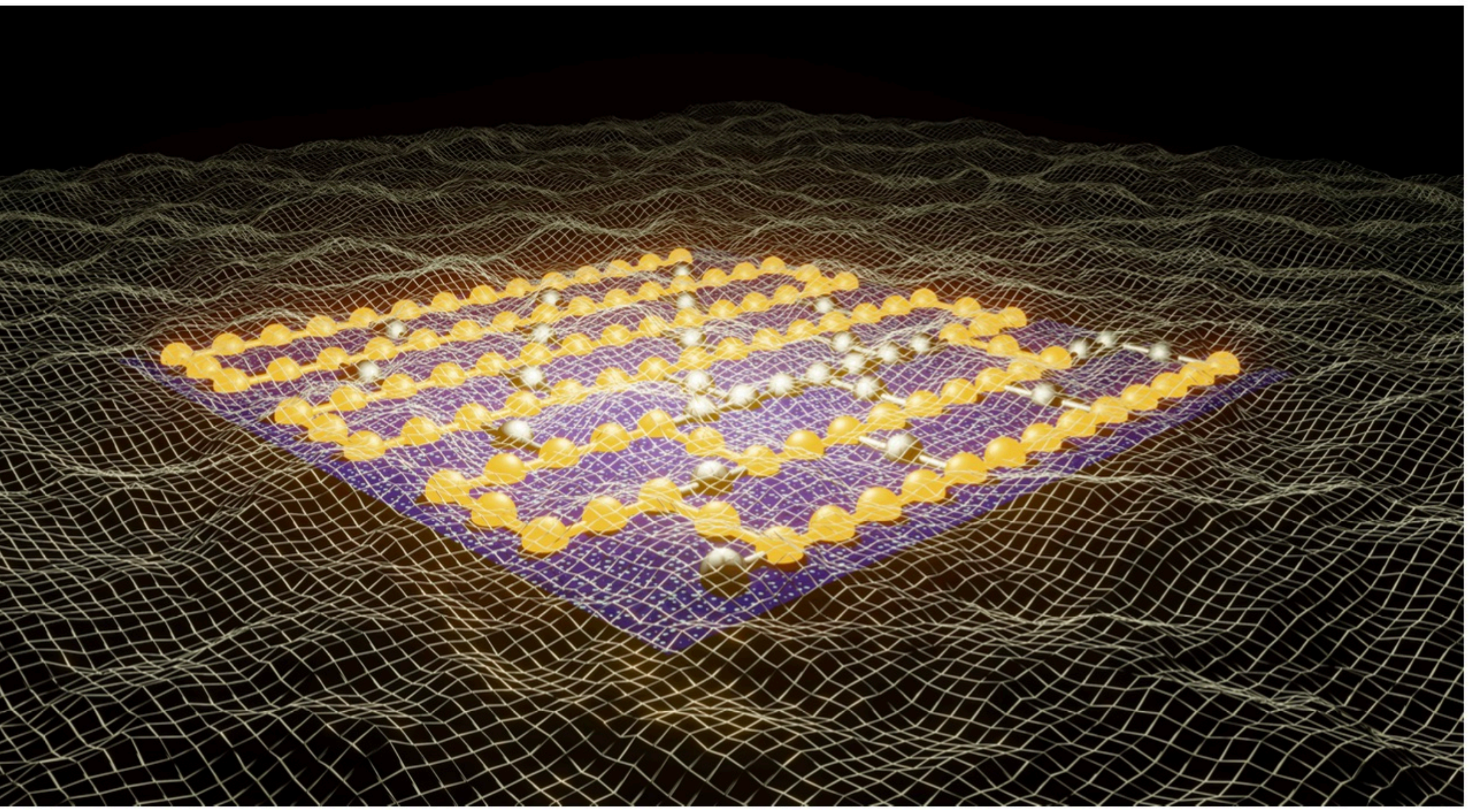
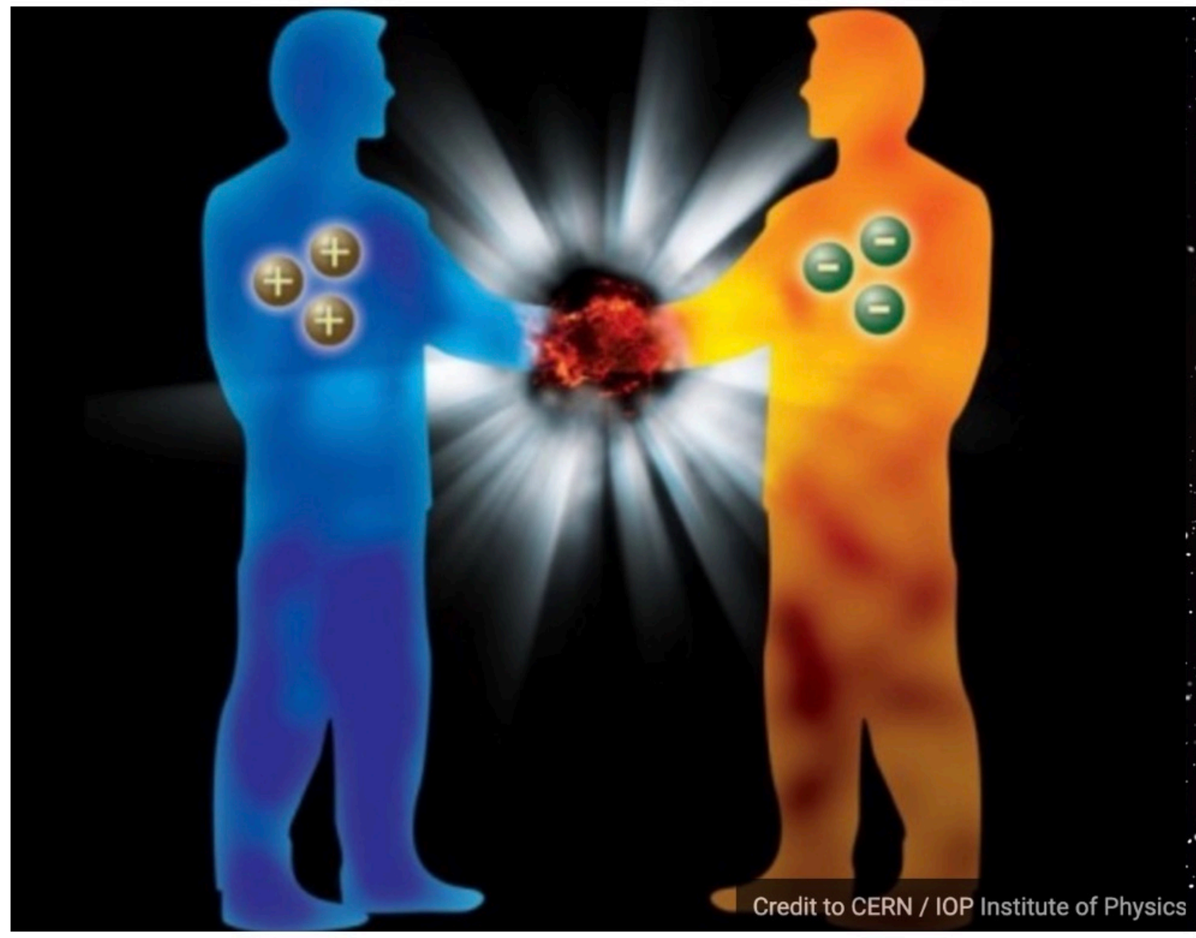
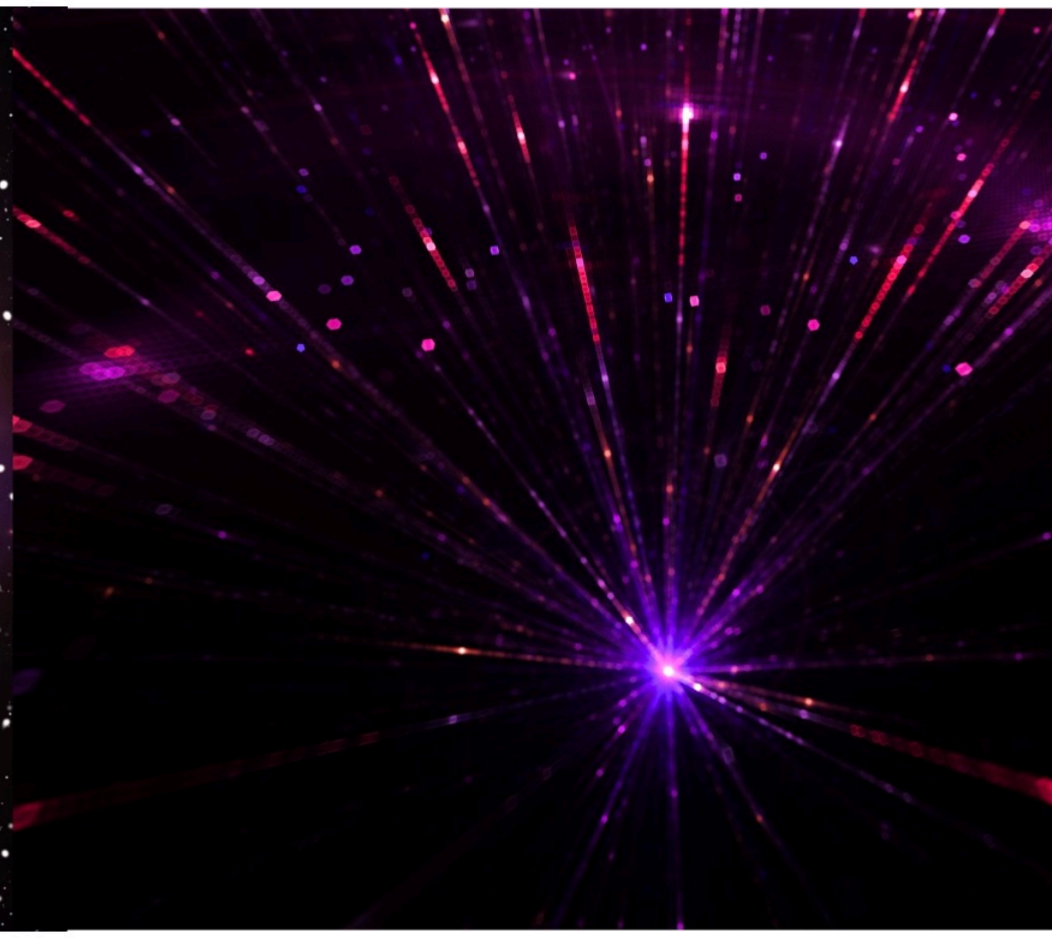
Quantum Simulation of Fundamental Physics





The Matter-Antimatter Asymmetry

Astrophysical Environments



Collisions and Reactions

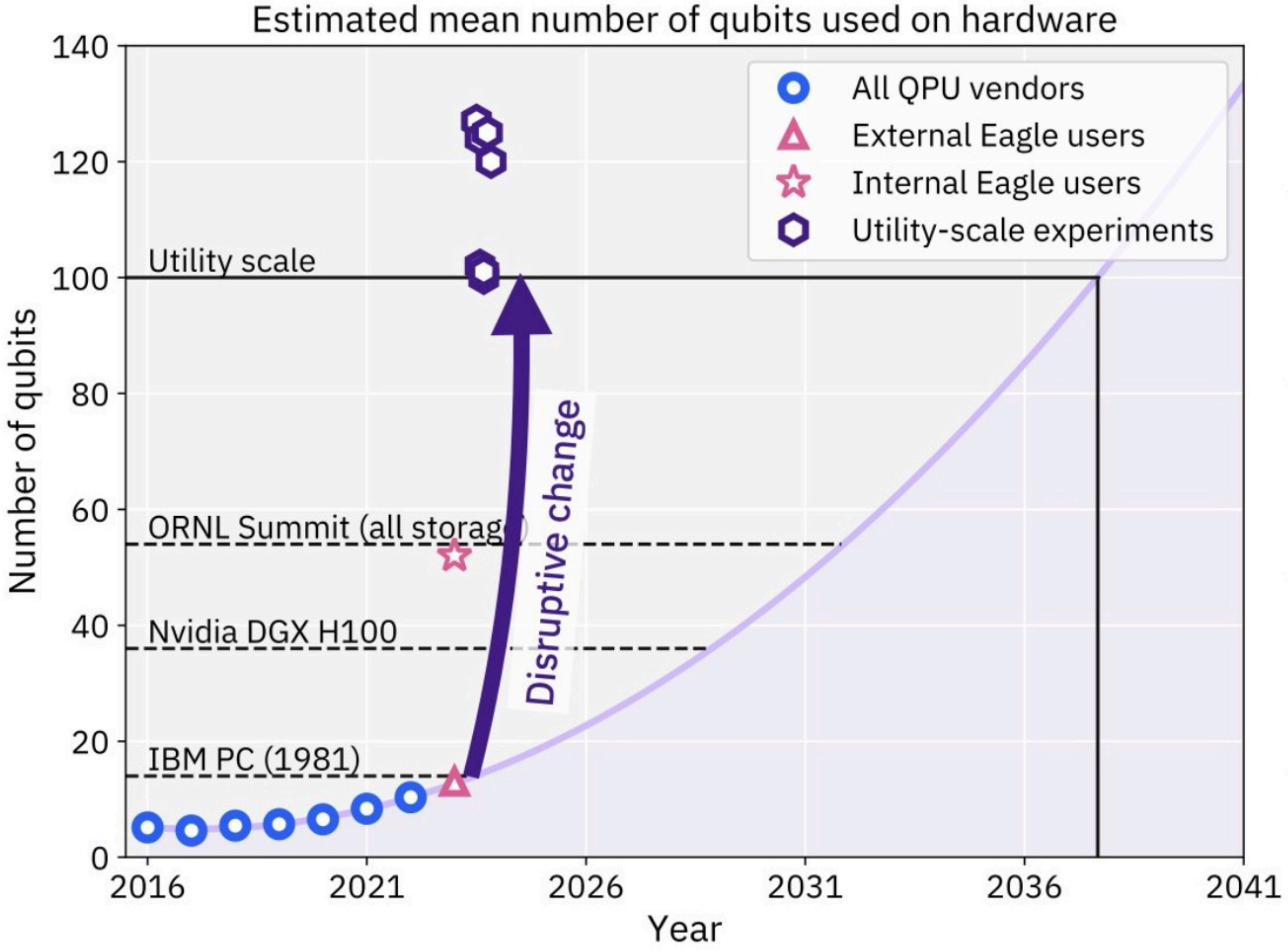
Martin Savage
InQubator for Quantum Simulation (IQuS), University of Washington

https://iqus.uw.edu/

IBM Quantum Summit - NYC December 2023

Utility-scale experiments

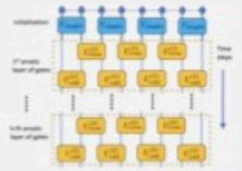
With quantum systems composed of 100+ qubits, researchers are beginning to explore algorithms and applications at scales beyond brute-force classical computation using IBM Quantum systems.



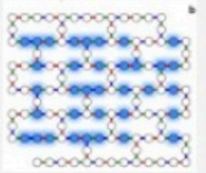
IBM **Quantum**

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

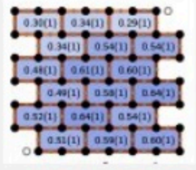
Simulating large-size quantum spin chains on cloud-based superconducting quantum computers
102 qubits / 3186 CX gates — arXiv:2207.09994



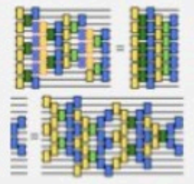
Uncovering Local Integrability in Quantum Many-Body Dynamics
124 qubits / 2641 CX gates — arXiv:2307.07552



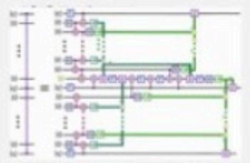
Realizing the Nishimori transition across the error threshold for constant-depth quantum circuits
125 qubits / 429 gates + meas. — arXiv:2309.02863



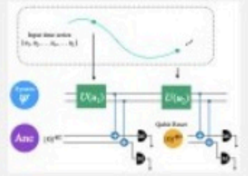
Scalable Circuits for Preparing Ground States on Digital Quantum Computers: The Schwinger Model Vacuum on 100 Qubits
100 qubits / 788 CX gates — arXiv:2308.04481



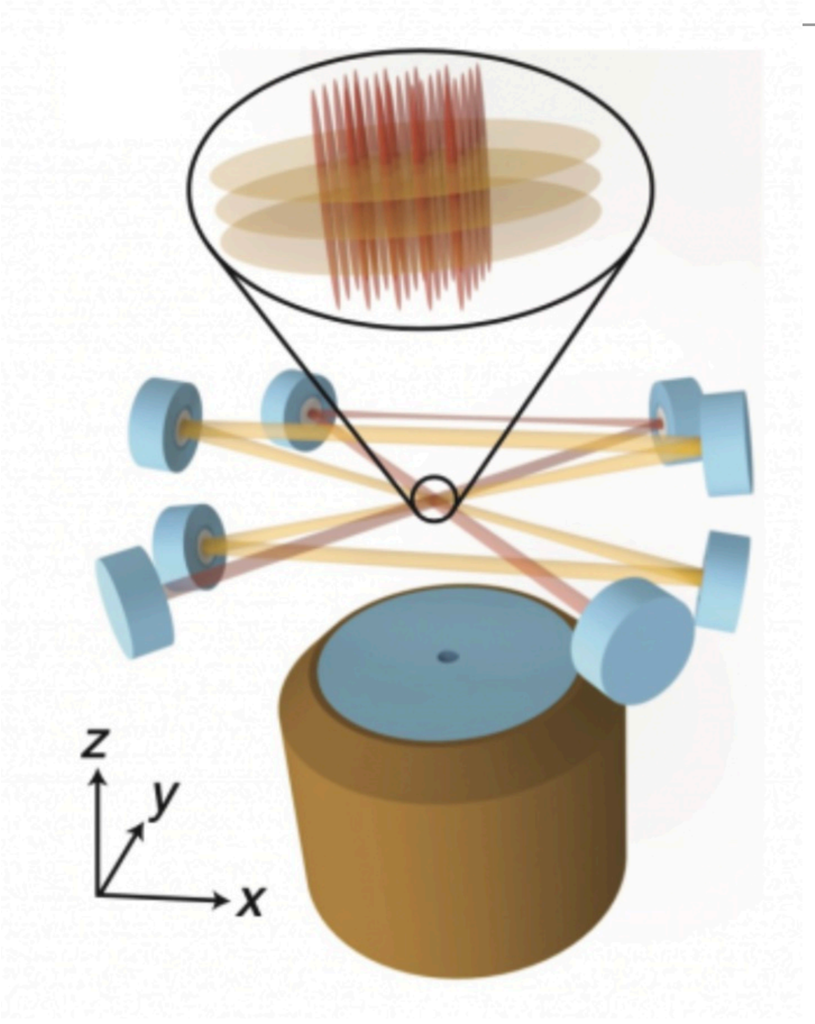
Efficient Long-Range Entanglement using Dynamic Circuits
101 qubits / 504 gates + meas. — arXiv:2308.13065



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)

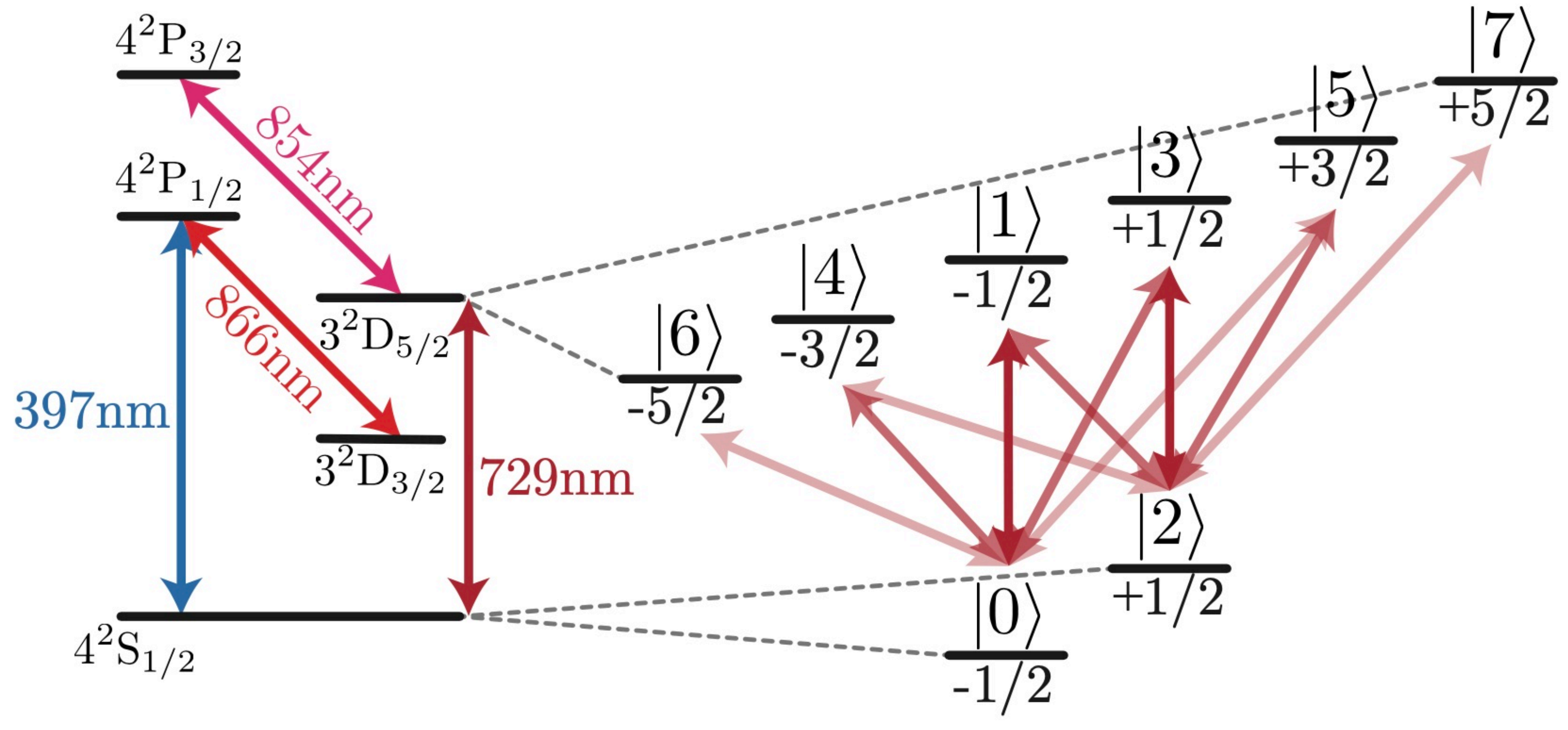
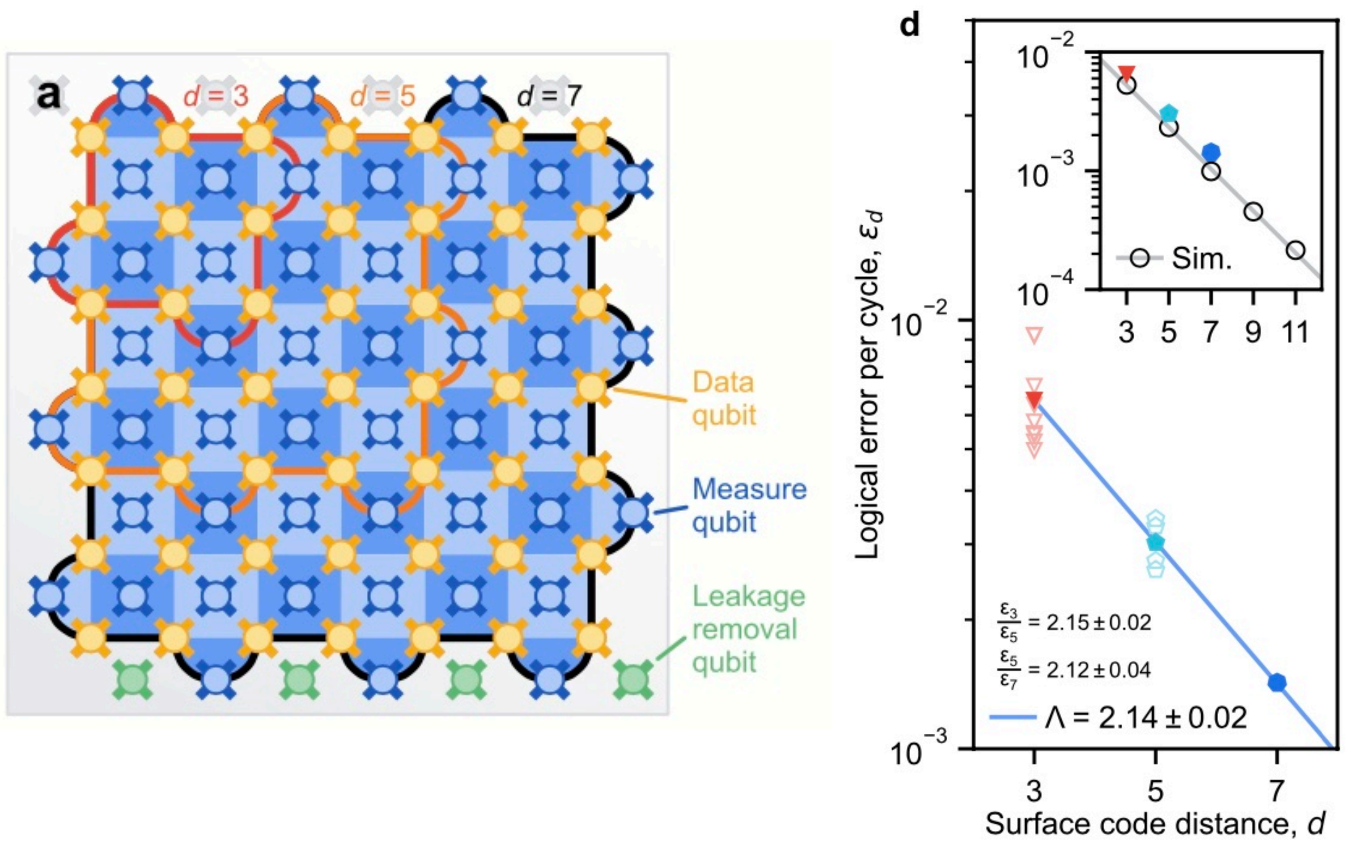
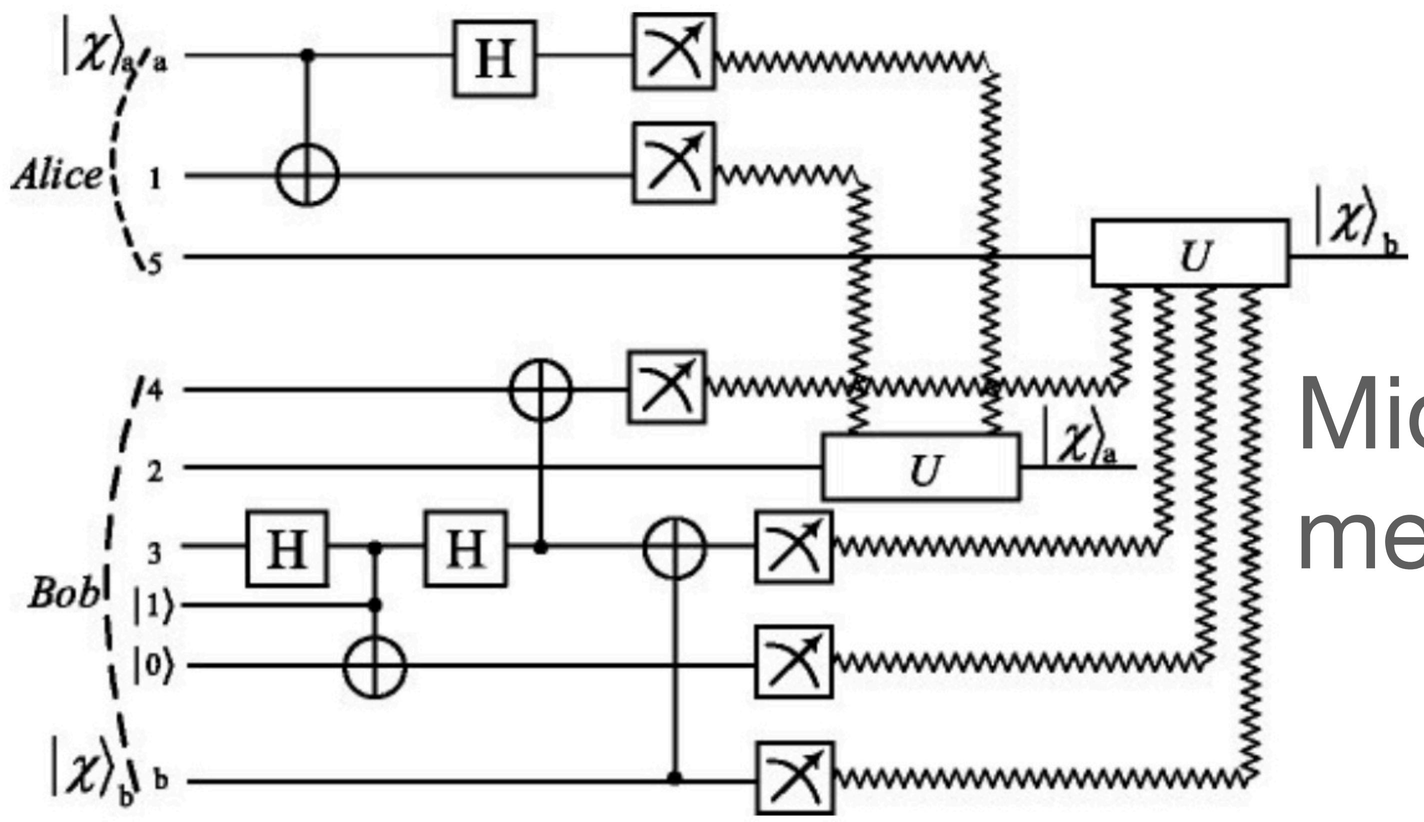


FIG. 1. **Level scheme of the $^{40}Ca^{+}$ ion.**

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

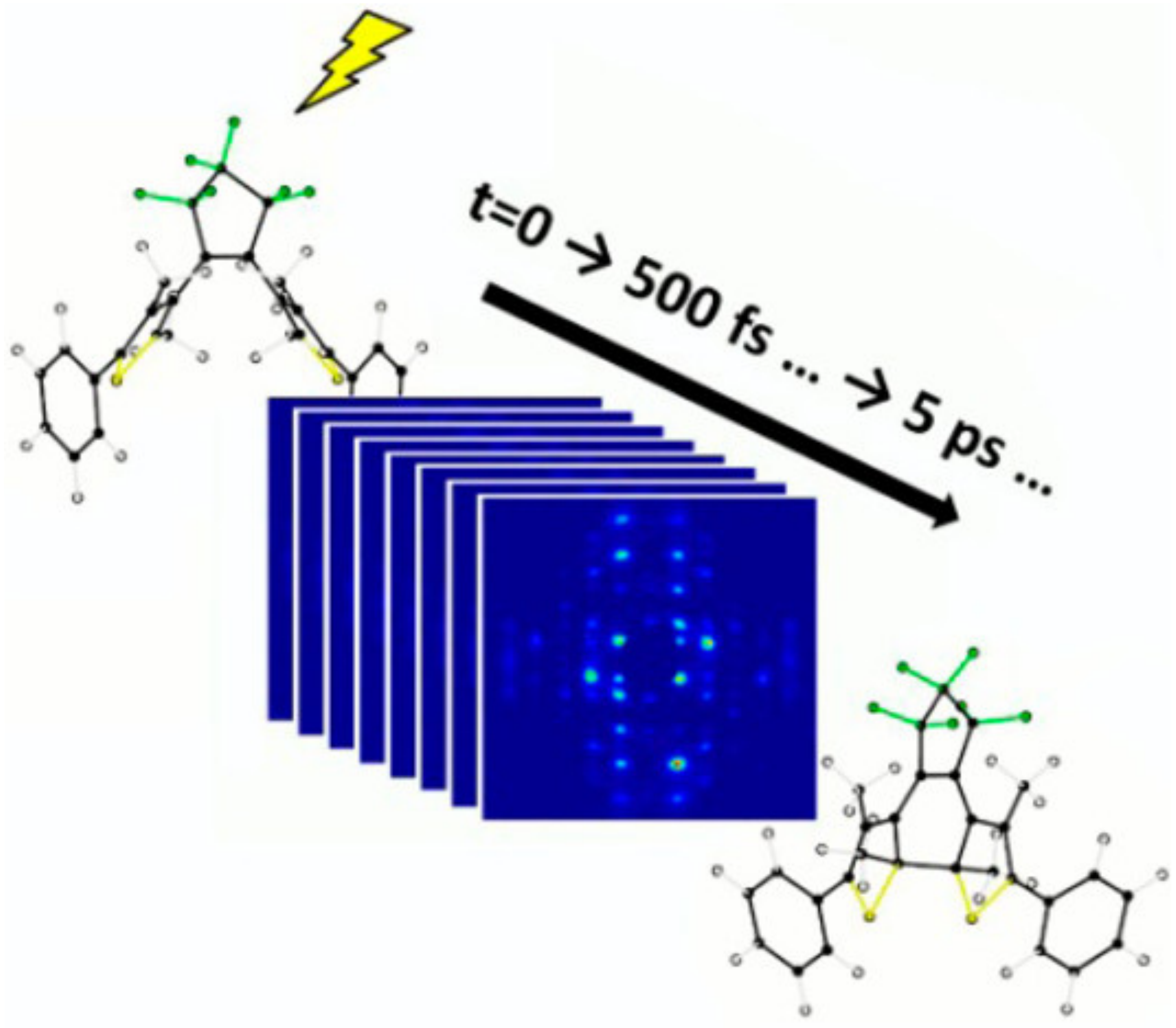
Perspective | Published: 21 June 2023

Quantum simulation of fundamental particles and forces

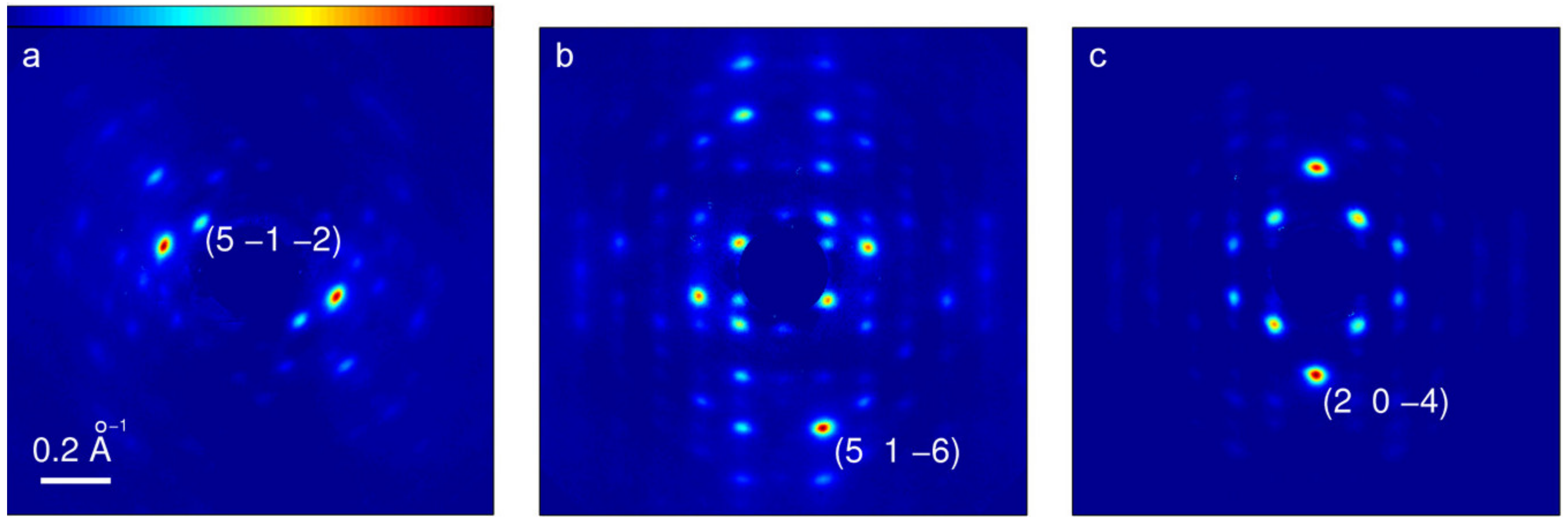
Christian W. Bauer, Zohreh Davoudi, Natalie Klco & Martin J. Savage

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

Real-Time Dynamics and Reaction Pathways



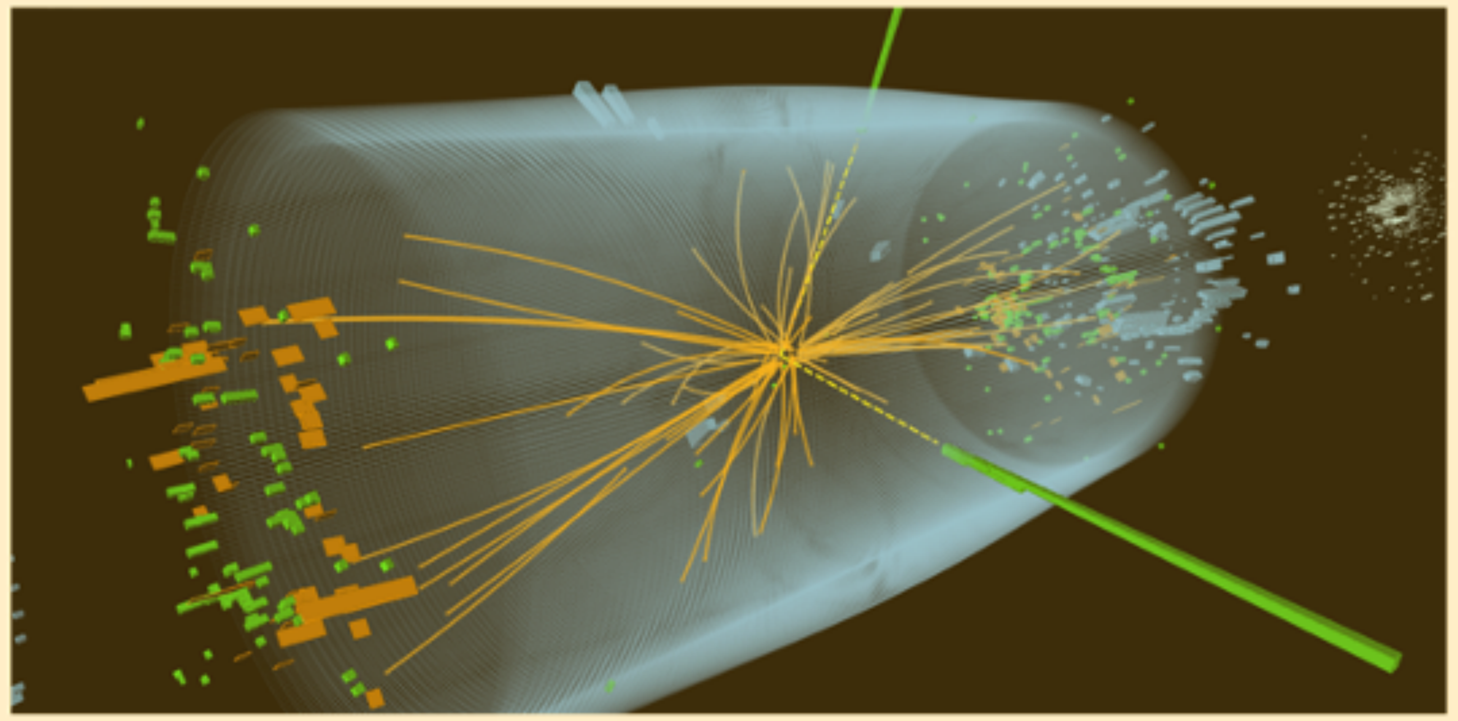
J. Phys. Chem. B 2013, 117, 49, 15894-15902



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

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

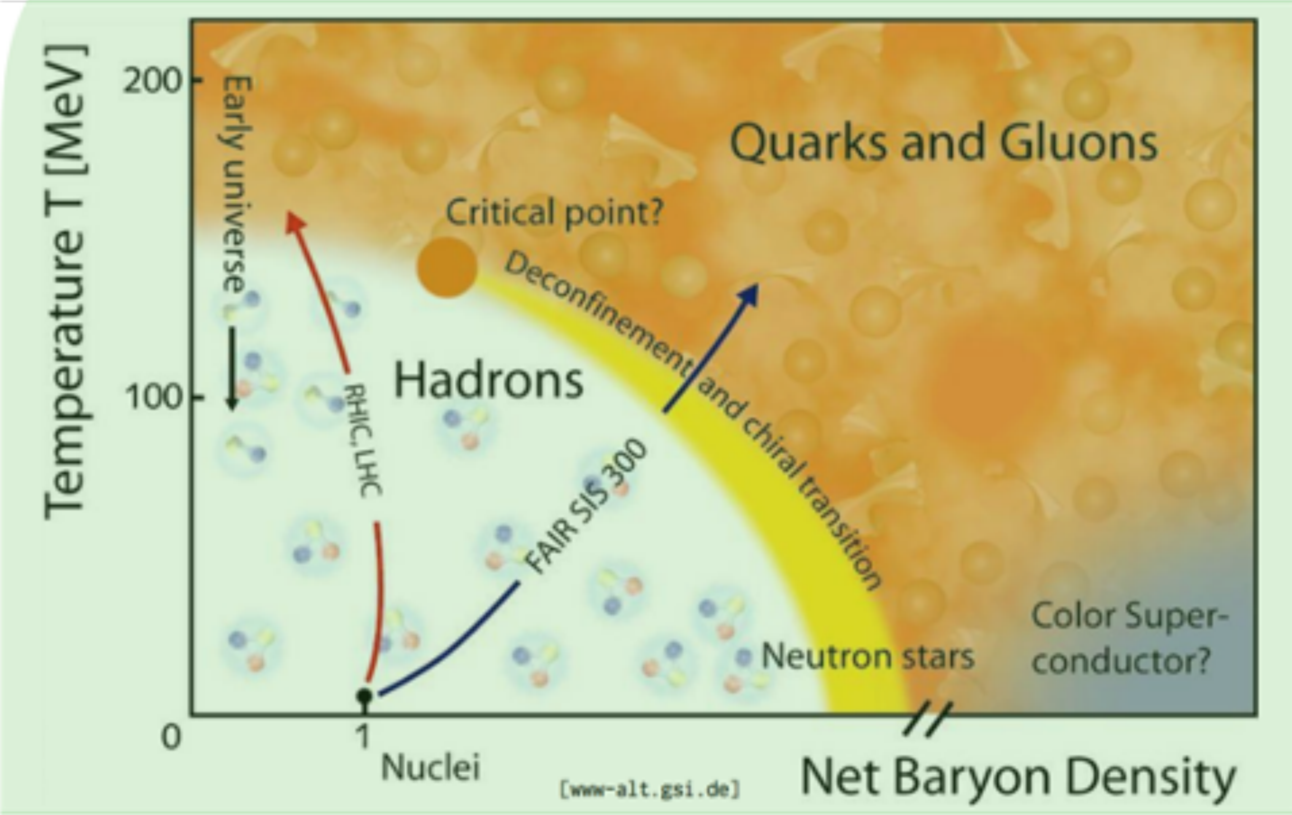
Low-energy reactions

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

Neutrino dynamics

Matter-antimatter asymmetry

BQP

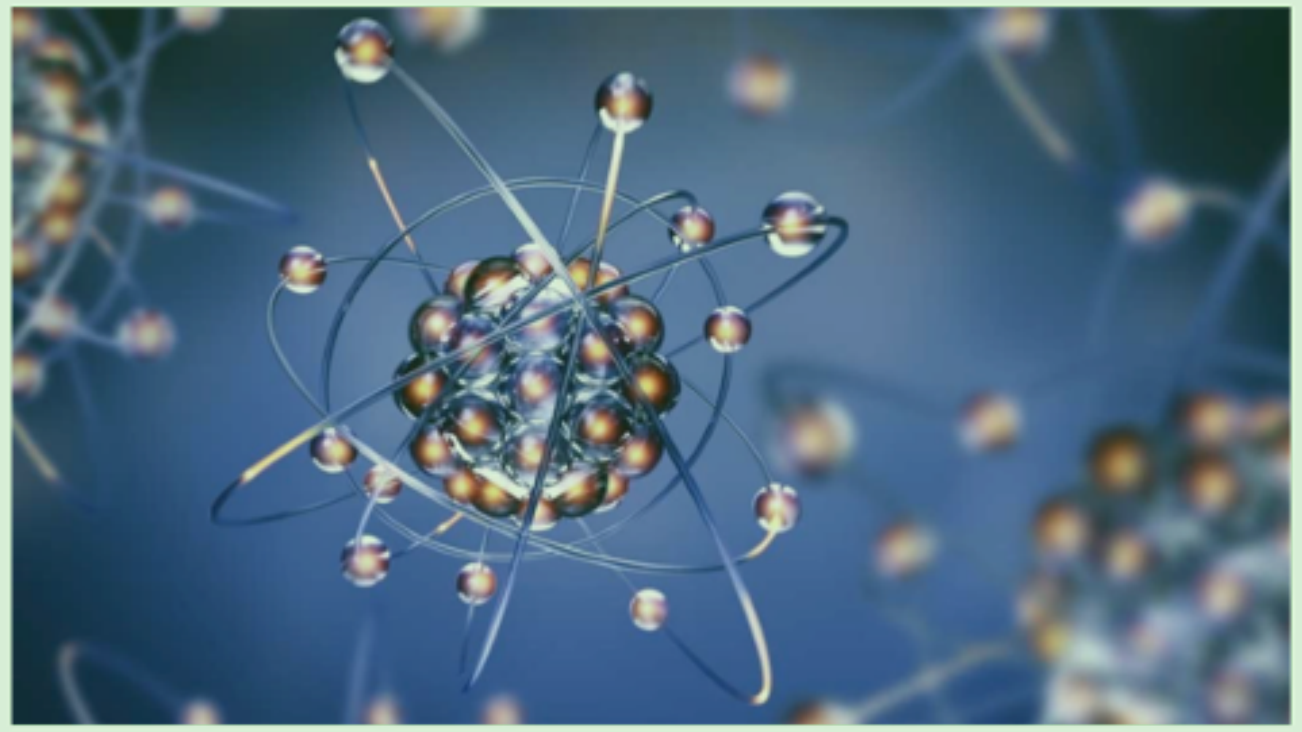


Equation of state of dense
hot matter and dynamics
viscosity, etc

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

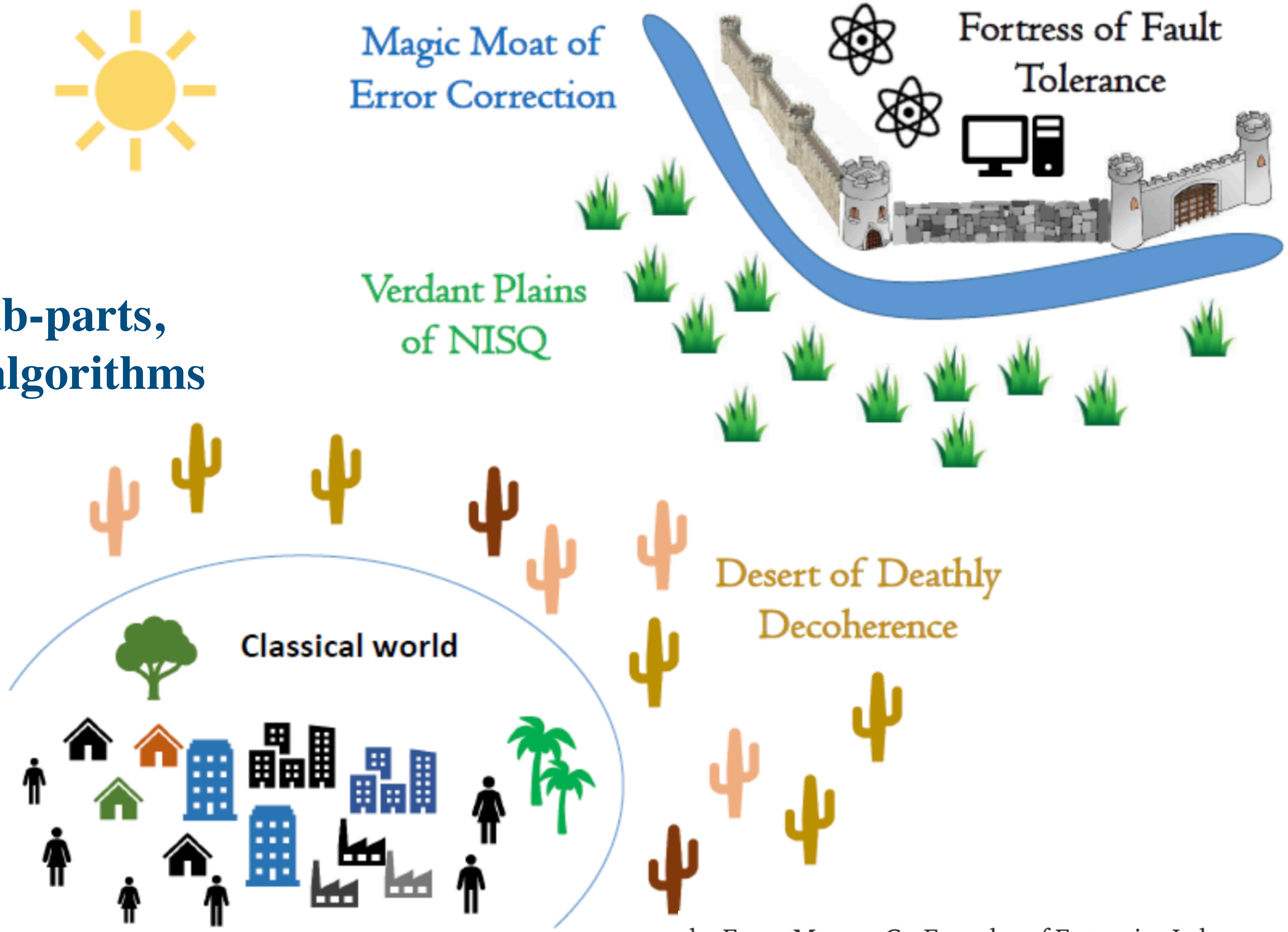
– symmetries

From Classical to Error-Corrected Quantum Computing

Precision simulations to compare with experiments and make reliable predictions

Insights, ideas, sub-parts, observables and algorithms

Insights, ideas, sub-parts, observables and algorithms



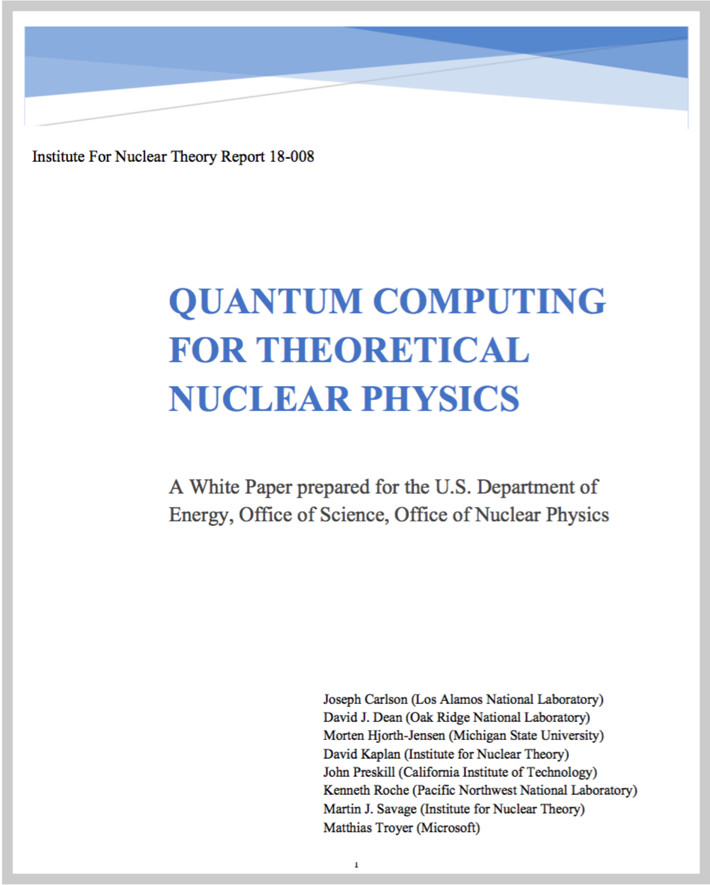
by Ewan Munro, Co-Founder of Entropica Labs.

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

Community Identified Opportunities and Priorities

Simulating lattice gauge theories within quantum technologies

Mari Carmen Bañuls, Rainer Blatt, Jacopo Catani, Alessio Celi, Juan Ignacio Cirac, Marcello Dalmonte, Leonardo Fallani, Karl Jansen, Maciej Lewenstein, Simone Montangero ✉, Christine A. Muschik, Benni Reznik, Enrique Rico, Luca Tagliacozzo, Karel Van Acoleyen, Frank Verstraete, Uwe-Jens Wiese, Matthew Wingate, Jakub Zakrzewski & Peter Zoller


Institute For Nuclear Theory Report 18-008

QUANTUM COMPUTING
FOR THEORETICAL
NUCLEAR PHYSICS

A White Paper prepared for the U.S. Department of Energy, Office of Science, Office of Nuclear Physics

Joseph Carlson (Los Alamos National Laboratory)
David J. Dean (Oak Ridge National Laboratory)
Morten Hjorth-Jensen (Michigan State University)
David Kaplan (Institute for Nuclear Theory)
John Preskill (California Institute of Technology)
Kenneth Roche (Pacific Northwest National Laboratory)
Martin J. Savage (Institute for Nuclear Theory)
Matthias Troyer (Microsoft)

1

Roadmap | Open Access

Quantum Simulation for High-Energy Physics

Christian W. Bauer *et al.*
PRX Quantum **4**, 027001 – Published 3 May 2023

Roadmap | Open Access

Quantum Computing for High-Energy Physics: State of the Art and Challenges

Alberto Di Meglio *et al.*
PRX Quantum **5**, 037001 – Published 5 August 2024

White paper on

Quantum Information Science and Technology for Nuclear Physics

Input into U.S. Long-Range Planning, 2023

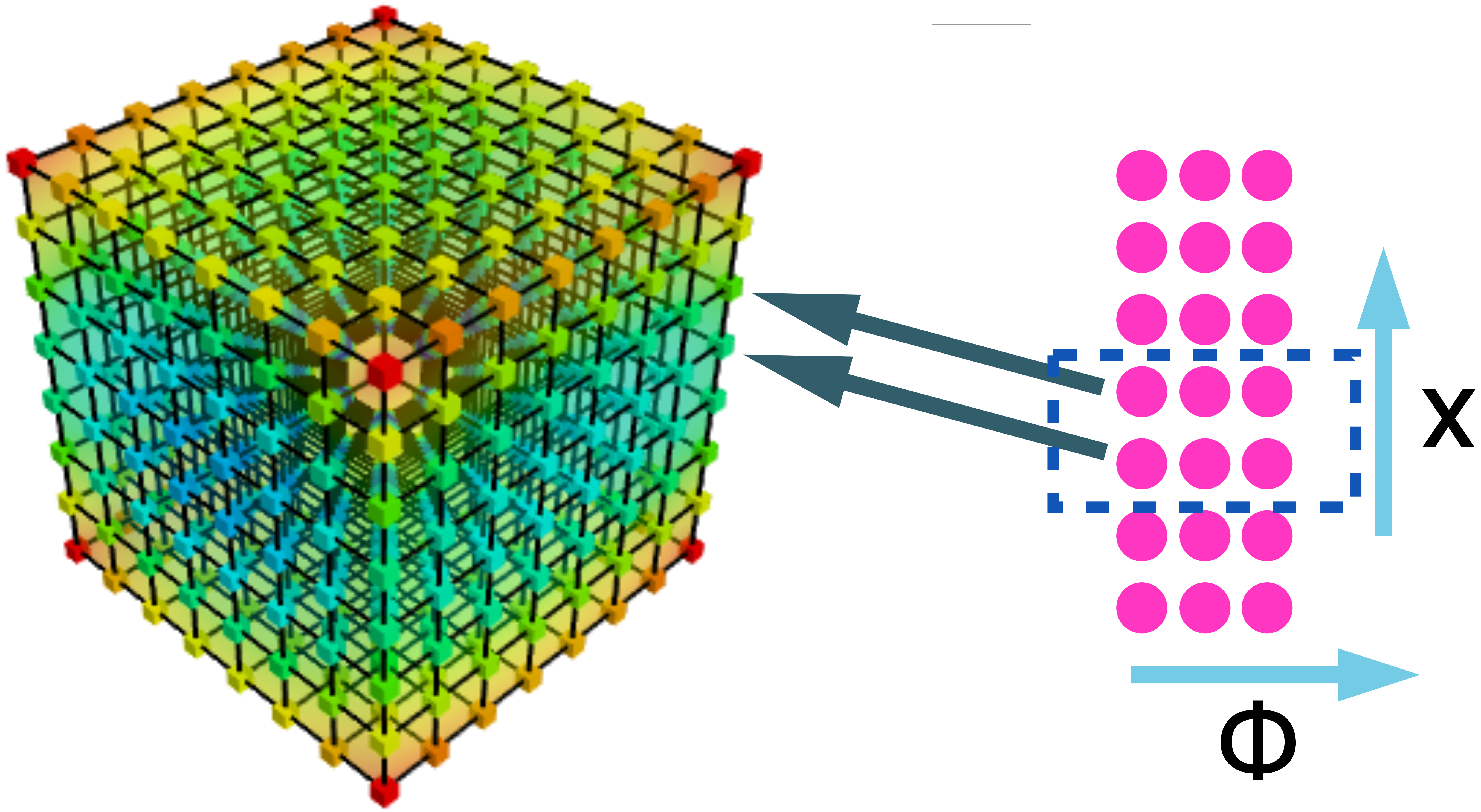
Table of Contents

Real-Time High-Energy Collisions of Matter

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

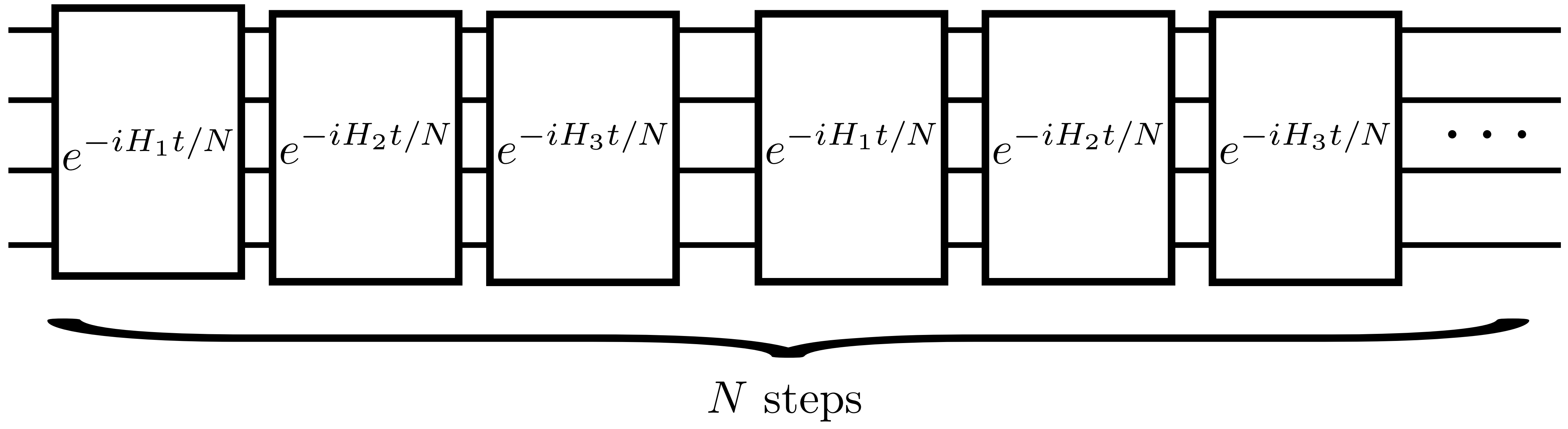
Digital To-Do List for Quantum Chromodynamics

1. **Map quarks and gluons on a quantum register of qubits, qutrits, …**



2. **Develop unitary operators to evolve initial wavefunctions forward in time**

$e^{-iHt} =$



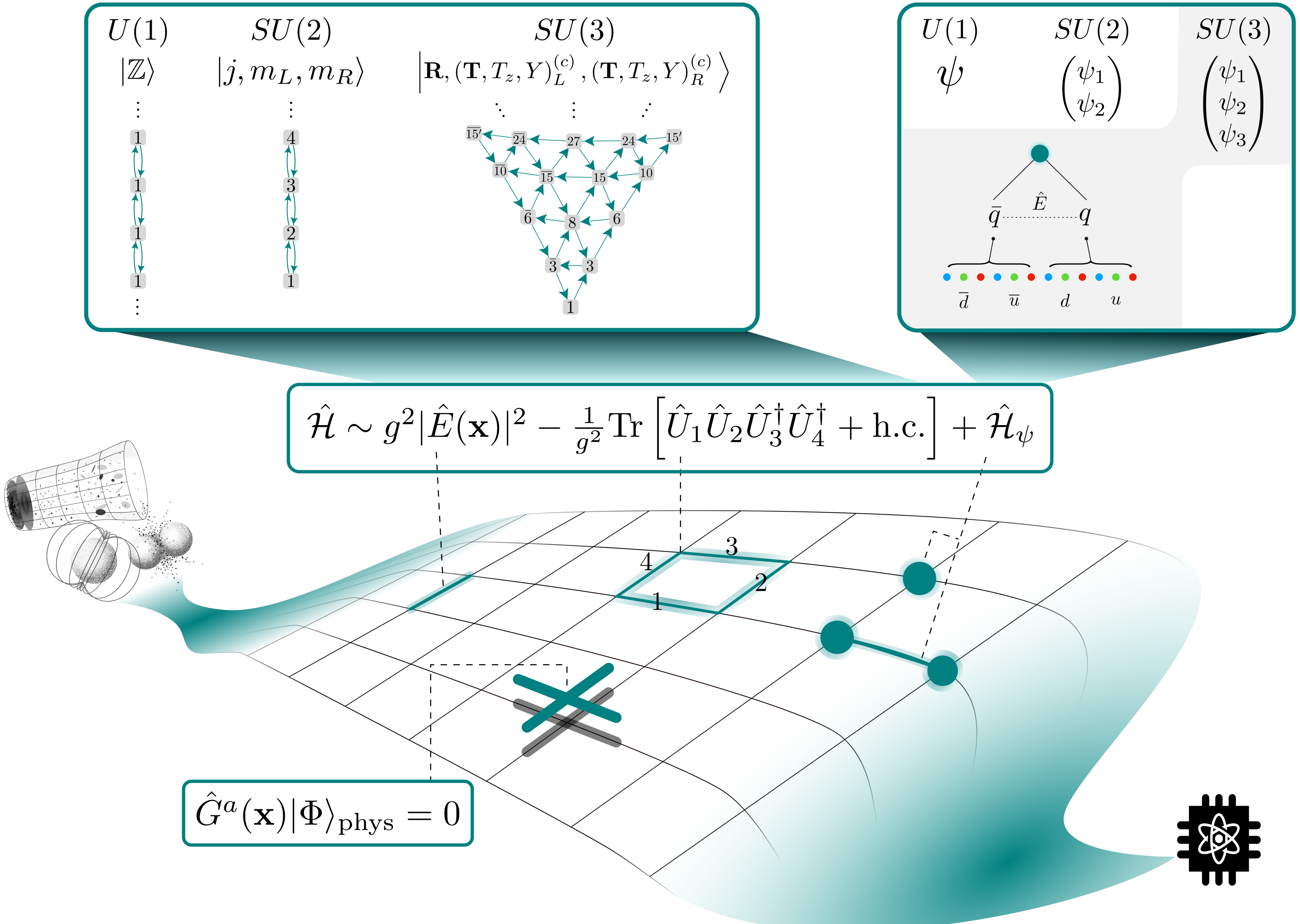
Simulating Lattice Gauge Field Theories

Hamiltonian
Kogut-Susskind
1970's

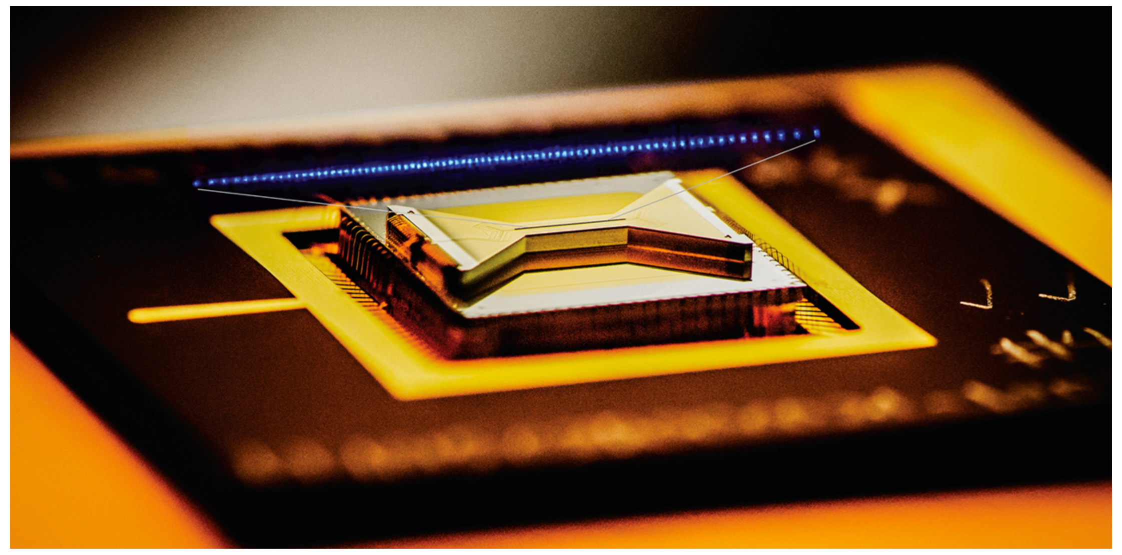
Yang-Mills:
Byrnes-Yamamoto
2005

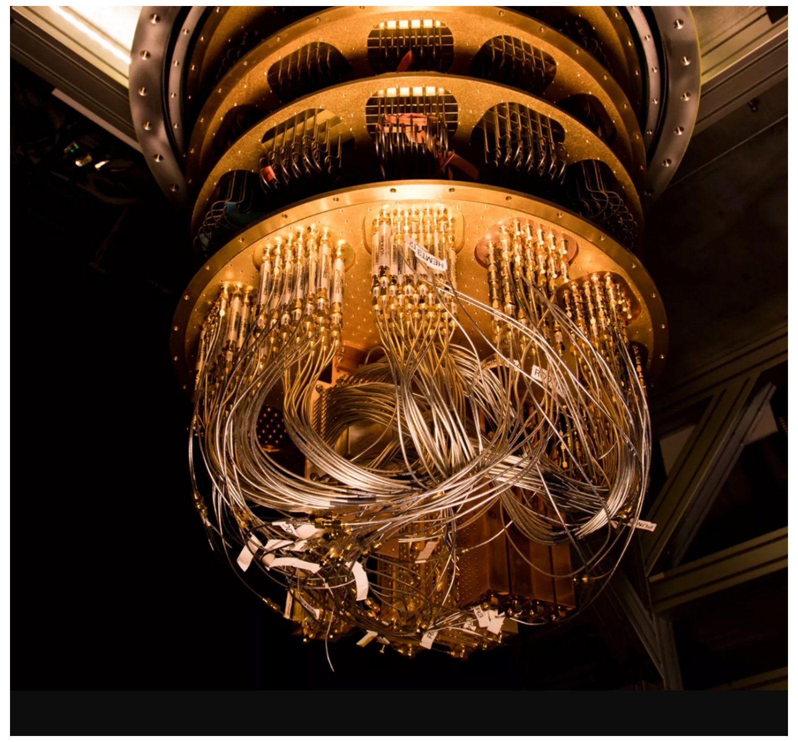
SU(N):
Zohar et al
(2013)

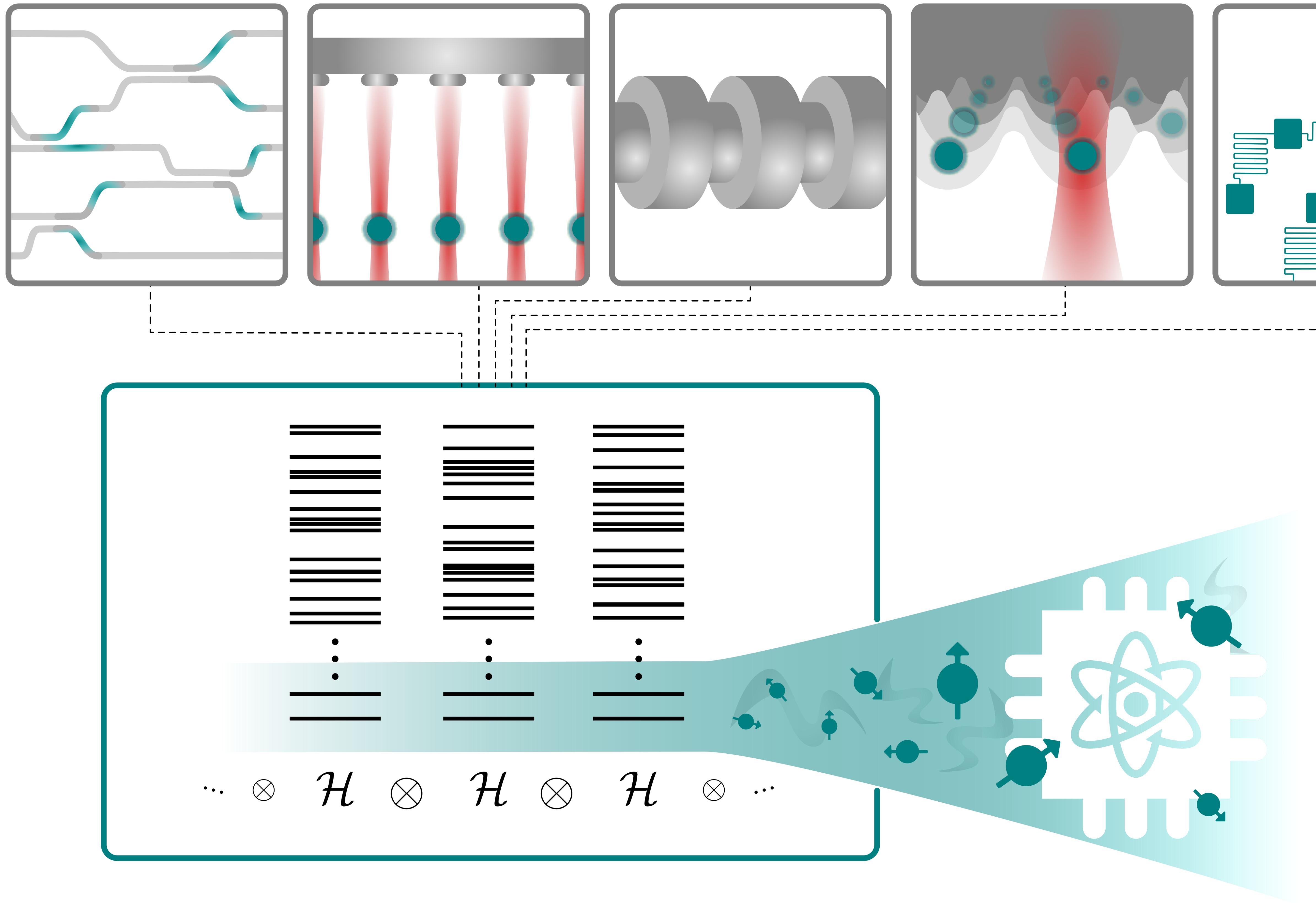
QLM
Banerjee et al
Tagliacozzo et al
(2013)

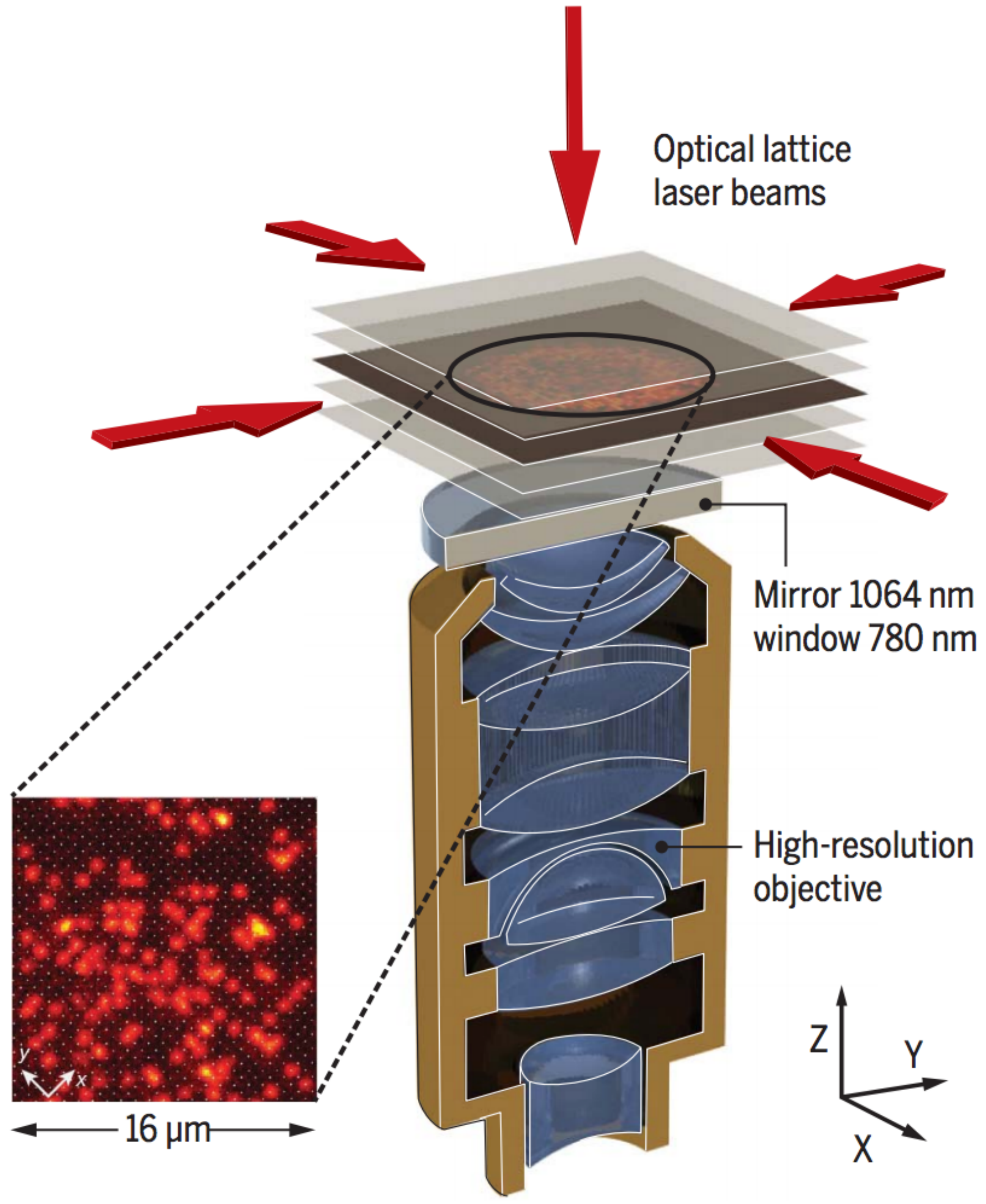


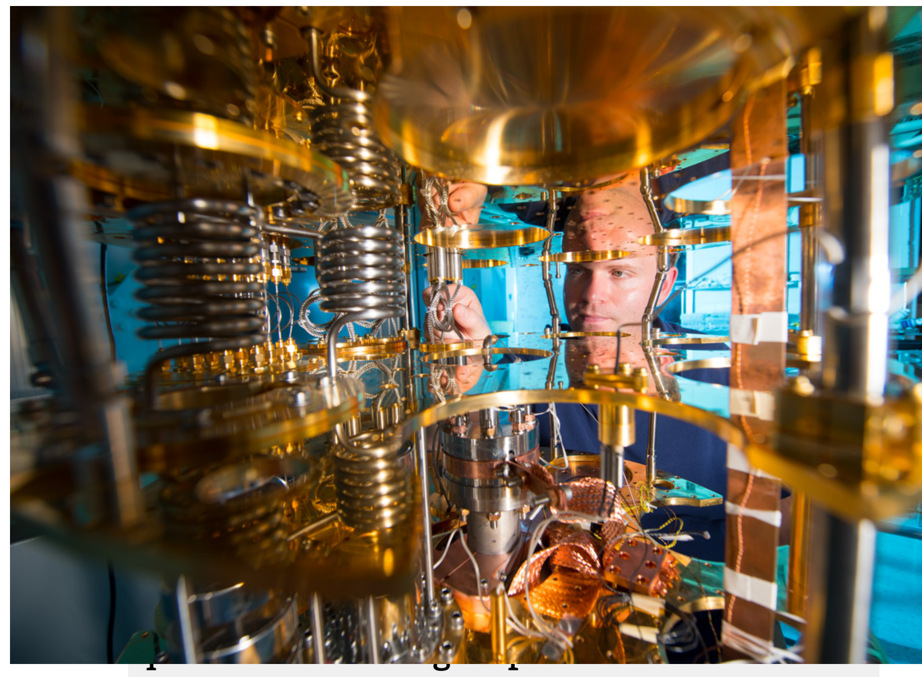
Encoding Systems in Multi-Hilbert Spaces Embedded in Large HPC systems

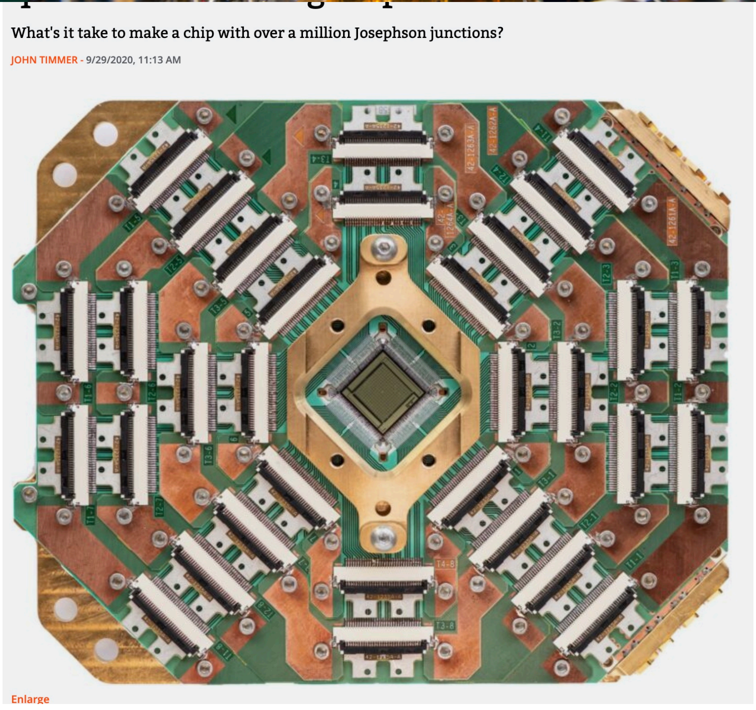












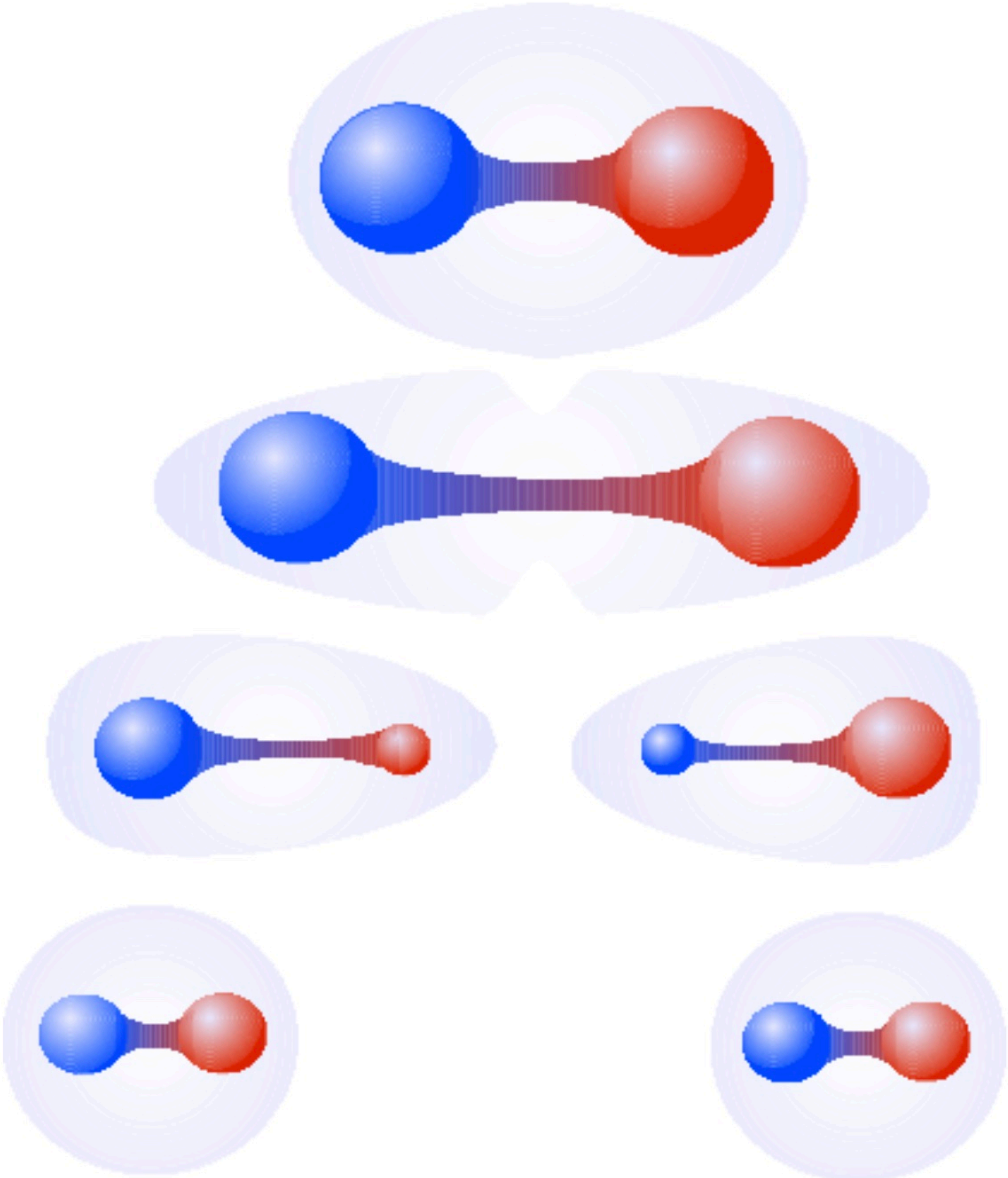
Map scalar, fermion and vector systems

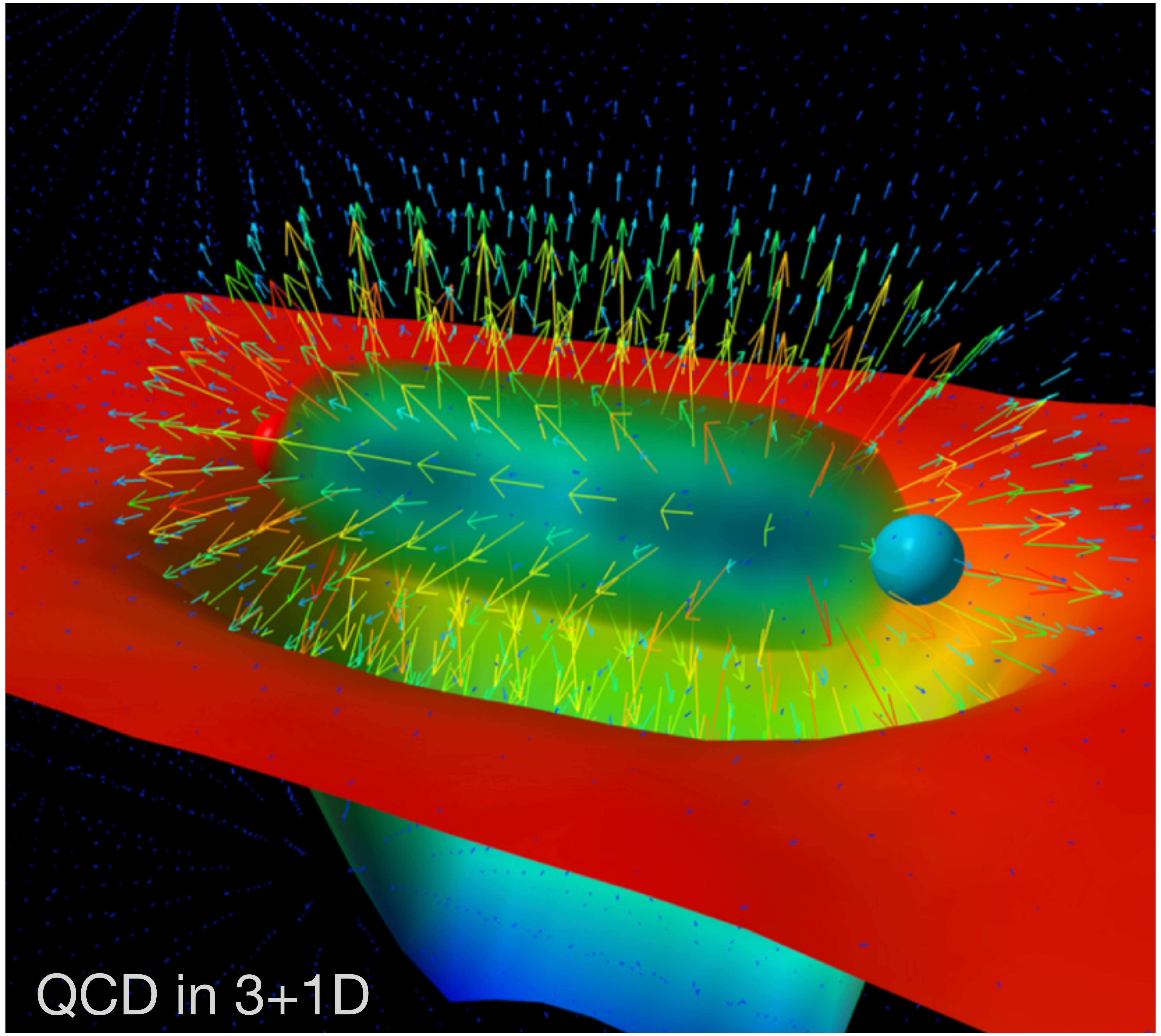
Optimize for target observables - Physics Aware

Human-intensive exploration

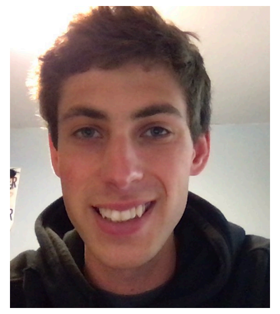
Low-Dimensional Models:

e.g., Quantum Electromagnetism in 1 Space and 1 Time Dimensions





This model is being used by several groups pursuing quantum simulations



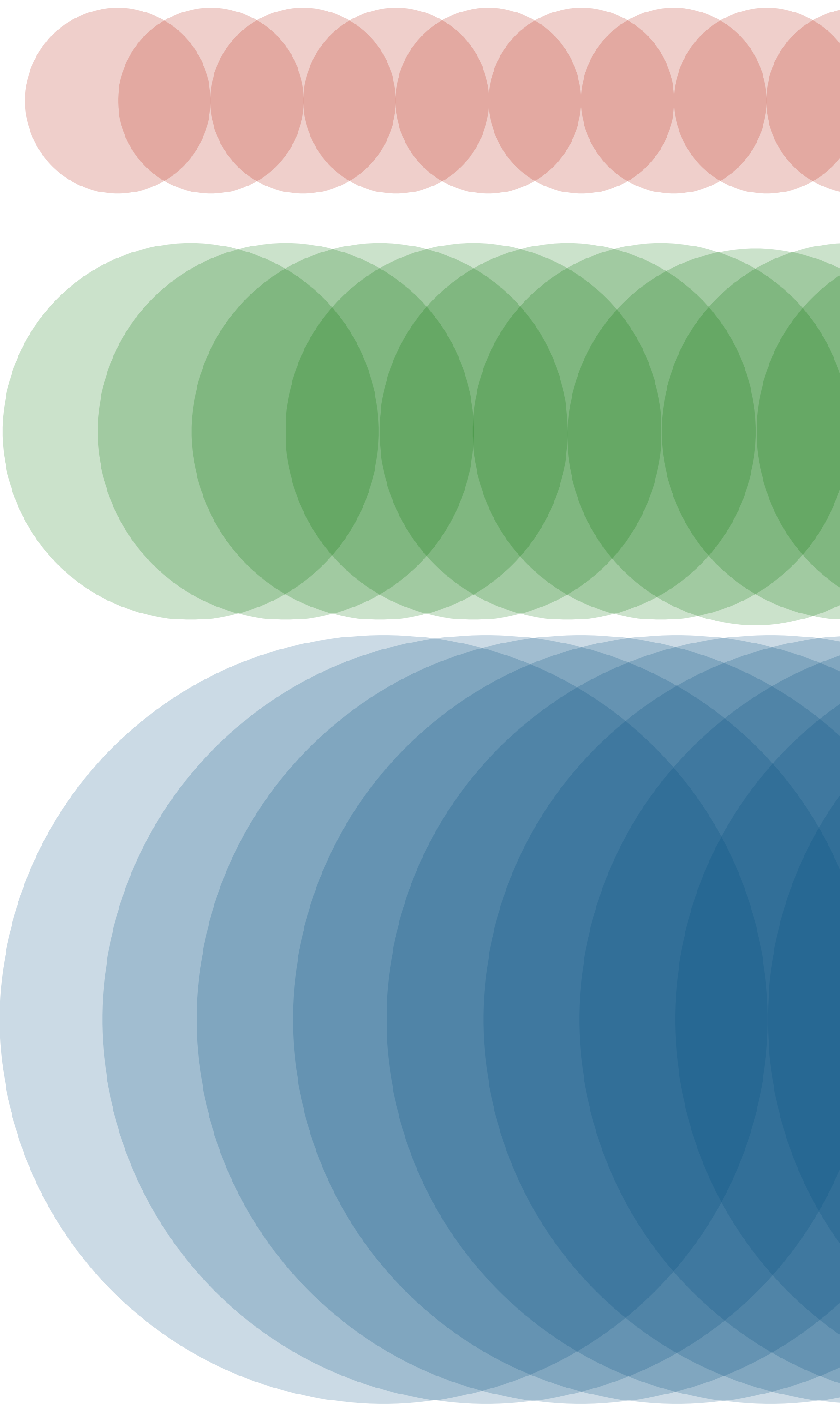
Confinement and Scalable Circuits

(2023-)

Roland Farrell, Marc Illa,
Anthony Ciavarella and MJS

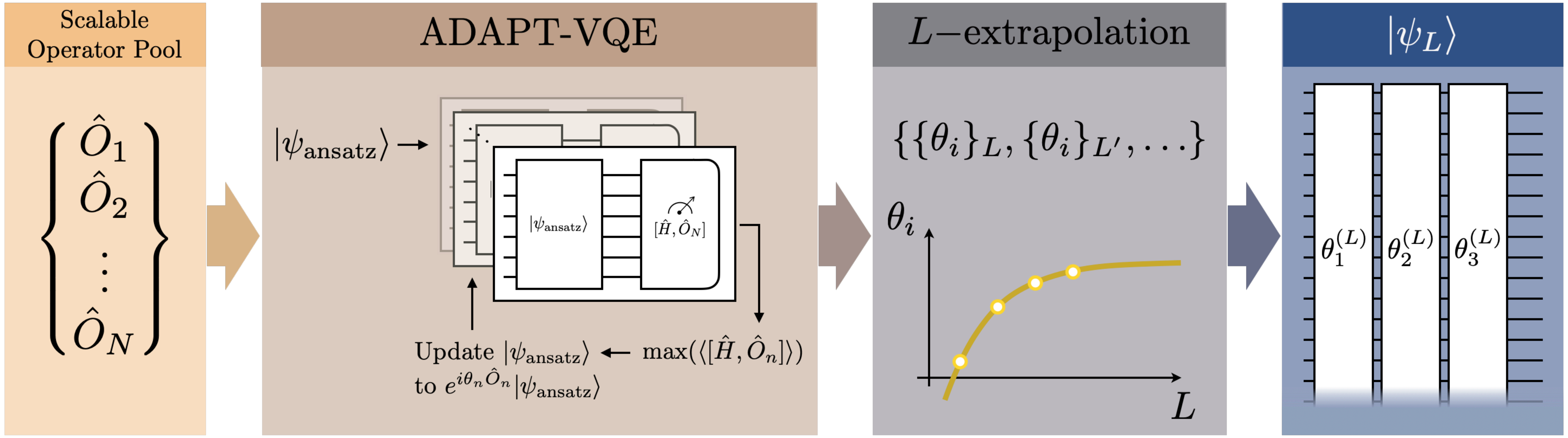
$$\hat{H} = \hat{H}_m + \hat{H}_{kin} + \hat{H}_{el} = \frac{m}{2}\sum_{j=0}^{2L-1}\left[(-1)^j\hat{Z}_j + \hat{I}\right] + \frac{1}{2}\sum_{j=0}^{2L-2}\left(\hat{\sigma}_j^+\hat{\sigma}_{j+1}^- + \text{h.c.}\right) + \frac{g^2}{2}\sum_{j=0}^{2L-2}\left(\sum_{k\leq j}\hat{Q}_k\right)^2$$

Local — Nearest Neighbor — Non-local



Symmetries and Confinement

Classical Extrapolations



Classical Optimization

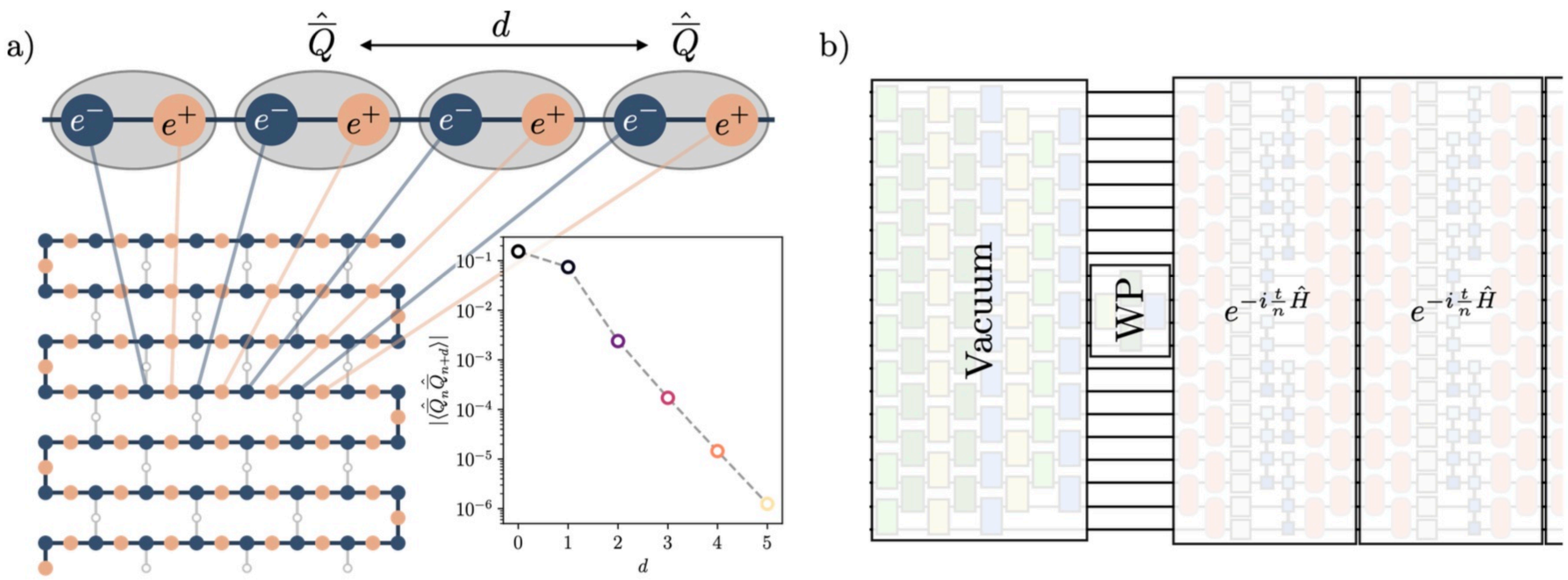
Quantum Implementation

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

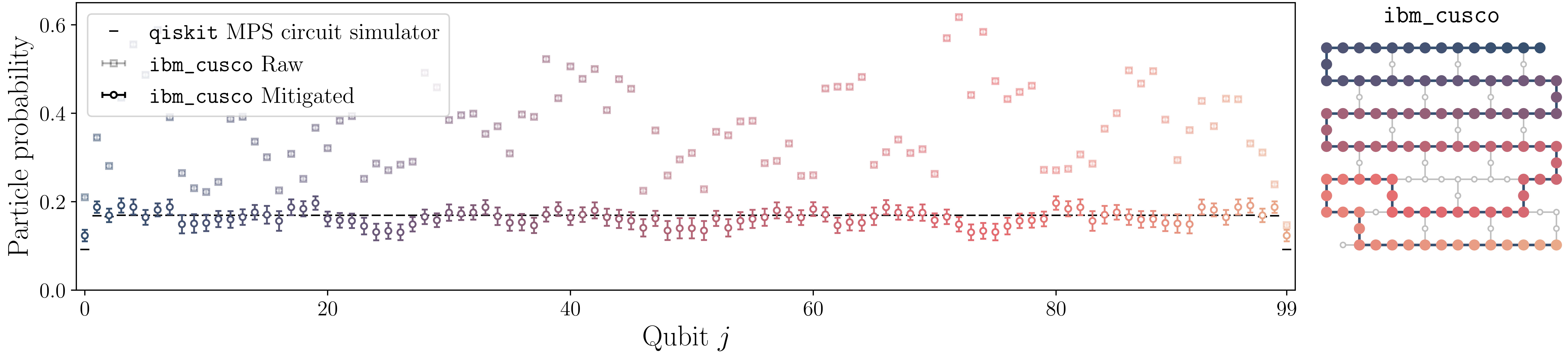
Quantum simulations of hadron dynamics in the Schwinger model using 112 qubits
Roland C. Farrell, Marc Illa, Anthony N. Ciavarella, and Martin J. Savage
Phys. Rev. D **109**, 114510 – Published 10 June 2024

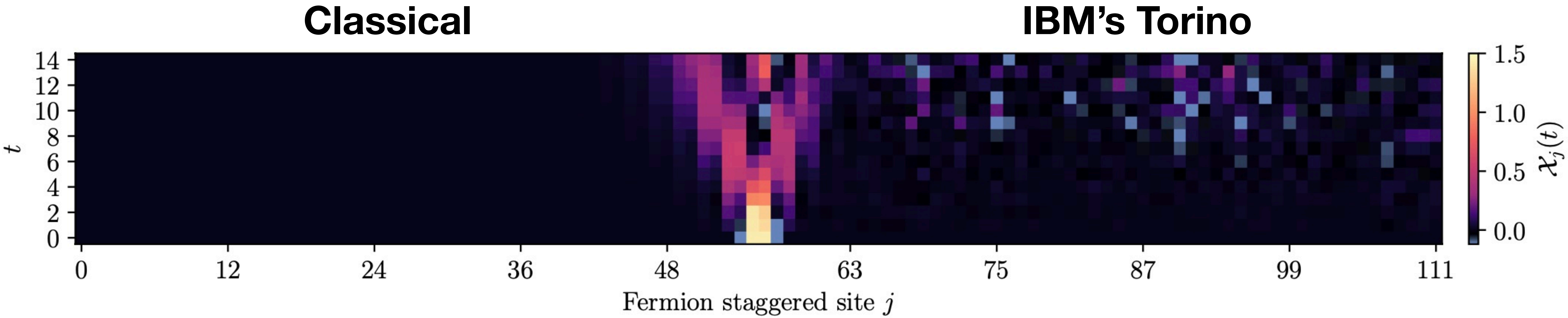
Builds upon ADAPT-VQE
by Sophia Economou *et al.*

The Schwinger Model on IBM PCs



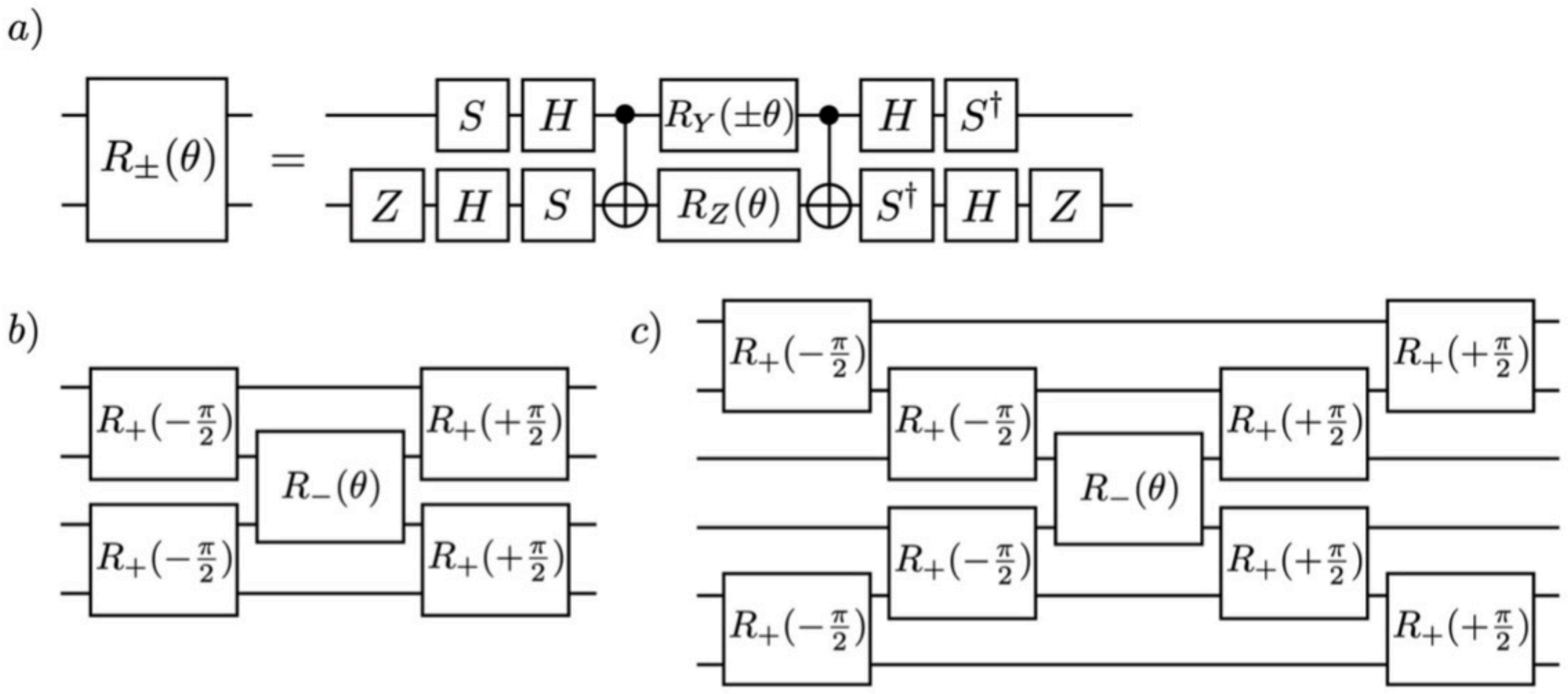
The Vacuum and Wavepacket Evolution

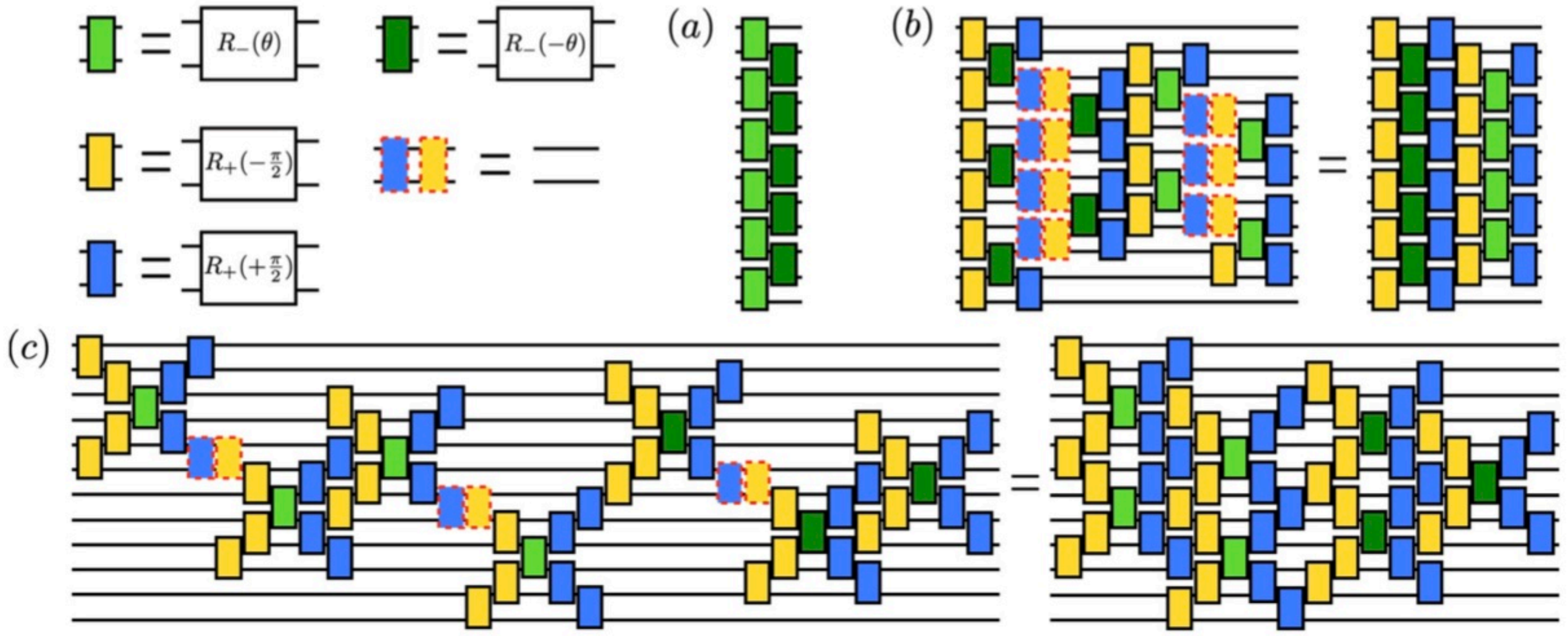


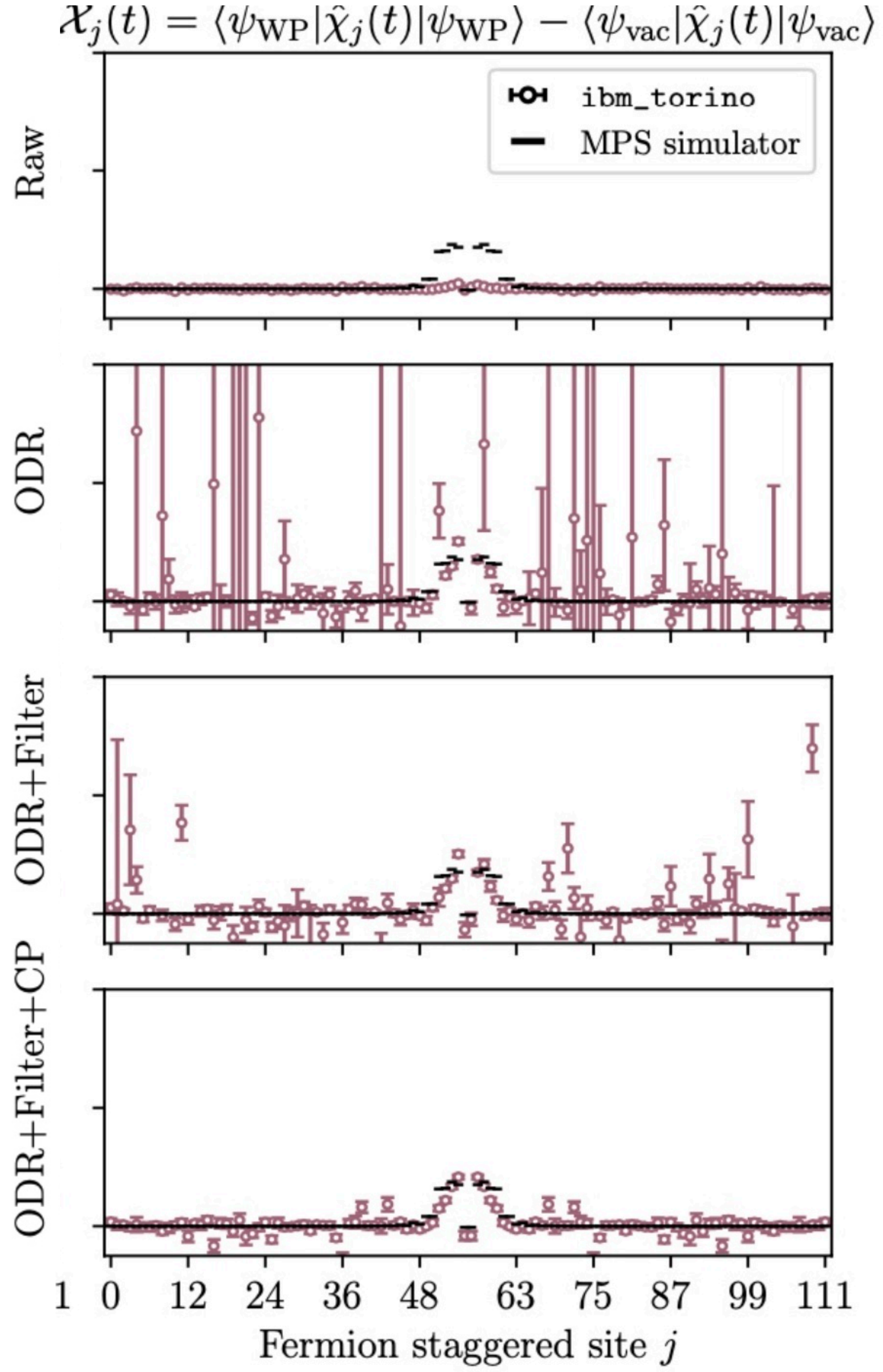


Production using IBM's QPU Torino

(The largest quantum simulation that had been performed)



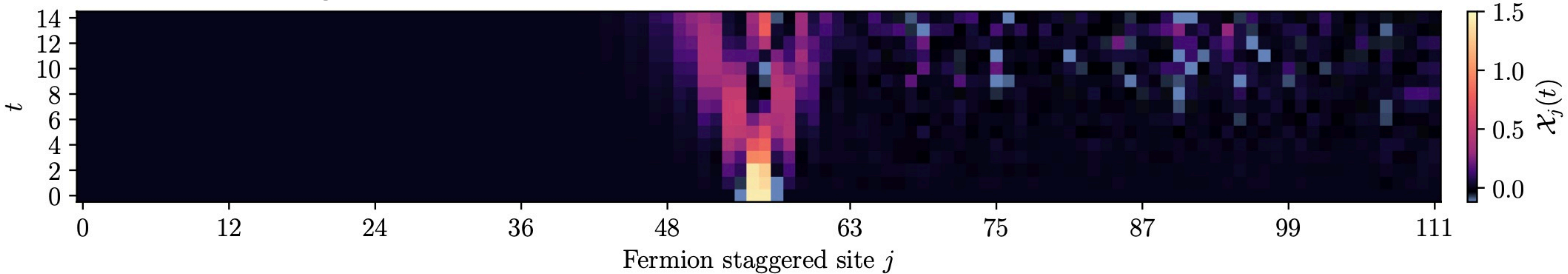




Production highlights

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

Classical **IBM's Torino**



Decoherence Renormalization

Mitigating Depolarizing Noise on Quantum Computers with Noise-Estimation Circuits

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

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

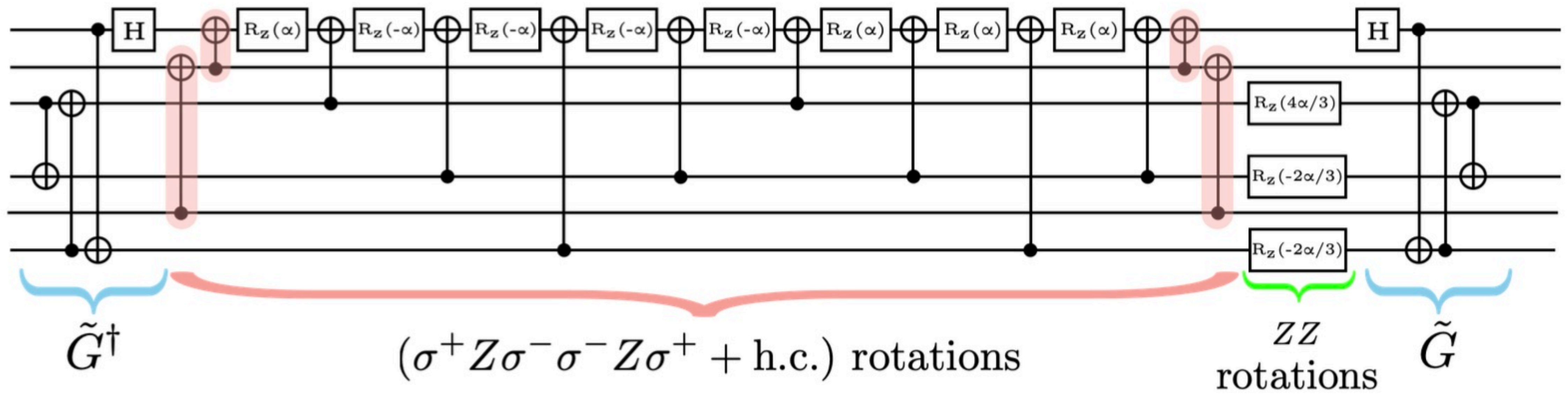
Sarmed A Rahman, Randy Lewis, Emanuele Mendicelli, and Sarah Powell
Department of Physics and Astronomy, York University, Toronto, Ontario, Canada, M3J 1P3

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

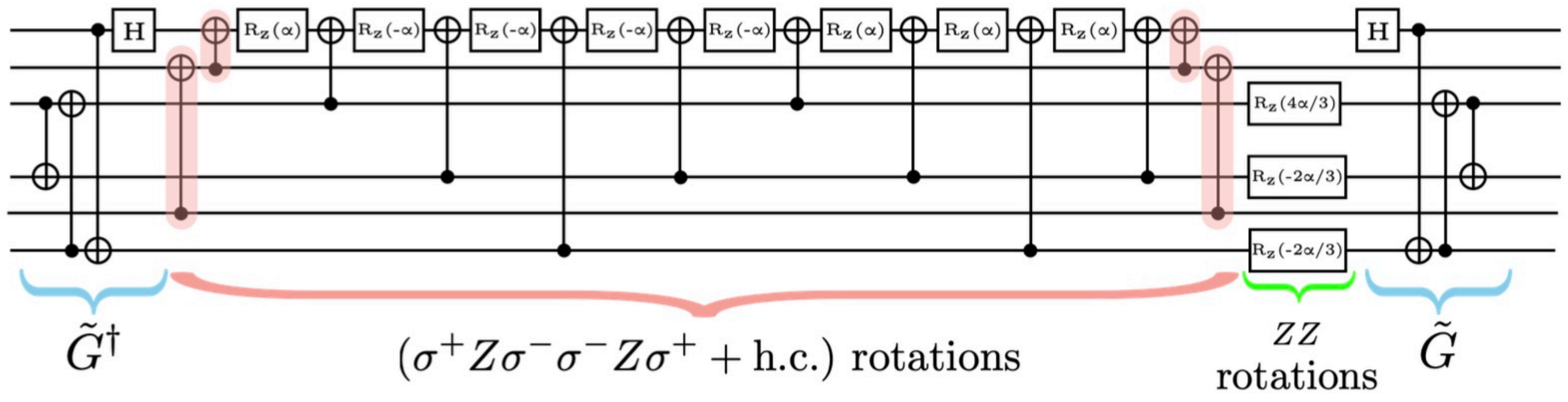
The device is approaching a classical, depolarized set of qubits as time goes by.

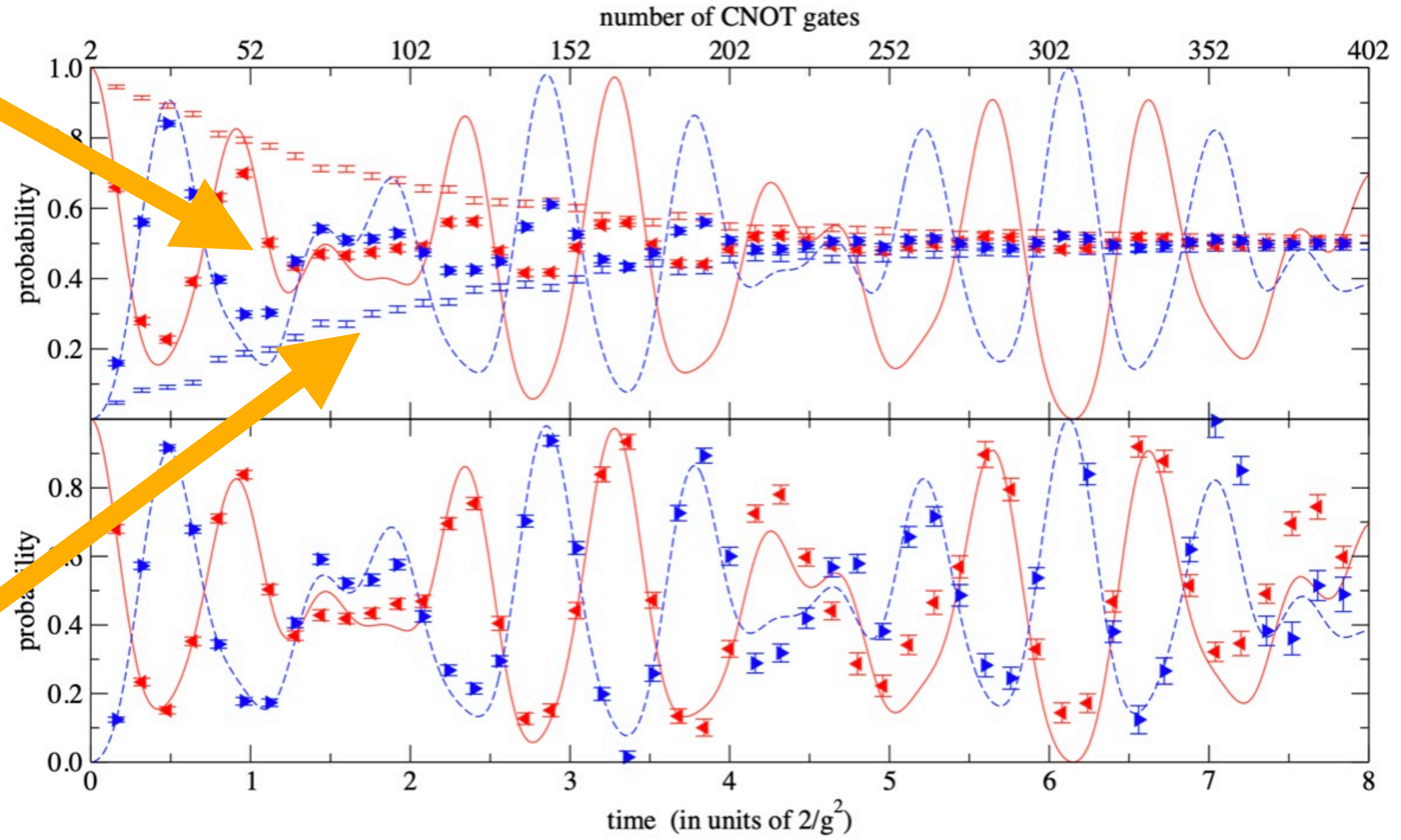
Mitigation methods are essential and effective

"Physics circuit"



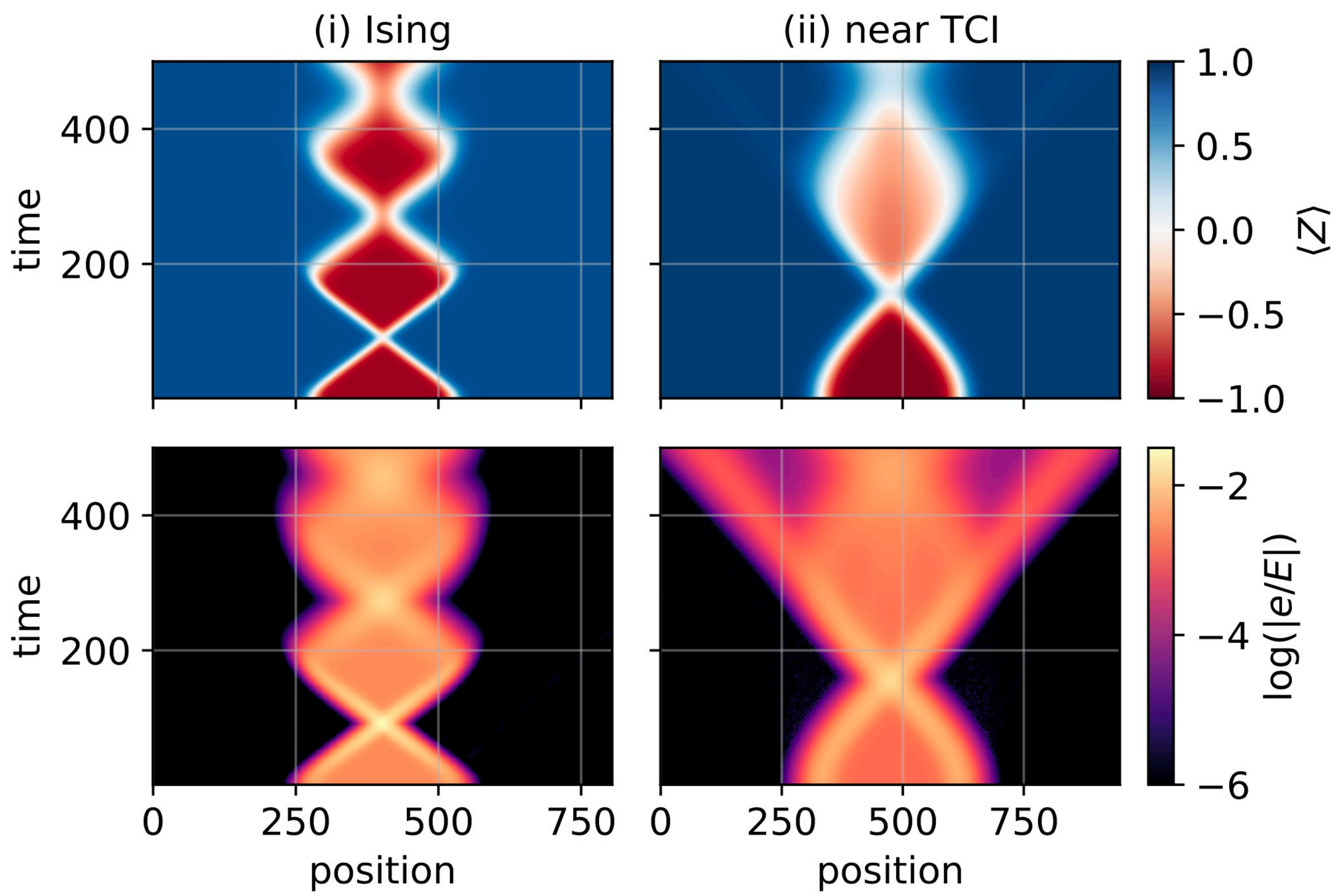
"Mitigation circuit" - all angles set to zero (e.g.)

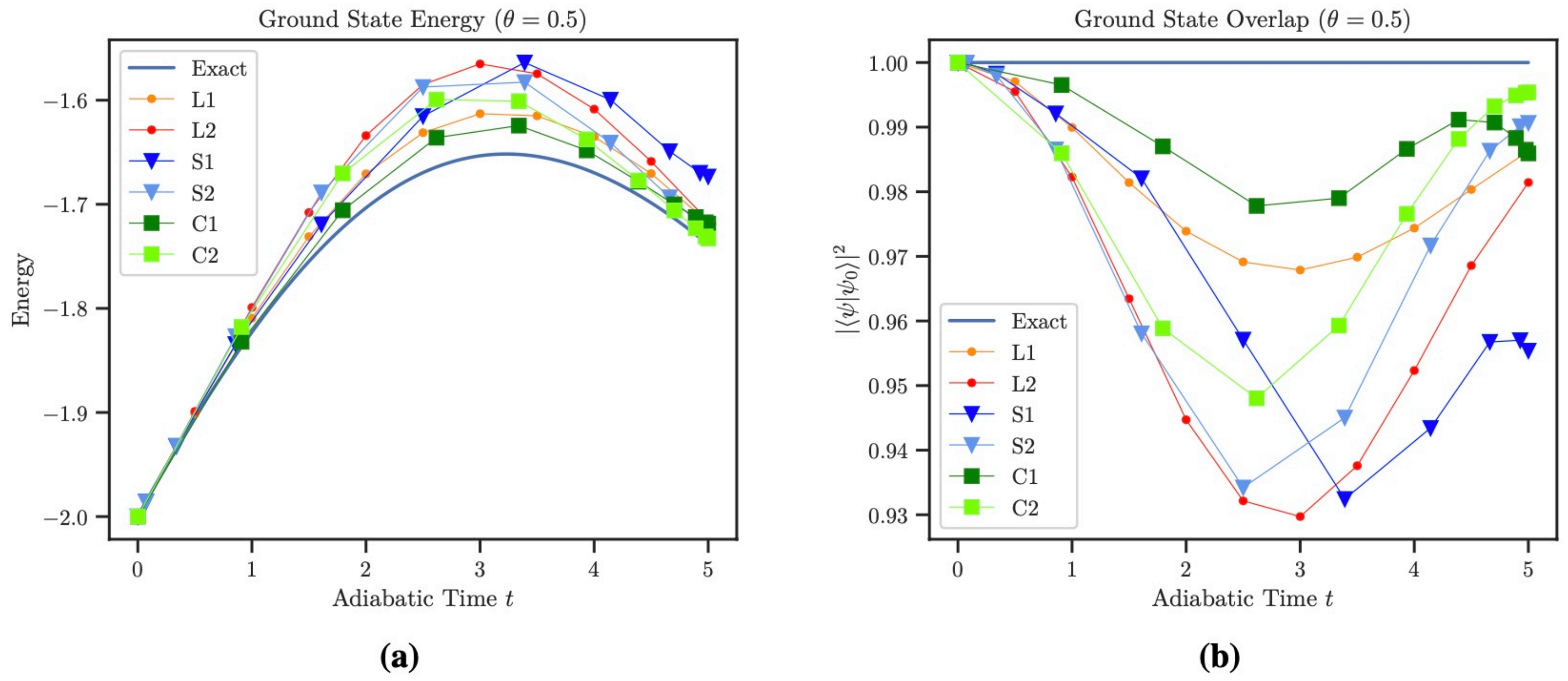




1+1D Preparations

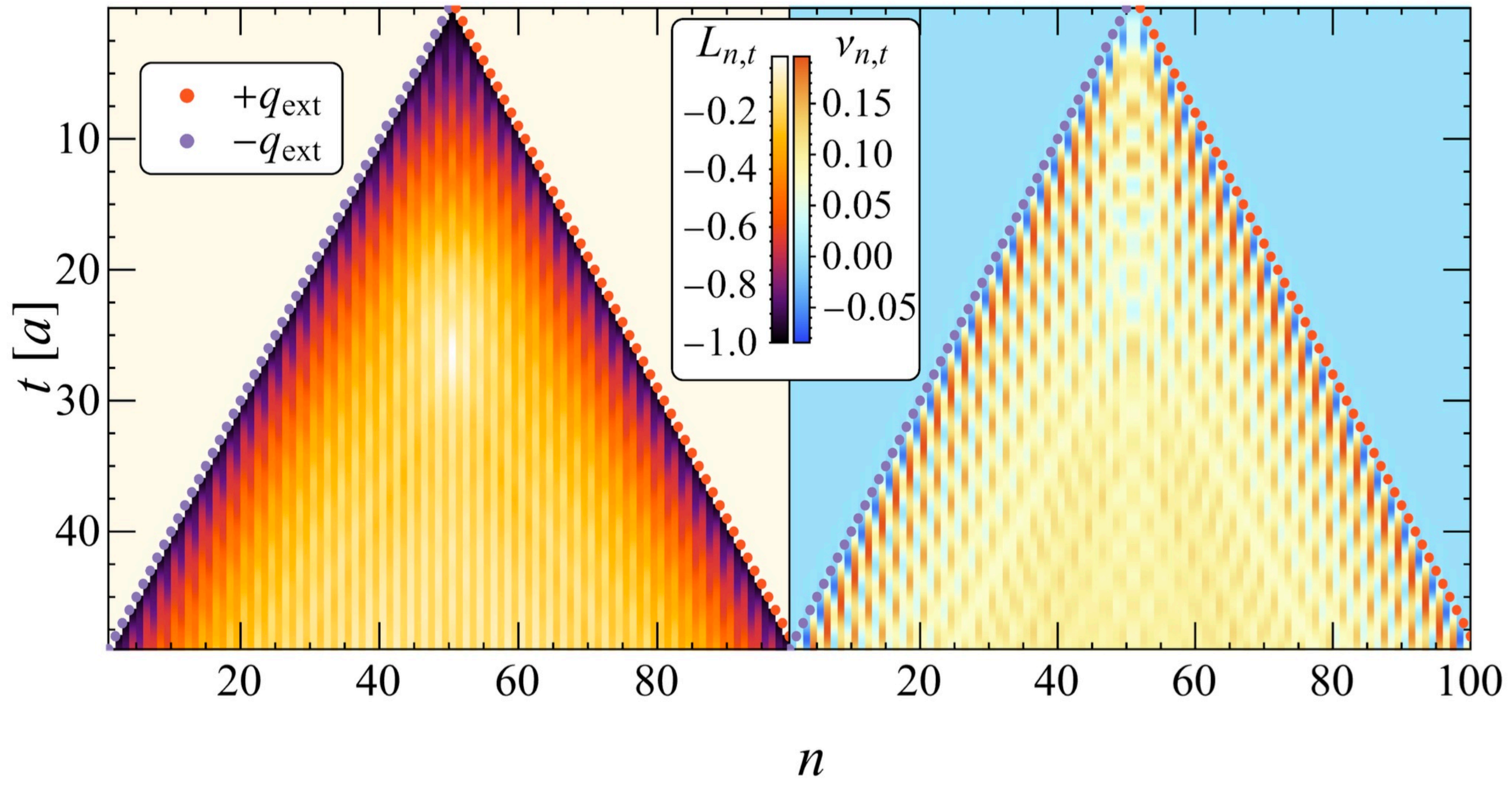
Ising+ , Milsted et al



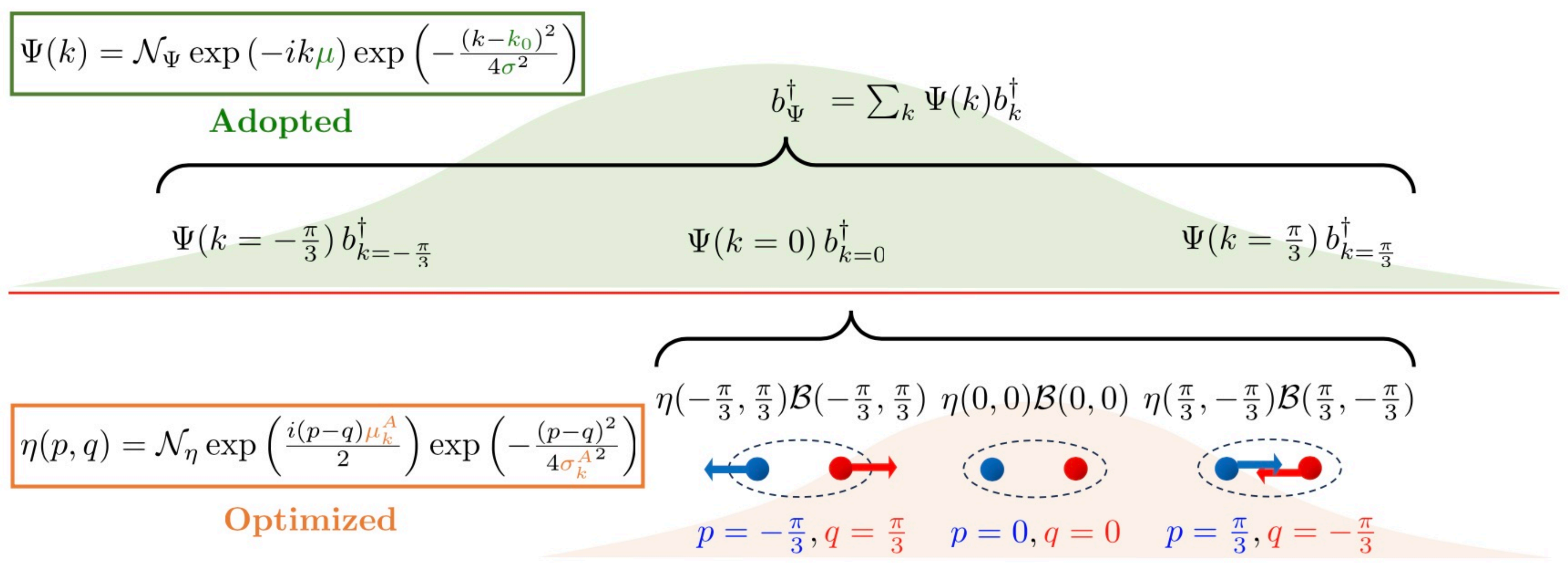


QAOA, Rodeo , Pederiva et al

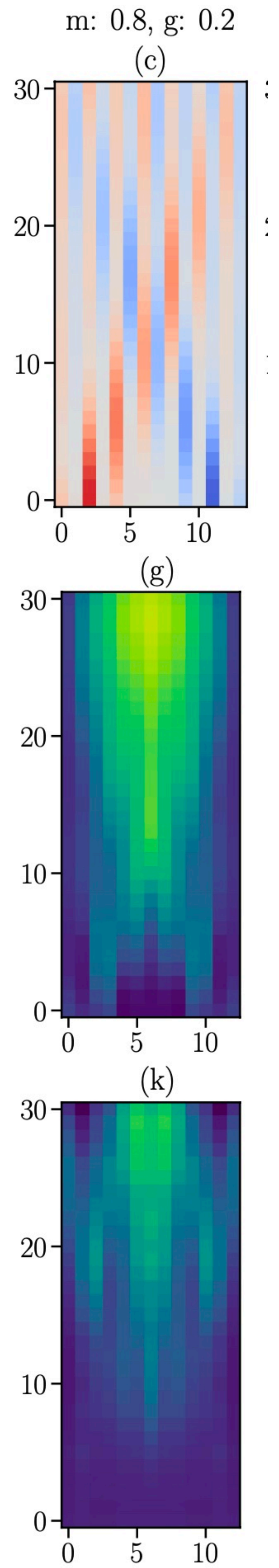
Hadronization , Florio et al



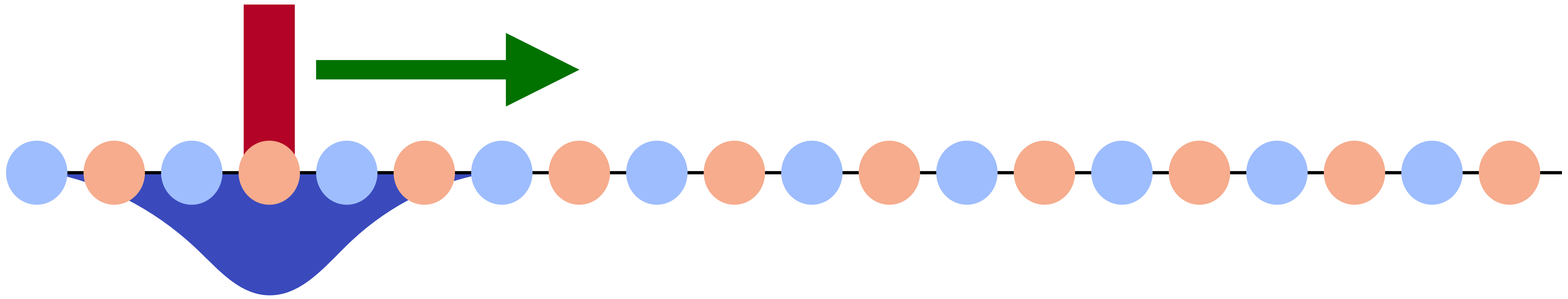
Wavepackets , Davoudi et al

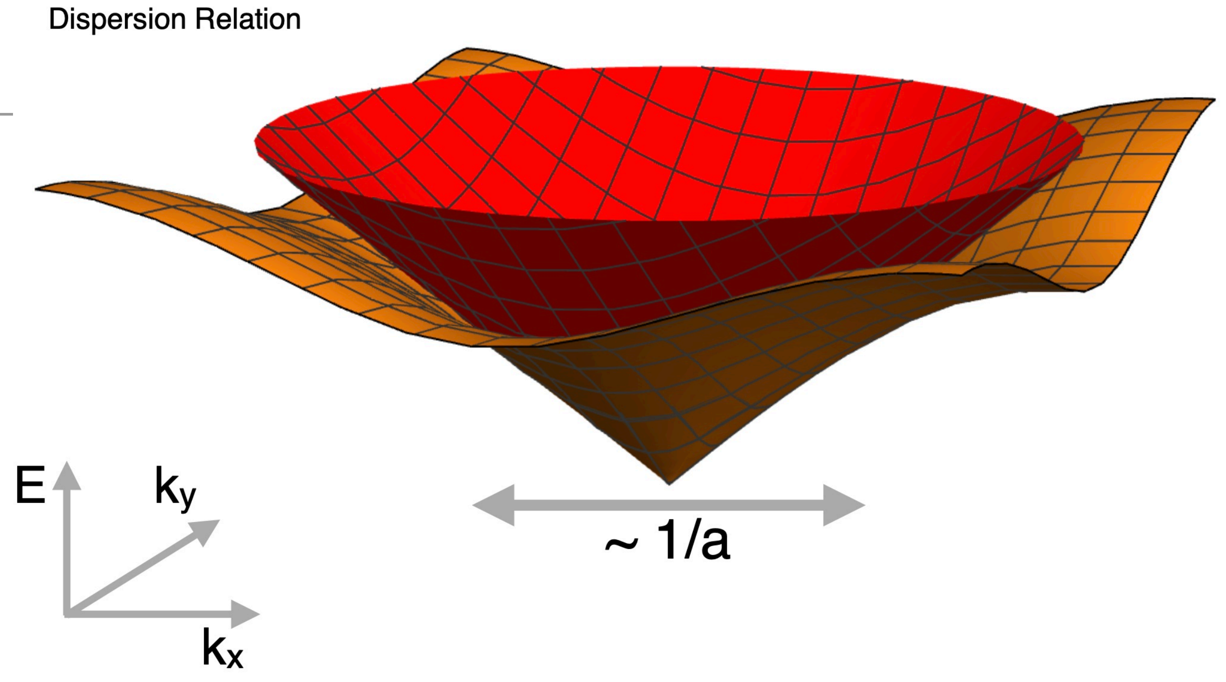


Thirring , Chai et al

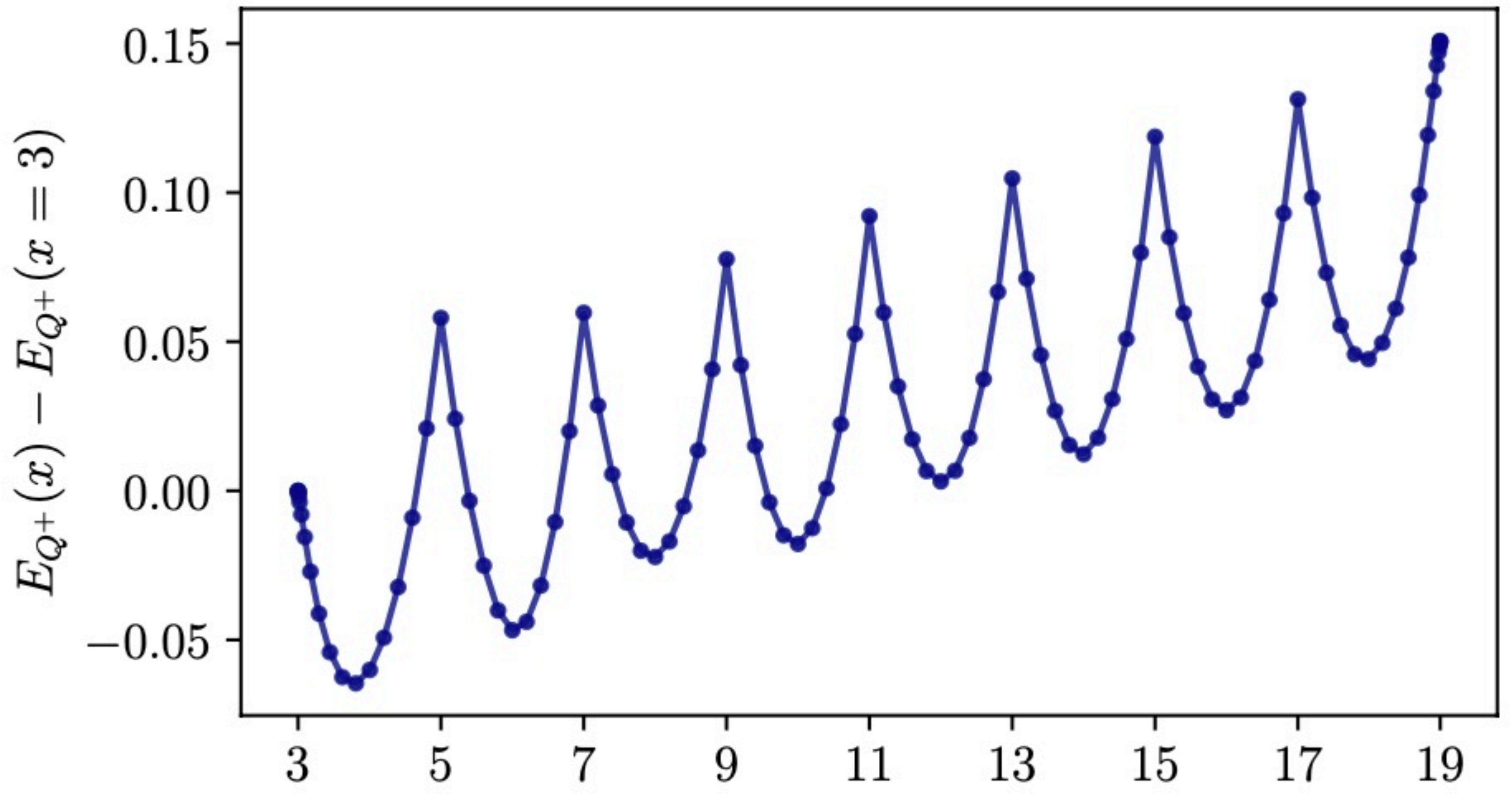


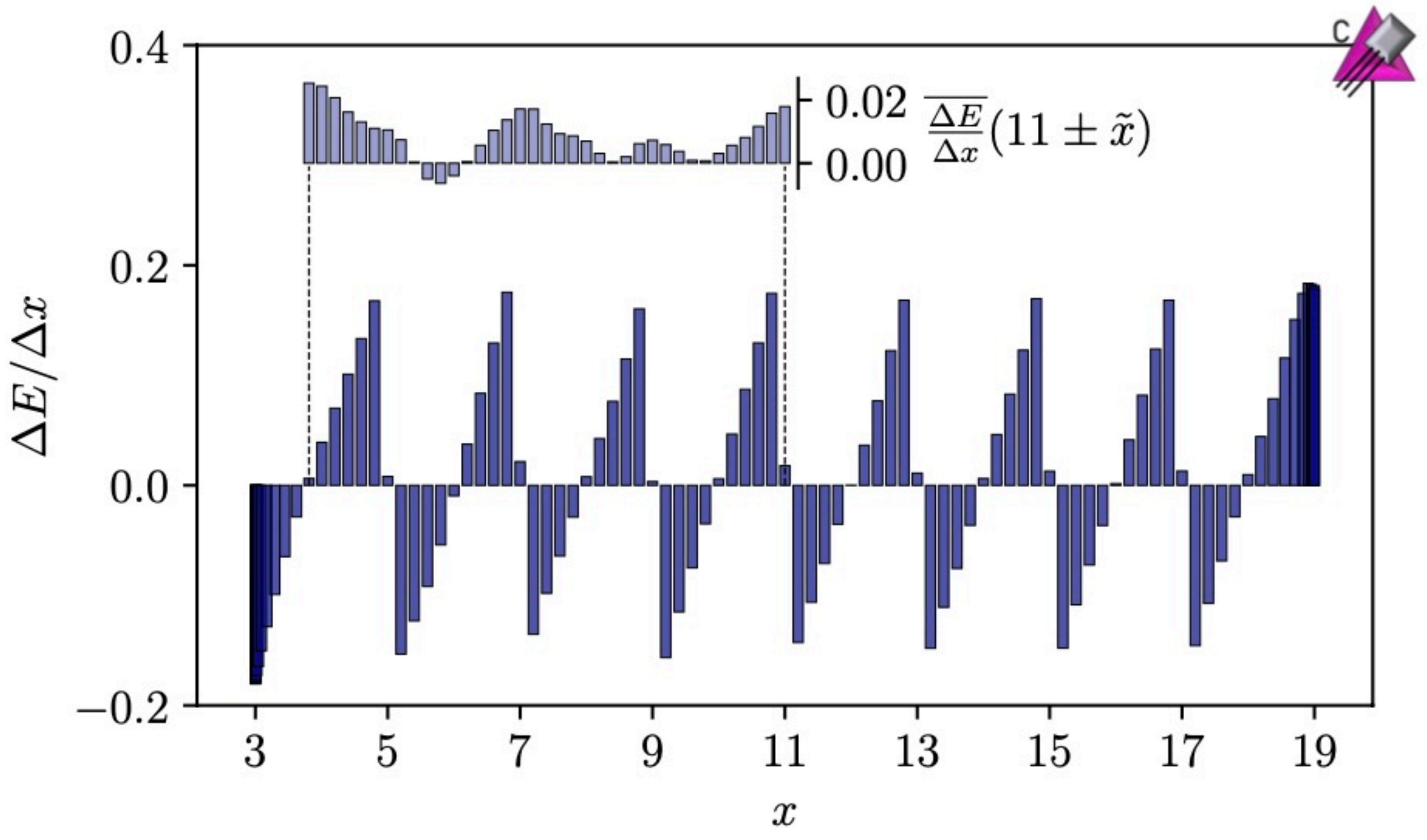
Lorentz Violation by Lattice Spacing

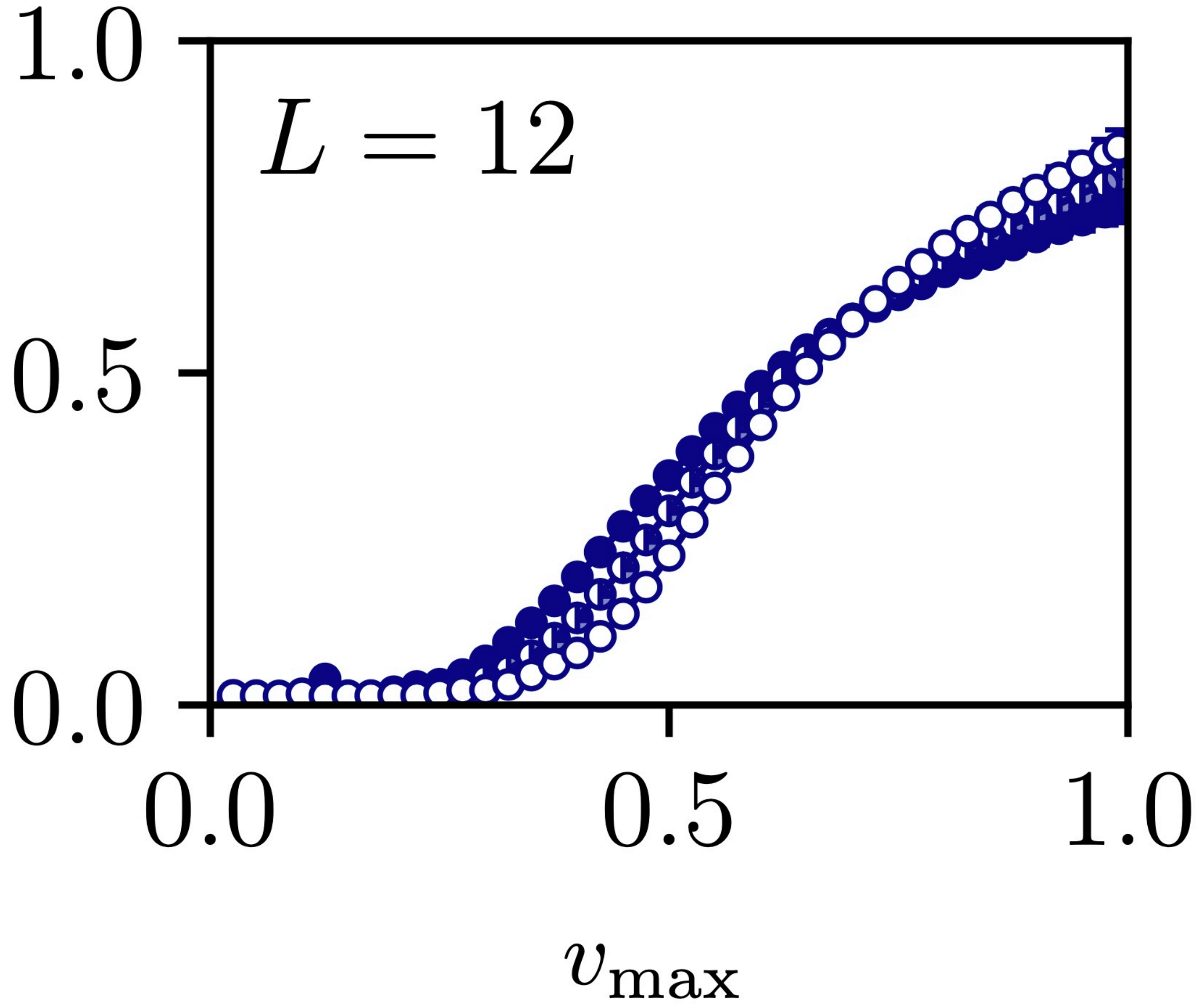




- Lorentz invariance dictates energy conservation at fixed velocity in vacuum
- Energy loss into the light degrees of freedom is
  - a lattice spacing artifact
  - creating hadrons with some probability on top of the vacuum - useful but not physics





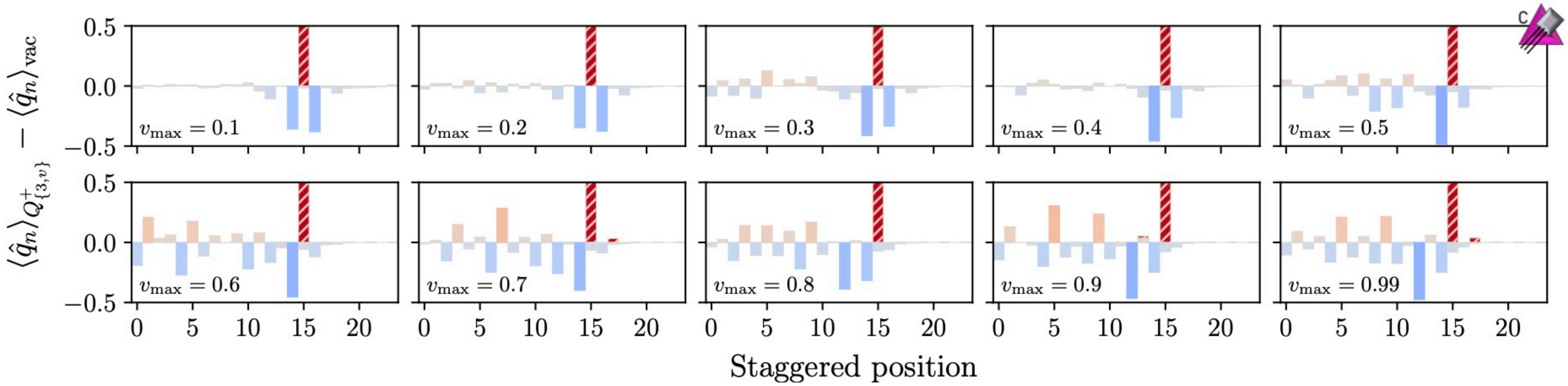


[Submitted on 10 May 2024]

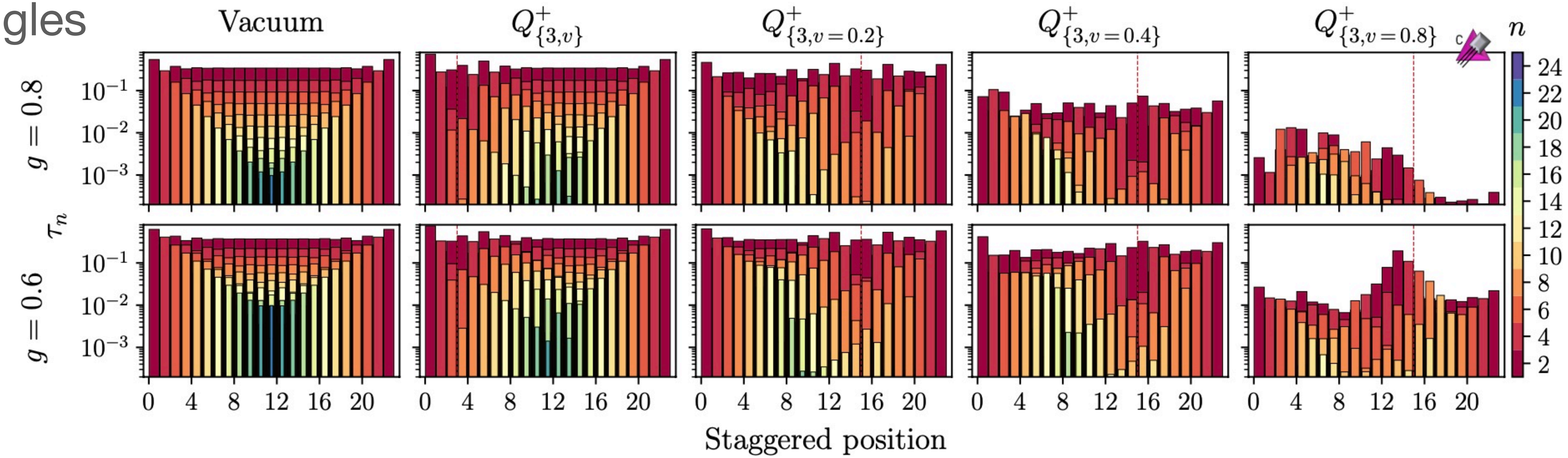
Steps Toward Quantum Simulations of Hadronization and Energy-Loss in Dense Matter

Roland C. Farrell, Marc Illa, Martin J. Savage

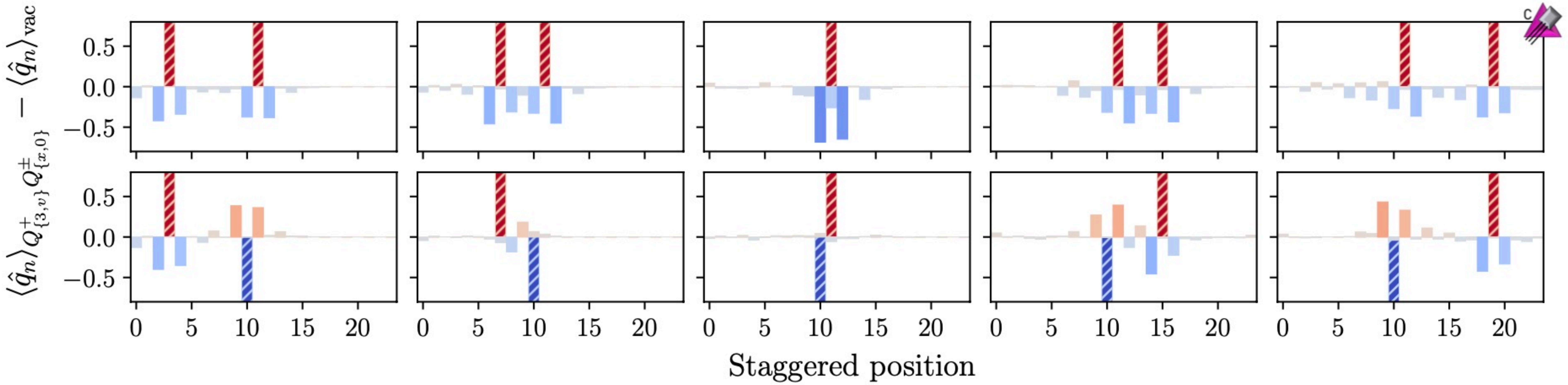
Lorentz Violation by the Lattice Spacing

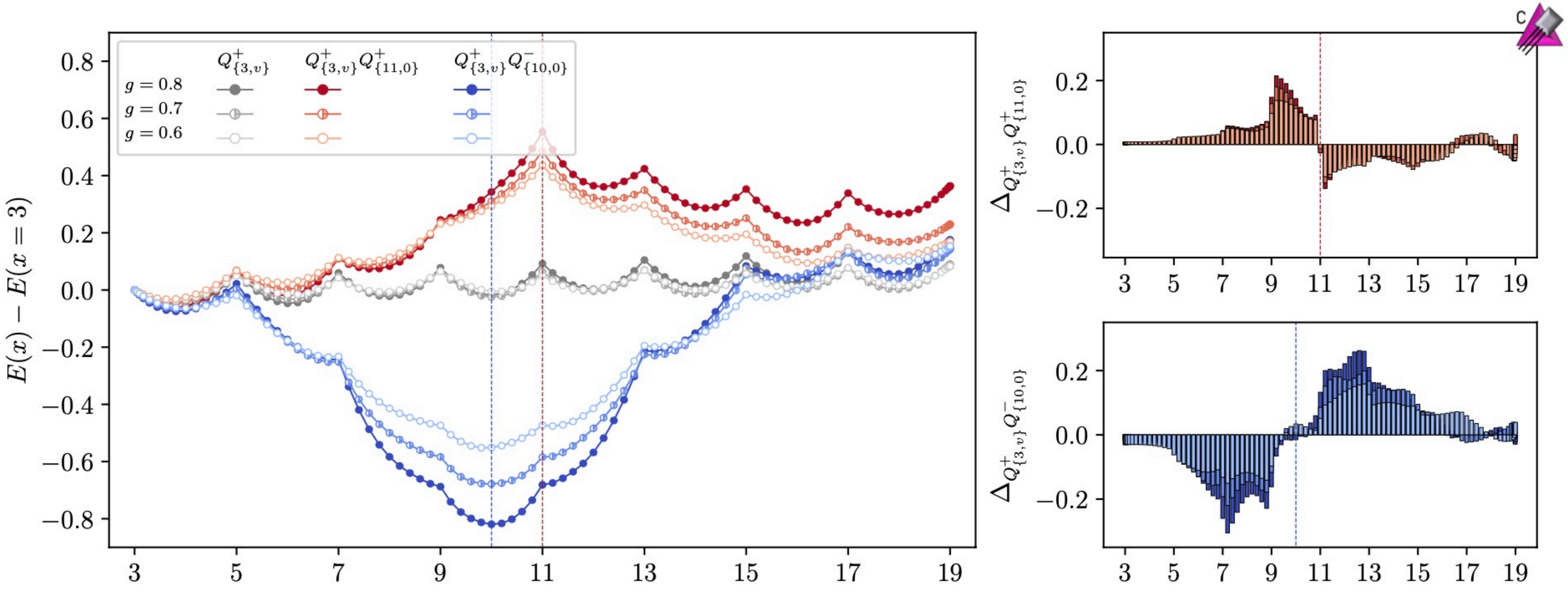


N-tangles

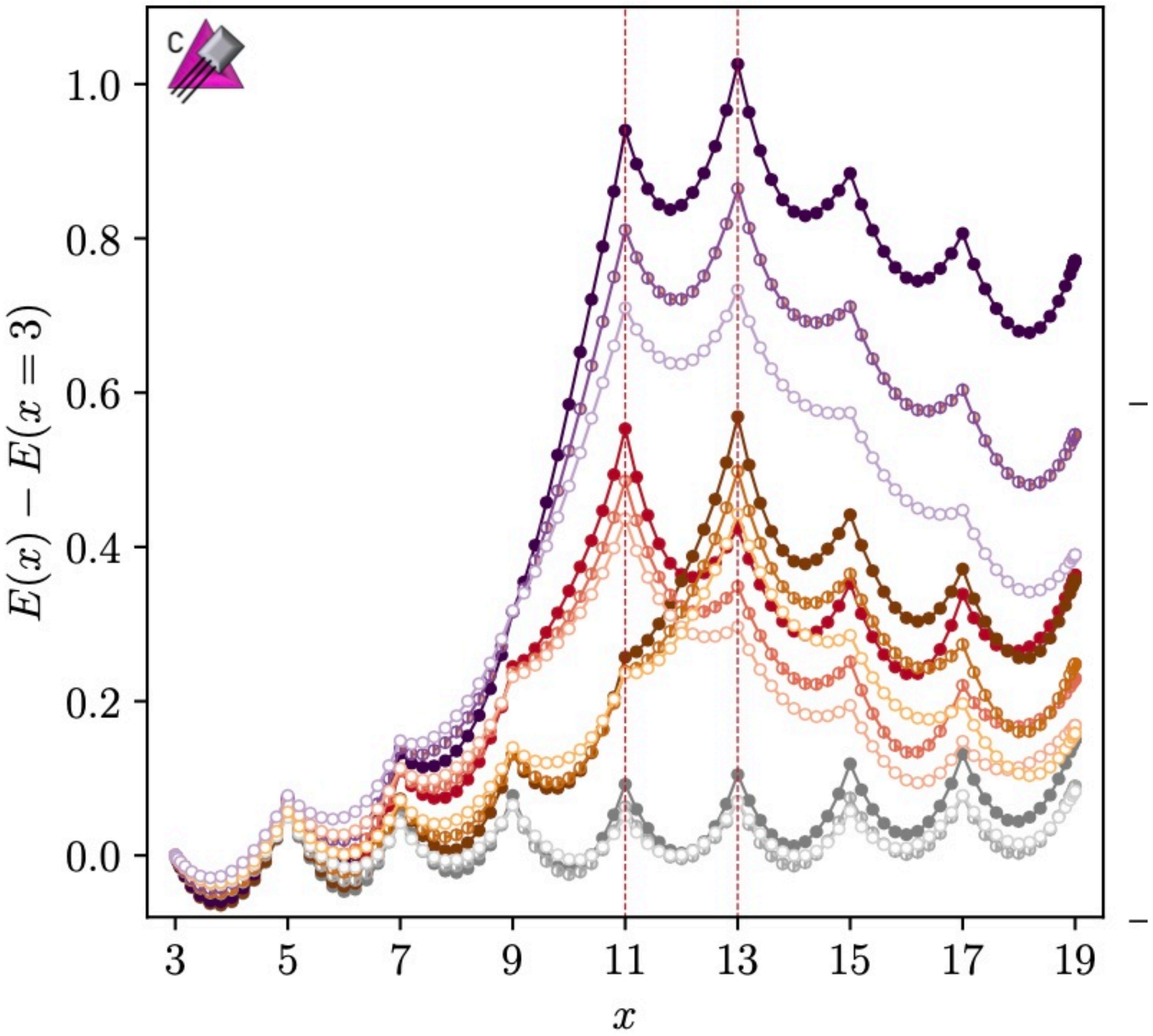


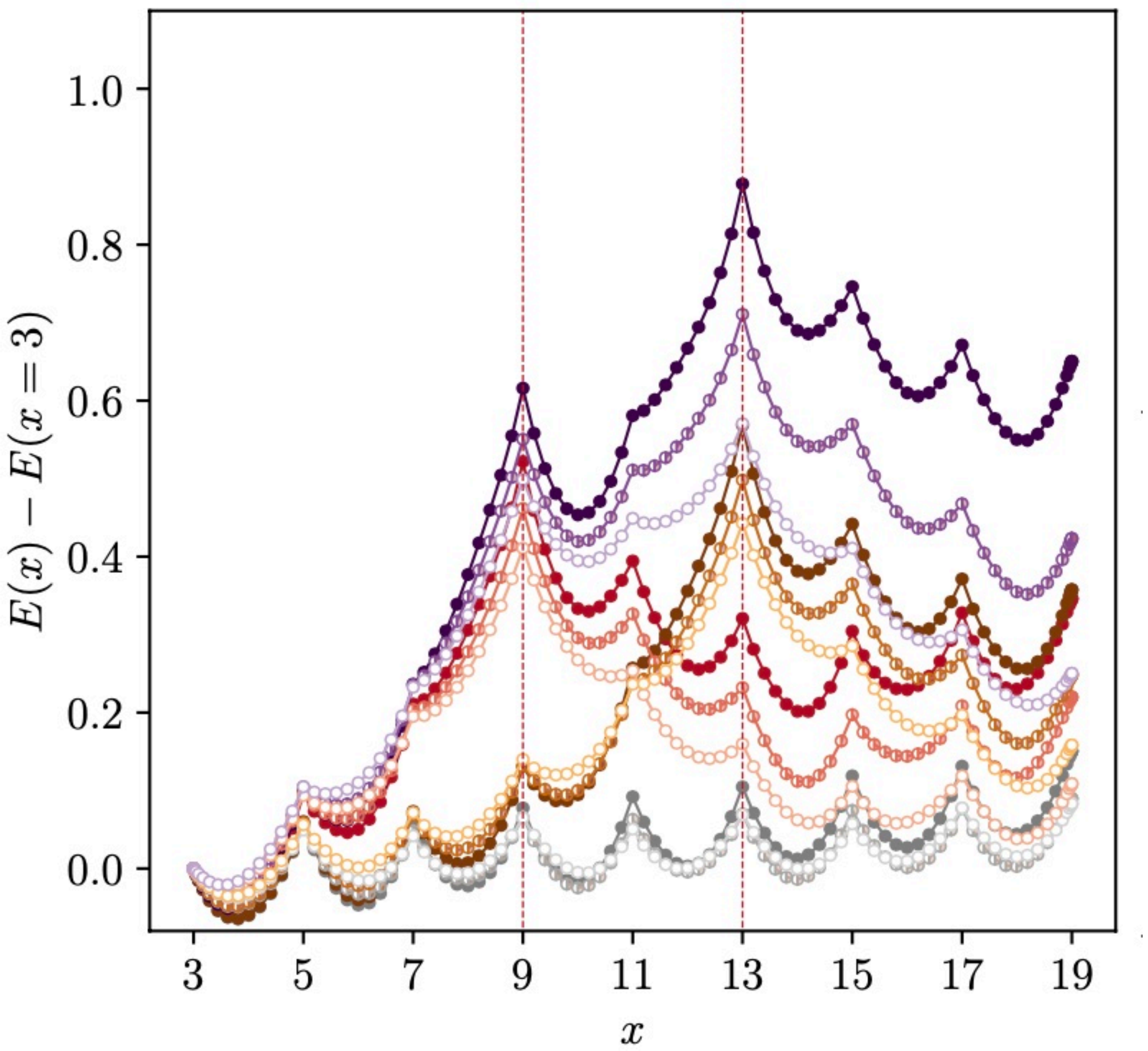
Colliding Partons



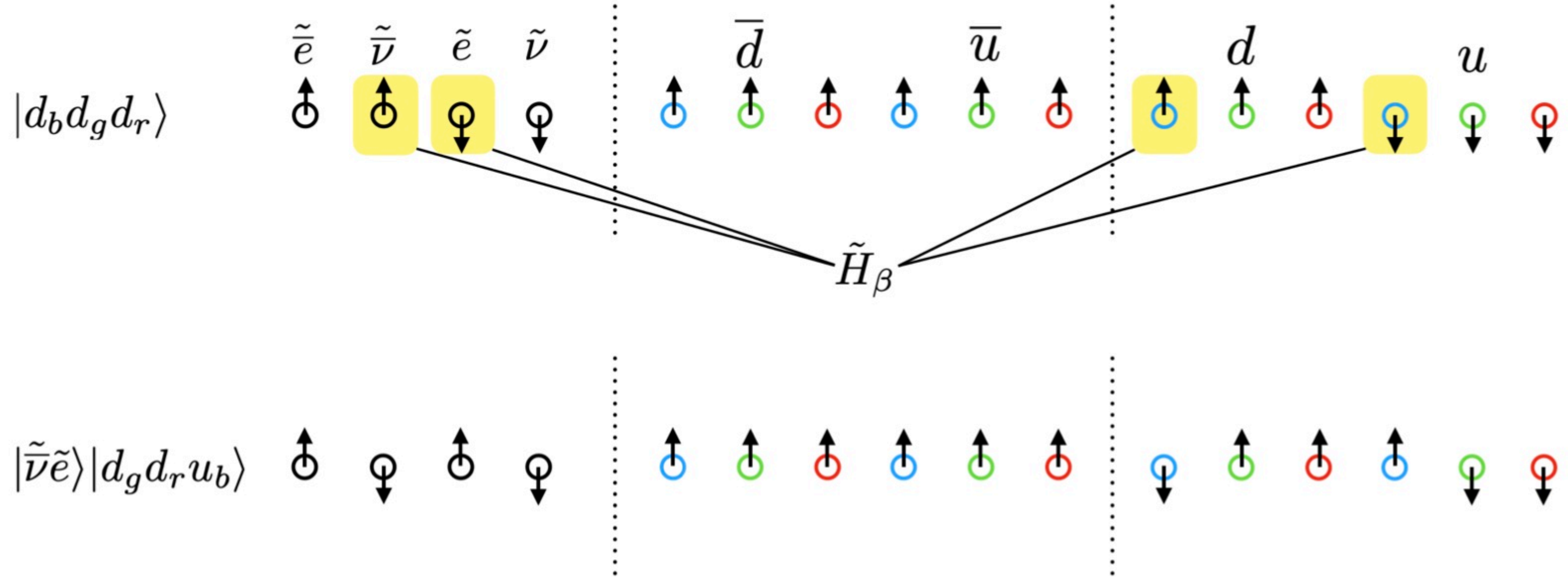


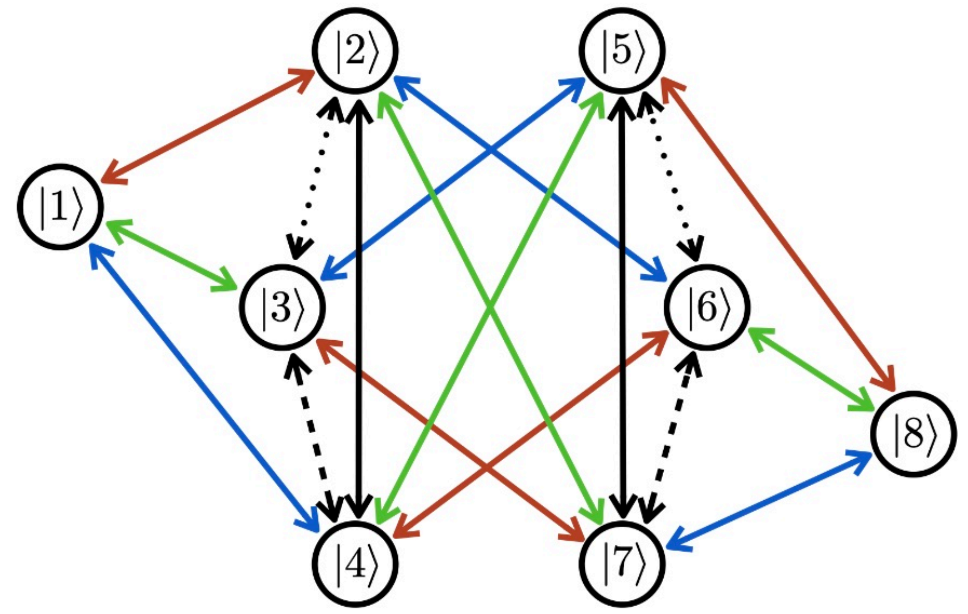
Matter and Coherence





1+1D QCD and Weak Decays (2022)



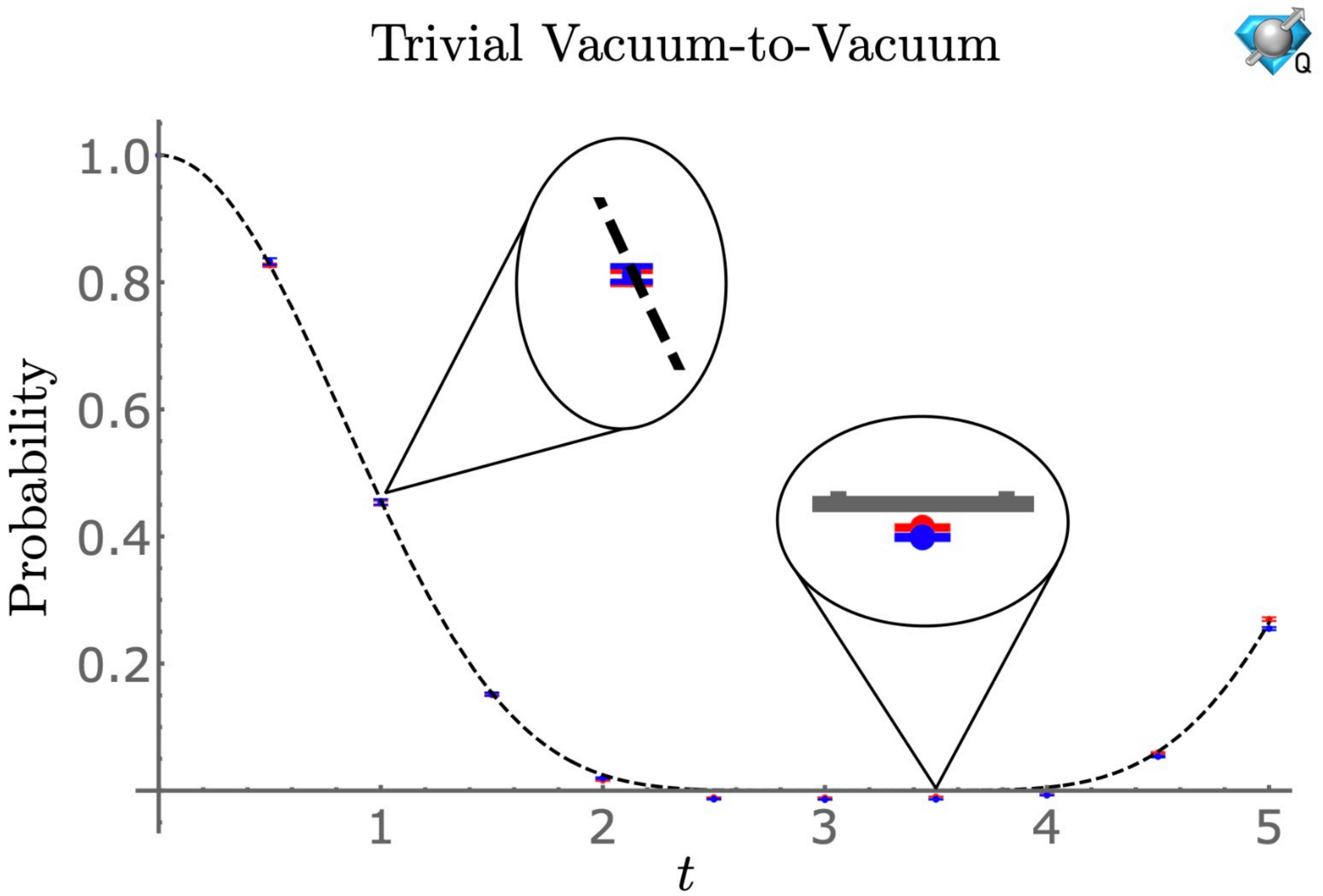


Editors' Suggestion

Access by University

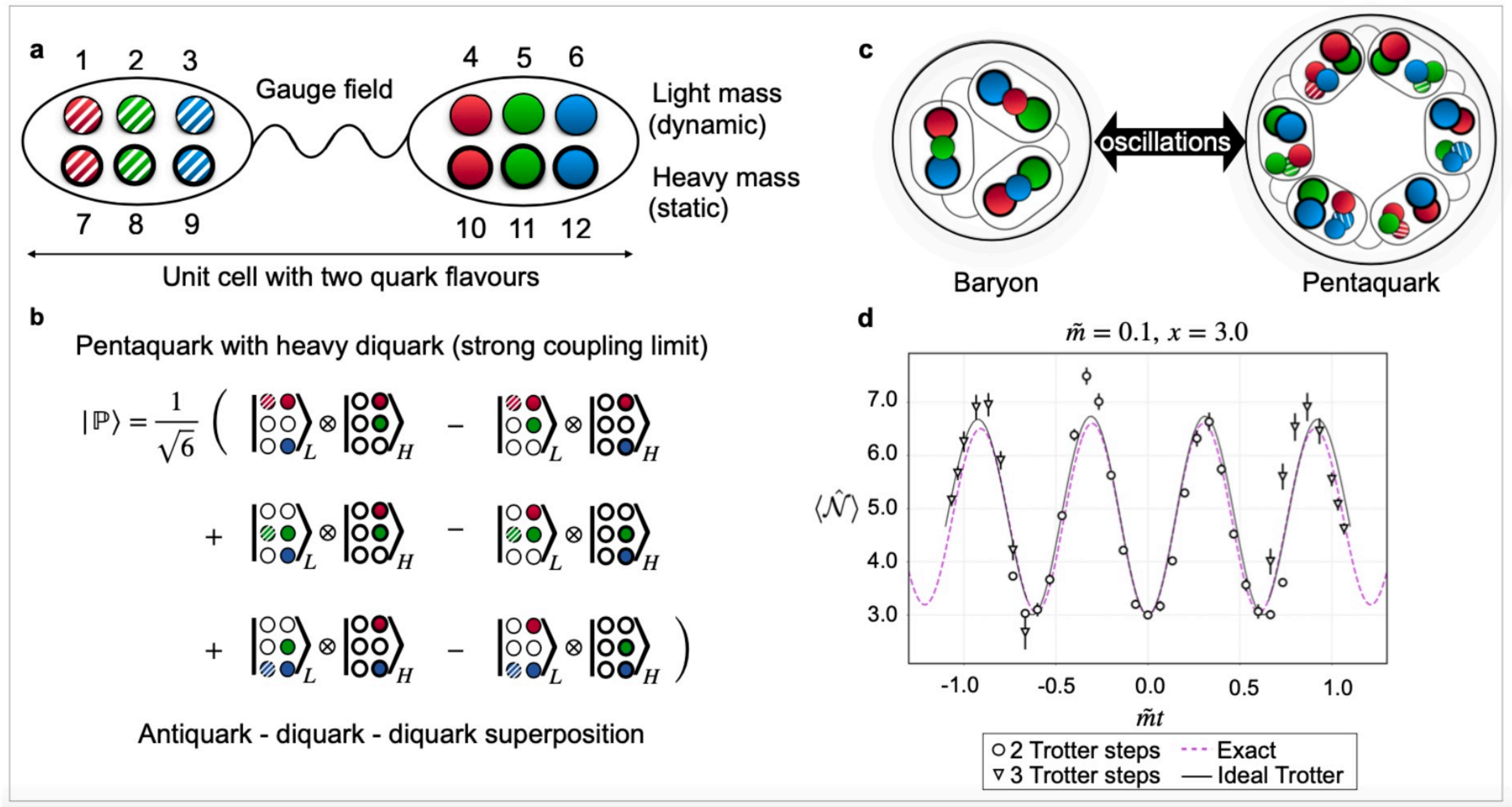
Qu8its for quantum simulations of lattice quantum chromodynamics

Marc Illa, Caroline E. P. Robin, and Martin J. Savage
Phys. Rev. D **110**, 014507 – Published 15 July 2024



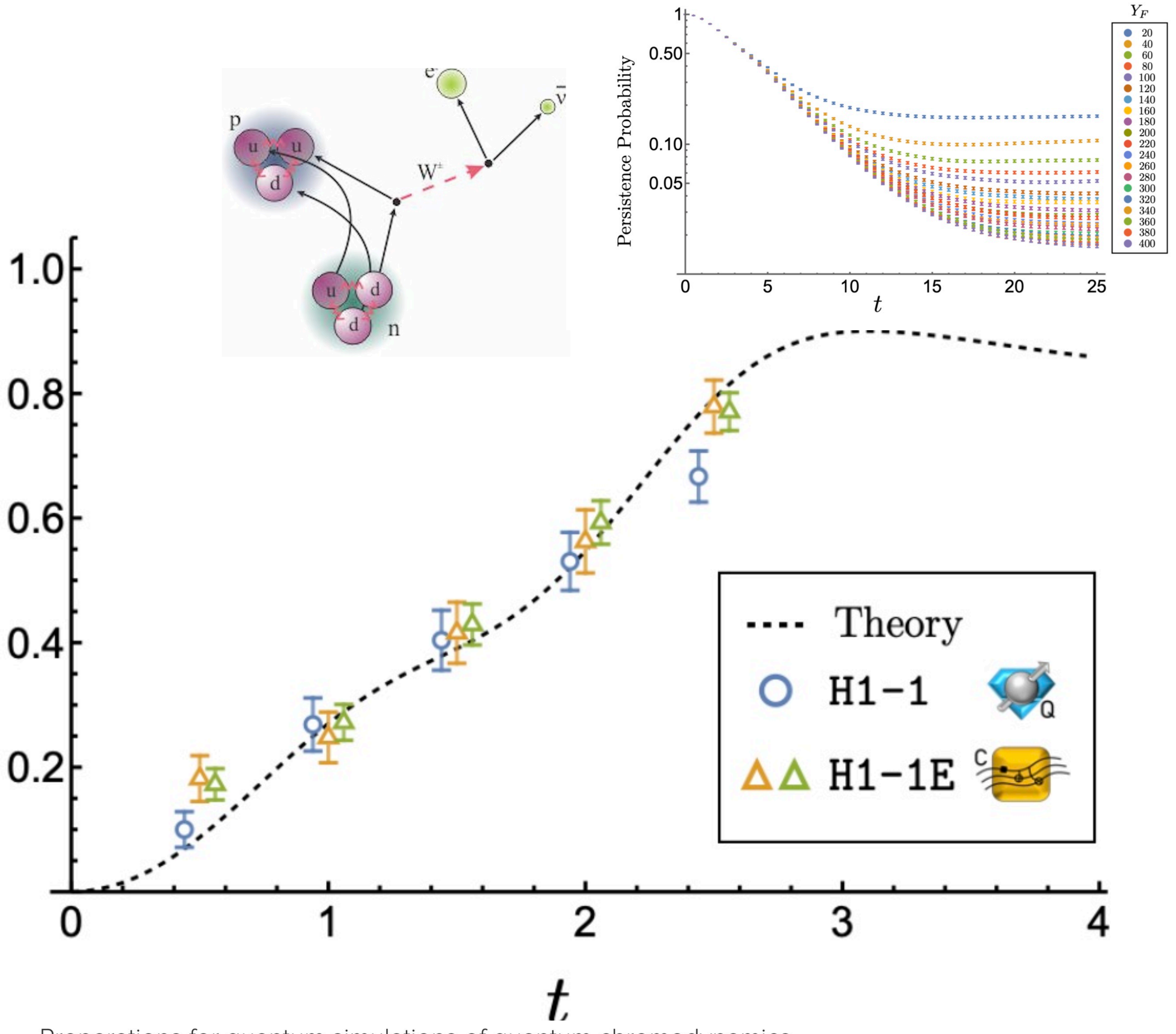
Preparations for quantum simulations of quantum chromodynamics in $1+1$ dimensions. I. Axial gauge

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



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

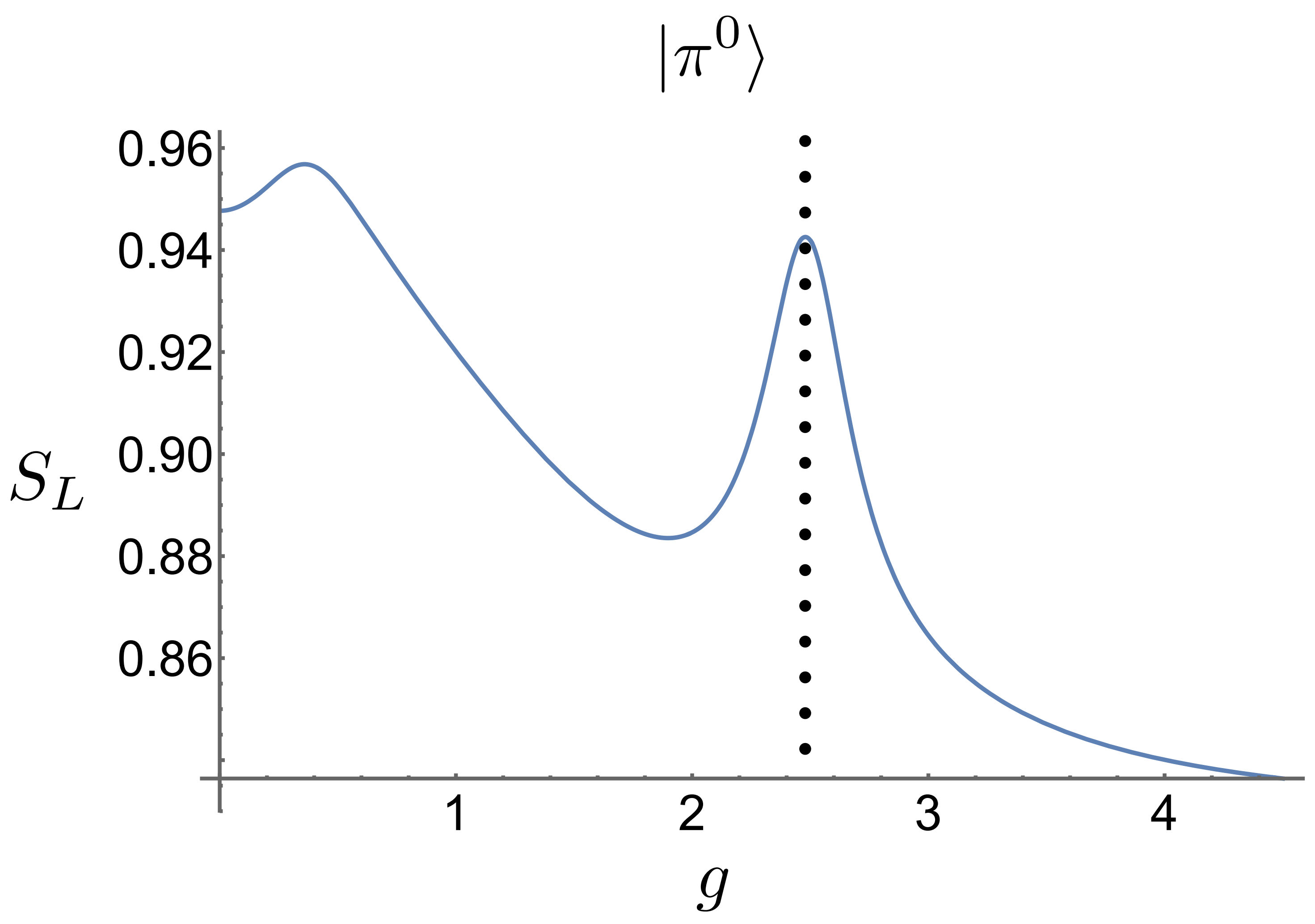
Yasar Y. Atas*,[1,2,†] Jan F. Haase*,[1,2,3,‡] Jinglei Zhang,[1,2,§] Victor Wei,[1,4] Sieglinde M.-L. Pfaendler,[5] Randy Lewis,[6] and Christine A. Muschik[1,2,7]

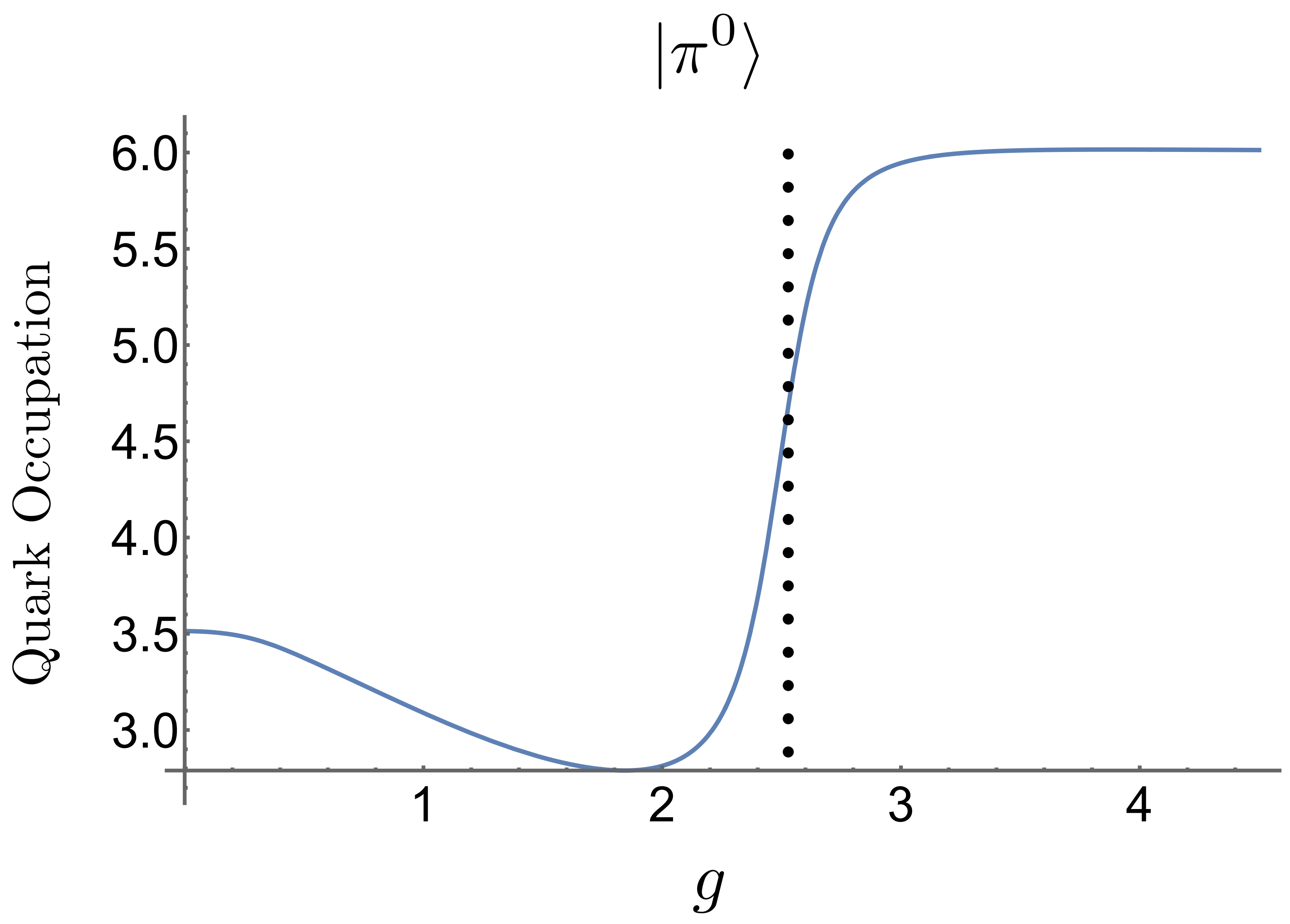


Preparations for quantum simulations of quantum chromodynamics in $1+1$ dimensions. II. Single-baryon β-decay in real time

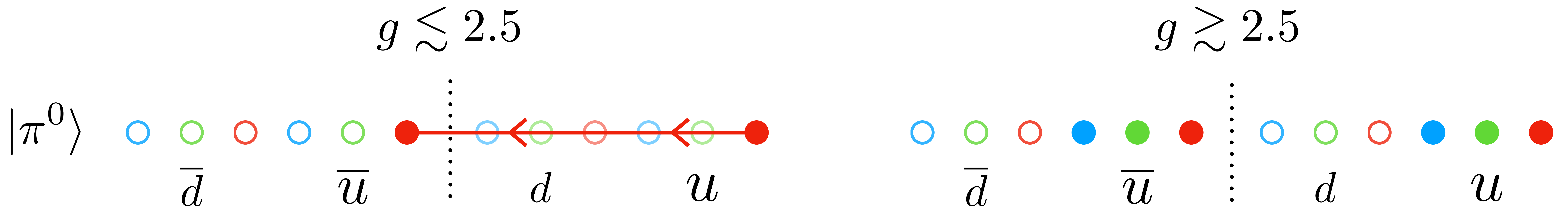
Roland C. Farrell, Ivan A. Chernyshev, Sarah J. M. Powell, Nikita A. Zemlevskiy, Marc Illa, and Martin J. Savage
Phys. Rev. D **107**, 054513 – Published 30 March 2023

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

Dynamical Quantum Phase Transitions

2018

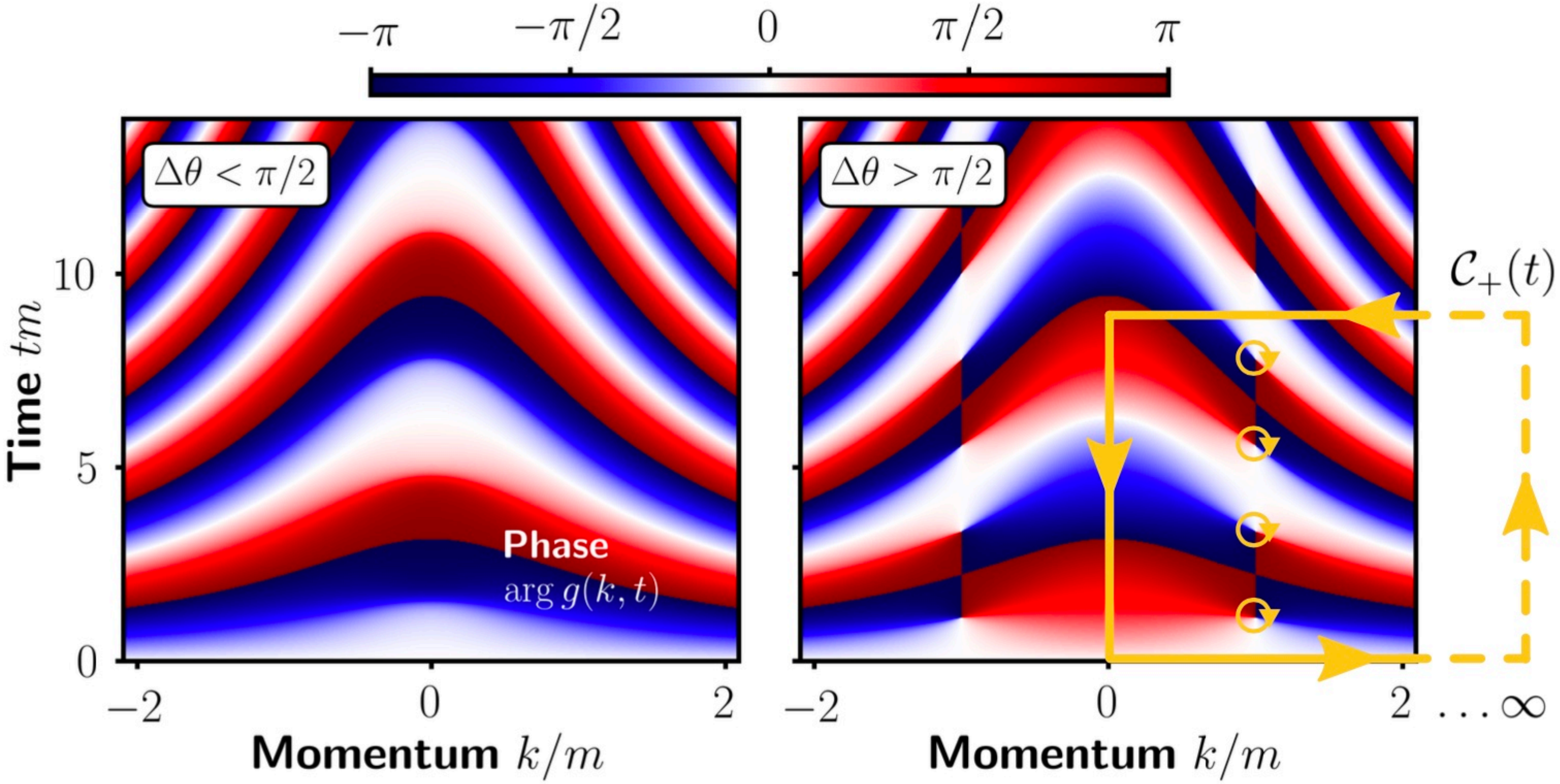
Dynamical topological transitions in the massive Schwinger model with a θ-term

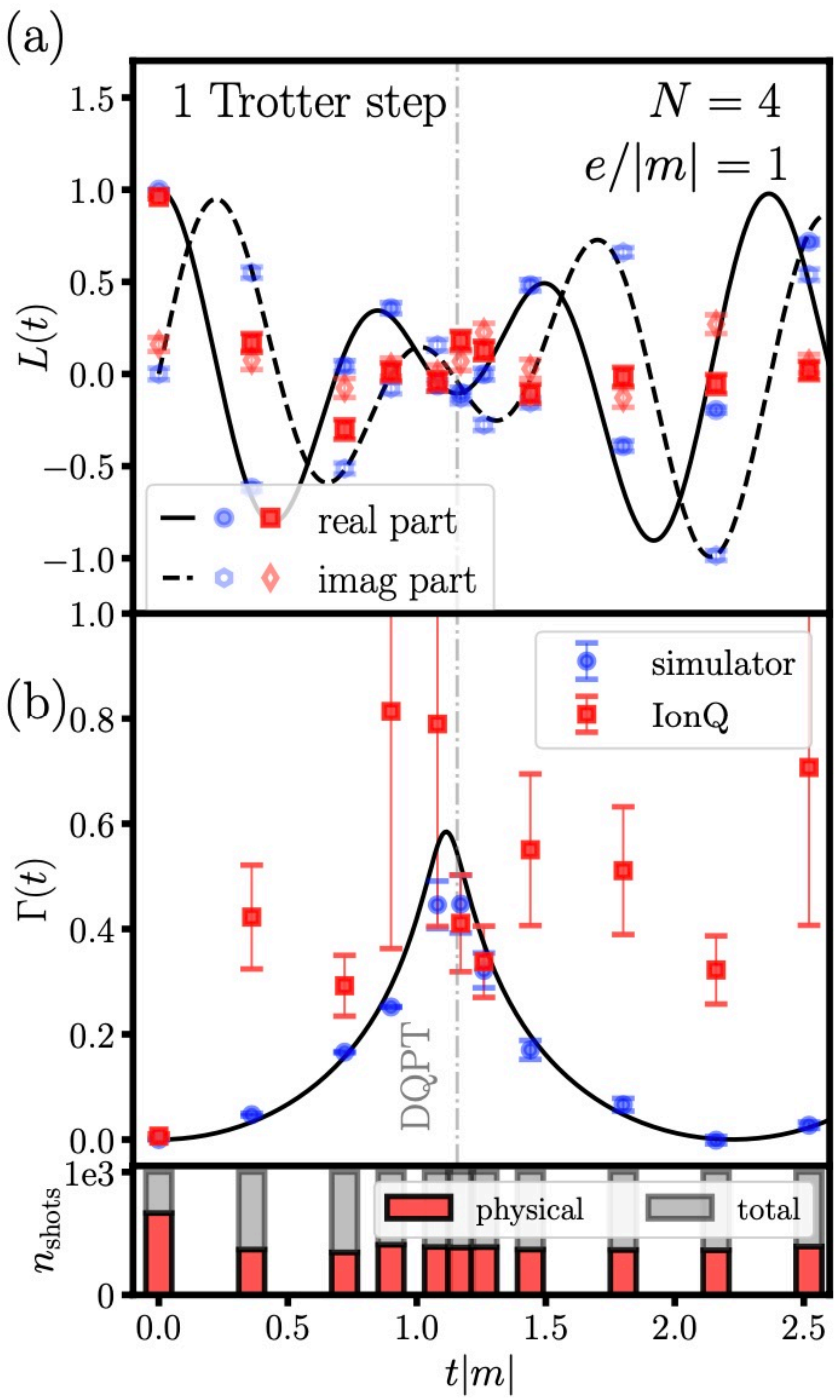
T. V. Zache,[1,*] N. Mueller,[2] J. T. Schneider,[1] F. Jendrzejewski,[3] J. Berges,[1] and P. Hauke[1,3]

2023

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

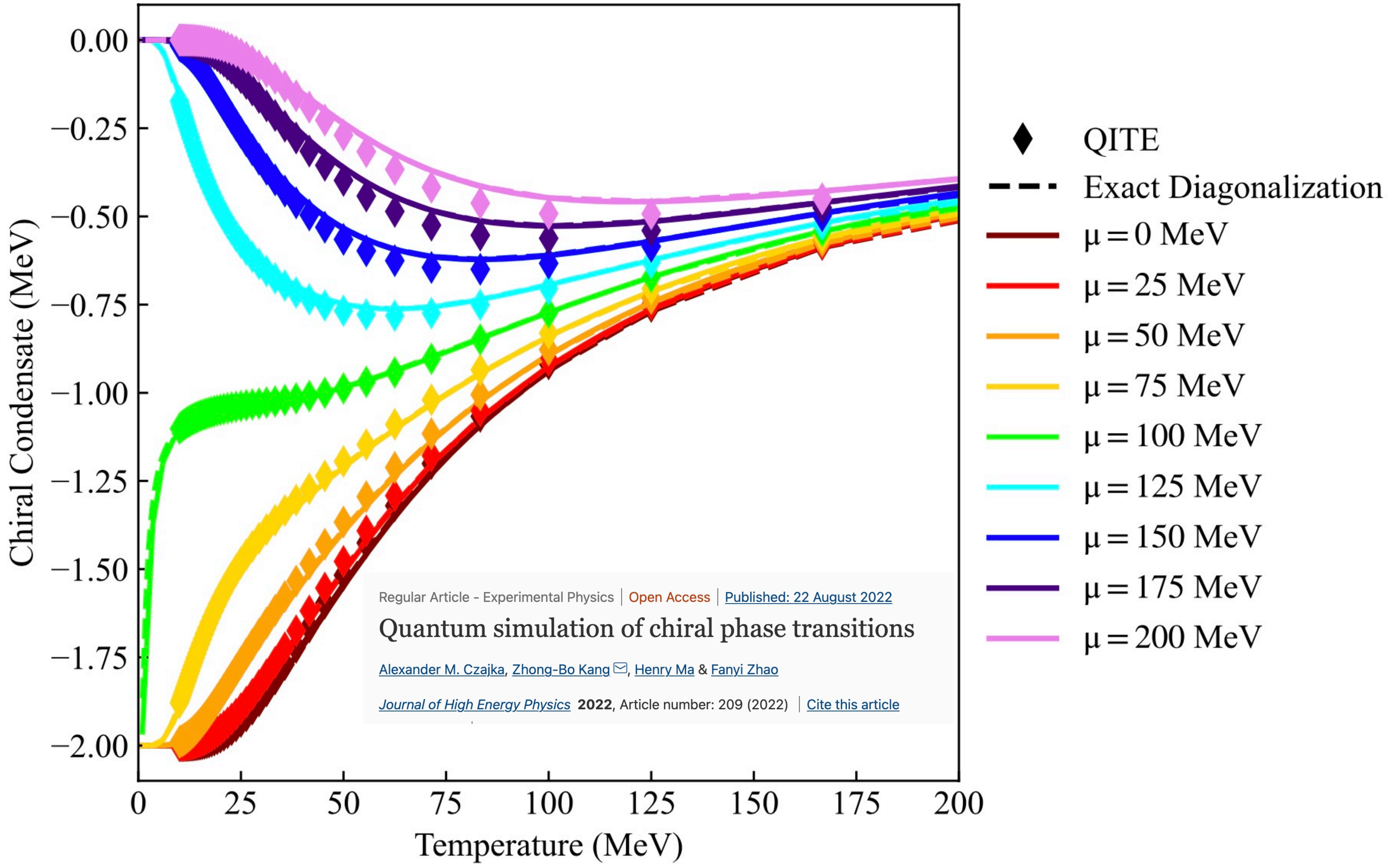
Niklas Mueller,[1,2,3,*] Joseph A. Carolan,[4] Andrew Connelly,[5]
Zohreh Davoudi,[1,6,†] Eugene F. Dumitrescu,[7,‡] and Kübra Yeter-Aydeniz[8]





Modeling the QCD Phase Diagram

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

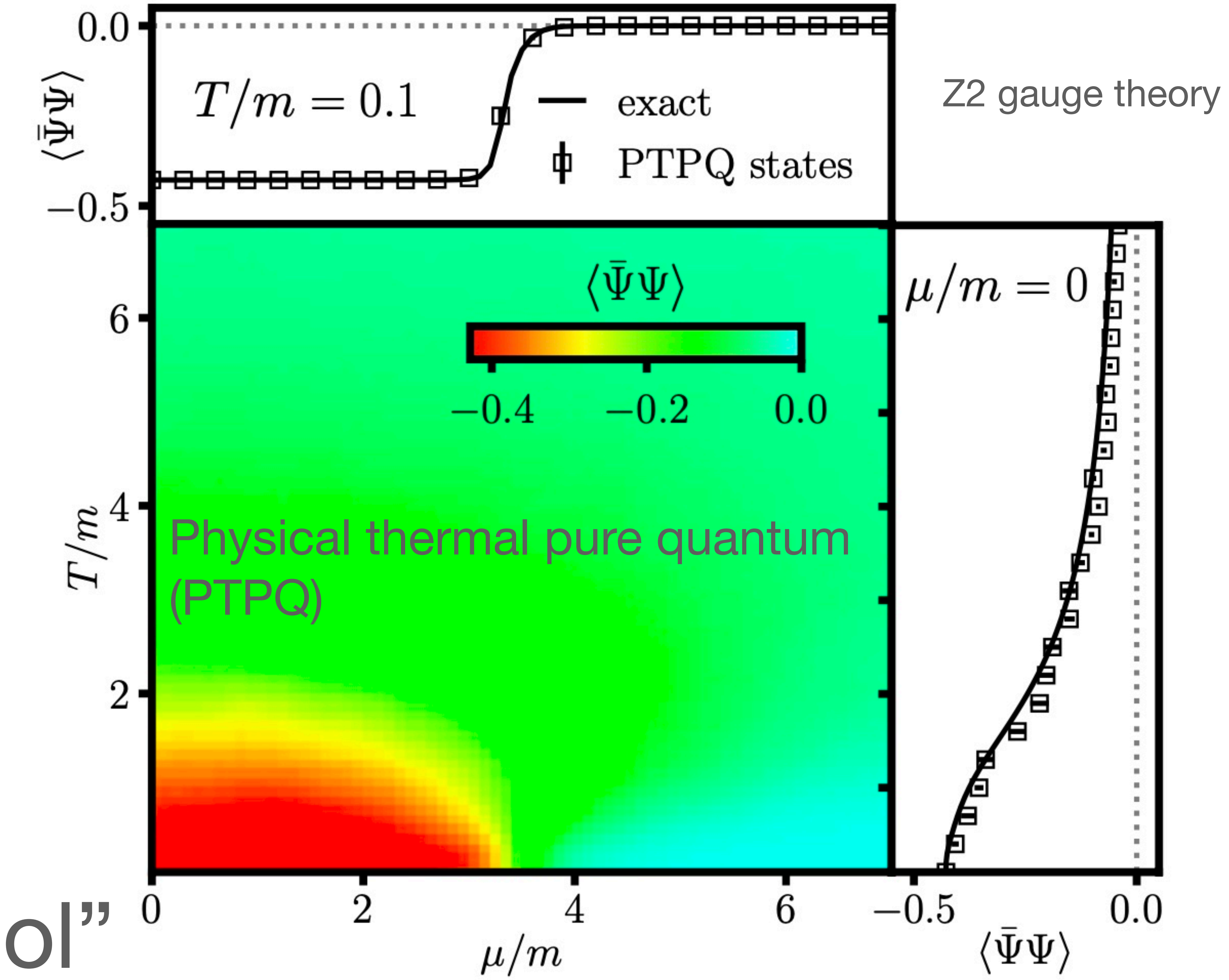


Toward Quantum Computing Phase Diagrams of Gauge Theories with Thermal Pure Quantum States

Zohreh Davoudi,[1,2,*] Niklas Mueller,[1,3,†] and Connor Powers[1,2,‡]

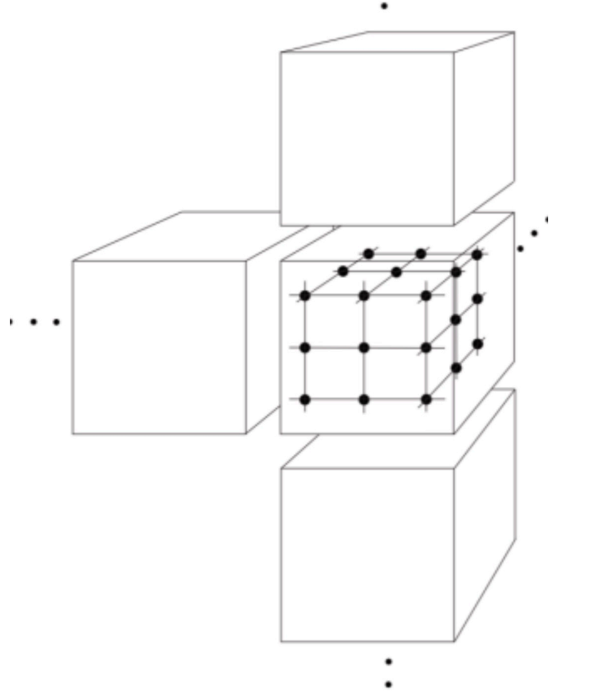
[1] *Maryland Center for Fundamental Physics and Department of Physics, University of Maryland, College Park, MD 20742, USA*
[2] *Institute for Robust Quantum Simulation, University of Maryland, College Park, Maryland 20742, USA*
[3] *Joint Quantum Institute, NIST/University of Maryland, College Park, MD 20742, USA*

Phys. Rev. Lett. **131**, 081901 – Published 21 August 2023



QITE algorithms to “cool”

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 ....

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

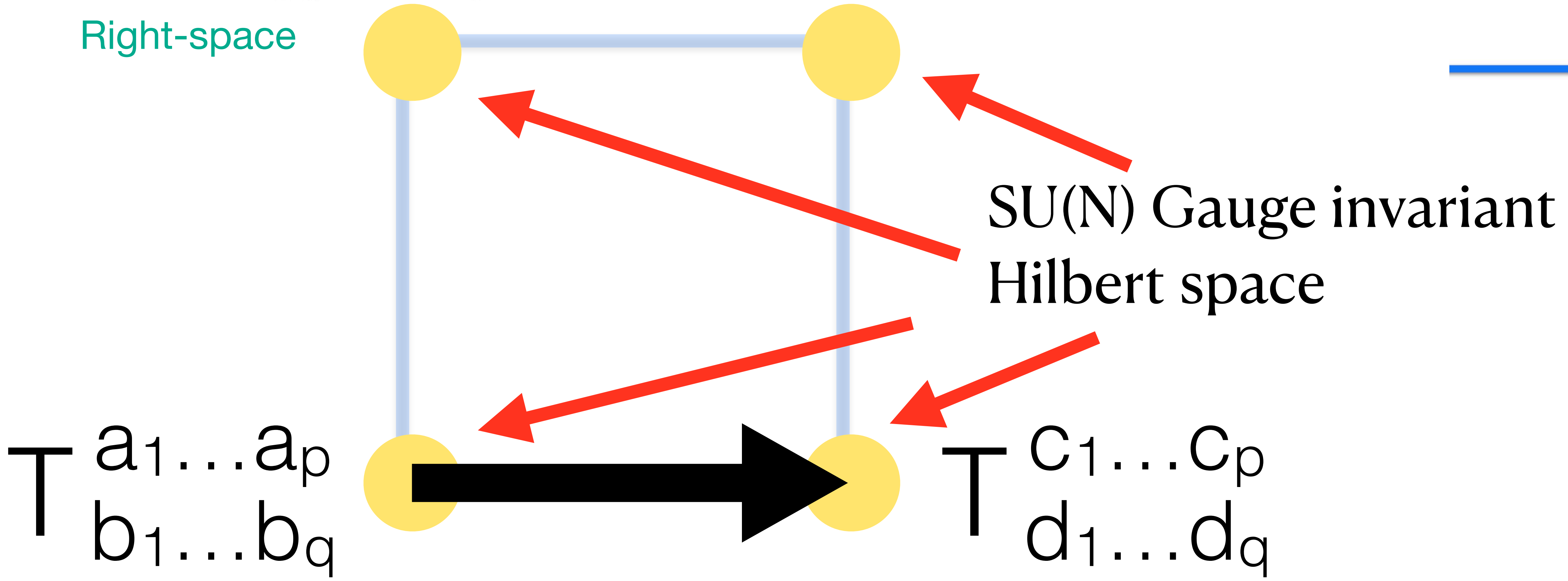
Electric Field Casimir operator

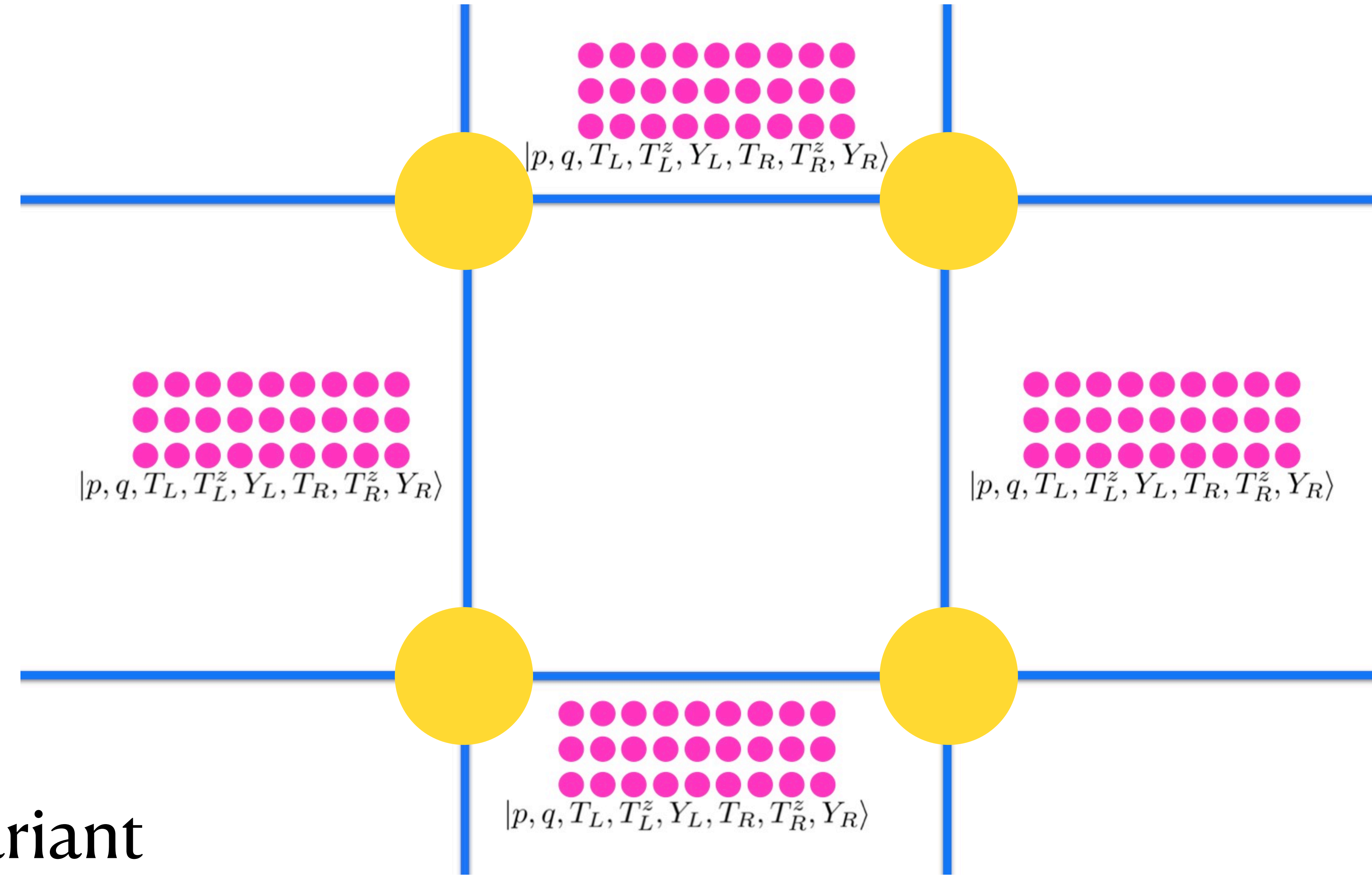
$$|p, q, T_L, T_L^z, Y_L, T_R, T_R^z, Y_R\rangle$$

Irrep Left-space Right-space

Magnetic Field operator

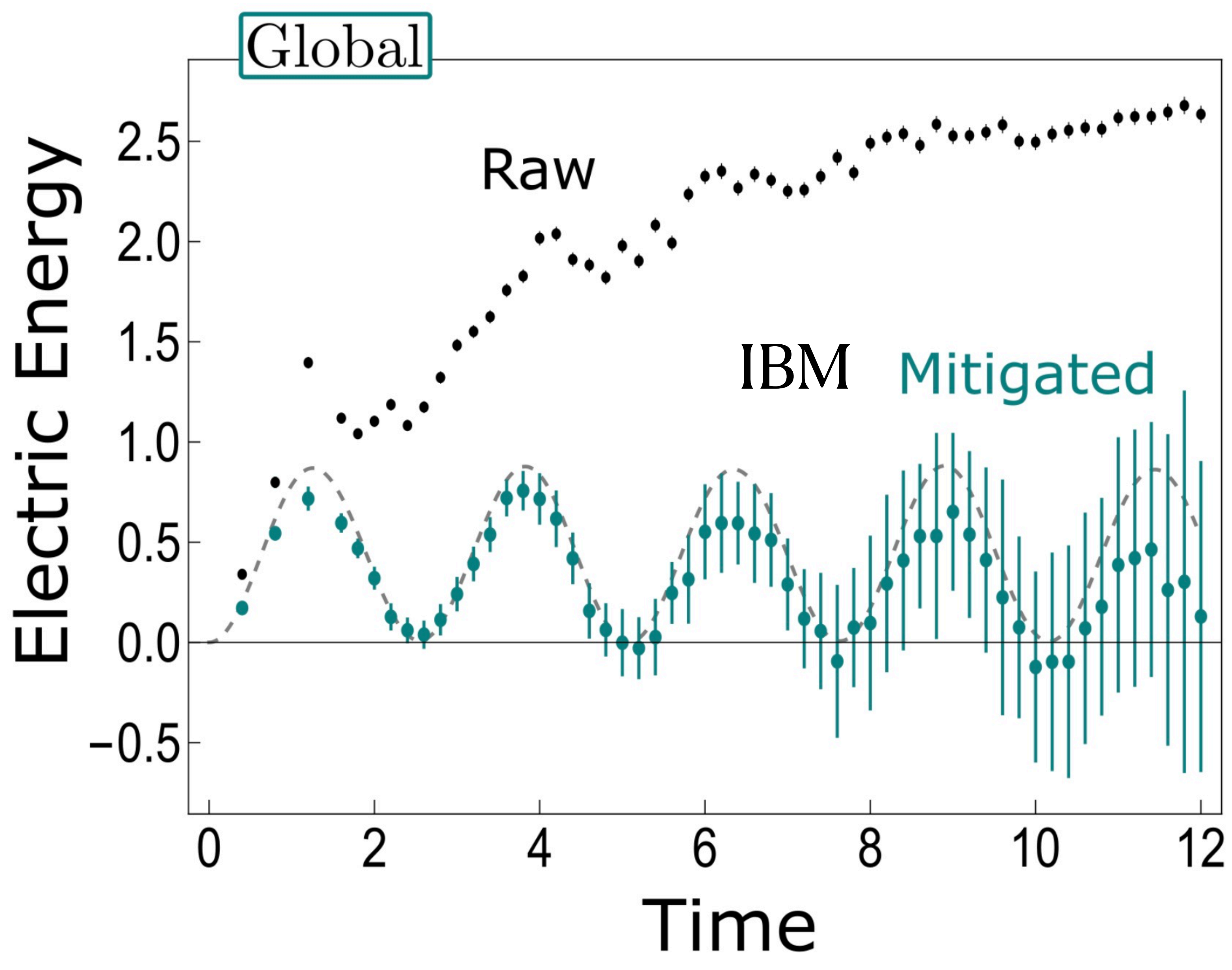
Off-diagonal on electric basis

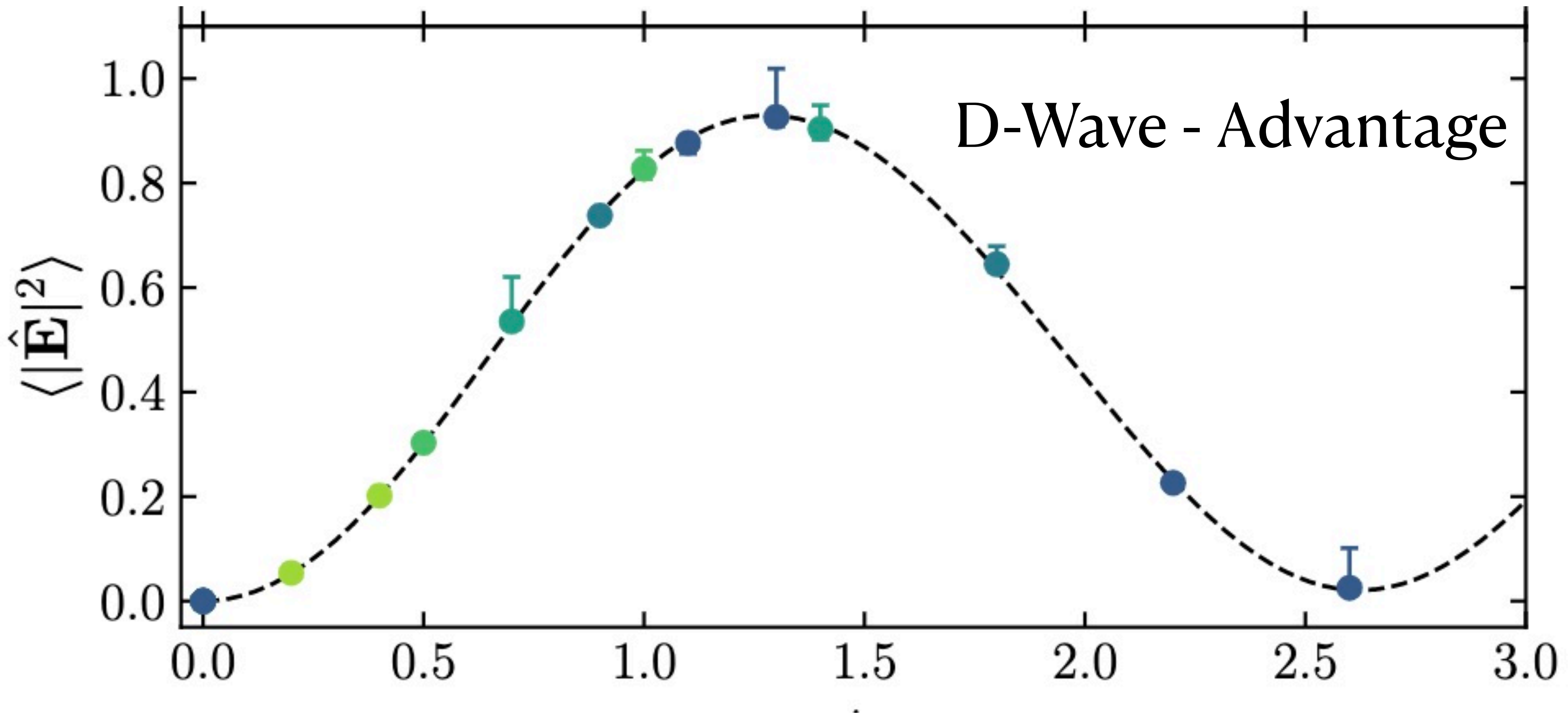


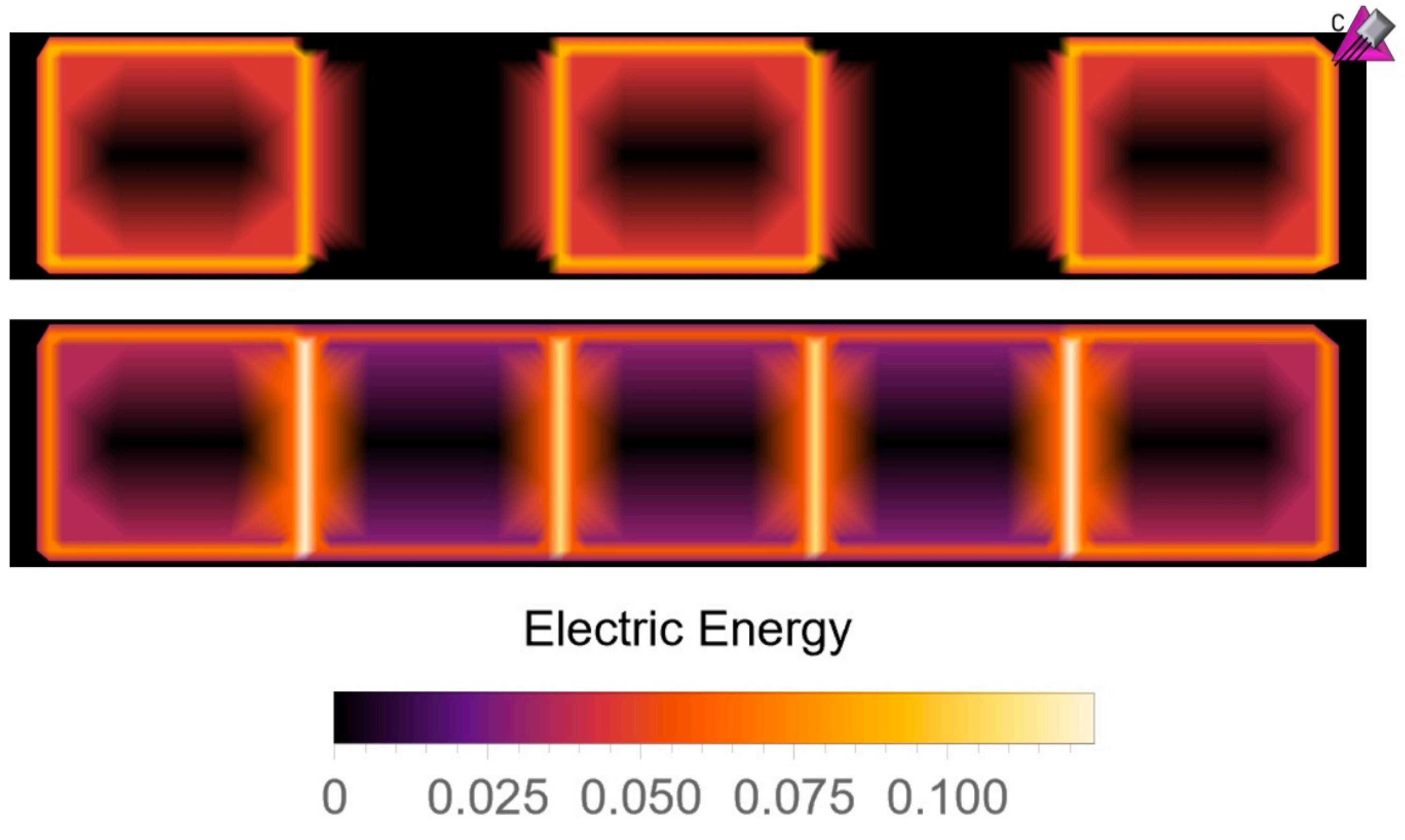


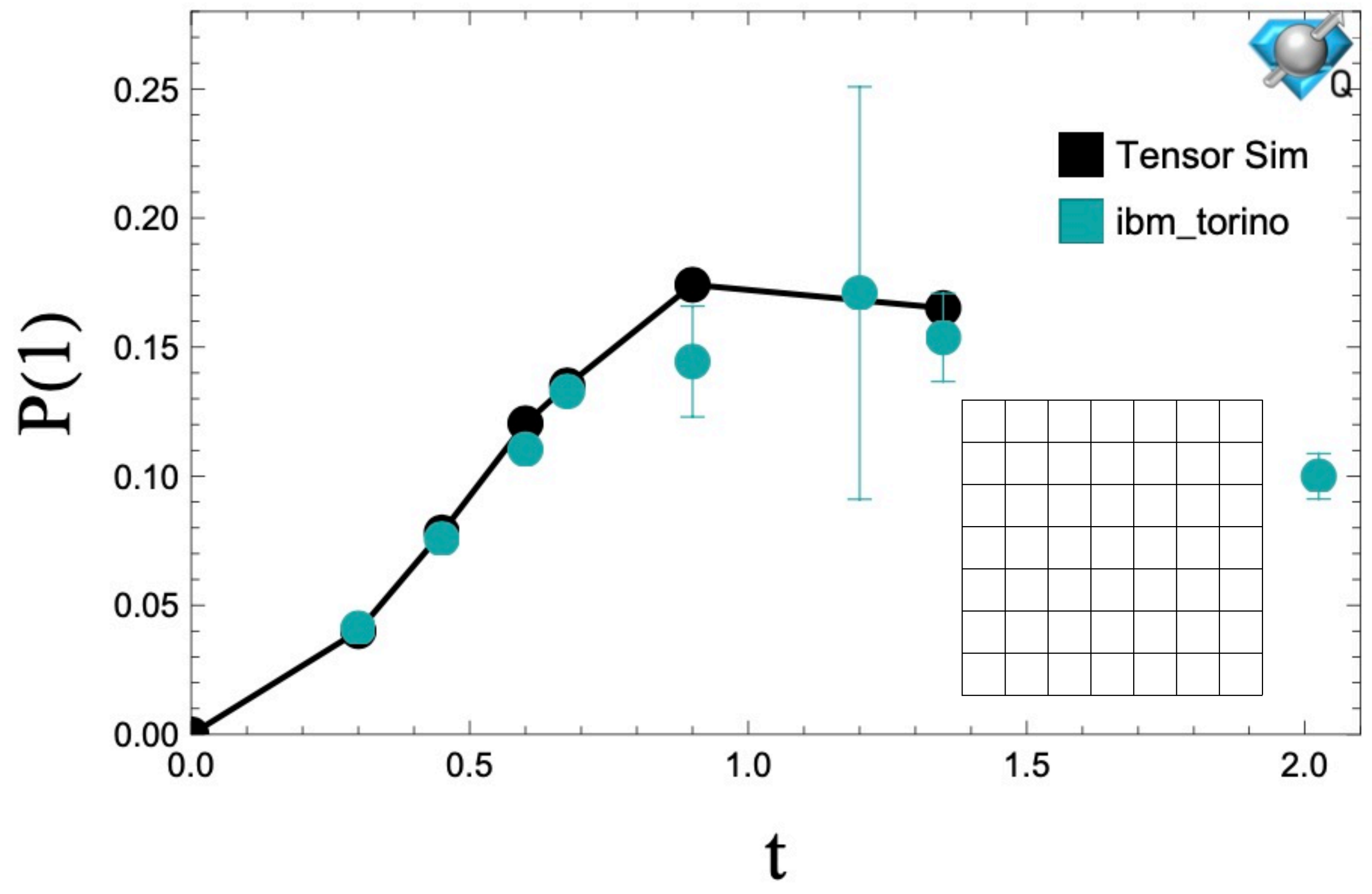
Truncations in irrep space !!!!!

SU(3) Yang-Mills Plaquettes - Examples





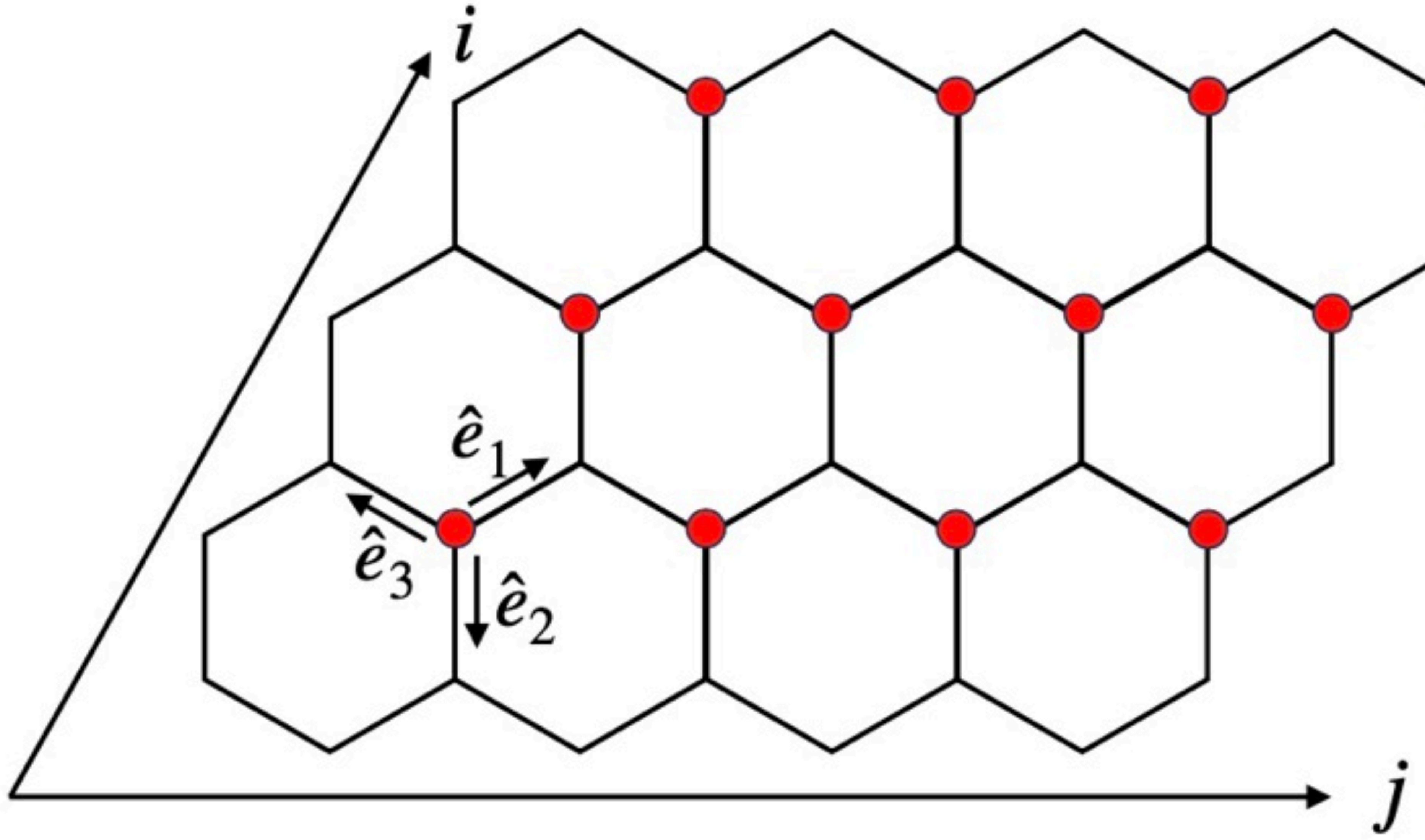




Transport Properties
Shear Viscosity in 2+1D SU(2)

Francesco Turro, Anthony Ciavarella and Xiaojun Yao

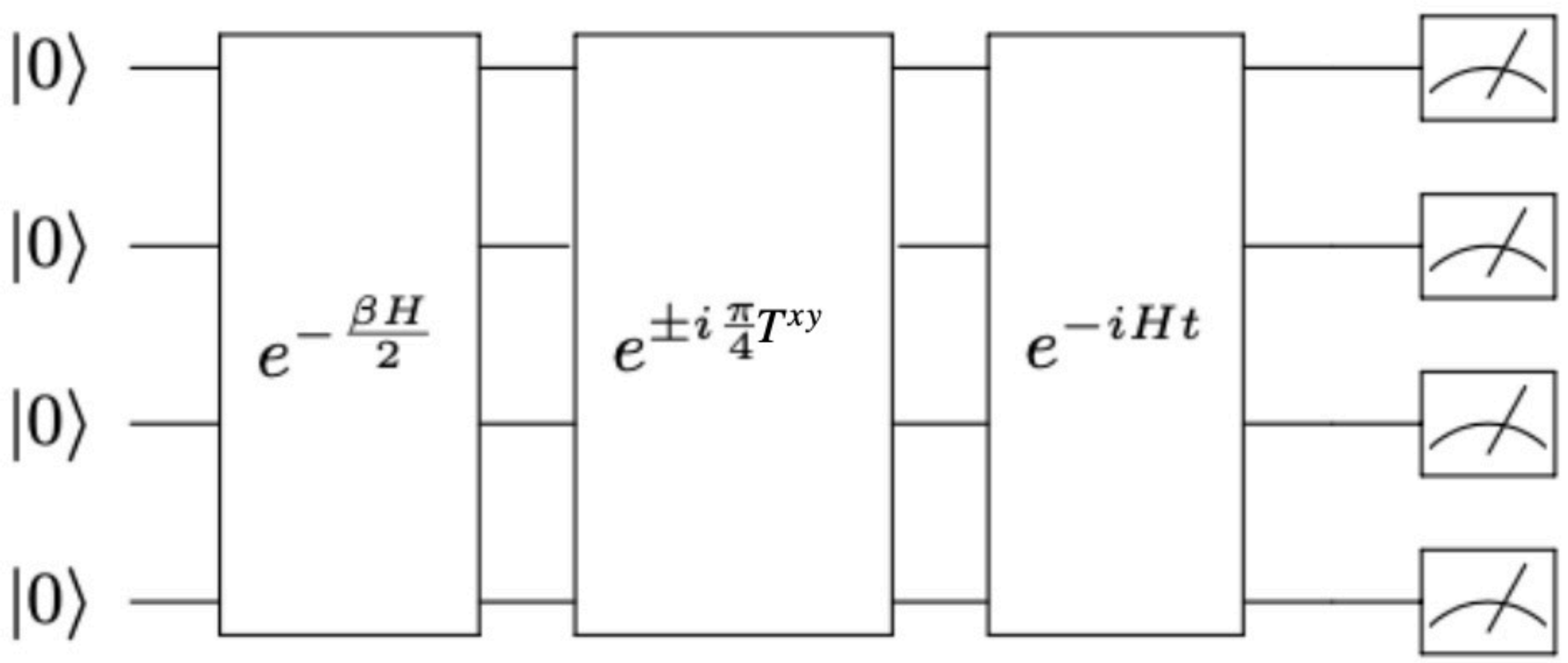
Berndt Mueller and Xiaojun Yao



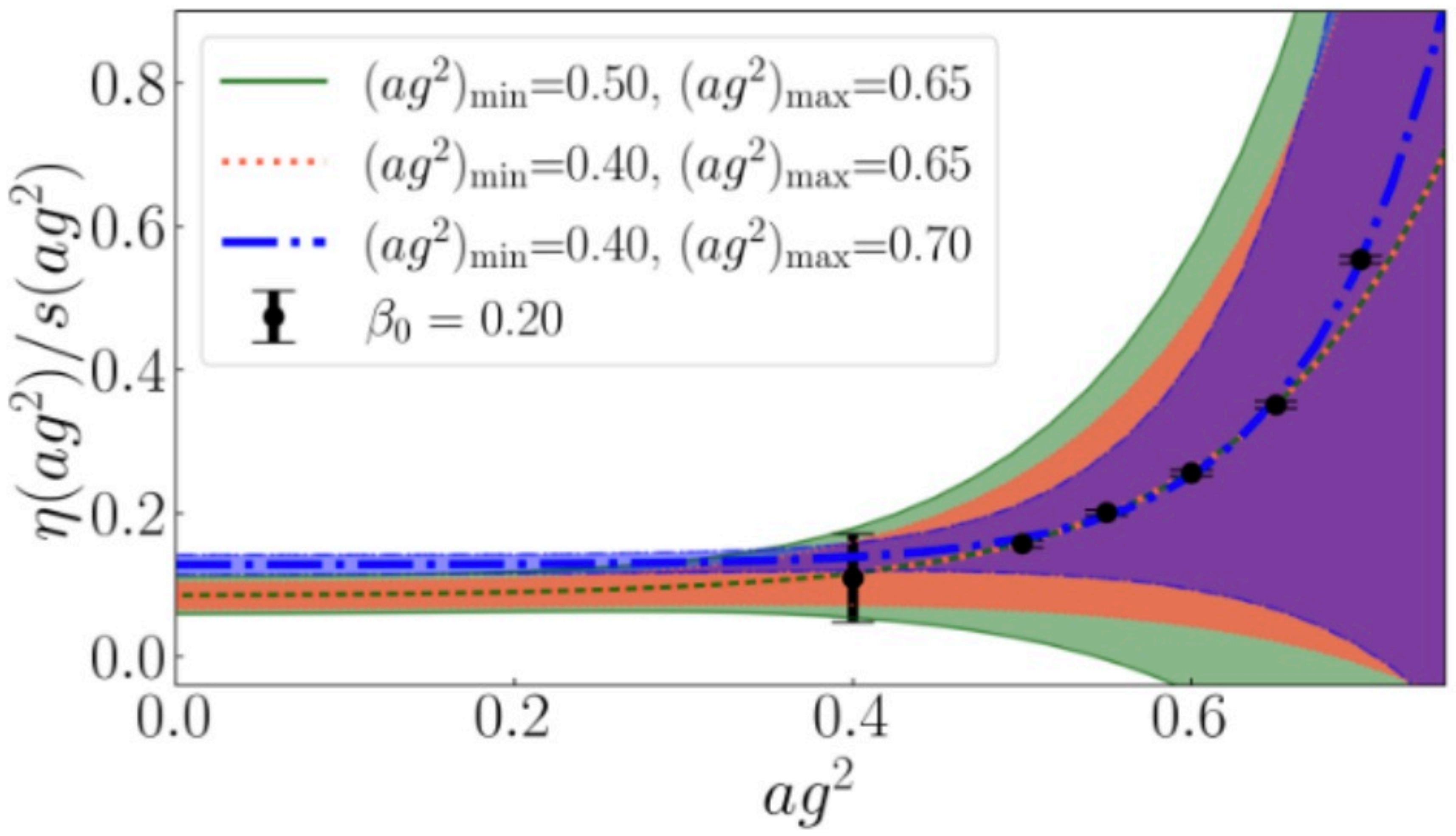
$$H = \frac{3\sqrt{3}g^2}{4}\sum_{\text{links}} E_i^a E_i^a - \frac{4\sqrt{3}}{9g^2a^2}\sum_{\text{plaqs}} \hexagon$$

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

Quantum algorithm for G_r^{xy}



On 4×4 lattice w/ $j_{\max} = 0.5$



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

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]

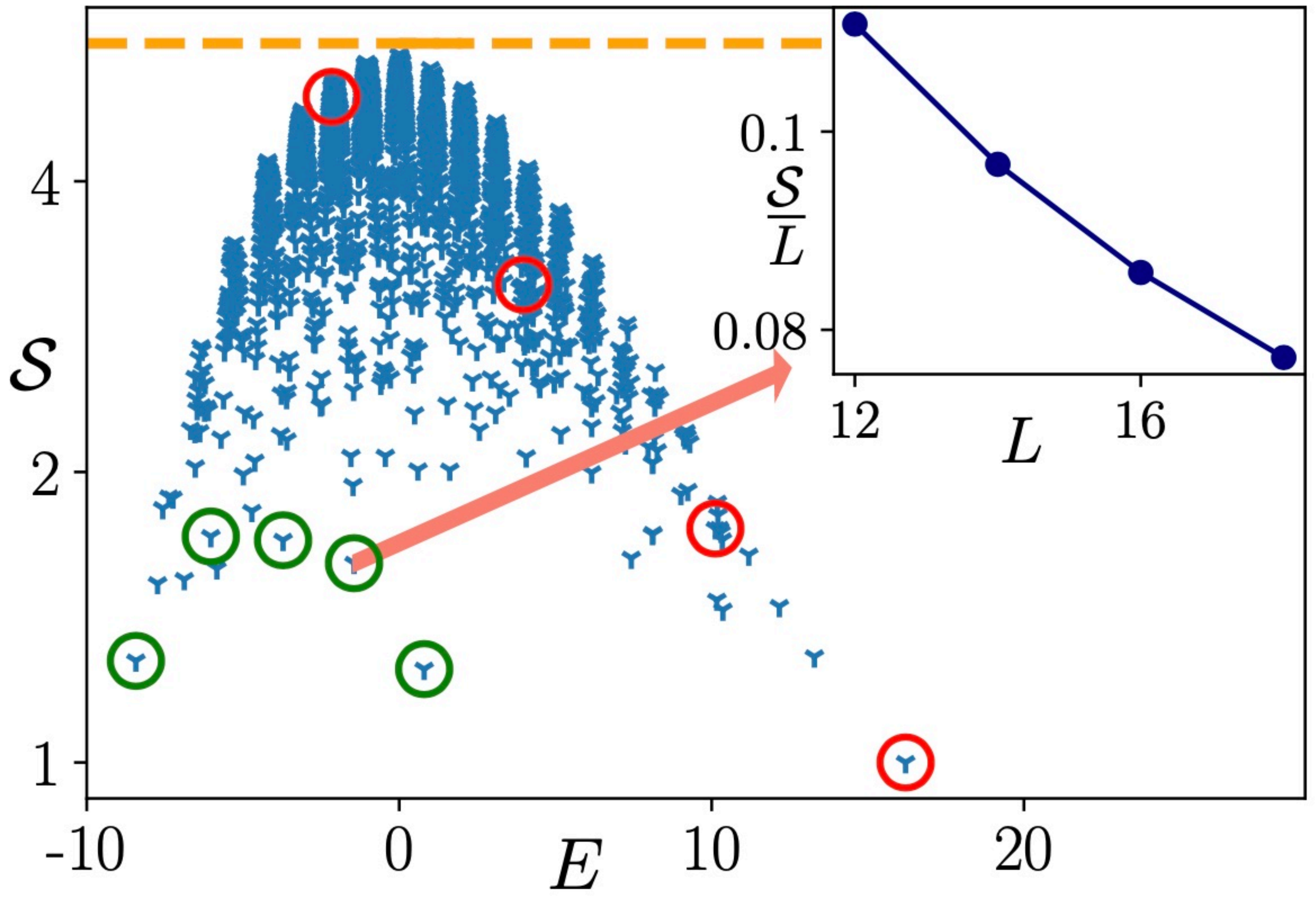
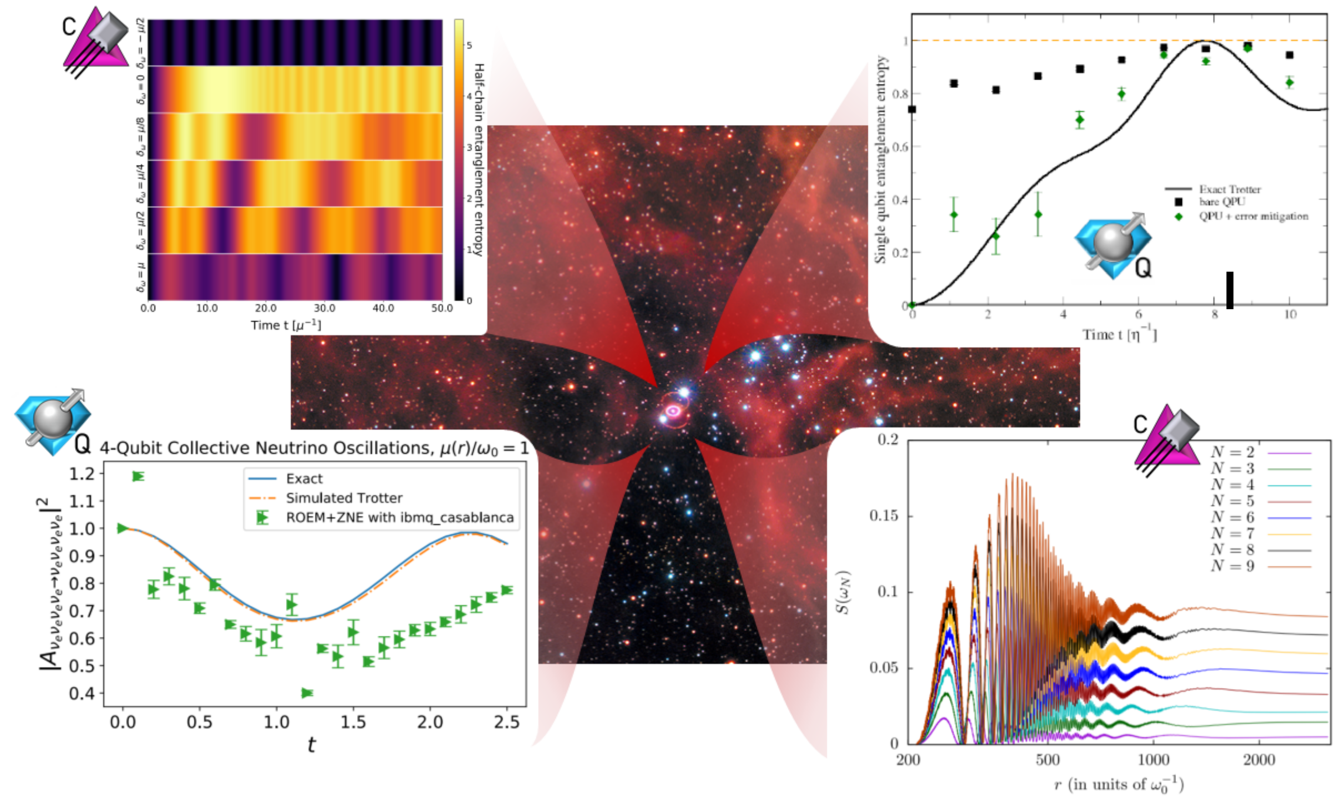


FIG. 4. The half-chain entanglement entropy($\mathcal{S}$) of all the eigenstates at $t = 0.2$, $h = 0.5$ for $L = 16$. The orange dashed line gives the $\mathcal{S}_{RMT}$ value. Circles denote different QMBS obtained via our tracking procedure. Green circles denote antimagnon-like family S_n^2 for $n = 0, 2, 4, 6, 8$ while red circles magnon-like states, S_n^1 with $n = 0, .., 6$ counting from the right hand side. *Inset:* The half-chain Entanglement Entropy divided by system size ($\frac{\mathcal{S}}{L}$) for S_2^2 state showing its sub-volume property as expected for QMBS.

- Anomalously-low bi-partite entanglement
- Distributed throughout spectrum
- Weakly connected to evolution Hamiltonian (cold sub-space)
- Delay thermalization

$$H = -t\sum_j \left(c_j^\dagger - c_j\right)\sigma^z_{j+1/2}\left(c^\dagger_{j+1} + c_{j+1}\right) - \mu\sum_j\left(c_j^\dagger c_j - \frac{1}{2}\right) - h\sum_j \sigma^x_{j+1/2}.$$

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

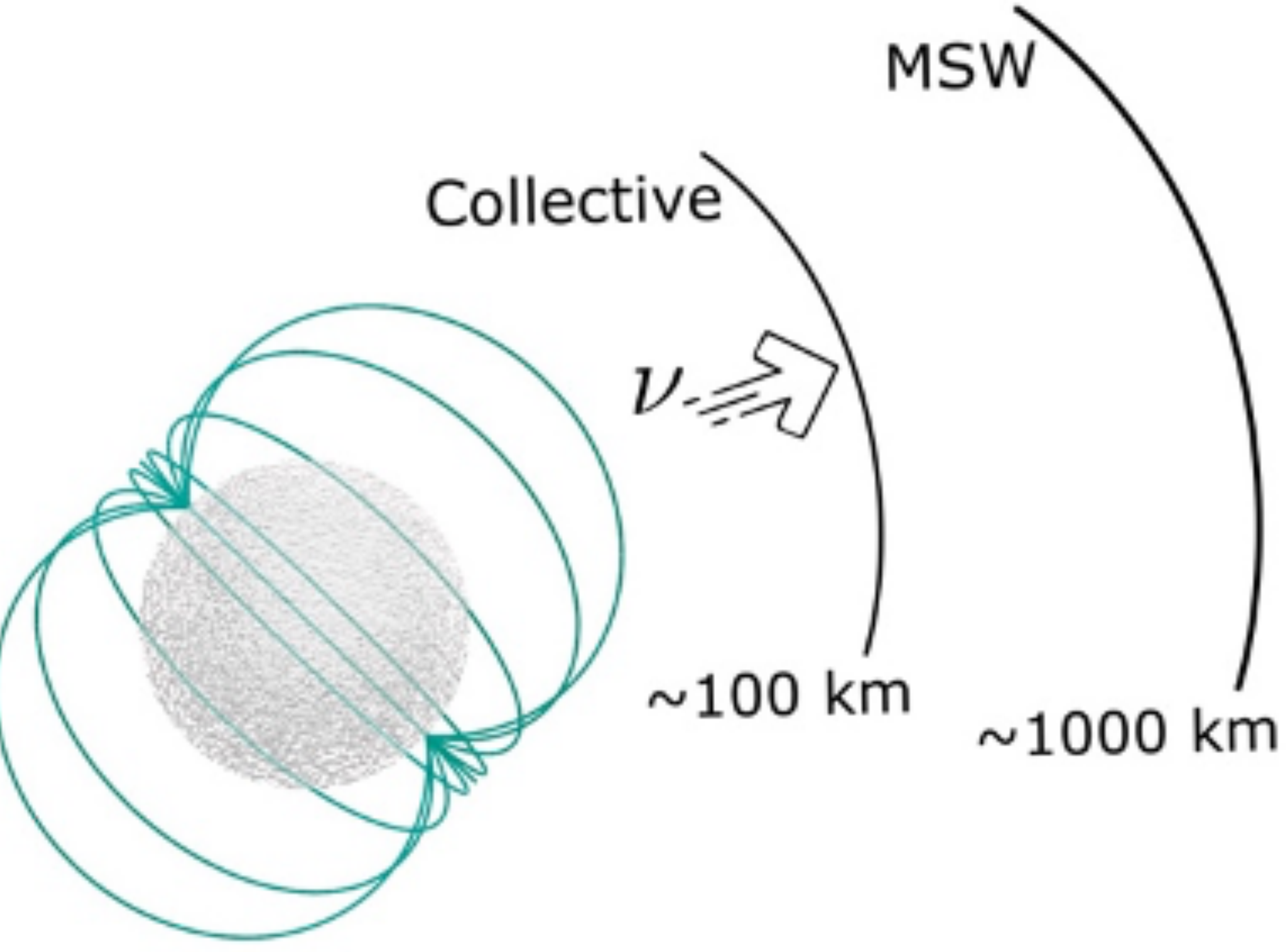


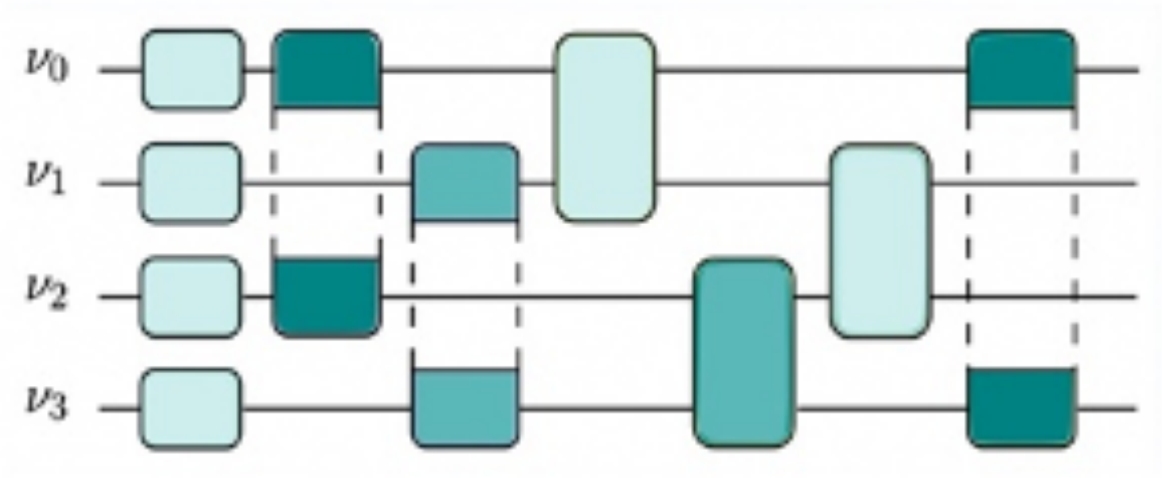
Amitrano, Balantekin, Pooser, Roggero, Siopsis, Pederiva, …..

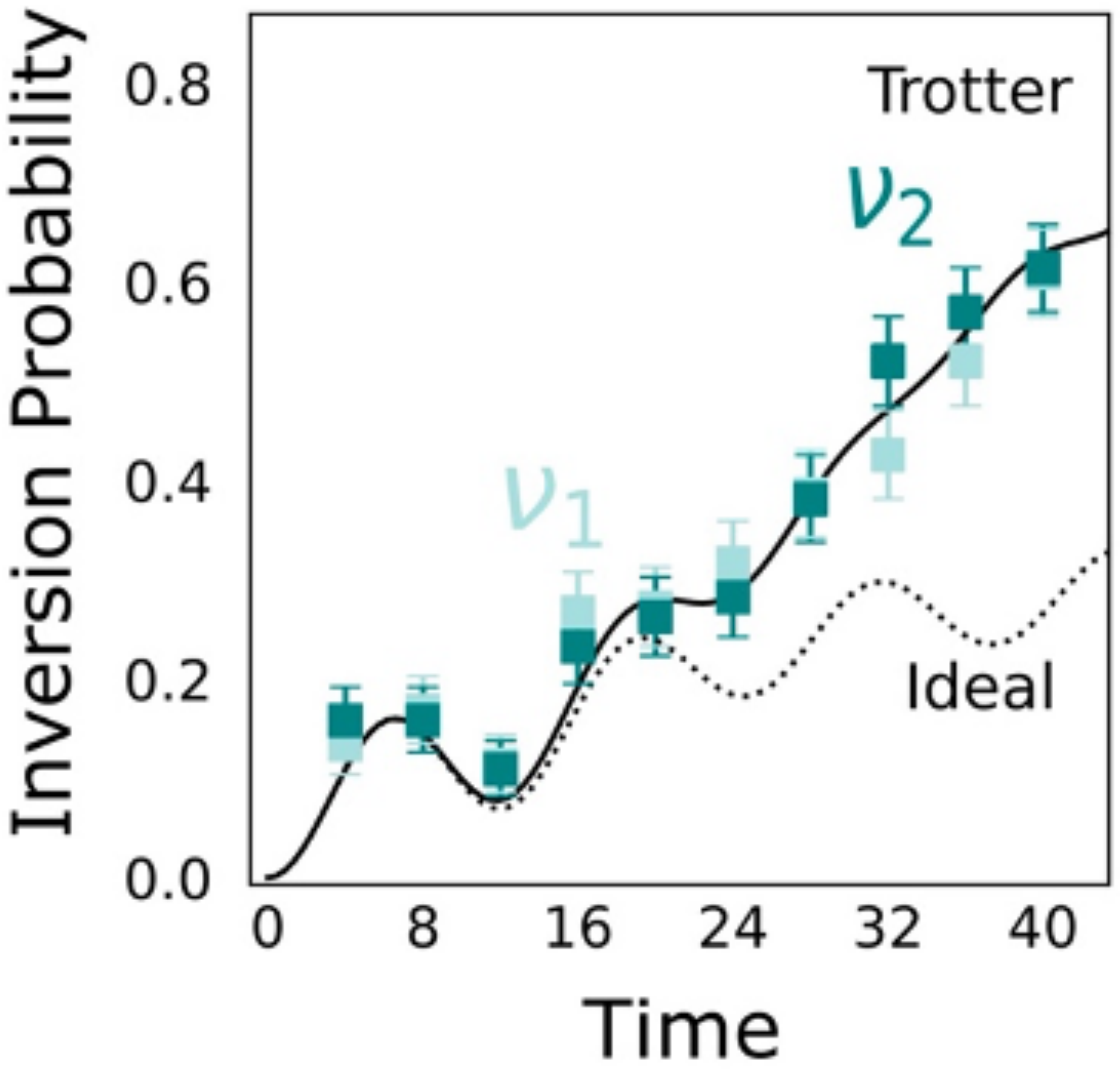
Neutrino Flavor Dynamics in Supernova

Multi-Neutrino Entanglement and Correlations in Dense Neutrino Systems
Marc Illa and Martin J. Savage
Phys. Rev. Lett. **130**, 221003 – Published 31 May 2023

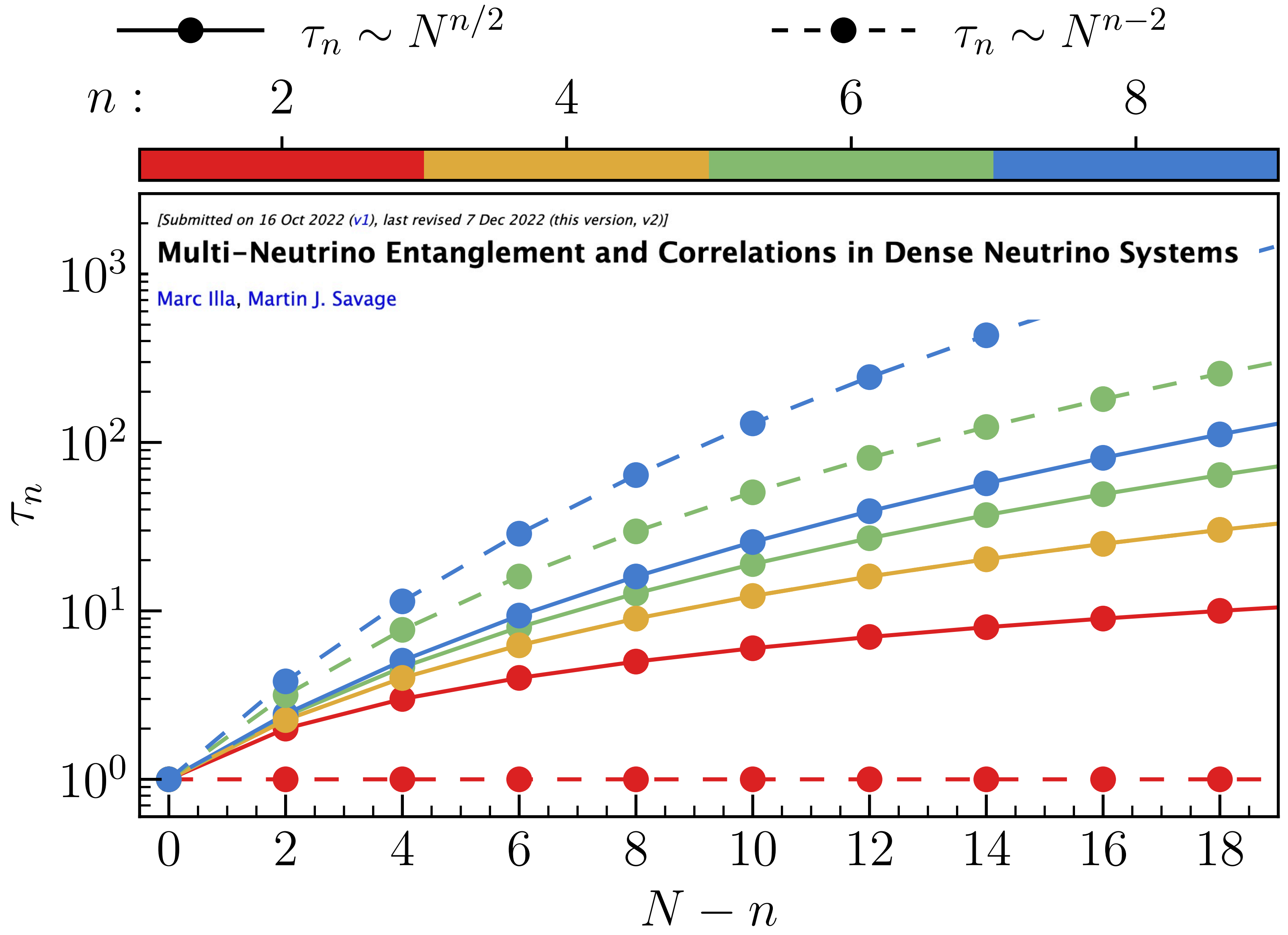
$$H_{FS} = -\sum_{k=1}^{N} \frac{\omega_k}{2}\sigma_k^z + \frac{\mu}{2N}\sum_{i<j}^{N} \mathcal{J}_{ij}\vec{\sigma}_i \cdot \vec{\sigma}_j$$







Multi-Neutrino Entanglement



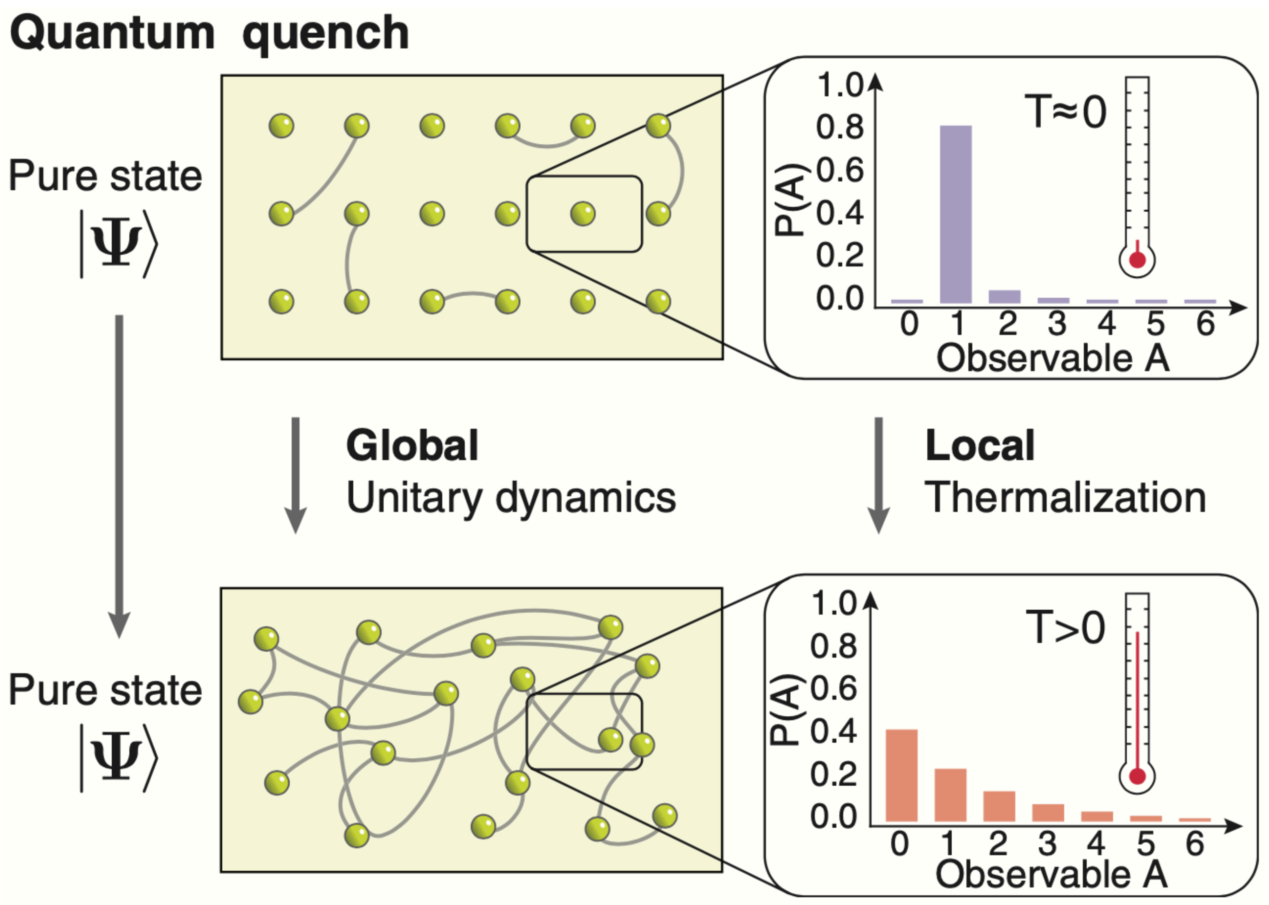
Entanglement and Thermalization

Many key QIS results and a large body of significant work - just starting to enter Nuclear and Particle Physics

STATISTICAL PHYSICS

Quantum thermalization through entanglement in an isolated many-body system

Adam M. Kaufman, M. Eric Tai, Alexander Lukin, Matthew Rispoli, Robert Schittko, Philipp M. Preiss, Markus Greiner*



Kaufman et al, Greiner, Science 353 (2016), p. 794
Polkovnikov, Sels, Science 353 (2016), p. 752

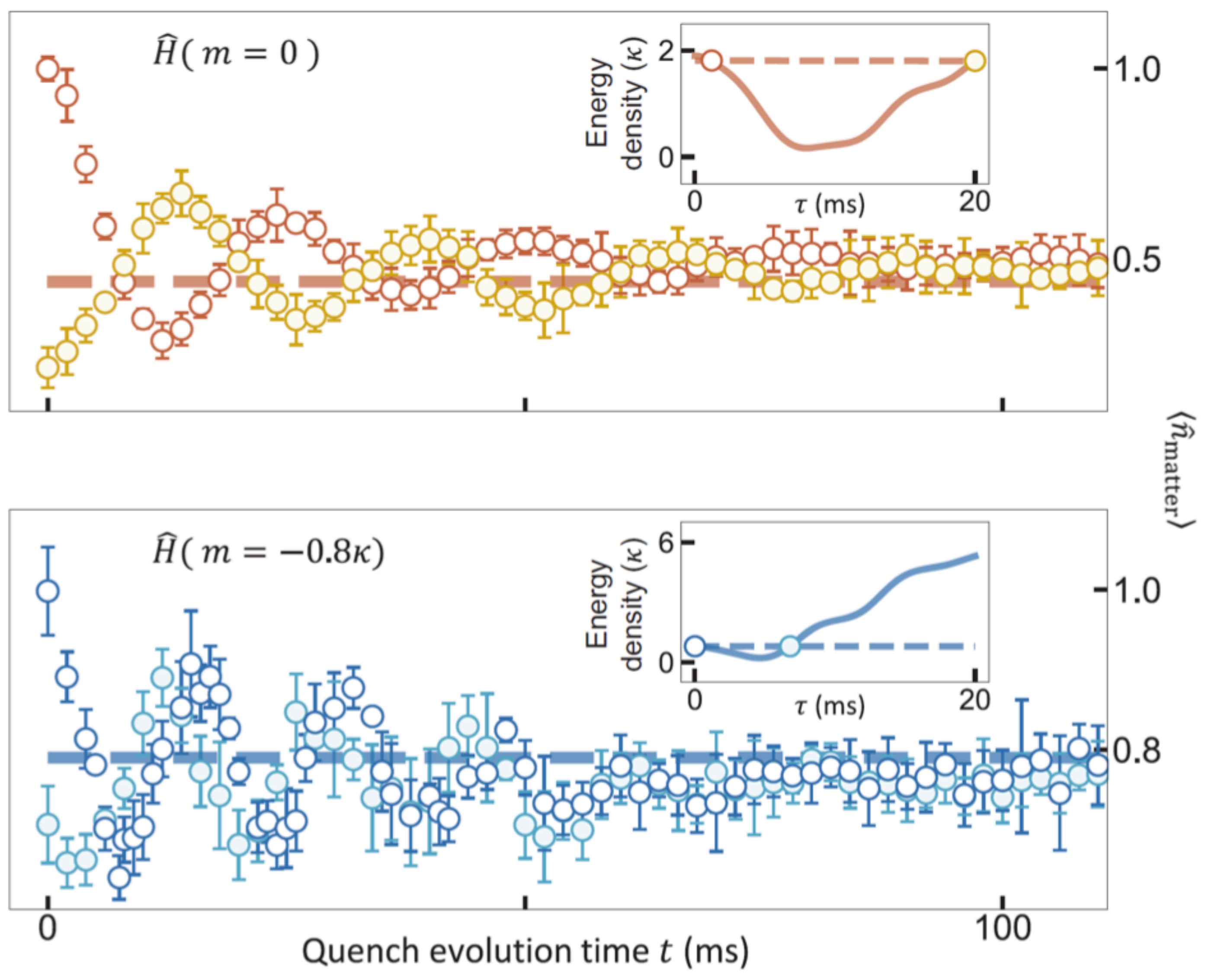
6 Rubidium atoms in an optical trap

Thermalization dynamics of a gauge theory on a quantum simulator

Science **377**, 311–314 (2022)

Zhao-Yu Zhou[1,2,3,4]*†, Guo-Xian Su[1,2,3,4]†, Jad C. Halimeh[5], Robert Ott[6], Hui Sun[1,2,3,4], Philipp Hauke[5], Bing Yang[3,7]‡, Zhen-Sheng Yuan[1,2,3,4,8], Jürgen Berges[6], Jian-Wei Pan[1,2,3,4,8]

U(1) lattice gauge theory, 71 sites ^{87}Rb



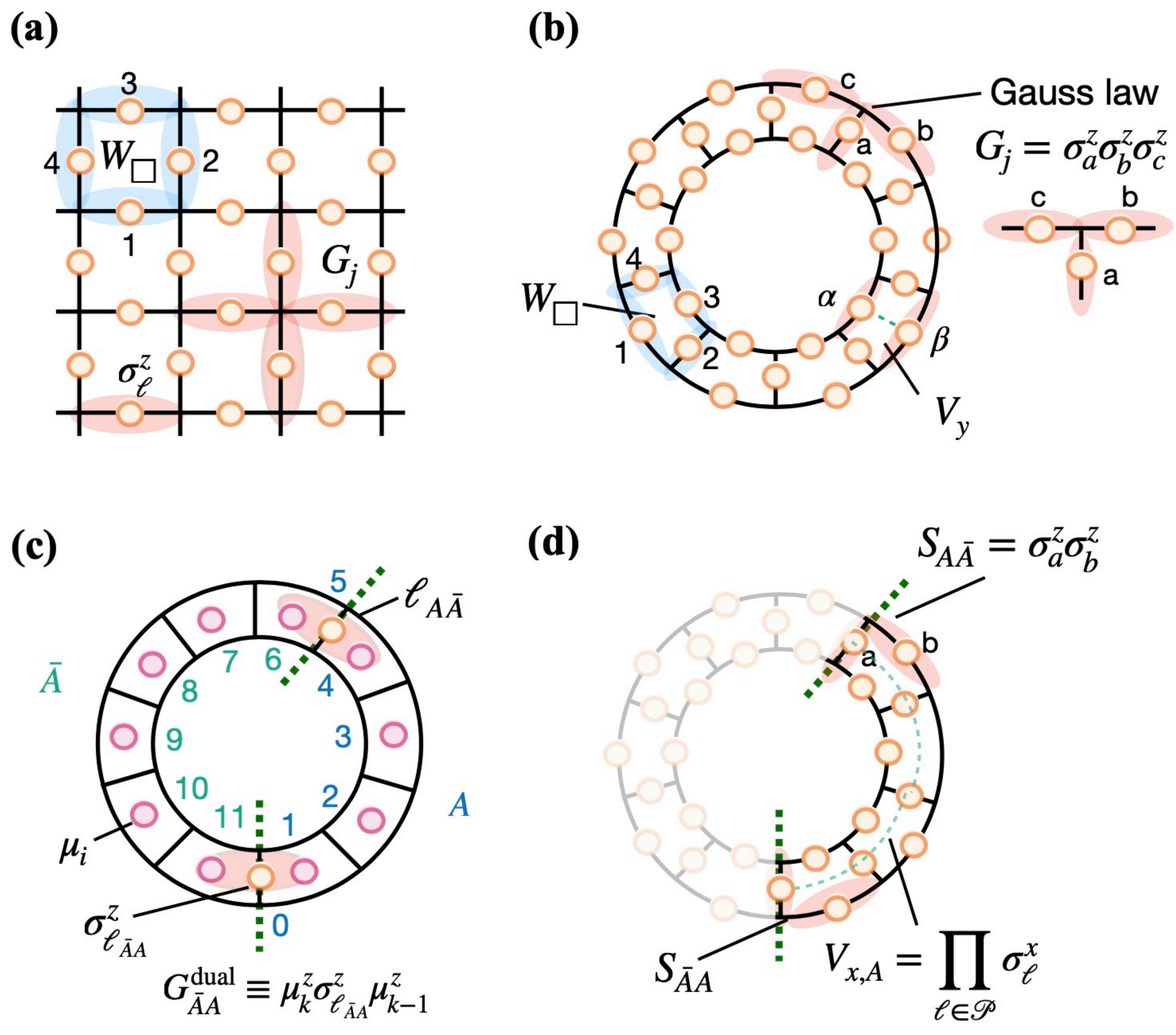
71 Rubidium atoms,
U(1) Lattice Gauge Theory

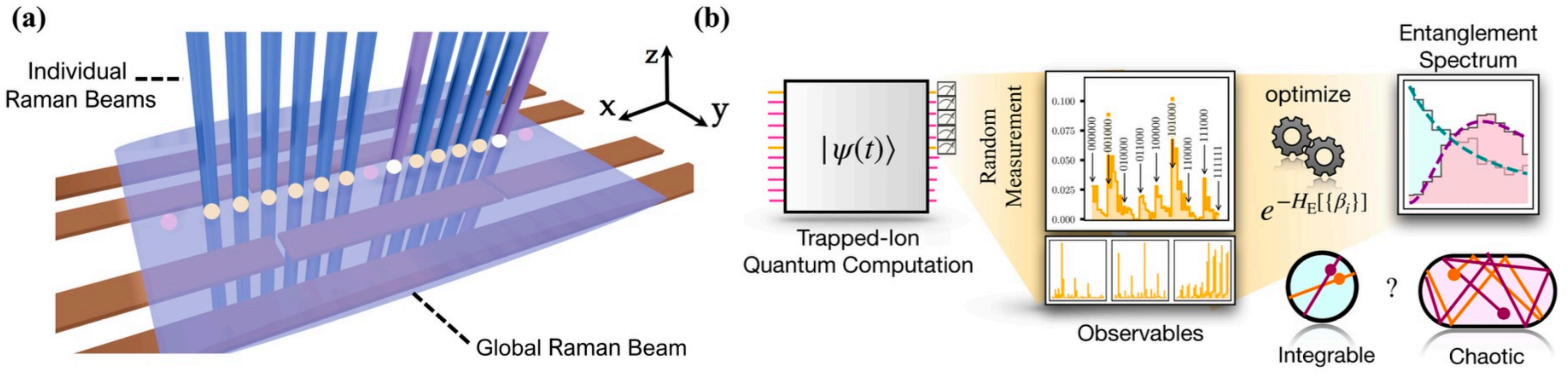
Slide content from Niklas Mueller

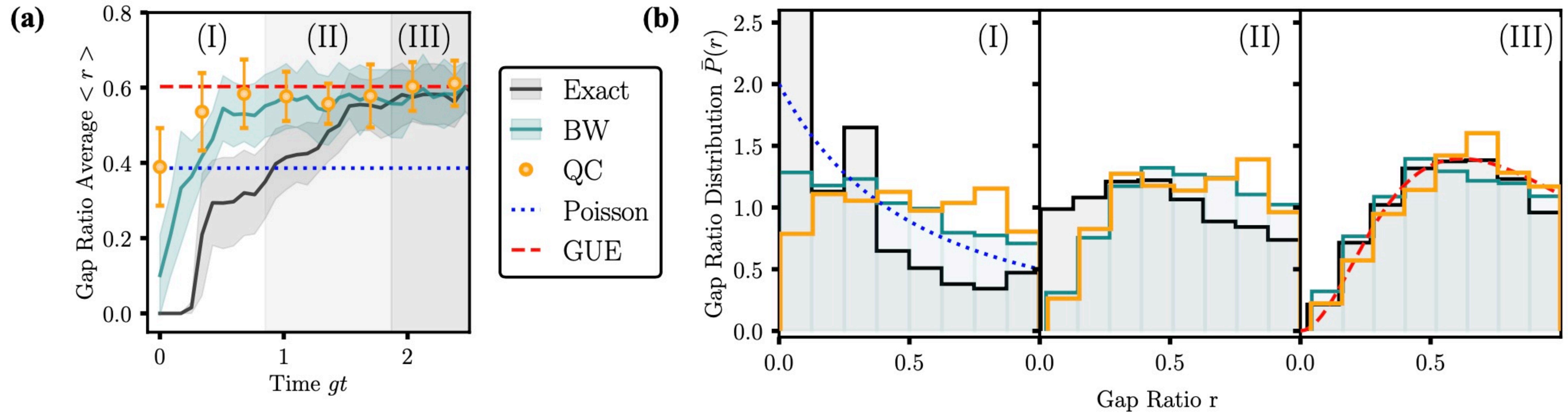
Entanglement and Thermalization

Quantum Computing Universal Thermalization Dynamics in a (2+1)D Lattice Gauge Theory

Niklas Mueller,[1,*] Tianyi Wang,[2,3,4] Or Katz,[3,5,6] Zohreh Davoudi,[7,8,4,9] and Marko Cetina[2,3,5,4]







Magic (non-Stabilizerness)

Aaronson+Gottesman

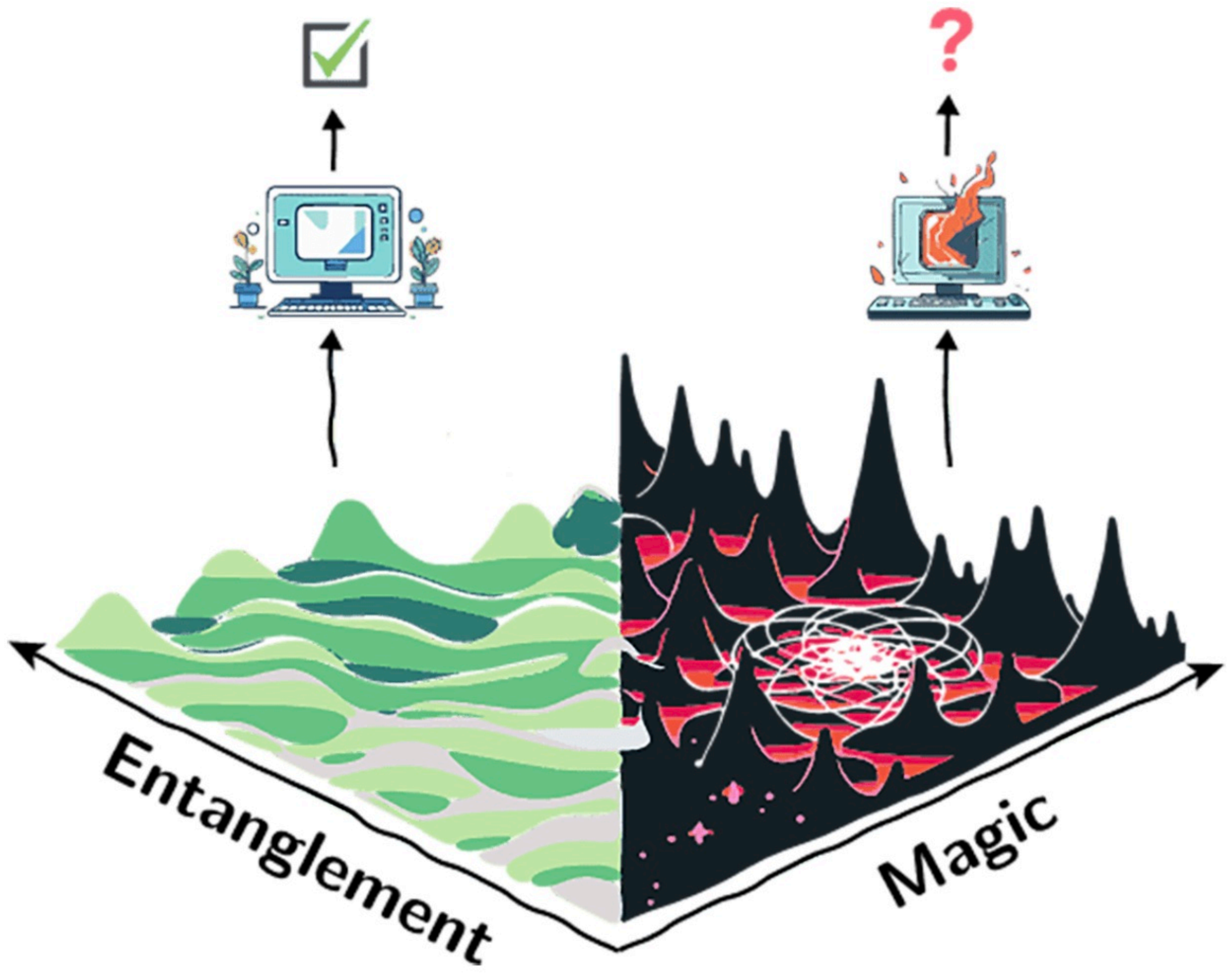
Classical gate set = $\mathrm{H} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$, $\mathrm{S} = \begin{pmatrix} 1 & 0 \\ 0 & i \end{pmatrix}$, $\mathrm{CNOT}_{12} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$

{ Classical gate set } $|0\rangle^{\otimes n}$ = $|\text{Stabilizer State}\rangle$

1-qubit : 6 stabilizer states
2-qubits: 60 stabilizer states
3-qubits: 1080 stabilizer states

Quantum resources required to prepare states that cannot be accessed using the classical gate set

Quantum gate set = Classical gate set + $\mathrm{T} = \begin{pmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{pmatrix}$



Magic-induced computational separation in entanglement theory

Andi Gu,[1] Salvatore F.E. Oliviero,[2] and Lorenzo Leone[3]

Magic are measures of non-stabilizerness

Classical computing needs scale exponentially with Magic

Entanglement and Magic Phase Transitions

Entanglement–magic separation in hybrid quantum circuits

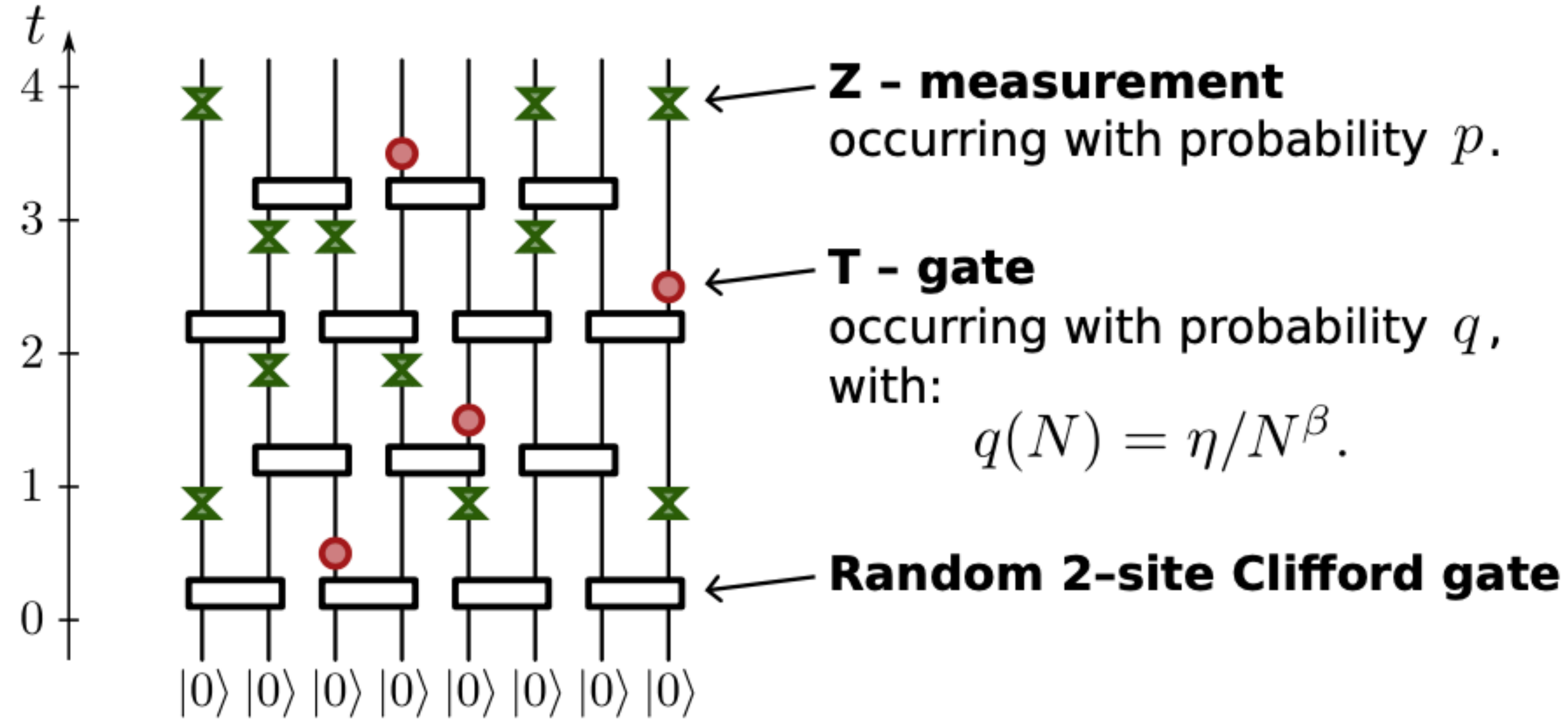
Gerald E. Fux,[1] Emanuele Tirrito,[1,2] Marcello Dalmonte,[1,3] and Rosario Fazio[1,4]

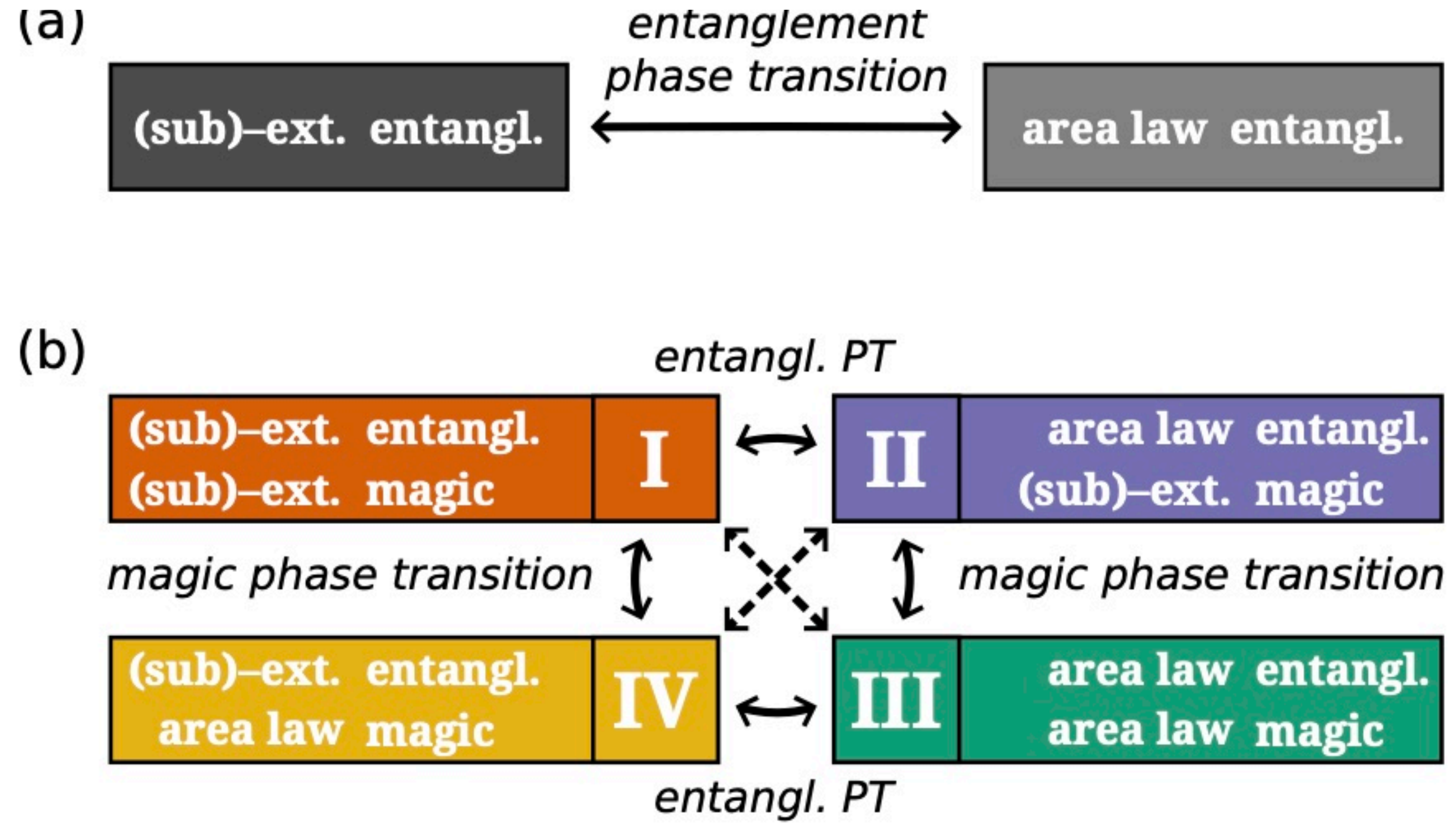
[1] *The Abdus Salam International Center for Theoretical Physics (ICTP), Strada Costiera 11, 34151 Trieste, Italy*
[2] *Pitaevskii BEC Center, CNR-INO and Dipartimento di Fisica, Università di Trento, Via Sommarive 14, Trento, I-38123, Italy*
[3] *Scuola Internazionale Superiore di Studi Avanzati (SISSA), Via Bonomea 265, 34136 Trieste, Italy*
[4] *Dipartimento di Fisica "E. Pancini", Università di Napoli "Federico II", Monte S. Angelo, I-80126 Napoli, Italy*

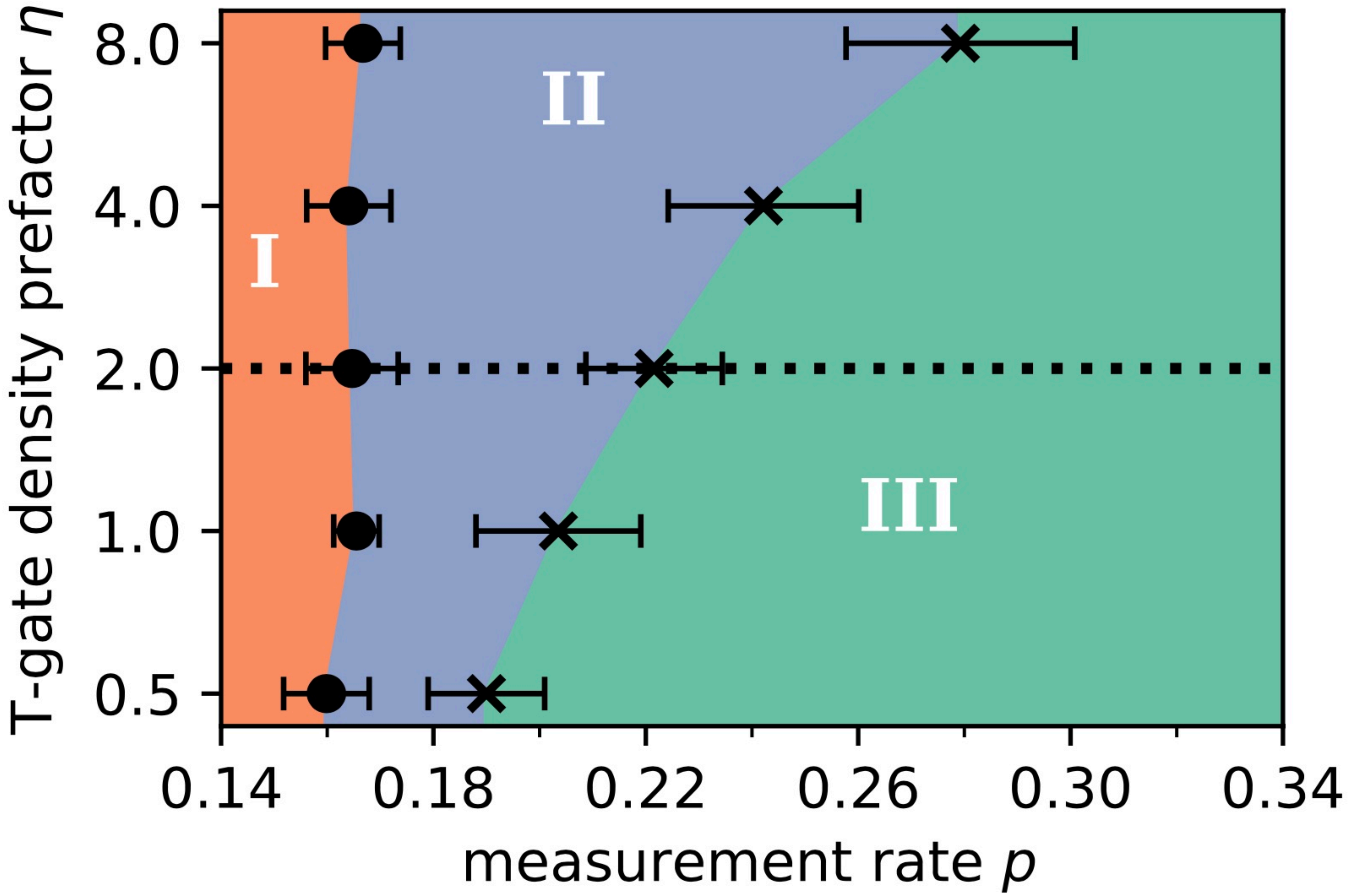
(Dated: December 12, 2023)

Magic phase transition and non-local complexity in generalized W State

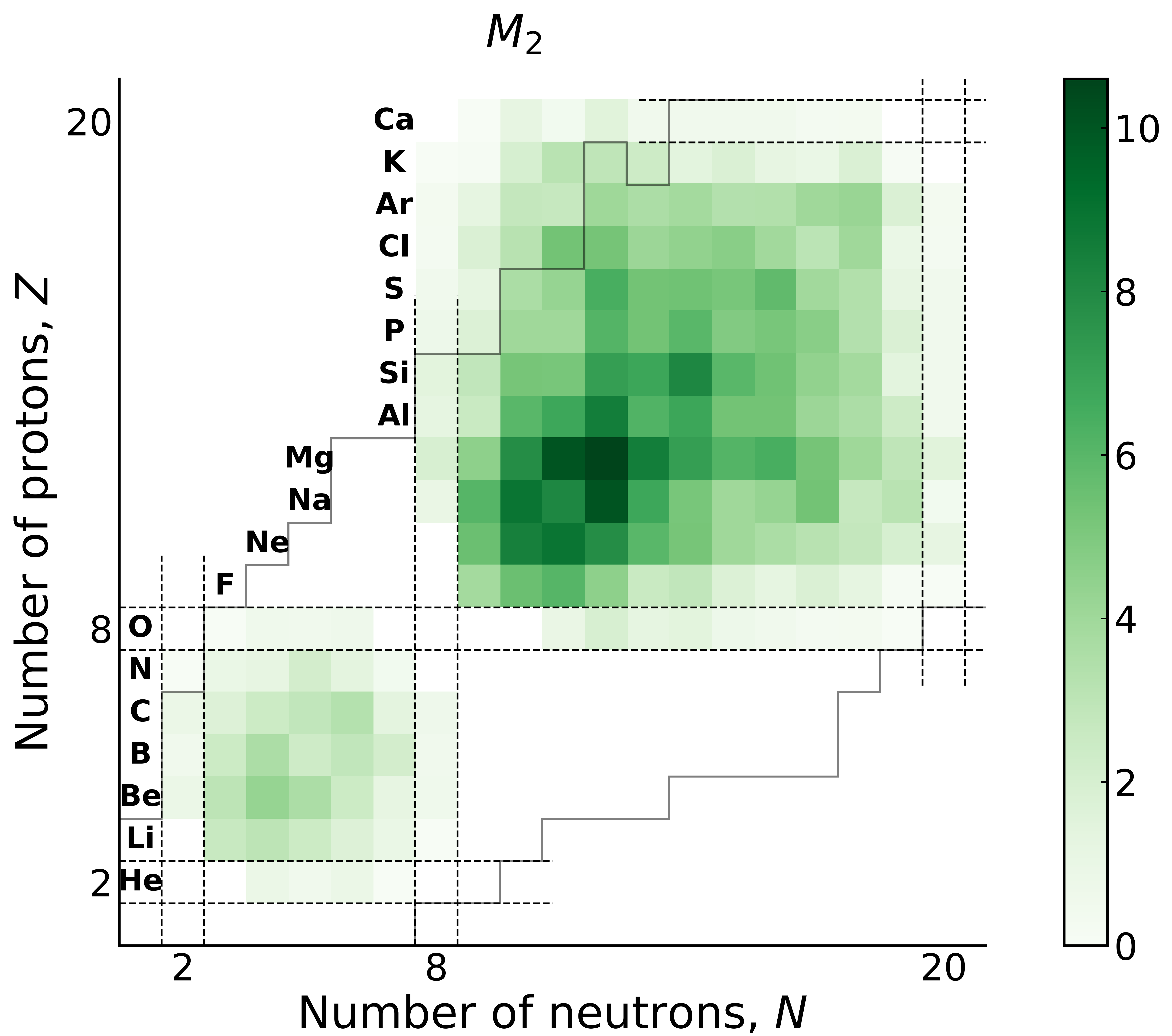
A. G. Catalano,[1,2] J. Odavić,[1,3,4] G. Torre,[1] A. Hamma,[3,4] F. Franchini,[1] and S. M. Giampaolo[1]







Magic and Multi-Partite Entanglement in Nuclei



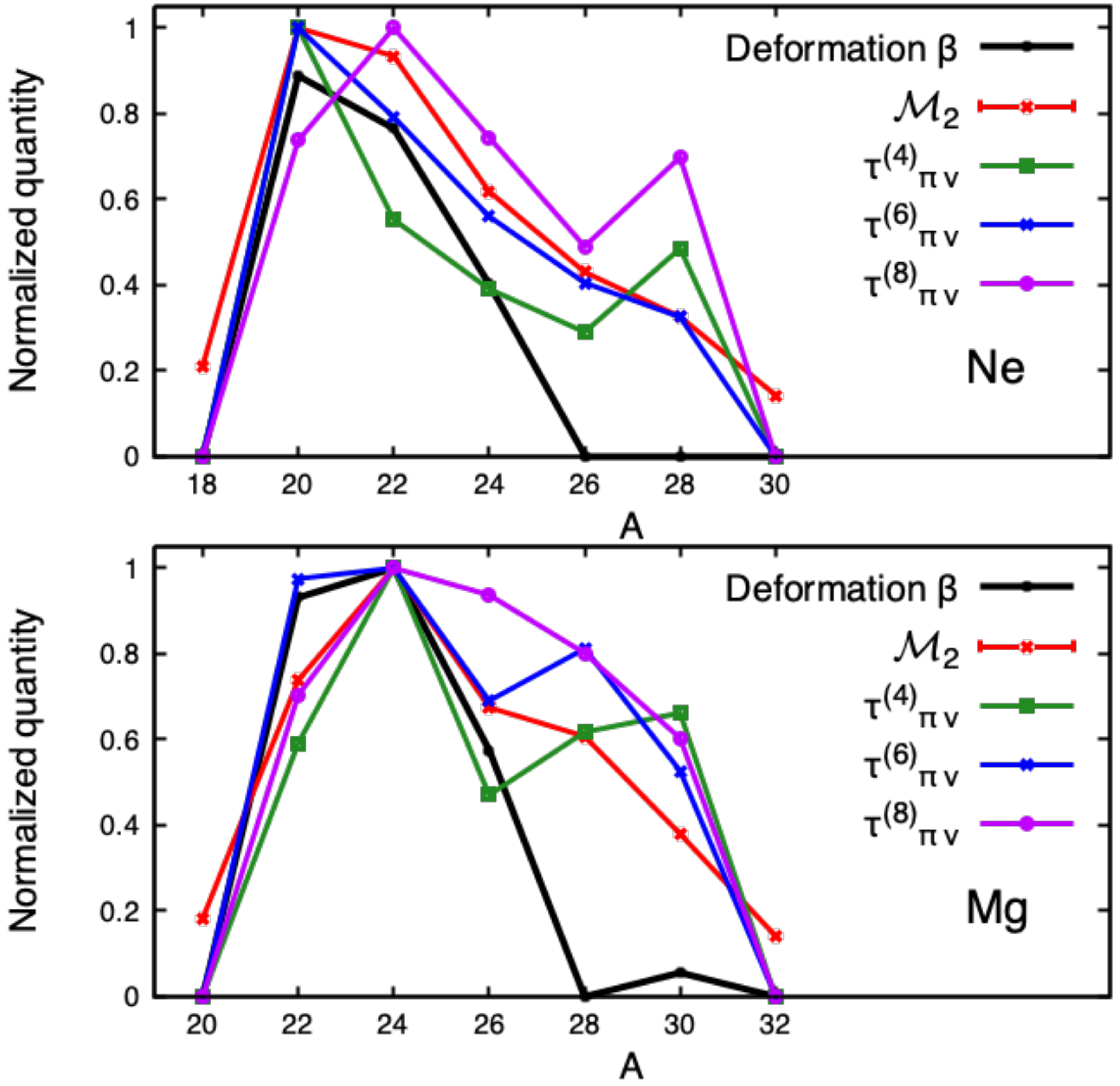

arXiv > nucl-th > arXiv:2409.12064

Nuclear Theory

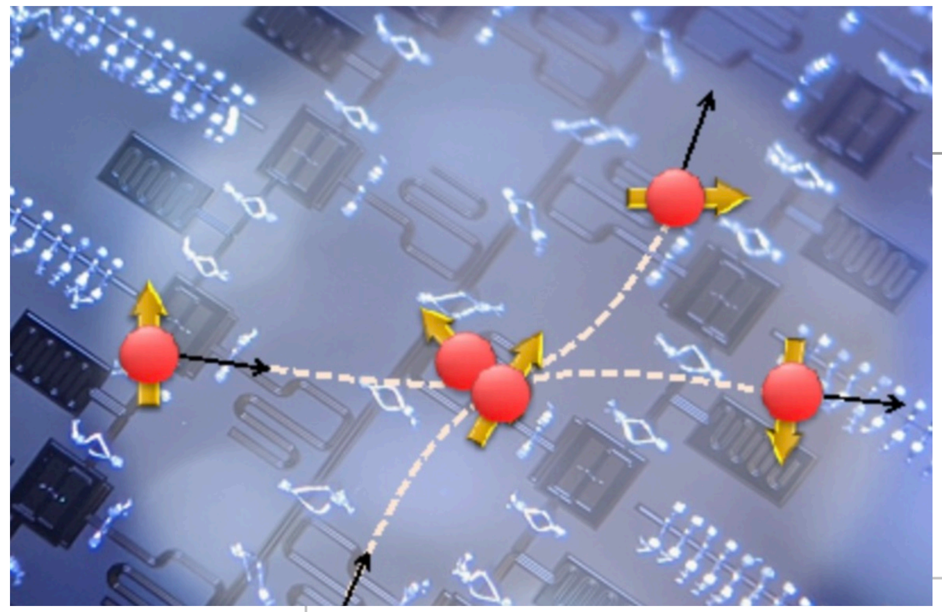
[Submitted on 18 Sep 2024]

Quantum Magic and Multi-Partite Entanglement in the Structure of Nuclei

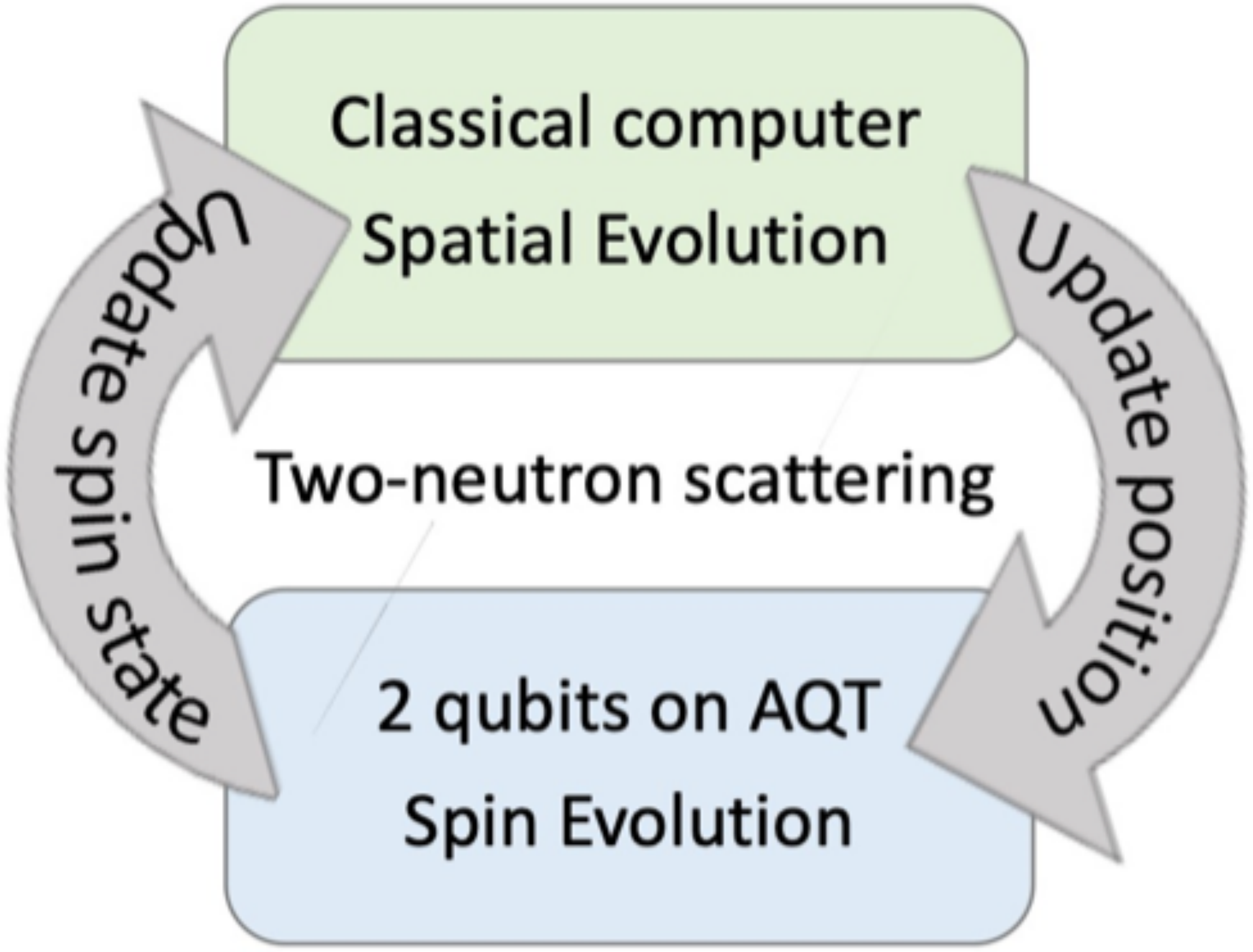
Florian Brökemeier, S. Momme Hengstenberg, James W. T. Keeble, Caroline E. P. Robin, Federico Rocco, Martin J. Savage

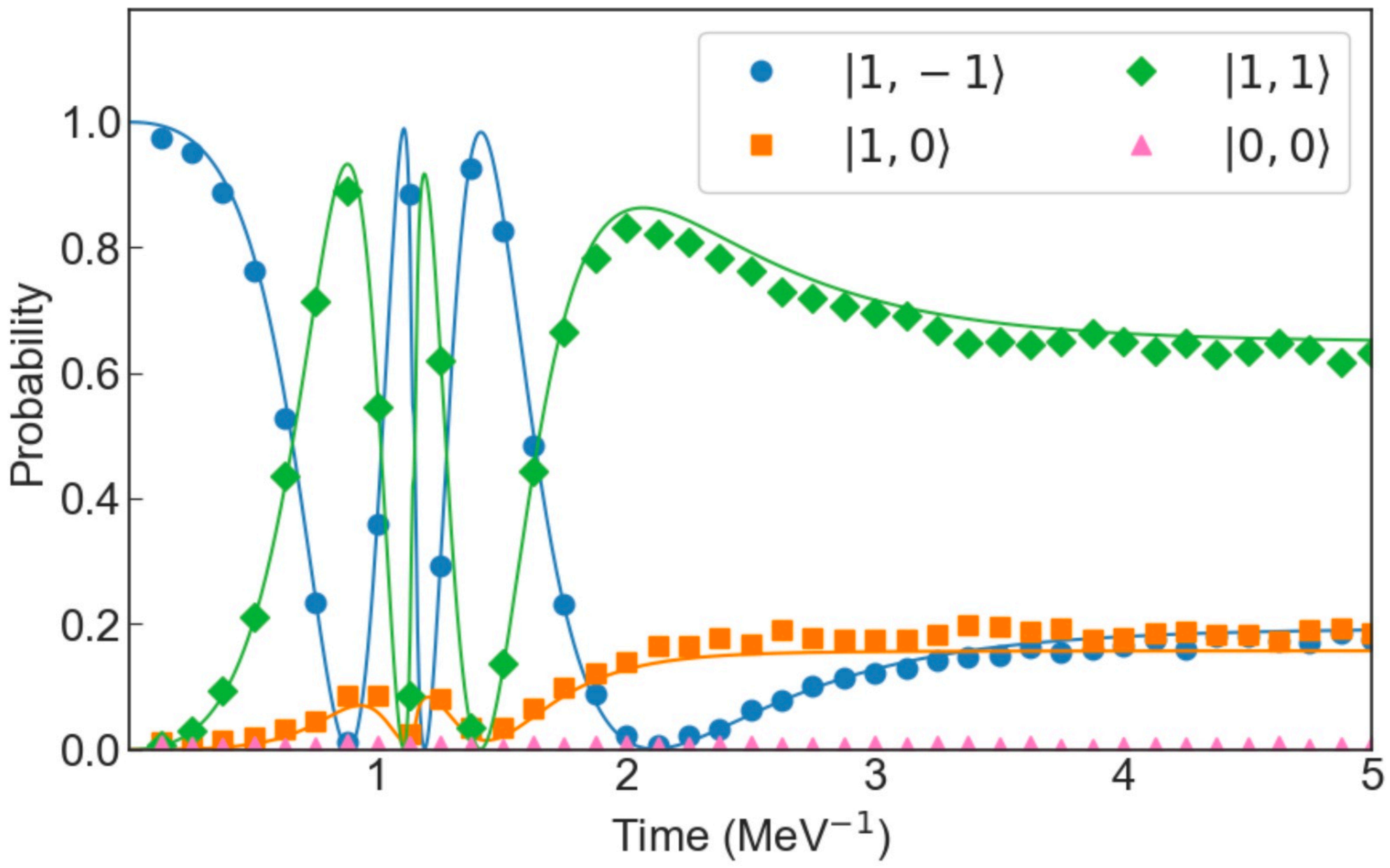


Neutron Scattering with Hybrid Quantum Simulation



LLNL+Trento

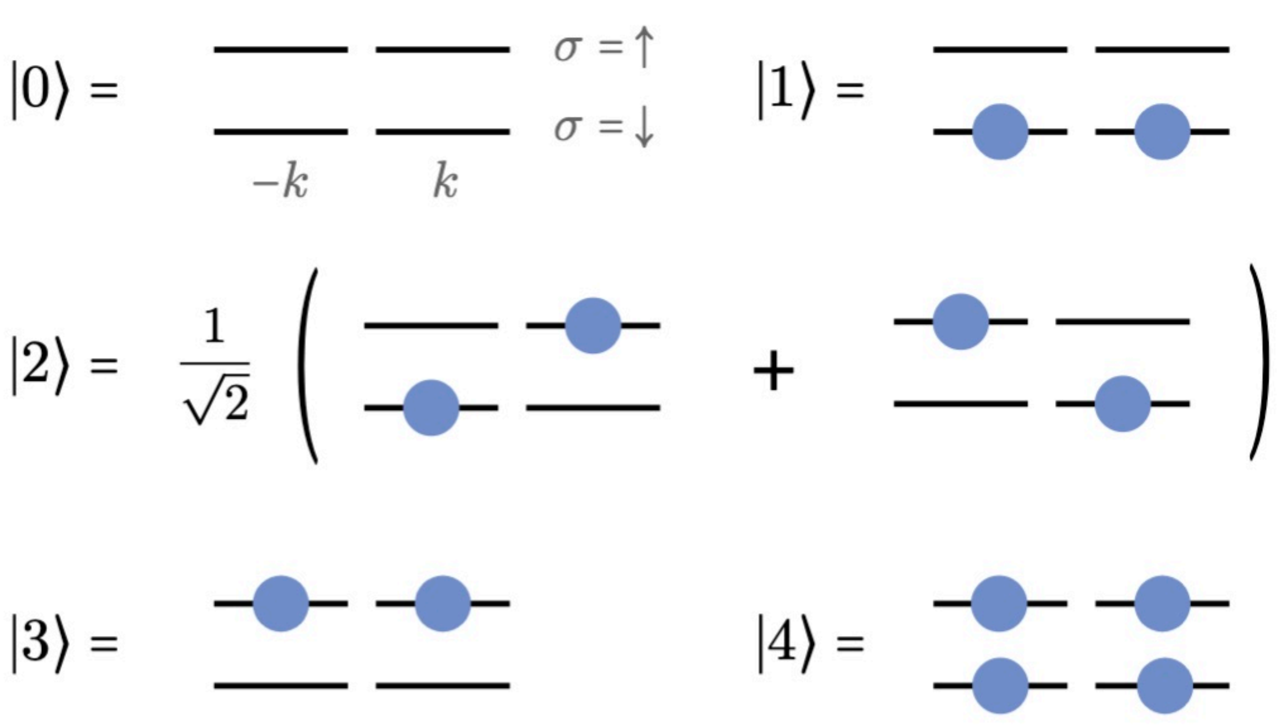


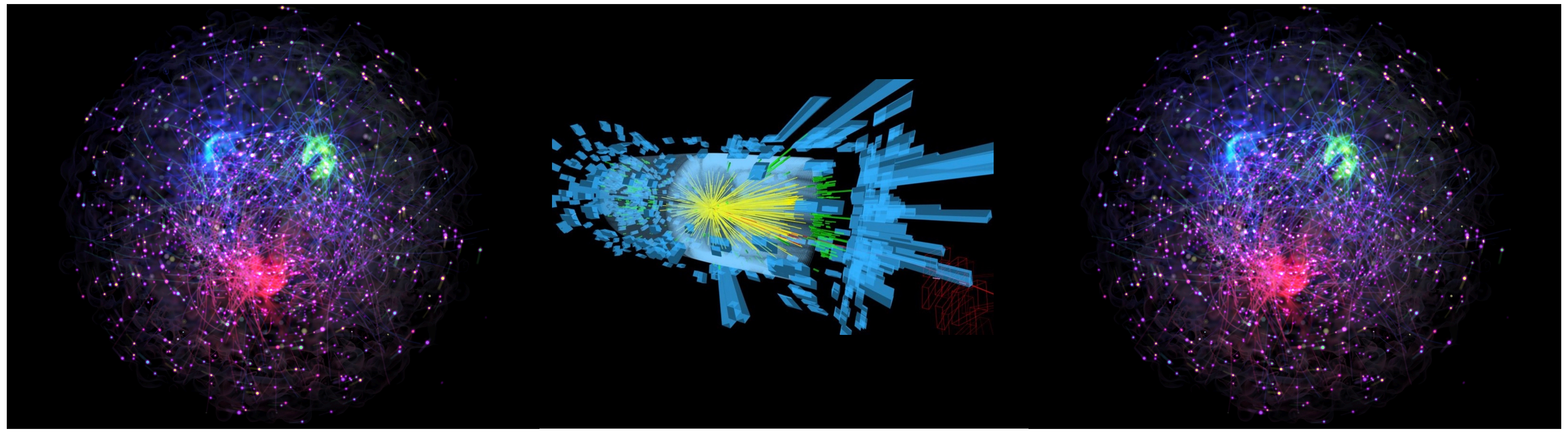


Lessons from the LMG and Agassi Models
"Sign Problems" in Evolution

Quantum Simulations of SO(5) Many-Fermion Systems using Qudits

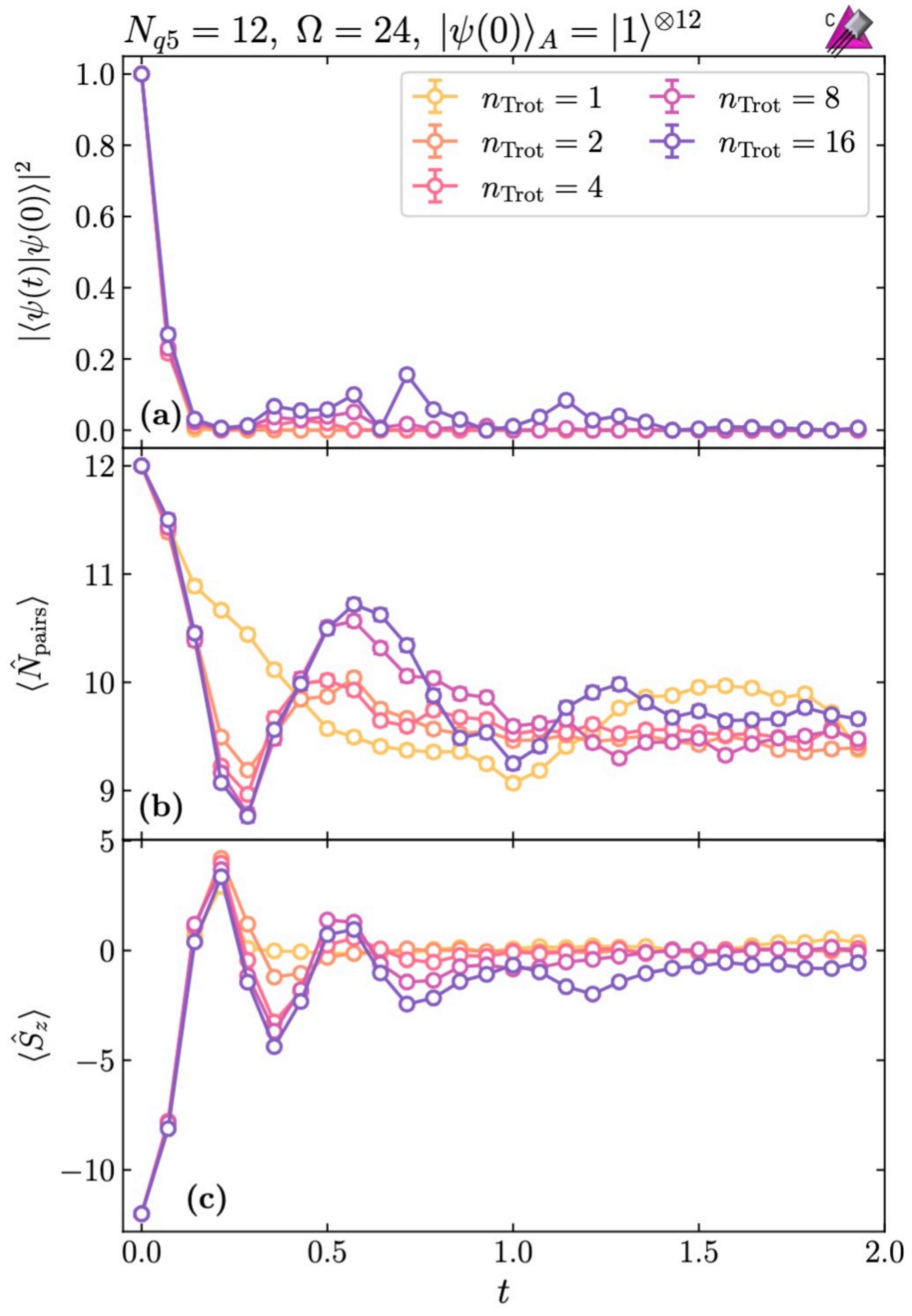
Marc Illa[1,*] Caroline E. P. Robin[2,3,†] and Martin J. Savage[1,‡]



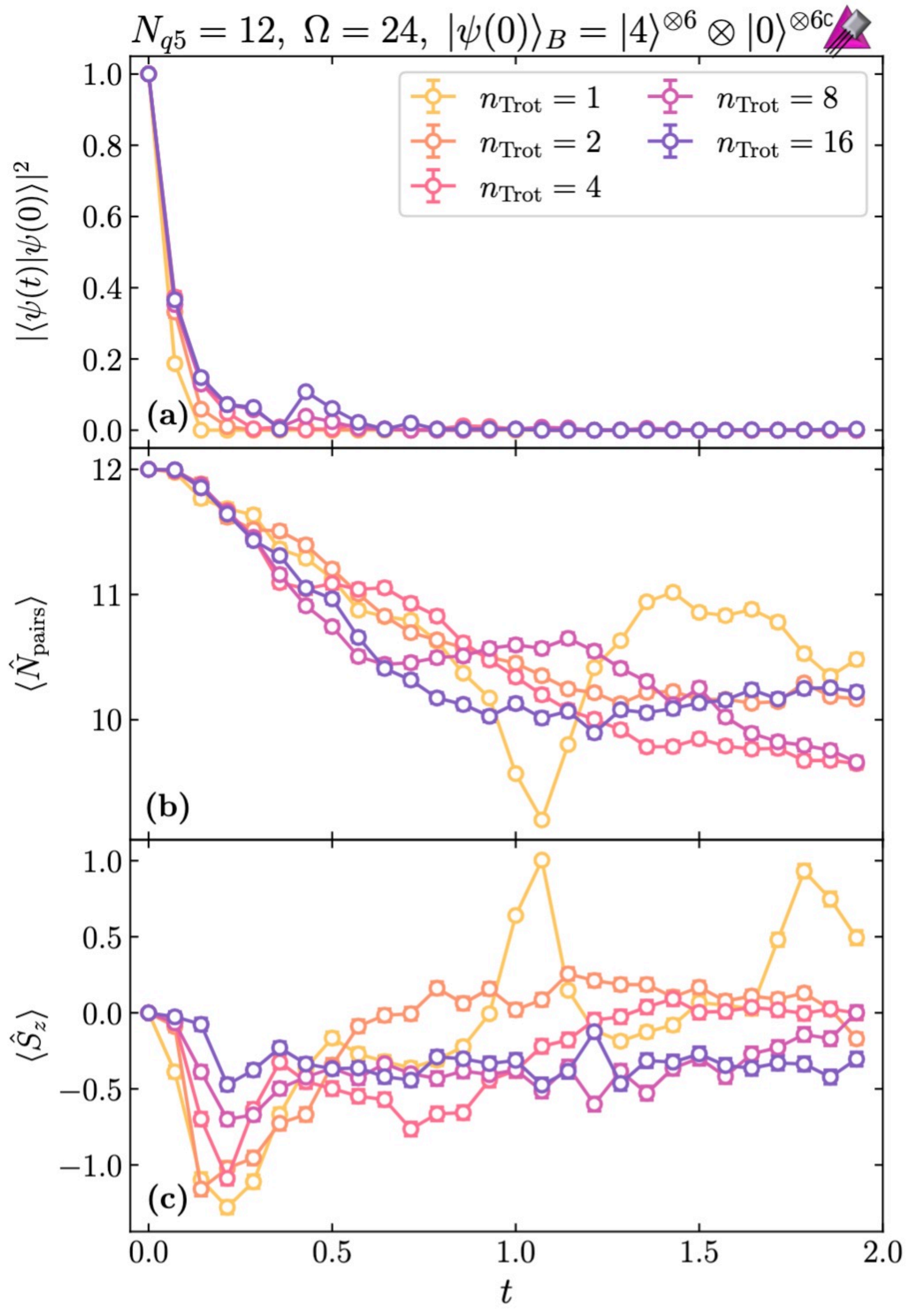


2 high-energetic energy particles collide to produce many lower energy particles

Low in spectrum



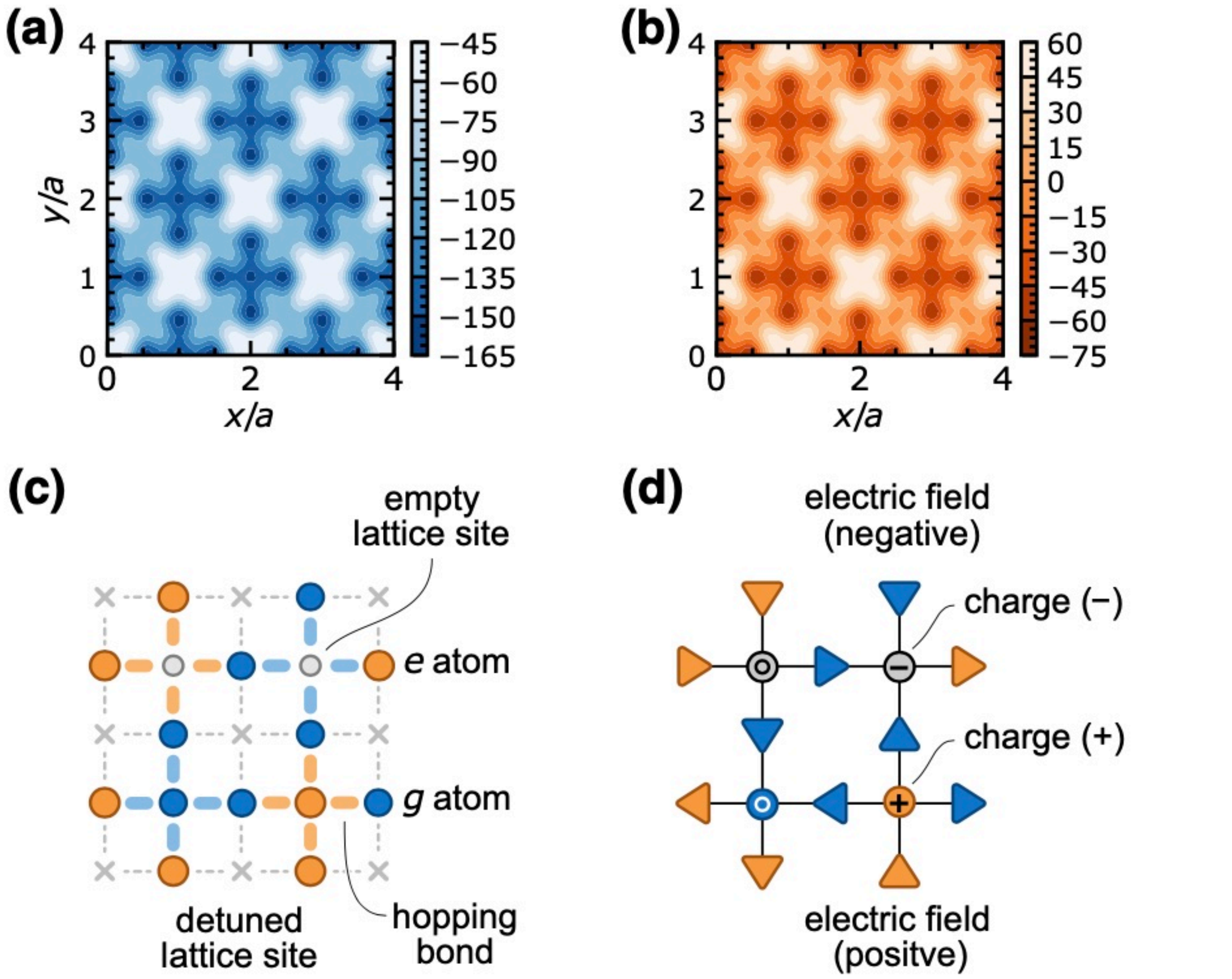
High in spectrum



Some New Directions

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

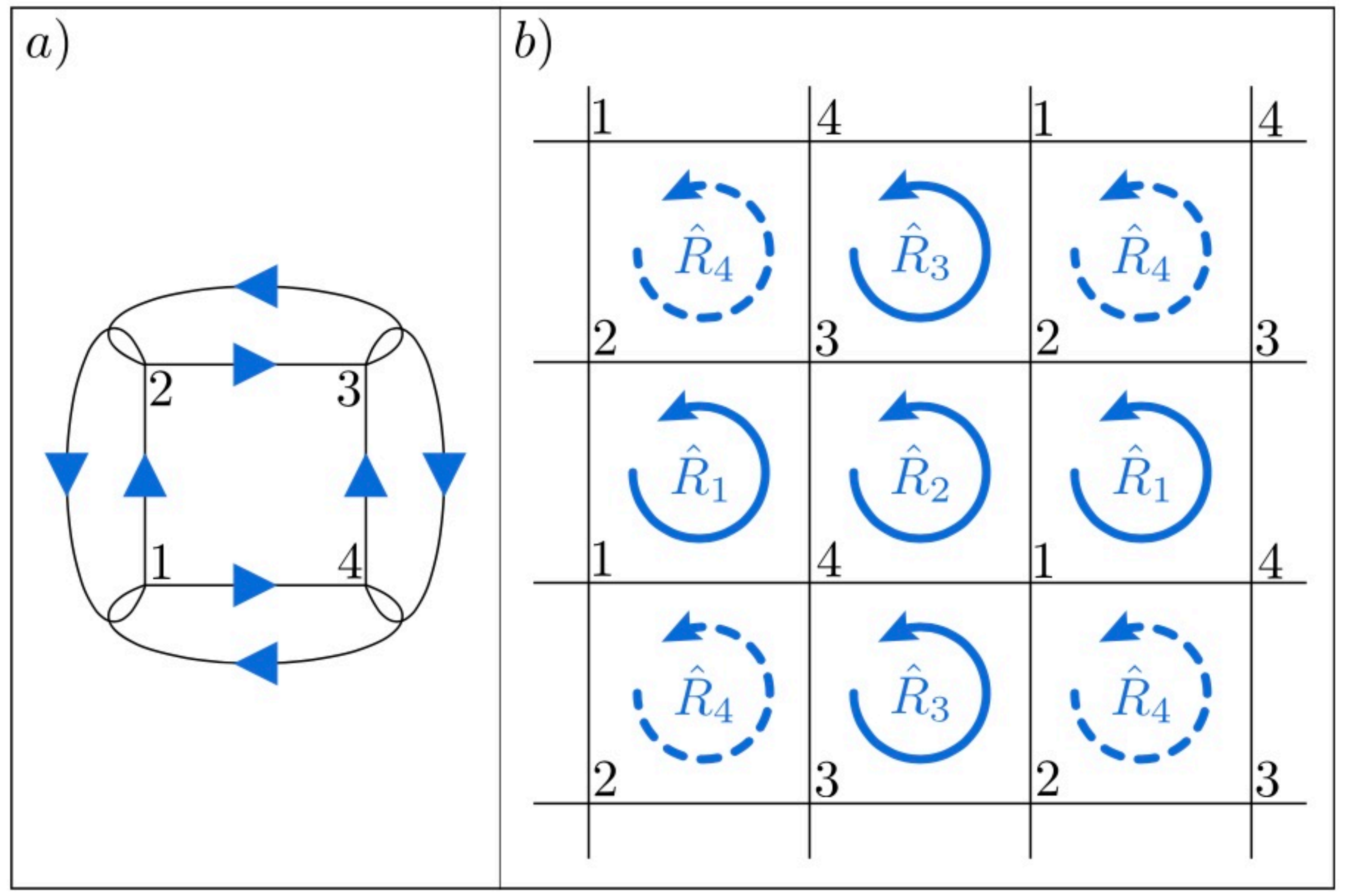
Federica Maria Surace,[1,*] Pierre Fromholz,[2,3,†] Nelson Darkwah Oppong,[4,5,§]
Marcello Dalmonte,[2,3] and Monika Aidelsburger[4,5,‡]



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

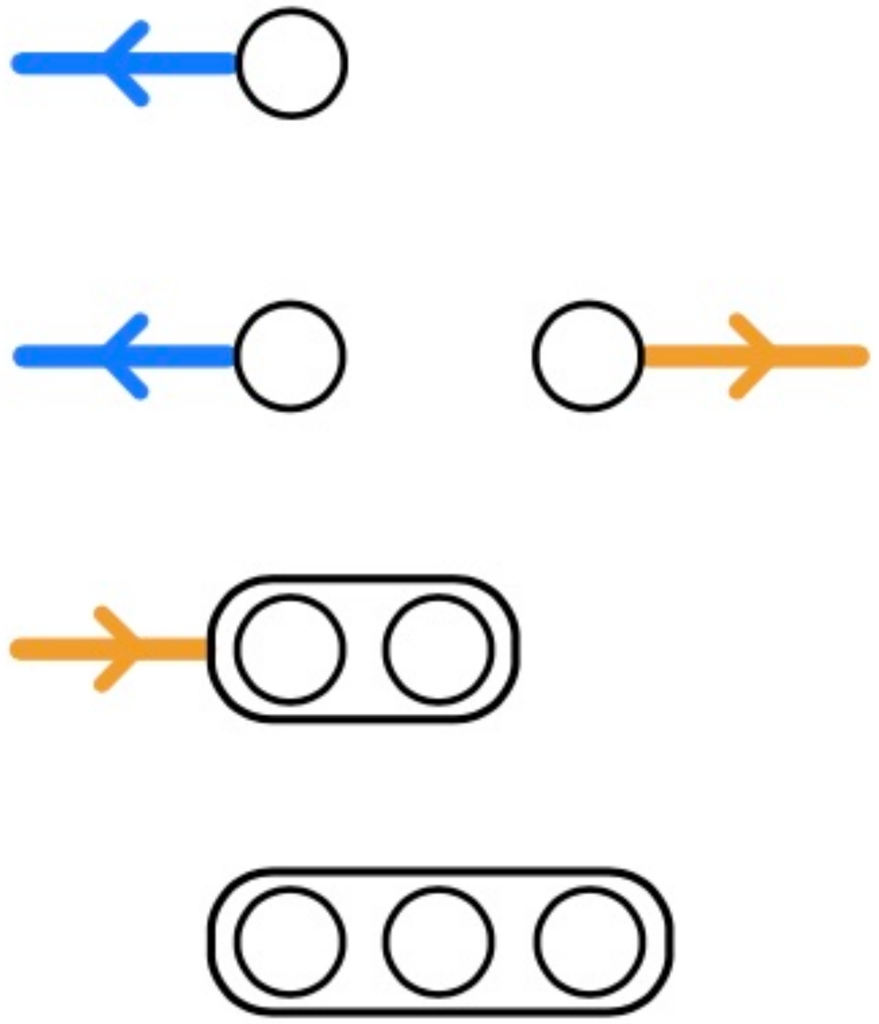
Jan F. Haase[1,2], Luca Dellantonio[1,2], Alessio Celi[3,4], Danny Paulson[1,2],
Angus Kan[1,2], Karl Jansen[5], and Christine A. Muschik[1,2,6]

2021



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,‡]



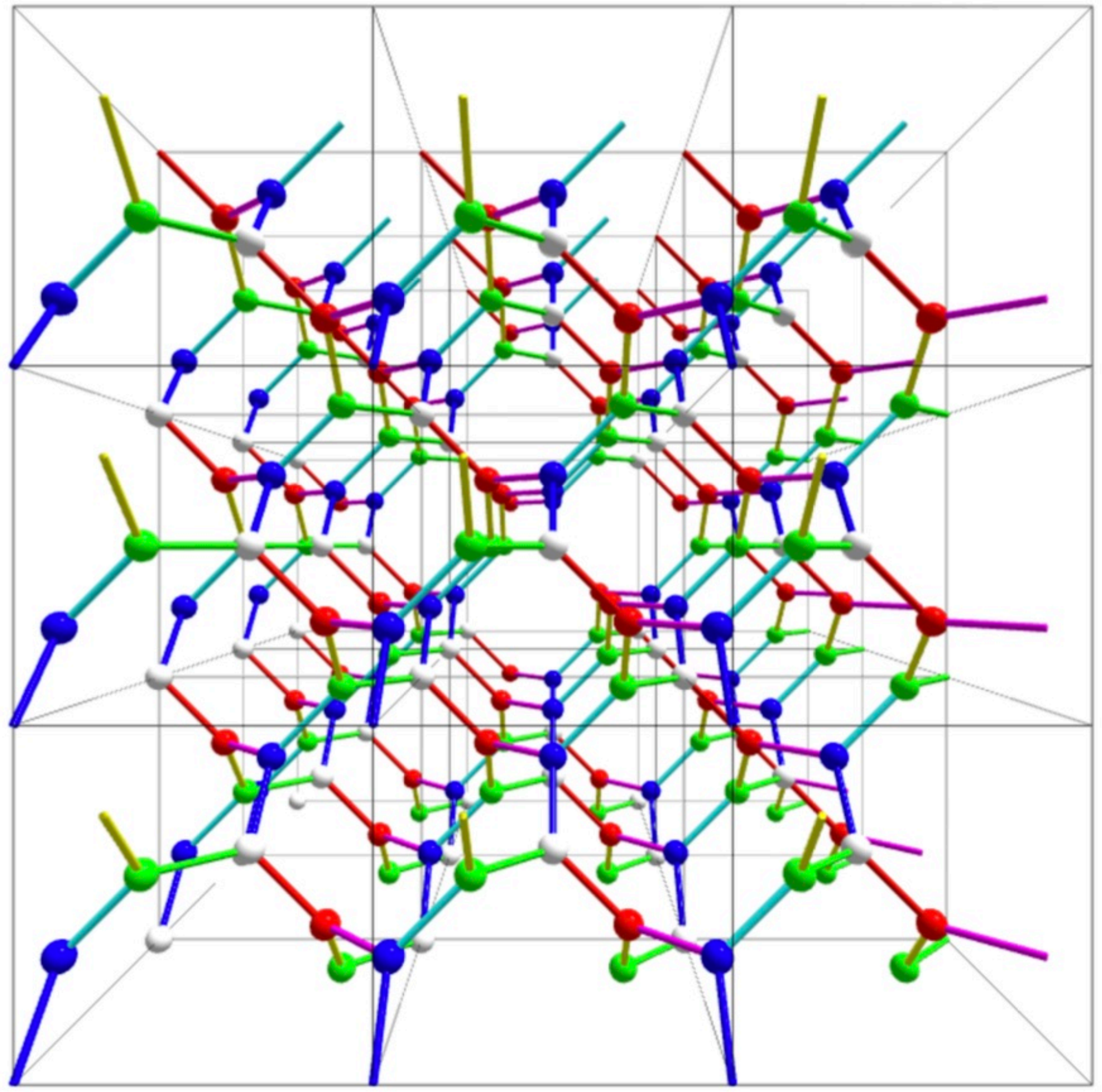
2018-2024

Some New Directions

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

Ali H. Z. Kavaki* and Randy Lewis†

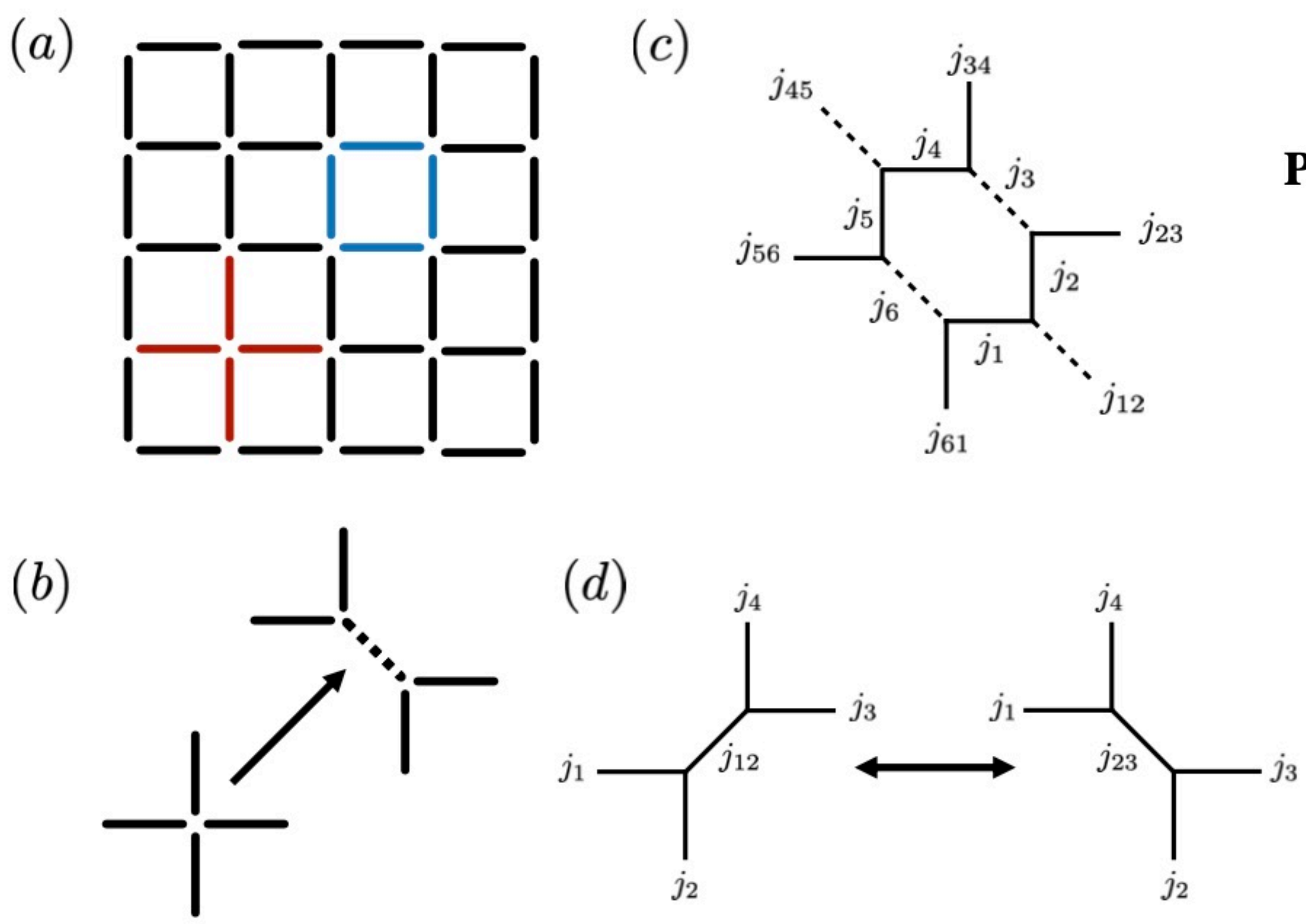
2024



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

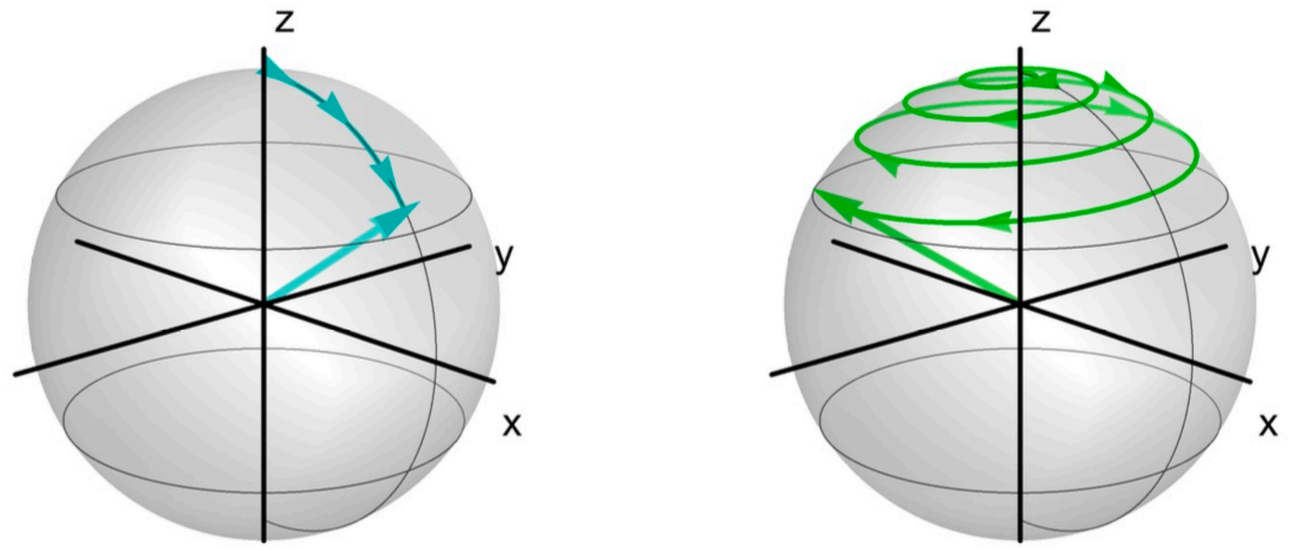
Torsten V. Zache,* Daniel González-Cuadra, and Peter Zoller

2023



State Preparation in the Heisenberg Model through Adiabatic Spiraling

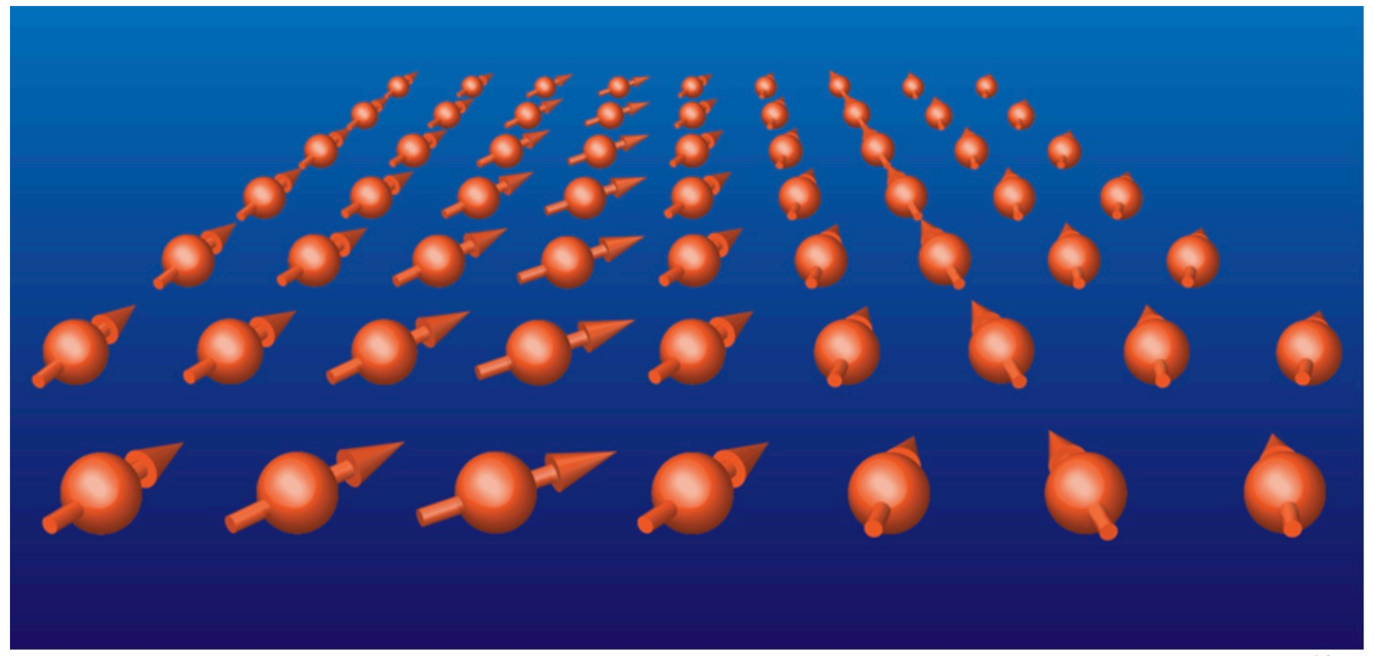
Anthony N. Ciavarella, Stephan Caspar, Marc Illa, and Martin J. Savage



(a) Laboratory (b) Interaction Picture

Preparation for Quantum Simulation of the 1+1D O(3) Non-linear σ-Model using Cold Atoms

Anthony N. Ciavarella,* Stephan Caspar,† Hersh Singh,‡ and Martin J. Savage§

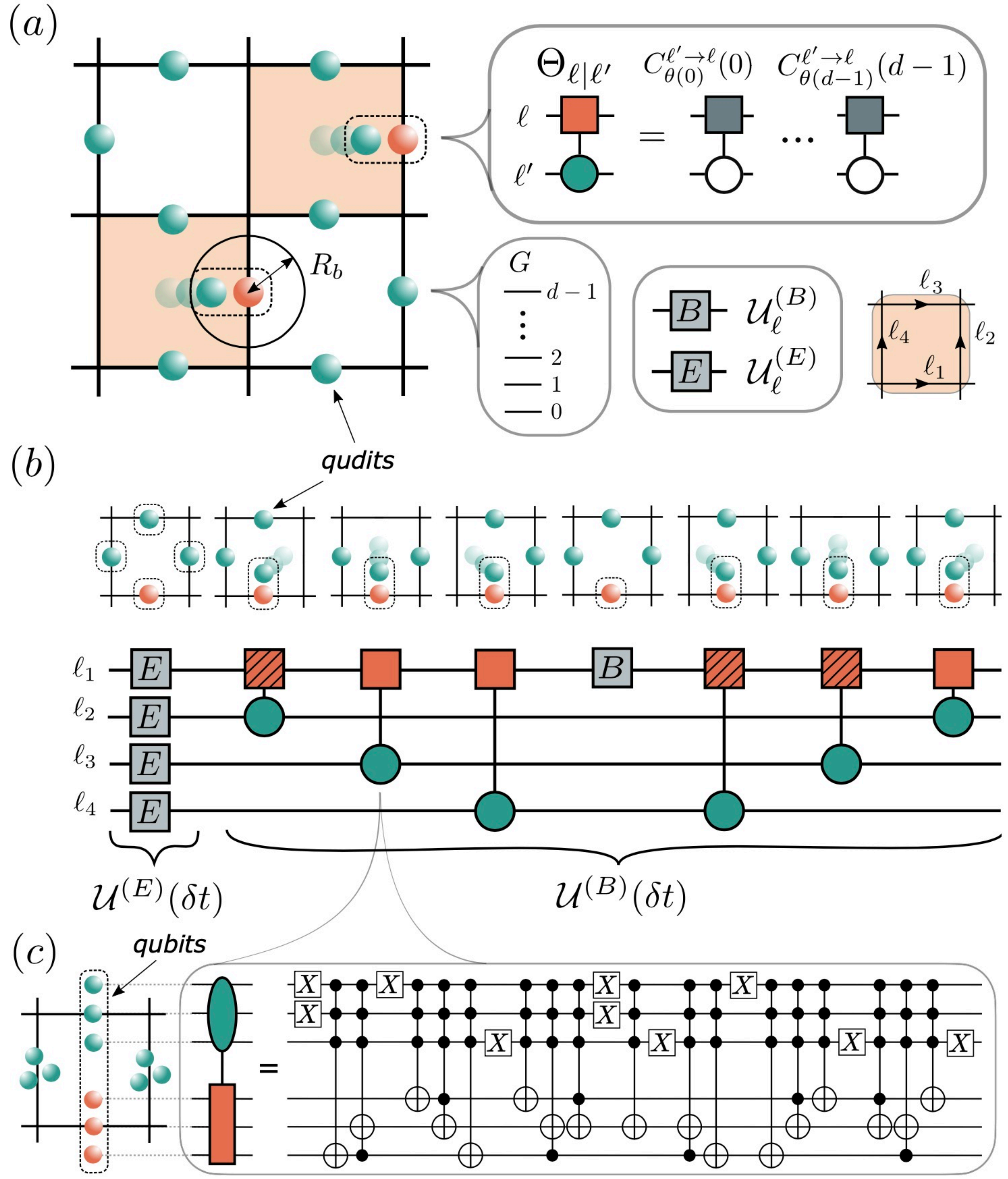


APS/Alan Stonebraker

Qudits

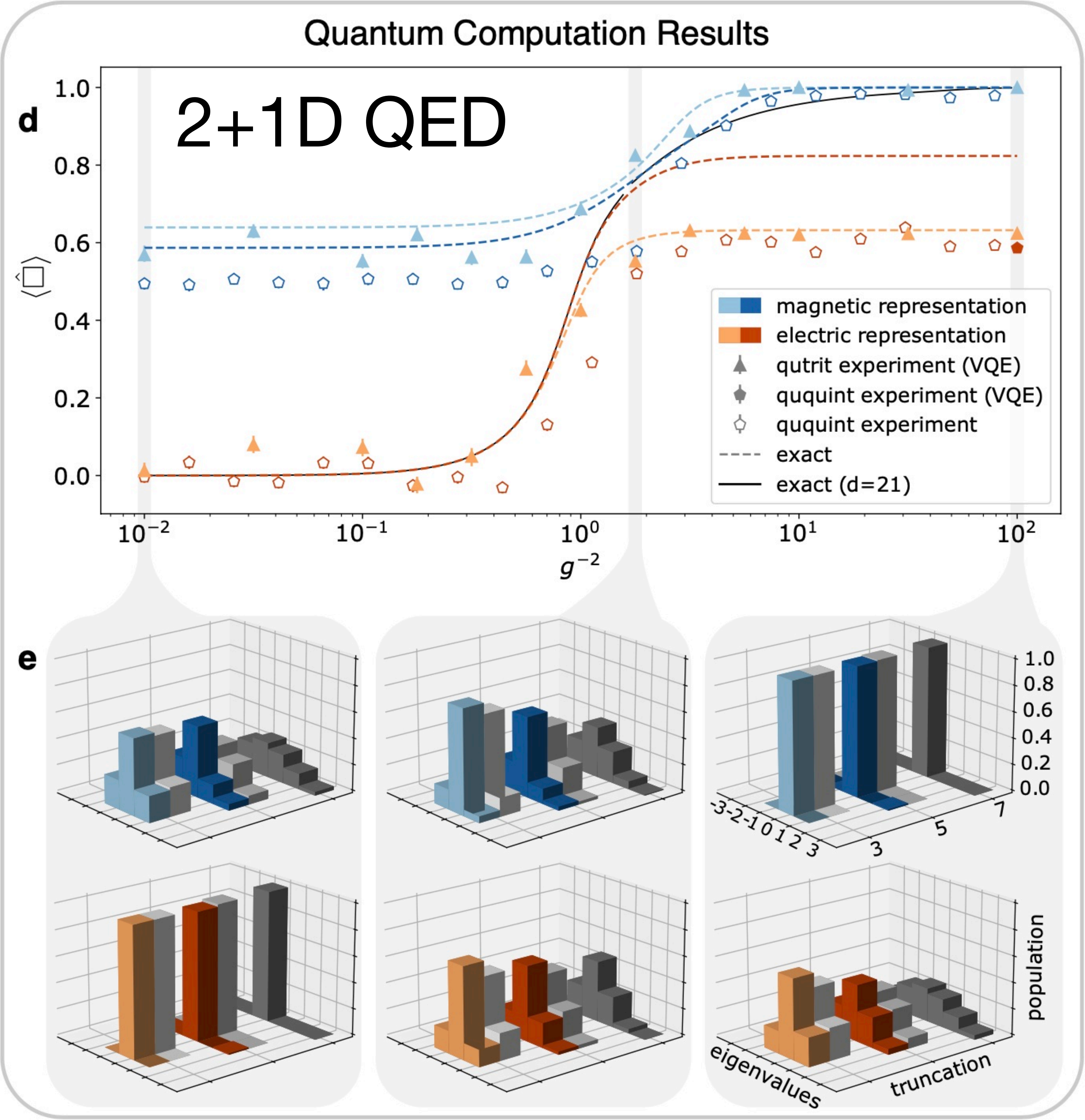
Hardware efficient quantum simulation of non-abelian gauge theories with qudits on Rydberg platforms

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]



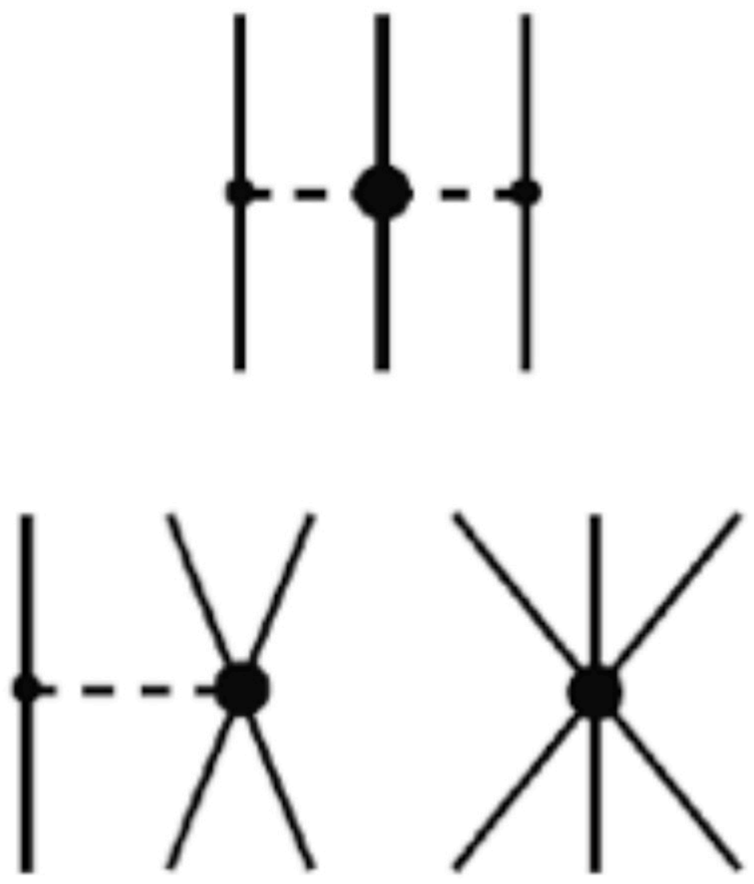
N-body Gates in Trapped Ion Systems
Co-Design in Action

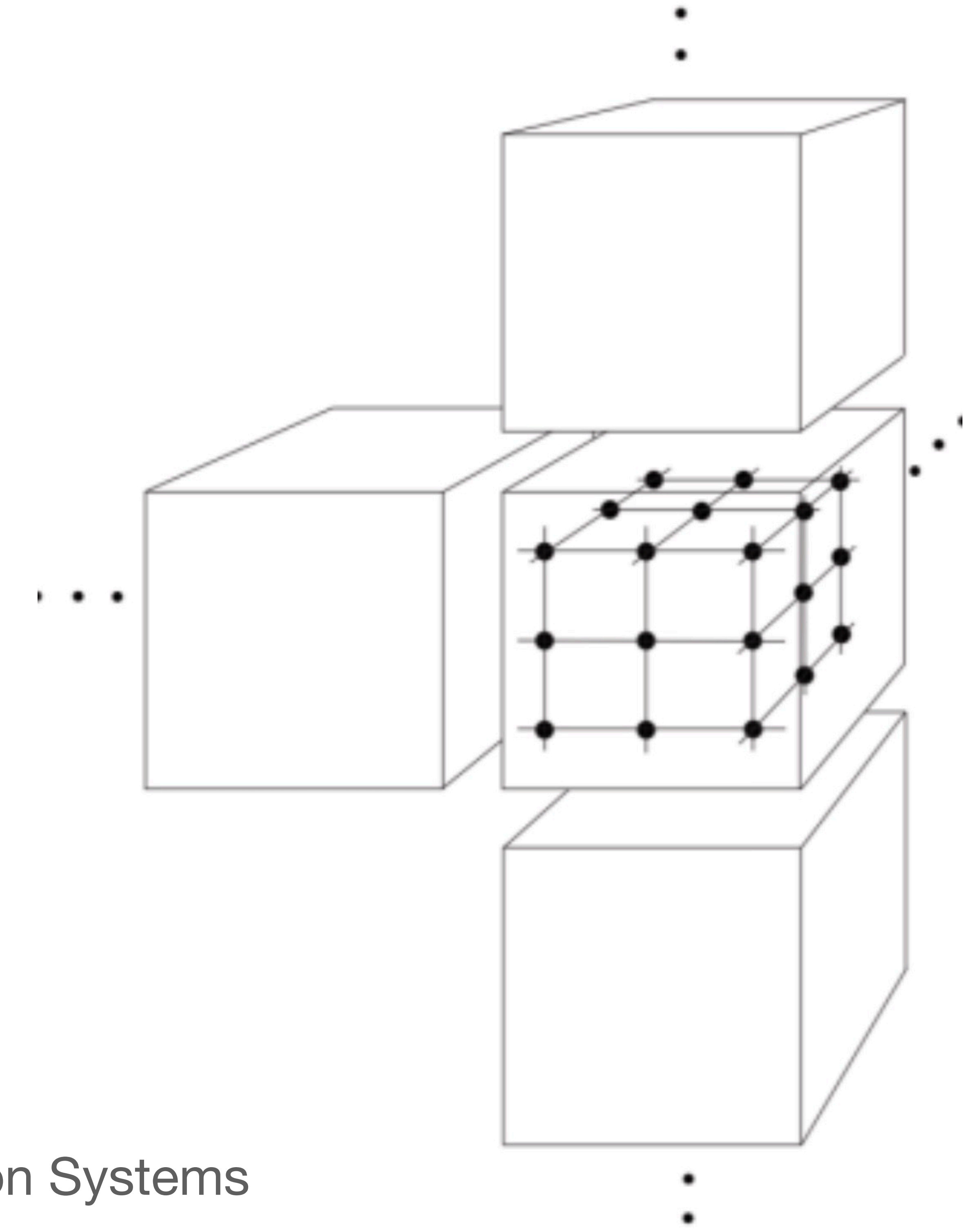
Engineering an Effective Three-spin Hamiltonian in Trapped-ion Systems for Applications in Quantum Simulation

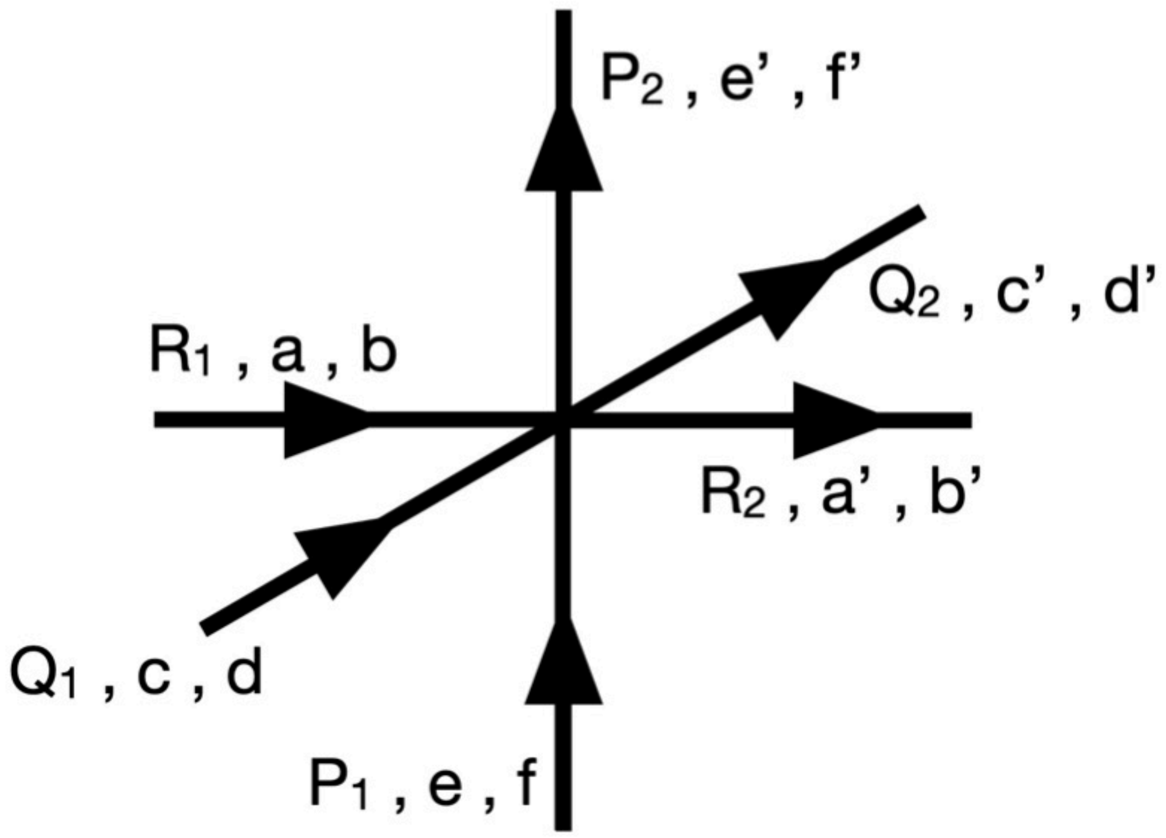
Bárbara Andrade,[1] Zohreh Davoudi,[2] Tobias Graß,[1] Mohammad Hafezi,[3,4] Guido Pagano,[5] and Alireza Seif[6,*]

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]







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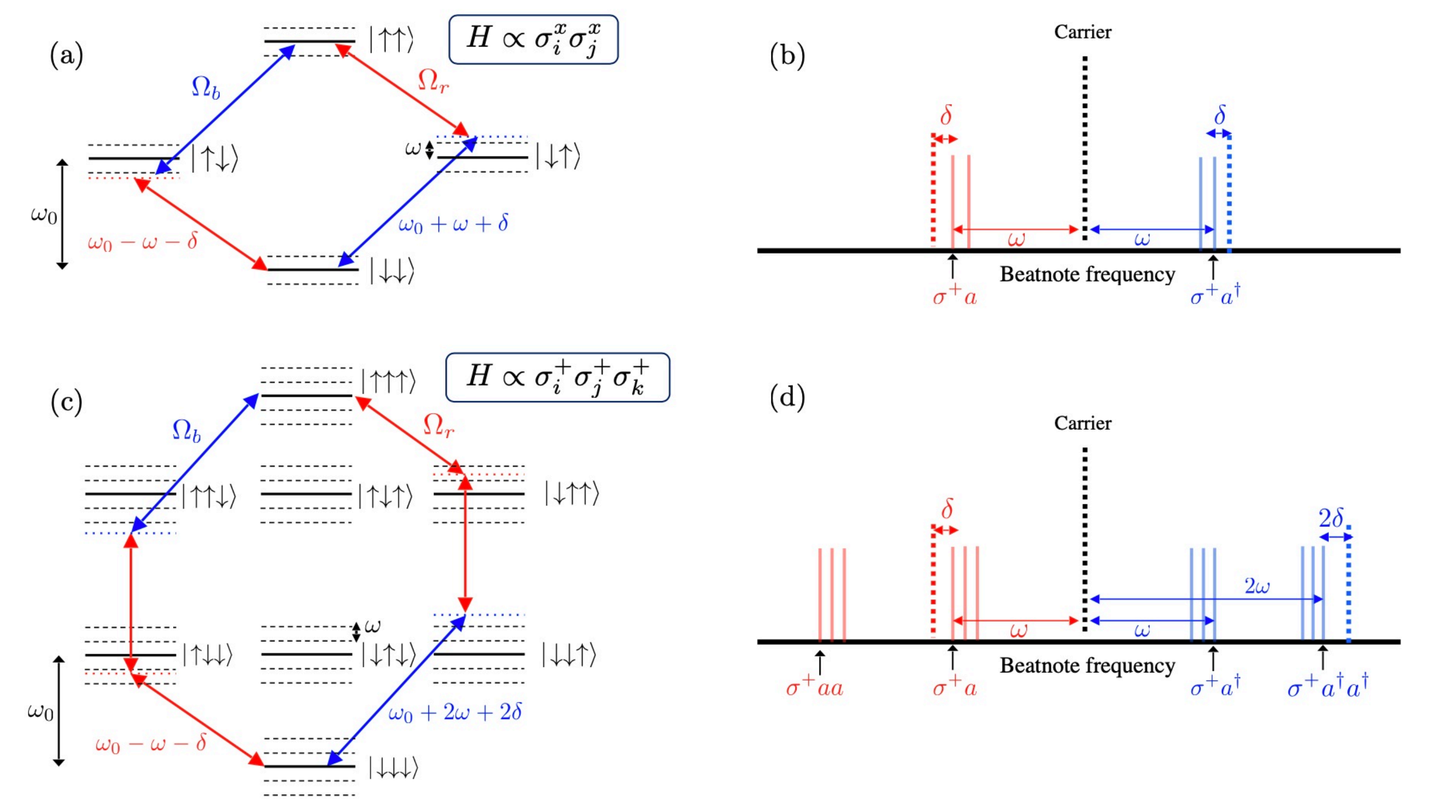
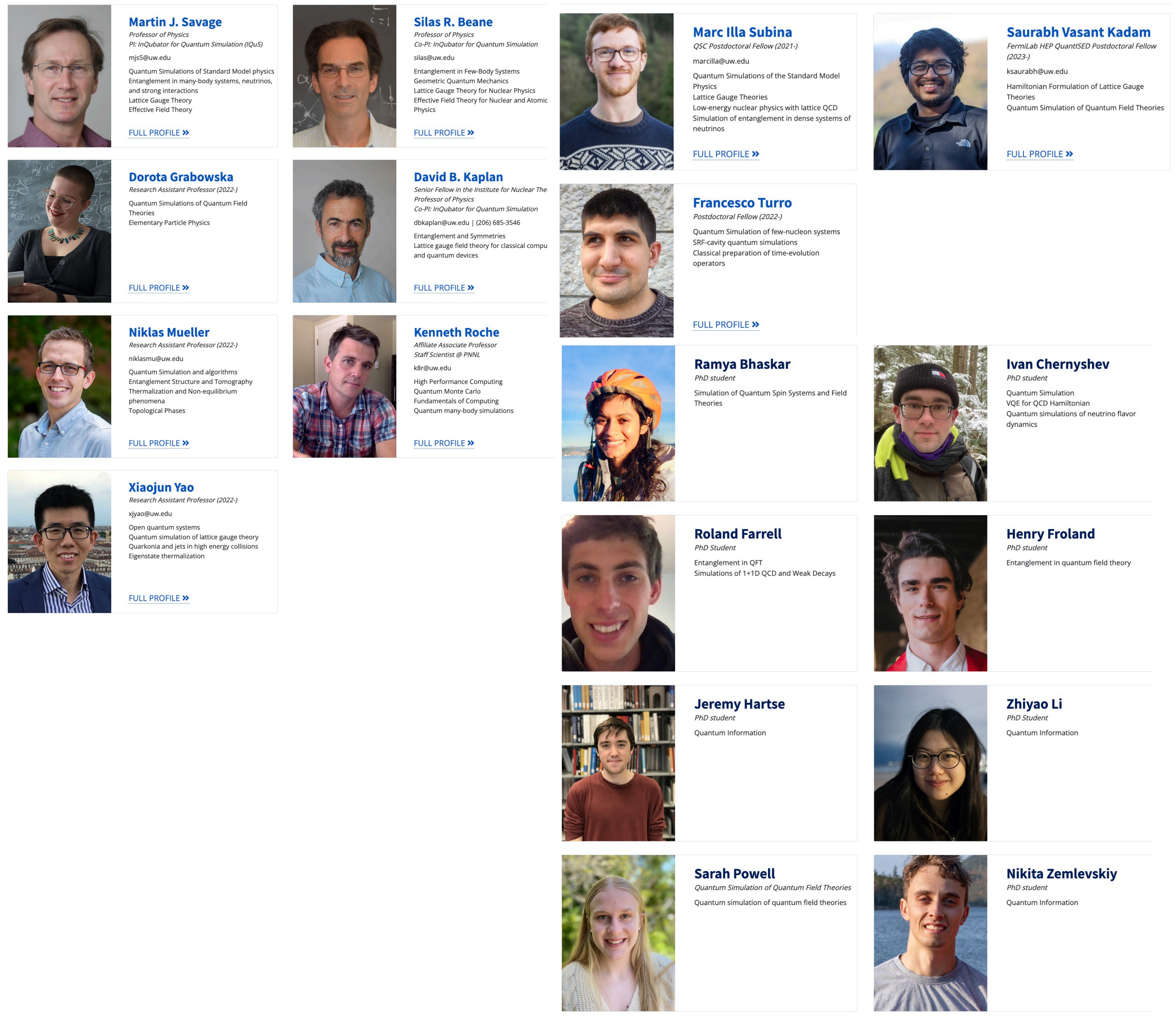


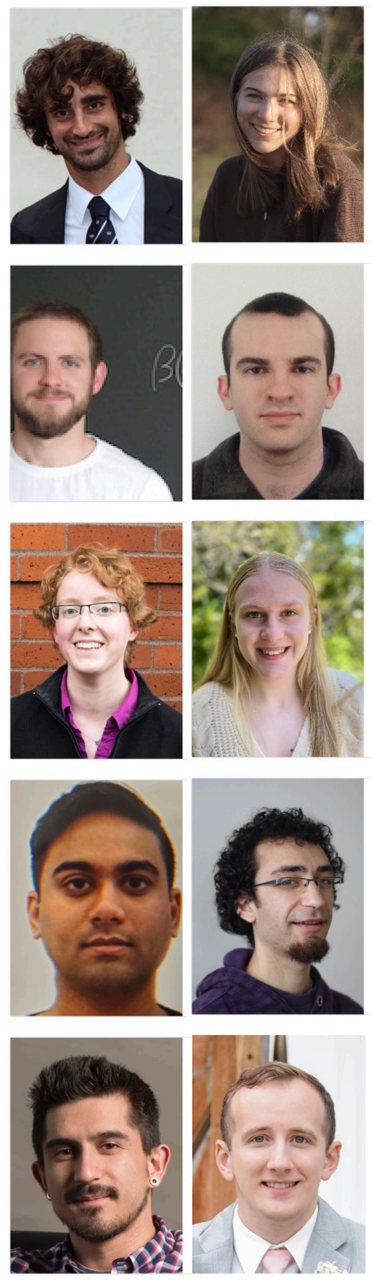
FIG. 1. (a,b) Traditional Mølmer-Sørensen scheme based on a pair of bichromatic laser beatnotes off-resonantly driving first-order spin-phonon couplings with symmetric detuning ($\pm\delta$), giving rise to an effective spin-spin interaction. The two-ion case is shown for simplicity. (c,d) Generalized 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 $\omega\,[\equiv \omega_{\rm com}]$ is the transverse center-of-mass frequency.

NNEFT with Trapped Ion Systems

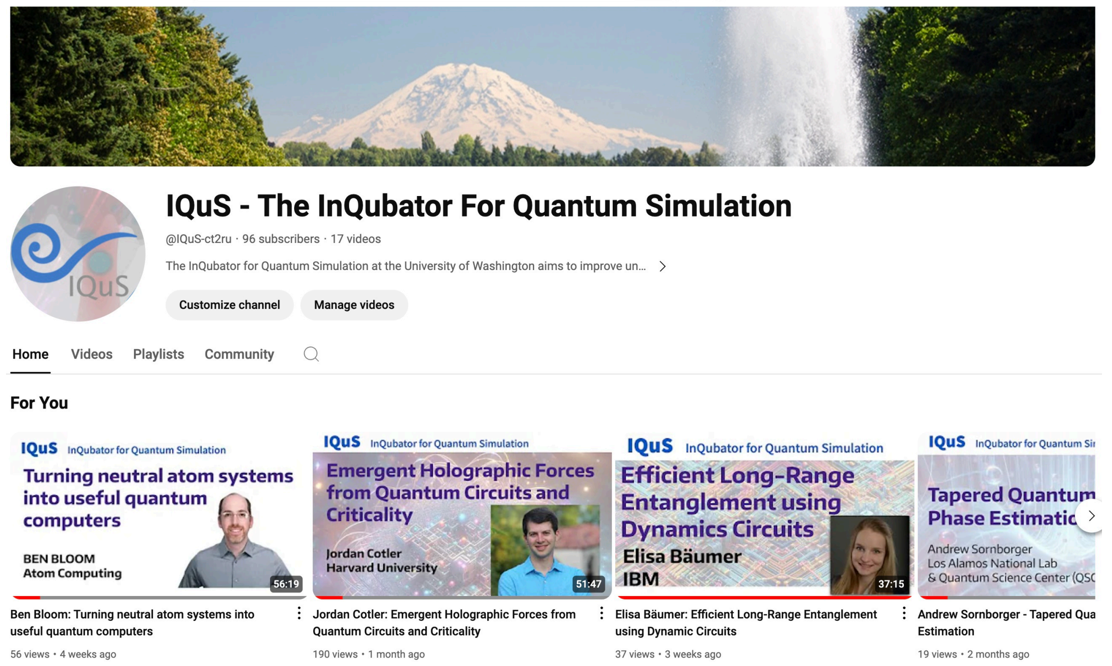
IQuS InQubator for Quantum Simulation

Workshops
Research
Visitors





TO ACCELERATE PROGRESS AT THE INTERFACE OF QUANTUM INFORMATION AND NUCLEAR PHYSICS



DOE OFFICE OF NUCLEAR PHYSICS

UW DEPARTMENT OF PHYSICS

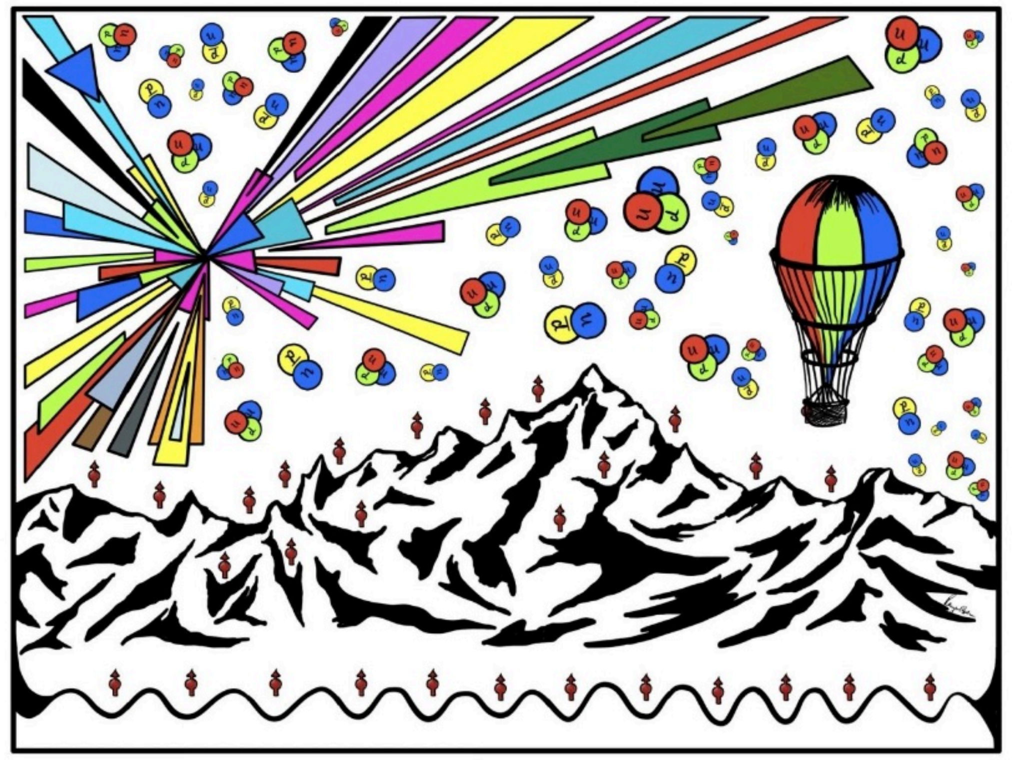
UW COLLEGE OF ARTS & SCIENCES

INSTITUTE for NUCLEAR THEORY

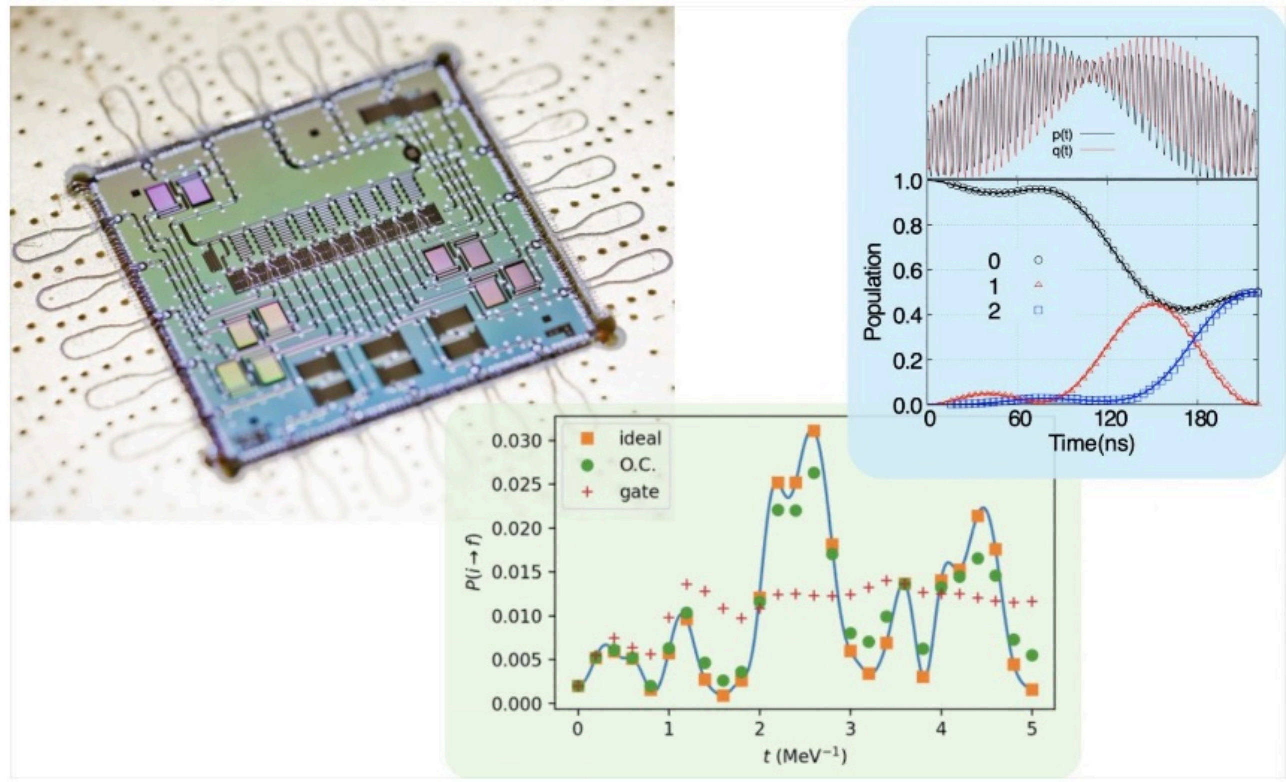
Workshops

Entanglement in Many-Body Systems: From Nuclei to Quantum Computers and Back

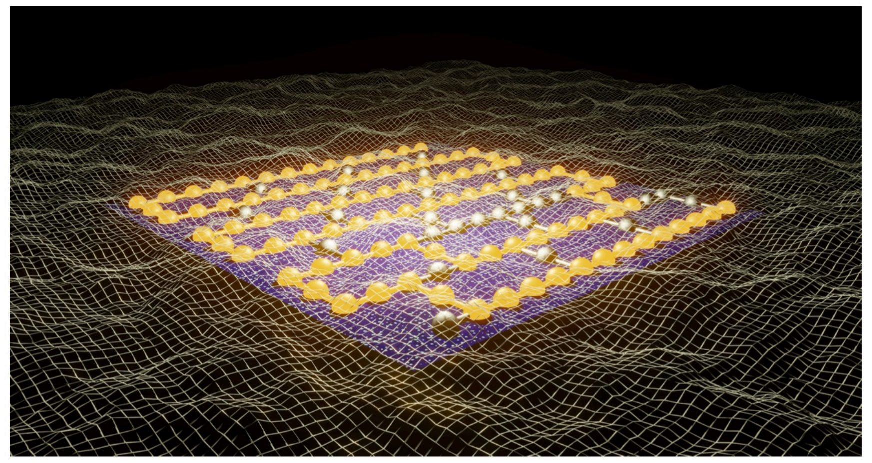
Thermalization, from Cold Atoms to Hot Quantum Chromodynamics



Pulses, Qudits and Quantum Simulations



The Near Future



The Matter-Antimatter Asymmetry   Astrophysical Environments   Collisions and Reactions

Quantum Information Science and Quantum Computers are here and now !!

- How we view quantum many-body systems for fundamental physics is rapidly changing
- Chasing quantum advantages for applications

1+1D Quantum Field Theory - Abelian and non-Abelian - great progress

- Early demonstrations of scalable paths forward for quantum simulations of important quantities
  - quantum simulations of both 1+1D QED and QCD in the near term
- Close to complete studies in 1+1 D, effective sandbox, heading to 2+1D and 3+1D

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

- Thermalization, collisions and transport
- Efforts to connect with experiment

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