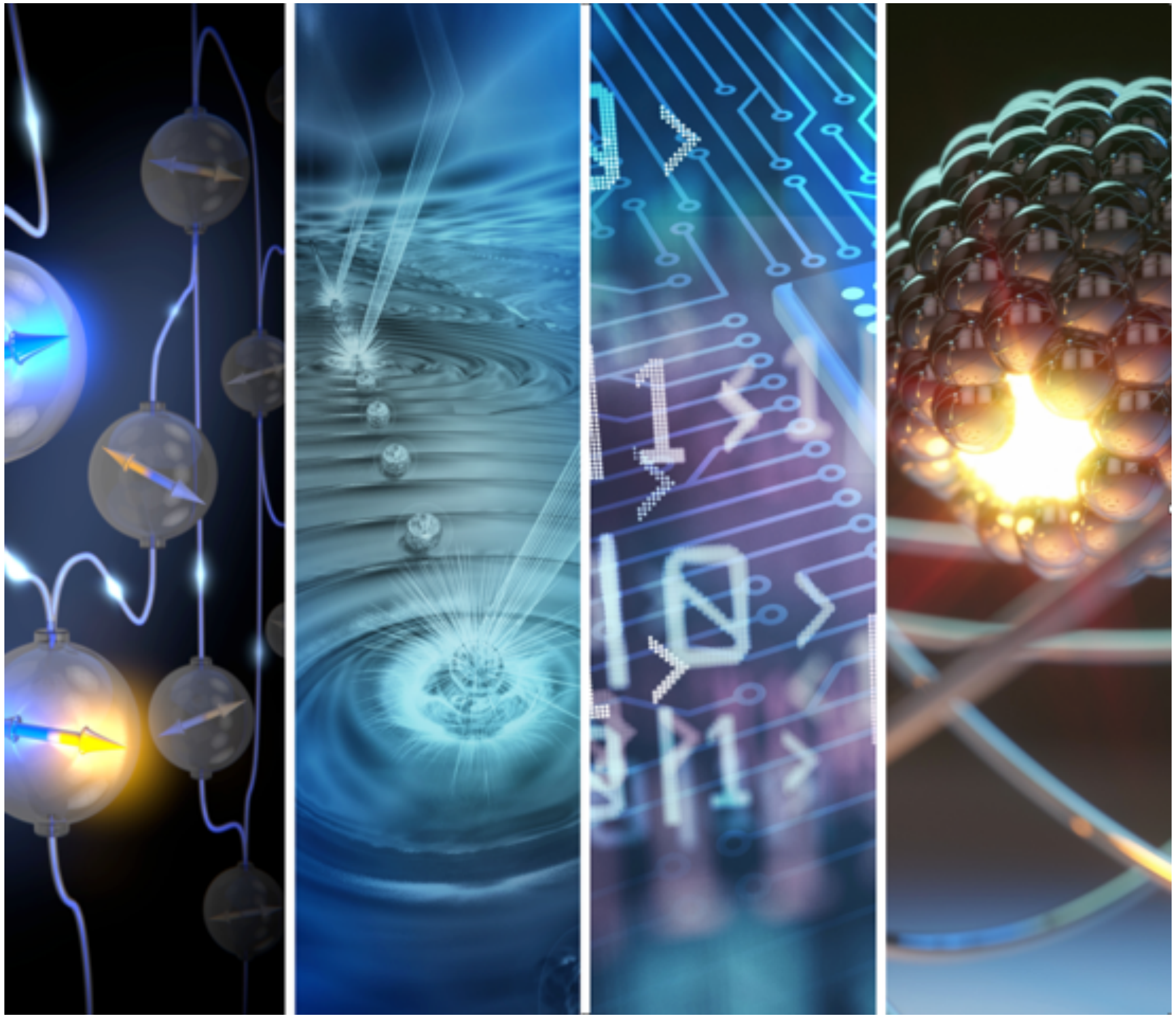
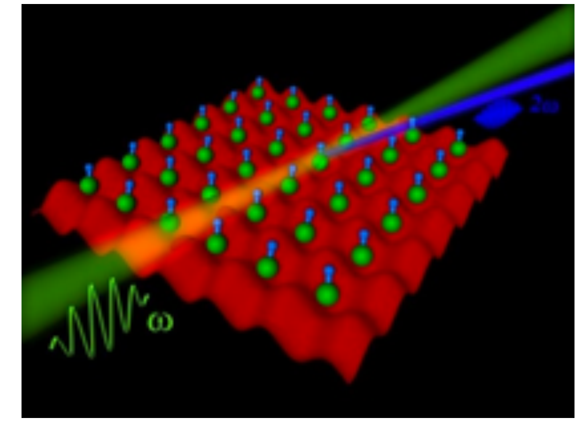
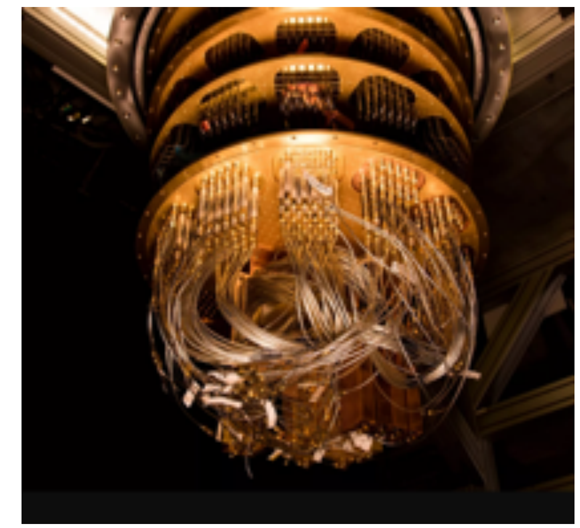
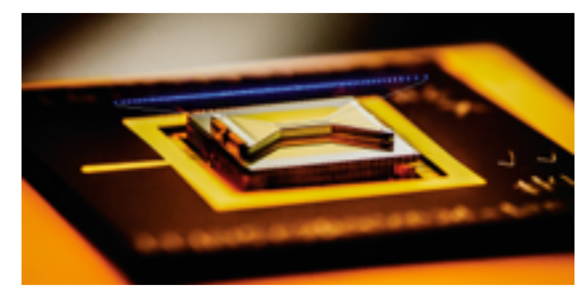








Intro to Quantum Computing

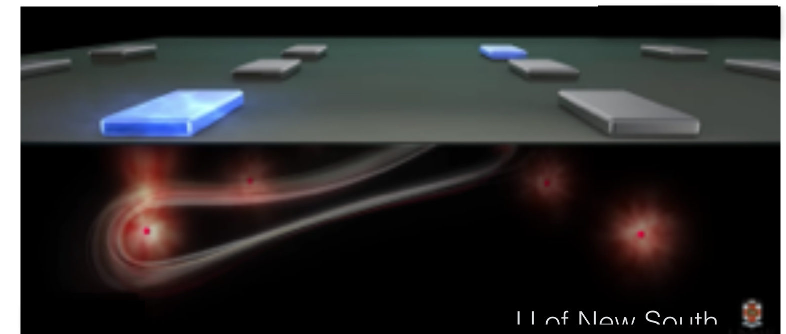
Workshop on Quantum Computing and Quantum Sensors
DESY, August 11, 2020

Martin J Savage

INSTITUTE for NUCLEAR THEORY

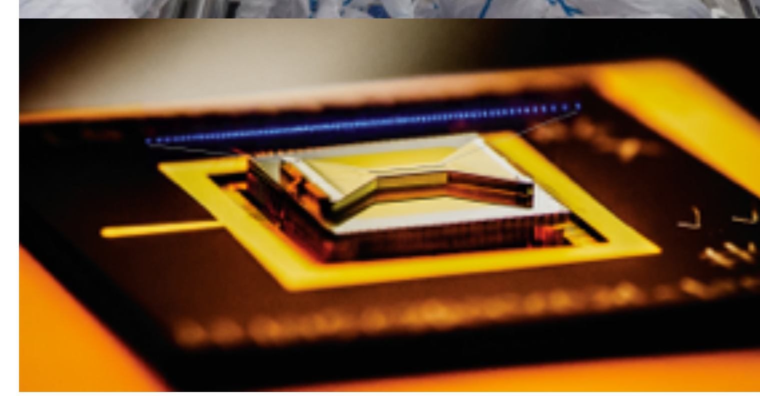
Quantum Information Science and Computing

- QIS: the nature, acquisition, storage, manipulation, computing, transmission, and interpretation of information.

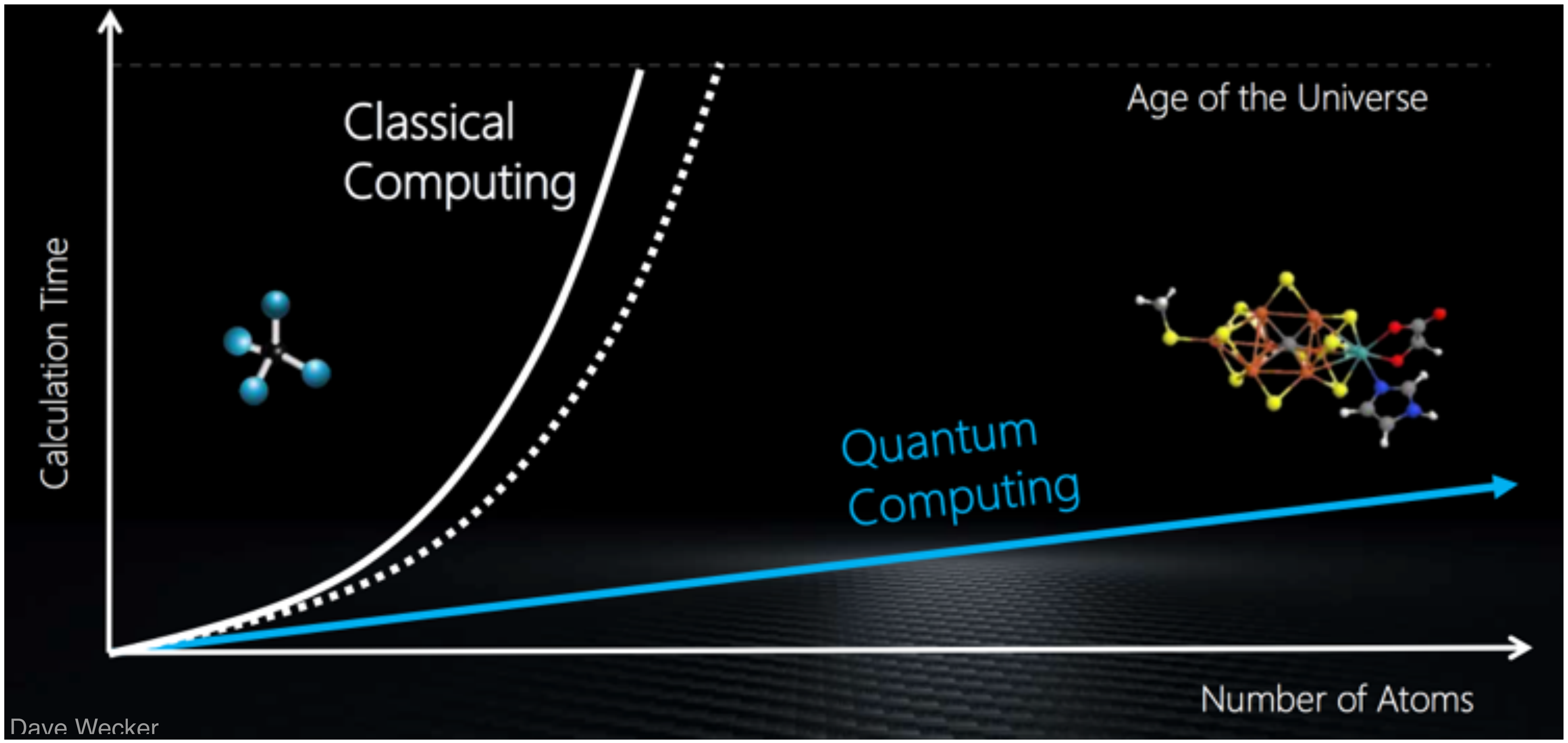


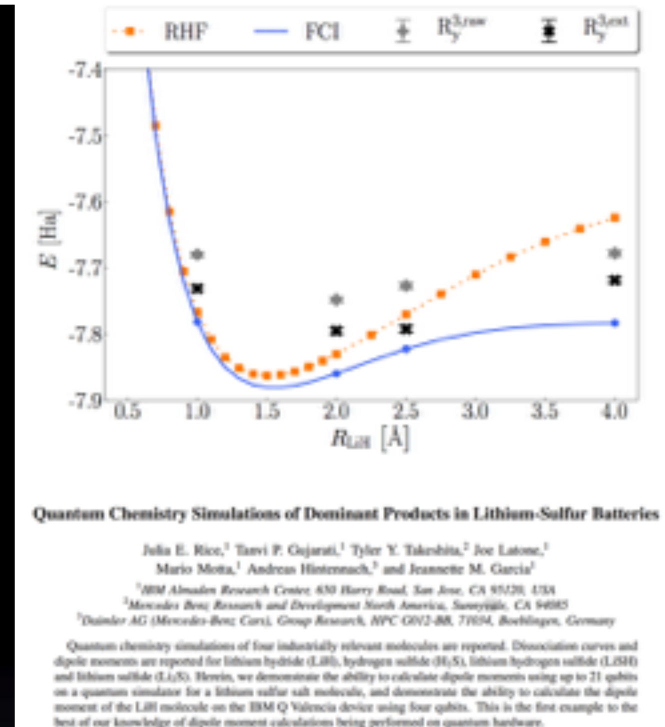
- Entanglement and superposition distinguish quantum information from classical information.

- Improving control of superposition and entanglement over macroscopic space-time volumes has produced first devices for quantum computation and quantum sensing. Defining the Quantum-2 era.



The Potential of Quantum Computing





5 qubits with techniques for 21

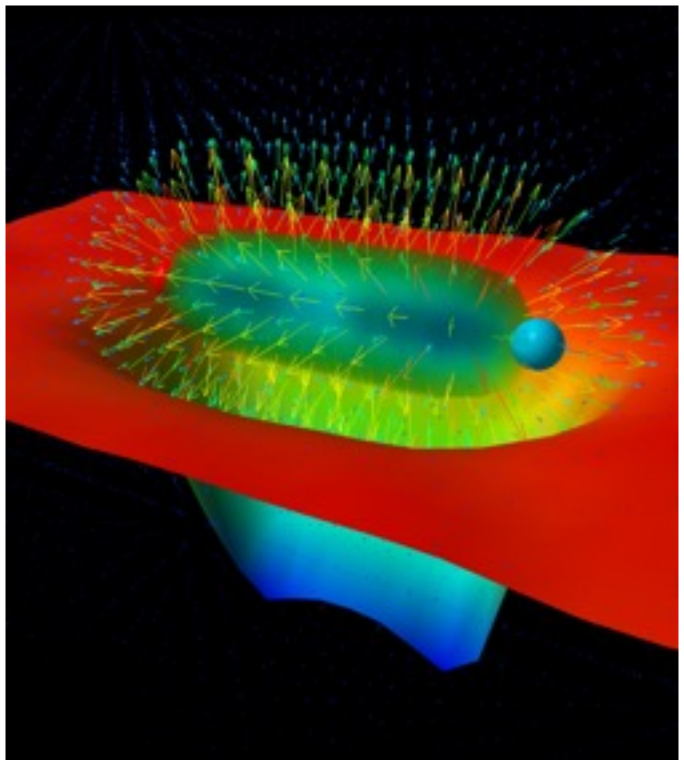
arXiv:2001.01120 [physics.chem-ph]

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

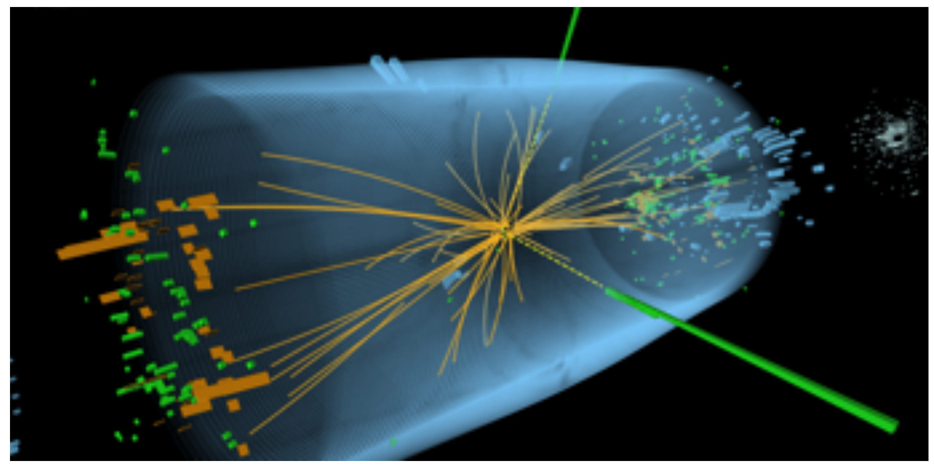
50 qubits : ~ 20 petabytes ~ Leadership-Class HPC facility

300 qubits : more states [10^{90}] than atoms in universe [10^{86}]

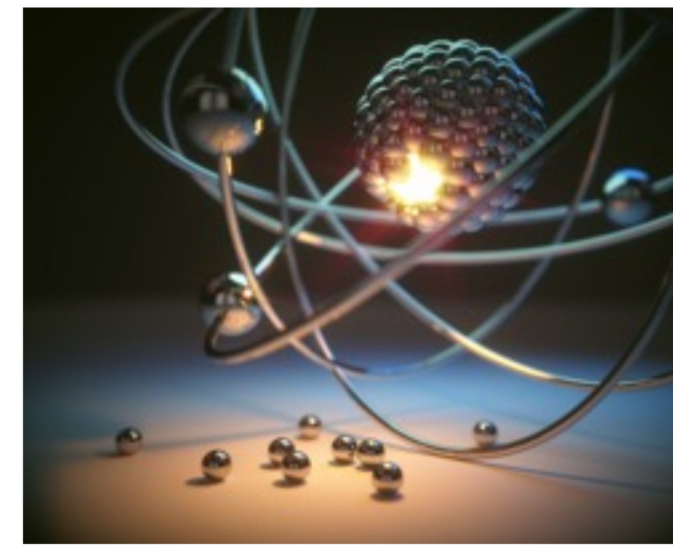
Where a quantum advantage may be achieved



Quantum Field Theories and Fundamental Symmetries
- indefinite particle number
- gauge symmetries and constraints
- entangled ground states

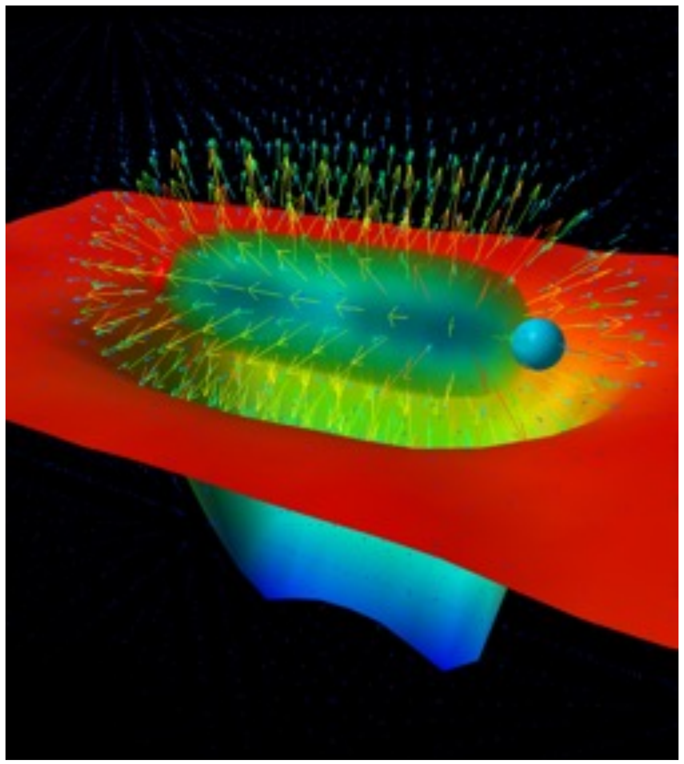


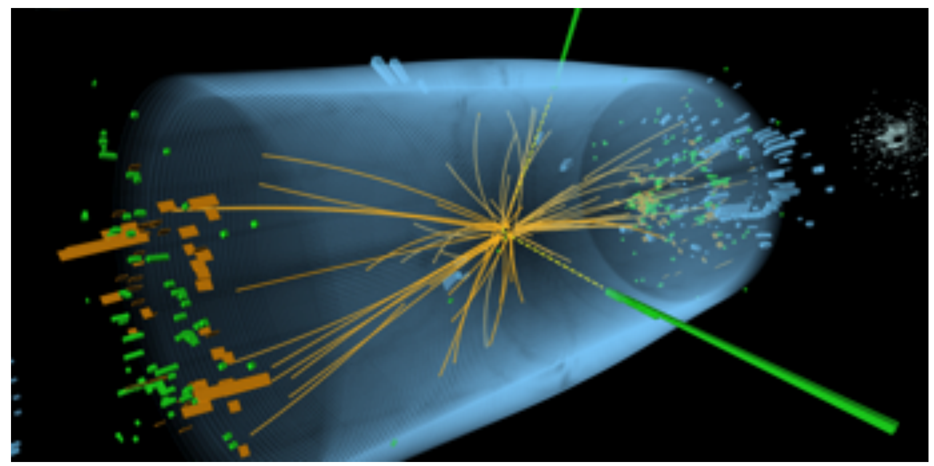
Real-Time Dynamics
- parton showers
- fragmentation
- neutrino-nucleus interactions
- neutrinos in matter
- early universe
- phase transitions - matter?
- non-equilibrium

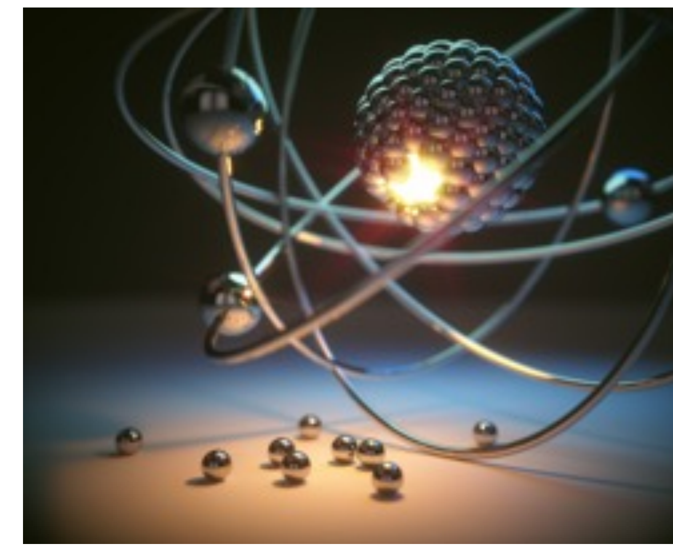


Dense Matter
- neutron stars
- gravity waves
- > medium nuclei
- chemical potentials

Where a quantum advantage may be achieved - 2







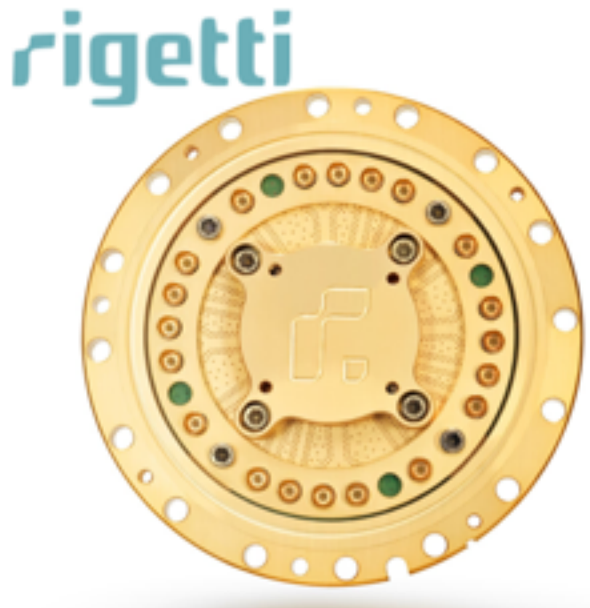
Classical Computing

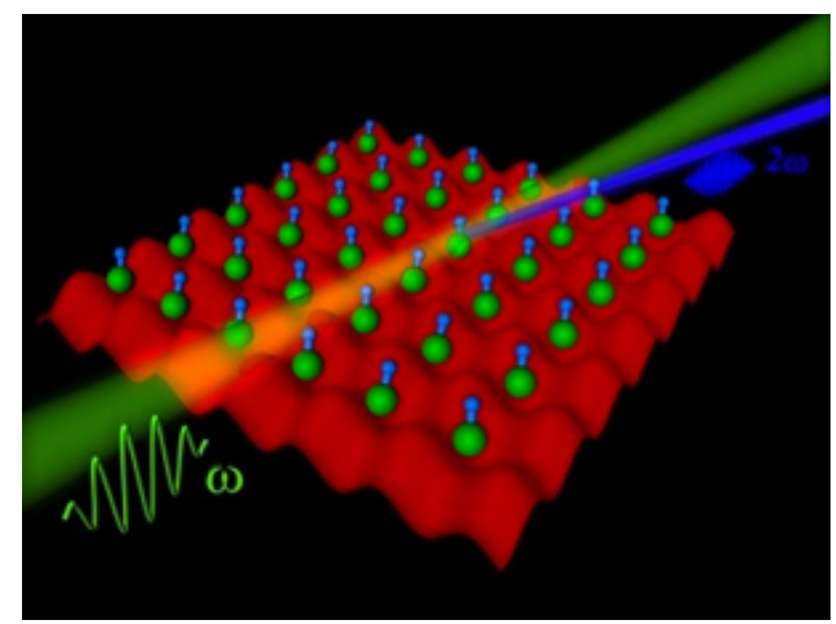
- Euclidean space
- high-lying states difficult
- signal-to-noise
- severe limitations for real-time or inelastic collisions or fragmentation

Quantum Computing

- real-time Minkowski space evolution
- exponentially-large Hilbert spaces
- S-matrix
- mitigated sign problem(s) (naively)
- integrals over phases

“First Qubits” for Scientific Applications



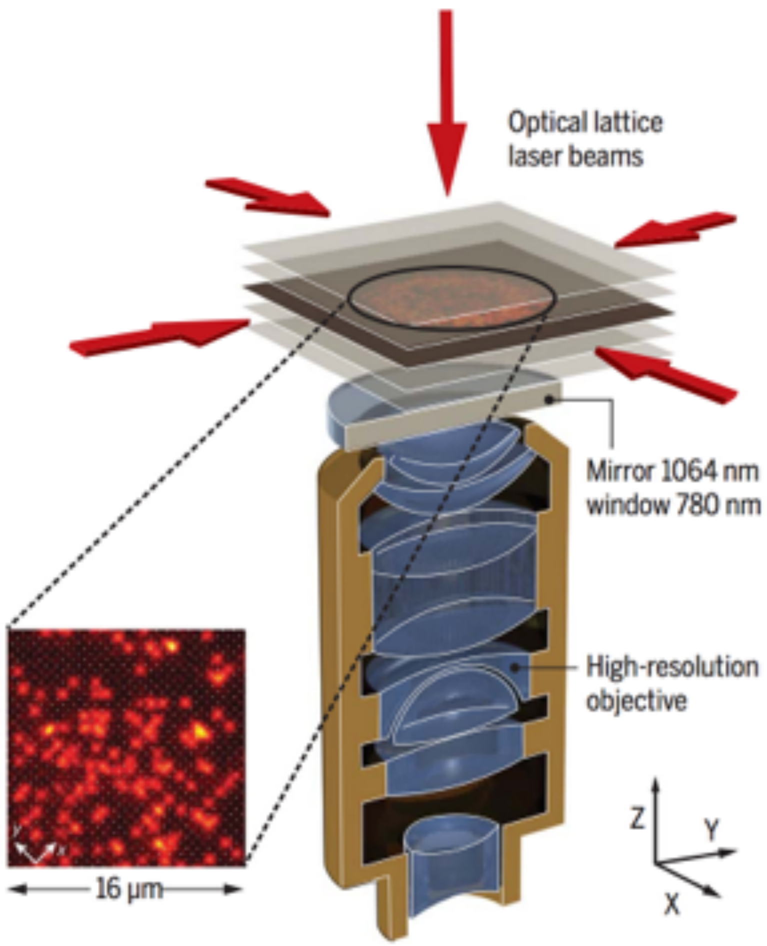


Hemmerling, Cornel, https://www.photonics.com/Article.aspx?AID=64150

NISQ-era quantum devices for applications

Analog, Digital and Hybrid Simulation

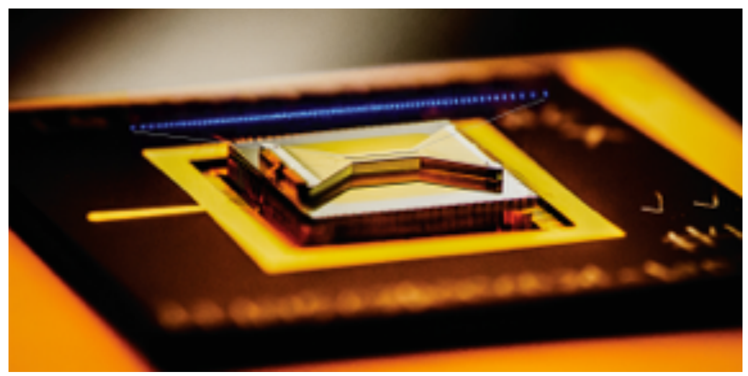
analog simulations

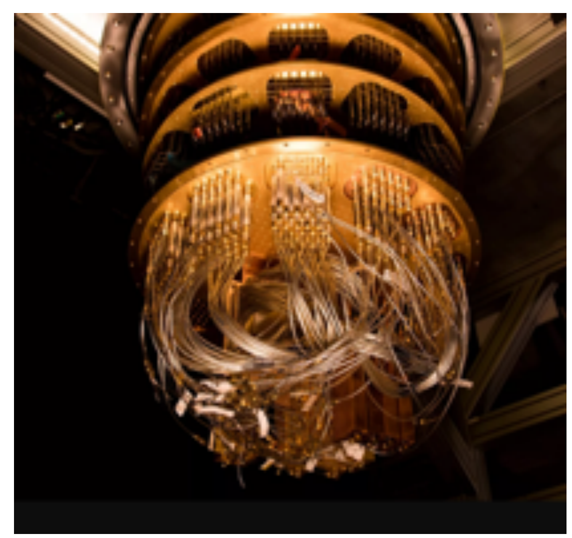


H : native to system
e.g. atoms in optical lattices
SRF cavities
BECs

systematics?

digital computations





e.g. trapped-ions,
superconducting qubits
H : universal gate sets

NISQ, a while before error-corrected

Hybrid

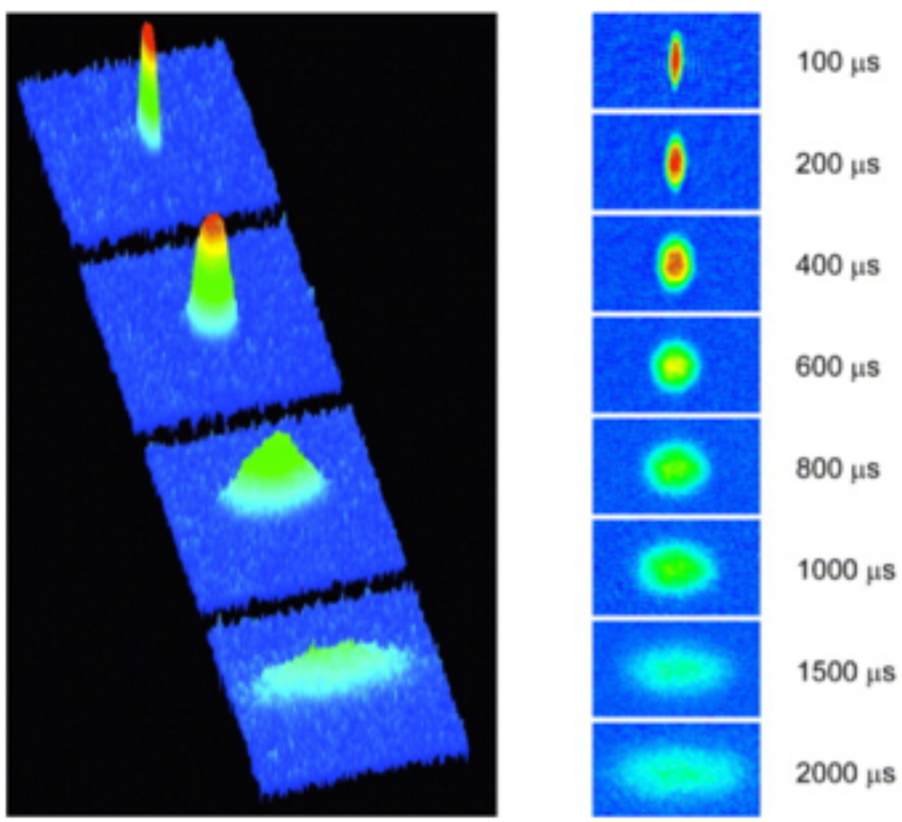
QPU “like” a GPU
for the intrinsically
quantum parts of the
computation

Scaling?

Analog Simulation (classic) examples

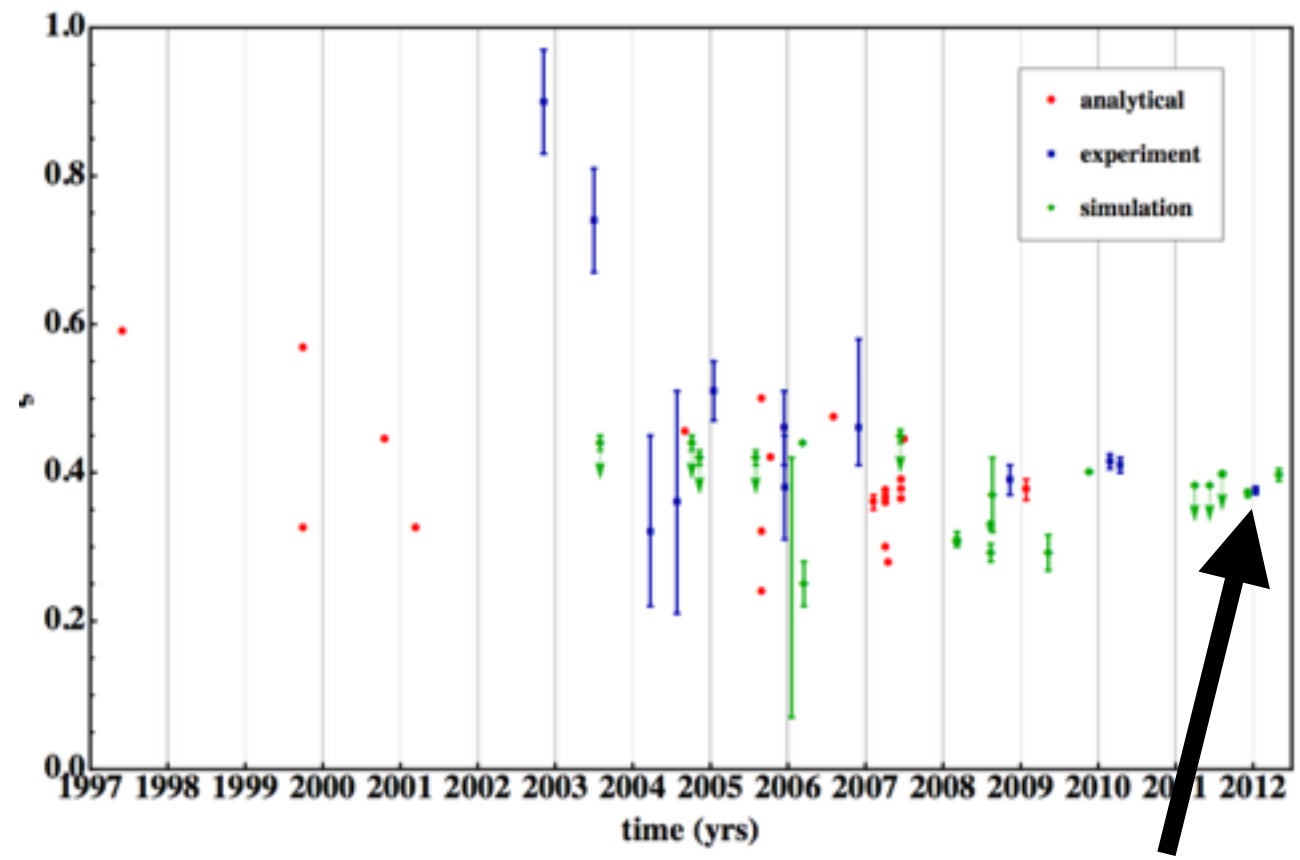
Allan Adams1, Lincoln D Carr2,3,6, Thomas Schäfer4, Peter Steinberg5 and John E Thomas4

Published 19 November 2012 • IOP Publishing and Deutsche Physikalische Gesellschaft
New Journal of Physics, Volume 14, November 2012



Elliptic flow

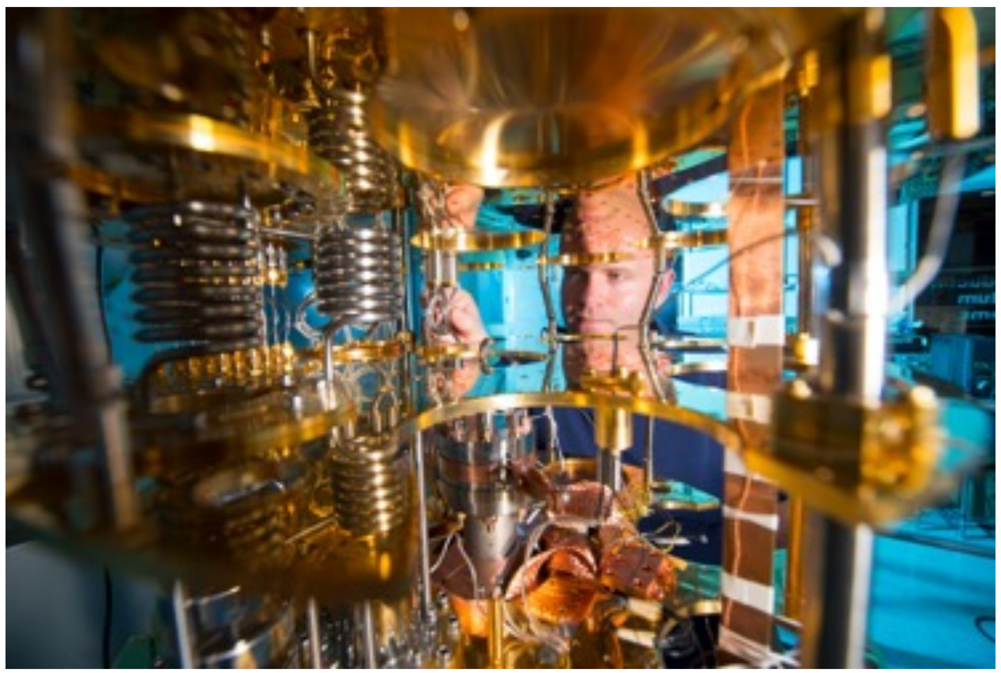
Endres *et al*, arXiv:1203.3169

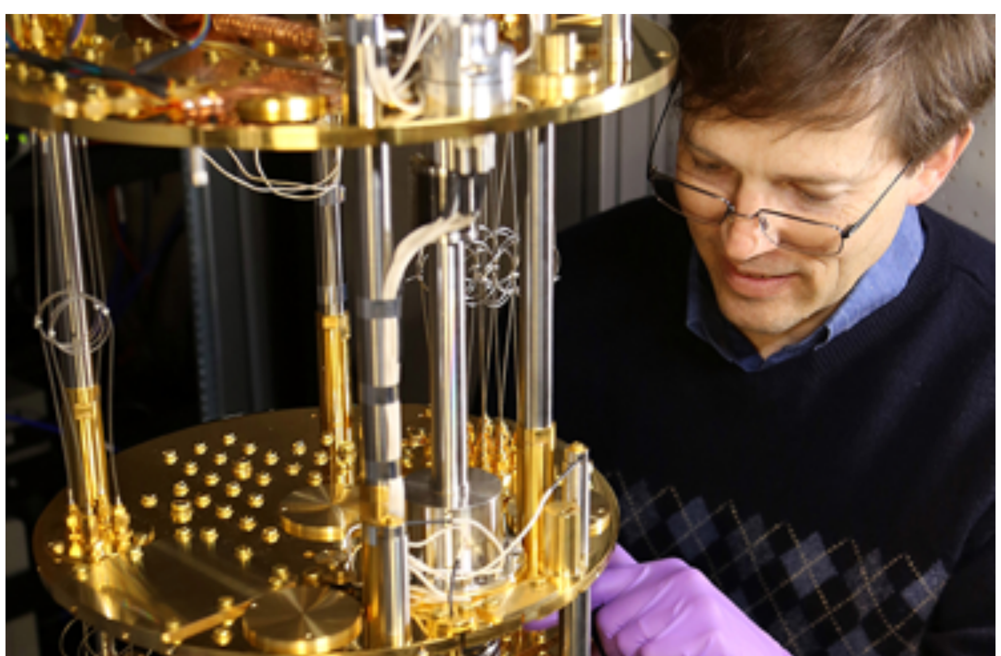


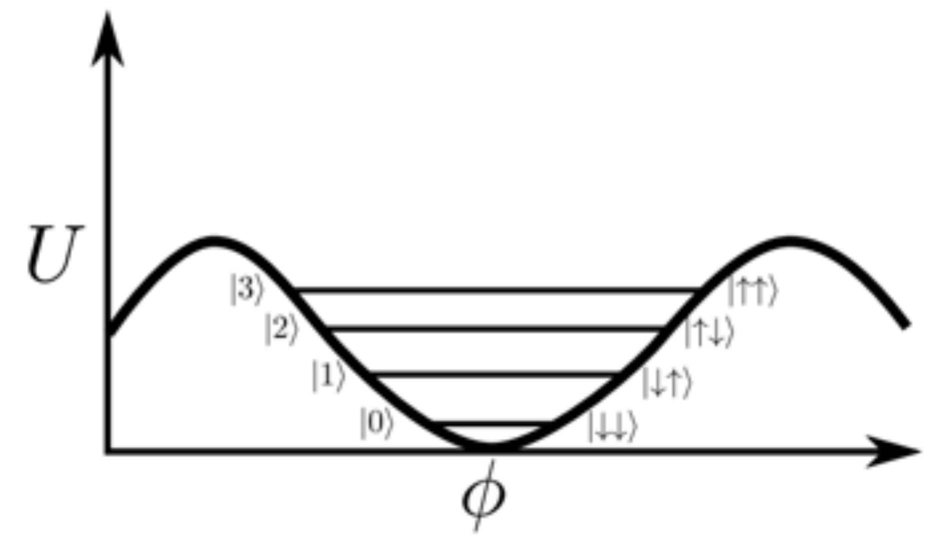
cold atom simulation

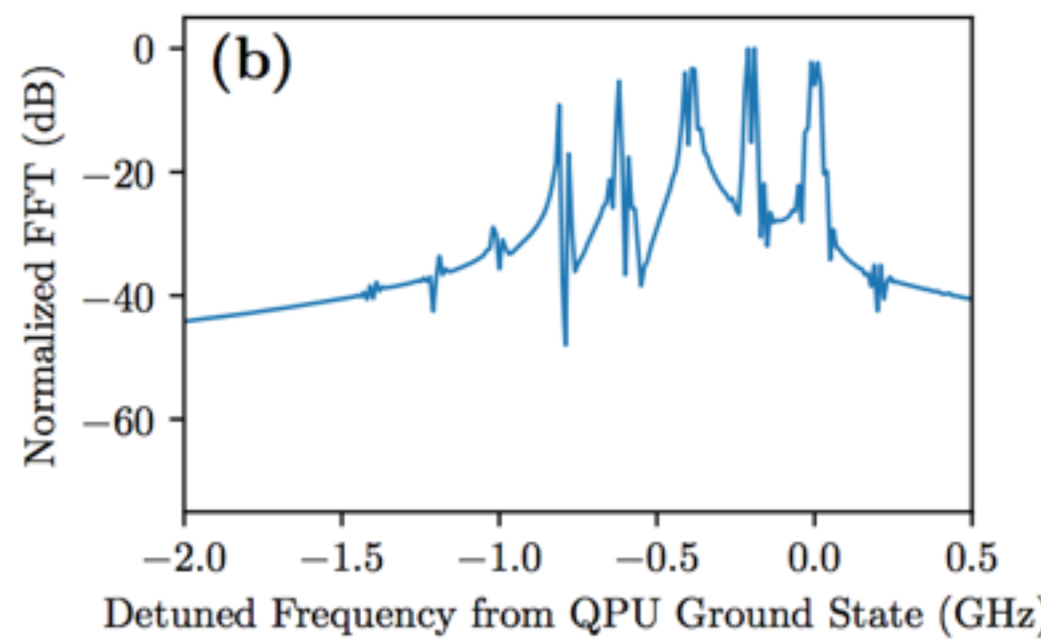
Analog Simulation examples
SRF cavities

LLNL and FermiLab









Toward nuclear reactions and field theory

Analog Simulation : Quantum Field Theory - ideas

Simulating Lattice Gauge Theories within Quantum Technologies

M.C. Bañuls[1,2], R. Blatt[3,4], J. Catani[5,6,7], A. Celi[3,8], J.I. Cirac[1,2], M. Dalmonte[9,10], L. Fallani[5,6,7], K. Jansen[11], M. Lewenstein[8,12,13], S. Montangero[7,14 a], C.A. Muschik[3], B. Reznik[15], E. Rico[16,17 b], L. Tagliacozzo[18], K. Van Acoleyen[19], F. Verstraete[19,20], U.-J. Wiese[21], M. Wingate[22], J. Zakrzewski[23,24], and P. Zoller[3]

arXiv:1911.00003v1 [quant-ph] 31 Oct 2019

Towards analog quantum simulations of lattice gauge theories with trapped ions

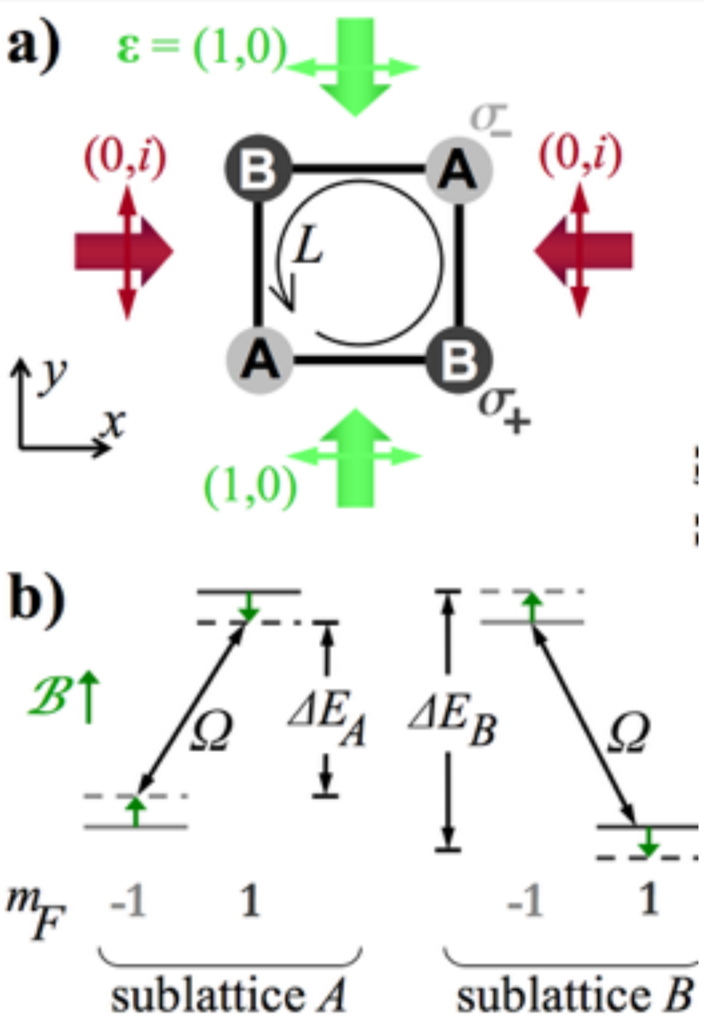
Zohreh Davoudi,[1,2,*] Mohammad Hafezi,[3,4] Christopher Monroe,[3,5] Guido Pagano,[3,5] Alireza Seif,[3] and Andrew Shaw[1]

arXiv:1908.03210v1 [quant-ph] 8 Aug 2019

Quantum Link Models
(see Schladaming lectures by Uwe-Jens Wiese, 2015)

A Framework for Simulating Gauge Theories with Dipolar Spin Systems

Di Luo,[1,2,*] Jiayu Shen,[1,*] Michael Highman,[1] Bryan K. Clark,[1,2] Brian DeMarco,[1] Aida X. El-Khadra,[1] and Bryce Gadway[1]
[1] Department of Physics and IQUIST, University of Illinois at Urbana-Champaign, IL 61801, USA
[2] Institute for Condensed Matter Theory, University of Illinois at Urbana-Champaign, IL 61801, USA



Hauke et al

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

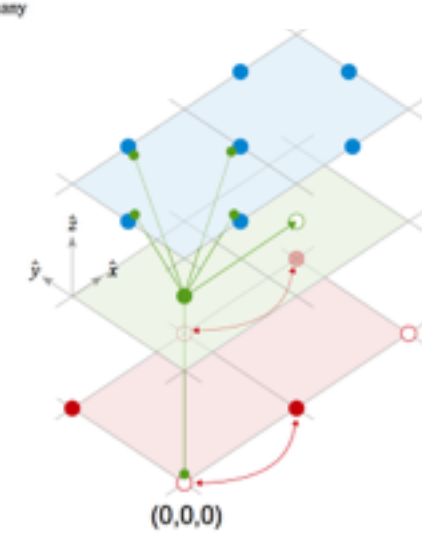


Figure 23: Different atomic species reside on different vertical layers. Green straight lines show how the auxiliary atoms have to move in order to realise interactions with the link atoms and the fermions, or to enter odd plaquettes. Red arrows show selective tunnelling of fermions across even horizontal links. From [152].

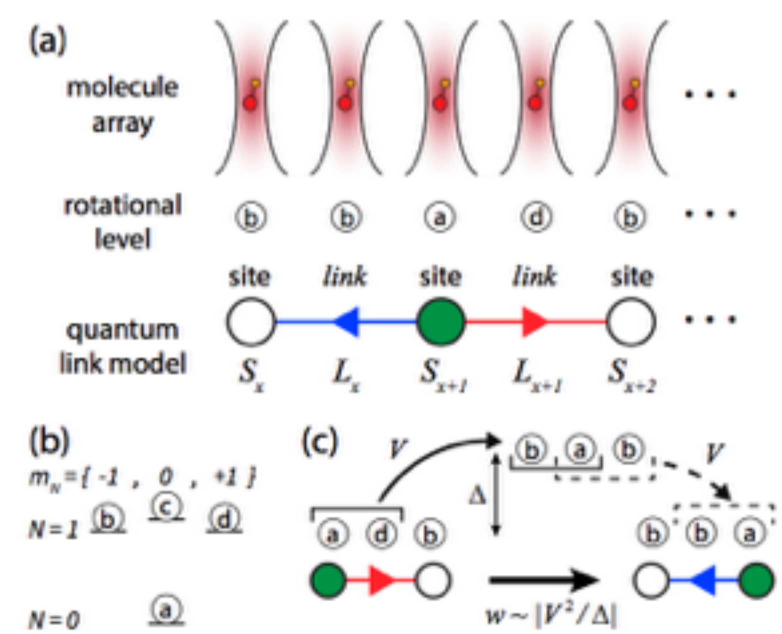
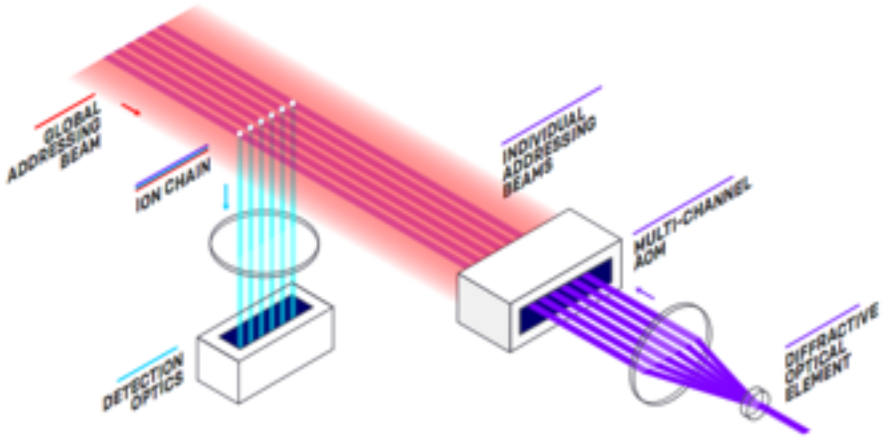


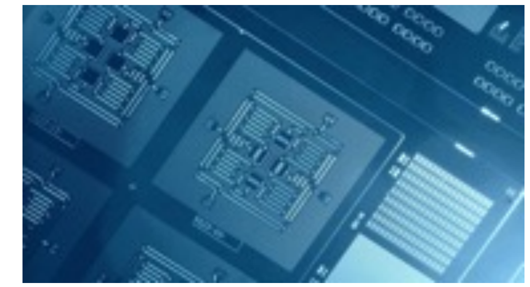
Figure 1. **Emulating quantum link models (QLMs) with arrays of dipolar molecules.** (a) Mapping between the rotational levels of molecules in an array and the sites and links of the QLM for spin $S = 1/2$. The designation of particular molecules as sites or links (S_x, L_x, S_{x+1}, L_{x+1} for a given unit cell) is enforced through local laser control of level-dependent light shifts. (b) Low-lying molecular rotational levels $|N, m_N\rangle$ and their redefinition in terms of states $|a\rangle$, $|b\rangle$, $|c\rangle$, and $|d\rangle$. (c) The hopping of "fermions" between sites and the associated spin operations on the links are realized by a second-order dipolar exchange of rotational excitations.

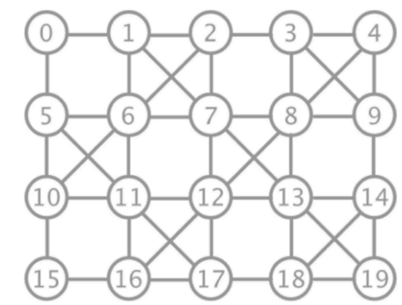
Digital Simulation



UMD/IonQ benchmarked
all-to-all 11 qubits 2018

Innesbruck - 20 qubits
Nature 2019



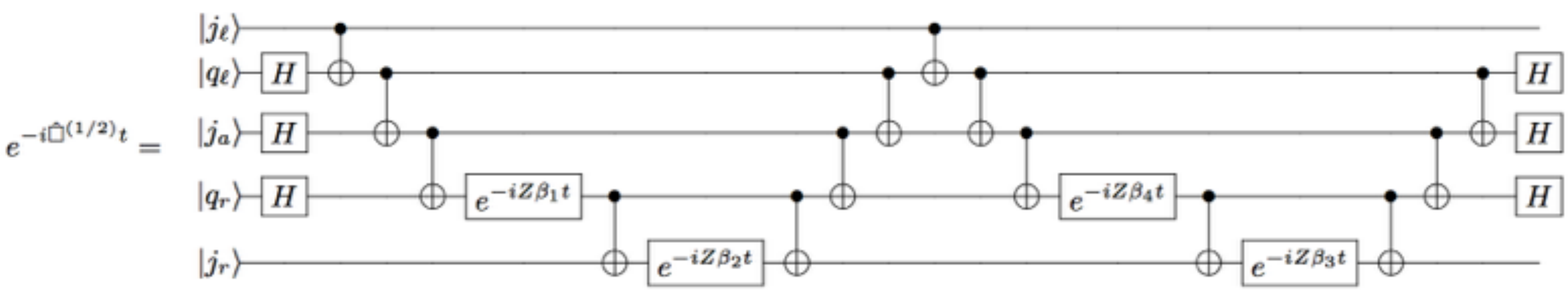


Average measurements	
Frequency (GHz)	4.97
T1 (μs)	89.59
T2 (μs)	58.66
Gate error (10^{-3})	1.84
Readout error (10^{-2})	8.38

IBM Q 20 Tokyo (20-qubits) — Modified from source

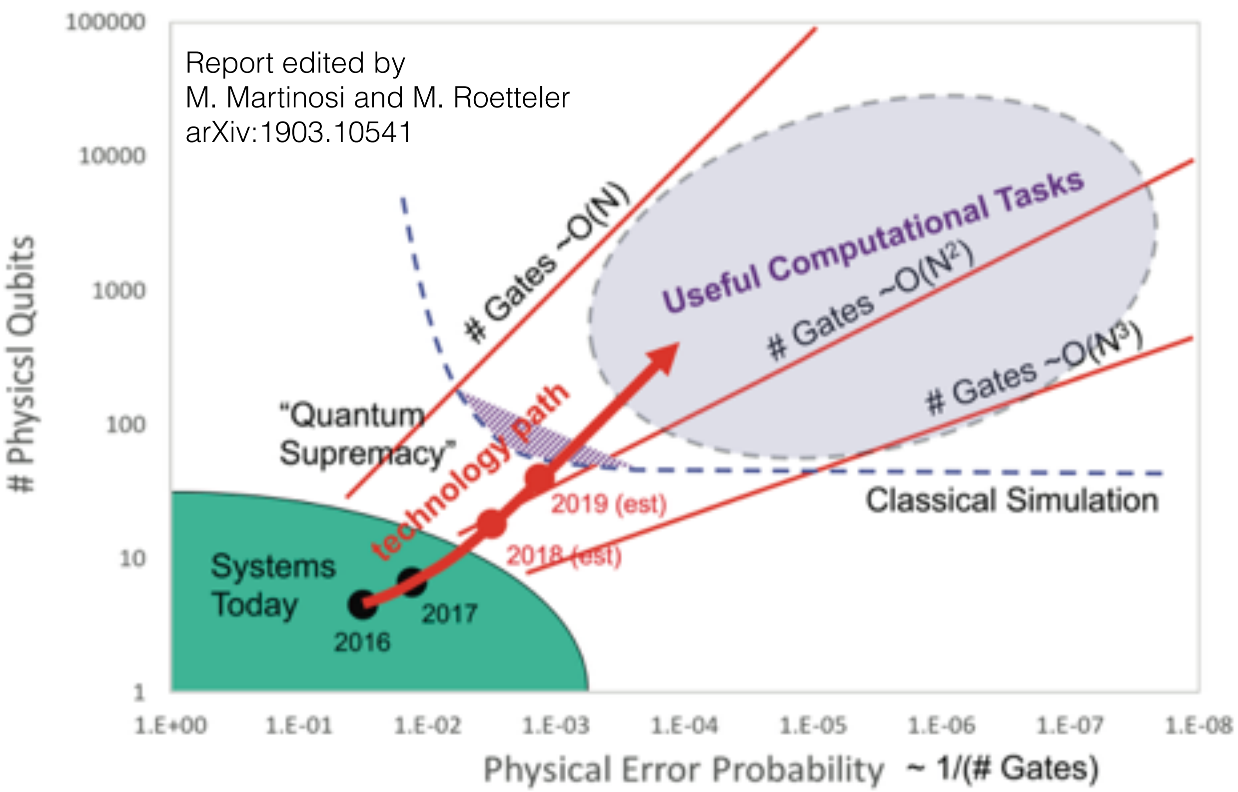
Unitary operations implemented through quantum circuits using a set of gates

e.g., entangling gate
CNOT(1;2) = $\Lambda_0 \otimes I + \Lambda_1 \otimes \sigma_x$



https://www.extremetech.com/extreme/204553-ibm-gets-closer-to-real-quantum-computing
https://medium.com/@jonathan_hui/qc-how-to-build-a-quantum-computer-with-superconducting-circuit-4c30b1b296cd

Digital Simulation



First Steps being taken
to understand our problems

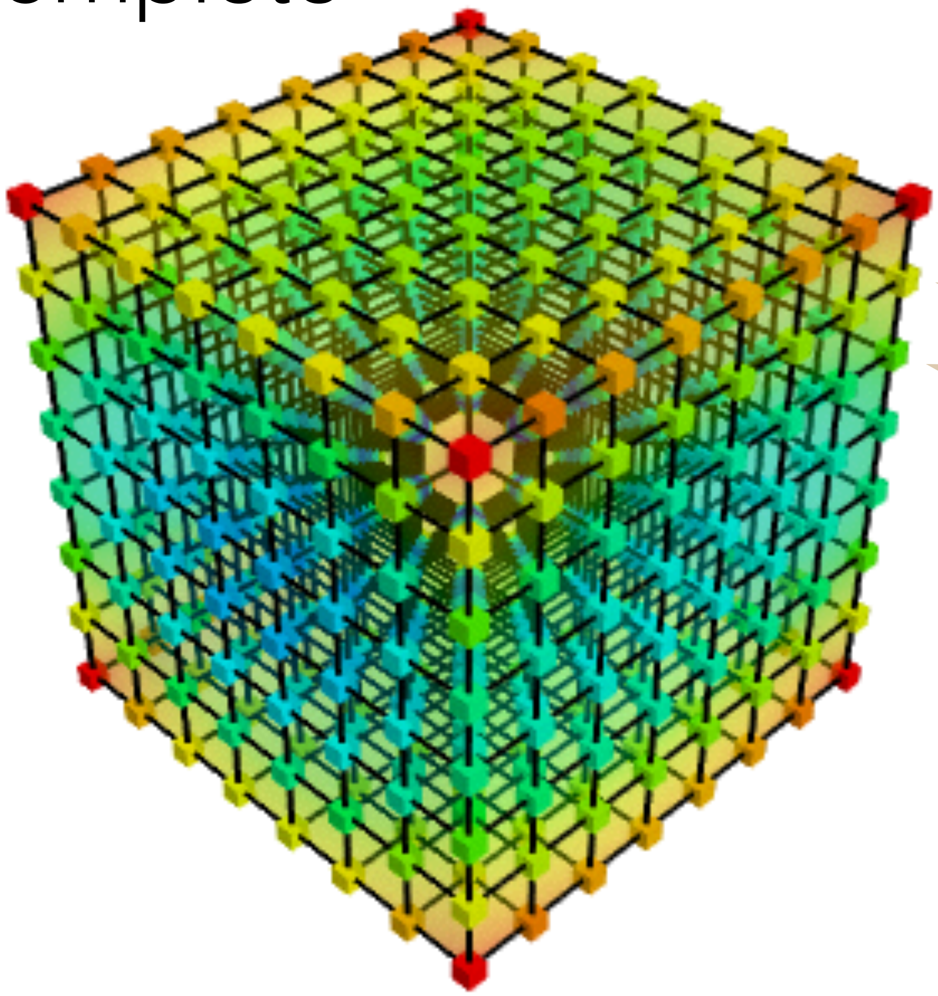
- Minimal or no error correction
- Few hundred qubits with modest gate depth
- Imperfect quantum gates/operations - like ``running experiments''
- Different ``flavors''
- NISQ-era is the next decade of quantum simulation
  - much to be gained during this period
  - learn by doing - just like all experiments
- Searching to find Quantum Advantage(s) in scientific applications

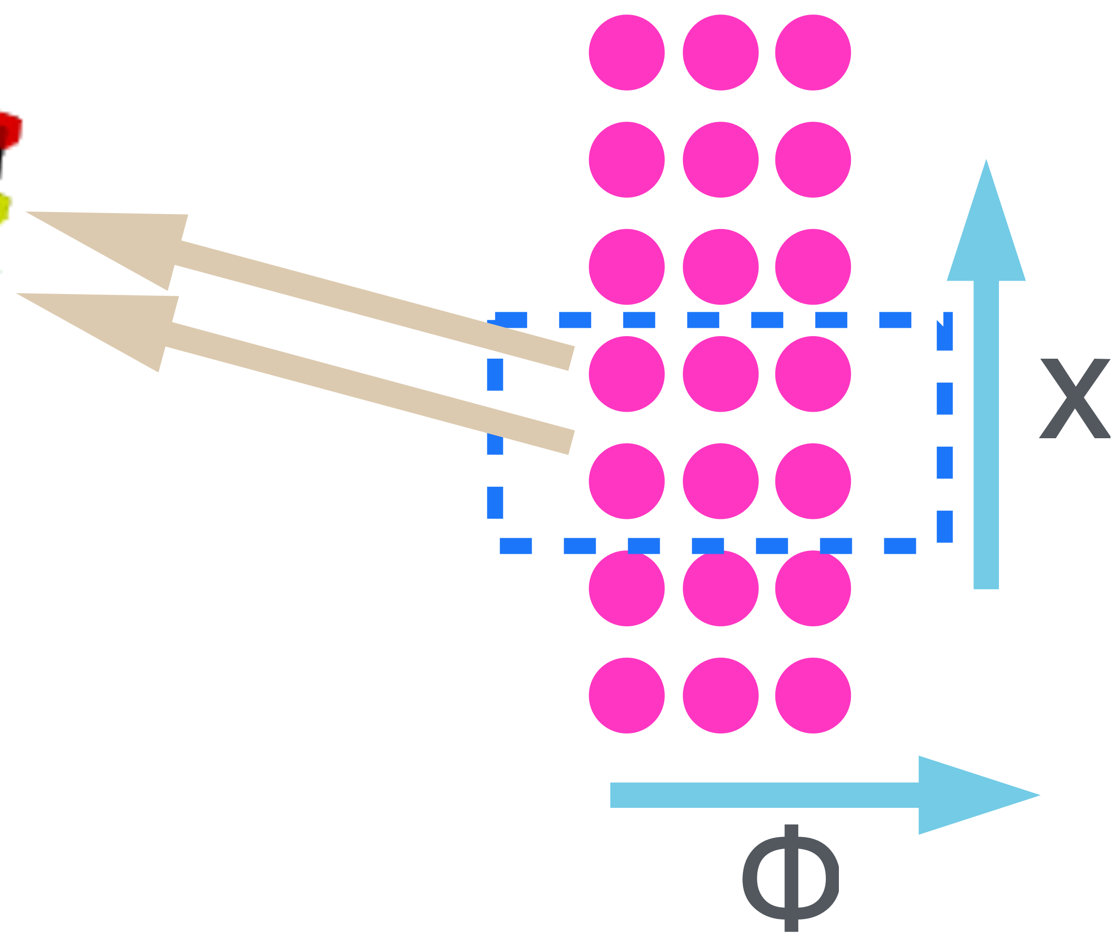
Generically, 3 "workflow phases"

1. **state preparation** - generally, entangled
2. **time-evolution** - Trotterized evolution operator
3. **measurement**

Scalar Field Theory
The Gold Standard - Jordan, Lee, Preskill

BQP-complete





- Discretize 3-d Space
- Define Hamiltonian on grid
- Trotterized time evolution
- Technology transfer from Lattice QCD
- Digitize field(s)

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

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

$$\hat{H}_\phi = b\sum_x \left(\frac{1}{2}\phi_j\phi_{j+1} + \frac{1}{2}\phi_j\phi_{j-1} - \phi_j^2 + \frac{1}{2}m^2\phi_j^2 + \frac{\lambda}{4!}\phi_j^4 \right)$$

Scattering Wavepackets in Scalar Field Theory

Quantum Computation of Scattering in Scalar Quantum Field Theories

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

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

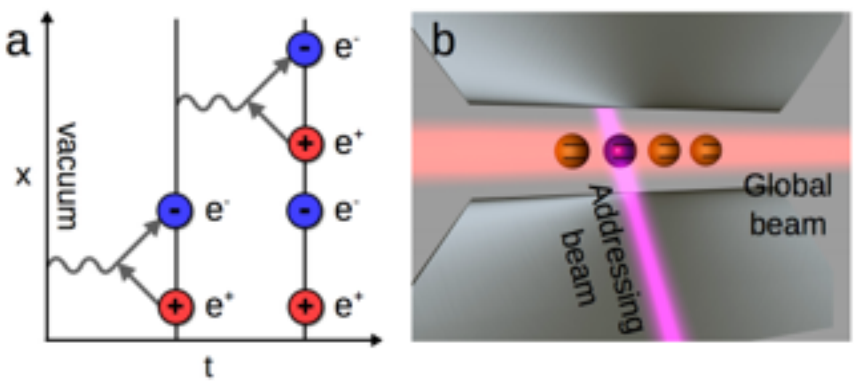
Digital Simulation
Dynamics in the Schwinger Model
Baby steps using small, 1dim systems

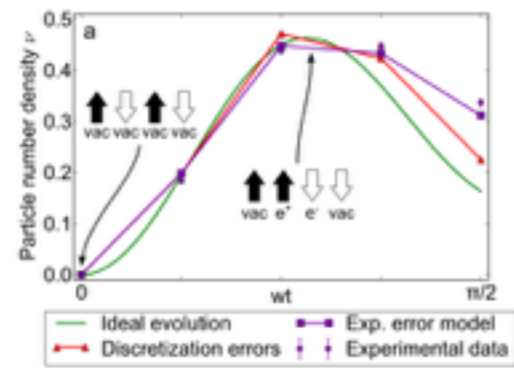
Real-time dynamics of lattice gauge theories with a few-qubit quantum computer

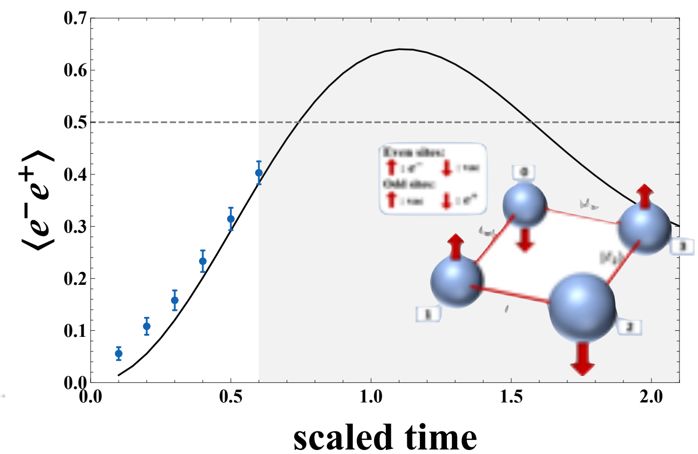
Esteban A. Martinez,[1,*] Christine Muschik,[2,3,*] Philipp Schindler,[1] Daniel Nigg,[1] Alexander Erhard,[1] Markus Heyl,[2,4] Philipp Hauke,[2,3] Marcello Dalmonte,[2,3] Thomas Monz,[1] Peter Zoller,[2,3] and Rainer Blatt[1,2]

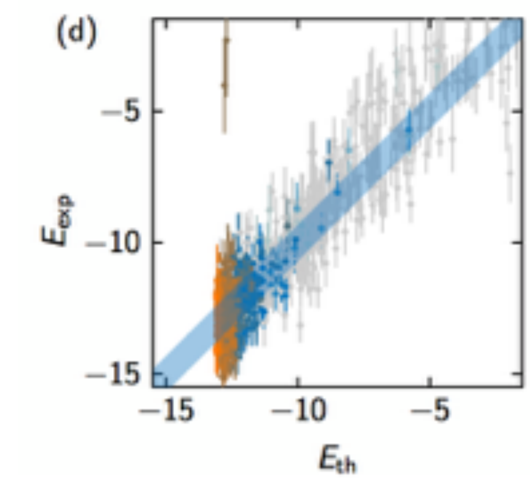
(2016)

1+1 dim QED





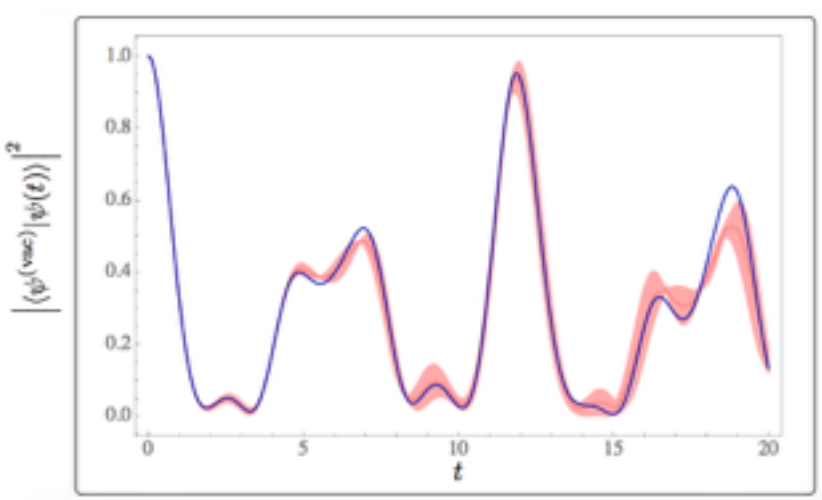




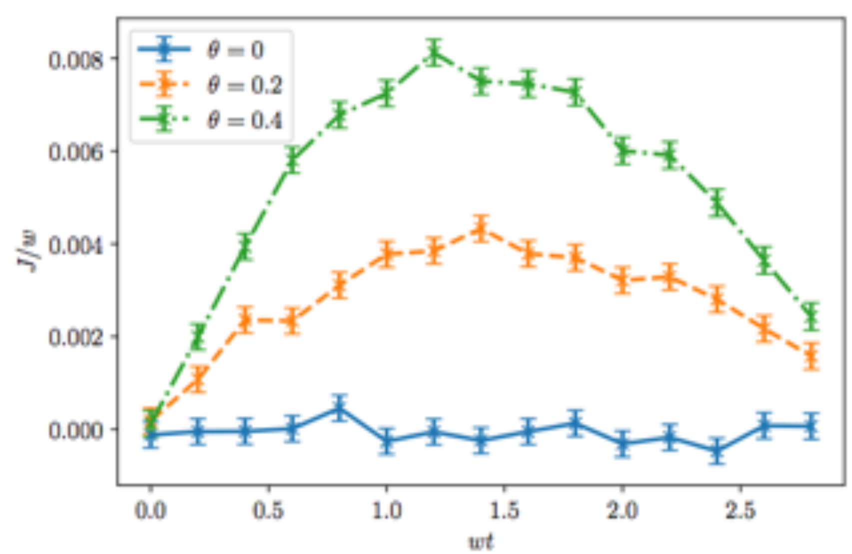
Innesbruck

ORNL-Washington-Basque

Innesbruck

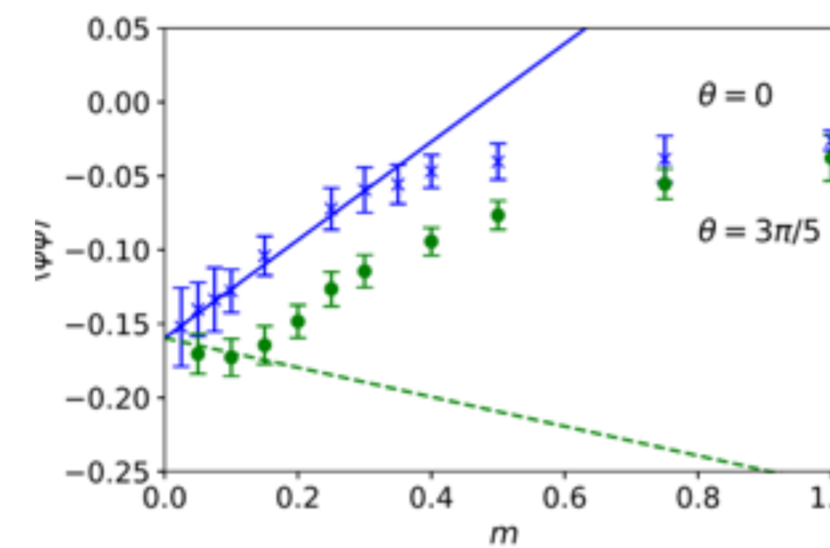


Maryland



(a) $M/w = 0.1$

BNL-Stonybrook



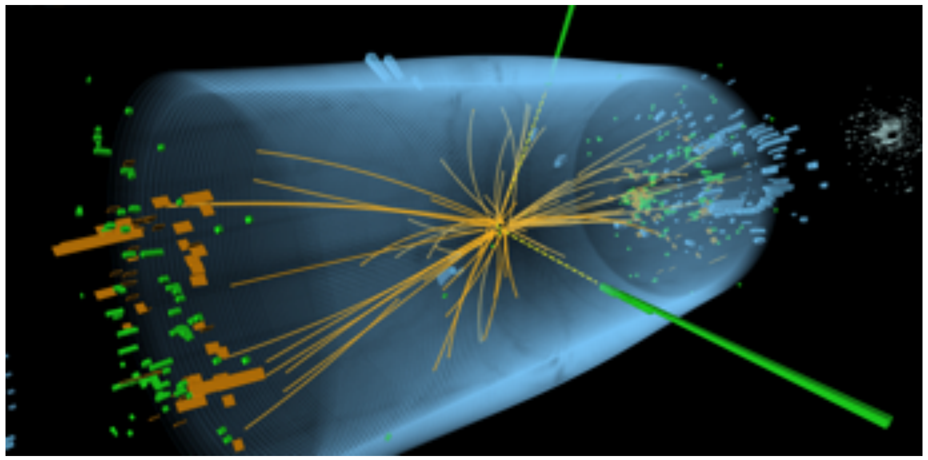
BNL-Oxford

Quantum Algorithms for Simulating the Lattice Schwinger Model

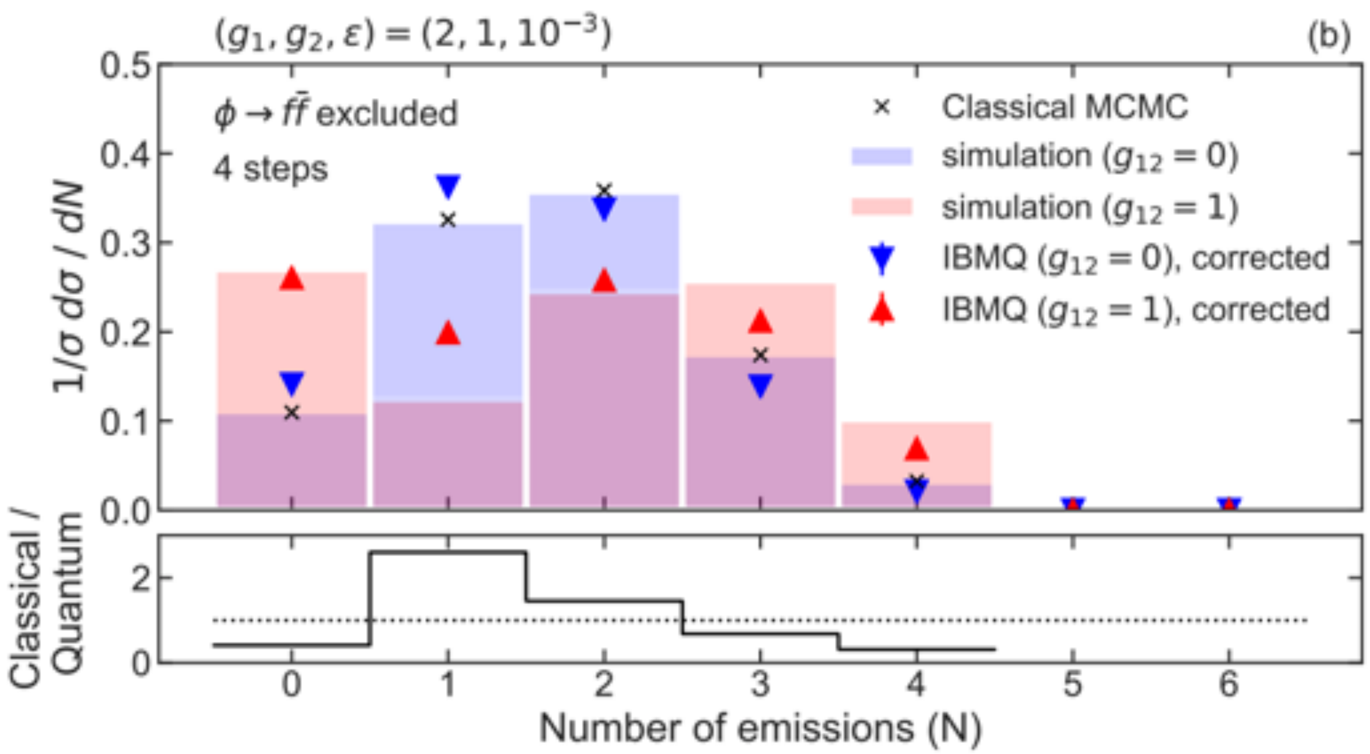
Shaw, Alexander F.[1], Lougovski, Pavel[1], Stryker, Jesse R.[2], and Wiebe, Nathan[3,4]

arXiv:2002.11146v1 [quant-ph]

Digital Simulation Examples



Towards fragmentation and hadronic structure



A quantum algorithm for high energy physics simulations

Christian W. Bauer, Wibe A. de Jong, Benjamin Nachman, Davide Provasoli, arXiv:1904.03196 [hep-ph]

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

Deeply inelastic scattering structure functions on a hybrid quantum computer

Niklas Mueller,* Andrey Tarasov,† and Raju Venugopalan‡
Physics Department, Brookhaven National Laboratory, Bldg. 510A, Upton, NY 11973, USA
(Dated: August 21, 2019)

Parton Physics on a Quantum Computer

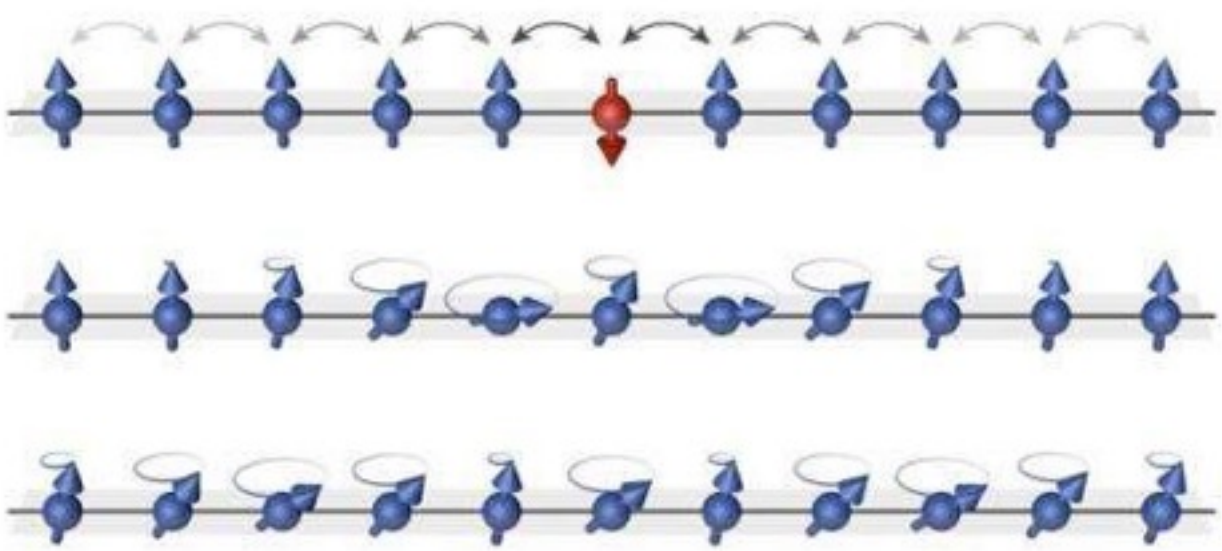
Henry Lamm,[1,*] Scott Lawrence,[1,†] and Yukari Yamauchi[1,‡]
(NuQS Collaboration)
[1] *Department of Physics, University of Maryland, College Park, Maryland 20742, USA*
(Dated: February 18, 2020)

Digital Simulation
The role of spin models
HEP Sandbox

e.g.

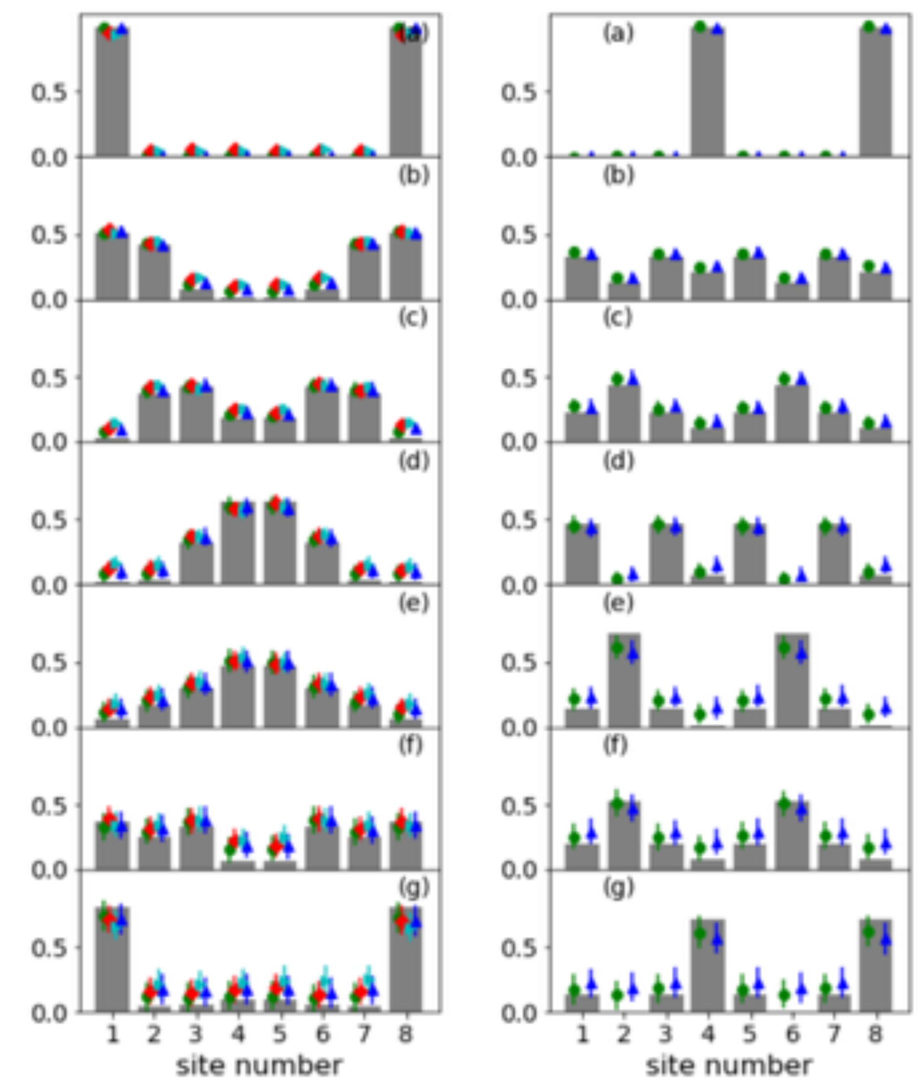
From spin chains to real-time thermal field theory using tensor networks

Mari Carmen Bañuls,[1,2,*] Michal P. Heller,[3,†] Karl Jansen,[4,‡]
Johannes Knaute,[3,5,§] and Viktor Svensson[6,3,¶]



https://phys.org/news/2013-03-scientists-coherent-propagation-impurity-chain.html

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



(A) open boundary conditions

(B) periodic boundary conditions

Unmuth-Yockey et al.

Matrix Elements
Toward Inelastic Neutrino Nucleus Interactions

Linear Response on a Quantum Computer

Alessandro Roggero* and Joseph Carlson†
Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, U

(Dated: April 13, 2018)

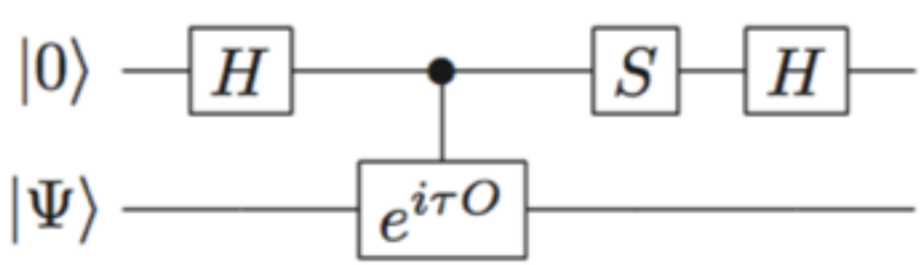
Short-depth circuits for efficient expectation value estimation

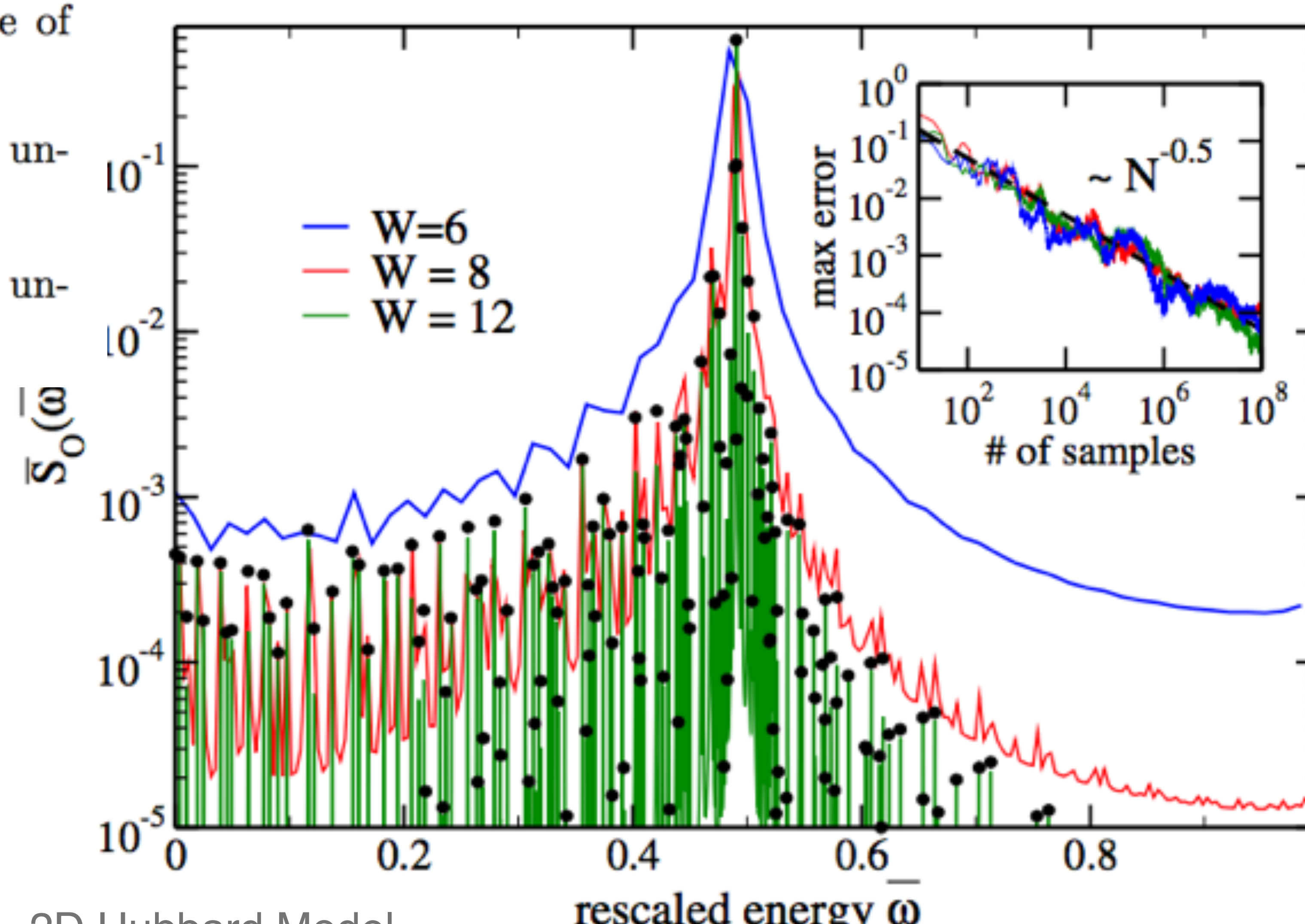
A. Roggero*
Institute for Nuclear Theory, University of Washington, Seattle, WA 98195, USA

A. Baroni†
Department of Physics and Astronomy University of South Carolina, 712 Main Street, Columbia, South Carolina 29208, USA

(Dated: May 22, 2019)

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

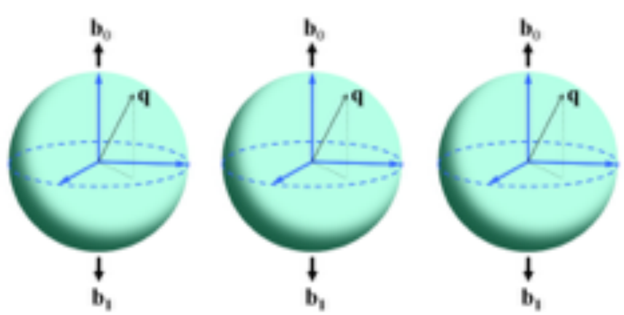


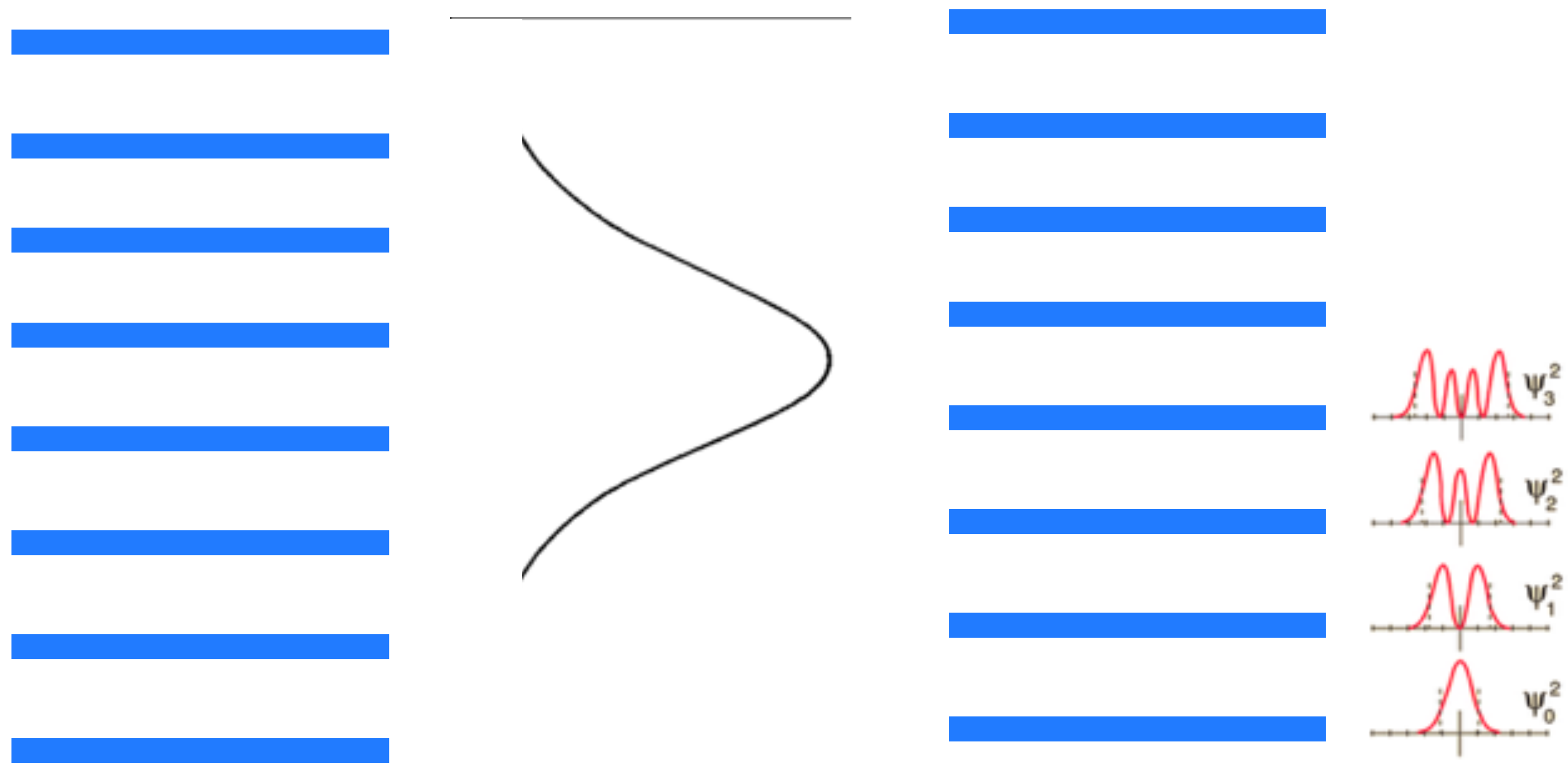


2D Hubbard Model

How to Digitize Scalar Fields

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





Field basis **Harmonic Oscillator**

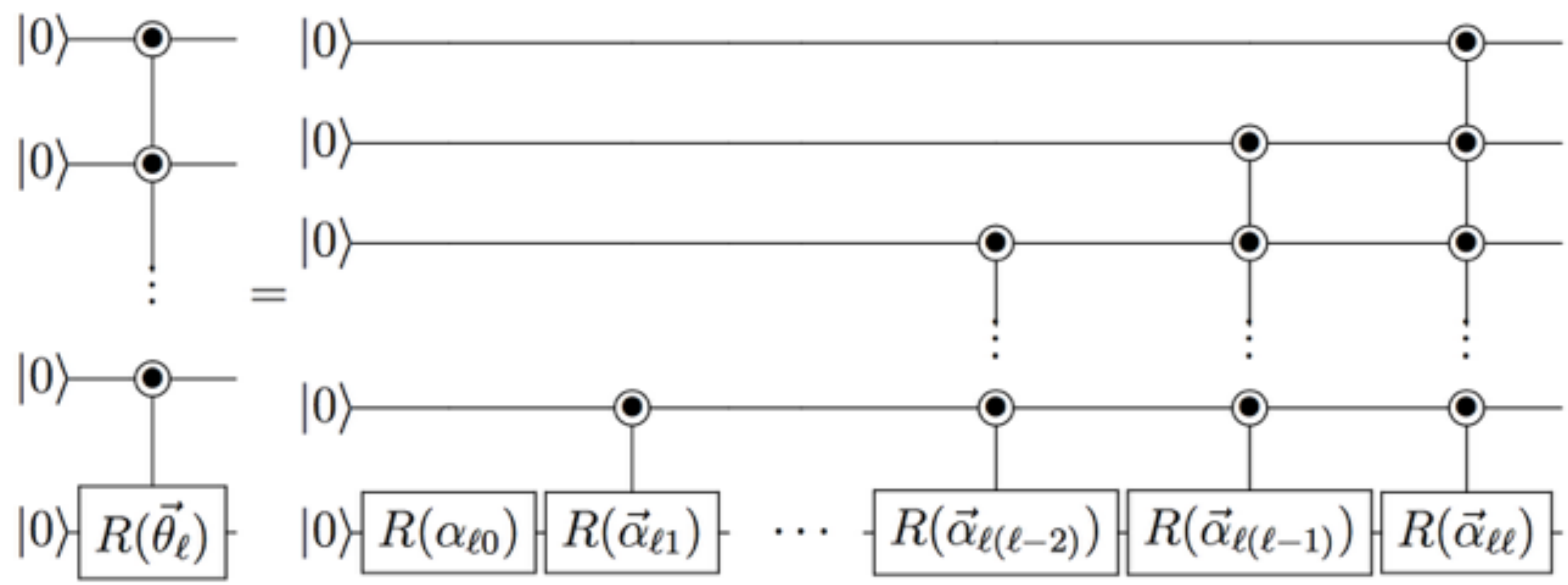
e.g., **3 Qubits = 8 States**

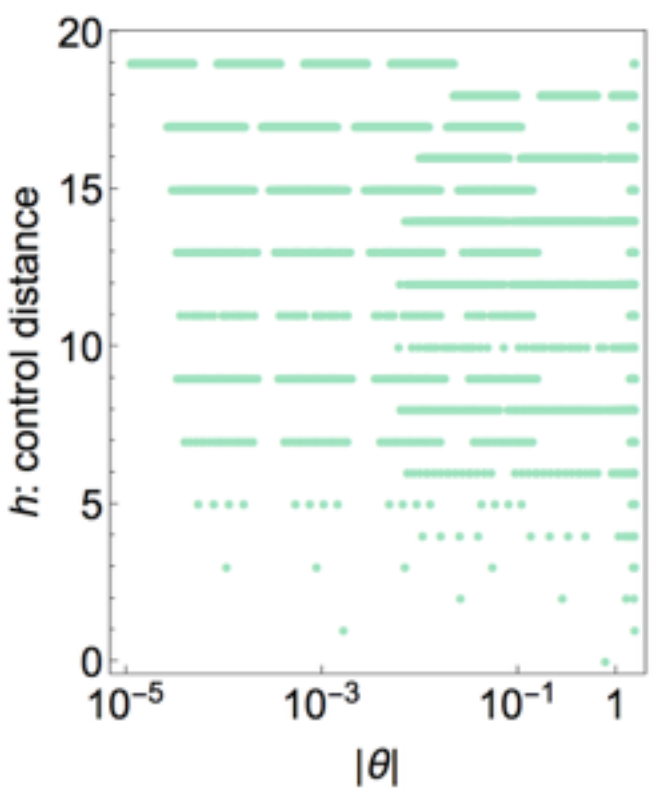
Jordan, Lee and Preskill - several works
Rolanda Somma [LANL]
Macridin, Spentzouris, … [FNAL]
Siopsis, Pooser, …[ORNL/UTK]
Klco,MJS [UW]

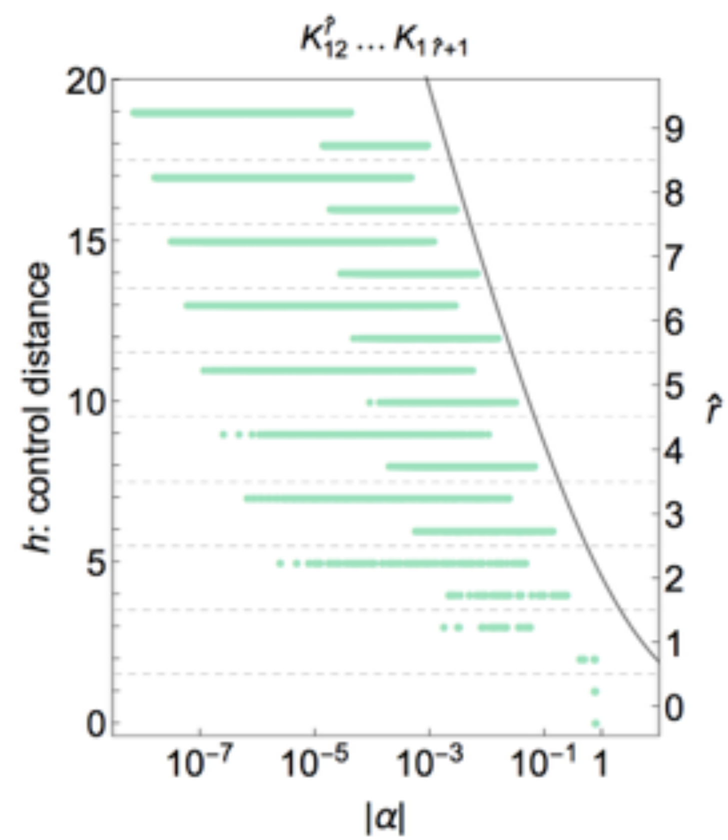
e.g., Gray-encoding
Olivia diMatteo *et al*

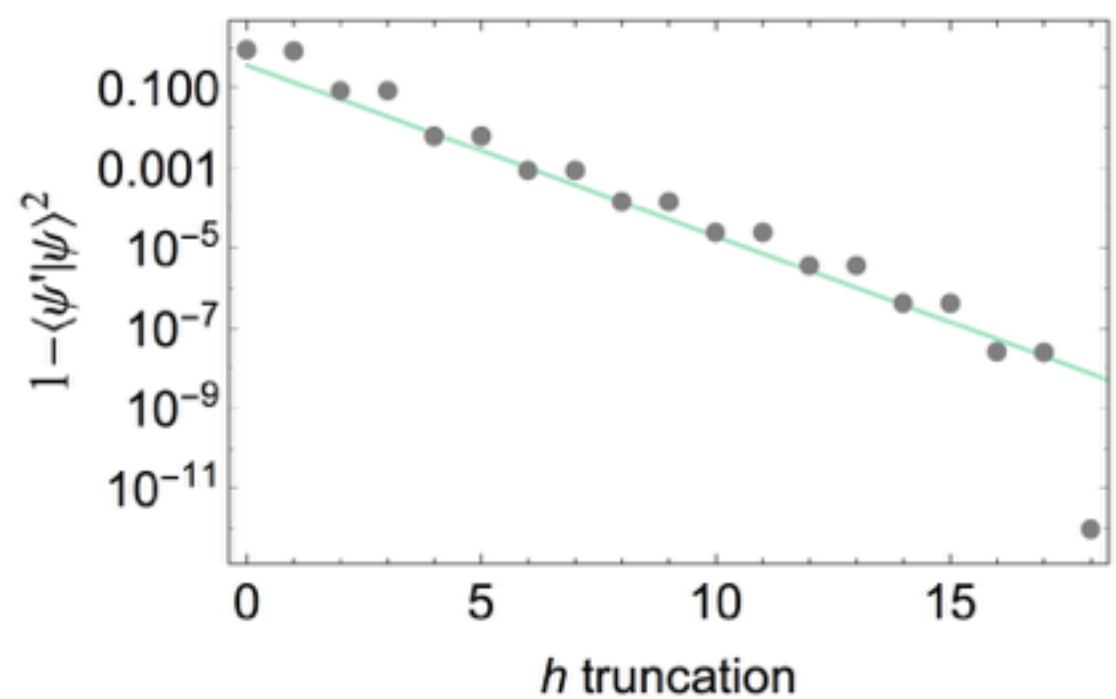
Localized State Preparation and the RG

Natalie Klco and MJS e-Print: 1912.03577 [quant-ph] e-Print: 2002.02018 [quant-ph]



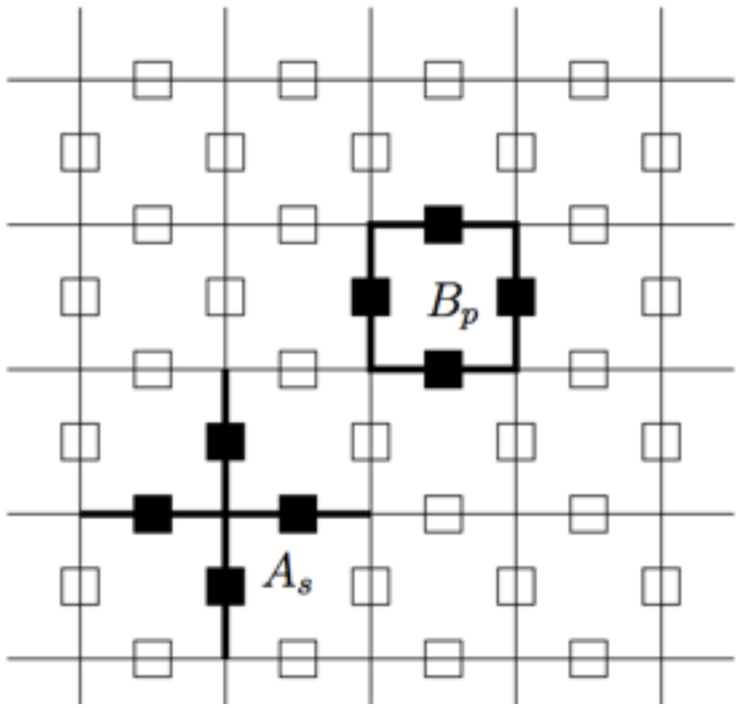


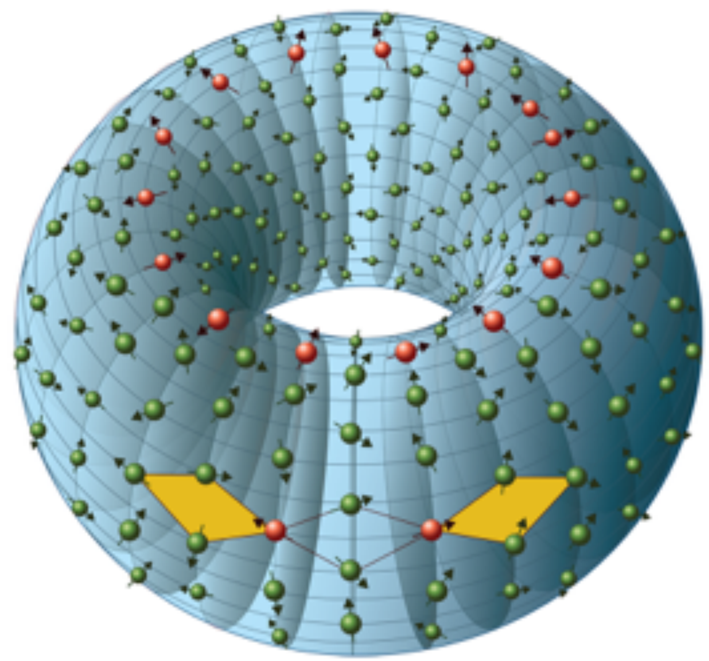




Digital Simulation
Lattice Theories: Logical Qubits and Error Correction

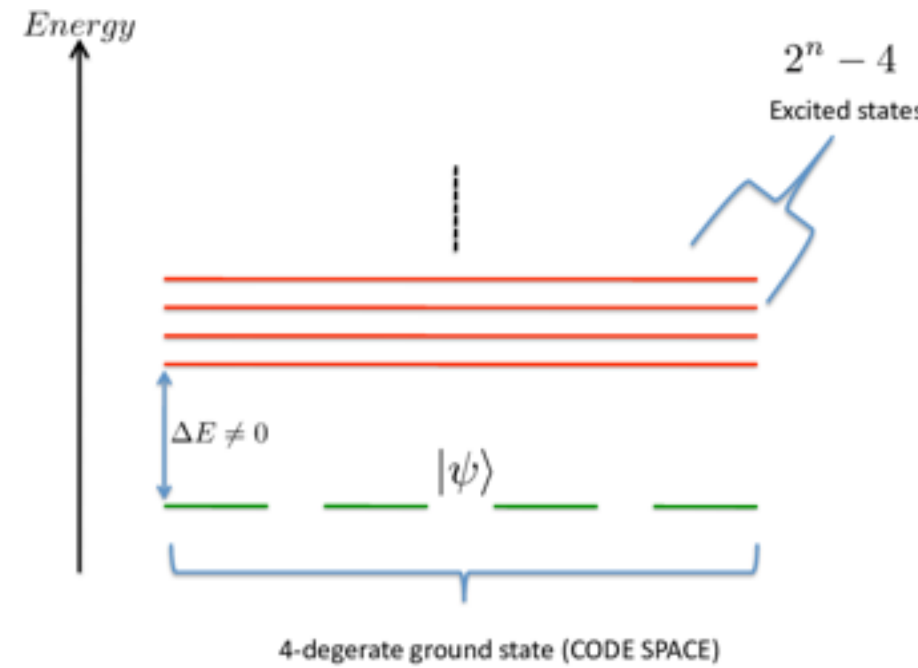
Kitaev (1997)

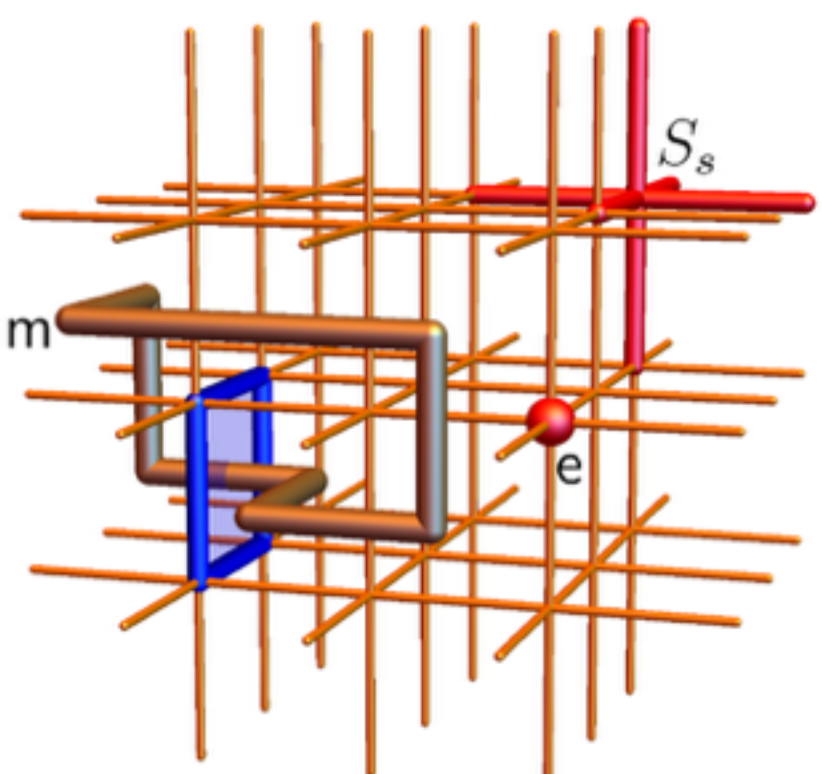




Kitaev-Laumann (2009)

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





Quantum Spin Liquids: a Review

Lucile Savary[1], Leon Balents[2]

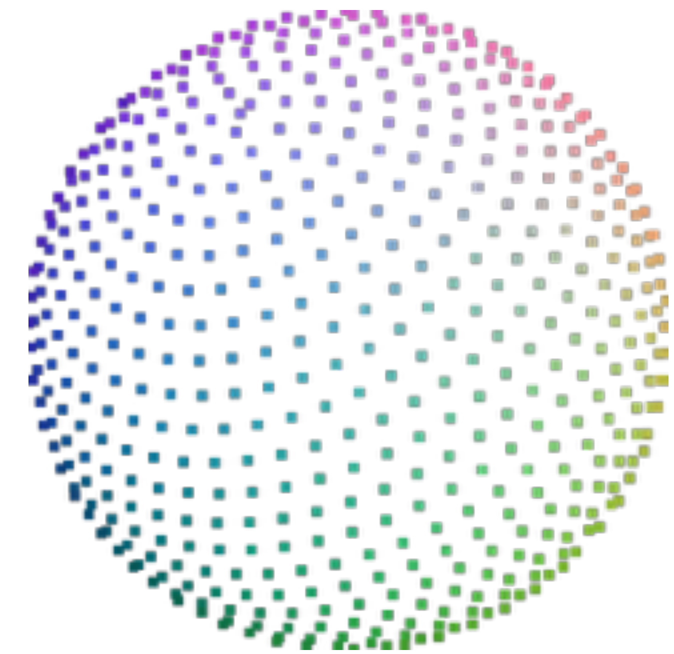
Starting down the Path
Digitizing SU(2) Gauge Theory

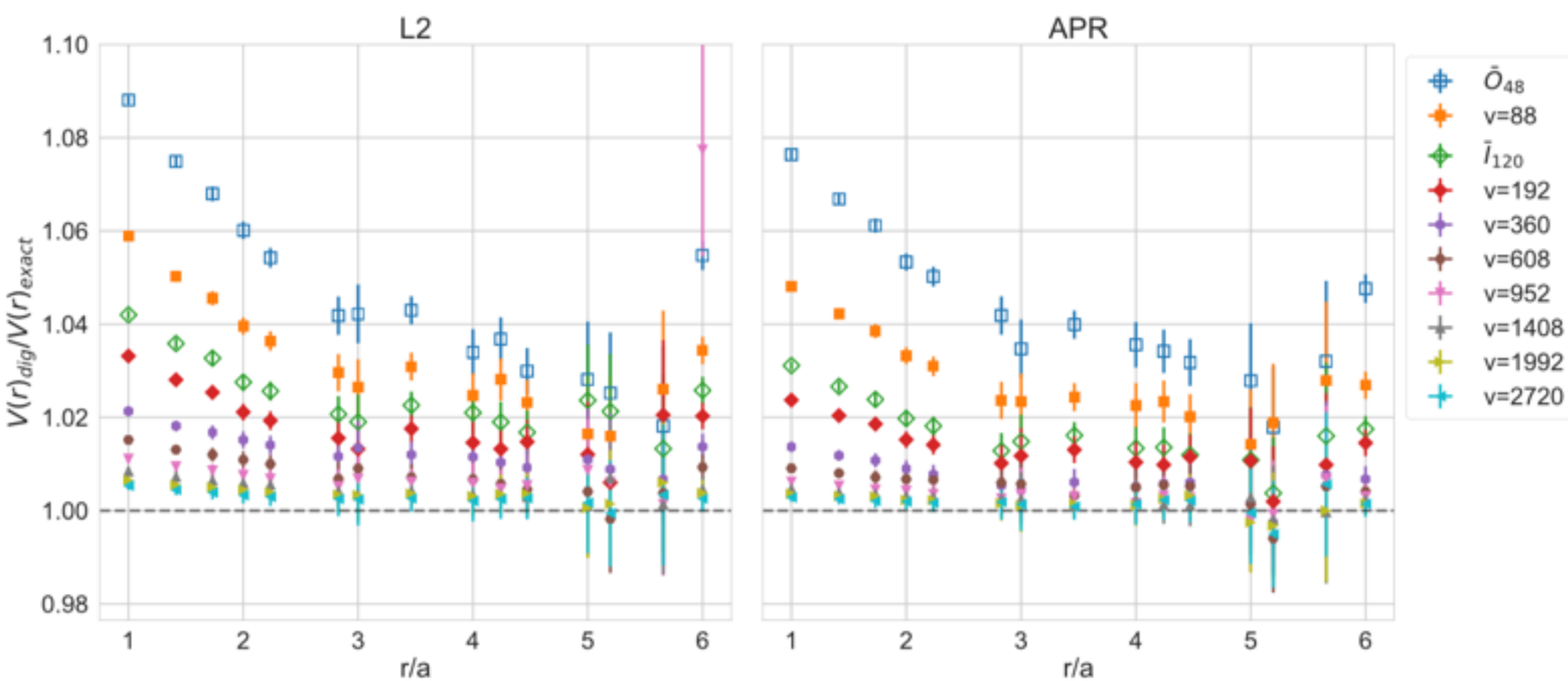
FermiLab

Digitizing Gauge Fields: Lattice Monte Carlo Results for Future Quantum Computers

Daniel C. Hackett,[1,*] Kiel Howe,[2,†] Ciaran Hughes,[2,‡]
William Jay,[1,2,§] Ethan T. Neil,[1,3,¶] and James N. Simone[2,**]

[1]*Department of Physics, University of Colorado, Boulder, Colorado 80309, USA*
[2]*Fermi National Accelerator Laboratory, Batavia, Illinois, 60510, USA*
[3]*RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973, USA*

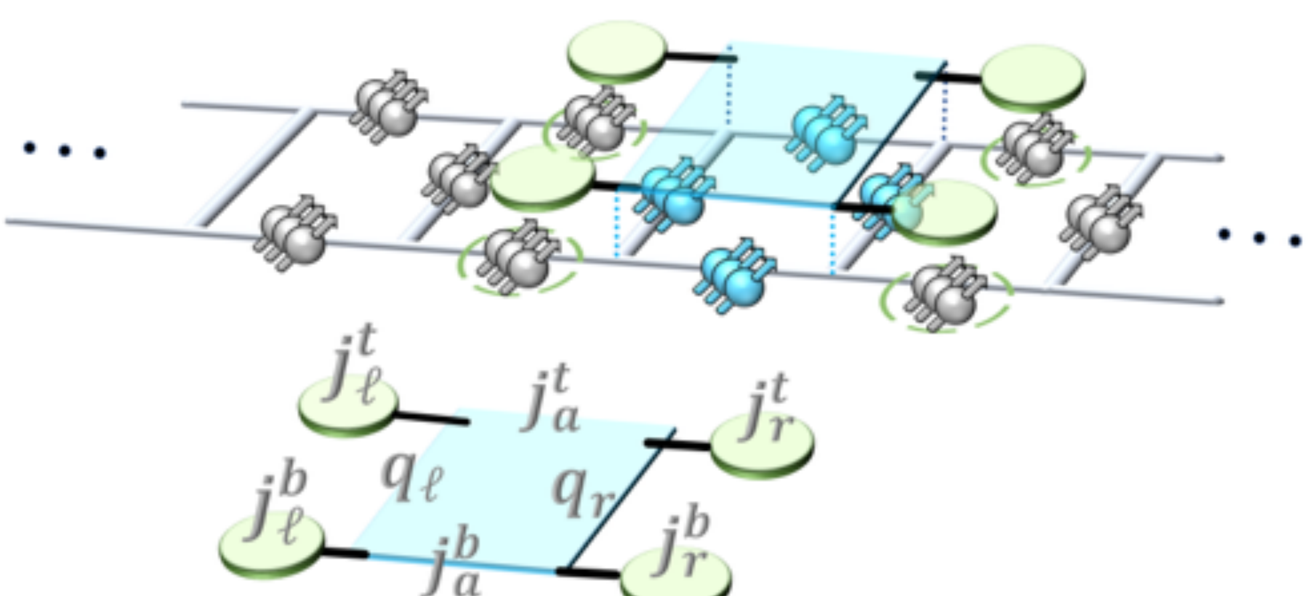




SU(2) Gauge Theory on IBMs Devices
Two plaquettes with j_{max}=1/2 … a toy

Simulating Lattice Gauge Theories within Quantum Technologies

M.C. Bañuls[1,2], R. Blatt[3,4], J. Catani[5,6,7], A. Celi[3,8], J.I. Cirac[1,2], M. Dalmonte[9,10], L. Fallani[5,6,7], K. Jansen[11], M. Lewenstein[8,12,13], S. Montangero[7,14 a], C.A. Muschik[3], B. Reznik[15], E. Rico[16,17 b], L. Tagliacozzo[18], K. Van Acoleyen[19], F. Verstraete[19,20], U.-J. Wiese[21], M. Wingate[22], J. Zakrzewski[23,24], and P. Zoller[3]

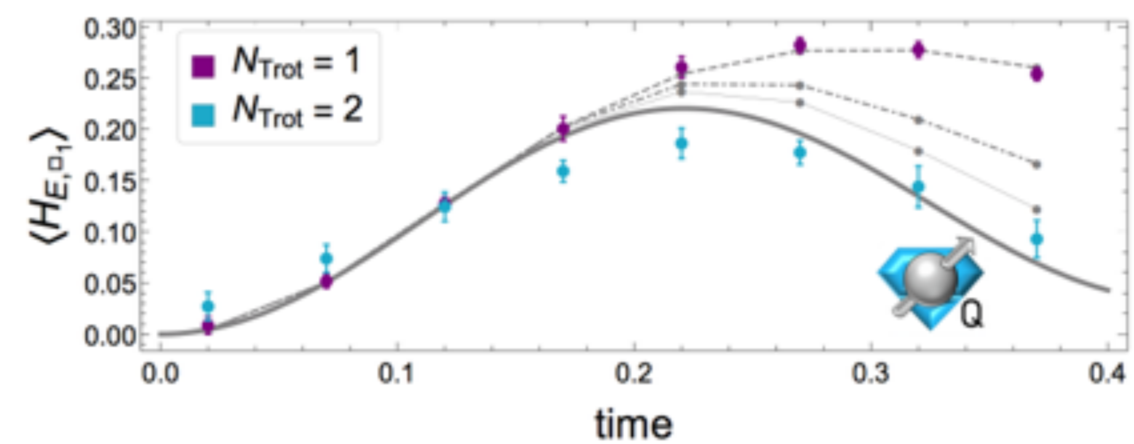


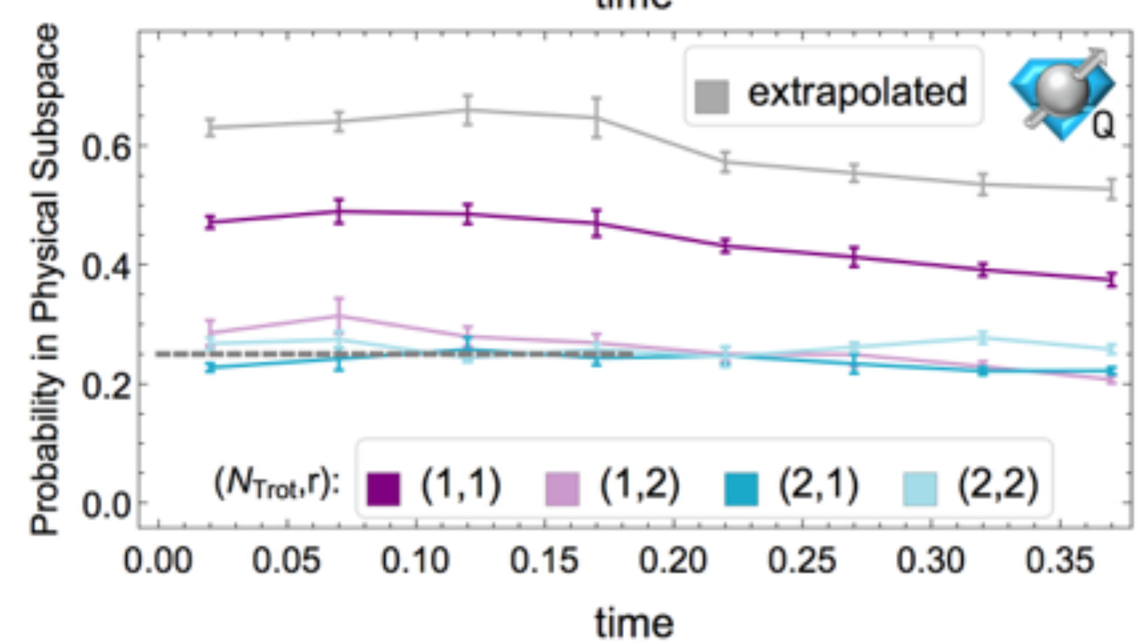
$$\mathcal{H}^{(1/2)} = \frac{1}{2g^2}\begin{pmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & -2 & 0 & 0 & 0 & 0 & 0 & -2 & 0 & 0 \\
0 & \frac{3g^4}{4} & 0 & 0 & 0 & 0 & -2 & 0 & 0 & 0 & 0 & 0 & -2 & 0 & 0 & 0 \\
0 & 0 & \frac{3g^4}{2} & 0 & 0 & -2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{2} \\
0 & 0 & 0 & \frac{9g^4}{4} & -2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{2} & 0 \\
0 & 0 & 0 & -2 & \frac{3g^4}{4} & 0 & 0 & 0 & 0 & -2 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & -2 & 0 & 0 & \frac{3g^4}{2} & 0 & 0 & -2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -2 & 0 & 0 & 0 & 0 & \frac{9g^4}{4} & 0 & 0 & 0 & 0 & -\frac{1}{2} & 0 & 0 & 0 & 0 \\
-2 & 0 & 0 & 0 & 0 & 0 & 0 & 3g^4 & 0 & 0 & -\frac{1}{2} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & -2 & 0 & 0 & \frac{3g^4}{2} & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{2} \\
0 & 0 & 0 & 0 & -2 & 0 & 0 & 0 & 0 & \frac{9g^4}{4} & 0 & 0 & 0 & 0 & -\frac{1}{2} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{2} & 0 & 0 & 3g^4 & 0 & 0 & -\frac{1}{2} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{2} & 0 & 0 & 0 & 0 & \frac{15g^4}{4} & -\frac{1}{2} & 0 & 0 & 0 \\
0 & -2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{2} & \frac{9g^4}{4} & 0 & 0 & 0 \\
-2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{2} & 0 & 0 & 3g^4 & 0 & 0 \\
0 & 0 & 0 & -\frac{1}{2} & 0 & 0 & 0 & 0 & 0 & -\frac{1}{2} & 0 & 0 & 0 & 0 & \frac{15g^4}{4} & 0 \\
0 & 0 & -\frac{1}{2} & 0 & 0 & 0 & 0 & 0 & -\frac{1}{2} & 0 & 0 & 0 & 0 & 0 & 0 & \frac{9g^4}{2}
\end{pmatrix}$$

SU(2) non-Abelian gauge field theory in one dimension on digital quantum computers

Natalie Klco, Jesse R. Stryker and Martin J. Savage[1]
[1] *Institute for Nuclear Theory, University of Washington, Seattle, WA 98195-1550, USA*
(Dated: August 19, 2019 - 13:7)

$$\hat{H} = \frac{g^2}{2}\sum_{\text{links}} \hat{E}^2 - \frac{1}{2g^2}\sum_{\square}\left(\hat{\square} + \hat{\square}^\dagger\right)$$





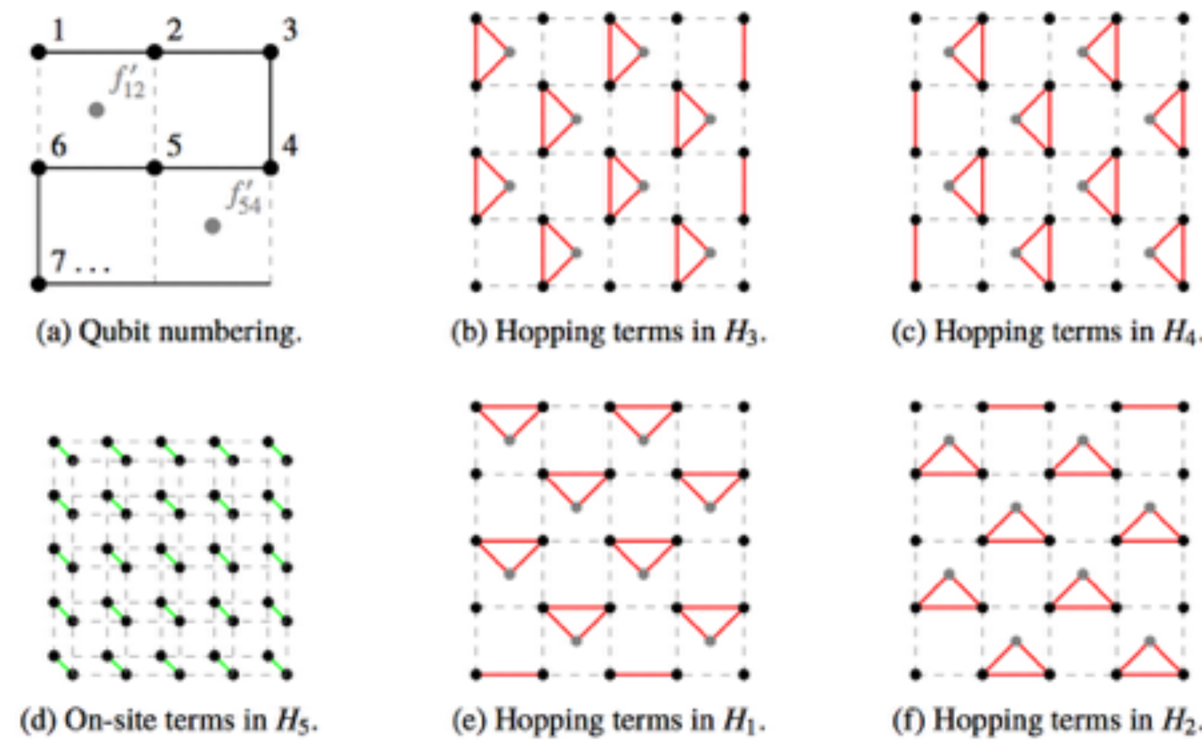
Digital Simulation
New ``Tricks”

Hamiltonian Simulation Algorithms for Near-Term Quantum Hardware

Laura Clinton[*1,2], Johannes Bausch[†1,3], and Toby Cubitt[‡1]

[1]PhaseCraft Ltd.
[2]Department of Computer Science, University College London
[3]Department of Applied Mathematics and Theoretical Physics, University of Cambridge

March 2020



(a) Qubit numbering. (b) Hopping terms in H_3. (c) Hopping terms in H_4.
(d) On-site terms in H_5. (e) Hopping terms in H_1. (f) Hopping terms in H_2.

$$H_{\mathrm{FH}} := \sum_{i=1}^{N} h_{\text{on-site}}^{(i)} + \sum_{i<j,\sigma} h_{\text{hopping}}^{(i,j,\sigma)} := u \sum_{i=1}^{N} a_{i\uparrow}^{\dagger} a_{i\uparrow} a_{i\downarrow}^{\dagger} a_{i\downarrow} + v \sum_{i<j,\sigma} \left(a_{i\sigma}^{\dagger} a_{j\sigma} + a_{j\sigma}^{\dagger} a_{i\sigma} \right).$$

$$h_{\text{on-site}}^{(i)} \rightarrow \frac{u}{4} \left(\mathbb{1} - Z_{i\uparrow}\right)\left(\mathbb{1} - Z_{i\downarrow}\right)$$
$$h_{\text{hopping,hor}}^{(i,j,\sigma)} \rightarrow \frac{v}{2} \left(X_{i,\sigma} X_{j,\sigma} Y_{f'_{ij},\sigma} + Y_{i,\sigma} Y_{j,\sigma} Y_{f'_{ij},\sigma} \right)$$
$$h_{\text{hopping,vert}}^{(i,j,\sigma)} \rightarrow \frac{v}{2} (-1)^{g(i,j)} \left(X_{i,\sigma} X_{j,\sigma} X_{f'_{ij},\sigma} + Y_{i,\sigma} Y_{j,\sigma} X_{f'_{ij},\sigma} \right),$$

Together with new Trotter product formulae error bounds, and a novel low-weight fermionic encoding, this improves upon state-of-the-art results by over three orders of magnitude in circuit-depth-equivalent.

$$e^{i\delta Z_1 Z_2 Z_3} \approx e^{-i\sqrt{\delta/2} Z_1 X_2} e^{i\sqrt{\delta/2} Y_2 Z_3} e^{i\sqrt{\delta/2} Z_1 X_2} e^{-i\sqrt{\delta/2} Y_2 Z_3},$$
$$e^{i\delta Z_1 Z_2 Z_3 Z_4} \approx e^{-i0.22\delta^{2/3} Y_2 Z_3 Z_4} e^{-i1.13\delta^{1/3} Z_1 X_2} e^{i0.44\delta^{2/3} Y_2 Z_3 Z_4} e^{i1.13\delta^{1/3} Z_1 X_2} e^{-i0.22\delta^{2/3} Y_2 Z_3 Z_4}.$$

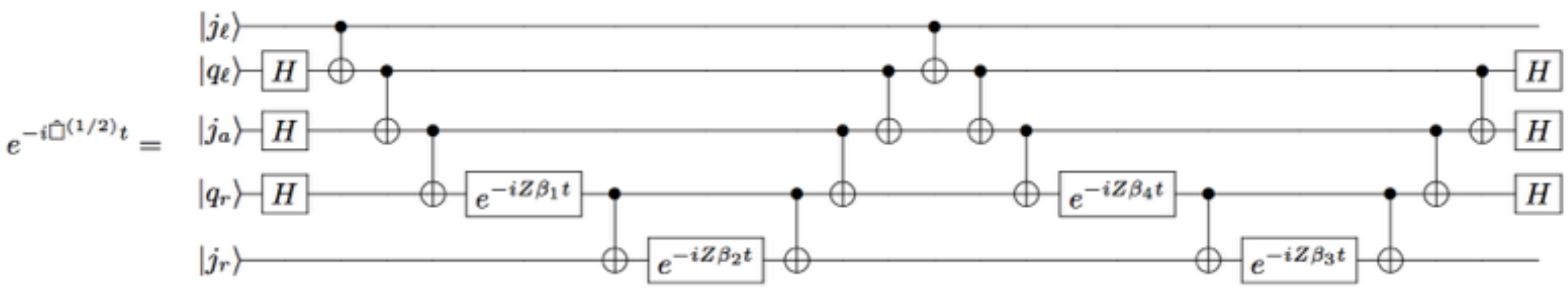
See also, Childs *et al*
https://arxiv.org/pdf/1912.08854.pdf

Digital Simulation
New ``Tricks”
Measurement-Error Correction

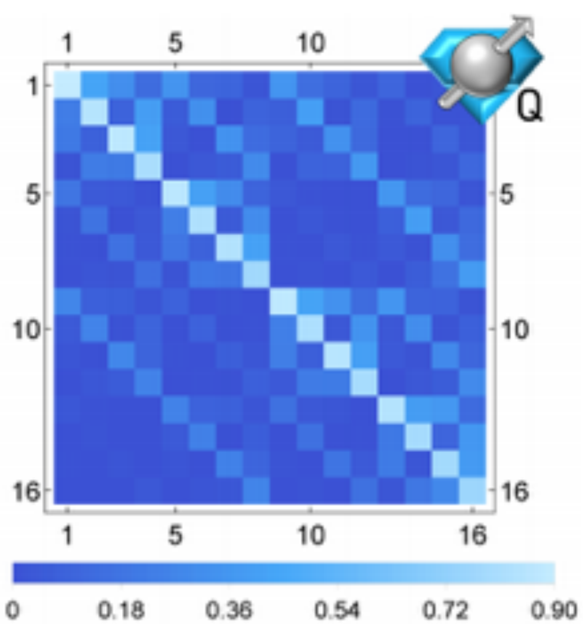
Measurement Error Mitigation in Quantum Computers Through Classical Bit-Flip Correction

Lena Funcke[1], Tobias Hartung[2], Karl Jansen[3], Stefan Kühn[4], Paolo Stornati[3,5], and Xiaoyang Wang[6]

promising development
may scale better
invertible by construction
see also IBM, Rigetti



Measure
qubits
|0> or |1>



$V_{device} = M.V_{mc}$

IBM protocol

Minimization to find M

Apply to all measurements

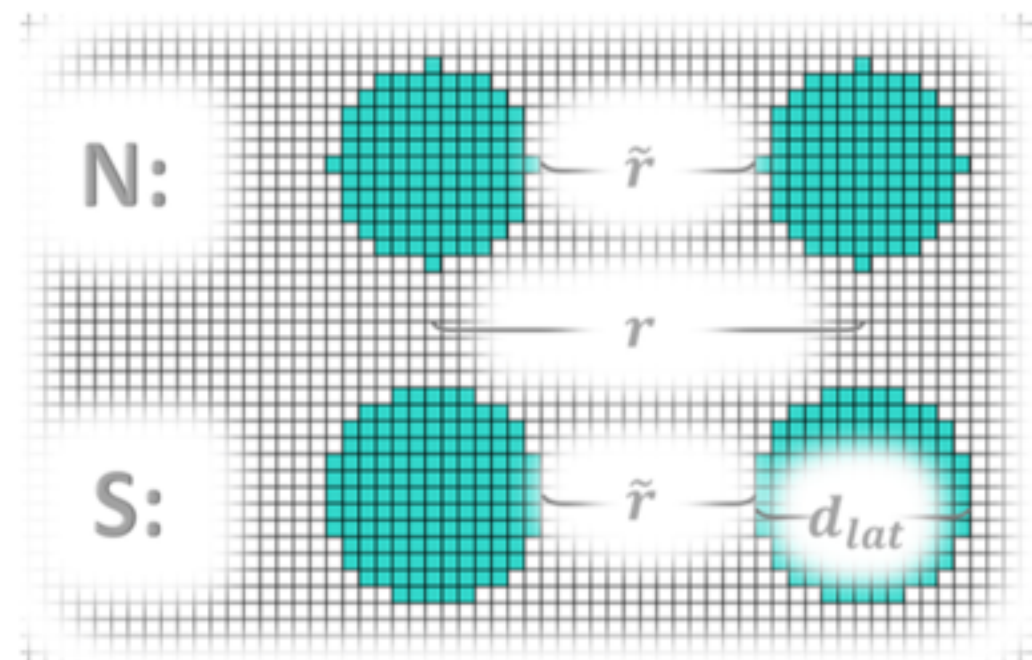
Costly to go to scale

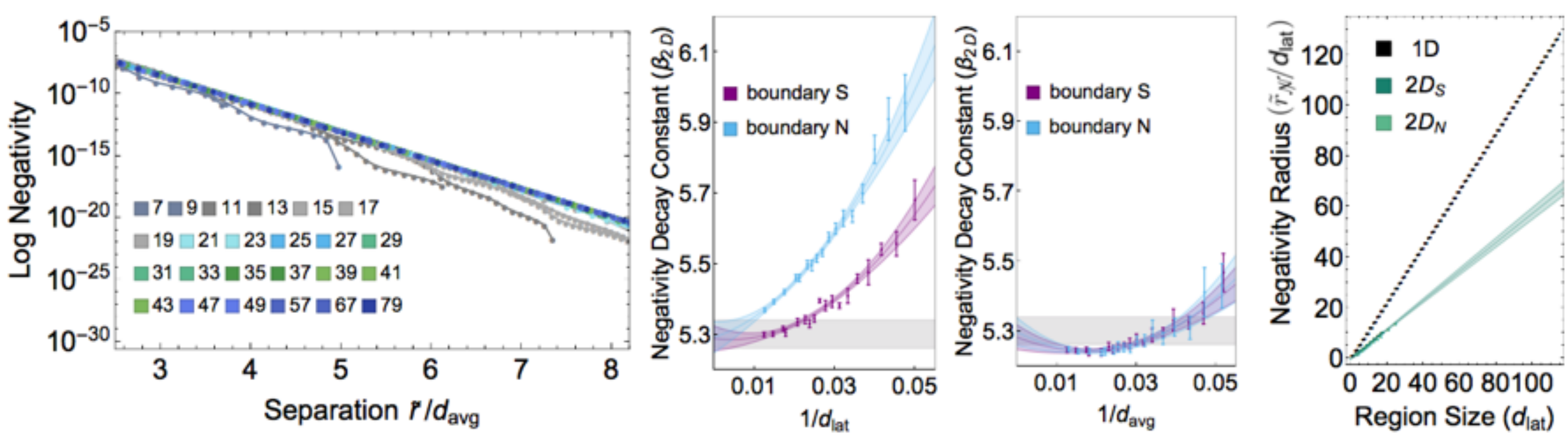
time-dependence -> high rep. rate

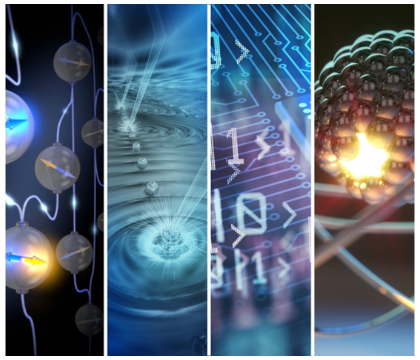
Lattice Simulations
Distillable Entanglement

Natalie Klco+MJS

“Harmonic Chains” > 2004
Reznik, Marcovitch, Retzker,
Plenio, Tonni, Calabrese, Cardy,….







Summary

- Quantum Simulations are expected to be able to address HEP problems inaccessible to HPC in the future
- ``spinning-up'' — develop algorithms, expertise and workforce to move toward solving beyond-classical problems.
- Qualitative new understandings likely to feed back into classical?
- Sensors and simulators are intertwined
- Diverse collaboration are essential,
  - HEP, NP, BES, QIS, expt, theory

FIN

Analog Simulation : dense matter example

Selection of different experimental systems/atoms, controls, (number of) species and accessible observables

New Frontier

non-equilibrium dynamics of strongly-interacting systems

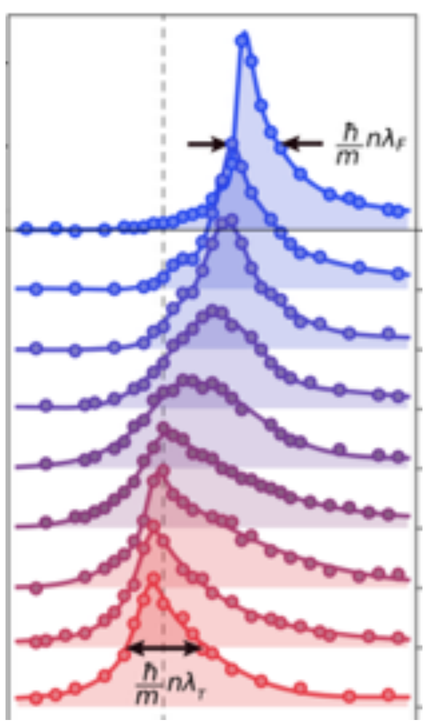
e.g. evolution of domain walls

Cold Atom Quantum Simulator for Dilute Neutron Matter

Munekazu Horikoshi
Institute for Photon Science and Technology, Graduate School of Science, The University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
hori@psc.t.u-tokyo.ac.jp

Makoto Kawata-Gonokami
Department of Physics, Graduate School of Science, The University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan

One example: Dilute neutron matter



Short-range correlations
The ``Contact''
Unitary Fermi Gas

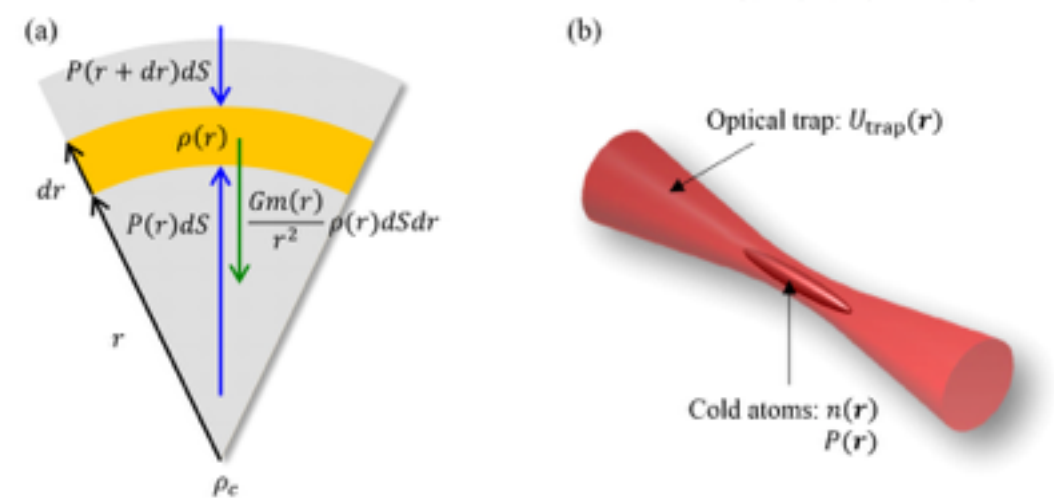


Fig. 5. (color online) Density and pressure distribution determined by the EOS. (a) Inside a neutron star. (b) Ultracold atoms trapped in an optical dipole trap.

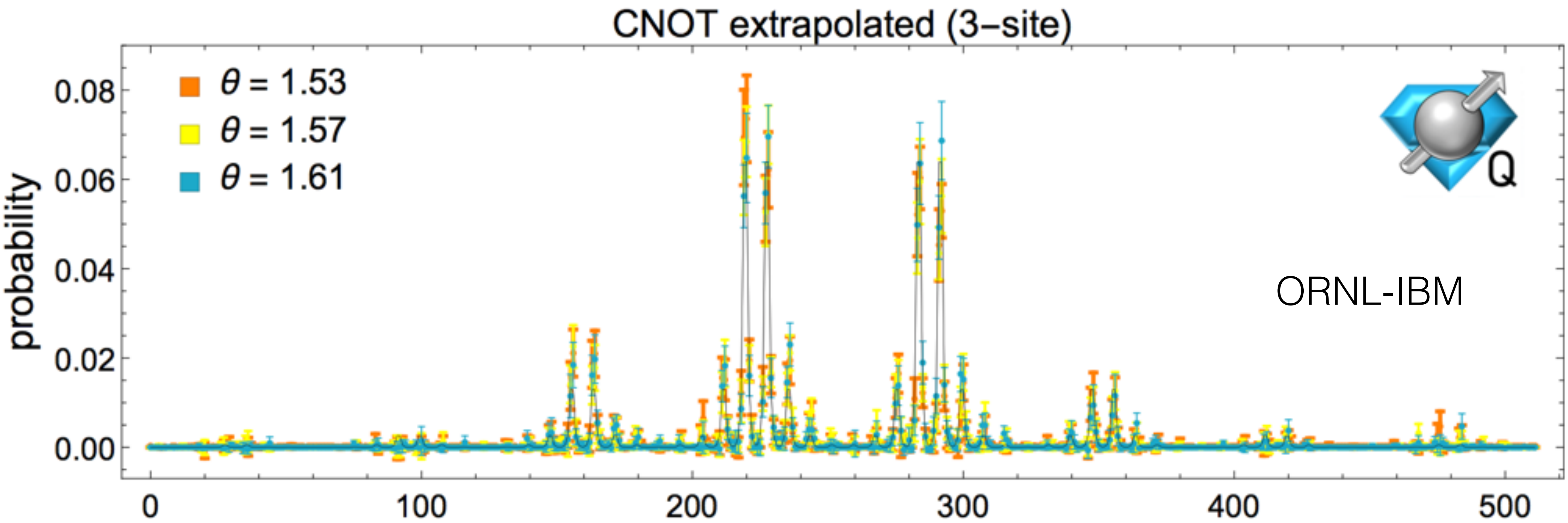
Biswaroop Mukherjee, Parth B. Patel, Zhenjie Yan, Richard J. Fletcher, Julian Struck, Martin W. Zwierlein
Spectral response and contact of the unitary Fermi gas, arXiv:1902.08548

https://arxiv.org/pdf/1901.00985.pdf

Symmetric Exponentials on Poughkeepsie
3-spatial sites

Natalie Klco and MJS

IBM Poughkeepsie



$n_Q=3 \otimes n_Q=3 \otimes n_Q=3 \quad | \phi(0)\, \phi(1)\, \phi(2) >$

Working with FermiLab to prepare entangled ground state

2+1, 3+1 Gauge Theories

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

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

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

Quantum Simulation of Gauge Theories
NuQS Collaboration (Henry Lamm et al.).
e-Print: arXiv:1903.08807 [hep-lat]