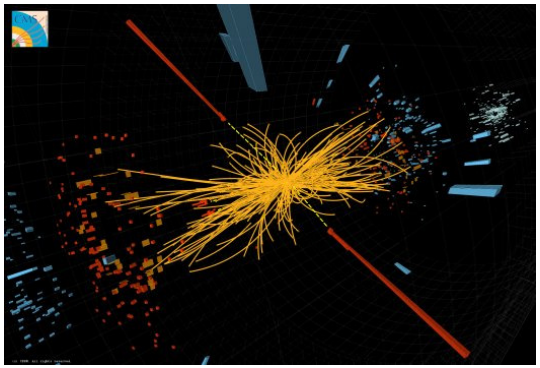
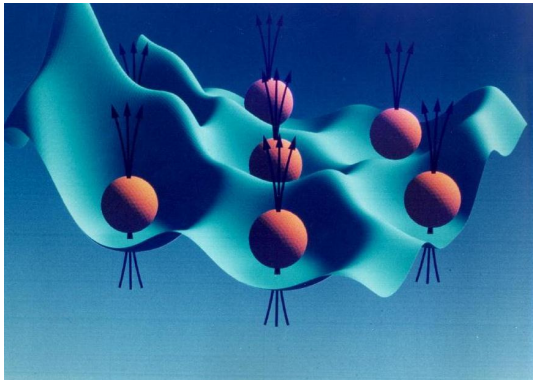
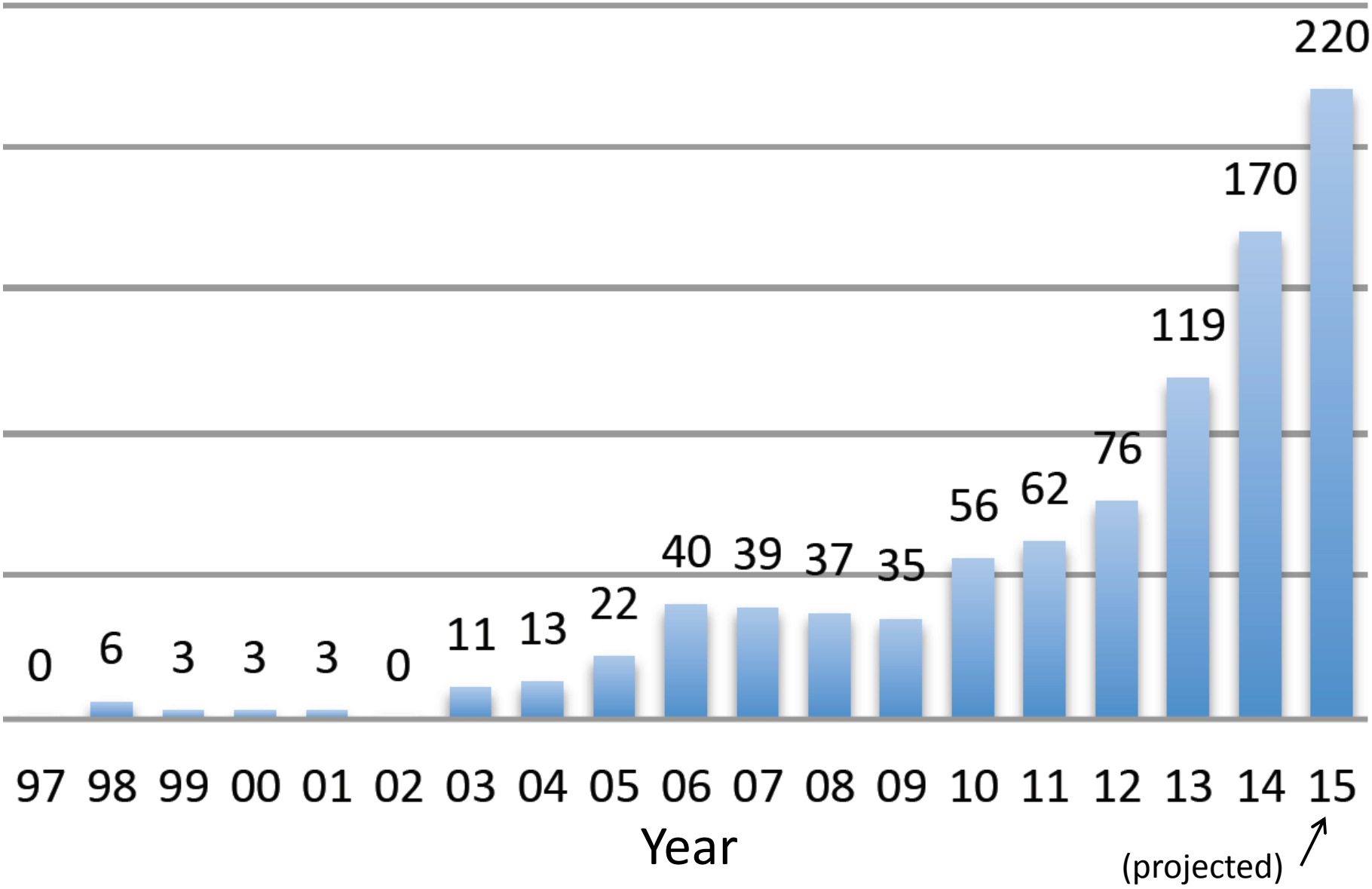
It from Qubit:

Simons Collaboration on Quantum Fields, Gravity, and Information

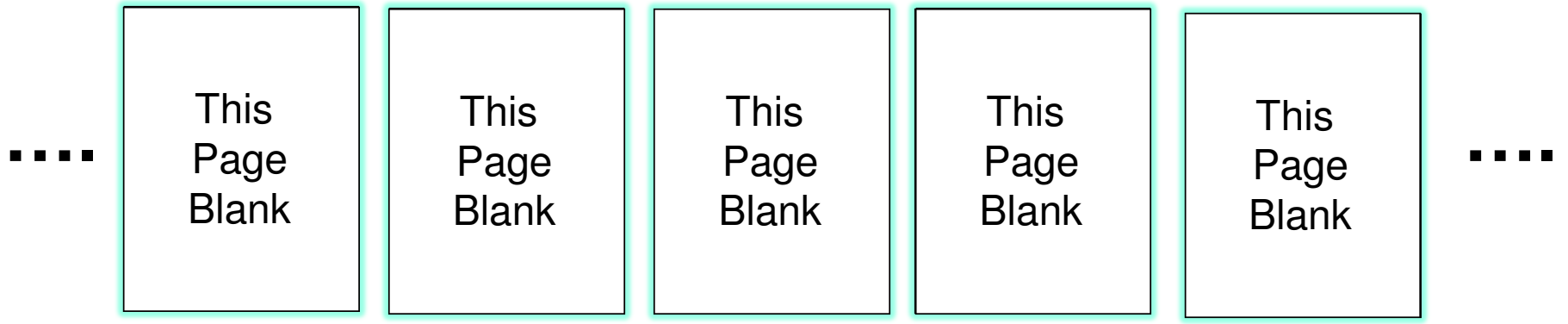
Frontiers of Physics

short distance	long distance	complexity
		
Higgs boson	Large scale structure	“More is different”
Neutrino masses	Cosmic microwave background	Many-body entanglement
Supersymmetry	Dark matter	Phases of quantum matter
Quantum gravity	Dark energy	Quantum computing
String theory		Emergent geometry

hep-th papers with “entanglement” in the title



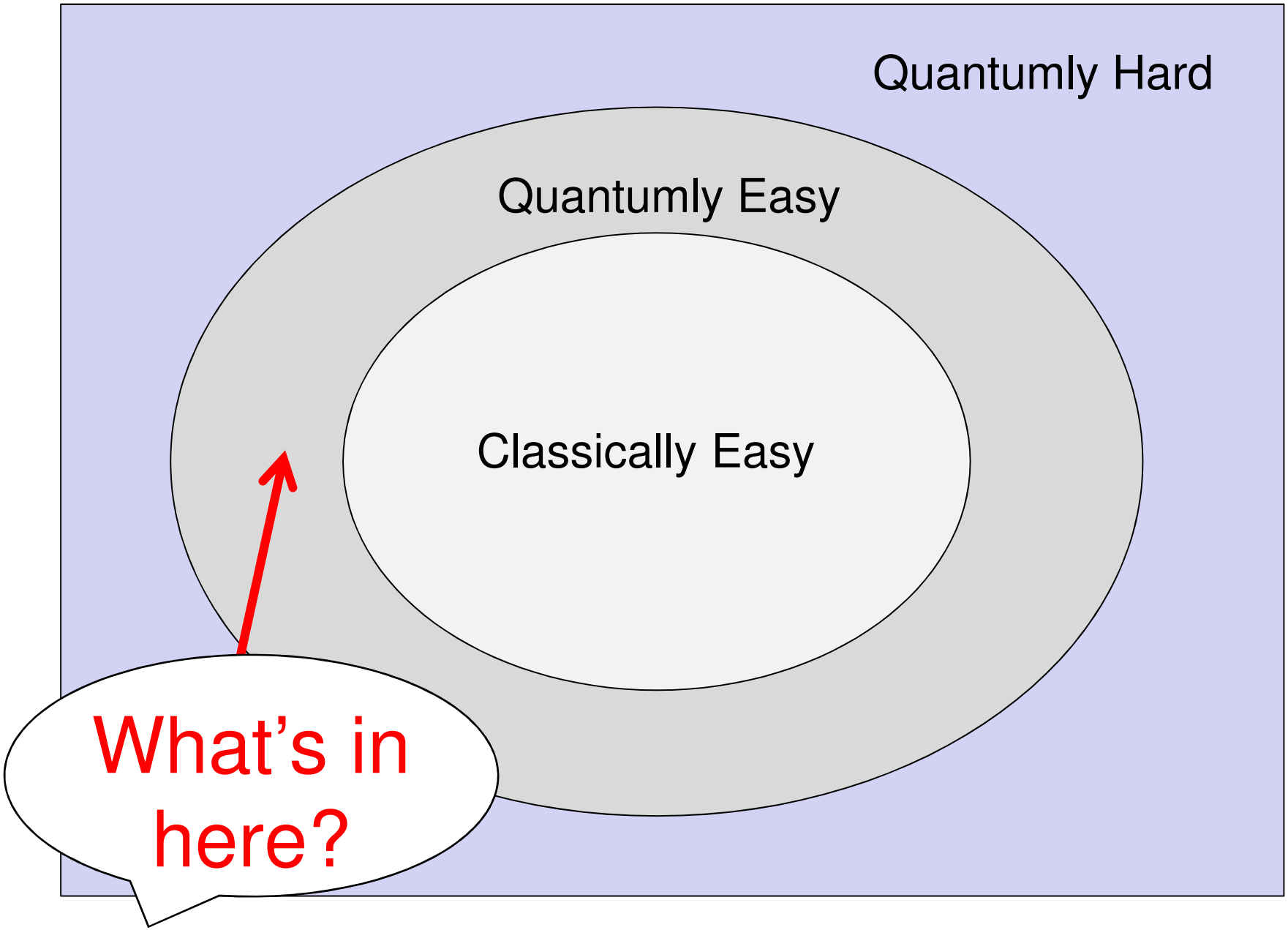
Quantum entanglement

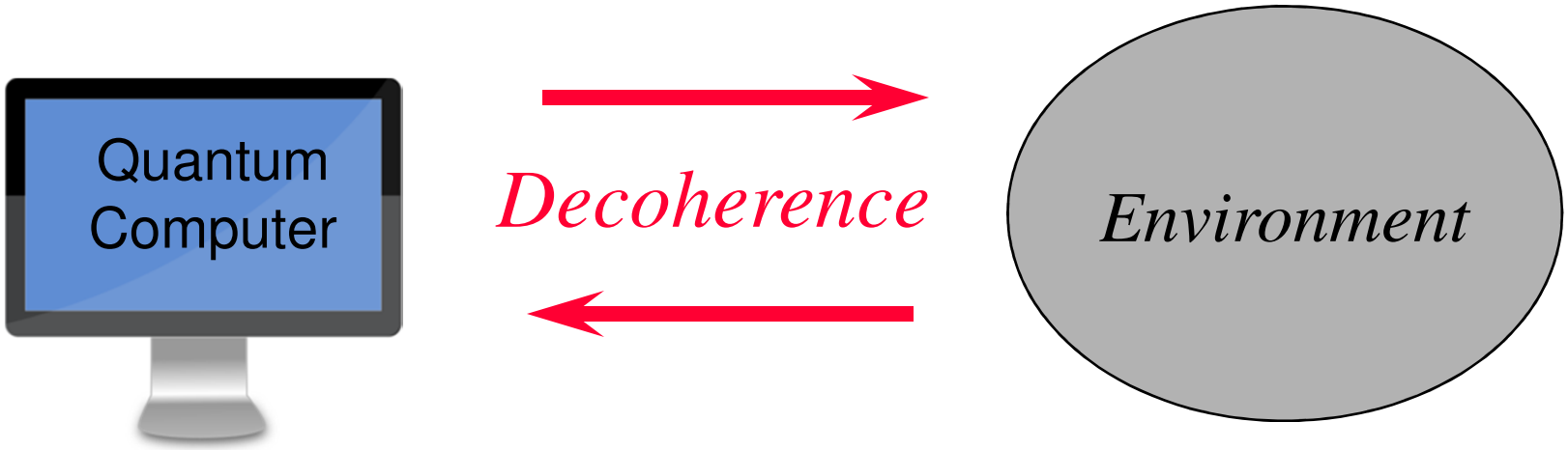


Nearly all the information in a typical entangled “quantum book” is encoded in the correlations among the “pages”.

You can't access the information if you read the book one page at a time.

Problems

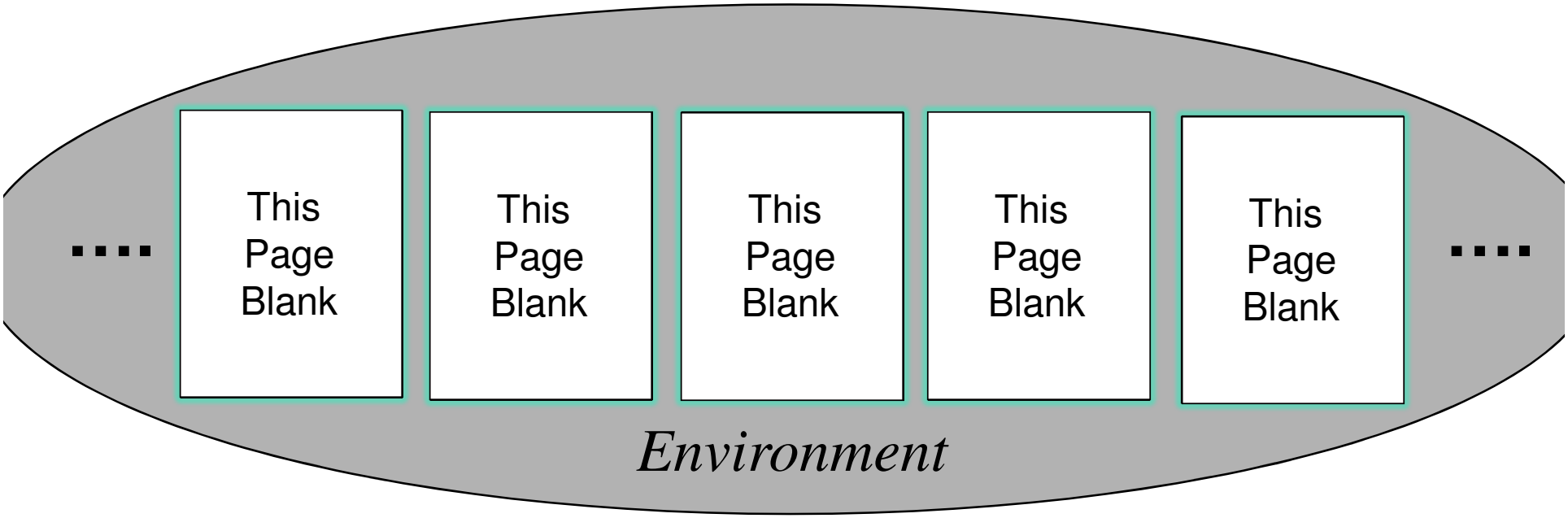

Quantumly Hard
Quantumly Easy
Classically Easy
What's in here?



ERROR!

To resist decoherence, we must prevent the environment from "learning" about the state of the quantum computer during the computation.

Quantum error correction



The protected “logical” quantum information is encoded in a highly entangled state of many physical qubits.

The environment can't access this information if it interacts locally with the protected system.

Five Big Questions

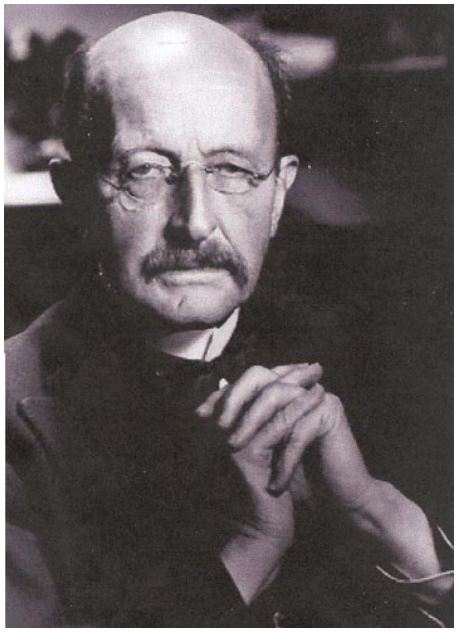
1) Does spacetime emerge from entanglement?

2) Do black holes have interiors? Does the universe exist outside our horizon?

3) What is the information-theoretic structure of quantum field theories?

4) Can quantum computers simulate all physical phenomena?

5) How does quantum information flow in time?



PARADOX!

When the theories we use to describe Nature lead to unacceptable or self-contradictory conclusions, we are faced with a great challenges and great opportunities….

Planck
1900

"*The ultraviolet catastrophe*"

In thermal equilibrium at nonzero temperature, the elelctromagnetic field carries an infinite energy per unit volume …

The end of classical physics!

Hawking
1975

"*The information loss puzzle*"

The radiation emitted by an evaporating black hole is featureless, revealing nothing about how the black hole formed …

The end of quantum physics?
(Or of relativistic causality?)

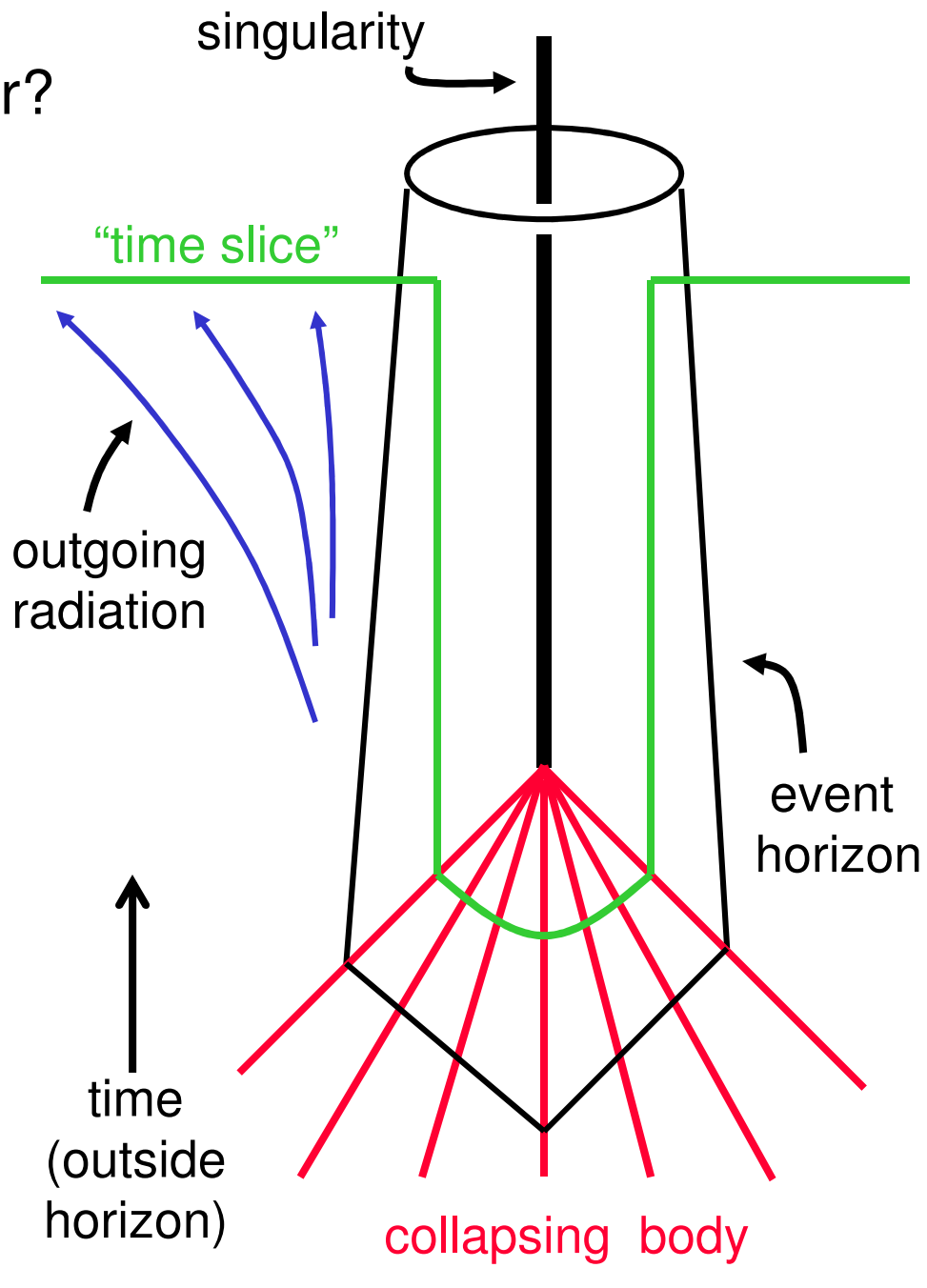
Information Puzzle:

Is a black hole a quantum cloner?

If information escapes from the black hole, then ..

The same (quantum) information is in two places at the same time!

We're stuck:
Either information is destroyed or cloning occurs. Either way, quantum physics needs revision.

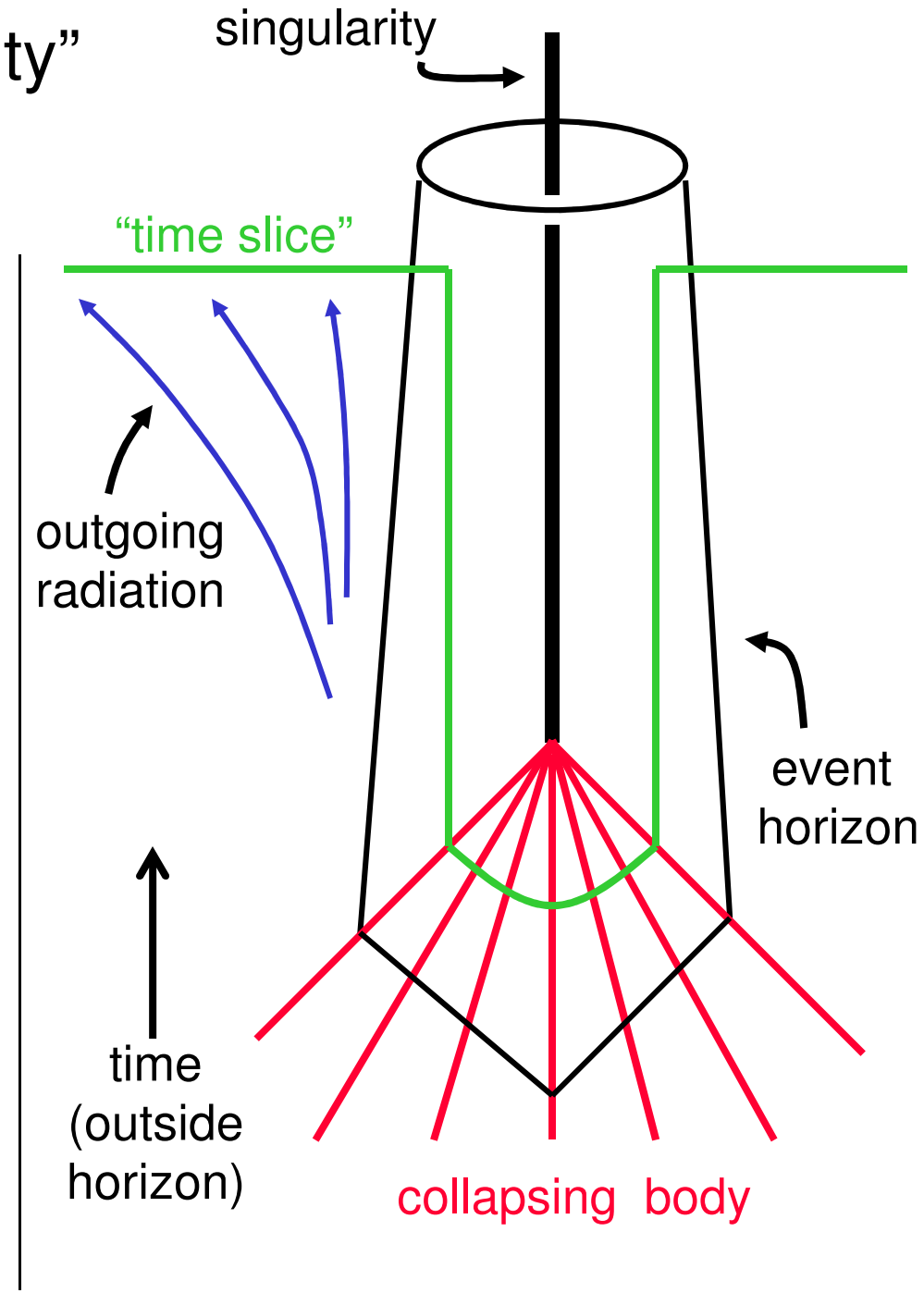


"Black hole complementarity"

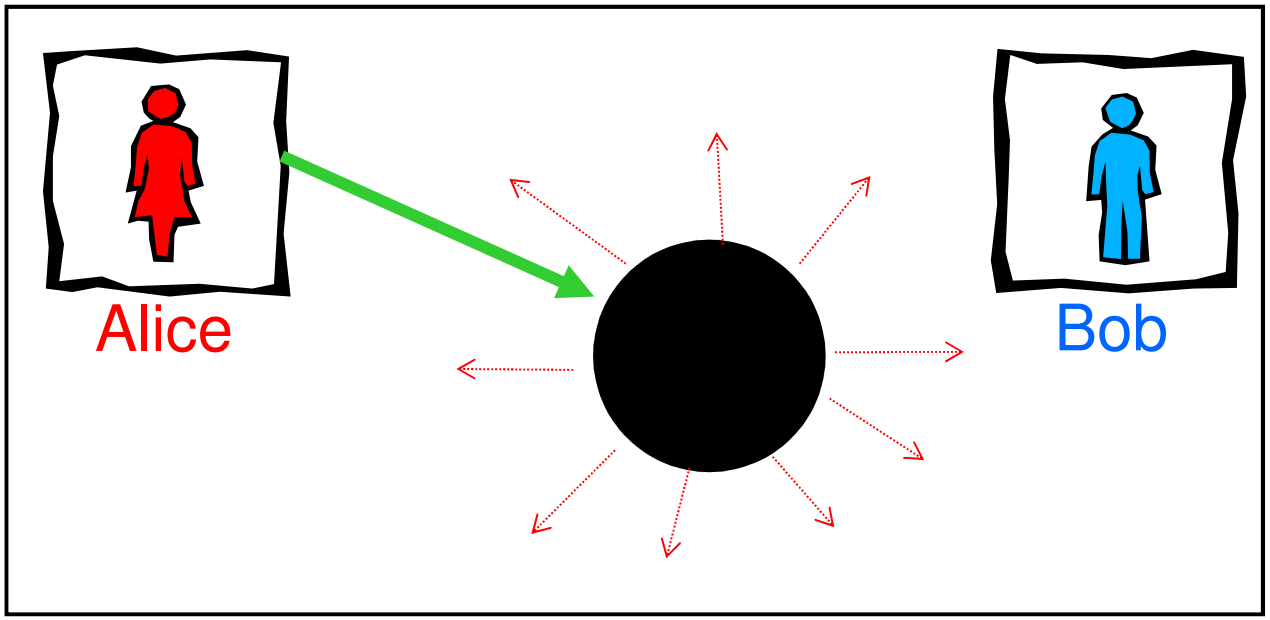
The inside and the outside are not two separate systems.

$$\mathcal{H} \neq \mathcal{H}_{\text{in}} \otimes \mathcal{H}_{\text{out}}$$

Rather, they are two different ways of looking at the *same* system. [Susskind 1993].



Black holes as mirrors



An old black hole scrambles information and reveals it quickly.

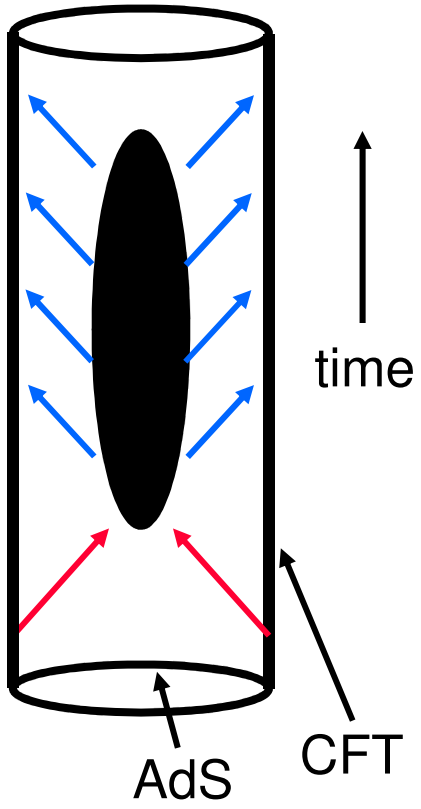
$$\Delta t_S = O\left(r_S \log r_S\right)$$

But not quite quickly enough for Alice to verify that the quantum information is in two places at once (both inside and outside the black hole). [Hayden-Preskill 2007, Susskind-Sekino 2008].

A black hole in a bottle

We can describe the formation and evaporation of a black hole using an "ordinary" quantum theory on the walls of the bottle, where information has nowhere to hide [Maldacena 1997].

A concrete realization of the "holographic principle" [Susskind 1994].



So at least in the one case where we think we understand how quantum gravity works, a black hole seems not to destroy information!

Even so, the mechanism by which information can escape from behind a putative event horizon remains murky.

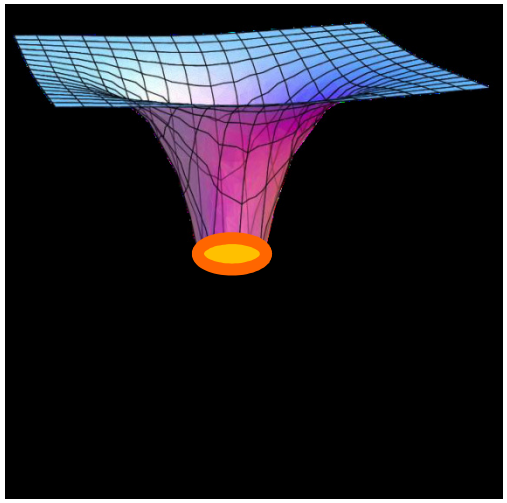
Black hole complementarity challenged

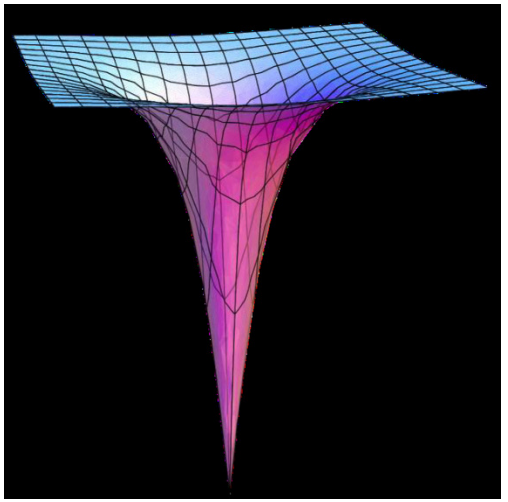
Three reasonable beliefs, not all true!

[Almheiri, Marolf, Polchinski, Sully (AMPS) 2012, Mathur 2009, Braunstein 2009]:

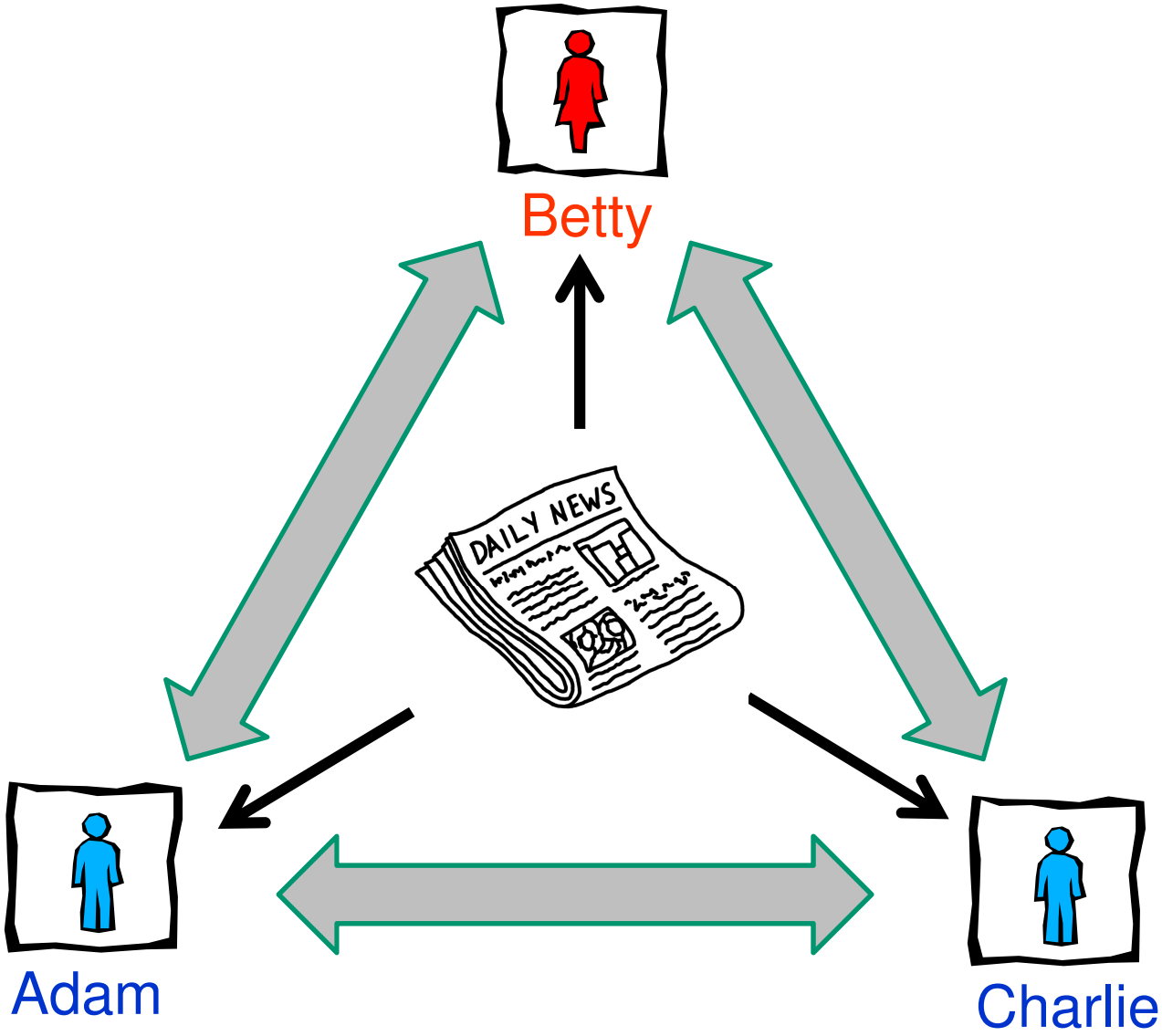
(1) The black hole "scrambles" information, but does not destroy it.
(2) An observer who falls through the black hole horizon sees nothing unusual (at least for a while).
(3) An observer who stays outside the black hole sees nothing unusual.

"Conservative" resolution: A "firewall" at the horizon, rather than (2).

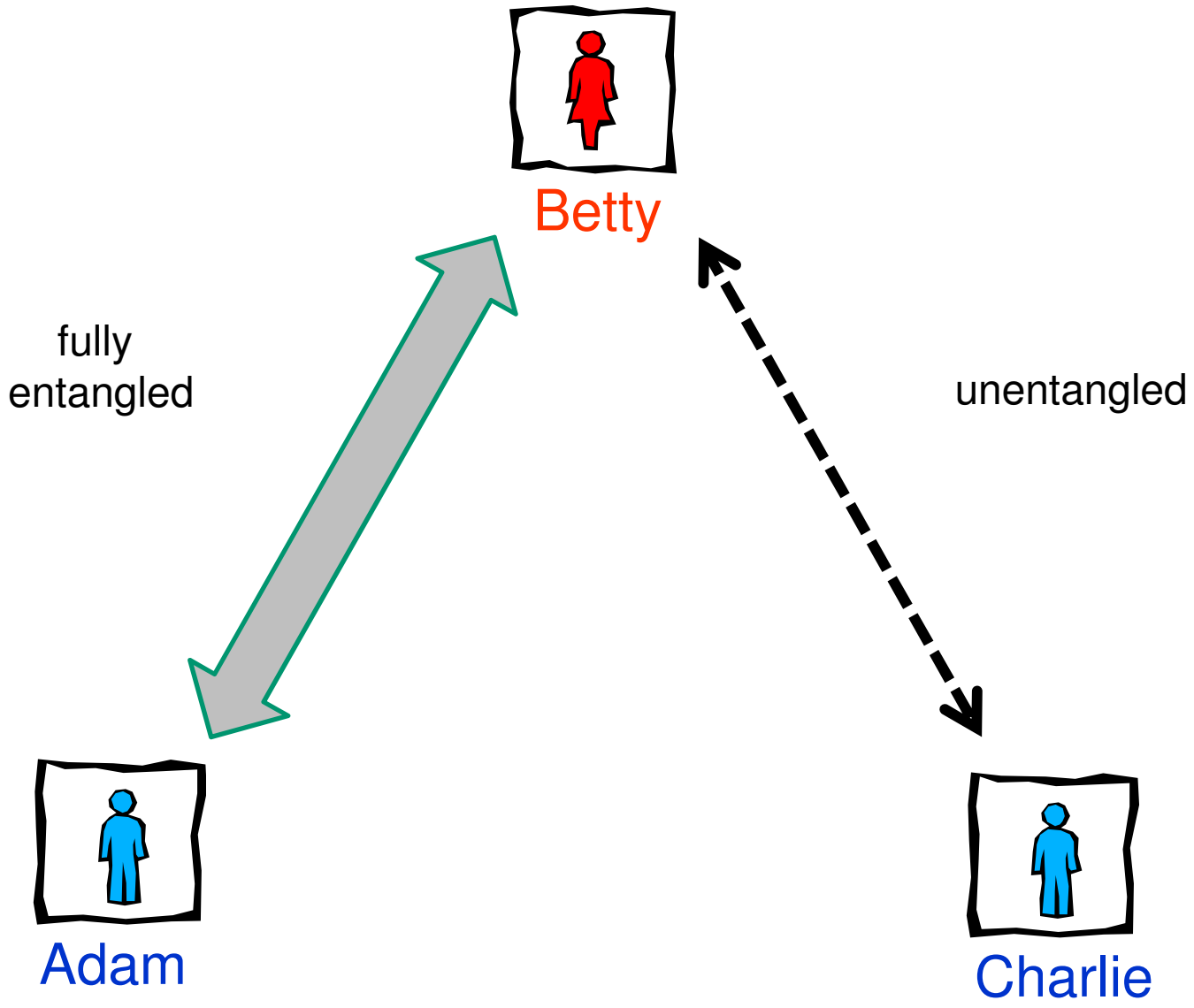




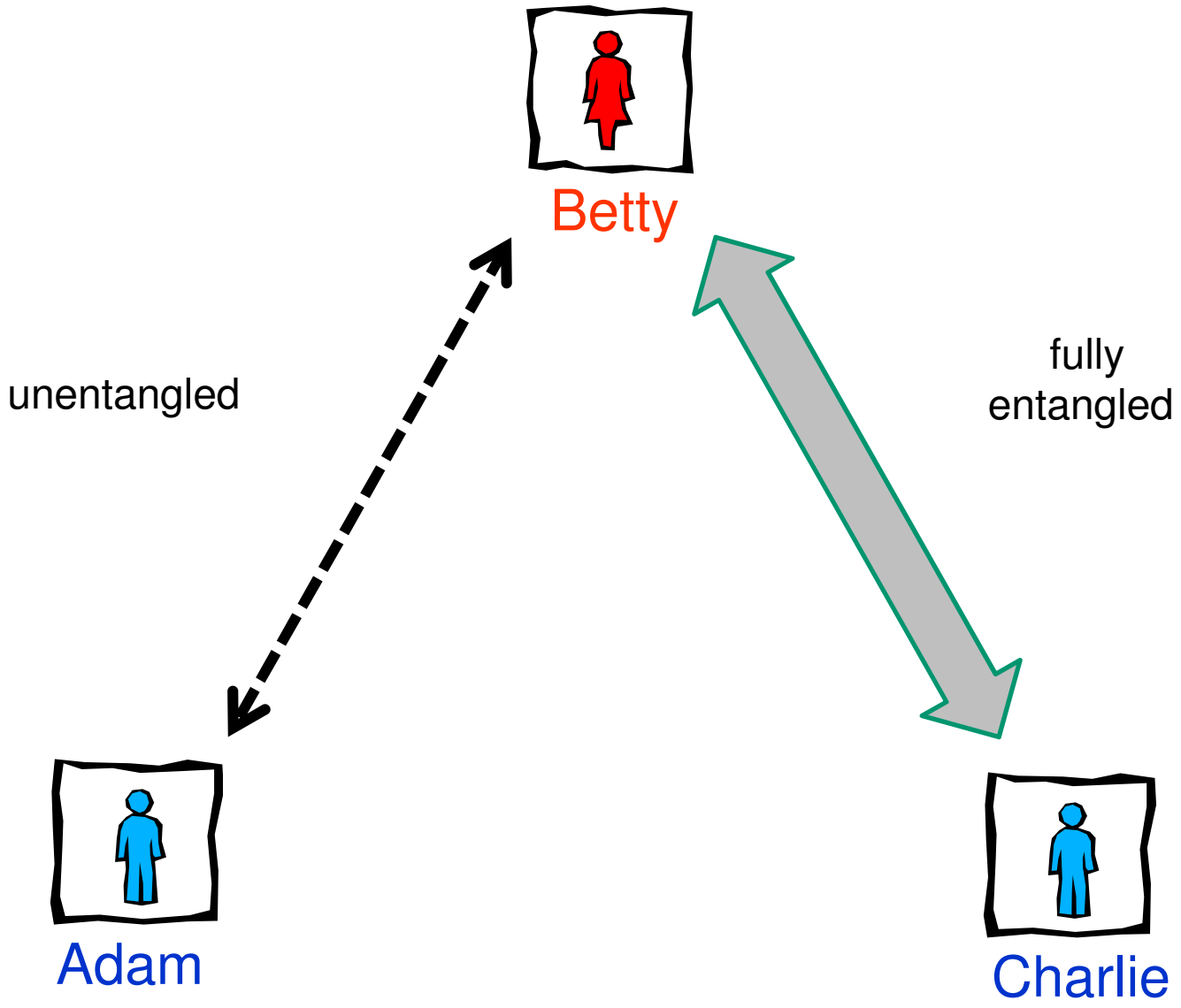
Classical correlations are polygamous



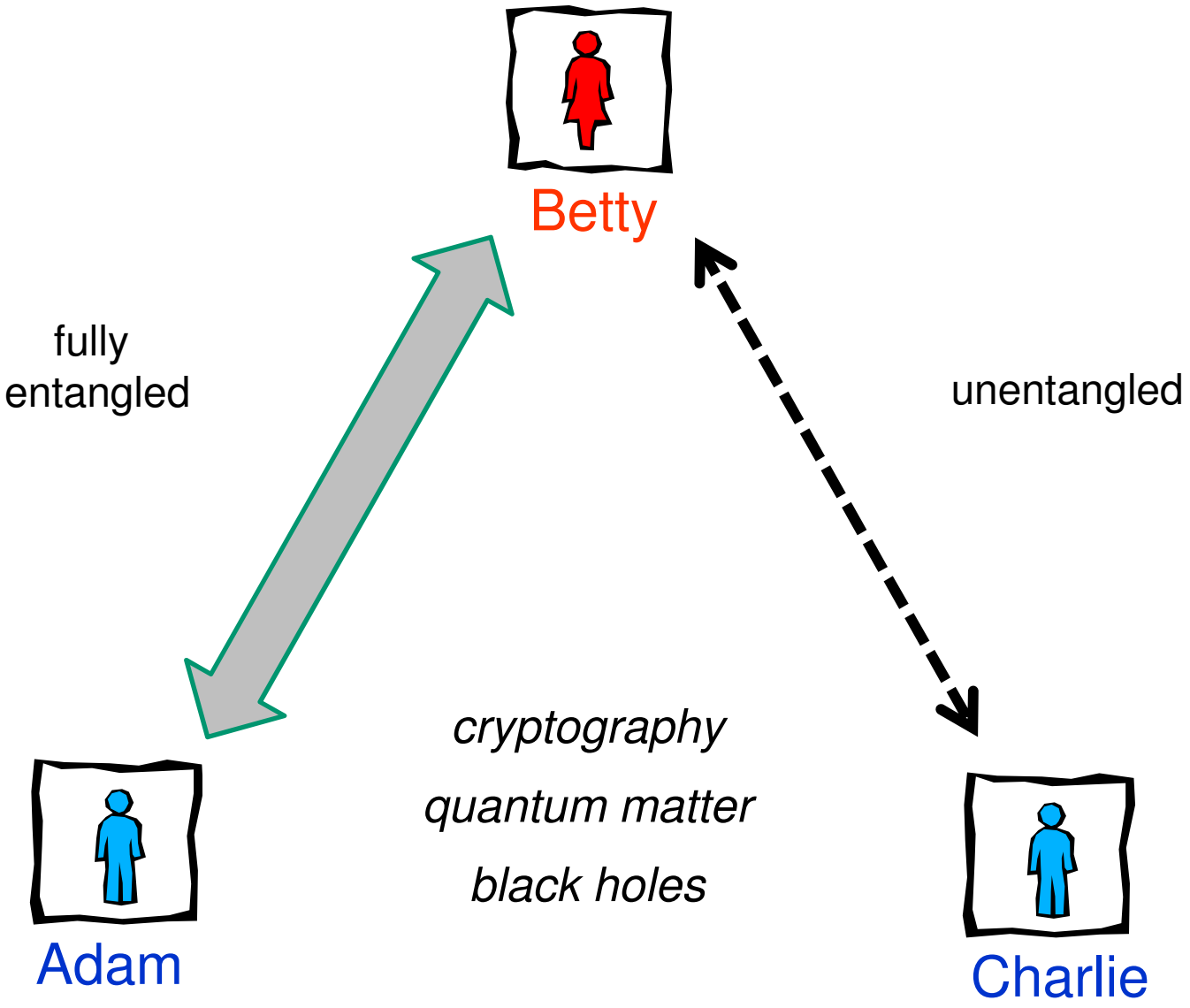
Quantum correlations are *monogamous*



Quantum correlations are *monogamous*



Monogamy is *frustrating*!



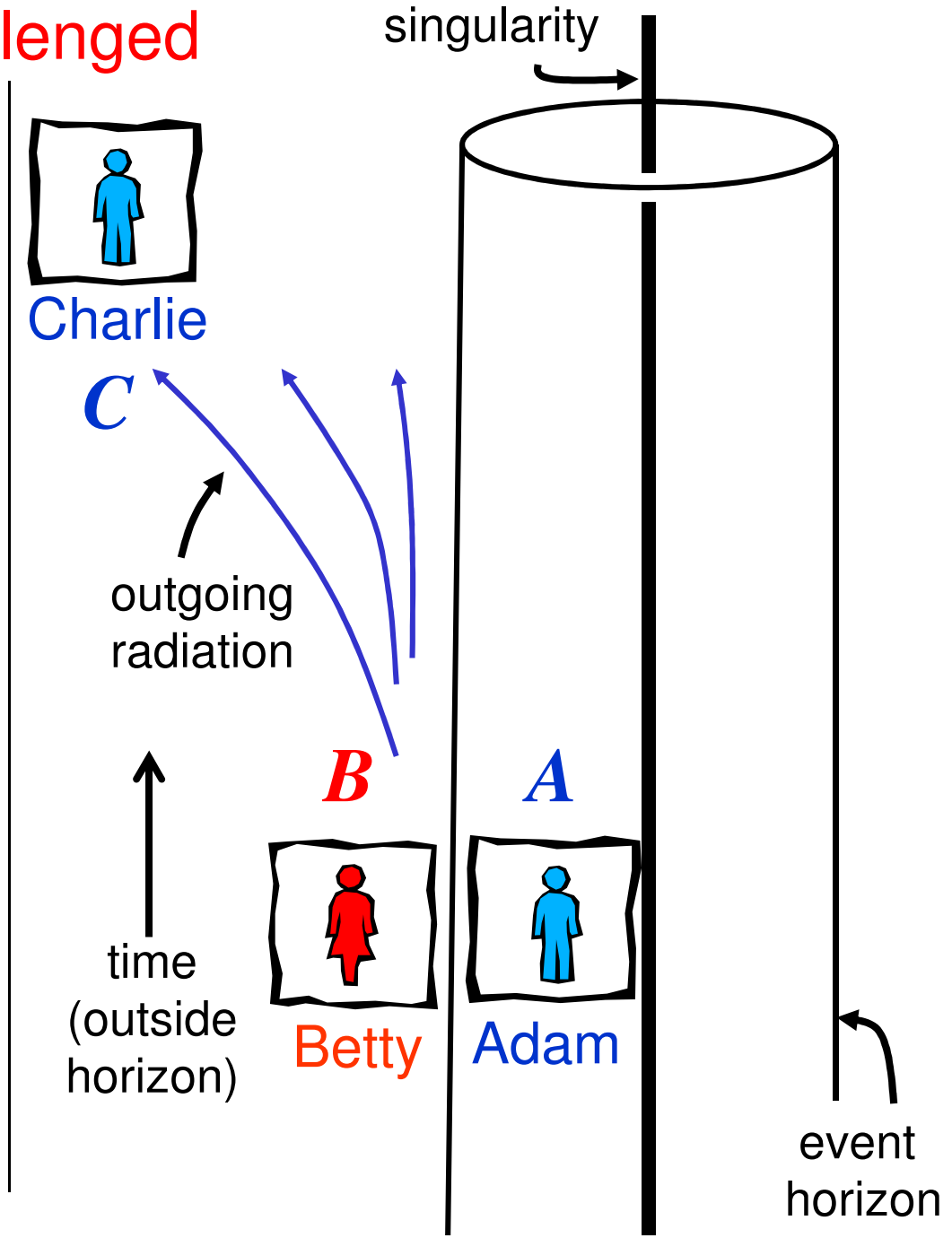
Complementarity Challenged

(1) For an old black hole, recently emitted radiation (B) is highly entangled with radiation emitted earlier (C) by the time it reaches Charlie.

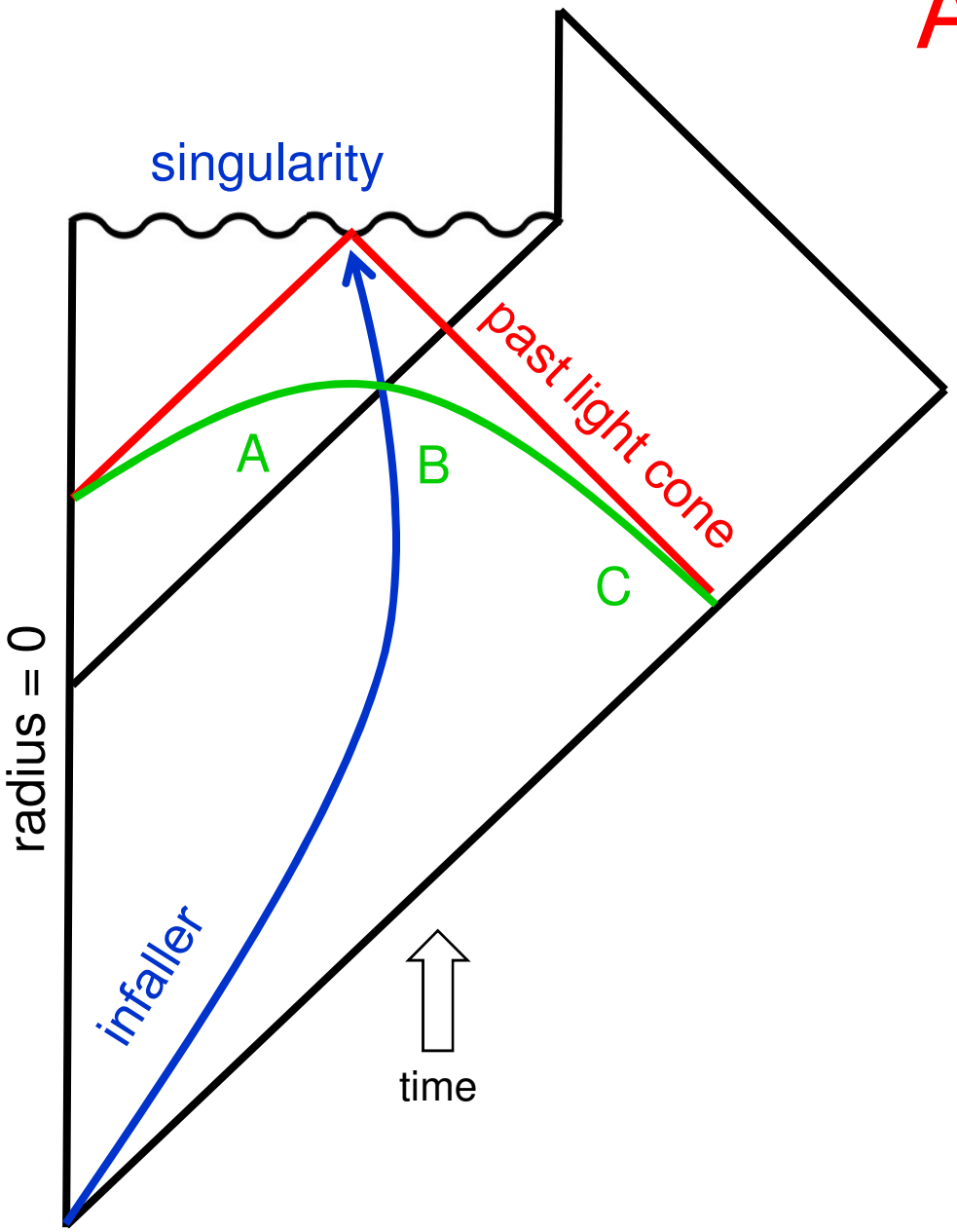
(2) If freely falling observer sees vacuum at the horizon, then the recently emitted radiation (B) is highly entangled with modes behind the horizon (A).

(3) If B is entangled with C by the time it reaches Charlie, it was already entangled with C at the time of emission from the black hole.

Monogamy of entanglement violated!



AMPS experiment



Now a single infalling agent, when still a safe distance from the singularity, can be informed that both the AB and BC entanglement have been confirmed, hence verifying a violation of the monogamy of entanglement.

What's inside a black hole?

A. An unlimited amount of stuff.

B. Nothing at all.

C. Some of the same stuff that is also outside the black hole.

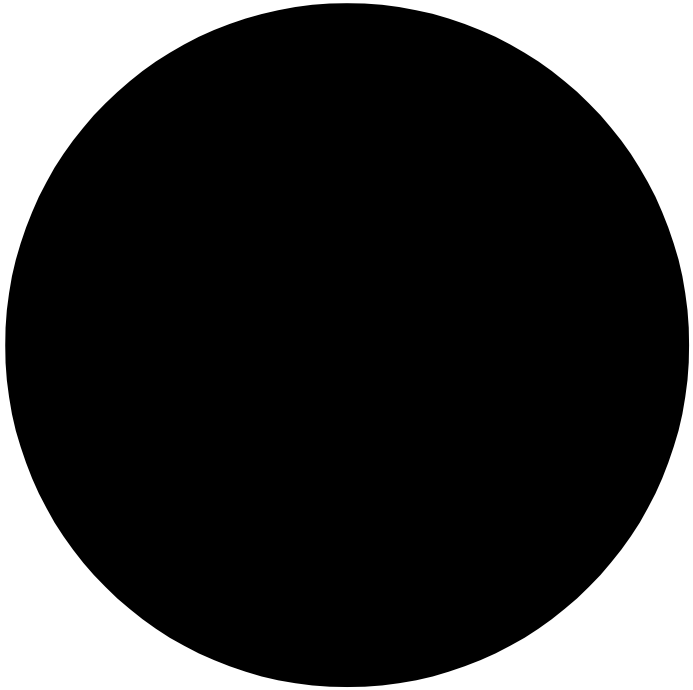
D. None of the above.

Do black holes have interiors?

Does the universe exist outside our horizon?

What is the information-theoretic structure of quantum field theories?

(Entanglement) Entropy = Area



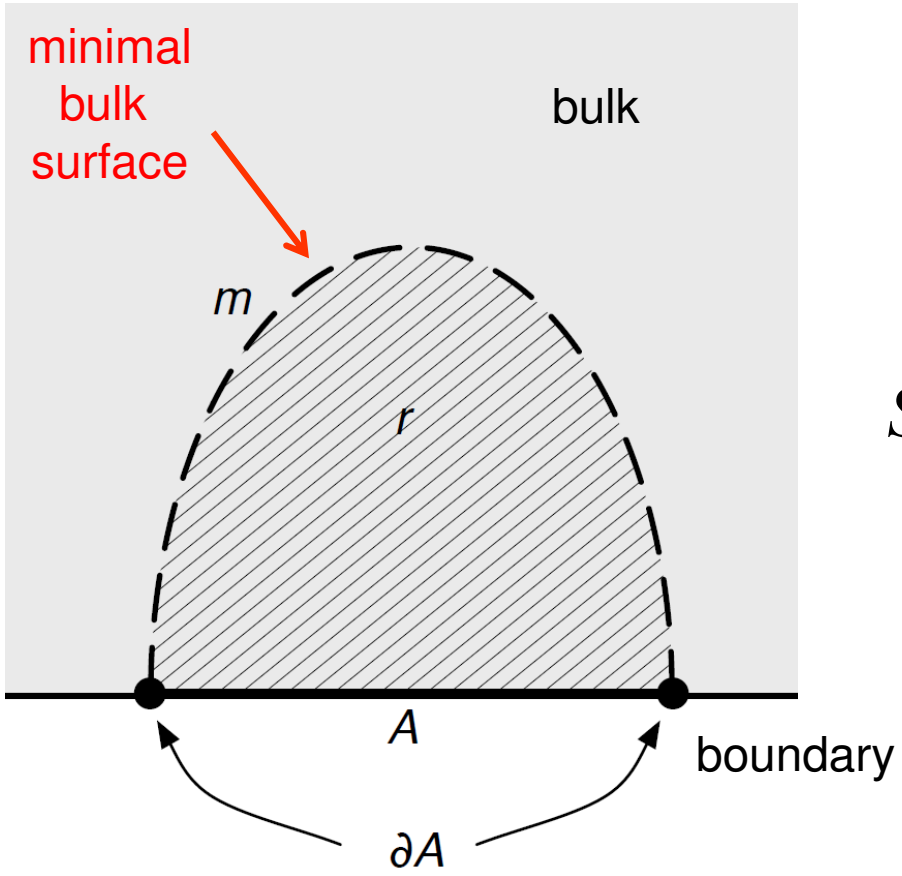
Bekenstein bound [Casini 2008]

Renormalization group flow [Casini-Huerta 2004, Myers 2011]

Topological order [Kitaev-Preskill 2006]

Does spacetime emerge from entanglement?

Holographic entanglement entropy



To compute entropy of region A in the boundary field theory, find minimal area of the bulk surface with the same boundary:

$$S(A) = \frac{1}{4G_N} \min_{\partial m = \partial A} \text{area}(\text{m}) + \cdots$$

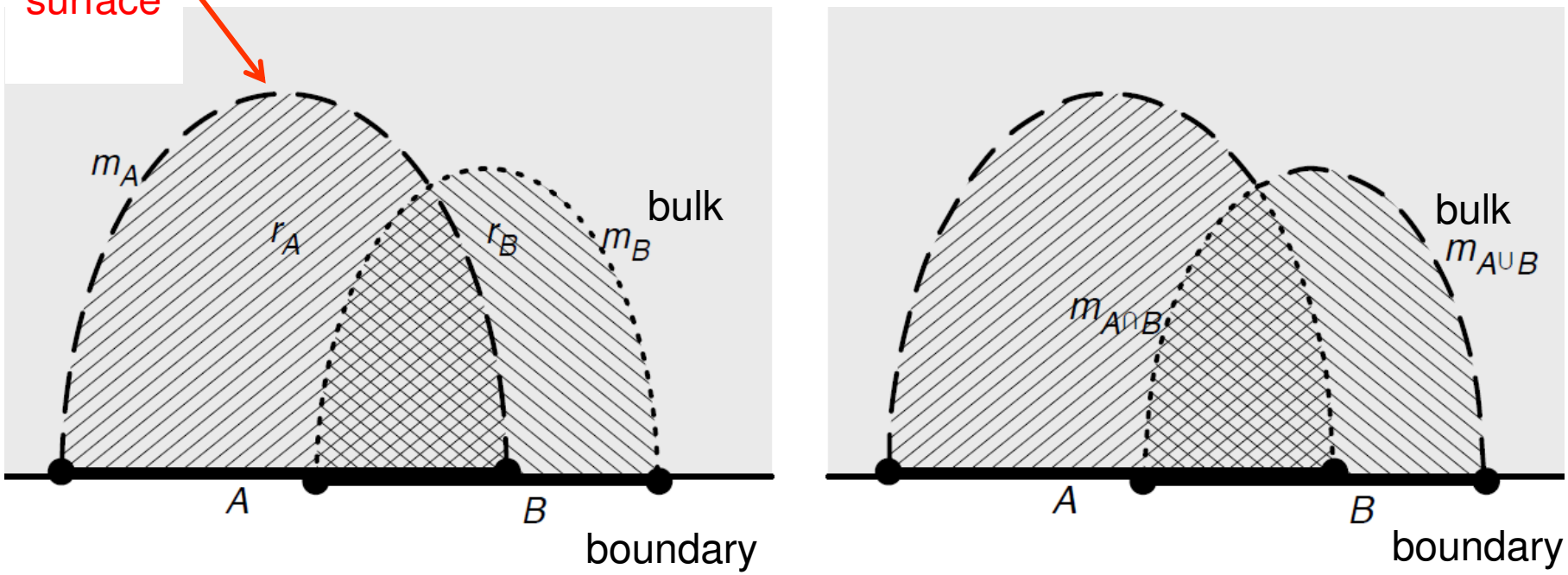
Ryu-Takayanagi 2006

Elaborated by Headrick, Casini, Myers, Hayden, Maloney, Balasubramanian, Marolf, Maldacena, Van Raamsdonk

Strong subadditivity from holography

$$S(A) + S(B) \geq S(A \cap B) + S(A \cup B)$$

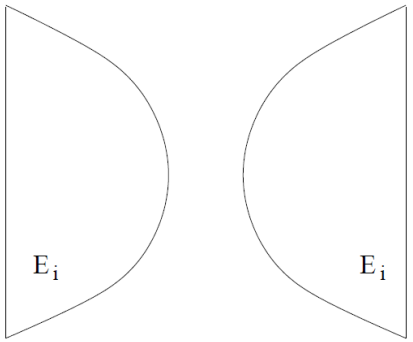
[Headrick-Takayanagi 2007]

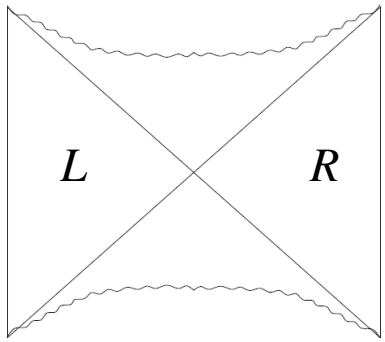


Nonpositive Tripartite Info: $I(A;B) + I(A;C) \leq I(A;BC)$

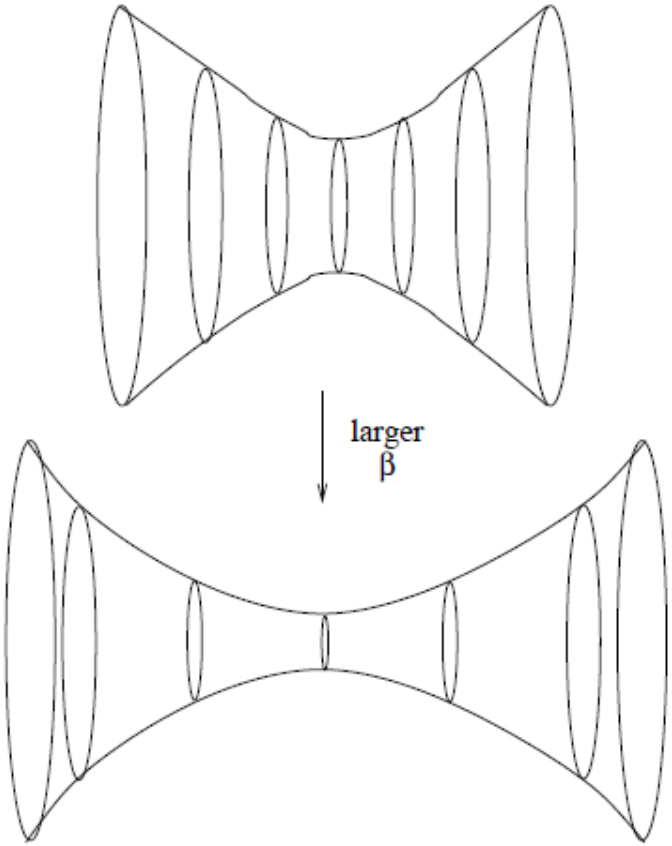
Monogamy of mutual information (for disjoint A, B, C). True for holographic theories, not in general. Hayden-Headrick-Maloney 2011

Building spacetime from quantum entanglement

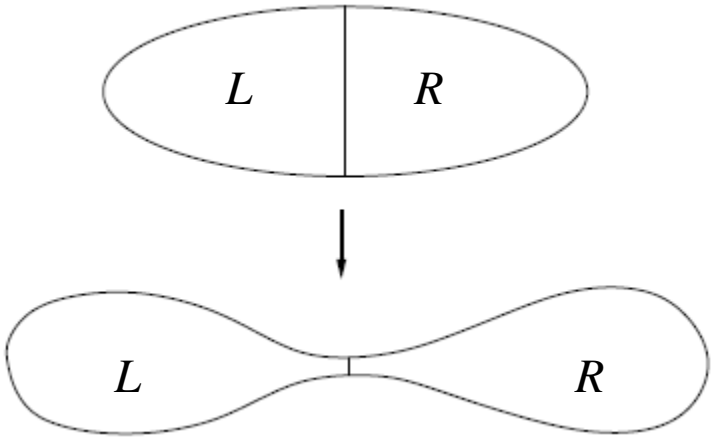
$$\sum_i e^{-\beta E_i/2}$$ 

$=$ 

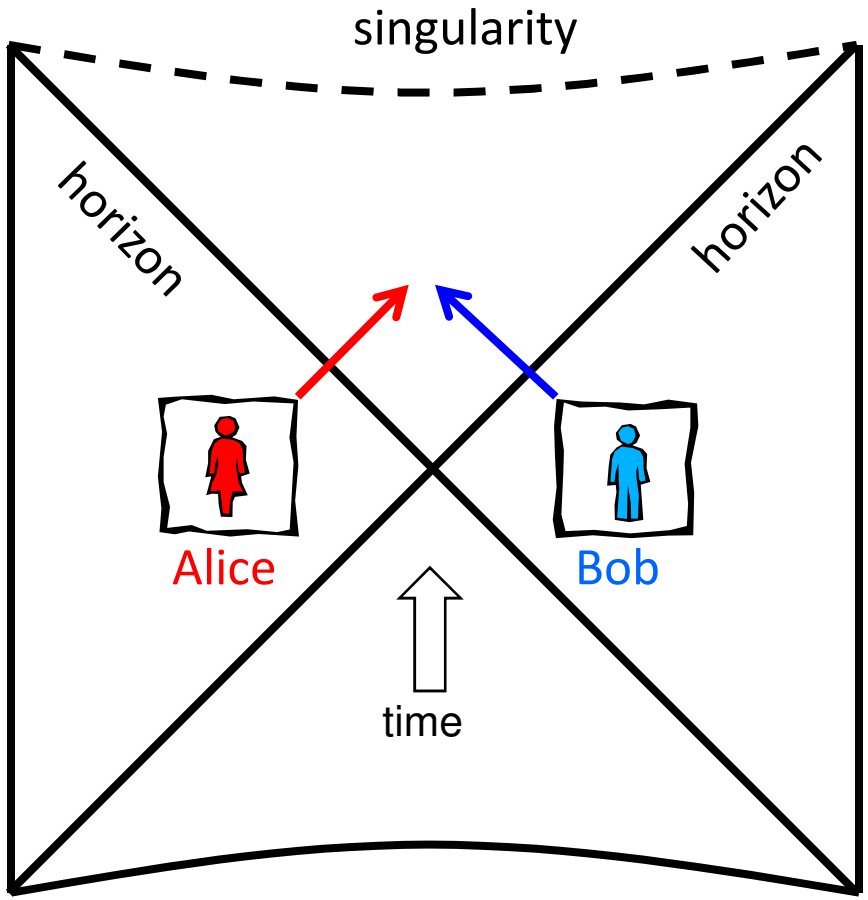
$$\sum_i e^{-\beta E_i/2} \, |E_i\rangle \otimes |E_i\rangle$$



A connected geometry is constructed as a superposition of disconnected geometries. The entangled state becomes a product state as the neck pinches off and the geometry becomes disconnected. [Maldacena 2003, Van Raamsdonk 2010, Maldacena-Susskind 2013].



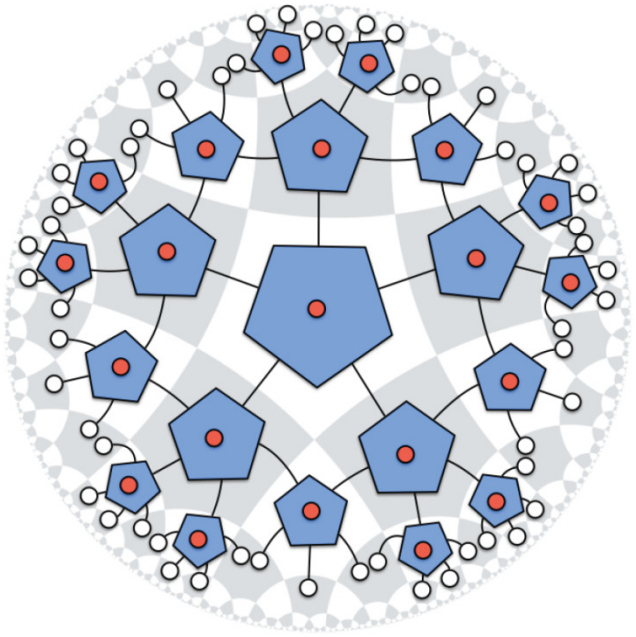
Love in a wormhole throat



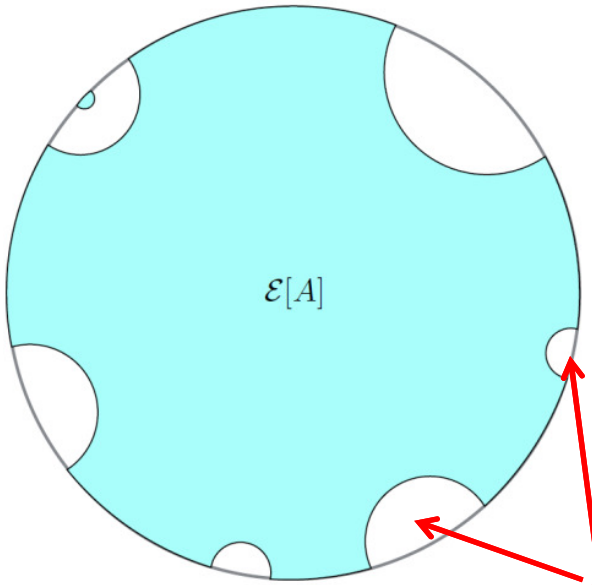
Alice and Bob are in different galaxies, but each lives near a black hole, and their black holes are connected by a wormhole. If both jump into their black holes, they can enjoy each other's company for a while before meeting a tragic end.

Is spacetime a quantum error-correcting code?

Local “logical” operators in the bulk mapped to “physical” operators on the boundary which are well protected against erasure of boundary degrees of freedom. [Pastawski-Yoshida-Harlow-Preskill 2015]



Holographic pentagon code



Deep entanglement wedge

erased regions

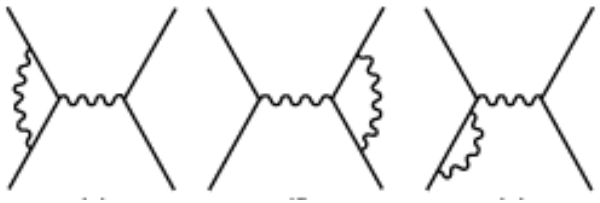
Bulk operators in the “entanglement wedge” of (disconnected) boundary region A can be reconstructed on A. [Headrick et al. 2014]

Can quantum computers simulate all physical phenomena?

Can quantum computers simulate all physical phenomena?

Both YES and NO are very interesting answers!

Quantum algorithms for quantum field theories



Classical methods have limited precision, particularly at strong coupling.

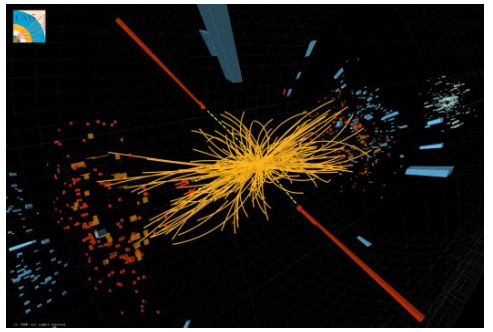
Can a quantum computer simulate particle collisions, even at high energy and strong coupling, using resources (number of qubits and gates) scaling polynomially with precision, energy, and number of particles? [Jordan-Lee-Preskill 2012, 2014]

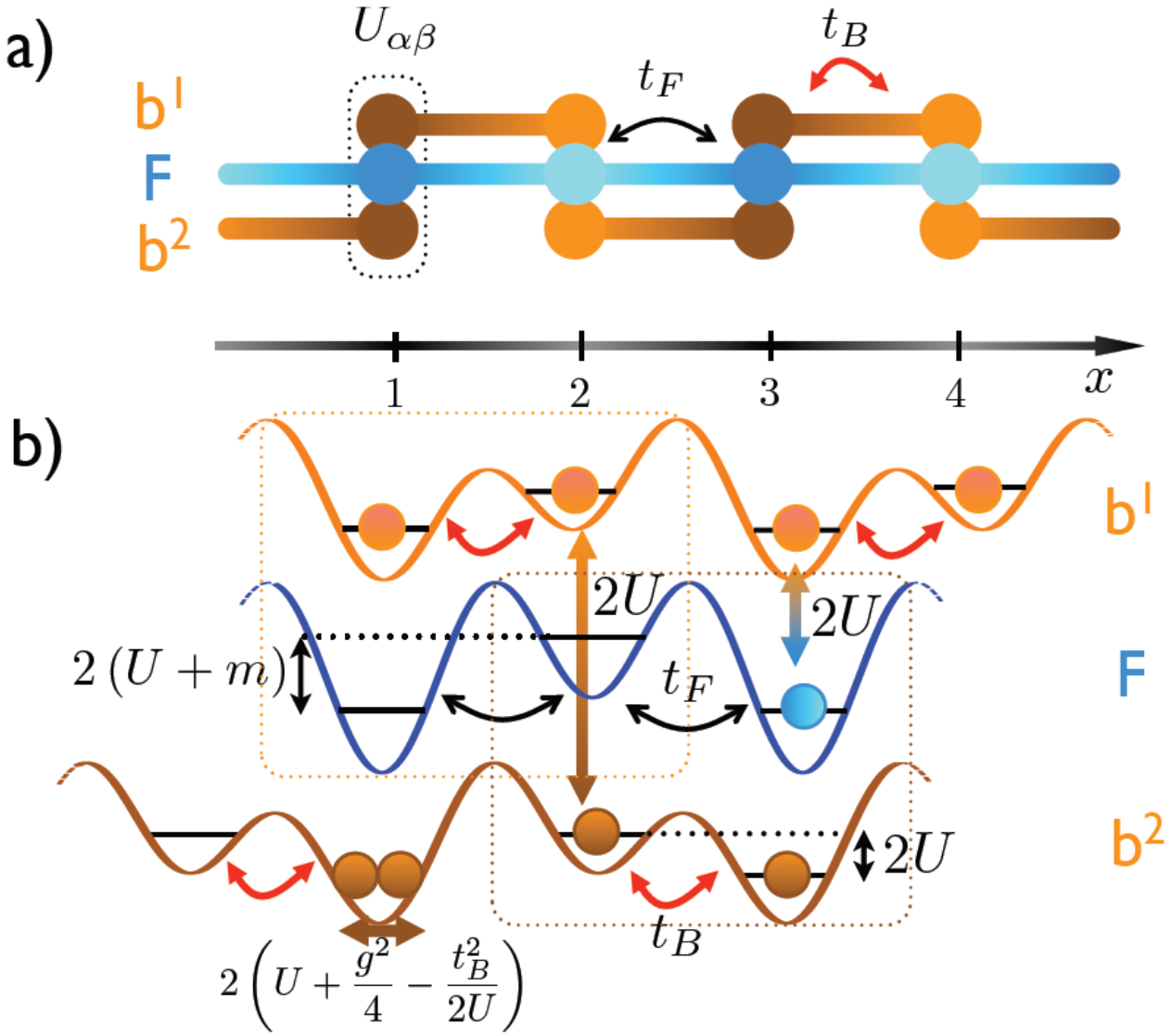
Challenges: State preparation, scaling with cutoff, massless particles, gauge theories, …

What about quantum gravity?

Bulk physics in AdS, Matrix Models, …

What is String Theory?





U.-J. Wiese, Toward Quantum Simulating QCD (2014)

How does quantum information flow in time?

What *is* time?

What *is* time?

Extensions of entanglement theory [Horodecki-Oppenheim 2013]

Beyond thermodynamics: “fluid dynamics” of entanglement.

Five Big Questions

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2) Do black holes have interiors? Does the universe exist outside our horizon?

3) What is the information-theoretic structure of quantum field theories?

4) Can quantum computers simulate all physical phenomena?

5) How does quantum information flow in time?

All interconnected!

Ooguri: I see that this new joint activity between quantum gravity and quantum information theory has become very exciting. Clearly entanglement must have something to say about the emergence of spacetime in this context.

Witten: I hope so. I'm afraid it's hard to work on, so in fact I've worked with more familiar kinds of questions.

Kavli IPMU News
December 2014

Notices of AMS
May 2015

“Now is the time for quantum information scientists to jump into .. black holes”

Beni Yoshida
QuantumFrontiers.com
March 2015