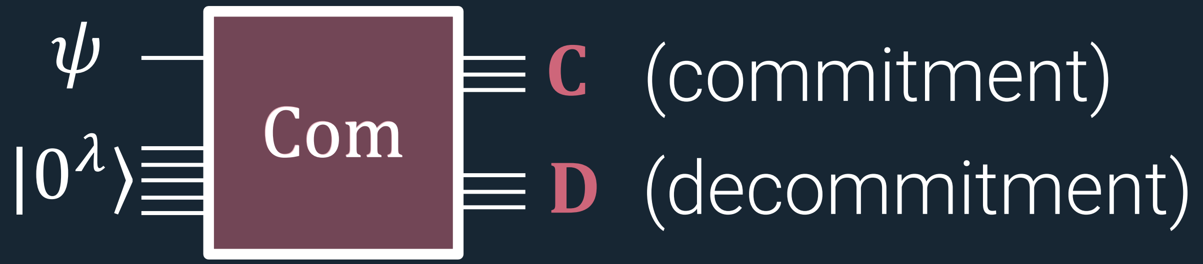




To verify $(\mathbf{C}, \mathbf{D})$, receiver applies $\mathtt{Com}^\dagger$ and checks if last λ bits are $\mathbf{0}$.

Security: Binding and Hiding



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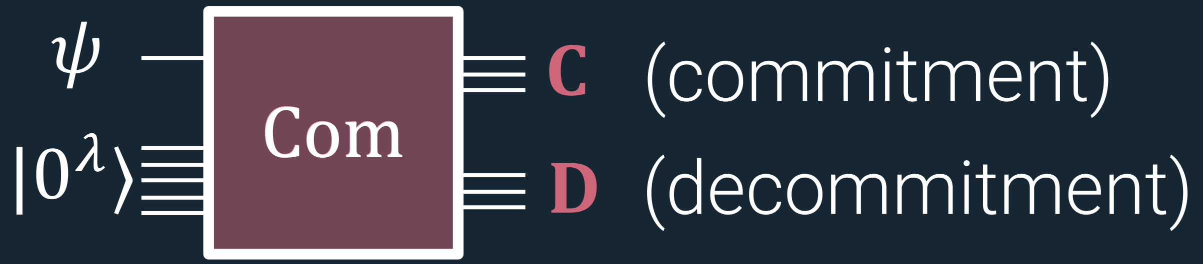

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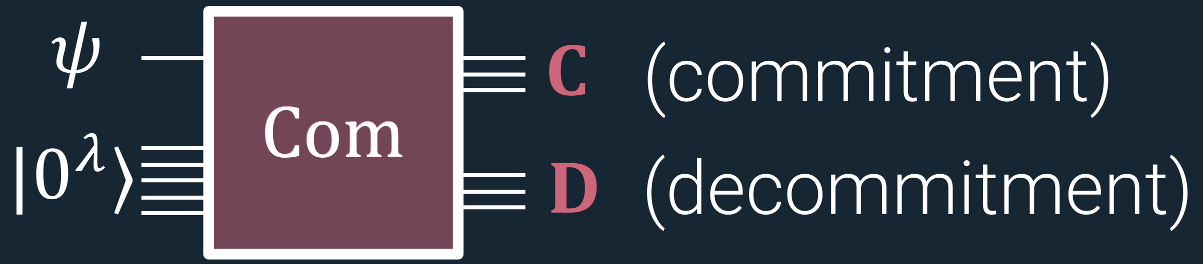

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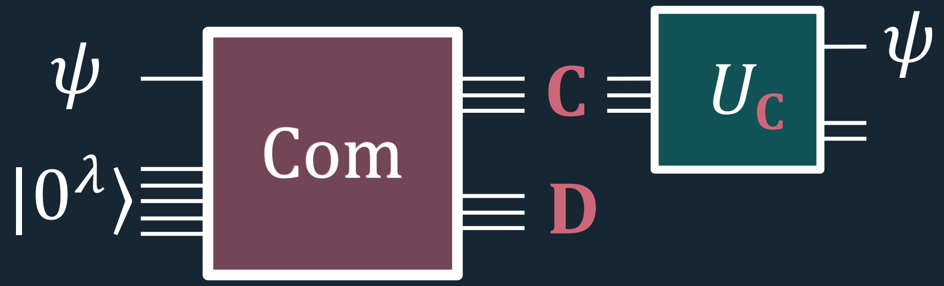
Exists an inefficient unitary $U_{\mathbf{C}}$ that recovers ψ from C alone.



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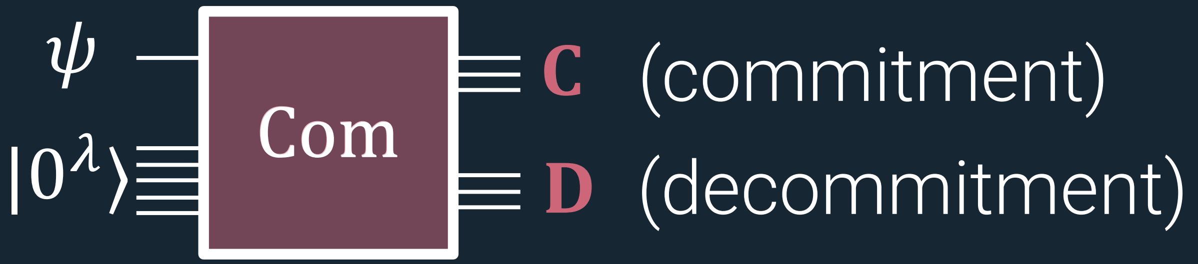

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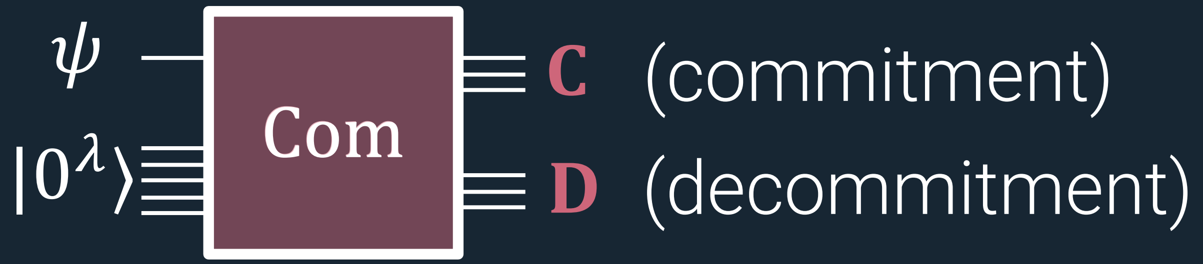

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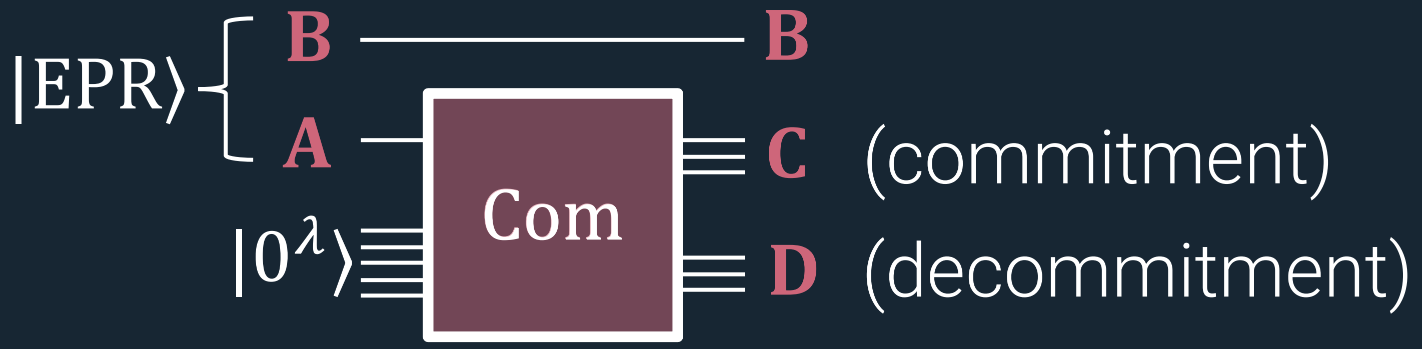
Crucial point: since adversary picks ψ, indistinguishability holds even if the adversary has a state entangled with ψ.

Commitments to the EPR State

Setup: Prepare $|\mathrm{EPR}\rangle_{\mathbf{AB}}$ and commit to $\mathbf{A}$.



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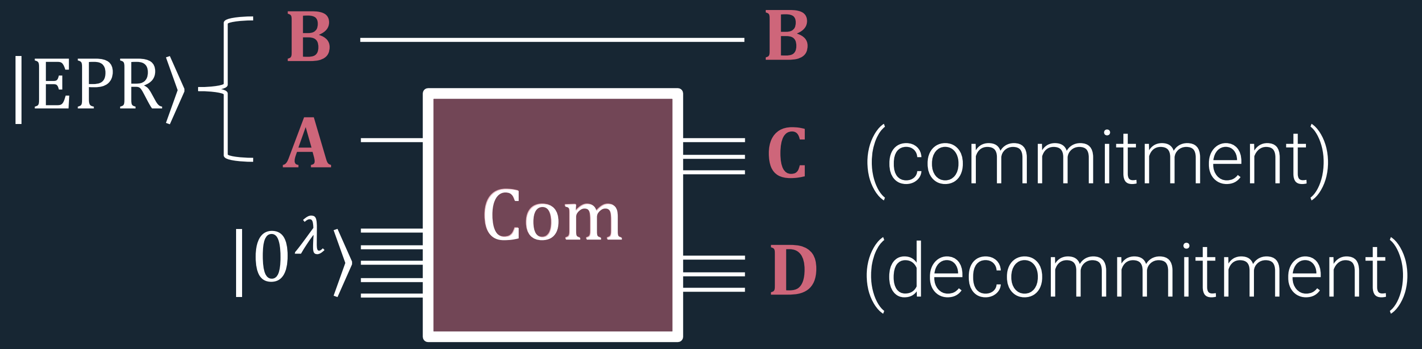

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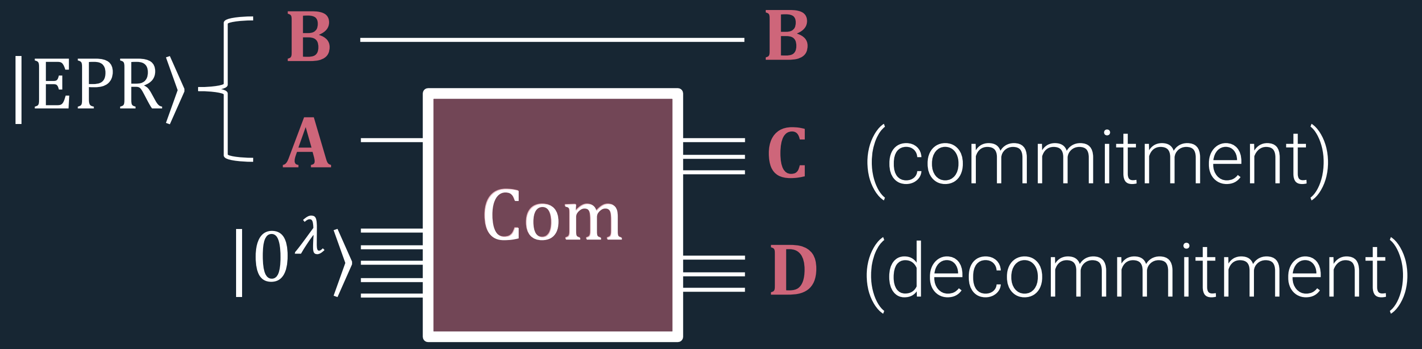

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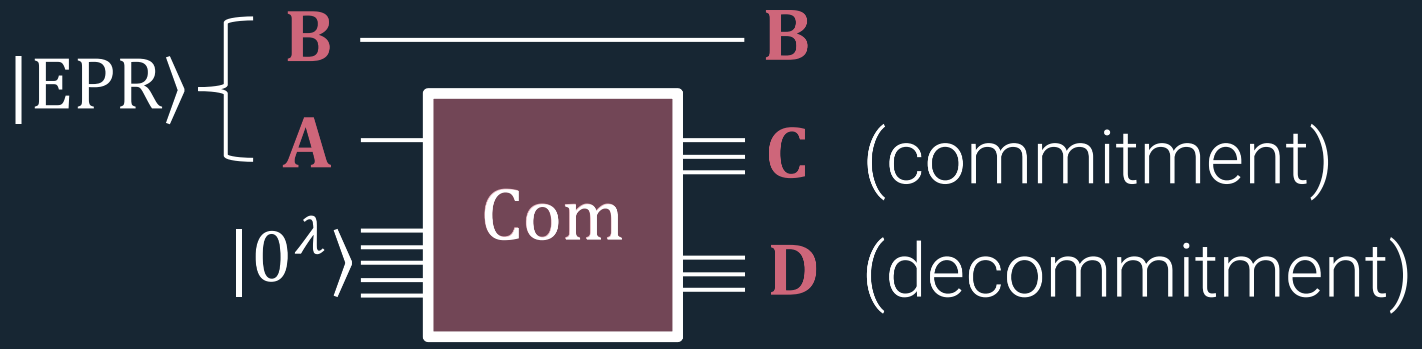

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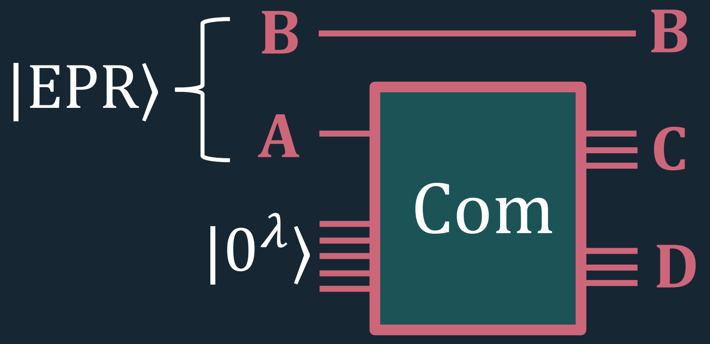
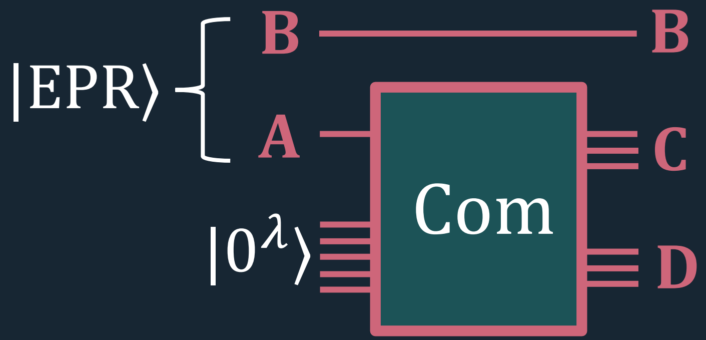
Fact: $(\mathbf{B}, \mathbf{C}')$ is distributed as $(\mathbf{B}', \mathbf{C})$ for $\mathbf{B}'$ maximally mixed.



Breaking Hiding of EPR Commitment:
Promised that **B** and **C** are maximally entangled, distinguish (**B**, **C**) from (**B′**, **C**) where **B′** is an unentangled, maximally mixed qubit.



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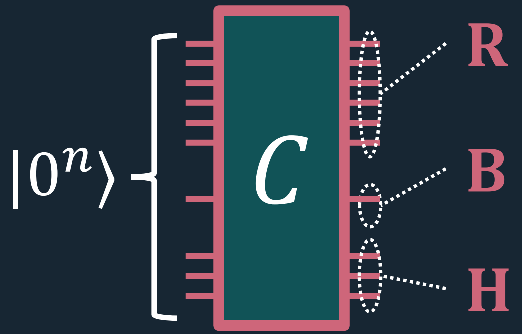
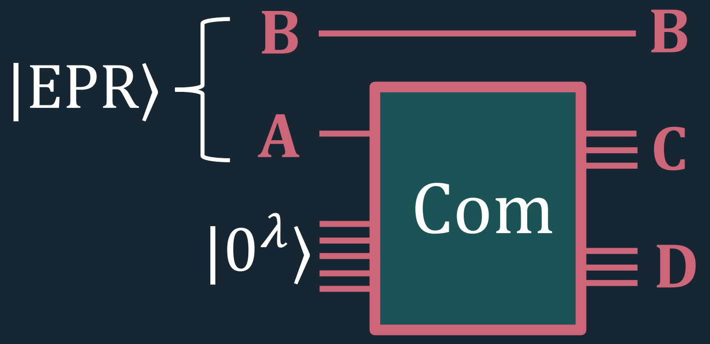


Radiation Distinguishing Problem:
Promised that **B** and R are maximally entangled, distinguish (**B**, **R**) from (**B′**, **R**) where **B′** is an unentangled, maximally mixed qubit.

Thus, quantum commitments → hard radiation distinguishing.



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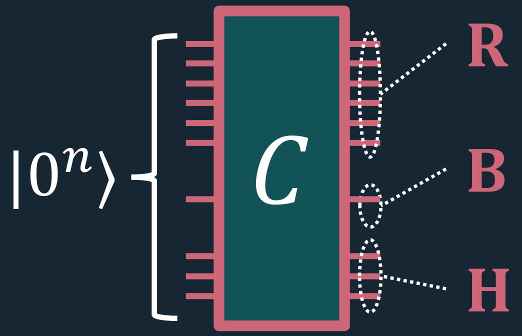

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One last thing: to show hard radiation distinguishing → crypto, need to show EPR commitments → commitments to any state.

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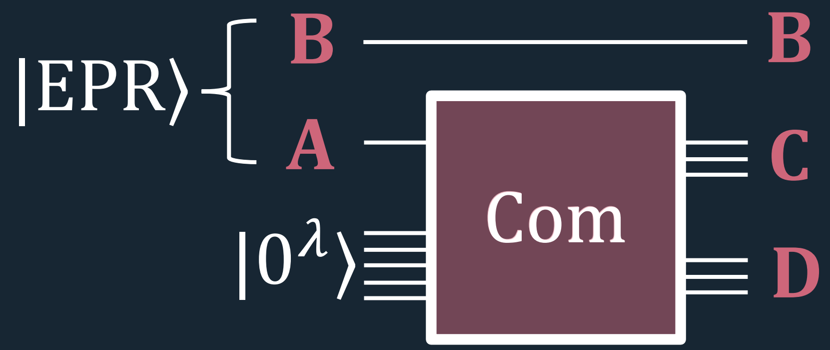

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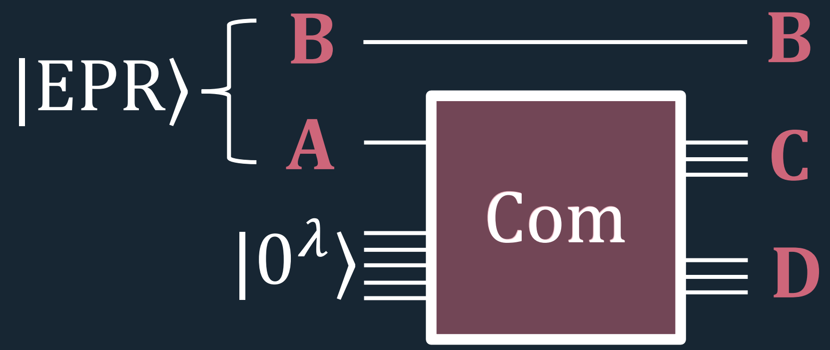

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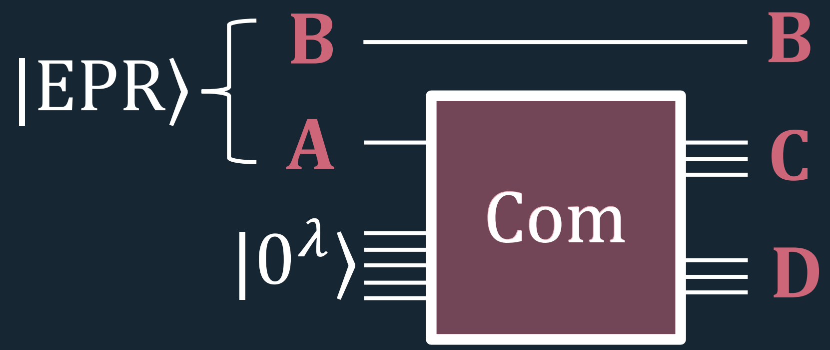

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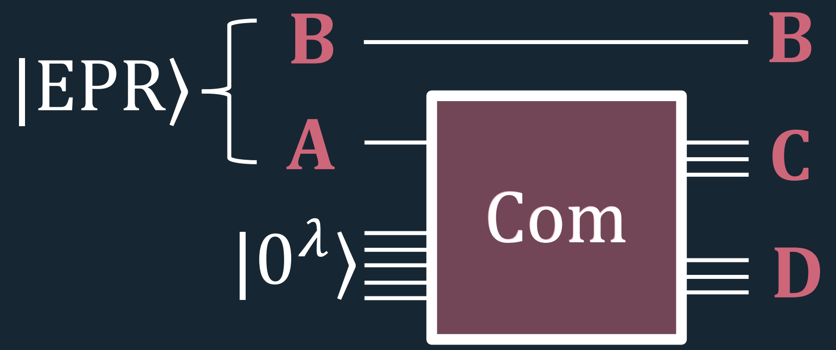

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Future research direction: give more evidence for hardness.

Given description of a random circuit C, how hard is it to distinguish $C|0^n\rangle$ from $C|1^n\rangle$ given $2n/3$ of the qubits?