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INSTITUTE for NUCLEAR THEORY

Comments on Quantum Computing

USQCD Allhands Meeting, FermiLab
April 20, 2018

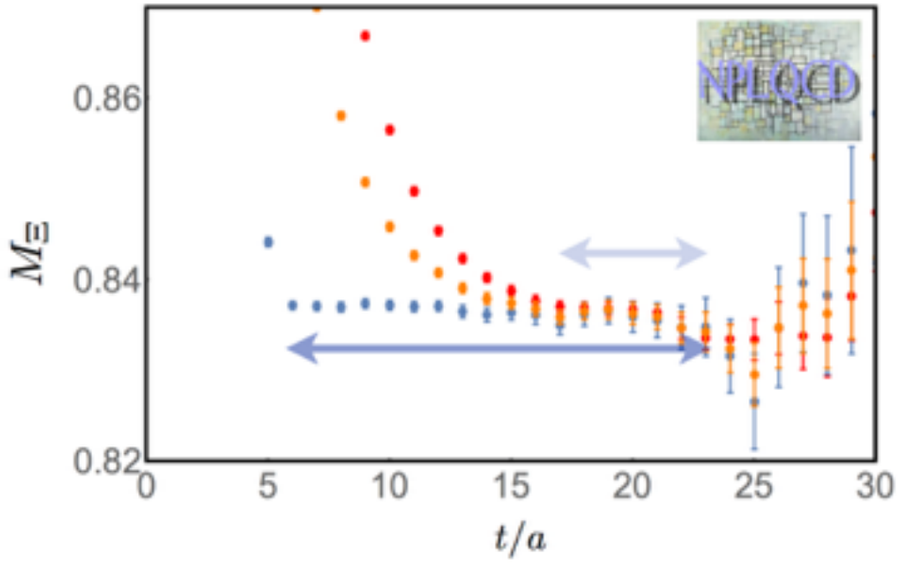
Martin J Savage

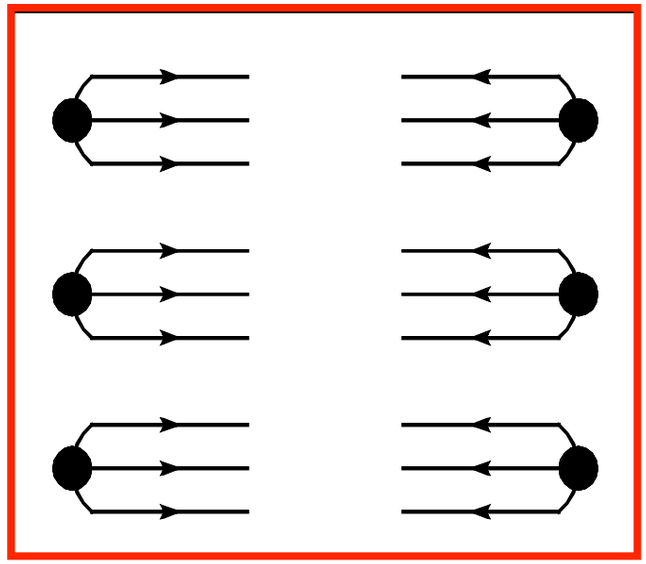
Institute for Nuclear Theory
University of Washington

USQCD

Q: Why should we think about QC ?
A: We have Beyond-Exascale Challenges

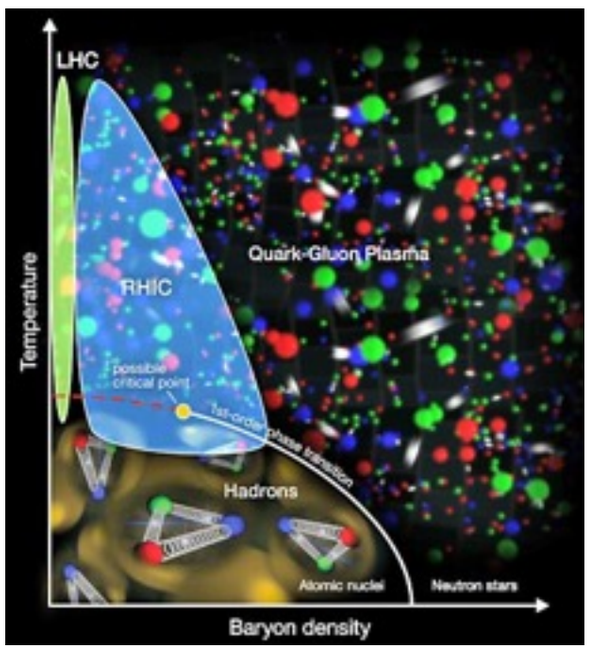
- **Signal-to-Noise = Sign Problem**





- **Large-scale contractions**

- **Sign Problem**



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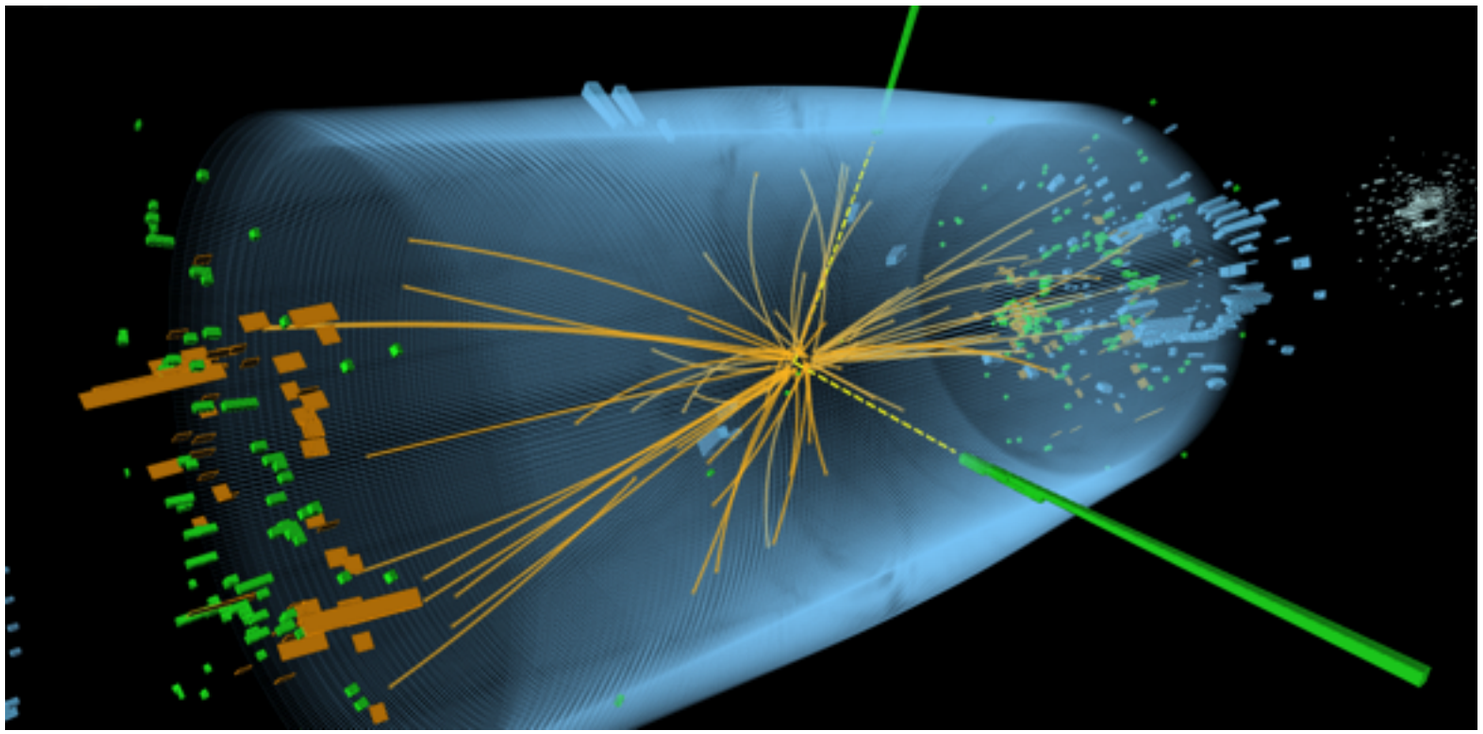
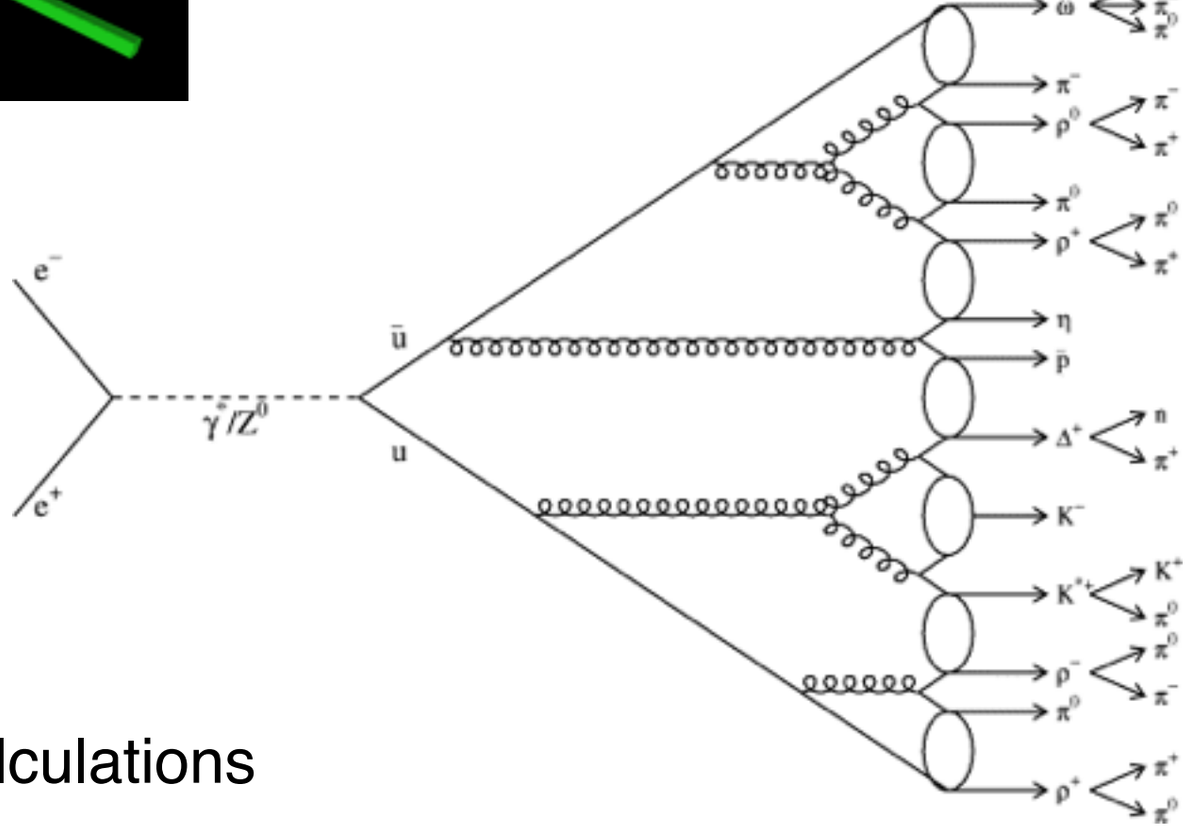
Fragmentation
Vacuum and In-Medium
Currently - out of scope





- Free-space and in-medium
- Diagnostic of state of dense and hot matter
  - heavy-ion collisions (e.g., jet quenching)
  - finite density and time evolution
- Highly-tuned phenomenology and pQCD calculations

Why Quantum Computing?

The sign problem and the desire for dynamical evolution of QCD systems, requiring ***beyond exascale classical computing*** resources, lead us to consider the potential of quantum information and computing. [2016-2017]

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

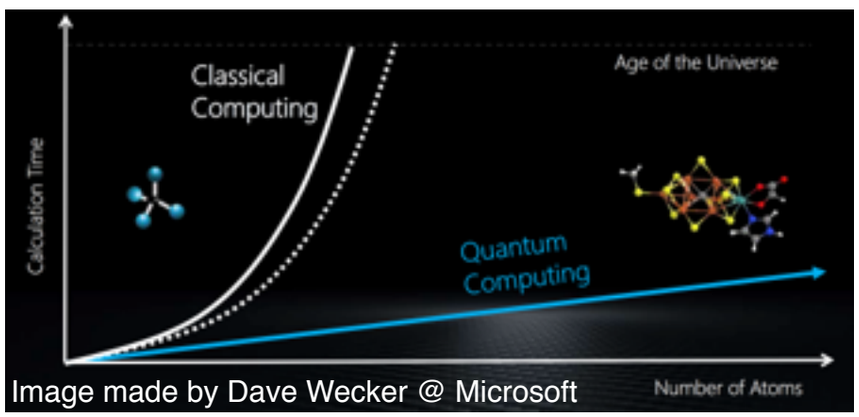
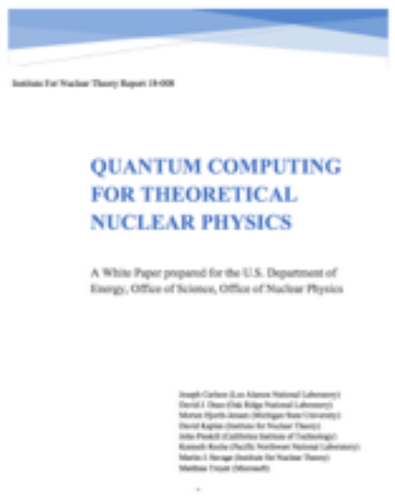


Image made by Dave Wecker @ Microsoft

Quantum Computing for Nuclear Physics
November 14-15, 2017



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

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

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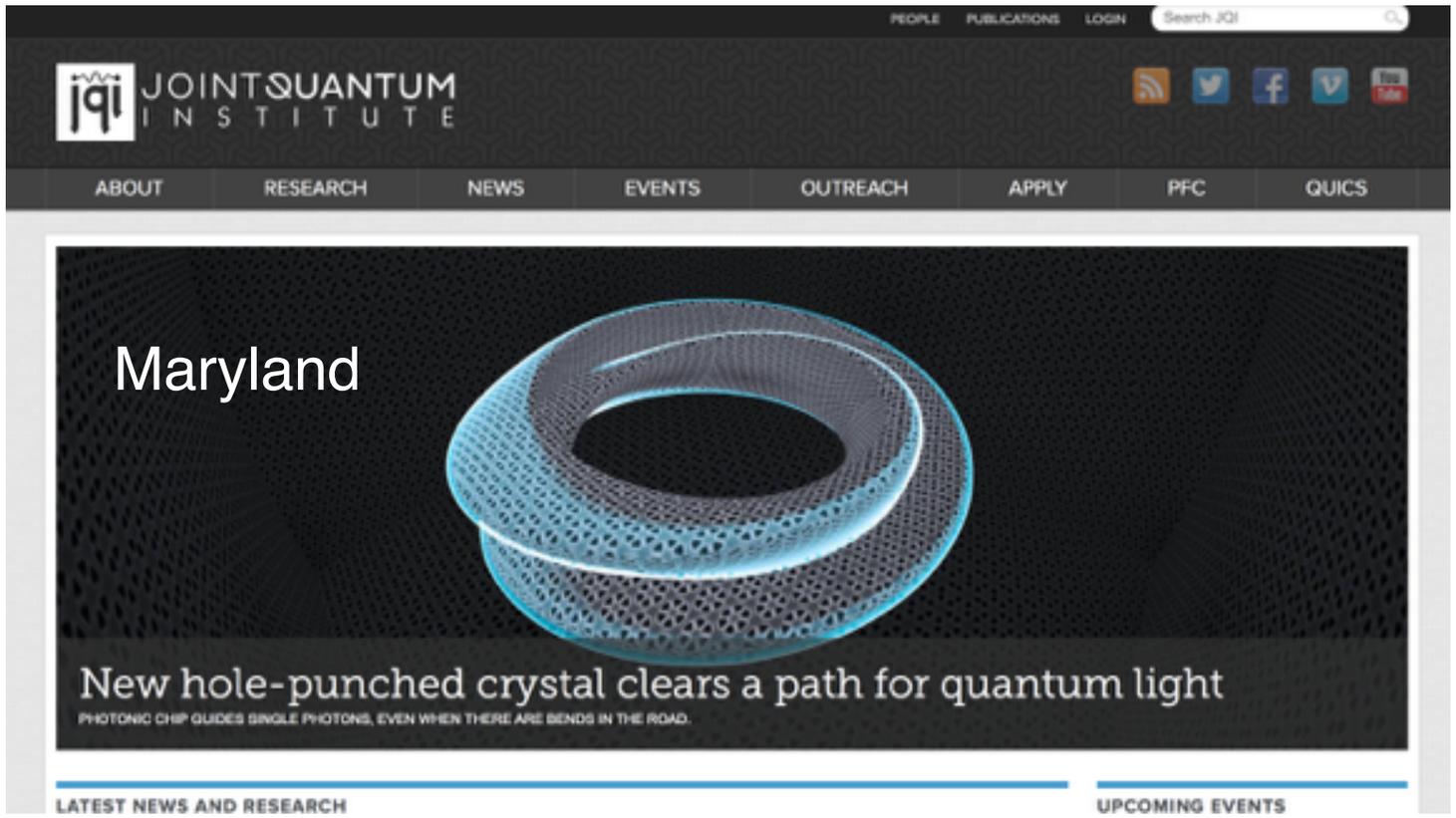
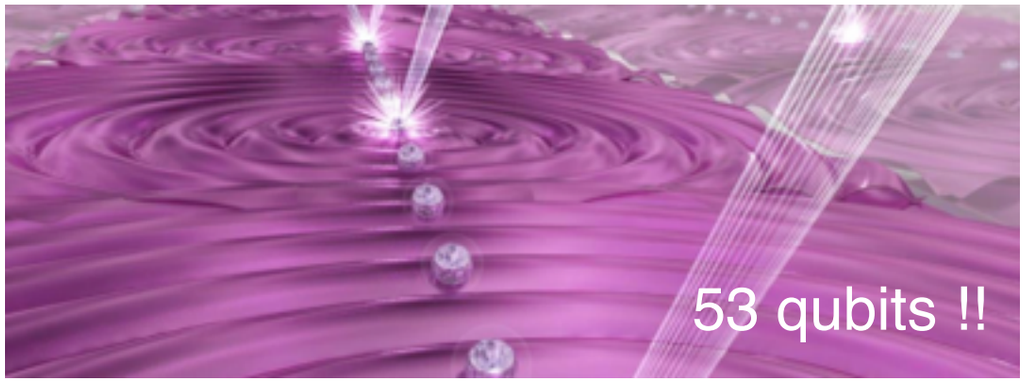
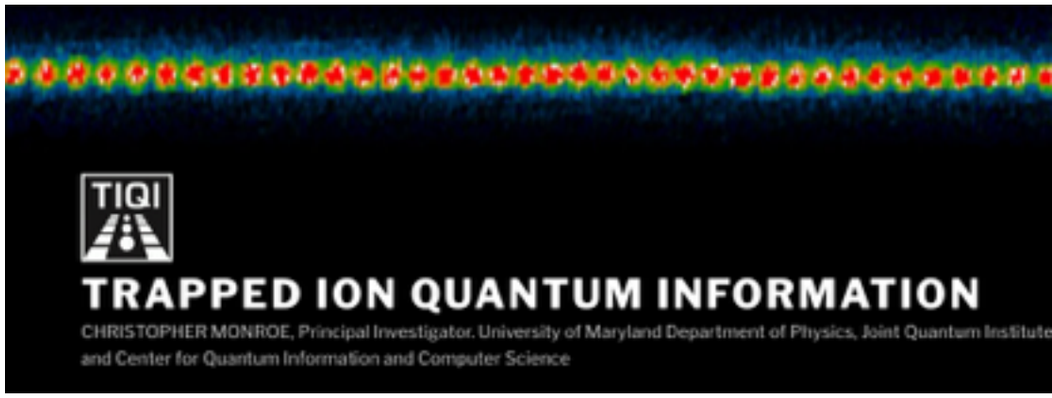
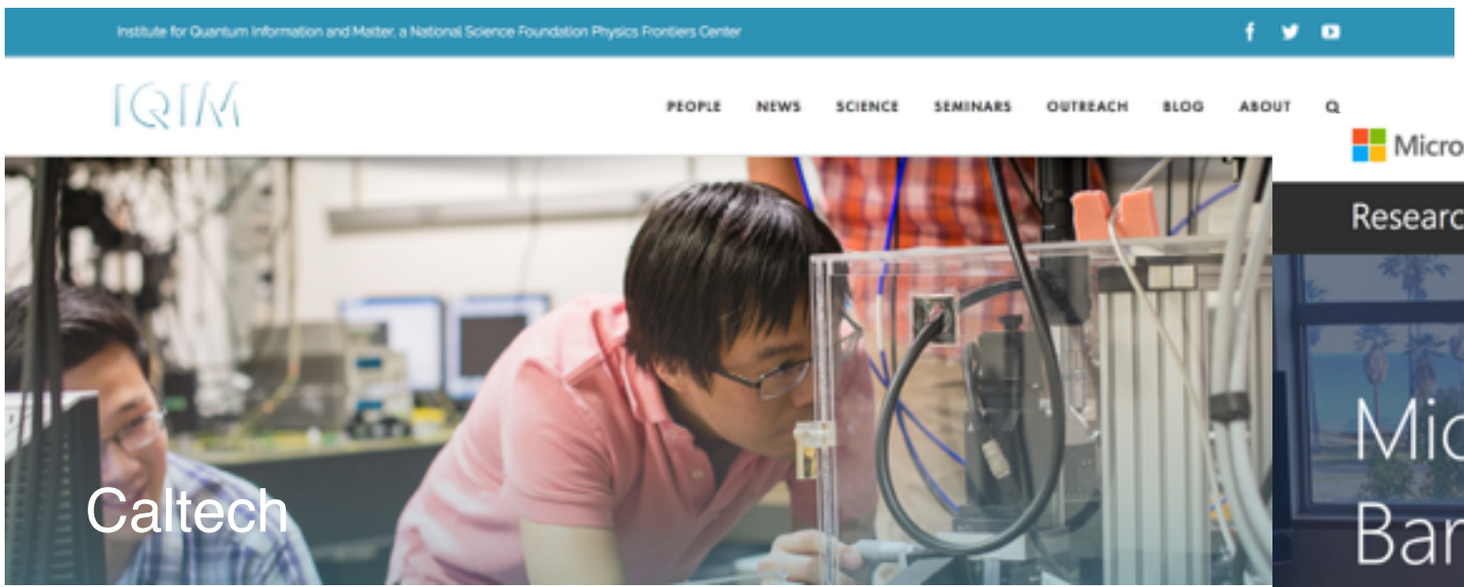
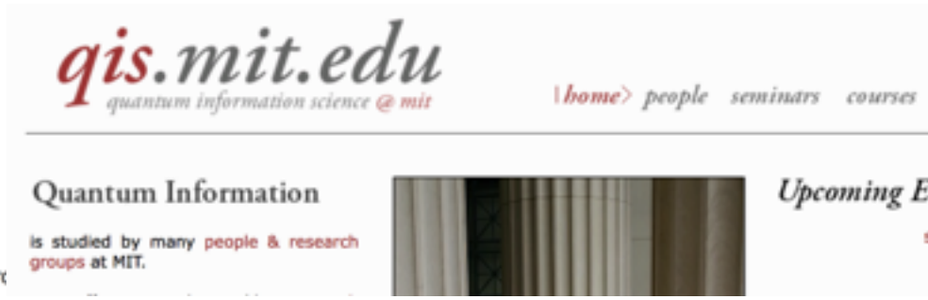
Quantum Computing



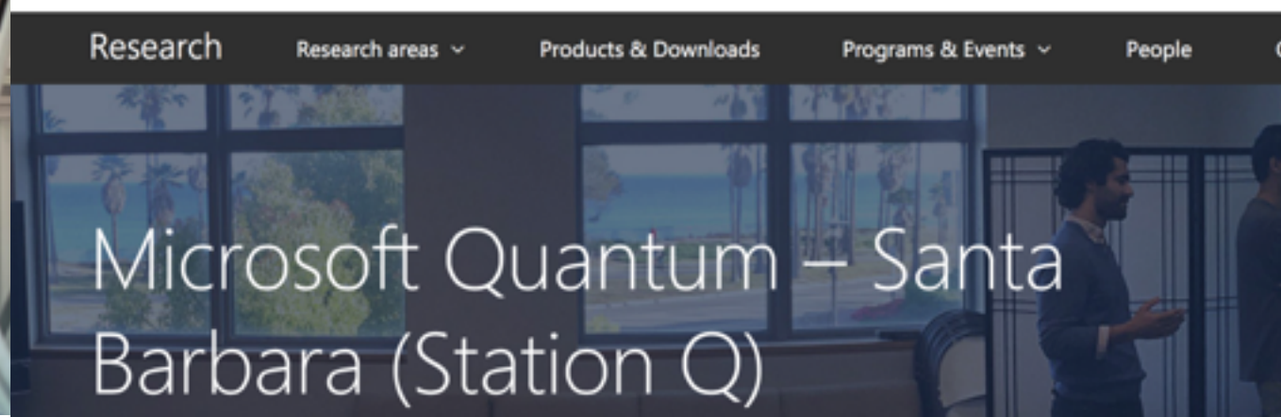








Microsoft Micr



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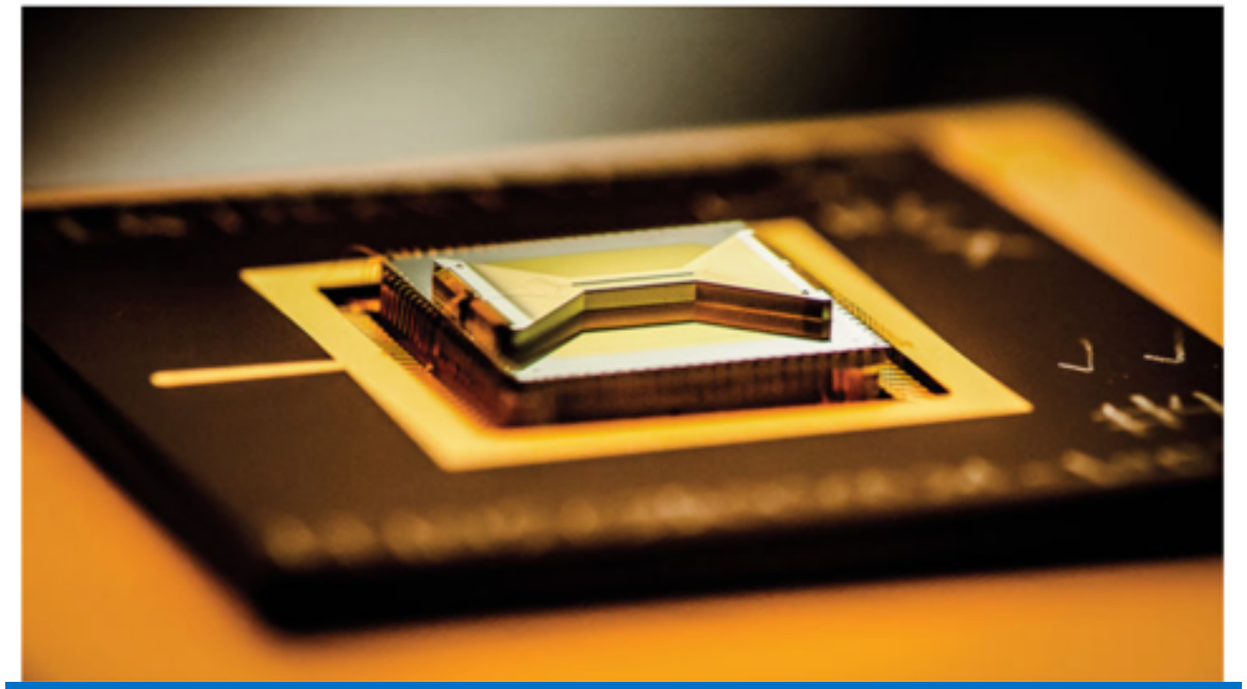
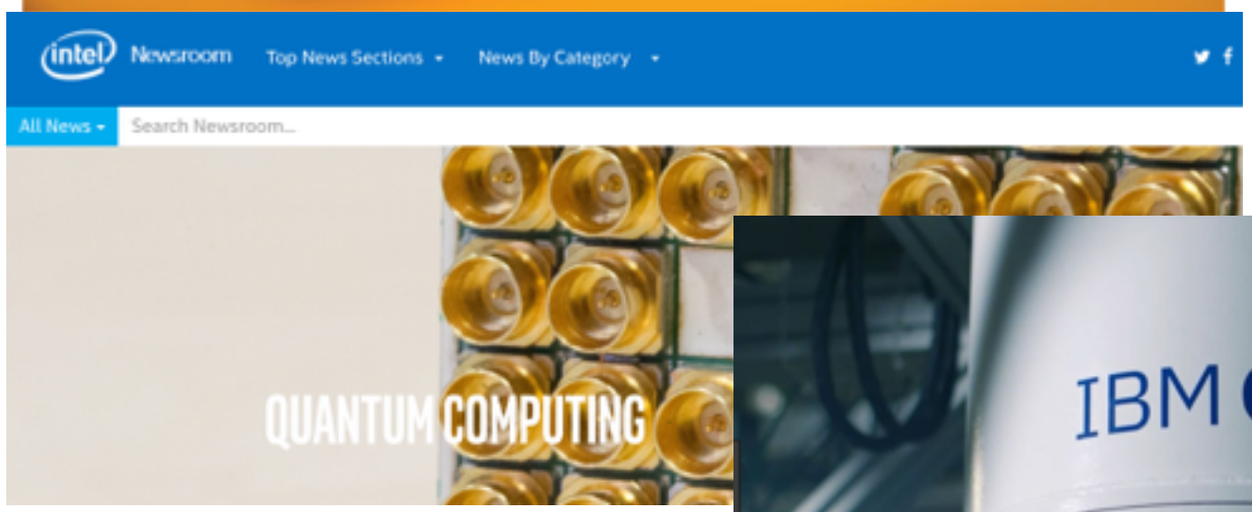
Quantum Computing





rigetti

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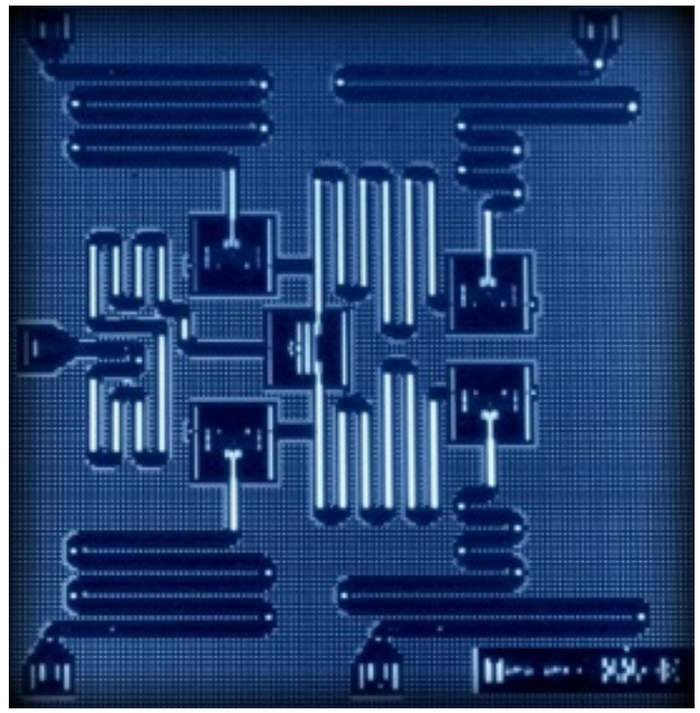
Quantum Computing - some of the hardware

D-wave : ~ 2000 qubits

Google : 72 superconducting qubits - not accessible at present



IBM : superconducting - 5, 5, 16, 20, 56 qubits systems - cloud access

Intel : 49 superconducting qubits - test chip

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

Microsoft : Majorana - nothing available yet

Rigetti : 19 superconducting qubits

The promise of Quantum Computing Parallel Processing

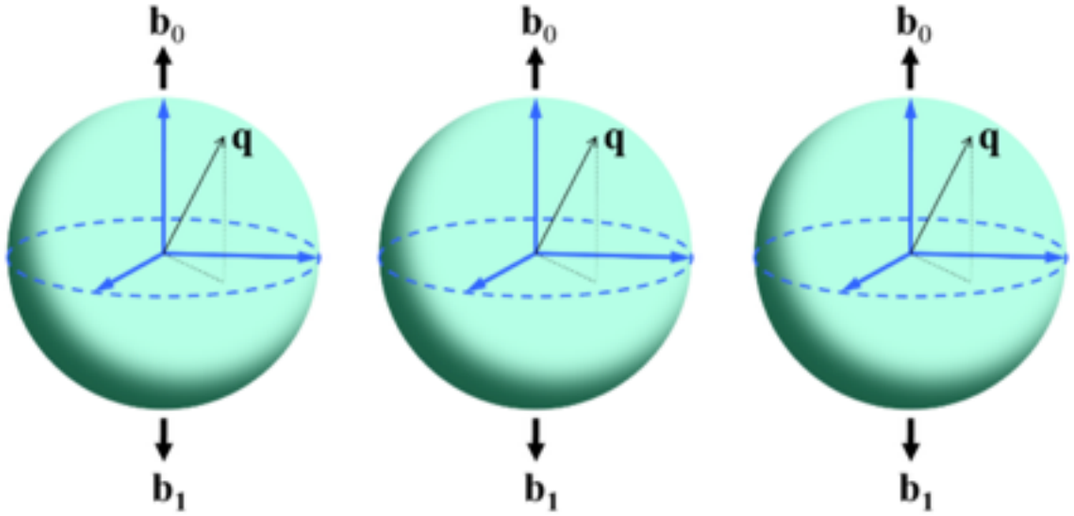
e.g., for a 3-bit computer (2^3 states)

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 could be in all states at once!

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



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

- $> \sim 50$ qubits : at capabilities of leadership class computers
- 300 qubits : more states than atoms in universe

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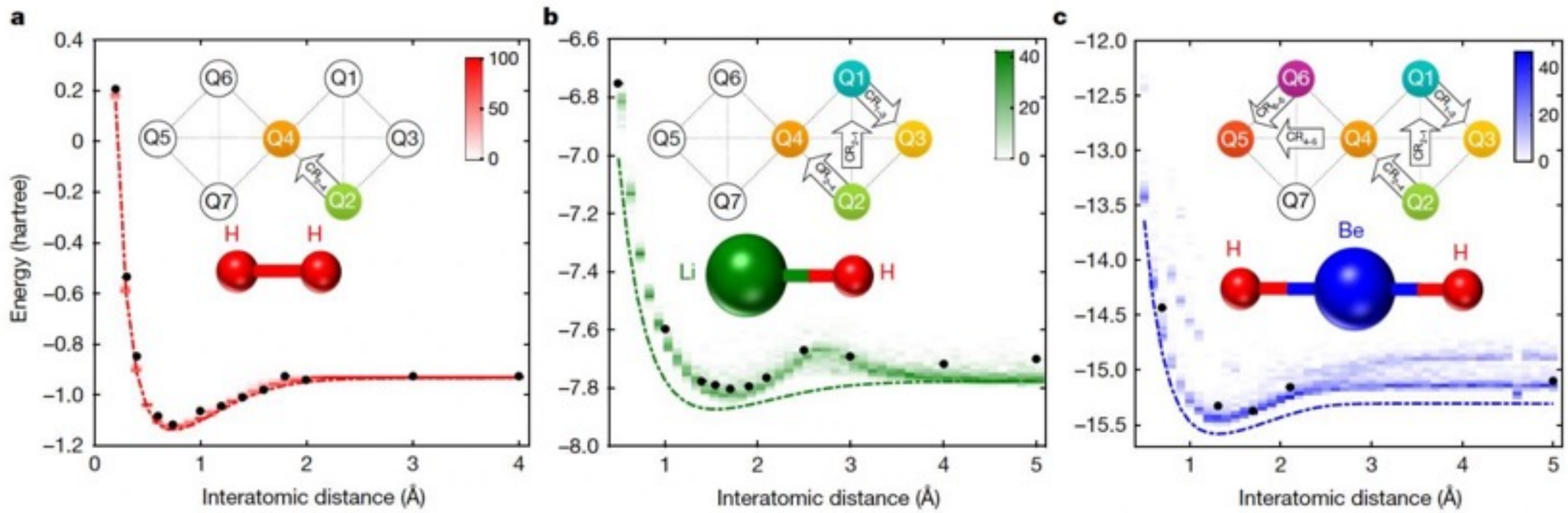
Molecules

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

September 14, 2017, IBM



Our answer to this combines a number of hardware-efficient techniques to attack the problem:

- First, a molecule's fermionic Hamiltonian is transformed into a qubit Hamiltonian, with a new efficient mapping that reduces the number of qubits required in the simulation.
- A hardware-efficient quantum circuit that utilizes the naturally available gate operations in the quantum processor is used to prepare trial ground states of the Hamiltonian.
- The quantum processor is driven to the trial ground state, and measurements are performed that allow us to evaluate the energy of the prepared trial state.
- The measured energy values are fed to a classical optimization routine that generates the next quantum circuit to drive the quantum processor to, in order to further reduce the energy.
- Iterations are performed until the lowest energy is obtained to the desired accuracy.

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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.

http://arxiv.org/abs/1801.03897

OAK RIDGE National Laboratory

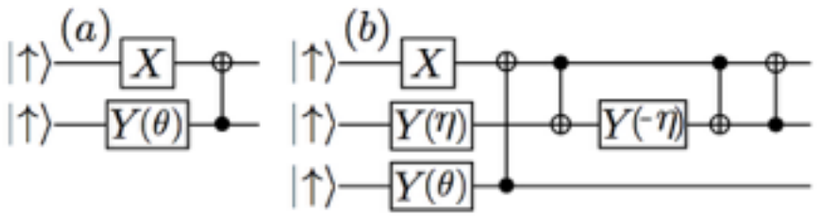
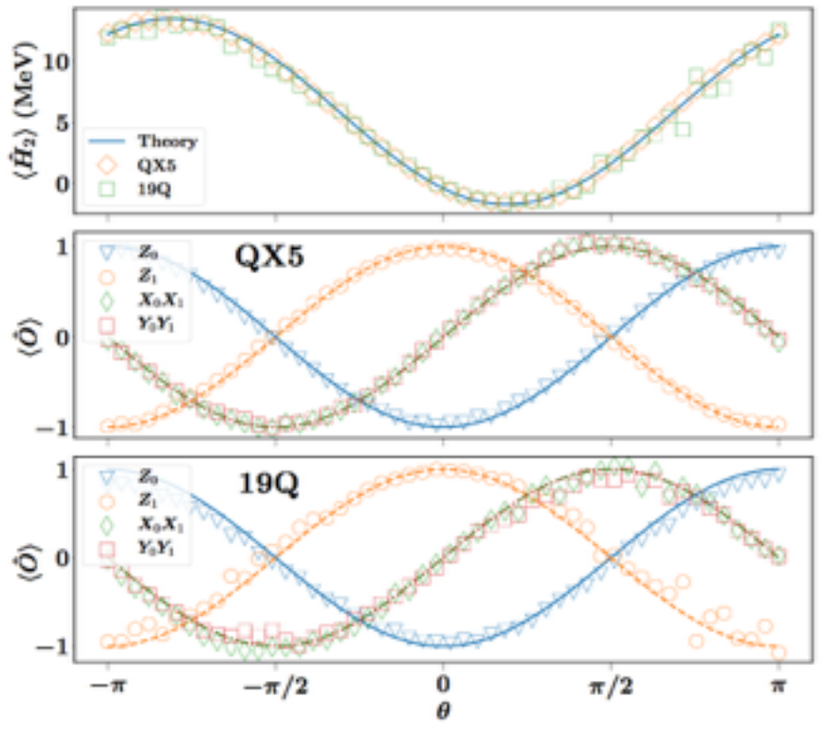


FIG. 1. Low-depth circuits that generate unitary rotations in Eq. (7) (panel a) and Eq. (8) (panel b). Also shown are the single-qubit gates of the Pauli X matrix, the rotation $Y(\theta)$ with angle θ around the Y axis, and the two-qubit CNOT gates.

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,

$$U(\theta) \equiv e^{\theta\left(a_0^\dagger a_1 - a_1^\dagger a_0\right)} = e^{i\frac{\theta}{2}(X_0 Y_1 - X_1 Y_0)}, \qquad (7)$$



Quantum Field Theory with Quantum Computers - Foundational Works

Simulating lattice gauge theories on a quantum computer

Tim Byrnes*
National Institute of Informatics, 2-1-2 Hitotsubashi, Chiyoda-ku, Tokyo 101-8430, Japan

Yoshihisa Yamamoto
E. L. Ginzton Laboratory, Stanford University, Stanford, CA 94305 and
National Institute of Informatics, 2-1-2 Hitotsubashi, Chiyoda-ku, Tokyo 101-8430, Japan
(Dated: February 1, 2008)

We examine the problem of simulating lattice gauge theories on a universal quantum computer. The basic strategy of our approach is to transcribe lattice gauge theories in the Hamiltonian formulation into a Hamiltonian involving only Pauli spin operators such that the simulation can be performed on a quantum computer using only one and two qubit manipulations. We examine three models, the U(1), SU(2), and SU(3) lattice gauge theories which are transcribed into a spin Hamiltonian up to a cutoff in the Hilbert space of the gauge fields on the lattice. The number of qubits required for storing a particular state is found to have a linear dependence with the total number of lattice sites. The number of qubit operations required for performing the time evolution corresponding to the Hamiltonian is found to be between a linear to quadratic function of the number of lattice sites, depending on the arrangement of qubits in the quantum computer. We remark that our results may also be easily generalized to higher SU(N) gauge theories.

Phys.Rev. A73 (2006) 022328

Quantum Computation of Scattering in Scalar Quantum Field Theories

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

[†] *National Institute of Standards and Technology, Gaithersburg, MD 20899*

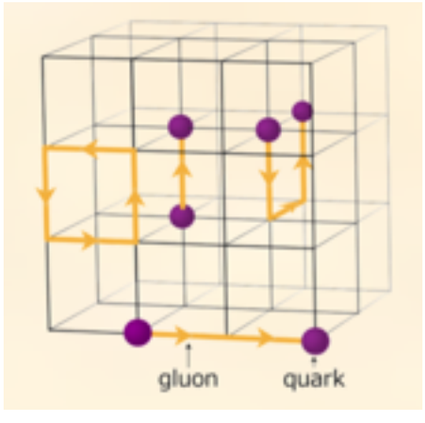
[‡] *University of Pittsburgh, Pittsburgh, PA 15260*

[§] *California Institute of Technology, Pasadena, CA 91125*

Abstract

Quantum field theory provides the framework for the most fundamental physical theories to be confirmed experimentally, and has enabled predictions of unprecedented precision. However, calculations of physical observables often require great computational complexity and can generally be performed only when the interaction strength is weak. A full understanding of the foundations and rich consequences of quantum field theory remains an outstanding challenge. We develop a quantum algorithm to compute relativistic scattering amplitudes in massive ϕ^4 theory in spacetime of four and fewer dimensions. The algorithm runs in a time that is polynomial in the number of particles, their energy, and the desired precision, and applies at both weak and strong coupling. Thus, it offers exponential speedup over existing classical methods at high precision or strong coupling.

Quantum Information and Computation 14, 1014-1080 (2014)



Detailed formalism for 3+1 quenched Hamiltonian Gauge Theory

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Quantum Field Theory - recent examples

Quantum sensors for the generating functional of interacting quantum field theories

A. Bermudez,[1,2,*] G. Aarts,[1] and M. Müller[1]

[1]*Department of Physics, College of Science, Swansea University, Singleton Park, Swansea SA2 8PP, United Kingdom*
[2]*Instituto de Física Fundamental, IFF-CSIC, Madrid E-28006, Spain*

Difficult problems described in terms of interacting quantum fields evolving in real time or ou
are abound in condensed-matter and high-energy physics. Addressing such problems via control
in atomic, molecular, and optical physics would be a breakthrough in the field of quantum sim
work, we present a quantum-sensing protocol to measure the generating functional of an inter
field theory and, with it, all the relevant information about its in or out of equilibrium phenomen
can be understood as a collective interferometric scheme based on a generalization of the notio
sources in quantum field theories, which make it possible to probe the generating functional. W
scheme can be realized in crystals of trapped ions acting as analog quantum simulators of self-in
quantum field theories.

arXiv:1702.05492
proposed method

arXiv:1704.02877

Quantum Simulation of the Abelian-Higgs Lattice Gauge Theory with Ultracold Atoms

Daniel González-Cuadra[1,2], Erez Zohar[2] and J. Ignacio Cirac[2]

[1] ICFO – The Institute of Photonic Sciences, Av. C.F. Gauss 3, E-08860, Castelldefels (Barcelona), Spain
[2] Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, D-85748 Garching, Germany

Dynamics of entanglement in expanding quantum fields

Jürgen Berges,[a] Stefan Floerchinger[a] and Raju Venugopalan[b]

arXiv:1712.09362 [hep-th]

arXiv:1802.07347 [quant-ph]

Electron-Phonon Systems on a Universal Quantum Computer

Alexandru Macridin, Panagiotis Spentzouris, James Amundson, Roni Harnik

Fermilab, P.O. Box 500, Batavia, Illinois 60510, USA

Quantum simulation of the universal features of the Polyakov loop

Jin Zhang[1], J. Unmuth-Yockey[2], A. Bazavov[3], S.-W. Tsai[1], and Y. Meurice[4]
[1] *Department of Physics and Astronomy, University of California, Riverside, CA 92521, USA*
[2]*Department of Physics, Syracuse University, Syracuse, New York 13244, USA*
[3], *Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, 48824, USA and*
[4] *Department of Physics and Astronomy, The University of Iowa, Iowa City, IA 52242, USA*
(Dated: March 30, 2018)

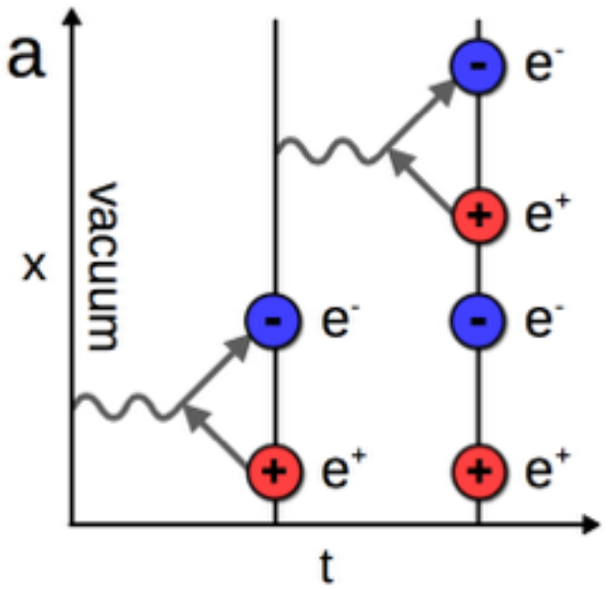
arXiv:1803.11166 [hep-lat]

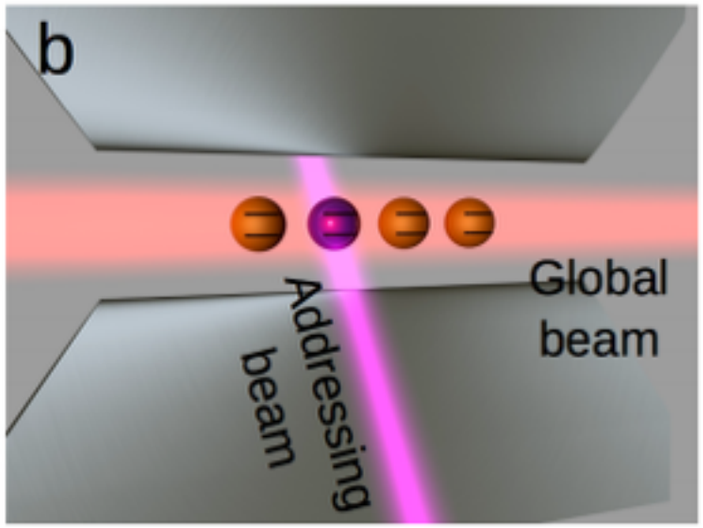
Starting Simple 1+1 Dim QED - Pivotal Paper

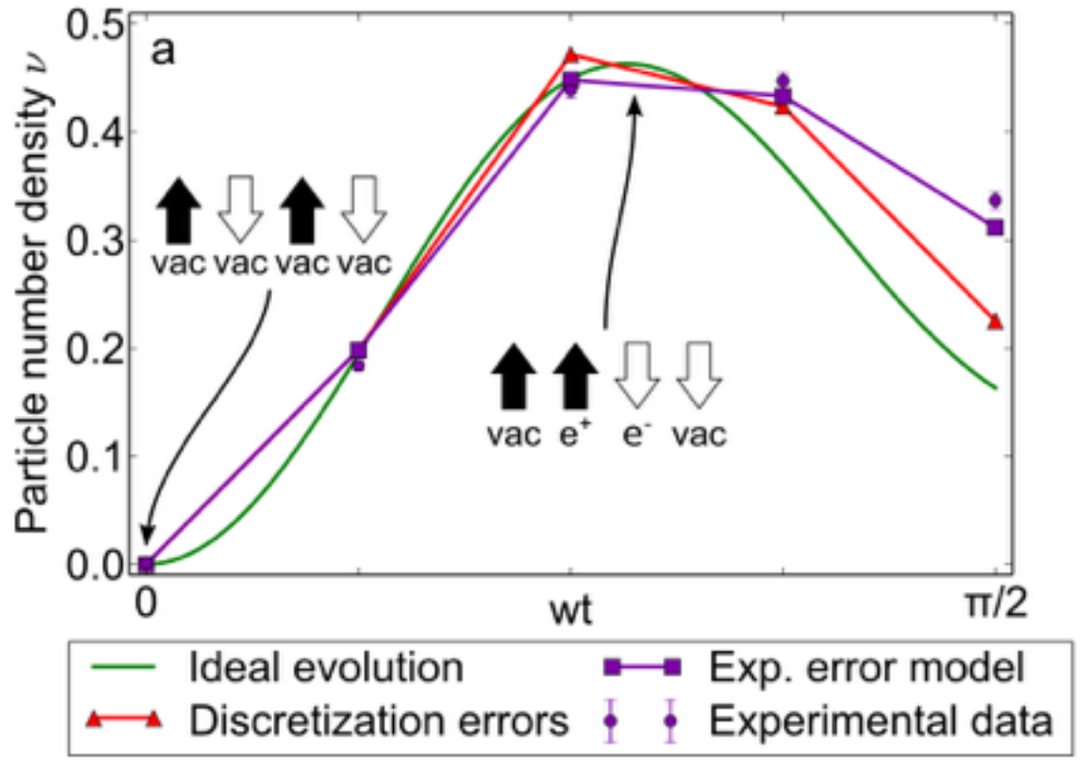
Real-time dynamics of lattice gauge theories with a few-qubit quantum computer

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)

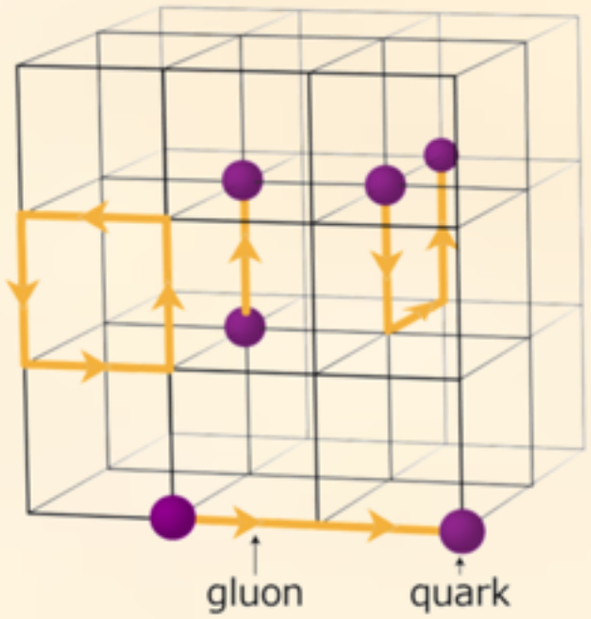






Based upon a string of $^{40}Ca^{+}$ trapped-ion quantum system
Simulates 4 qubit system with long-range couplings = 2-spatial-site Schwinger Model
> 200 gates per Trotter step

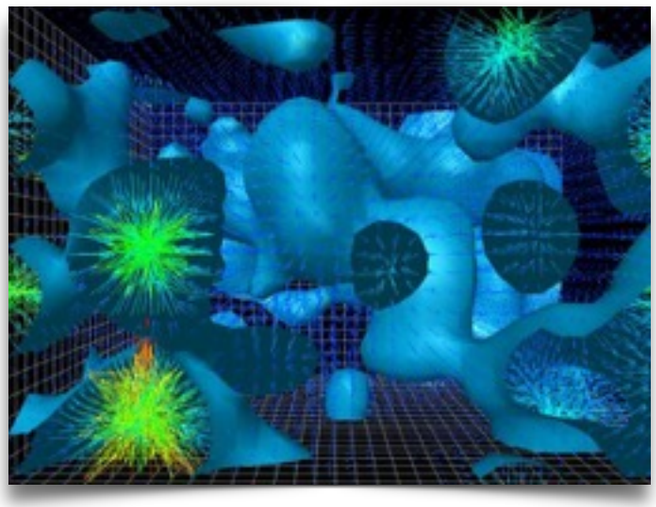
Gauge Field Theories
e.g. QCD



Color	Flavor	Component
• 	• Up • Down • Strange	• $\begin{pmatrix}\Psi_1\\ \Psi_2\\ \Psi_3\\ \Psi_4\end{pmatrix}$

Natalie Klco

32^3 lattice requires naively > 4 million qubits !



State Preparation - a critical element

$|\text{random}\rangle = a\,|0\rangle + b\,|(\pi\,\pi)\rangle + c\,|(\pi\,\pi\,\pi\,\pi)\rangle + \ldots + d\,|(GG)\rangle + \ldots$

Conventional lattice QCD likely to play a key role in QFT on QC

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ASCR supported QC for QFT

Two ORNL-led research teams receive $10.5 million to advance quantum computing for scientific applications

ORNL's Pavel Lougovski (left) and Raphael Pooser will lead research teams working to advance quantum computing for scientific applications. Credit: Oak Ridge National Laboratory, U.S. Dept. of Energy (hi-res image)

OAK RIDGE National Laboratory

DOE-ASCR

Heterogeneous Digital-Analog Quantum Dynamics Simulations

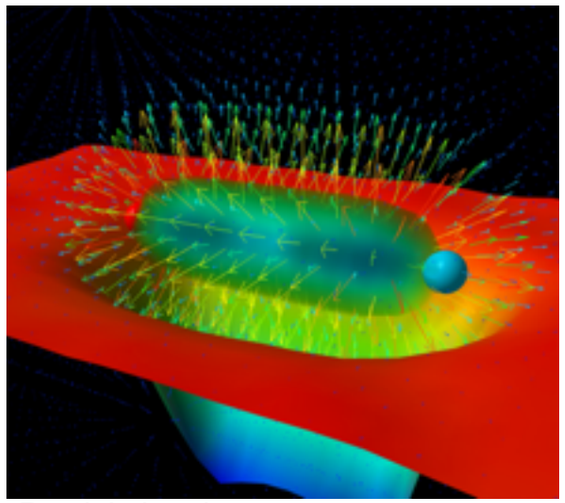
Methods and Interfaces for Quantum Acceleration of Scientific Applications

Starting Simple 1+1 Dim QED Construction

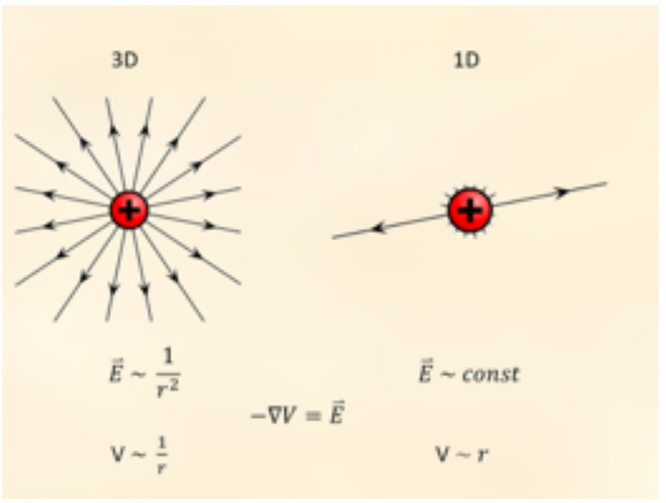
"Quantum computing makes you think about your calculations very differently than programming a classical computer," says Natalie Klco.
// MEDIA CREDIT: WHITNEY SANCHEZ

$$\mathcal{L} = \overline{\psi}\left(i\not{D} - m\right)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

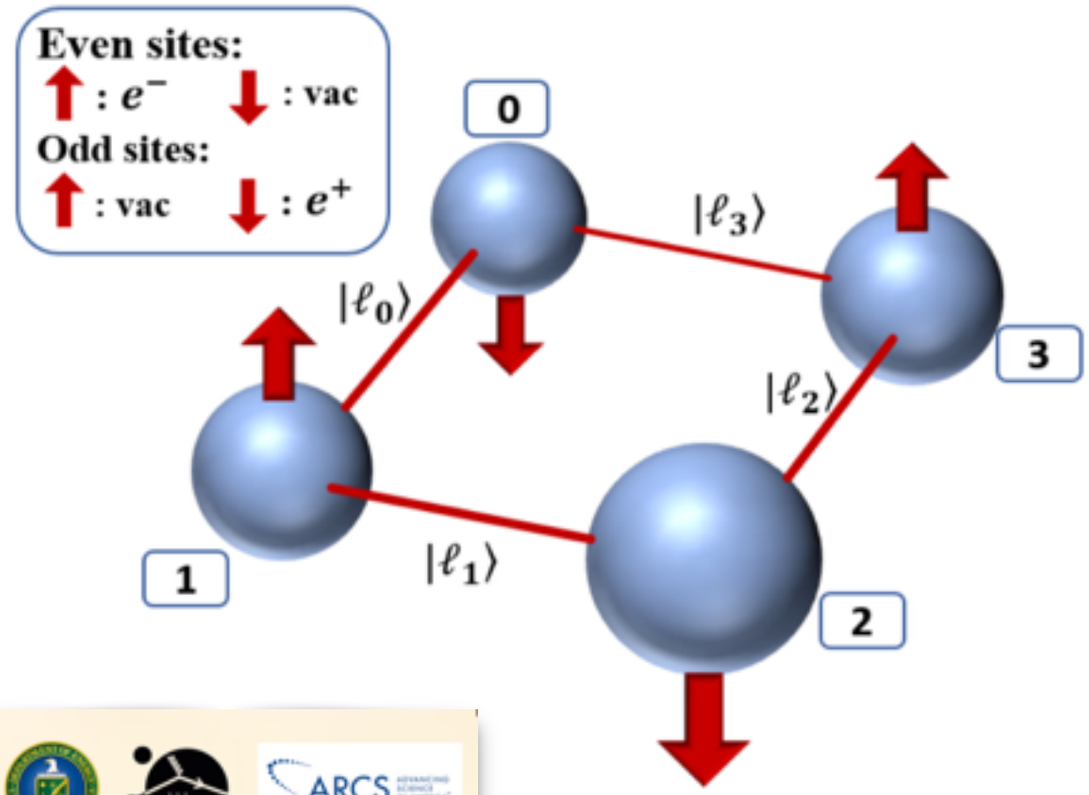
- Charge screening, confinement
- fermion condensate



Derek Leinweber



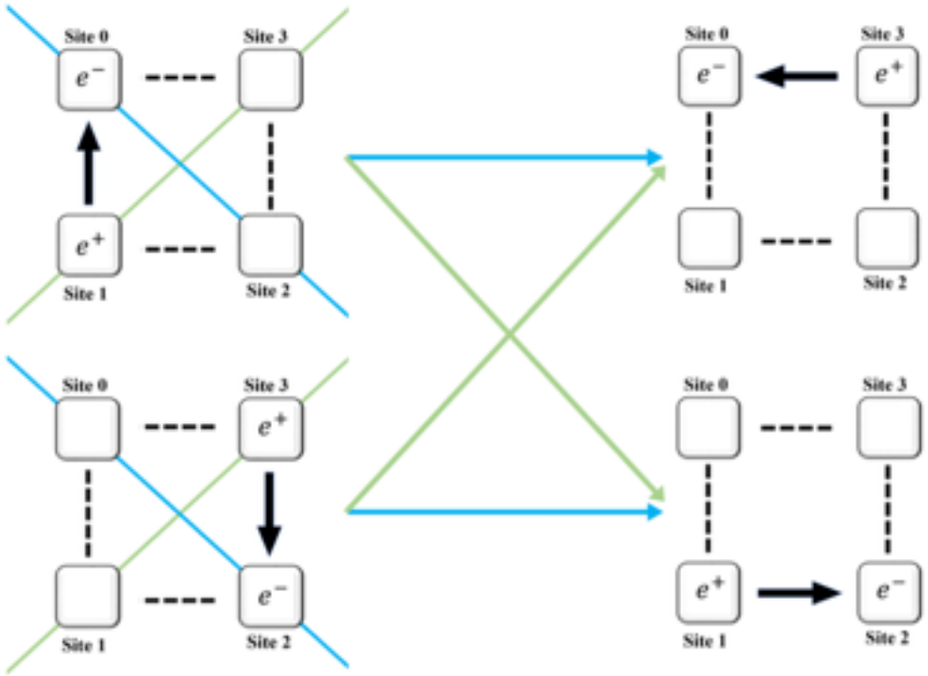
Natalie Klco

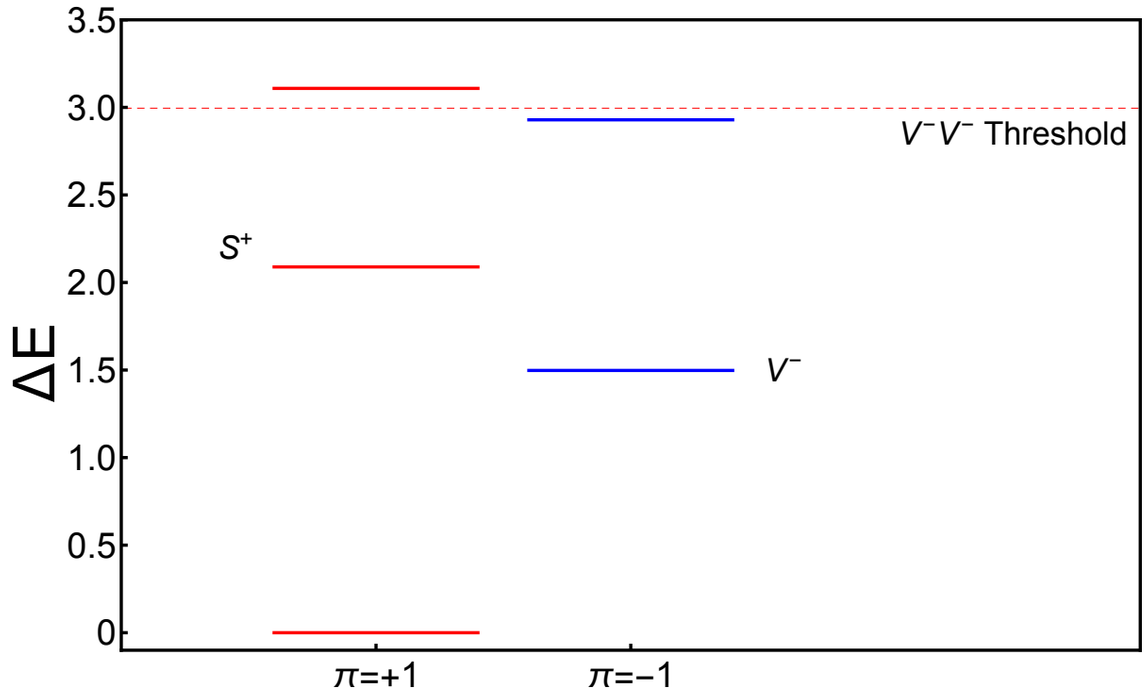


$$\hat{H} = x \sum_{n=0}^{N_{fs}-1} \left(\sigma_n^+ L_n^- \sigma_{n+1}^- + \sigma_{n+1}^+ L_n^+ \sigma_n^-\right)$$
$$+ \sum_{n=0}^{N_{fs}-1} \left(l_n^2 + \frac{\mu}{2}(-)^n \sigma_n^z\right) \quad .$$

Quantum-Classical Dynamical Calculations of the Schwinger Model 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.
arXiv:1803.03326 [quant-ph]

Starting Simple 1+1 Dim QED Symmetries





- Gauss's Law
- (Angular) Momentum
- Parity

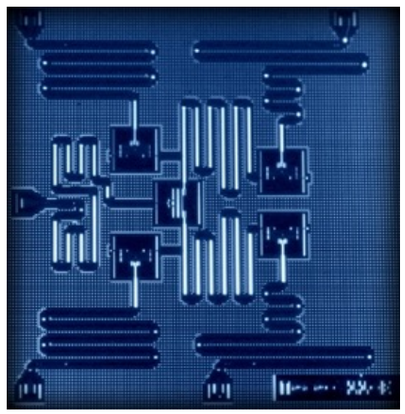
physical sites	Nq_{lattice}	D_{lattice}	D_{physical}	$D_{\mathbf{k=0}}$	D_{even}	D_{odd}	$\text{Nq}^{\mathbf{k=0}}_{\text{even}}$	$\text{Nq}^{\mathbf{k=0}}_{\text{odd}}$
1	6	64	5	-	3	2	2	1
2	12	4.1×10^3	13	9	5	4	3	2
4	24	1.7×10^7	117	35	19	16	5	4
6	36	6.9×10^{10}	1,186	210	110	100	7	7
8	48	2.8×10^{14}	12,389	1,569	801	768	10	10
10	60	1.2×10^{18}	130,338	13,078	6,593	6,485	13	13
12	72	4.7×10^{21}	1,373,466	114,584	57,468	57,116	16	16

Classical pre-processing
Can this be done *in situ* ?

Classical post-processing

Starting Simple 1+1 Dim QED Living NISQ - IBM Classically Computed U(t)

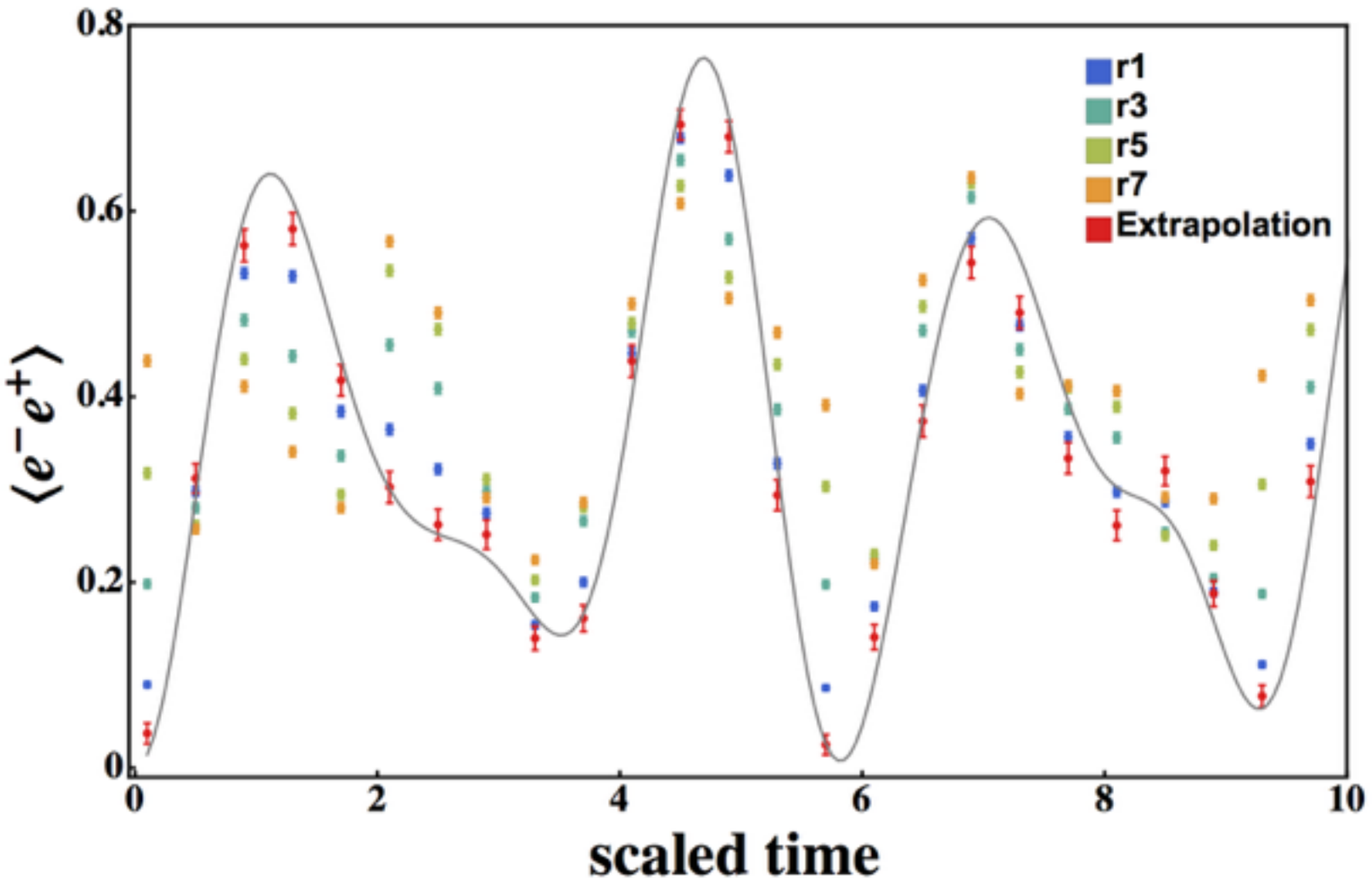
USQCD

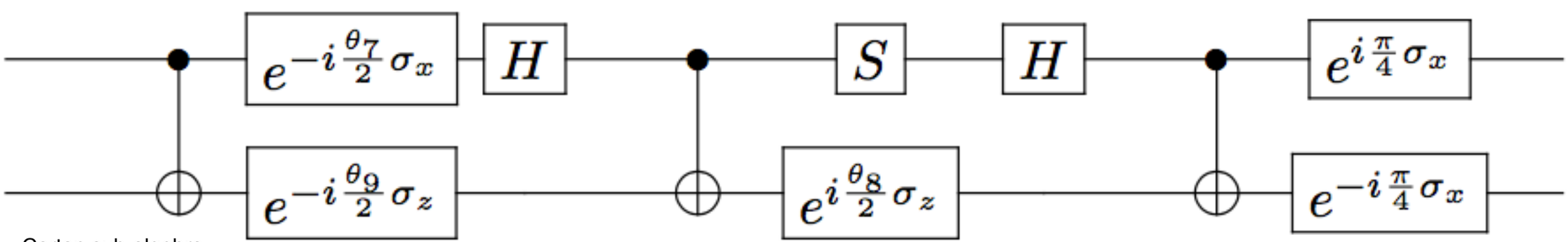


OAK RIDGE National Laboratory

INSTITUTE for NUCLEAR THEORY

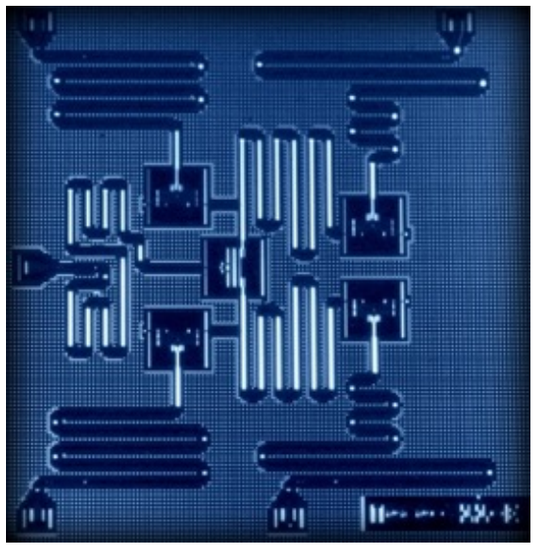
ibmqx2 - cloud-access
8K shots per point





Cartan sub-algebra

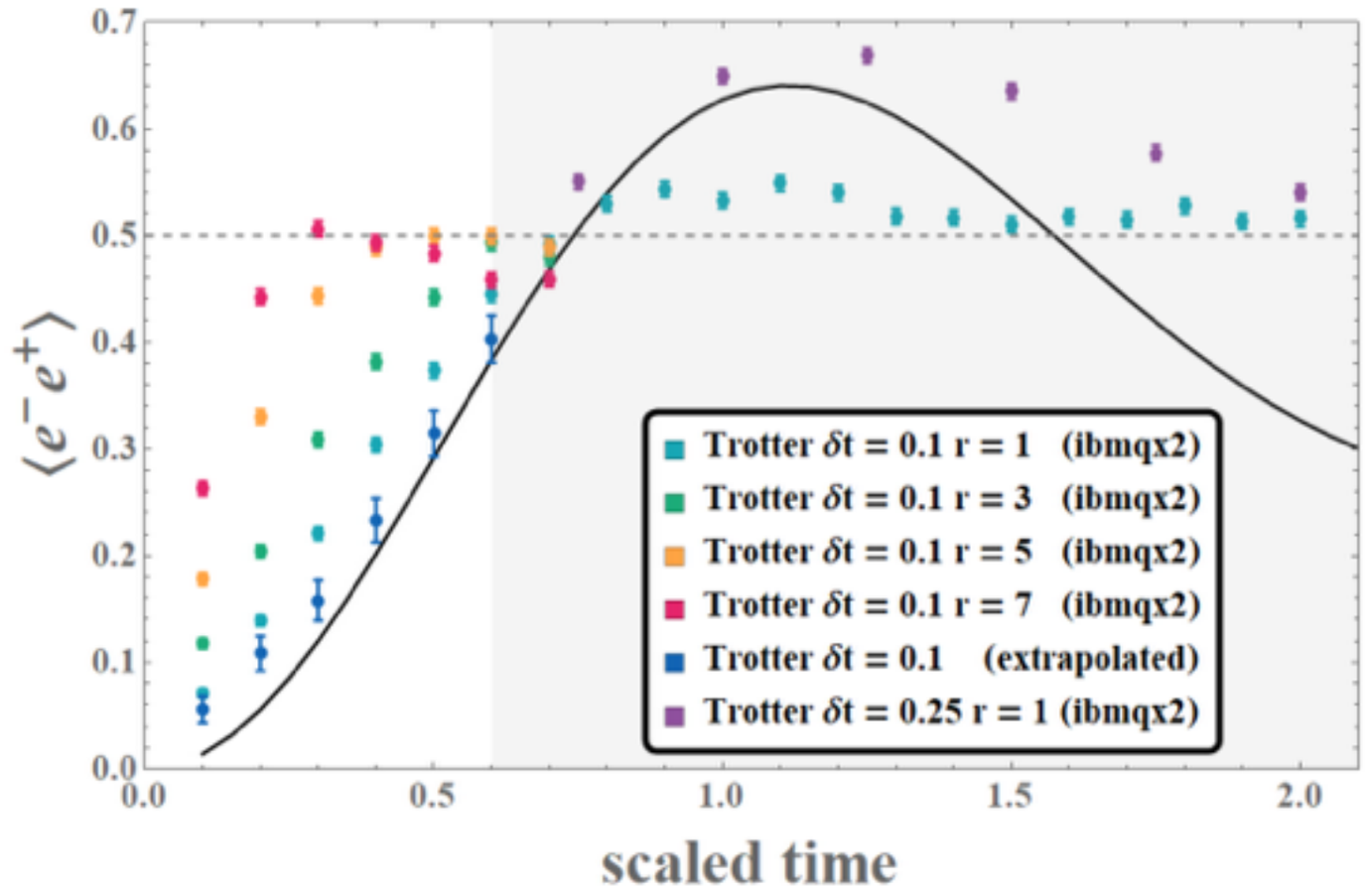
Starting Simple 1+1 Dim QED
Living NISQ - IBM
Trotter U(t)



T2 (μs)	55.20	65.10	47.00	35.10	37.60

$$e^{-iHt} = e^{-i\sum_j H_j t} = \lim_{N_{\text{Trot.}}\to\infty} \left(\prod_j e^{-iH_j \delta t} \right)^{N_{\text{Trot.}}}$$

$$\begin{aligned} \mathrm{H} = & \frac{x}{\sqrt{2}}\, \sigma_x \otimes \sigma_x \; + \; \frac{x}{\sqrt{2}}\, \sigma_y \otimes \sigma_y \; - \; \mu\, \sigma_z \otimes \sigma_z \\ & + x \left(1 + \frac{1}{\sqrt{2}}\right)\, I \otimes \sigma_x \; - \; \frac{1}{2}\, I \otimes \sigma_z \\ & - \; (1+\mu)\; \sigma_z \otimes I \; + x \left(1 - \frac{1}{\sqrt{2}}\right)\; \sigma_z \otimes \sigma_x \end{aligned}$$



3.6 QPU-s and 260 IBM units

[``Capacity computing" - required only 2 of the 5 qubits on the chip - 5 CNOT gates per step]

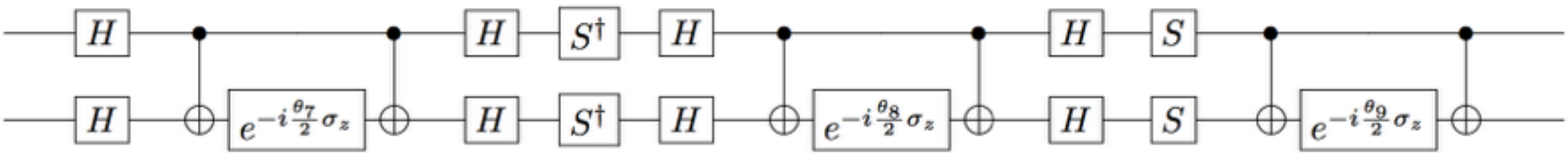
USQCD

Hamiltonian to Circuit
Trotter

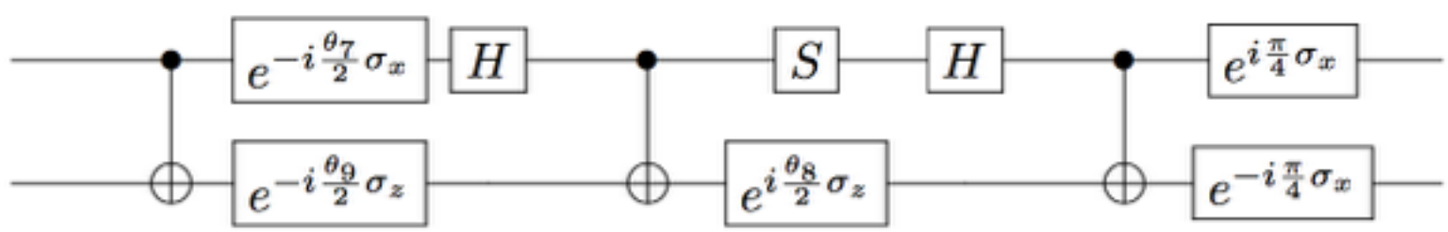
$$\mathrm{H} = \frac{x}{\sqrt{2}}\,\sigma_x \otimes \sigma_x \;+\; \frac{x}{\sqrt{2}}\,\sigma_y \otimes \sigma_y \;-\; \mu\,\sigma_z \otimes \sigma_z$$
$$+\, x\left(1+\frac{1}{\sqrt{2}}\right)\, I \otimes \sigma_x \;-\; \frac{1}{2}\, I \otimes \sigma_z$$
$$-\; (1+\mu)\;\sigma_z \otimes I \;+ x\left(1-\frac{1}{\sqrt{2}}\right)\;\sigma_z \otimes \sigma_x$$

$$e^{-iHt} = e^{-i\sum_j H_j t} = \lim_{N_{\mathrm{Trot.}}\to\infty}\left(\prod_j e^{-iH_j\delta t}\right)^{N_{\mathrm{Trot.}}}$$

$e^{-\frac{i}{2}(\theta_7\sigma_x\otimes\sigma_x+\theta_8\sigma_y\otimes\sigma_y+\theta_9\sigma_z\otimes\sigma_z)} =$



$e^{-\frac{i}{2}(\theta_7\sigma_x\otimes\sigma_x+\theta_8\sigma_y\otimes\sigma_y+\theta_9\sigma_z\otimes\sigma_z)} =$



Cloud Access to NISQ devices
Chroma Vs Python3

```
:// $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) ;
  }
```

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.

```
    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])
```

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.

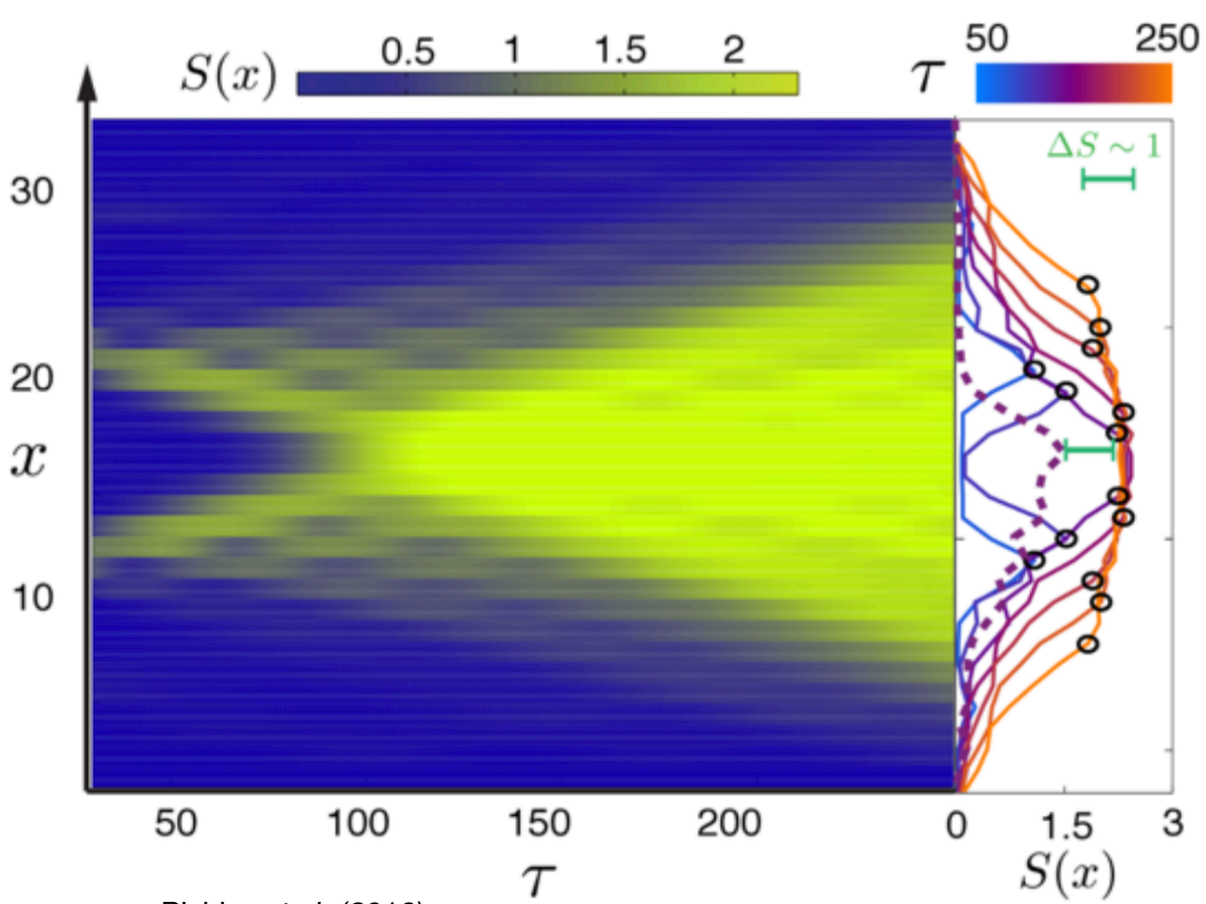
USQCD

Quantum Field Theory and Quantum Information

Are there new insights into the forces of nature and/or calculational techniques to be had by thinking in terms of quantum information?

Preskill, Swingle, Hsu, and others

Entanglement entropy in scattering (tensor networks)



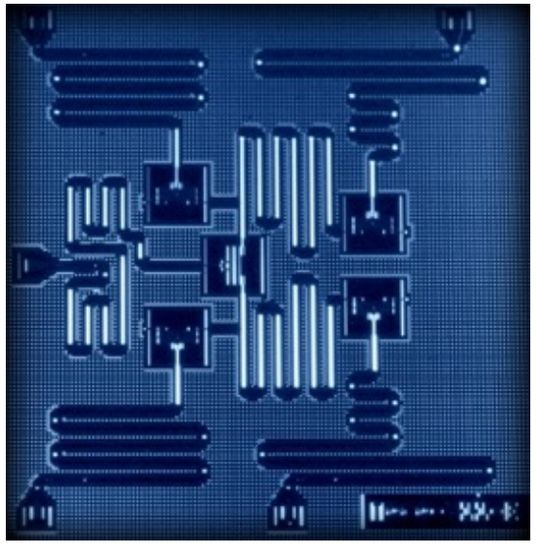
Pichler *et al. (2016)*

New ways to arrange QCD calculations ?
New ways to address QCD analytically ?

Entanglement in HEP and NP systems is starting to be considered

USQCD

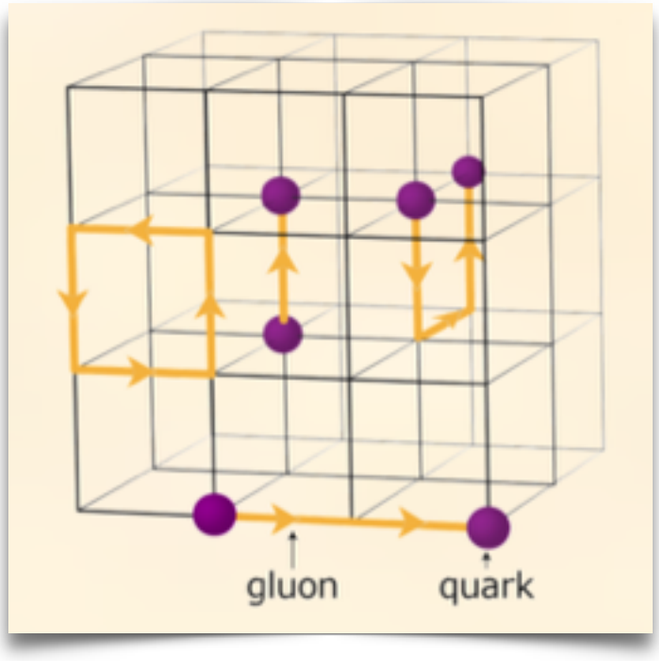
Possible Near Future ?
QPU accelerators ?



USQCD

Summary

- **Finite density** systems, **larger nuclei**, and **dynamics** require beyond-exascale calculations.



- Quantum Information Science and Quantum Computing offer the possibility of providing a Quantum Advantage for QCD.

- Collaborations between universities, national laboratories and technology companies now forming around QIS, QC and the domain sciences

- Wise for USQCD to consider near-term quantum possibilities - algorithms and code for QPUs

FIN