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
Lukin
Harvard

Peter
Shor
MIT

Stephen
Jordan
NIST

Juan
Maldacena
IAS

Jacob
Taylor
NIST

Patrick
Hayden
Stanford

John
Preskill
Caltech

Carl
Williams
NIST

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.

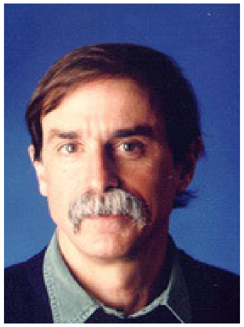
Two-level atoms in a high-finesse microcavity, strongly coupled to cavity modes of the electromagnetic field.

Linear optics with efficient single-photon sources and detectors.

Nuclear spins in semiconductors, and in liquid state NMR.

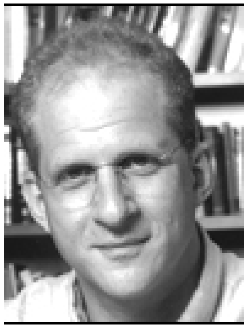
Nitrogen vacancy centers in diamond.

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



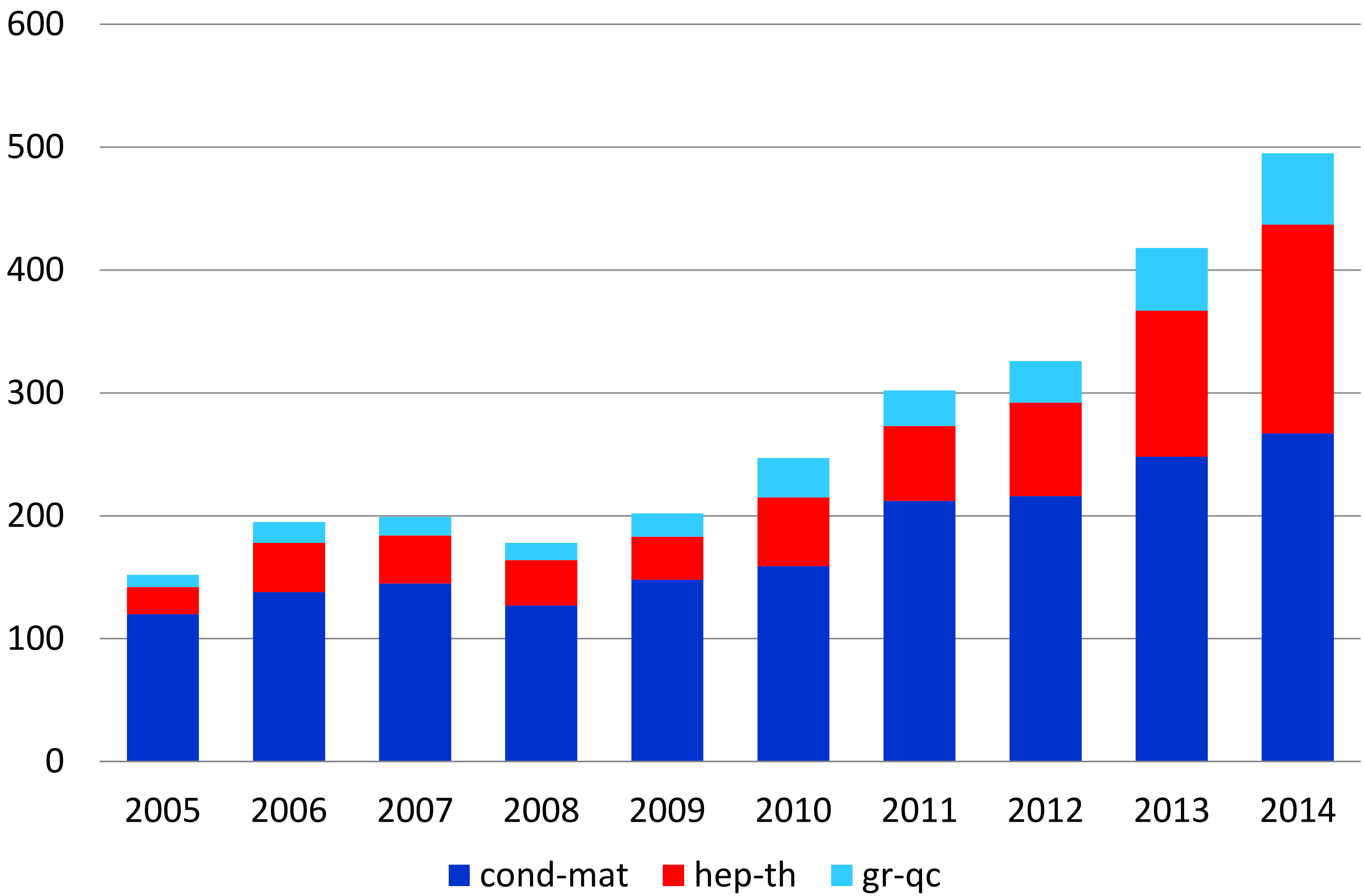
Wineland

Blatt

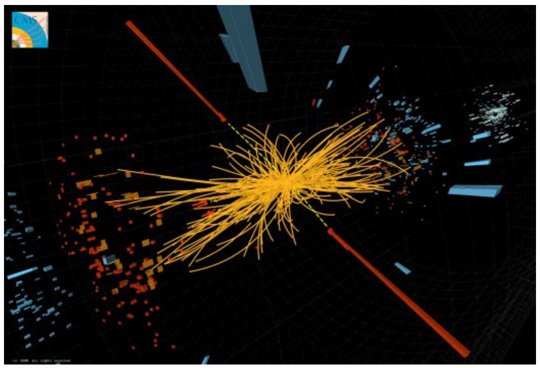
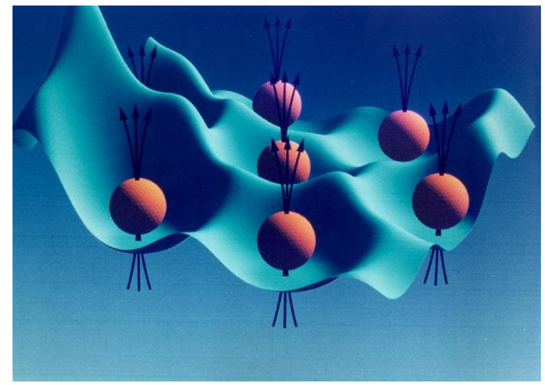


Marcus

arXiv papers with “entanglement” in the title



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

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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.

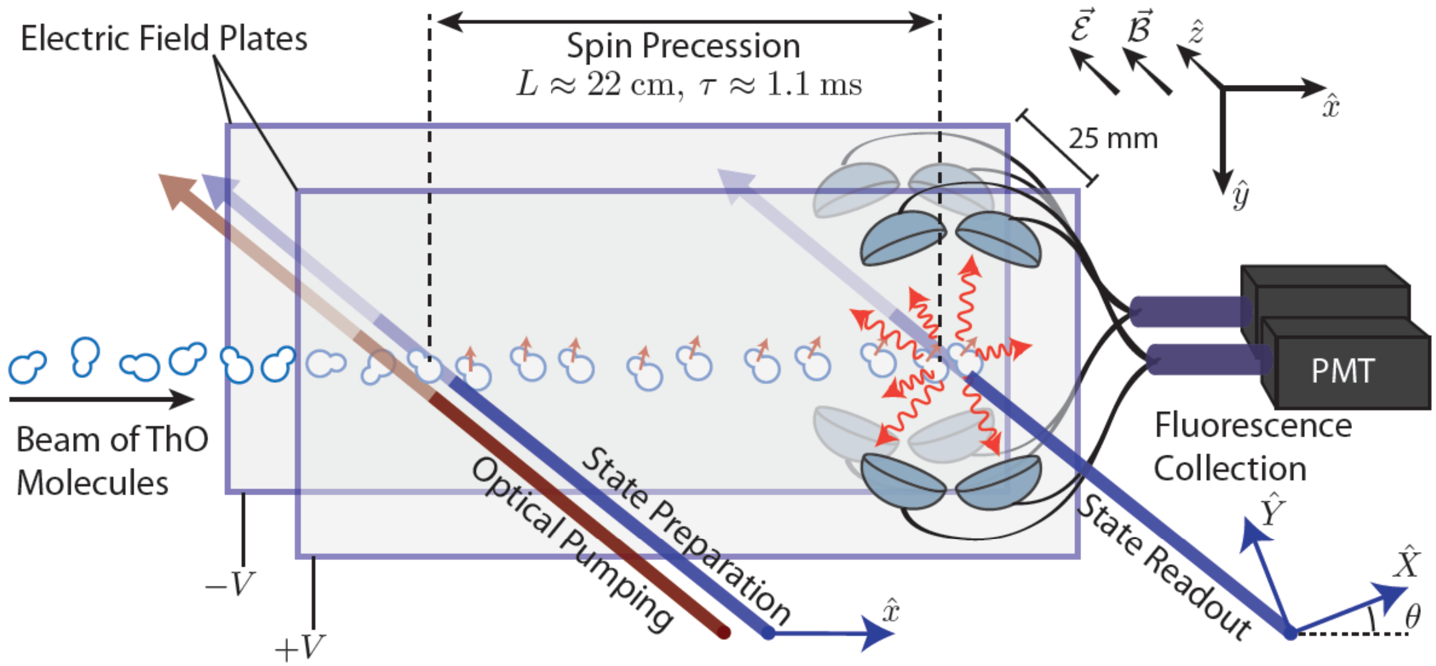
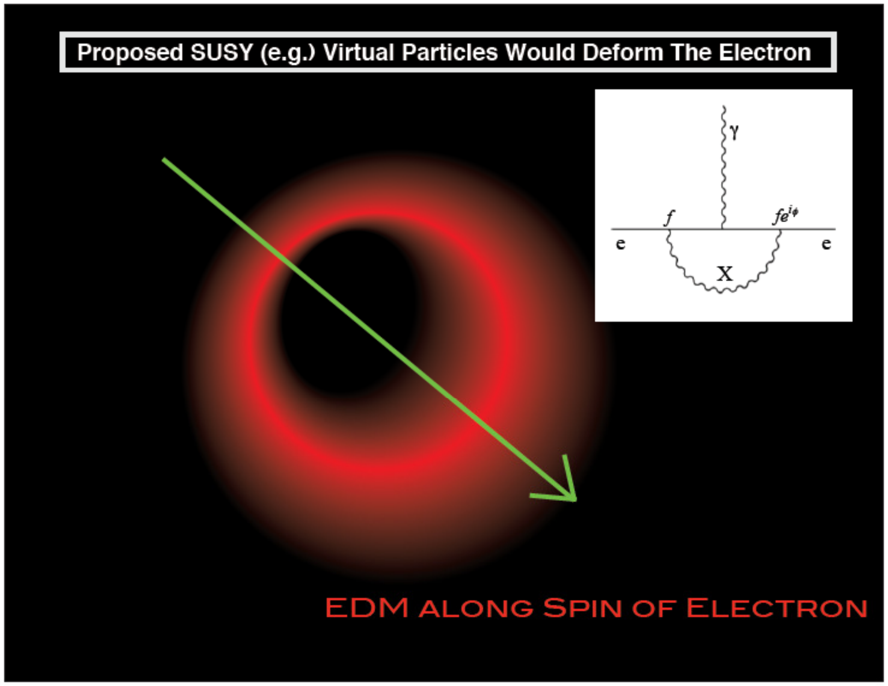


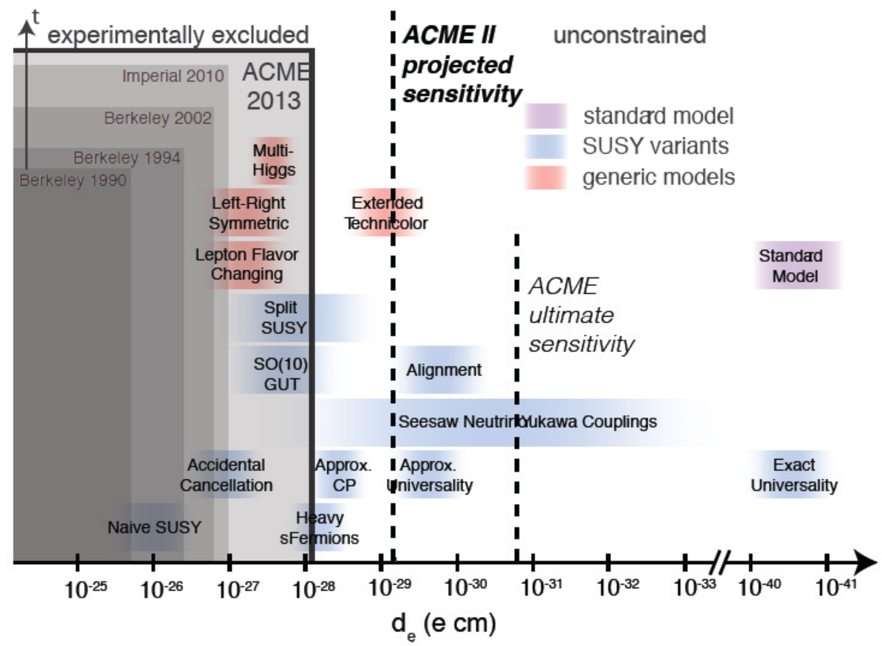
FIG. 1. Schematic of the apparatus (not to scale). A collimated pulse of ThO molecules enters a magnetically shielded region. An aligned spin state (smallest red arrows), prepared via optical pumping, precesses in parallel electric and magnetic fields. The final spin alignment is read out by a laser 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

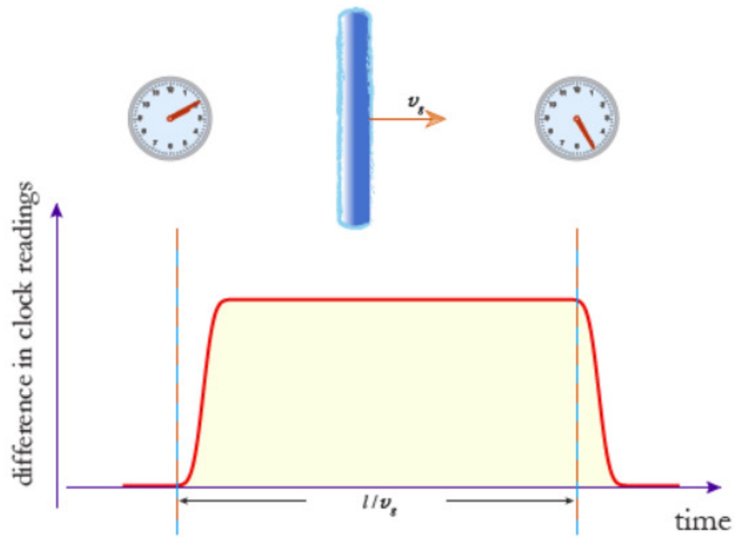


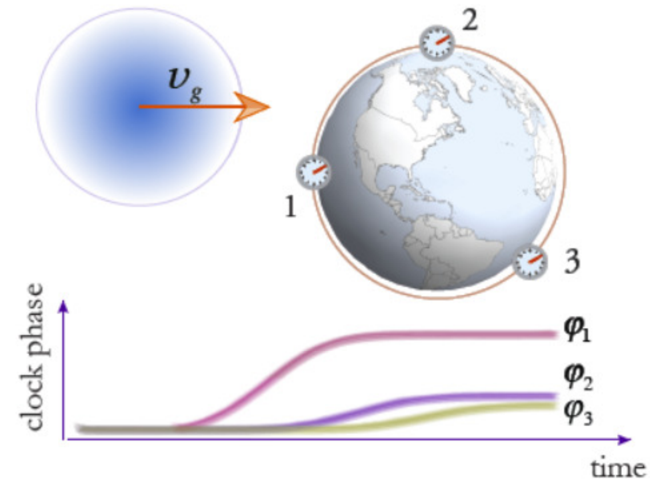


Measurements are ultimately limited by quantum noise

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

Listening to dark matter with a network of atomic clocks/sensors





Derevianko and Pospelov, Nature Phys. 10, 933 (2014)

- Differential signals last for ~30 s for transcontinental networks, ~200 s for GPS
- X-correlations between clocks are important as
  once a year short-duration events can be dismissed as outliers
- Other possibilities: networks of magnetometers (Budker et al), LIGO, …

PHYSICAL REVIEW X 4, 021030 (2014)

Proposal for a Cosmic Axion Spin Precession Experiment (CASPEr)

Dmitry Budker,[1,5] Peter W. Graham,[2] Micah Ledbetter,[3] Surjeet Rajendran,[2] and Alexander O. Sushkov[4]
[1]*Department of Physics, University of California, Berkeley, California 94720, USA and Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[2]*Department of Physics, Stanford Institute for Theoretical Physics, Stanford University, Stanford, California 94305, USA*

What credible deviations from conventional quantum theory are experimentally testable?

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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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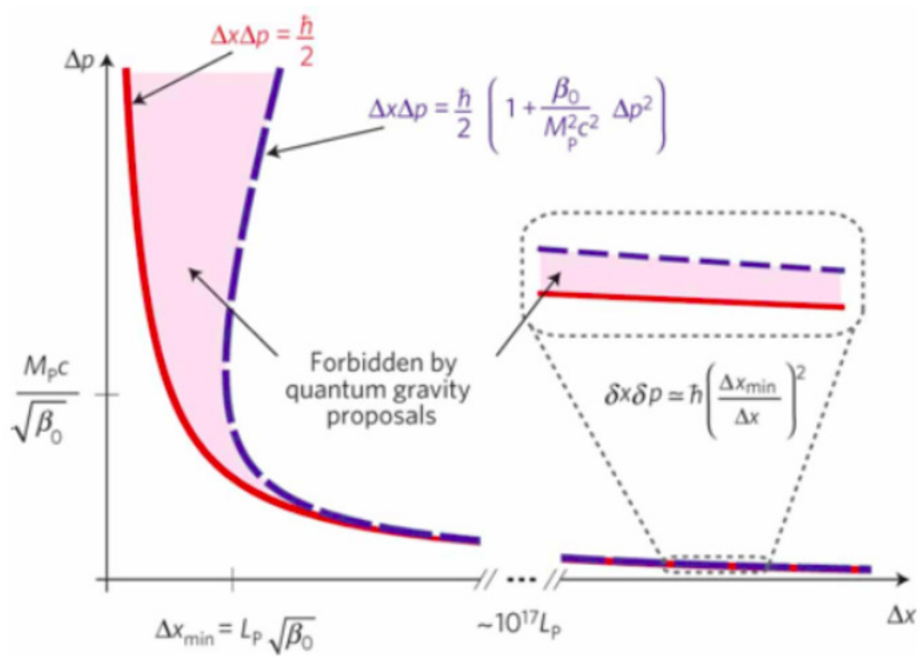
Deutsche Physikalische Gesellschaft DPG | IOP Institute of Physics

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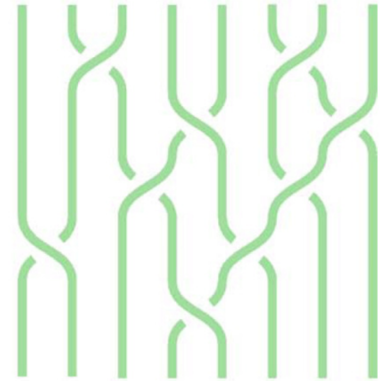
Exact or approximate solutions to NP-hard problems with significant speedups with respect to classical algorithms?

Small quantum computer as testbed for algorithms.

Applications of scattering theory.

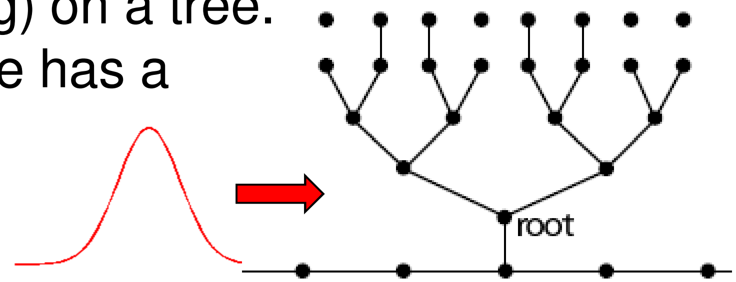
Theoretical and experimental exploration of adiabatic quantum computing.

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.

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

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

Can quantum computers efficiently simulate all physical phenomena?

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Both YES and NO are interesting answers!

Quantum field theory has a local Hamiltonian.

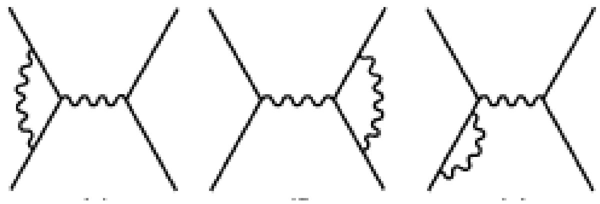
Gauge theories, massless particles, improved scaling of cost with error, tensor network approaches, …

Nonperturbative quantum field theory.

Strongly coupled string theory?

What is string theory?

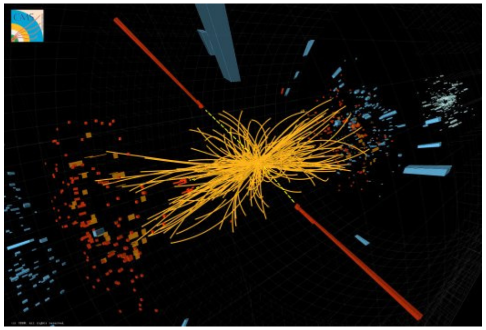
Quantum algorithms for quantum field theories



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?

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Euclidean Monte Carlo methods limited to static properties.

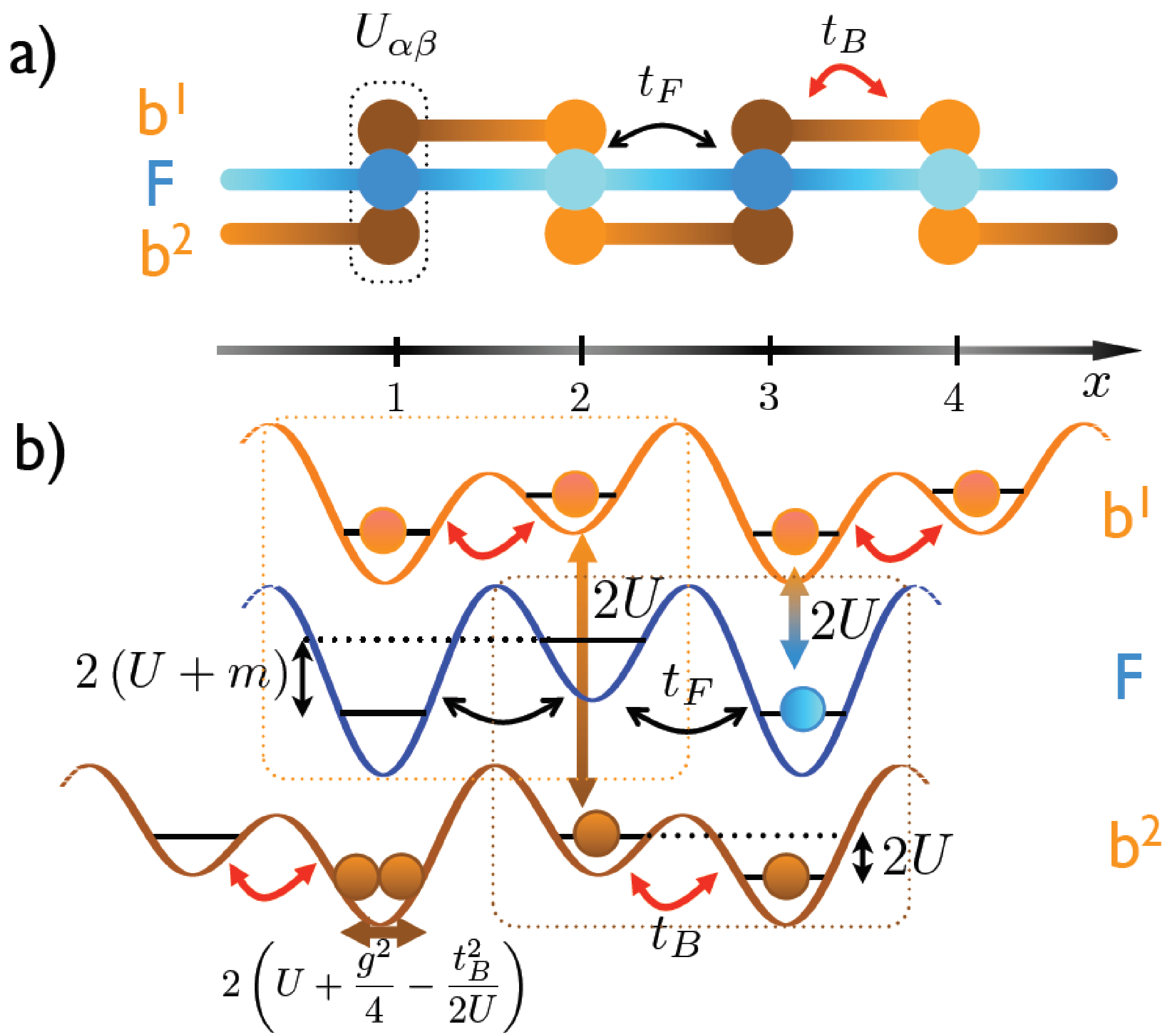
Real time evolution is hard classically, may be easy quantumly.

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.

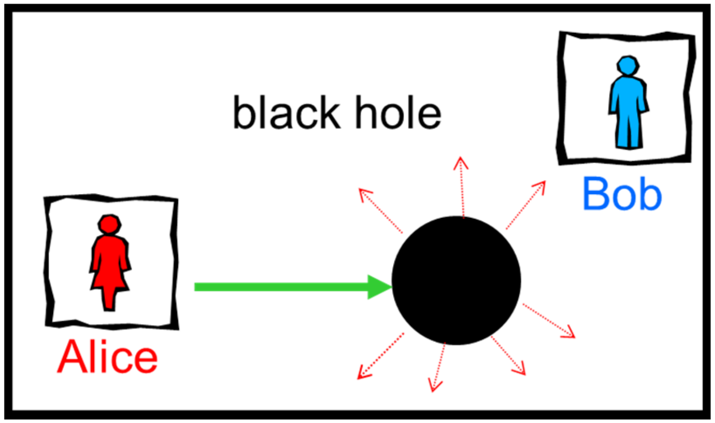
Witten: I hope so. I'm afraid it's hard to work on, so in fact I've worked with more familiar kinds of questions.

Kavli IPMU News
December 2014

What's inside a black hole?

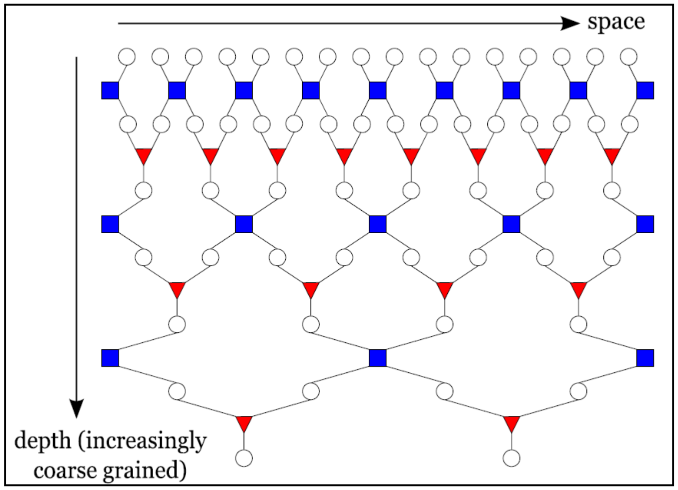
Quantum error correction: "black holes as mirrors" and bulk/boundary correspondence.

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?

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Entanglement is a "resource theory"

Other resources, e.g. in thermodynamics.

What is entanglement in time?

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/