

Quantum Information and Quantum Computing for Fundamental Physics



National Nuclear Physics Summer School 2026

Seattle, WA

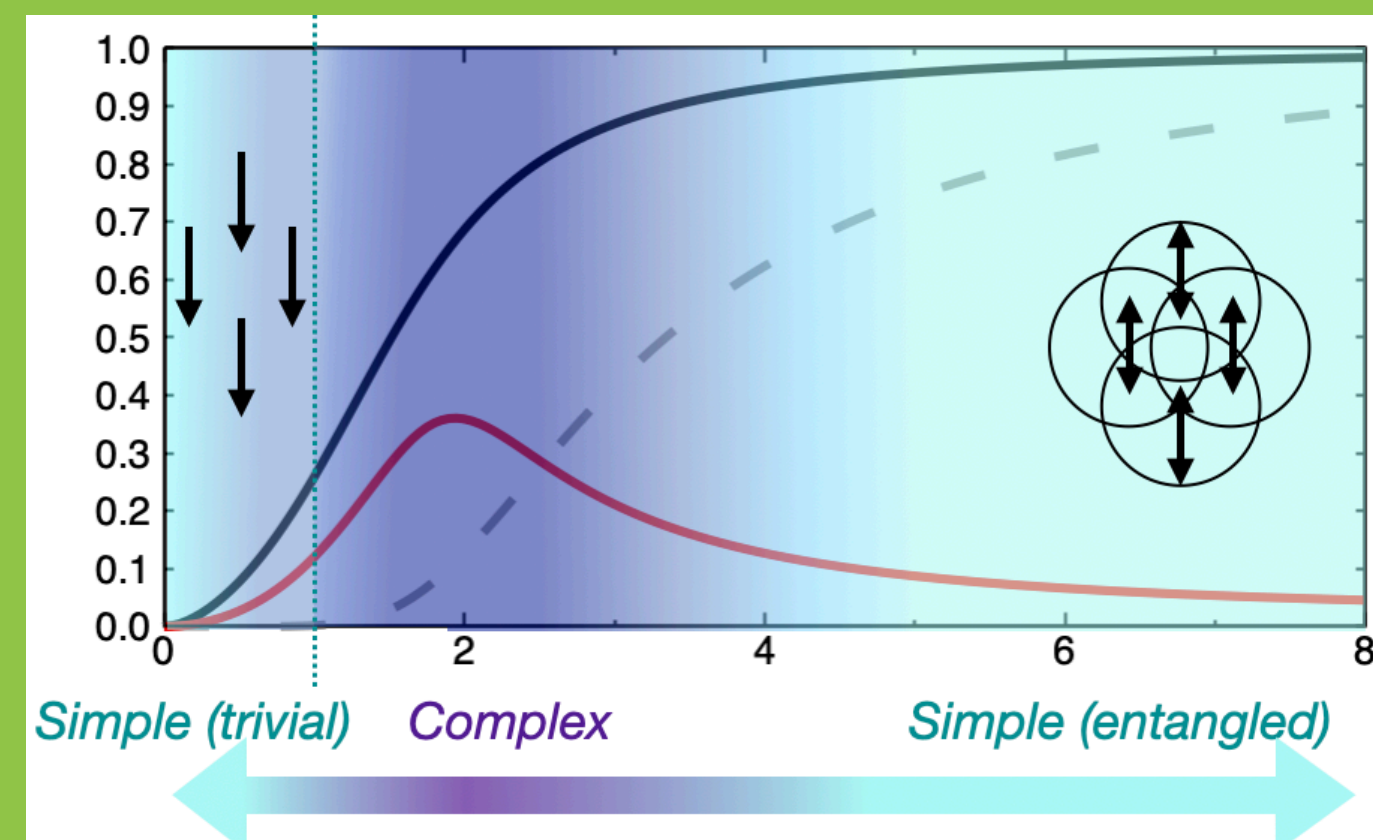
June 29 - July 11, 2026

Martin Savage
InQubator for Quantum Simulation
University of Washington

Part-3:
Quantum Computing and Simulation

Part-2

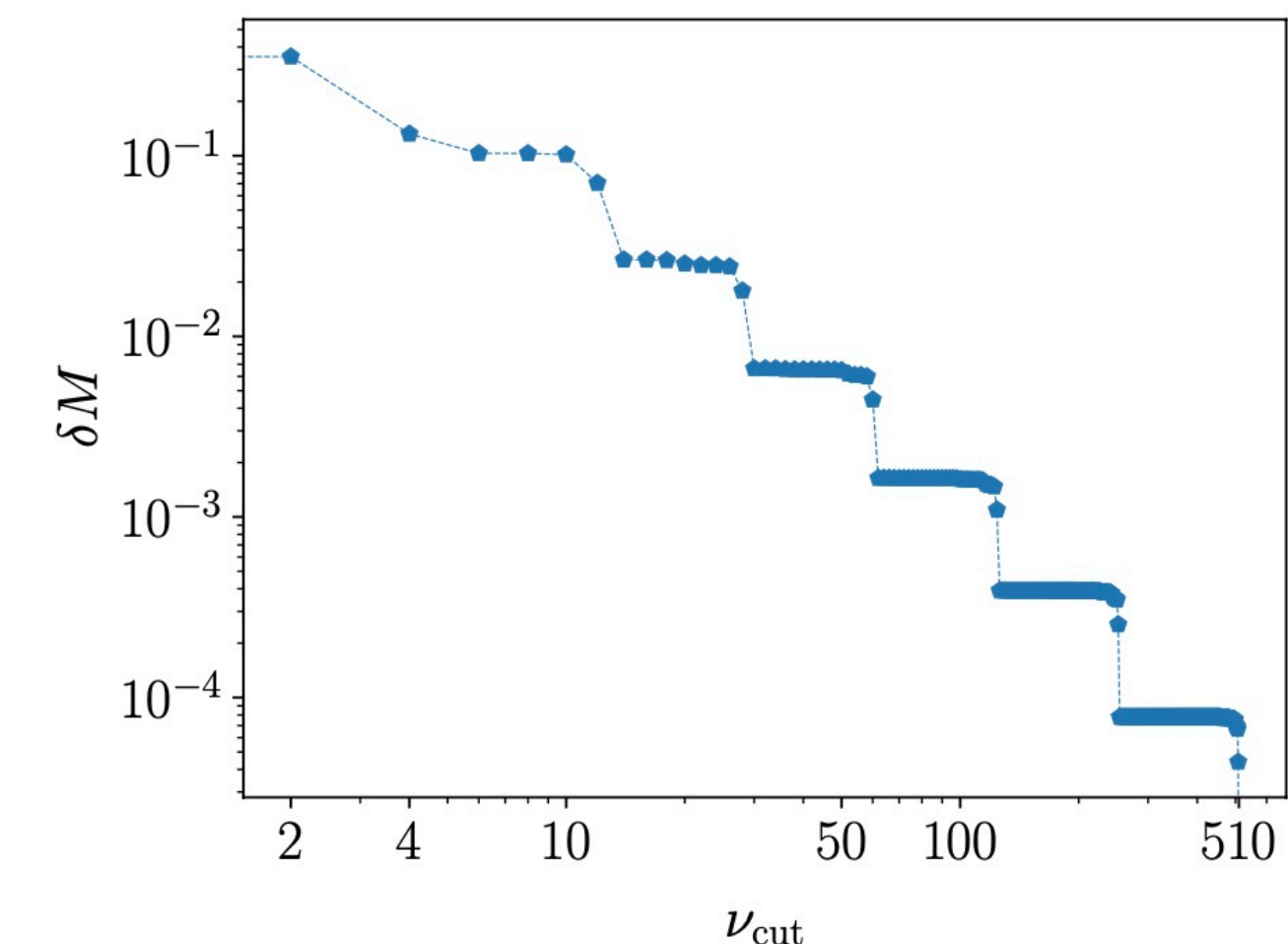
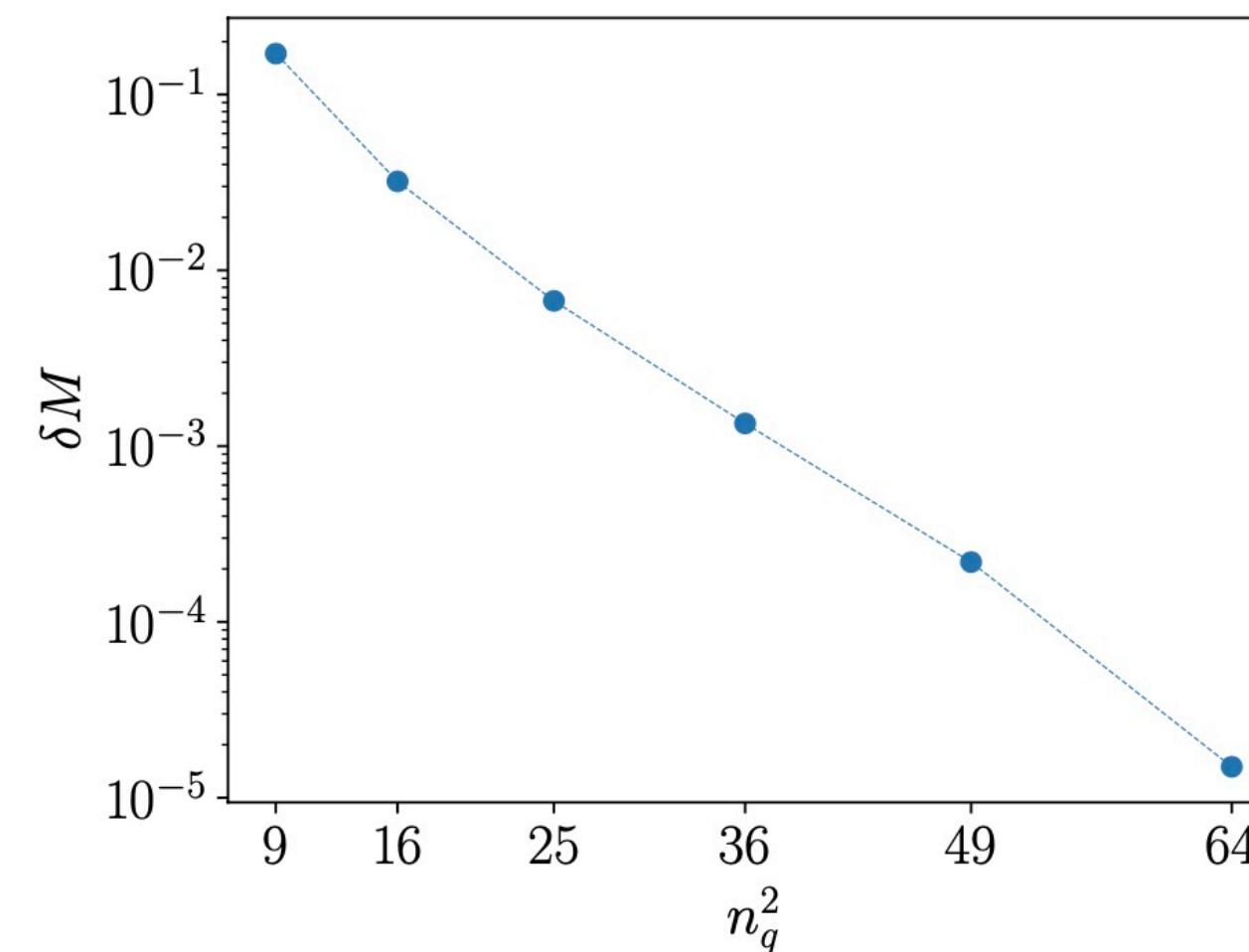
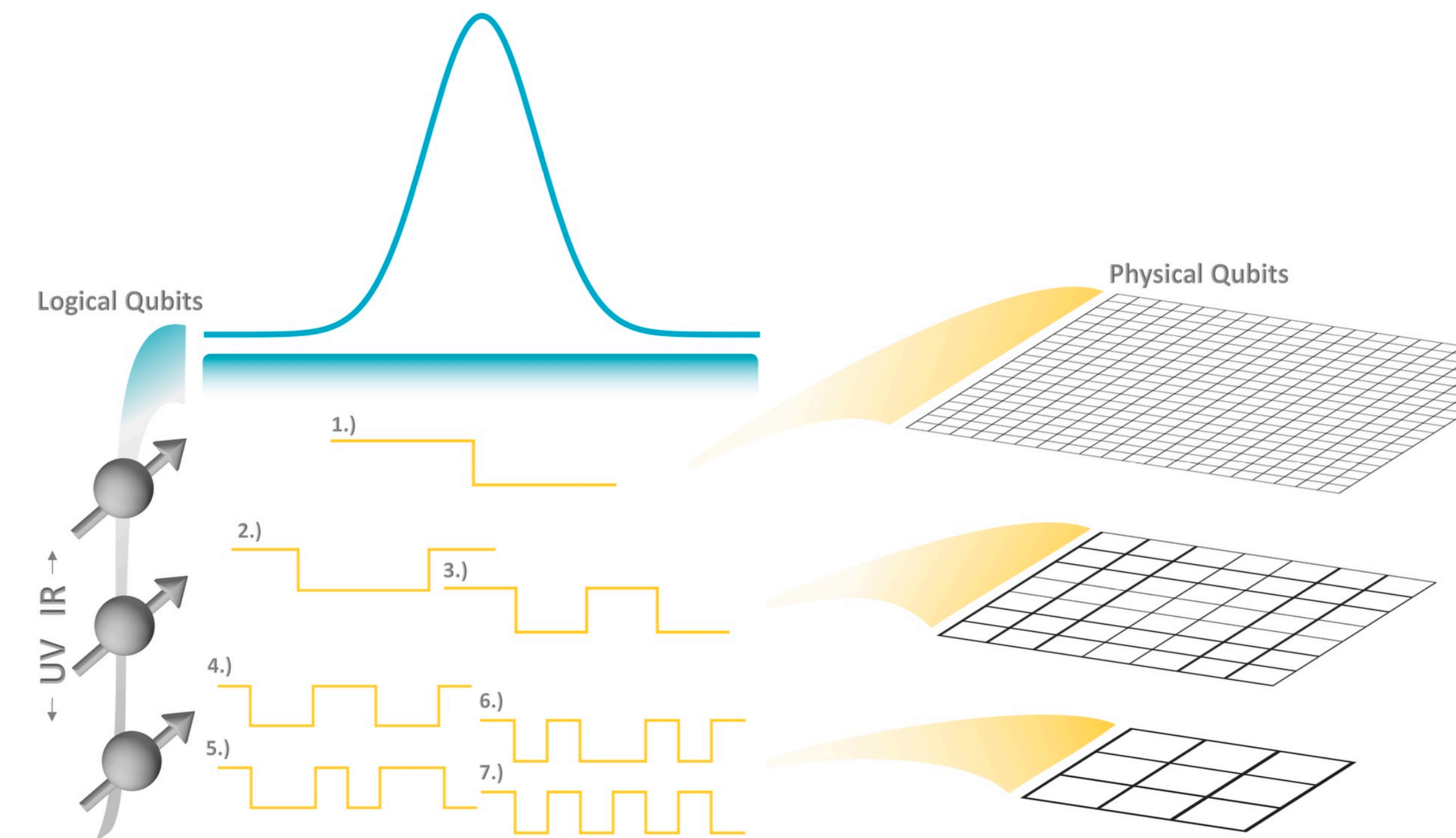
Quantum Complexity



End of Day-1

From NISQ to Fault Tolerant - Sequency Hierarchies

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



UV versus IR qubits



Hierarchical qubit maps and hierarchically implemented quantum error correction

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

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

• e-Print: [2407.13835](https://arxiv.org/abs/2407.13835) [quant-ph] Zhiyao Li ,* Dorota M. Grabowska ,† and Martin J. Savage ,‡

N-Tangles

$$\tau_n(|\psi\rangle) = | \langle \psi | \tilde{\psi} \rangle |^2 \quad , \quad |\tilde{\psi}\rangle = \hat{Y}_{i_1} \hat{Y}_{i_2} \dots \hat{Y}_{i_n} |\psi\rangle^*$$

$$|GHZ\rangle_4 = \frac{1}{\sqrt{2}} [|0000\rangle + |1111\rangle]$$

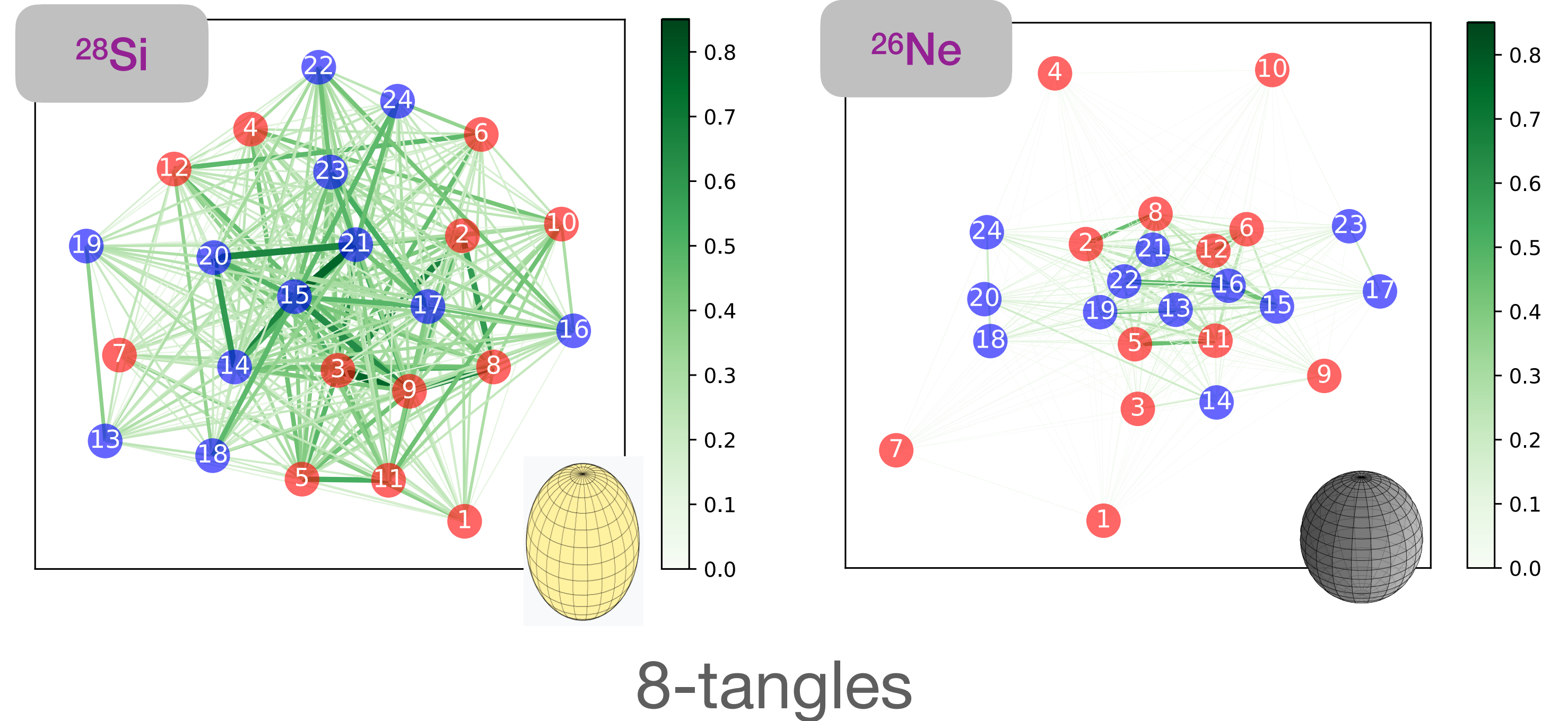
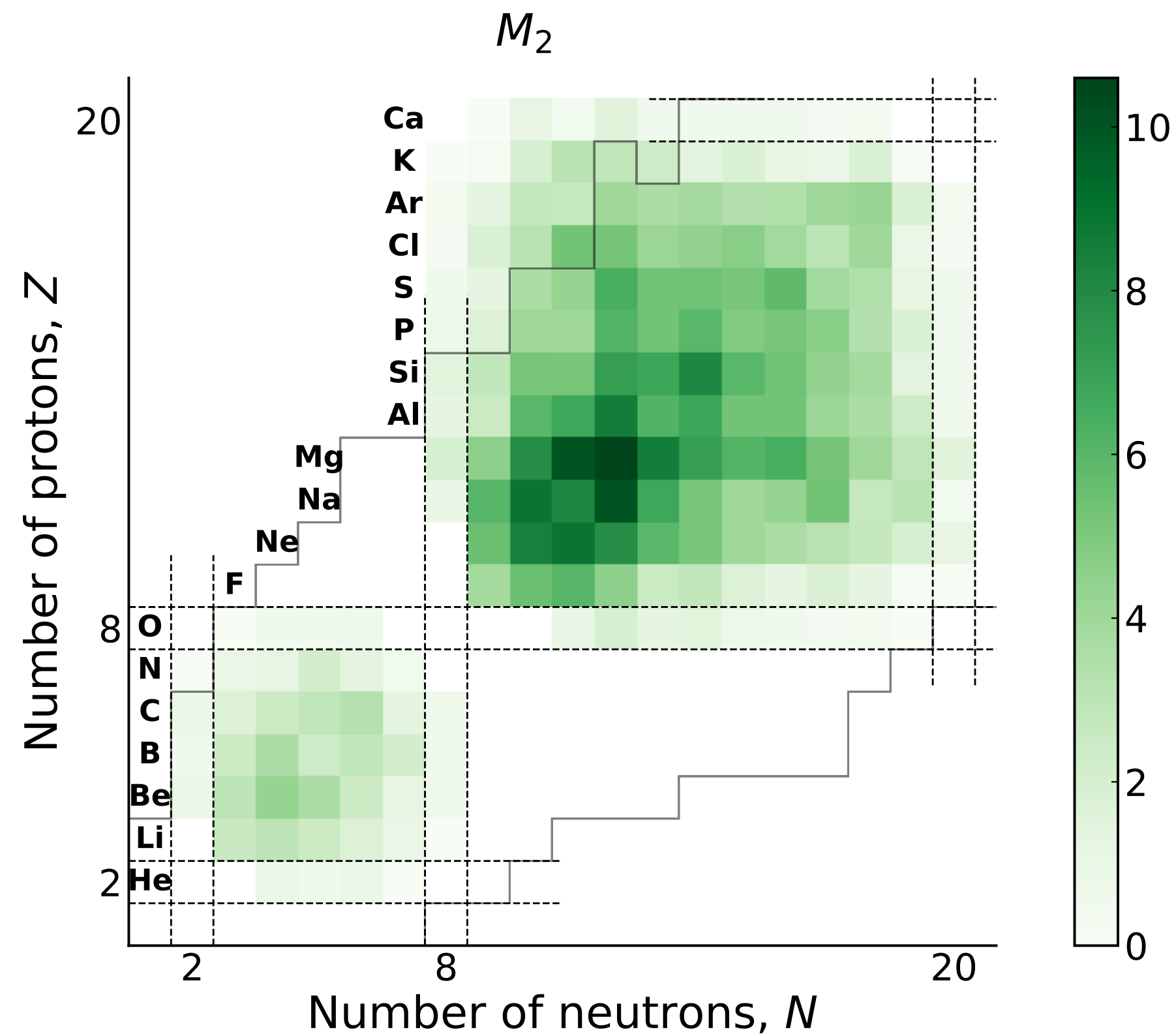
$$\hat{Y}^{\otimes 4} |GHZ\rangle_4 = \frac{1}{\sqrt{2}} [|0000\rangle + |1111\rangle] \quad , \quad \hat{Y}^{\otimes 2} \hat{I}^{\otimes 2} |GHZ\rangle_4 = -\frac{1}{\sqrt{2}} [|1100\rangle + |0011\rangle]$$

Magic and Multi-Partite Entanglement in Nuclei

Quantum magic and multipartite entanglement in the structure of nuclei

[Florian Brökemeier](#) ¹, [S. Momme Hengstenberg](#) ¹, [James W. T. Keeble](#) ¹, [Caroline E. P. Robin](#) ^{1,2,*},
[Federico Rocco](#) ¹, and [Martin J. Savage](#) ^{3,†}

Show more ▾

Phys. Rev. C **111**, 034317 – Published 11 March, 2025DOI: <https://doi.org/10.1103/PhysRevC.111.034317>

Magic and Multi-Partite Entanglement in Nuclei

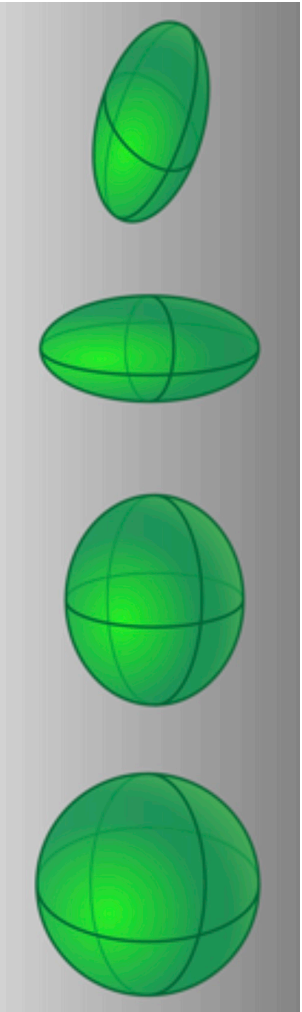
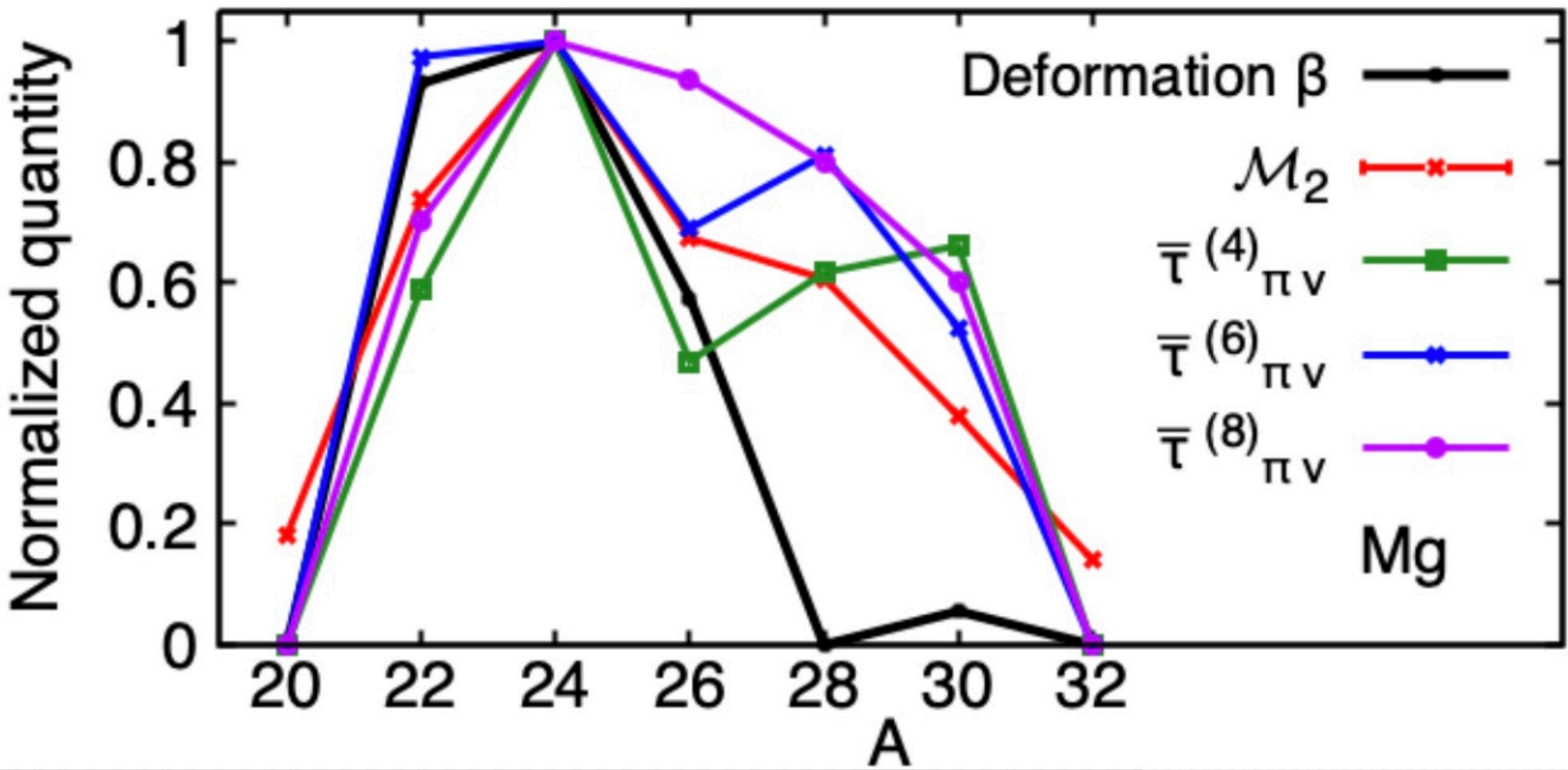
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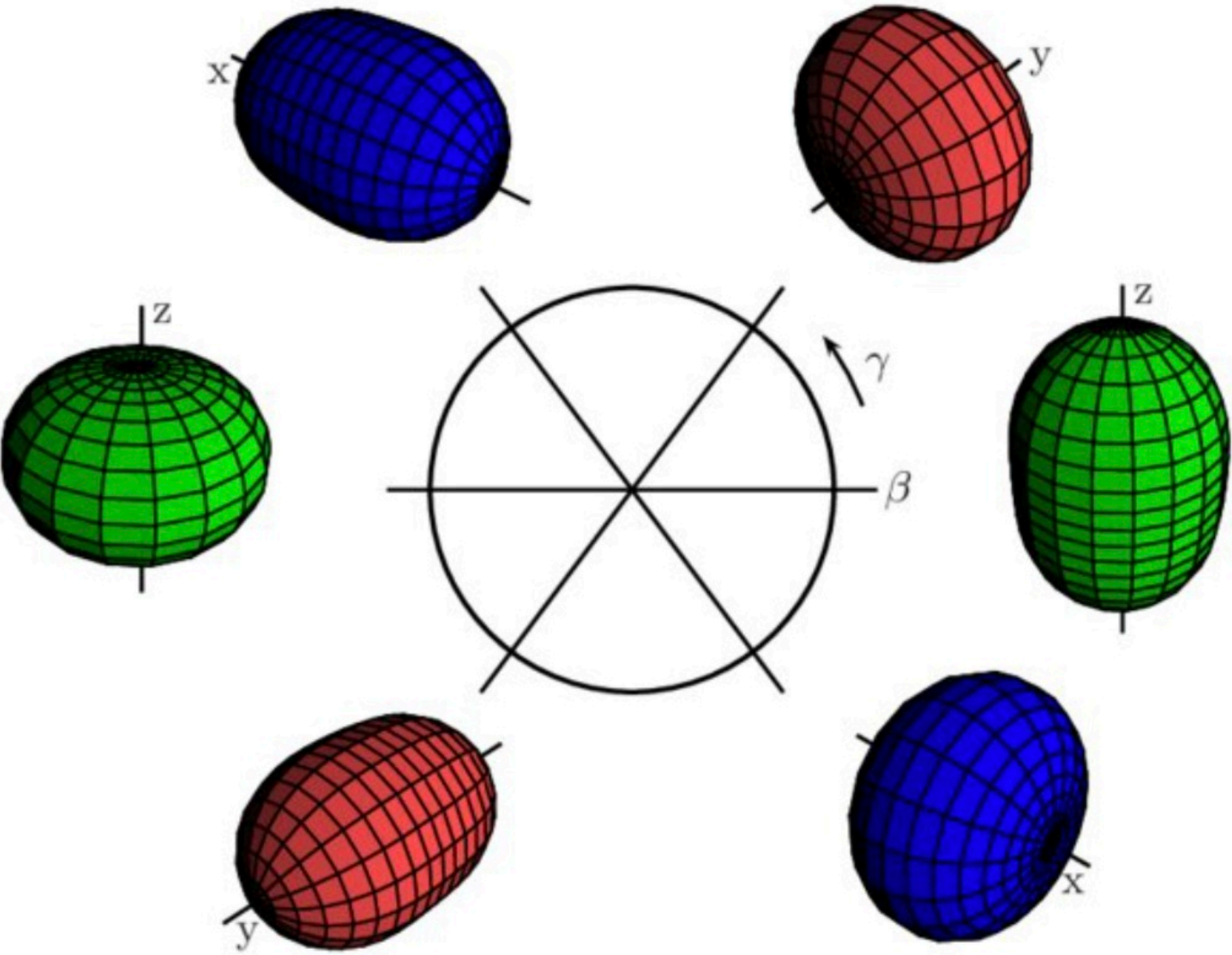
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Phys. Rev. C **111**, 034317 – Published 11 March, 2025

DOI: <https://doi.org/10.1103/PhysRevC.111.034317>



Shape co-existence

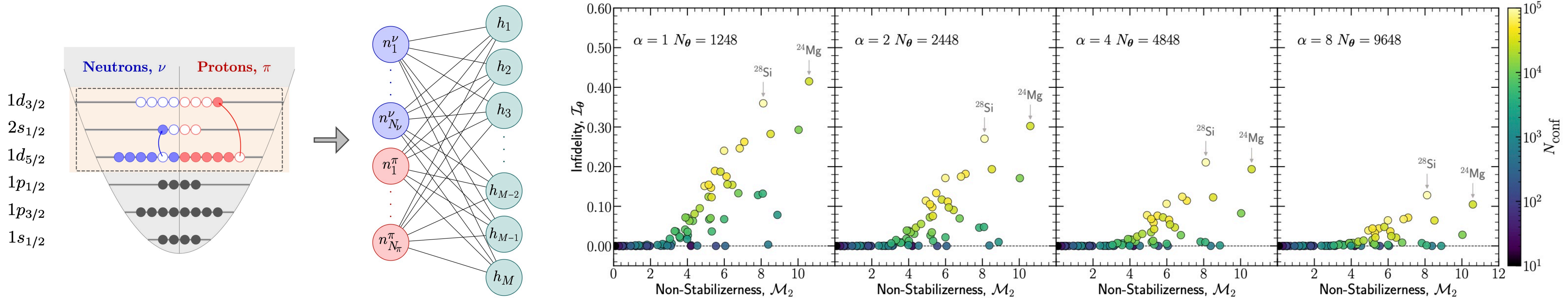


Restricted Boltzmann Machines Infidelity and Quantum Complexity

Neural Quantum States in Non-Stabilizer Regimes: Benchmarks with Atomic Nuclei

James W. T. Keeble ^{1,*} Alessandro Lovato ^{2,3,4,†} and Caroline E. P. Robin ^{1,5,‡}

arXiv:2603.28646v1 [nucl-th] 30 Mar 2026



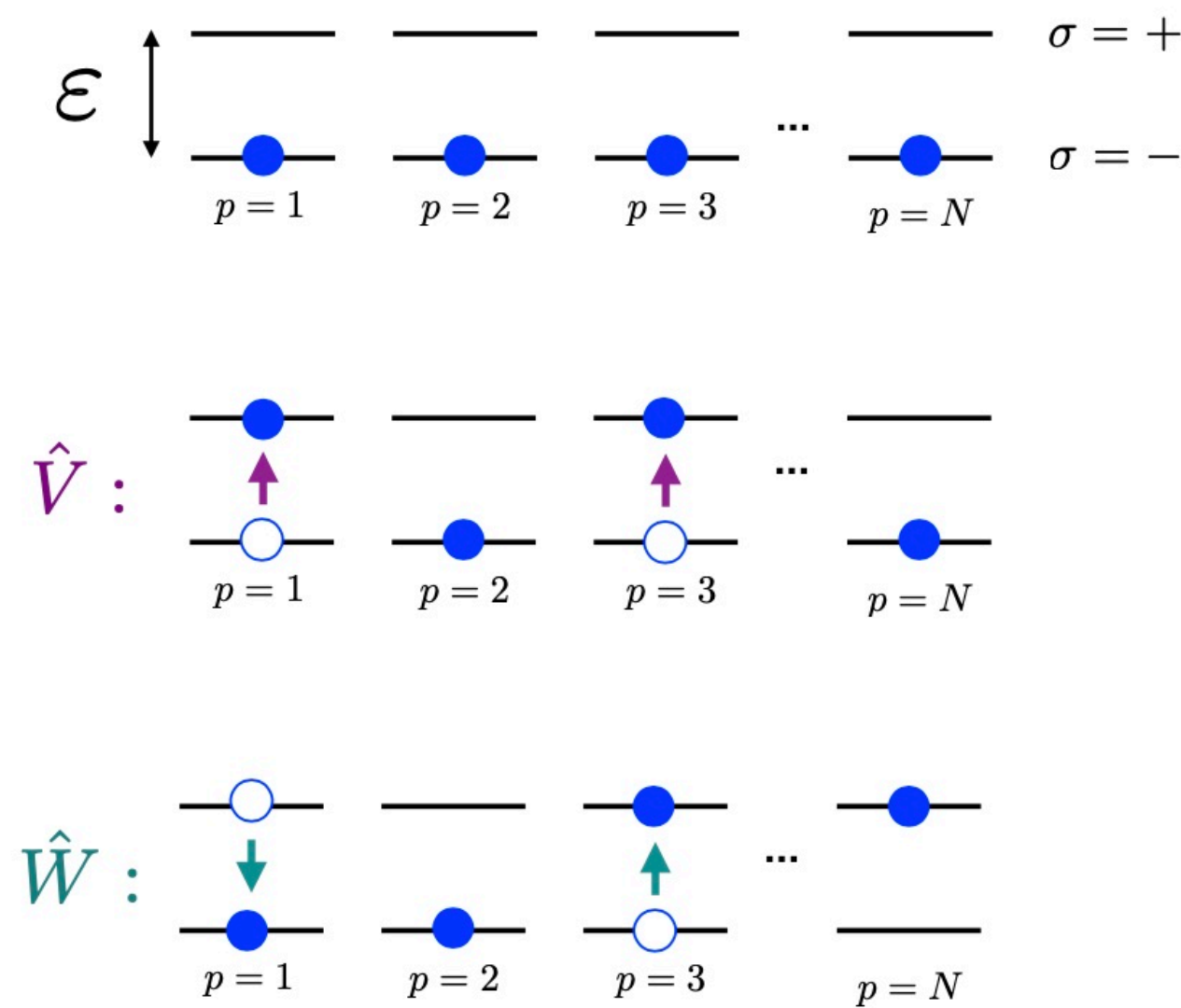
Complexity Rearrangement, Effective Model Spaces and Symmetries

[Home](#) > [The European Physical Journal A](#) > [Article](#)

Multi-body entanglement and information rearrangement in nuclear many-body systems: a study of the Lipkin–Meshkov–Glick model

Regular Article – Theoretical Physics | Published: 17 October 2023
 Volume 59, article number 231, (2023) [Cite this article](#)

[S. Momme Hengstenberg](#), [Caroline E. P. Robin](#)  & [Martin J. Savage](#)



$$\begin{aligned} \hat{H} &= \frac{\varepsilon}{2} \sum_{\sigma p} \sigma \hat{c}_{p\sigma}^\dagger \hat{c}_{p\sigma} - \frac{V}{2} \sum_{pq\sigma} \hat{c}_{p\sigma}^\dagger \hat{c}_{q\sigma}^\dagger \hat{c}_{q-\sigma} \hat{c}_{p-\sigma} \\ &\quad - \frac{W}{2} \sum_{pq\sigma} \hat{c}_{p\sigma}^\dagger \hat{c}_{q-\sigma}^\dagger \hat{c}_{q\sigma} \hat{c}_{p-\sigma} \, , \\ &= \varepsilon \hat{J}_z - \frac{V}{2} \left(\hat{J}_+^2 + \hat{J}_-^2 \right) - \frac{W}{2} \left(\hat{J}_+ \hat{J}_- + \hat{J}_- \hat{J}_+ - \hat{N} \right) \, . \end{aligned}$$

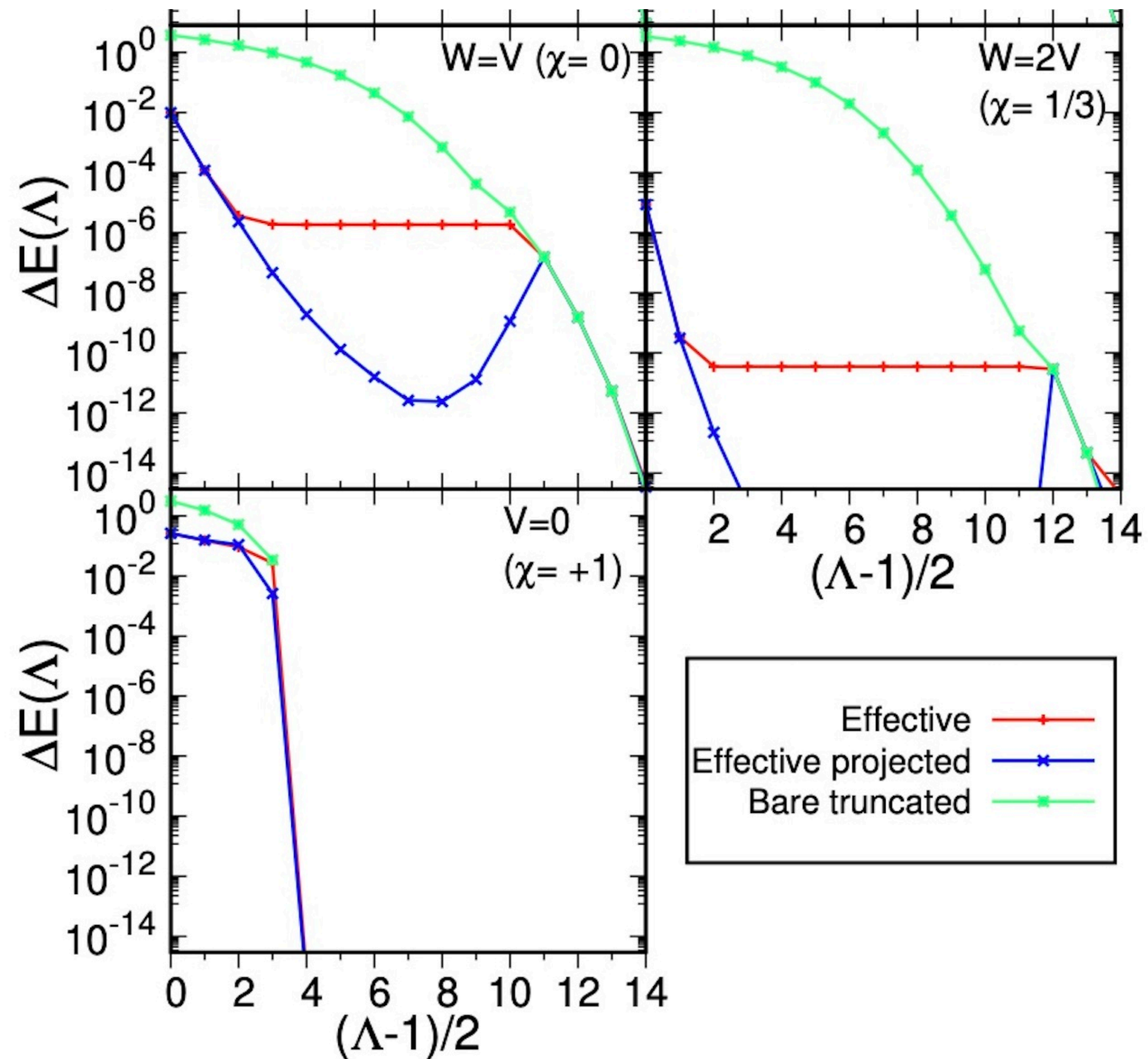
$$\begin{pmatrix} \hat{c}_{p+}(\beta) \\ \hat{c}_{p-}(\beta) \end{pmatrix} = \begin{pmatrix} \cos(\beta/2) & -\sin(\beta/2) \\ \sin(\beta/2) & \cos(\beta/2) \end{pmatrix} \begin{pmatrix} \hat{c}_{p+} \\ \hat{c}_{p-} \end{pmatrix}$$

Full theory has rotational symmetry

Truncated Hamiltonian does not

Angular optimization of truncated space

Complexity Rearrangement, Effective Model Spaces and Symmetries

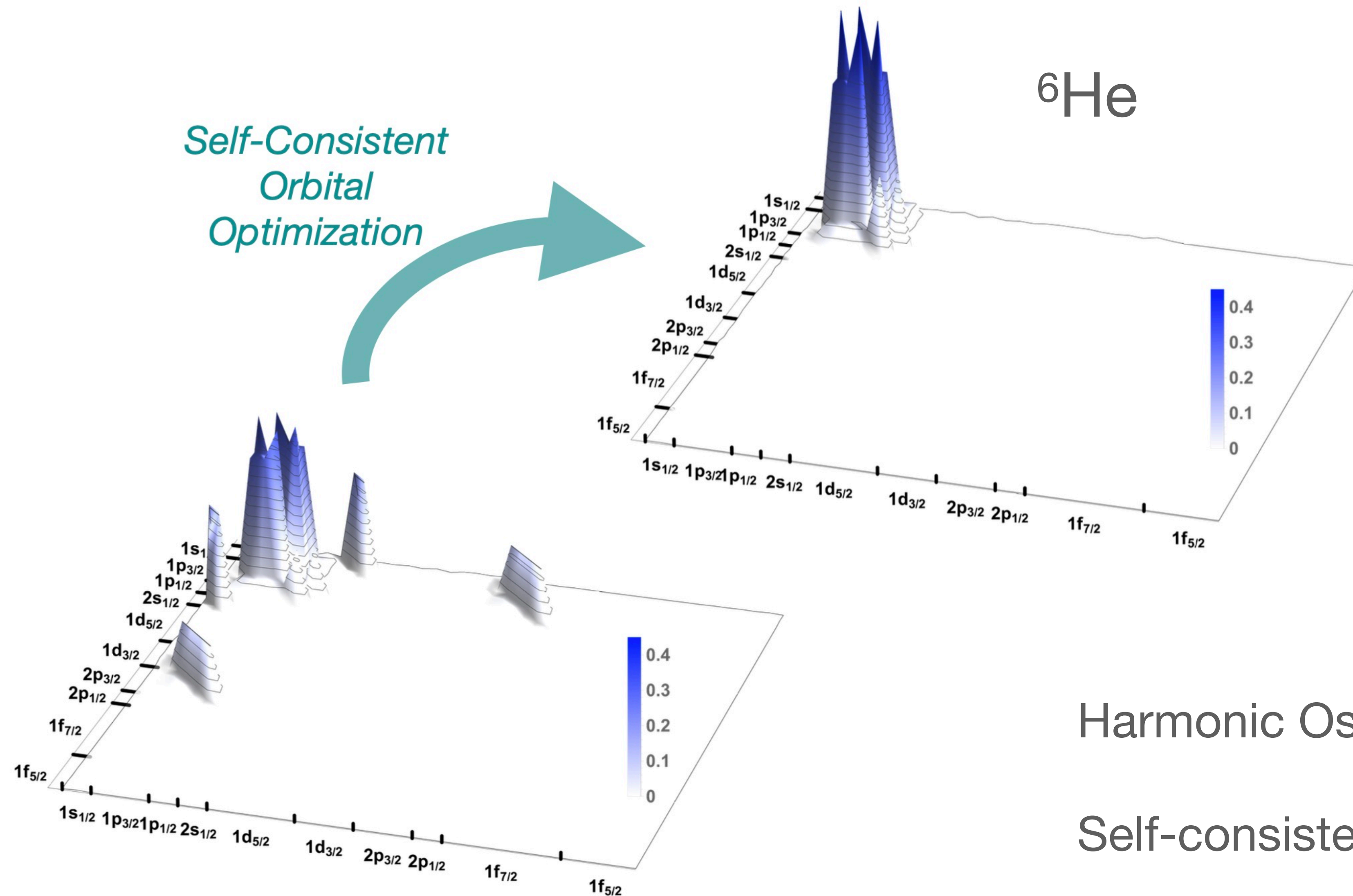


Naive truncation: power law corrections

Optimized truncation: exponential corrections over some of the Hilbert space

Likely to be of utility more generally for EFT developments

Complexity Rearrangement, Effective Model Spaces and Symmetries



Harmonic Oscillator wave function (lower)

Self-consistent wave function (upper)

Stabilizer Acceleration in Many-Body Systems

Stabilizer-accelerated quantum many-body ground-state estimation

Caroline E. P. Robin *

Show more ▾

Phys. Rev. A **112**, 052408 – Published 3 November, 2025 Ex

$$\hat{H} = \underbrace{\sum_{P \in \mathcal{S}} a_P \hat{P}}_{\hat{H}_{stab}} + \underbrace{\sum_{P \in \mathcal{G}_N(H) \not\in \mathcal{S}} a_P \hat{P}}_{\hat{W}} \qquad |\Psi_s\rangle = \prod_{i=1}^N C_i |G\rangle = \prod_{i=1}^N C_i \prod_{e \in E} \text{CZ}_e |+\rangle^{\otimes N}$$

Explore all possible decompositions into Stabilizer Groups

$$\tilde{H} = \frac{1}{2} \sum_i Z_i - \frac{\bar{v}_x}{2(N-1)} \sum_{i < j} (X_i X_j + \chi Y_i Y_j)$$

$$\langle -Z_1, -Z_2, ..., -Z_N \rangle \quad \langle Y_1 Y_N, Y_2 Y_N, ..., Y_{N-1} Y_N, (-1)^{\bar{N}} Z_1 Z_2 ... \check{Z}_N \rangle \quad \langle X_1 X_N, X_2 X_N, ..., X_{N-1} X_N, (-1)^N Z_1 Z_2 ... Z_N \rangle$$

Stabilizer Acceleration in Many-Body Systems

Stabilizer-accelerated quantum many-body ground-state estimation

Caroline E. P. Robin *

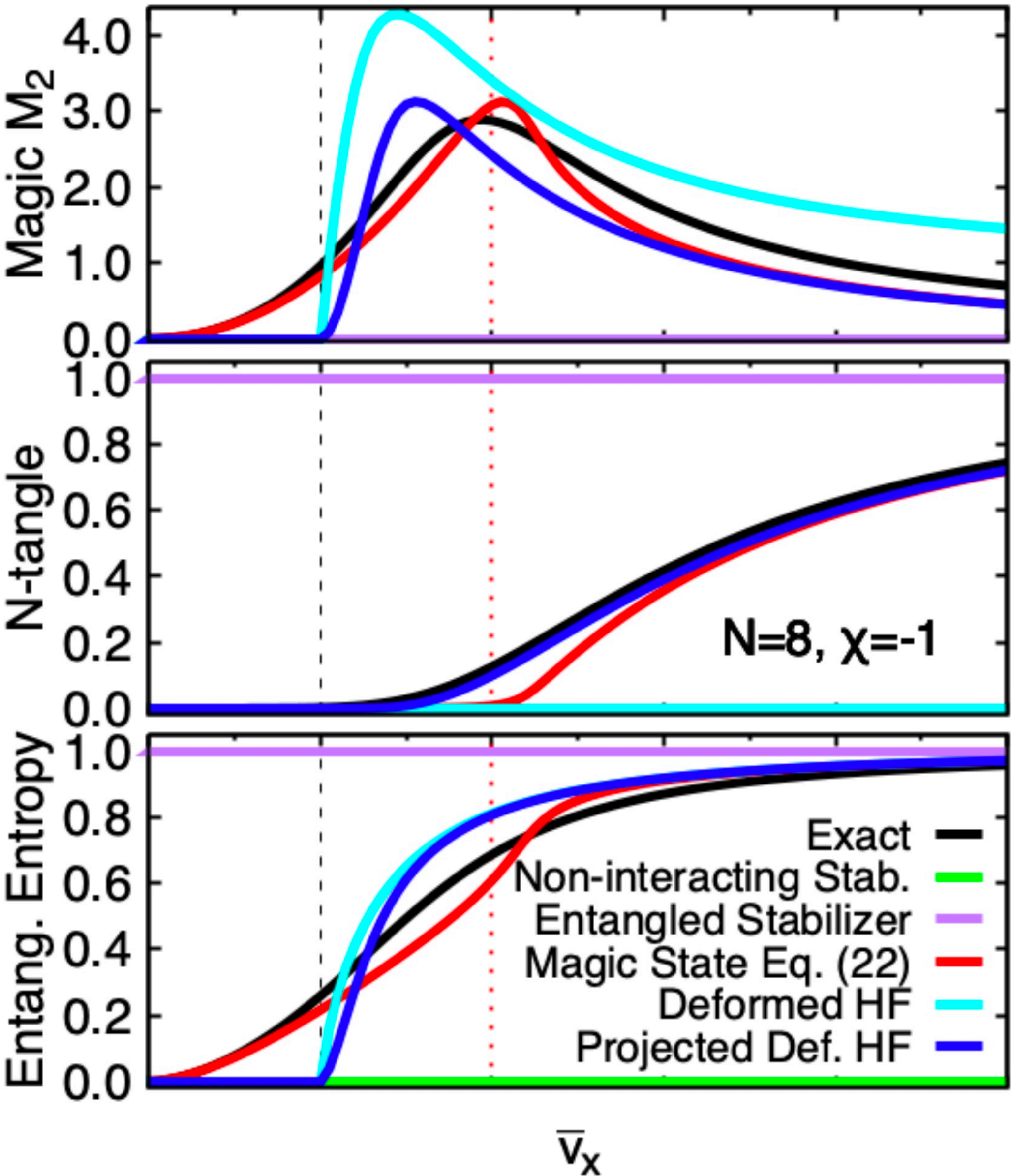
Show more 

Phys. Rev. A 112, 052408 – Published 3 November, 2025

Ex

$$\tilde{H} = \frac{1}{2} \sum_i Z_i - \frac{\bar{v}_x}{2(N-1)} \sum_{i < j} (X_i X_j + \chi Y_i Y_j)$$

$$\begin{aligned} |\Phi(\theta)\rangle &= e^{-\theta \hat{J}_z} |\Psi_{s,2}\rangle^{(N)}, \\ &= \prod_{i=1}^N e^{-\theta Z_i} |\Psi_{s,2}\rangle^{(N)} \end{aligned}$$

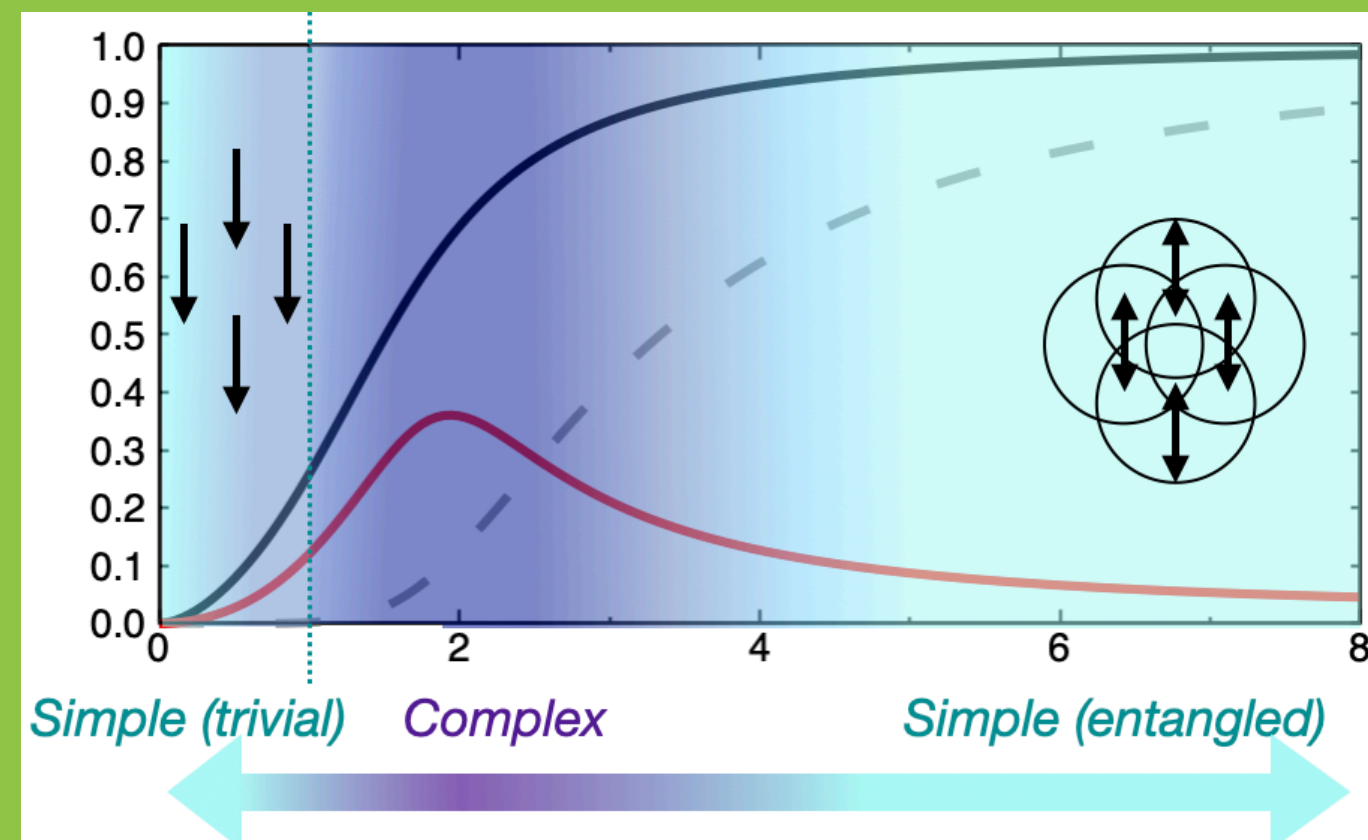


Part-2

Quantum Complexity

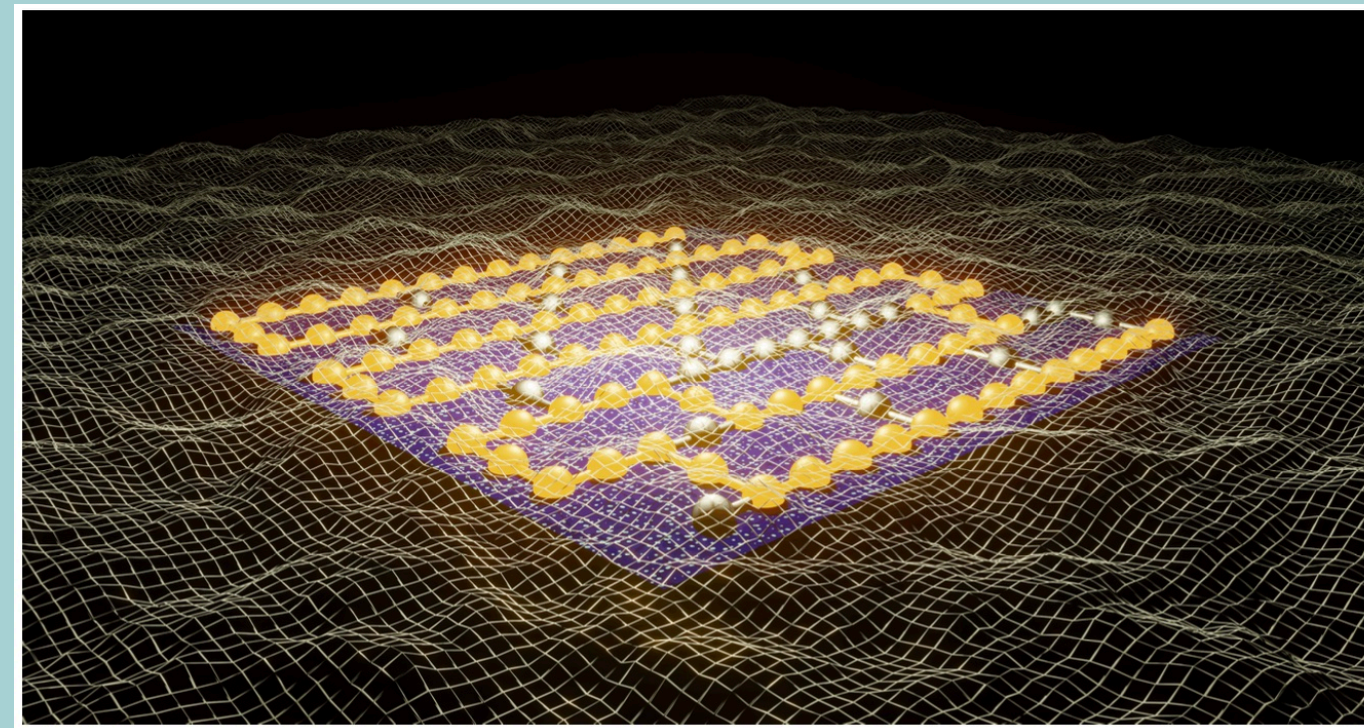
Quantum Complexity for Fundamental Quantum Many-Body Systems

- Essential for optimal quantum simulations in fundamental physics - balancing quantum and classical resources
- At the beginning stages
- Potentially new methods for classical simulations



Part-3

Quantum Computing and Simulation



Focus on digital and lattice

Early 1980's - Feynman's Vision

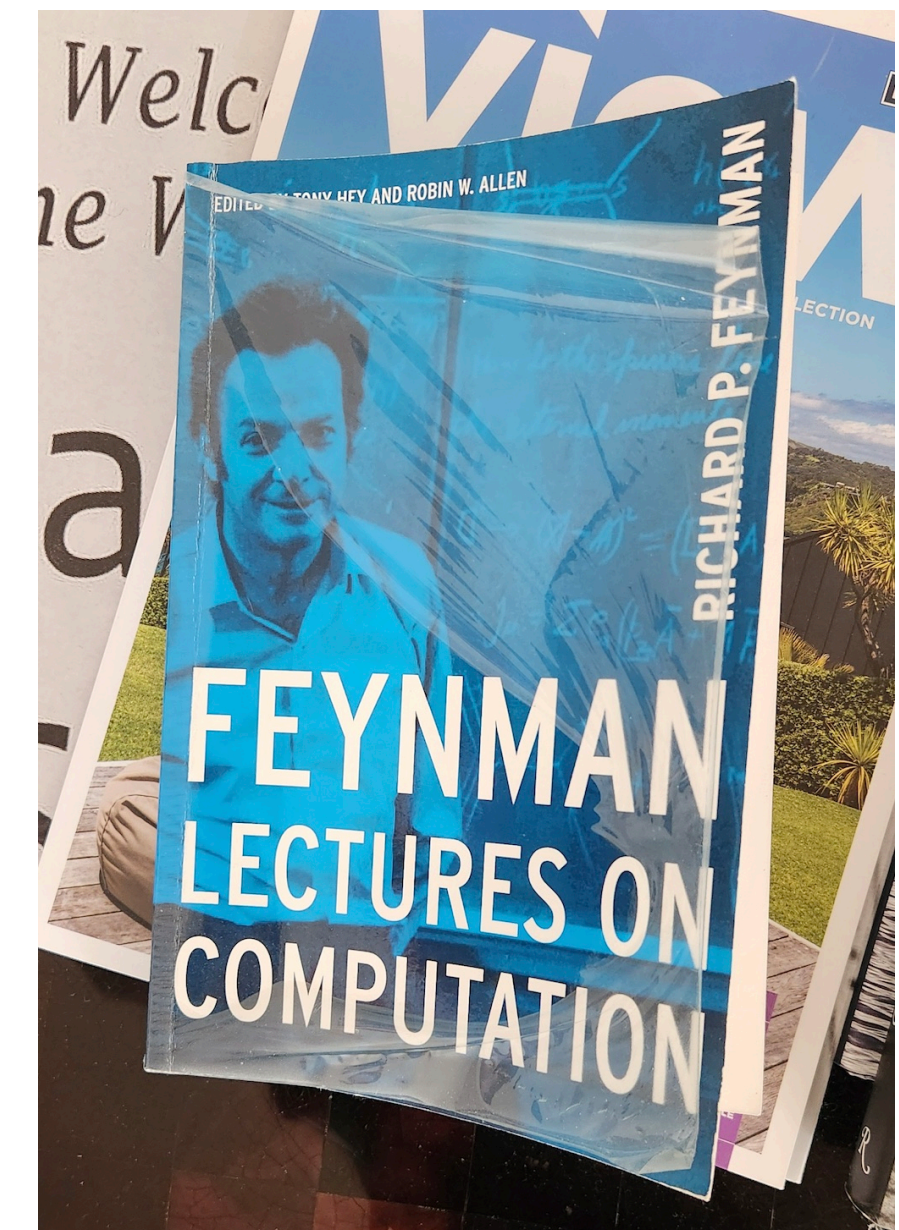
(age: 63)

Simulating Physics with Computers

Richard P. Feynman

Department of Physics, California Institute of Technology, Pasadena, California 91107

Received May 7, 1981



**4. QUANTUM COMPUTERS—UNIVERSAL QUANTUM
SIMULATORS**

**5. CAN QUANTUM SYSTEMS BE PROBABILISTICALLY
SIMULATED BY A CLASSICAL COMPUTER?**

15 Years Later

Universal Quantum Simulators

SETH LLOYD [Authors Info & Affiliations](#)

SCIENCE • 23 Aug 1996 • Vol 273, Issue 5278 • pp. 1073-1078 • [DOI: 10.1126/science.273.5278.1073](#)

Abstract

Feynman's 1982 conjecture, that quantum computers can be programmed to simulate any local quantum system, is shown to be correct.

Reliable Quantum Computers

John Preskill¹

California Institute of Technology, Pasadena, CA 91125, USA

Abstract

The new field of *quantum error correction* has developed spectacularly since its origin less than two years ago. Encoded quantum information can be protected from errors that arise due to uncontrolled interactions with the environment. Recovery from errors can work effectively even if occasional mistakes occur during the recovery procedure. Furthermore, encoded quantum information can be *processed* without serious propagation of errors. Hence, an arbitrarily long quantum computation can be performed reliably, provided that the average probability of error per quantum gate is less than a certain critical value, the *accuracy threshold*. A quantum computer storing about 10^6 qubits, with a probability of error per quantum gate of order 10^{-6} , would be a formidable factoring engine. Even a smaller, less accurate quantum computer would be able to perform many useful tasks.

This paper is based on a talk presented at the ITP Conference on Quantum Coherence and Decoherence, 15-18 December 1996.

Teleportation, No-cloning, Entanglement Distillation,

Error-correction - Shor, Steane, Calderbanks, Bacon, Preskill,

Time evolution with controlled systematic errors is efficient for quantum computers.

37 Years Later

Quantum Computing in the NISQ era and beyond

John Preskill

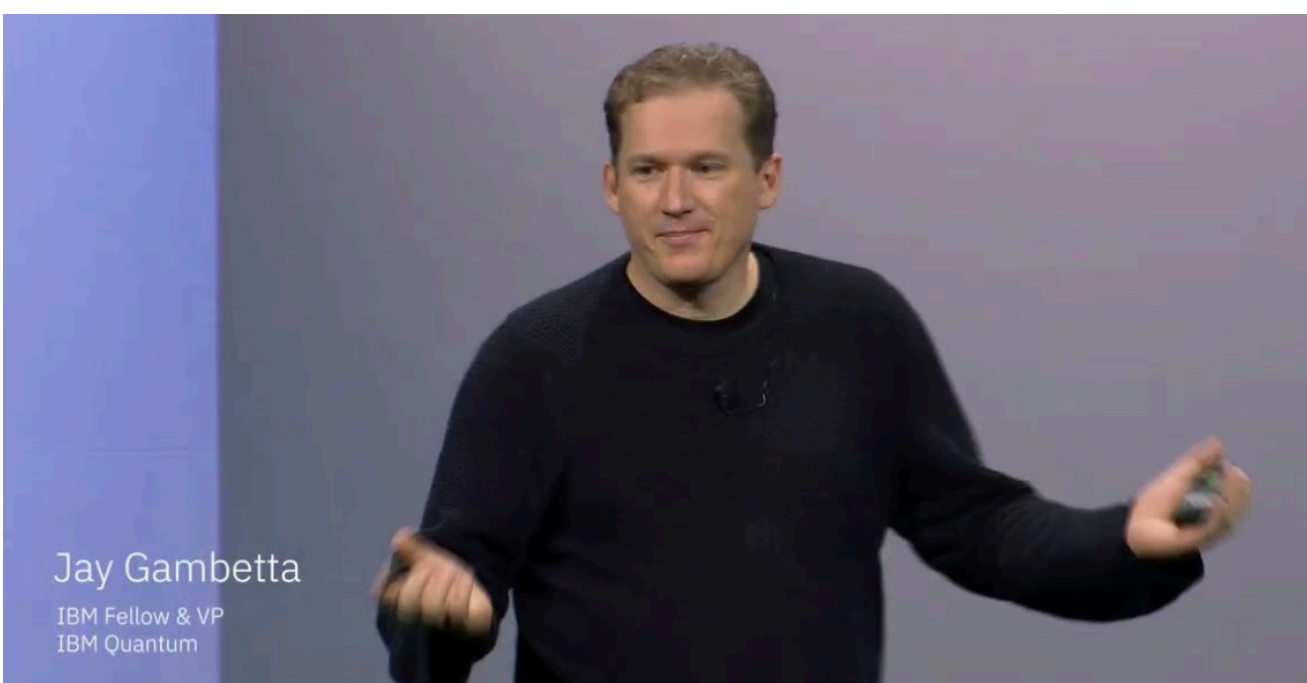
Institute for Quantum Information and Matter and Walter Burke Institute for Theoretical Physics,
California Institute of Technology, Pasadena CA 91125, USA

30 July 2018

Noisy Intermediate-Scale Quantum (NISQ) technology will be available in the near future. Quantum computers with 50-100 qubits may be able to perform tasks which surpass the capabilities of today's classical digital computers, but noise in quantum gates will limit the size of quantum circuits that can be executed reliably. NISQ devices will be useful tools for exploring many-body quantum physics, and may have other useful applications, but the 100-qubit quantum computer will not change the world right away — we should regard it as a significant step toward the more powerful quantum technologies of the future. Quantum technologists should continue to strive for more accurate quantum gates and, eventually, fully fault-tolerant quantum computing.

Hardware, Error-Correction, Fault-Tolerance, Algorithms, Applications — Co-design

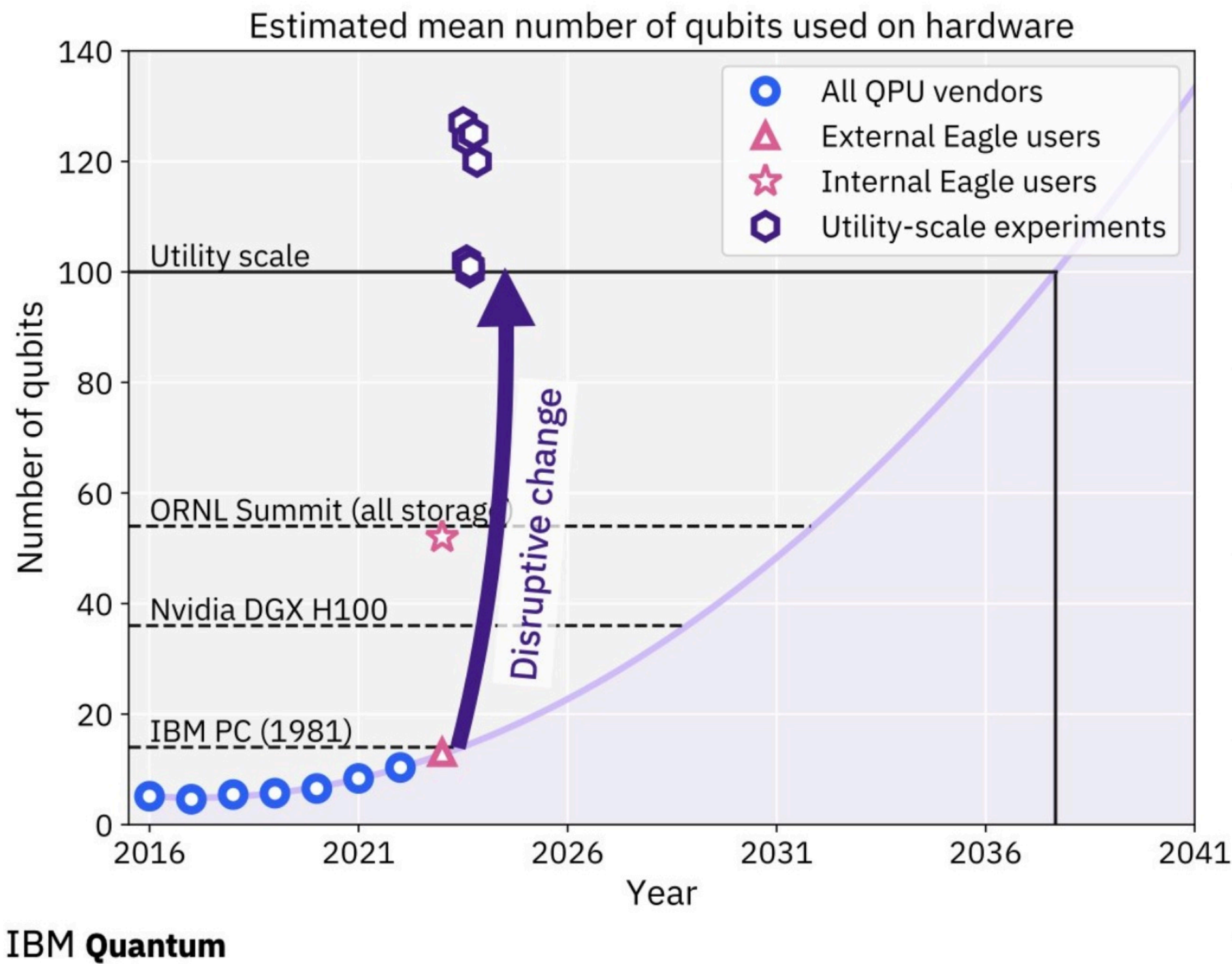
Cloud-accessible quantum computers, led by IBM



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](#).



Evidence for the utility of quantum computing before fault tolerance

127 qubits / 2880 CX gates

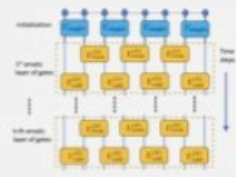
Nature, 618, 500 (2023)



Simulating large-size quantum spin chains on cloud-based superconducting quantum computers

102 qubits / 3186 CX gates

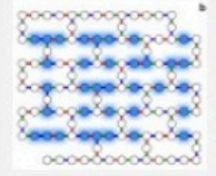
arXiv:2207.09994



Uncovering Local Integrability in Quantum Many-Body Dynamics

124 qubits / 2641 CX gates

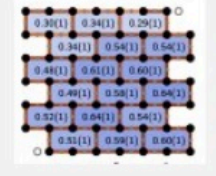
arXiv:2307.07552



Realizing the Nishimori transition across the error threshold for constant-depth quantum circuits

125 qubits / 429 gates + meas.

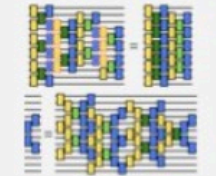
arXiv:2309.02863



Scalable Circuits for Preparing Ground States on Digital Quantum Computers: The Schwinger Model Vacuum on 100 Qubits

100 qubits / 788 CX gates

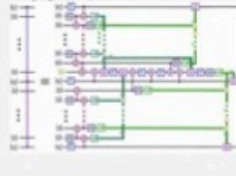
arXiv:2308.04481



Efficient Long-Range Entanglement using Dynamic Circuits

101 qubits / 504 gates + meas.

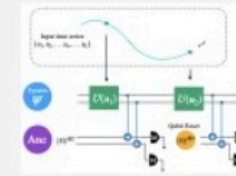
arXiv:2308.13065



Quantum reservoir computing with repeated measurements on superconducting devices

120 qubits / 49470 gates + meas.

arXiv:2310.06706



43 Years Later

Beyond NISQ: The Megaquop Machine

JOHN PRESKILL, Institute for Quantum Information and Matter, California Institute of Technology, USA

Today's Noisy Intermediate-Scale Quantum (NISQ) computers have scientific value, but quantum machines with broad practical value must be protected against noise using quantum error correction and fault-tolerant protocols. Recent studies of quantum error correction on actual hardware are opening a new era of quantum information processing. Error-corrected computers capable of performing one million quantum operations or more may be realized soon, raising a compelling question for the quantum community: What are the potential uses of these megaquop machines?

Keynote address at the Q2B 2024 Conference in Silicon Valley on 11 December 2024.

Demonstrations of logical qubits with fidelities greater than physical qubit fidelity.

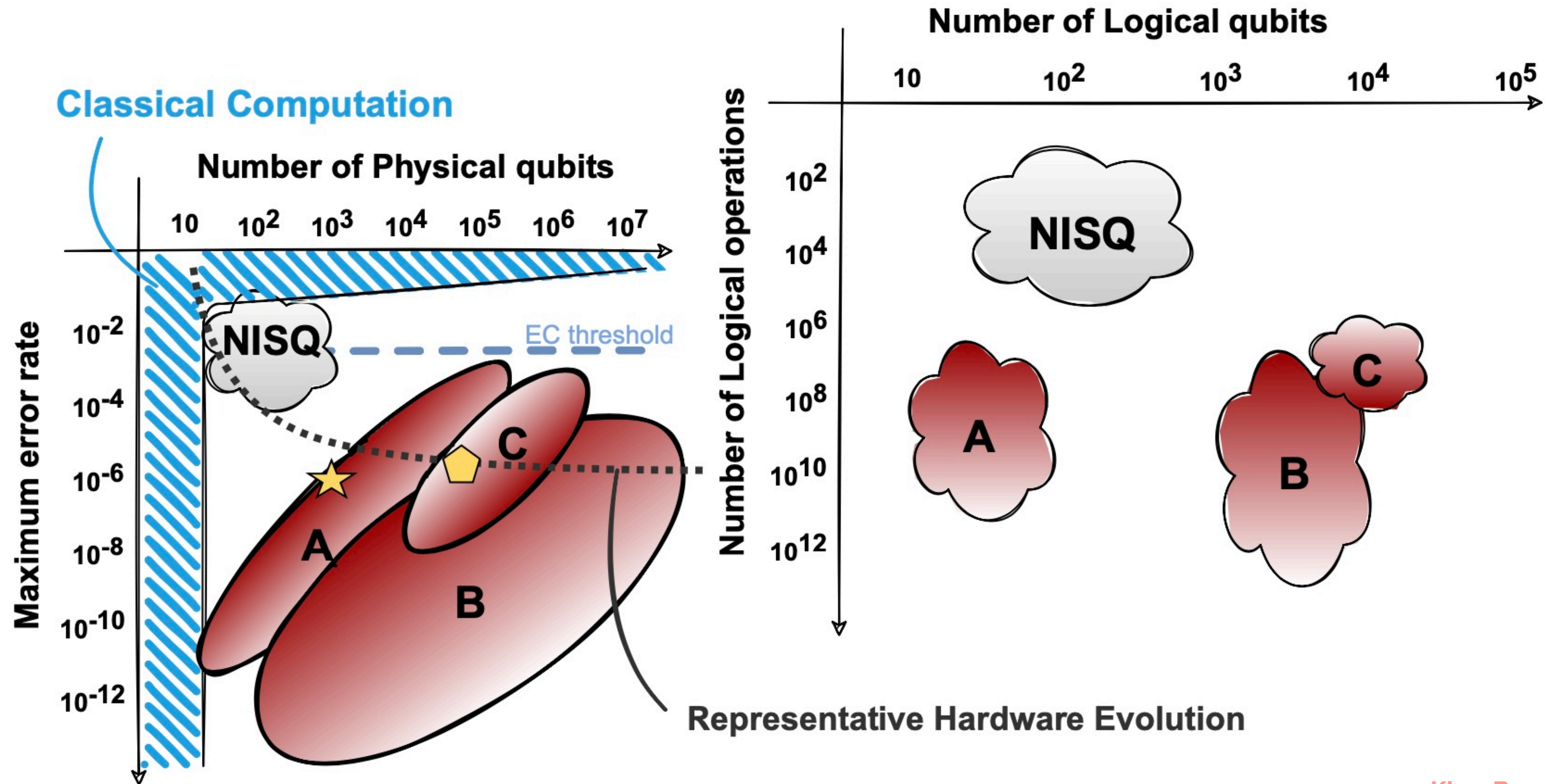
Department of Energy Road Map

Energy Department Announces Initiative to Create and Deploy the World's First Scientifically Relevant, Fault-Tolerant Quantum Computers

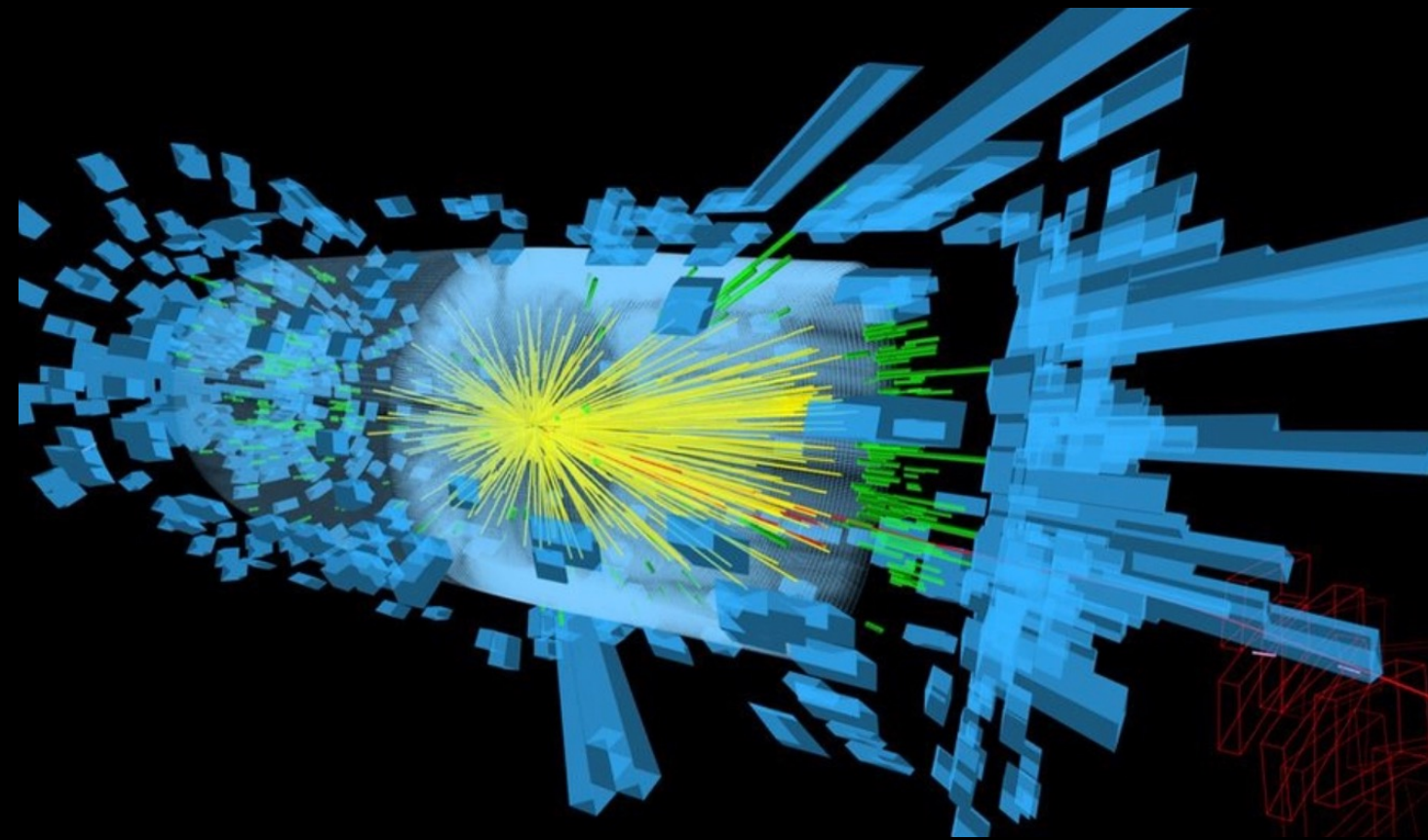
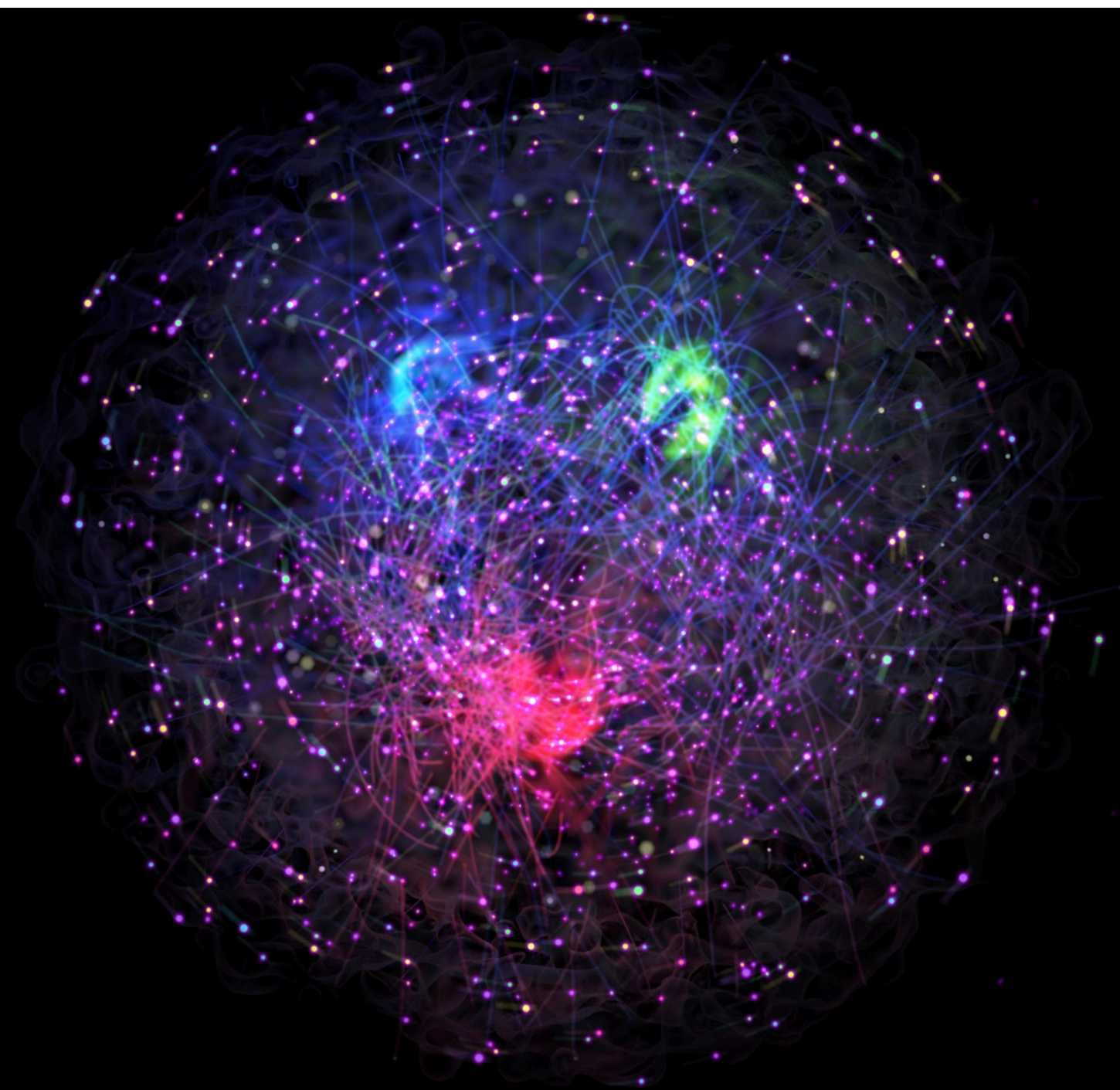
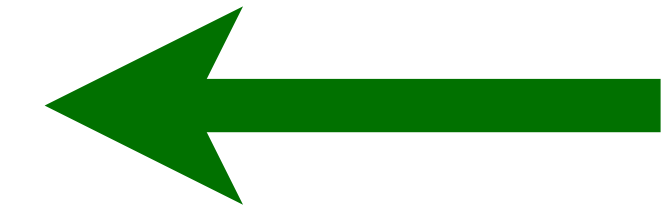
June 23, 2026

WASHINGTON—The U.S. Department of Energy (DOE) today announced the establishment of the ambitious new Quantum Genesis initiative to develop and deploy the world's first fault-tolerant, scientifically relevant quantum computing capability for research and development by 2028. The Quantum Genesis effort will serve as a foundational element of the broader Genesis Mission, designed to usher in a new era of computational power for the nation to accelerate scientific discovery and innovation.

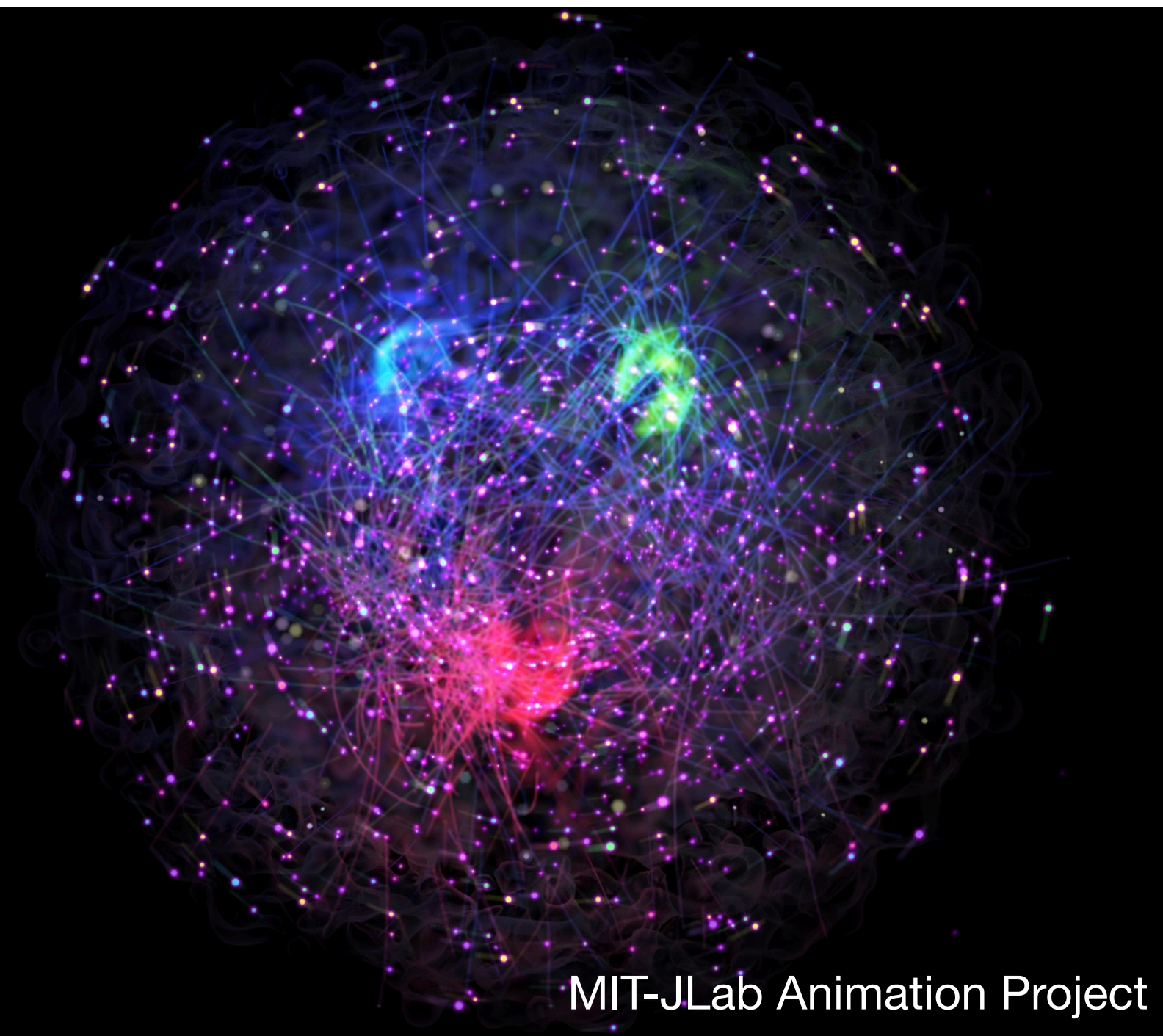
Quantum Simulation in the NISQ Era



Real-Time High-Energy Collisions of Matter



CERN event

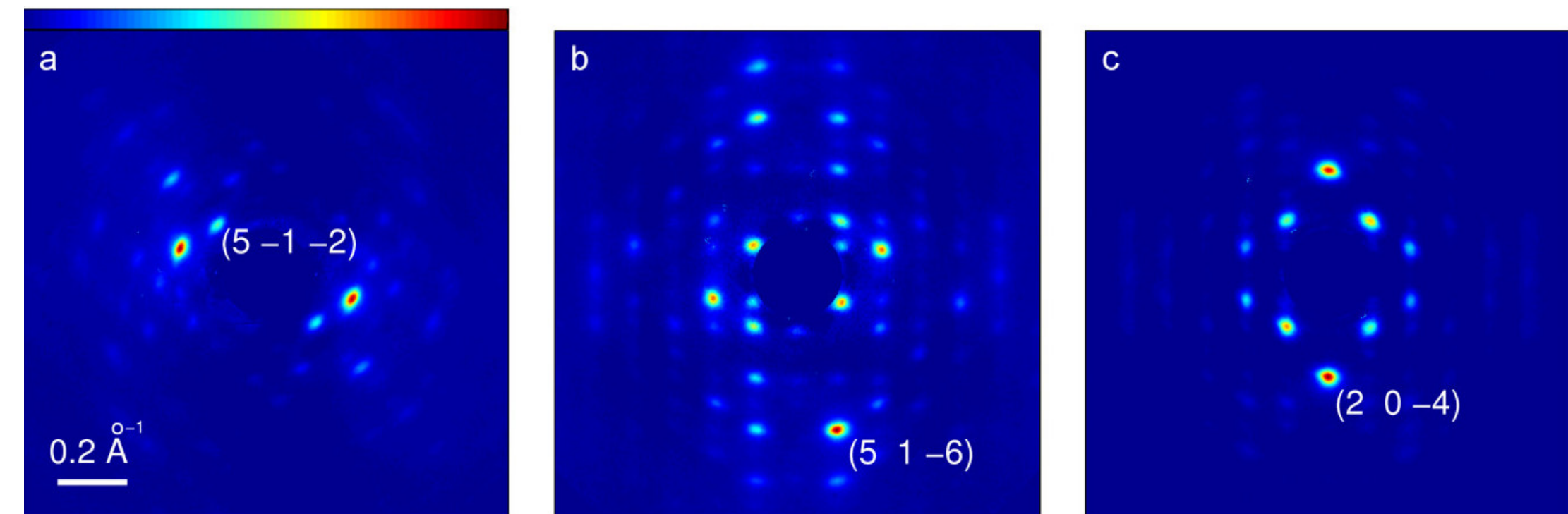
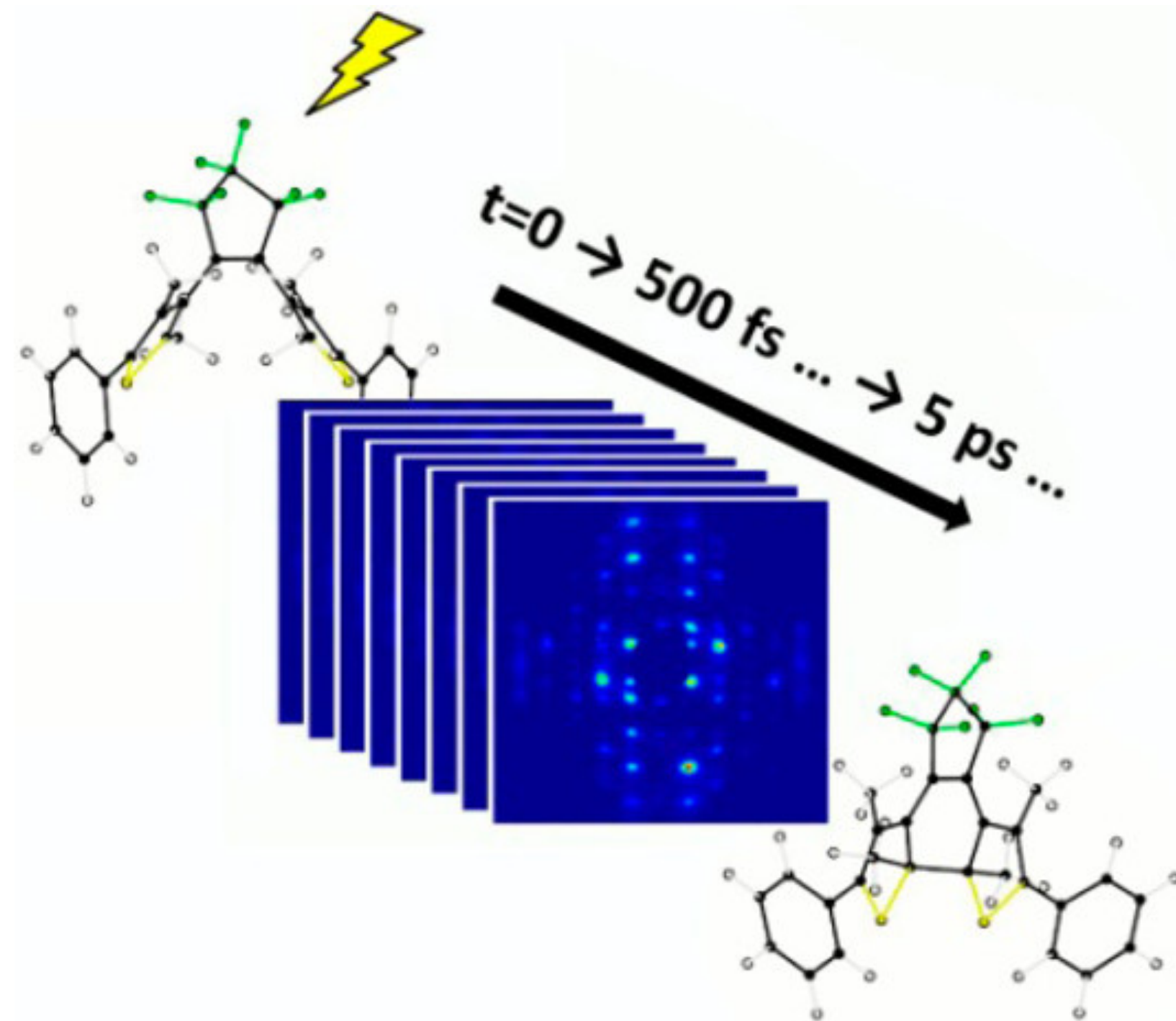


MIT-JLab Animation Project

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

A number of significant efforts working toward this objective

Real-Time Dynamics and Reaction Pathways



J. Phys. Chem. B 2013, 117, 49, 15894-15902

Femto-second chemistry reveals reaction mechanisms
Quantum simulations will reveal the reactions pathways of QCD

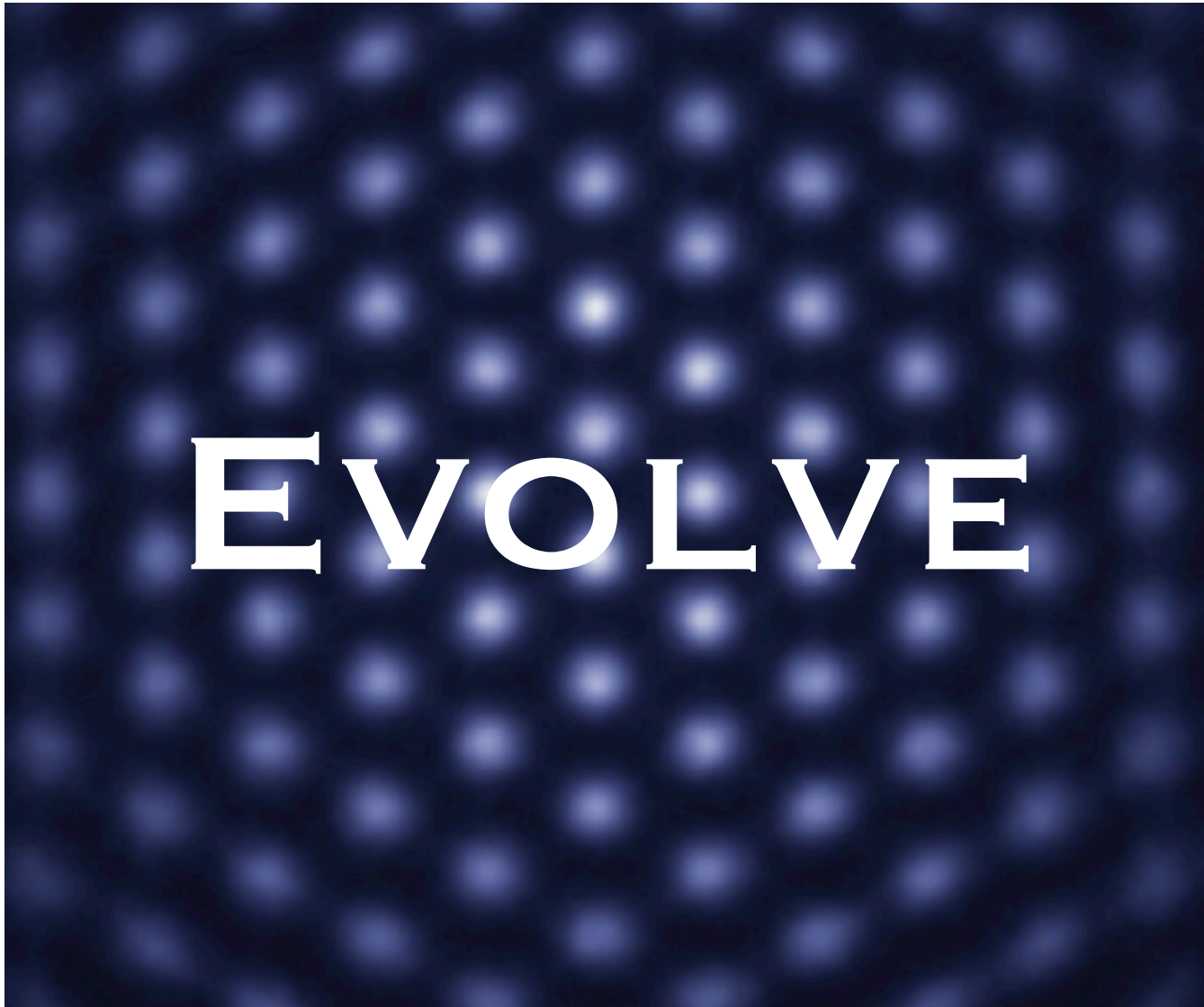
Why not wait until the quantum computers of the future arrive?



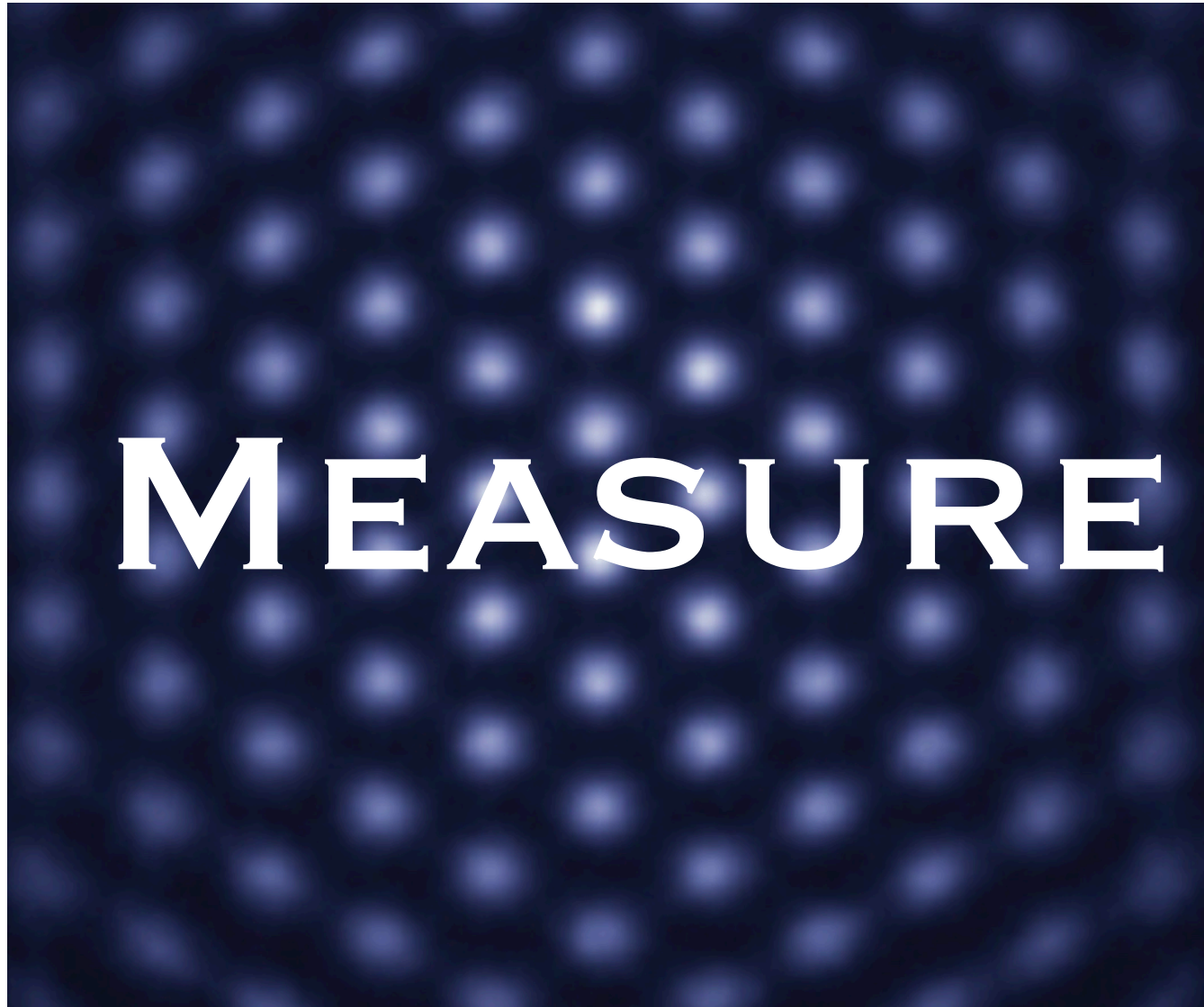
Steps to Perform using a Digital Quantum Computer

A dark blue square with a pattern of small, glowing white dots, resembling a starry night sky. The word "PREPARE" is centered in a white, serif, all-caps font.

PREPARE

A dark blue square with a pattern of small, glowing white dots, resembling a starry night sky. The word "EVOLVE" is centered in a white, serif, all-caps font.

EVOLVE

A dark blue square with a pattern of small, glowing white dots, resembling a starry night sky. The word "MEASURE" is centered in a white, serif, all-caps font.

MEASURE

REPEAT

Gold-Standard - Scalar Field Theory

Quantum Computation of Scattering in Scalar Quantum Field Theories

Stephen P. Jordan,^{†§} Keith S. M. Lee,^{‡§} and John Preskill ^{§ *}

2011

2017

BQP-completeness of scattering in scalar quantum field theory

Stephen P. Jordan^{1,2}, Hari Krovi³, Keith S. M. Lee⁴, and John Preskill⁵

¹National Institute of Standards and Technology, Gaithersburg, MD, USA

²Joint Center for Quantum Information and Computer Science, University of Maryland, College Park, MD, USA

³Quantum Information Processing Group, Raytheon BBN Technologies, Cambridge, MA, USA

⁴Centre for Quantum Information & Quantum Control and Department of Physics, University of Toronto, Toronto, ON, Canada

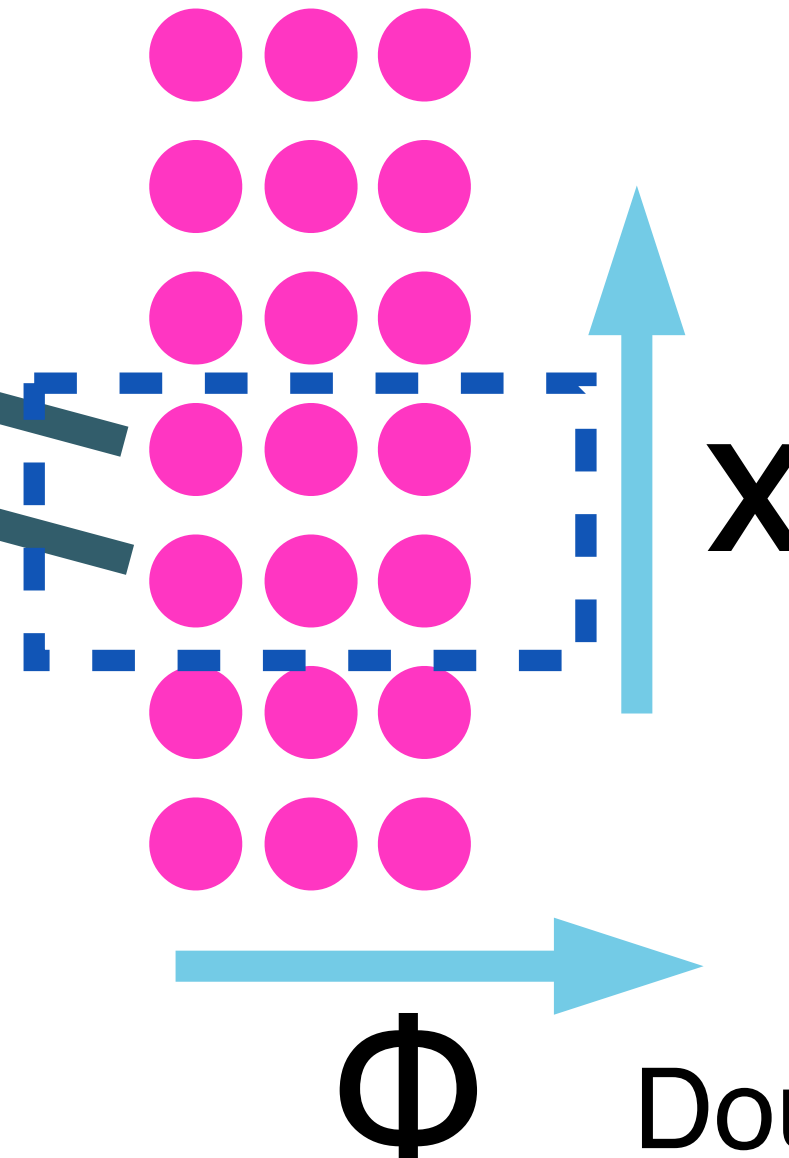
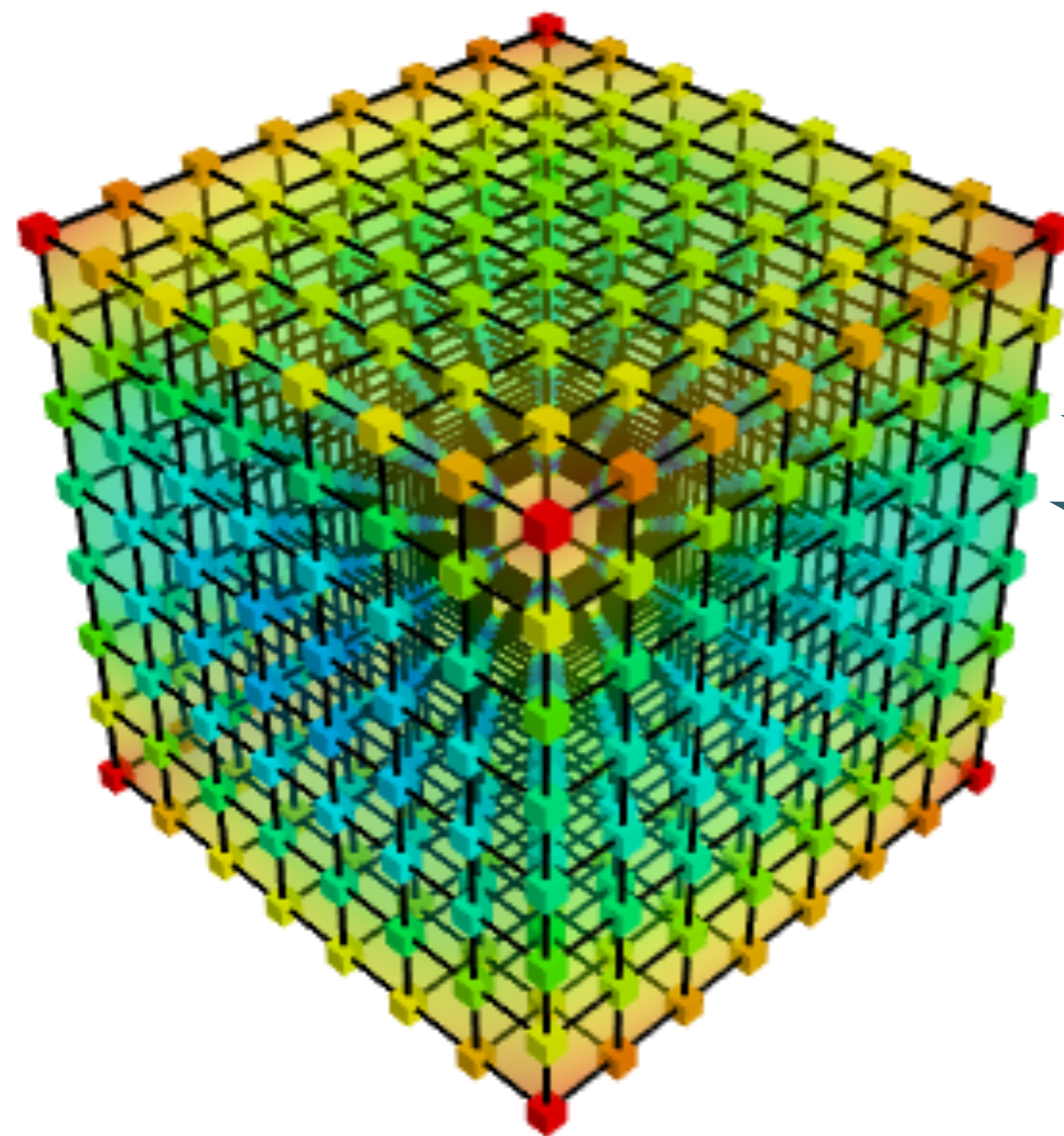
⁵Institute for Quantum Information and Matter, California Institute of Technology, Pasadena, CA, USA

Published: 2018-01-08, volume 2, page 44

Eprint: [arXiv:1703.00454v4](https://arxiv.org/abs/1703.00454v4)

Doi: <https://doi.org/10.22331/q-2018-01-08-44>

Citation: Quantum 2, 44 (2018).



Φ

Double exponential convergence of field digitization

- Nyquist-Shannon - JLP, FNAL, UW
- QFT and exact conjugate-momentum space operator

Lattice Scalar Field Theory

$$\mathcal{H} = \frac{1}{2}\hat{\Pi}^2 + \frac{1}{2}|\nabla\hat{\phi}|^2 + \frac{1}{2}m^2\hat{\phi}^2 + \frac{\lambda}{4!}\hat{\phi}^4 = \hat{T} + \hat{V} \quad \text{Continuum and continuous}$$

$$\left[\hat{\phi}(\mathbf{x}), \hat{\Pi}(\mathbf{y}) \right] = i\hbar\delta^3(\mathbf{x} - \mathbf{y}) \qquad \hat{\Pi}(\mathbf{x}) = -i\hbar\frac{\delta}{\delta\phi(\mathbf{x})}$$

$$H^{\text{latt.}} = a^d \sum_{\mathbf{x}} \left(\frac{1}{2}\hat{\Pi}^2 - \frac{1}{2a^2}\hat{\phi}(x) \sum_j^d \left(\hat{\phi}(x + \boldsymbol{\mu}_j) + \hat{\phi}(x - \boldsymbol{\mu}_j) \right) + \frac{1}{2} \left(m_0^2 + \frac{2d}{a^2} \right) \hat{\phi}^2 + \frac{\lambda_0}{4!}\hat{\phi}^4 \right) .$$

Digital Lattice Scalar Field Theory

$$\left(\frac{1}{2}m^2\hat{\phi}^2 + \frac{\lambda}{4!}\hat{\phi}^4 \right) |\phi\rangle = \left(\frac{1}{2}m^2\phi^2 + \frac{\lambda}{4!}\phi^4 \right) |\phi\rangle$$

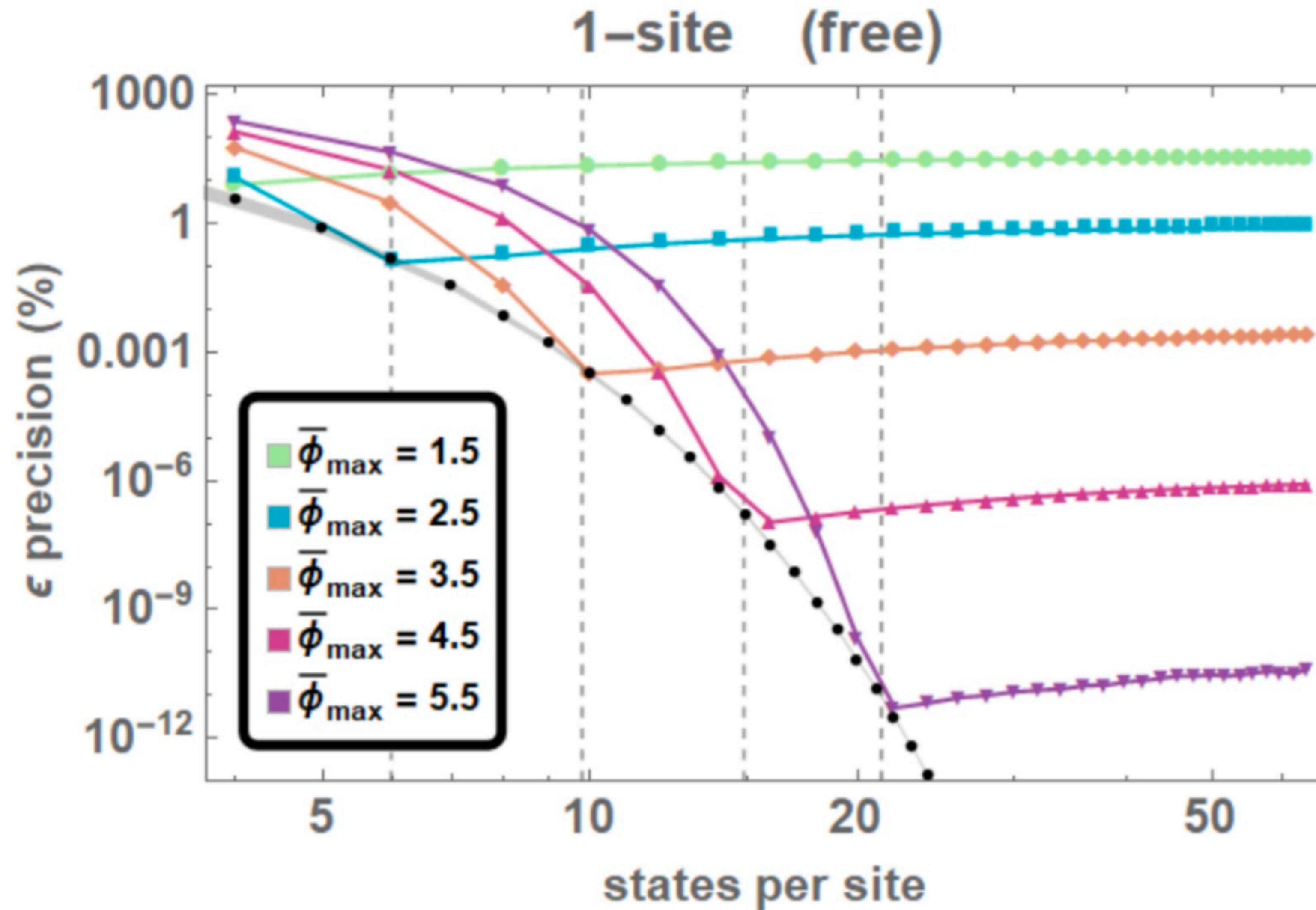
$$\phi = -\phi_{\max} + j\delta_{\phi} \quad , \quad \delta_{\phi} = \frac{2\phi_{\max}}{n_s - 1} \quad , \quad j \in [0, n_s - 1]$$

$$\langle\phi' | \hat{\Pi}_{\text{exact}}^2 |\phi\rangle = V^\dagger . \hat{P}^2 . V \quad \text{with} \quad \hat{P} \rightarrow \text{diag} (k_{\phi})$$

Nyquist-Shannon Sampling

$$\phi = \text{diag} (-7, -5, -3, -1, +1, +3, +5, +7) \frac{\phi_{\max}}{7}$$
$$k_{\phi} = \text{diag} (-7, -5, -3, -1, +1, +3, +5, +7) \frac{\pi}{8\delta_{\phi}} \quad .$$

Digital Lattice Scalar Field Theory



Time Evolution

Introduction to Trotterization

$$\hat{H} = \hat{K} + \hat{V}$$

$$|\psi\rangle(t) = \hat{U}(t) |\psi\rangle_0 \quad , \quad \hat{U}(t) = e^{-i\hat{H}t}$$

- For nQ=3, $8 \times 8 - 1 = 63$ angles to determine from $U(t)$ for exact circuit implementation.
- This is doable, but not scalable!

$$\hat{U}(t) = e^{-i\hat{H}T} = \left[e^{-i\hat{H}\Delta t} \right]^{T/\Delta t}$$

$$\hat{U}(t) = e^{-i\hat{H}T} = \lim_{\Delta t \rightarrow 0} \left[e^{-i(\hat{K} + \hat{V})\Delta t} \right]^{T/\Delta t}$$

Time Evolution

Introduction to Trotterization

$$\hat{U}(t) = e^{-i\hat{H}T} = \lim_{\Delta t \rightarrow 0} \left[e^{-i(\hat{K} + \hat{V})\Delta t} \right]^{T/\Delta t} \quad \left[\hat{K}, \hat{V} \right]$$

$$e^{-i\hat{K}\Delta t} e^{-i\hat{V}\Delta t} = e^{-i(\hat{K} + \hat{V})\Delta t} + \mathcal{O}(\Delta t^2) \quad \text{LO}$$

$$e^{-i\hat{K}\Delta t/2} e^{-i\hat{V}\Delta t} e^{-i\hat{K}\Delta t/2} = e^{-i(\hat{K} + \hat{V})\Delta t} + \mathcal{O}(\Delta t^3)$$

$$e^{-i\hat{V}\Delta t/2} e^{-i\hat{K}\Delta t} e^{-i\hat{V}\Delta t/2} = e^{-i(\hat{K} + \hat{V})\Delta t} + \mathcal{O}(\Delta t^3) \quad \text{NLO}$$

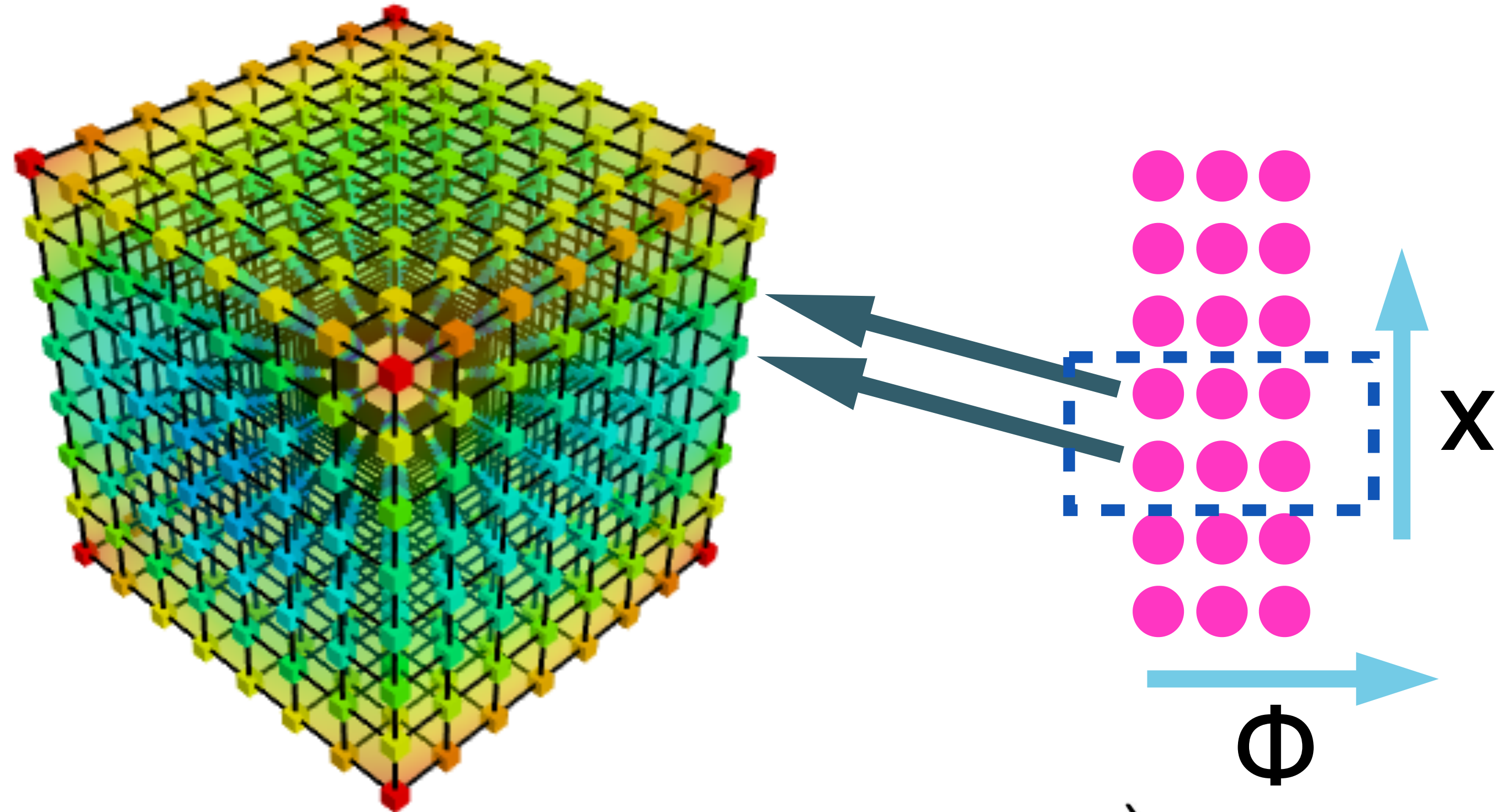
JLP for nQ=3

$$e^{-i\tilde{H}_3 t} = \lim_{M \rightarrow \infty} \left(\begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \end{array} \left[\Phi_3 \left(\frac{t}{2M} \frac{4}{49} \bar{\phi}_{max}^2 \right) \right] \left[QFT_{sym} \right] \begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \end{array} \left[\Phi_3 \left(\frac{t}{2M} \frac{49\pi^2}{64\bar{\phi}_{max}^2} \right) \right] \begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \end{array} \left[QFT_{sym}^{-1} \right] \begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \end{array} \right)^M$$

Time Evolution

JLP for 3+1D

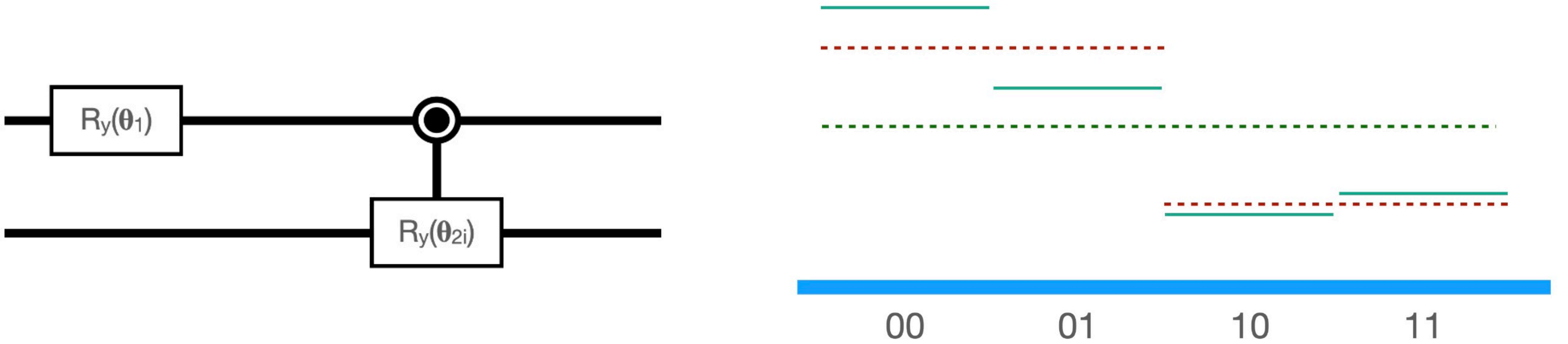
$$N_Q = n_Q \times L^3$$



$$H = \frac{1}{2} \sum_{\mathbf{n}}^{L-1, L-1, L-1} \left(\hat{\Pi}_{\mathbf{n}}^2 + m^2 \hat{\phi}_{\mathbf{n}}^2 - \sum_{j=x,y,z} \hat{\phi}_{\mathbf{n}} (\hat{\phi}_{\mathbf{n}+\mu_j} + \hat{\phi}_{\mathbf{n}-\mu_j} - 2\hat{\phi}_{\mathbf{n}}) \right)$$

$$= \frac{1}{2} \sum_{\mathbf{n}}^{L-1, L-1, L-1} \left(\hat{\Pi}_{\mathbf{n}}^2 + (m^2 + 6) \hat{\phi}_{\mathbf{n}}^2 - \sum_{j=x,y,z} \hat{\phi}_{\mathbf{n}} (\hat{\phi}_{\mathbf{n}+\mu_j} + \hat{\phi}_{\mathbf{n}-\mu_j}) \right)$$

State Preparation



$$|\psi'\rangle = \left(\hat{\Lambda}_0 \otimes \hat{R}_y(\theta_{20}) + \hat{\Lambda}_1 \otimes \hat{I} \right) \left(\hat{\Lambda}_0 \otimes \hat{I} + \hat{\Lambda}_1 \otimes \hat{R}_y(\theta_{21}) \right) \left(\hat{R}_y(\theta_1) \otimes \hat{I} \right) |\psi\rangle ,$$

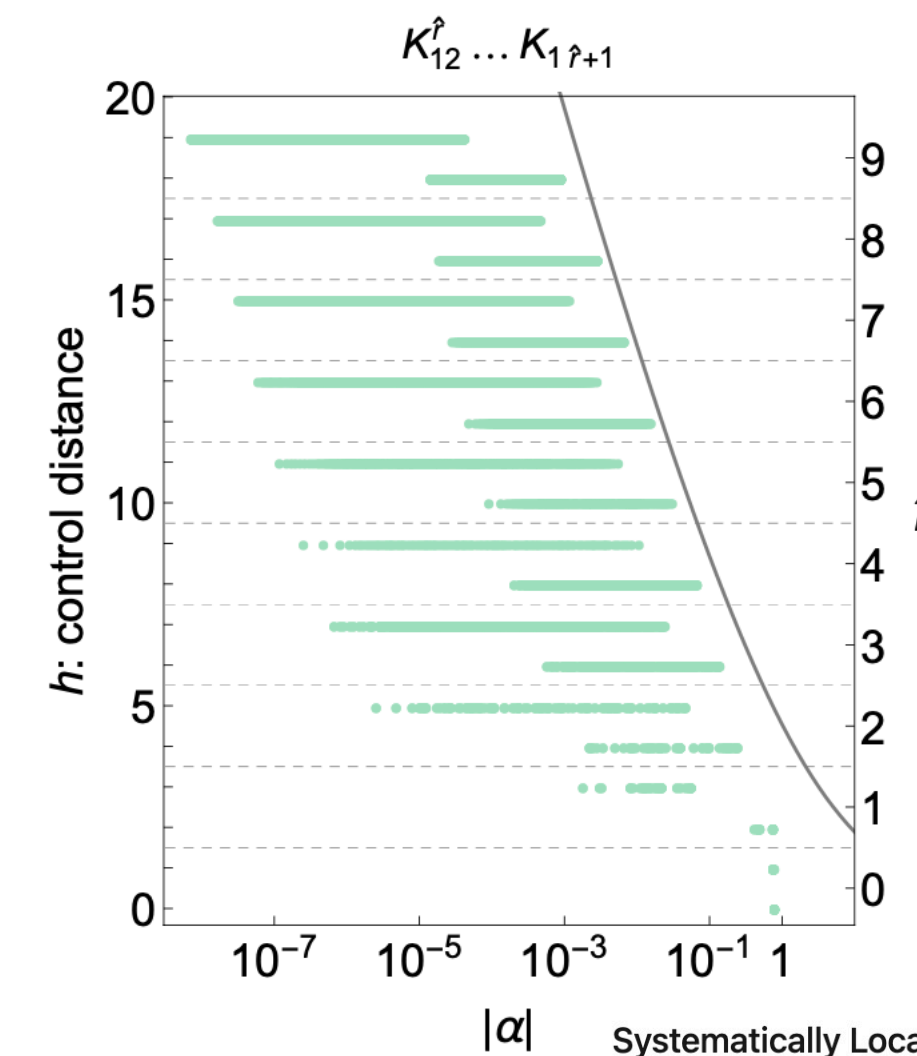
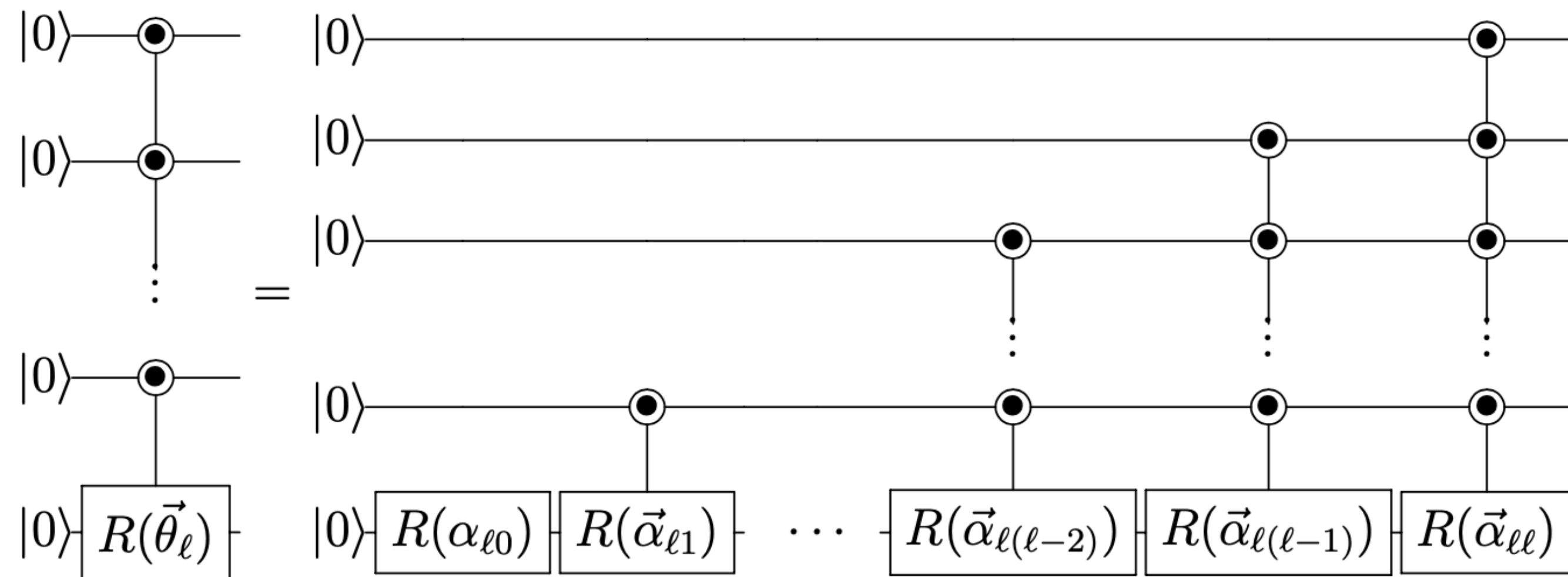
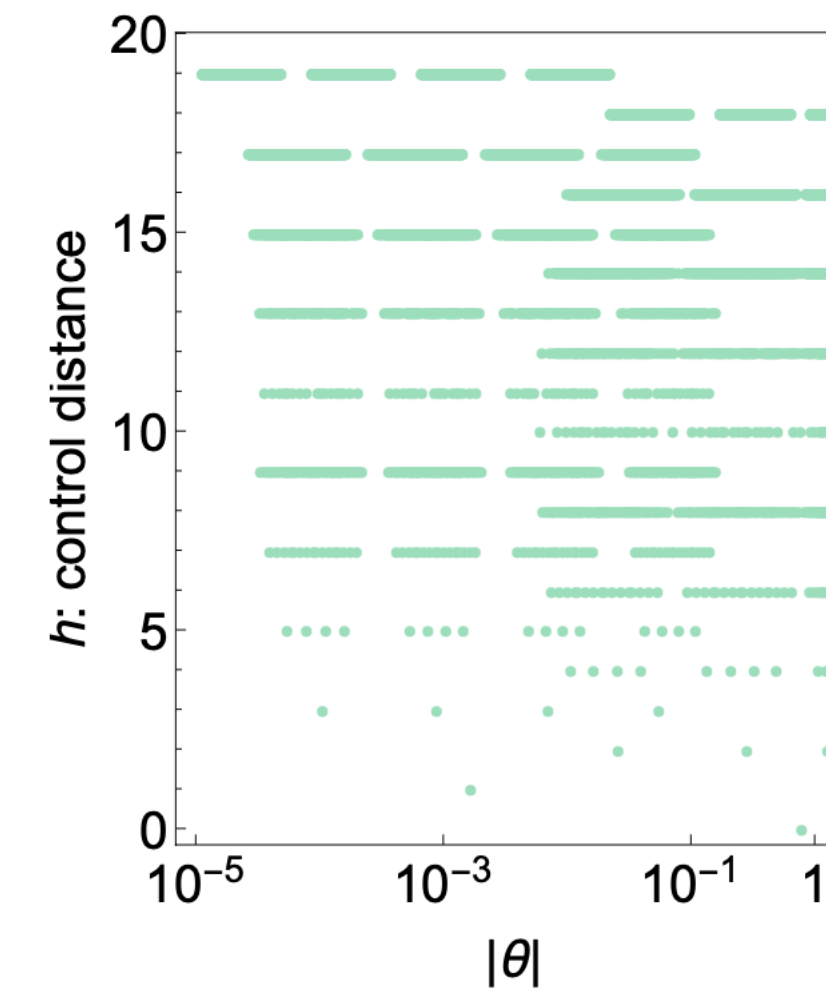
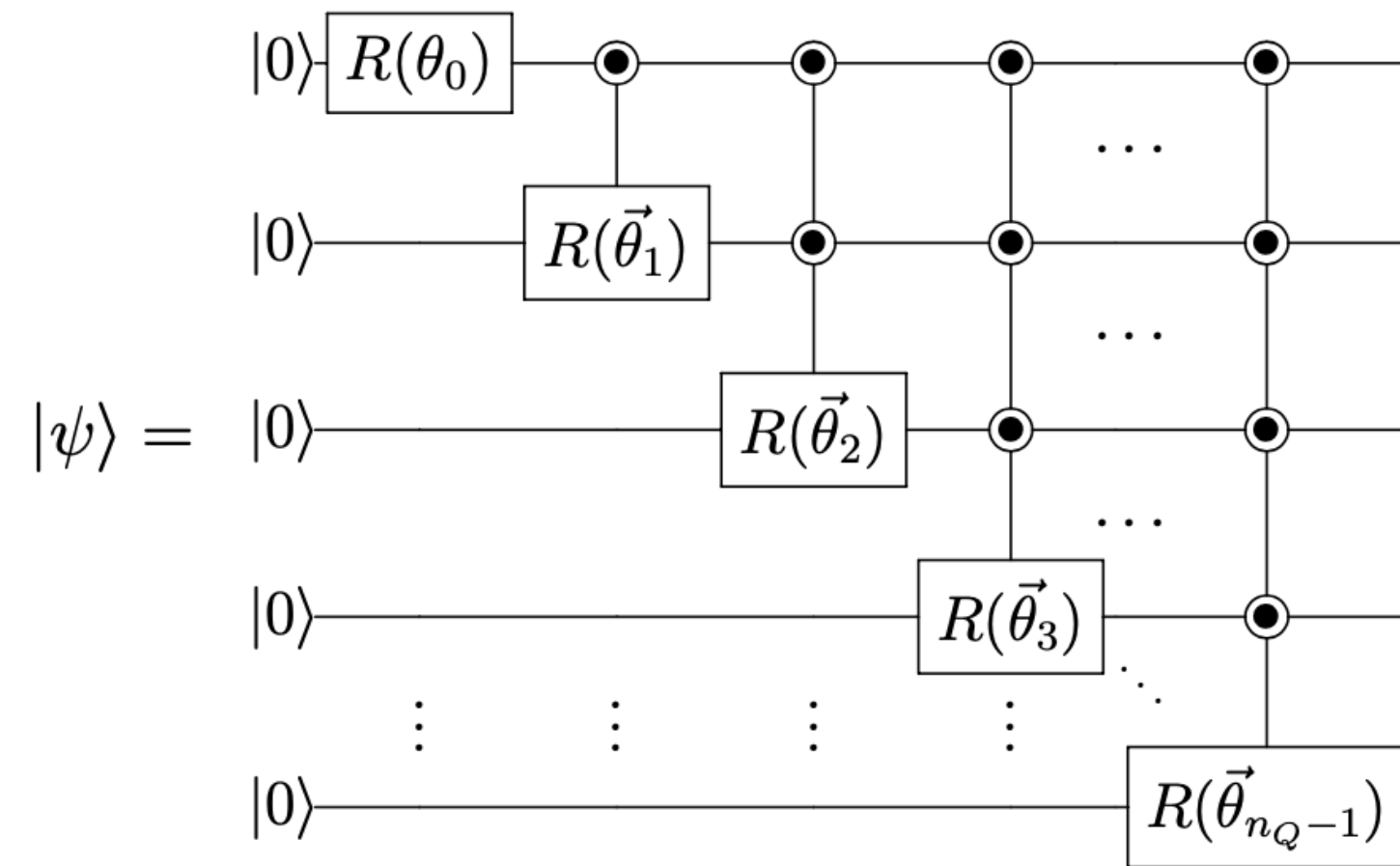
$$= \left(\hat{\Lambda}_0 \otimes \hat{R}_y(\theta_{20}) + \hat{\Lambda}_1 \otimes \hat{R}_y(\theta_{21}) \right) \left(\hat{R}_y(\theta_1) \otimes \hat{I} \right) |\psi\rangle ,$$

$$|00\rangle \rightarrow \cos \frac{\theta_1}{2} |00\rangle + \sin \frac{\theta_1}{2} |10\rangle$$

$$\rightarrow \cos \frac{\theta_1}{2} \left(\cos \frac{\theta_{20}}{2} |00\rangle + \sin \frac{\theta_{20}}{2} |01\rangle \right) + \sin \frac{\theta_1}{2} \left(\cos \frac{\theta_{21}}{2} |10\rangle + \sin \frac{\theta_{21}}{2} |11\rangle \right)$$

$$\rightarrow \cos \frac{\theta_1}{2} \cos \frac{\theta_{20}}{2} |00\rangle + \cos \frac{\theta_1}{2} \sin \frac{\theta_{20}}{2} |01\rangle + \sin \frac{\theta_1}{2} \cos \frac{\theta_{21}}{2} |10\rangle + \sin \frac{\theta_1}{2} \sin \frac{\theta_{21}}{2} |11\rangle$$

Physics-Aware Mapping and State Preparation



Correlation length allows for fixed-point angles to be determined exponentially well with small-scale simulations

Systematically Localizable Operators for Quantum Simulations of Quantum Field Theories

Natalie Klco (Washington U., Seattle), Martin J. Savage (Dec 7, 2019)

Published in: *Phys.Rev.A* 102 (2020) 1, 012619 • e-Print: [1912.03577](https://arxiv.org/abs/1912.03577) [quant-ph]

Fixed-point quantum circuits for quantum field theories

Natalie Klco (Washington U., Seattle), Martin J. Savage (Washington U., Seattle) (Feb 5, 2020)

Published in: *Phys.Rev.A* 102 (2020) 5, 052422 • e-Print: [2002.02018](https://arxiv.org/abs/2002.02018) [quant-ph]

Scattering in Lattice Scalar Field Theory

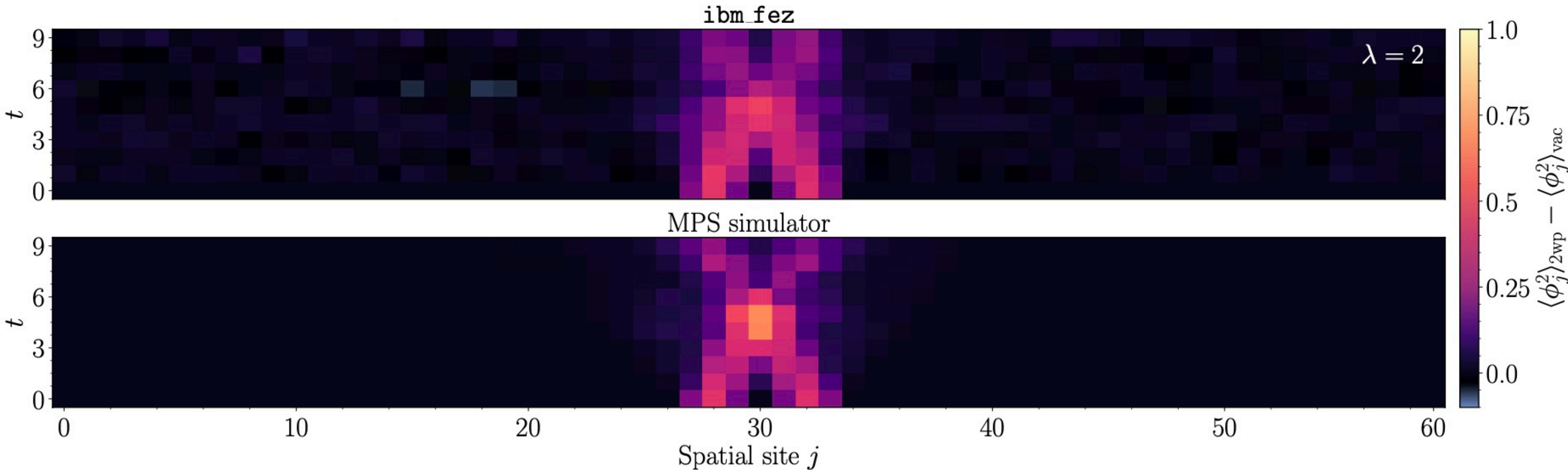
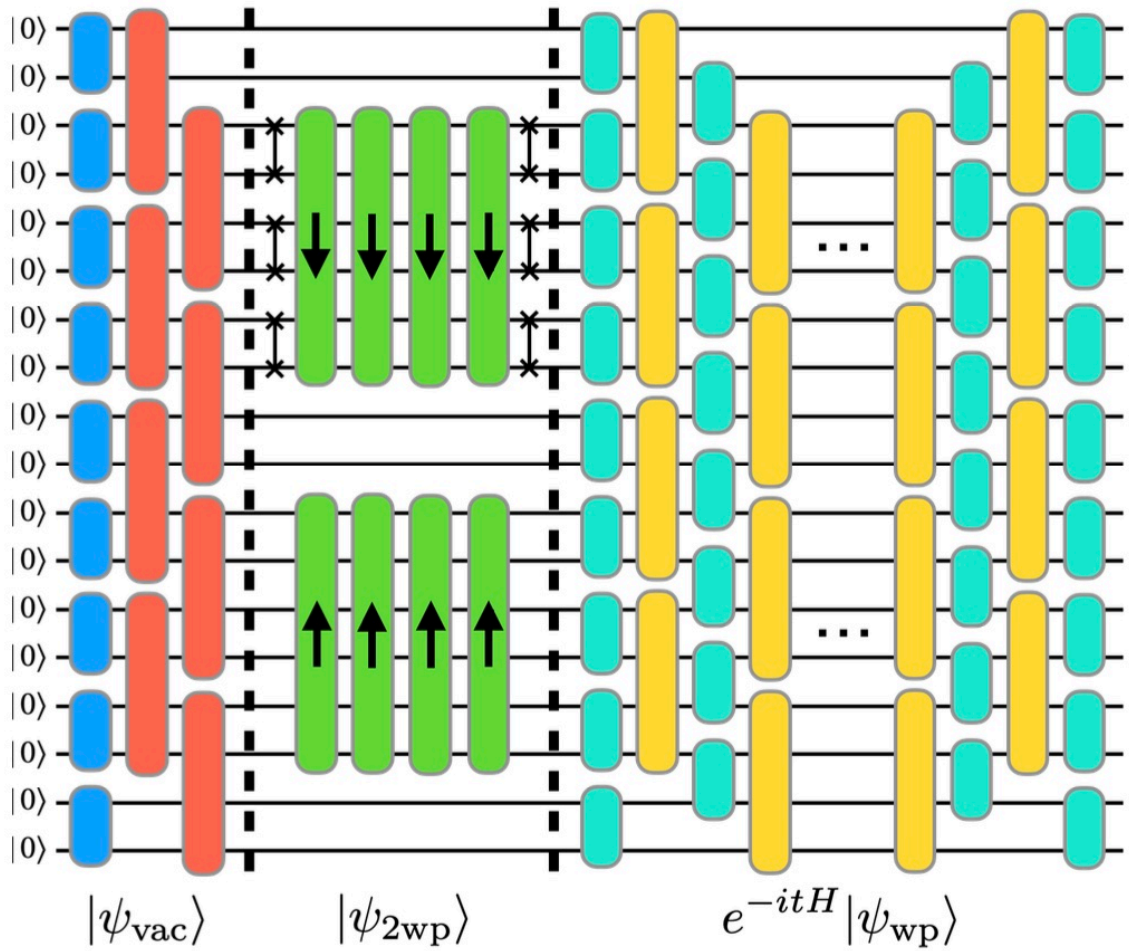
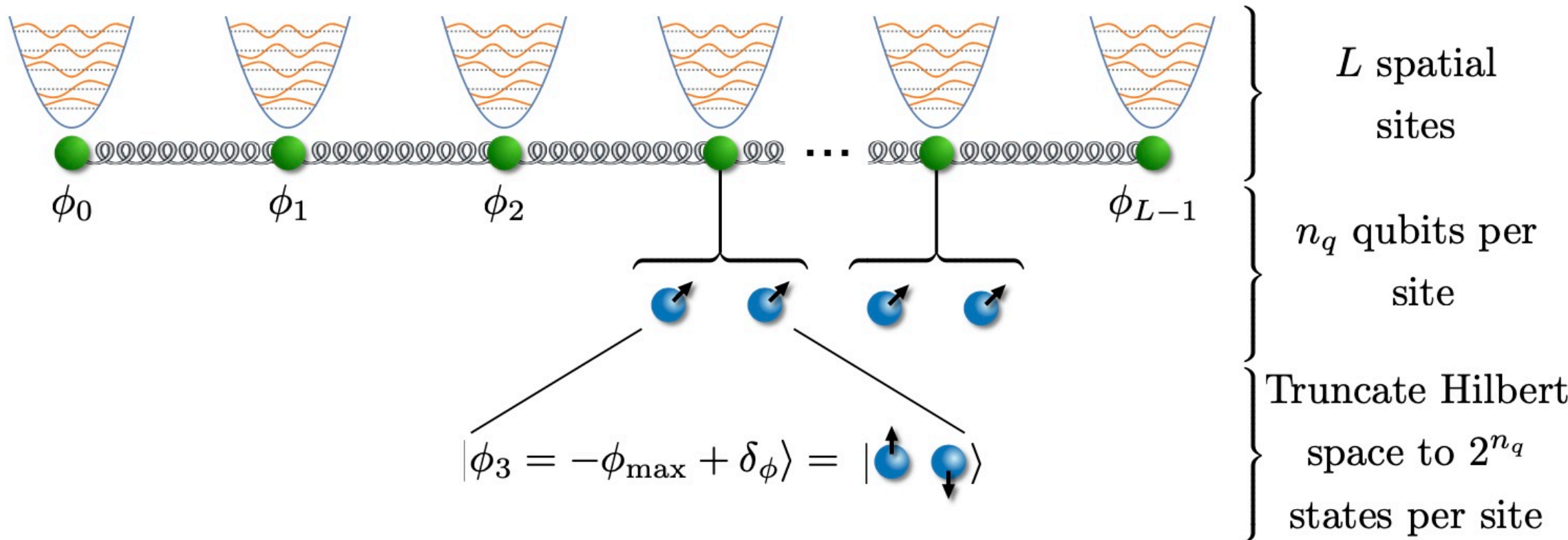


Scalable quantum simulations of scattering in scalar field theory on 120 qubits

[Nikita A. Zemlevskiy](#) *

Show more

Phys. Rev. D **112**, 034502 – Published 4 August, 2025



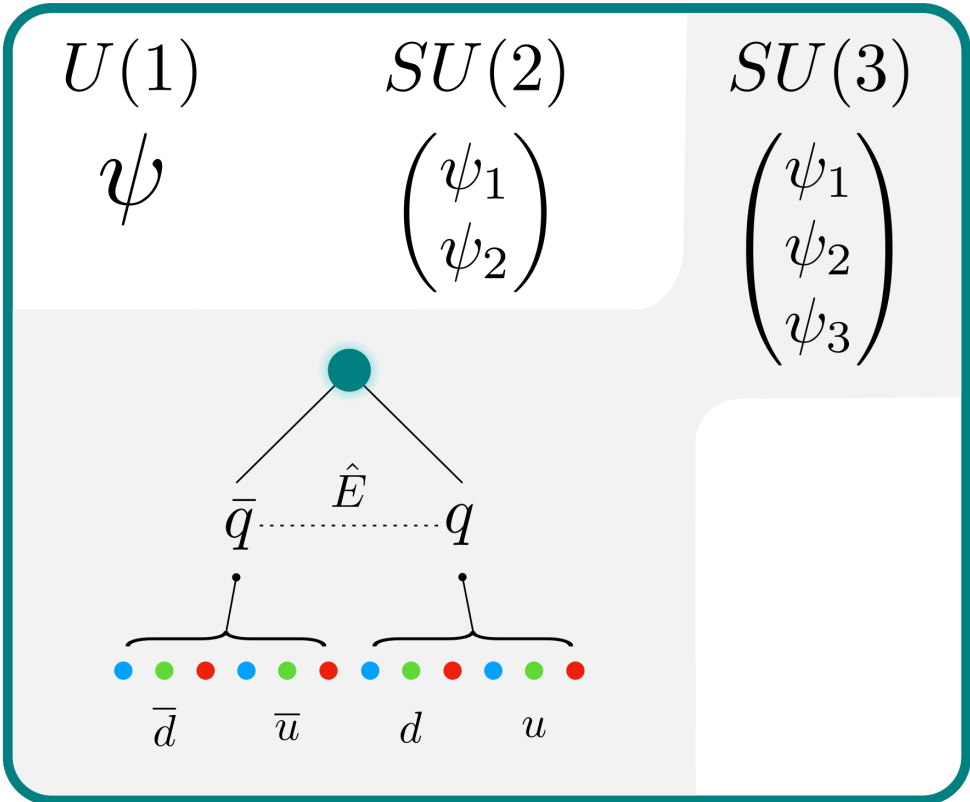
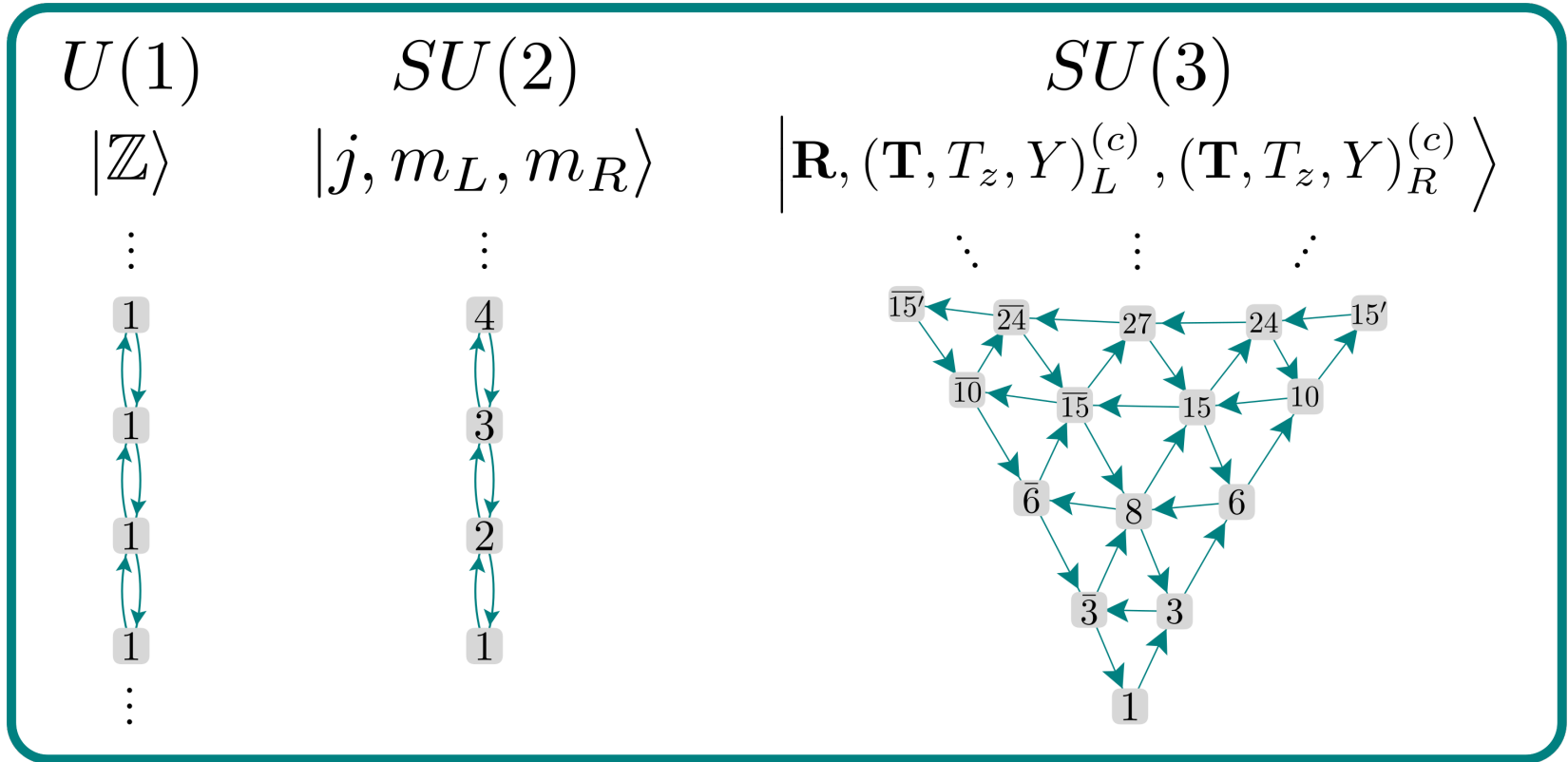
Simulating Lattice Gauge Field Theories

Hamiltonian
Kogut-Susskind
1970's

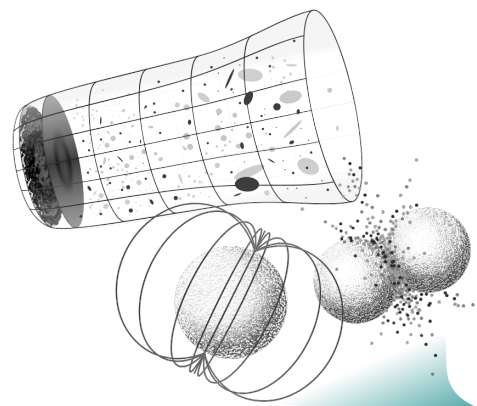
Yang-Mills:
Byrnes-Yamamoto
2005

SU(N):
Zohar et al
(2013)

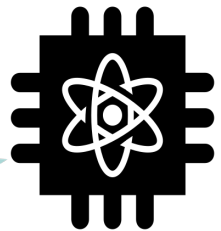
QLM
Banerjee et al
Tagliacozzo et al
(2013)



$$\hat{\mathcal{H}} \sim g^2 |\hat{E}(\mathbf{x})|^2 - \frac{1}{g^2} \text{Tr} \left[\hat{U}_1 \hat{U}_2 \hat{U}_3^\dagger \hat{U}_4^\dagger + \text{h.c.} \right] + \hat{\mathcal{H}}_\psi$$



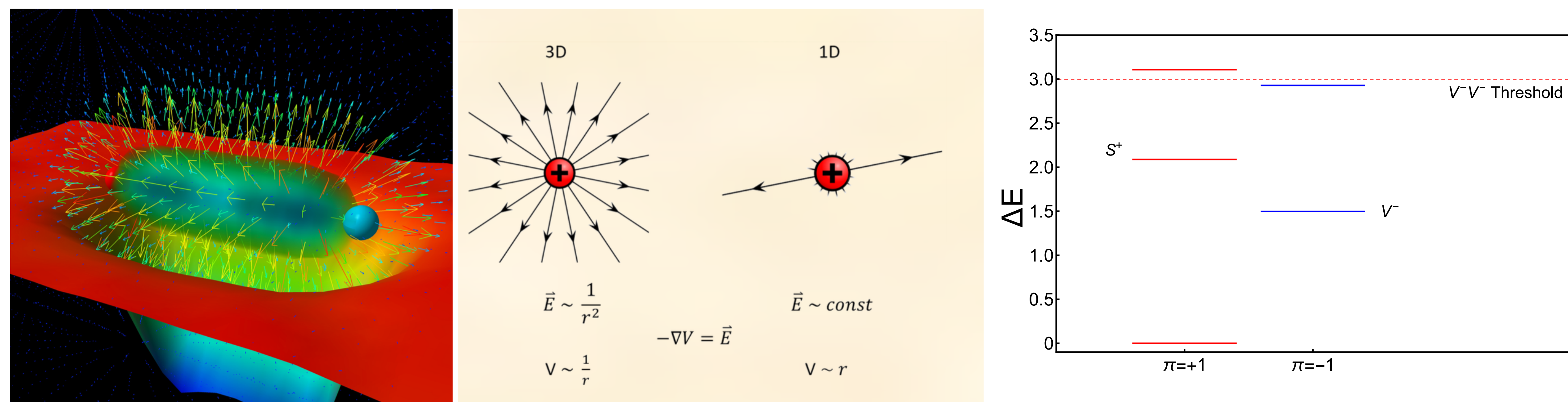
$$\hat{G}^a(\mathbf{x}) |\Phi\rangle_{\text{phys}} = 0$$



Quantum Electrodynamics in 1+1 Dimensions

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

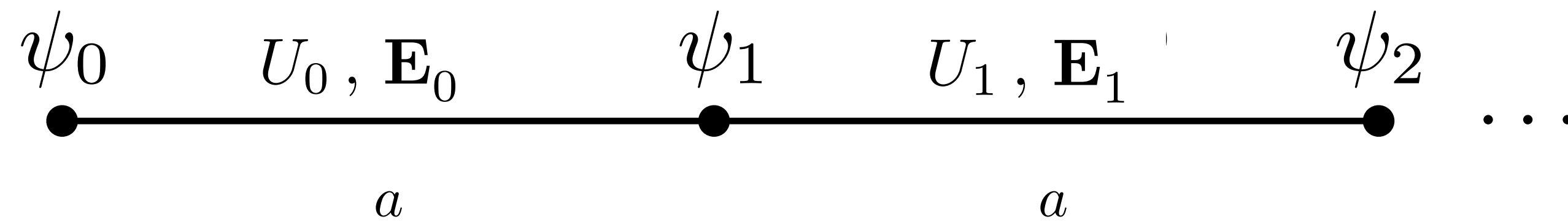
- Charge screening, confinement
- Fermion condensate
- Gap
- Translationally invariant vacuum



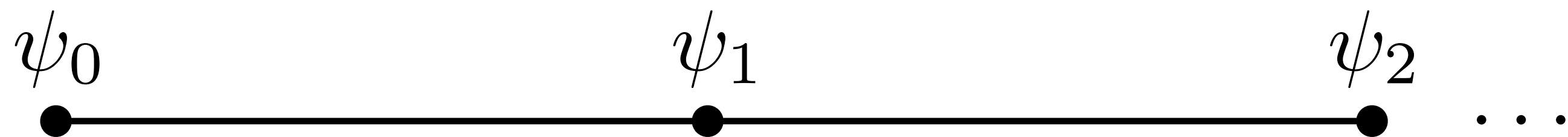
This model is being used by several groups pursuing quantum simulations

Lattice Hamiltonian in 1+1D

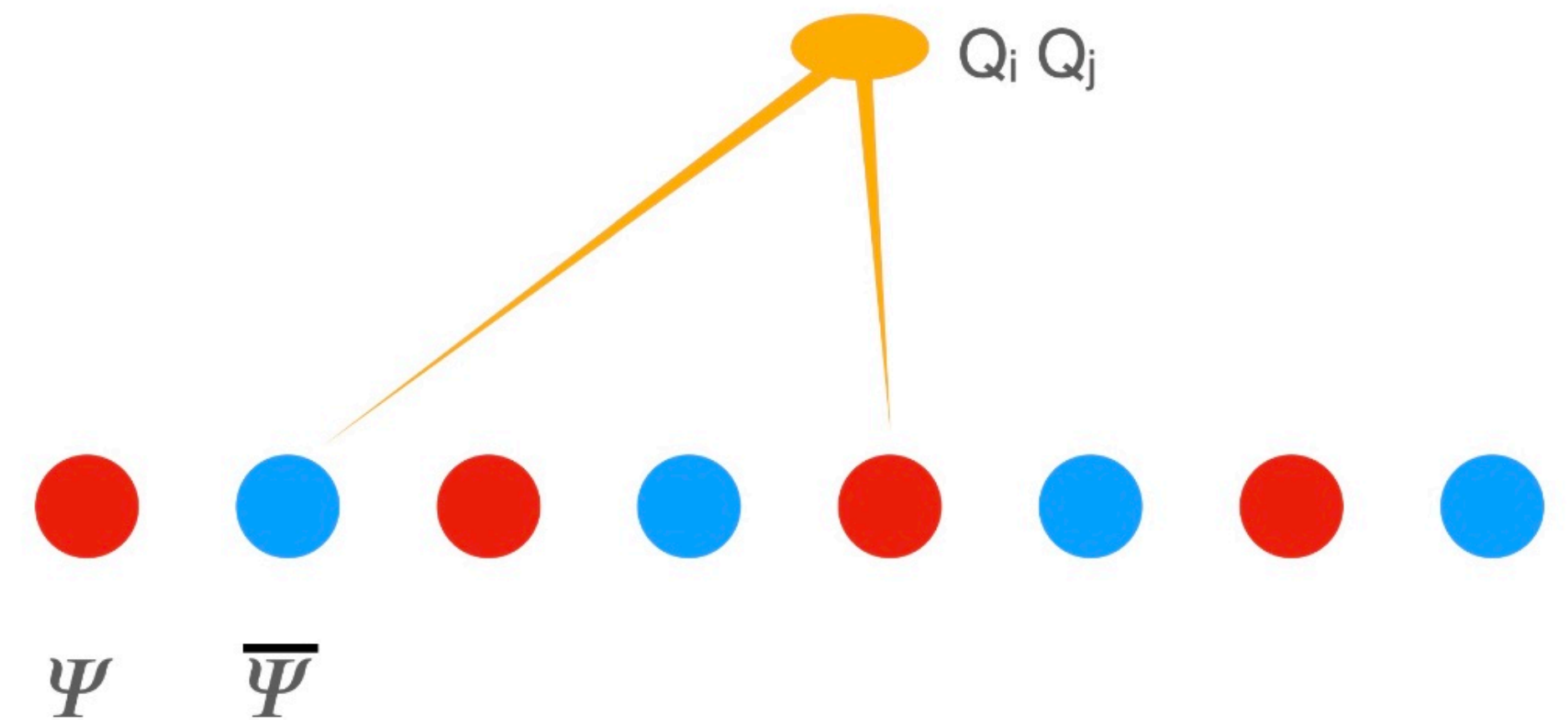
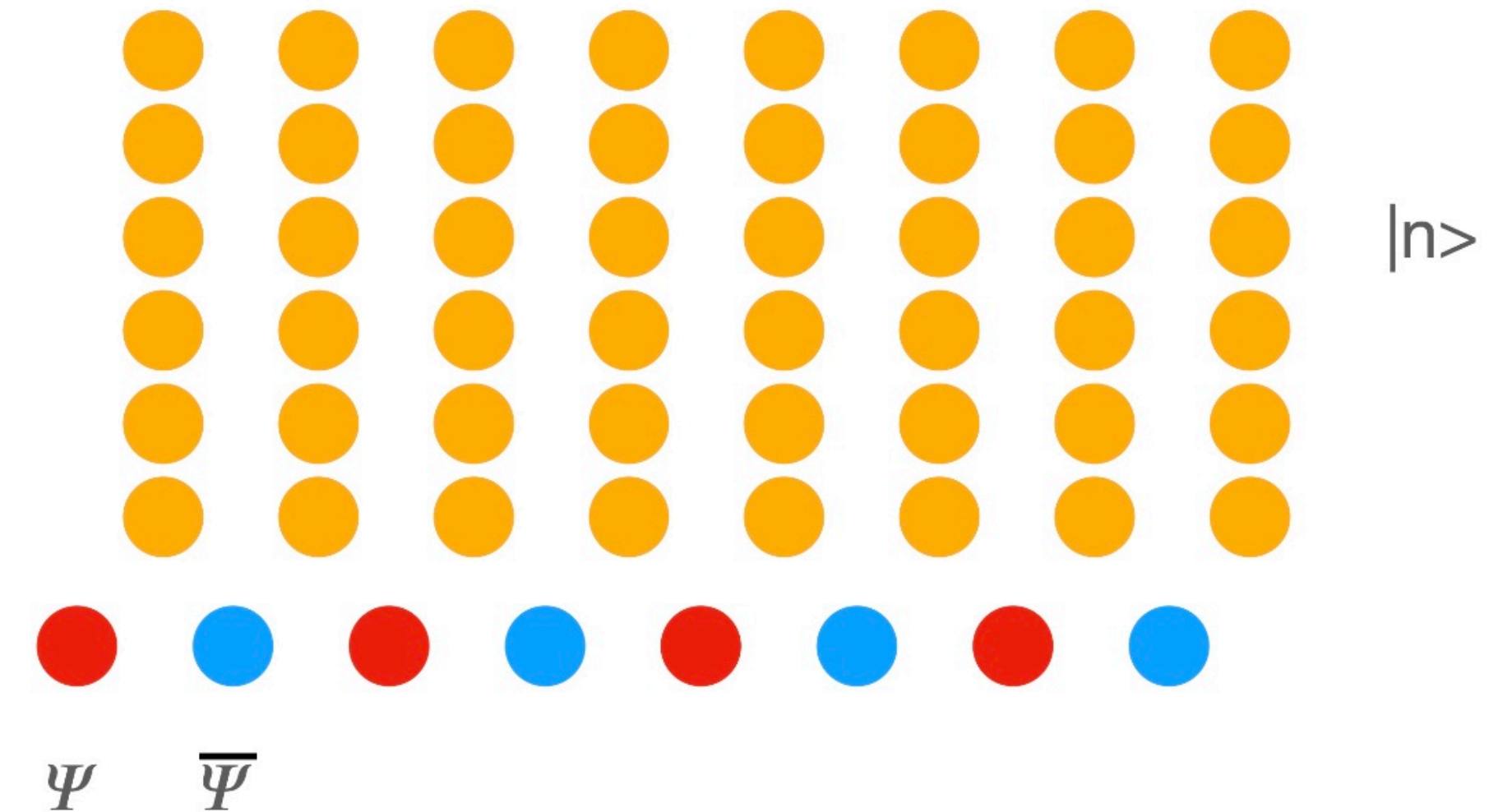
- which gauge to choose?



Weyl gauge



Axial gauge



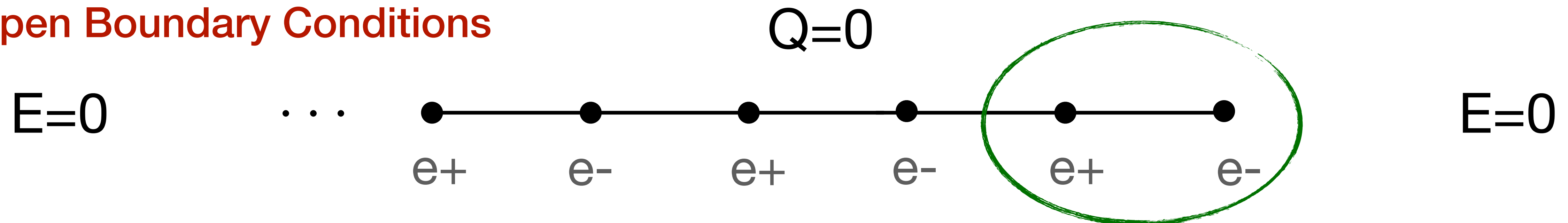
Quantum Resources required to evolve over some time interval similar (!)

JW Mapping with OBCs

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

$$\hat{Q}_k = \underbrace{-\frac{1}{2} \left[\hat{Z}_k + (-1)^k \hat{I} \right]}_{\text{Local}} \quad \chi = \underbrace{\frac{1}{2L} \sum_{j=0}^{2L-1} \left\langle (-1)^j \hat{Z}_j + \hat{I} \right\rangle}_{\text{Local}} \equiv \frac{1}{2L} \sum_{j=0}^{2L-1} \chi_j$$

Open Boundary Conditions



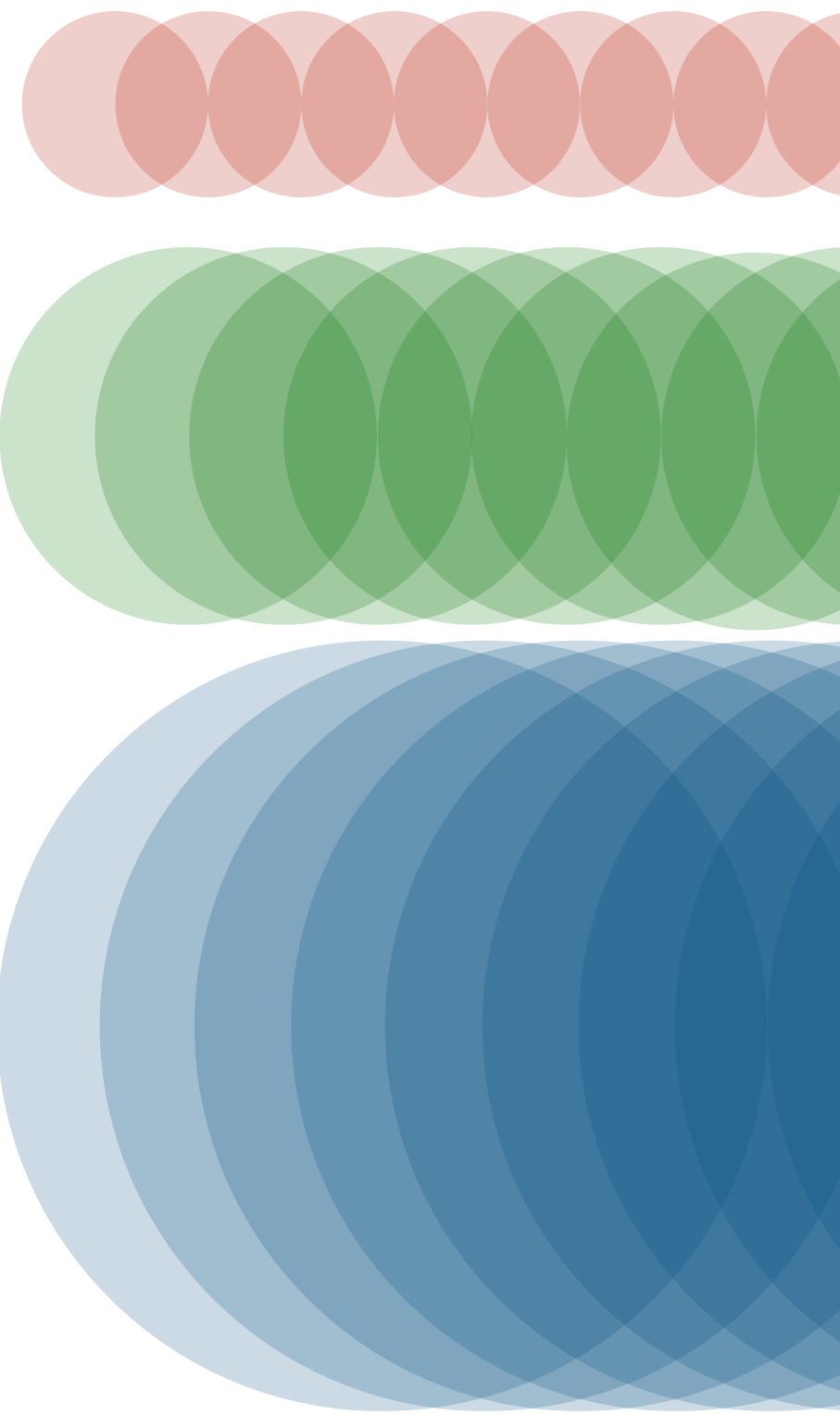
Confinement and Scalable Circuits

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

Local

Nearest Neighbor

Non-local

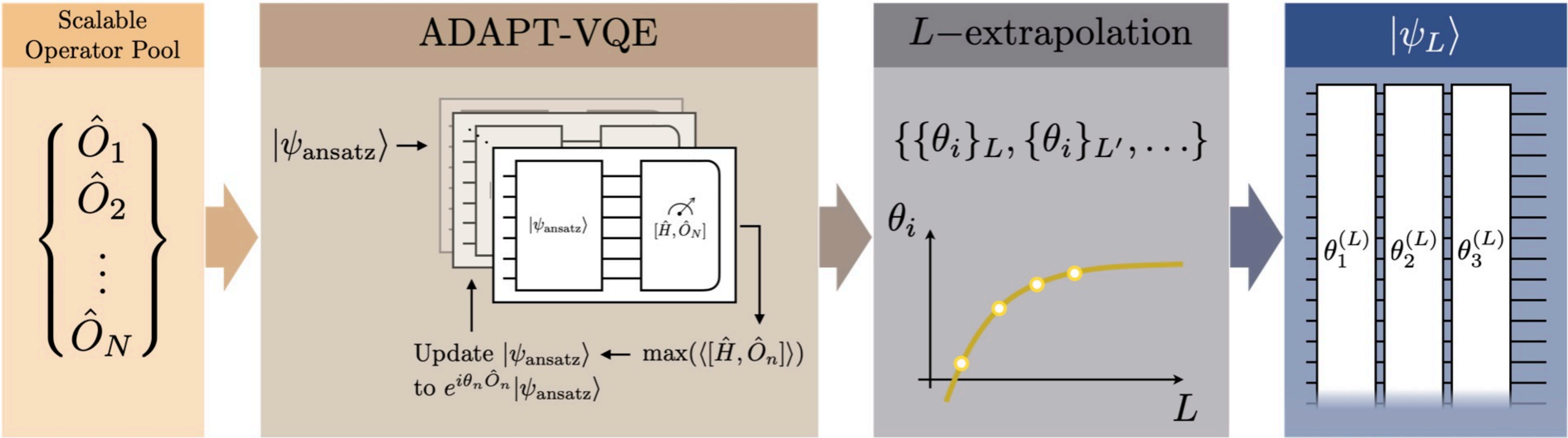


Symmetries and Confinement

Classical Optimization

Classical Extrapolations

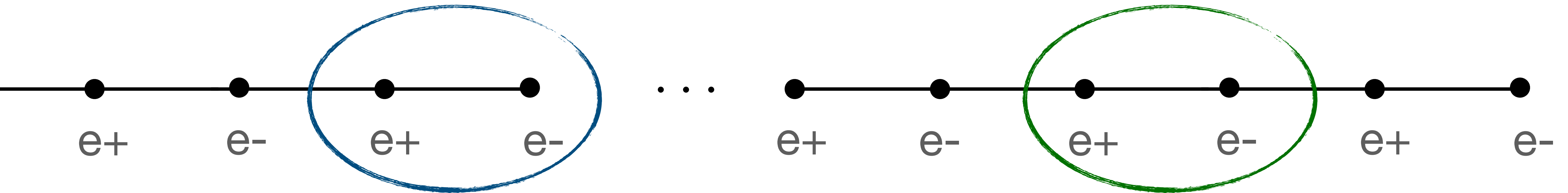
Quantum Implementation



Confinement is emergent

i.e. the Hamiltonian inspection is not enough for efficient implementation

Confinement Means



$$\langle Q_i Q_j \rangle$$

Vanishes exponentially with increasing separation
—with a length scale set by the gap

Truncation of non-local term(s) in the Hamiltonian will converge rapidly

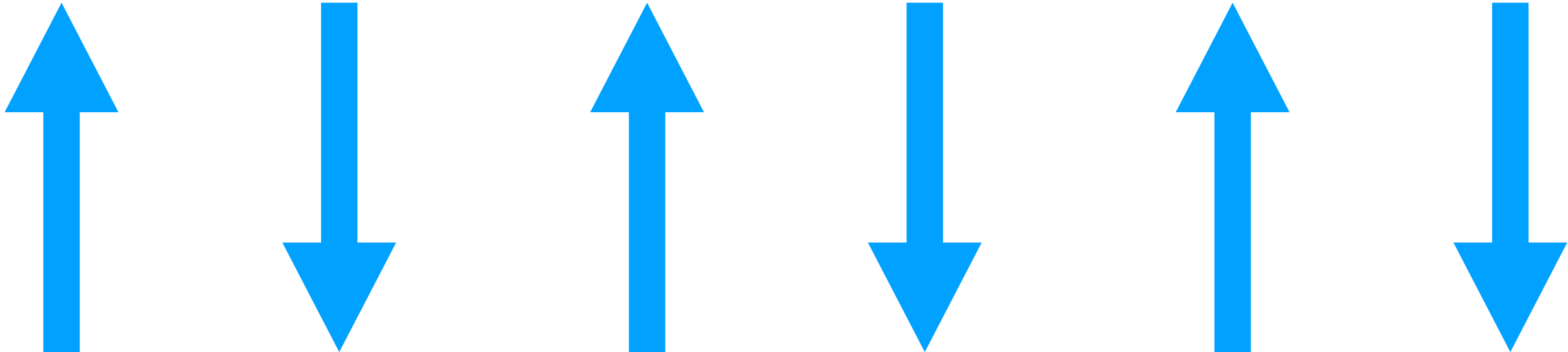
Scalable Operators: Volume and Surface

$$\hat{\Theta}_m^V = \frac{1}{2} \sum_{n=0}^{2L-1} (-1)^n \hat{Z}_n , \quad \dots \quad \begin{array}{ccccccccc} \bullet & \text{---} & \bullet & \text{---} & \bullet & \text{---} & \bullet & \text{---} & \bullet & \text{---} & \bullet \\ \text{e+} & & \text{e-} & & \text{e+} & & \text{e-} & & \text{e+} & & \text{e-} \end{array}$$

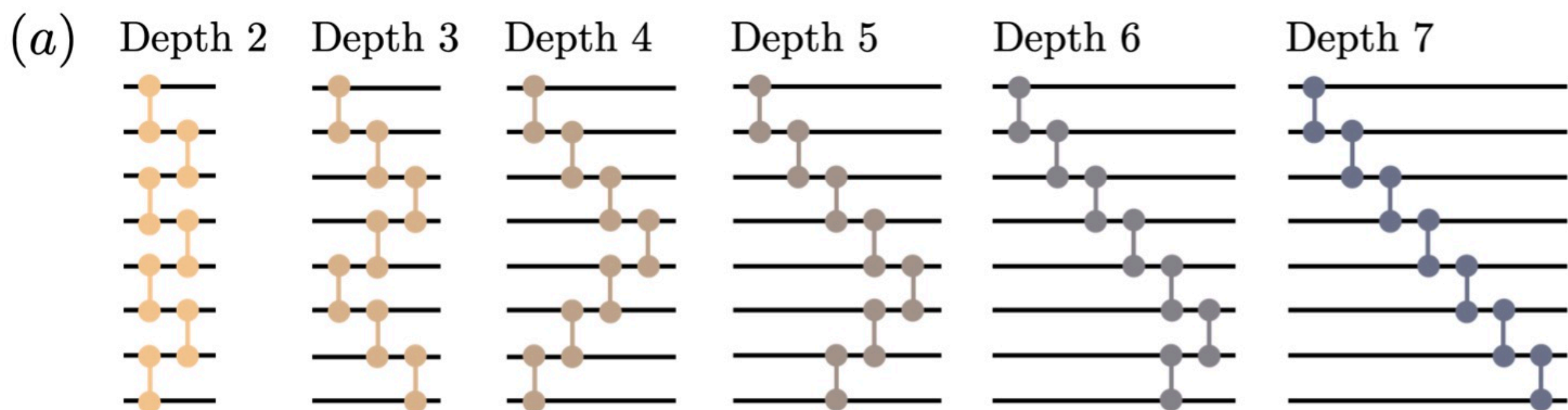
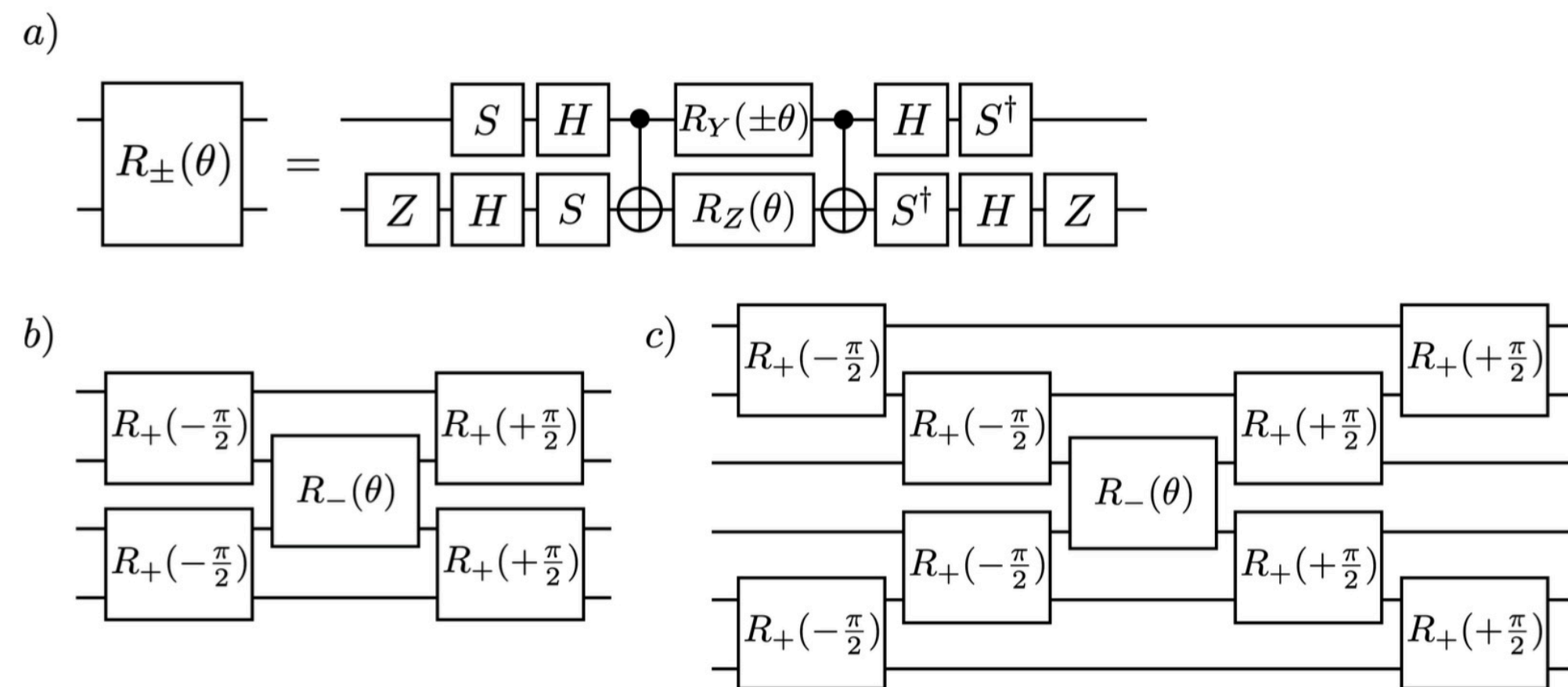
$$\hat{\Theta}_h^V(d) = \frac{1}{4} \sum_{n=0}^{2L-1-d} \left(\hat{X}_n \hat{Z}^{d-1} \hat{X}_{n+d} + \hat{Y}_n \hat{Z}^{d-1} \hat{Y}_{n+d} \right) ,$$

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

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



Scalable Operators: Circuits



(b)

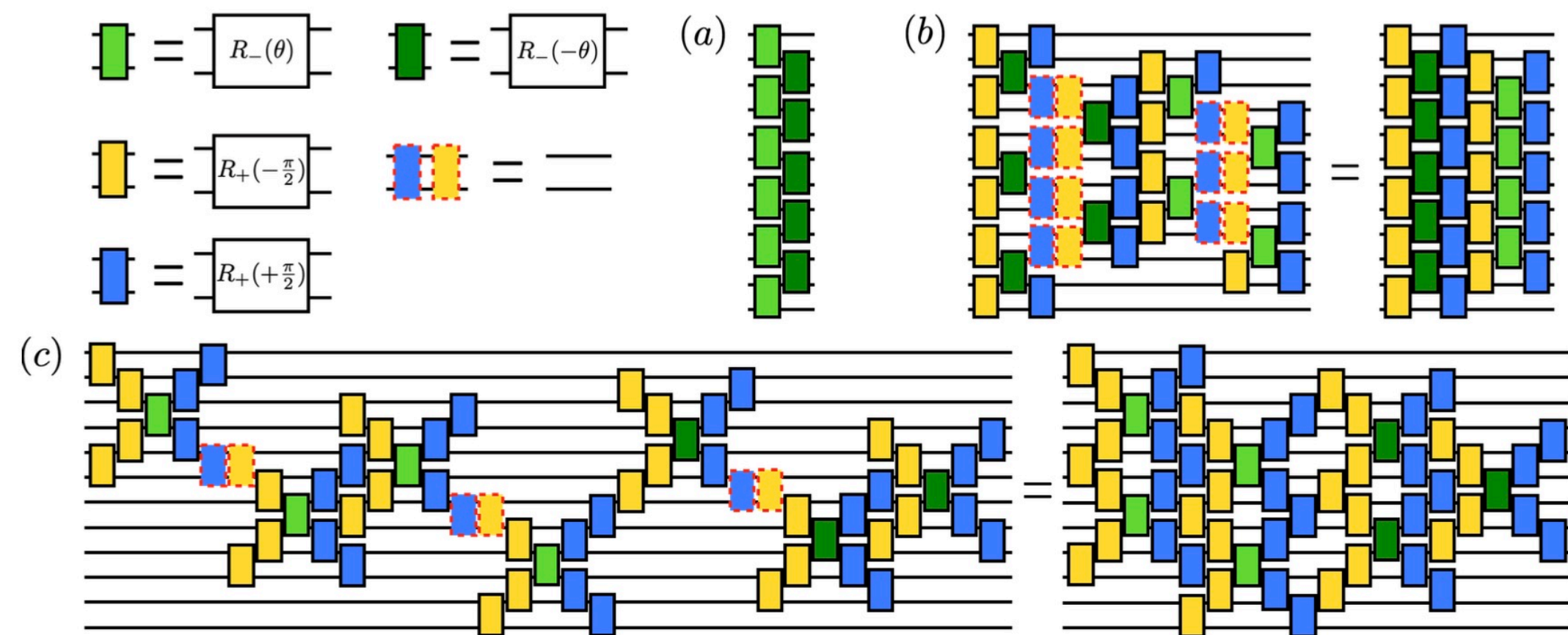
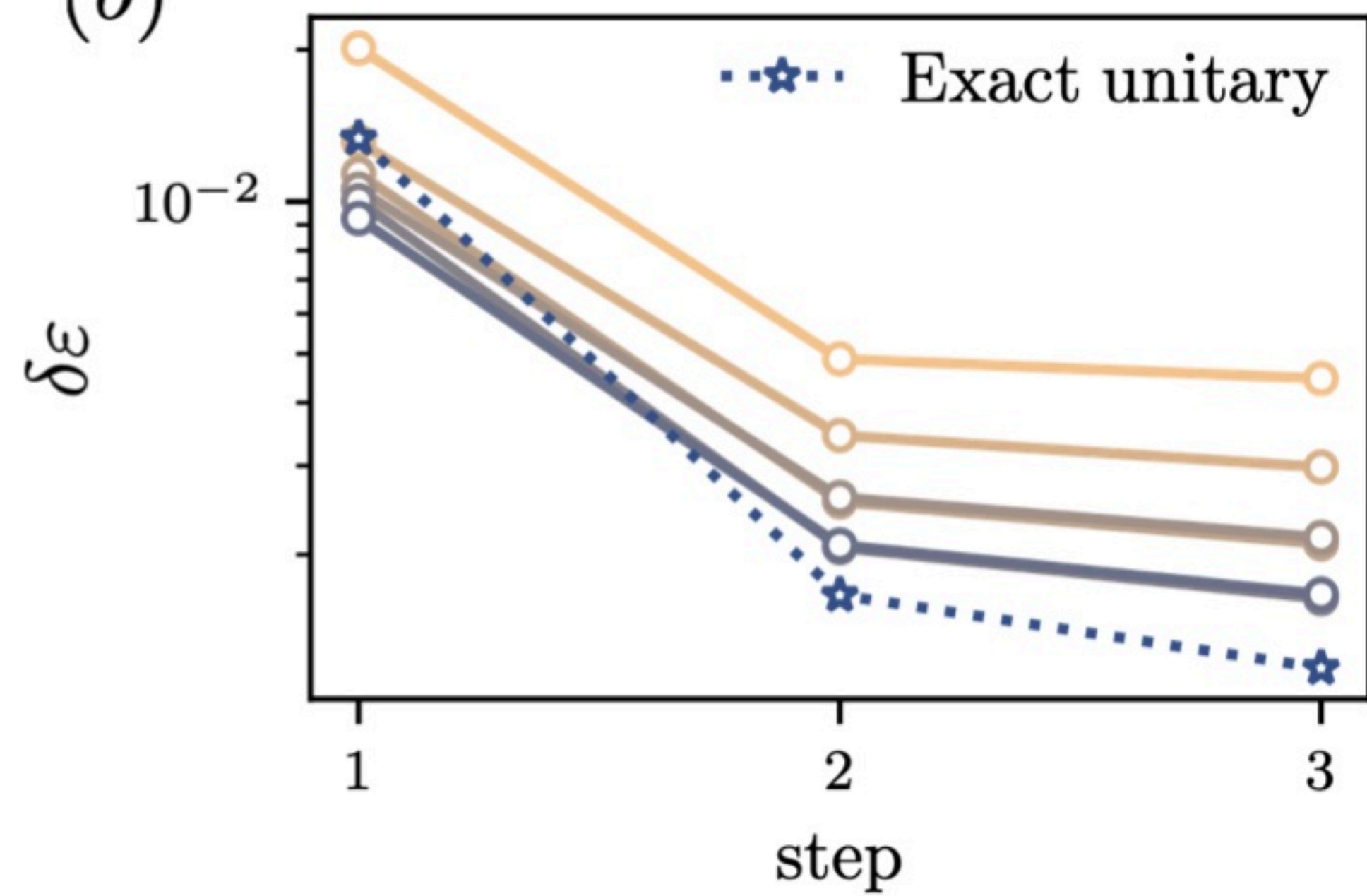
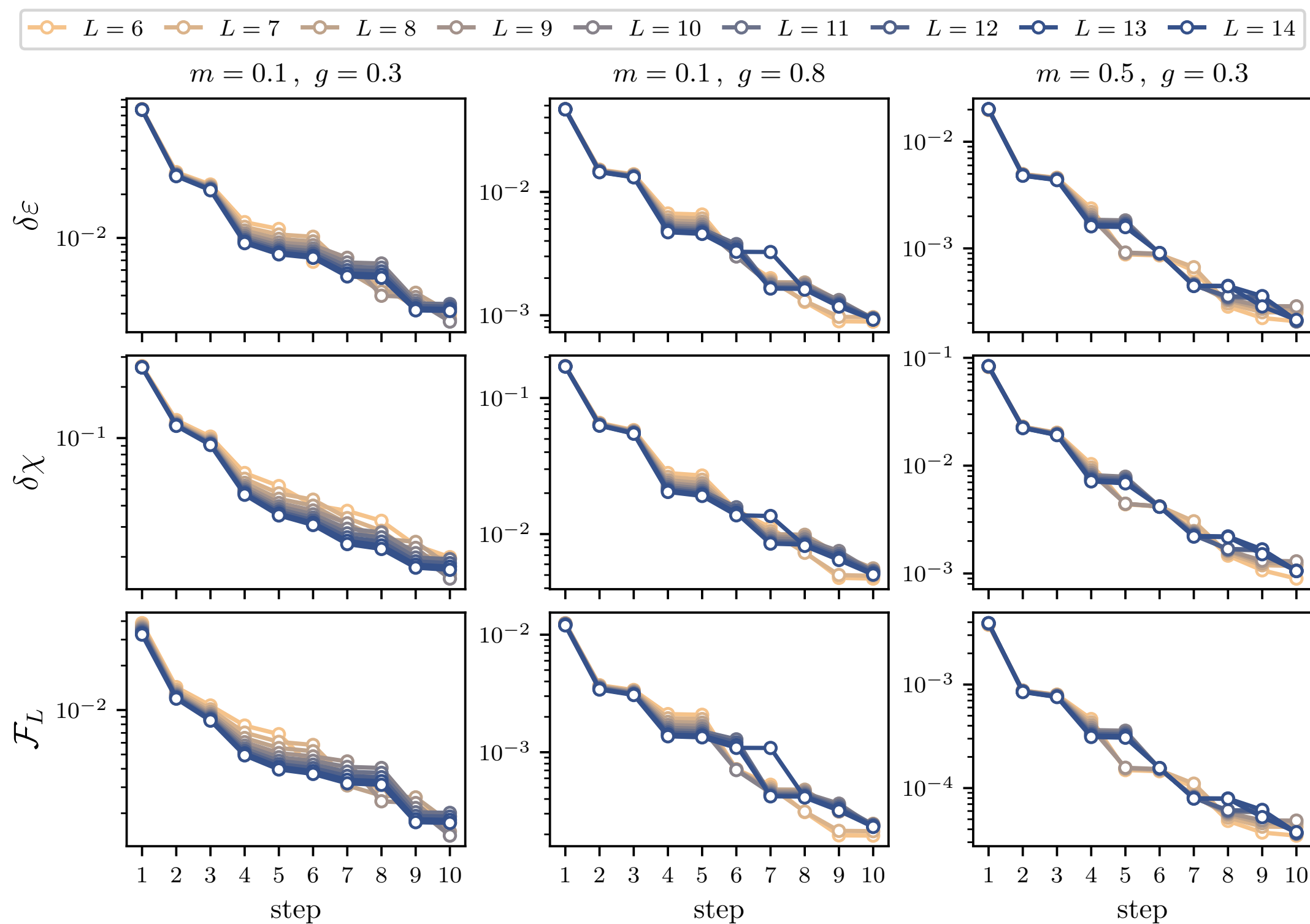
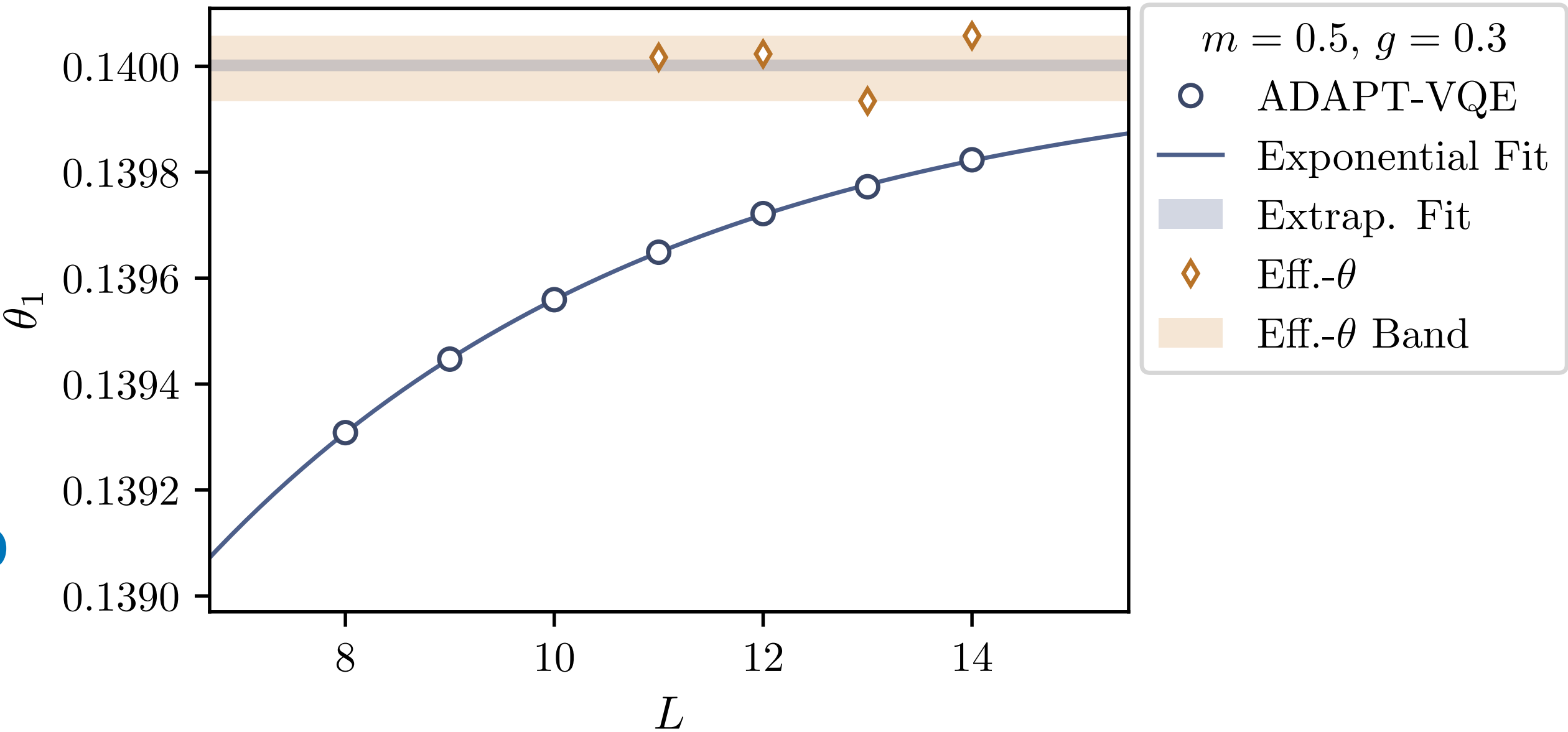


FIG. 4. Simplifications of quantum circuits for the Trotterized unitaries corresponding to (a) $\hat{O}_{mh}^V(1)$, (b) $\hat{O}_{mh}^V(3)$, and (c) $\hat{O}_{mh}^V(5)$ for $L = 6$, as explained in the main text. Cancellations between $R_{+}(\pm\frac{\pi}{2})$ are highlighted with red-dashed-outlined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

Scalable Operators: Convergence of Layers



$L \backslash \theta_i$	$\hat{O}_{mh}^V(1)$	$\hat{O}_{mh}^V(3)$	$\hat{O}_{mh}^V(5)$	$\hat{O}_{mh}^V(1)$	$\hat{O}_{mh}^V(7)$	$\hat{O}_{mh}^S(0,1)$	$\hat{O}_{mh}^V(7)$
6	0.18426	-0.03540	0.00731	0.11866	—	0.06895	-0.00182
7	0.18440	-0.03574	0.00729	0.11864	—	0.06867	-0.00177
8	0.13931	-0.03727	0.00760	0.08870	—	0.06925	-0.00183
9	0.13945	-0.03714	0.00755	0.08849	—	0.06904	-0.00180
10	0.13956	-0.03703	0.00752	0.08832	-0.00178	0.06888	—
11	0.13965	-0.03695	0.00749	0.08819	-0.00177	0.06875	—
12	0.13972	-0.03688	0.00747	0.08808	-0.00176	0.06865	—
13	0.13977	-0.03683	0.00745	0.08800	-0.00175	0.06856	—
14	0.13982	-0.03678	0.00744	0.08793	-0.00174	0.06849	—
∞	0.1400	-0.0366	0.0074	0.0877	-0.0017	0.0682	—



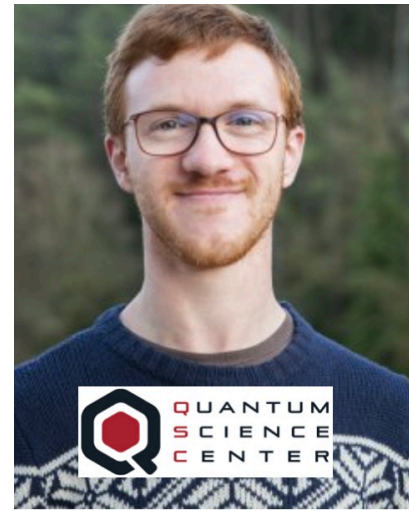
Global Optimization of parameters at each step

Vacuum and Wavepacket Preparation and Evolution of U(1) Theory in 1+1D

IBM Quantum



Roland Farrell



Marc Illa



Anthony Ciavarella

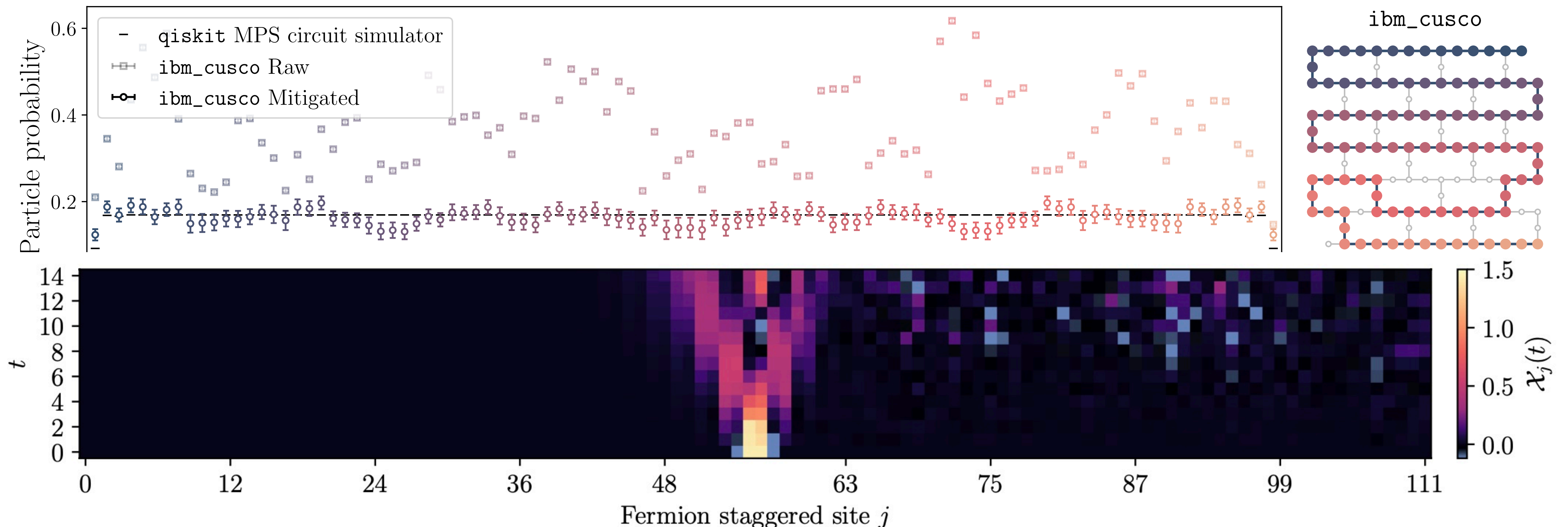
Scalable Circuits for Preparing Ground States on Digital Quantum Computers: The Schwinger Model Vacuum on 100 Qubits

Roland C. Farrell, Marc Illa, Anthony N. Ciavarella, and Martin J. Savage
PRX Quantum **5**, 020315 – Published 18 April 2024

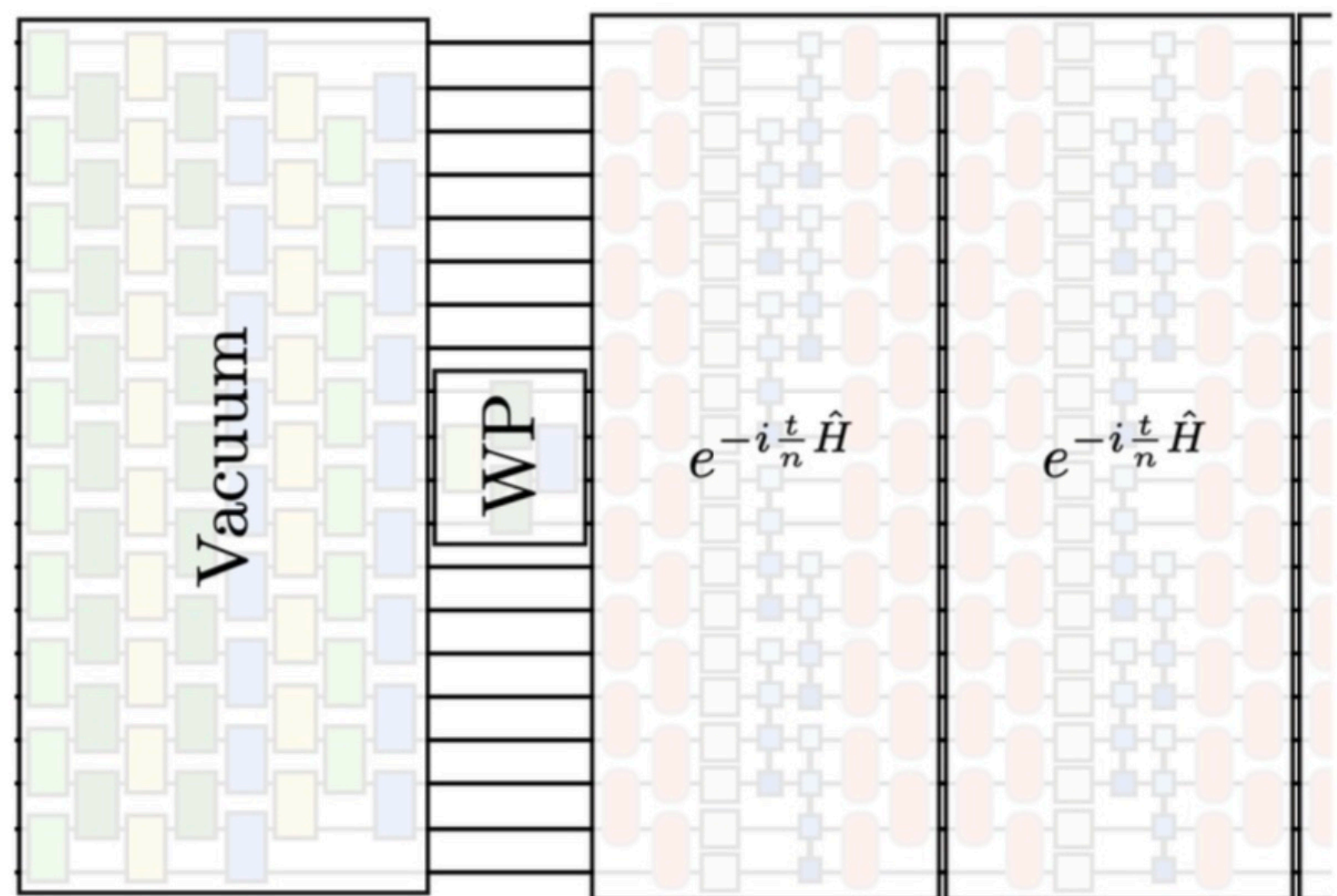
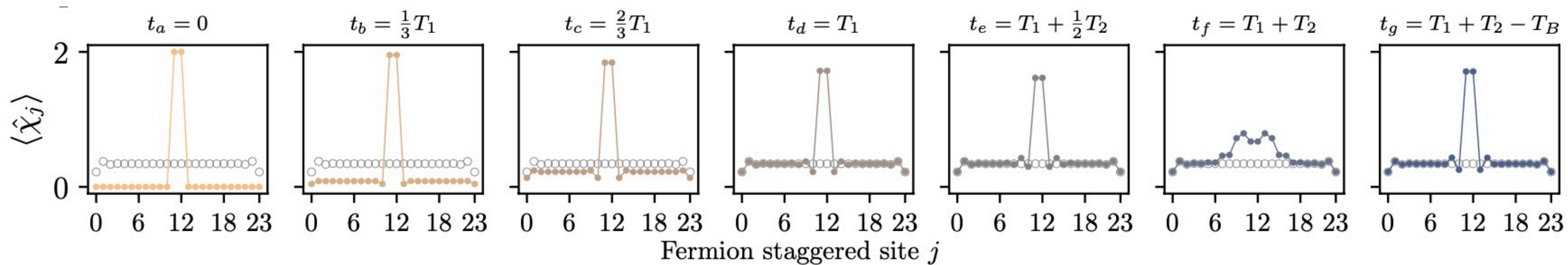
Quantum simulations of hadron dynamics in the Schwinger model using 112 qubits

Roland C. Farrell, Marc Illa, Anthony N. Ciavarella, and Martin J. Savage
Phys. Rev. D **109**, 114510 – Published 10 June 2024

Beams/Pulses of Hadrons



The Vacuum and Wavepackets



$$e^{i\theta\hat{O}_{mh}(1,1)} = \boxed{} = \boxed{}$$

$$e^{i\theta\hat{O}_{mh}(2,2)} = \boxed{} \boxed{} = \boxed{} \boxed{} \boxed{} \boxed{} = \boxed{} \boxed{}$$

$$\begin{aligned} \boxed{} &= R_-^{(XY)}(+\theta) \\ \boxed{} &= R_+^{(XY)}(-\theta) \\ \boxed{} &= R_+^{(XY)}(-\frac{\pi}{2}) \\ \boxed{} \boxed{} &= \text{---} \\ \boxed{} &= R_+^{(XY)}(+\frac{\pi}{2}) \end{aligned}$$

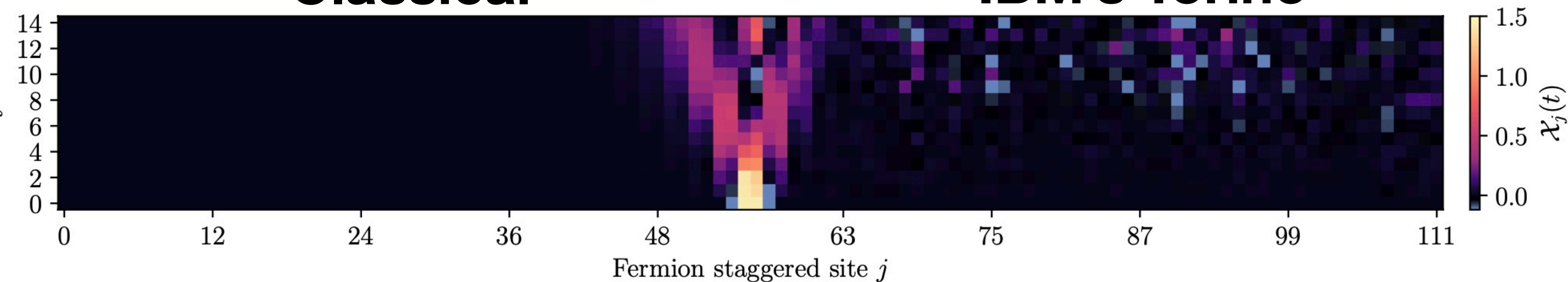
Production using IBM's Heron Processor Torino

Production Highlights

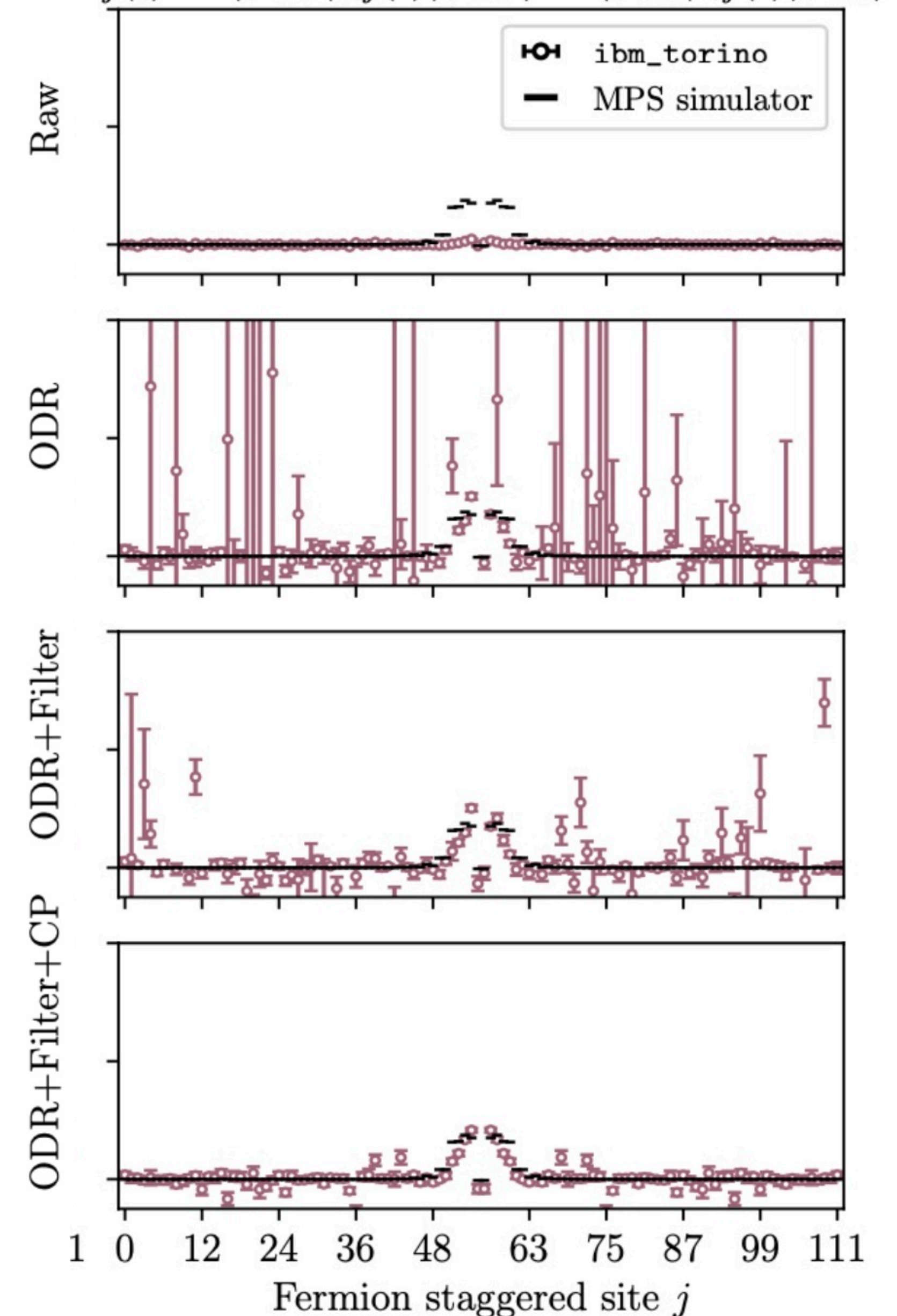
- 14K CNOTs for 14 Trotter steps
- 1.05 Trillion total CNOTs applied
- 154 Million shots
- 112 qubits x 370 depth

Classical

IBM's Torino



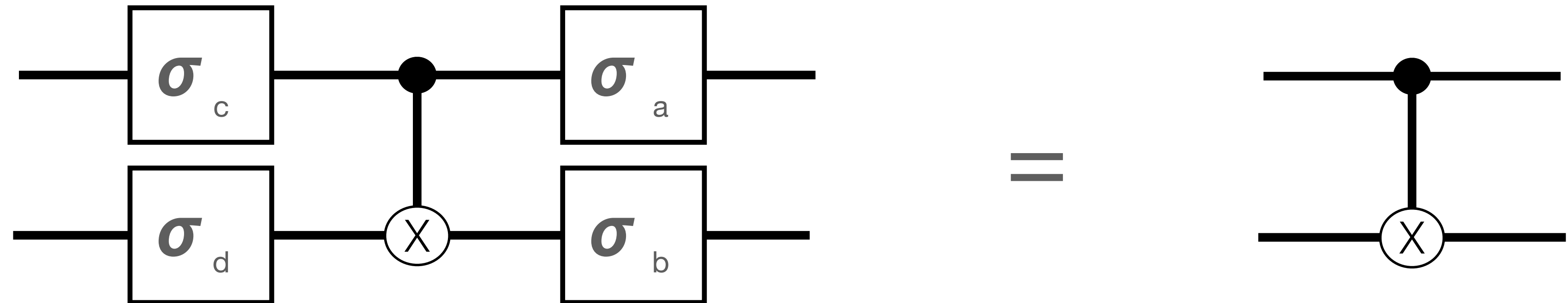
$$\chi_j(t) = \langle \psi_{\text{WP}} | \hat{\chi}_j(t) | \psi_{\text{WP}} \rangle - \langle \psi_{\text{vac}} | \hat{\chi}_j(t) | \psi_{\text{vac}} \rangle$$



Error Mitigation - NISQ-Life

IBM

Pauli-Twirling



Coherent errors from the control and target transformed to incoherent, averaged over all channels

Mitigating depolarizing noise on quantum computers with noise-estimation circuits

Miroslav Urbanek,^{1,*} Benjamin Nachman,² Vincent R. Pascuzzi,²
Andre He,^{2,†} Christian W. Bauer,² and Wibe A. de Jong^{1,‡}

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 18, 2022)

Post-Selection

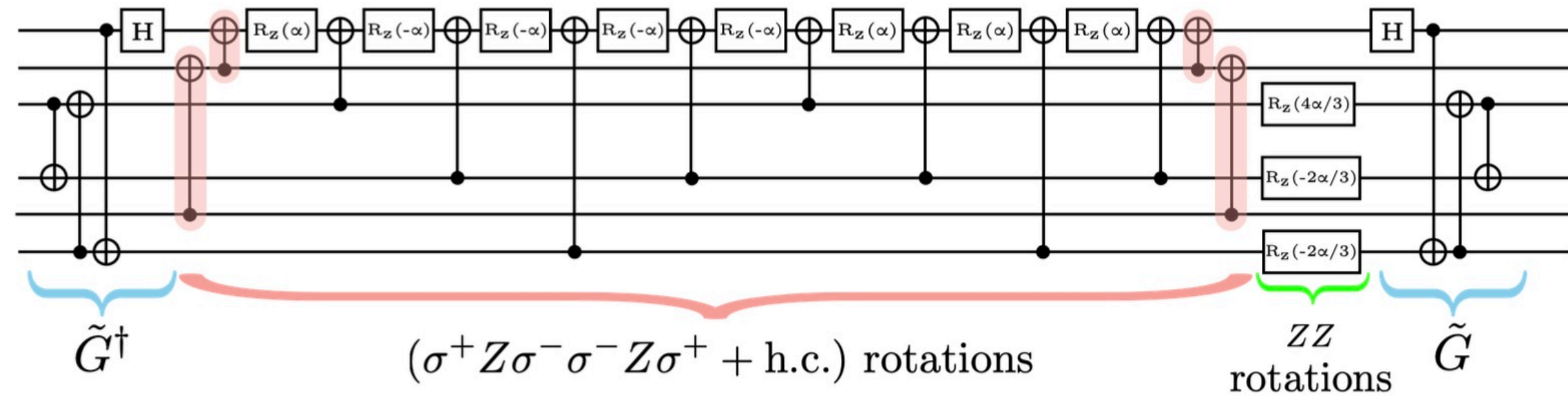
Device Hilbert space $\ggg$ Physical Hilbert space

Select only members of measurement ensemble entirely in Physical space

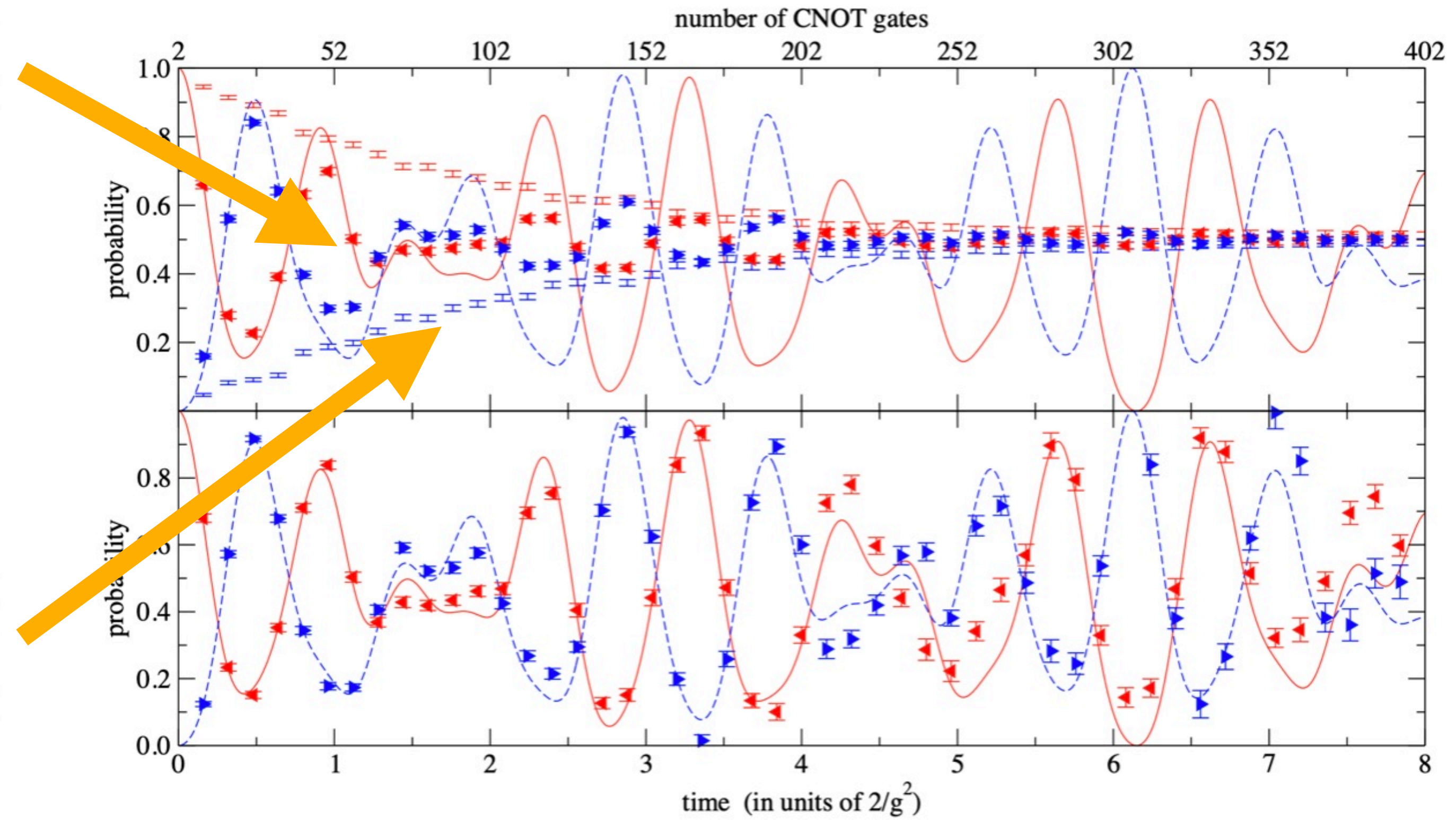
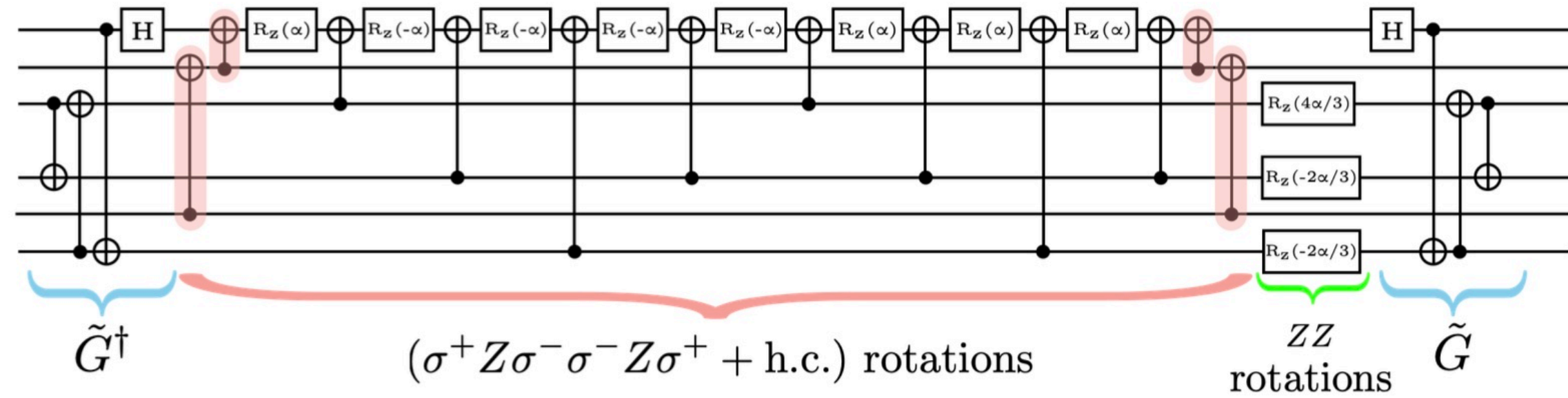
Eliminates order-p errors.

Error Mitigation - Decoherence Renormalization

“Physics circuit”

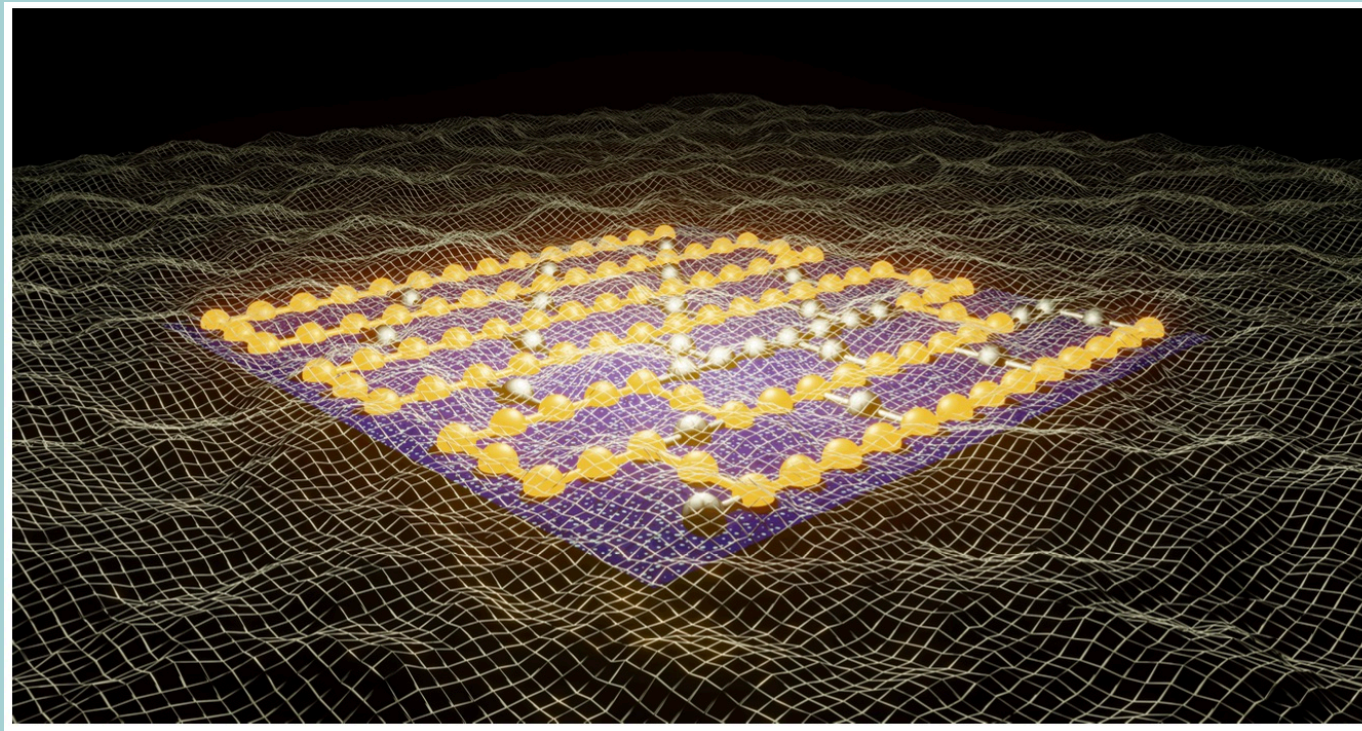


“Mitigation circuit”
- all angles set to zero (e.g.)



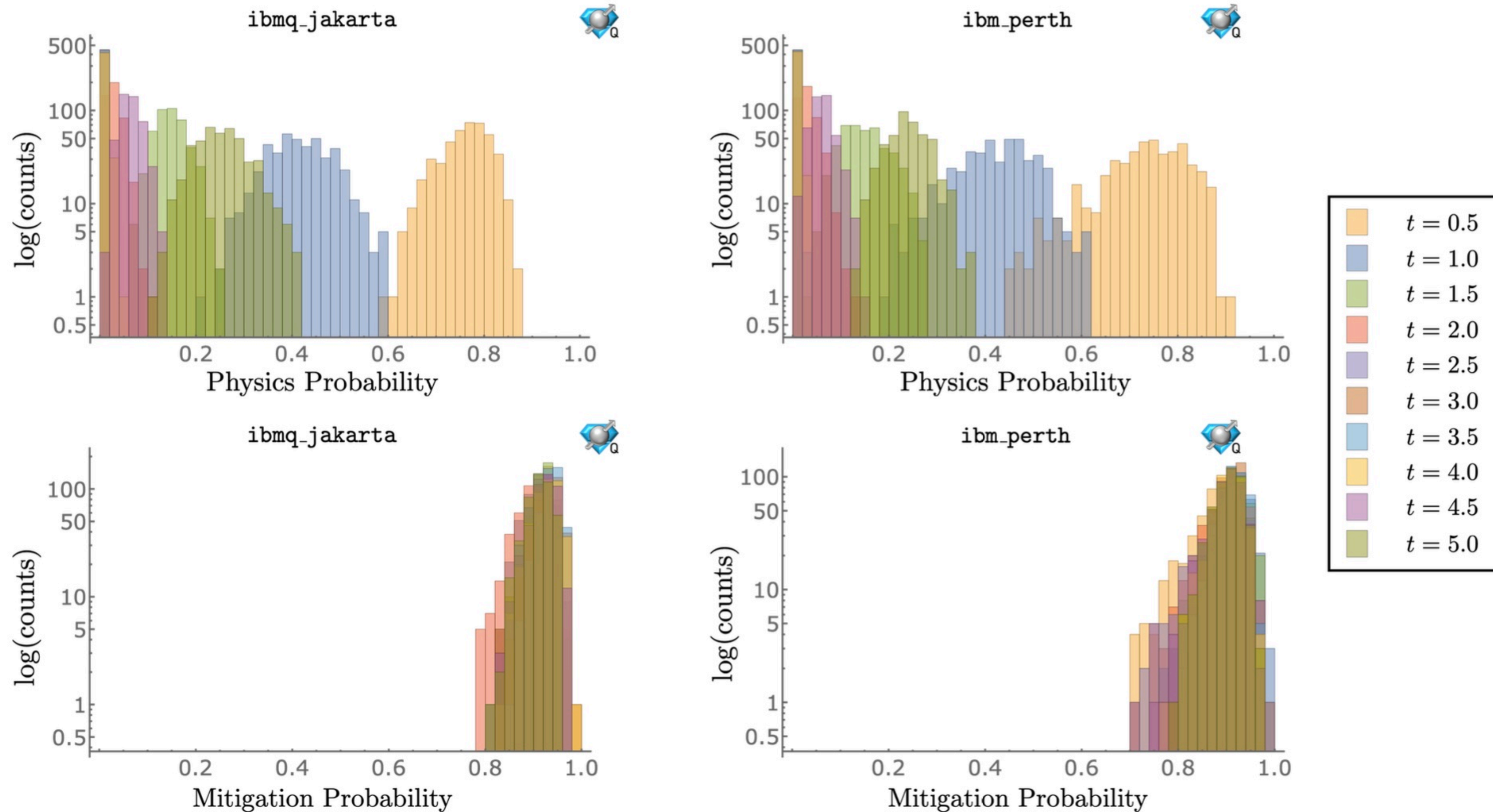
Part-3

Quantum Computing and Simulation



End of Day-2

Error Mitigation - Pauli Twirling



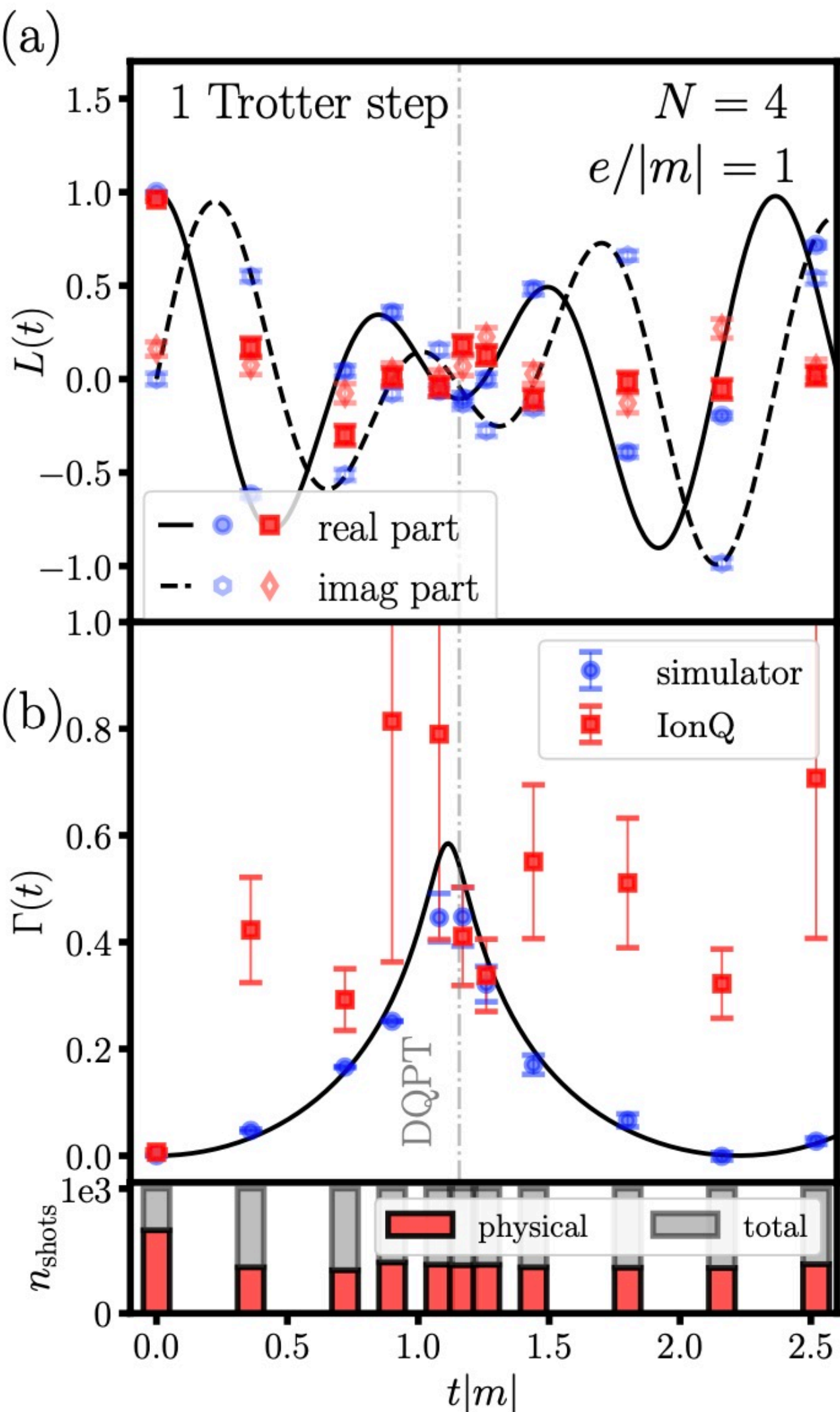
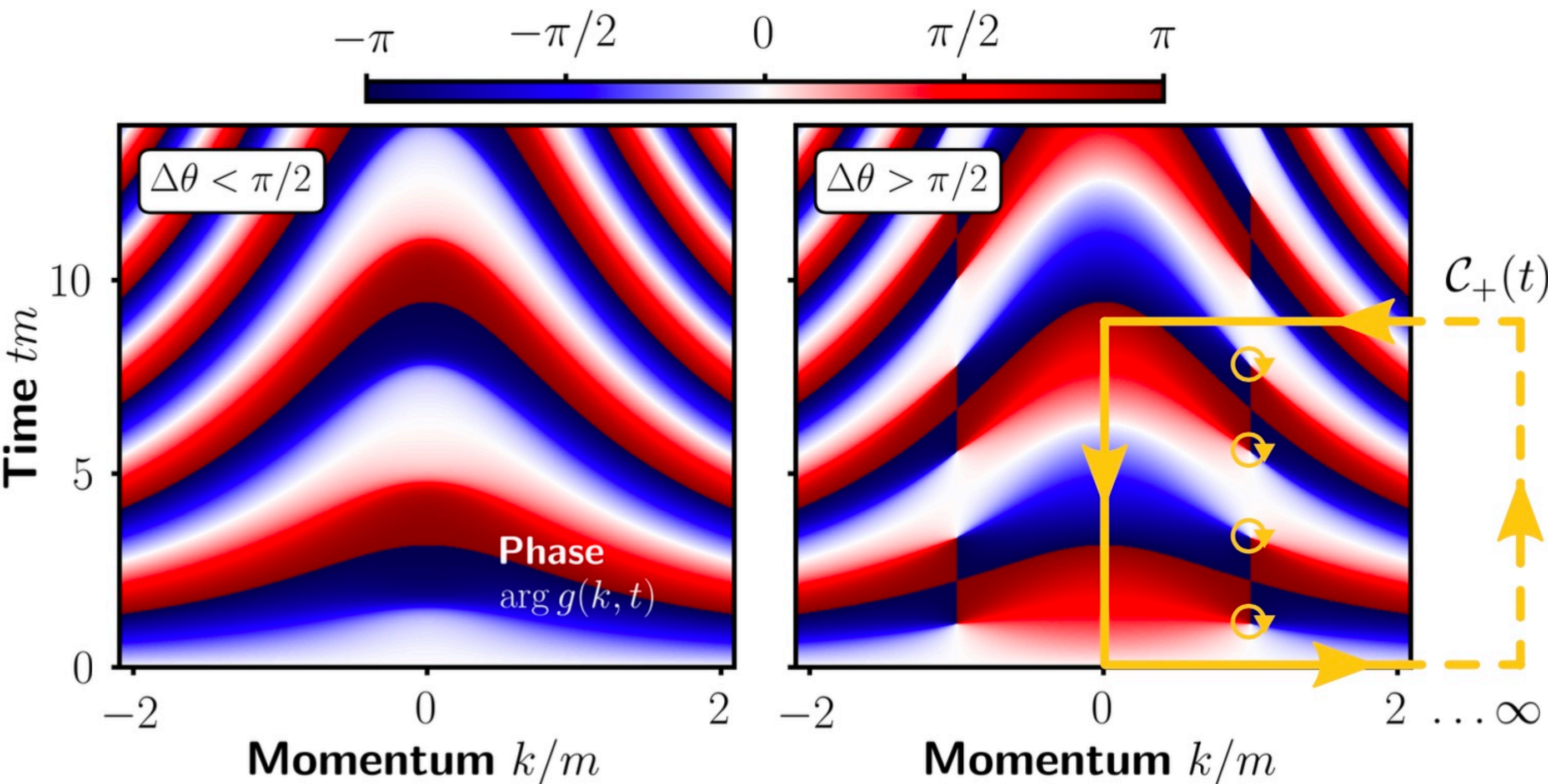
Dynamical Quantum Phase Transitions

Dynamical topological transitions in the massive Schwinger model with a θ -term

T. V. Zache,^{1,*} N. Mueller,² J. T. Schneider,¹ F. Jendrzejewski,³ J. Berges,¹ and P. Hauke^{1,3}

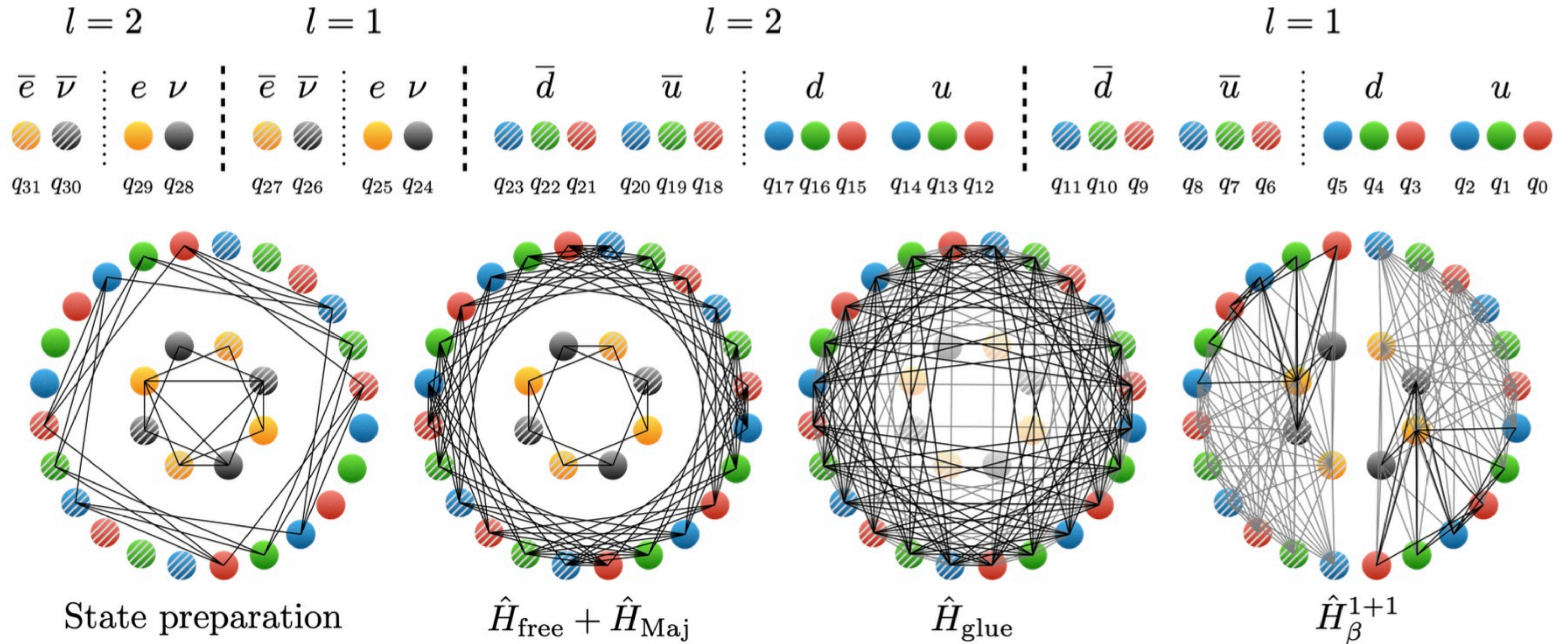
Quantum computation of dynamical quantum phase transitions and entanglement tomography in a lattice gauge theory

Niklas Mueller,^{1,2,3,*} Joseph A. Carolan,⁴ Andrew Connelly,⁵
Zohreh Davoudi,^{1,6,†} Eugene F. Dumitrescu,^{7,‡} and Kübra Yeter-Aydeniz⁸



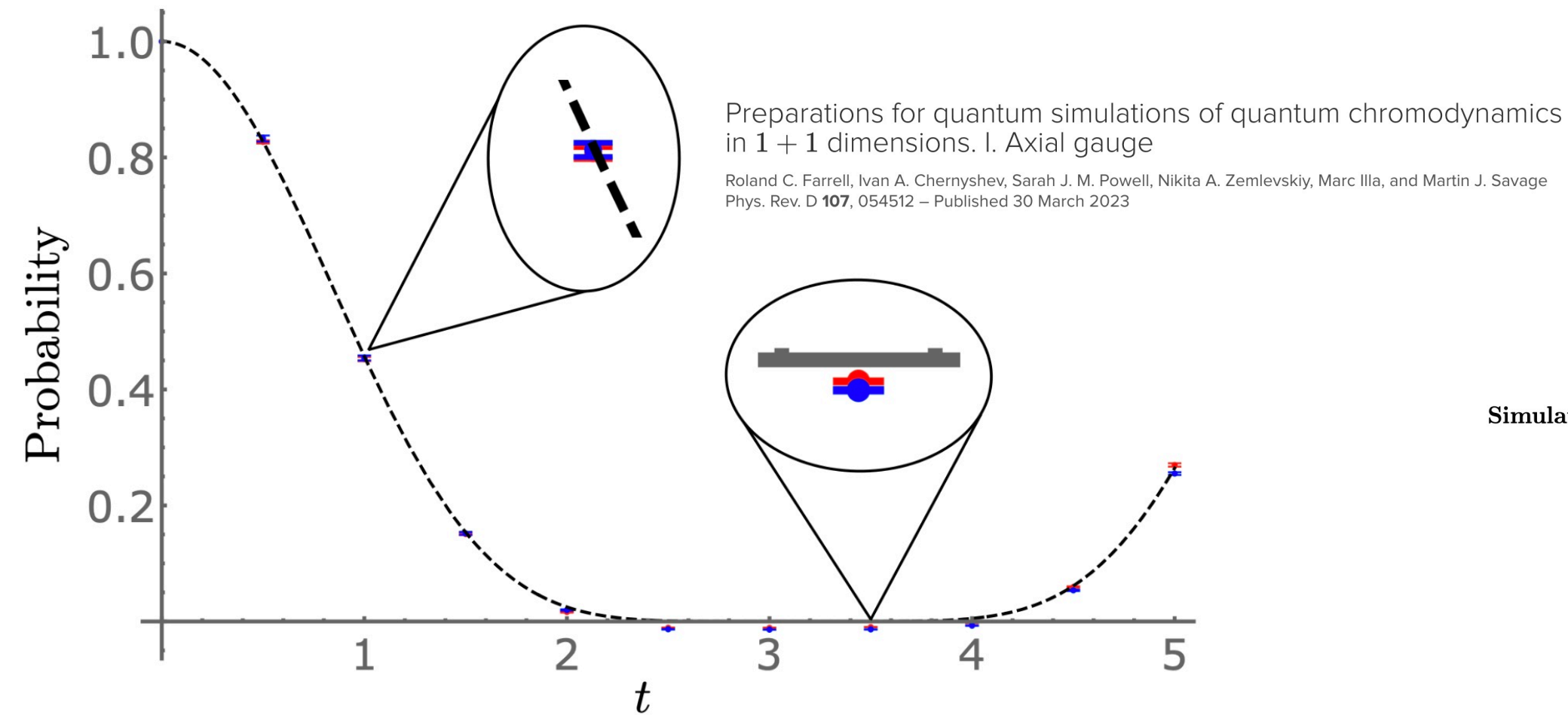
1+1D SU(N) and Quantum Chromodynamics

8



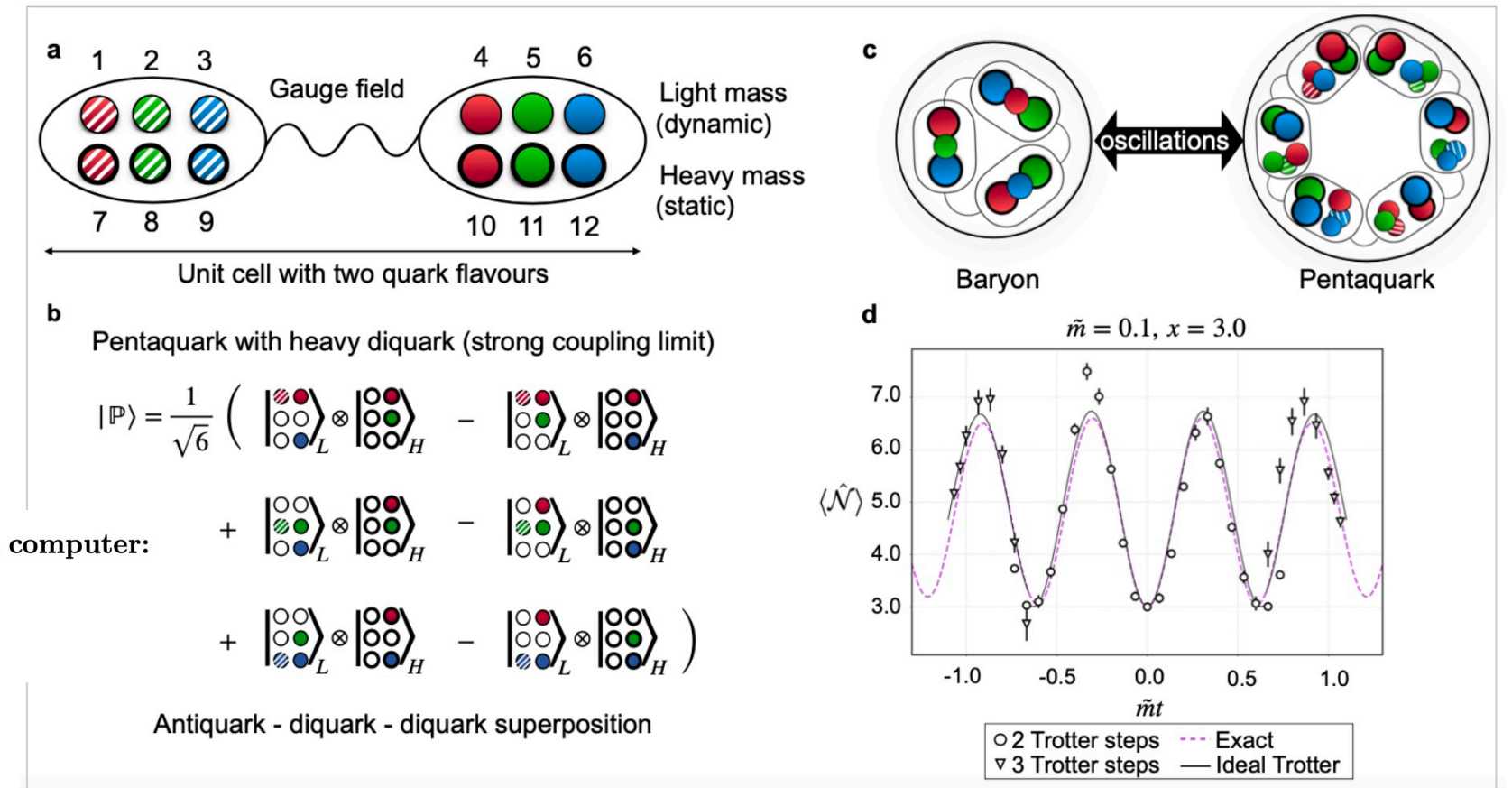
1+1D QCD and Decays

Trivial Vacuum-to-Vacuum

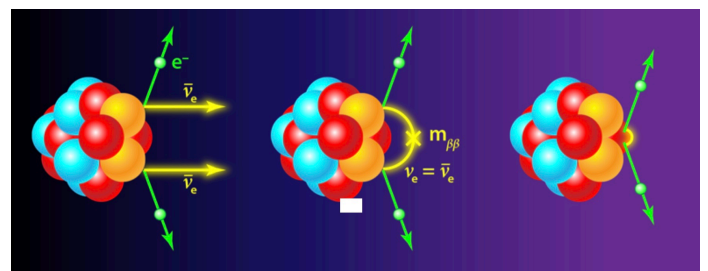
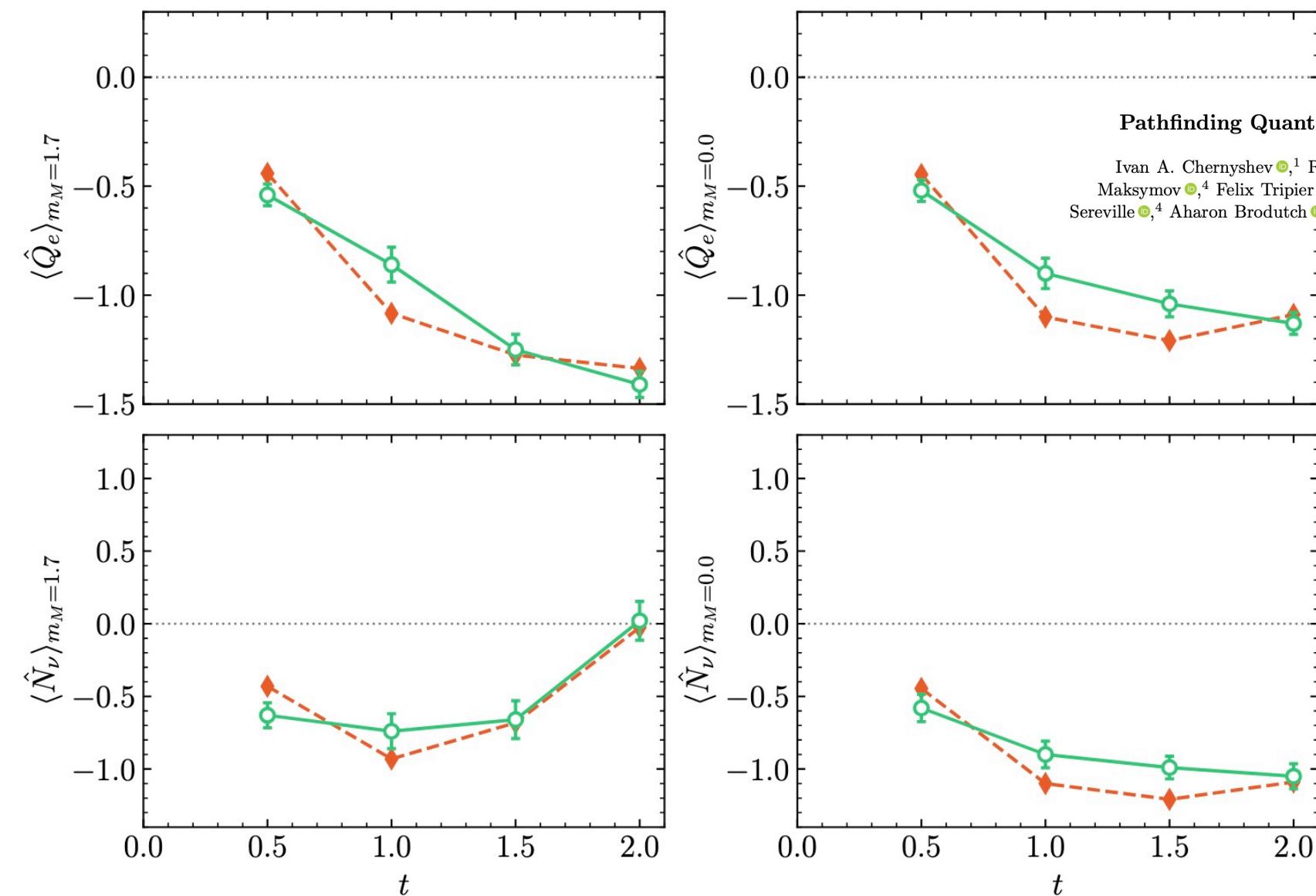
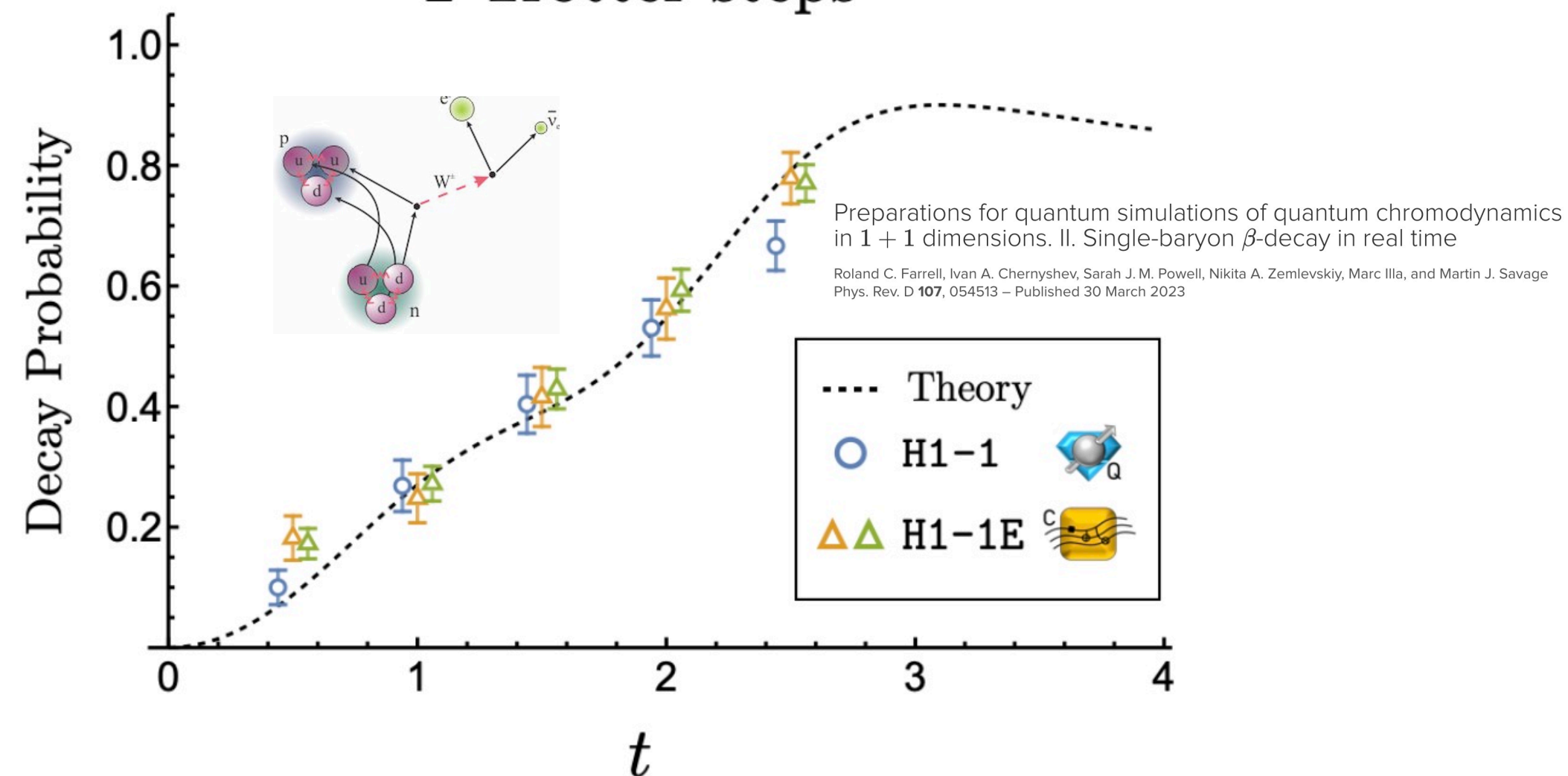


Simulating one-dimensional quantum chromodynamics on a quantum computer: Real-time evolutions of tetra- and pentaquarks

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}

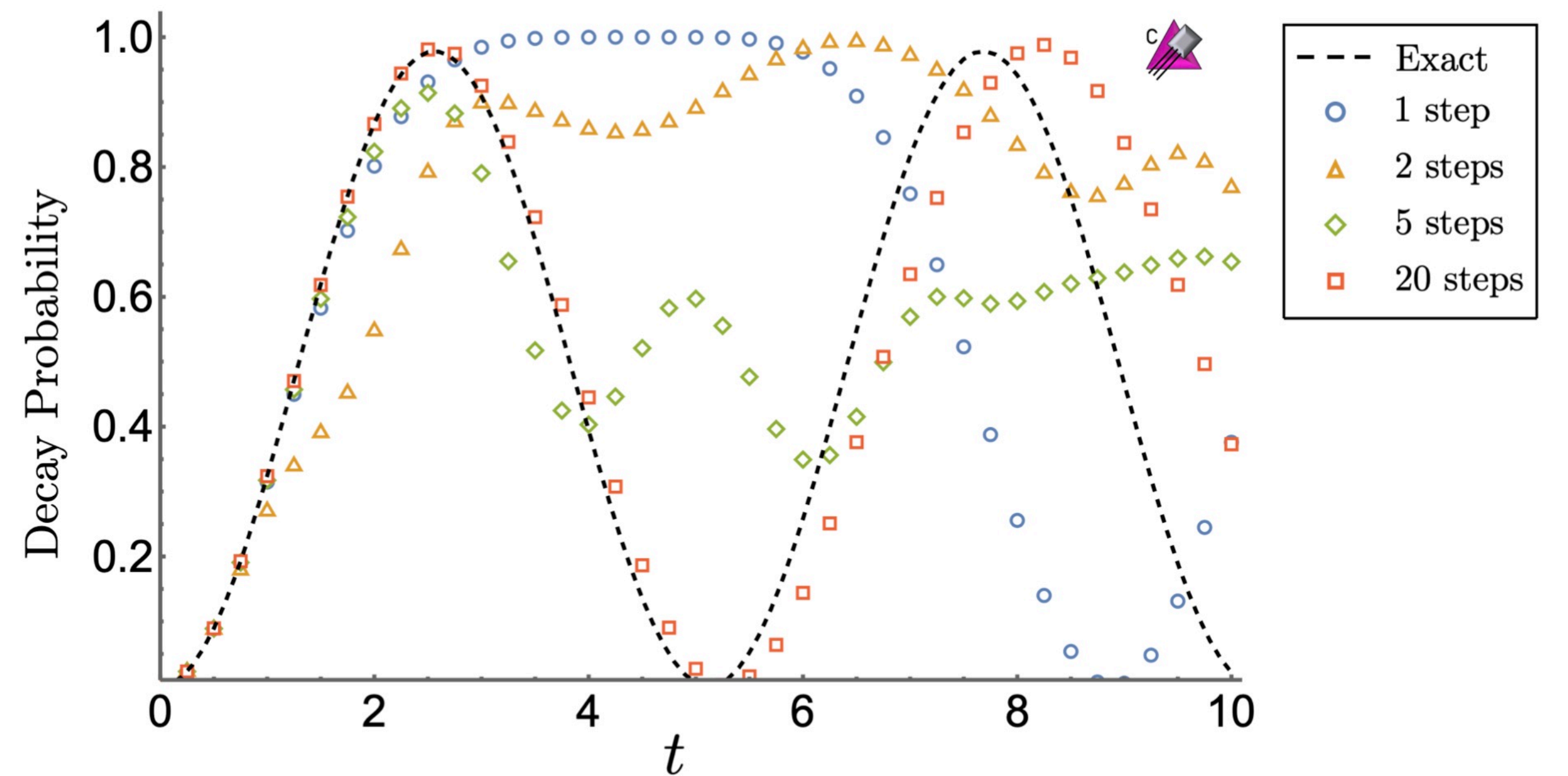


2 Trotter steps

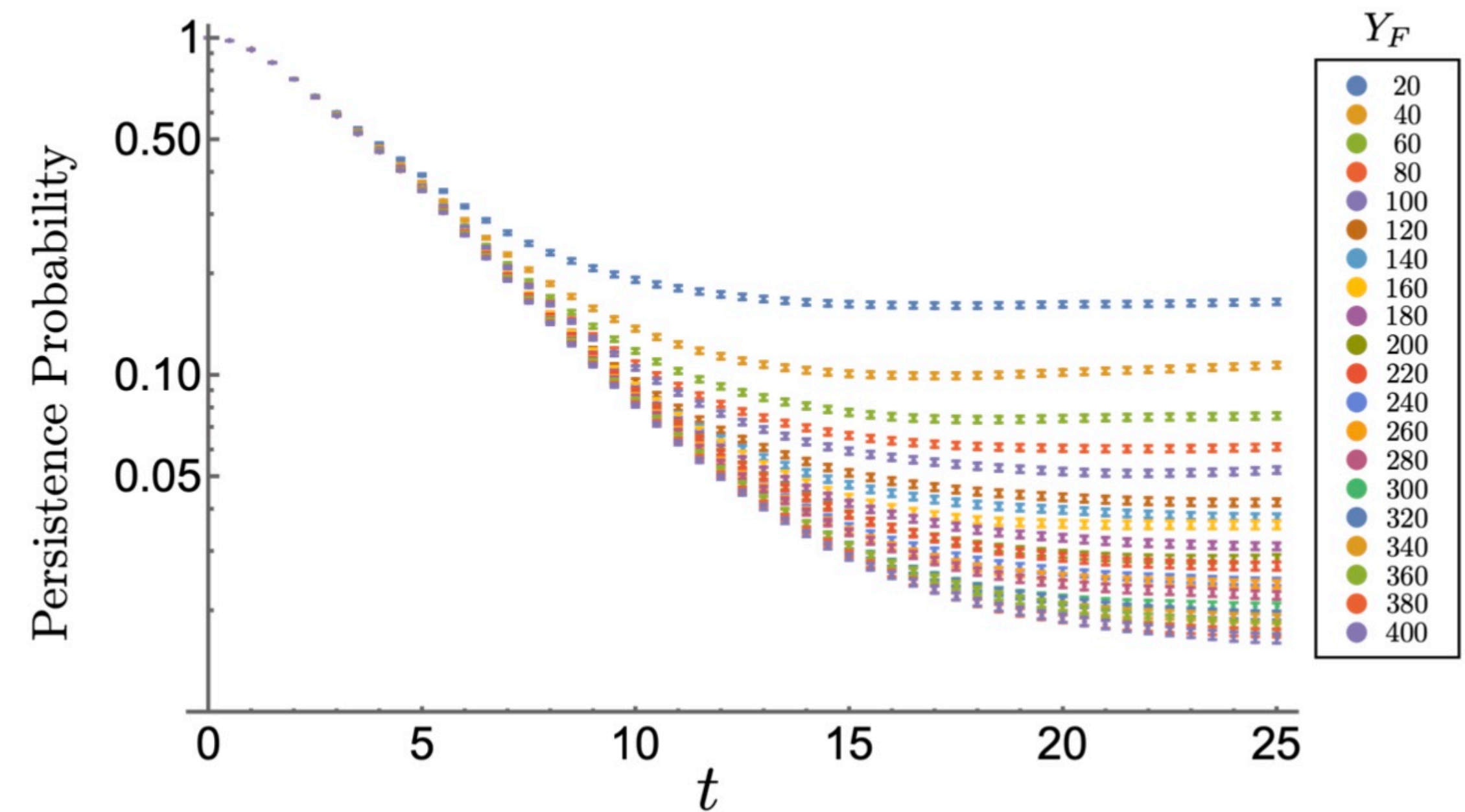


Weak Decays : Expectations

—Recovering Real-time Exponential-Decay



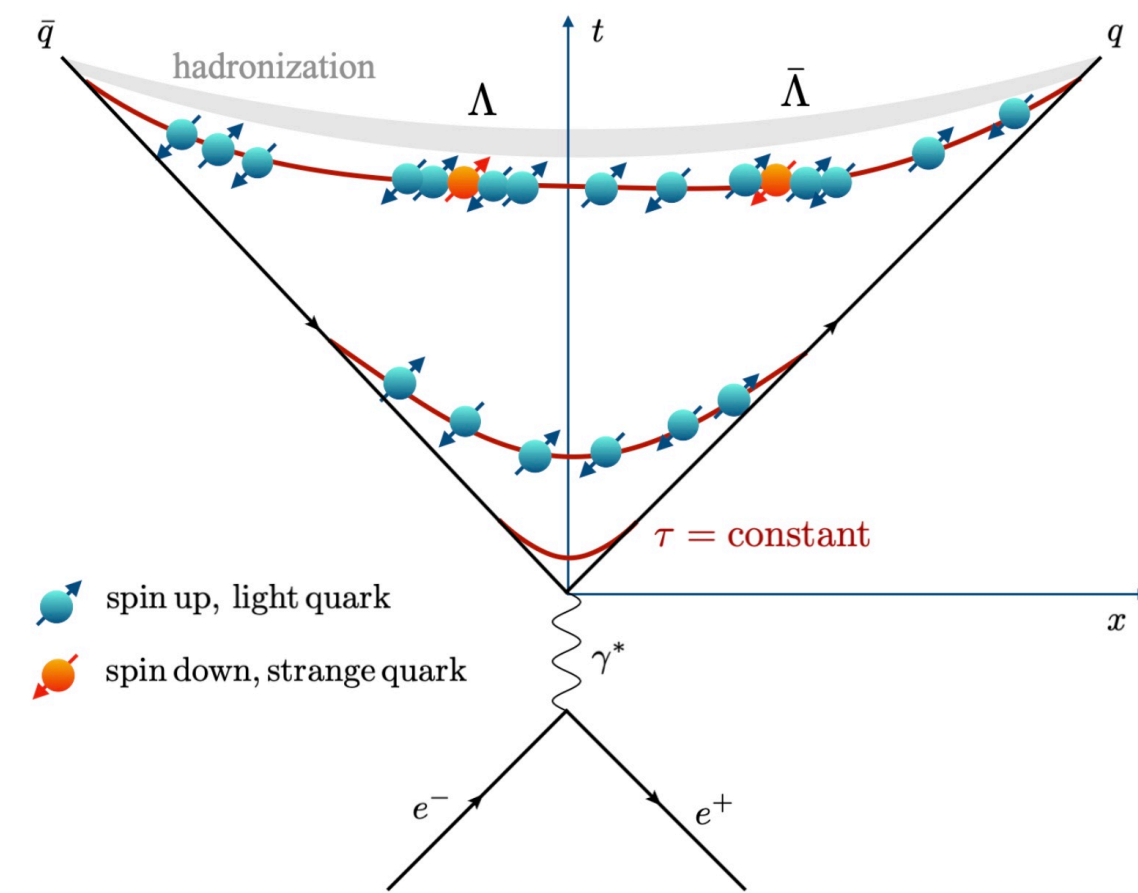
One available final state



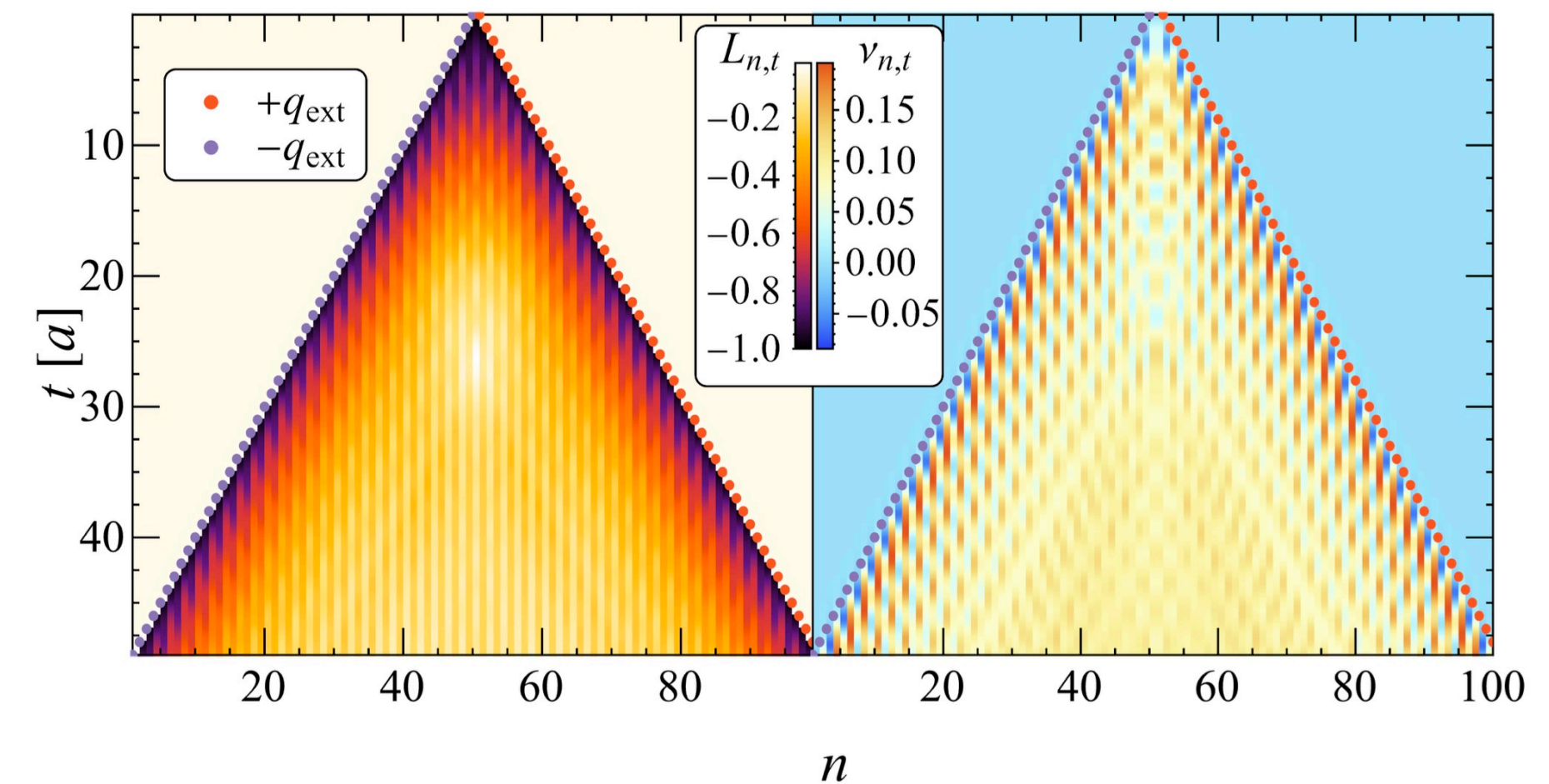
Y_F available final states

Hadronization and Fragmentation

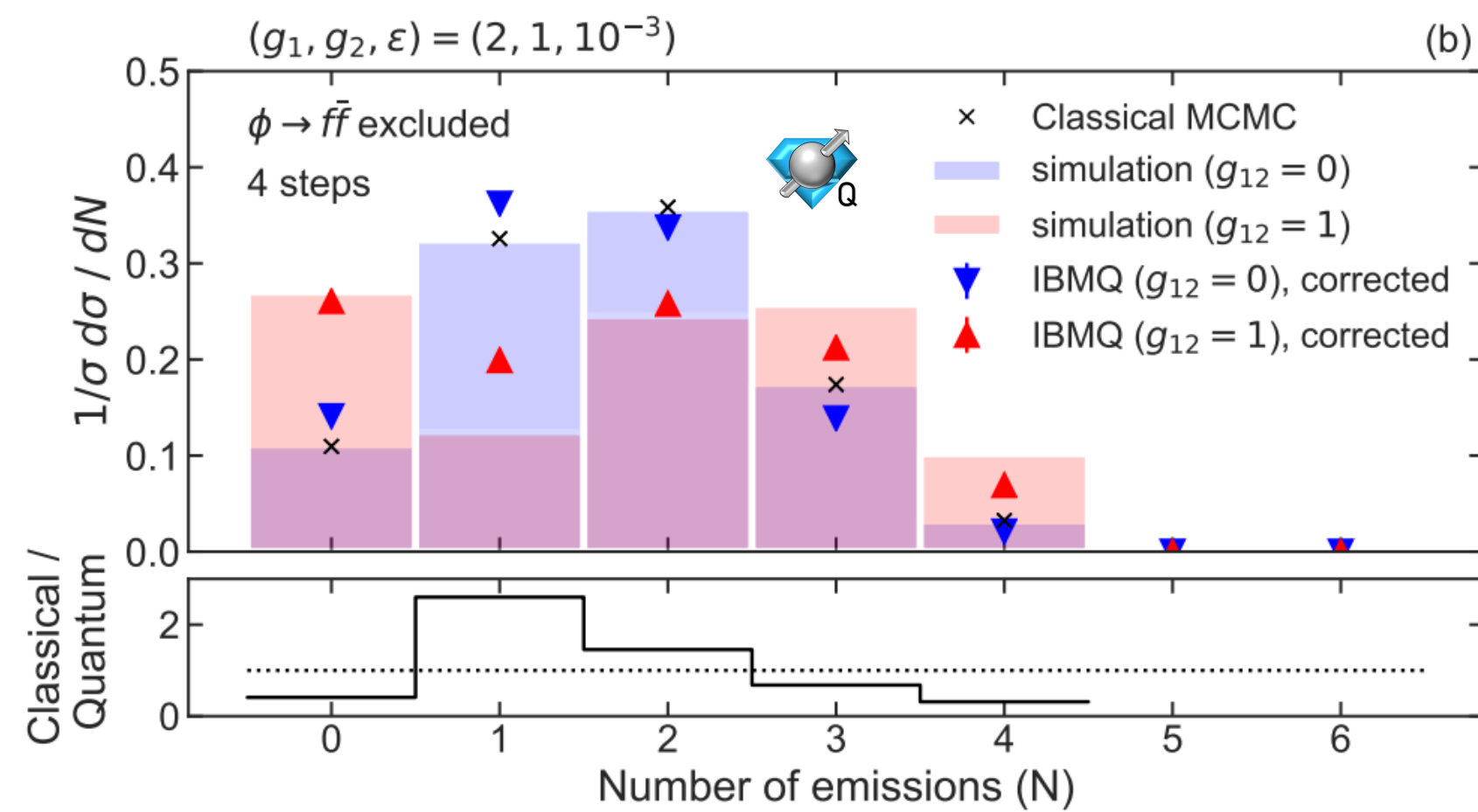
Baryon Entanglement, Barata *et al*, Gong *et al*



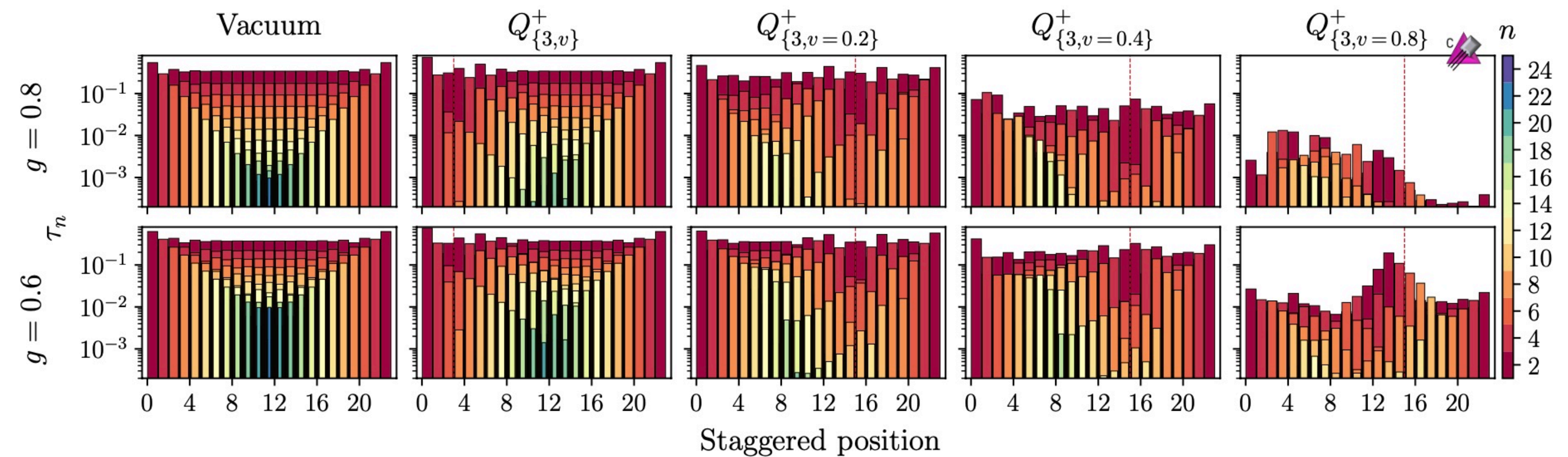
Hadronization, Florio *et al*



Fragmentation, Bauer *et al*

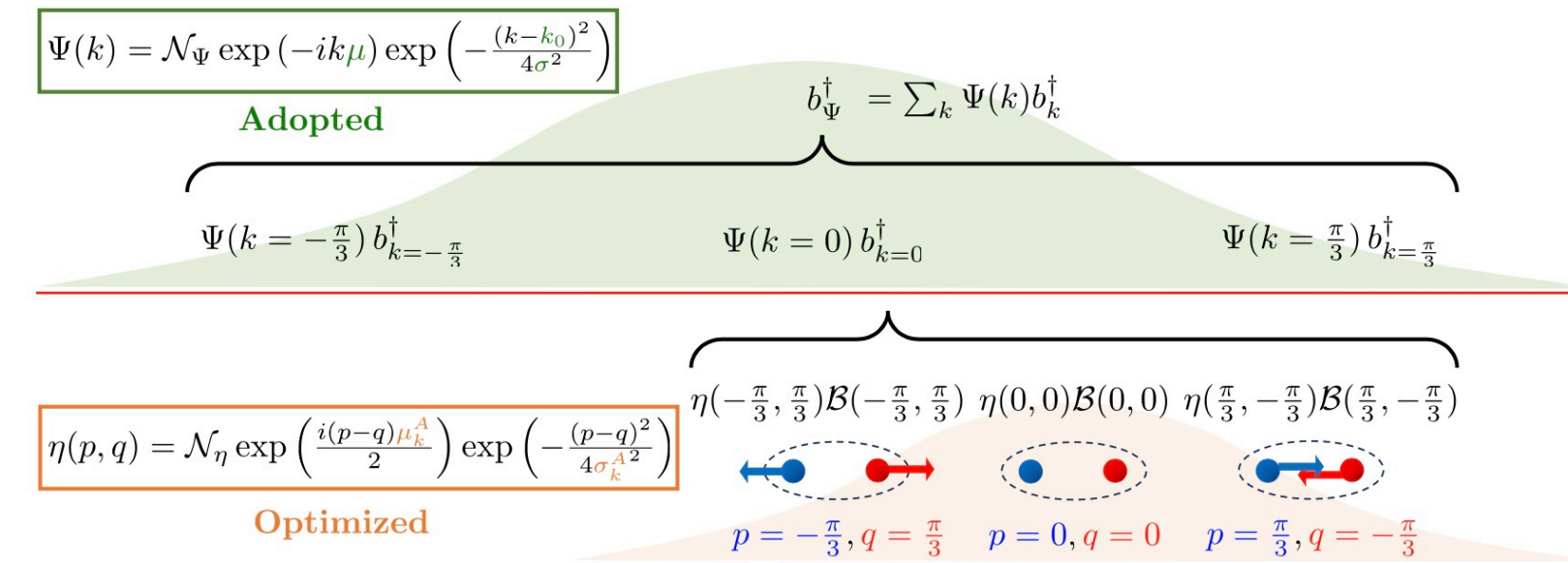
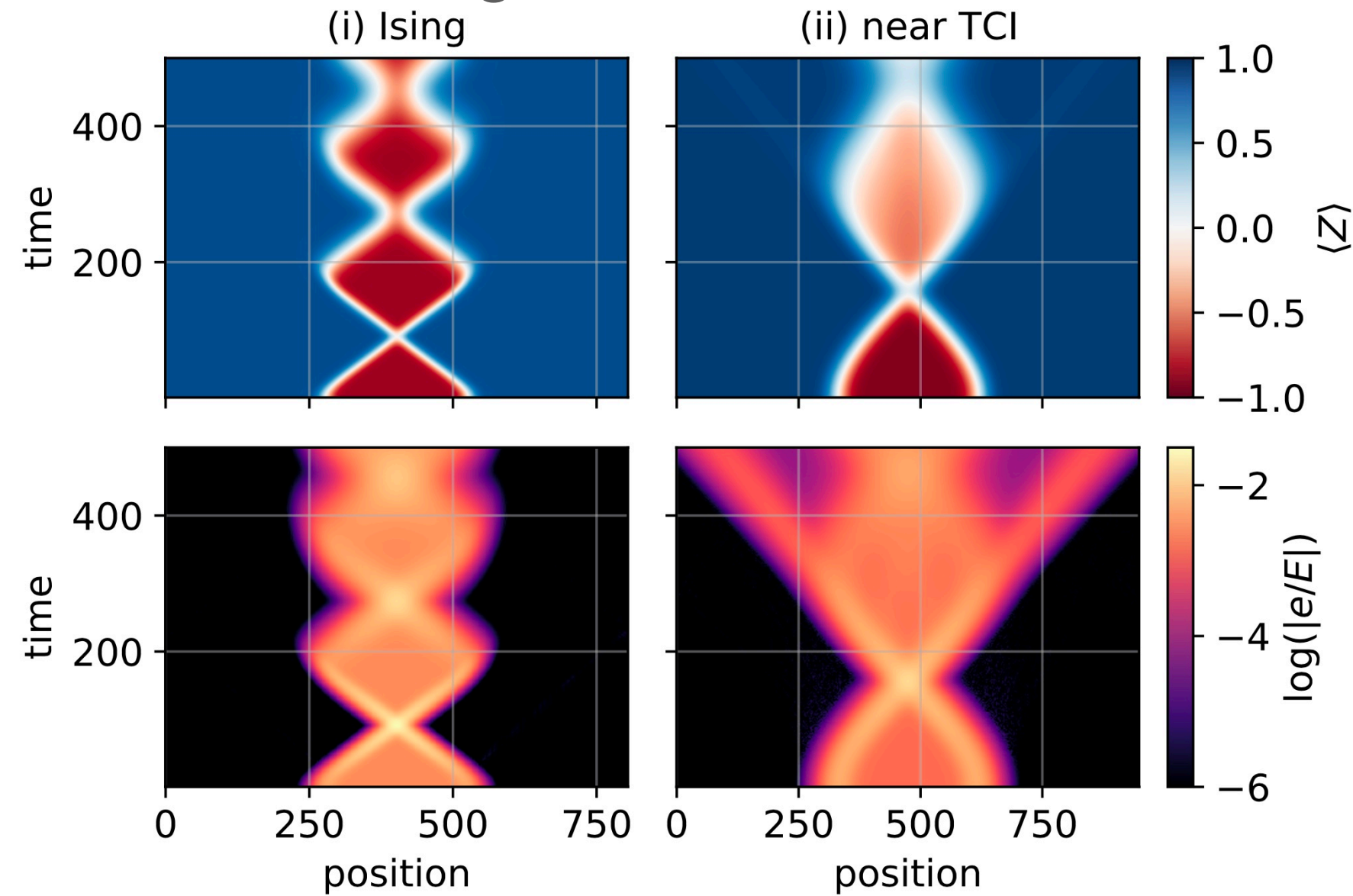


Energy Loss and Multi-partite Entanglement, Farrell *et al*



1+1D Preparing for the Future

Ising+ , Milsted et al



Wavepackets ,
Davoudi et al

Thirring model , Chai et al

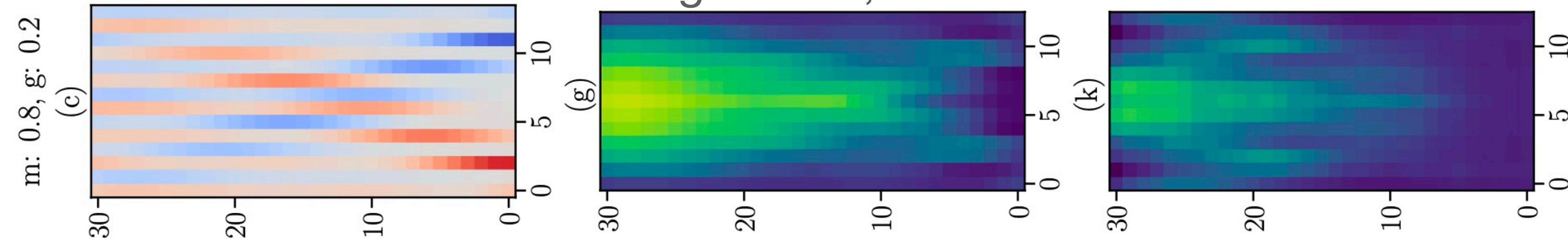
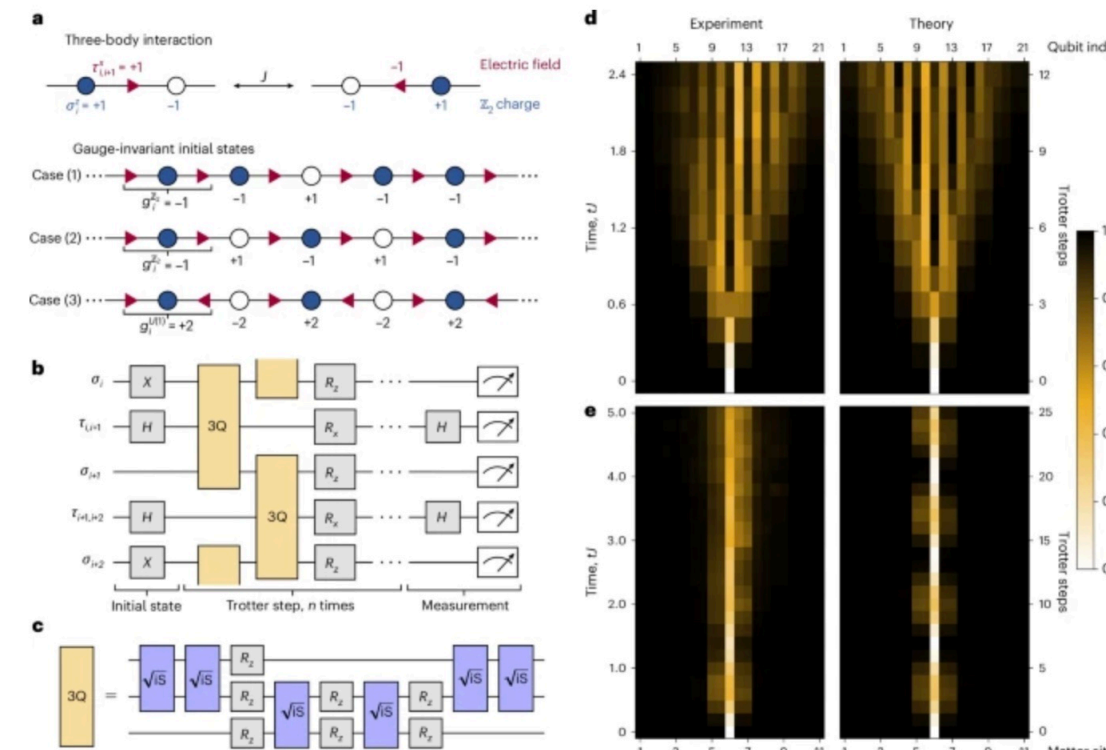
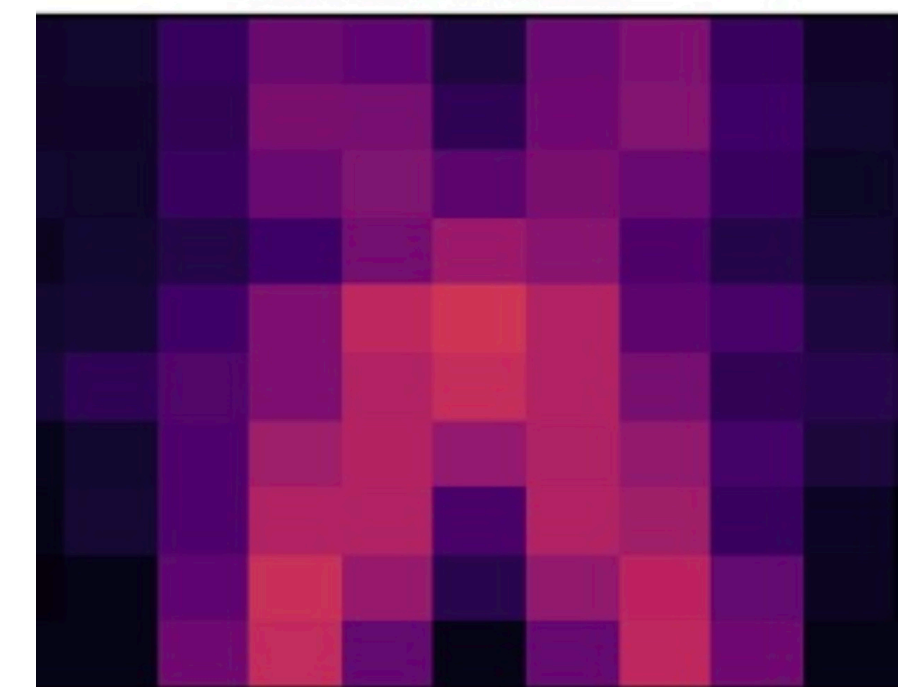


Fig. 1: Simulating confinement in a $\mathbb{Z}_2$ LGT on a digital superconducting chip.

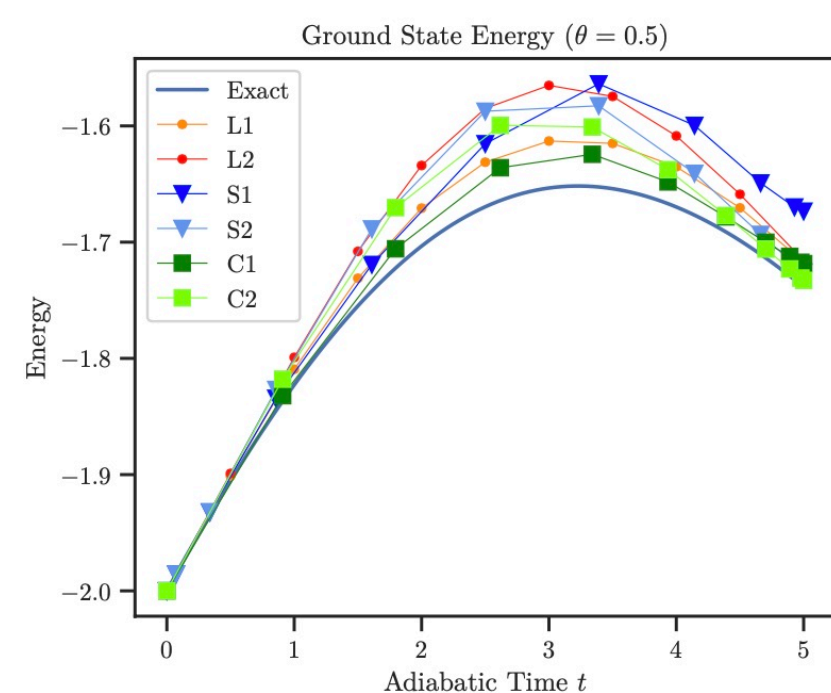


Confinement in Z2, Mildenerger et al

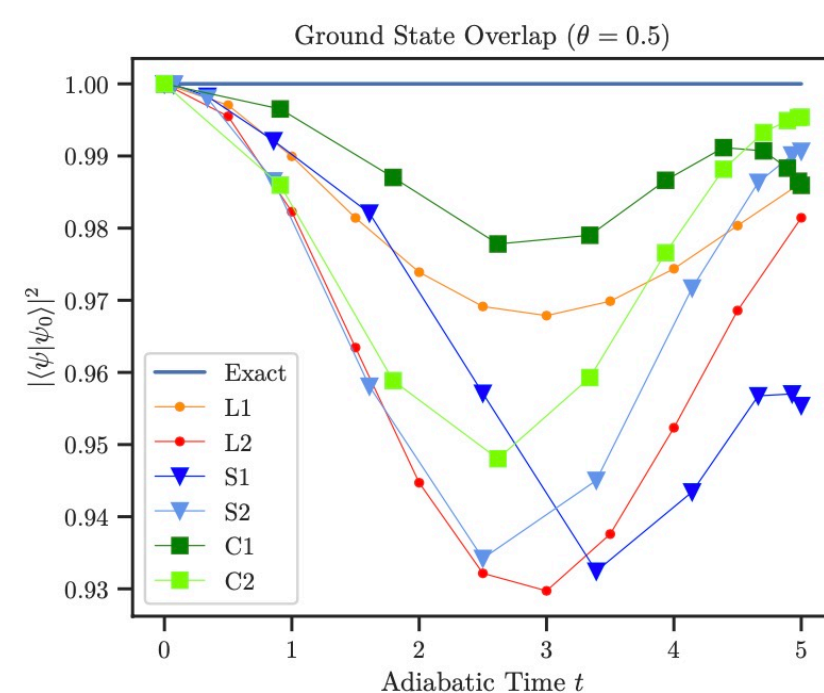
ibm fez



Scalar FT, Zemlevskiy



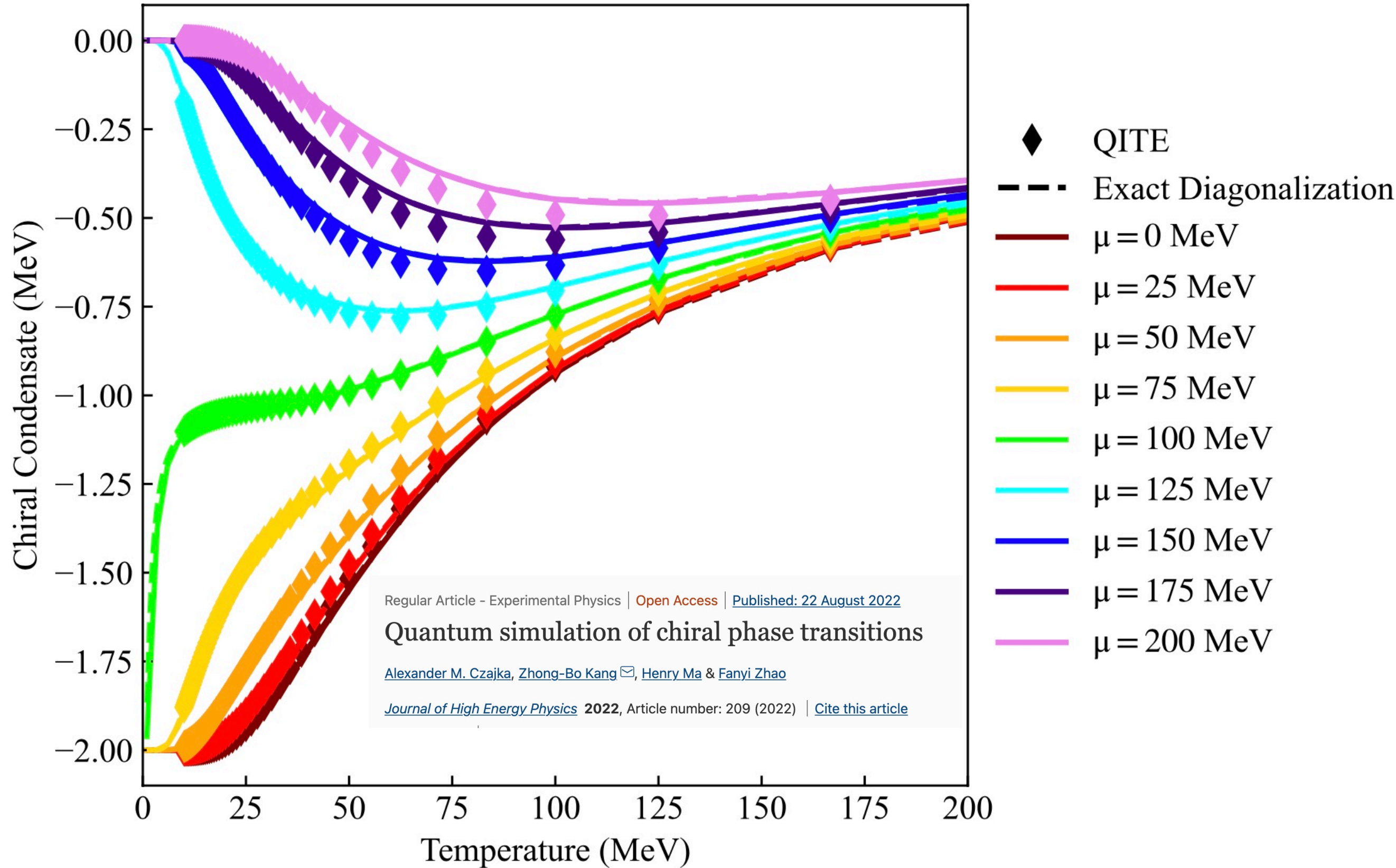
(a) QAOA, Rodeo , Pederiva et al



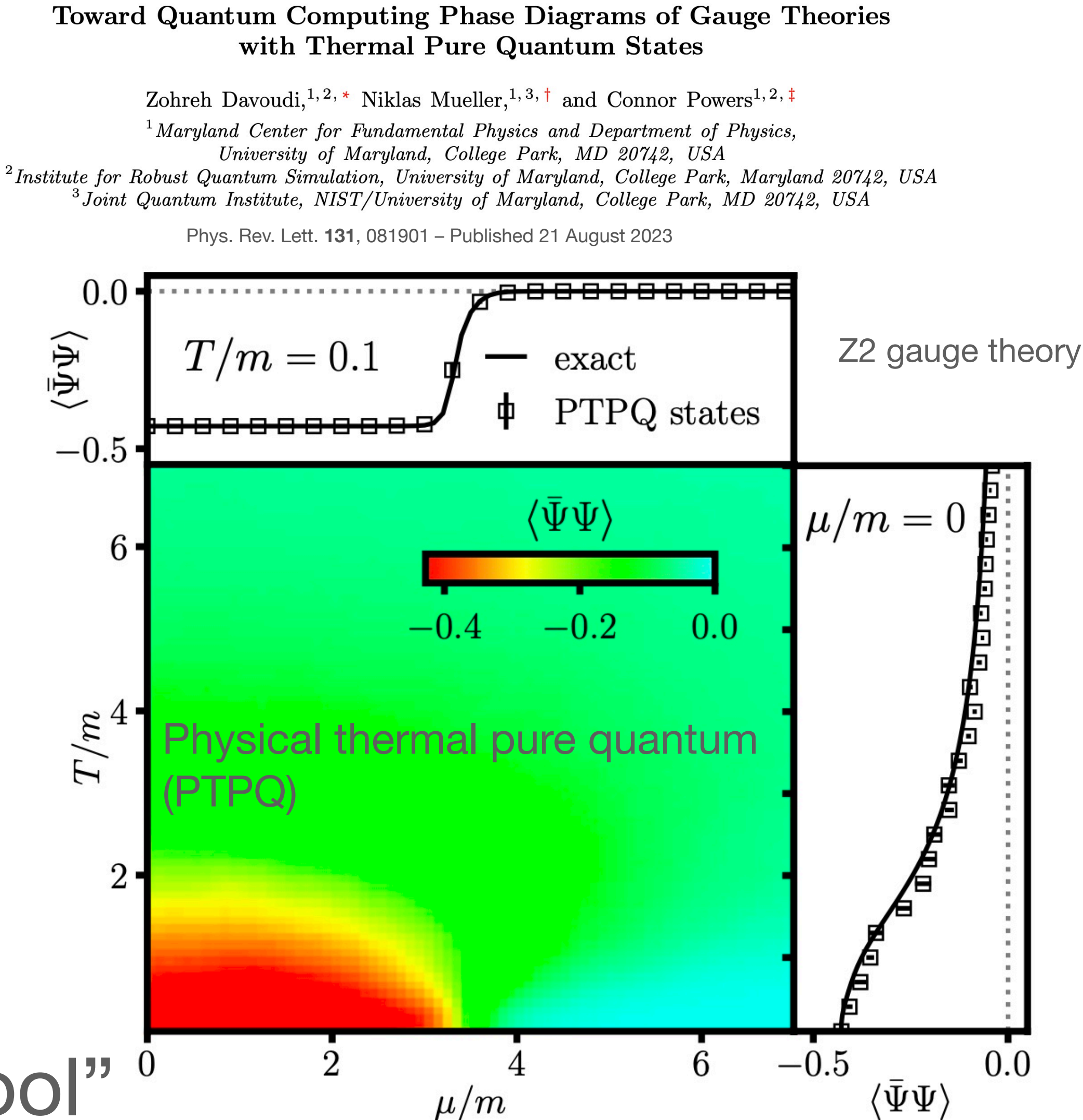
(b)

Modeling the QCD Phase Diagram

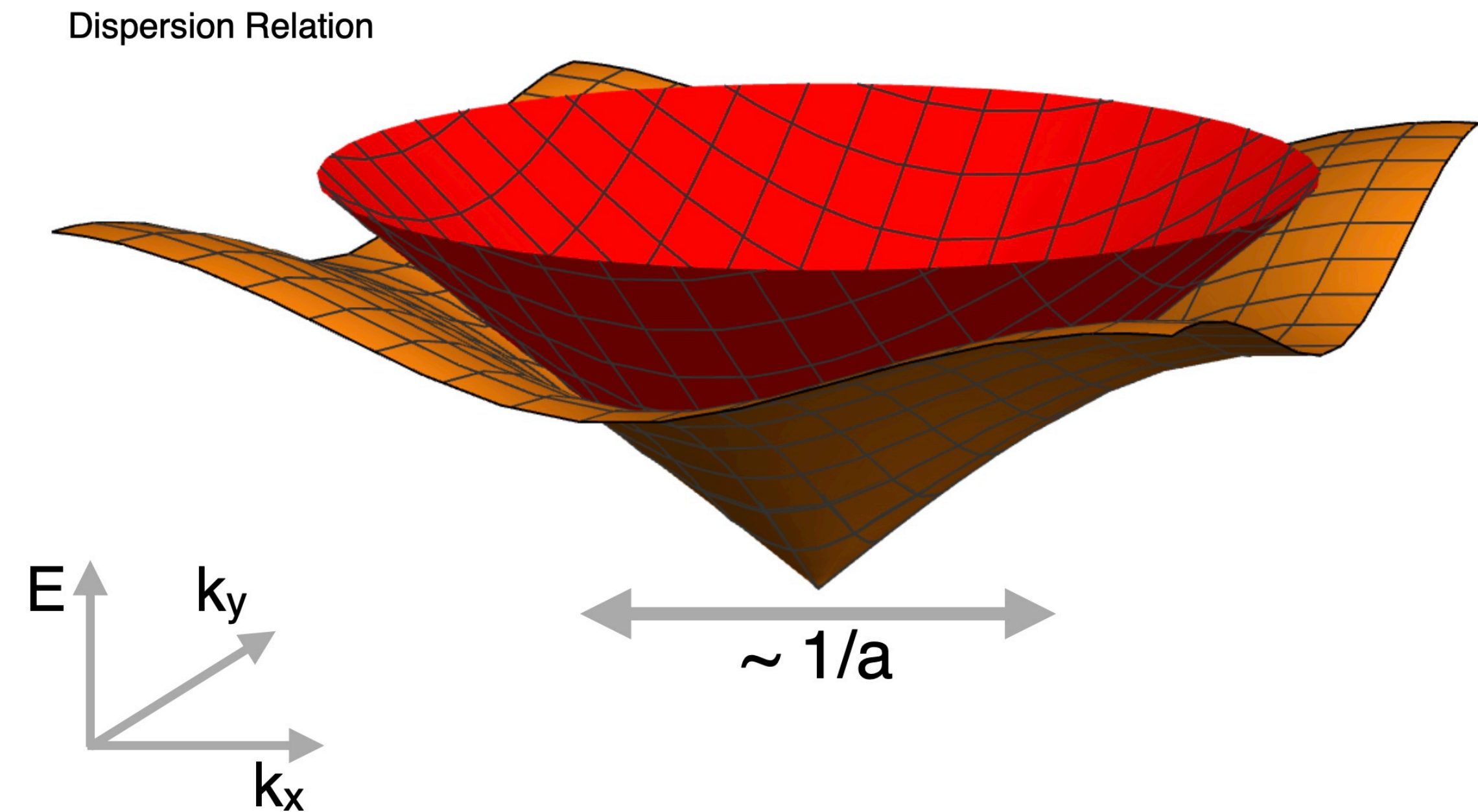
$$\mathcal{H} = \bar{\psi}(i\gamma_1\partial_1 + m)\psi - g(\bar{\psi}\psi)^2 - \mu\bar{\psi}\gamma_0\psi$$



QITE algorithms to “cool”



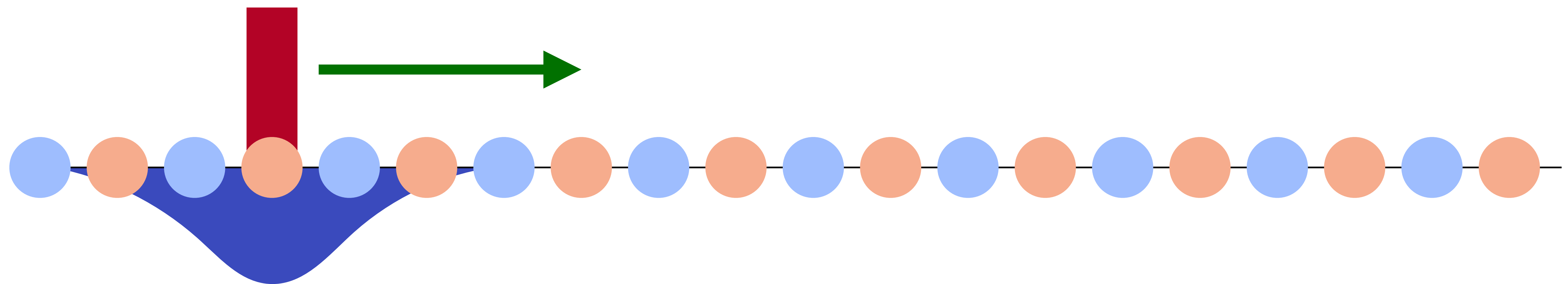
Systematics in Scattering ??



- High enough energy in collision will lead to quantum advantage
 - The bond dimension is growing (exp) with energy
- What is physics and what is systematic error must be quantified

Abelian Gauge Theory: Moving in the Lattice Vacuum Classical Simulations

Heavy Quark : constant speed, well-defined position - implemented via Gauss’s law

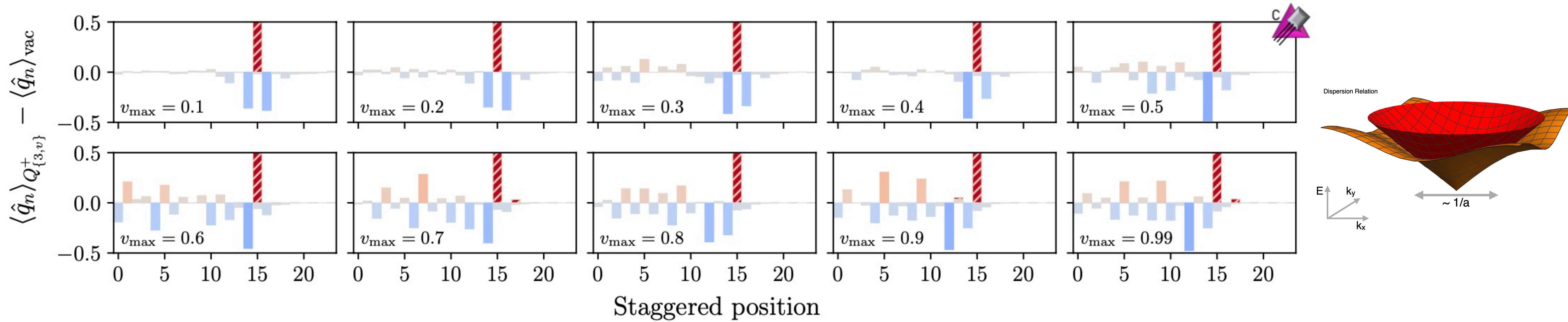


Composite Hadron
charge screening, confinement

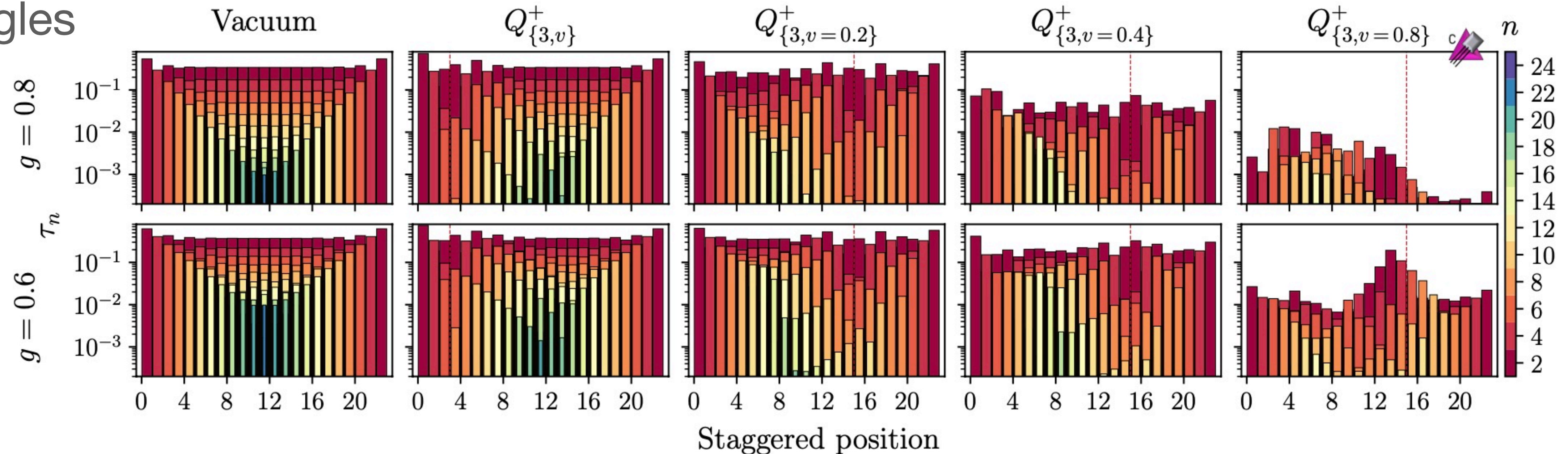
No energy-loss or hadronization in a Lorentz Invariant system (continuum)

Heavy quarks provide control for colliding partons

Energy Loss, Hadronization and ‘‘Damage’’ to Multi-Partite Entanglement in the Vacuum

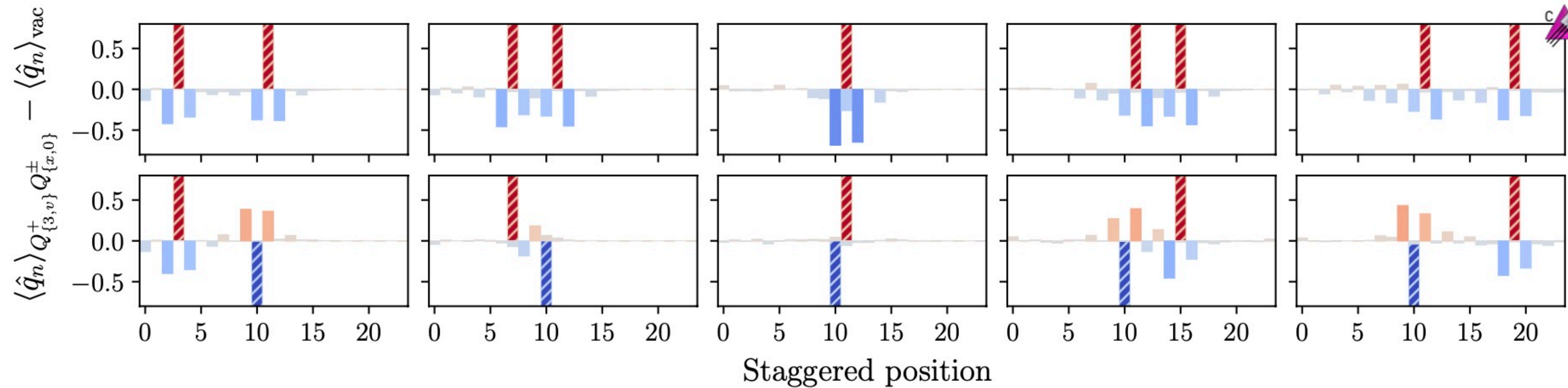


n-tangles

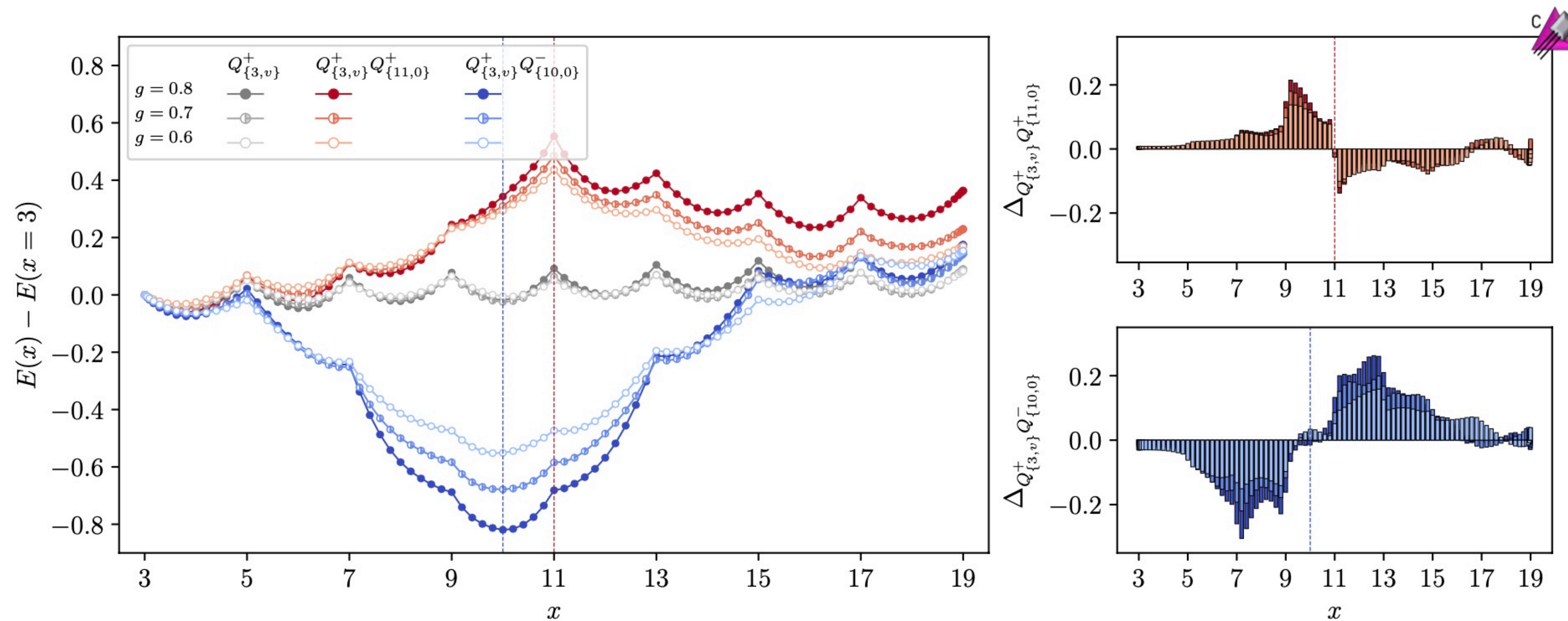


Colliding Partons

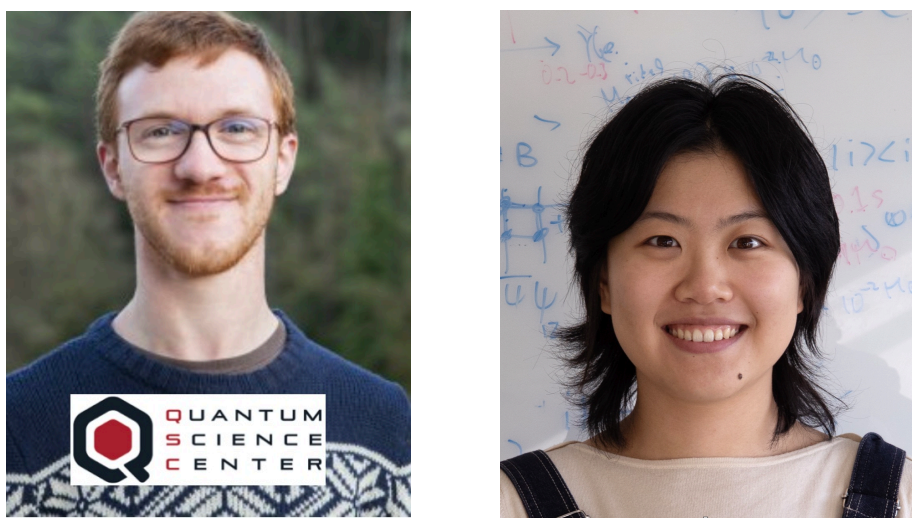
— One Static Background Heavy Quark



$v_{\text{max}}=0.2$

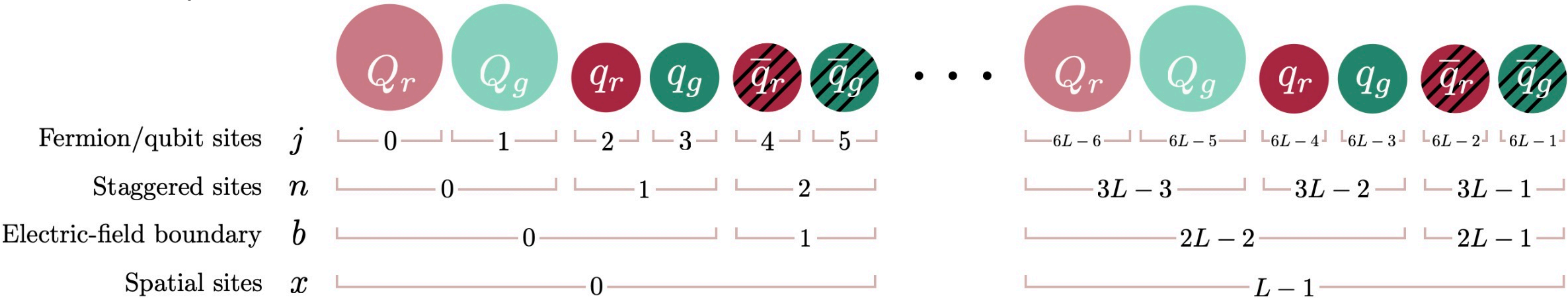


Leading parton collisions
dominate energy loss



Energy-Loss in Non-Abelian Gauge Theories: Quantum Simulations using IBM

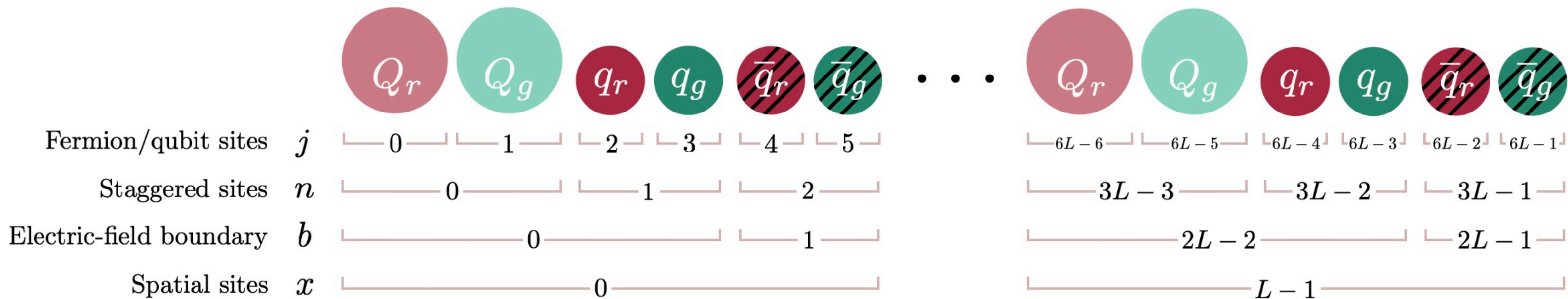
Marc Illa, Zhiyao Li



$$\hat{H} = \hat{H}_k + \hat{H}_m + \hat{H}_g + \hat{H}_\lambda$$

$$E_b^{(a)} \propto \sum_{n=0}^{b+1+\lfloor b/2 \rfloor} \hat{Q}_n^{(a)}$$

The SU(2) Hamiltonian



$$\hat{Q}_n^{(1)} = \frac{1}{2} \left(\hat{\sigma}_{2n}^+ \hat{\sigma}_{2n+1}^- + \hat{\sigma}_{2n}^- \hat{\sigma}_{2n+1}^+ \right) \quad , \quad \hat{Q}_n^{(2)} = \frac{-i}{2} \left(\hat{\sigma}_{2n}^+ \hat{\sigma}_{2n+1}^- - \hat{\sigma}_{2n}^- \hat{\sigma}_{2n+1}^+ \right) \quad , \quad \hat{Q}_n^{(3)} = \frac{1}{4} \left(\hat{Z}_{2n} - \hat{Z}_{2n+1} \right)$$

$$\hat{H} = \hat{H}_k + \hat{H}_m + \hat{H}_g + \hat{H}_\lambda$$

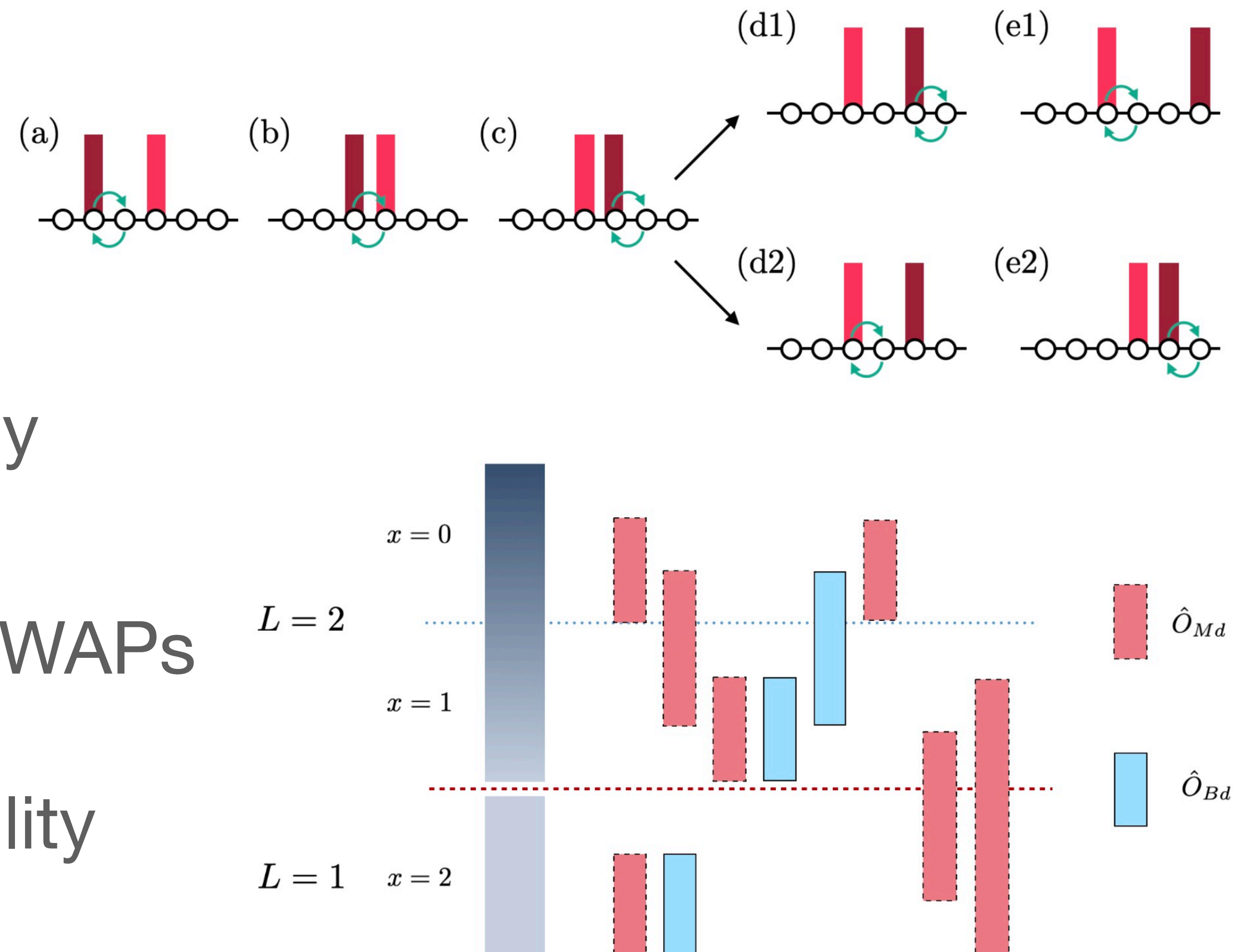
$$\hat{H}_k = -\frac{1}{2} \sum_{n \in q} \sum_{c=0,1} \left(\hat{\sigma}_{2n+c}^+ \hat{Z}_{2n+1+c} \hat{\sigma}_{2n+2+c}^- + \text{h.c.} \right) - \frac{1}{2} \sum_{n \in \bar{q}} \sum_{c=0,1} \left(\hat{\sigma}_{2n+c}^+ \hat{Z}_{2n+1+c} \hat{Z}_{2n+2+c} \hat{Z}_{2n+3+c} \hat{\sigma}_{2n+4+c}^- + \text{h.c.} \right)$$

$$\hat{H}_m = m_Q \sum_{n \in Q} \frac{1}{2} \left(\hat{I} + \hat{Z} \right)_n + m_q \sum_{n \in q} \frac{1}{2} \left(\hat{I} + \hat{Z} \right)_n + m_{\bar{q}} \sum_{n \in \bar{q}} \frac{1}{2} \left(\hat{I} - \hat{Z} \right)_n \rightarrow \frac{m_q}{2} \sum_{n \in q, \bar{q}} \sum_{c=0,1} (-1)^{\eta_n} \hat{Z}_{2n+c}$$

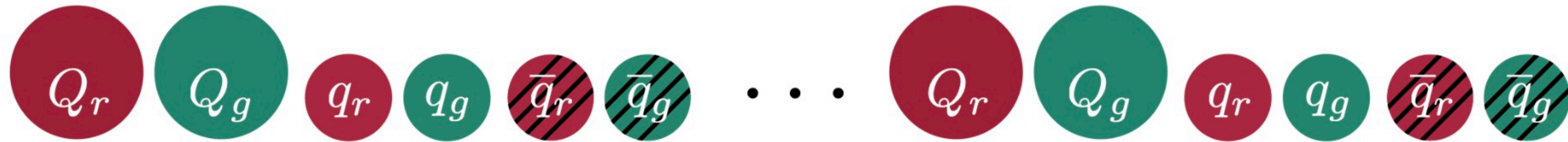
$$\hat{H}_g = \frac{g^2}{2} \sum_{a=1,2,3} \sum_{b=0}^{2L-2} \left(E_b^{(a)} \right)^2 \quad , \quad \hat{H}_\lambda = \frac{\lambda^2}{2} \sum_{a=1,2,3} \left(E_{b=2L-1}^{(a)} \right)^2 \quad E_b^{(a)} \propto \sum_{n=0}^{b+1+\lfloor b/2 \rfloor} \hat{Q}_n^{(a)}$$

Four New Ingredients - Beyond U(1)

- Color entanglement
 - Hadron interpolating operators
- Heavy-quark motion discrete only
 - by FSWAPs
- Lattice spacing artifacts from FSWAPs
- Domain Decomposition - scalability

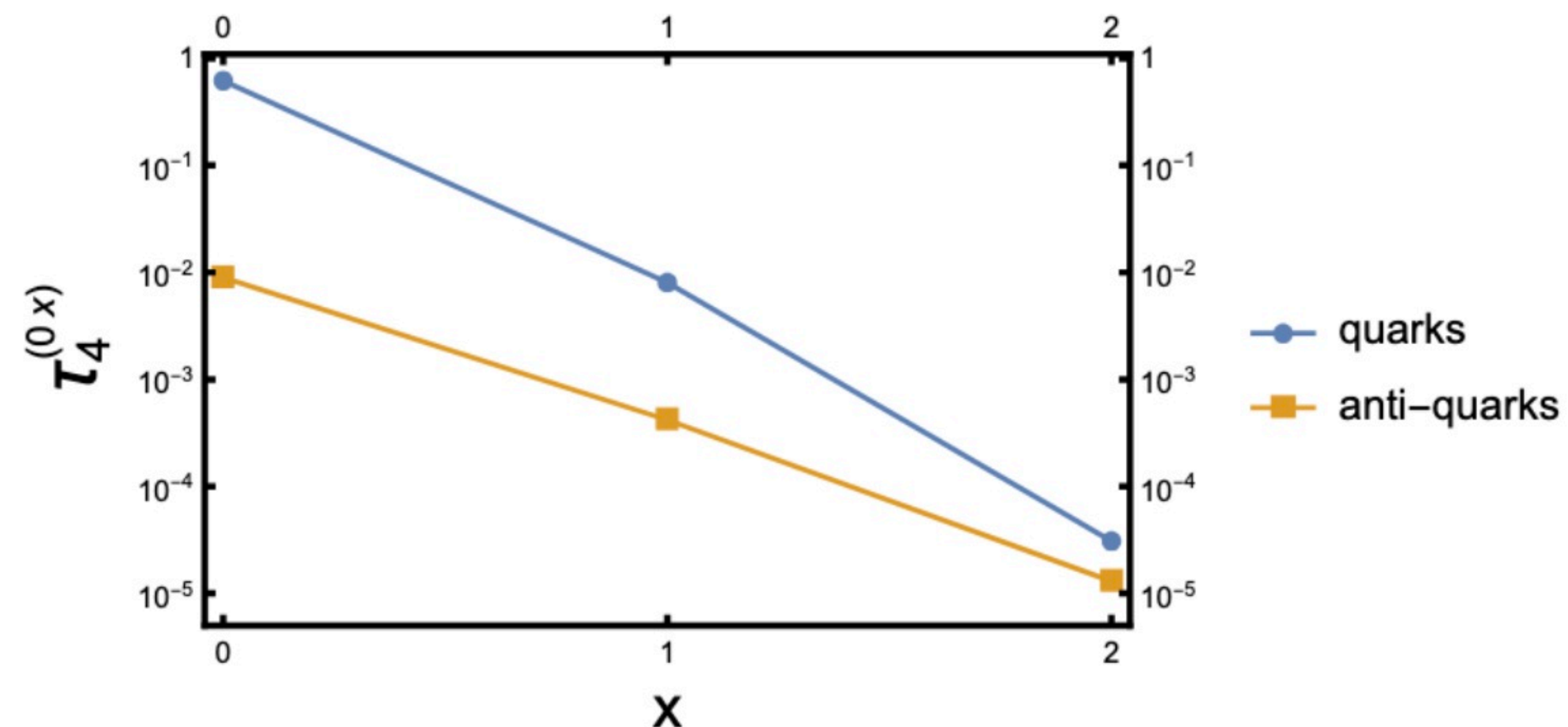


Elaboration : Color Entanglement

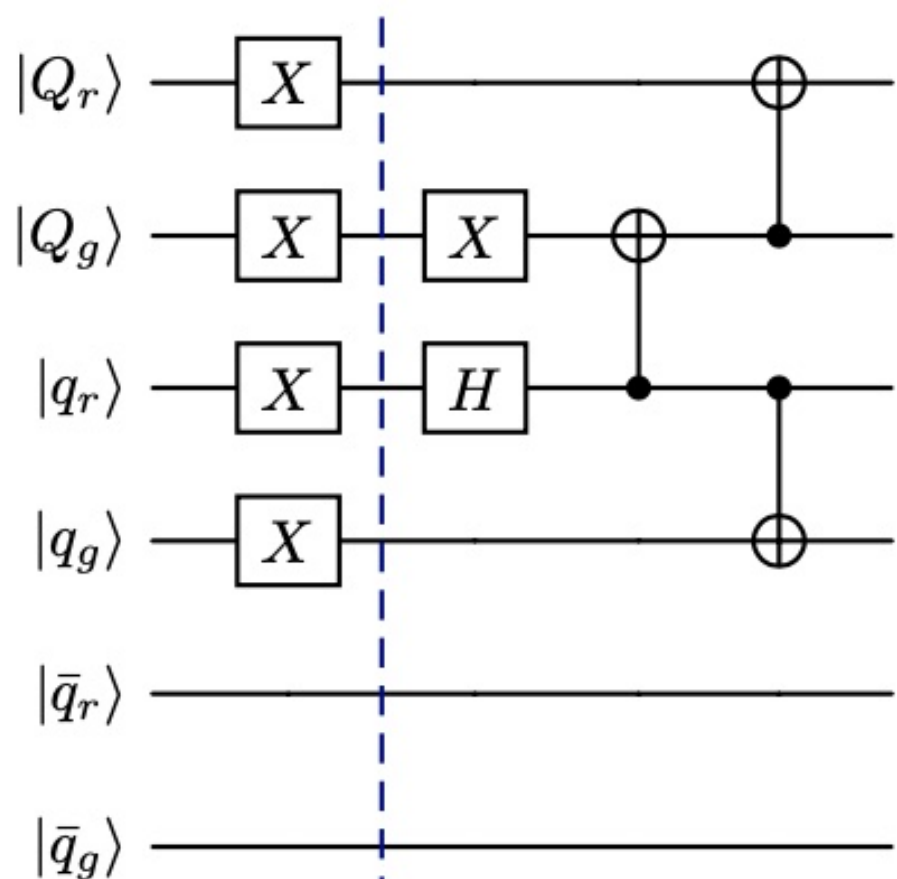


Heavy-Quark
positioned here

$$|I; 3, 1, x = 0\rangle = 0.273228 | \uparrow \downarrow \downarrow \uparrow \uparrow \downarrow \downarrow \downarrow \uparrow \uparrow \downarrow \downarrow \downarrow \uparrow \uparrow \rangle - 0.273228 | \downarrow \uparrow \uparrow \downarrow \uparrow \uparrow \downarrow \downarrow \downarrow \uparrow \uparrow \downarrow \downarrow \downarrow \uparrow \uparrow \rangle \\ - 0.161826 | \uparrow \downarrow \downarrow \uparrow \uparrow \downarrow \downarrow \downarrow \uparrow \uparrow \downarrow \downarrow \downarrow \uparrow \uparrow \rangle - 0.161826 | \downarrow \uparrow \uparrow \downarrow \downarrow \uparrow \downarrow \downarrow \uparrow \uparrow \downarrow \downarrow \downarrow \uparrow \uparrow \rangle + \dots ,$$



Note: An obvious waste of Hilbert space!!
Working toward dynamical re-assignment



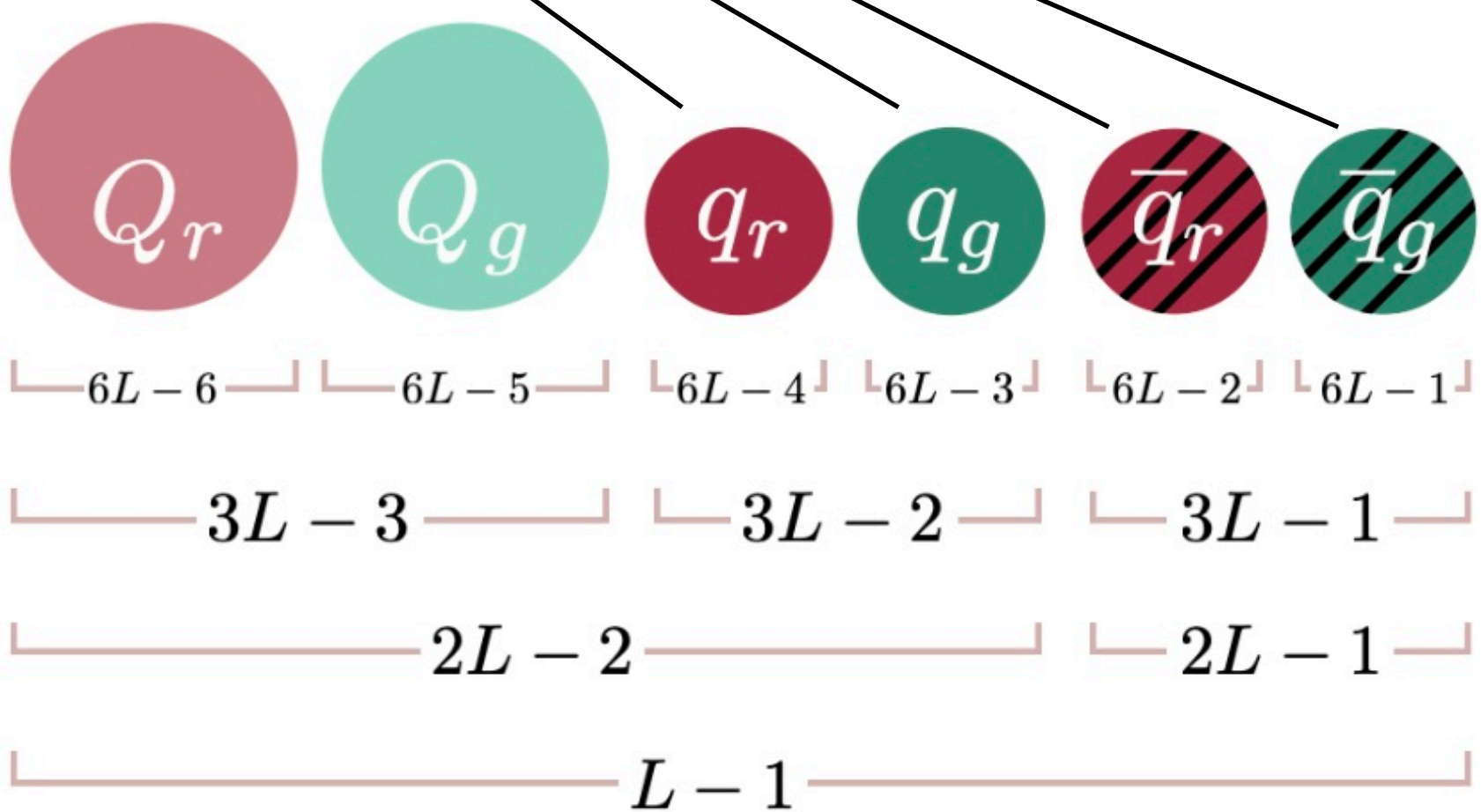
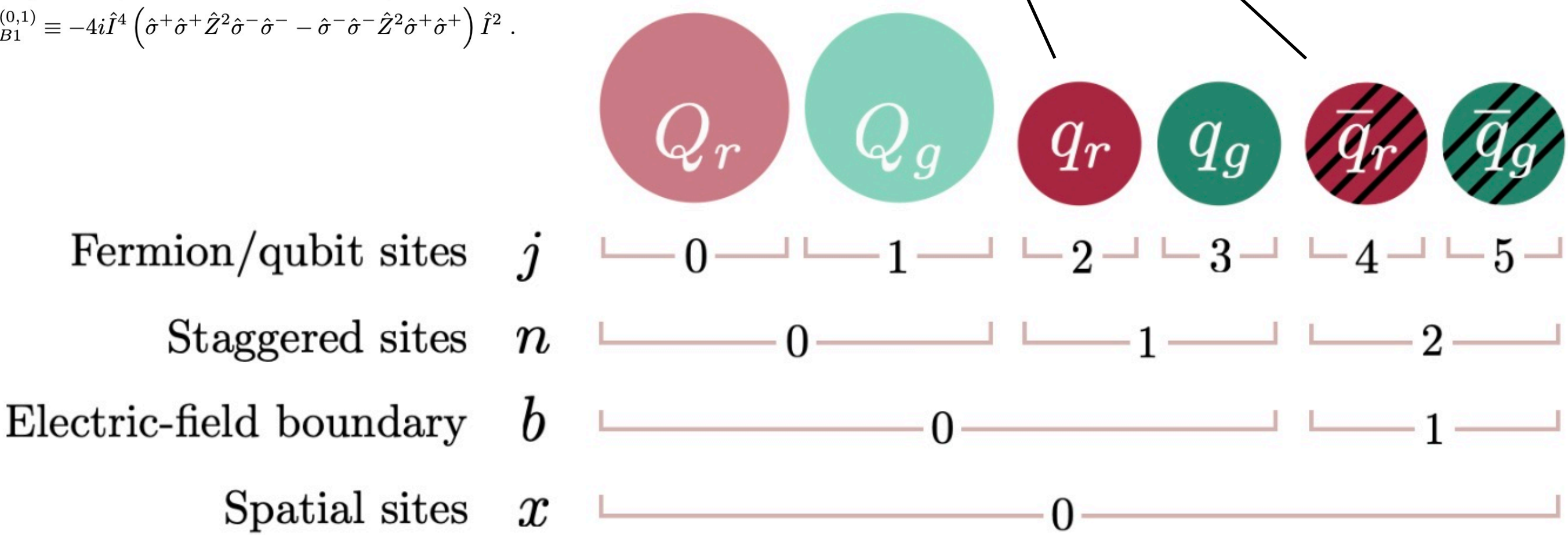
Elaboration : HPC Optimization

Color-singlet operators in the ADAPT-VQE pool

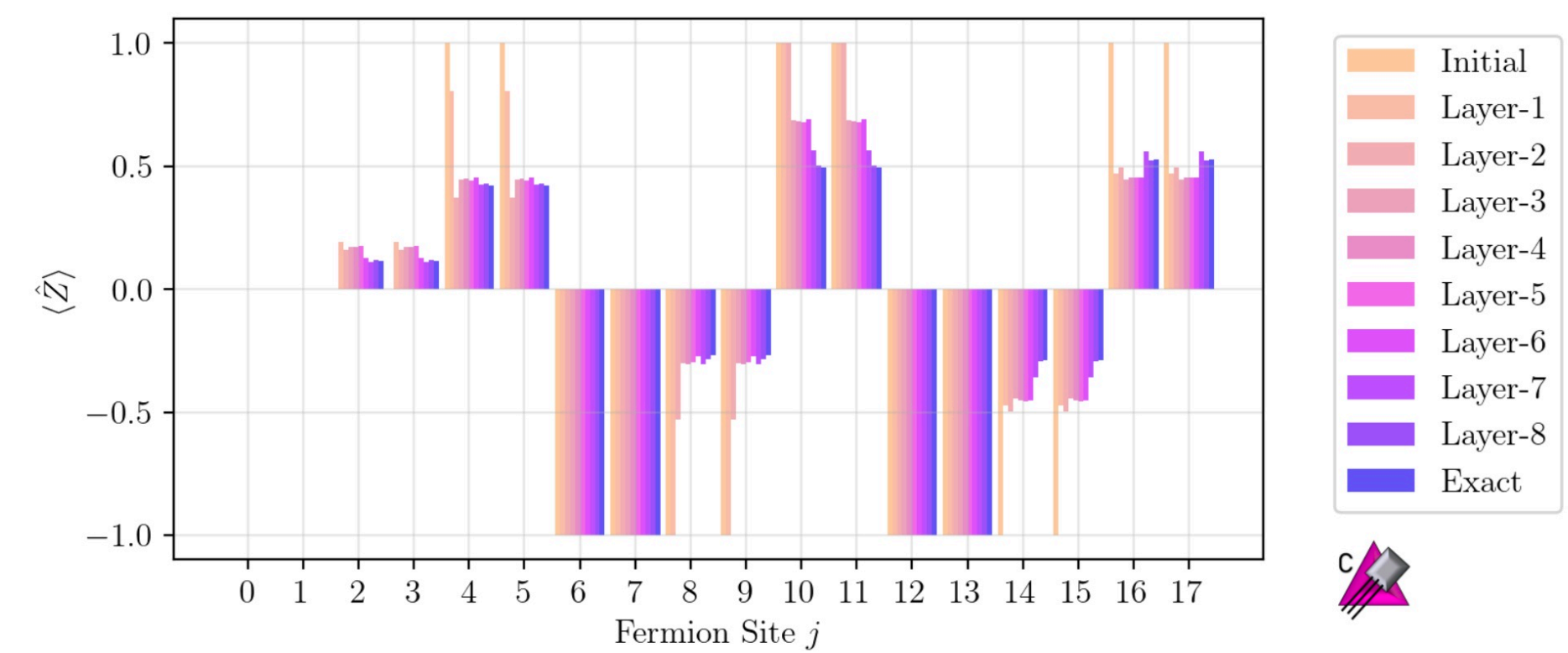
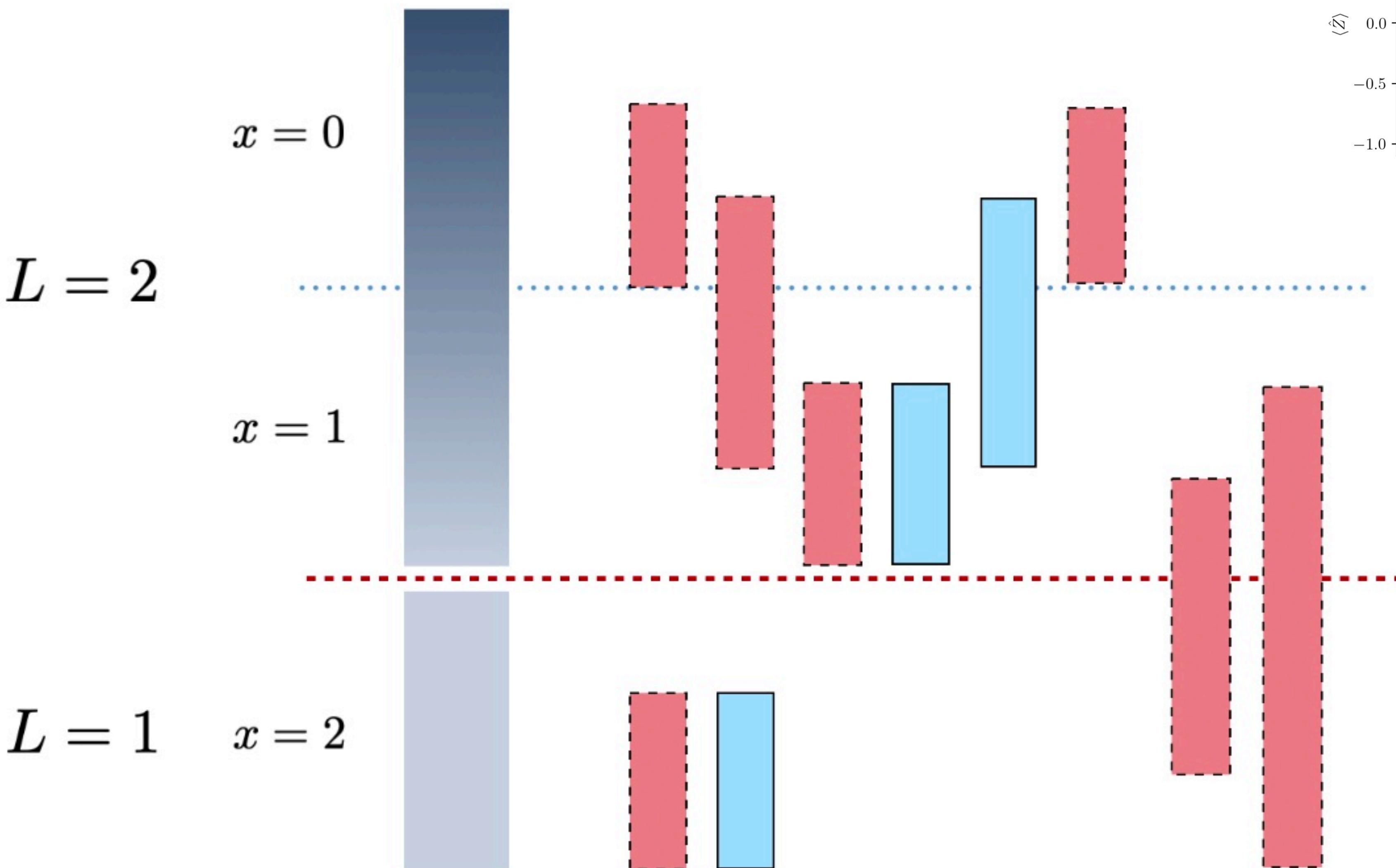
- form factors and position

$$\hat{U}_{L=2}^{n_Q=1} = e^{-i\theta_6 \hat{O}_{M0}^{(0)}} e^{-i\theta_5 \hat{O}_{B1}^{(0,1)}} e^{-i\theta_4 \hat{O}_{B0}^{(1)}} e^{-i\theta_3 \hat{O}_{M0}^{(1)}} e^{-i\theta_2 \hat{O}_{M1}^{(0,1)}} e^{-i\theta_1 \hat{O}_{M0}^{(0)}}$$

$$\begin{aligned} \hat{O}_{M0}^{(0)} &\equiv \hat{I}^2 \left(\hat{X} \hat{Z} \hat{Y} \hat{I} - \hat{Y} \hat{Z} \hat{X} \hat{I} + \hat{I} \hat{X} \hat{Z} \hat{Y} - \hat{I} \hat{Y} \hat{Z} \hat{X} \right) \hat{I}^6, \\ \hat{O}_{M0}^{(1)} &\equiv \hat{I}^8 \left(\hat{X} \hat{Z} \hat{Y} \hat{I} - \hat{Y} \hat{Z} \hat{X} \hat{I} + \hat{I} \hat{X} \hat{Z} \hat{Y} - \hat{I} \hat{Y} \hat{Z} \hat{X} \right), \\ \hat{O}_{M1}^{(0,1)} &\equiv -\hat{I}^4 \left(\hat{X} \hat{Z}^3 \hat{Y} \hat{I} - \hat{Y} \hat{Z}^3 \hat{X} \hat{I} + \hat{I} \hat{X} \hat{Z}^3 \hat{Y} - \hat{I} \hat{Y} \hat{Z}^3 \hat{X} \right) \hat{I}^2, \\ \hat{O}_{B0}^{(0)} &\equiv 4i\hat{I}^2 \left(\hat{\sigma}^+ \hat{\sigma}^+ \hat{\sigma}^- \hat{\sigma}^- - \hat{\sigma}^- \hat{\sigma}^- \hat{\sigma}^+ \hat{\sigma}^+ \right) \hat{I}^6, \\ \hat{O}_{B0}^{(1)} &\equiv 4i\hat{I}^8 \left(\hat{\sigma}^+ \hat{\sigma}^+ \hat{\sigma}^- \hat{\sigma}^- - \hat{\sigma}^- \hat{\sigma}^- \hat{\sigma}^+ \hat{\sigma}^+ \right), \\ \hat{O}_{B1}^{(0,1)} &\equiv -4i\hat{I}^4 \left(\hat{\sigma}^+ \hat{\sigma}^+ \hat{Z}^2 \hat{\sigma}^- \hat{\sigma}^- - \hat{\sigma}^- \hat{\sigma}^- \hat{Z}^2 \hat{\sigma}^+ \hat{\sigma}^+ \right) \hat{I}^2. \end{aligned}$$

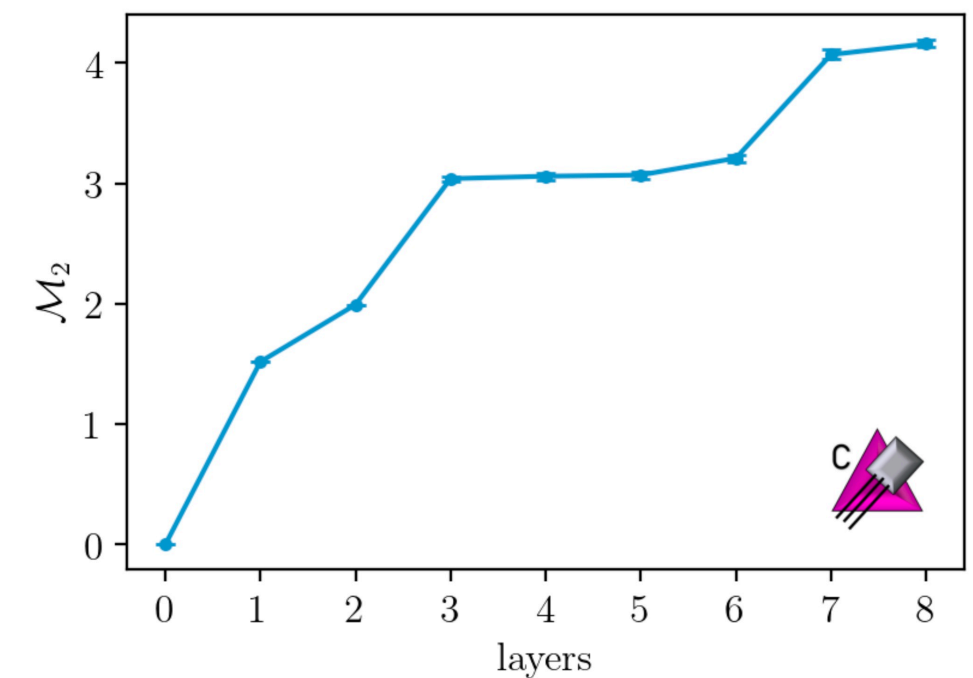


Elaboration : Domain Decomposition

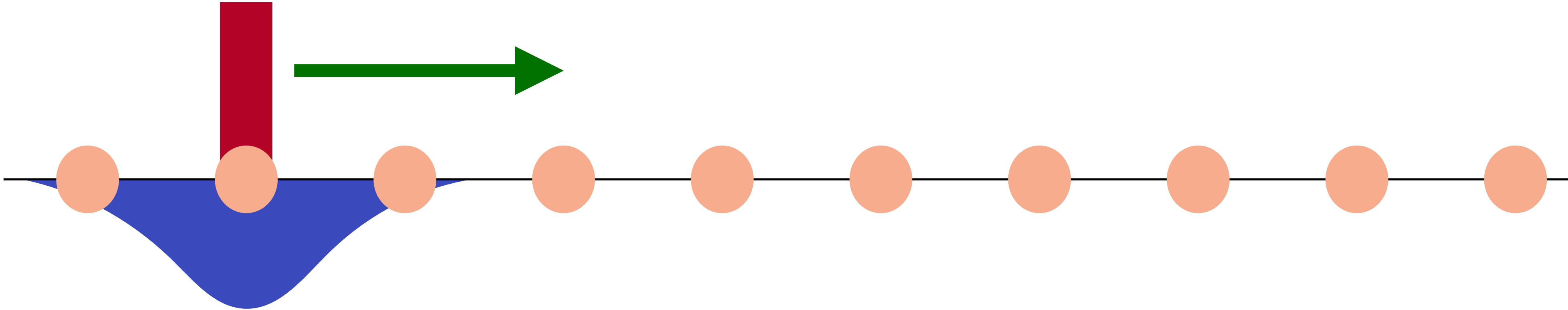


$$\hat{O}_{Md}$$

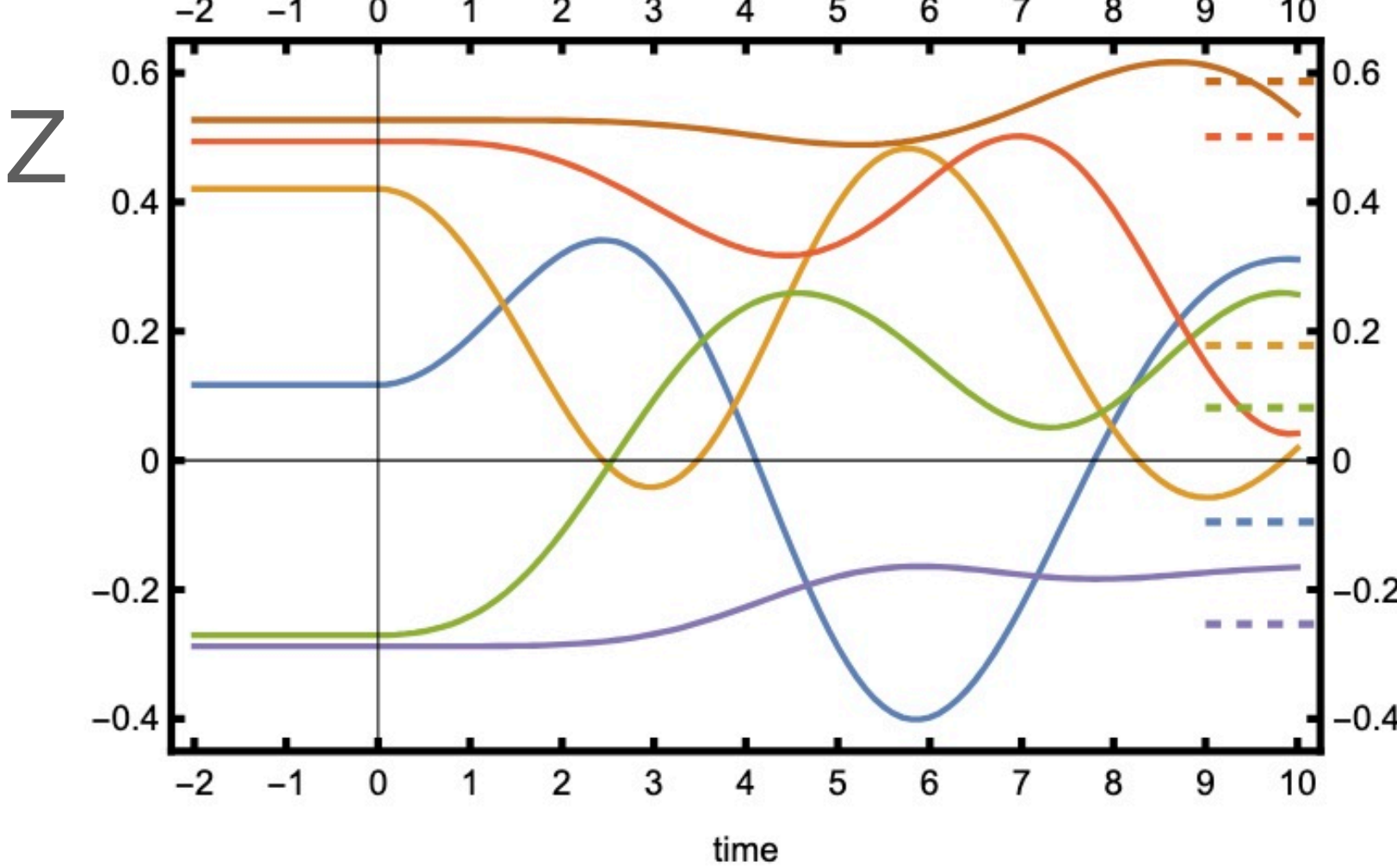
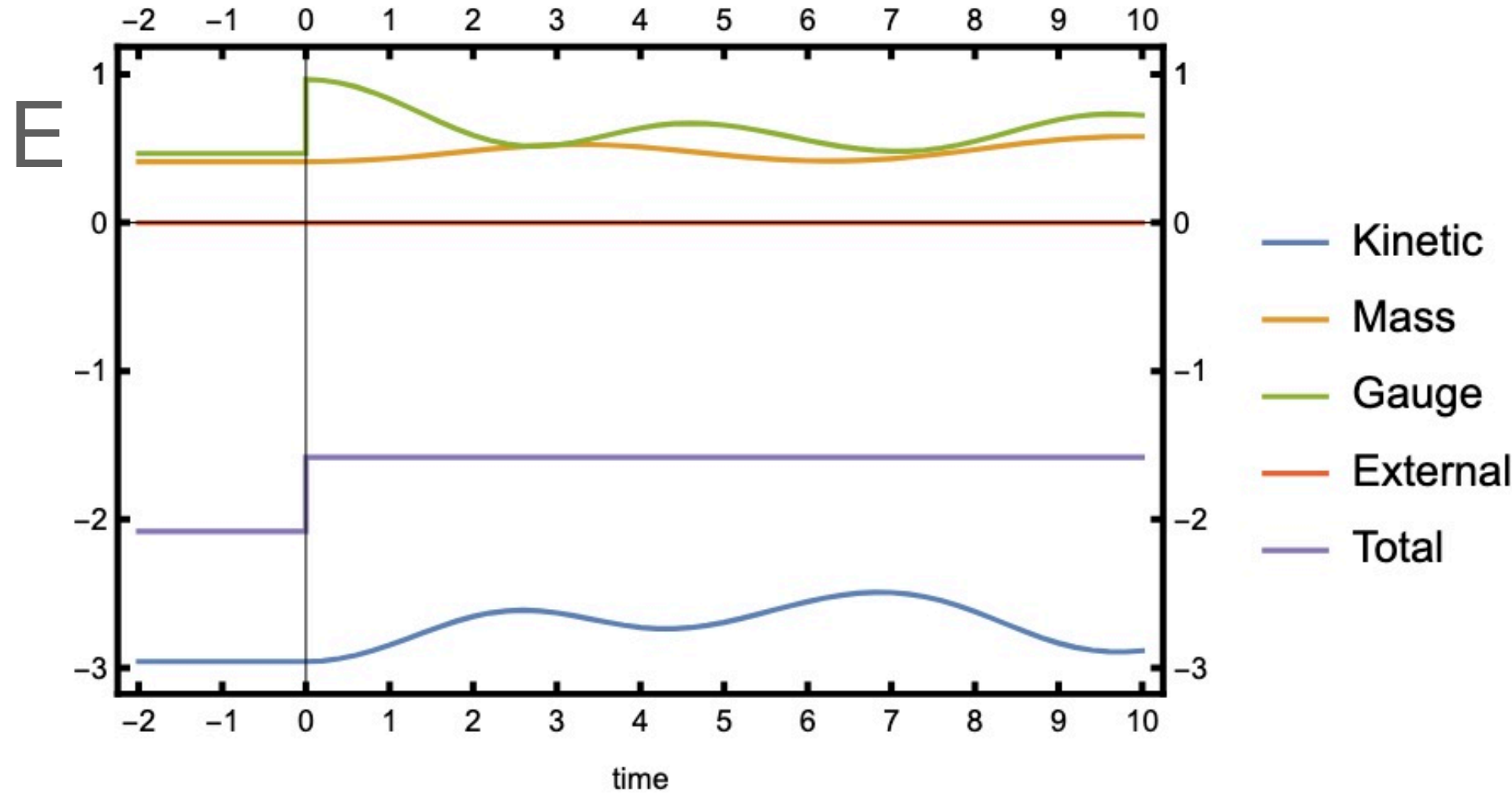
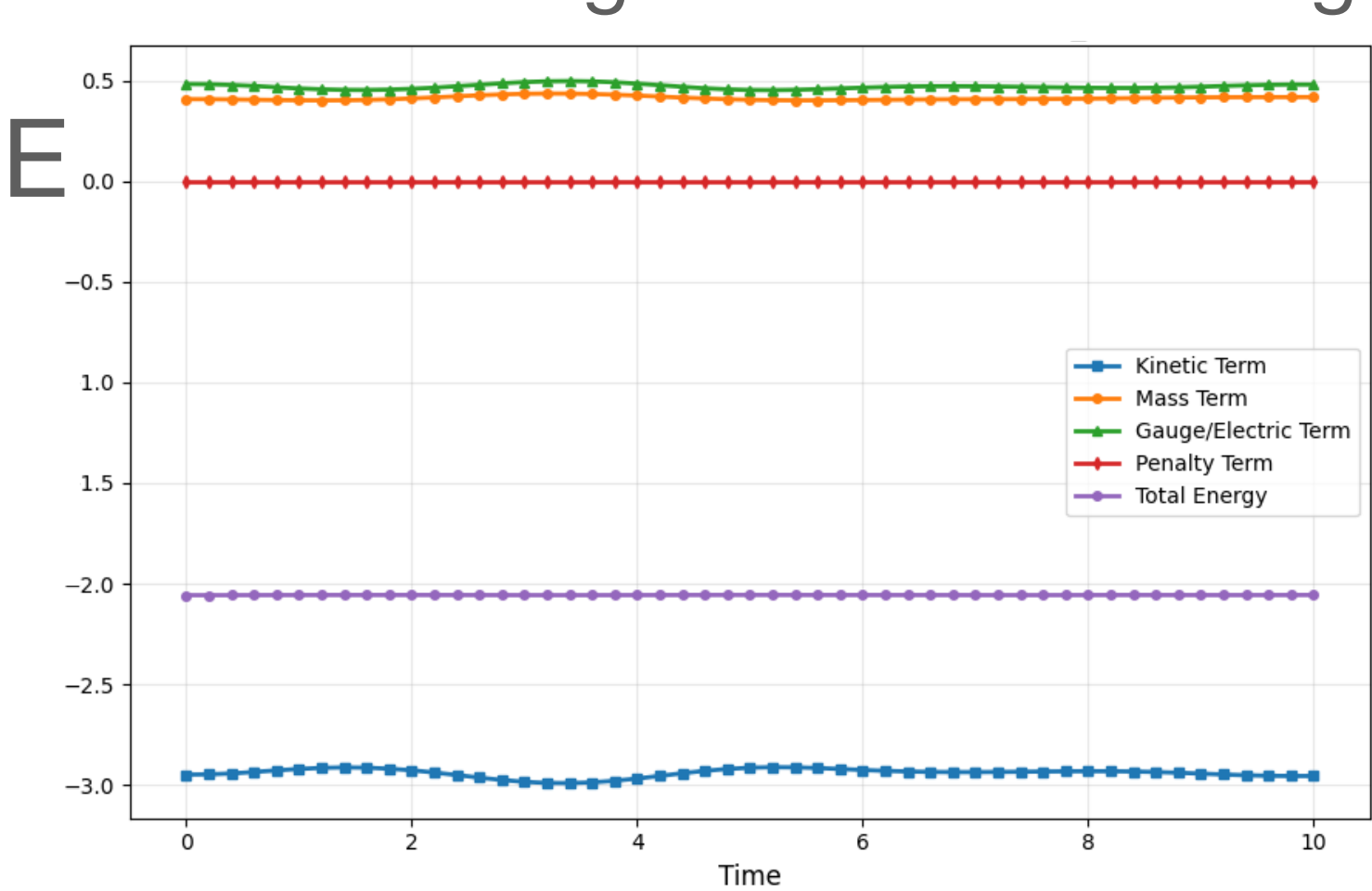
$$\hat{O}_{Bd}$$



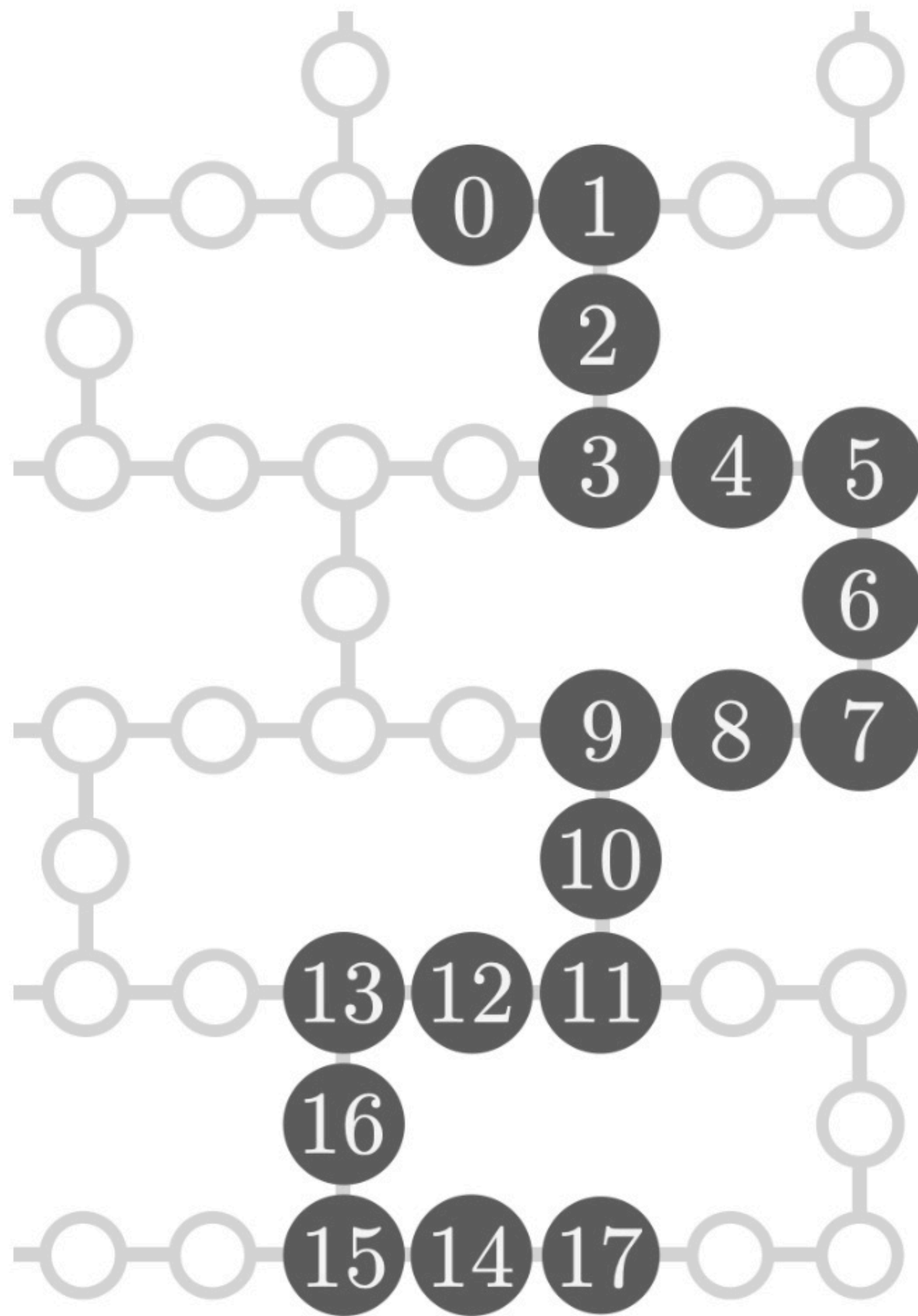
Classical Results



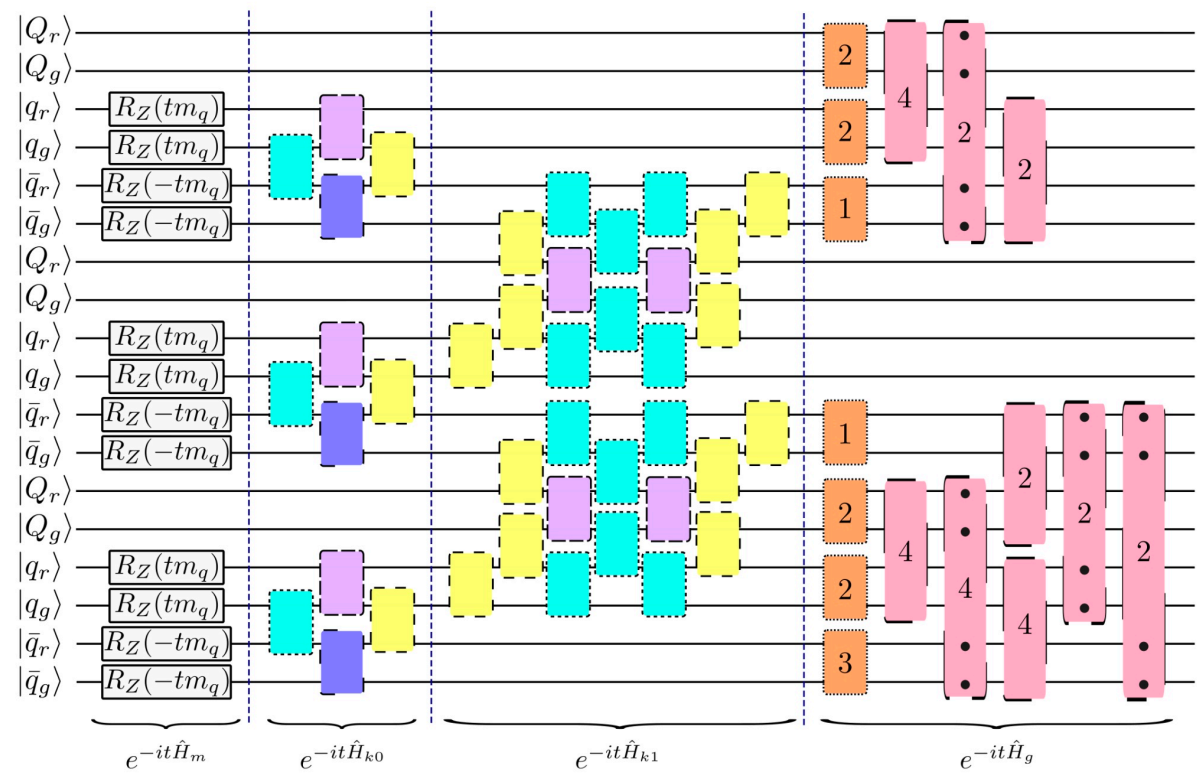
Trotterized ground state heating



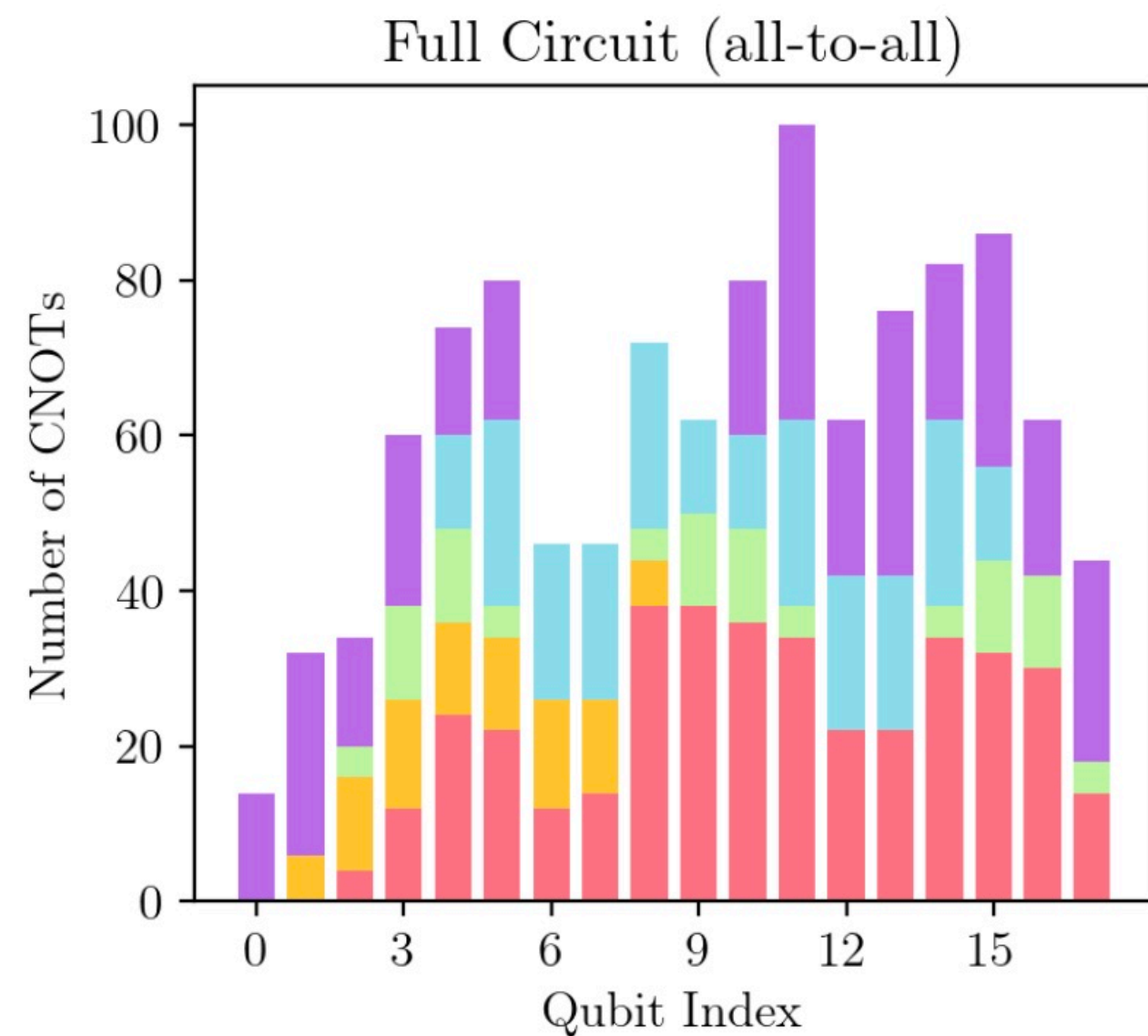
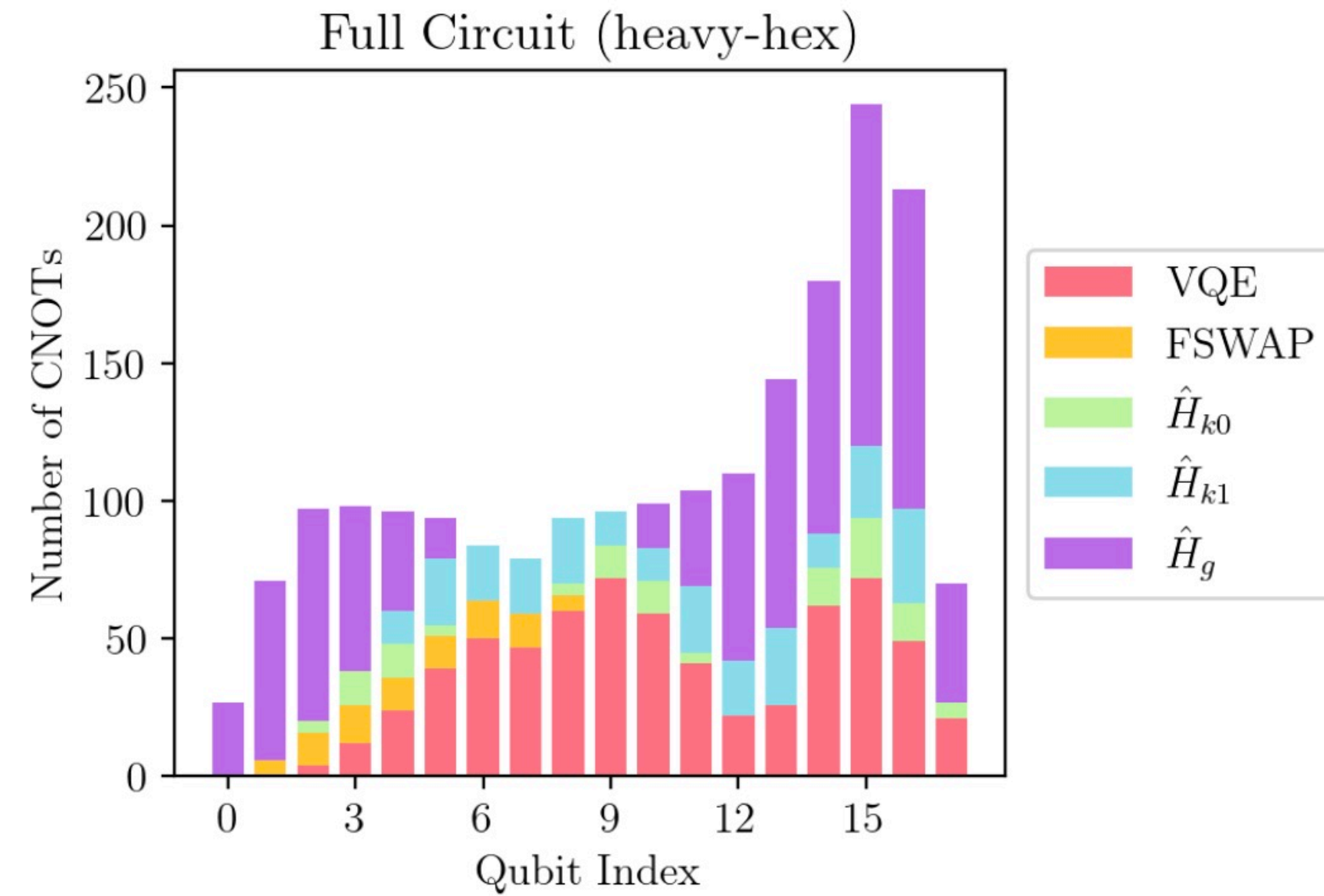
Resources and Layout for L=3



Time ev.	CZ All-to-All	CZ Transpiled
$\hat{H}_{k0}$	6	11
$\hat{H}_{k1}$	14	19
$\hat{H}_g$ (total)	78	202
$\hat{Q}_n \hat{Q}_{n+1}$	16	41
$\hat{Q}_n \hat{Q}_{n+2}$	16	43
$\hat{Q}_n \hat{Q}_{n+3}$	16	49



Production



1) Prepare the L=3 Ground State on 18 qubits of ibm_pittsburgh

- HPC optimized ADAPT-VQE (fidelity > 99.5)

2) t=0 : Shift Q from x=0 to x=1 using FSWAP

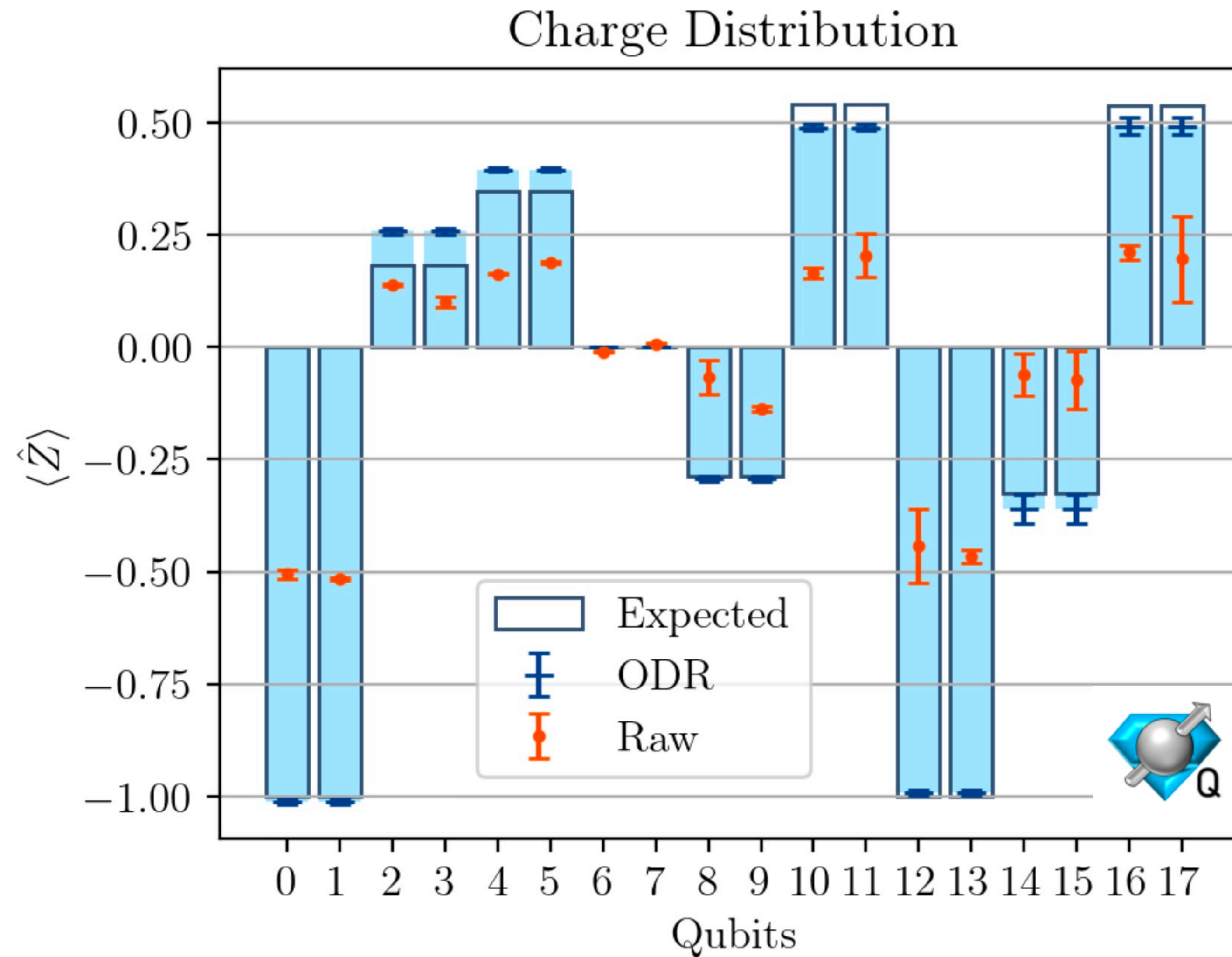
3a) One 2nd-Order Trotter step from t=0 to t=1

3b) Measure the energy in the light quarks

Total 2-Qubit Depth = 398
(after transpilation)

Charge Distribution

IBM Quantum



4517 gates: `OrderedDict({'sx': 1957, 'rz': 1452, 'cz': 1004, 'x': 104})`

Depth: 1350

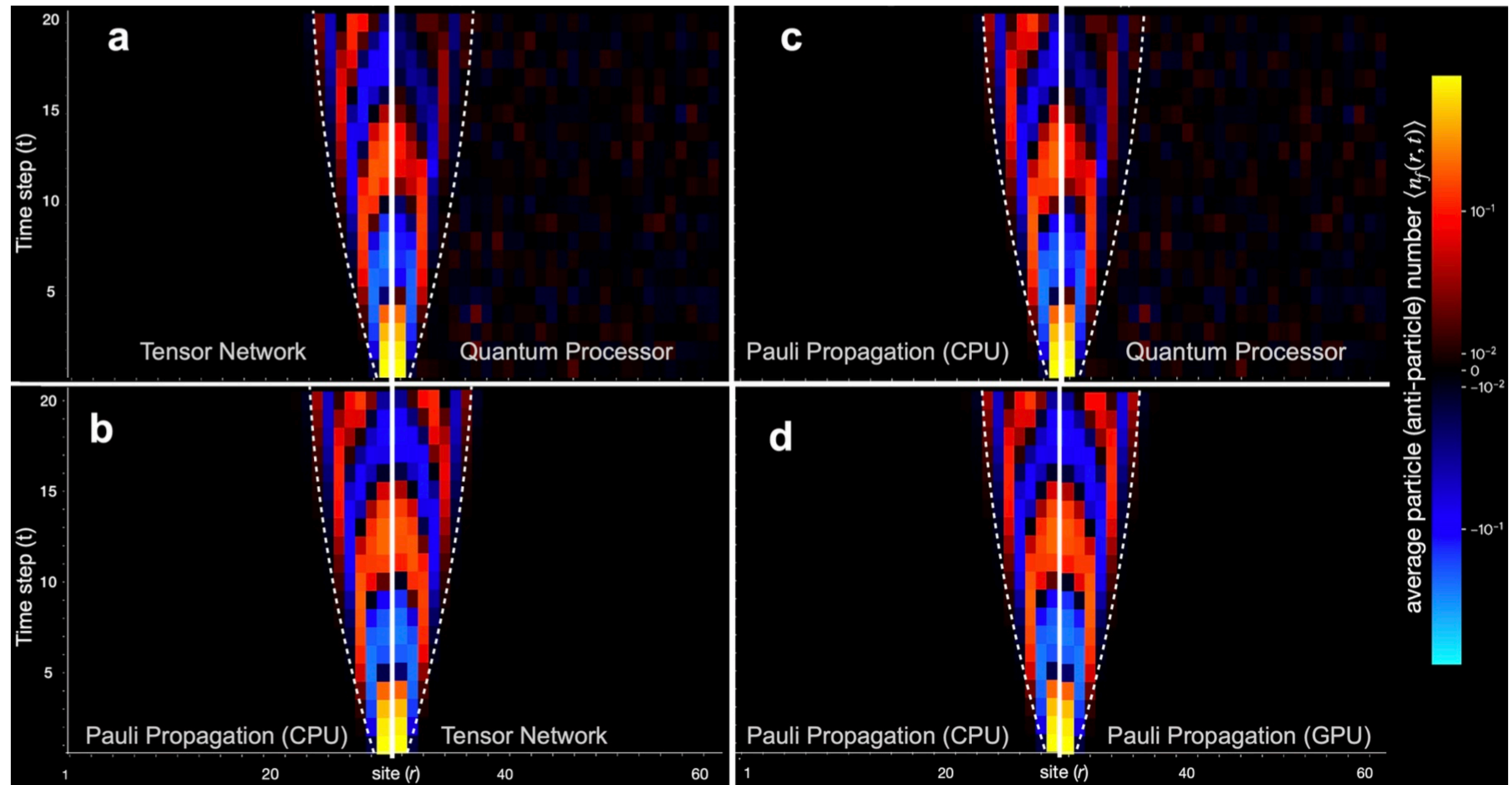
Two-qubit gate depth: 456

from an early implementation

Wavepacket Evolution in 1+1D SU(2)

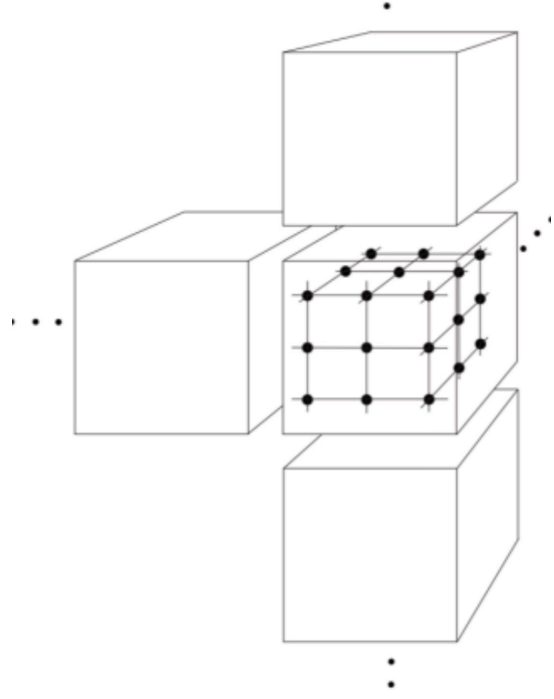
Observation of Robust and Coherent Non-Abelian Hadron Dynamics on Noisy Quantum Processors

Fran Ilčić^{1,*}, Ritajit Majumdar^{2,*}, Emil Mathew^{1,*}, Md. Osama Ali¹,
Nathan Earnest-Noble³ & Indrakshi Raychowdhury^{1,**}



Dynamical Gauge Fields - Yang-Mills

Byrnes-Yamamoto — Kogut-Susskind



Many ways to map/distribute the field(s) in the UV (lattice spacing)
Consider the Kogut-Susskind basis = electric basis

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

Electric Field Casimir operator

$$|p, q, T_L, T_L^z, Y_L, T_R, T_R^z, Y_R\rangle$$

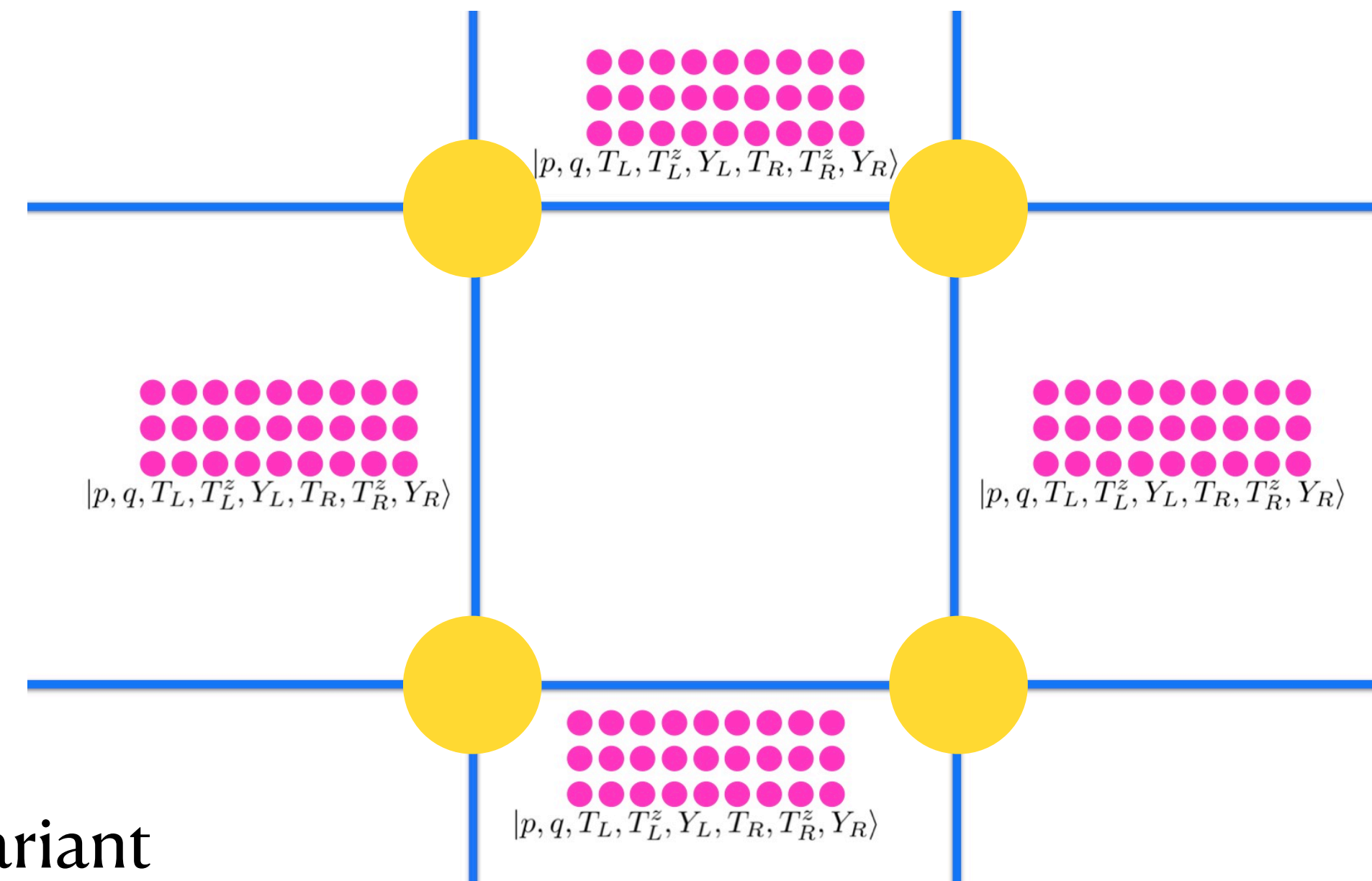
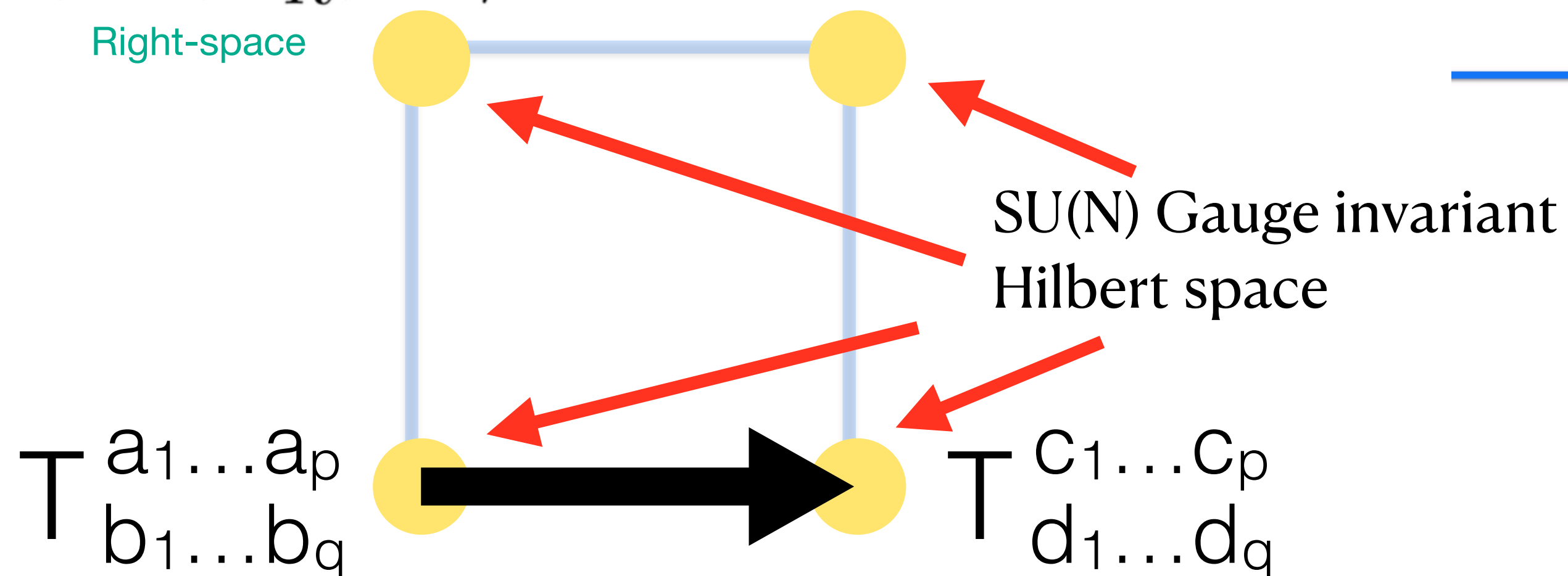
Irrep

Left-space

Right-space

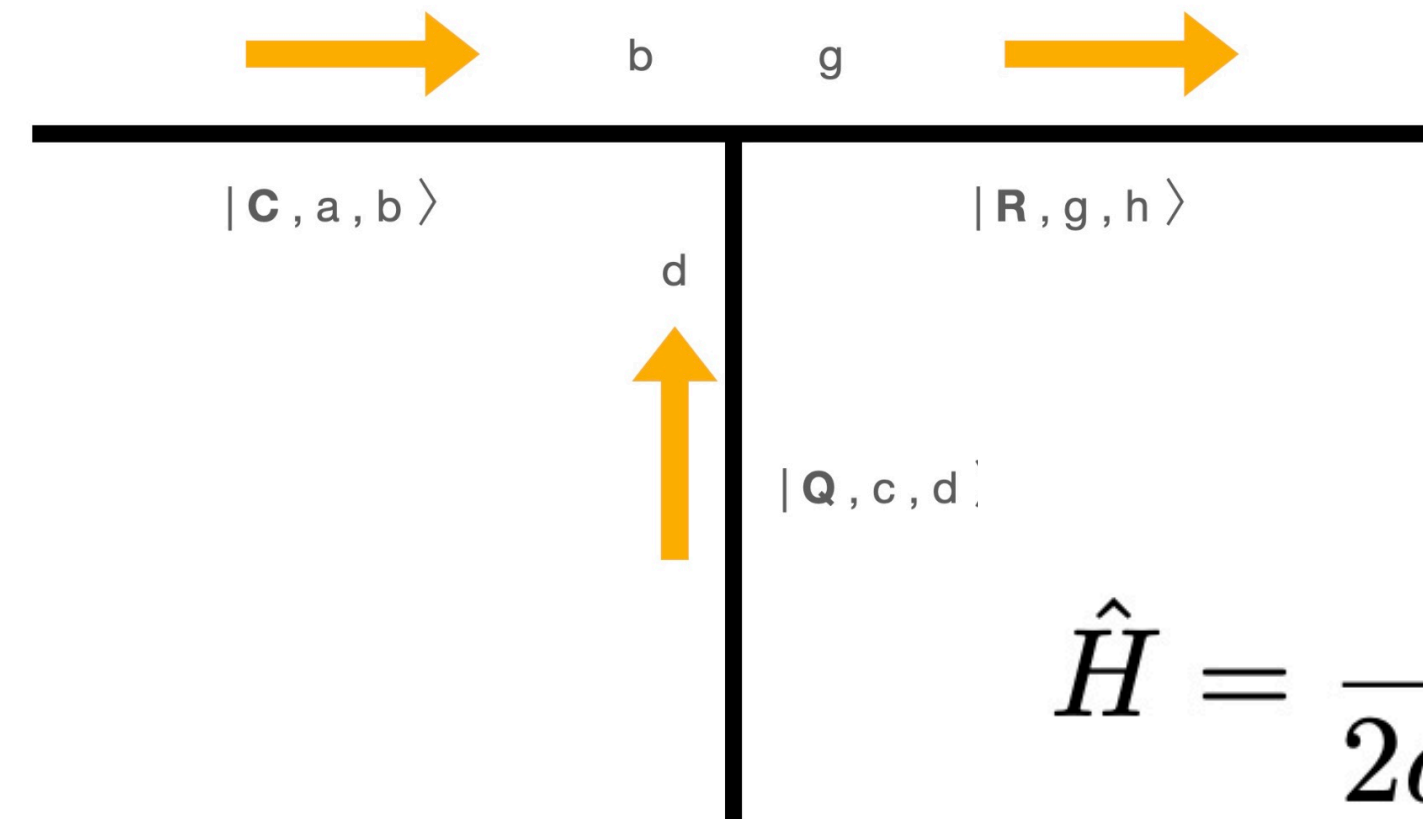
Magnetic Field operator

Off-diagonal on electric basis



Truncations in irrep space !!!!!

Why Non-Abelian is More Complex than Abelian



$$\hat{H} = \frac{g^2}{2a^{d-2}} \sum_{b, \text{links}} |\hat{\mathbf{E}}^{(b)}|^2 + \frac{1}{2a^{4-d}g^2} \sum_{\text{plaquettes}} \left[2N_c - \hat{\square}(\mathbf{x}) - \hat{\square}^\dagger(\mathbf{x}) \right]$$

$$\begin{aligned} \hat{\square}(\mathbf{x}) &= \text{Tr} \left[\hat{U}^{\mathbf{3}}(\mathbf{x}, \mathbf{x} + a\boldsymbol{\mu}) \hat{U}^{\mathbf{3}}(\mathbf{x} + a\boldsymbol{\mu}, \mathbf{x} + a\boldsymbol{\mu} + a\boldsymbol{\nu}) \hat{U}^{\mathbf{3}}(\mathbf{x} + a\boldsymbol{\mu} + a\boldsymbol{\nu}, \mathbf{x} + a\boldsymbol{\nu}) \hat{U}^{\mathbf{3}}(\mathbf{x} + a\boldsymbol{\nu}, \mathbf{x}) \right] \\ &= \hat{U}_{\alpha, \beta}^{\mathbf{3}} \hat{U}_{\beta, \gamma}^{\mathbf{3}} \left(\hat{U}_{\gamma, \delta}^{\mathbf{3}} \right)^\dagger \left(\hat{U}_{\delta, \alpha}^{\mathbf{3}} \right)^\dagger, \end{aligned}$$

$$\hat{U}_{\alpha, \beta}^{\mathbf{r}} |\mathbf{R}, a, b\rangle = \sum_{\oplus \mathbf{R}', \vec{\Gamma}} \sum_{a' b'} \sqrt{\frac{\dim(\mathbf{R})}{\dim(\mathbf{R}')}} |\mathbf{R}', a', b'\rangle \langle \mathbf{R}, a, \mathbf{r}, \alpha | \mathbf{R}', a' \rangle_{\Gamma_1} \langle \mathbf{R}', b' | \mathbf{R}, b, \mathbf{r}, \beta \rangle_{\Gamma_2}$$

Yang-Mills

First Attempts at SU(2) in 2+1D

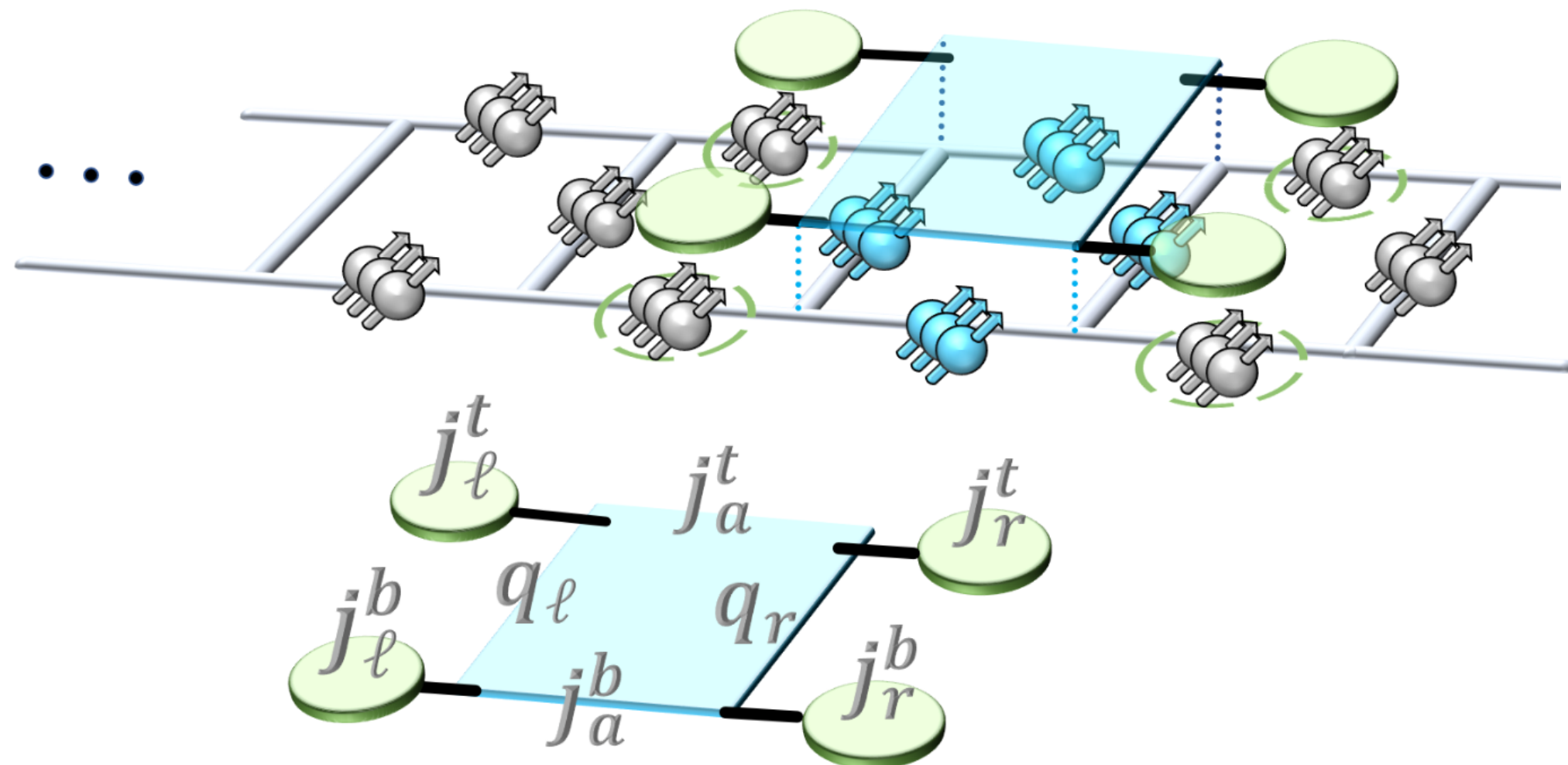
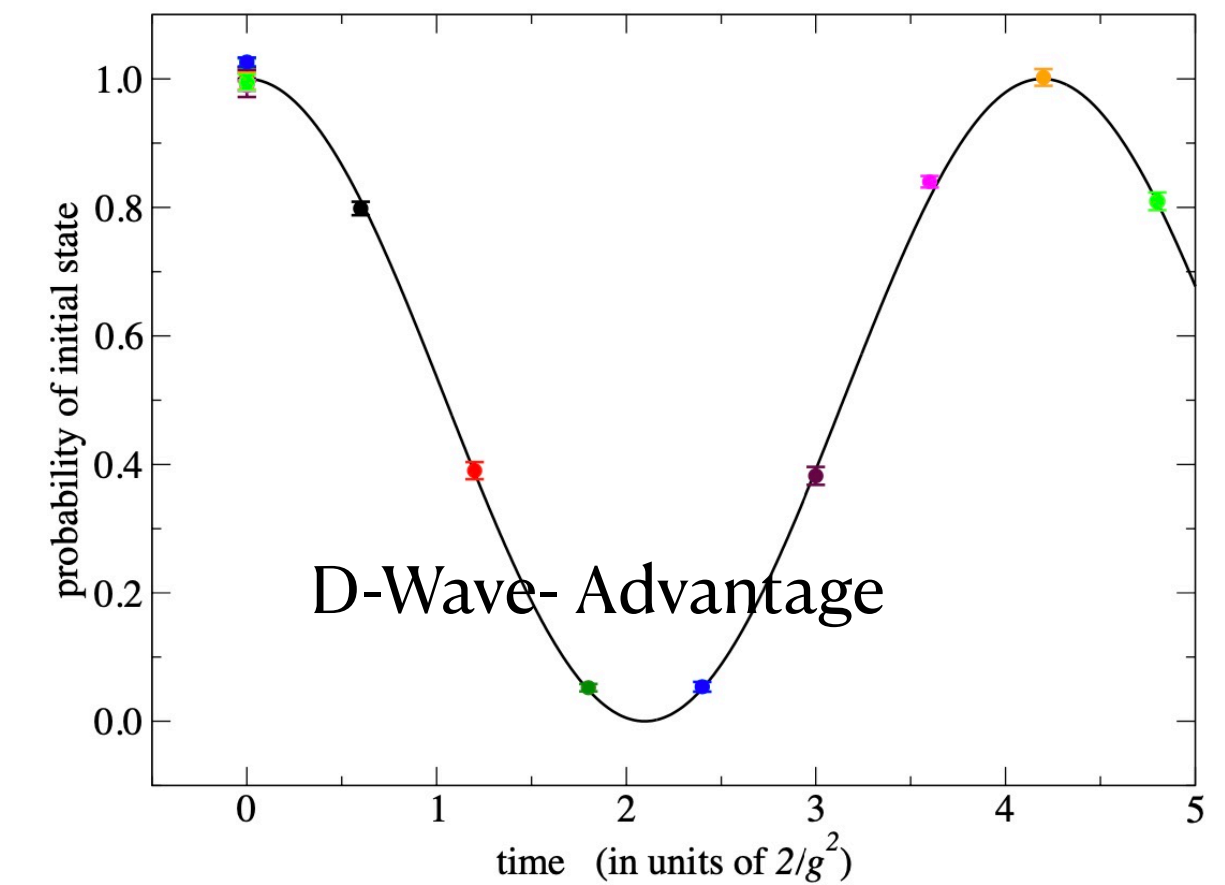
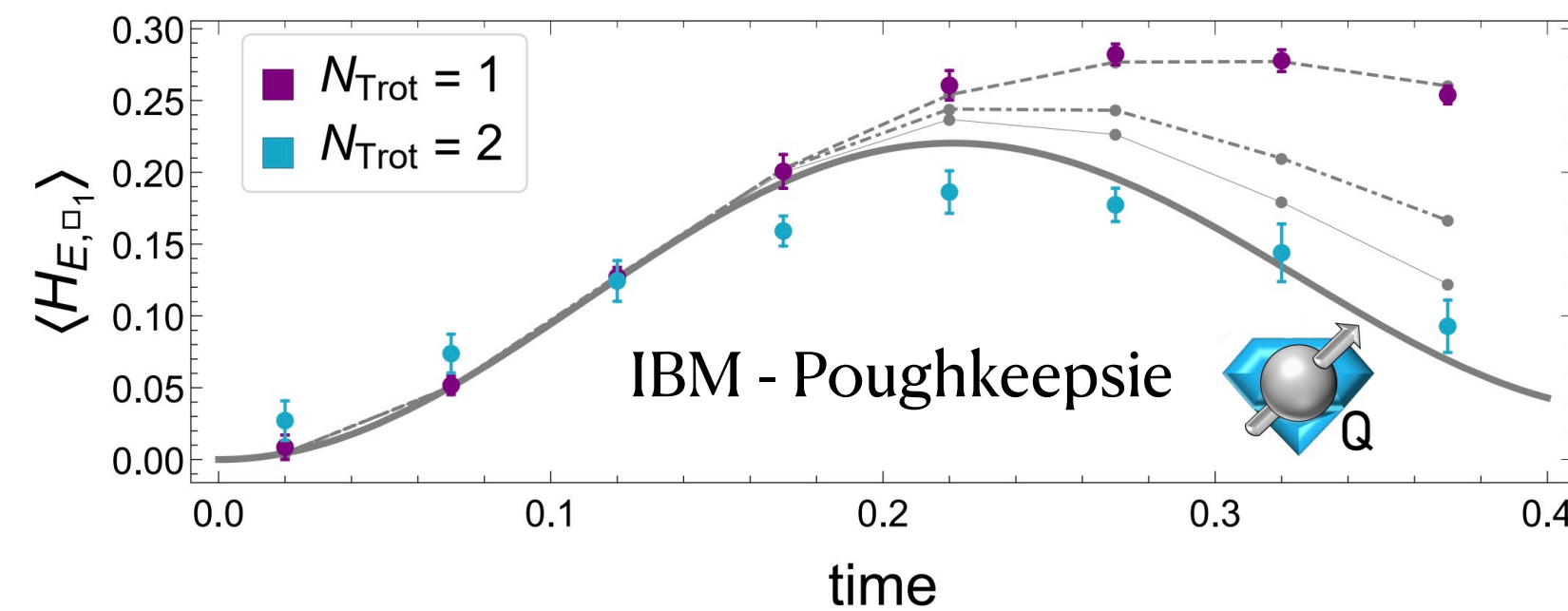


Also see Mari Carmen Banuls, Karl Jansen et al

$$\begin{matrix} T & a_1 \dots a_p \\ & b_1 \dots b_q \end{matrix} \xrightarrow{\text{Gauge Invariance}} R(p, q)$$

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

Natalie Klco, Jesse R. Stryker and Martin J. Savage¹
¹Institute for Nuclear Theory, University of Washington, Seattle, WA 98195-1550, USA
 (Dated: August 19, 2019 - 13:7)



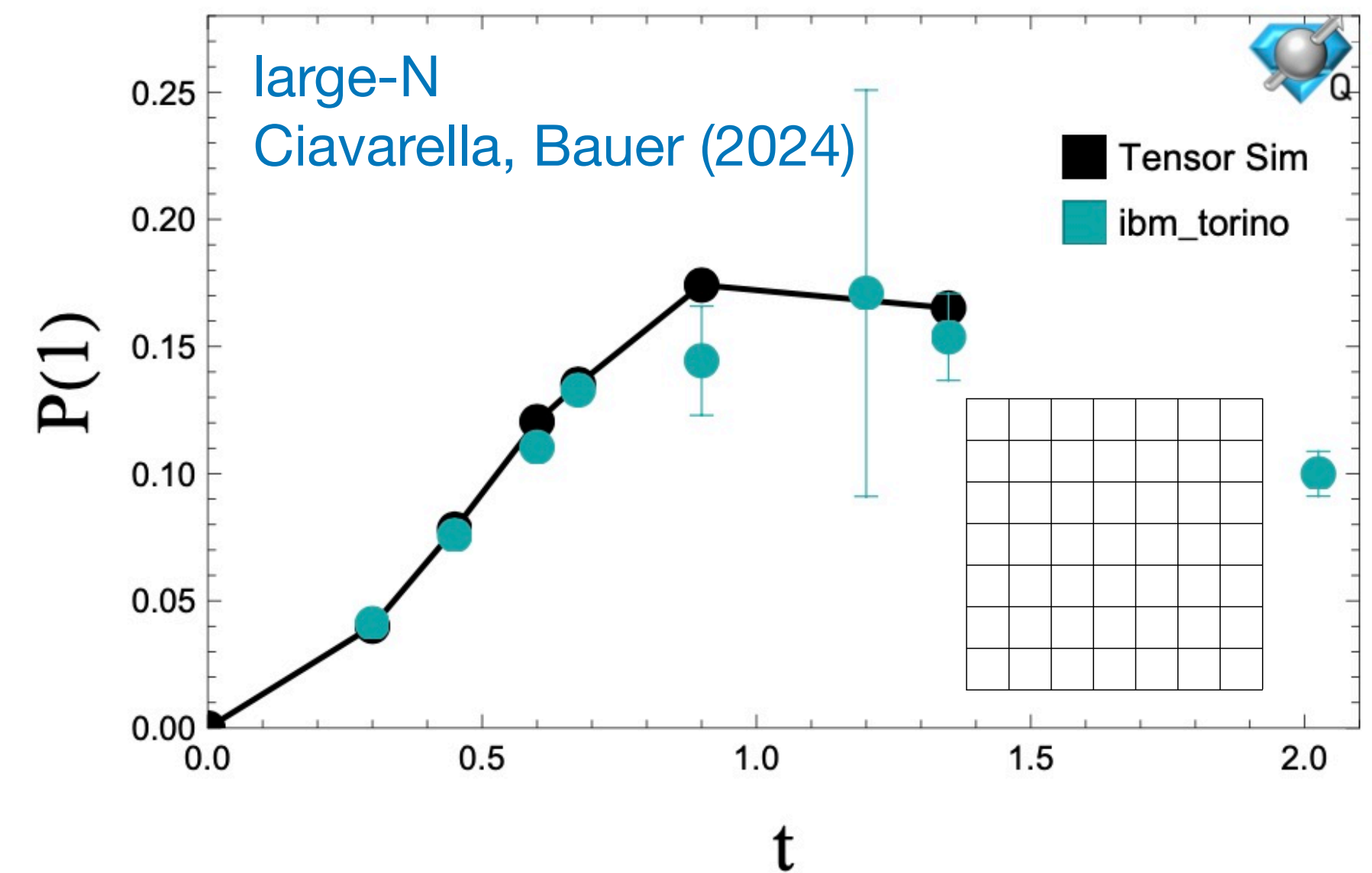
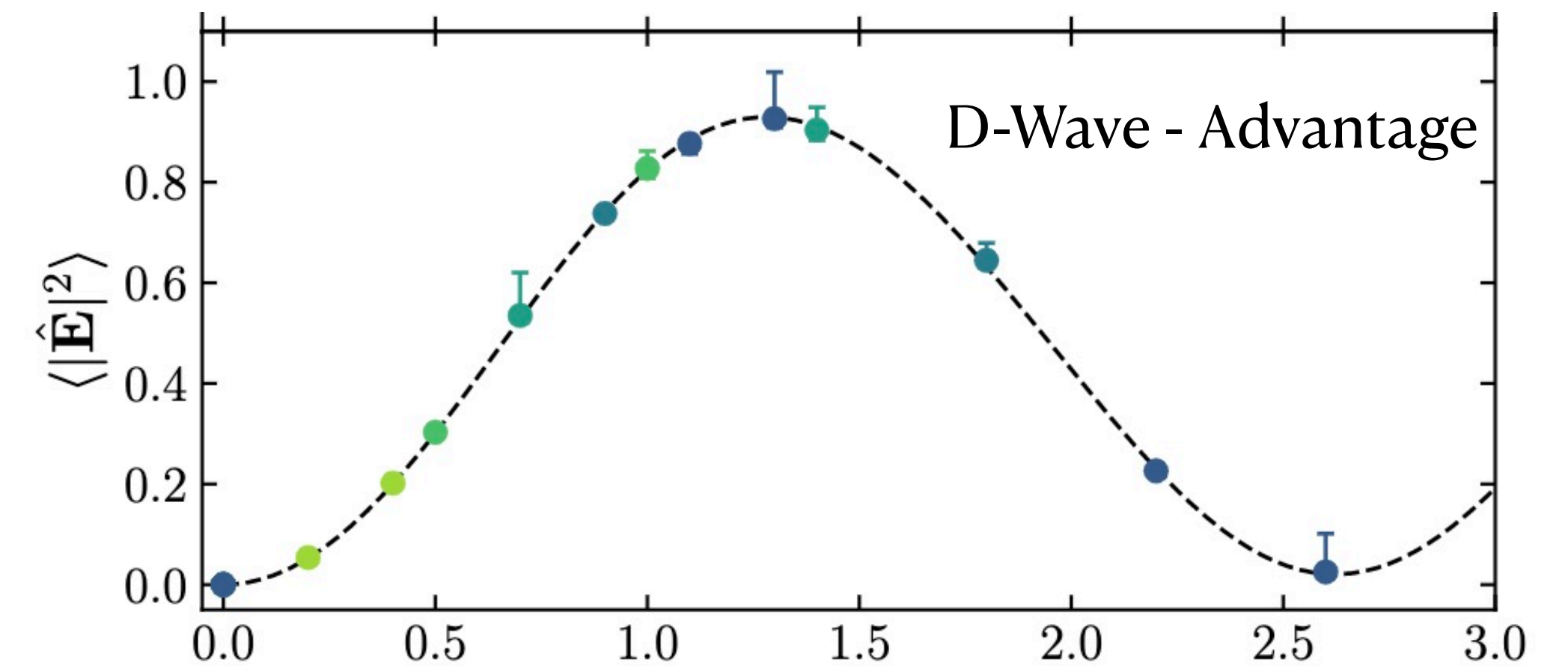
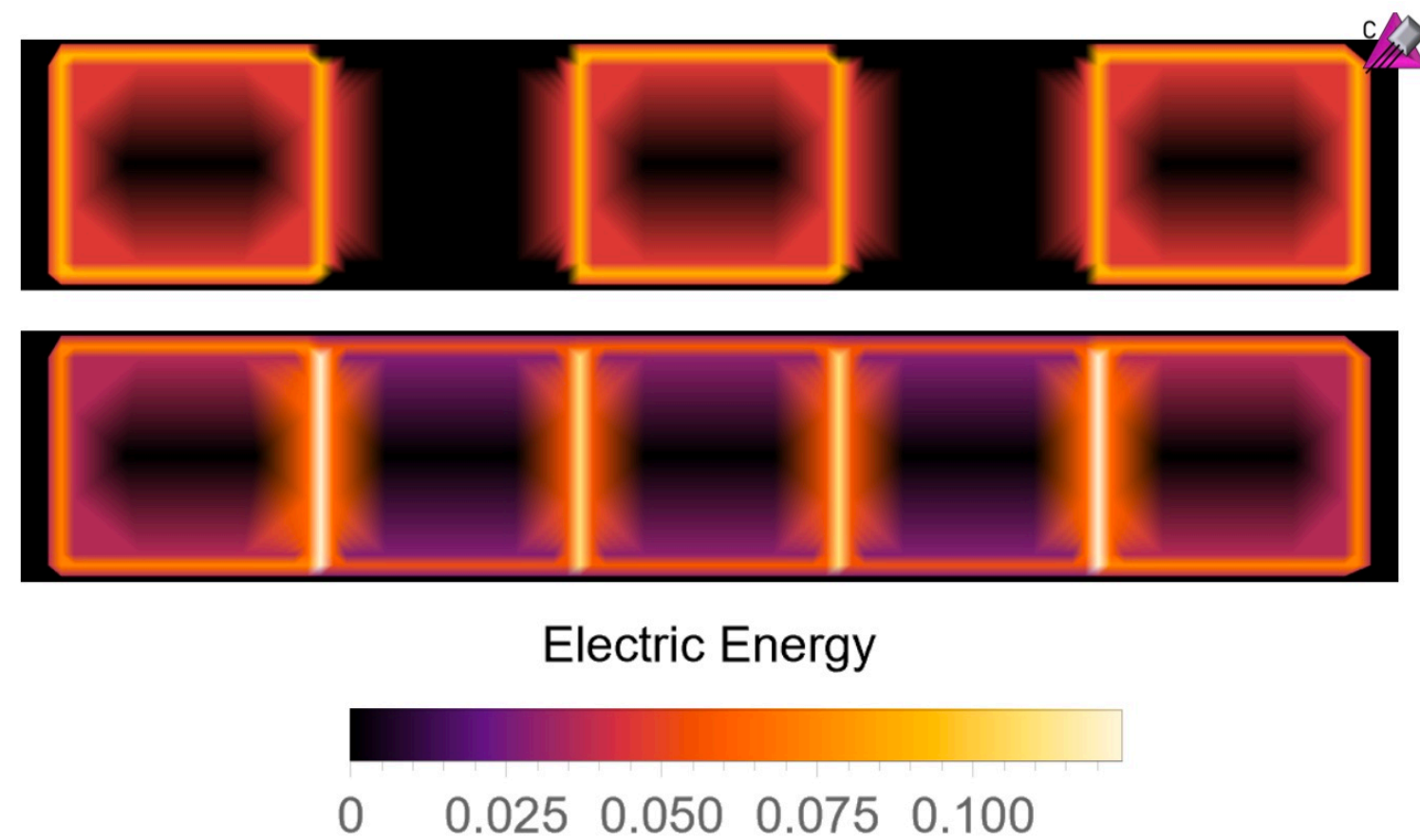
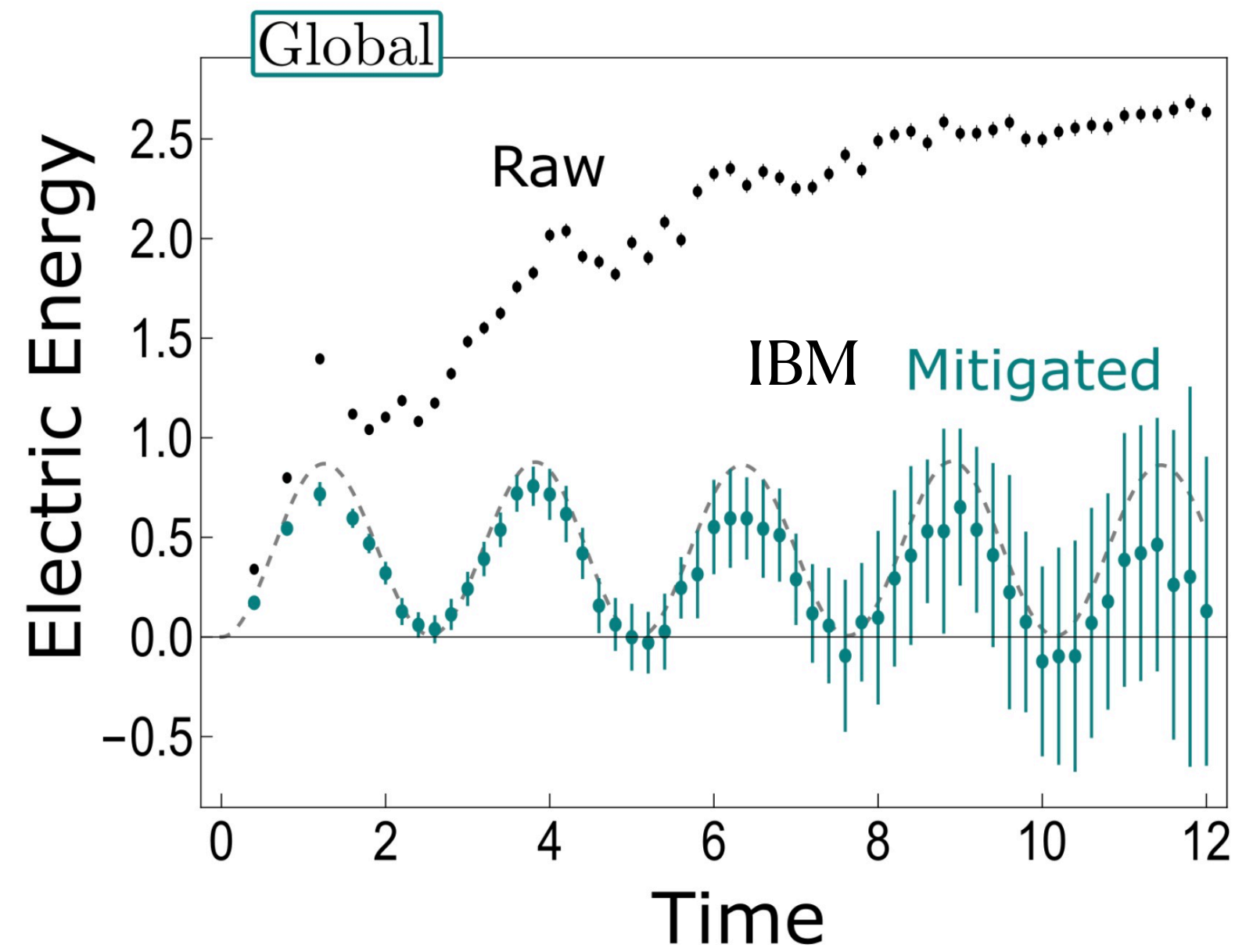
- Only dynamical gauge fields
- Gauge Variant Completions (GVC)
- Severely truncated in field space
- 2D, but really 1D

SU(2) lattice gauge theory on a quantum annealer

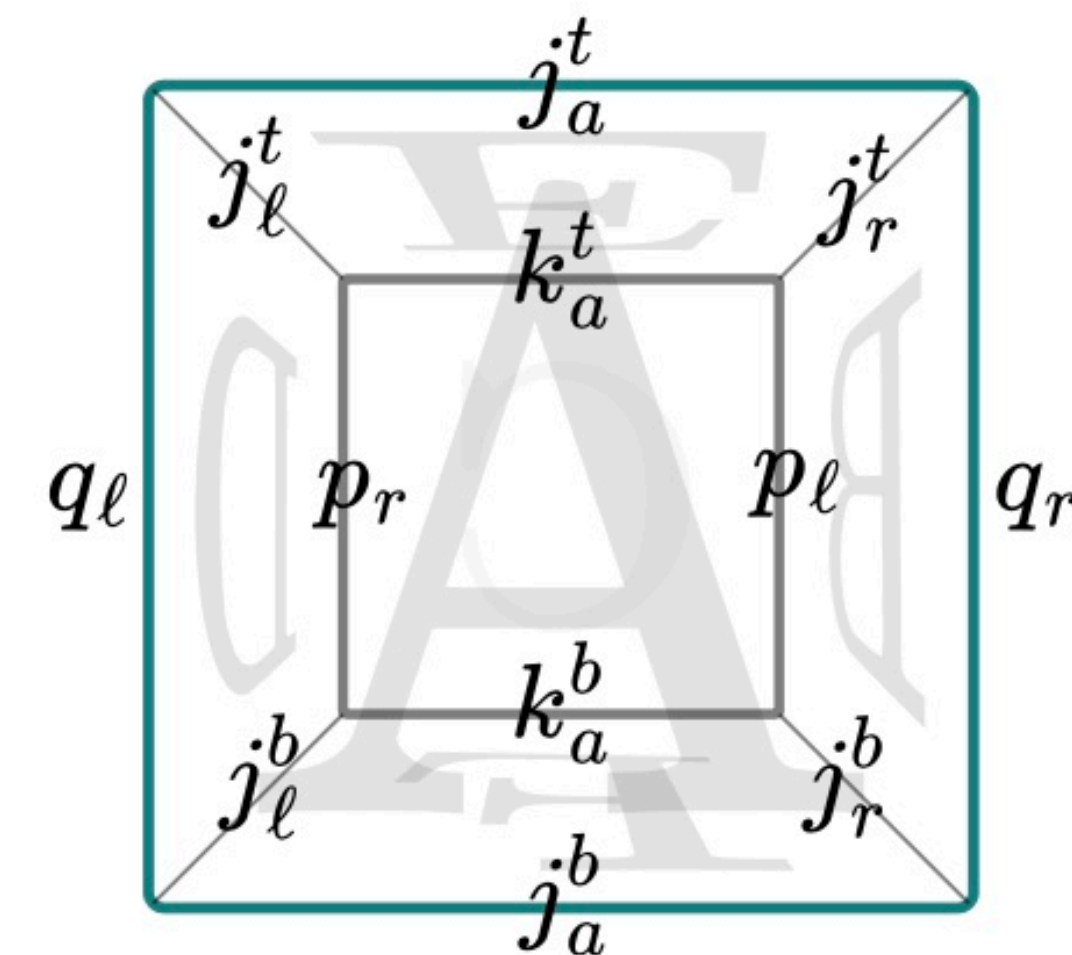
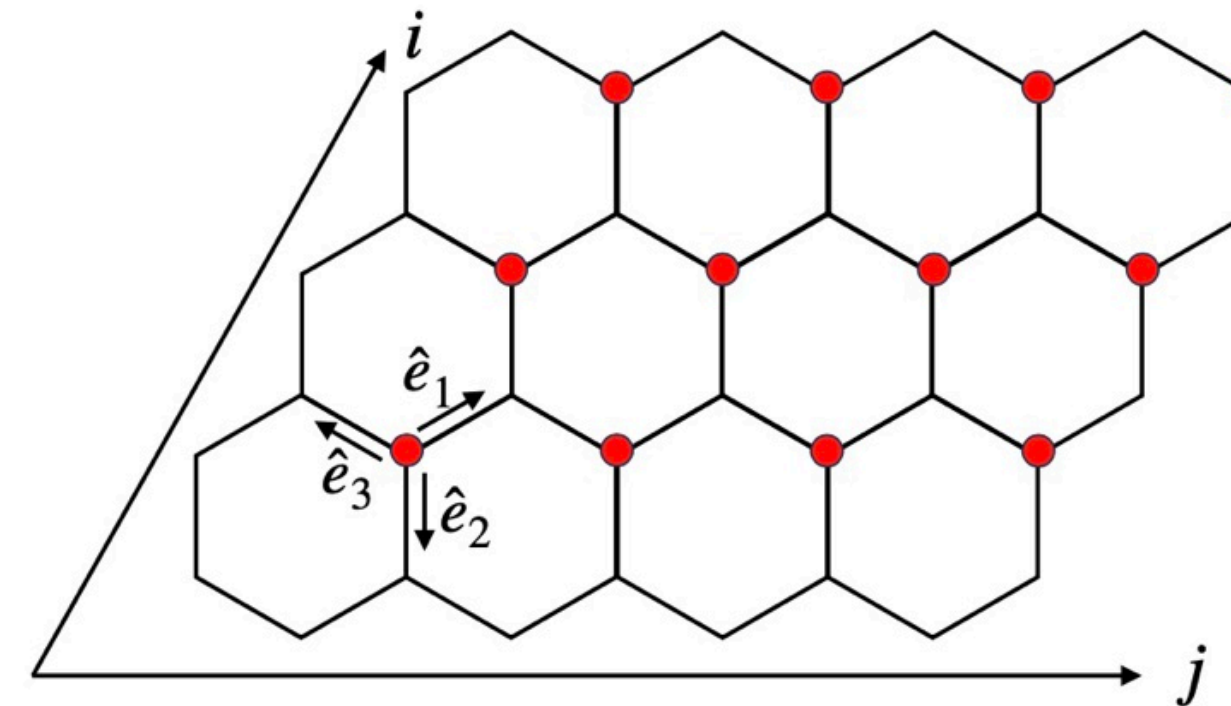
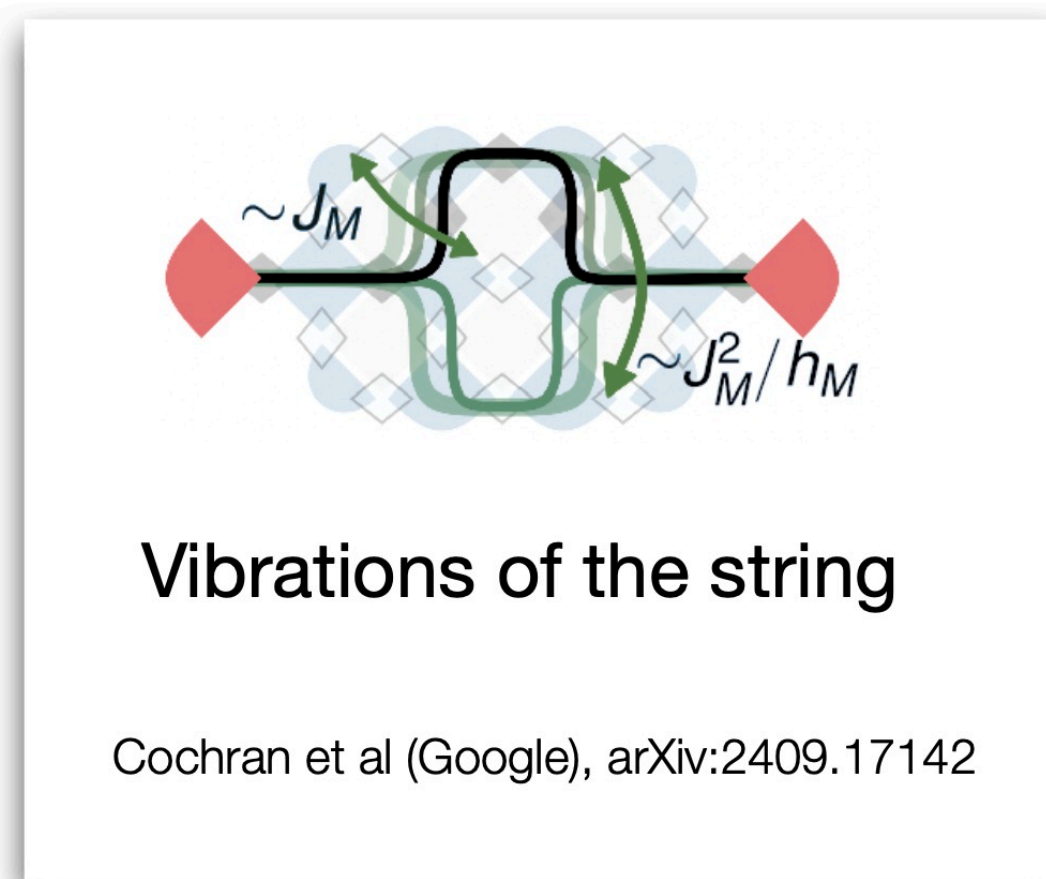
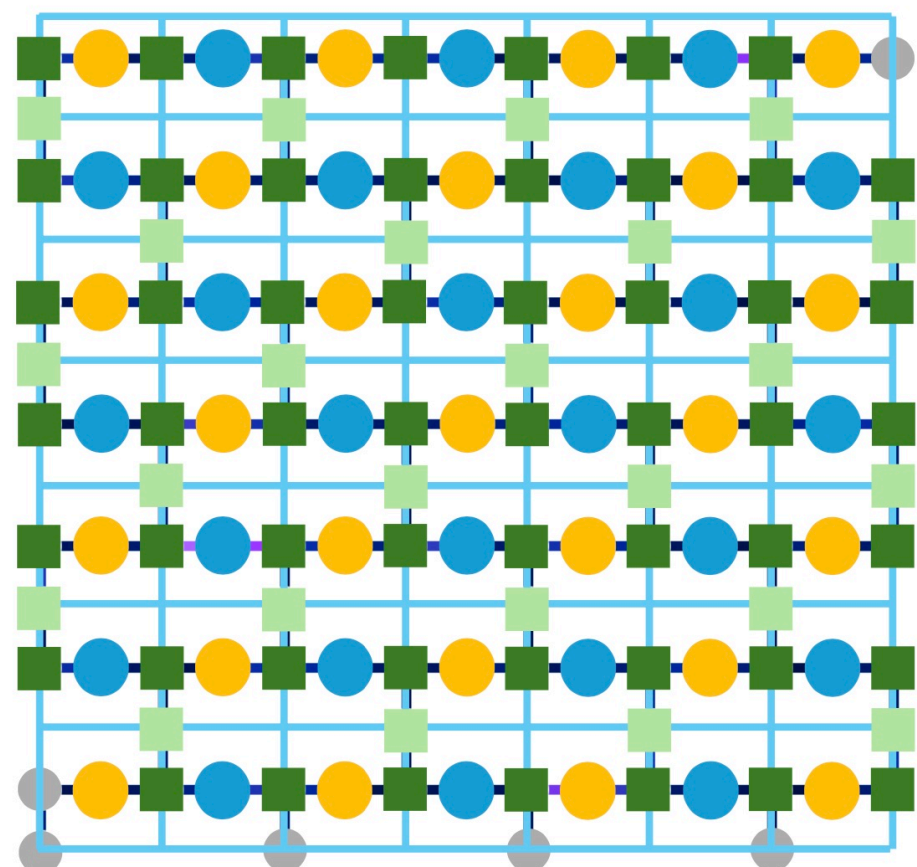
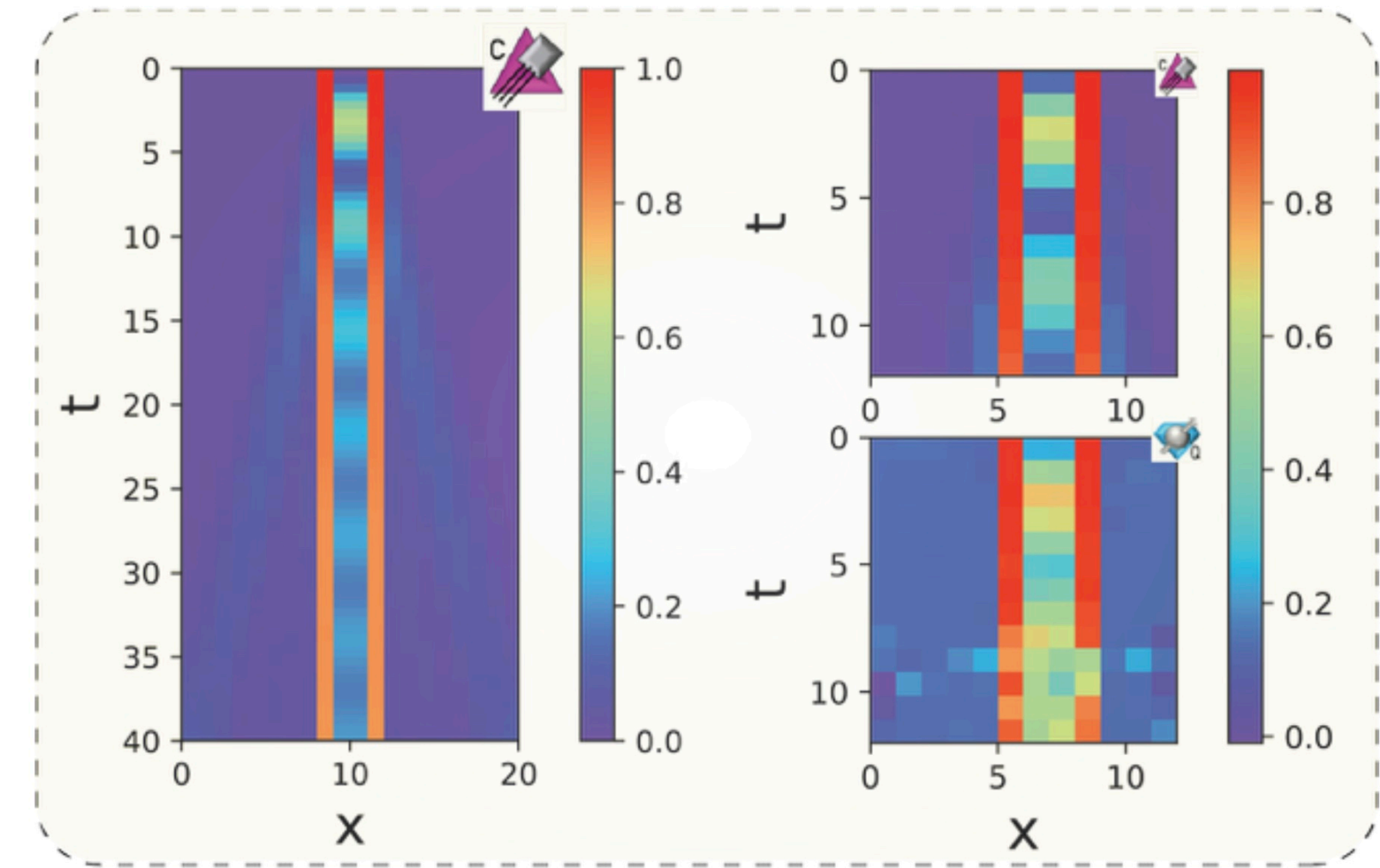
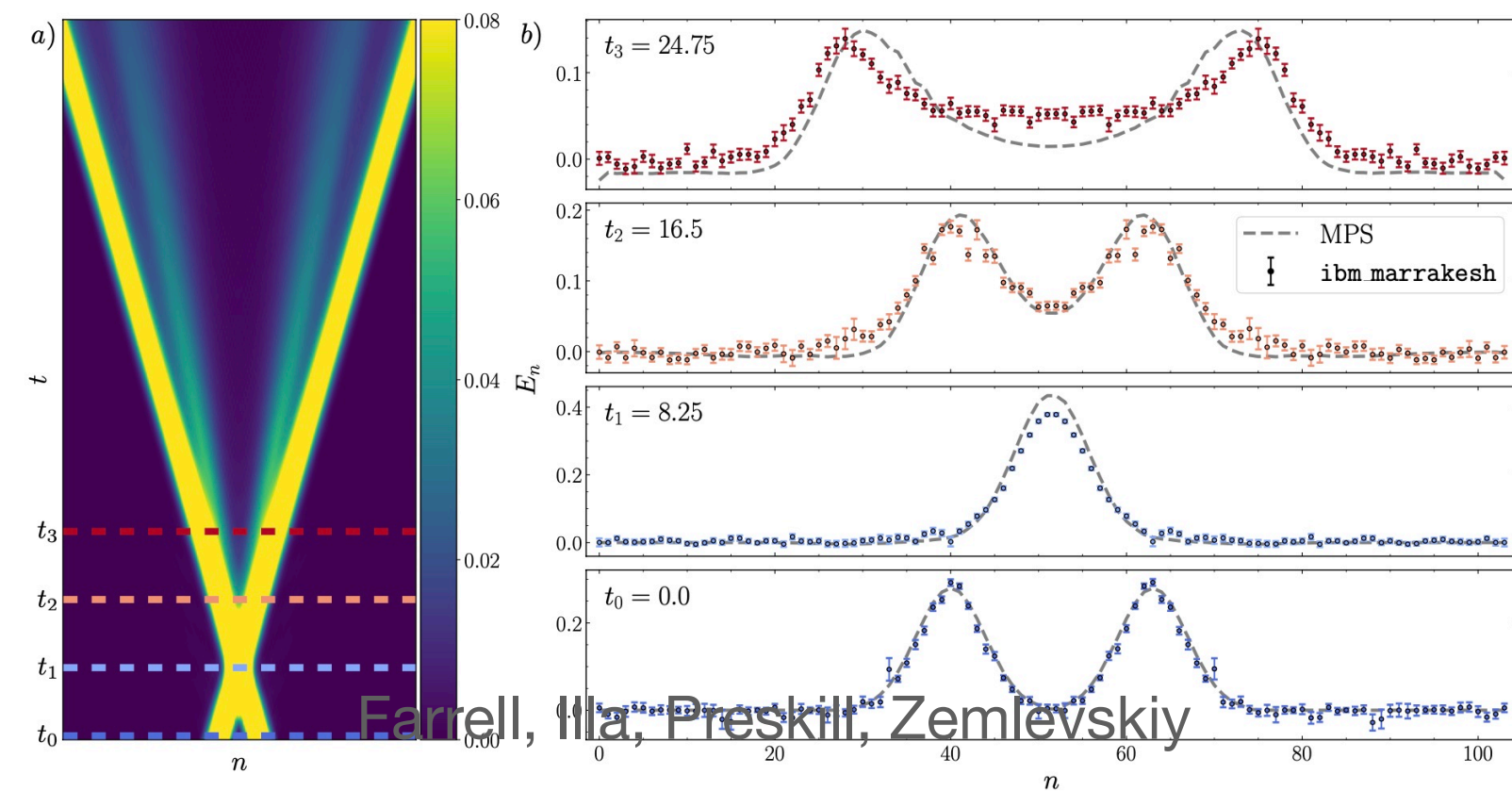
Sarmed A Rahman, Randy Lewis, Emanuele Mendicelli, and Sarah Powell
 Department of Physics and Astronomy, York University, Toronto, Ontario, M3J 1P3, Canada
 (Dated: August 3, 2021)

Plaquette chain will collapse to 1+1 dim in continuum limit

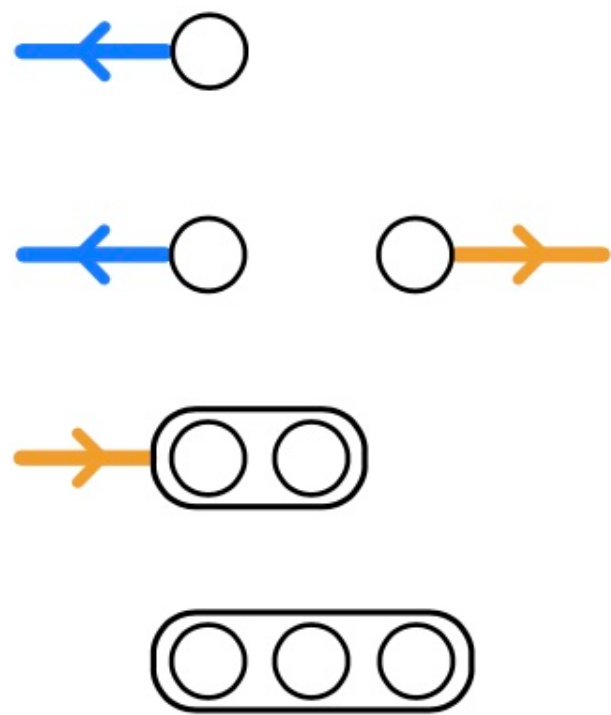
SU(3) Yang-Mills Plaquettes - Examples



Some Recent Simulation Results

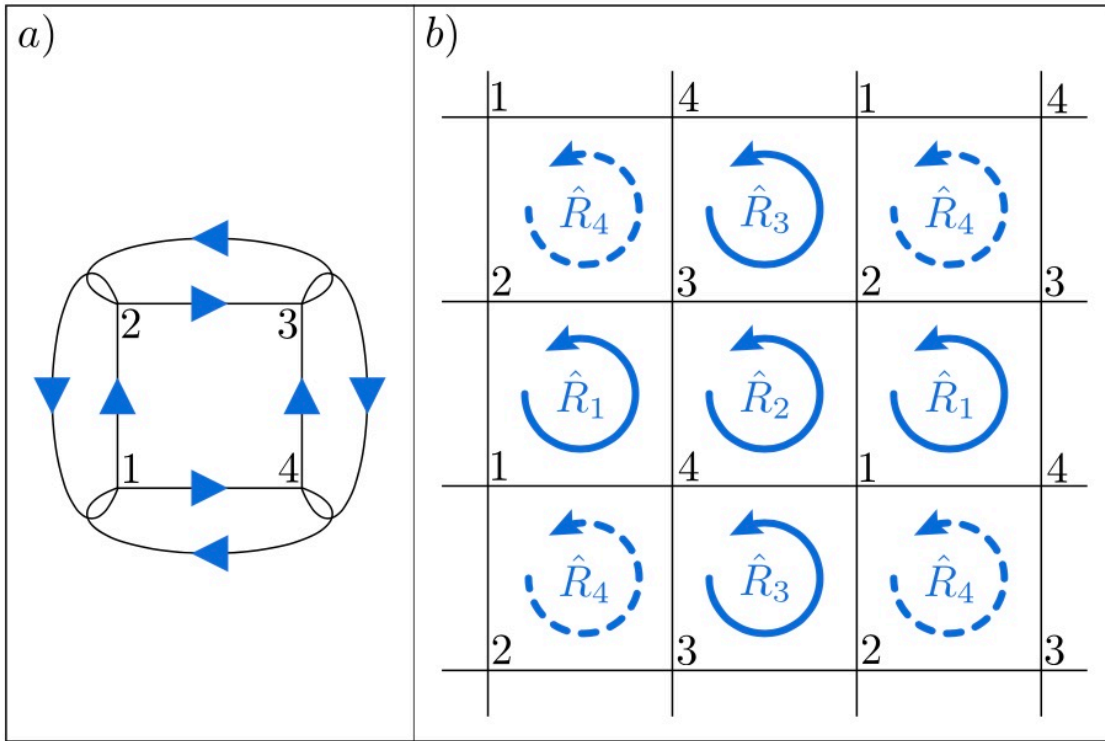


Taming Non-Abelian Gauge Space



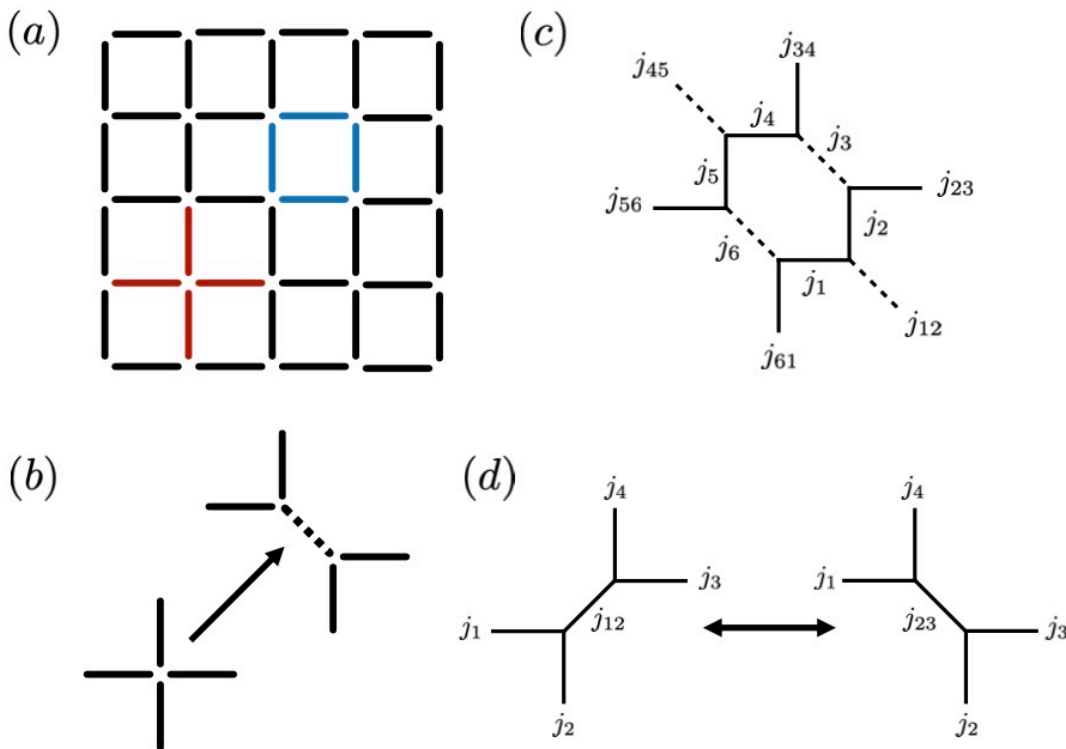
Loop-string-hadron formulation of an $SU(3)$ gauge theory with dynamical quarks

Saurabh V. Kadam,^{1,*} Indrakshi Raychowdhury,^{2,†} and Jesse R. Stryker^{1,‡}



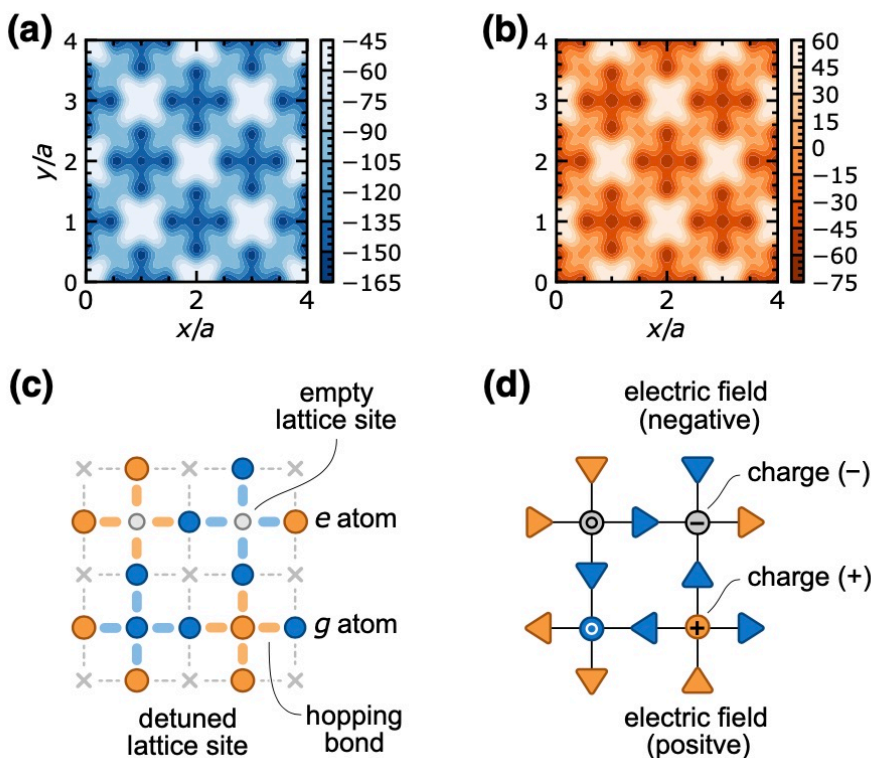
A resource efficient approach for quantum and classical simulations of gauge theories in particle physics

Jan F. Haase^{1,2}, Luca Dellantonio^{1,2}, Alessio Celi^{3,4}, Danny Paulson^{1,2}, Angus Kan^{1,2}, Karl Jansen⁵, and Christine A. Muschik^{1,2,6}



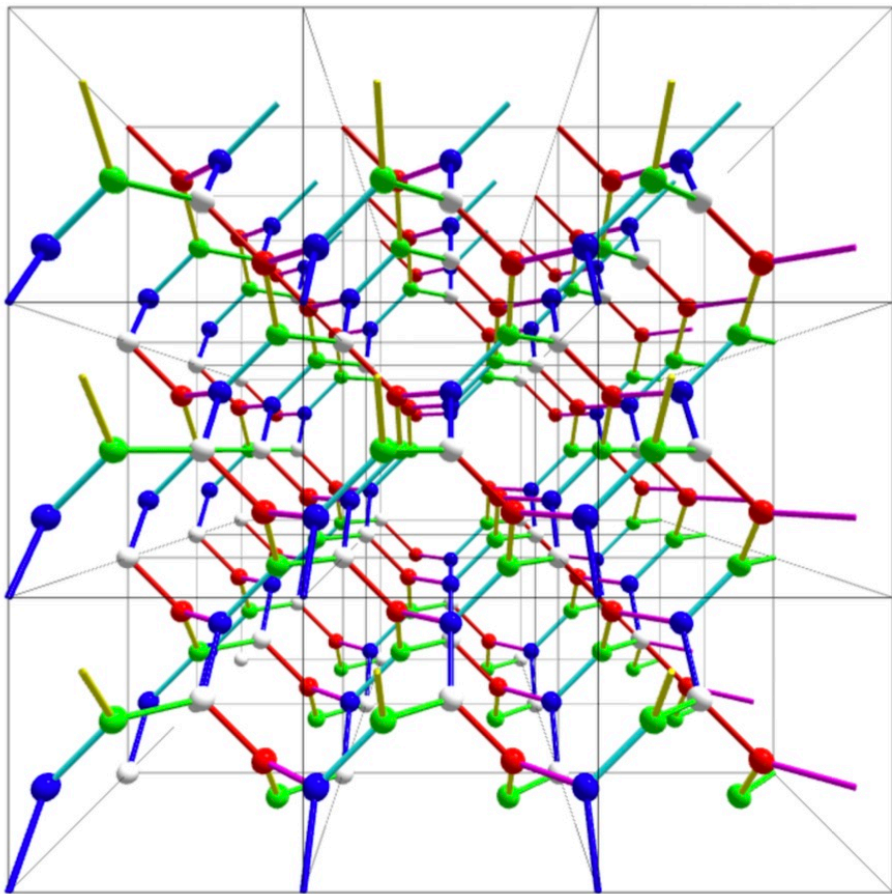
Quantum and classical spin network algorithms for q -deformed Kogut-Susskind gauge theories

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



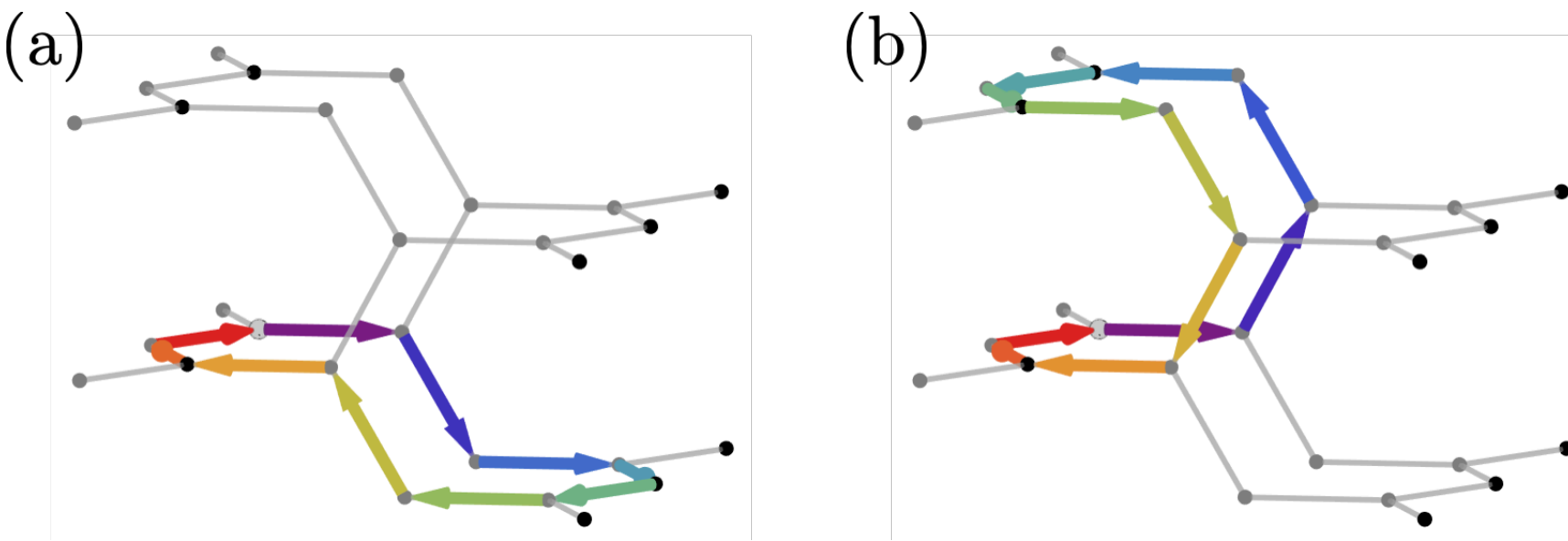
Ab Initio Derivation of Lattice-Gauge-Theory Dynamics for Cold Gases in Optical Lattices

Federica Maria Surace^{1,*} Pierre Fromholz^{2,3,†} Nelson Darkwah Oppong^{4,5,§} Marcello Dalmonte^{2,3} and Monika Aidelsburger^{4,5,‡}



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

Ali H. Z. Kavaki^{*} and Randy Lewis[†]



[Submitted on 12 Mar 2025]

Improved Honeycomb and Hyper-Honeycomb Lattice Hamiltonians for Quantum Simulations of Non-Abelian Gauge Theories

Marc Illa, Martin J. Savage, Xiaojun Yao

Transport Properties

Shear Viscosity in 2+1D SU(2)



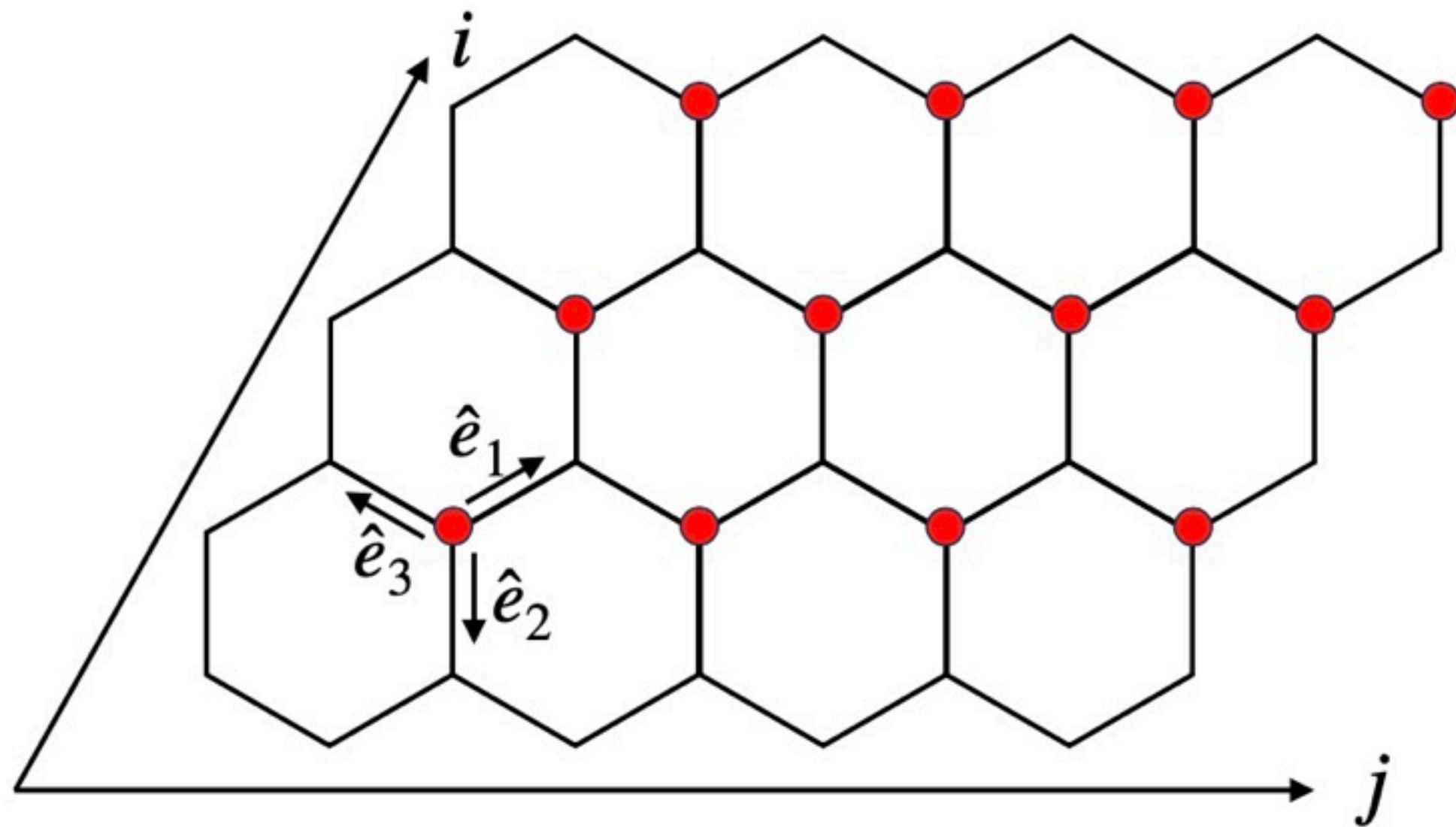
Editors' Suggestion

Open Access

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

Berndt Mueller and Xiaojun Yao

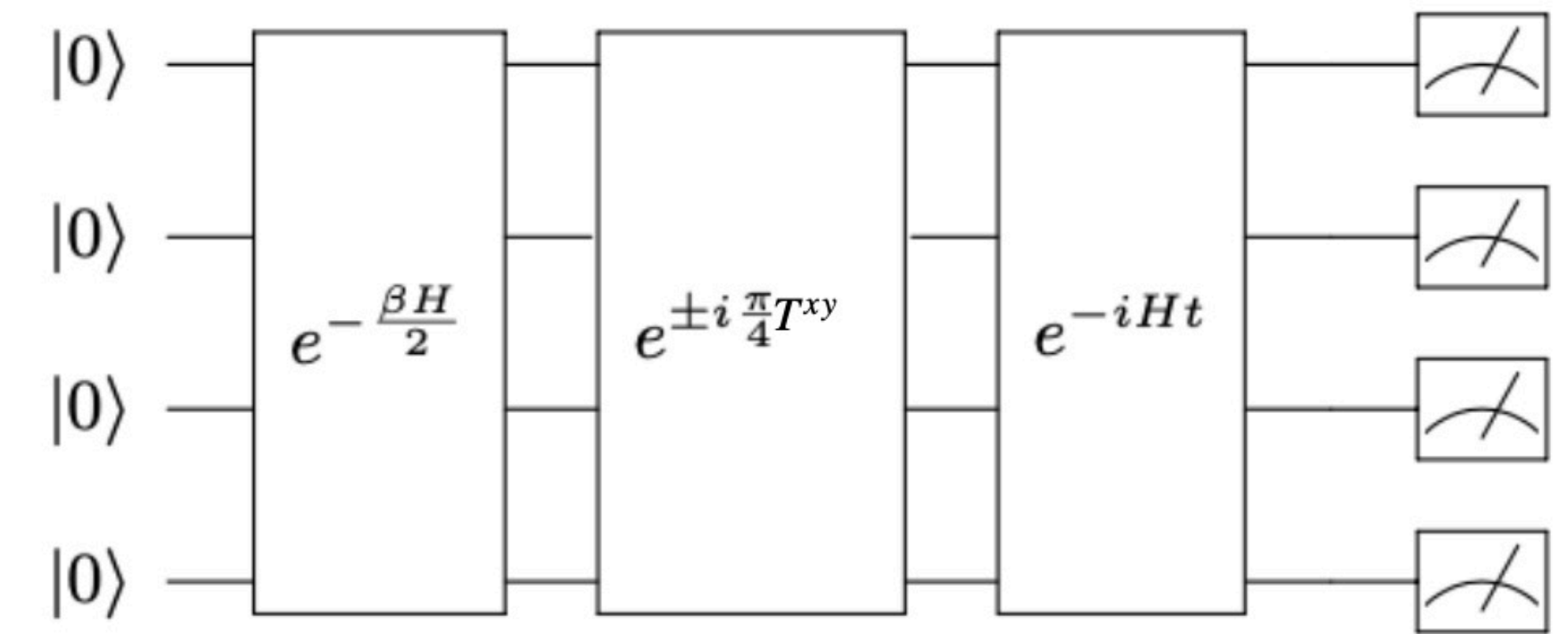
Francesco Turro, Anthony Ciavarella, and Xiaojun Yao
Phys. Rev. D **109**, 114511 – Published 13 June 2024



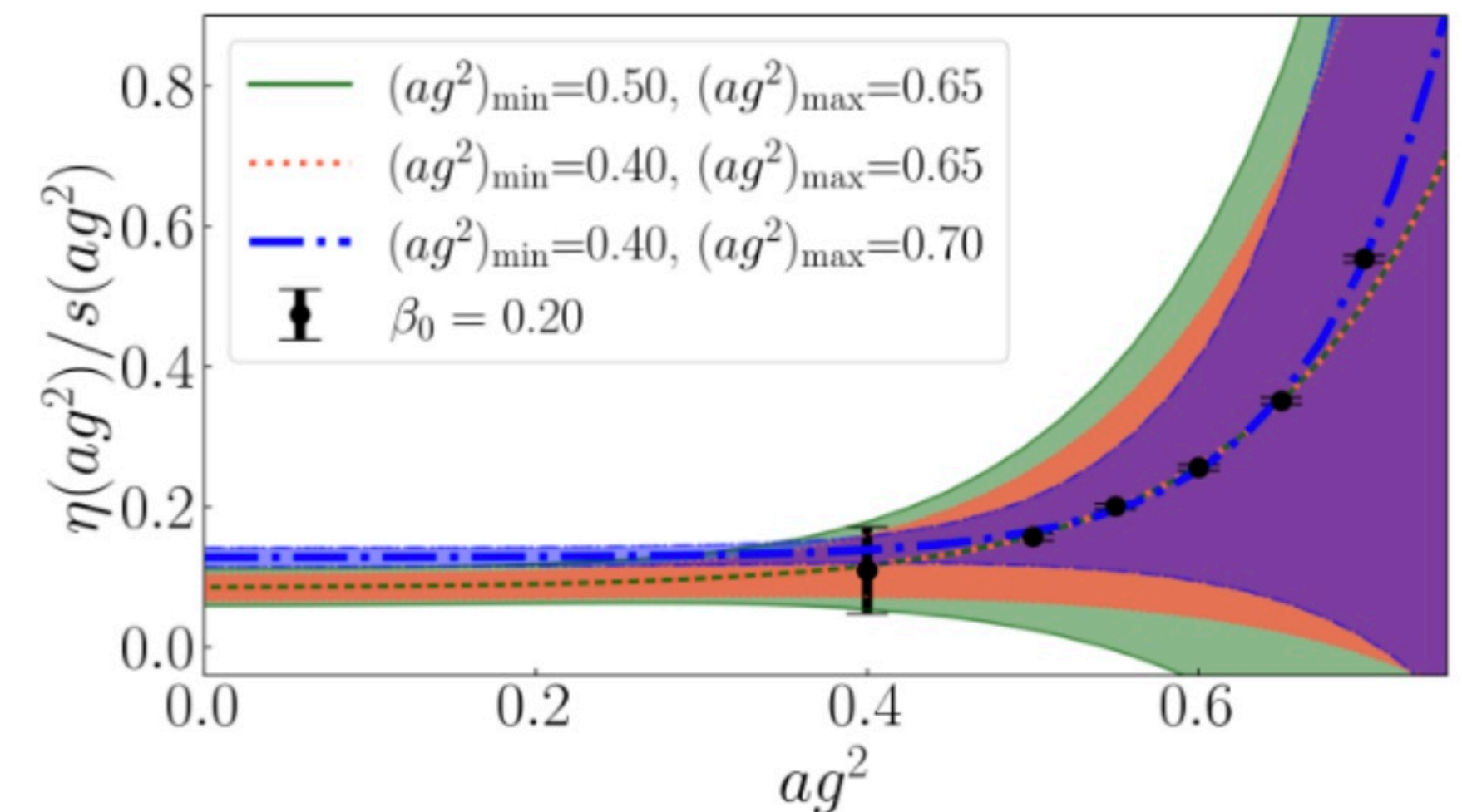
$$H = \frac{3\sqrt{3}g^2}{4} \sum_{\text{links}} E_i^a E_i^a - \frac{4\sqrt{3}}{9g^2 a^2} \sum_{\text{plaqs}} \text{Hexagon}$$

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

Quantum algorithm for G_r^{xy}



On 4×4 lattice w/ $j_{\text{max}} = 0.5$

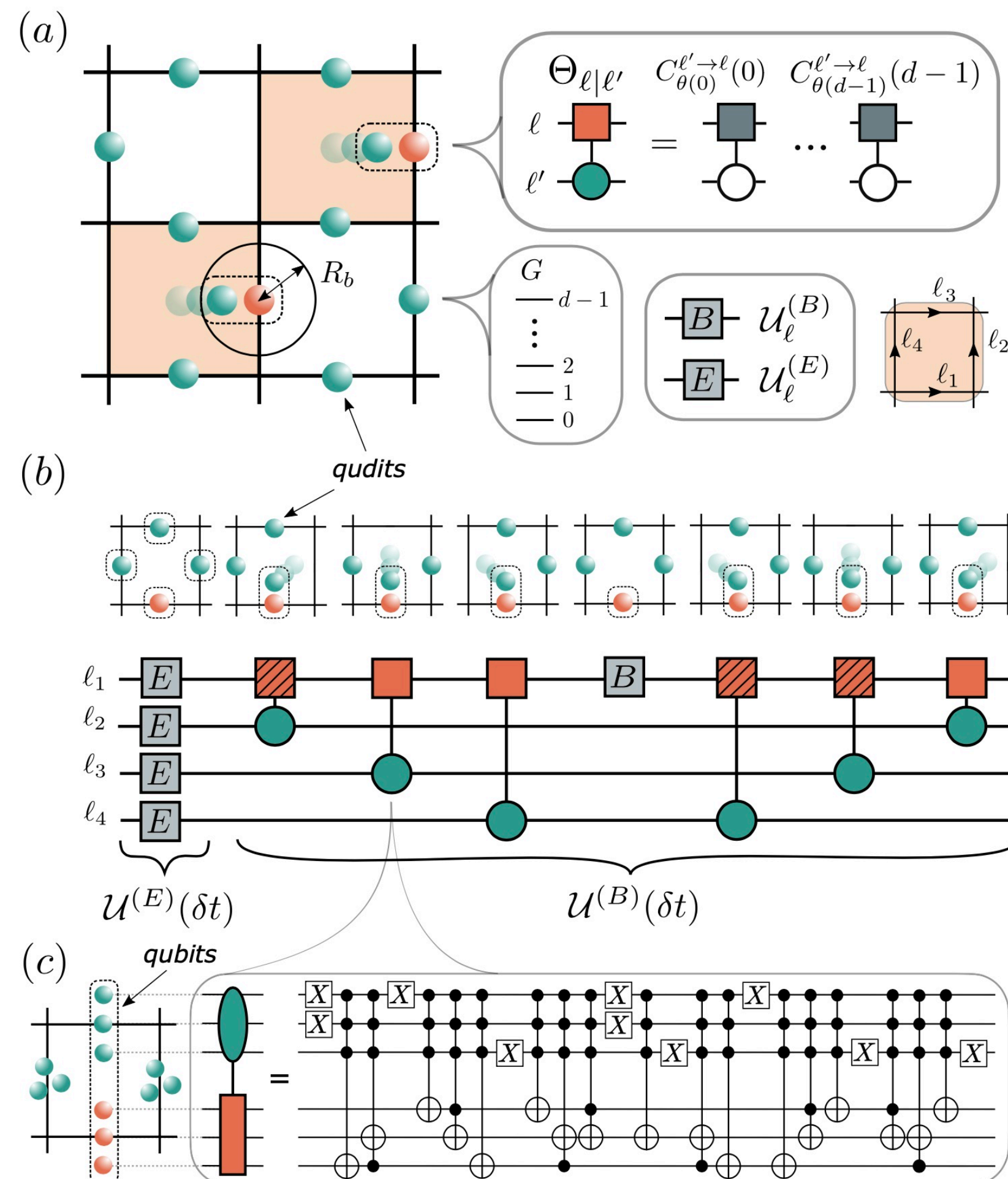


At the Quantum Limit, same as liquid created in heavy-ion collisions

Qudits

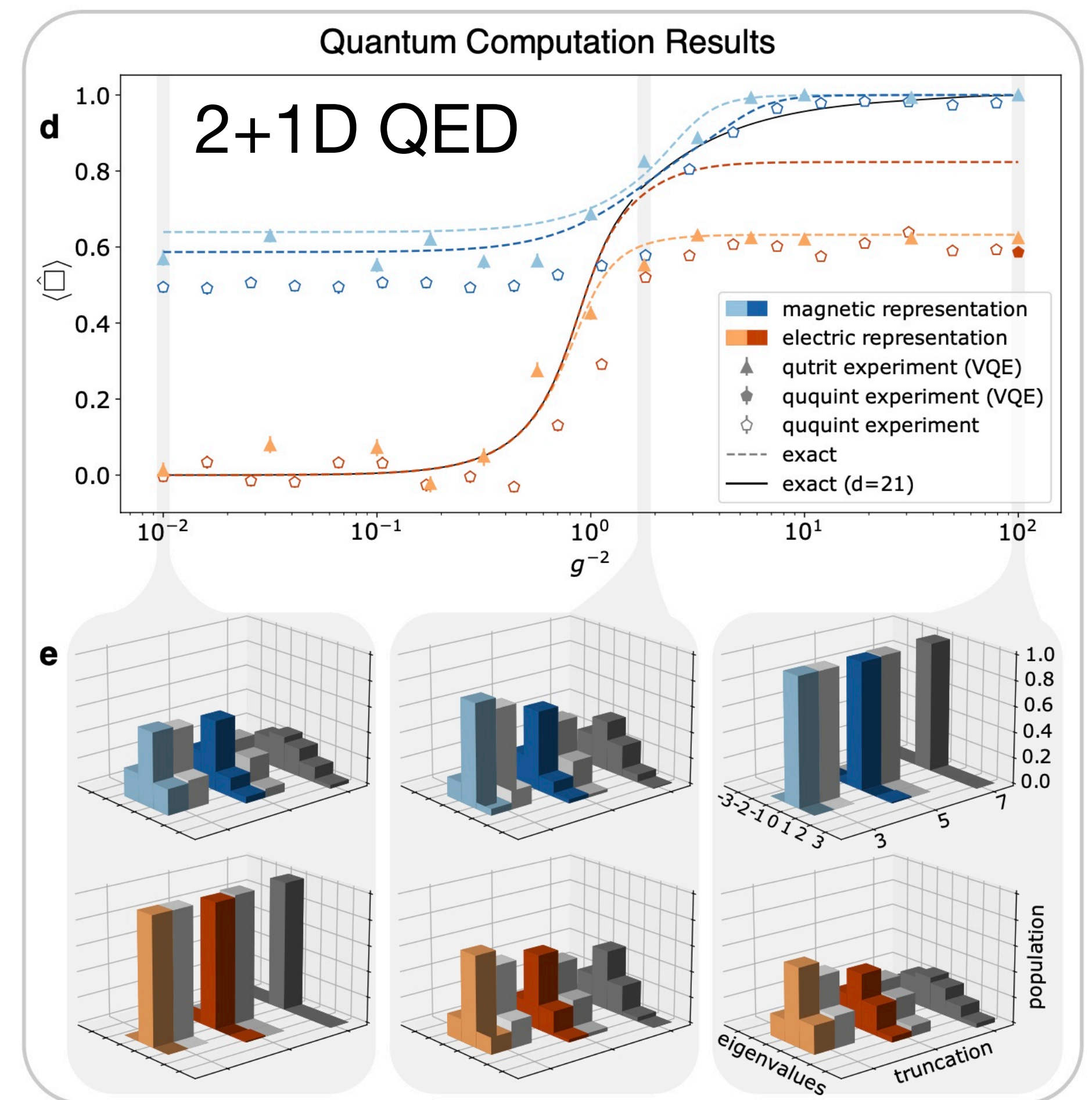
Hardware efficient quantum simulation of non-abelian gauge theories with qudits on Rydberg platforms

Daniel González-Cuadra,^{1,2,*} Torsten V. Zache,^{1,2,*} Jose Carrasco,¹ Barbara Kraus,¹ and Peter Zoller^{1,2}

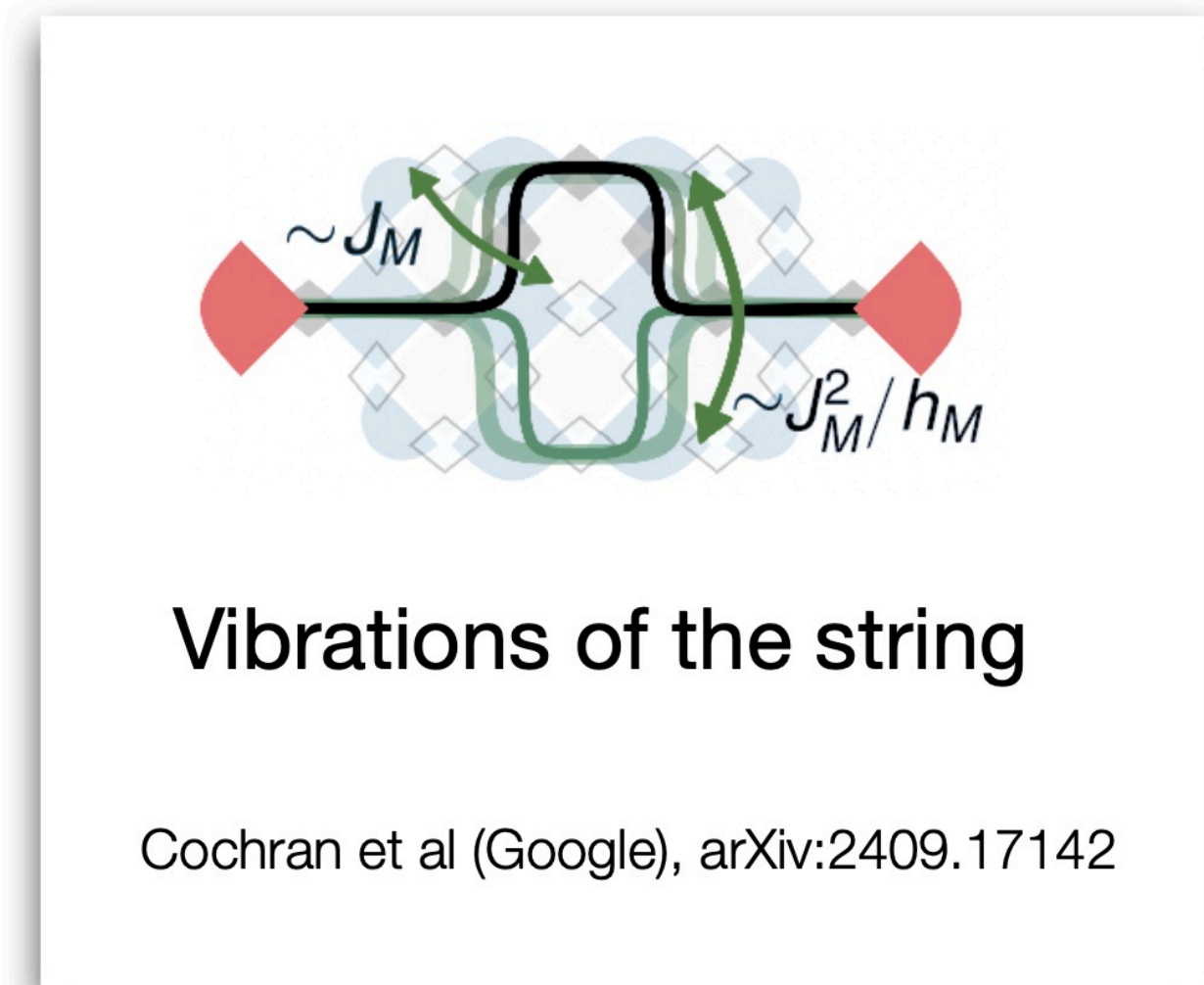
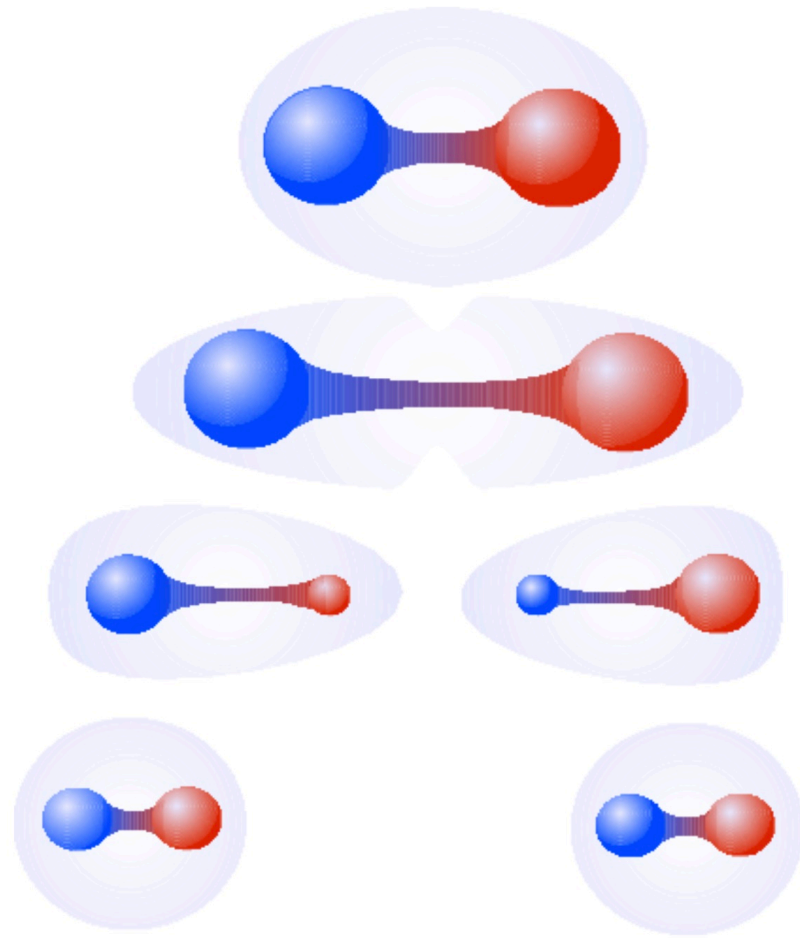


Simulating 2D lattice gauge theories on a qudit quantum computer

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



String Breaking as an Example



Quantum simulation of string breaking: summary

Models

1+1D

- Z_2 LGT, trapped ions
- $SU(2)$ LGT, superconducting qubits
- $U(1)$ LGT, atoms in optical lattices

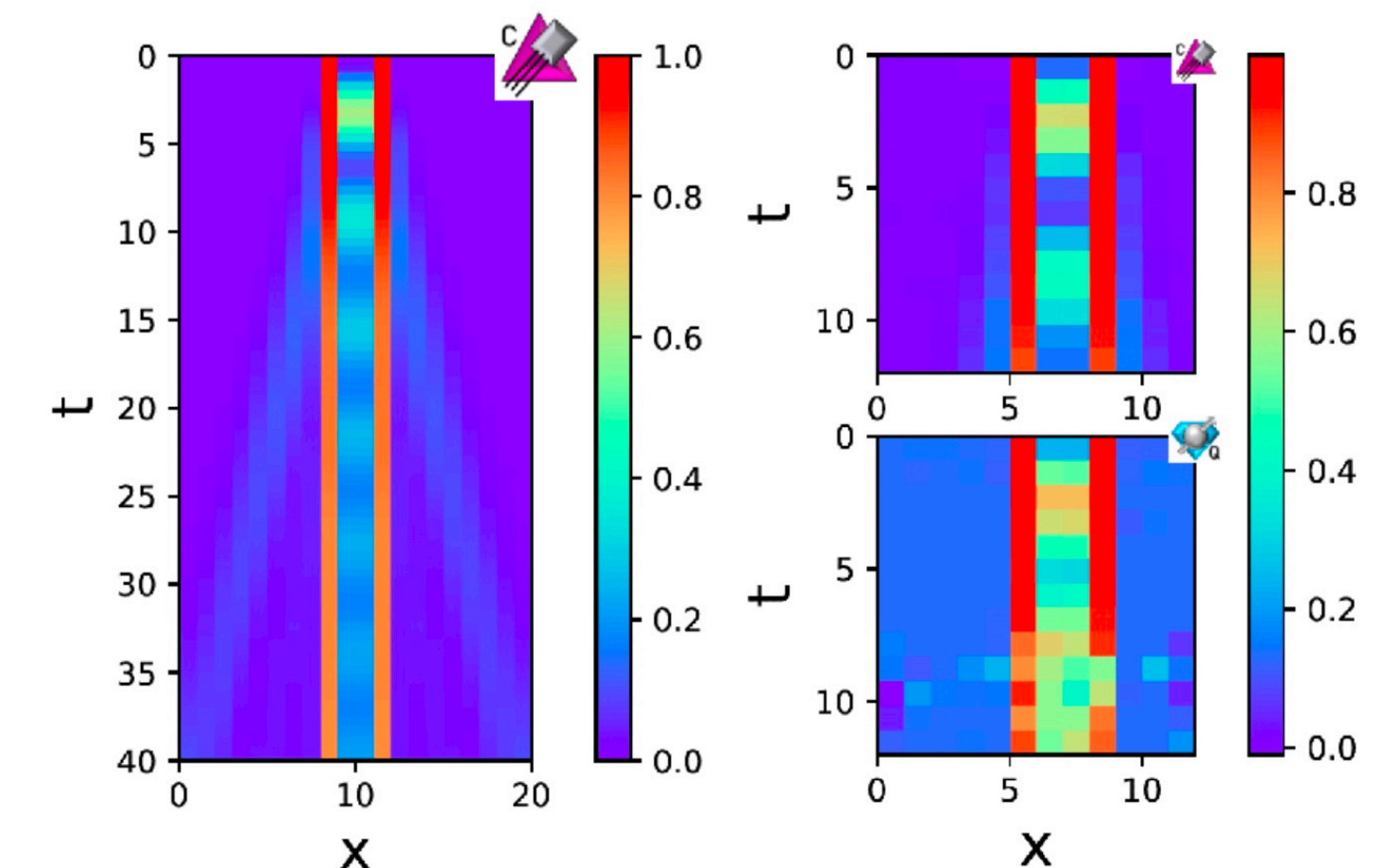
2+1D

- Z_2 LGT, superconducting qubits
- $U(1)$ LGT, Rydberg atom arrays

Phenomenology

- Ground state
- Quench dynamics
 - Resonant string breaking
- Dynamics of strings in 2+1D
- **Ramp dynamics**

$SU(2)$ lattice gauge theory 1+1D



Entanglement in Particle Detection

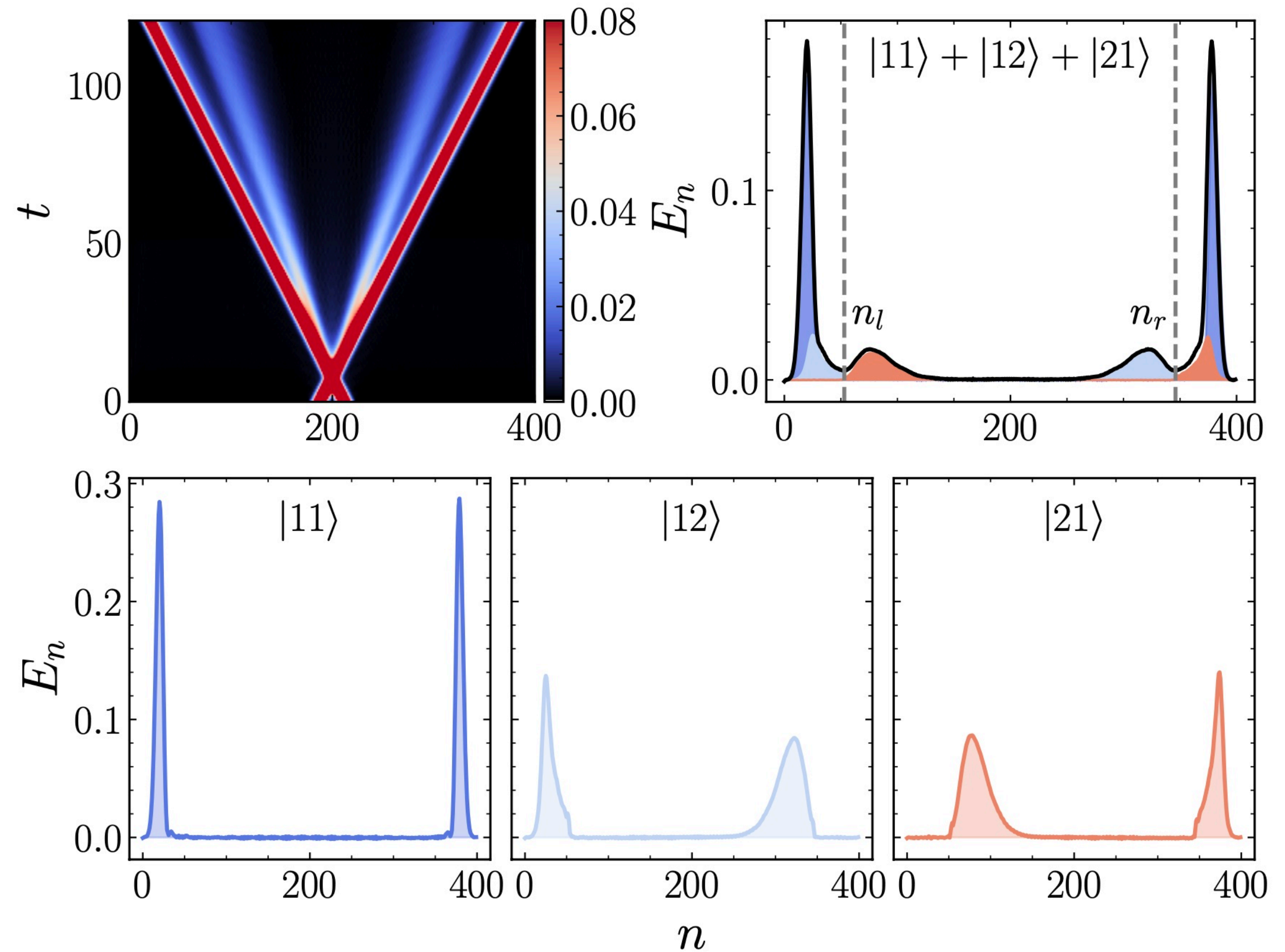
Exclusive Scattering Channels from Entanglement Structure in Real-Time Simulations

Nikita A. Zemlevskiy ^{1,*}

¹*InQubator for Quantum Simulation (IQUS), Department of Physics,
University of Washington, Seattle, WA 98195, USA*

(Dated: May 21, 2026)

$$\begin{aligned}
 |1(k_i)\rangle|1(-k_i)\rangle &\rightarrow \alpha|1^{(11)}(-k_i)\rangle|1^{(11)}(k_i)\rangle \\
 &+ \beta|1^{(12)}(-k_f)\rangle|2^{(12)}(k_f)\rangle \\
 &+ \gamma|2^{(21)}(-k_f)\rangle|1^{(21)}(k_f)\rangle \\
 &\equiv |f\rangle,
 \end{aligned}$$



Scar States in Gauge Theories and Delayed Thermalization

March 2022

Scar States in Deconfined $\mathbb{Z}_2$ Lattice Gauge Theories

Adith Sai Aramthottil,¹ Utso Bhattacharya,² Daniel González-Cuadra,^{2,3,4}
Maciej Lewenstein,^{2,5} Luca Barbiero,^{6,2} and Jakub Zakrzewski^{1,7}

- Distributed throughout spectrum
- Weakly connected to evolution Hamiltonian (cold sub-space)
- Delay thermalization

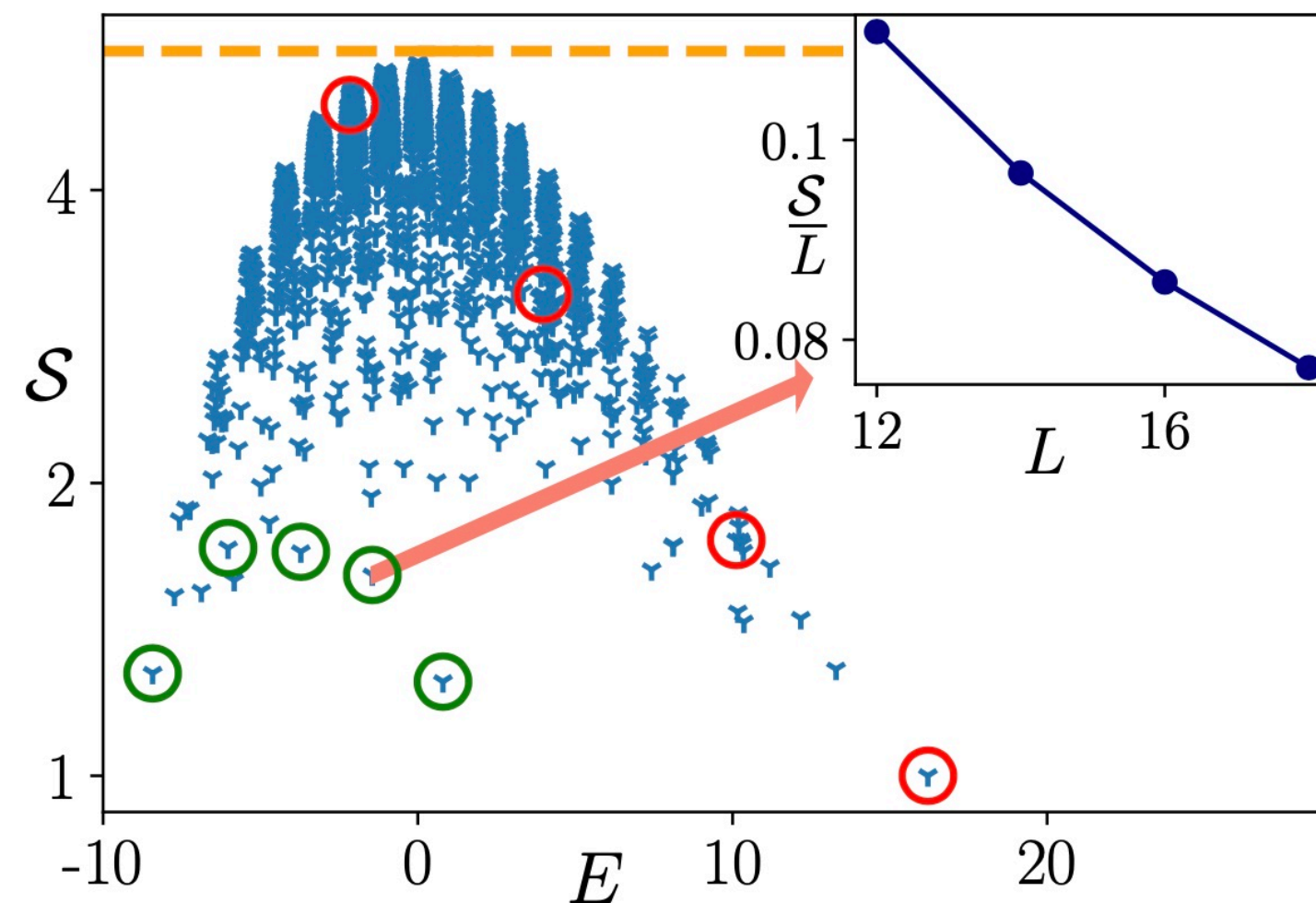


FIG. 4. The half-chain entanglement entropy($\mathcal{S}$) of all the eigenstates at $t = 0.2$, $h = 0.5$ for $L = 16$. The orange dashed line gives the $\mathcal{S}_{RMT}$ value. Circles denote different QMBS obtained via our tracking procedure. Green circles denote antimagnon-like family $\mathcal{S}_n^2$ for $n = 0, 2, 4, 6, 8$ while red circles magnon-like states, $\mathcal{S}_n^1$ with $n = 0, \dots, 6$ counting from the right hand side. *Inset:* The half-chain Entanglement Entropy divided by system size ($\frac{\mathcal{S}}{L}$) for $\mathcal{S}_2^2$ state showing its sub-volume property as expected for QMBS.

$$H = -t \sum_j \left(c_j^\dagger - c_j \right) \sigma_{j+1/2}^z \left(c_{j+1}^\dagger + c_{j+1} \right) - \mu \sum_j \left(c_j^\dagger c_j - \frac{1}{2} \right) - h \sum_j \sigma_{j+1/2}^x.$$

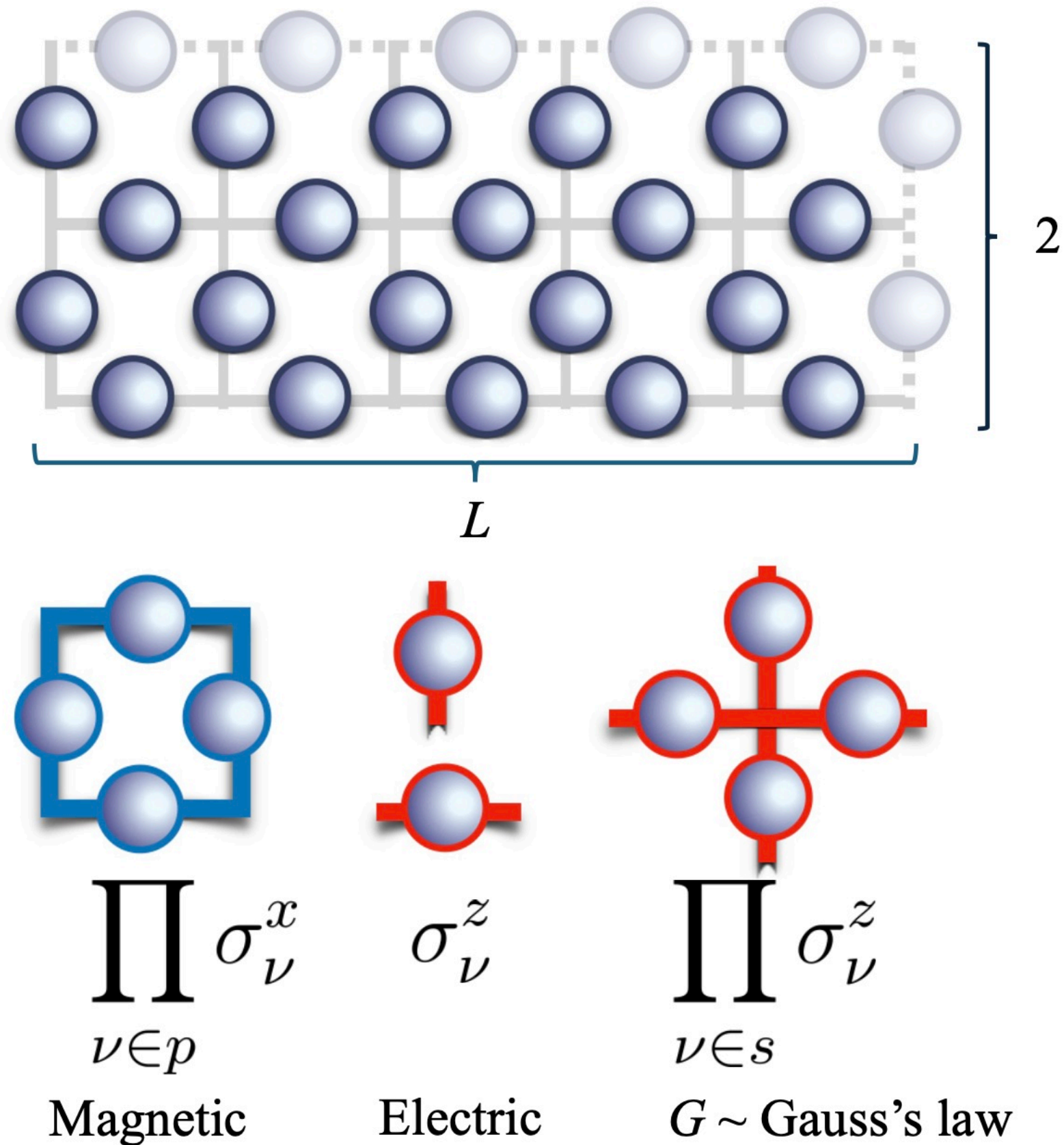
- Previously: only confining systems exhibited scars
- Shown to exist in de-confined regime
- Shown not to exist in confining regime

Stabilizer Scars

[Jeremy Hartse](#)^{1,*}, [Lukasz Fidkowski](#)², and [Niklas Mueller](#)^{1,3,4}

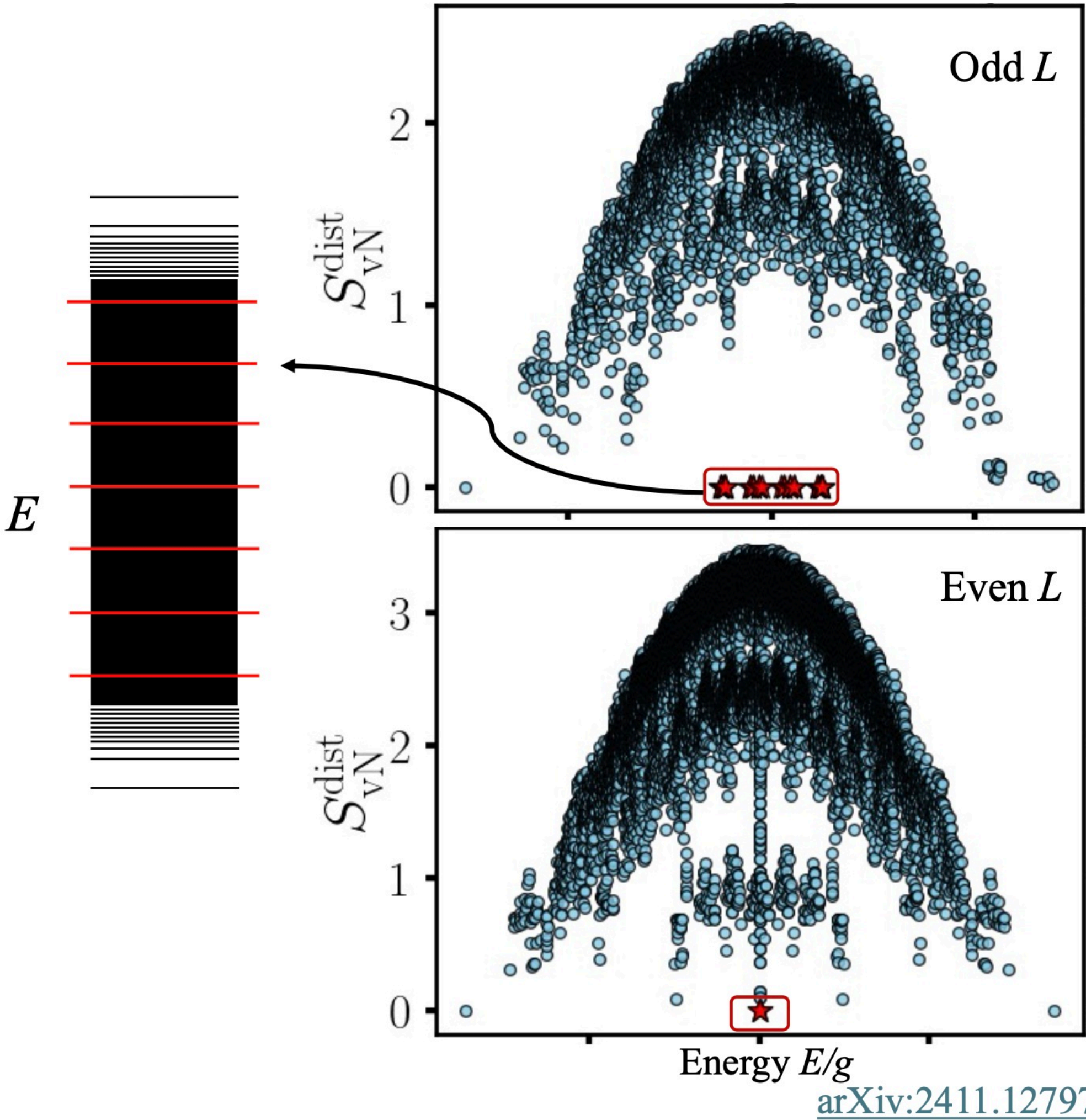
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Phys. Rev. Lett. **135**, 060402 – Published 6 August, 2025



Entanglement and Thermalization

Stabilizer Scars

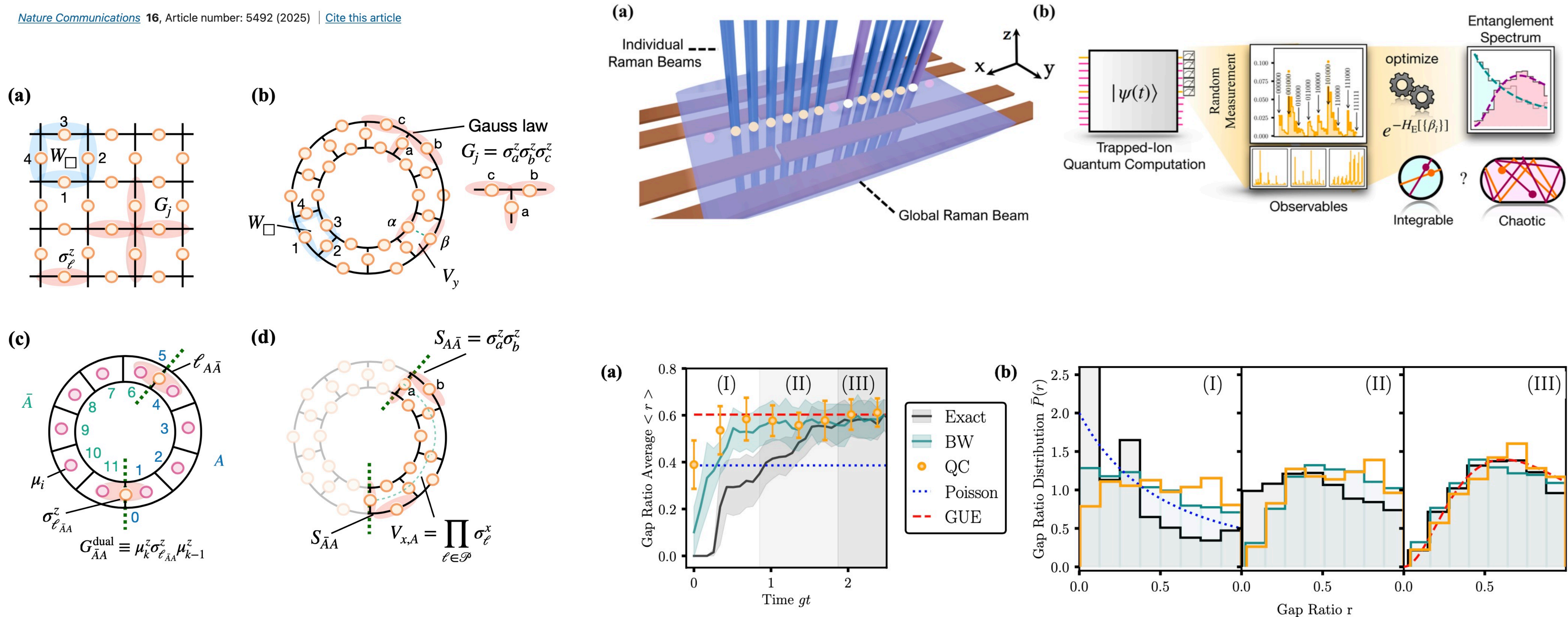


Entanglement and Thermalization

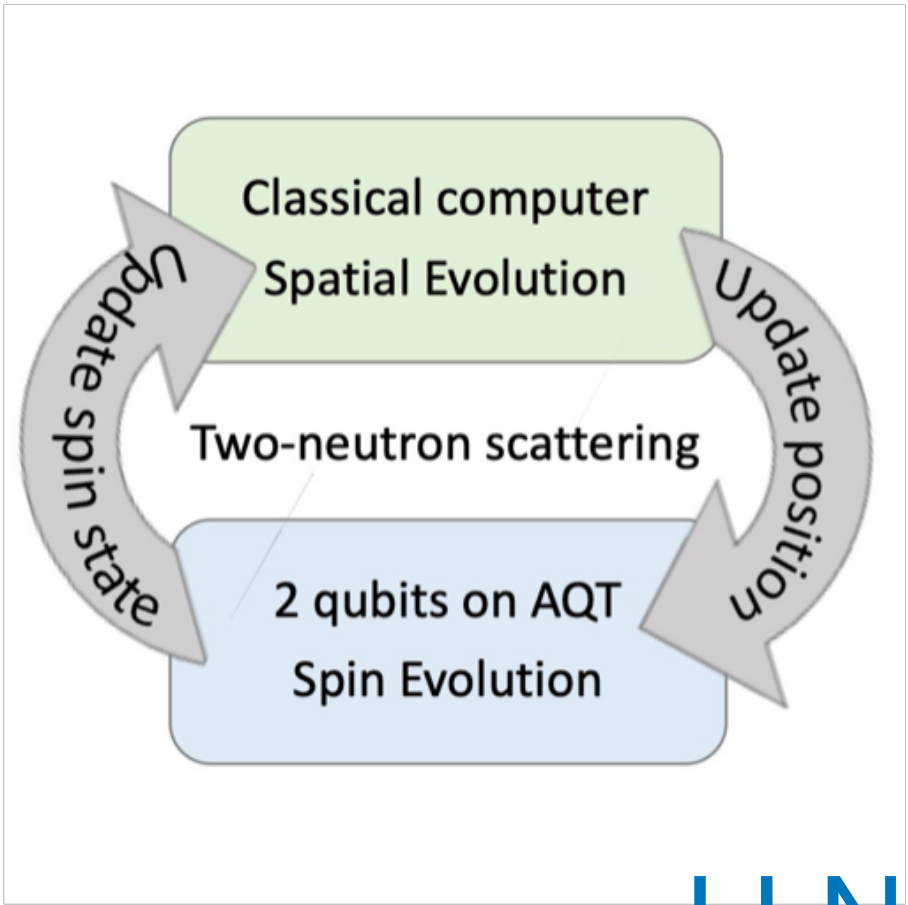
Quantum computing universal thermalization dynamics in a (2 + 1)D Lattice Gauge Theory

Niklas Mueller [✉](#), Tianyi Wang, Or Katz, Zohreh Davoudi & Marko Cetina

Nature Communications **16**, Article number: 5492 (2025) | [Cite this article](#)



Nuclear Structure and Reactions



LLNL+Trento

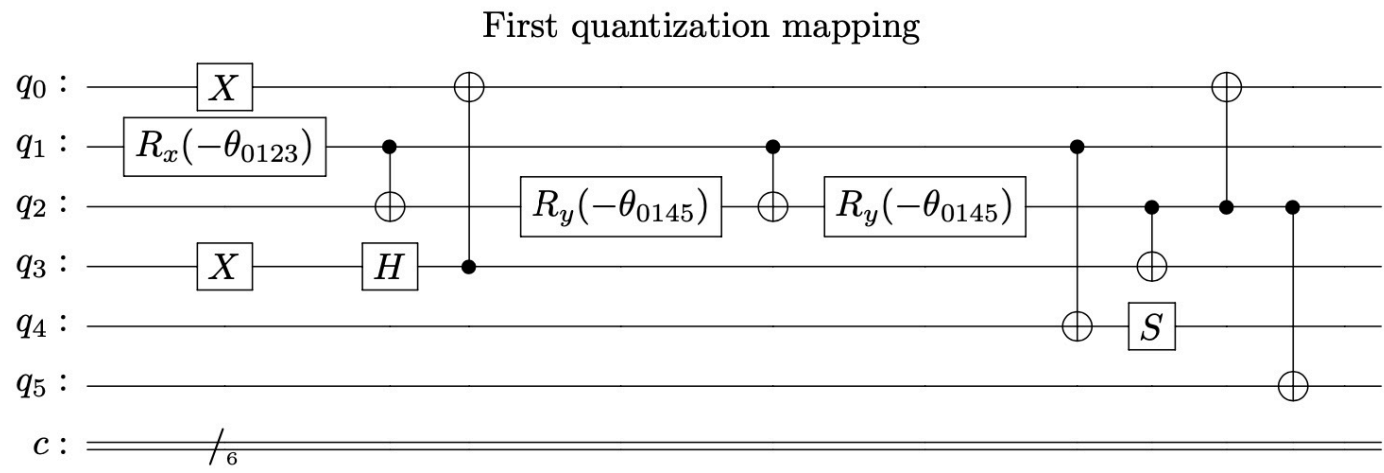
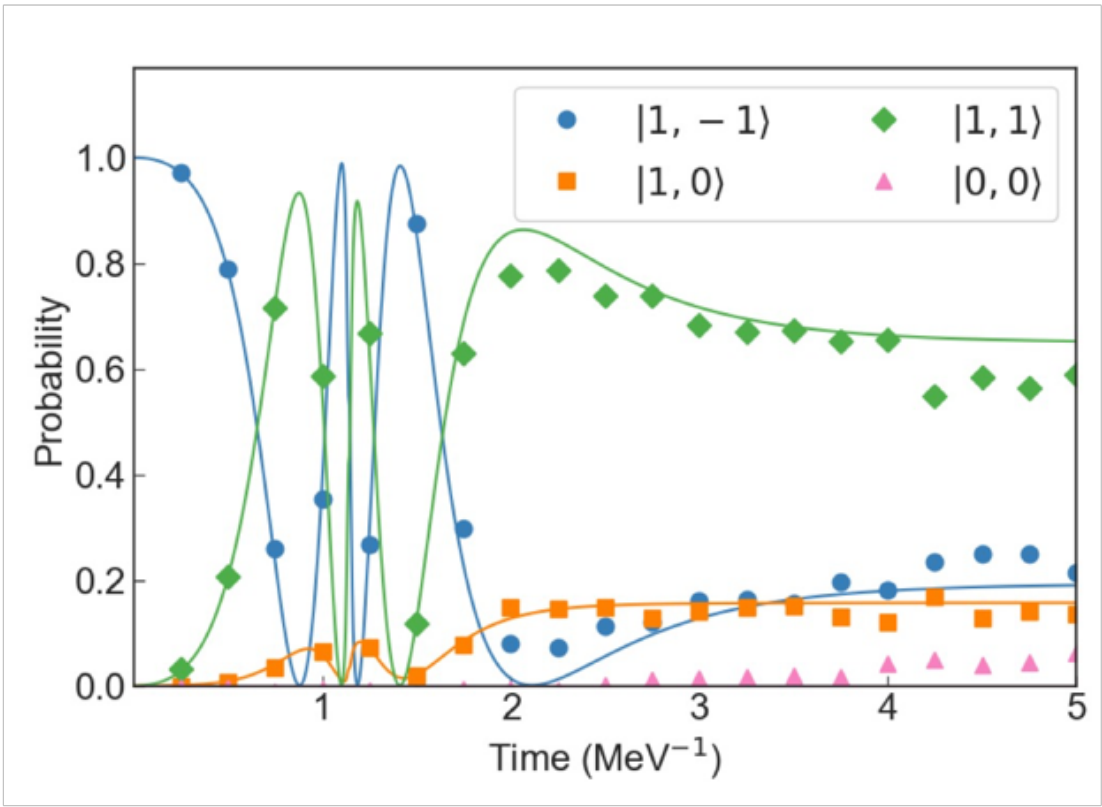
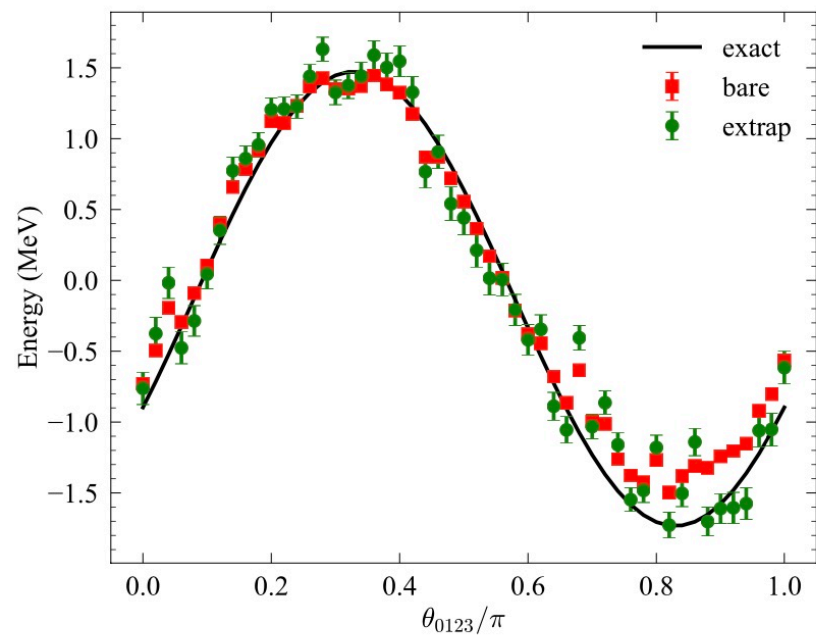
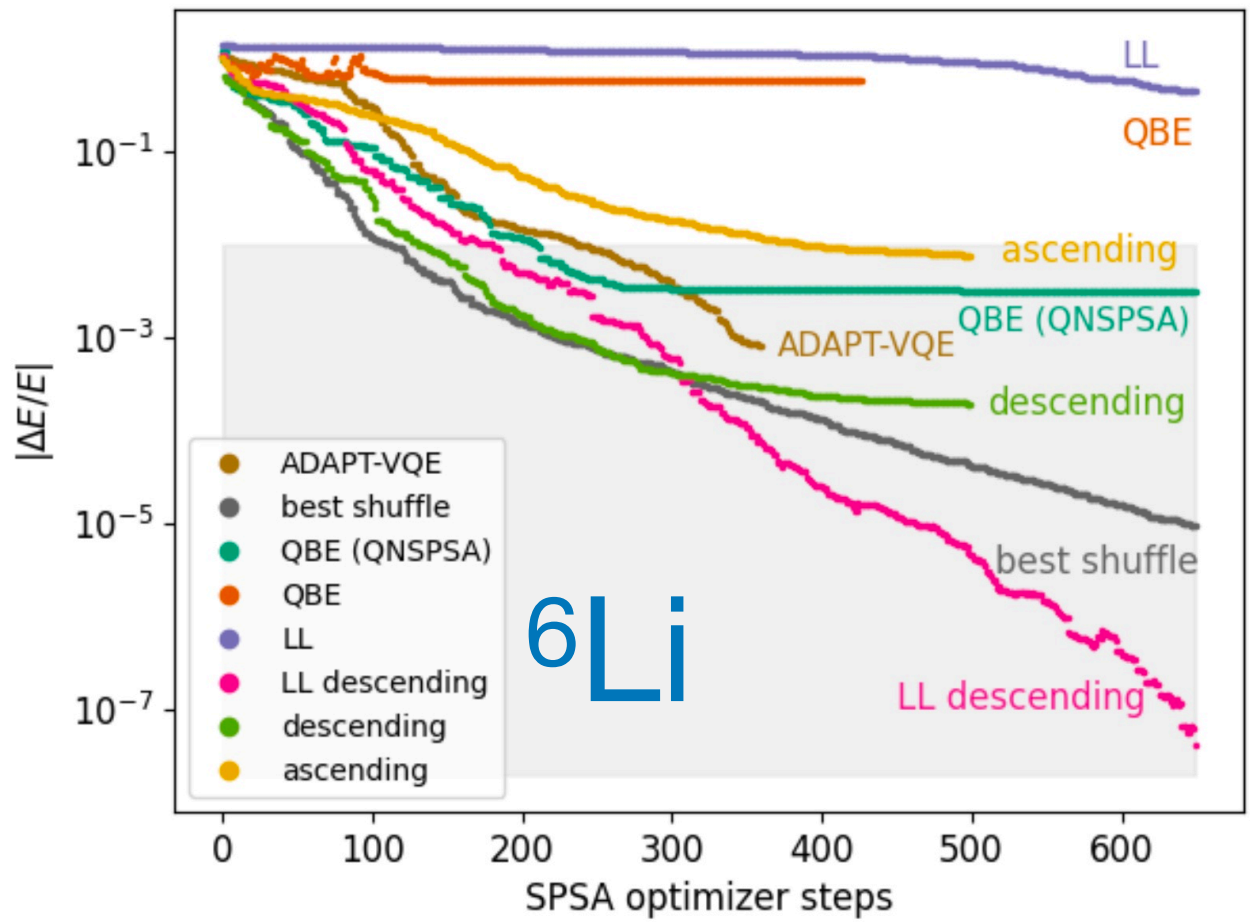


TABLE 1. Summary of the results for the ground-state energy for different systems in different

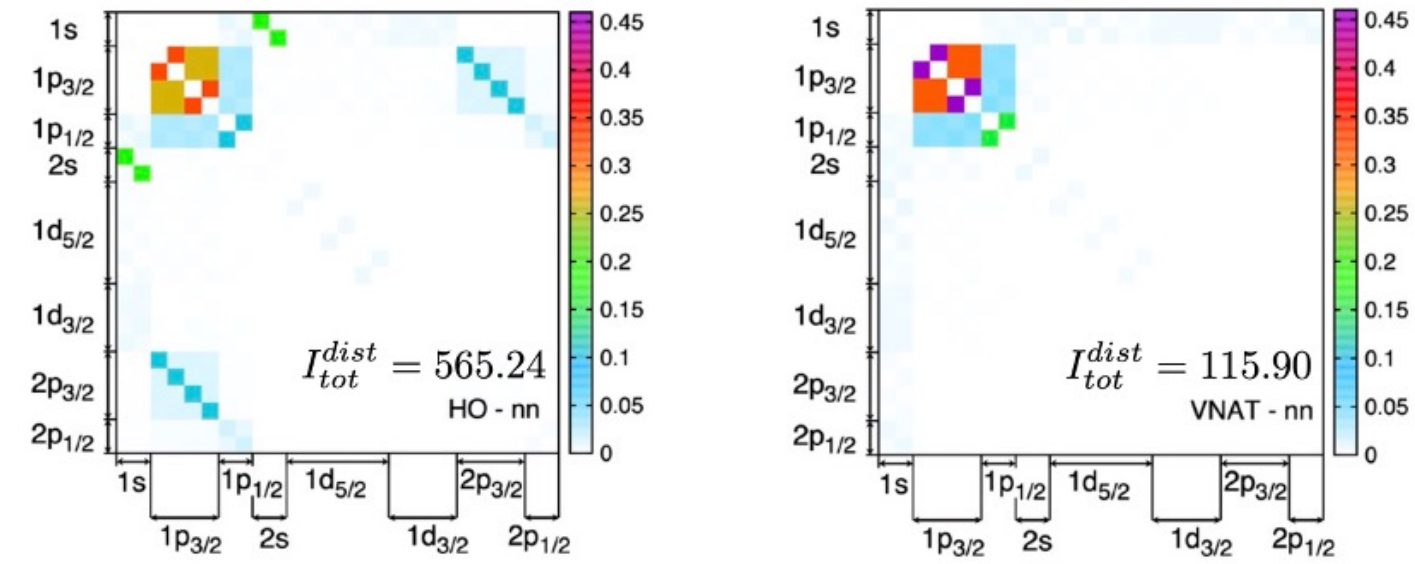
Nucleus	Model Space	E_{exact} (MeV)	E_{HF} (MeV)	$E_{\text{HF}} + \text{corr}$ (MeV)	Number paramet
${}^6\text{He}$	p	-3.91	-0.90	-3.85	2
${}^8\text{Be}$	p	-31.12	-26.12	-26.79	12
${}^8\text{Be}^*$	p	-31.12	-26.12	-29.37	76
${}^8\text{Be}^{**}$	p	-31.12	-26.12	-30.67	112
${}^{20}\text{O}$	sd	-23.93	-21.29	-23.18	10
${}^{22}\text{O}$	sd	-35.27	-32.98	-35.14	35



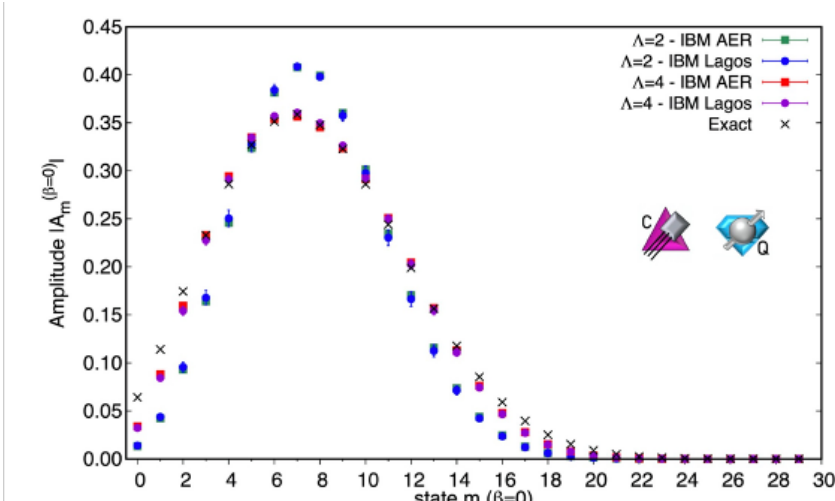
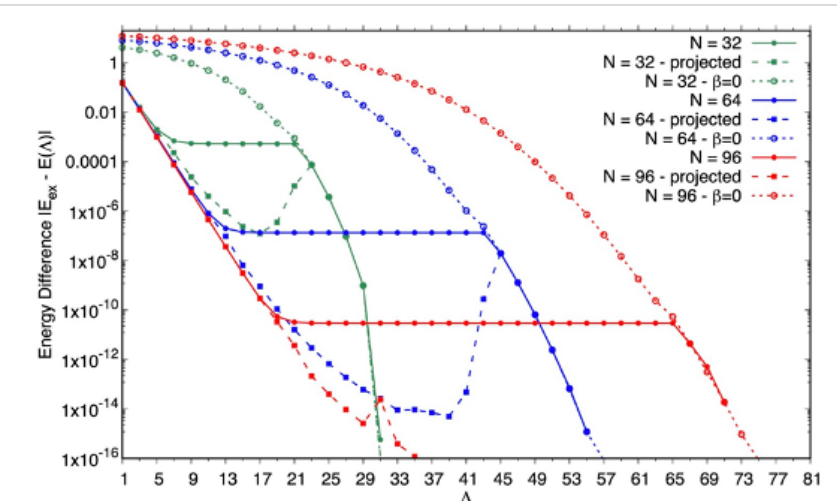
LANL



ORNL, AWS, CERN, UTK, UGeneva,



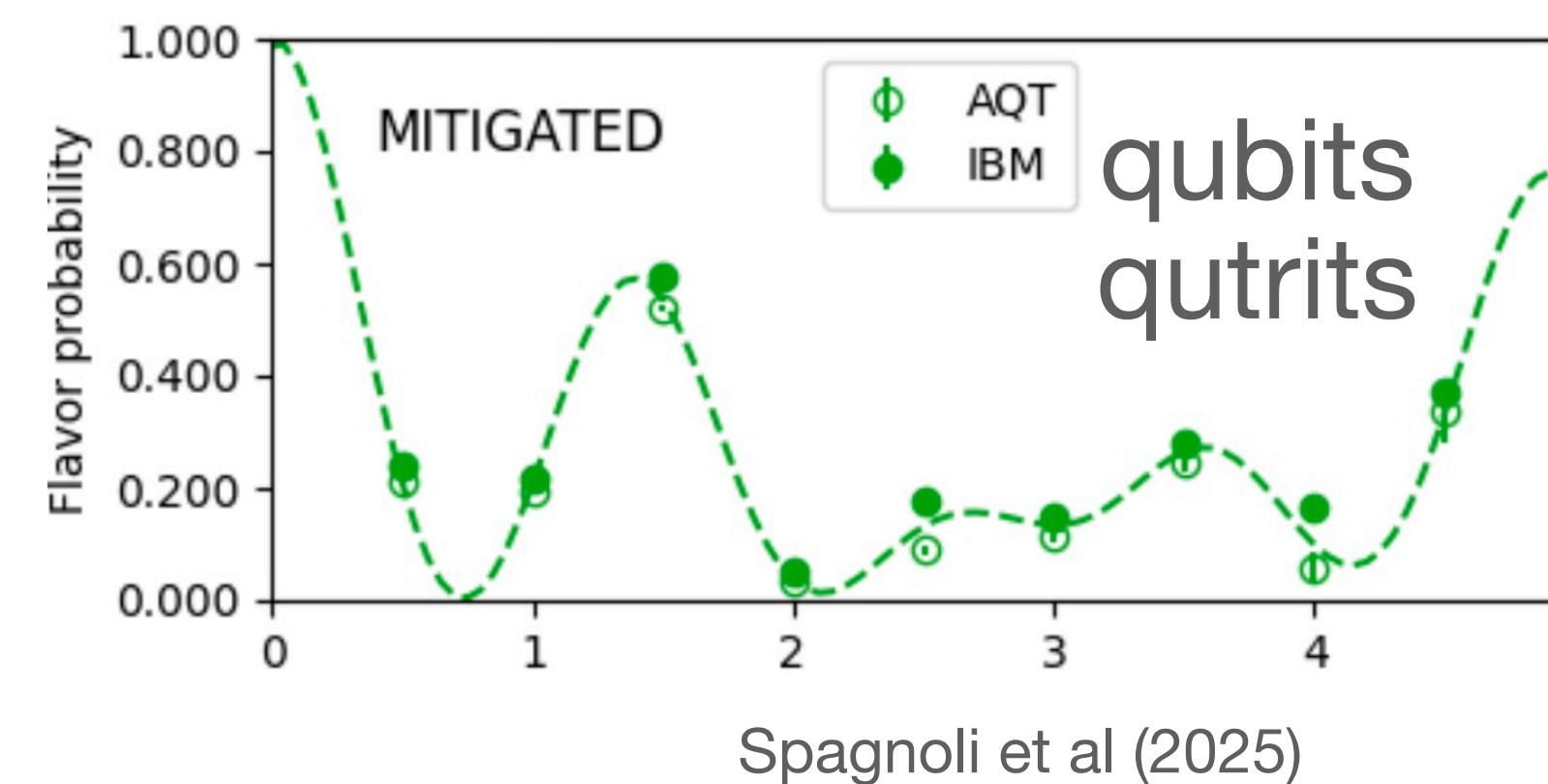
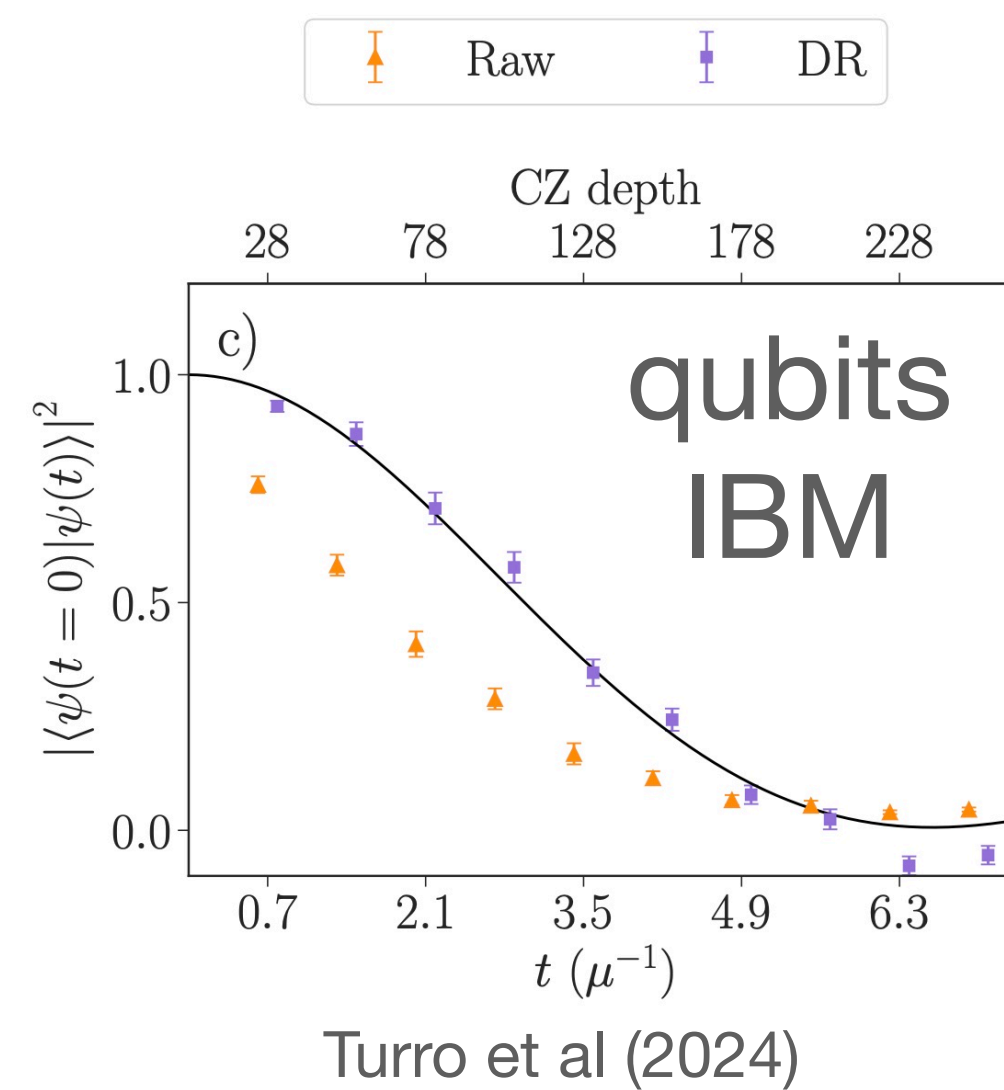
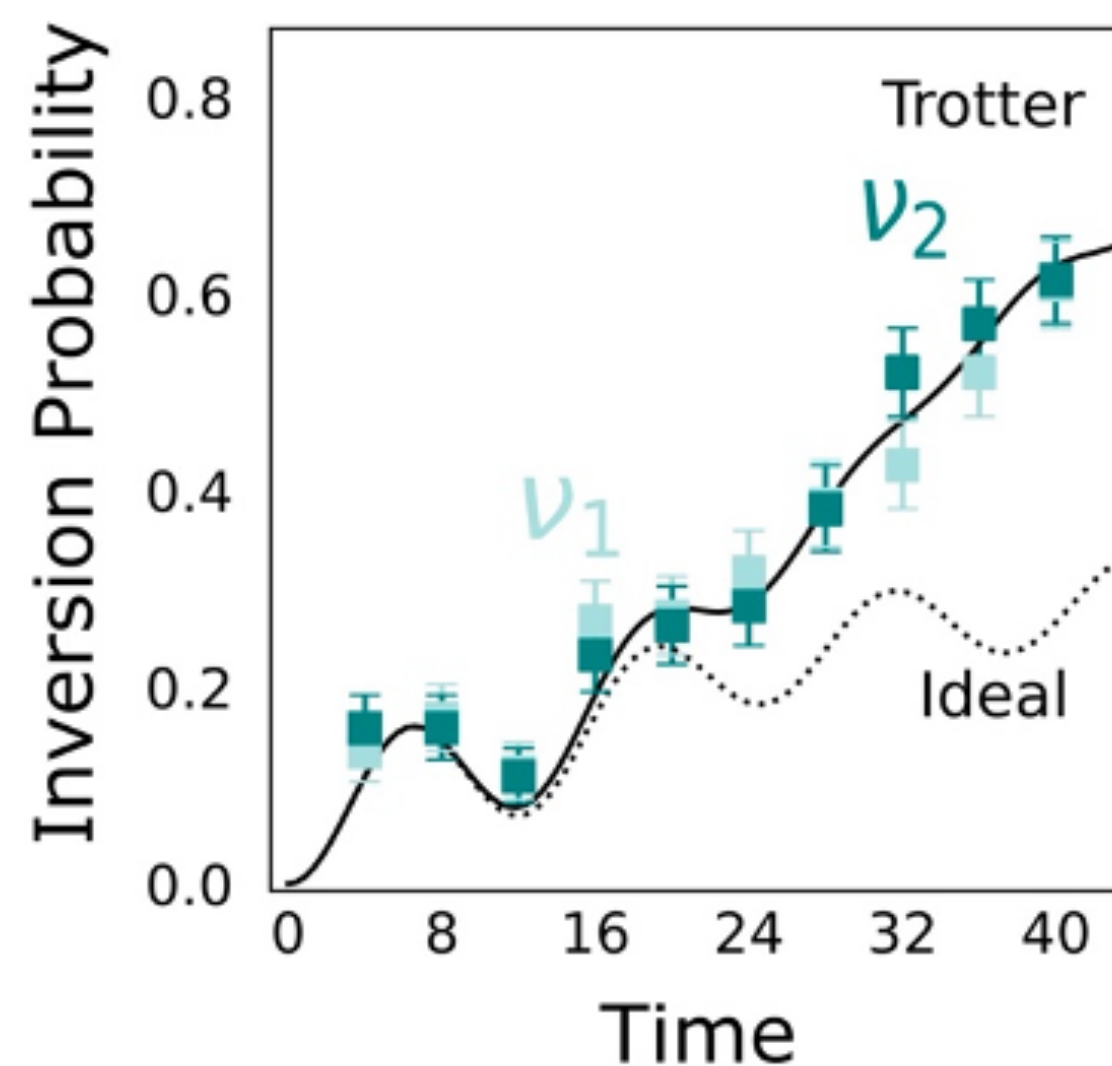
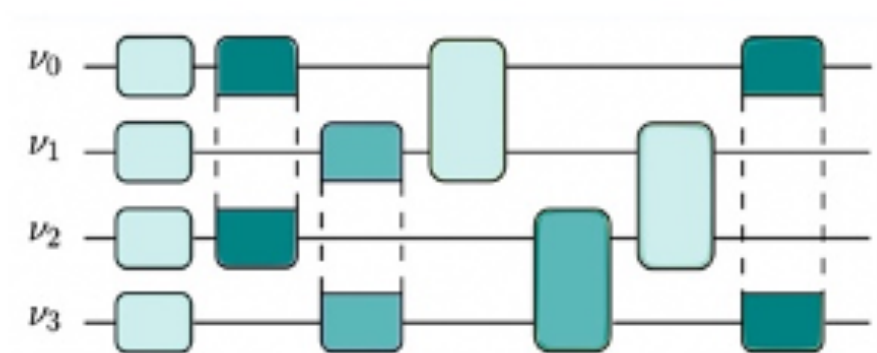
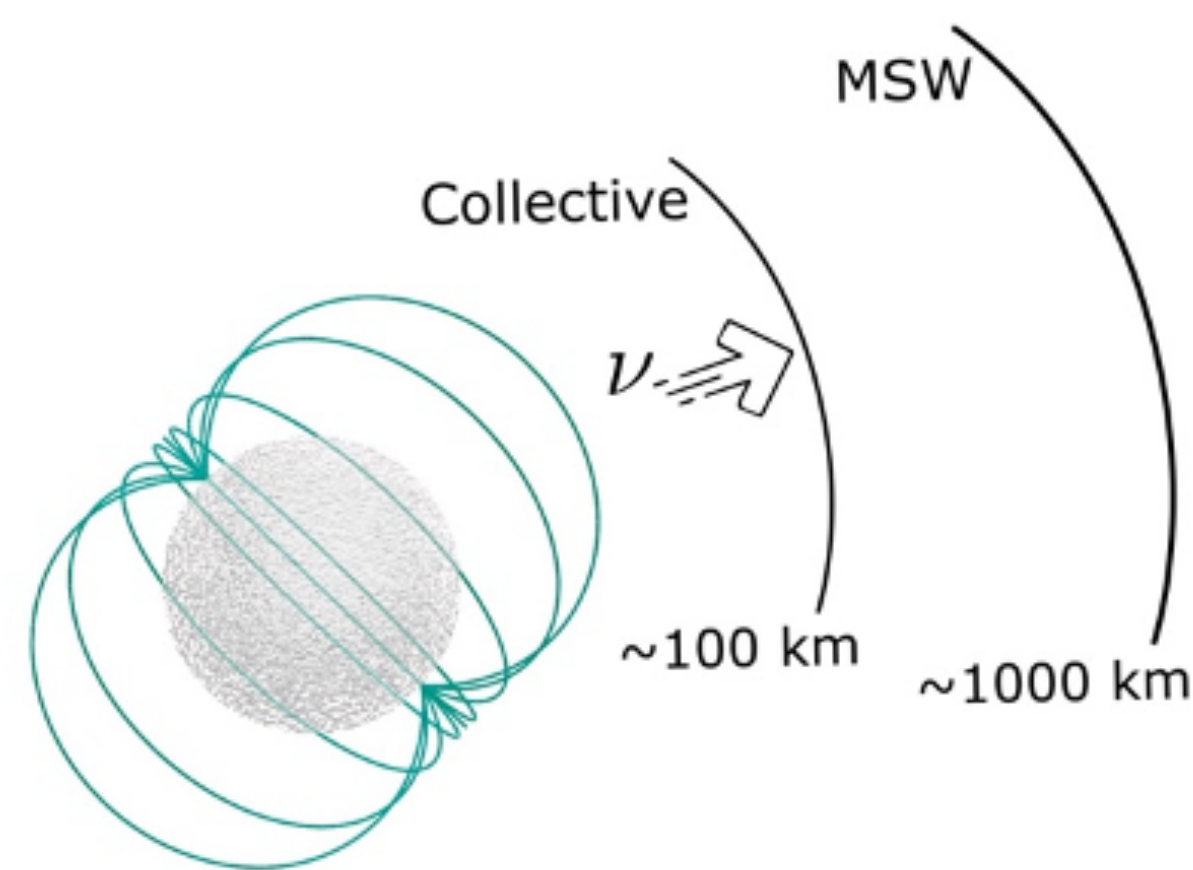
Bielefeld, IQuS



$$H_{FS} = - \sum_{k=1}^N \frac{\omega_k}{2} \sigma_k^z + \frac{\mu}{2N} \sum_{i < j}^N \mathcal{J}_{ij} \vec{\sigma}_i \cdot \vec{\sigma}_j$$

Neutrino Flavor Dynamics in Supernova

Simulations with qubits and qutrits



N-body Gates in Trapped Ion Systems

Co-Design in Action

Engineering an Effective Three-spin Hamiltonian in Trapped-ion Systems
for Applications in Quantum Simulation

Bárbara Andrade,¹ Zohreh Davoudi,² Tobias Graß,¹ Mohammad Hafezi,^{3,4} Guido Pagano,⁵ and Alireza Seif^{6,*}

N-body interactions between trapped ion qubits via spin-dependent squeezing

Or Katz,^{1,2,3,*} Marko Cetina,^{1,3} and Christopher Monroe^{1,2,3,4}

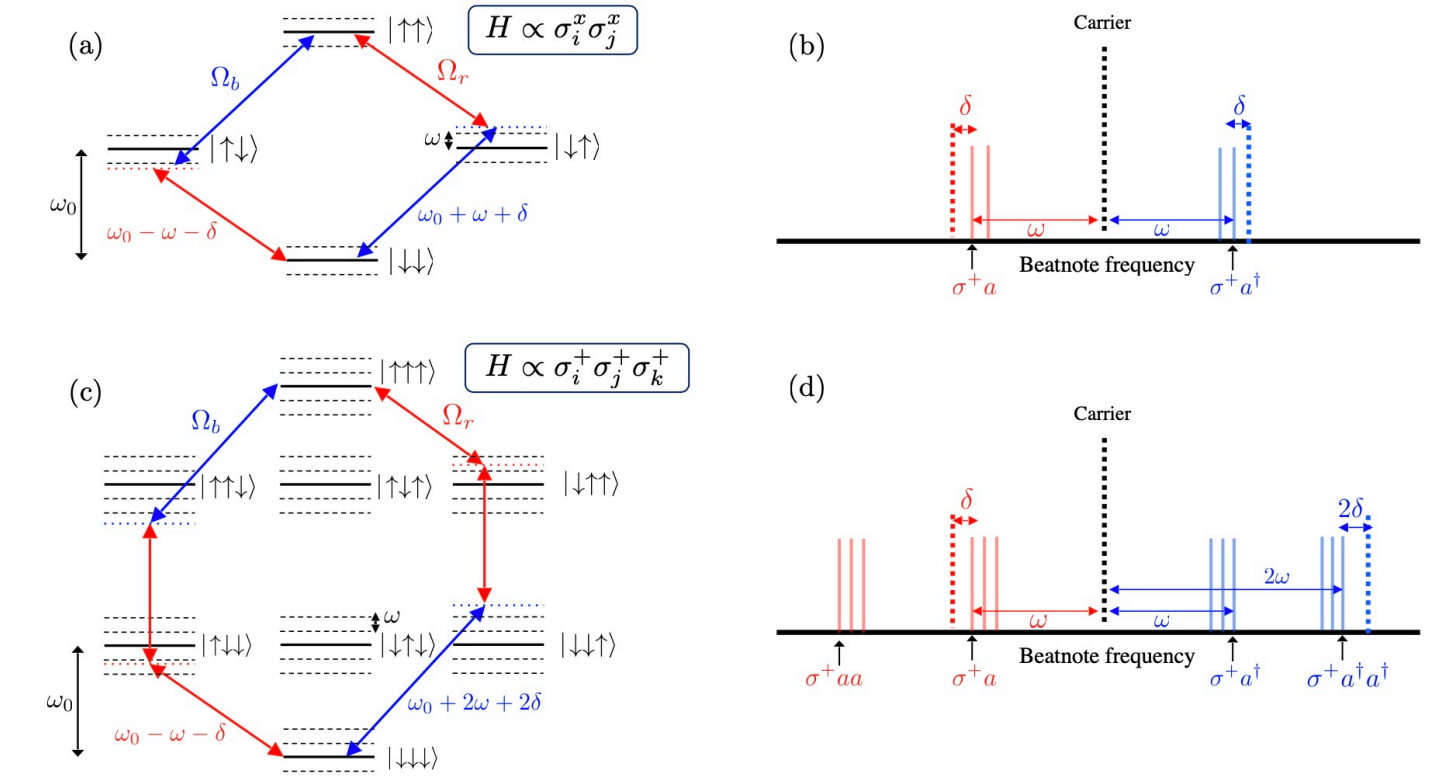
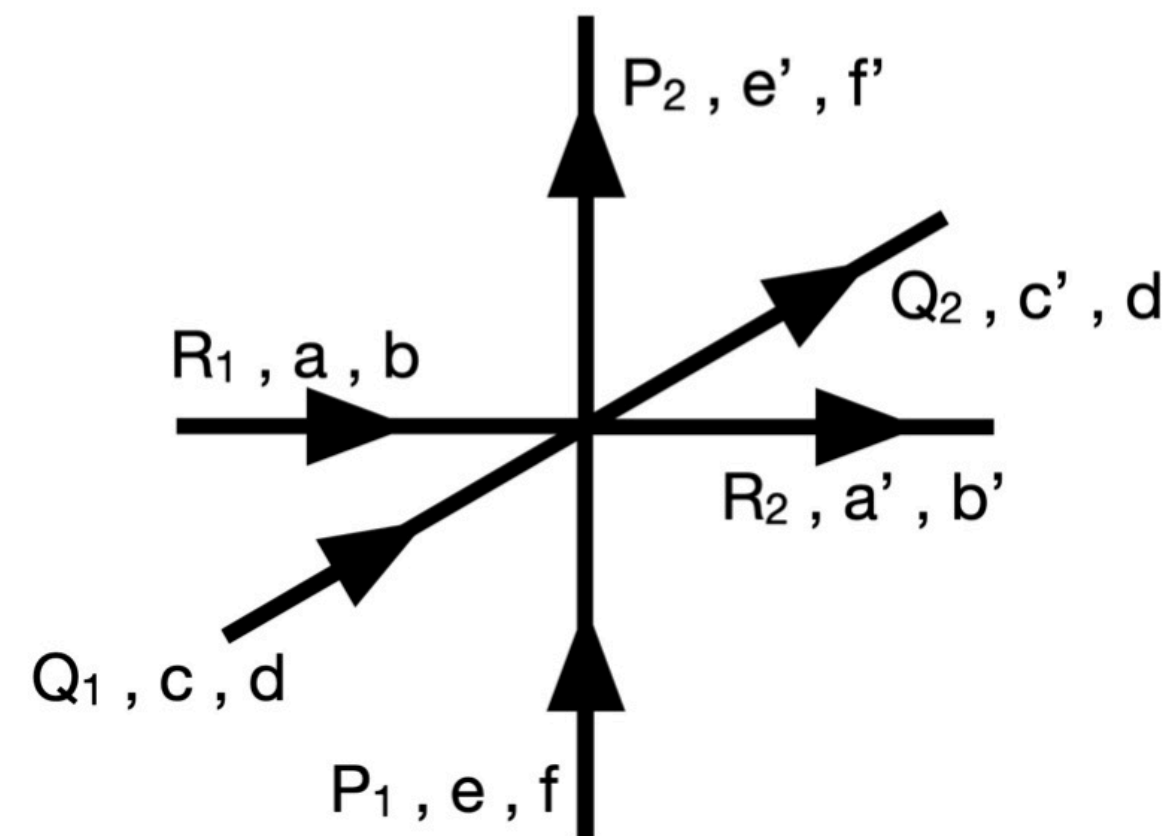
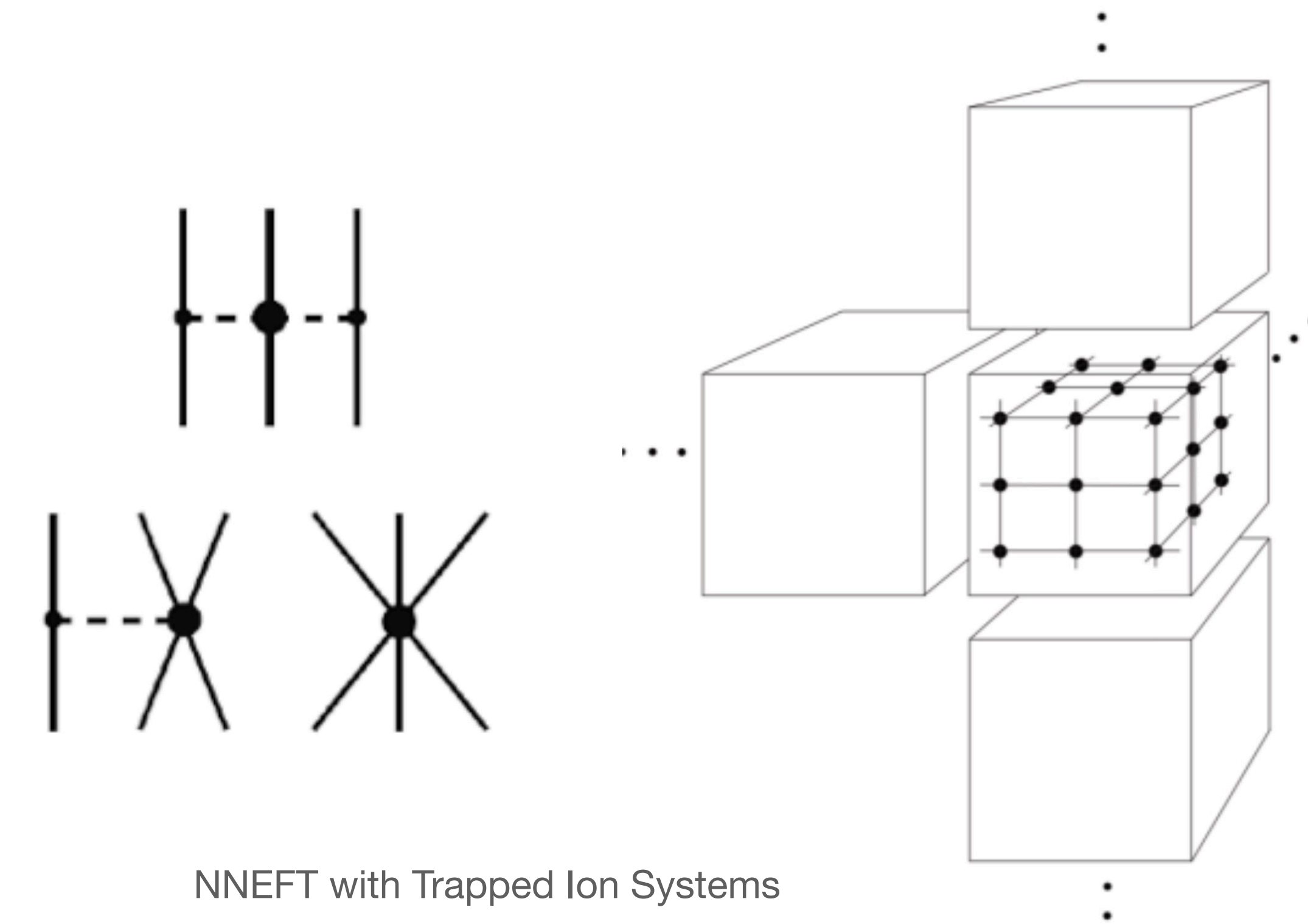
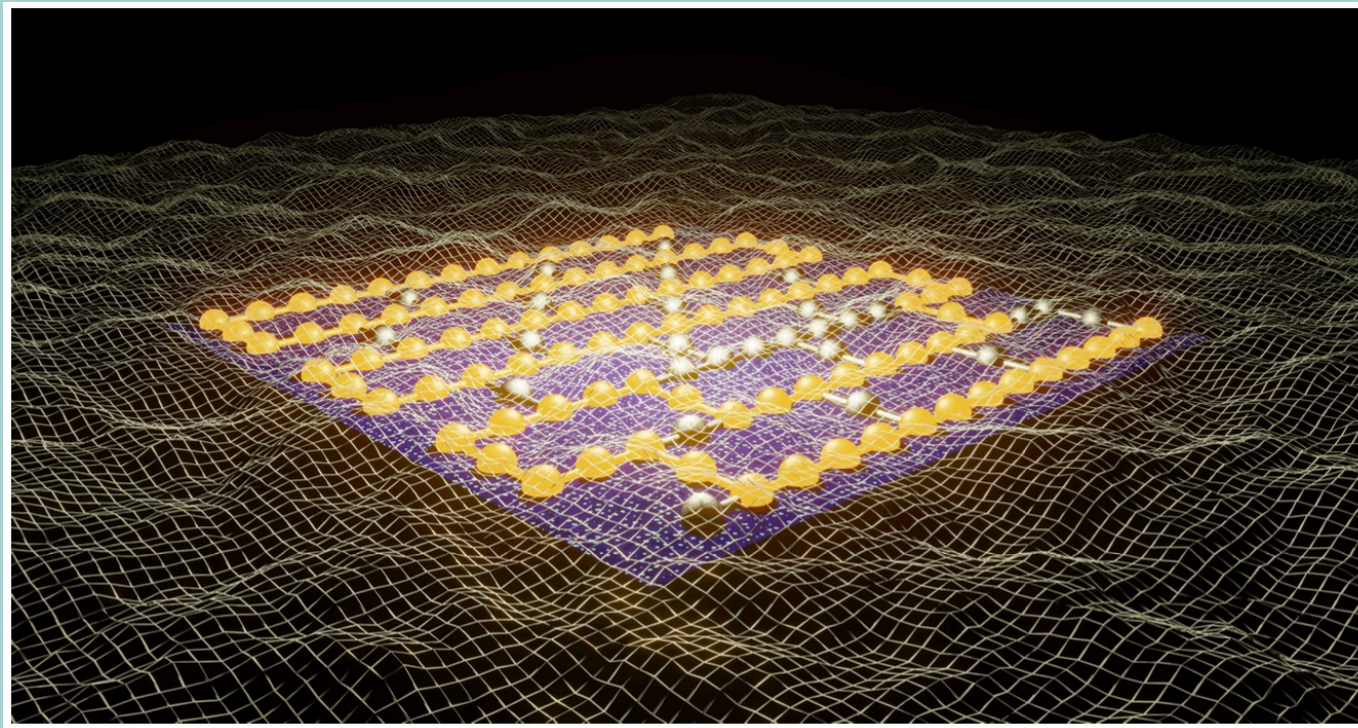


FIG. 1. (a,b) Traditional Mølmer-Sørensen scheme based on a pair of bichromatic laser beatnotes off-resonantly driving first-order spin-phonon couplings with symmetric detuning ($\pm\delta$), giving rise to an effective spin-spin interaction. The two-ion case is shown for simplicity. (c,d) Generalized Mølmer-Sørensen scheme to generate an effective three-spin coupling. A second-order blue sideband is driven with twice the detuning (2δ) as the first-order red ($-\delta$) sideband. As shown in (c), this process creates two virtual phonons with a second-order process and annihilates the same number of phonons through two first-order processes. Note that only two out of several possibilities are depicted. In all subfigures, Ω_r and Ω_b are the Rabi frequencies of the red and blue beatnotes, respectively. ω_0 is the qubit frequency, and $\omega [\equiv \omega_{\text{com}}]$ is the transverse center-of-mass frequency.

Part-3

Quantum Computing and Simulation



- No quantum advantage yet
- Single lattice spacings - no tunings
- Percent-level or larger errors. [c/w classical]
- Single volumes
- 1+1D, with few 2+1D (no quarks), no 3+1D
- Low-field irrep truncations
- 10 or so Trotter steps before signal to noise degrades
- ~ 100 qubits x 400 depth
- Preparation and new/developing ideas for 2+1D and 3+1D
- First studies of error-correction/fault tolerance
- Nascent benchmarking
- No HEP (or NP) code-base(s)/workflows
- 1+1D fermions are easy

FIN