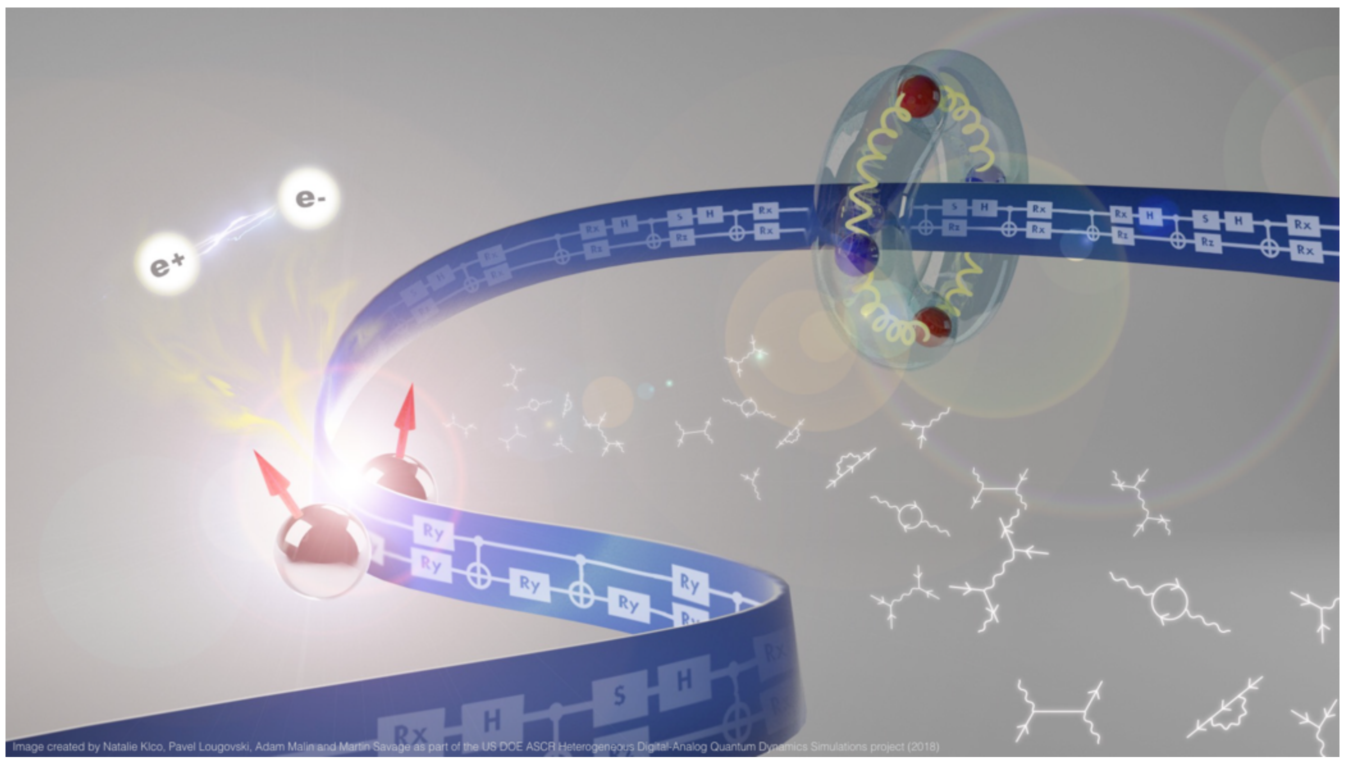
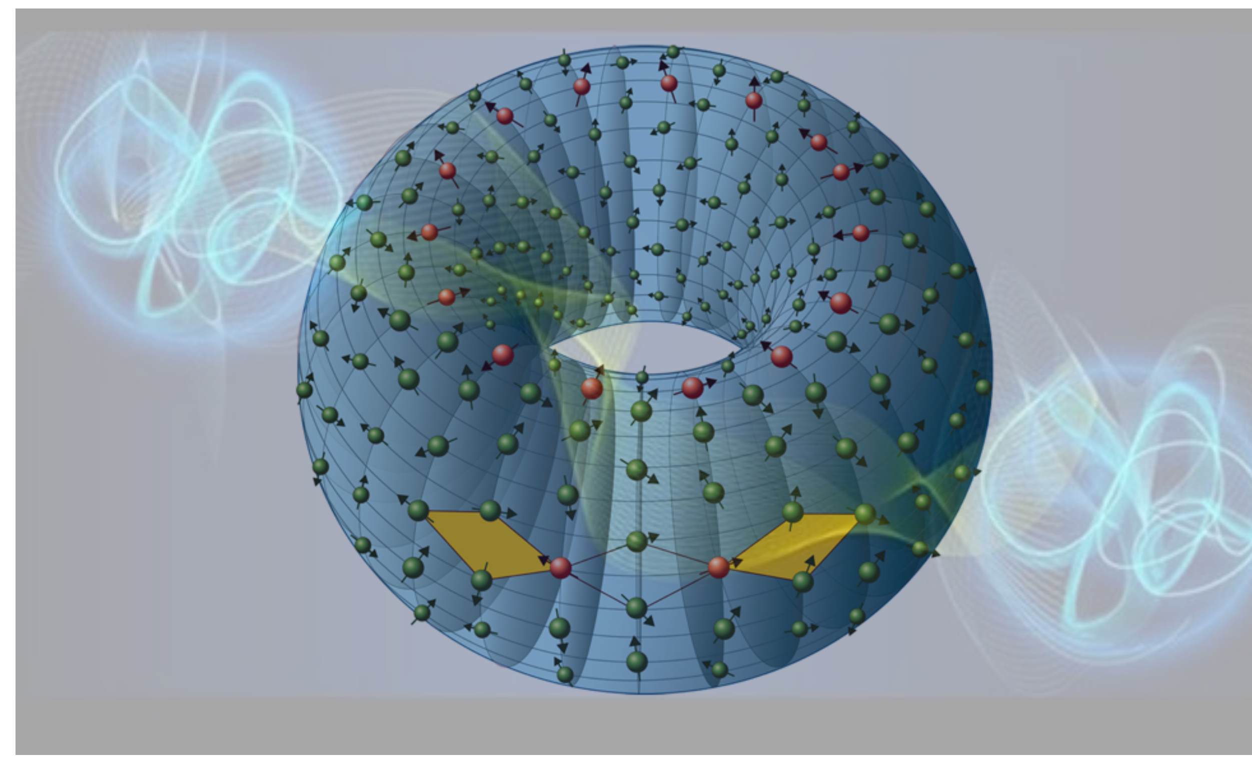
Center for Frontiers in Nuclear Science





QCD and Quantum Computing

Inaugural Symposium
Center For Nuclear Science, Nov 27, 2018

Martin J Savage

INSTITUTE for NUCLEAR THEORY

Feynman's Vision

Simulating Physics with Computers

Richard P. Feynman

Department of Physics, California Institute of Technology, Pasadena, California 91107

Received May 7, 1981

4. QUANTUM COMPUTERS—UNIVERSAL QUANTUM SIMULATORS

5. CAN QUANTUM SYSTEMS BE PROBABILISTICALLY SIMULATED BY A CLASSICAL COMPUTER?

Exascale Computing Needs

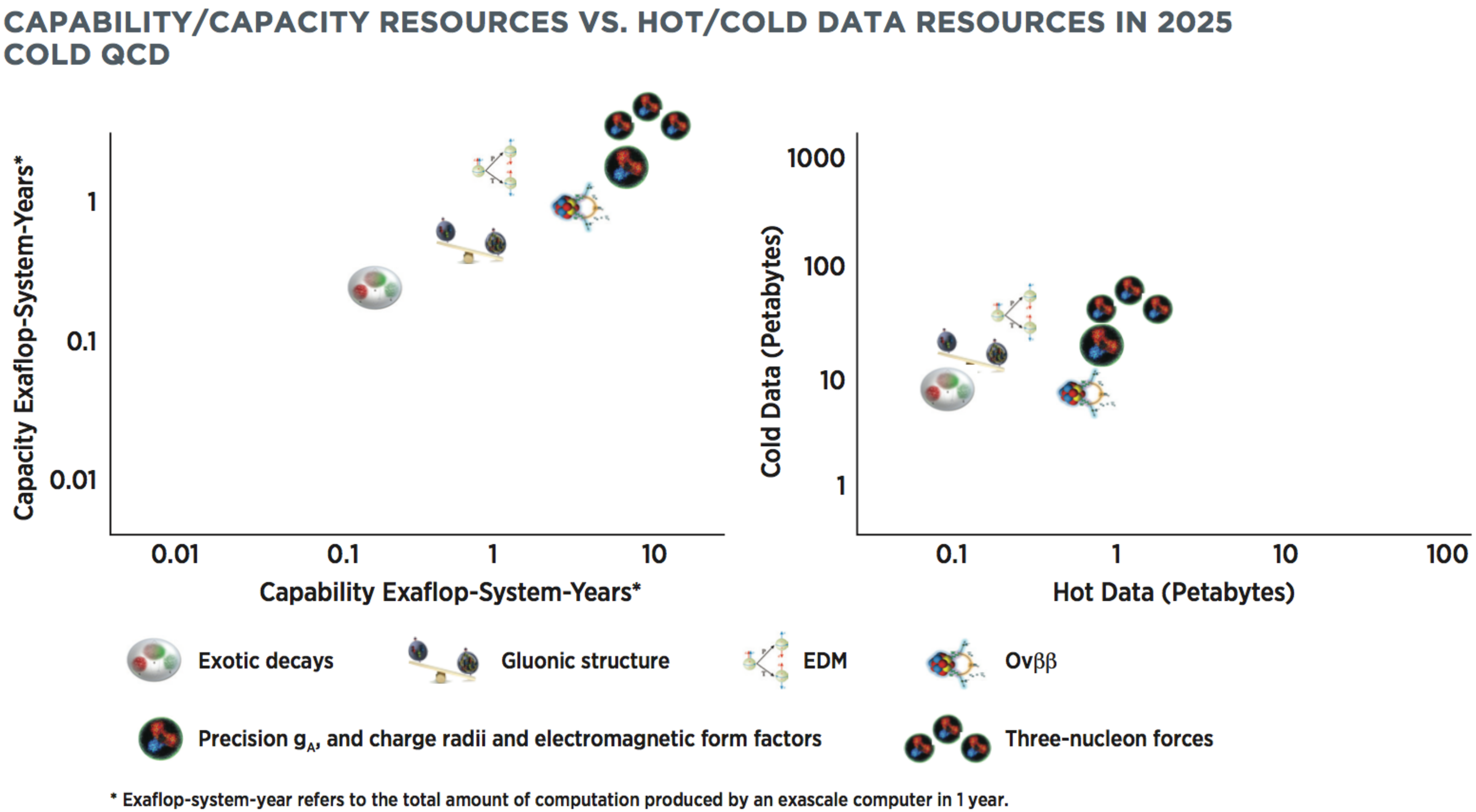
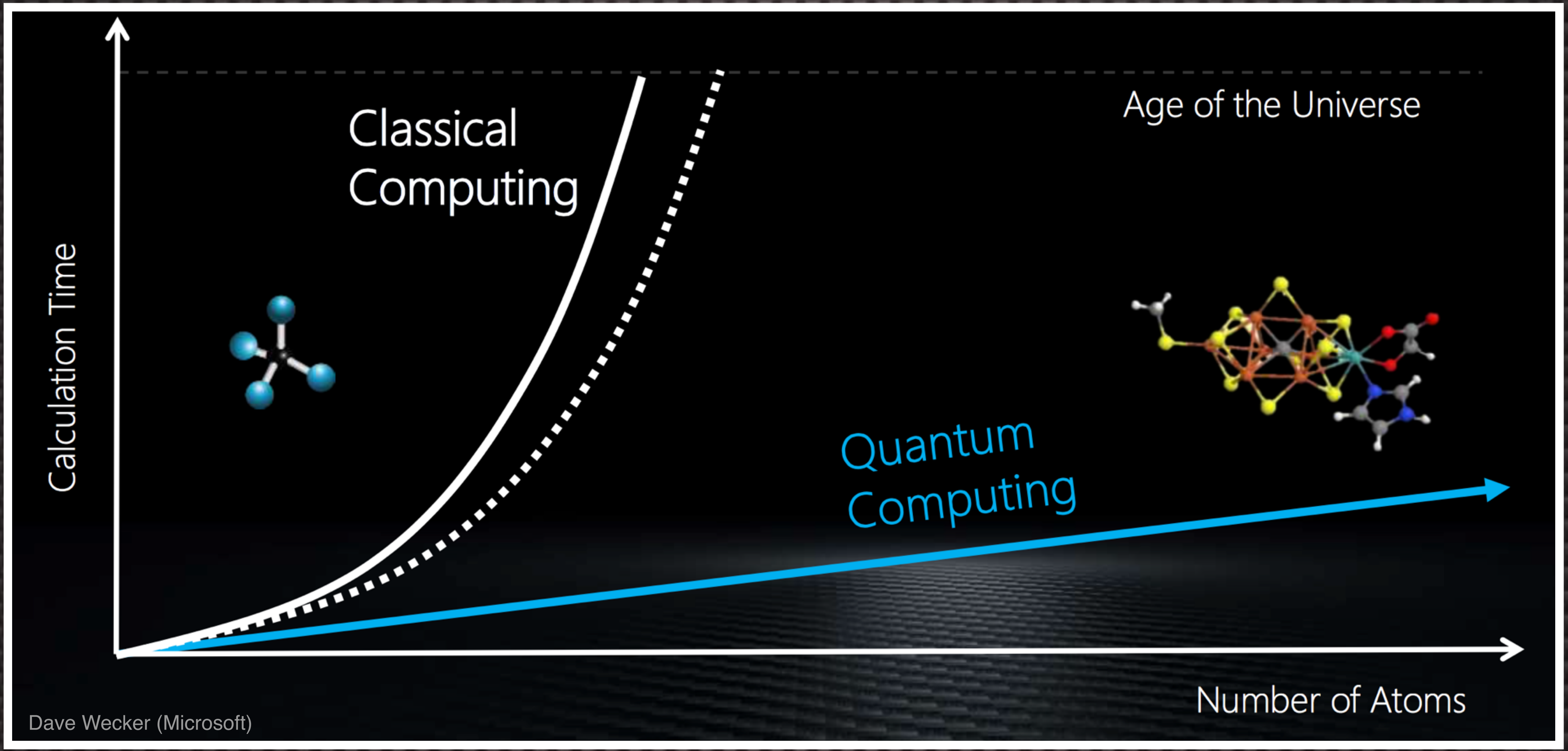


Figure 3-40. The capability and capacity computing resource requirements (left panel) and the hot and cold data requirements (right panel) in 2025 to accomplish the science objectives of the Cold QCD program.

- Finite Density requires beyond-exascale classical computing
- Explicit time evolution of QCD not considered

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

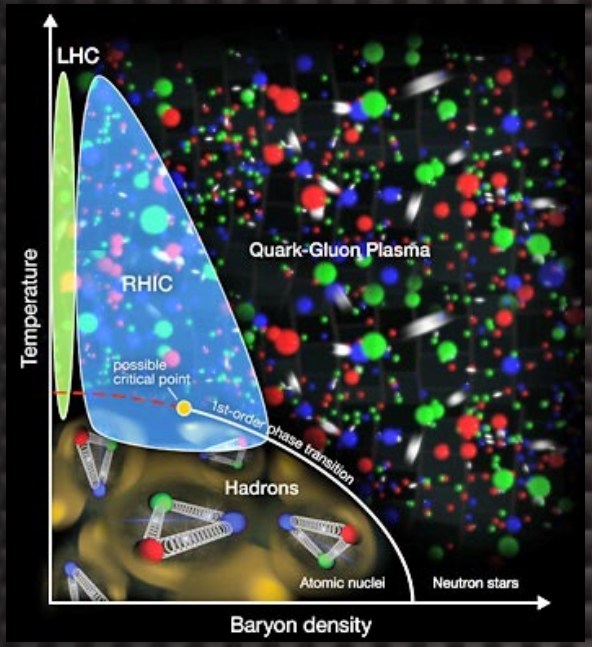
Slide: Dave Wecker (Microsoft)

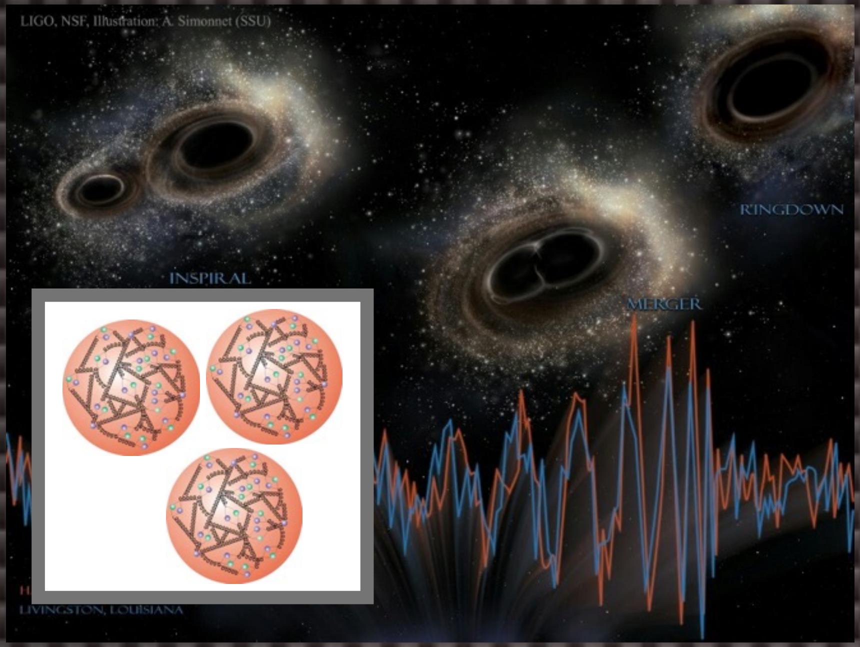
[solution to 1 part per million]

“First Qubits” for Applications

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

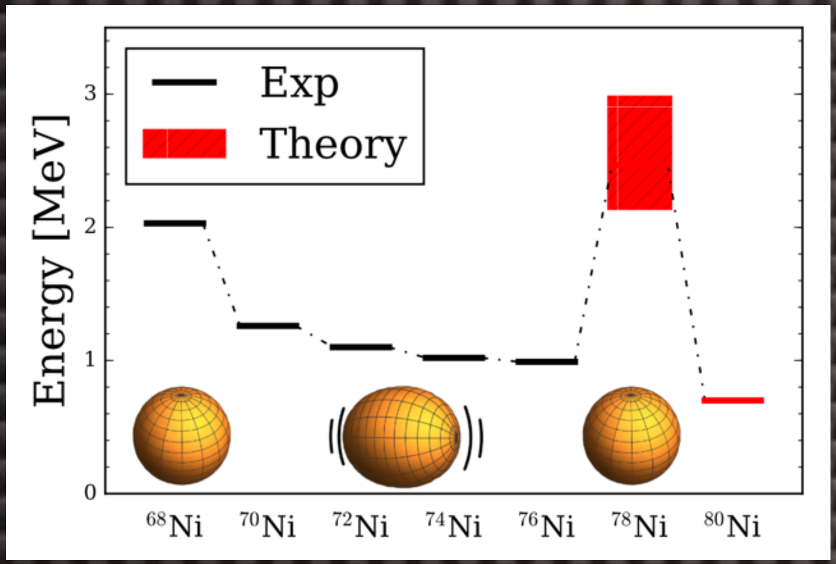
Quantum Many-Body Systems





Finite Density Systems
- Quantum Monte Carlo
- Sign Problem(s) in Sampling

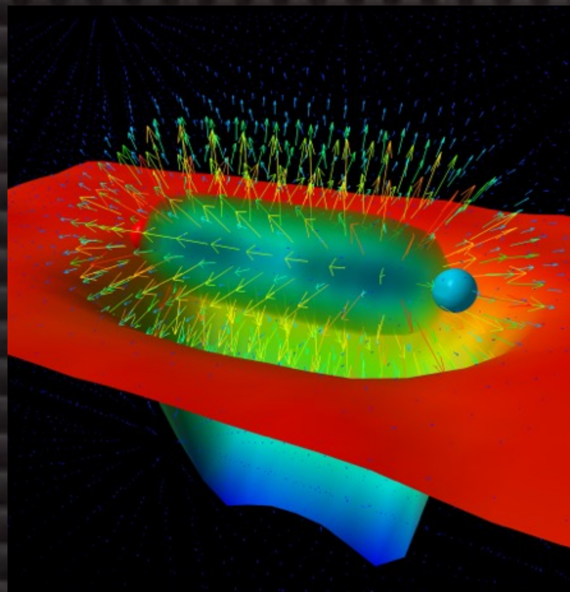
Nuclear Many-Body Problem
- Schrodinger Eqn.
- Hilbert space grows exponentially with particles

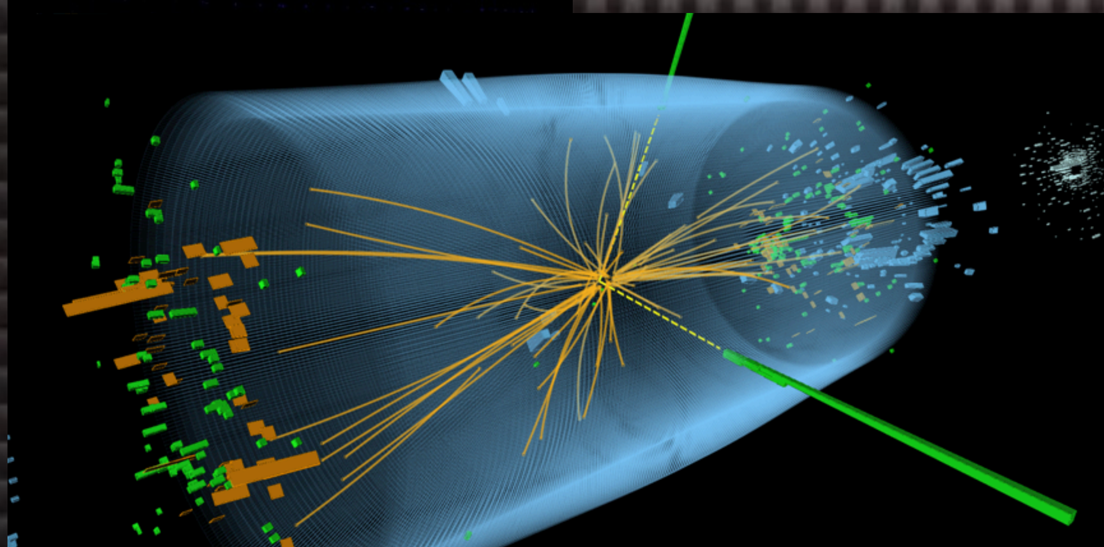


Classical Computing
- Exponentially large resources
- Exponentially growing memory for large nuclei

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

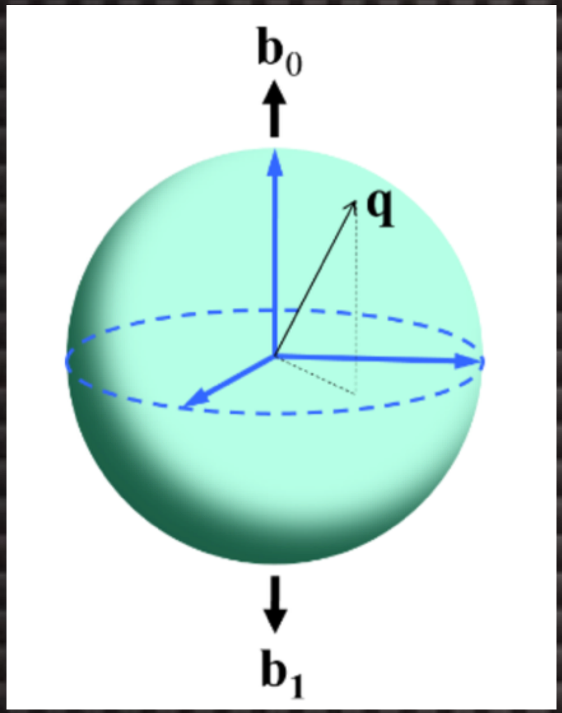
Classical Computing

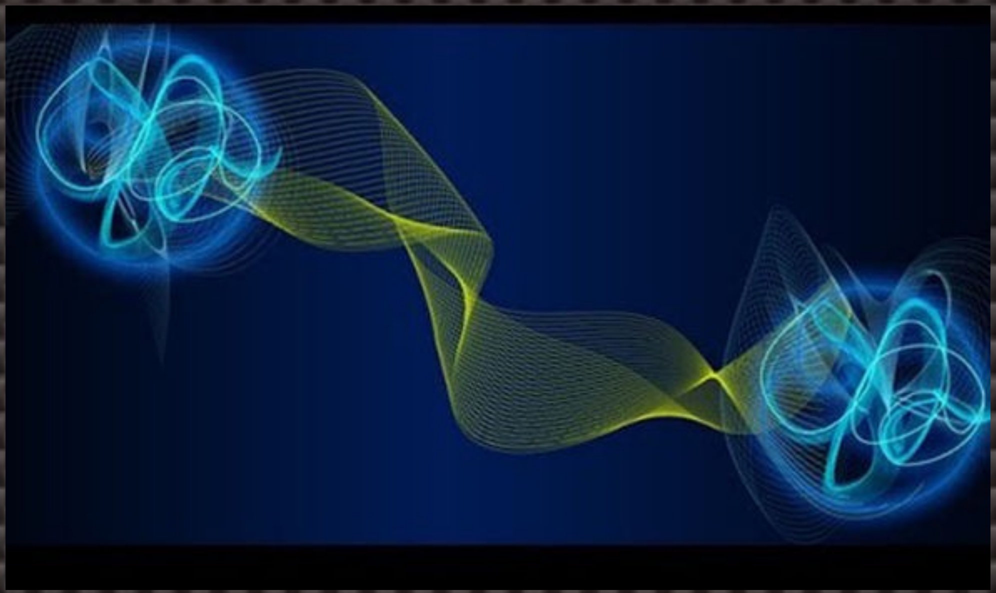
- Euclidean space
- high-lying states difficult
- Signal-to-noise
- Severe limitations for real-time or inelastic collisions or fragmentation

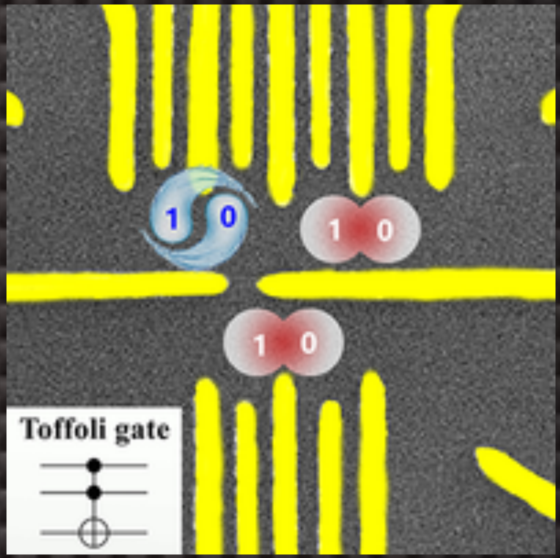
Quantum Computing

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

The Elements of Quantum Computing







Qubits

Entanglement
and Superposition

Unitary Operations
and Measurements

At the Heart of Quantum Computing

Massively Parallel Processing, Nonlocality and Entanglement

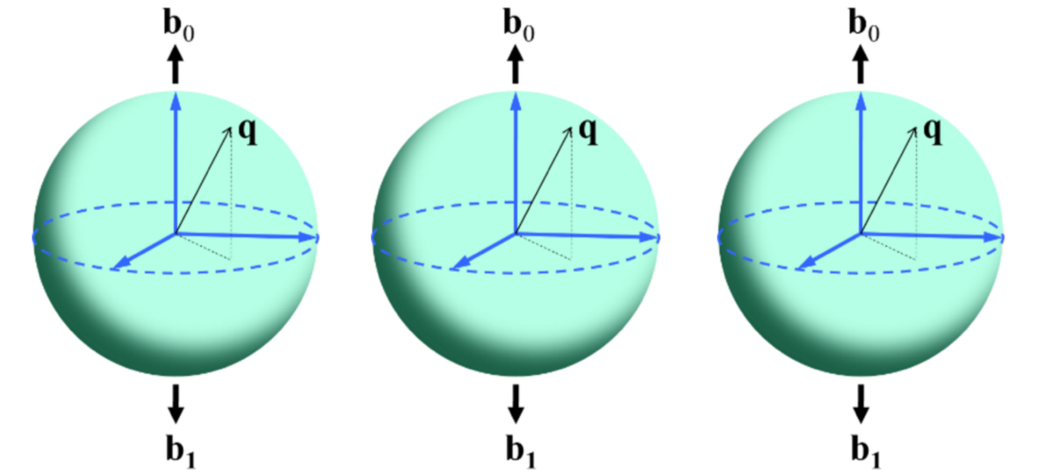
e.g., for a 3-bit computer (2^3 states)

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

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



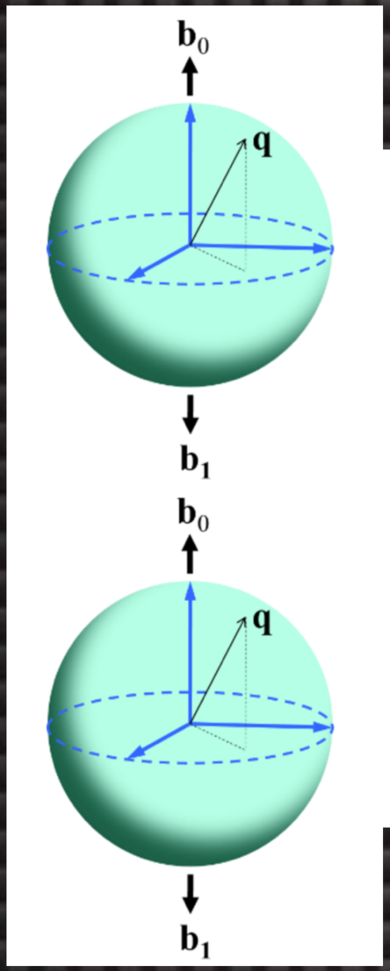
$$H^{\otimes 3}|000\rangle = \frac{1}{\sqrt{2}}[|0\rangle + |1\rangle] \otimes \frac{1}{\sqrt{2}}[|0\rangle + |1\rangle] \otimes \frac{1}{\sqrt{2}}[|0\rangle + |1\rangle]$$

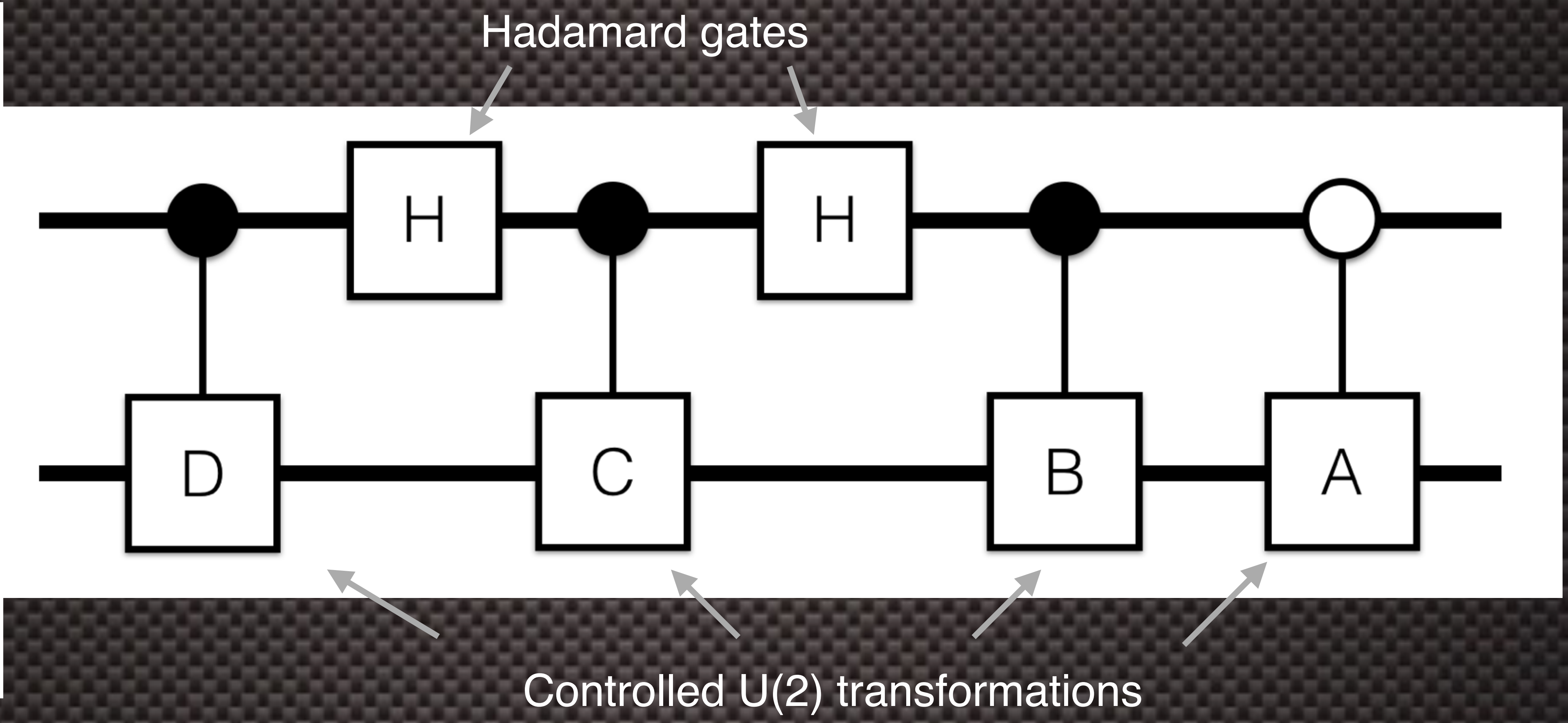
Once system mapped onto qubits, unitary operations used to compute and process information

At the Heart of Quantum Computing

Massively Parallel Processing, Nonlocality and Entanglement

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





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

The Noisy 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

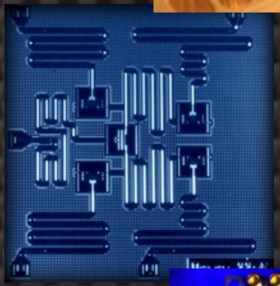
- Understanding the application of ``Quantum" to Scientific Applications, and identifying attributes of future quantum devices.

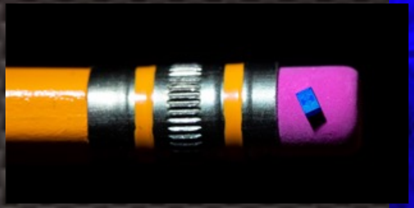
Quantum Computing
Examples of Available Hardware
and Technology Companies - US + Ca

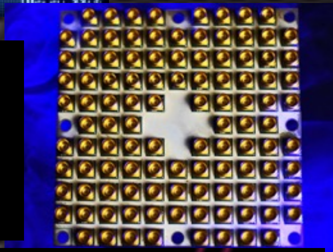
D-wave : ~ 2000 superconducting qubits, quantum annealing

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

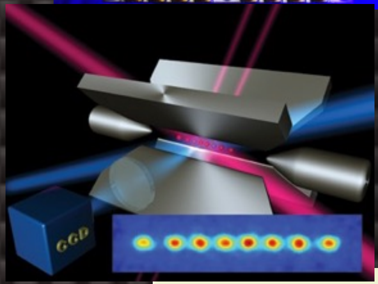
IBM : superconducting - 5,14,16, 20 qubits systems - cloud access



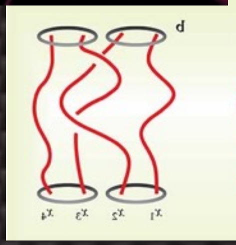




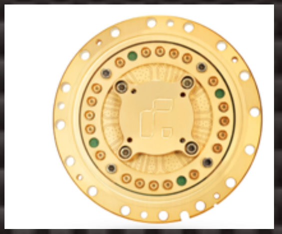
Intel : 49 superconducting qubits, progress in silicon



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



Microsoft : Majorana (topological) - in development



Rigetti : 8, 19 superconducting qubits with 128 coming

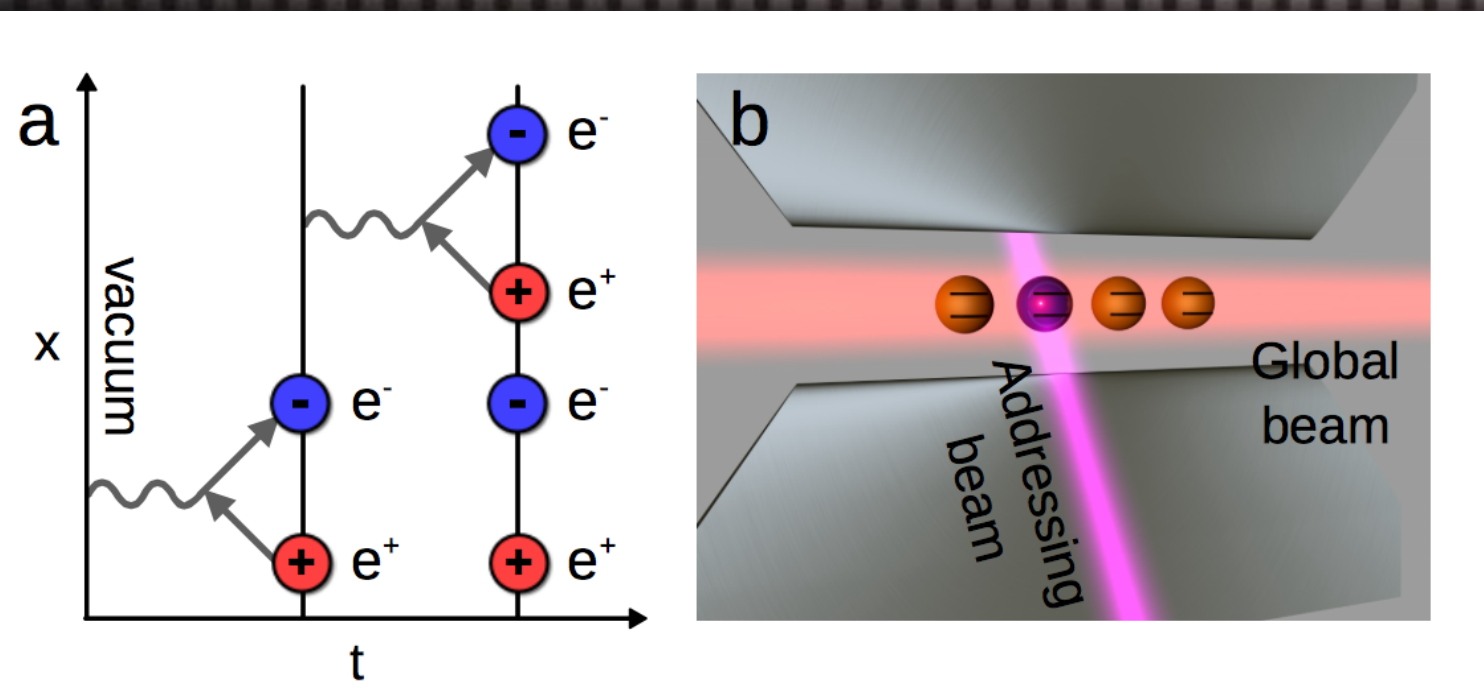
A First Quantum Computation in Quantum Field Theory 1+1-Dim QED

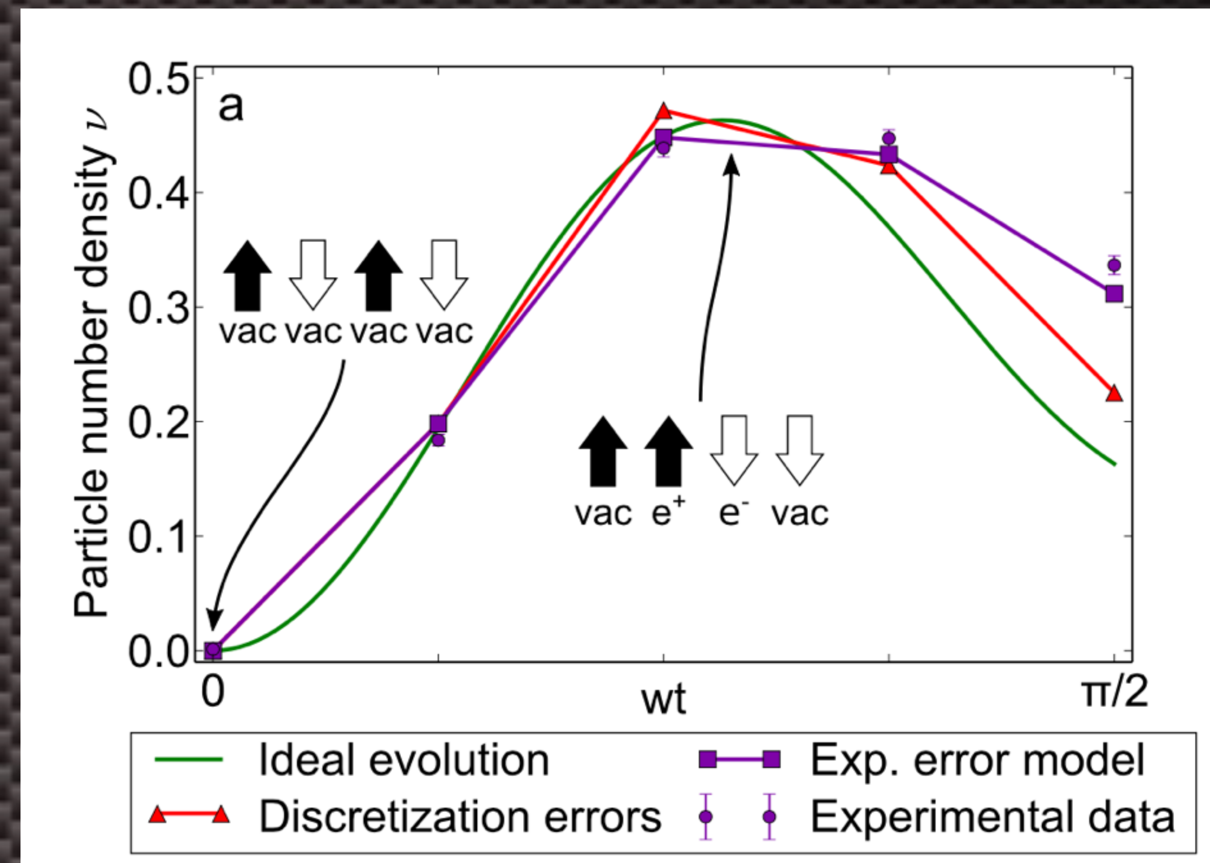
2016

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

Developments in Field Theory for QC/QIS
(a few examples only)

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)

DOE High-Energy Physics Projects Related to Quantum Computing for QCD (Fall of 2018)

Kruczenski, Luis Martin	Quantum Information in a strongly interacting quantum simulator: from gauge/string theory duality to analogue black holes
Bousso, Raphael	The Geometry and Flow of Quantum Information: From Quantum Gravity to Quantum Technology

Meurice, Yannick	Foundations of Quantum Computing for Gauge Theories and Quantum Gravity
Hubeny, Veronika	Entanglement in String Theory and the Emergence of Geometry

Love, Peter	Towards practical quantum simulation for High Energy Physics
Harlow, Daniel	Algebraic Approach Toward Quantum Information in Quantum Field Theory and Holography
Spiropulo, Maria	Quantum Machine Learning and Quantum Computation Frameworks for HEP (QMLQCF)

Bhattacharya, Tanmoy	Quantum Computing for Quantum Field Theories and Chiral Fermions
Gupta, Rajan	Quantum Computing for Neutrino-Nucleus Dynamics
Yoon, Boram	Quantum Machine Learning Enhancing Lattice QCD Calculations of Matrix Elements for Beyond the Standard Model Physics Search

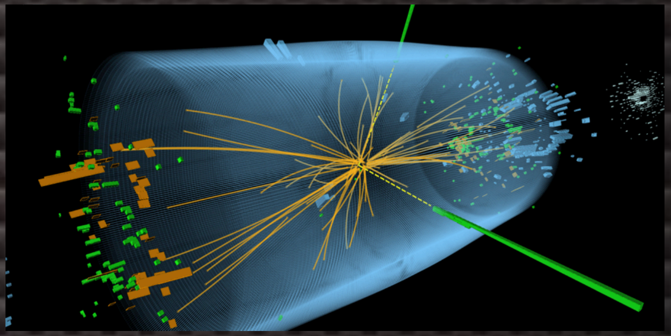
Carena, Marcela	Quantum Information Science for Applied Quantum Field Theory

FermiLab, Caltech and Institute for Nuclear Theory

https://academicjobsonline.org/ajo/jobs/12792

Perdue, Gabriel	Quantum Computing for Neutrino-Nucleus Dynamics
Mcguigan, Michael	Foundations of Quantum Computing for Gauge Theories and Quantum Gravity

Entanglement and Fragmentation and QFT

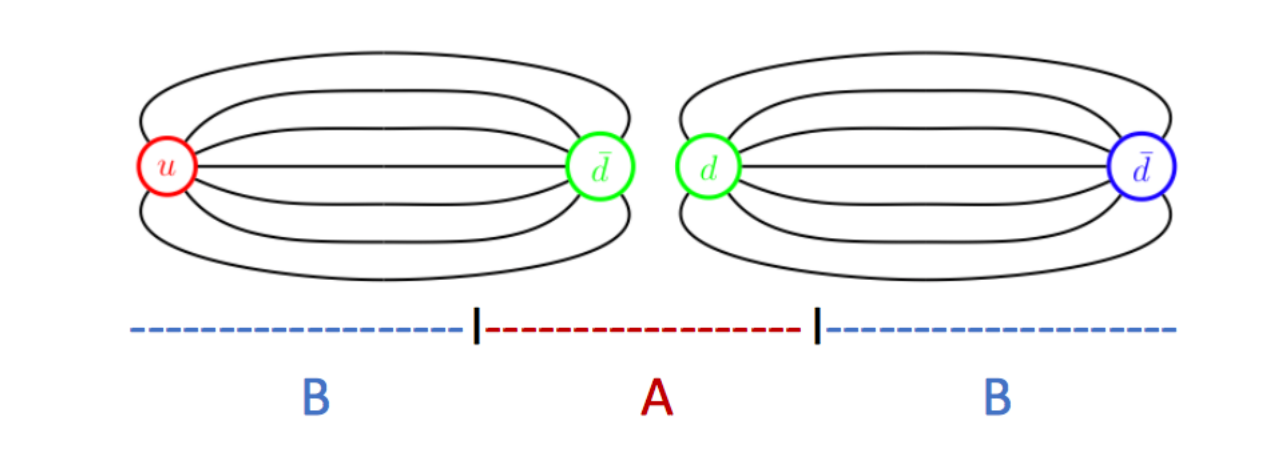


Deep inelastic scattering as a probe of entanglement
Dmitri E. Kharzeev (RIKEN BNL & SUNY, Stony Brook), Eugene M. Levin (Santa Maria U., Valparaiso & Tel Aviv U.). Feb 12, 2017.
Published in **Phys.Rev. D95 (2017) no.11, 114008**

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**

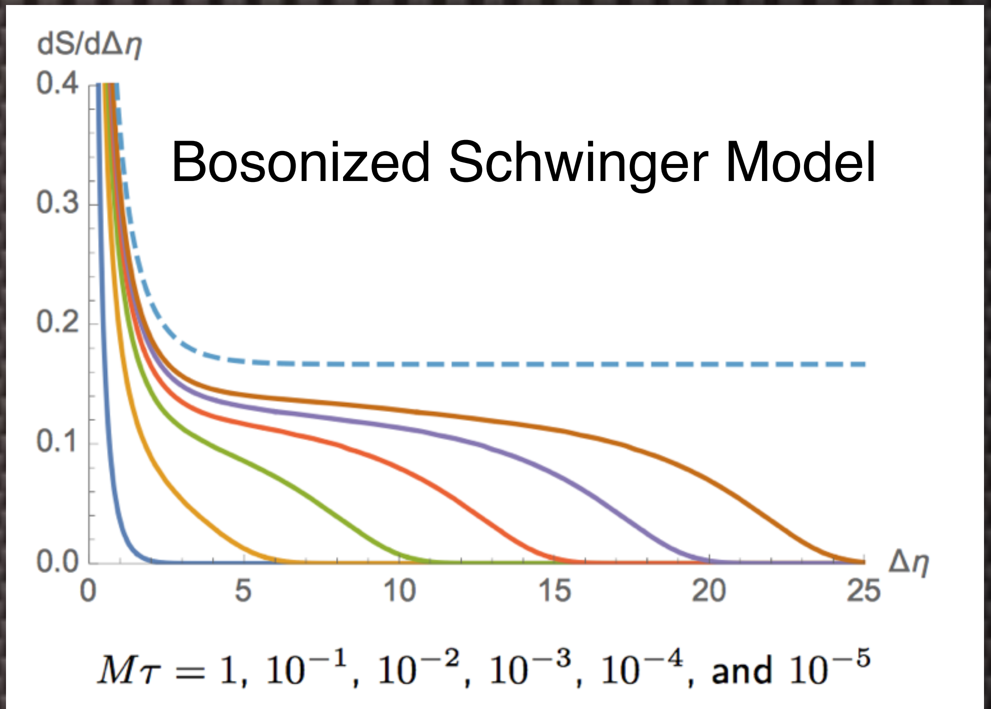
APS Medal for Exceptional Achievement in Research: Invited article on entanglement properties of quantum field theory
Edward Witten, Rev.Mod.Phys. 90 (2018) no.4, 045003,
e-Print: **arXiv:1803.04993 [hep-th]**

Center for Frontiers in Nuclear Science



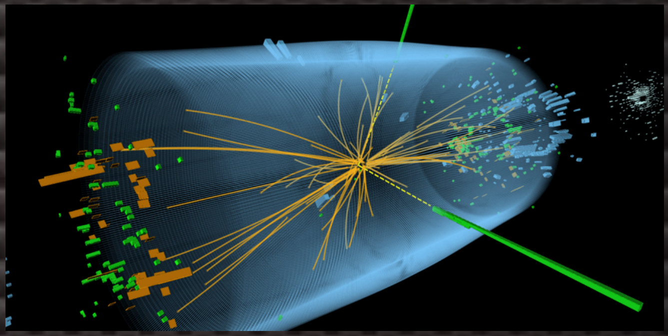
Quantum Entanglement at Collider Energies

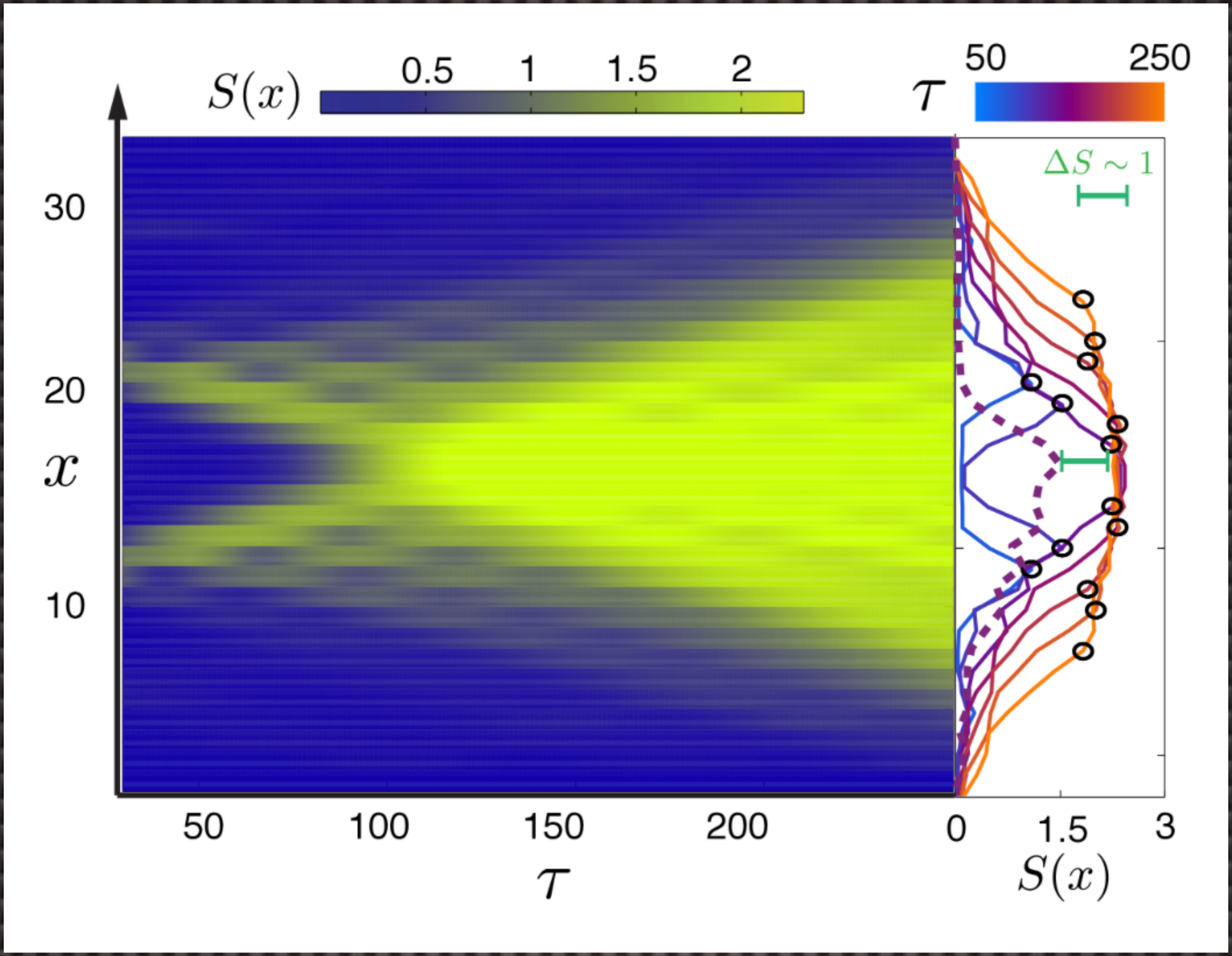
10-12 September 2018
CFNS Stony Brook



Entanglement and Fragmentation and QFT

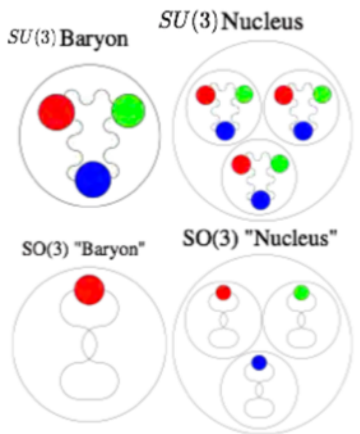
Real-time Dynamics in U(1) Lattice Gauge Theories with Tensor Networks
T. Pichler (Ulm U.), M. Dalmonte (Innsbruck U., Quant. Opt. and Info. & Innsbruck U.), E. Rico (Basque U., Bilbao & IPCMS, Strasbourg & IKERBASQUE, Bilbao), P. Zoller (Innsbruck U. & Innsbruck U., Quant. Opt. and Info.), S. Montangero (Ulm U.).
Phys.Rev. X6 (2016) no.1, 011023, e-Print: arXiv:1505.04440 [cond-mat.quant-gas]





QFTs Toward QCD for NP

a)



b)

	3-d QCD	1-d $SO(3)$	2-d $SO(3)$
gauge symmetry	$SU(3)$	$SO(3)$	$SO(3)$
chiral symmetry	$SU(2)_L \times SU(2)_R$	$\mathbb{Z}_2$	$\mathbb{Z}_2 \times \mathbb{Z}_2$
flavor symmetry	$SU(2)_{L=R}$	$\mathbb{1}$	$\mathbb{Z}_2$
baryon symmetry	$U(1)$	$U(1)$	$U(1)$
charge conjugation	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}_2$
parity	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}_2$

Quantum Link Models and Quantum Simulation of Gauge Theories

Uwe-Jens Wiese

Albert Einstein Center for Fundamental Physics
Institute for Theoretical Physics, Bern University

u^b
UNIVERSITÄT BERN
AEC ALBERT EINSTEIN CENTER FOR FUNDAMENTAL PHYSICS

Winter School:
Intersections Between QCD and Condensed Matter
Schladming, Styria, 2015

FNSNF Swiss National Science Foundation

erc European Research Council

SO(3) "Nuclear Physics" with ultracold Gases☆

E. Rico[a,*], M. Dalmonte[b], P. Zoller[c],
D. Banerjee[d,e], M. Bögli[d], P. Stebler[d], U.-J. Wiese[d]

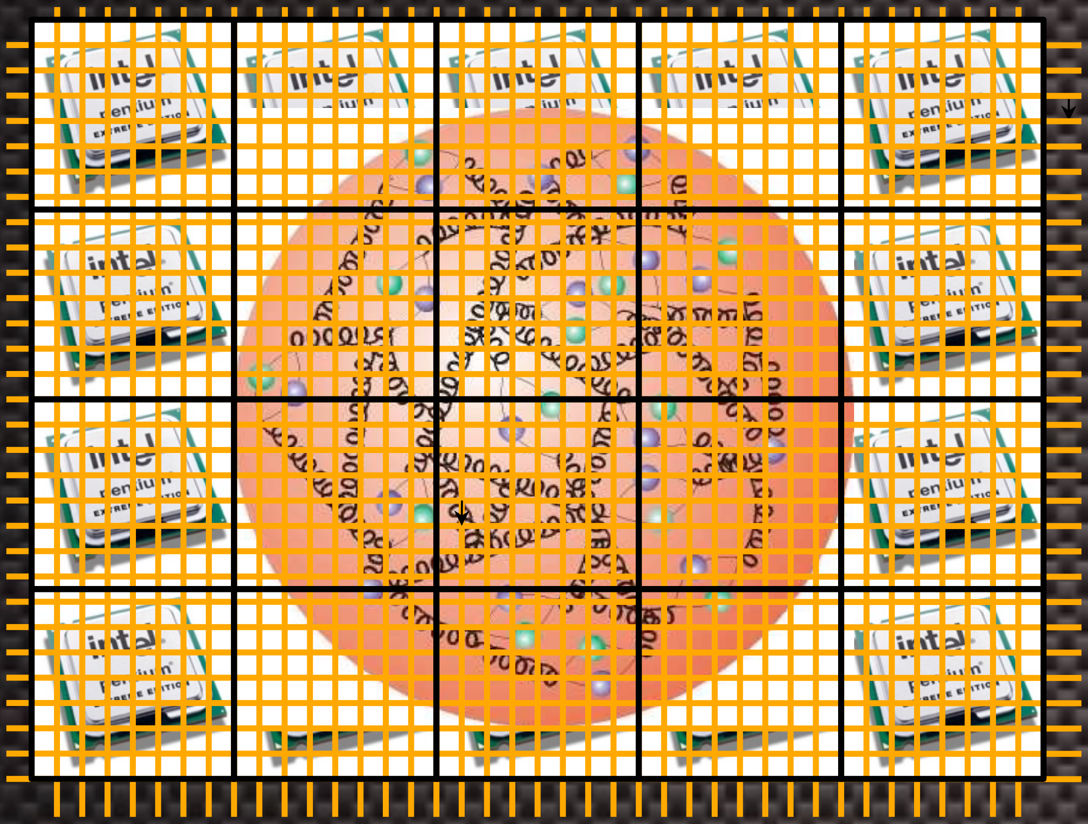
[a]*IKERBASQUE, Basque Foundation for Science, Maria Diaz de Haro 3, E-48013 Bilbao, Spain and Department of Physical Chemistry, University of the Basque Country UPV/EHU, Apartado 644, E-48080 Bilbao, Spain*
[b]*International Center for Theoretical Physics, 34151 Trieste, Italy*
[c]*Institute for Theoretical Physics, Innsbruck University, and Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences, A-6020 Innsbruck, Austria*
[d]*Albert Einstein Center for Fundamental Physics, Institute for Theoretical Physics, University of Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland*
[e]*NIC, DESY, Platanenallee 6, 15738 Zeuthen, Germany*

Abstract

An *ab initio* calculation of nuclear physics from Quantum Chromodynamics (QCD), the fundamental $SU(3)$ gauge theory of the strong interaction, remains an outstanding challenge. Here, we discuss the emergence of key elements of nuclear physics using an $SO(3)$ lattice gauge theory as a toy model for QCD. We show that this model is accessible to state-of-the-art quantum simulation experiments with ultracold atoms in an optical lattice. First, we demonstrate that our model shares characteristic many-body features with QCD, such as the spontaneous breakdown of chiral symmetry, its restoration at finite baryon density, as well as the existence of few-body bound states. Then we show that in the one-dimensional case, the dynamics in the gauge invariant sector can be encoded as a spin $S = \frac{3}{2}$ Heisenberg model, i.e., as quantum magnetism, which has a natural realization with bosonic mixtures in optical lattices, and thus sheds light on the connection between non-Abelian gauge theories and quantum magnetism.

Keywords: ultracold atoms | Lattice gauge theories | Quantum simulation

Lattice Quantum Chromodynamics
- Discretized Spacetime



Lattice Spacing :
$a << 1/\Lambda\chi$

(Nearly Continuum)

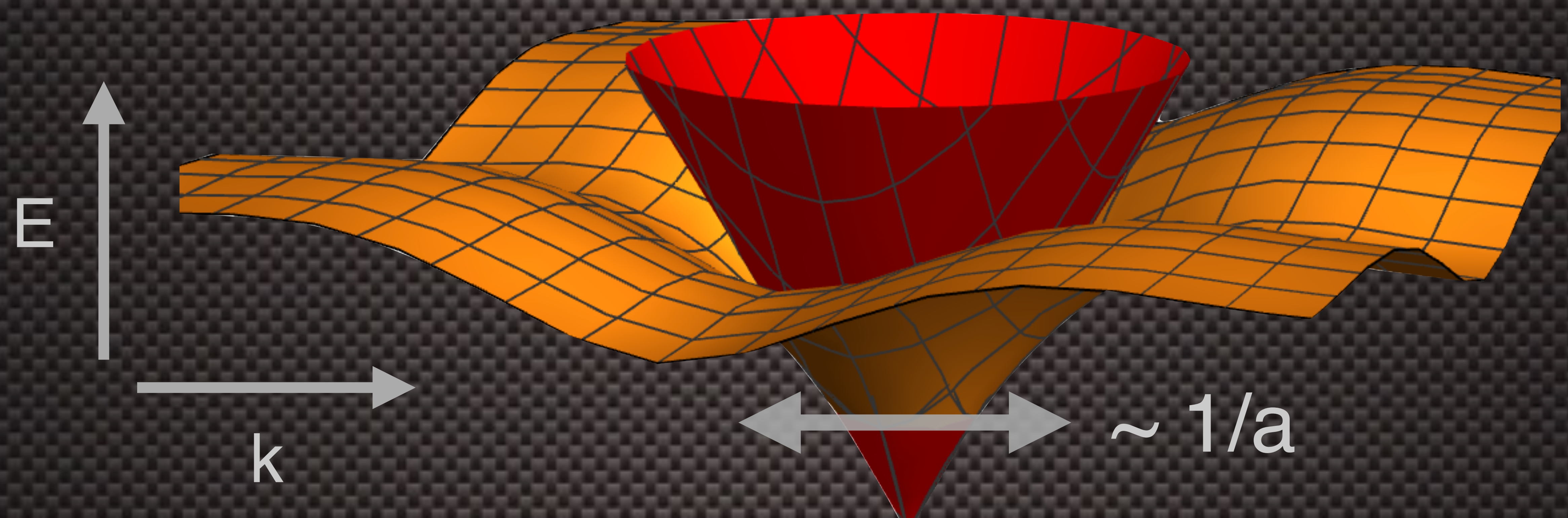
Lattice Volume :
$m_\pi L >> 2\pi$

(Nearly Infinite Volume)

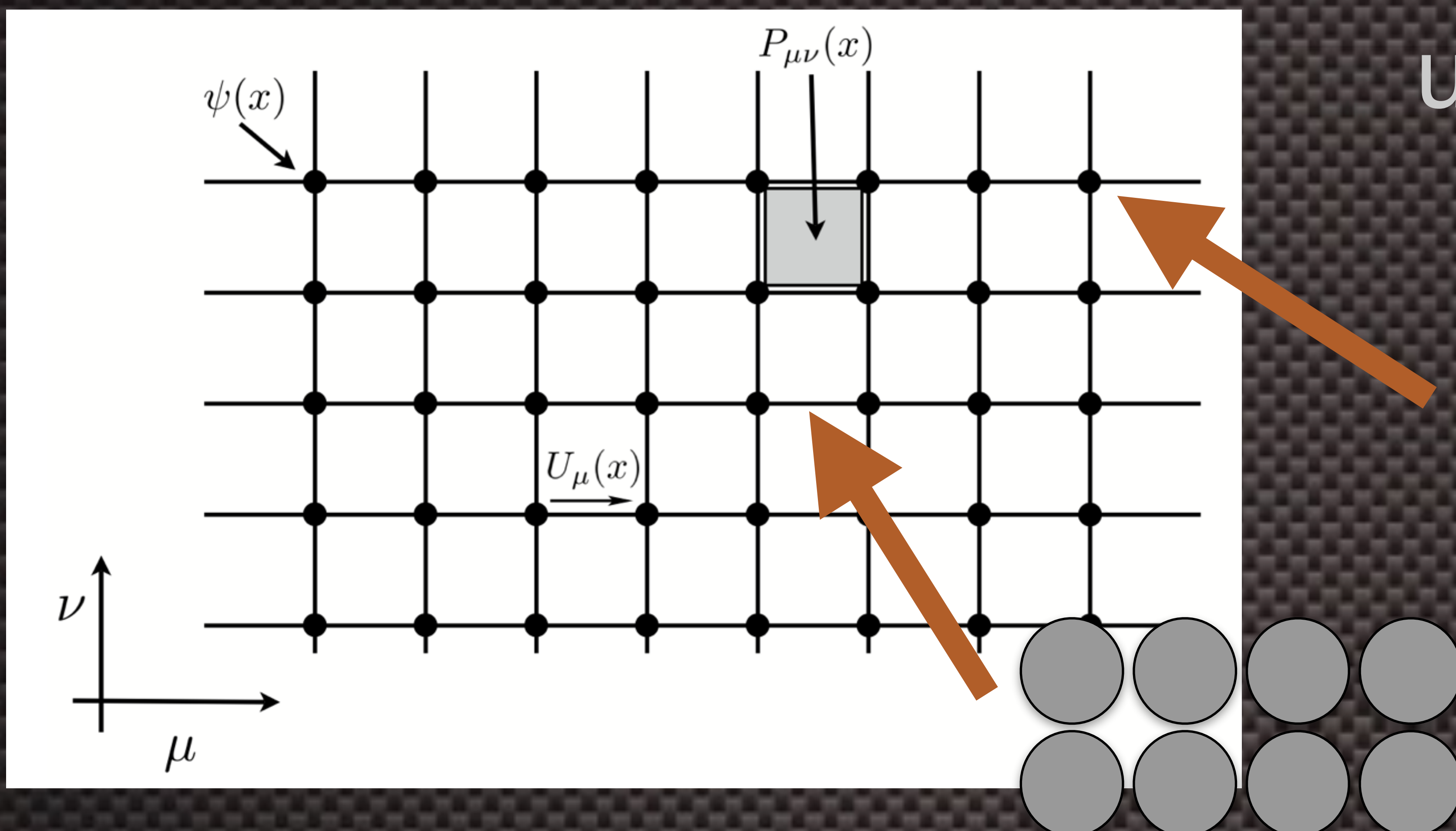
Digitization of Theory onto Qubits

Extrapolation to

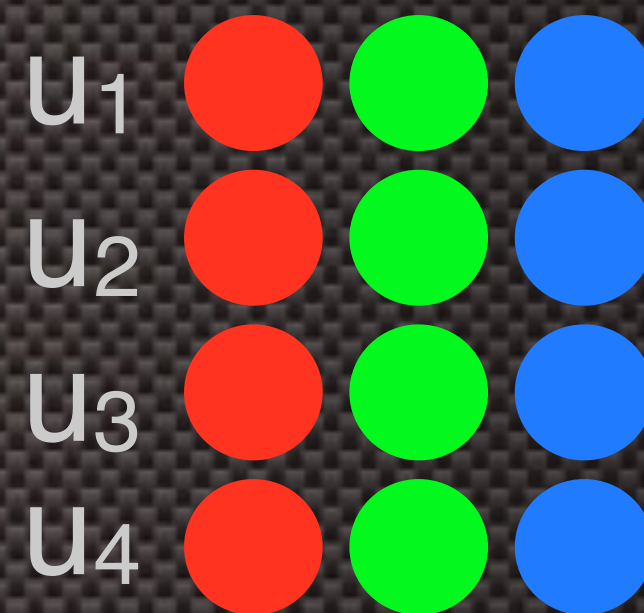
$a=0$ and $L = \infty$ and $\delta\Phi = 0$



(Very) Naive Mapping of QCD onto QC

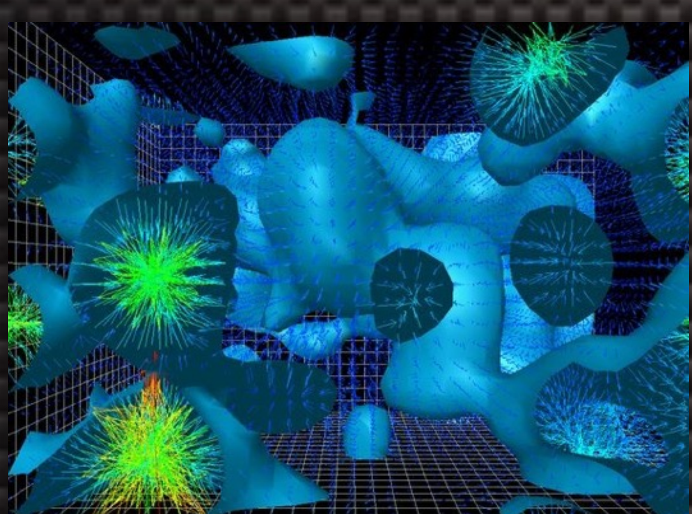


up-quark qubits



+ d,s,c

32^3 lattice requires naively > 4 million qubits !



State Preparation - a critical element

I random > = a I0> + b I(pi pi)> + c I (pi pi pi pi) > + …. + d I (GG) > + ….

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

Gauge Theories are Just Complicated

Created by Martin Savage in 2018

Naive mapping:

Most states mapped to qubits do not satisfy constraints

Exponentially large redundancies - gauge symmetries

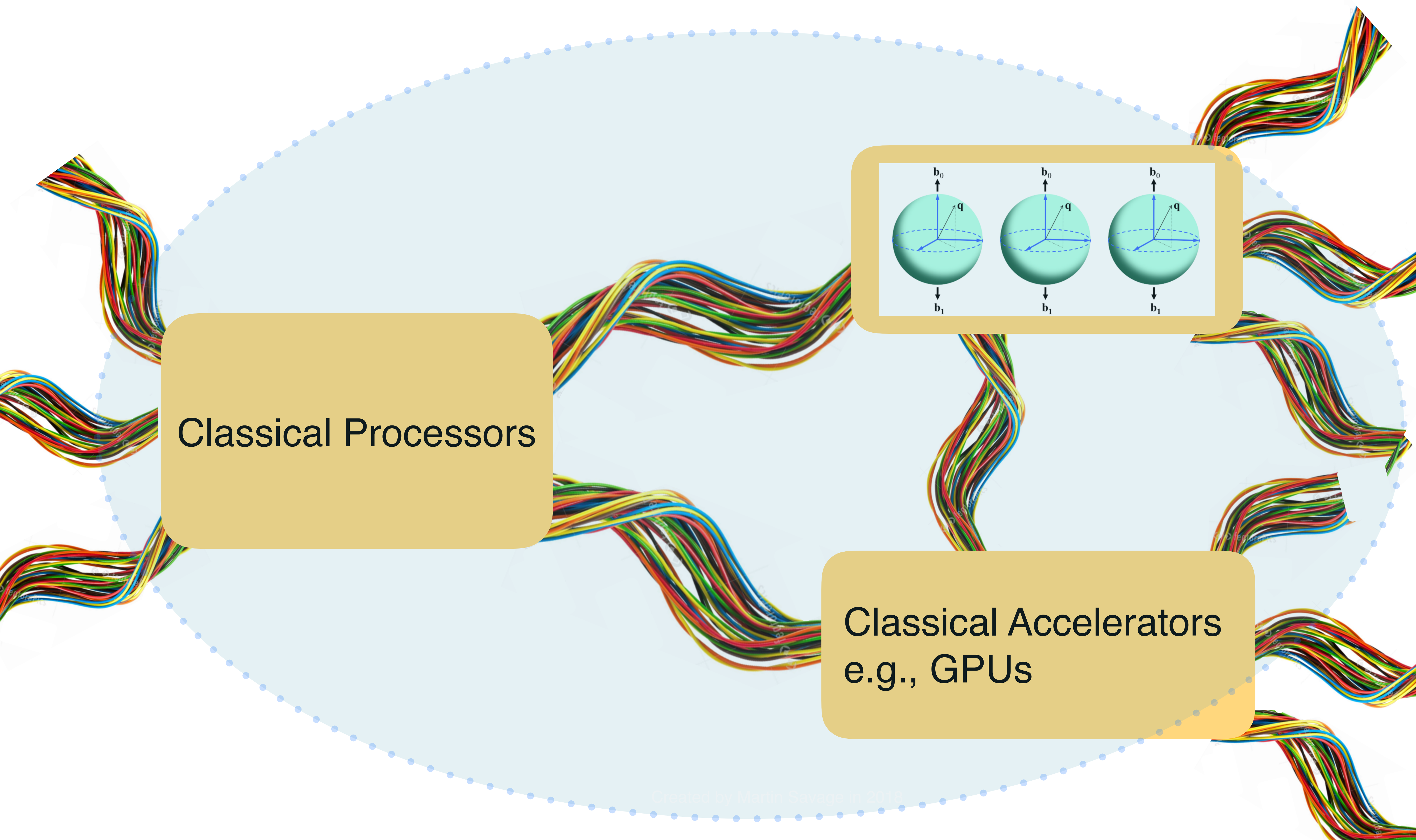
Methods to compress Hilbert space to physical

State preparation and role of classical calcs.

Chiral gauge theories?

Near term: move along paths with presently ``doable'', but informative, quantum calculations towards real-time and finite density QCD

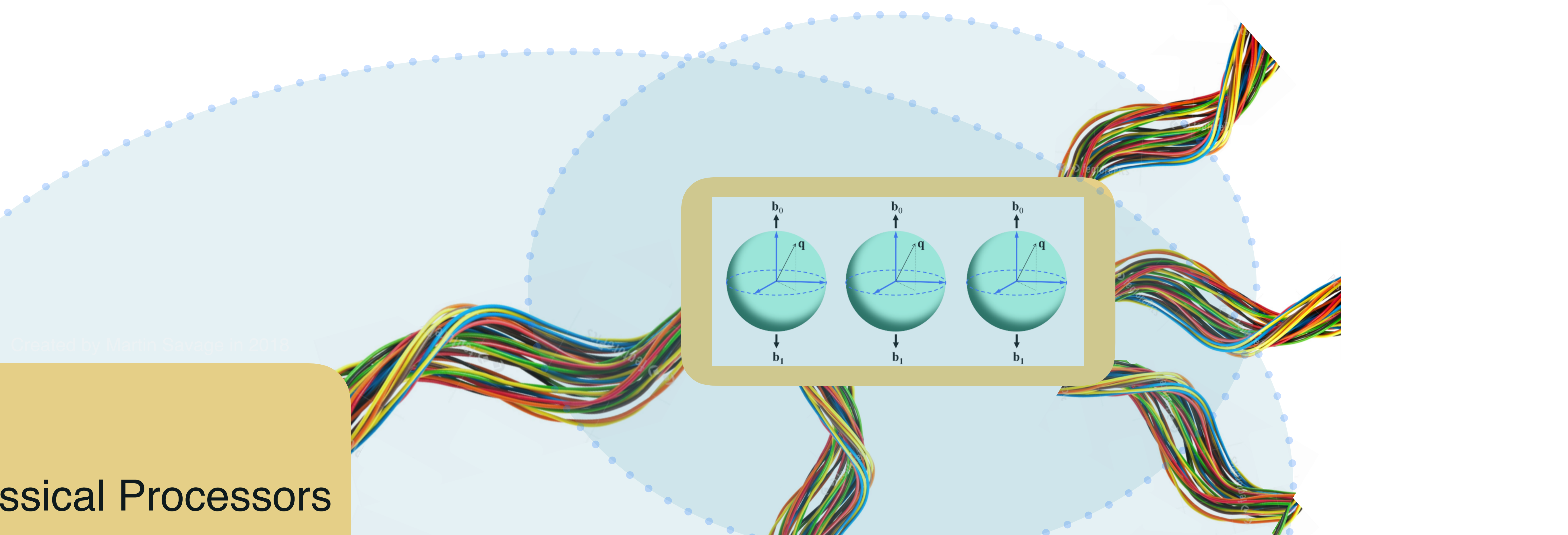
Early Days:
QPU Accelerators and Hybrid Computations



Early Days:
QPU Accelerators and Hybrid Computations

Classical-Quantum Hybrid calculations appear to be the near future
e.g. Bayesian estimations on classical computers to specify quantum computation

- Speed-up bootleneck components of Lattice QCD computations
  - contractions ? propagators ?
- Identify appropriate components
- How to push/pull to/from QPU
- Similar approach, but different in substance, to GPUs



Classical-Quantum Hybrid Systems

Oak Ridge National Laboratory

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.

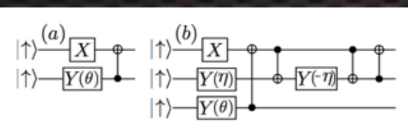
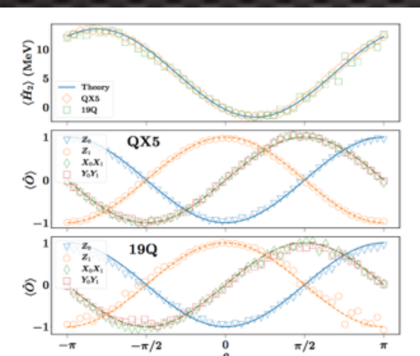


FIG. 1. Low-depth circuits that generate unitary rotations in Eq. (7) (panel a) and Eq. (8) (panel b). Also shown are the single-qubit gates of the Pauli X matrix, the rotation $Y(\theta)$ with angle θ around the Y axis, and the two-qubit CNOT gates.

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,

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



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

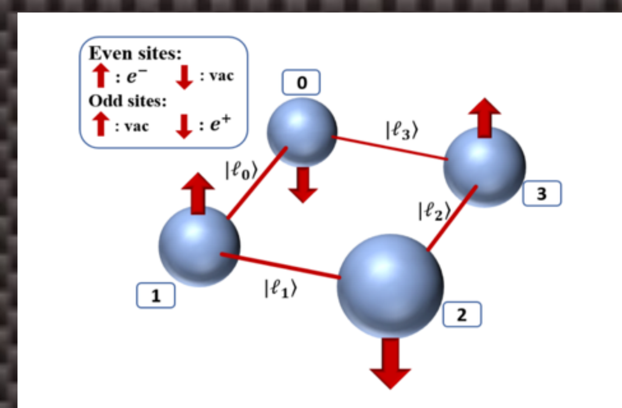
Hsuan-Hao Lu[1], Natalie Klco[2], Joseph M. Lukens[3], Titus D. Morris[3], Aaina Bansal[4], Andreas Ekström[5], Gaute Hagen[6,4], Thomas Papenbrock[4,6], Andrew M. Weiner[1], Martin J. Savage[2], and Pavel Lougovski[3,*]

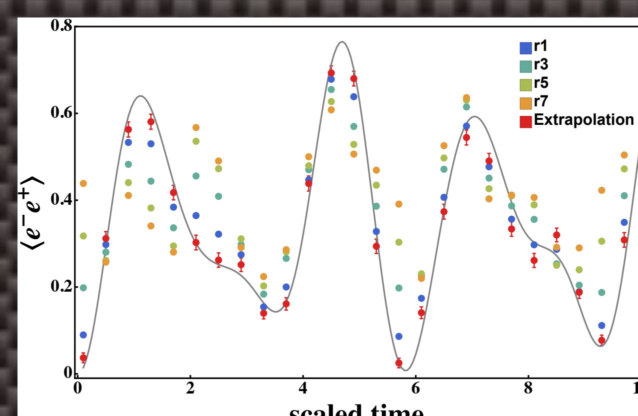
e-Print: arXiv:1810.03959 [quant-ph]

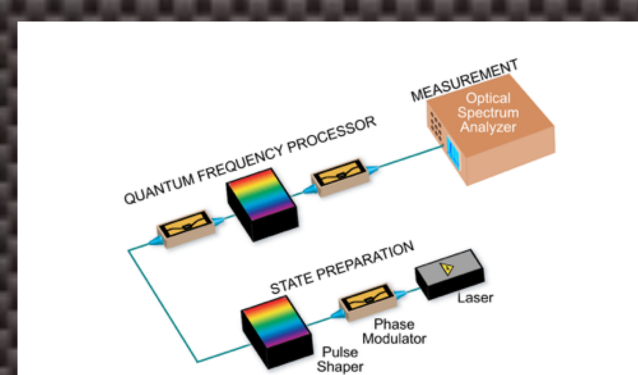
Quantum-classical computation of Schwinger model dynamics using quantum computers

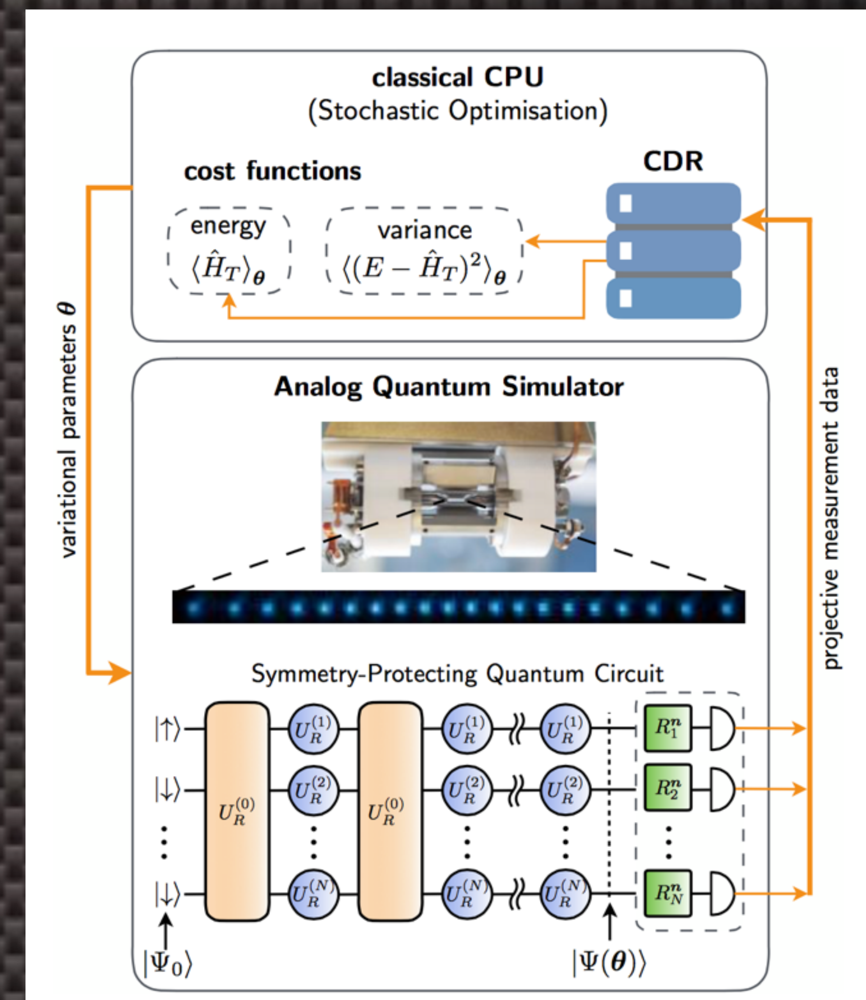
N. Klco, E. F. Dumitrescu, A. J. McCaskey, T. D. Morris, R. C. Pooser, M. Sanz, E. Solano, P. Lougovski, and M. J. Savage

Phys. Rev. A **98**, 032331 – Published 28 September 2018







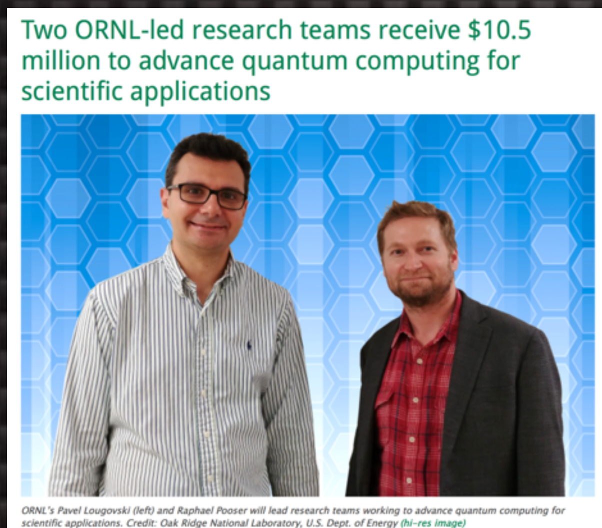


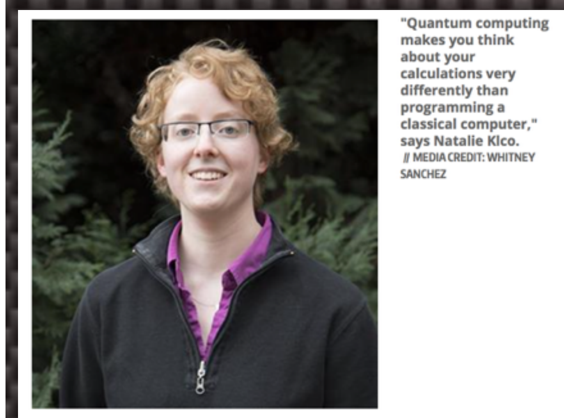
Self-Verifying Variational Quantum Simulation of the Lattice Schwinger Model

Christian Kokail *et al.*. e-Print: arXiv:1810.03421 [quant-ph]

Our ORNL Team

Starting Simple: 1+1 Dim QED





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, and M. J. Savage

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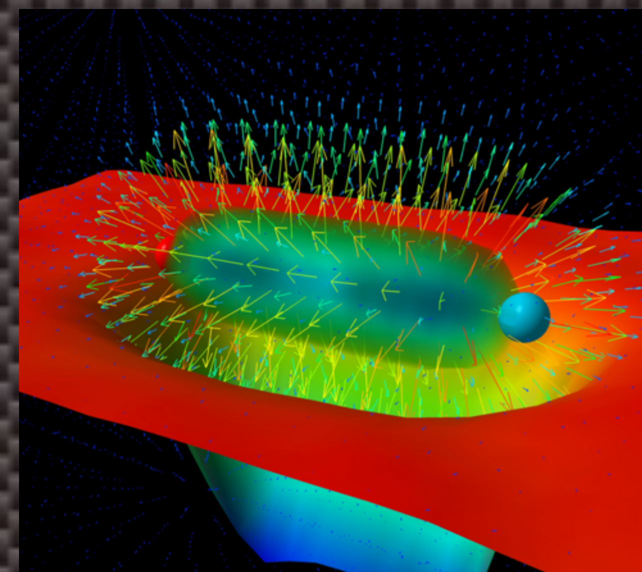
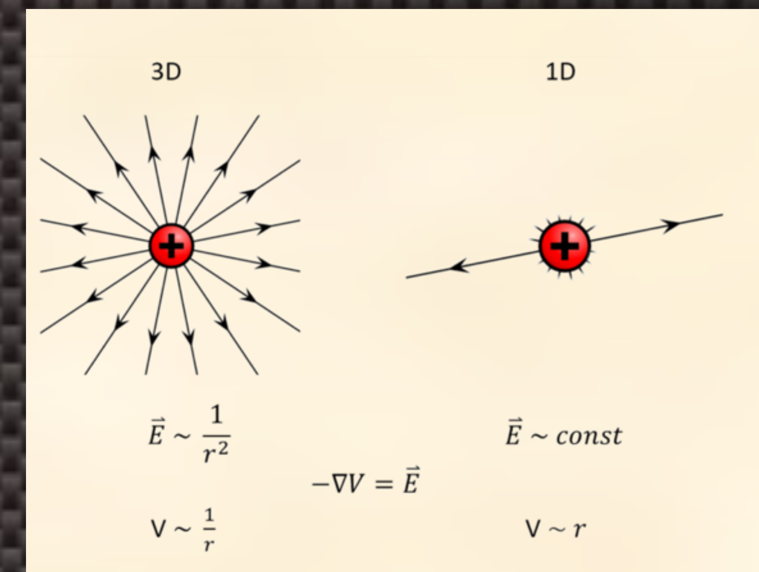
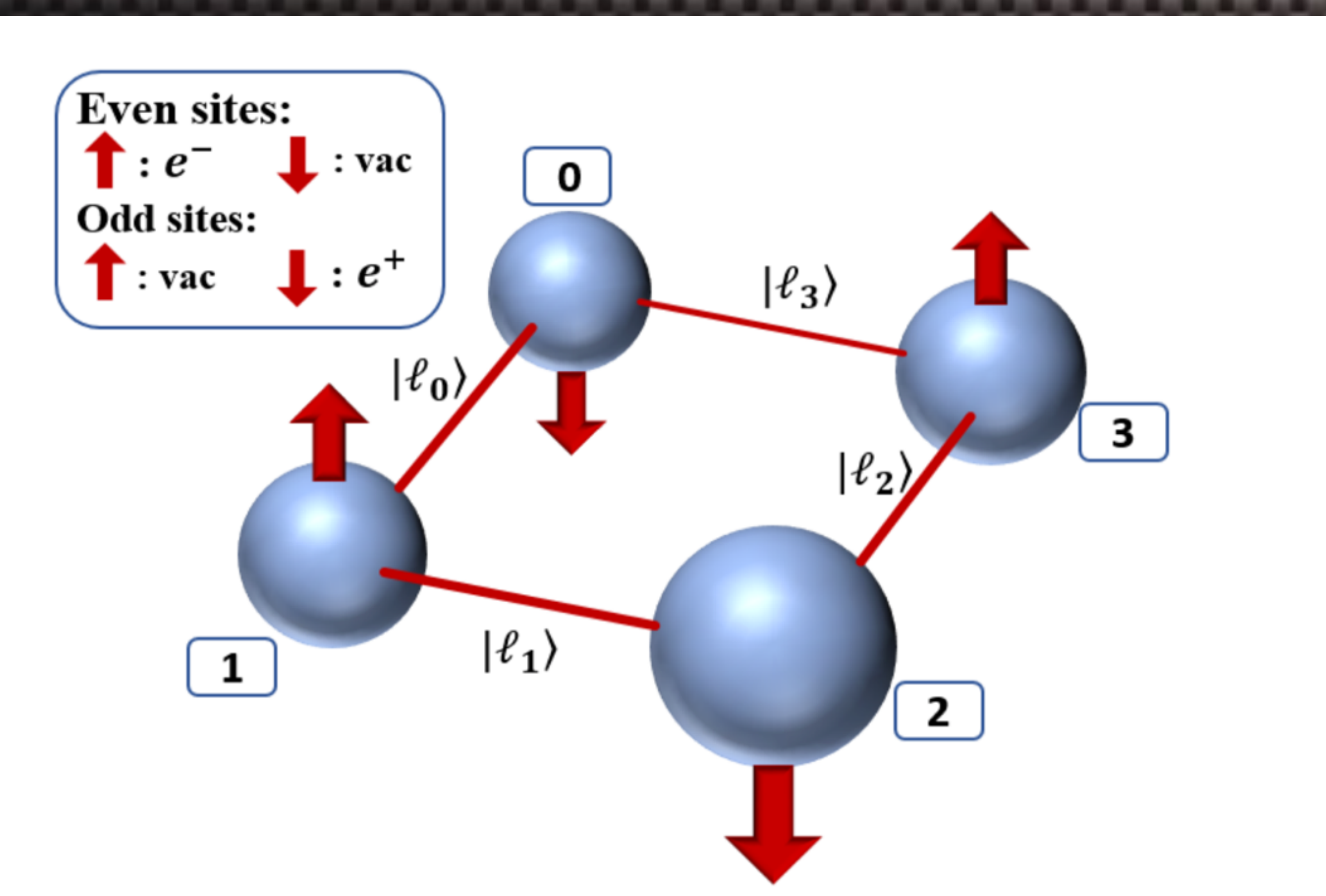


Derek Leinweber



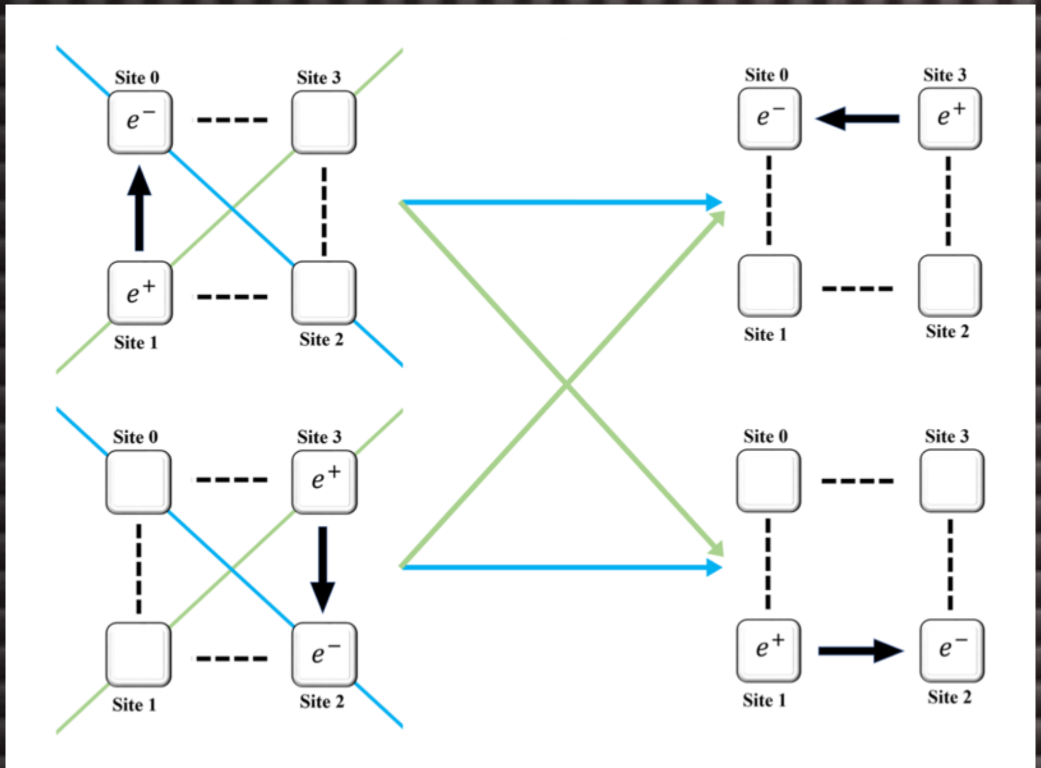
Natalie Klco



- Charge screening
- Confinement
- Fermion condensate
- Hadrons and nuclei

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

Symmetries and the Size of the Hilbert Space



Classical pre-processing

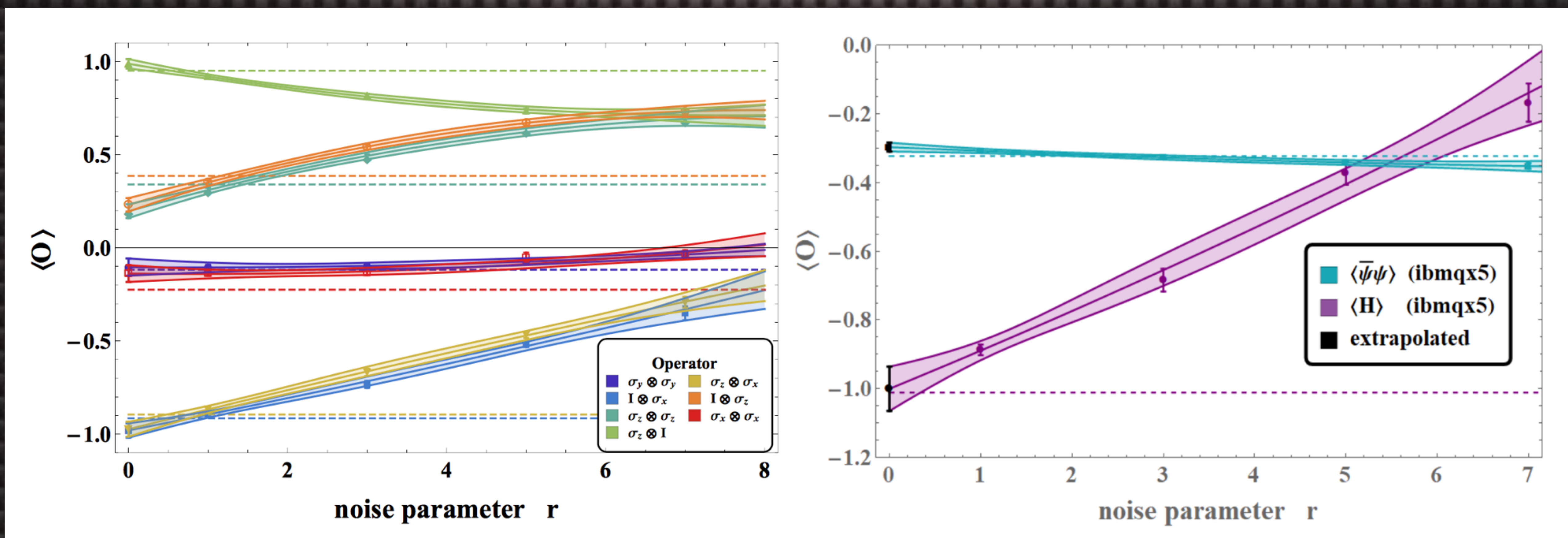
Can this be done *in situ* ?

Classical post-processing

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

VQE - GS Preparation
Classical-Quantum Hybrid Calculation

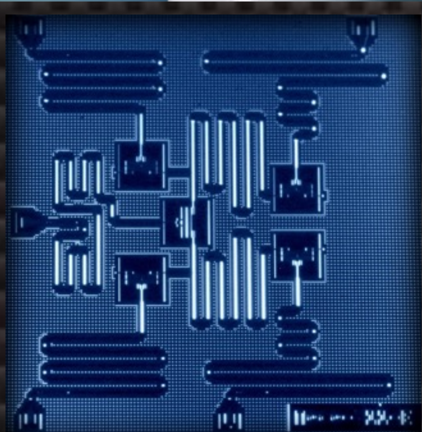
Oak Ridge National Laboratory



r = Number of CNOT-gates per CNOT-gate

Parameters in quantum circuit optimized classically (Bayesian)

Living NISQ - IBM
Classically Computed U(t)

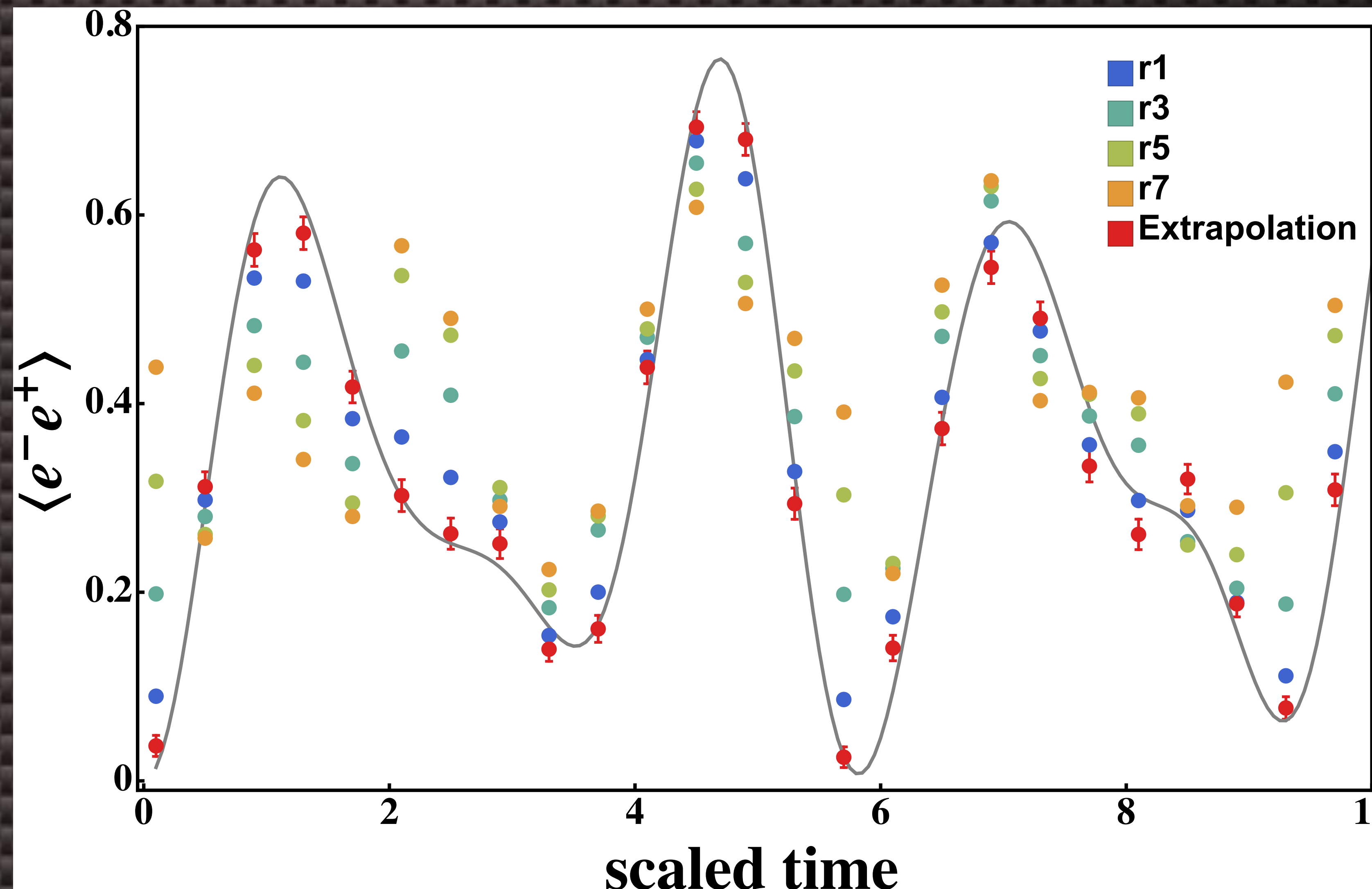


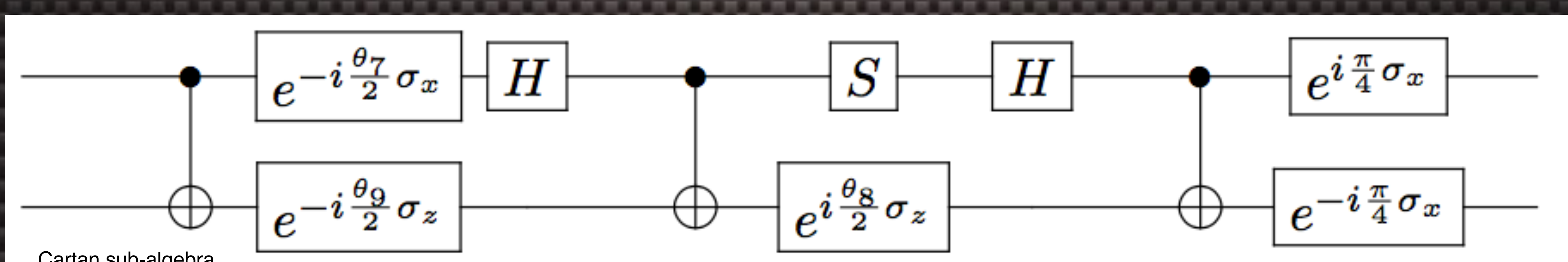
Oak Ridge National Laboratory

Institute for Nuclear Theory

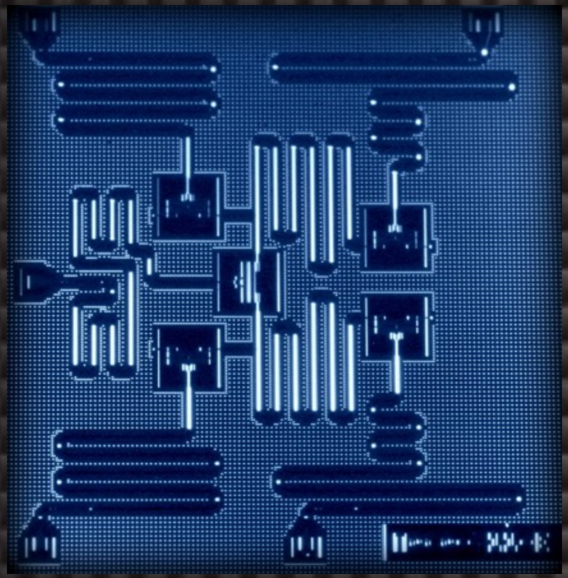
ibmqx2 - cloud-access

8K shots per point





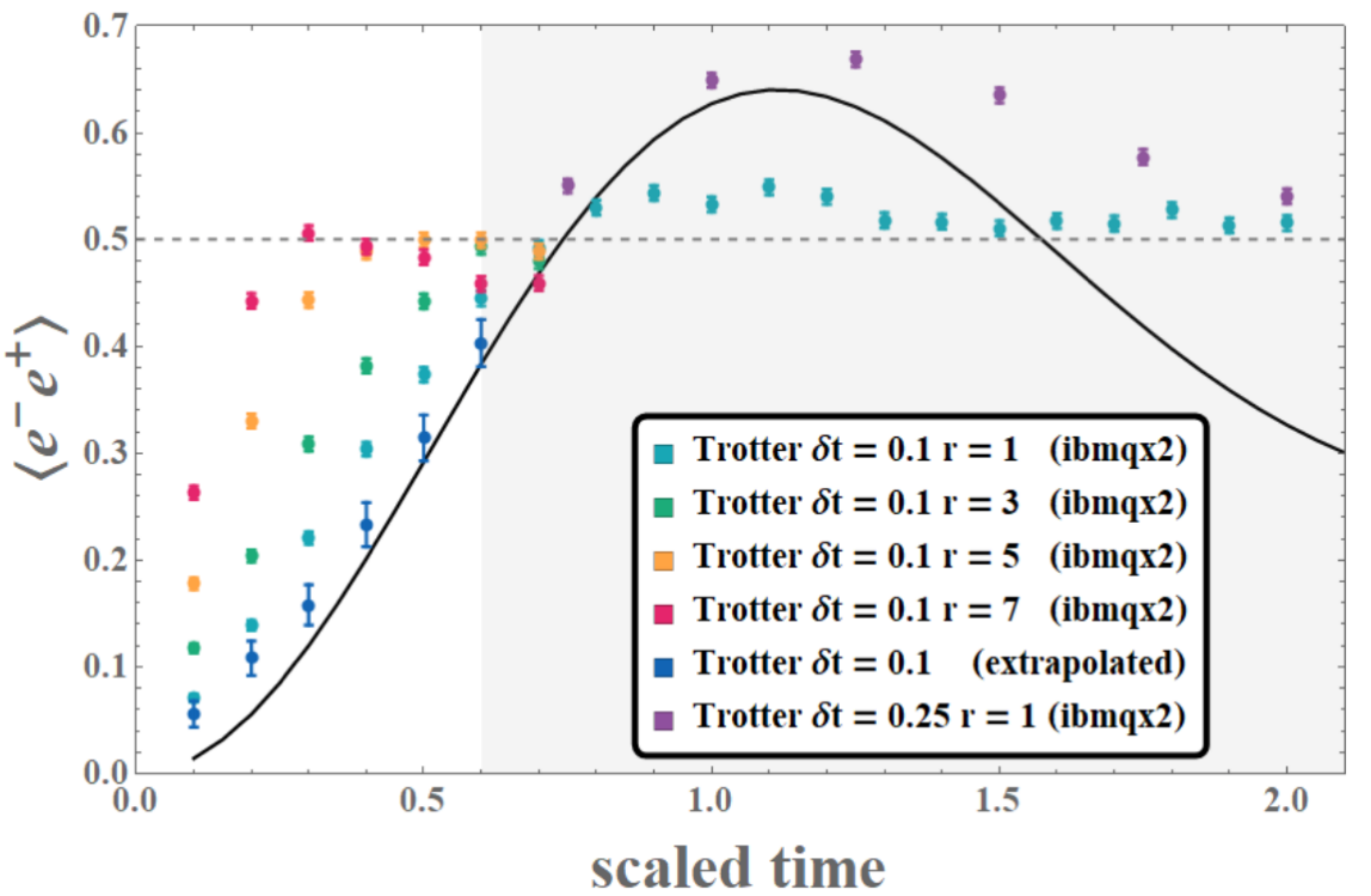
Living NISQ - IBM
Trotter Evolution U(t)



T2 (μs)	55.20	65.10	47.00	35.10	37.60

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

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



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

3.6 QPU-s and 260 IBM units

Cloud Access: 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) ;
  }
```

USQCD

NPLQCD

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.

Subatomic Simulations with an All-Optical Quantum Frequency Processor

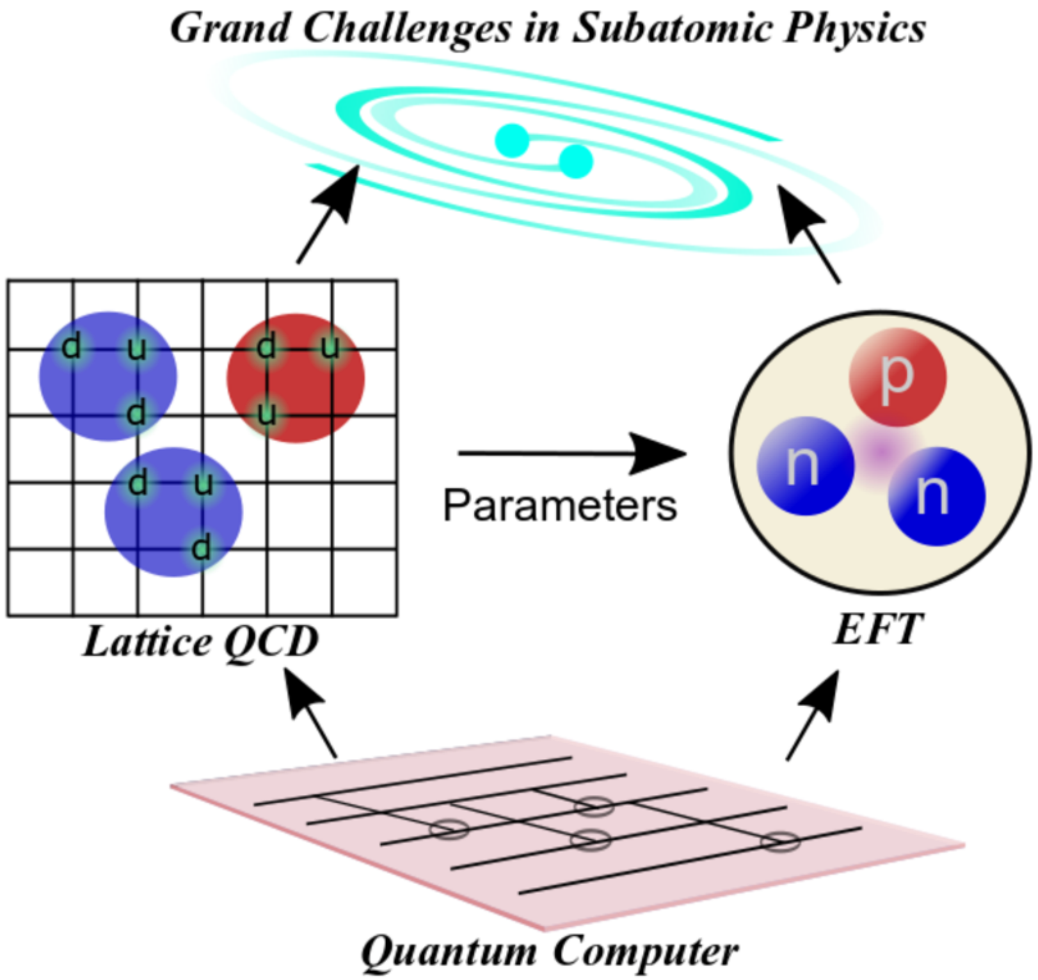
Simulations of Subatomic Many-Body Physics on a Quantum Frequency Processor

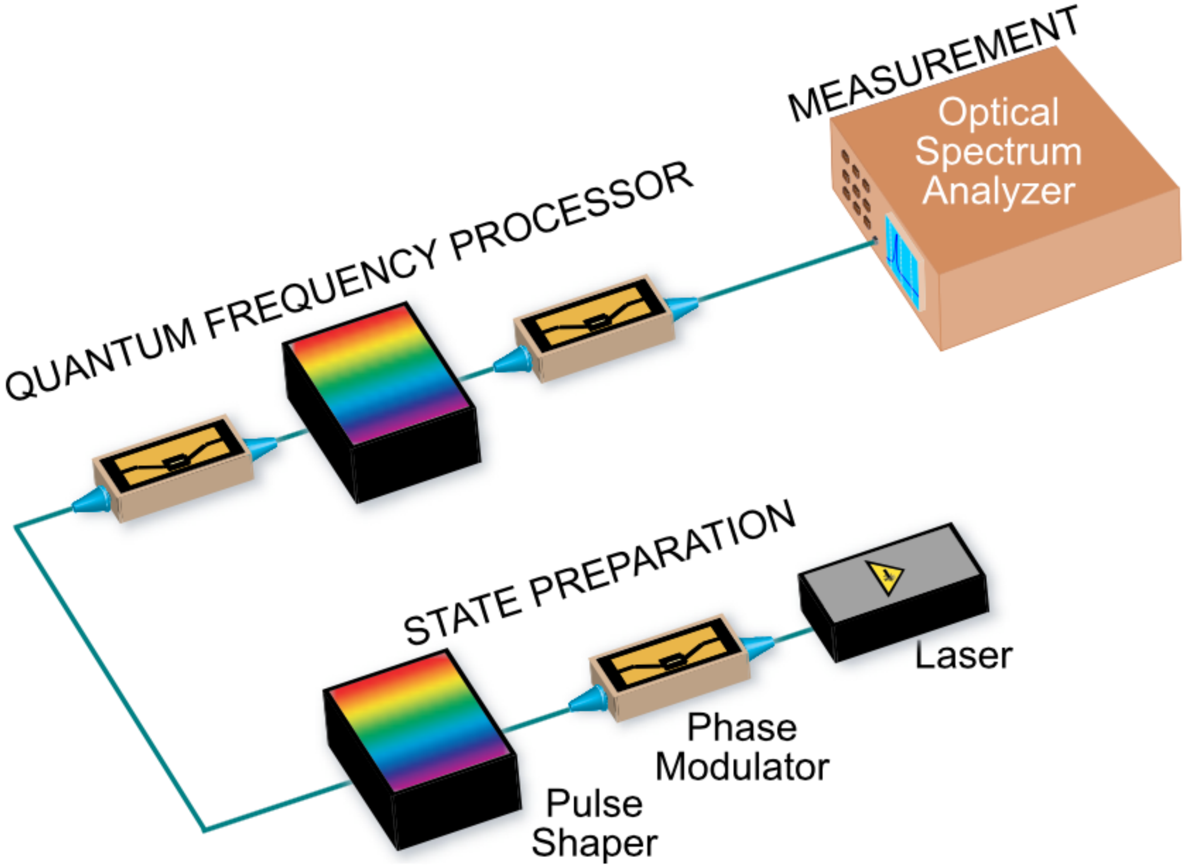
Hsuan-Hao Lu[1], Natalie Klco[2], Joseph M. Lukens[3], Titus D. Morris[3], Aaina Bansal[4], Andreas Ekström[5], Gaute Hagen[6,4], Thomas Papenbrock[4,6], Andrew M. Weiner[1], Martin J. Savage[2], and Pavel Lougovski[3,*]

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

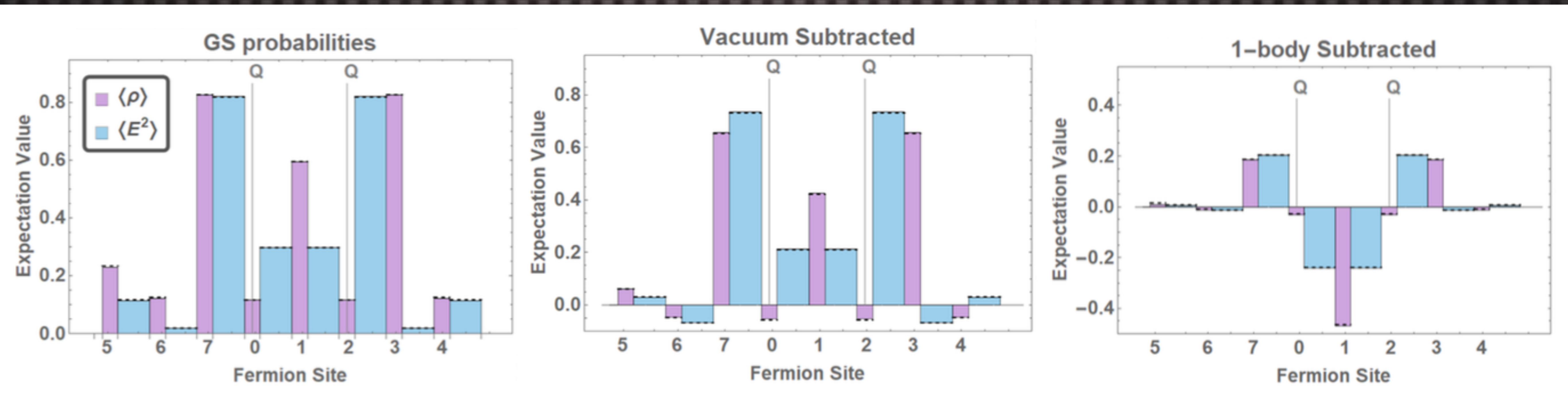
Pavel Lougovski

Oak Ridge National Laboratory





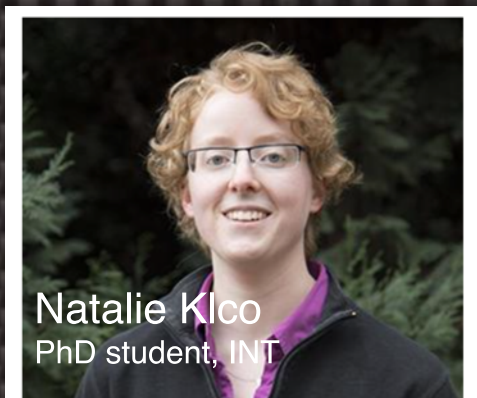
All-Optical QFT
2-Hadron Forces in the Schwinger Model



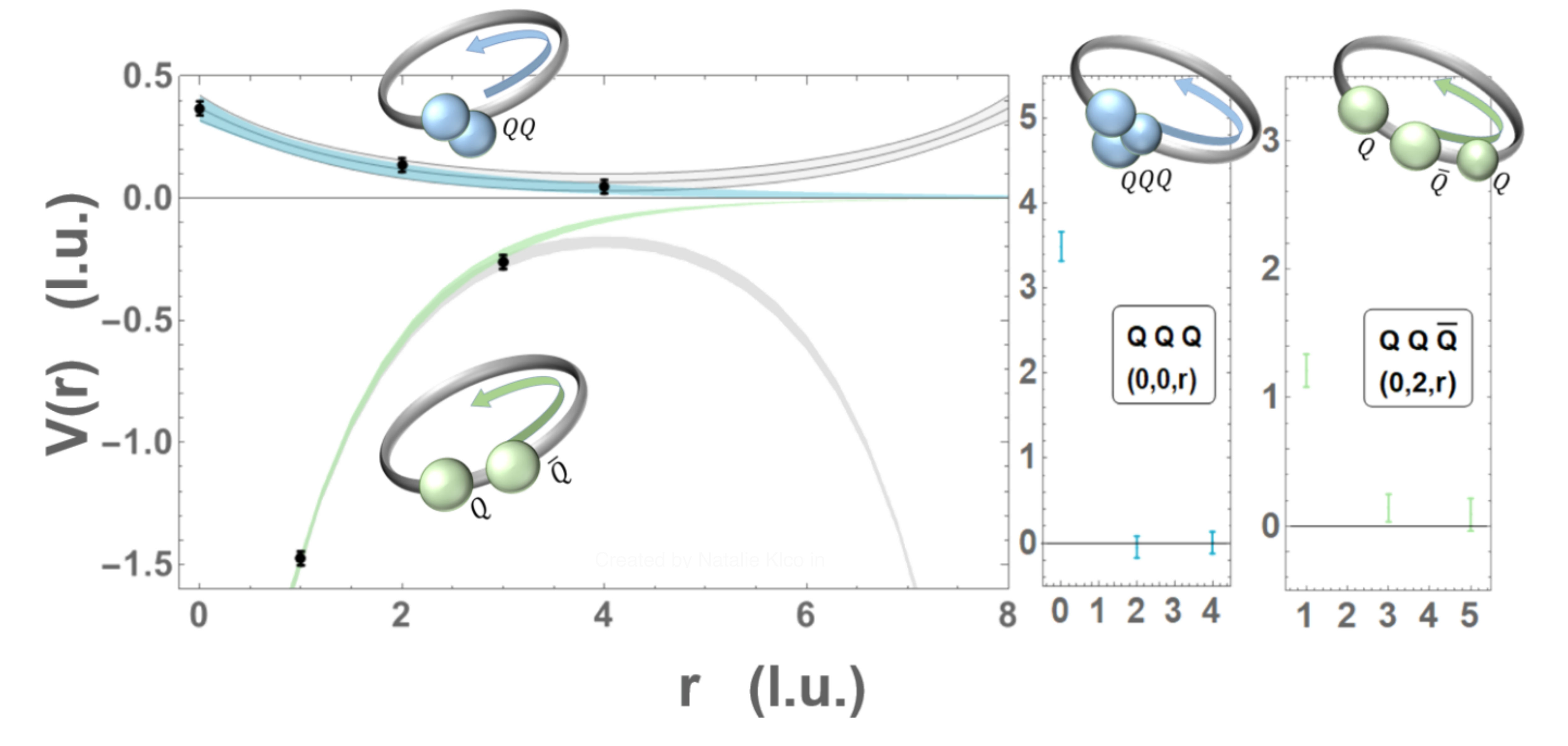
VQE :

$$|\Psi\rangle = \cos\phi\,|10\cdots0\rangle - \frac{\sin\phi}{\phi}\sum_{k=1}^{d-1}\theta_k|0\cdots1_k\cdots0\rangle$$

- single photon states in frequency comb
- 68-dim Hilbert space (largest to date)
- entanglement prepared classically
  - is a classical calculation …
- next: entangle multiple photons in the device

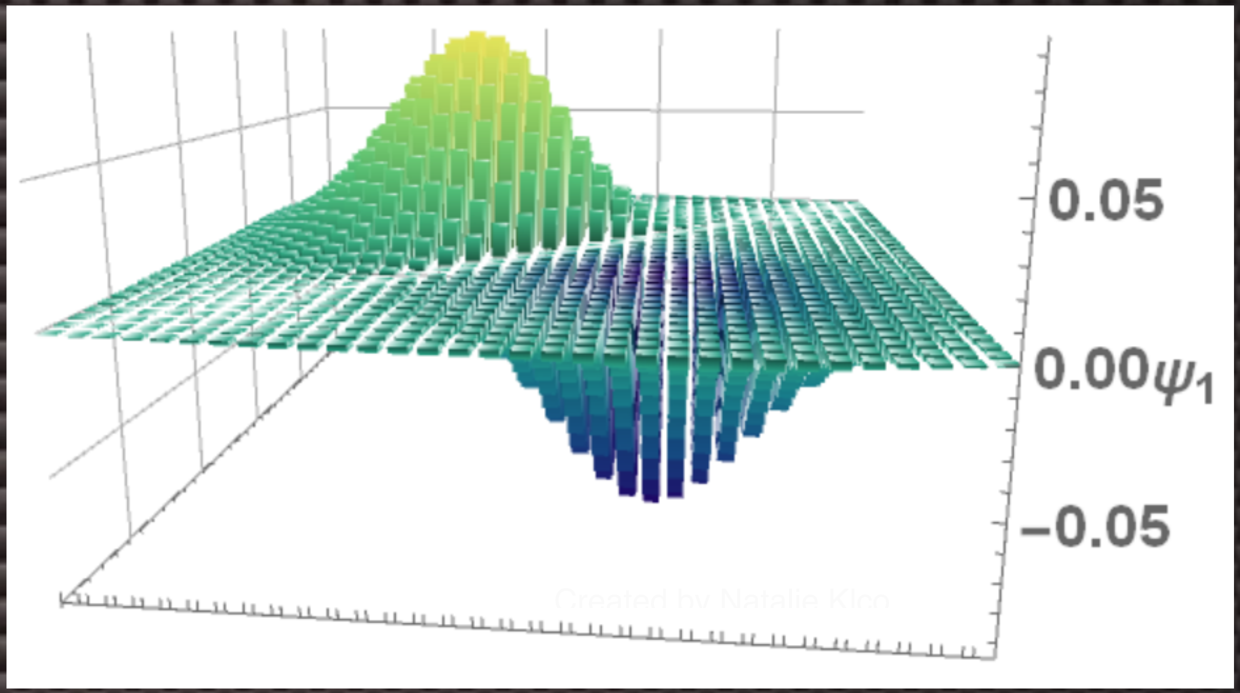


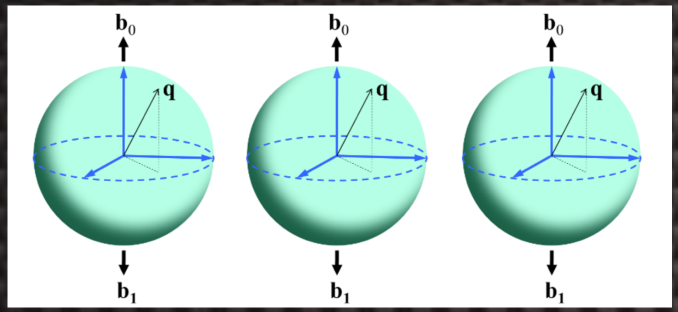
2 and 3-Hadron Potentials in the Schwinger Model



Digitizing Quantum Fields

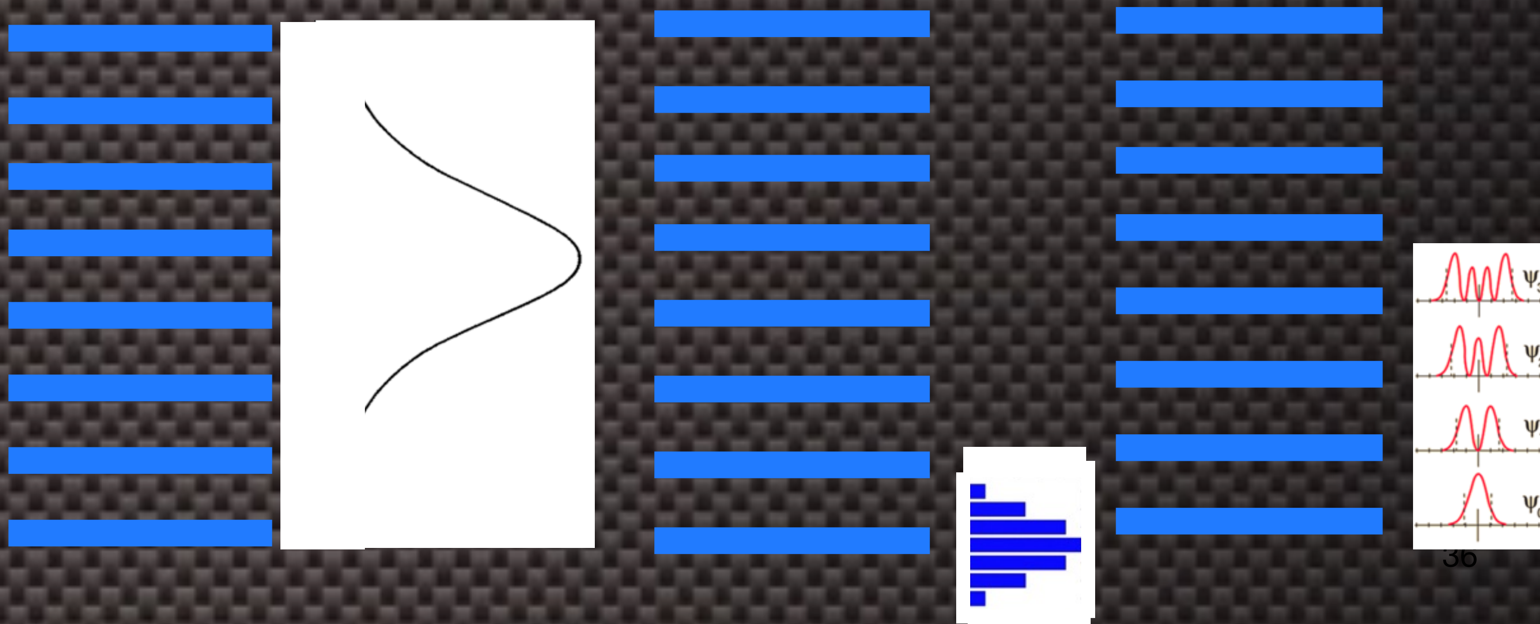
What is the optimal way to map field theories onto NISQ-era quantum computers?





3 Qubits = 8 States

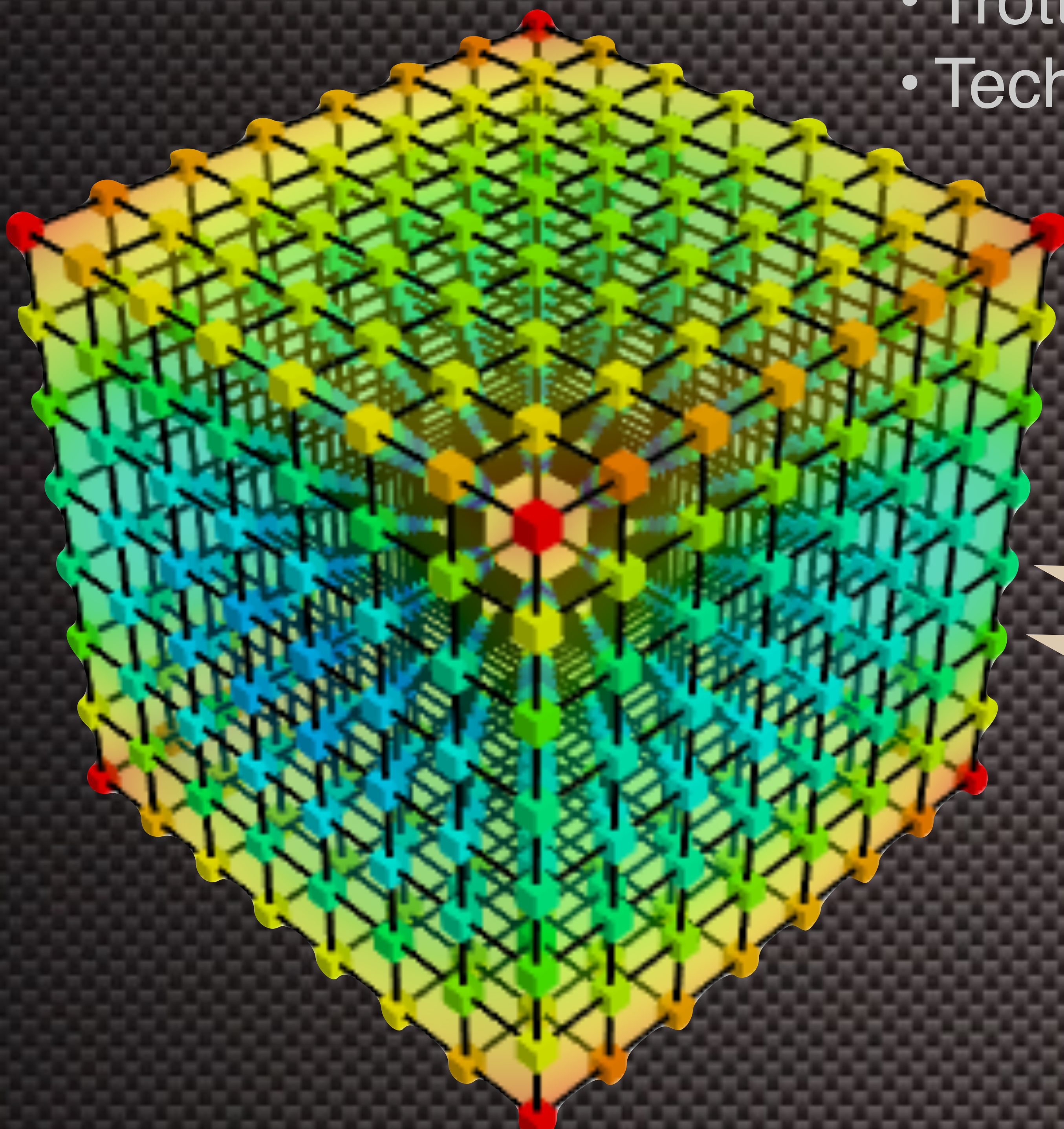
Jordan, Lee and Preskill - several works
Macridin et al, FNAL
Klco and MJS, INT



Discretizing and Digitization of Field Theory

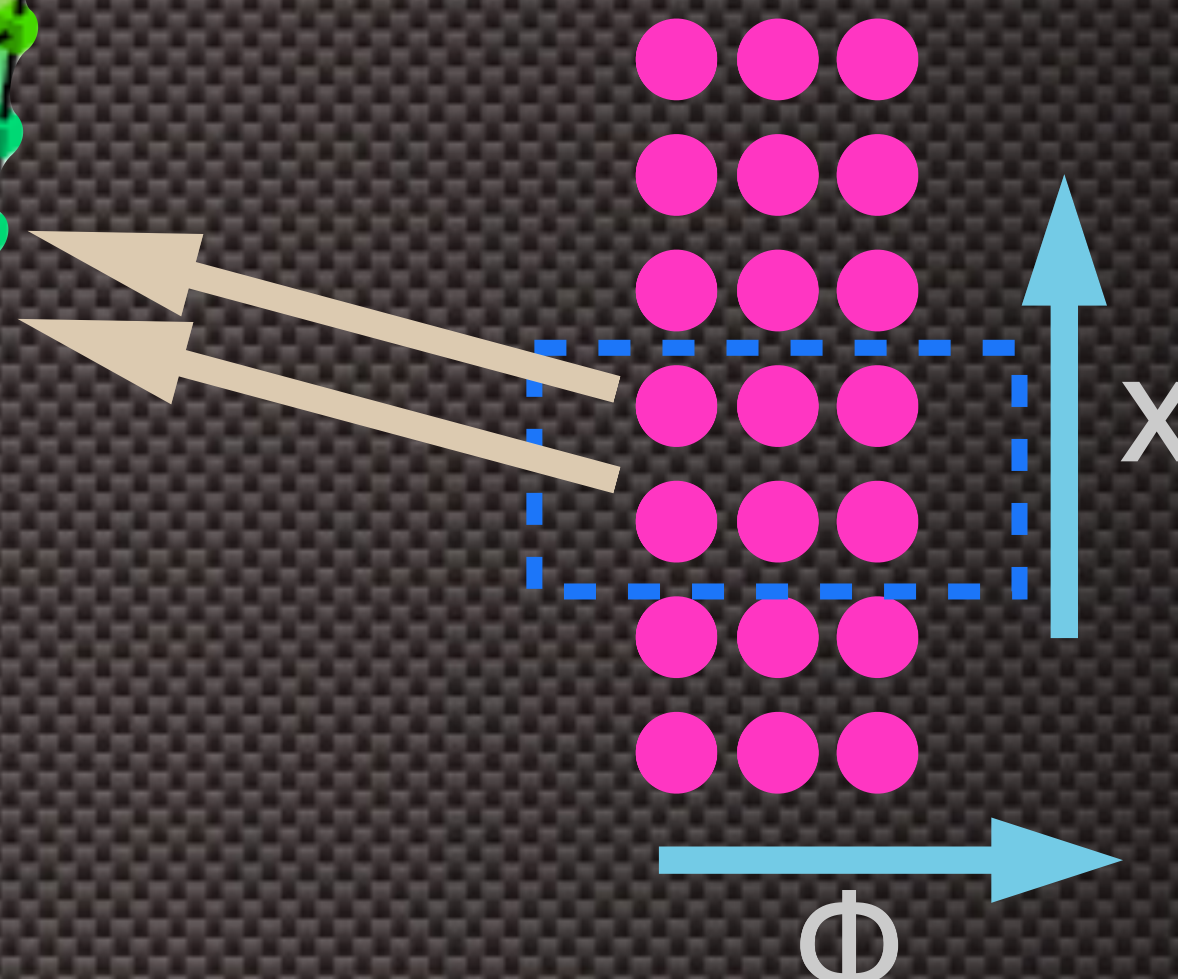
Jordan, Lee and Preskill - several works

- Discretize 3-d Space
- Define Hamiltonian on grid
- Trotterized time evolution
- Technology transfer from Lattice QCD



Parallelizes easily at the circuit level

- dual layer application per Trotter step



Digitizing Fields

Jordan, Lee and Preskill - several works

Simulating physical phenomena by quantum networks
R. Somma, G. Ortiz, J. E. Gubernatis, E. Knill, and R. Laflamme
Phys. Rev. A **65**, 042323 – Published 9 April 2002

Quantum simulation of quantum field theory using continuous variables
Kevin Marshall (Toronto U.), Raphael Pooser (Oak Ridge & Tennessee U.), George Siopsis (Tennessee U.), Christian Weedbrook (Unlisted, CA). Phys.Rev. A92 (2015) no.6, 063825 ,
e-Print: arXiv:1503.08121 [quant-ph]

Quantum Computation of Scattering Amplitudes in Scalar Quantum Electrodynamics
Kübra Yeter-Aydeniz (Tennessee Tech. U.), George Siopsis (Tennessee U.). Sep 7, 2017. 9 pp.
Published in **Phys.Rev. D97 (2018) no.3, 036004**
e-Print: **arXiv:1709.02355 [quant-ph]**

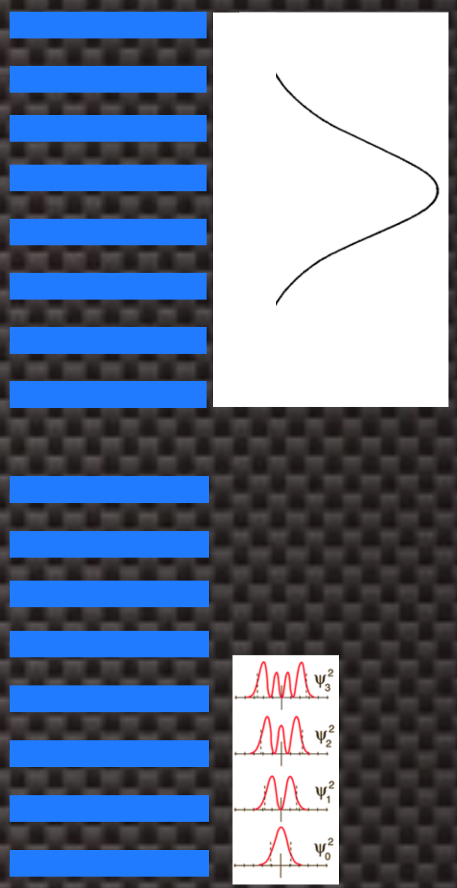
Electron-Phonon Systems on a Universal Quantum Computer
Alexandru Macridin, Panagiotis Spentzouris, James Amundson, Roni Harnik (Fermilab)
e-Print: **arXiv:1802.07347 [quant-ph]**

Digitization of Scalar Fields for NISQ-Era Quantum Computing
Natalie Klco, Martin Savage
e-Print: **arXiv:1808.10378 [quant-ph]**

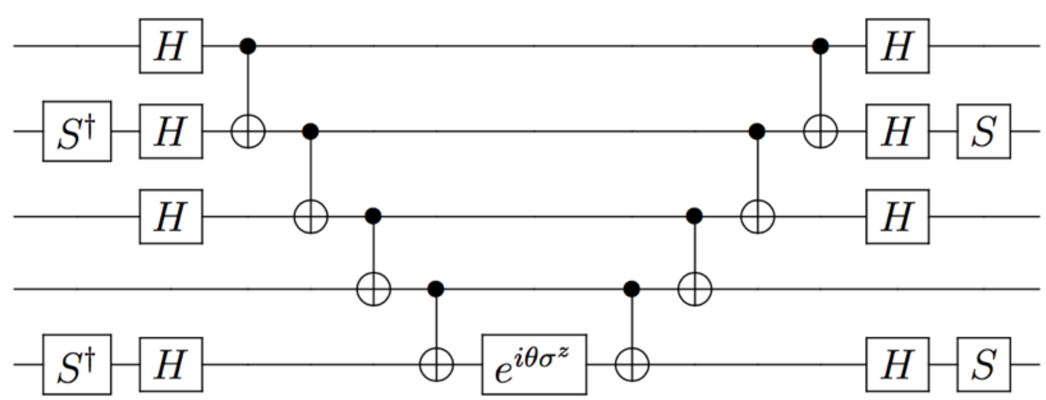
Digitizing Gauge Fields: Lattice Monte Carlo Results for Future Quantum Computers
Daniel C. Hackett (Colorado U.), Kiel Howe, Ciaran Hughes (Fermilab), William Jay (Colorado U. & Fermilab), Ethan T. Neil (Colorado U. & RIKEN BNL), James N. Simone (Fermilab). Nov
e-Print: **arXiv:1811.03629 [quant-ph]**

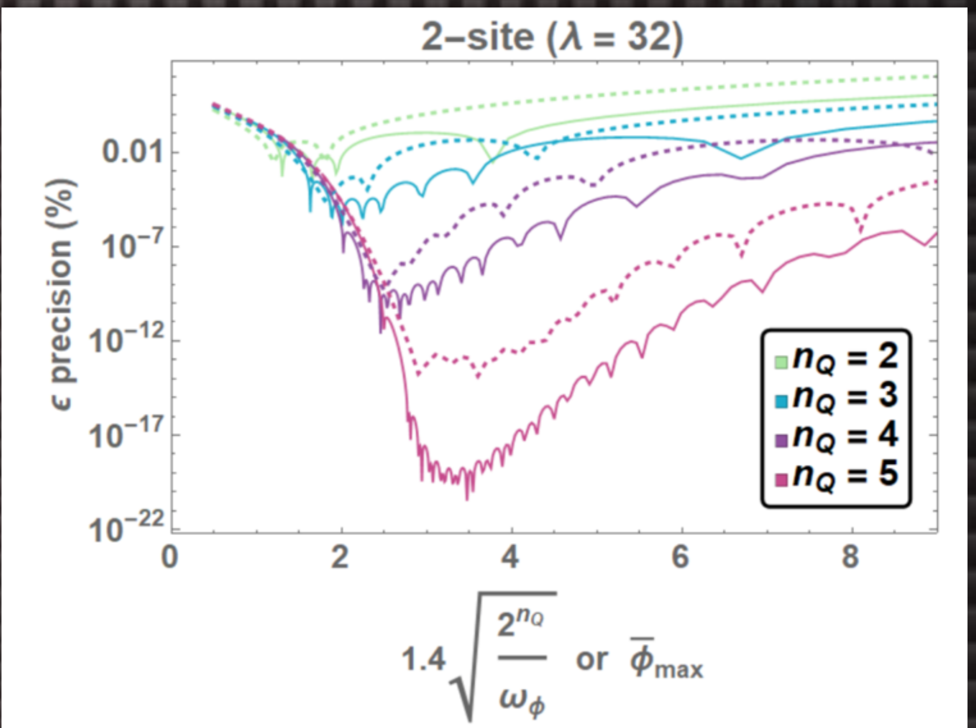
Digitizing Scalar Field Theory

Basis	n_Q	0-body	1-body	2-body	3-body	4-body	5-body	6-body	QFT	CNOTs
JLP	2	1	8	2					✓	8
	3	1	14	6					✓	24
	4	1	20	12					✓	48
	5	1	26	20					✓	80
	6	1	32	30					✓	120
JLP	n_Q	1	$6n_Q - 4$	$2 * \binom{n_Q}{2}$					✓	$8\binom{n_Q}{2}$
$\mathrm{HO}_{\omega\equiv1}$	2	1	2							0
	3	1	3							0
	4	1	4							0
	5	1	5							0
	6	1	6							0
$\mathrm{HO}_{\omega\equiv1}$	n_Q	1	n_Q							0
$\mathrm{HO}_{\omega\neq1}$	2	1	3	1						2
	3	1	4	4	3					20
	4	1	5	5	11	7				96
	5	1	6	6	16	26	15			352
	6	1	7	7	22	42	57	31		1120



$$e^{i\theta\ \sigma^x\otimes\sigma^y\otimes\sigma^x\otimes\sigma^z\otimes\sigma^y} =$$





Digitization of Scalar Fields for NISQ-Era Quantum Computing
Natalie Klco, MJS , e-Print: arXiv:1808.10378 [quant-ph]

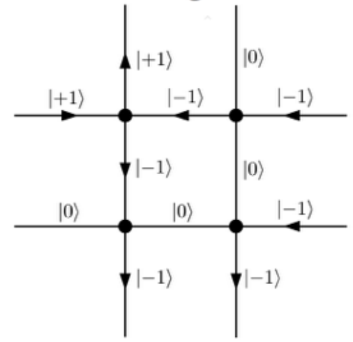
2+1, 3+1 QFT

Recent study: Formulating Abelian U(1) gauge theories *without superfluous degrees of freedom*

- Hilbert space of U(1) states specified by integer $\mathbf{E}$ values
- *Physical* states satisfy **Gauss law constraint**

$$\nabla \cdot \mathbf{E} - \rho = 0$$

→ Expensive qubits <u>wasted</u> simulating enormous unphysical subspace
→ Noise will bump a state into unphysical space



Options?

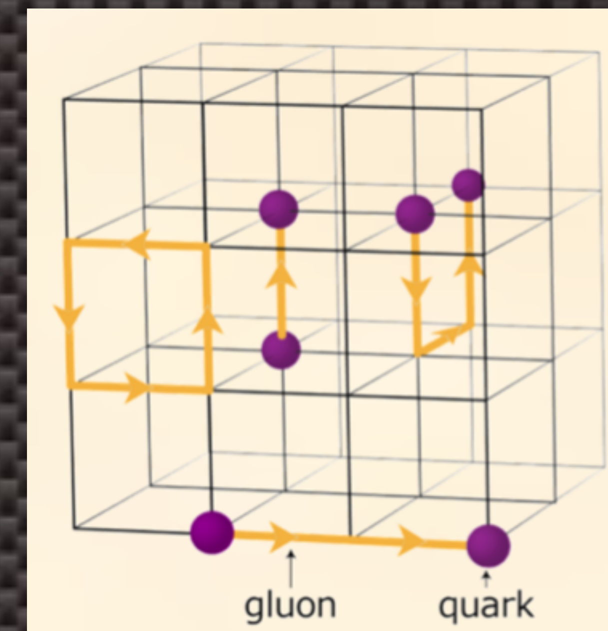
1) Eliminate unphysical/redundant degrees of freedom
   - Limited success
   - Usually sacrifice locality
   - Small systems: OK

D. Kaplan & JRS, '18 (arXiv:1806.08797)

2) Find different variables

3) Live with superfluous degrees of freedom
   - Must **enforce constraints**
   - More practical for large systems

Slide by Jesse Stryker (UW)



Gauss's Law, Duality, and the Hamiltonian Formulation of U(1) Lattice Gauge Theory
David B. Kaplan, Jesse R. Stryker, arXiv:1806.08797 [hep-lat]

SU(2) lattice gauge theory: Local dynamics on nonintersecting electric flux loops
Ramesh Anishetty, Indrakshi Raychowdhury, Phys.Rev. D90 (2014) no.11, 114503 arXiv:1408.6331 [hep-lat]

Digital quantum simulation of lattice gauge theories in three spatial dimensions
Julian Bender, Erez Zohar, Alessandro Farace, J. Ignacio Cirac, New J.Phys. 20 (2018) no.9, 093001, arXiv:1804.02082 [quant-ph]

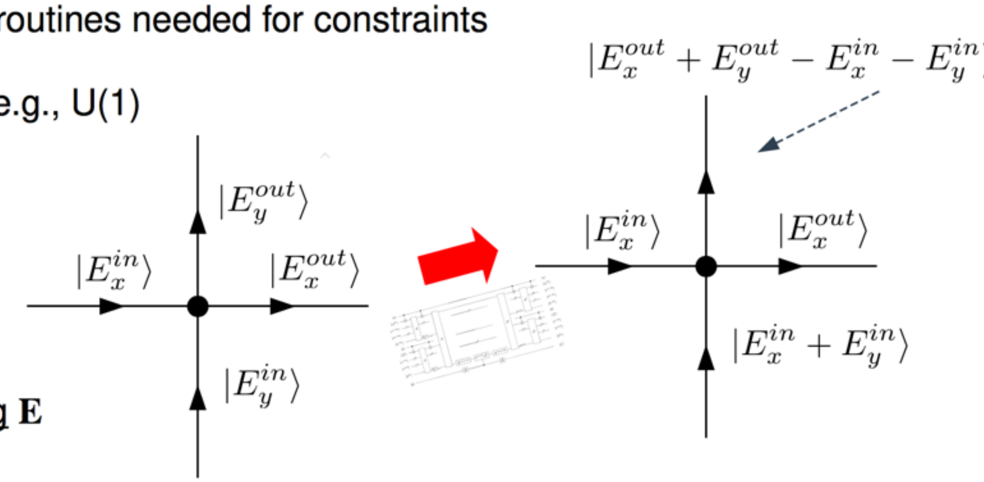
More recent goal: Elucidate algorithms involved in simulating gauge theories
- Focusing on conventional $\mathbf{E}$ description

Work in progress: Characterize routines needed for constraints

Example: Abelian gauge theory, e.g., U(1)

1) How to verify a state is physical?
2) How to prepare interesting physical states?

General state is *superposition* of different configurations
→ Want to enforce constraints <u>without measuring</u> $\mathbf{E}$



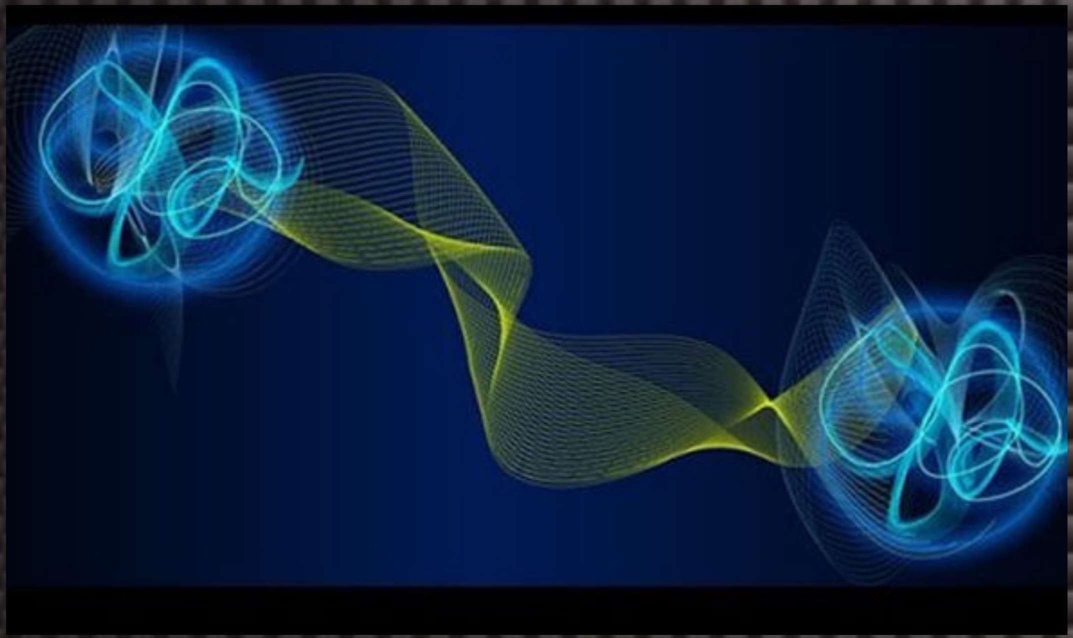
Solution to 1):

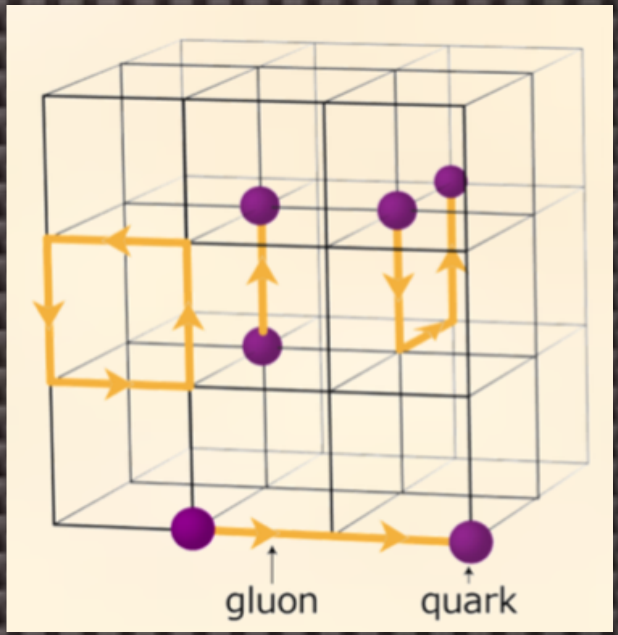
- Evaluate constraint at some site
- Measure *constraint*
  - If 0 → Gauss law good ✔ → Uncompute
  - If not 0 → Reject state ✘
    OR Try to fix it; then uncompute

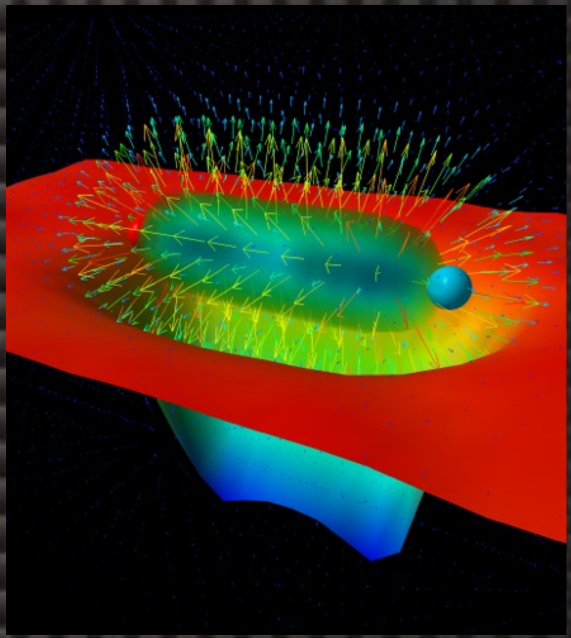
Next?
- Algorithmic applications
- Finalize non-Abelian version
- Analyze resource requirements

Slide by Jesse Stryker (UW)

Summary







Quantum Computing and QIS now entering QCD

- Significant potential for disruption with new understandings and capabilities
  - address exponentially difficult challenges - finite-density and dynamics
  - will not replace LQCD with classical computing
- Lattice QCD likely the appropriate tool - Hamiltonian formulation
  - technology transfer is underway
  - low-dimensional, simple systems being ``stood up”

QFT developments will likely impact QC

- lattices of qubits required for logical qubits and error-correction

FIN