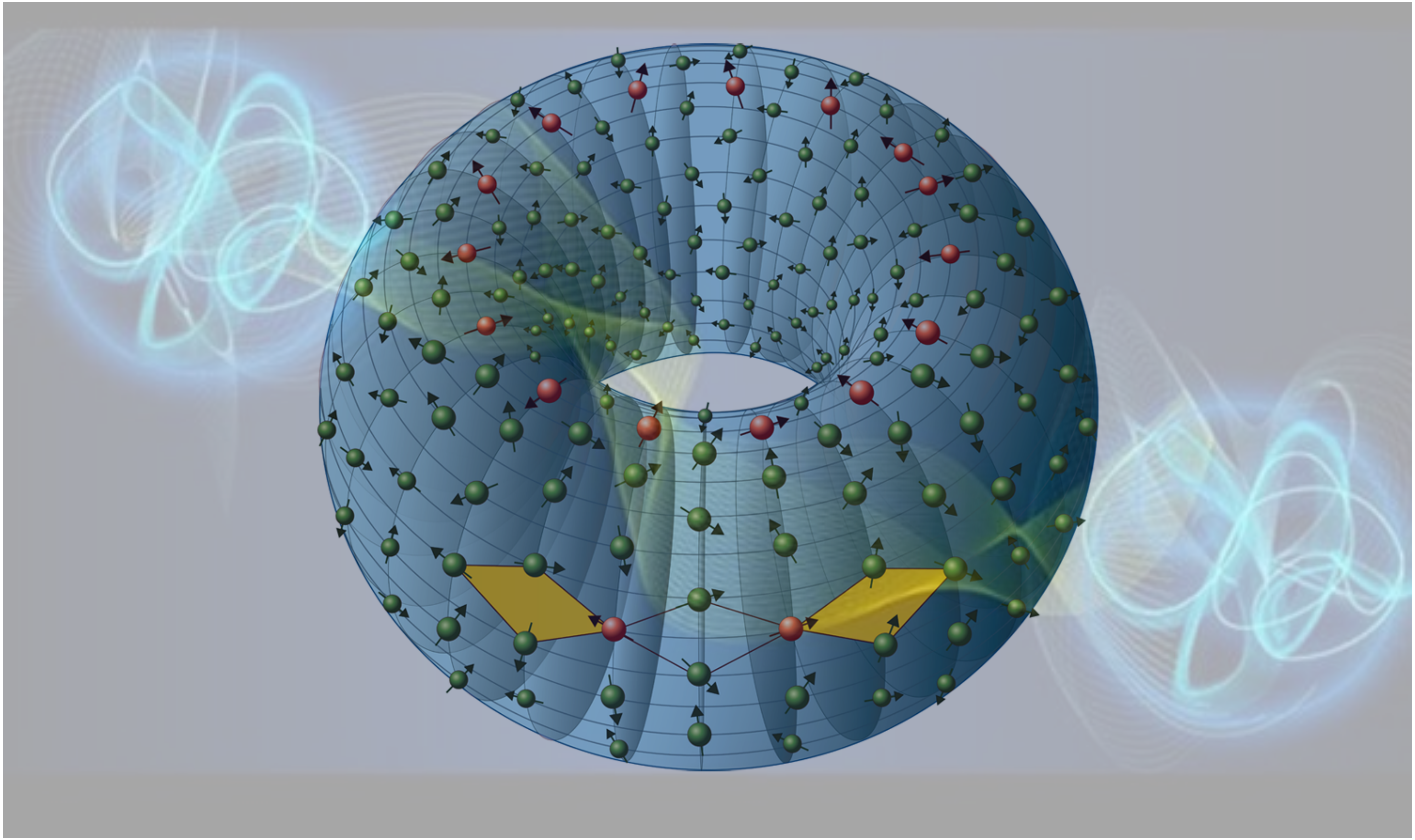


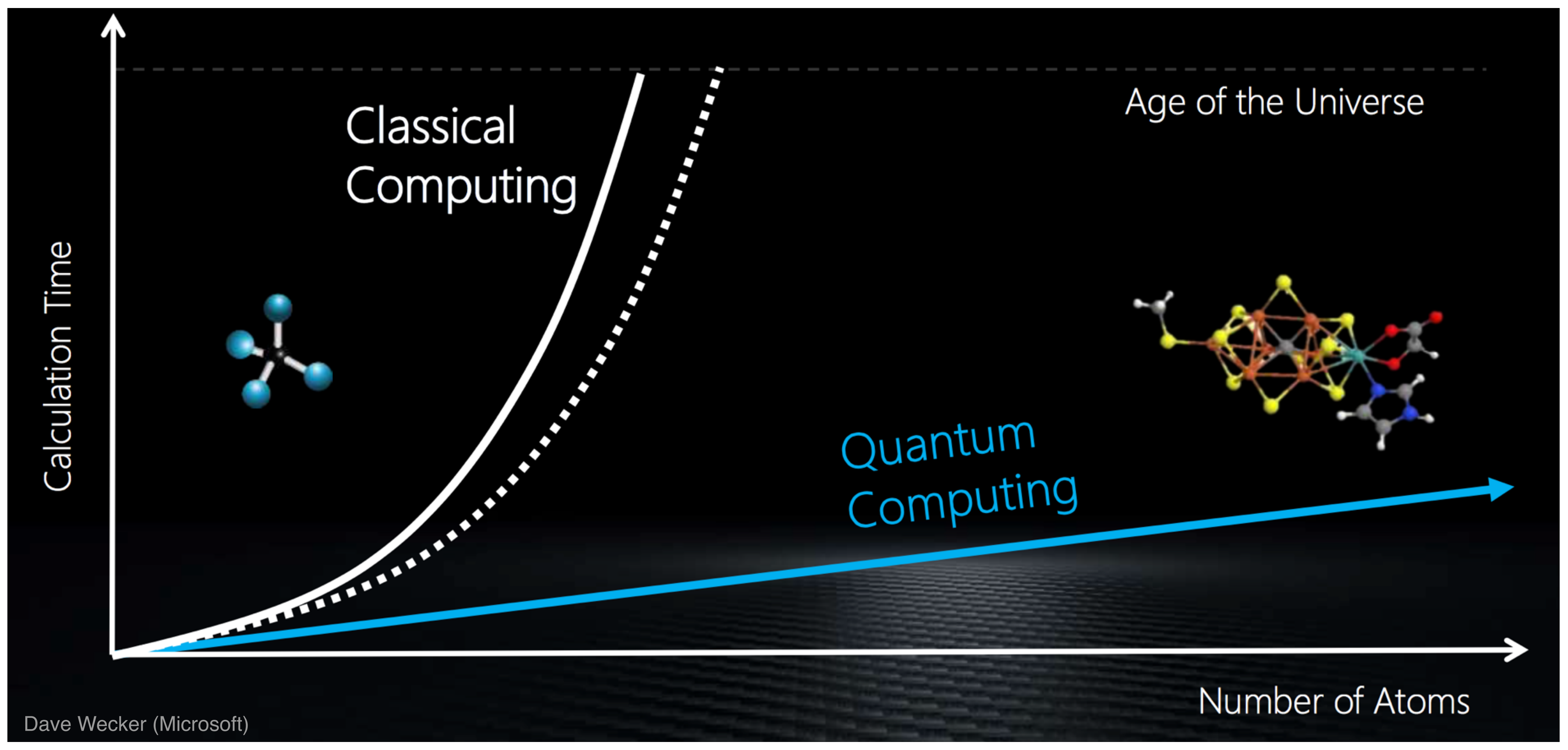
Quantum Computing and Quantum Information for Nuclear Physics

Presentation to NSAC
Washington DC, Nov 2, 2018

Martin J Savage

INSTITUTE for NUCLEAR THEORY

The Potential of Quantum Computing

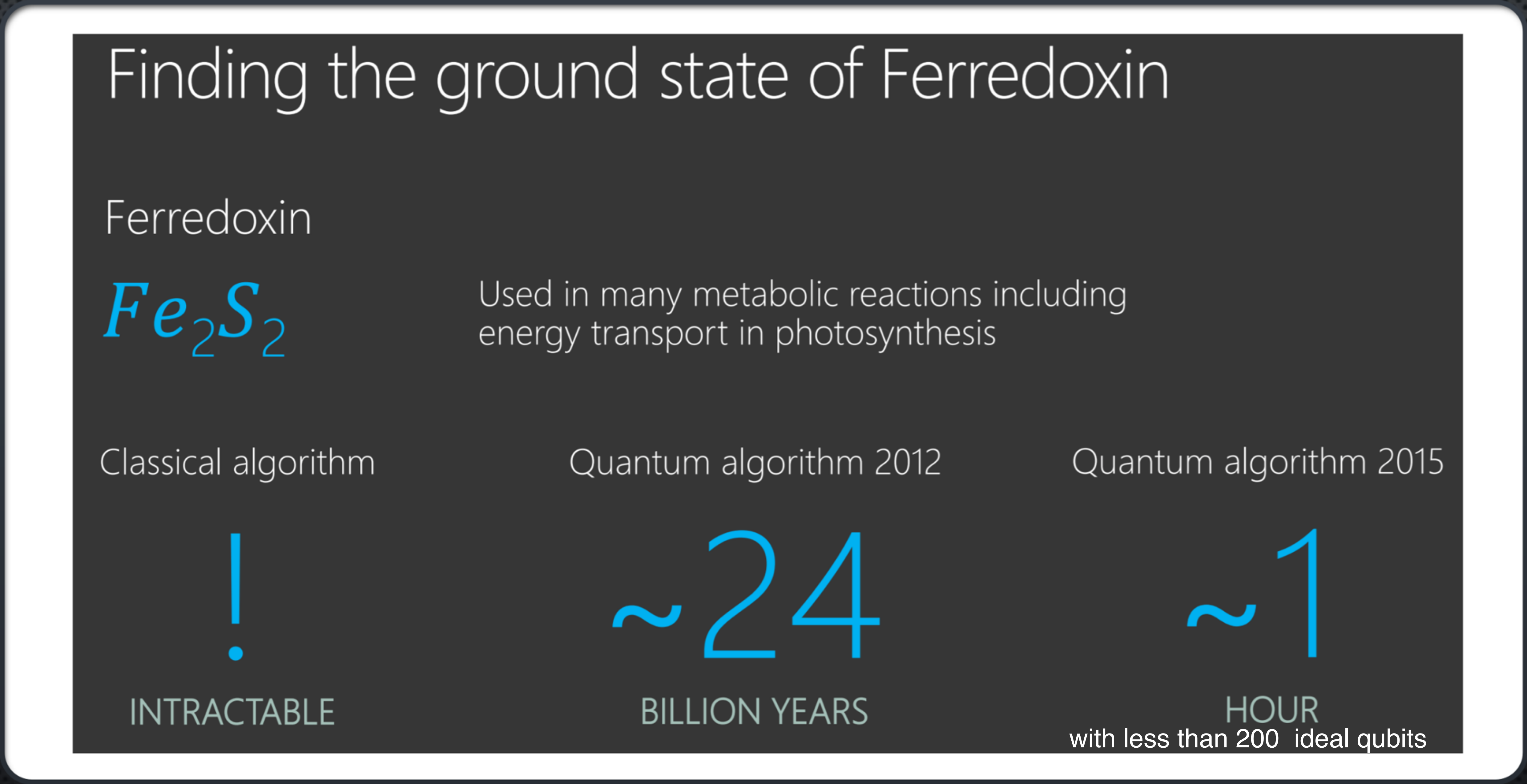


~ 100 qubit devices can address problems in chemistry that are beyond classical computing

50 qubits : ~ 20 petabytes ~ Leadership-Class HPC facility

300 qubits : more states [10^{90}] than atoms in universe [10^{86}]

The Potential of Quantum Computing



Finding the ground state of Ferredoxin

Ferredoxin

Fe_2S_2

Used in many metabolic reactions including energy transport in photosynthesis

Classical algorithm	Quantum algorithm 2012	Quantum algorithm 2015
!	~24	~1
INTRACTABLE	BILLION YEARS	HOUR

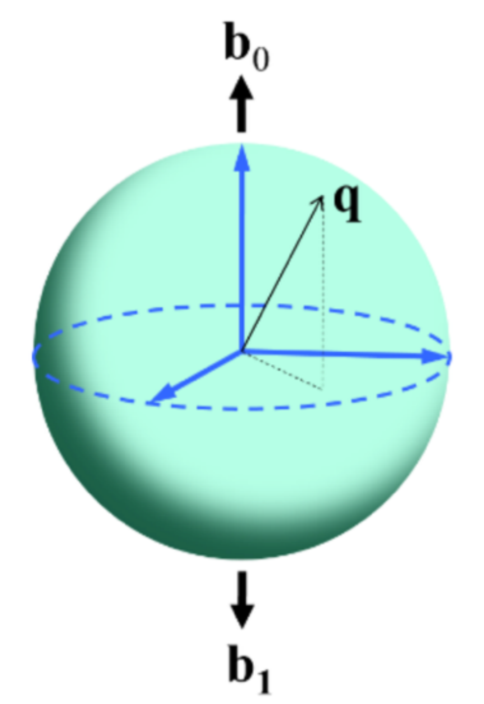
with less than 200 ideal qubits

Slide: Dave Wecker (Microsoft)

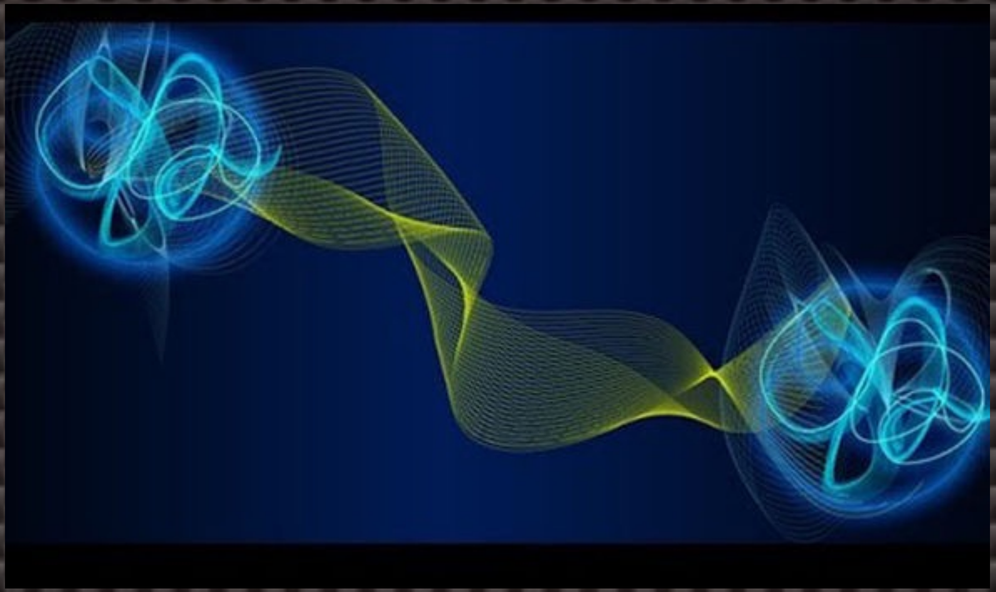
Slide by Natalie Klco (Oct 2018)

[solution to 1 part per million]

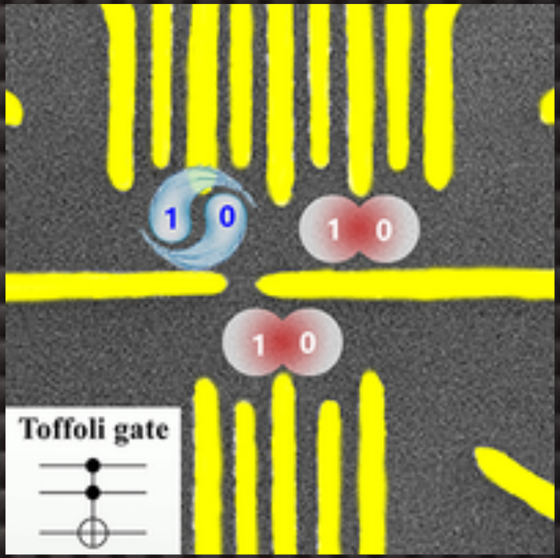
Quantum Computing and Quantum Information



Qubits

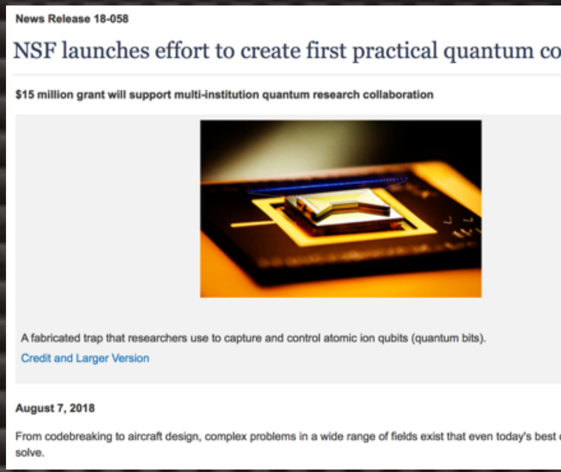


Entanglement
and Superposition



Unitary Operations
and Measurements

“First Qubits” for Applications


News Release 18-058

NSF launches effort to create first practical quantum co

$15 million grant will support multi-institution quantum research collaboration

A fabricated trap that researchers use to capture and control atomic ion qubits (quantum bits).

Credit and Larger Version

August 7, 2018

From codebreaking to aircraft design, complex problems in a wide range of fields exist that even today's best
solve.

- In cases:
- Tech companies, national laboratories and universities are working together to develop hardware
- Technology companies are making their quantum devices available for computations via the cloud
- Laboratories and companies are making their hardware available through collaboration

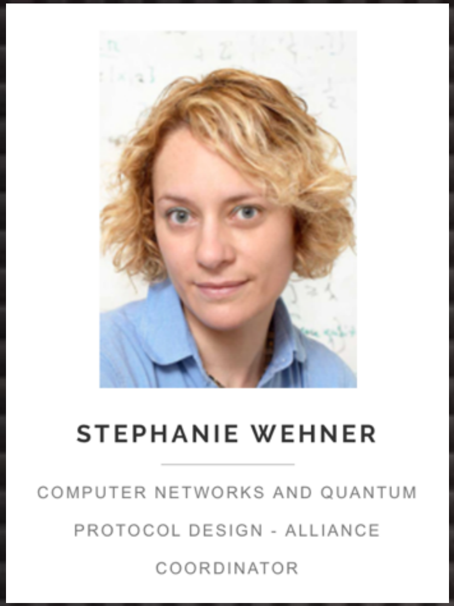
Quantum Communication
Recent

EU Awards Ten Million Euro to European Quantum Internet Alliance to Speed up Development of Quantum Internet

1 day 2 hours ago by Delft University of Technology

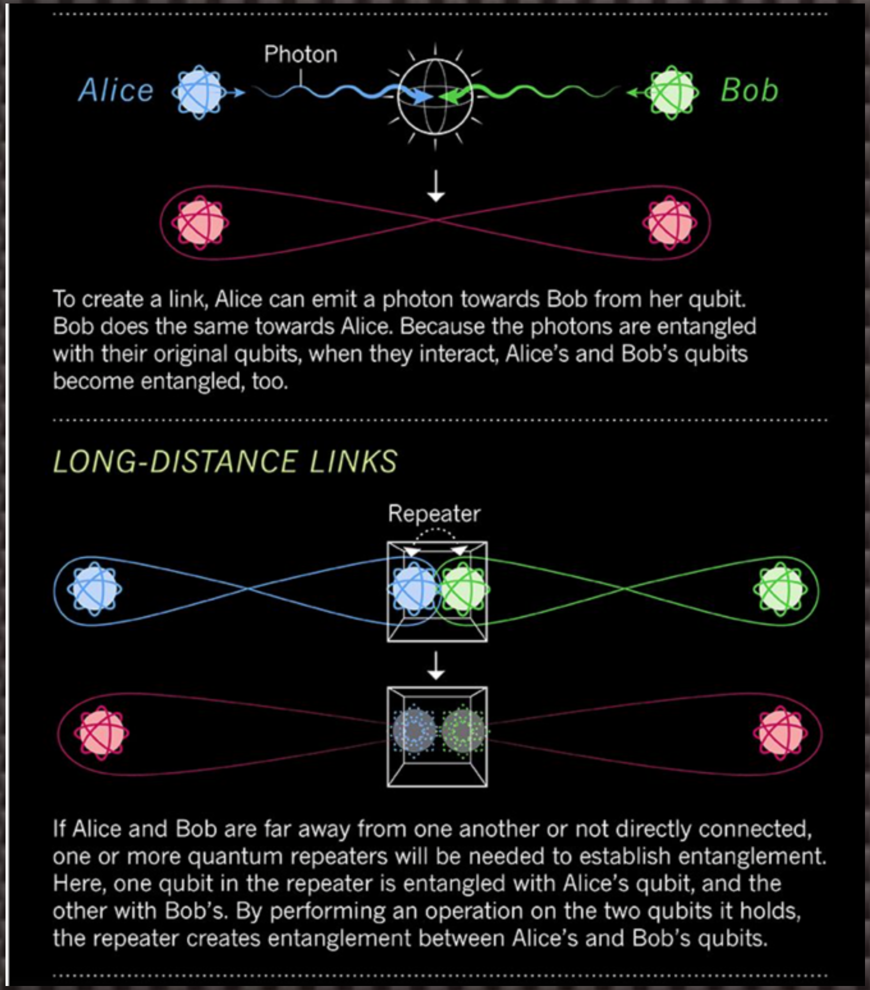
(Image Source: TU Delft/Scixel)

October (2018)



STEPHANIE WEHNER

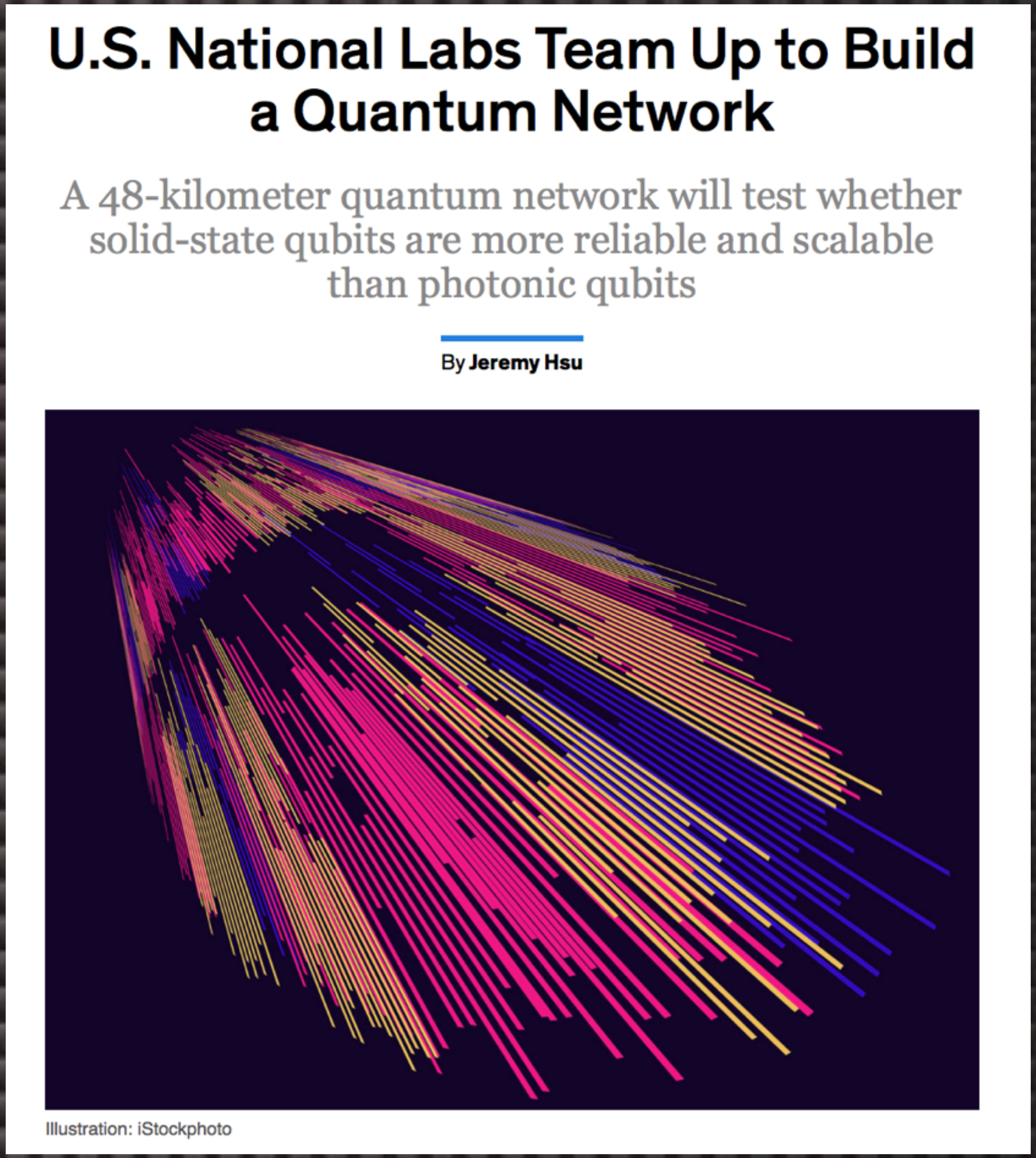
COMPUTER NETWORKS AND QUANTUM PROTOCOL DESIGN - ALLIANCE COORDINATOR



To create a link, Alice can emit a photon towards Bob from her qubit. Bob does the same towards Alice. Because the photons are entangled with their original qubits, when they interact, Alice's and Bob's qubits become entangled, too.

LONG-DISTANCE LINKS

If Alice and Bob are far away from one another or not directly connected, one or more quantum repeaters will be needed to establish entanglement. Here, one qubit in the repeater is entangled with Alice's qubit, and the other with Bob's. By performing an operation on the two qubits it holds, the repeater creates entanglement between Alice's and Bob's qubits.



U.S. National Labs Team Up to Build a Quantum Network

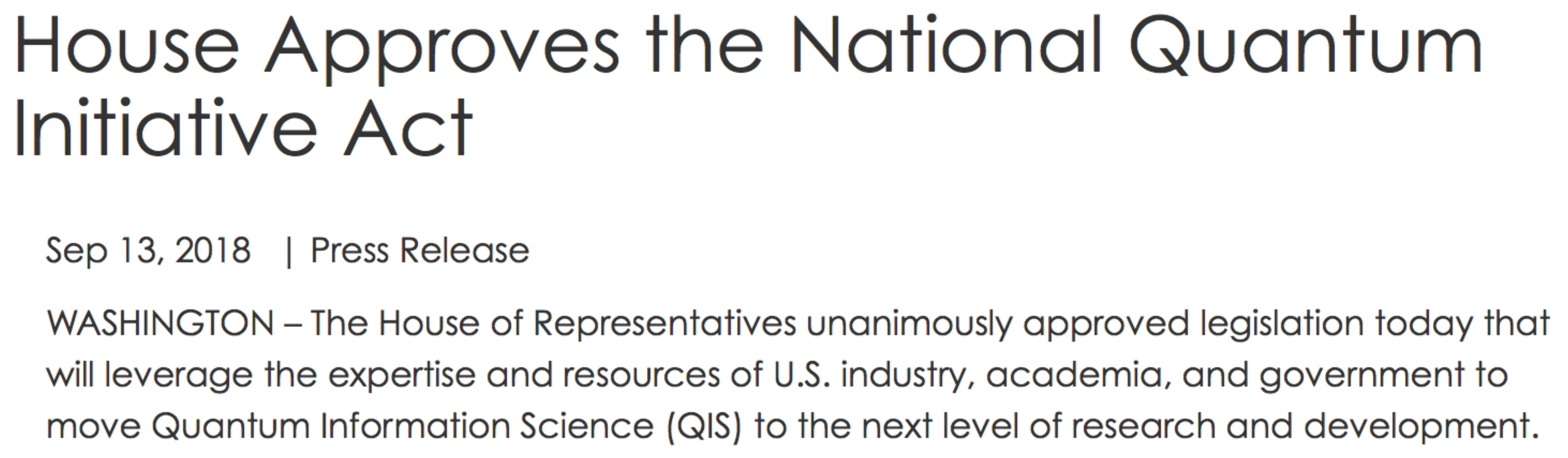
A 48-kilometer quantum network will test whether solid-state qubits are more reliable and scalable than photonic qubits

By **Jeremy Hsu**

Illustration: iStockphoto

FNAL to ANL

October (2018)



House Approves the National Quantum Initiative Act

Sep 13, 2018 | Press Release

WASHINGTON – The House of Representatives unanimously approved legislation today that will leverage the expertise and resources of U.S. industry, academia, and government to move Quantum Information Science (QIS) to the next level of research and development.

https://science.house.gov/news/press-releases/house-approves-national-quantum-initiative-act

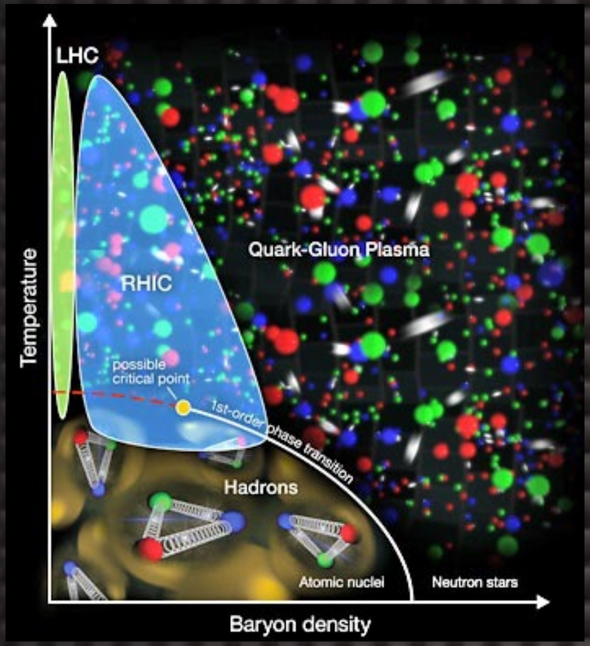
Motivation(s) for Nuclear Physics

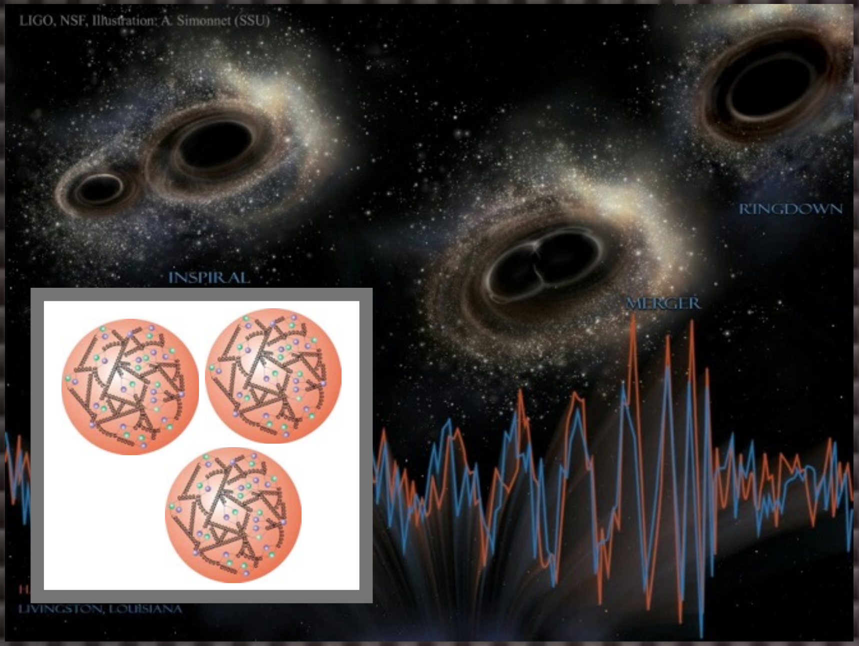
Quantum Information and Quantum Computing has the potential

- to provide improvements in sensing and detection.
- to perform fully-controlled large-scale simulations of quantum many-body systems and of the standard model. To integrate with and complement classical computing (not replace).
- for transforming the handling of data.

Currently there is no explicitly demonstrated Quantum Advantage for any scientific application, but ….

Quantum Many-Body Systems



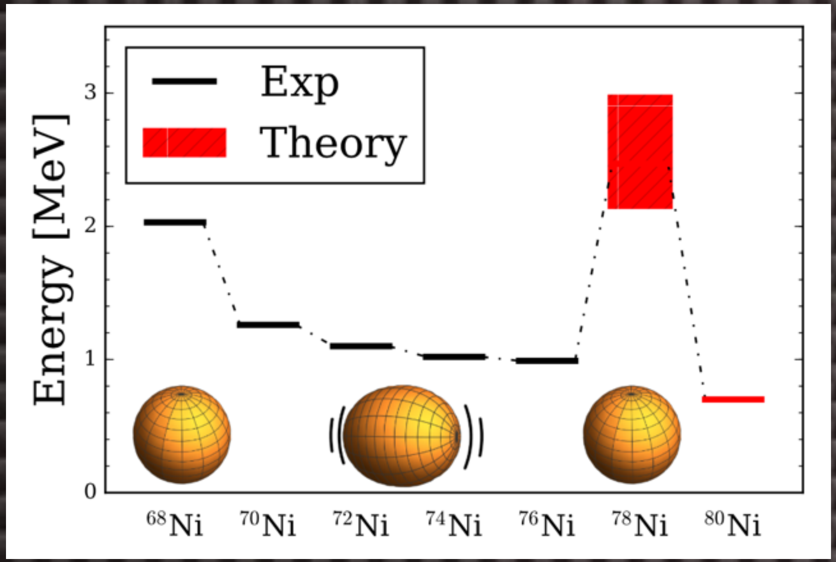

LIGO, NSF, Illustration: A. Simonnet (SSU)

Finite Density Systems

- Quantum Monte Carlo
- Sign Problem(s) in Sampling

Nuclear Many-Body Problem

- Schrodinger Eqn.
- Hilbert space grows exponentially with particles



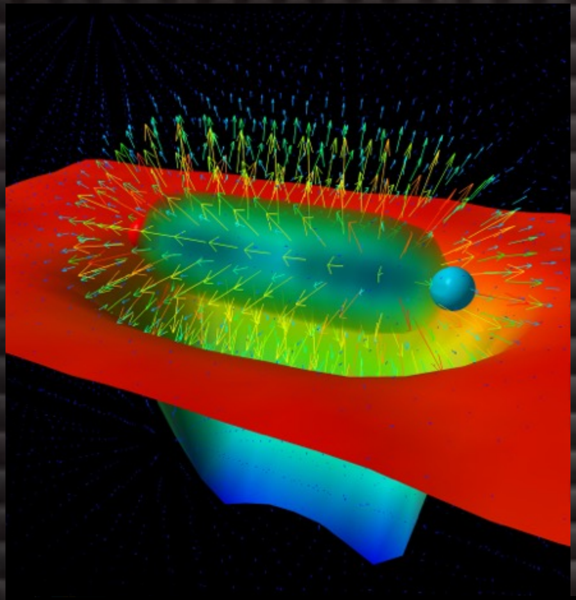
Classical Computing

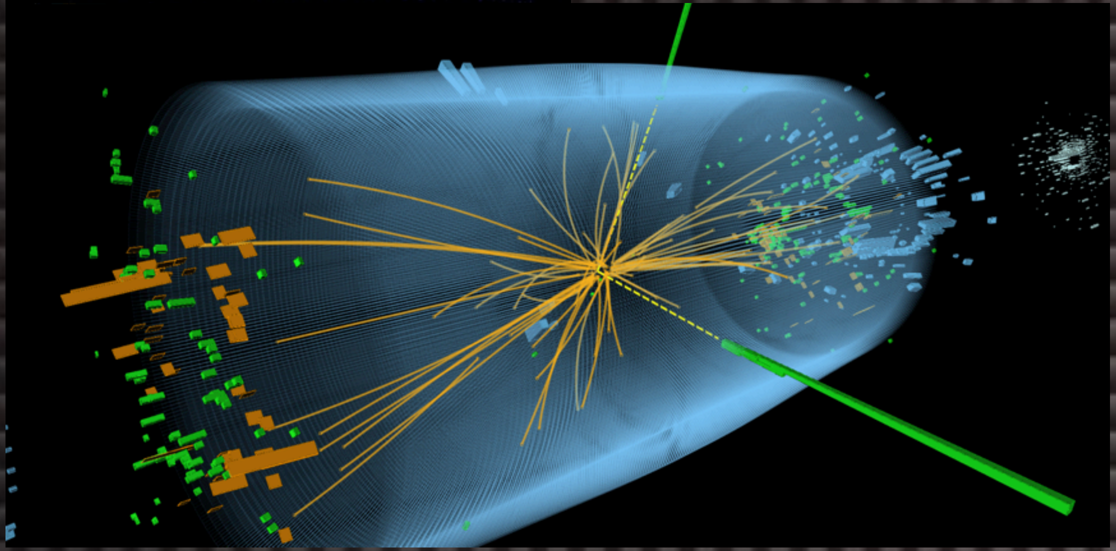
- Exponentially large resources
- Exponentially growing memory for large nuclei

Quantum Computing

- No sign problem (naively)
- Real-time evolution
- Hilbert space grows exponentially with number of qubits
  - i.e. 1 qubit doubles size

The Standard Model





Quantum Field Theories and Fundamental Symmetries

- indefinite particle number
- gauge symmetries and constraints

Real-Time Evolution

- Integrals over phases
- Fragmentation
- Neutrinos in dense matter

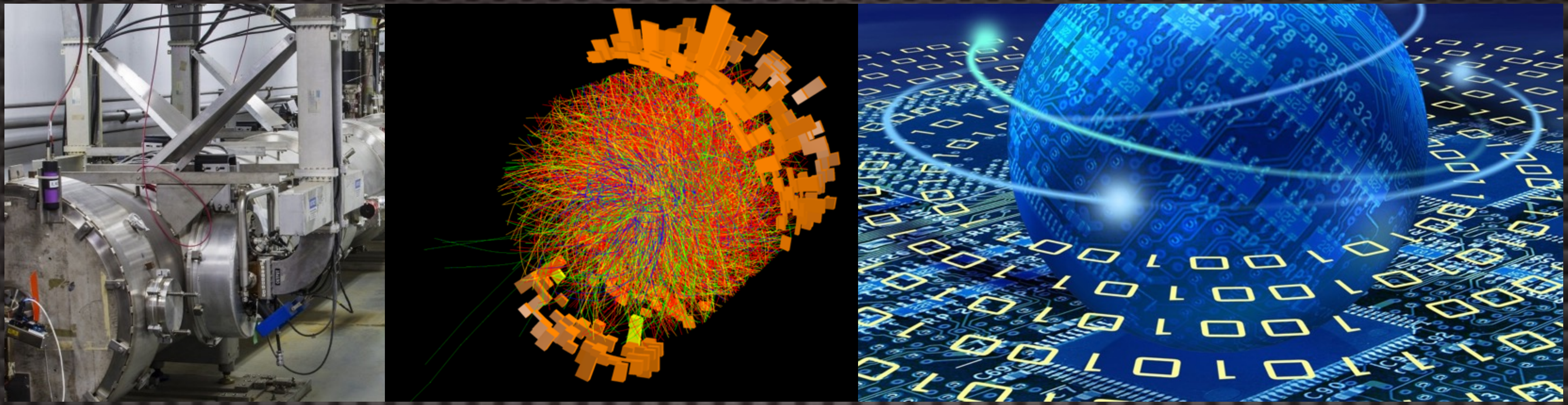
Classical Computing

- Euclidean space
- high-lying states difficult
- Signal-to-noise
- Severe limitations for real-time or inelastic collisions or fragmentation

Quantum Computing

- Real-time evolution
- S-matrix
- No sign problem(s) (naively)

Sensing and Detection



Classical Computing
e.g.
Classical Sensing : precision ~ $1/\sqrt{N}$

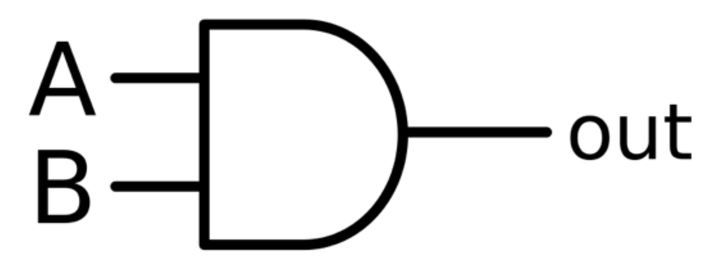
Classical DataBase Searching : time ~ N

Quantum Computing
e.g.
Quantum Sensing : precision ~ $1/N$

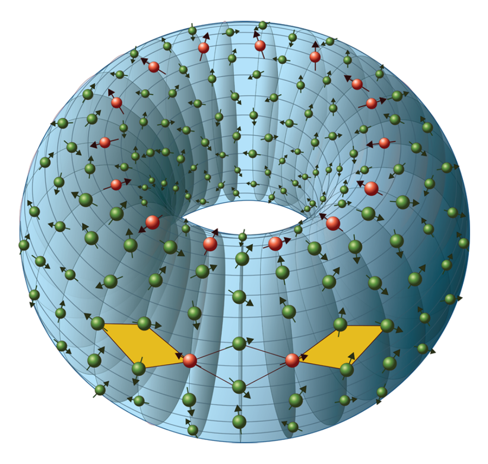
Quantum DataBase Searching : time ~ $\sqrt{N}$

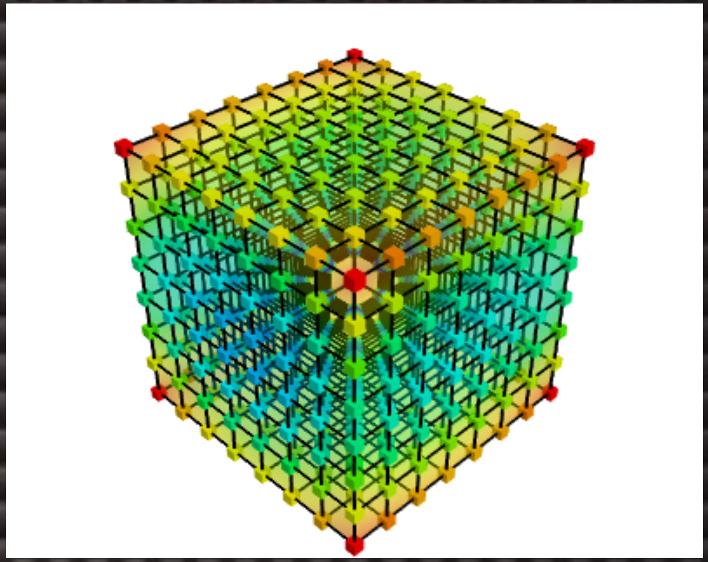
QC and QIS for Scientific Applications
Highlights of Trajectory to the Present

1980 - 2000
Benioff, Manin, Feynman, Deutsch, IBM and reversability
First quantum algorithms

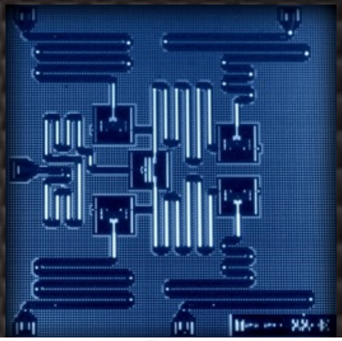


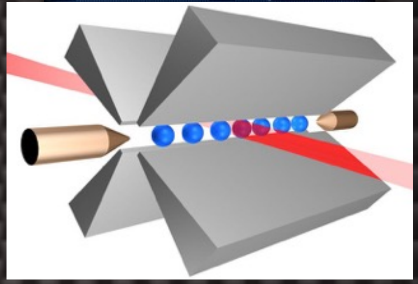
2000 - 2010
Proof-of-principle demonstrations
Initial QC hardware
Error correction and control theory
Spin-chains and scalar field theories





2010-2018
Focus on practicality and improving quality and control
Circuit design and synthesis
Cloud-based access to NISQ hardware
First simulations of light nuclei and simple quantum field theories
Entanglement and improving algorithms





Based on a slide by David Dean

At the Heart of Quantum Computing

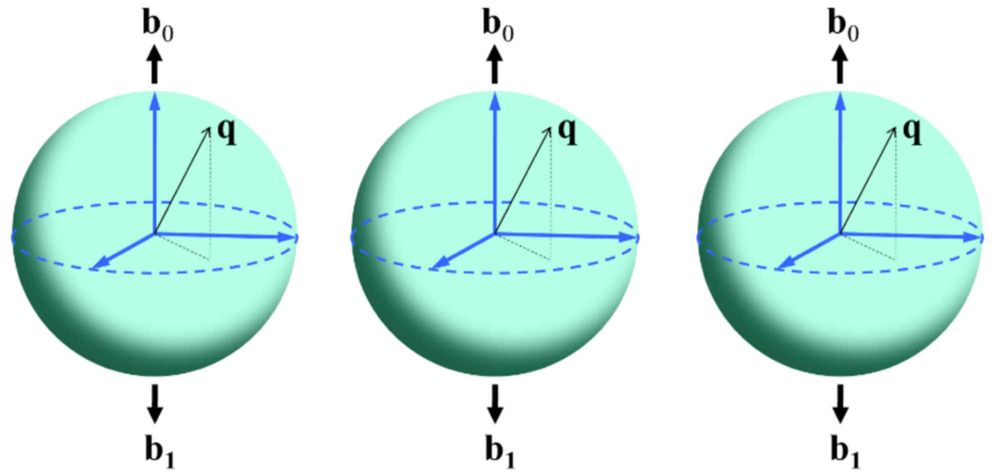
Massively Parallel Processing, Nonlocality and Entanglement

e.g., for a 3-bit computer (2^3 states)
Classical computer in 1 of 8 possible states

$$|\psi\rangle = |000\rangle \text{ or } |001\rangle \text{ or } |010\rangle \text{ or } |100\rangle \text{ or } |011\rangle \text{ or } |101\rangle \text{ or } |110\rangle \text{ or } |111\rangle$$

Quantum computer can be in a combination of all states at once

$$|\psi\rangle = \alpha_1 |000\rangle + \alpha_2 |001\rangle + \alpha_3 |010\rangle + \alpha_4 |100\rangle + \alpha_5 |011\rangle + \alpha_6 |101\rangle + \alpha_7 |110\rangle + \alpha_8 |111\rangle$$



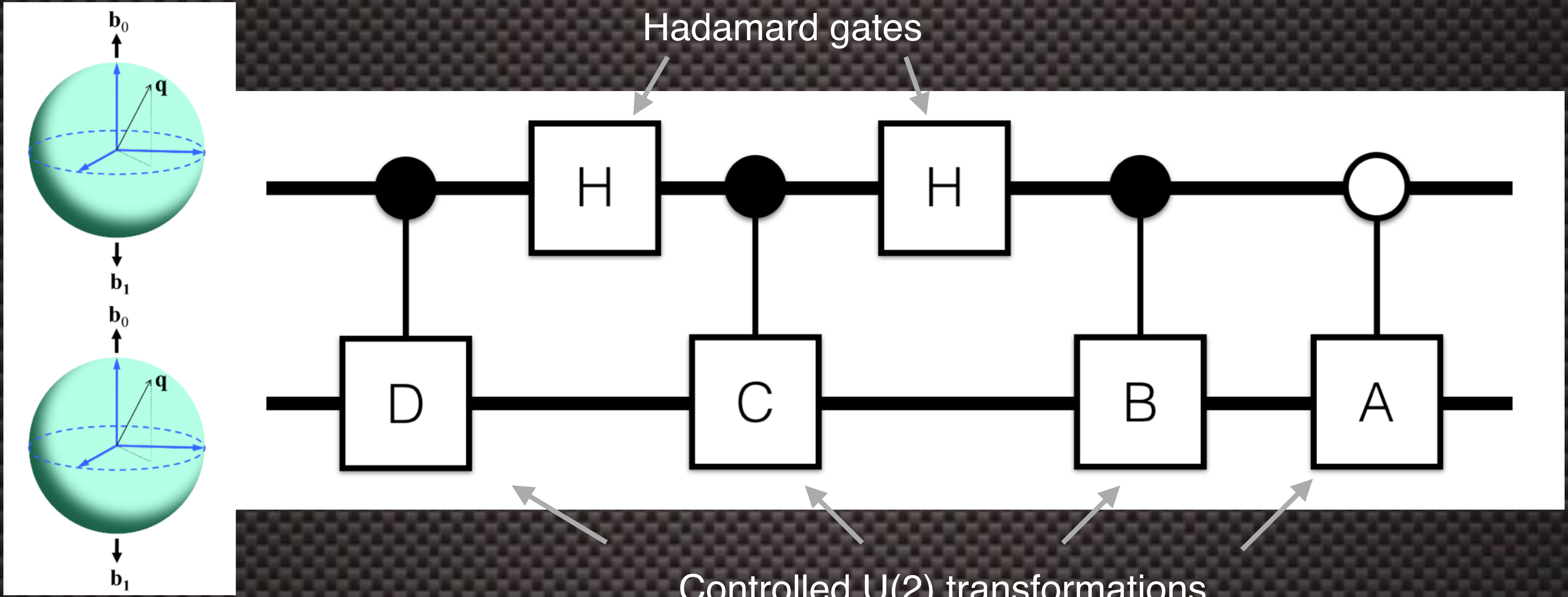
$$H^{\otimes 3}|000\rangle = \frac{1}{\sqrt{2}}[|0\rangle + |1\rangle] \otimes \frac{1}{\sqrt{2}}[|0\rangle + |1\rangle] \otimes \frac{1}{\sqrt{2}}[|0\rangle + |1\rangle]$$

Once system mapped onto qubits, unitary operations used to compute and process information

At the Heart of Quantum Computing

Massively Parallel Processing, Nonlocality and Entanglement

e.g. 2-qubits, unitary transformations between 4 states : U(4) transformations



Hadamard gates

Controlled U(2) transformations

$$\hat{U}_4(\theta_1, ...\theta_{16})\ |00\rangle\ =\ \alpha\ |00\rangle\ +\ \beta\ |01\rangle\ +\ \gamma\ |10\rangle\ +\ \rho\ |11\rangle$$

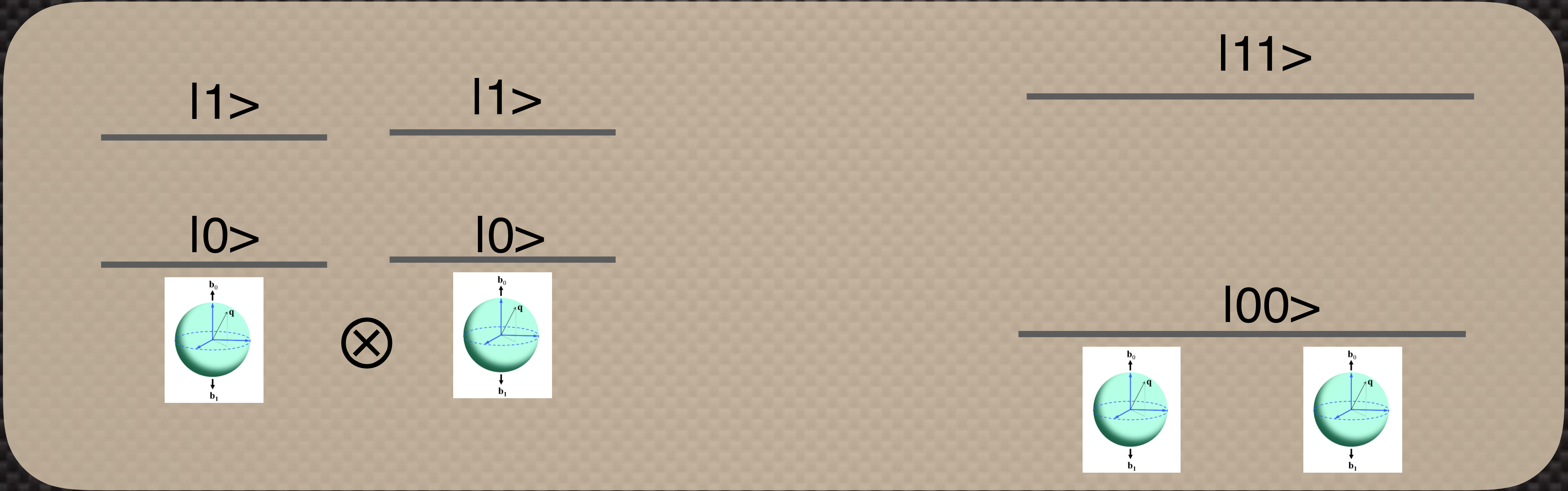
Quantum Sensing, Metrology and Lithography

Nonlocality and Entanglement

e.g., $H \sim \beta\, \sigma_z$ a new type of coupling

20th Century Detection
``independent qudits”

21st Century Detection
entangled ``qudits”


$|1\rangle$ $|1\rangle$
$|0\rangle$ $|0\rangle$
$\otimes$

$|11\rangle$
$|00\rangle$

Uncaptioned in measurement scales as

$$\Delta\beta \sim 1/(t\sqrt{N})$$

Uncertainty in measurement scales as

$$\Delta\beta \sim 1/(t\,N)$$

[Slide content from talk by Alexey Gorshkov at ANL, Intersections Between Nuclear Physics and Quantum Information, March 2018]

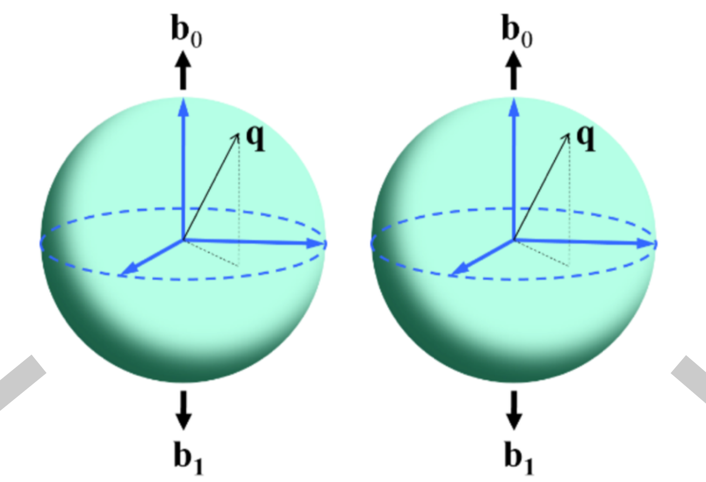
Space-Based Quantum Keys

e.g., Quantum Teleportation

https://www.sciencemag.org/news/2017/06/china-s-quantum-satellite-achieves-spooky-action-record-distance

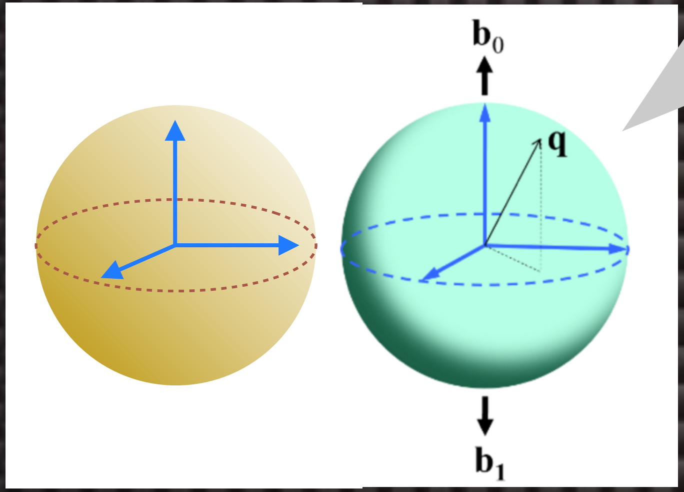
Entangled qubit pair created in Satellite

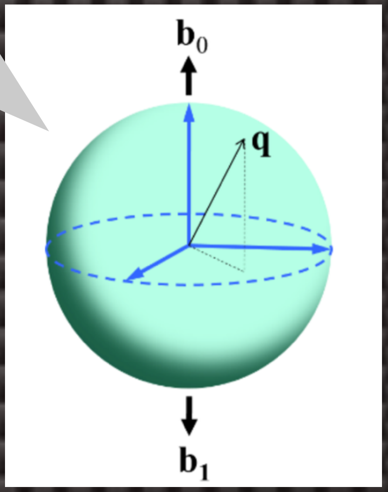
9/17 : Quantum secure video call between China and Austria



Satellite

Ground Station



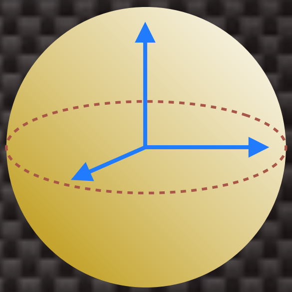


Satellite

- One sent to earth station
- Entangled by CNOT gate and Hadamard Gate
- Pair is measured
- Measure. The classical ``number '' of the collapsed state, N=1,2,3,or 4 from l00> , l01> ,l 10> or l11> is sent back to satellite

Classical Number(s)

- N dictates the applied unitary operation1=I , 2=X , 3=Y , 4=Z



Satellite

Quantum State demolished on Earth BUT teleported to the Satellite

The Noise Intermediate-Scale Quantum (NISQ) Era

John Preskill - Jan 2018

- No or little error correction in hardware or software [requires > x10 qubits]

- Expect to have a few hundred qubits with modest gate depth (decoherence of devices)

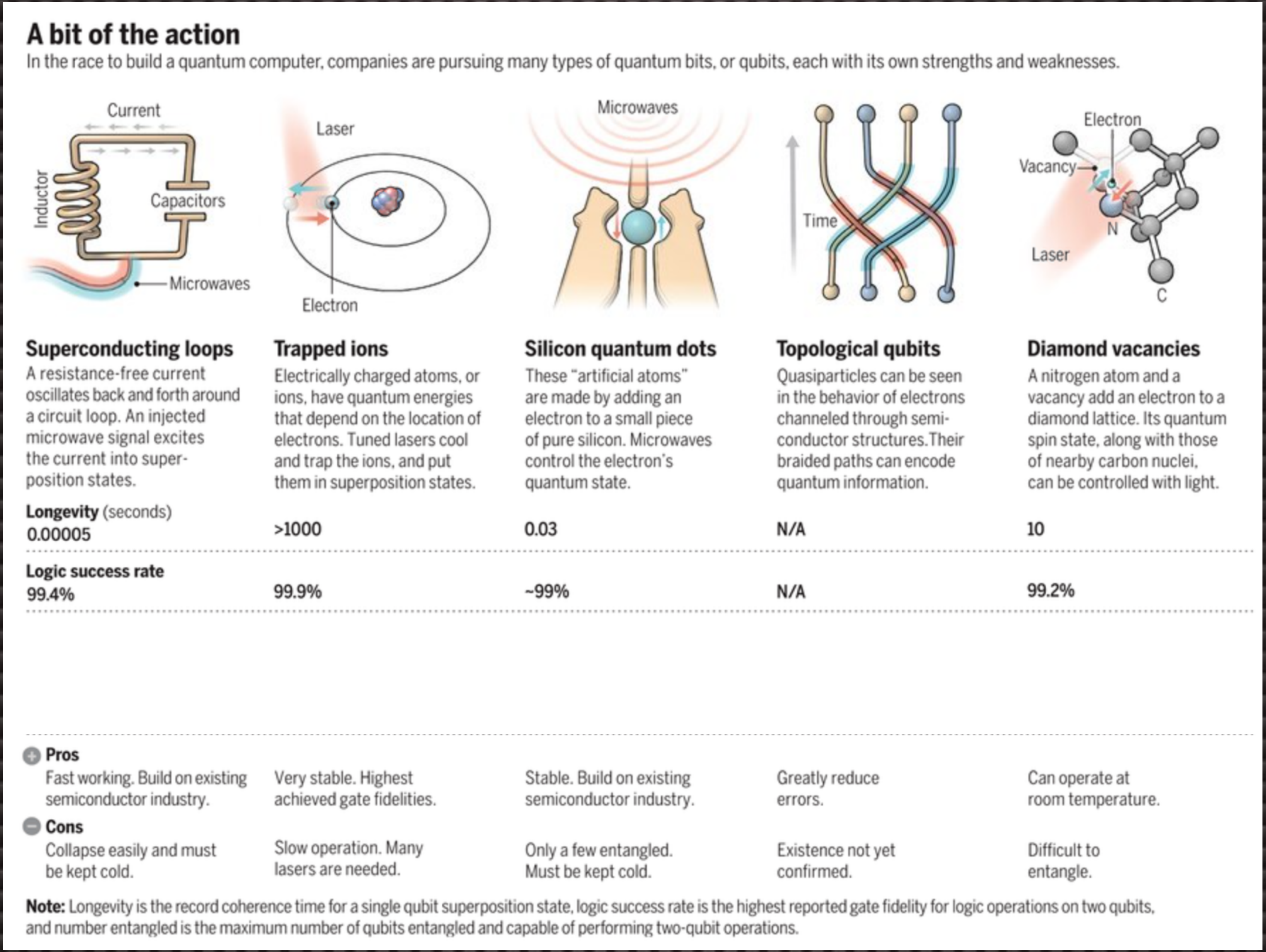
- Imperfect quantum gates/operations

- NISQ-era ~ several years Not going to be a near term magic bullet
  - will not replace classical computing

- Searching to find Quantum Advantage(s) for one or more systems

- Understanding the application of ``Quantum" to Scientific Applications, and identifying attributes of future quantum devices.

Quantum Computing: Qubits



A bit of the action

In the race to build a quantum computer, companies are pursuing many types of quantum bits, or qubits, each with its own strengths and weaknesses.

Superconducting loops	**Trapped ions**	**Silicon quantum dots**	**Topological qubits**	**Diamond vacancies**
A resistance-free current oscillates back and forth around a circuit loop. An injected microwave signal excites the current into superposition states.	Electrically charged atoms, or ions, have quantum energies that depend on the location of electrons. Tuned lasers cool and trap the ions, and put them in superposition states.	These "artificial atoms" are made by adding an electron to a small piece of pure silicon. Microwaves control the electron's quantum state.	Quasiparticles can be seen in the behavior of electrons channeled through semiconductor structures. Their braided paths can encode quantum information.	A nitrogen atom and a vacancy add an electron to a diamond lattice. Its quantum spin state, along with those of nearby carbon nuclei, can be controlled with light.
Longevity (seconds) 0.00005	>1000	0.03	N/A	10
Logic success rate 99.4%	99.9%	~99%	N/A	99.2%
Pros Fast working. Build on existing semiconductor industry.	Very stable. Highest achieved gate fidelities.	Stable. Build on existing semiconductor industry.	Greatly reduce errors.	Can operate at room temperature.
Cons Collapse easily and must be kept cold.	Slow operation. Many lasers are needed.	Only a few entangled. Must be kept cold.	Existence not yet confirmed.	Difficult to entangle.

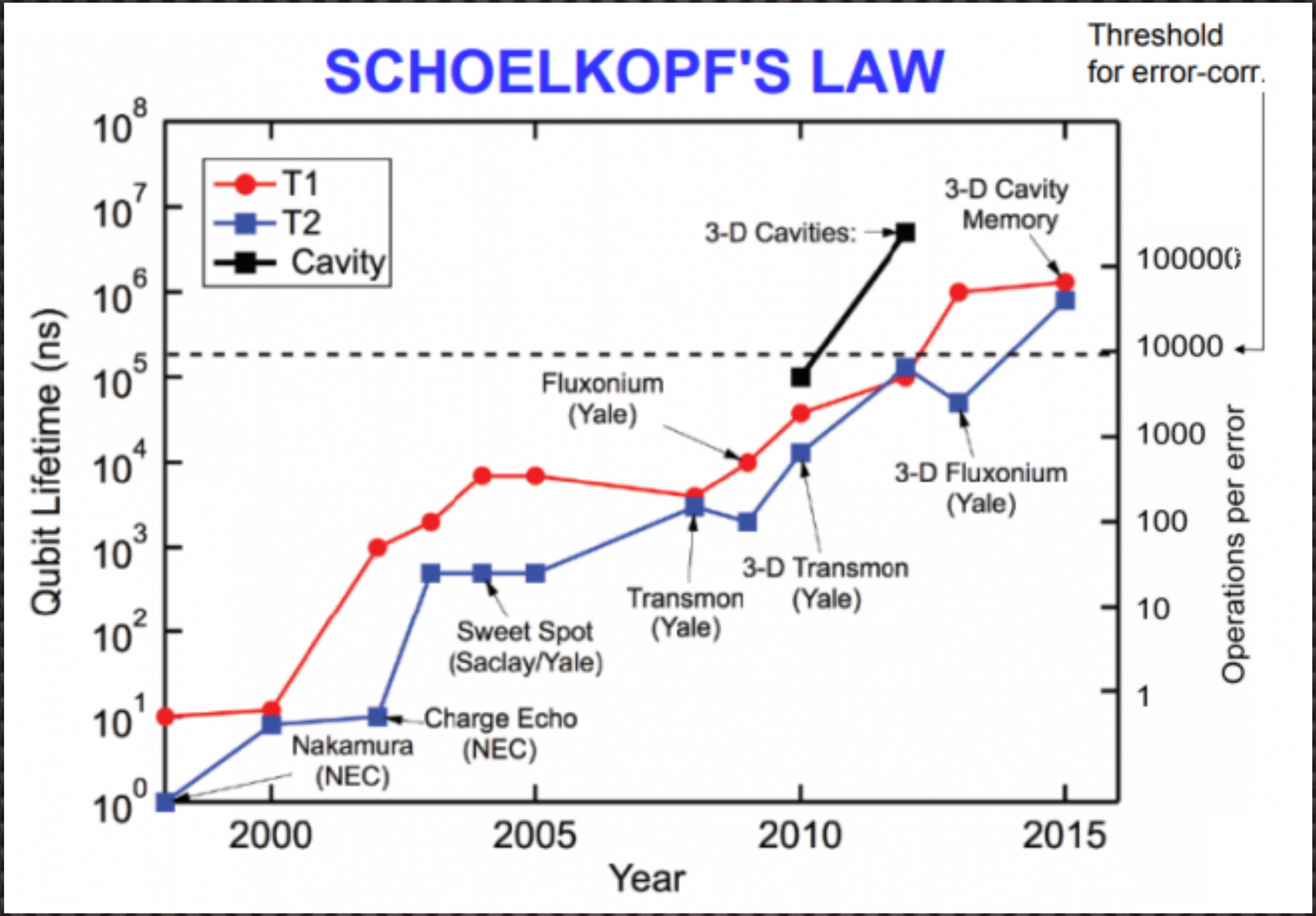
Note: Longevity is the record coherence time for a single qubit superposition state, logic success rate is the highest reported gate fidelity for logic operations on two qubits, and number entangled is the maximum number of qubits entangled and capable of performing two-qubit operations.

Efforts at National Laboratories, Technology Companies and Universities developing such devices and other types, e.g. cold atoms, qudits.

Science, December 2016, based on David Dean slide

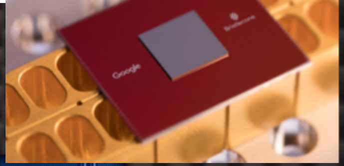
Example of Hardware Improvement

Quantum coherence time of superconducting qubits has improved analogously to Moore’s Law

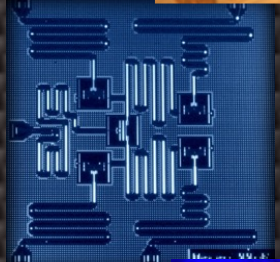


Quantum Computing
Examples of Available Hardware and Technology Companies - US + Ca

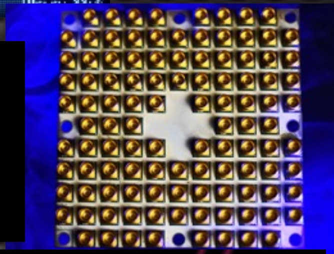
D-wave : ~ 2000 superconducting qubits, quantum annealing



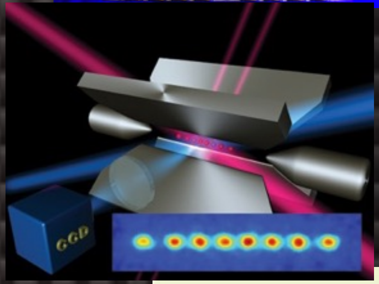
Google : 72 superconducting qubits - 2-qubit error < 0.5%



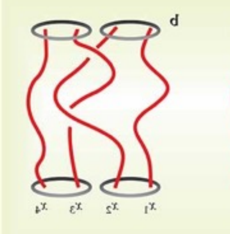
IBM : superconducting - 5,14,16, 20 qubits systems - cloud access



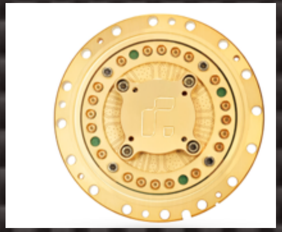
Intel : 49 superconducting qubits, progress in silicon



IonQ : trapped ions, 53-qubit system, cloud access coming



Microsoft : Majorana (topological) - in development

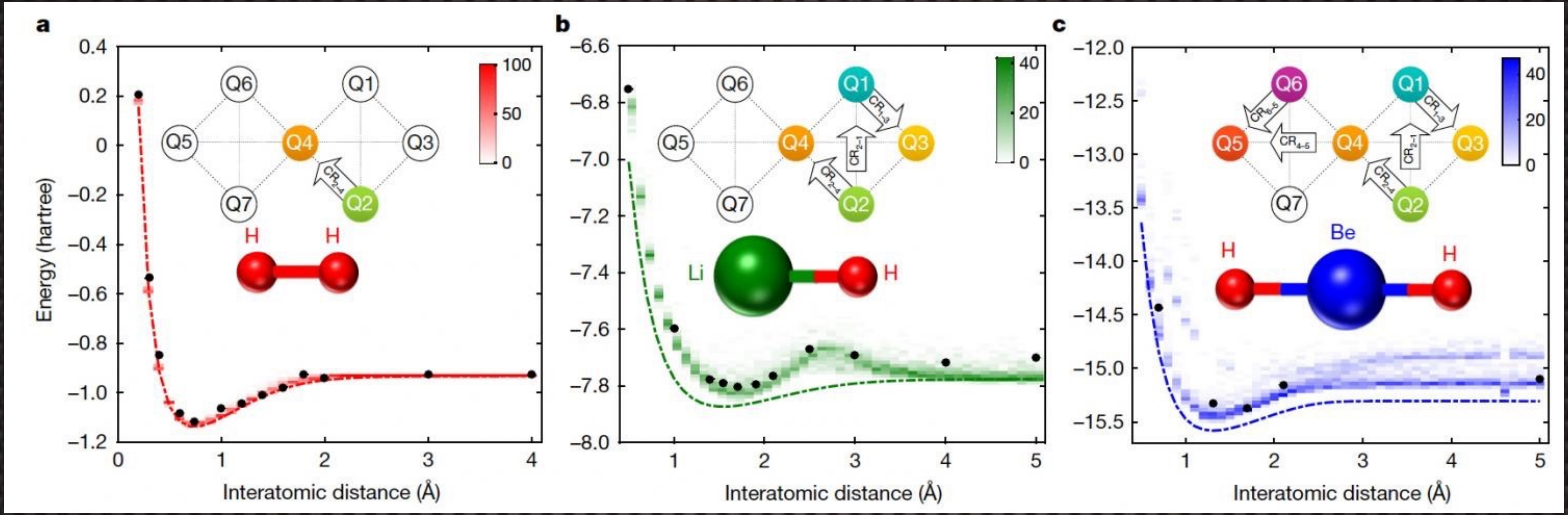


Rigetti : 8, 19 superconducting qubits with 128 coming

e.g. IBM’s Calculations of Ground States of Molecules

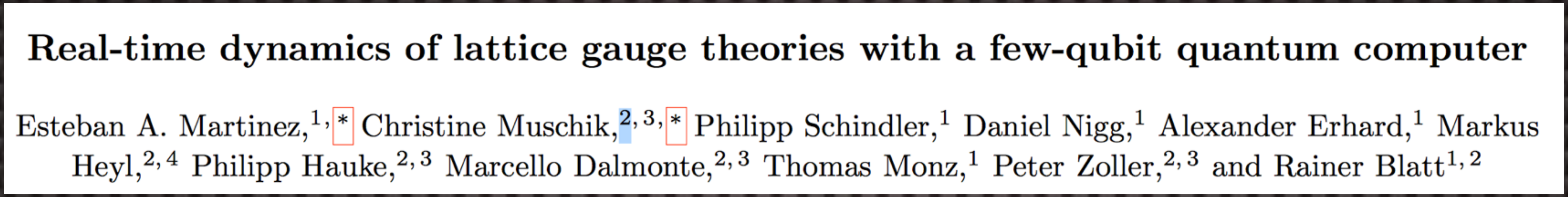
How to measure a molecule's energy using a quantum computer

September 14, 2017, IBM



A First Quantum Computation in Quantum Field Theory
1+1-Dim QED

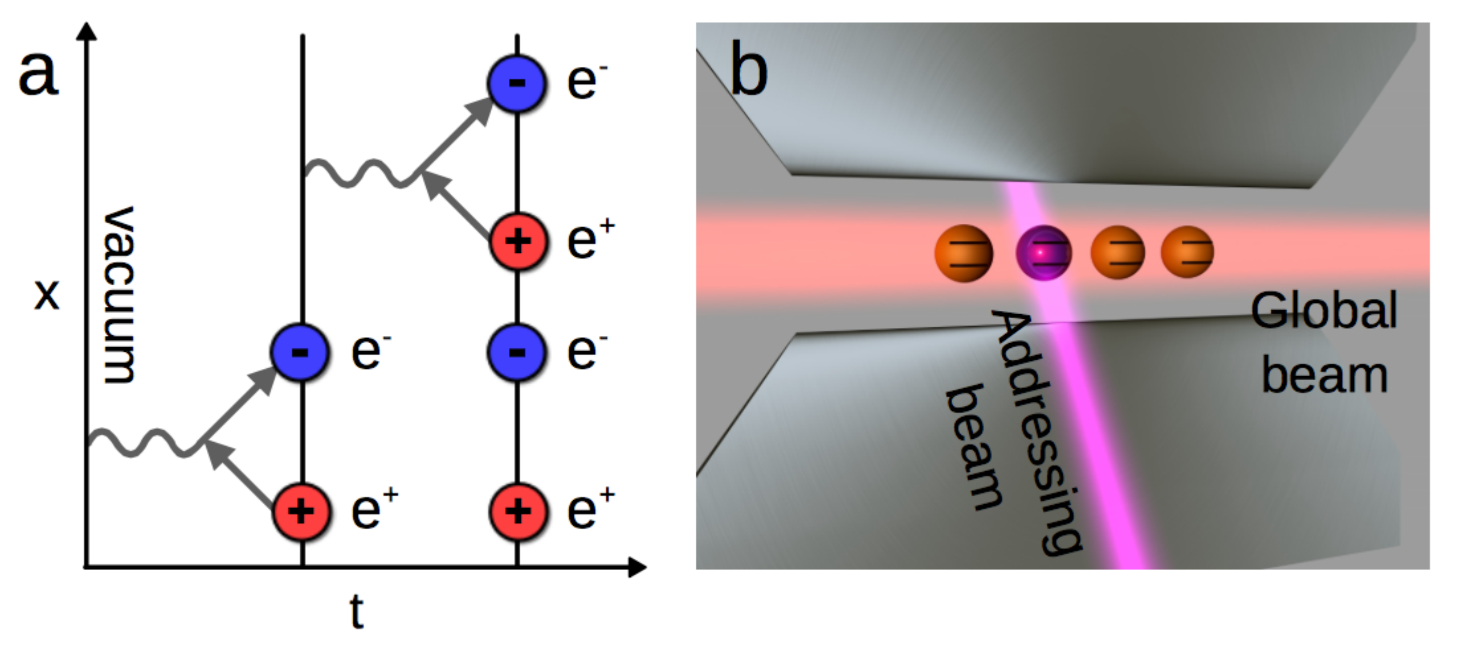
2016

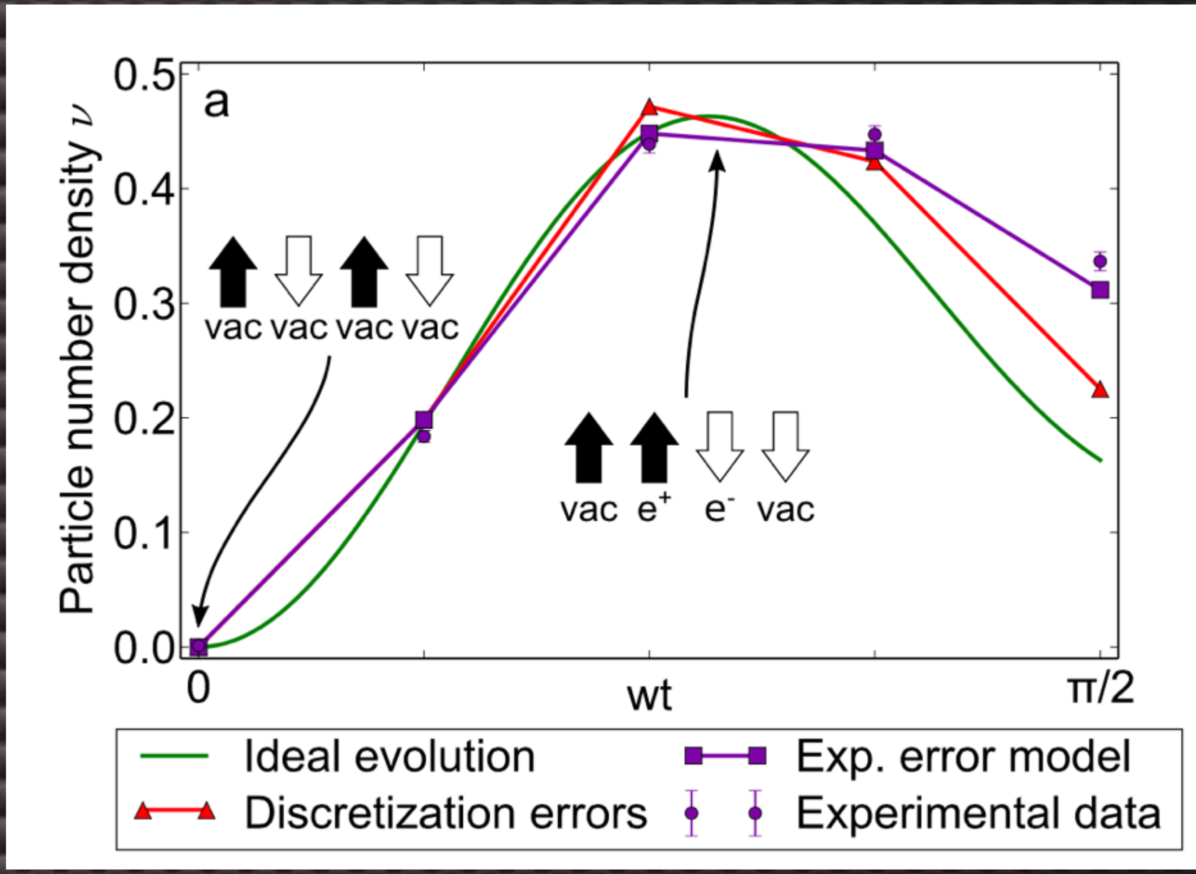


Real-time dynamics of lattice gauge theories with a few-qubit quantum computer

Esteban A. Martinez,[1,*] Christine Muschik,[2,3,*] Philipp Schindler,[1] Daniel Nigg,[1] Alexander Erhard,[1] Markus Heyl,[2,4] Philipp Hauke,[2,3] Marcello Dalmonte,[2,3] Thomas Monz,[1] Peter Zoller,[2,3] and Rainer Blatt[1,2]

(2016)



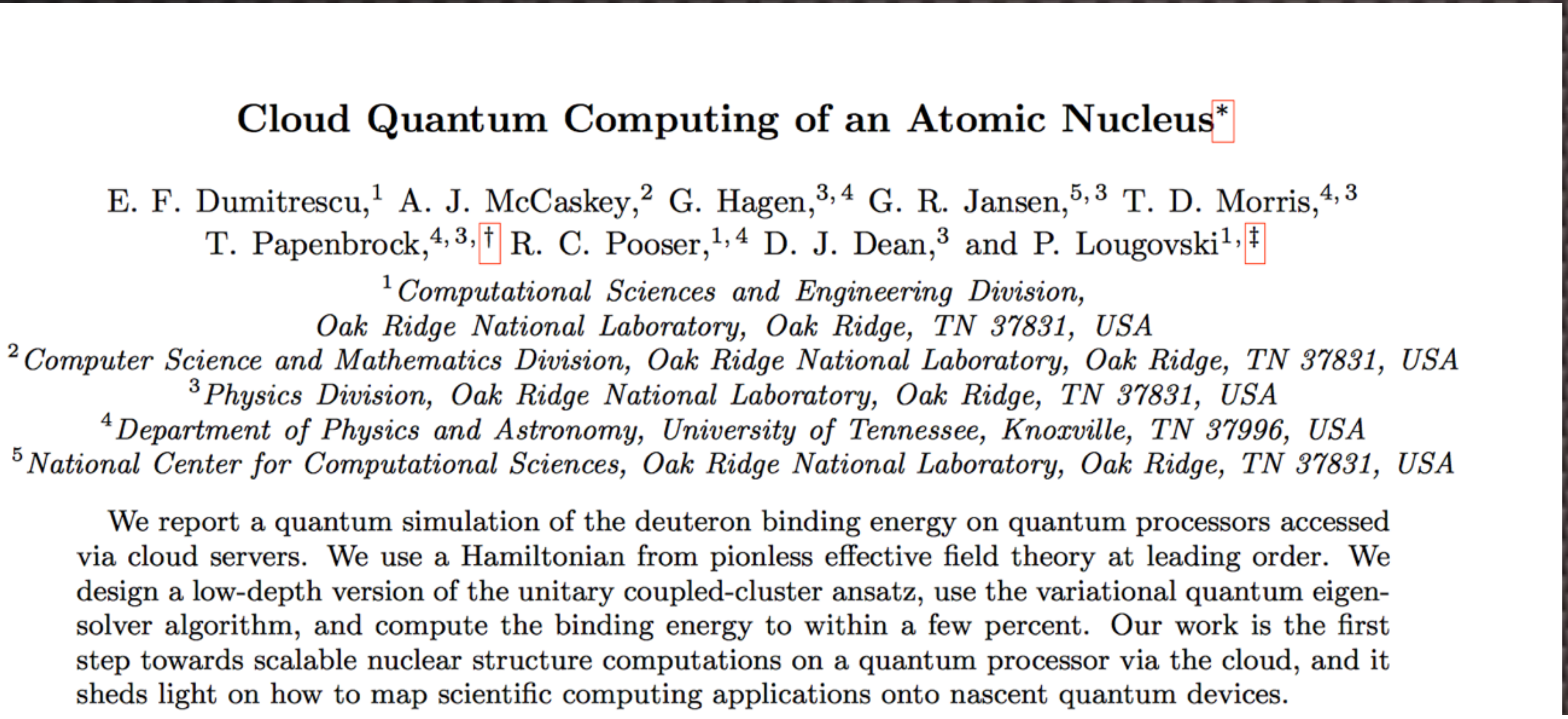


Based upon a string of ^{40}Ca$^+$ trapped-ion quantum system

Simulates 4 qubit system with long-range couplings = 2-spatial-site Schwinger Model

Real-Time evolution of the quantum fields, implementing > 200 gates per Trotter step

``Time = 0`` for Quantum Computing in Nuclear Physics



Cloud Quantum Computing of an Atomic Nucleus*

E. F. Dumitrescu,[1] A. J. McCaskey,[2] G. Hagen,[3,4] G. R. Jansen,[5,3] T. D. Morris,[4,3]
T. Papenbrock,[4,3,†] R. C. Pooser,[1,4] D. J. Dean,[3] and P. Lougovski[1,‡]
[1] *Computational Sciences and Engineering Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA*
[2] *Computer Science and Mathematics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA*
[3] *Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA*
[4] *Department of Physics and Astronomy, University of Tennessee, Knoxville, TN 37996, USA*
[5] *National Center for Computational Sciences, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA*

We report a quantum simulation of the deuteron binding energy on quantum processors accessed via cloud servers. We use a Hamiltonian from pionless effective field theory at leading order. We design a low-depth version of the unitary coupled-cluster ansatz, use the variational quantum eigensolver algorithm, and compute the binding energy to within a few percent. Our work is the first step towards scalable nuclear structure computations on a quantum processor via the cloud, and it sheds light on how to map scientific computing applications onto nascent quantum devices.

THAT'S ONE SMALL STEP FOR [A] MAN,
ONE **GIANT** LEAP FOR Nuclear Physics

http://arxiv.org/abs/1801.03897

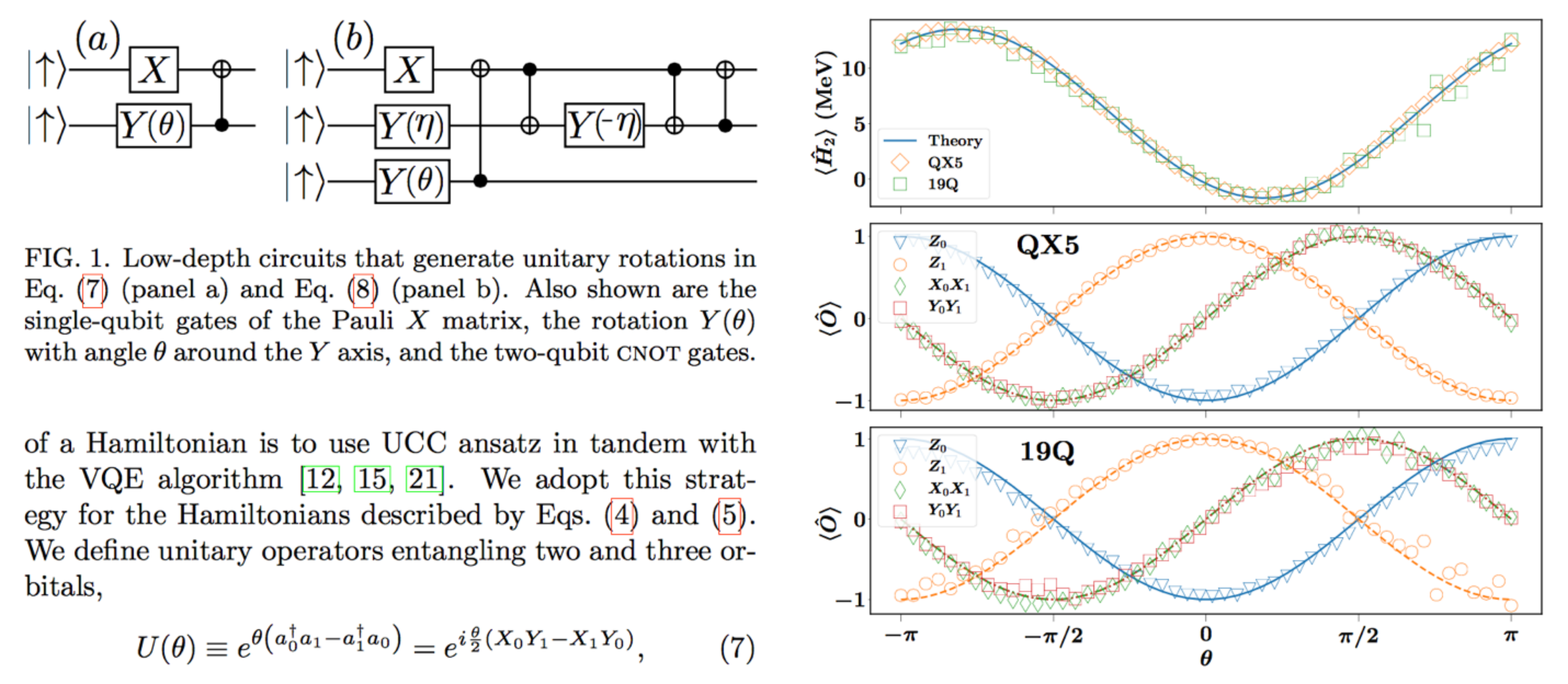


FIG. 1. Low-depth circuits that generate unitary rotations in Eq. (7) (panel a) and Eq. (8) (panel b). Also shown are the single-qubit gates of the Pauli X matrix, the rotation $Y(\theta)$ with angle θ around the Y axis, and the two-qubit CNOT gates.

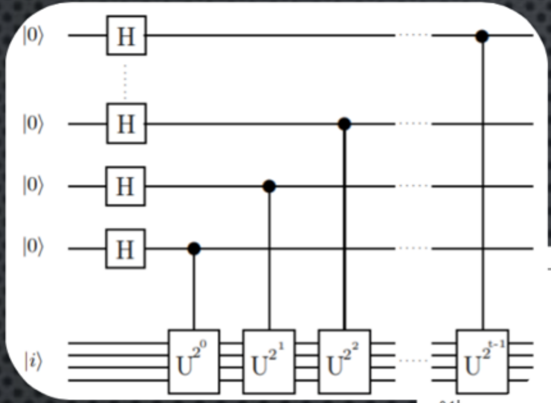
of a Hamiltonian is to use UCC ansatz in tandem with the VQE algorithm [12, 15, 21]. We adopt this strategy for the Hamiltonians described by Eqs. (4) and (5). We define unitary operators entangling two and three orbitals,

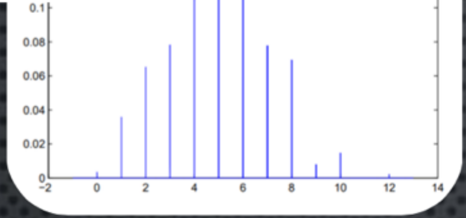
$$U(\theta) \equiv e^{\theta\left(a_0^\dagger a_1 - a_1^\dagger a_0\right)} = e^{i\frac{\theta}{2}(X_0Y_1 - X_1Y_0)}, \qquad (7)$$

Cloud Quantum Computing of an Atomic Nucleus
E.F. Dumitrescu, A.J. McCaskey, G. Hagen, G.R. Jansen, T.D. Morris, T. Papenbrock, R.C. Pooser, D.J. Dean, P. Lougovski. Jan 11, 2018. 6 pp.
Published in **Phys.Rev.Lett. 120 (2018) no.21, 210501**

First Demonstrations in Nuclear Many-Body Systems

Many-Body Studies





Ovrum, Hjorth-Jensen (2007)

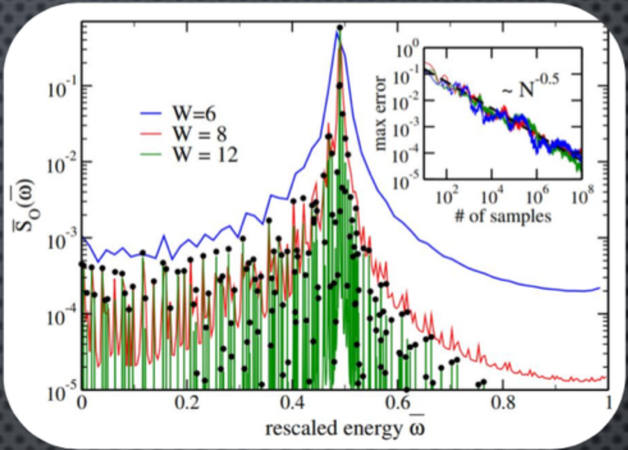
Energy measurement probability

$$\alpha\ \left|\langle\psi_f|\psi_i\rangle\right|^2$$

JW-transform Hubbard model

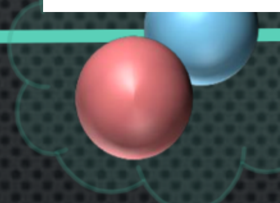
Linear Response Functions

Carlson, Roggero (2018)

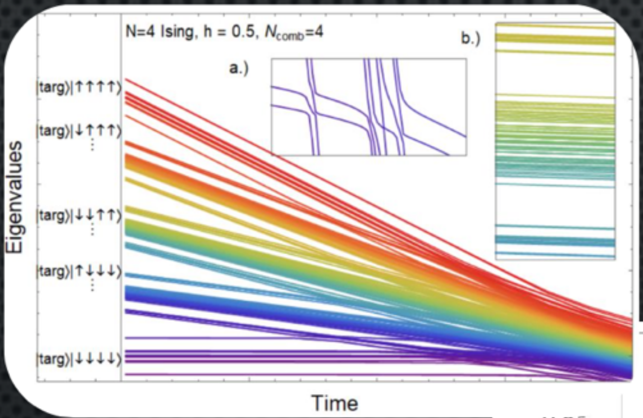


$$\sum_\nu \left|\langle\psi_\nu|\,\hat{O}\,|\psi_0\rangle\right|^2 \delta(E_\nu - E_0 - \omega)$$

dynamic linear response and exclusive information

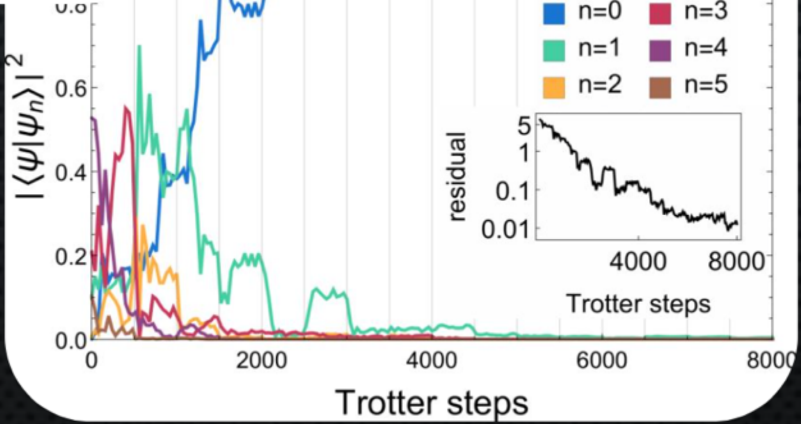


Spectral Combing



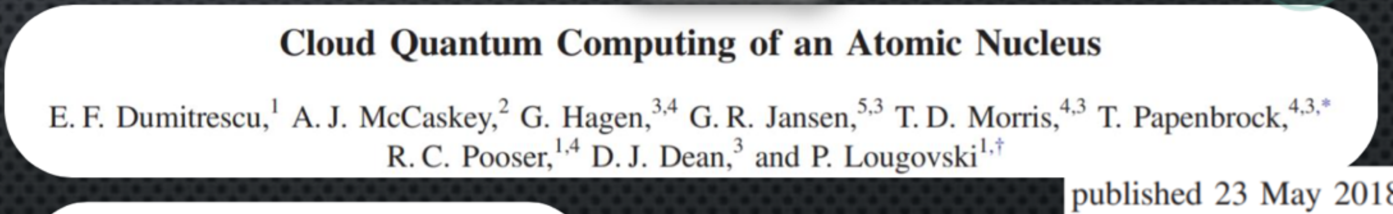
Kaplan, Klco, Roggero (2017)

Time-dependent auxiliary system = comb



Exponential level crossings send target system to ground state

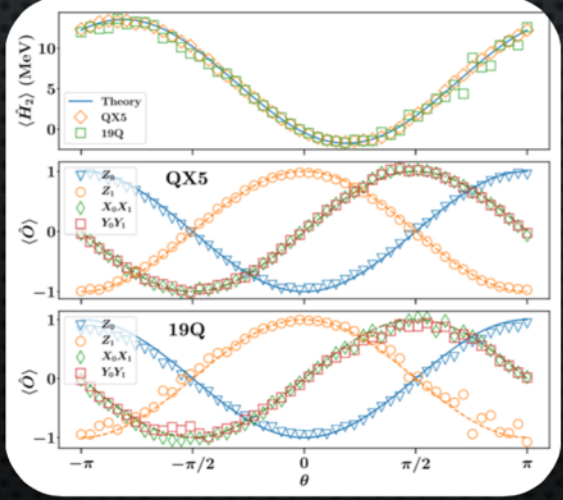
The Deuteron



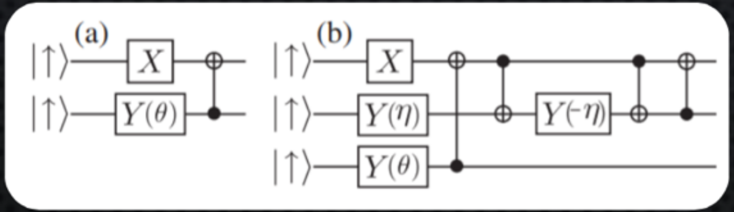
Cloud Quantum Computing of an Atomic Nucleus

E. F. Dumitrescu,[1] A. J. McCaskey,[2] G. Hagen,[3,4] G. R. Jansen,[5,3] T. D. Morris,[4,3] T. Papenbrock,[4,3,*] R. C. Pooser,[1,4] D. J. Dean,[3] and P. Lougovski[1,†]

published 23 May 201



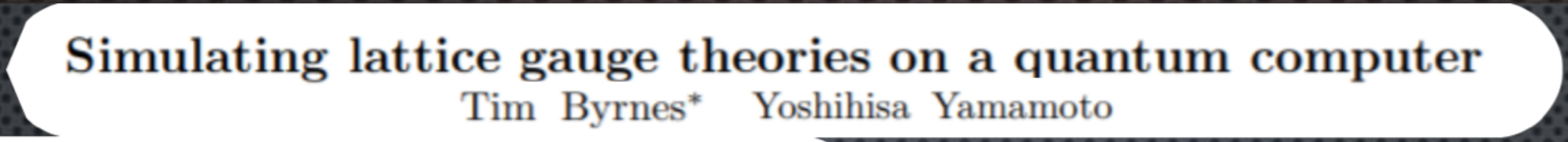
Variational Quantum Eigensolver



Slide by Natalie Klco (Oct 2018)

Developments in Field Theory for QC/QIS (many more than are shown)

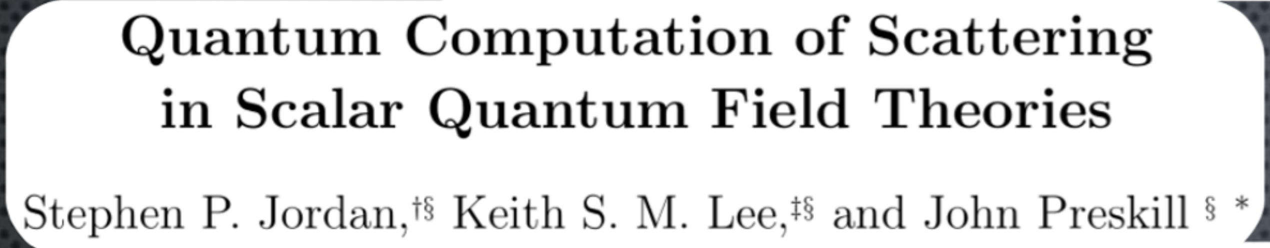
2005



Simulating lattice gauge theories on a quantum computer

Tim Byrnes* Yoshihisa Yamamoto

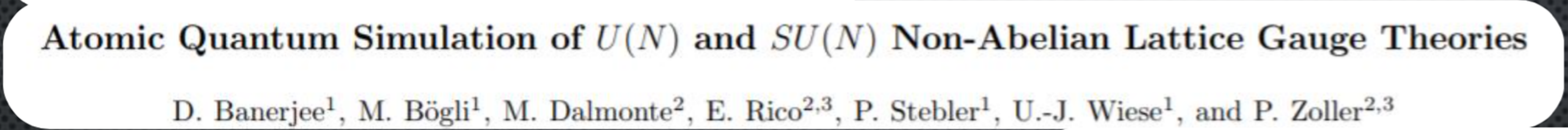
2012



Quantum Computation of Scattering in Scalar Quantum Field Theories

Stephen P. Jordan,†§ Keith S. M. Lee,‡§ and John Preskill § *

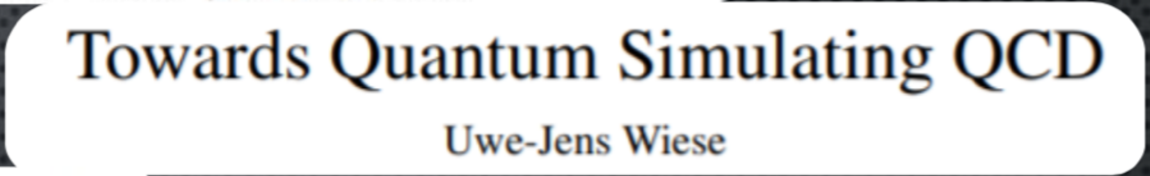
2013



Atomic Quantum Simulation of $U(N)$ and $SU(N)$ Non-Abelian Lattice Gauge Theories

D. Banerjee^{1}, M. Bögli^{1}, M. Dalmonte^{2}, E. Rico^{2,3}, P. Stebler^{1}, U.-J. Wiese^{1}, and P. Zoller^{2,3}

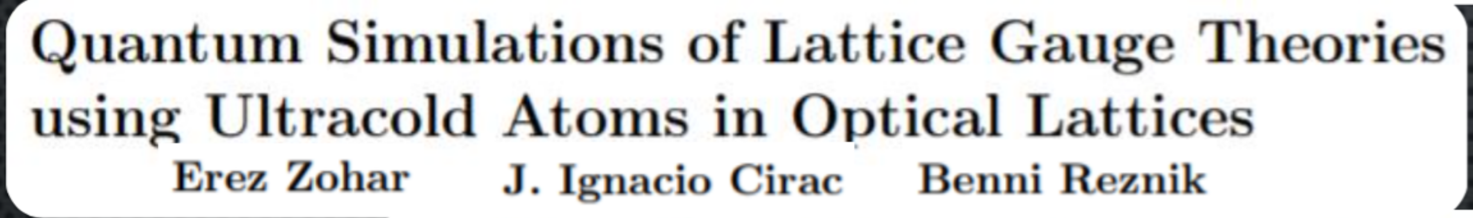
2014



Towards Quantum Simulating QCD

Uwe-Jens Wiese

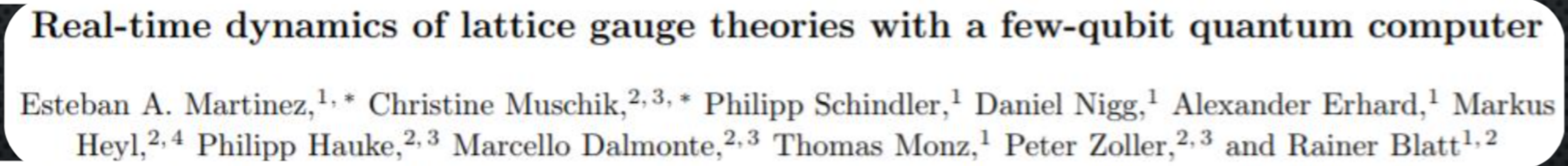
2015



Quantum Simulations of Lattice Gauge Theories using Ultracold Atoms in Optical Lattices

Erez Zohar J. Ignacio Cirac Benni Reznik

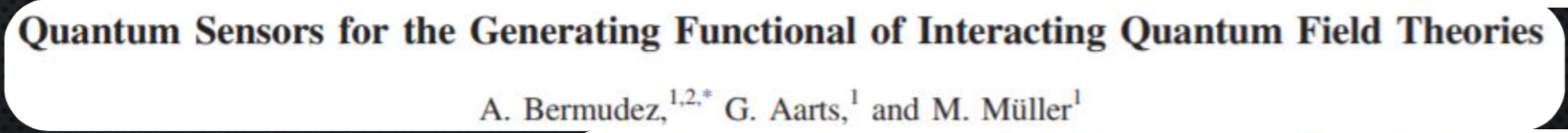
2016



Real-time dynamics of lattice gauge theories with a few-qubit quantum computer

Esteban A. Martinez,^{1,*} Christine Muschik,^{2,3,*} Philipp Schindler,^{1} Daniel Nigg,^{1} Alexander Erhard,^{1} Markus Heyl,^{2,4} Philipp Hauke,^{2,3} Marcello Dalmonte,^{2,3} Thomas Monz,^{1} Peter Zoller,^{2,3} and Rainer Blatt^{1,2}

2017



Quantum Sensors for the Generating Functional of Interacting Quantum Field Theories

A. Bermudez,^{1,2,*} G. Aarts,^{1} and M. Müller^{1}

2018

Gauss's Law, Duality, and the Hamiltonian Formulation of U(1) Lattice Gauge Theory

David B. Kaplan* and Jesse R. Stryker†

Institute for Nuclear Theory, Box 351550, University of Washington, Seattle, WA 98195-1550

Slide by Natalie Klco (Oct 2018)

Quantum Field Theory on Superconducting Qubits
1+1-Dim QED

Hybrid Classical-Quantum ``System”

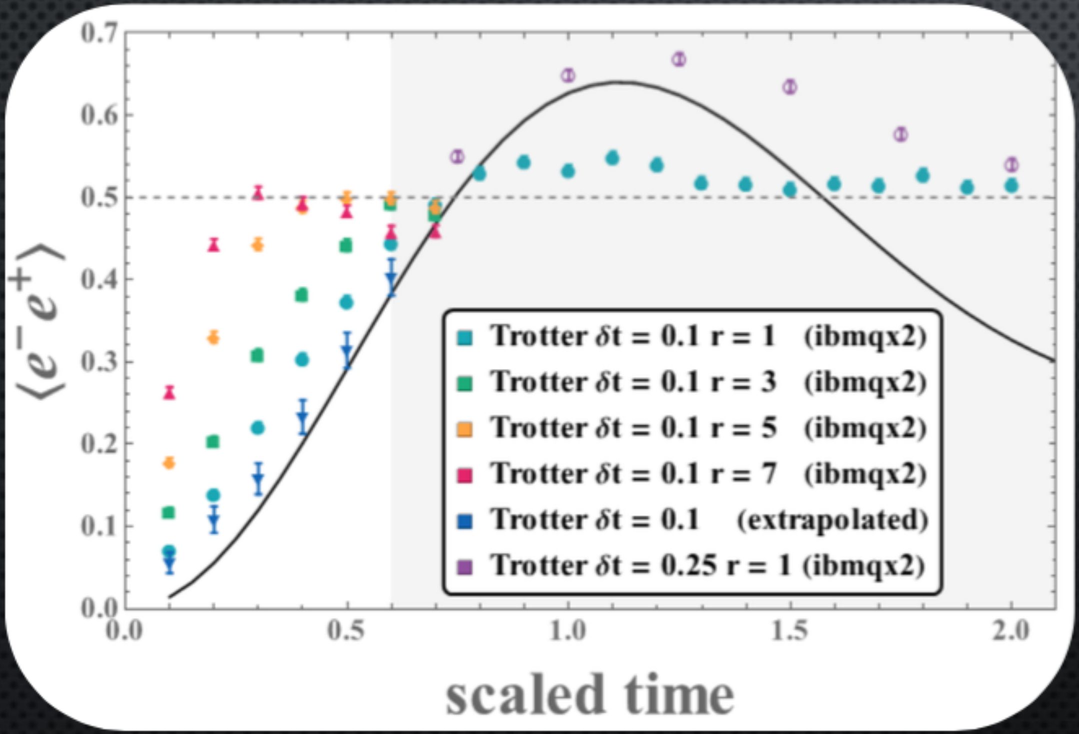
Quantum-classical computation of Schwinger model dynamics using quantum computers
N. Klco, E.F. Dumitrescu, A.J. McCaskey, T.D. Morris, R.C. Pooser, M. Sanz, E. Solano, **P. Lougovski**, M.J. Savage,
Mar 8, 2018. Phys.Rev. A98 (2018) no.3, 032331

Trotterized time evolution

Discretized time evolution requires long coherence

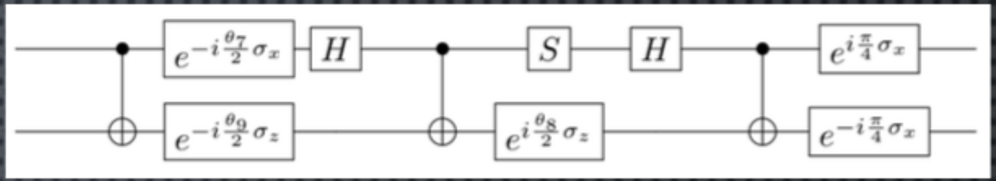
$$e^{-iHt} = e^{-i\sum_j H_j t} \approx \left(\prod_j e^{-i H_j \frac{t}{N}}\right)^N$$

3.6 QPU·s



Only 15 angles define arbitrary SU(4) matrix

3-CNOT gates. Gate depth: 14. Not Scalable.

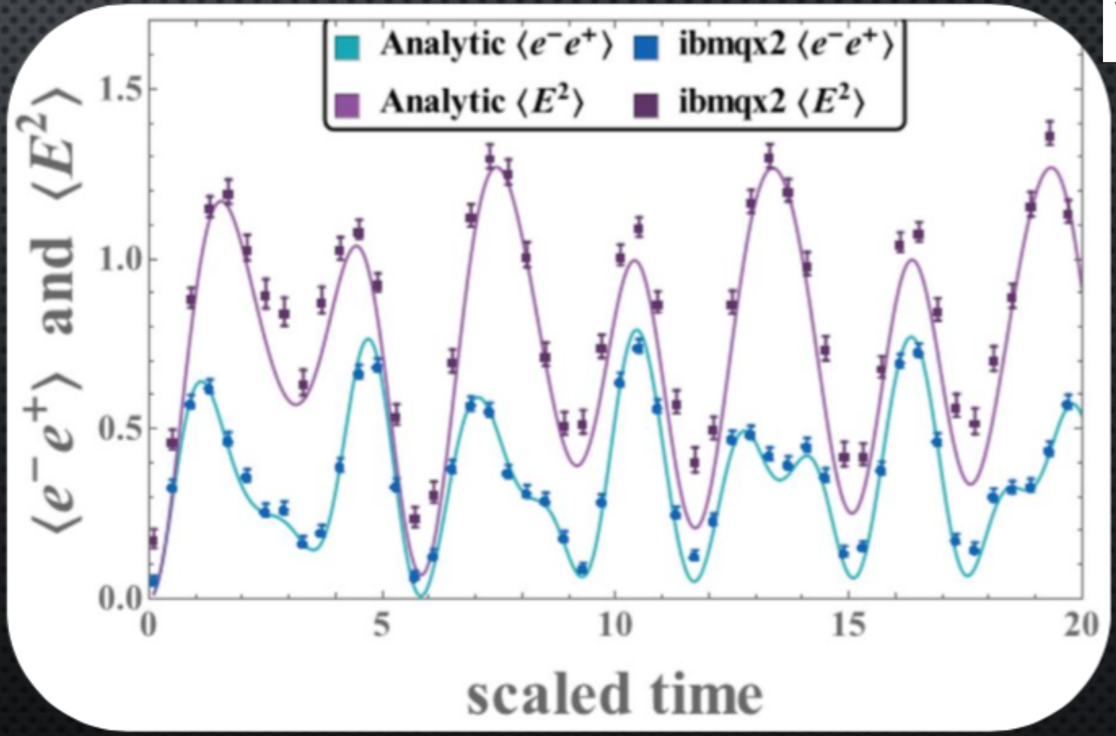


Vidal, Dawson (2003)

OAK RIDGE
National Laboratory

INSTITUTE for
NUCLEAR THEORY

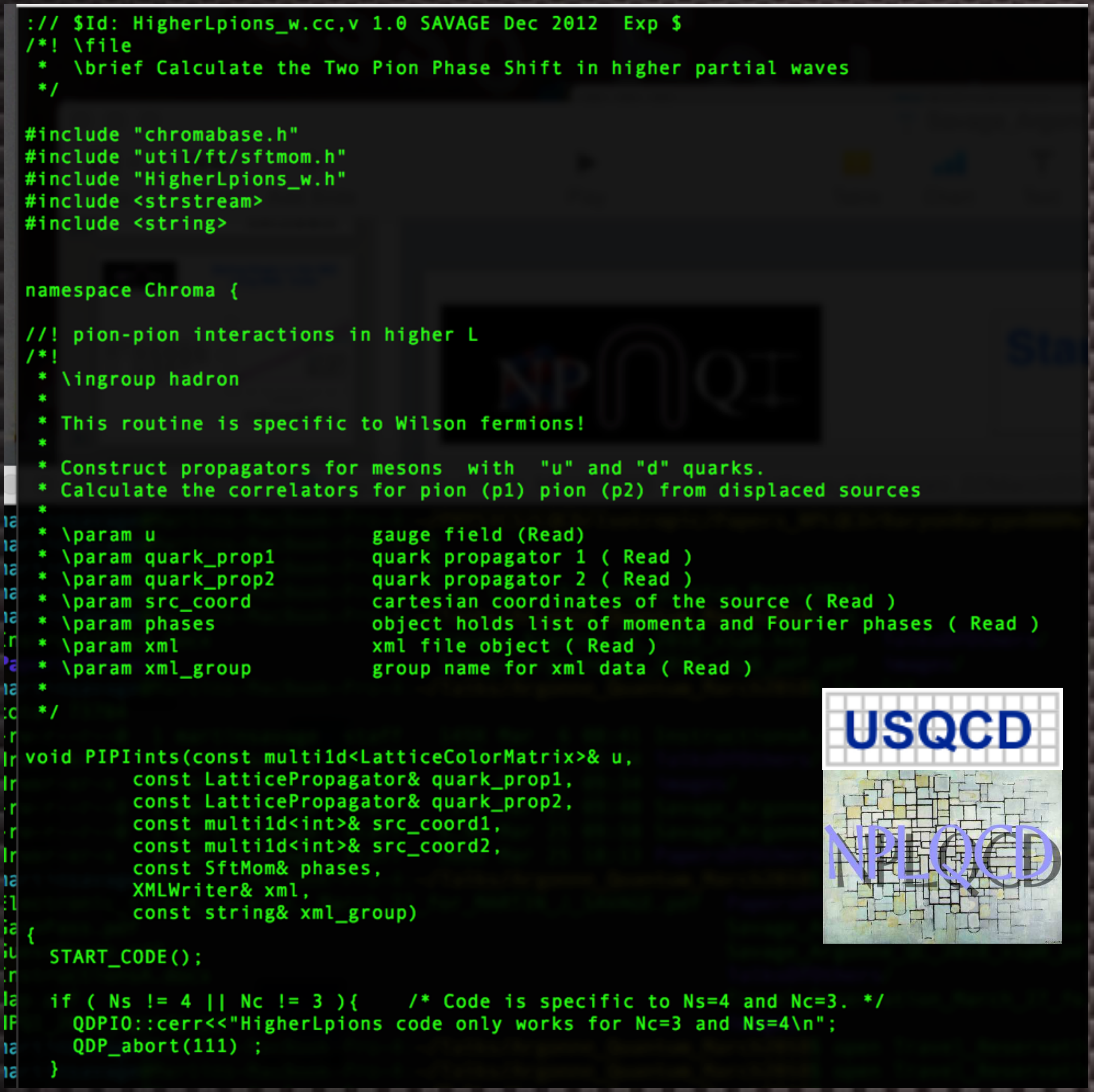
12.3 QPU·s



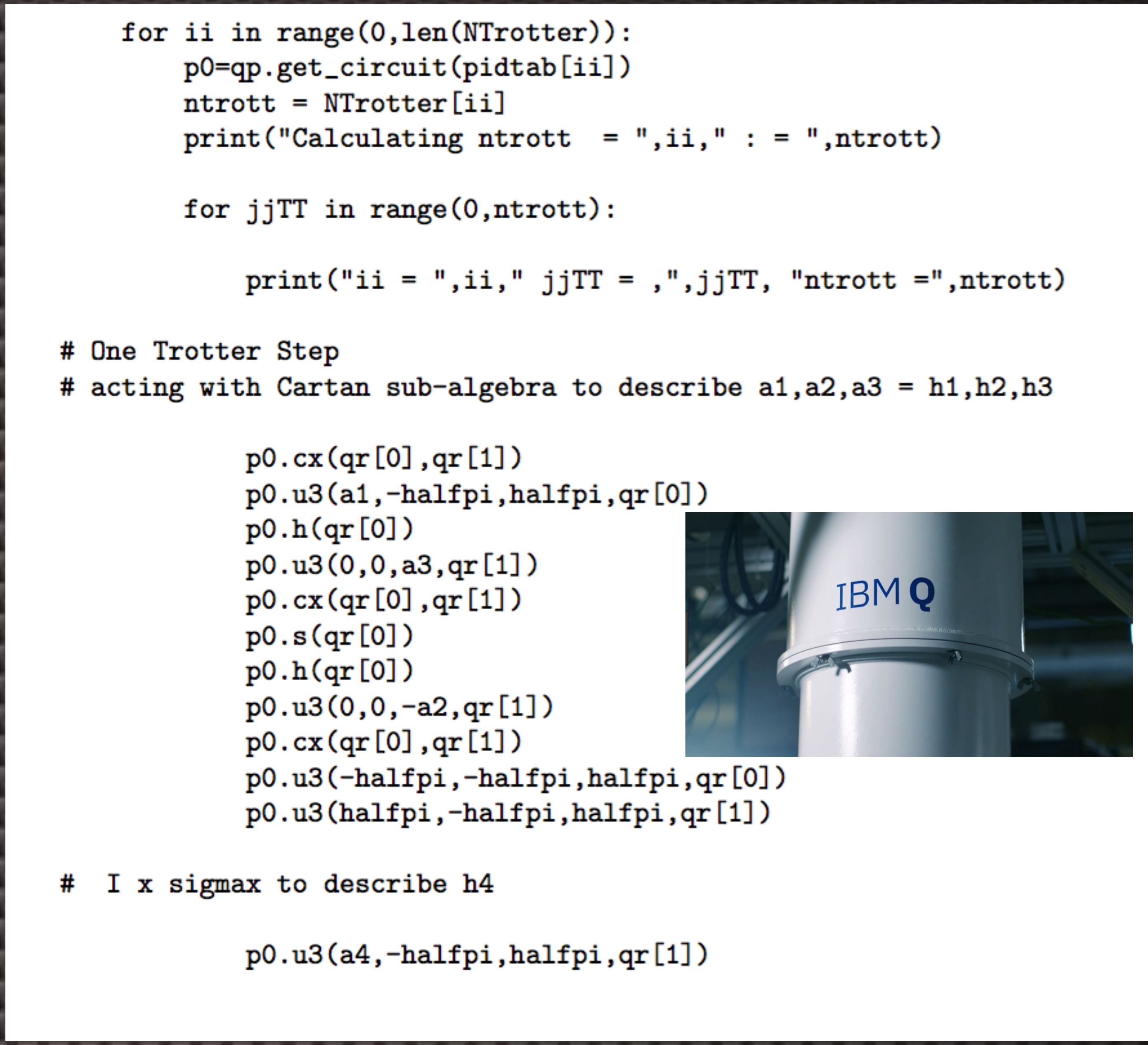
ArXiv :1803.03326

Slide by Natalie Klco (Oct 2018)

1+1 Dim QED
Low Barrier for ``Entry”



```
:// $Id: HigherLpions_w.cc,v 1.0 SAVAGE Dec 2012  Exp $
/*! \file
 *  \brief Calculate the Two Pion Phase Shift in higher partial waves
 */

#include "chromabase.h"
#include "util/ft/sftmom.h"
#include "HigherLpions_w.h"
#include <strstream>
#include <string>


namespace Chroma {

//! pion-pion interactions in higher L
/*!
 * \ingroup hadron
 *
 * This routine is specific to Wilson fermions!
 *
 * Construct propagators for mesons  with  "u" and "d" quarks.
 * Calculate the correlators for pion (p1) pion (p2) from displaced sources
 *
 * \param u                    gauge field (Read)
 * \param quark_prop1          quark propagator 1 ( Read )
 * \param quark_prop2          quark propagator 2 ( Read )
 * \param src_coord            cartesian coordinates of the source ( Read )
 * \param phases               object holds list of momenta and Fourier phases ( Read )
 * \param xml                  xml file object ( Read )
 * \param xml_group            group name for xml data ( Read )
 *
 */

void PIPIints(const multi1d<LatticeColorMatrix>& u,
         const LatticePropagator& quark_prop1,
         const LatticePropagator& quark_prop2,
         const multi1d<int>& src_coord1,
         const multi1d<int>& src_coord2,
         const SftMom& phases,
         XMLWriter& xml,
         const string& xml_group)
{
  START_CODE();

  if ( Ns != 4 || Nc != 3 ){    /* Code is specific to Ns=4 and Nc=3. */
    QDPIO::cerr<<"HigherLpions code only works for Nc=3 and Ns=4\n";
    QDP_abort(111) ;
  }
```



```
  for ii in range(0,len(NTrotter)):
    p0=qp.get_circuit(pidtab[ii])
    ntrott = NTrotter[ii]
    print("Calculating ntrott  = ",ii," : = ",ntrott)

    for jjTT in range(0,ntrott):

      print("ii = ",ii," jjTT = ,",jjTT, "ntrott =",ntrott)

# One Trotter Step
# acting with Cartan sub-algebra to describe a1,a2,a3 = h1,h2,h3

      p0.cx(qr[0],qr[1])
      p0.u3(a1,-halfpi,halfpi,qr[0])
      p0.h(qr[0])
      p0.u3(0,0,a3,qr[1])
      p0.cx(qr[0],qr[1])
      p0.s(qr[0])
      p0.h(qr[0])
      p0.u3(0,0,-a2,qr[1])
      p0.cx(qr[0],qr[1])
      p0.u3(-halfpi,-halfpi,halfpi,qr[0])
      p0.u3(halfpi,-halfpi,halfpi,qr[1])

#  I x sigmax to describe h4

      p0.u3(a4,-halfpi,halfpi,qr[1])
```

Lattice QCD application ***chroma*** code written by Savage (2012) for NPLQCD, adapted from other ***chroma*** codes written by Robert Edwards and Balint Joo [JLab, USQCD, SciDAC].

C++

Displaced propagator sources generate hadronic blocks projected onto cubic irreps. to access meson-meson scattering amplitudes in L>0 partial waves.

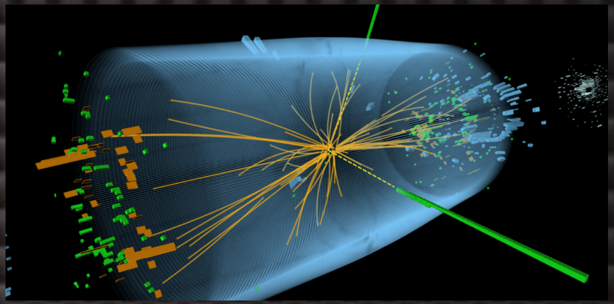
Python3 code written by Savage (2018) to access IBM quantum devices through ``the cloud” (through ORNL). IBM templates and example codes.

Calculates Trotter evolution of +ve parity sector of the 2-spatial-site Schwinger Model.

Entanglement and Fragmentation

Deep inelastic scattering as a probe of entanglement
Dmitri E. Kharzeev (RIKEN BNL & SUNY, Stony Brook), Eugene M. Levin (Santa Maria U., Valparaiso & Tel Aviv U.). Feb 12, 2017.
Published in **Phys.Rev. D95 (2017) no.11, 114008**

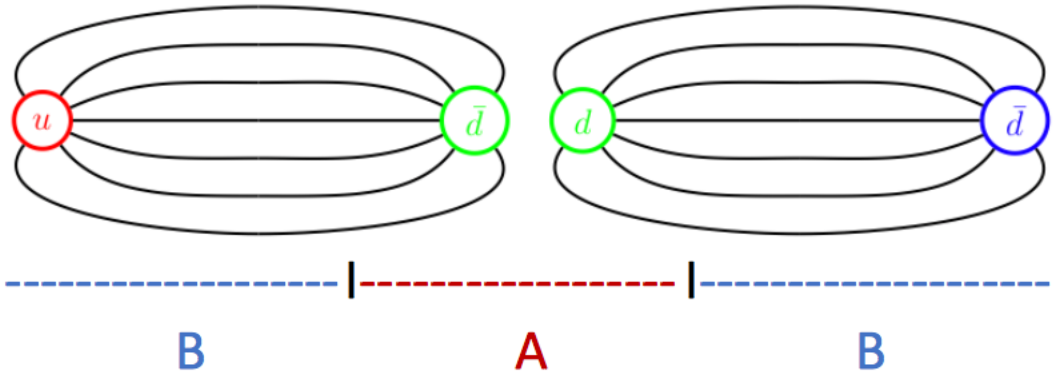
Dynamics of entanglement in expanding quantum fields
Jürgen Berges, Stefan Floerchinger (U. Heidelberg, ITP), Raju Venugopalan (Brookhaven). Dec 26, 2017.
Published in **JHEP 1804 (2018) 145**

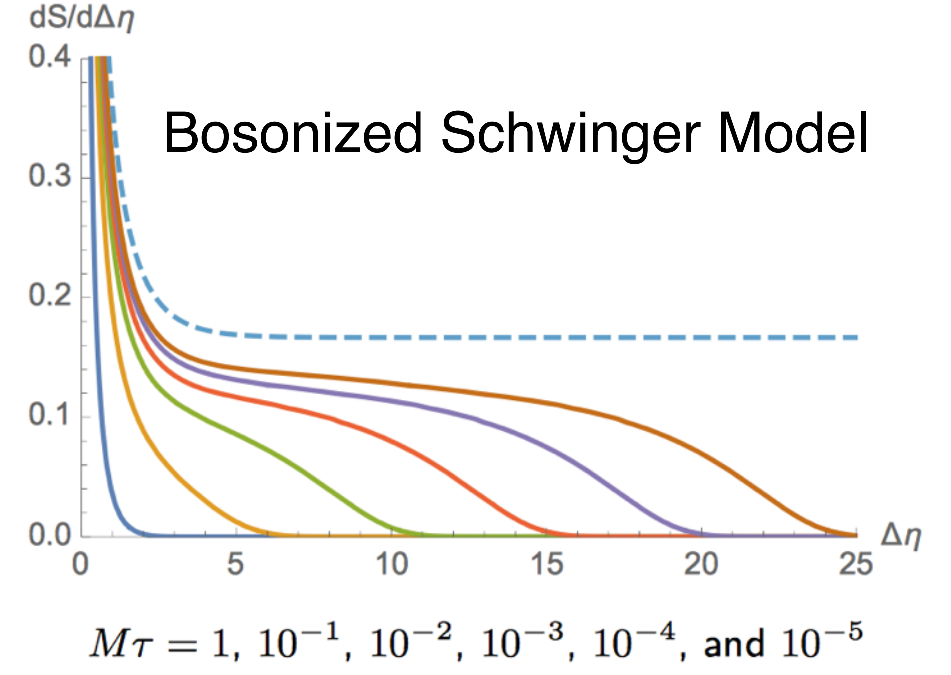


Stony Brook University

Real-time Dynamics in U(1) Lattice Gauge Theories with Tensor Networks

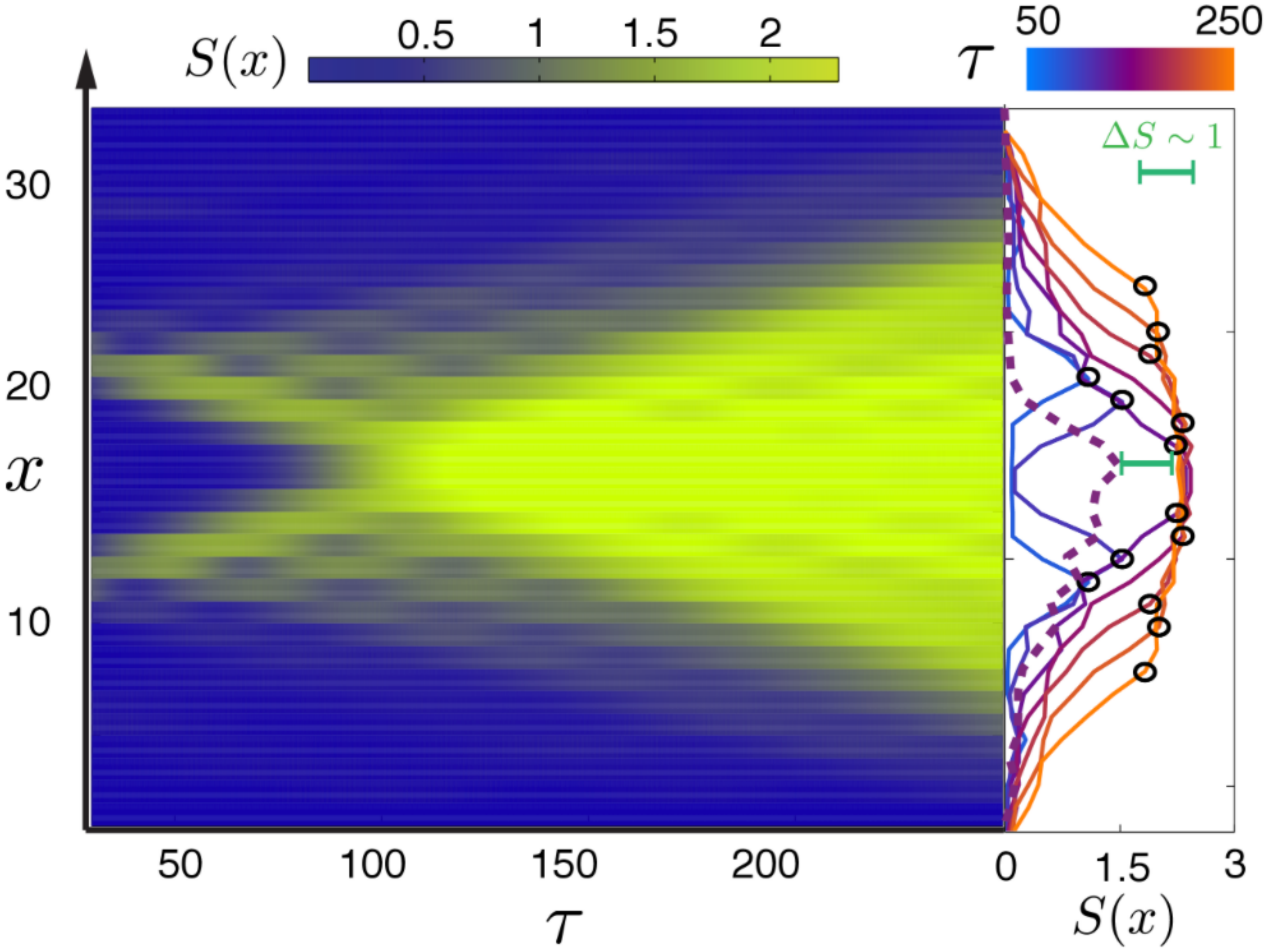
T. Pichler,[1] M. Dalmonte,[2,3] E. Rico,[4,5,6] P. Zoller,[2,3] and S. Montangero[1]





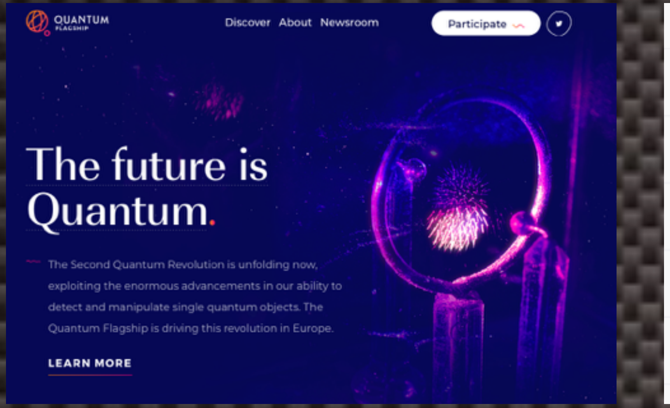
Bosonized Schwinger Model

$M\tau = 1,\ 10^{-1},\ 10^{-2},\ 10^{-3},\ 10^{-4}$, and 10^{-5}



QC and QIS in the International Community
2 significant examples

Europe



The future is Quantum.

The Second Quantum Revolution is unfolding now, exploiting the enormous advancements in our ability to detect and manipulate single quantum objects. The Quantum Flagship is driving this revolution in Europe.

Quantum Flagship in a nutshell.

01 1b € Quantum Technology will be funded with at least one billion Euro by the European Commission.

02 10+ yrs Flagship's timescale

03 5000+ researchers residing in all EU and associated countries involved

04 140 Research and Innovation Actions (RIA) proposals submitted in response of the first Quantum Flagship call

China

Investing heavily in all related areas of QIS and QC
e.g., Alibaba - qubits/devices and QIS

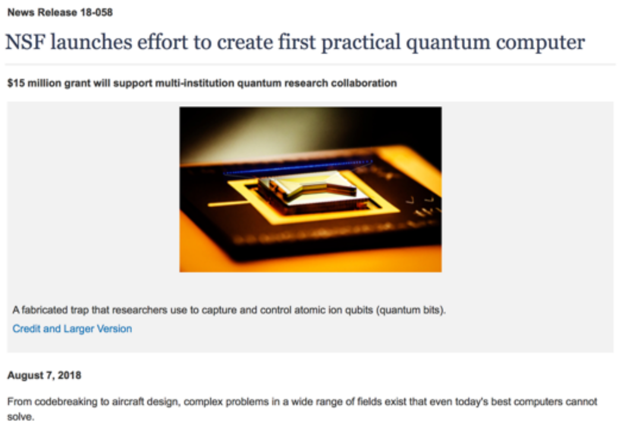
Generally:

- Investments in field theory and sensors
- Other efforts Nuclear Physics are beginning

QC and QIS in Broader Community

US

ASCR Report on a Quantum Computing Testbed for Science



News Release 18-058

NSF launches effort to create first practical quantum computer

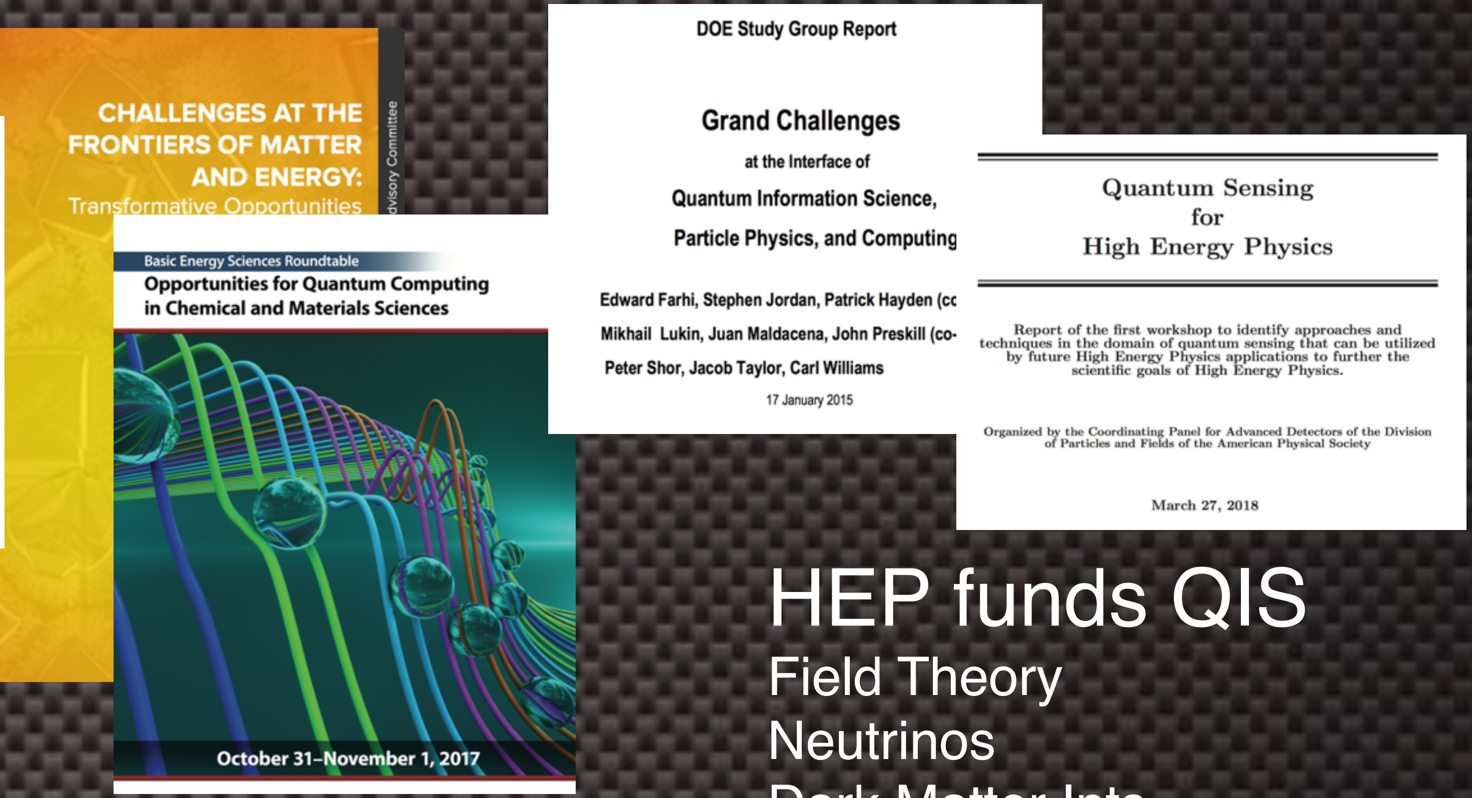
$15 million grant will support multi-institution quantum research collaboration

A fabricated trap that researchers use to capture and control atomic ion qubits (quantum bits).

Credit and Larger Version

August 7, 2018

From codebreaking to aircraft design, complex problems in a wide range of fields exist that even today's best computers cannot solve.



CHALLENGES AT THE FRONTIERS OF MATTER AND ENERGY: Transformative Opportunities

Basic Energy Sciences Roundtable

Opportunities for Quantum Computing in Chemical and Materials Sciences

October 31–November 1, 2017

DOE Study Group Report

Grand Challenges

at the Interface of

Quantum Information Science,

Particle Physics, and Computing

Edward Farhi, Stephen Jordan, Patrick Hayden (cc

Mikhail Lukin, Juan Maldacena, John Preskill (co-

Peter Shor, Jacob Taylor, Carl Williams

17 January 2015

Quantum Sensing
for
High Energy Physics

Report of the first workshop to identify approaches and techniques in the domain of quantum sensing that can be utilized by future High Energy Physics applications to further the scientific goals of High Energy Physics.

Organized by the Coordinating Panel for Advanced Detectors of the Division of Particles and Fields of the American Physical Society

March 27, 2018

HEP funds QIS

Field Theory

Neutrinos

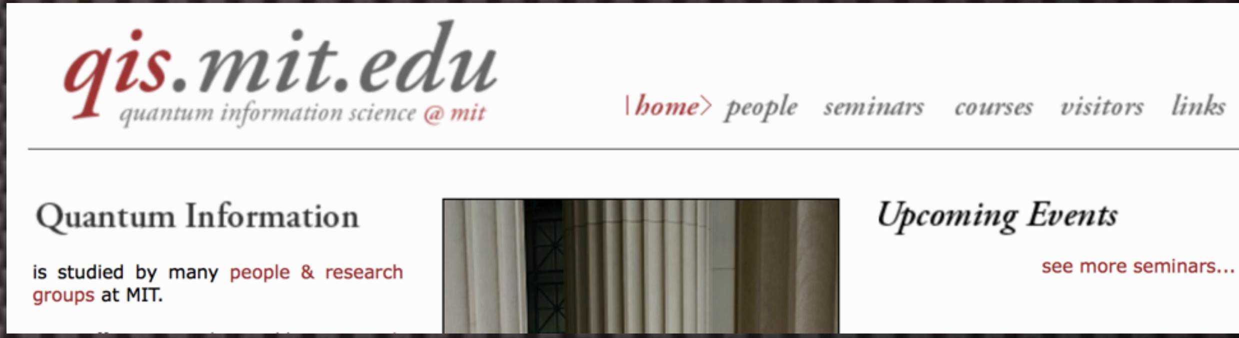
Dark Matter Ints.

New hole-punched crystal clears a path for quantum light

PHOTONIC CHIP GUIDES SINGLE PHOTONS, EVEN WHEN THERE ARE BENDS IN THE ROAD.

U of Maryland

USQCD Lattice QCD consortium

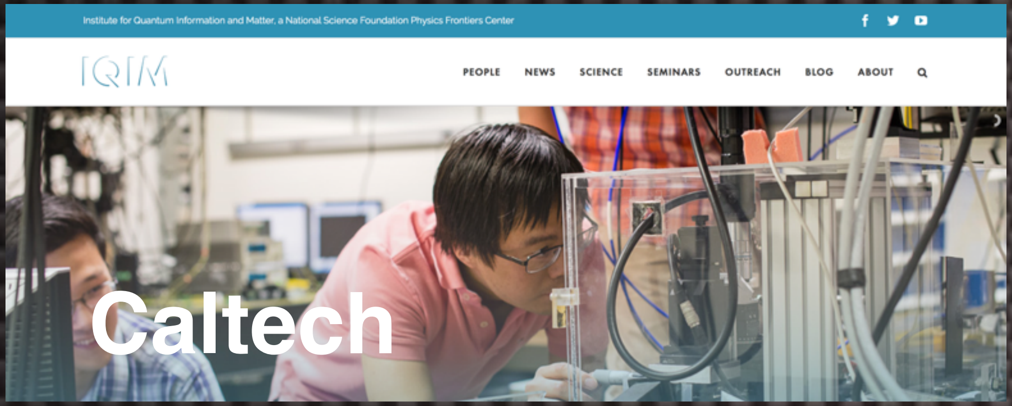


Quantum Information

is studied by many people & research groups at MIT.

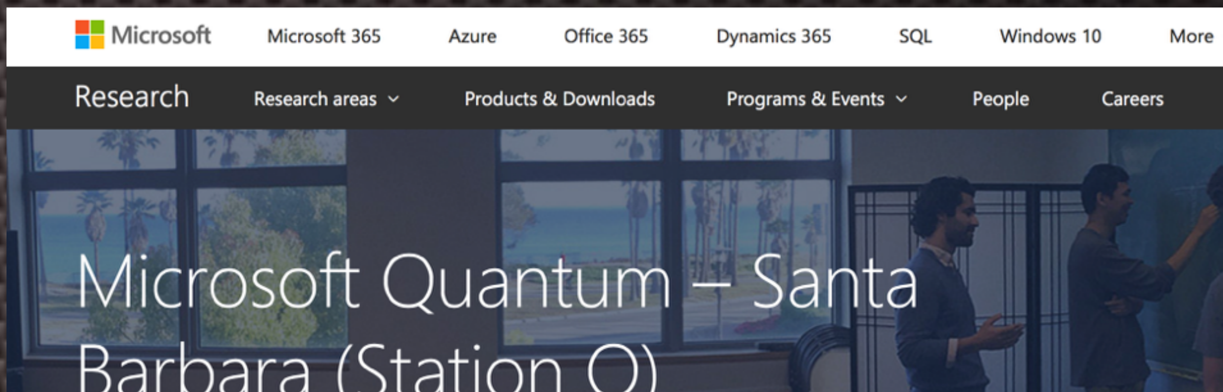
Upcoming Events

see more seminars...



Institute for Quantum Information and Matter, a National Science Foundation Physics Frontiers Center

Caltech



Microsoft Quantum – Santa Barbara (Station Q)

Activities in Nuclear Physics

JOINT CENTER FOR QUANTUM INFORMATION AND COMPUTER SCIENCE

Workshop on Computational Complexity and High Energy Physics
July-31 — August 2, 2017

Near-term Applications of Quantum Computing

6-7 December 2017
Fermilab - Wilson Hall
US/Central timezone

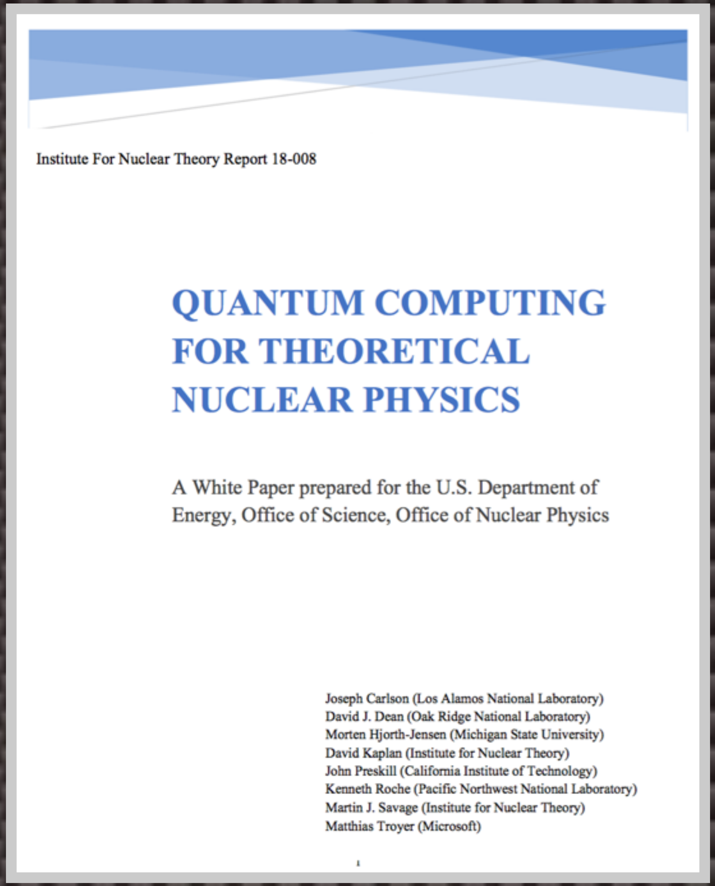
Near-term Applications of Quantum Computing, December 6-7, 2017

OAK RIDGE
National Laboratory

David Dean as Head of Physics Division ahead of all others in NP

INSTITUTE for NUCLEAR THEORY

Quantum Computing for Nuclear Physics
November 14-15, 2017



Institute For Nuclear Theory Report 18-008

QUANTUM COMPUTING FOR THEORETICAL NUCLEAR PHYSICS

A White Paper prepared for the U.S. Department of Energy, Office of Science, Office of Nuclear Physics

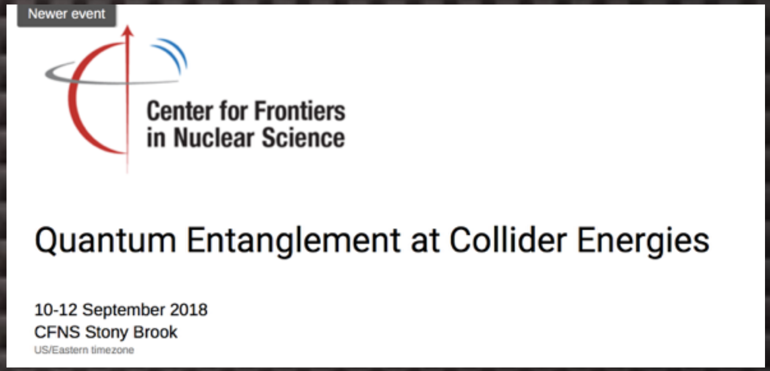
Joseph Carlson (Los Alamos National Laboratory)
David J. Dean (Oak Ridge National Laboratory)
Morten Hjorth-Jensen (Michigan State University)
David Kaplan (Institute for Nuclear Theory)
John Preskill (California Institute of Technology)
Kenneth Roche (Pacific Northwest National Laboratory)
Martin J. Savage (Institute for Nuclear Theory)
Matthias Troyer (Microsoft)

1

INT Report 18-008

NP ∩ QI

Intersections Between Nuclear Physics and Quantum Information
Argonne National Laboratory
March 28-30, 2018



Center for Frontiers in Nuclear Science

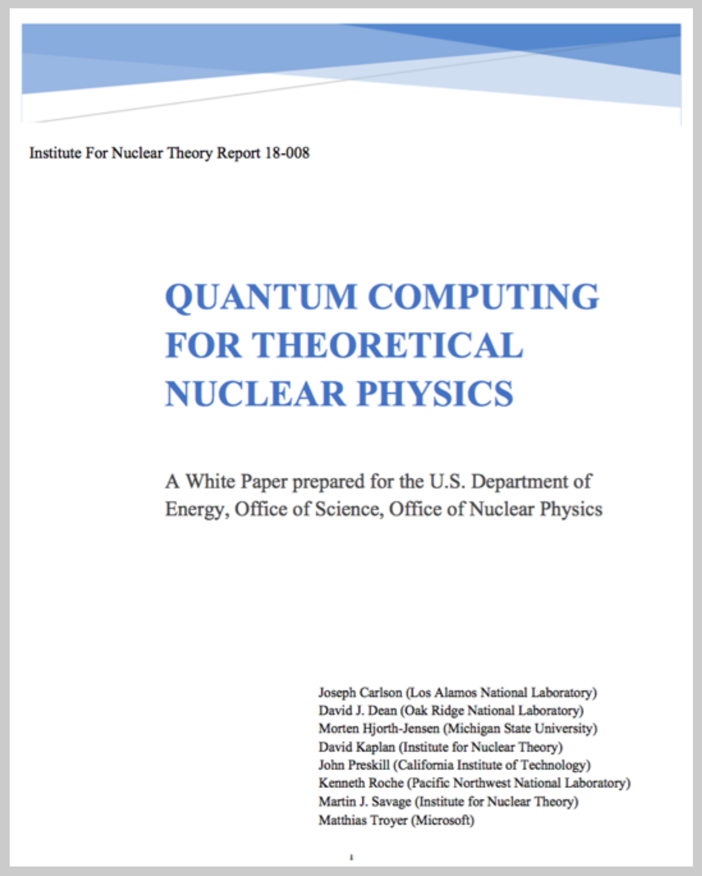
Quantum Entanglement at Collider Energies

10-12 September 2018
CFNS Stony Brook
US/Eastern timezone

Stony Brook
September 10-12, 2018

DOE NP funds a modest number of proposals in 2018

Activities in Nuclear Theory



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Kenneth Roche (Pacific Northwest National Laboratory)
Martin J. Savage (Institute for Nuclear Theory)
Matthias Troyer (Microsoft)

INT Report 18-008

Seattle, November 2017

A broad, multi-institutional program has been funded by DOE to hold two community-wide meetings, and to partially-support 2 junior scientists.

First meeting:
January 23-25 in Santa Fe
(Los Alamos)

Los Alamos NATIONAL LABORATORY EST.1943
THE UNIVERSITY OF TENNESSEE KNOXVILLE
INSTITUTE for NUCLEAR THEORY
UNIVERSITY OF MARYLAND 1856
UCSD
MSU
W
OAK RIDGE National Laboratory
MIT
Argonne NATIONAL LABORATORY
NC

Stony Brook University

Expertise and Nuclear Physics

Expertise in other domains will be important for Nuclear Physics

- Chemistry
- Quantum Information and Computing
- High-Energy Physics
- Condensed Matter
- ASCR
- Photonics
- Computer Science
- Technology Companies
- …

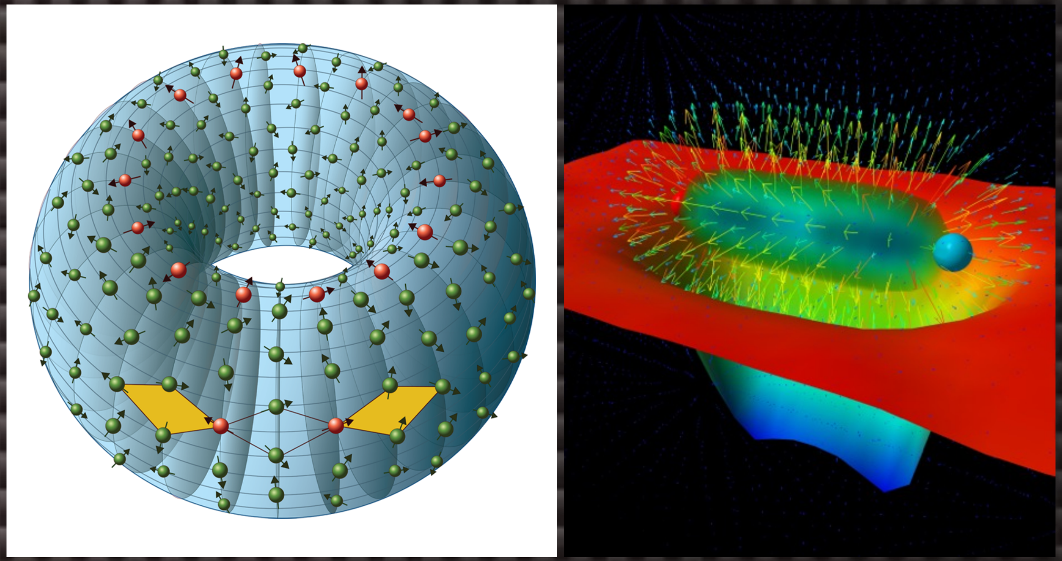
International expertise will be valuable

Workforce development/adaptation just starting

Broader Impacts

e.g.

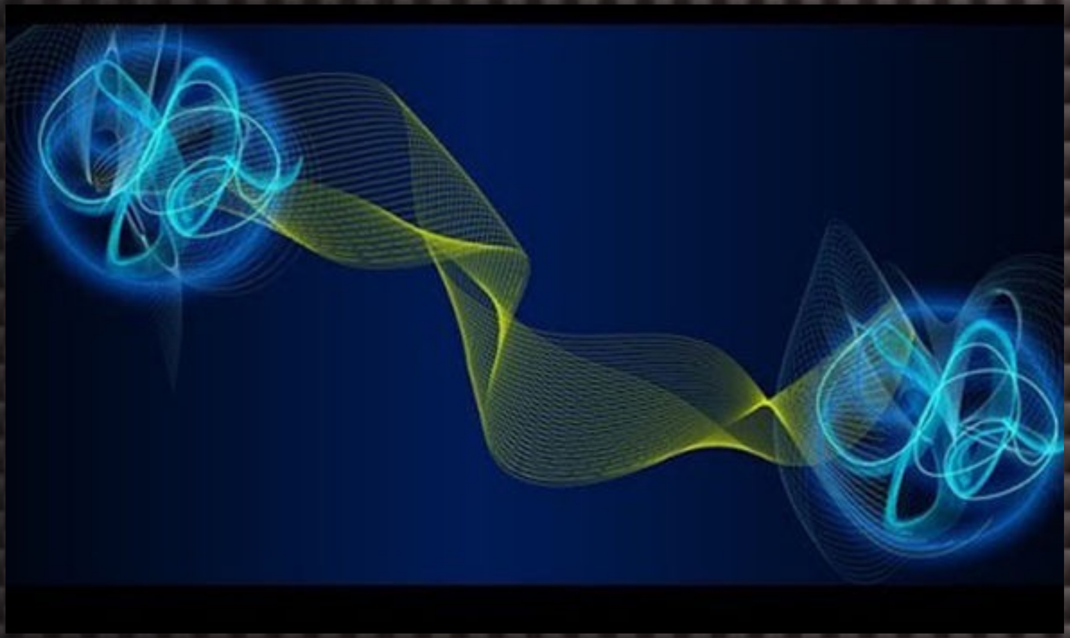
- Quantum many-body systems
  - Error correction
  - Topological structures
- Sensors
- Device design
- Workforce development
  - undergraduate and graduate students are excited and engaged

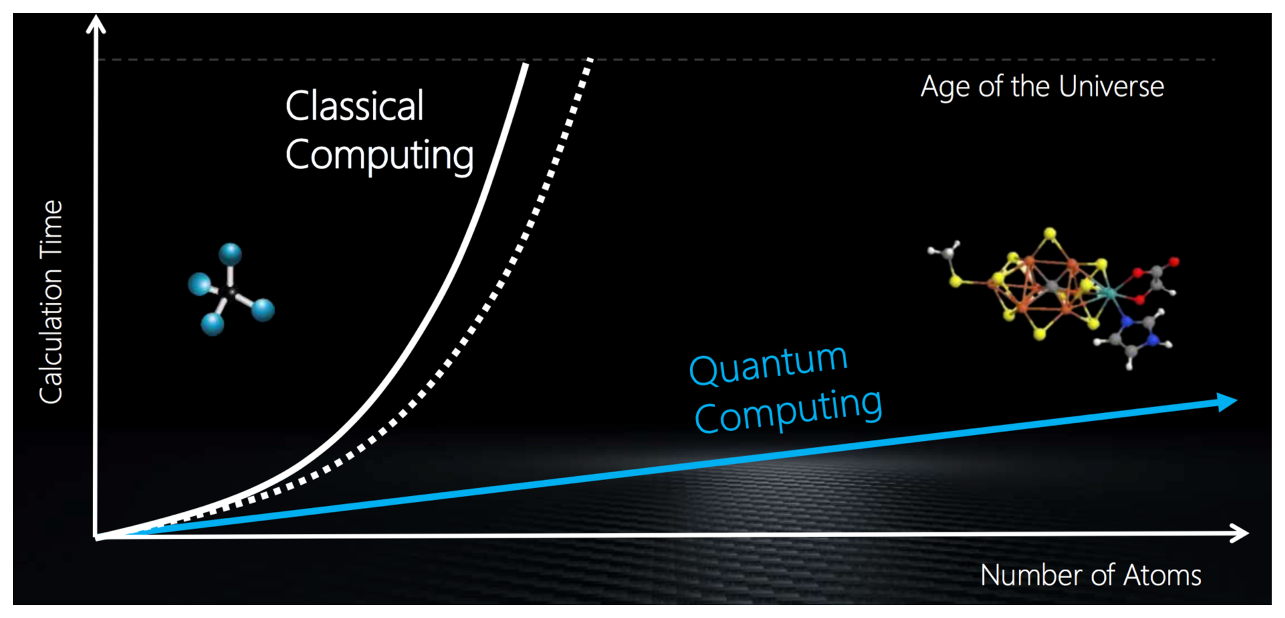


Anticipated to be of benefit to

- QIS + QC
- Technology companies
- High-Energy Physics
- Condensed matter
- Chemistry
- Quantum communication
- Quantum encryption
- …

Summary





QC and QIS are now entering Nuclear Physics

- Significant potential to disruptively enhance the NP research program
  - address exponentially difficult challenges
- A limited fraction of community is actively engaged
- Community is starting to organize
- Workforce training critical
- NP has broad systemic fundamental knowledge of quantum many-body systems - anticipated to be valuable in QC and QIS development and other scientific applications

Charge to NSAC related to QC+QIS is timely

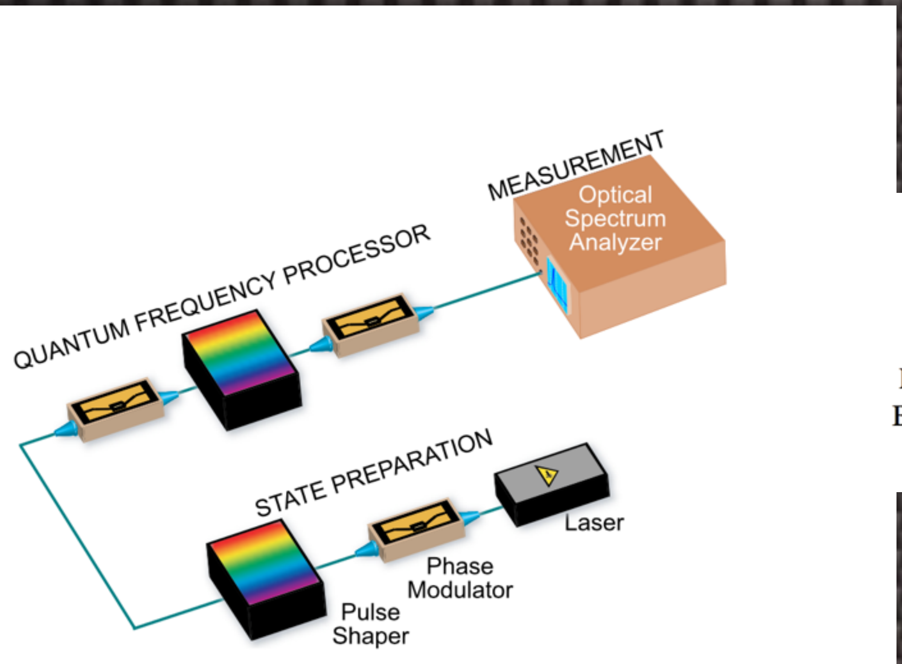
FIN

Field Theory on All-Optical QFP QED and Nuclear EFT

OAK RIDGE National Laboratory

HDAQDS Heterogeneous Digital-Analog Quantum Dynamics Simulations

ASCR



Simulations of Subatomic Many-Body Physics on a Quantum Frequency Processor

Hsuan-Hao Lu[1], Natalie Klco[2], Joseph M. Lukens[3], Titus D. Morris[3], Aaina Bansal[4], Andreas Ekström[5], Gaute Hagen[6,4], Thomas Papenbrock[4,6], Andrew M. Weiner[1], Martin J. Savage[2], and Pavel Lougovski[3,*]

e-Print: **arXiv:1810.03959 [quant-ph]**