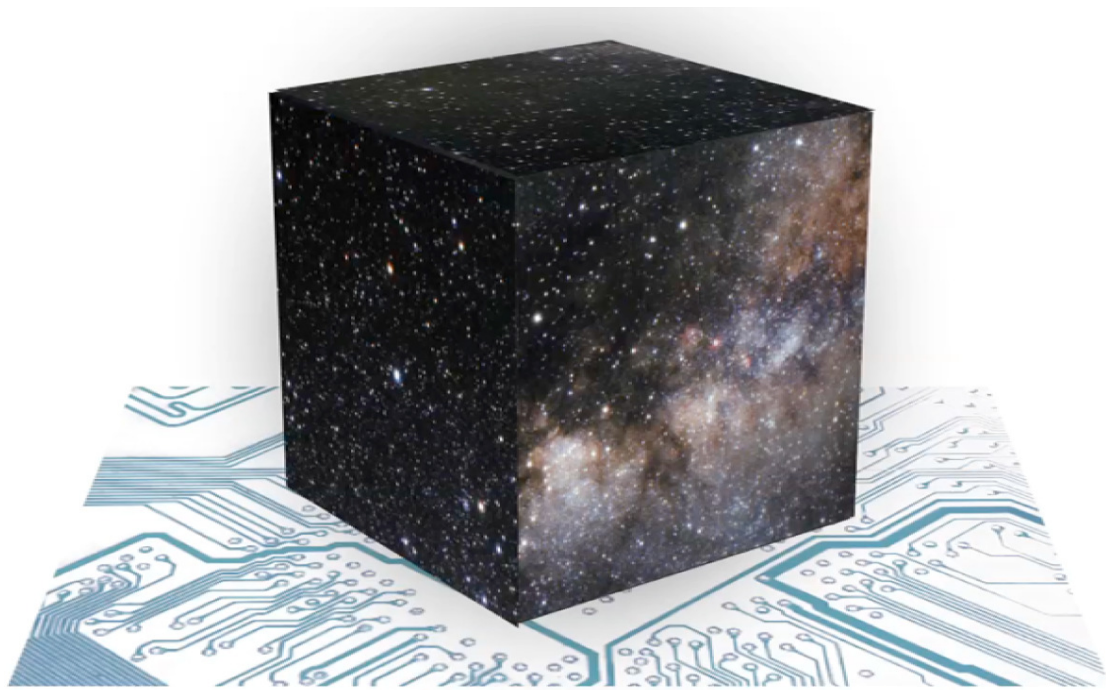
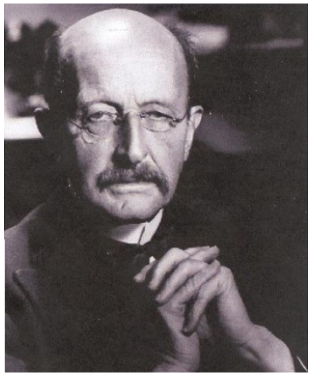
Quantum computing and the entanglement frontier



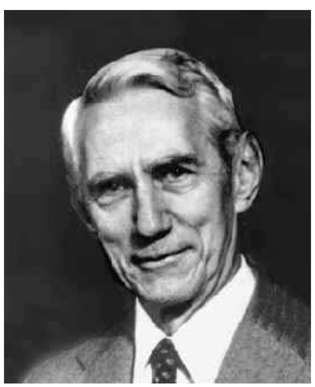
INSTITUTE FOR QUANTUM INFORMATION AND MATTER

John Preskill
NAS Annual Meeting
29 April 2018

Quantum Information Science


Planck

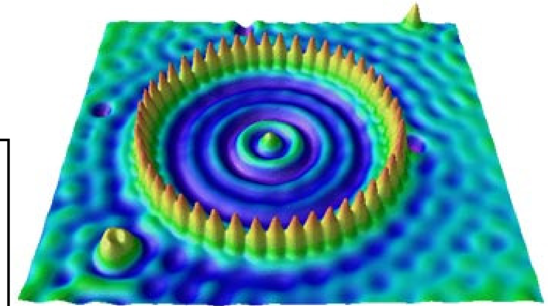

Turing


Shannon

quantum theory
+ computer science
+ information theory

↓

quantum information science



What I won’t say much about today

Quantum cryptography

Privacy founded on fundamental laws of quantum physics.

Quantum networking

Distributing quantumness around the world.

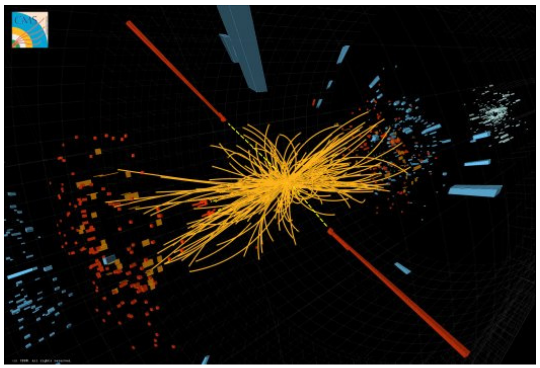
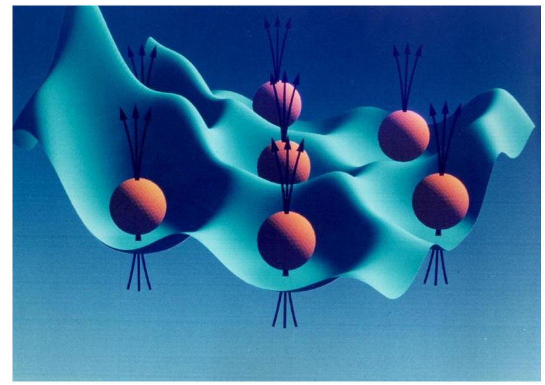
Quantum sensing

Improving sensitivity and spatial resolution.

Today we will focus on quantum computing.

Which uses some of the same hardware as the above applications.

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	Gravitational waves	Quantum spacetime

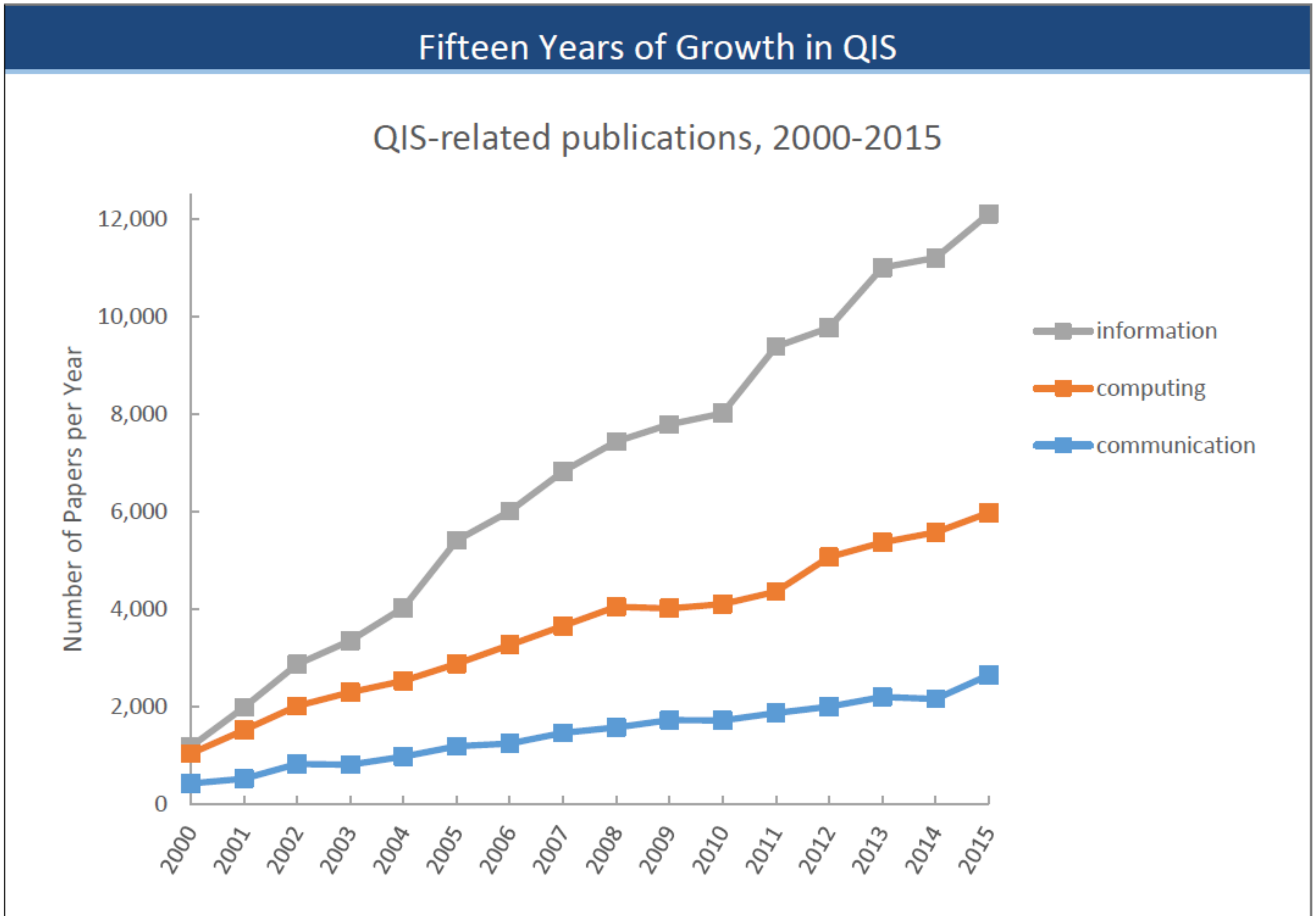
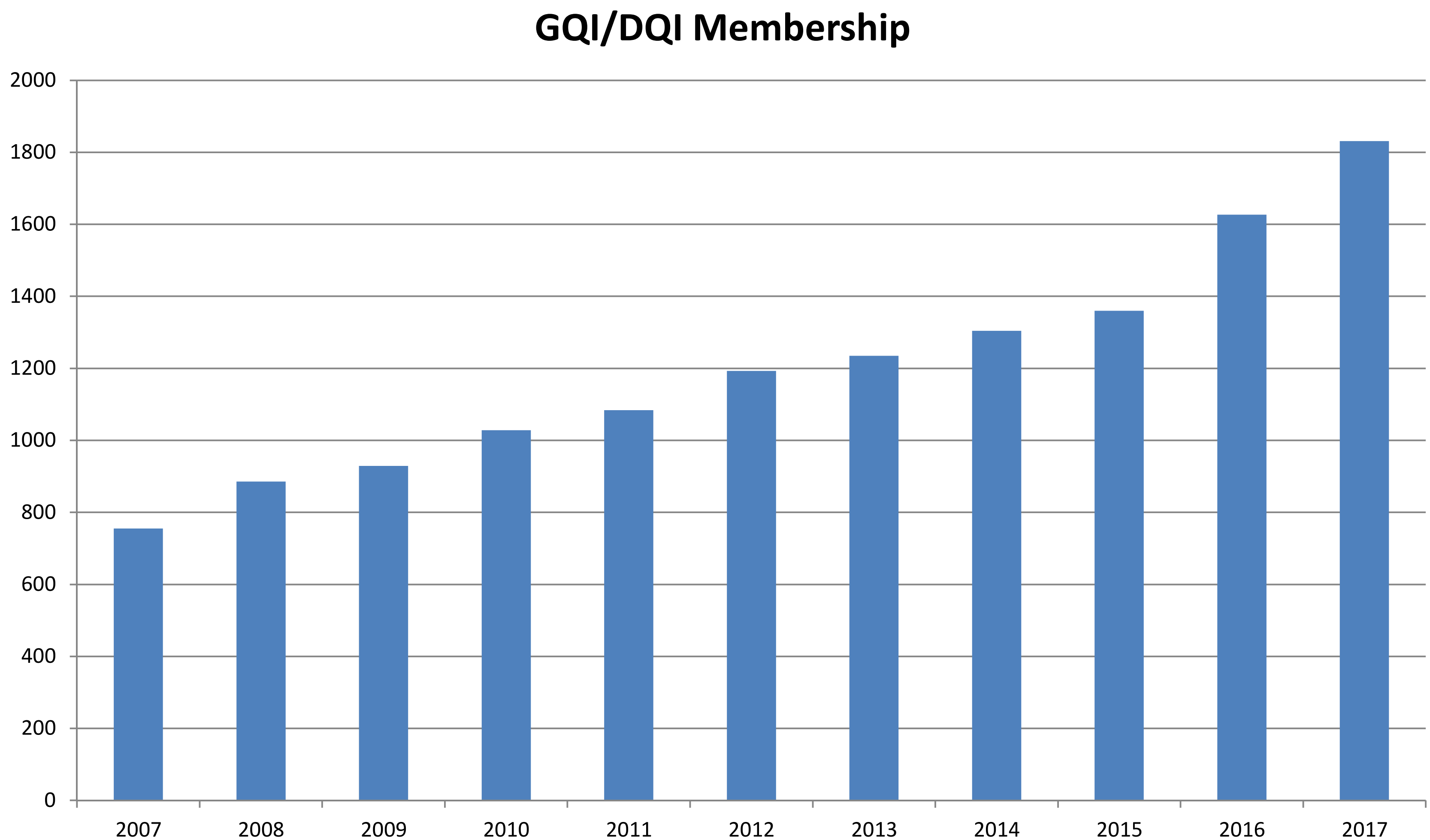


Figure 1. A Google Scholar search for publications (excluding patents and citations) containing the terms "quantum information," "quantum computing," and "quantum communication" illustrates how the field has grown in recent years.

Source: ADVANCING QUANTUM INFORMATION SCIENCE: NATIONAL CHALLENGES AND OPPORTUNITIES Produced by the Interagency Working Group on Quantum Information Science of the Subcommittee on Physical Sciences, National Science and Technology Council, July 2016

APS Division of Quantum Information



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

(Founded 2005. Membership is 57% students.)

Two fundamental ideas

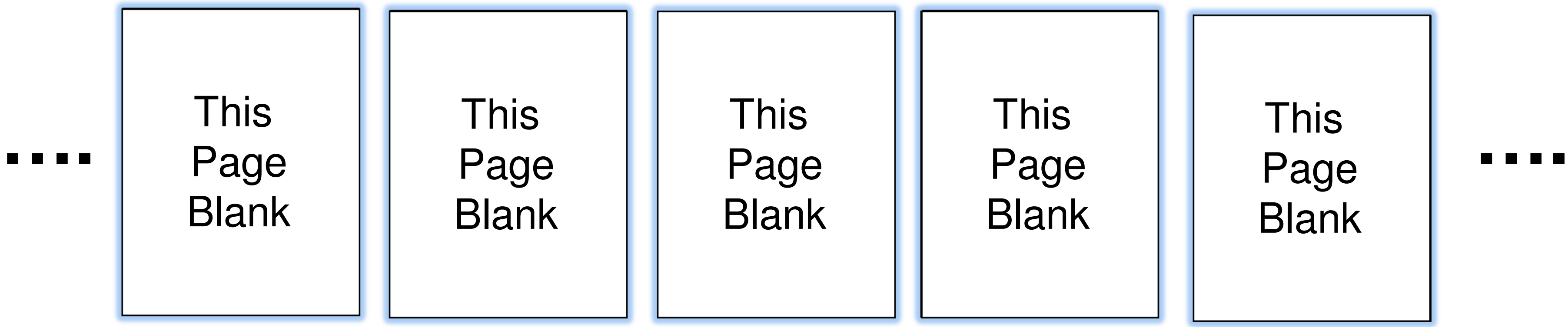
(1) *Quantum complexity*

Why we think quantum computing is powerful.

(2) *Quantum error correction*

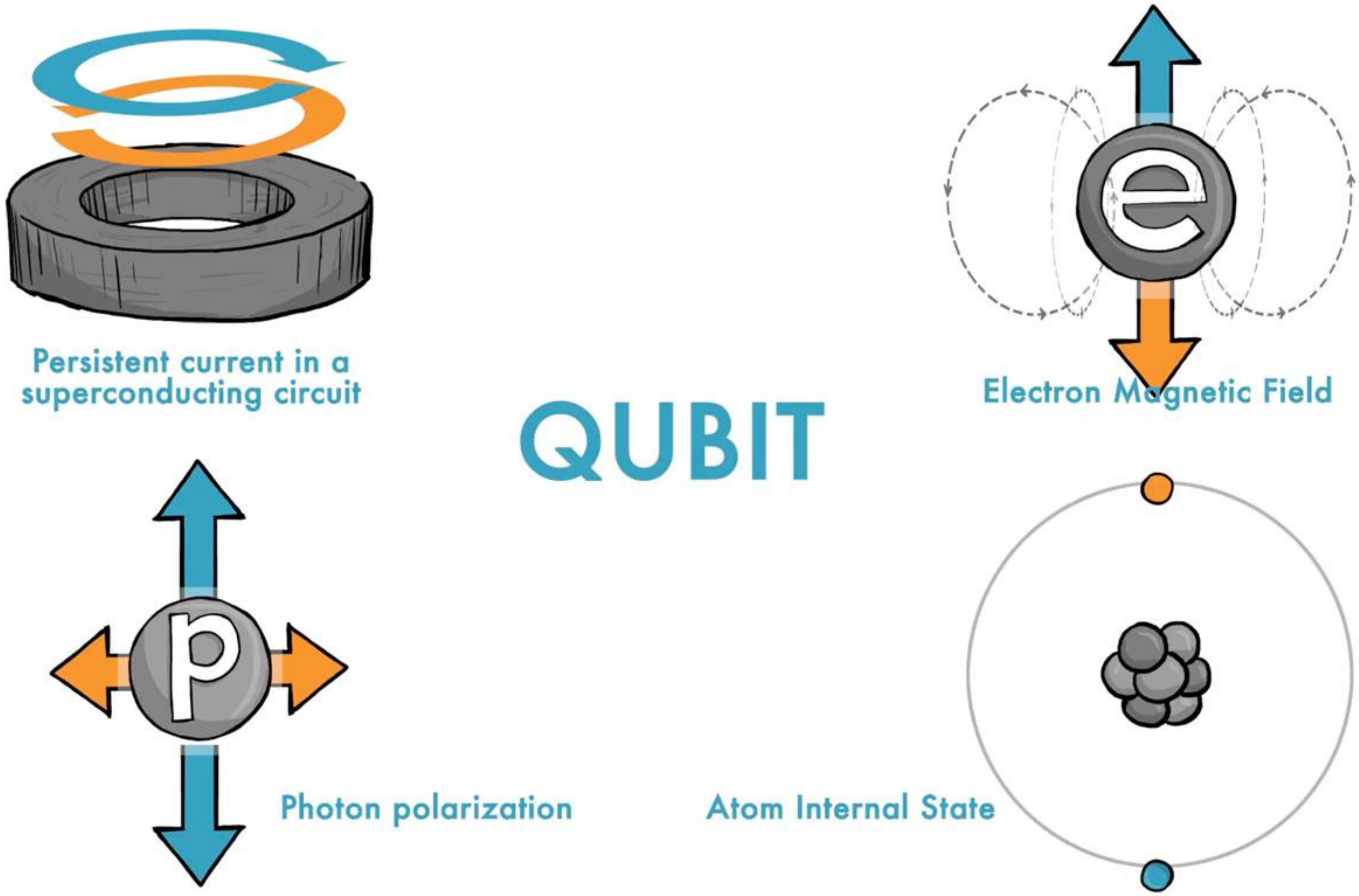
Why we think quantum computing is scalable.

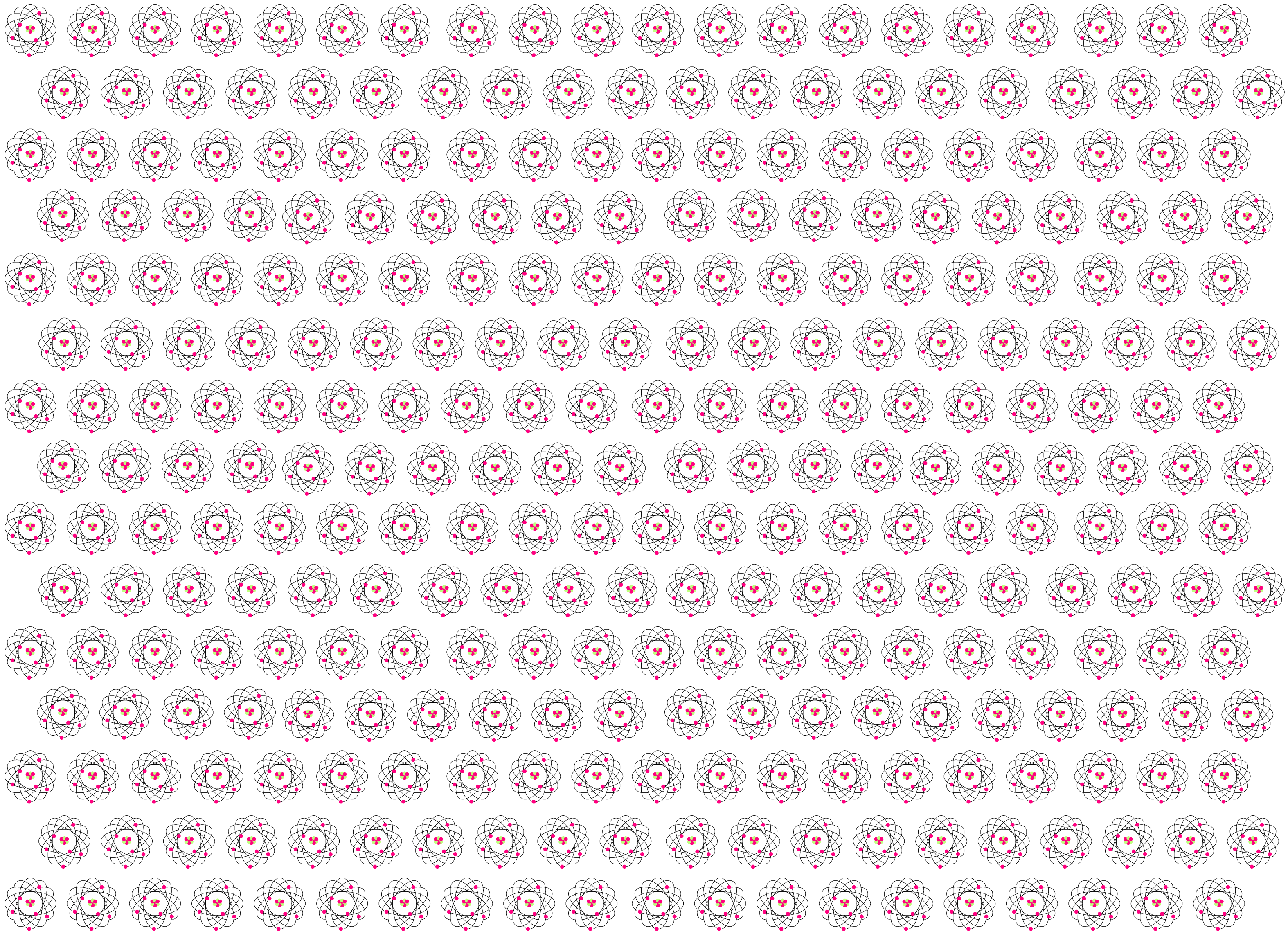
Quantum entanglement



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.


Persistent current in a superconducting circuit
Electron Magnetic Field
QUBIT
Photon polarization
Atom Internal State



A complete description of a typical quantum state of just 300 qubits requires more bits than the number of atoms in the visible universe.

Why we think quantum computing is powerful

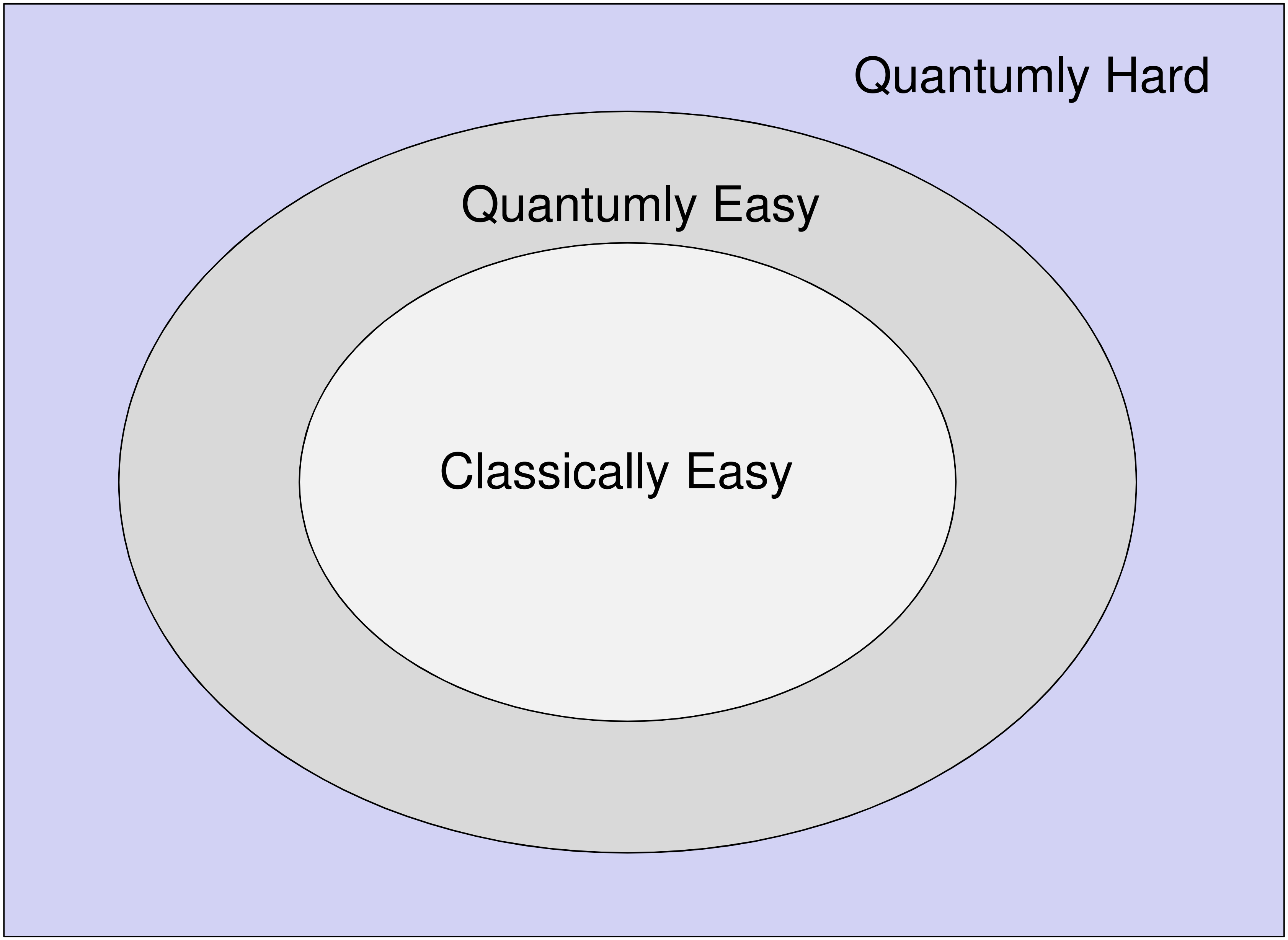
(1) Problems believed to be hard classically, which are easy for quantum computers. Factoring is the best known example.

(2) Complexity theory arguments indicating that quantum computers are hard to simulate classically.

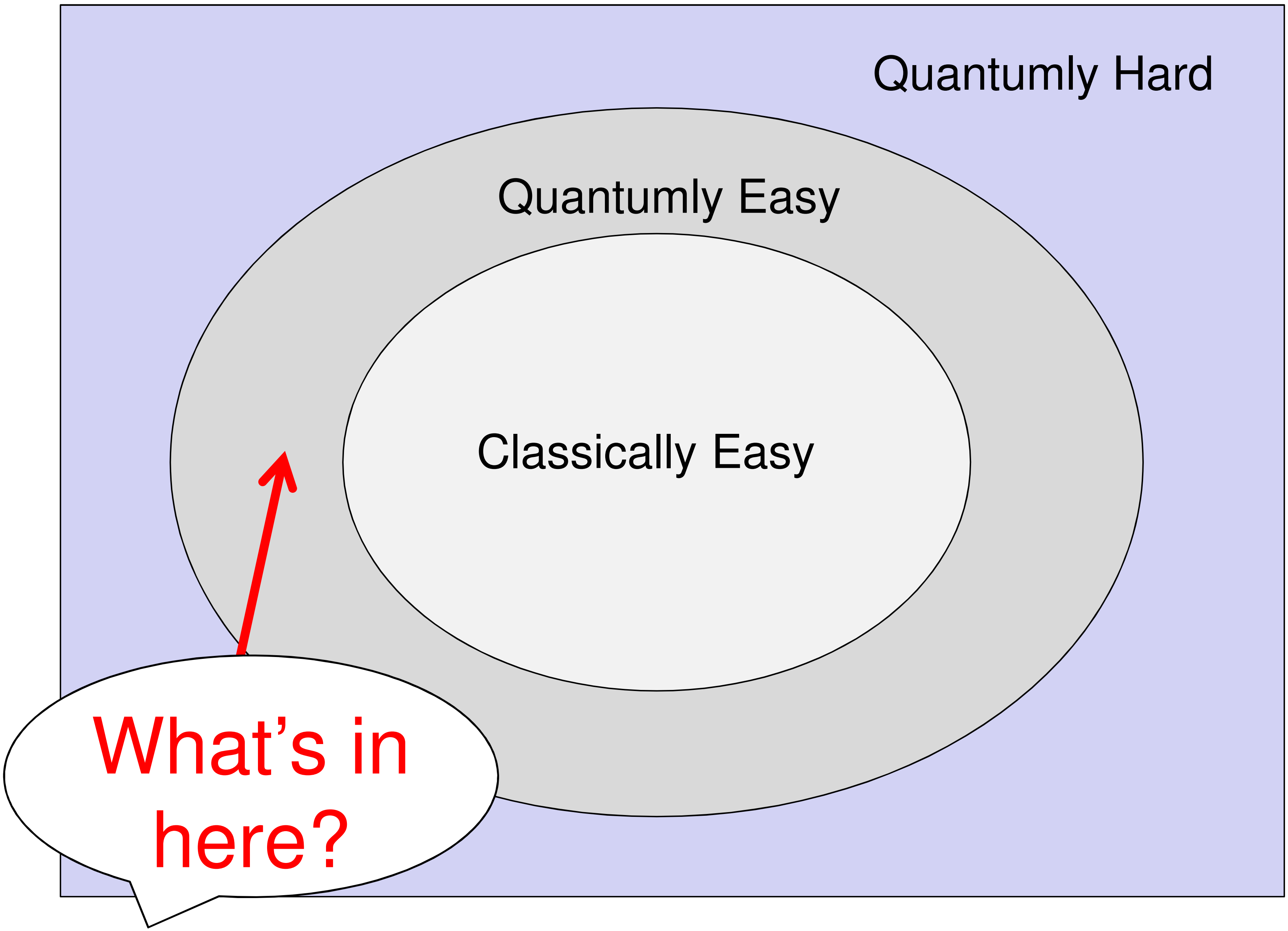
(3) We don’t know how to simulate a quantum computer efficiently using a digital (“classical”) computer. The cost of the best known simulation algorithm rises exponentially with the number of qubits.

But … the power of quantum computing is limited. For example, we don’t believe that quantum computers can efficiently solve worst-case instances of NP-hard optimization problems (e.g., the traveling salesman problem).

Problems



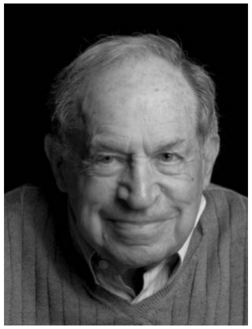
Problems

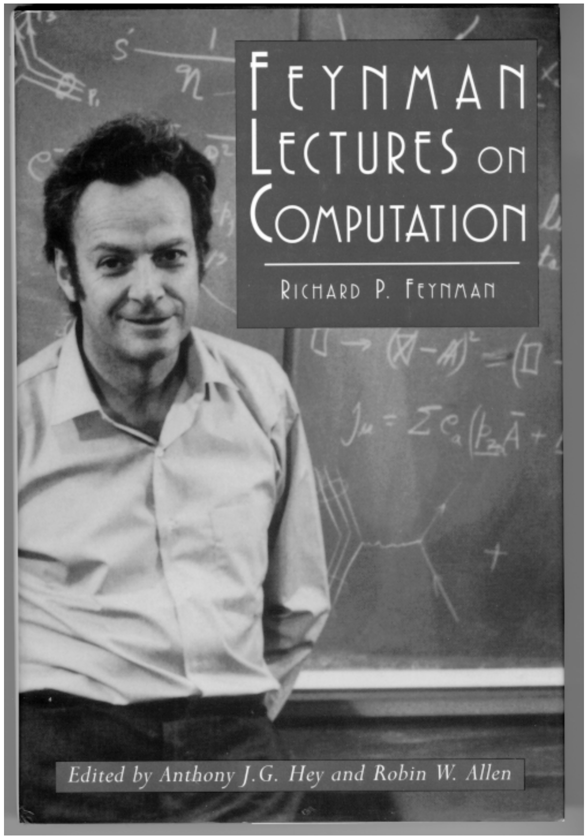

Quantumly Hard
Quantumly Easy
Classically Easy
What's in here?

"The theory of everything?"

"The Theory of Everything is not even remotely a theory of every thing … We know this equation is correct because it has been solved accurately for small numbers of particles (isolated atoms and small molecules) and found to agree in minute detail with experiment. However, it cannot be solved accurately when the number of particles exceeds about 10. No computer existing, or that will ever exist, can break this barrier because it is a catastrophe of dimension … We have succeeded in reducing all of ordinary physical behavior to a simple, correct Theory of Everything only to discover that it has revealed exactly nothing about many things of great importance."

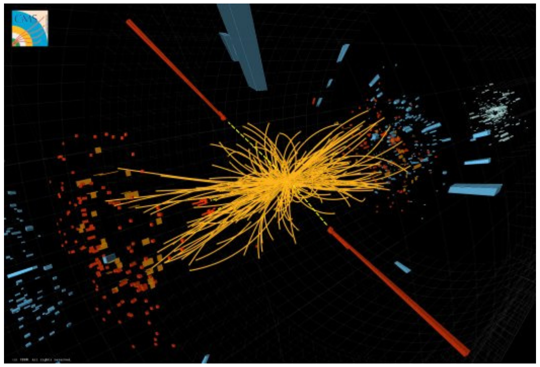
R. B. Laughlin and D. Pines, PNAS 2000.

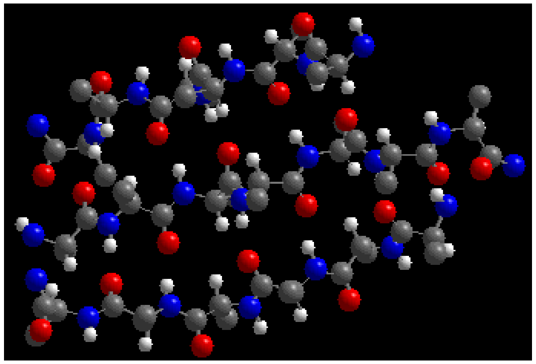


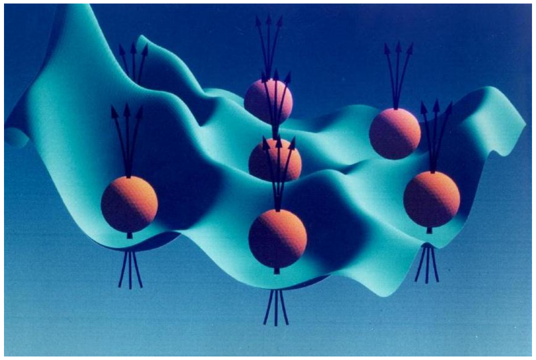


“Nature isn’t classical, dammit, and if you want to make a simulation of Nature, you’d better make it quantum mechanical, and by golly it’s a wonderful problem because it doesn’t look so easy.”

R. P. Feynman, 1981

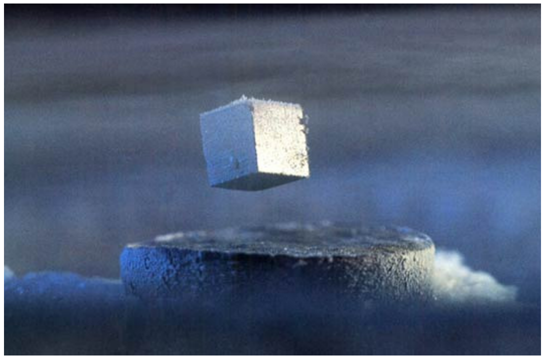

particle collision

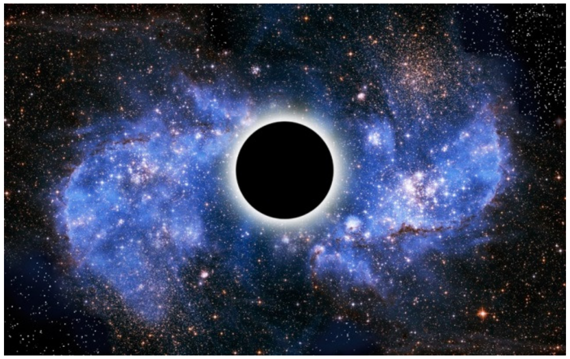

molecular chemistry


entangled electrons

A quantum computer can simulate efficiently any physical process that occurs in Nature.

(Maybe. We don't actually know for sure.)


superconductor


black hole


early universe

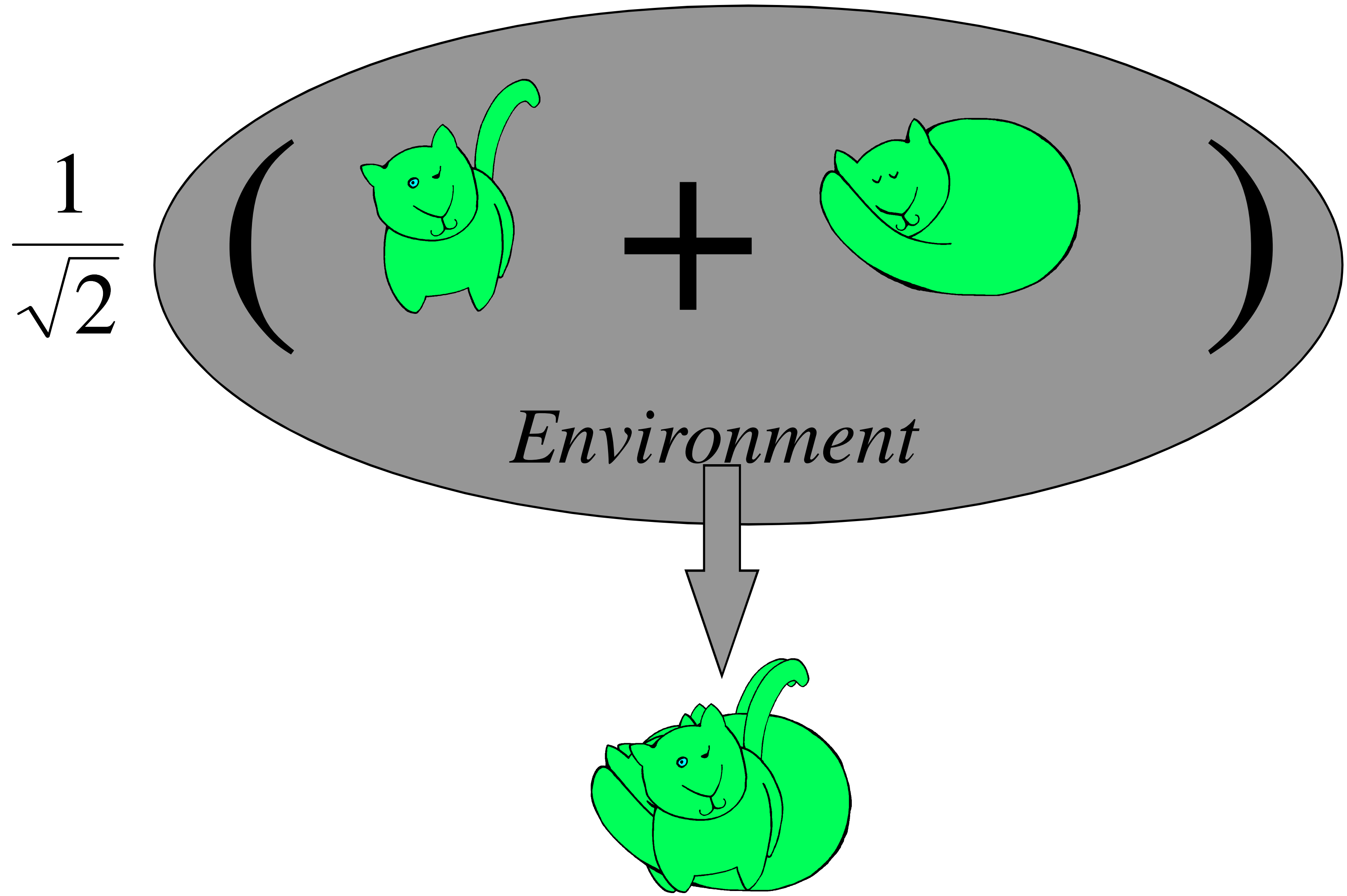
Why quantum computing is hard

We want qubits to interact strongly with one another.

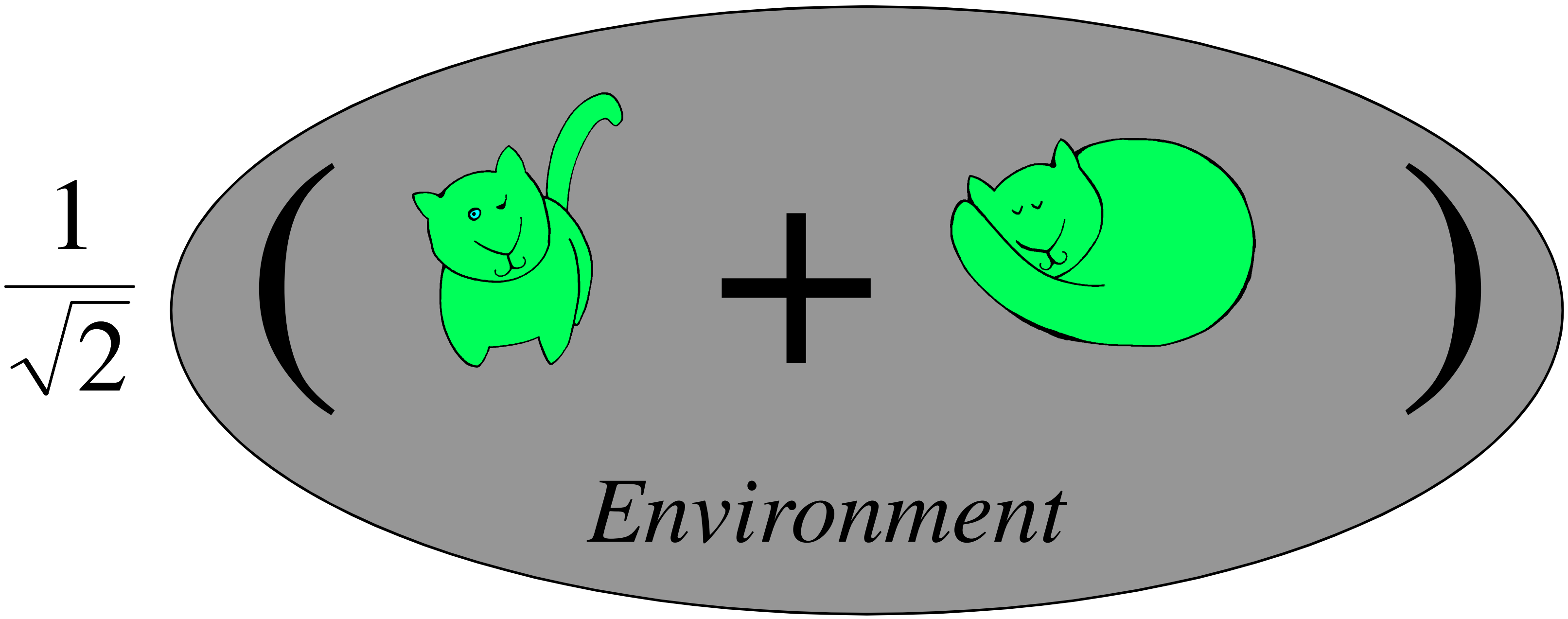
We don’t want qubits to interact with the environment.

Except when we control or measure them.

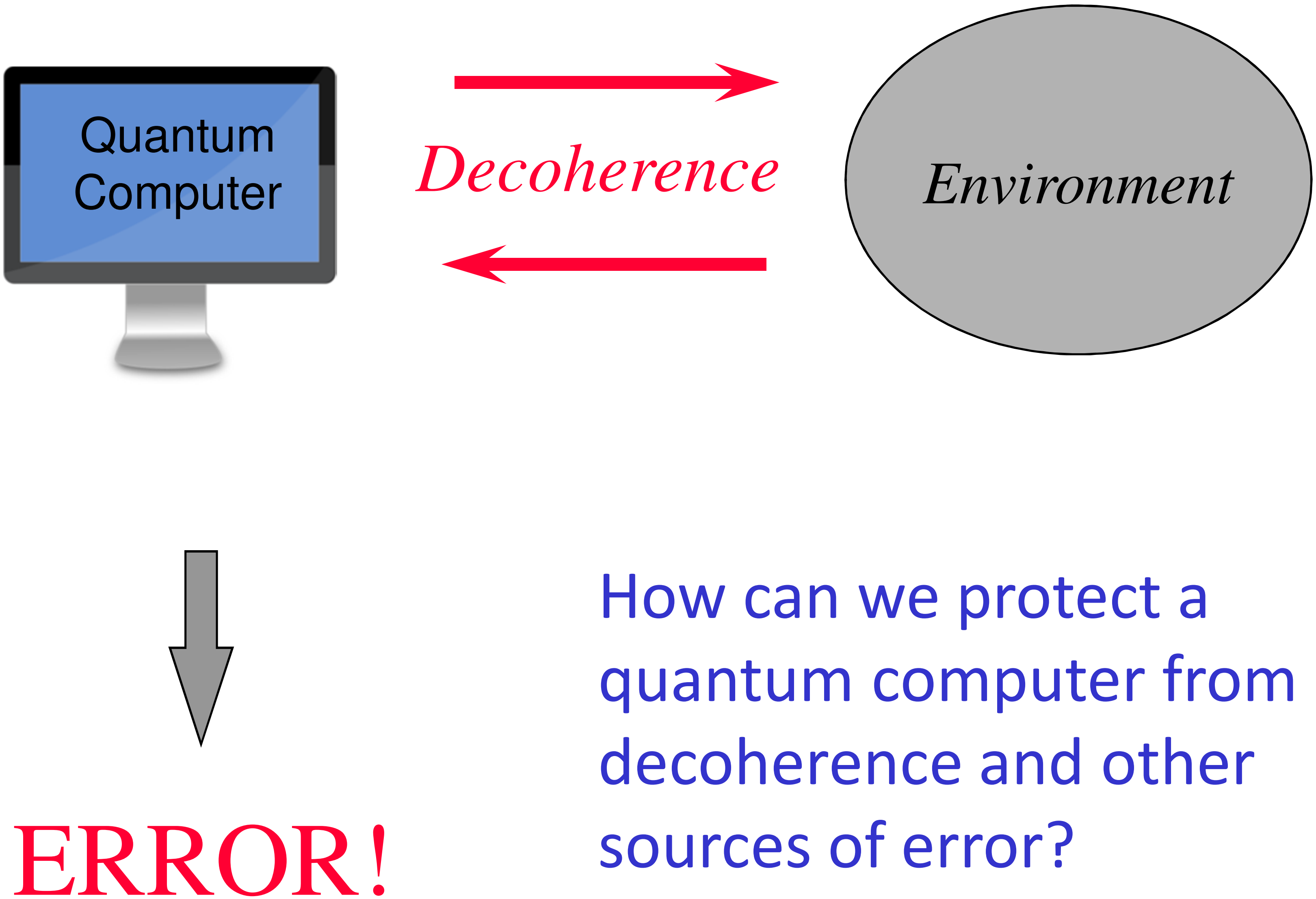
Decoherence



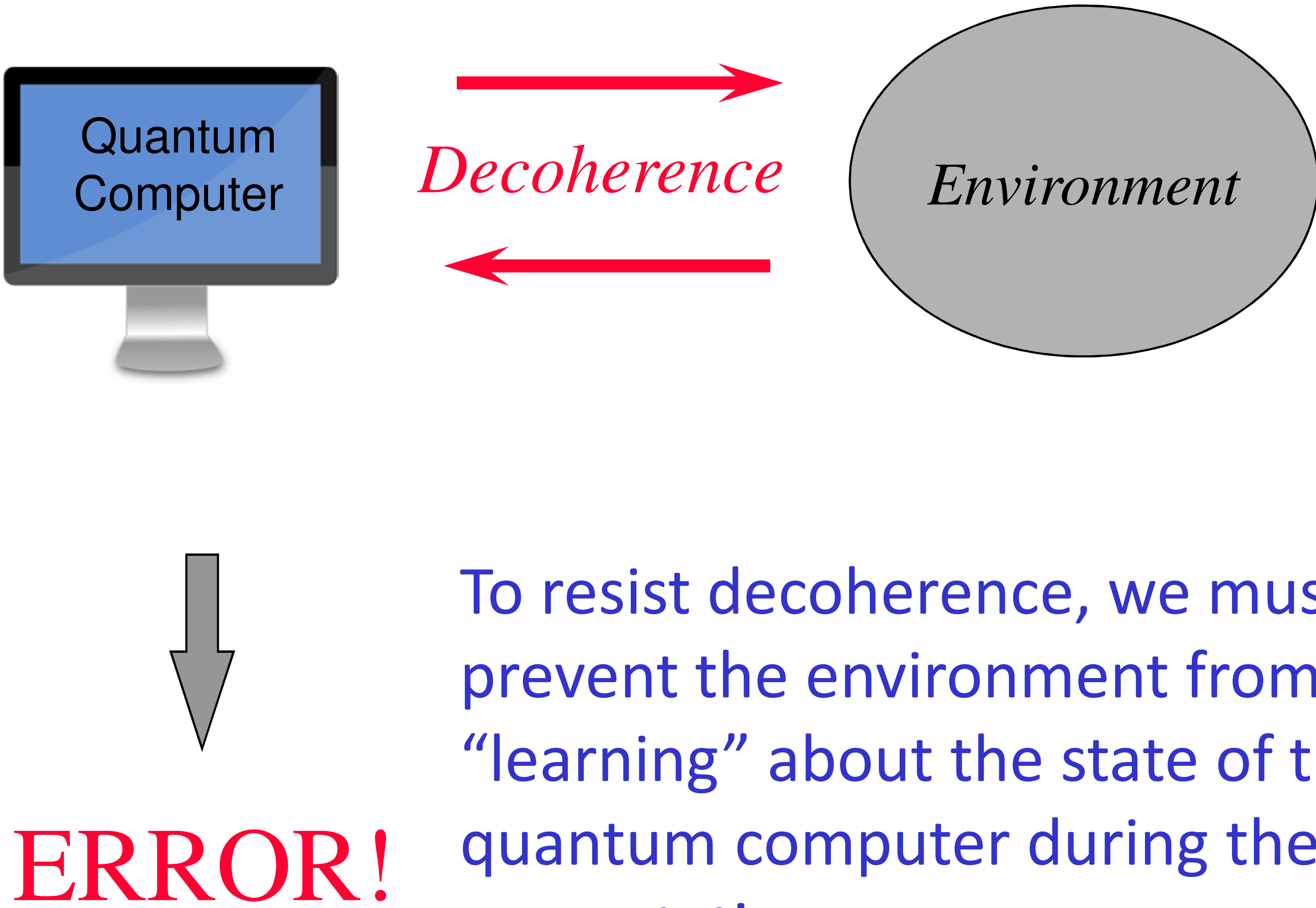
Decoherence



Decoherence explains why quantum phenomena, though observable in the microscopic systems studied in the physics lab, are not manifest in the macroscopic physical systems that we encounter in our ordinary experience.

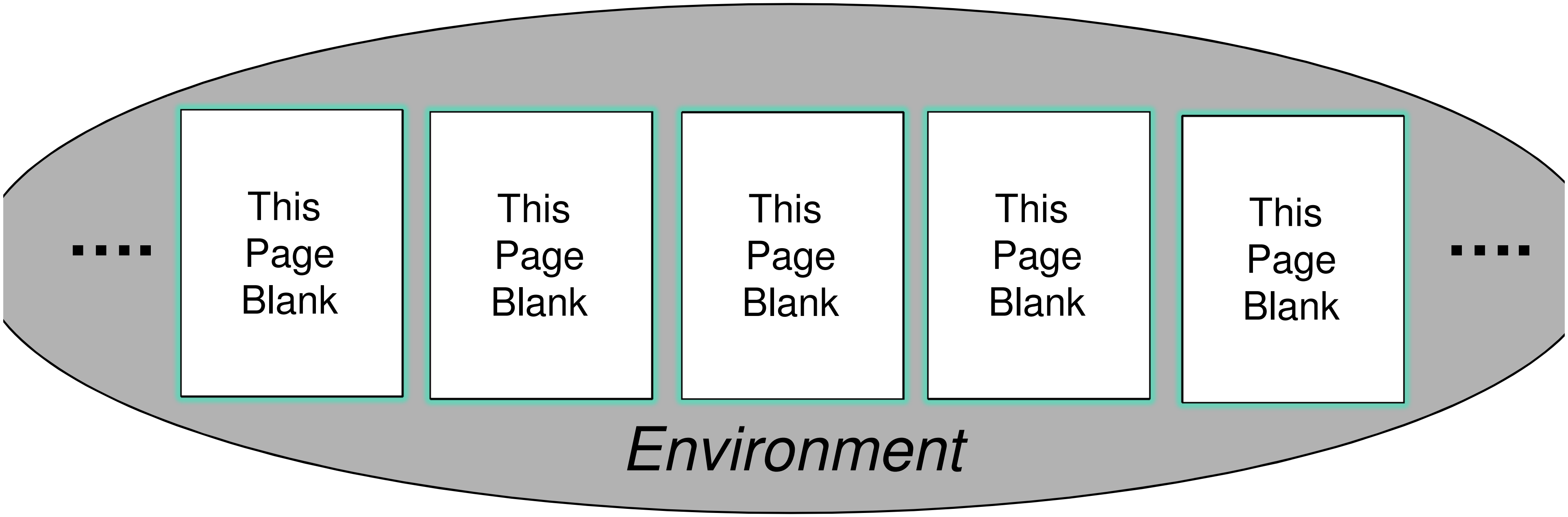


How can we protect a quantum computer from decoherence and other sources of error?



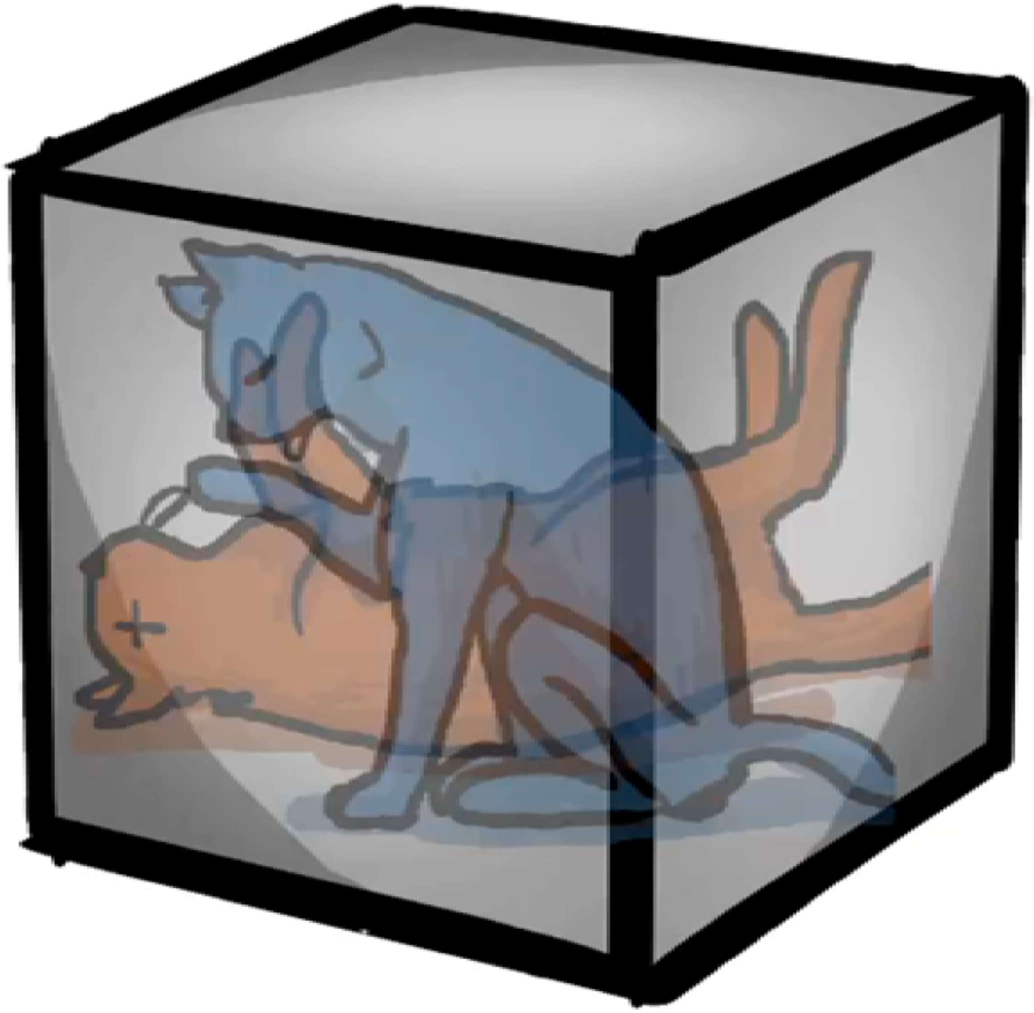
To resist decoherence, we must prevent the environment from "learning" about the state of the quantum computer during the computation.

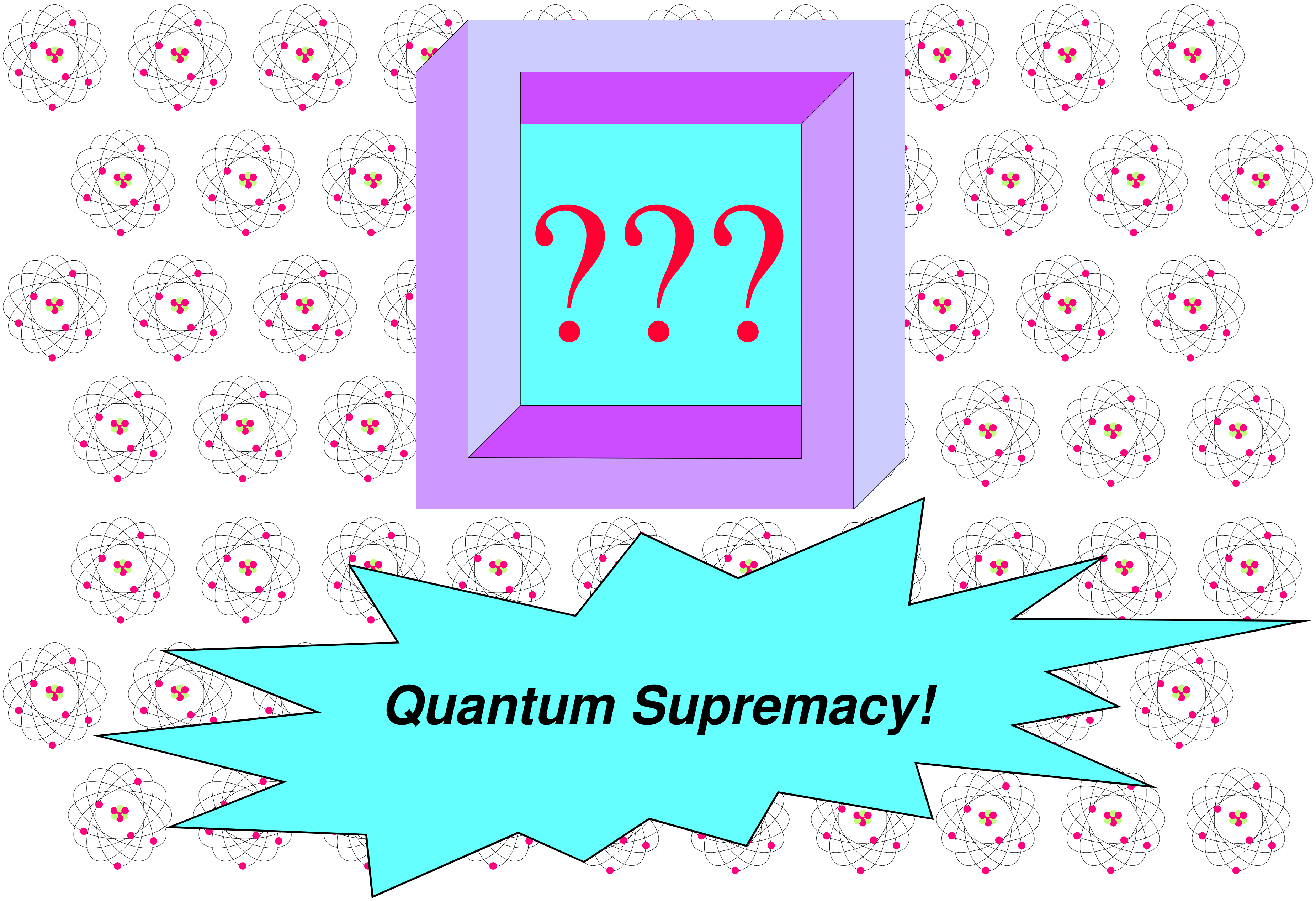
Quantum error correction



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.




???
Quantum Supremacy!

Quantum computing in the NISQ Era

The (noisy) 50-100 qubit quantum computer is coming soon.
(*NISQ* = noisy intermediate-scale quantum.)

NISQ devices cannot be simulated by brute force using the most powerful currently existing supercomputers.

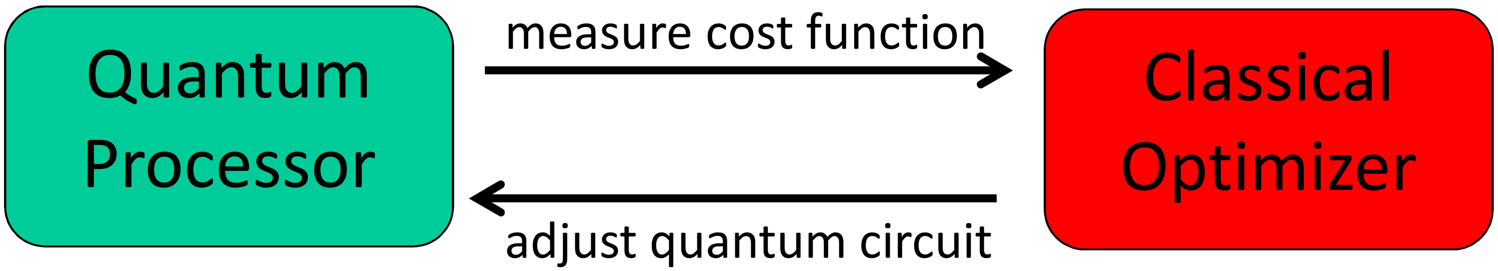
Noise limits the computational power of NISQ-era technology.

NISQ will be an interesting tool for exploring physics. It *might* also have useful applications. But we're not sure about that.

NISQ will not change the world by itself. Rather it is a step toward more powerful quantum technologies of the future.

Potentially transformative scalable quantum computers may still be decades away. We're not sure how long it will take.

Hybrid quantum/classical optimizers



We don’t expect a quantum computer to solve worst case instances of NP-hard problems, but it might find better approximate solutions, or find them faster.

Classical optimization algorithms (for both classical and quantum problems) are sophisticated and well-honed after decades of hard work.

We don’t know whether NISQ devices can do better, but we can try it and see how well it works.

The steep climb to scalability

NISQ-era quantum devices will not be protected by quantum error correction. Noise will limit the scale of computations that can be executed accurately.

Quantum error correction (QEC) will be essential for solving some hard problems. But QEC carries a high overhead cost in number of qubits & gates.

This cost depends on both the hardware quality and algorithm complexity. With today's hardware, solving (say) useful chemistry problems may require hundreds to thousands of physical qubits for each protected logical qubit.

To reach scalability, we must cross the daunting "quantum chasm" from hundreds to millions of physical qubits. This may take a while.

Advances in qubit technology, systems engineering, algorithm design, and theory can hasten the arrival of the fully fault-tolerant quantum computer.

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?

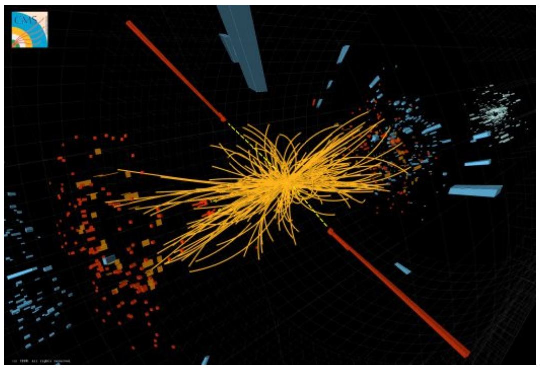
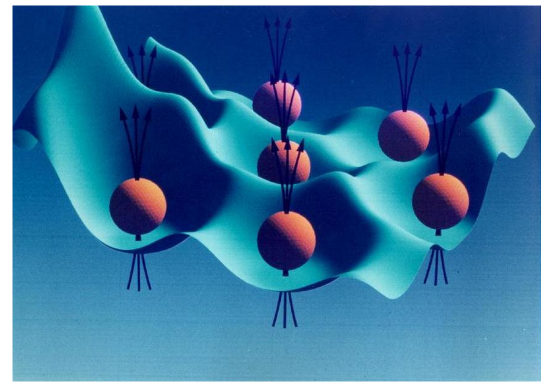
Are there obstacles that will prevent us from building quantum computers as a matter of principle?

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

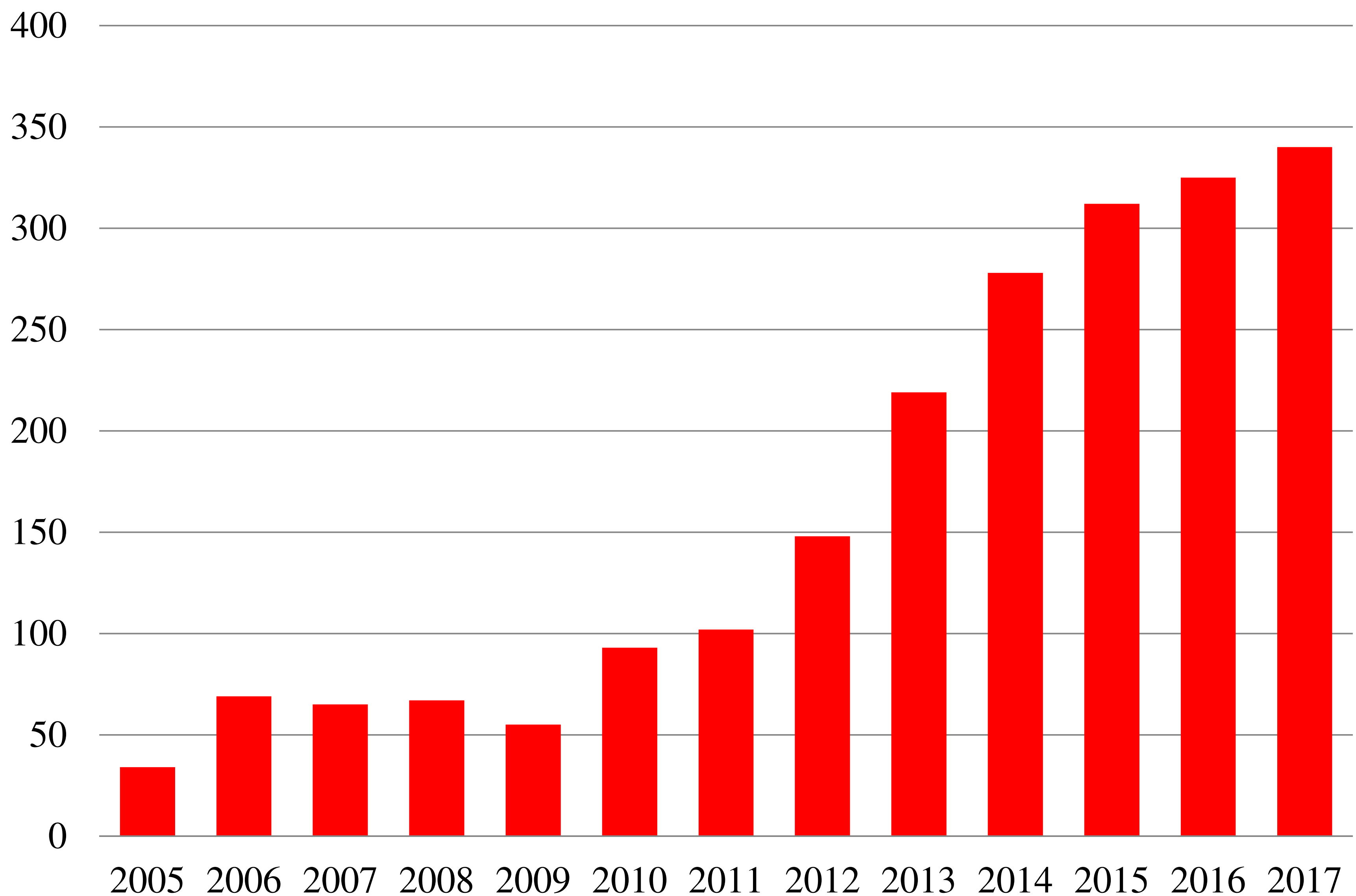
3. *How* will we build one?

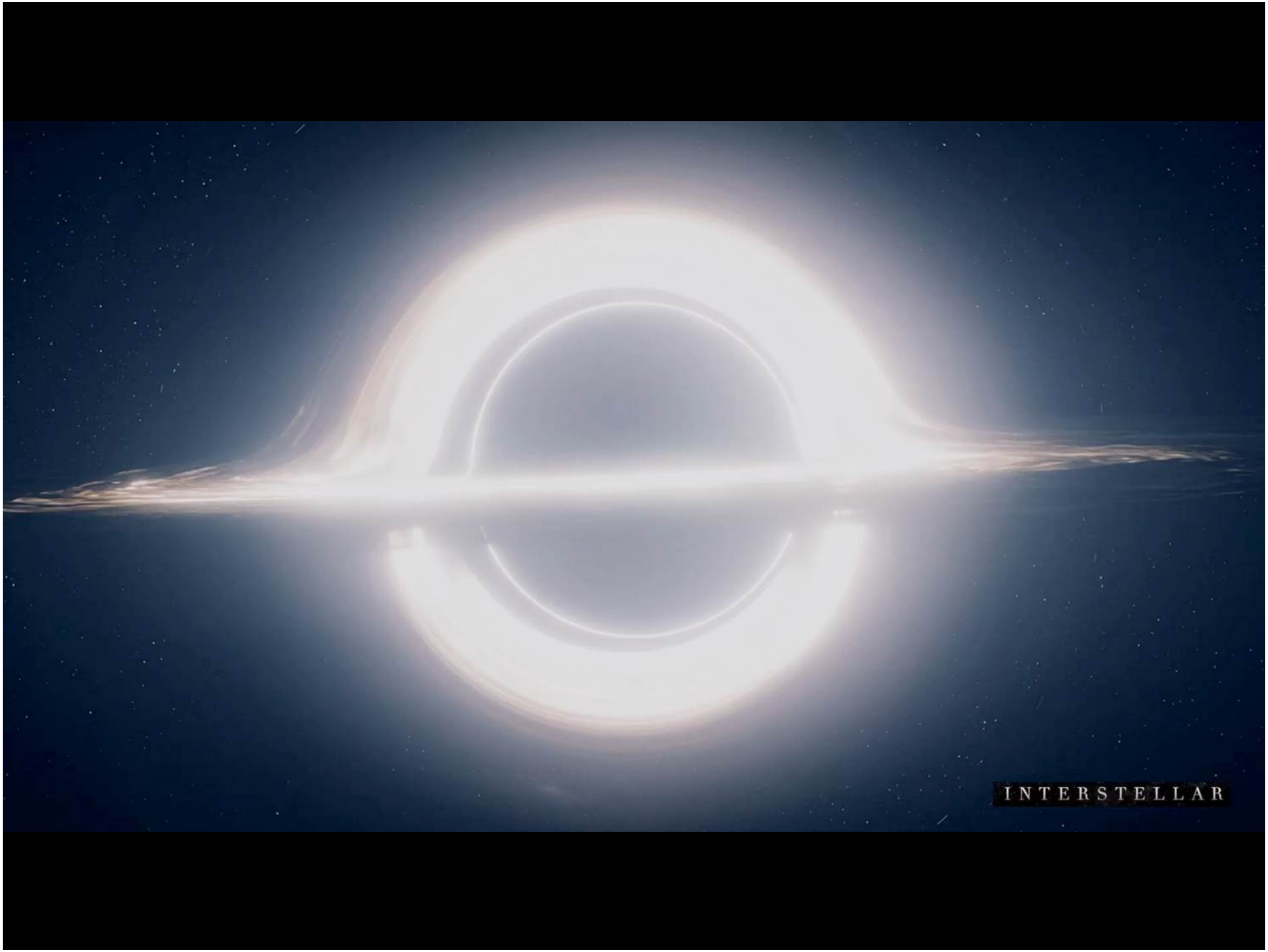
What kind of quantum hardware is potentially scalable to large systems?

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	Gravitational waves	Quantum spacetime

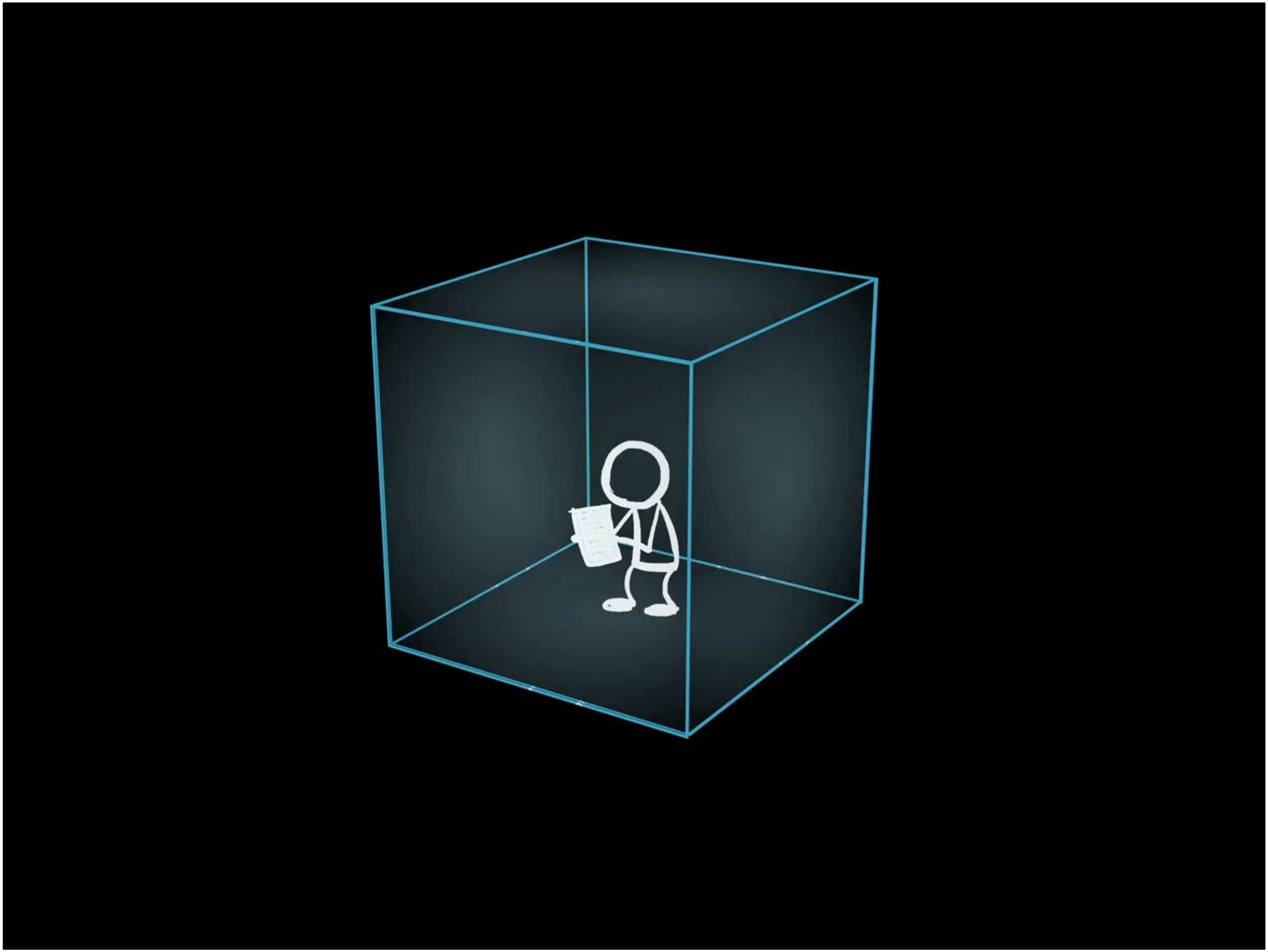
hep-th papers with “entanglement” in the abstract

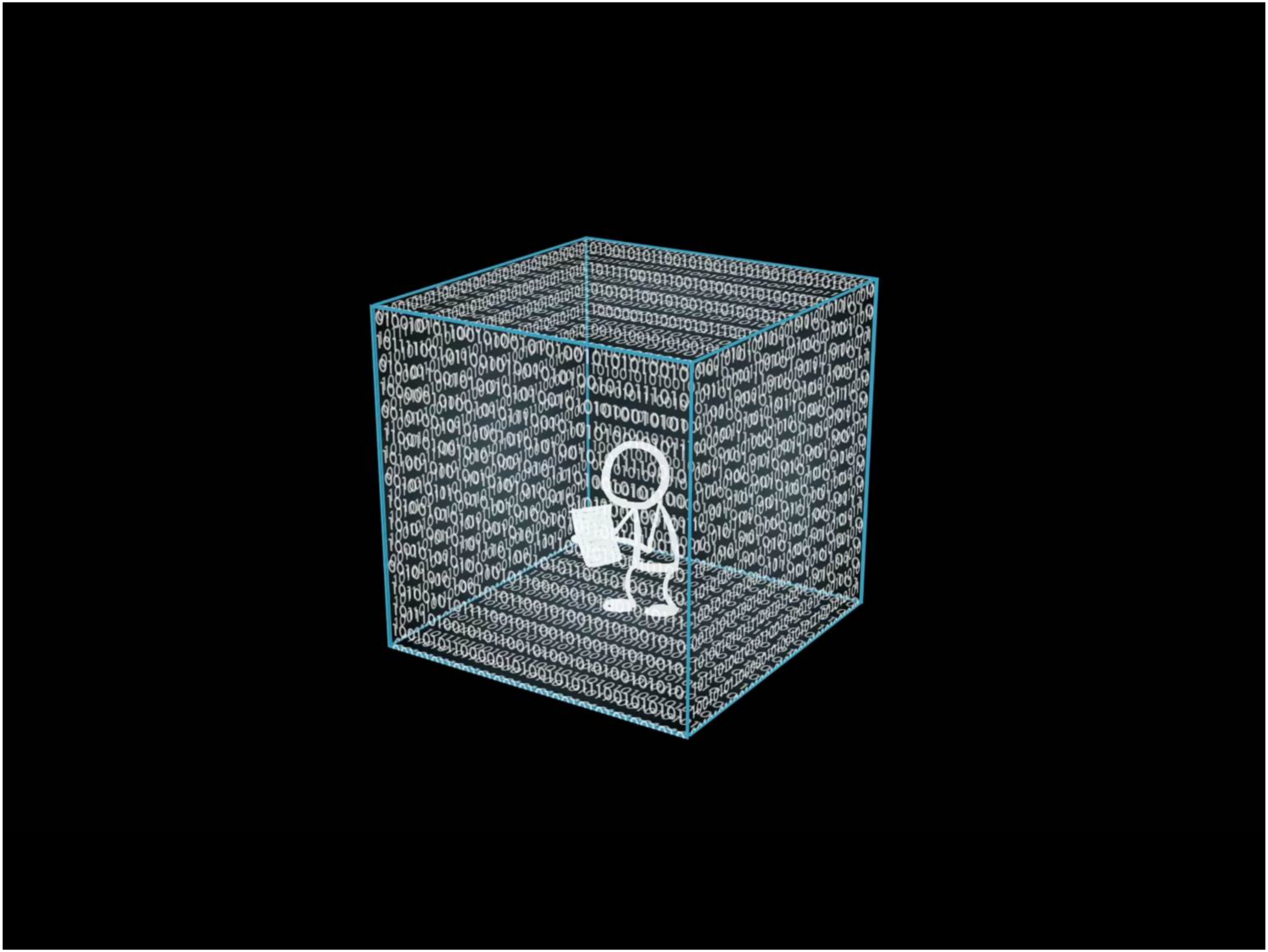


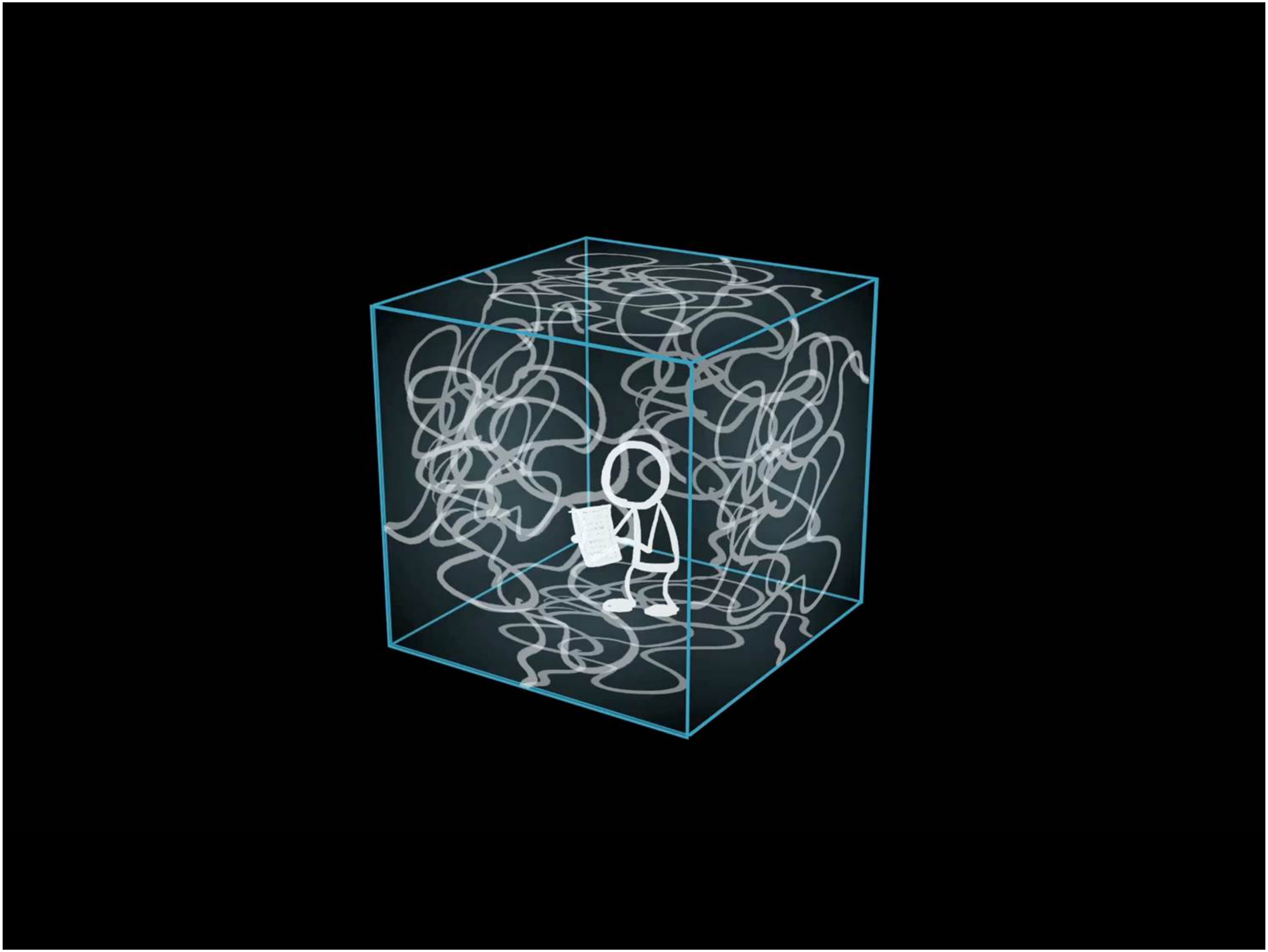

INTERSTELLAR

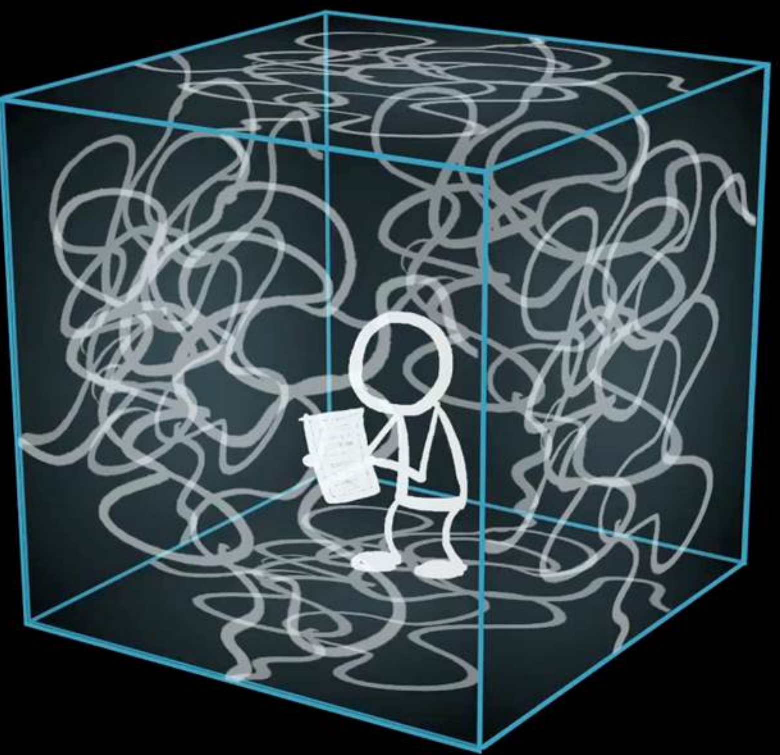

THE HOLOGRAPHIC PRINCIPLE
INTERSTELLAR

[redacted]



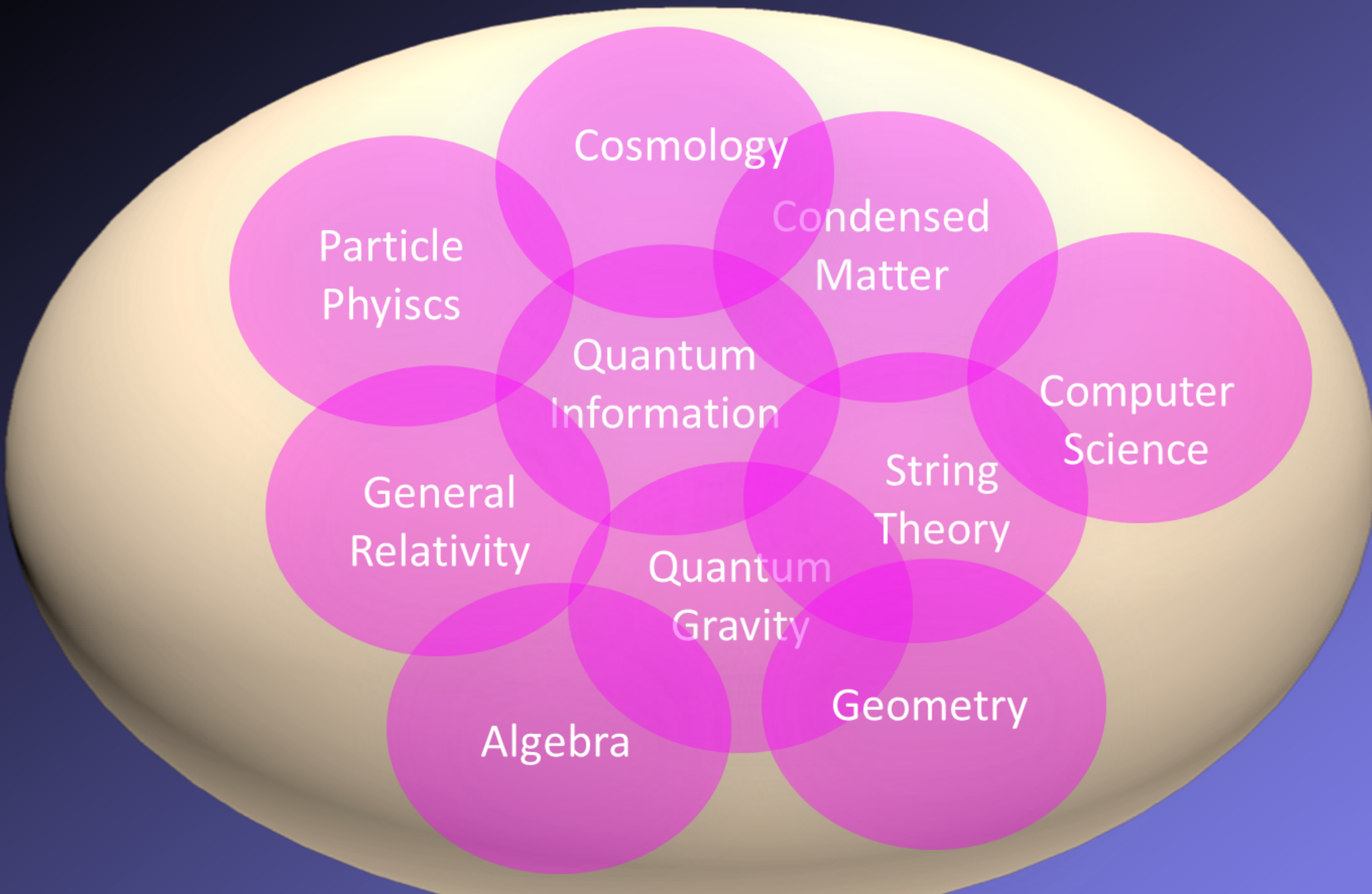






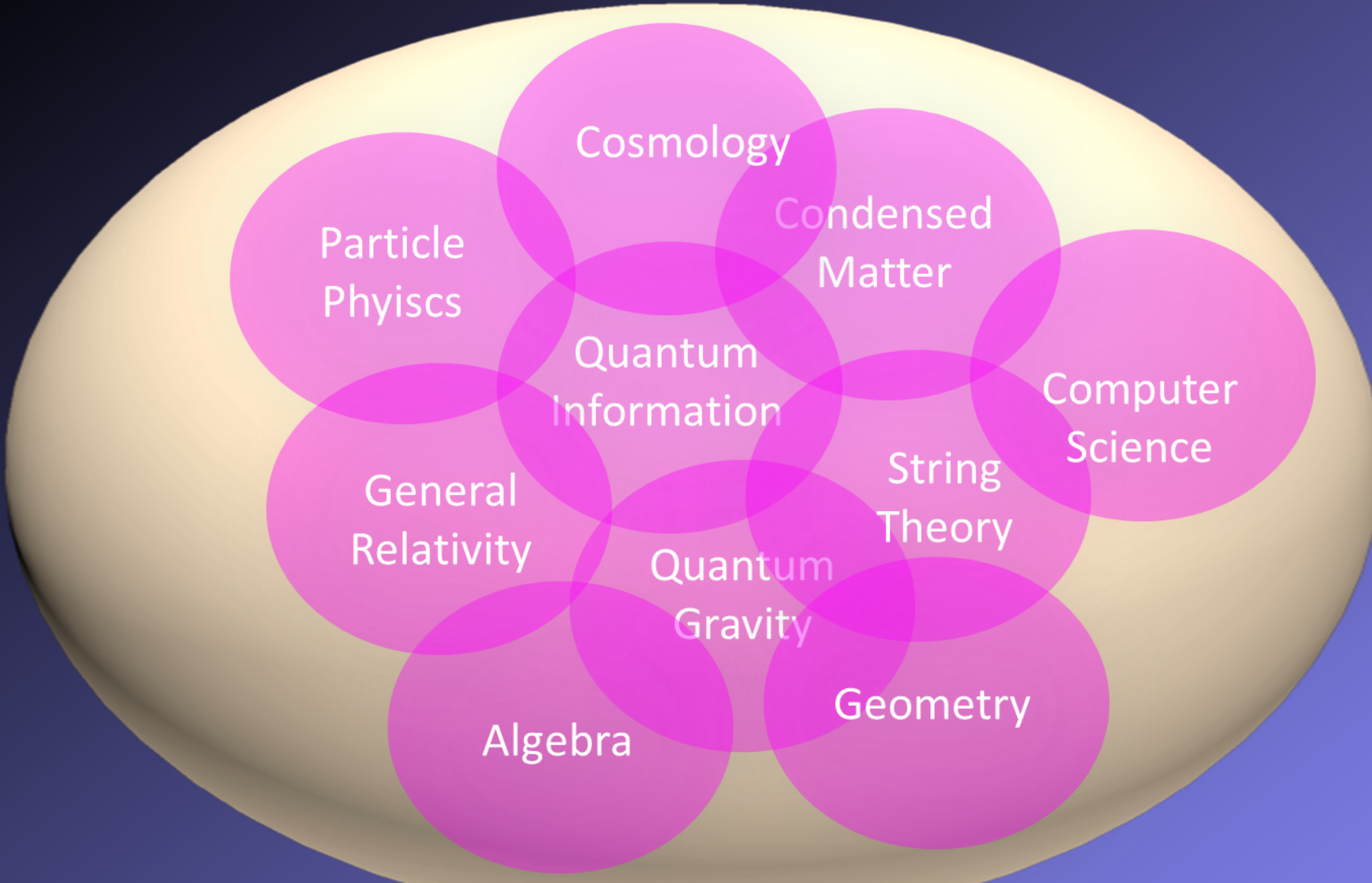
Entanglement is what holds space together.

Unity of Theoretical Physics

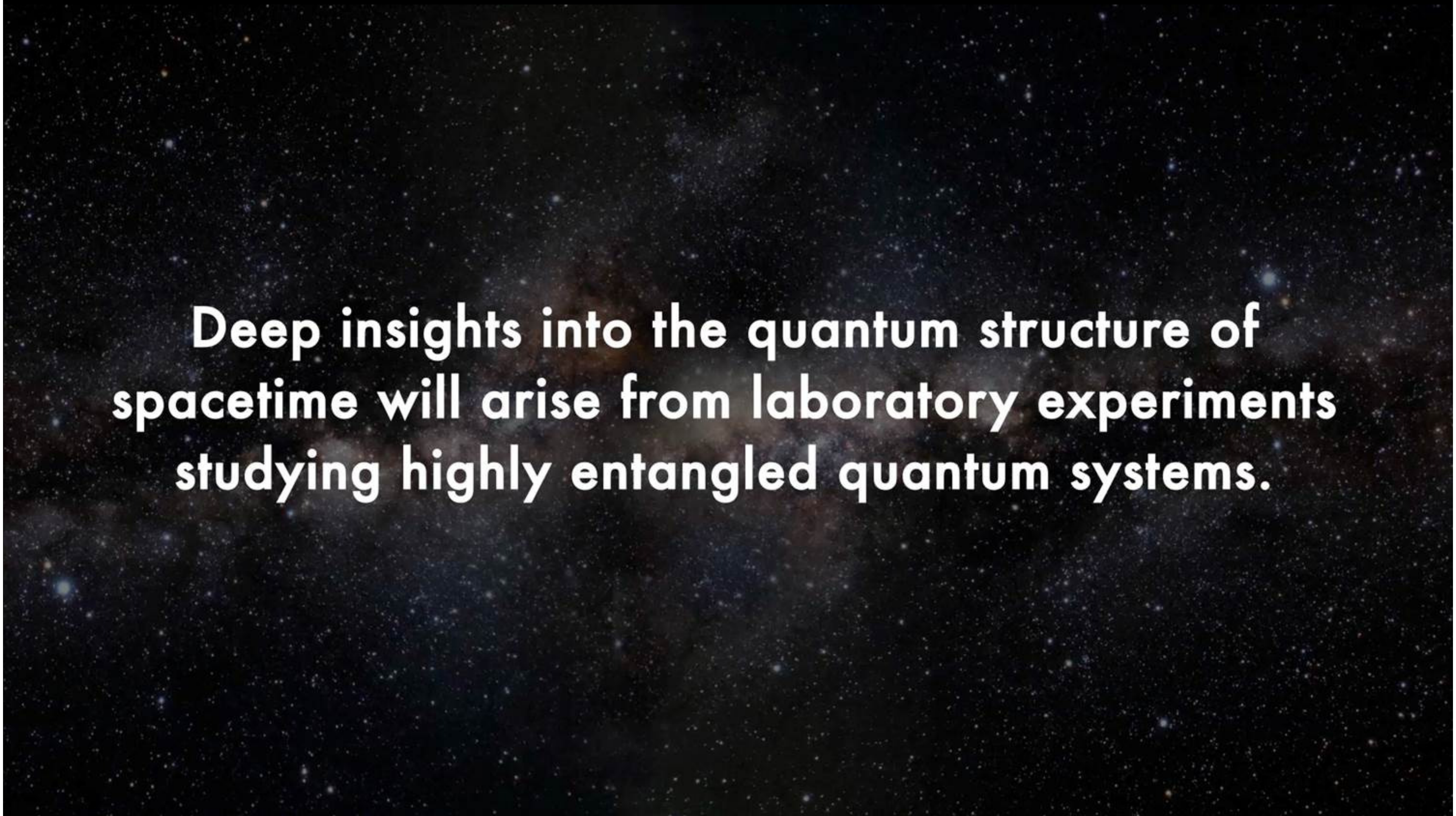


From: Robbert Dijkgraaf at the inauguration of Caltech’s Burke Institute.

Unity of ~~Theoretical~~ Physics

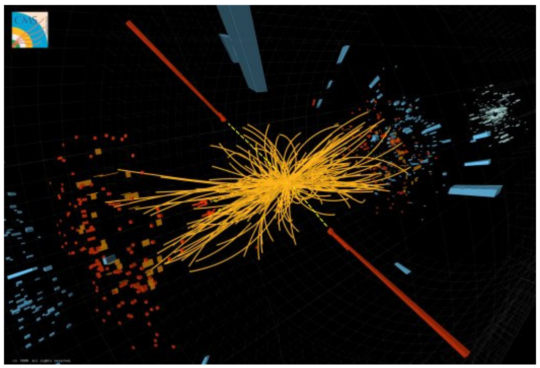


From: Robbert Dijkgraaf at the inauguration of Caltech’s Burke Institute.


Deep insights into the quantum structure of spacetime will arise from laboratory experiments studying highly entangled quantum systems.

Frontiers of Physics

short distance

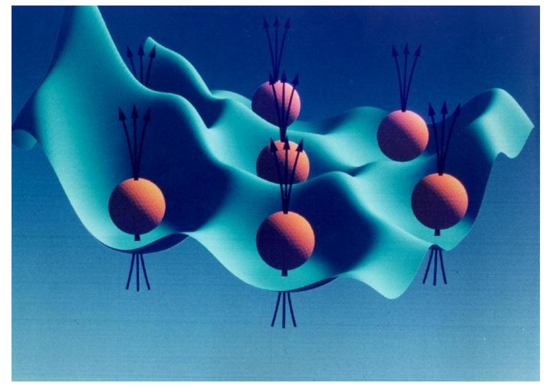


- Higgs boson
- Neutrino masses
- Supersymmetry
- Quantum gravity
- String theory

long distance

- Large scale structure
- Cosmic microwave background
- Dark matter
- Dark energy
- Gravitational waves

complexity



- “More is different”
- Many-body entanglement
- Phases of quantum matter
- Quantum computing
- Quantum spacetime