Quantum Simulations using Scalable Quantum Circuits

FIRST WORKSHOP ON MANY-BODY QUANTUM MAGIC *(MBQM2024)*

Abu Dhabi, November, 2024

Martin Savage
InQubator for Quantum Simulation (IQuS),
University of Washington

IQuS

https://iqus.uw.edu/

QUANTUM SCIENCE CENTER

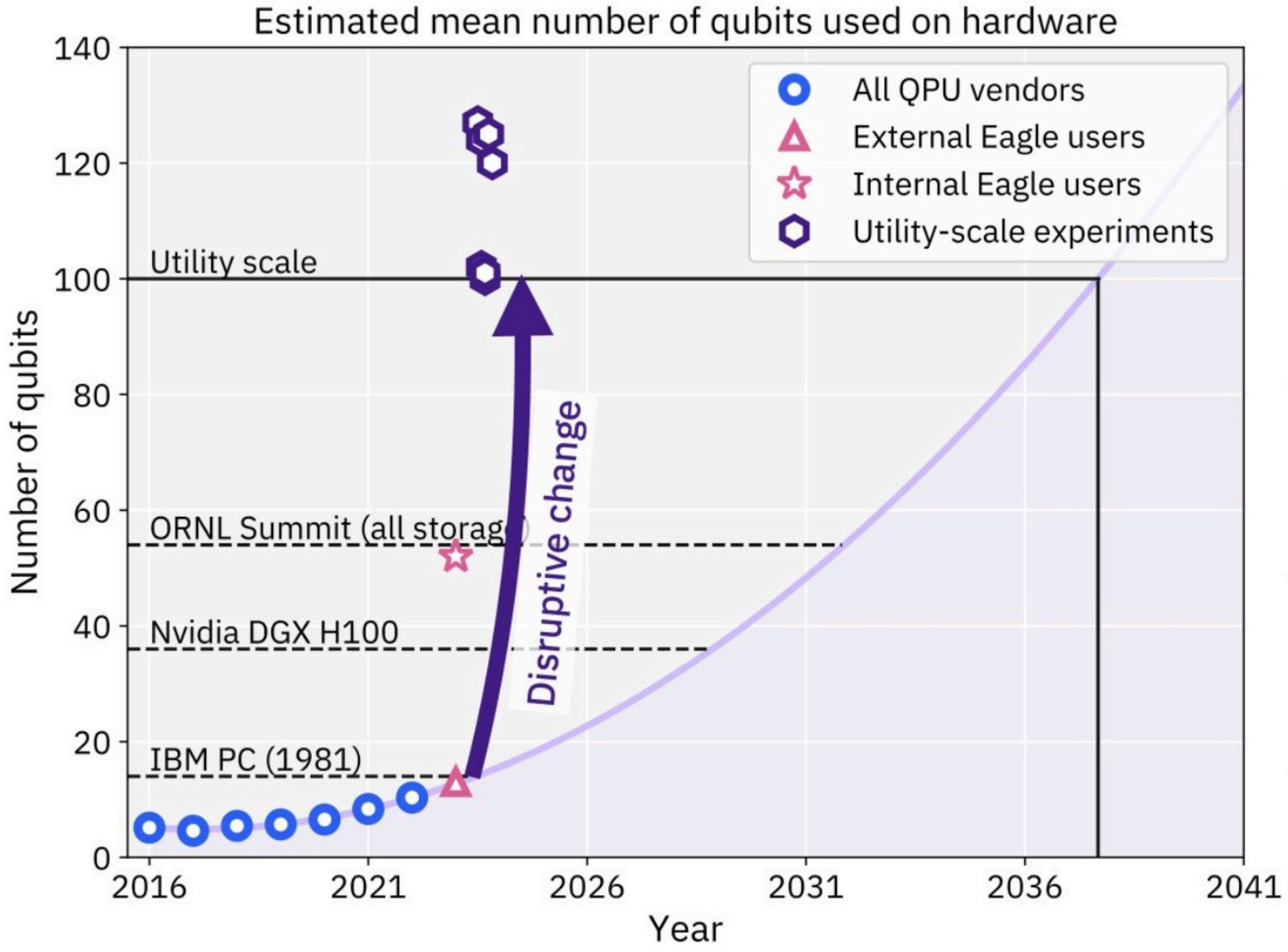
Office of Science
U.S. Department of Energy

Oak Ridge National Laboratory

IBM Quantum Summit - NYC December 2023

Utility-scale experiments

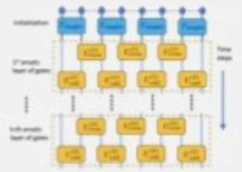
With quantum systems composed of 100+ qubits, researchers are beginning to explore algorithms and applications at scales beyond brute-force classical computation using IBM Quantum systems.



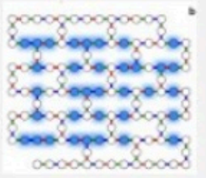
IBM **Quantum**

Evidence for the utility of quantum computing before fault tolerance
127 qubits / 2880 CX gates — Nature, **618**, 500 (2023)

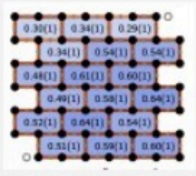
Simulating large-size quantum spin chains on cloud-based superconducting quantum computers
102 qubits / 3186 CX gates — arXiv:2207.09994



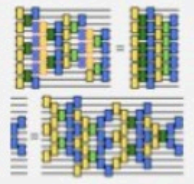
Uncovering Local Integrability in Quantum Many-Body Dynamics
124 qubits / 2641 CX gates — arXiv:2307.07552



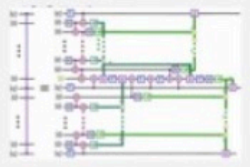
Realizing the Nishimori transition across the error threshold for constant-depth quantum circuits
125 qubits / 429 gates + meas. — arXiv:2309.02863



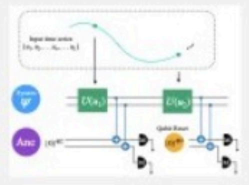
Scalable Circuits for Preparing Ground States on Digital Quantum Computers: The Schwinger Model Vacuum on 100 Qubits
100 qubits / 788 CX gates — arXiv:2308.04481



Efficient Long-Range Entanglement using Dynamic Circuits
101 qubits / 504 gates + meas. — arXiv:2308.13065



Quantum reservoir computing with repeated measurements on superconducting devices
120 qubits / 49470 gates + meas. — arXiv:2310.06706

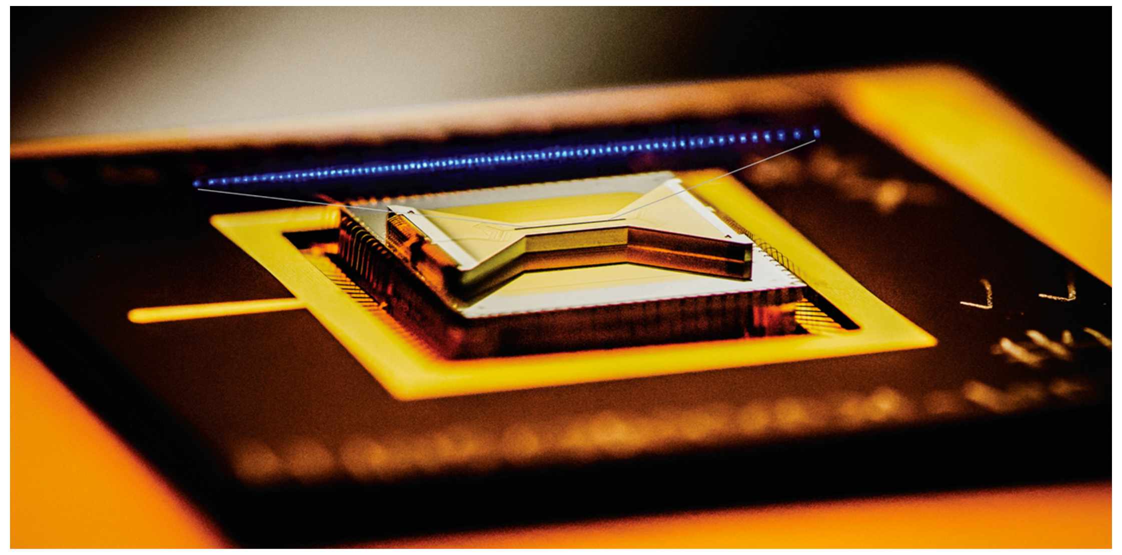


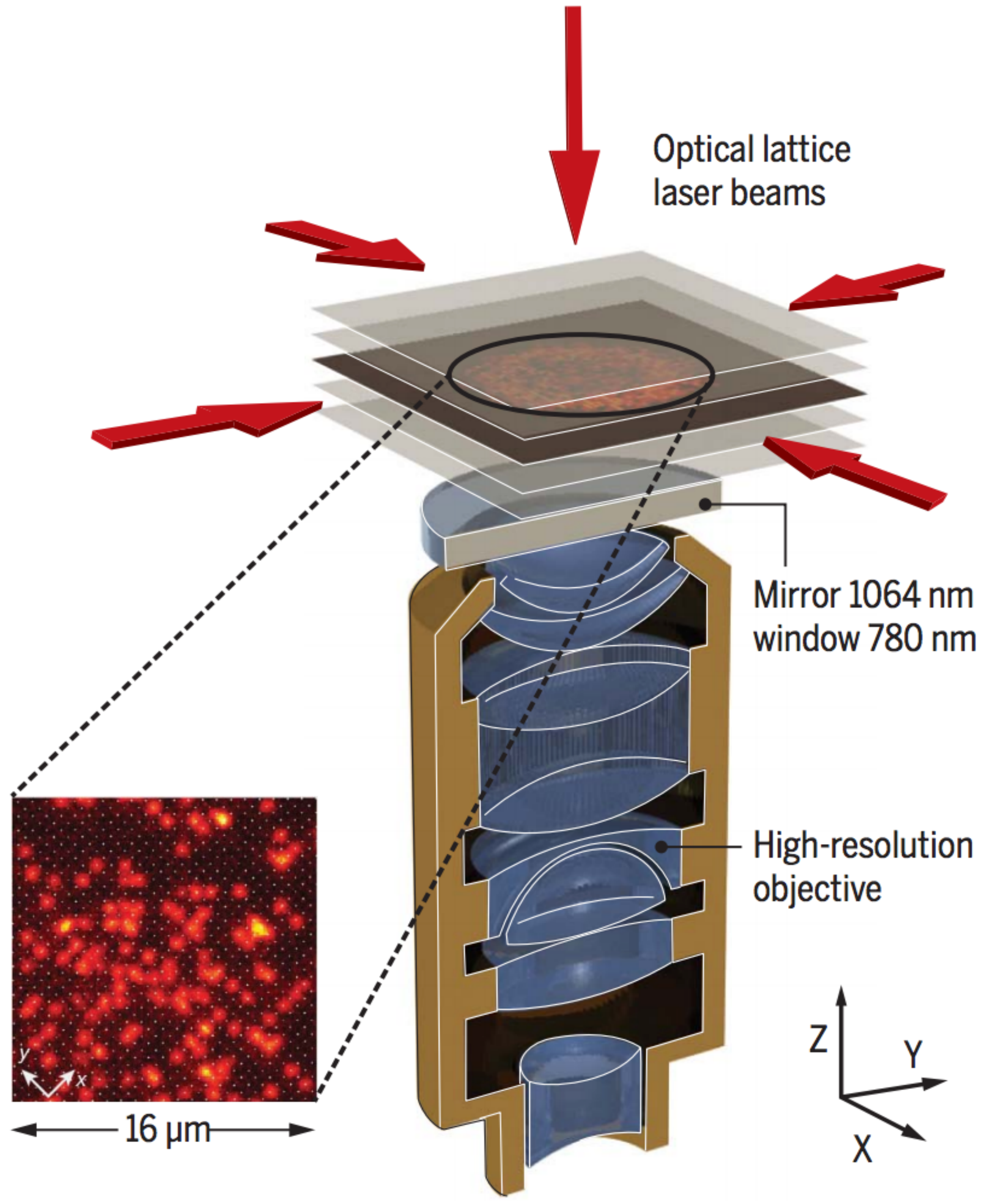
Real-Time High-Energy Collisions of Matter

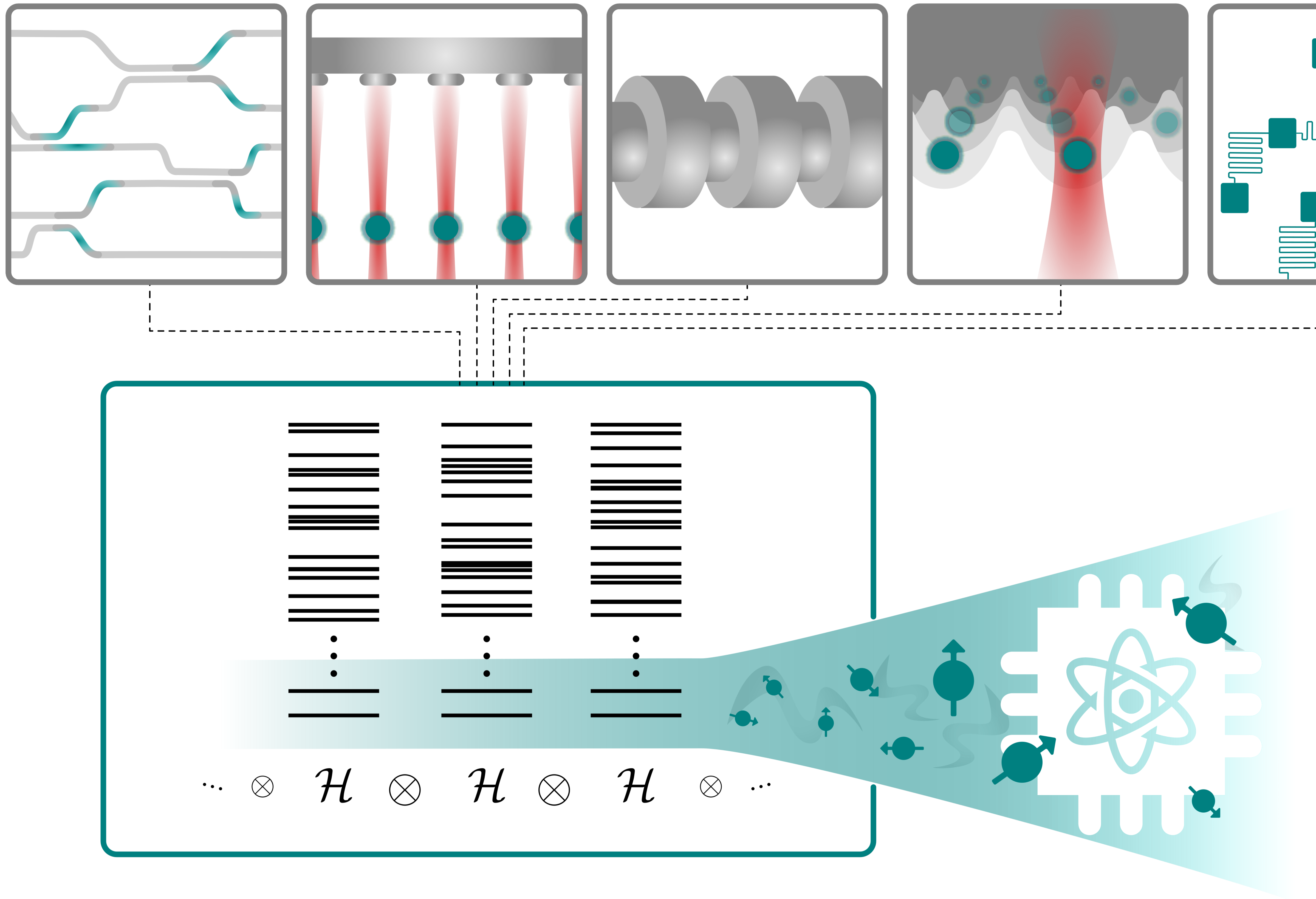
Classic work by Jordan, Lee and Preskill in Scalar Field Theory

A number of significant efforts working toward this objective

Encoding Systems in Multi-Hilbert Spaces Embedded in Large HPC systems

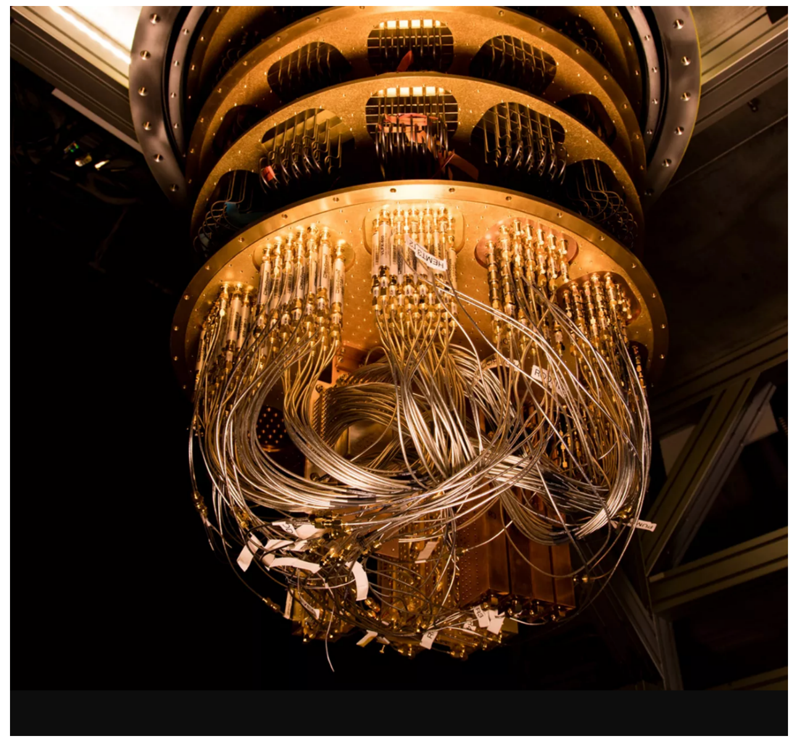


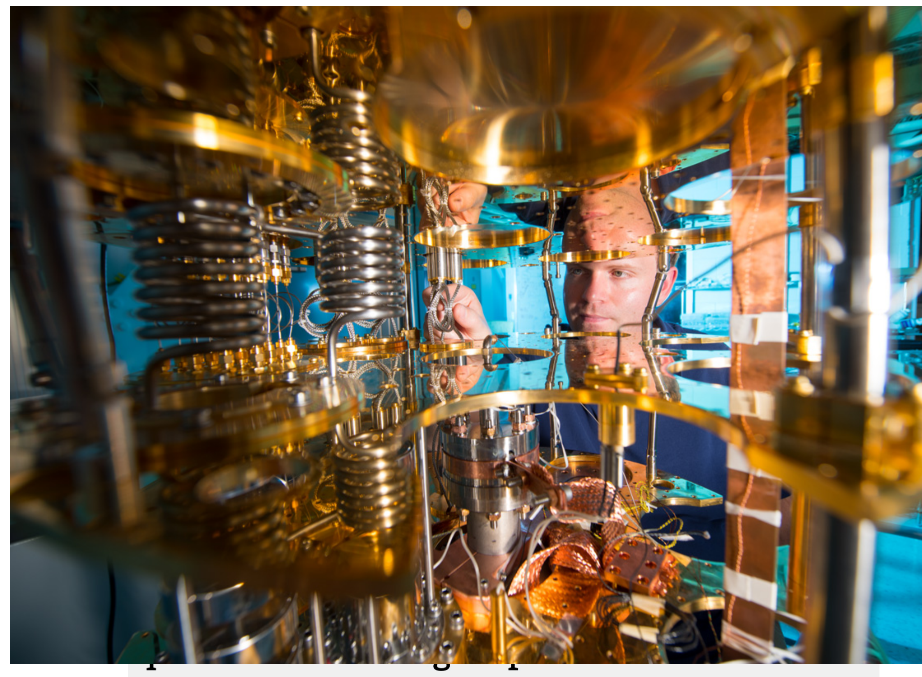


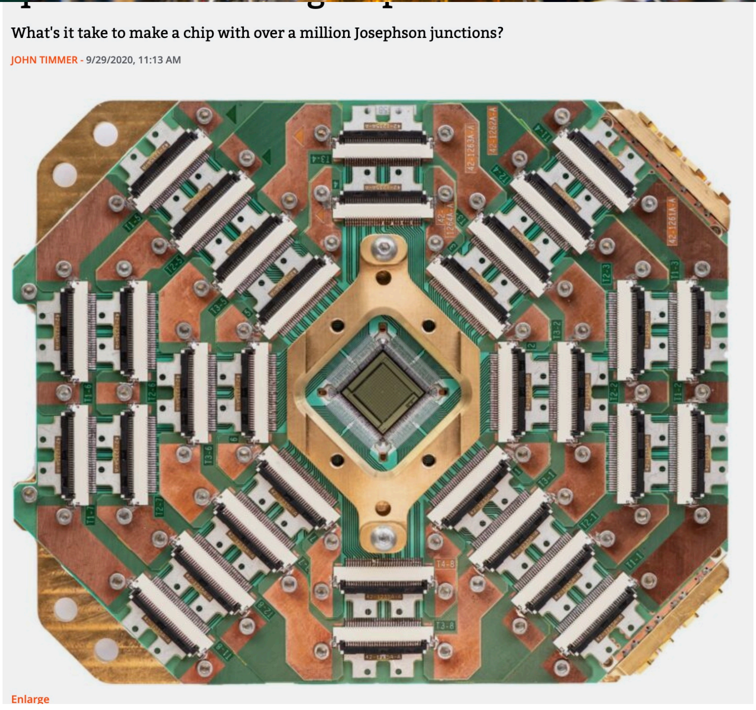


Map scalar, fermion and vector systems

Optimize for target observables - Physics Aware







Human-intensive exploration

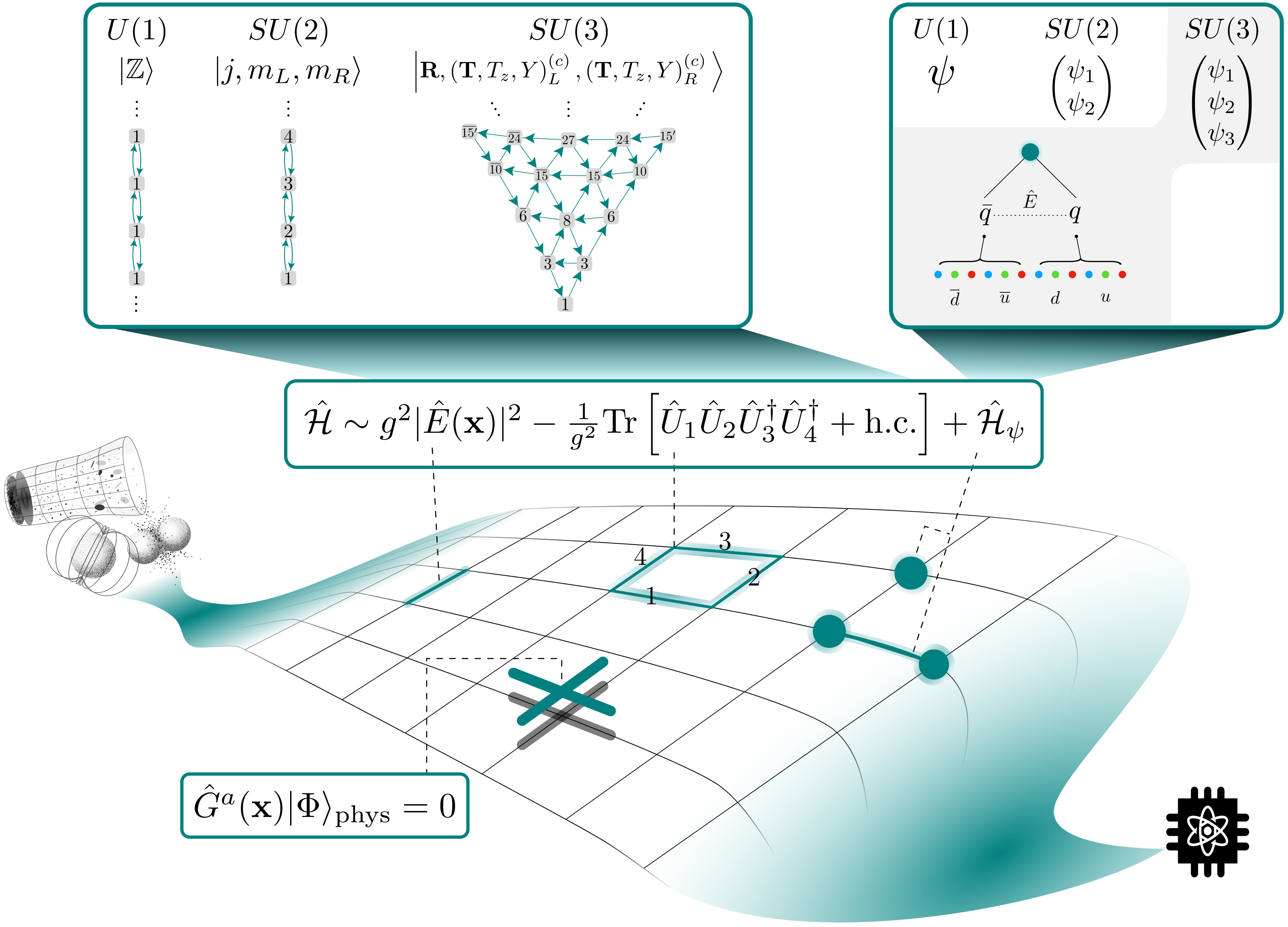
Simulating Lattice Gauge Field Theories

Hamiltonian
Kogut-Susskind
1970's

Yang-Mills:
Byrnes-Yamamoto
2005

SU(N):
Zohar et al
(2013)

QLM
Banerjee et al
Tagliacozzo et al
(2013)



Limits
Continuum
Infinite Volume

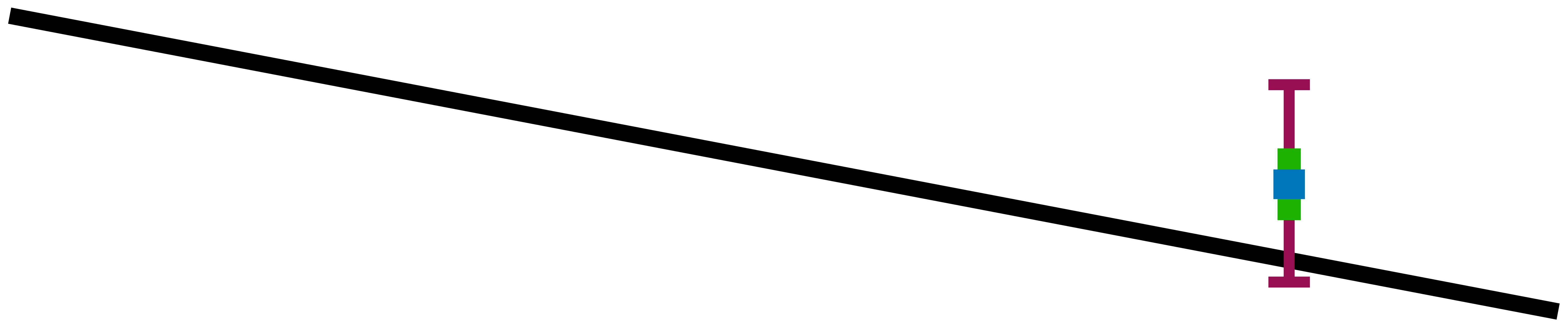
Getting There Sooner

Considerations

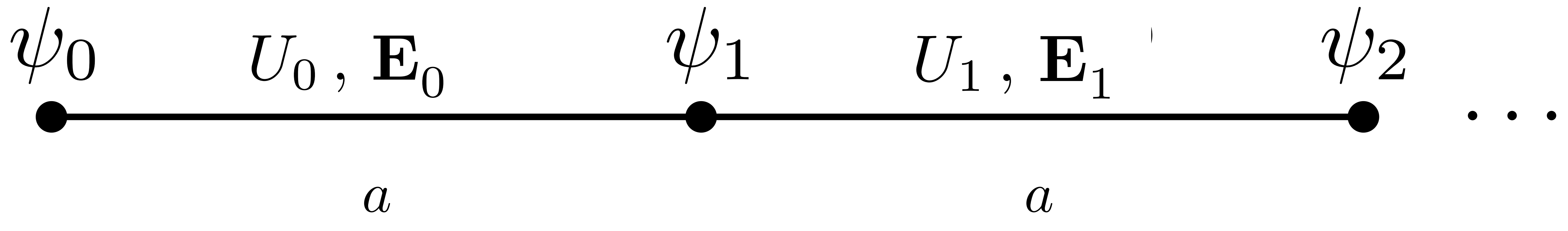
- Suite(s) of productions runs, iteratively tuned to interpolate/extrapolate to nature
- Minimize use of QPU and maximize use of HPC for numerics
- Maximize analytic results
- Utilize Hamiltonians that are simple, and nearby target

Exponential approaches are good!

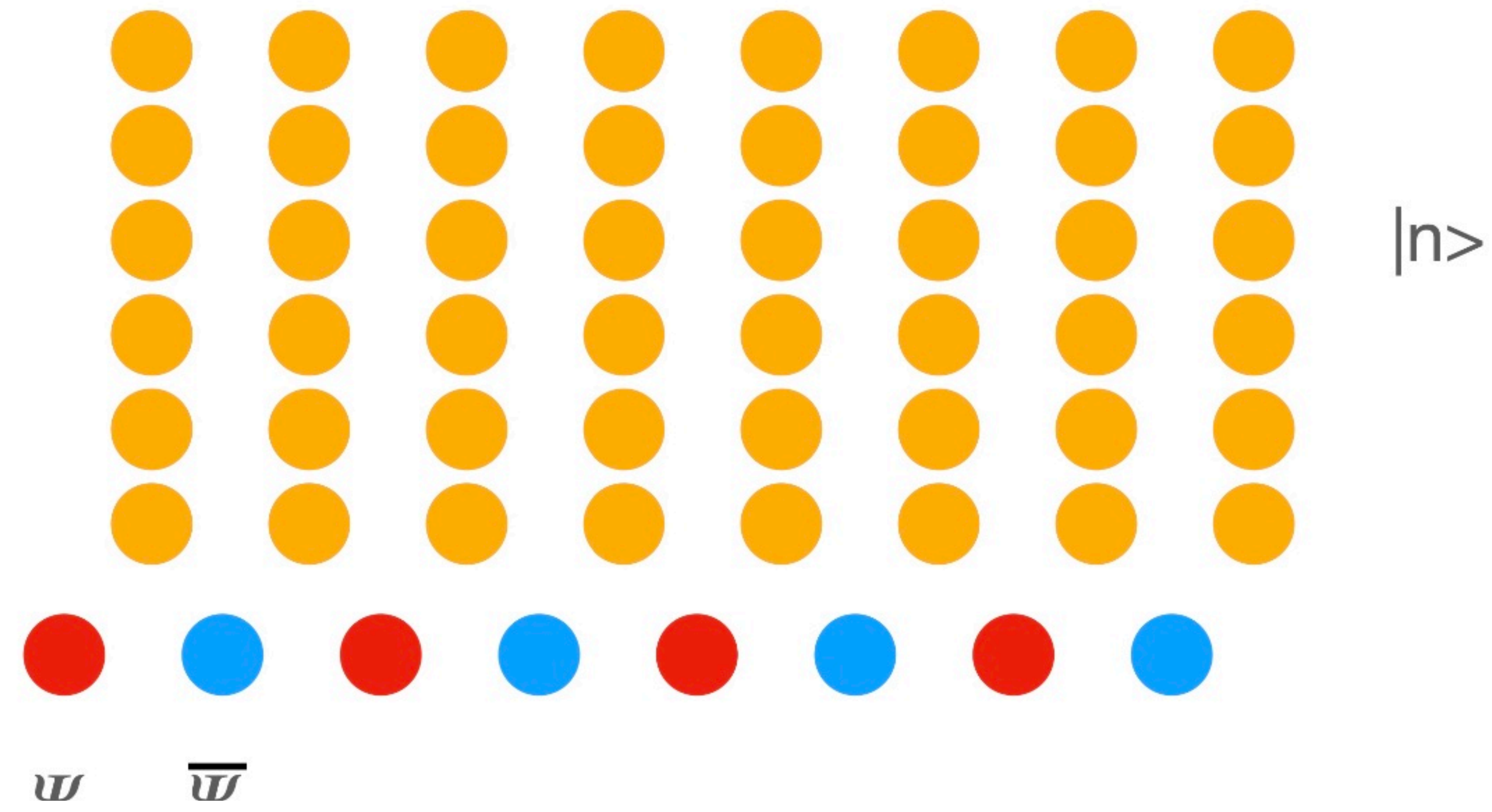
Pursue ``Gottesman+Knill organization”

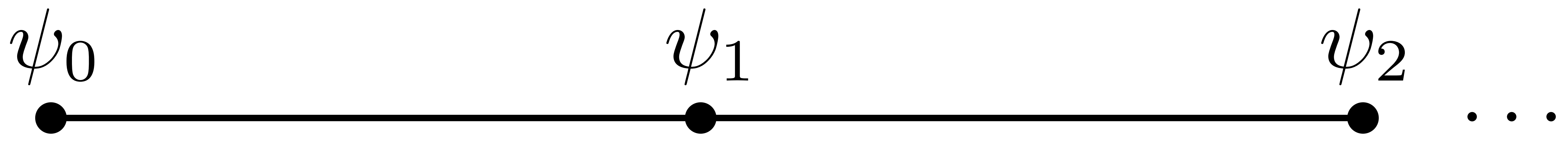


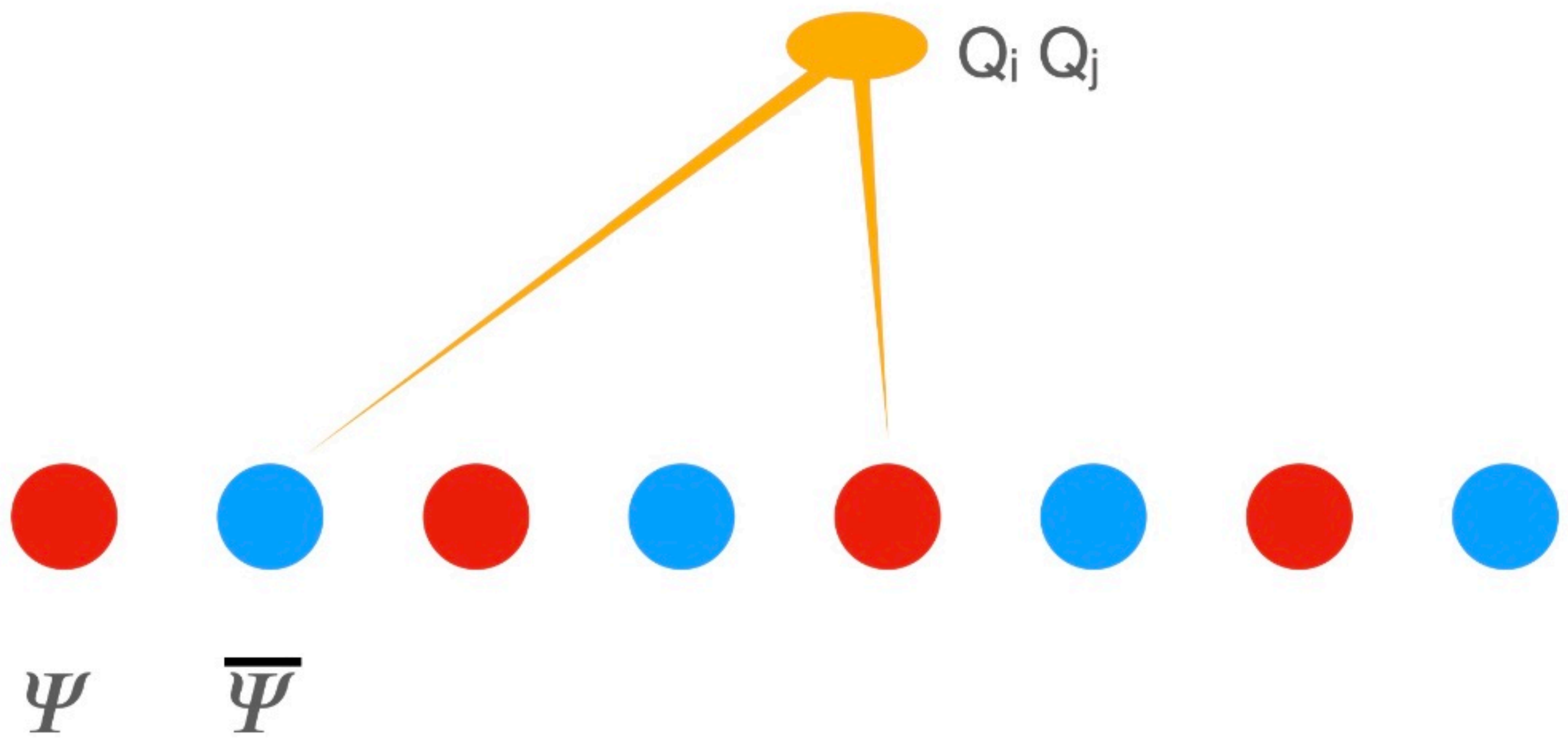
Lattice Hamiltonian in 1+1D - Which Gauge to Choose?



Weyl gauge

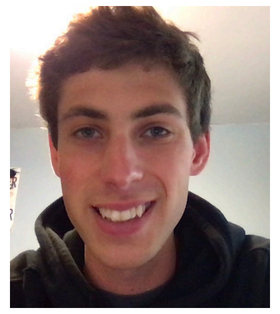






Axial gauge

``Cost'' for evolving over some time interval similar



Confinement and Scalable Circuits

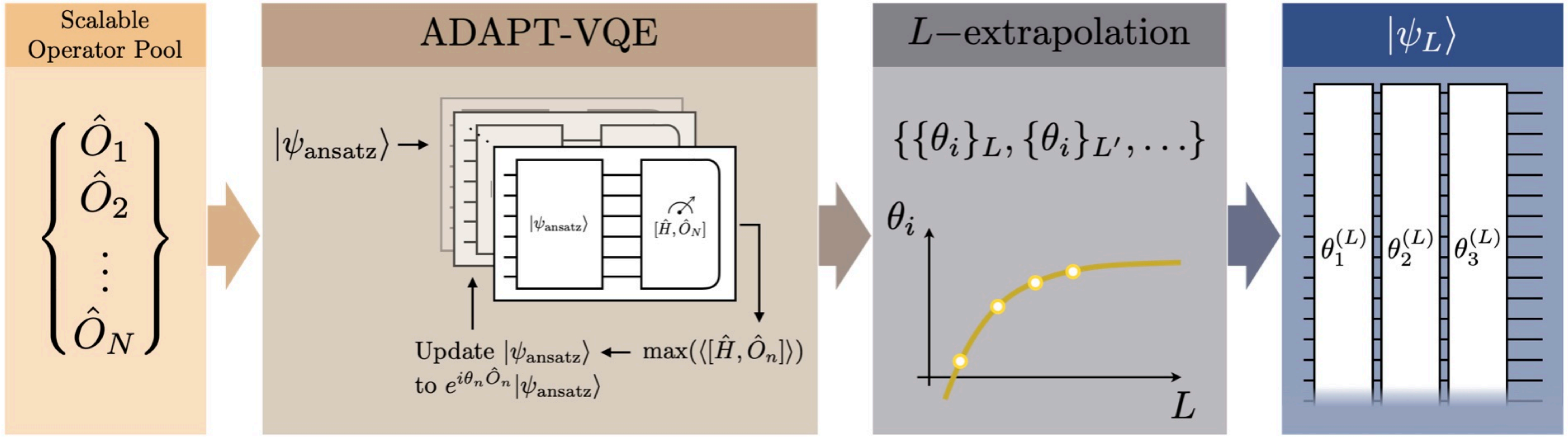
(2023-)

Roland Farrell, Marc Illa,
Anthony Ciavarella and MJS

$$\hat{H} = \hat{H}_m + \hat{H}_{kin} + \hat{H}_{el} = \frac{m}{2}\sum_{j=0}^{2L-1}\left[(-1)^j \hat{Z}_j + \hat{I}\right] + \frac{1}{2}\sum_{j=0}^{2L-2}\left(\hat{\sigma}_j^+ \hat{\sigma}_{j+1}^- + \text{h.c.}\right) + \frac{g^2}{2}\sum_{j=0}^{2L-2}\left(\sum_{k\le j}\hat{Q}_k\right)^2$$

Local — Nearest Neighbor — Non-local

Symmetries and Confinement — **Classical** Optimization — **Classical** Extrapolations — **Quantum** Implementation



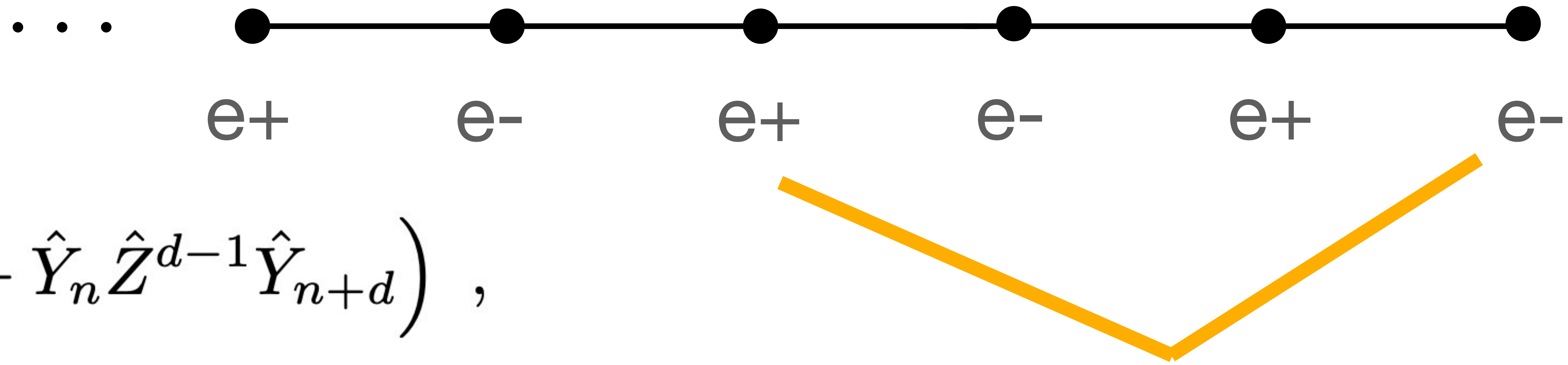
Scalable Circuits for Preparing Ground States on Digital Quantum Computers: The Schwinger Model Vacuum on 100 Qubits
Roland C. Farrell, Marc Illa, Anthony N. Ciavarella, and Martin J. Savage
PRX Quantum **5**, 020315 – Published 18 April 2024

Quantum simulations of hadron dynamics in the Schwinger model using 112 qubits
Roland C. Farrell, Marc Illa, Anthony N. Ciavarella, and Martin J. Savage
Phys. Rev. D **109**, 114510 – Published 10 June 2024

Builds upon ADAPT-VQE by Sophia Economou *et al.*

Scalable Operators: Volume and Surface

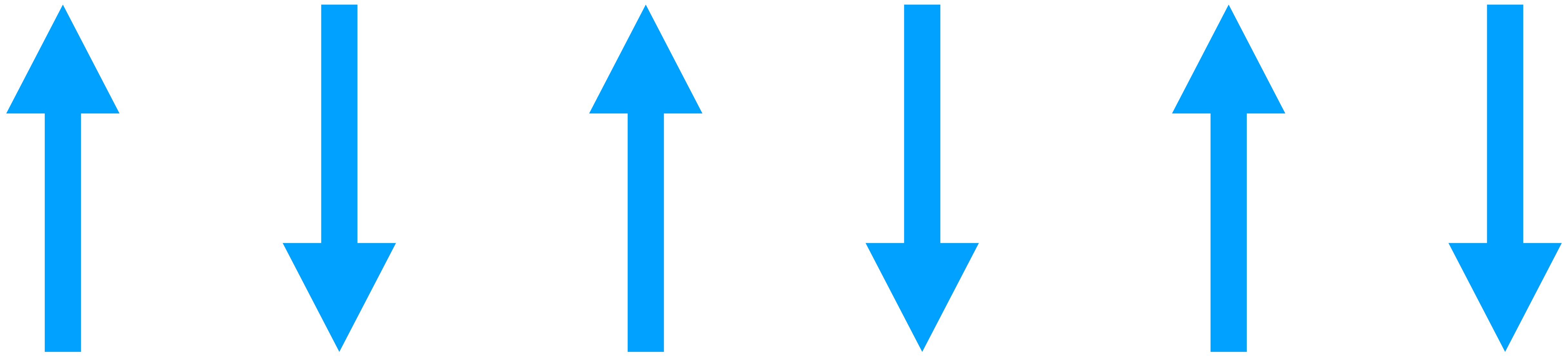
$$\hat{\Theta}^V_m = \frac{1}{2}\sum_{n=0}^{2L-1}(-1)^n\hat{Z}_n \ ,$$



$$\hat{\Theta}^V_h(d) = \frac{1}{4}\sum_{n=0}^{2L-1-d}\left(\hat{X}_n\hat{Z}^{d-1}\hat{X}_{n+d} + \hat{Y}_n\hat{Z}^{d-1}\hat{Y}_{n+d}\right) \ ,$$

$$\hat{\Theta}^S_m(d) = (-1)^d\frac{1}{2}\left(\hat{Z}_d - \hat{Z}_{2L-1-d}\right) \ ,$$

$$\hat{\Theta}^S_h(d) = \frac{1}{4}\left(\hat{X}_1\hat{Z}^{d-1}\hat{X}_{d+1} + \hat{Y}_1\hat{Z}^{d-1}\hat{Y}_{d+1} \ + \ \hat{X}_{2L-2-d}\hat{Z}^{d-1}\hat{X}_{2L-2} + \hat{Y}_{2L-2-d}\hat{Z}^{d-1}\hat{Y}_{2L-2}\right)$$



Scalable Operators: Circuits

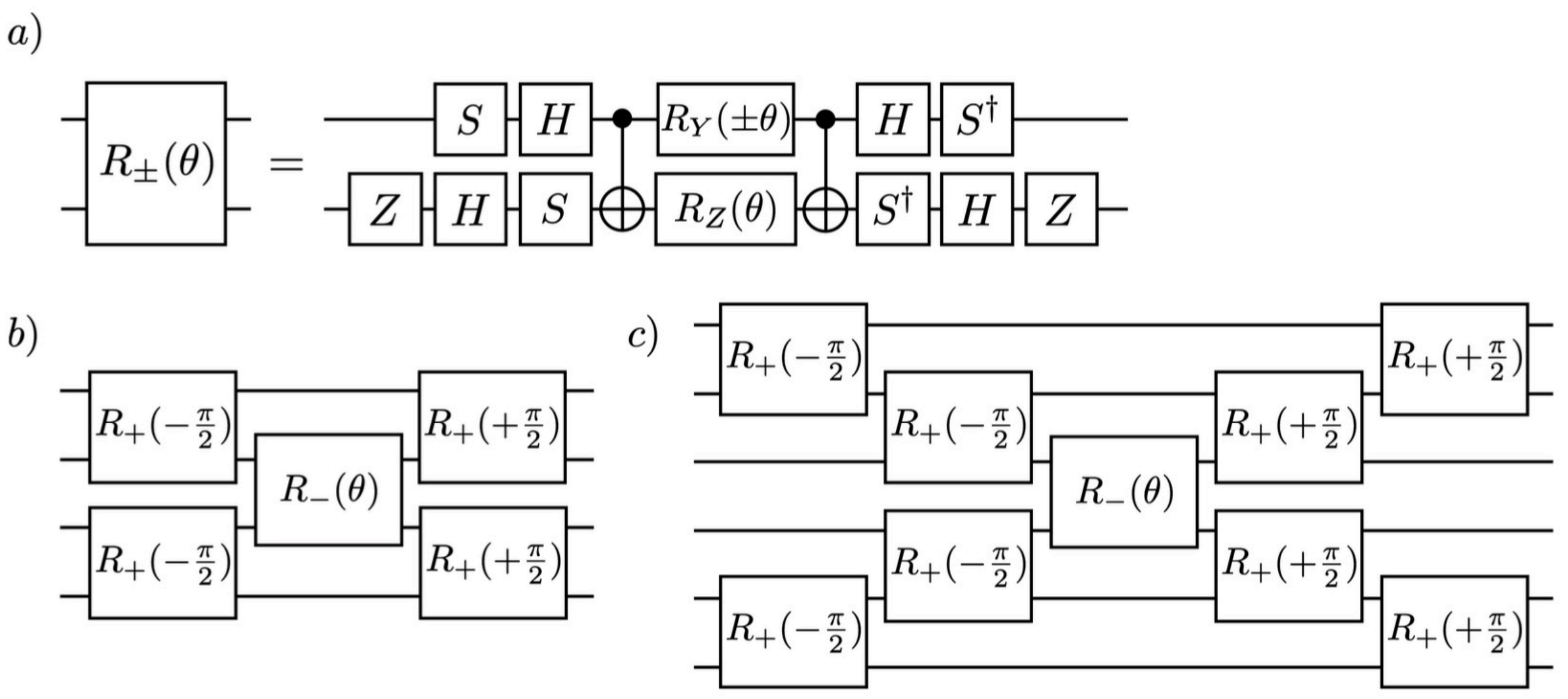


FIG. 3. (a) The definition of the $R_{\pm}(\theta)$ gate, which implements $\exp[i\theta/2(\hat{X}\hat{Y} \pm \hat{Y}\hat{X})]$. The $R_{\pm}(\theta)$ gate is used to implement (b) $\exp[-i\theta/2(\hat{X}\hat{Z}^2\hat{Y} - \hat{Y}\hat{Z}^2\hat{X})]$ and (c) $\exp[i\theta/2(\hat{X}\hat{Z}^4\hat{Y} - \hat{Y}\hat{Z}^4\hat{X})]$ (note the change in sign).

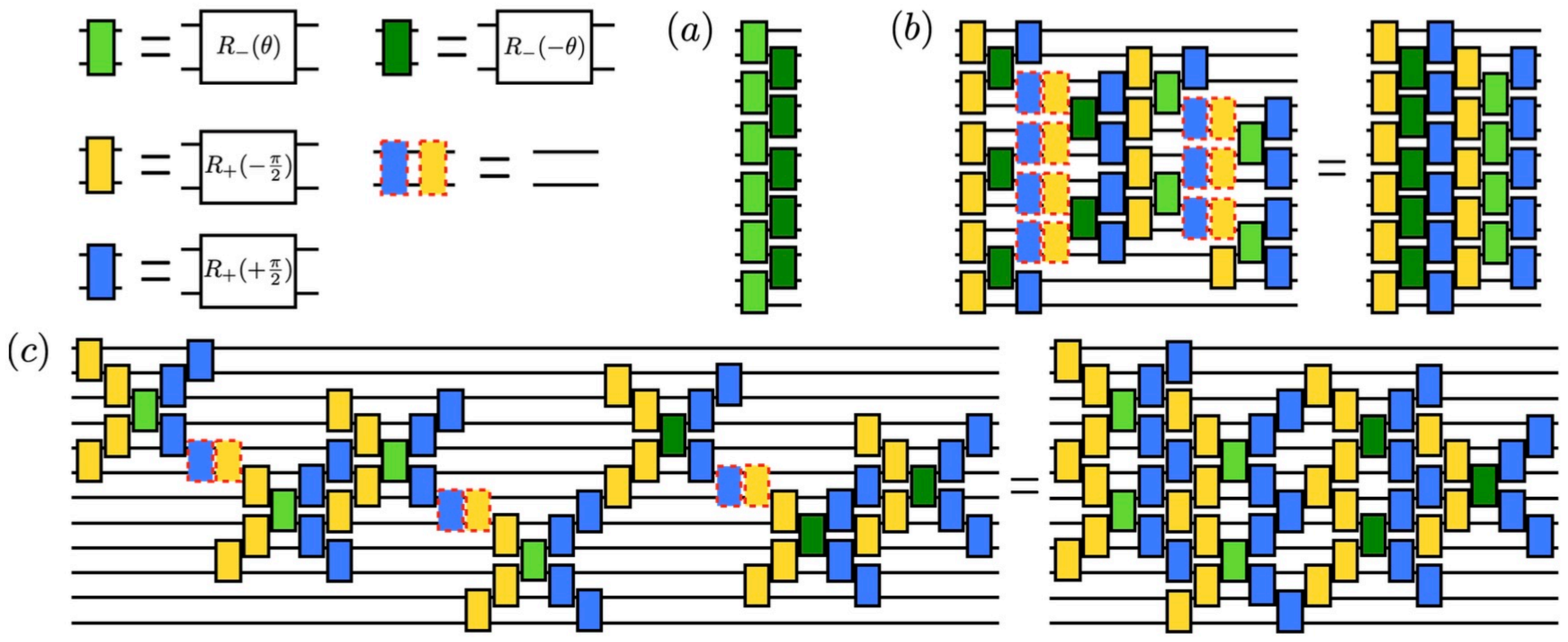
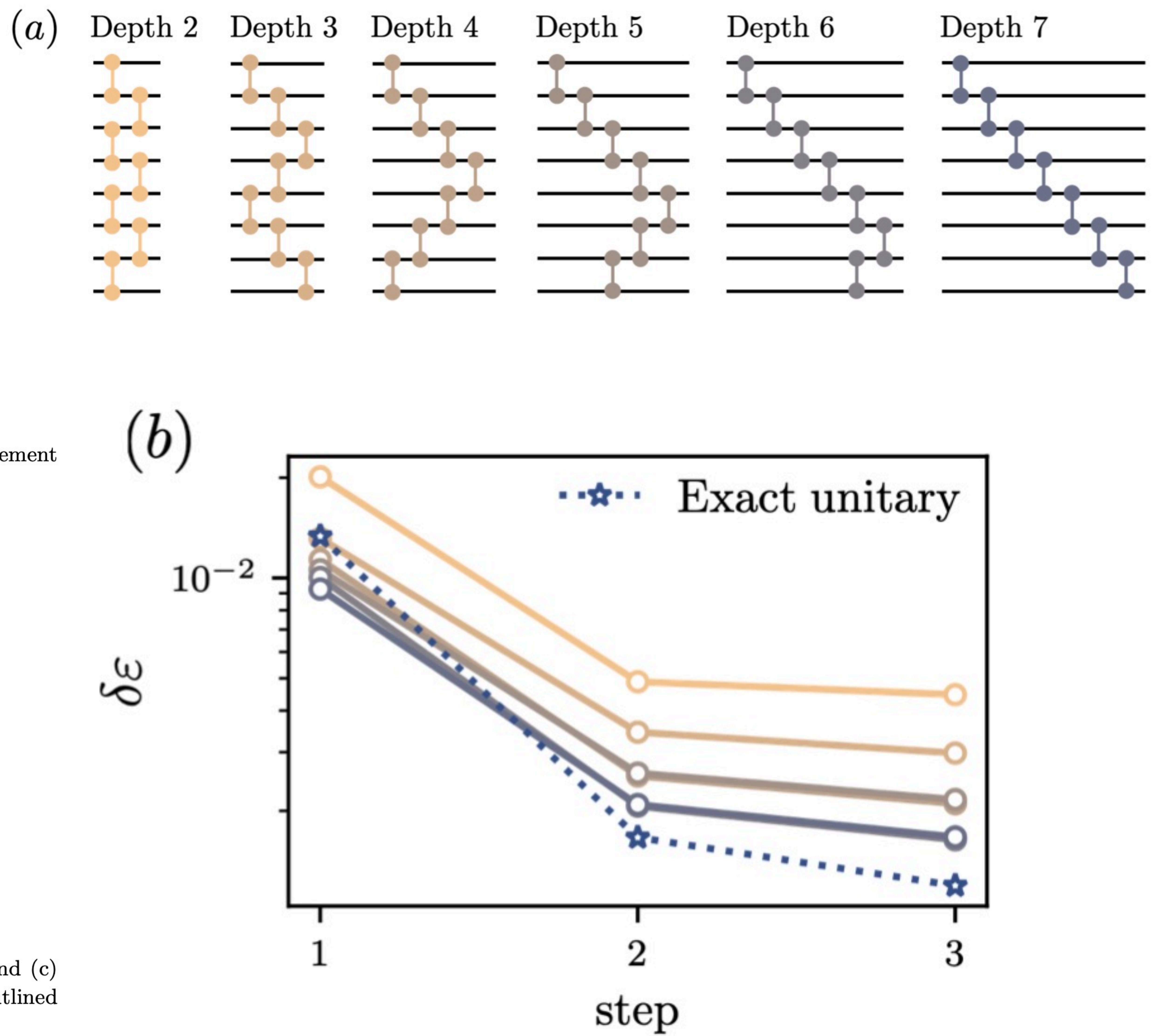


FIG. 4. Simplifications of quantum circuits for the Trotterized unitaries corresponding to (a) $\hat{O}^V_{mh}(1)$, (b) $\hat{O}^V_{mh}(3)$, and (c) $\hat{O}^V_{mh}(5)$ for $L = 6$, as explained in the main text. Cancellations between $R_+(\pm\frac{\pi}{2})$ are highlighted with red-dashed-outlined boxes.



Decoherence Renormalization

Mitigating Depolarizing Noise on Quantum Computers with Noise-Estimation Circuits

Miroslav Urbanek, Benjamin Nachman, Vincent R. Pascuzzi, Andre He, Christian W. Bauer, and Wibe A. de Jong
Phys. Rev. Lett. **127**, 270502 – Published 27 December 2021

Self-mitigating Trotter circuits for SU(2) lattice gauge theory on a quantum computer

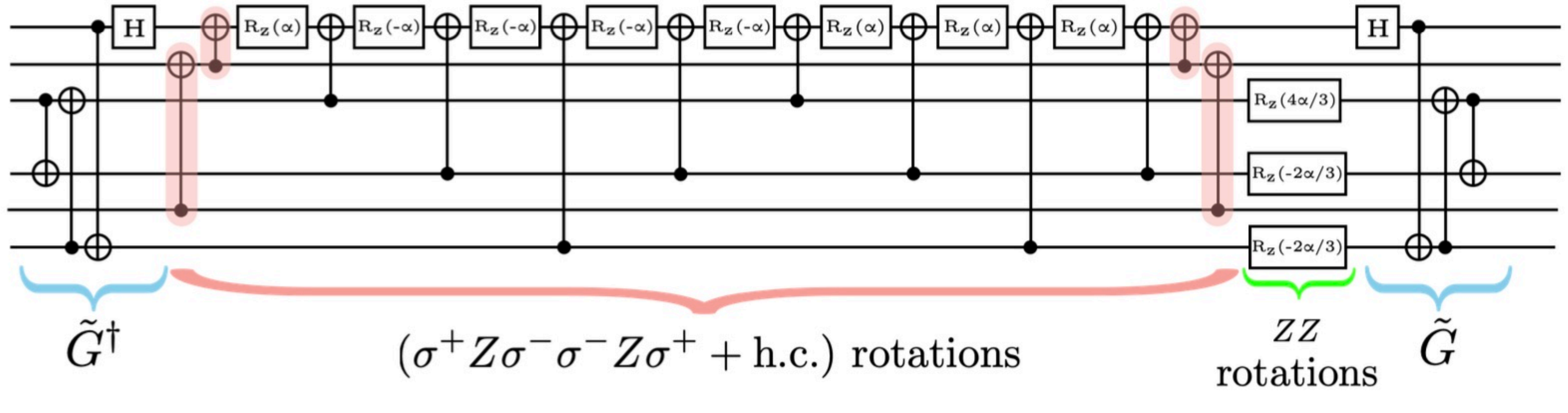
Sarmed A Rahman, Randy Lewis, Emanuele Mendicelli, and Sarah Powell
Department of Physics and Astronomy, York University, Toronto, Ontario, Canada, M3J 1P3

(Dated: May 2022. Updated: October 2022.)

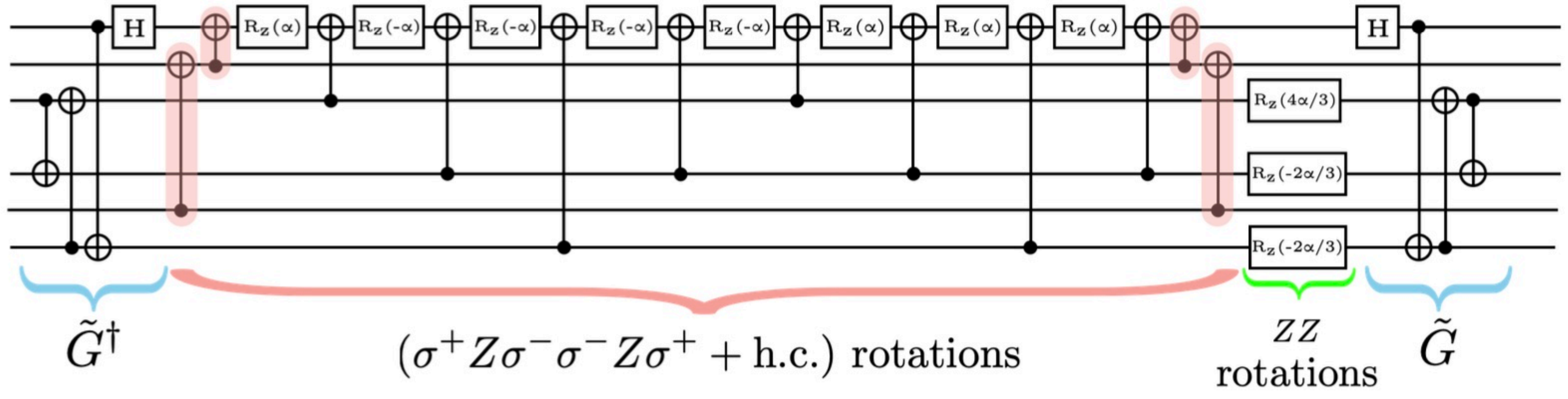
The device is approaching a classical, depolarized set of qubits as time goes by.

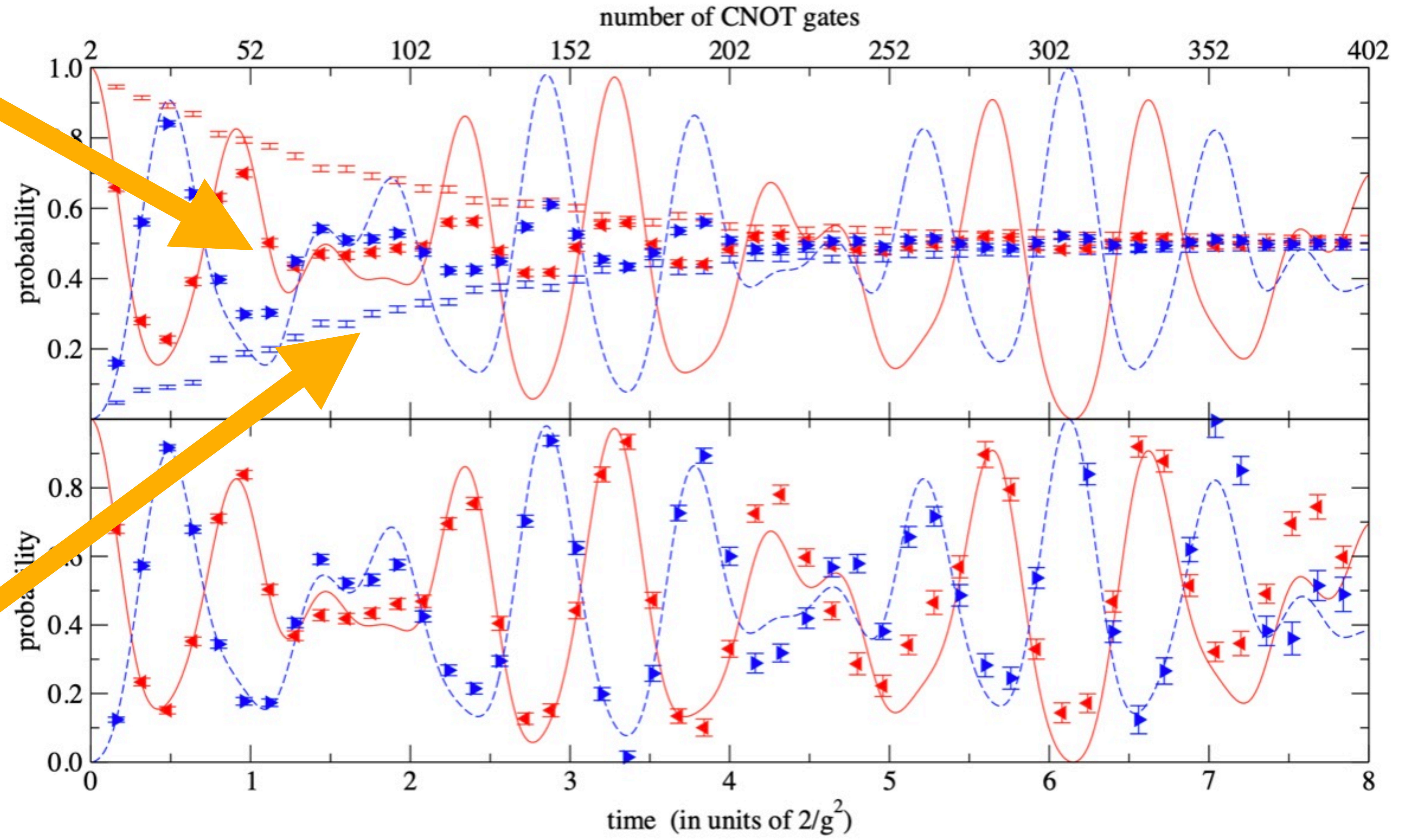
Mitigation methods are essential and effective

"Physics circuit"

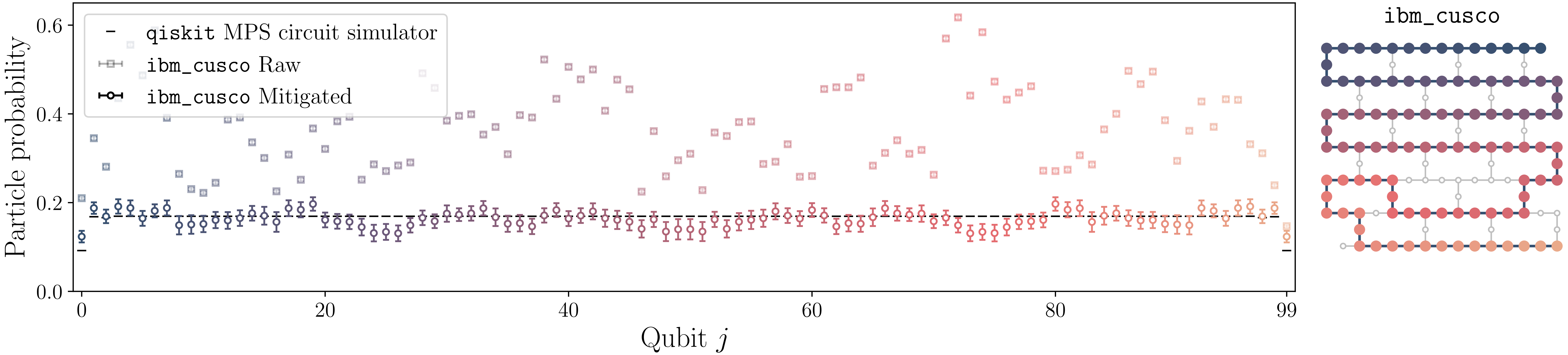


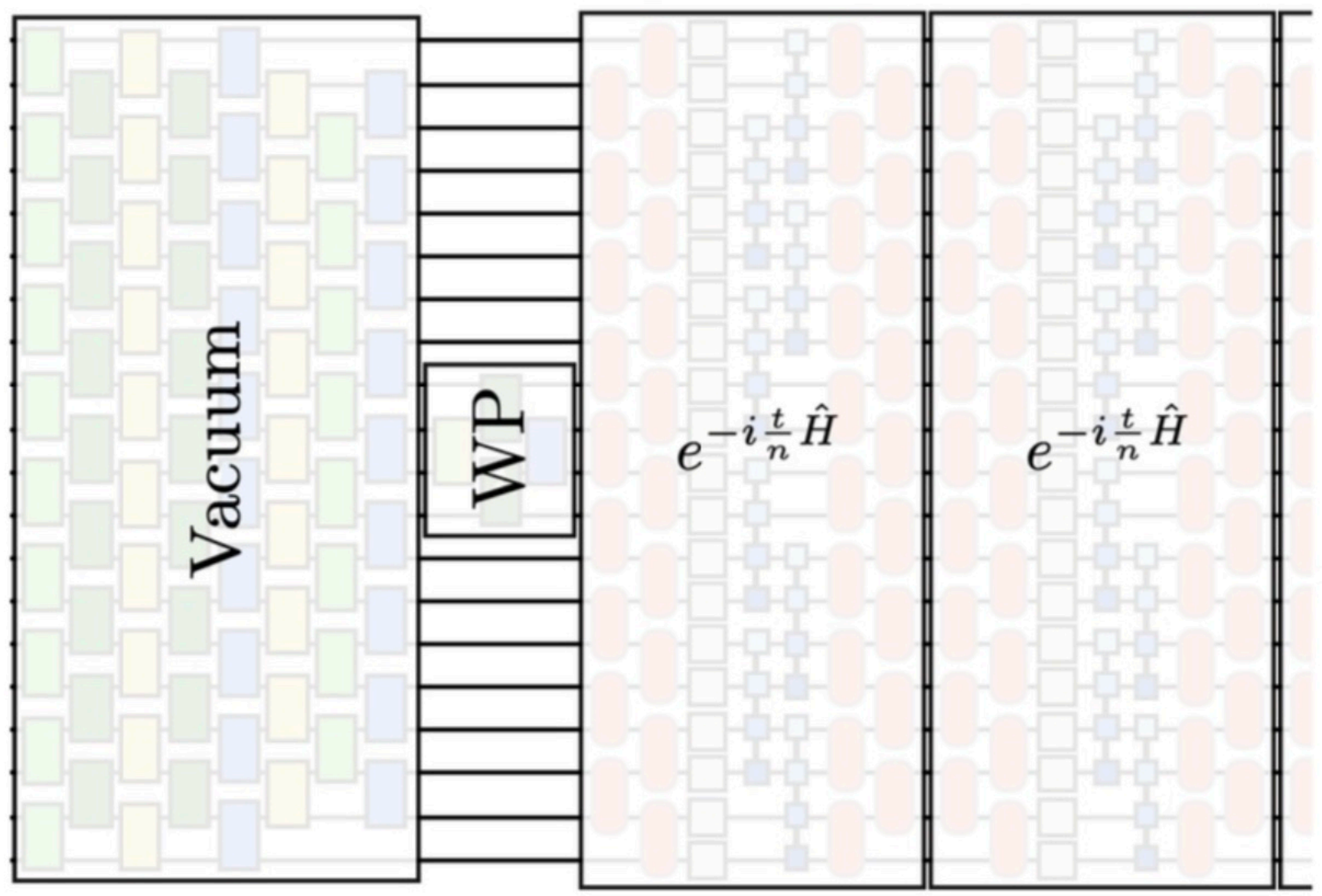
"Mitigation circuit" - all angles set to zero (e.g.)

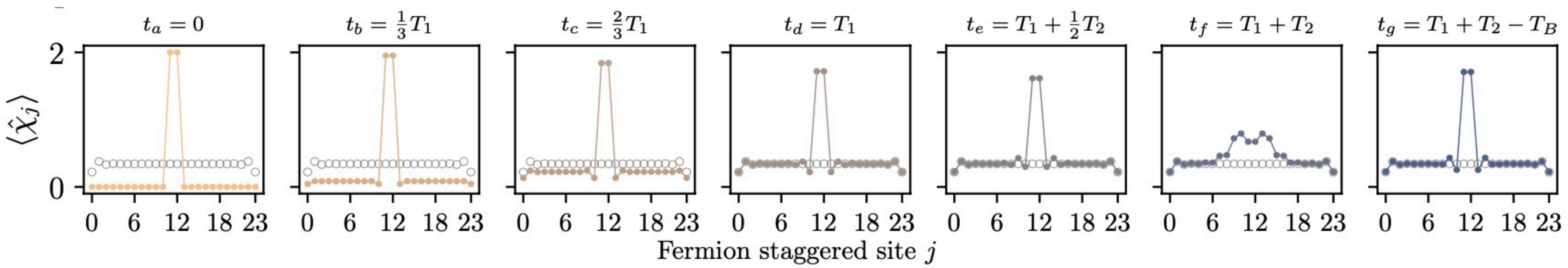


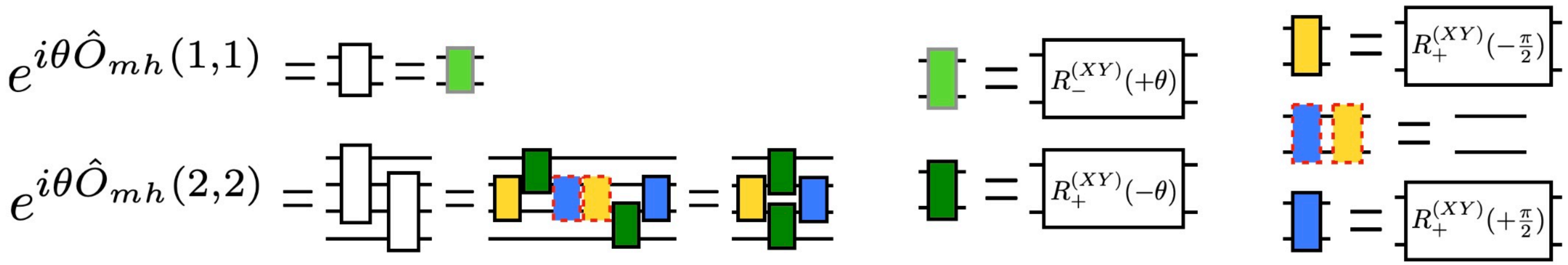


The Vacuum and Wavepackets



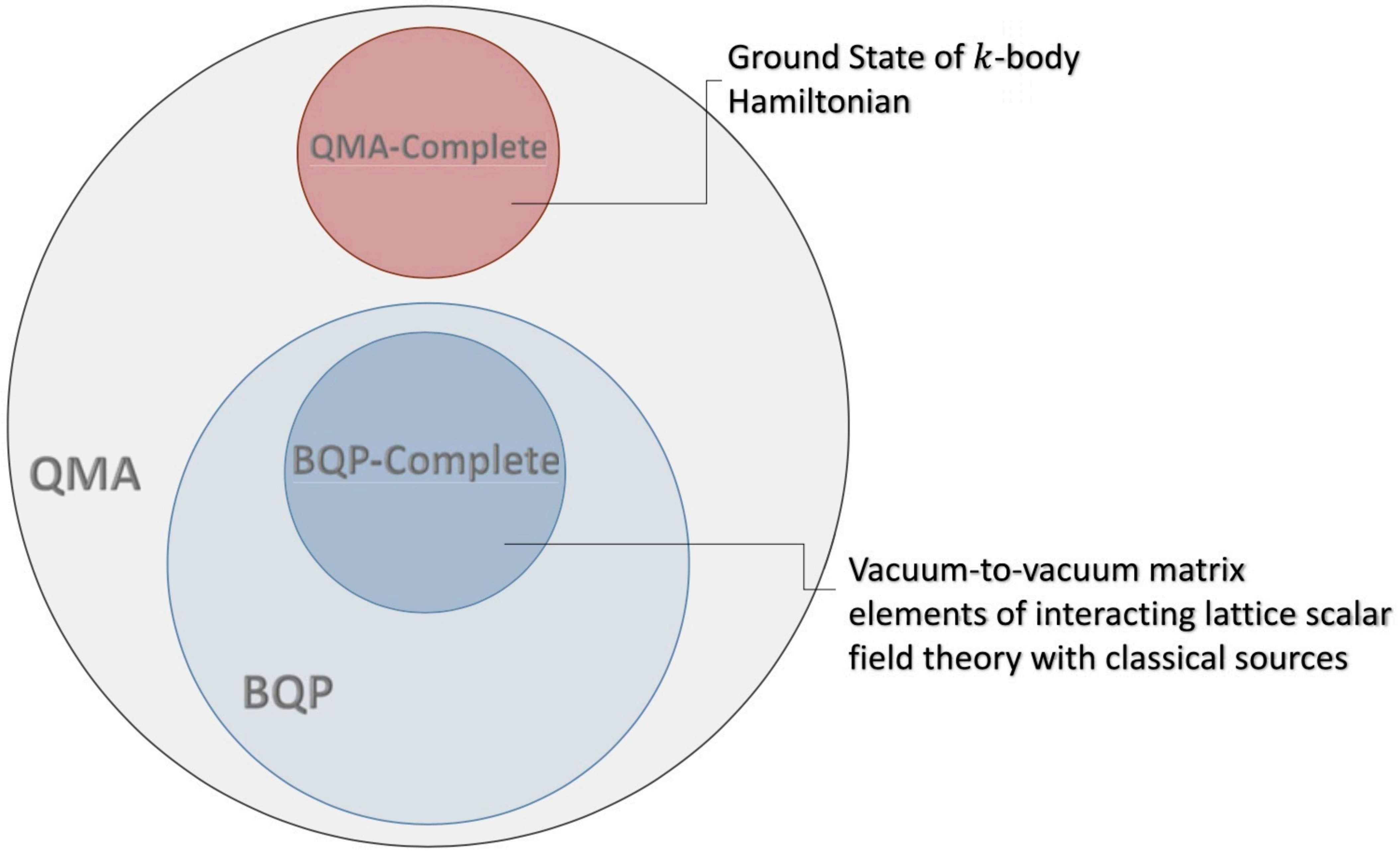






Wavepacket Evolution

Scalar Field Theory
Resource Scaling and Target Precision



Scaling

- system size
- precision

Jordan, Lee, Preskill Papers are the Gold Standard for Quantum Simulations of Scalar Field Theory

Two recent works:

arXiv > quant-ph > arXiv:2407.13819

Quantum Physics

[Submitted on 18 Jul 2024]

Optimized Quantum Simulation Algorithms for Scalar Quantum Field Theories

Andrew Hardy, Priyanka Mukhopadhyay, M. Sohaib Alam, Robert Konik, Layla Hormozi, Eleanor Rieffel, Stuart Hadfield, João Barata, Raju Venugopalan, Dmitri E. Kharzeev, Nathan Wiebe

arXiv > quant-ph > arXiv:2411.02486

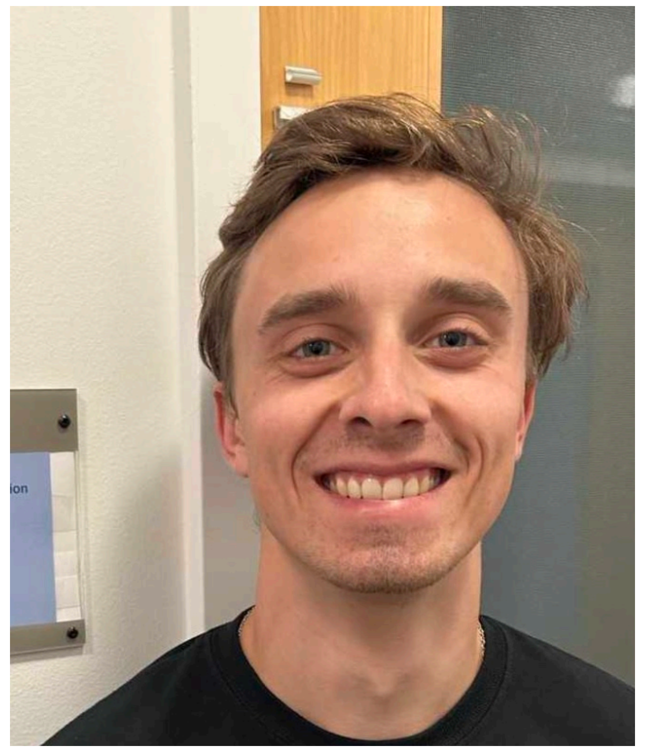
Quantum Physics

[Submitted on 4 Nov 2024]

Scalable Quantum Simulations of Scattering in Scalar Field Theory on 120 Qubits

Nikita A. Zemlevskiy

Scattering Wavepackets in Scalar Field Theory



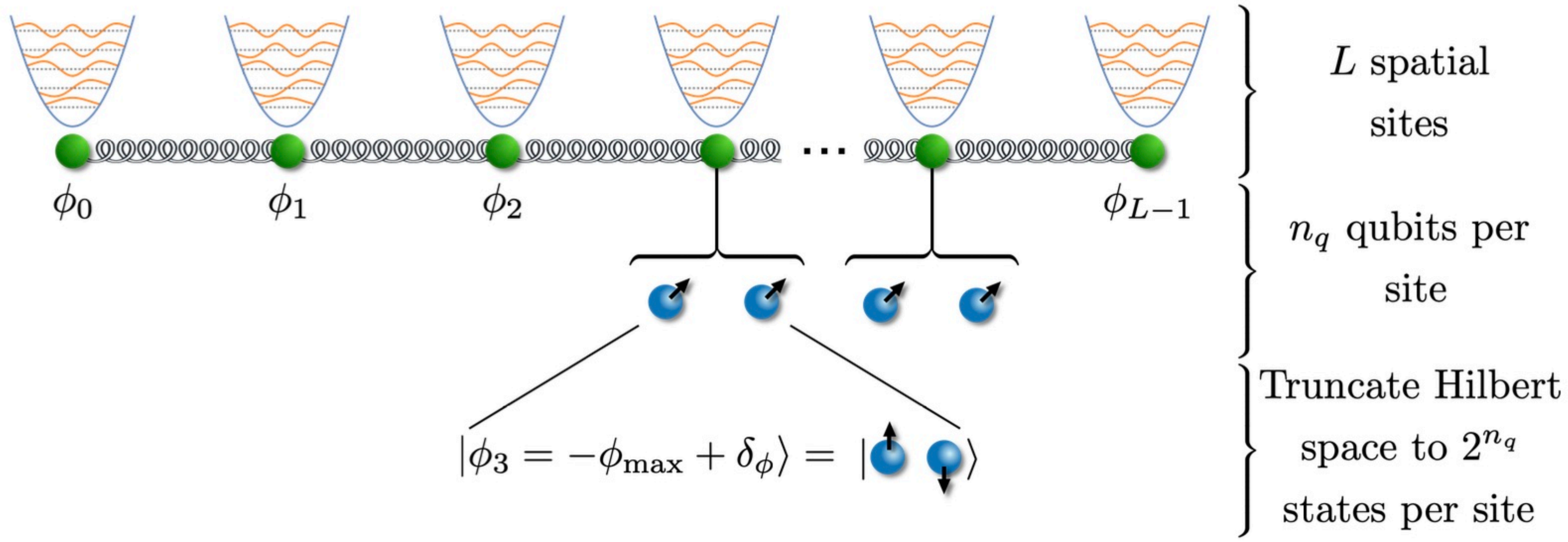
arXiv > quant-ph > arXiv:2411.02486

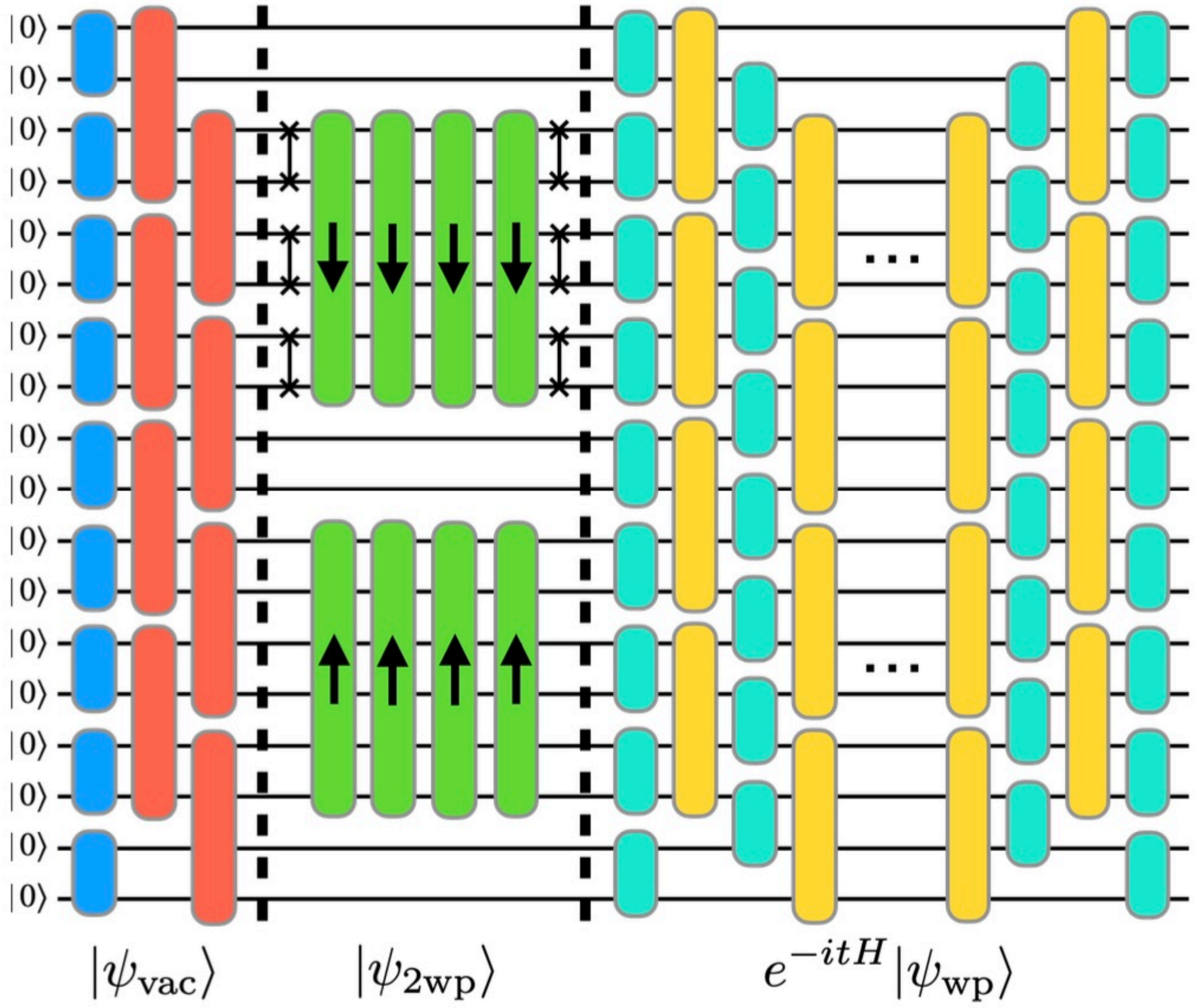
Quantum Physics

[Submitted on 4 Nov 2024]

Scalable Quantum Simulations of Scattering in Scalar Field Theory on 120 Qubits

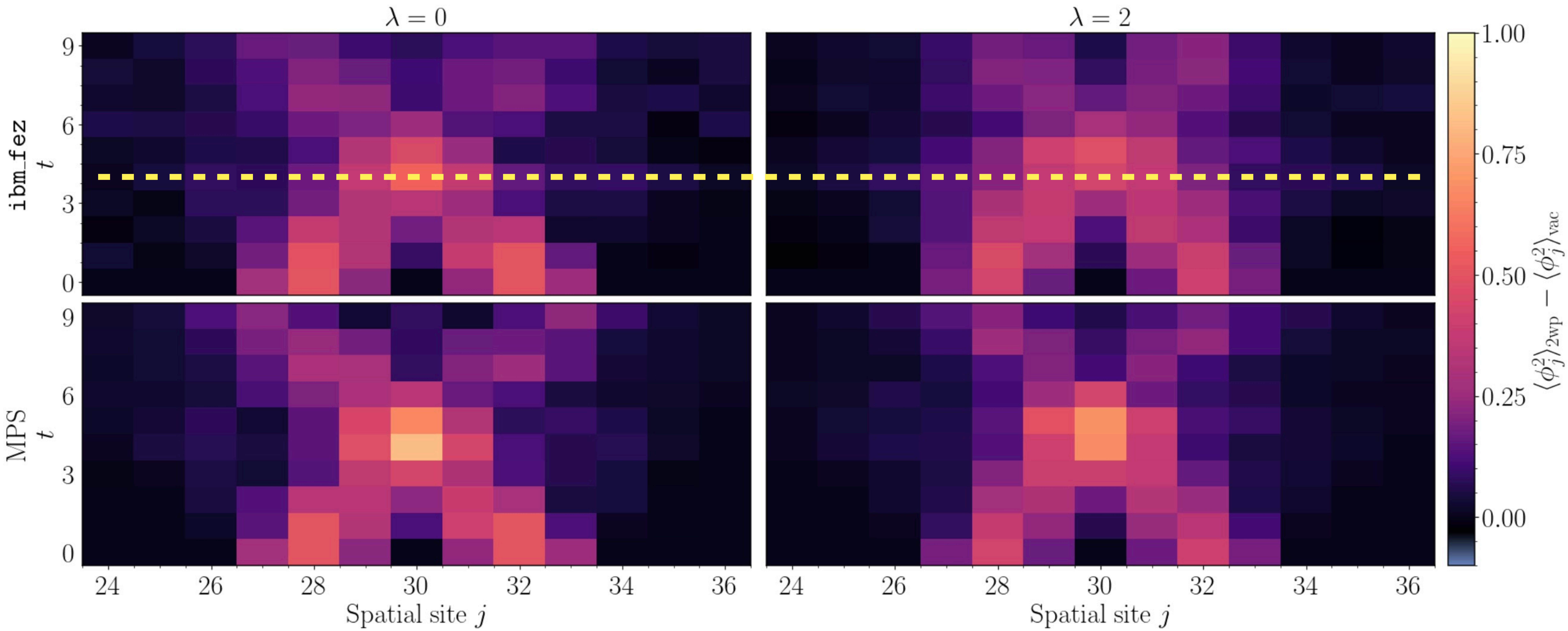
Nikita A. Zemlevskiy





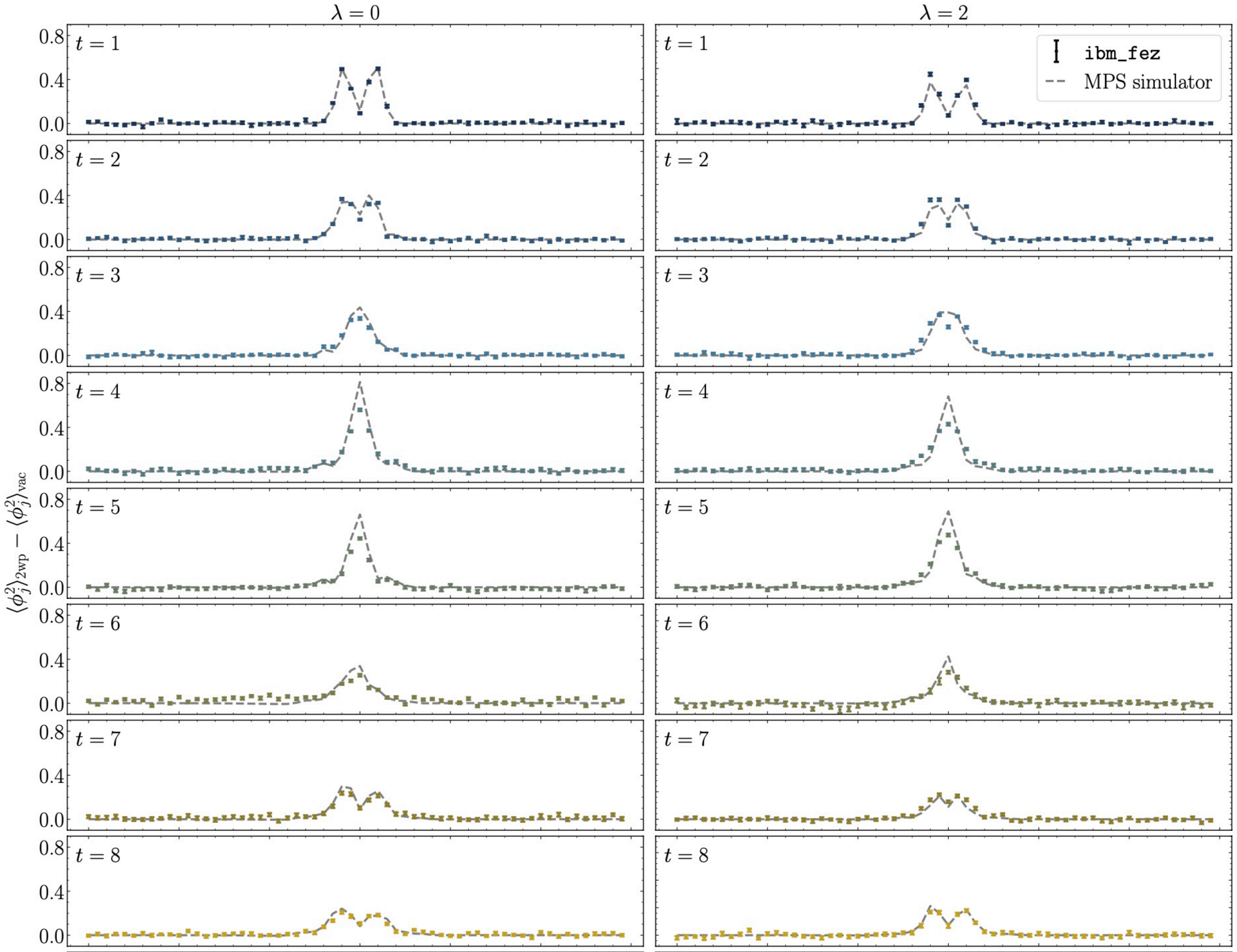
Variationally-optimized compressed scalable quantum circuits for time-evolution

Scattering in Scalar Field Theory



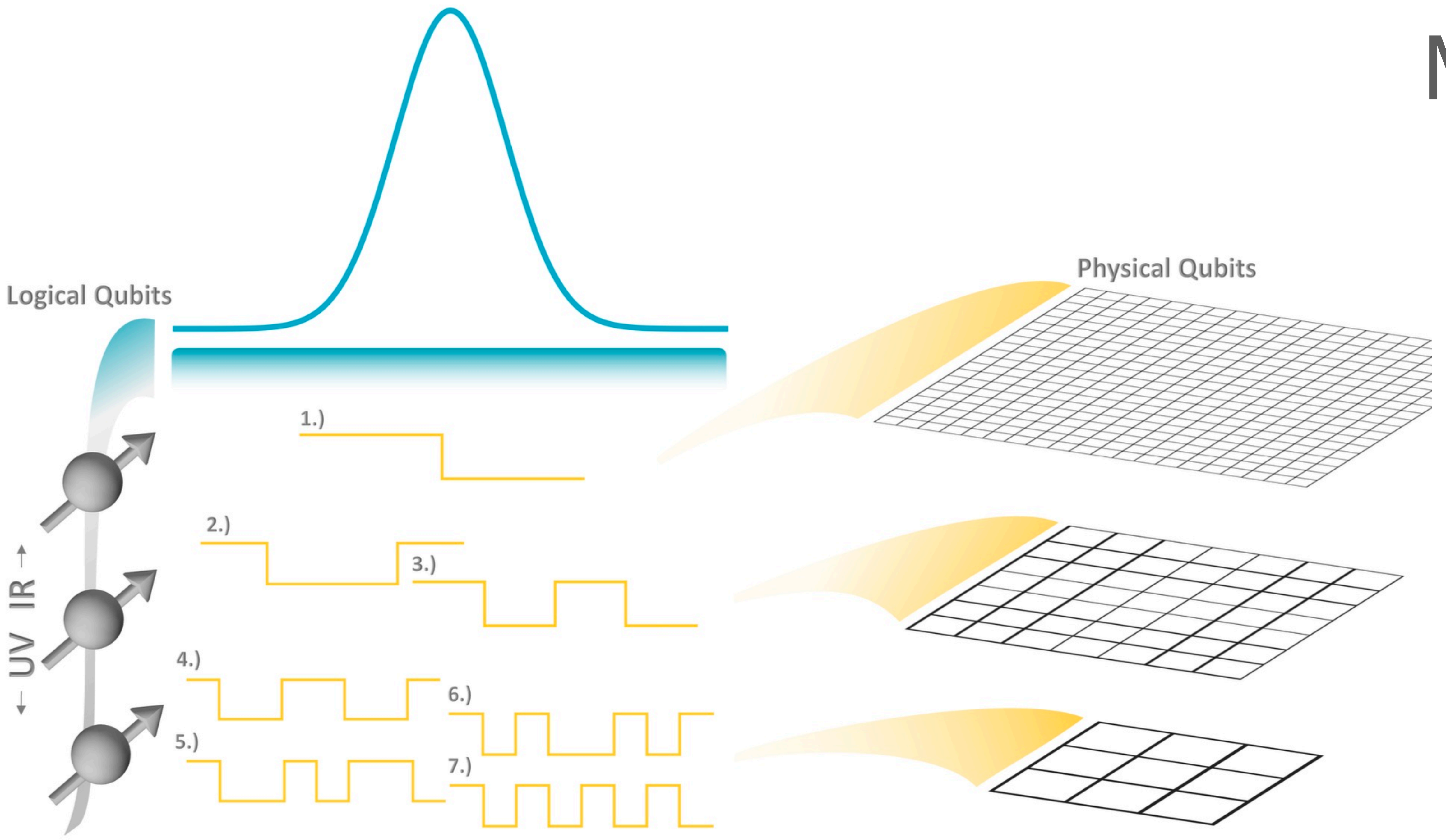
Scalable multi-qubit decoherence renormalization from the vacuum data

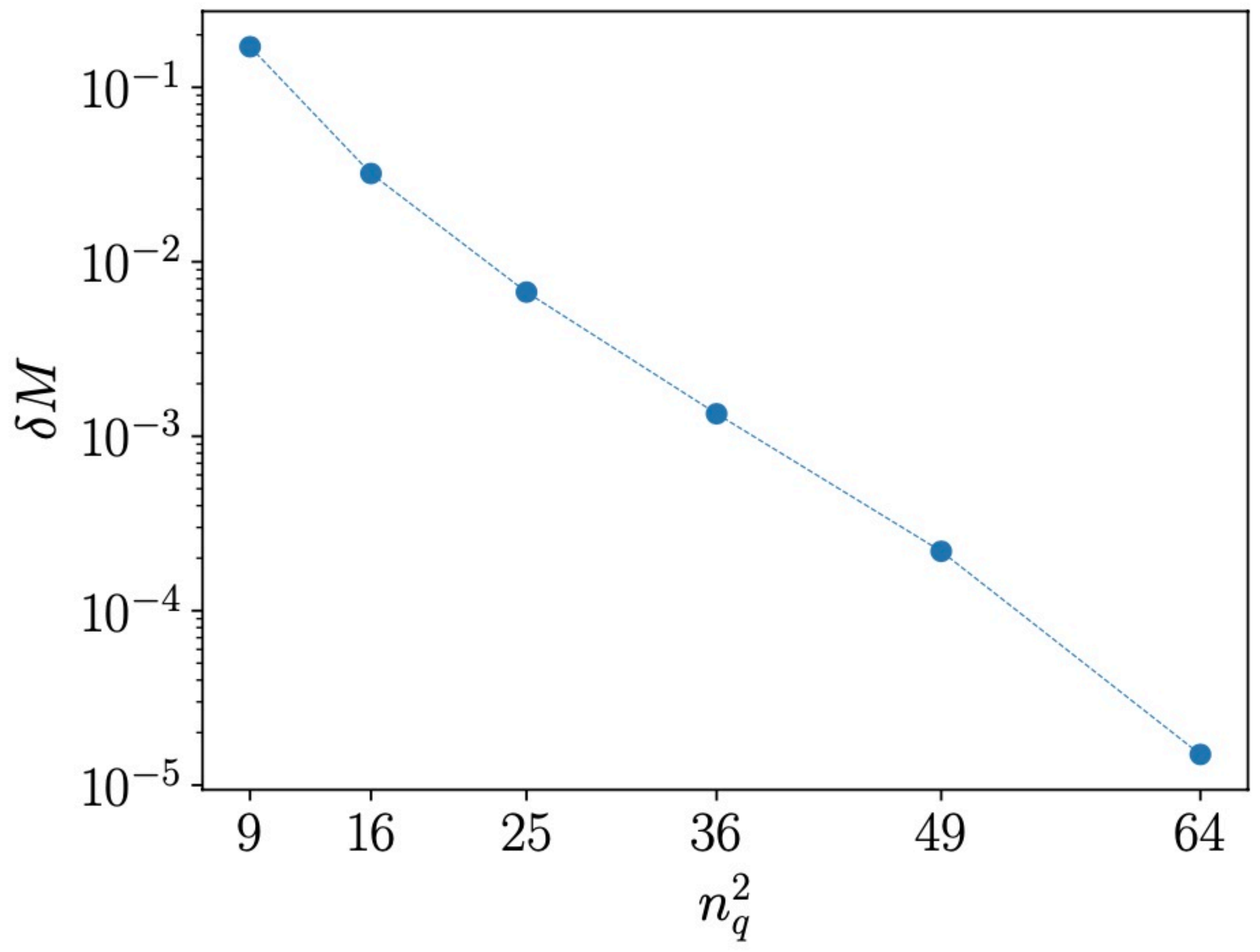
Scattering in Scalar Field Theory

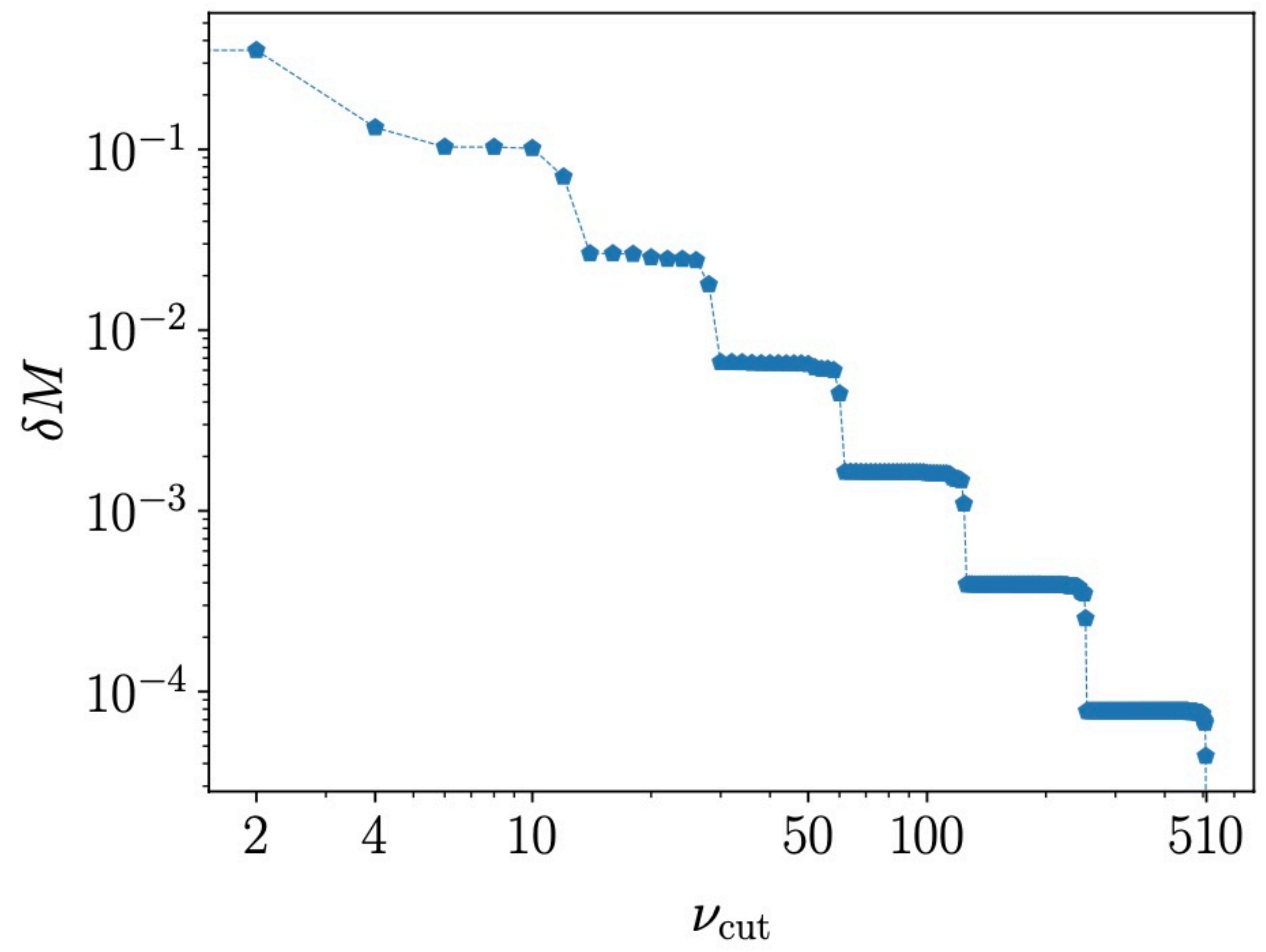


From NISQ to Fault Tolerant
Sequency Hierarchies

Magic in a Gaussian: $\mathcal{M}_{\text{lin}} = 0.362007$







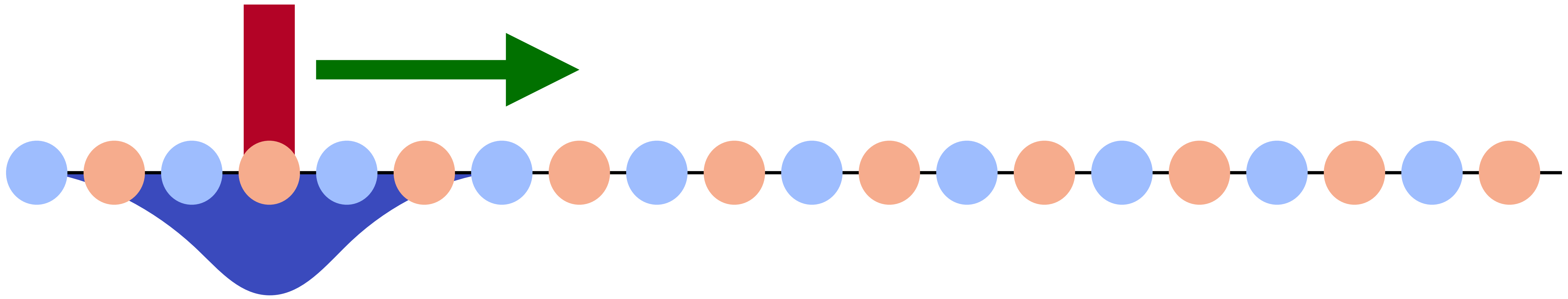
Hierarchical qubit maps and hierarchically implemented quantum error correction

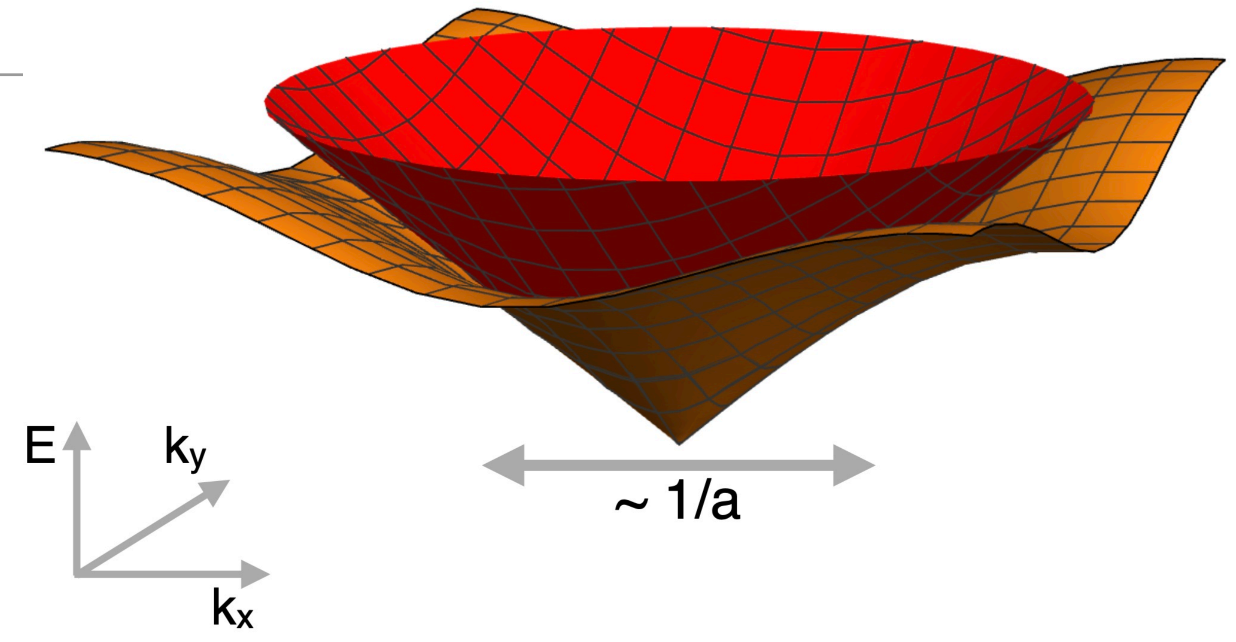
Natalie Klco and Martin J. Savage
Phys. Rev. A **104**, 062425 – Published 15 December 2021

Sequency Hierarchy Truncation (SeqHT) for Adiabatic State Preparation and Time Evolution in Quantum Simulations

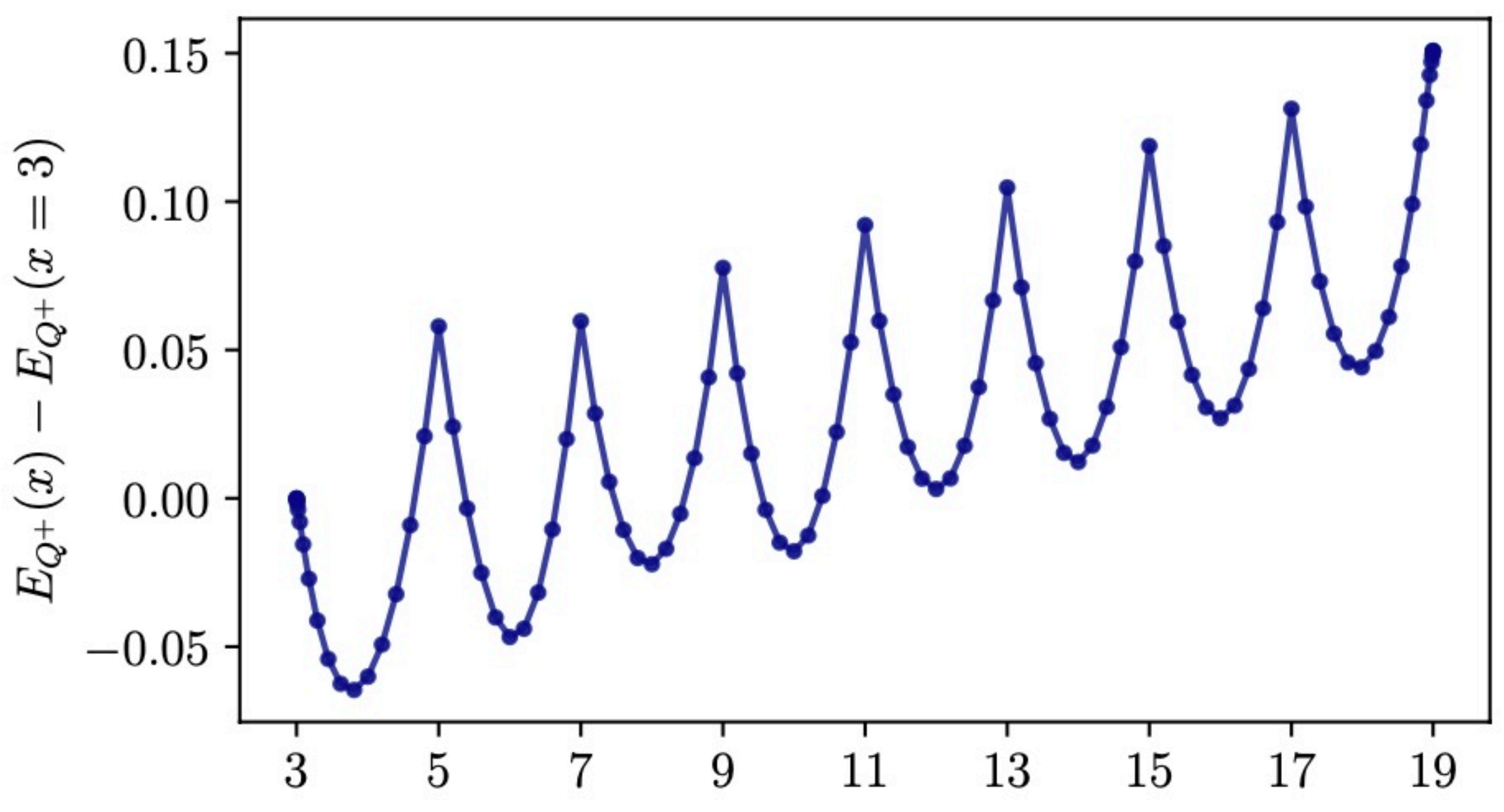
Zhiyao Li,* Dorota M. Grabowska,† and Martin J. Savage‡

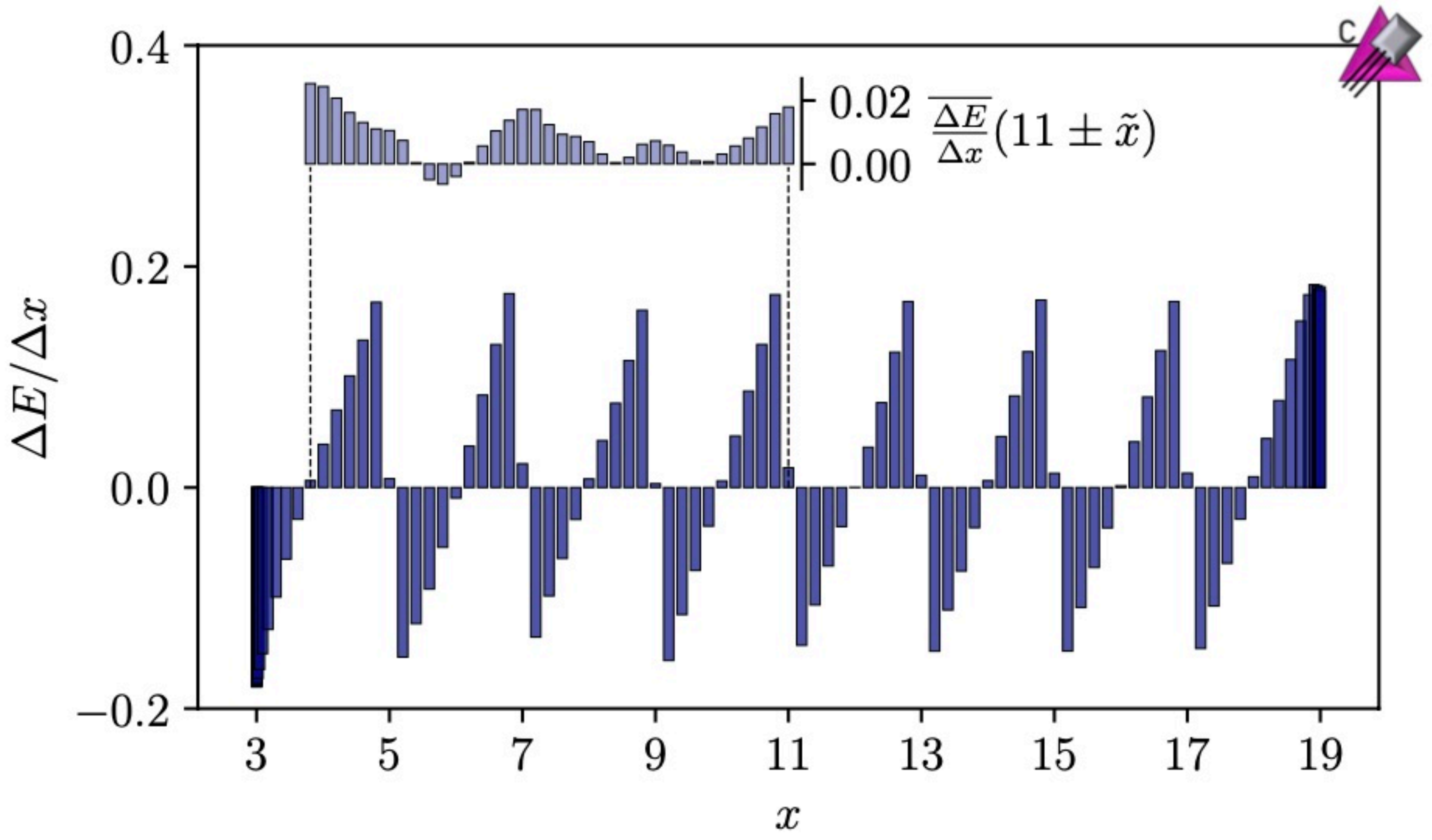
Lorentz Violation by Lattice Spacing

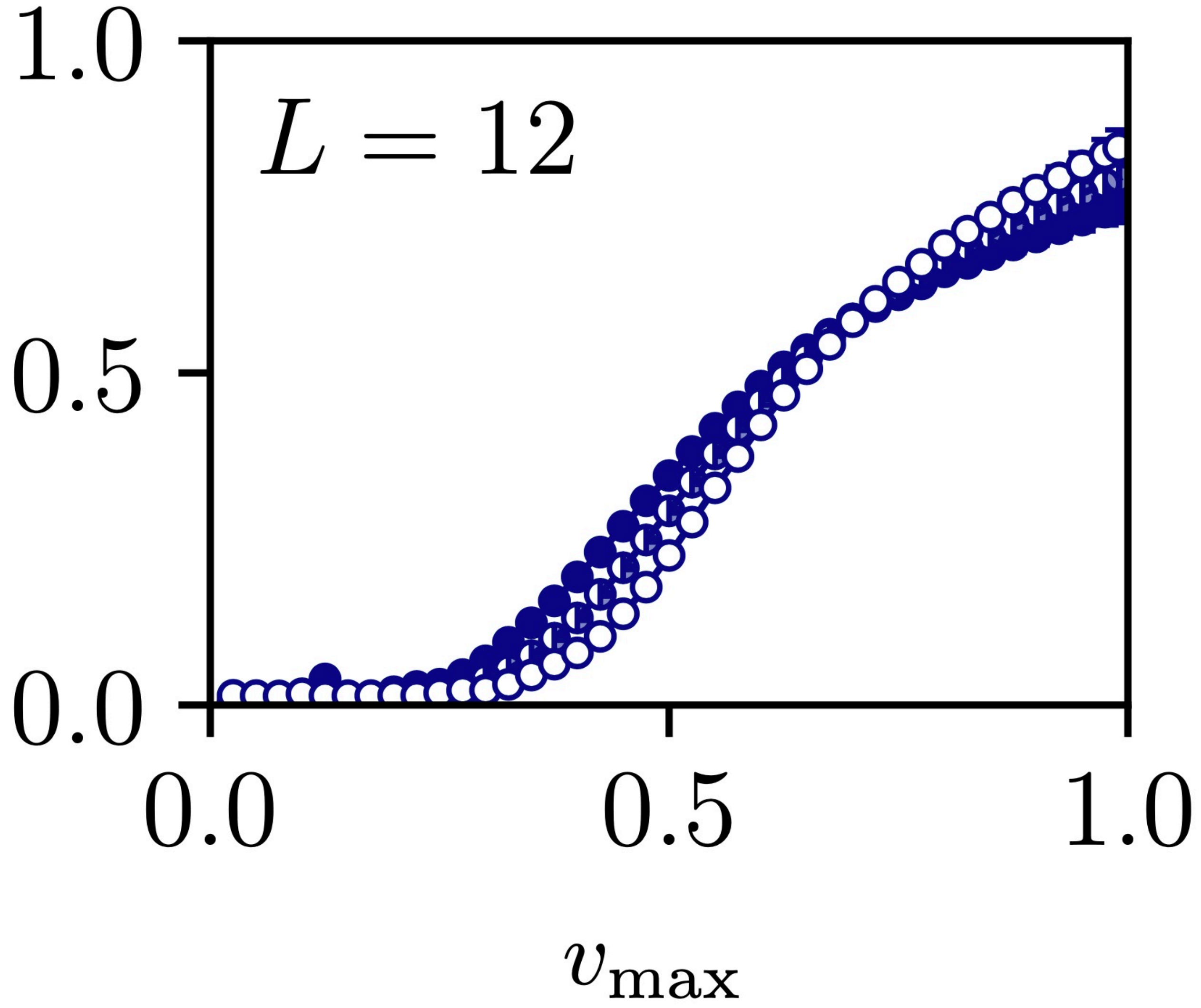




- Lorentz invariance dictates energy conservation at fixed velocity in vacuum
- Energy loss into the light degrees of freedom is
  - a lattice spacing artifact
  - creating hadrons with some probability on top of the vacuum - useful but not physics

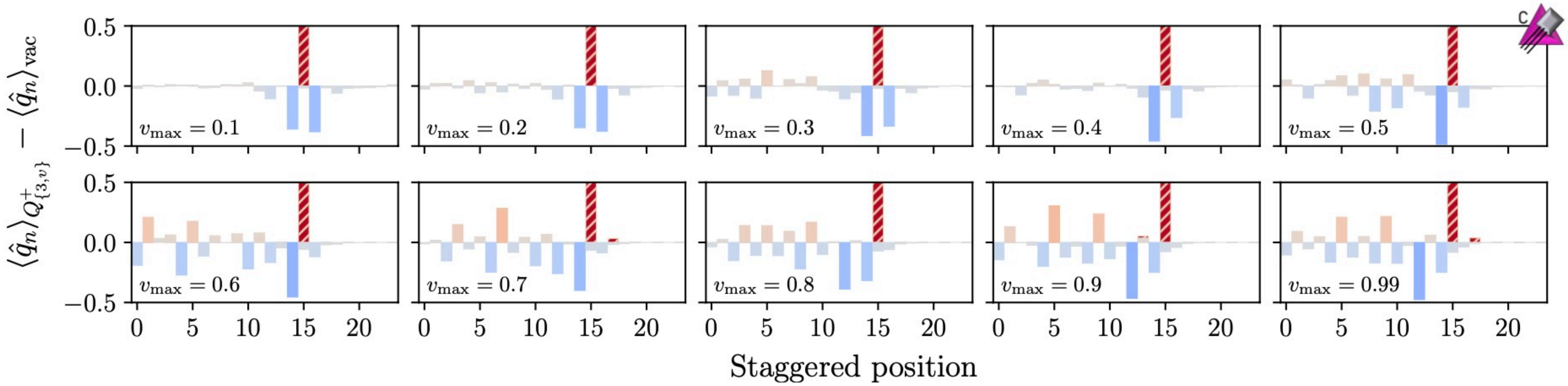




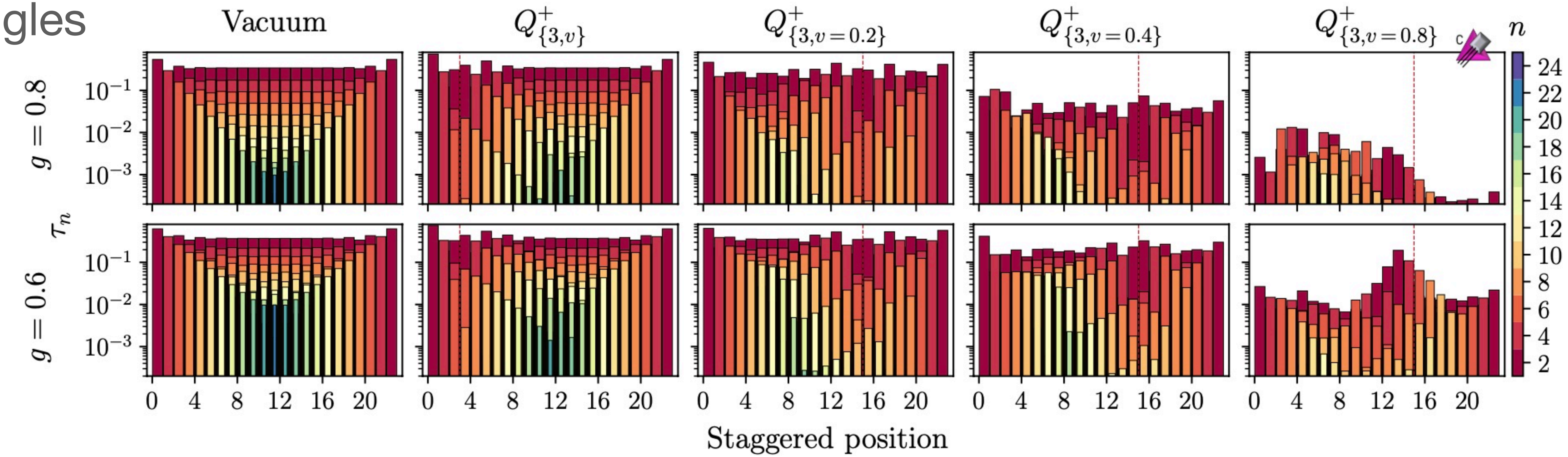


[Submitted on 10 May 2024]
Steps Toward Quantum Simulations of Hadronization and Energy-Loss in Dense Matter
Roland C. Farrell, Marc Illa, Martin J. Savage

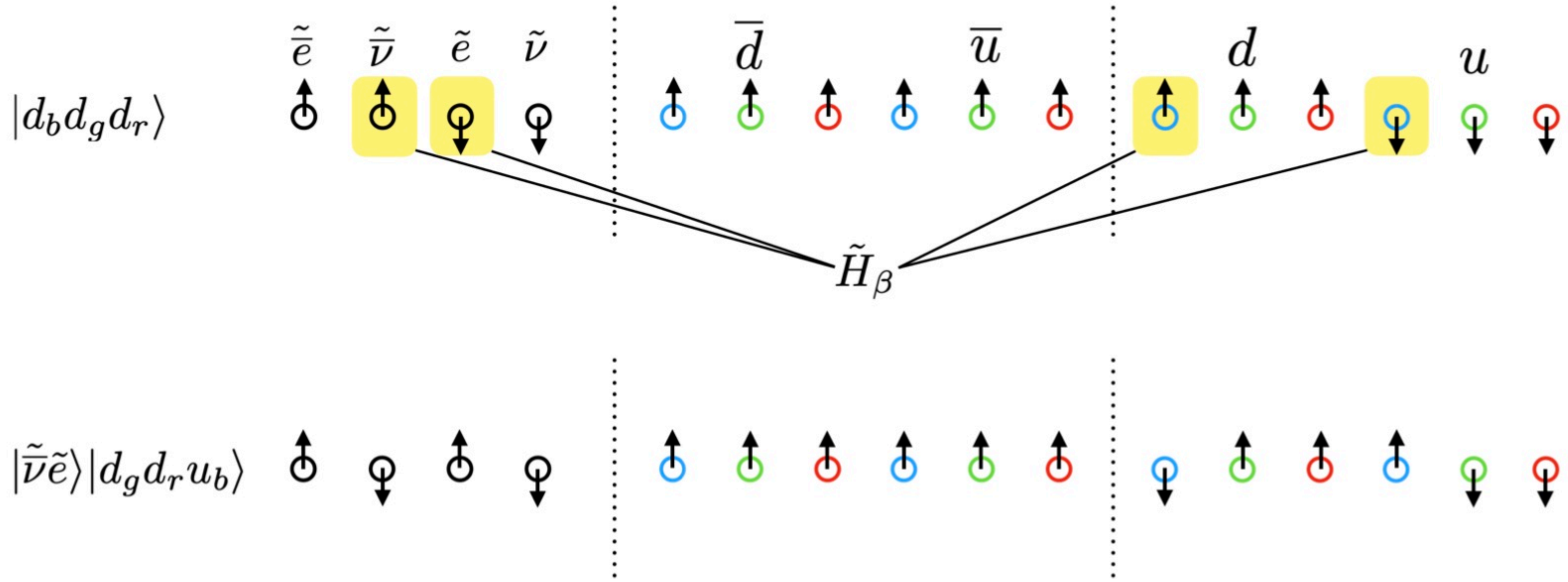
Lorentz Violation by the Lattice Spacing



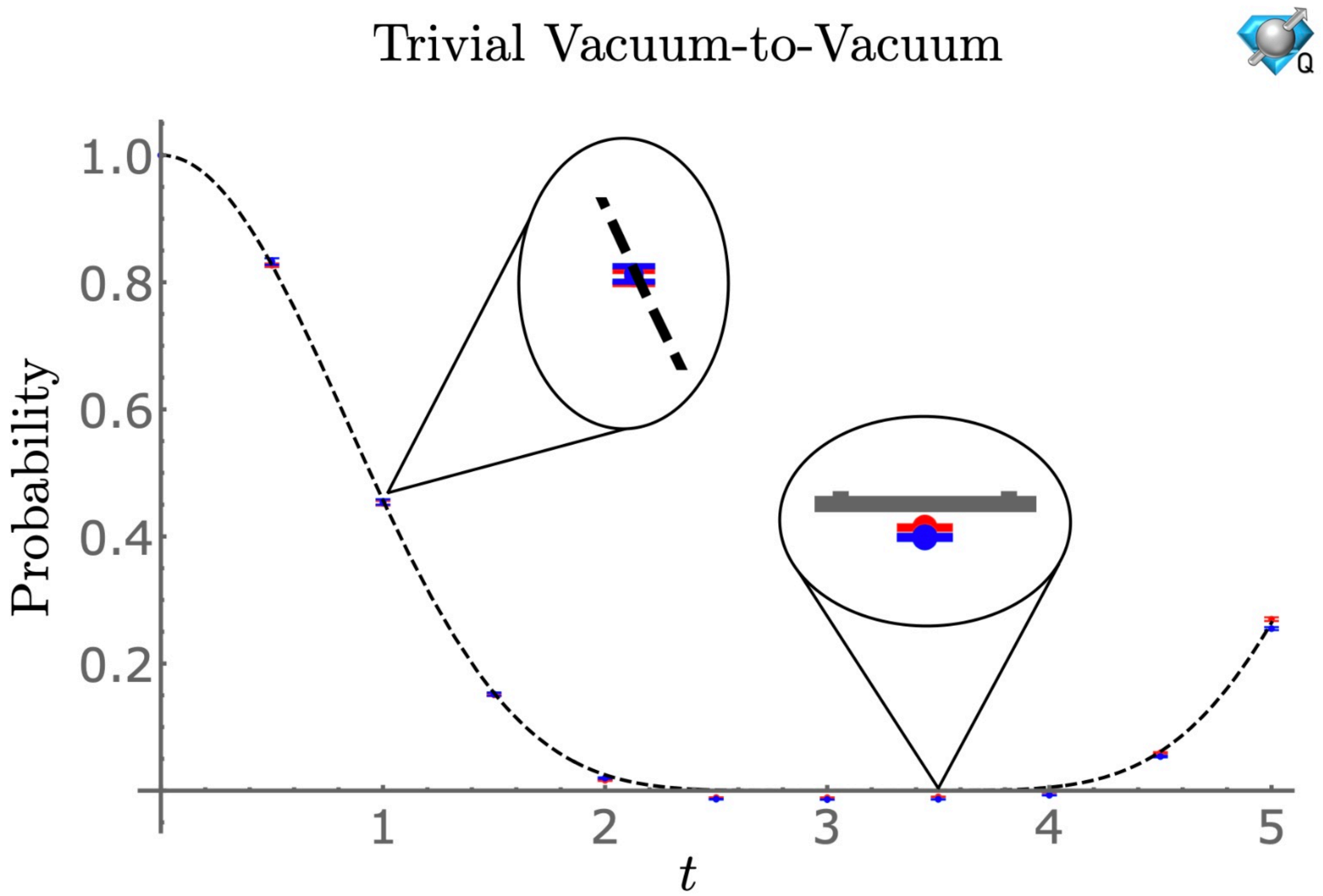
n-tangles



1+1D QCD and Weak Decays (2022)

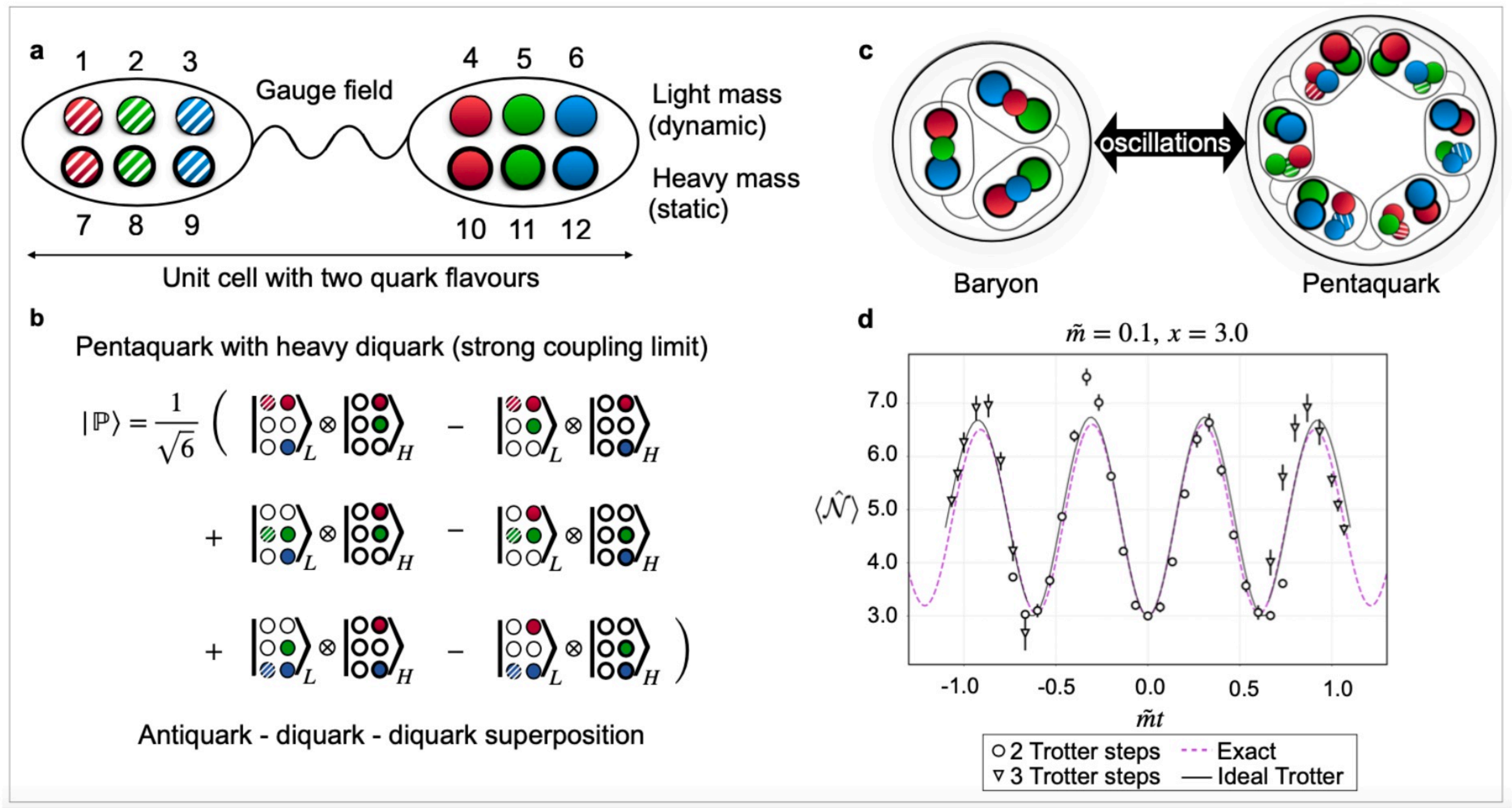


Naively Trotterized time evolution violates charge for Nc >= 3 !



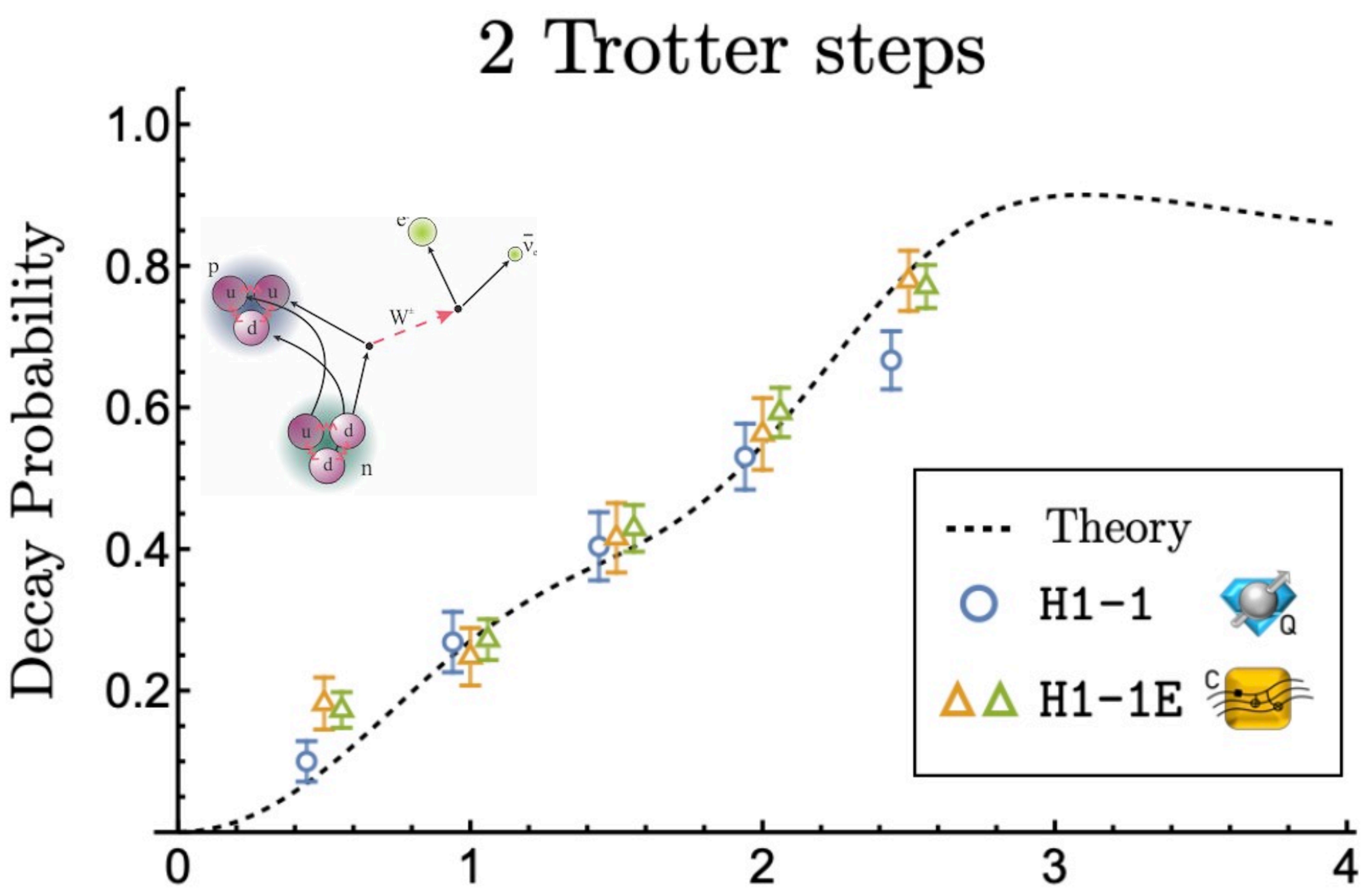
Preparations for quantum simulations of quantum chromodynamics in 1 + 1 dimensions. I. Axial gauge

Roland C. Farrell, Ivan A. Chernyshev, Sarah J. M. Powell, Nikita A. Zemlevskiy, Marc Illa, and Martin J. Savage
Phys. Rev. D **107**, 054512 – Published 30 March 2023



Simulating one-dimensional quantum chromodynamics on a quantum computer: Real-time evolutions of tetra- and pentaquarks

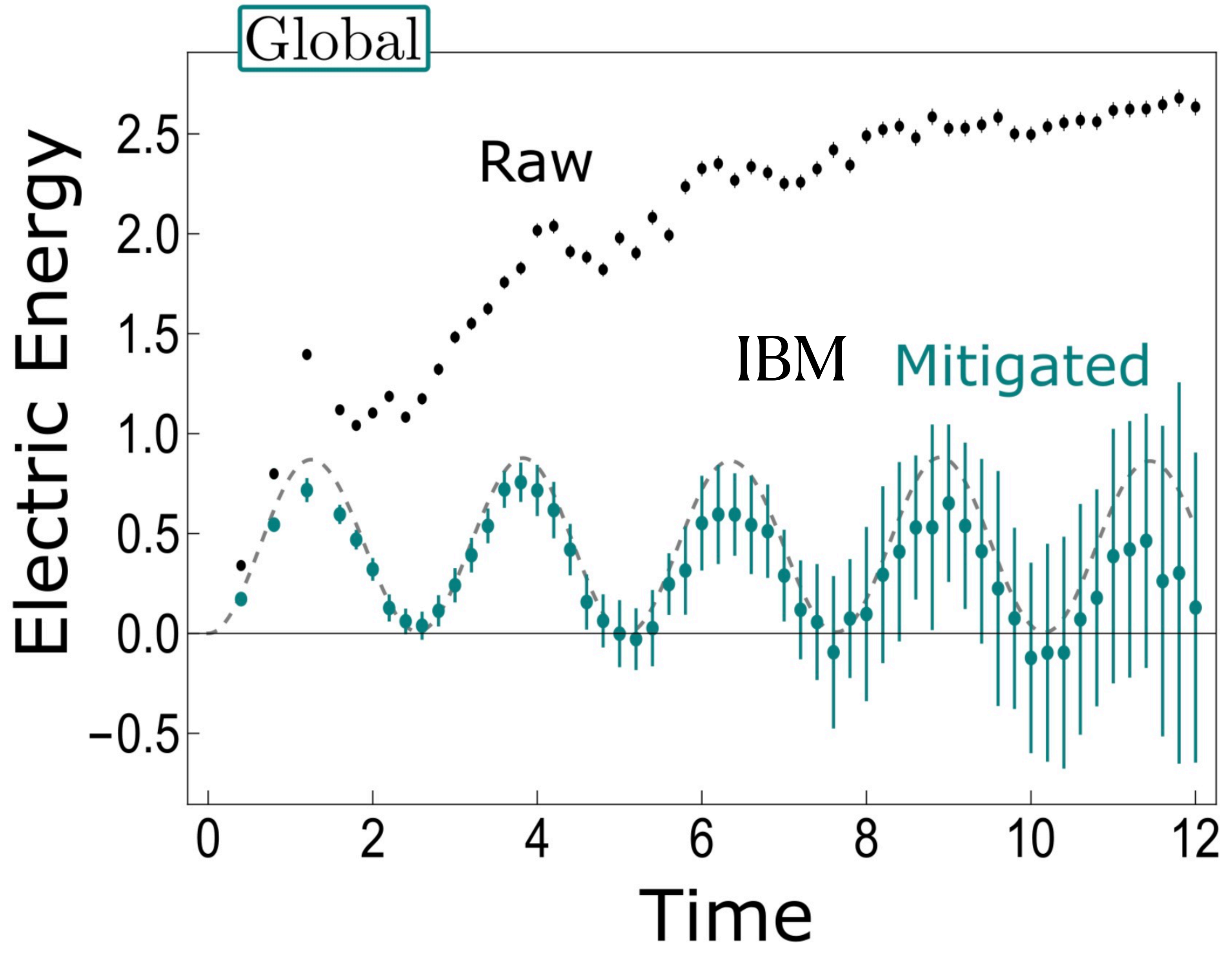
Yasar Y. Atas*,[1,2,†] Jan F. Haase*,[1,2,3,‡] Jinglei Zhang,[1,2,§] Victor Wei,[1,4] Sieglinde M.-L. Pfaendler,[5] Randy Lewis,[6] and Christine A. Muschik[1,2,7]

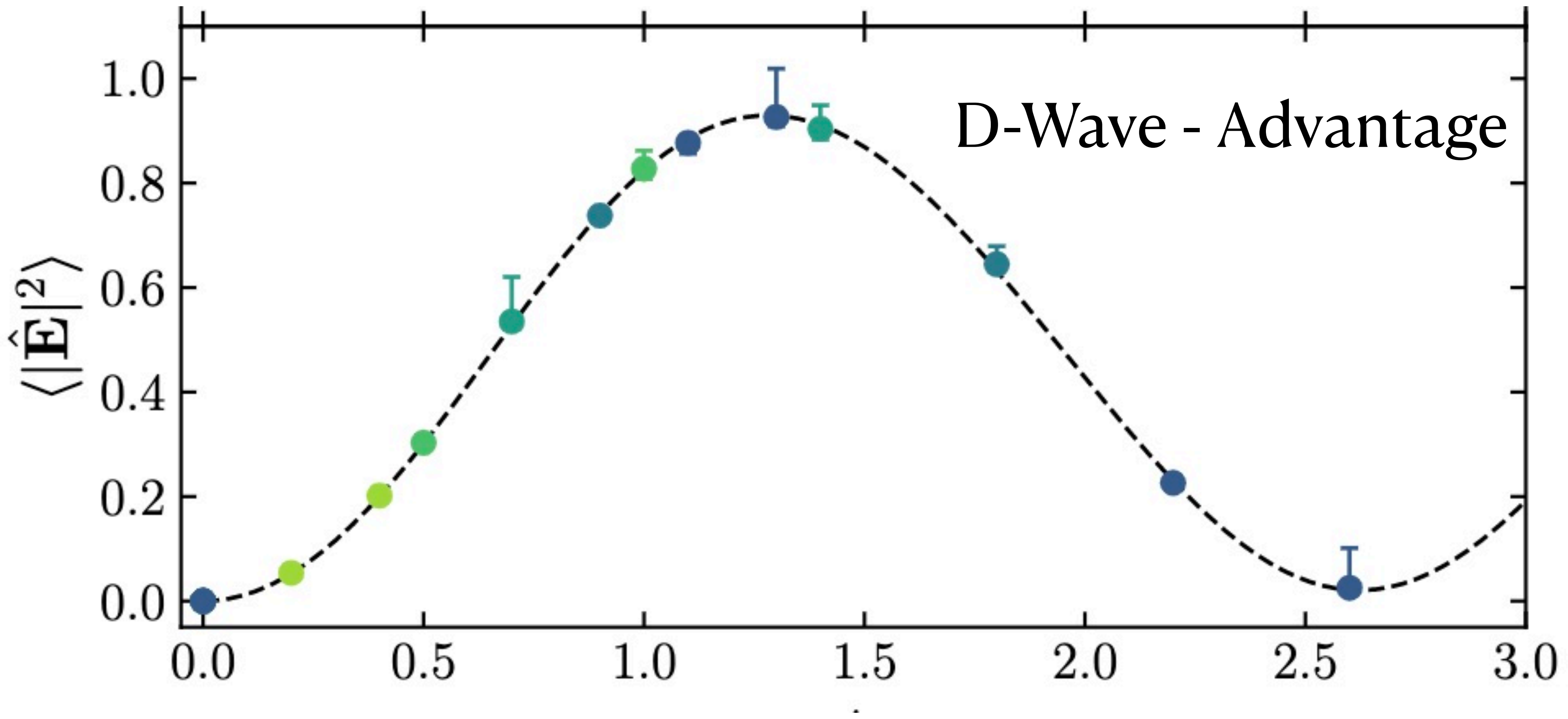


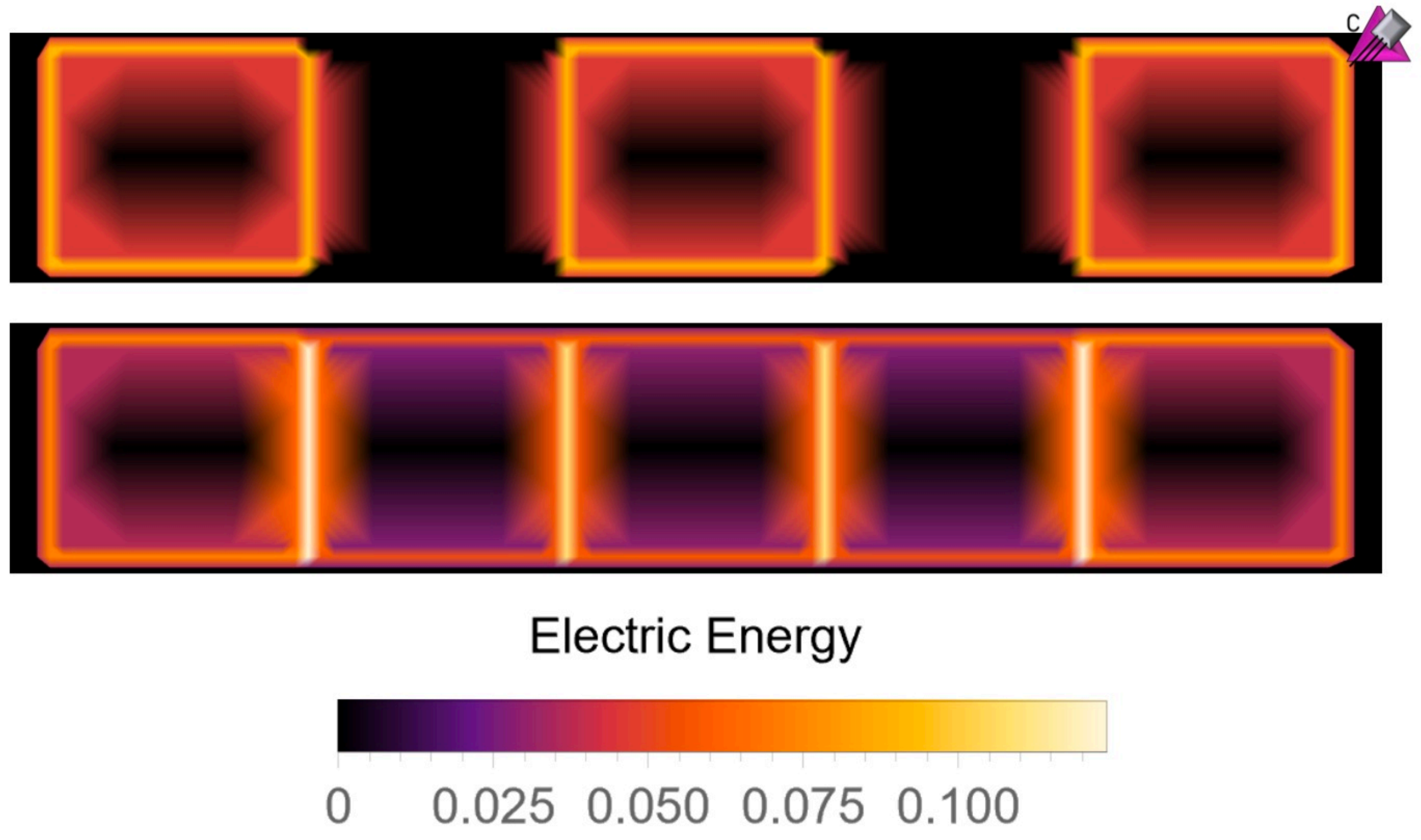
Preparations for quantum simulations of quantum chromodynamics in 1 + 1 dimensions. II. Single-baryon β-decay in real time

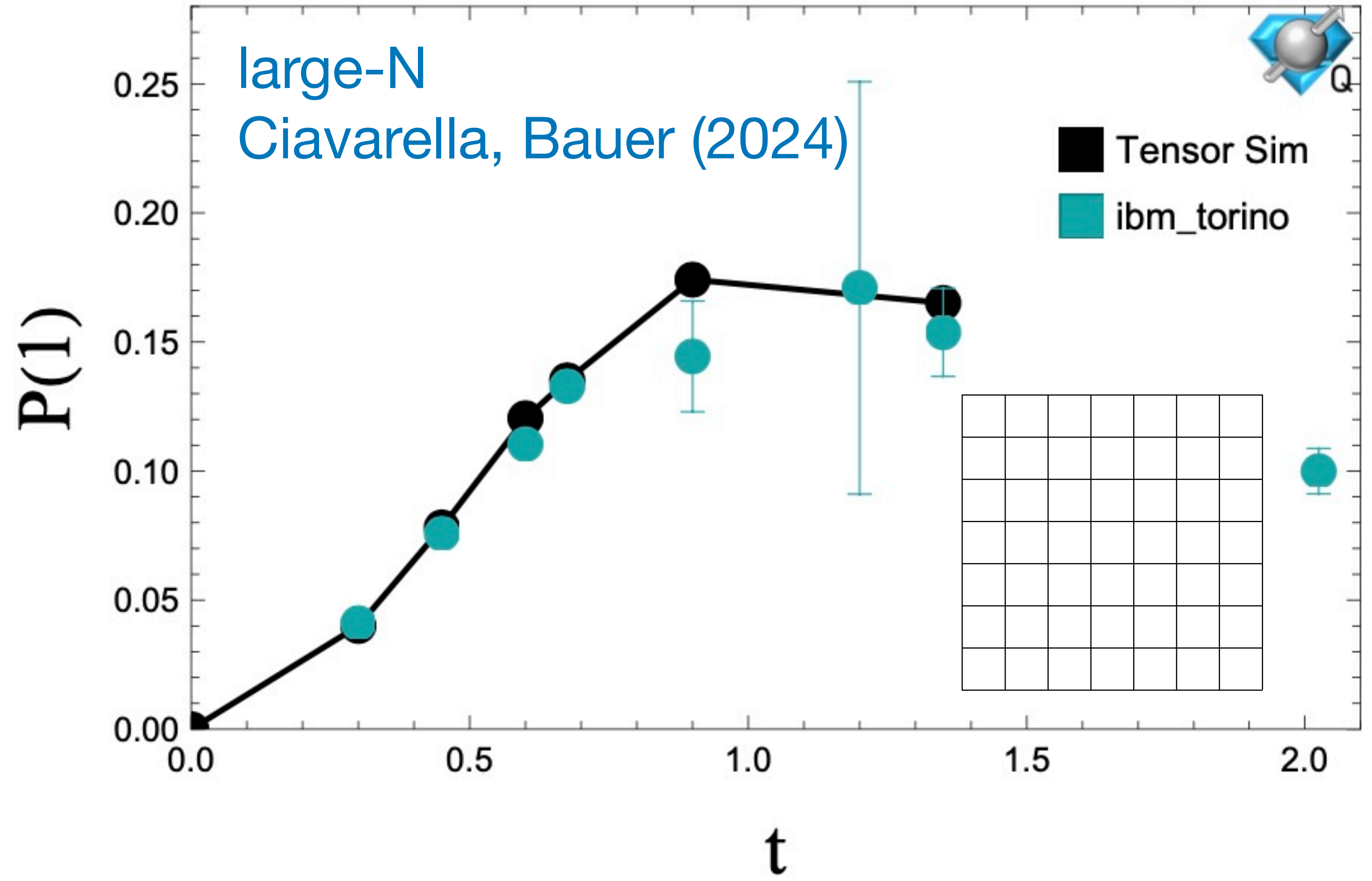
Roland C. Farrell, Ivan A. Chernyshev, Sarah J. M. Powell, Nikita A. Zemlevskiy, Marc Illa, and Martin J. Savage
Phys. Rev. D **107**, 054513 – Published 30 March 2023

SU(3) Yang-Mills Plaquettes - Examples









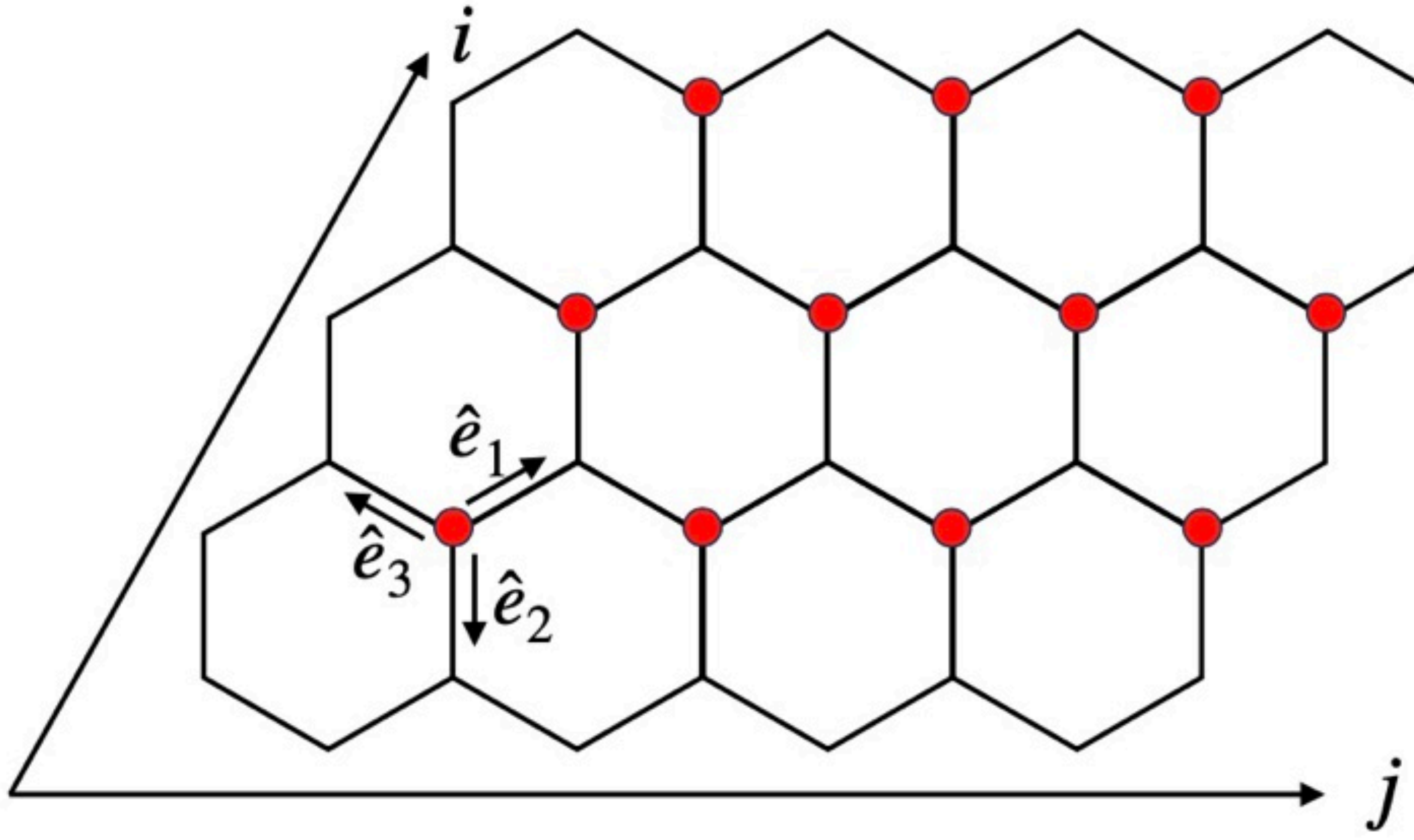
Transport Properties
Shear Viscosity in 2+1D SU(2)

Editors' Suggestion | Open Access

Classical and quantum computing of shear viscosity for $(2+1)D$ SU(2) gauge theory

Francesco Turro, Anthony Ciavarella, and Xiaojun Yao
Phys. Rev. D **109**, 114511 – Published 13 June 2024

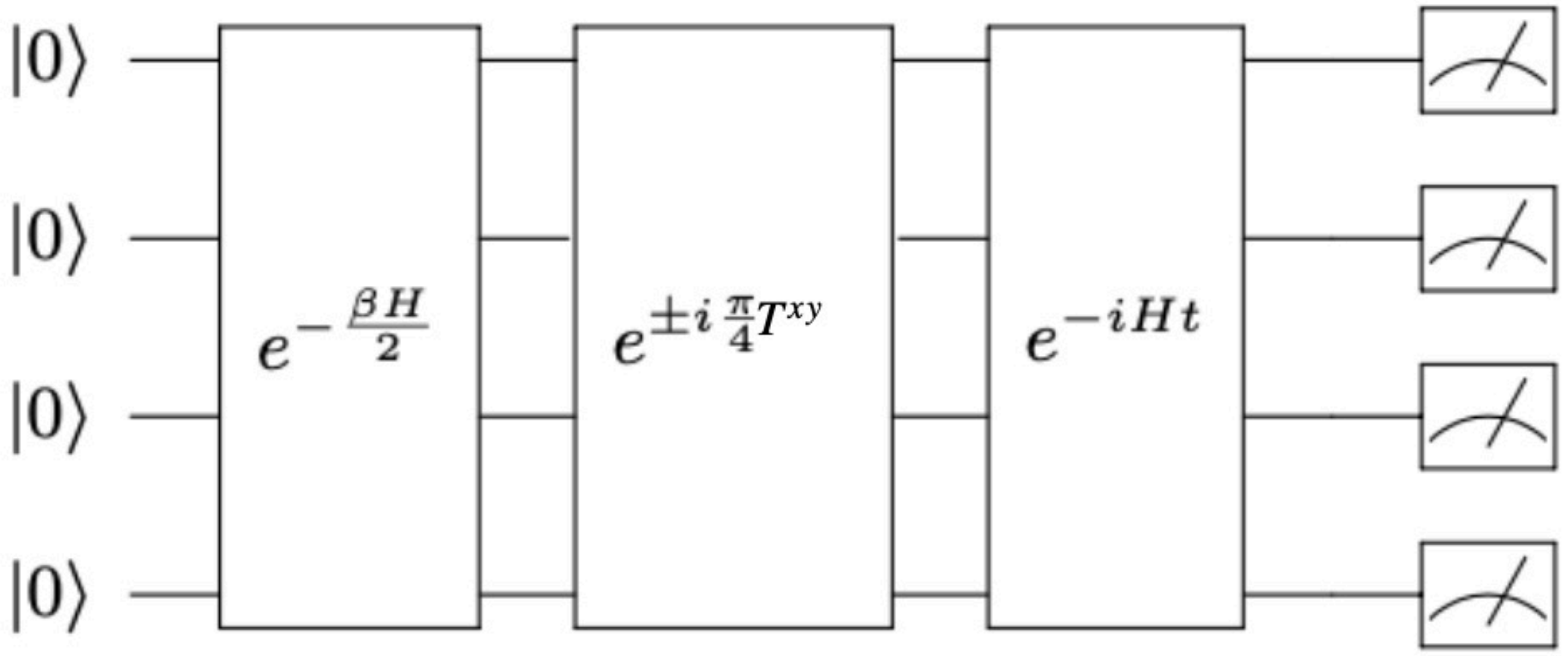
Berndt Mueller and Xiaojun Yao



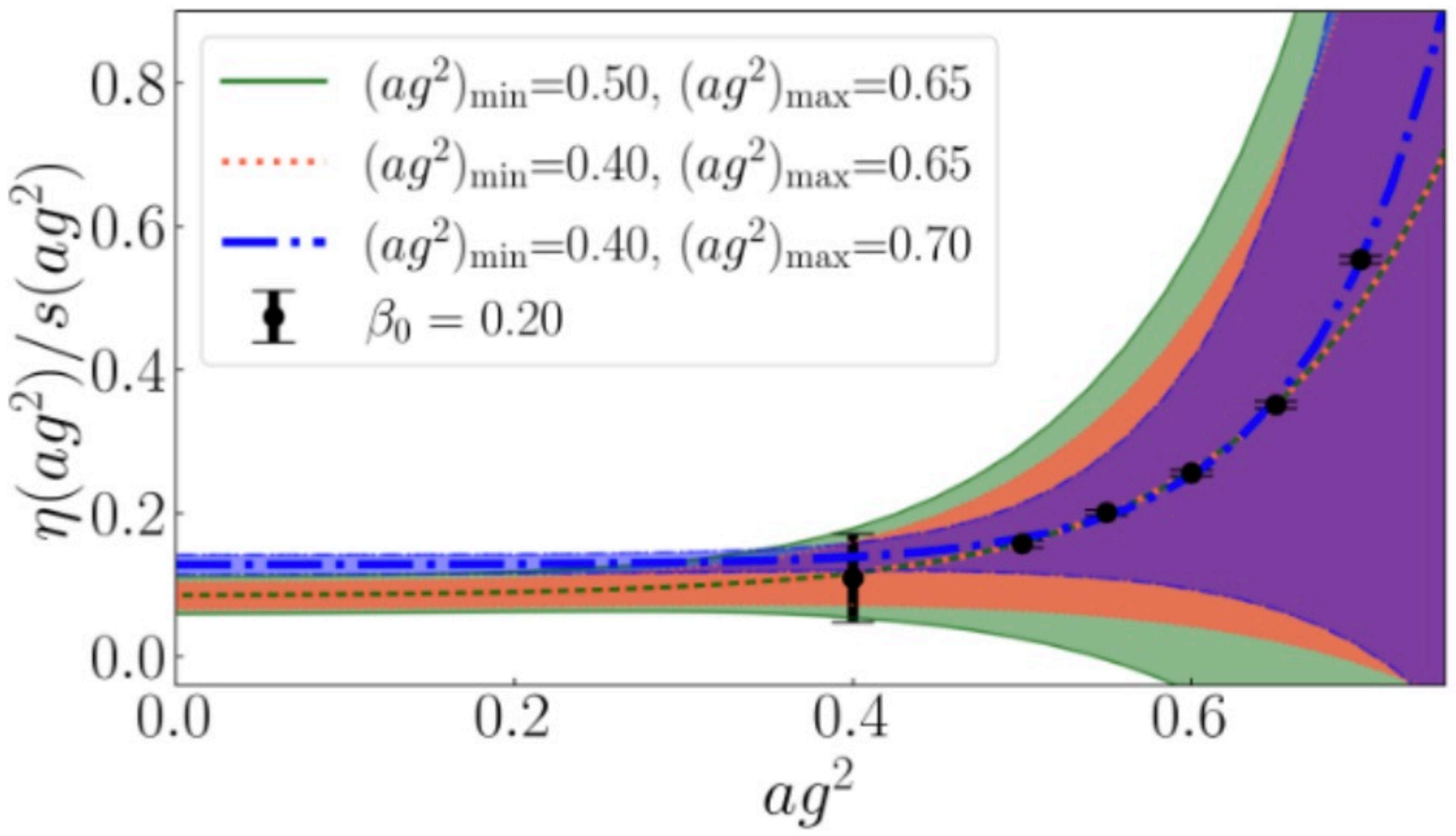
$$H = \frac{3\sqrt{3}g^2}{4}\sum_{\text{links}} E_i^a E_i^a - \frac{4\sqrt{3}}{9g^2a^2}\sum_{\text{plaqs}} \hexagon$$

$$T^{xy} = -\frac{g^2}{\sqrt{3}a^2}\left((E_1^a)^2 - (E_3^a)^2\right)$$

Quantum algorithm for G_r^{xy}



On 4×4 lattice w/ $j_{\max} = 0.5$



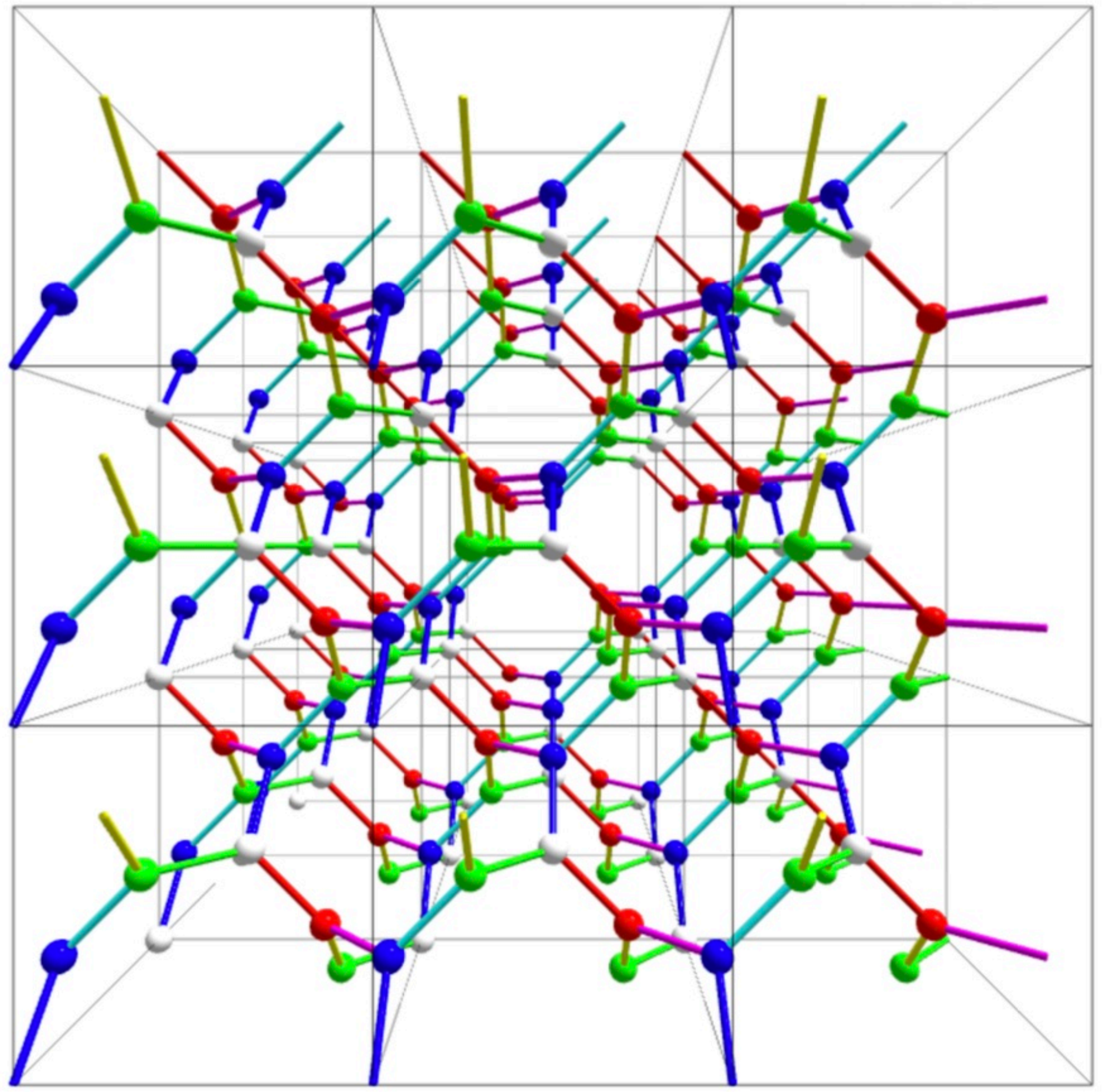
At the Quantum Limit, same as liquid created in heavy-ion collisions

Example New Directions

From square plaquettes to triamond lattices for SU(2) gauge theory

Ali H. Z. Kavaki* and Randy Lewis†

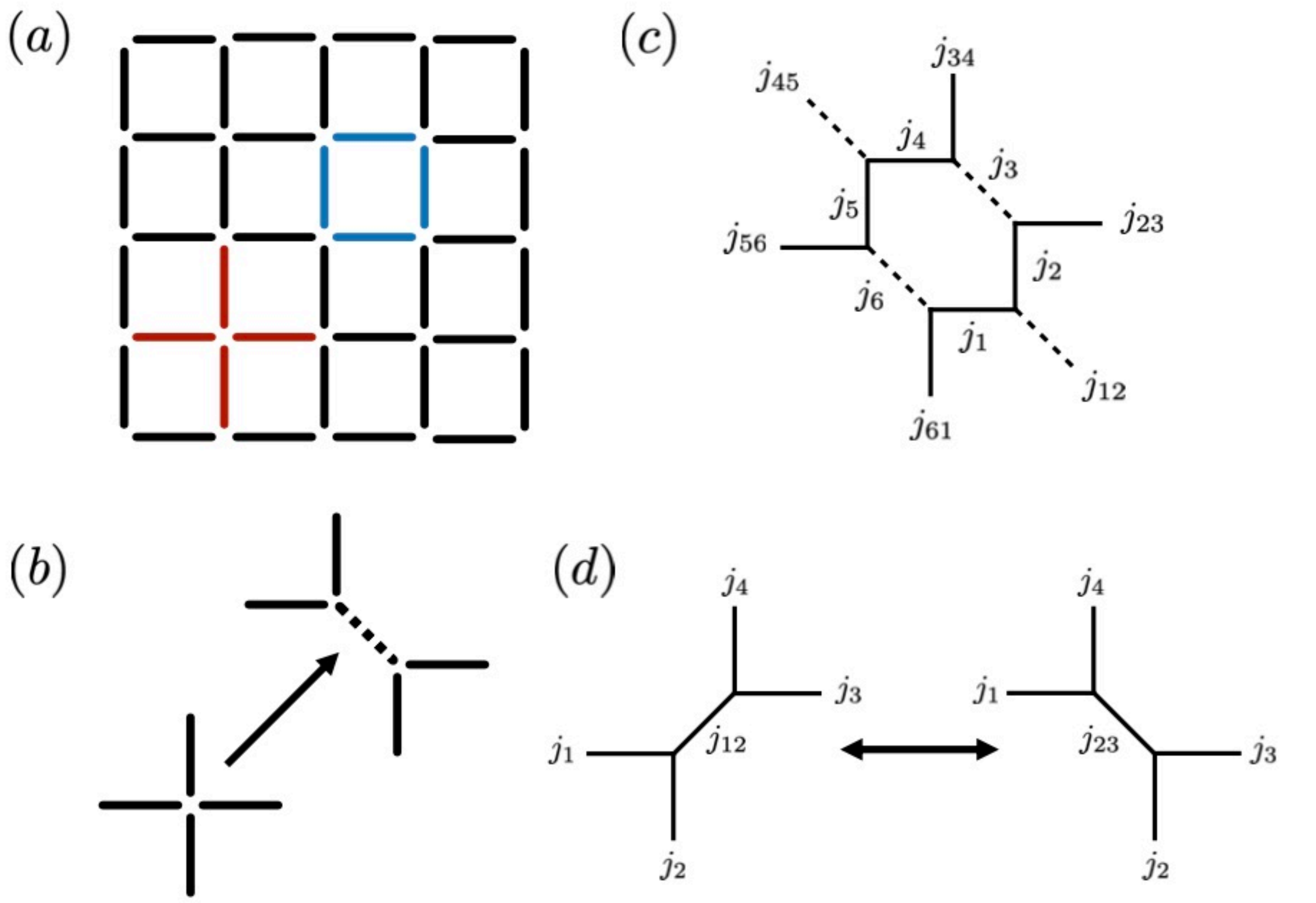
2024



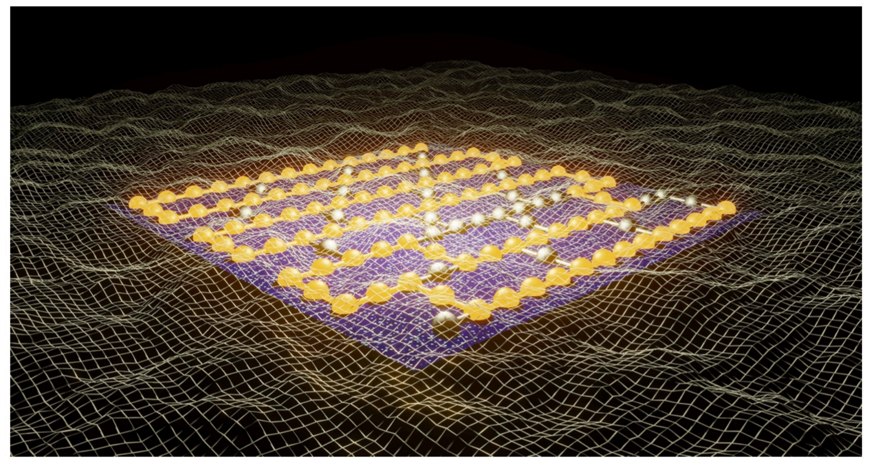
Quantum and classical spin network algorithms for q-deformed Kogut-Susskind gauge theories

Torsten V. Zache,* Daniel González-Cuadra, and Peter Zoller

2023



Summary and Outlook



The Matter-Antimatter Asymmetry   Astrophysical Environments   Collisions and Reactions

Quantum simulations of gauge theories are advancing

Anticipate a continuous evolution from NISQ to fault tolerance

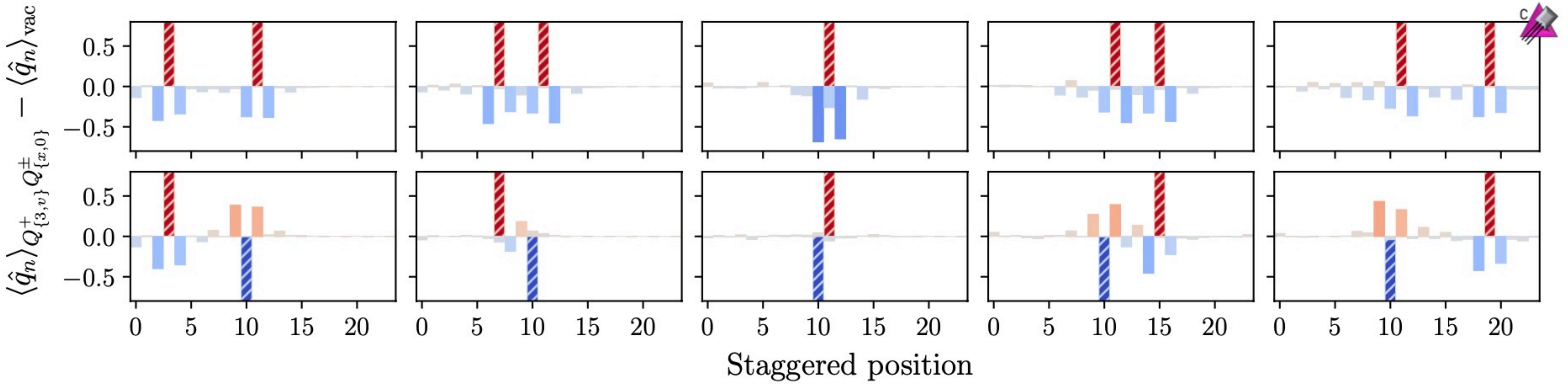
Understanding how to organize magic and entanglement is important

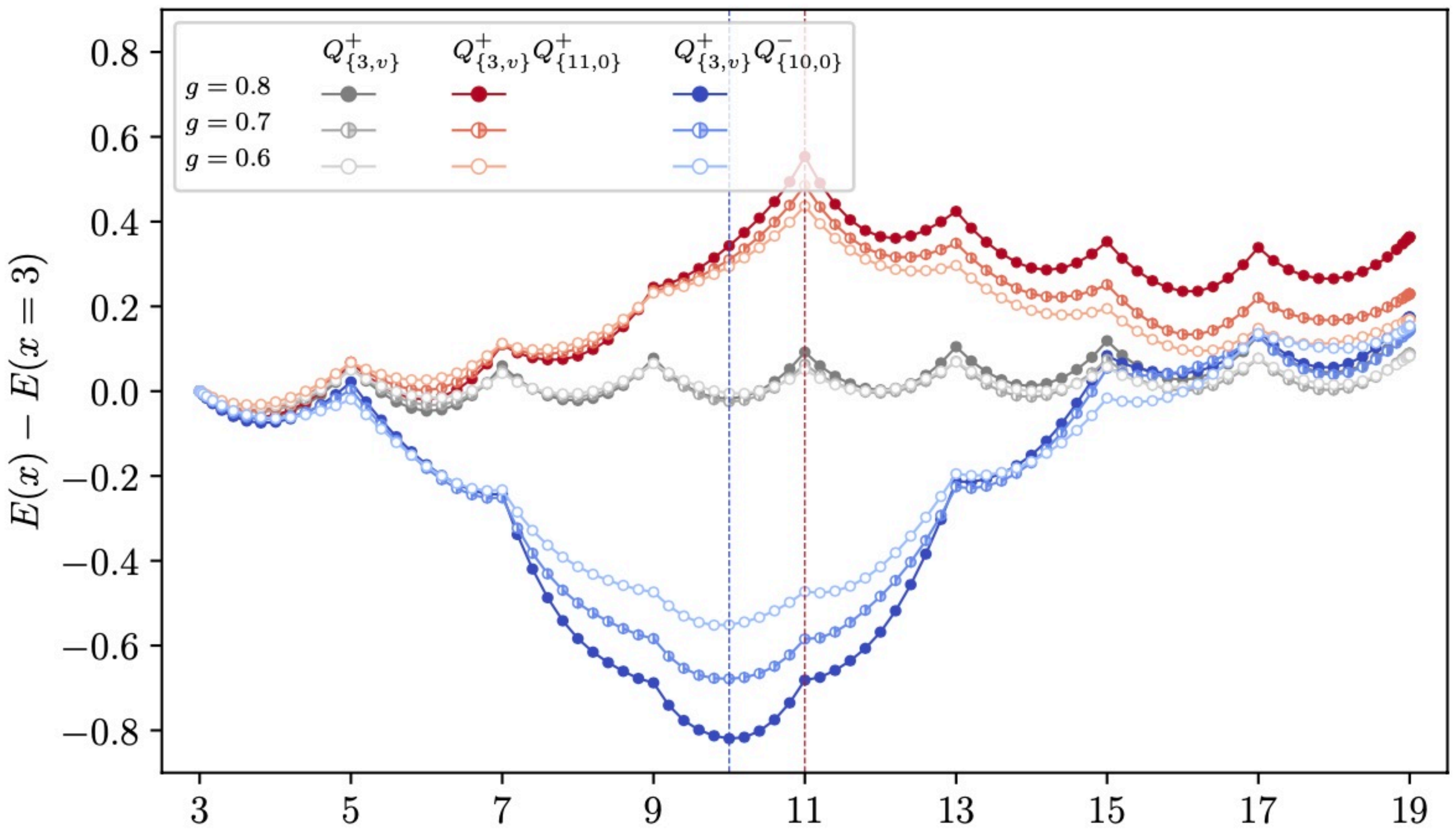
2+1 and 3+1 Quantum Field Theory - Abelian and non-Abelian

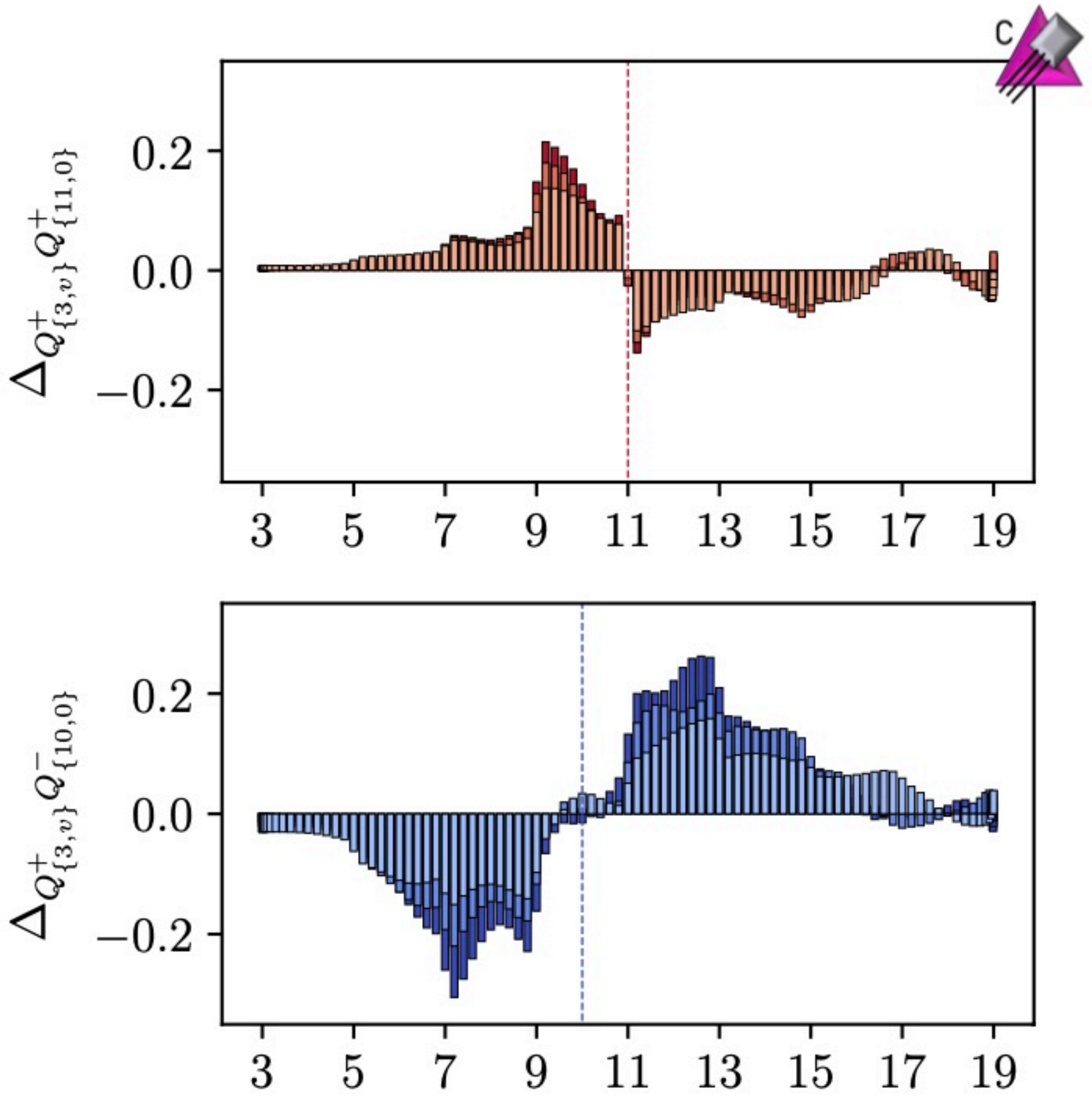
- Frameworks and algorithms, quantum spin-liquids, topology
- Thermalization, collisions and transport
- Efforts to connect with experiment

FIN

Colliding Partons



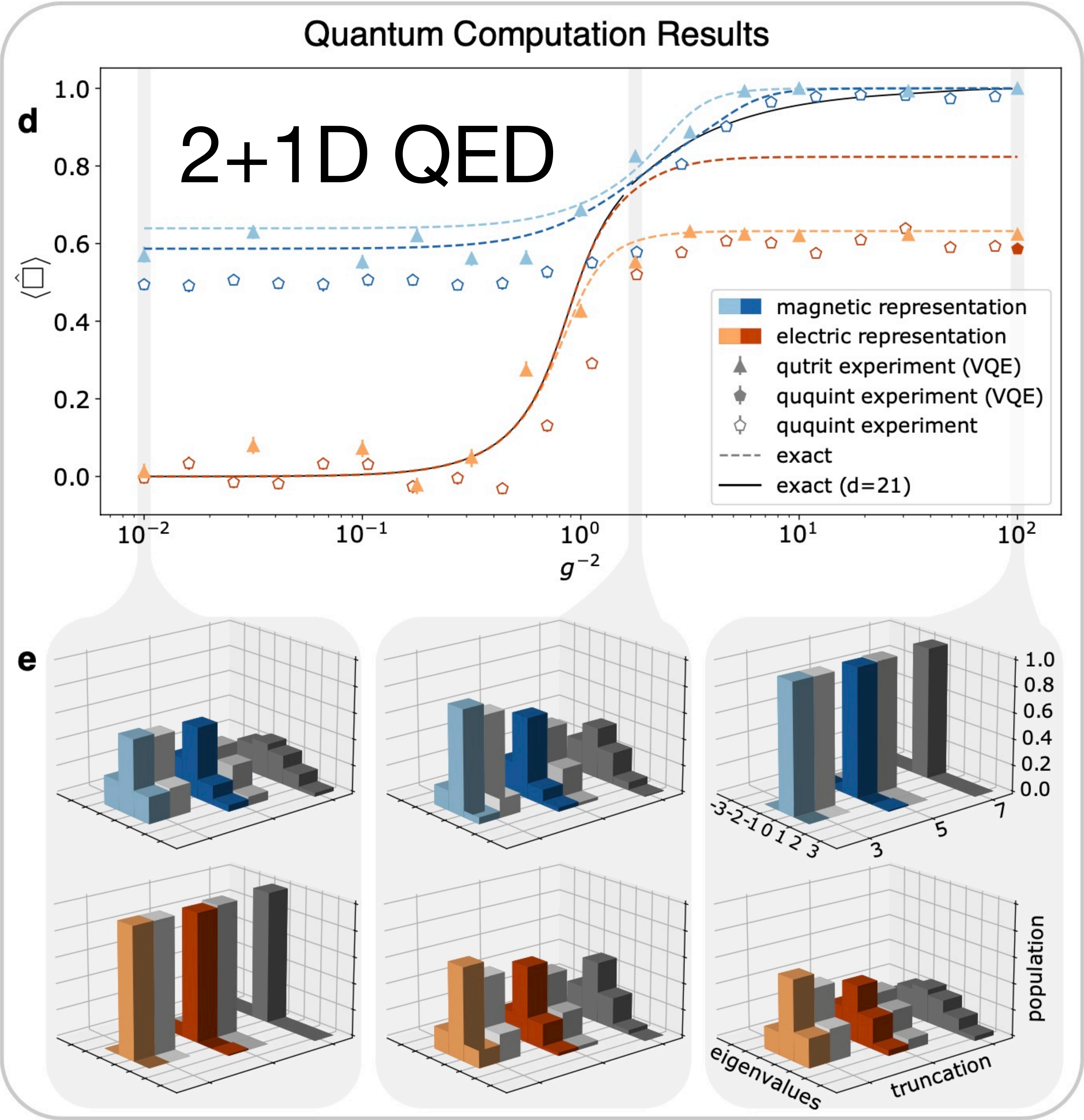




Qudits

Simulating 2D lattice gauge theories on a qudit quantum computer

Michael Meth,[1] Jan F. Haase,[2,3,4] Jinglei Zhang,[2,3] Claire Edmunds,[1] Lukas Postler,[1] Andrew J. Jena,[2,3] Alex Steiner,[1] Luca Dellantonio,[2,3,5] Rainer Blatt,[1,6,7] Peter Zoller,[8,6] Thomas Monz,[1,7] Philipp Schindler,[1] Christine Muschik*,[2,3,9] and Martin Ringbauer*[1]



Pure-gauge 4 plaquettes

Editors' Suggestion

Access by University

Qu8its for quantum simulations of lattice quantum chromodynamics

Marc Illa, Caroline E. P. Robin, and Martin J. Savage

Phys. Rev. D **110**, 014507 – Published 15 July 2024