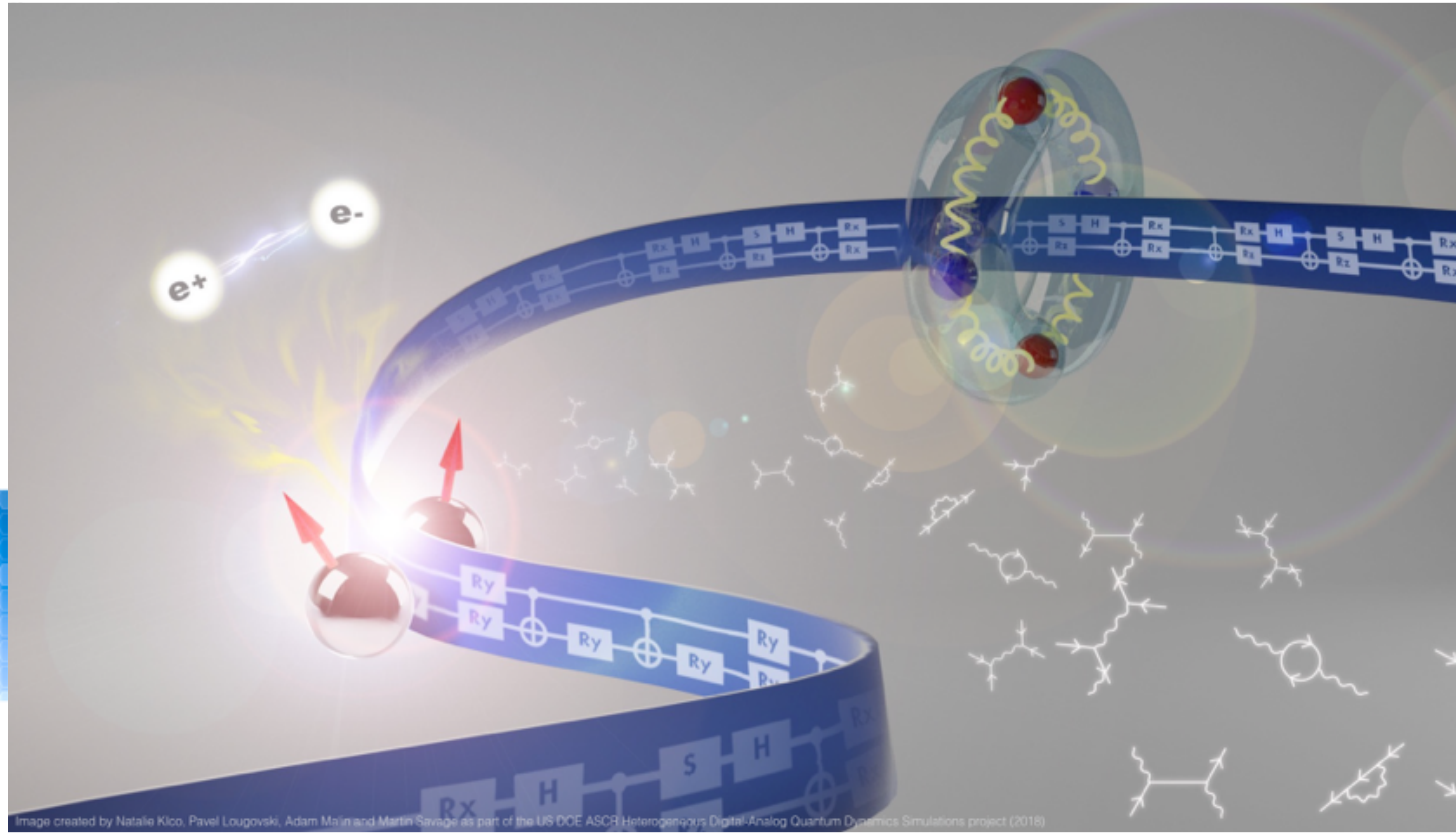
Natalie Klco (INT/UW)

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

Pavel Lougovski
Raphael Pooser
(ORNL)

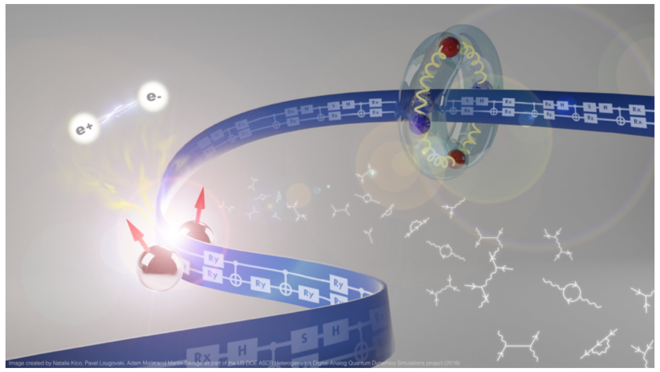


Quantum Field Theory with Quantum Computing

Quantum Entanglement at Collider Energies
StonyBrook, September 10-12, 2018

Martin J Savage

INSTITUTE for NUCLEAR THEORY

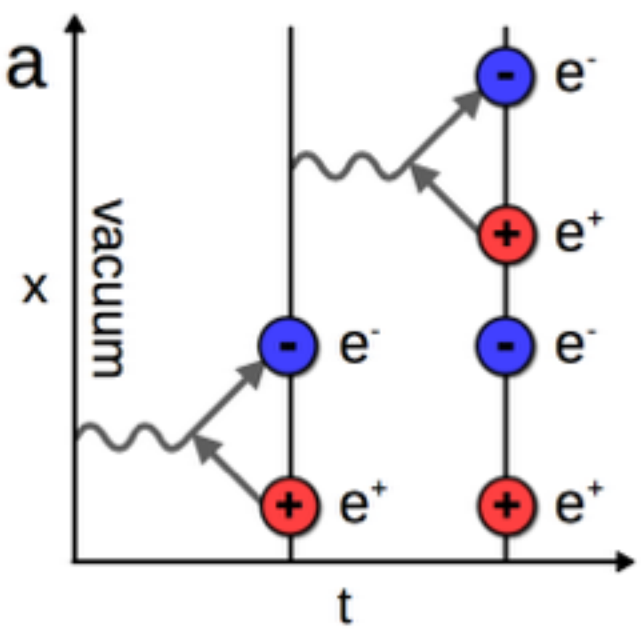


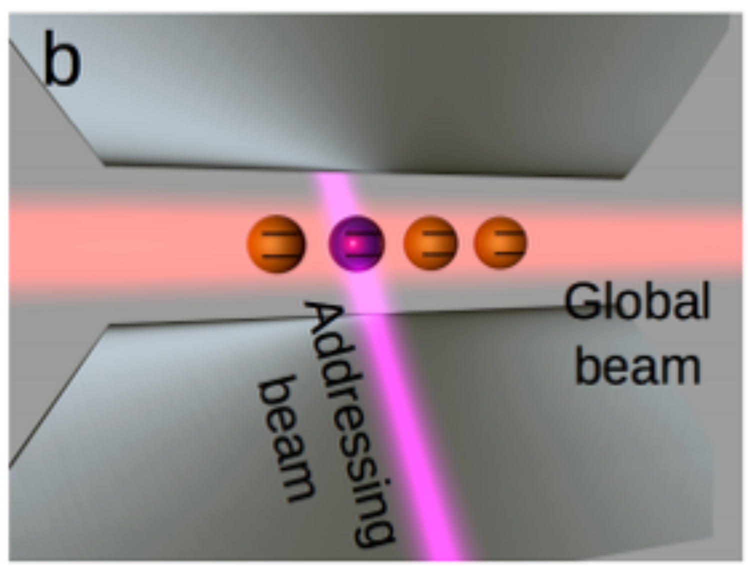
The paper that Caught My Attention

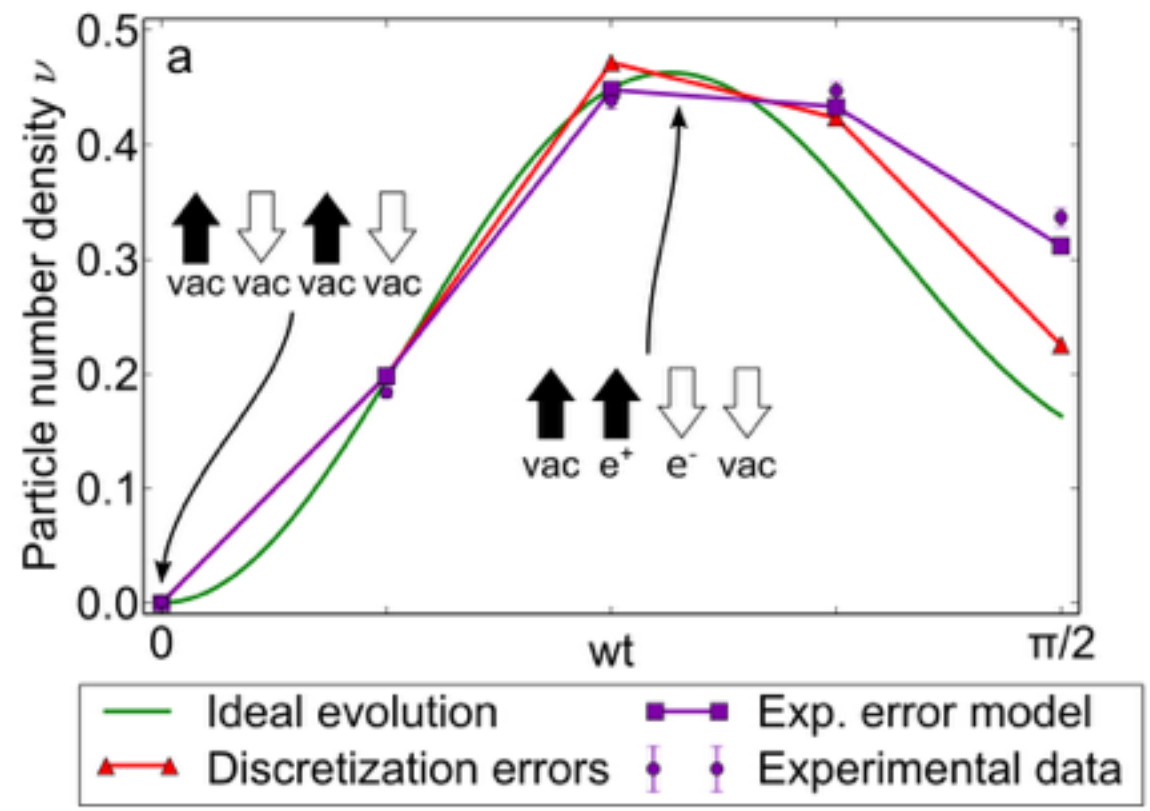
Real-time dynamics of lattice gauge theories with a few-qubit quantum computer

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]

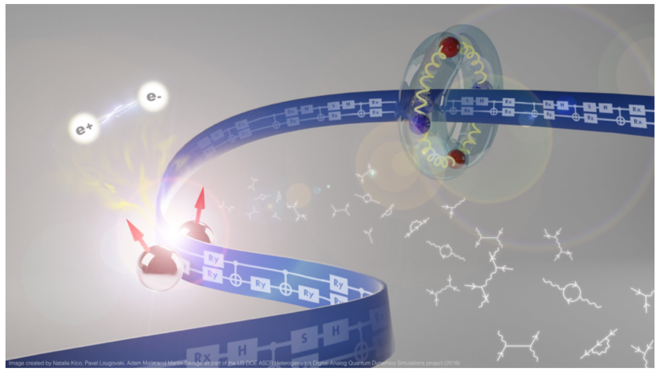
(2016)



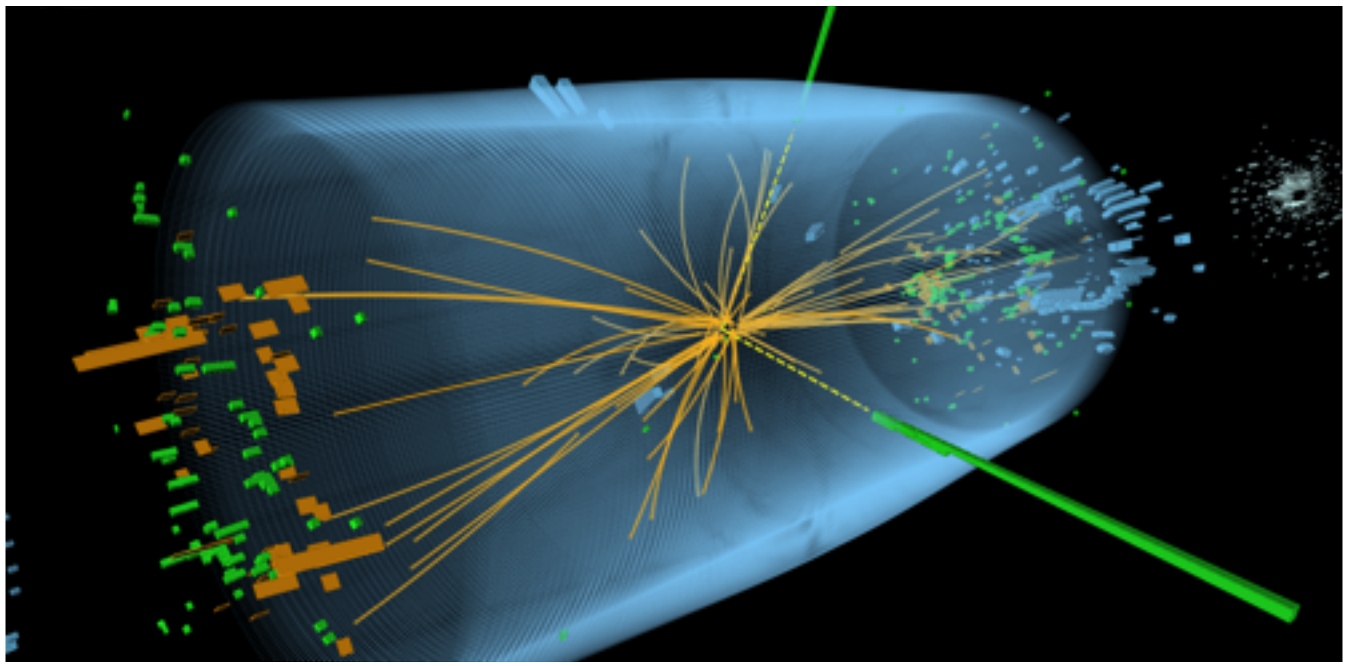


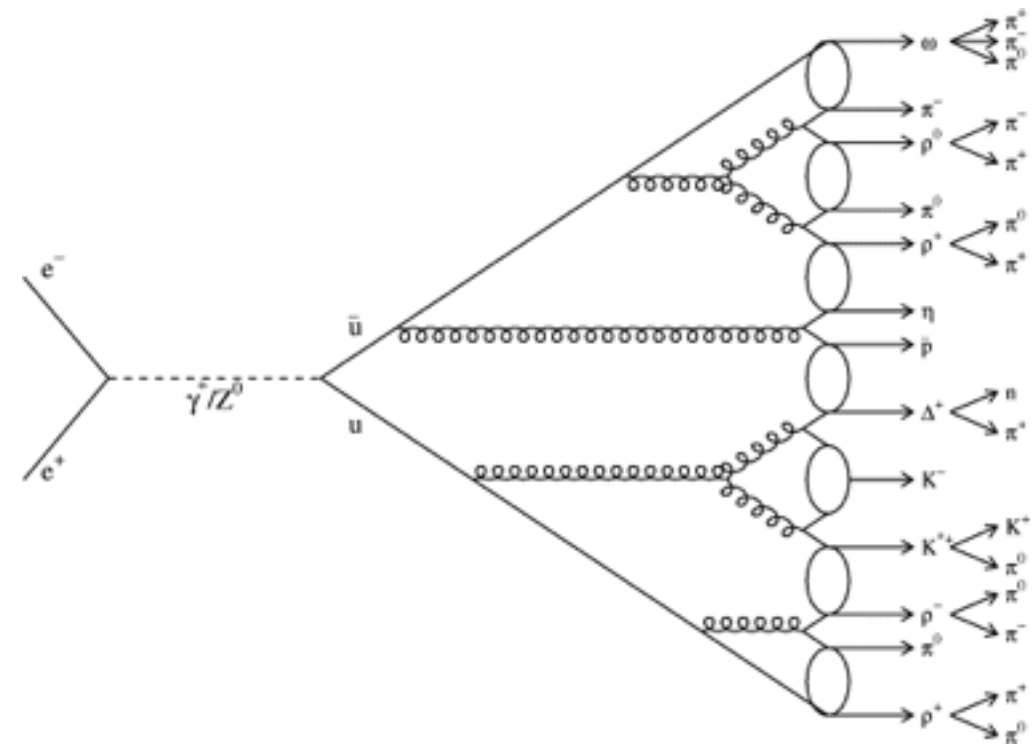


Based upon a string of $^{40}Ca^{+}$ trapped-ion quantum system
Simulates 4 qubit system with long-range couplings = 2-spatial-site Schwinger Model
> 200 gates per Trotter step



Inelastic Processes
Fragmentation Vacuum and In-Medium
Nuclear Reactions

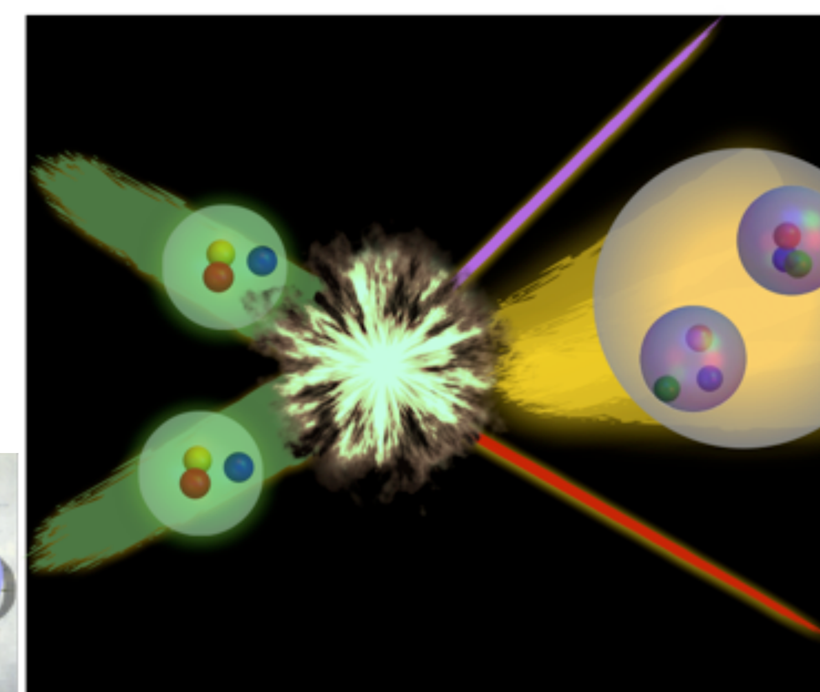




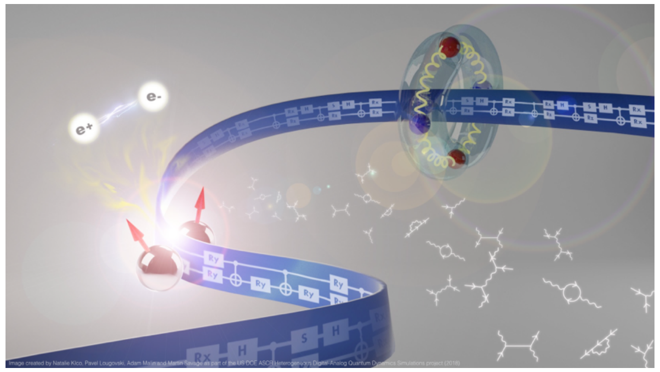
Free-space and in-medium

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

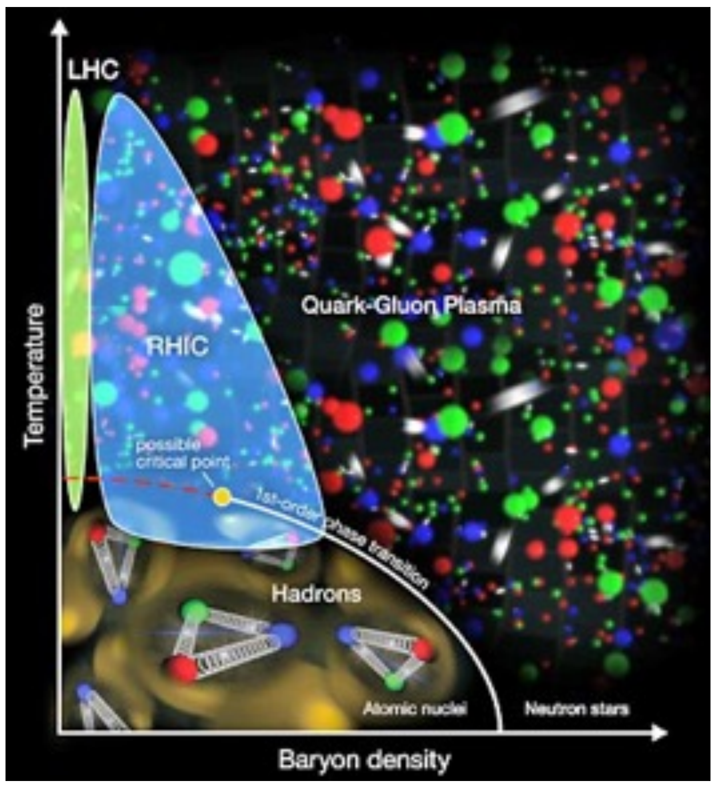


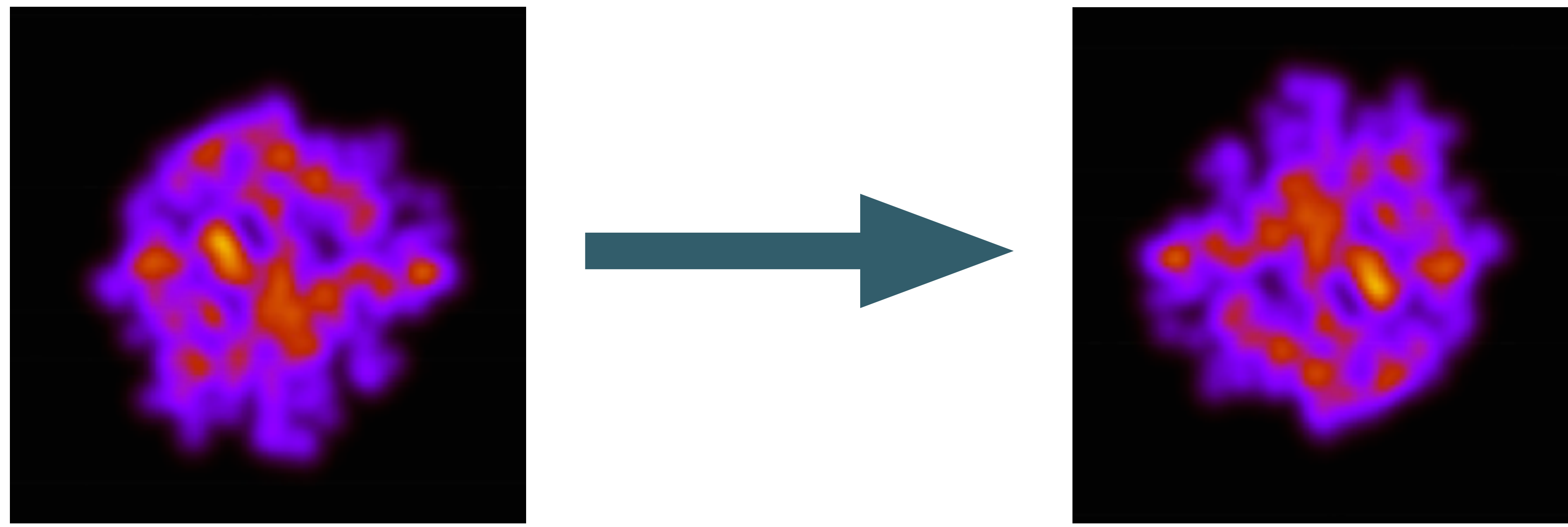
Nuclear reactions that are inaccessible, e.g. proton-proton fusion
NPLQCD: first calculations using lattice QCD in 2016



“ Features - Finite Density “

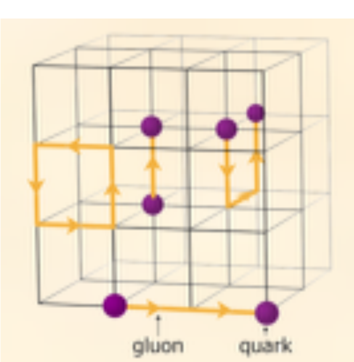
Time evolution of system with baryon number, isospin, electric charge, strangeness, …..
Currents, viscosity, non-equilibrium dynamics - real-time evolution



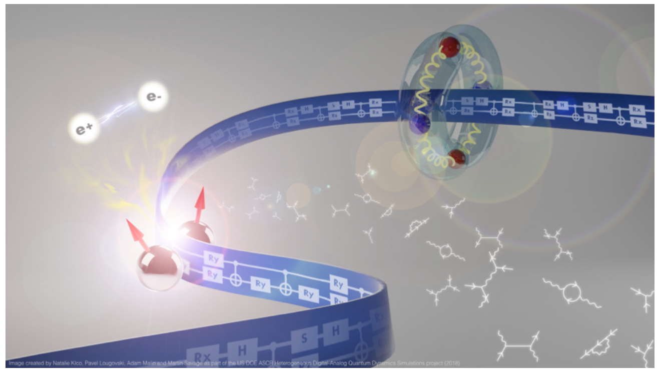


Sign Problem

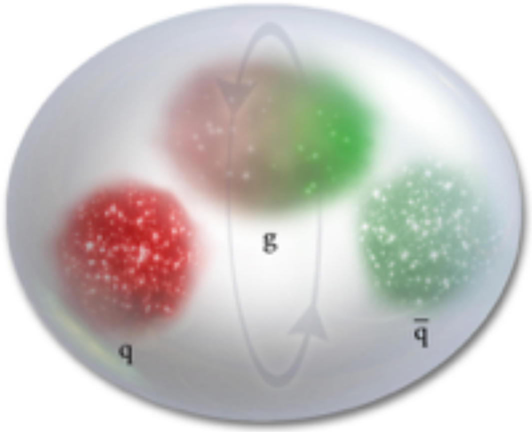
$$\langle\hat{\theta}\rangle \sim \int \mathcal{D}\mathcal{U}_\mu \; \hat{\theta}[\mathcal{U}_\mu] \; \det[\kappa[\mathcal{U}_\mu]] \; e^{-S_{YM}}$$

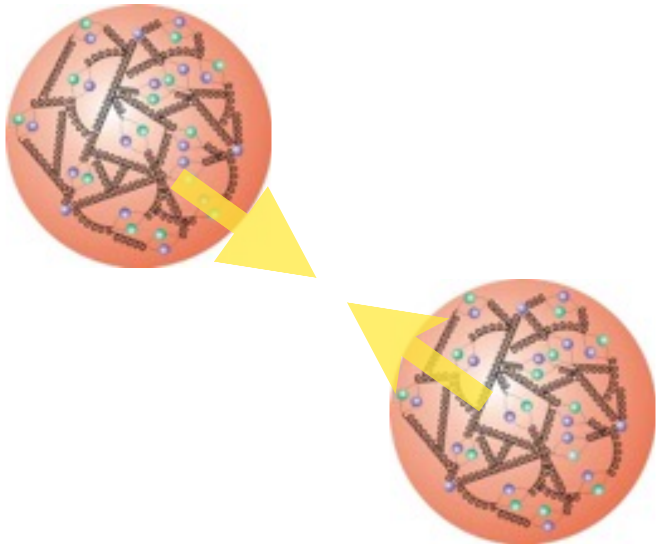


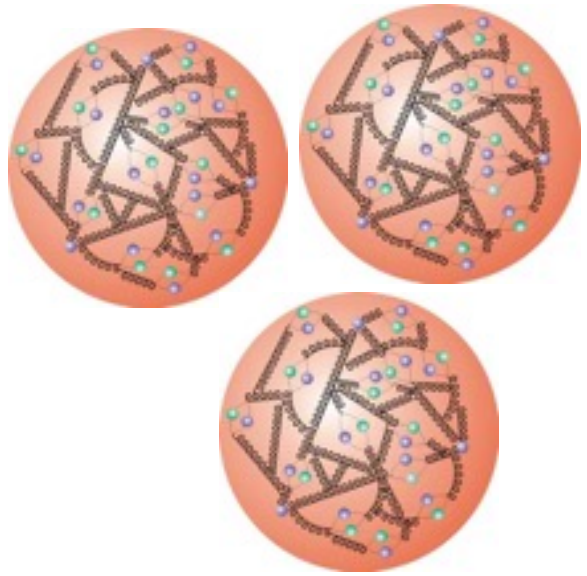
Complex for non-zero chemical potential



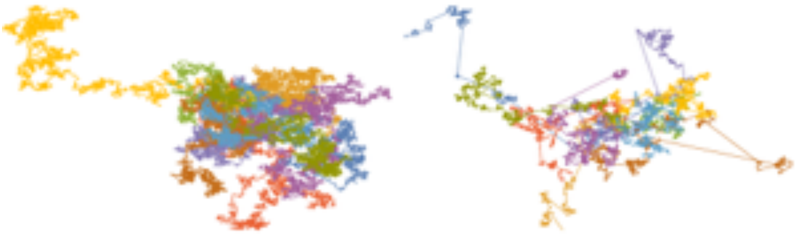
“ Features “

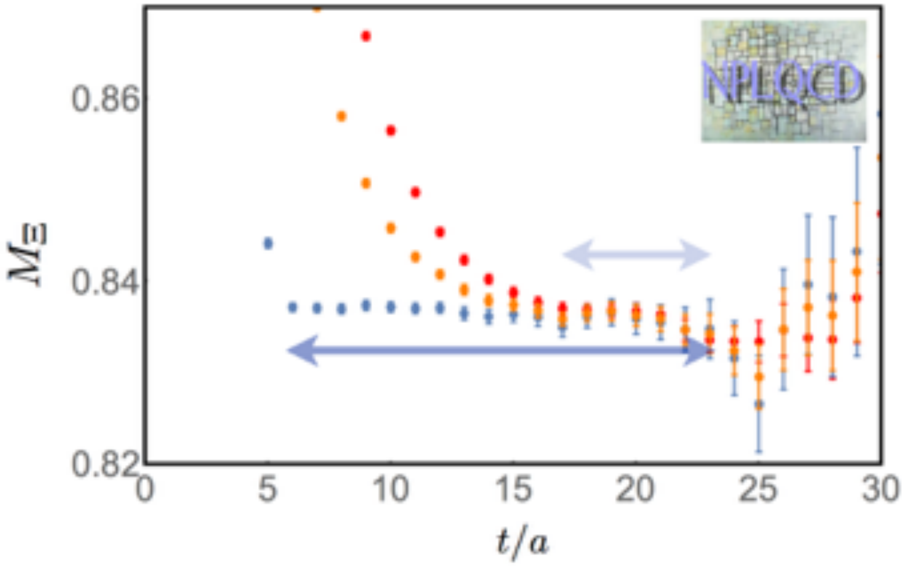


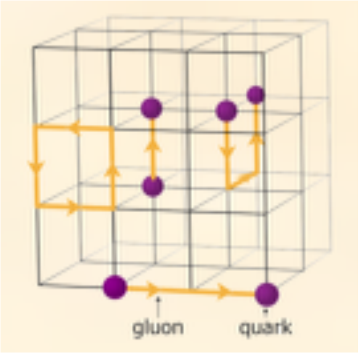




Signal to Noise Problem [Sign Problem]

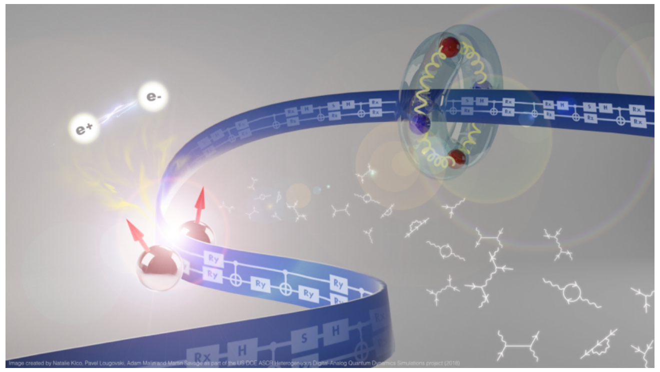




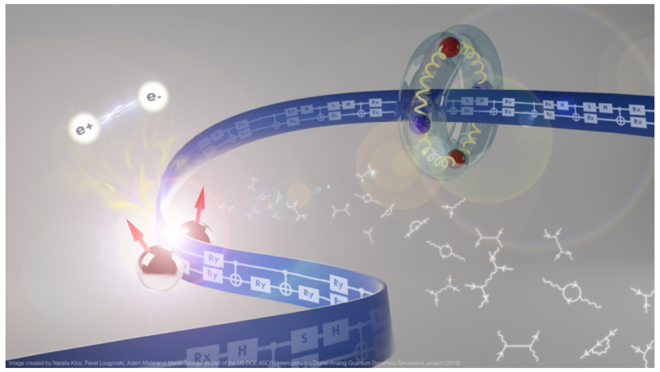


Statistical sampling of the path integral is the limiting element

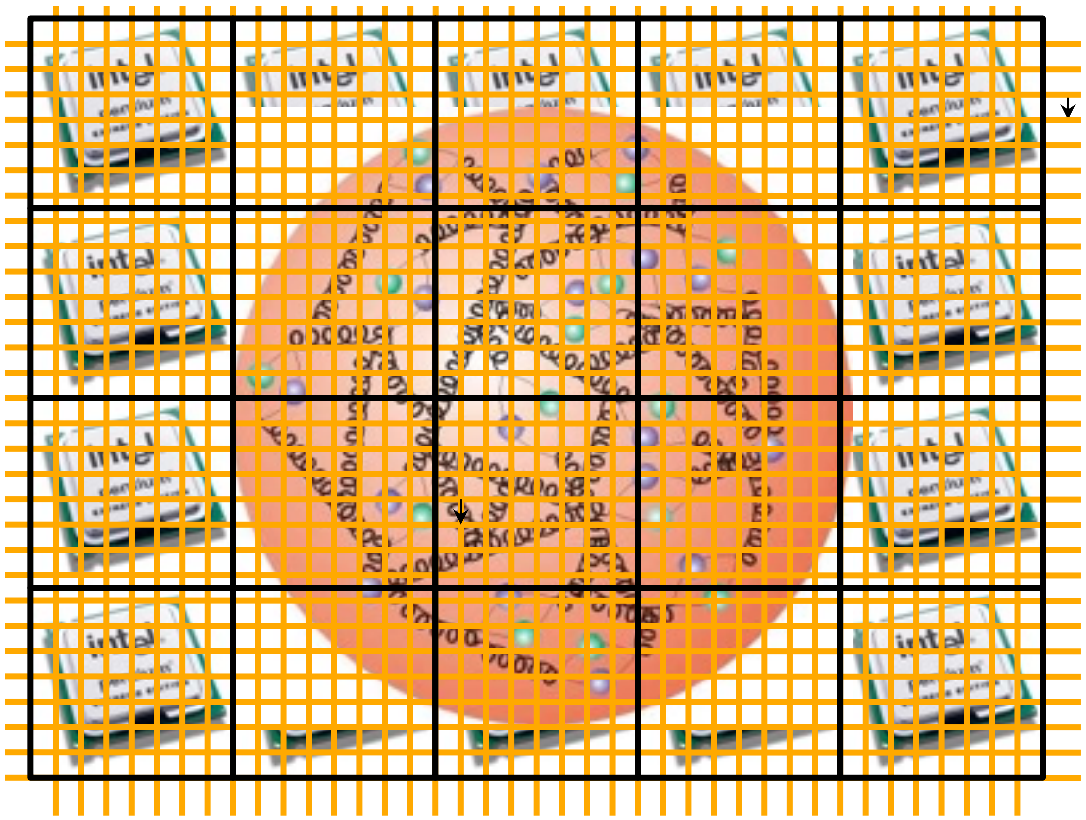
Michael Wagman, PhD Thesis



Quantum Computing
- We are now Entering the NISQ Era



Lattice Quantum Chromodynamics - Discretized Euclidean Spacetime



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

(Nearly Continuum)

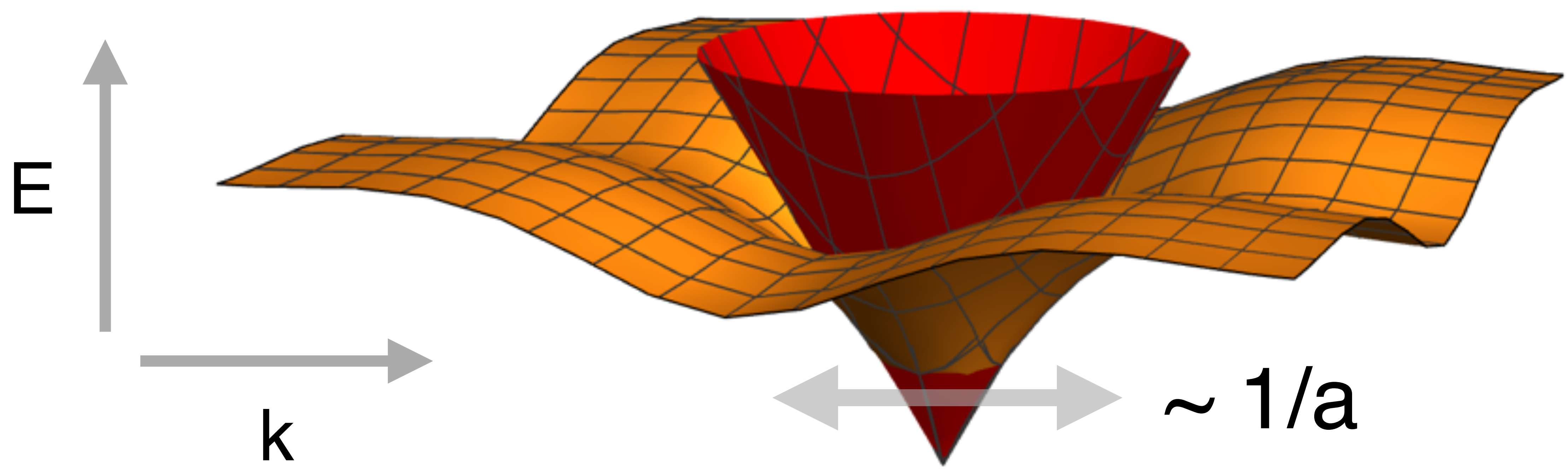
Lattice Volume : $m_\pi L >> 2\pi$

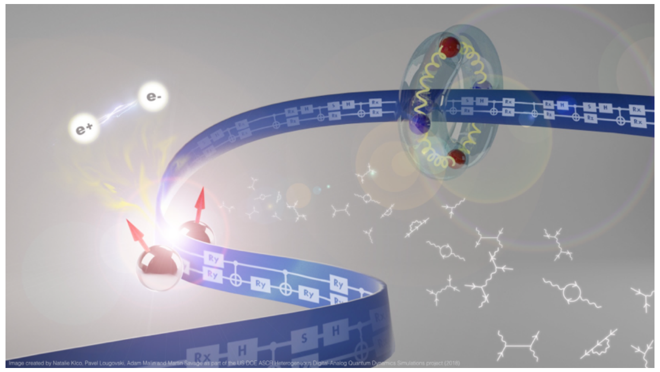
(Nearly Infinite Volume)

Digitization of Theory onto Qubits

Extrapolation to

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





QFT with QCs
- Foundational Works

Simulating lattice gauge theories on a quantum computer

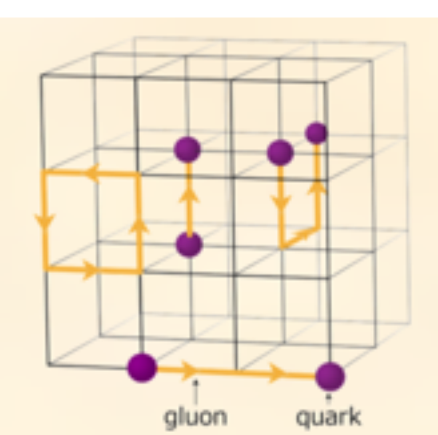
Tim Byrnes*
National Institute of Informatics, 2-1-2 Hitotsubashi, Chiyoda-ku, Tokyo 101-8430, Japan

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



Detailed formalism for 3+1 quenched Hamiltonian Gauge Theory

RESEARCH ARTICLE

Quantum Algorithms for Quantum Field Theories

Stephen P. Jordan[1,*], Keith S. M. Lee[2], John Preskill[3]
+ See all authors and affiliations

Science 01 Jun 2012:
Vol. 336, Issue 6085, pp. 1130-1133
DOI: 10.1126/science.1217069

Quantum Computation of Scattering in Scalar Quantum Field Theories

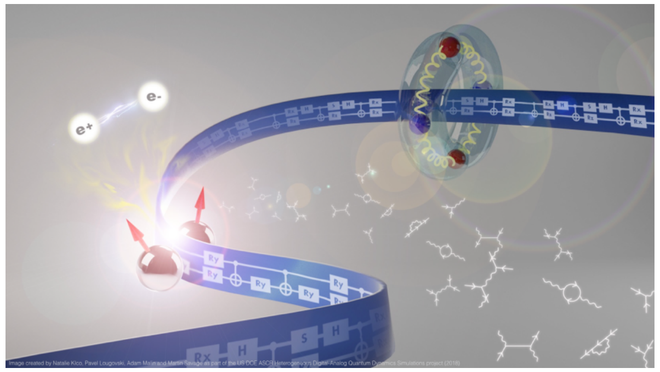
Stephen P. Jordan,[†§] Keith S. M. Lee,[‡§] and John Preskill [§ *]

[†] *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)



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*
[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 are abound in condensed-matter and high-energy physics. Addressing such problems via controll in atomic, molecular, and optical physics would be a breakthrough in the field of quantum simu work, we present a quantum-sensing protocol to measure the generating functional of an intera field theory and, with it, all the relevant information about its in or out of equilibrium phenomena

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

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

Dynamics of entanglement in expanding quantum fields

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

Electron-Phonon Systems on a Universal Quantum Computer

Alexandru Macridin, Panagiotis Spentzouris, James Amundson, Roni Harnik
0, Batavia, Illinois 60510, USA

Quantum simulation of the universal features of the Polyakov loop

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

U(1) Wilson lattice gauge theories in digital quantum simulators

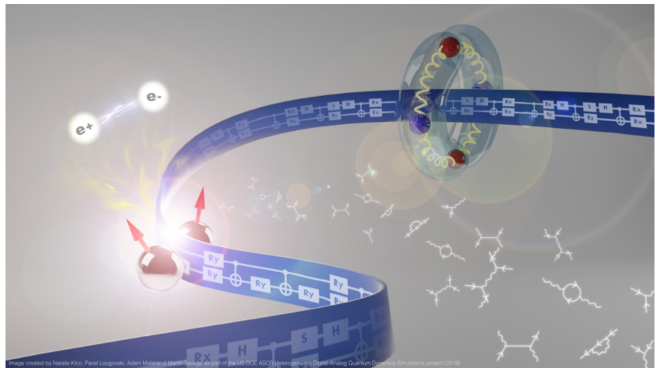
Christine Muschik[1,2], Markus Heyl[2,3], Esteban Martinez[4], Thomas Monz[4], Philipp Schindler[4], Berit Vogell[1,2], Marcello Dalmonte[1,5], Philipp Hauke[1,2], Rainer Blatt[4,6], Peter Zoller[1,6]

Eliminating fermionic matter fields in lattice gauge theories

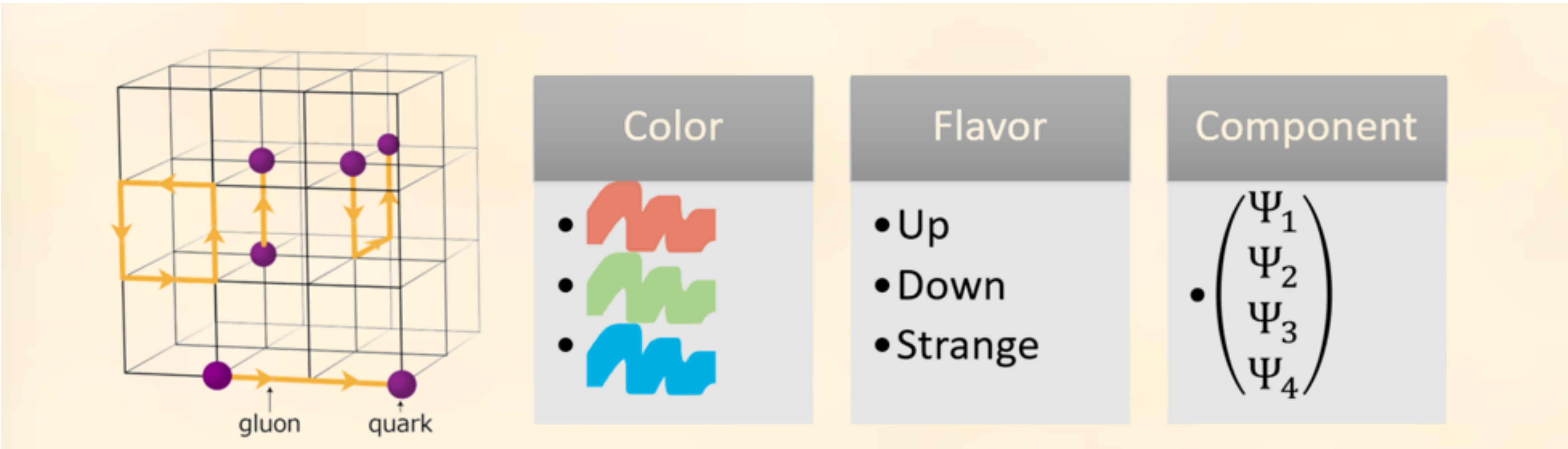
Erez Zohar and J. Ignacio Cirac
Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 G
(Dated: May 16, 2018)

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

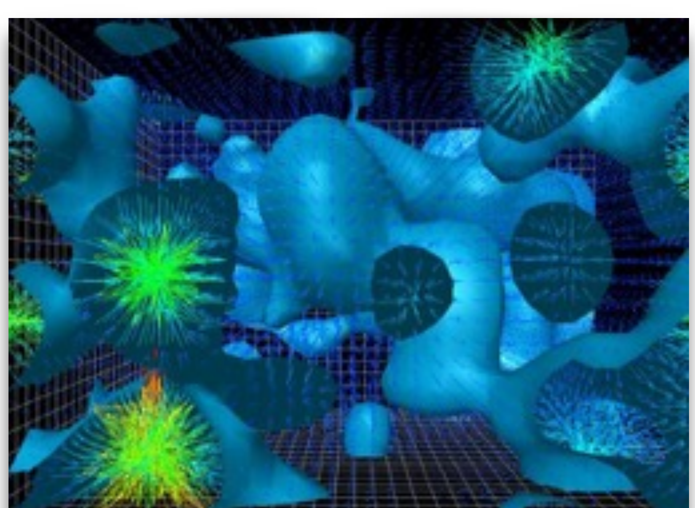


Gauge Field Theories e.g. QCD



Natalie Klco

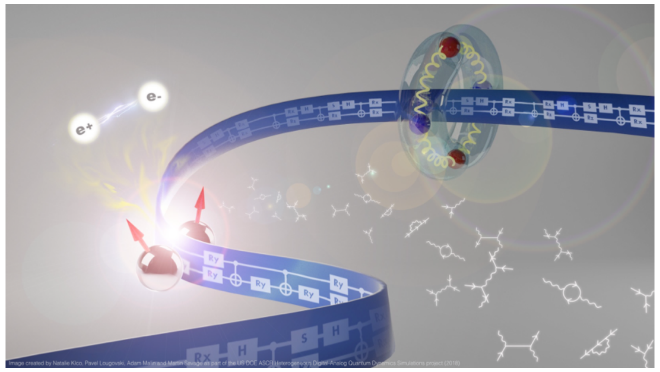
32^3 lattice requires naively > 4 million qubits !



State Preparation - a critical element

l random > = a l0> + b l(pi pi)> + c l (pi pi pi pi) > + …. + d l (GG) > + ….

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



Gauge Theories
- more complicated

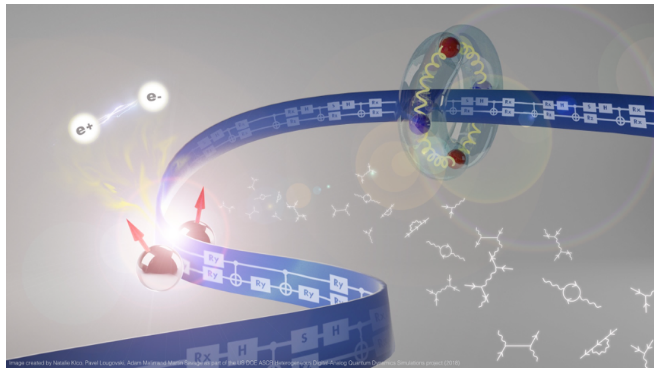
Naive mapping:

Most states mapped to qubits do not satisfy constraints

Exponentially large redundancies - gauge symmetries

Methods to compress Hilbert space to physical

Chiral gauge theories?



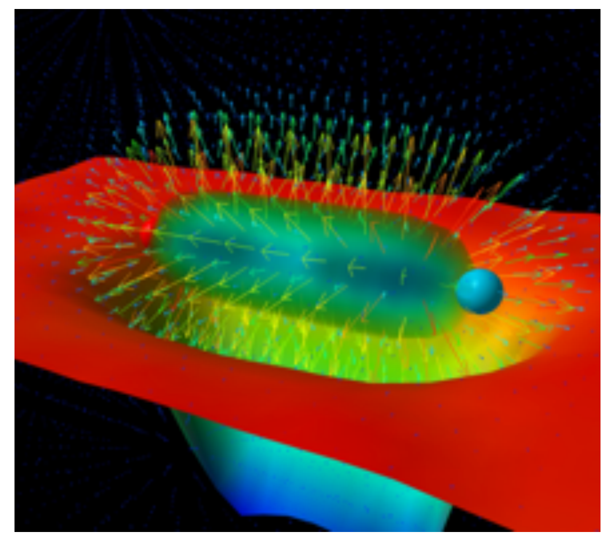
Starting Simple 1+1 Dim QED Construction

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

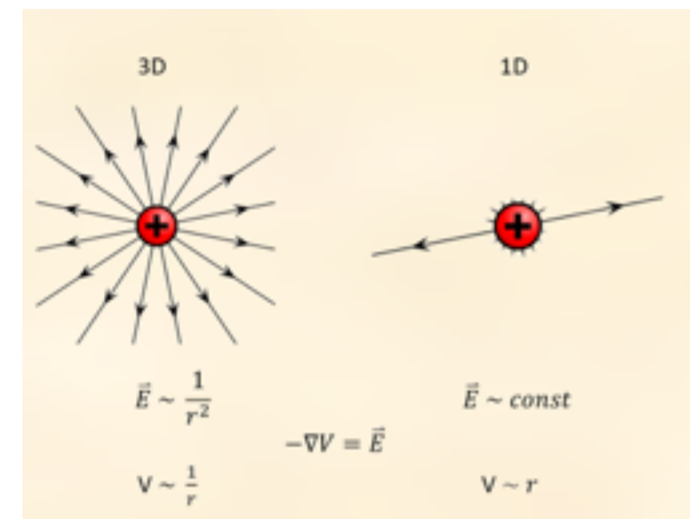
"Quantum computing makes you think about your calculations very differently than programming a classical computer," says Natalie Klco. // MEDIA CREDIT: WHITNEY SANCHEZ

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

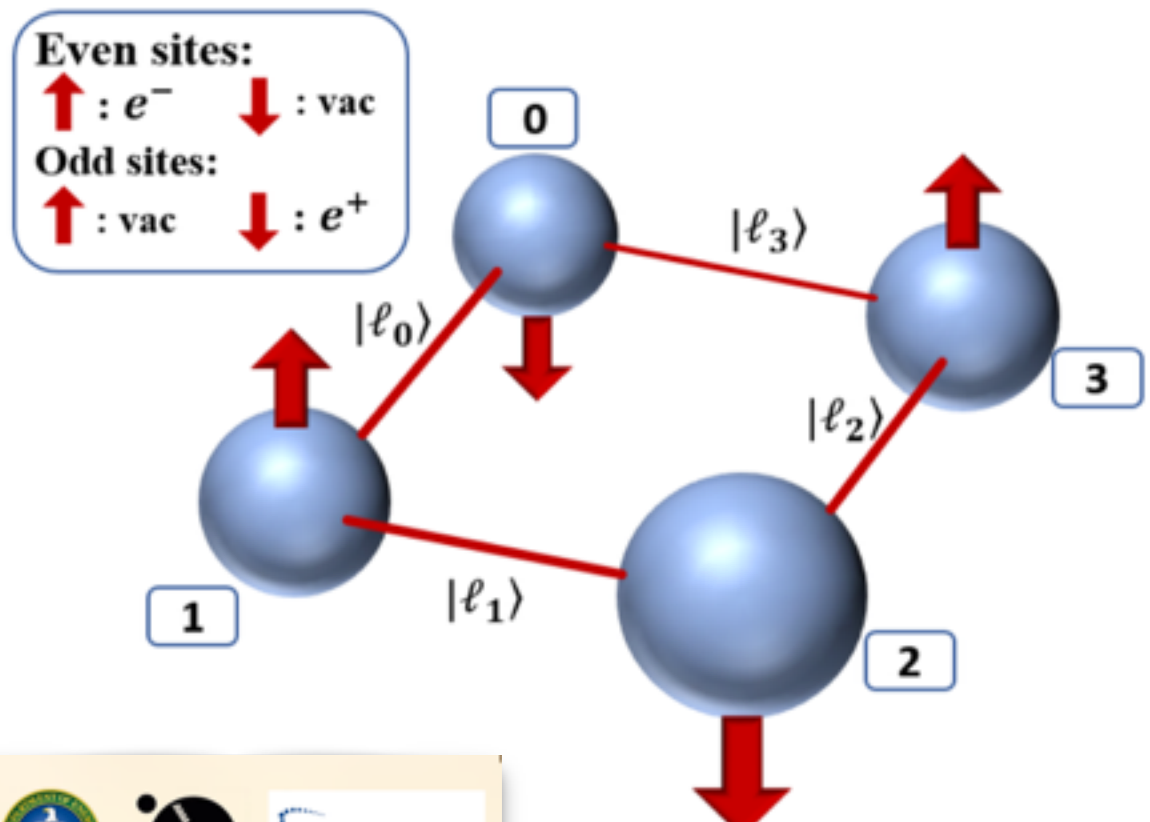
- Charge screening, confinement
- fermion condensate



Derek Leinweber

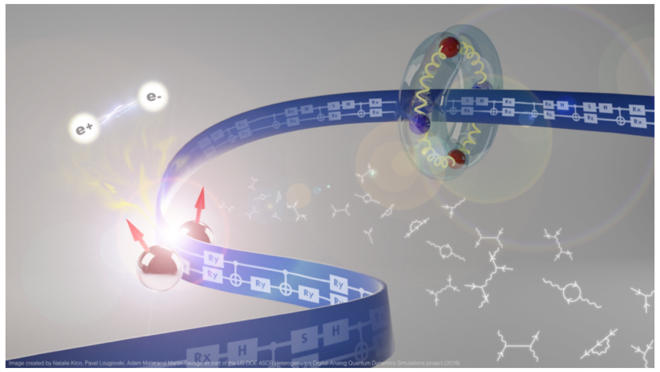


Natalie Klco

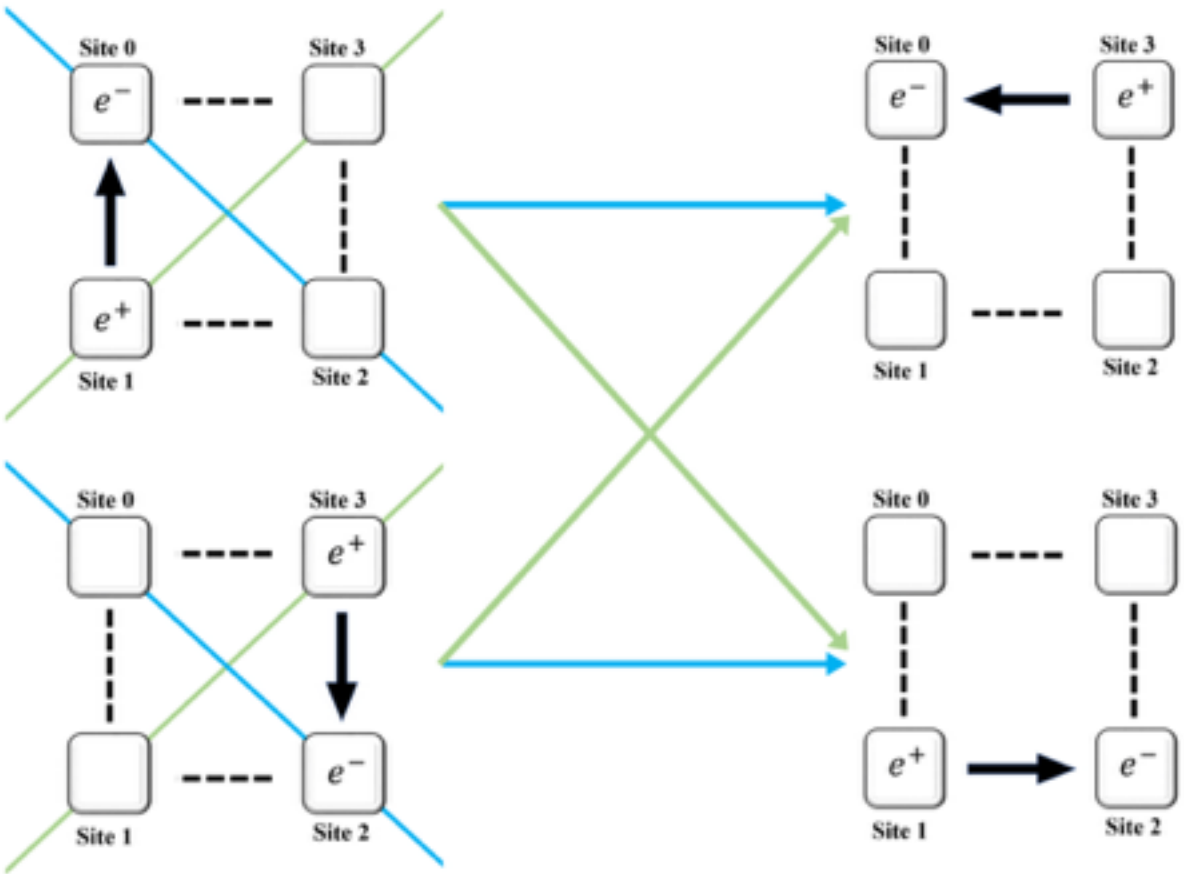


$$\hat{H} = x\sum_{n=0}^{N_{fs}-1}\left(\sigma_n^+ L_n^- \sigma_{n+1}^- + \sigma_{n+1}^+ L_n^+ \sigma_n^-\right) + \sum_{n=0}^{N_{fs}-1}\left(l_n^2 + \frac{\mu}{2}(-)^n \sigma_n^z\right) .$$

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] . To appear in PRA.



Starting Simple 1+1 Dim QED State Compression



$$|\phi_1\rangle = |\cdot\cdot\cdot\cdot\rangle|0000\rangle$$
$$|\phi_2\rangle = |\cdot\cdot\cdot\cdot\rangle|1111\rangle$$
$$|\phi_3\rangle = |\cdot\cdot\cdot\cdot\rangle|-1-1-1-1\rangle$$
$$|\phi_4\rangle = |e^-e^+\cdot\cdot\rangle|-1000\rangle$$
$$|\phi_5\rangle = |\cdot\cdot e^-e^+\rangle|00-10\rangle$$
$$|\phi_6\rangle = |e^-e^+\cdot\cdot\rangle|0111\rangle$$
$$|\phi_7\rangle = |\cdot\cdot e^-e^+\rangle|1101\rangle$$

$$|\phi_8\rangle = |e^-e^+e^-e^+\rangle|-10-10\rangle$$
$$|\phi_9\rangle = |e^-e^+e^-e^+\rangle|0101\rangle$$
$$|\phi_{10}\rangle = |e^-\cdot\cdot e^+\rangle|-1-1-10\rangle$$
$$|\phi_{11}\rangle = |e^-\cdot\cdot e^+\rangle|0001\rangle$$
$$|\phi_{12}\rangle = |\cdot e^+e^-\cdot\rangle|0100\rangle$$
$$|\phi_{13}\rangle = |\cdot e^+e^-\cdot\rangle|-10-1-1\rangle$$

$$|\psi_1\rangle_{\mathbf{k=0}} = |\phi_1\rangle$$
$$|\psi_2\rangle_{\mathbf{k=0}} = |\phi_2\rangle$$
$$|\psi_3\rangle_{\mathbf{k=0}} = |\phi_3\rangle$$
$$|\psi_4\rangle_{\mathbf{k=0}} = \frac{1}{\sqrt{2}}\ [\ |\phi_4\rangle + |\phi_5\rangle\ ]$$
$$|\psi_5\rangle_{\mathbf{k=0}} = \frac{1}{\sqrt{2}}\ [\ |\phi_6\rangle + |\phi_7\rangle\ ]$$

$$|\psi_6\rangle_{\mathbf{k=0}} = |\phi_8\rangle$$
$$|\psi_7\rangle_{\mathbf{k=0}} = |\phi_9\rangle$$
$$|\psi_8\rangle_{\mathbf{k=0}} = \frac{1}{\sqrt{2}}\ [\ |\phi_{10}\rangle + |\phi_{13}\rangle\ ]$$
$$|\psi_9\rangle_{\mathbf{k=0}} = \frac{1}{\sqrt{2}}\ [\ |\phi_{11}\rangle + |\phi_{12}\rangle\ ]$$

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.
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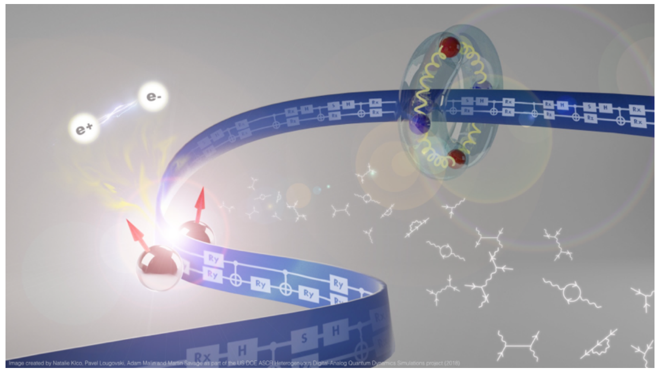
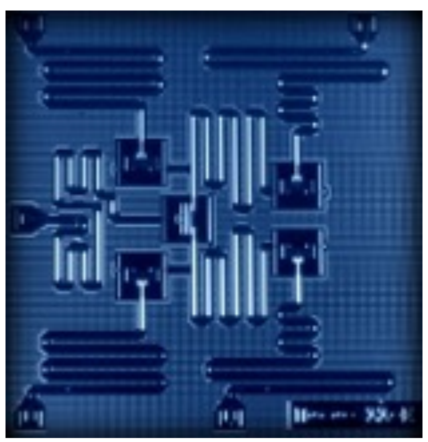


Starting Simple 1+1 Dim QED
Living NISQ - IBM
Apply Classically Computed U(t)

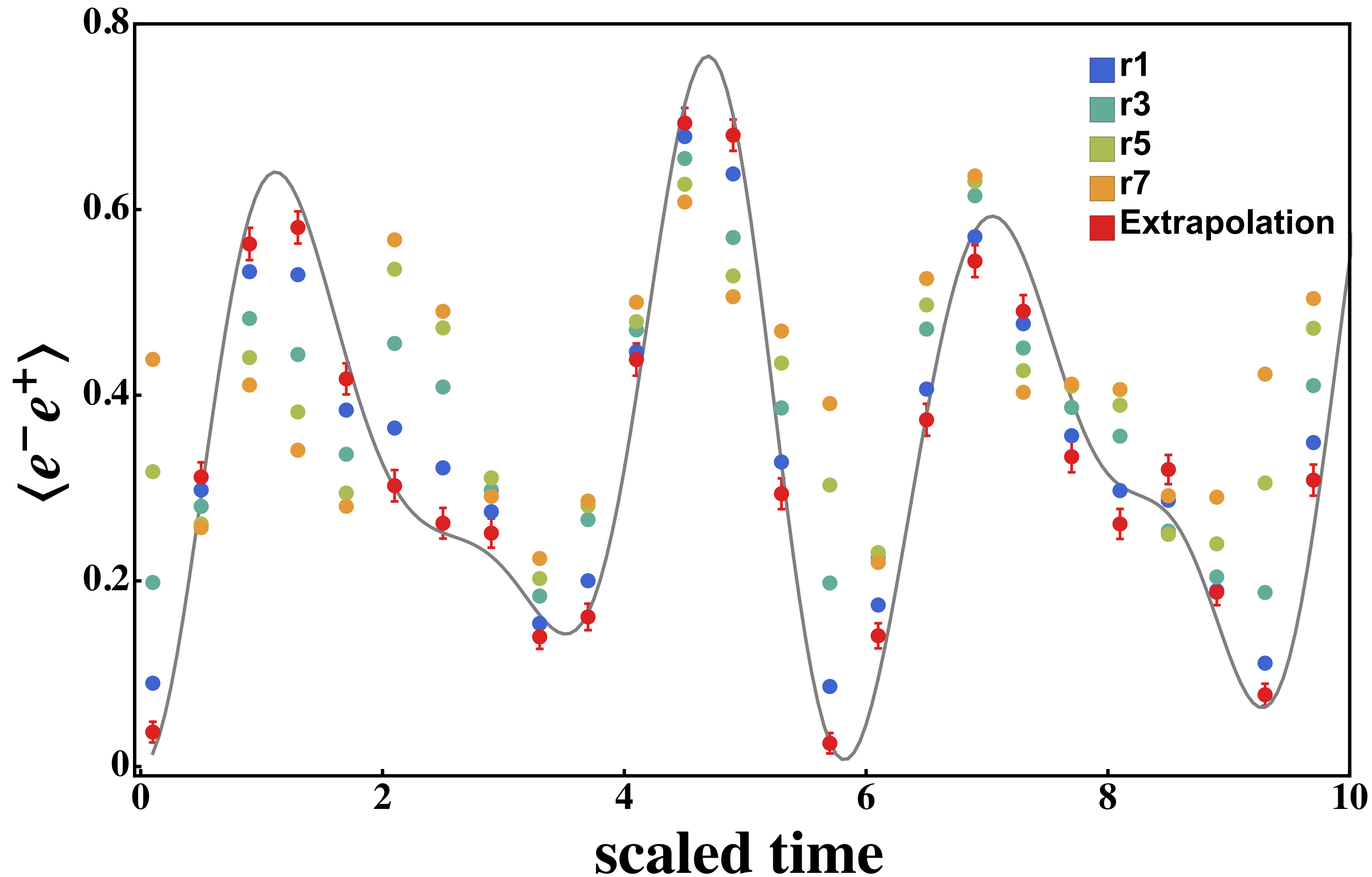


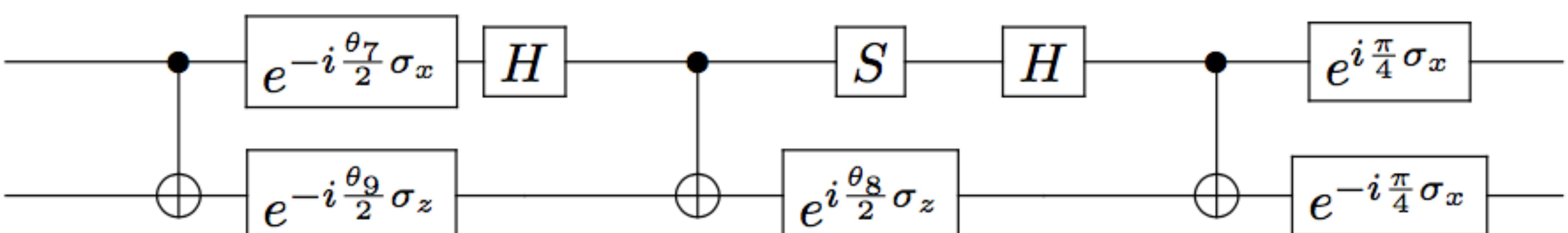
Oak Ridge National Laboratory

Institute for Nuclear Theory

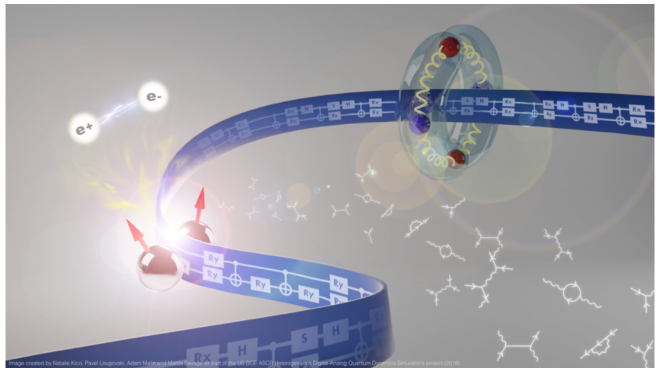
ibmqx2 - cloud-access

8K shots per point

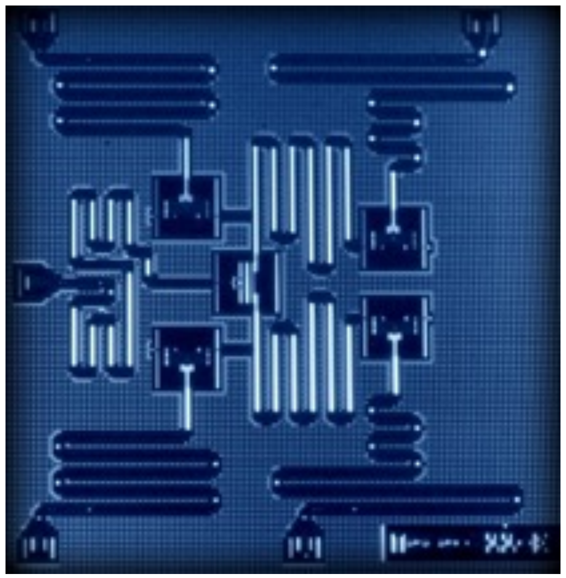




Cartan sub-algebra

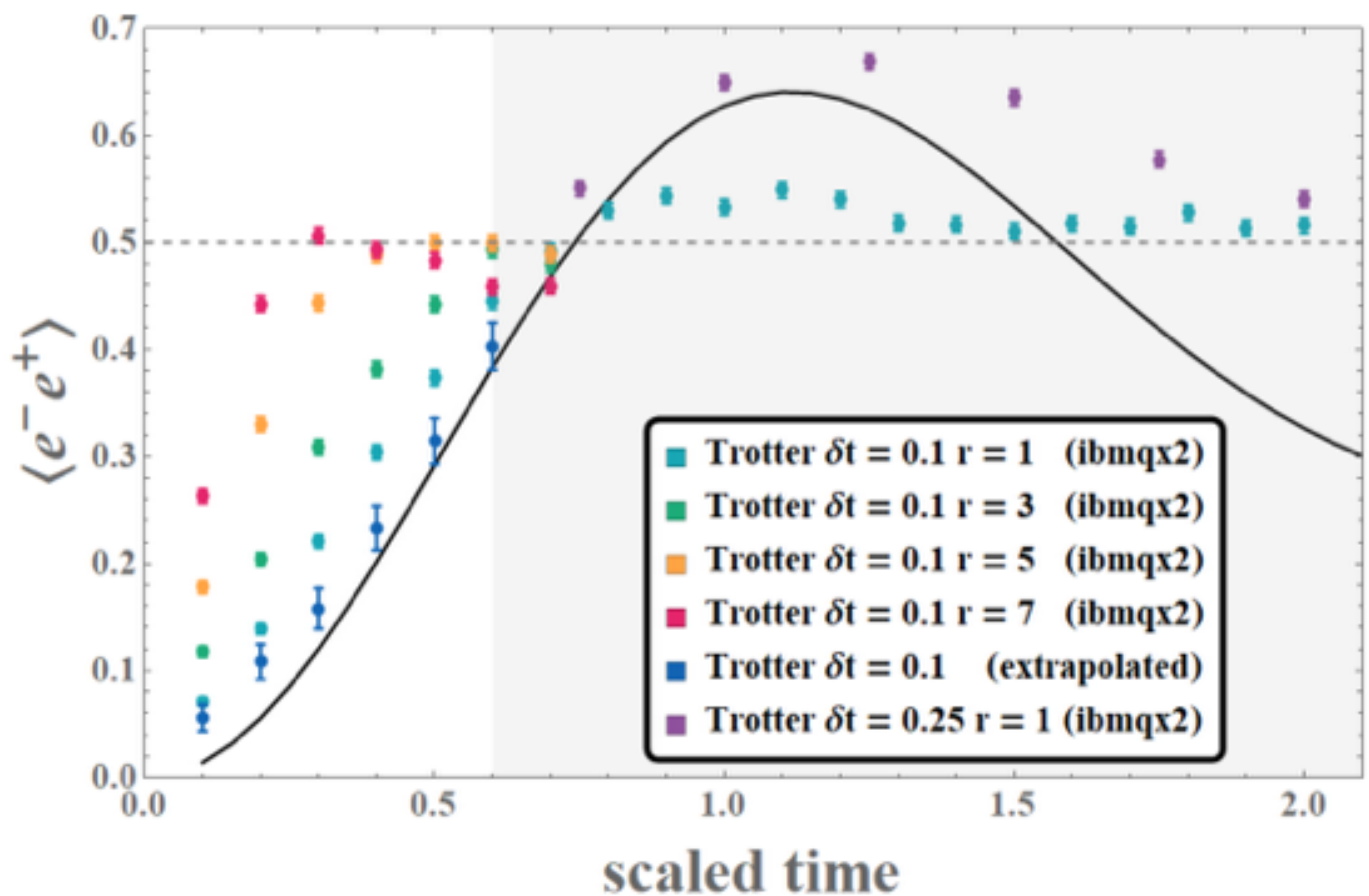


Starting Simple 1+1 Dim QED Living NISQ - IBM - Hybrid Trotter Evolution U(t)



T2 (μs)	55.20	65.10	47.00	35.10	37.60

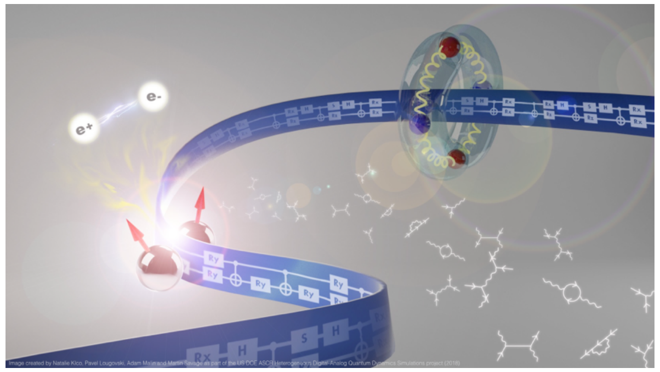
$$e^{-iHt} = e^{-i\sum_j H_j t} = \lim_{N_{\mathrm{Trot.}}\to\infty} \left(\prod_j e^{-iH_j \delta t} \right)^{N_{\mathrm{Trot.}}}$$



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

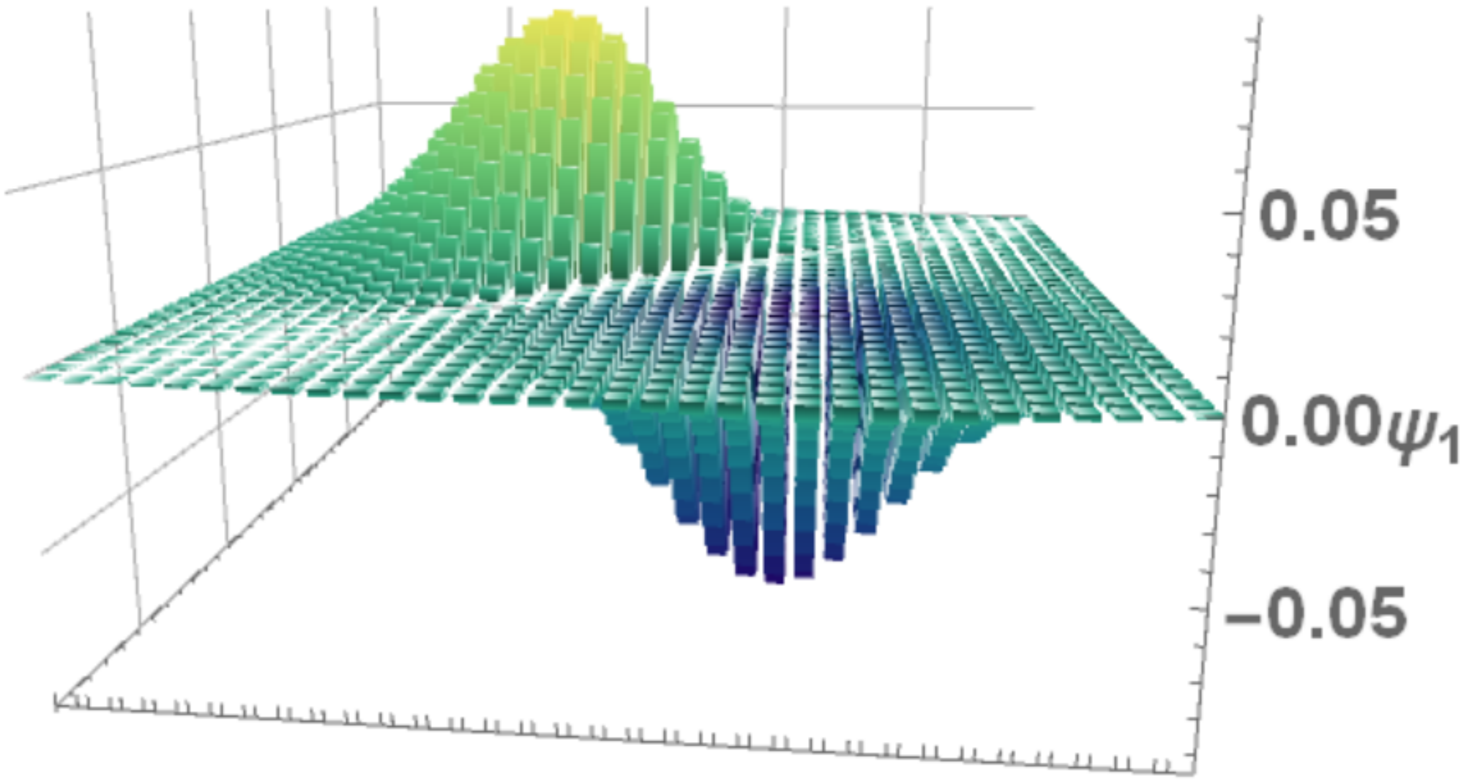
3.6 QPU-s and 260 IBM units

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

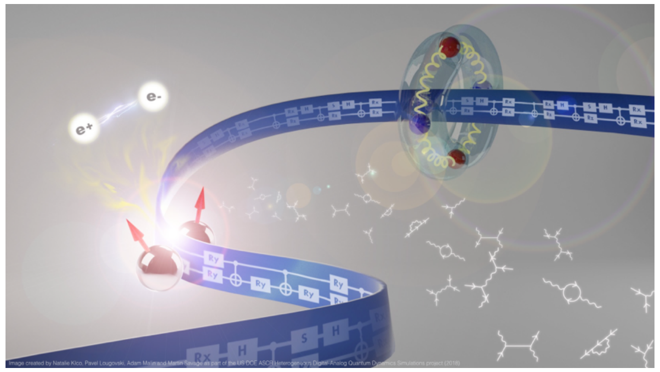


Digitizing Scalar Field Theory

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



Jordan, Lee and Preskill - several works



Digitizing Scalar Field Theory - works

Jordan, Lee and Preskill - several works

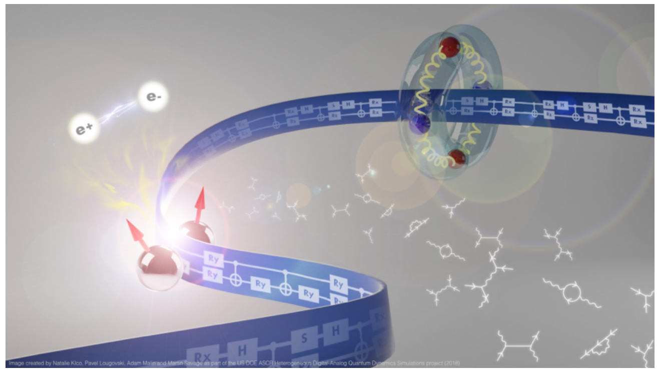
Simulating physical phenomena by quantum networks
R. Somma, G. Ortiz, J. E. Gubernatis, E. Knill, and R. Laflamme
Phys. Rev. A **65**, 042323 – Published 9 April 2002

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

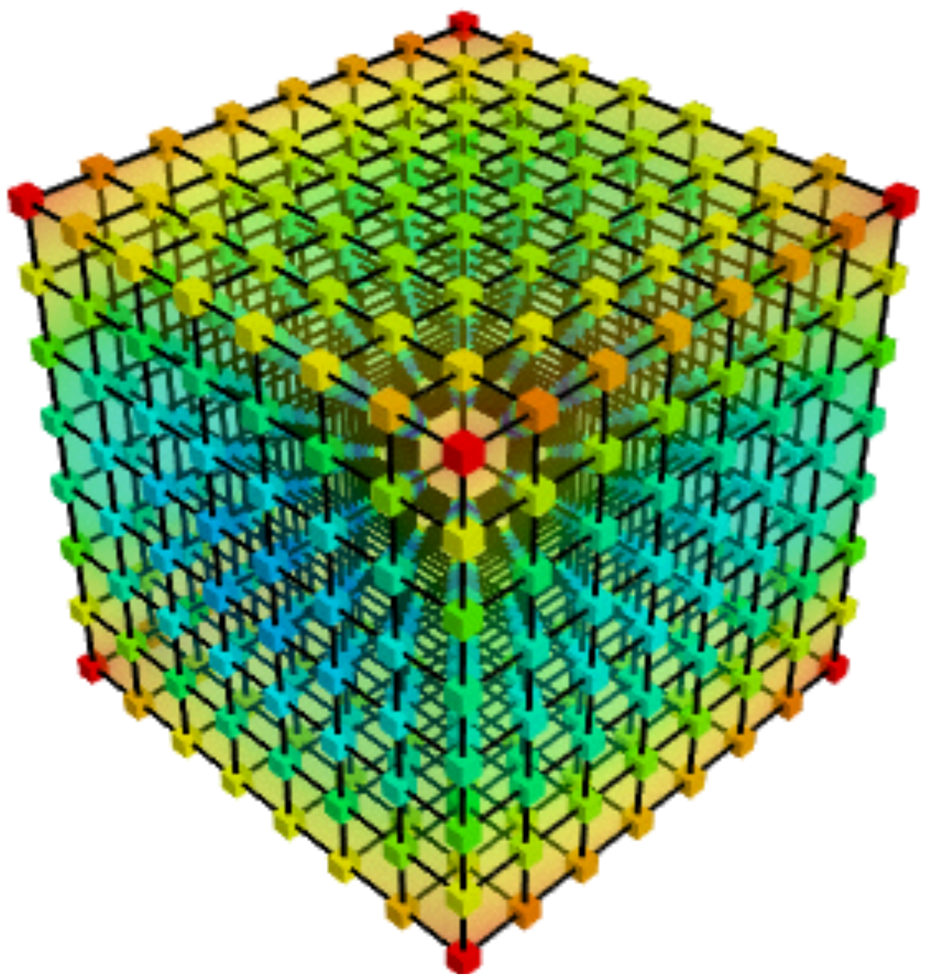
Quantum Computation of Scattering Amplitudes in Scalar Quantum Electrodynamics
Kübra Yeter-Aydeniz (Tennessee Tech. U.), George Siopsis (Tennessee U.). Sep 7, 2017. 9 pp.
Published in **Phys.Rev. D97 (2018) no.3, 036004**
e-Print: **arXiv:1709.02355 [quant-ph]**

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

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



Discretizing Scalar Field Theory on Spatial Grid

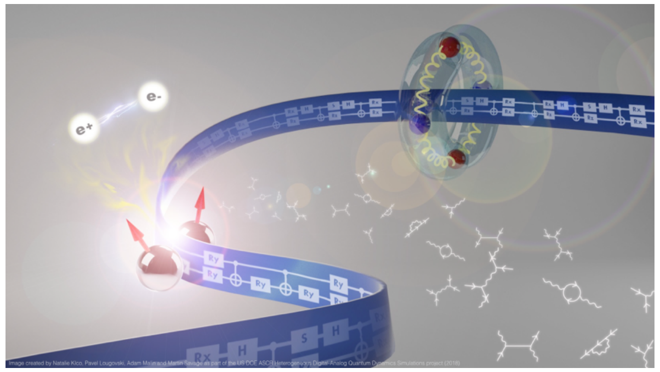


- Discretize 3-d Space
- Define Hamiltonian on grid
- Trotterized time evolution
- Technology transfer from Lattice QCD

$$\hat{H} = \hat{H}_{\Pi} + \hat{H}_{\phi}$$

$$\hat{\mathcal{H}}_{\Pi} = \frac{1}{2}\Pi^2 \quad , \quad \hat{\mathcal{H}}_{\phi} = \frac{1}{2}(\nabla\phi)^2 + \frac{1}{2}m^2\phi^2 + \frac{\lambda}{4!}\phi^4$$

$$\hat{H}_{\phi} = b\sum_{x}\left(\frac{1}{2}\phi_j\phi_{j+1} + \frac{1}{2}\phi_j\phi_{j-1} - \phi_j^2 + \frac{1}{2}m^2\phi_j^2 + \frac{\lambda}{4!}\phi_j^4 \right) \quad , \quad \hat{H}_{\Pi} = b\sum_{x}\hat{\mathcal{H}}_{\Pi_j}$$



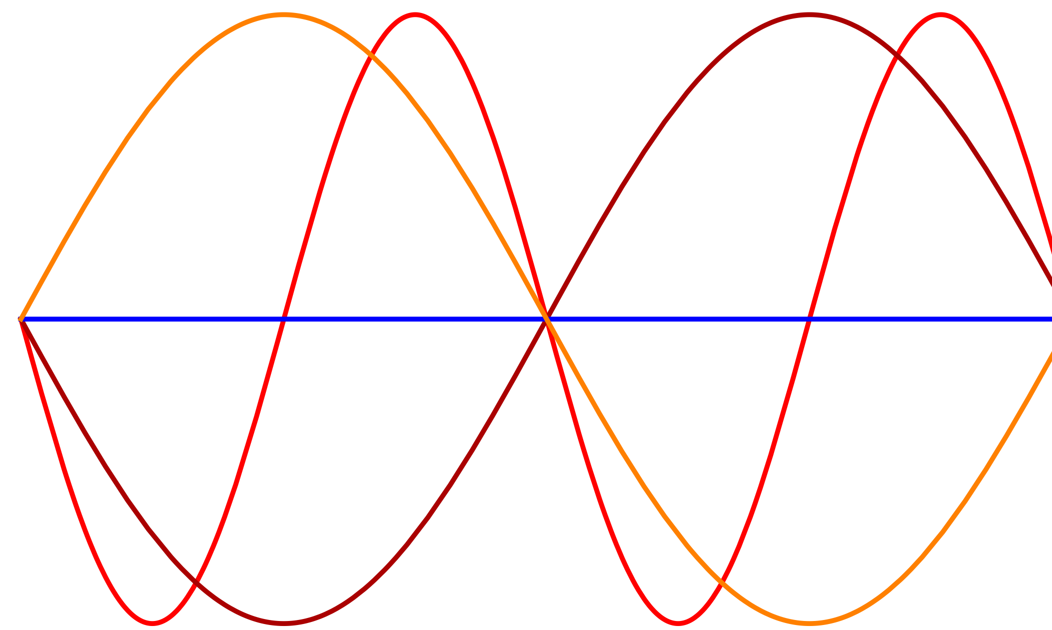
Discretizing Scalar Field Theory on Spatial Grid Momentum Mode Expansion

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

e.g. 1-dim with a = 1 and L=2

k = 0 and +π

$|\psi\rangle = |n_1\rangle \otimes |n_2\rangle$



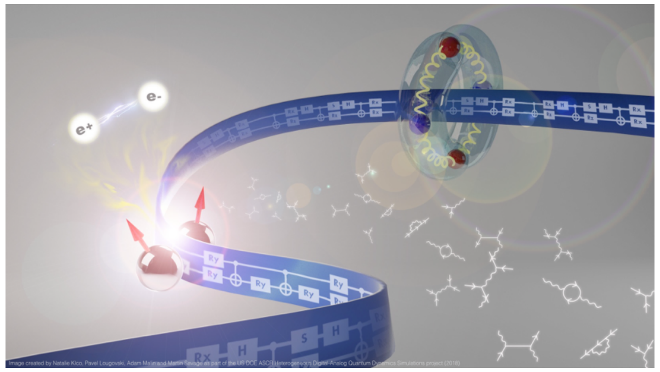
$$\sqrt{L}\,\hat{\phi}(0) = \frac{1}{\sqrt{2\omega_0}}\left(\hat{a}_0 + \hat{a}_0^\dagger\right) + \frac{1}{\sqrt{2\omega_\pi}}\left(\hat{a}_1 + \hat{a}_1^\dagger\right)$$

$$\sqrt{L}\,\hat{\phi}(b) = \frac{1}{\sqrt{2\omega_0}}\left(\hat{a}_0 + \hat{a}_0^\dagger\right) - \frac{1}{\sqrt{2\omega_\pi}}\left(\hat{a}_1 + \hat{a}_1^\dagger\right)$$

$$\hat{\phi}(\mathbf{x}) = \int \frac{d^3\mathbf{k}}{(2\pi)^3\sqrt{2\omega_k}}\left[\,\hat{a}_\mathbf{k} e^{i\mathbf{k}\cdot\mathbf{x}} + \hat{a}_\mathbf{k}^\dagger e^{-i\mathbf{k}\cdot\mathbf{x}}\,\right]$$

$$\hat{H}_I = \frac{b\lambda}{4!}\left(\hat{\phi}(0)^4 + \hat{\phi}(b)^4\right)$$
$$= \frac{\lambda}{192b}\left(\frac{1}{\omega_0^2}\left(\hat{a}_0 + \hat{a}_0^\dagger\right)^4 \otimes \hat{I} + \frac{1}{\omega_1^2}\hat{I} \otimes \left(\hat{a}_1 + \hat{a}_1^\dagger\right)^4 + \frac{6}{\omega_0\omega_1}\left(\hat{a}_0 + \hat{a}_0^\dagger\right)^2 \otimes \left(\hat{a}_1 + \hat{a}_1^\dagger\right)^2\right)$$

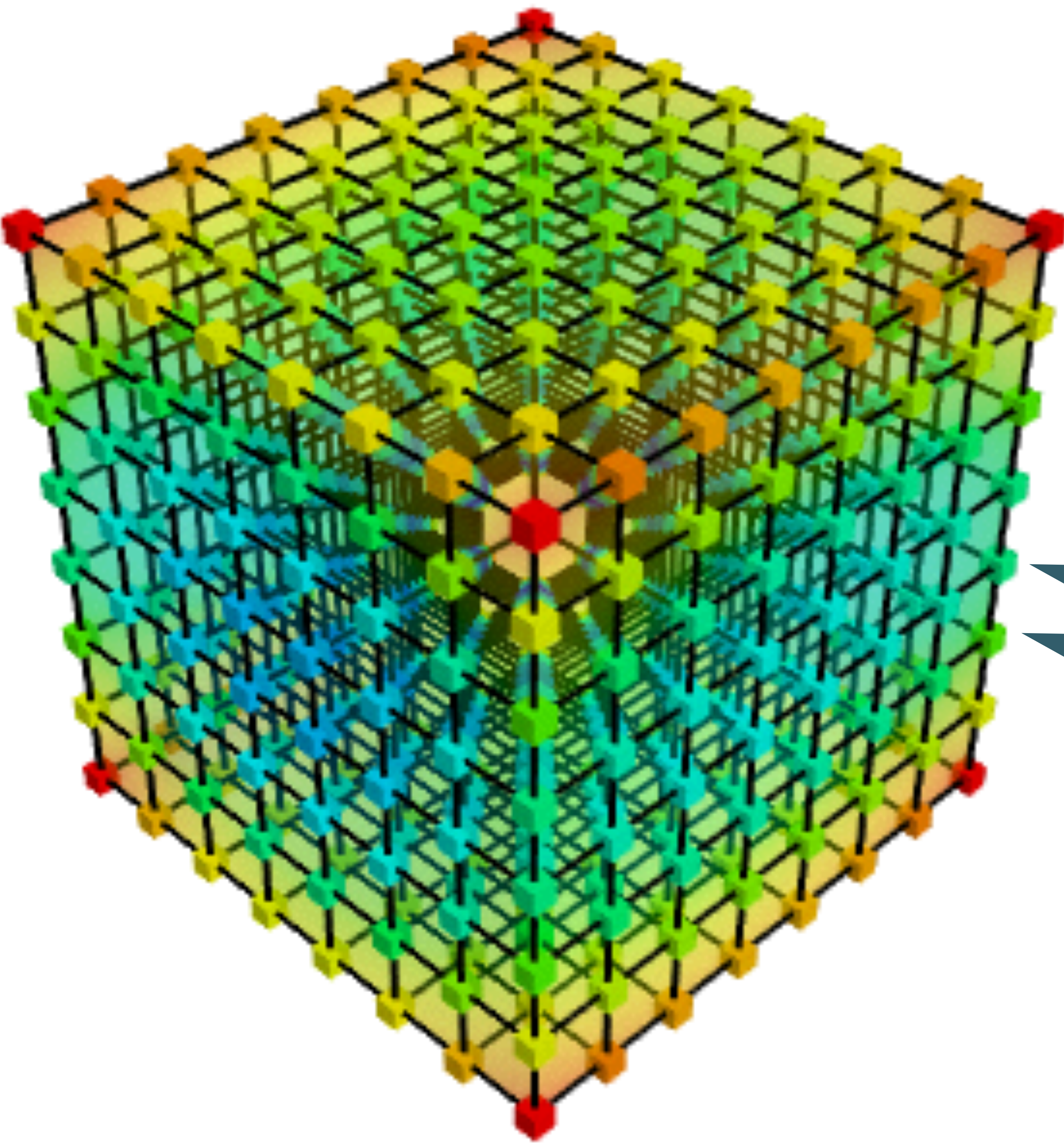
Extensive and non-local interactions in k-space

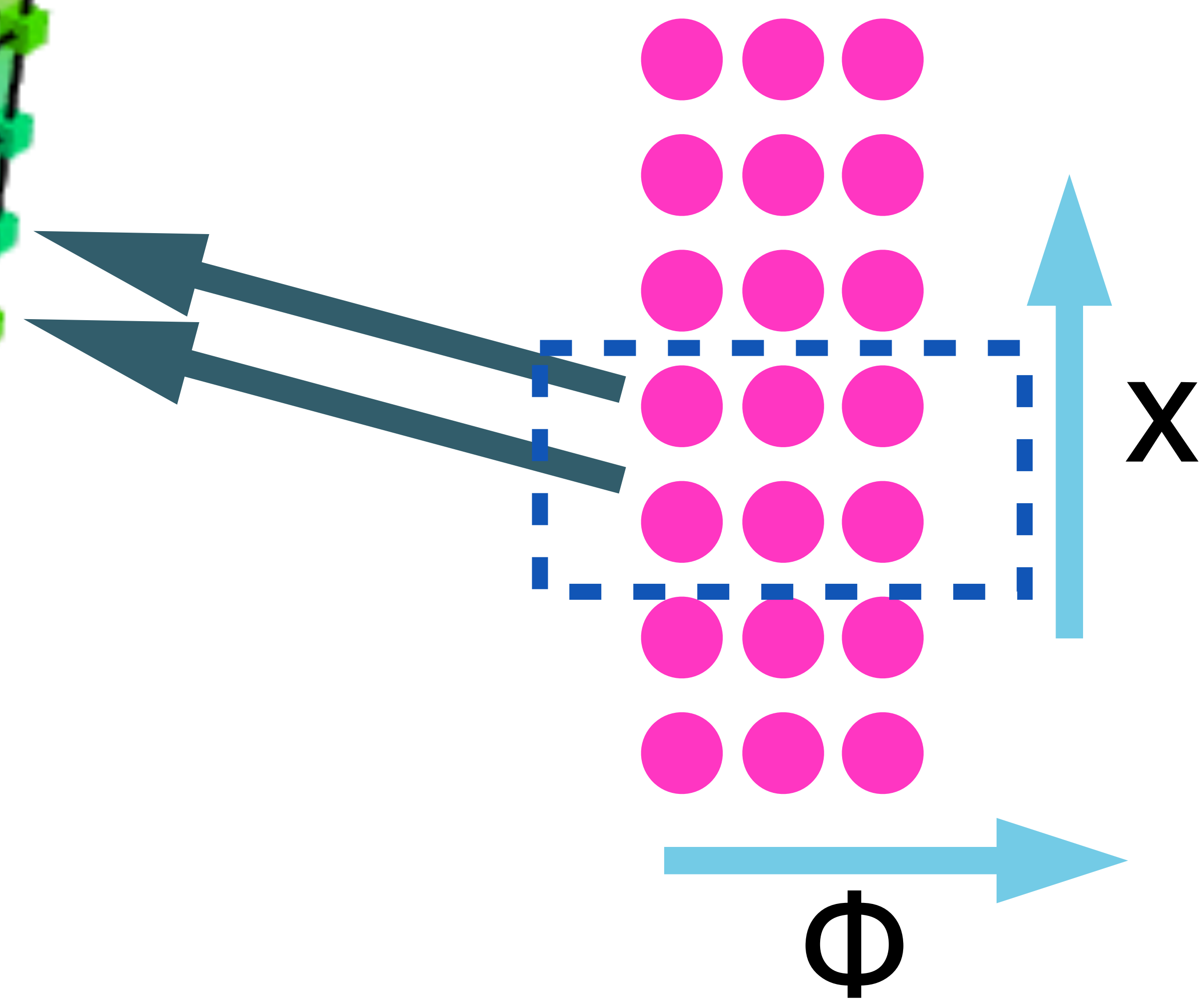


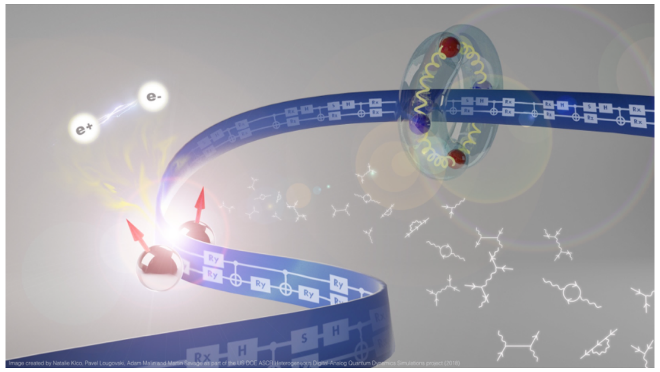
Discretizing Scalar Field Theory on Spatial Grid
Position-Space Formulations

Parallelizes easily at the circuit level

- dual layer application per Trotter step

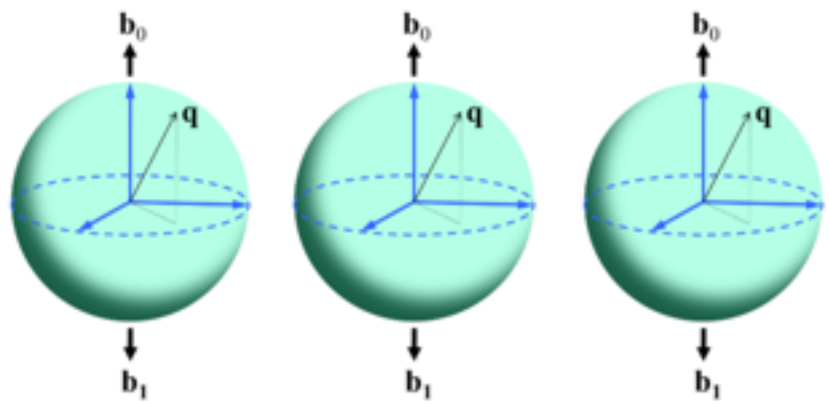




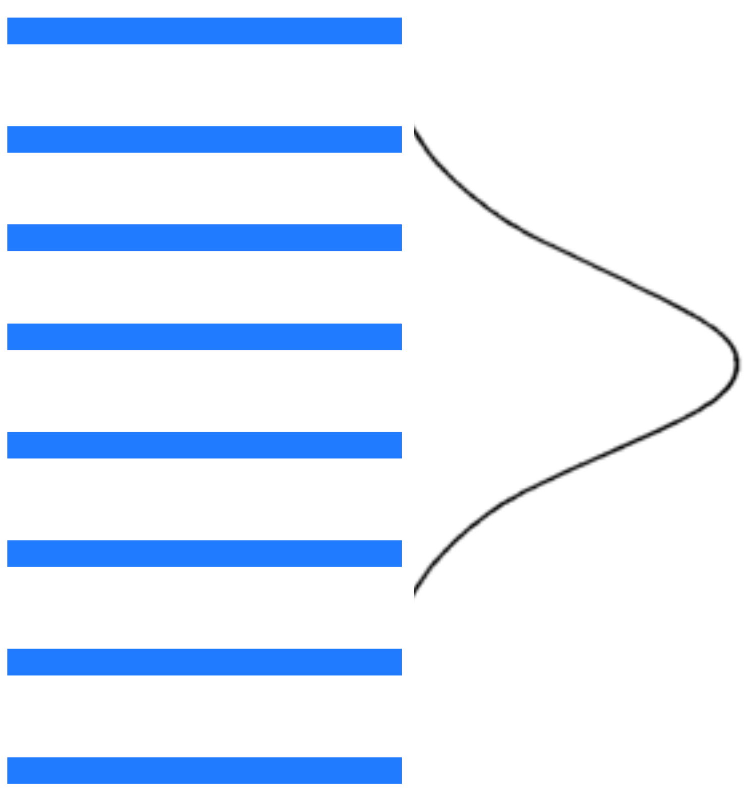


Digitizing Scalar Field Theory at each Spatial Site Position-Space Formulations

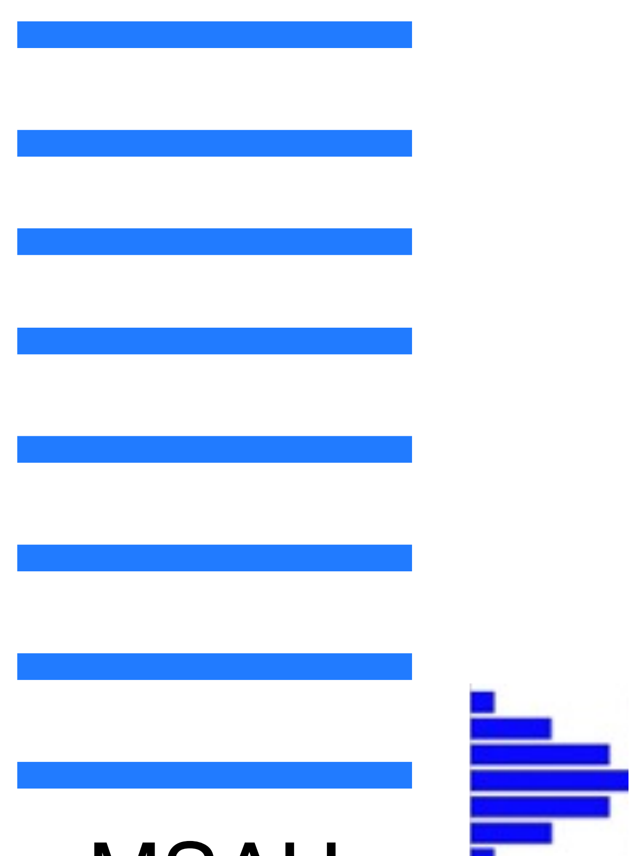
Determine basis to define field and conjugate momentum at each spatial site



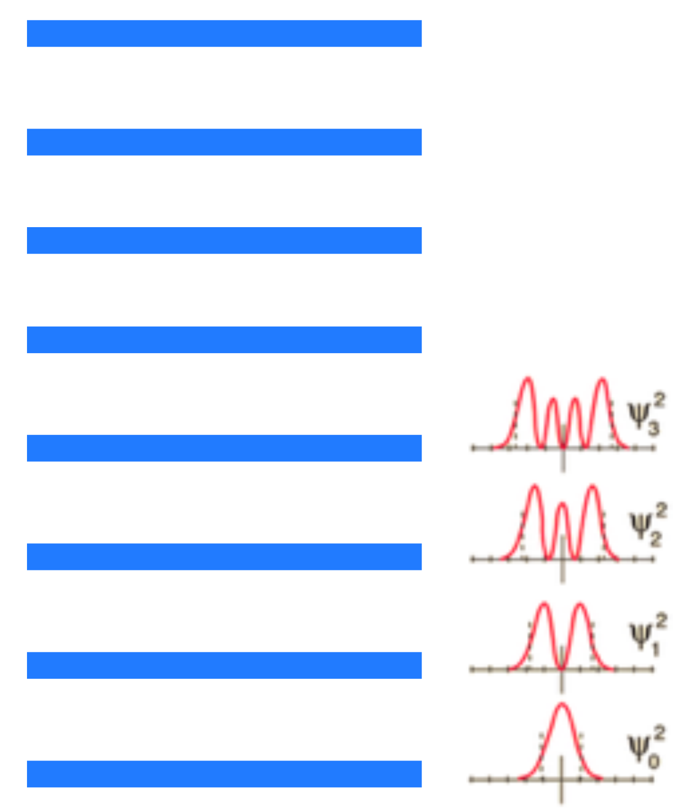
- Eigenstates of field operator (JLP)
- Discretized Harmonic Oscillator (MSAH)
- Eigenstates of Harmonic Oscillator



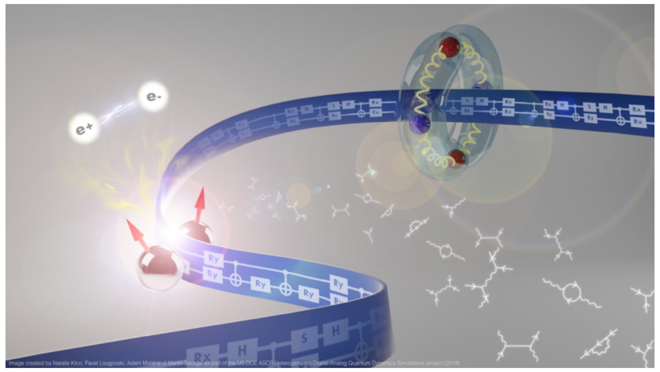
JLP



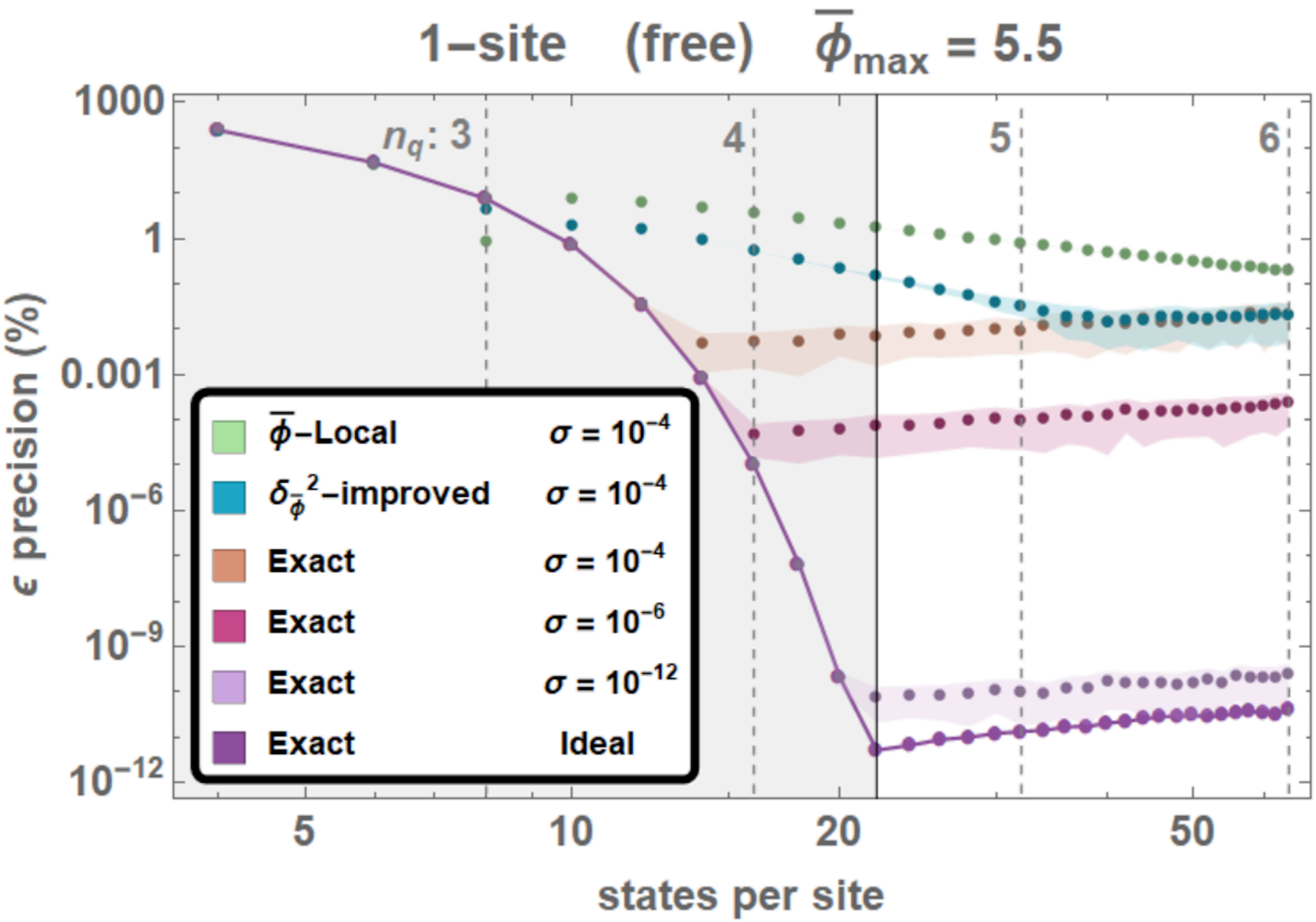
MSAH



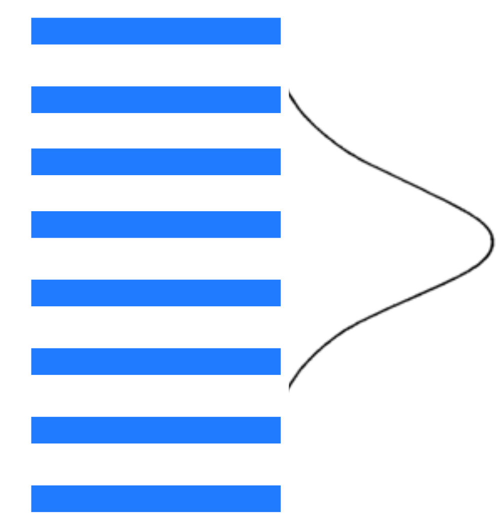
HO

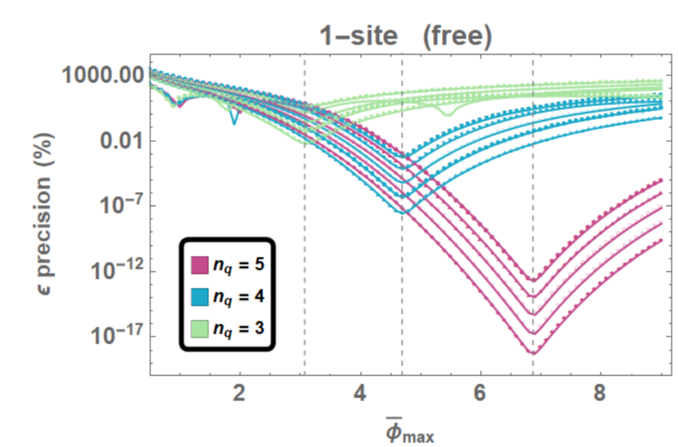


Digitizing Scalar Field Theory at each Spatial Site

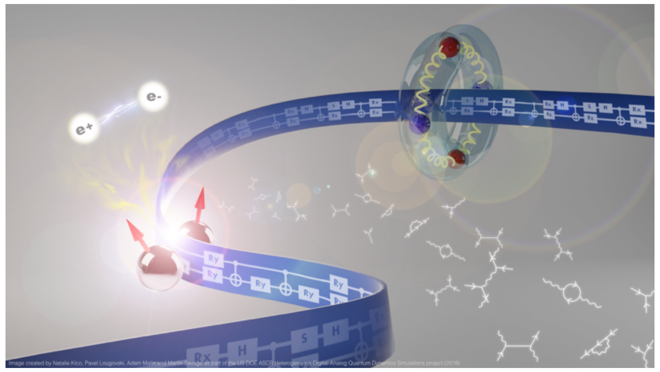


Field-operator basis





- Nyquist-Shannon Sampling Theorem (MSAH)
- QuFoTr allows application of exact conjugate momentum operator (not finite difference approx)
- Noise provides limit to precision in energy eigenvalues from exact Hamiltonian

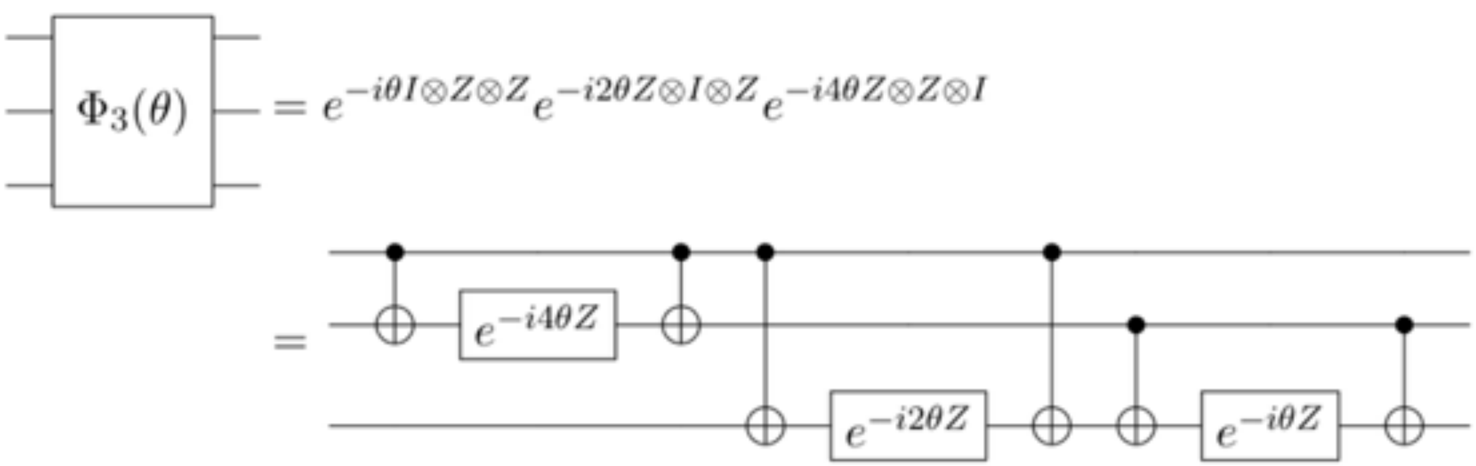


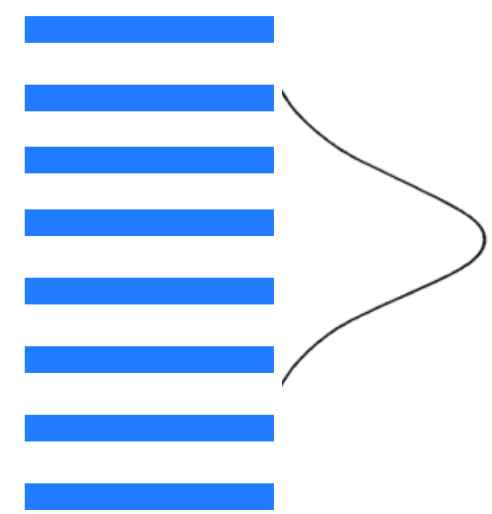
Digitizing Scalar Field Theory at each Spatial Site

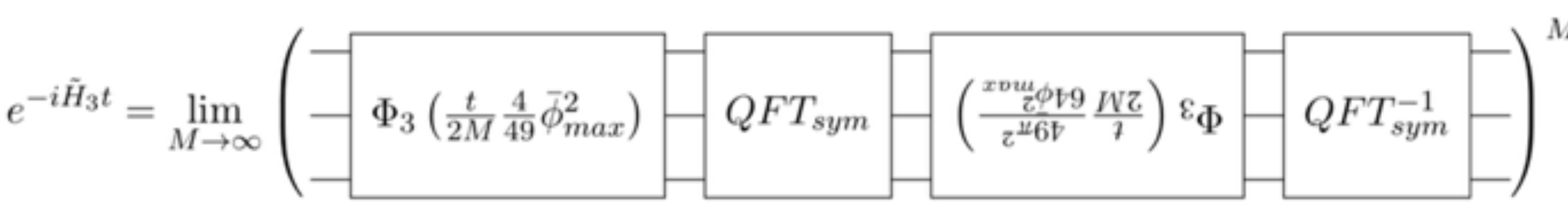
$$\tilde{\phi}^2 = \frac{4}{49}\,\bar{\phi}^2_{\rm max}\,\mathcal{O}_0^{(n_Q=3)} \quad , \quad \tilde{\Pi}^2 = \frac{49\pi^2}{64\,\bar{\phi}^2_{\rm max}}\,\mathcal{O}_0^{(n_Q=3)}$$

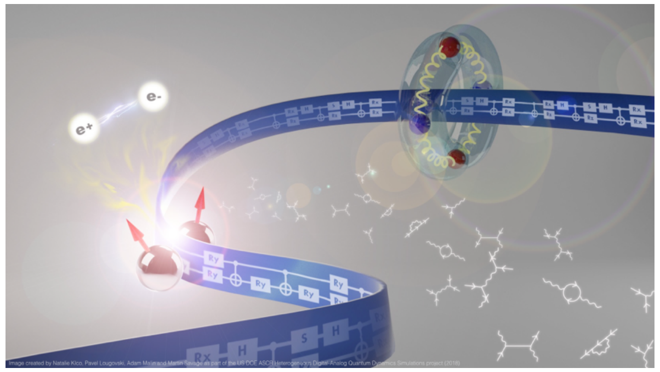
$$\mathcal{O}_0^{(n_Q=3)} = 4\,\sigma^z\otimes\sigma^z\otimes I_2 + 2\,\sigma^z\otimes I_2\otimes\sigma^z + I_2\otimes\sigma^z\otimes\sigma^z + \frac{21}{4}\,I$$

$$= \mathcal{O}_{03}^{(n_Q=3)} + \frac{21}{4}\,I \quad ,$$



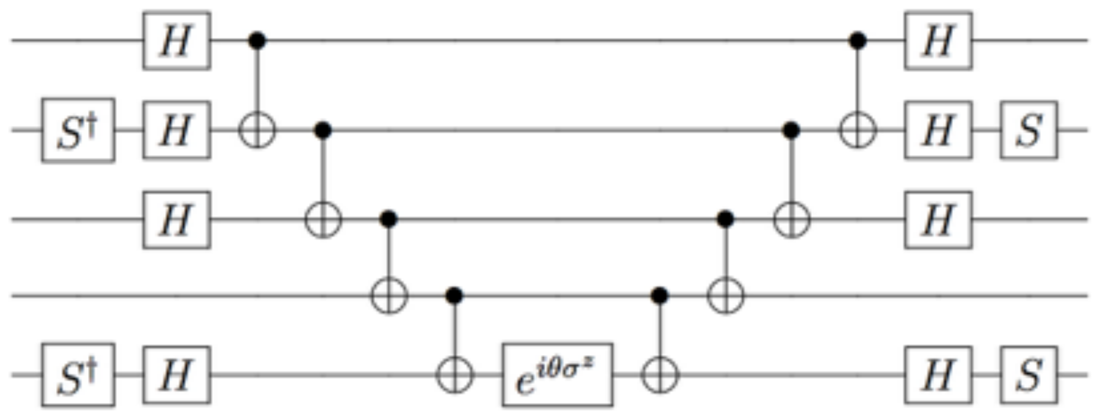




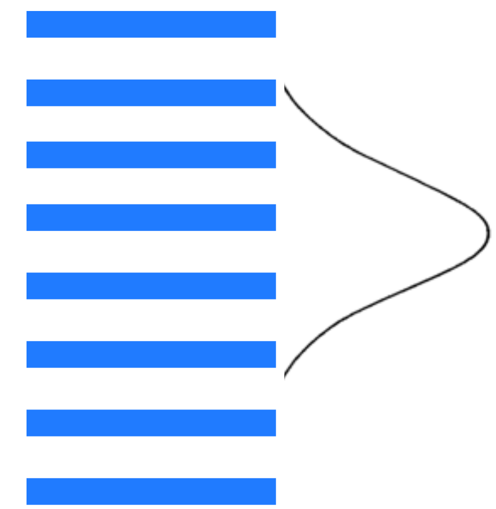


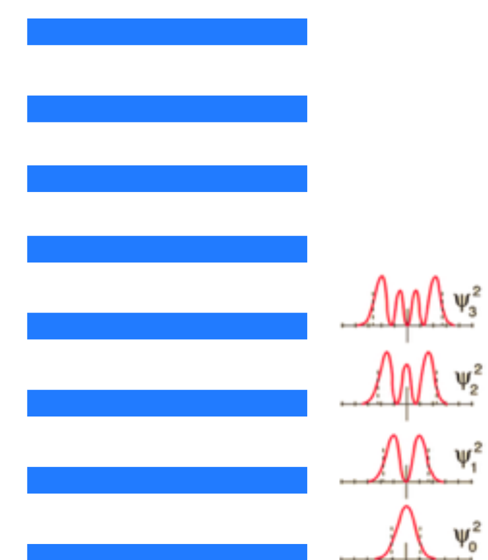
Digitizing Scalar Field Theory

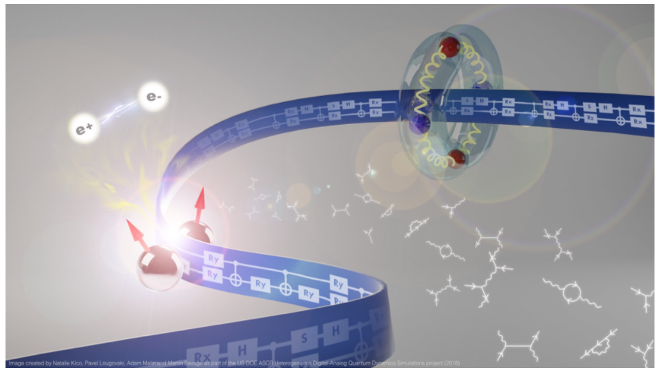
$$e^{i\theta\ \sigma^x \otimes \sigma^y \otimes \sigma^x \otimes \sigma^z \otimes \sigma^y} =$$



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

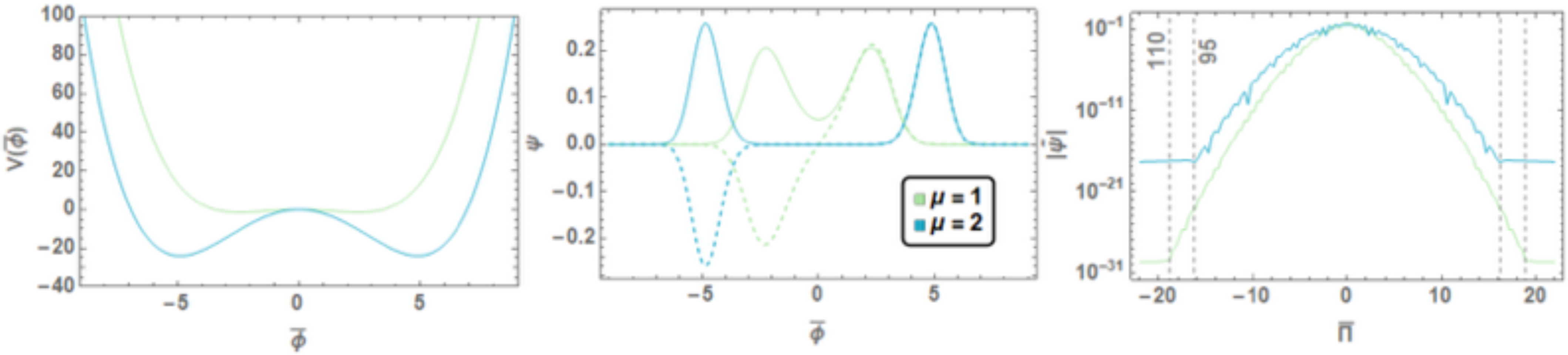


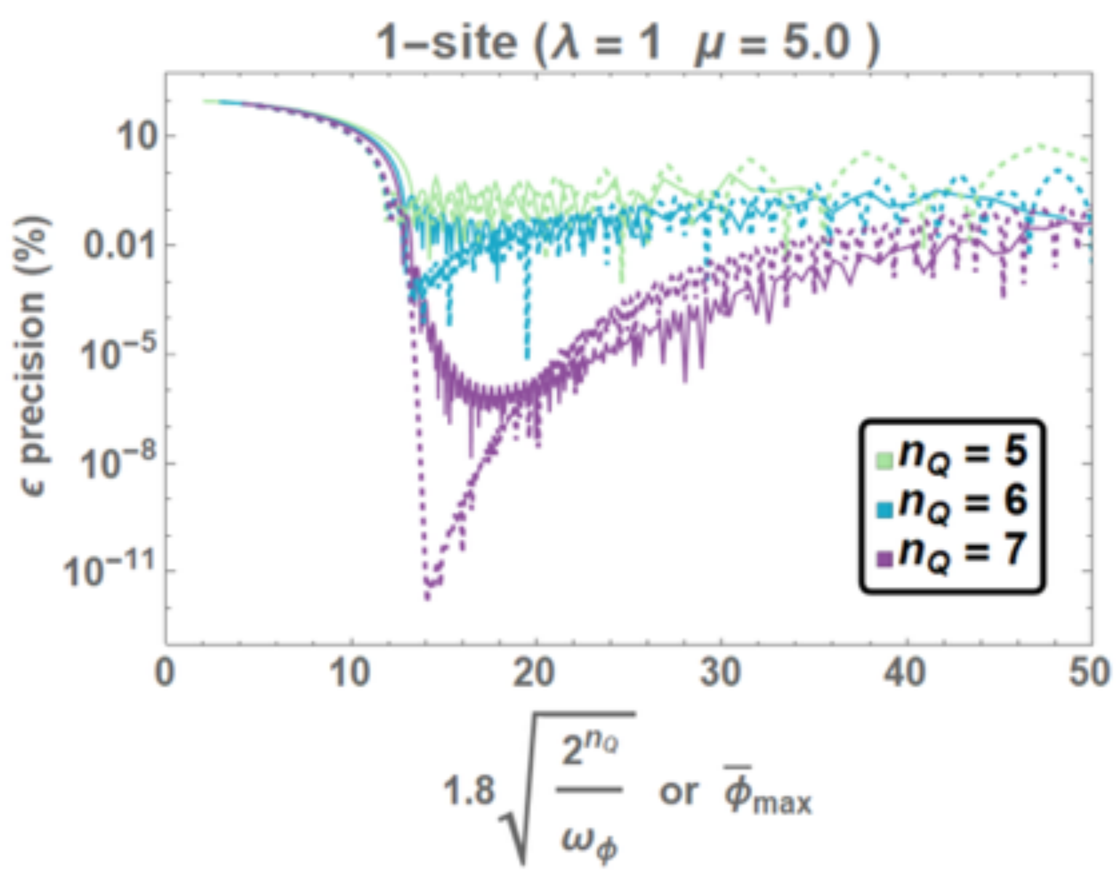


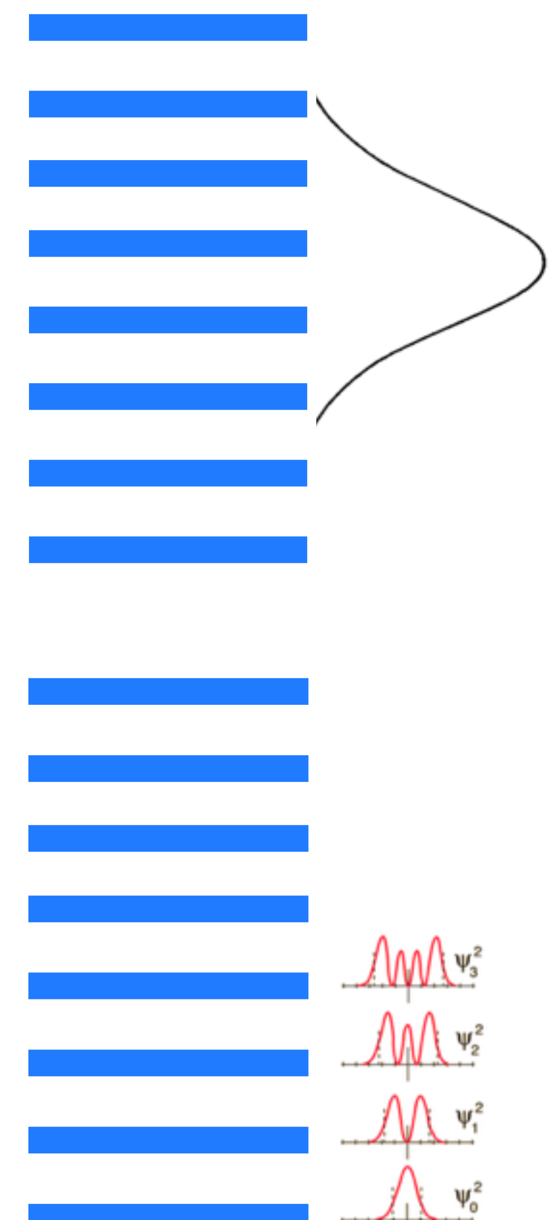


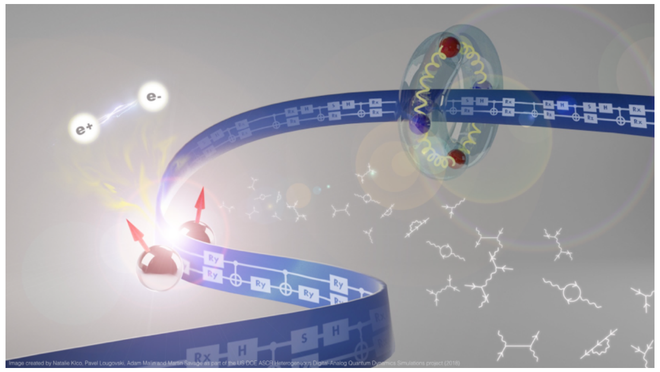
Digitizing Scalar Field Theory at each Spatial Site

e.g., de-localized wavefunctions in field space







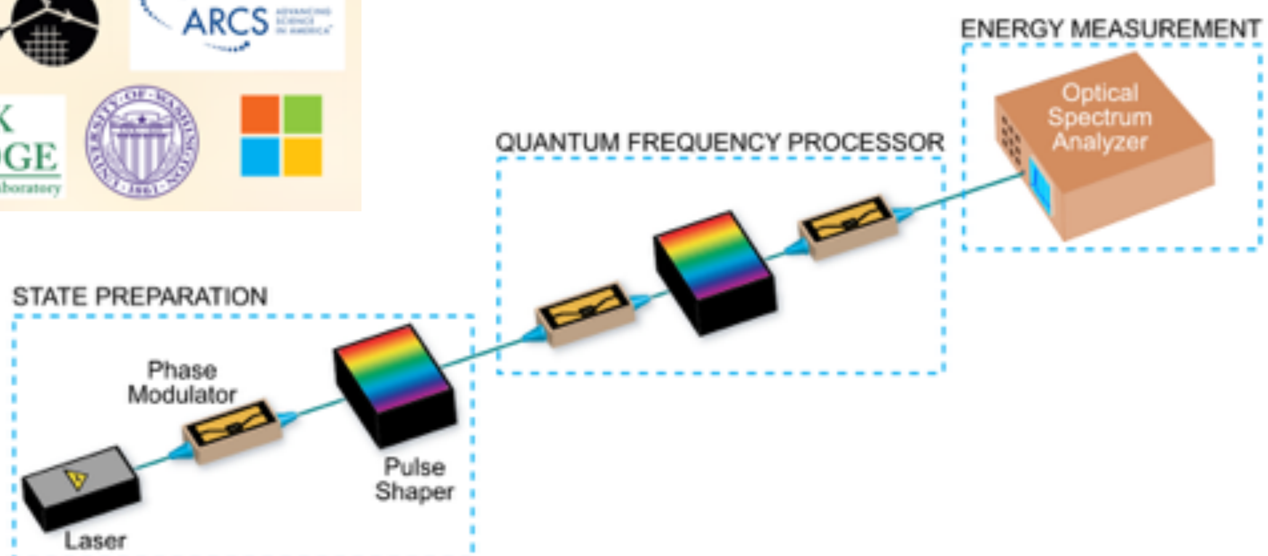


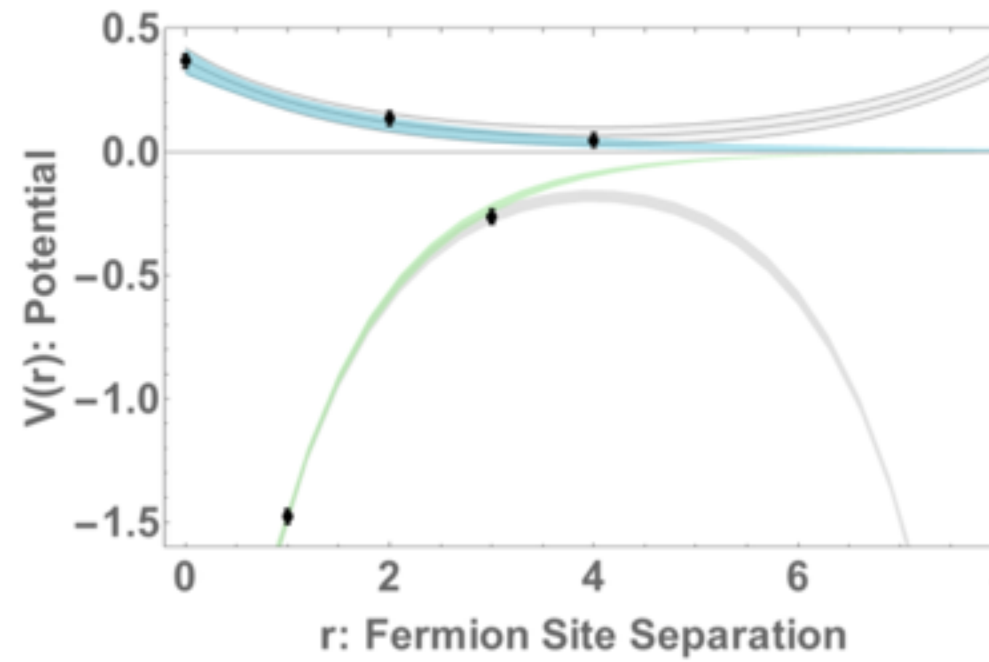
All-Optical Frequency Processor Schwinger Model

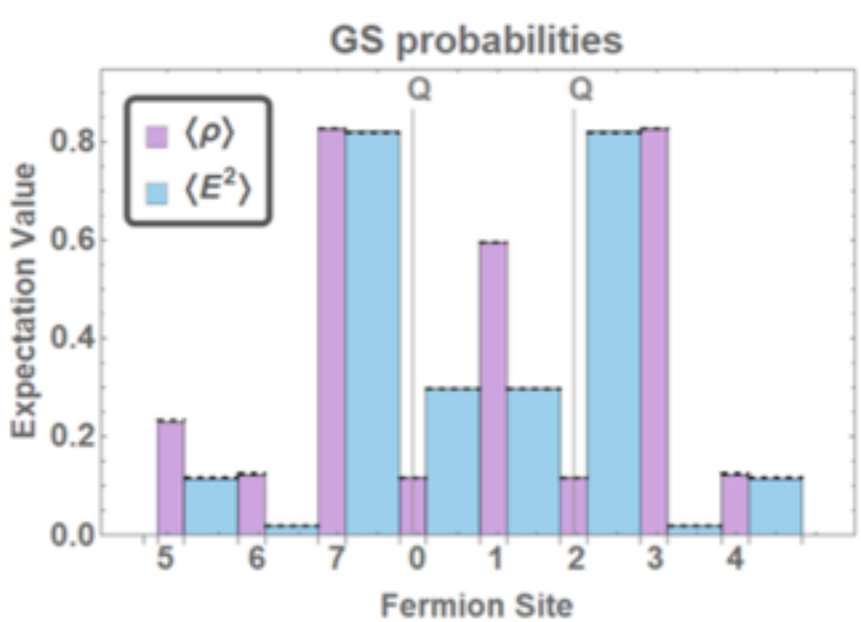
(to appear on the arXiv soon)

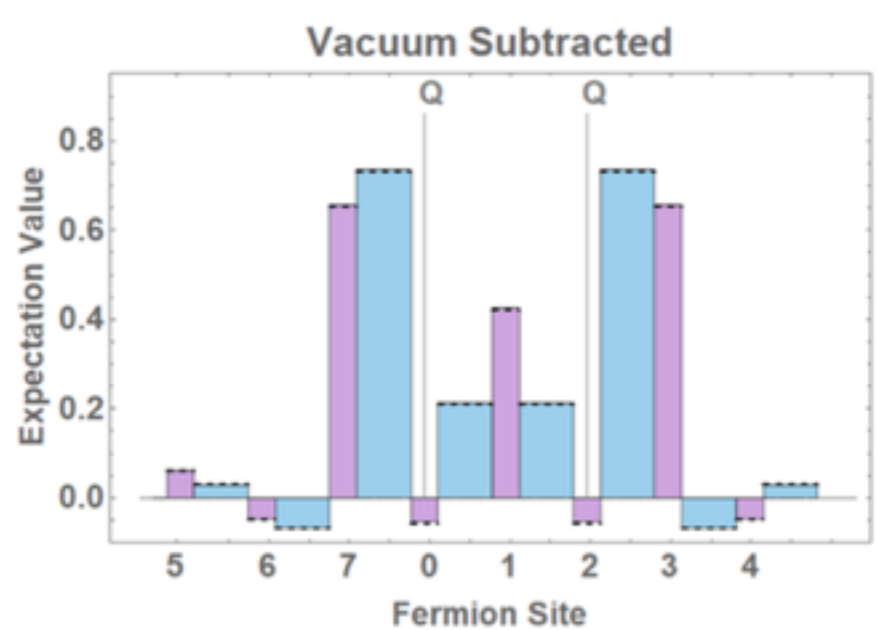
Simulations of Subatomic Many-Body Physics on a Quantum Frequency Processor

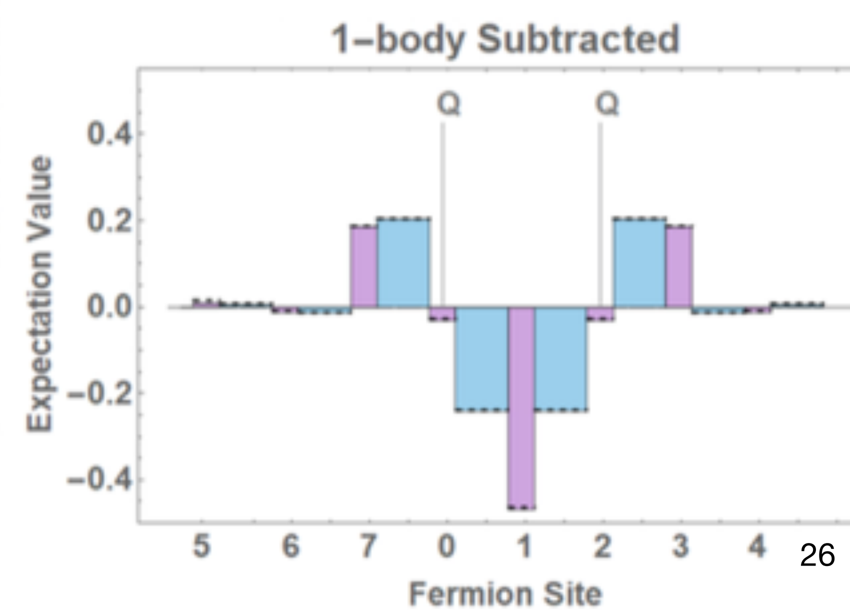
Hsuan-Hao Lu[1], Joseph M. Lukens[2], Natalie Klco[3], Martin J. Savage[3], Titus D. Morris[2], Aaina Bansal[4], Andreas Ekström[5], Gaute Hagen[6,4], Thomas Papenbrock[4,6], Andrew M. Weiner[1], and Pavel Lougovski[2,*]

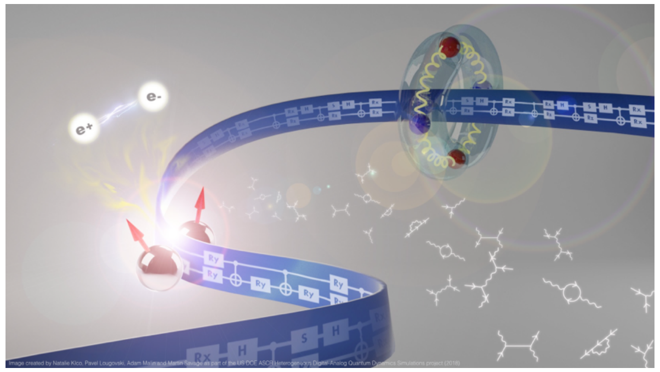






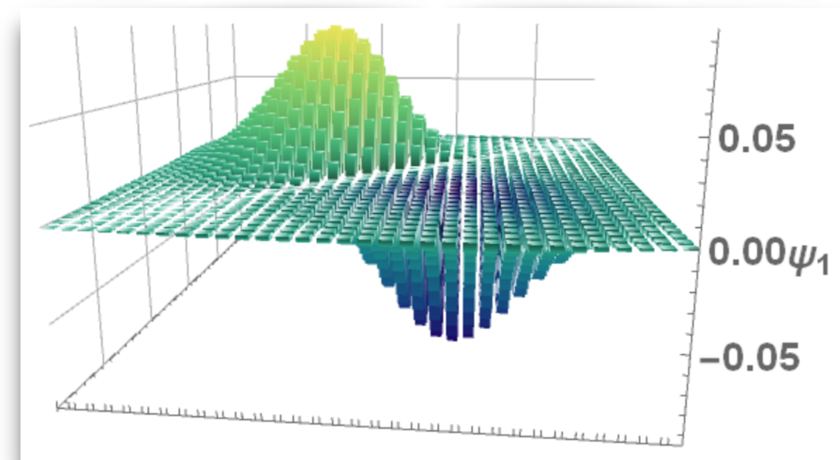






Summary

- QC and QIS offer the possibility of a *Quantum Advantage* in QFTs

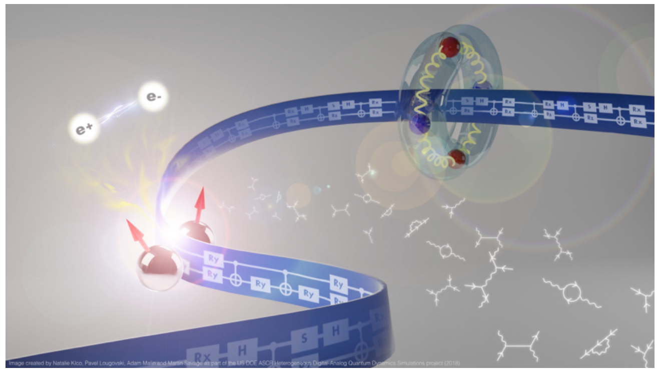


- Address Grand Challenge problems in NP and HEP
  - finite density and real-time evolution

- Mapping QFTs, particularly gauge theories, onto quantum devices is a present-day focus.

- Algorithm and circuit design are critical
  - fundamental change in thinking
  - likely benefit others areas

FIN



The promise of Quantum Computing

Parallel Processing of quantum states and information

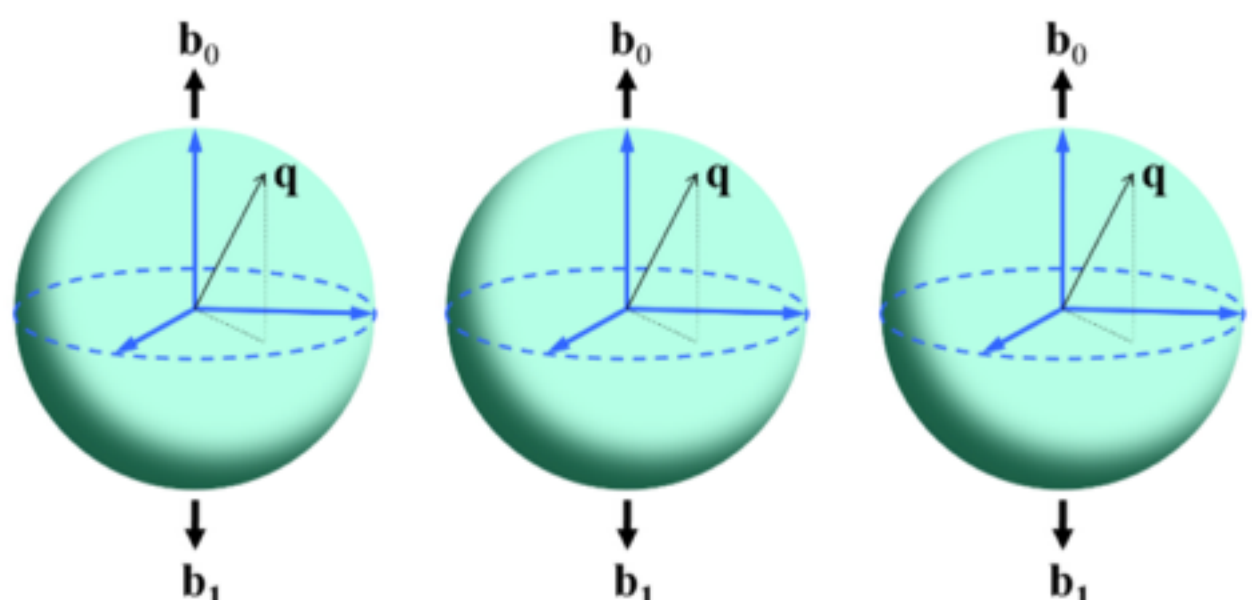
e.g., for a 3-bit computer (2^3 states)

Classical computer in 1 of 8 possible states

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

Quantum computer could be in all states at once!

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



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