Pursuing the Quantum Advantage for QCD

Martin J Savage

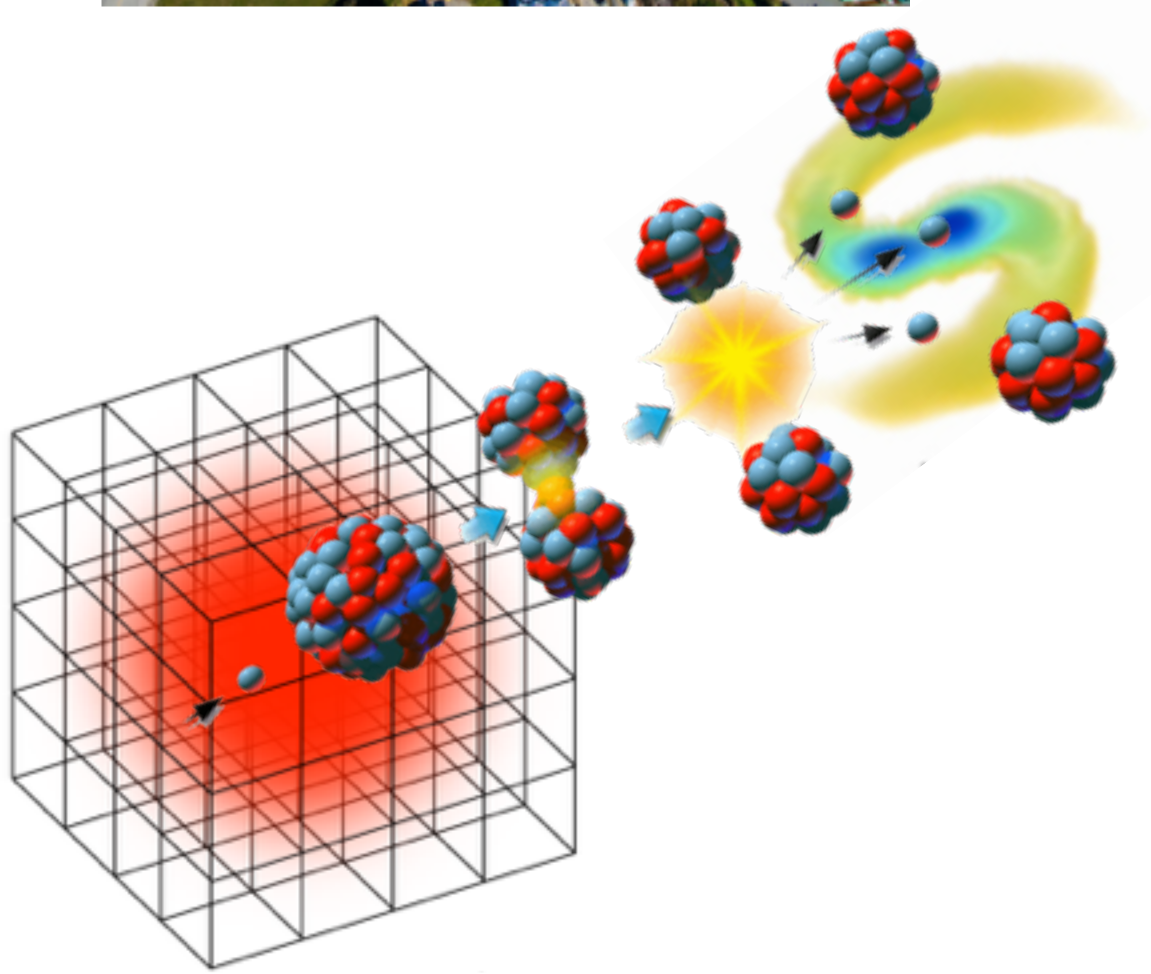
INSTITUTE for NUCLEAR THEORY

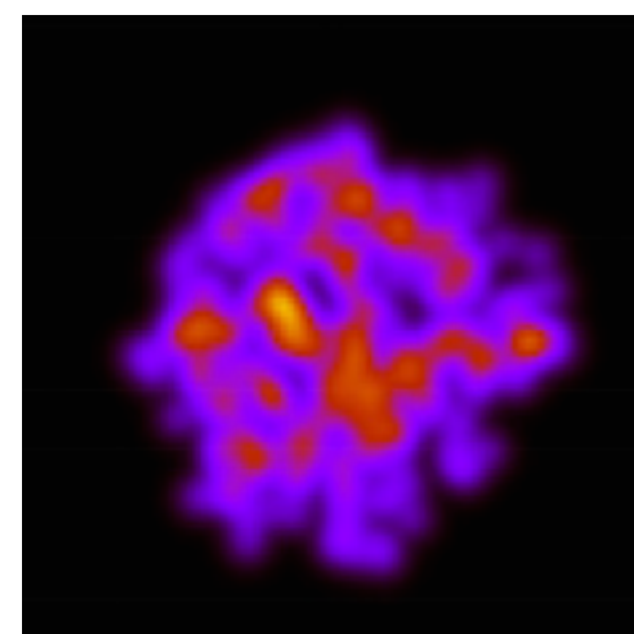
Intersections between Nuclear Physics and Quantum Information

March 28, 2018

The Objective

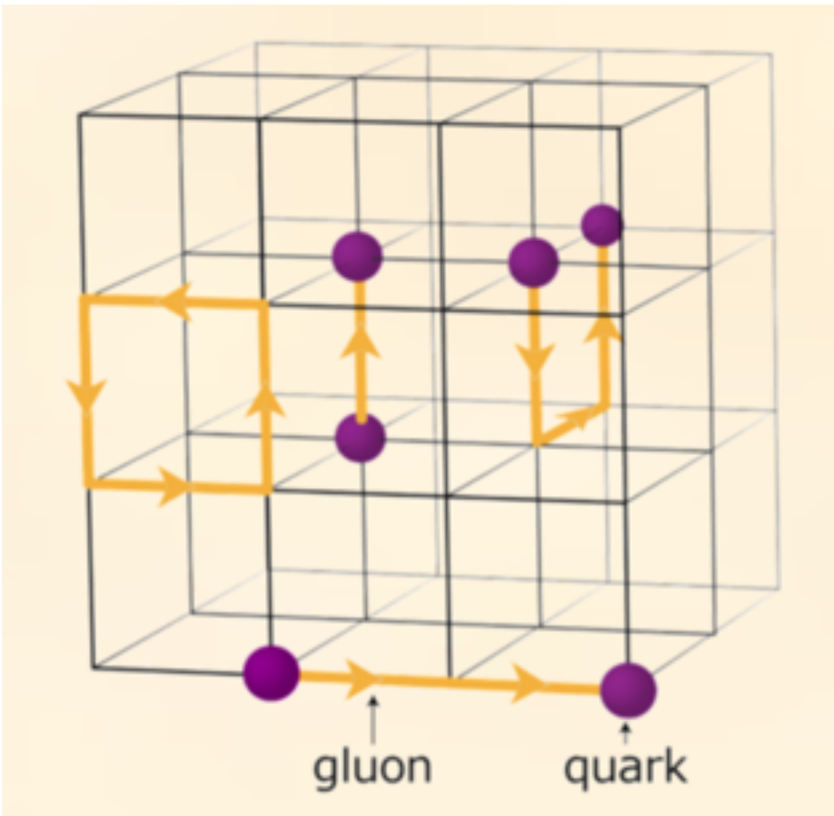
Imagine being able to predict — with unprecedented accuracy and precision — the structure of the proton and neutron, and the forces between them, directly from the dynamics of quarks and gluons, and then using this information in calculations of the structure and reactions of atomic nuclei and of the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



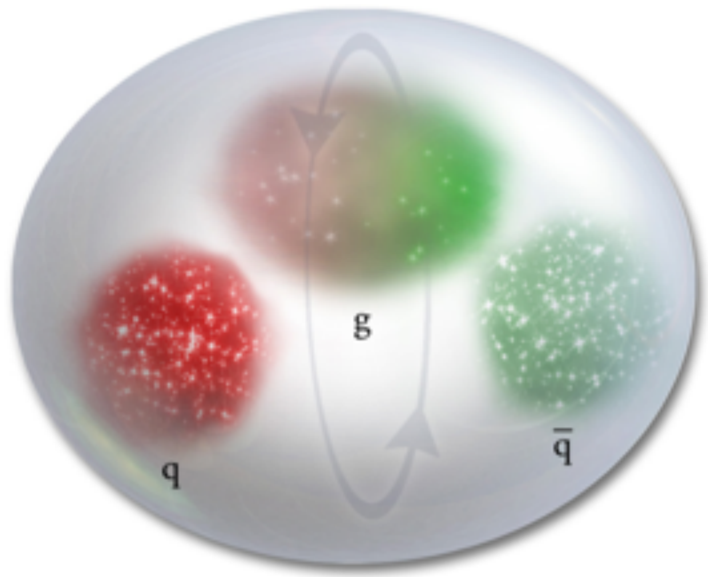


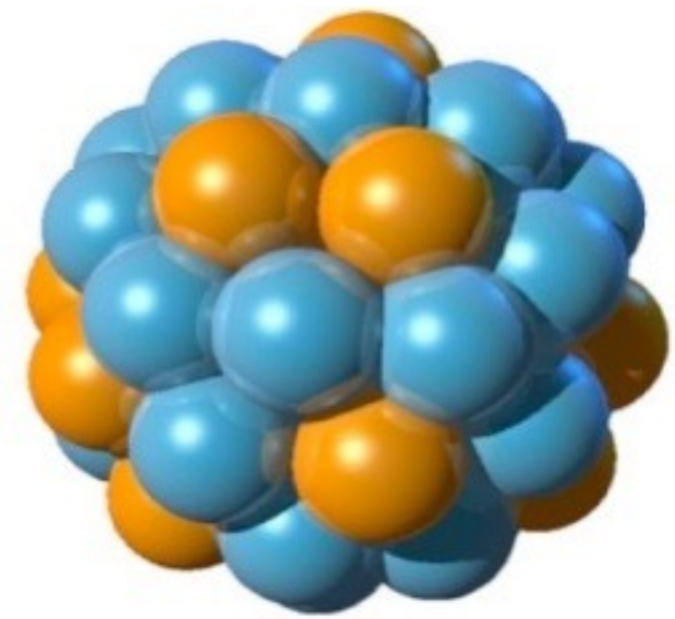
See also talks by David Dean and Peter Petreczky this morning.

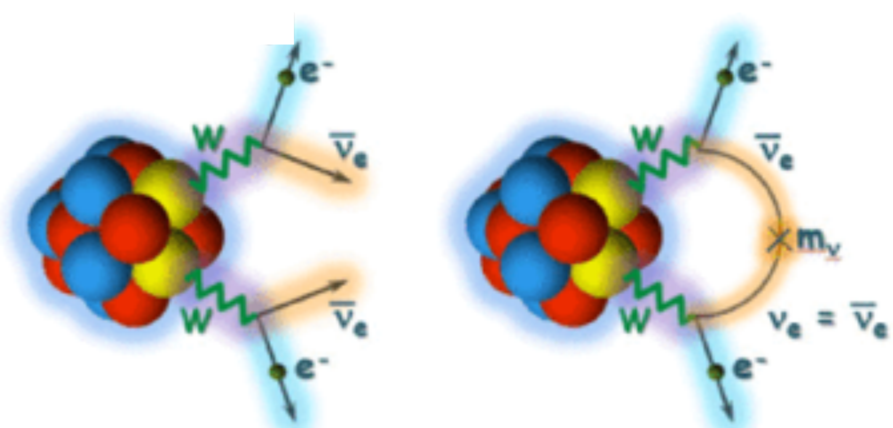
e.g., Hadrons and Nuclei

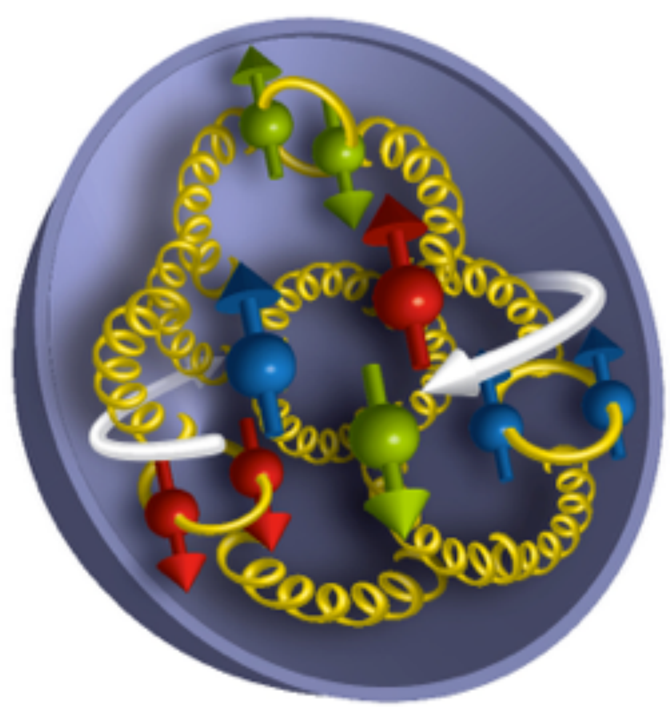


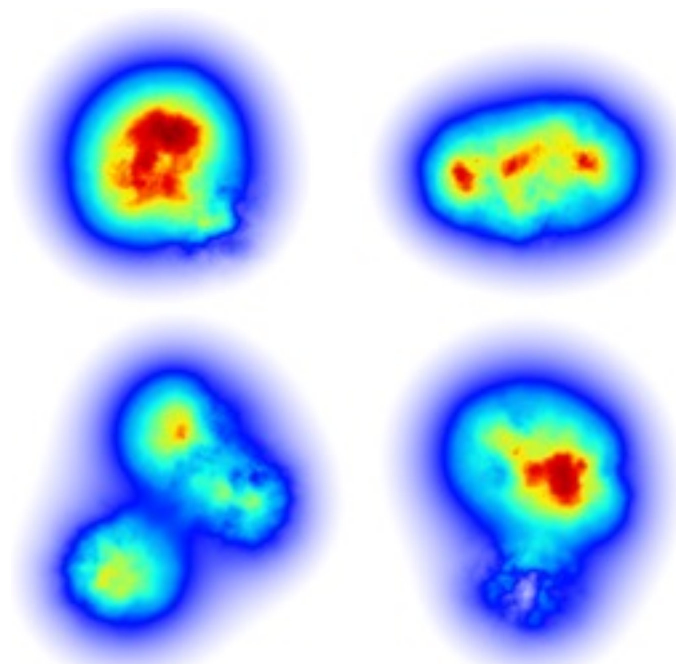
~10% of Leadership Class Computing resources





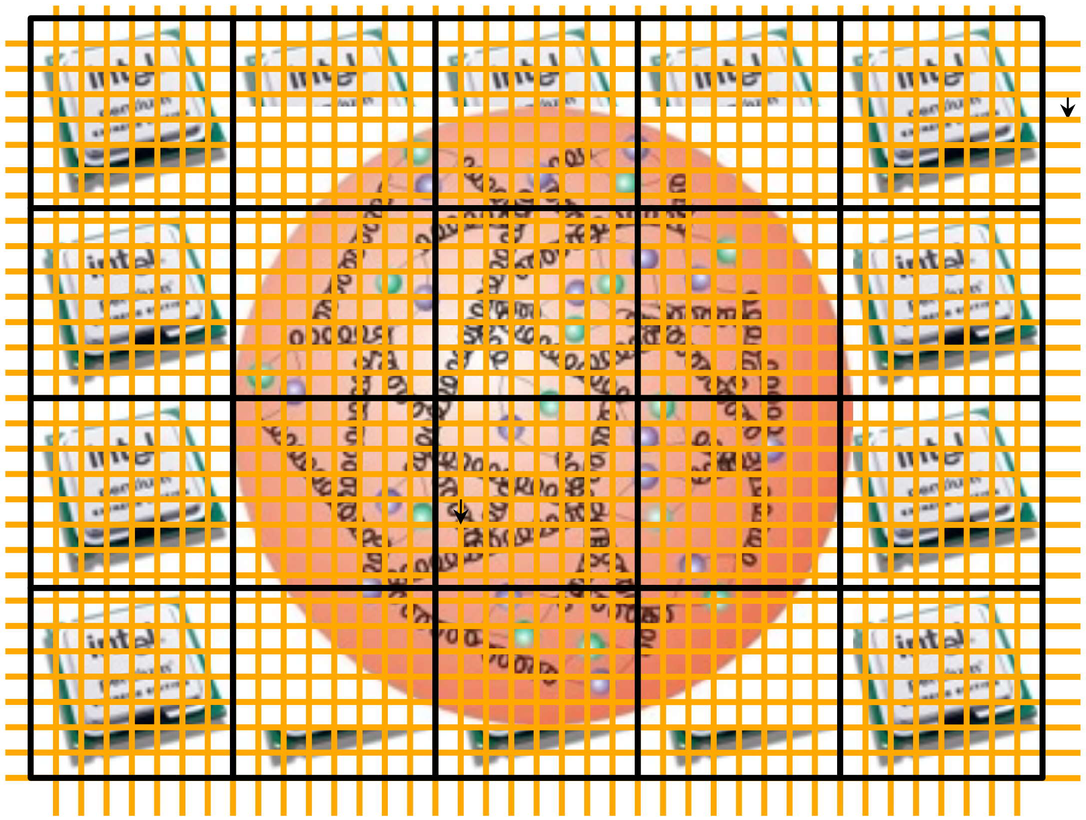






Static quantities with exascale computing …. **reactions** and **dynamics** remain ``difficult”

Lattice Quantum Chromodynamics - Discretized Euclidean Spacetime

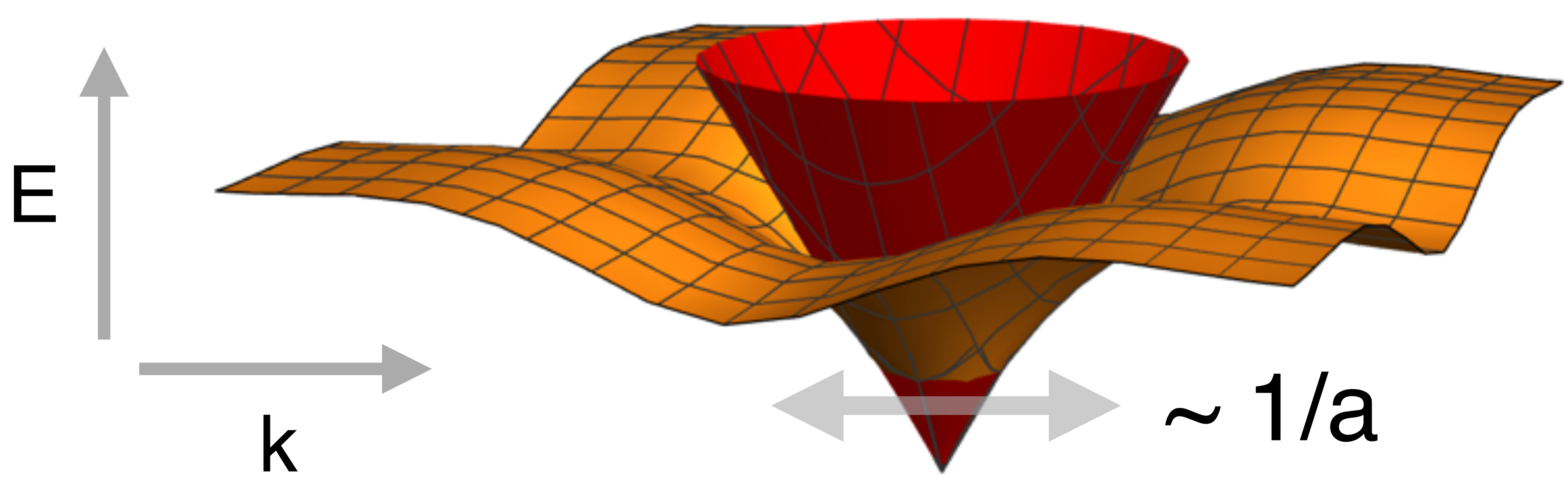


Lattice Spacing : $a \ll 1/\Lambda_\chi$ (Nearly Continuum)

Lattice Volume : $m_\pi L \gg 2\pi$ (Nearly Infinite Volume)

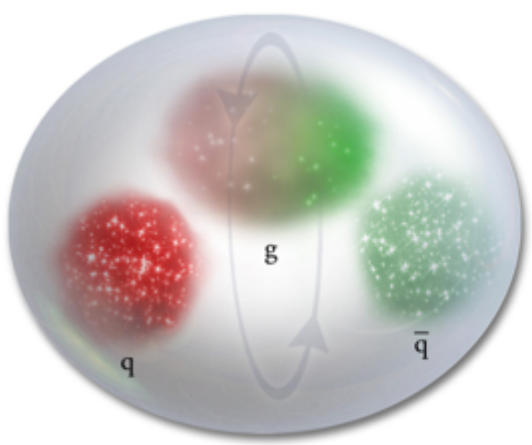
Extrapolation to $a = 0$ and $L = \infty$

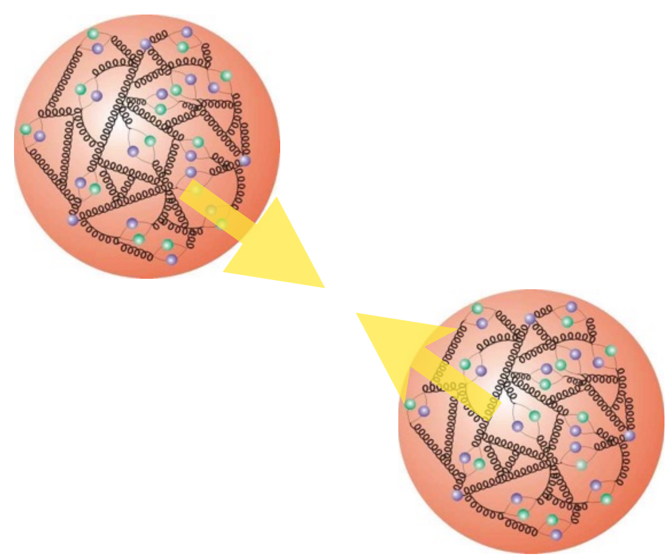
Systematically remove non-QCD parts of calculation through effective field theories



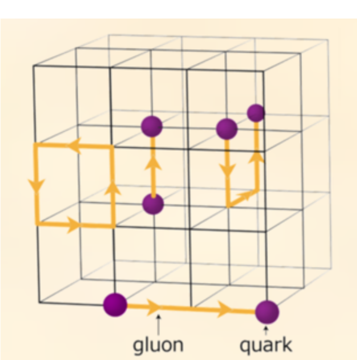
“ Features “

S-matrix elements, equilibrium properties, definite quantum numbers, e.g., 2 neutrons and 1 proton





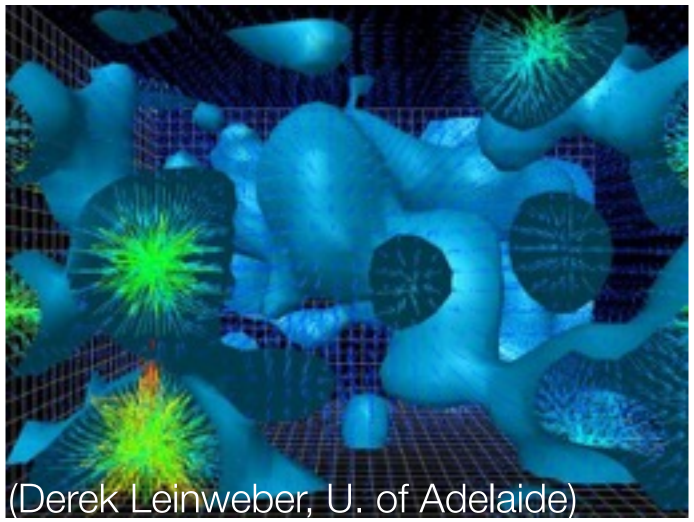
Signal to Noise Problem
[Sign Problem]



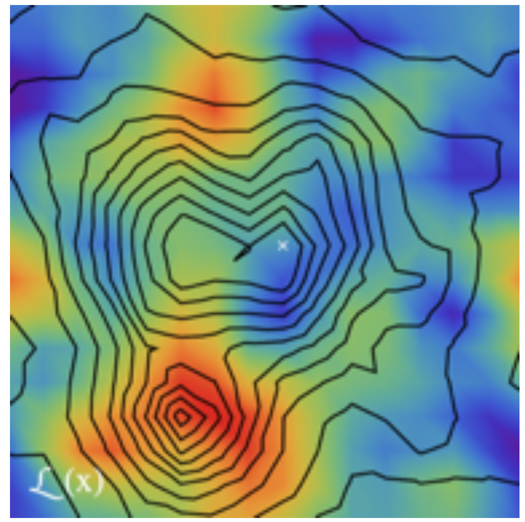
Statistical sampling of the path integral is the limiting element

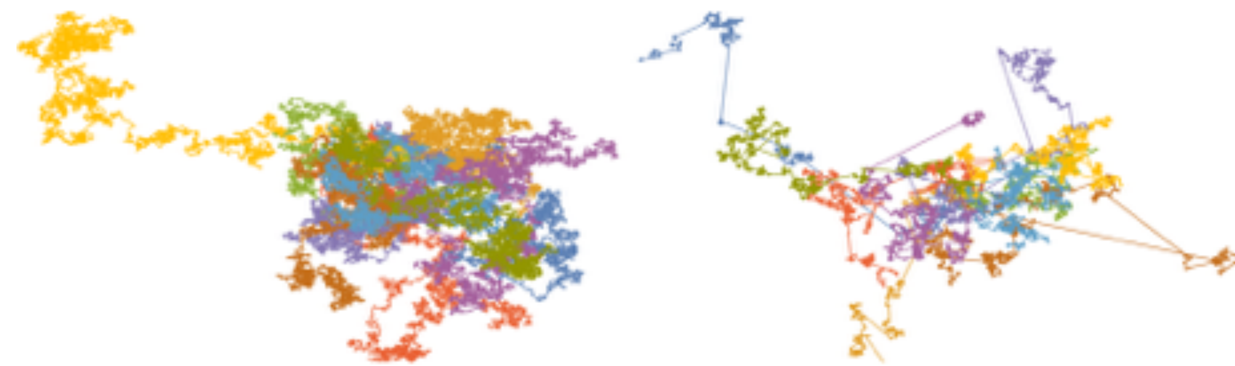
“ Features “

Michael Wagman, PhD Thesis

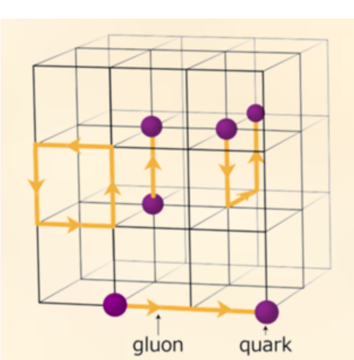


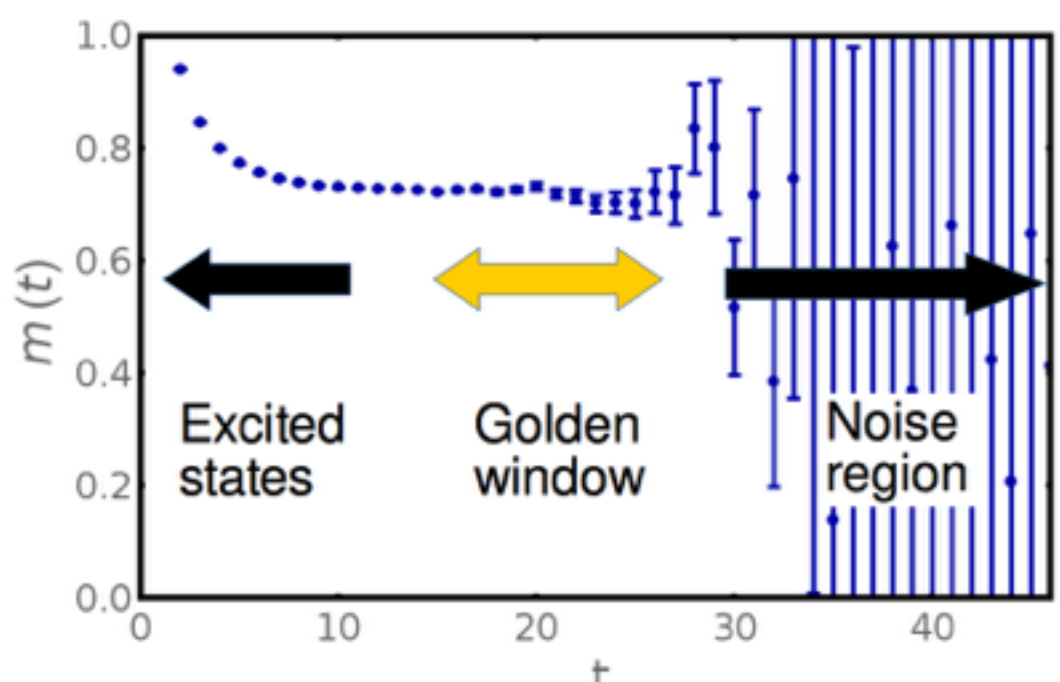
(Derek Leinweber, U. of Adelaide)





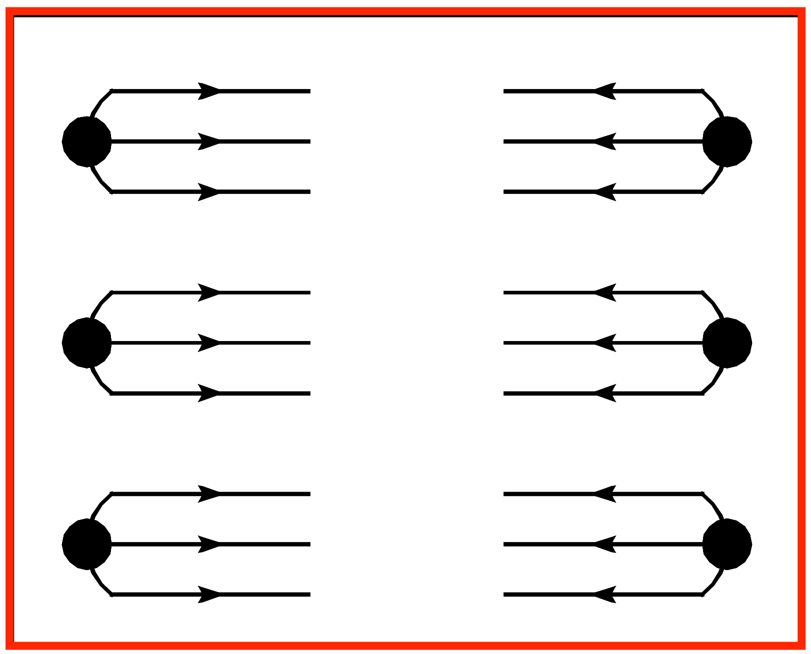
$$C(t) = e^{R(t)+i\theta(t)} \rightarrow \frac{1}{N}\sum_{U_i} e^{R(t;U_i)+i\theta(t;U_i)}$$





“ Features “

Large number of quark contractions

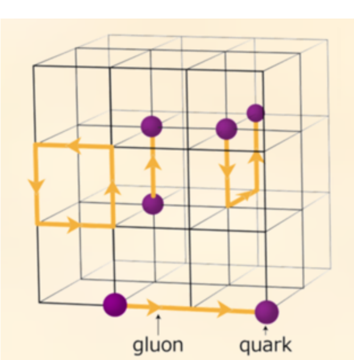


Proton : $N^{\text{cont}} = 2$

^{235}U : $N^{\text{cont}} = 10^{1494}$

$$N_{\text{cont.}} = u!d!s! \quad (\text{Naive})$$
$$= (A+Z)!(2A-Z)!s!$$

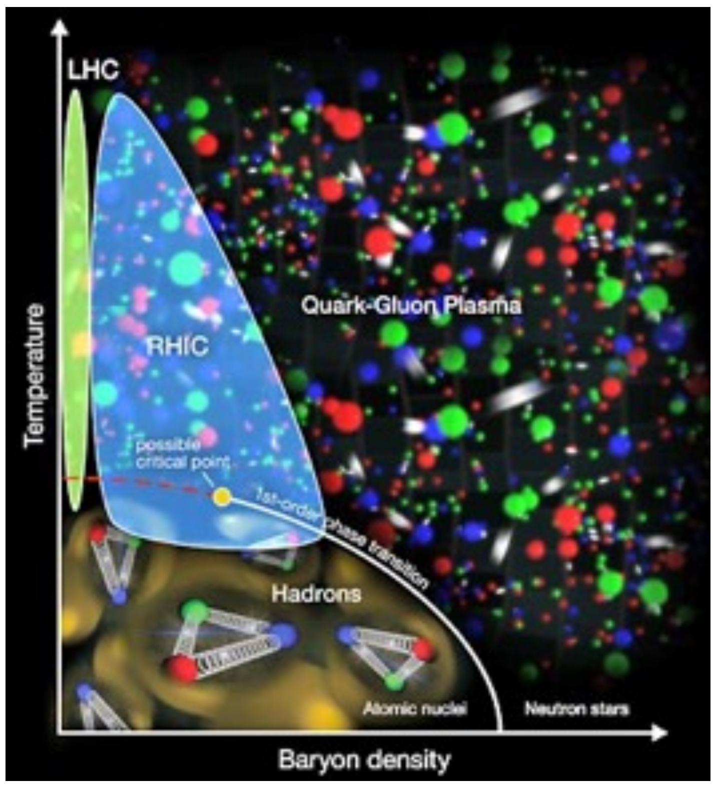
Symmetries provide significant reduction (NPLQCD, PACS - 2010)

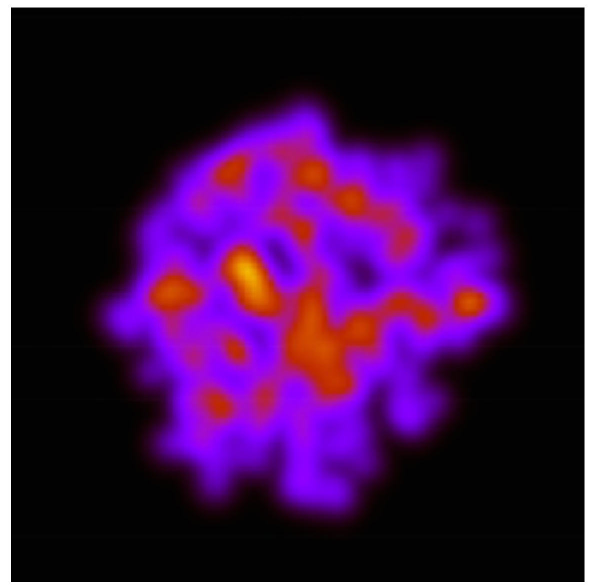


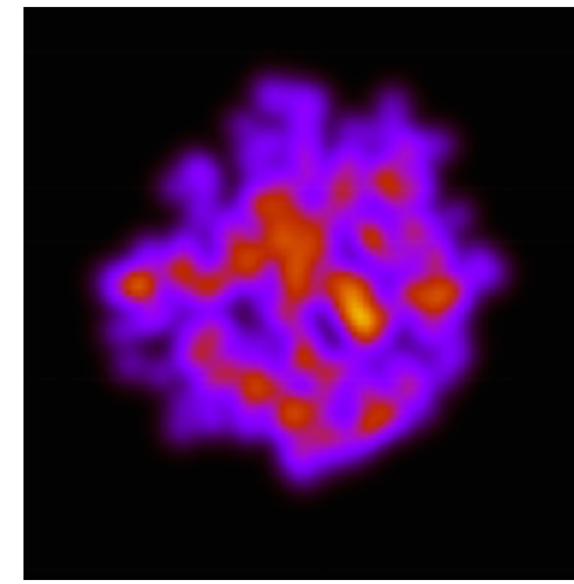
$$^{3}\text{He} \quad : \quad 2880 \rightarrow 93$$

“ Features - Finite Density “

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

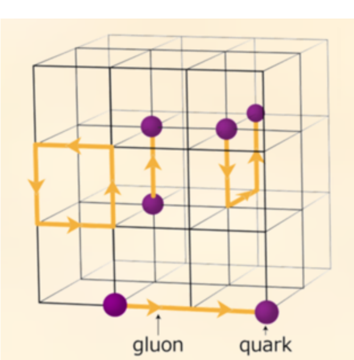






Sign Problem

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



Complex for non-zero chemical potential

“ Features “

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

Taylor expansion in μ/T (methodology)

$$\boxed{\frac{p(\vec{\mu},T)}{T^4} = \sum_{i,j,k=0}^{\infty} \frac{1}{i!j!k!}\chi_{i,j,k}^{BQS}(T)\left(\frac{\mu_B}{T}\right)^i\left(\frac{\mu_Q}{T}\right)^j\left(\frac{\mu_S}{T}\right)^k}$$

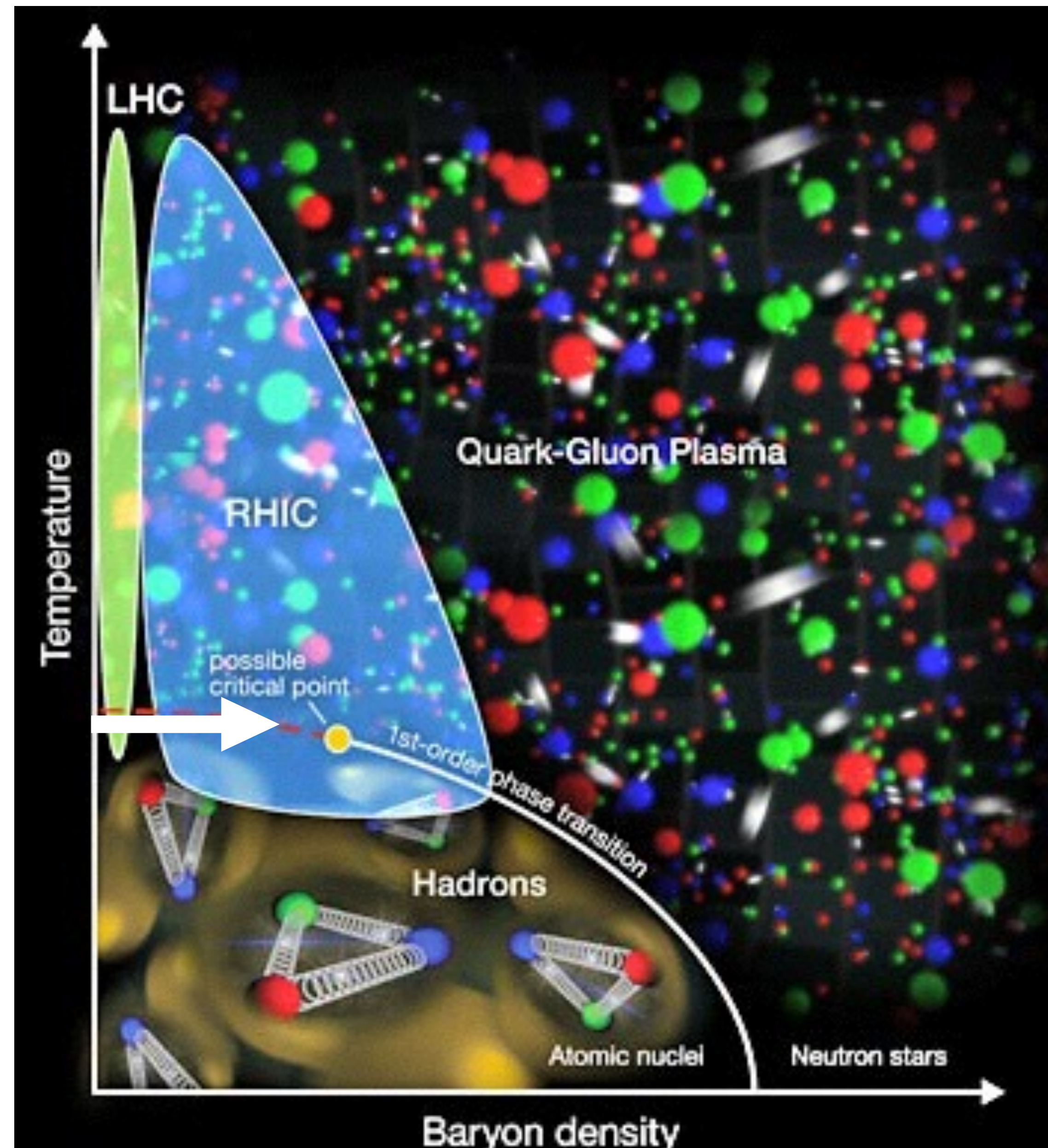
with $\chi_{i,j,k}^{BQS}(T) = \frac{1}{VT^3}\left.\frac{\partial^{i+j+k}\ln Z(\vec{\mu},T)}{\partial\hat{\mu}_B^i\partial\hat{\mu}_Q^j\partial\hat{\mu}_S^k}\right|_{\vec{\mu}=0}$ and $\hat{\mu}=\mu/T$

Example:

$$\frac{\partial^2 \ln Z}{\partial\mu^2} = \left\langle \mathrm{Tr}\left[M^{-1}M''\right]\right\rangle - \left\langle \mathrm{Tr}\left[M^{-1}M'M^{-1}M'\right]\right\rangle + \left\langle \mathrm{Tr}\left[M^{-1}M'\right]^2\right\rangle$$

$$\simeq \left\langle n^2(x)\bigcirc\right\rangle - \left\langle n(x)\bigcirc n(y)\right\rangle + \left\langle n(x)\bigcirc\bigcirc n(y)\right\rangle$$

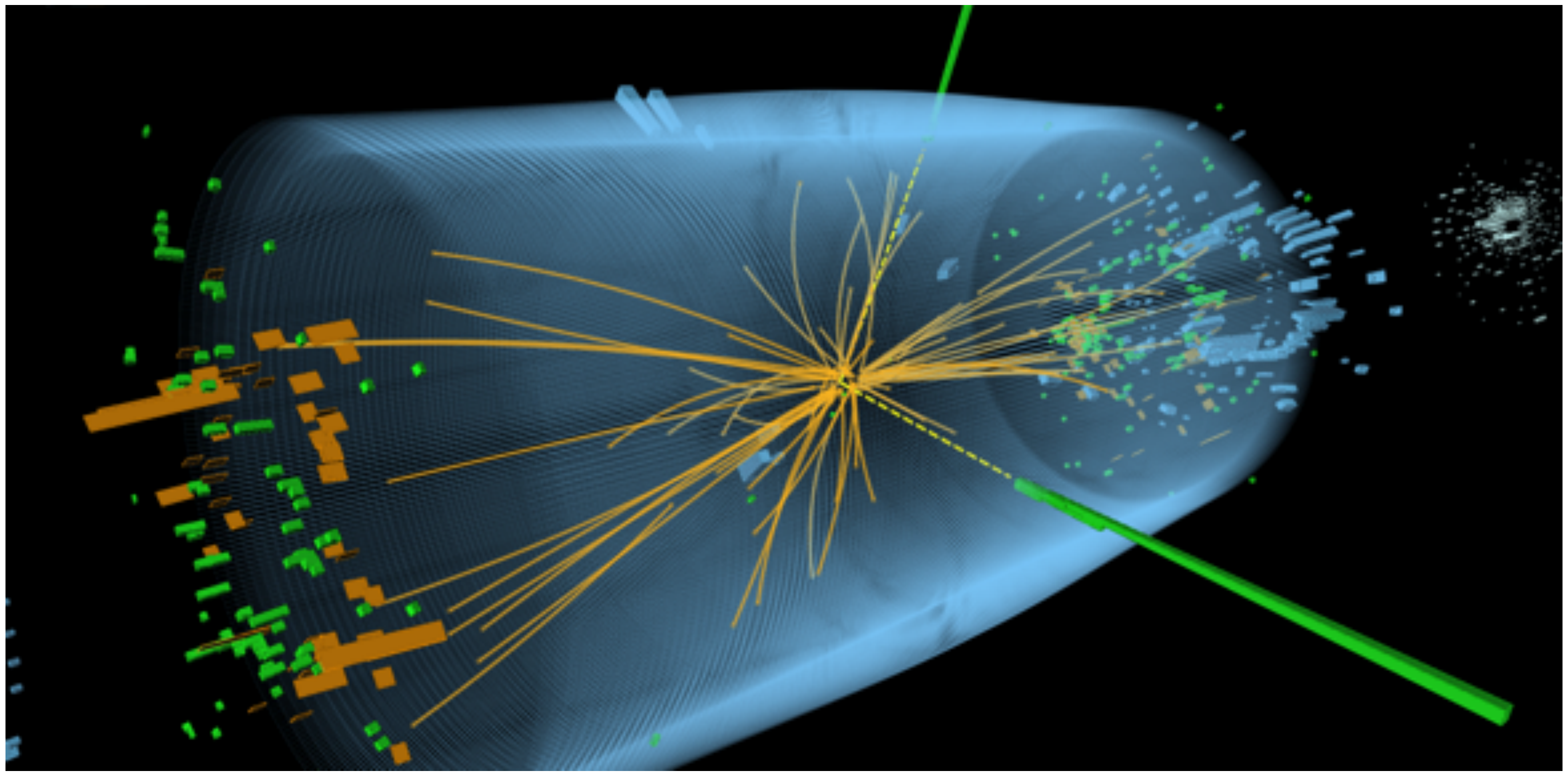
C. Schmidt, SIGN 2017, INT-17-64W, Seattle, WA, USA 6



USQCD

In production - large resource requirements - limits are visible

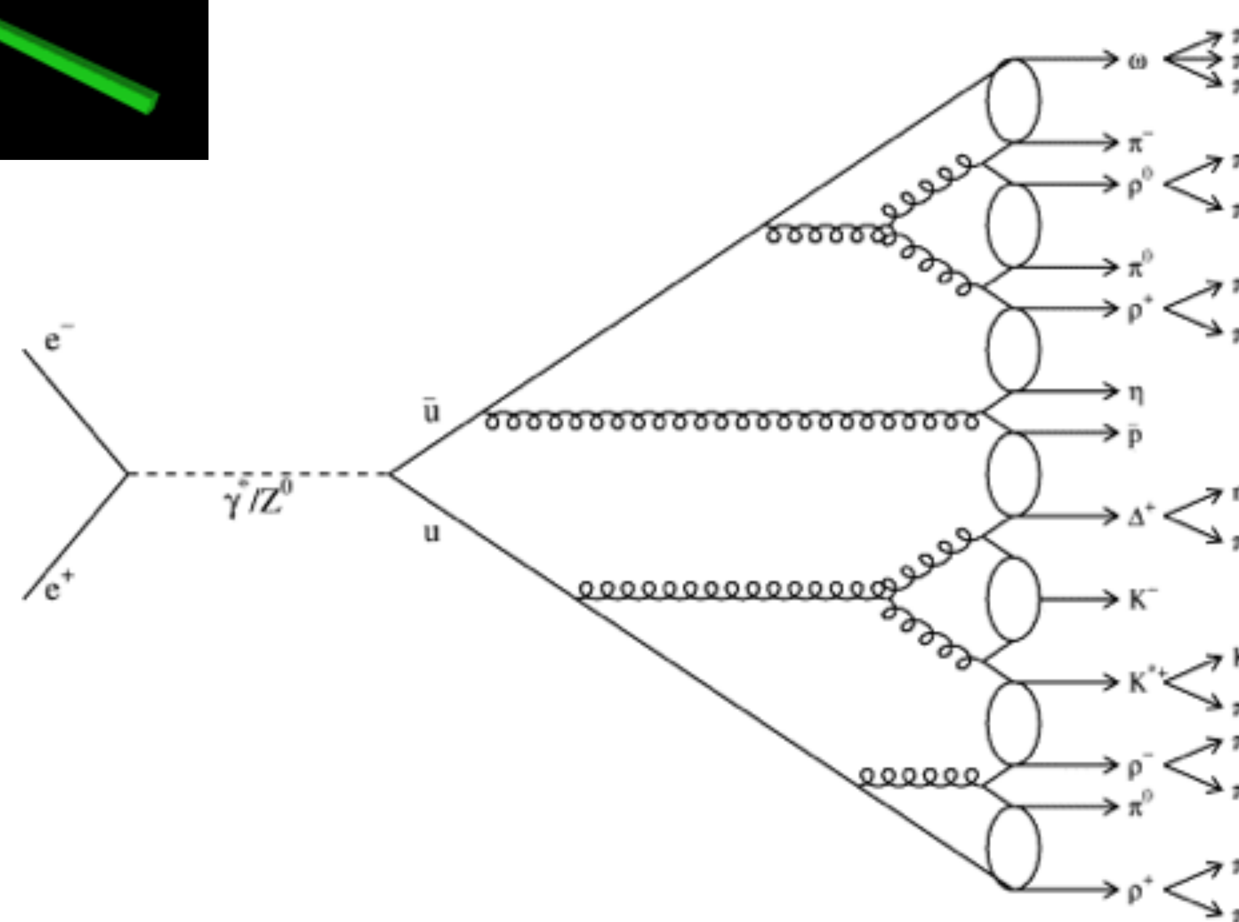
Fragmentation
Vacuum and In-Medium



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



Great talk by Stefan Floerchinger this afternoon

Why Quantum Computing?

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

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

Quantum Computing for Nuclear Physics
November 14-15, 2017

Intersections Between Nuclear Physics and Quantum Information
November 14-15, 2017

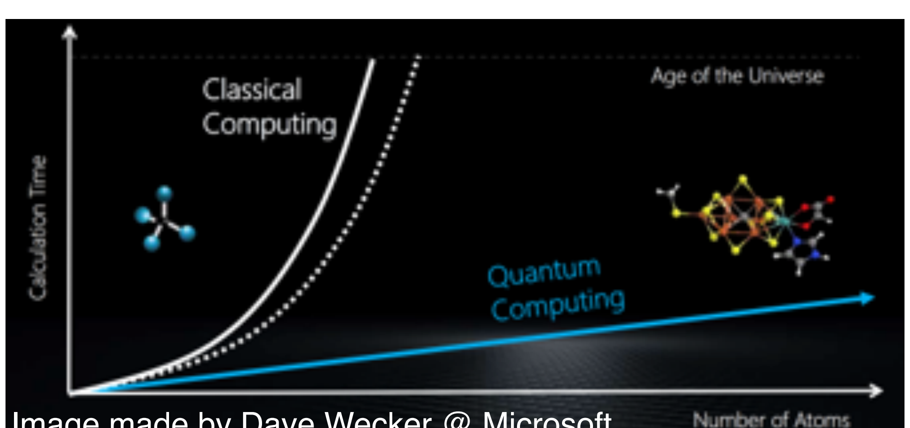
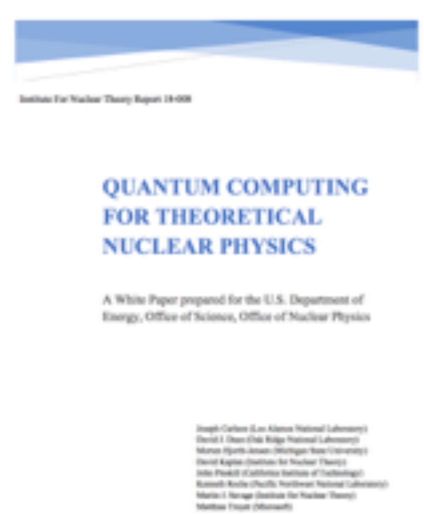


Image made by Dave Wecker @ Microsoft


QUANTUM COMPUTING
FOR THEORETICAL
NUCLEAR PHYSICS

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

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

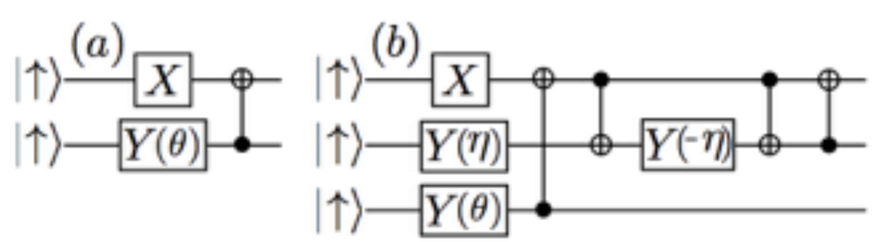
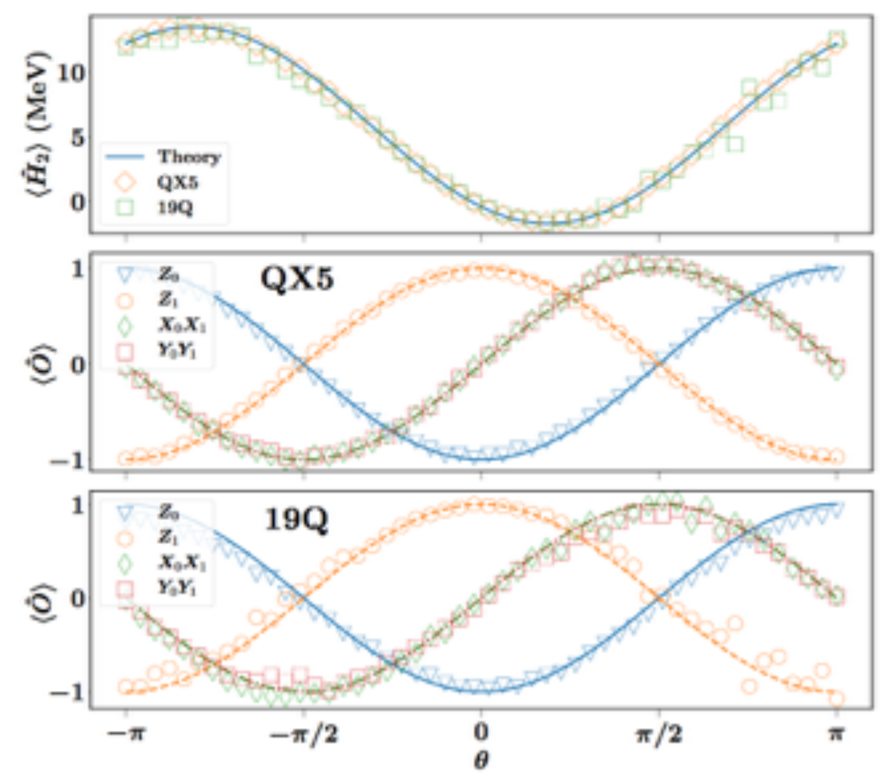


FIG. 1. Low-depth circuits that generate unitary rotations in Eq. (7) (panel a) and Eq. (8) (panel b). Also shown are the single-qubit gates of the Pauli X matrix, the rotation $Y(\theta)$ with angle θ around the Y axis, and the two-qubit CNOT gates.

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,

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



See talk by David Dean this morning.

Quantum Field Theory with Quantum Computers - Foundational Works

Simulating lattice gauge theories on a quantum computer

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

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

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

Phys.Rev. A73 (2006) 022328

Quantum Computation of Scattering in Scalar Quantum Field Theories

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

[†] *National Institute of Standards and Technology, Gaithersburg, MD 20899*
[‡] *University of Pittsburgh, Pittsburgh, PA 15260*
[§] *California Institute of Technology, Pasadena, CA 91125*

Abstract

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

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

Detailed formalism for 3+1 Hamiltonian Gauge Theory

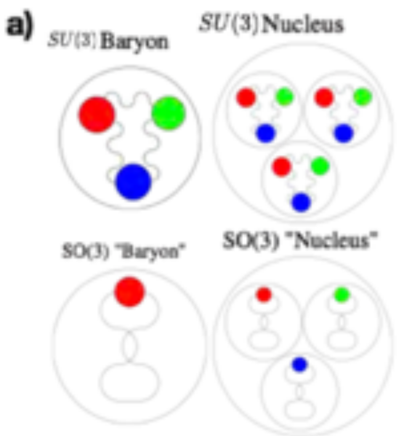
Discretrized spatial volume - no quarks

10^4 spatial lattice sites would require 10^5 * D qubits ,
D=size of register defining value of the field

Scalar Field Theory - Hamiltonian is nice

Quantum Field Theory

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

European Research Council

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]

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[b]International Center for Theoretical Physics, 34151 Trieste, Italy
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[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

Quantum Field Theory
- recent examples

Quantum sensors for the generating functional of interacting quantum field theories

A. Bermudez,[1,2,*] G. Aarts,[1] and M. Müller[1]
[1]*Department of Physics, College of Science, Swansea University, Singleton Park, Swansea SA2 8PP, United Kingdom*
[2]*Instituto de Física Fundamental, IFF-CSIC, Madrid E-28006, Spain*

Difficult problems described in terms of interacting quantum fields evolving in real time or out of equilibrium are abound in condensed-matter and high-energy physics. Addressing such problems via controlled experiments in atomic, molecular, and optical physics would be a breakthrough in the field of quantum simulations. In this work, we present a quantum-sensing protocol to measure the generating functional of an interacting quantum field theory and, with it, all the relevant information about its in or out of equilibrium phenomena. Our protocol can be understood as a collective interferometric scheme based on a generalization of the notion of Schwinger sources in quantum field theories, which make it possible to probe the generating functional. We show that our scheme can be realized in crystals of trapped ions acting as analog quantum simulators of self-interacting scalar quantum field theories.

arXiv:1704.02877

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

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

arXiv:1702.05492
proposed method

Electron-Phonon Systems on a Universal Quantum Computer

Alexandru Macridin, Panagiotis Spentzouris, James Amundson, Roni Harnik
Fermilab, P.O. Box 500, Batavia, Illinois 60510, USA

arXiv:1802.07347 [quant-ph]

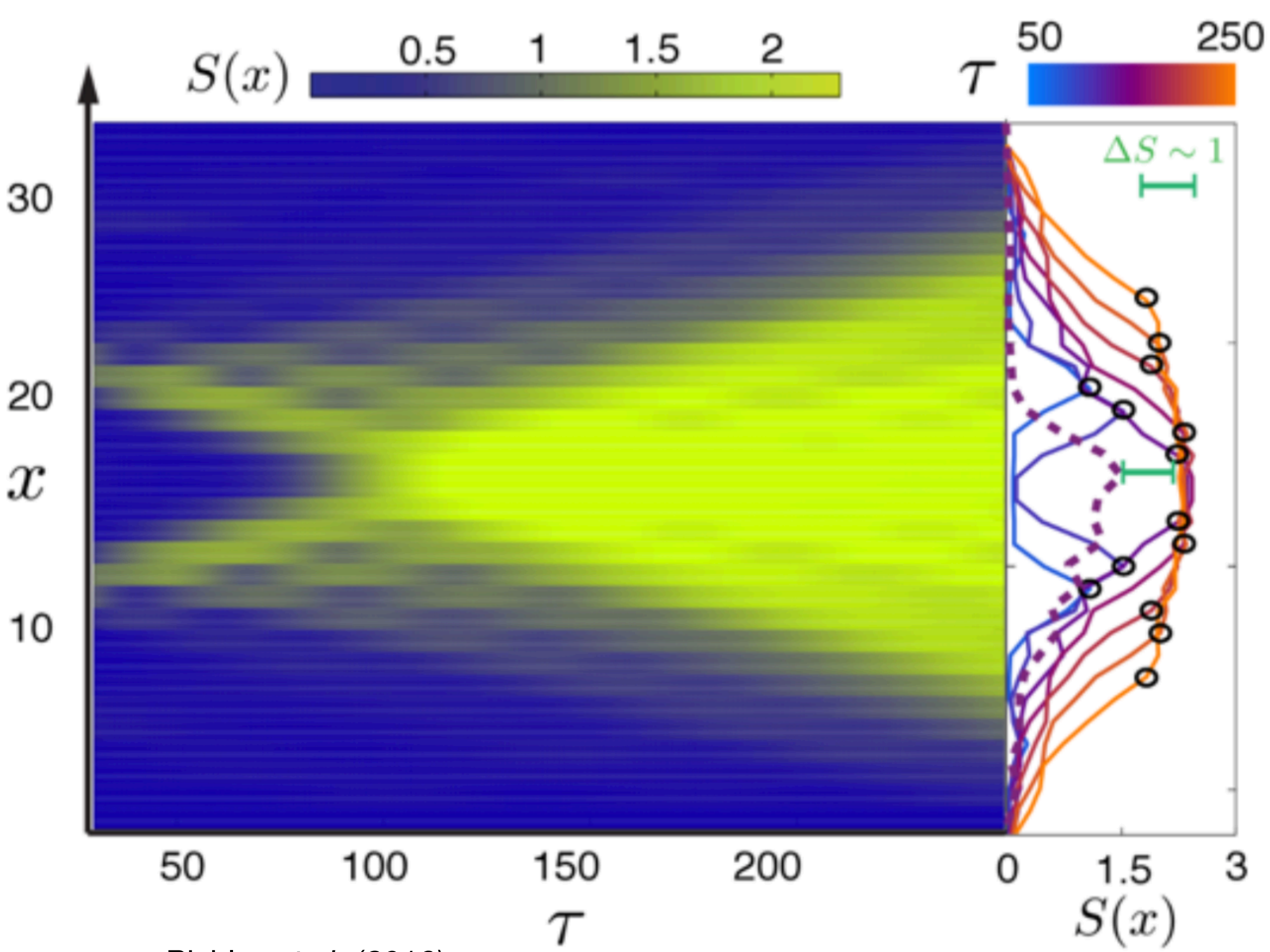
Roggero and Carlson - coherent nuclear responses to external probes
arXiv:1804.?????? [quant-ph]

Quantum Field Theory and Quantum Information

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

Preskill, Swingle, and others

Entanglement entropy in scattering (tensor networks)



Pichler *et al. (2016)*

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

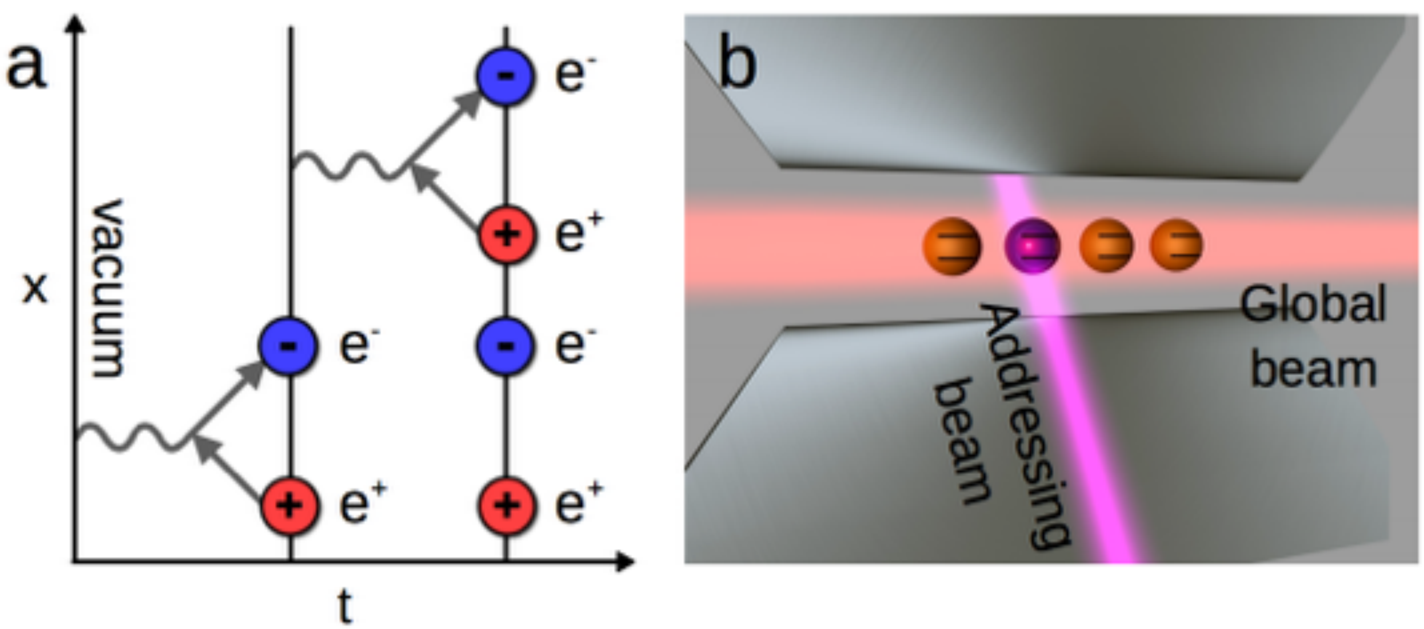
Entanglement in HEP and NP systems is starting to be considered,
e.g. fragmentation

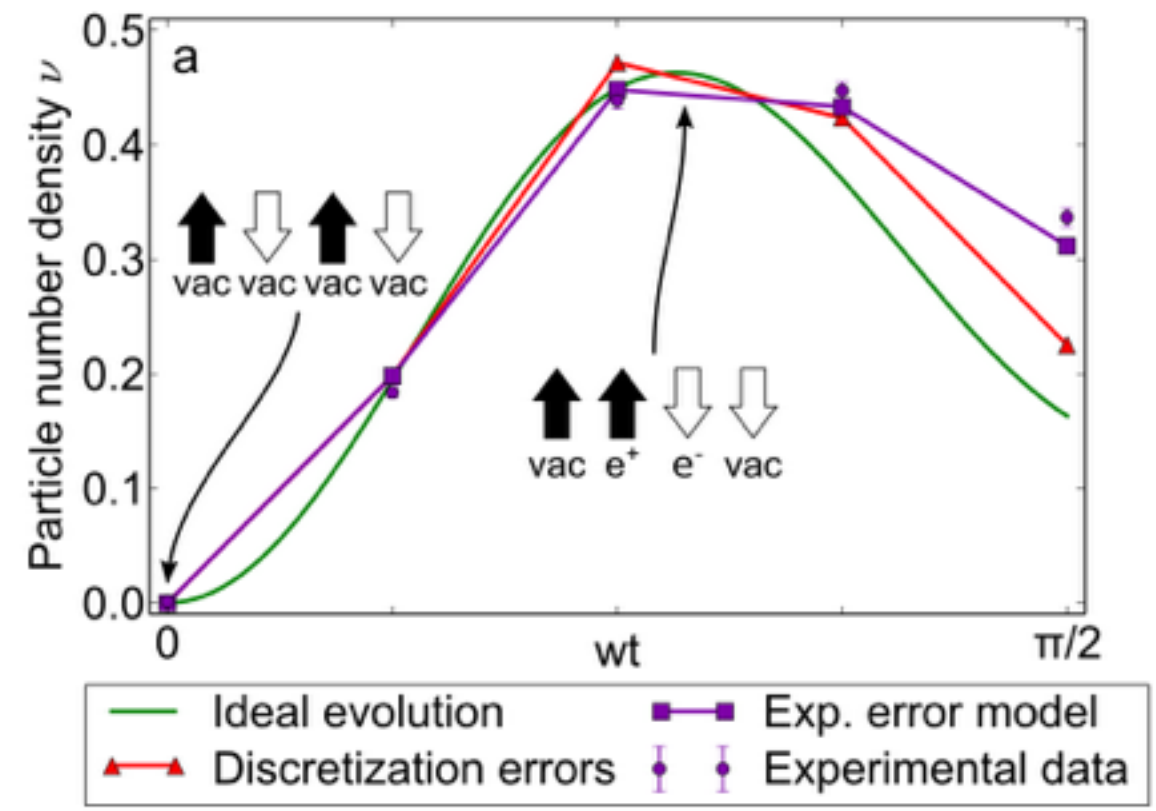
Starting Simple 1+1 Dim QED - Pivotal Paper

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

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

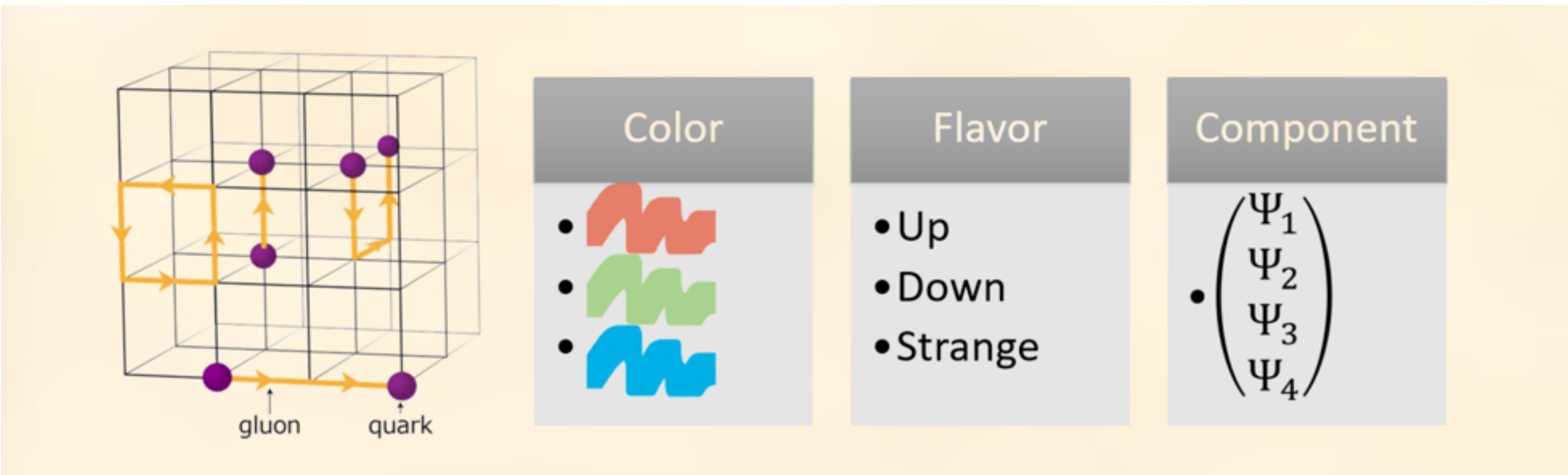
(2016)





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

Gauge Field Theories
e.g. QCD



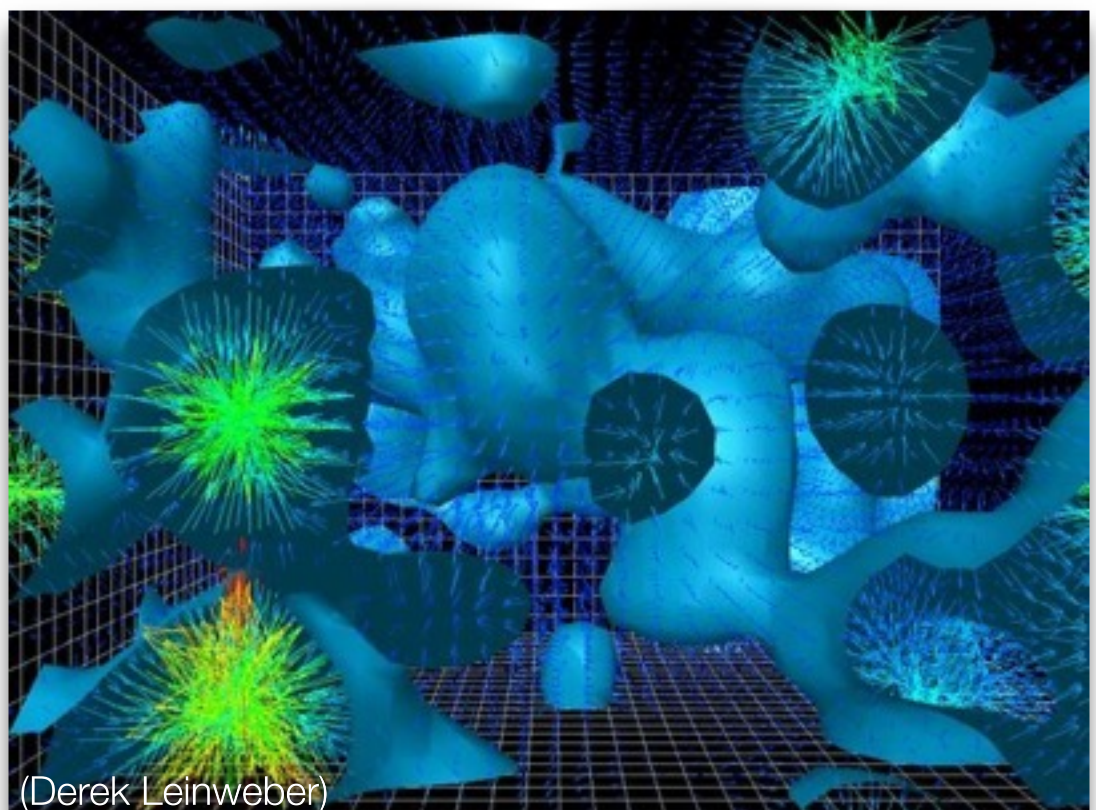
Natalie Klco

32^3 lattice requires naively > 4 million qubits !

What is the QCD Vacuum : $E^a |0\rangle = 0$?

Random fields at each point in spacetime is far from ground state.
- generally all 0++ states will be populated with some amplitude

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



1 vacuum configuration

Probability $e^{-S_{QCD}}$

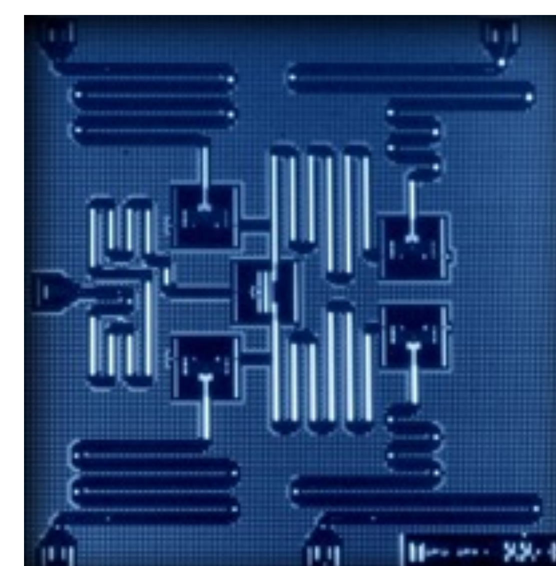
Classical Lattice QCD calculations will likely be required to provide initialization of vacuum. How to do this ? What are the algorithms?
e.g. parallel of tensor methods in 1-dim ?
but no explicit fermions,..

QC for QFT
Start Simple

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

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

INSTITUTE for NUCLEAR THEORY



DOE-ASCR

Heterogeneous Digital-Analog Quantum Dynamics Simulations

Methods and Interfaces for Quantum Acceleration of Scientific Applications

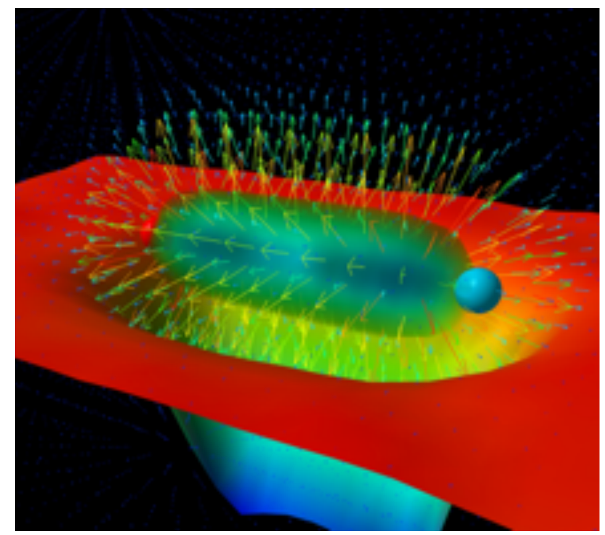
Quantum-Classical Dynamical Calculations of the Schwinger Model using Quantum Computers
N. Klco, E.F. Dumitrescu, A.J. McCaskey, T.D. Morris, R.C. Pooser, M. Sanz, E. Solano, P. Lougovski, M.J. Savage.
arXiv:1803.03326 [quant-ph]

Starting Simple 1+1 Dim QED Construction

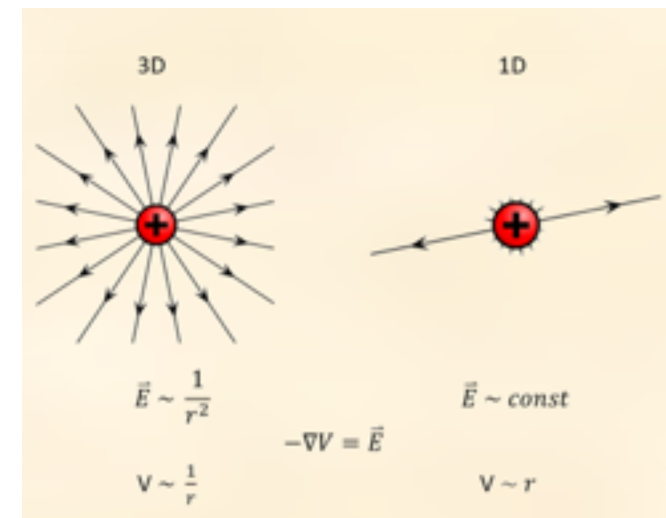
Excellent introductions to Schwinger Model, Gauge Theories and the state of the field by Christine Muschik and Erez Zohar this morning

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

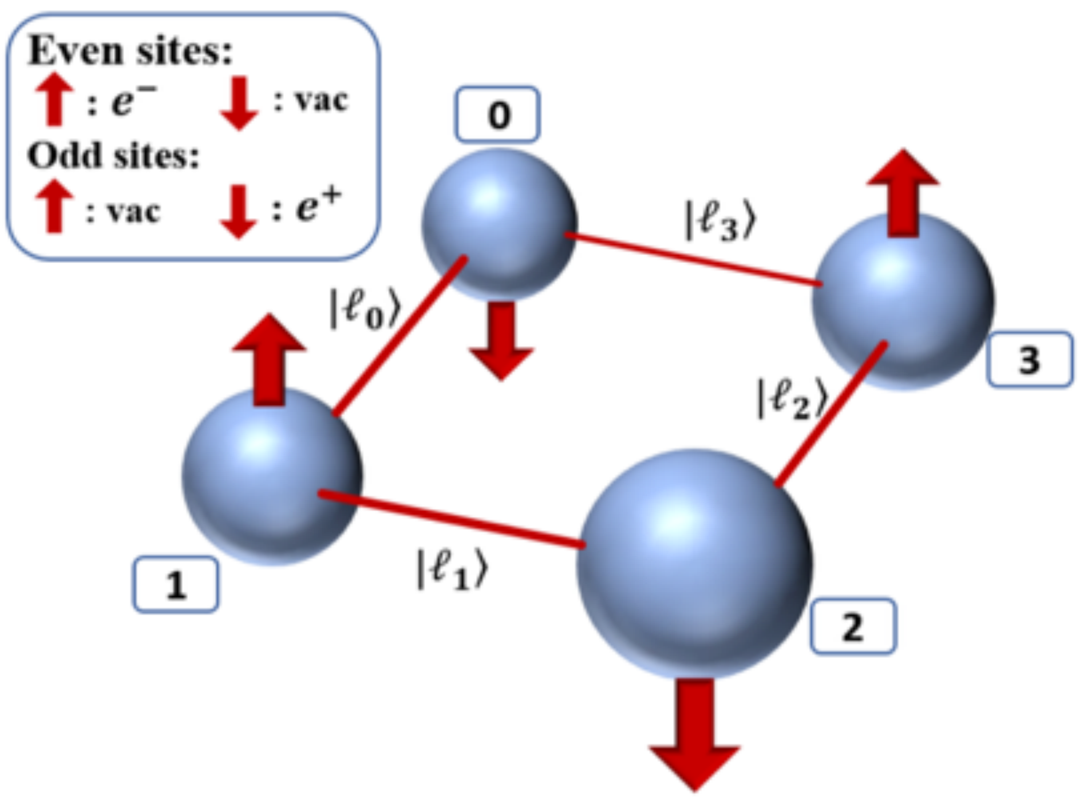
- Charge screening, confinement
- fermion condensate



Derek Leinweber



Natalie Klco

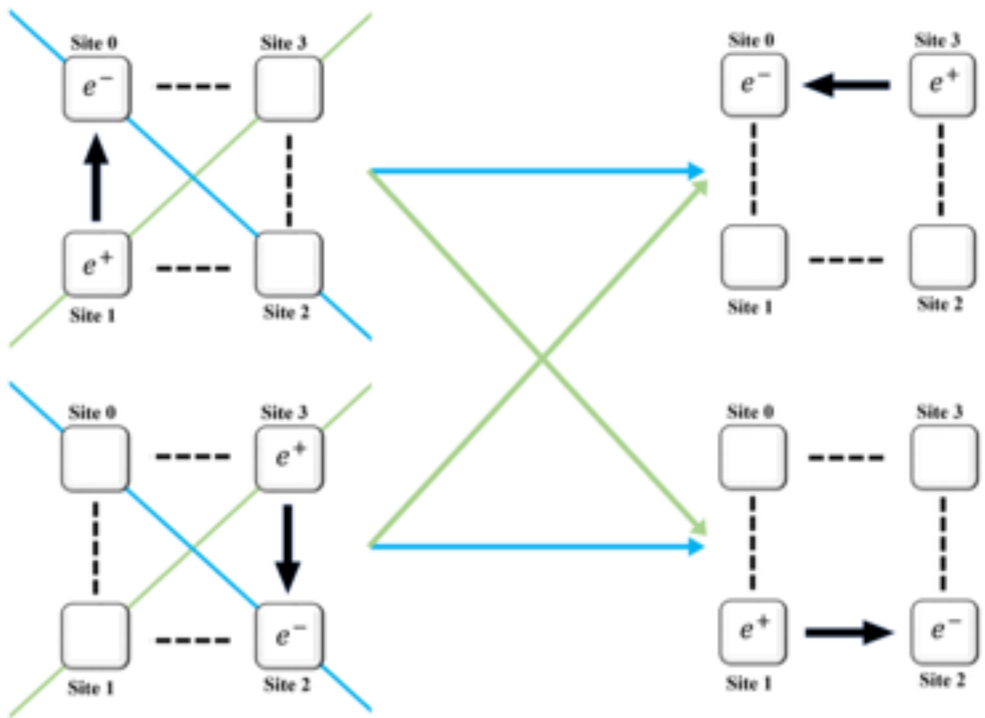


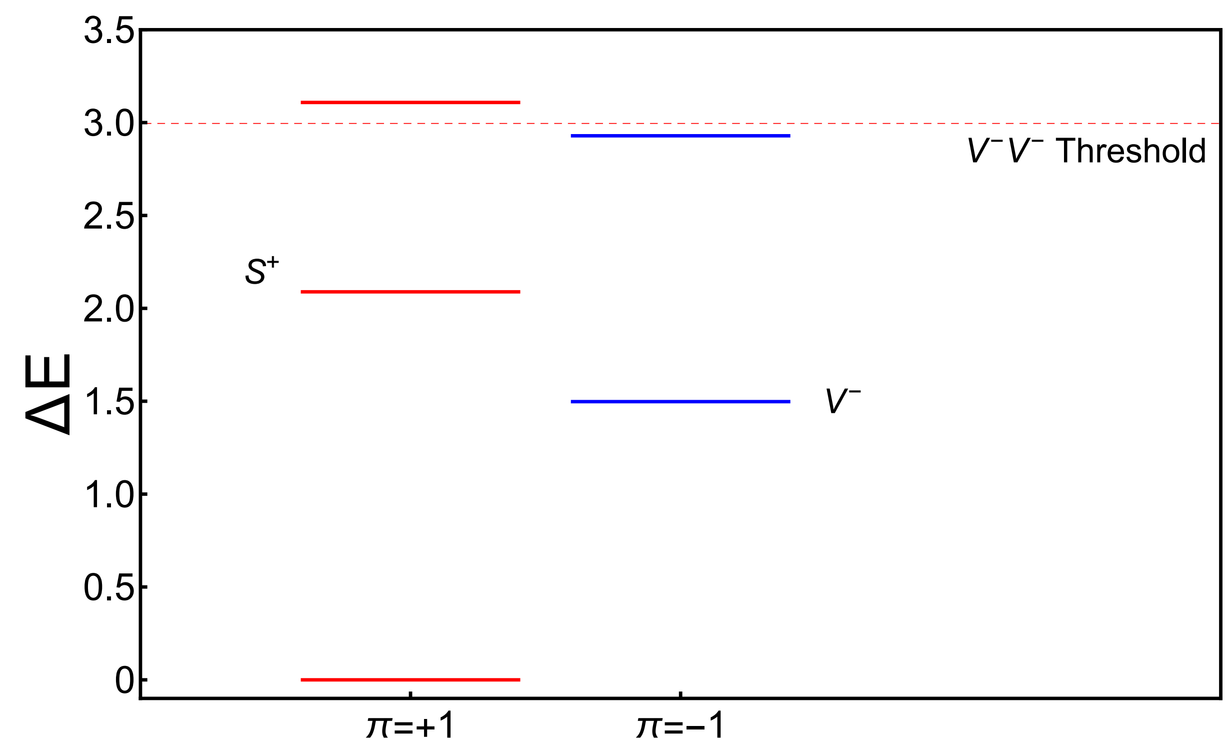
$$\hat{H} = x \sum_{n=0}^{N_{fs}-1} \left(\sigma_n^+ L_n^- \sigma_{n+1}^- + \sigma_{n+1}^+ L_n^+ \sigma_n^-\right)$$

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

- Clearly, this is just a start - far from infinite-volume and continuum limits
- Will require improved (Symanzik-like) actions, effective field theories, etc

Starting Simple 1+1 Dim QED Symmetries





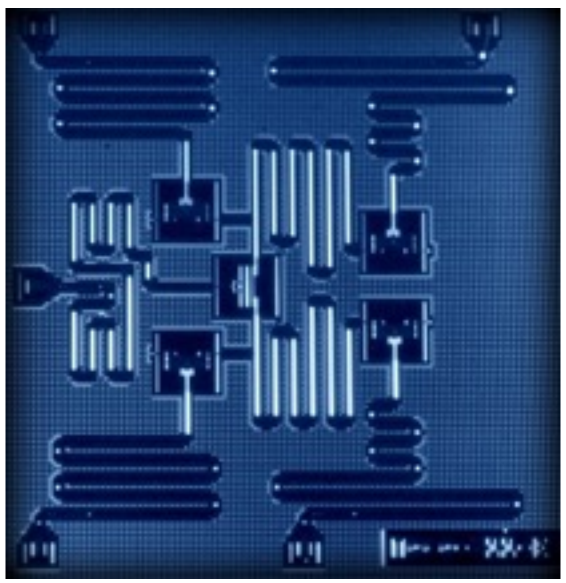
- Gauss's Law
- (Angular) Momentum
- Parity

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

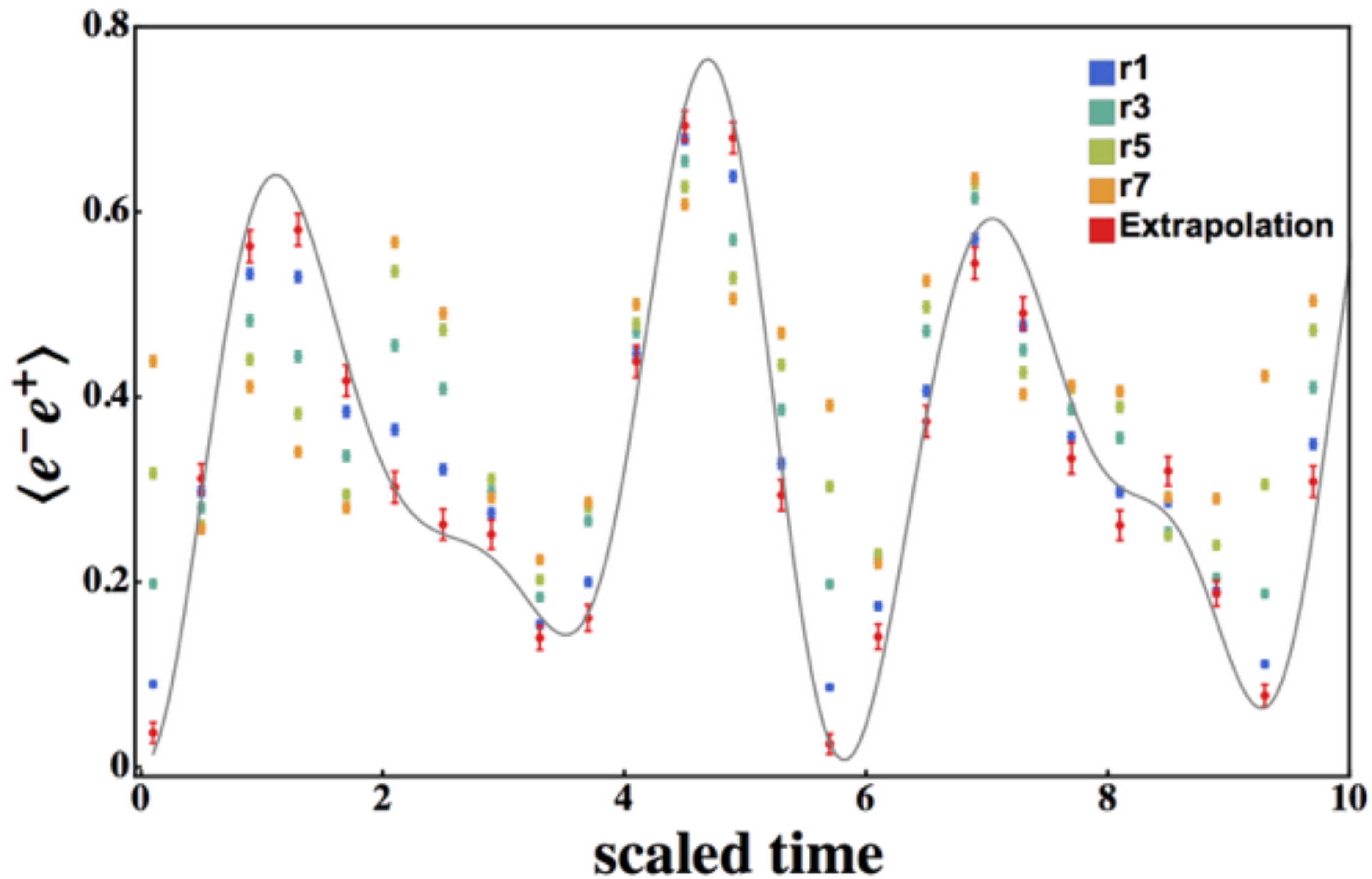
Classical pre-processing
Can this be done *in situ* ?

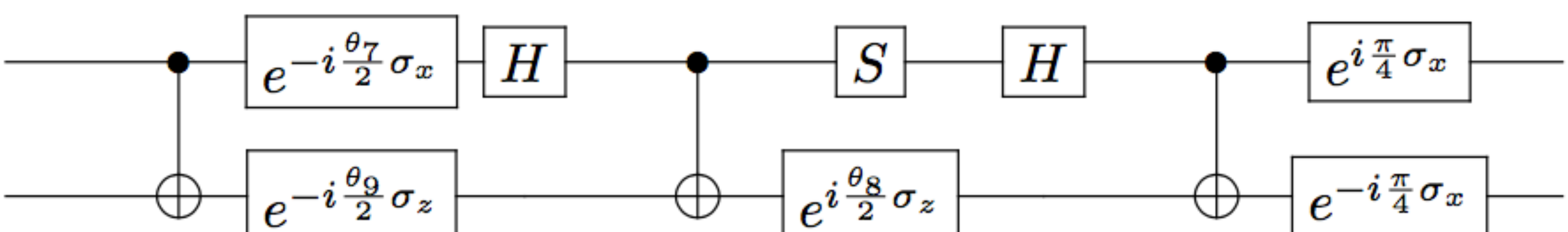
Classical post-processing

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



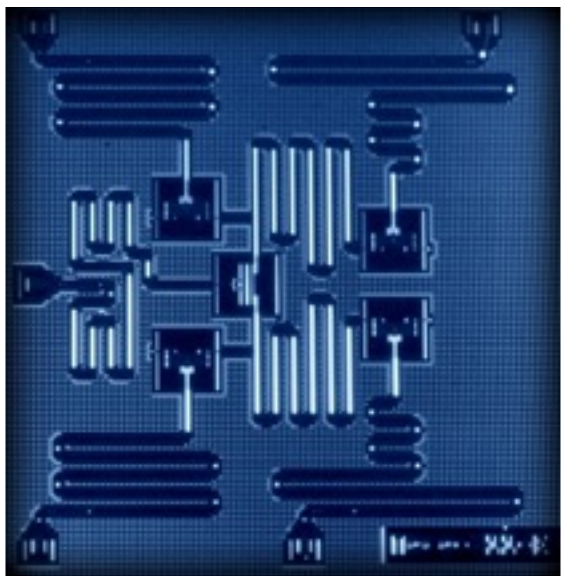
ibmqx2
8K shots per point





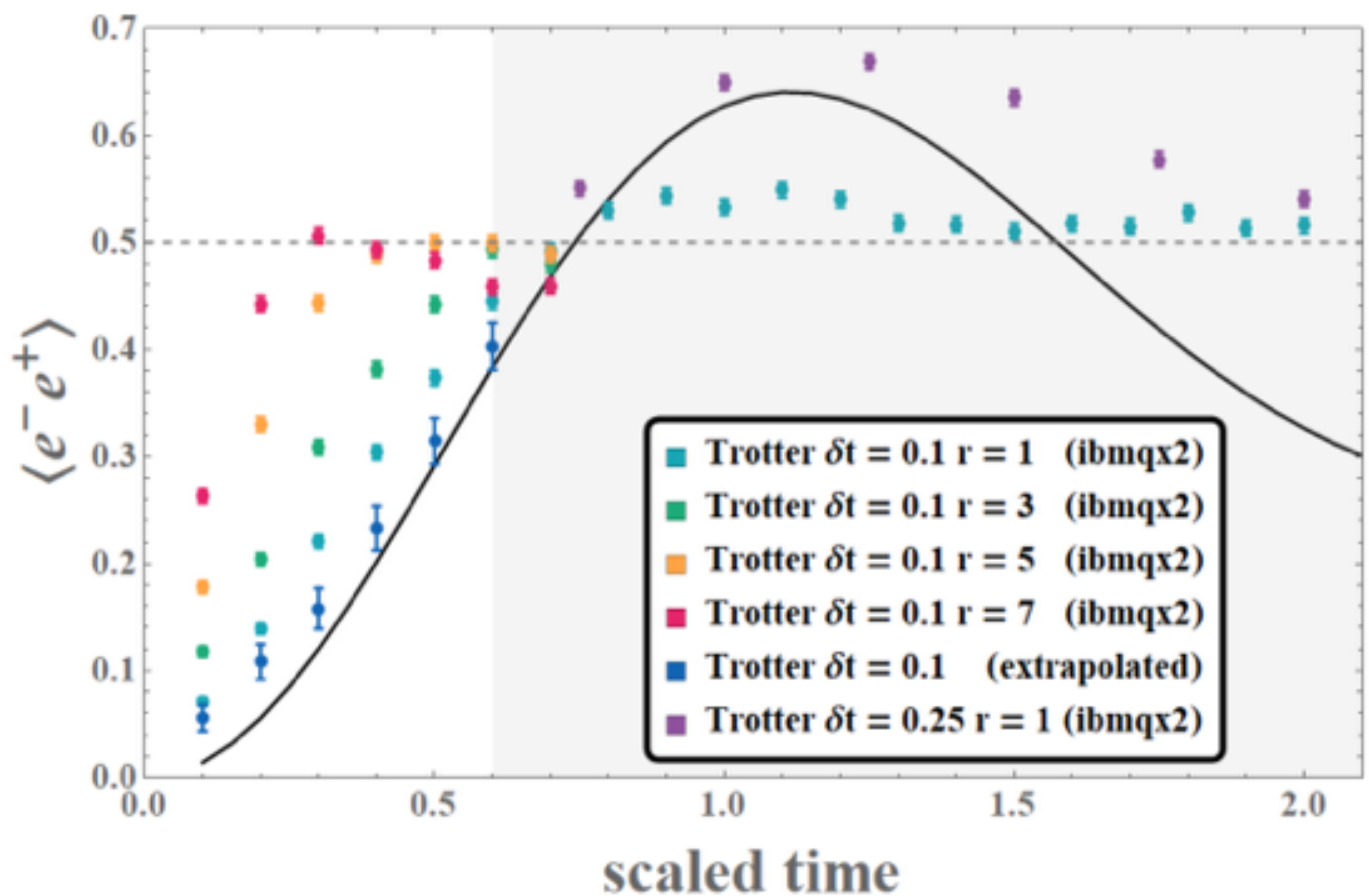
Cartan sub-algebra

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



T2 (μs)	55.20	65.10	47.00	35.10	37.60

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



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

3.6 QPU-s and 260 IBM units

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

Starting Simple 1+1 Dim QED
Simple Coding
Chroma Vs Python3

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

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


namespace Chroma {

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

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

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

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

c++

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

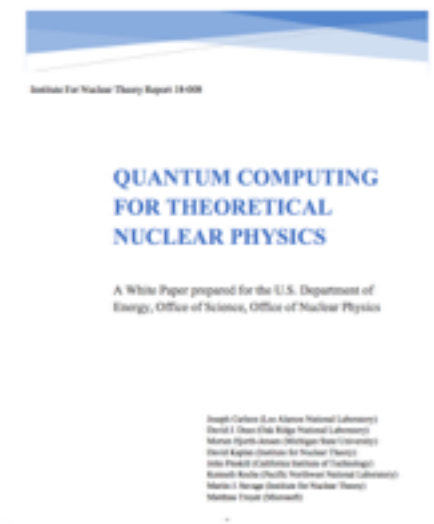
```
    for ii in range(0,len(NTrotter)):
        p0=qp.get_circuit(pidtab[ii])
        ntrott = NTrotter[ii]
        print("Calculating ntrott  = ",ii," : = ",ntrott)

        for jjTT in range(0,ntrott):

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

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

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

#  I x sigmax to describe h4

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

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

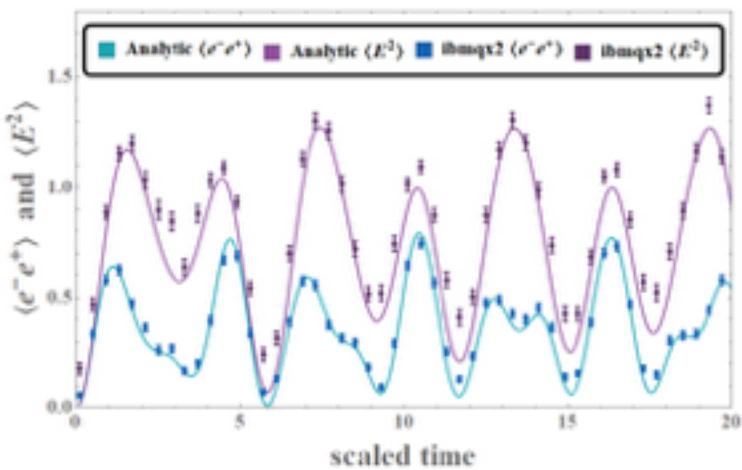
Calculates Trotter evolution of +ve parity sector of the 2-spatial-site Schwinger Model.

Summary

- Exascale conventional computing will provide required precision for many experimentally important quantities in NP and HEP.
- Important **finite density** systems (including modest size nuclei) and **dynamics** require exponentially challenging calculations.
- Integrating QC into science domains to complement conventional computing is an exciting prospect.
- QFTs on QCs are important for NP and HEP … start simple … explore all architectures
- NISQ-era coherence times and noise present challenges
- Workforce development is essential - competing with Tech. companies for junior scientists is challenging
- For the future: machine benchmarking (application time to solution), code verification, …


QUANTUM COMPUTING
FOR THEORETICAL
NUCLEAR PHYSICS

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



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