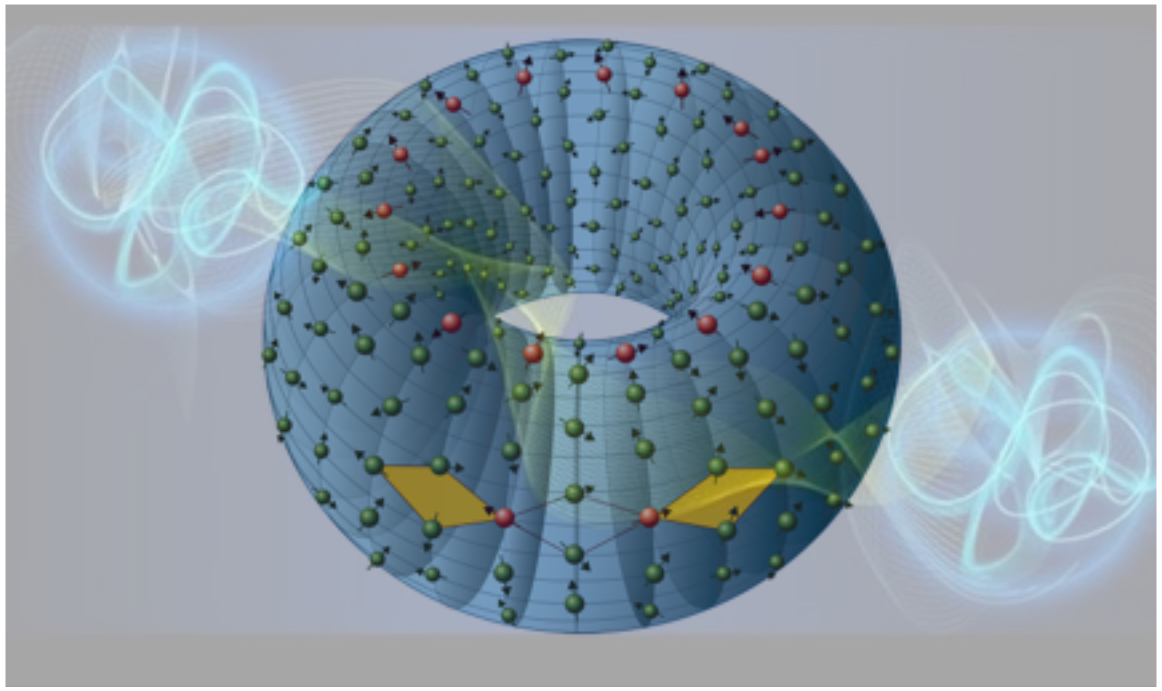
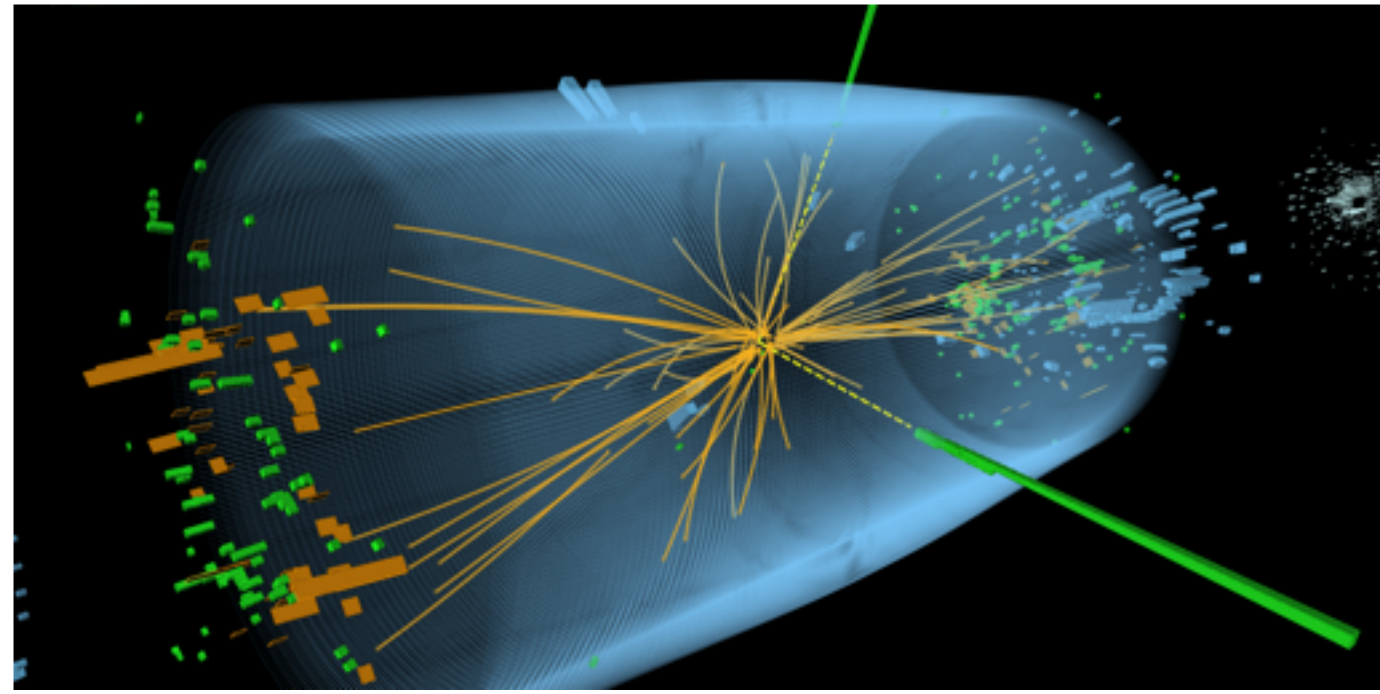




Quantum Simulation for Nuclear Physics

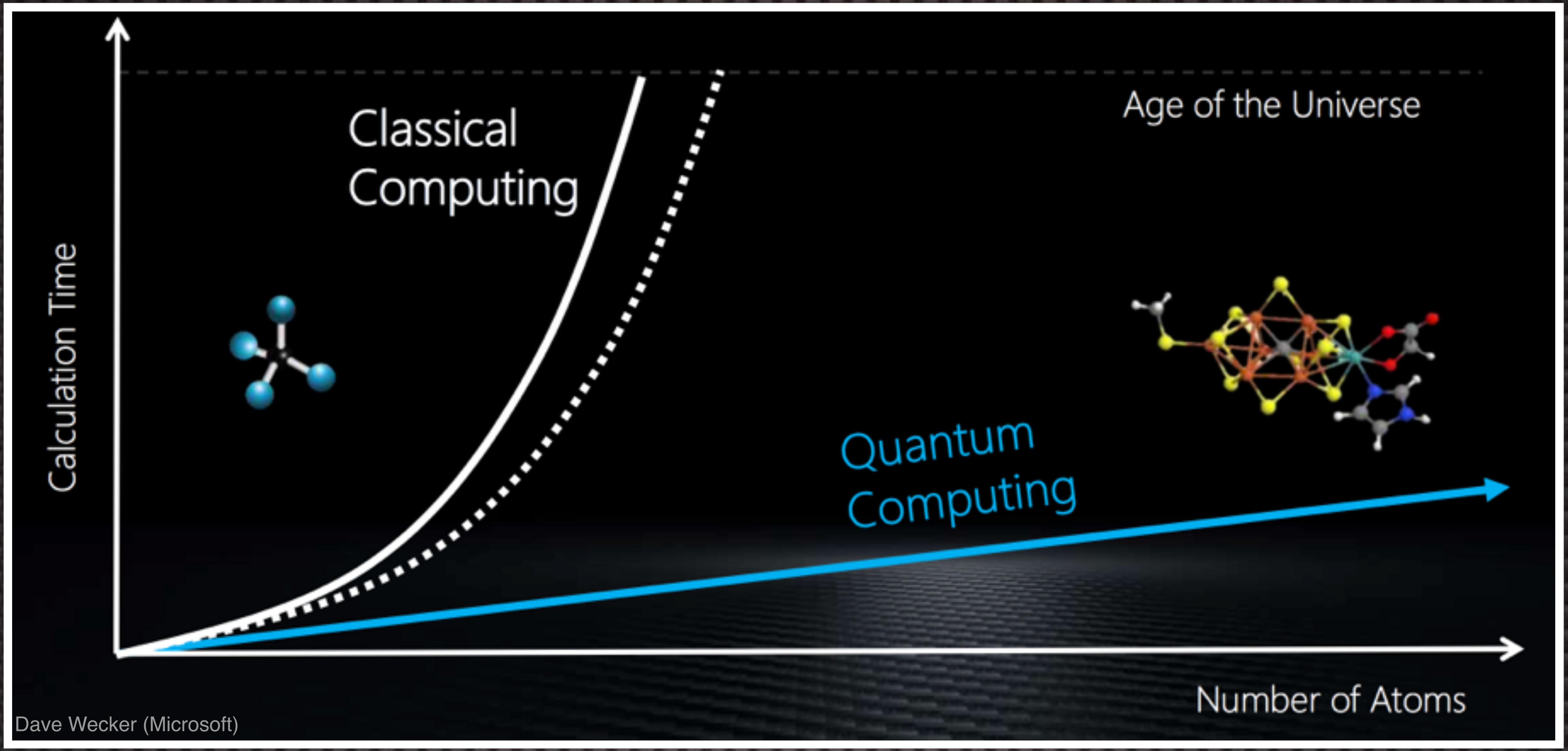
(a US centric viewpoint)

Università Di Pavia, June (2019)

Martin J Savage

INSTITUTE for NUCLEAR THEORY

The Potential of Quantum Computing

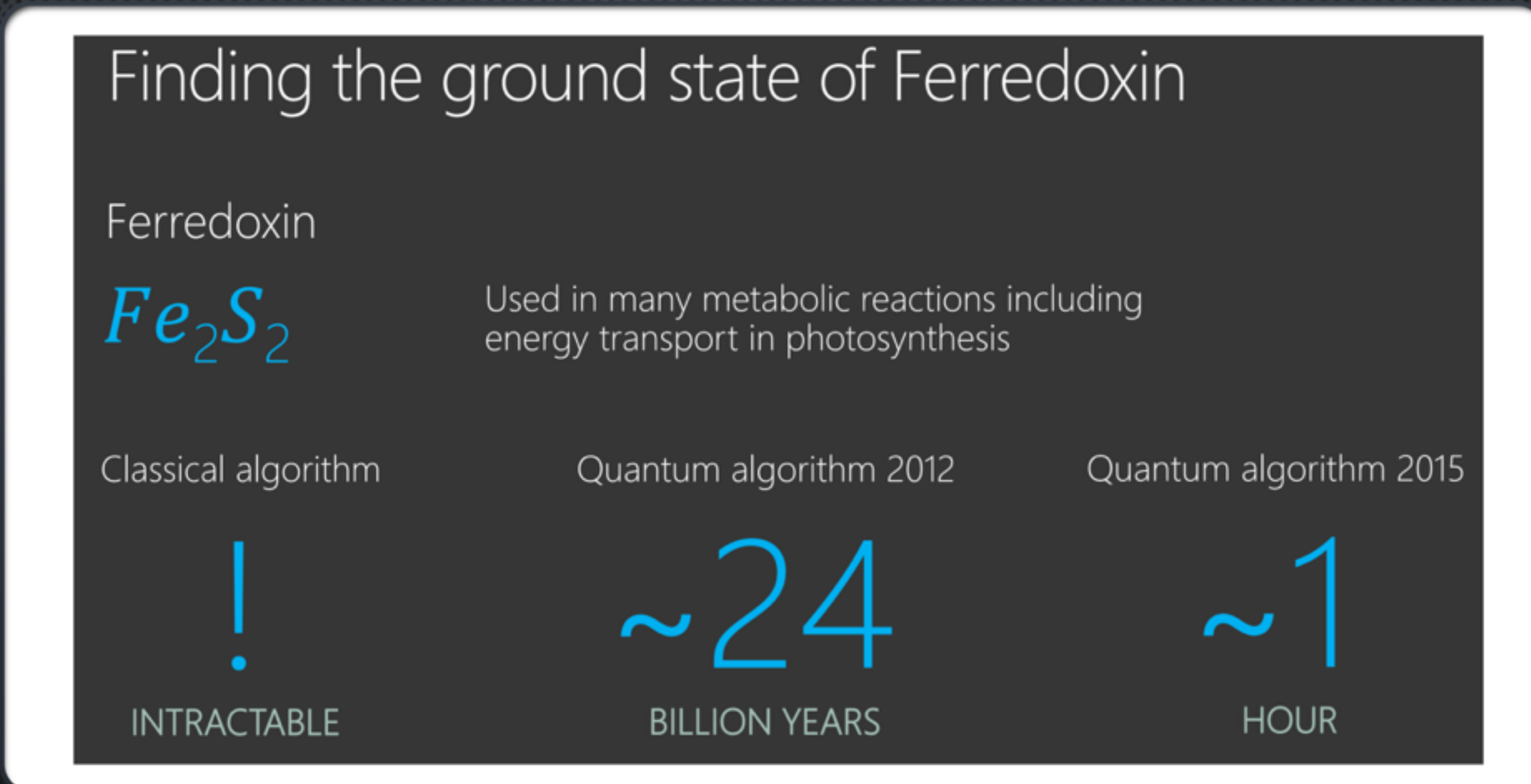


~ 100 qubit devices can address problems in chemistry that are beyond classical computing

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



Slide: Dave Wecker (Microsoft)

[solution to 1 part per million]

with less than 200 ideal qubits

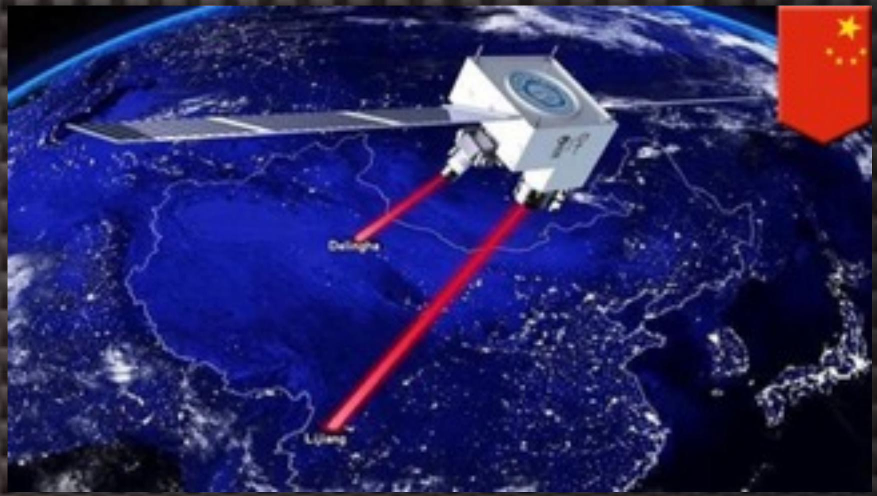
Reinforces the importance of algorithms and thinking hard about a given problem

Space-Based Quantum Keys

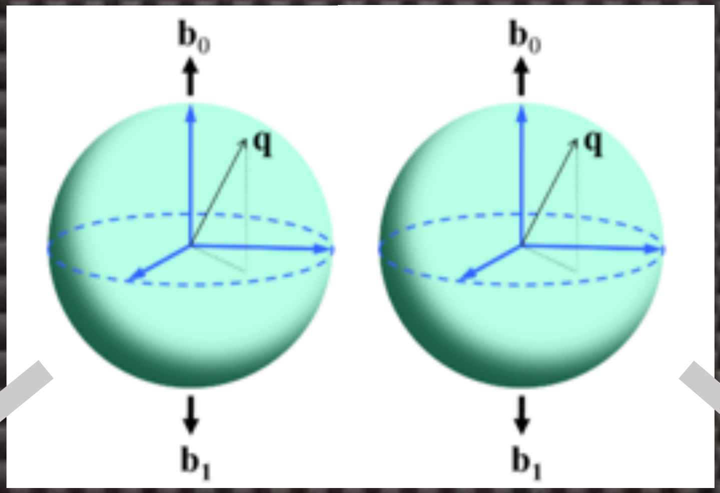
e.g., Quantum Teleportation

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

Entangled qubit pair created in Satellite

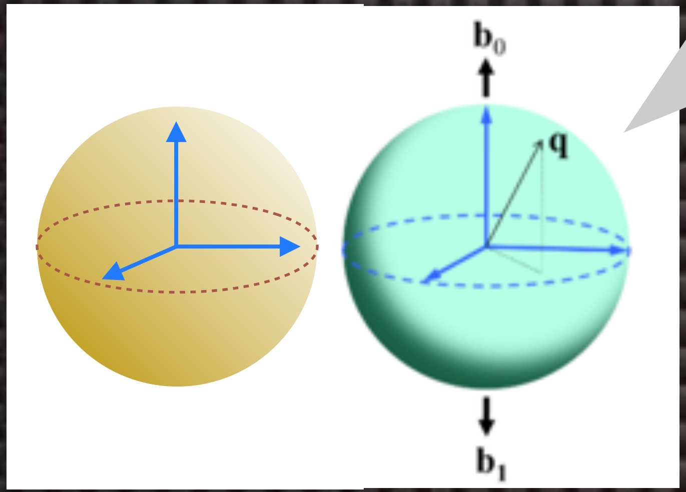


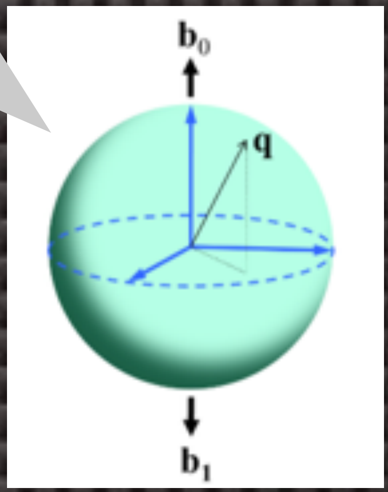
9/17 : Quantum secure video call between China and Austria



Satellite

Ground Station



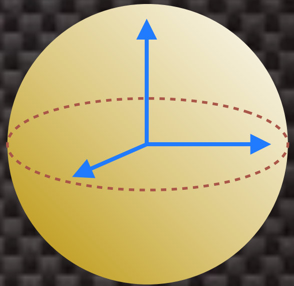


Satellite

- 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

National Quantum Initiative

https://www.congress.gov/bill/115th-congress/house-bill/6227/text

One Hundred Fifteenth Congress
of the
United States of America

AT THE SECOND SESSION

Begun and held at the City of Washington on Wednesday, the third day of January, two thousand and eighteen

An Act

To provide for a coordinated Federal program to accelerate quantum research and development for the economic and national security of the United States.

Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled,

SECTION 1. SHORT TITLE; TABLE OF CONTENTS.

(a) Short Title.—This Act may be cited as the "National Quantum Initiative Act".

(b) Table Of Contents.—The table of contents of this Act is as follows:

EXECUTIVE OFFICE OF THE PRESIDENT OF THE UNITED STATES
NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

NATIONAL STRATEGIC OVERVIEW FOR QUANTUM INFORMATION SCIENCE

Product of the
SUBCOMMITTEE ON QUANTUM INFORMATION SCIENCE
under the
COMMITTEE ON SCIENCE
of the
NATIONAL SCIENCE & TECHNOLOGY COUNCIL

SEPTEMBER 2018

TITLE I—NATIONAL QUANTUM INITIATIVE

SEC. 101. NATIONAL QUANTUM INITIATIVE PROGRAM.

(a) In General.—The President shall implement a National Quantum Initiative Program.

(b) Requirements.—In carrying out the Program, the President, acting through Federal agencies, councils, working groups, subcommittees, and the Coordination Office, as the President considers appropriate, shall—

(1) establish the goals, priorities, and metrics for a 10-year plan to accelerate development of quantum information science and technology applications in the United States;

(2) invest in fundamental Federal quantum information science and technology research, development, demonstration, and other activities to achieve the goals established under paragraph (1);

(3) invest in activities to develop a quantum information science and technology workforce pipeline;

(4) provide for interagency planning and coordination of Federal quantum information science and technology research, development, demonstration, standards engagement, and other activities under the Program;

(5) partner with industry and universities to leverage knowledge and resources; and

(6) leverage existing Federal investments efficiently to advance Program goals and priorities established under paragraph (1).

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?

"First Qubits" for Applications

- National Laboratories, Tech Companies and Universities are working together to develop hardware
- Some Technology companies are making quantum devices available for computations via the cloud
- Laboratories and companies are making hardware available through collaboration

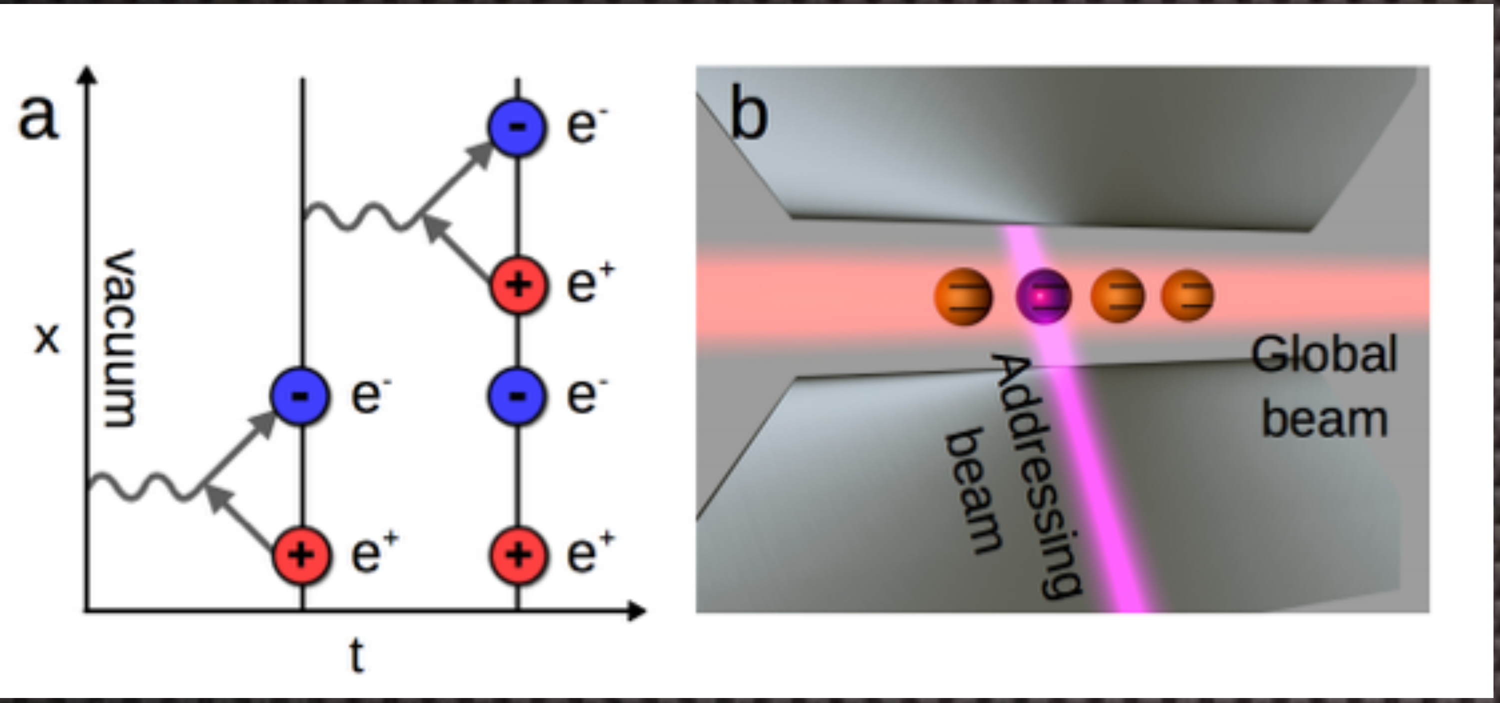
t = 0: A First Quantum Computation in Quantum Field Theory: 1+1-Dim QED

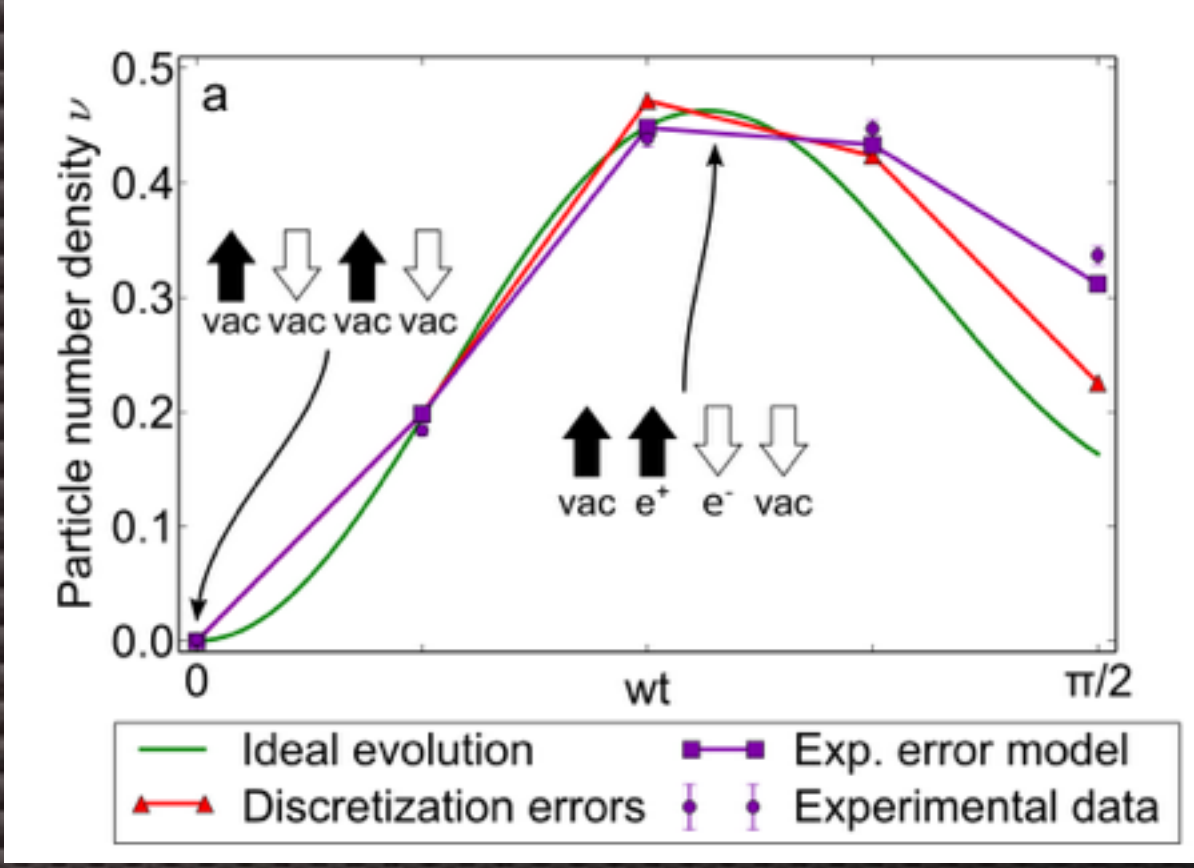
2016

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)



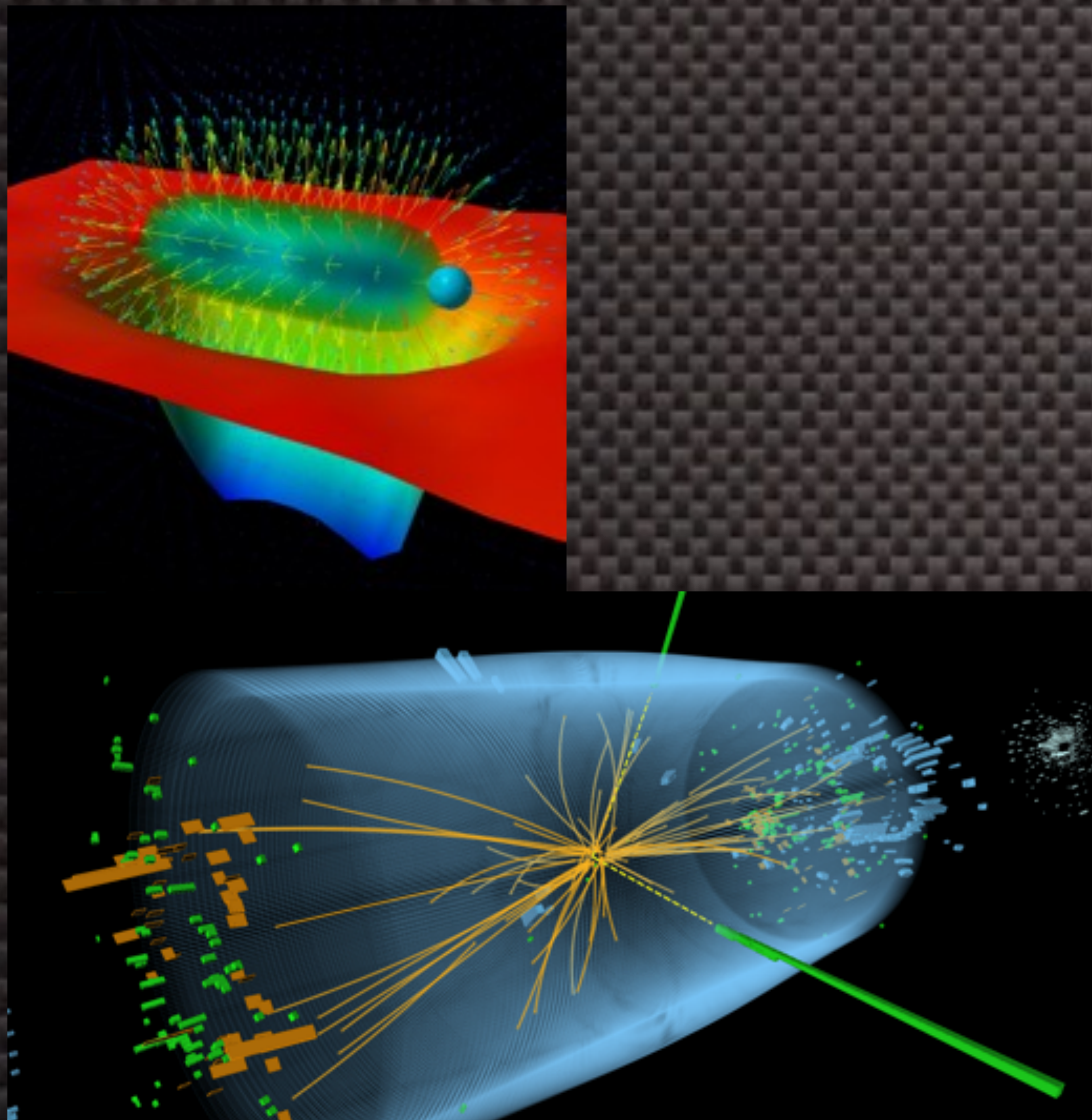


Based upon a string of $^{40}Ca^{+}$ trapped-ion quantum system

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

The Standard Model



Quantum Field Theories and Fundamental Symmetries

- indefinite particle number
- gauge symmetries and constraints
- entangled ground states

Real-Time Dynamics

- Parton showers
- Fragmentation
- Neutrino Interactions with nuclei
- Neutrinos in matter
- Early Universe
- Phase Transition - creating Baryons
- non-equilibrium

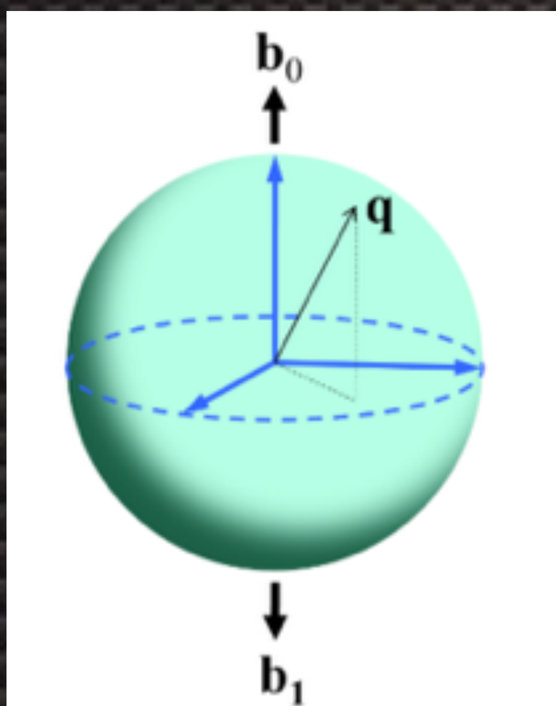
Classical Computing

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

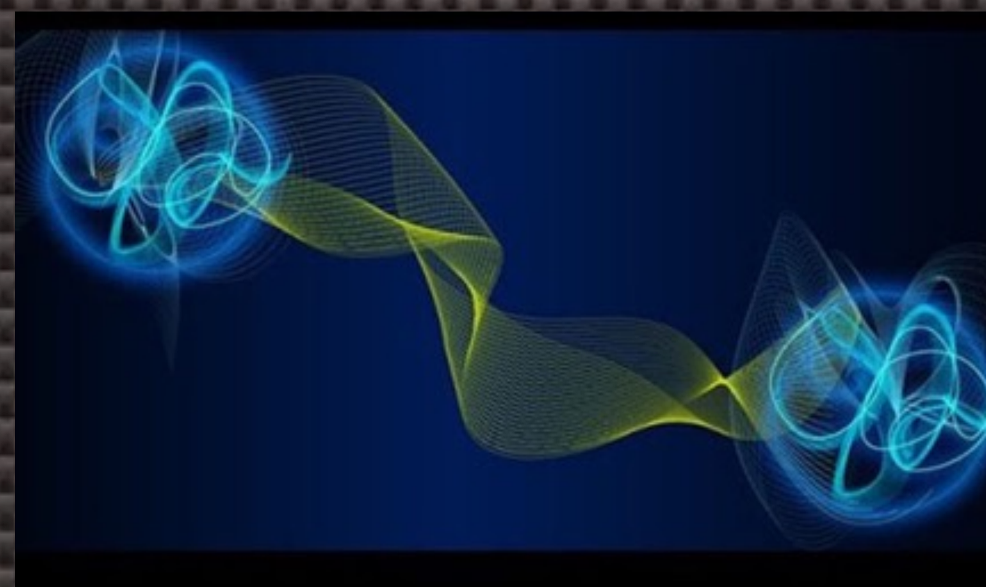
Quantum Computing

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

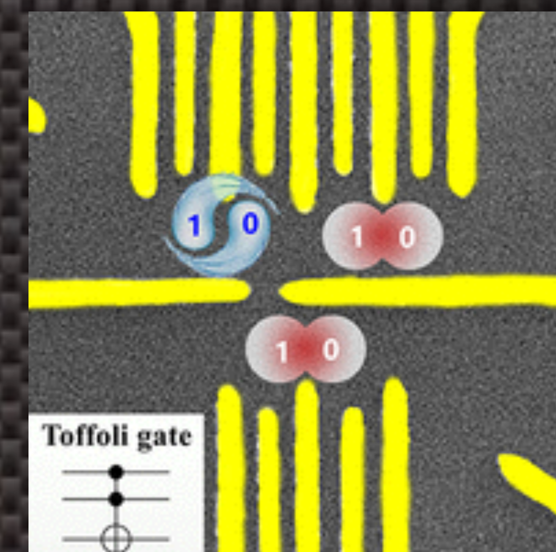
The Basic Elements of Quantum Computing



Qubits



Entanglement
and Superposition



Unitary Operations
and Measurements

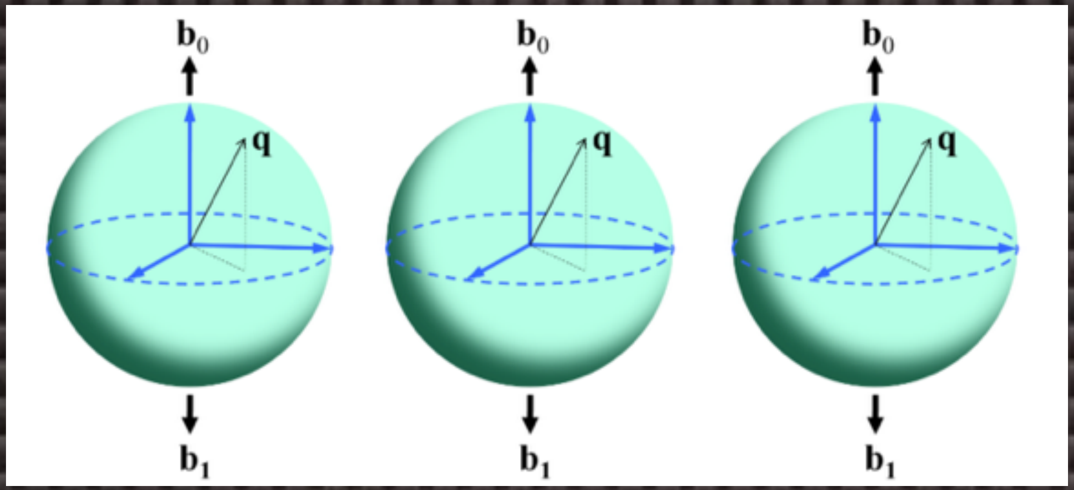
At the Heart of Quantum Computing
Parallel Processing, Nonlocality and Entanglement

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

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

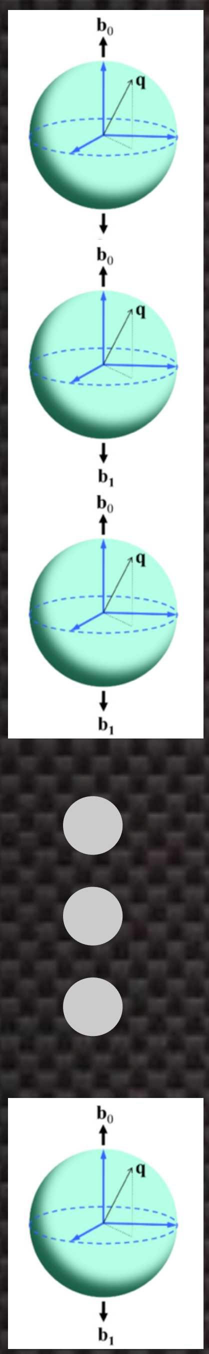
Quantum computer can be in a combination of all states at once

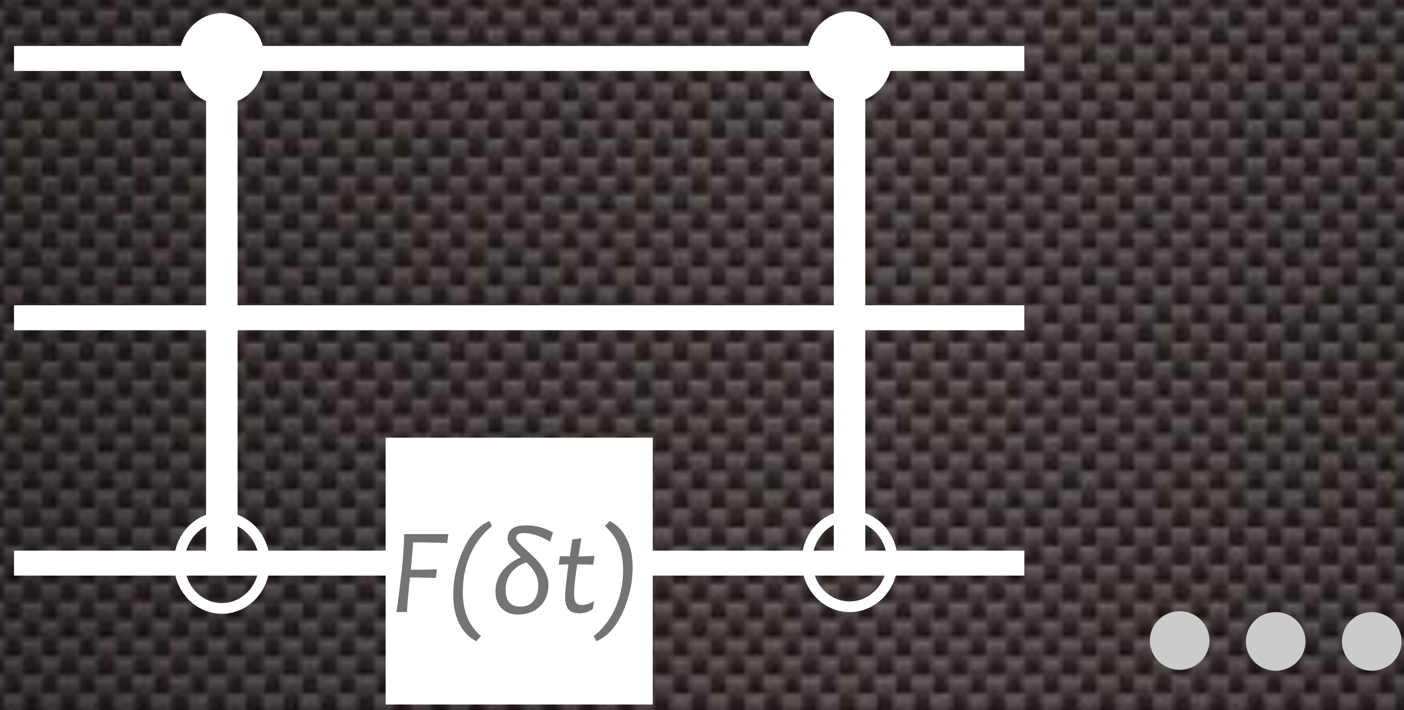
$$|\psi\rangle \;=\; \alpha_1\,|000\rangle + \alpha_2\,|001\rangle + \alpha_3\,|010\rangle + \alpha_4\,|100\rangle + \alpha_5\,|011\rangle + \alpha_6\,|101\rangle + \alpha_7\,|110\rangle + \alpha_8\,|111\rangle$$



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

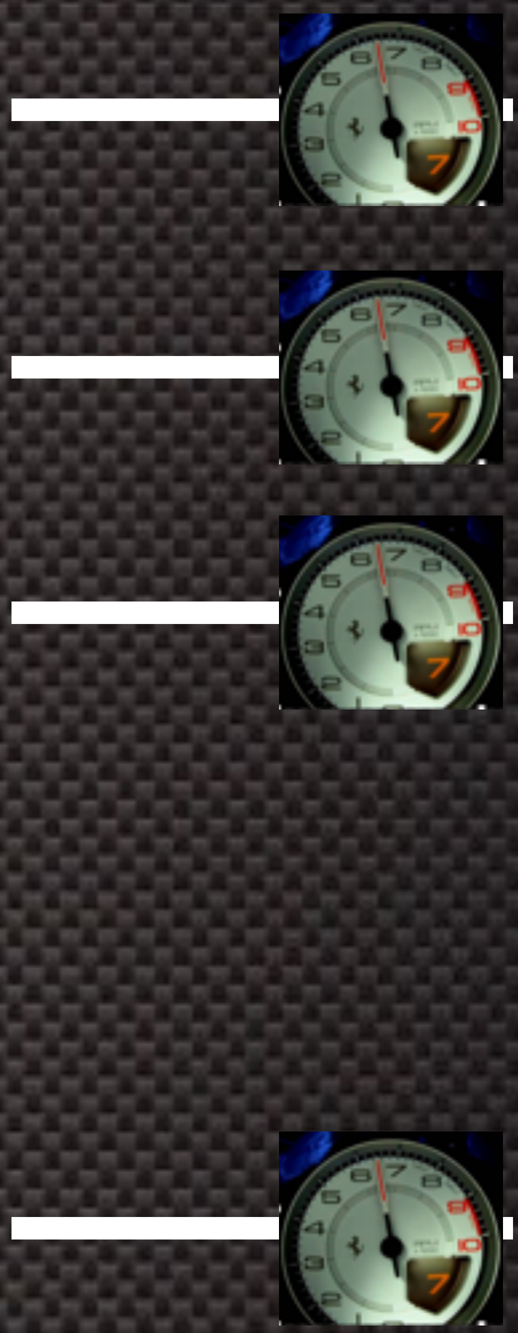
Evolution





$$U(\delta t) = e^{-i H \delta t}$$

$$= e^{-i T \delta t}\, e^{-i V \delta t}\, e^{-i R \delta t^2} \cdots$$



Prepare

Evolve

Measure

Simulation in the Noisy Intermediate-Scale Quantum (NISQ) Era > 5-10 Years

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.

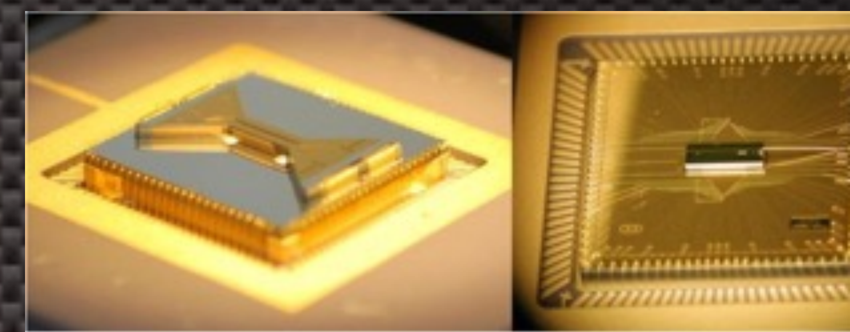
Quantum Computing: Qubits

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 super-position 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 semi-conductor 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.



Sandia

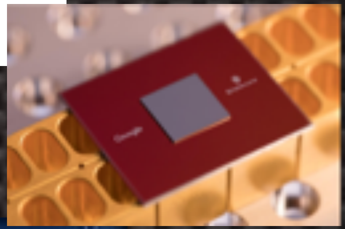
Universities, National Laboratories, Technology Companies, and other government agencies developing such devices and other types

e.g., nuclei implanted in Si, coupled to quantum dots

Science, December 2016, based on David Dean slide

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

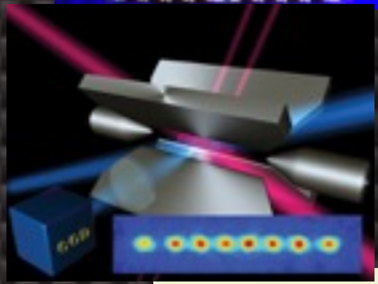
D-wave : ~ 2000 superconducting qubits, quantum annealing



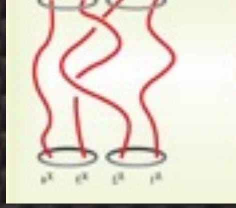
Google : 72 , …. superconducting qubits

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

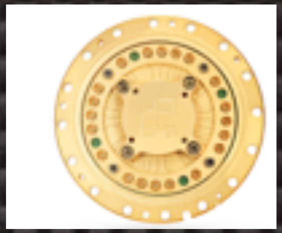
Intel : 49 superconducting qubits, progress in silicon



IonQ : trapped ions, 53-qubit system



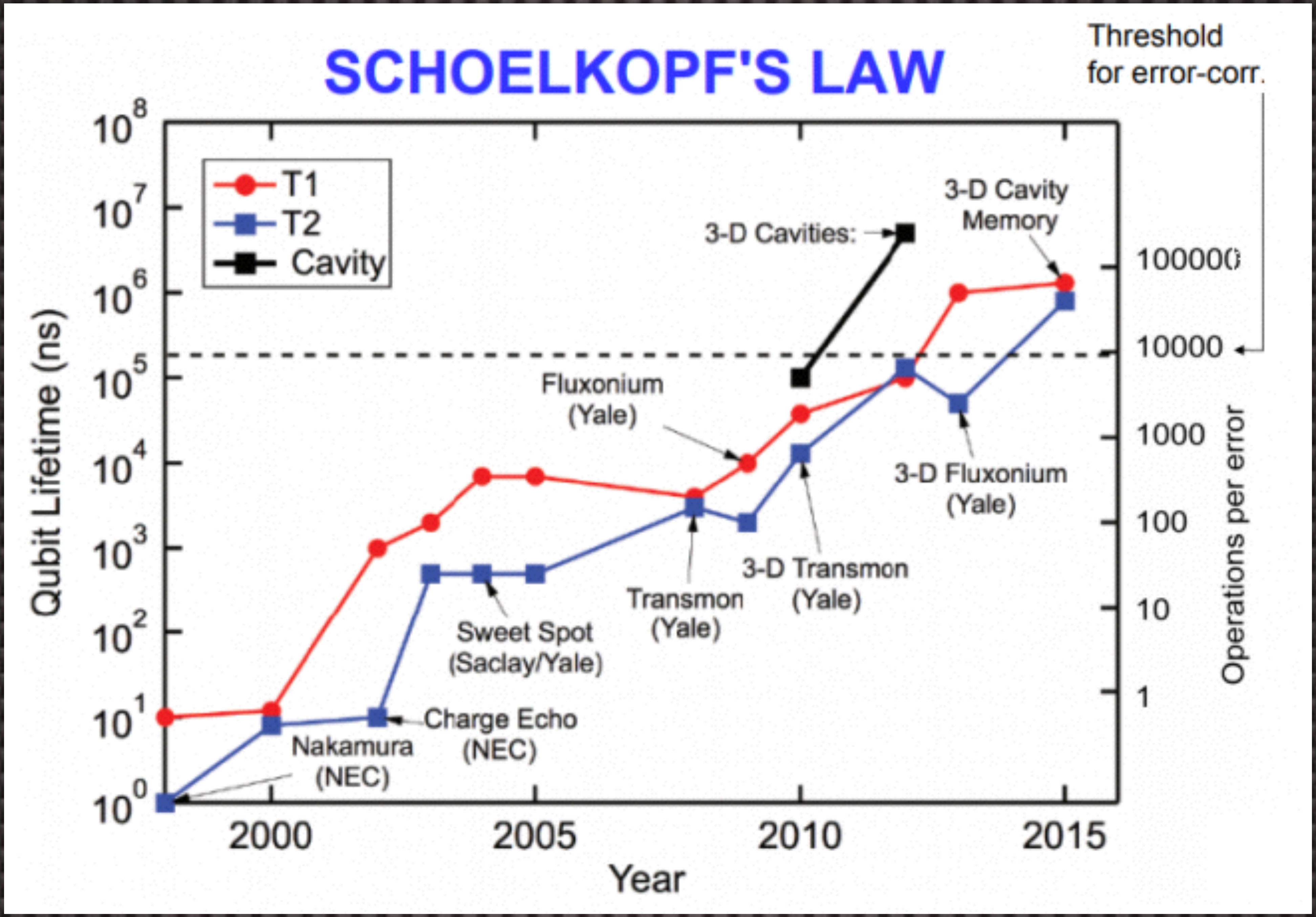
Microsoft : Majorana (topological) - in development



Rigetti : 8, 19 superconducting qubits with 128 coming

Example of Hardware Improvement

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

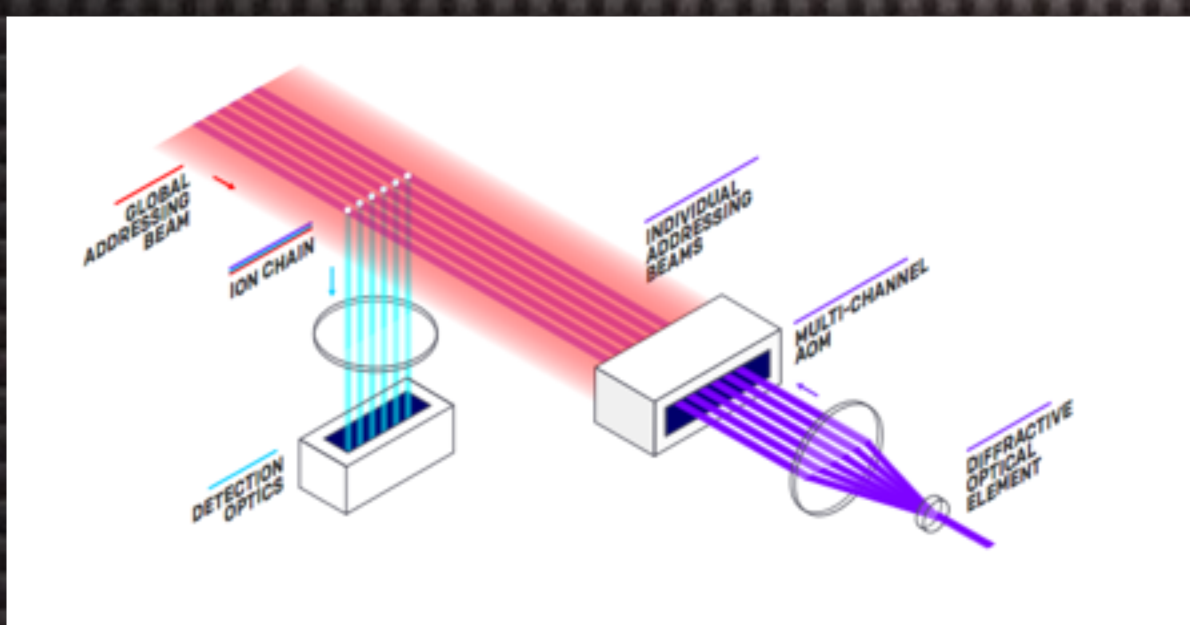


Example of Hardware Improvement

Benchmarking an 11-qubit quantum computer

K. Wright,[1,*] K. M. Beck,[1] S. Debnath,[1] J. M. Amini,[1] Y. Nam,[1] N. Grzesiak,[1] J.-S. Chen,[1] N. C. Pisenti,[1] M. Chmielewski,[1,2] C. Collins,[1] K. M. Hudek,[1] J. Mizrahi,[1] J. D. Wong-Campos,[1] S. Allen,[1] J. Apisdorf,[1] P. Solomon,[1] M. Williams,[1] A. M. Ducore,[1] A. Blinov,[1] S. M. Kreikemeier,[1] V. Chaplin,[1] M. Keesan,[1] C. Monroe,[1,2] and J. Kim[1,3]

[1]*IonQ, Inc., College Park, MD 20740, USA*
[2]*Joint Quantum Institute and Department of Physics, University of Maryland, College Park, MD 20742, USA*
[3]*Department of Electrical and Computer Engineering, Duke University, Durham, NC 27708, USA*



1	2	3	4	5	6	7	8	9	10	Ion 0 / Ion 1
$98.5^{+0.1}_{-0.3}$	$97.7^{+0.4}_{-0.5}$	$98.5^{+0.1}_{-0.3}$	$97.2^{+0.4}_{-0.5}$	$98.5^{+0.1}_{-0.3}$	$96.9^{+0.5}_{-0.5}$	$97.2^{+0.3}_{-0.5}$	$98.7^{+0.4}_{-0.5}$	$95.5^{+0.4}_{-0.6}$	$97.1^{+0.1}_{-0.3}$	0
	$97.7^{+0.4}_{-0.6}$	$98.9^{+0.1}_{-0.3}$	$98.2^{+0.1}_{-0.3}$	$97.4^{+0.1}_{-0.3}$	$97.8^{+0.1}_{-0.3}$	$98.1^{+0.1}_{-0.3}$	$98.4^{+0.1}_{-0.3}$	$97.7^{+0.3}_{-0.5}$	$97.9^{+0.1}_{-0.3}$	1
		$98.0^{+0.2}_{-0.3}$	$97.5^{+0.3}_{-0.4}$	$96.5^{+0.5}_{-0.6}$	$98.4^{+0.1}_{-0.3}$	$98.0^{+0.1}_{-0.3}$	$97.2^{+0.3}_{-0.5}$	$97.3^{+0.1}_{-0.3}$	$96.0^{+0.6}_{-0.6}$	2
			$96.4^{+0.4}_{-0.5}$	$97.4^{+0.1}_{-0.3}$	$97.1^{+0.4}_{-0.5}$	$98.9^{+0.1}_{-0.3}$	$96.0^{+0.3}_{-0.5}$	$98.0^{+0.1}_{-0.3}$	$97.7^{+0.1}_{-0.3}$	3
				$98.6^{+0.3}_{-0.6}$	$97.3^{+0.4}_{-0.4}$	$97.3^{+0.5}_{-0.5}$	$98.3^{+0.4}_{-0.5}$	$97.8^{+0.1}_{-0.3}$	$96.5^{+0.5}_{-0.6}$	4
					$96.5^{+0.4}_{-0.6}$	$97.1^{+0.3}_{-0.5}$	$98.4^{+0.3}_{-0.4}$	$95.1^{+0.5}_{-0.7}$	$96.7^{+0.5}_{-0.6}$	5
						$96.2^{+0.4}_{-0.6}$	$97.2^{+0.3}_{-0.6}$	$98.1^{+0.4}_{-0.5}$	$98.2^{+0.4}_{-0.5}$	6
							$97.3^{+0.4}_{-0.6}$	$98.5^{+0.3}_{-0.3}$	$97.3^{+0.4}_{-0.6}$	7
								$96.7^{+0.4}_{-0.5}$	$97.0^{+0.3}_{-0.6}$	8
									$97.5^{+0.4}_{-0.5}$	9

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

Simulating lattice gauge theories on a quantum computer
Tim Byrnes* Yoshihisa Yamamoto

2005

Quantum Computation of Scattering in Scalar Quantum Field Theories
Stephen P. Jordan,[†§] Keith S. M. Lee,[†§] and John Preskill [§ *]

2012

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]

2013

2014

Towards Quantum Simulating QCD
Uwe-Jens Wiese

Quantum Simulations of Lattice Gauge Theories using Ultracold Atoms in Optical Lattices
Erez Zohar J. Ignacio Cirac Benni Reznik

2015

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]

Quantum Sensors for the Generating Functional of Interacting Quantum Field Theories
A. Bermudez,[1,2,*] G. Aarts,[1] and M. Müller[1]

2017

Slide by Natalie Klco (Oct 2018)

``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

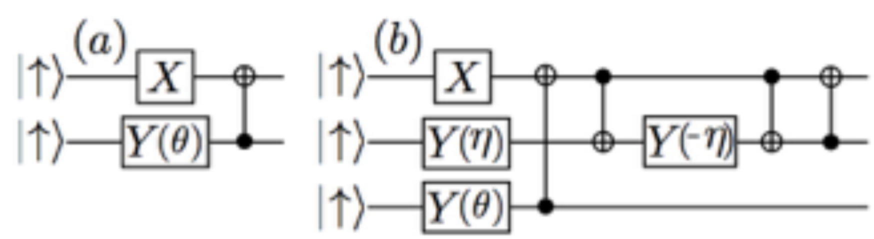
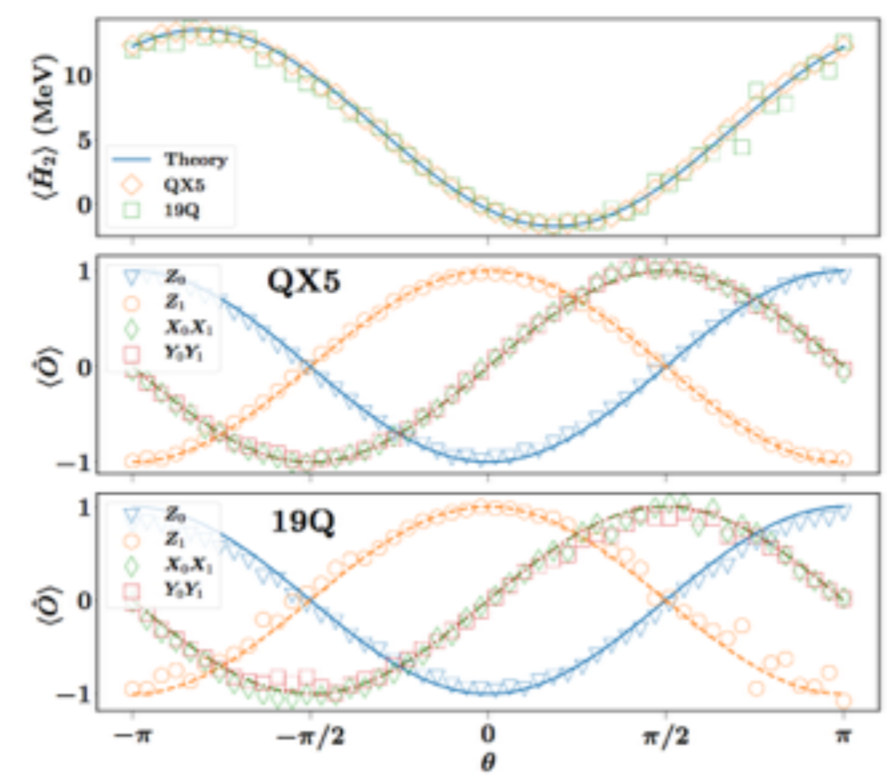


FIG. 1. Low-depth circuits that generate unitary rotations in Eq. (7) (panel a) and Eq. (8) (panel b). Also shown are the single-qubit gates of the Pauli X matrix, the rotation $Y(\theta)$ with angle θ around the Y axis, and the two-qubit CNOT gates.

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,

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

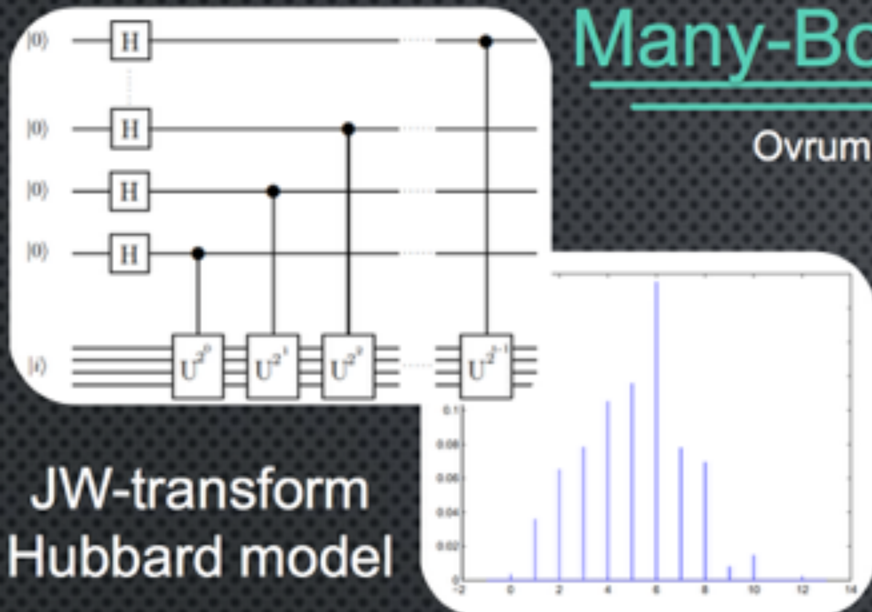


Cloud Quantum Computing of an Atomic Nucleus
E.F. Dumitrescu, A.J. McCaskey, G. Hagen, G.R. Jansen, T.D. Morris, T. Papenbrock, R.C. Pooser, D.J. Dean, P. Lougovski. Jan 11, 2018. 6 pp.
Published in **Phys.Rev.Lett. 120 (2018) no.21, 210501**

First Demonstrations in Nuclear Many-Body Systems

Many-Body Studies

Ovrum, Hjorth-Jensen (2007)

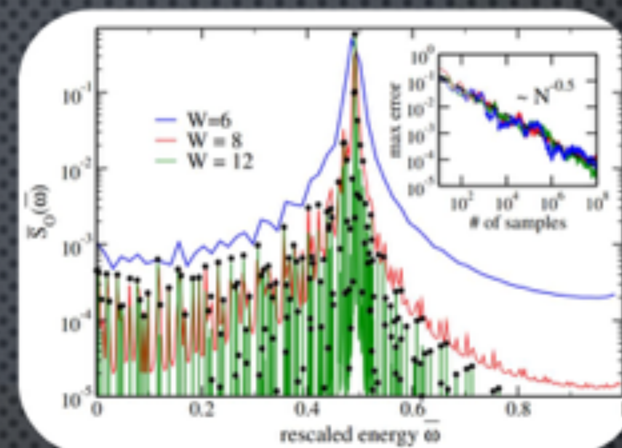


Energy measurement probability $\alpha\ |\langle\psi_f|\psi_i\rangle|^2$

JW-transform Hubbard model

Linear Response Functions

Carlson, Roggero (2018)



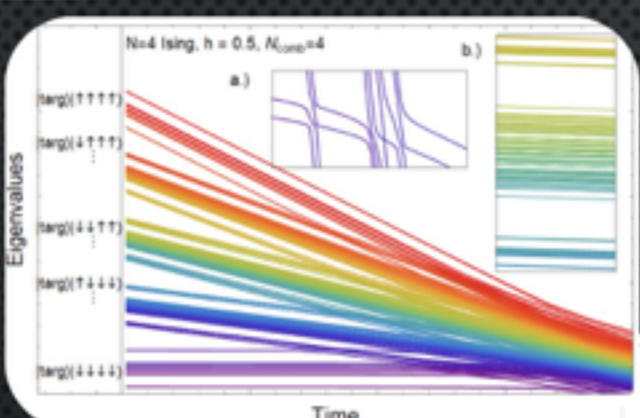
$$\sum_\nu |\langle\psi_\nu|\,\hat{O}\,|\psi_0\rangle|^2\,\delta(E_\nu - E_0 - \omega)$$

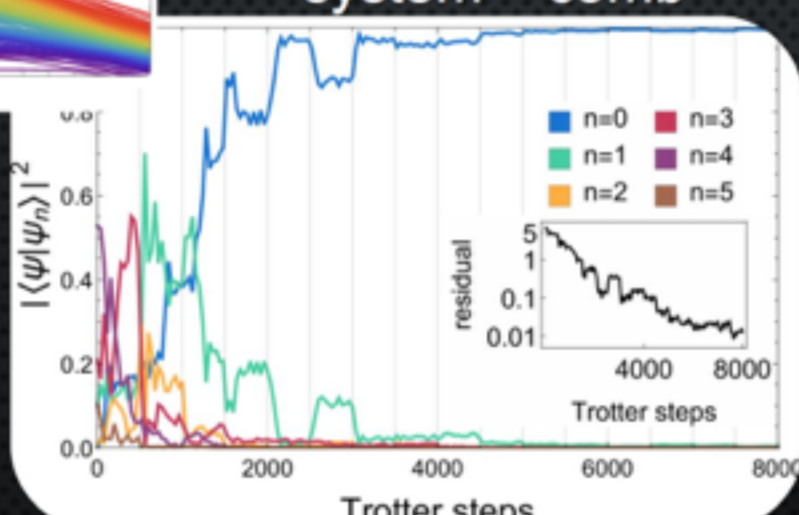
dynamic linear response and exclusive information

Spectral Combing

Kaplan, Klco, Roggero (2017)

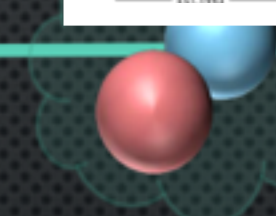
Time-dependent auxiliary system = comb





Exponential level crossings send target system to ground state

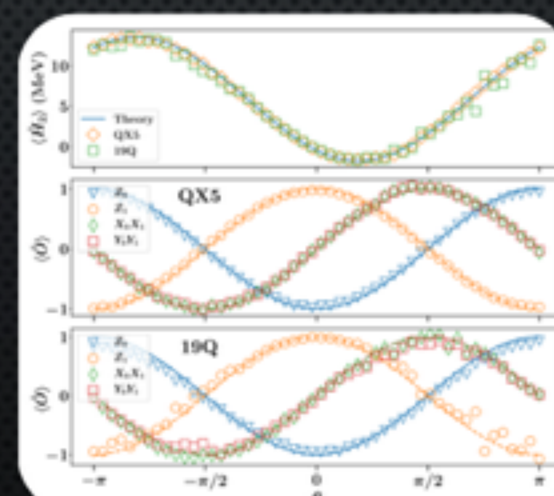
The Deuteron



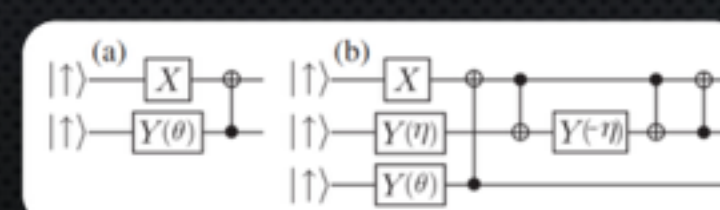
Cloud Quantum Computing of an Atomic Nucleus

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 2018



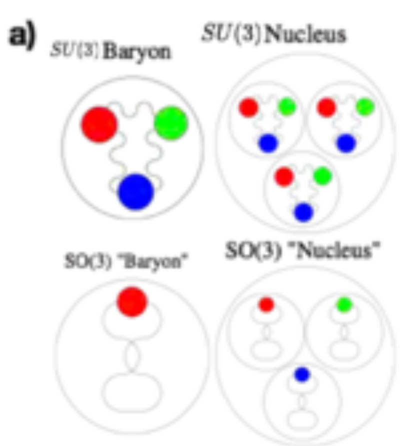
Variational Quantum Eigensolver



Slide by Natalie Klco (Oct 2018)

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

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

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

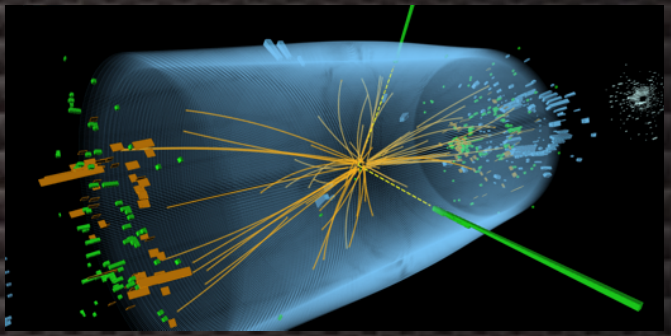
arXiv:1802.00022v1 [cond-mat.quant-gas] 31 Jan 2018

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

Entanglement and Fragmentation and QFT

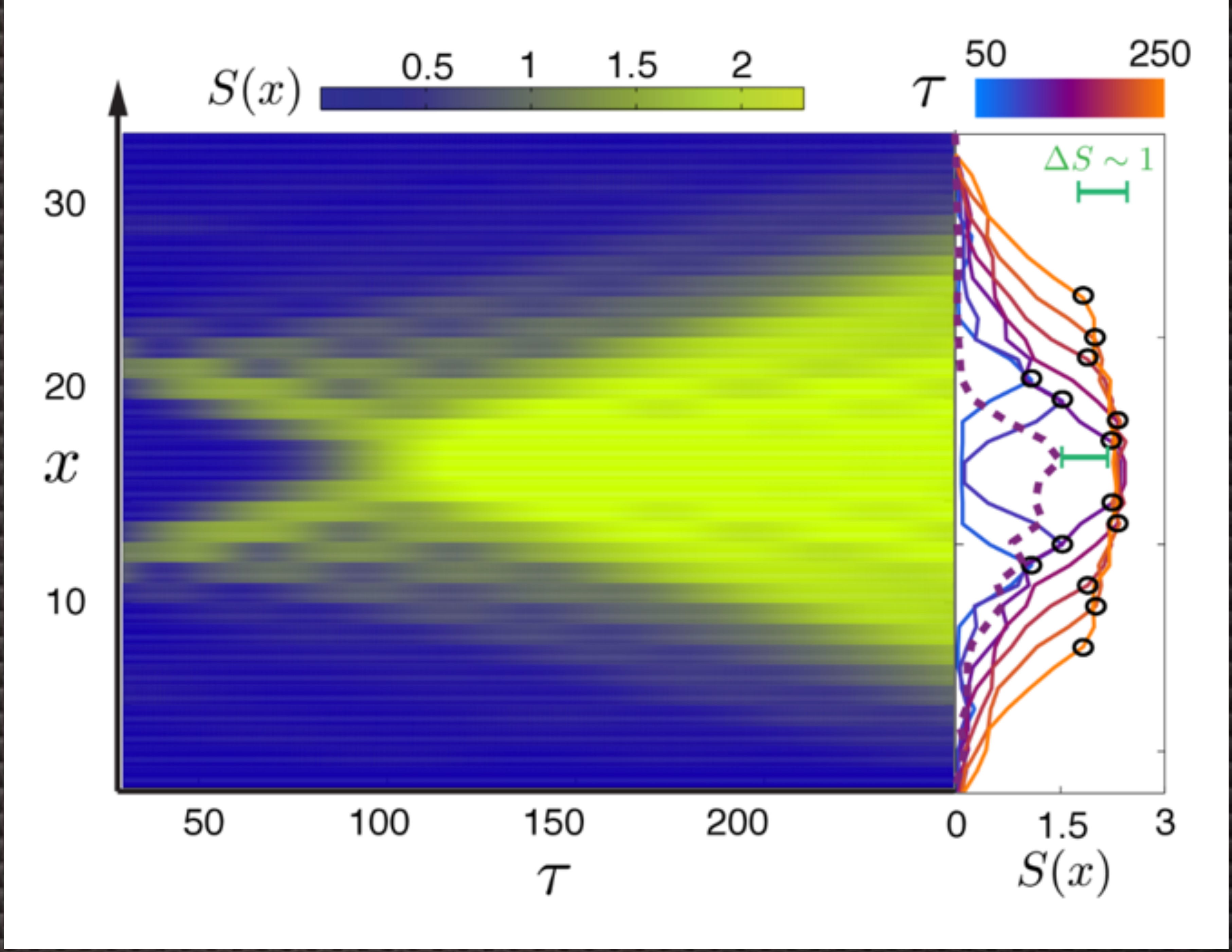


Real-time Dynamics in U(1) Lattice Gauge Theories with Tensor Networks
T. Pichler (Ulm U.), M. Dalmonte (Innsbruck U., Quant. Opt. and Info. & Innsbruck U.), E. Rico (Basque U., Bilbao & IPCMS, Strasbourg & IKERBASQUE, Bilbao), P. Zoller (Innsbruck U. & Innsbruck U., Quant. Opt. and Info.), S. Montangero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

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]**



Entanglement and Fragmentation and QFT

A quantum algorithm for high energy physics simulations

Christian W. Bauer,[*] Benjamin Nachman,[†] and Davide Provasoli[‡]
Physics Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

Wibe A. de Jong[§]
Computational Research Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
(Dated: April 9, 2019)

arXiv:1904.03196v1 [hep-ph] 5 Apr 2019

$$\mathcal{L} = \bar{f}_1(i\partial\!\!\!/ + m_1)f_1 + \bar{f}_2(i\partial\!\!\!/ + m_2)f_2 + (\partial_\mu\phi)^2 + g_1\bar{f}_1 f_1\phi + g_2\bar{f}_2 f_2\phi + g_{12}\left[\bar{f}_1 f_2 + \bar{f}_2 f_1\right]\phi\,.$$

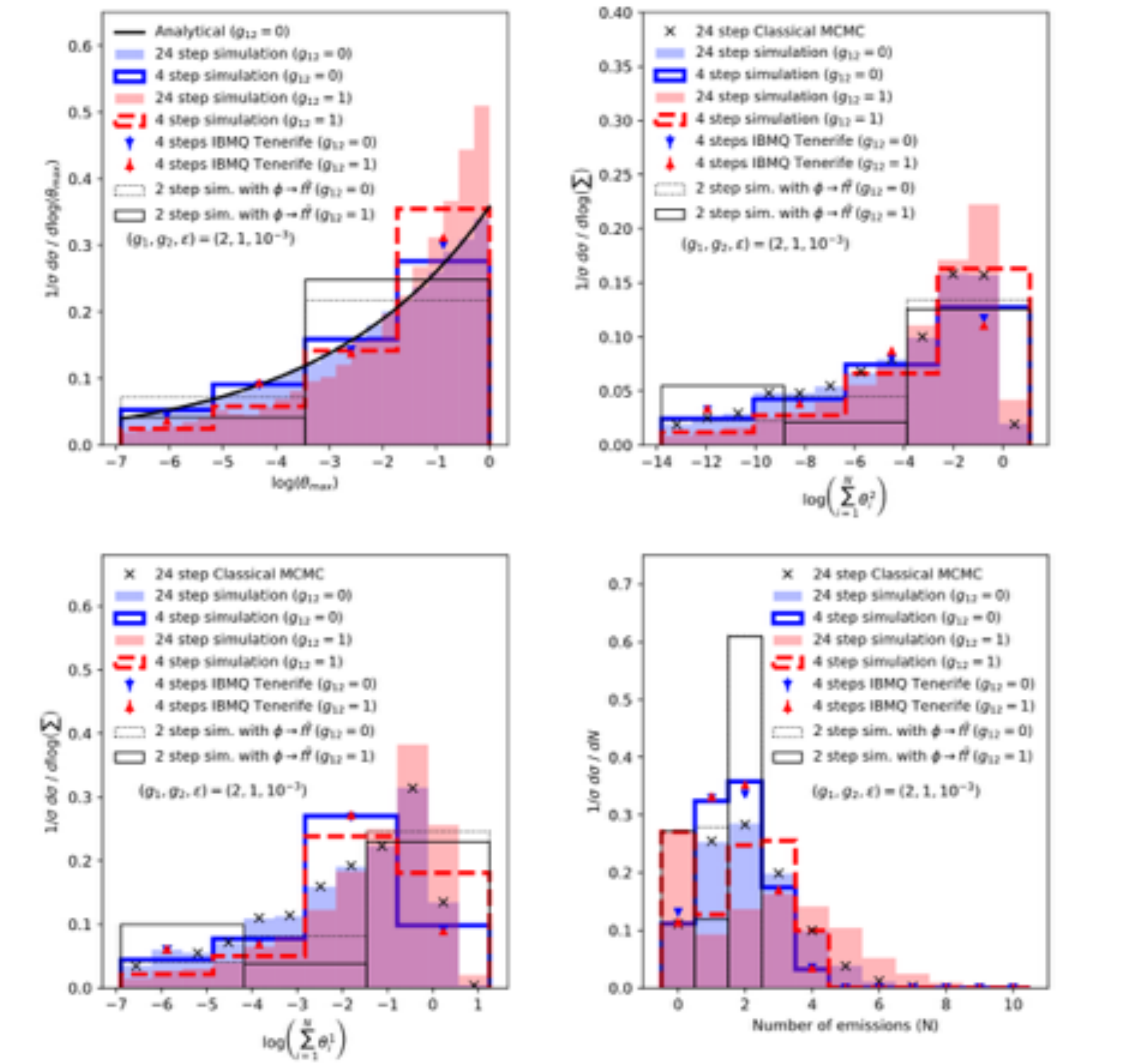


FIG. 2: The normalized differential cross section of the observables $\sum_i \theta_i^\alpha$ for $\alpha = 0$ (bottom right), $\alpha = 1$ (bottom left), $\alpha = 2$ (top right), and $\alpha = \infty$ (top left). The $\alpha = \infty$ case is simply represented as the angle of the first emission. Interference effects are turned on ($g_{12} = 0$) and off ($g_{12} = 0$), where the classical simulations/calculations are expected to agree with the quantum simulations and measurements. As a demonstration of the full circuit with $\phi \to f\bar{f}$ is also included with two simulated steps both with $g_{12} = 0$ and $g_{12} = 1$. Over 10^5 events contribute to each line.

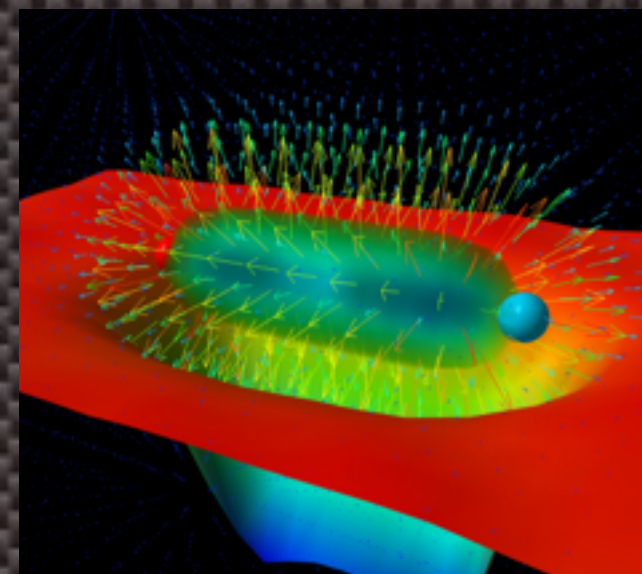
Starting Simple: 1+1 Dim QED
The Schwinger Model

ASCR

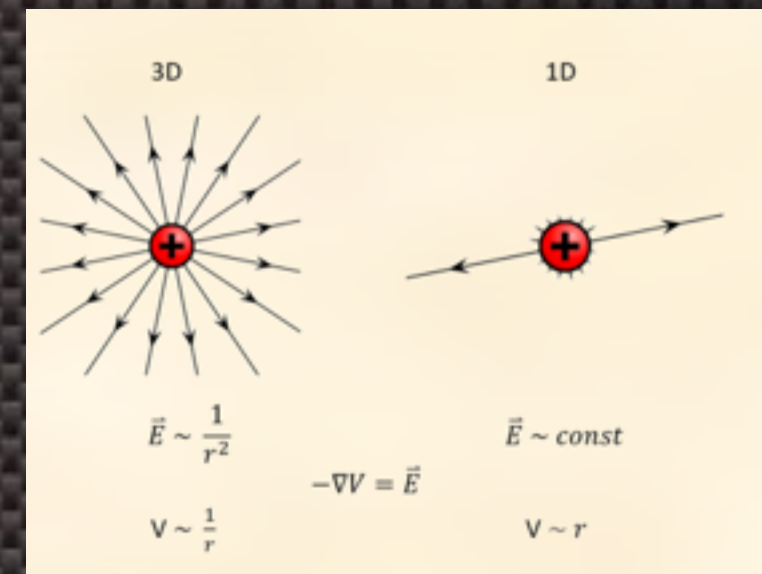
Quantum-classical computation of Schwinger model dynamics using quantum computers

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

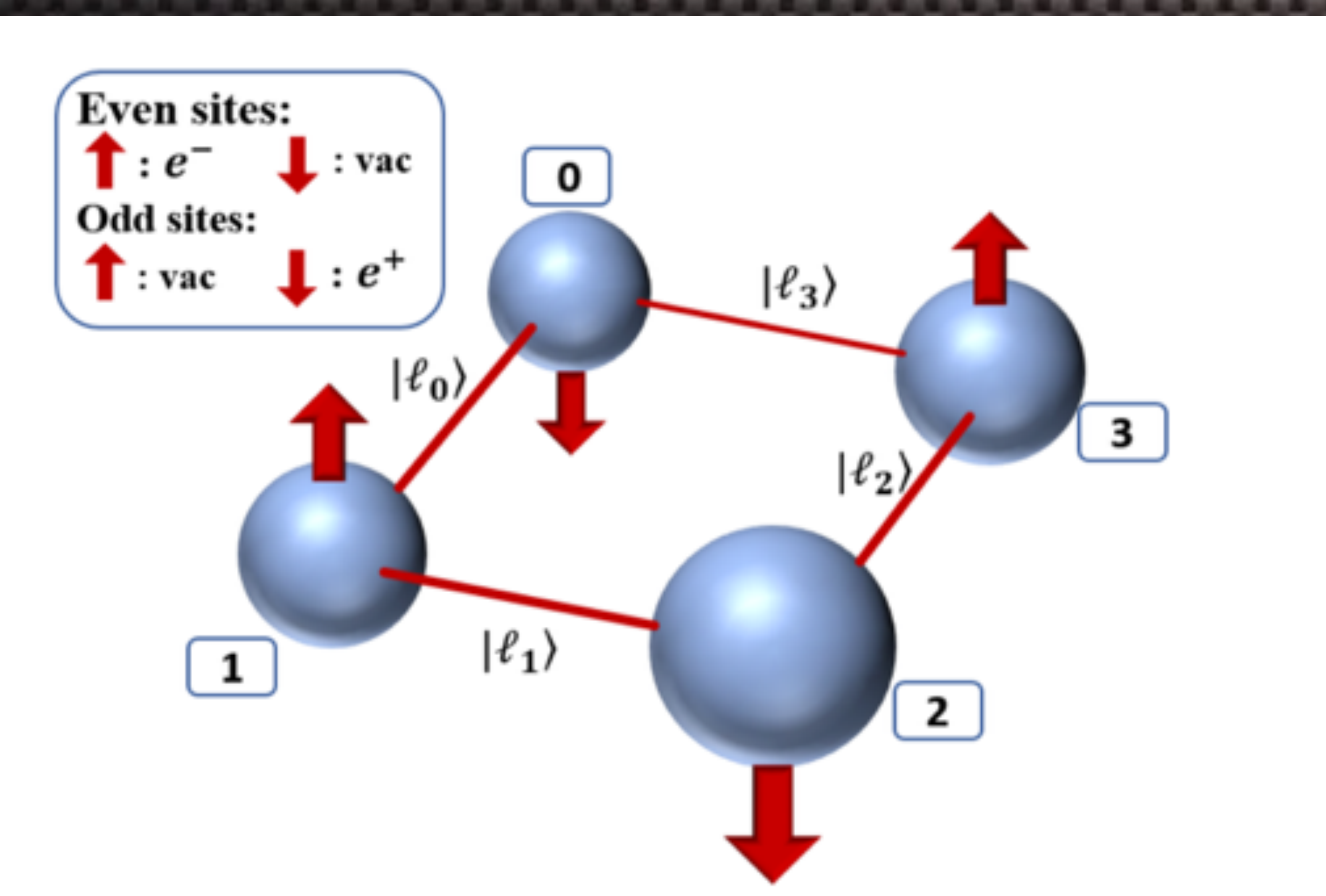
Phys. Rev. A **98**, 032331 – Published 28 September 2018



Derek Leinweber



Natalie Klco

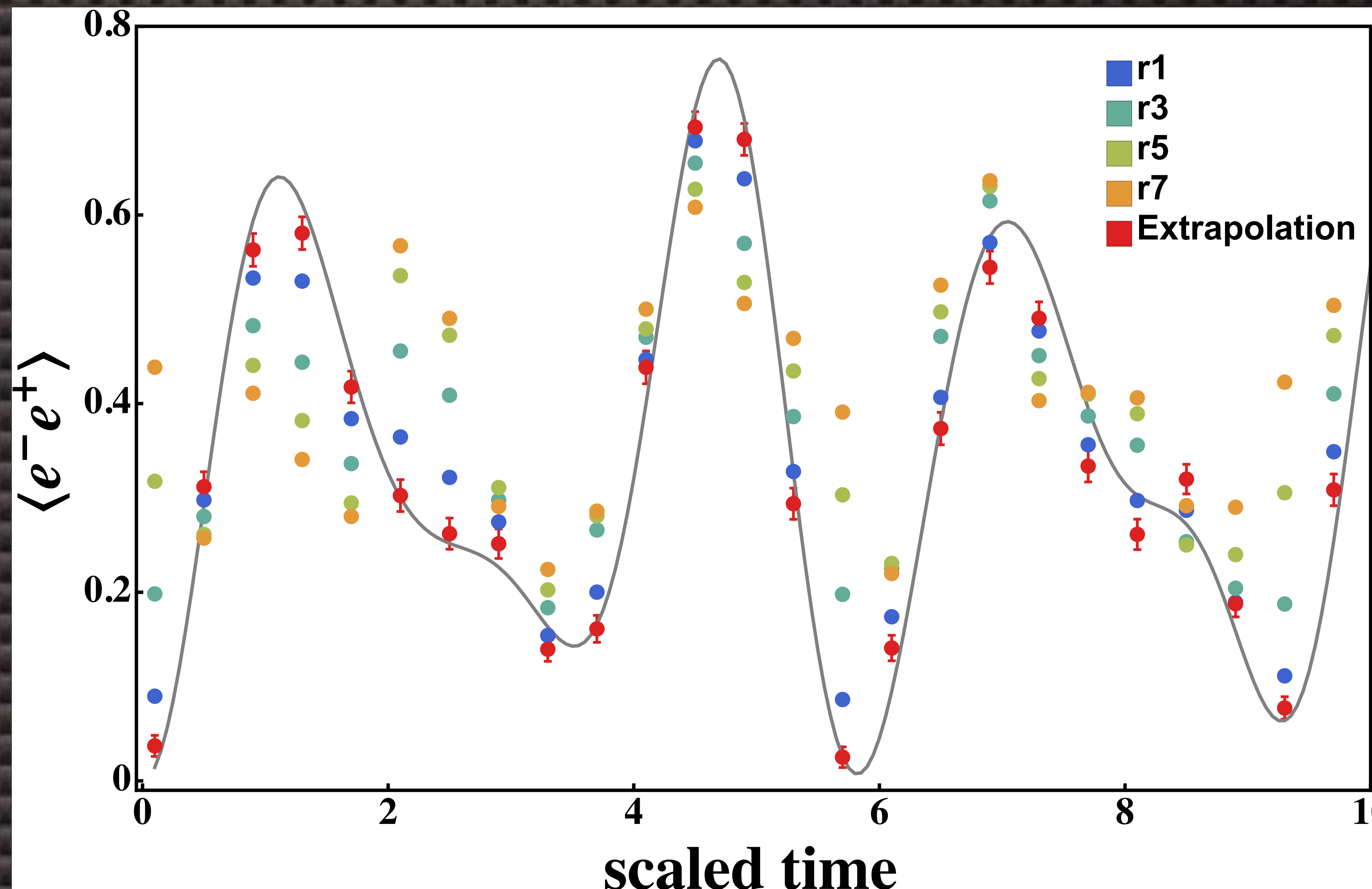


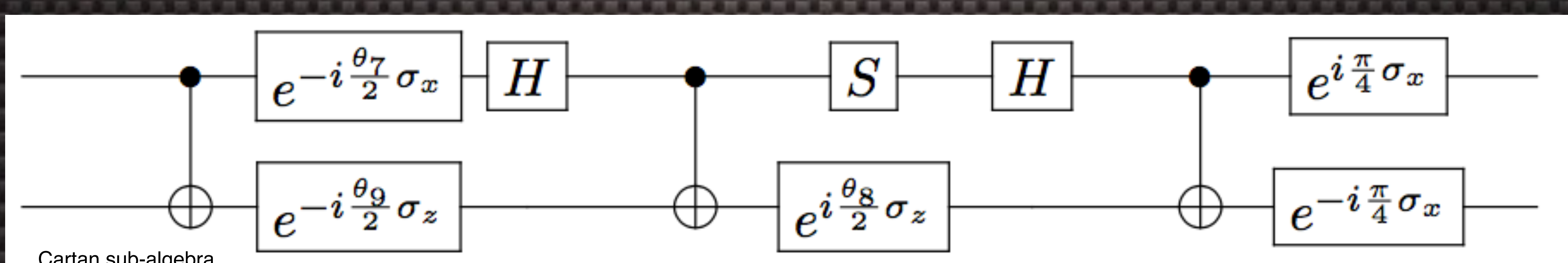
- Charge screening
- Confinement
- Fermion condensate
- Hadrons and nuclei

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

Living NISQ - IBM
Classically Computed U(t)

ibmqx2 - cloud-access
8K shots per point

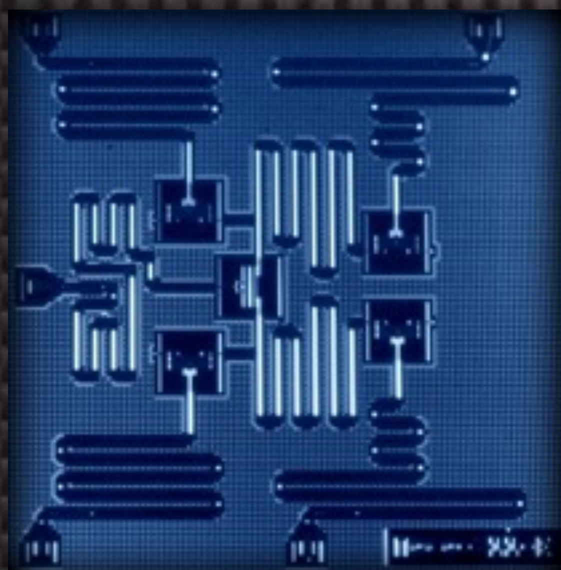




Oak Ridge National Laboratory

Living NISQ - IBM
Trotter Evolution U(t)

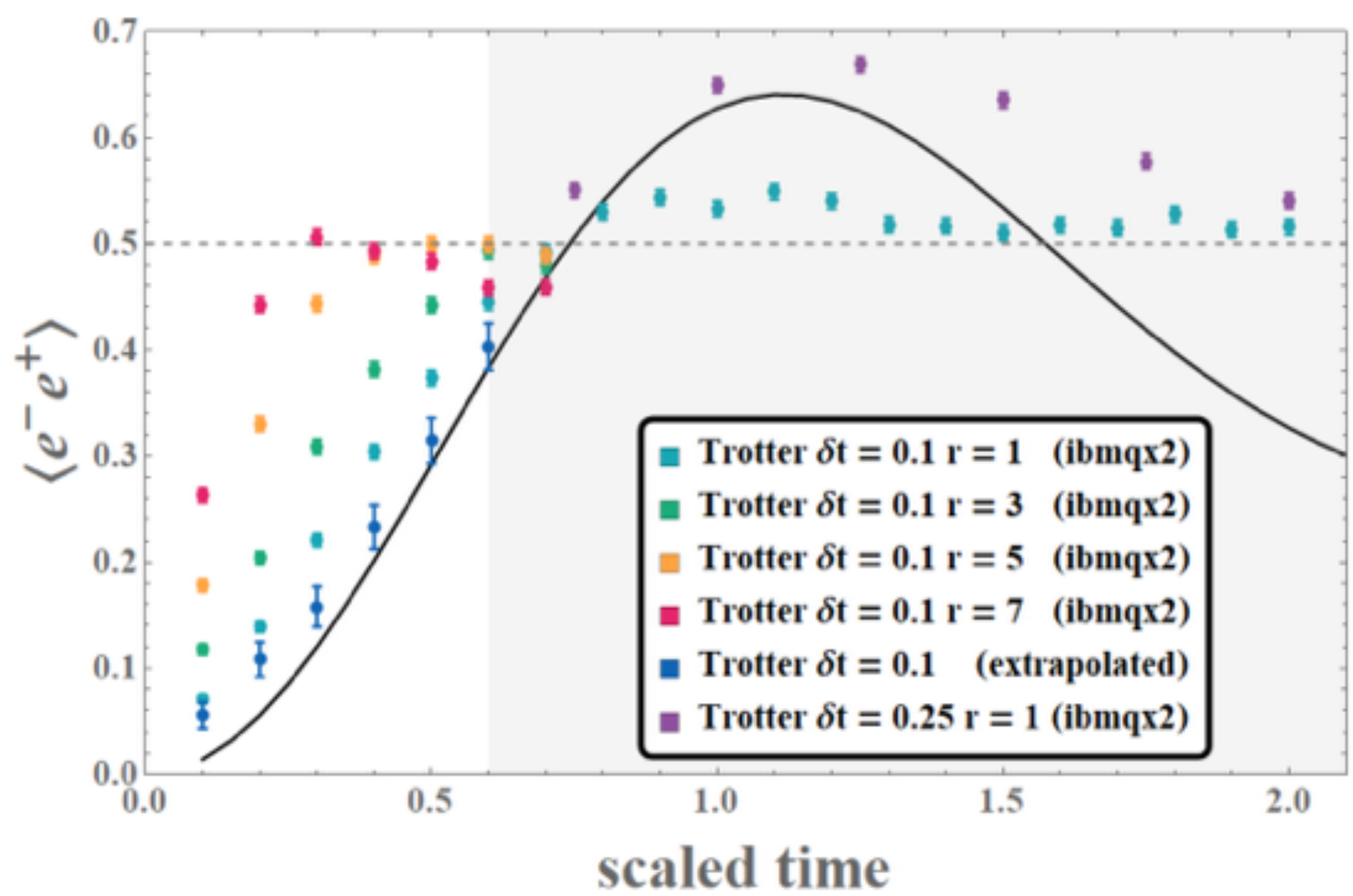
2 spatial lattice sites



T2 (μs)	55.20	65.10	47.00	35.10	37.60

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

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

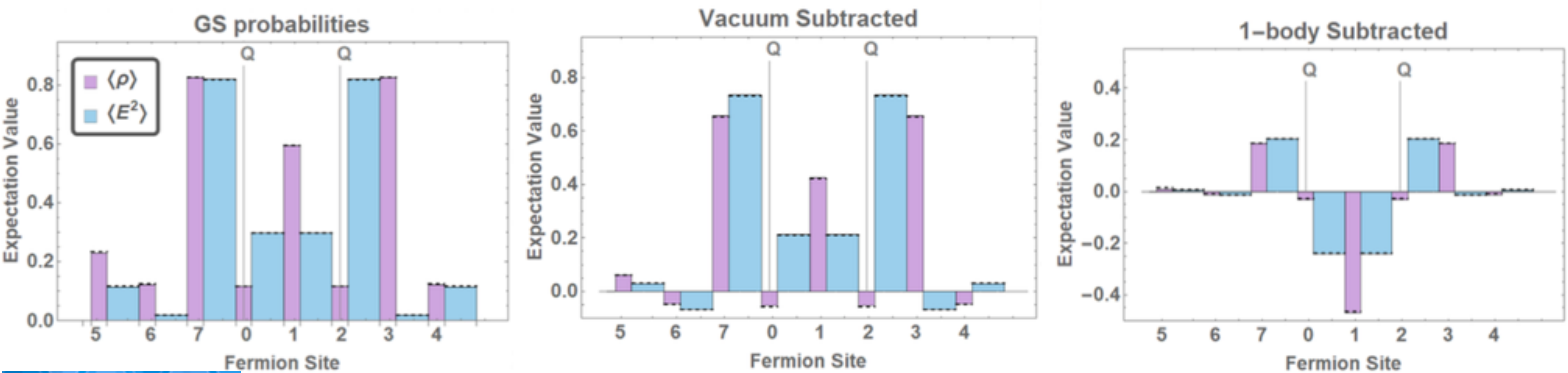


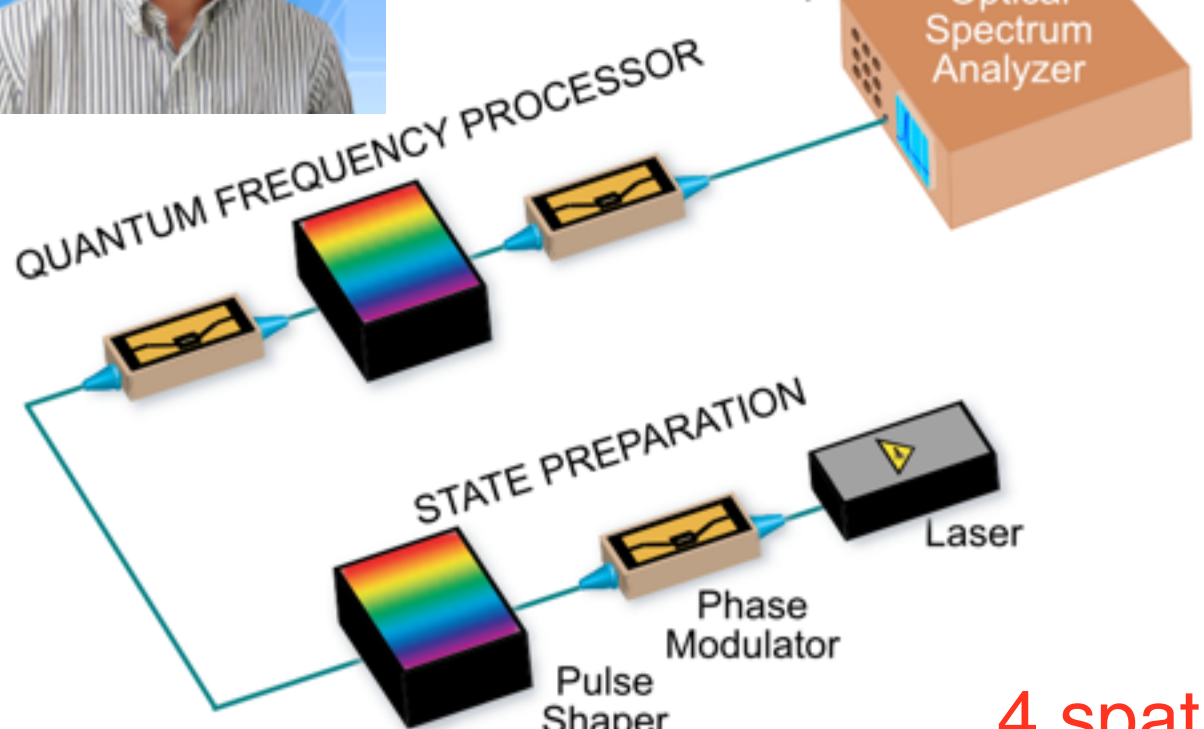
[``Capacity computing" - required only 2 of the 5 qubits on the chip]

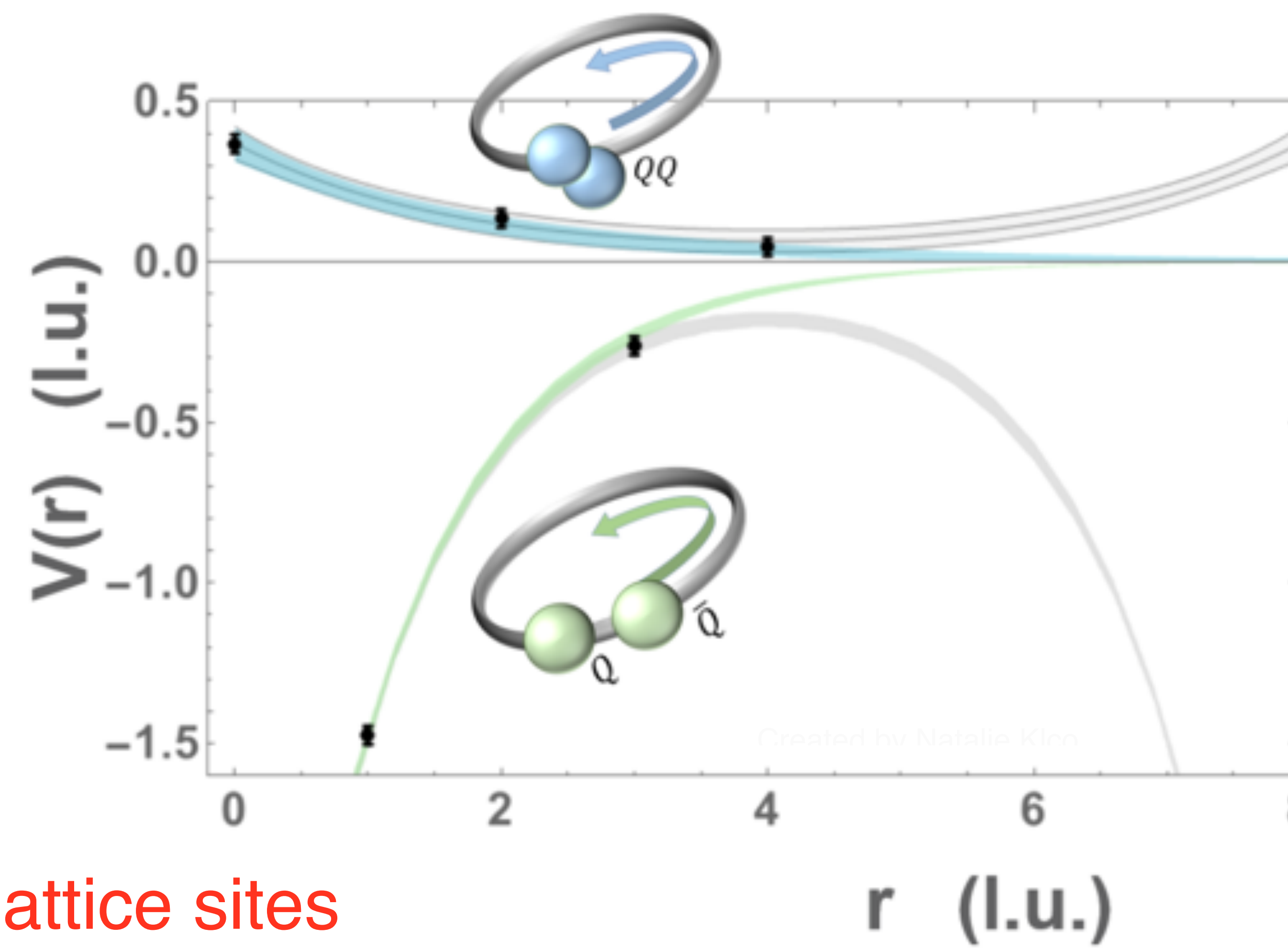
3.6 QPU-s and 260 IBM units

Interactions in the Schwinger Model
Photons and VQE

Hsuan-Hao Lu et al.
e-Print: arXiv:1810.03959





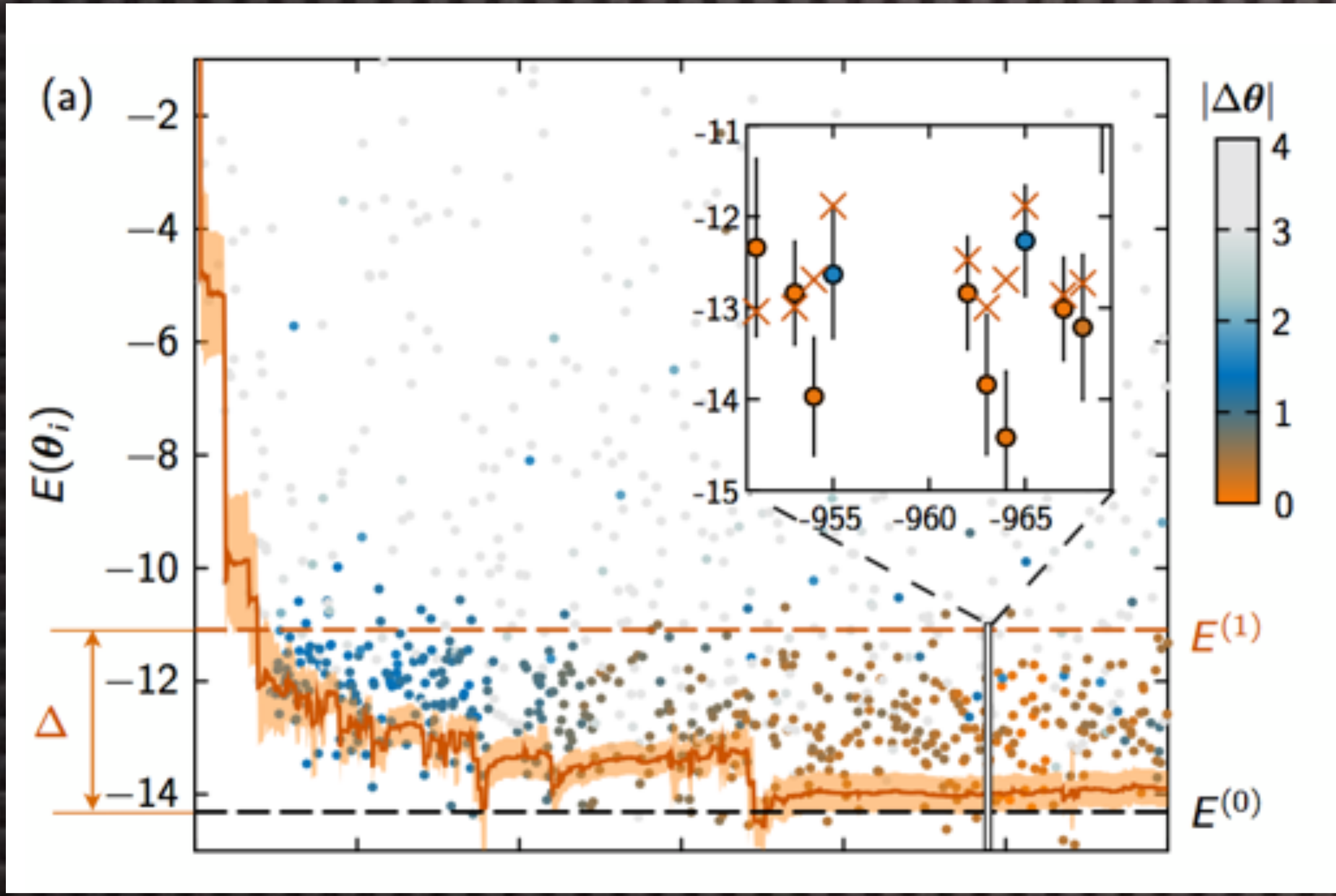


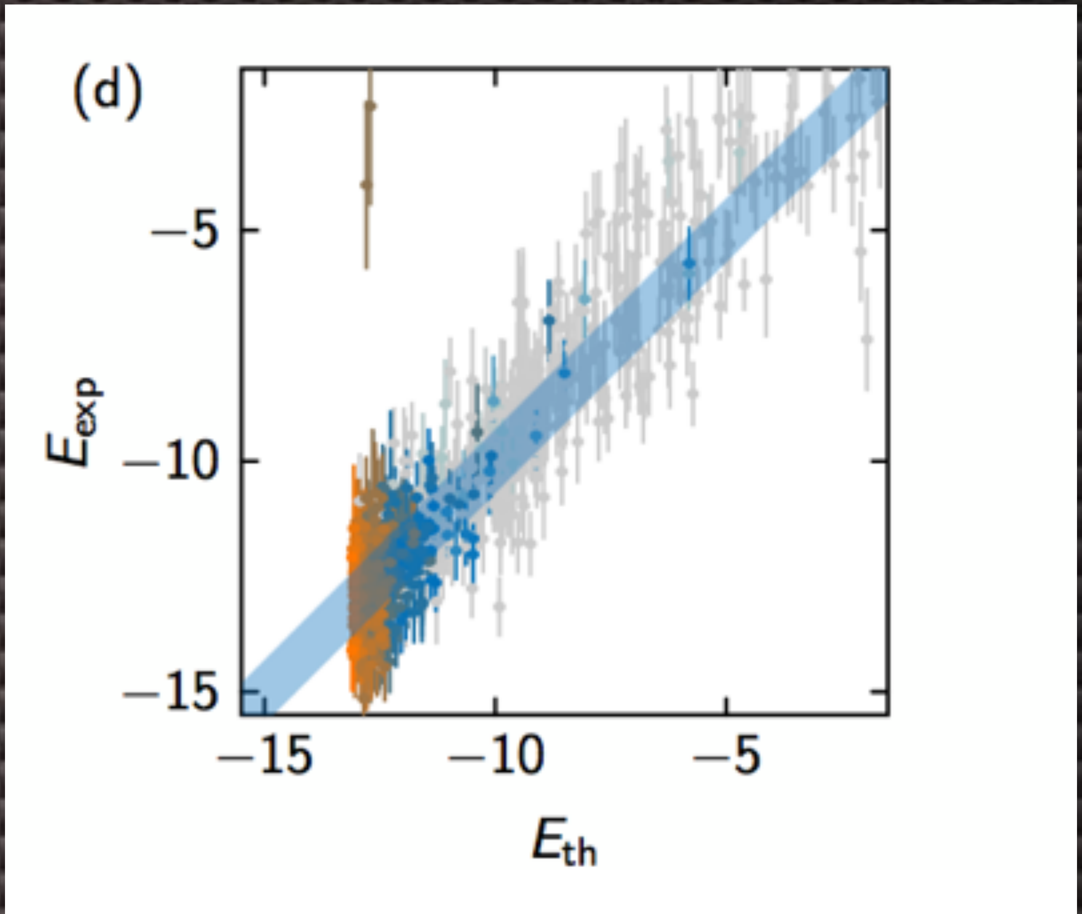
4 spatial lattice sites

The Schwinger Model

Self-Verifying Variational Quantum Simulation of the Lattice Schwinger Model

C. Kokail*, C. Maier*, R. van Bijnen*, T. Brydges, M. K. Joshi,
P. Jurcevic, C. A. Muschik, P. Silvi, R. Blatt, C. F. Roos, and P. Zoller
Center for Quantum Physics, and Institute for Experimental Physics, University of Innsbruck and Institute for Quantum Optics and Quantum Information, Austrian Academy of Sciences, Innsbruck, Austria
(Dated: April 10, 2019)





Schwinger Model ground state VQE

20 qubits = 10 spatial lattice sites

Gauge constraint imposed explicitly, with background vanishing electric field

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]** **Phys.Rev.Lett. 121 (2018) no.11, 110504**

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

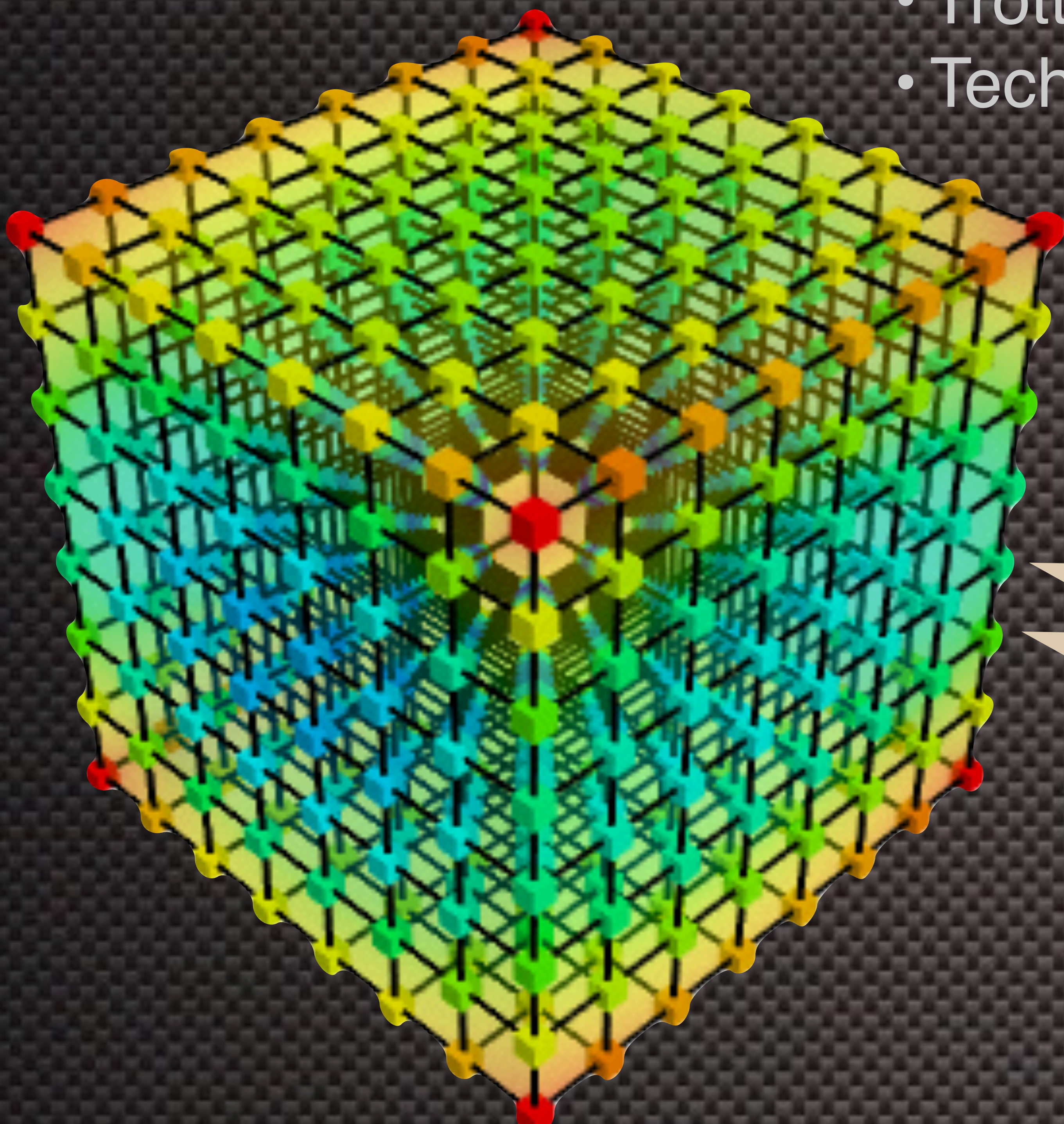
Digitizing Gauge Fields: Lattice Monte Carlo Results for Future Quantum Computers
Daniel C. Hackett (Colorado U.), Kiel Howe, Ciaran Hughes (Fermilab), William Jay (Colorado U. & Fermilab), Ethan T. Neil (Colorado U. & RIKEN BNL), James N. Simone (Fermilab). Nov
e-Print: **arXiv:1811.03629 [quant-ph]**

Scalar Quantum Field Theories as a Benchmark for Near-Term Quantum Computers
Kubra Yeter-Aydeniz, Eugene F. Dumitrescu, Alex J. McCaskey, Ryan S. Bennink, Raphael C. Pooser, George Siopsis.
Published in Phys.Rev. A99 (2019) no.3, 032306

Sigma models on quantum computers
NuQS Collaboration (Andrei Alexandru (George Washington U. & Maryland U.) et al.). Mar 15, 2019. 5 pp.
e-Print: arXiv:1903.06577 [hep-lat]

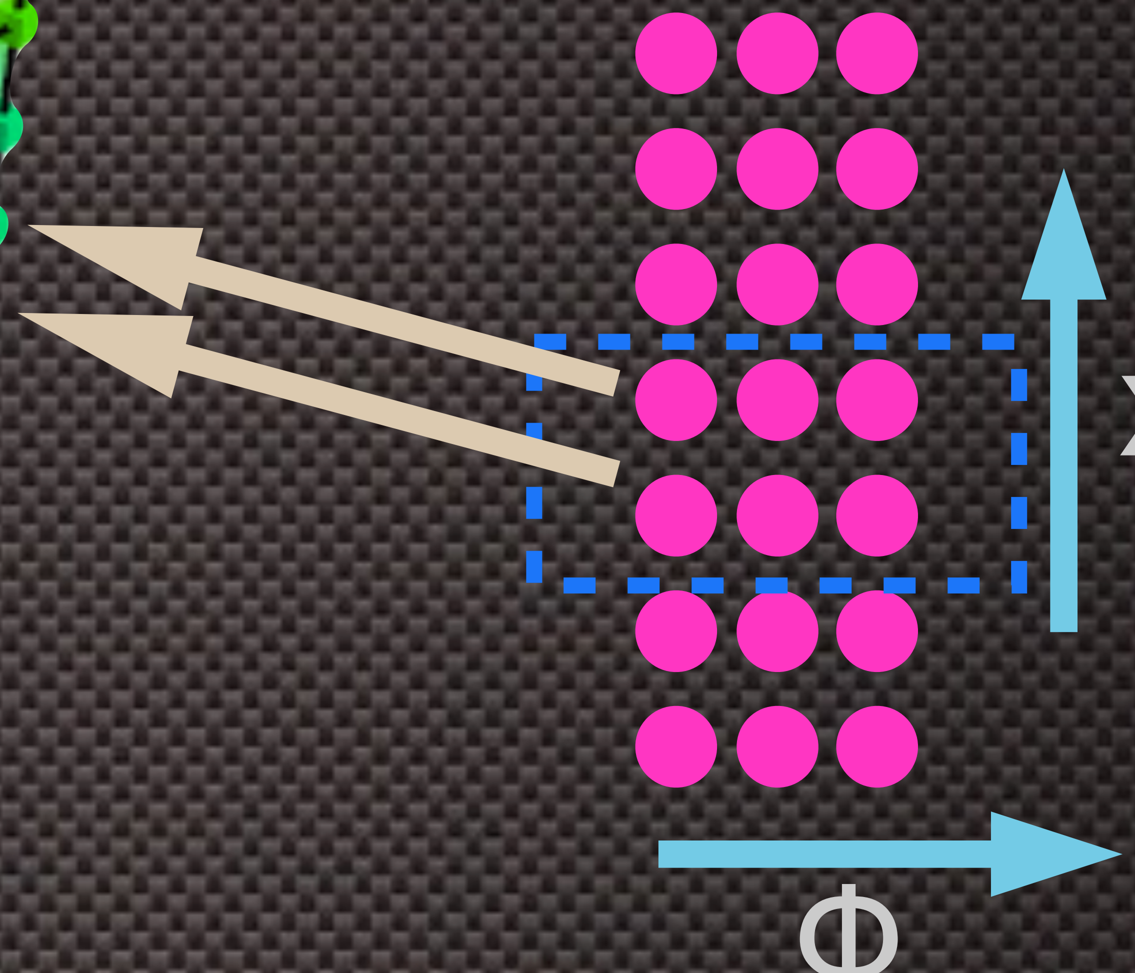
Discretizing and Digitization of Field Theory

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



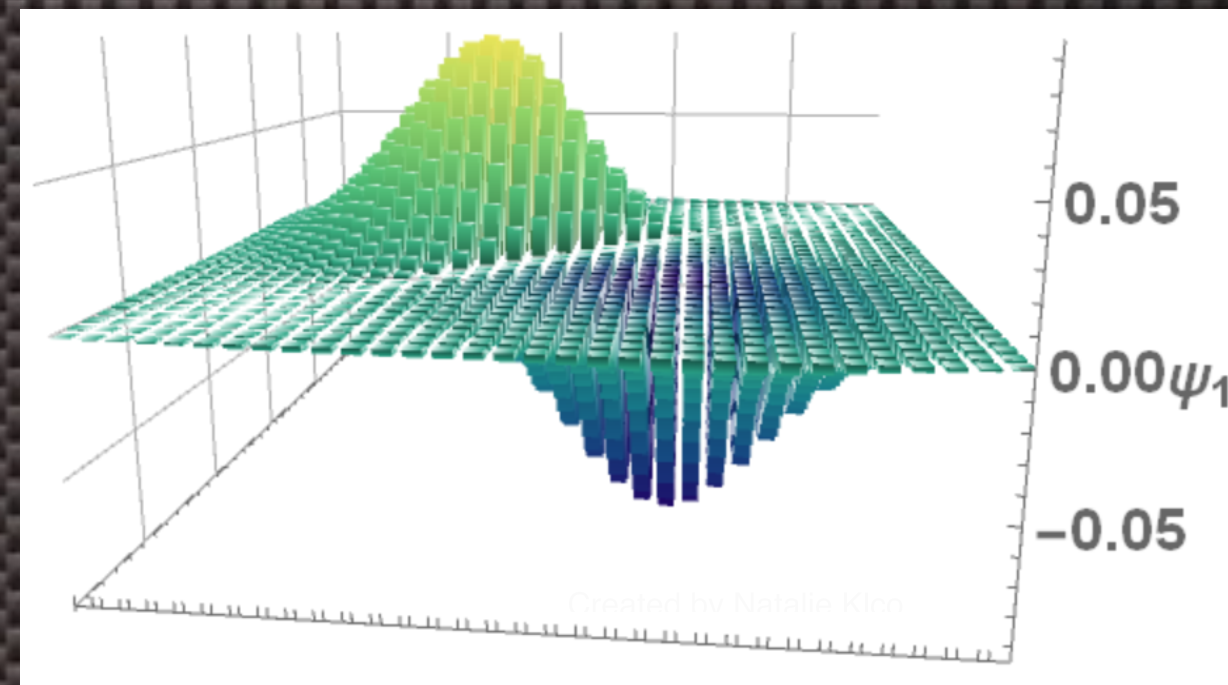
Parallelizes easily at the circuit level

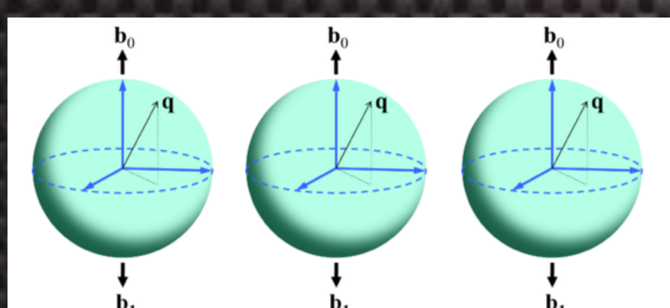
- dual layer application per Trotter step



Digitizing Quantum Fields

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





3 Qubits = 8 States

Field basis

Harmonic Oscillator

Jordan, Lee and Preskill - several works
Macridin, Spentzouris, Amundson and Harnik [FNAL]
Klco, MJS

Scattering Wavepackets in Scalar Field Theory

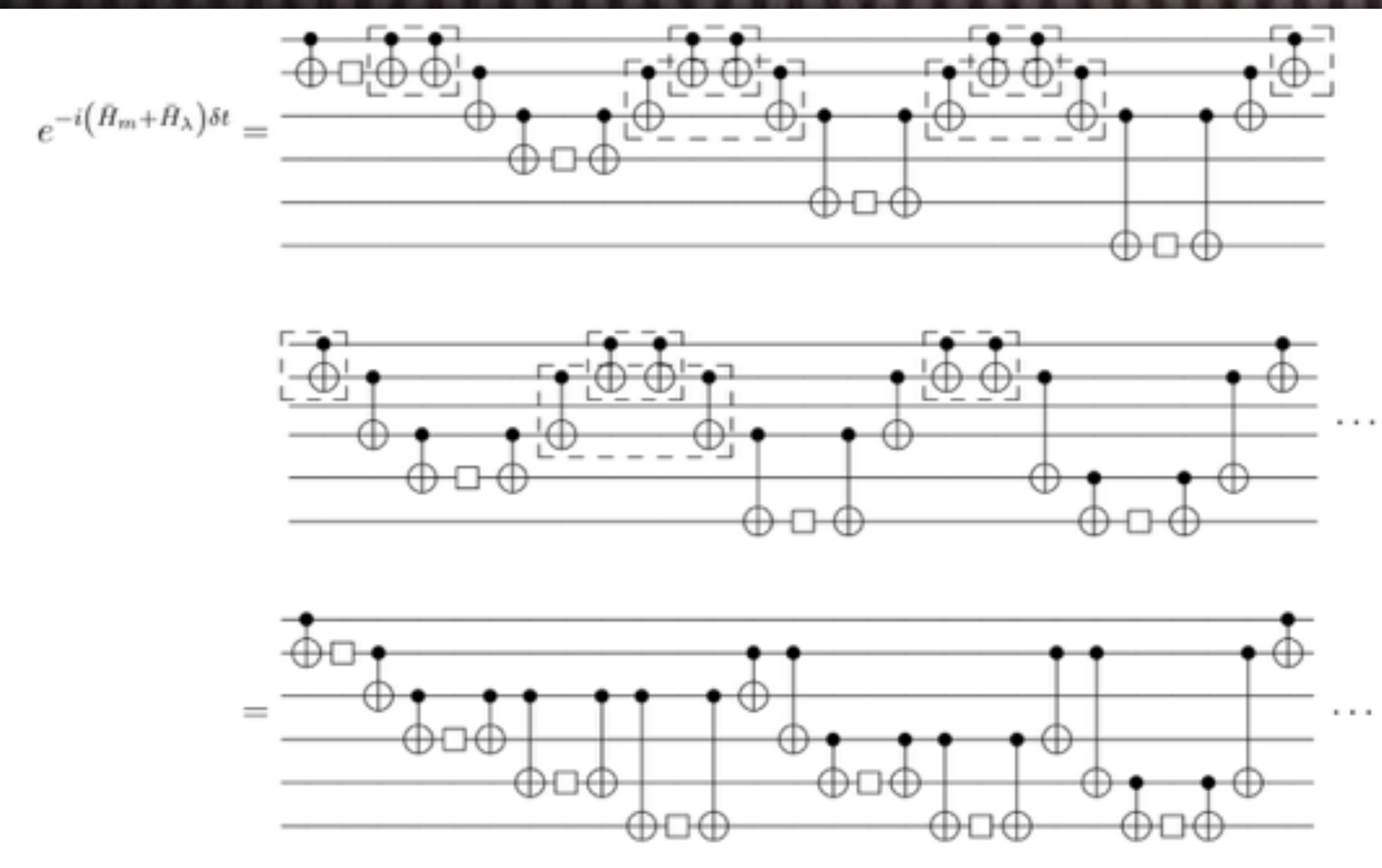
Quantum Computation of Scattering in Scalar Quantum Field Theories

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

1. **Exponentially difficult to initialize interacting theory**
2. **Create wavepackets of free theory**
3. **Adiabatically evolve the system to interacting system**
4. **Evolve the prepared state forward**
5. **Ediabatically evolve systems to free theory OR introduce localized detectors into the simulation**

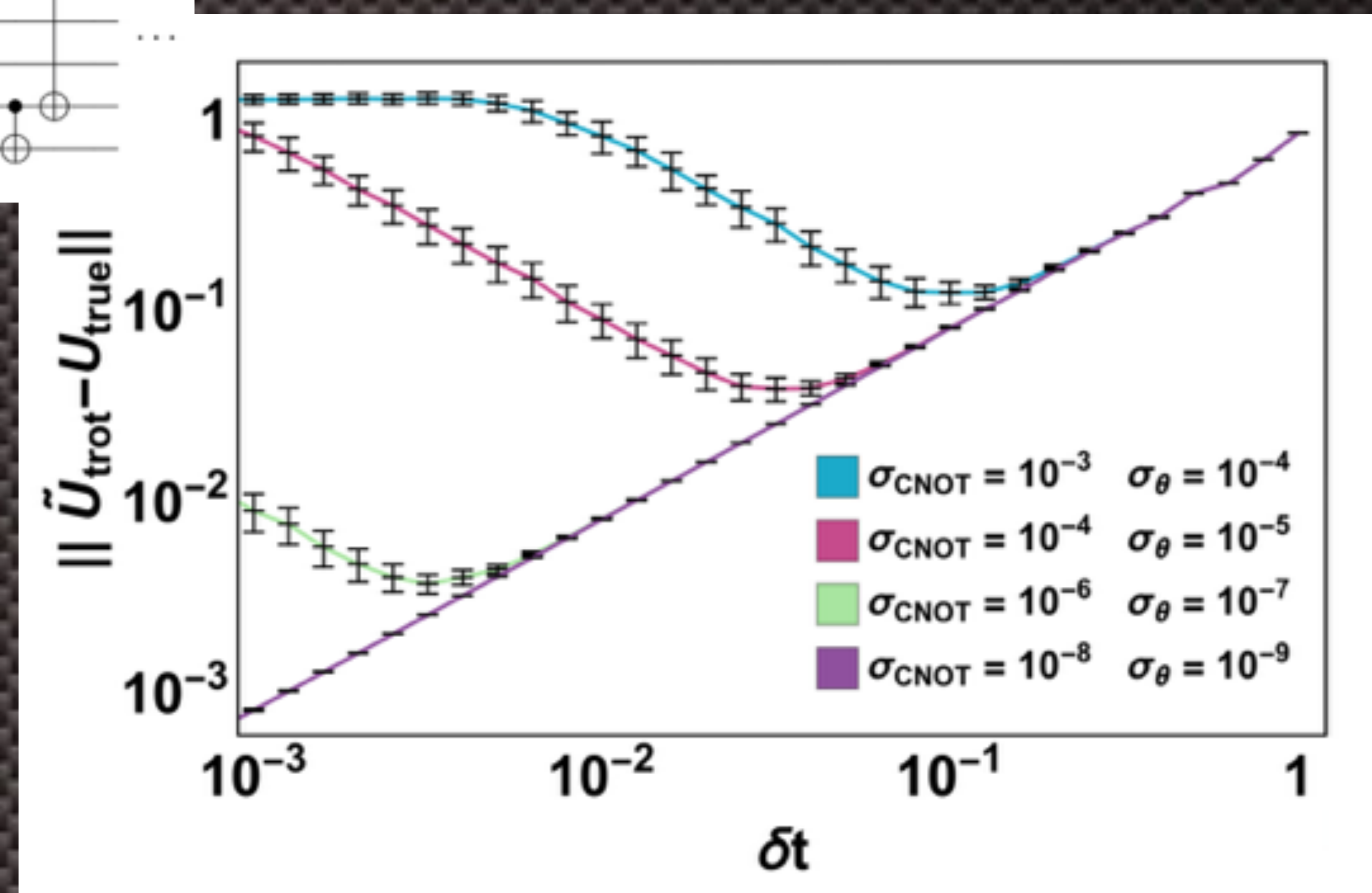
Discretizing and Digitization of Field Theory
Trotterization trade off with Device Noise

Natalie Klco,MJS



``Manual" gate reduction

$$e^{-i\,T\,\delta t}\;e^{-i\,V\,\delta t}\;e^{-i\,R\,\delta t^2}$$

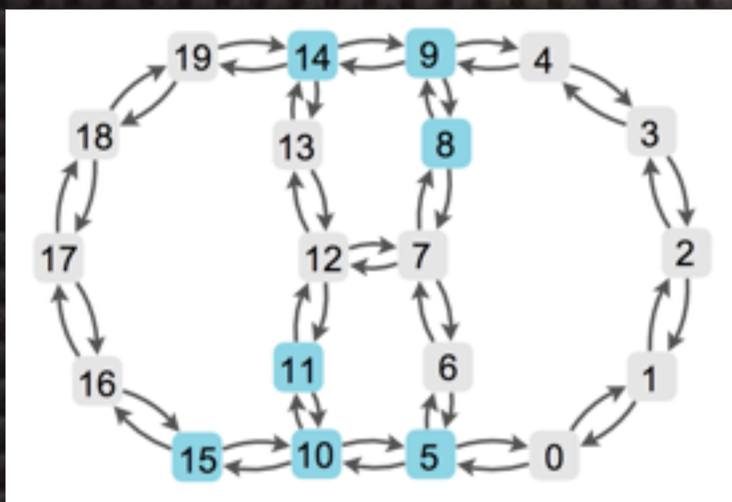


Gaussian noise model simulation with n_Q=3

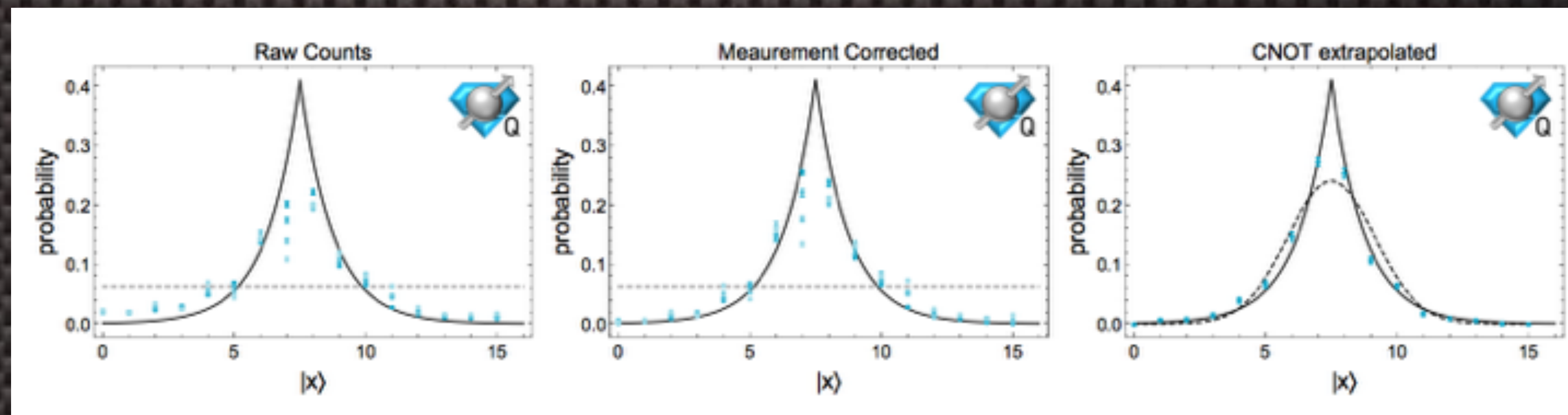
Minimally-Entangled State Preparation for 1-site

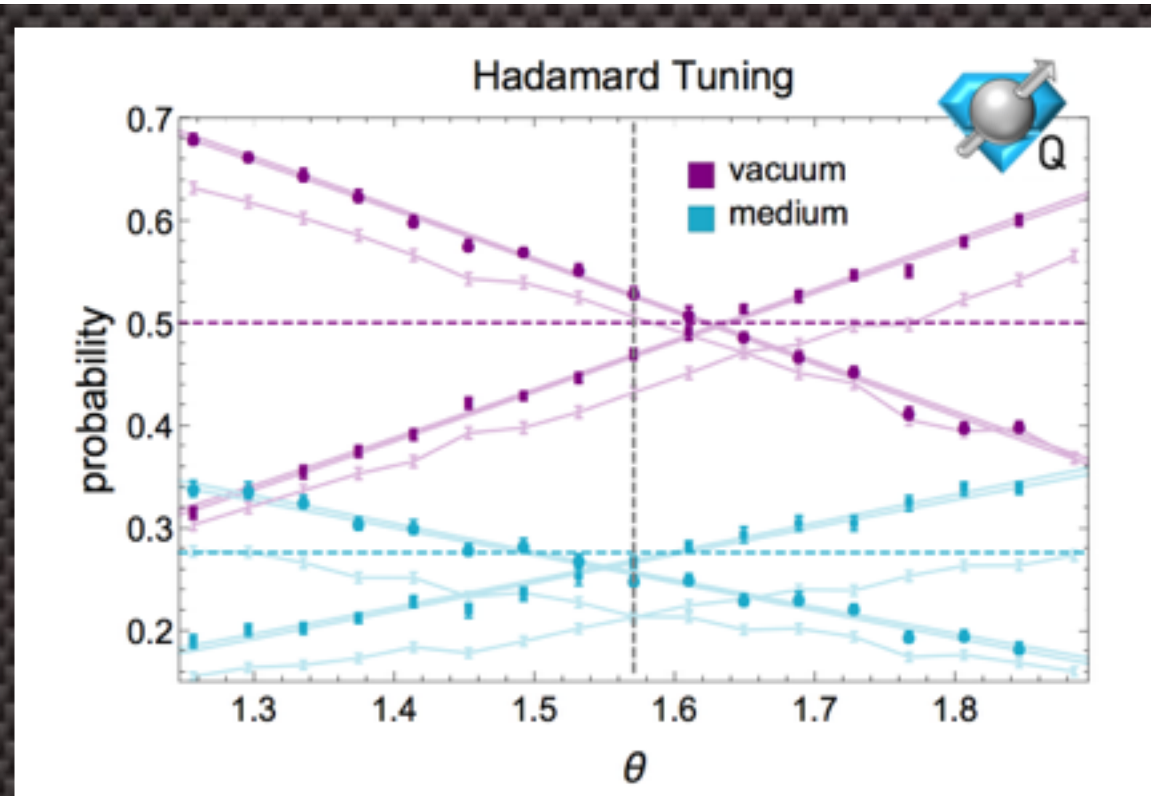
Natalie Klco+MJS

Gaussian ~ 2^{n_Q} while Symmetric Exponential ~ n_Q
"Sommer - inflation"



IBM's Poughkeepsie

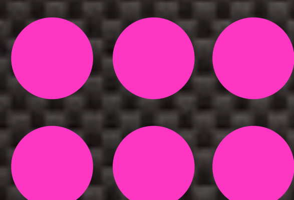


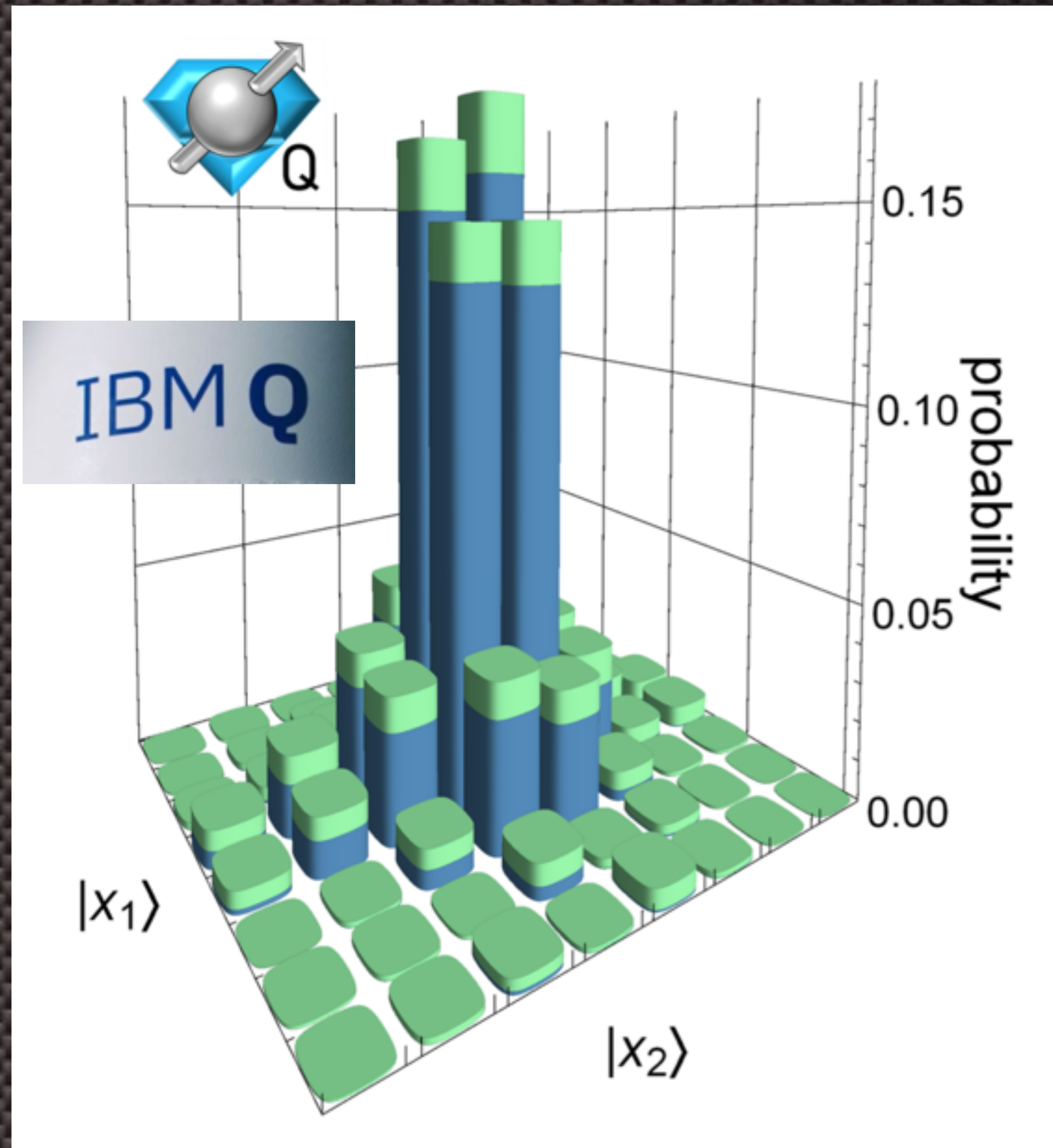


Inline Workflow for calibration purposes

Minimally-Entangled State Preparation for 2- and 3-site

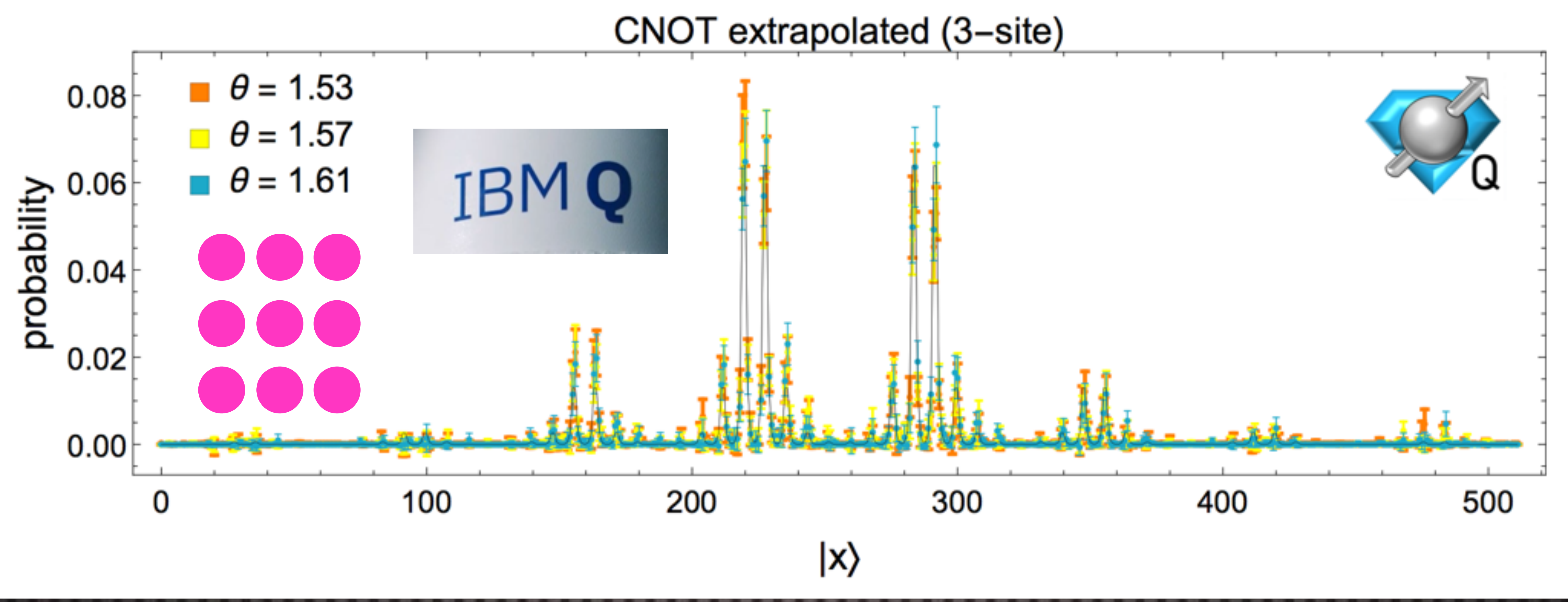
Natalie Klco+MJS





Minimally-Entangled State Preparation for 2- and 3-site

Natalie Klco+MJS



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?

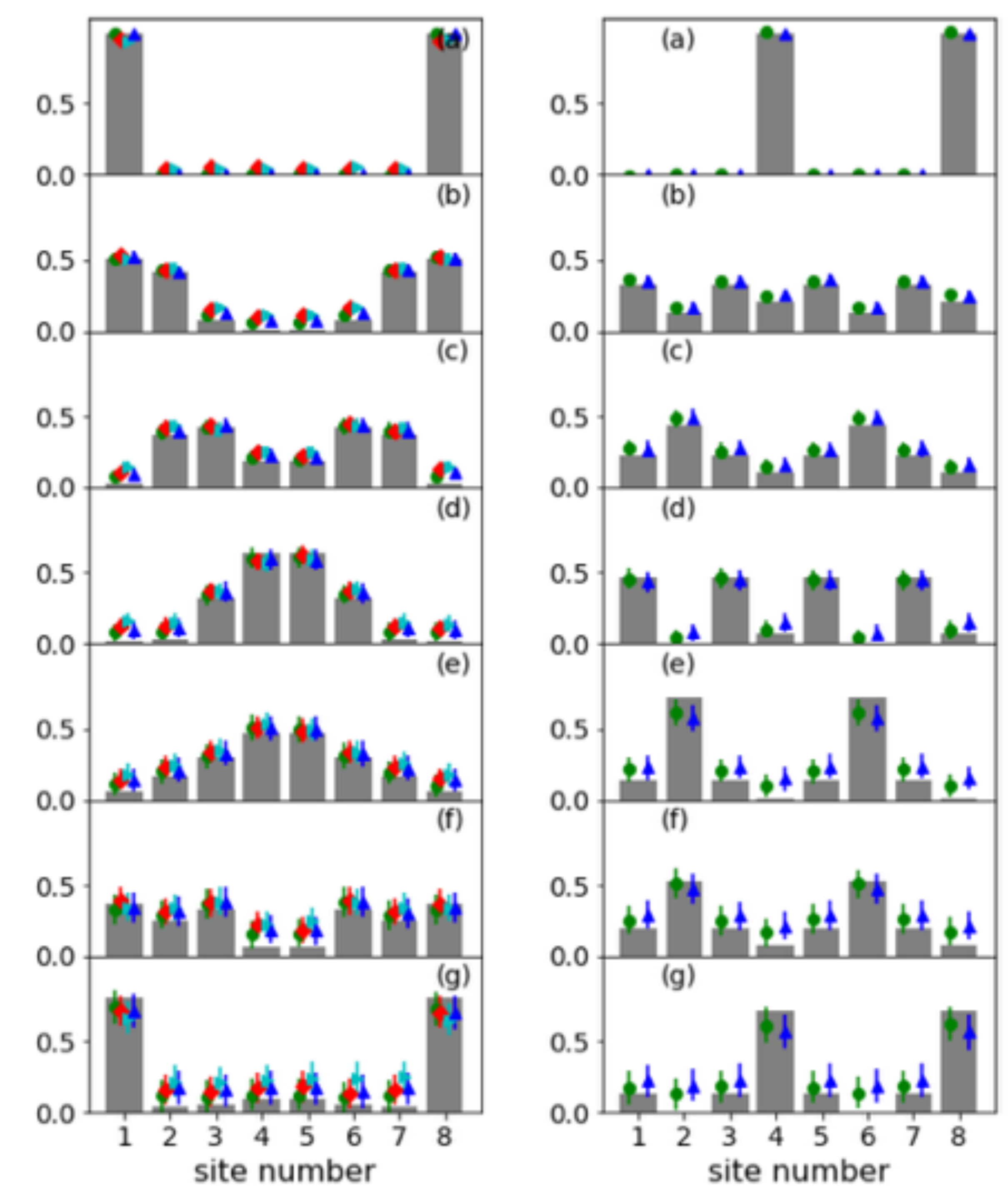
Near term: move along paths with presently ``doable'', but informative, quantum calculations towards real-time and finite density QCD

Low-Dimensional Spin Systems
Toward Gauge Theories

Quantum simulation of scattering in the quantum Ising model

Erik Gustafson[1], Y. Meurice[1], and Judah Unmuth-Yockey[2]
[1] *Department of Physics and Astronomy, The University of Iowa, Iowa City, IA 52242, USA* and
[2] *Department of Physics, Syracuse University, Syracuse, NY 13244 USA*
(Dated: February 5, 2019)

$$H_{obc} = -J \sum_{i=1}^{N_s - 1} \hat{\sigma}_i^x \hat{\sigma}_{i+1}^x - h_T \sum_{i=1}^{N_s} \hat{\sigma}_i^z .$$



(A) open boundary conditions

(B) periodic boundary conditions

Low-dim models are a great sandbox for exploring new ideas
- e.g., Fragmentation

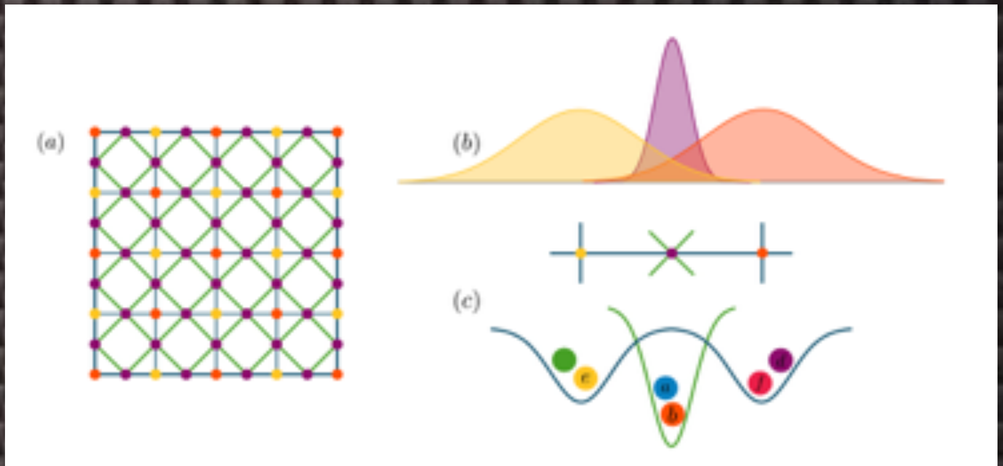
Starting down the Path
Low-Dimensional Gauge Theories

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

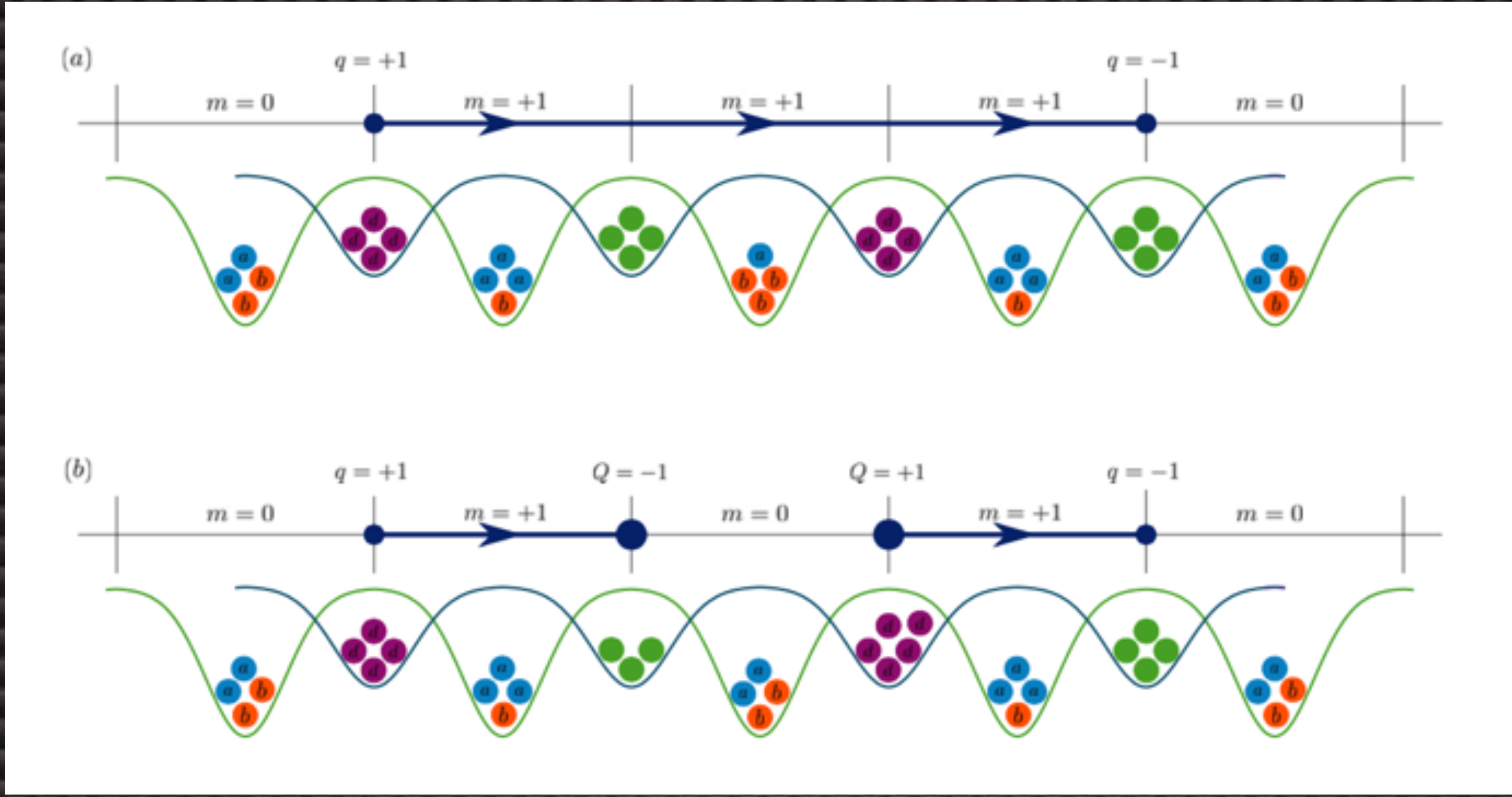
Daniel González-Cuadra[1,2], Erez Zohar[2] and J. Ignacio Cirac[2]

[1] ICFO – The Institute of Photonic Sciences, Av. C.F. Gauss 3, E-08860, Castelldefels (Barcelona), Spain

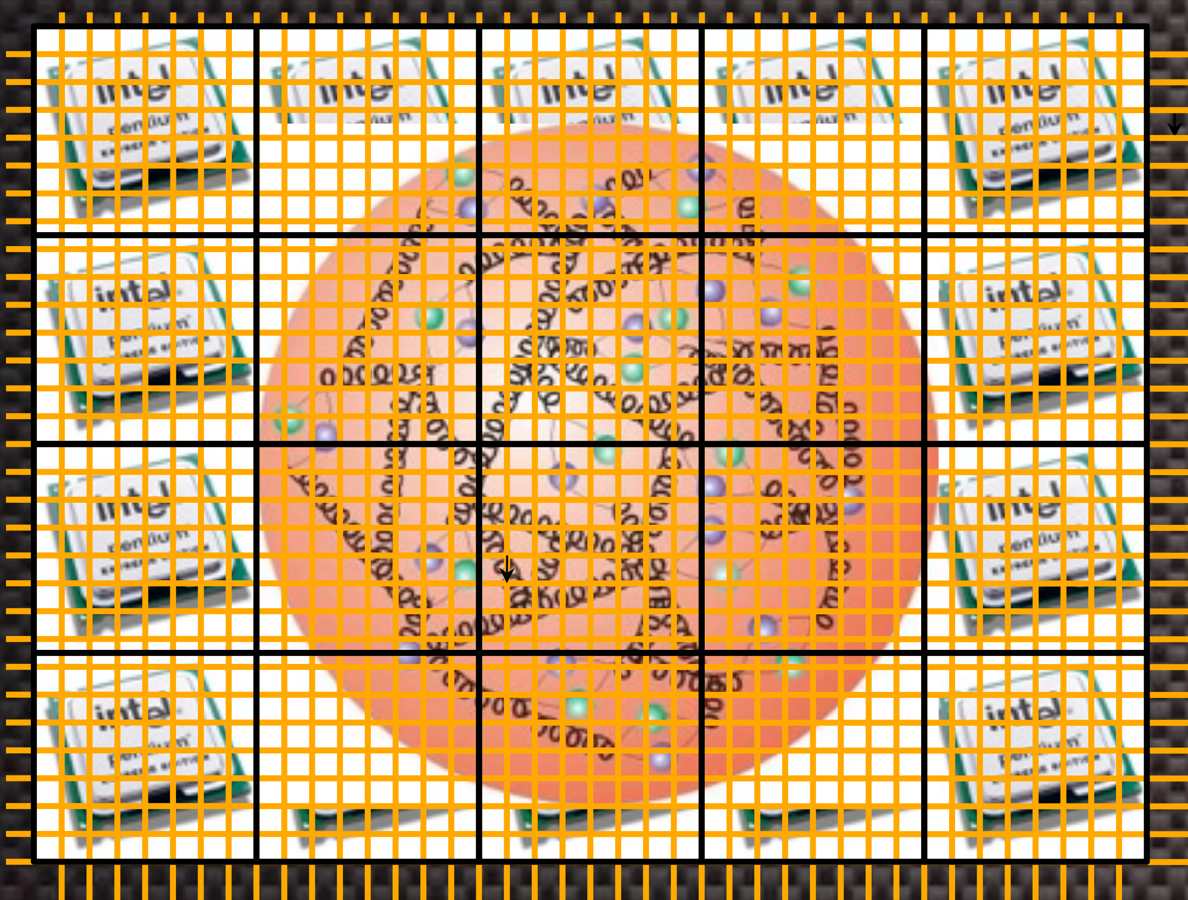
[2] Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, D-85748 Garching, Germany



The formalism required for the simulation



New ways to think about simulating QFTs



e.g.,

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]

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]

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]

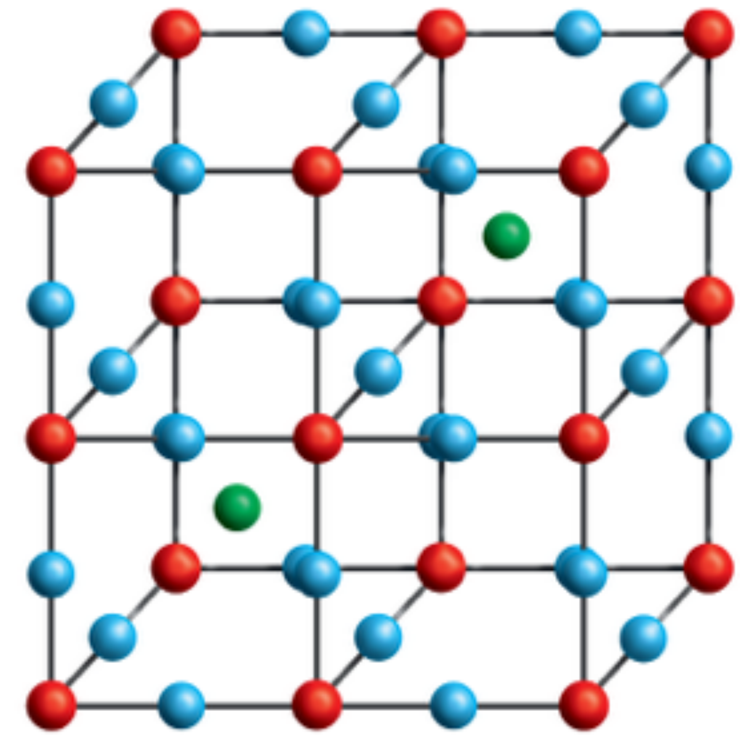
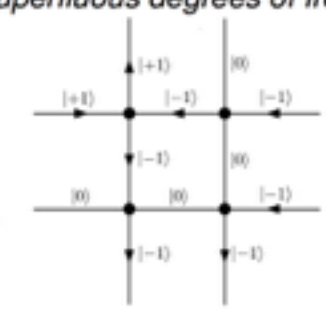


Figure 2. The physical system consists of the gauge fields residing on the links (blue) and the matter fields on the vertices (red). The auxiliary degrees of freedom (green) are located in the center of every second cube (either even or odd).

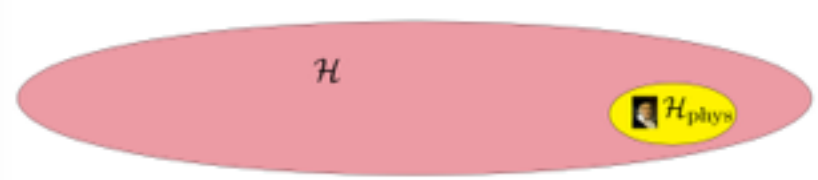
Recent study: Formulating Abelian U(1) gauge theories *without superfluous degrees of freedom*

- 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?

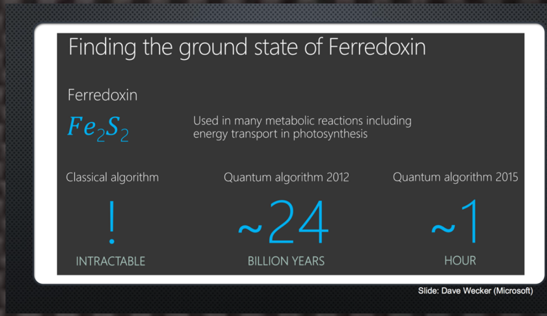
1) Eliminate unphysical/redundant degrees of freedom
   - Limited success
   - Usually sacrifice locality
   - Small systems: OK

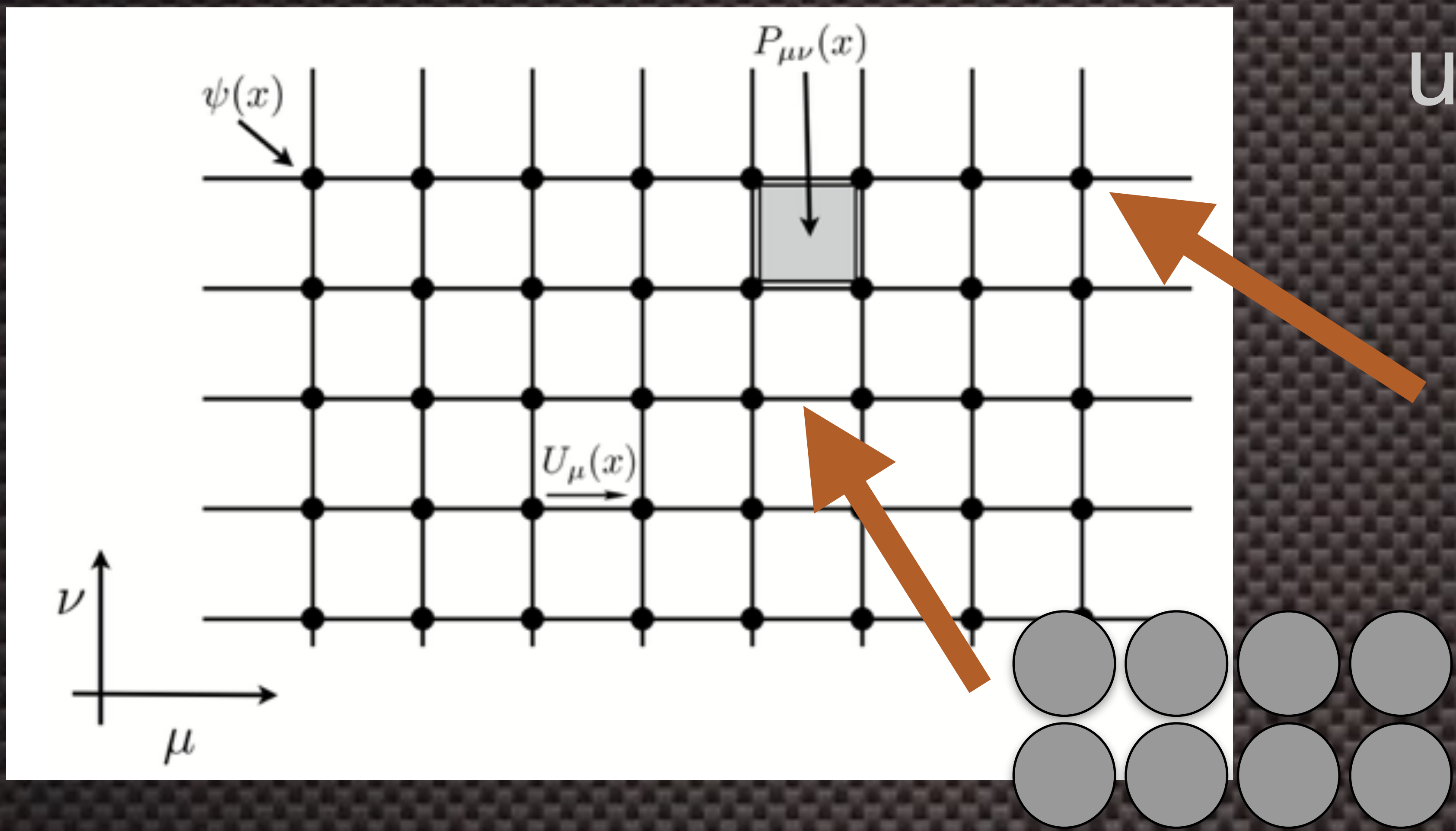
D. Kaplan & JRS, '18 (arXiv:1806.08797)

2) Find different variables

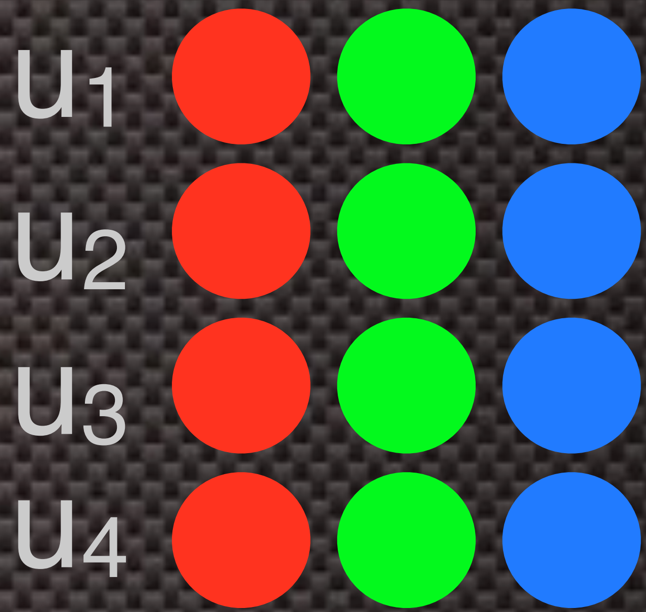
3) Live with superfluous degrees of freedom
   - Must **enforce constraints**
   - More practical for large systems

(Very) Naive Mapping of QCD onto QC



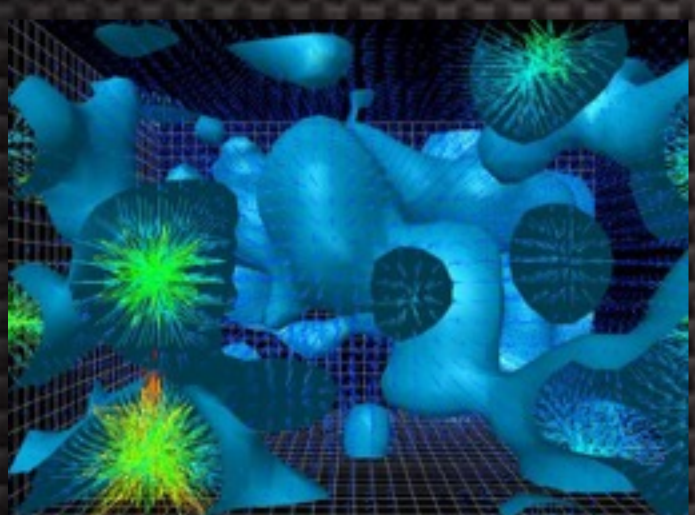


up-quark qubits



+ 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) > + ….

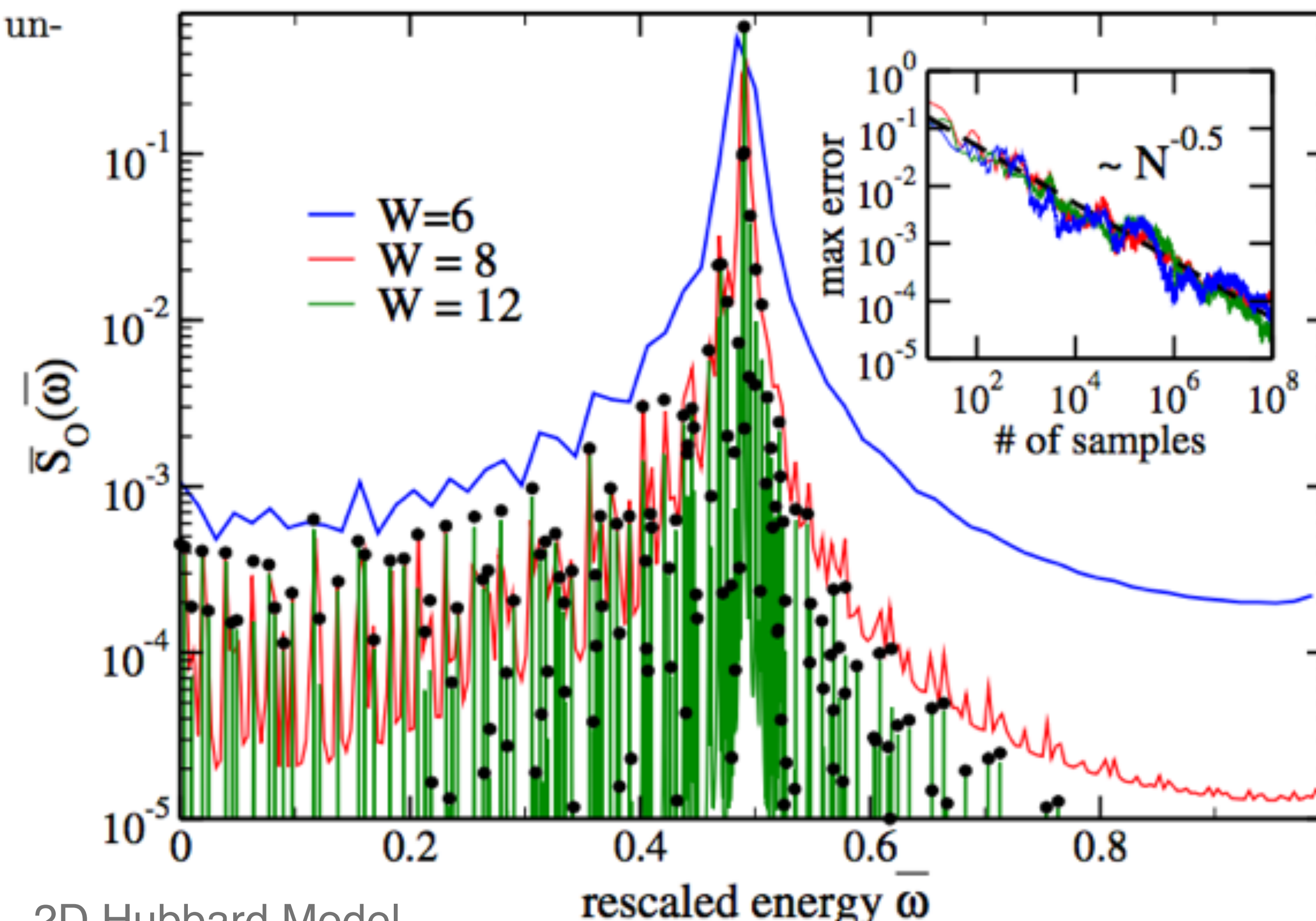
Classical lattice QCD may play a key role in QFT on QC

Neutrino Nucleus

Linear Response on a Quantum Computer

Alessandro Roggero* and Joseph Carlson†
Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA
(Dated: April 13, 2018)

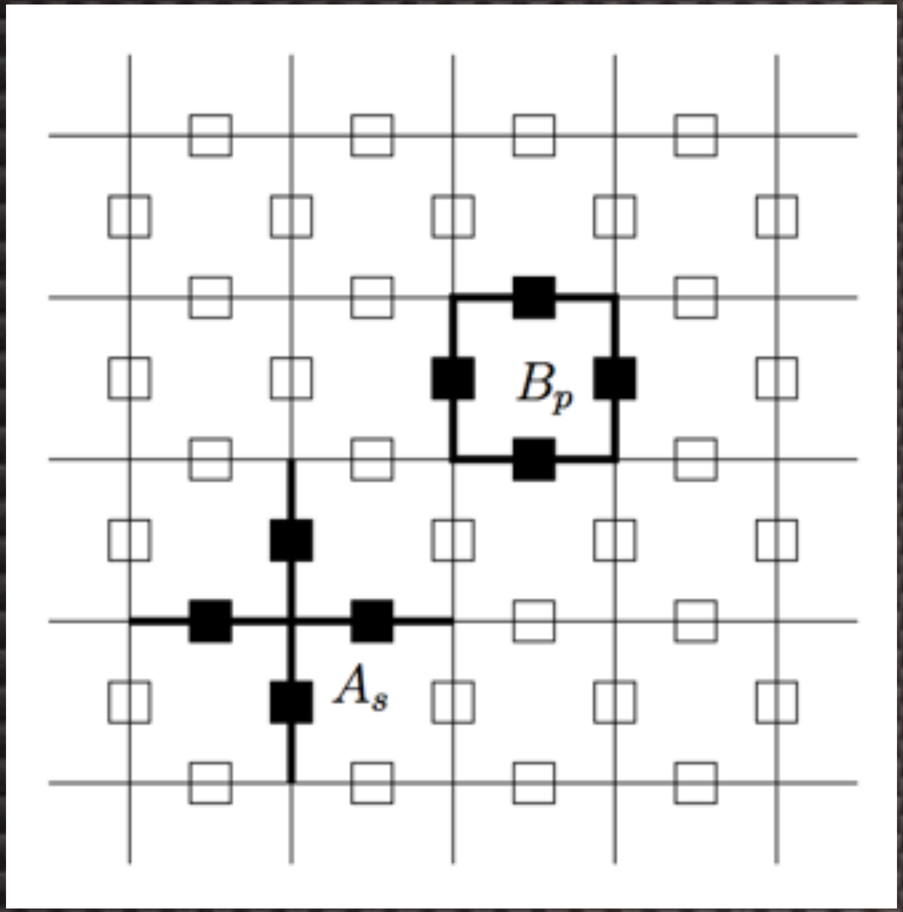
- a unitary $\hat{U}_G$ which prepares the ground-state of the Hamiltonian of interest
- a unitary $\hat{U}_O$ which implements time evolution under $\hat{O}$ for a short time $\gamma < poly(\delta_S)$
- a unitary $\hat{U}_t$ which implements time evolution under the system Hamiltonian for time t

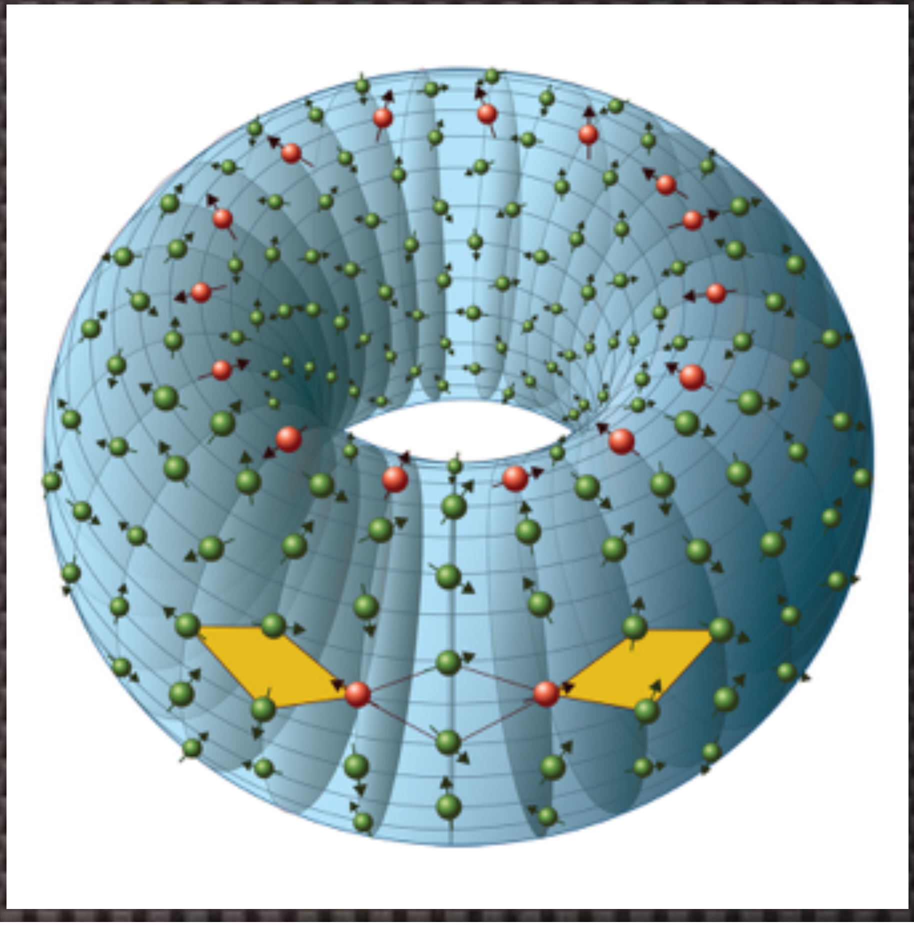


2D Hubbard Model

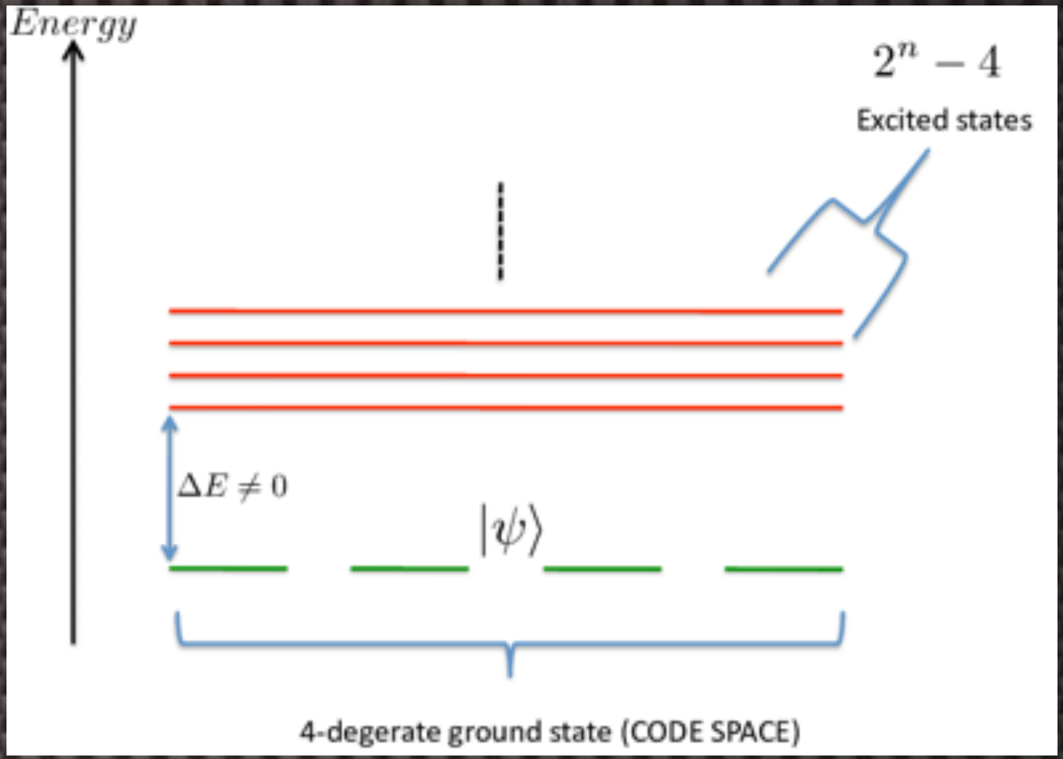
Quantum Computing for Neutrino Nucleus Dynamics
Gabriel Perdue, Rajan Gupta, + …..

(Lattice) Field Theory for QIS and QC ?





$$H_T = -J_e \sum_s A_s - J_m \sum_p B_p$$

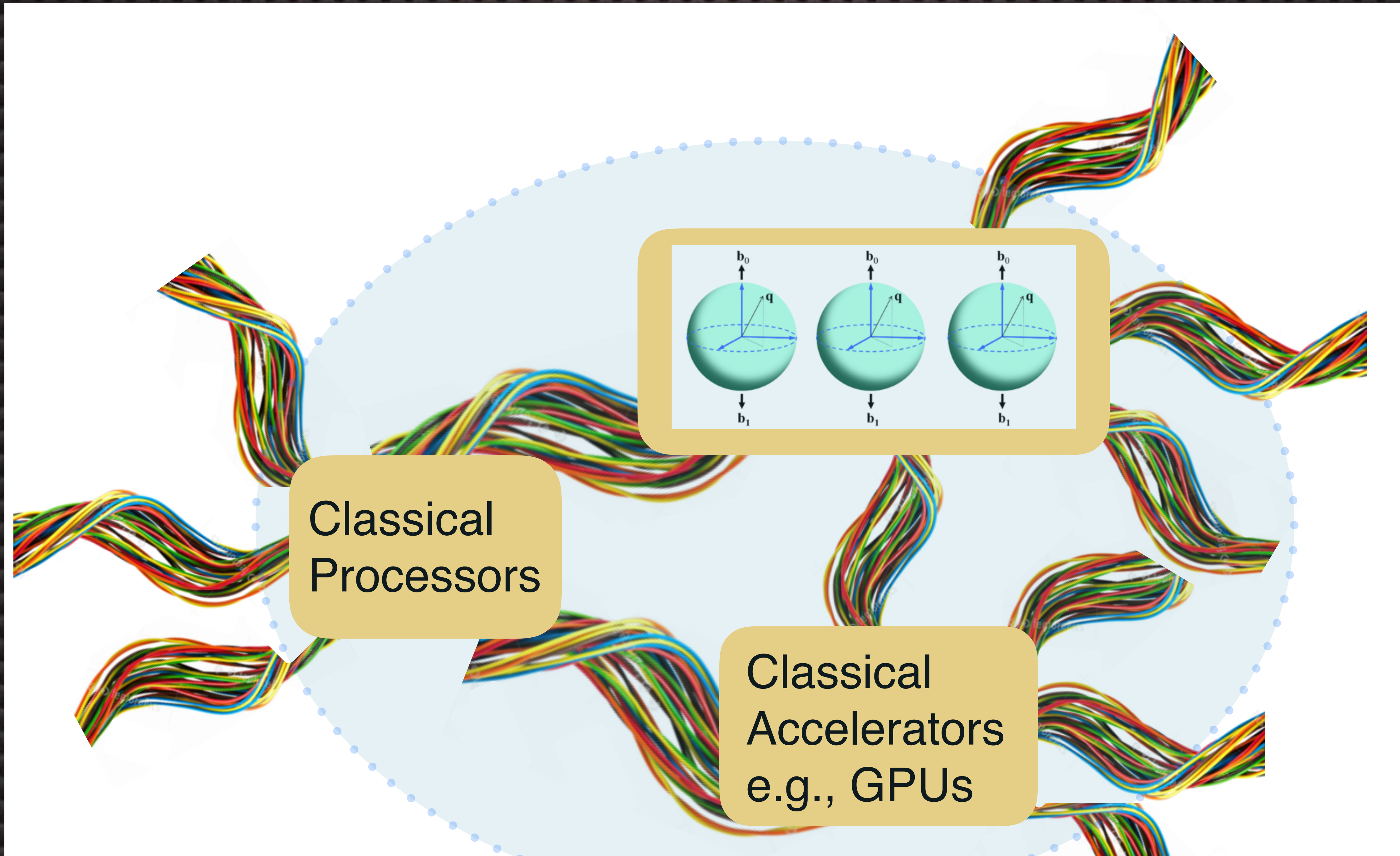


Toric Code is Z_2 lattice gauge field theory

QPU Accelerators and Hybrid Computations - Nodes

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

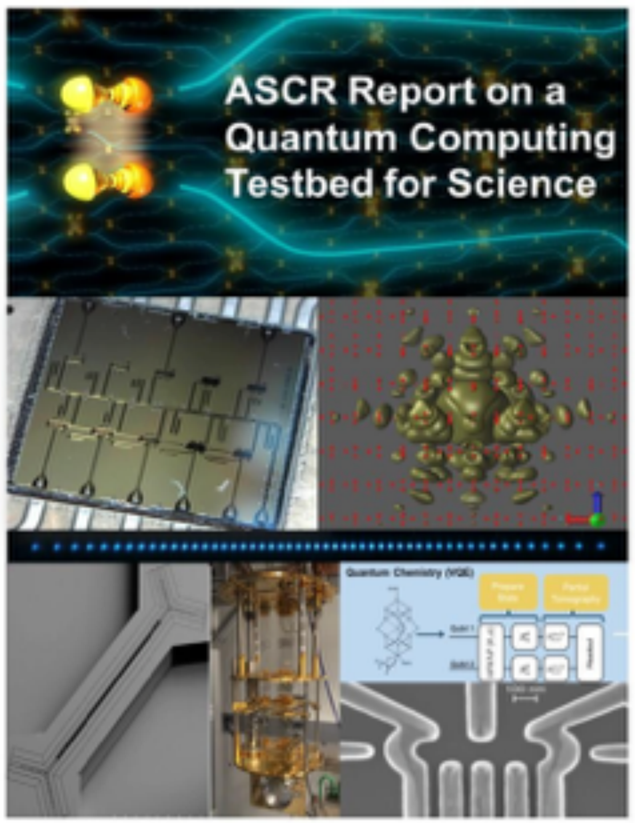
- Speed-up bootleneck components of Lattice QCD computations
  - contractions ? propagators ?
- Identify appropriate components

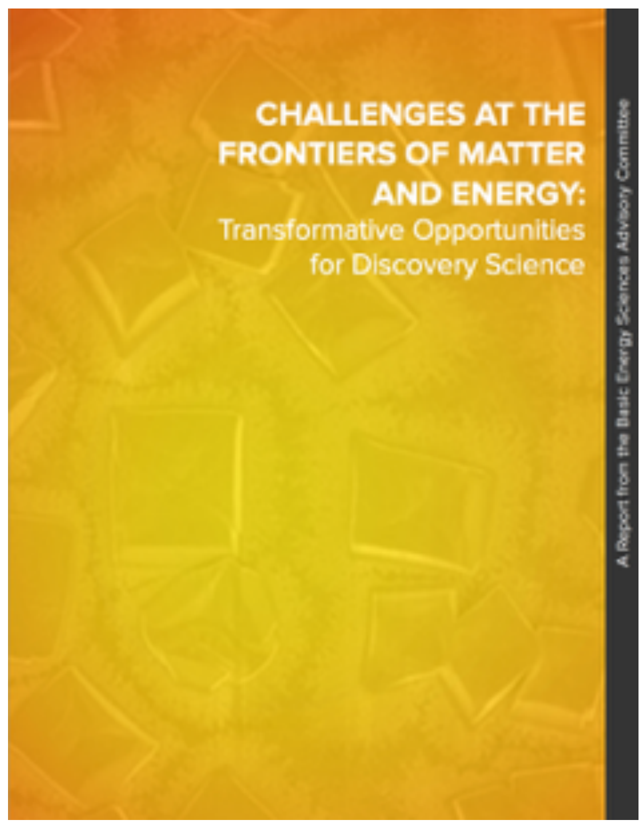


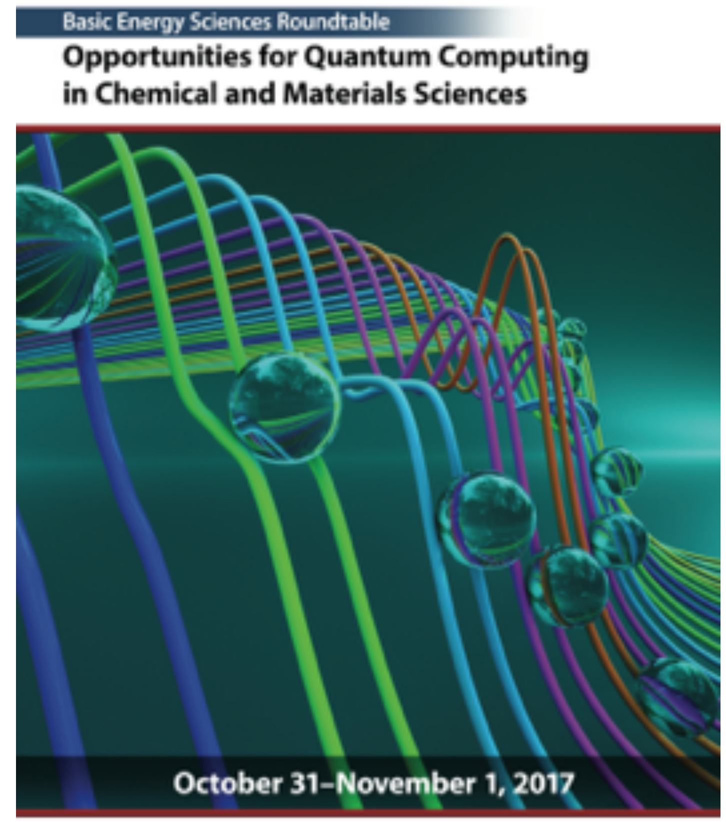
Desirable Infrastructure

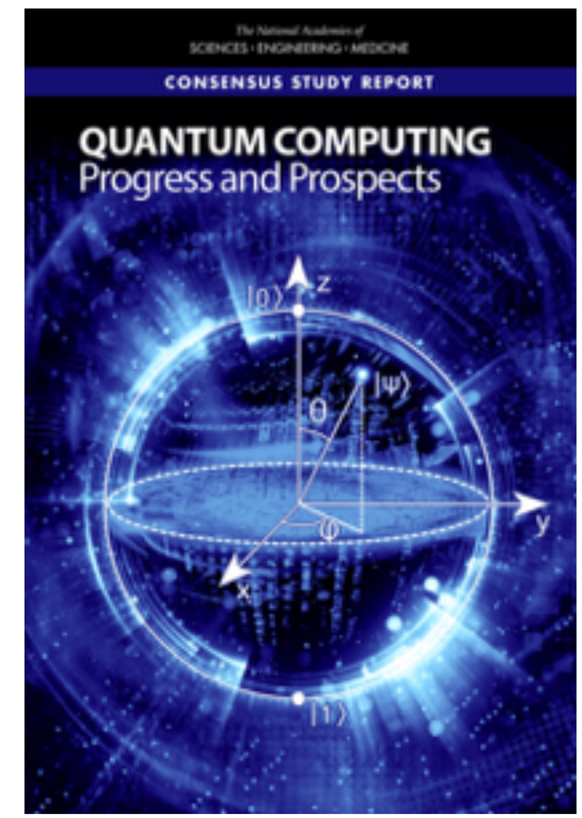
- **Efficient Ideal Simulators at scale, > 30 qubits**
  - Many ideas and algorithms to explore
  - requires HPC and efficient parallel code
- **Noisy simulators - realistic noise models**
  - different architectures
  - requires HPC and efficient parallel code
- **Access to cutting edge hardware**
  - support
- **Focus on Algorithms and Circuit design**
  - collaboration with QIS+QC scientists
  - Lattice Gauge Theory
- **Co-design**
- **Quantum Workforce**

QC and QIS in Broader Community









DOE Study Group Report

Grand Challenges

at the Interface of

Quantum Information Science,

Particle Physics, and Computing

Edward Farhi, Stephen Jordan, Patrick Hayden (co-chair),
Mikhail Lukin, Juan Maldacena, John Preskill (co-chair),
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

+ . . .

Community Activities in Nuclear Physics

Joint Center for Quantum Information and Computer Science

Computational Complexity and HEP
July-31 — August 2, 2017

Oak Ridge National Laboratory

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

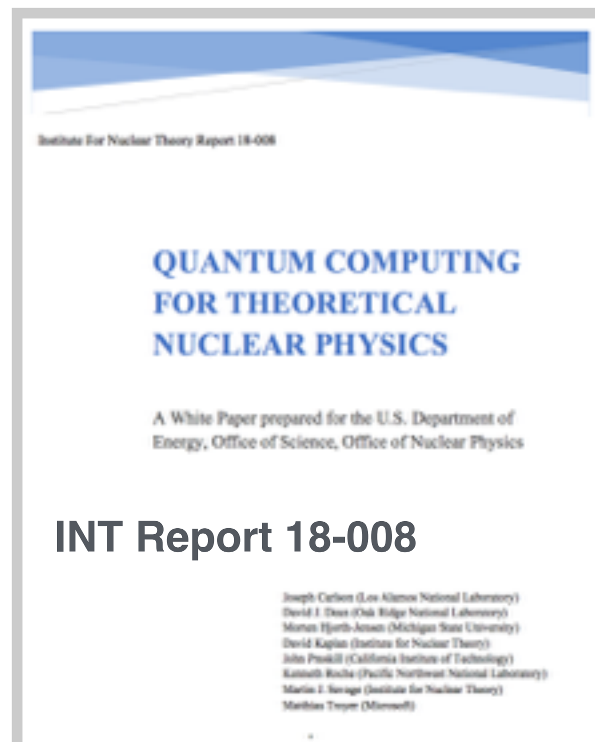
Newer event

Center for Frontiers in Nuclear Science

Quantum Entanglement at Collider Energies

10-12 September 2018
CFNS Stony Brook
Stony Brook
September 10-12, 2018

Institute for Nuclear Theory

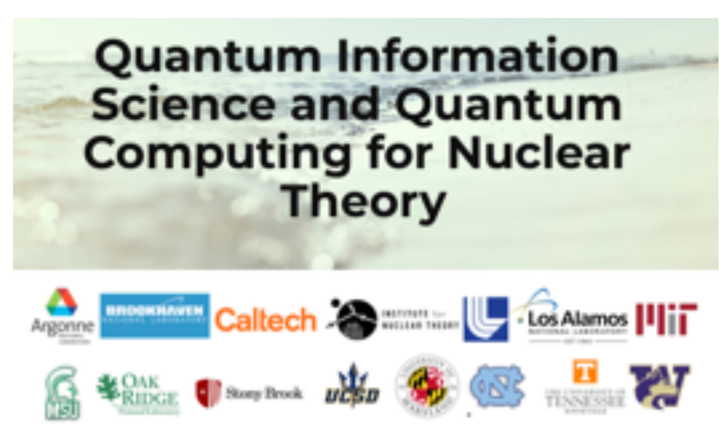

Institute For Nuclear Theory Report 18-008

QUANTUM COMPUTING FOR THEORETICAL NUCLEAR PHYSICS

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

INT Report 18-008

Quantum Computing for Nuclear Physics
November 14-15, 2017



NPQI

Intersections Between NP and QIS
Argonne National Laboratory
March 28-30, 2018

NSAC Quantum Information and Quantum Computing Subcommittee


Photo by Michelle Shinn

Douglas Beck (UIUC)
Amber Boehnlein (JLab)
Joseph Carlson (LANL)
David Dean (ORNL)
Matthew Dietrich (ANL)
William Fairbanks Jr (CSU)
Joseph Formaggio (MIT)
Markus Greiner (Harvard)

David Hertzog (UW)
Christine Muschik (Waterloo)
Jeffrey Nico (NIST)
Alan Poon (LBNL)
John Preskill (Caltech)
Sofia Quaglioni (LLNL)
Krishna Rajagopal (MIT)
Martin Savage (INT)

Subcommittee Meetings

MEETING #1

Bethesda, Maryland

Nuclear Physics Exploration of the Quantum Information Science and Quantum Computing Landscape

March 28-29, 2019

Doubletree by Hilton, 8120 Wisconsin Ave, Bethesda, Maryland 20814

Identify Opportunities for NP

- Experiment
- Data
- Theory
- Computation and Simulation
- Applications

MEETING #2

Seattle, Washington

Quantum Computing and Quantum Information Science: A Deep Dive

April 30 - May 1, 2019

University of Washington, HUB

NP for QIS and QC

- Identify components of NP program, e.g. Isotopes
- Dual impact components

Identify NP specific

Sensing and Simulation are major areas

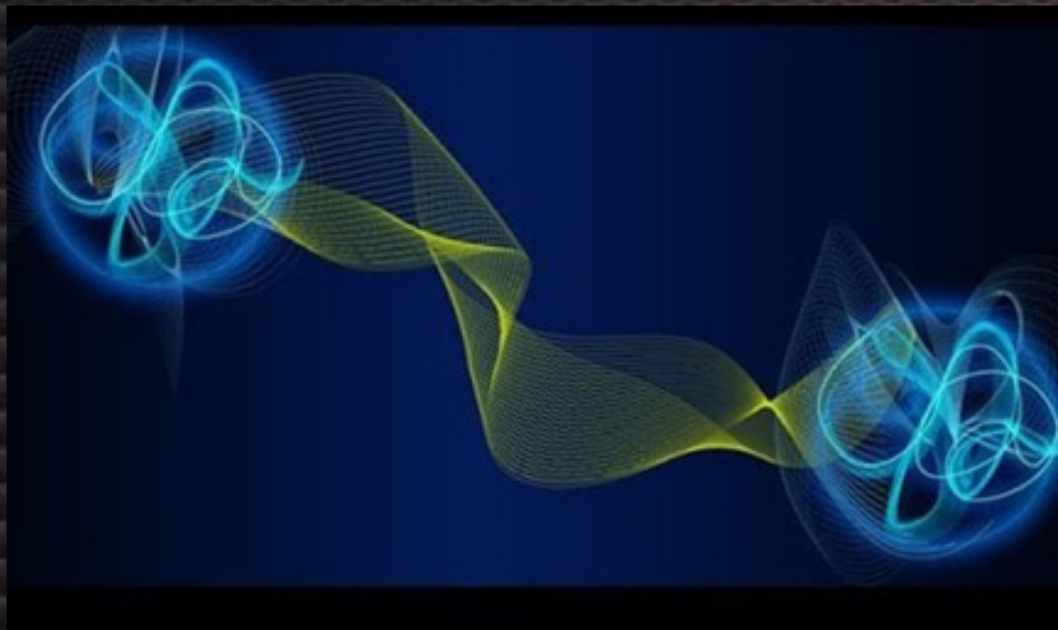
NP: Significant expertise and technology that will be important

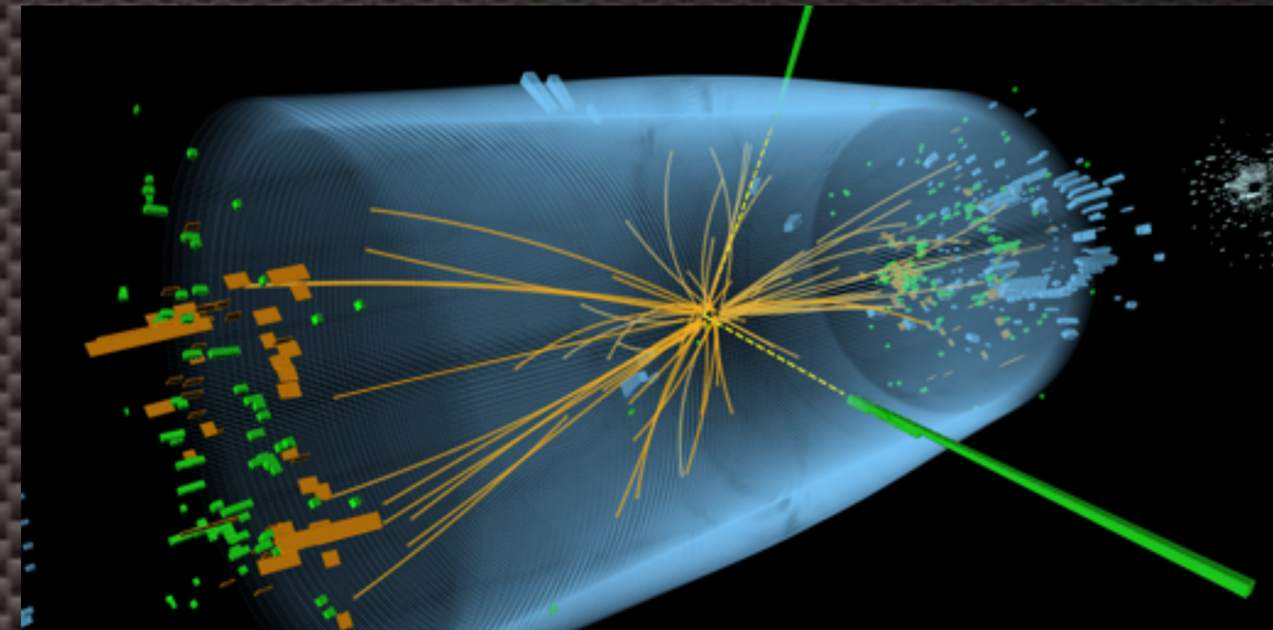
Can benefit substantially from QIS and QC developments

Examples of Possible Contributions to QIS from Nuclear Experimental Program

- Cryogenics experiences, especially with lowest temperatures and large volumes, e.g. including CUORE, nEDM, ADMX, …
- Low background experiments (ultra-pure materials, negligible natural radioactivity)
- Experience with low S/N measurements
- Readout of very cold electronics and electronics multiplexing
- Particle detection with high single particle sensitivity (0vbb, Dark Matter, …)
- Experience with large system controls and operations
- Superconducting RF cavities and microwave measurement techniques. High Q resonators; Squid amplifiers.
- Big data analysis techniques
- Collaborative work toward single goals
- Quantum Many-Body and Lattice Field Theory expertise
- Nuclear Isotopes Program
- Workforce development

Looking Forward





QC and QIS for QFT and QCD

- New understandings and capabilities
  - address exponentially difficult challenges in Nuclear Physics
    - dynamics, fragmentation, nuclei, nuclear reactions, dense matter, ….
  - complement, accelerate and not replace classical HPC
  - low-dimensional, simple systems being ``stood up”

QFT and Quantum Many-Body techniques for QC and QIS

- e.g., Scrambling, error-correction, quantum memory

FIN

Motivation(s) for Nuclear Physics

Quantum Information Science 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 ….