Scalable Quantum Circuits for Confining Theories -

Simulating the Schwinger Model using more than 100 qubits and One Trillion CNOT Gates

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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

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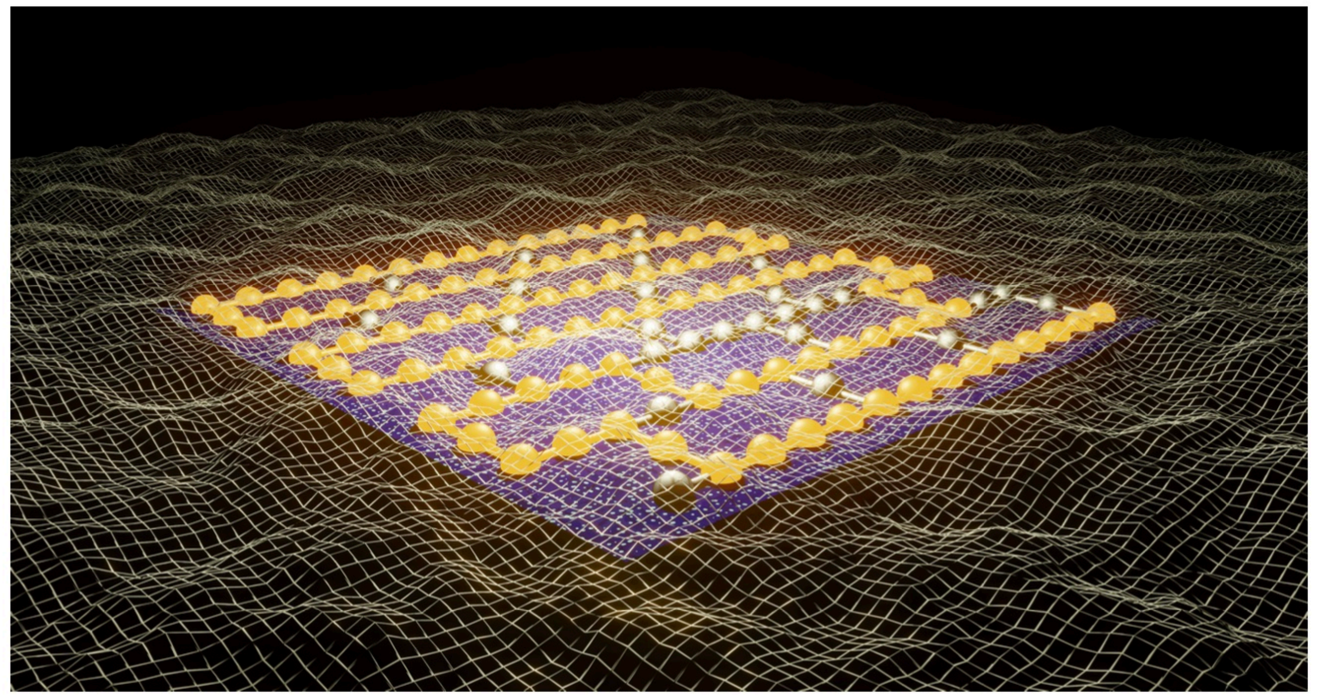
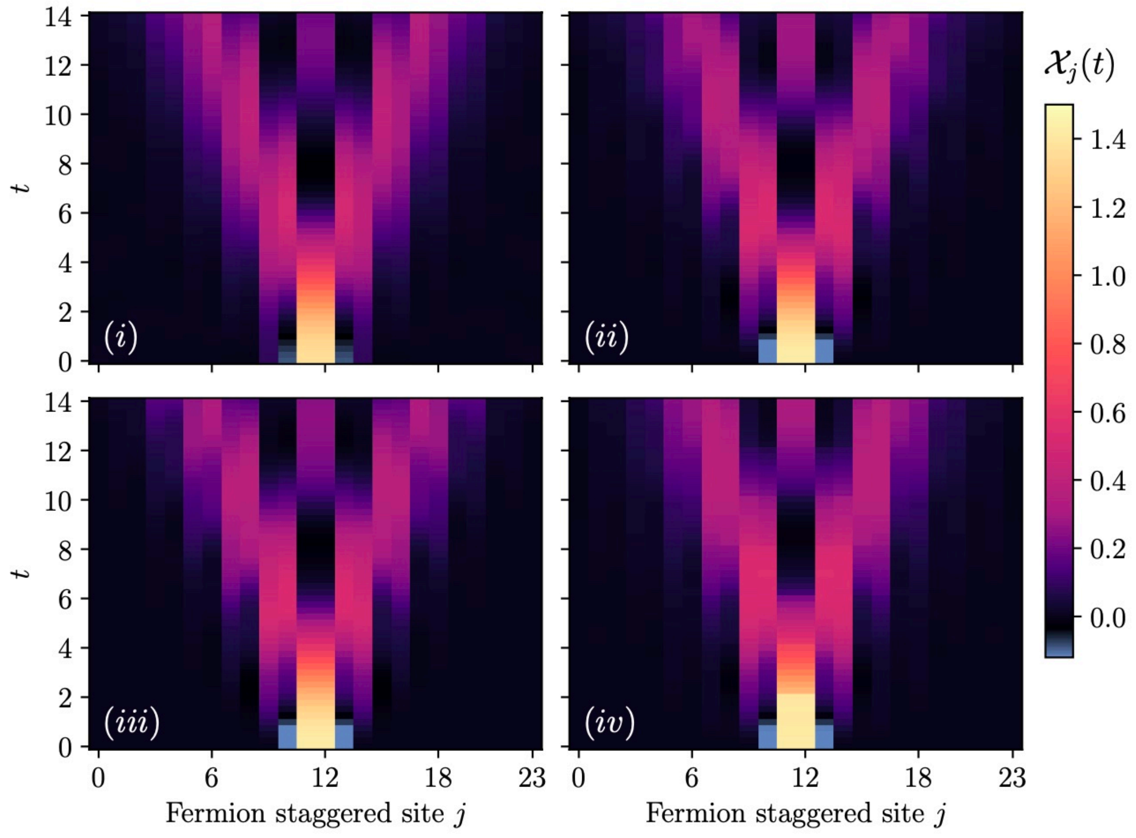
Quantum simulations of hadron dynamics in the Schwinger model using 112 qubits

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





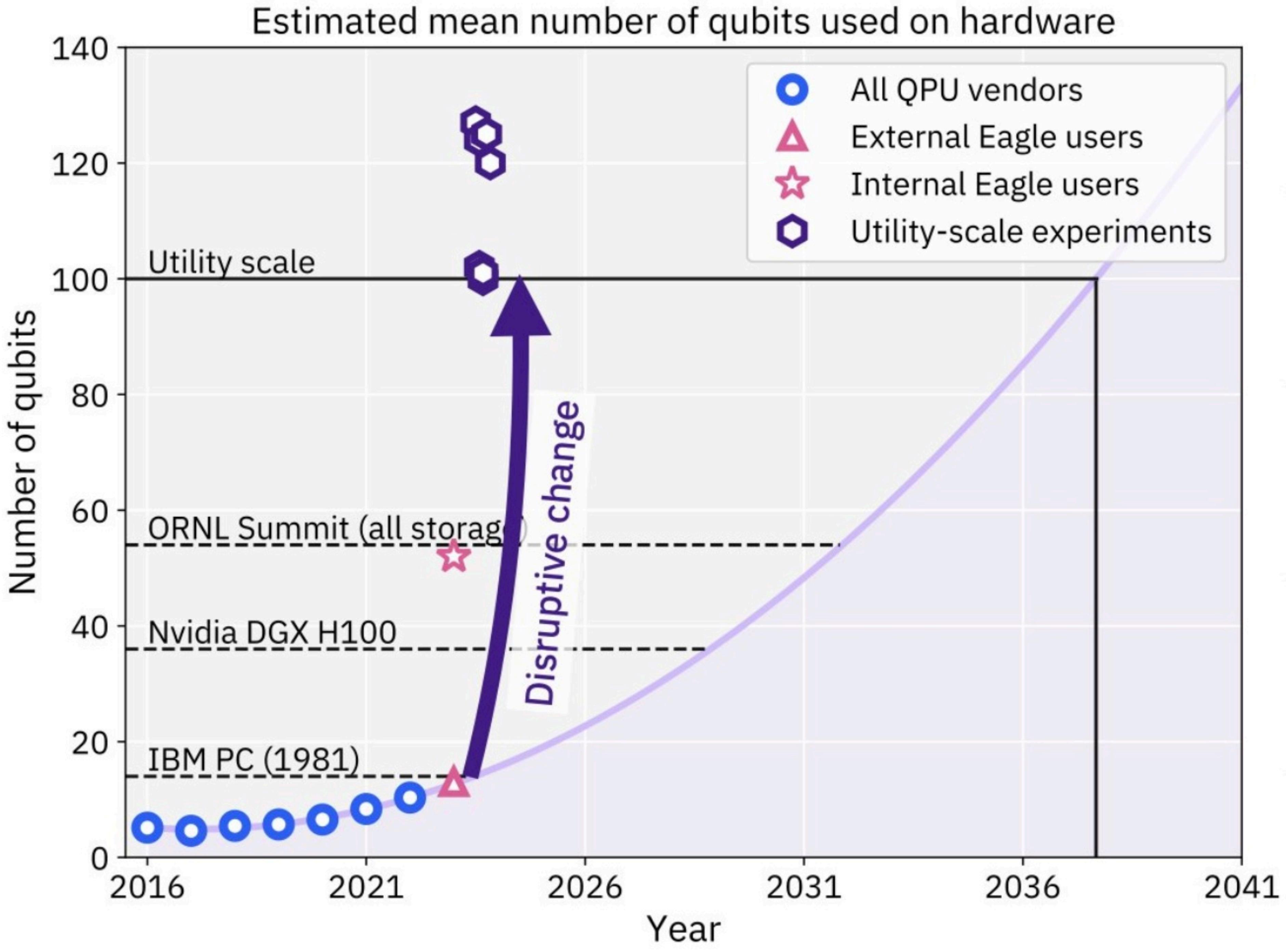
Roland Farrell, Marc Illa, Anthony Ciavarella and Martin Savage
InQubator for Quantum Simulation (IQuS), University of Washington

INT 15 October 2024

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

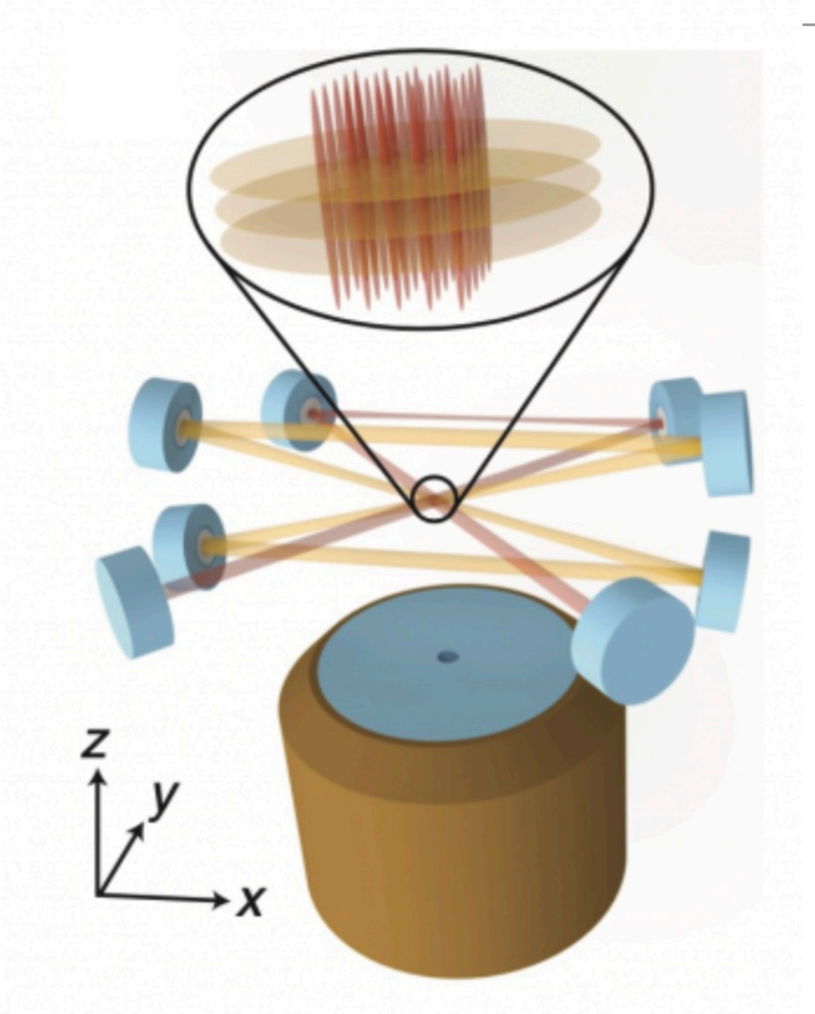
Realizing the Nishimori transition across the error threshold for constant-depth quantum circuits
125 qubits / 429 gates + meas. — arXiv:2309.02863

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

Select Recent Advances in Quantum Computing



Cold-Atom arrays with Optical Tweezers

4 Logical Qubits
32-qubit H2-1 trapped ions
(Quantinuum-Microsoft)

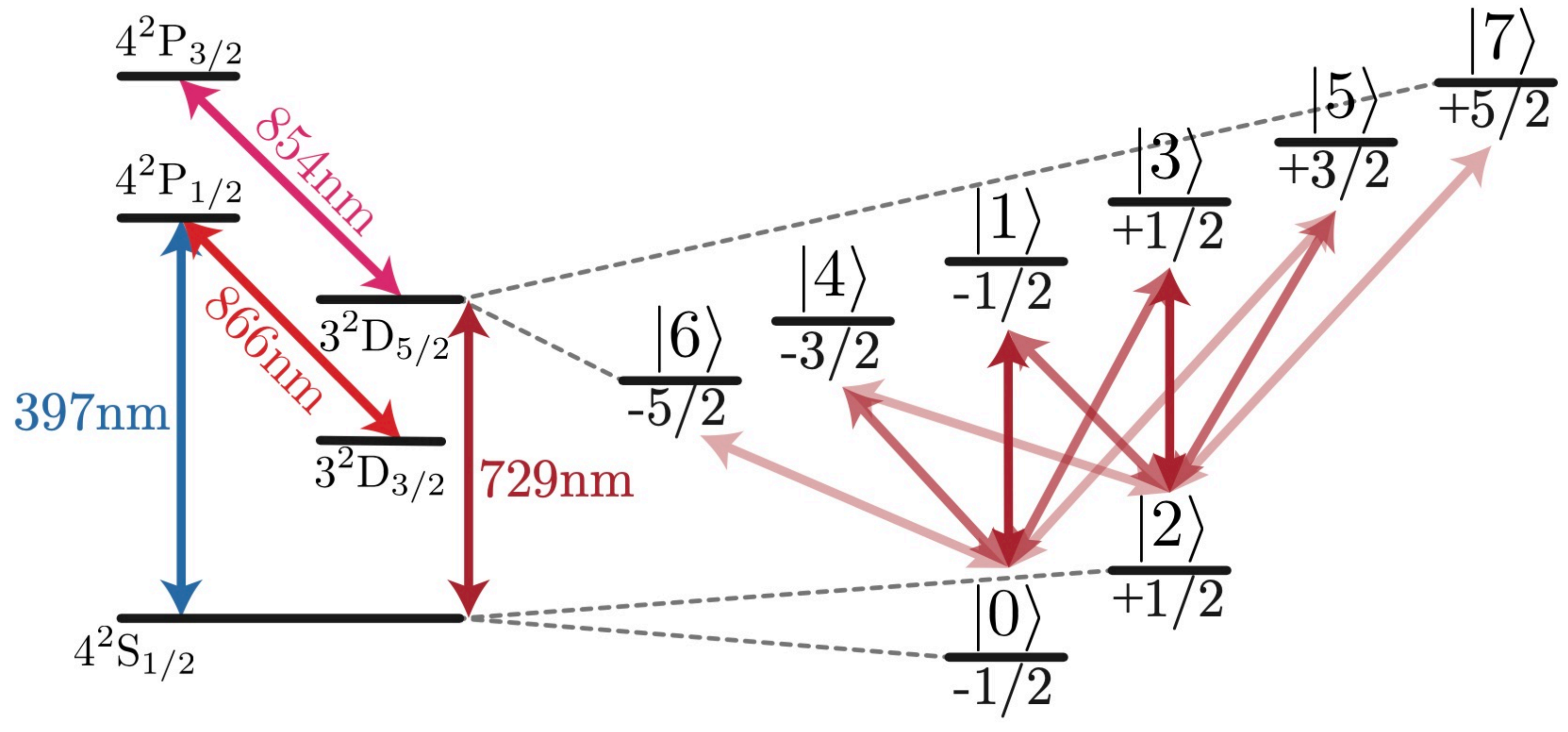
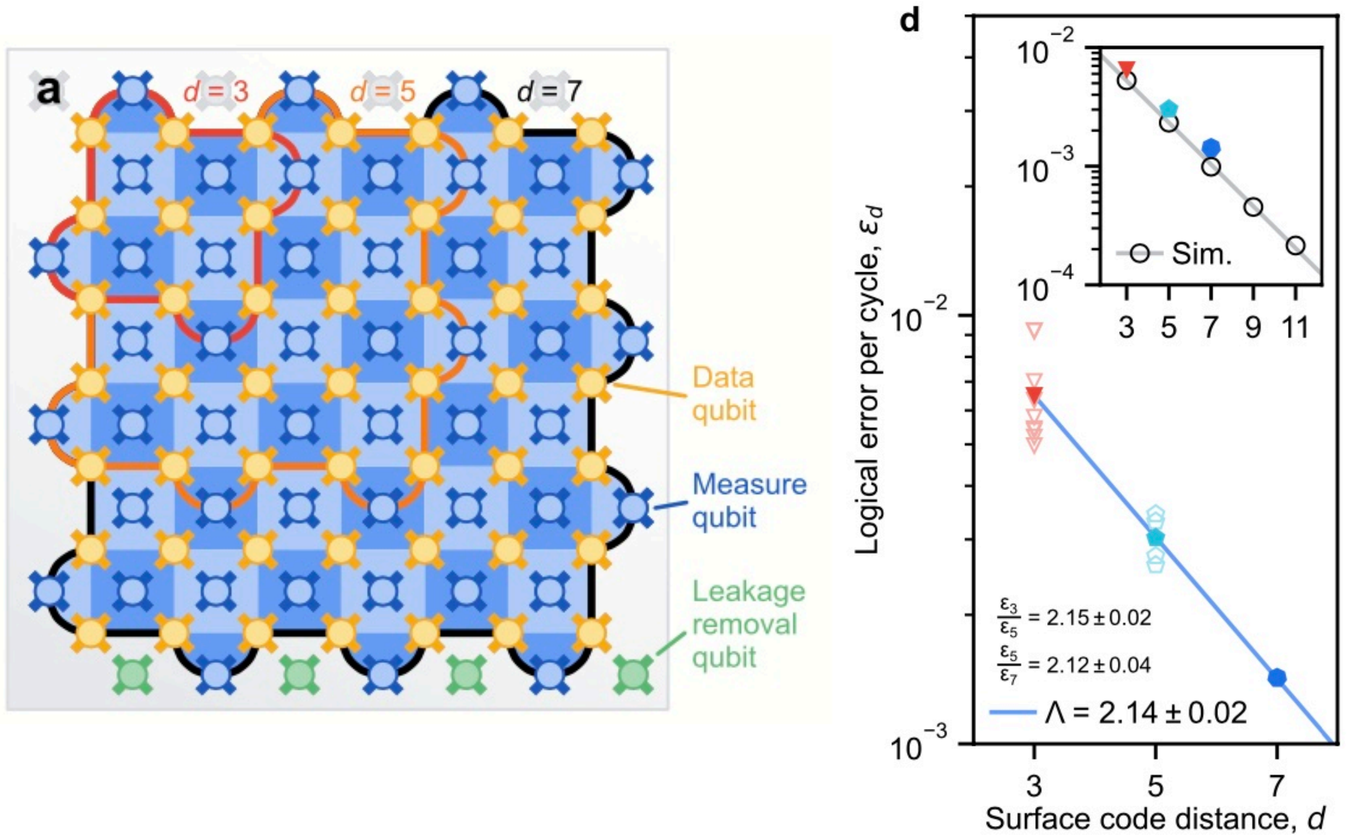
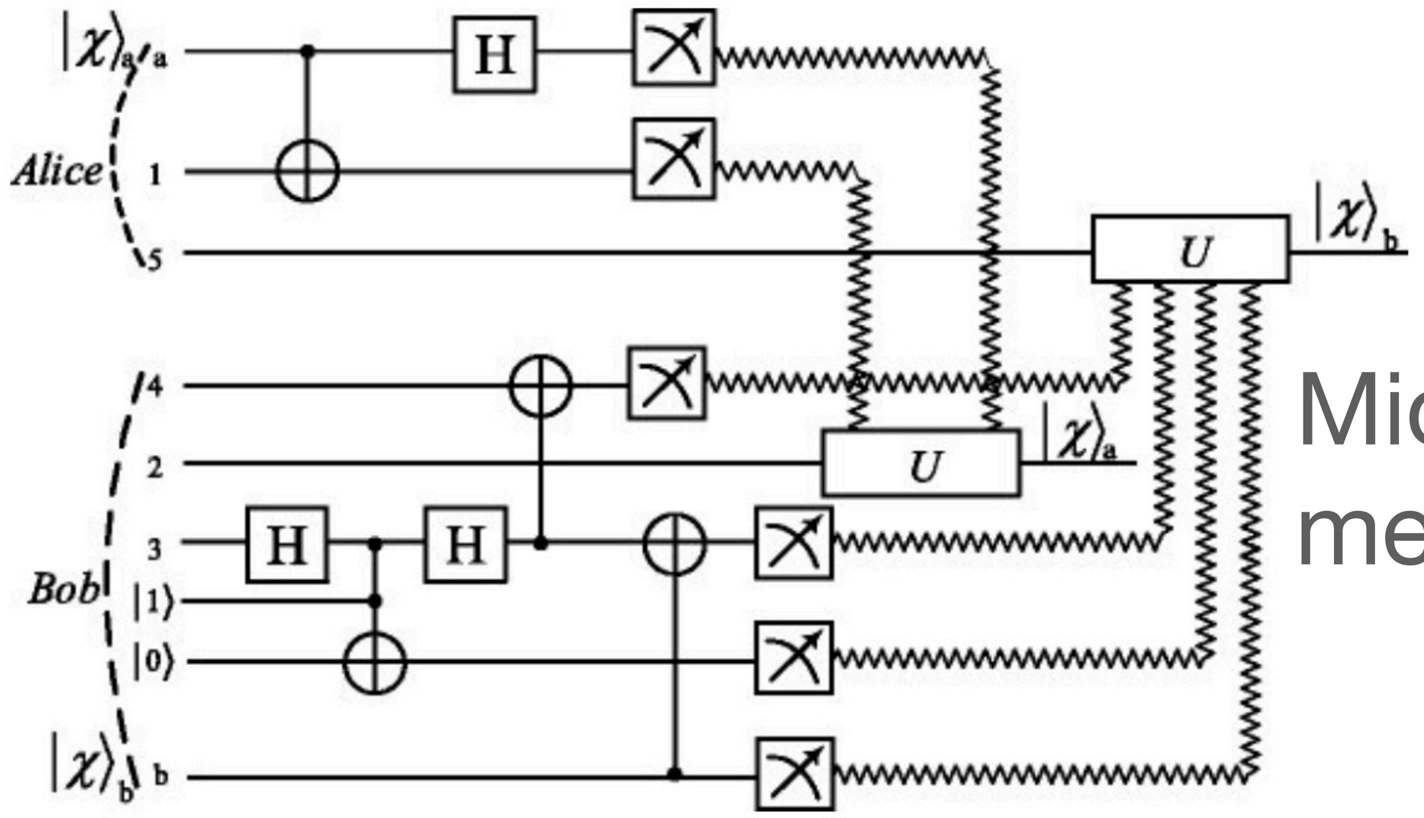


FIG. 1. **Level scheme of the $^{40}Ca^+$ ion.**

Qudits with trapped ions

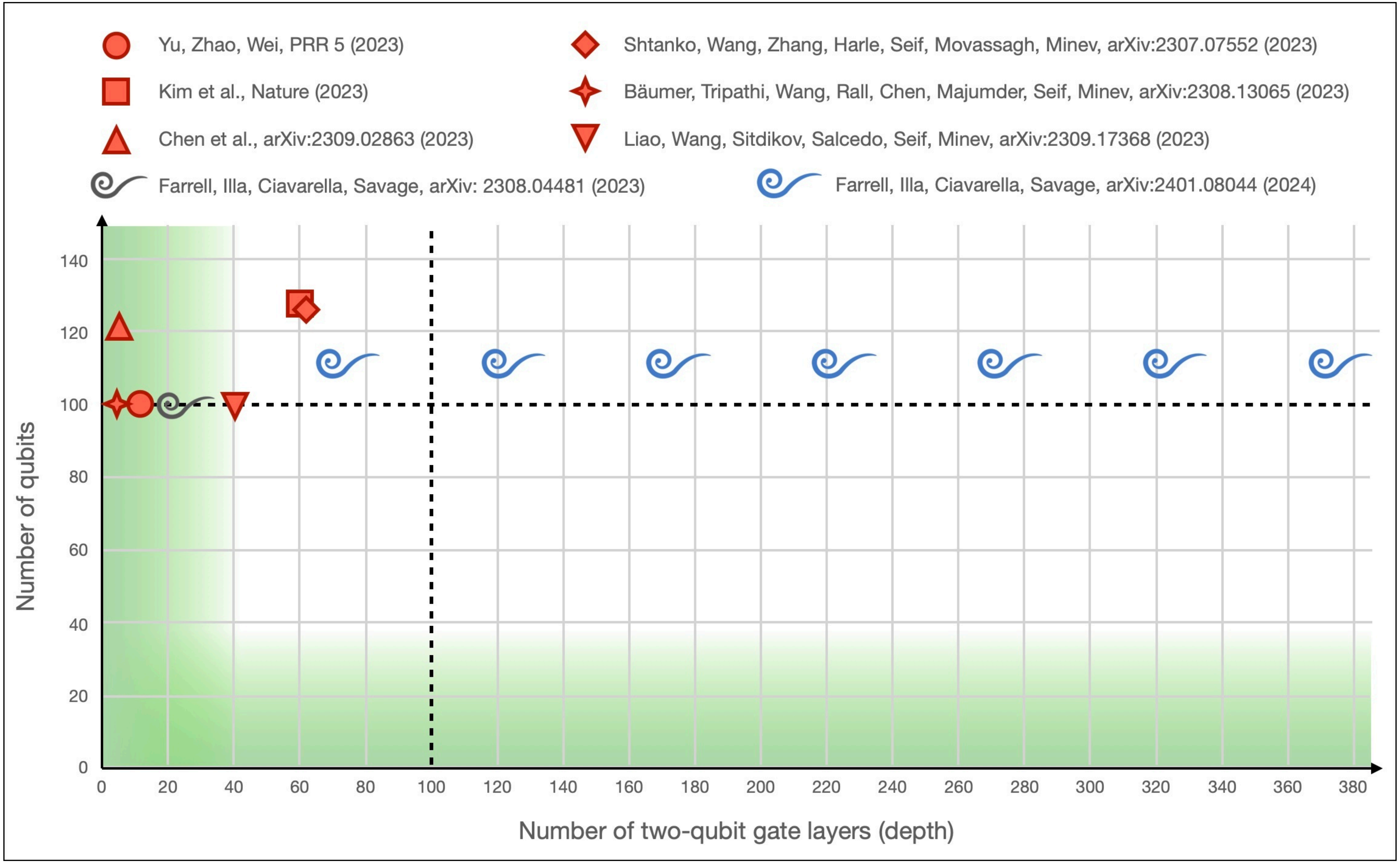


Surface code
>100 superconducting qubits



Mid-circuit measurements

Bidirectional Teleportation Protocol in Quantum Wireless Multi-hop Network
June 2018 · International Journal of Theoretical ... 57(4)
DOI: 10.1007/s10773-018-3698-2
Rui Cai · Xu-Tao Yu · Zai-Chen Zhang



Yu, Zhao, Wei, PRR 5 (2023)
Kim et al., Nature (2023)
Chen et al., arXiv:2309.02863 (2023)
Farrell, Illa, Ciavarella, Savage, arXiv: 2308.04481 (2023)
Shtanko, Wang, Zhang, Harle, Seif, Movassagh, Minev, arXiv:2307.07552 (2023)
Bäumer, Tripathi, Wang, Rall, Chen, Majumder, Seif, Minev, arXiv:2308.13065 (2023)
Liao, Wang, Sitdikov, Salcedo, Seif, Minev, arXiv:2309.17368 (2023)
Farrell, Illa, Ciavarella, Savage, arXiv:2401.08044 (2024)
Number of qubits
0
20
40
60
80
100
120
140
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
Number of two-qubit gate layers (depth)

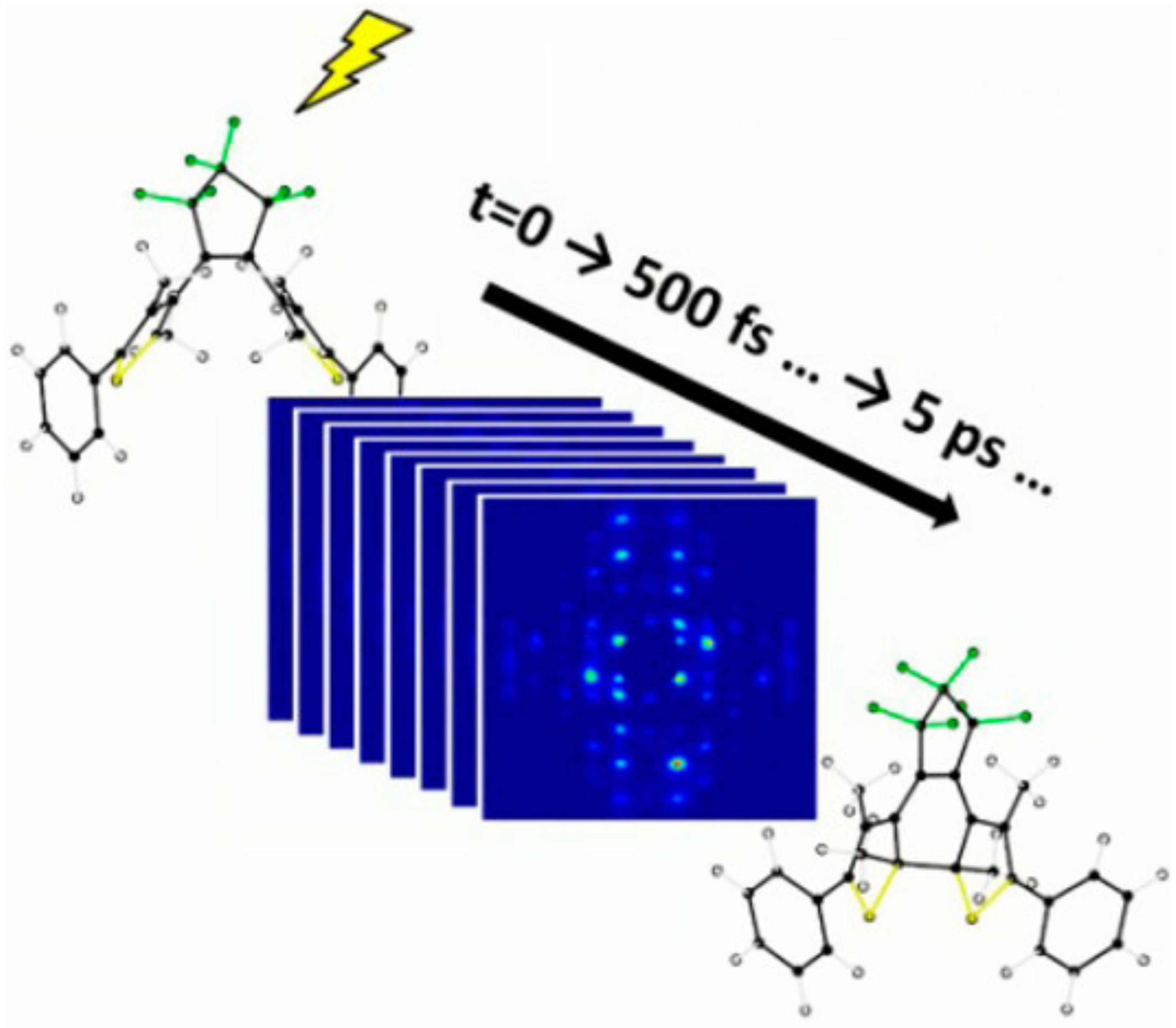
Perspective | Published: 21 June 2023

Quantum simulation of fundamental particles and forces

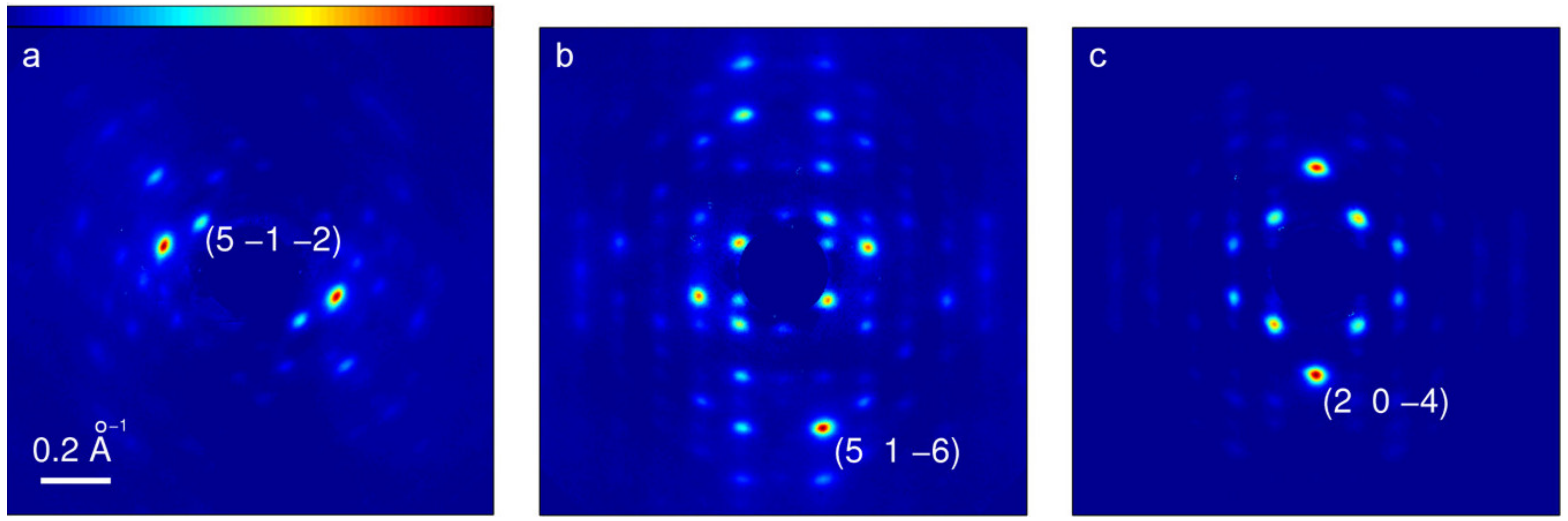
Christian W. Bauer, Zohreh Davoudi, Natalie Klco & Martin J. Savage

Nature Reviews Physics **5**, 420–432 (2023) | Cite this article

Real-Time Dynamics and Reaction Pathways



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

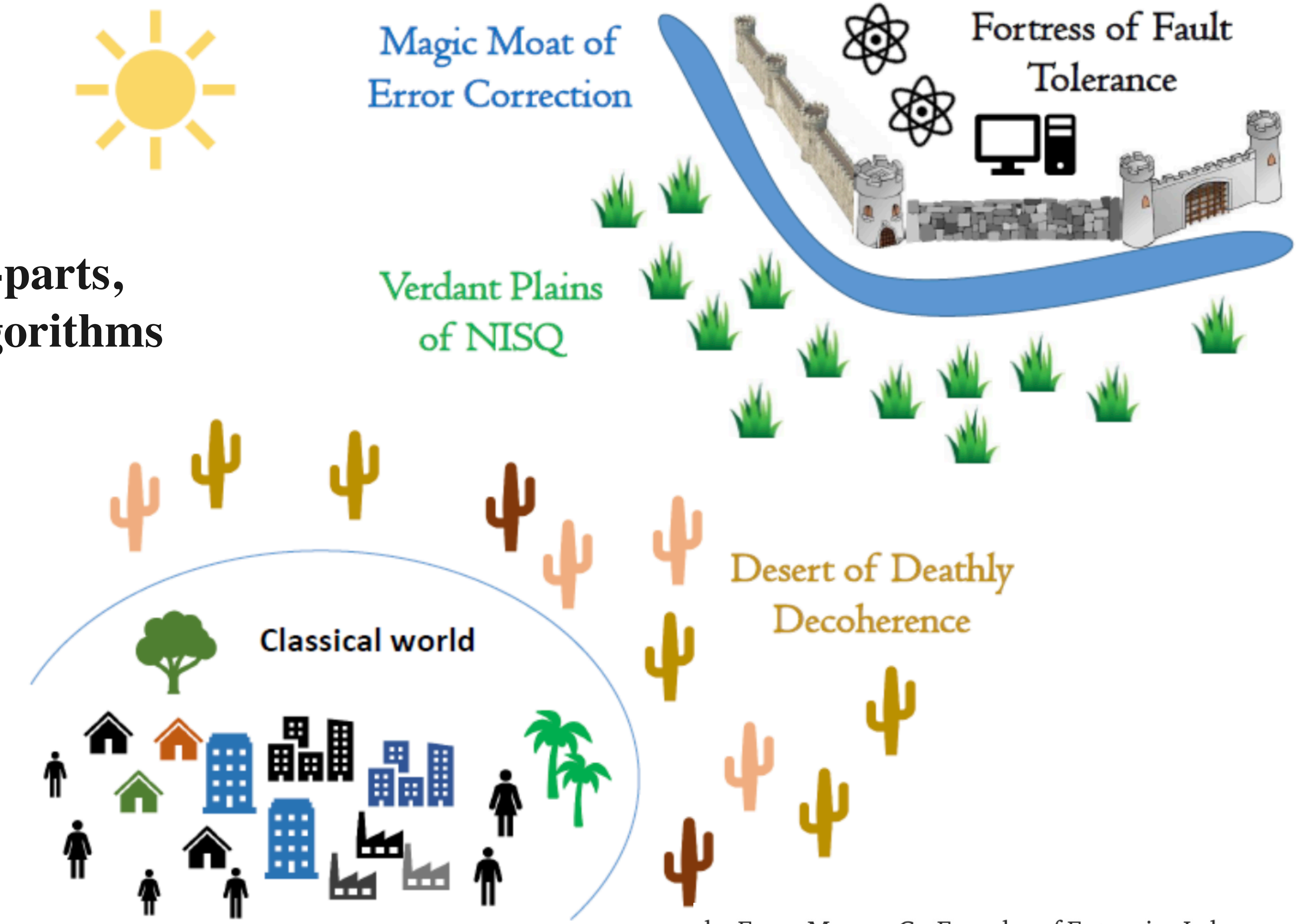


Femto-second chemistry reveals reaction mechanisms
Quantum simulations will reveal the reactions pathways of QCD

Quantum Simulation in the NISQ Era

Today: Error Mitigation and Dreaming of Correction

Insights, ideas, sub-parts, observables and algorithms



Precision simulations to compare with experiments and make reliable predictions

by Ewan Munro, Co-Founder of Entropica Labs.

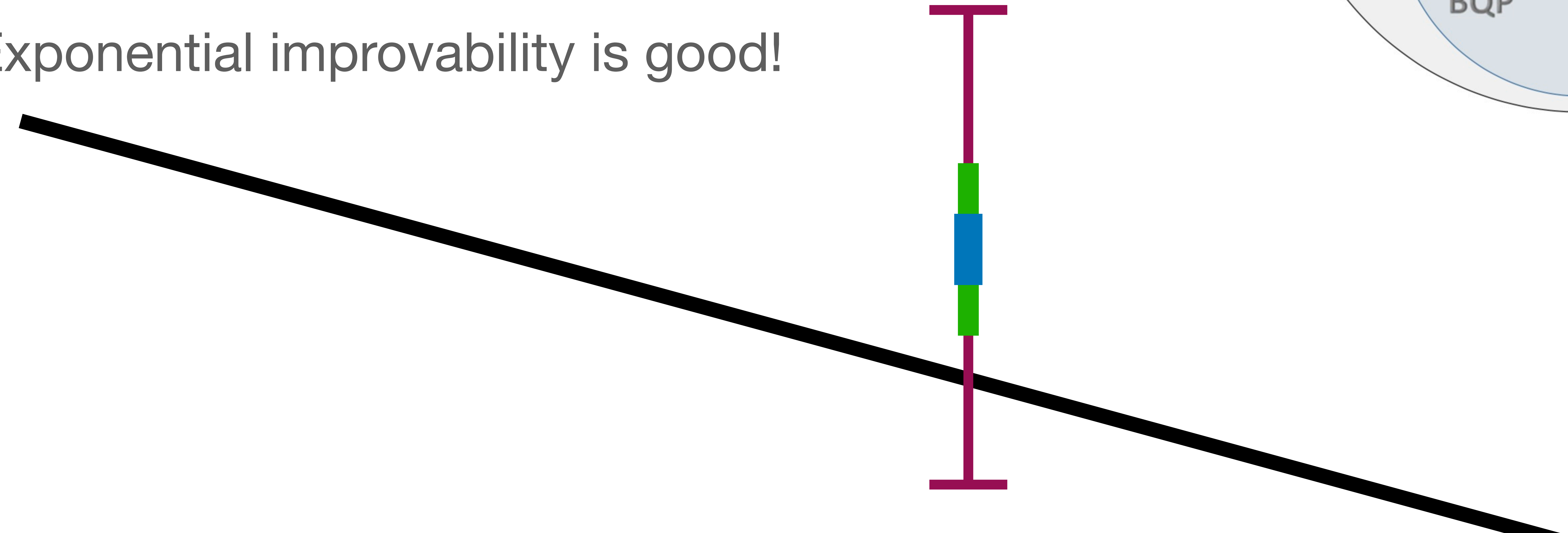
Landscape of quantum computing from an error correction perspective. Inspired by a figure by Daniel Gottesman.

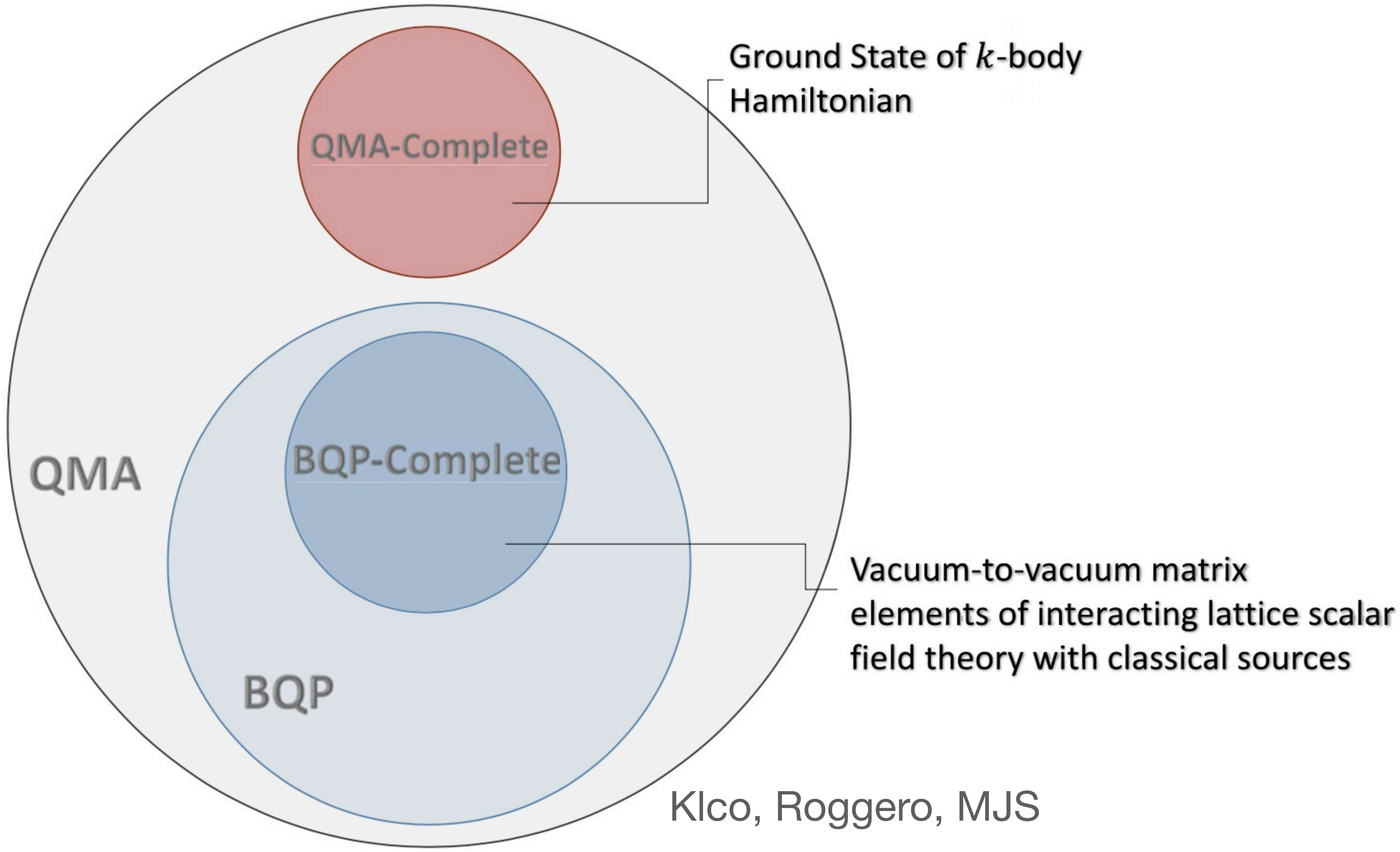
Errors are a Defining Consideration in Simulations

Theory errors, mapping errors , algorithm errors, workflow errors, device errors, analysis errors .....

Can find the source(s) of the largest errors and relax the others.

Exponential improvability is good!





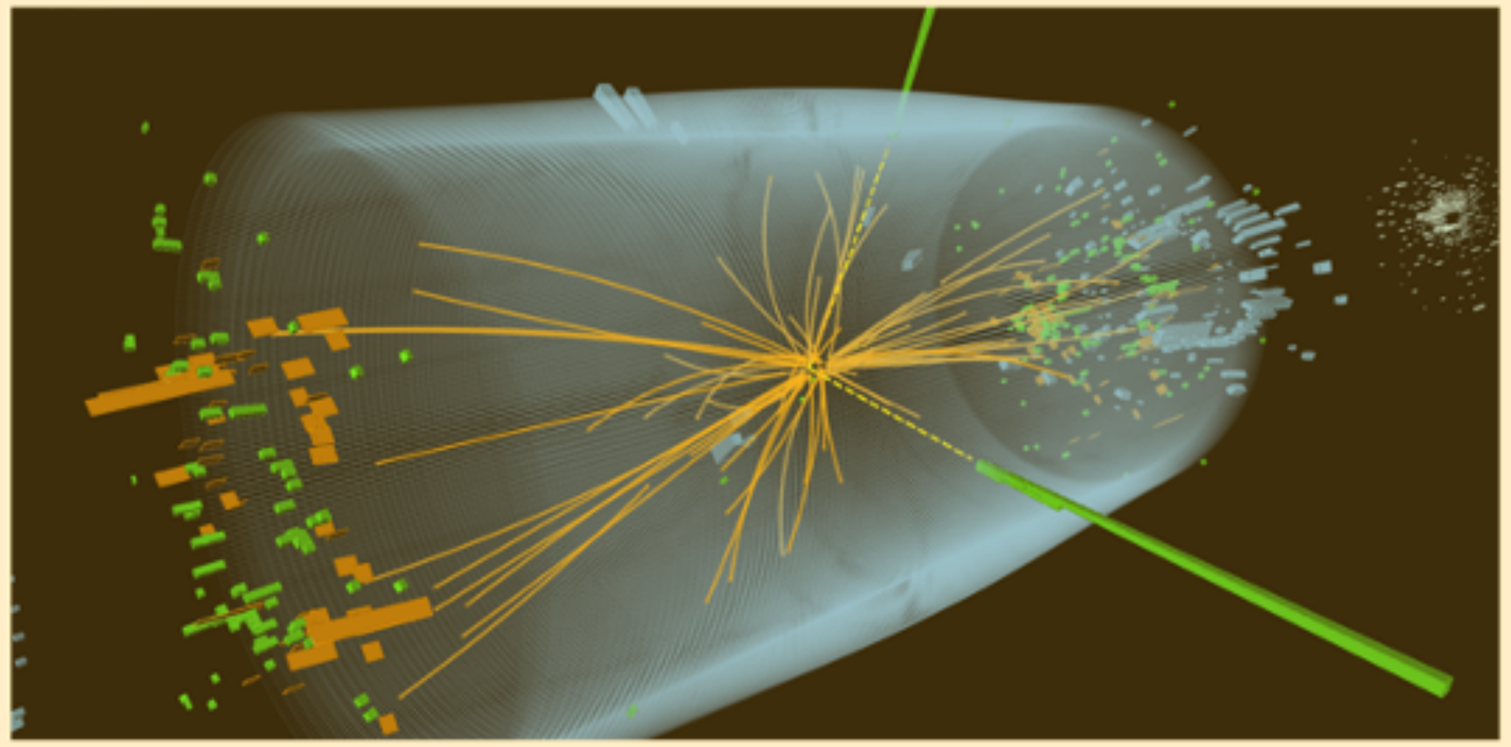
Klco, Roggero, MJS

Scaling
- system size
- precision

Rahul Trivedi

Simulation Objectives for the Standard Model and Beyond

Gauge Theories and Descendent Effective Field Theories and Models



Real-time dynamics
particle production, fragmentation
vacuum and in medium

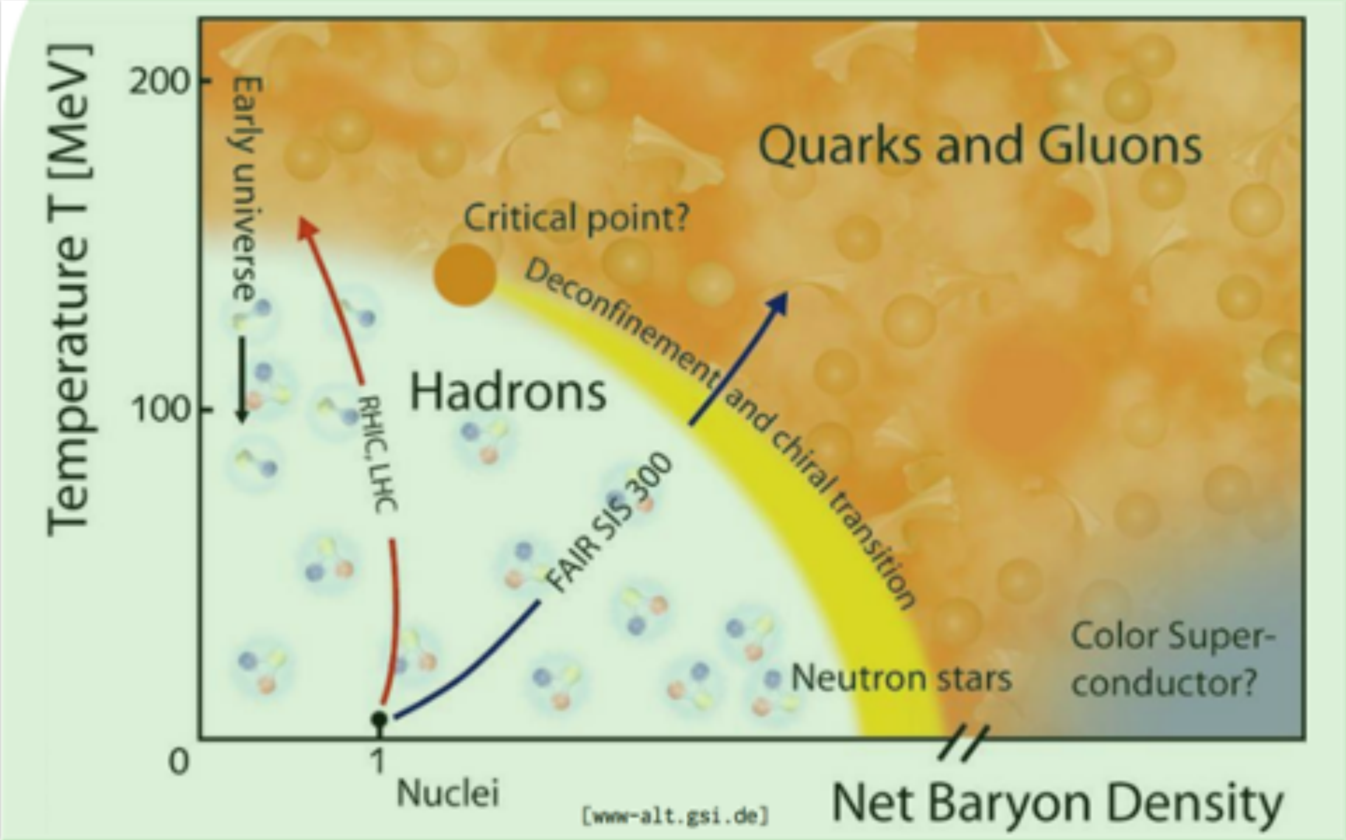
Low-energy reactions

Electroweak processes (e.g., nu-A)

Neutrino dynamics

Matter-antimatter asymmetry

BQP

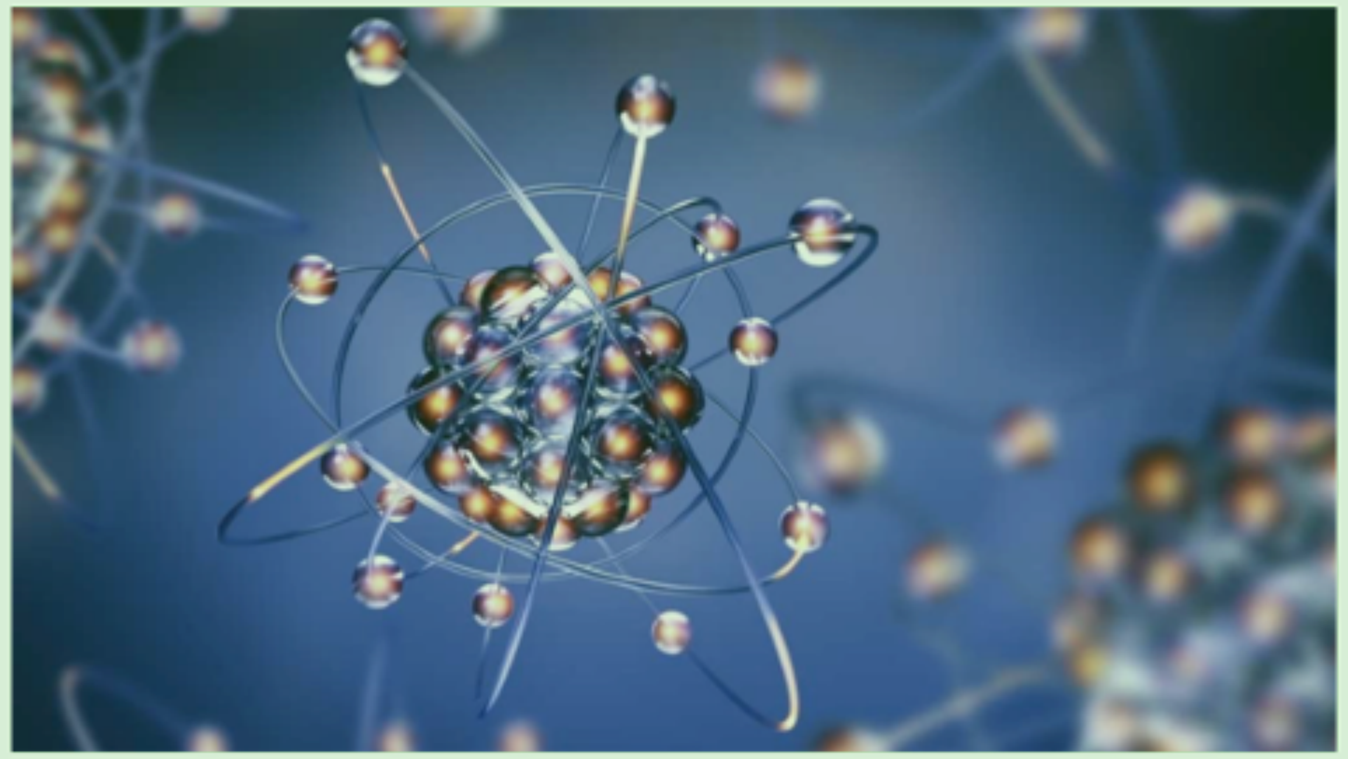


Equation of state of dense
hot matter and dynamics
viscosity, etc

Conquering some "sign problems"

The early universe

Supernova/Neutron stars

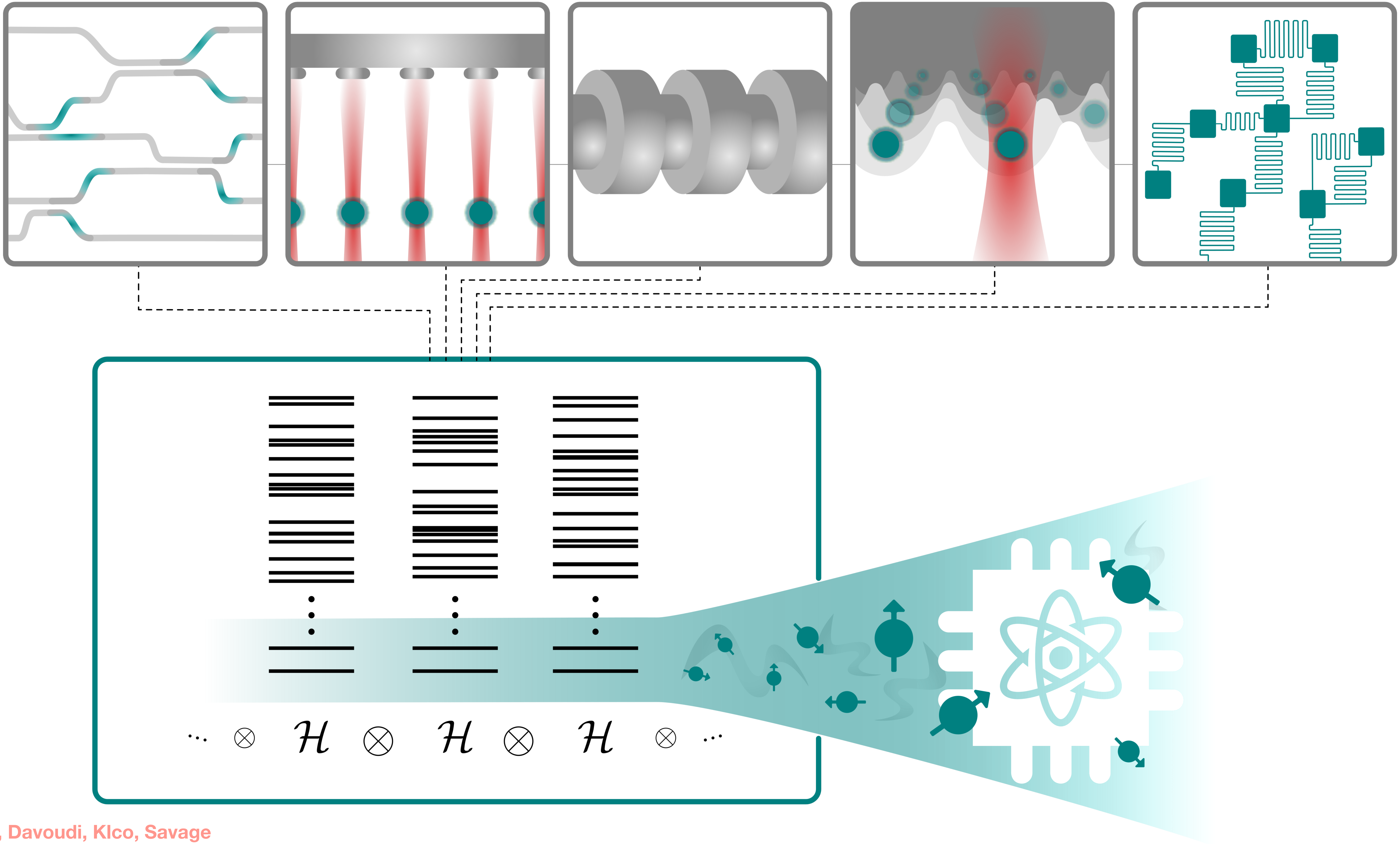


Precision structure and interactions
of nuclei

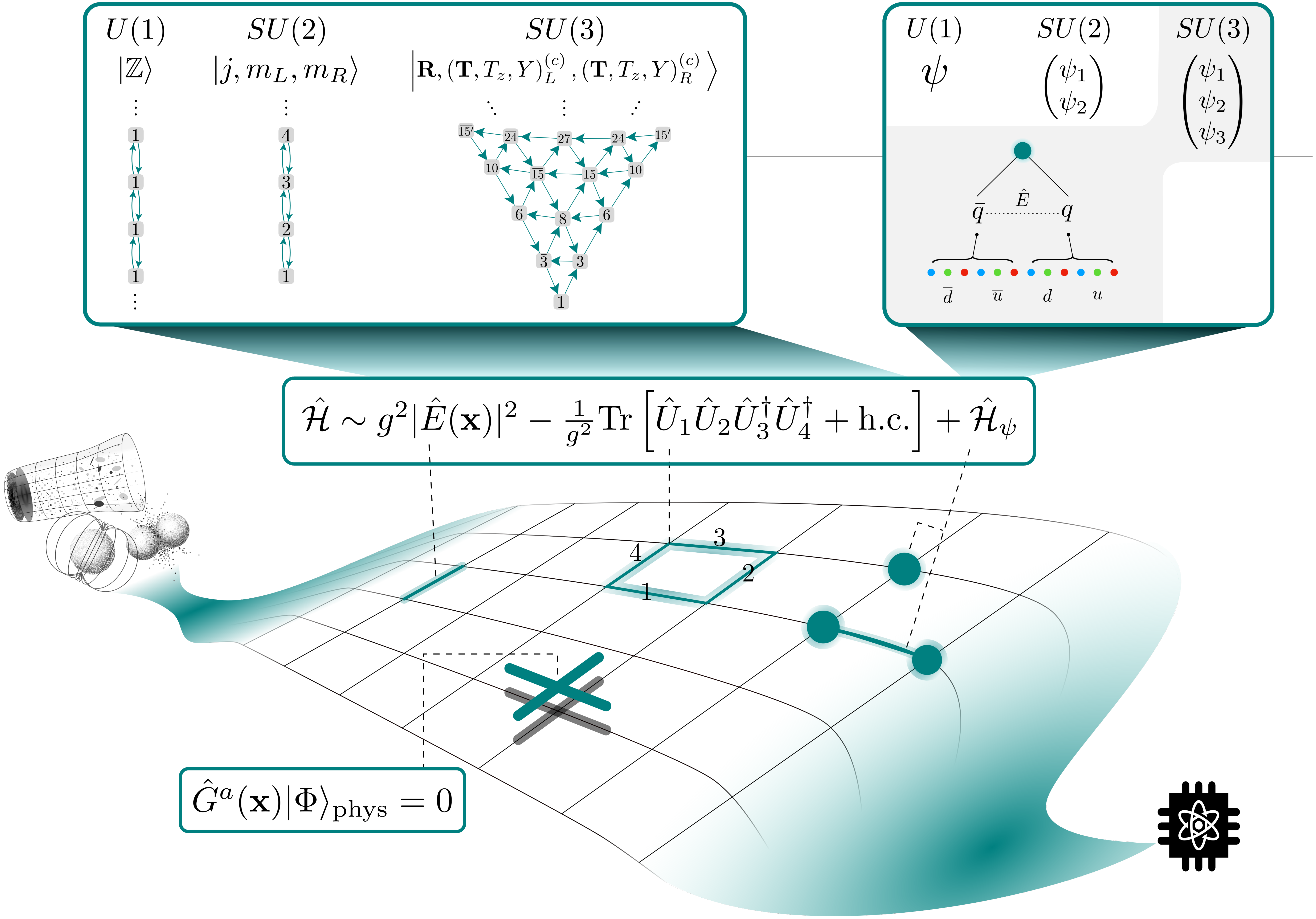
Many-body systems

Rare processes, double-beta decay

QMA
– symmetries

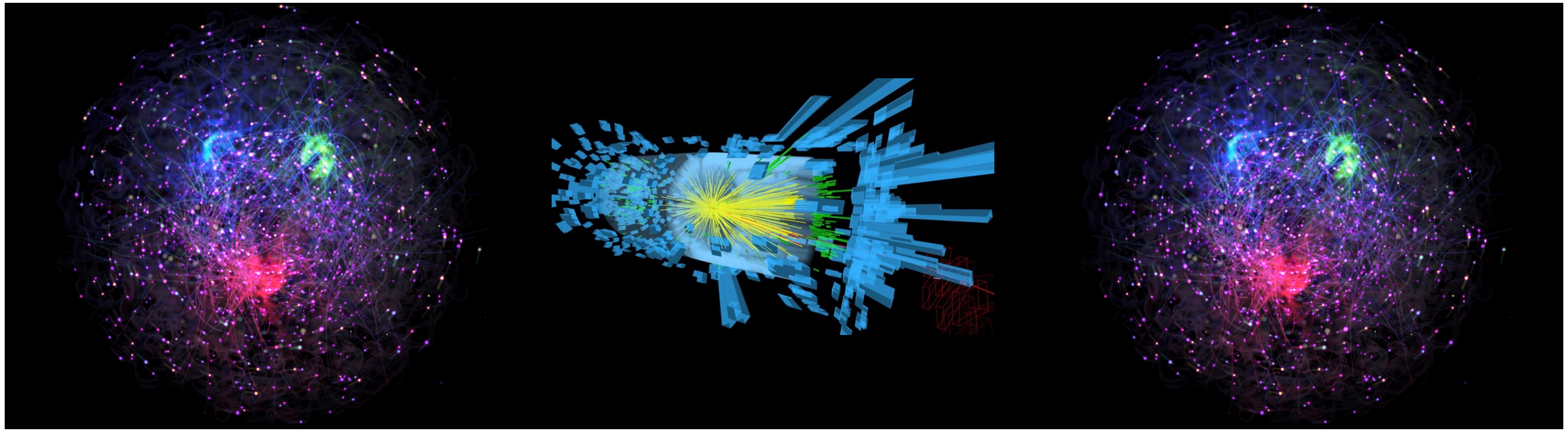


Bauer, Davoudi, Klco, Savage



Bauer, Davoudi, Klco, Savage

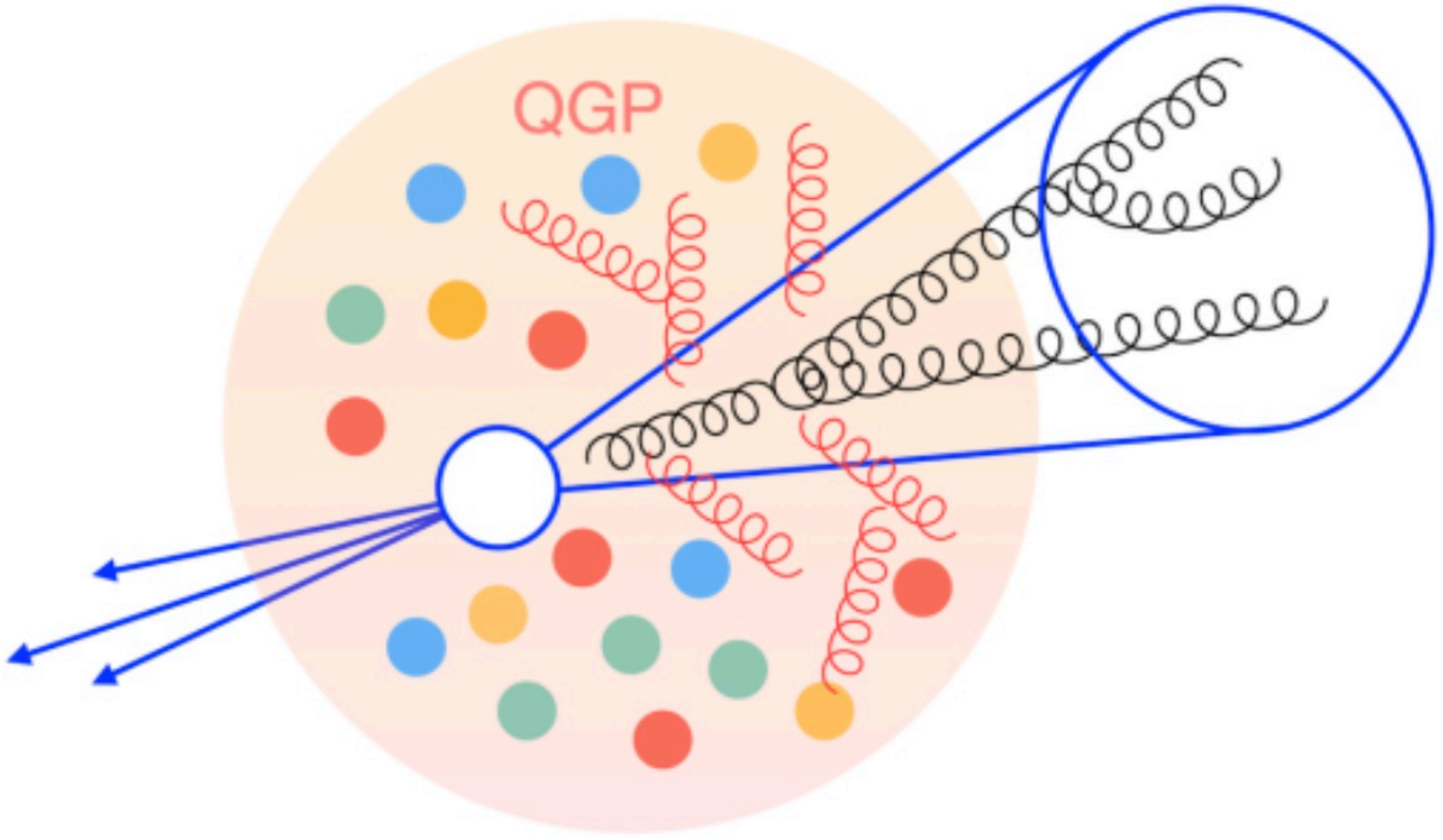
Hadronization and Fragmentation



For example, jet production, energy-loss, hadronization

3+1D, quantum chromodynamics, quarks+gluons

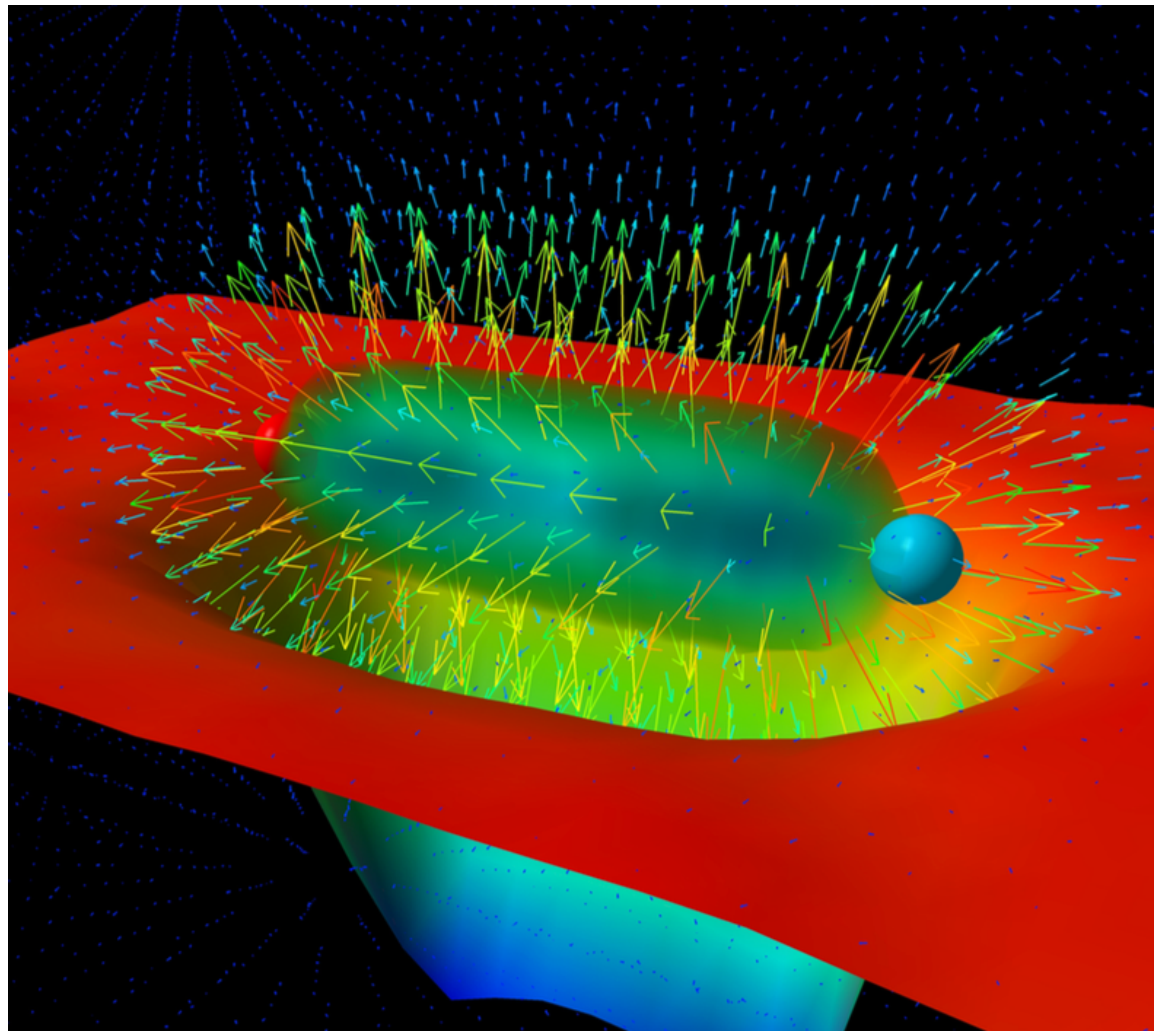
Event generators constrained by decades of precise data,
Asymptotic freedom, effective field theory relations,
Lacks entanglement and quantum coherence.
Major classical computing resource requirement.

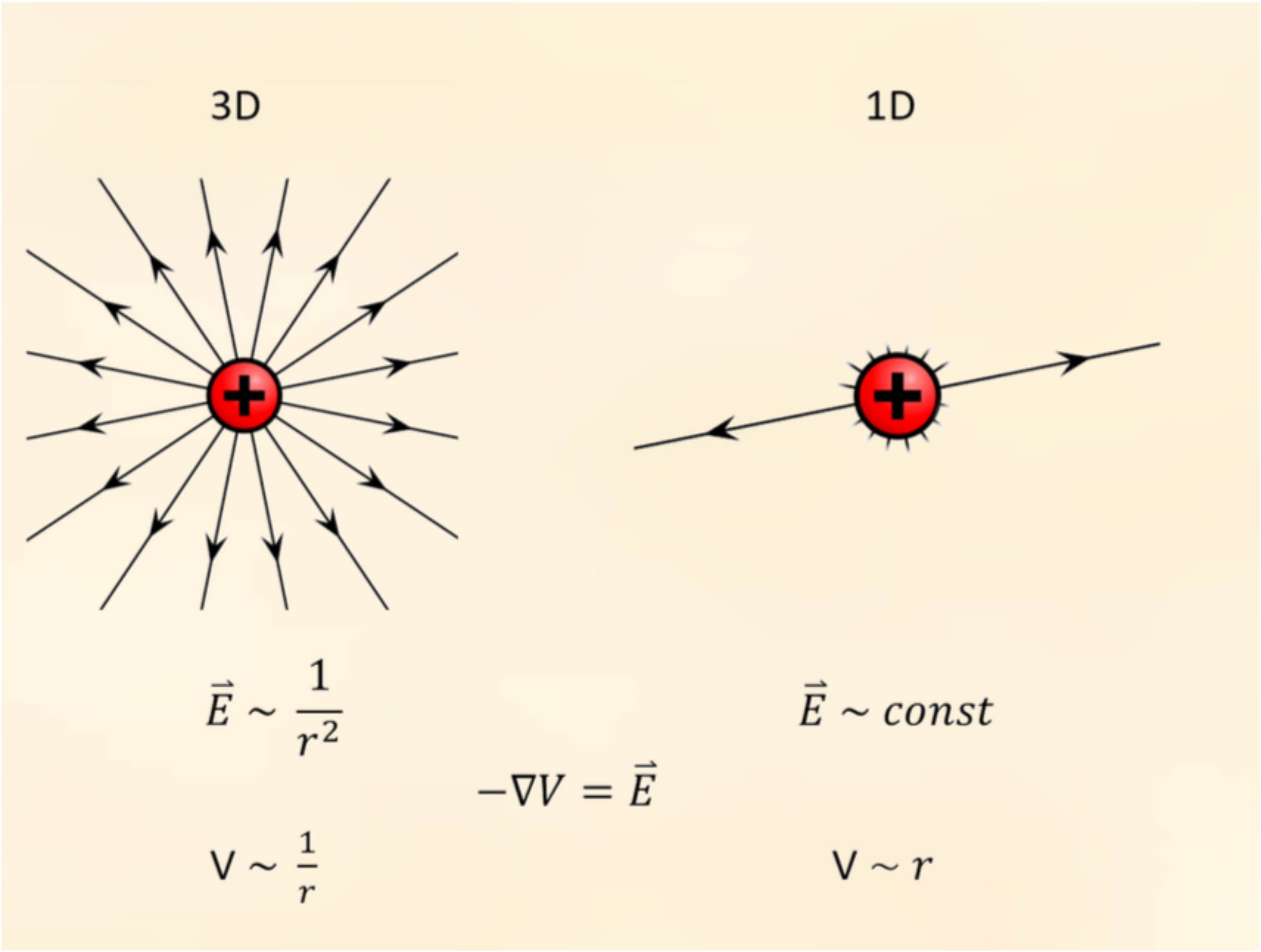


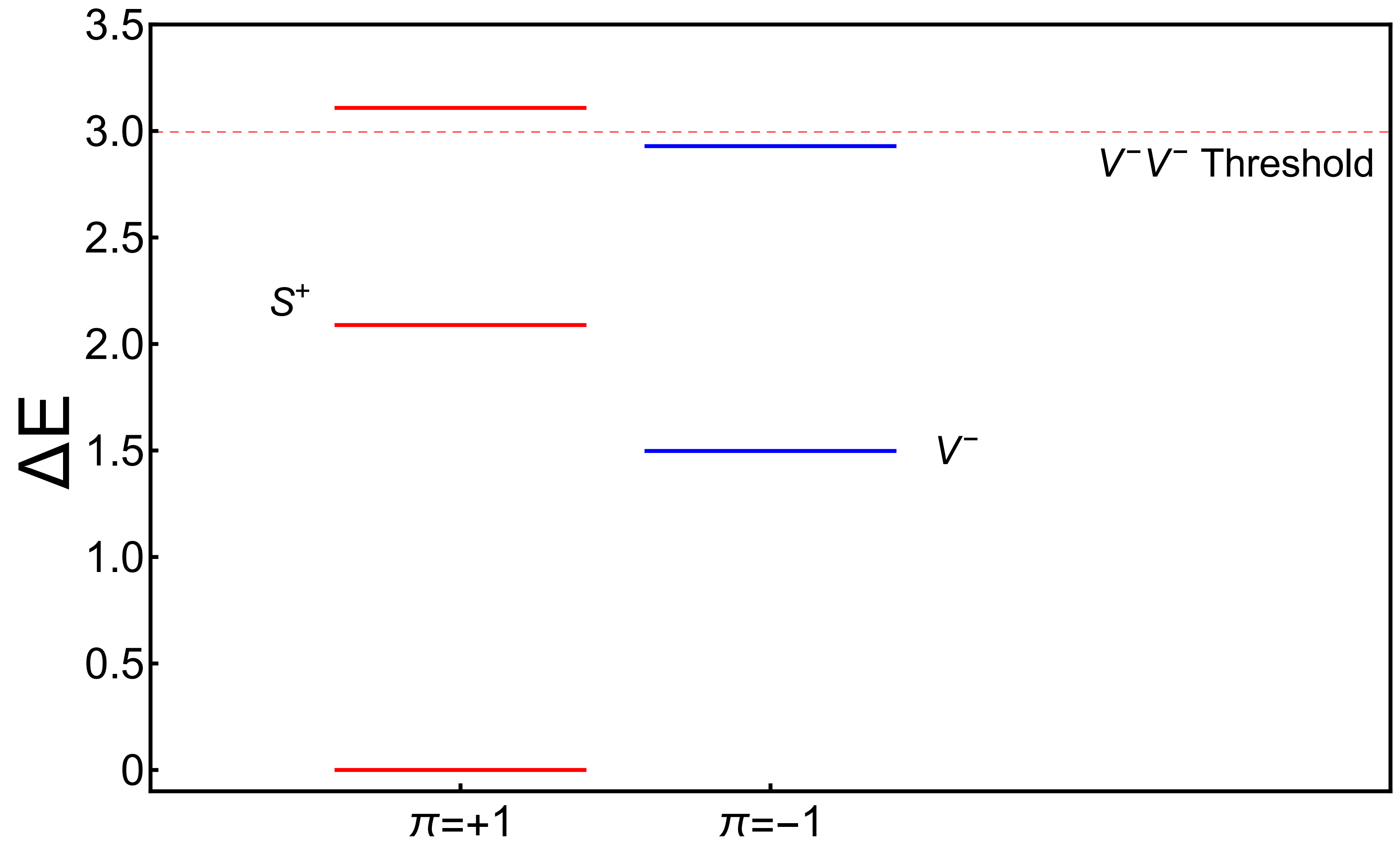
Quantum Electrodynamics in 1+1 Dimensions

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

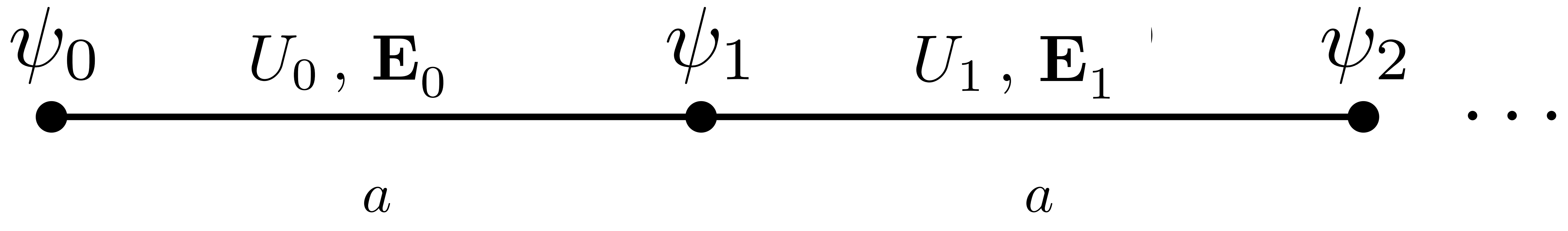
- Charge screening, confinement
- Fermion condensate
- Gap
- Translationally invariant vacuum

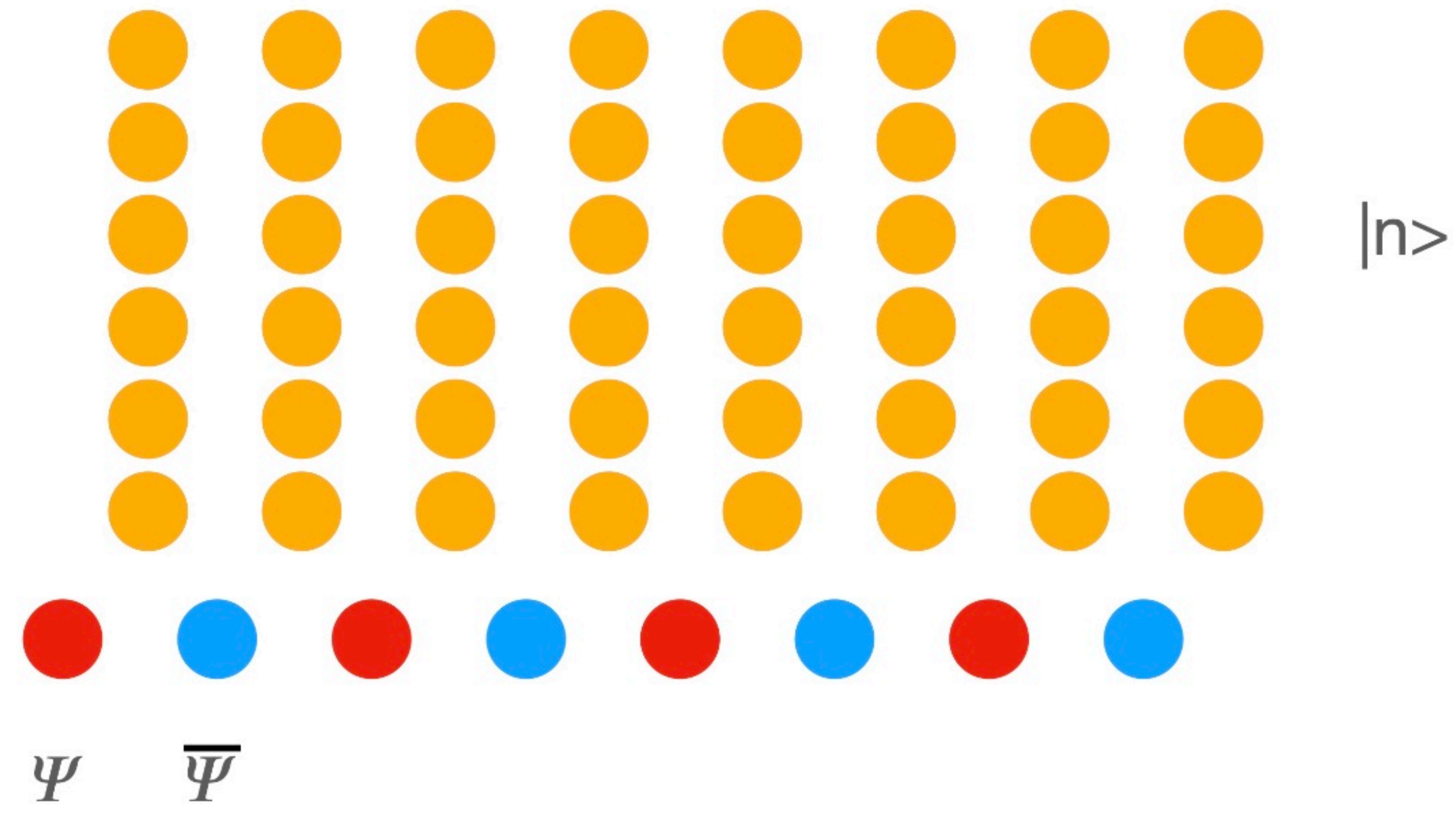




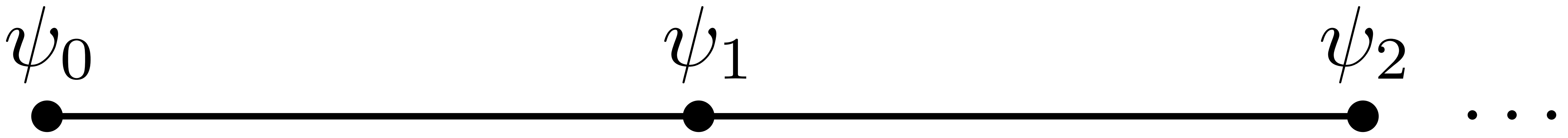


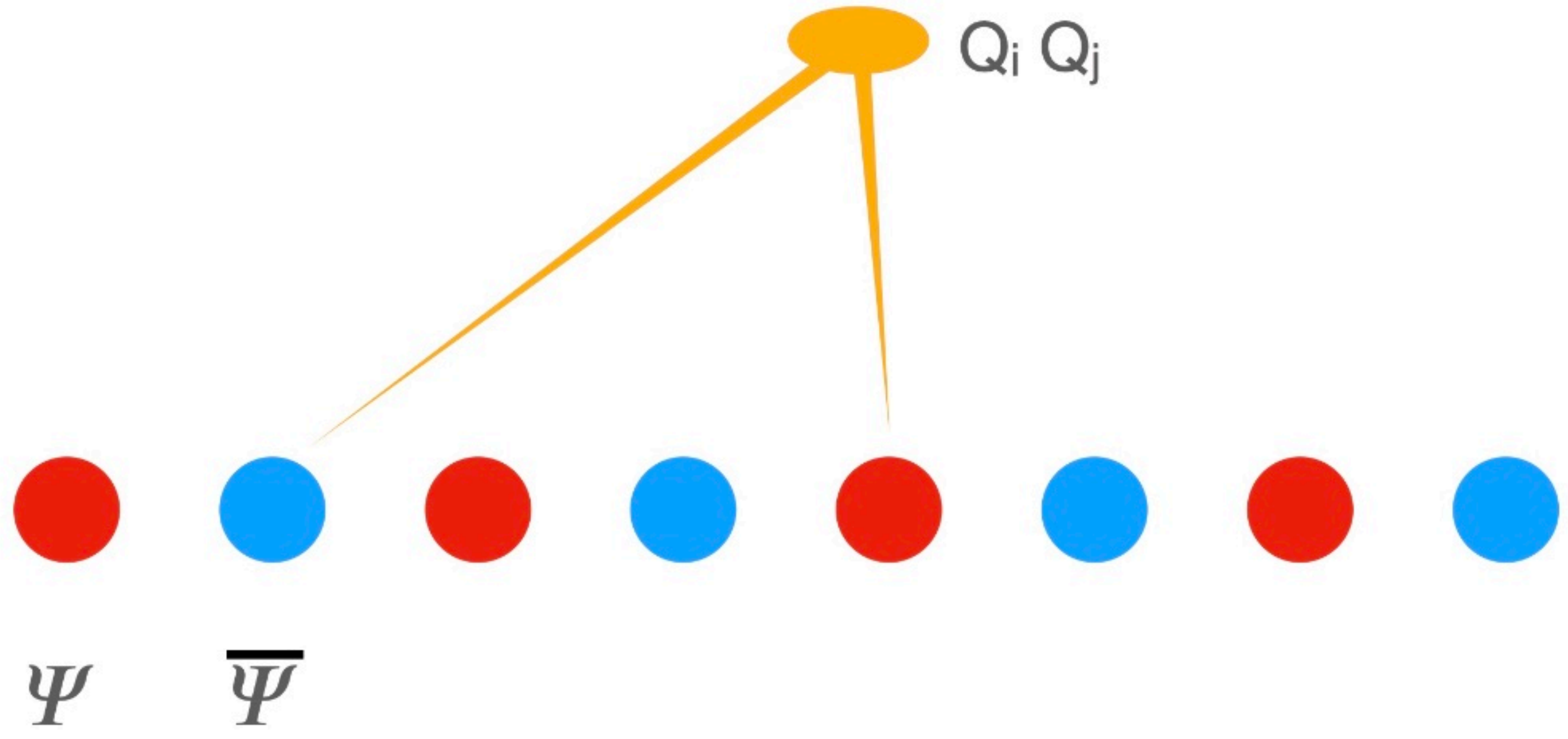
Lattice Hamiltonian in 1+1D - Which Gauge to Choose?





Weyl gauge





Axial gauge

Jordan-Wigner Mapping with OBCs

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

Local — Nearest Neighbor — Non-local

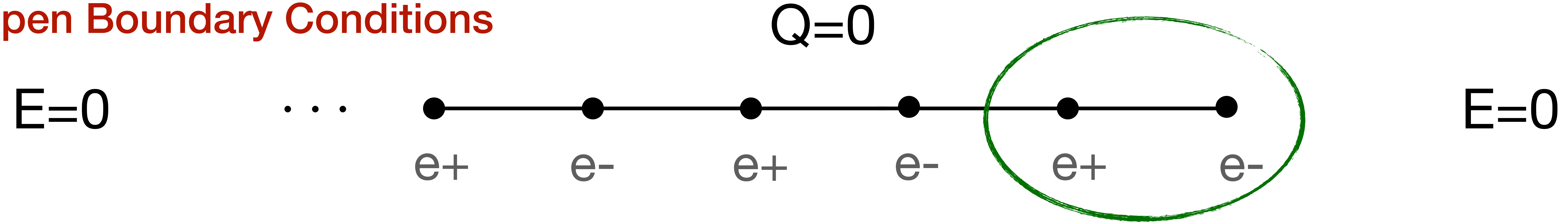
$$\hat{Q}_k = -\frac{1}{2}\left[\hat{Z}_k + (-1)^k\hat{I}\right]$$

Local

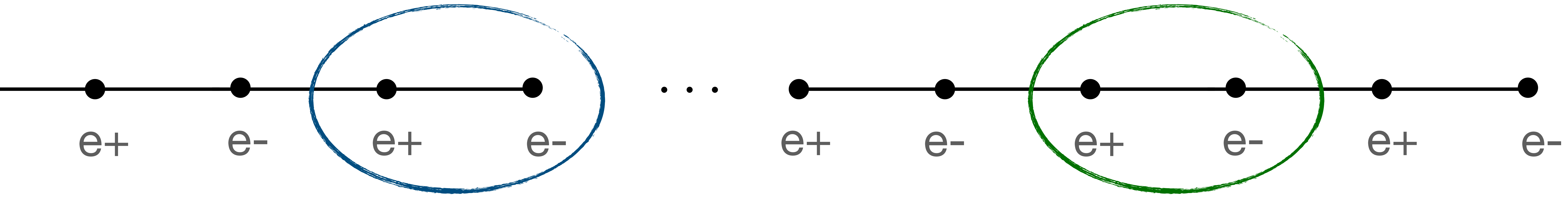
$$\chi = \frac{1}{2L}\sum_{j=0}^{2L-1}\left\langle(-1)^j\hat{Z}_j + \hat{I}\right\rangle \equiv \frac{1}{2L}\sum_{j=0}^{2L-1}\chi_j$$

Local

Open Boundary Conditions



Confinement Means .....



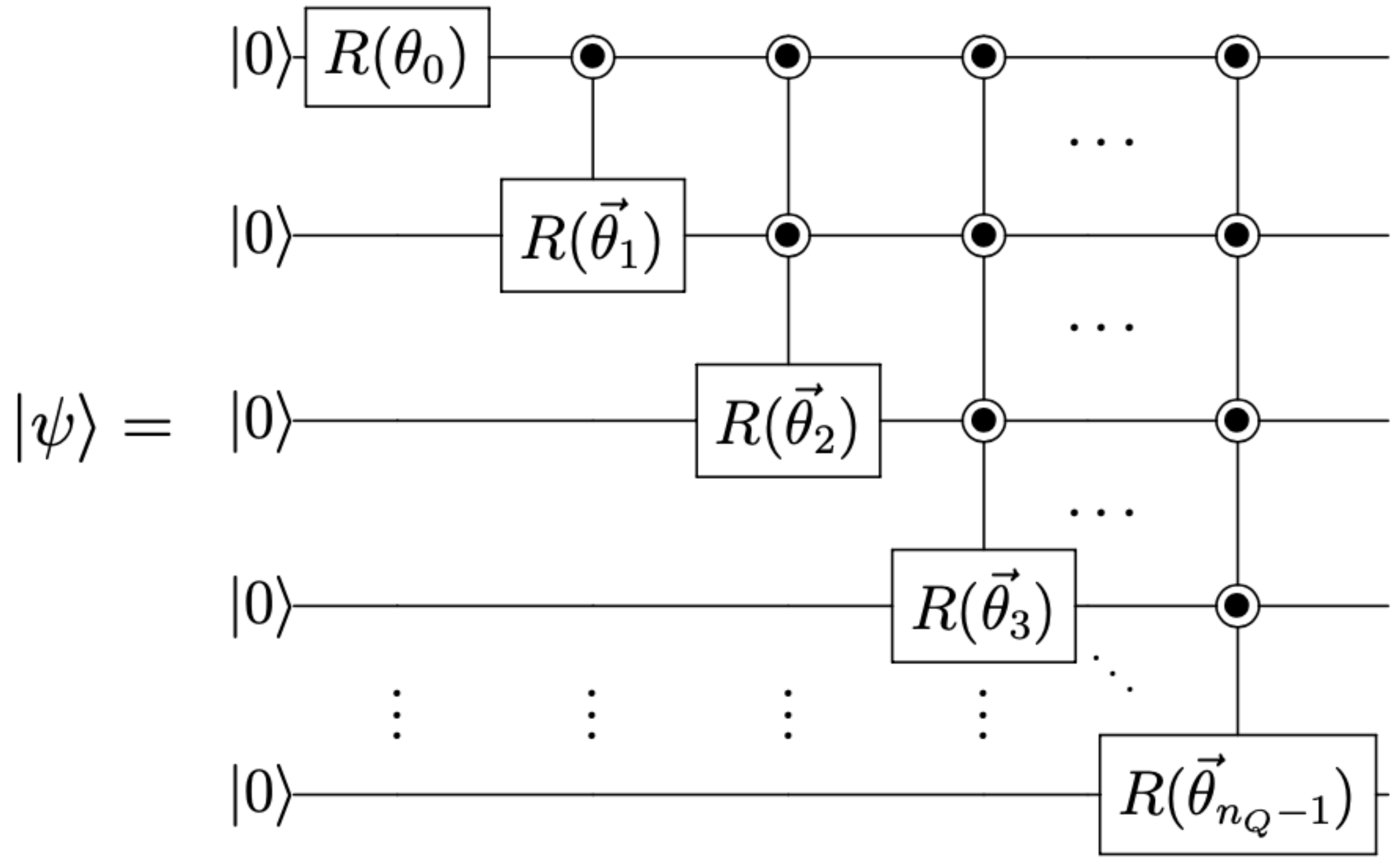
$< Q_i \, Q_j >$

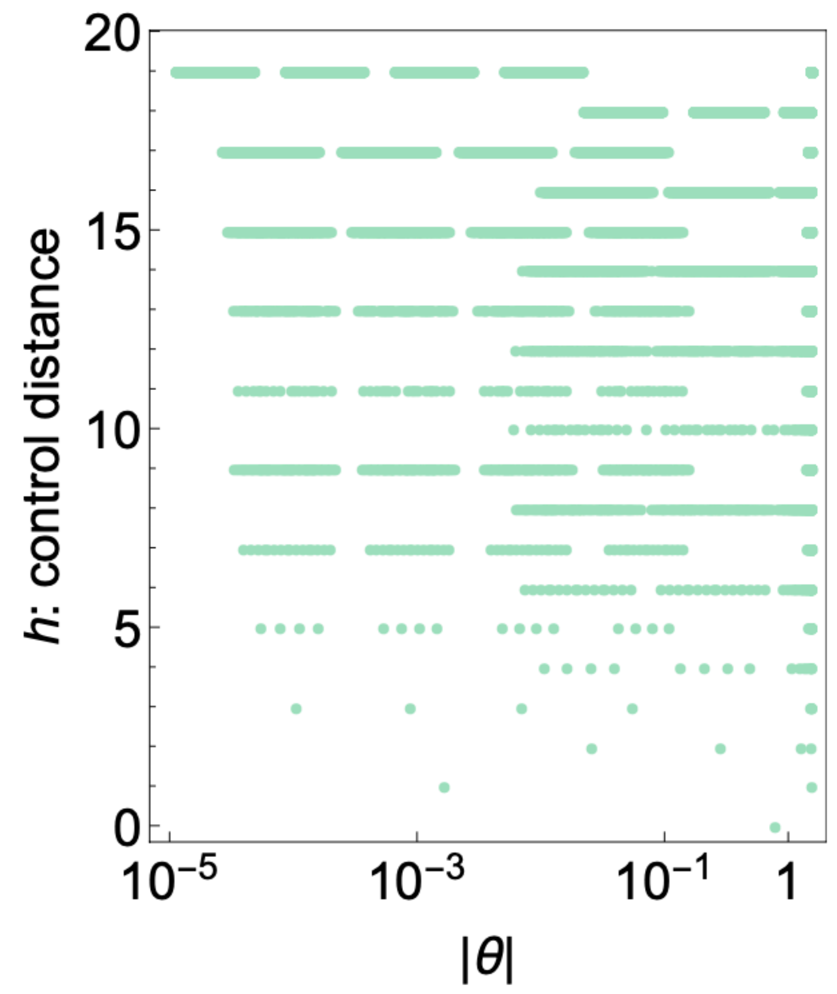
Vanishes exponentially with increasing separation
—with a length scale set by the gap

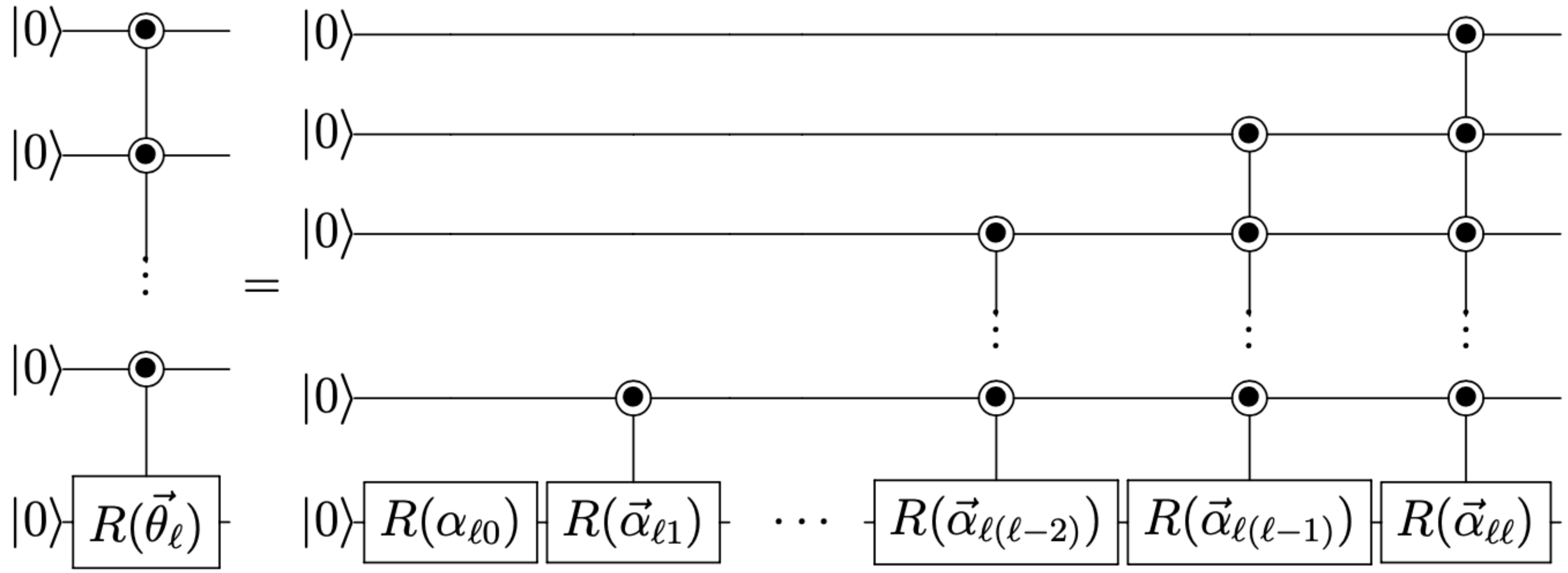
Truncation of non-local term(s) in the Hamiltonian will converge rapidly

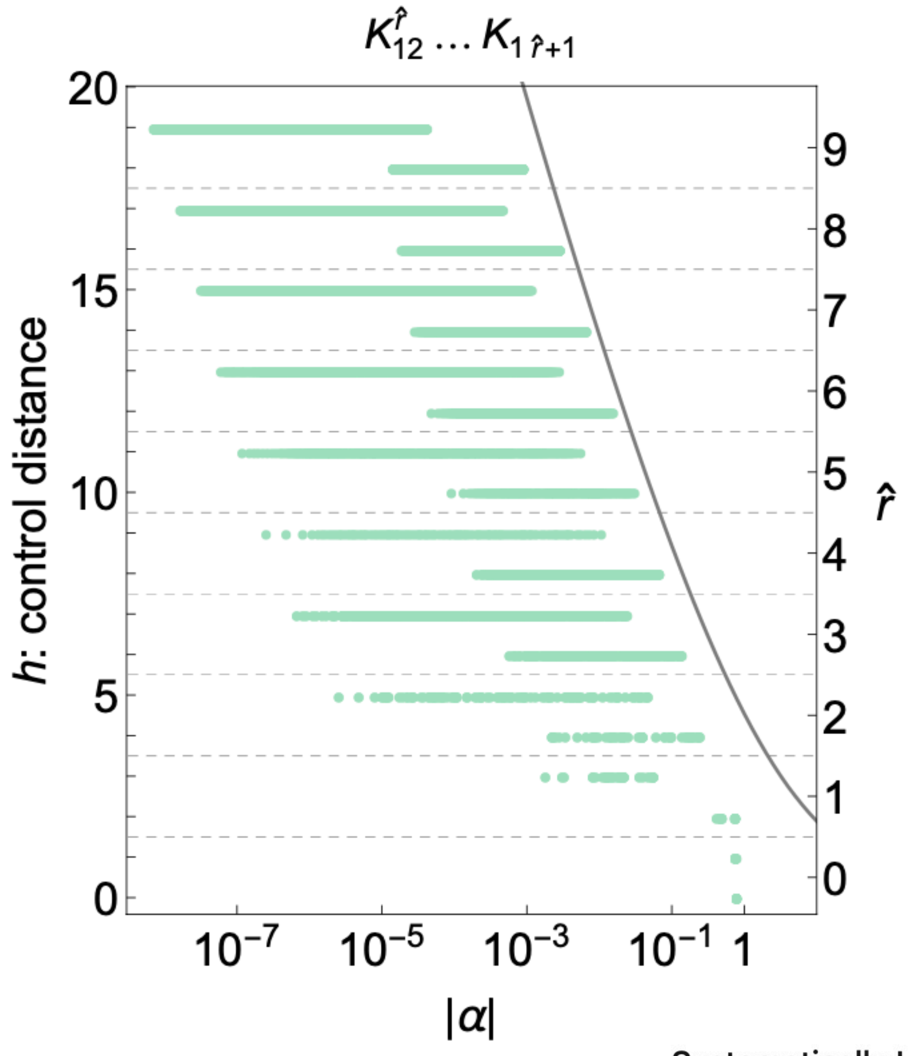
Building in Correlations
Bounded in the IR and UV - Confinement Scale

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 [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 [quant-ph]

Preparing the Vacuum: Outline of Strategy
Introducing … SC-ADAPT-VQE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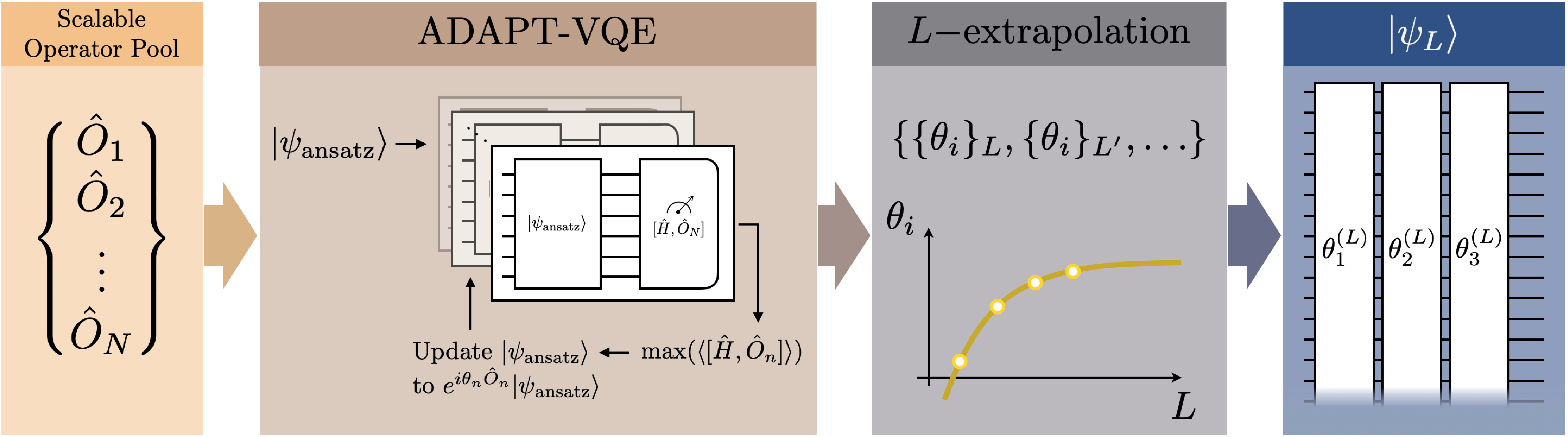
Scalable Circuits for Preparing Ground States on Digital Quantum Computers: The Schwinger Model Vacuum on 100 Qubits
Roland C. Farrell, Marc Illa, Anthony N. Ciavarella, and Martin J. Savage
PRX Quantum 5, 020315 – Published 18 April 2024

Symmetries and Confinement

Classical Optimization

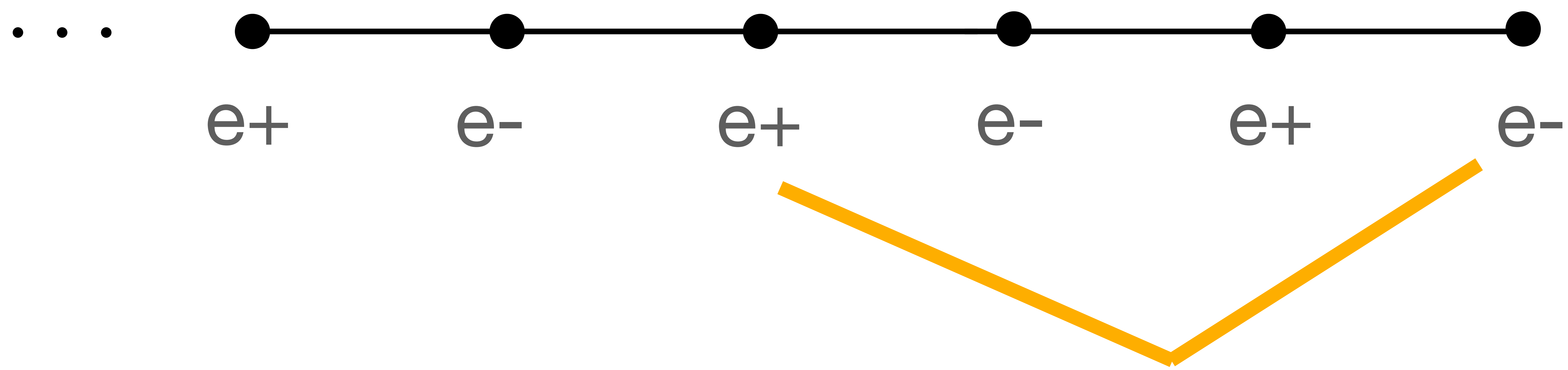
Classical Extrapolations

Quantum Implementation



Adaptive Derivative-Assembled Pseudo-Trotter ansatz Variational Quantum Eigensolver (ADAPT-VQE)

Scalable Operators: Volume and Surface



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

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

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

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

Real wavefunction from real initial wavefunction : (all) symmetries in operators

Scalable Operators: Volume and Surface

$$\{\hat{O}\} = \left\{\hat{O}^V_{mh}(d)\ ,\ \hat{O}^S_{mh}(0,d)\ ,\ \hat{O}^S_{mh}(1,d)\right\}\ ,$$

$$\hat{O}^V_{mh}(d) \equiv i\left[\hat{\Theta}^V_m, \hat{\Theta}^V_h(d)\right] = \frac{1}{2}\sum_{n=0}^{2L-1-d}(-1)^n\left(\hat{X}_n\hat{Z}^{d-1}\hat{Y}_{n+d} - \hat{Y}_n\hat{Z}^{d-1}\hat{X}_{n+d}\right)\ ,$$

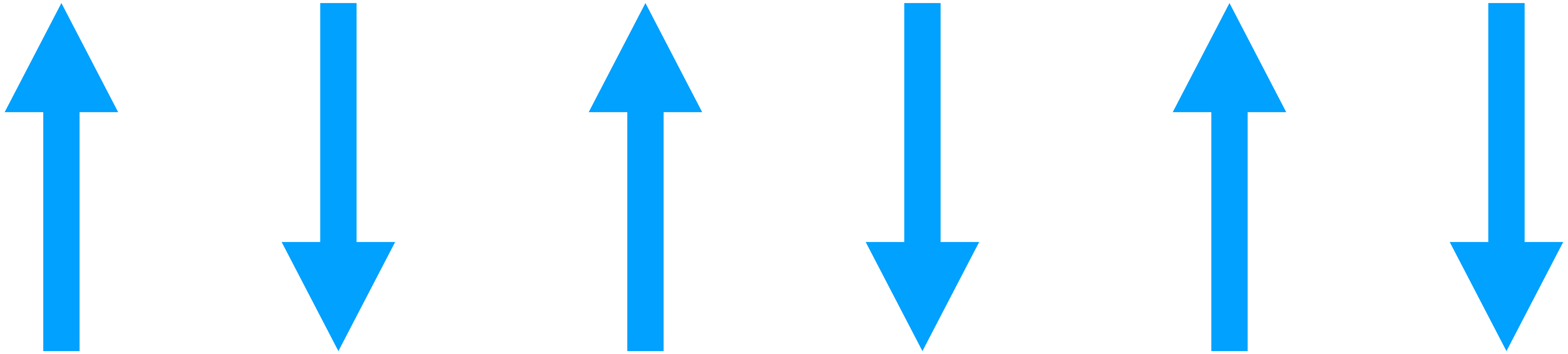
$$\hat{O}^S_{mh}(0,d) \equiv i\left[\hat{\Theta}^S_m(0), \hat{\Theta}^V_h(d)\right] = \frac{1}{4}\left(\hat{X}_0\hat{Z}^{d-1}\hat{Y}_d - \hat{Y}_0\hat{Z}^{d-1}\hat{X}_d - \hat{Y}_{2L-1-d}\hat{Z}^{d-1}\hat{X}_{2L-1} + \hat{X}_{2L-1-d}\hat{Z}^{d-1}\hat{Y}_{2L-1}\right)\ ,$$

$$\hat{O}^S_{mh}(1,d) \equiv i\left[\hat{\Theta}^S_m(1), \hat{\Theta}^S_h(d)\right] = \frac{1}{4}\left(\hat{Y}_1\hat{Z}^{d-1}\hat{X}_{d+1} - \hat{X}_1\hat{Z}^{d-1}\hat{Y}_{d+1} + \hat{Y}_{2L-2-d}\hat{Z}^{d-1}\hat{X}_{2L-2} - \hat{X}_{2L-2-d}\hat{Z}^{d-1}\hat{Y}_{2L-2}\right)$$

Trotterized to minimize circuit depth for a given level of precision.

Confinement means finite correlation length : Max d operators are limited

Strong Coupling Vacuum — Why?



Build on top of strong-coupling vacuum where long-distance physics is correct
- limit ``workload” to correlated regions.

g = infinity   or   Hopping = 0 — same wavefunction

Scalable Operators: Circuits

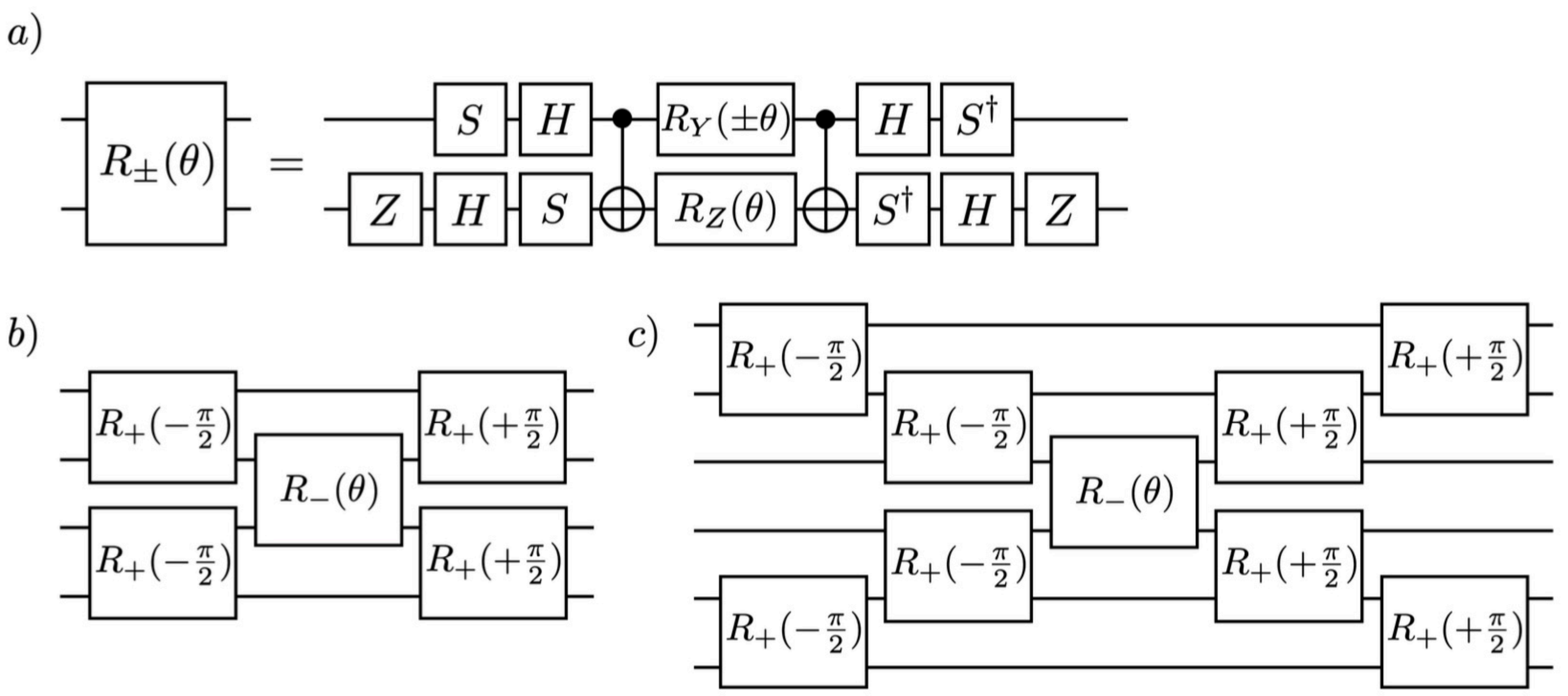


FIG. 3. (a) The definition of the $R_\pm(\theta)$ gate, which implements $\exp[i\theta/2(\hat{X}\hat{Y} \pm \hat{Y}\hat{X})]$. The $R_\pm(\theta)$ gate is used to implement (b) $\exp[-i\theta/2(\hat{X}\hat{Z}^2\hat{Y} - \hat{Y}\hat{Z}^2\hat{X})]$ and (c) $\exp[i\theta/2(\hat{X}\hat{Z}^4\hat{Y} - \hat{Y}\hat{Z}^4\hat{X})]$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

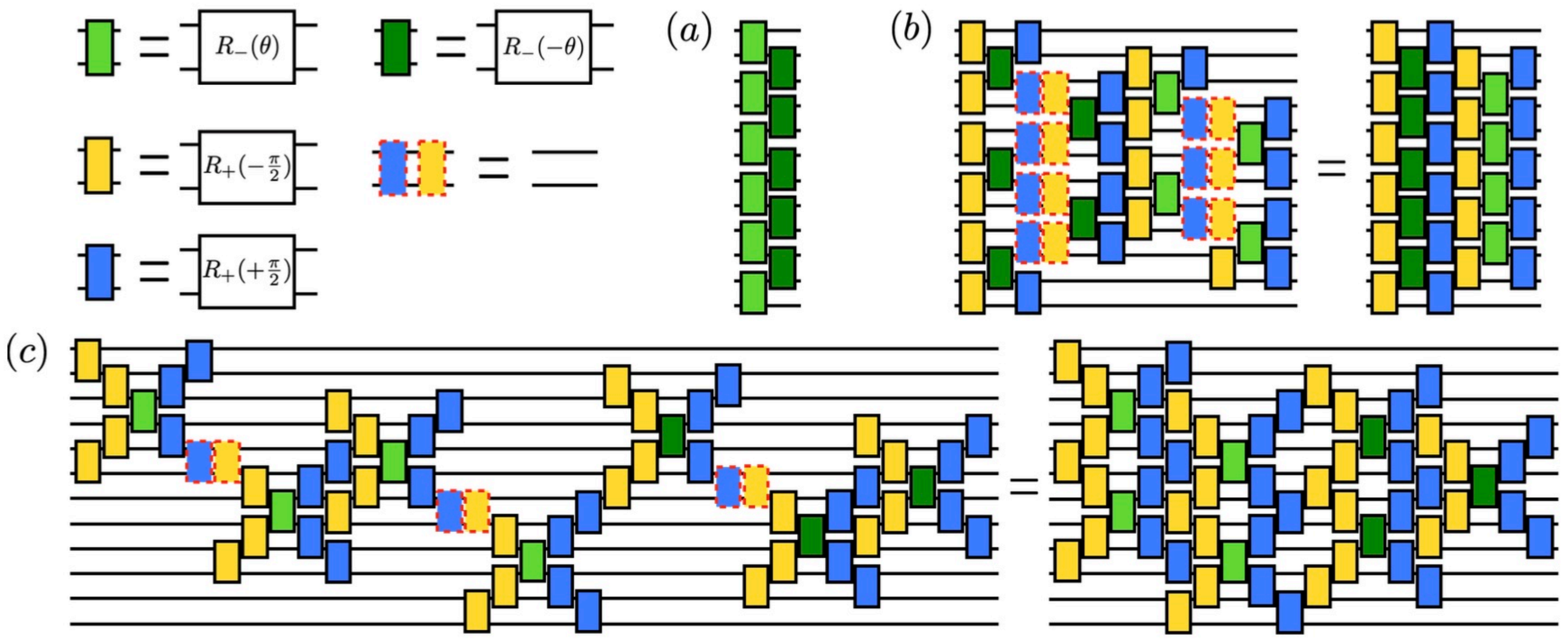
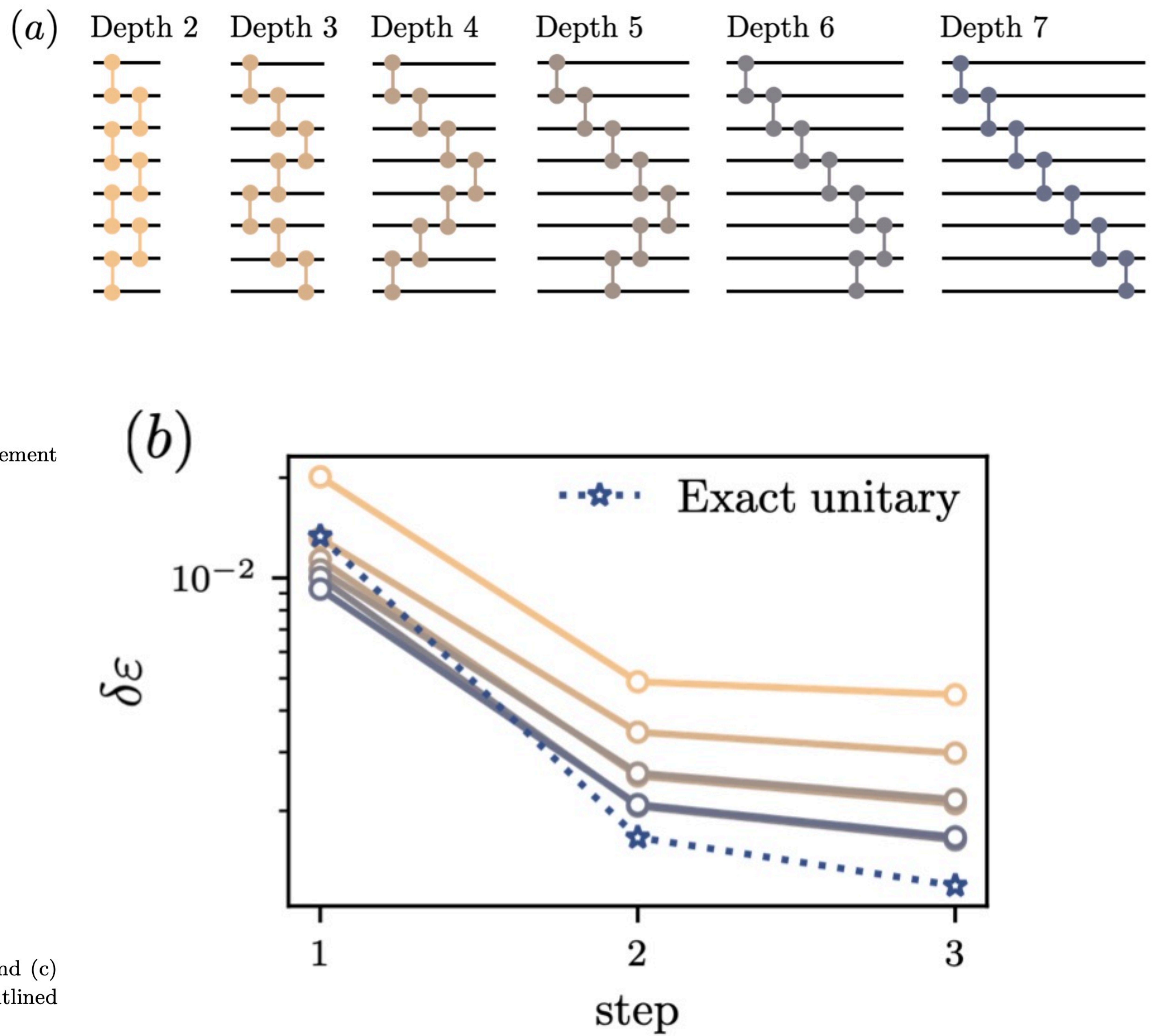
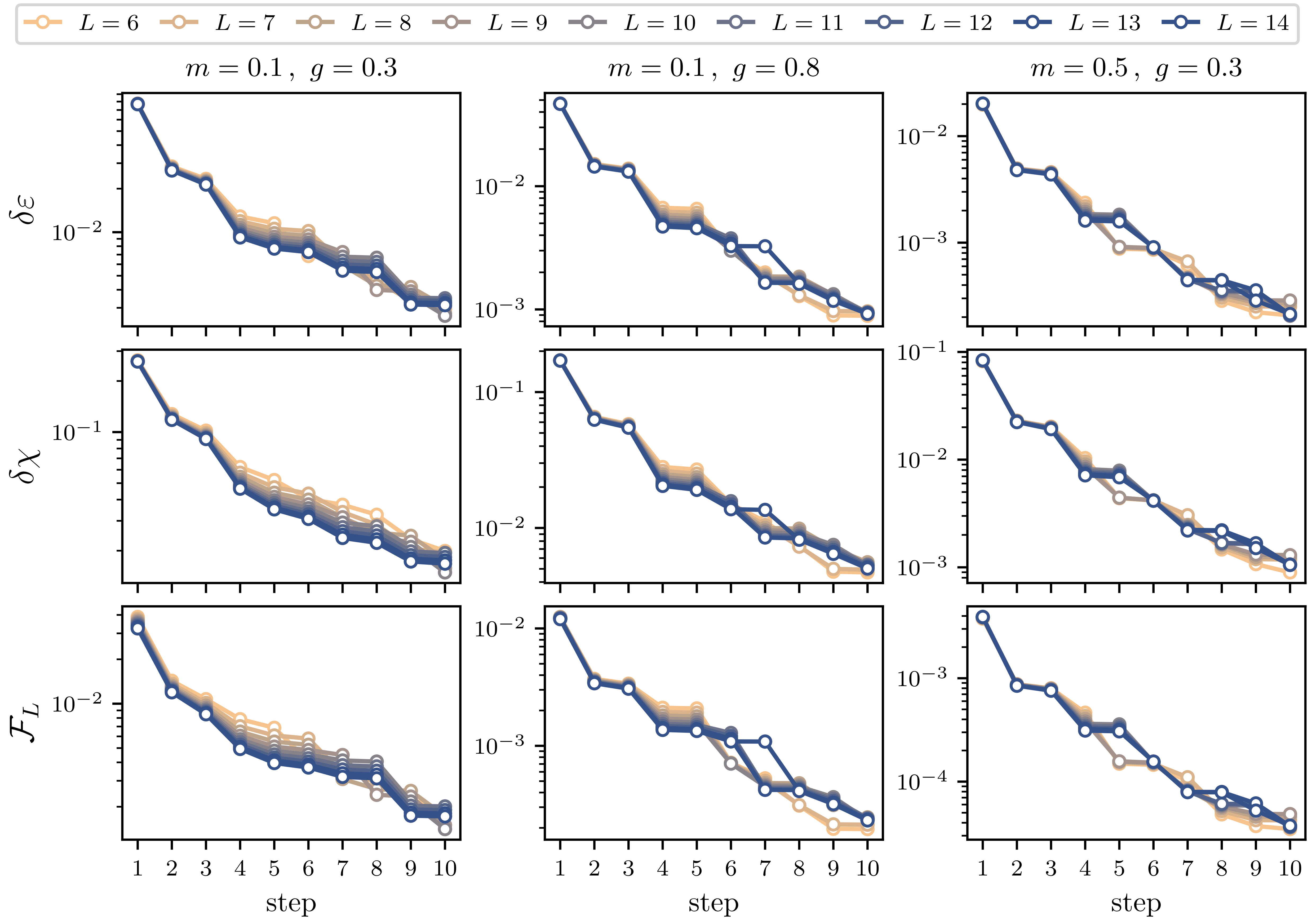


FIG. 4. Simplifications of quantum circuits for the Trotterized unitaries corresponding to (a) $\hat{O}^V_{mh}(1)$, (b) $\hat{O}^V_{mh}(3)$, and (c) $\hat{O}^V_{mh}(5)$ for $L = 6$, as explained in the main text. Cancellations between $R_+(\pm\frac{\pi}{2})$ are highlighted with red-dashed-outlined boxes.



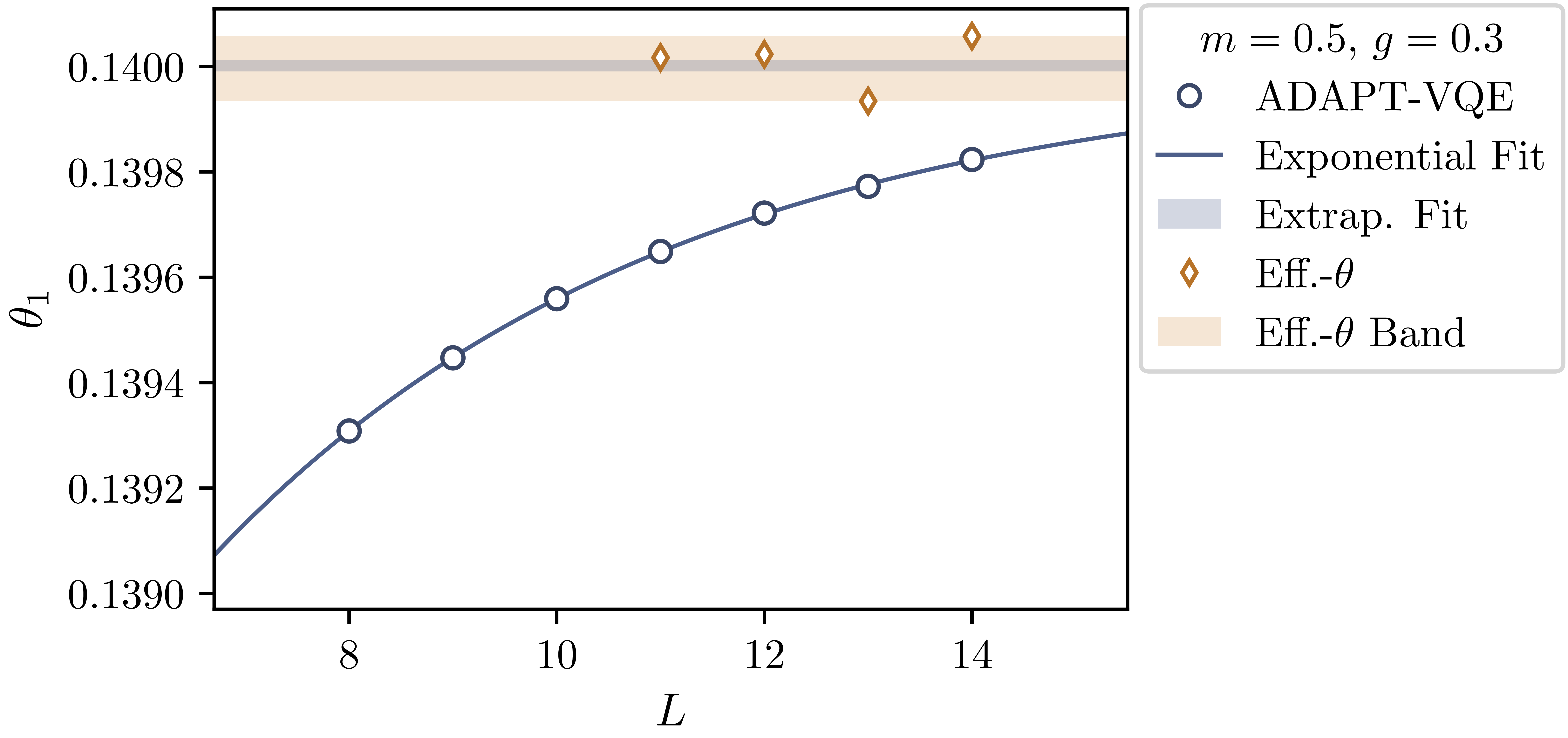
Scalable Operators: Convergence of Layers



$L \backslash \theta_i$	$\hat{O}^V_{mh}(1)$	$\hat{O}^V_{mh}(3)$	$\hat{O}^V_{mh}(5)$	$\hat{O}^V_{mh}(1)$	$\hat{O}^V_{mh}(7)$	$\hat{O}^S_{mh}(0,1)$	$\hat{O}^V_{mh}(7)$
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

Scalable Operators: Convergence of Parameters



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.)

Works well today .....

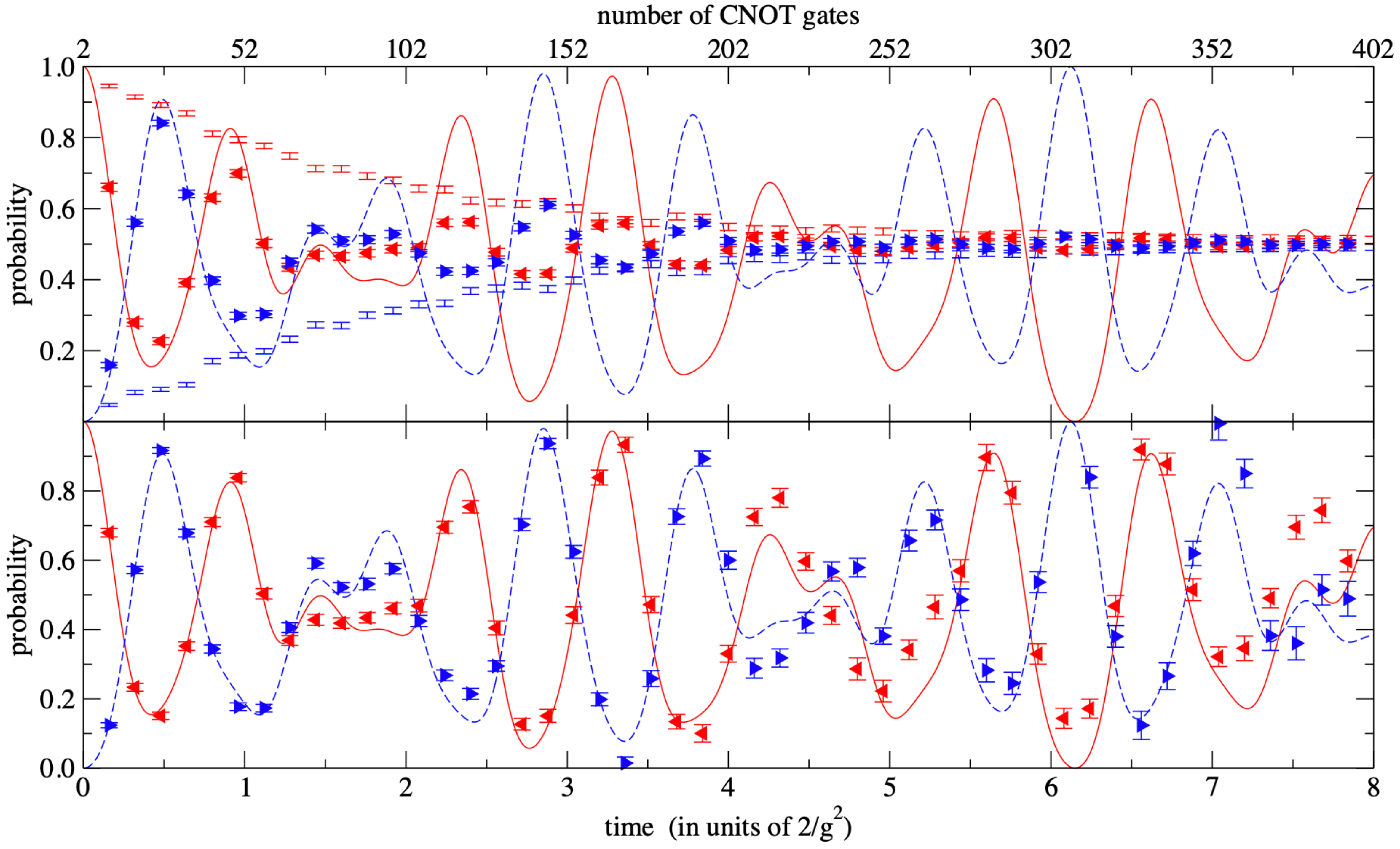
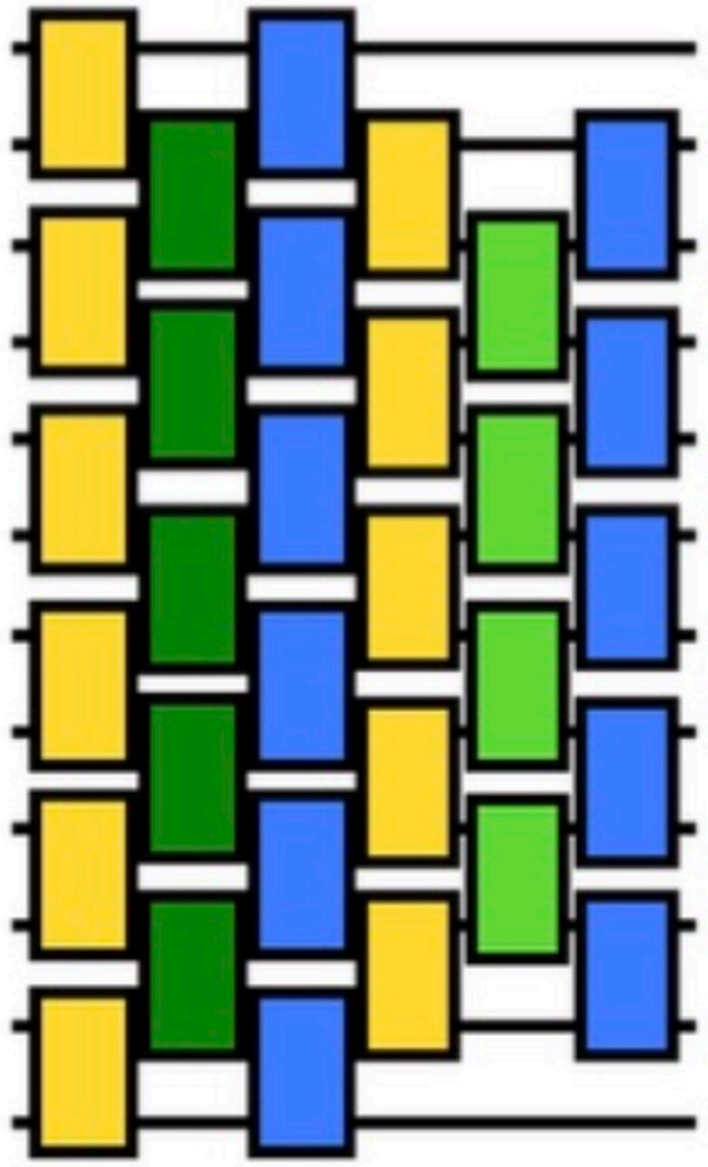


FIG. 3. Time evolution by self-mitigation on a two-plaquette lattice from the initial state of Fig. 1 with gauge coupling $x = 2.0$ and time step $dt = 0.08$. In both panels, the red solid (blue dashed) curve is the exact probability of the left (right) plaquette being measured to have $j = \frac{1}{2}$. **Upper panel:** The red left-pointing (blue right-pointing) triangles are the physics data computed from the `ibm_lagos` quantum processor. The red (blue) error bars without symbols are the mitigation data computed on `ibm_lagos` from the same circuit but with half the steps forward in time and then half backward in time. **Lower panel:** The triangles are the physics results obtained by applying Eq. (8) to the data from the upper panel.

Operator Decoherence Renormalization

Localized Error Mitigation for Localized Observables

Errors in New York should not impact simulations in Seattle, i.e. errors are in the laboratory
…… use local mitigation strategies



Angles from ADAPT-VQE
Vacuum of 1+1 QED

Physics wavefunction

Angles = 0 [Clifford]

Mitigation wavefunction

Strong-coupling vacuum

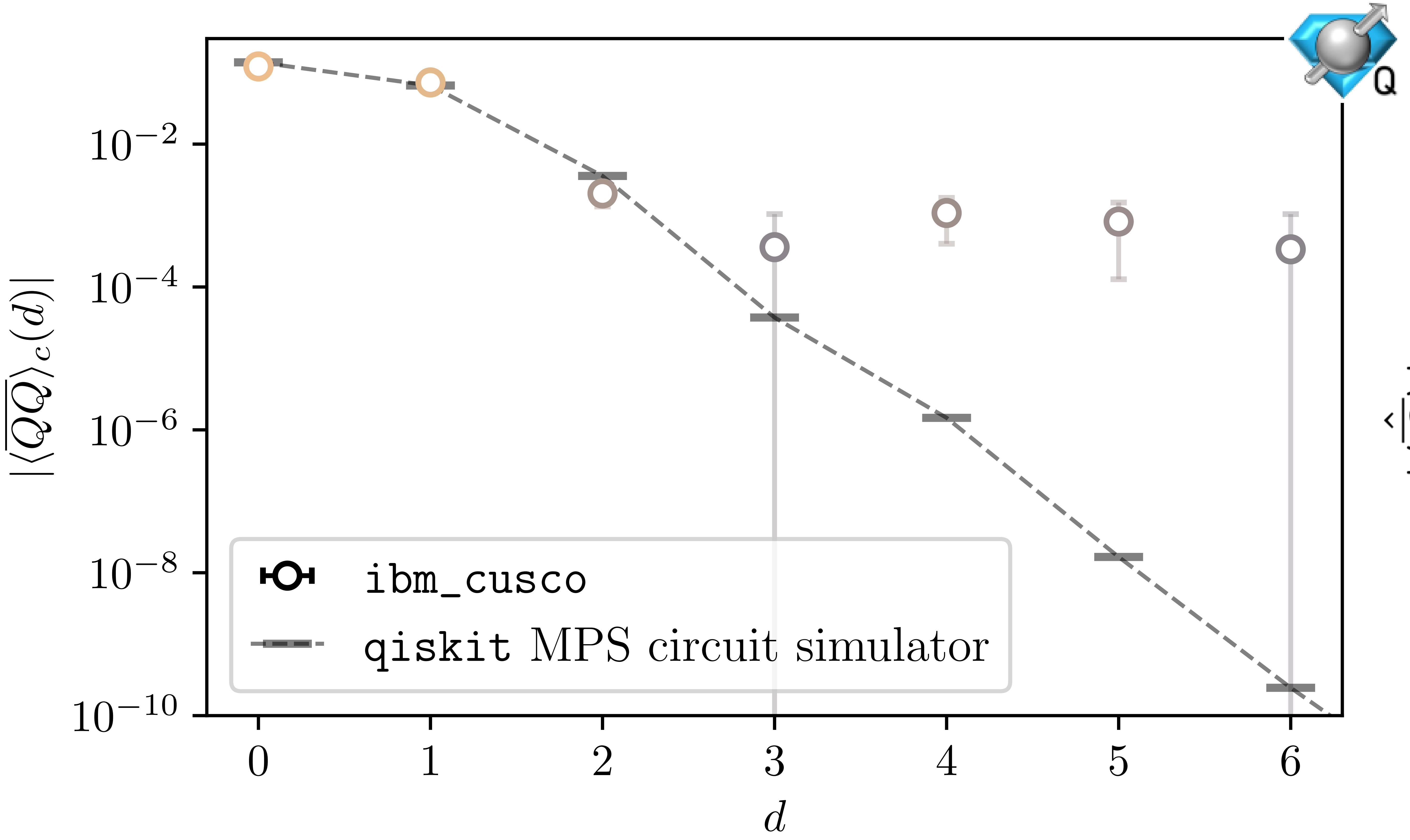
Known values for observables of interest

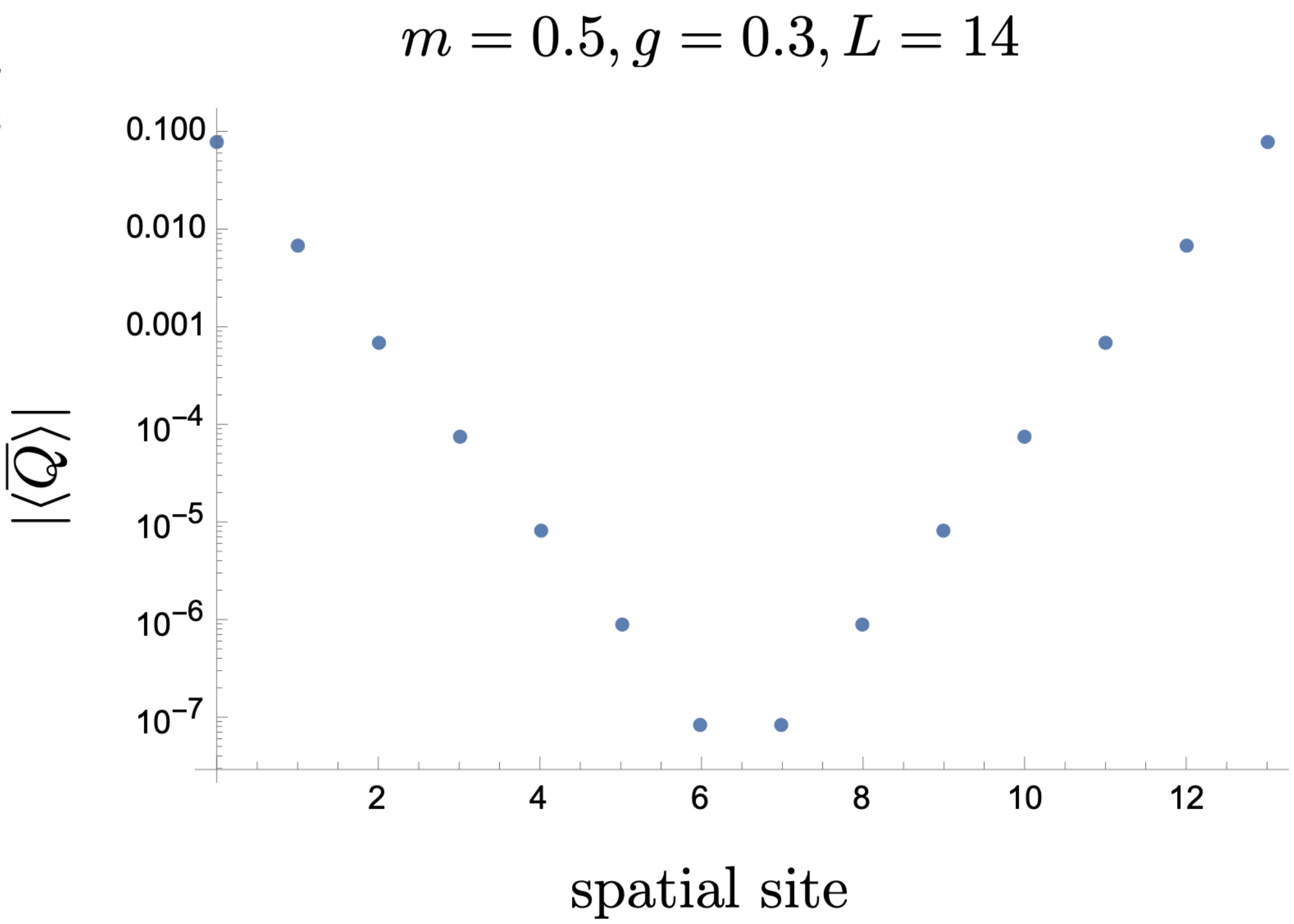
$$\rho \rightarrow \sum_{i=1}^{4^N} \eta_i \hat{P}_i \rho \hat{P}_i \qquad \langle \hat{O} \rangle_{\mathrm{meas}} = \sum_{i=1}^{4^N} \eta_i \, \mathrm{Tr}\left(\hat{P}_i \hat{O} \hat{P}_i \rho \right) \qquad \langle \hat{O} \rangle_{\mathrm{meas}} = (1 - \eta_O) \langle \hat{O} \rangle_{\mathrm{pred}}$$

For each different Pauli-string operator forming observable, e.g., Z Z

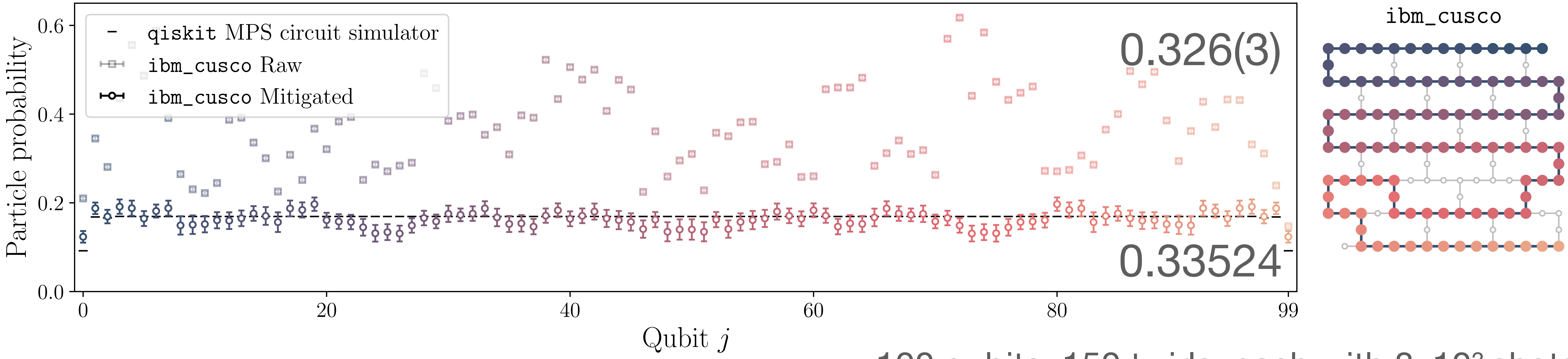
Charge-Charge Correlations

Twirls and statistics limited





Production on IBM's 127-Qubit Eagles

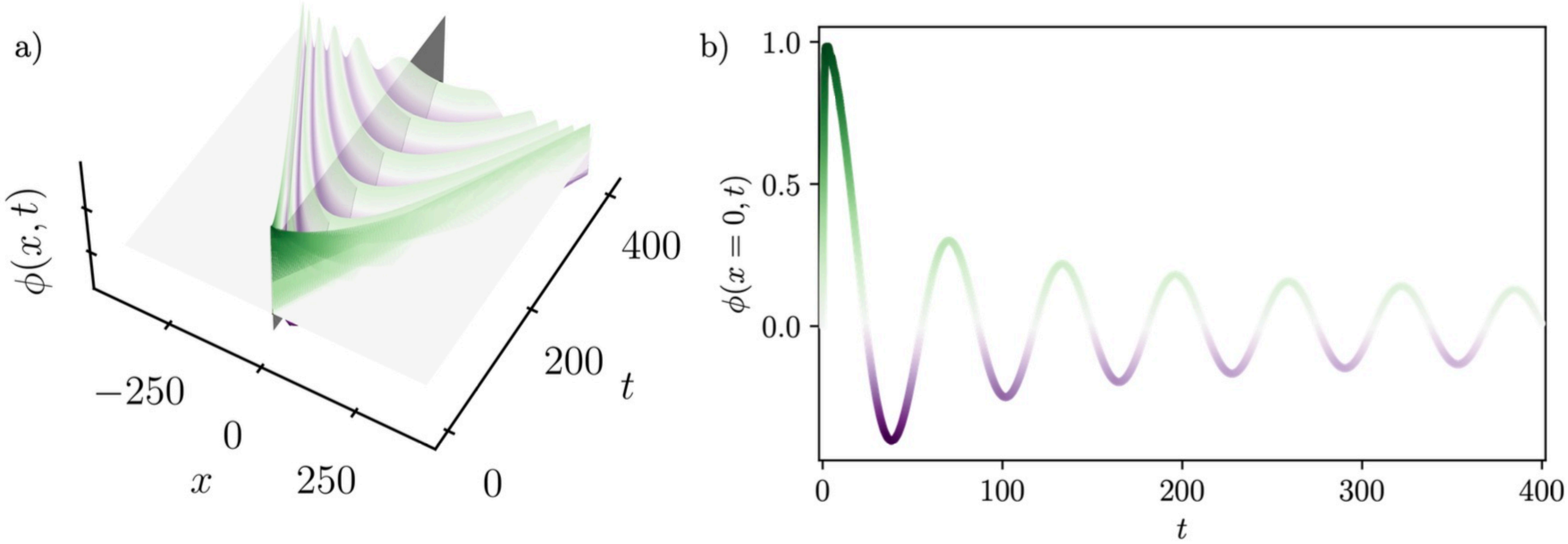


100 qubits, 150 twirls, each with $8\text{x}10^3$ shots

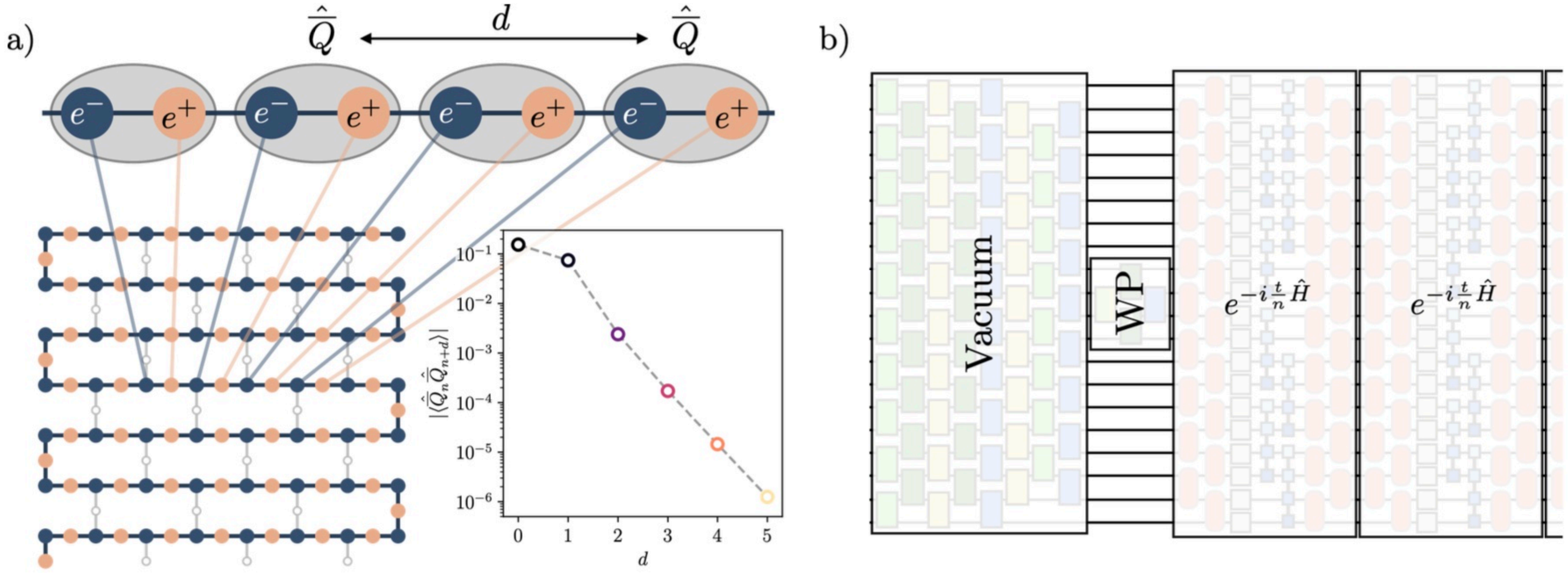
- SC-ADAPT-VQE
  - 2-layers, expect systematic errors at ~ 1%, ~700 CNOTS
  - 3-layers explored ~1300 CNOTS
- Operator decoherence renormalization (ODR)
  - With and without readout error mitigation
- Run on MPS for classical comparison for L<=100
- Modest number of twirls as circuit elements repeat - ~150

Wavepacket Preparation
Naive Expectations

Preparing beams of ``protons”
- we don’t know their wavefunction from first principles
- Let the system do it for us!



The Protocol

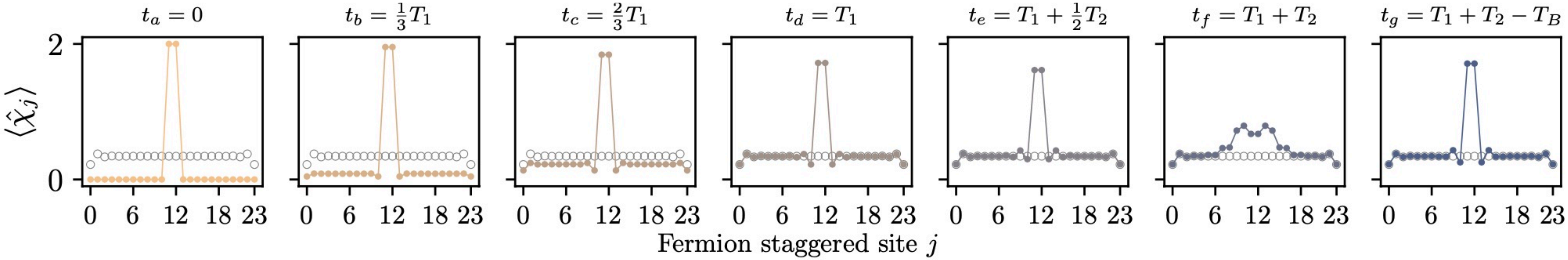


Wavepacket Preparation

Modest-sized Wave Packet to ``Match” to

$$|\psi_{\mathrm{WP}}\rangle_{\mathrm{init}} = \hat{X}_{L-1}\hat{X}_L|\Omega_0\rangle$$

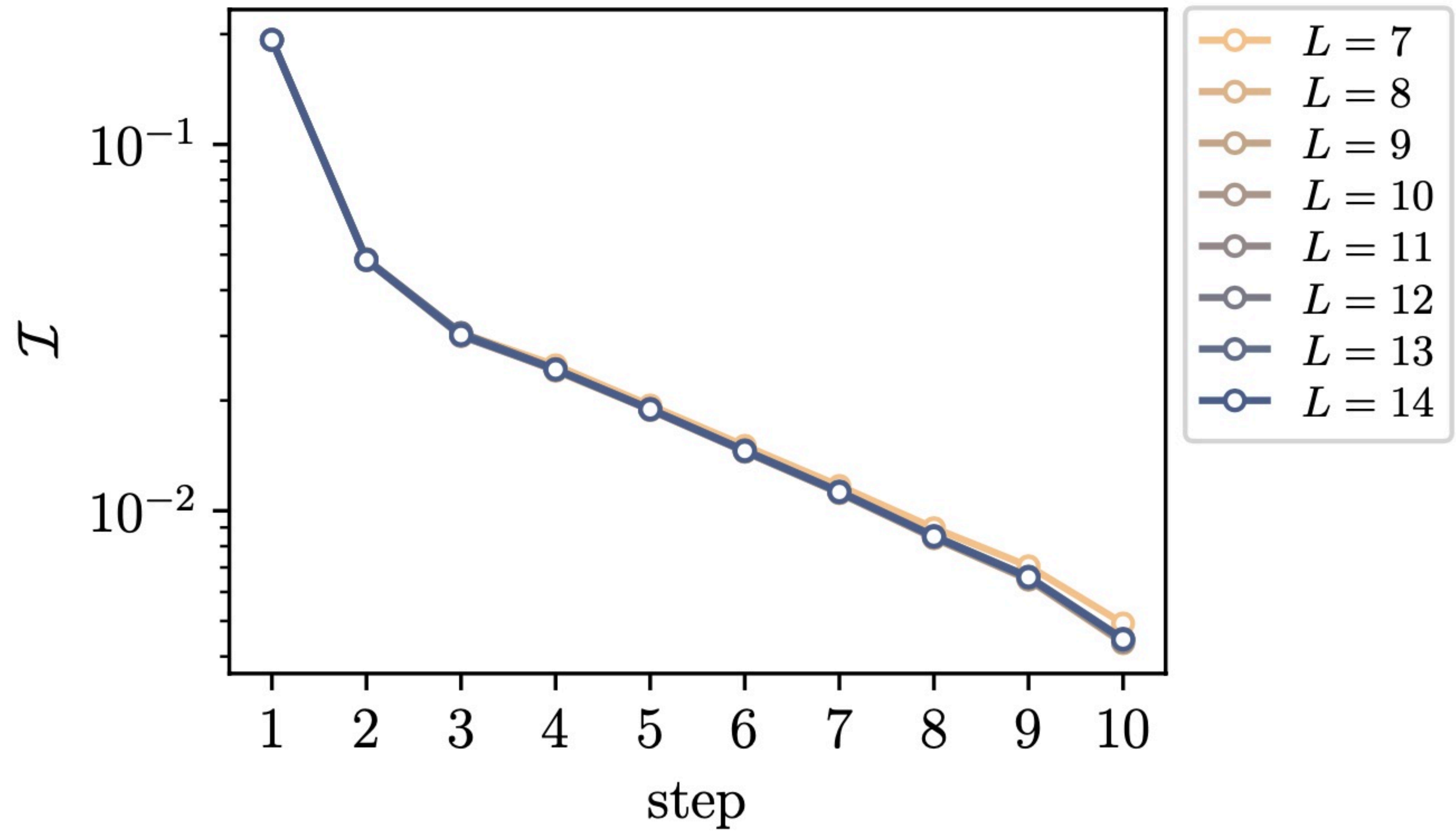
$$\hat{H}_{\mathrm{ad}}(t) = \begin{cases} \hat{H}_m + \hat{H}_{el} + \frac{t}{T_1}\left[\hat{H}_{kin} \; - \; \frac{1}{2}(\sigma^+_{L-2}\sigma^-_{L-1} + \sigma^+_L\sigma^-_{L+1} + \mathrm{h.c.})\right] & 0 < t \leq T_1 \;, \\ \hat{H}_m + \hat{H}_{el} + \hat{H}_{kin} \; - \; \left(1 - \frac{t-T_1}{T_2}\right)\frac{1}{2}(\sigma^+_{L-2}\sigma^-_{L-1} + \sigma^+_L\sigma^-_{L+1} + \mathrm{h.c.}) & T_1 < t \leq T_1 + T_2 \;. \end{cases}$$



Classical Simulations

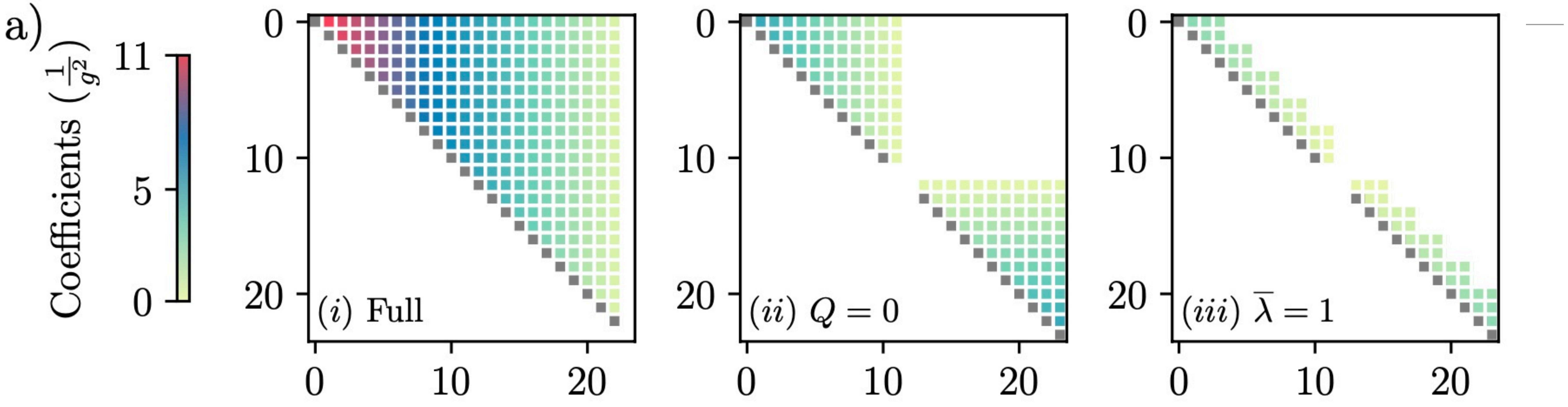
Wavepacket Preparation on the Vacuum Matching to Quantum Circuits

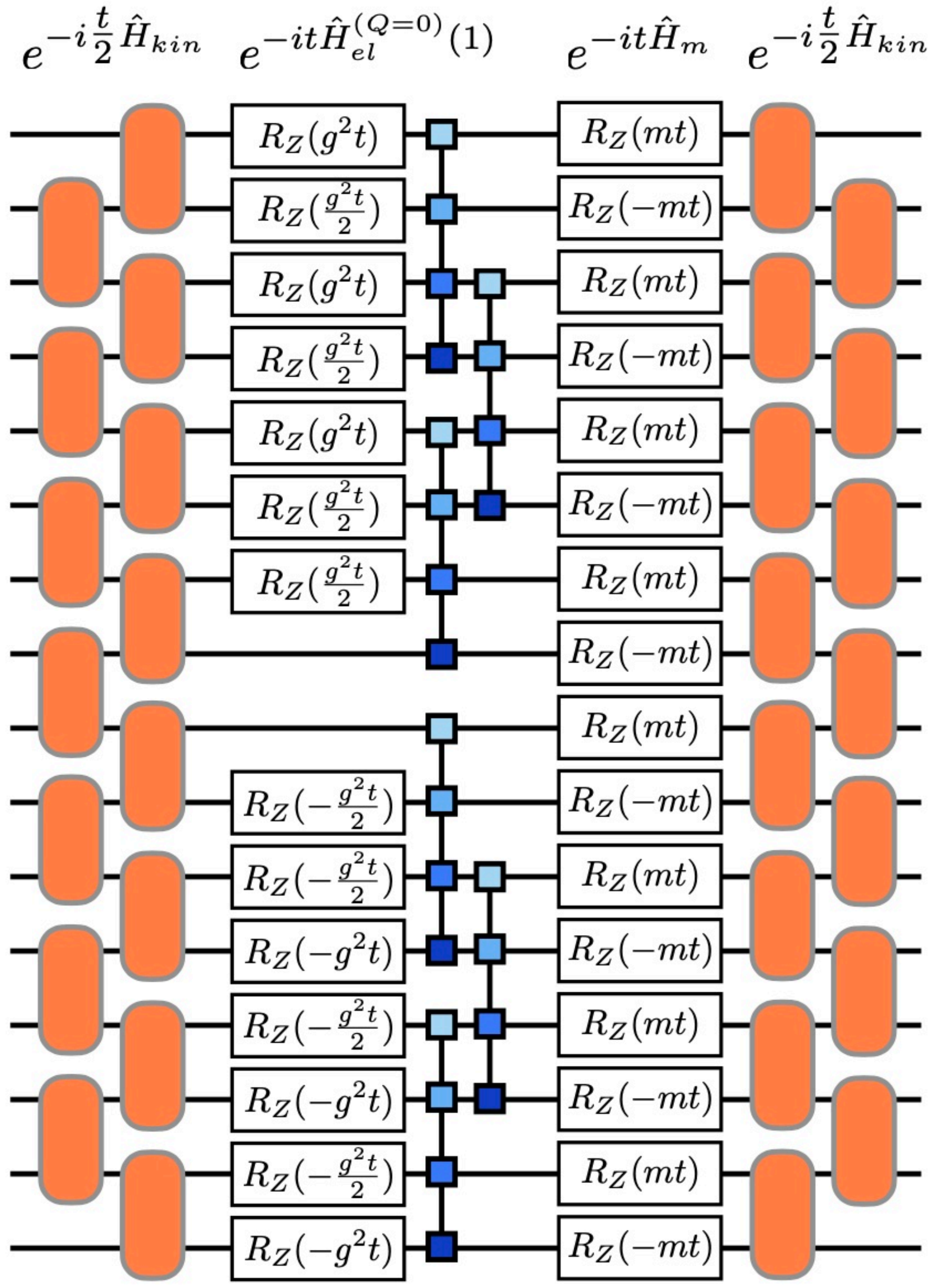
$$
\begin{aligned}
\{\hat{O}\}_{\mathrm{WP}} &= \{\hat{O}_{mh}(n,d),\, \hat{O}_h(n,d),\, \hat{O}_m(n)\}\ , \\
\hat{O}_{mh}(n,d) &= \frac{1}{2}\left[\hat{X}_{L-n}\hat{Z}^{d-1}\hat{Y}_{L-n+d} - \hat{Y}_{L-n}\hat{Z}^{d-1}\hat{X}_{L-n+d} \ +\ (-1)^{d+1}\left(1-\delta_{L-n,\gamma}\right)\left(\hat{X}_{\gamma}\hat{Z}^{d-1}\hat{Y}_{\gamma+d} - \hat{Y}_{\gamma}\hat{Z}^{d-1}\hat{X}_{\gamma+d}\right)\right]\ , \\
\hat{O}_{h}(n,d) &= \frac{1}{2}\left[\hat{X}_{L-n}\hat{Z}^{d-1}\hat{X}_{L-n+d} + \hat{Y}_{L-n}\hat{Z}^{d-1}\hat{Y}_{L-n+d} \ +\ (-1)^{d+1}\left(1-\delta_{L-n,\gamma}\right)\left(\hat{X}_{\gamma}\hat{Z}^{d-1}\hat{X}_{\gamma+d} + \hat{Y}_{\gamma}\hat{Z}^{d-1}\hat{Y}_{\gamma+d}\right)\right]\ ,
\end{aligned}
\tag{12}
$$

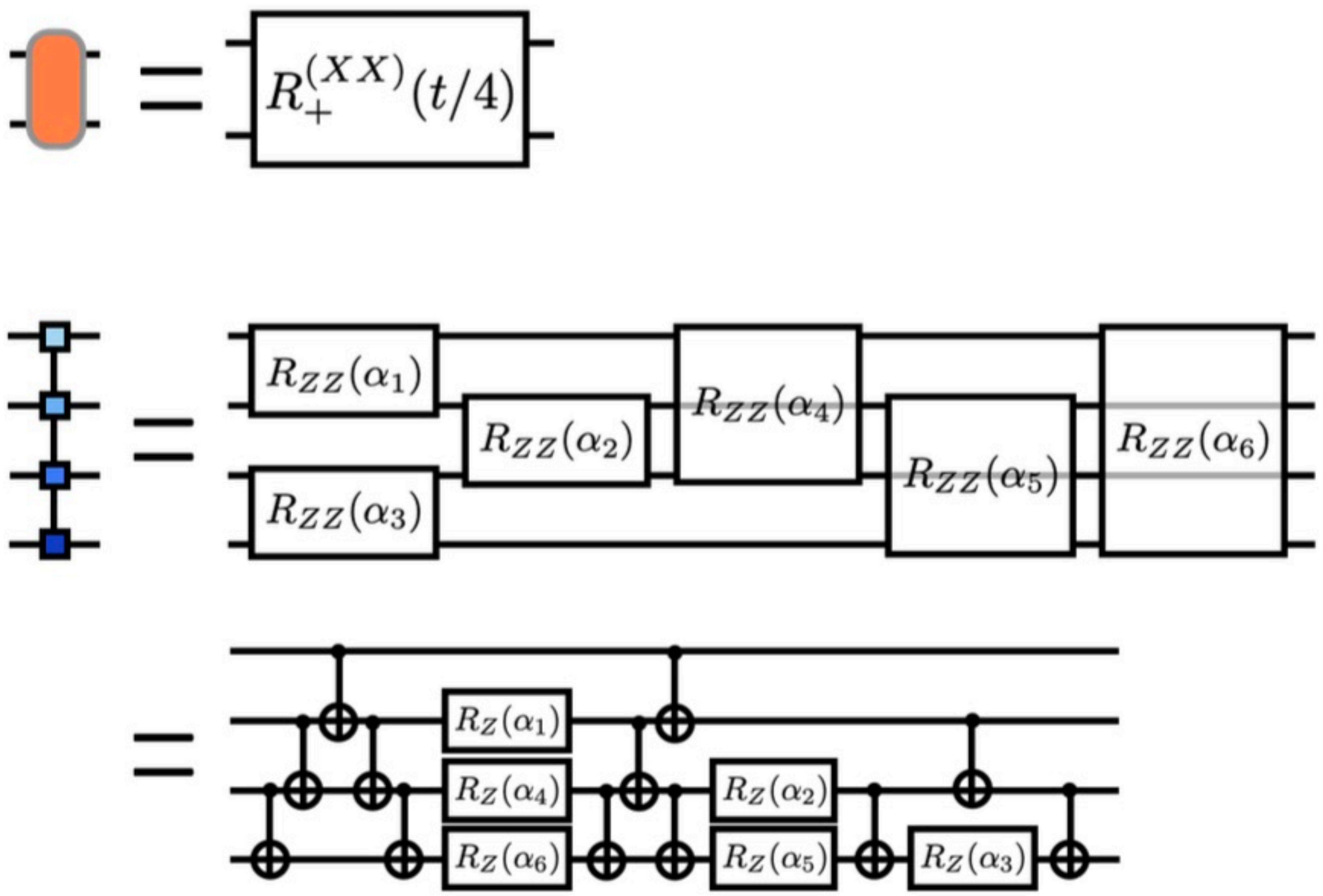


$$\mathcal{I} = 1 - |\langle \psi_{\mathrm{WP}} | \psi_{\mathrm{ansatz}} \rangle|^2$$

Truncations in Electric Interactions
Confinement



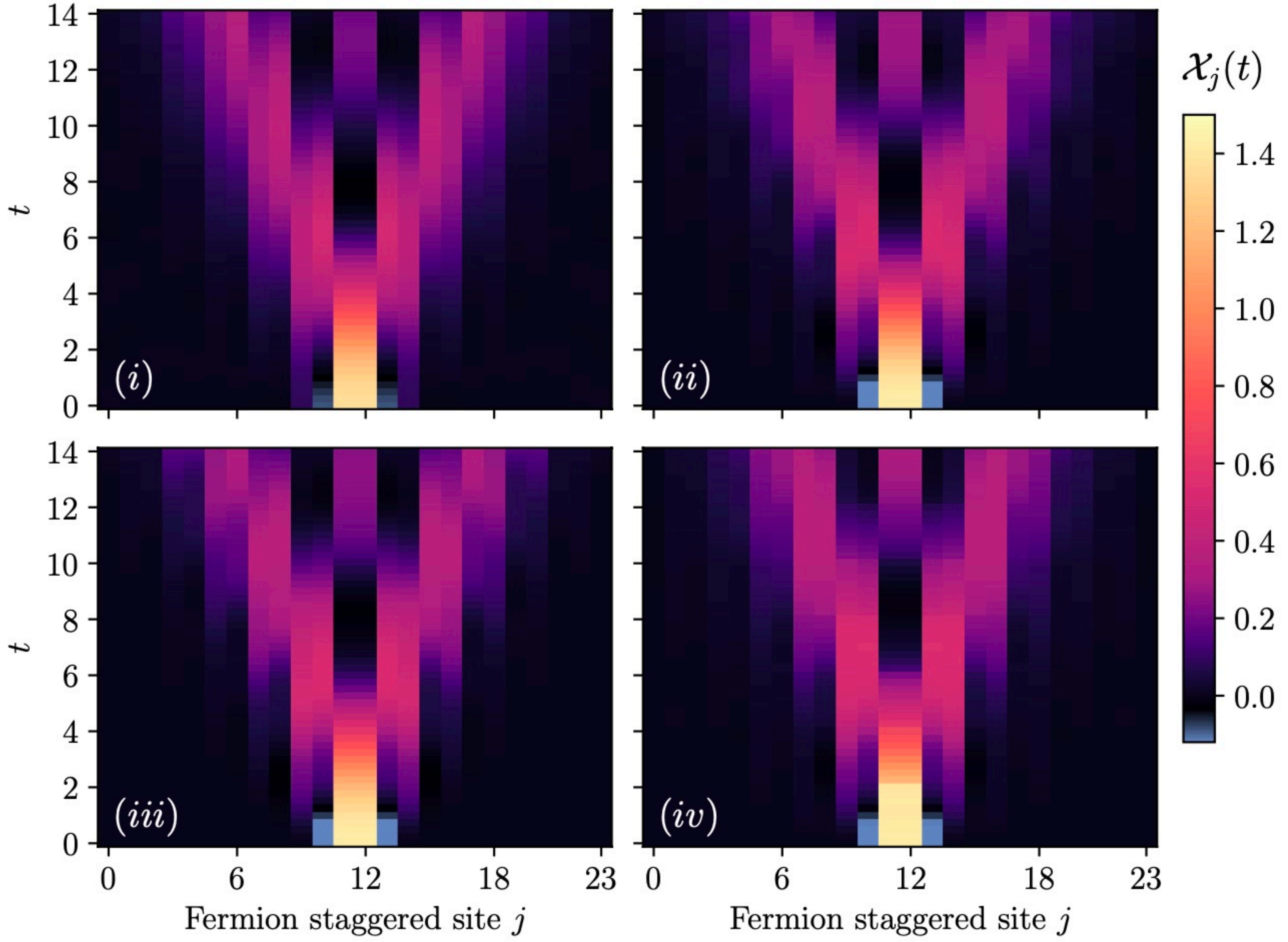




Verifying Systematic Approximations (Classical)

Exact

2-step SC-Adapt-VQE
Truncated Electric H
Exact evolution



2-step SC-Adapt-VQE
Exact evolution

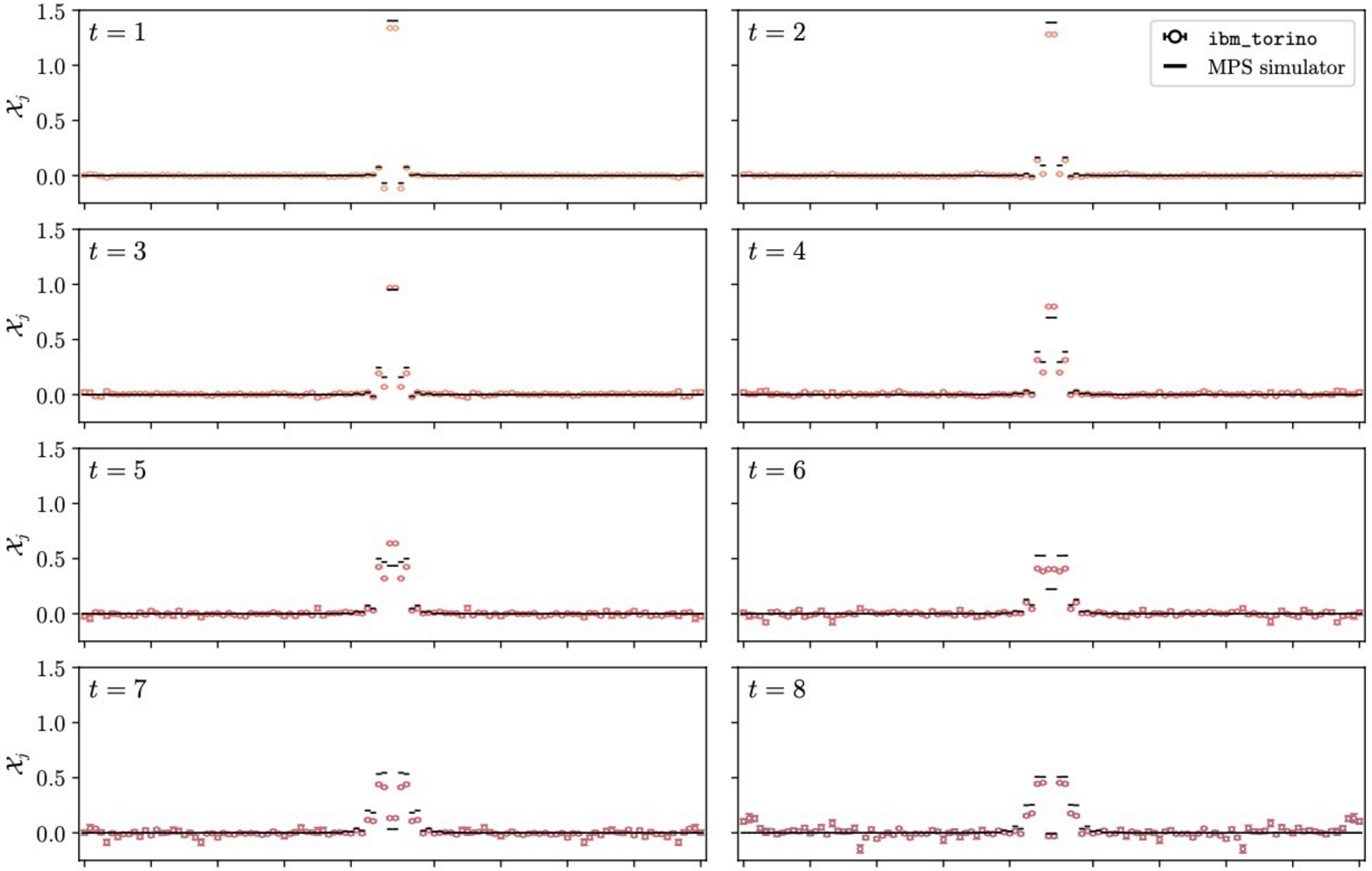
2-step SC-Adapt-VQE
Truncated Electric H
2nd-order Trotter

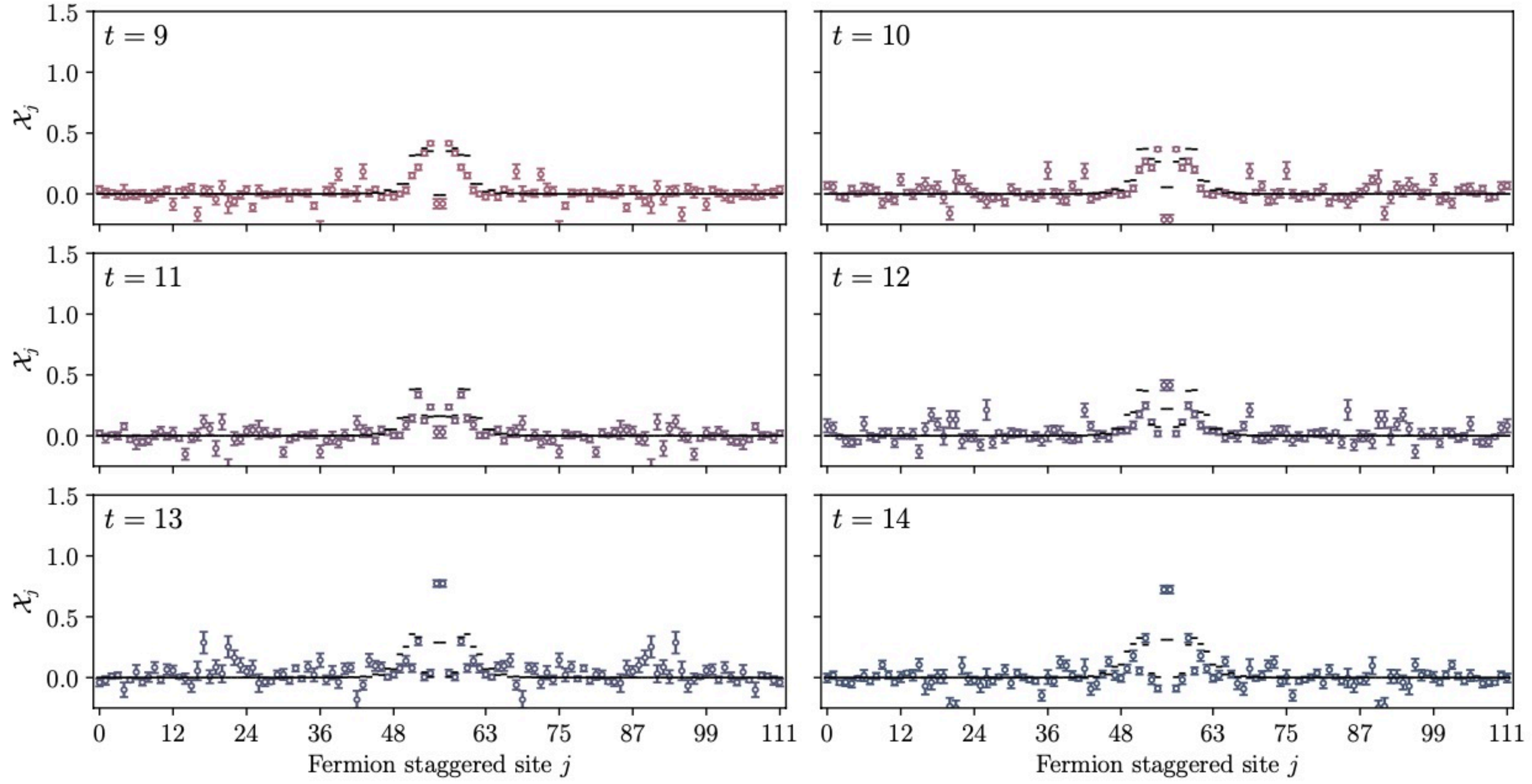
Production Details using IBM's Torino

t	N_T	# of CNOTs (per t)	CNOT depth (per t)	# of distinct circuits (per t)	# of twirls (per circuit)	# of shots (per twirl)	Executed CNOTs ($\times 10^9$)	Total # of shots ($\times 10^6$)
1 & 2	2	2,746	70	4	480	8,000	$4 \times 2 \times 10.5$	$4 \times 2 \times 3.8$
3 & 4	4	4,598	120	4	480	8,000	$4 \times 2 \times 17.7$	$4 \times 2 \times 3.8$
5 & 6	6	6,450	170	4	480	8,000	$4 \times 2 \times 24.8$	$4 \times 2 \times 3.8$
7 & 8	8	8,302	220	4	480	8,000	$4 \times 2 \times 31.9$	$4 \times 2 \times 3.8$
9 & 10	10	10,154	270	4	160	8,000	$4 \times 2 \times 13.0$	$4 \times 2 \times 1.3$
11 & 12	12	12,006	320	4	160	8,000	$4 \times 2 \times 15.4$	$4 \times 2 \times 1.3$
13 & 14	14	13,858	370	4	160	8,000	$4 \times 2 \times 17.7$	$4 \times 2 \times 1.3$
Totals							1.05×10^{12}	1.54×10^8

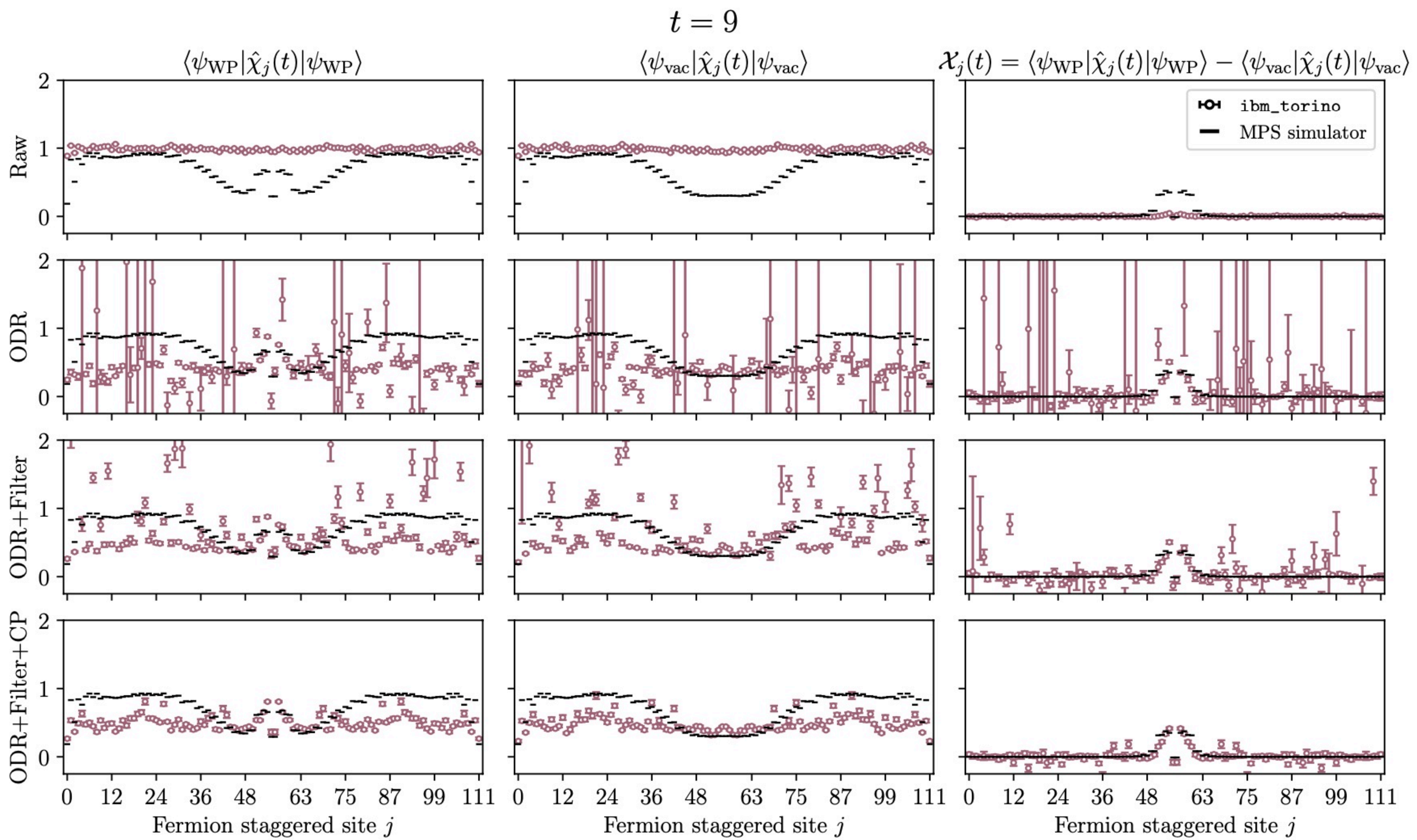
Results on 112 Qubits with up to 14 Trotter Steps

“Side-By-Side” Comparison





The Key Role of Error Mitigation



1+1D QCD (2022)

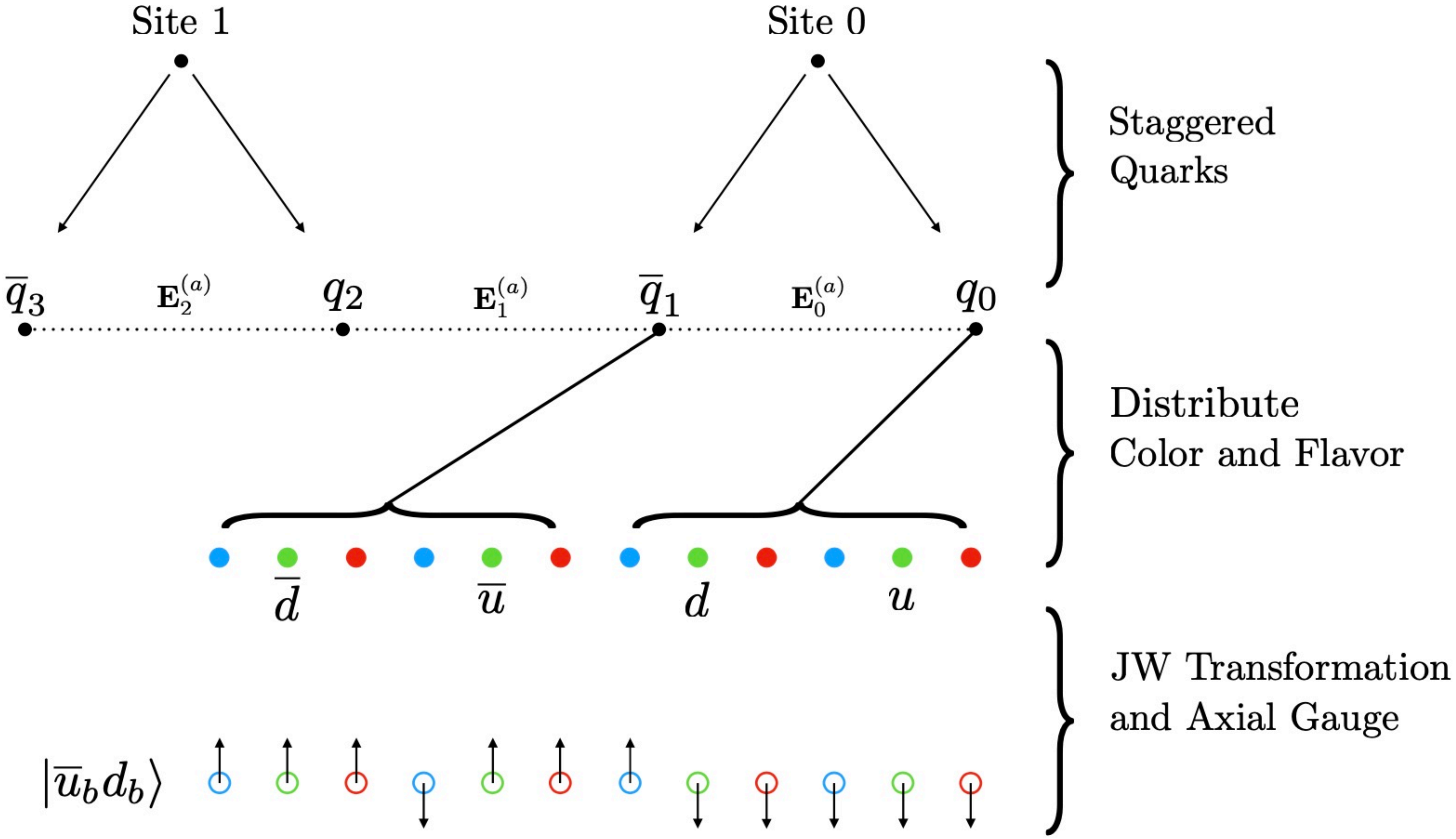
Building on the works of others, Banuls, Dirac, Jansen, Muschik, Lewis, ….

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

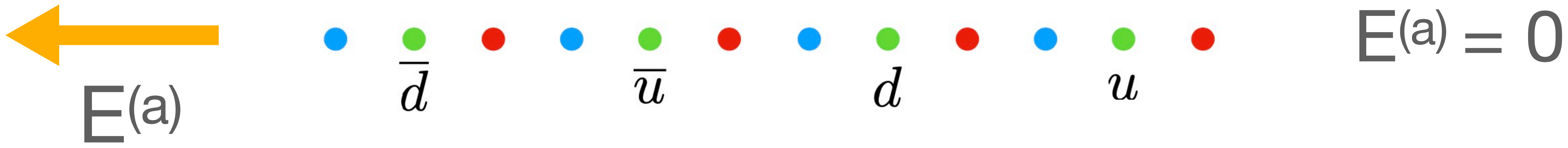
Roland C. Farrell, Ivan A. Chernyshev, Sarah J. M. Powell, Nikita A. Zemlevskiy, Marc Illa, and Martin J. Savage
Phys. Rev. D **107**, 054512 – Published 30 March 2023

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

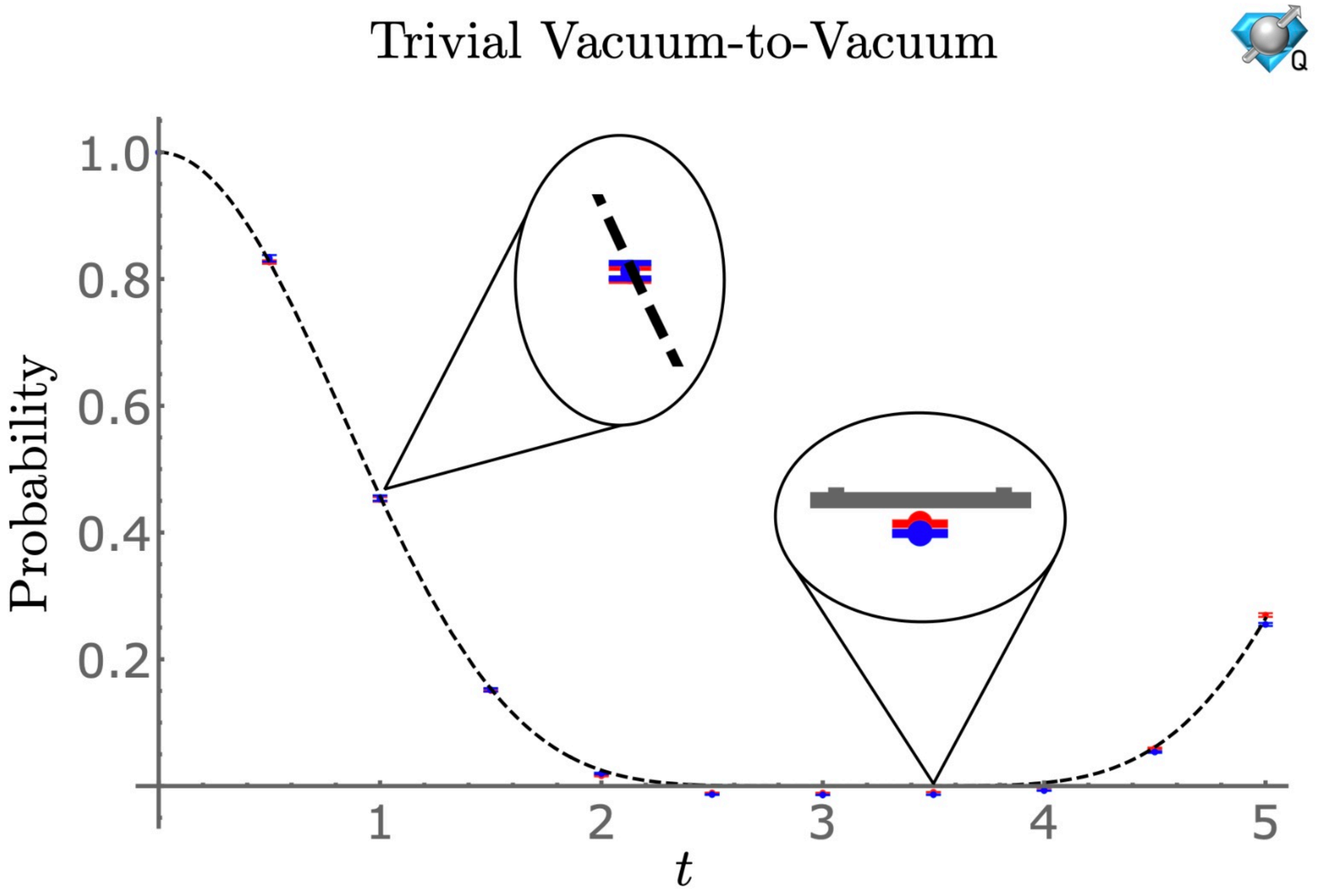
Roland C. Farrell, Ivan A. Chernyshev, Sarah J. M. Powell, Nikita A. Zemlevskiy, Marc Illa, and Martin J. Savage
Phys. Rev. D **107**, 054513 – Published 30 March 2023

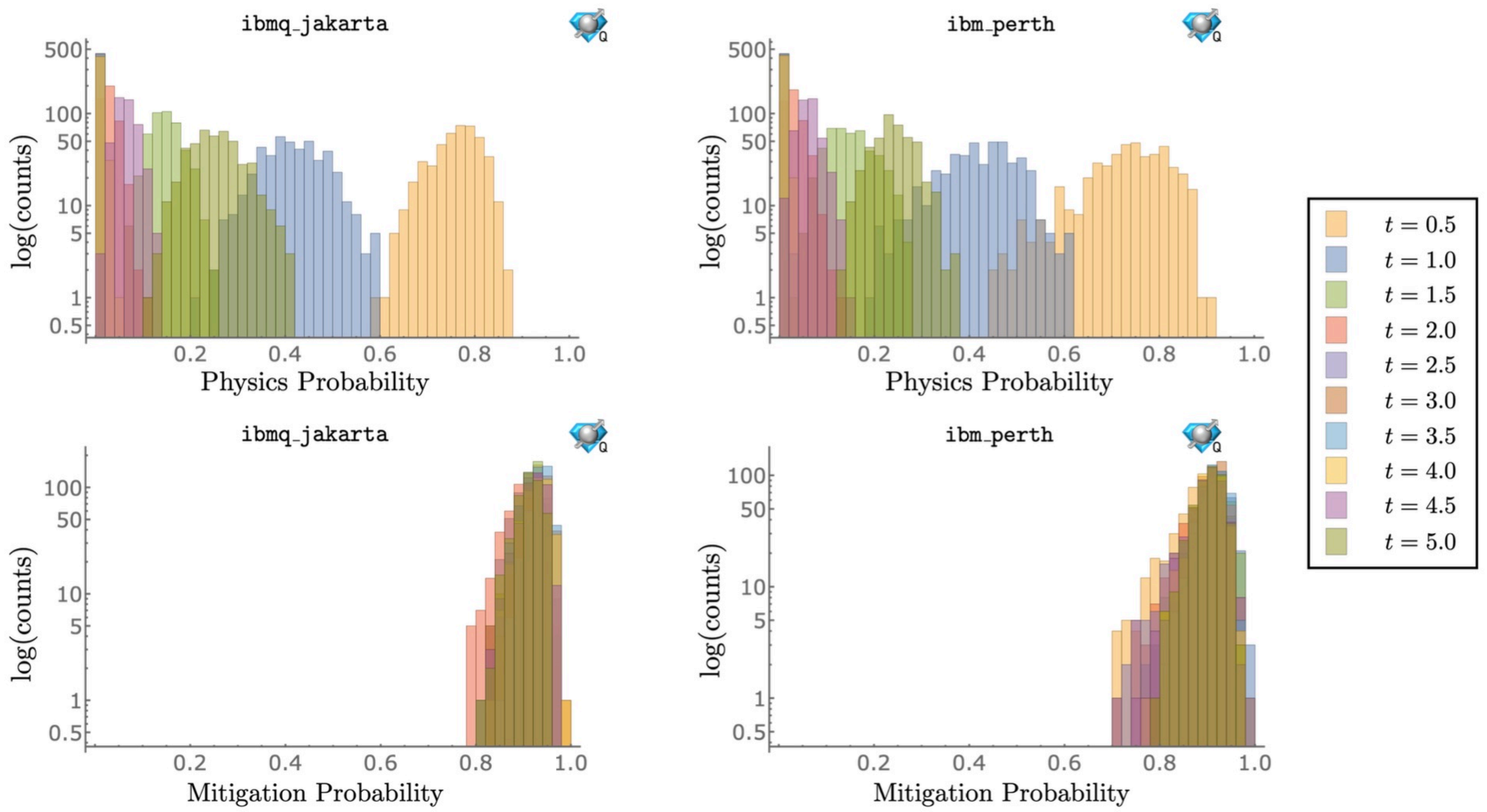


Color edge states



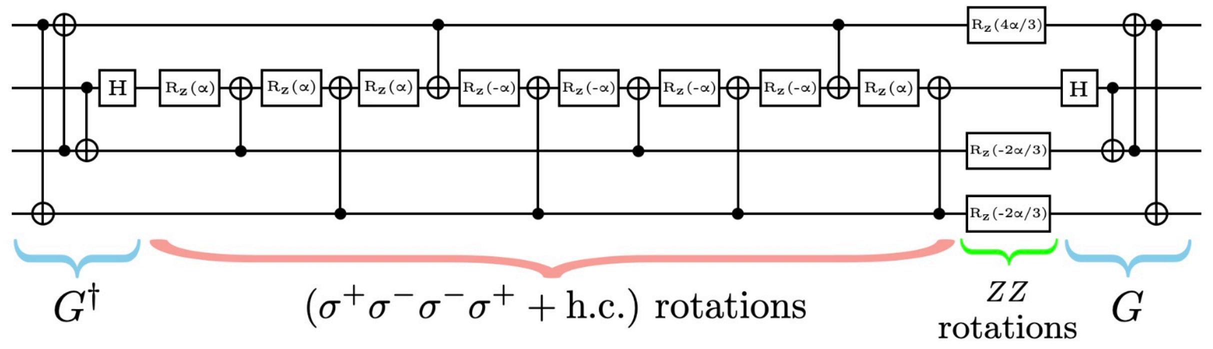
Simulations using IBM's Quantum Computers
1-site, 3 colors, 1 flavor

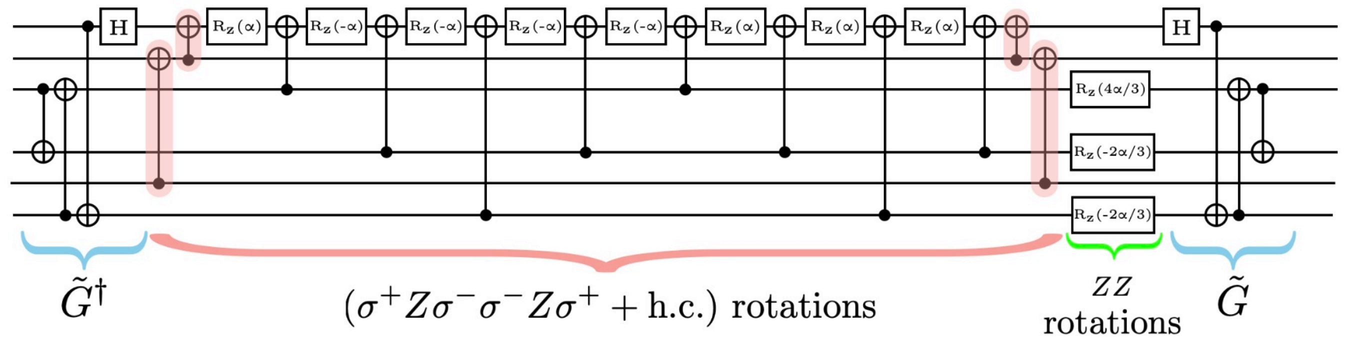




IBM 7 qubit Perth and Jakarta

34 CNOTs per step
447 Pauli-Twirled circuits
1000 shots per circuits

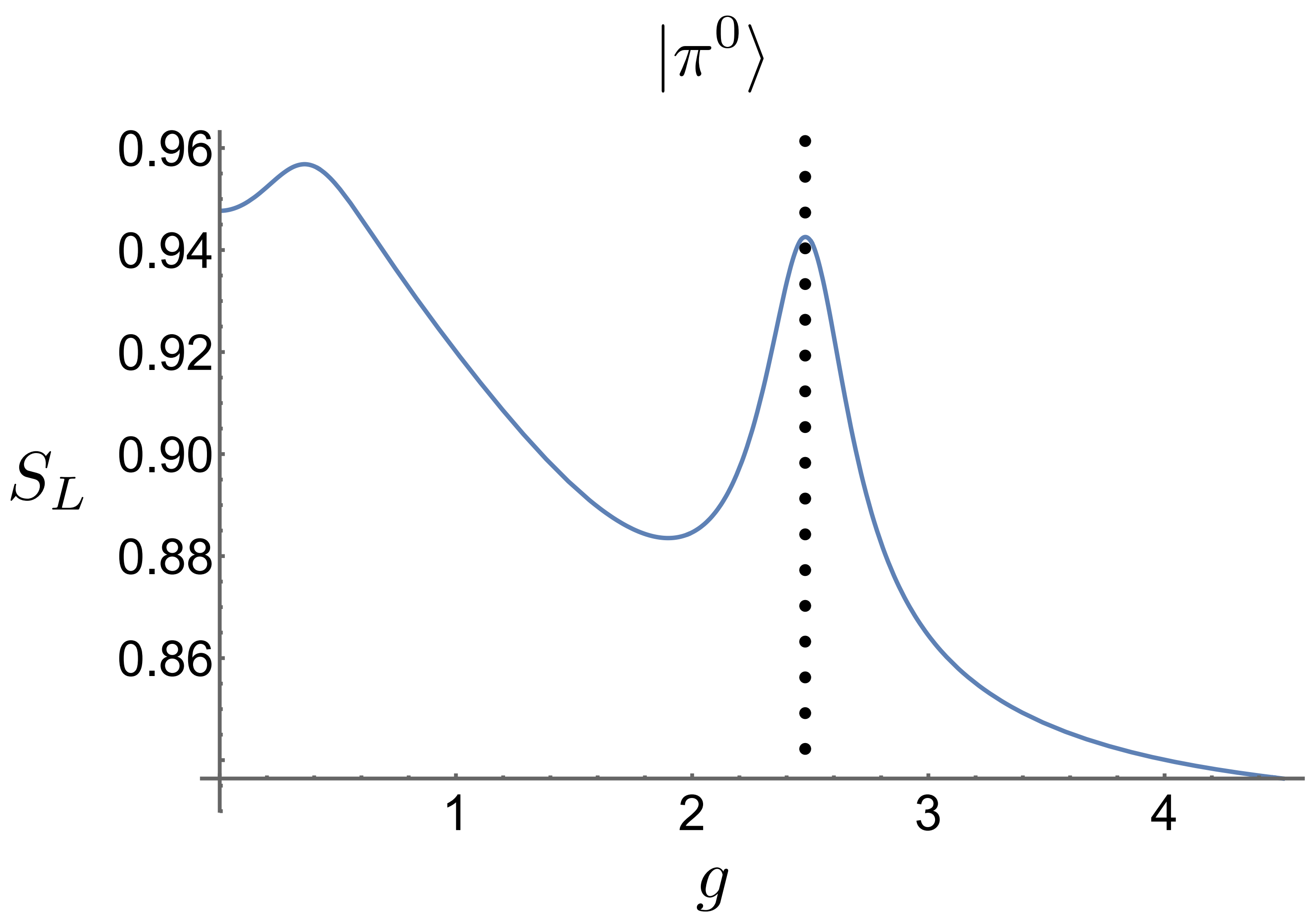


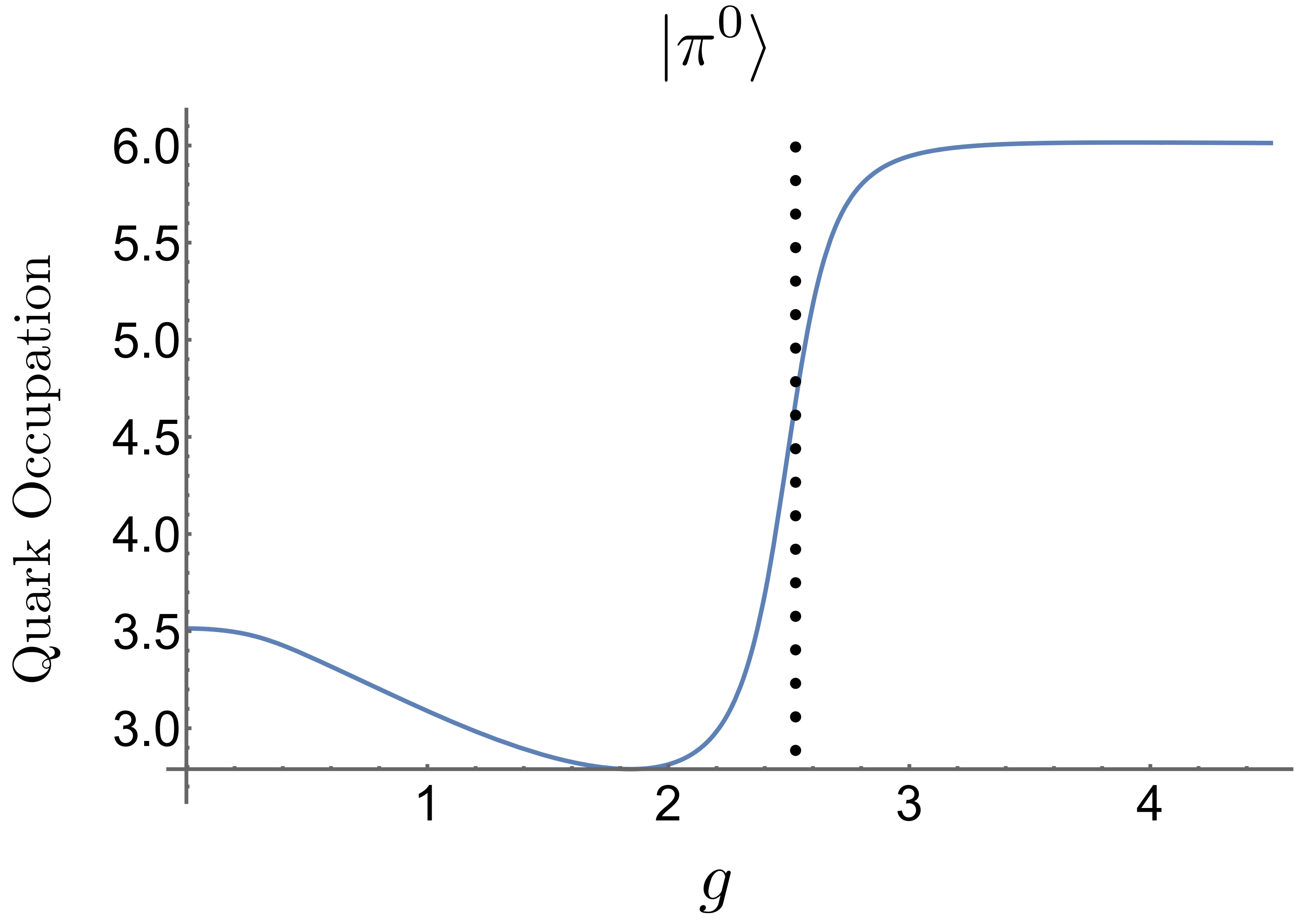


Dynamic Decoupling
Pauli-Twirling
Post selection
De-coherence renormalization

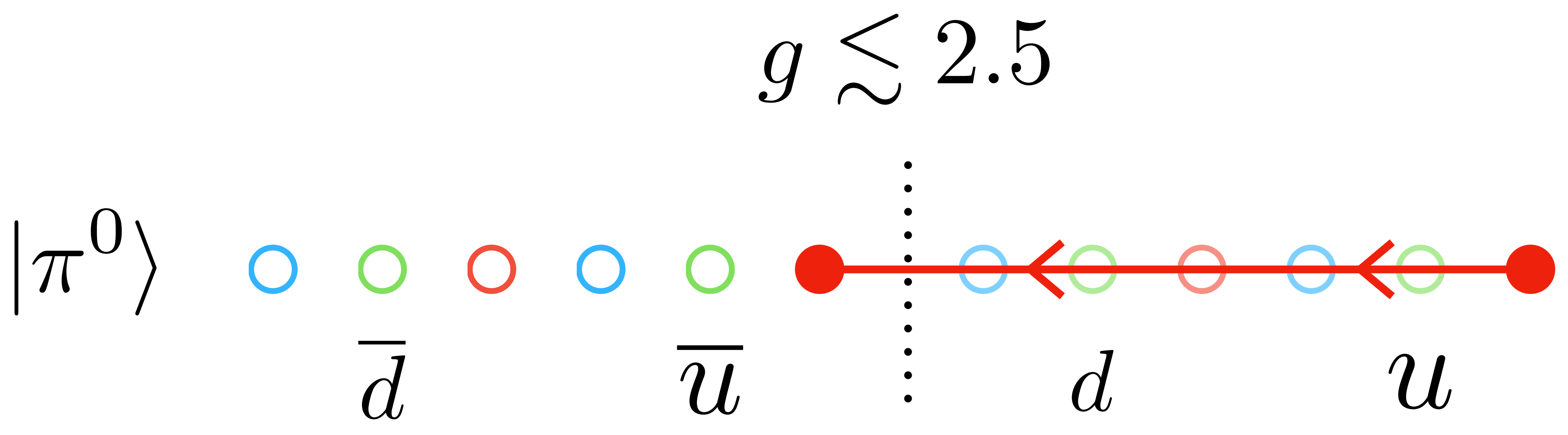
Number of CNOT gates for one Trotter step of $SU(3)$			
L	$N_f = 1$	$N_f = 2$	$N_f = 3$
1	30	114	242
2	228	878	1,940
5	1,926	7,586	16,970
10	8,436	33,486	75,140
100	912,216	3,646,086	8,201,600

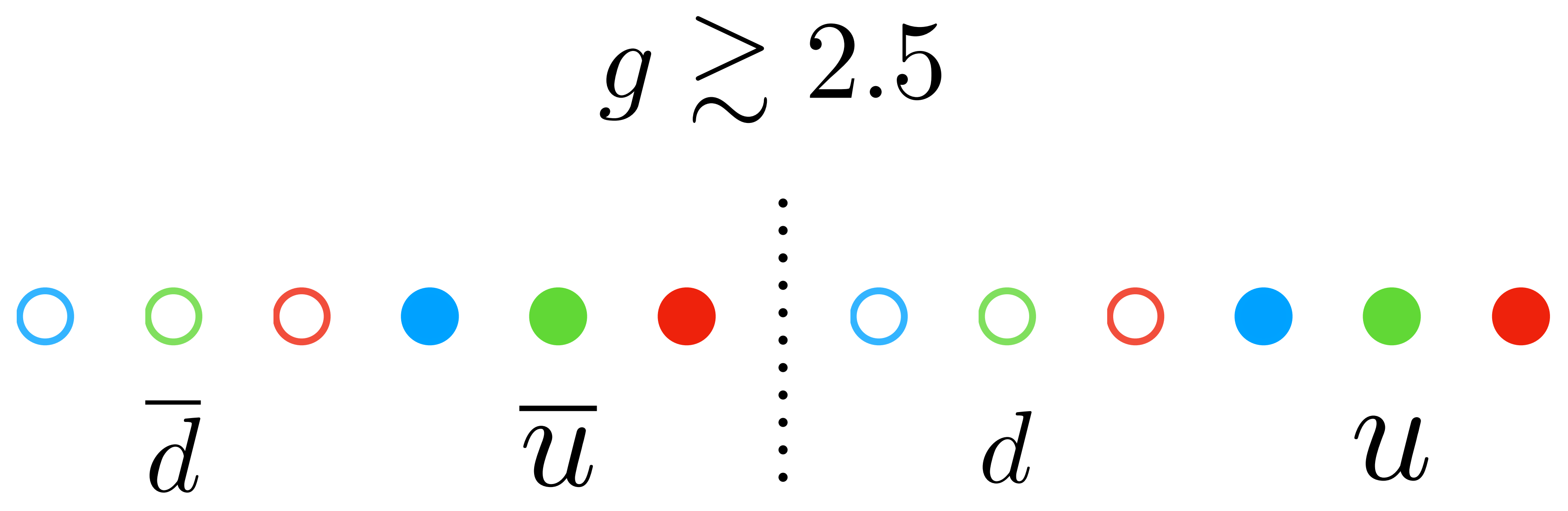
Entanglement structure in the mesons for $L = 2$





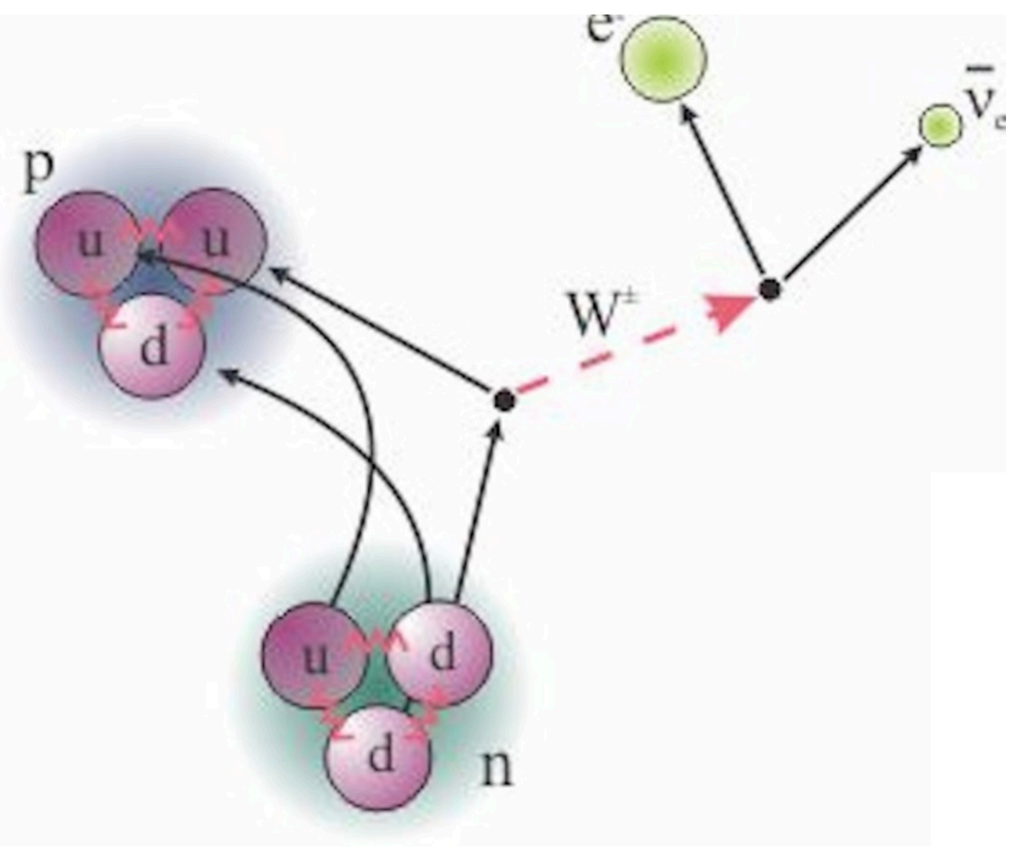
Peak in entanglement coincides with transition from quark-antiquark to baryon-anti-baryon structure

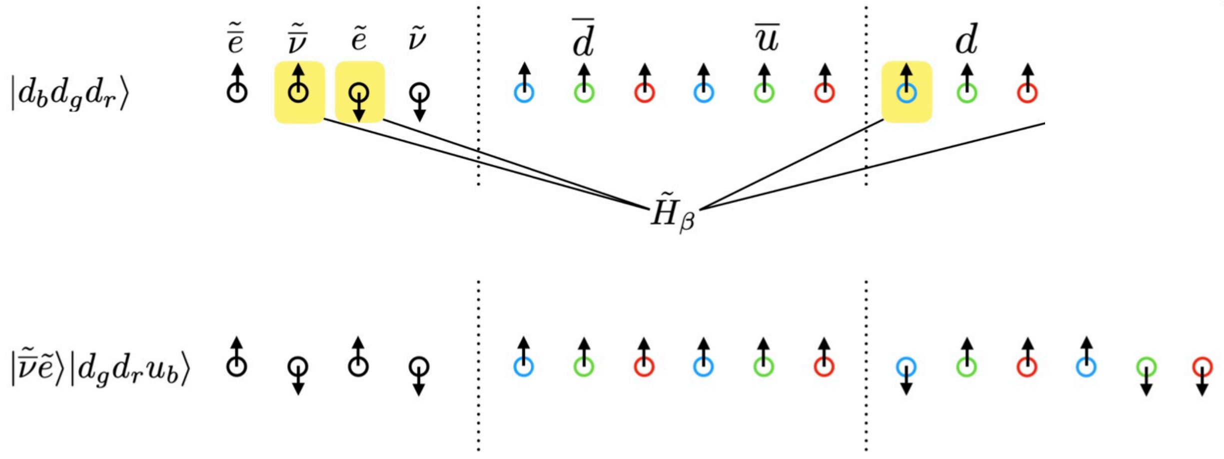


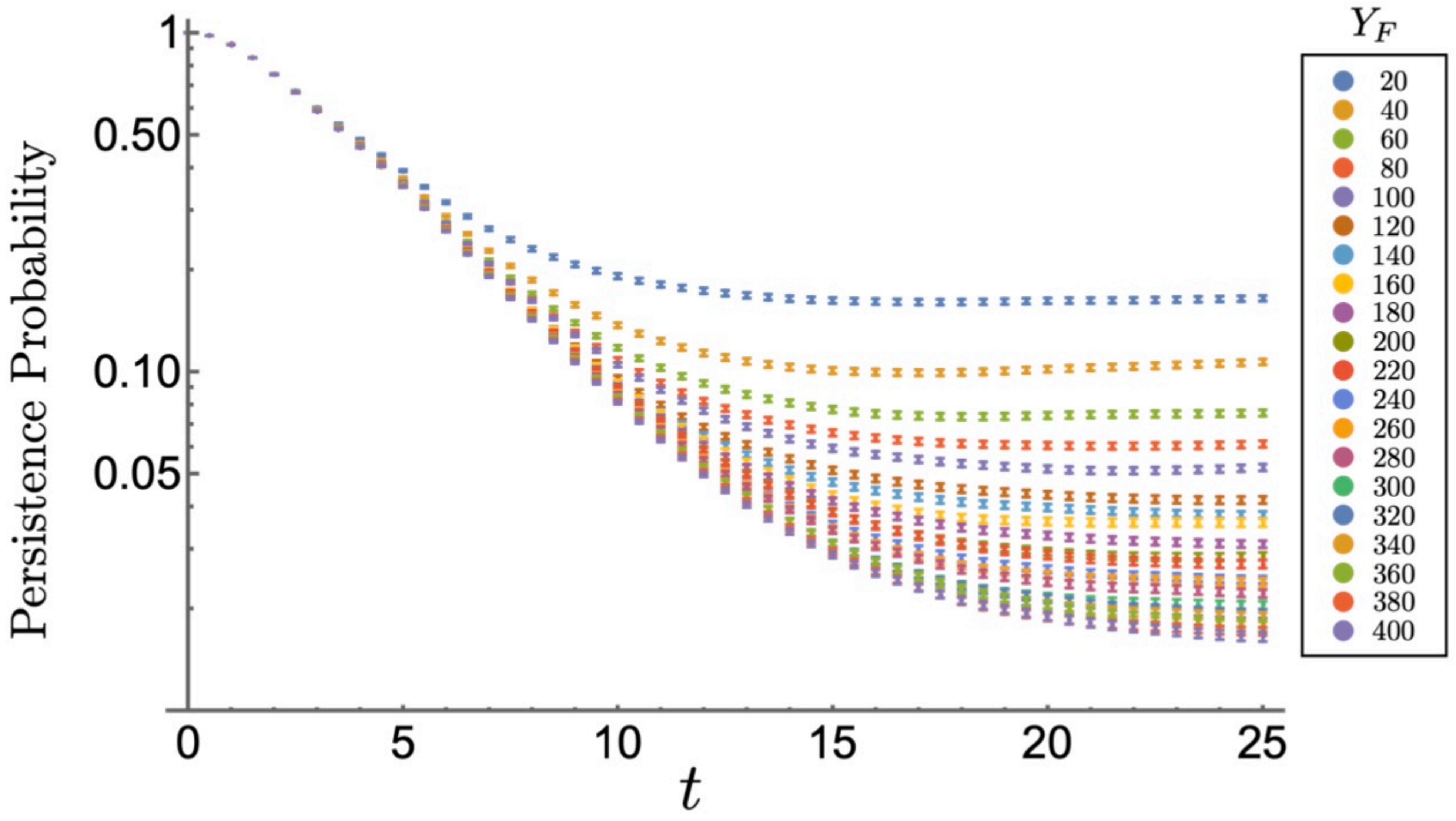


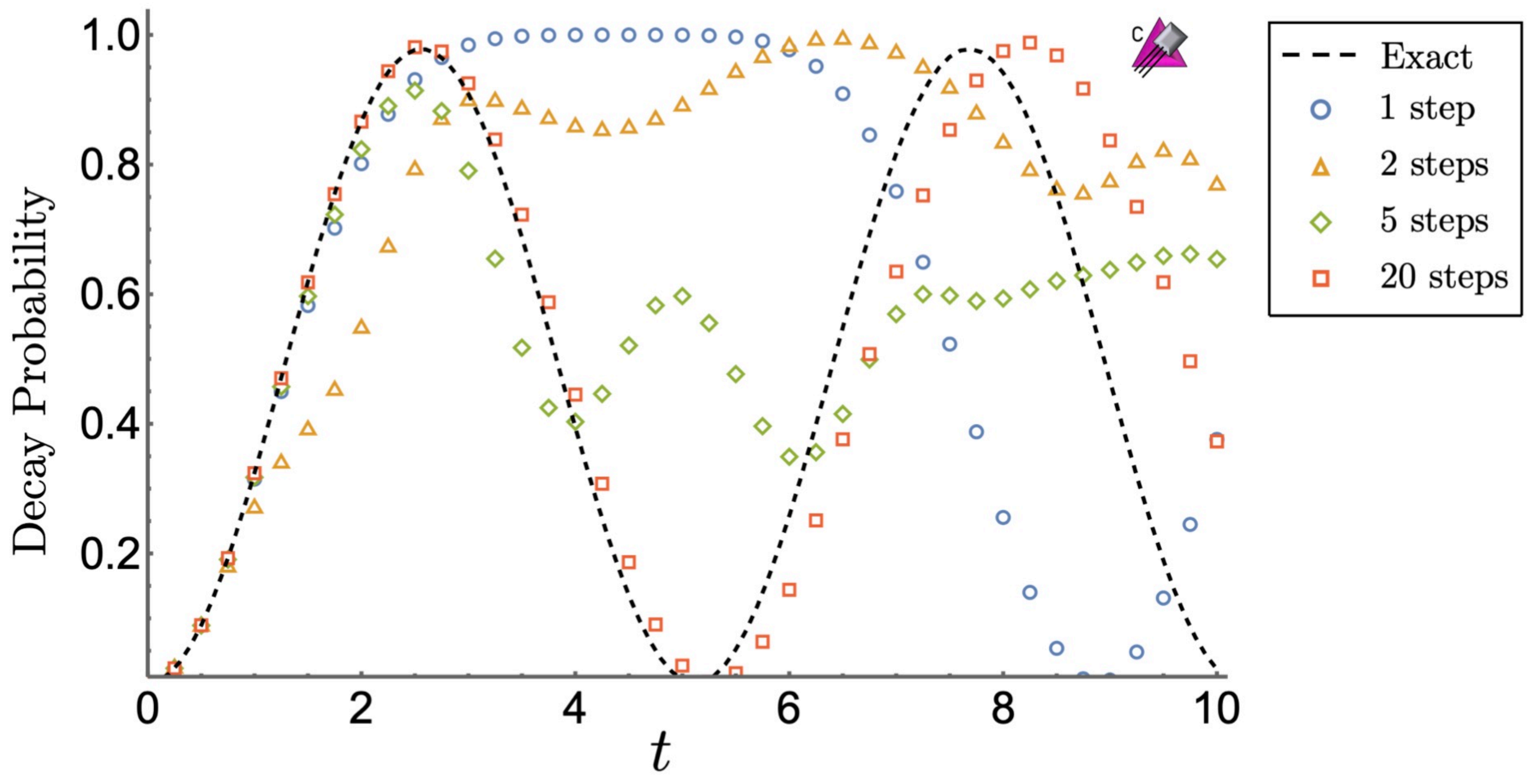
Balance between mass and gauge-field energies

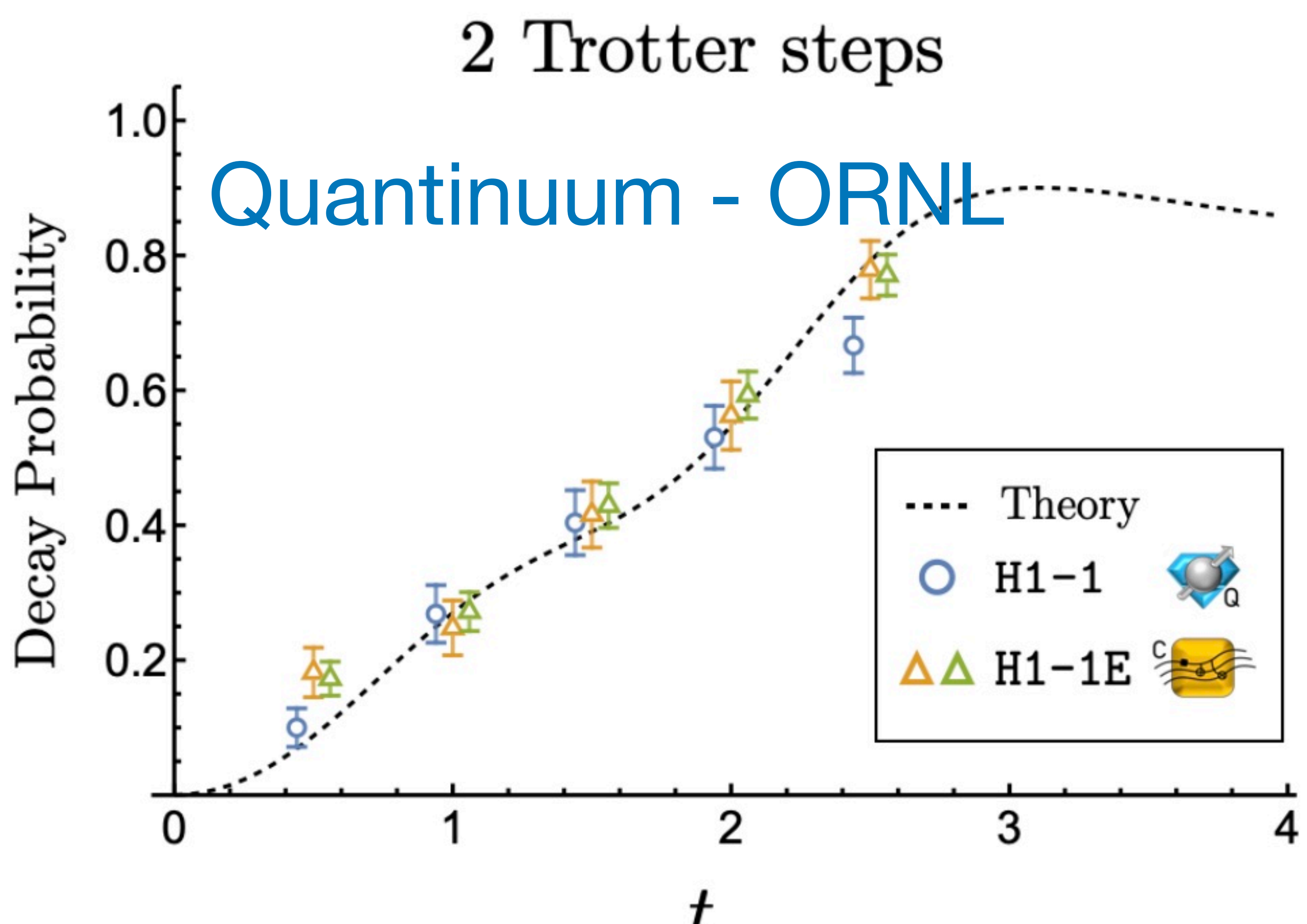
Real-time Exponential-Decay Weak Interactions



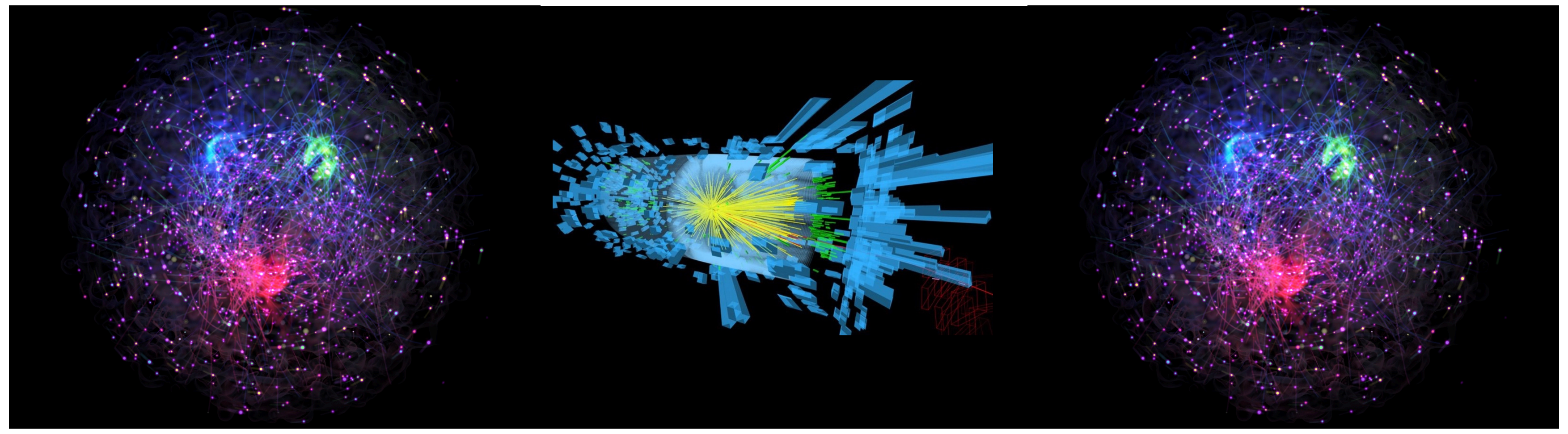








(Classical) Steps Toward Hadronization and Fragmentation (in 1+1D)

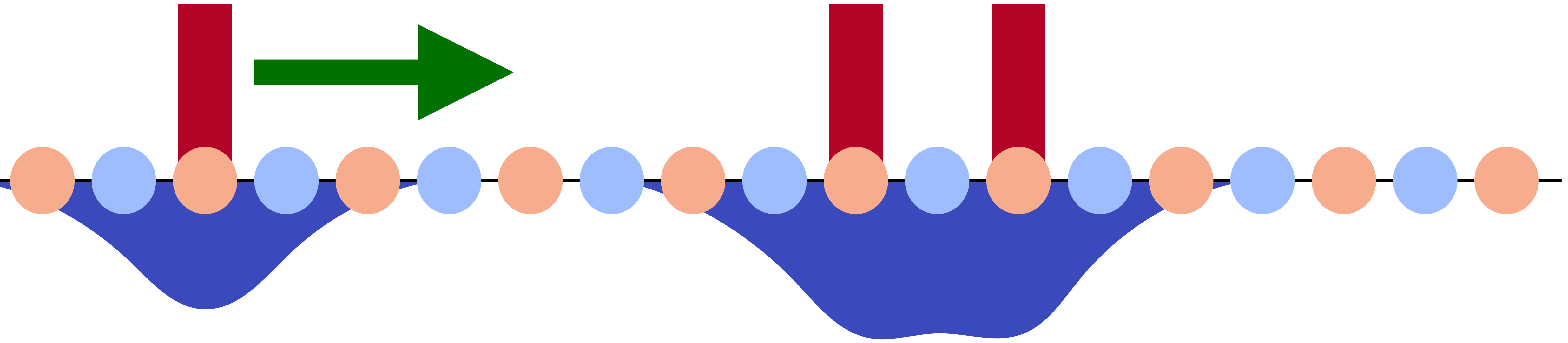


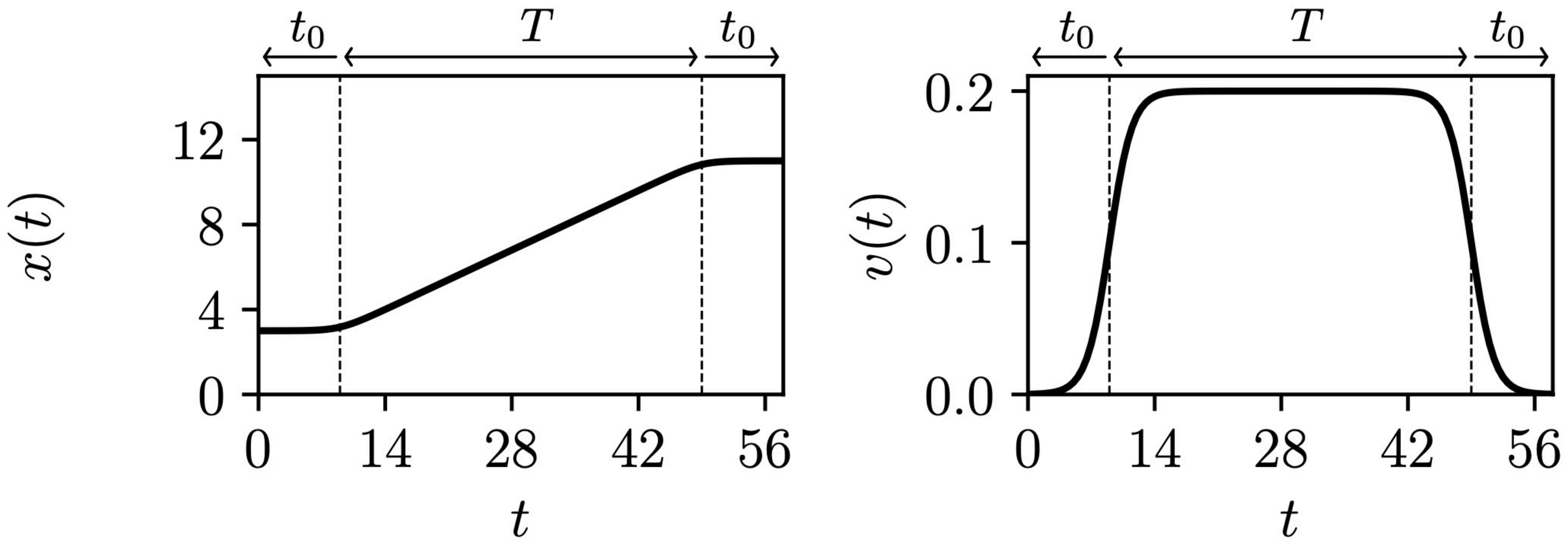
Steps Toward Quantum Simulations of Hadronization and Energy-Loss in Dense Matter

Roland C. Farrell (U. Washington, Seattle (main) and U. Bern, AEC), Marc Illa (U. Washington, Seattle (main)), Martin J. Savage (U. Washington, Seattle (main)) (May 10, 2024)

e-Print: 2405.06620 [quant-ph]

Classical background charges



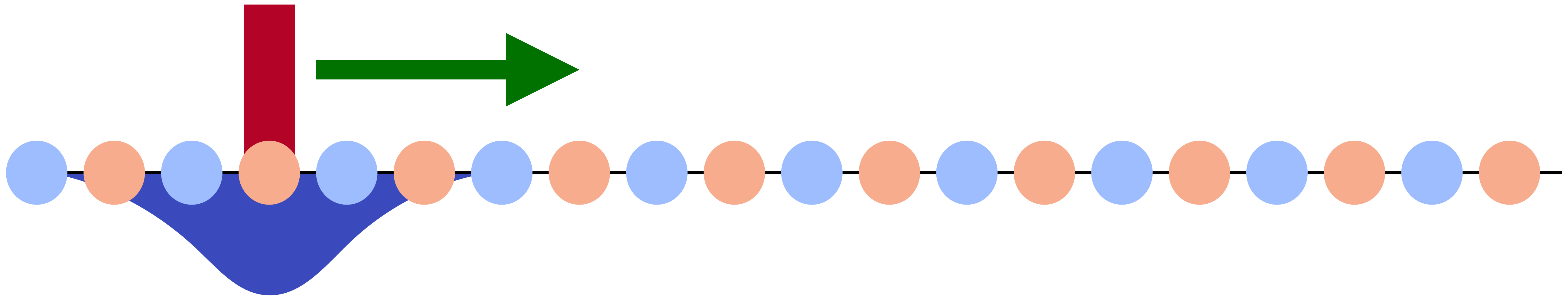


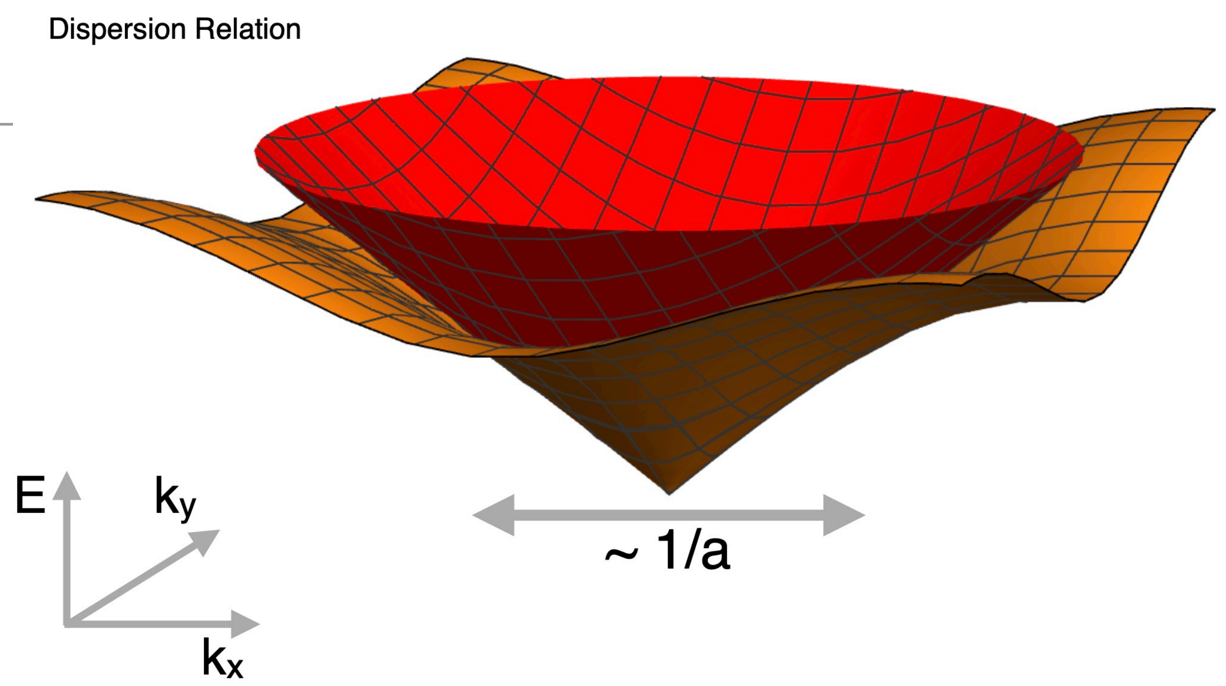
Continuum and infinite volume limits

- Lattice spacing taken to zero
  - recover Lorentz symmetry, special relativity
- Length taken to Infinity
- Fixed physics with parametrically suppressed corrections

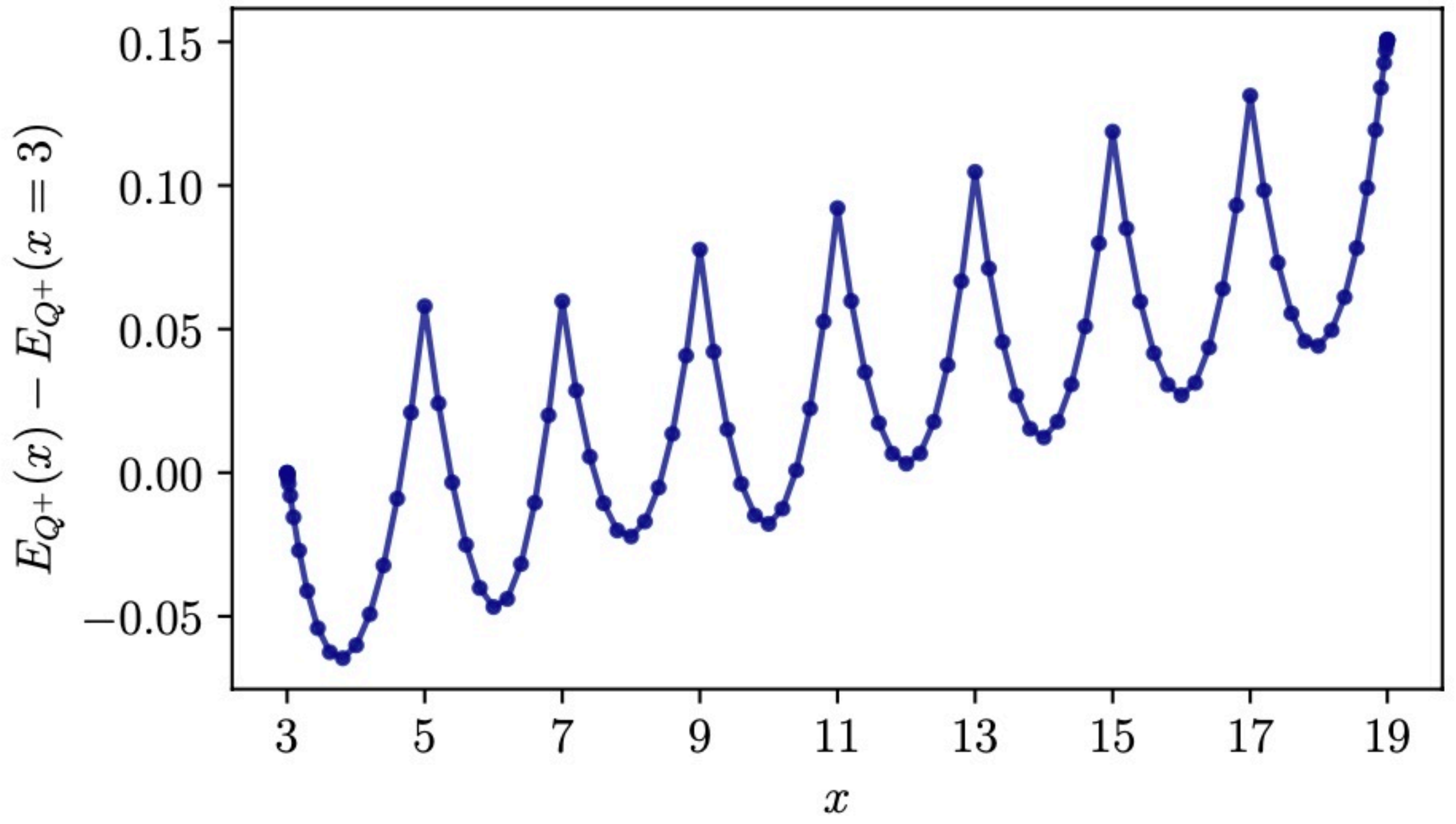
- Present quantum resources ~ limit lattice size and spacing (number of sites)
  - Classical HPC simulations only at present - quantum circuit depth
- Lattice spacing artifacts large

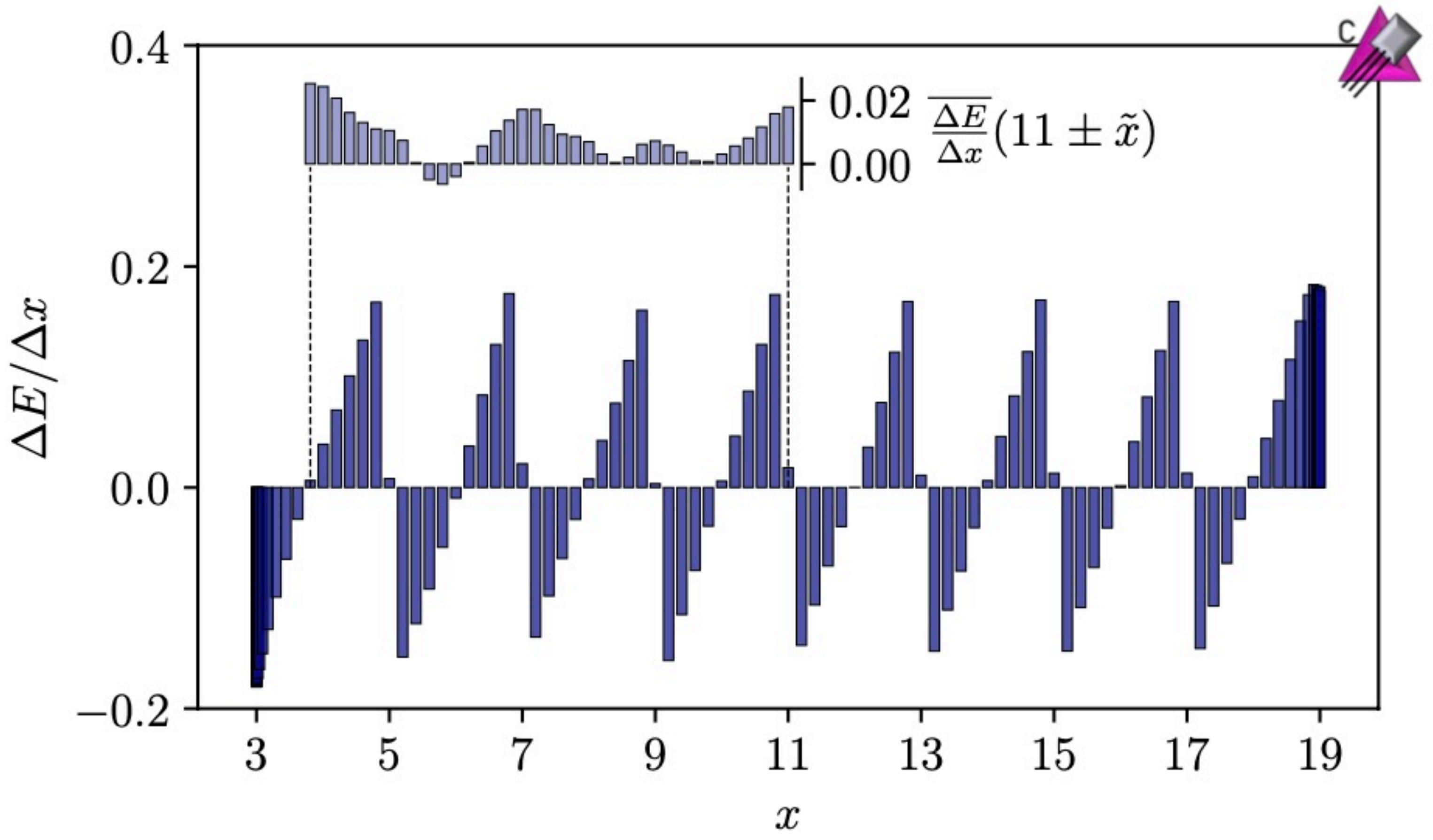
Lorentz Violation by Lattice Spacing

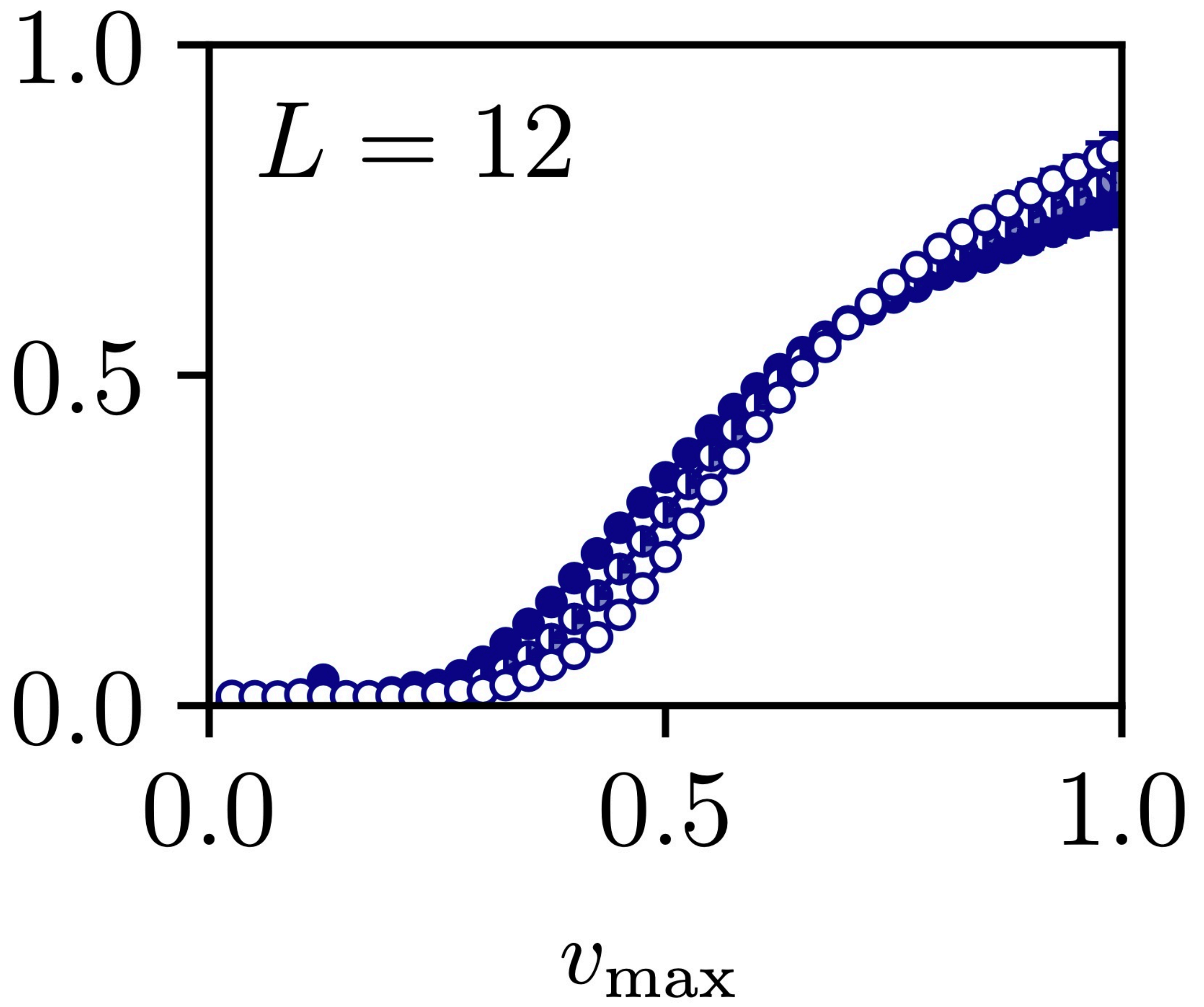




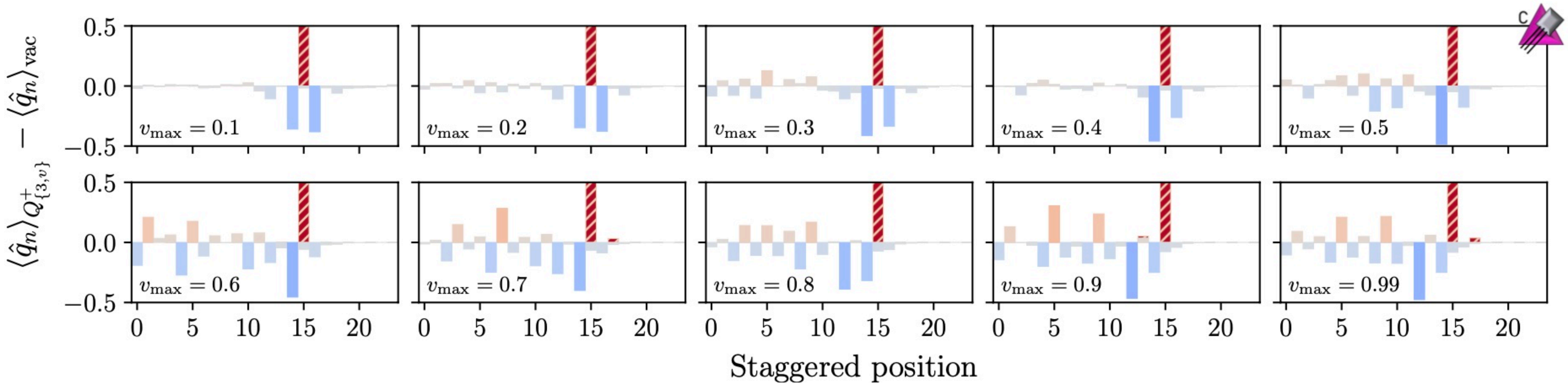
- Lorentz invariance dictates energy conservation at fixed velocity in vacuum
- Energy loss into the light degrees of freedom is
  - a lattice spacing artifact
  - creating hadrons with some probability on top of the vacuum - useful but not physics



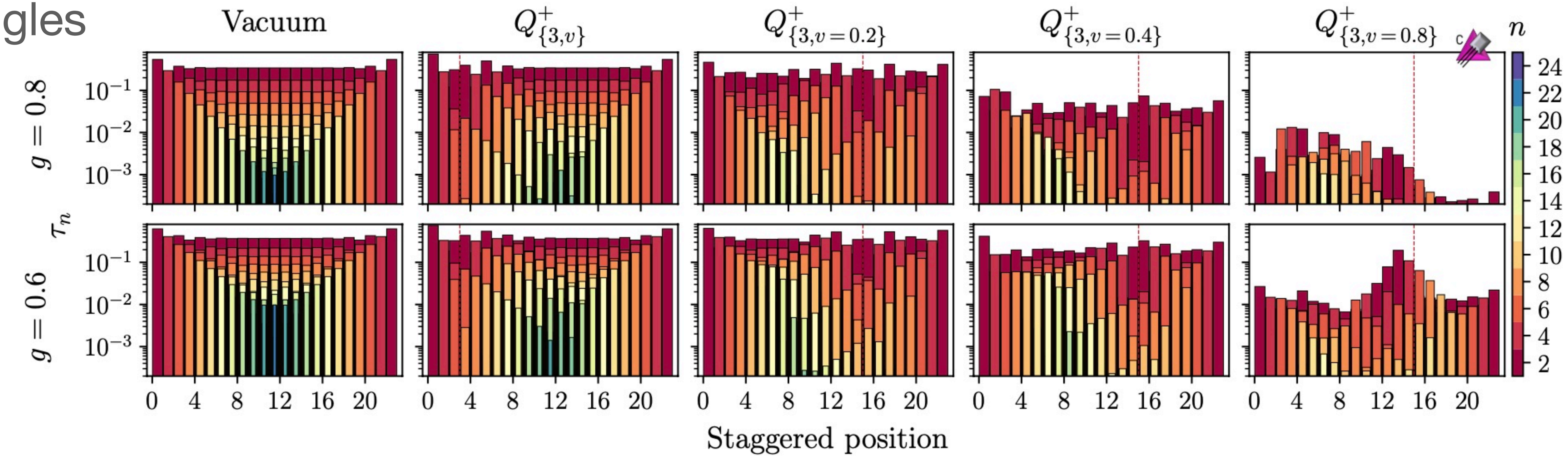




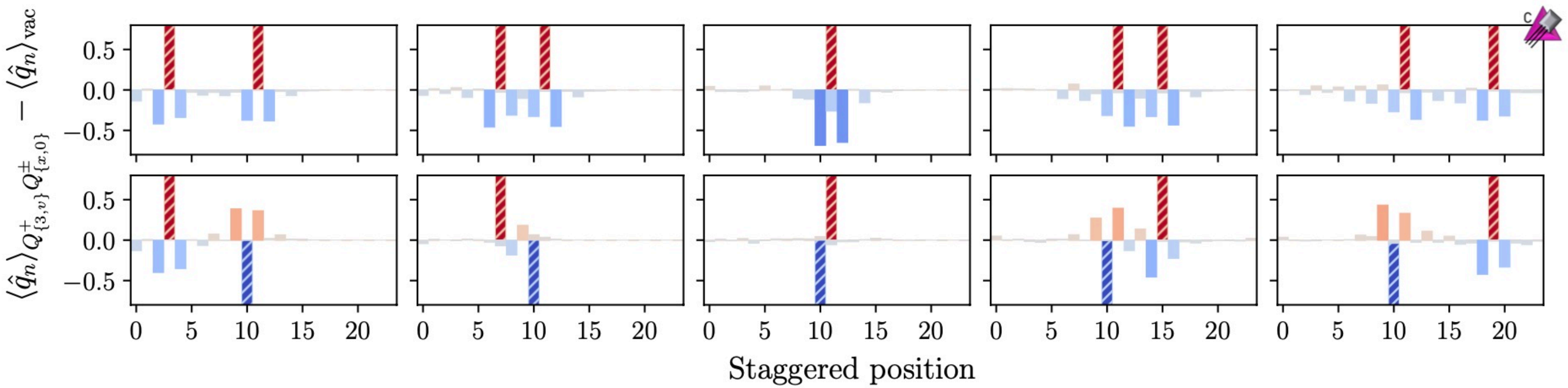
Lorentz Violation by the Lattice Spacing

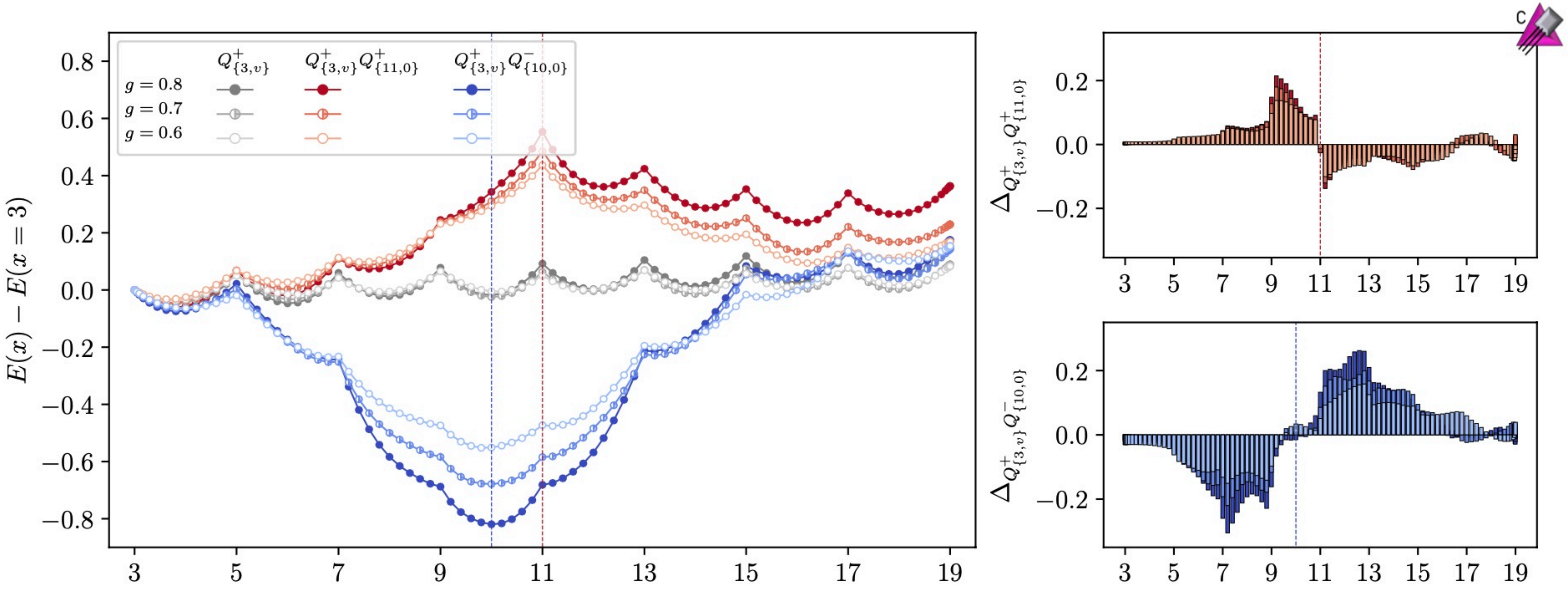


n-tangles

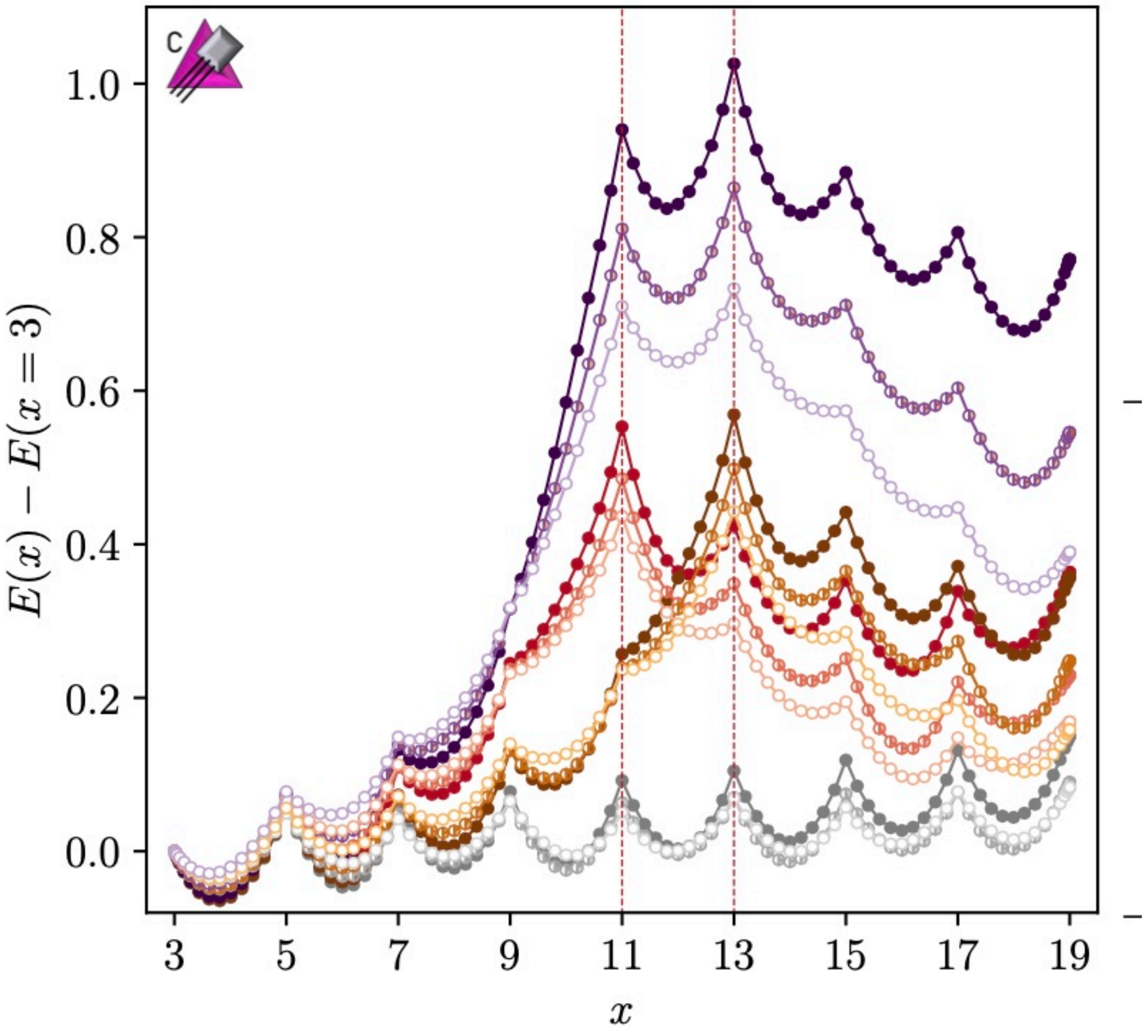


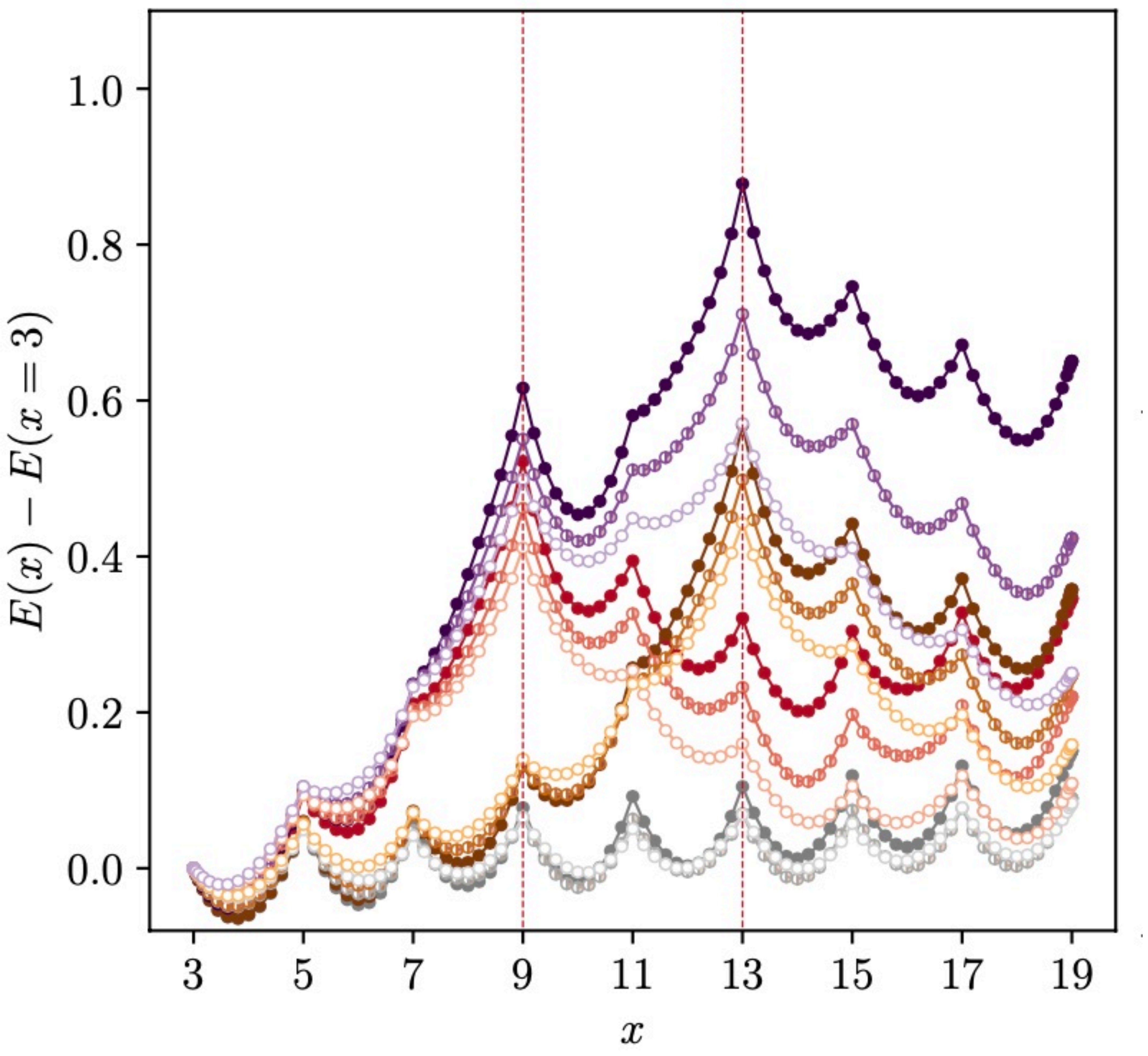
Colliding Partons





Matter and Coherence





Dynamical Quantum Phase Transitions

2018

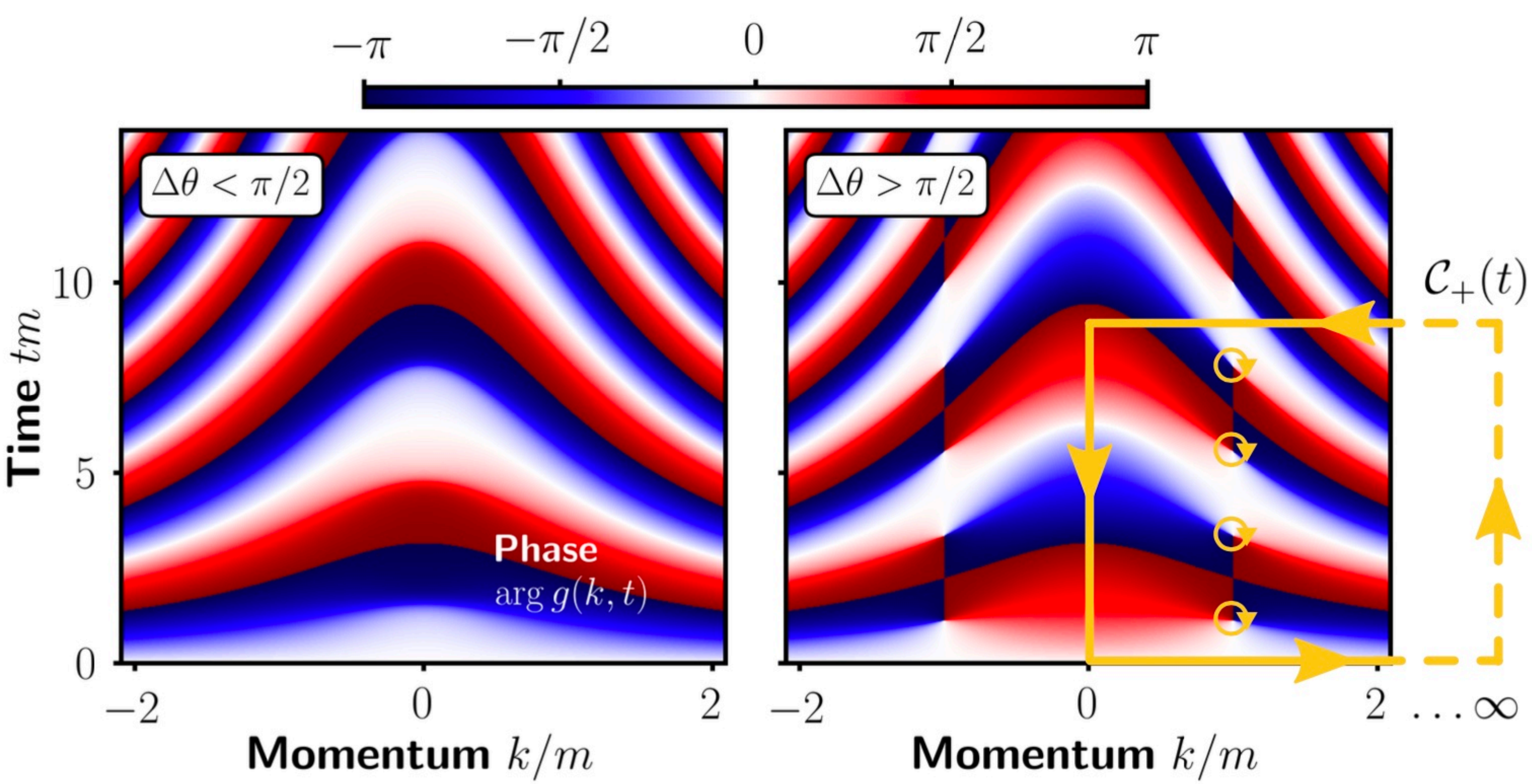
Dynamical topological transitions in the massive Schwinger model with a θ-term

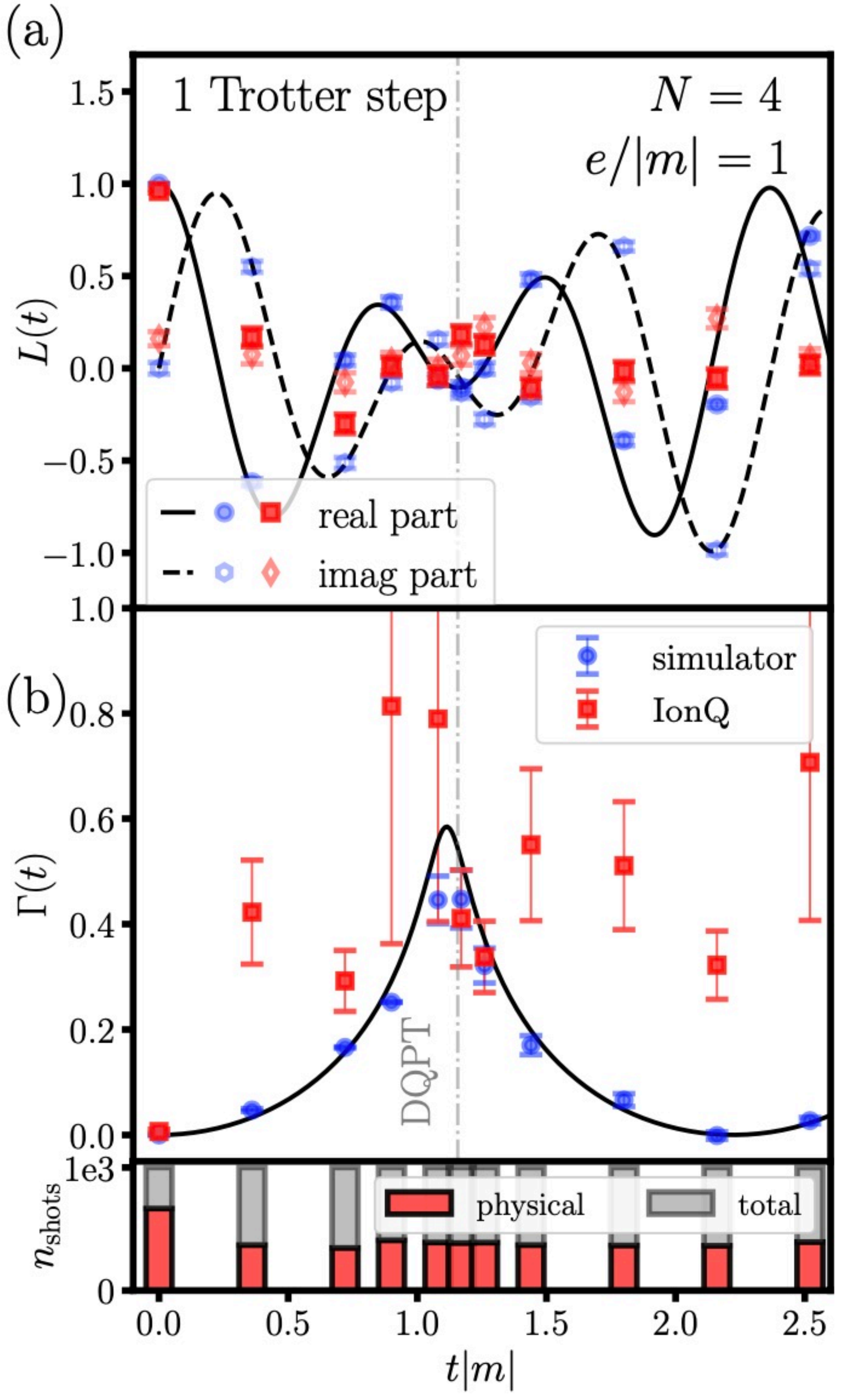
T. V. Zache,[1,*] N. Mueller,[2] J. T. Schneider,[1] F. Jendrzejewski,[3] J. Berges,[1] and P. Hauke[1,3]

2023

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

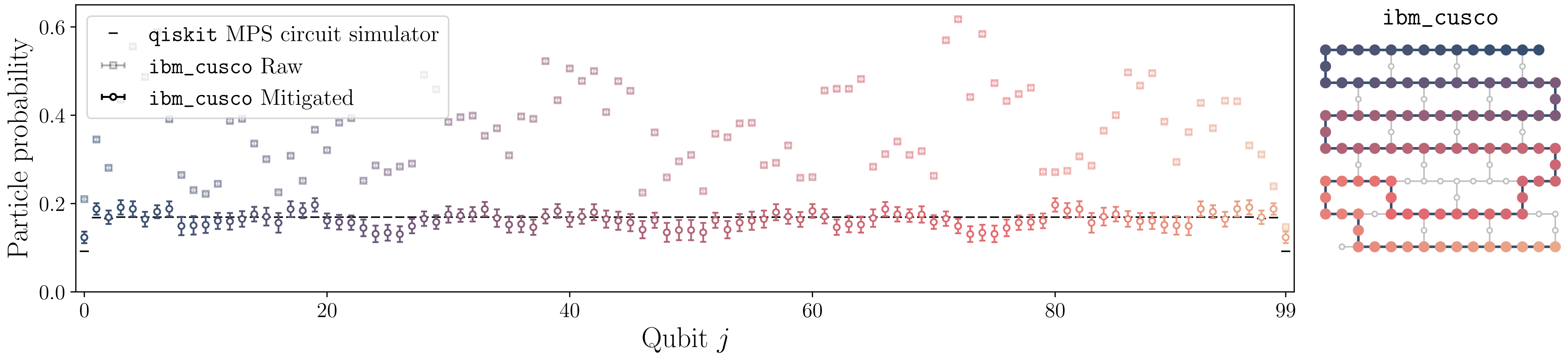
Niklas Mueller,[1,2,3,*] Joseph A. Carolan,[4] Andrew Connelly,[5]
Zohreh Davoudi,[1,6,†] Eugene F. Dumitrescu,[7,‡] and Kübra Yeter-Aydeniz[8]

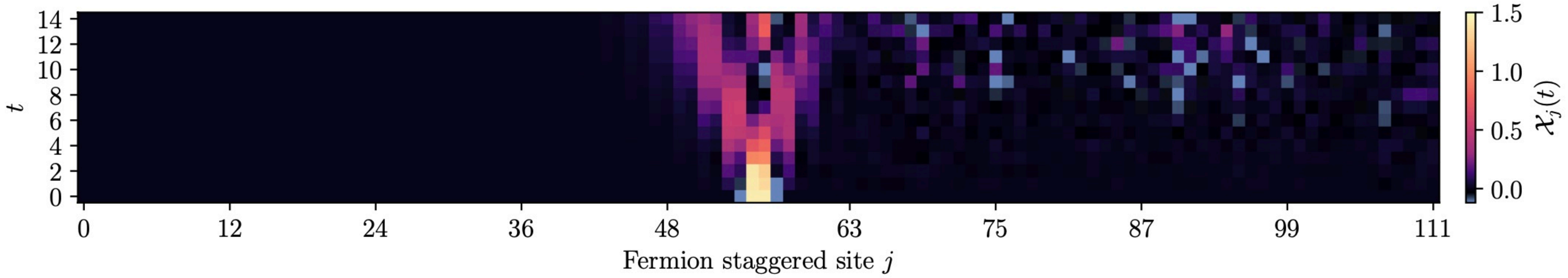




Summary

Roland Farrell
Marc Illa
Anthony Ciavarella

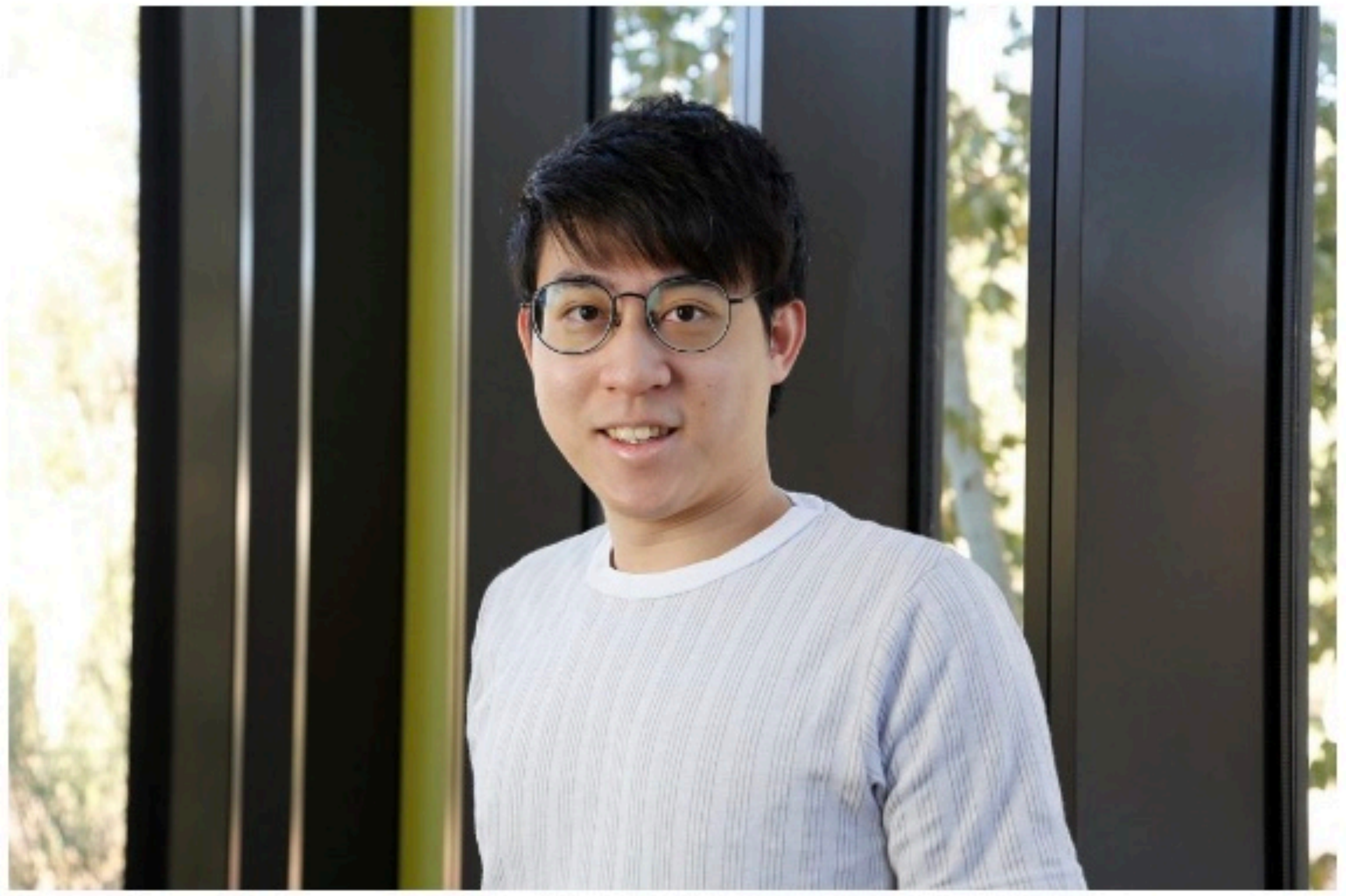




- Quantum Simulations are essential for advancing capabilities in describing dynamical quantum systems…. Standard Model physics and beyond.
- 1+1D systems are a key developmental arena for 3+1D simulations
  - conceptual, algorithmic, workflow, co-design
  - confinement, charge screening, fermion condensate, hadrons
- We introduced of scalable quantum circuits for lattice QFT simulations, and showed our results from >100 qubits, >14k entangling gates
- Quantum Magic and Multi-partite Entanglement are ``new" areas being pursued
  (see Caroline Robin's talk tomorrow)

Office of Science
U.S. Department of Energy
QUANTUM SCIENCE CENTER
OAK RIDGE National Laboratory

Seminar

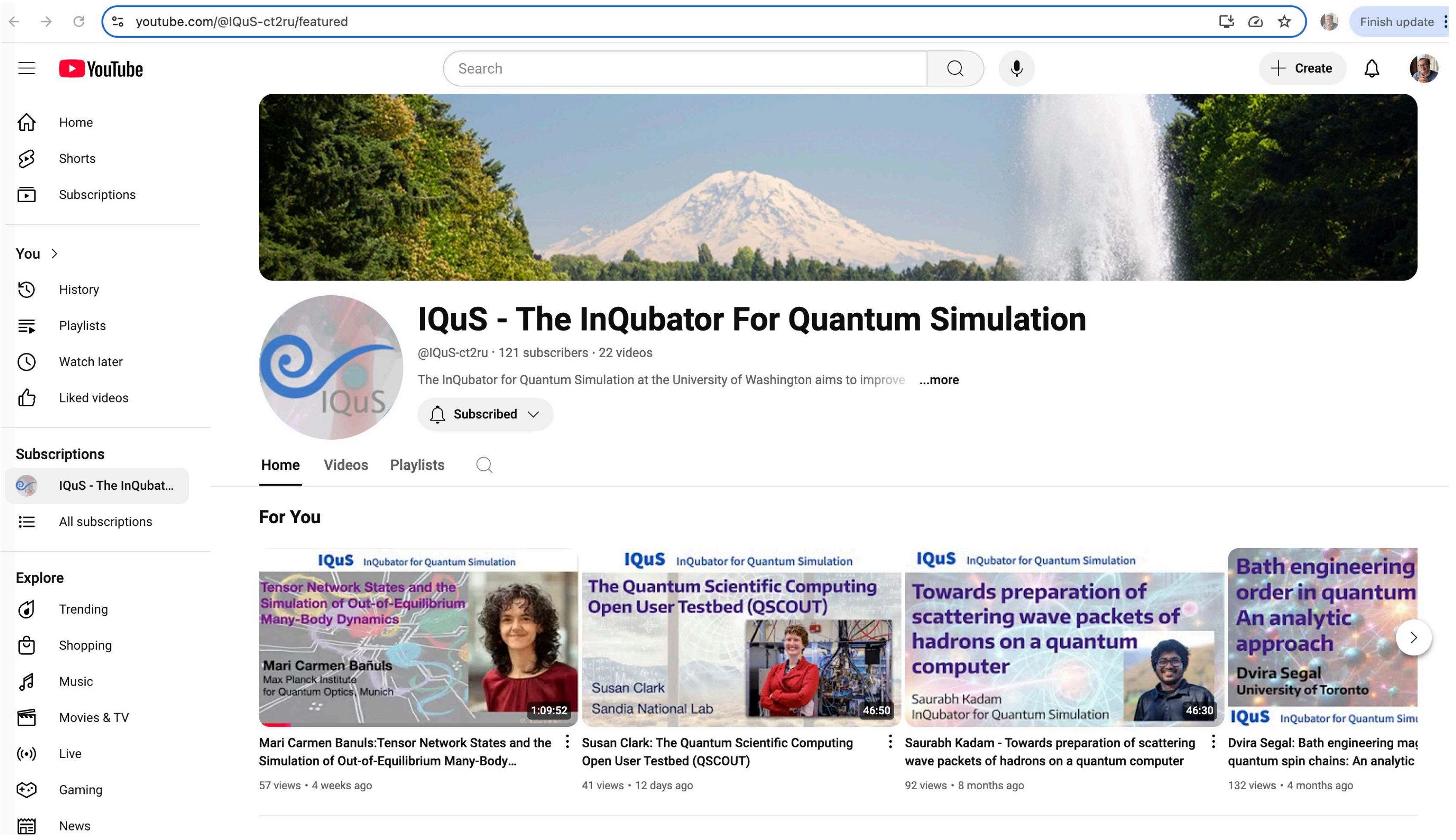


Wednesday Oct 16 2024 1:30 pm - 2:30 pm

What cannot be learned in the quantum universe?

Hsin-Yuan (Robert) Huang, Google Quantum AI and Caltech. Online participation available.

C520 Physics and Astronomy Building



FIN