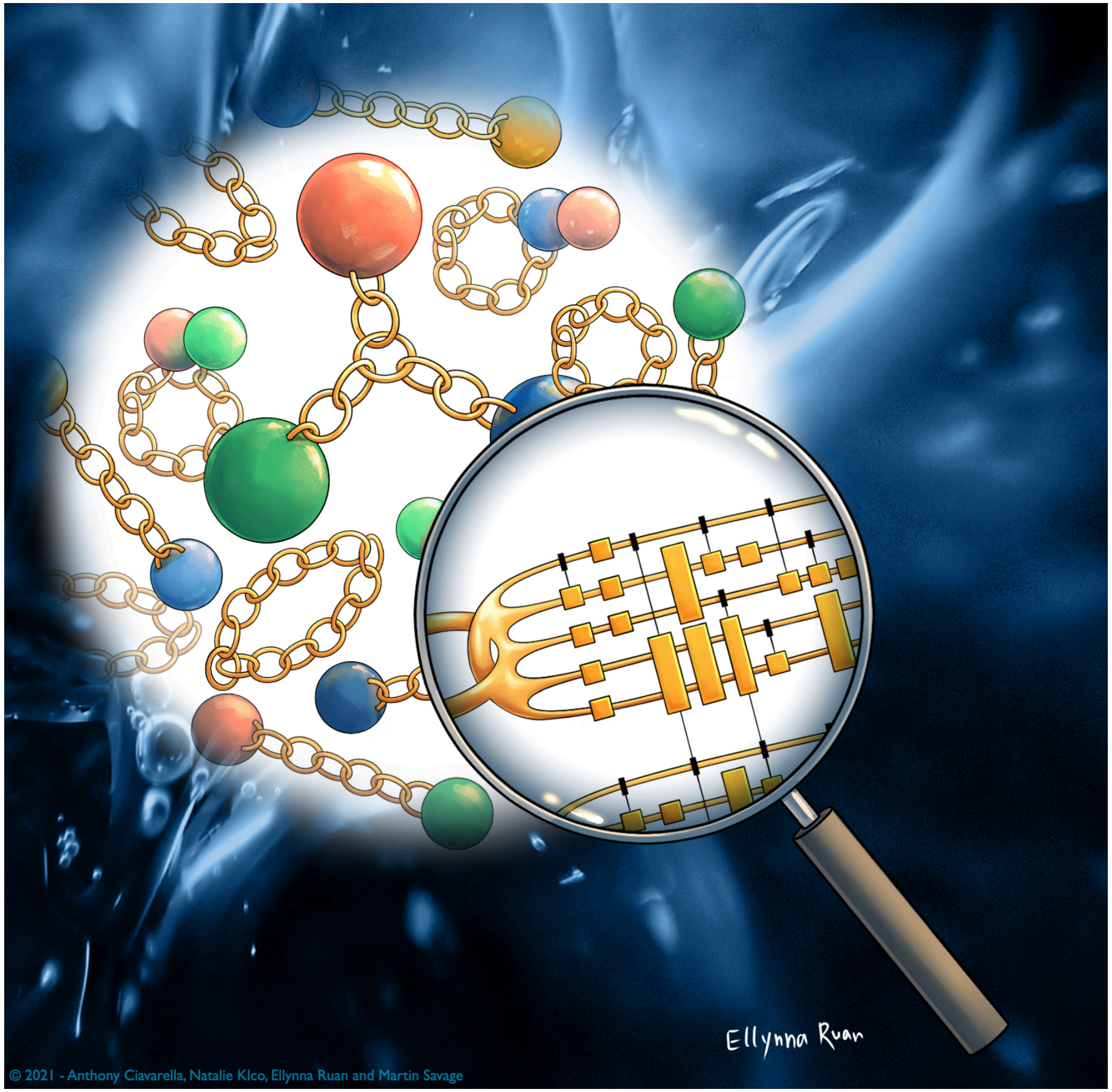


Quantum Simulations For HEP and NP

Quantum Field Theories

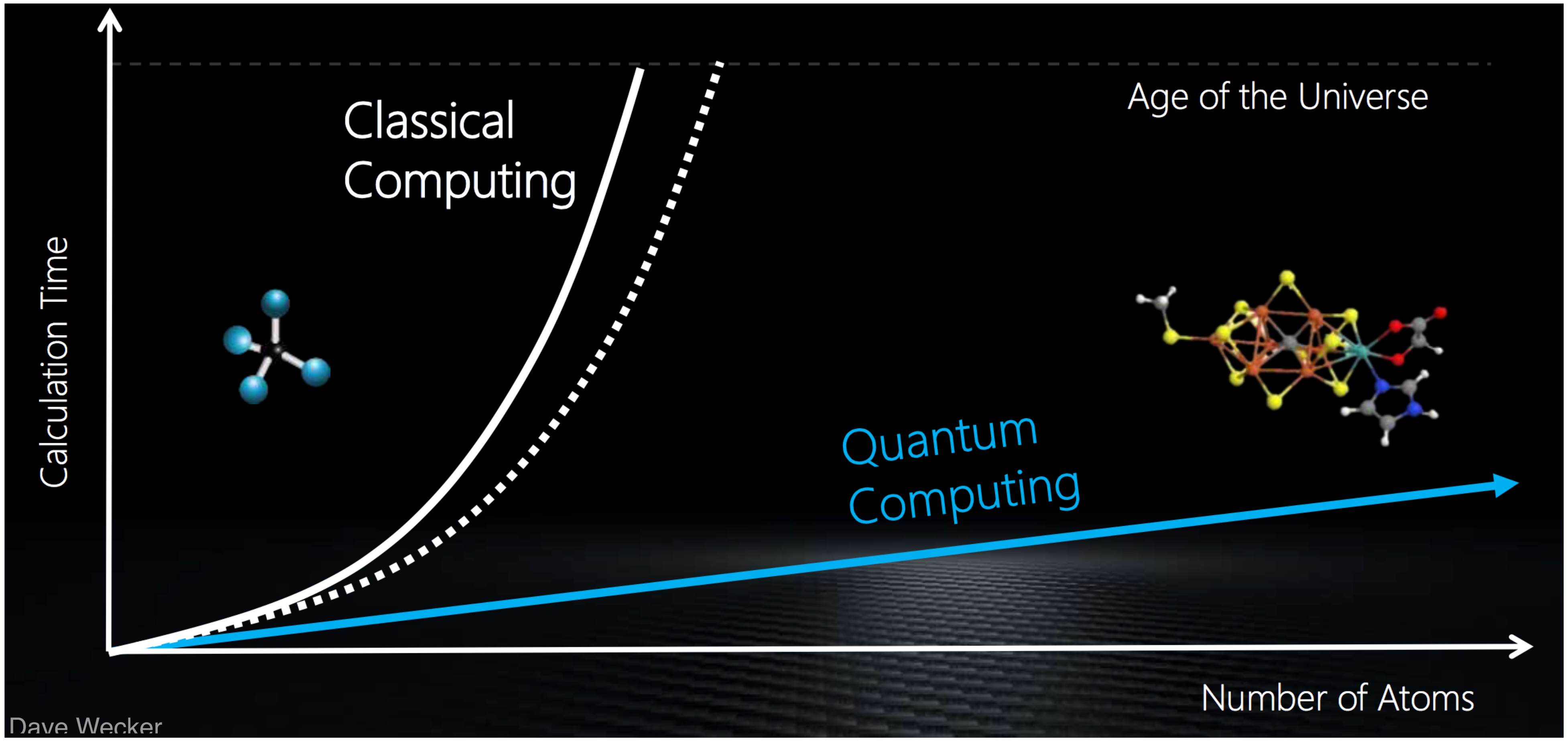
Martin J Savage

InQubator for Quantum Simulation (IQuS)

UNIVERSITY of WASHINGTON

LBNL, April 29, 2021

The Potential of Quantum Computing



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

50 qubits : ~ 20 petabytes ~ HPC facility

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

2019 : First Quantum Advantage in Computing

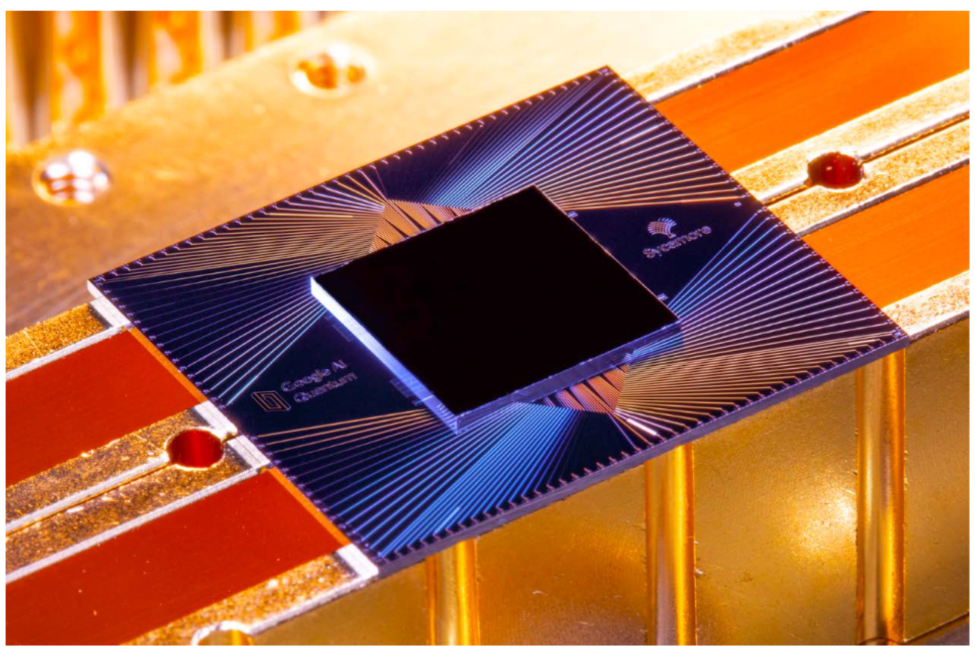
Nature **574**, pages 505–510 (2019), 23 October 2019

Article

Quantum supremacy using a programmable superconducting processor

https://doi.org/10.1038/s41586-019-1666-5
Received: 22 July 2019
Accepted: 20 September 2019
Published online: 23 October 2019

Frank Arute[1], Kunal Arya[1], Ryan Babbush[1], Dave Bacon[1], Joseph C. Bardin[1,2], Rami Barends[1], Rupak Biswas[3], Sergio Boixo[1], Fernando G. S. L. Brandao[1,4], David A. Buell[1], Brian Burkett[1], Yu Chen[1], Zijun Chen[1], Ben Chiaro[5], Roberto Collins[1], William Courtney[1], Andrew Dunsworth[1], Edward Farhi[1], Brooks Foxen[1,5], Austin Fowler[1], Craig Gidney[1], Marissa Giustina[1], Rob Graff[1], Keith Guerin[1], Steve Habegger[1], Matthew P. Harrigan[1], Michael J. Hartmann[1,6], Alan Ho[1], Markus Hoffmann[1], Trent Huang[1], Travis S. Humble[7], Sergei V. Isakov[1], Evan Jeffrey[1],



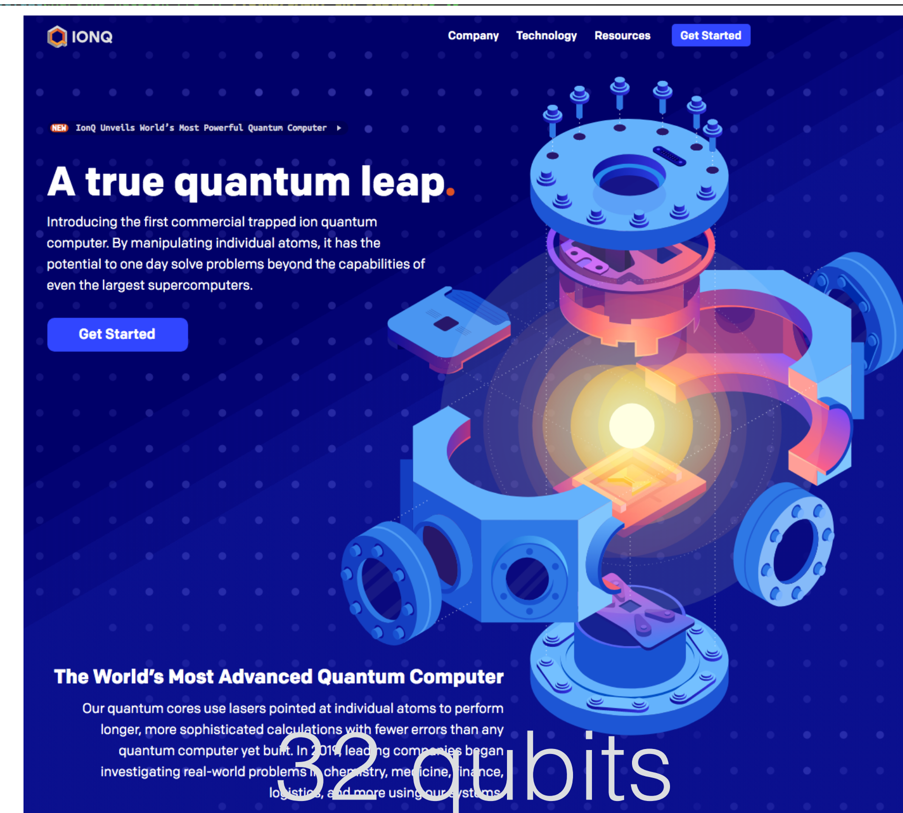
Credit: Erik Lucero/Google

In mid-September, the *Financial Times* revealed that Google was preparing to publish a scientific paper showing that it had built a 54-qubit quantum computer that could solve a maths problem in 3 minutes and 20 seconds that would take the world's fastest supercomputer around 10,000 years to solve.

IBM

IBM Research Blog | Topics | Labs | About

October 21, 2019 | Written by: Edwin Pednault, John Gunnels

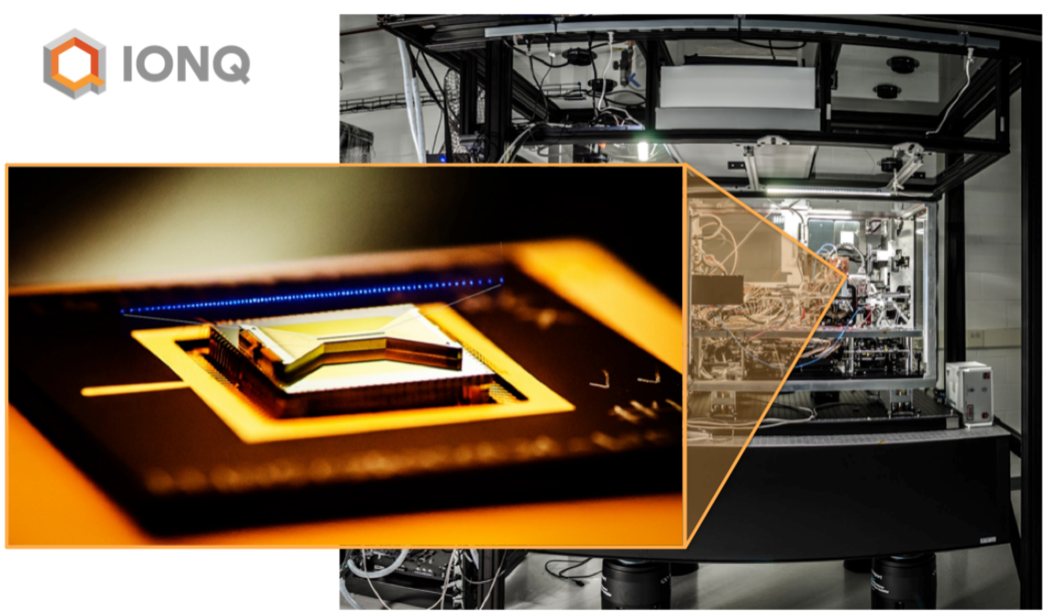


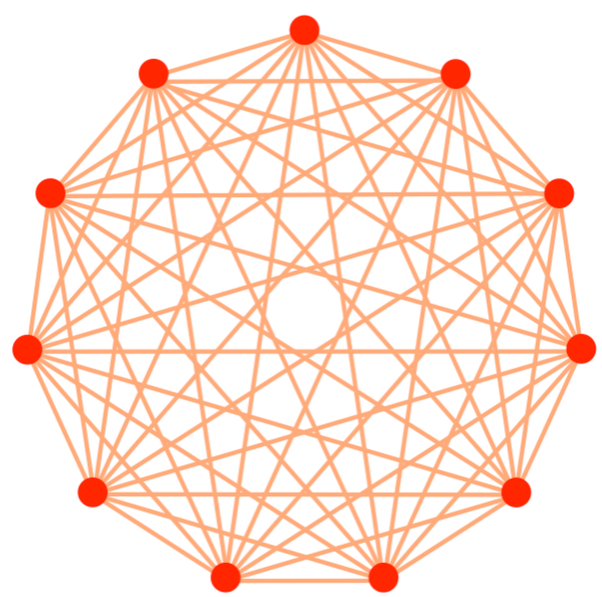
32 qubits

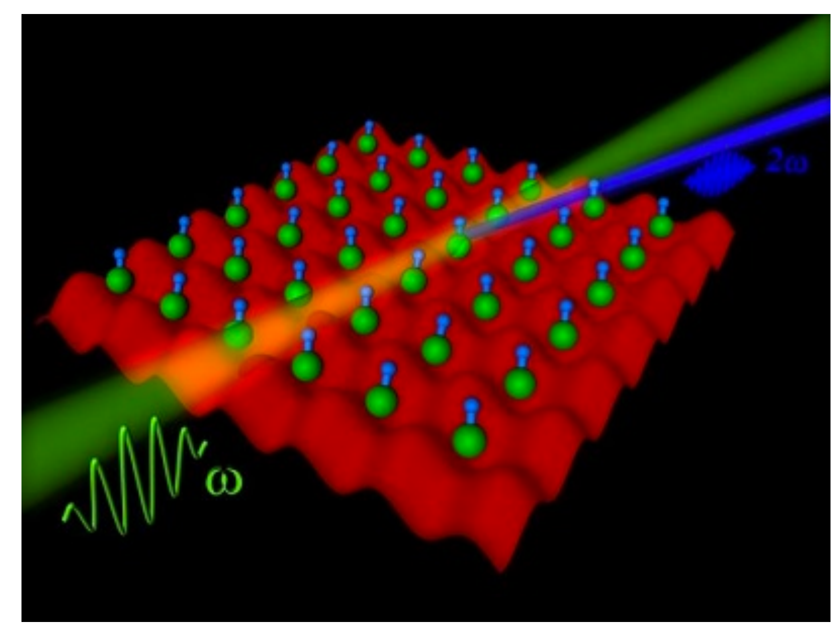
2017 : First Quantum Devices for Scientific Applications

rigetti

IONQ





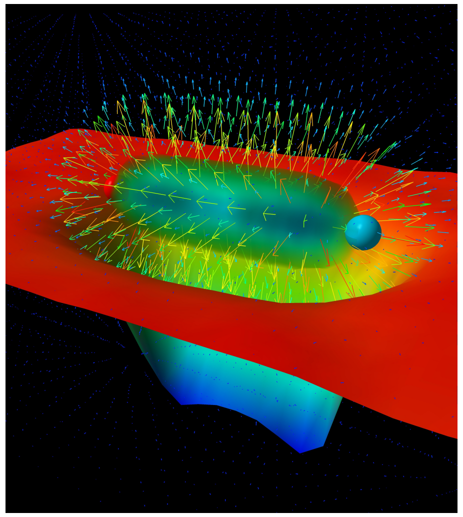


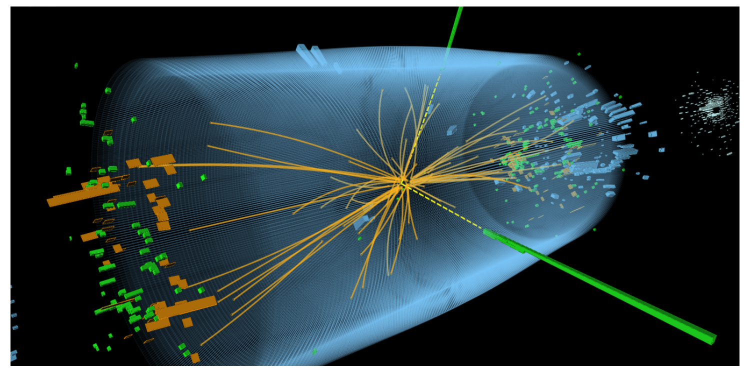
Hemmerling, Cornel, https://www.photonics.com/Article.aspx?AID=64150

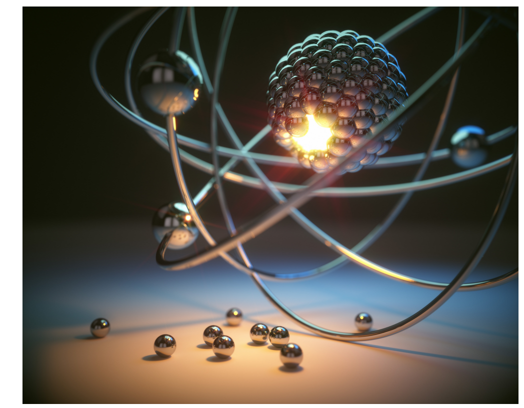
NISQ-era quantum devices for applications

Looking for a quantum advantage

Do not scale well for classical computers





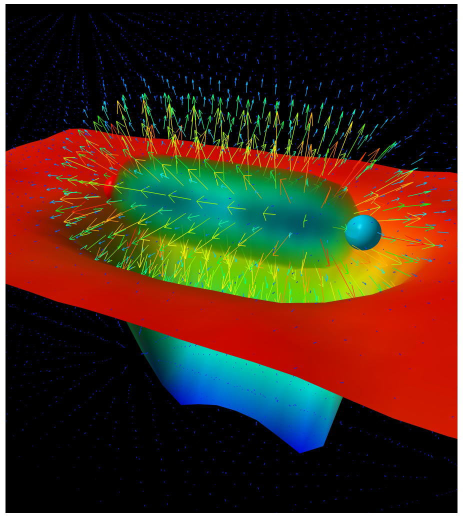


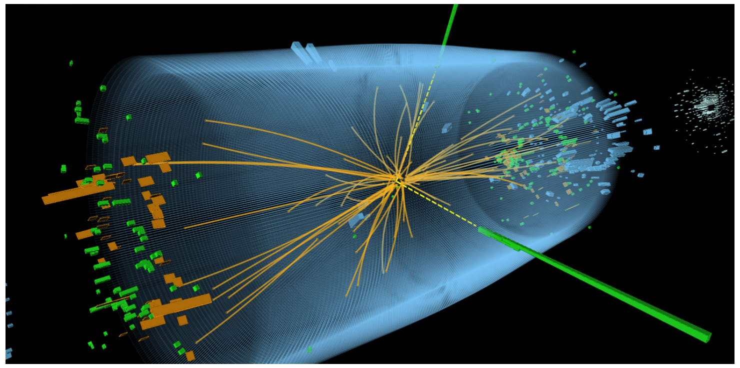
- Real-time Minkowski space evolution
  - highly-inelastic processes, fragmentation, S-matrices
  - non-equilibrium systems

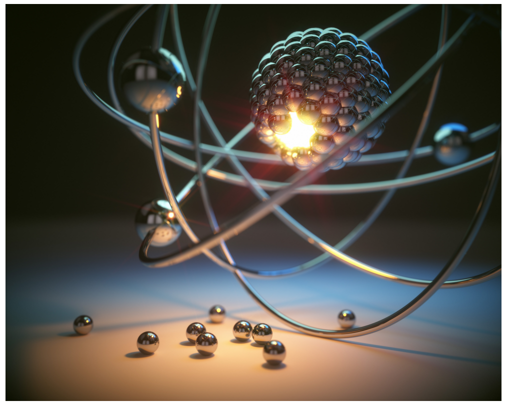
- Large Hilbert spaces - quantum field theories, large nuclei

- High-density - potentially mitigate classical sign problem(s)

HEP and NP Theory







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

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

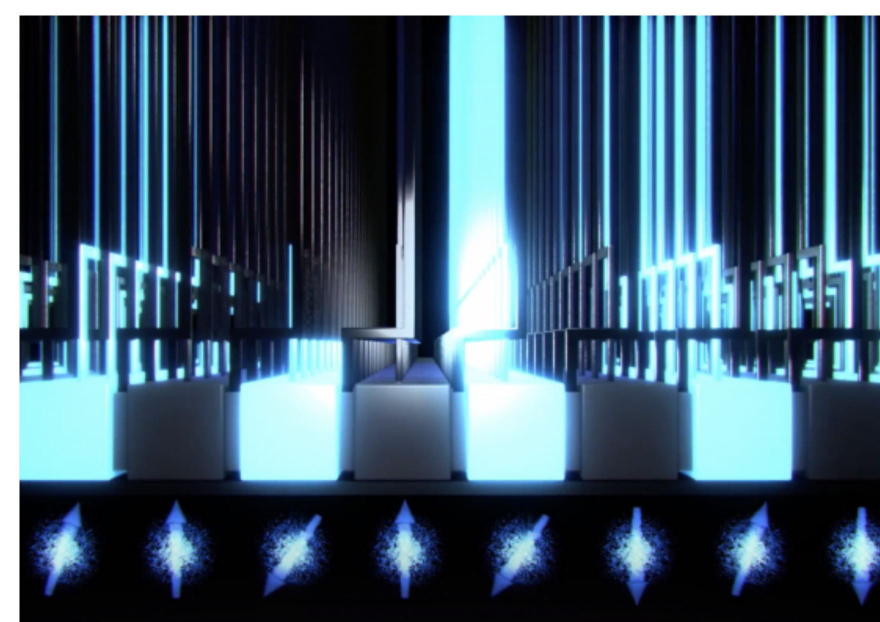
Matter
- neutron stars
- gravity waves ?
- Heavy nuclei
- chemical potentials
- entanglement

Where to look for a Quantum Advantage in Scientific Applications

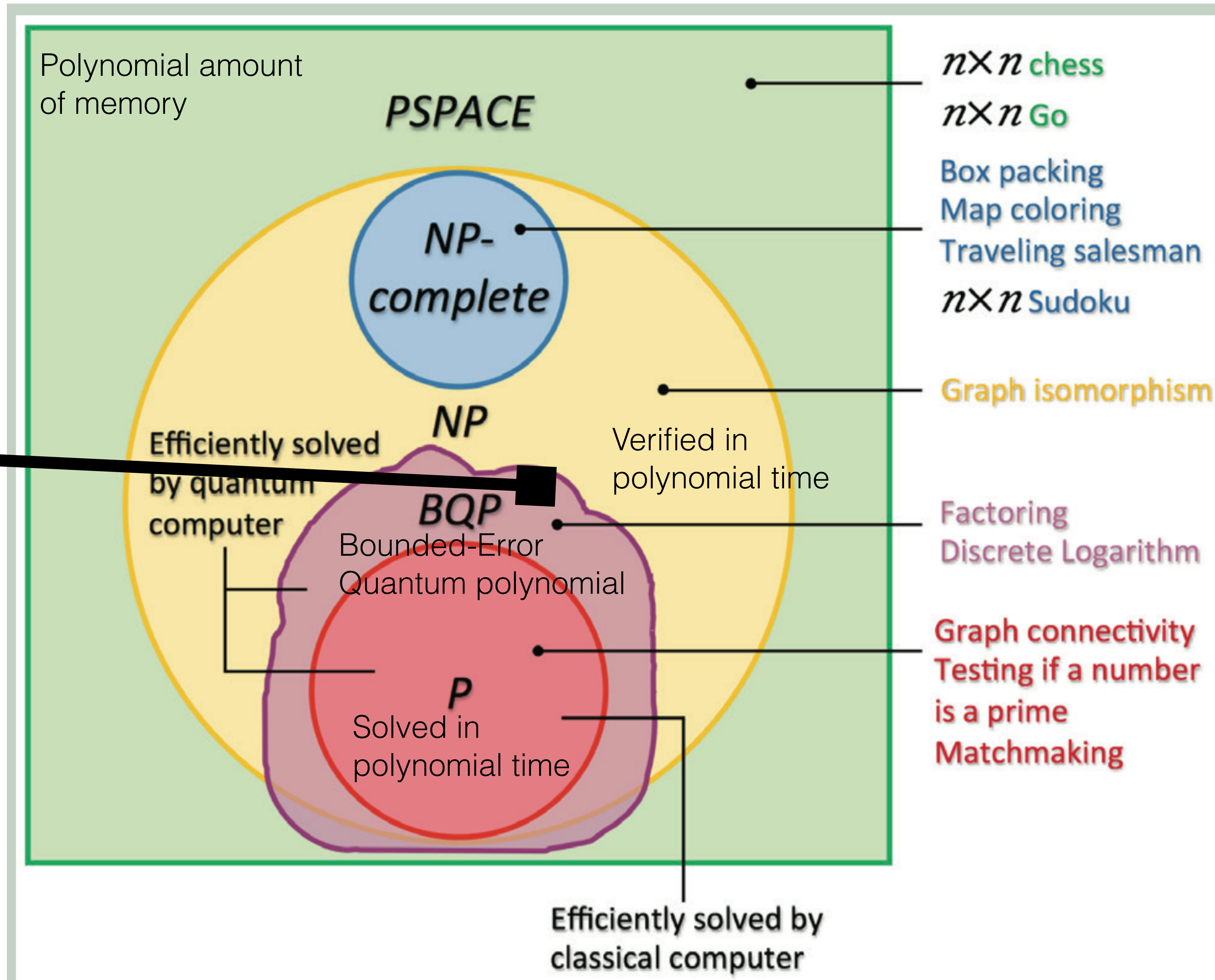
If a classical computer can solve the problem,
why “compete” using a quantum device?

Use quantum devices to solve (parts of) the problems that classical computers can’t solve “at scale”

“ Gotta *know* your problems”



Complexity

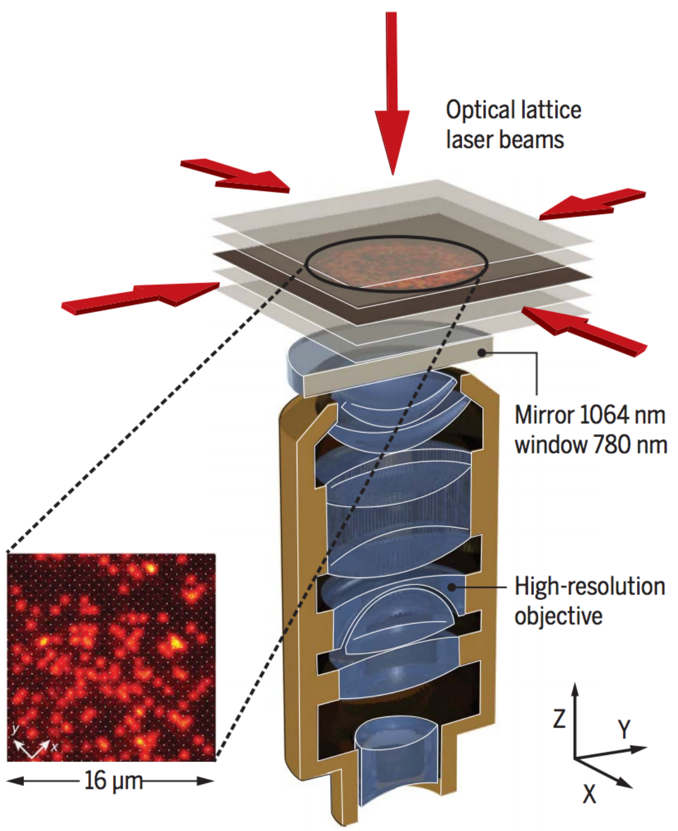


Scalar field theory

Scott Aaronson, Sci. Am.

A Simulation “Continuum”

Analog

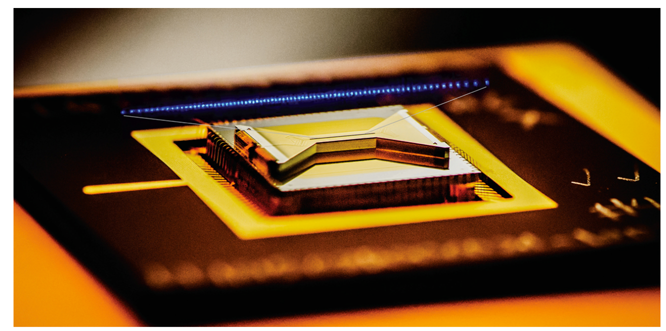


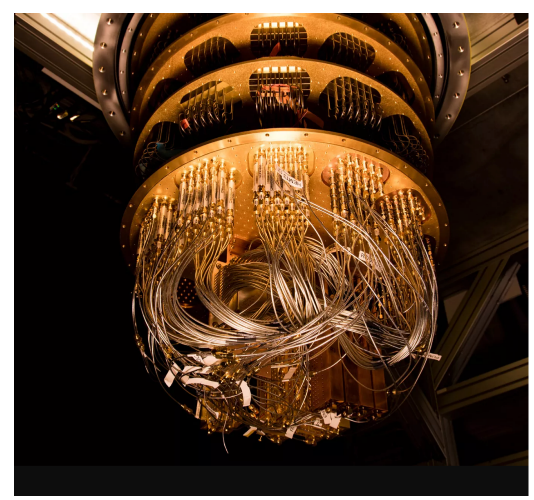
H : native to system

e.g. atoms in optical lattices
BECs

systematics?

Digital





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

NISQ, waiting for error-correction

Hybrid

QPU for the intrinsically quantum parts of the computation

Scaling?

SRF cavities

Jacob F. Sherson, Christof Weitenberg, Manuel Endres, Marc Cheneau, Immanuel Bloch, and Stefan Kuhr. Single-atom-resolved fluorescence imaging of an atomic Mott insulator. Nature, 467(7311):68–72, 09 2010.

Analog Simulation : Quantum Field Theory - Recent

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]

Eur.Phys.J.D 74 (2020) 8, 165 • e-Print: 1911.00003 [quant-ph]

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

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

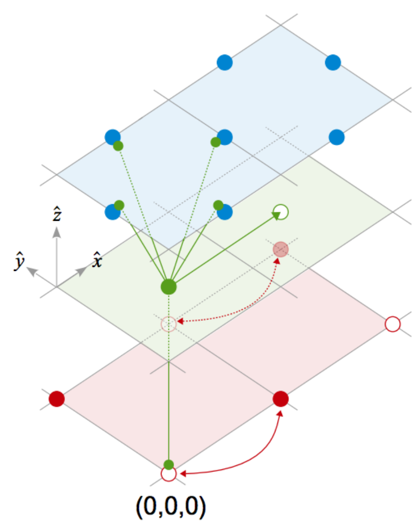


Figure 23: Different atomic species reside on different vertical layers. Green straight lines show how the auxiliary atoms have to move in order to realise interactions with the link atoms and the fermions, or to enter odd plaquettes. Red arrows show selective tunnelling of fermions across even horizontal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

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*

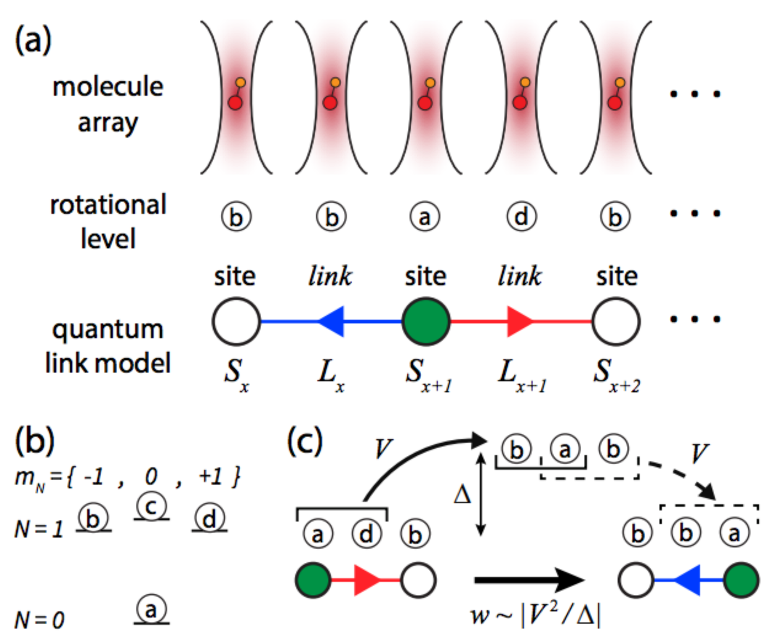
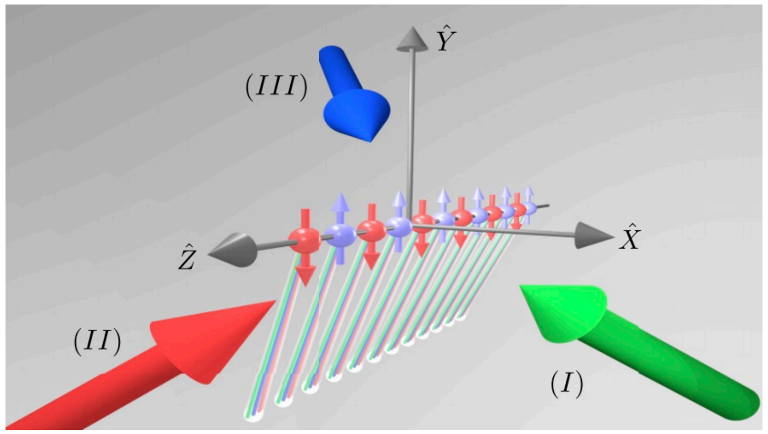


Figure 1. **Emulating quantum link models (QLMs) with arrays of dipolar molecules.** (a) Mapping between the rotational levels of molecules in an array and the sites and links of the QLM for spin $S = 1/2$. The designation of

Towards analog quantum simulations of lattice gauge theories with trapped ions

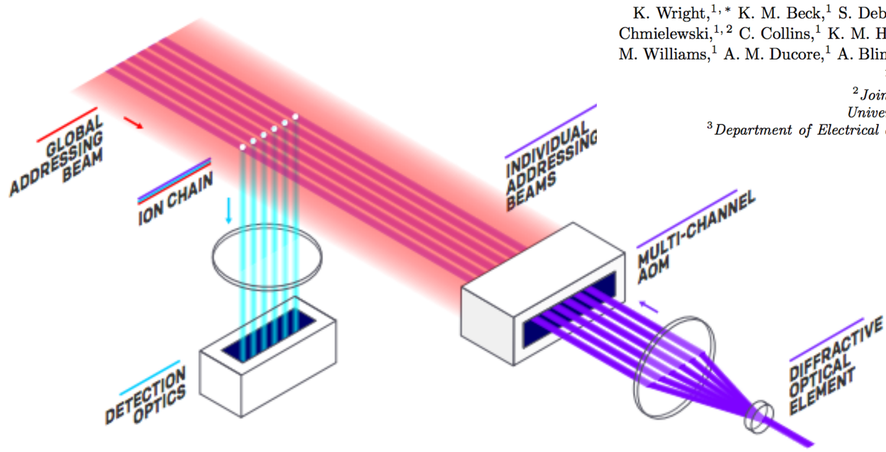
Zohreh Davoudi,[1,2] Mohammad Hafezi,[3,4] Christopher Monroe,[3,5] Guido Pagano,[3,5,6] Alireza Seif,[3] and Andrew Shaw[1]
[1] *Maryland Center for Fundamental Physics and Department of Physics, University of Maryland, College Park, Maryland 20742, USA*
[2] *RIKEN Center for Accelerator-based Sciences, Wako 351-0198, Japan*
[3] *Joint Quantum Institute and Department of Physics, University of Maryland, College Park, Maryland 20742, USA*
Department of Electrical and Computer Engineering and Institute for Research in Electronics and Applied Physics, University of Maryland, College Park, Maryland 20742, USA
[5] *Joint Center for Quantum Information and Computer Science, University of Maryland, College Park, Maryland 20742, USA*
[6] *Department of Physics and Astronomy, Rice University, Houston, Texas 77005, USA*

(Received 21 August 2019; accepted 5 February 2020; published 8 April 2020)



of possibilities for quantum simulations of complex physical systems. Here we devise practical proposals for analog simulation of simple lattice gauge theories whose dynamics can be mapped onto spin-spin interactions in any dimension. These include 1+1D quantum electrodynamics, 2+1D Abelian Chern-Simons theory coupled to fermions, and 2+1D pure Z_2 gauge theory. The scheme proposed, along with the optimization protocol applied,

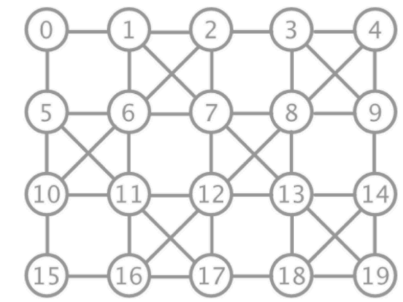
Basics of Digital Simulation
e.g., discrete representation of a function



Benchmarking an 11-qubit quantum computer

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

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



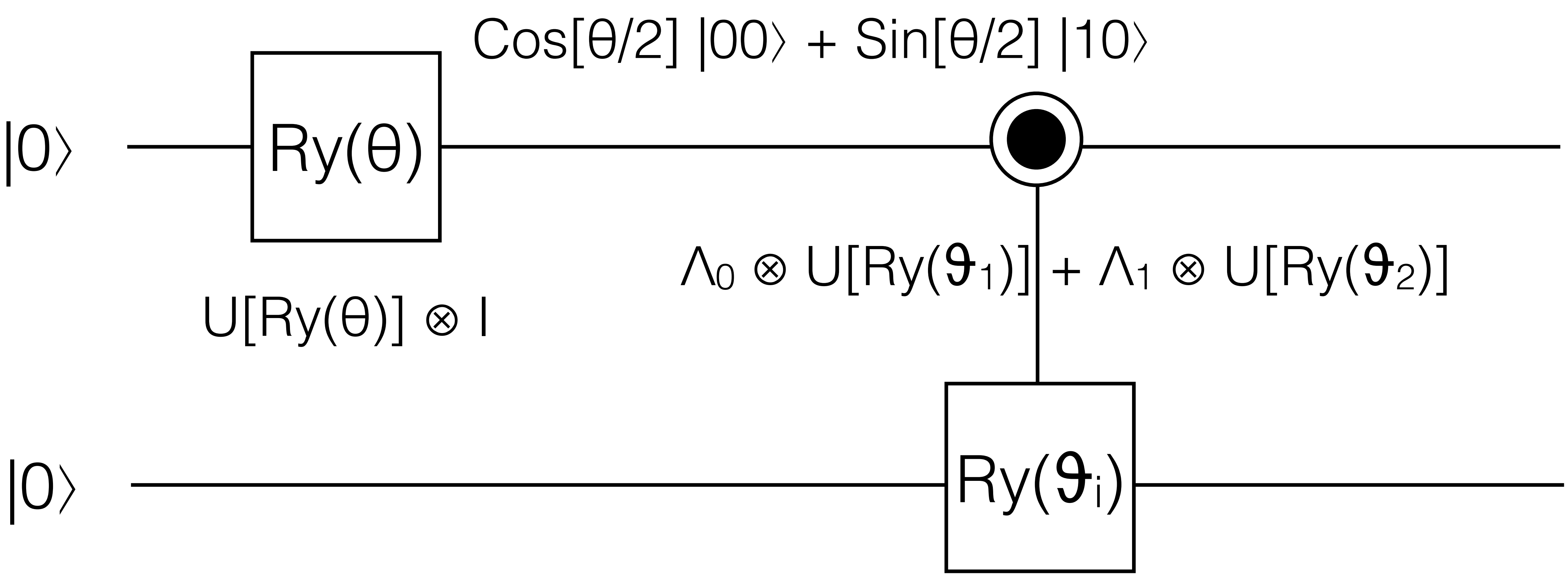
Average measurements	
Frequency (GHz)	4.97
T1 (μs)	89.59
T2 (μs)	58.66
Gate error (10^{-3})	1.84
Readout error (10^{-2})	8.38

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

Fully microwave-tunable universal gates in superconducting qubits with linear couplings and fixed transition frequencies

Chad Rigetti and Michel Devoret
Department of Applied Physics, Yale University, New Haven, Connecticut 06520-8284, USA

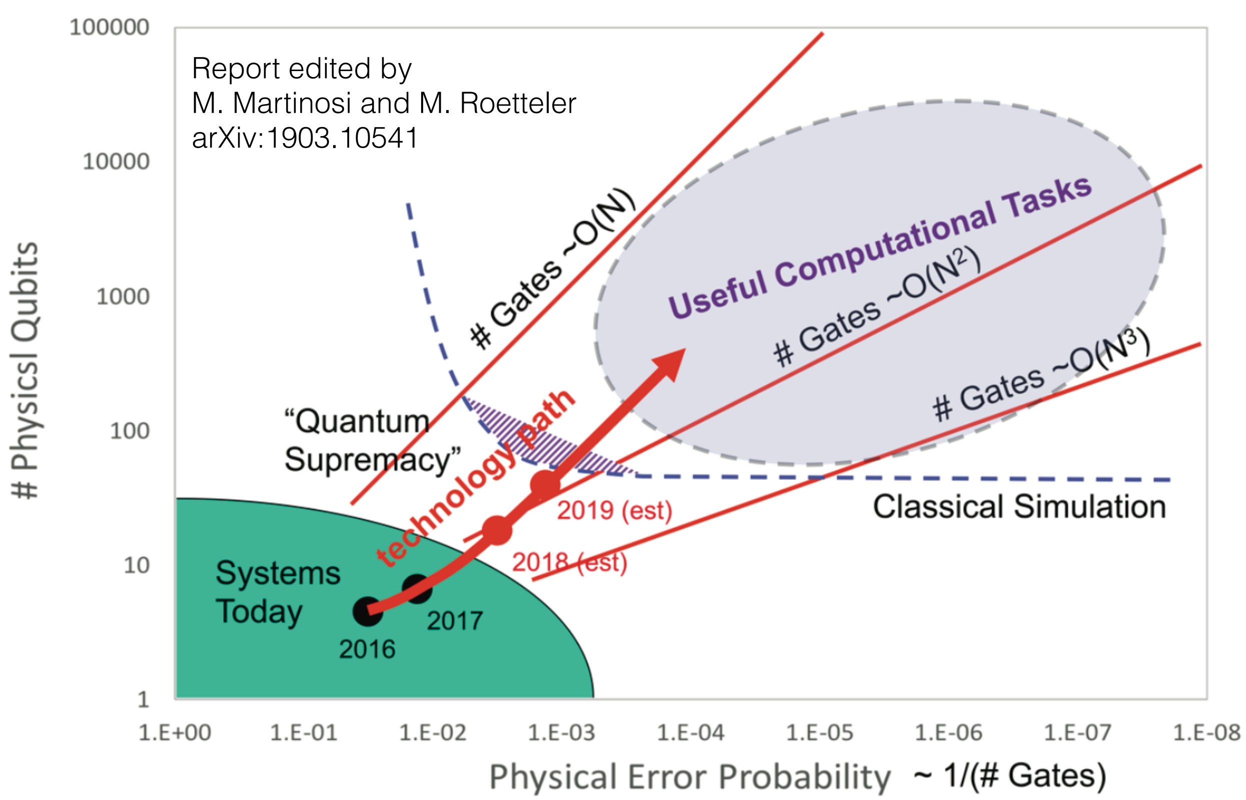
(Received 27 September 2009; revised manuscript received 10 March 2010; published 5 April 2010)



e.g., a 4-dim Hilbert space

$\mathrm{Cos}[\theta/2]\,\mathrm{Cos}[\vartheta_1/2]\,|00\rangle + \mathrm{Cos}[\theta/2]\,\mathrm{Sin}[\vartheta_1/2]\,|01\rangle + \mathrm{Sin}[\theta/2]\,\mathrm{Cos}[\vartheta_2/2]\,|10\rangle + \mathrm{Sin}[\theta/2]\,\mathrm{Sin}[\vartheta_2/2]\,|11\rangle$

Digital Simulation during the NISQ Era



- 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
- Searching for Quantum Advantage(s)

"Typically", 3 workflow phases

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

Simulation of Collective Neutrino Oscillations on a Quantum Computer

Benjamin Hall,[1] Alessandro Roggero,[2,3] Alessandro Baroni,[4] and Joseph Carlson[4]
[1]*Facility for Rare Isotope Beams (FRIB), Michigan State University, East Lansing, MI 48824, USA*
[2]*Institute for Nuclear Theory, University of Washington, Seattle, WA 98195, USA*
[3]*InQubator for Quantum Simulation (IQuS), Department of Physics, University of Washington, Seattle, WA 98195, USA*
[4]*Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA*
(Dated: February 26, 2021)

Entanglement and Many-Body effects in Collective Neutrino Oscillations

Alessandro Roggero[1]
[1]*InQubator for Quantum Simulation (IQuS), Department of Physics, University of Washington, Seattle, WA 98195, USA*
(Dated: February 23, 2021)

Neutrino Evolution

First simulations, entanglement using a quantum devices

$$H = \sum_{k=1}^{N} \vec{b} \cdot \vec{\sigma}_k + \sum_{p<q}^{N} J_{pq} \vec{\sigma}_p \cdot \vec{\sigma}_q$$

$$J_{pq} = (1 - \cos(\theta_{pq}))$$

Pauli matrices in neutrino flavor space

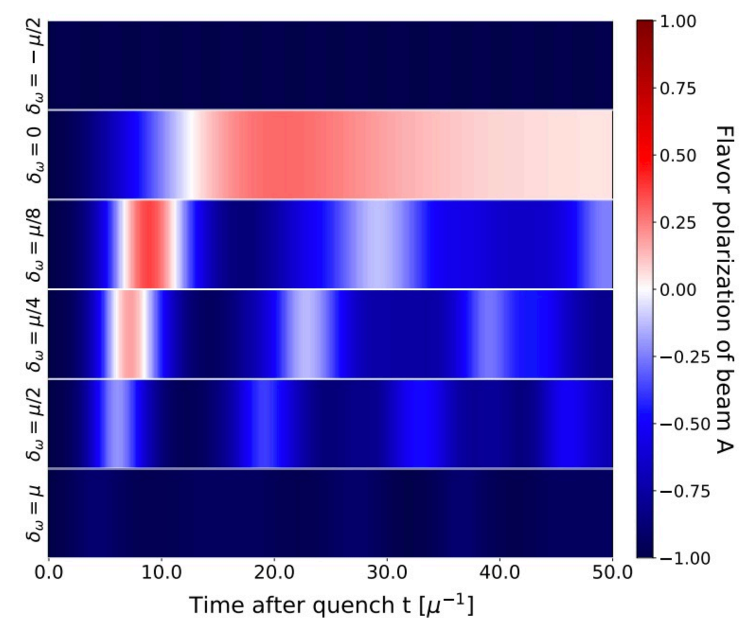


FIG. 1. (Color online) Flavor polarization per particle $\langle J_z^A(t)\rangle/(N/4)$ of neutrinos in the A beam as a function of time for six values of the energy asymmetry parameter δ_ω/μ (from top to bottom): $-0.5, 0.0, 0.125, 0.25, 0.5, 1.0$.

Entanglement and collective flavor oscillations in a dense neutrino gas

Michael J. Cervia,[1,*] Amol V. Patwardhan,[1,2,†]
A. B. Balantekin,[1,‡] S. N. Coppersmith,[1,3,§] and Calvin W. Johnson[4,¶]
[1]*Department of Physics, University of Wisconsin–Madison, Madison, Wisconsin 53706, USA*
[2]*Department of Physics, University of California, Berkeley, CA 94720-6300, USA*
[3]*School of Physics, The University of New South Wales, Syd*
[4]*Department of Physics, San Diego State University, San*
(Dated: October 9, 2019

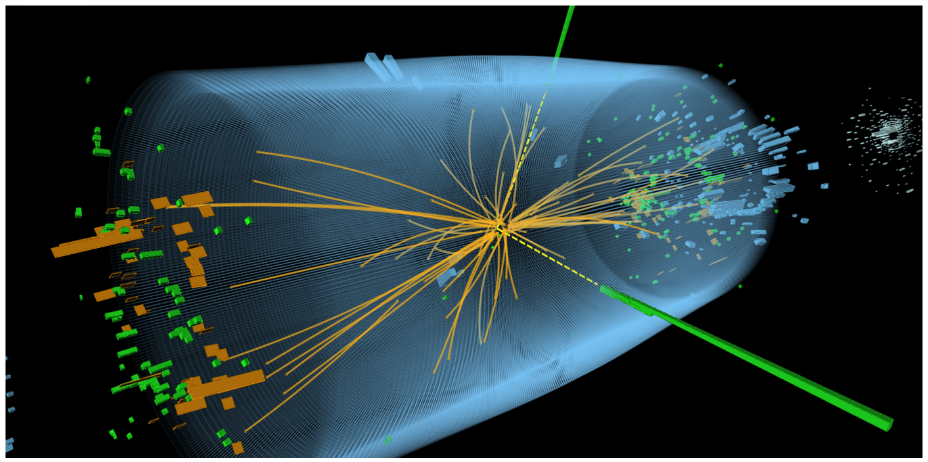
Quantum simulation of neutrino oscillations with trapped ions

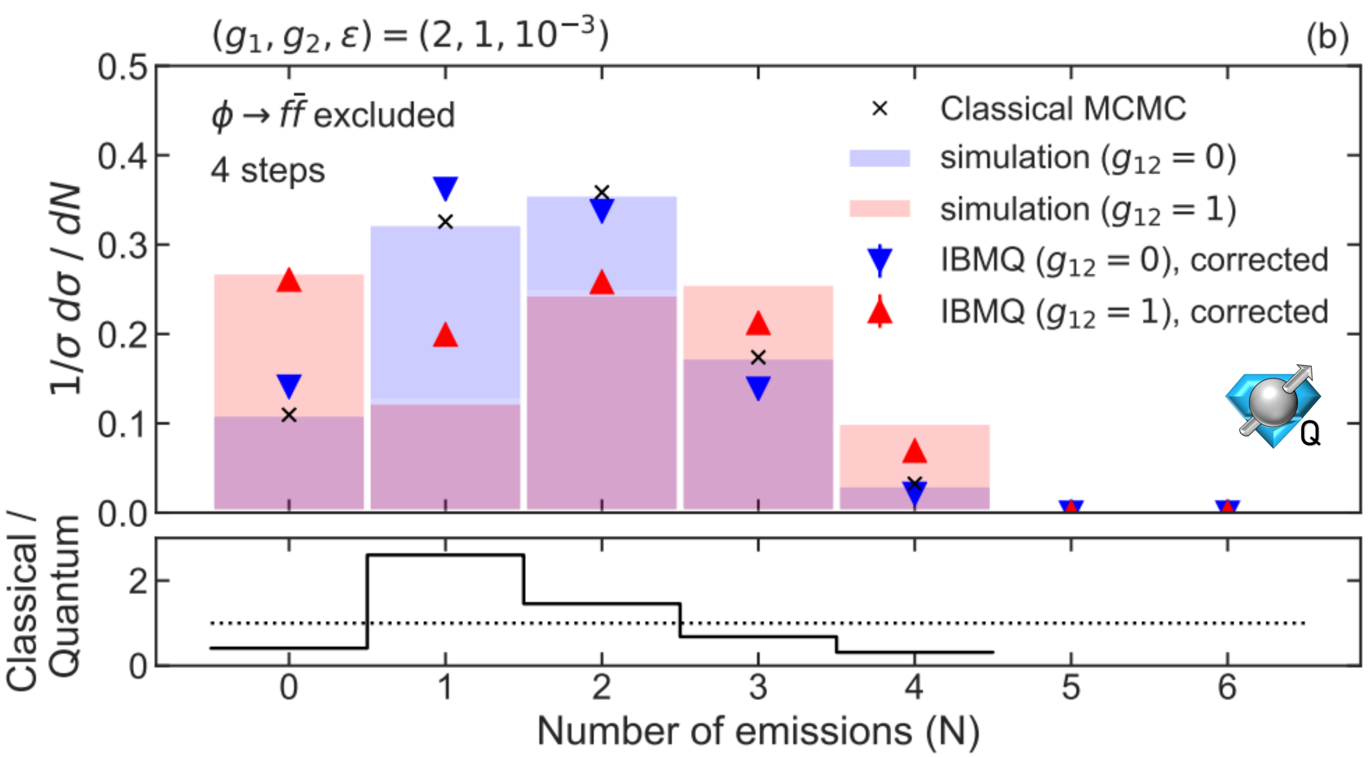
C Noh[1], B M Rodríguez-Lara[1] and D G Angelakis[1,2]
[1] Centre for Quantum Technologies, National University of Singapore, 2 Science
University of Crete, Chania, Crete, Greece,
mitris.angelakis@googlemail.com

Neutrino oscillations in a quantum processor

C. A. Argüelles[1] and B. J. P. Jones[2]
[1]*Laboratory for Nuclear Science, Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[2]*Department of Physics, University of Texas at Arlington, Arlington, Texas 76019, USA*

Fragmentation and Collisions





A quantum algorithm for high energy physics simulations
Christian W. Bauer, Wibe A. de Jong, Benjamin Nachman, Davide Provasoli, arXiv:1904.03196 [hep-ph]

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

Simulating Collider Physics on Quantum Computers using Effective Field Theories
Christian W. Bauer, Benjamin Nachman, Marat Freytsis, arXiv:2102.05044 [hep-ph]

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)

Kink Scattering in Spin Models

elastic and inelastic - fragmentation

arXiv.org > quant-ph > arXiv:2012.07243

Quantum Physics

[Submitted on 14 Dec 2020]

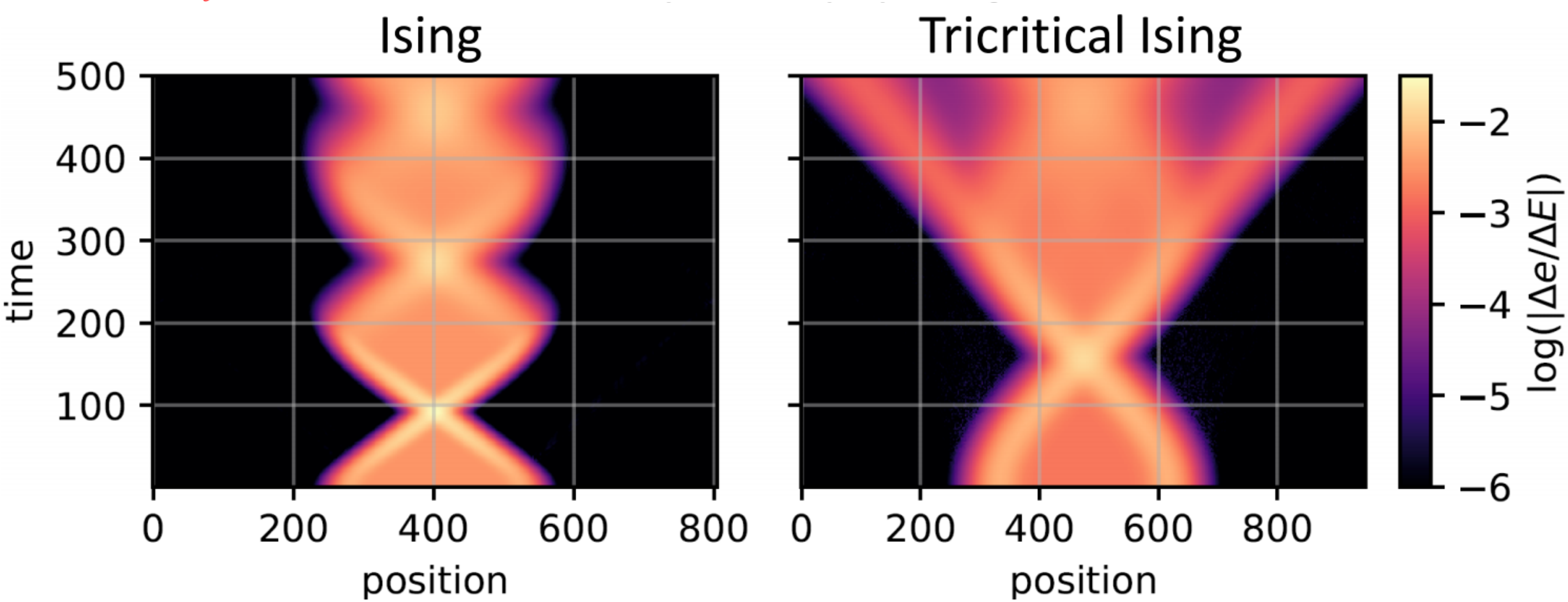
Collisions of false-vacuum bubble walls in a quantum spin chain

Ashley Milsted, Junyu Liu, John Preskill, Guifre Vidal

Also work by A Gorshkov and collaborators

Explicit symmetry breaking (false vacuum)

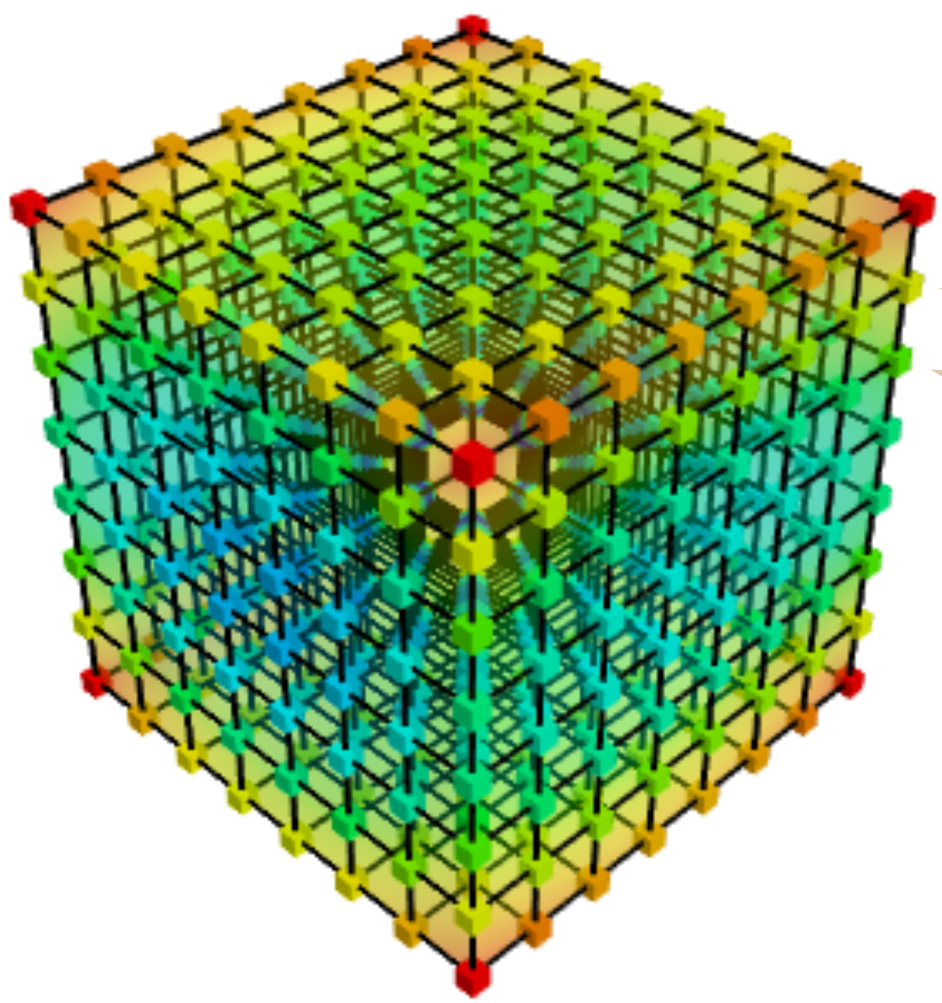
$$H=\sum_{j=1}^{N}\left[-Z_jZ_{j+1}-gX_j-hZ_j+\lambda\left(X_jZ_{j+1}Z_{j+2}+Z_jZ_{j+1}X_{j+2}\right)\right]$$

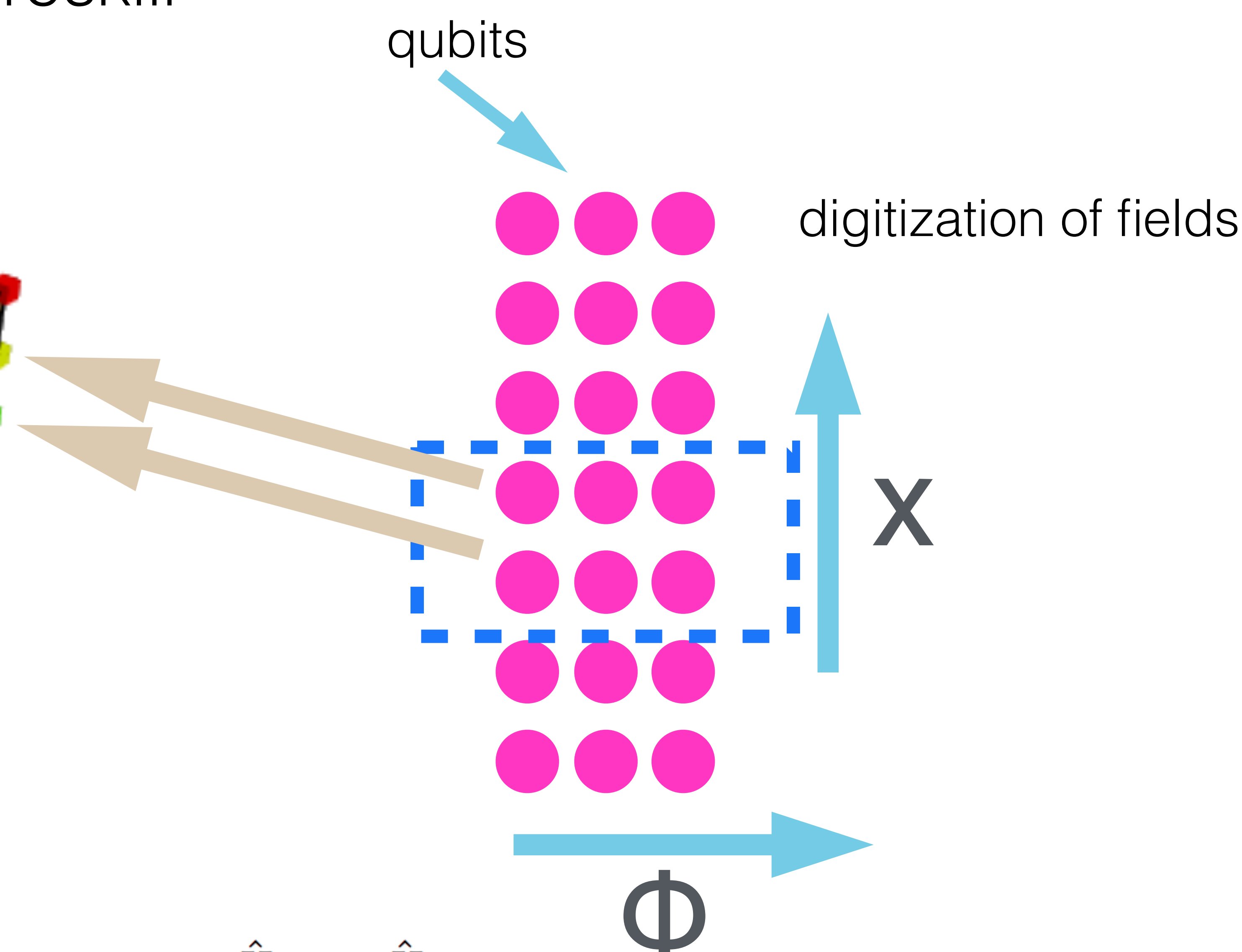


Scalar Field Theory
The Gold Standard - Jordan, Lee, Preskill ; > 2010
Digital Quantum Simulation

BQP-complete - Jordan, Lee, Preskill

1 number at each point in space





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

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

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

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

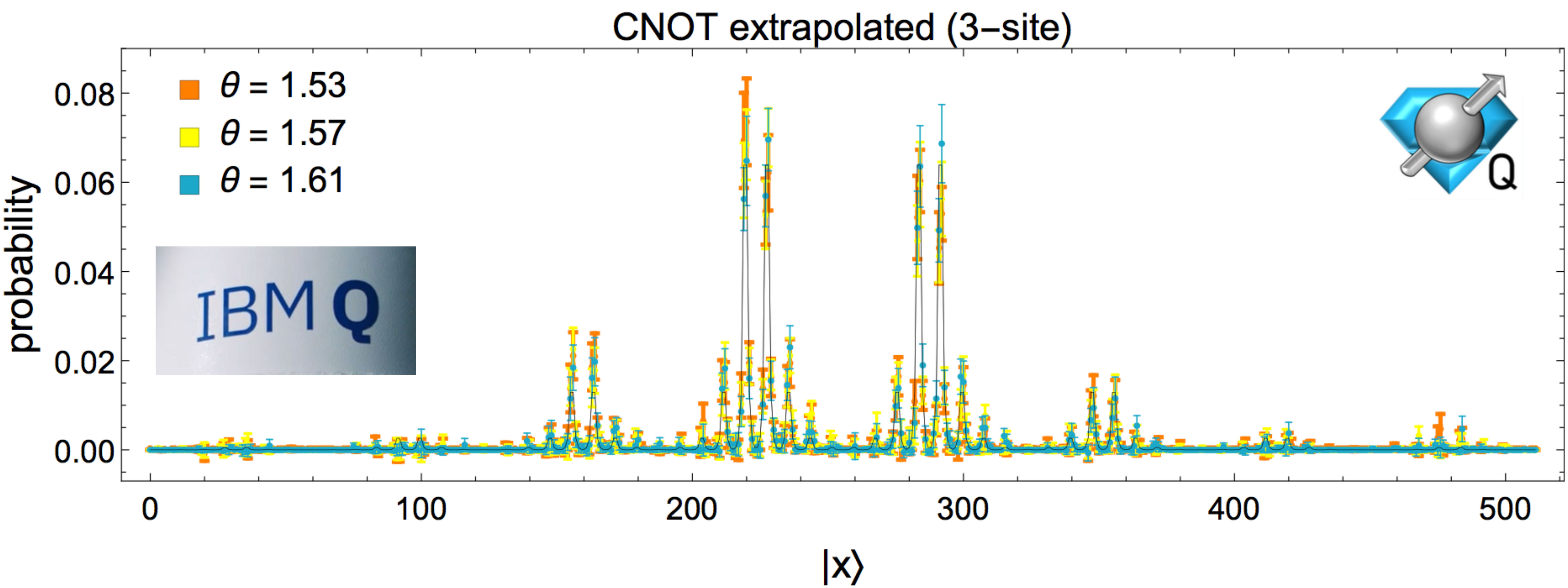
Scattering Wavepackets in Scalar Field Theory

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**

Three Lattice Sites in Scalar Field Theory
3 qubits per site



Natalie Klco and MJS

Quantum Circuits Organized to Reflect the Physics

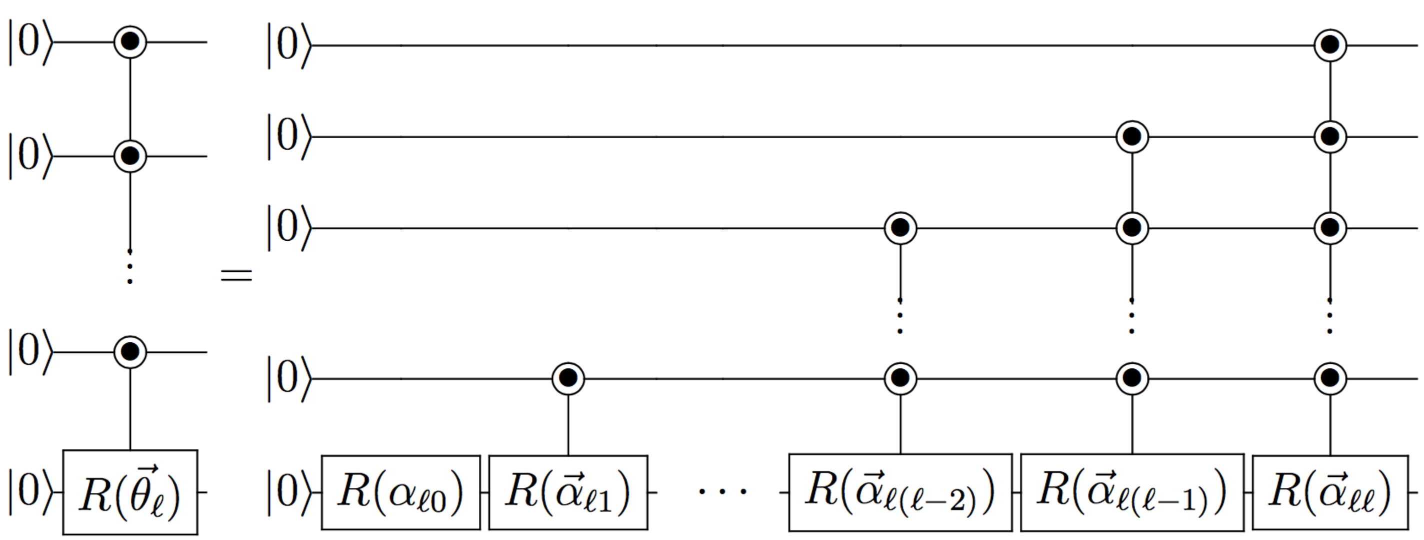
Scalar Field Theory

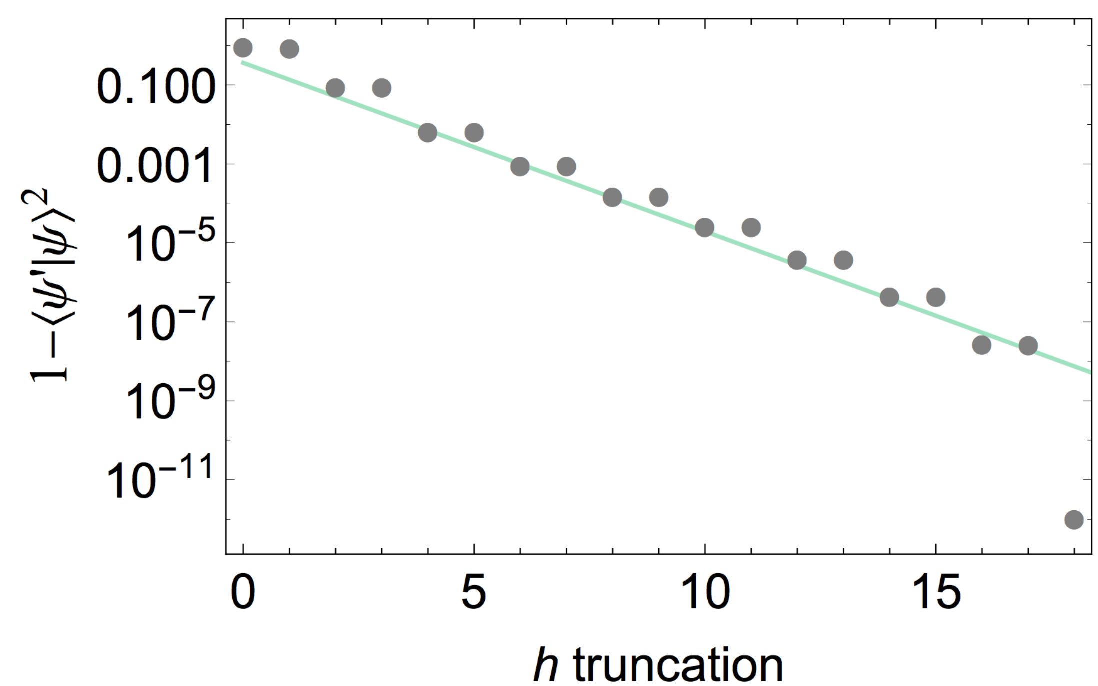
Natalie Klco and MJS

Phys.Rev.A 102 (2020) 5, 052422

Phys.Rev.A 102 (2020) 1, 012619

- Jordan, Lee, Preskill
- ORNL/UTK, FNAL, LANL, UW, ….





RG fixed-point angles

- classical simulation of a few Compton wavelengths
- used for beyond classical state prep
- analogous to domain decomposition

Gauge Theories

A number of different frameworks being pursued
The focus of recent workshop

Quantum Simulation of Strong Interactions (QuaSI) Workshop 1 : Theoretical Strategies for Gauge Theories

IQuS InQubator for Quantum Simulation

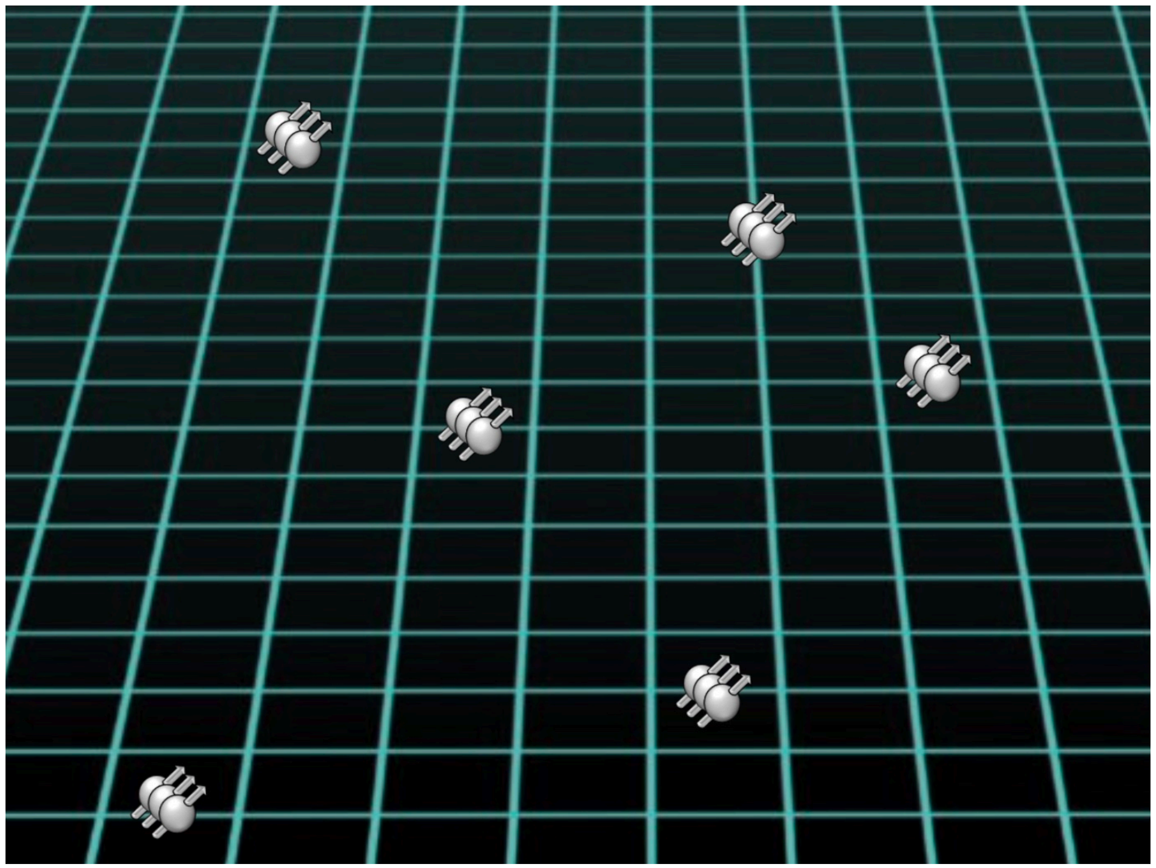
Organizers: Christian Bauer (LBNL), Zohreh Davoudi (UMD), Natalie Klco (Caltech) and Erez Zohar (Jerusalem).

Jun 01 - 07 2021

Quantum Simulation of Strong Interactions (QuaSI) Workshop 2 : Implementation Strategies for Gauge Theories

A community-led study of strategies for implementing gauge theory simulations on quantum architectures.

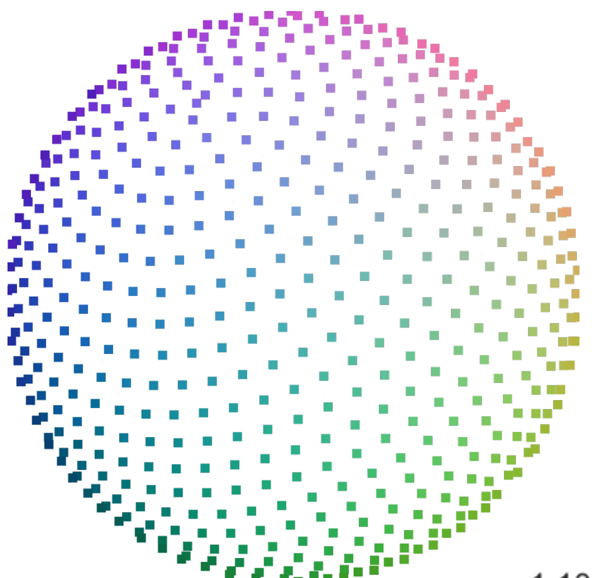
Gauge Theories



- Finite lattice to support the fields
- 3-dim
- Real-time Hamiltonian evolution
- Fields mapped to qubits/qudits
- Hybrid - tasks for QPU?

- Different mappings (most “efficient” path to continuum physics?)
  - “qubits arranged” with fermions on sites and gauge fields on links (KS)
  - or continuum fields de-localized. (e.g. quantum link models)
  - truncations/samplings in gauge rotations or irreps
  - and/or Integrate out gauge freedoms
  - and/or Gauss’s law explicit/implicit, error correction to enforce

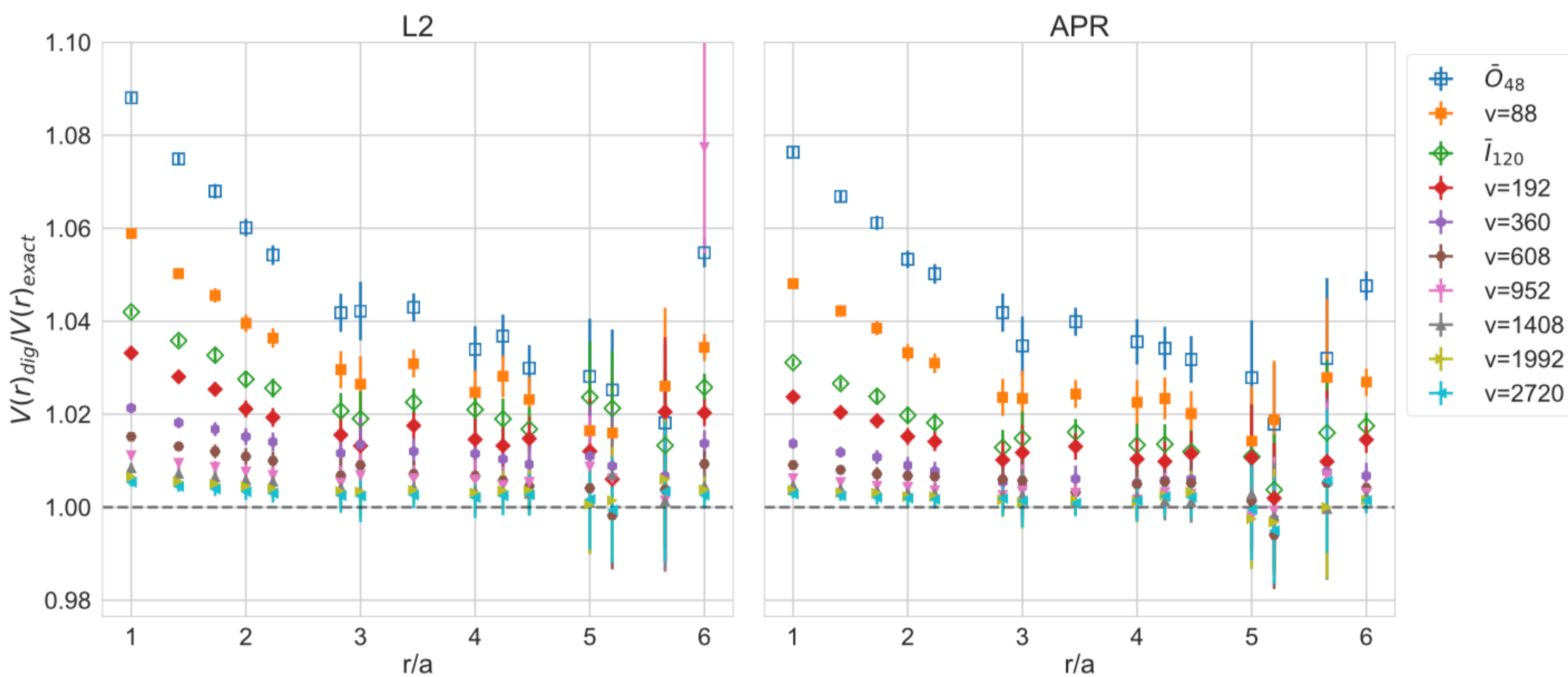
Starting down the Path
Digitizing SU(2) Gauge Theory



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*



Gluon Field Digitization via Group Space Decimation for Quantum Computers

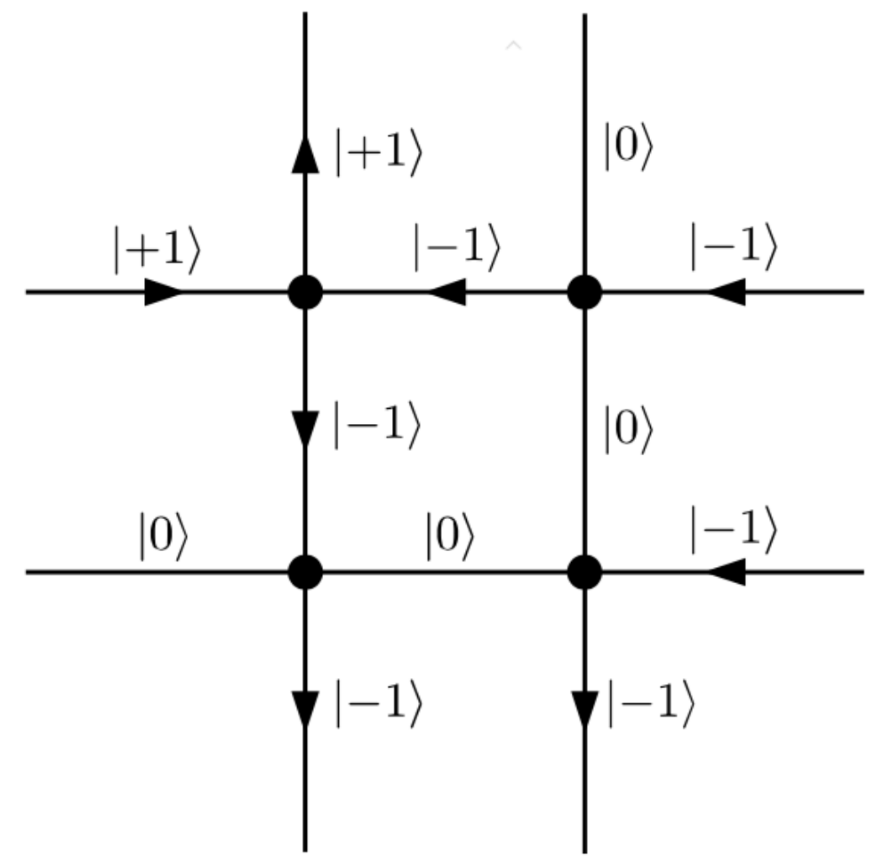
Yao Ji,[1,2,*] Henry Lamm,[3,†] and Shuchen Zhu[4,‡]

Gauge Theories

Simulating Lattice Gauge Theories within Quantum Technologies

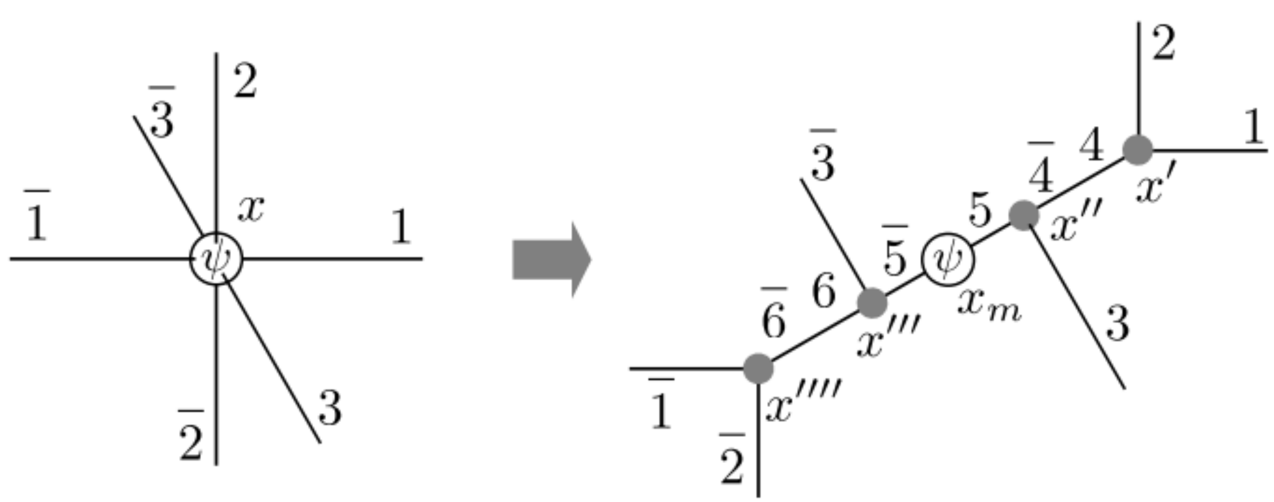
M.C. Bañuls[1,2], R. Blatt[3,4], J. Catani[5,6,7], A. Celi[3,8], J.I. Cirac[1,2], M. Dalmonte[9,10], L. Fallani[5,6,7], K. Jansen[11], M. Lewenstein[8,12,13], S. Montangero[7,14 a], C.A. Muschik[3], B. Reznik[15], E. Rico[16,17 b], L. Tagliacozzo[18], K. Van Acoleyen[19], F. Verstraete[19,20], U.-J.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

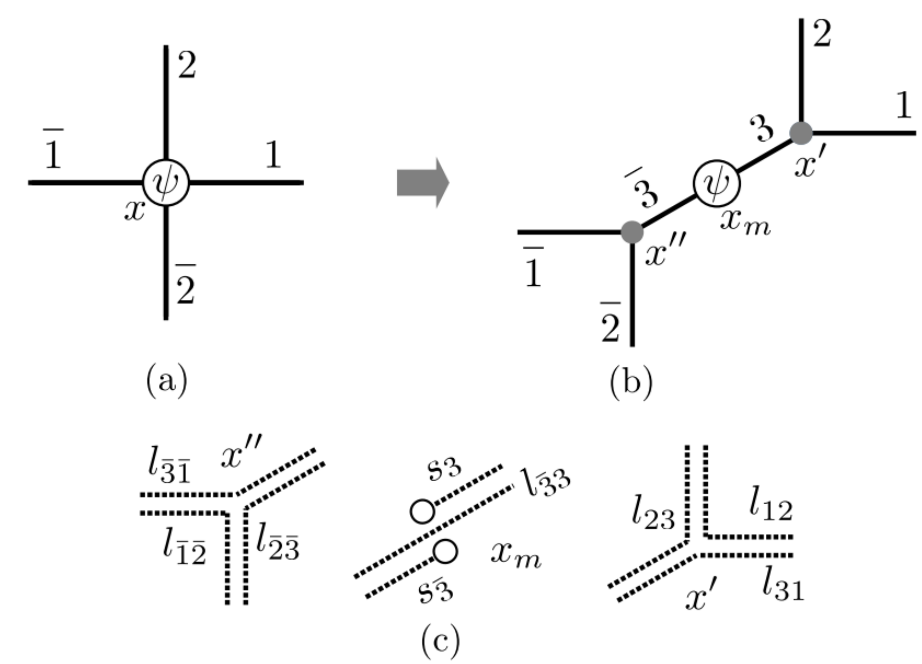
arXiv:1911.00003v1 [quant-ph] 31 Oct 2019



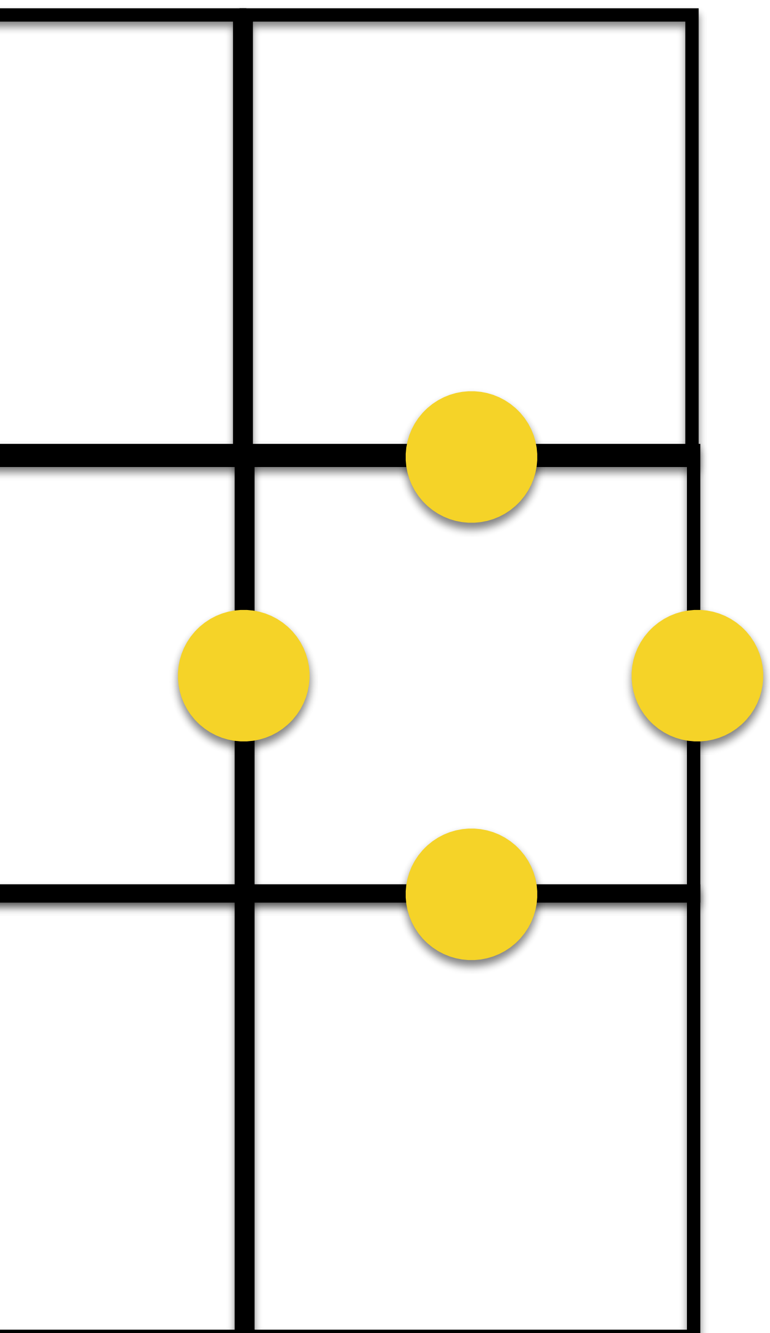
Many interesting recent contributions
- rapid progress by theorists
- rapid progress in devices

For example:
- Gauss's Law constraints
- Oracles and error-correction
- Loop-String-Hadron (Raychowdhuri and Stryker)





Quantum Implementations Utilizing Entanglement e.g. Z_2 theory

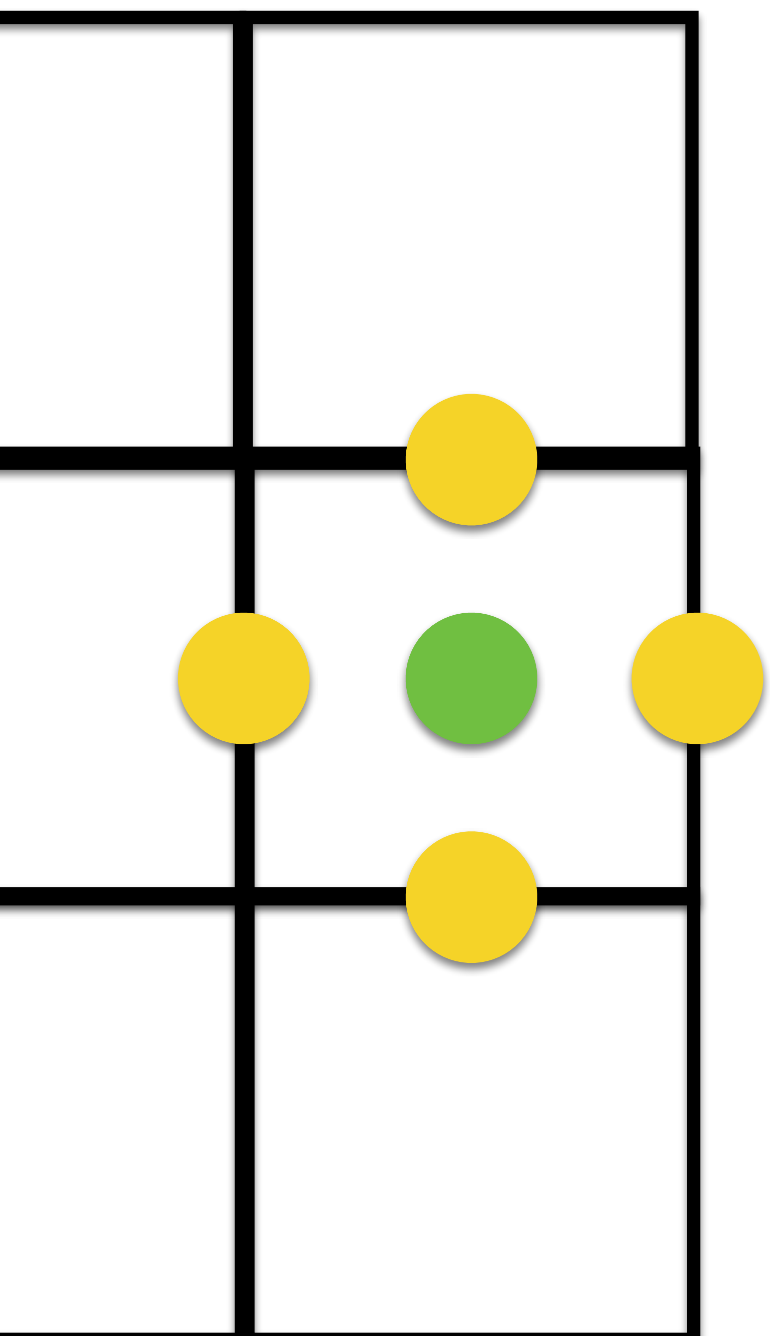


We want the value of the plaquette operator

$$\sigma_4^x \sigma_3^x \sigma_2^x \sigma_1^x$$

Erez Zohar

Quantum Implementations Utilizing Entanglement e.g. Z_2 theory



We want the value of the plaquette operator

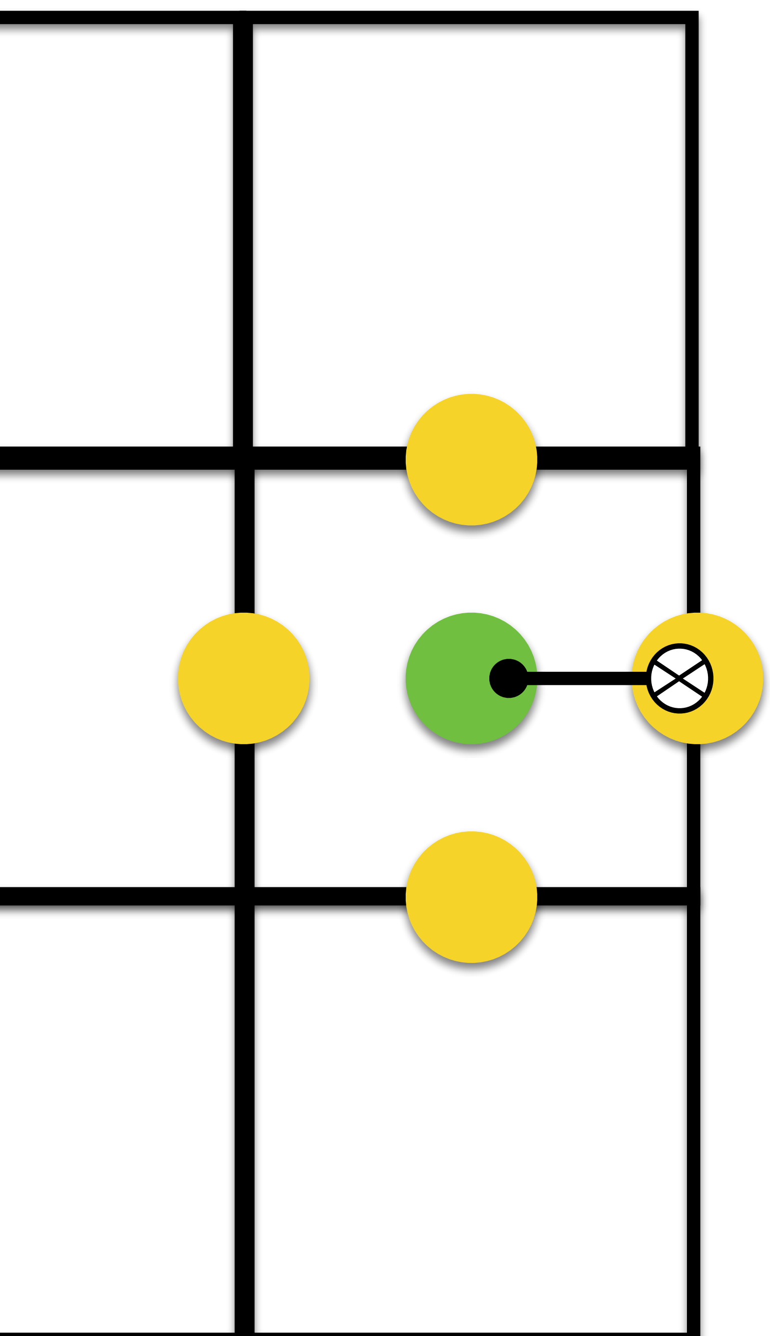
$$\sigma_4^x \sigma_3^x \sigma_2^x \sigma_1^x$$

$$|c\rangle \sim |0\rangle + |1\rangle$$

introduce auxillary qubits
- a commonly used and useful resource

Erez Zohar

Quantum Implementations Utilizing Entanglement e.g. Z_2 theory



We want the value of the plaquette operator

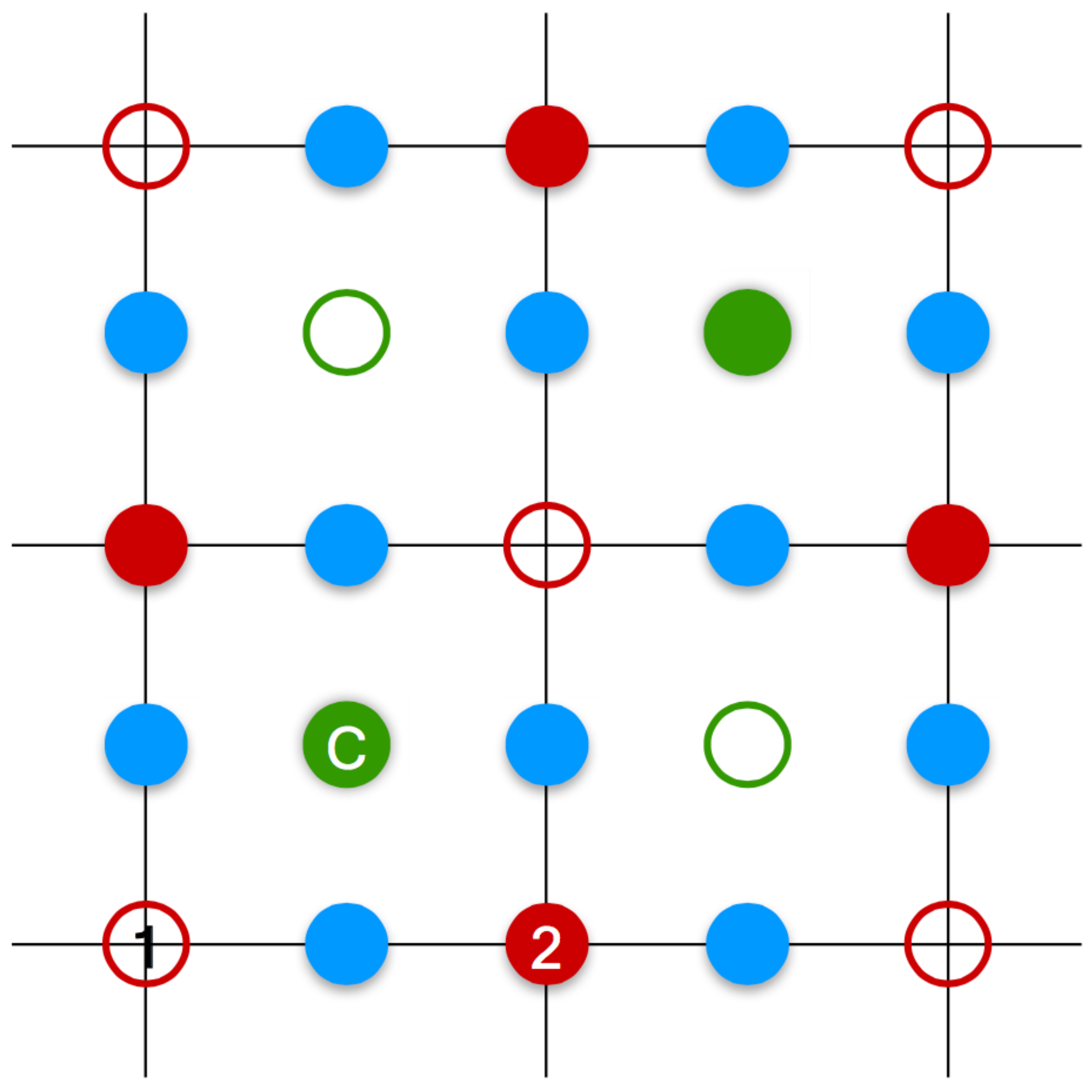
$$\sigma_4^x \, \sigma_3^x \, \sigma_2^x \, \sigma_1^x$$

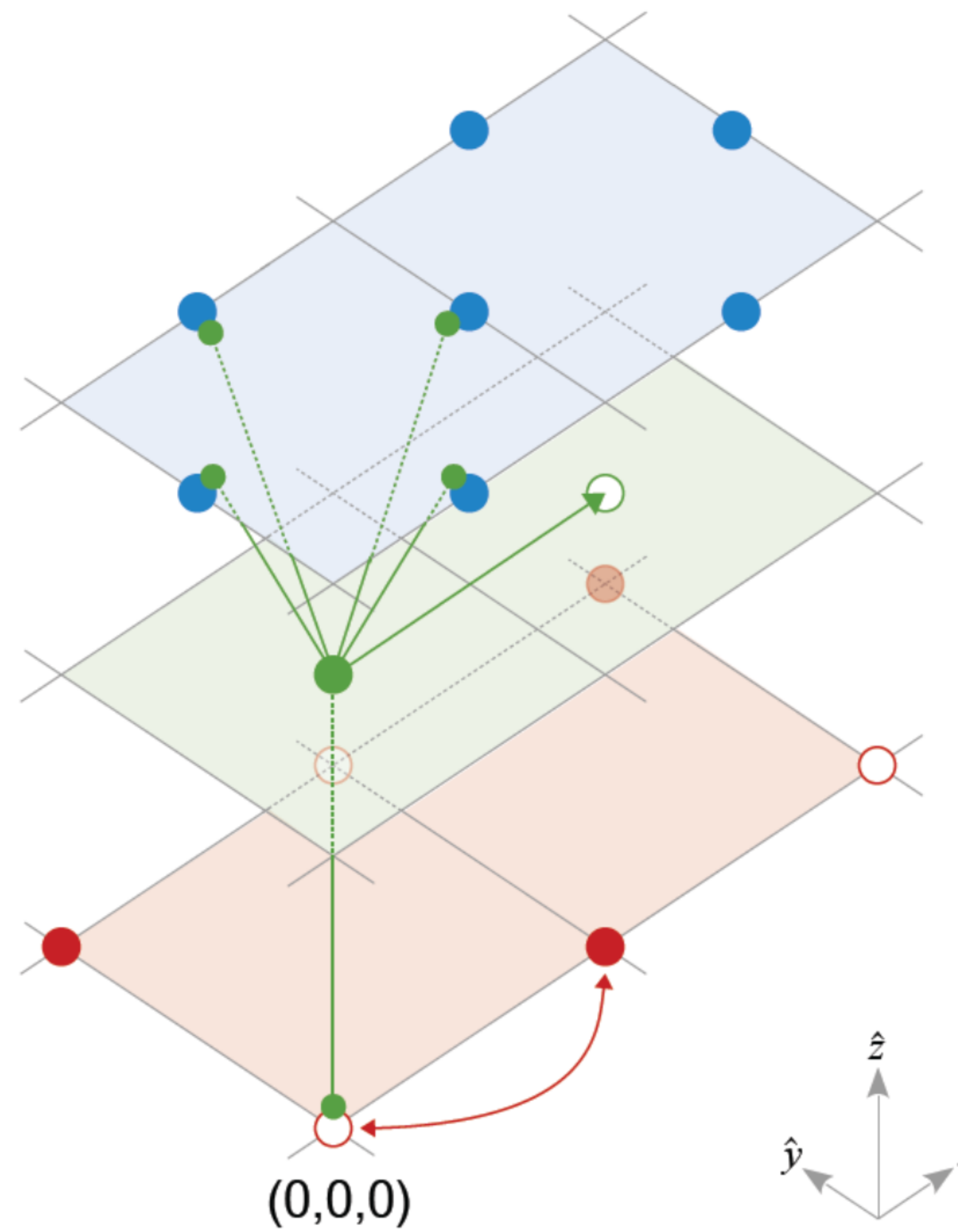
$$U\,|c\rangle \sim |\,0\,\rangle + \sigma_1^x \otimes |\,1\,\rangle$$

Analogous sequence of operations enables accumulation of evolution operator onto auxillary qubits

Erez Zohar

Quantum Implementations Utilizing Entanglement e.g. Z_2 theory





E. Zohar, A. Farace, B. Reznik, J. I. Cirac, PRA 2017.

E. Zohar, A. Farace, B. Reznik, J. I. Cirac, PRL 2017.

(slide from Reznik's UMD presentation)

Schwinger Model at Scale
Estimating Quantum Resource Needs

Quantum Algorithms for Simulating the Lattice Schwinger Model

Alexander F. Shaw[1,5], Pavel Lougovski[1], Jesse R. Stryker [2], and Nathan Wiebe[3,4]

[1]Quantum Information Science Group, Computational Sciences and Engineering Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, U.S.A.

[2]Institute for Nuclear Theory, University of Washington, Seattle, WA 98195-1550, U.S.A.

[3]Department of Physics, University of Washington, Seattle, WA 98195, U.S.A.

[4]Pacific Northwest National Laboratory, Richland, WA 99354, U.S.A.

[5]Department of Physics, University of Maryland, College Park, Maryland 20742, U.S.A.

August 5, 2020

Corollary 9 (Trotterized Time Evolution Cost in Fault-Tolerant Model). *Consider any $\delta > 0$ (Trotter error), $T \in \mathbb{R}$ (total evolution time), and let $V(t)$ be the second-order Trotter-Suzuki decomposition of e^{-iHt} as defined as in (38). Additionally, let μ be a constant and x be lower bounded by a constant (i.e. $x \in \Omega(1)$).*

Under these assumptions, there exists an $s \in \mathbb{N}$ (Trotter steps) such that $\|V(T/s)^s - e^{-iHT}\| \leq \delta$, where $V(T/s)^s$ consists of $N_{\exp}$ matrix exponentials and

$$N_{\exp} \in O\left(\frac{N^{3/2}T^{3/2}\Lambda x^{1/2}}{\delta^{1/2}}\right). \tag{92}$$

Furthermore, there exists an implementation of the Trotter decomposition within spectral-norm error δ of e^{-iHT} that requires a number of T-gates in

$$\widetilde{O}\left(\frac{N^{3/2}T^{3/2}\Lambda x^{1/2}}{\delta^{1/2}}\right), \tag{93}$$

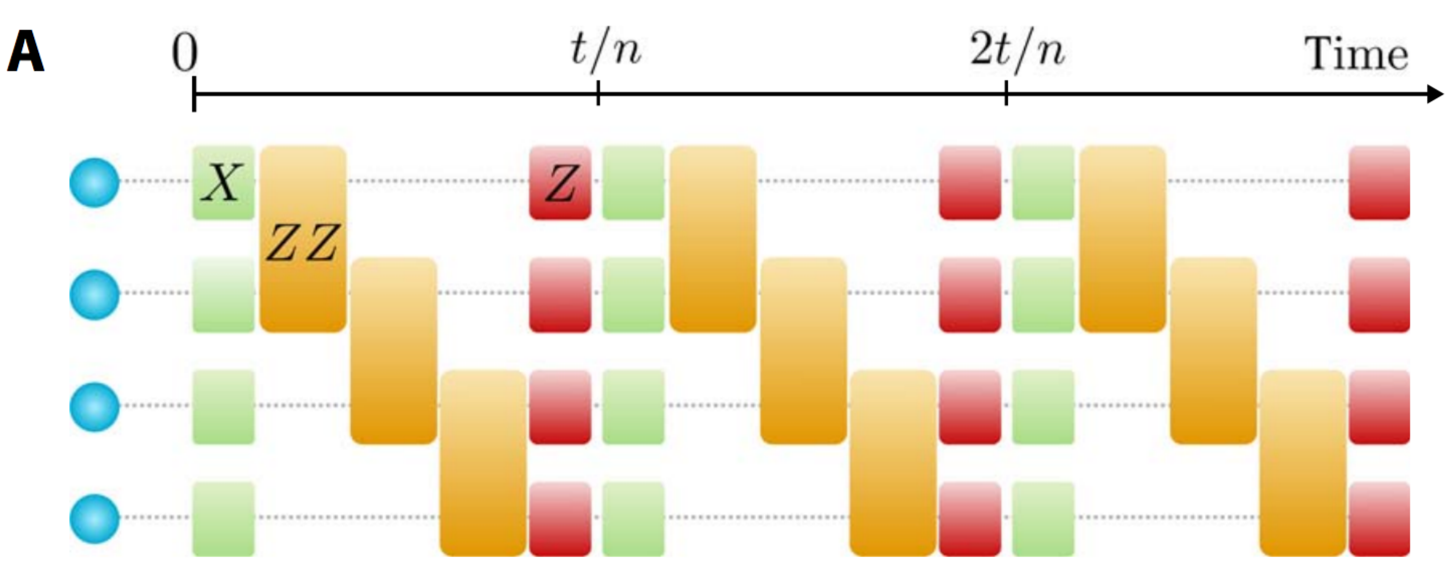
where $\widetilde{O}(\cdot)$ is equivalent to $O(\cdot)$ but with all non-dominant sub-polynomial factors in the scaling suppressed.

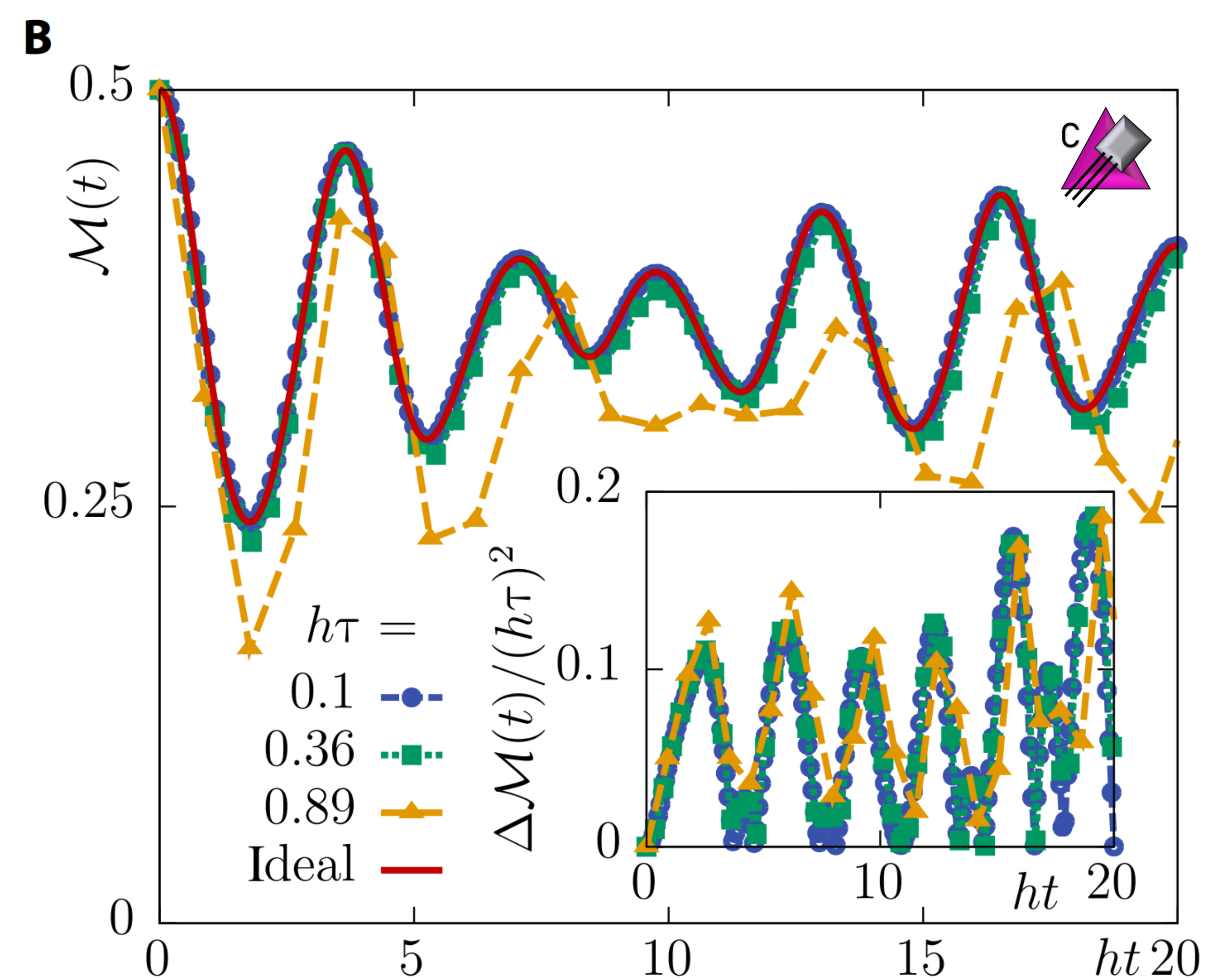
Real Time Evolution
Trotterization

e.g., H= Ha + Hb

$$e^{-i\,Hb\,\delta t}\; e^{-i\,Ha\,\delta t}\; e^{-i\,Hb\,\delta t}\; e^{-i\,Ha\,\delta t} \ldots\; e^{-i\,Ha\,\delta t}\, |\Psi\rangle$$

$$\rightarrow\; e^{-i\,H\,t}\, |\Psi\rangle$$





Heyl, Hauke, Zoller, Science 2019

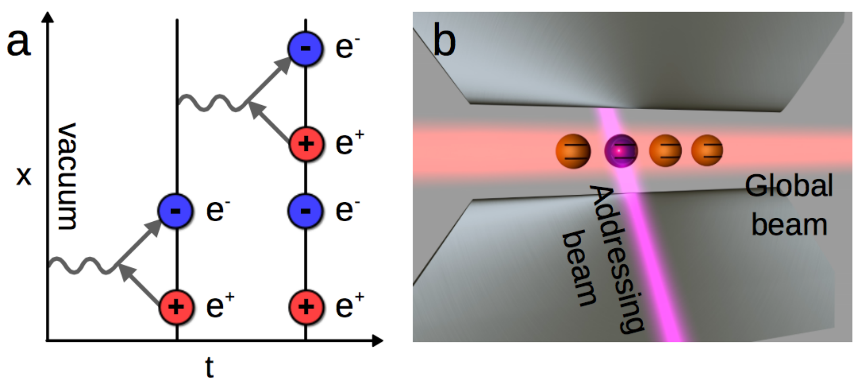
Dynamics in the Schwinger Model
1-dim systems

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

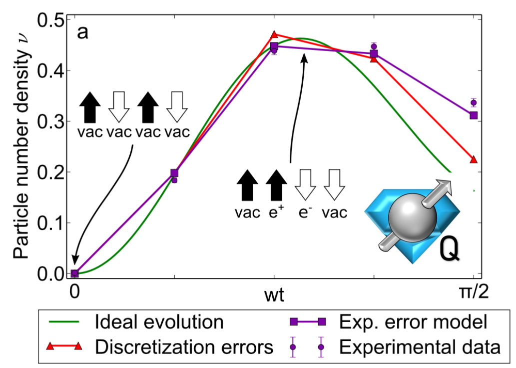
Esteban A. Martinez,[1,*] Christine Muschik,[2,3,*] Philipp Schindler,[1] Daniel Nigg,[1] Alexander Erhard,[1] Markus Heyl,[2,4] Philipp Hauke,[2,3] Marcello Dalmonte,[2,3] Thomas Monz,[1] Peter Zoller,[2,3] and Rainer Blatt[1,2]

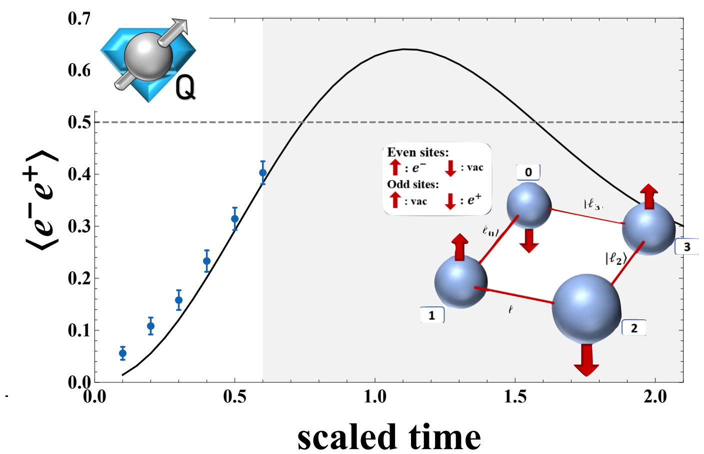
(2016)

1+1 dim QED

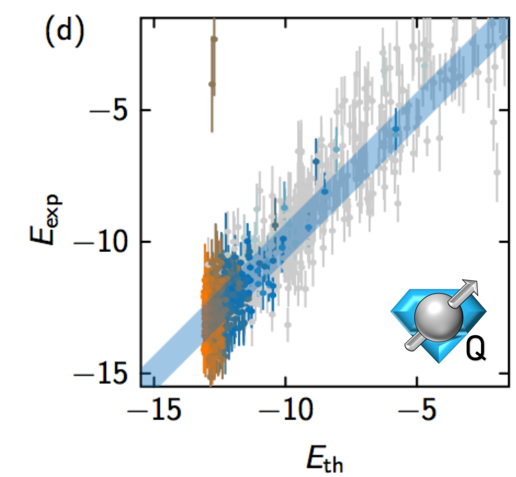


Innesbruck

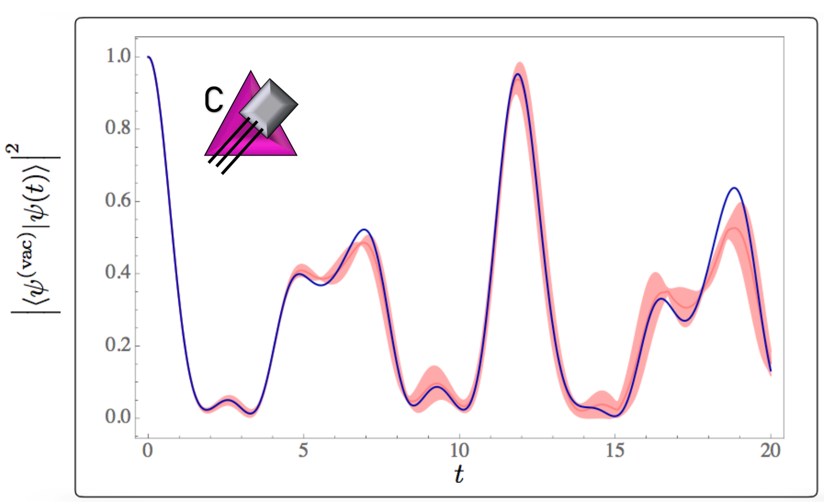




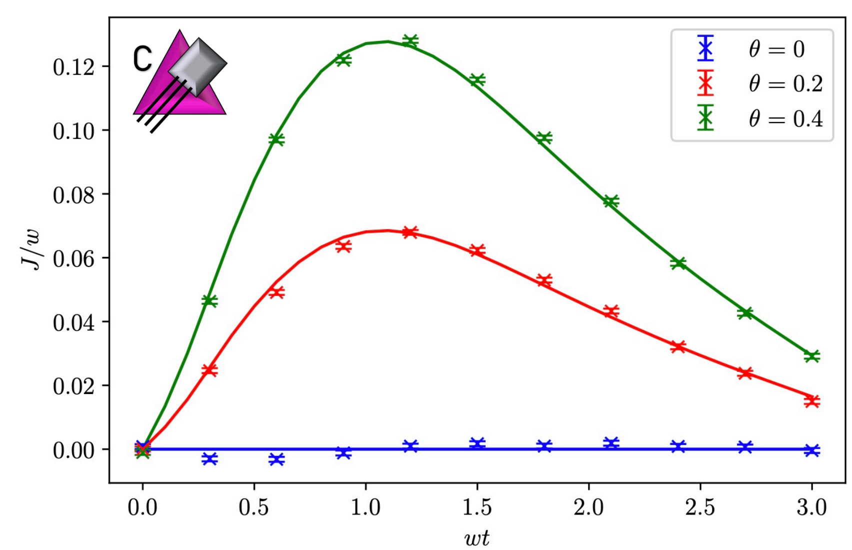
ORNL-Washington-Basque



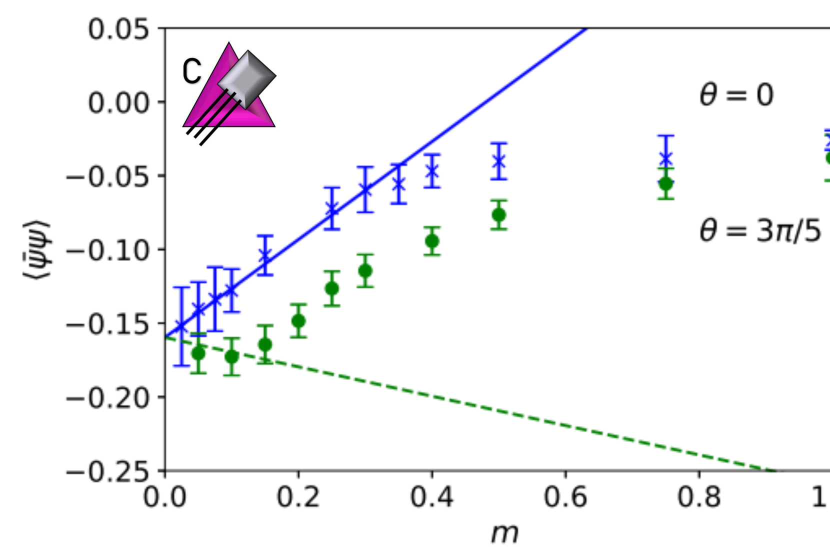
Innesbruck



Maryland



Kharzeev-Kikuchi



Chakraborty, Honda, Izubuchi, Tomiya

Quantum Algorithms for Simulating the Lattice Schwinger Model

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

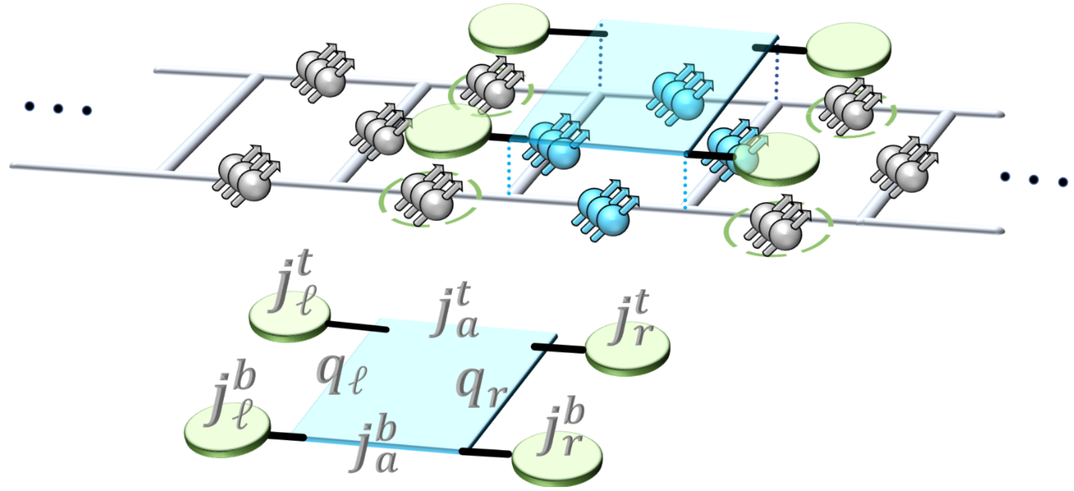
Quantum 2020-08-10, volume 4, page 306

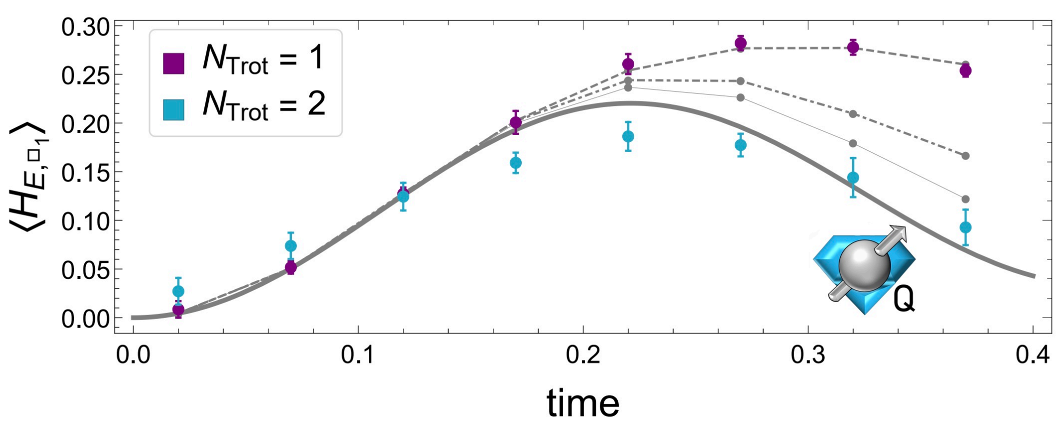
arXiv:2002.11146v1 [quant-ph]

SU(2) in low-dimensions

Kogut-Susskind, 1970s

Byrnes and Yamamoto, 2005





- Only dynamical gauge fields
- Gauge Variant Completions (GVC)
- Severely truncated in field space
- 2D, but really 1D

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*

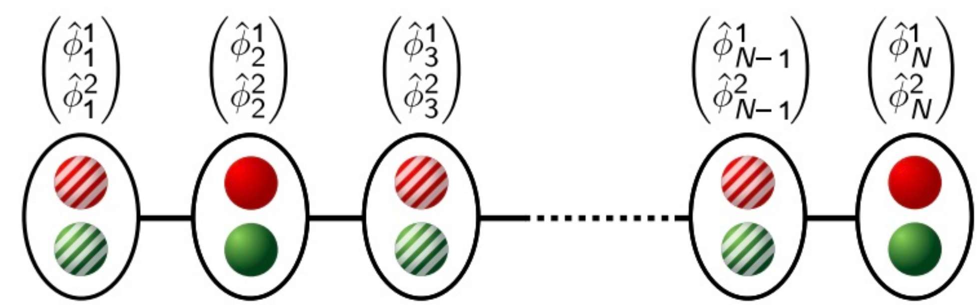
(Dated: August 19, 2019 - 13:7)

SU(2) lattice gauge theory on a quantum annealer

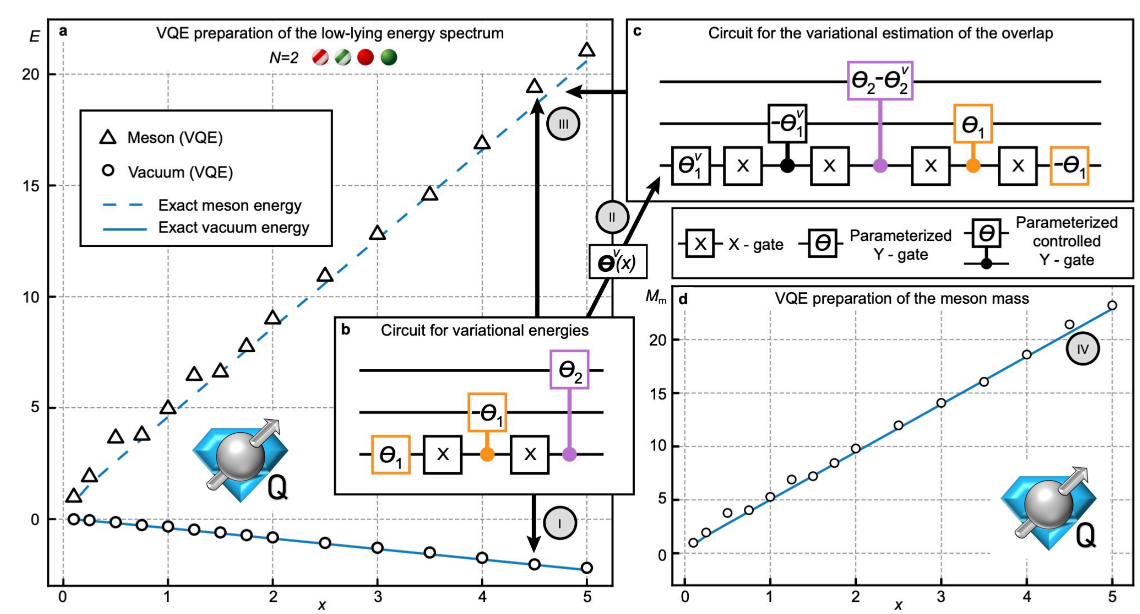
Sarmed A Rahman, Randy Lewis, Emanuele Mendicelli, and Sarah Powell

Department of Physics and Astronomy, York University, Toronto, Ontario, Canada, M3J 1P3

(Dated: March 15, 2021)



- Matter fields
- Non-dynamical gauge fields



SU(2) hadrons on a quantum computer

Yasar Atas *,[1,2,†] Jinglei Zhang *,[1,2,‡] Randy Lewis,[3] Amin Jahanpour,[1,2] Jan F. Haase,[1,2,§] and Christine A. Muschik[1,2,4]

- e-Print: 2102.08920 [quant-ph]

Toward Quantum Chromodynamics

PHYSICAL REVIEW A
covering atomic, molecular, and optical physics and quantum information

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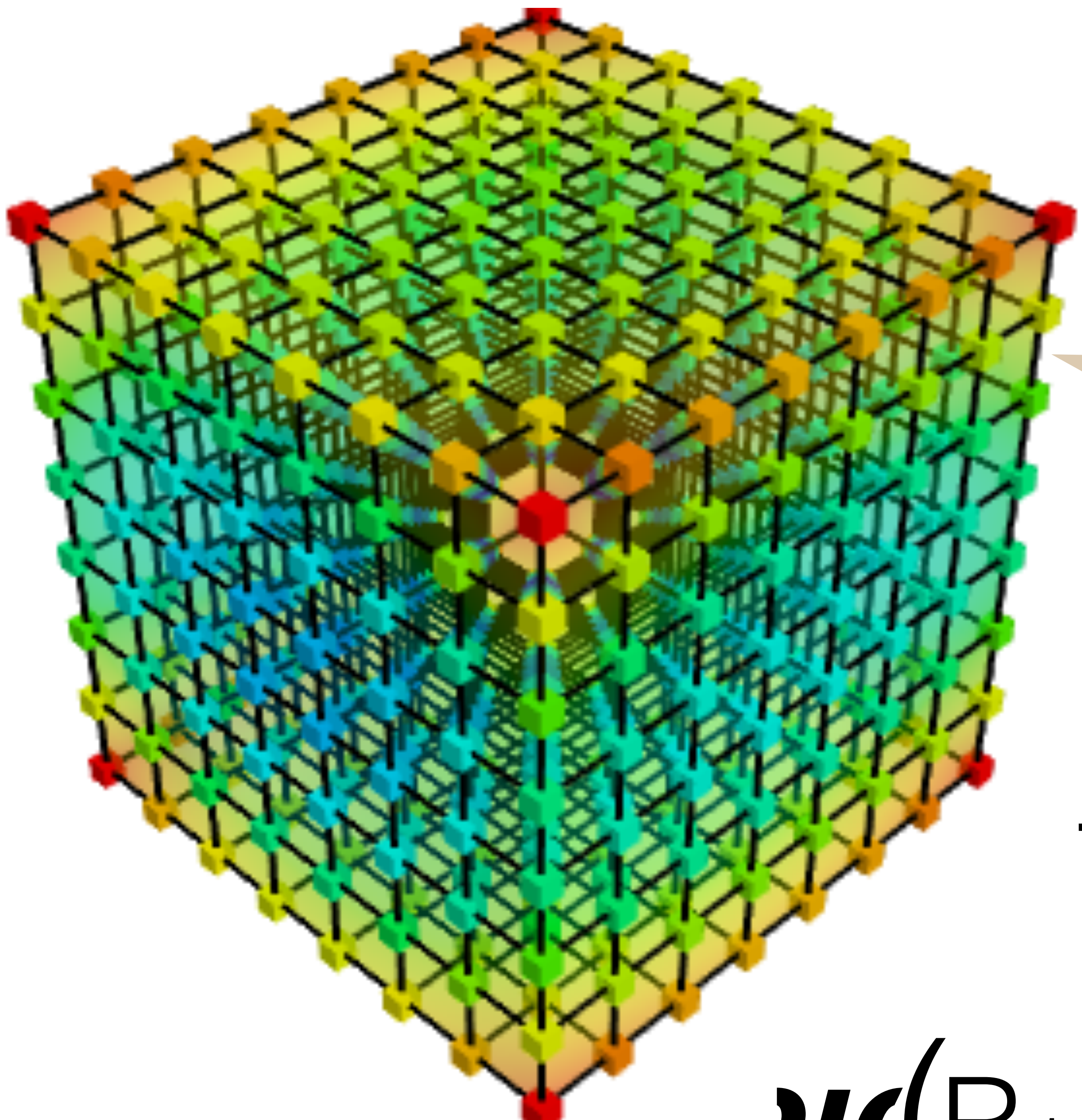
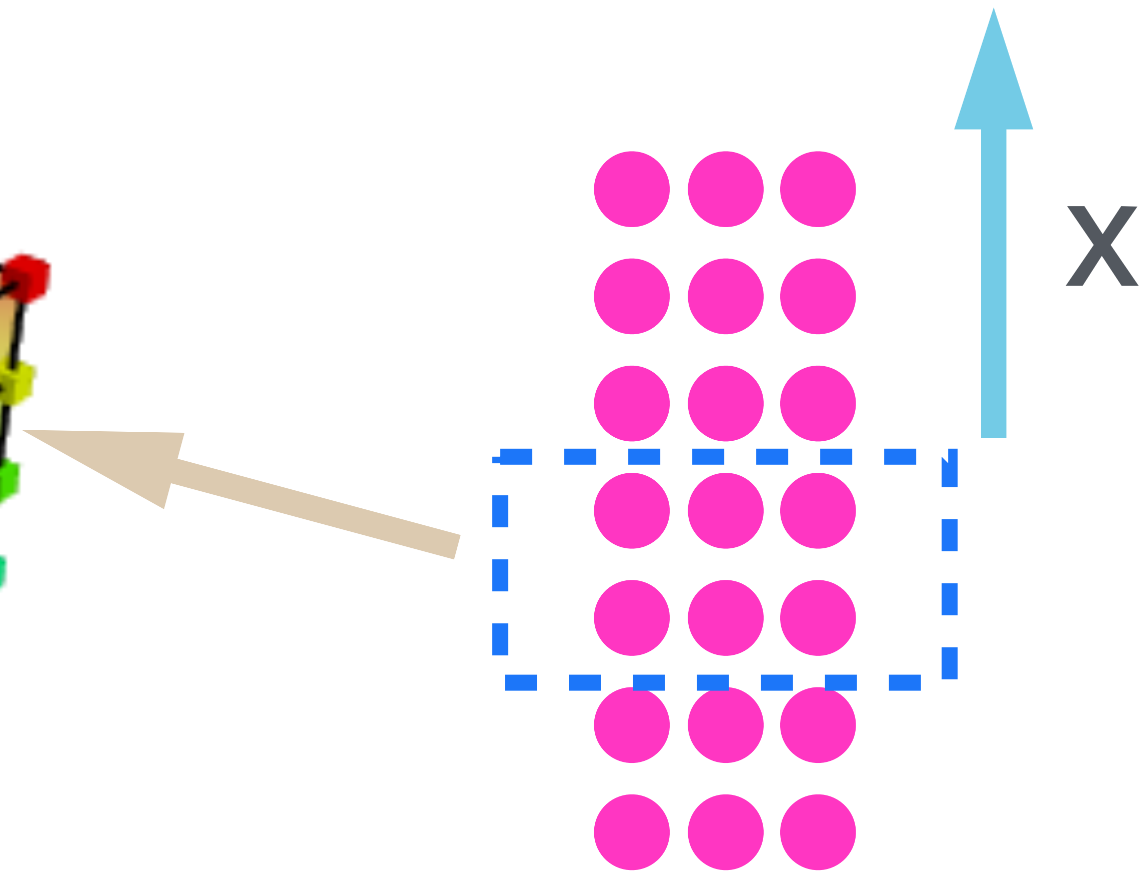
Simulating lattice gauge theories on a quantum computer

Tim Byrnes and Yoshihisa Yamamoto
Phys. Rev. A **73**, 022328 – Published 17 February 2006

One of a number of frameworks





$$T^{a_1 \ldots a_p}_{b_1 \ldots b_q} \xrightarrow[\text{Gauge Invariance}]{} R(p,q)$$

$$\boldsymbol{\psi}\left(R_1\,, R_2 \qquad\qquad R_{L3}\right)$$

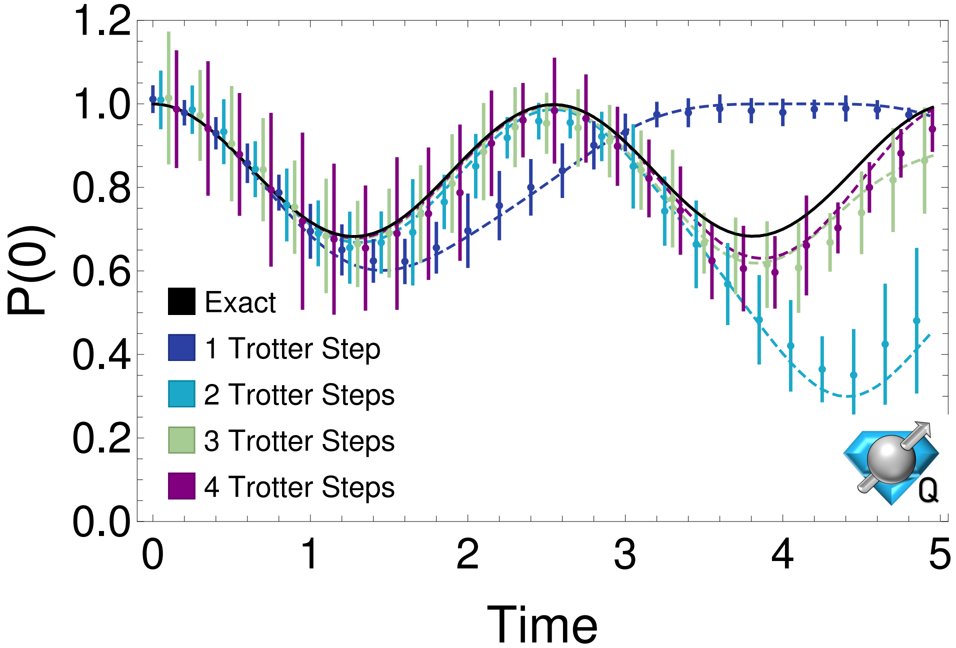
Toward QCD

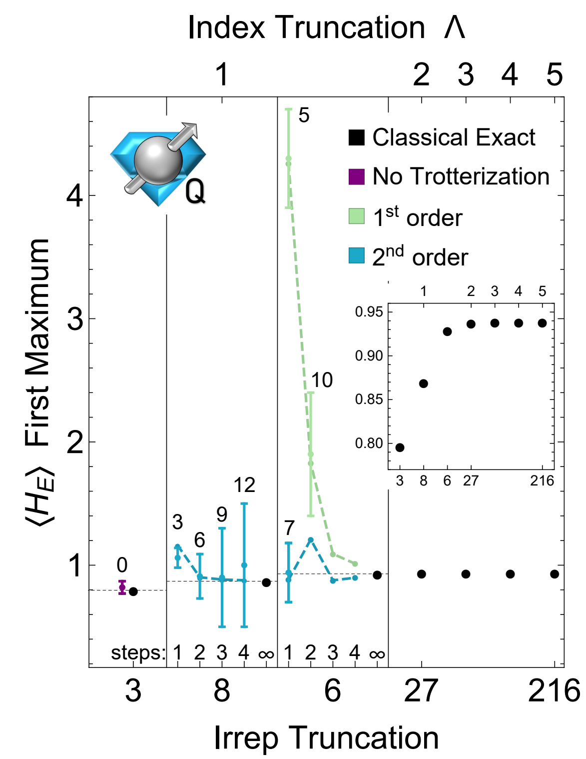
A Trailhead for Quantum Simulation of SU(3) Yang-Mills Lattice Gauge Theory in the Local Multiplet Basis

2021 Anthony Ciavarella,[1,*] Natalie Klco,[2,†] and Martin J. Savage[1,‡]

Ciavarella, Klco, MJS

Benchmarks





Global Basis

does not scale

$$|\psi_1^{(\mathbf{1}\mathbf{3}\bar{\mathbf{3}};++)}\rangle = |\chi(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})\rangle$$

$$|\psi_2^{(\mathbf{1}\mathbf{3}\bar{\mathbf{3}};++)}\rangle = \frac{1}{2}\left[\, |\chi(\mathbf{3},\bar{\mathbf{3}},\bar{\mathbf{3}},\mathbf{1},\mathbf{3},\mathbf{1})\rangle + |\chi(\bar{\mathbf{3}},\mathbf{3},\mathbf{3},\mathbf{1},\bar{\mathbf{3}},\mathbf{1})\rangle + |\chi(\mathbf{1},\mathbf{3},\mathbf{1},\mathbf{3},\bar{\mathbf{3}},\bar{\mathbf{3}})\rangle + |\chi(\mathbf{1},\bar{\mathbf{3}},\mathbf{1},\bar{\mathbf{3}},\mathbf{3},\mathbf{3})\rangle \,\right]$$

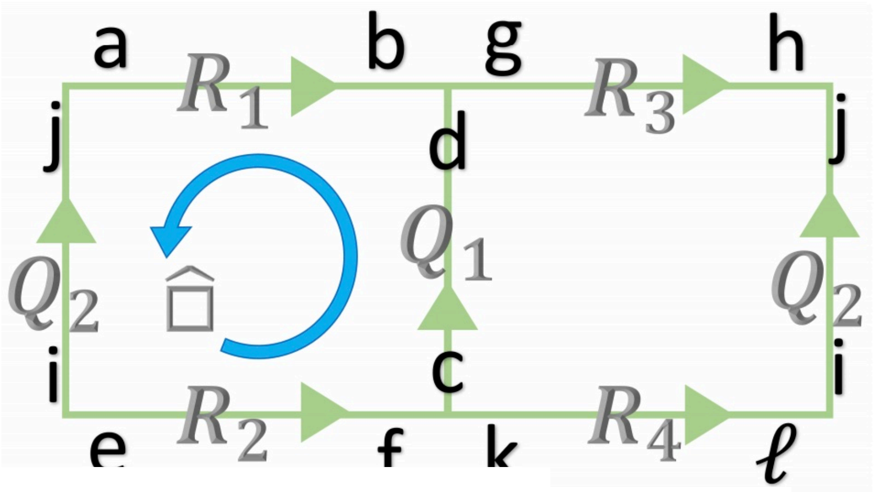
$$|\psi_3^{(\mathbf{1}\mathbf{3}\bar{\mathbf{3}};++)}\rangle = \frac{1}{\sqrt{2}}\left[\, |\chi(\mathbf{3},\mathbf{1},\bar{\mathbf{3}},\mathbf{3},\mathbf{1},\bar{\mathbf{3}})\rangle + |\chi(\bar{\mathbf{3}},\mathbf{1},\mathbf{3},\bar{\mathbf{3}},\mathbf{1},\mathbf{3})\rangle \,\right]$$

.....

- These are the states mapped to the device
- H is formed from matrix elements between these states

Toward QCD

Including **1** , **3** , $\overline{\mathbf{3}}$, **8** on each link only



$\mathbf{R_3}, \mathbf{Q_2}, \mathbf{R_4})\rangle$

$$|\psi_1^{(\mathbf{1}\mathbf{3}\overline{\mathbf{3}}\mathbf{8};+++)}\rangle = |\chi(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})\rangle \quad ,$$

$$|\psi_{2a}^{(\mathbf{1}\mathbf{3}\overline{\mathbf{3}}\mathbf{8};+++)}\rangle = \frac{1}{2}\left[\, |\chi(\mathbf{3},\overline{\mathbf{3}},\overline{\mathbf{3}},\mathbf{1},\mathbf{3},\mathbf{1})\rangle + |\chi(\overline{\mathbf{3}},\mathbf{3},\mathbf{3},\mathbf{1},\overline{\mathbf{3}},\mathbf{1})\rangle + |\chi(\mathbf{1},\mathbf{3},\mathbf{1},\mathbf{3},\overline{\mathbf{3}},\overline{\mathbf{3}})\rangle + |\chi(\mathbf{1},\overline{\mathbf{3}},\mathbf{1},\overline{\mathbf{3}},\mathbf{3},\mathbf{3})\rangle \,\right]$$

$$|\psi_{2b}^{(\mathbf{1}\mathbf{3}\overline{\mathbf{3}}\mathbf{8};+++)}\rangle = \frac{1}{\sqrt{2}}\left[\, |\chi(\mathbf{3},\mathbf{1},\overline{\mathbf{3}},\mathbf{3},\mathbf{1},\overline{\mathbf{3}})\rangle + |\chi(\overline{\mathbf{3}},\mathbf{1},\mathbf{3},\overline{\mathbf{3}},\mathbf{1},\mathbf{3})\rangle \,\right] \quad ,$$

$$|\psi_3^{(\mathbf{1}\mathbf{3}\overline{\mathbf{3}}\mathbf{8};+++)}\rangle = \frac{1}{\sqrt{2}}\left[\, |\chi(\mathbf{8},\mathbf{1},\mathbf{1},\mathbf{8},\mathbf{1},\mathbf{1})\rangle + |\chi(\mathbf{1},\mathbf{1},\mathbf{8},\mathbf{1},\mathbf{1},\mathbf{8})\rangle \,\right] \quad ,$$

$$\vdots$$

$$|\psi_9^{(\mathbf{1}\mathbf{3}\overline{\mathbf{3}}\mathbf{8};+++)}\rangle = |\chi(\mathbf{8},\mathbf{8},\mathbf{8},\mathbf{8},\mathbf{8},\mathbf{8})\rangle$$

- 15 basis states (4 qubits)
- Max electric energy ~ 6*3
- 8 $\otimes$ 8 $\otimes$ 8

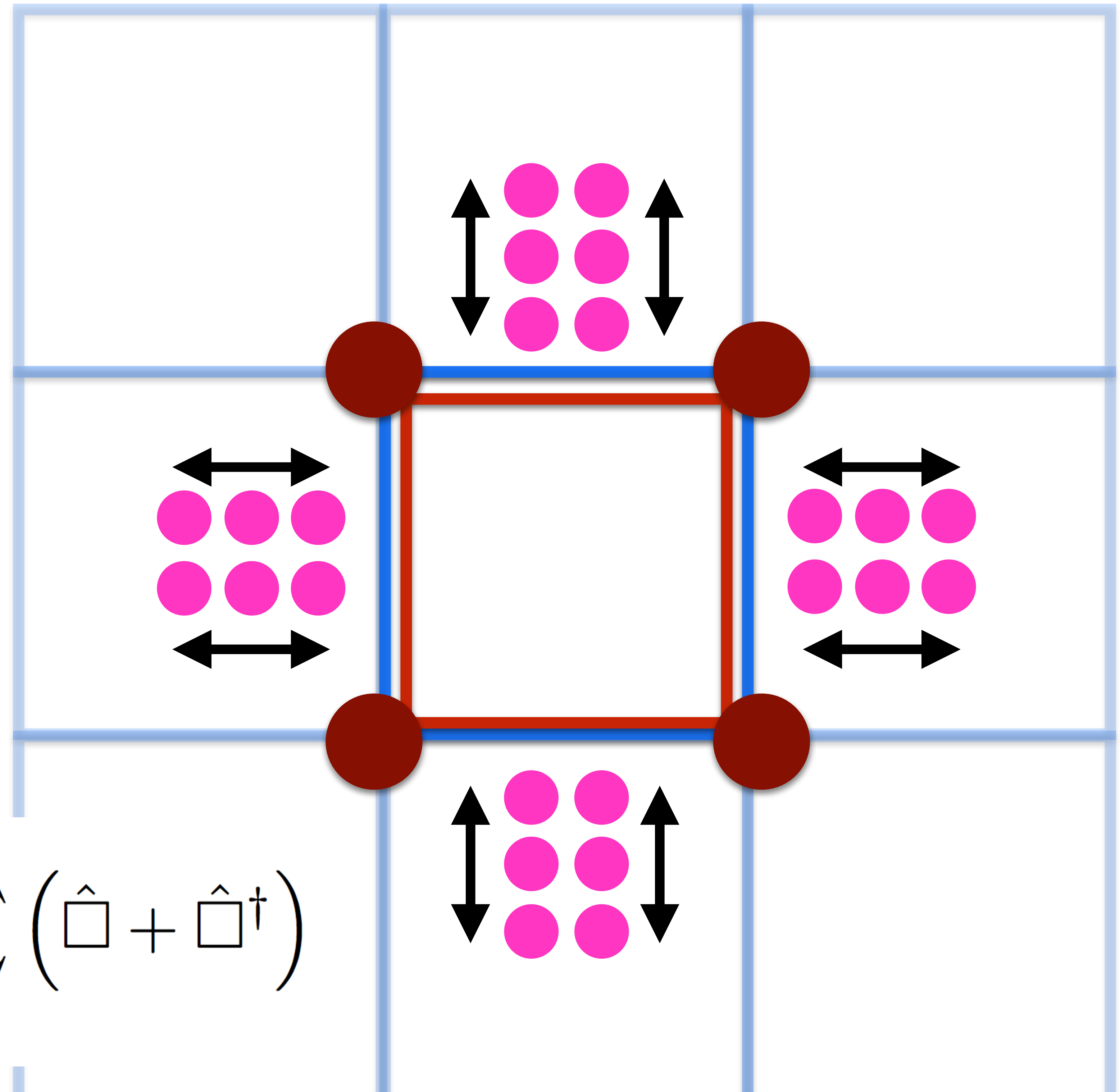
Keeping states with Casimir above 6-threshold includes only part of that higher-energy space

Toward QCD

Local Basis Scales

Building on Byrnes+Yamamoto

- Integrate over gauge space at each vertex (classical - Banuls *et al*, Klco, Stryer+MJS)
- Controlled plaquette operators
- Qudits seem natural for link registers



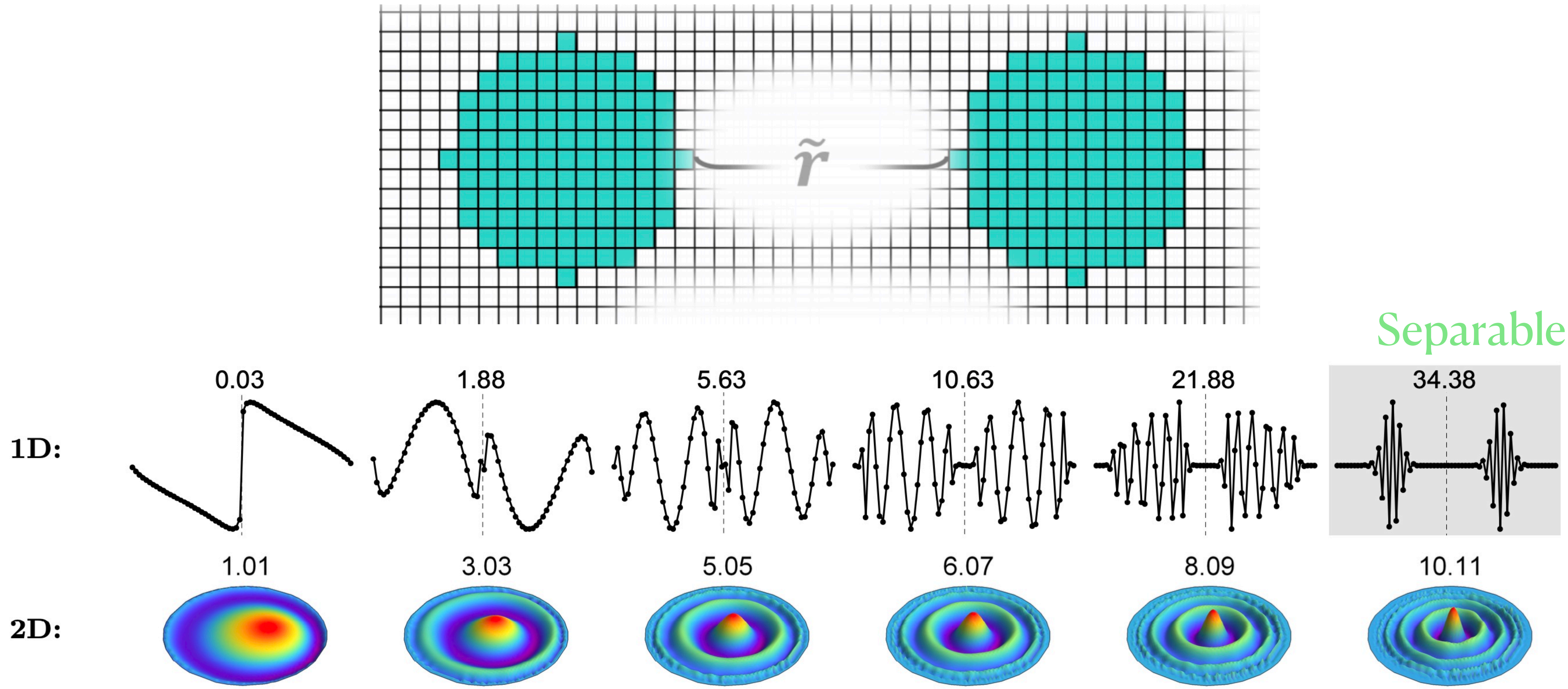
$$\hat{H} = \frac{g^2}{2} \sum_{\text{links}} \hat{E}^2 - \frac{1}{2g^2} \sum_{\Box} \left(\hat{\Box} + \hat{\Box}^\dagger \right)$$

Geometric Quantum Information Structure in Quantum Fields and their Lattice Simulation
Natalie Klco, MJS, *Phys.Rev.D* 103 (2021) 6, 065007, e-Print: 2008.03647 [quant-ph]
Entanglement Spheres and a UV-IR connection in Effective Field Theories
Natalie Klco, MJS, e-Print: 2103.14999 [hep-th]

Vacuum Negativity and Separability in 1D, 2D, 3D

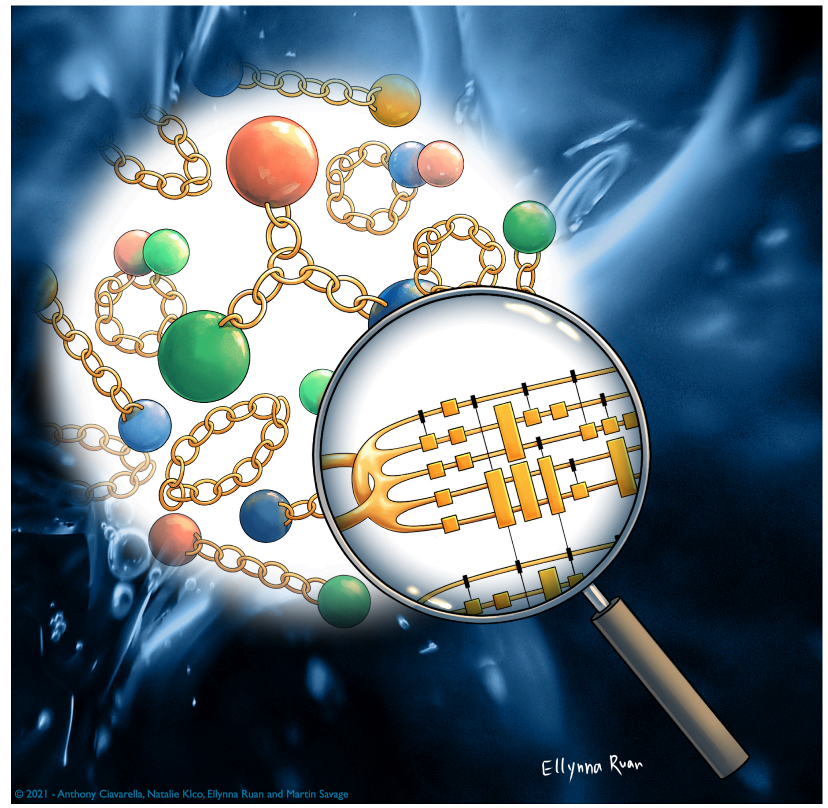
Massless, noninteracting scalar field theory … short-distance strong interactions

Entanglement in harmonic chains - Reznik and many others



The long-distance structure of entanglement is determined by the UV structure of the theory - UV-IR connection

Summary



Quantum simulations of gauge theories are beginning

- Advances in control of entanglement, coherences, quantum devices, ….
- Access to quantum devices ….
- Key to addressing non-equilibrium dynamics, fragmentation, early universe dynamics, inelastic processes, neutrino dynamics, …..
- circa1970s for lattice QCD
- Theory of entanglement and coherence crucial for simulation
- Exciting lines of investigations and theoretical proposals

FIN

InQubator for Quantum Simulation

https://iqus.uw.edu

IQuS InQubator for Quantum Simulation

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InQubator for Quantum Simulation

Nuclear physics is expected to advance and be advanced by quantum information science research in quantum many-body systems, quantum field theories and fundamental physics.

Our Mission

IQuS aims to improve understanding of strongly interacting, correlated matter and complex quantum systems of importance to nuclear physics and quantum information science, from the familiar to the exotic, using quantum simulations and emerging theoretical techniques where quantum entanglement and coherence are essential ingredients. Local researchers, visitors, and community-driven workshops at the Institute of Nuclear Theory, along with close connections with national laboratories and technology companies, will help create and disseminate new ideas and grow a quantum-ready workforce.

Workshops

/ Workshops

Workshops

Bringing people together to exchange ideas, to create, and to gain deeper understandings of nuclear physics, quantum information and quantum simulation is at the core of the InQubator. Visiting researchers from diverse backgrounds and expertise, join with local researchers to address cutting edge issues in quantum simulations of quantum many-body systems and field theories.

We are seeking community-driven proposals for 1-week or 2 week workshops to bring together a diverse group of ~20 experts from universities, labs and tech companies to address key challenges in simulating quantum many-body systems and field theories. Our workshops will be held in the Institute for Nuclear Theory (INT) spacetime, and visitors will have access to offices, desks, interaction spaces, and seminar room.

We are seeking proposals for workshops focused on topics with a high potential for disruptive gains. Our Scientific Advisory Board, in consultation with IQuS faculty, will review proposals and select workshops/programs to accelerate advances in quantum simulations.

Covid-19 has delayed our in-person workshops until late 2021. We anticipate a modest number of virtual meetings prior to in-person meetings for this reason.

Edit

Workshops
- Upcoming Workshops
- Past Workshops
- Submit a Workshop Proposal

SUBMIT A WORKSHOP PROPOSAL

Call for 2022 – 2023 IQuS Workshop Proposals »

UPCOMING WORKSHOPS

APRIL 2021

06 APR — **QUANTUM SIMULATION OF STRONG INTERACTIONS (QUASI) WORKSHOP 1 : THEORETICAL STRATEGIES FOR GAUGE THEORIES**

Tuesday , Cyber Space

EVENT DETAIL