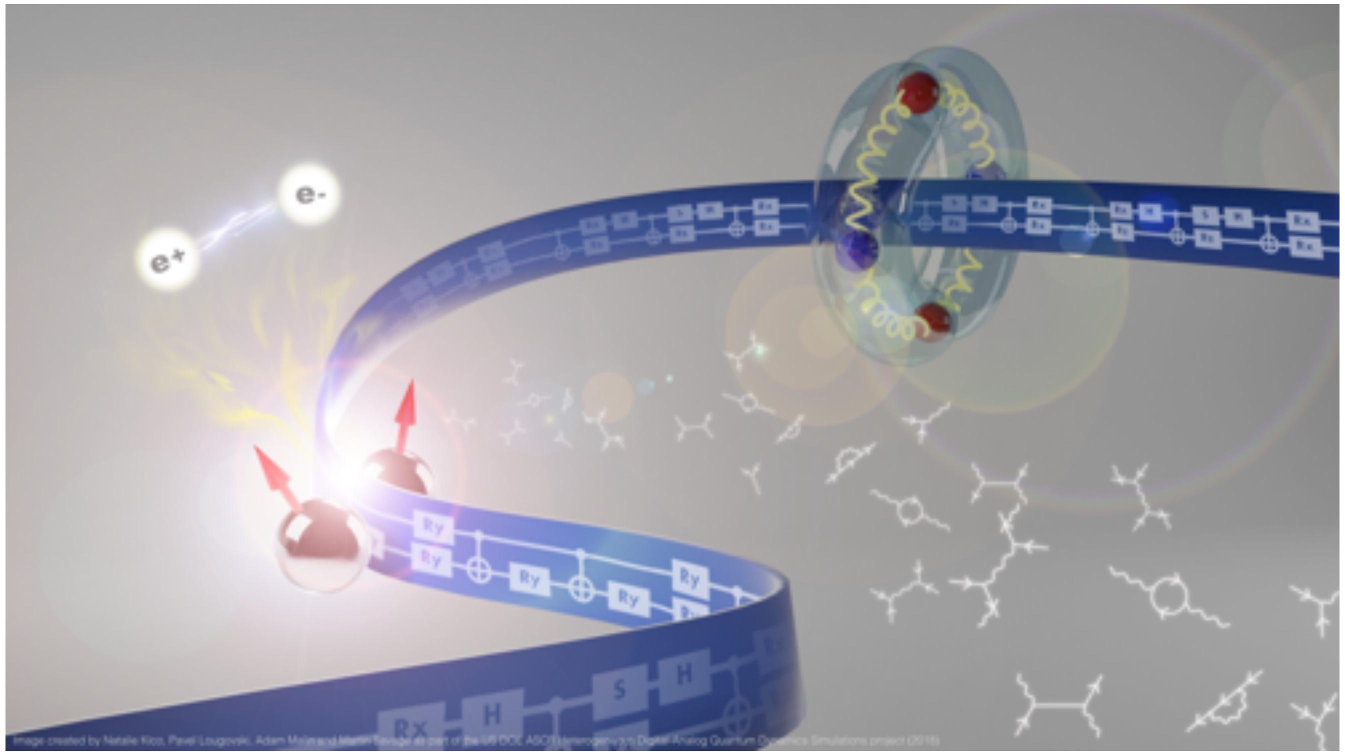
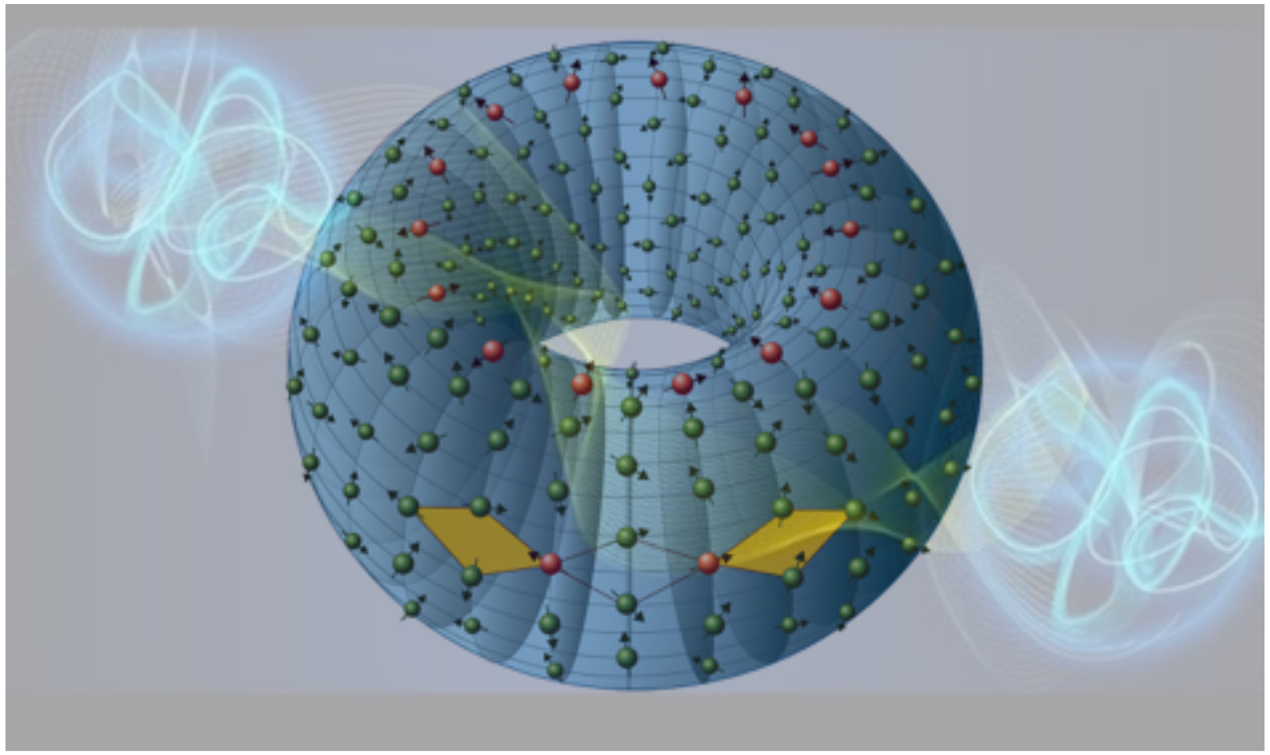
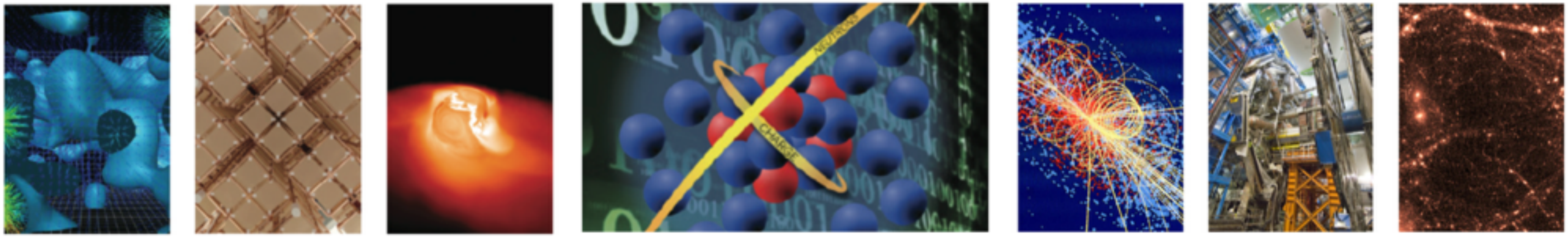


Image created by Natalie Klco, Pavel Lougovski, Adam Molina and Martin Savage as part of the US DOE ASCR Heterogeneous Digital-Analog Quantum Dynamics Simulations project (2018)





Quantum Computing and Quantum Information for Nuclear Physics Grand Challenge Problems

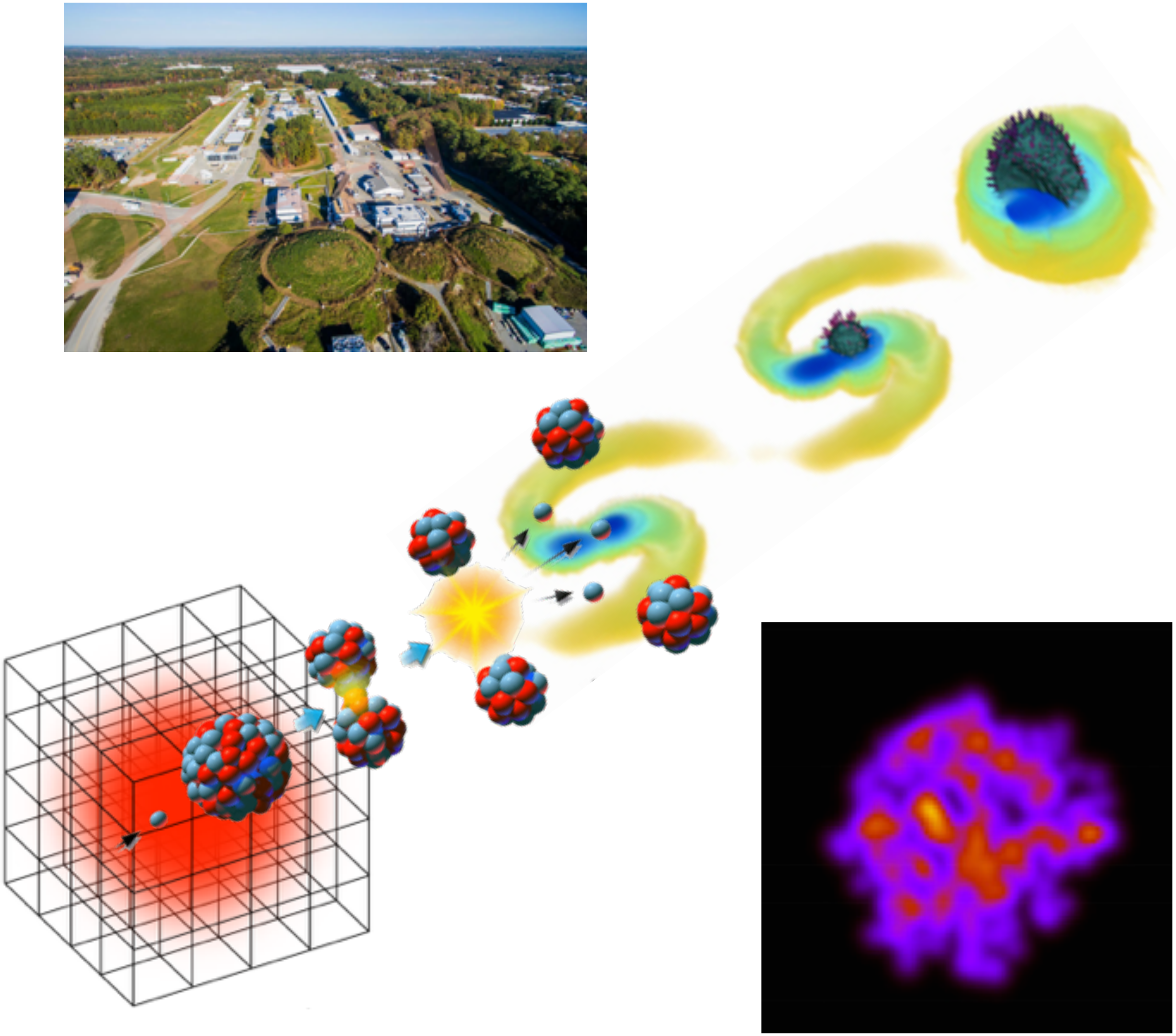
DESY Zeuthen, Colloquium, 5 March, 2019

Martin J Savage

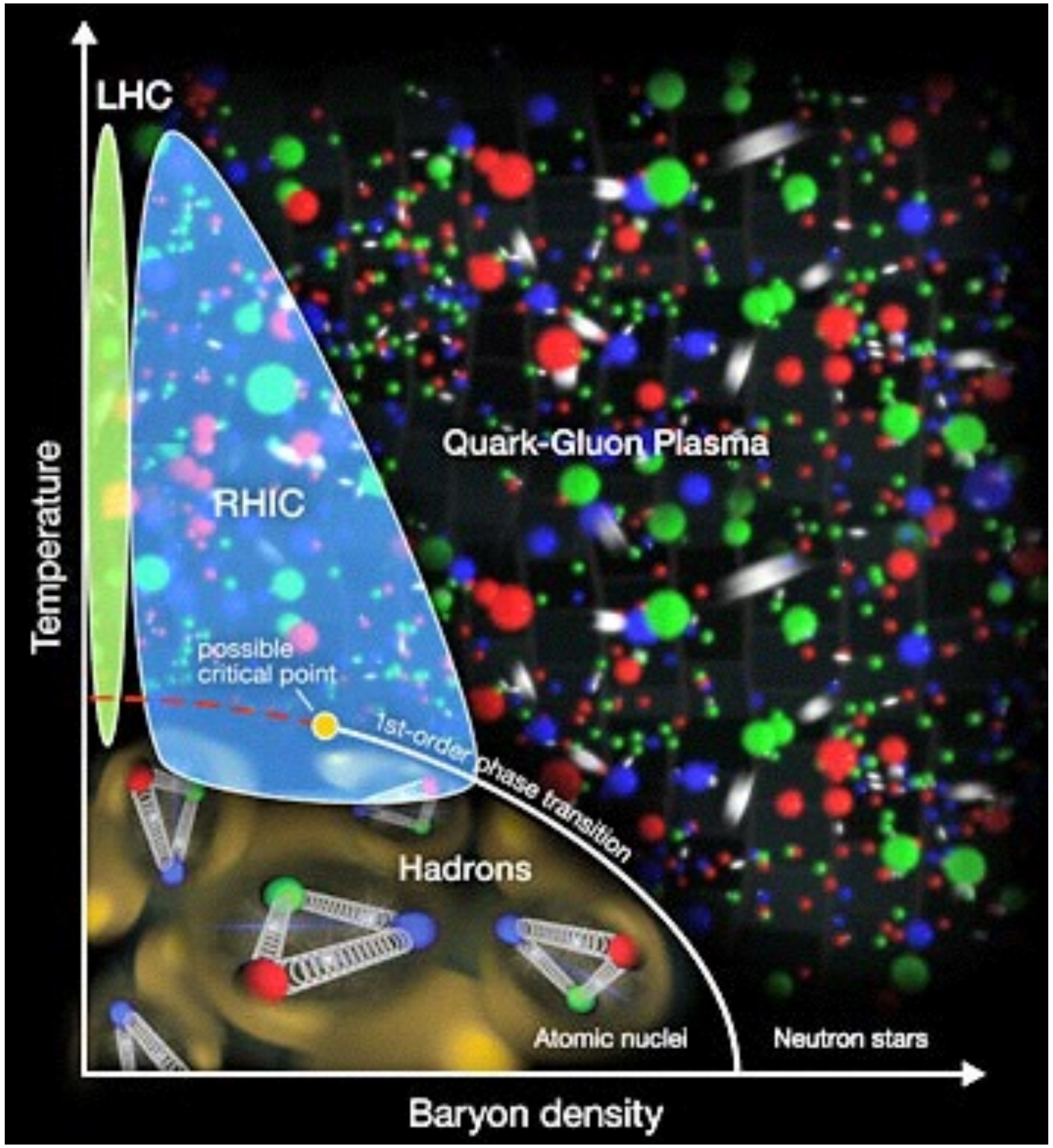
INSTITUTE for NUCLEAR THEORY

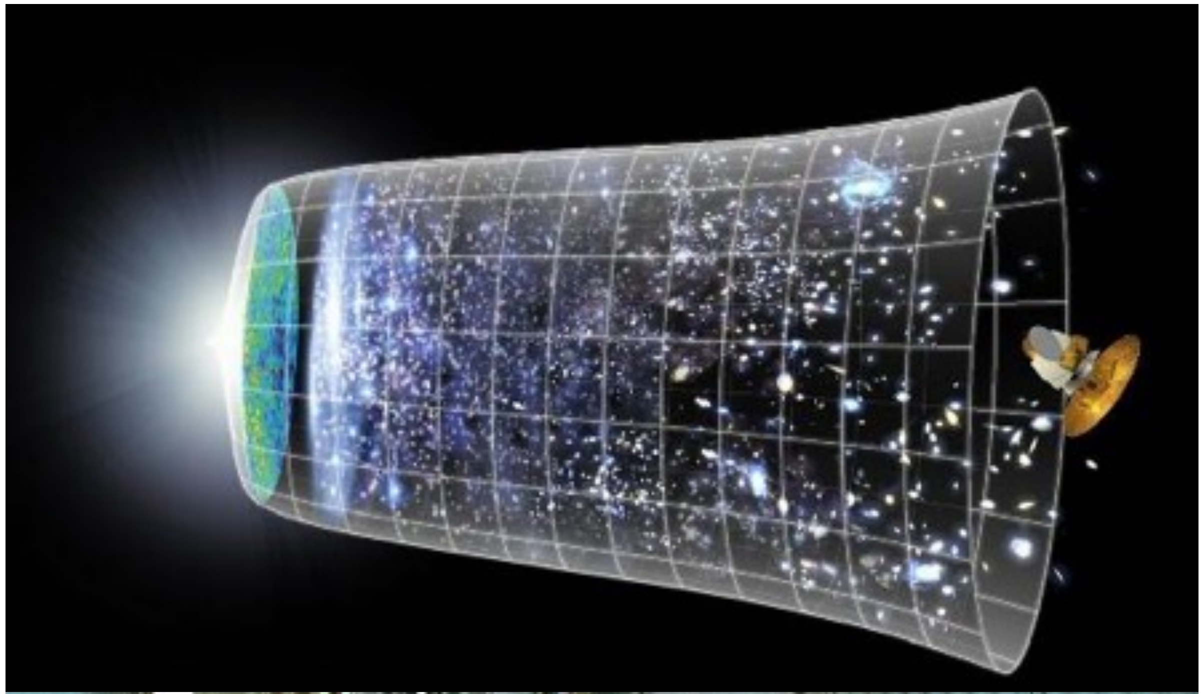
An Objective of Nuclear Physics Research

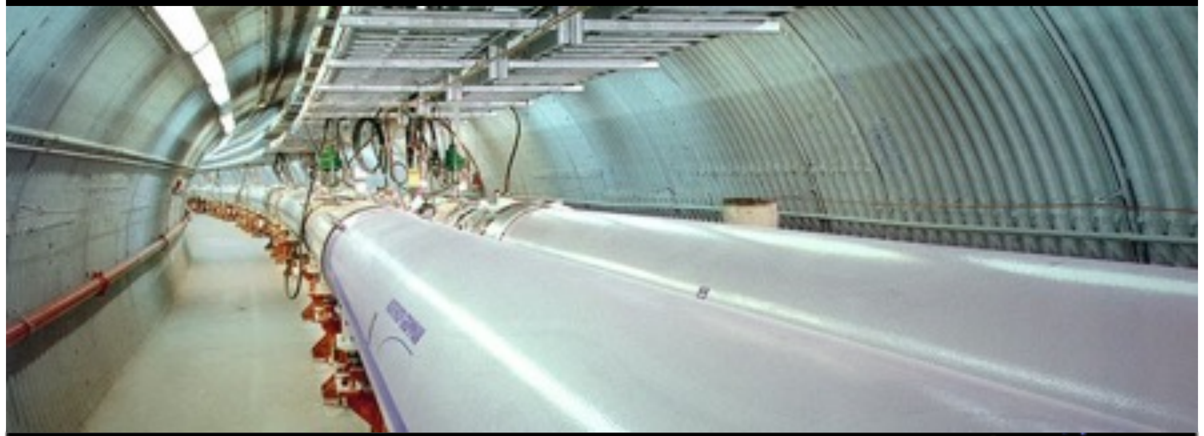
Imagine being able to predict — with unprecedented accuracy and precision — the structure of the proton and neutron, and the forces between them, directly from the dynamics of quarks and gluons, and then using this information in calculations of the structure and reactions of atomic nuclei and of the properties of dense neutron stars...

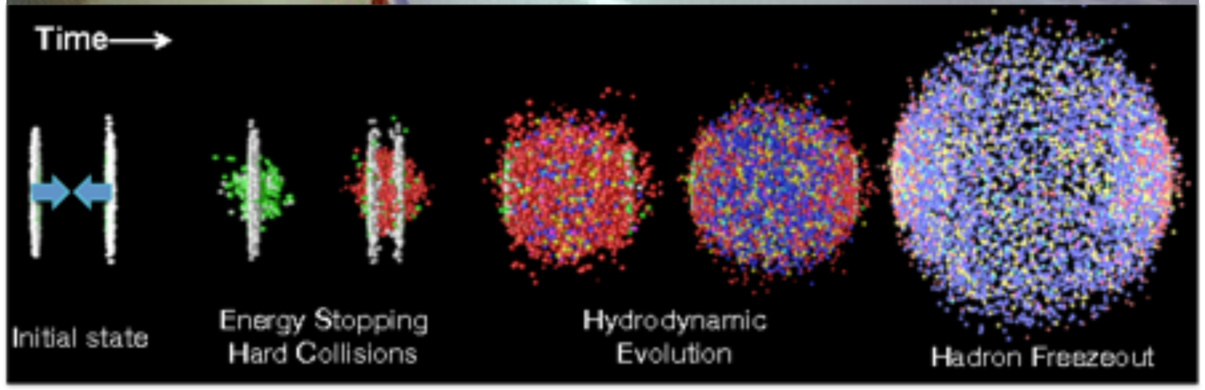


Dynamics of Hot and Dense Matter

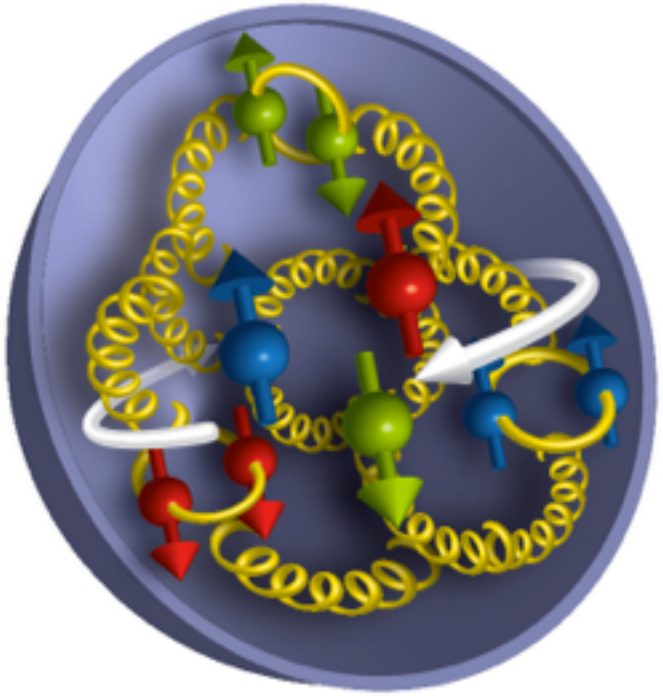


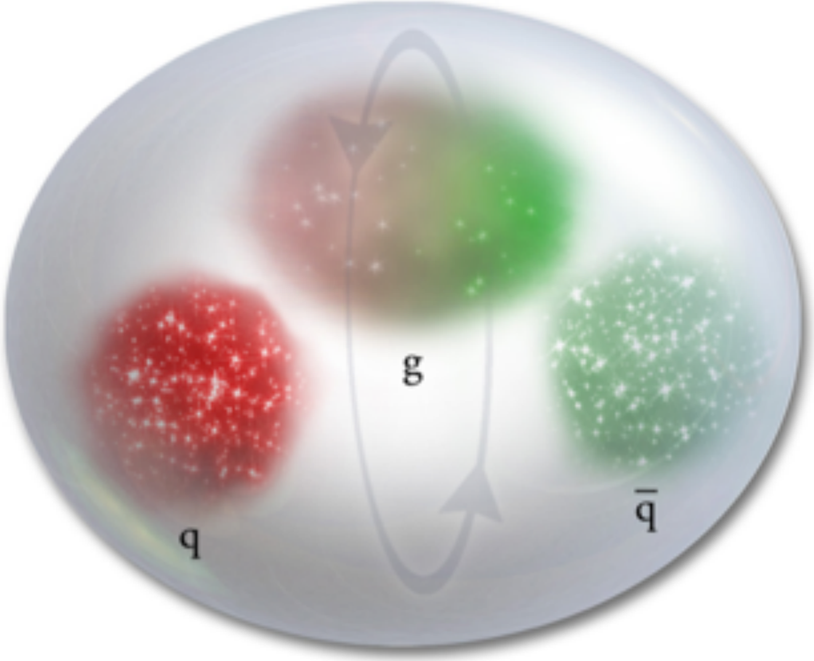


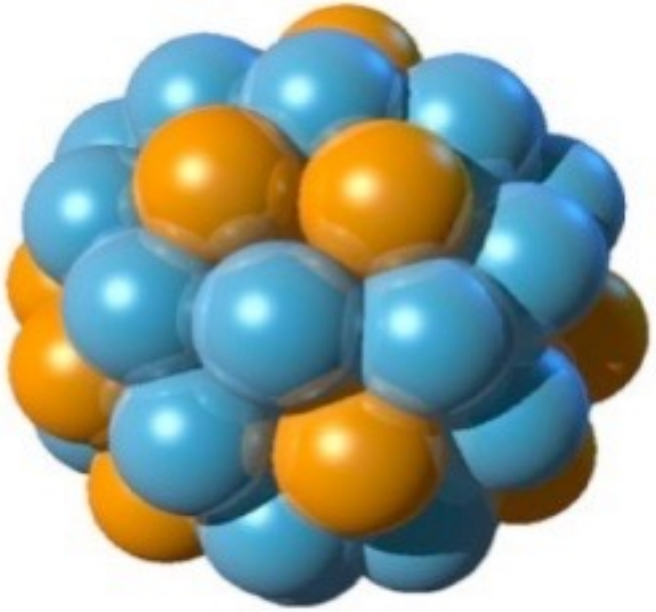


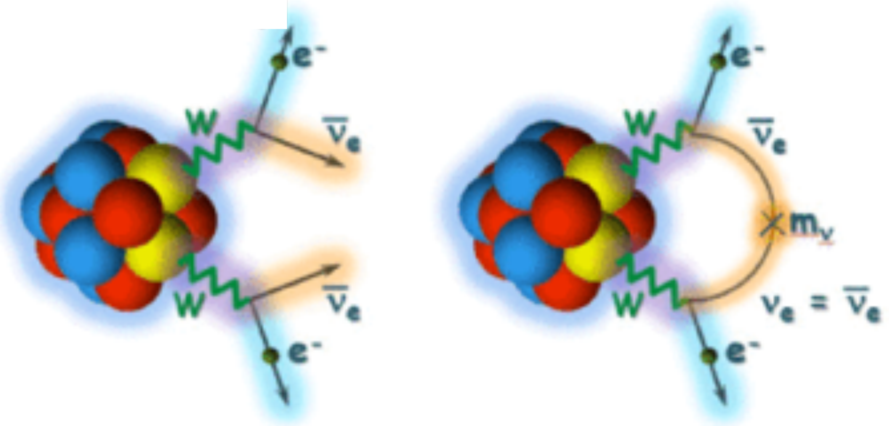


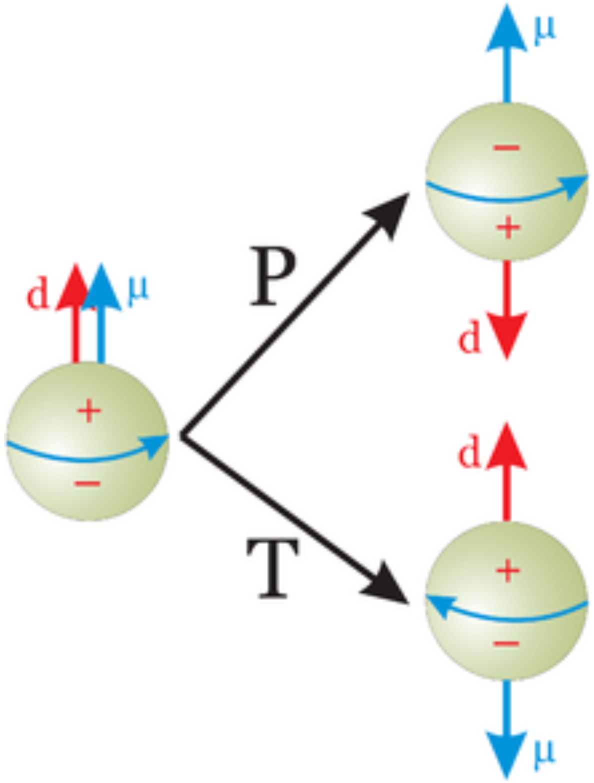
The Structure and Interactions of Strongly Interacting Matter

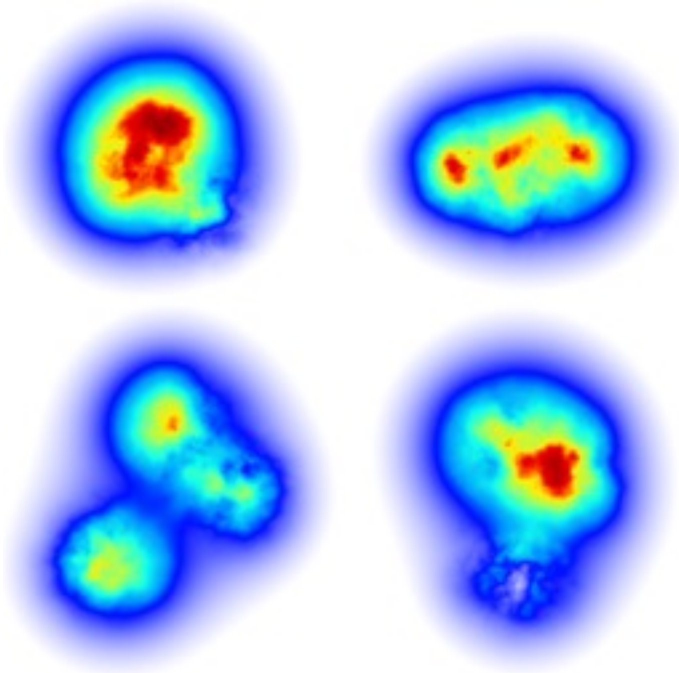




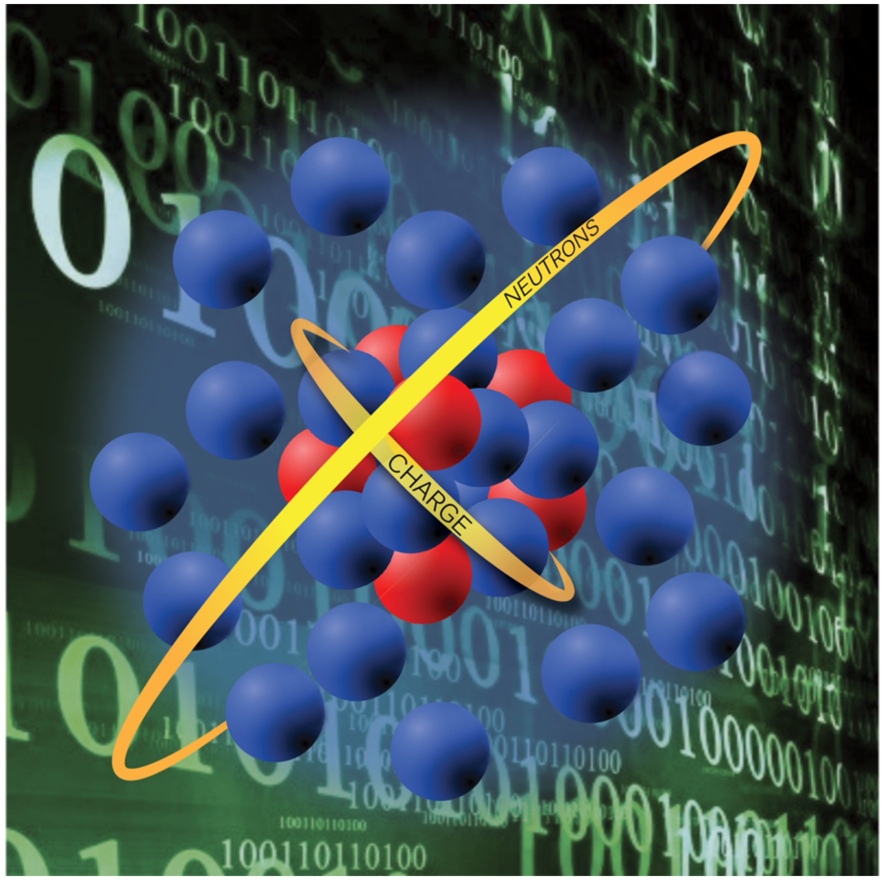


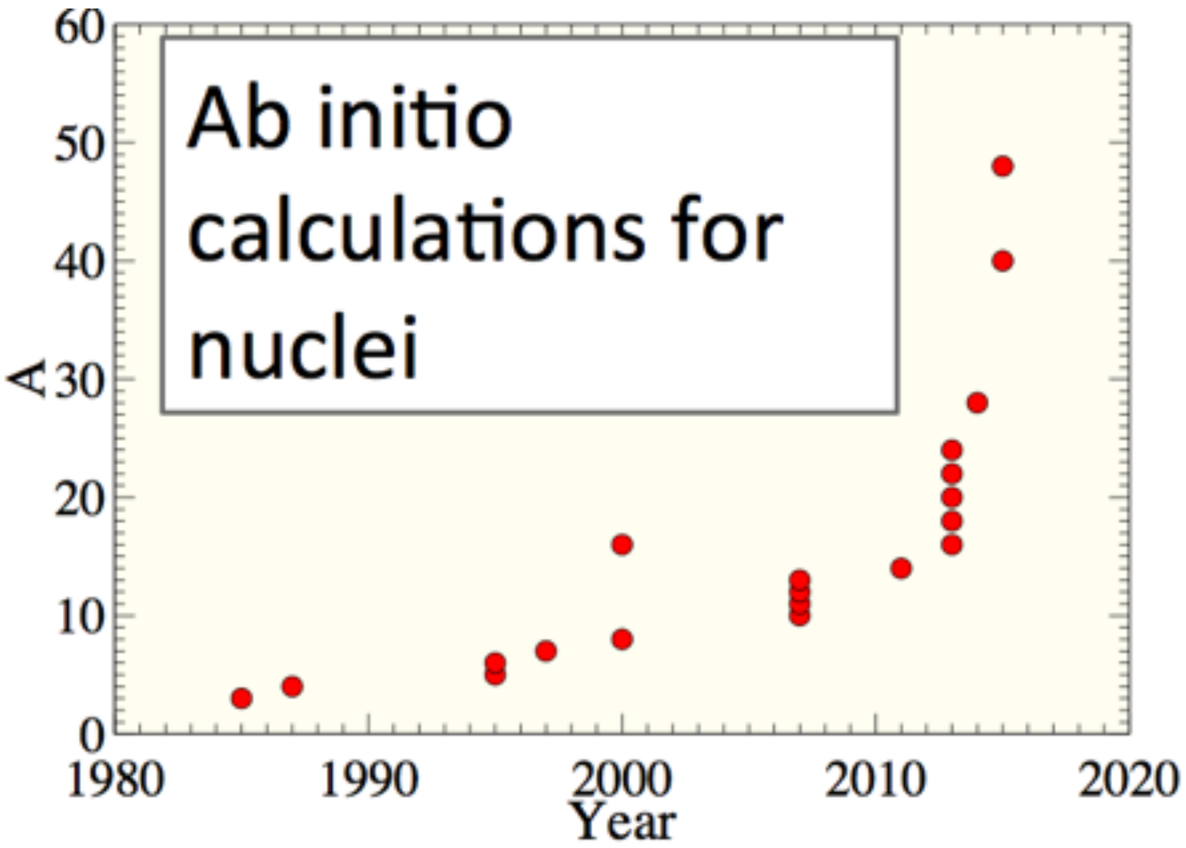




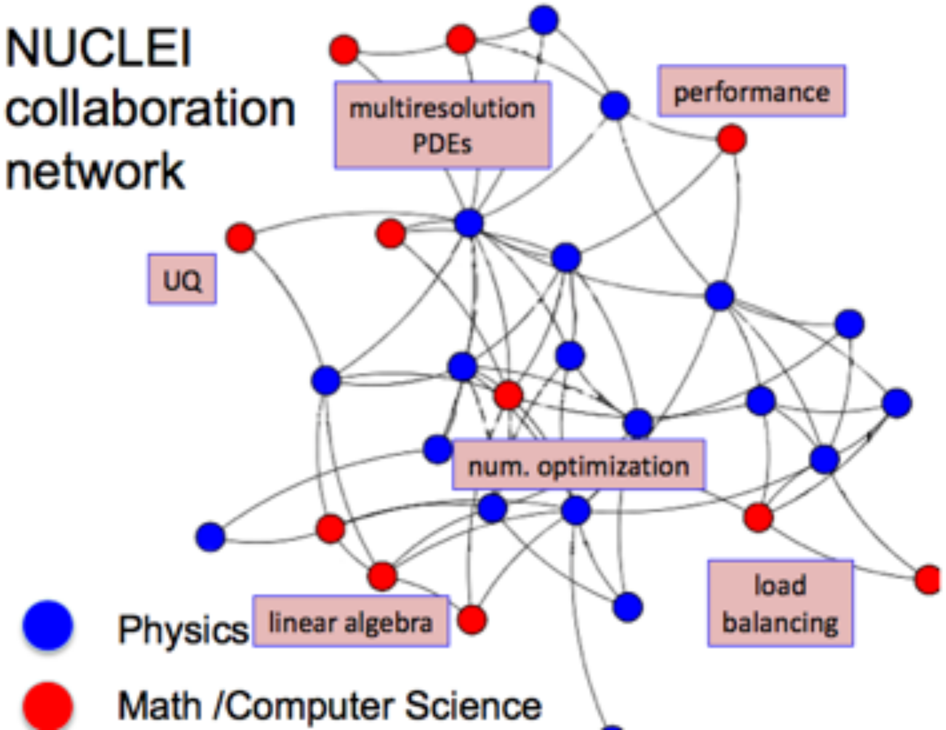


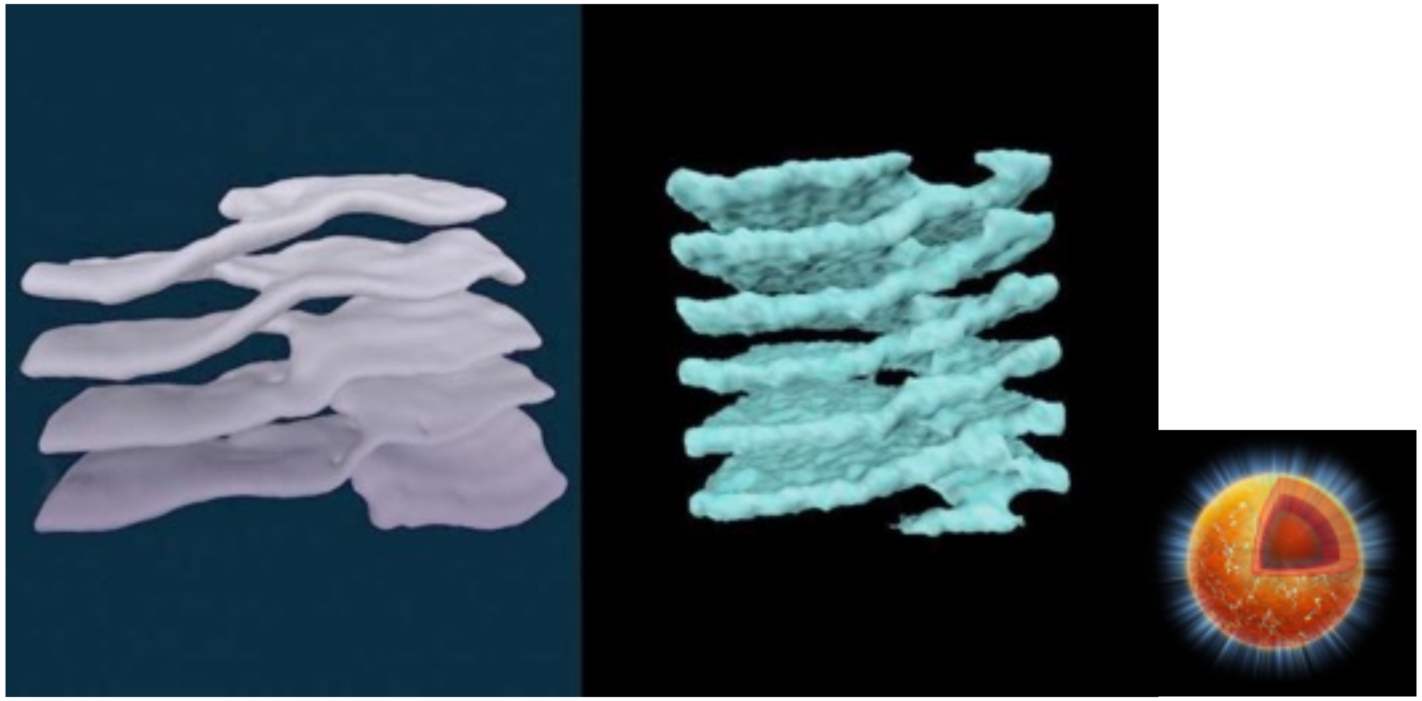
Nuclei and Nuclear Matter



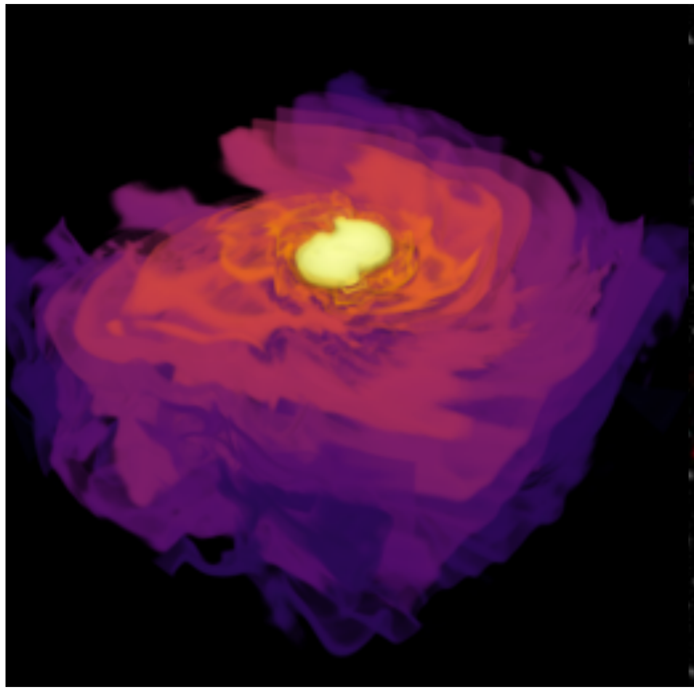


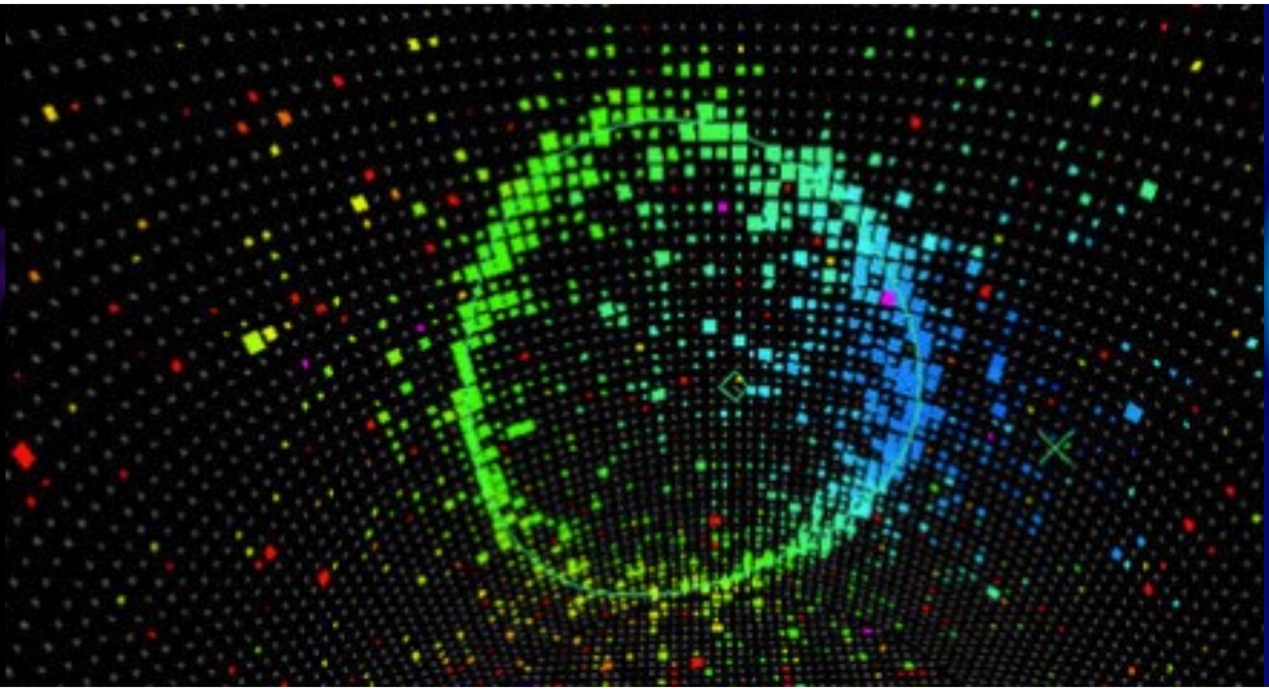
NUCLEI collaboration network

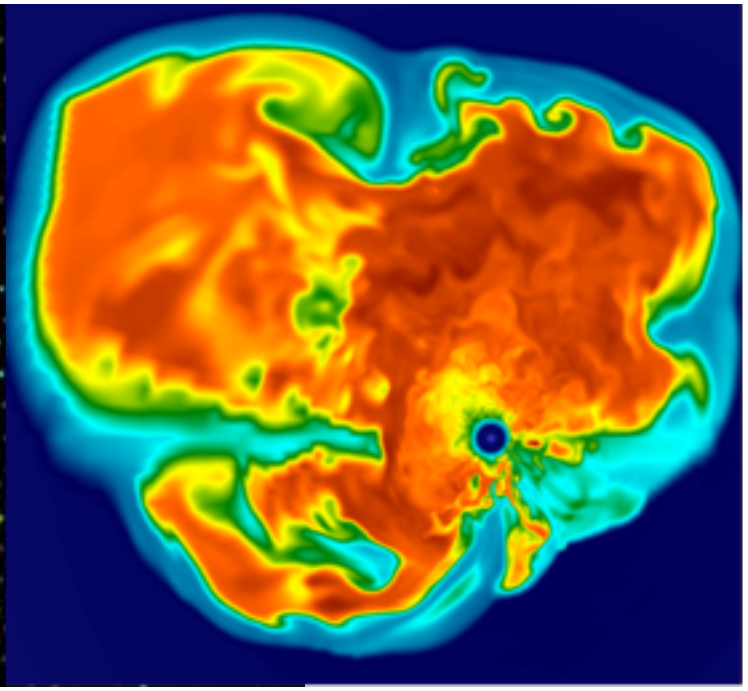


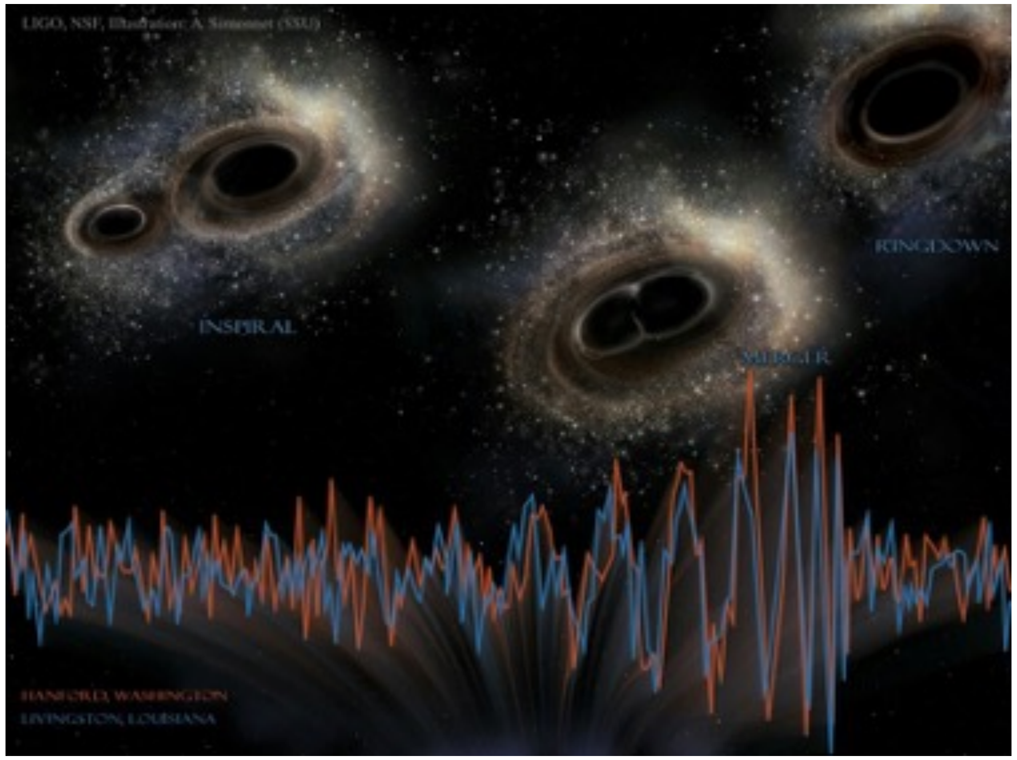


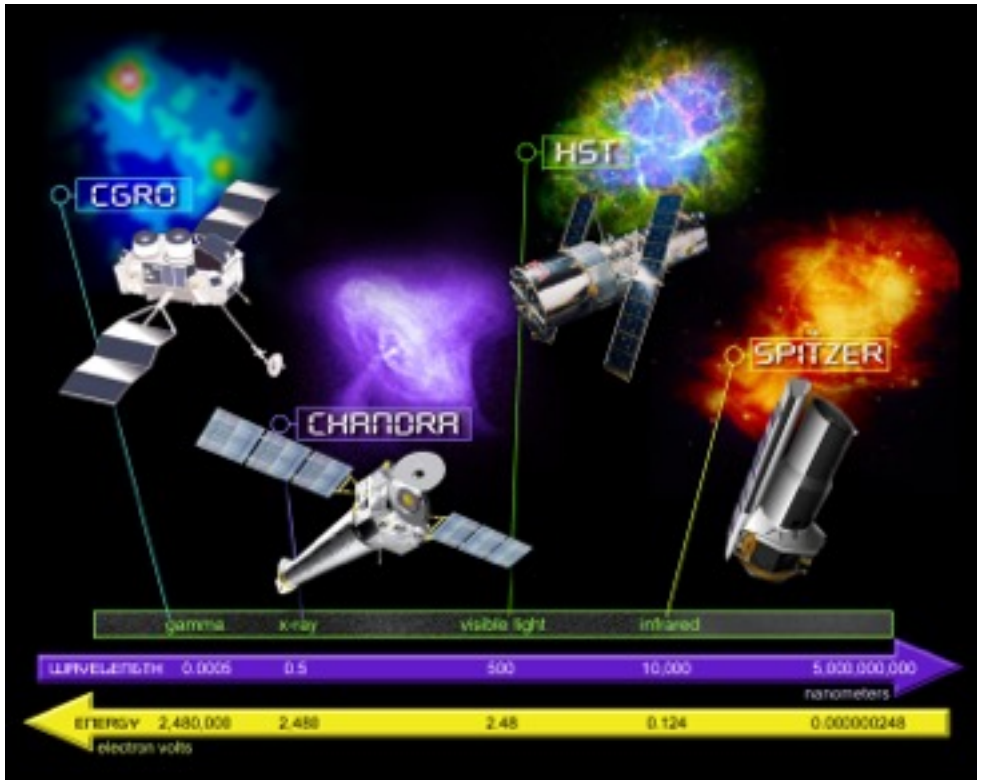
Nuclear Astrophysics





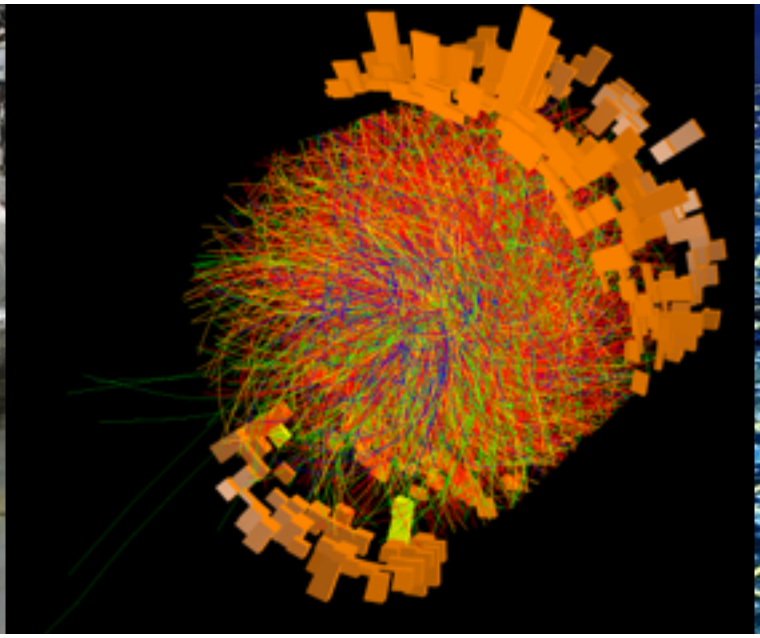


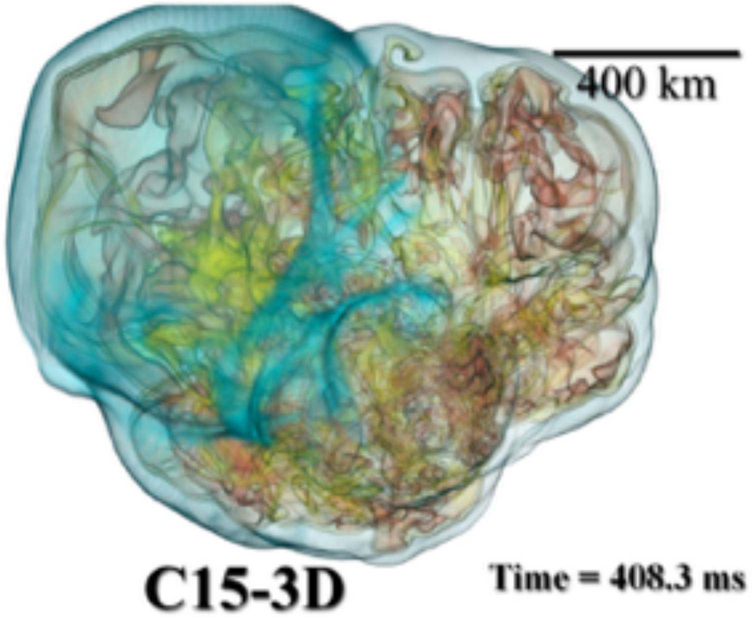




High-Performance Computing for US NP

High Performance Computing is essential for NP research program



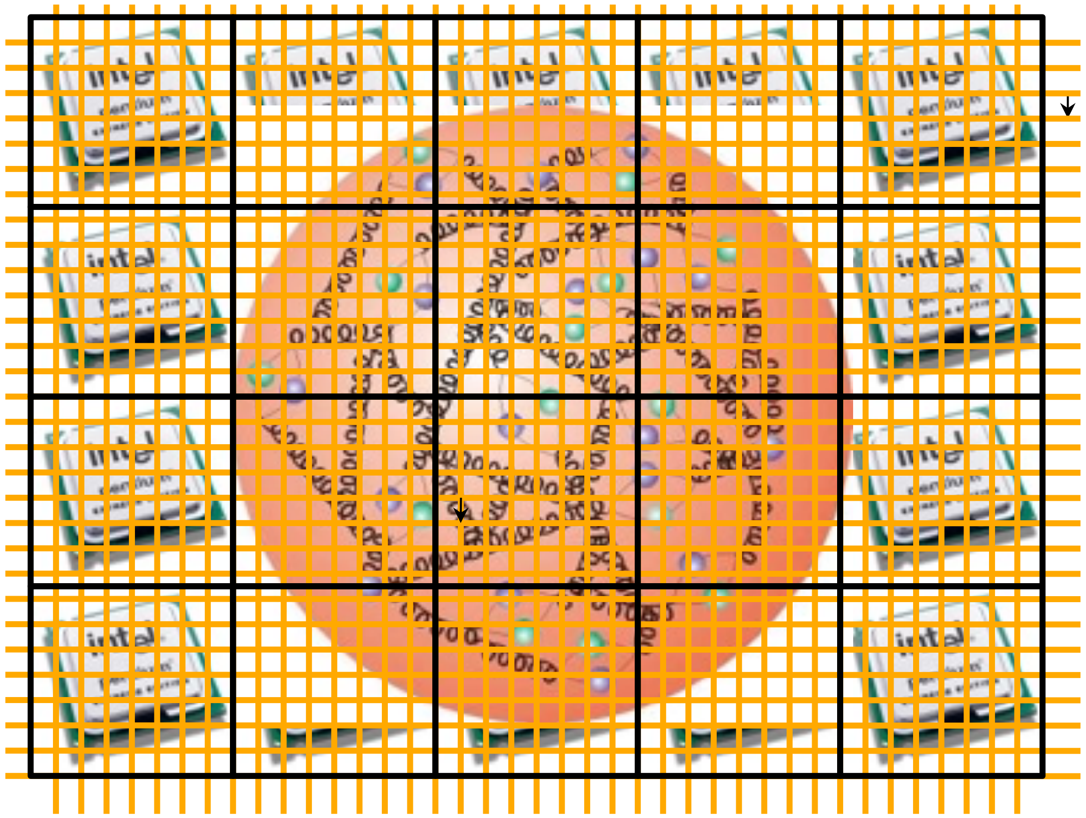


1. Design and Optimization of the vibrant NP experimental program ~ $1.2 Bn enterprise for construction+operations, ~4000 users

2. Acquisition and handling of experimental data

3. Large-scale simulations and calculations of emergent complex systems from subatomic to cosmological

Dynamics of Quarks and Gluons
Lattice Quantum Chromodynamics
A Lattice Gauge Theory



Lattice Spacing :

$a << 1/\Lambda\chi$

(Nearly Continuum)

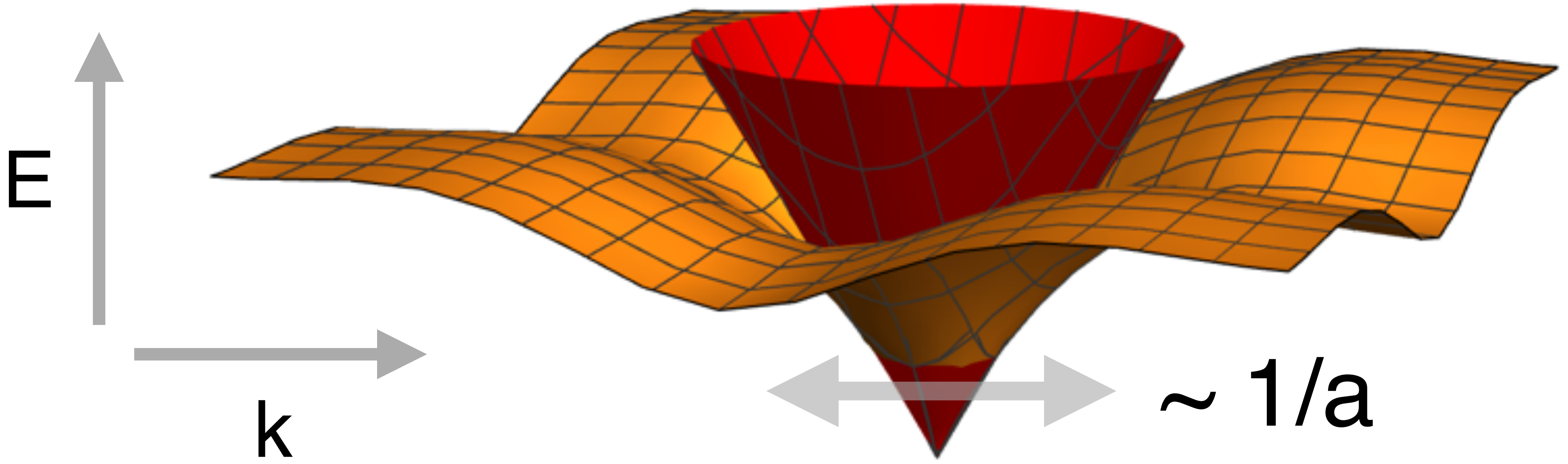
Lattice Volume :

$m_\pi L >> 2\pi$

(Nearly Infinite Volume)

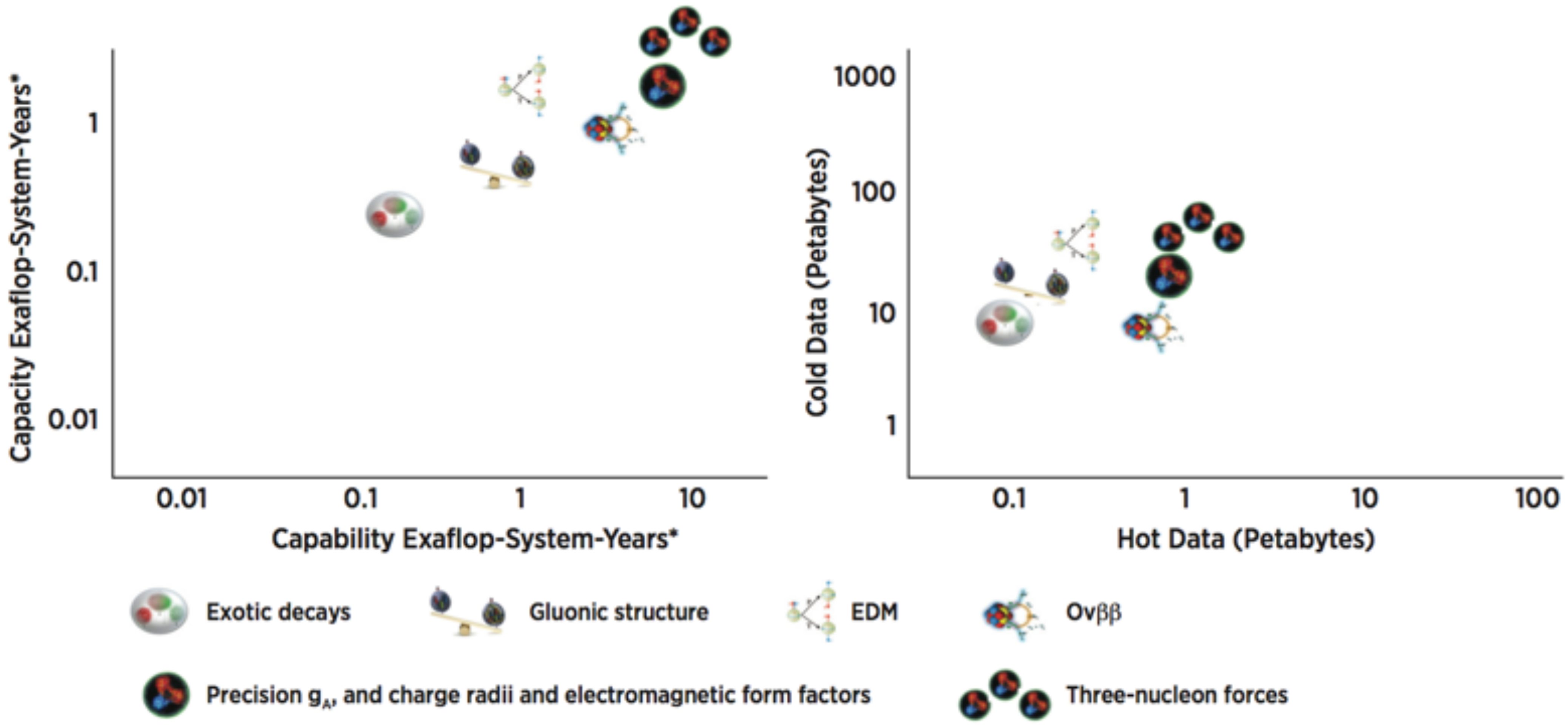
Extrapolation to $a = 0$ and $L = \infty$

Systematically remove non-QCD parts of calculation through effective field theories



Exascale Computing Needs

CAPABILITY/CAPACITY RESOURCES VS. HOT/COLD DATA RESOURCES IN 2025
COLD QCD



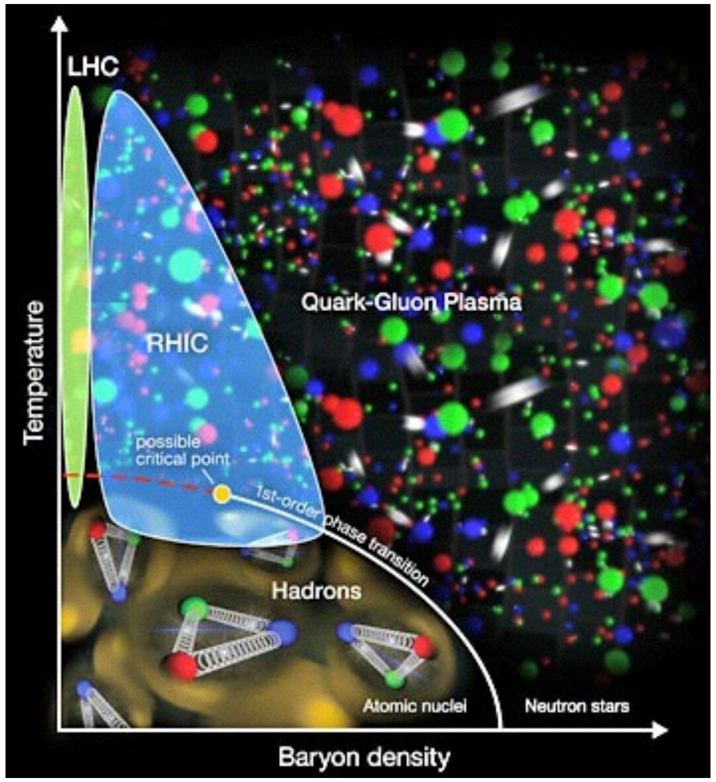
* Exaflop-system-year refers to the total amount of computation produced by an exascale computer in 1 year.

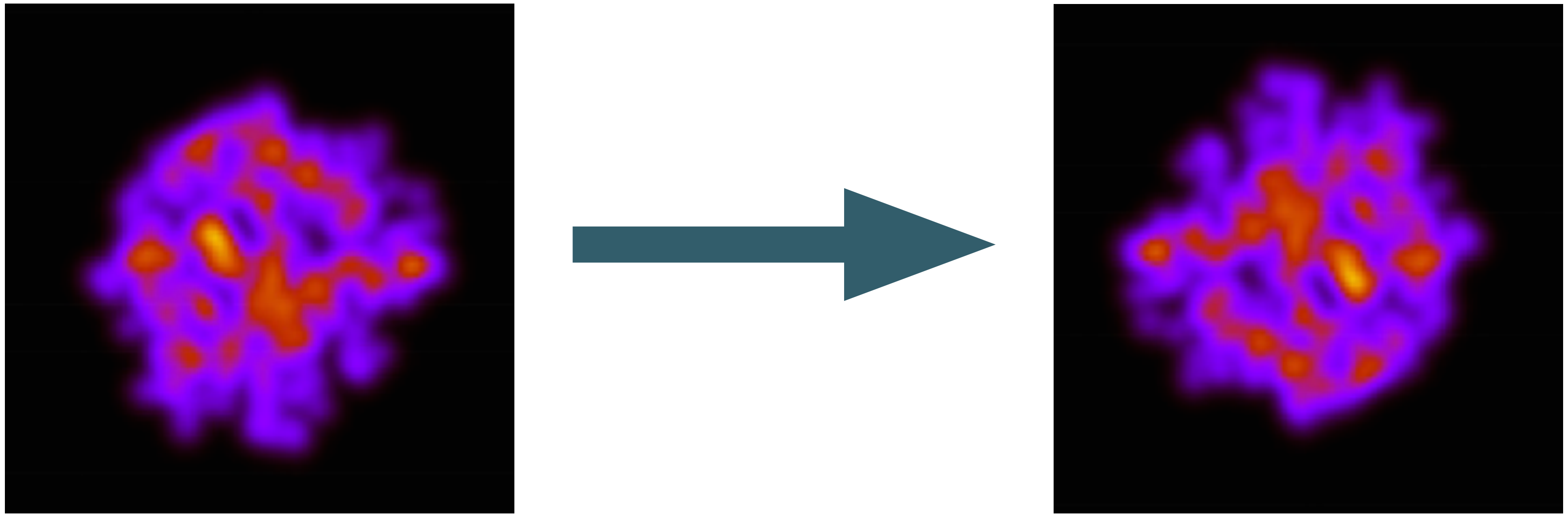
Figure 3-40. The capability and capacity computing resource requirements (left panel) and the hot and cold data requirements (right panel) in 2025 to accomplish the science objectives of the Cold QCD program.

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

“ Features - Finite Density “

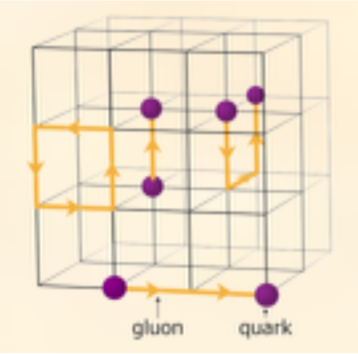
Time evolution of system with baryon number, isospin, electric charge, strangeness, …..
Currents, viscosity, non-equilibrium dynamics - real-time evolution





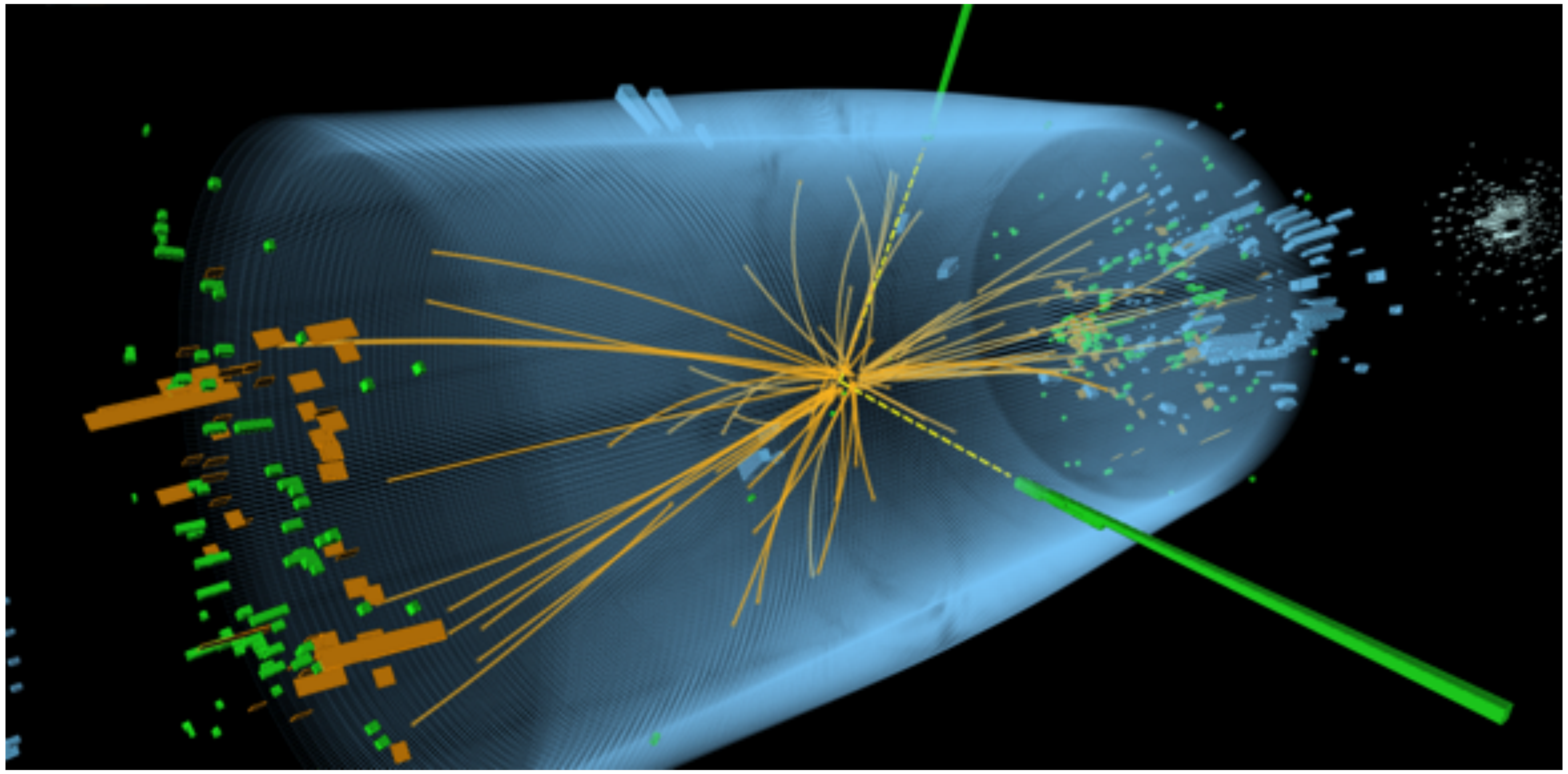
Sign Problem

$$\langle\hat{\theta}\rangle \sim \int \mathcal{D}\mathcal{U}_\mu \; \hat{\theta}[\mathcal{U}_\mu] \; \det[\kappa[\mathcal{U}_\mu]] \; e^{-S_{YM}}$$



Complex for non-zero chemical potential

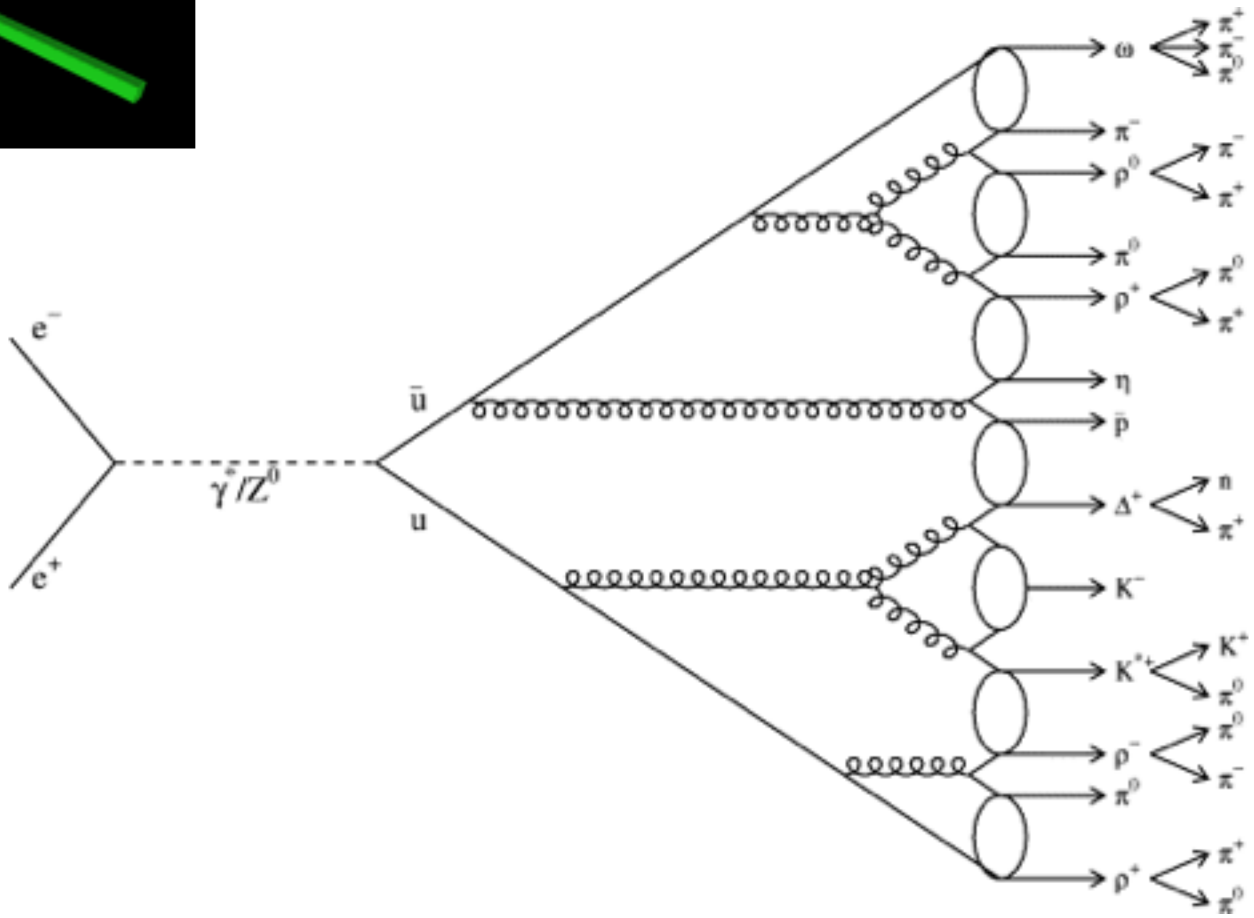
Fragmentation
Vacuum and In-Medium



Free-space and in-medium

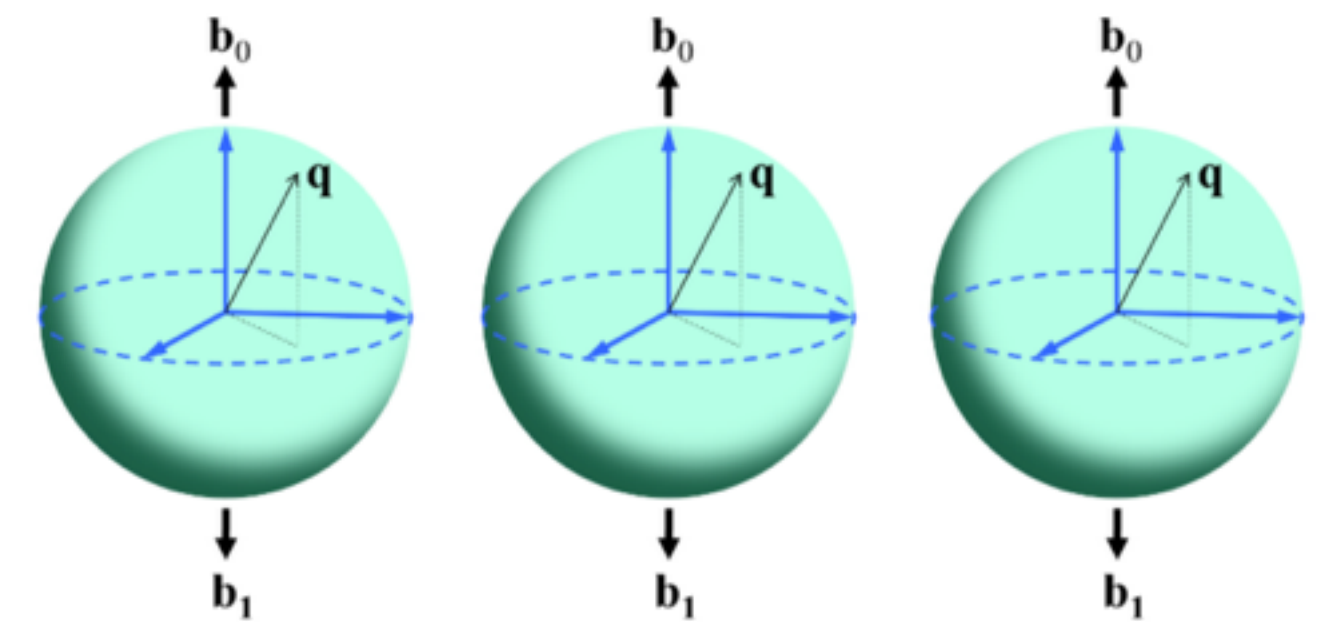
Diagnostic of state of dense and hot matter
- heavy-ion collisions (e.g., jet quenching)
- finite density and time evolution

Highly-tuned phenomenology and pQCD calculations



At the Heart of Quantum Computing

Nonlocality and Entanglement



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

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

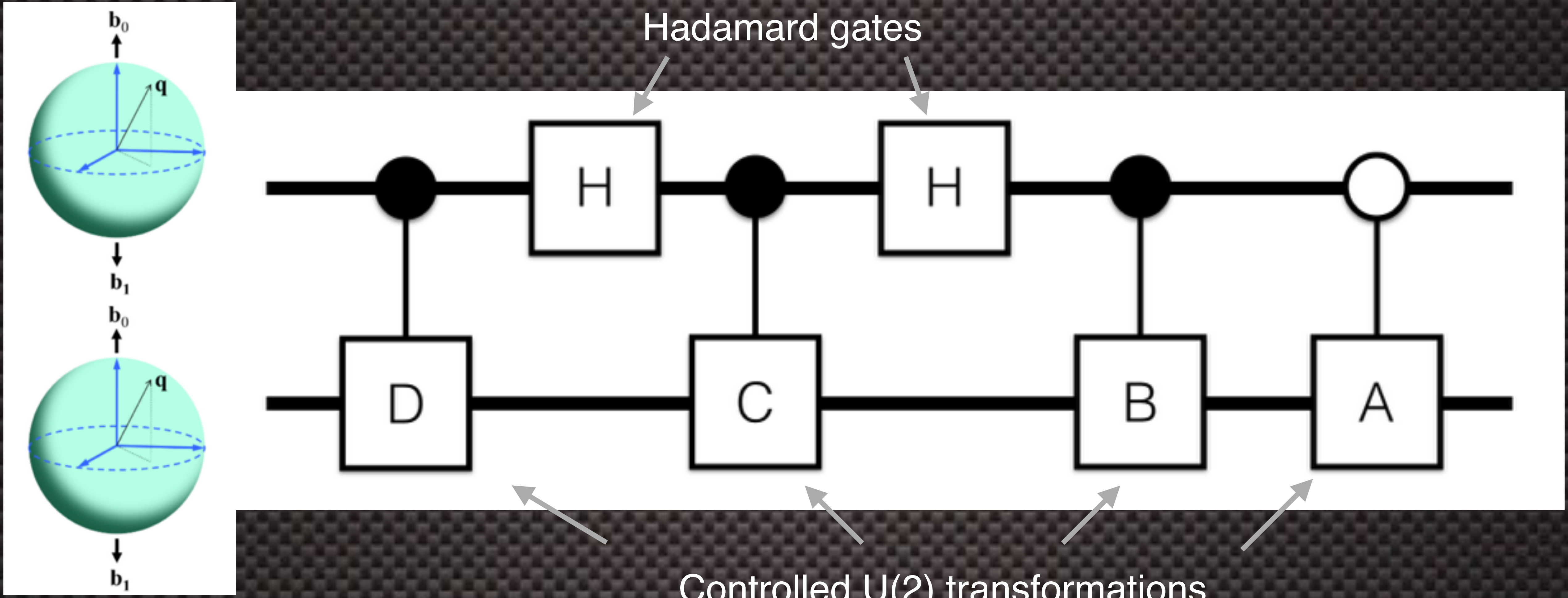
can be in a combination of all states at once

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

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

At the Heart of Gate-Based Quantum Computing

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

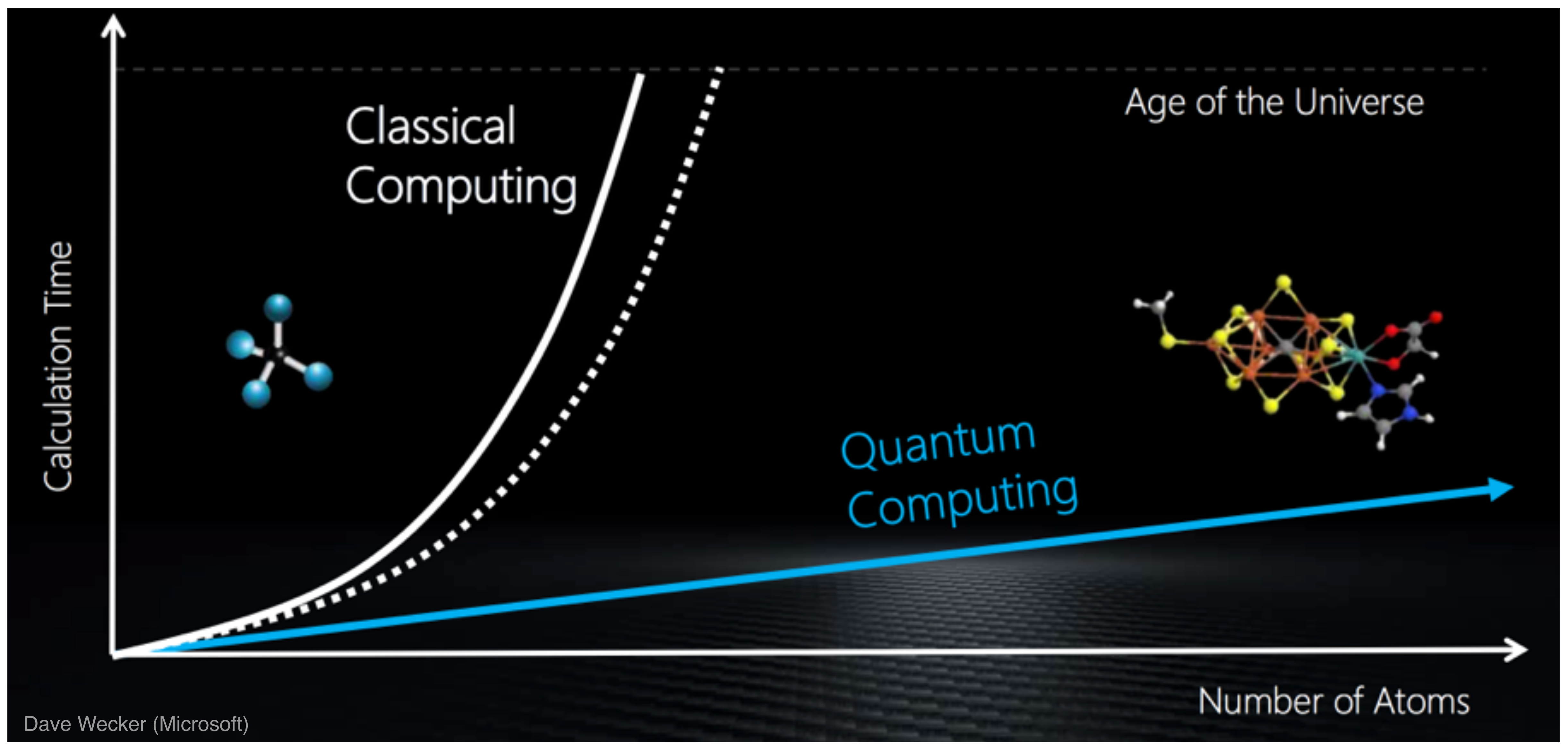


Hadamard gates

Controlled U(2) transformations

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

The Potential of Quantum Computing



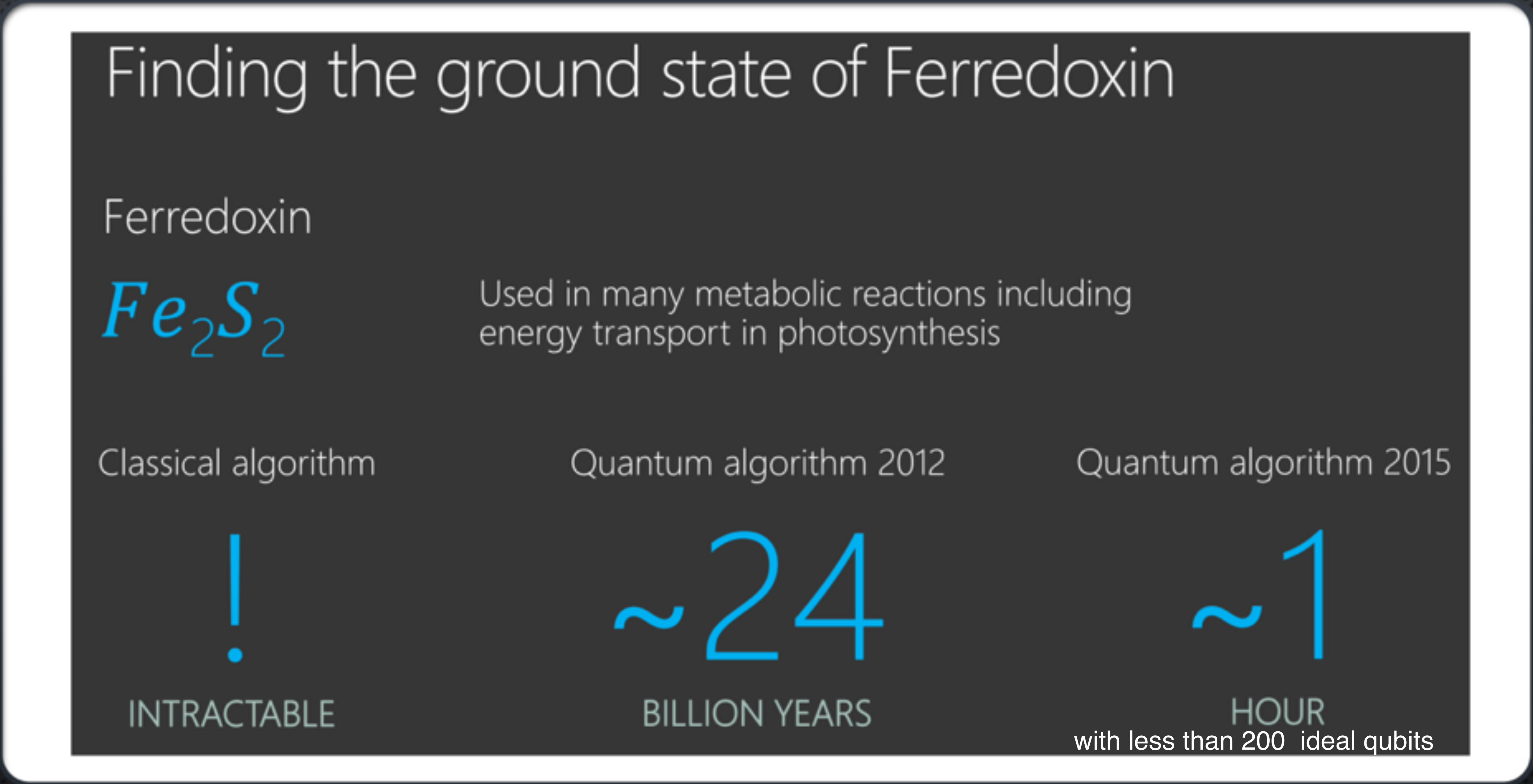
Dave Wecker (Microsoft)

~ 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 in US

- 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

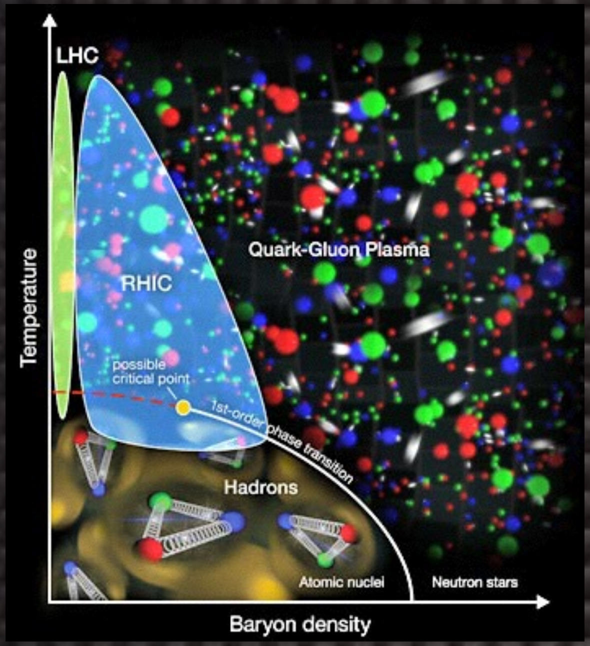
Motivation(s) for Nuclear Physics

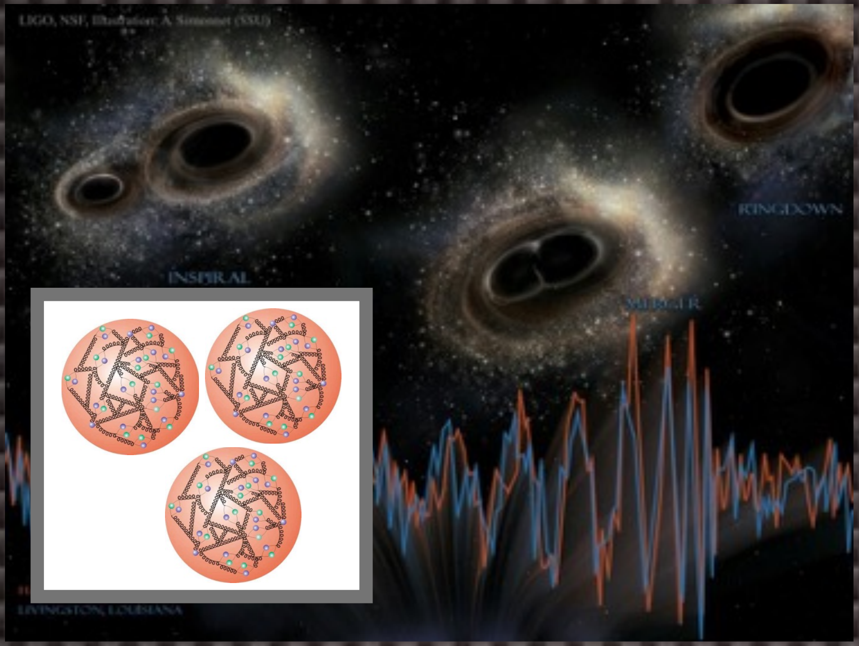
Quantum Information and Quantum Computing has the potential

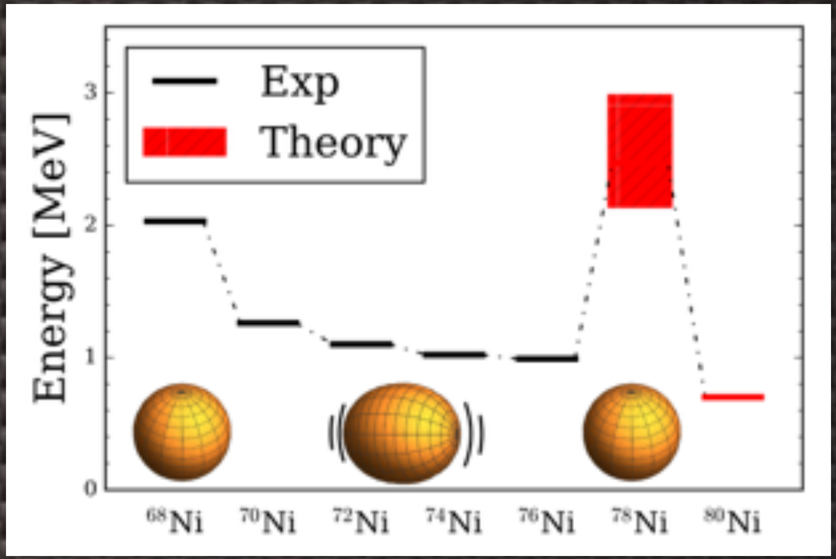
- to provide improvements in sensing and detection.
- to perform fully-controlled large-scale simulations of quantum many-body systems and of the standard model. To integrate with and complement classical computing (not replace).
- for transforming the handling of data.

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

Quantum Many-Body Systems







Finite Density Systems

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

Nuclear Many-Body Problem

- Schrodinger Eqn.
- Hilbert space grows exponentially with particles

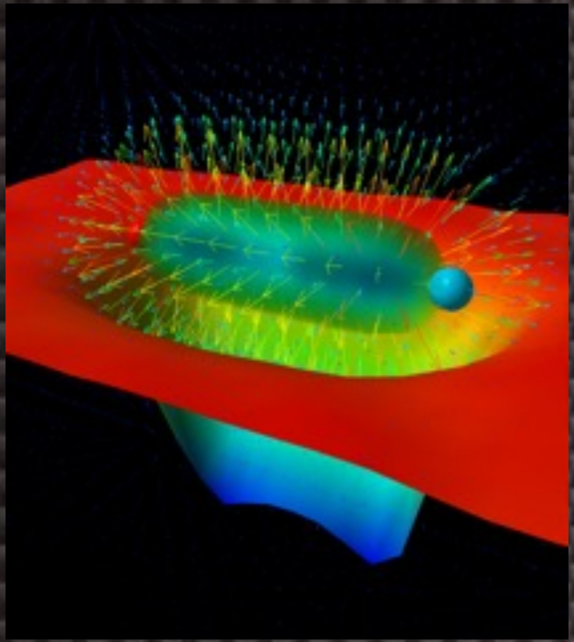
Classical Computing

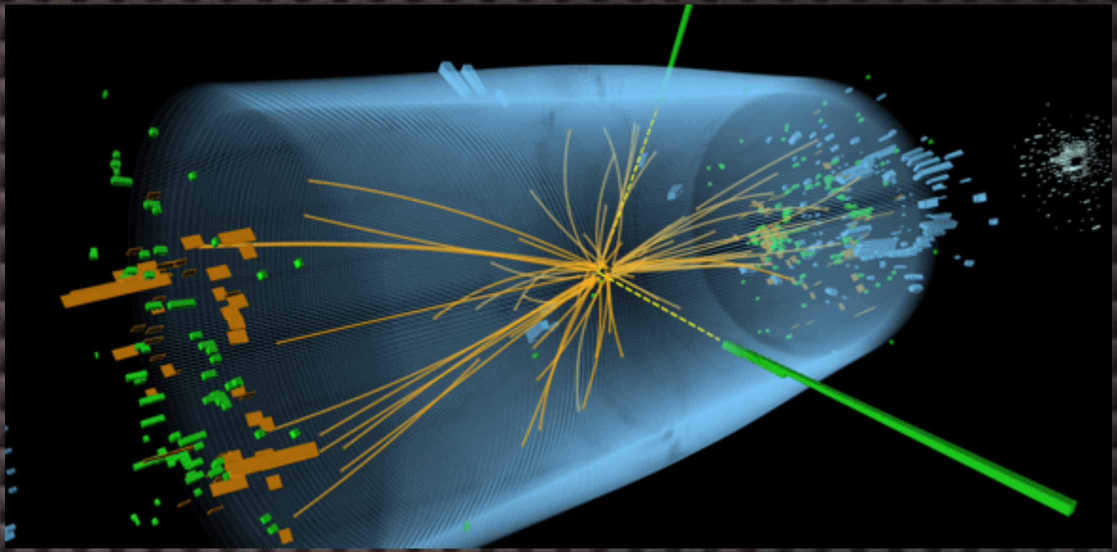
- Exponentially large resources
- Exponentially growing memory for large nuclei

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
- topology

Classical Computing

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

Real-Time Evolution

- Integrals over phases
- Fragmentation
- Neutrinos in dense matter

Quantum Computing

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

Bringing communities together
QIS: New ways of thinking and techniques

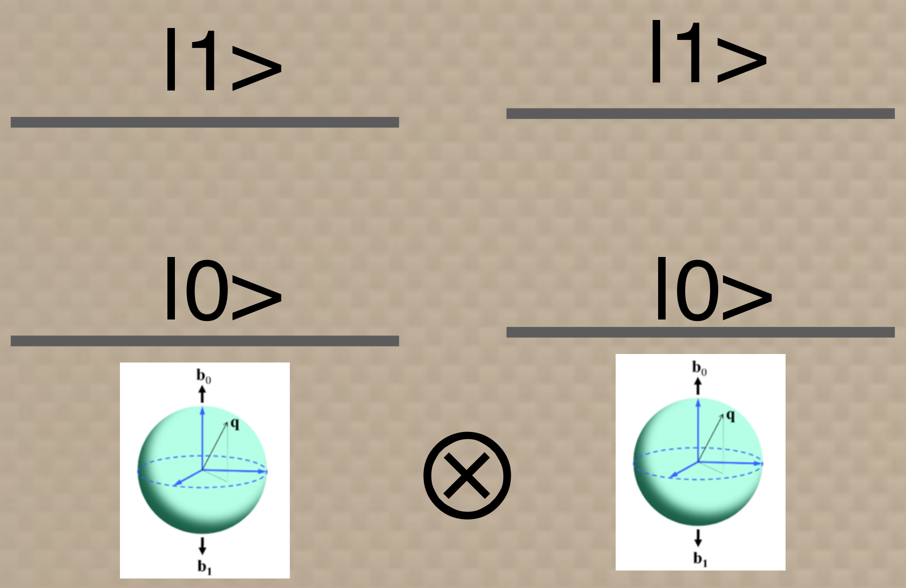
Quantum Sensing, Metrology and Lithography

Nonlocality and Entanglement

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

20th Century Detection
``independent qudits”

21st Century Detection
entangled ``qudits”


|1> |1>
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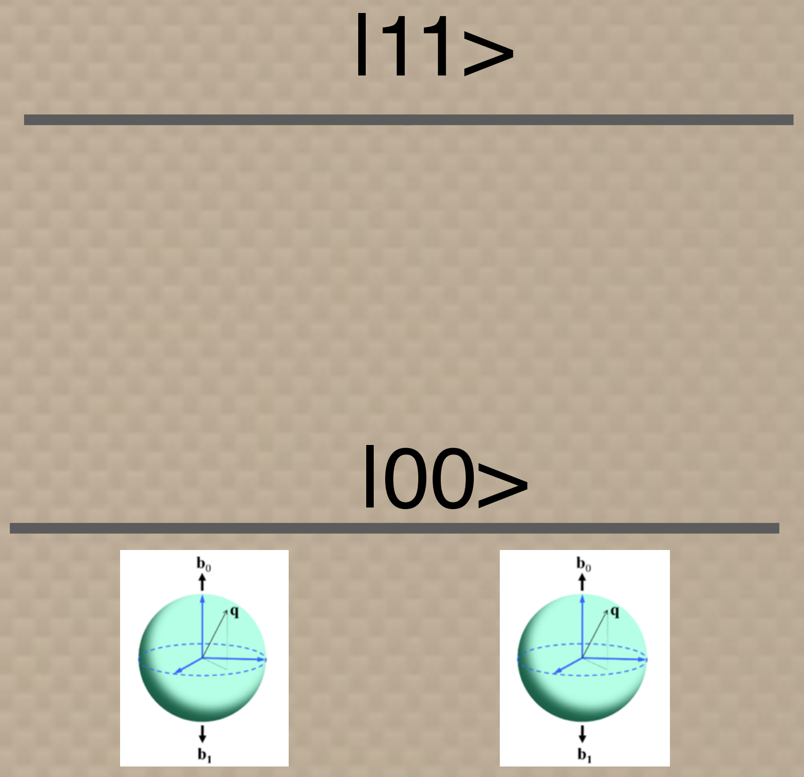
⊗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Uncertainty in measurement scales as

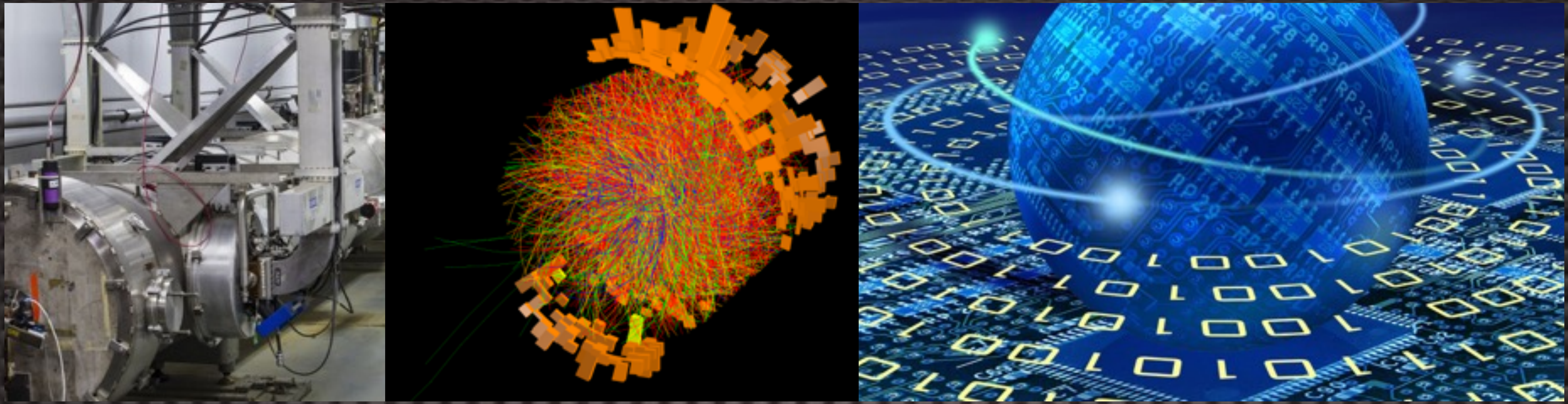
$$\Delta\beta \sim 1/(t \sqrt{N})$$

Uncertainty in measurement scales as

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

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

Sensing and Detection



Classical Computing
e.g.
Classical Sensing : precision ~ 1/√N

Classical DataBase Searching : time ~ N

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

Quantum DataBase Searching : time ~ √N

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)

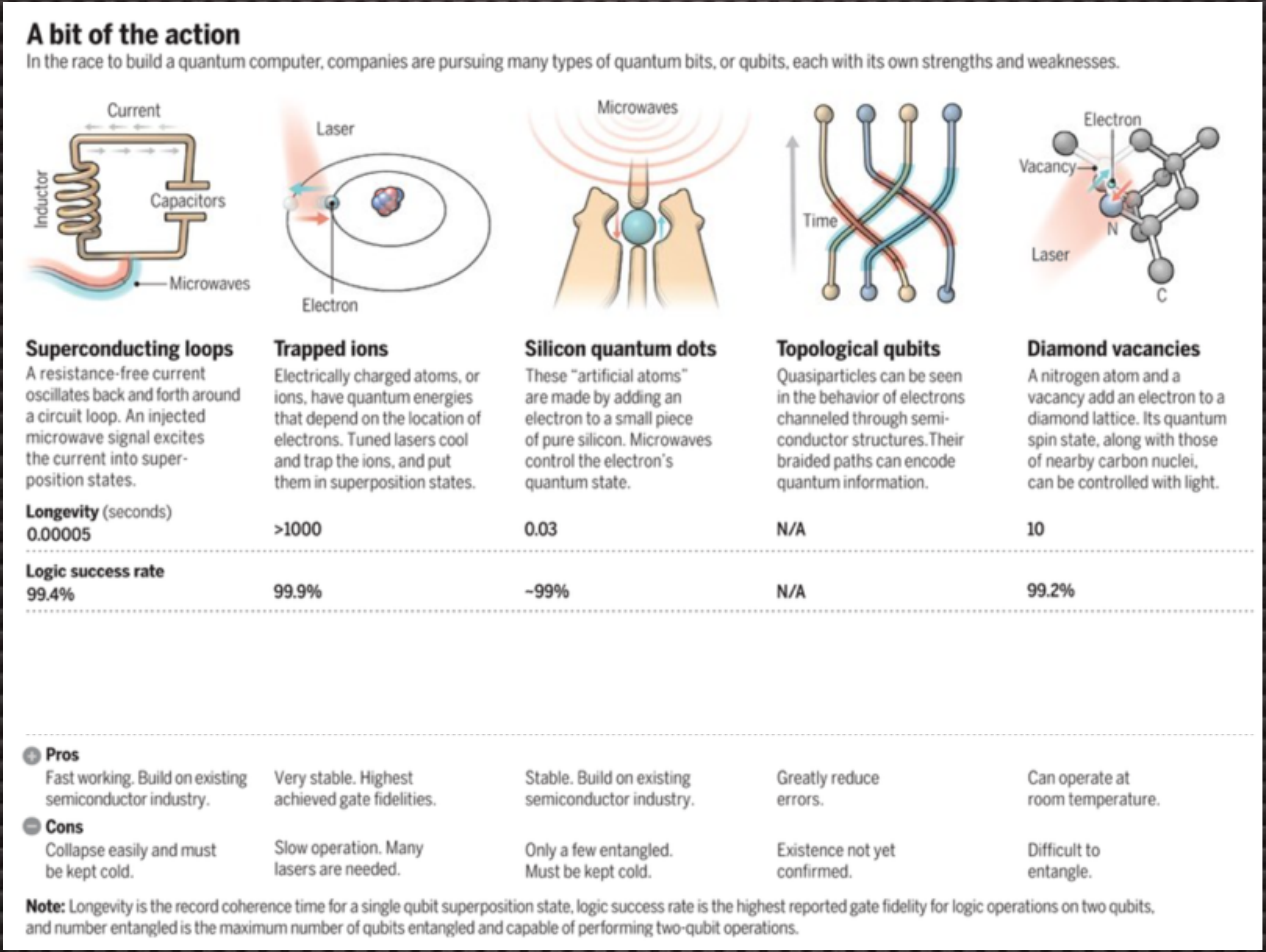
- Imperfect quantum gates/operations

- 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: Qubits



A bit of the action

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

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

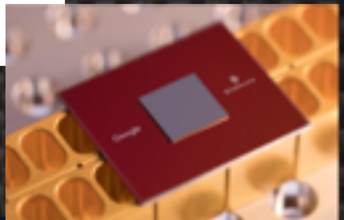
Note: Longevity is the record coherence time for a single qubit superposition state, logic success rate is the highest reported gate fidelity for logic operations on two qubits, and number entangled is the maximum number of qubits entangled and capable of performing two-qubit operations.

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

Science, December 2016, based on David Dean slide

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

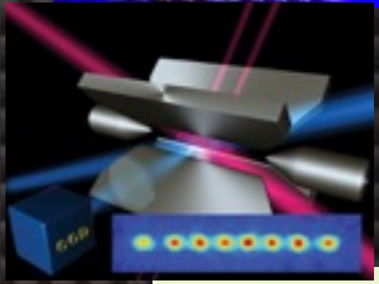
D-wave : ~ 2000 superconducting qubits, quantum annealing



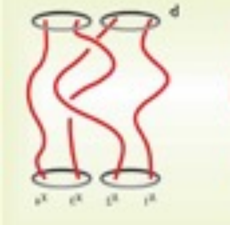
Google : 72 superconducting qubits - 2-qubit error < 0.5%

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

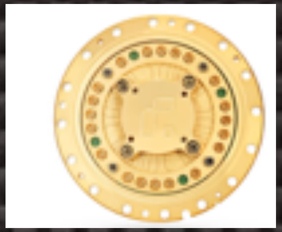
Intel : 49 superconducting qubits, progress in silicon



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

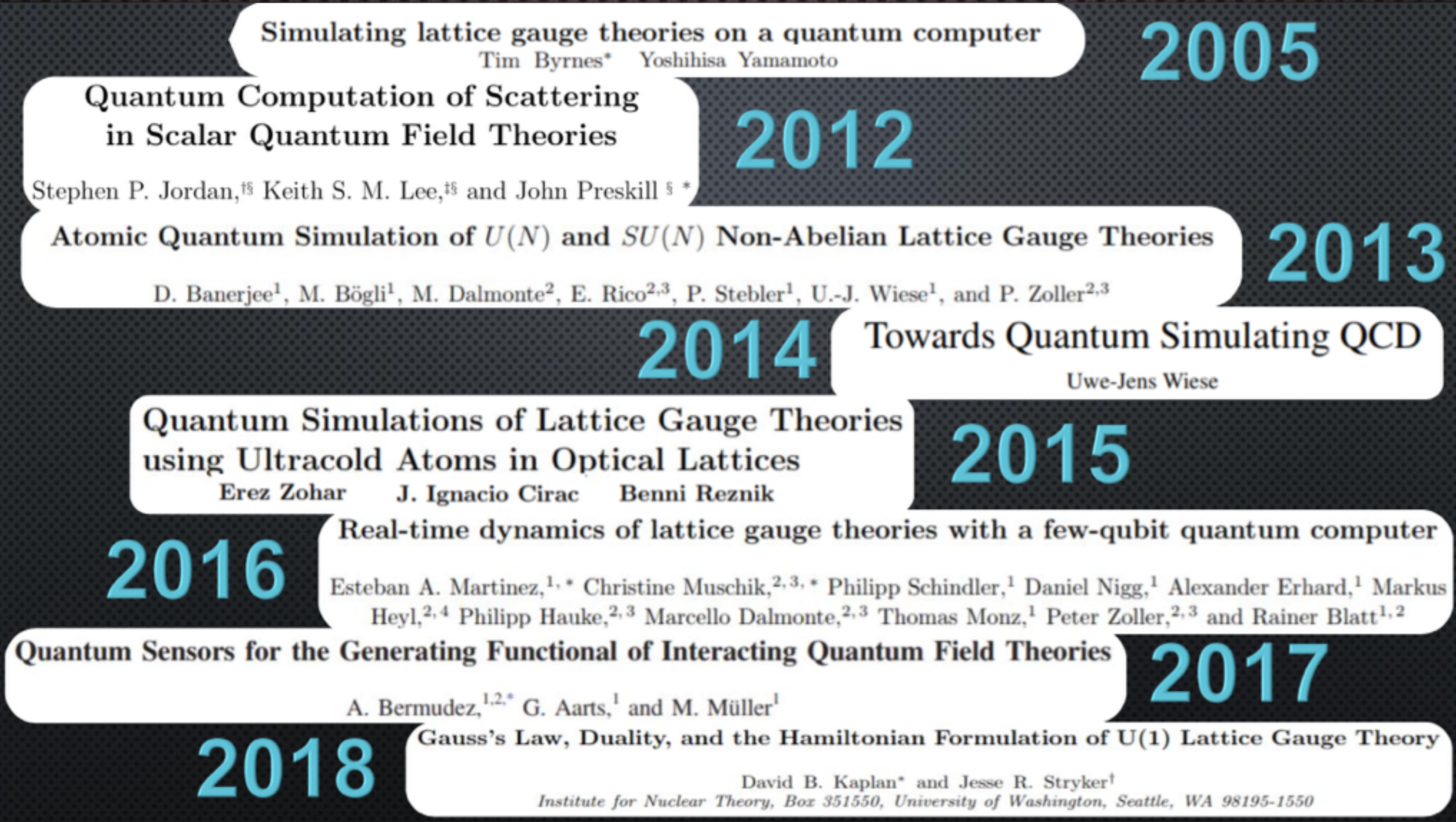


Microsoft : Majorana (topological) - in development



Rigetti : 8, 19 superconducting qubits with 128 coming

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

2018

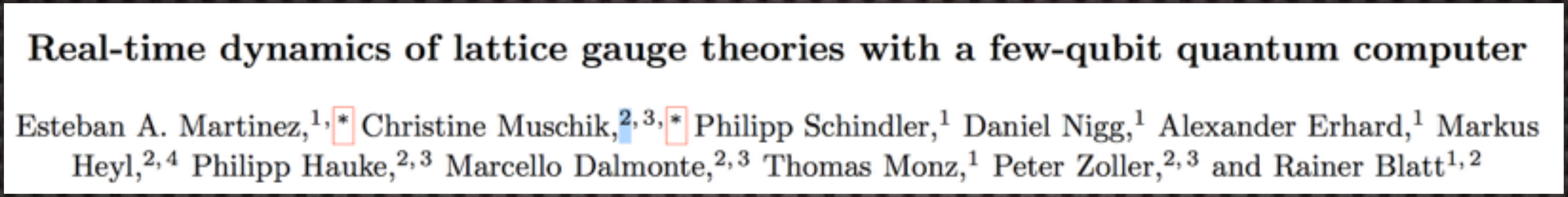
Gauss's Law, Duality, and the Hamiltonian Formulation of U(1) Lattice Gauge Theory

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)

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

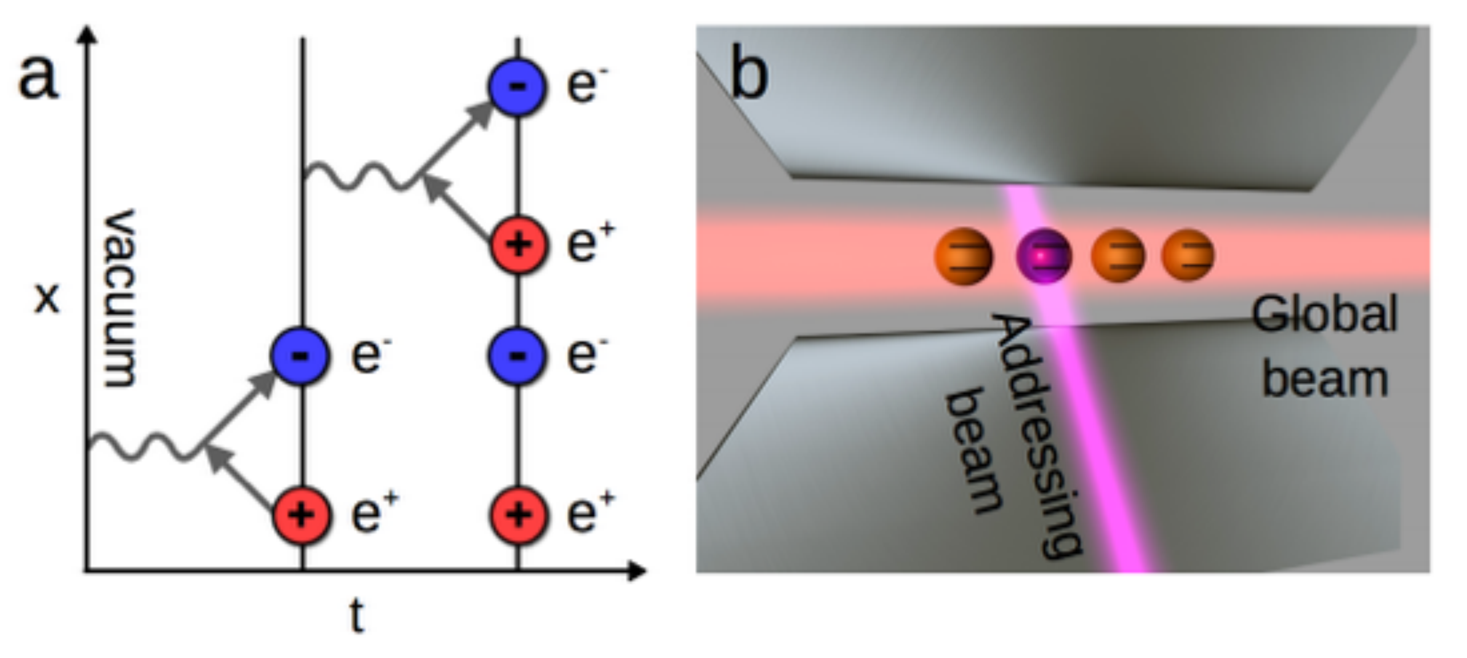
2016

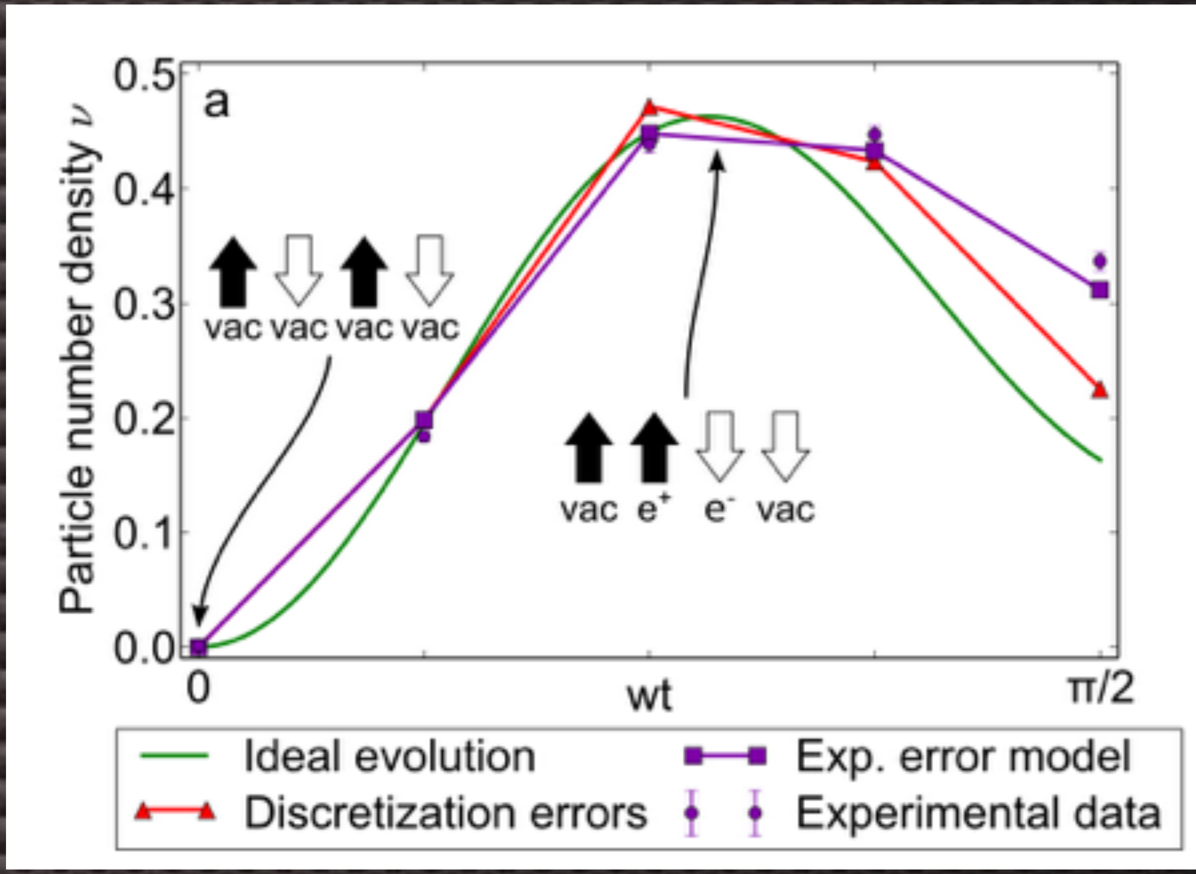


Real-time dynamics of lattice gauge theories with a few-qubit quantum computer

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

(2016)



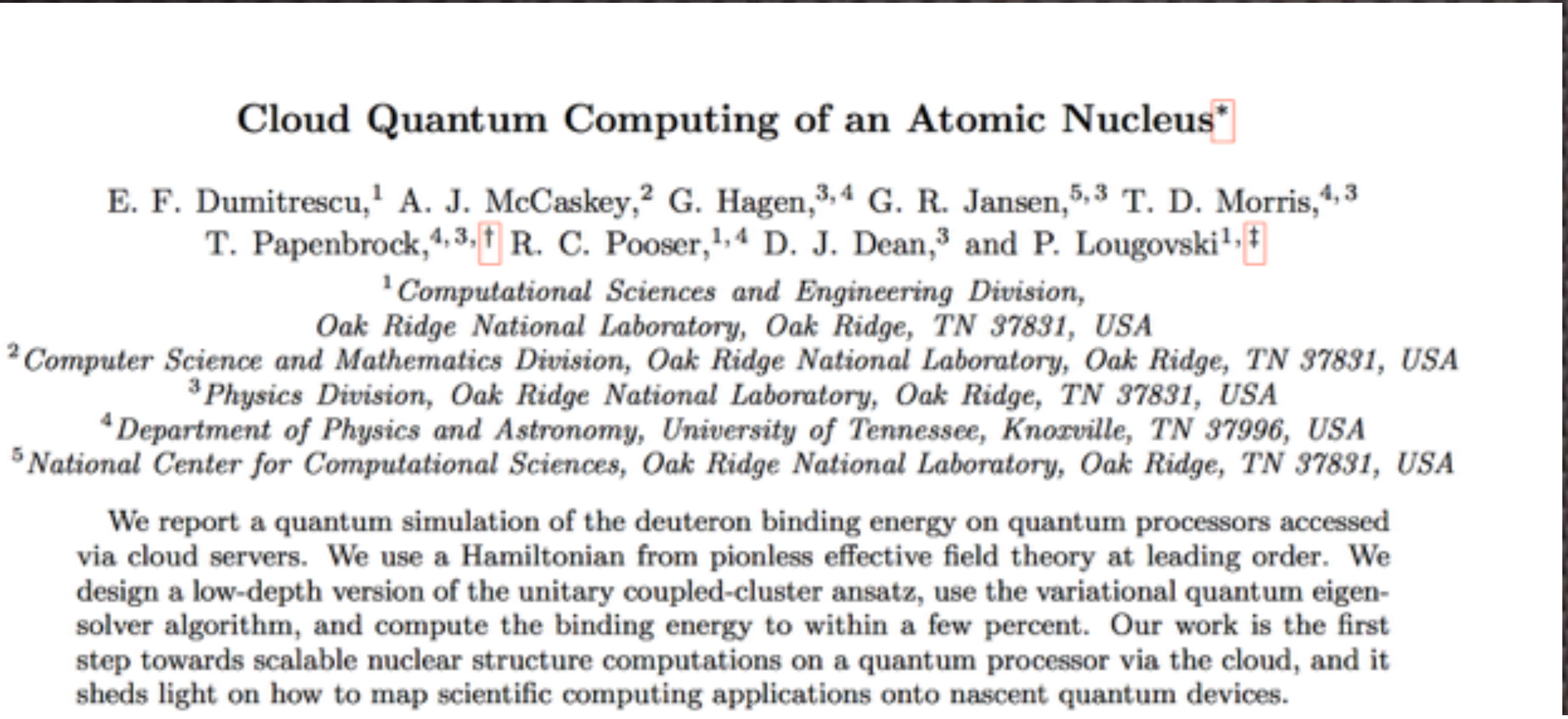


Based upon a string of $^{40}Ca^{+}$ trapped-ion quantum system

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

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

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



Cloud Quantum Computing of an Atomic Nucleus*

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

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

http://arxiv.org/abs/1801.03897

OAK RIDGE
National Laboratory

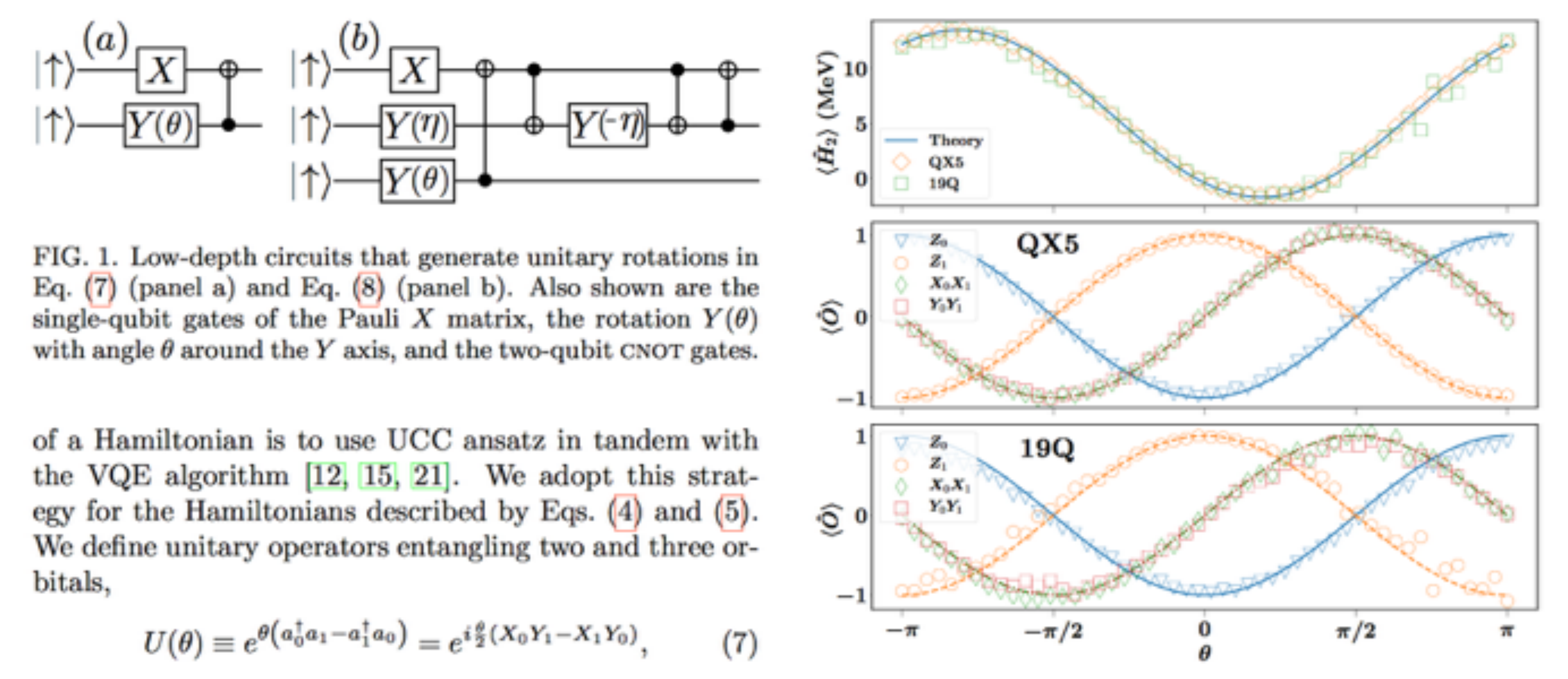


FIG. 1. Low-depth circuits that generate unitary rotations in Eq. (7) (panel a) and Eq. (8) (panel b). Also shown are the single-qubit gates of the Pauli X matrix, the rotation $Y(\theta)$ with angle θ around the Y axis, and the two-qubit CNOT gates.

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,

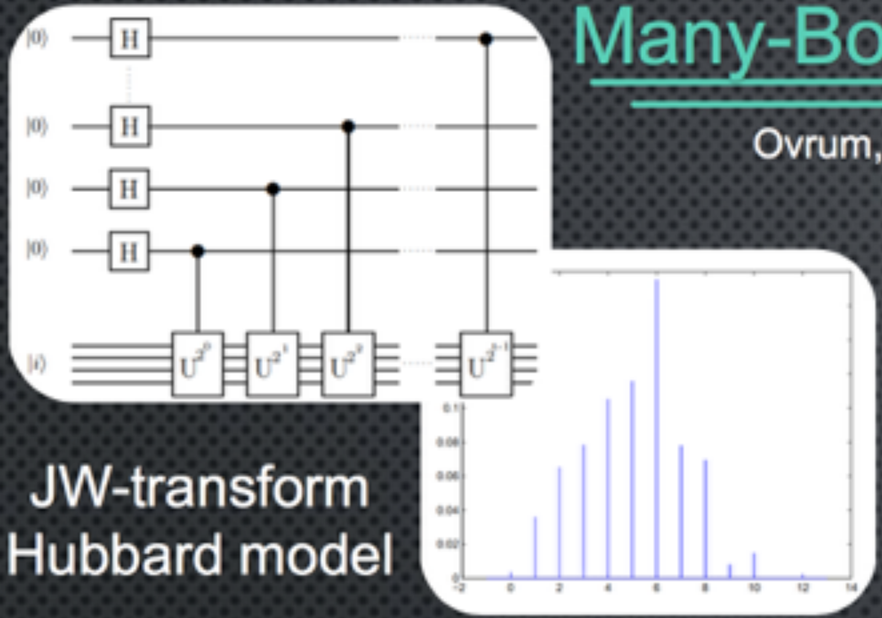
$$U(\theta) \equiv e^{\theta(a_0^\dagger a_1 - a_1^\dagger a_0)} = e^{i\frac{\theta}{2}(X_0Y_1 - X_1Y_0)}, \qquad (7)$$

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

First Demonstrations in Nuclear Many-Body Systems

Many-Body Studies

Ovrum, Hjorth-Jensen (2007)



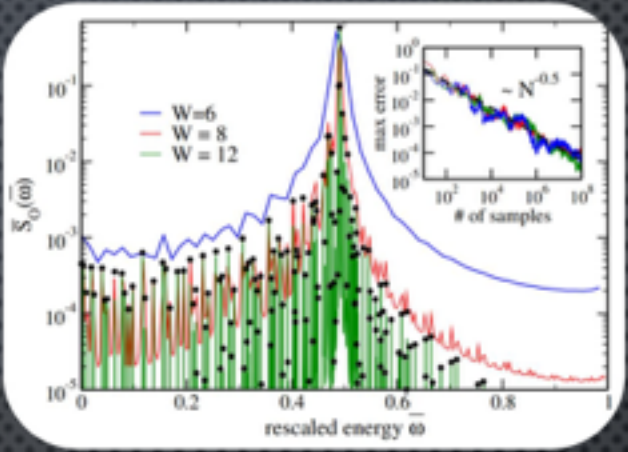
Energy measurement probability

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

JW-transform Hubbard model

Linear Response Functions

Carlson, Roggero (2018)



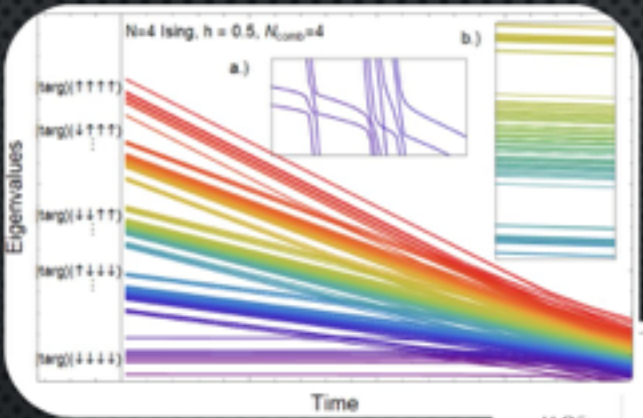
$$\sum_\nu |\langle\psi_\nu|\,\hat{O}\,|\psi_0\rangle|^2\,\delta(E_\nu - E_0 - \omega)$$

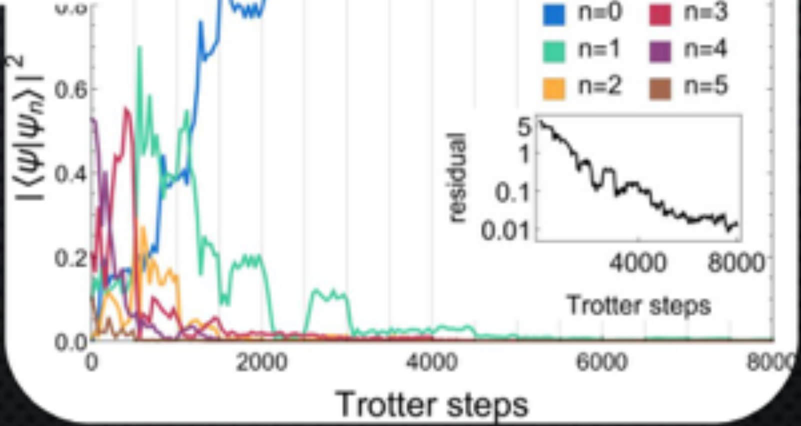
dynamic linear response and exclusive information

Spectral Combing

Kaplan, Klco, Roggero (2017)

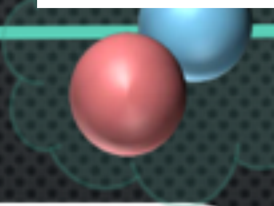
Time-dependent auxiliary system = comb





Exponential level crossings send target system to ground state

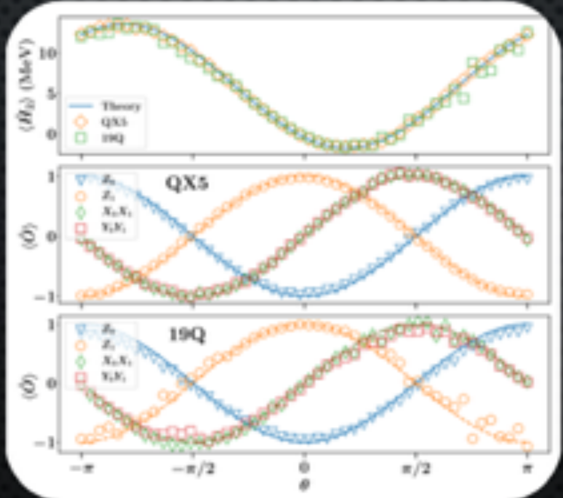
The Deuteron



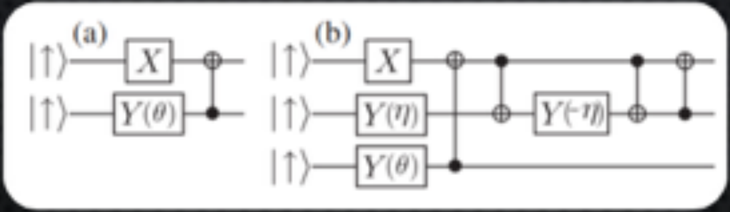
Cloud Quantum Computing of an Atomic Nucleus

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 201

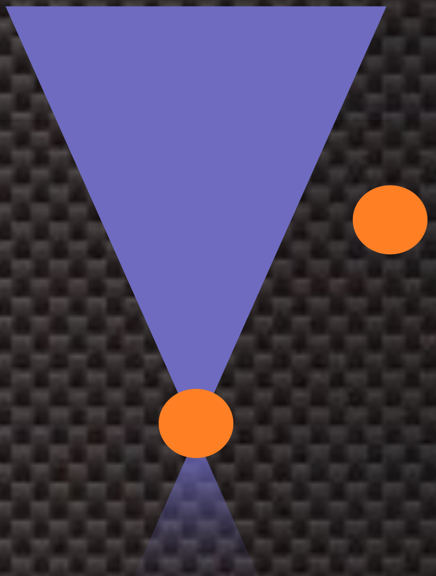


Variational Quantum Eigensolver



Slide by Natalie Klco (Oct 2018)

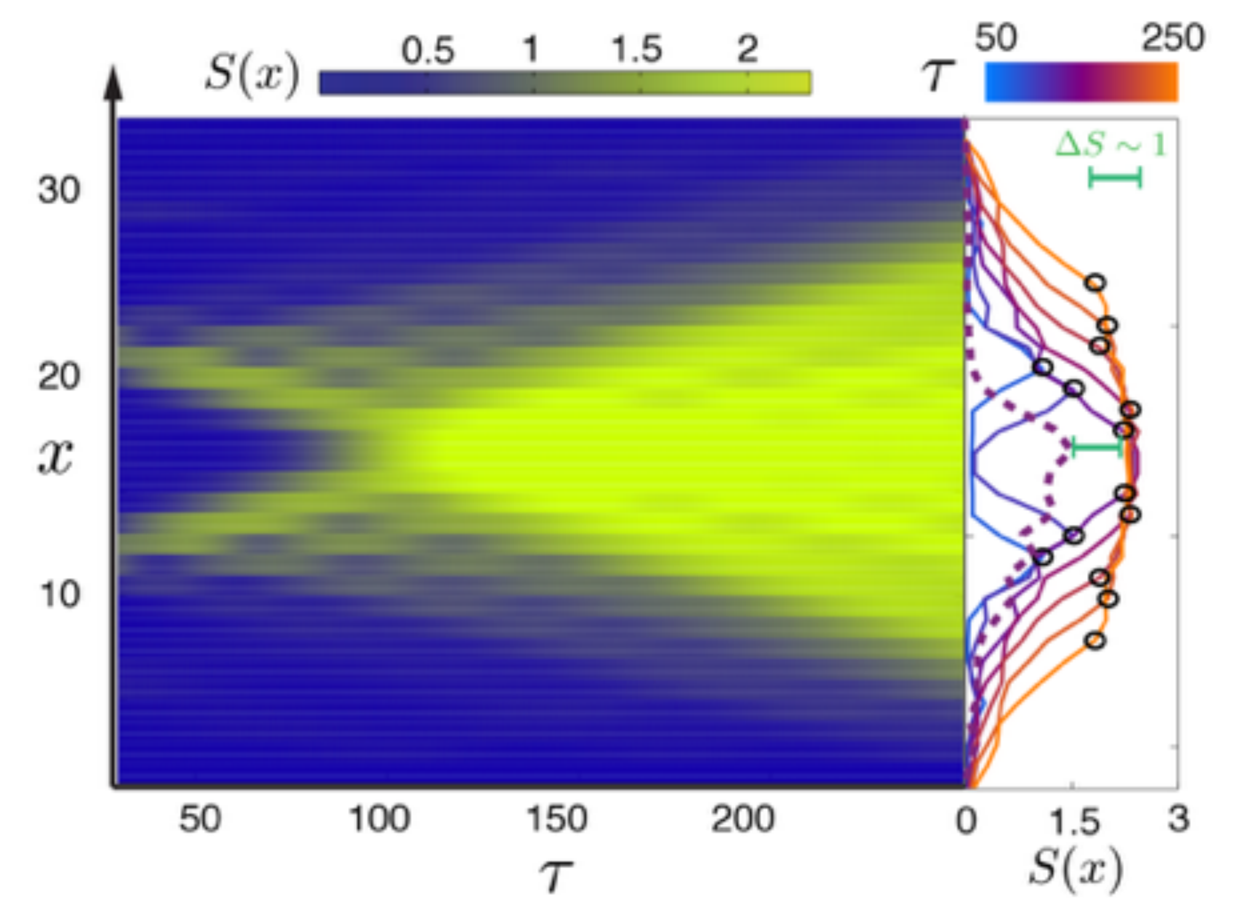
Entanglement, Fragmentation and QFT

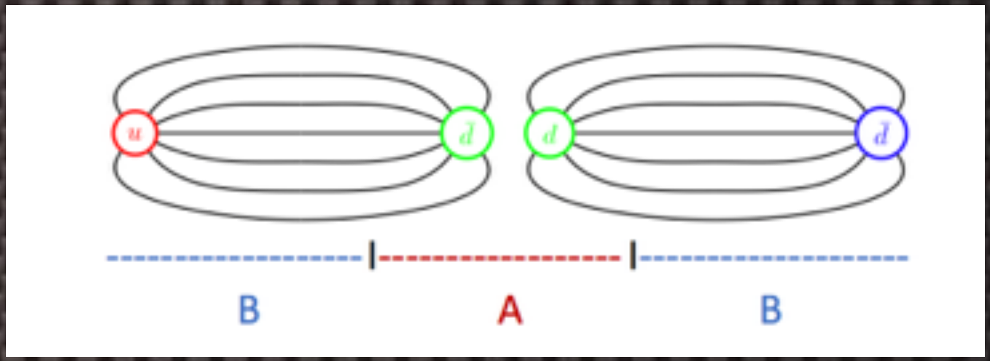


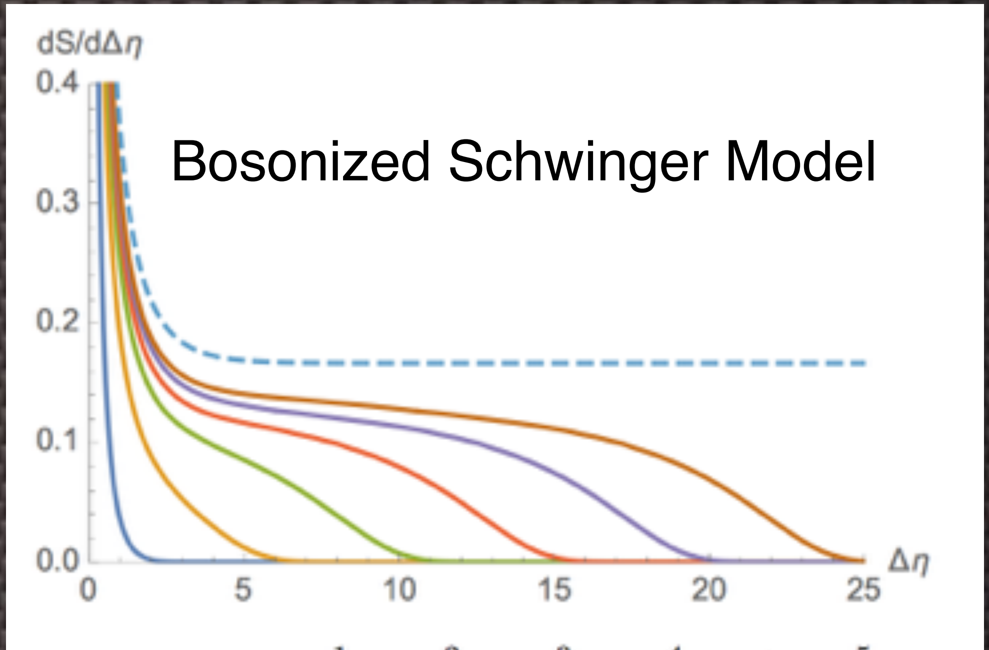
Real-time Dynamics in U(1) Lattice Gauge Theories with Tensor Networks
T. Pichler (Ulm U.), M. Dalmonte (Innsbruck U., Quant. Opt. and Info. & Innsbruck U.), E. Rico (Basque U., Bilbao & IPCMS, Strasbourg & IKERBASQUE, Bilbao), P. Zoller (Innsbruck U. & Innsbruck U., Quant. Opt. and Info.), S. Montangero (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**



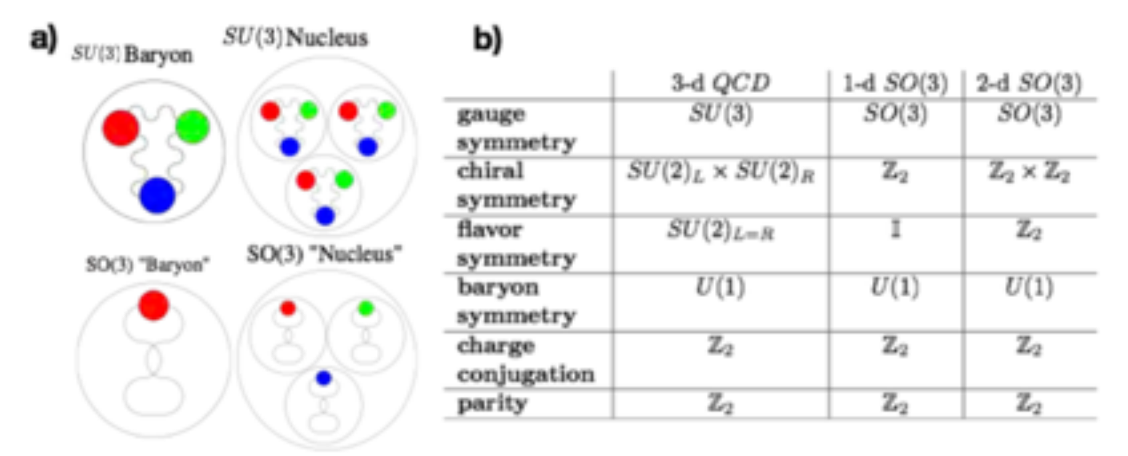




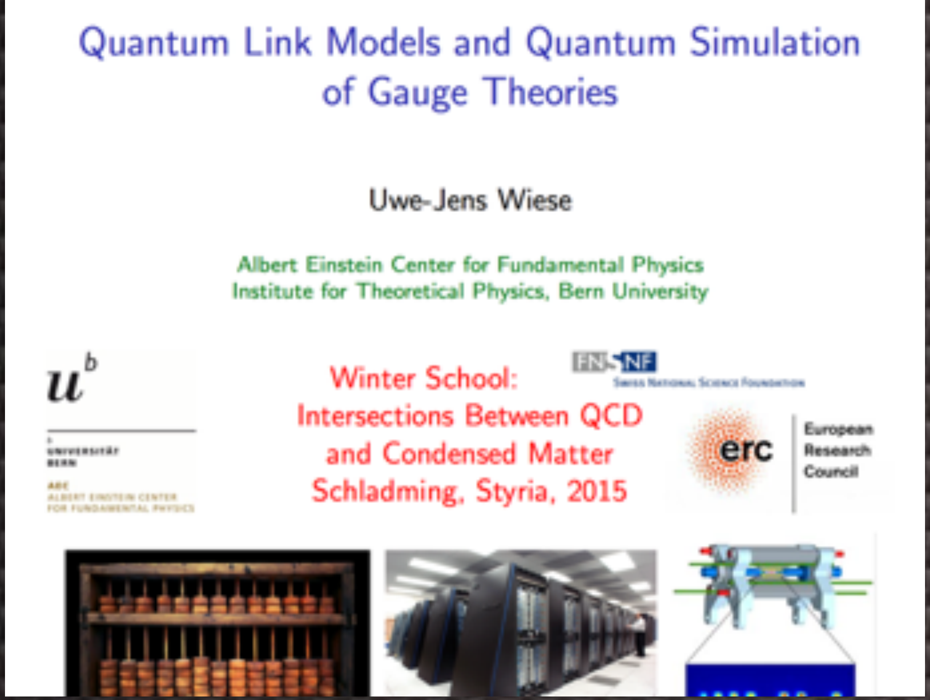
Bosonized Schwinger Model

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

QFTs Toward QCD for NP



	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

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

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]

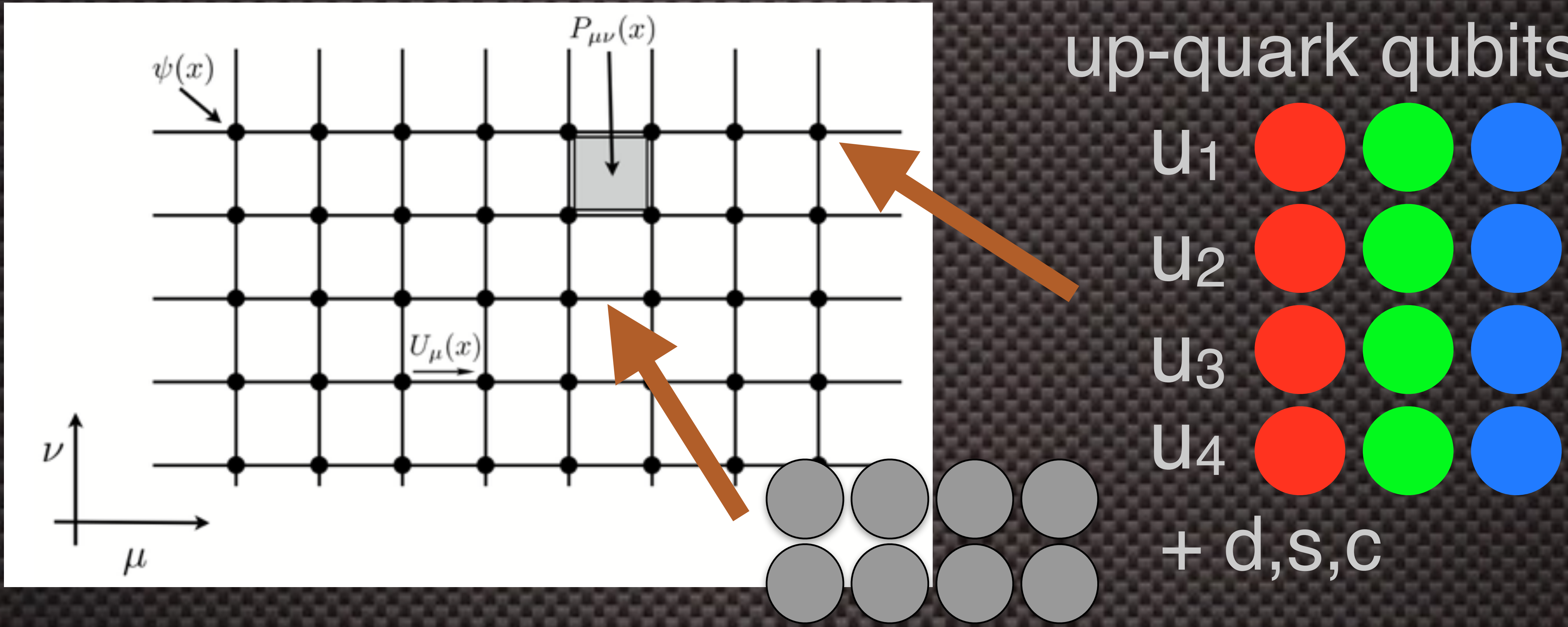
[a]*IKERBASQUE, Basque Foundation for Science, Maria Diaz de Haro 3, E-48013 Bilbao, Spain and Department of Physical Chemistry, University of the Basque Country UPV/EHU, Apartado 644, E-48080 Bilbao, Spain*
[b]*International Center for Theoretical Physics, 34151 Trieste, Italy*
[c]*Institute for Theoretical 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

(Very, Most) Naive Mapping of QCD onto QC



up-quark qubits

u_1

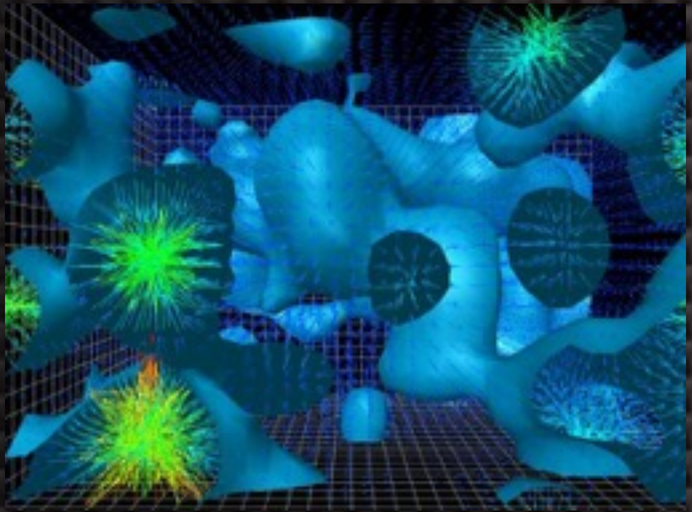
u_2

u_3

u_4

+ d,s,c

32^3 lattice requires naively > 4 million qubits !



State Preparation - a critical element

| random > = a |0> + b |(pi pi)> + c | (pi pi pi pi) > + …. + d | (GG) > + ….

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

Tensor methods, ….

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

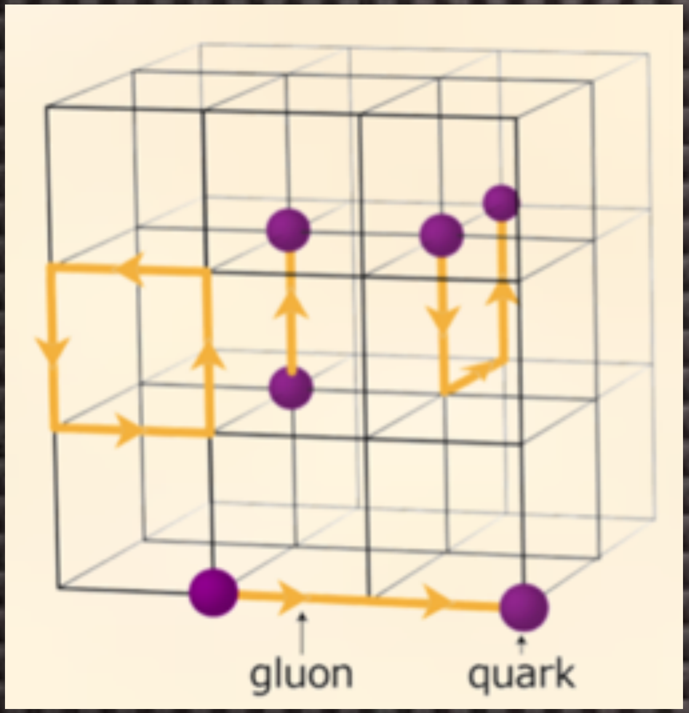
Methods to compress Hilbert space to physical

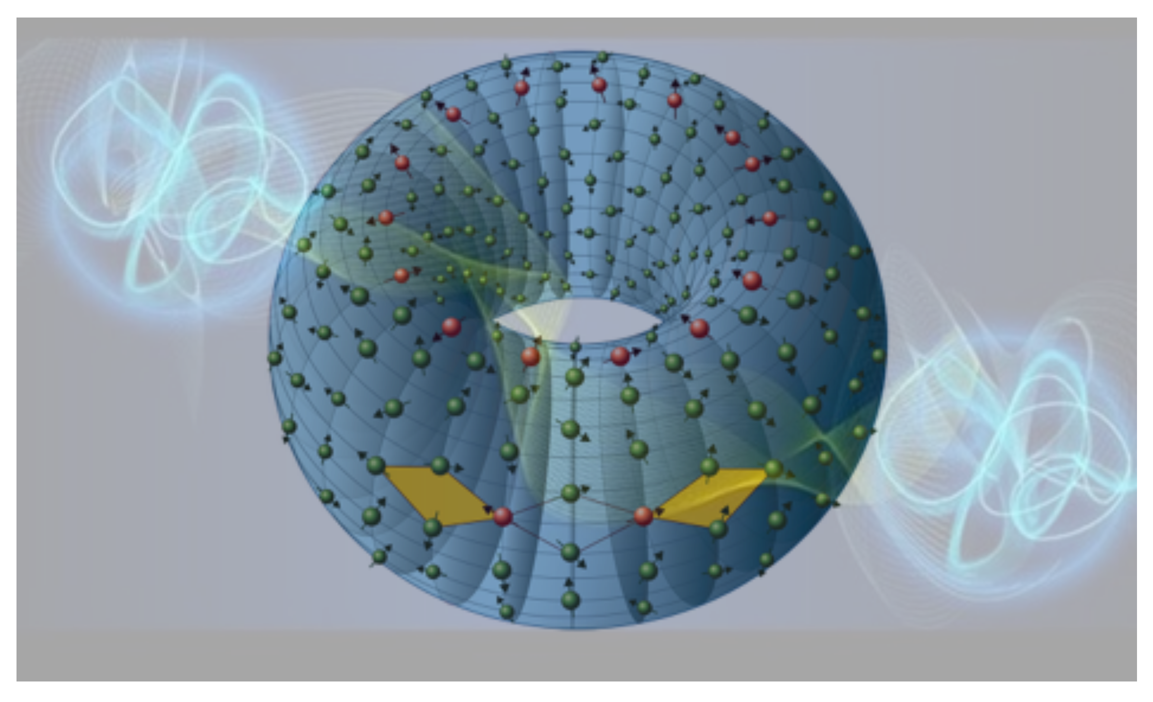
State preparation and role of classical calcs.

Chiral gauge theories?

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

Low-Dimensional Gauge Field Theories





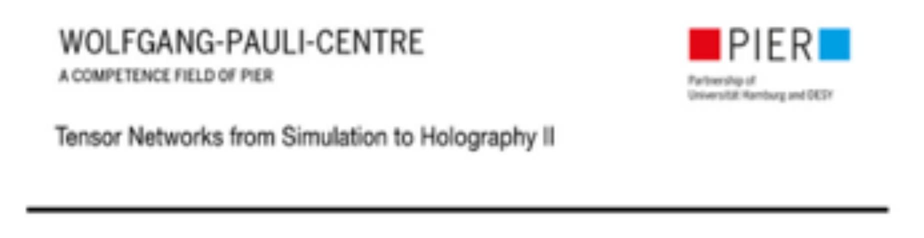
Design of an error-correcting quantum computer:
quantum many-body problem, quantum field theory

Low-dimensional lattice field theories with gapped, topologically-stabilized degenerate ground states

At the intersection of condensed matter, high-energy and nuclear physics, quantum information science and computer science

e.g., 2+1 dim U(1) Higgs lattice field theory and Kitaev's toric code for error-corrected (logical) qubits

Bringing communities together
QIS: New ways of thinking and techniques



WOLFGANG-PAULI-CENTRE
A COMPETENCE FIELD OF PIER

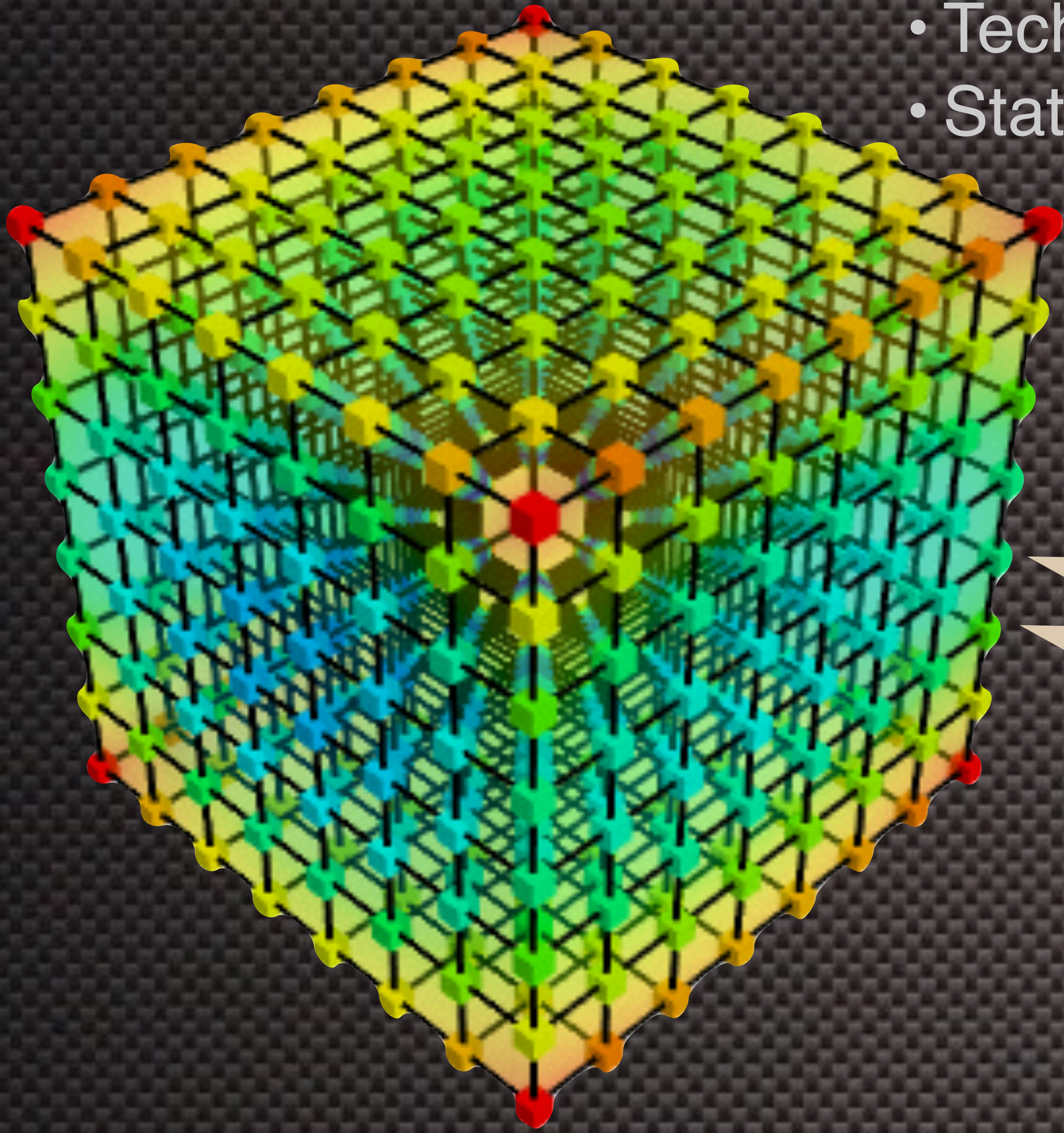
PIER
Partnership of
Universität Hamburg and DESY

Tensor Networks from Simulation to Holography II

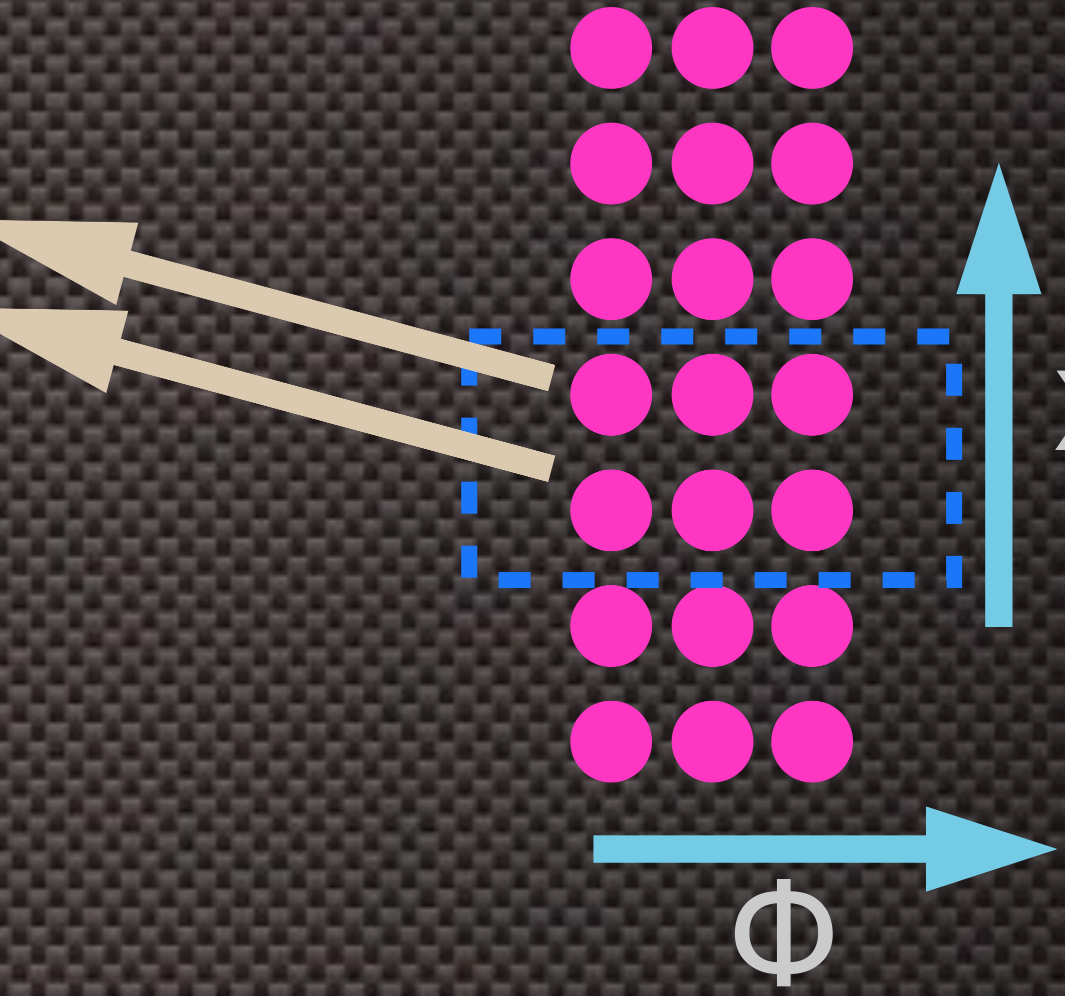
Discretizing and Digitization of Field Theory

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

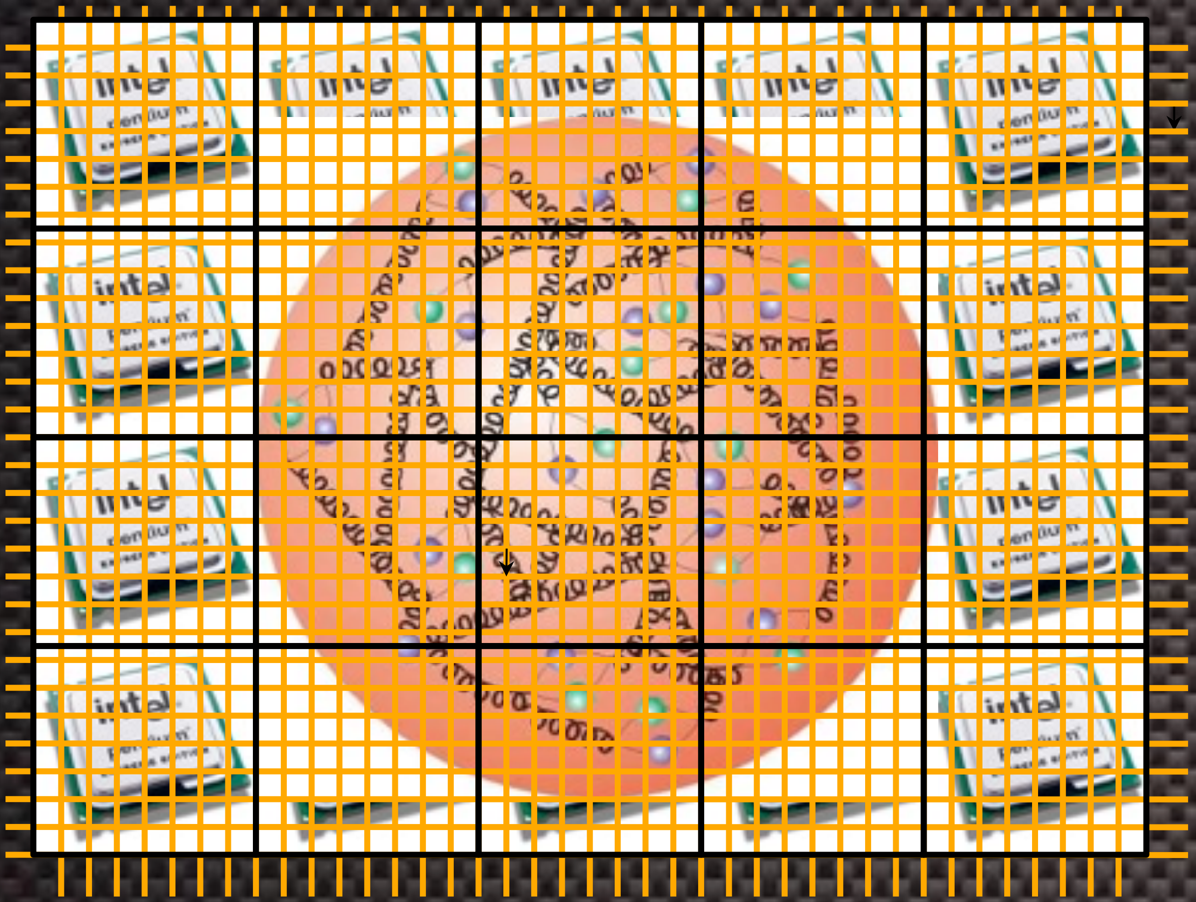
- Discretize 3-d Space
- Define Hamiltonian on grid
- Trotterized time evolution
- Technology transfer from Lattice QCD
- State preparation?



Parallelizes easily at the circuit level
- dual layer application per Trotter step



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]

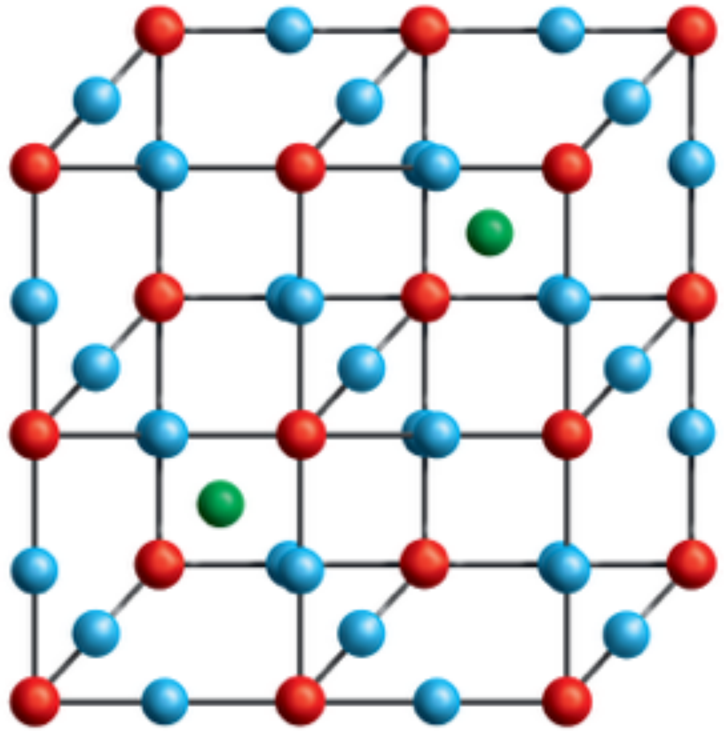
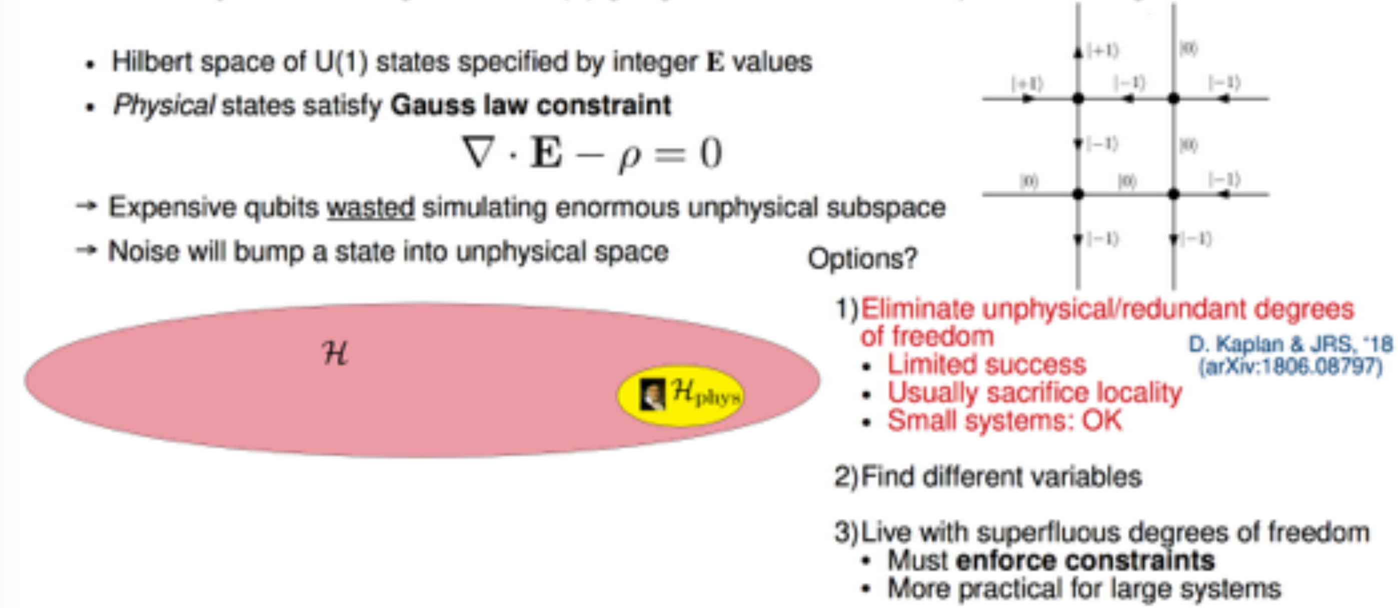


Figure 2. The physical system consists of the gauge fields residing on the links (blue) and the matter fields on the vertices (red). The auxiliary degrees of freedom (green) are located in the center of every second cube (either even or odd).



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

- Hilbert space of U(1) states specified by integer **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?

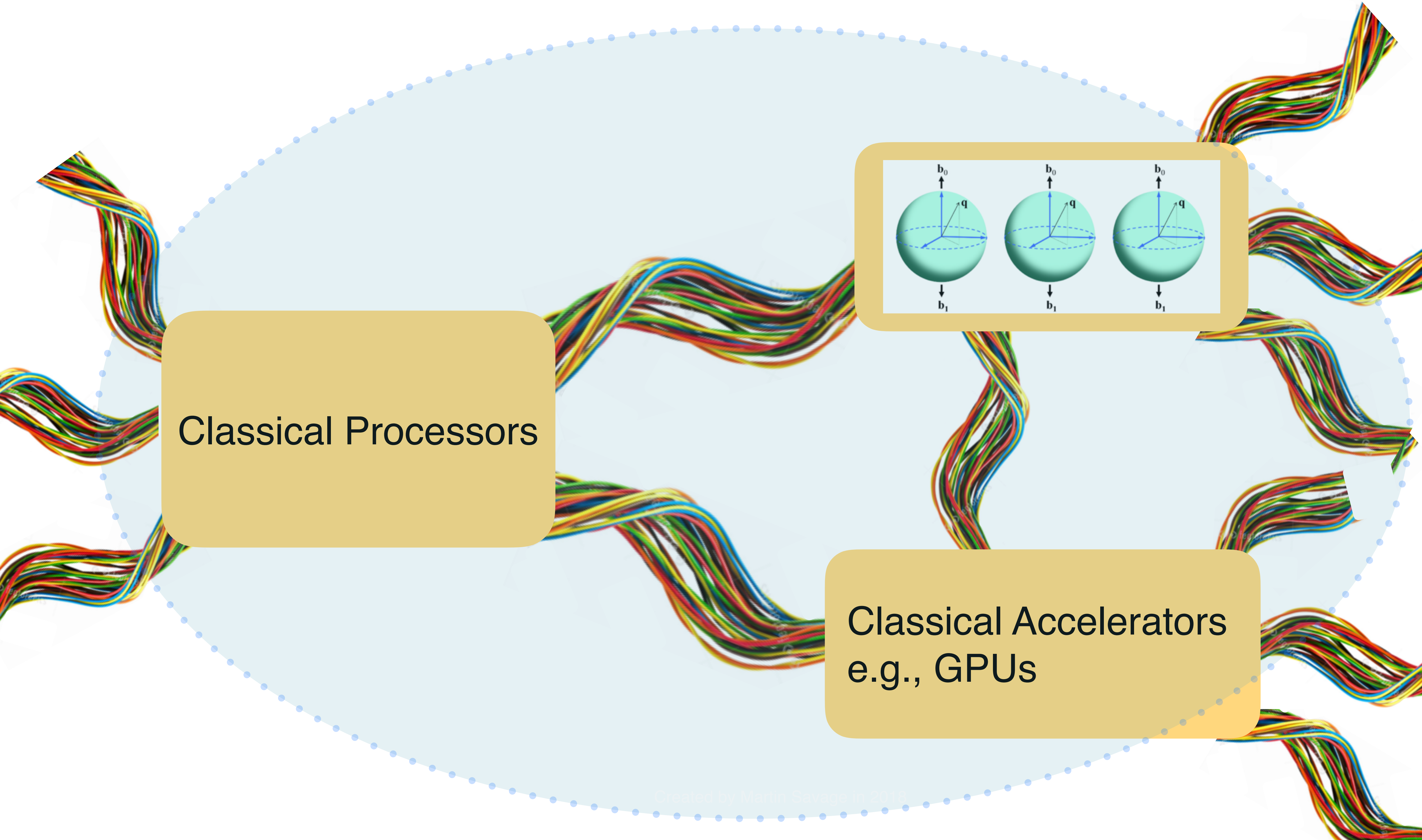
1) Eliminate unphysical/redundant degrees of freedom
   - Limited success
   - Usually sacrifice locality
   - Small systems: OK

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

Early Days:
QPU Accelerators and Hybrid Computations



Classical Processors

Classical Accelerators
e.g., GPUs

Starting Simple: 1+1 Dim QED

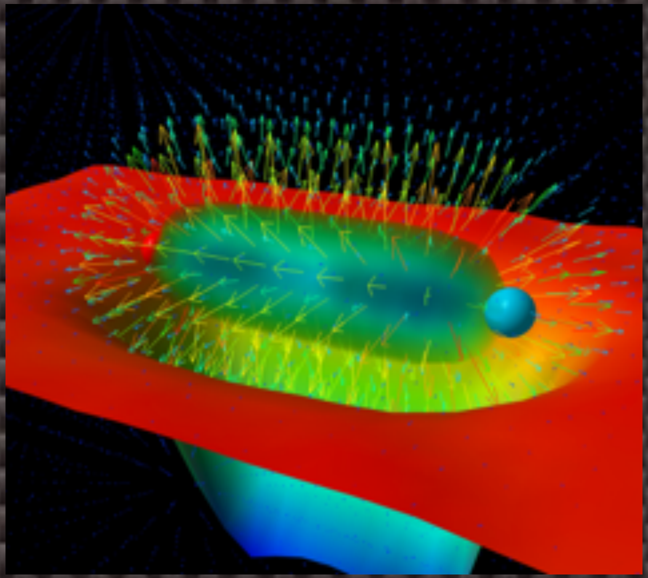
Two ORNL-led research teams receive $10.5 million to advance quantum computing for scientific applications

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

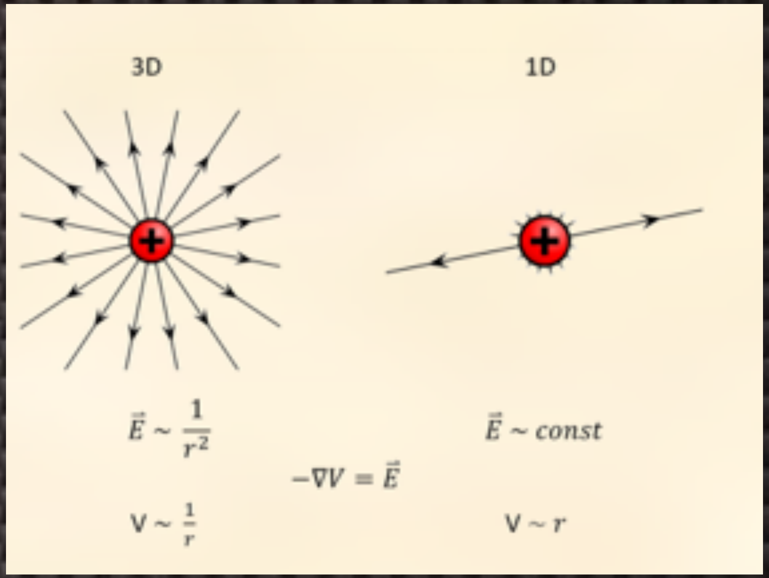
Quantum-classical computation of Schwinger model dynamics using quantum computers

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

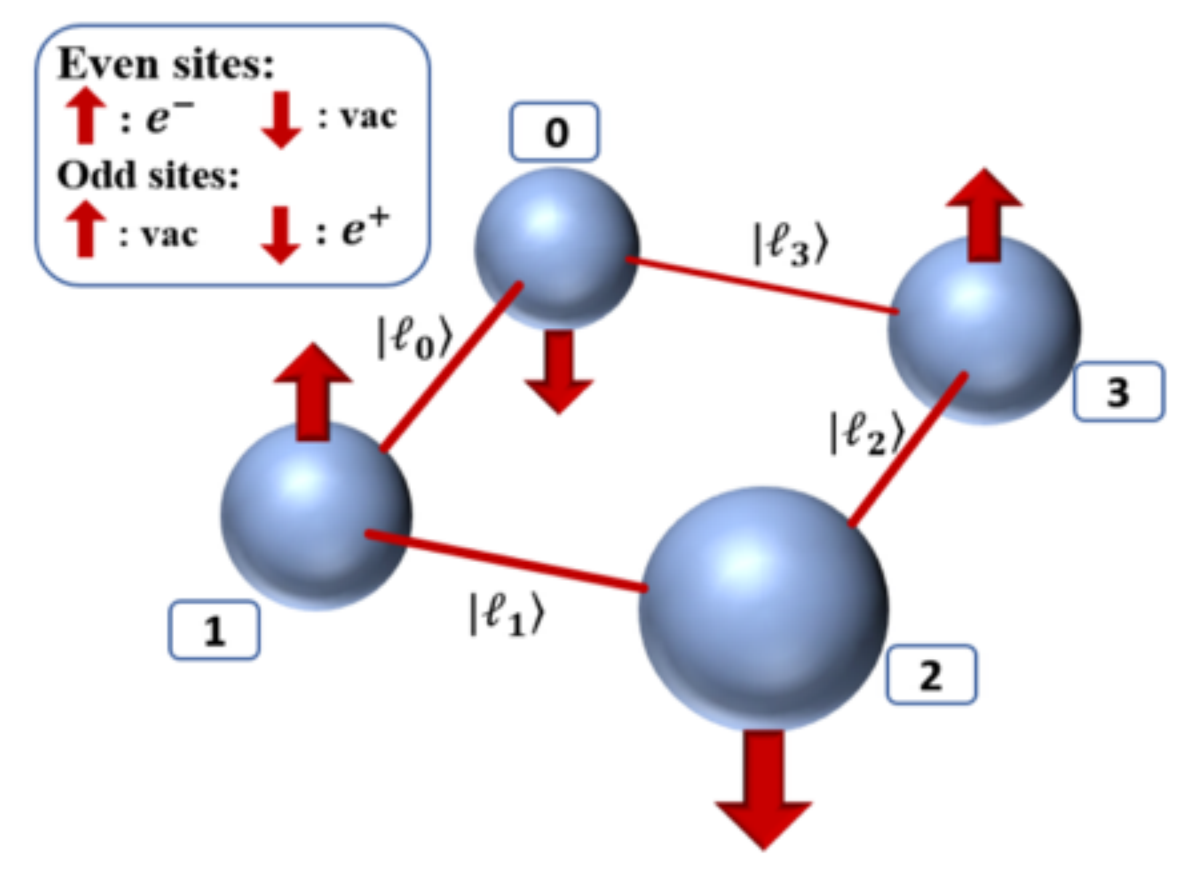


Derek Leinweber



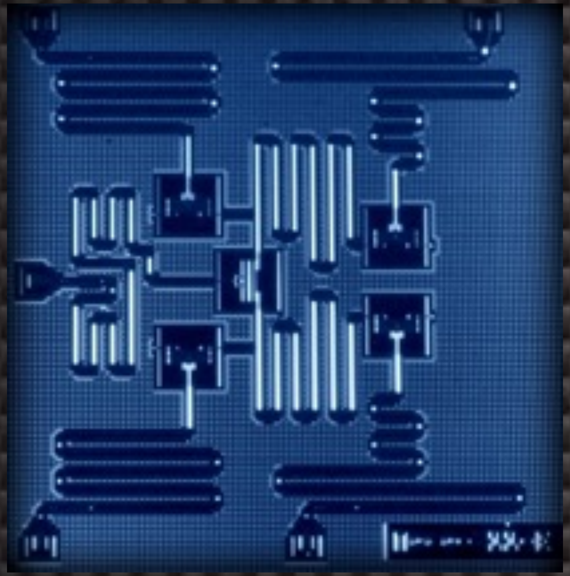
Natalie Klco

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



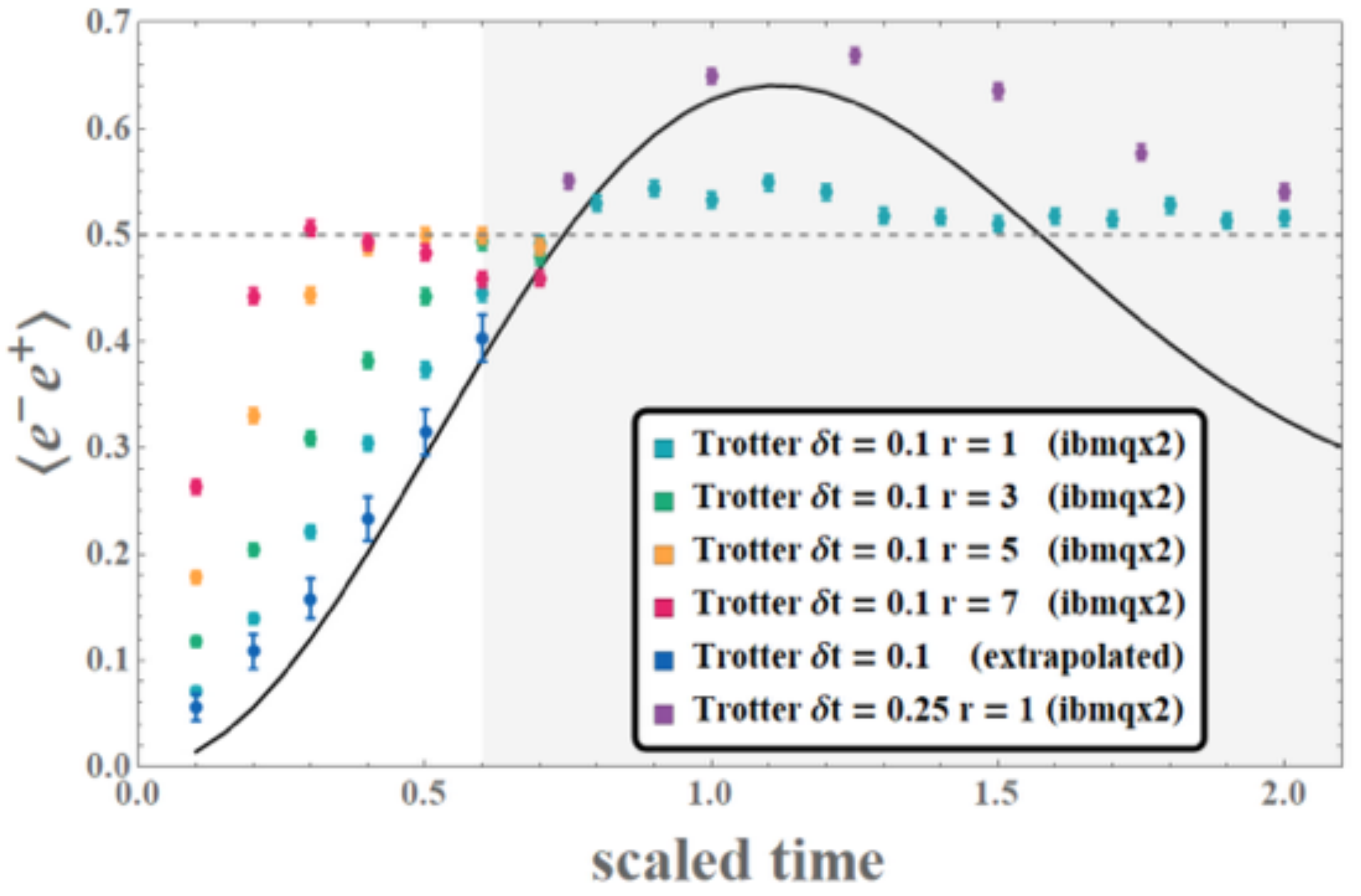
$$\hat{H} = x\sum_{n=0}^{N_{fs}-1}\left(\sigma_n^+ L_n^- \sigma_{n+1}^- + \sigma_{n+1}^+ L_n^+ \sigma_n^-\right) + \sum_{n=0}^{N_{fs}-1}\left(l_n^2 + \frac{\mu}{2}(-)^n \sigma_n^z\right) .$$

Living NISQ - IBM
Trotter Evolution U(t)



T2 (μs)	55.20	65.10	47.00	35.10	37.60

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



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

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

3.6 QPU-s and 260 IBM units

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) ;
  }
```

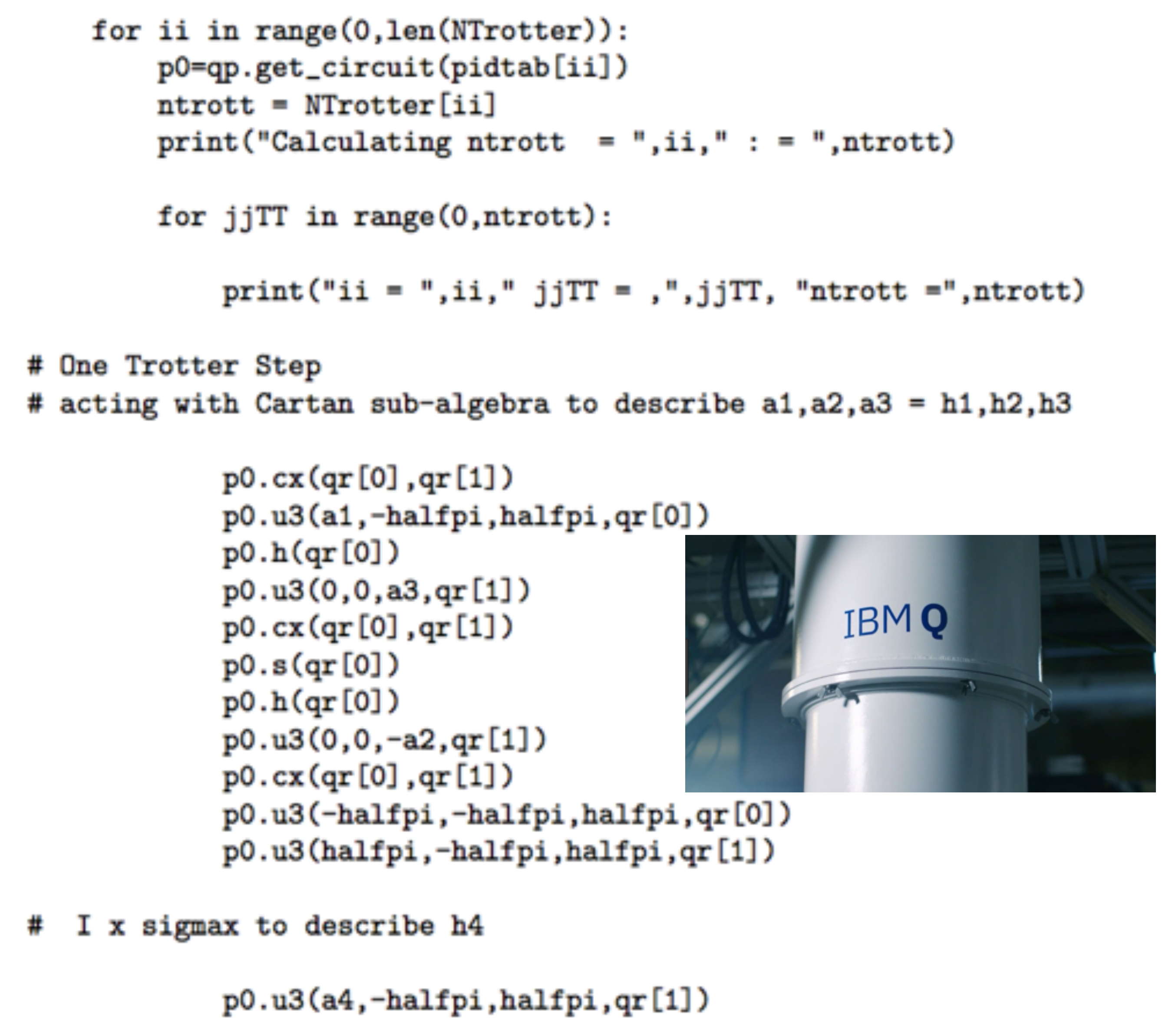
USQCD

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.

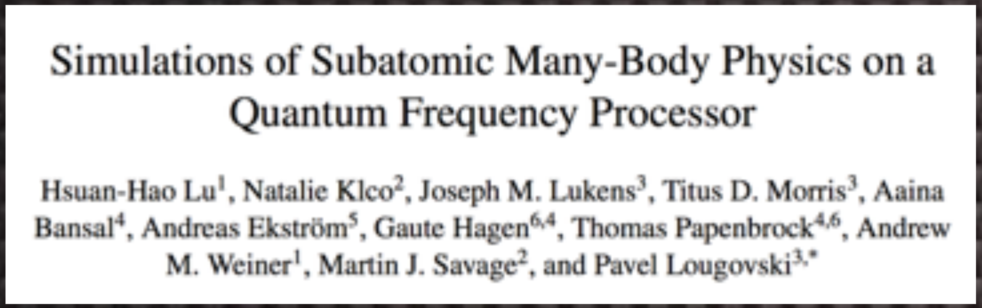


```
    for ii in range(0,len(NTrotter)):
        p0=qp.get_circuit(pidtab[ii])
        ntrott = NTrotter[ii]
        print("Calculating ntrott  = ",ii," : = ",ntrott)

        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



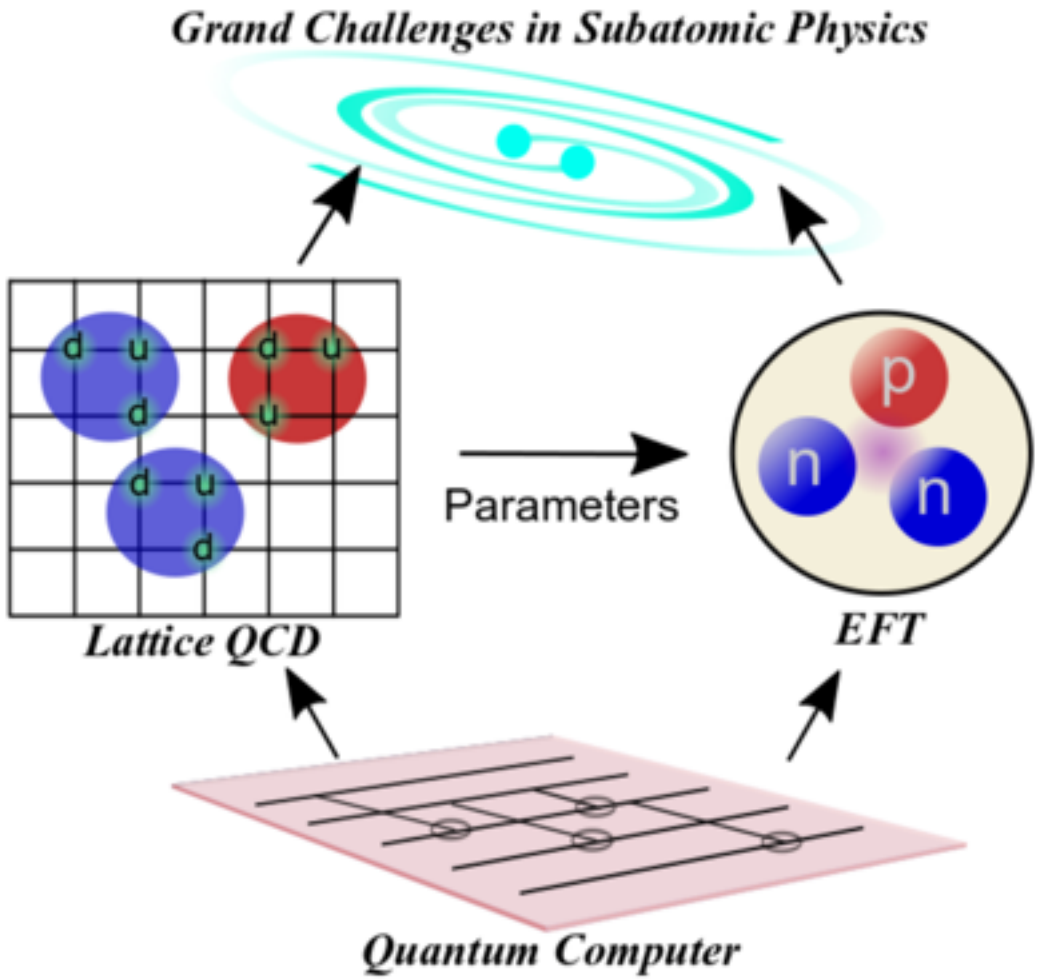
Simulations of Subatomic Many-Body Physics on a Quantum Frequency Processor

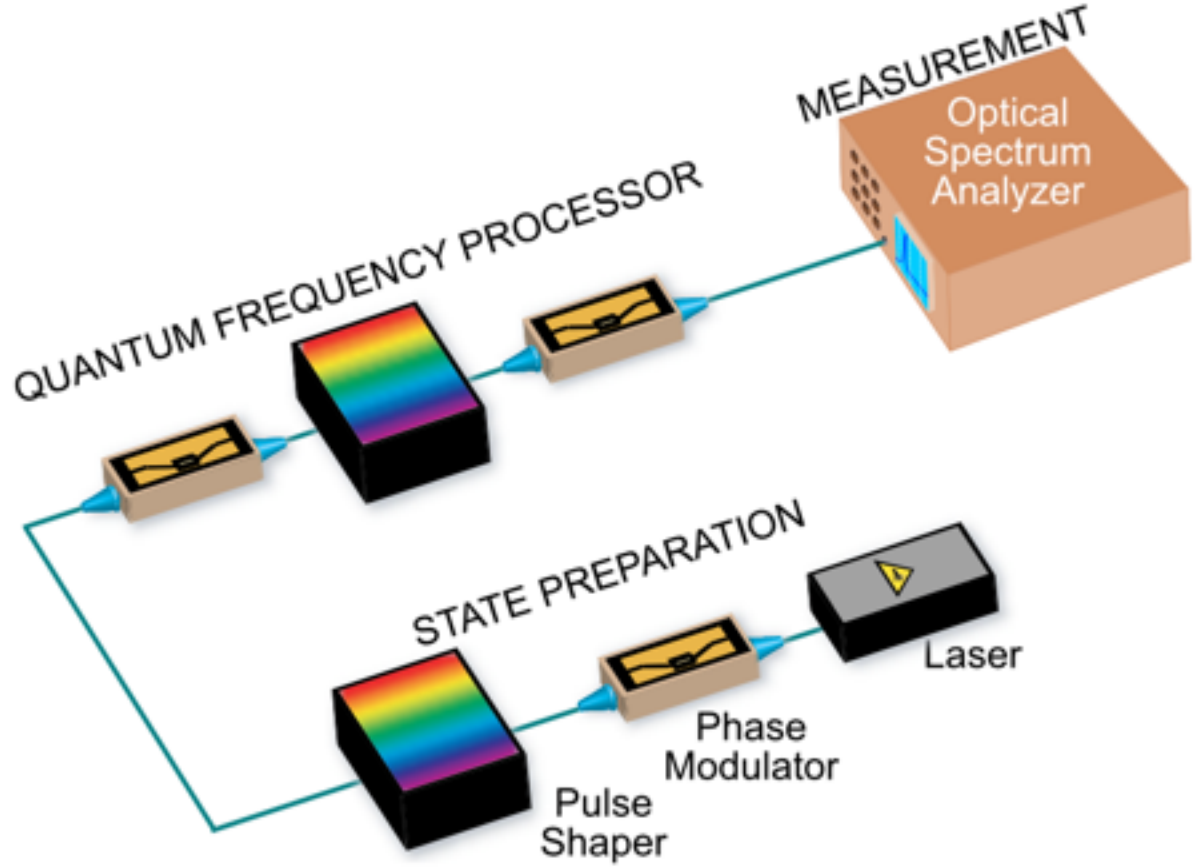
Hsuan-Hao Lu[1], Natalie Klco[2], Joseph M. Lukens[3], Titus D. Morris[3], Aaina Bansal[4], Andreas Ekström[5], Gaute Hagen[6,4], Thomas Papenbrock[4,6], Andrew M. Weiner[1], Martin J. Savage[2], and Pavel Lougovski[3,*]

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

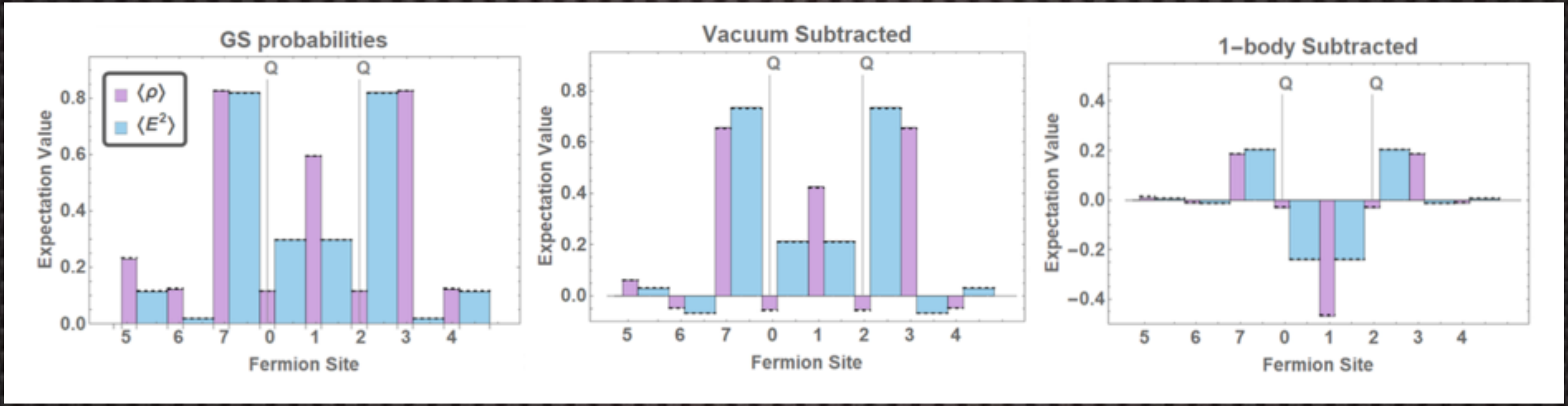
Pavel Lougovski

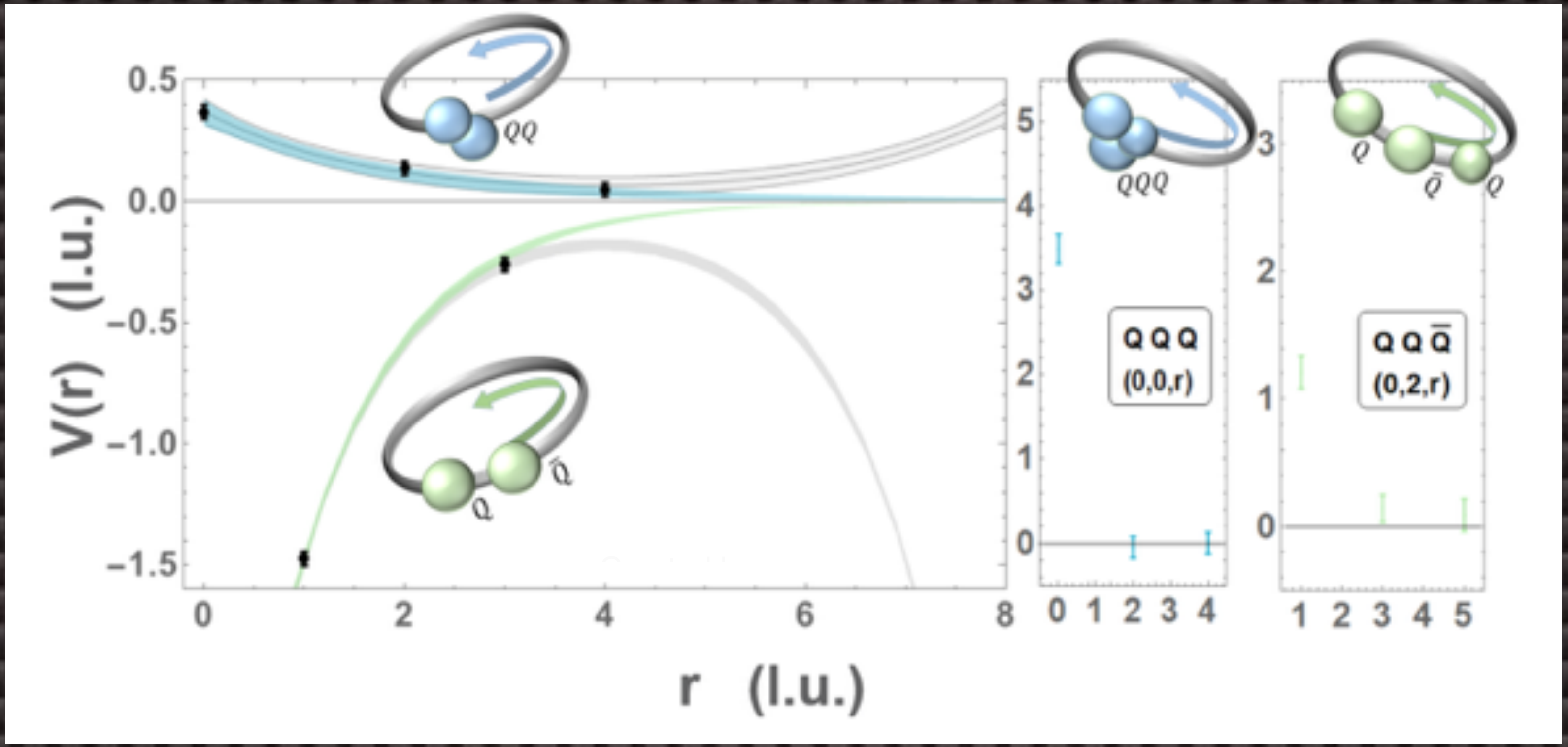
Oak Ridge National Laboratory





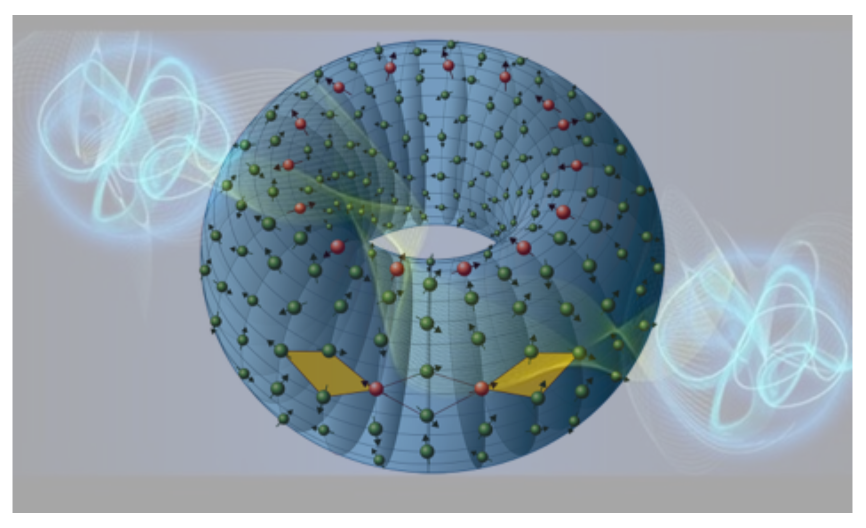
2 and 3-Hadron Interactions in the Schwinger Model

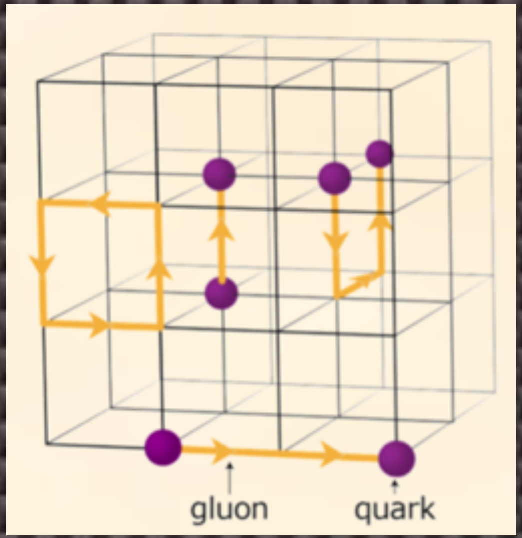


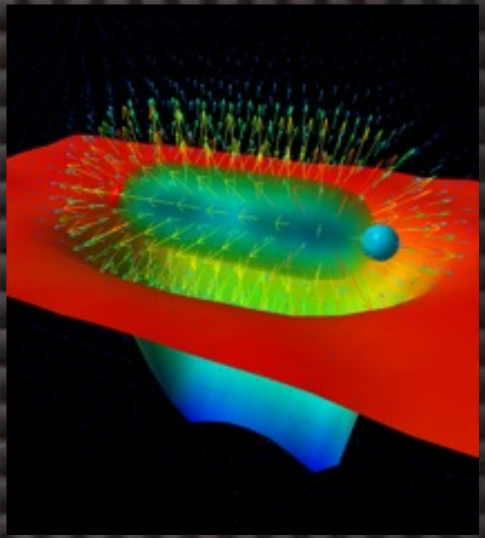


Verstraete and collaborators, Jansen and collaborators have explored much larger systems with precision

Summary







QC and QIS now entering NP (and HEP) in US

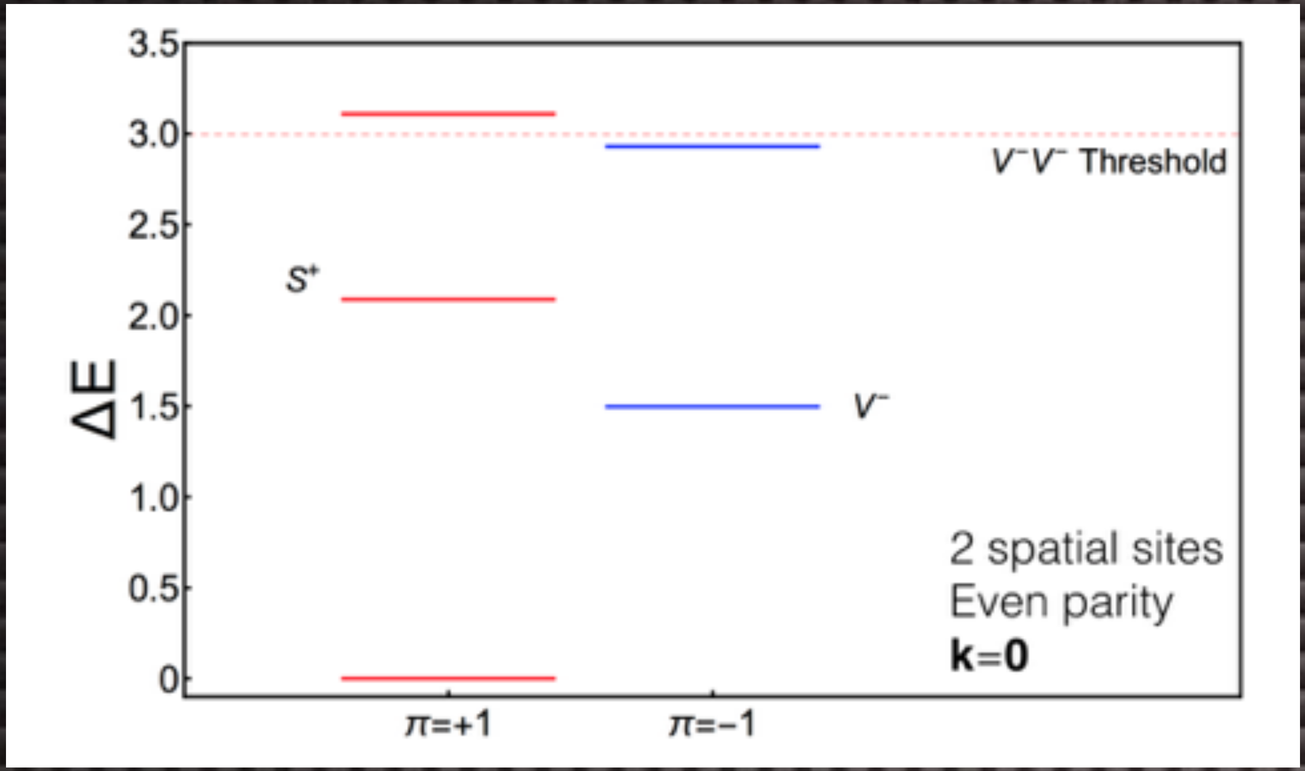
- Significant potential for disruption with new understandings and capabilities
  - address exponentially difficult challenges - finite-density and dynamics
- Lattice QCD techniques for Hamiltonian formulation
  - technology transfer is underway
  - low-dimensional, simple systems being ``stood up''

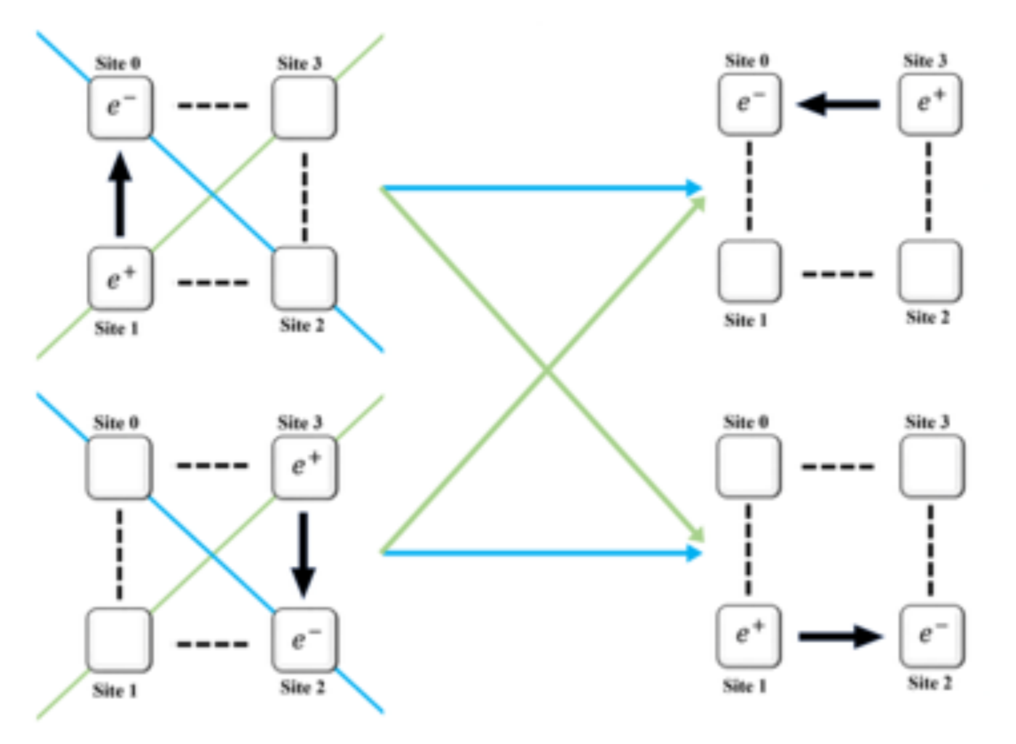
Lattice QFT developments likely to impact QC

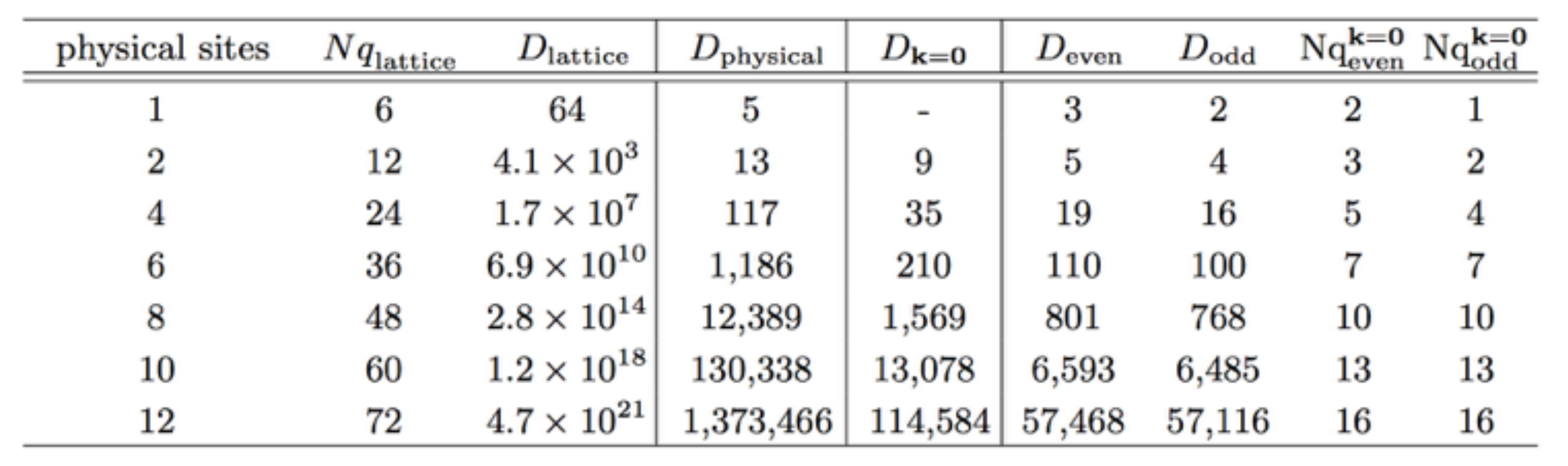
- lattices of qubits required for logical qubits and error-correction - quantum many-body systems
- stability of topological field configurations

FIN

Spectrum and Symmetries







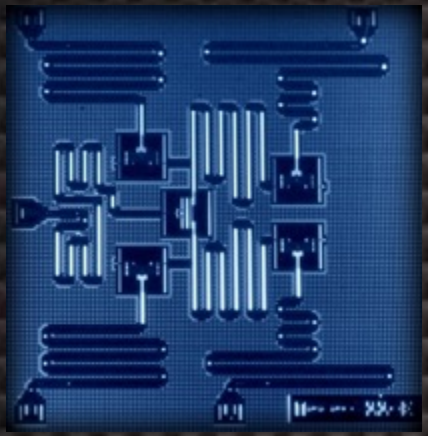
physical sites	Nq_{lattice}	D_{lattice}	D_{physical}	$D_{\mathbf{k=0}}$	D_{even}	D_{odd}	$\text{Nq}^{\mathbf{k=0}}_{\text{even}}$	$\text{Nq}^{\mathbf{k=0}}_{\text{odd}}$
1	6	64	5	-	3	2	2	1
2	12	4.1×10^3	13	9	5	4	3	2
4	24	1.7×10^7	117	35	19	16	5	4
6	36	6.9×10^{10}	1,186	210	110	100	7	7
8	48	2.8×10^{14}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

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

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

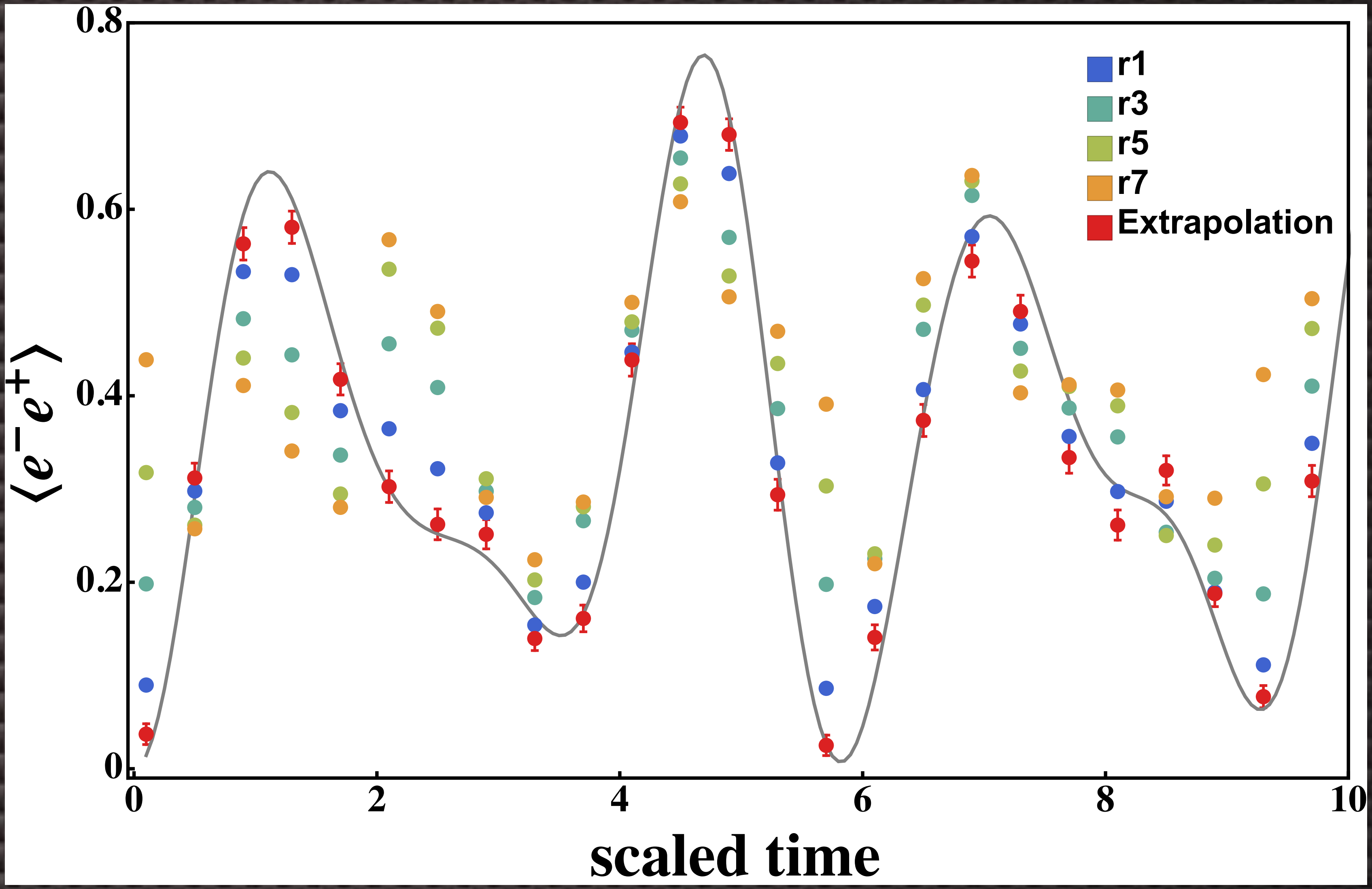
Living NISQ - IBM
Classically Computed U(t)

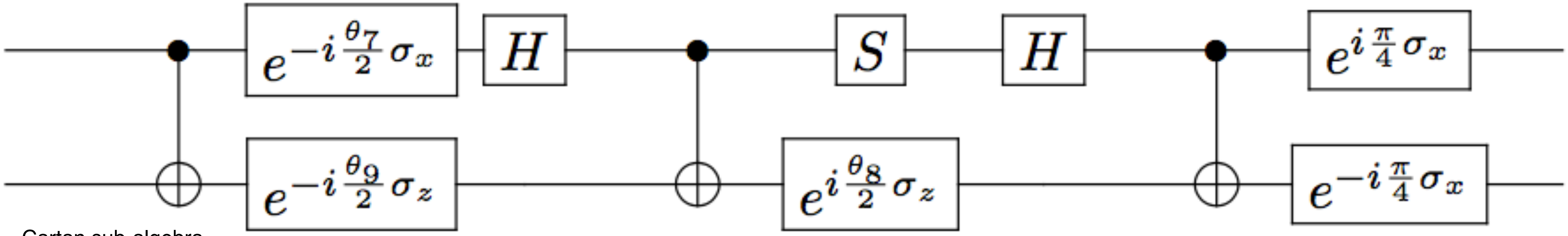


OAK RIDGE National Laboratory

INSTITUTE for NUCLEAR THEORY

ibmqx2 - cloud-access

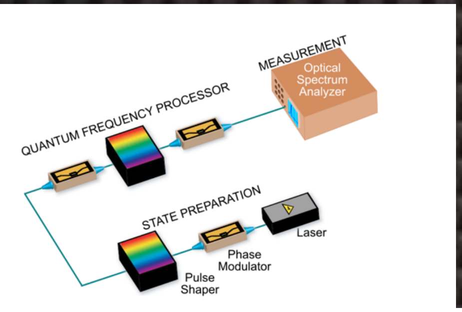




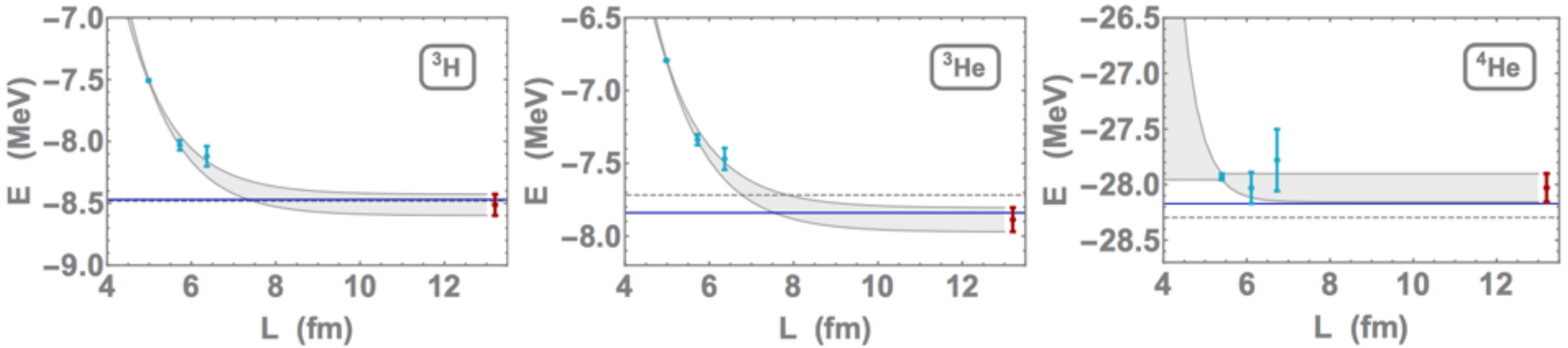
Cartan sub-algebra

All-Optical QFT
Light Nuclei

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



Papenbrock, Hagen, …



NLO Pionless EFT matched to experiment

L == equivalent Harmonic Oscillator Model Space Truncation