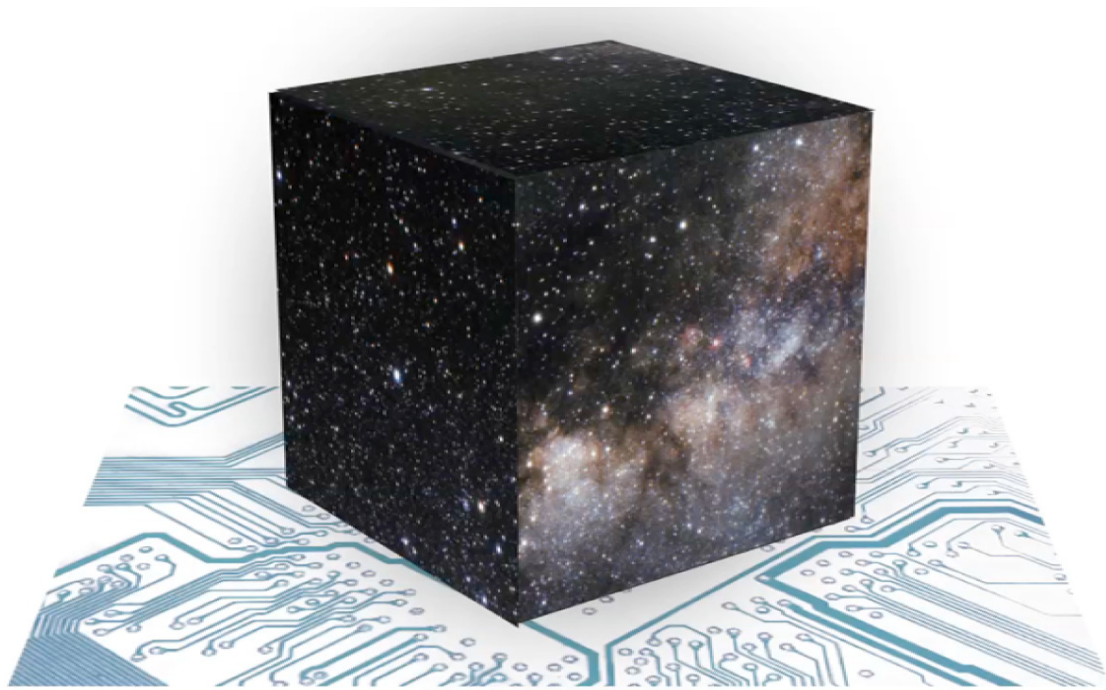
Our Quantum Future



INSTITUTE FOR QUANTUM INFORMATION AND MATTER

GORDON AND BETTY MOORE FOUNDATION

John Preskill

SQuInT Workshop

20 February 2016

SQuInt Kickoff Meeting, 18 December 1998, IBM Almaden (Isaac Chuang Photo)

17th Annual SQuInT Meeting, February 2015, Berkeley

Quantum information: its future impact on physics

John Preskill

SQUINT Kickoff Meeting
IBM Almaden Research Center
18 December 1998

I want to say a few words about the potential implications of quantum information theory for the future of physics. I feel that quantum information has earned a lasting and prominent place at the foundations of computer science. But at present it seems rather isolated from most of the rest of physics. I would like to see that change in the future. How might it change?

So I am selling a vision of the future in which quantum information secures it central position at the foundations of computer science, but also erects bridges that connect with precision measurement, condensed matter physics, quantum gravity, and other fields that we can only guess at today. And I advocate in particular a program to carry out a rich classification of the phases that can be exhibited by highly entangled many-body systems.

JOURNAL OF MODERN OPTICS, 2000, VOL. 47, NO. 2/3, 127–137

Quantum information and physics: some future directions

JOHN PRESKILL

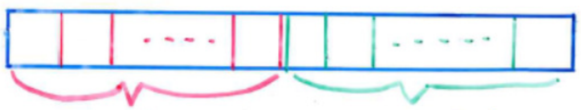
Lauritsen Laboratory of High Energy Physics, California Institute of Technology, Pasadena, CA 91125, USA

(*Received 7 April 1999*)

Abstract. I consider some promising future directions for quantum information theory that could influence the development of 21st century physics. Advances in the theory of the distinguishability of superoperators may lead to new strategies for improving the precision of quantum-limited measurements. A better grasp of the properties of multi-partite quantum entanglement may lead to deeper understanding of strongly-coupled dynamics in quantum many-body systems, quantum field theory, and quantum gravity.

Many-body entanglement

(A) A prototype: QECC (nondegenerate)



2t   n-2t

$\rho^{(2t)} \propto \mathbb{1}$

Information encoded globally

(B) Frustration $\Longrightarrow$ Entanglement

[FQHE, antiferro, ⋮]

• Ground state degen ~ $(a)^{\text{genus}}$

• Bulk entanglement $\Leftrightarrow$ edge excitations

– What other ways to characterize entangled ground states?

– How to use entanglement for Q.I. storage?

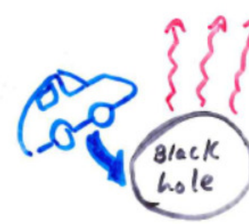
(C) Bulk-boundary interaction

Boundary excitation   antiferromagnetic spin chain $\exp\left[S_{\text{zero temp}}\right] \neq$ integer

(universal) entanglement

↑ UNIVERSAL!

(D) Holographic Universe!



Why does bulk physics seem local?

SQuInT Kickoff, 18 December 1998

Many-body entanglement

Ⓐ A prototype: QECC (nondegenerate)

$$\underbrace{\boxed{\;|\;|\;\cdots\;|\;}}_{2t}\underbrace{\boxed{\;|\;|\;\cdots\;|\;}}_{n-2t}$$

$\rho^{(2t)} \propto \mathbb{1}$

Information encoded globally

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[FQHE, antiferro, !]

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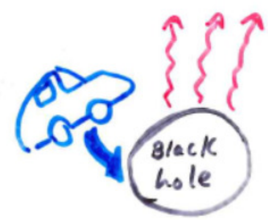


Why does bulk physics seem local?

I have the same ideas, 17 years later.

What are your ideas about the future impact of quantum information on physical science?

#SQuInT16

2. Quantum information theory and precision measurement

The connections between quantum information and precision measurement are explored in a separate article [6], which I will only summarize here.

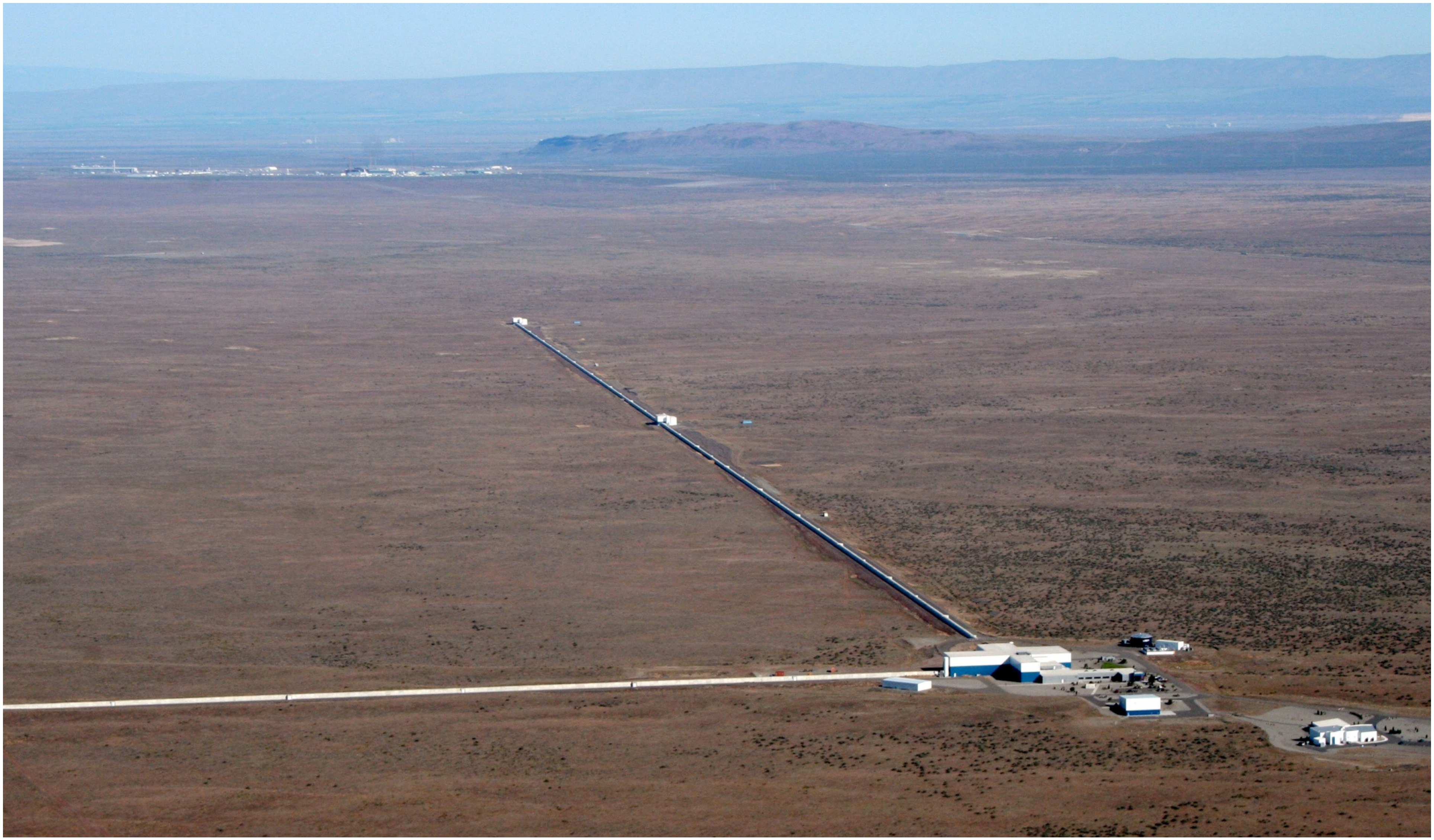
My own interest in the quantum limitations on precision measurement has been spurred in part by Caltech's heavy involvement in the LIGO project, the Laser Interferometer Gravitational-Wave Observatory [7]. LIGO is scheduled to begin collecting data in 2002, and a major upgrade is planned for two years later, which will boost the optical power in the interferometer and improve the sensitivity. In its most sensitive frequency band, the LIGO II observatory will actually be operating at the standard quantum limit (SQL) for detection of a weak classical force by monitoring a free mass. (In this case, the SQL corresponds to a force that nudges an 11 kg mass by about 10^{-17} cm at a frequency of 100 Hz.)

Then within another 4 years (by 2008), another upgrade is expected, which will boost the sensitivity in the most critical frequency band beyond the SQL. Even an improvement by a factor of two can have a very significant pay-off, for a factor of two in sensitivity means a factor of 8 in event rate. But the design of the LIGO III detection system is still largely undecided—clever innovations will be needed. So Big Science will meet quantum measurement in the first decade of the new century, and ideas from quantum information theory may steer the subsequent developments in detection of gravitational waves and other weak forces.

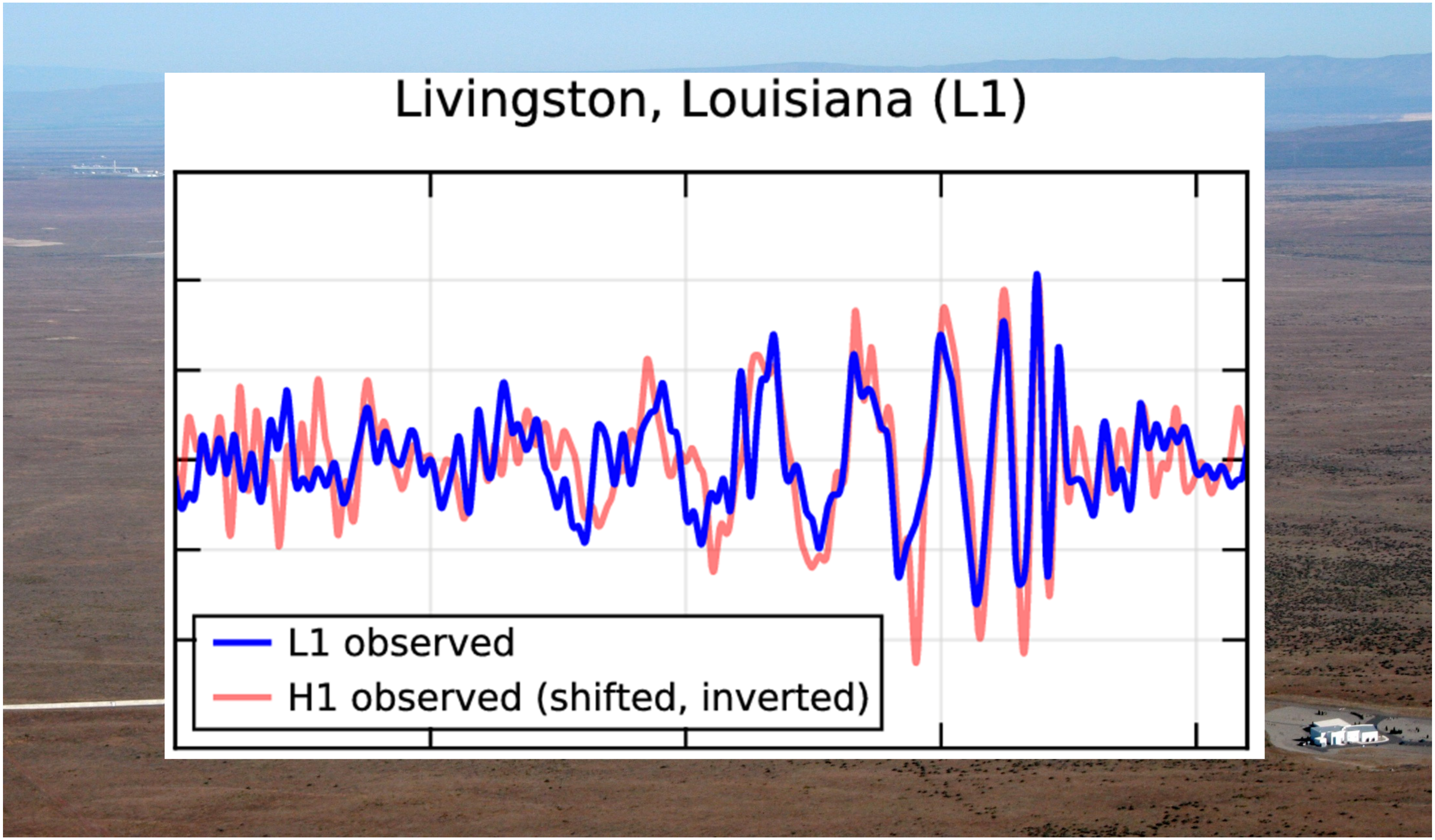
LIGO!

GW150914

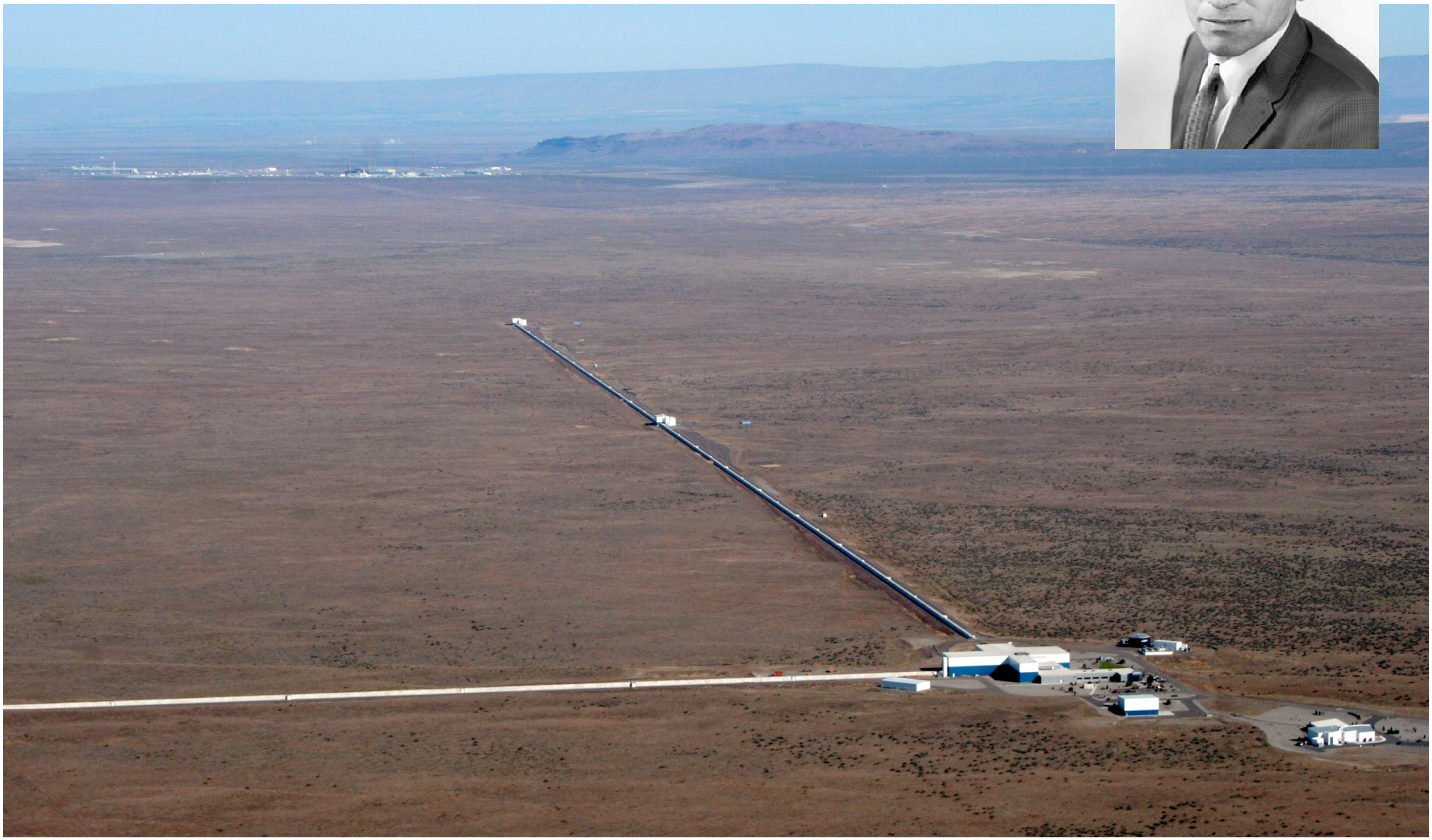
LIGO!



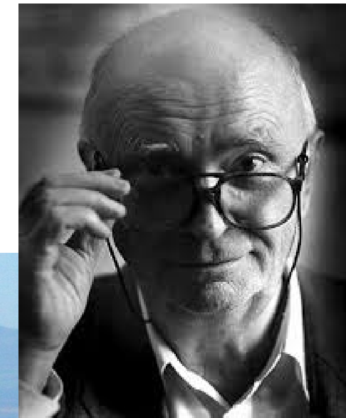
LIGO!

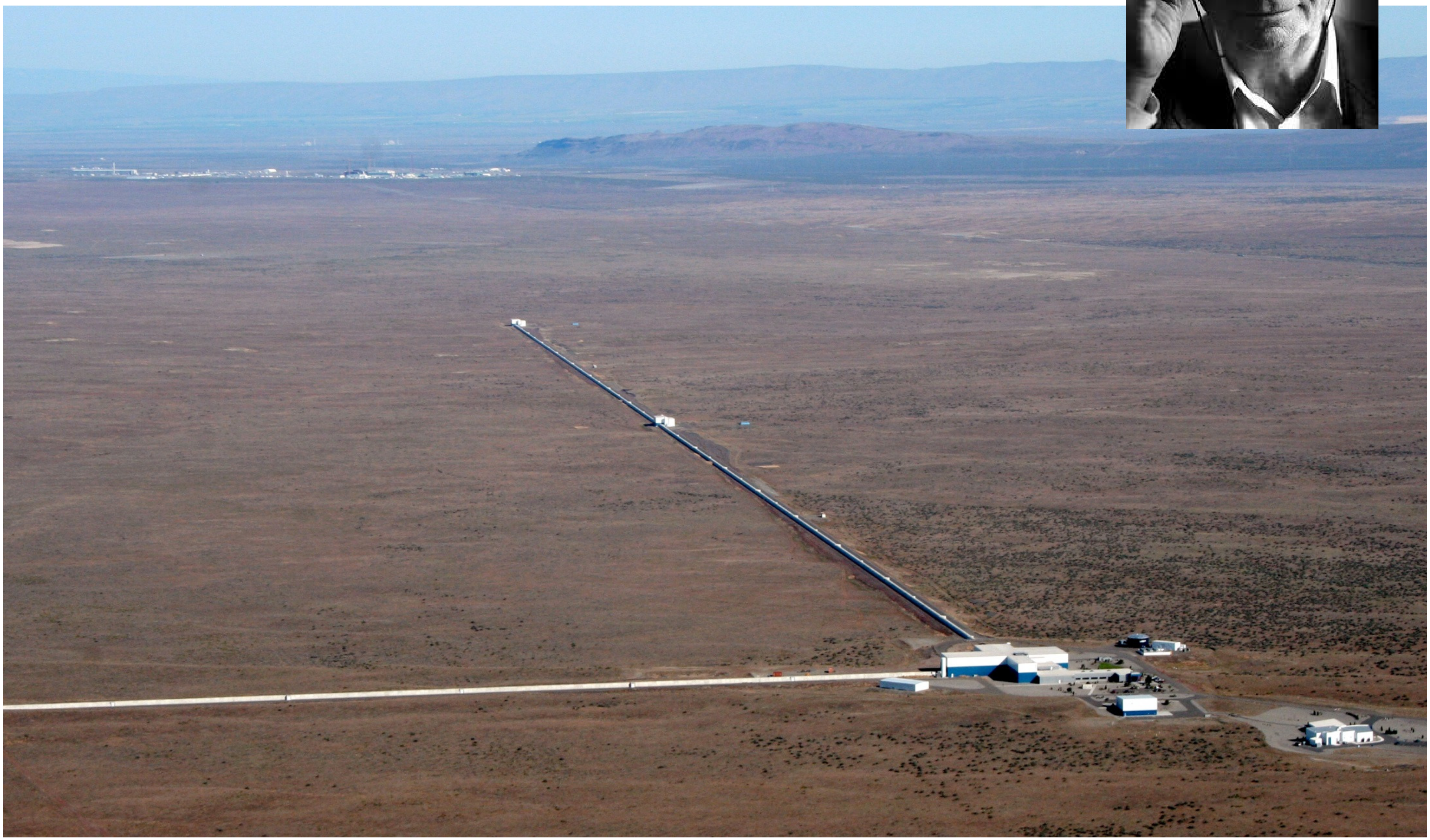

Livingston, Louisiana (L1)
L1 observed
H1 observed (shifted, inverted)

Joe Weber audaciously believed gravitational waves can be detected on earth.

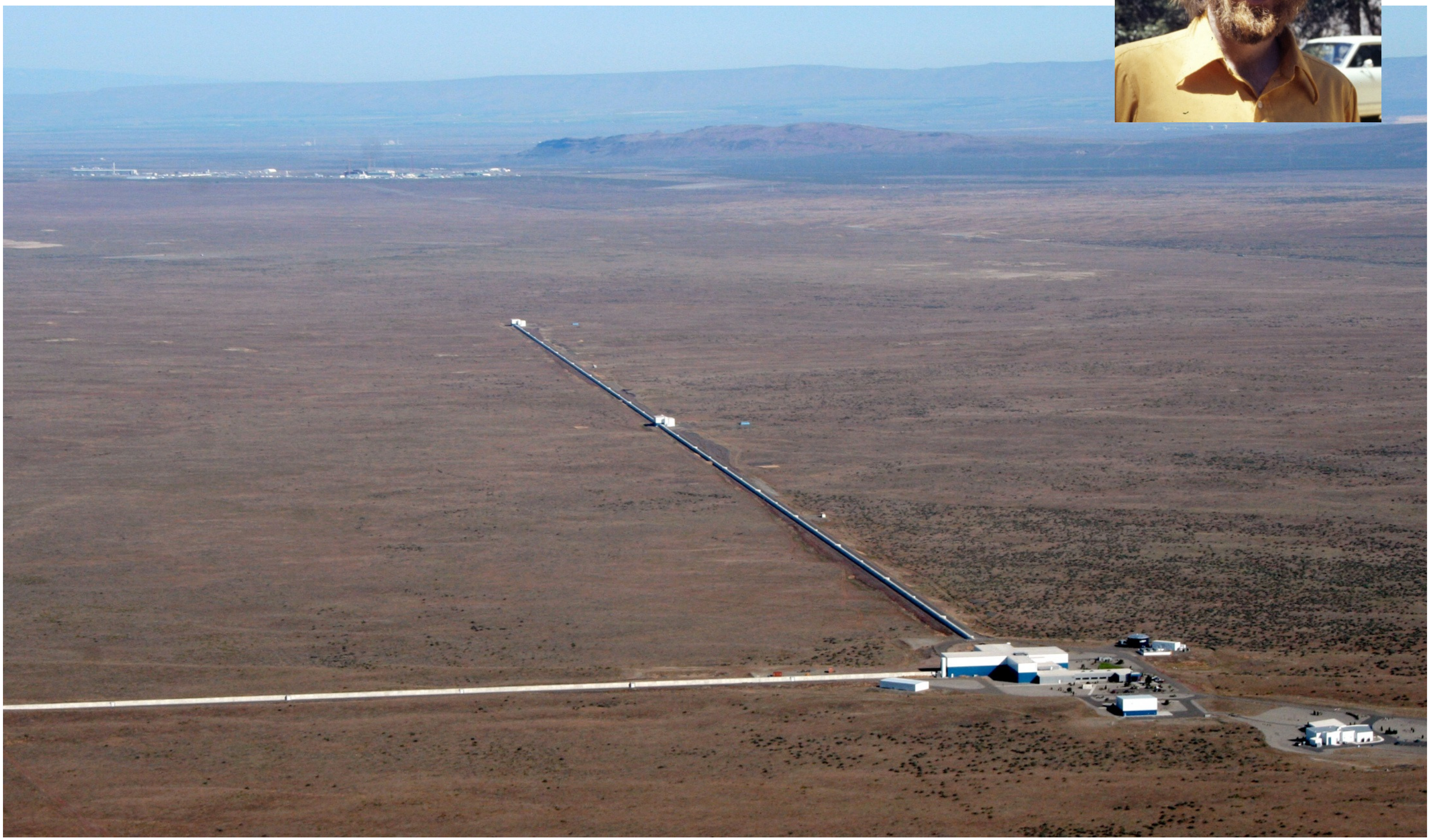


Vladimir Braginsky realized that quantum effects limit the precision of gravitational wave detectors.

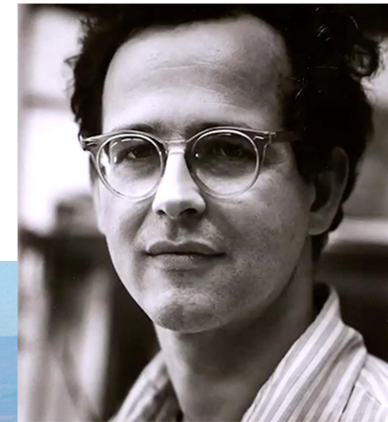


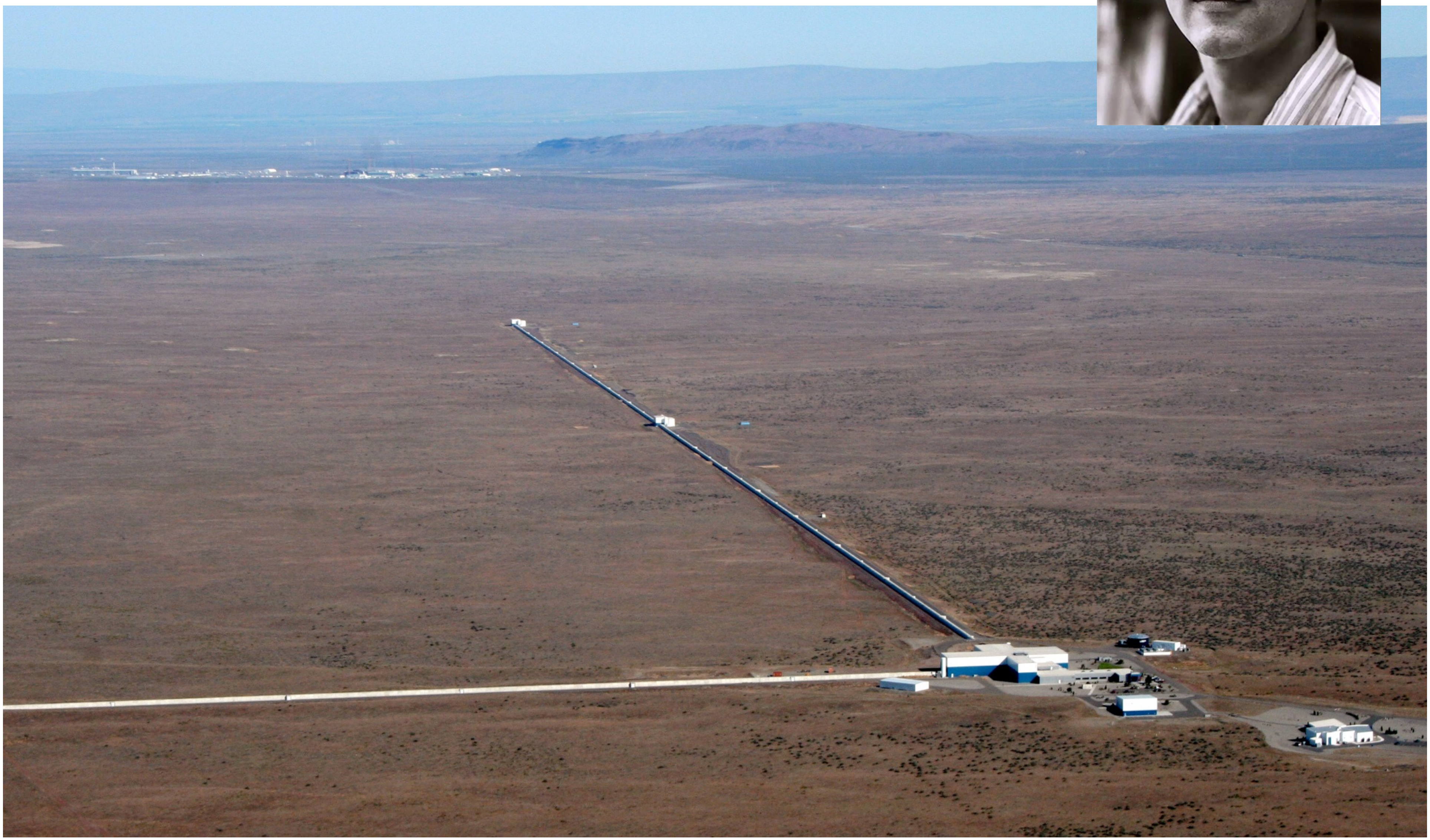


Kip Thorne foresaw that strain sensitivity 10^{-21} would be needed for successful detection.

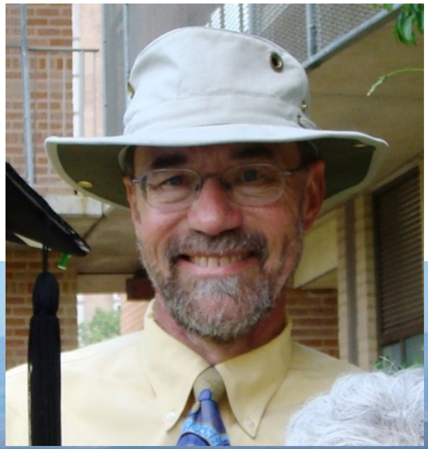


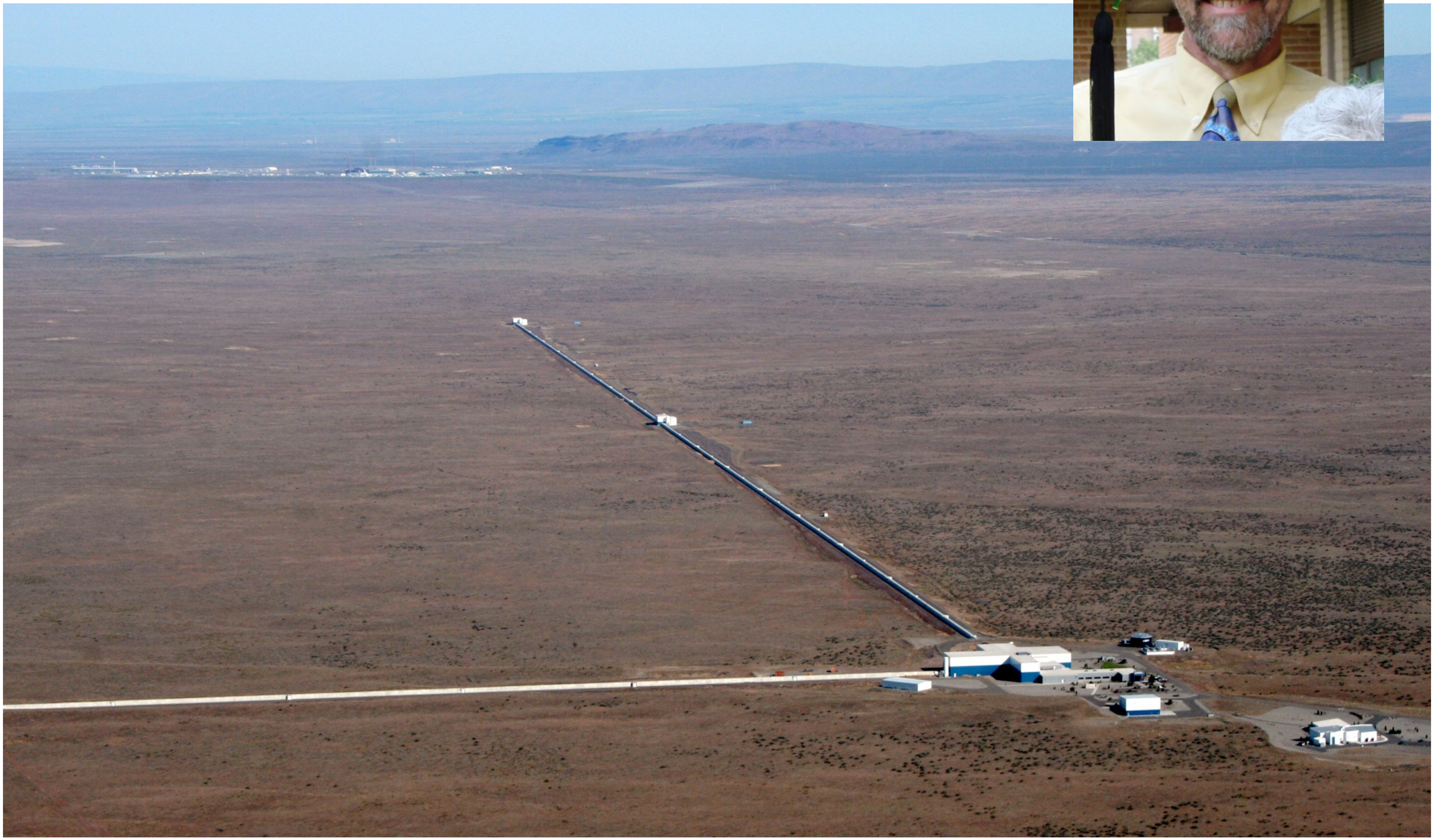
Rai Weiss invented LIGO in 1972.



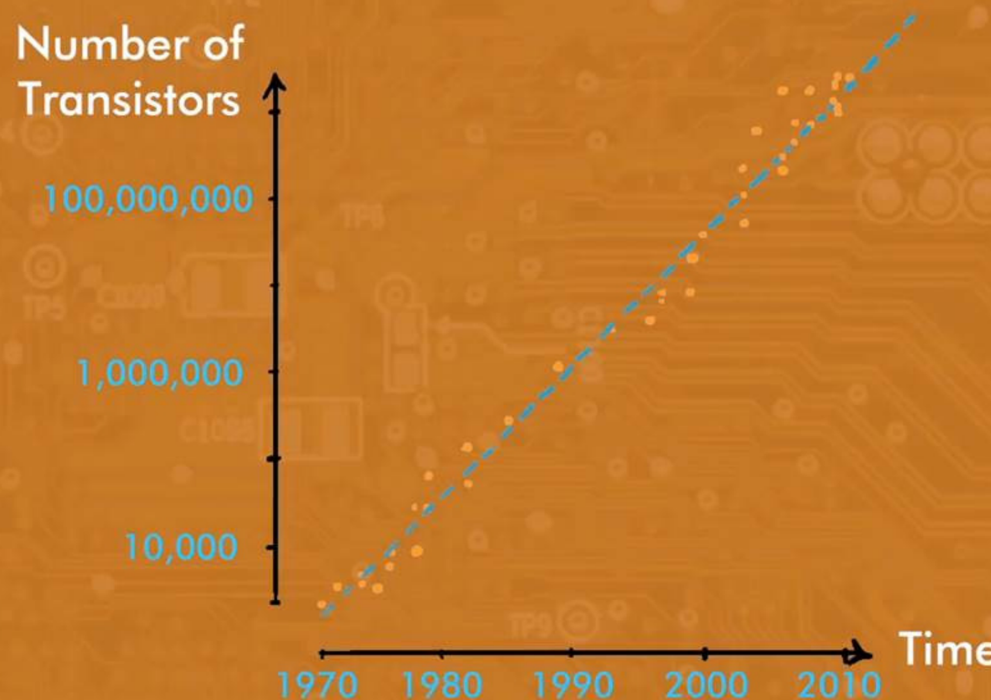


Surpassing the standard quantum limit
with squeezed light (Caves 1981).





Moore's Law

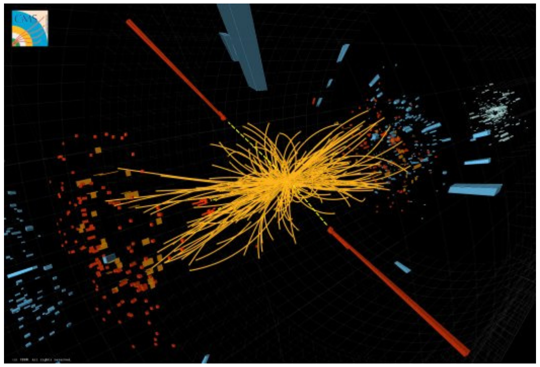
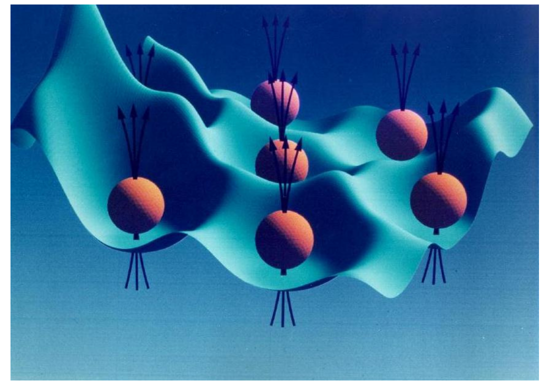


Number of Transistors
100,000,000
1,000,000
10,000
Time
1970
1980
1990
2000
2010


Google
IBM
hp
Raytheon
LOCKHEED MARTIN
intel
NORTHROP GRUMMAN
Microsoft

Quantum Summit, Caltech, 27 January 2016
IQIM YouTube Channel

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

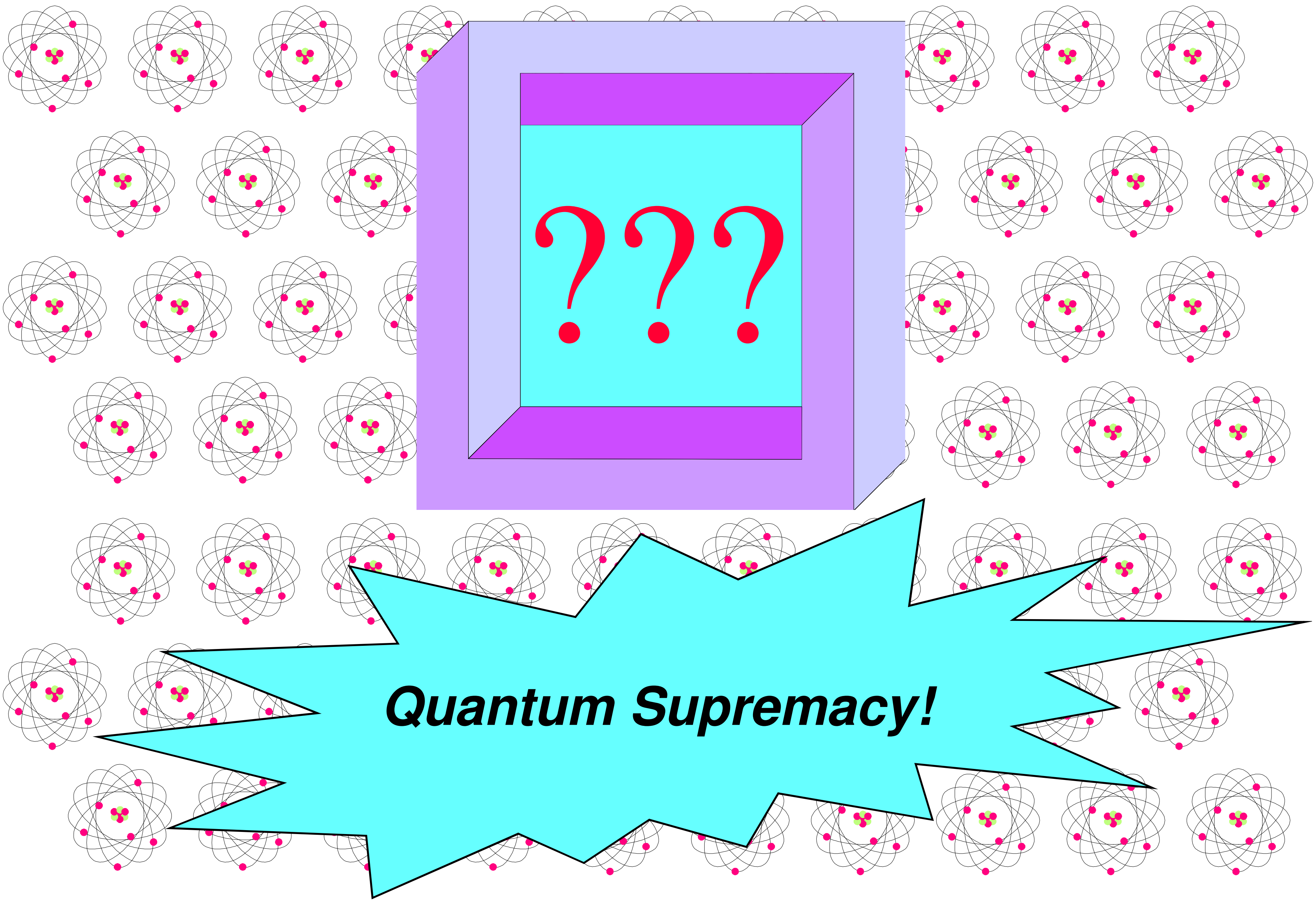
Can we control complex quantum systems and if so what are the scientific and technological implications?

(104 characters)

Can we control complex quantum systems and if so what are the scientific and technological implications?

How would *you* distill the essence of quantum information science to just one (tweetable) question?

#SQuInT16


???
Quantum Supremacy!

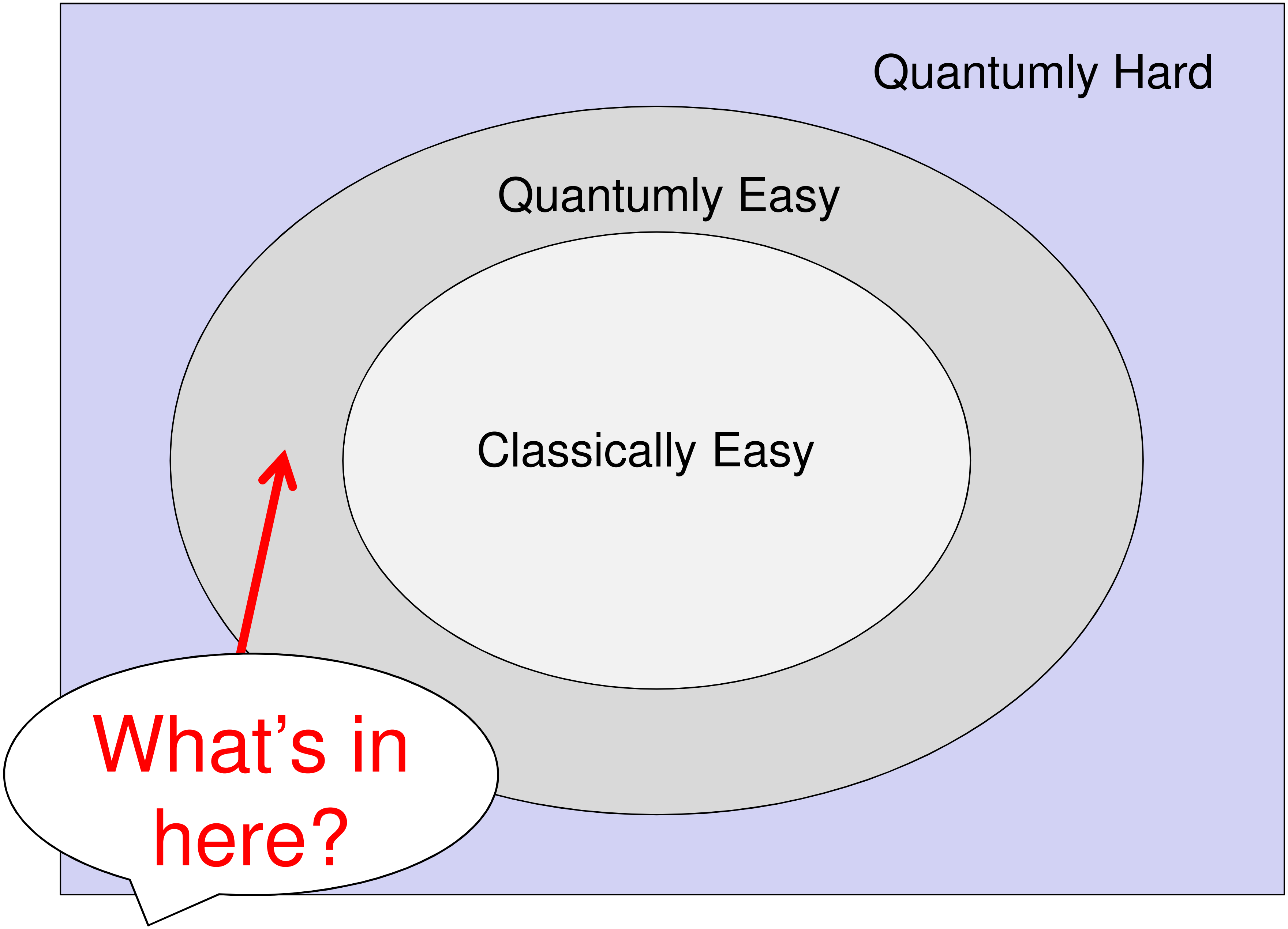
If not "quantum supremacy" then what should we call it?

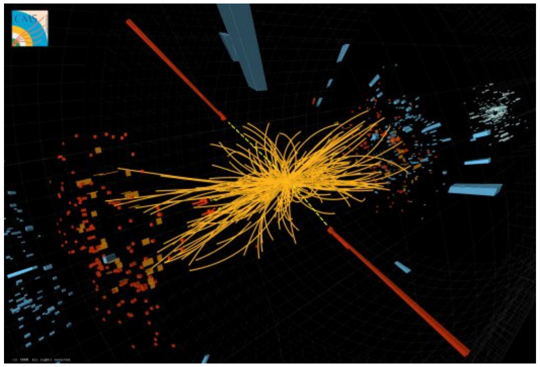
#SQuInT16

"Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical."

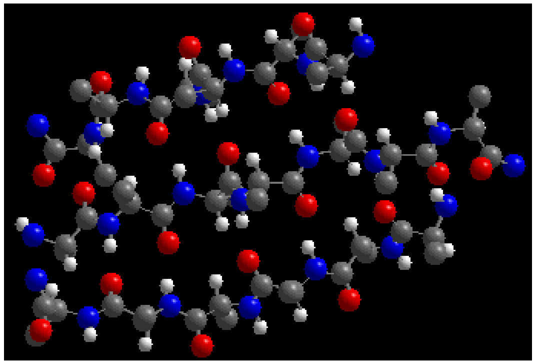
Caltech Course 1983-84: Potentialities and Limitations of Computing Machines

Problems

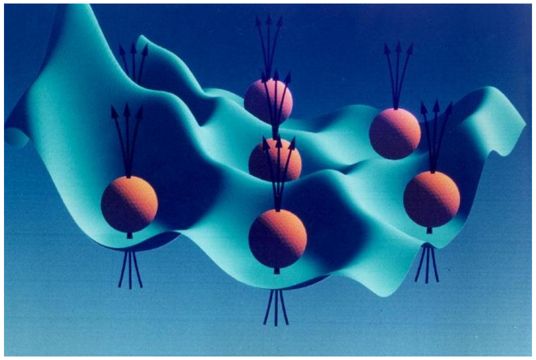

Quantumly Hard
Quantumly Easy
Classically Easy
What's in here?



particle collision



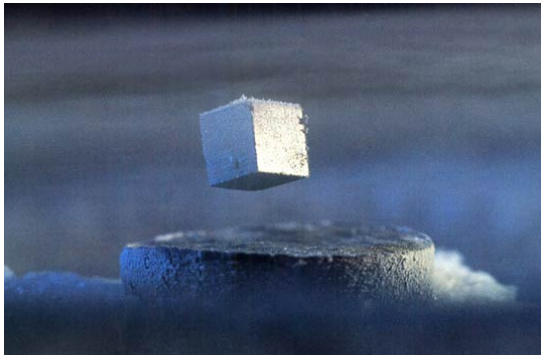
molecular chemistry



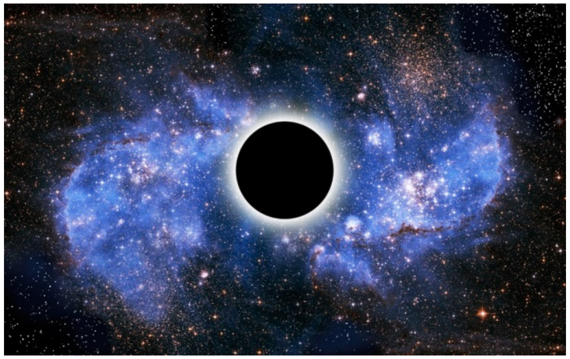
entangled electrons

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

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?

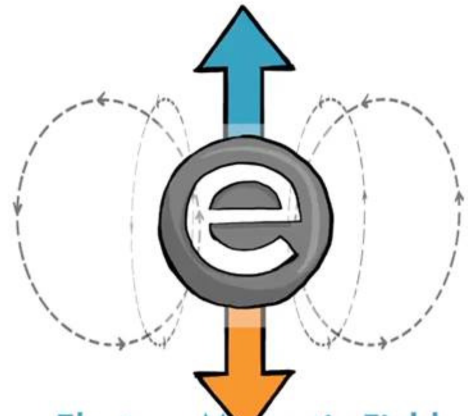
Using quantum error correction, we can overcome the damaging effects of noise at a reasonable overhead cost.

3. *How* will we build one?

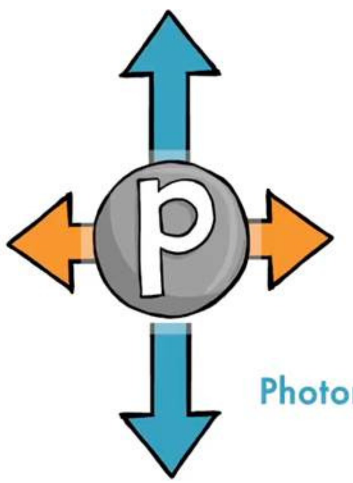
What kind of quantum hardware is potentially scalable to large systems?

QUBIT

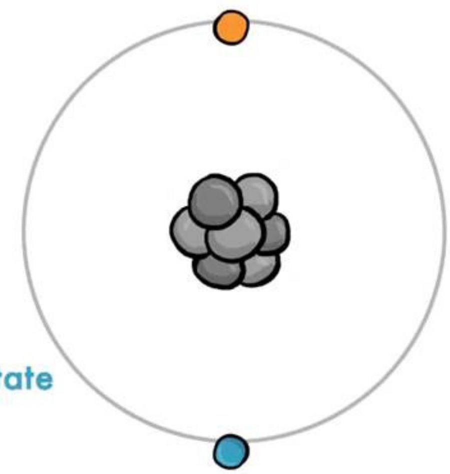
Persistent current in a superconducting circuit



Electron Magnetic Field

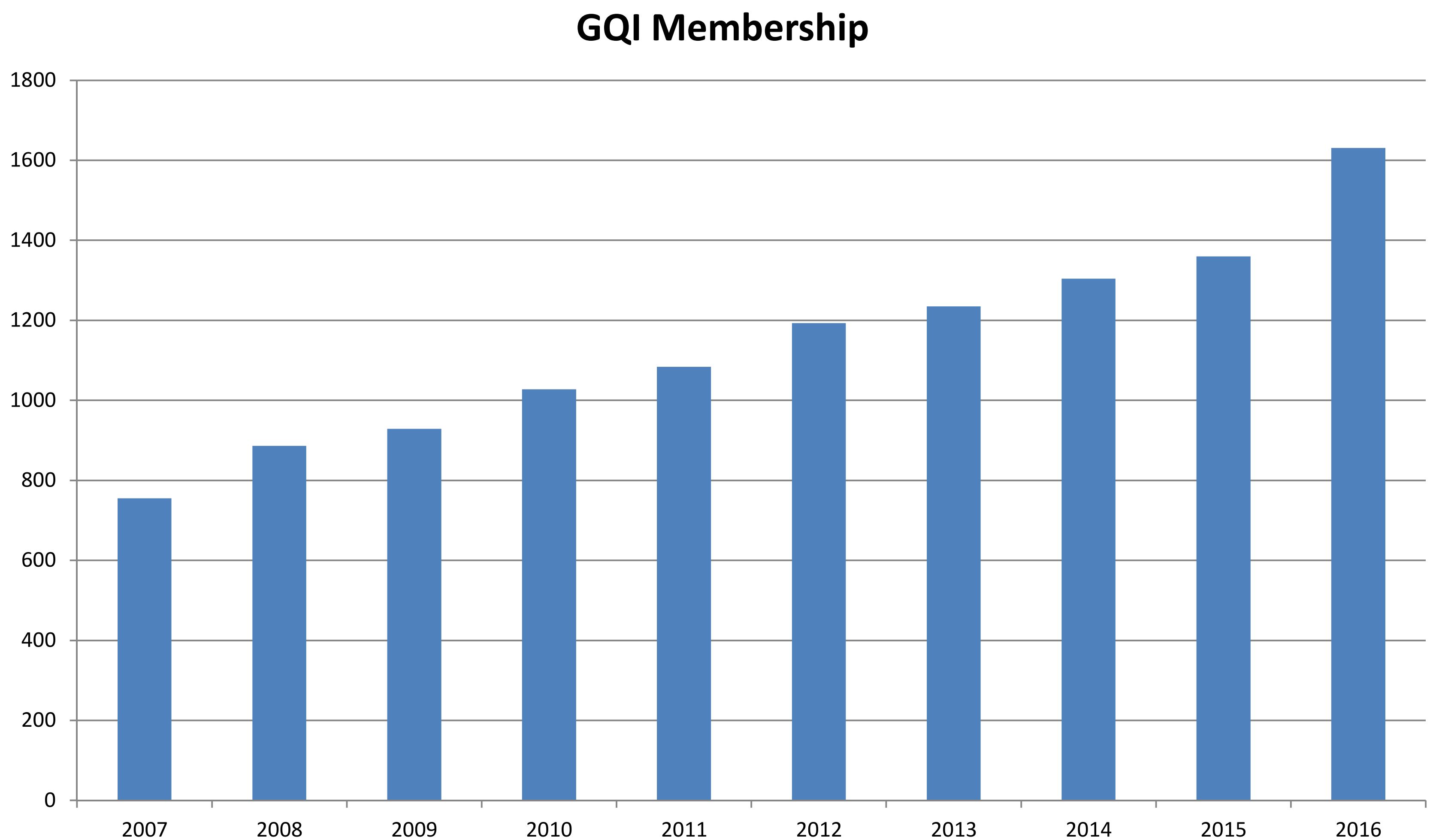


Photon polarization



Atom Internal State

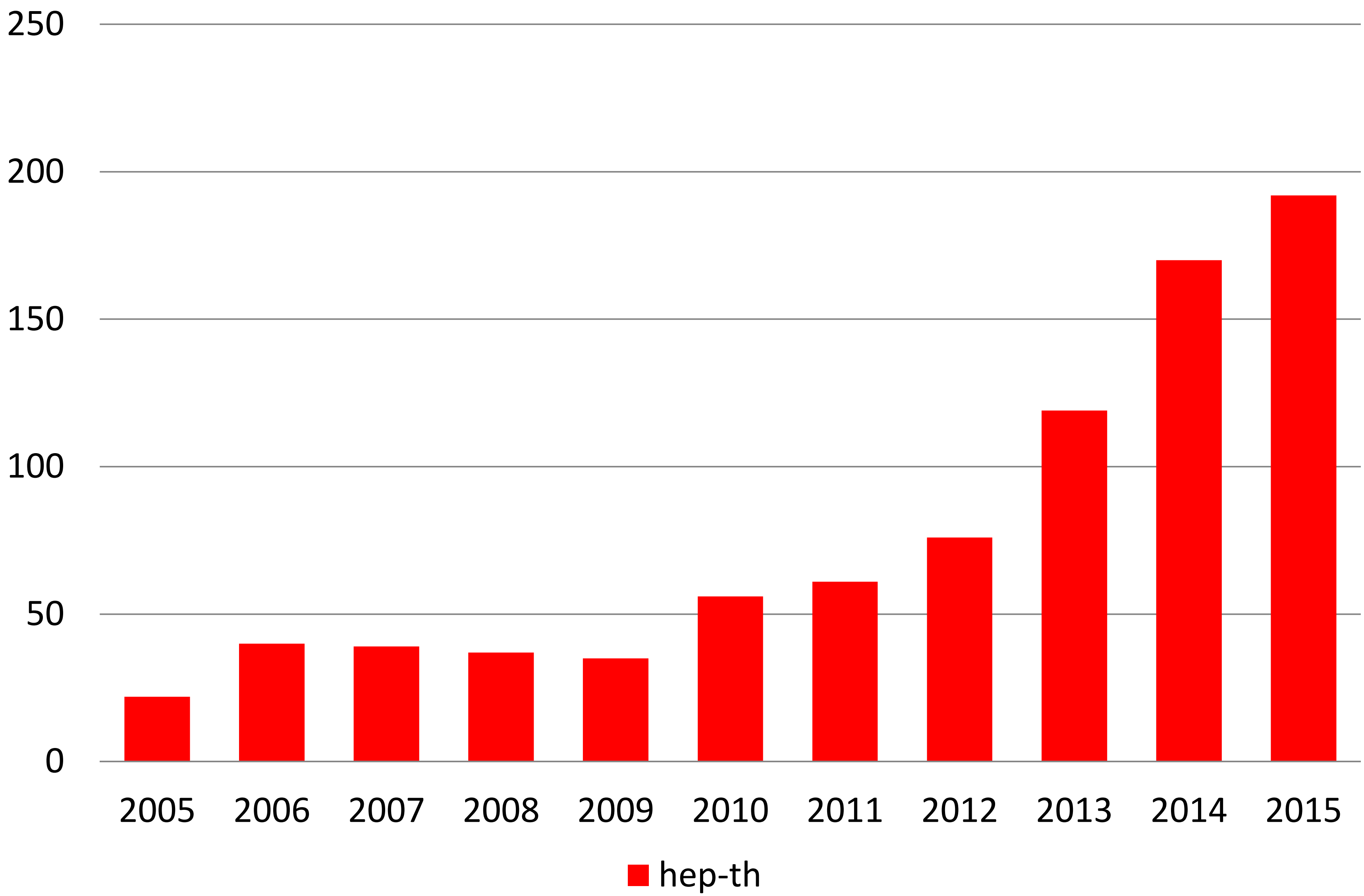
APS Topical Group on Quantum Information

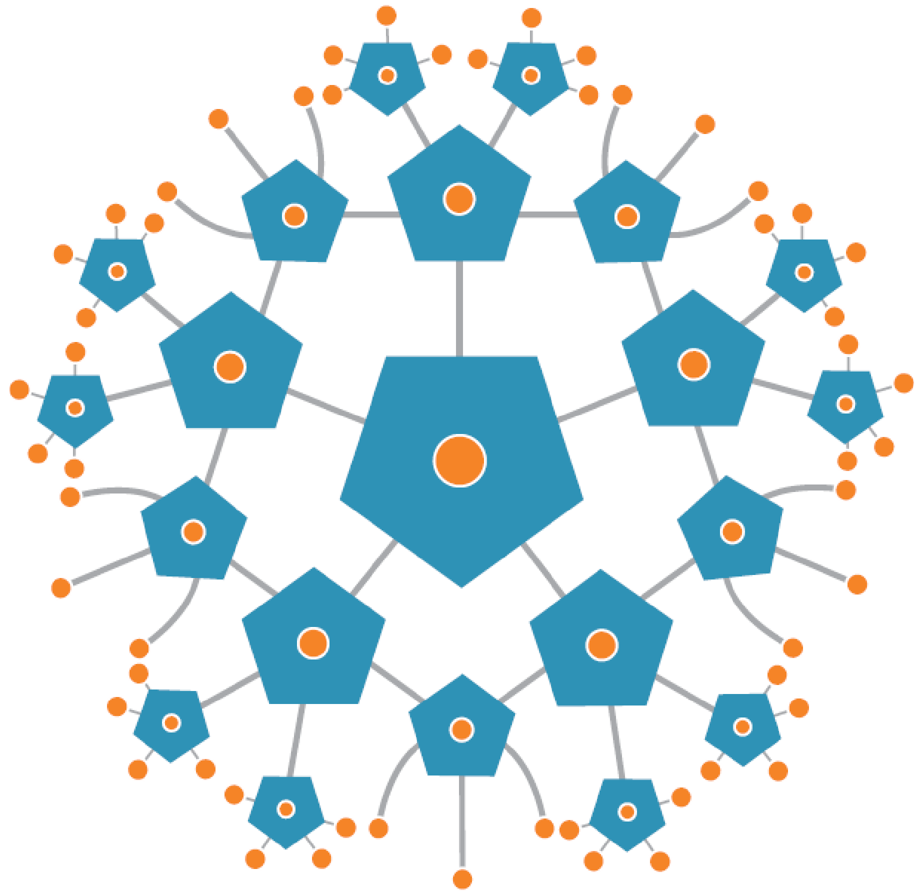


http://www.aps.org/membership/units/statistics.cfm

(Founded 2005. Membership is 57% students.)

hep-th papers with “entanglement” in the title





One Entangled Evening

A Celebration of Feynman's Quantum Legacy

TUESDAY, JANUARY 26, 2016


QUANTUM CARD
Quantum Encryption

Can classical public key cryptosystems be resistant to quantum attacks?

Can classical public key cryptosystems be resistant to quantum attacks?

Lattice based.

McEliece.

Other.

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).

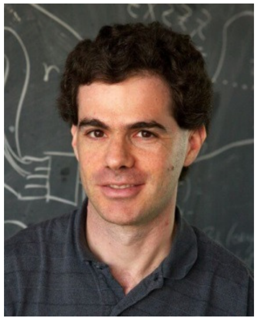
PRL 109, 070503 (2012) PHYSICAL REVIEW LETTERS week ending 17 AUGUST 2012

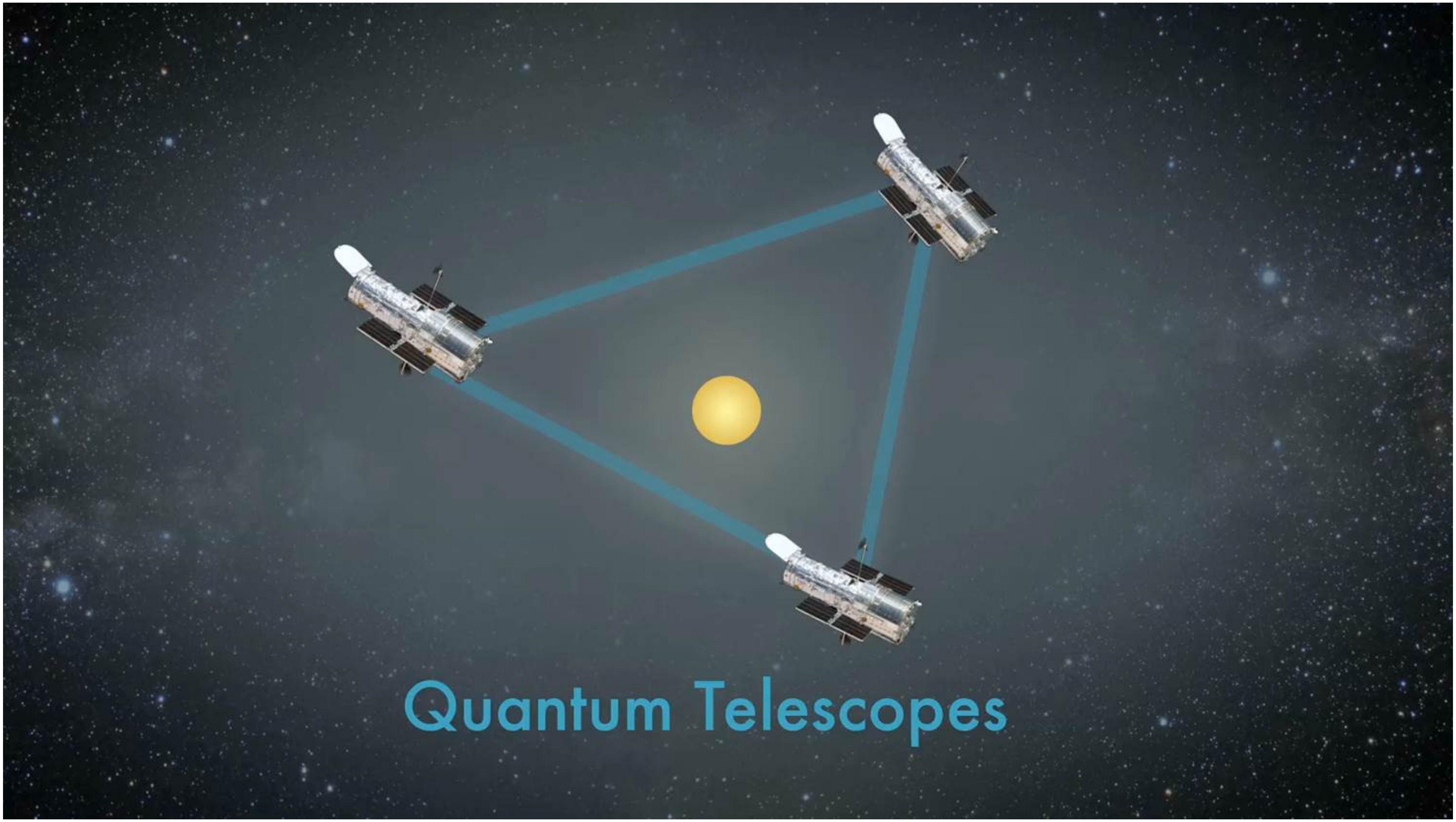
Longer-Baseline Telescopes Using Quantum Repeaters

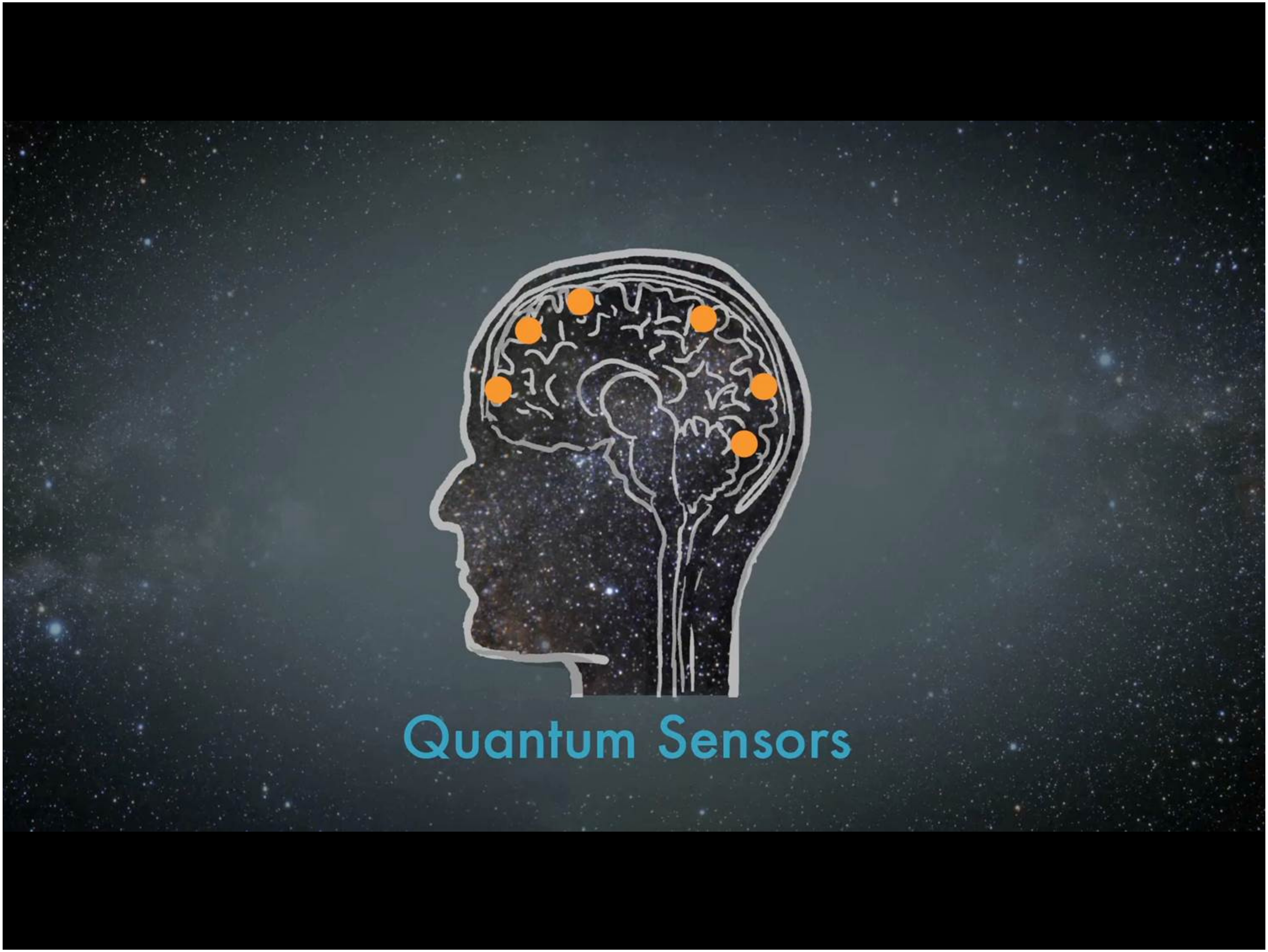
Daniel Gottesman*
Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada

Thomas Jennewein†
Institute for Quantum Computing, University of Waterloo, Waterloo, Ontario, Canada

Sarah Croke‡
Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada



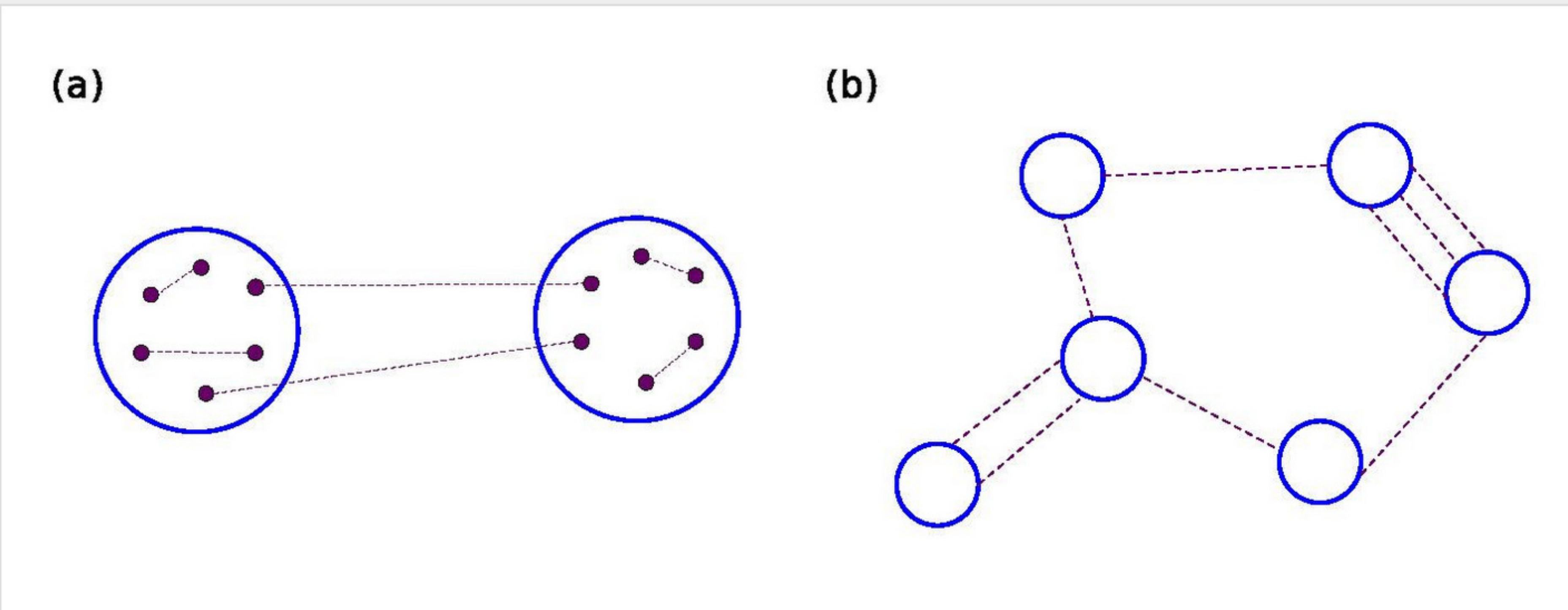



Quantum Sensors

Quantum cognition: The possibility of processing with nuclear spins in the brain

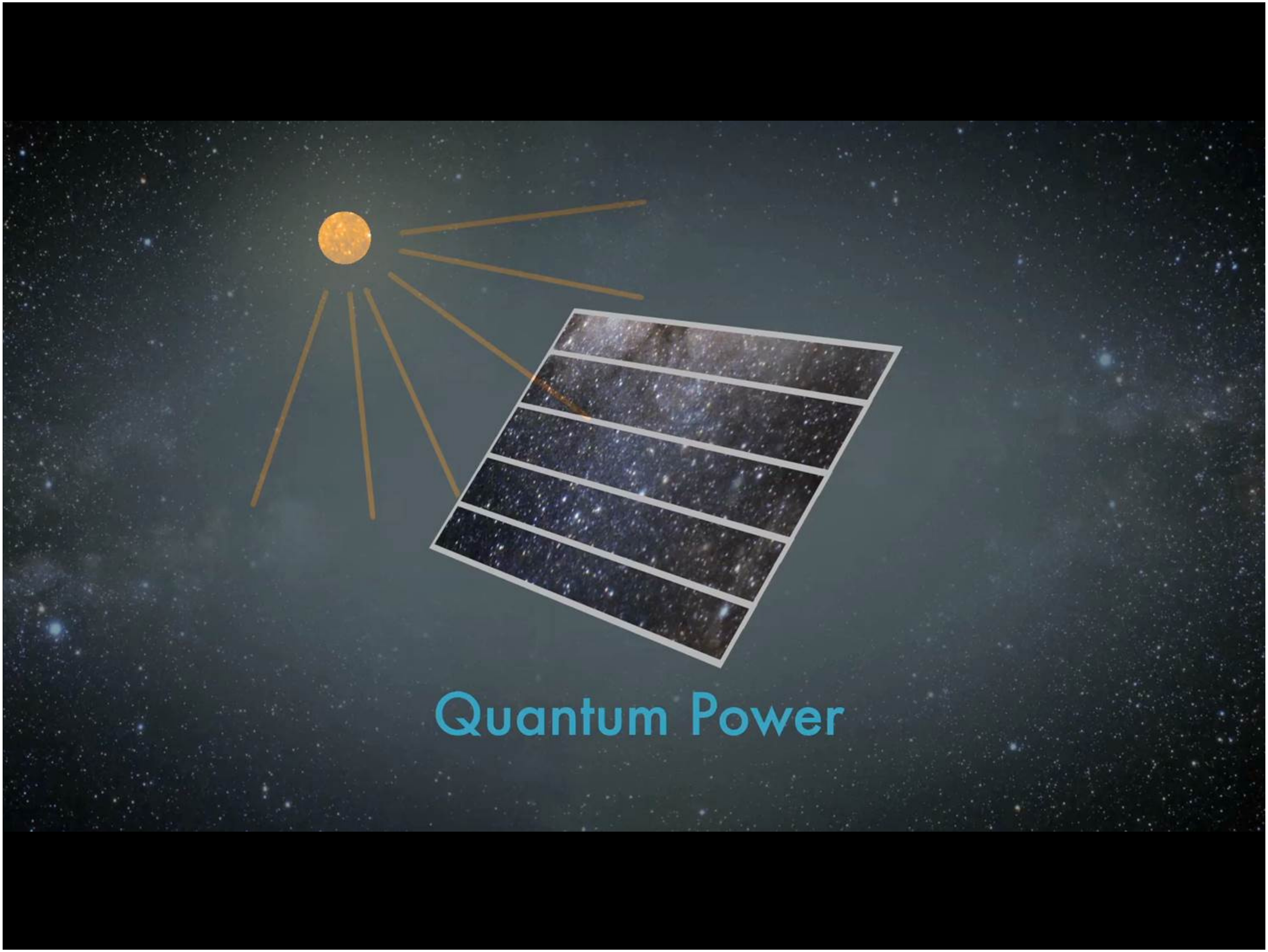
Matthew P.A. Fisher

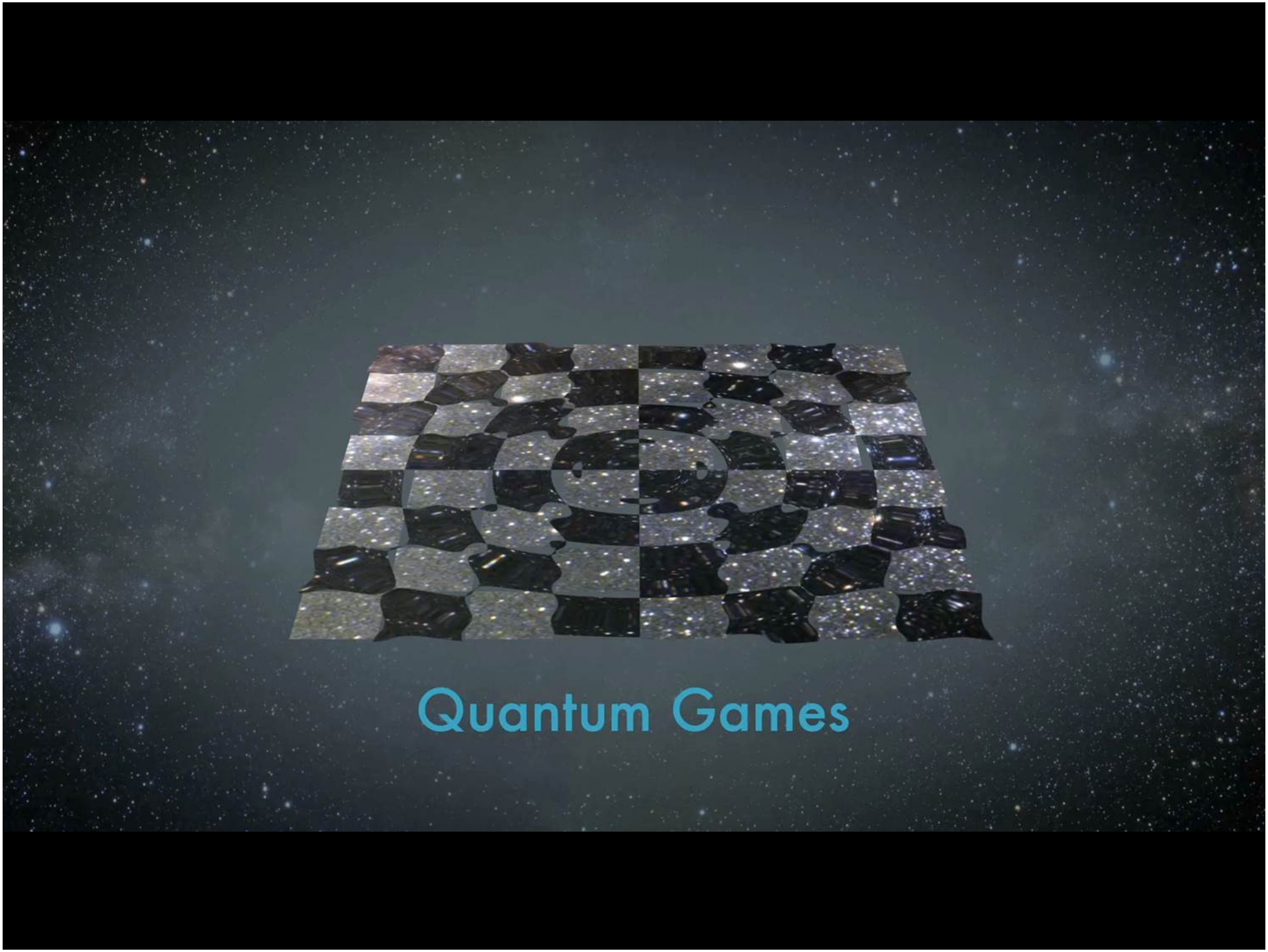
Department of Physics, University of California, Santa Barbara, CA 93106, United States

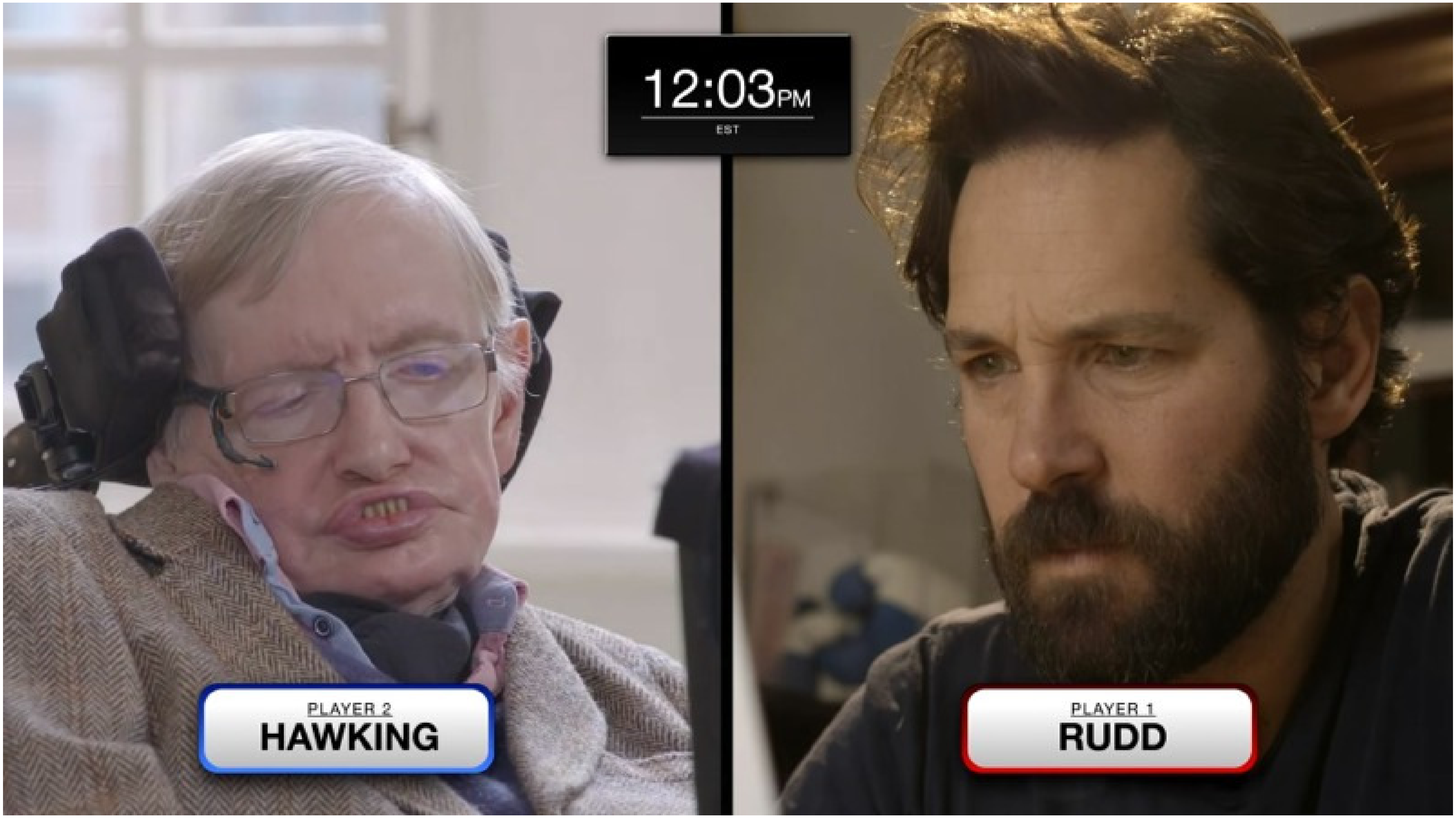


— (a) Two entangled Posner clusters. Each dot is a P-31 nuclear spin, and each dashed line represents a singlet pair. (b) Many entangled Posner clusters. [From Fisher 2015]

http://quantumfrontiers.com/2015/11/06/wouldnt-you-like-to-know-whats-going-on-in-my-mind/


Quantum Power


Quantum Games



Anyone Can Quantum

http://iqim.caltech.edu/one-entangled-evening/

IQIM
INSTITUTE FOR QUANTUM INFORMATION AND MATTER

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.

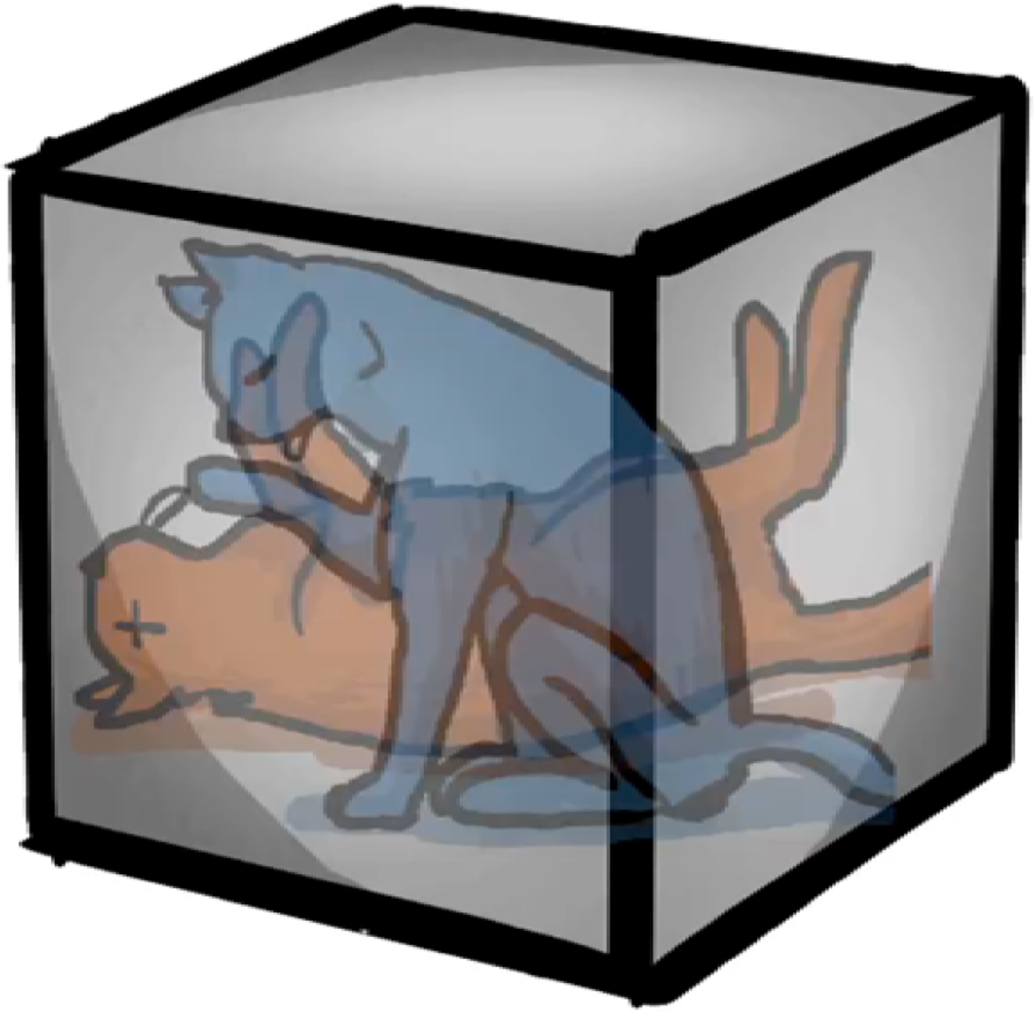
Quantum repeaters.

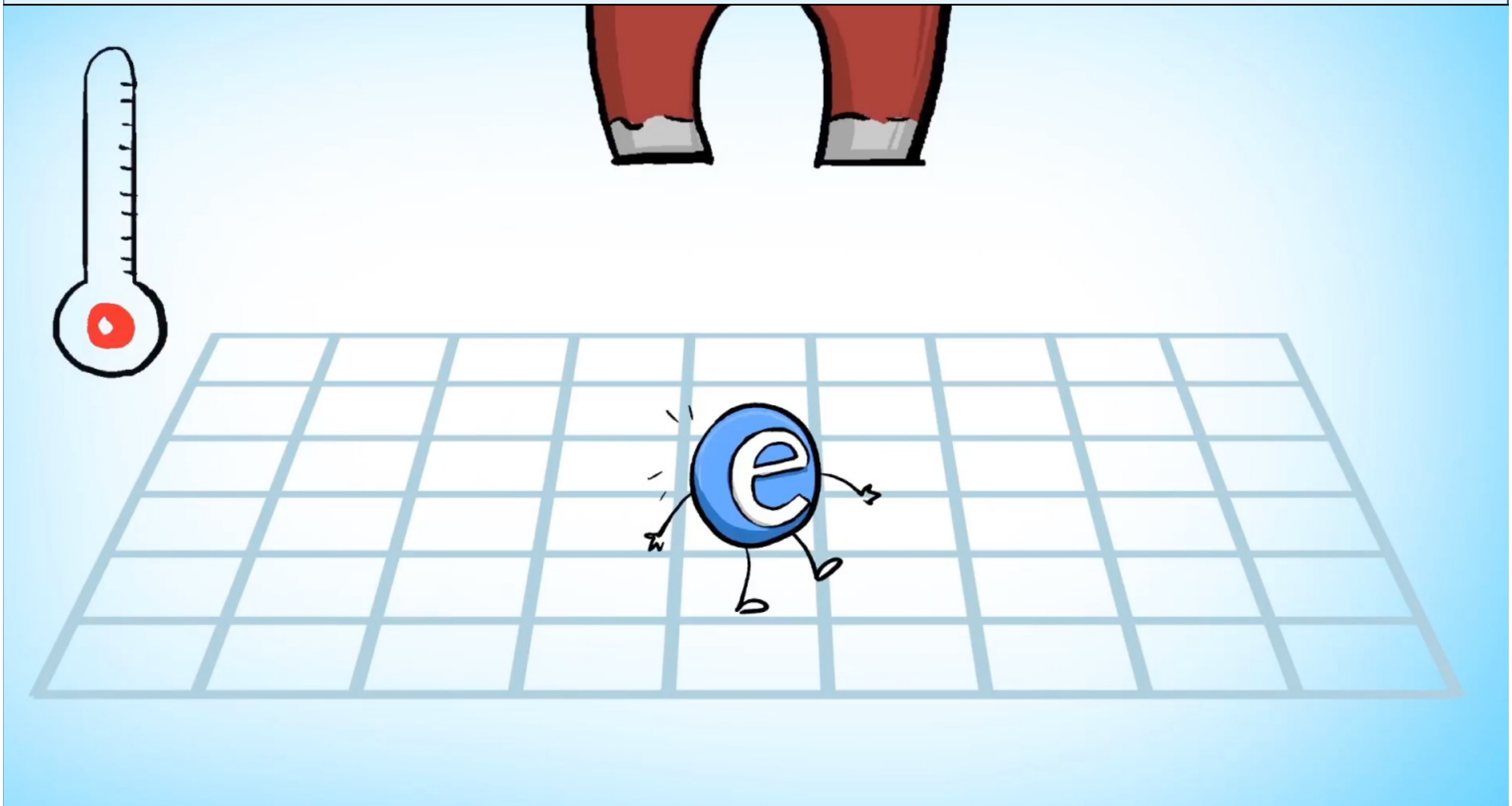
Entangled clocks and sensors.

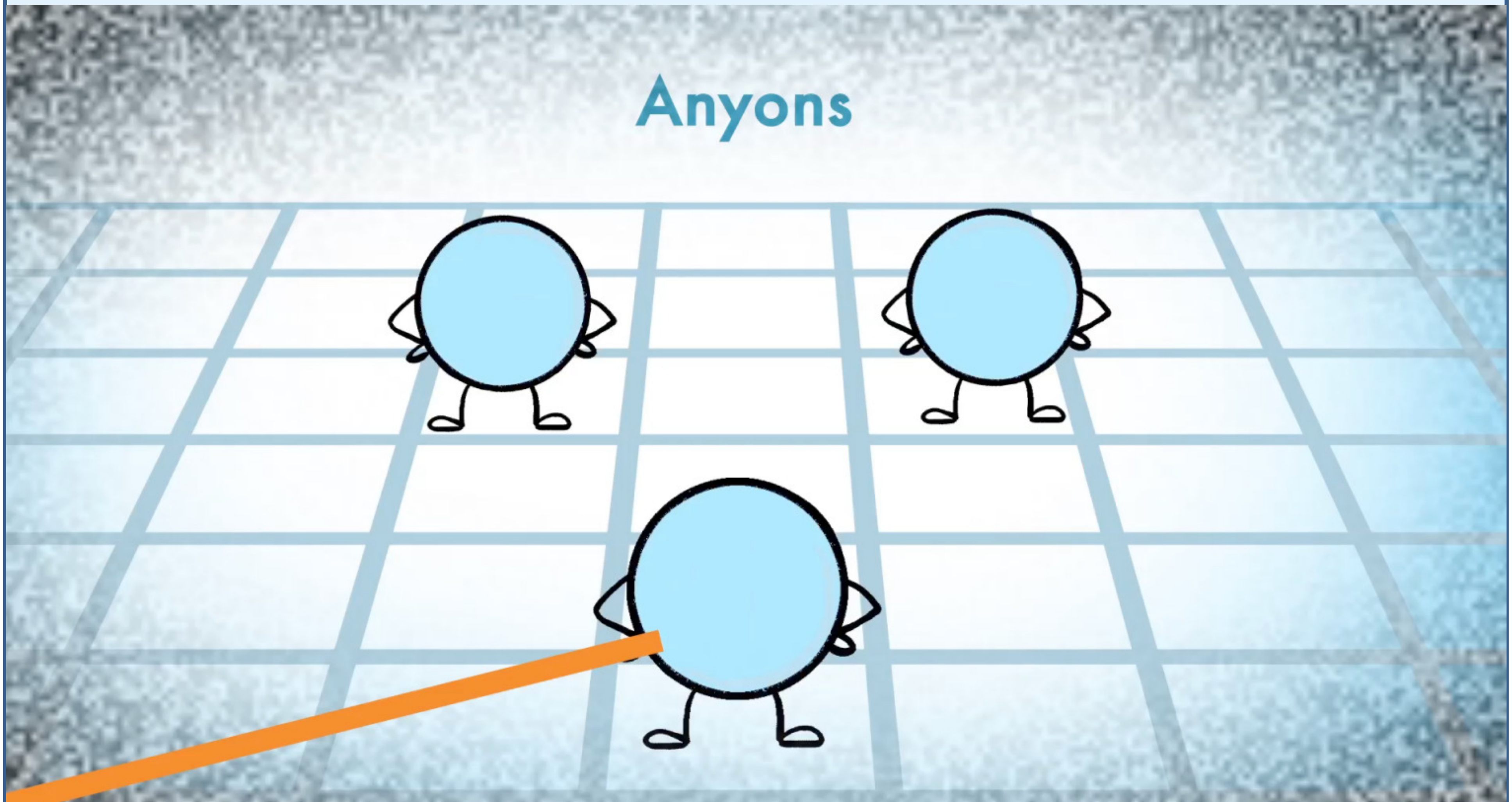
Quantum simulation.

Quantum annealing.

Can we build a quantum hard drive?



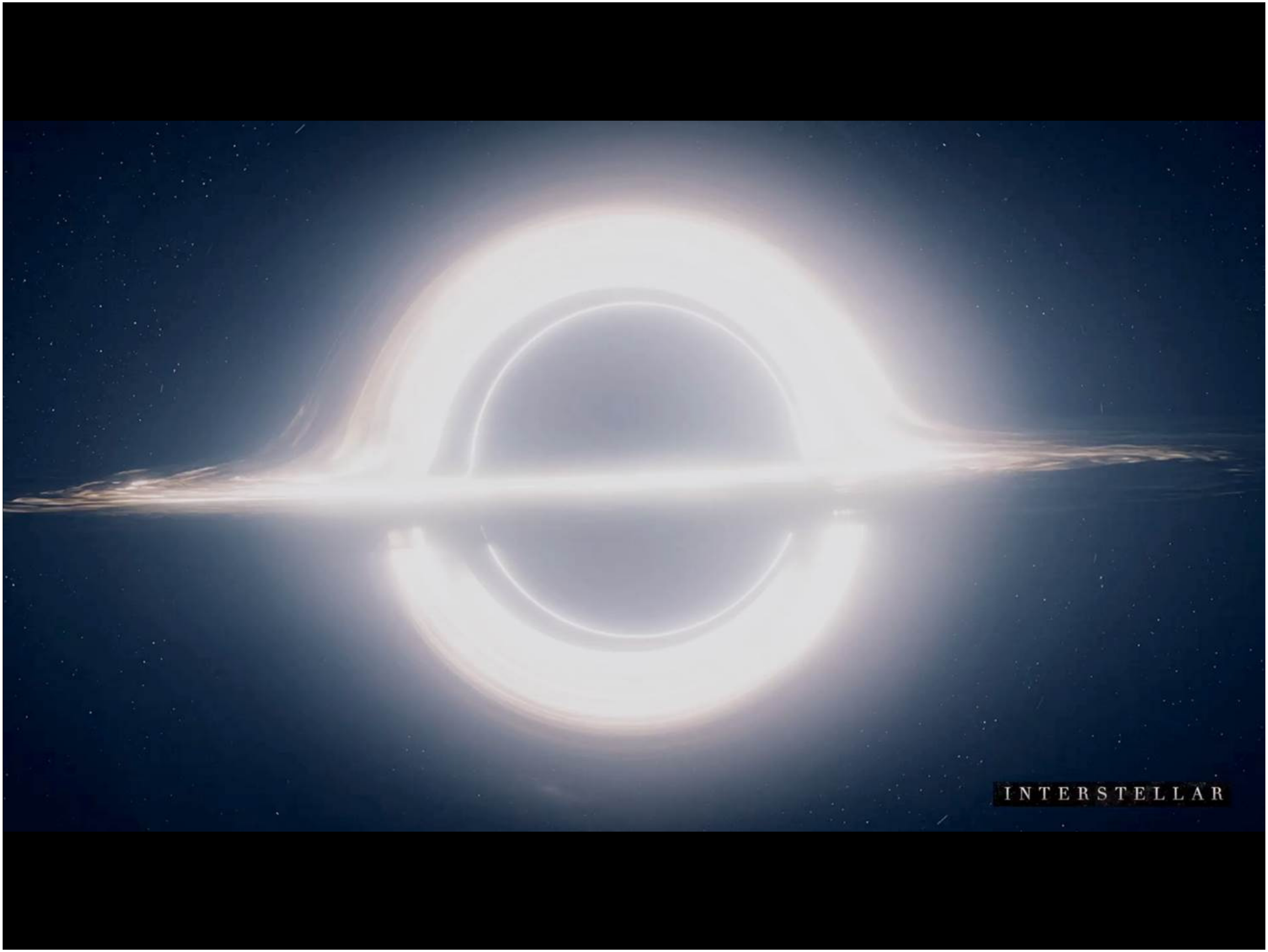


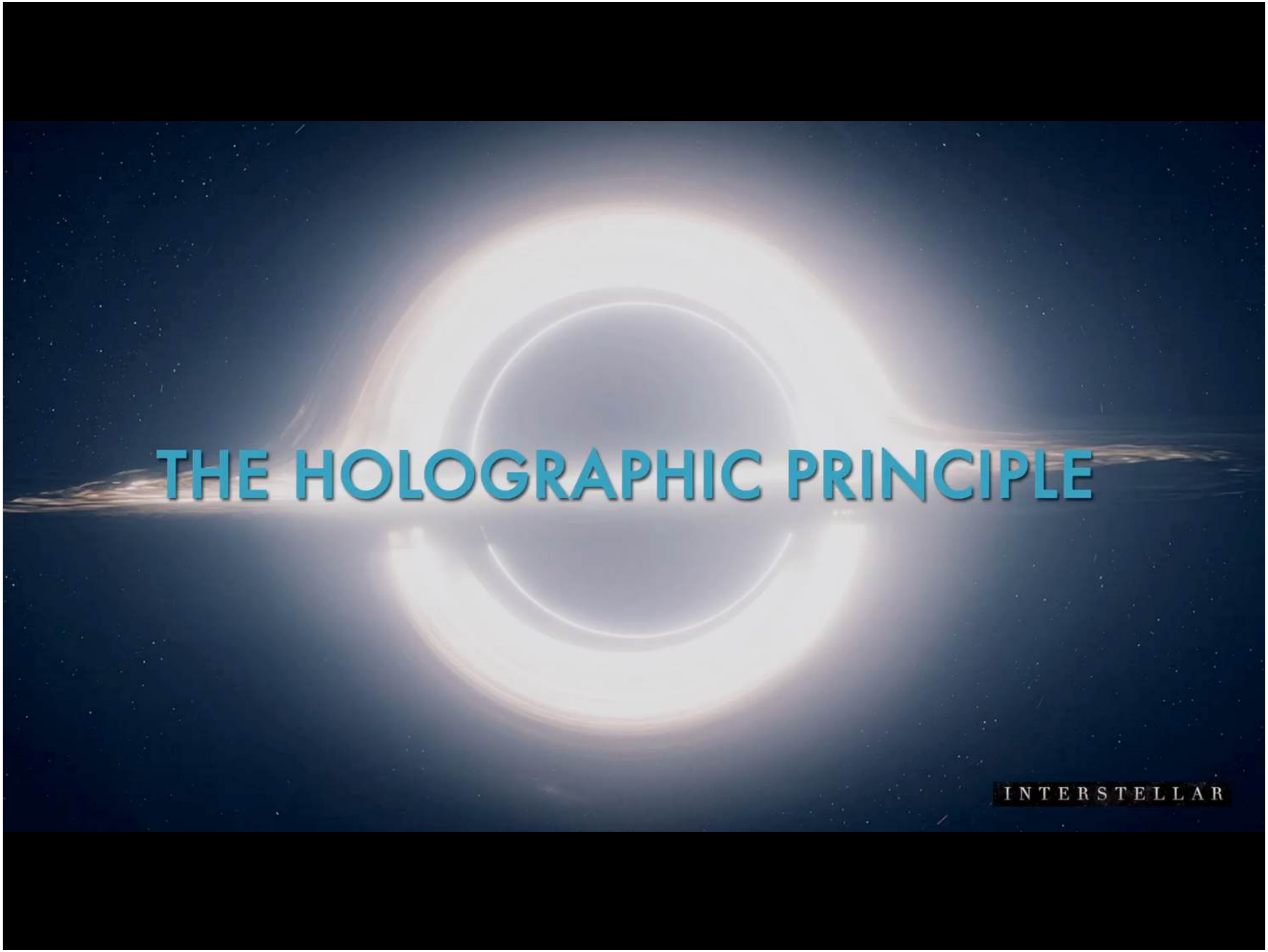

Anyons

Self-correcting quantum memory

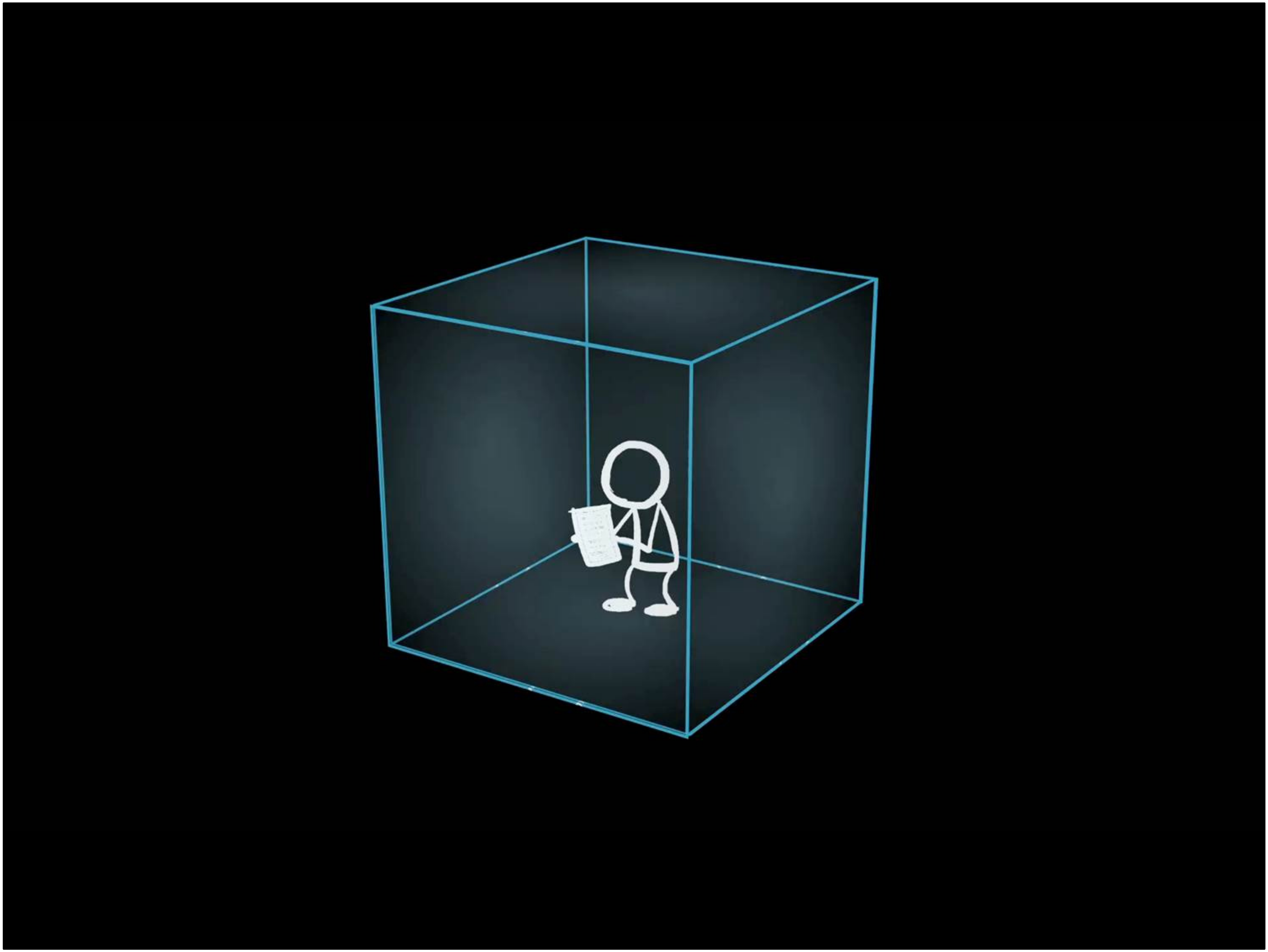
1) Finite-dimensional spins.
2) Bounded-strength local interactions.
3) Nontrivial codespace.
4) Perturbative stability.
5) Efficient decoding.
6) Exponential memory time at nonzero temperature.

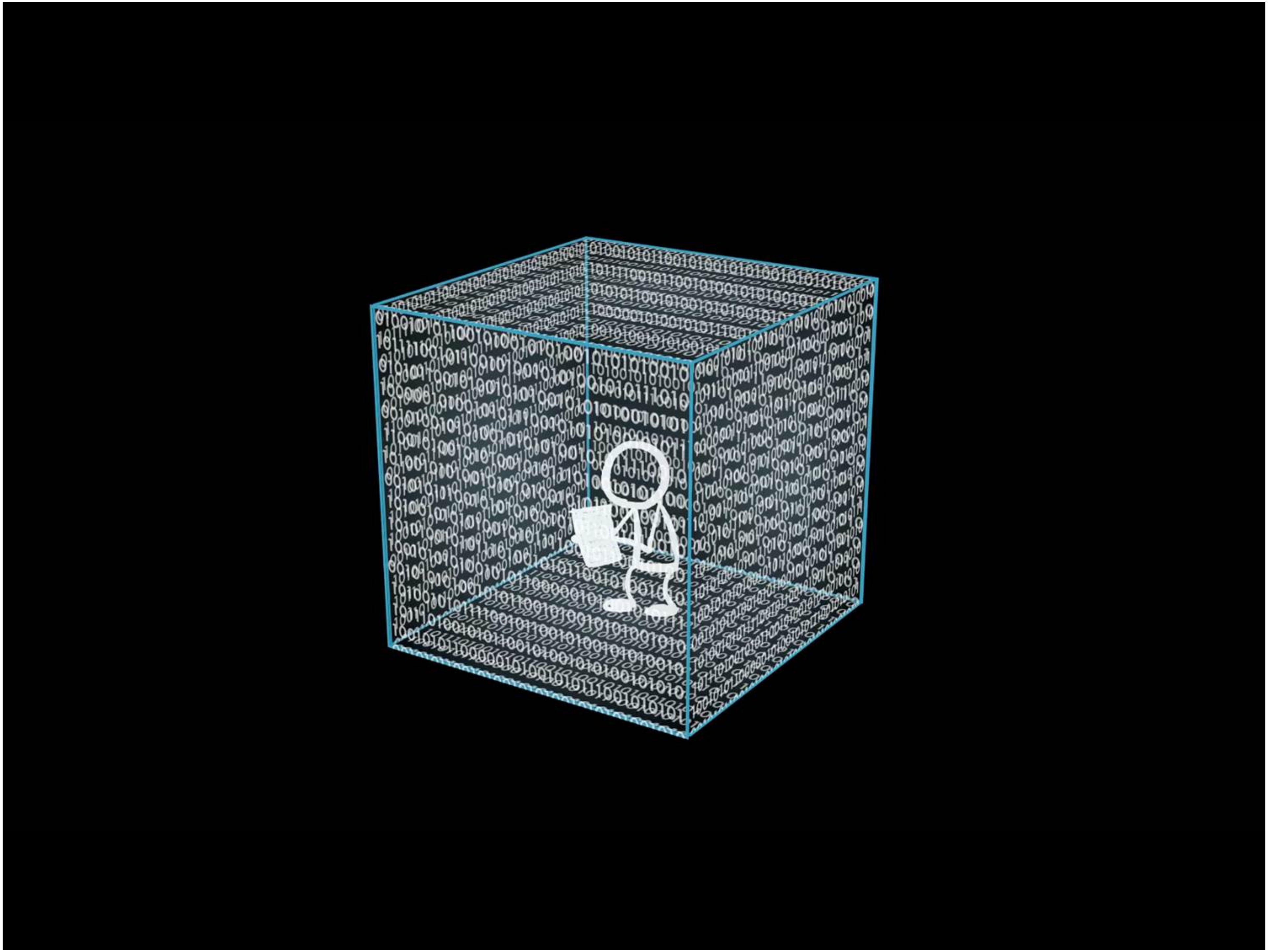
The 4D toric code obeys all the rules, but what about < 4 dimensions?

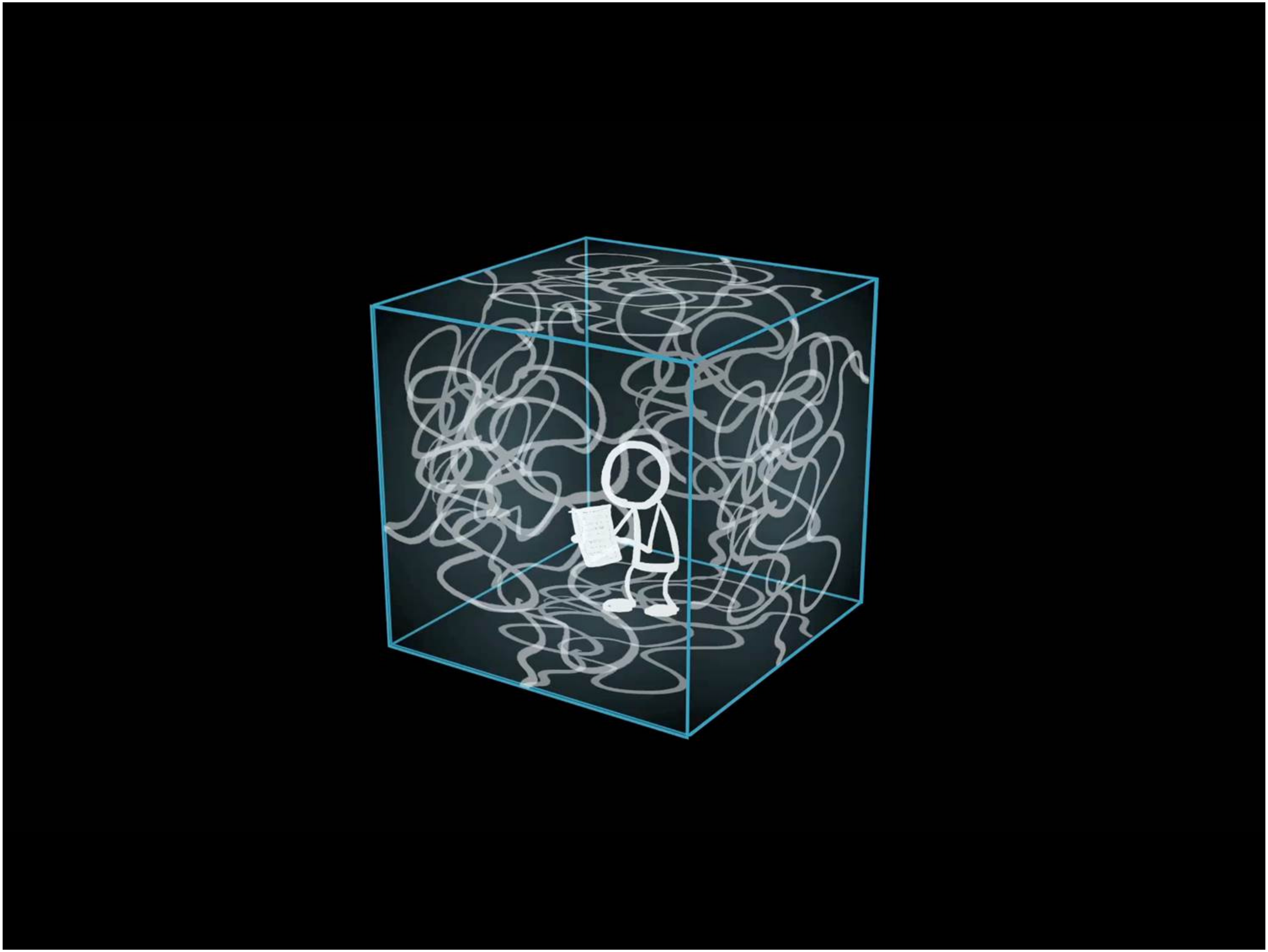

INTERSTELLAR

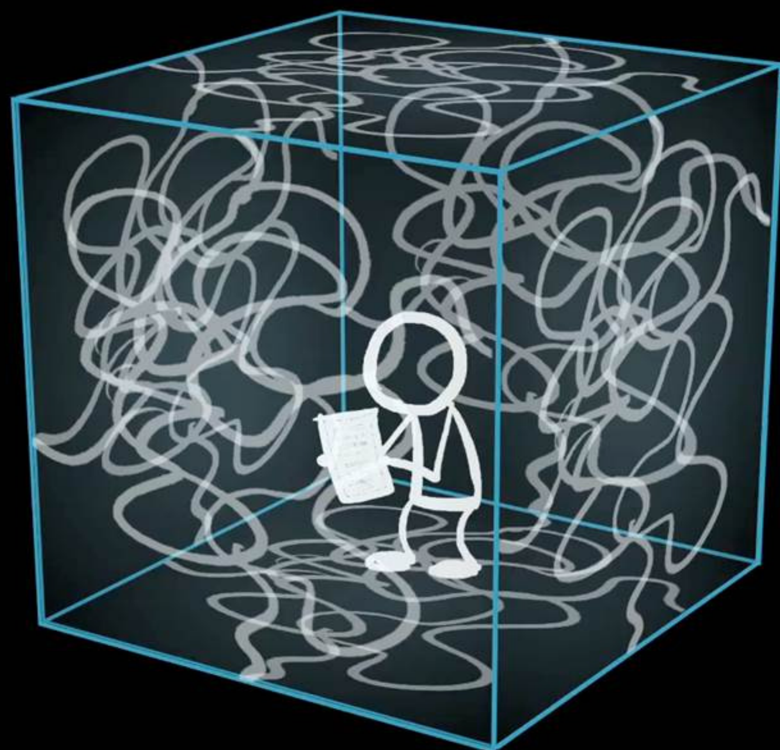

THE HOLOGRAPHIC PRINCIPLE
INTERSTELLAR

[redacted]



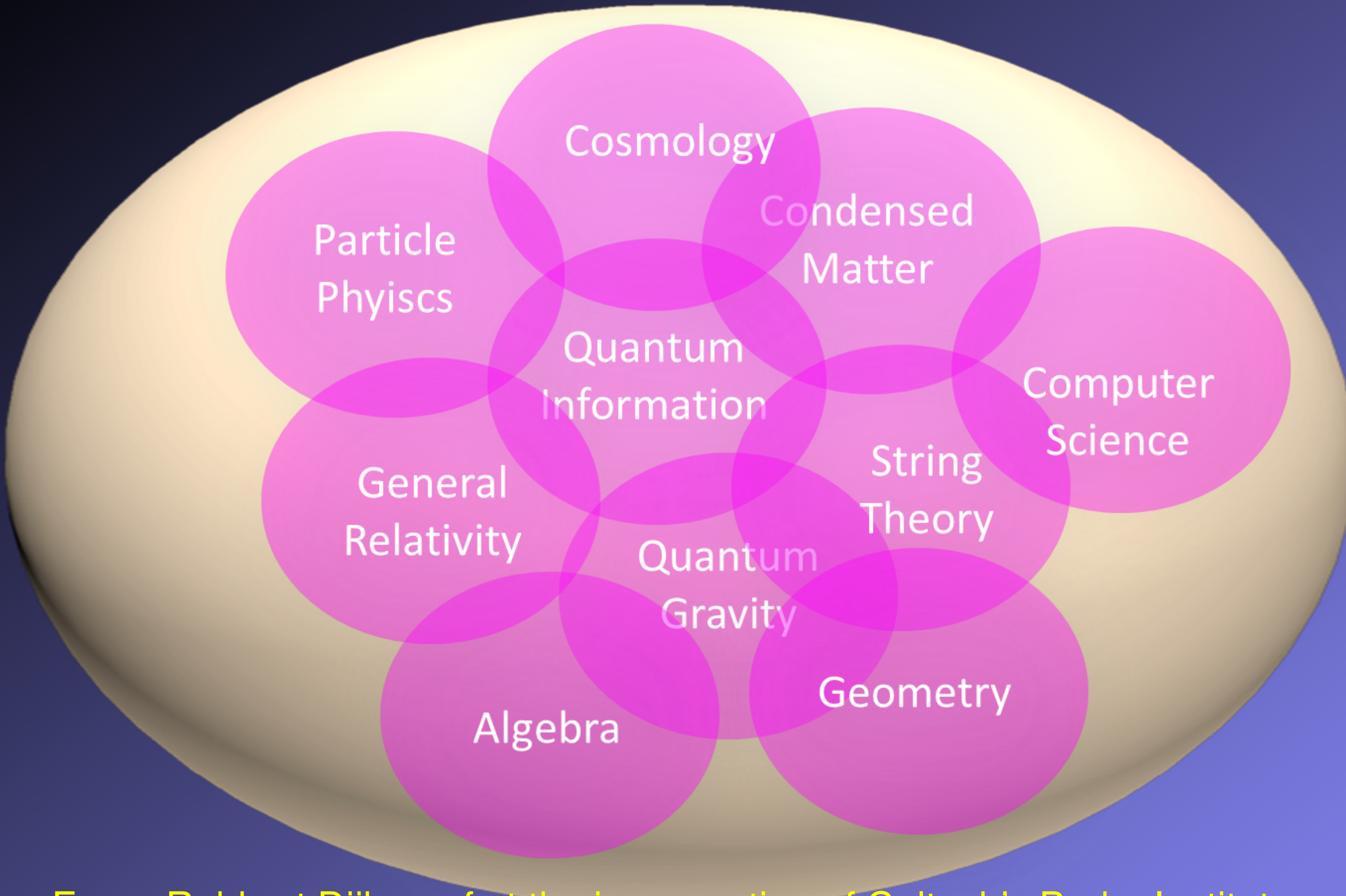






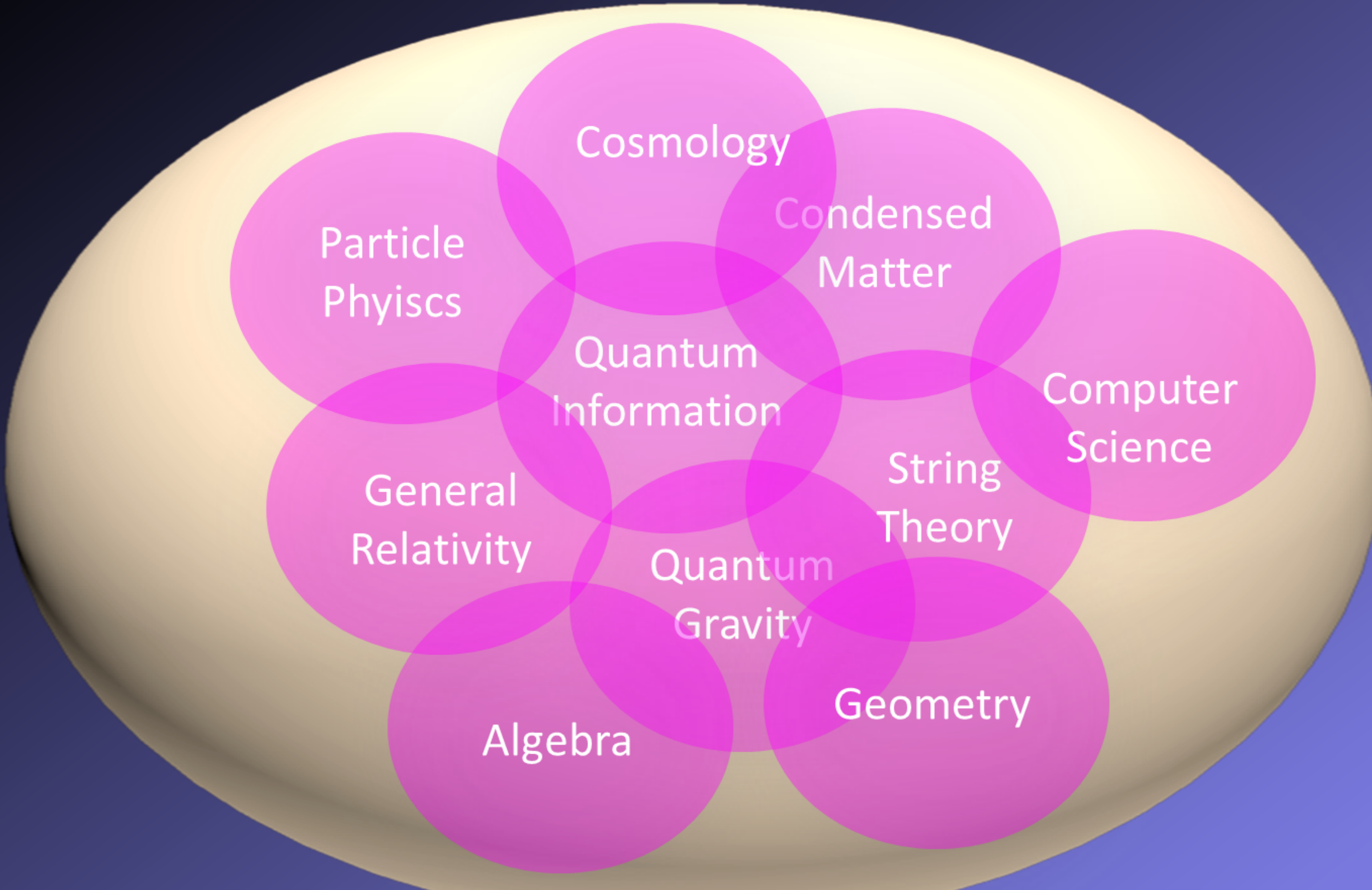
Entanglement is what holds space together.

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.

Quantumists ≈ Biologists

quantum gravity = life

boundary theory = chemistry

quantum information theorists = chemists

quantum gravity theorists = biologists

what we want = molecular biology

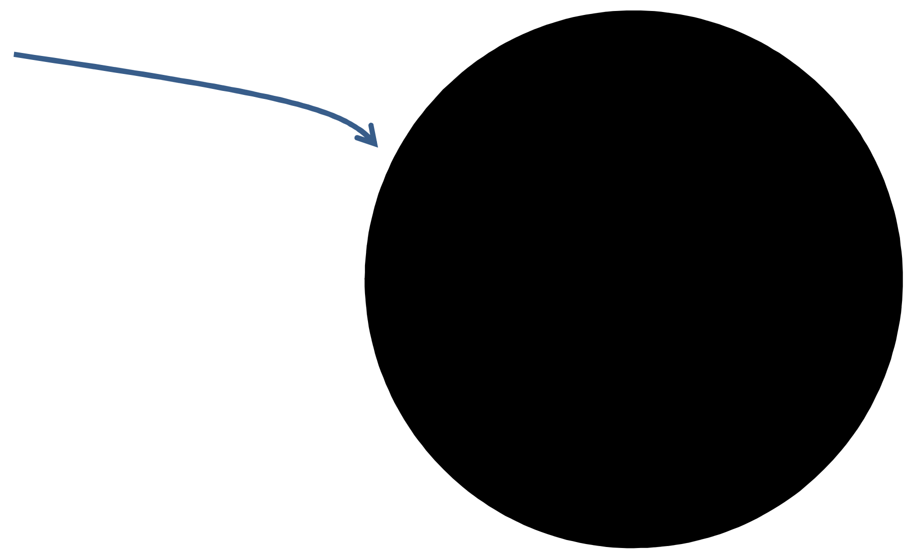
black hole information problem = fruit fly

understanding the big bang = curing cancer

Slide concept stolen from Juan Maldacena

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

Beni Yoshida
QuantumFrontiers.com
March 2015



LIGO!

GW150914

One Entangled Evening …

Once we have dreamt it, we can make it so.
Once we have dreamt it, we can make it so!