# Study Group Report:

# *Grand Challenges at the Interface of Quantum Information Science, Particle Physics, and Computing*

John Preskill
Caltech

HEPAP, 7 April 2015

http://science.energy.gov/hep/news-and-resources/reports/

# Study Group Report:

# *Grand Challenges at the Interface of Quantum Information Science, Particle Physics, and Computing*

*The Study Group met on 11 December 2014 at DOE headquarters in Gemantown, MD.*

*Convened by Advanced Scientific Computing Research (ASCR) and High Energy Physics (HEP).*

*All members made presentations, with representatives from DOE and other US government agencies also participating.*

*Our report was distilled from the presentations and discussions.*

http://science.energy.gov/hep/news-and-resources/reports/

# Study Group Report:

## *Grand Challenges at the Interface of Quantum Information Science, Particle Physics, and Computing*

Edward
Farhi
MIT

Mikhail
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Peter
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Jordan
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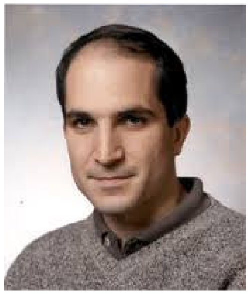

Juan
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# Three Questions About Quantum Computers

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?

# 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.

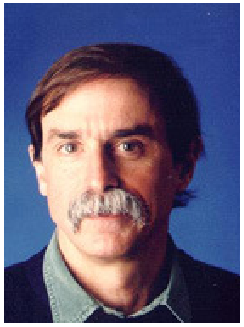
Two-level atoms in a high-finesse microcavity, strongly coupled to cavity modes of the electromagnetic field.

Linear optics with efficient single-photon sources and detectors.

Nuclear spins in semiconductors, and in liquid state NMR.

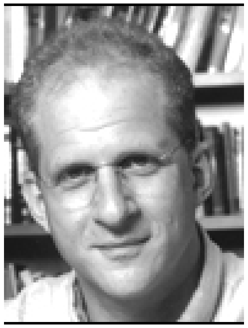
Nitrogen vacancy centers in diamond.

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



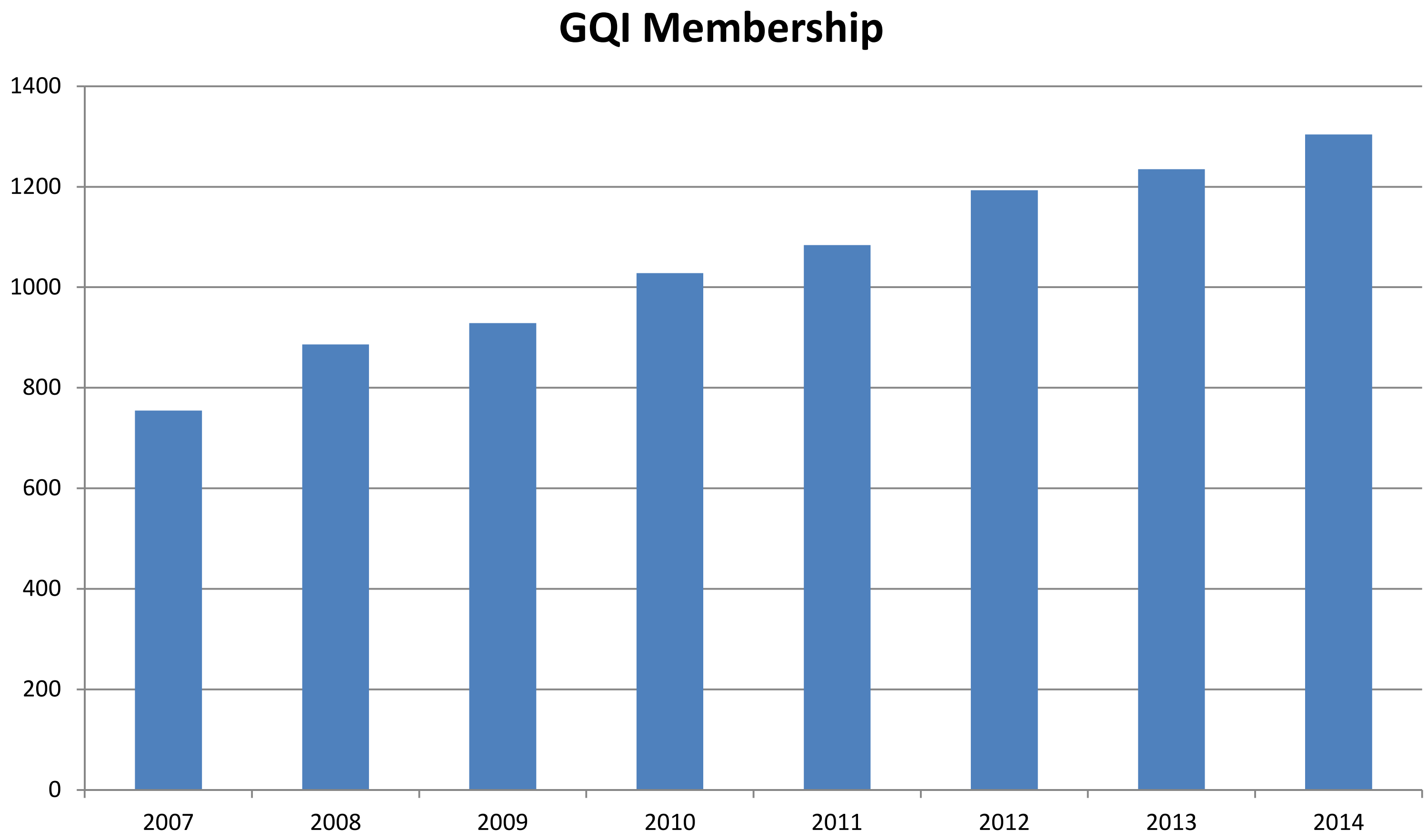
Wineland

Blatt



Marcus

# APS Topical Group on Quantum Information

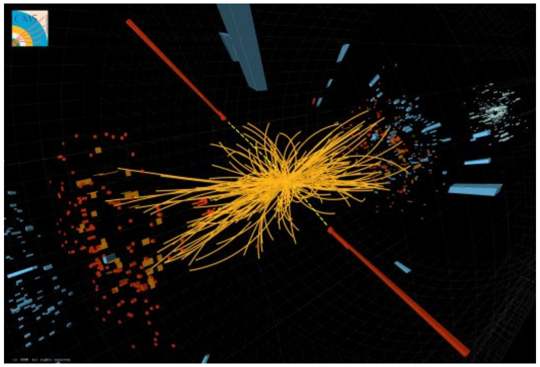


http://www.aps.org/membership/units/statistics.cfm

(Founded 2005. Membership is 57% students.)

# Frontiers of Physics

## short distance



Higgs boson

Neutrino masses

Supersymmetry

Quantum gravity

String theory

## long distance

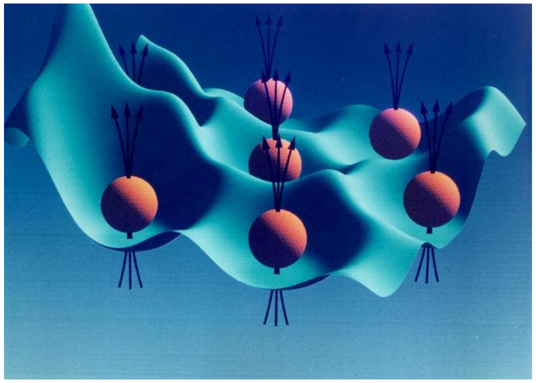
Large scale structure

Cosmic microwave background

Dark matter

Dark energy

## complexity



“More is different”

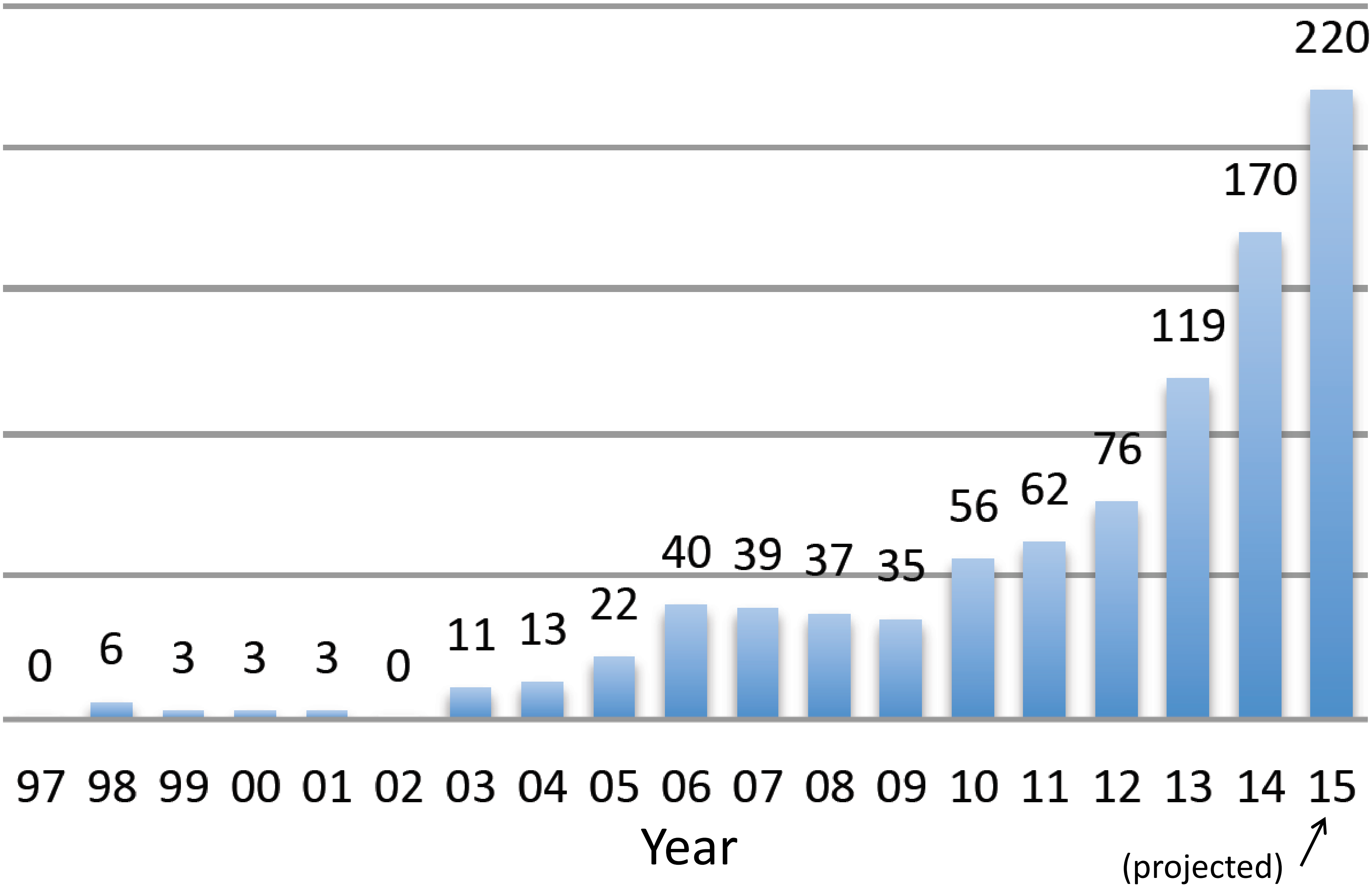
Many-body entanglement

Phases of quantum matter

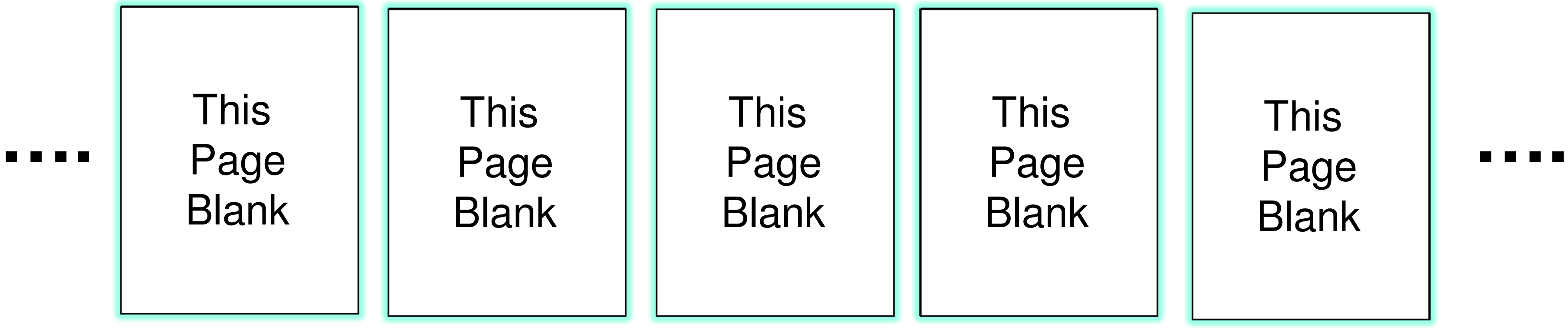
Quantum computing

Emergent geometry

# hep-th papers with “entanglement” in the title



# Quantum entanglement

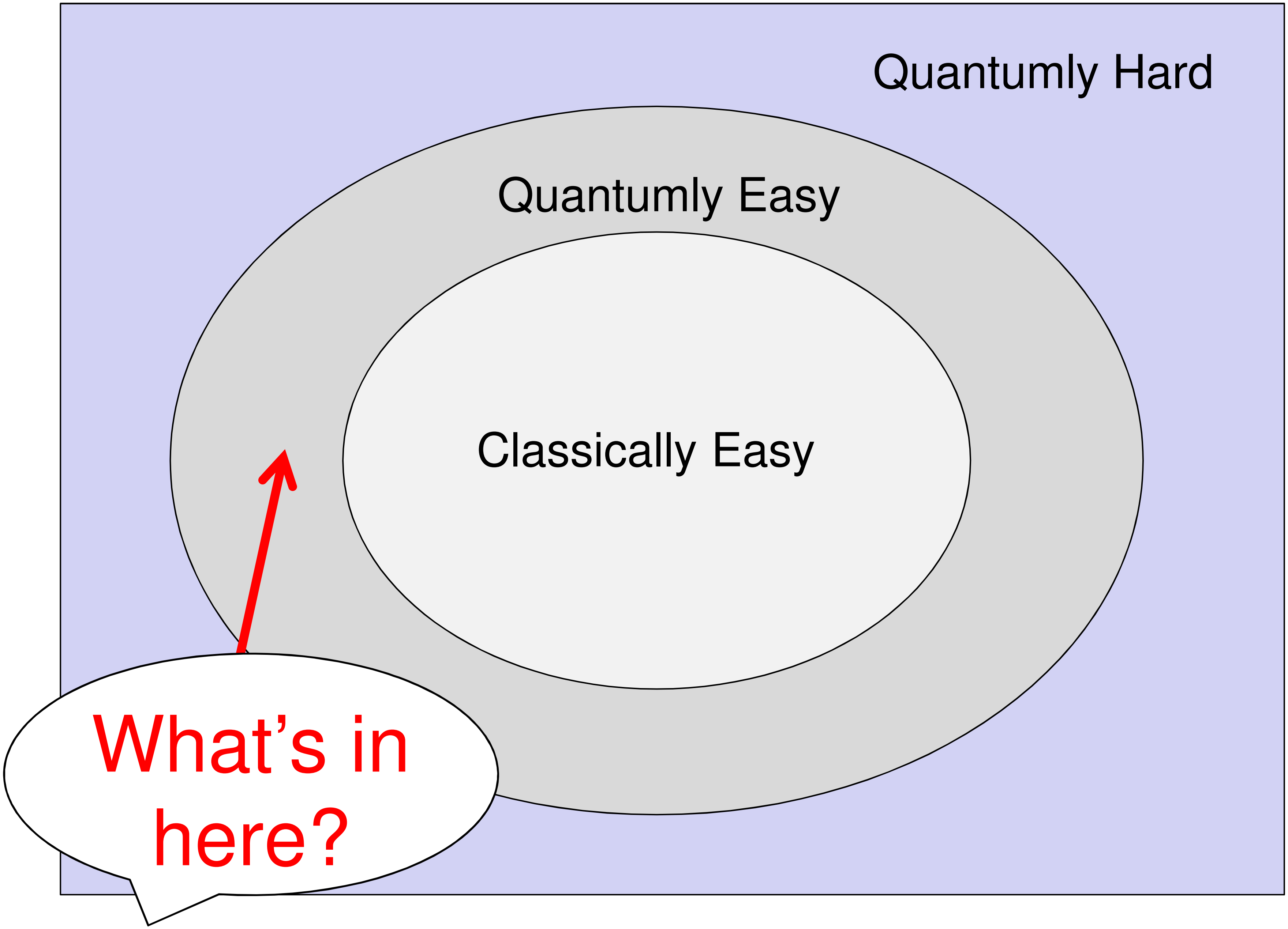


…. This Page Blank This Page Blank This Page Blank This Page Blank This Page Blank ….

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

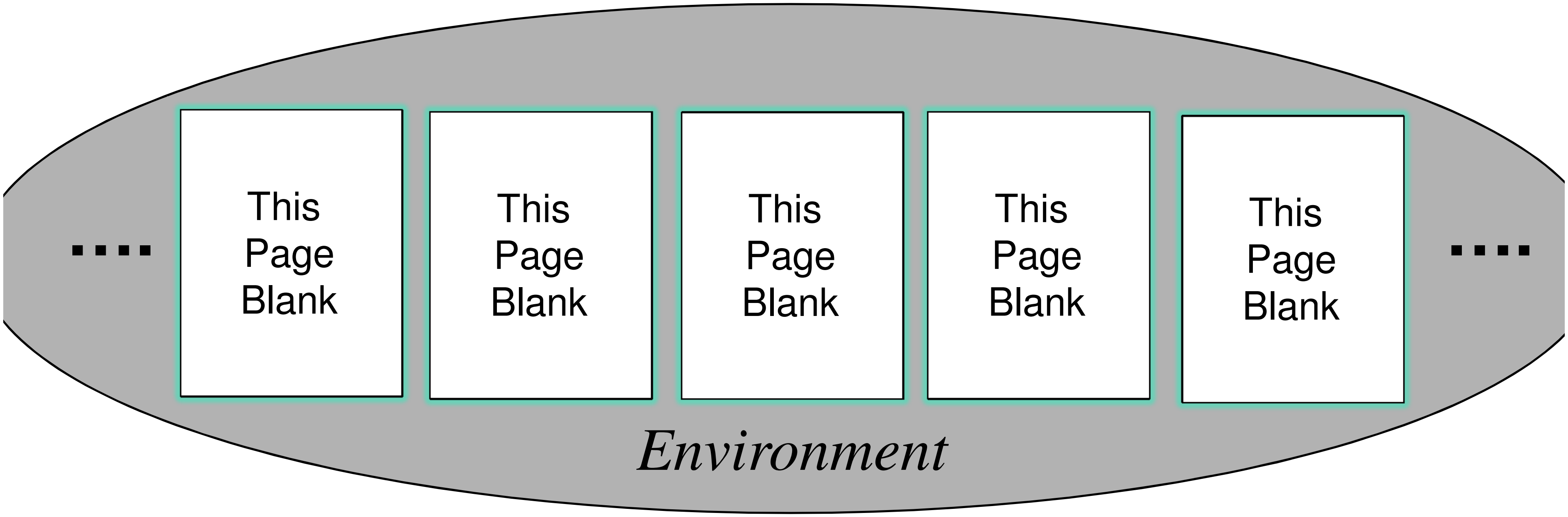
Classically Easy

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.

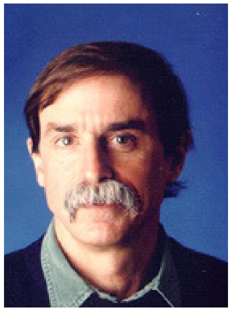
# Quantum error correction



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.

# Some recently reported error rates


Wineland

Ion trap – one-qubit gates:

~ $2 \times 10^{-5}$ [NIST]


Blatt

Ion trap – two-qubit gates:

~ $5 \times 10^{-3}$ [Innsbruck]

Superconducting circuits – two-qubit gates

~ $6 \times 10^{-3}$ [UCSB]


Martinis

Quantum error correction becomes effective when gate error rates are low enough, and the overhead cost of error correction improves as hardware becomes more reliable.

Error rates are estimated by performing “circuits” of variable size, and observing how the error in the final readout grows with circuit size.

What new measurement strategies, exploiting quantum coherence and entanglement, can probe fundamental physics with unprecedented precision?

# What new measurement strategies, exploiting quantum coherence and entanglement, can probe fundamental physics with unprecedented precision?

Entanglement for more accurate clocks and sensors.

Electric dipole moments of atoms and molecules.

Dark matter, e.g. axions.

Time-dependent fundamental constants, e.g. dark energy models.

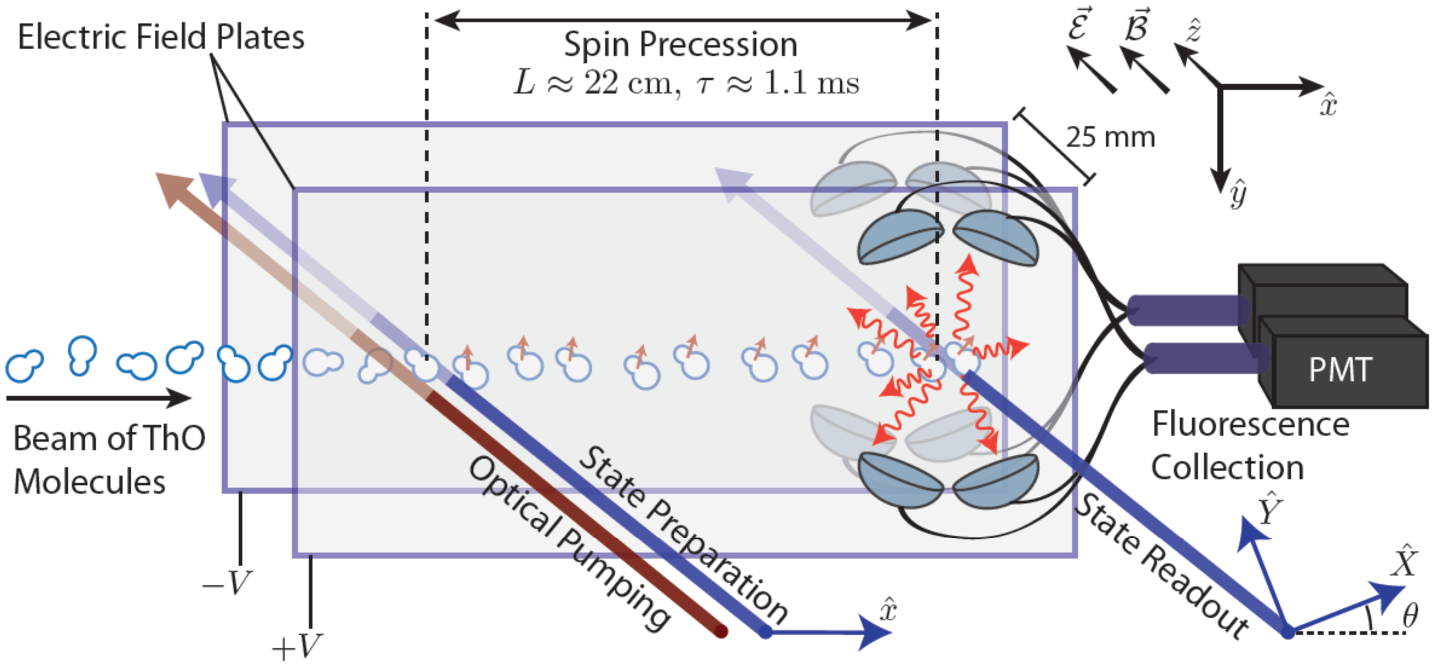
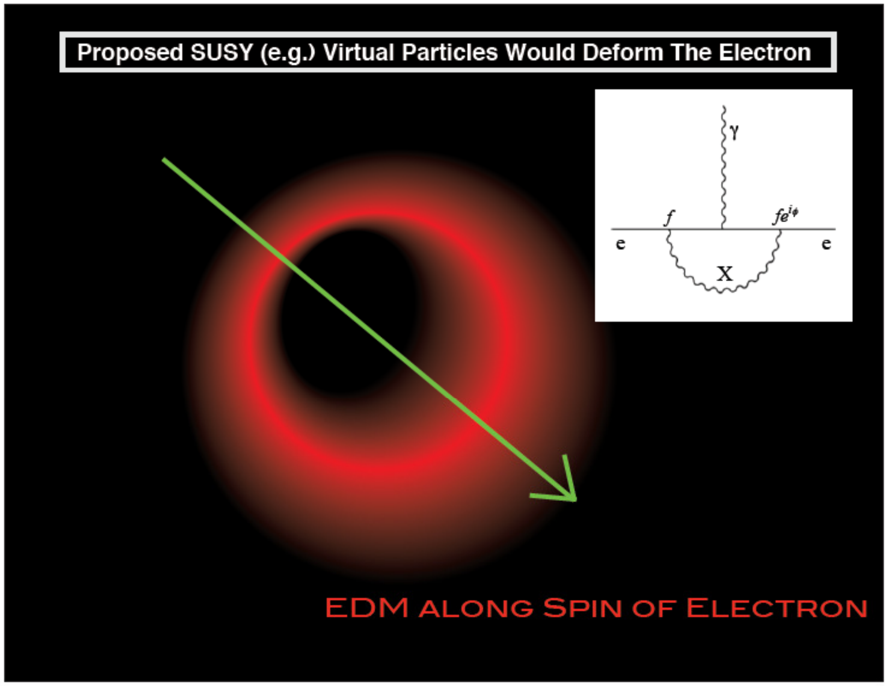


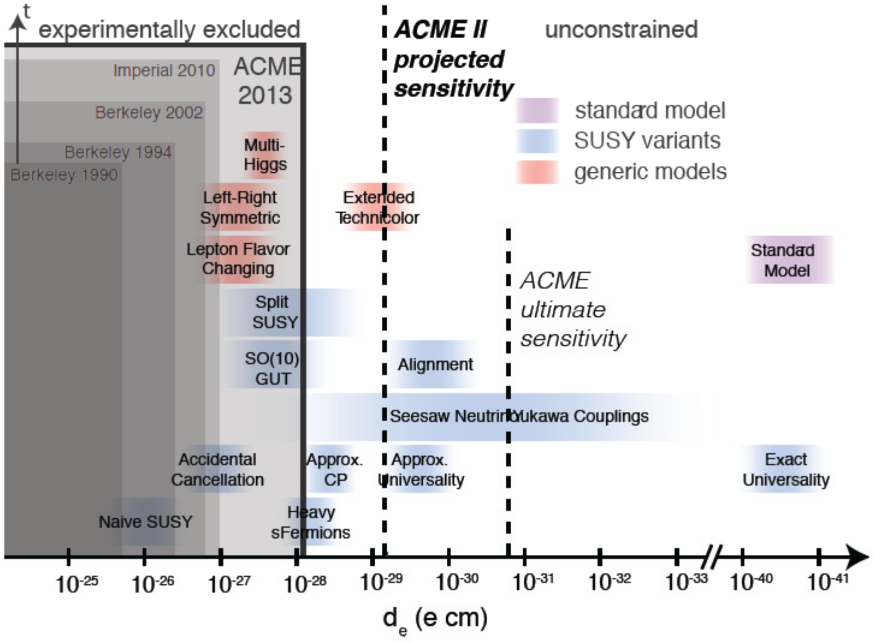
FIG. 1. Schematic of the apparatus (not to scale). A collimated pulse of ThO molecules enters a magnetically shielded region. An aligned spin state (smallest red arrows), prepared via optical pumping, precesses in parallel electric and magnetic fields. The final spin alignment is read out by a laser with rapidly alternating linear polarizations, $\hat{X}, \hat{Y}$, with the resulting fluorescence collected and detected with photomultiplier tubes (PMTs).

ACME Collaboration, Order of magnitude smaller limit on the electric dipole moment of the electron (2014) – ($< 10^{-28}$ e cm).

# Precision measurements to probe fundamental physics

## Example: ACME collaboration

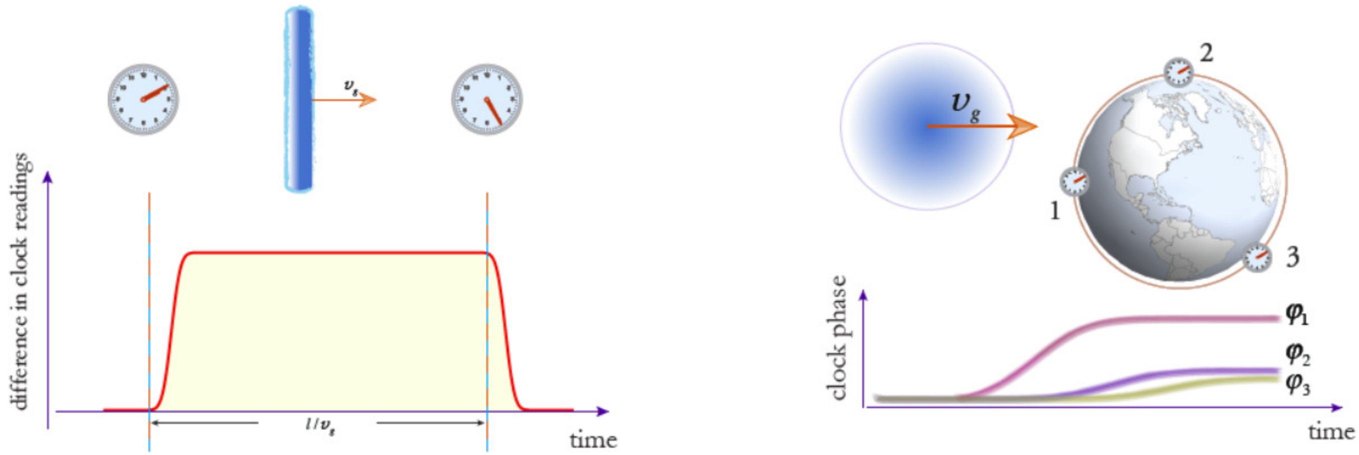




Measurements are ultimately limited by quantum noise

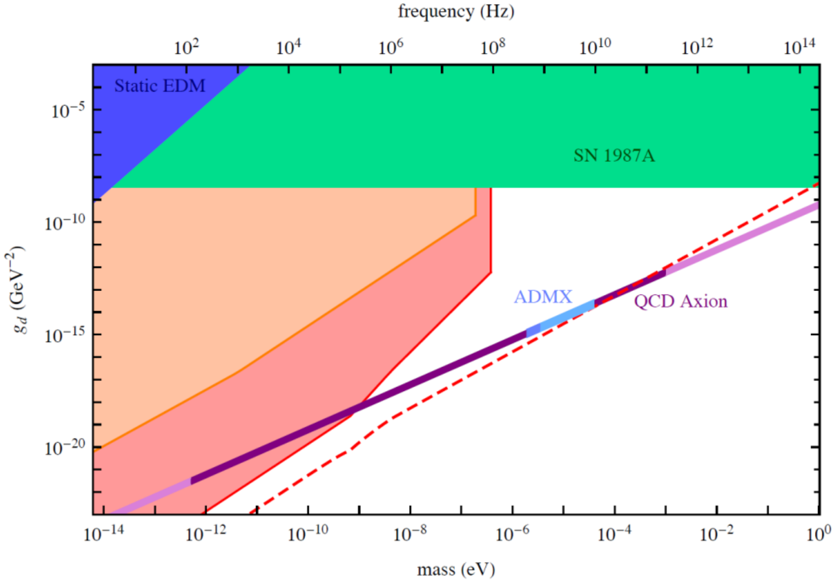
standard quantum noise ~ $1/\sqrt{N}$ improves with entanglement

# Listening to dark matter with a network of atomic clocks



Transient variation in fundamental constants due to dark matter solitons.
Derevianko and Pospelov, 2014.

# Detecting axion dark matter with a magnetometer network



Time-dependent EDM due to coherently oscillating axion field, potentially detectable in axion parameter regime inaccessible by other methods.

Budker et al. (CASPEr), 2014.

# What credible deviations from conventional quantum theory are experimentally testable?

# What credible deviations from conventional quantum theory are experimentally testable?

Scalable quantum computing tests QM in a new regime.

Nonlinear corrections to Schrodinger equation, spontaneous wave function collapse models.

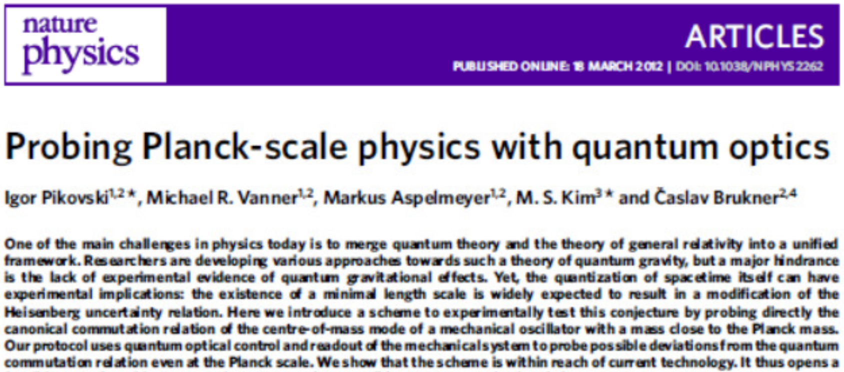
Macroscopic interference via optomechanics.

Are there small deformation of QM that make sense?

# Example: looking for space-time discreteness

If continuum theories breakdown at/ near Planck scale… $[x,p] \neq i\hbar$

**Test this with optomechanics?**



nature physics

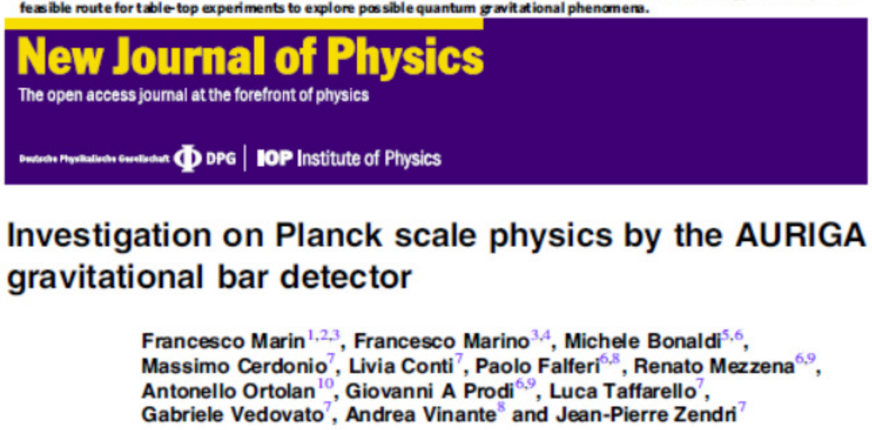
ARTICLES

PUBLISHED ONLINE: 18 MARCH 2012 | DOI: 10.1038/NPHYS2262

## Probing Planck-scale physics with quantum optics

Igor Pikovski[1,2]*, Michael R. Vanner[1,2], Markus Aspelmeyer[1,2], M. S. Kim[3]* and Časlav Brukner[2,4]

**One of the main challenges in physics today is to merge quantum theory and the theory of general relativity into a unified framework. Researchers are developing various approaches towards such a theory of quantum gravity, but a major hindrance is the lack of experimental evidence of quantum gravitational effects. Yet, the quantization of spacetime itself can have experimental implications: the existence of a minimal length scale is widely expected to result in a modification of the Heisenberg uncertainty relation. Here we introduce a scheme to experimentally test this conjecture by probing directly the canonical commutation relation of the centre-of-mass mode of a mechanical oscillator with a mass close to the Planck mass. Our protocol uses quantum optical control and readout of the mechanical system to probe possible deviations from the quantum commutation relation even at the Planck scale. We show that the scheme is within reach of current technology. It thus opens a feasible route for table-top experiments to explore possible quantum gravitational phenomena.**



New Journal of Physics

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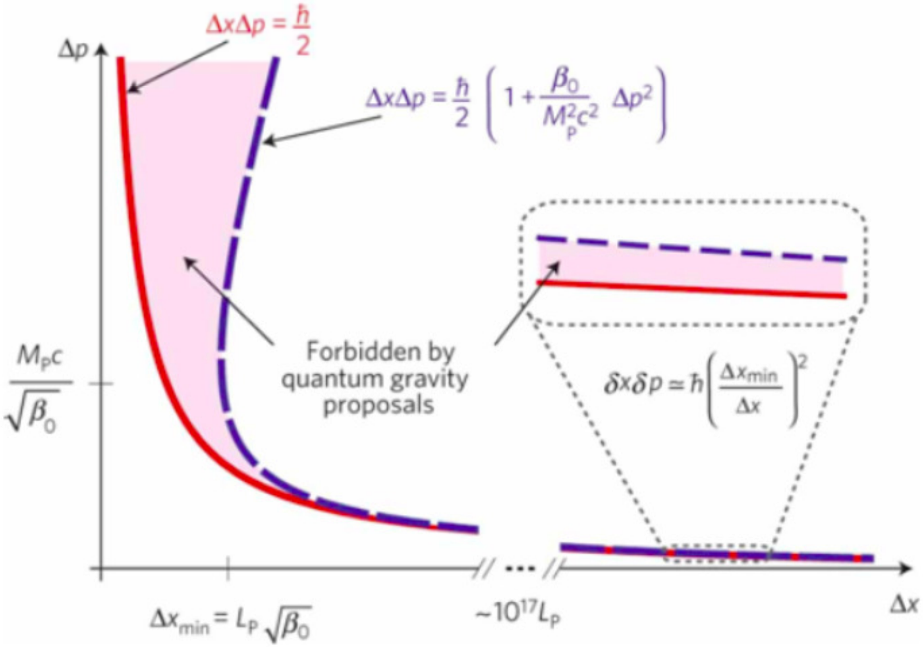
Deutsche Physikalische Gesellschaft DPG | IOP Institute of Physics

## Investigation on Planck scale physics by the AURIGA gravitational bar detector

Francesco Marin[1,2,3], Francesco Marino[3,4], Michele Bonaldi[5,6], Massimo Cerdonio[7], Livia Conti[7], Paolo Falferi[6,8], Renato Mezzena[6,9], Antonello Ortolan[10], Giovanni A Prodi[6,9], Luca Taffarello[7], Gabriele Vedovato[7], Andrea Vinante[8] and Jean-Pierre Zendri[7]



# What physics insights can inspire new applications for quantum computers?

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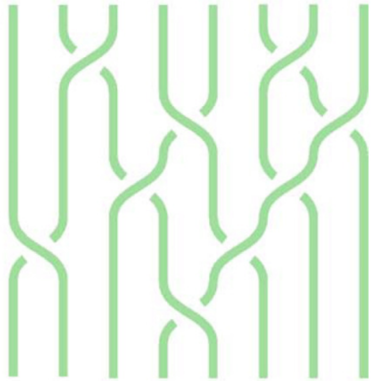
Exact or approximate solutions to NP-hard problems with significant speedups with respect to classical algorithms?

Small quantum computer as testbed for algorithms.

Applications of scattering theory.

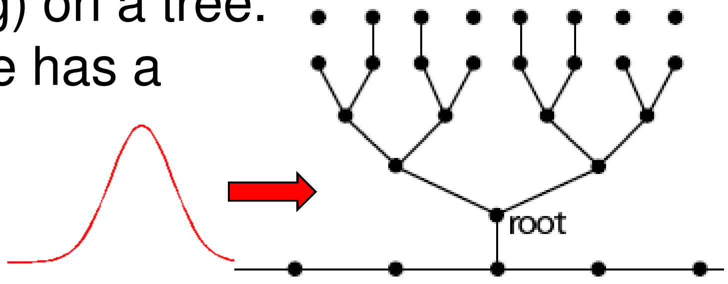
Theoretical and experimental exploration of adiabatic quantum computing.

# Physics and algorithms



Approximating knot invariants (Freedman et al. 2000).
Idea: simulating topological quantum field theory.
Application: Unforgeable quantumly verifiable money.
Speedup: superpolynomial

Evaluation of Boolean formulas (Farhi et al. 2007)
Idea: simulating quantum walk (i.e. scattering) on a tree.
Application: Determining if a two-player game has a winning strategy.
Speedup: polynomial ($N^{.5}$ vs. $N^{.753}$, where N is the number of leaves on the tree)



Quantum approaches to (approximately) solving optimization problems

-- Power of adiabatic quantum computing (→ D-Wave Systems).

-- Other approaches to quantum (approximate) combinatorial optimization.

-- Experimental testbeds to explore applications of small quantum computers.

(Many more quantum algorithms at math.nist.gov/quantum/zoo/)

# Can quantum computers efficiently simulate all physical phenomena?

# Can quantum computers efficiently simulate all physical phenomena?

Both YES and NO are interesting answers!

Quantum field theory has a local Hamiltonian.

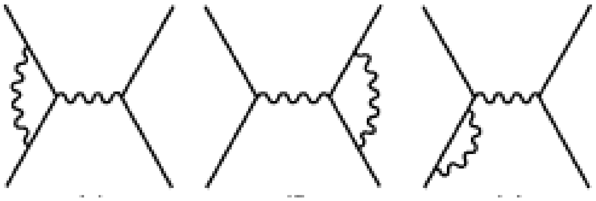
Gauge theories, massless particles, improved scaling of cost with error, tensor network approaches, …

Nonperturbative quantum field theory.

Strongly coupled string theory?

What is string theory?

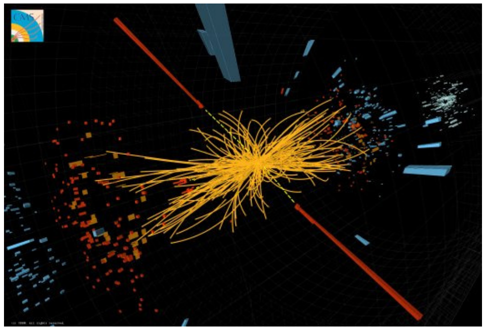
# Quantum algorithms for quantum field theories



Classical methods have limited precision, particularly at strong coupling.

A quantum computer can 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.

Not yet fully settled for gauge theories or theories with massless particles. Would like to improve scaling of cost with error.



Does the quantum circuit model capture the computational power of Nature?

How can quantum simulators and quantum computers deepen our understanding of quantum field theory and quantum gravity?

# How can quantum simulators and quantum computers deepen our understanding of quantum field theory and quantum gravity?

Euclidean Monte Carlo methods limited to static properties.

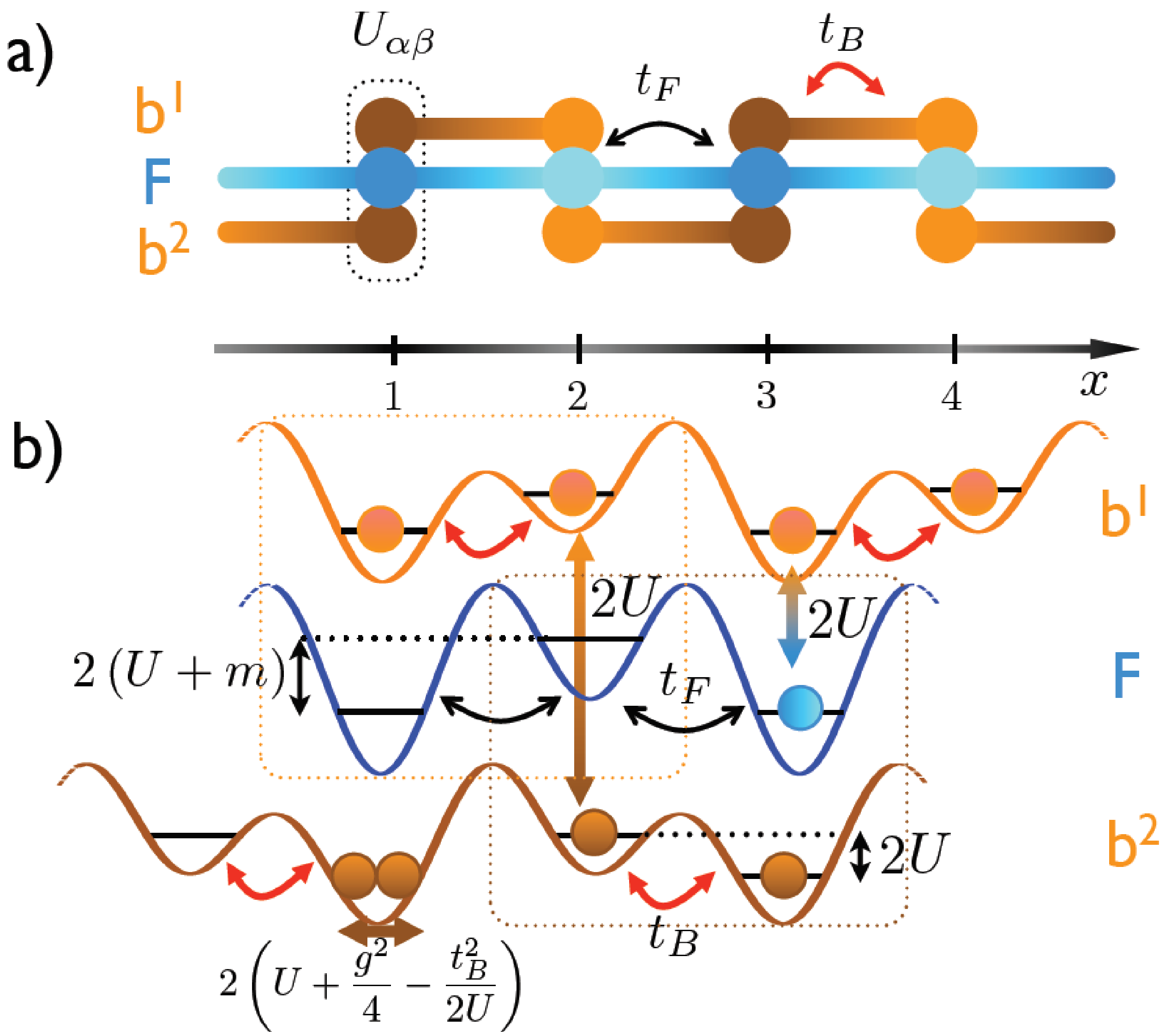
Real time evolution is hard classically, may be easy quantumly.

Nuclear matter at finite density, QCD event generators.

String theory for e.g. nonsupersymmetric, cosmological spacetimes.

Analog is noisy, digital can be error corrected.

Atoms, molecules, ions, superconducting circuits, …



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

# Does space emerge from entanglement?

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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).

Einstein field equations from entanglement (Van Raamsdonk et al. 2014).

Computational complexity as geometry (Susskind 2014).

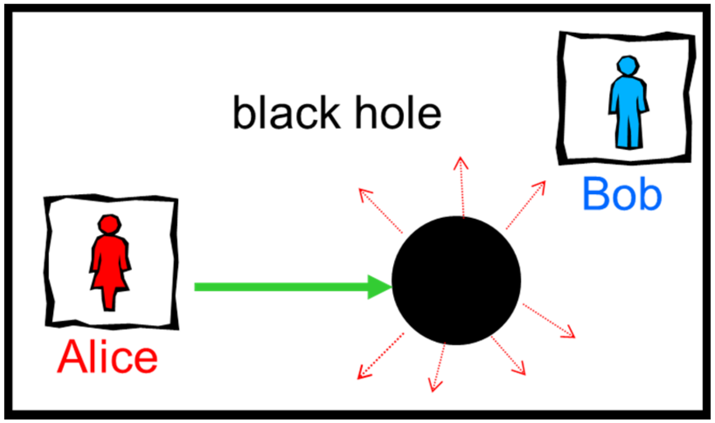
The boundary-bulk dictionary as a quantum error-correcting code (Almheiri, Dong, Harlow 2014).

**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

# What’s inside a black hole?

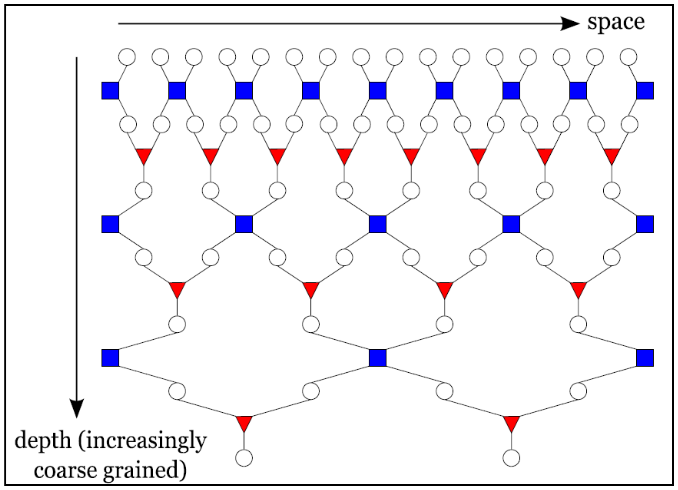


Quantum error correction: “black holes as mirrors” and bulk/boundary correspondence.

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?

# How can entanglement theory be extended?

# How can entanglement theory be extended?

Entanglement is a “resource theory”

Other resources, e.g. in thermodynamics.

What is entanglement in time?

Can time be emergent?

# Funding

NSF PHY: Physics at the Information Frontier (PIF)
Center for Quantum Information and Control (UNM, Arizona)
Physics Frontiers Centers (PFC):
Joint Quantum Institute (Maryland)
Institute for Quantum Information and Matter (Caltech)

NSF CISE: Computing and Communication Foundations (CCF)

NSF: Coordination with DMR, AMO, TAMOP, MP

ARO/NSA: Quantum Algorithms (QA)

ARO/LPS: Quantum Characterization, Verification, and Validation (QCVV)

Other: NIST, IARPA, DARPA, NSA, ARL, AFRL, NRL, …

No longer: IARPA Quantum Computer Science (QCS)
DARPA Quantum Entanglement Science and Technology (QuEST)

Industry: Microsoft, IBM, Google, D-Wave, …

Elsewhere: Canada, Europe, Australia, Asia, Israel.

# Grand Challenges

What new measurement strategies, exploiting quantum coherence and entanglement, can probe fundamental physics with unprecedented precision?

What credible deviations from conventional quantum theory are experimentally testable?

What physics insights can inspire new applications for quantum computers?

Can quantum computers efficiently simulate all physical phenomena?

How can quantum simulators and quantum computers deepen our understanding of quantum field theory and quantum gravity?

Does space emerge from entanglement?

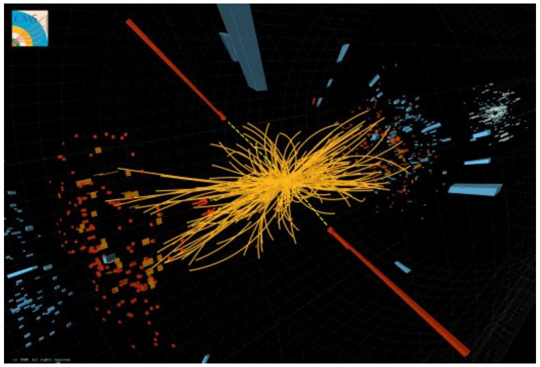
How can entanglement theory be extended?

Remark: Common tools, techniques, and goals overlap
with the research agendas of HEP, ASCR, BES.

http://science.energy.gov/hep/news-and-resources/reports/

# Frontiers of Physics

## short distance

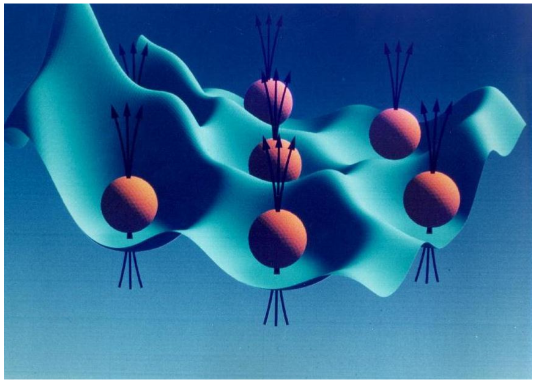


- Higgs boson
- Neutrino masses
- Supersymmetry
- Quantum gravity
- String theory

## long distance

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

## complexity

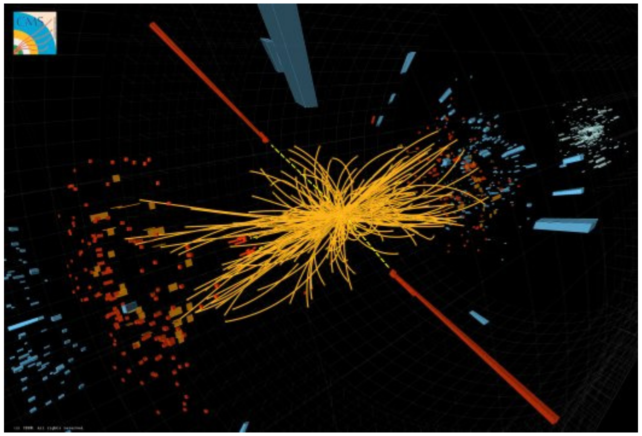


- “More is different”
- Many-body entanglement
- Phases of quantum matter
- Quantum computing
- Emergent geometry

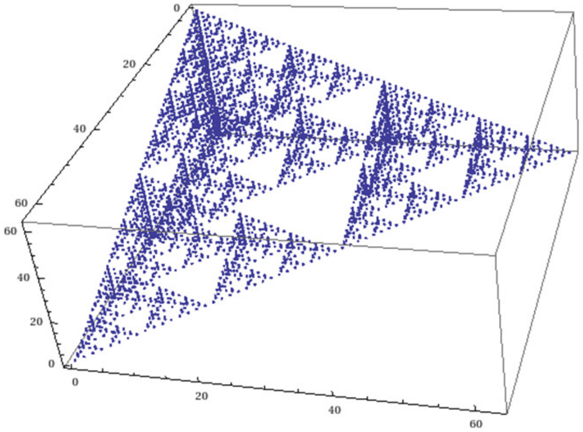
# Additional Slides

# Quantum entanglement in the 21st century

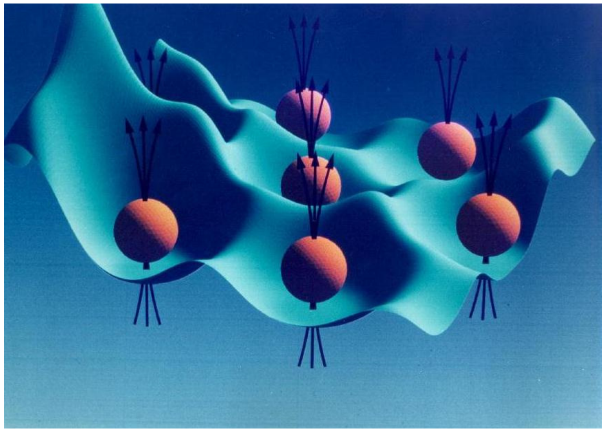
## Algorithms



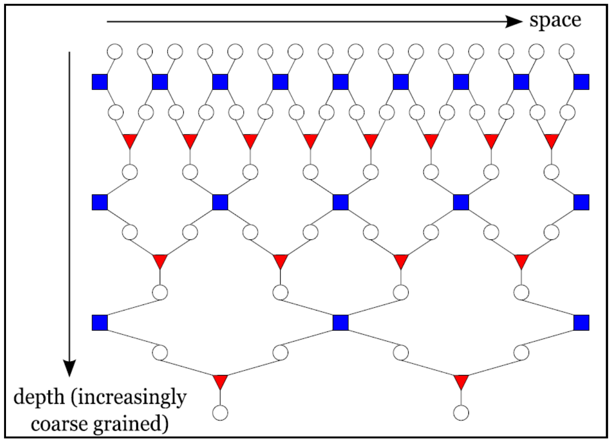
## Error Correction



## Matter



## Spacetime



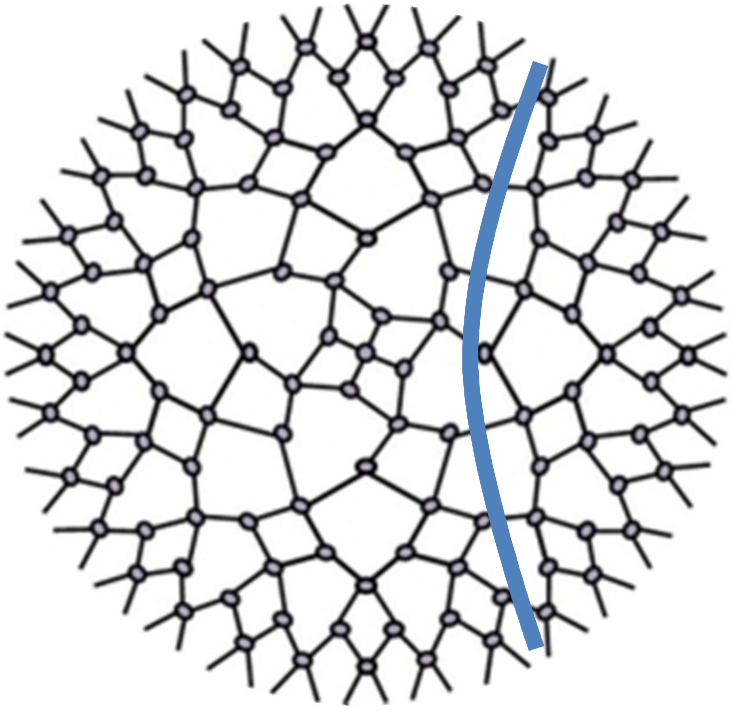
# Holographic entanglement entropy

Ryu & Takayanagi (2006):

entanglement in boundary CFT ~ bulk geometry geometry in its gravitational dual

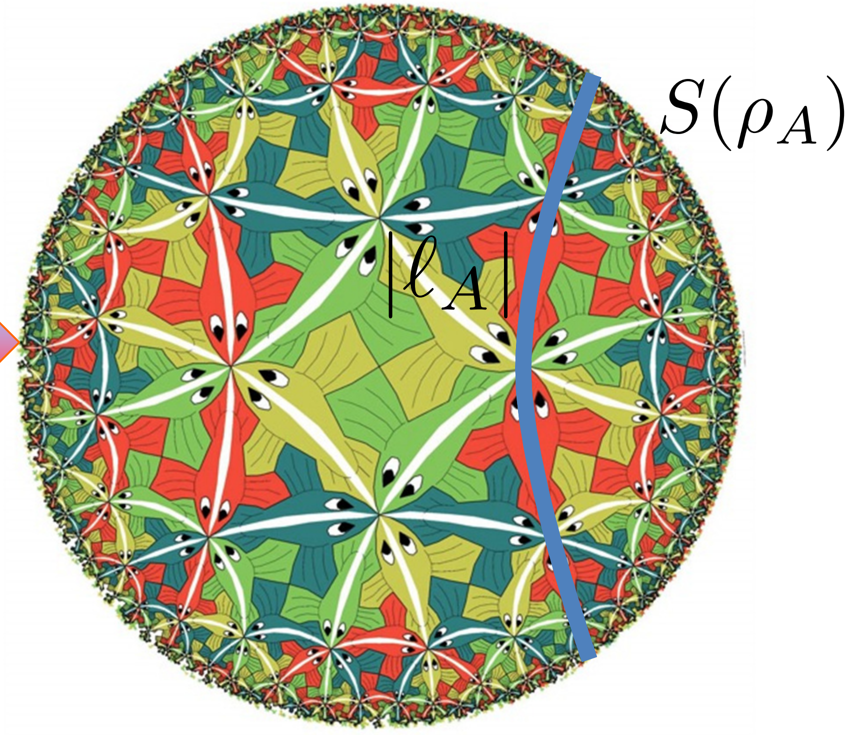
## bulk distance = boundary entanglement entropy

MERA

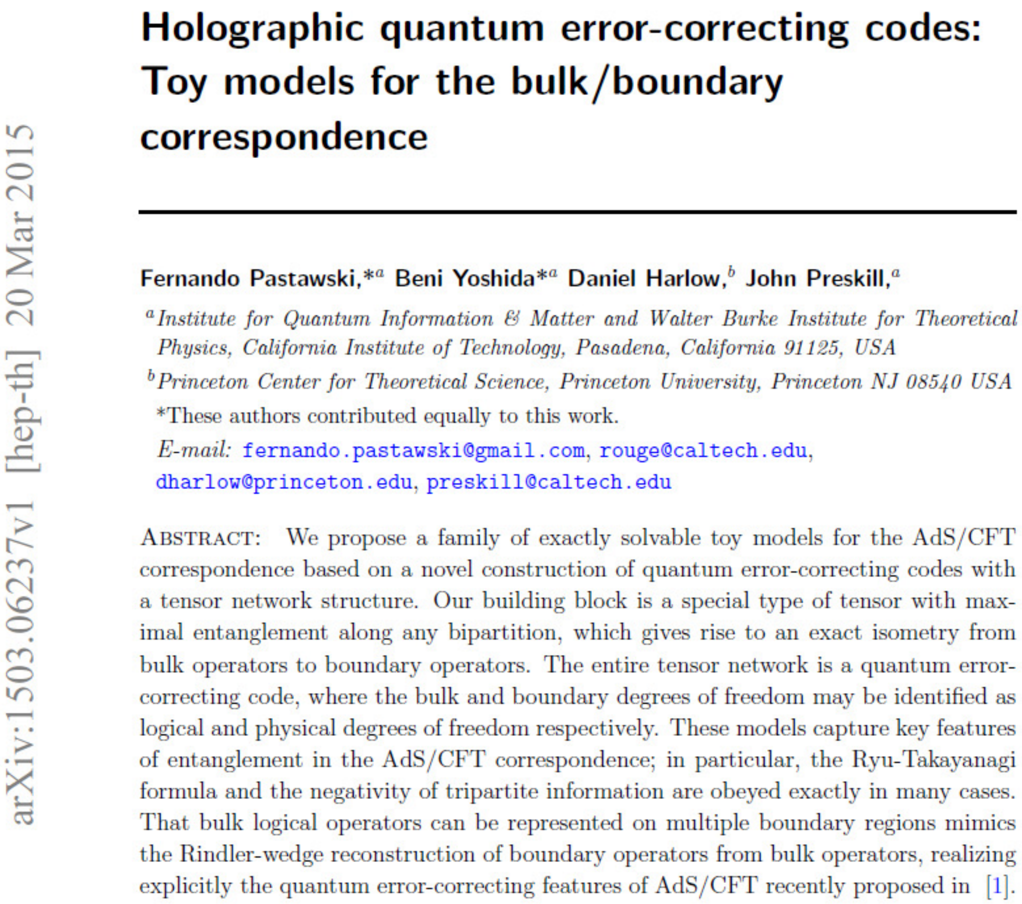


Class of Quantum Many-Body States That Can Be Efficiently Simulated, Guifre Vidal (2006)

AdS metric



Entanglement renormalization and holography, Brian Swingle (2009)



arXiv:1503.06237v1 [hep-th] 20 Mar 2015

# Holographic quantum error-correcting codes: Toy models for the bulk/boundary correspondence

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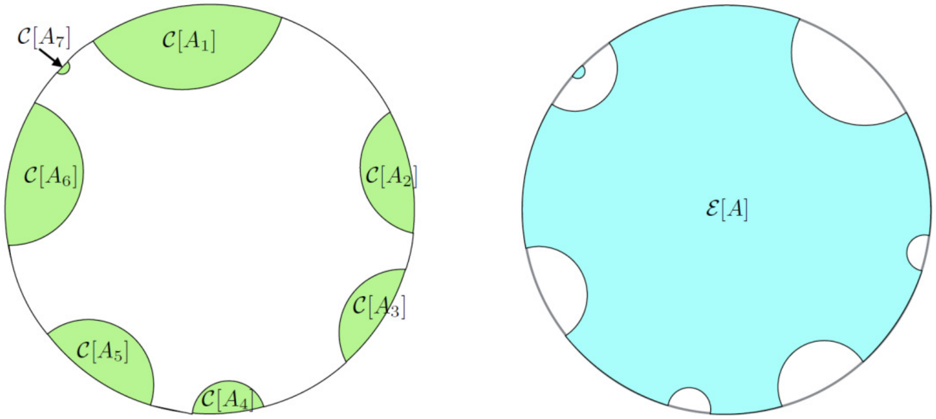
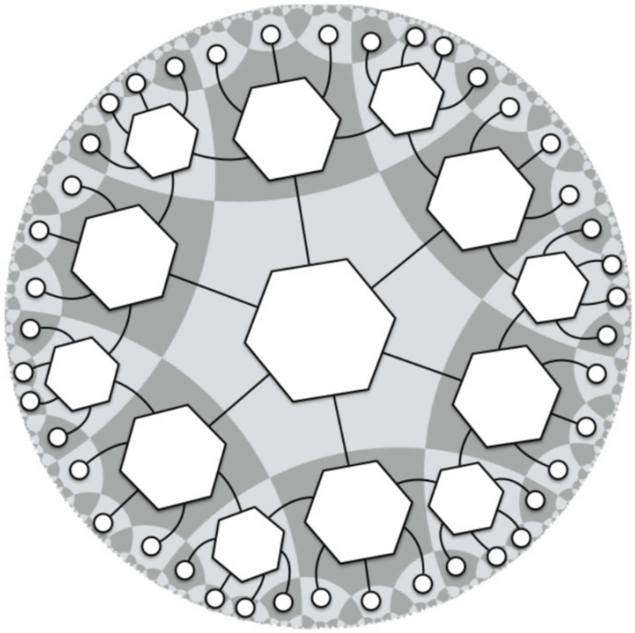
ABSTRACT: We propose a family of exactly solvable toy models for the AdS/CFT correspondence based on a novel construction of quantum error-correcting codes with a tensor network structure. Our building block is a special type of tensor with maximal entanglement along any bipartition, which gives rise to an exact isometry from bulk operators to boundary operators. The entire tensor network is a quantum error-correcting code, where the bulk and boundary degrees of freedom may be identified as logical and physical degrees of freedom respectively. These models capture key features of entanglement in the AdS/CFT correspondence; in particular, the Ryu-Takayanagi formula and the negativity of tripartite information are obeyed exactly in many cases. That bulk logical operators can be represented on multiple boundary regions mimics the Rindler-wedge reconstruction of boundary operators from bulk operators, realizing explicitly the quantum error-correcting features of AdS/CFT recently proposed in [1].

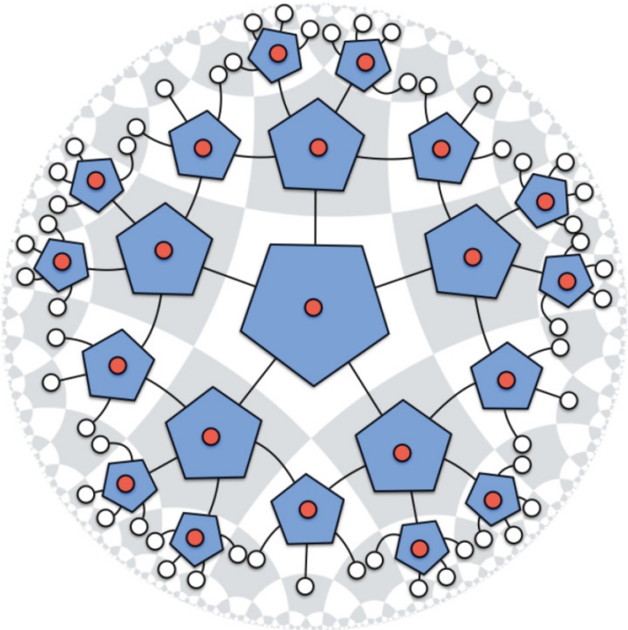


(a) Shallow causal wedge

(b) Deep entanglement wedge



(a) Holographic hexagon state



(b) Holographic pentagon code

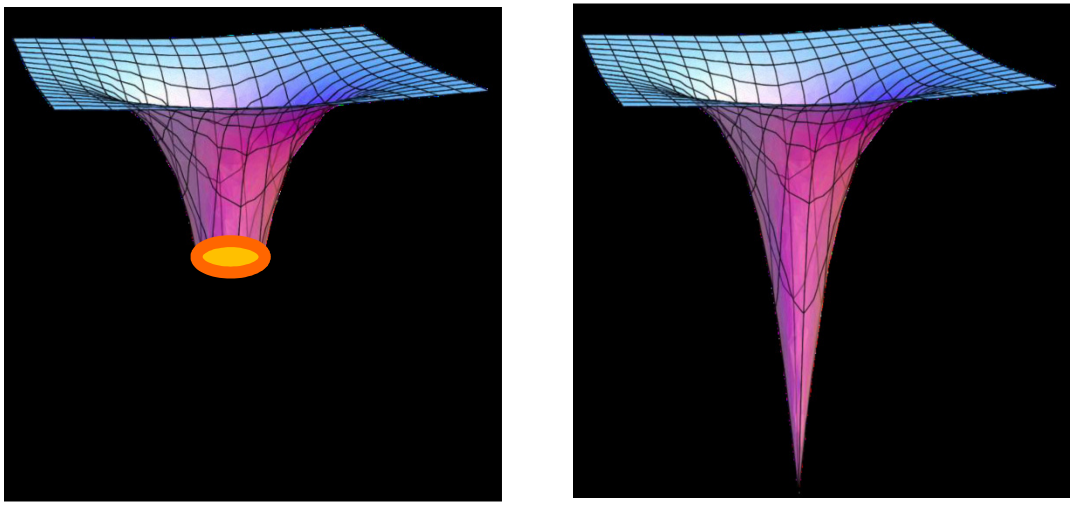
# Black hole complementarity challenged

Three reasonable beliefs, not all true!

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

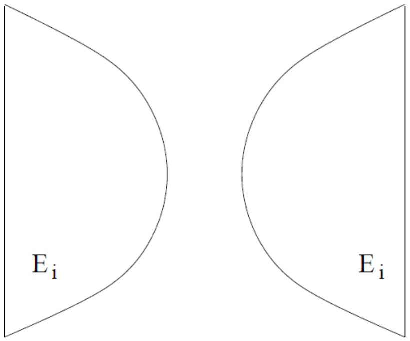
(1) The black hole "scrambles" information, but does not destroy it.
(2) An observer who falls through the black hole horizon sees nothing unusual (at least for a while).
(3) An observer who stays outside the black hole sees nothing unusual.

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



# Building spacetime from quantum entanglement

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



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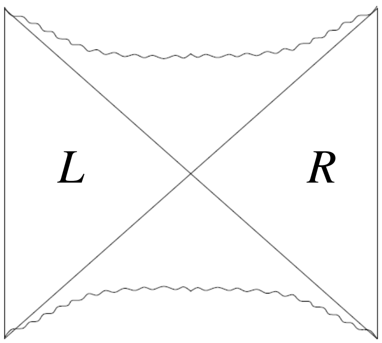
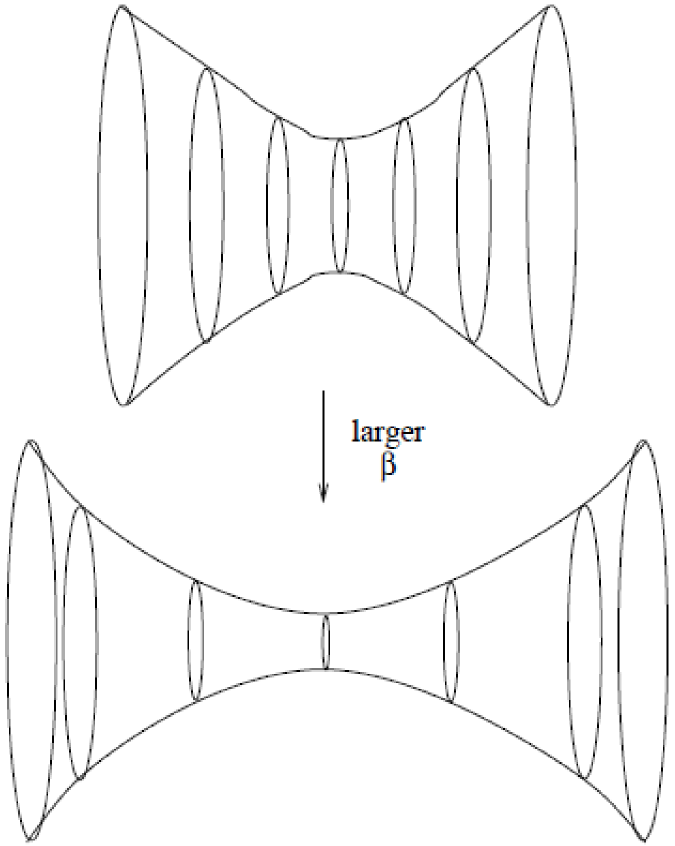
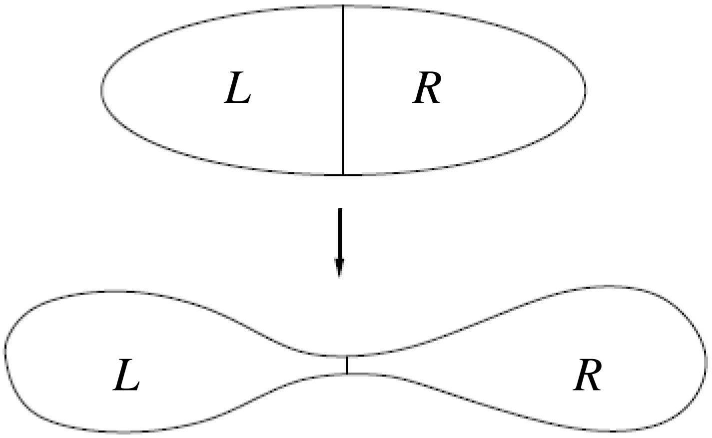


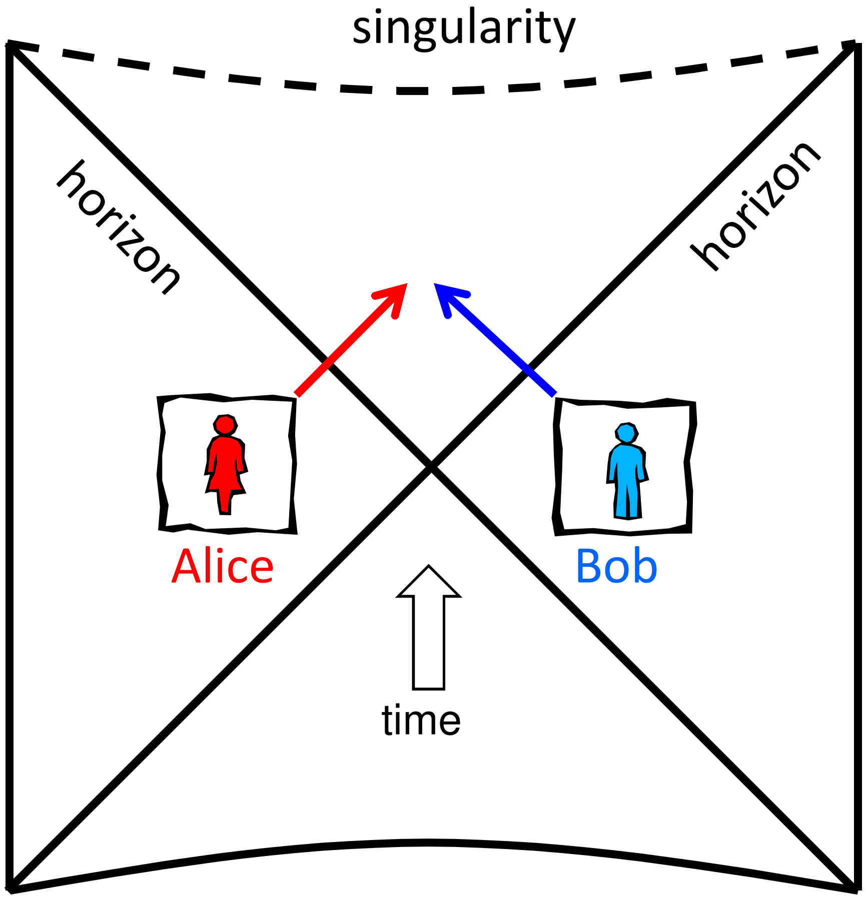
$$\sum_i e^{-\beta E_i/2} \,|\, E_i\rangle \otimes |\, E_i\rangle$$



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. (Van Raamsdonk 2010).

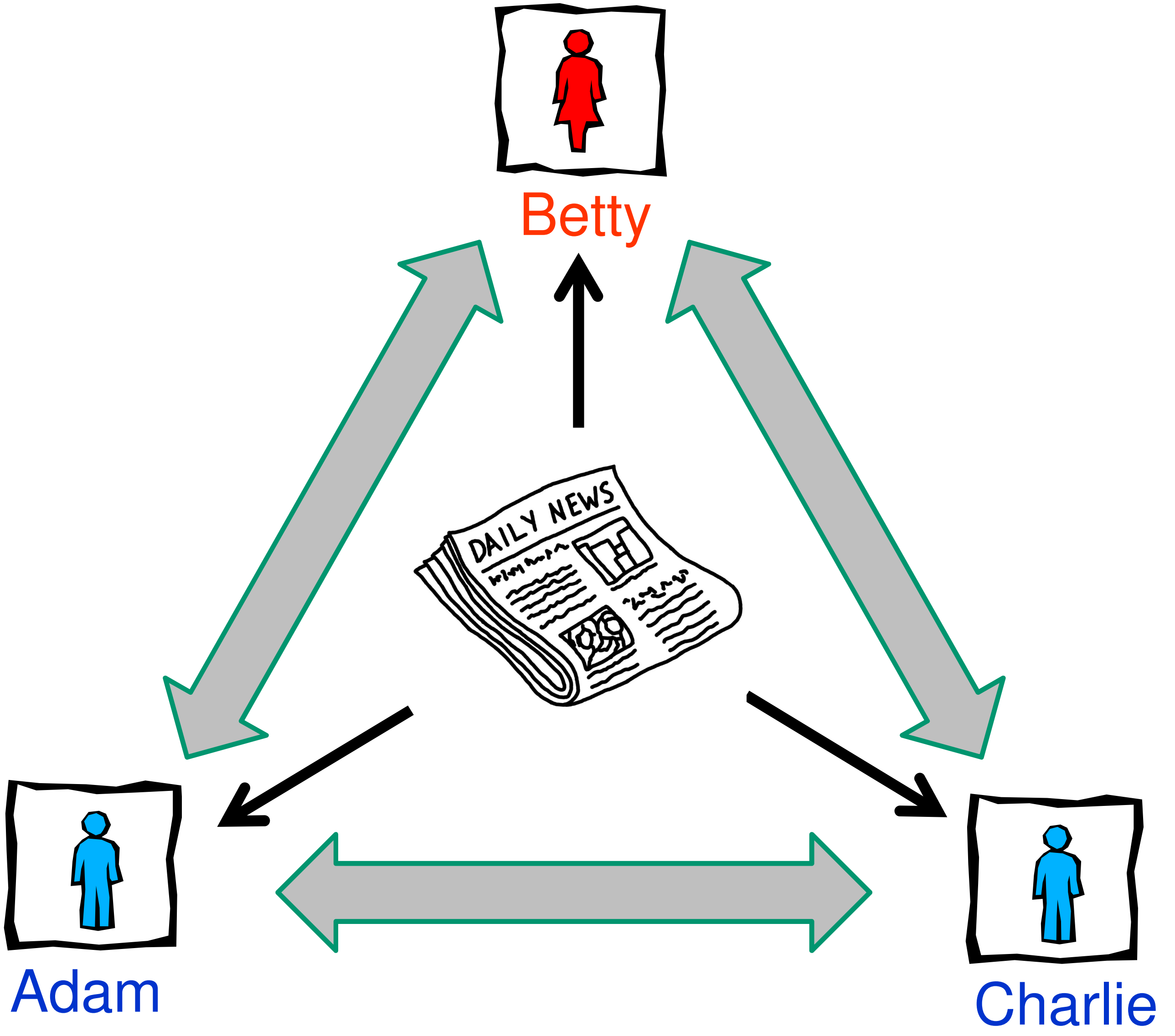


# Love in a wormhole throat

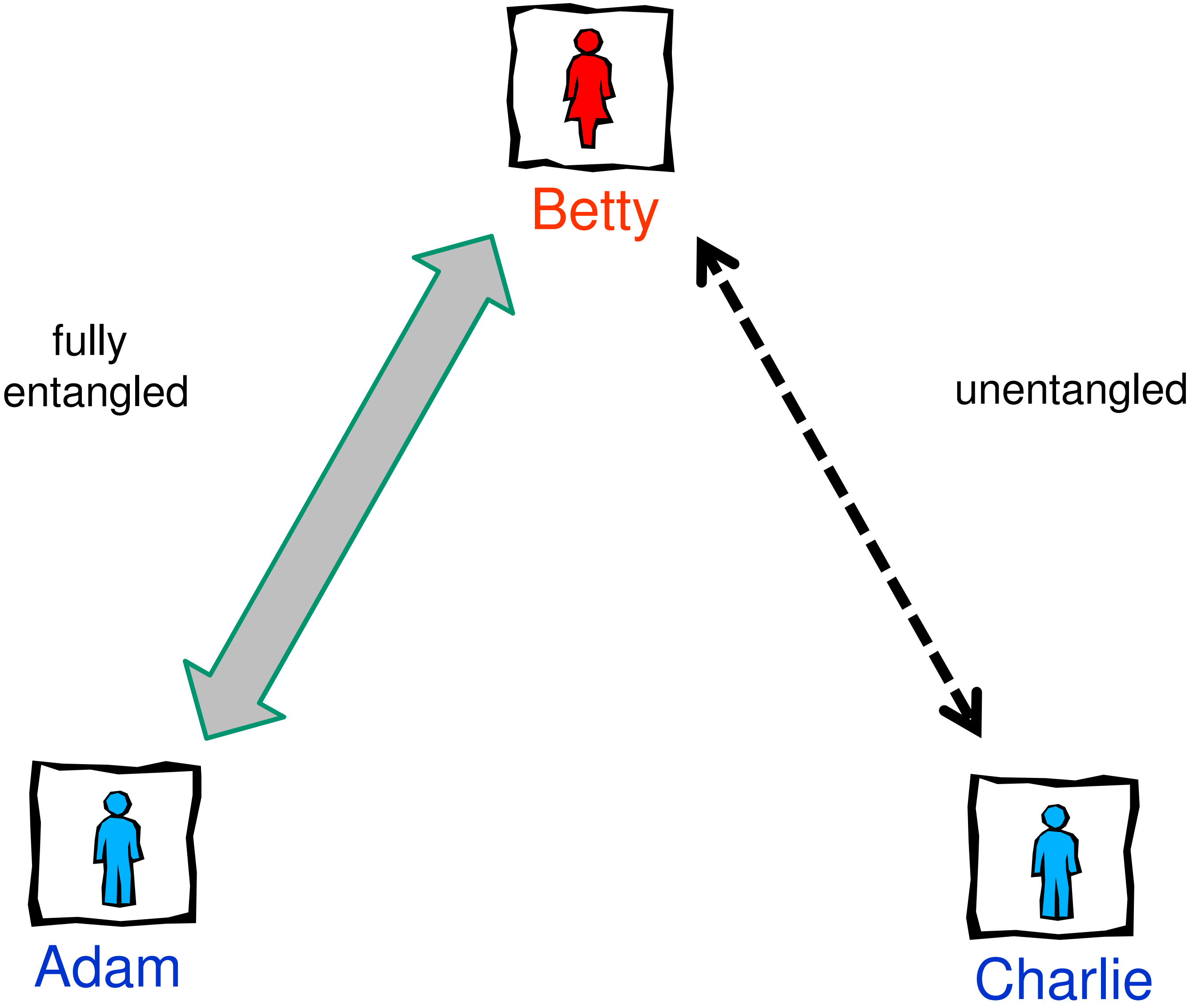


Alice and Bob are in different galaxies, but each lives near a black hole, and their black holes are connected by a wormhole. If both jump into their black holes, they can enjoy each other’s company for a while before meeting a tragic end.

# Classical correlations are polygamous



# Quantum correlations are *monogamous*



Betty

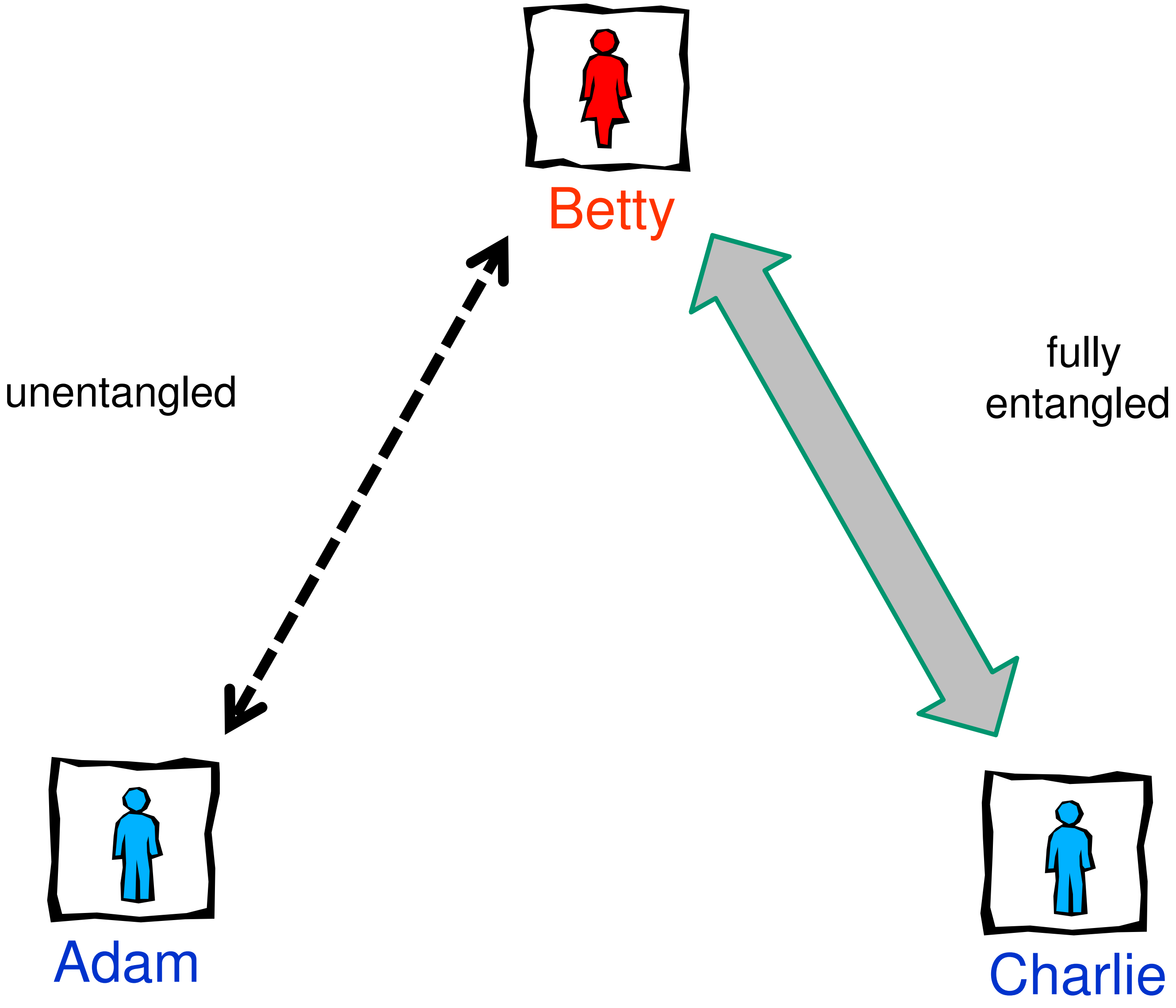
fully
entangled

unentangled

Adam

Charlie

# Quantum correlations are *monogamous*



Betty

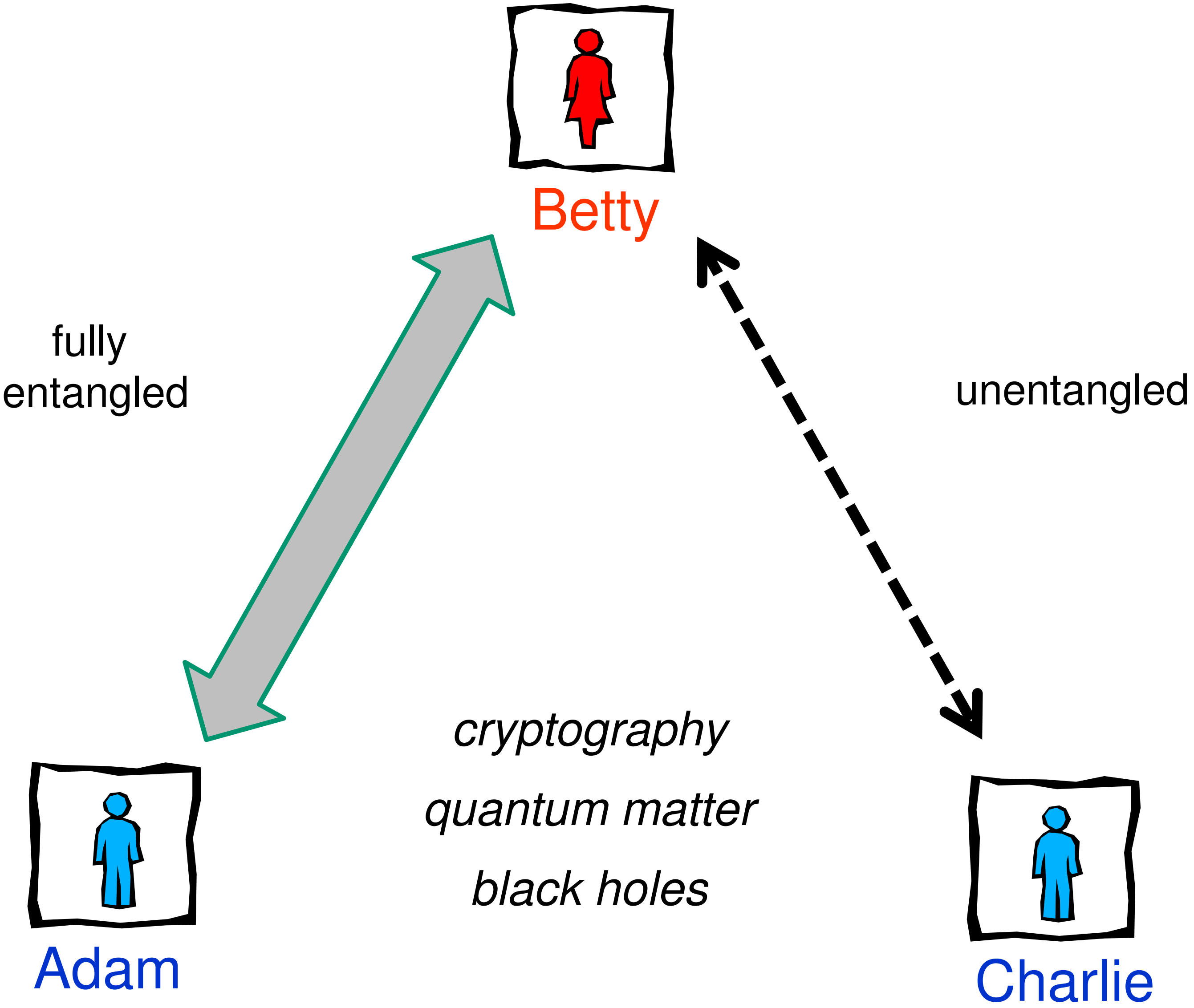
unentangled

fully
entangled

Adam

Charlie

# Monogamy is *frustrating*!



Betty

fully
entangled

unentangled

*cryptography*

*quantum matter*

*black holes*

Adam

Charlie

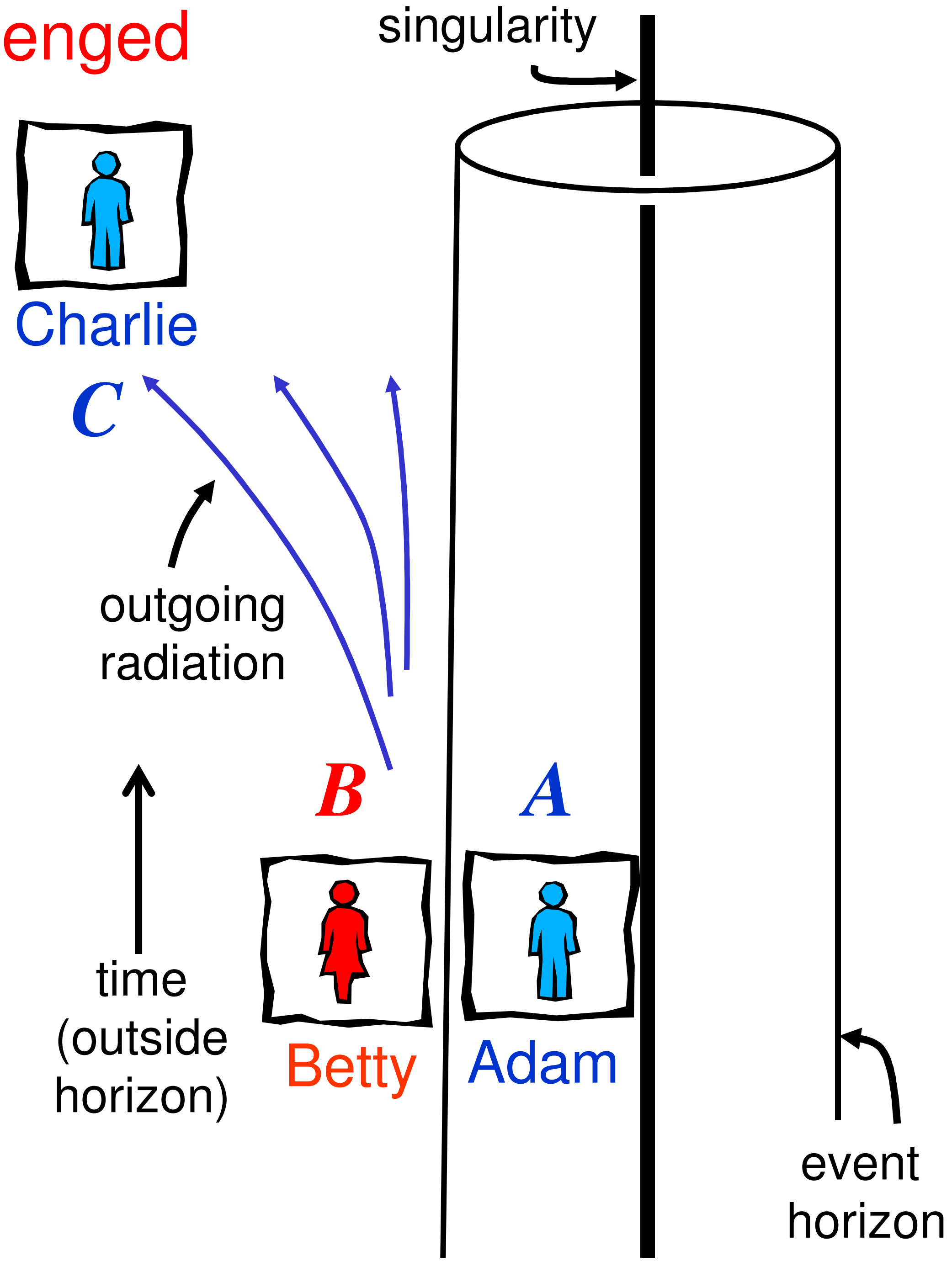
# Complementarity Challenged

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

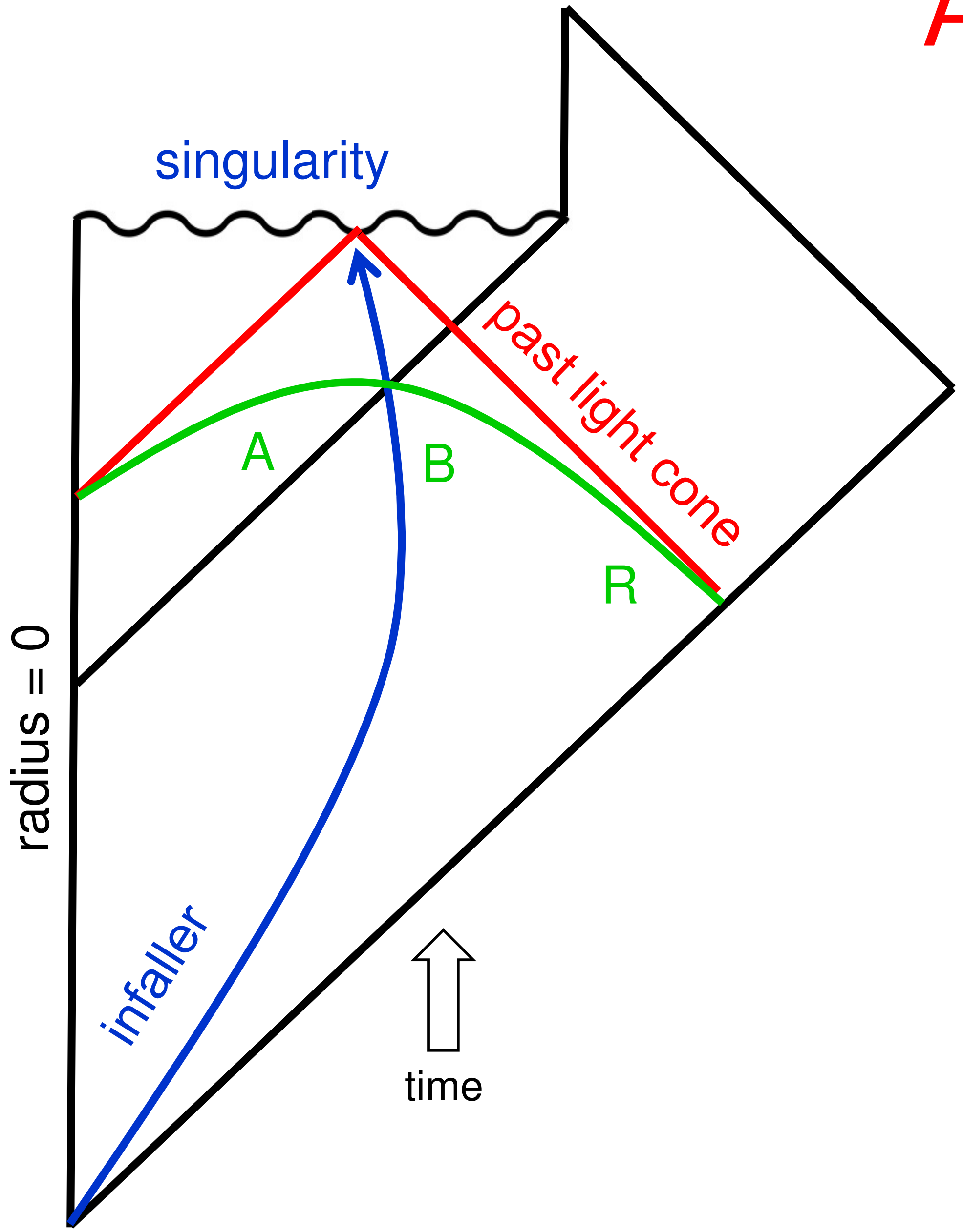
(2) If freely falling observer sees vacuum at the horizon, then the recently emitted radiation (B) is highly entangled with modes behind the horizon (A).

(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

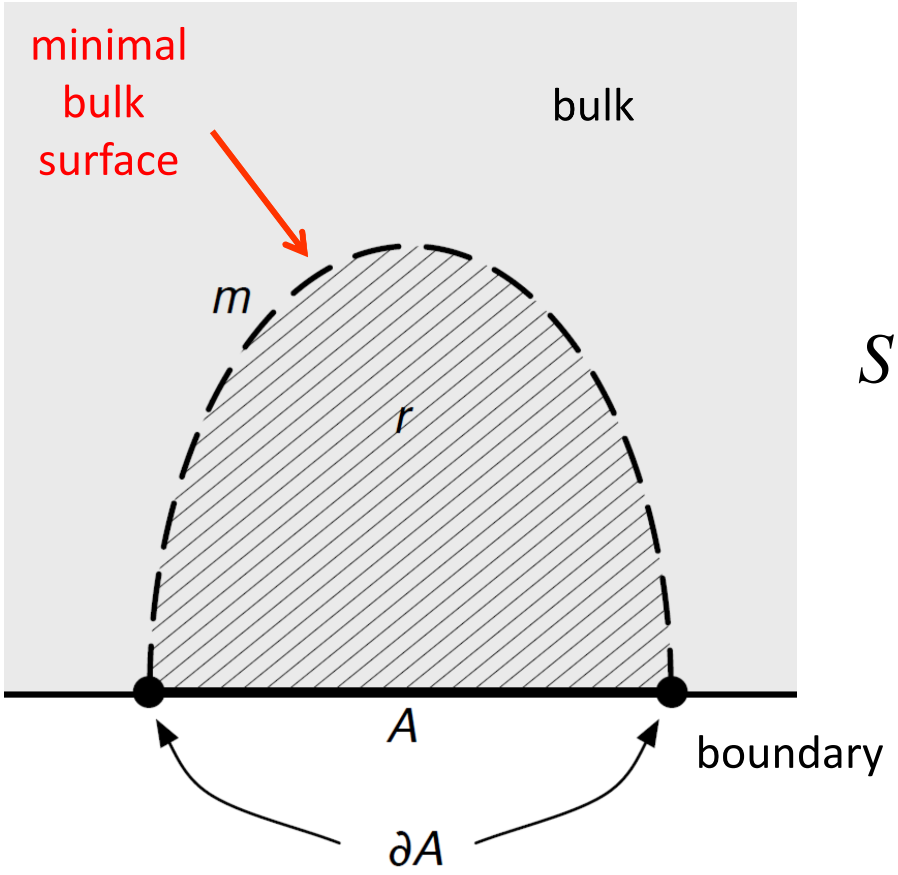


Now a single infalling agent, when still a safe distance from the singularity, can be informed that both the AB and BR entanglement have been confirmed, hence verifying a violation of the monogamy of entanglement.

In contrast to the cloning experiment described earlier, there is no need for super-Planckian signals, because the infaller need not wait for information to be radiated before crossing the horizon.

What happens when this experiment is attempted?

# 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:

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

Ryu and Takayanagi 2006

Recover, for example, in 1+1 dimensional conformal field theory:

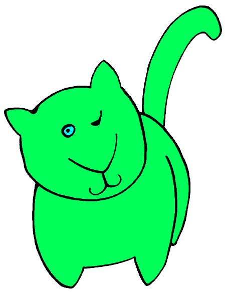
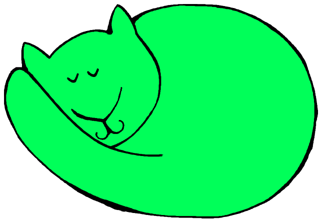
$$S(A(L)) = \frac{c}{3} \log(L/a) + \cdots$$

# “Testing quantum mechanics”

-- “Loophole free” Bell inequality experiments (photons).

-- “Cat states” (macroscopic superpositions).

-- Complex highly-entangled systems (toward “quantum supremacy”).

$\frac{1}{\sqrt{2}}\Big($  $+$  $\Big)$

What is the alternative to quantum theory?

# Who has the biggest cat?

$^{238}$U, C$_{60}$, spin squeezing, superconducting (flux qubits), optomechanics, Bose-Einstein condensates … How to compare?

$$\frac{1}{\sqrt{2}}\left( |\uparrow\rangle^{\otimes N} + |\nearrow\rangle^{\otimes N} \right)$$

$$\text{"}catiness\text{"} = N / N_{meas} \approx N\left(1 - \left|\langle \nearrow | \uparrow \rangle\right|^2\right)$$

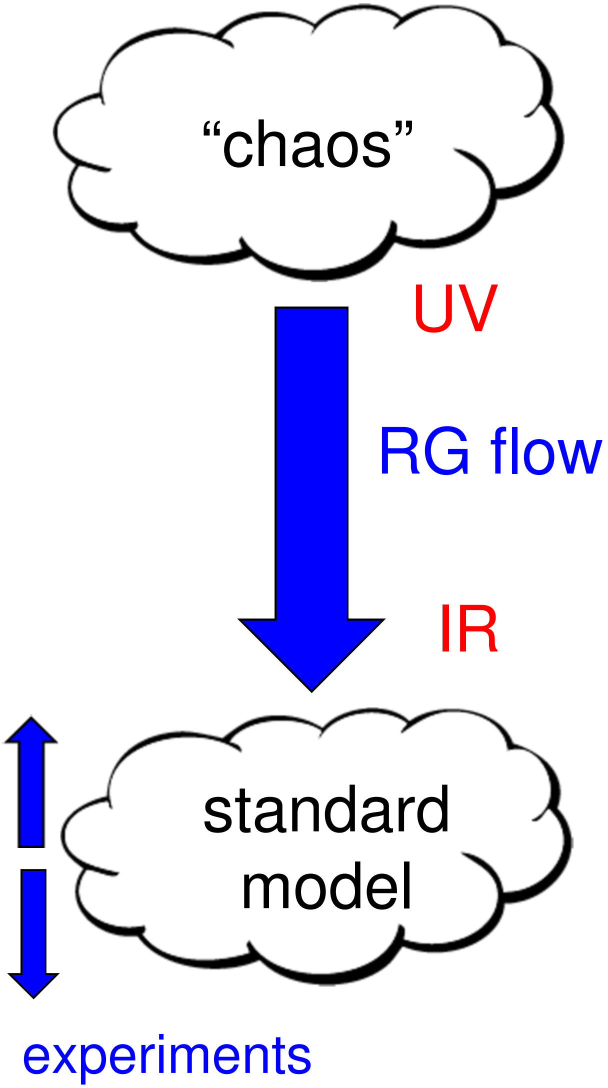
(how may spins we’d measure to collapse the superposition)

-- answer depends on choice of decomposition into subsystems.

-- catiness may depend on spatial separation, or masses.

-- we can’t compare “tests” of quantum theory using different platforms unless we know what we’re testing!

# Emergent quantum mechanics?



-- What principles constrain the “chaos”?

-- Relax unitarity (and locality) in the UV?

-- Violation of unitarity, Lorentz invariance, gauge invariance relevant in the IR?

-- Energy nonconservation and violation of general covariance?

-- Cf. *Quantum error correction*. Encode protected information in highly entangled states, so the information is well protected against environmental decoherence.

-- Dissipation needed to drain entropy introduced by noise. Nonunitary dynamics could provide the necessary dissipation.

-- “Eternal qubits,” engineered to have very long coherence times, might be realized fairly soon.

-- Either “topological codes” or a hierarchy of codes within codes.

# arXiv papers with “entanglement” in the title