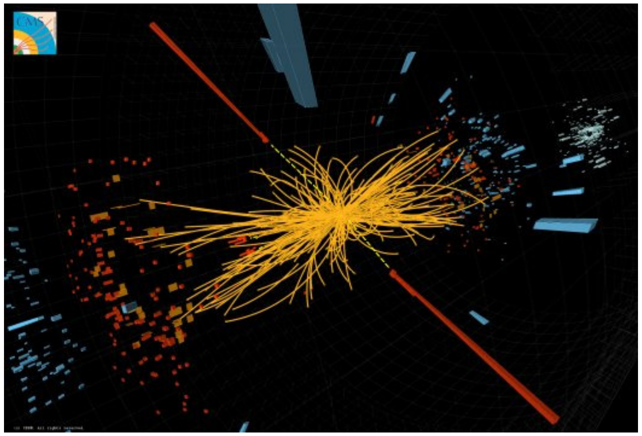
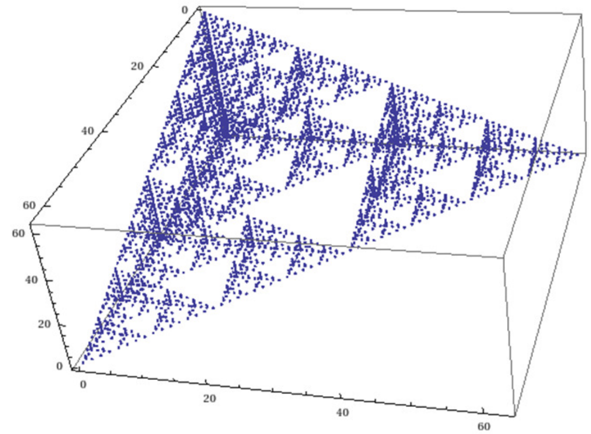
Quantum entanglement in the 21st century

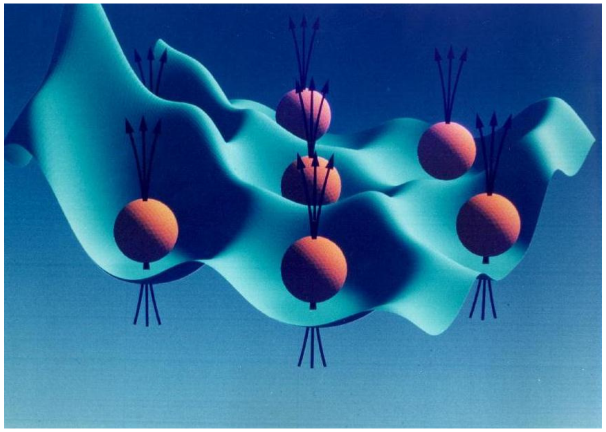
Algorithms



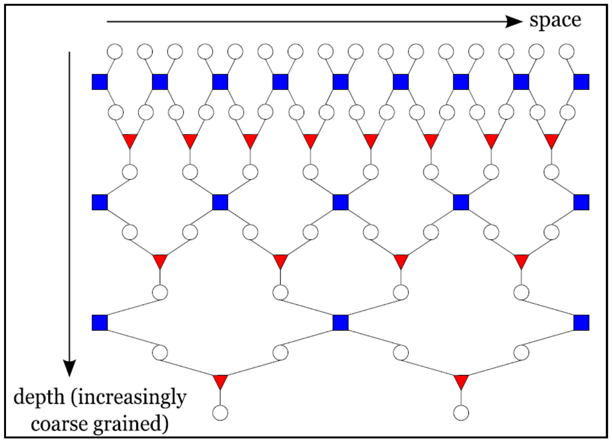
Error Correction



Matter



Spacetime



Three Questions About Quantum Computers

1. *Why* build one?

How will we use it, and what will we learn from it?

A quantum computer may be able to simulate efficiently any process that occurs in Nature!

2. *Can* we build one?

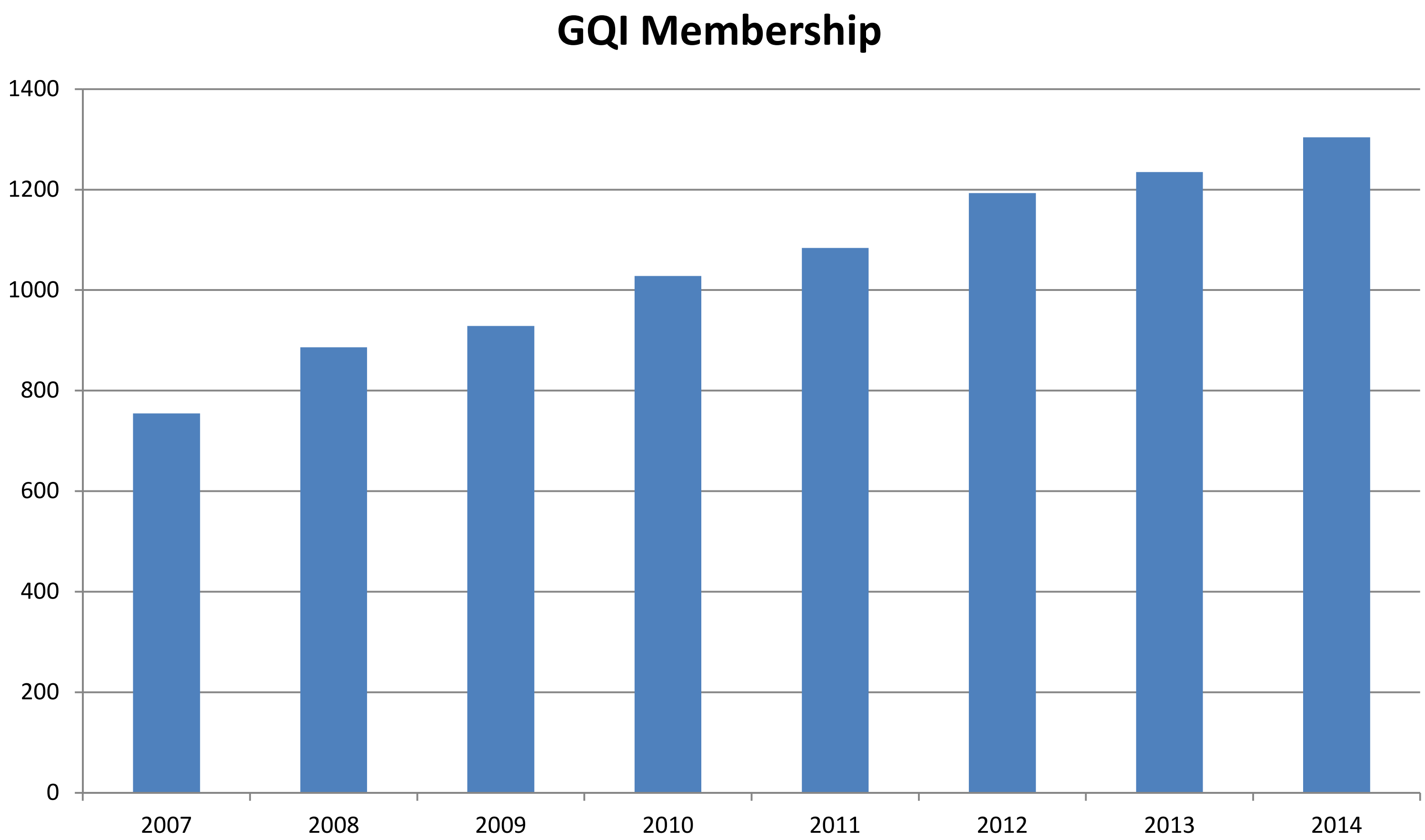
Are there obstacles that will prevent us from building quantum computers as a matter of principle?

Using quantum error correction, we can overcome the damaging effects of noise at a reasonable overhead cost.

3. *How* will we build one?

What kind of quantum hardware is potentially scalable to large systems?

APS Topical Group on Quantum Information



http://www.aps.org/membership/units/statistics.cfm

(Founded 2005. Membership is 57% students.)

Quantum Hardware

Schoelkopf

Martinis

Yacoby

Two-level ions in a Paul trap, coupled to “phonons.”

Superconducting circuits with Josephson junctions.

Electron spin (or charge) in quantum dots.

Cold neutral atoms in optical lattices.

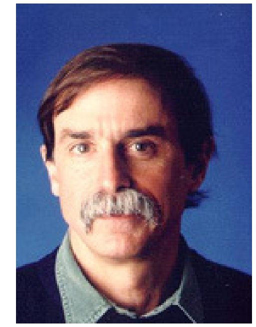
Two-level atoms in a high-finesse microcavity, strongly coupled to cavity modes of the electromagnetic field.

Linear optics with efficient single-photon sources and detectors.

Nuclear spins in semiconductors, and in liquid state NMR.

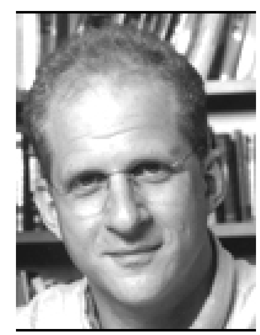
Nitrogen vacancy centers in diamond.

Anyons in fractional quantum Hall systems, quantum wires, etc.



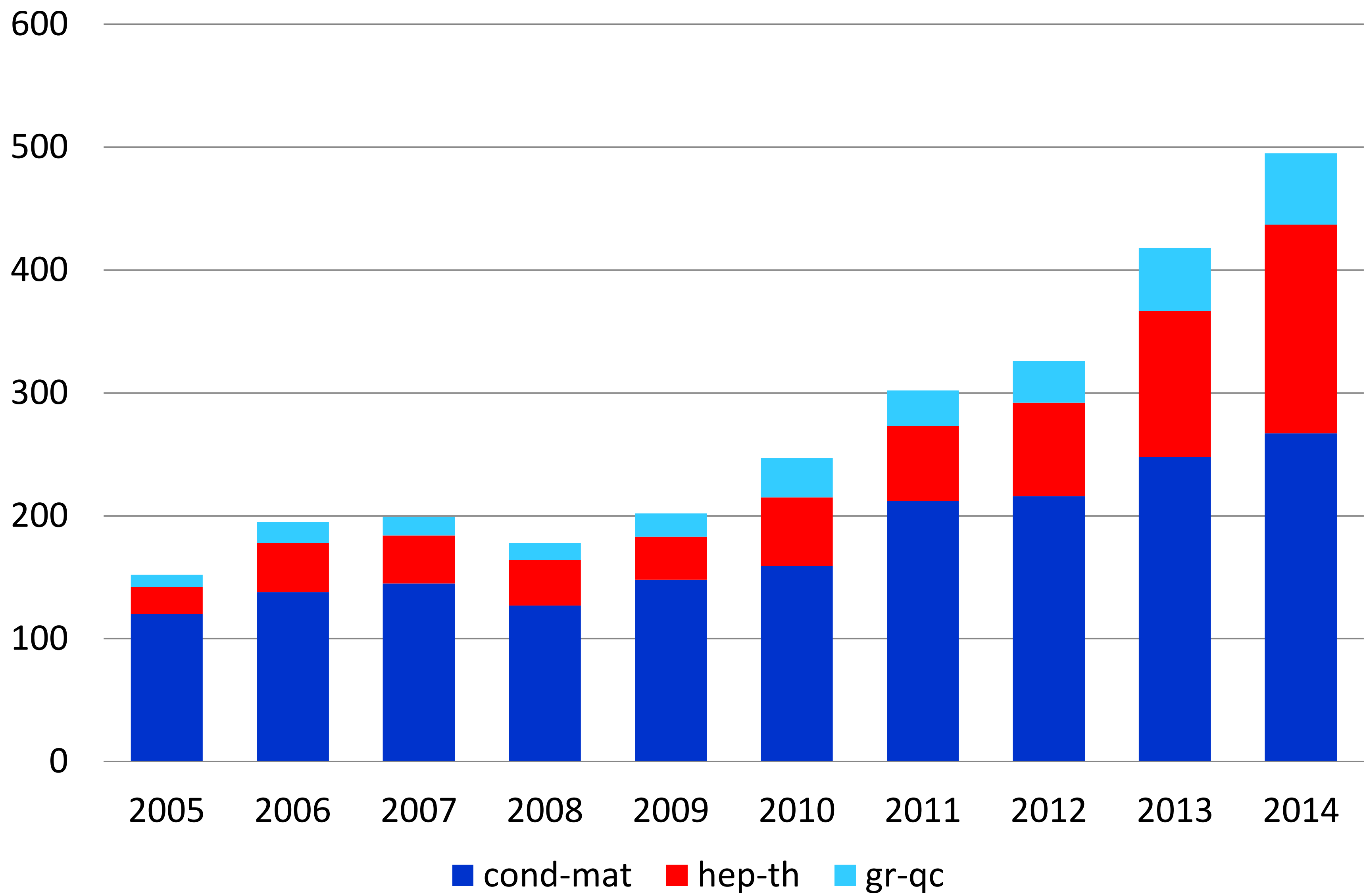
Wineland

Blatt



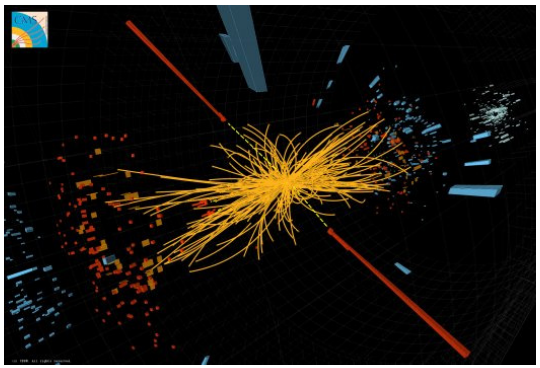
Marcus

arXiv papers with “entanglement” in the title



Frontiers of Physics

short distance



Higgs boson

Neutrino masses

Supersymmetry

Quantum gravity

String theory

long distance

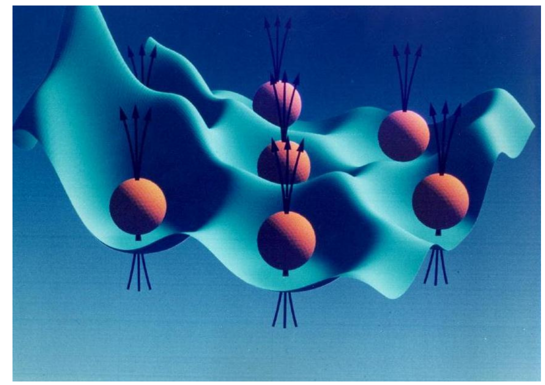
Large scale structure

Cosmic microwave background

Dark matter

Dark energy

complexity



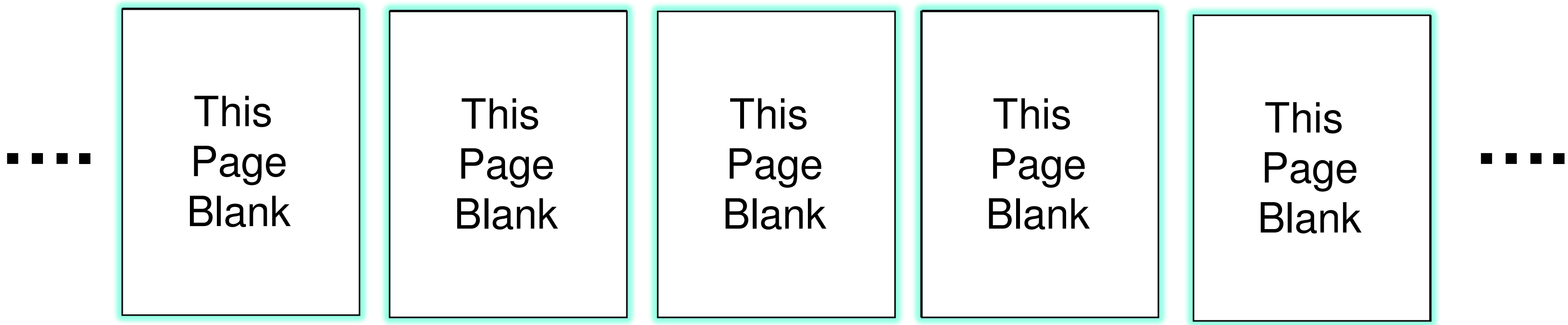
“More is different”

Many-body entanglement

Phases of quantum matter

Quantum computing

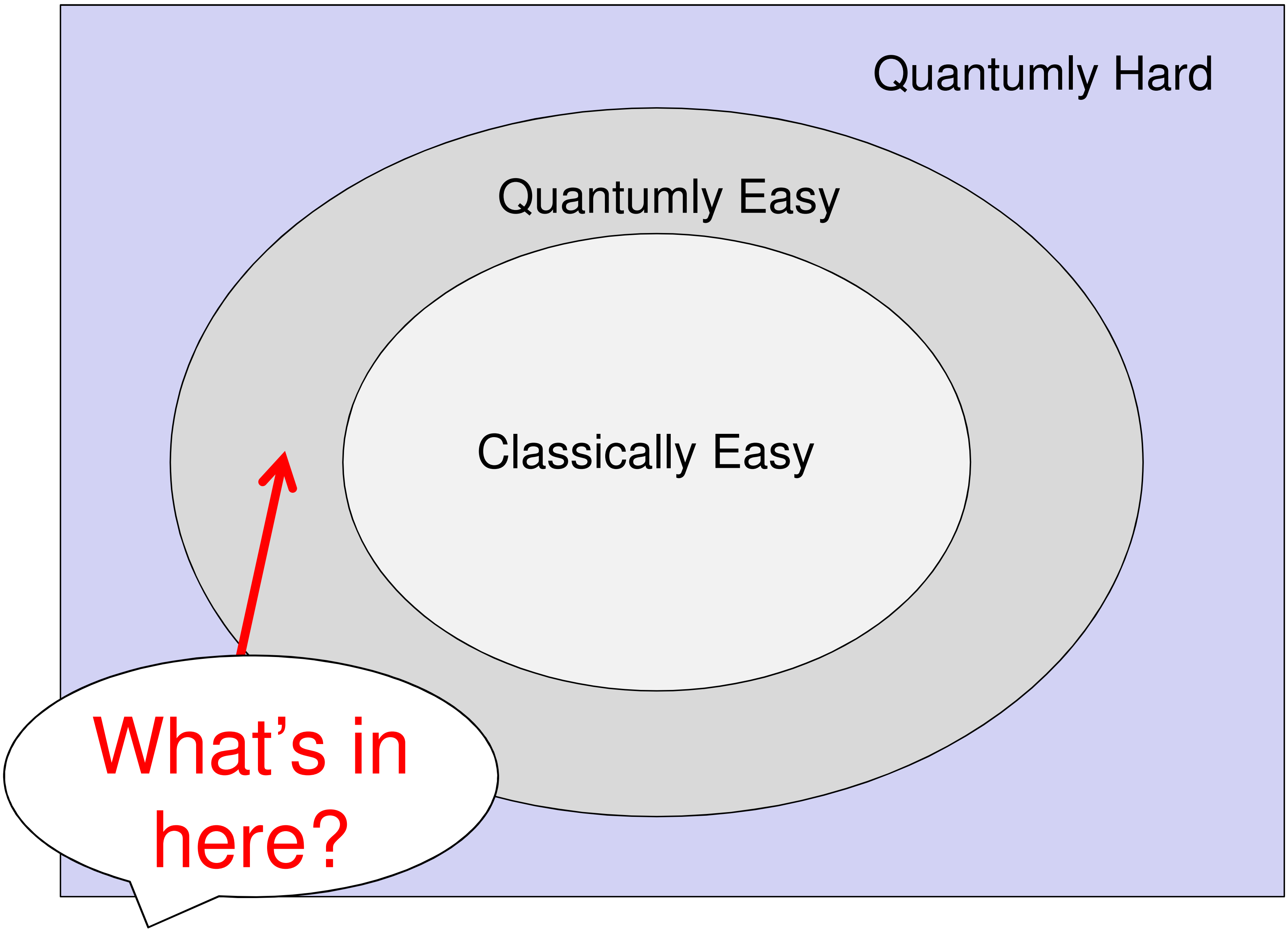
Quantum entanglement



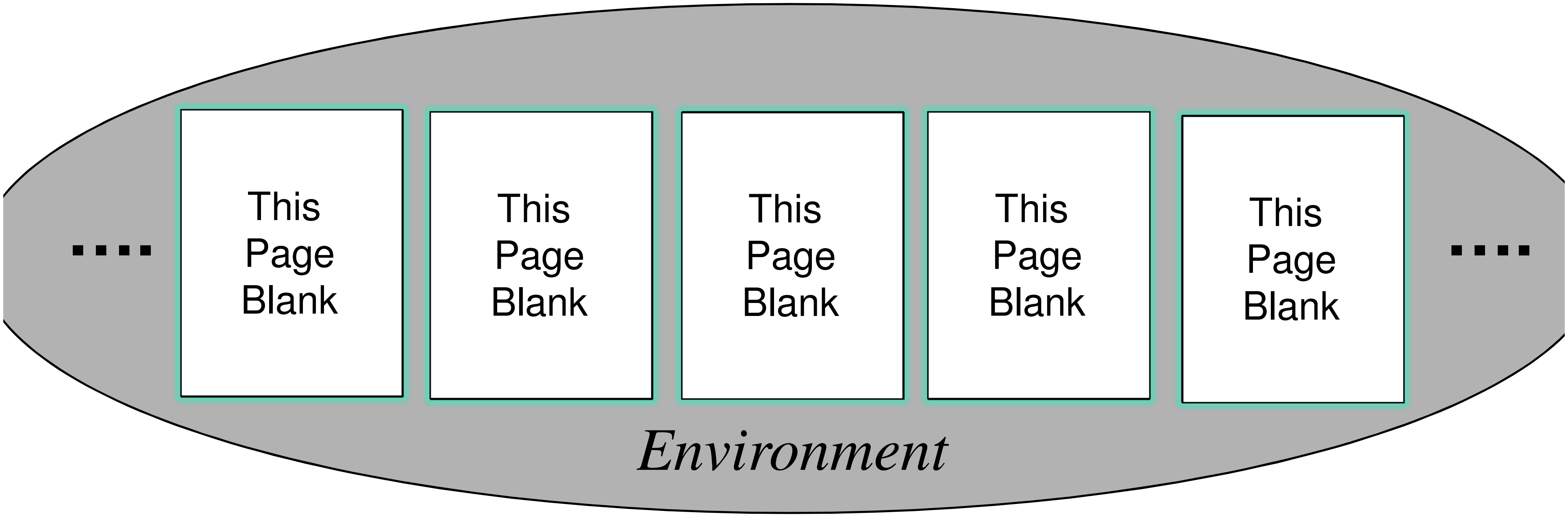
Nearly all the information in a typical entangled “quantum book” is encoded in the correlations among the “pages”.

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?

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.

What can we do with a small quantum computer?

What can we do with a small quantum computer?

Learn how to make a big quantum computer.

Quantum repeaters.

Entangled clocks and sensors.

Quantum simulation.

Quantum annealing.

Can classical public key cryptosystems be resistant to quantum attacks?

Can classical public key cryptosystems be resistant to quantum attacks?

Lattice based.

McEliece.

Other.

Can quantum computers improve approximate solutions to combinatorial optimization problems?

Can quantum computers improve approximate solutions to combinatorial optimization problems?

Quantum annealing.

Quantum Approximate Optimization Algorithm (Farhi et al. 2014).

What are the applications of the quantum algorithm for solving linear equations?

What are the applications of the quantum algorithm for solving linear equations?

Sample solution of Ax = b with exp. speedup (Harrow et al. 2009).

A well-conditioned and easy to simulate, $|b\rangle$ easily prepared, …

Maxwell's equations (Clader et al. 2013).

Effective resistance in electrical network (Wang 2013).

Machine learning, big data (Lloyd et al. 2014).

What can we do with a quantum network?

What can we do with a quantum network?

Quantum key distribution, and other quantum protocols.

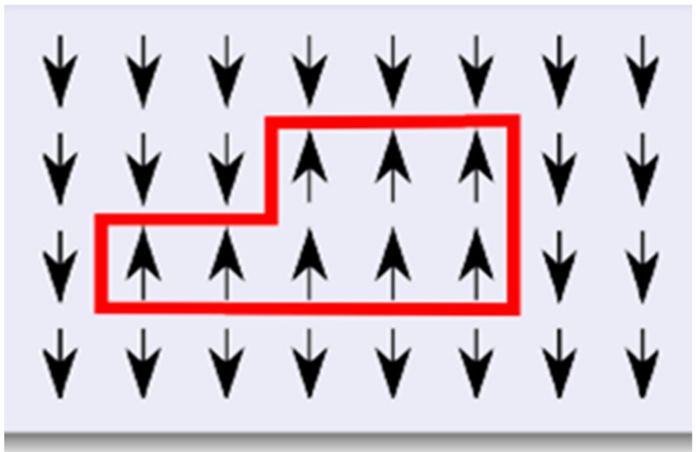
A global clock (Lukin, Ye et al. 2014).

Long-baseline optical interferometry (Gottesman et al. 2012).

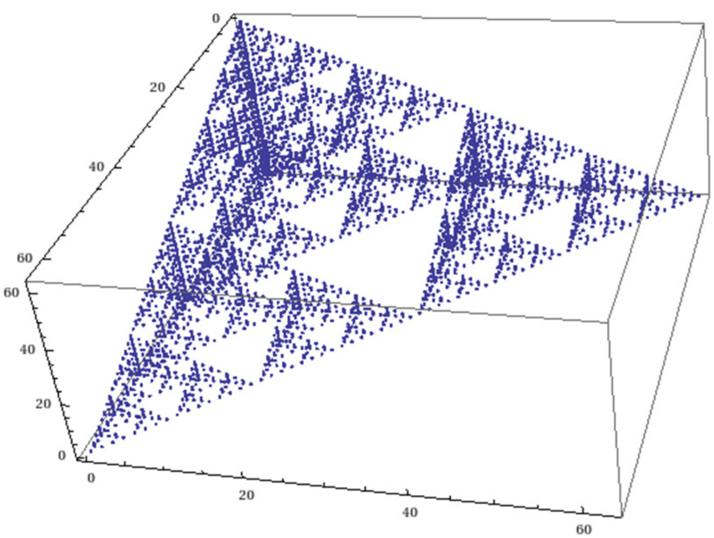
Can we build a quantum hard drive?

Excitations in local classical and quantum codes

Mobile pointlike excitations:
1D Ising model, 2D toric code



No pointlike excitations:
2D Ising model, 4D toric code

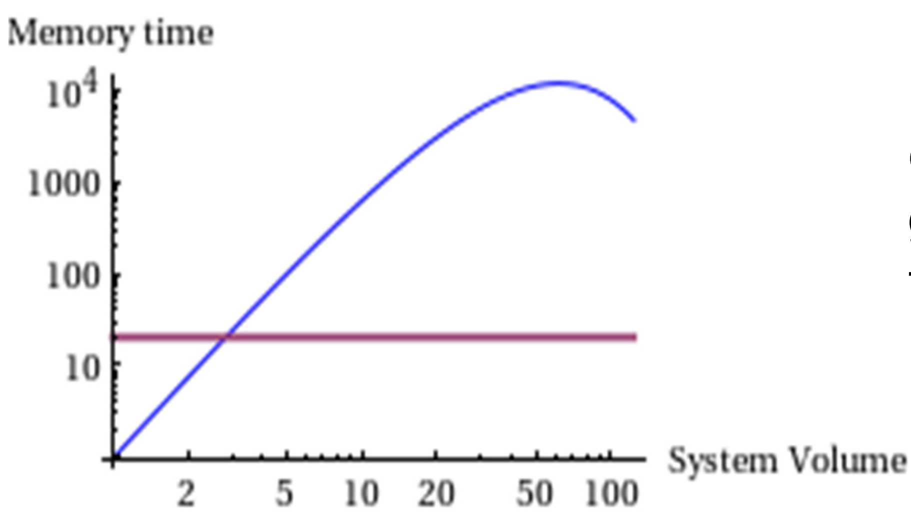


Immobile pointlike excitations:
3D Haah code (2011).

There are mobile point defects in any "*scale-invariant*" translation-invariant 3D stabilizer code (Yoshida 2011).

Memory time

Bravyi-Haah 2011



Because of the logarithmically increasing height of the logical energy barrier, the memory time grows like a power of volume for small system size.

$$t_{mem} \sim V^{\Omega(\beta)}$$

$$\left(\beta = (\text{temperature})^{-1}\right)$$

But once the system size grows beyond an optimal size, the entropy of the defects grows exponentially with volume, overwhelming the logarithmic energy cost. Thus the memory time is a constant depending on the temperature.

$$V^* \sim e^{\Omega(\beta)}$$

$$t^*_{mem} \sim e^{\Omega(\beta^2)}$$

Michnicki 2012: Energy barrier $O(L^{2/3})$ in 3D code w/o translation invariance.

Self-correcting quantum memory

1) Finite-dimensional spins.

2) Bounded-strength local interactions.

3) Nontrivial codespace.

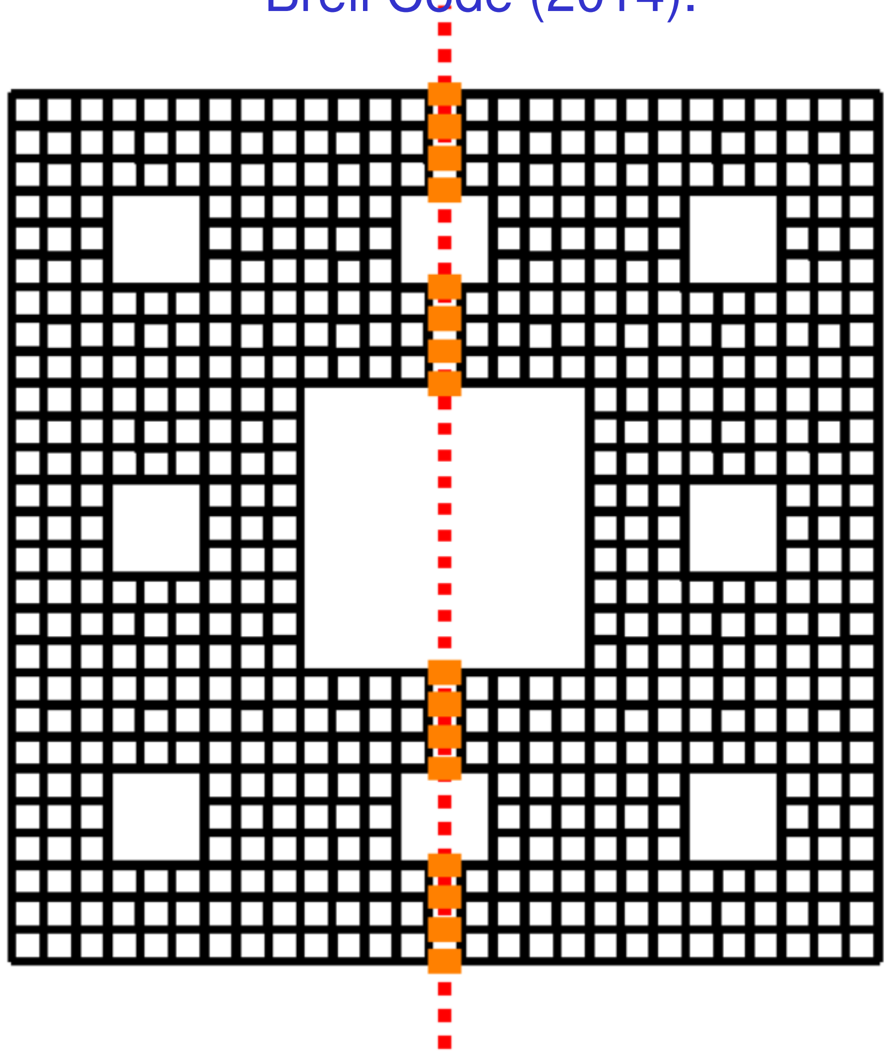
4) Perturbative stability.

5) Efficient decoding.

6) Exponential memory time at nonzero temperature.

The 4D toric code obeys all the rules, but what about < 4 dimensions?

Low distortion 3D embedding of a 4D code:
Brell Code (2014).



Has a finite temperature phase transition,
but is it perturbatively stable?

What can we learn from analog and digital quantum simulators?

What can we learn from analog and digital quantum simulators?

Analog is noisy, digital can be error corrected.

Atoms, molecules, ions, superconducting circuits, …

Goal: learn about quantum phenomena that are hard to simulate classically.

Robust, universal properties may be accessible through crude quantum simulations.

Can quantum computers efficiently simulate all physical phenomena?

Can quantum computers efficiently simulate all physical phenomena?

Both YES and NO are interesting answers!

Real time evolution in chemistry and non-equilibrium stat. mech.

Quantum field theory: gauge theories, massless particles, improved scaling of cost with error, tensor network approaches, …

What is String Theory?

Does spacetime emerge from quantum entanglement?

Does spacetime emerge from quantum entanglement?

Relation between boundary entanglement entropy and bulk entanglement in AdS spacetime (Ryu and Takayanagi 2006).

Tensor network description of bulk geometry (Swingle 2009).

ER=EPR (entanglement=wormholes) (Van Raamsdonk 2010, MS 2013).

Computational complexity as geometry (Susskind 2014)

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

Prepared for submission to JHEP

Bulk Locality and Quantum Error Correction in AdS/CFT

Ahmed Almheiri,[a] **Xi Dong,**[a] **Daniel Harlow**[b]

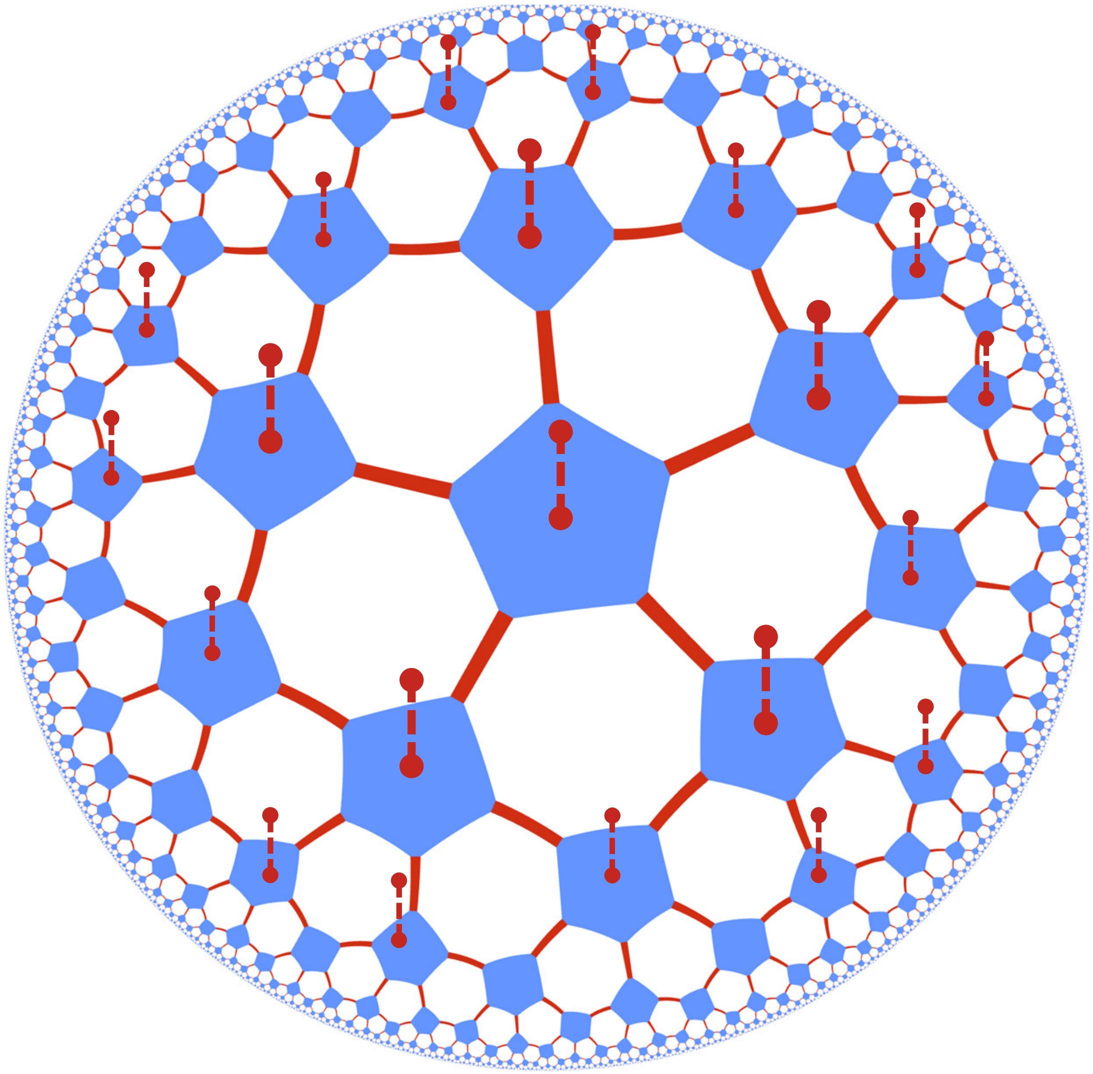
[a] *Stanford Institute for Theoretical Physics, Department of Physics, Stanford University, Stanford, CA 94305, USA*

[b] *Princeton Center for Theoretical Science, Princeton University, Princeton NJ 08540 USA*

E-mail: almheiri@stanford.edu, xidong@stanford.edu, dharlow@princeton.edu

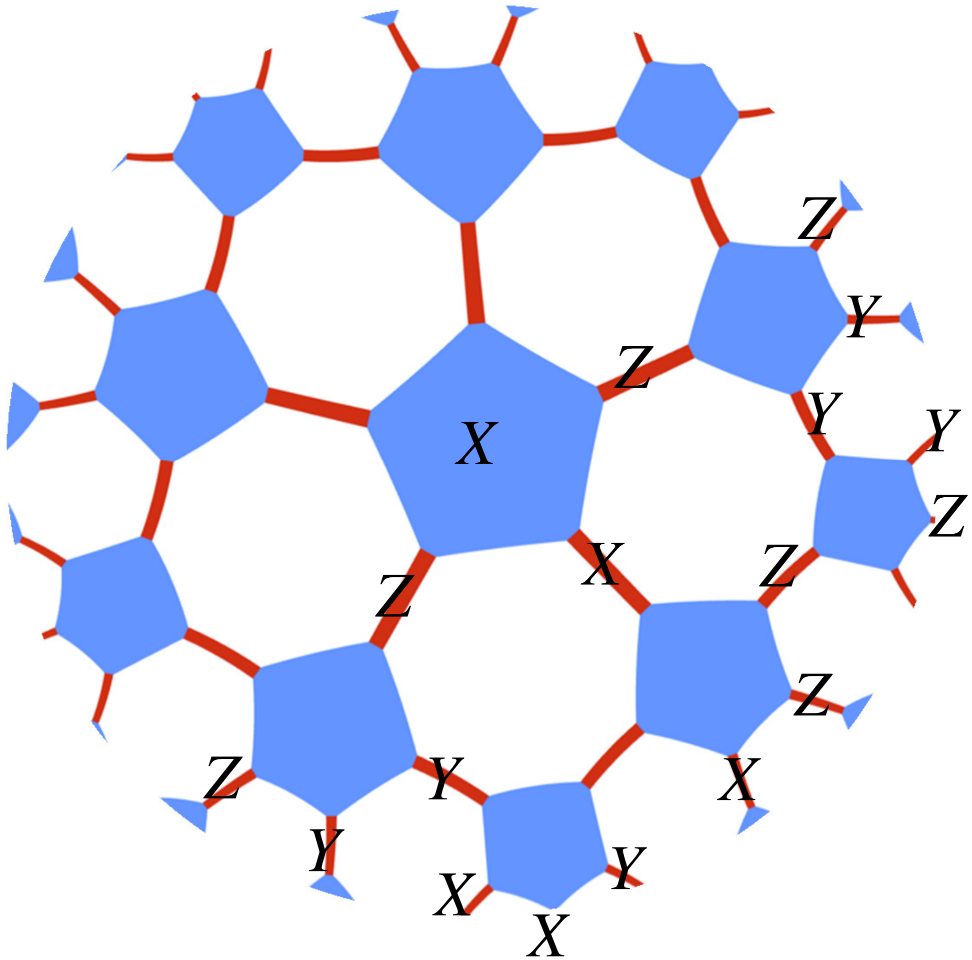
Abstract: We point out a connection between the emergence of bulk locality in

Holographic Quantum Code



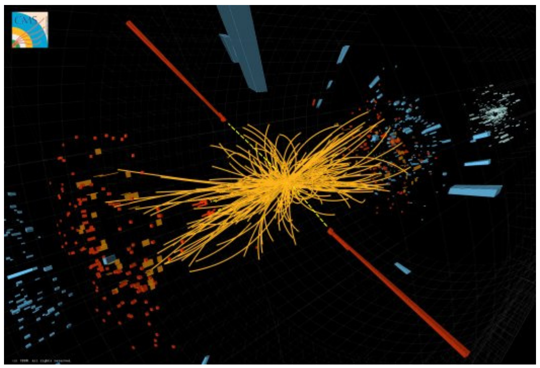
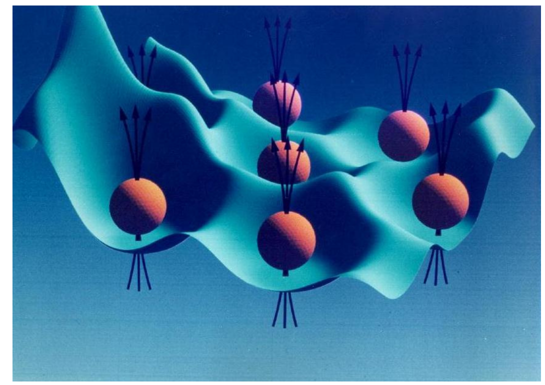
HArlow, Pastawski, Preskill, Yoshida = HAPPY

Holographic QECC
Bulk-Boundary Dictionary



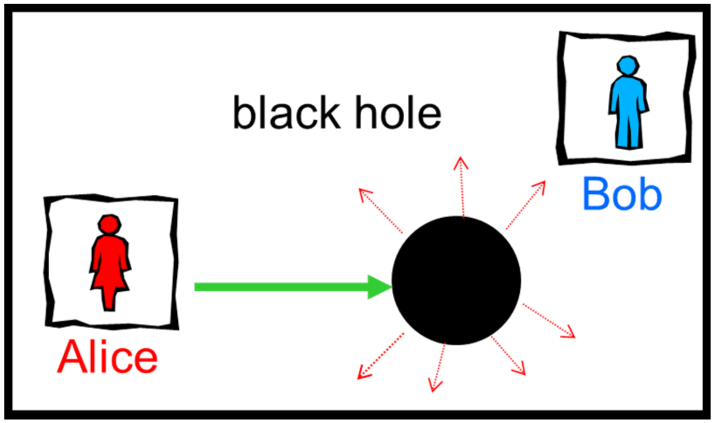
HArlow, Pastawski, Preskill, Yoshida = HAPPY

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		

What's inside a black hole?

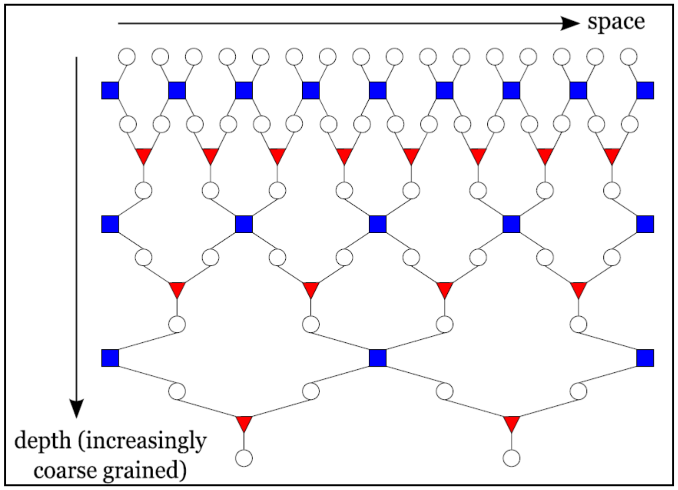
Quantum error correction: "black holes as mirrors" and bulk/boundary correspondence.



Computational complexity: "fast scrambling" by black holes, hardness of decoding Hawking radiation, complexity and geometry.

Monogamy of entanglement and the structure of Hawking radiation.

ER = EPR. Correspondence between entanglement and wormholes.



Tensor network description of bulk geometry.

Einstein field equations in the bulk as a property of entanglement on the boundary.

How does geometry emerge (or fail to emerge) from something more fundamental?