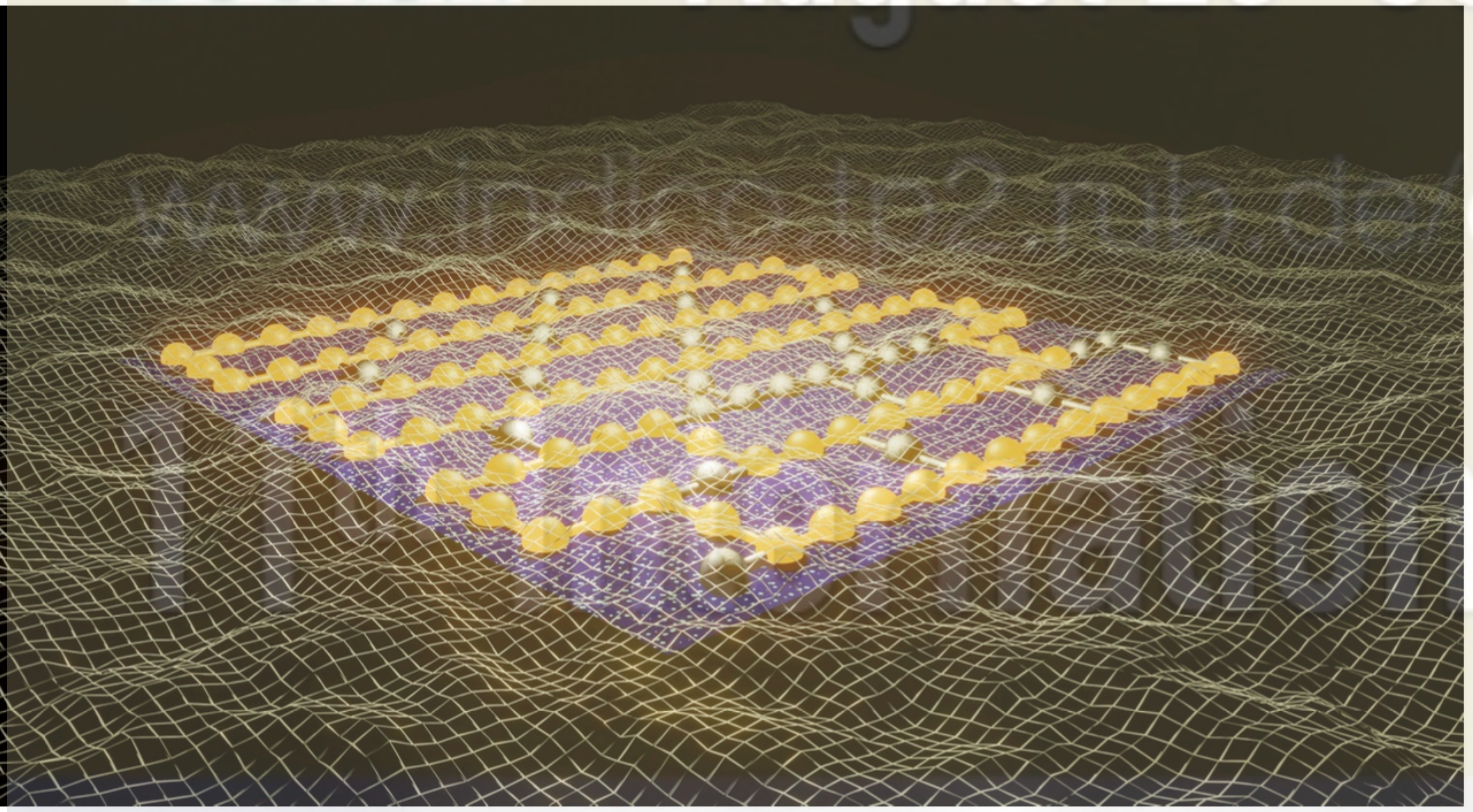
Quantum Simulation of Fundamental Physics



The Matter-Antimatter Asymmetry

Astrophysical Environments

Collisions and Reactions

Martin Savage
InQubator for Quantum Simulation (IQuS), University of Washington
(40+10 mins)

https://iqus.uw.edu/

QUANTUM SCIENCE CENTER

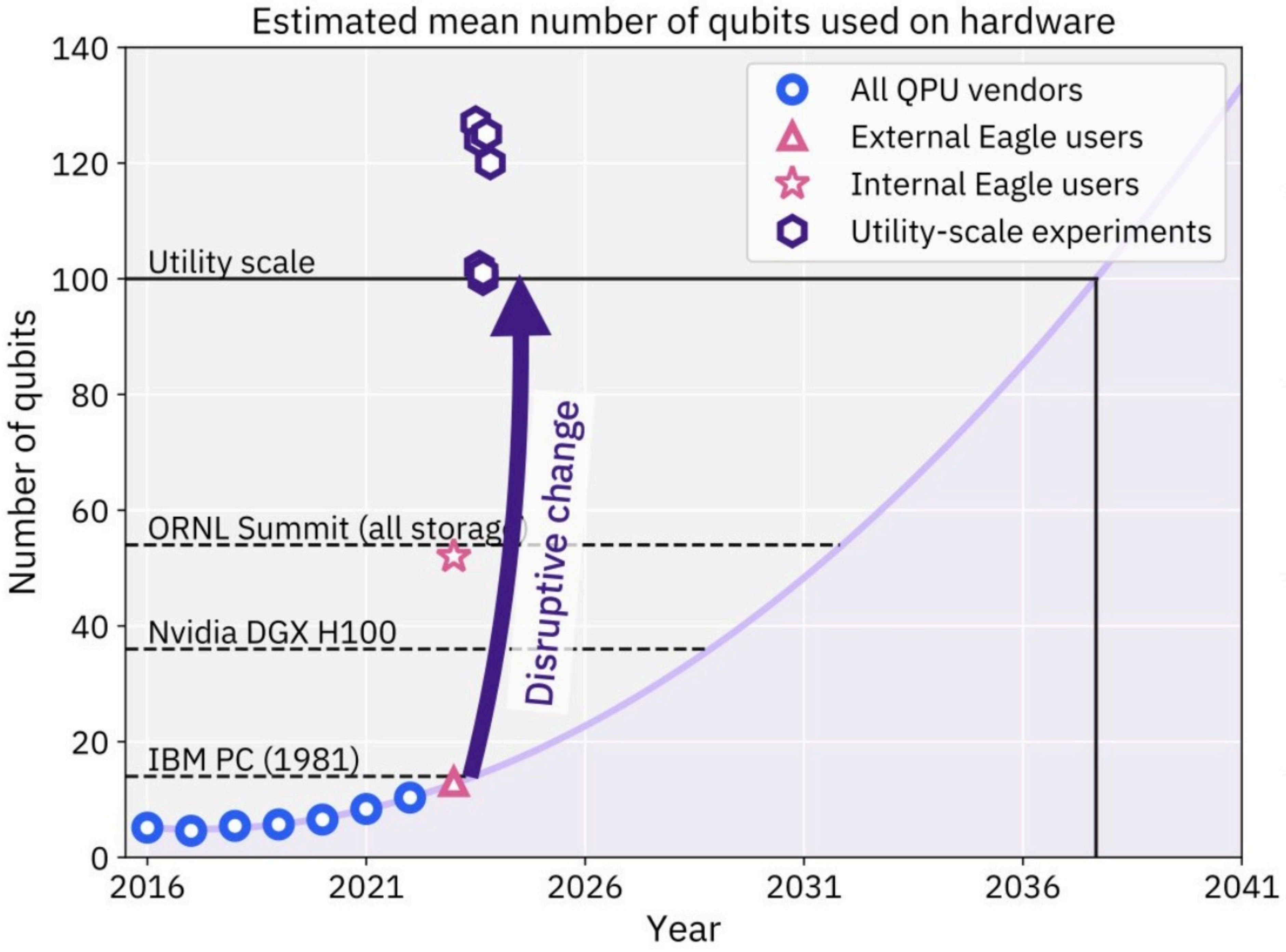
Office of Science
U.S. Department of Energy

OAK RIDGE National Laboratory

IBM Quantum Summit - NYC December 2023

Utility-scale experiments

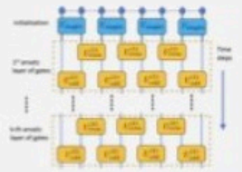
With quantum systems composed of 100+ qubits, researchers are beginning to explore algorithms and applications at scales beyond brute-force classical computation using IBM Quantum systems.



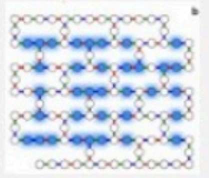
IBM **Quantum**

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

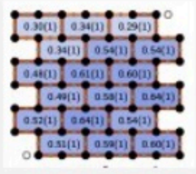
Simulating large-size quantum spin chains on cloud-based superconducting quantum computers
102 qubits / 3186 CX gates — arXiv:2207.09994



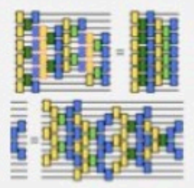
Uncovering Local Integrability in Quantum Many-Body Dynamics
124 qubits / 2641 CX gates — arXiv:2307.07552



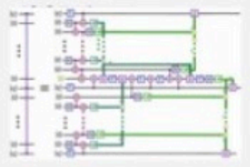
Realizing the Nishimori transition across the error threshold for constant-depth quantum circuits
125 qubits / 429 gates + meas. — arXiv:2309.02863



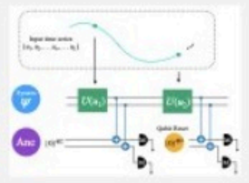
Scalable Circuits for Preparing Ground States on Digital Quantum Computers: The Schwinger Model Vacuum on 100 Qubits
100 qubits / 788 CX gates — arXiv:2308.04481



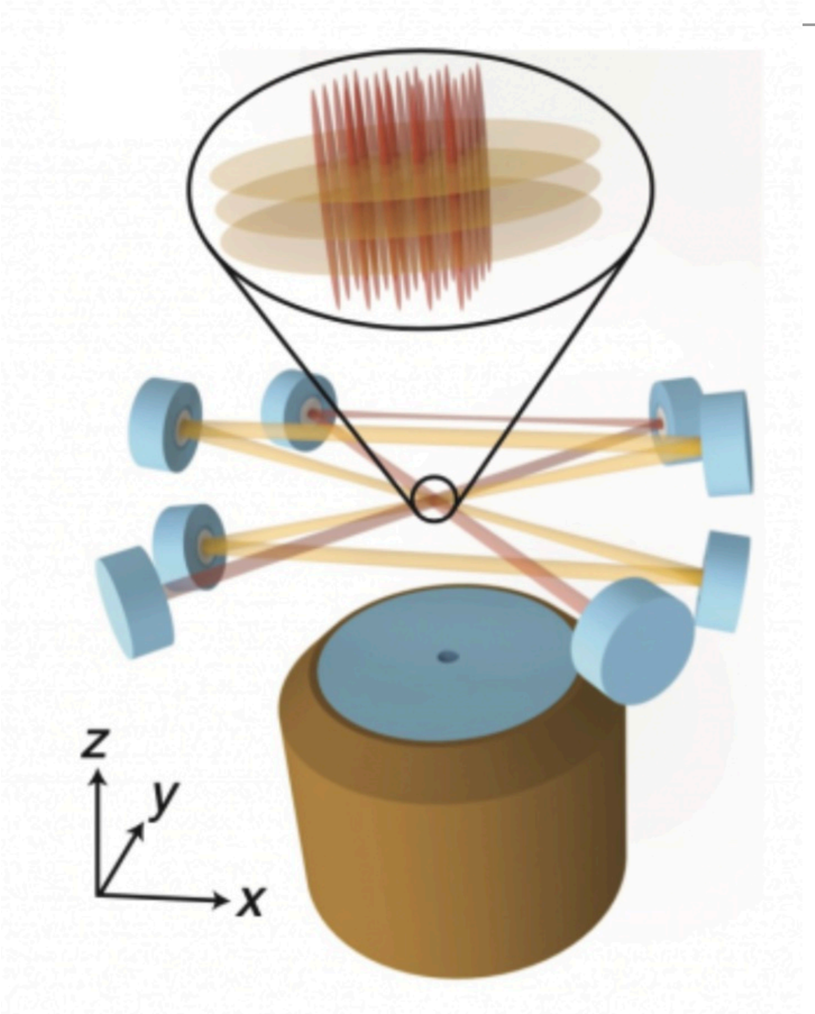
Efficient Long-Range Entanglement using Dynamic Circuits
101 qubits / 504 gates + meas. — arXiv:2308.13065



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



Select Recent Advances in Quantum Computing



Cold-Atom arrays with
Optical Tweezers

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

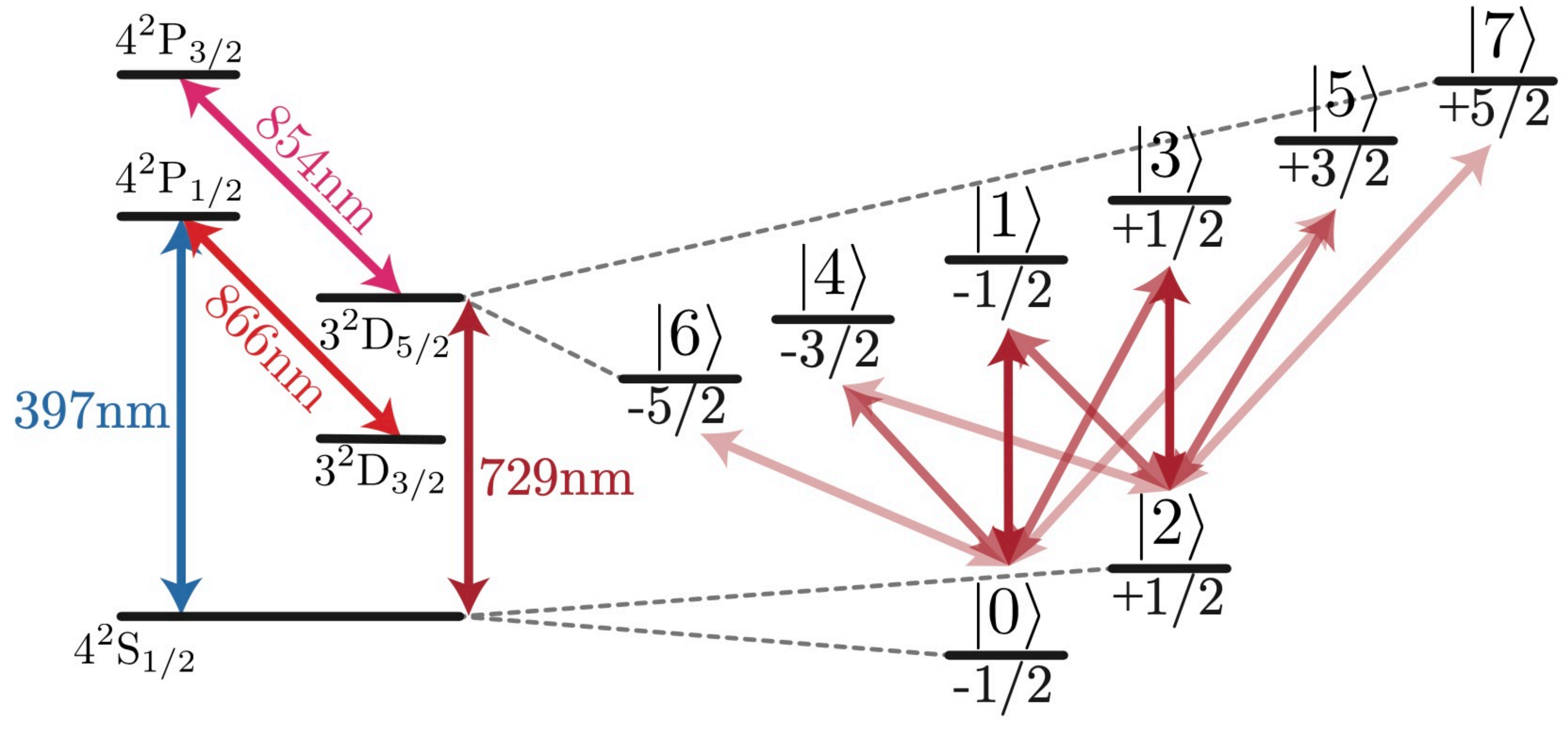
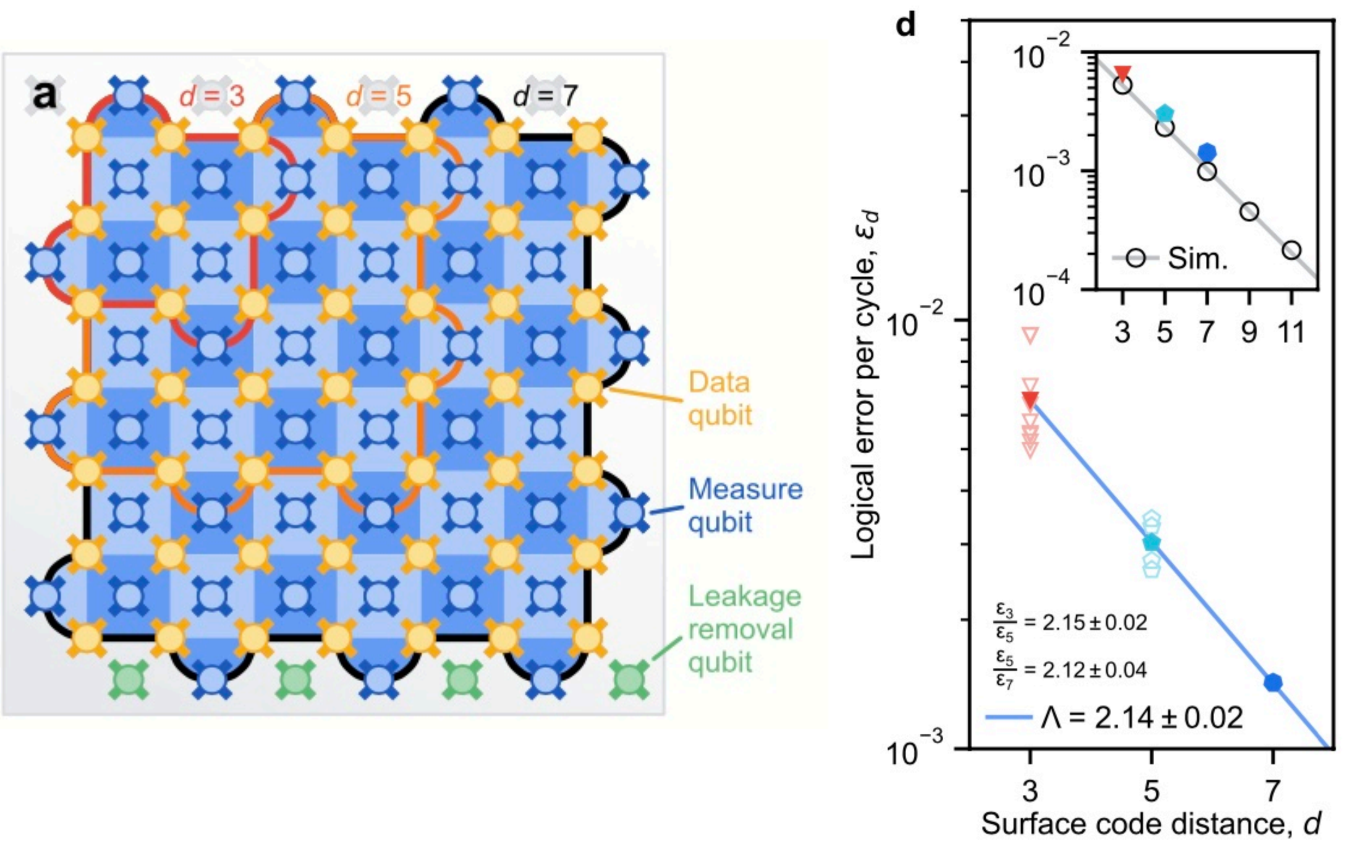
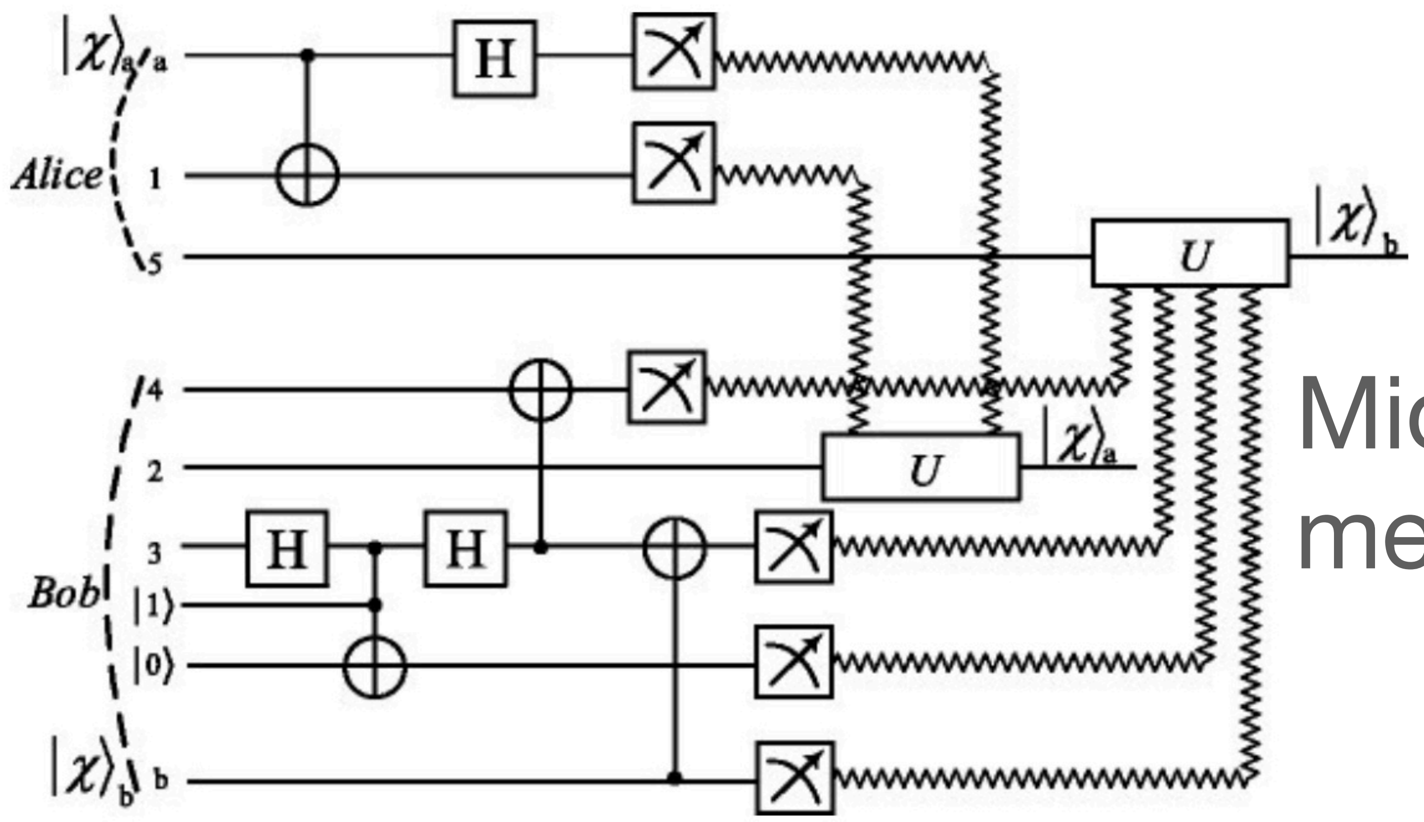


FIG. 1. **Level scheme of the $^{40}Ca^+$ ion.**

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

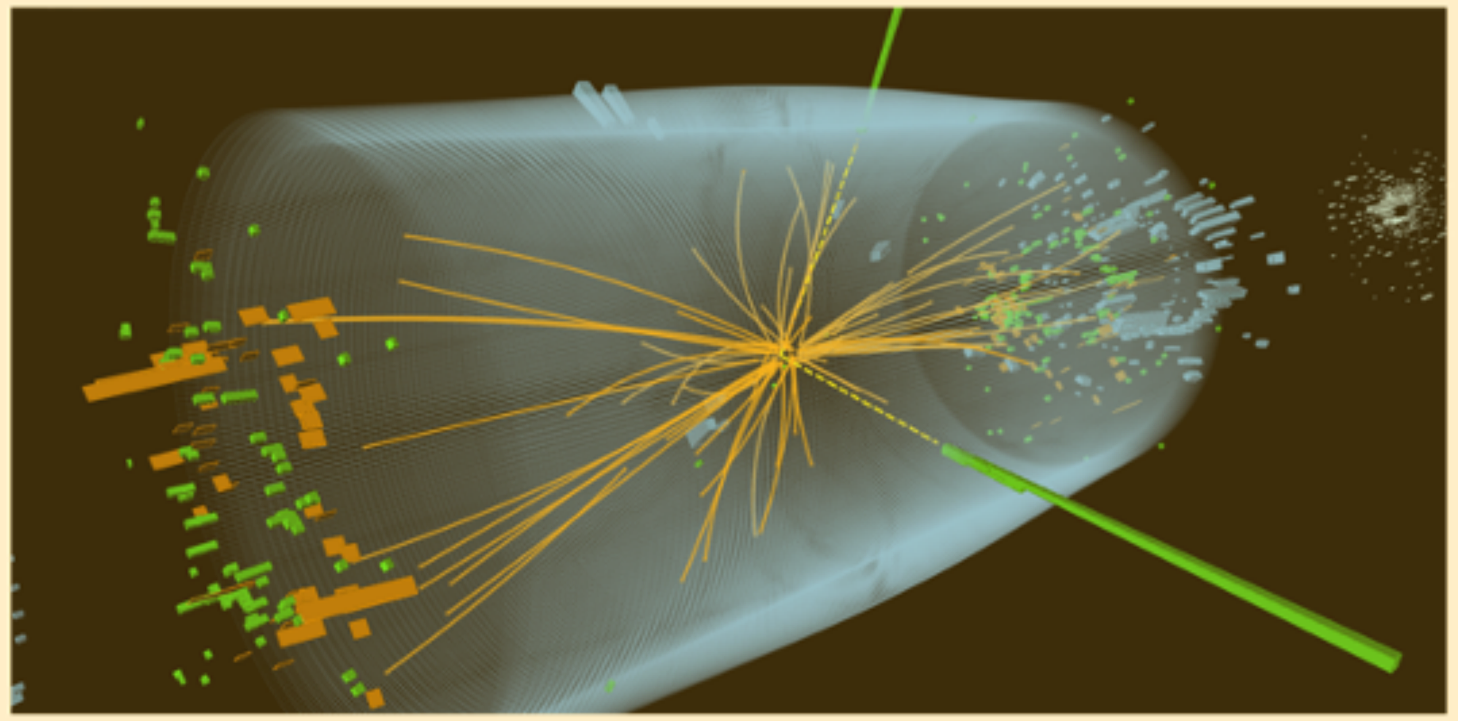
Quantum simulation of fundamental particles and forces

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

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

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

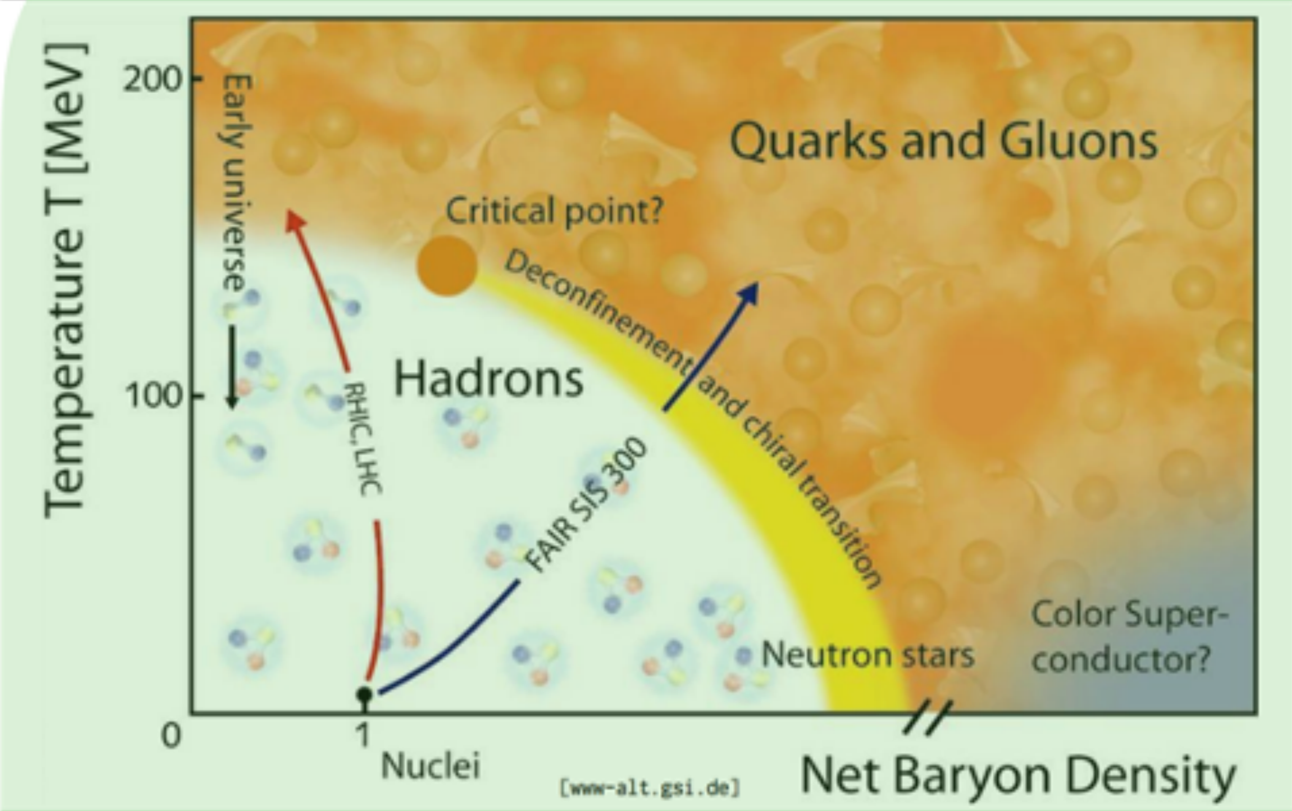
Low-energy reactions

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

Neutrino dynamics

Matter-antimatter asymmetry

BQP

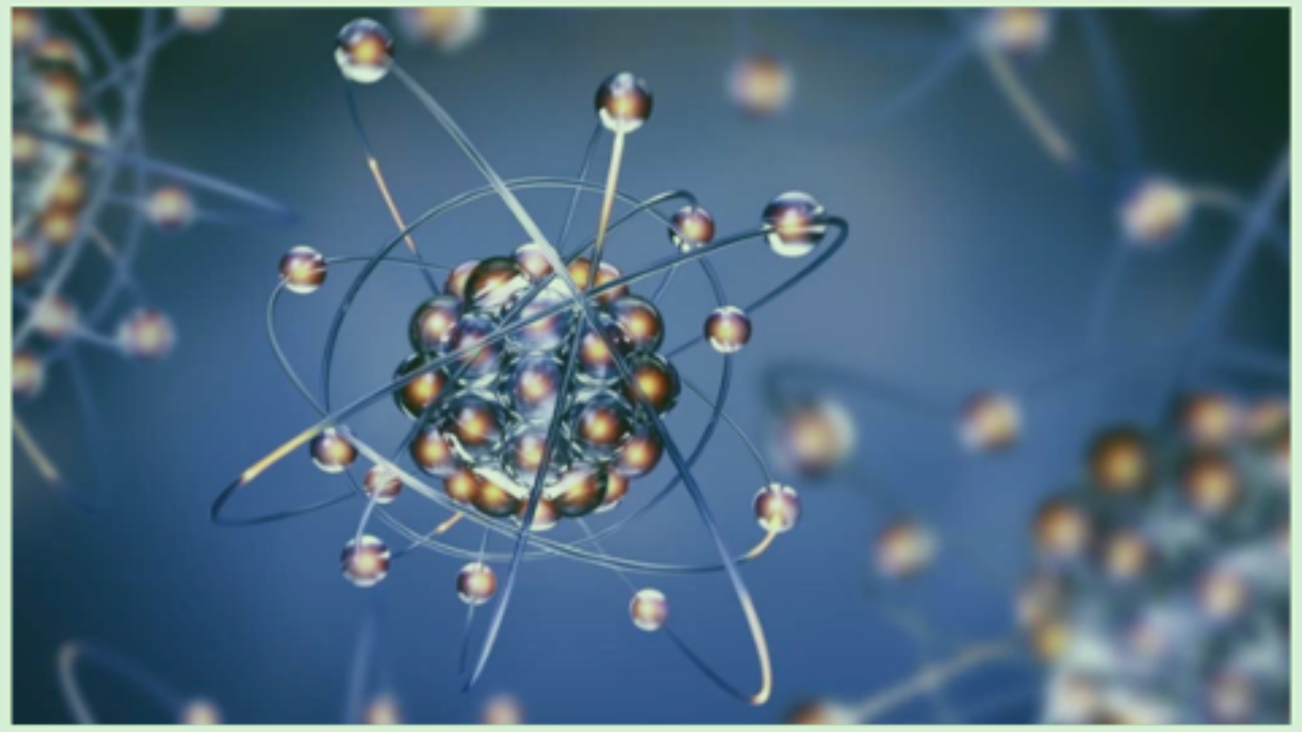


Equation of state of dense
  hot matter and dynamics
  viscosity, etc

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

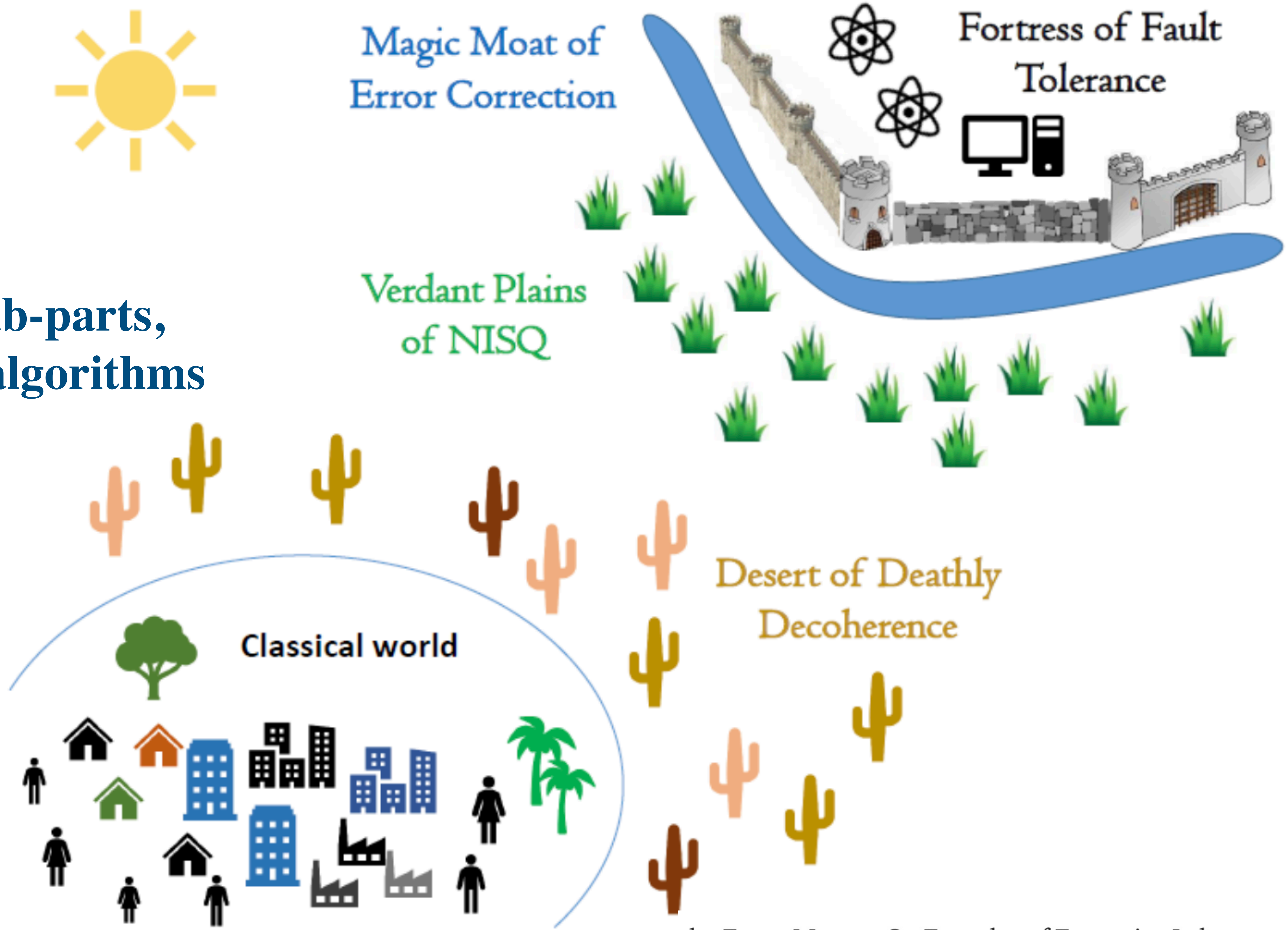
– symmetries

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

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

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)

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

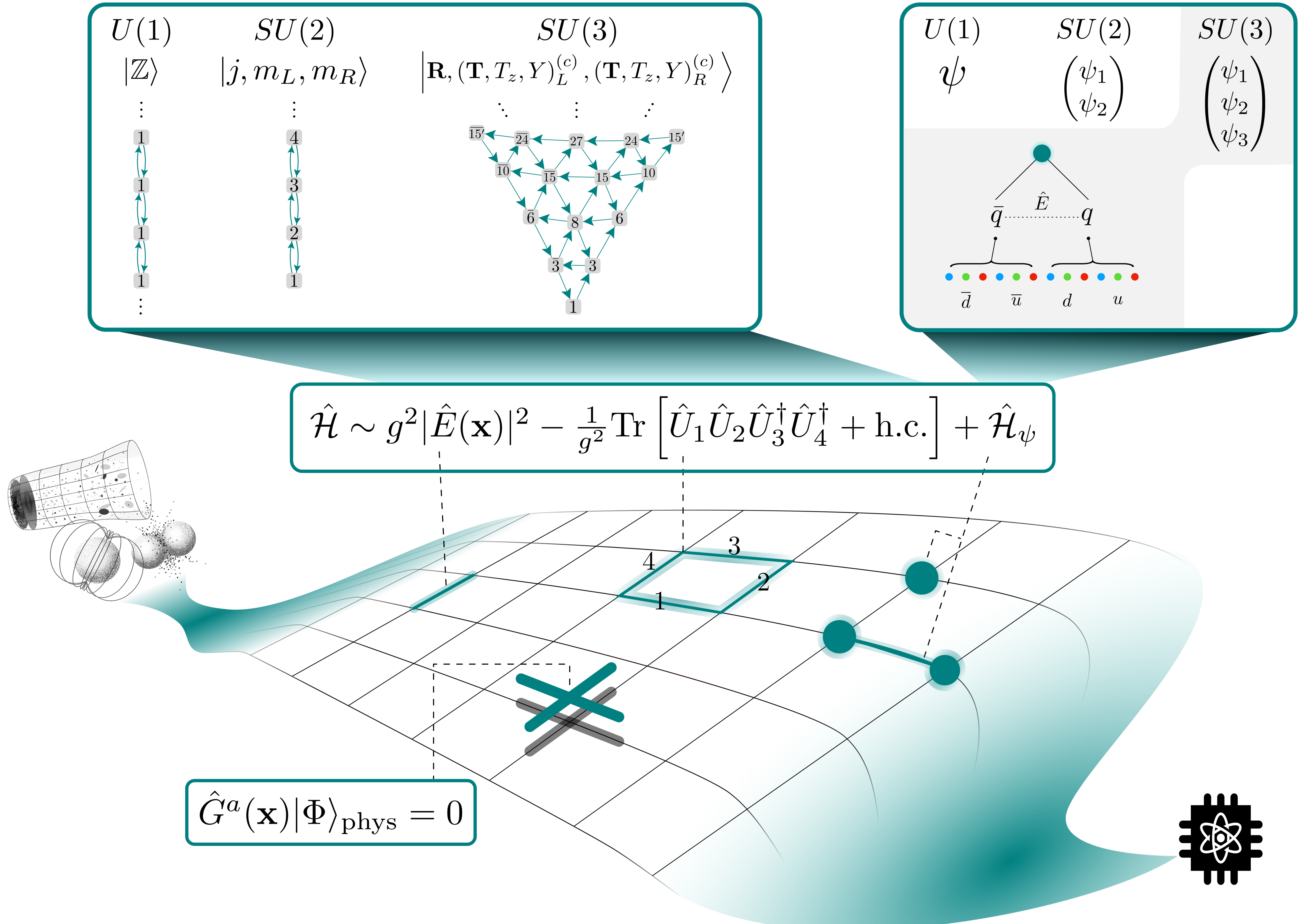
Simulating Lattice Gauge Field Theories

Hamiltonian
Kogut-Susskind
1970's

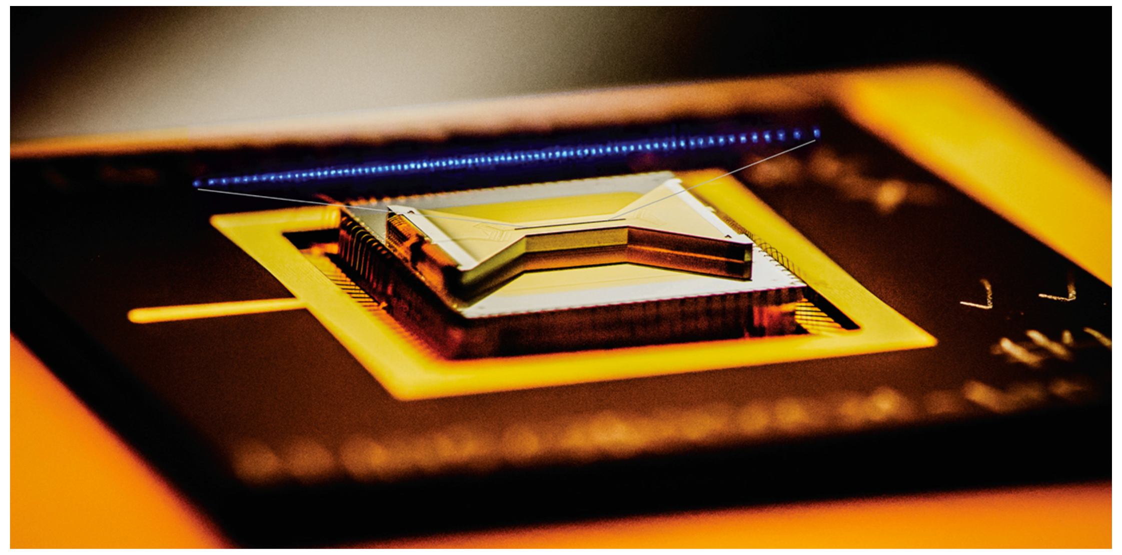
Yang-Mills:
Byrnes-Yamamoto
2005

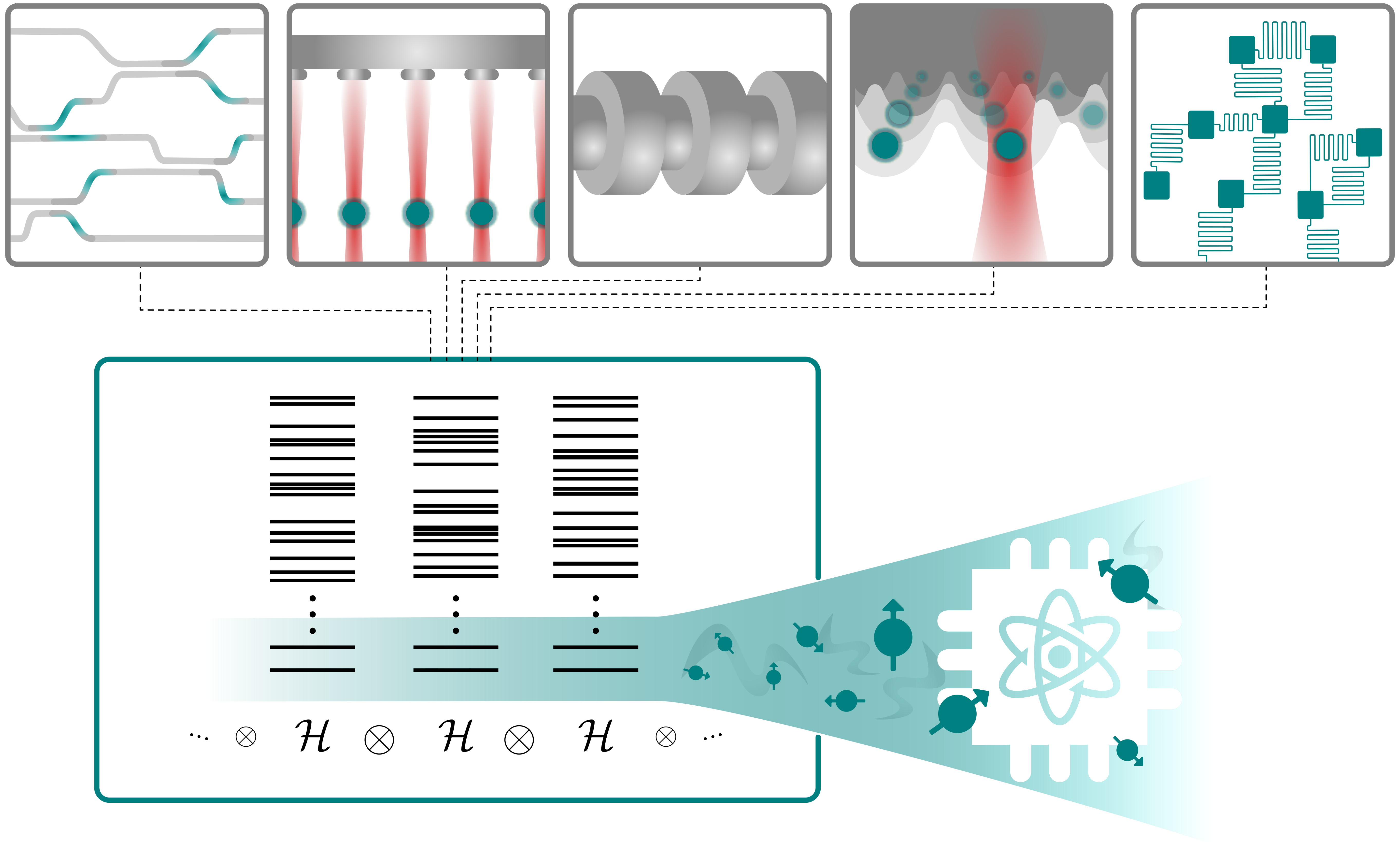
SU(N):
Zohar et al
(2013)

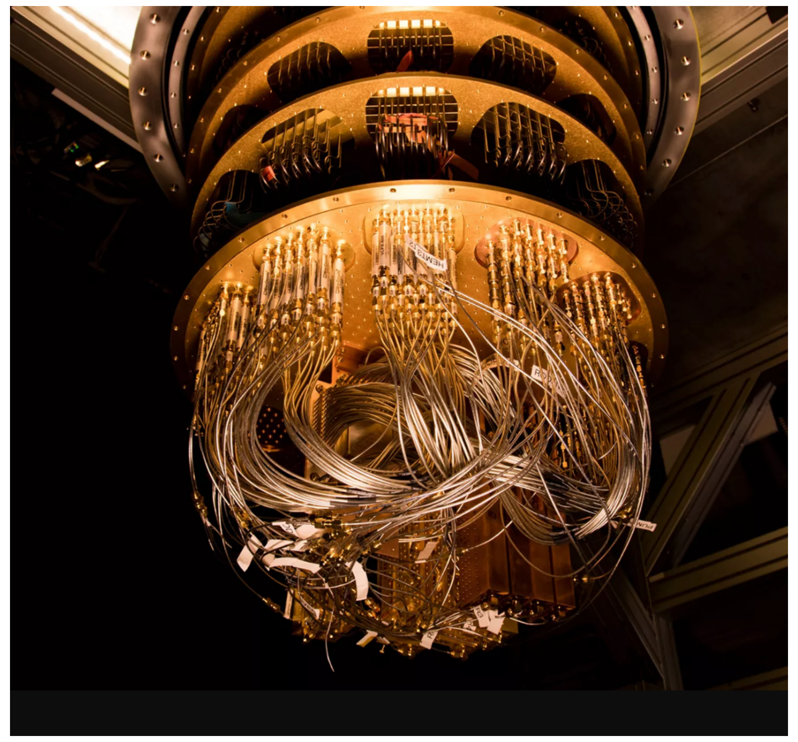
QLM
Banerjee et al
Tagliacozzo et al
(2013)

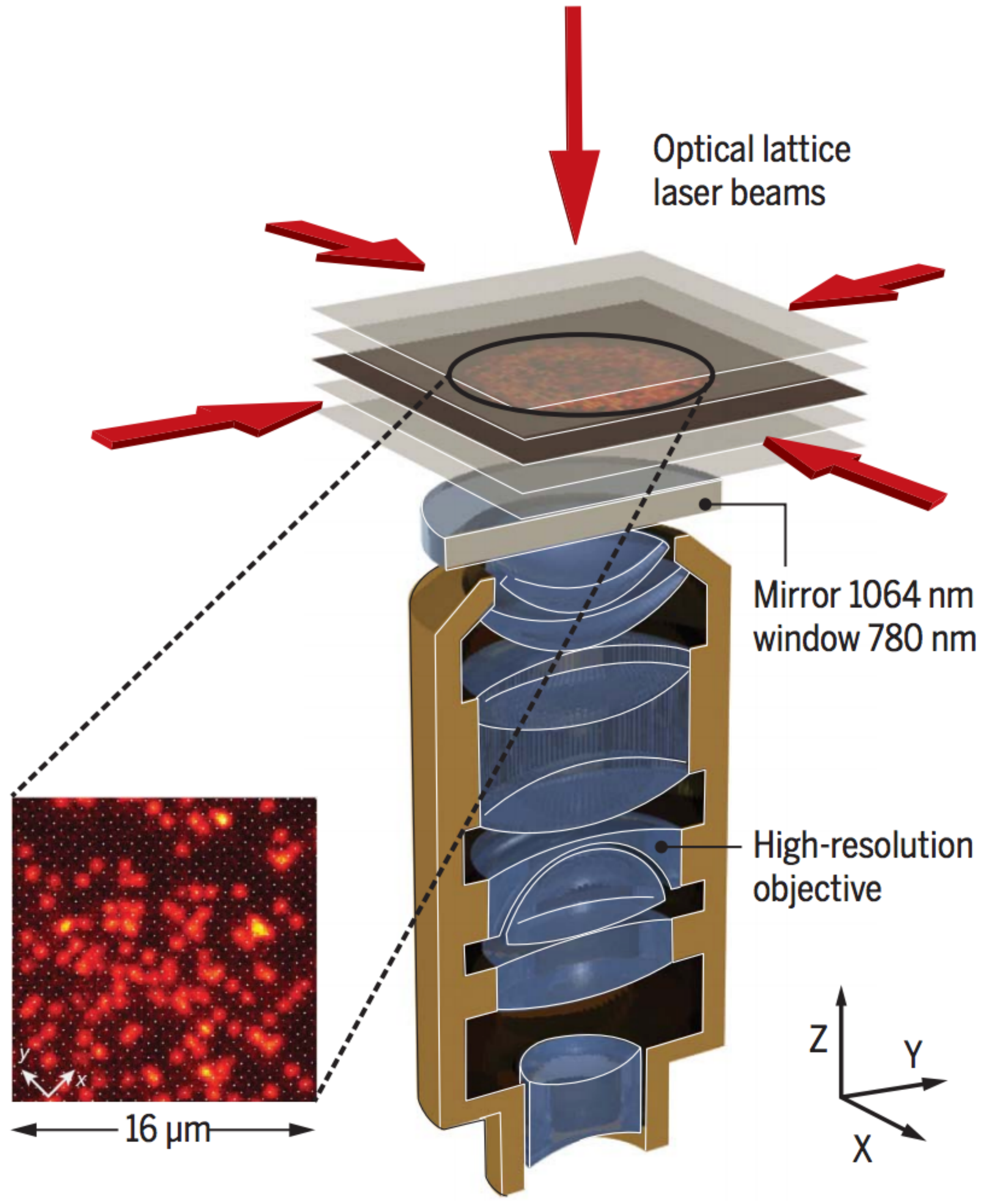


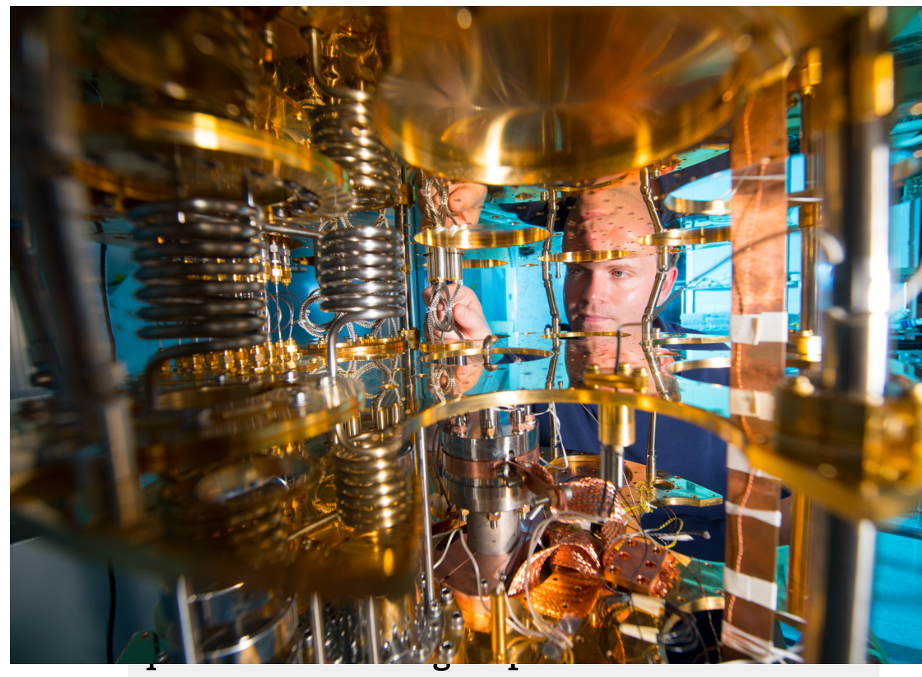
Encoding Systems in Multi-Hilbert Spaces Embedded in Large HPC systems

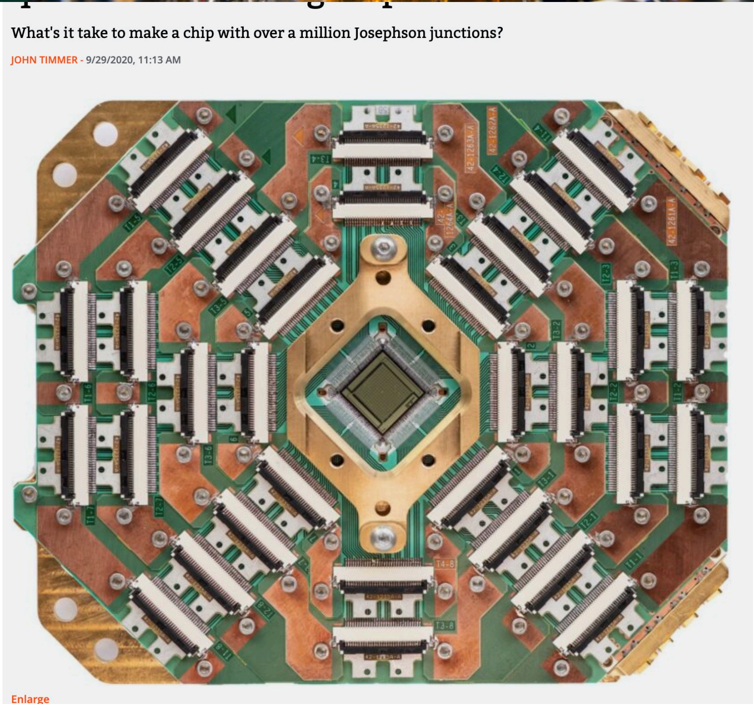












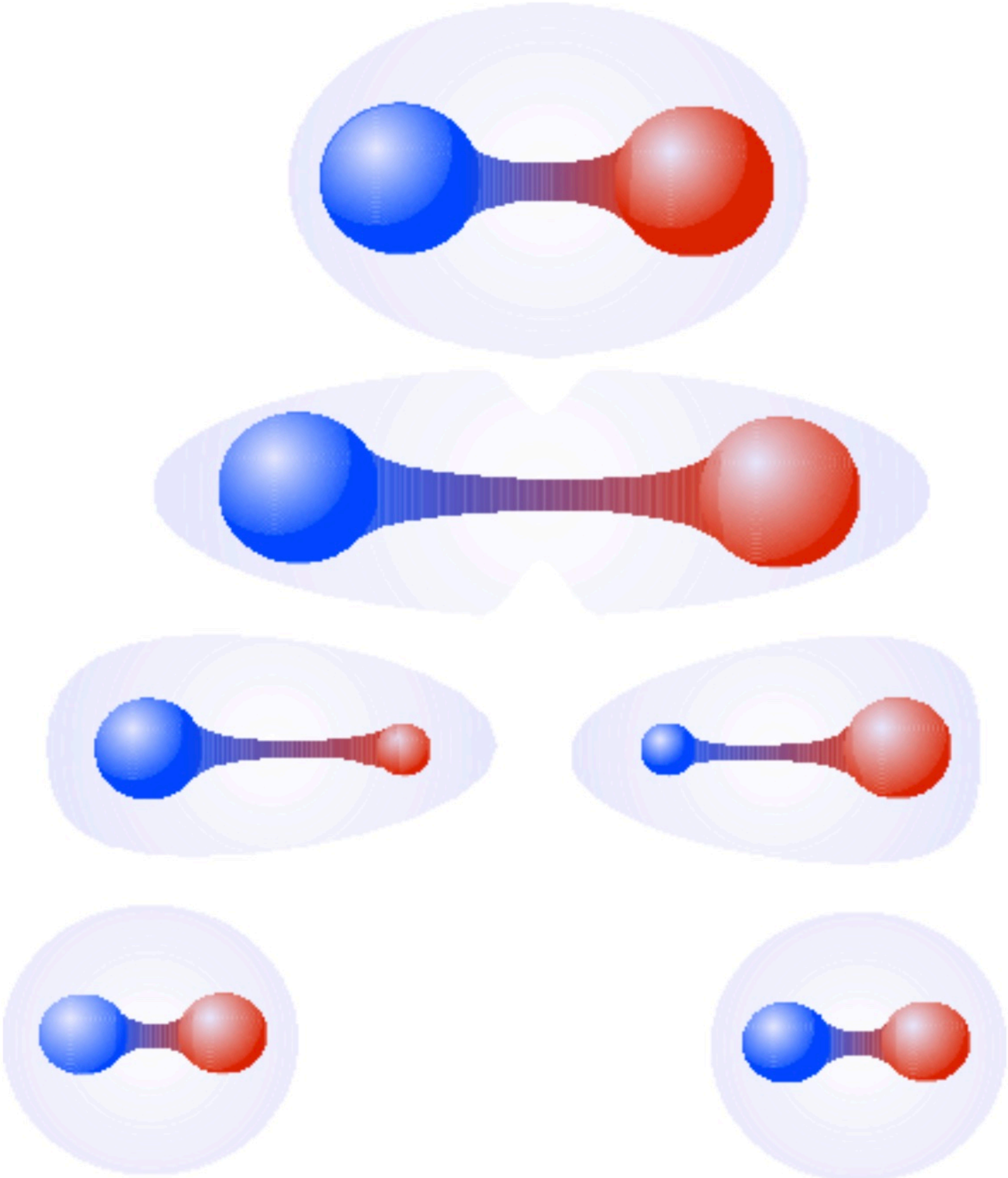
Map scalar, fermion and vector systems

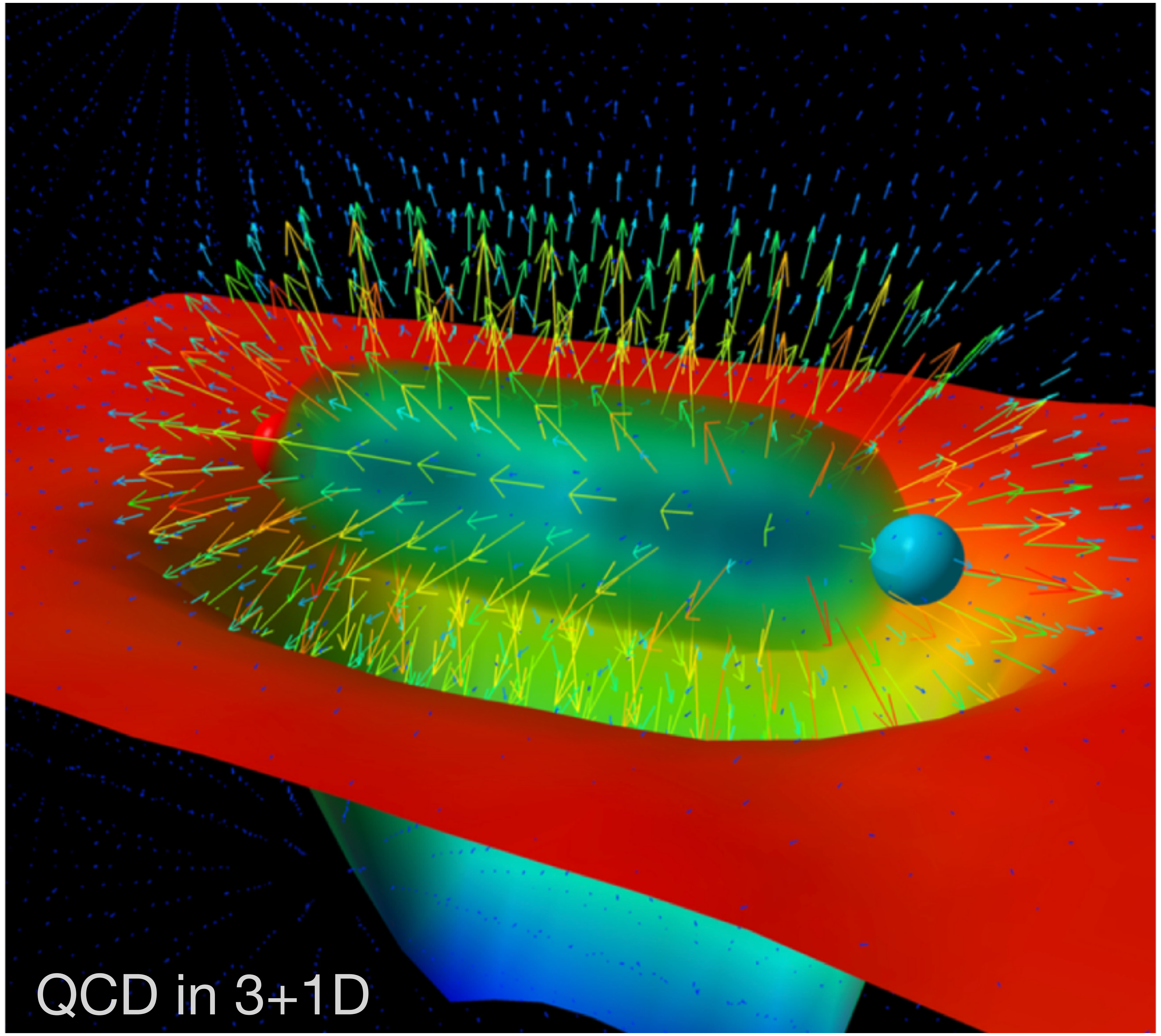
Optimize for target observables - Physics Aware

Human-intensive exploration

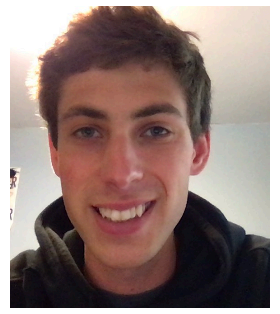
Low-Dimensional Models:

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

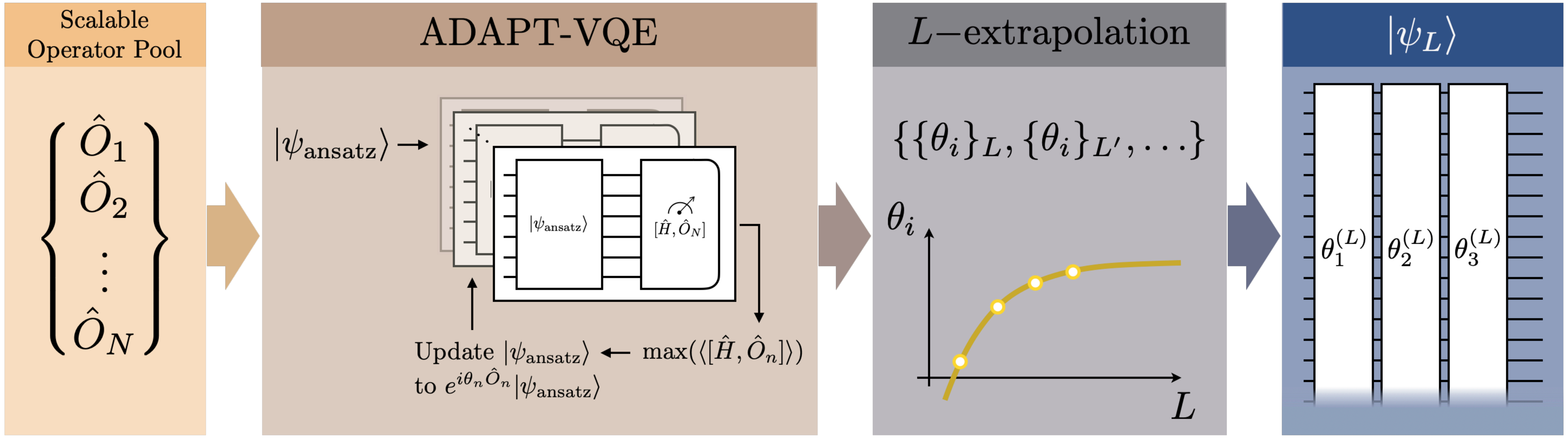
(2023-)

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



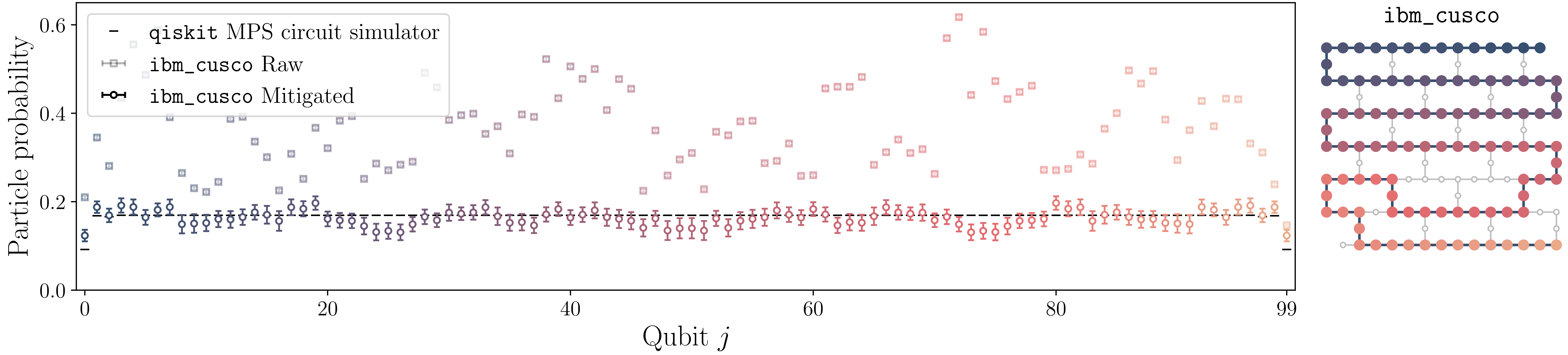
Classical Optimization — **Quantum** Implementation

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

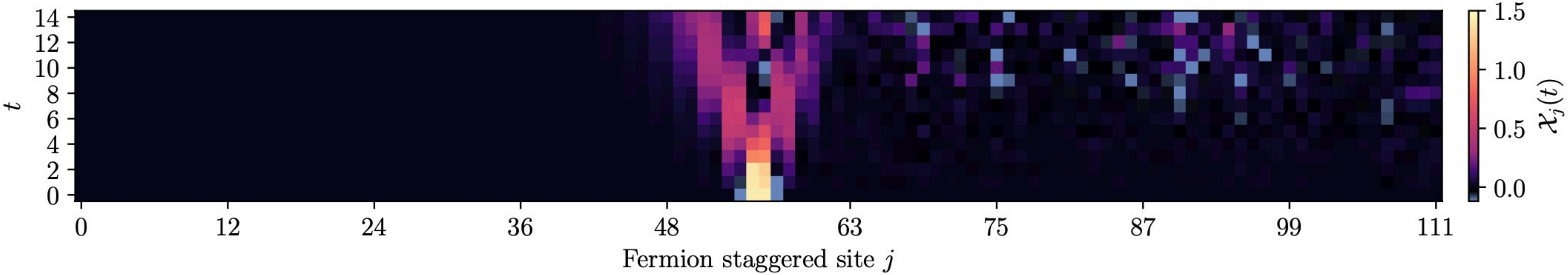
Quantum simulations of hadron dynamics in the Schwinger model using 112 qubits
Roland C. Farrell, Marc Illa, Anthony N. Ciavarella, and Martin J. Savage
Phys. Rev. D **109**, 114510 – Published 10 June 2024

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

The Vacuum and Wavepacket Evolution

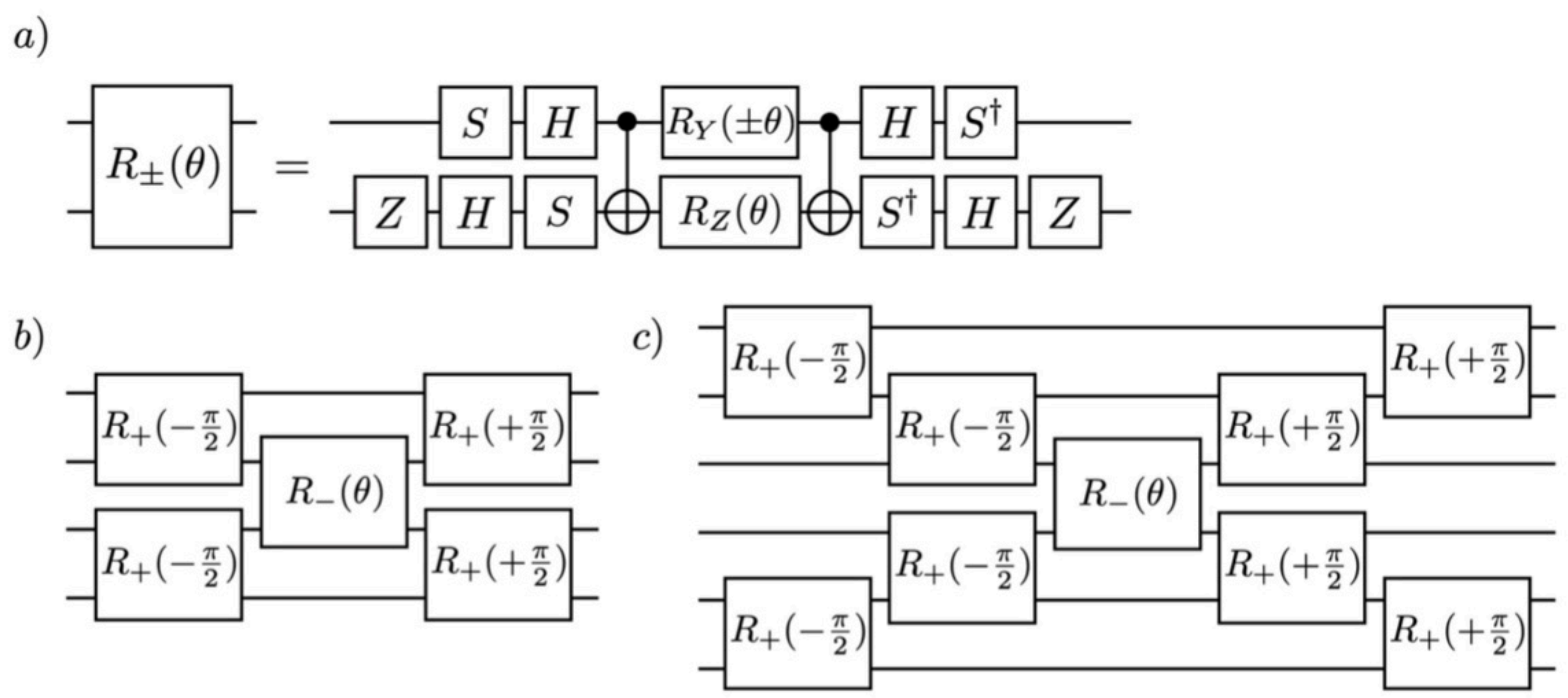


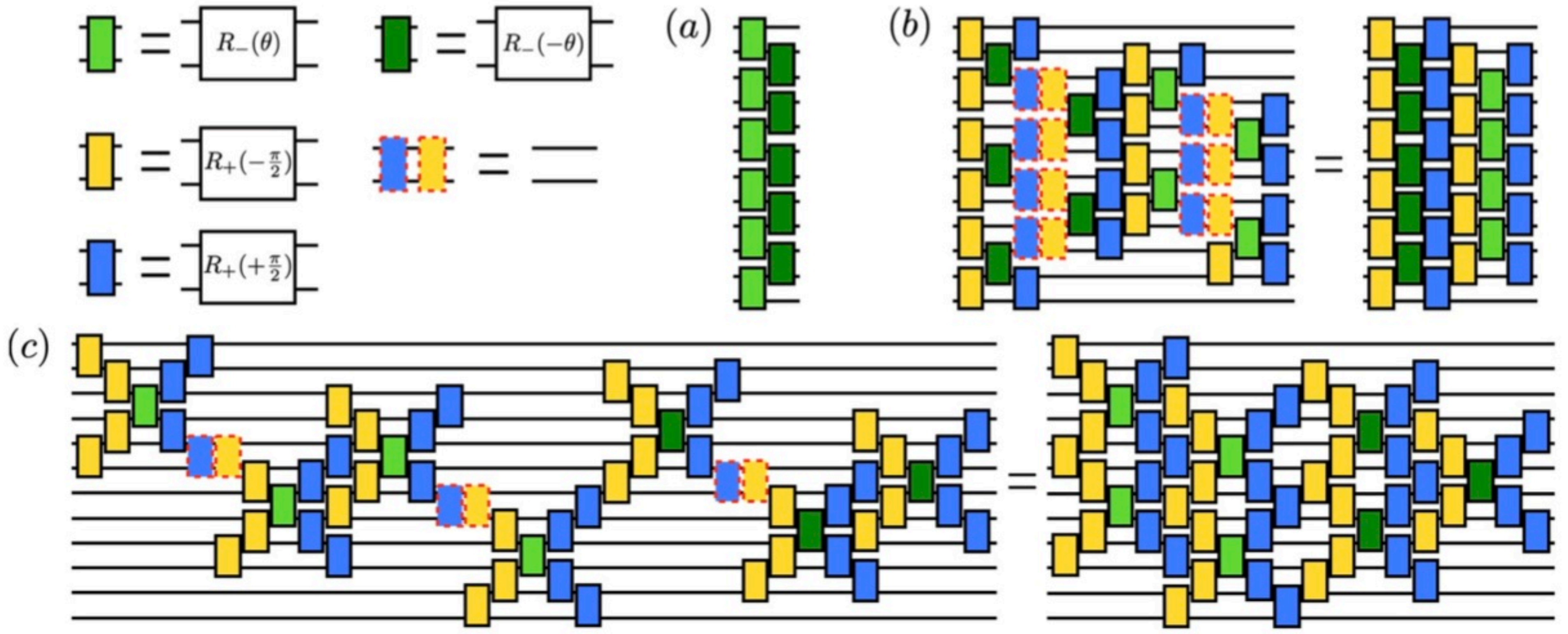
Classical | IBM's Torino



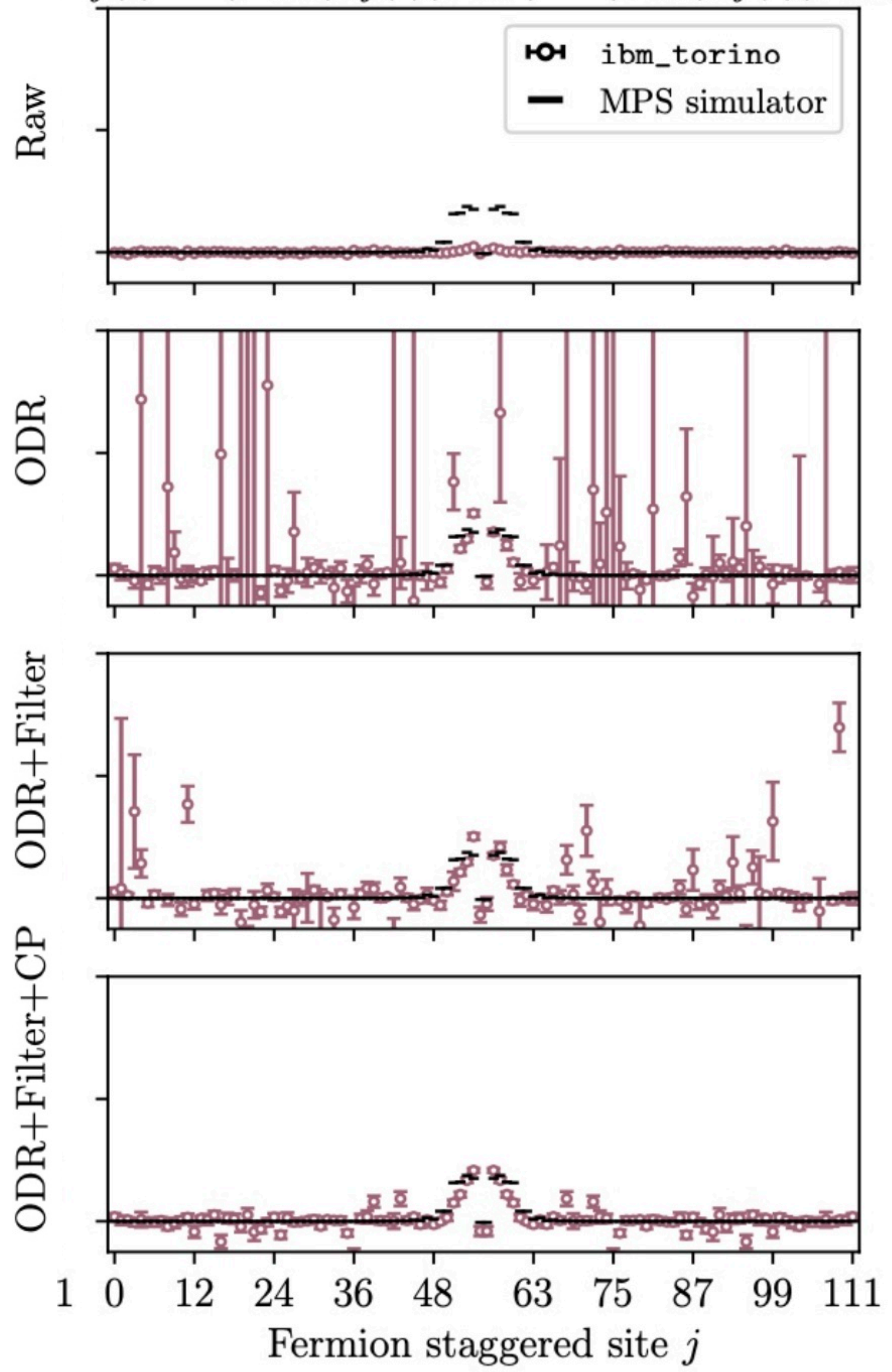
Production using IBM's QPU Torino

(The largest quantum simulation that had been performed)



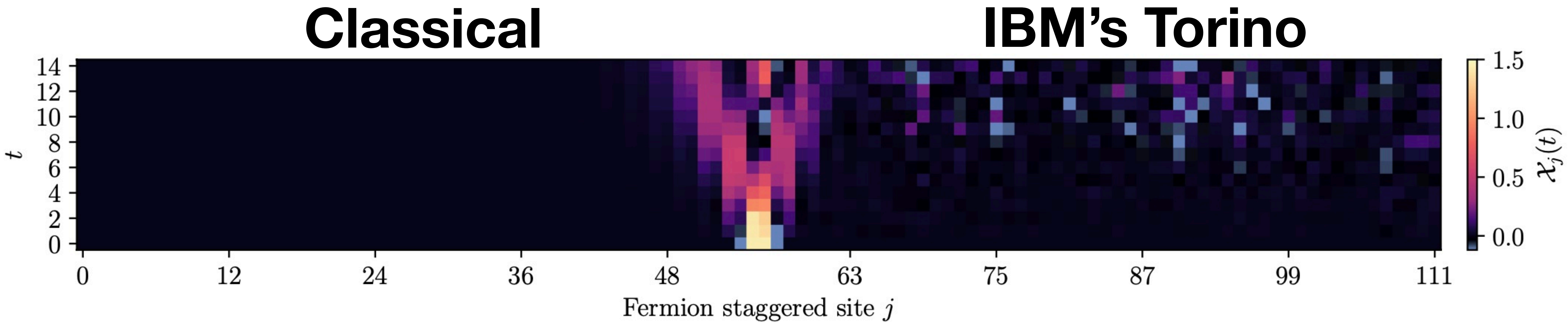


$\mathcal{X}_j(t) = \langle\psi_{WP}|\hat{\chi}_j(t)|\psi_{WP}\rangle - \langle\psi_{vac}|\hat{\chi}_j(t)|\psi_{vac}\rangle$



Production highlights

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



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

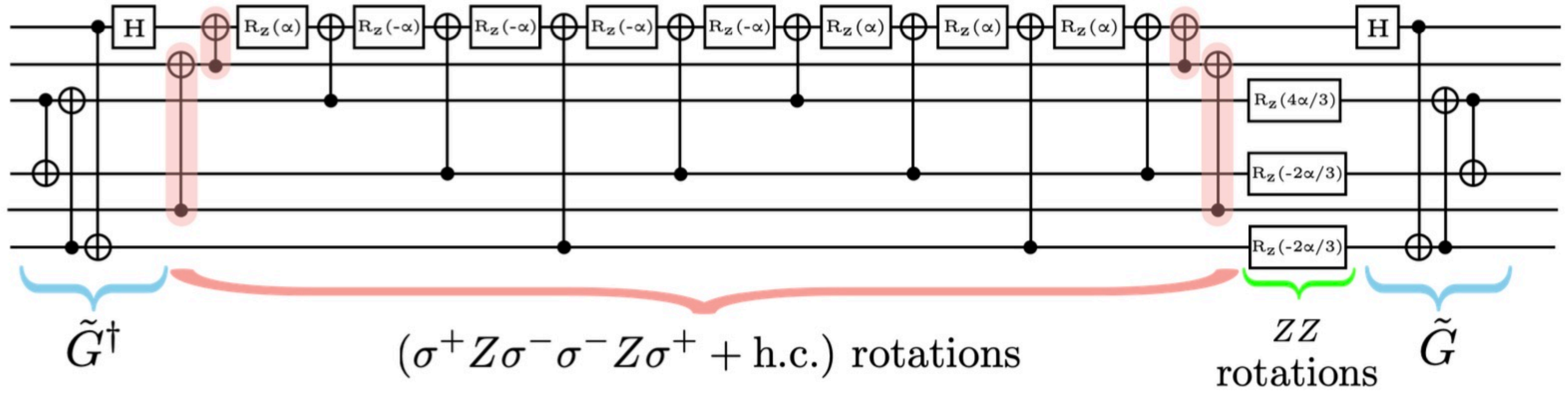
Sarmed A Rahman, Randy Lewis, Emanuele Mendicelli, and Sarah Powell
Department of Physics and Astronomy, York University, Toronto, Ontario, Canada, M3J 1P3

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

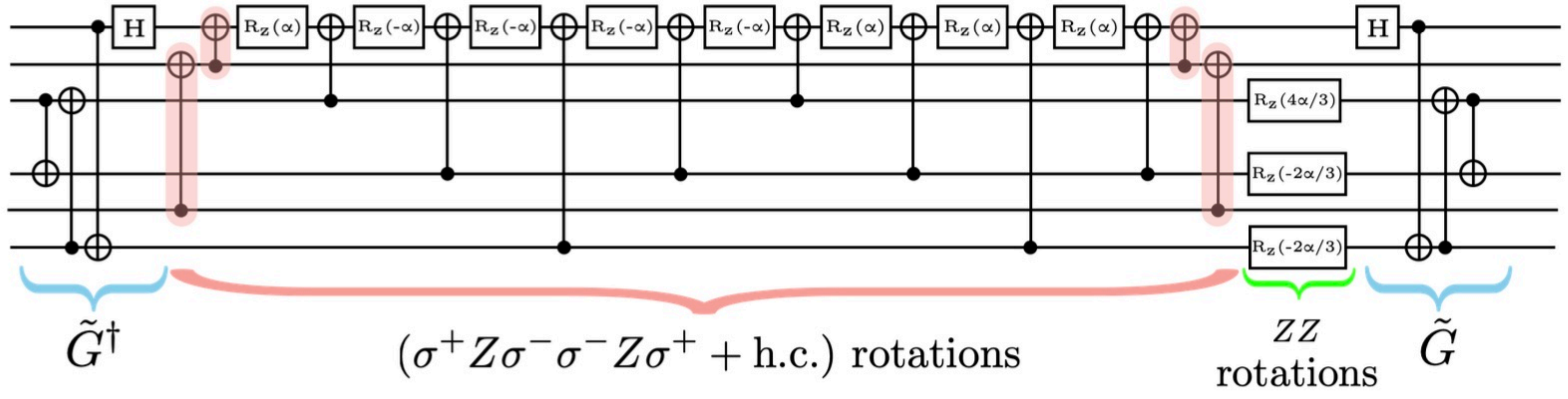
The device is approaching a classical, depolarized set of qubits as time goes by.

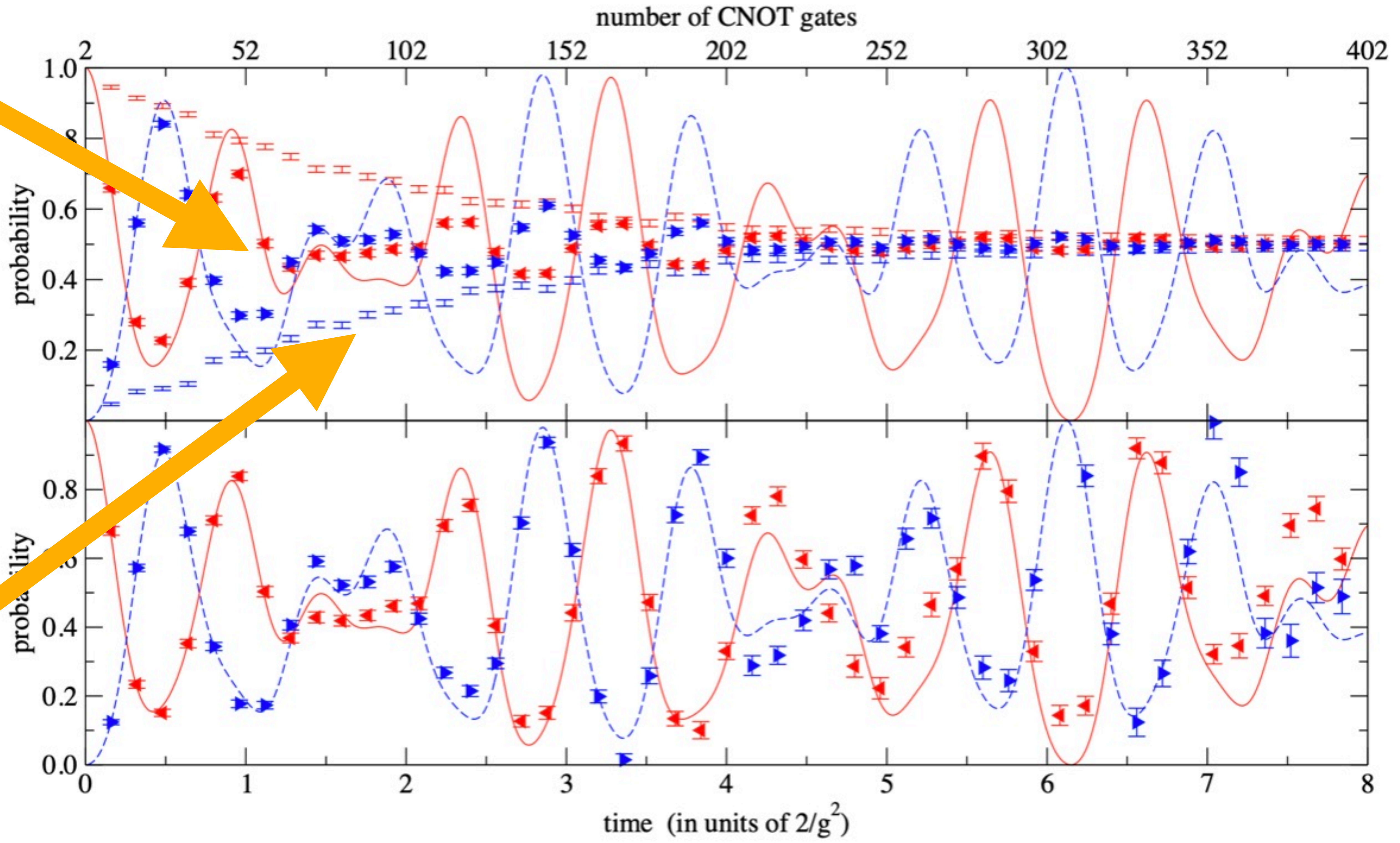
Mitigation methods are essential and effective

"Physics circuit"



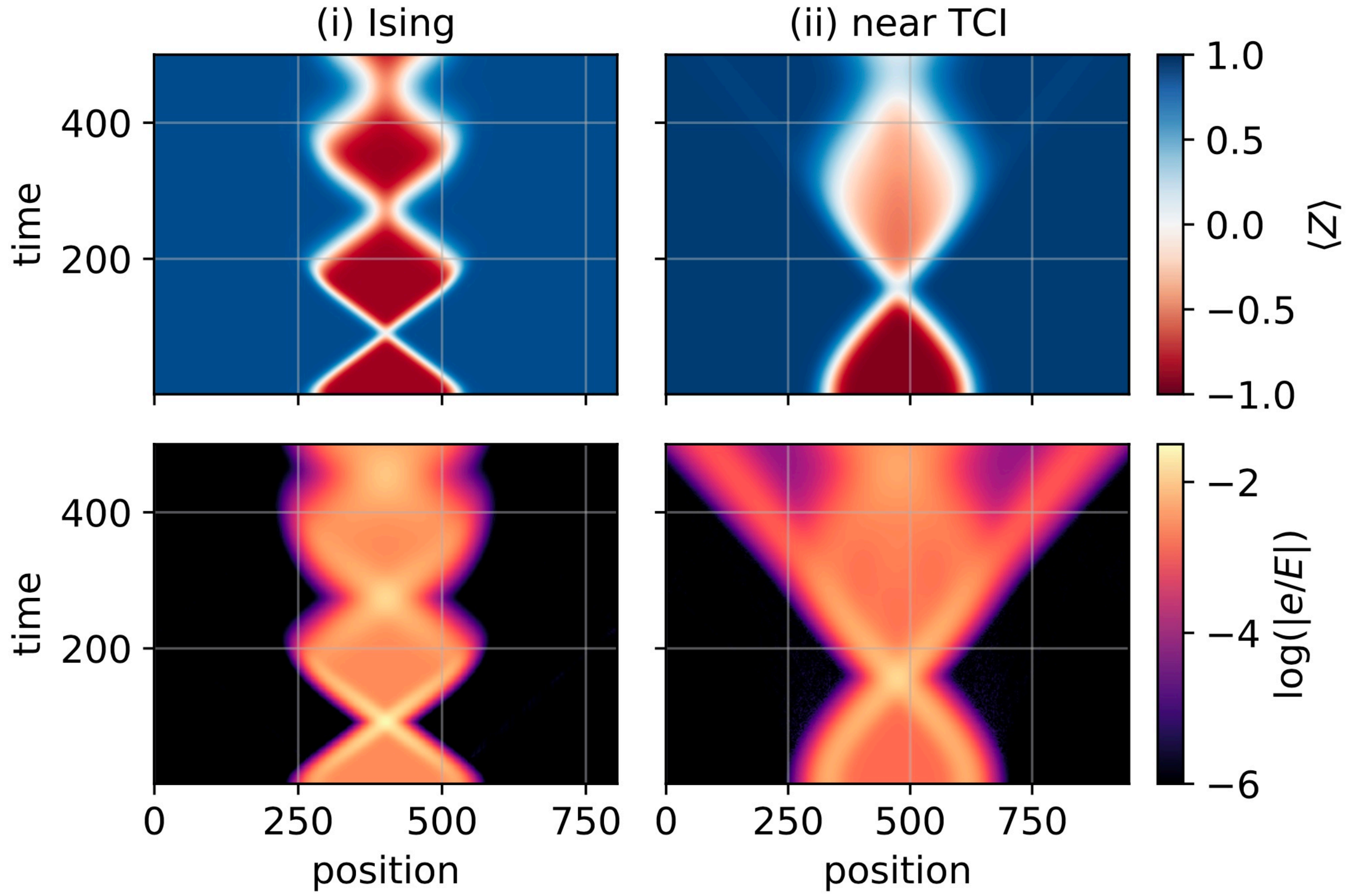
"Mitigation circuit" - all angles set to zero (e.g.)

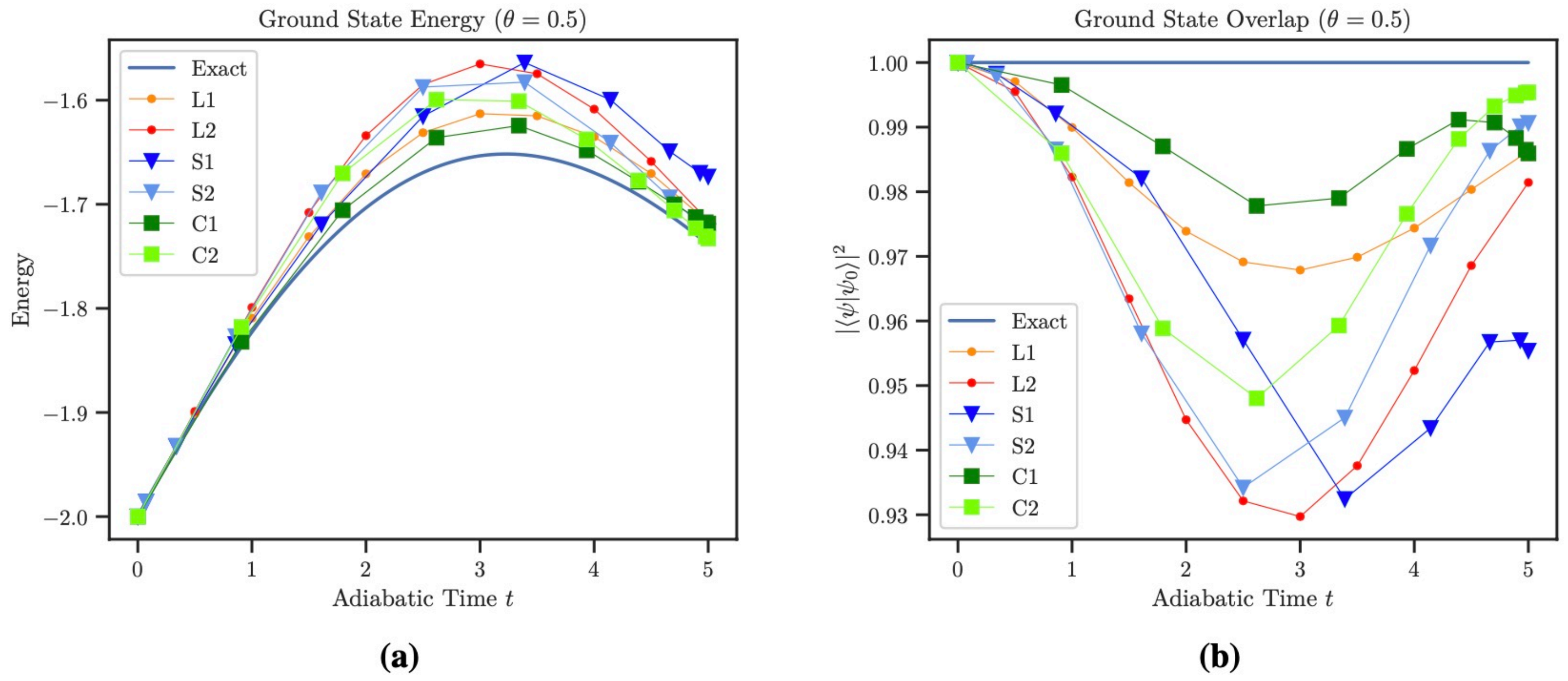




1+1D Preparations

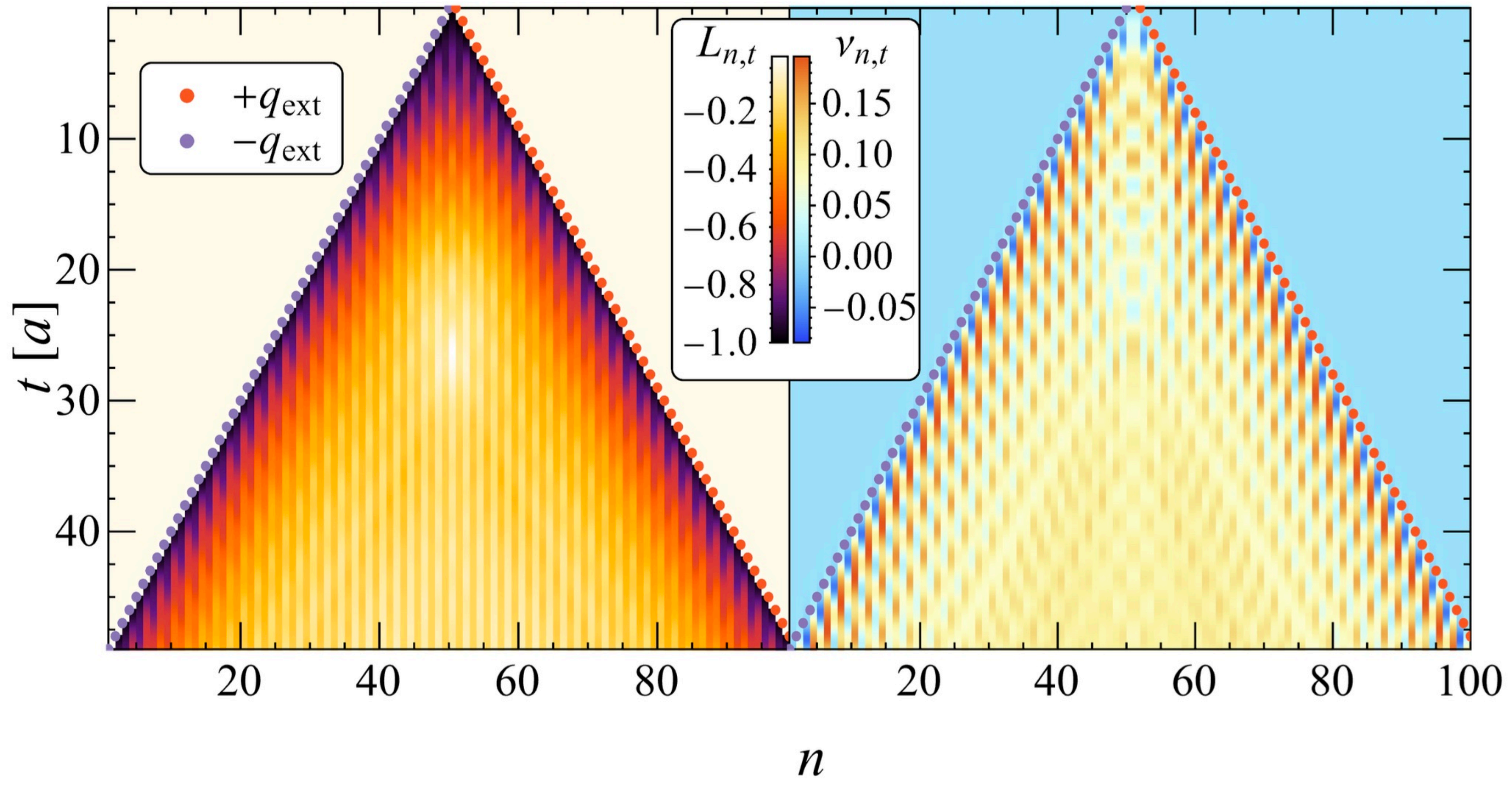
Ising+ , Milsted et al



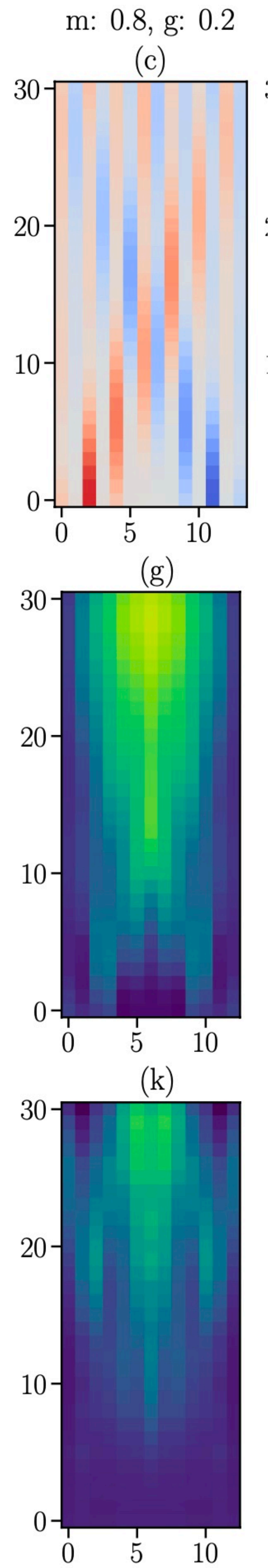


QAOA, Rodeo , Pederiva et al

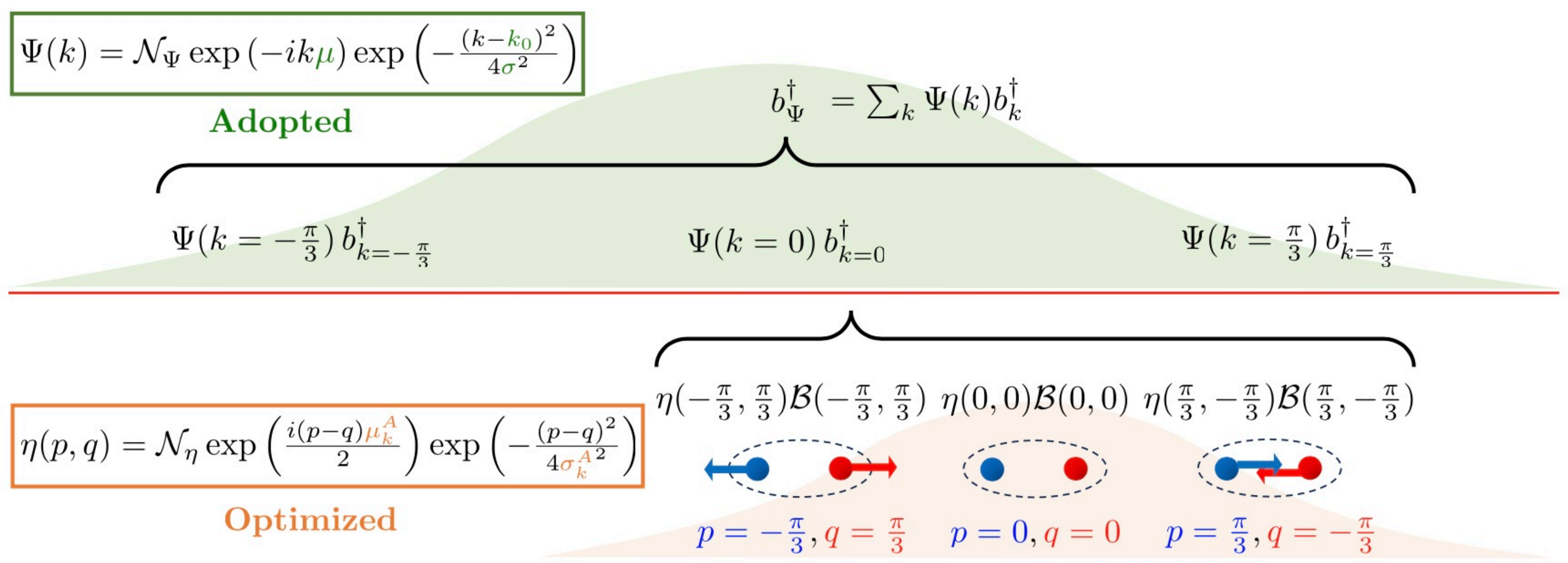
Hadronization , Florio et al



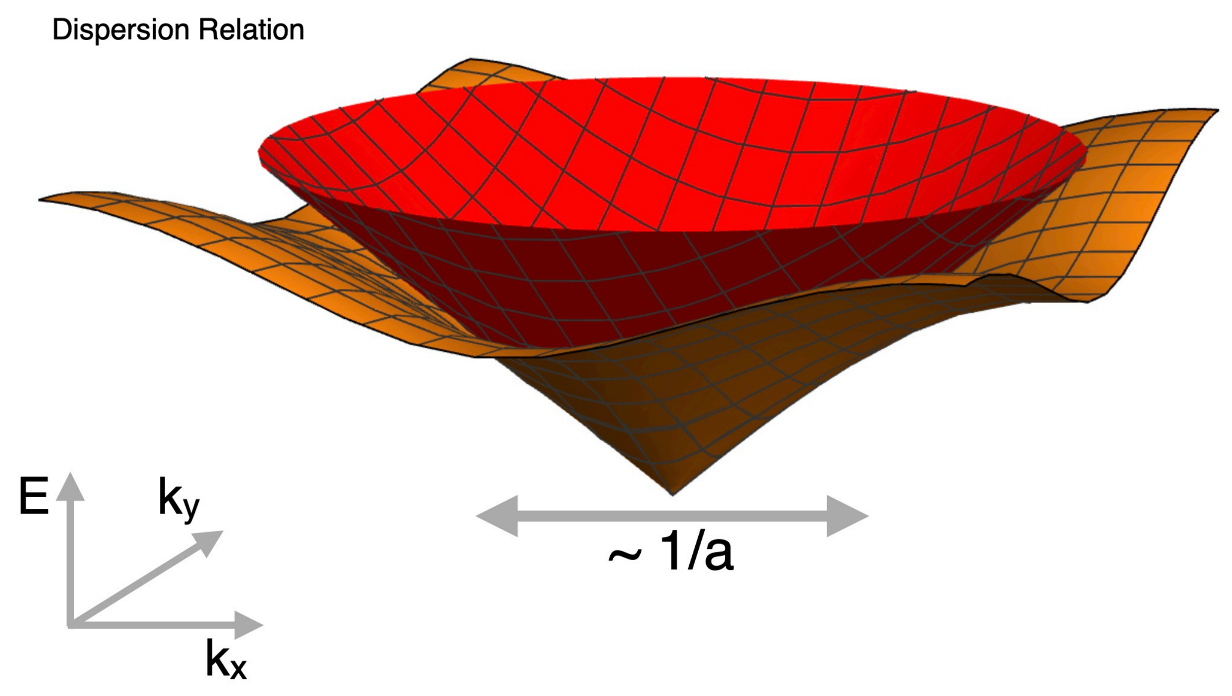
Thirring , Chai et al

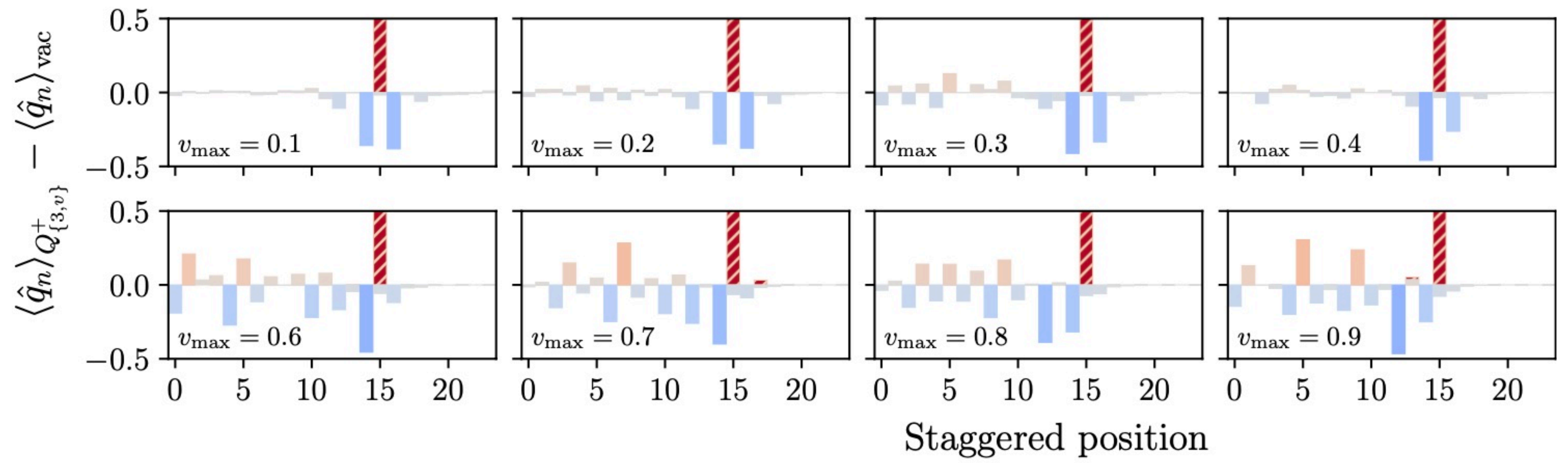


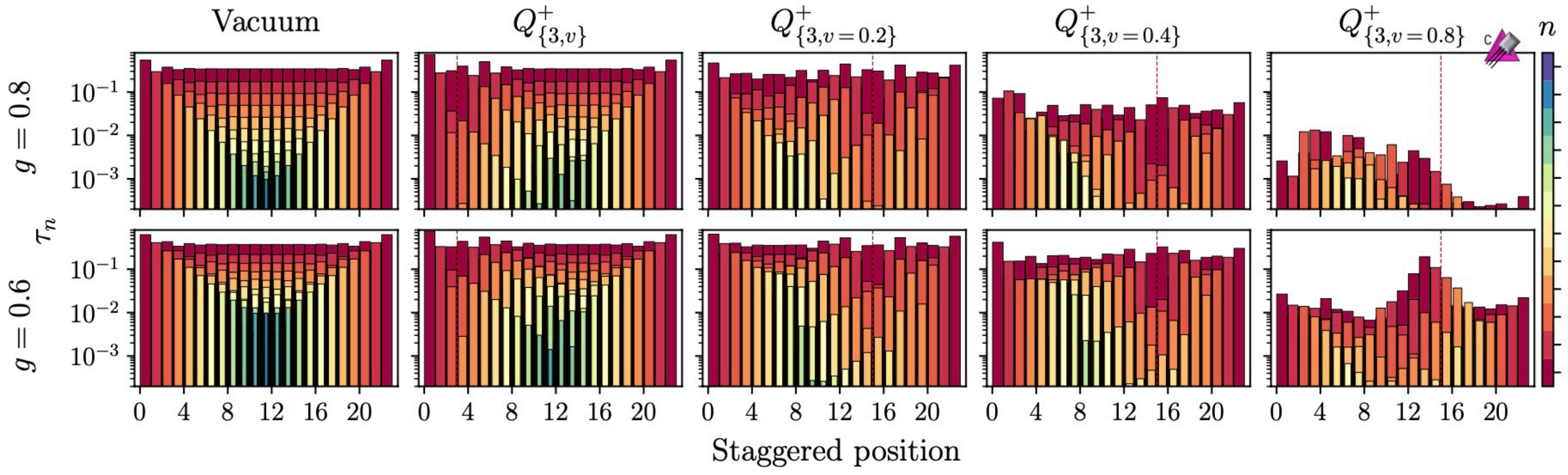
Wavepackets , Davoudi et al

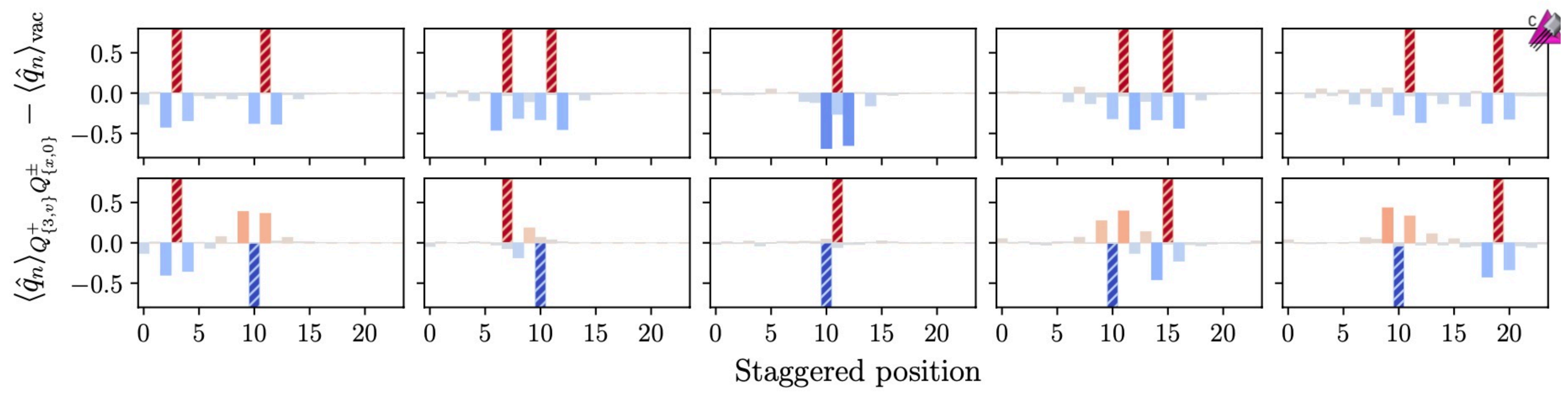


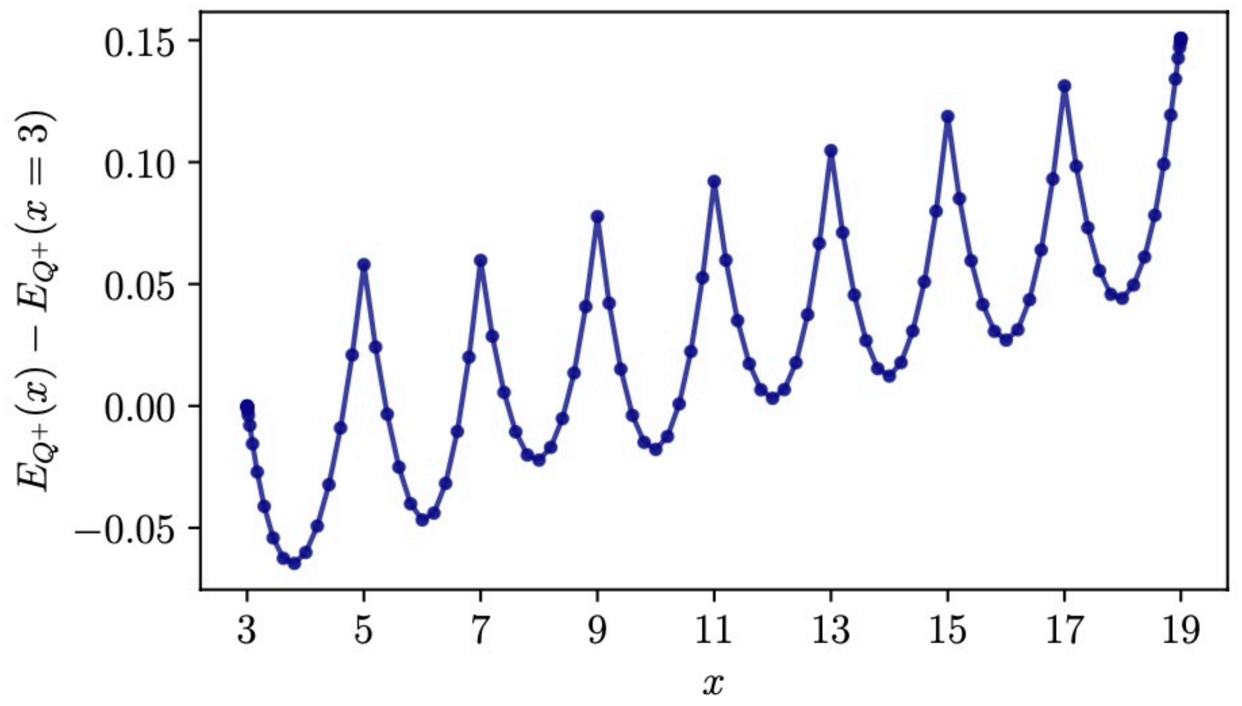
Colliding Partons, Energy Loss and Hadronization

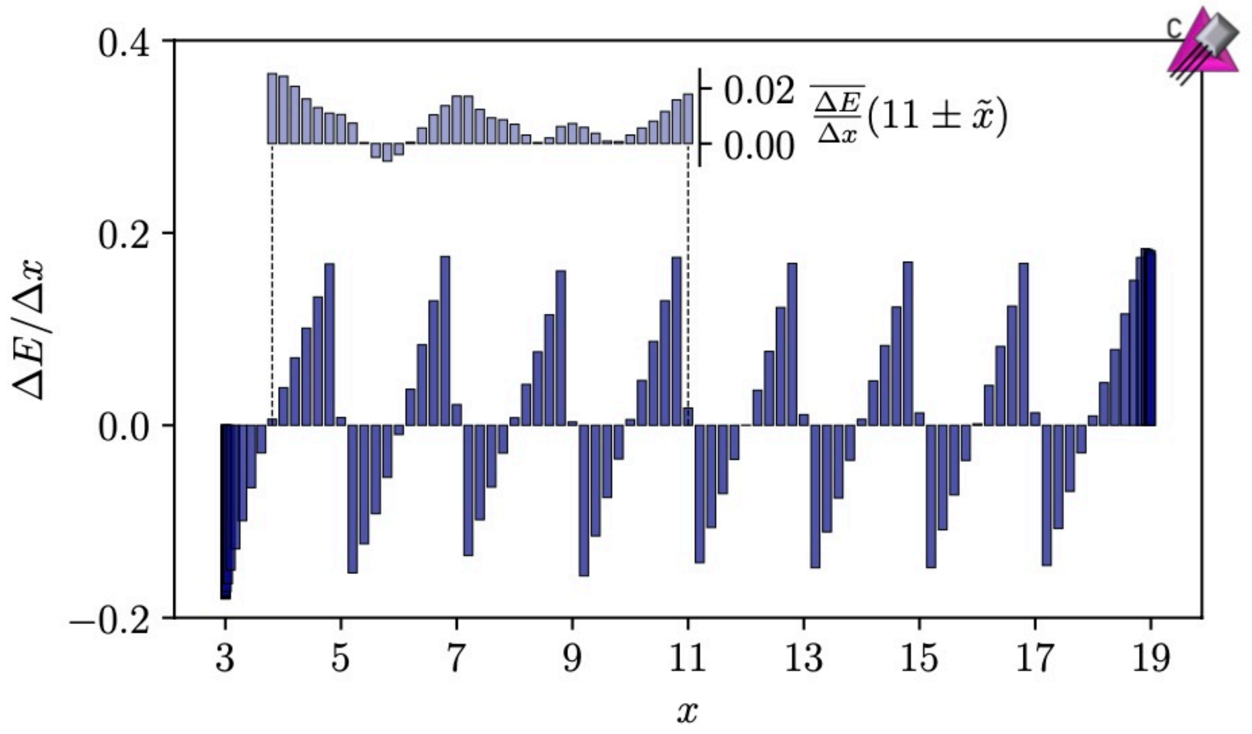




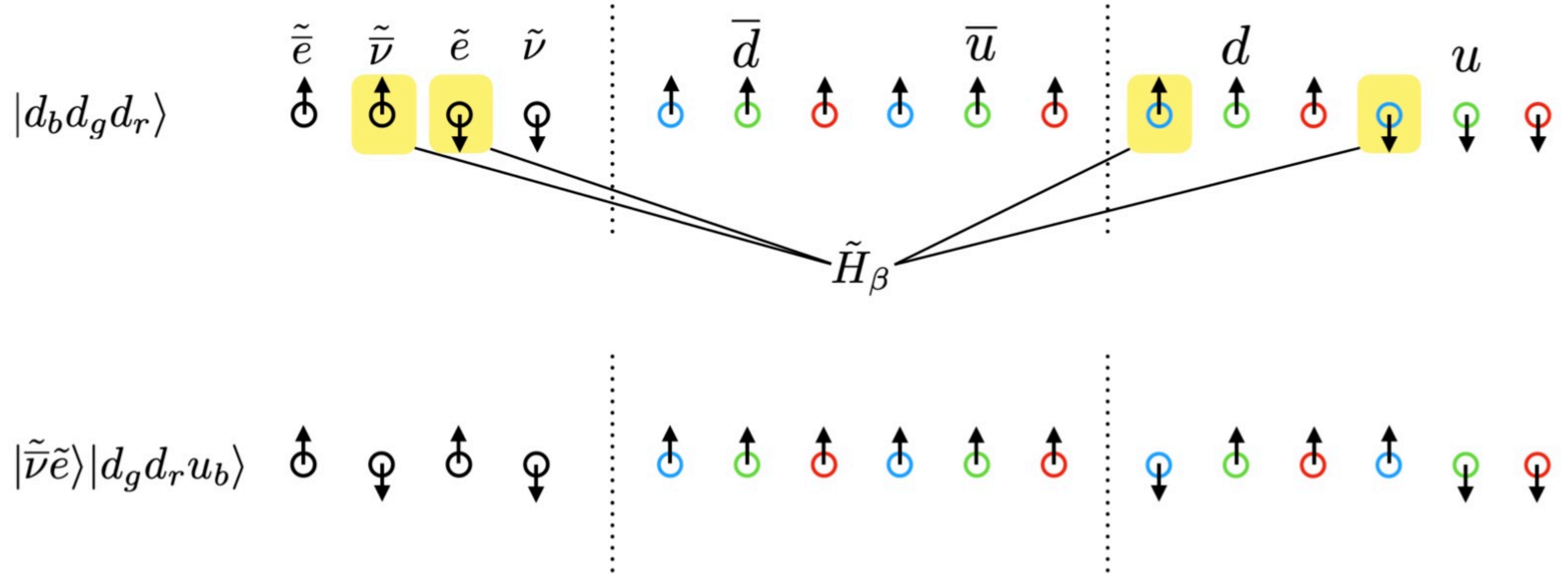


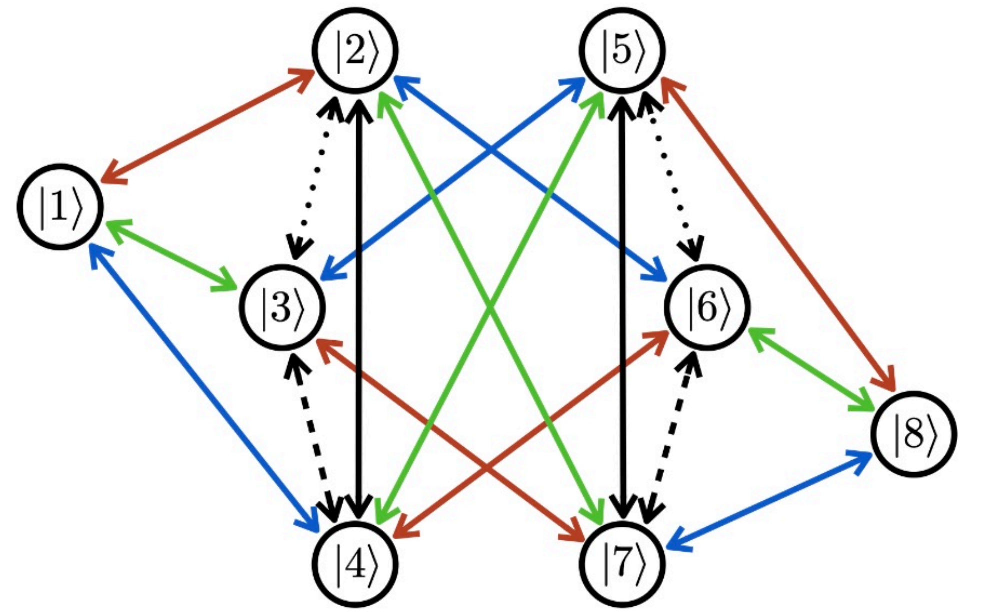






1+1D QCD and Weak Decays (2022)



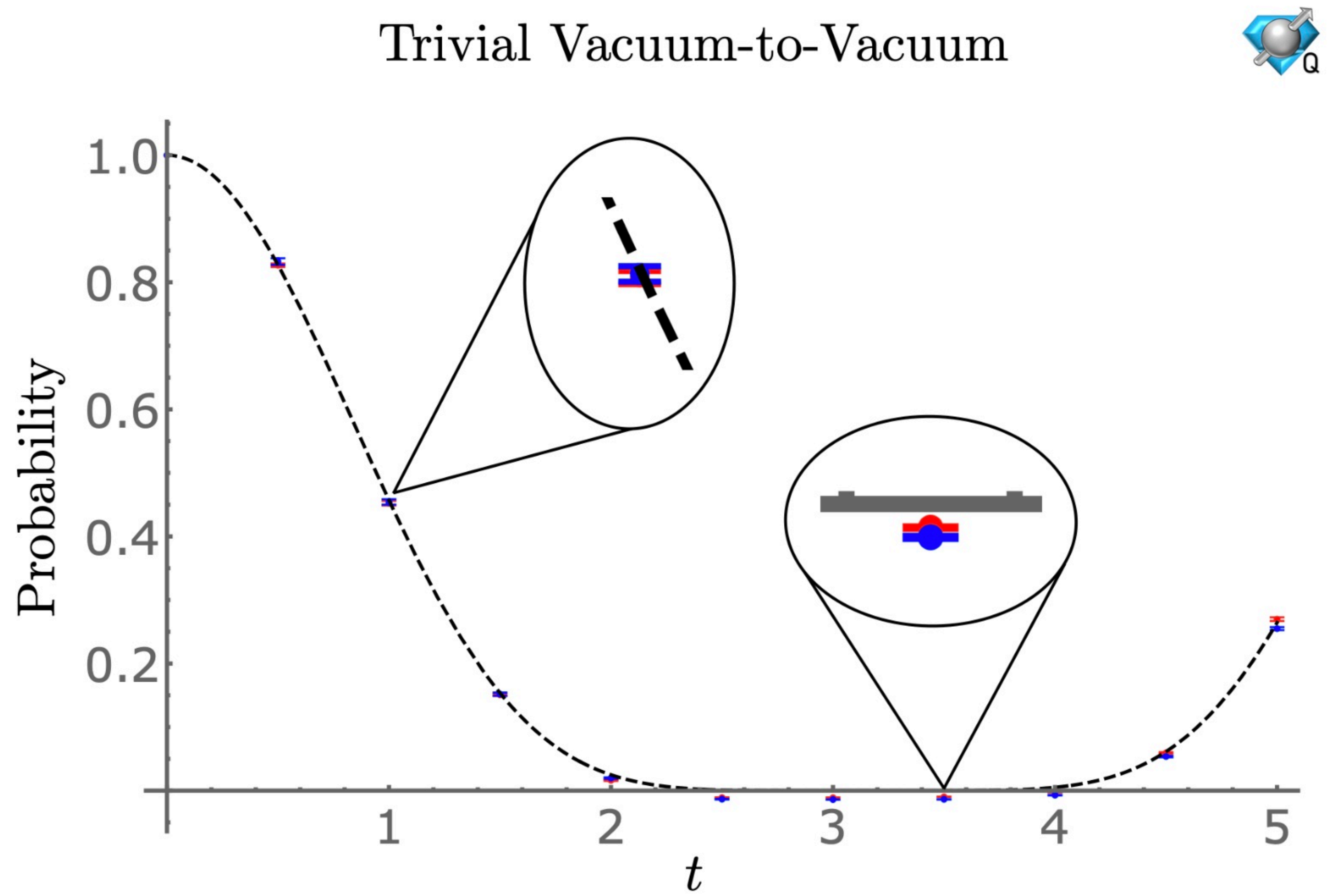


Editors' Suggestion

Access by University

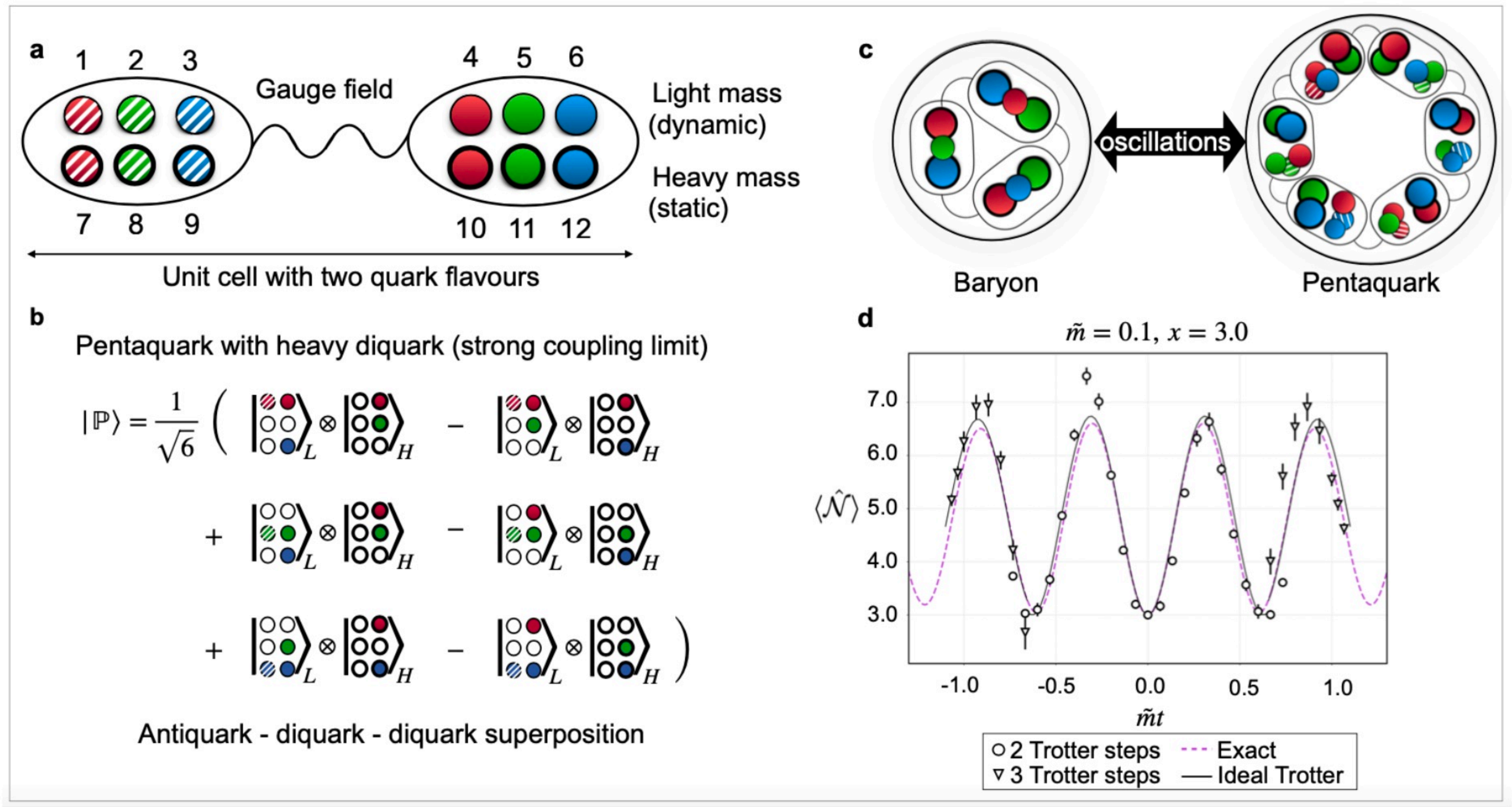
Qu8its for quantum simulations of lattice quantum chromodynamics

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



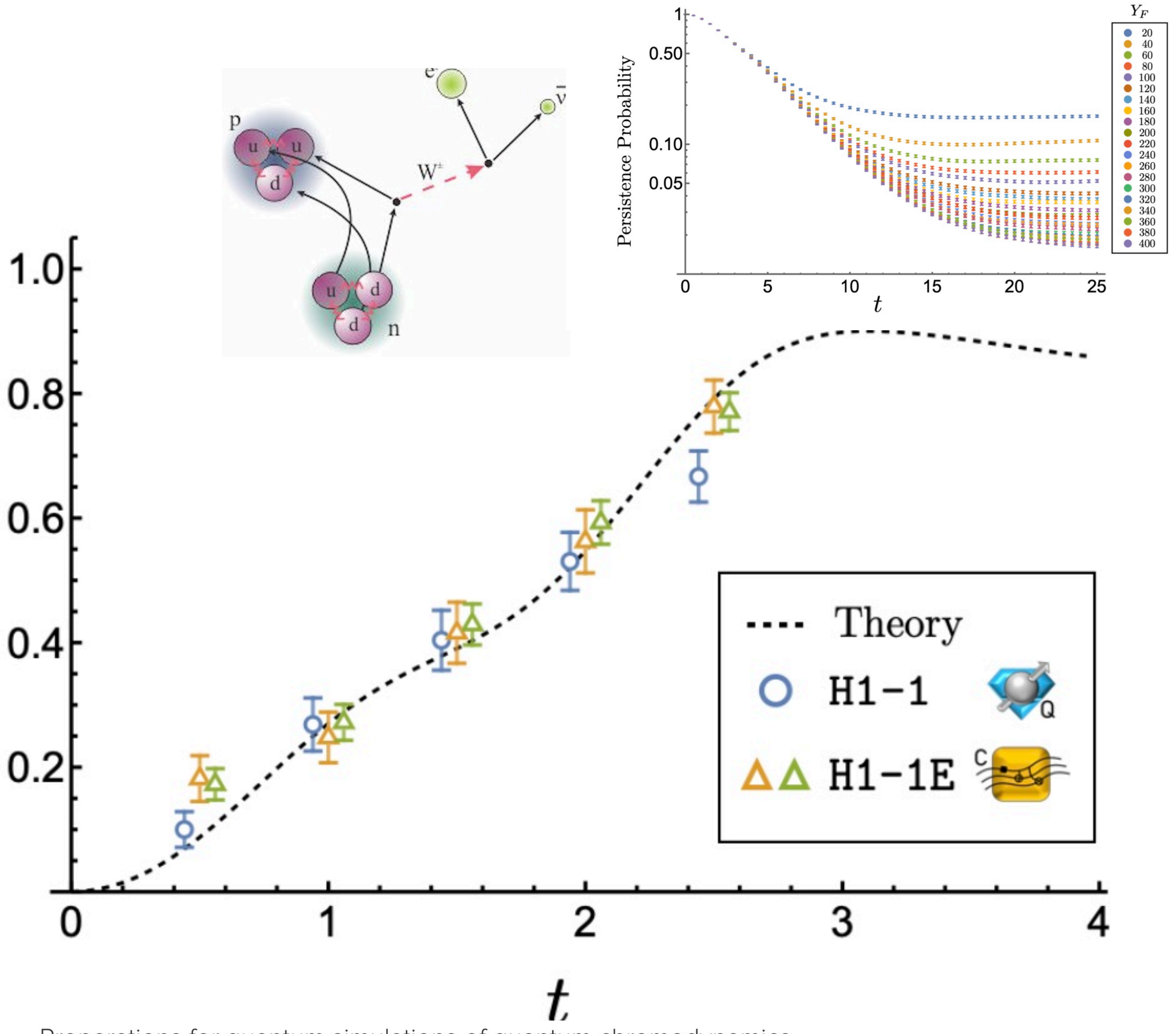
Preparations for quantum simulations of quantum chromodynamics in $1+1$ dimensions. I. Axial gauge

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

Dynamical Quantum Phase Transitions

2018

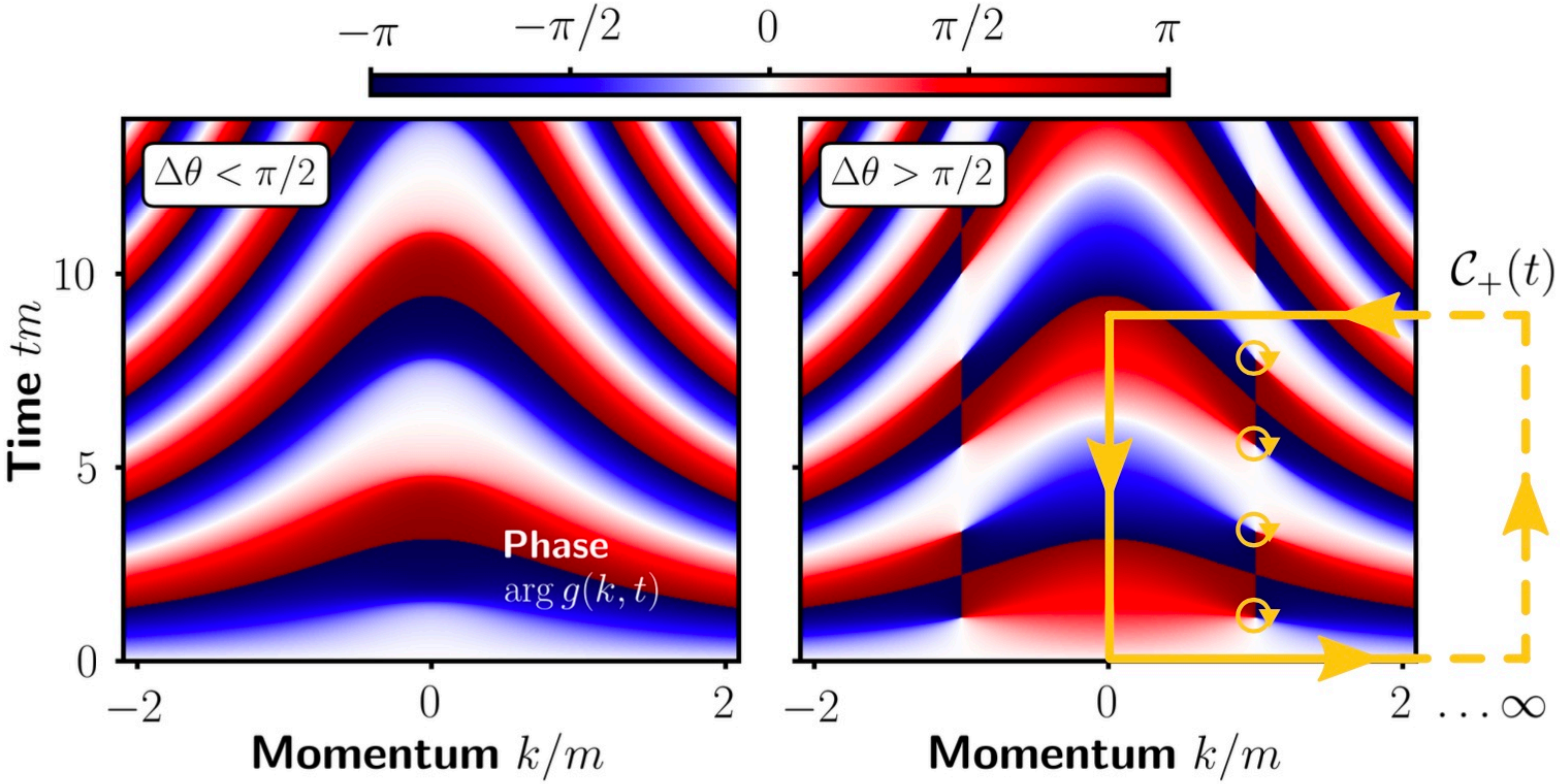
Dynamical topological transitions in the massive Schwinger model with a θ-term

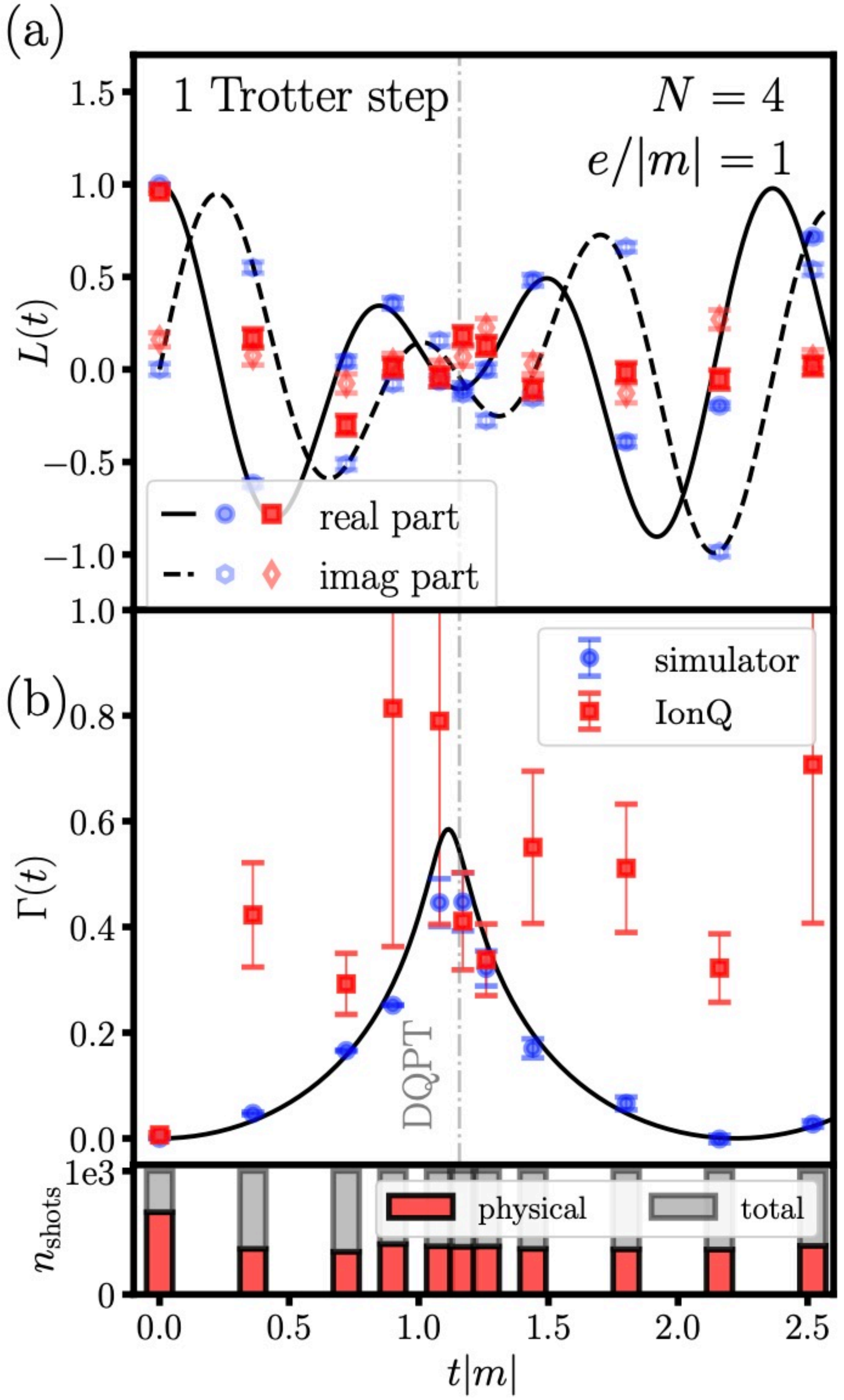
T. V. Zache,[1,*] N. Mueller,[2] J. T. Schneider,[1] F. Jendrzejewski,[3] J. Berges,[1] and P. Hauke[1,3]

2023

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

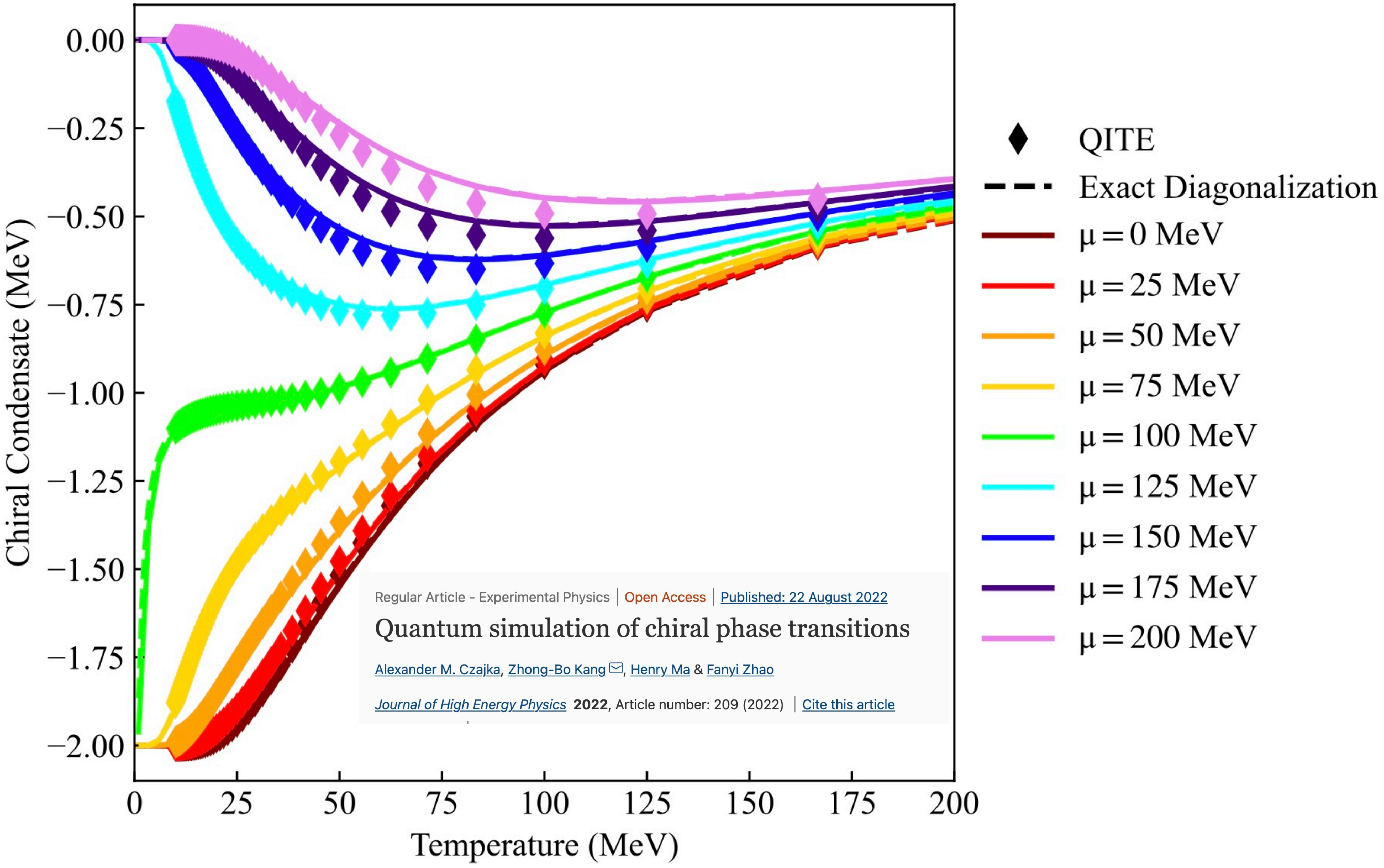
Niklas Mueller,[1,2,3,*] Joseph A. Carolan,[4] Andrew Connelly,[5]
Zohreh Davoudi,[1,6,†] Eugene F. Dumitrescu,[7,‡] and Kübra Yeter-Aydeniz[8]





Modeling the QCD Phase Diagram

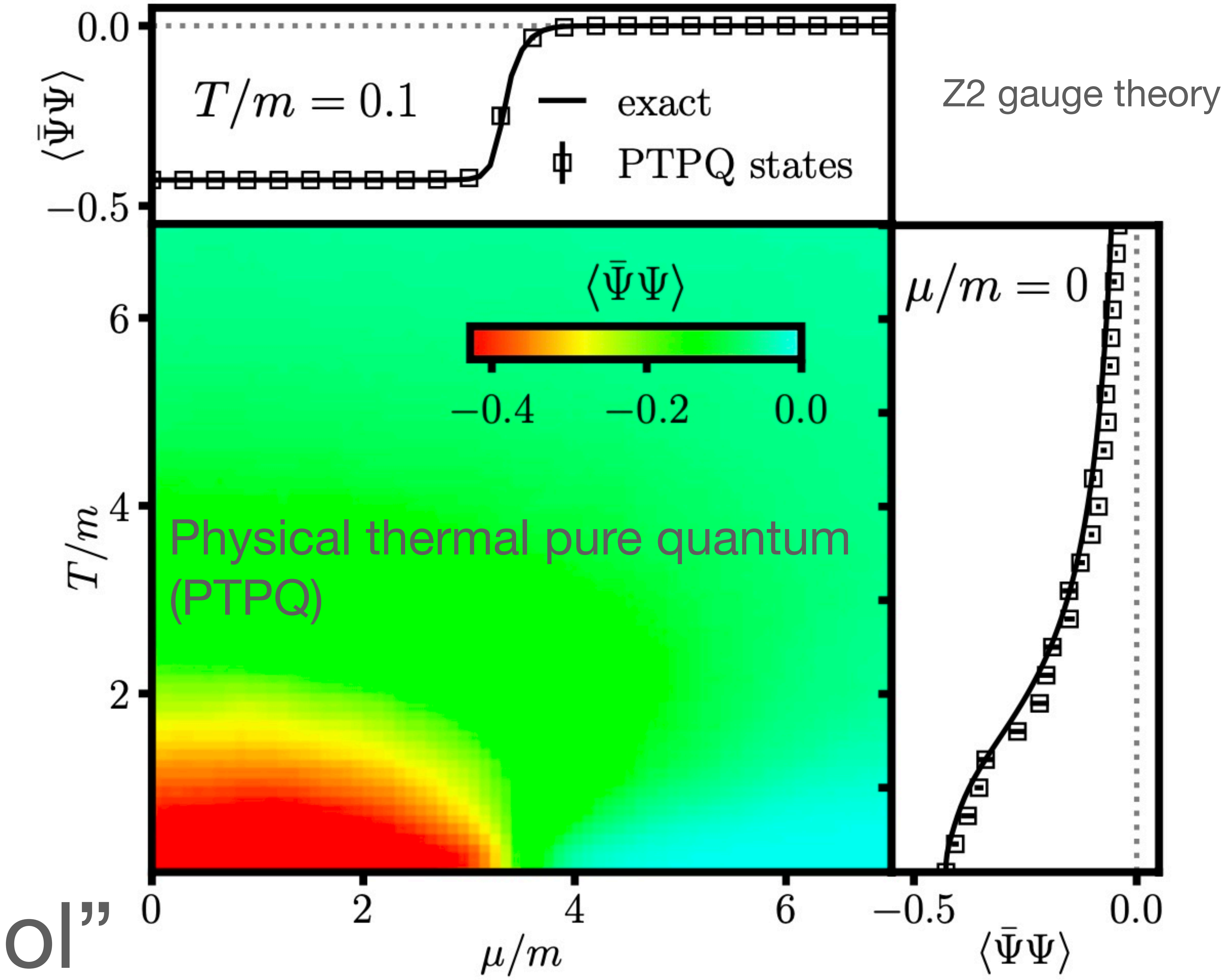
$$\mathcal{H} = \bar{\psi}(i\gamma_1\partial_1 + m)\psi - g(\bar{\psi}\psi)^2 - \mu\bar{\psi}\gamma_0\psi$$



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

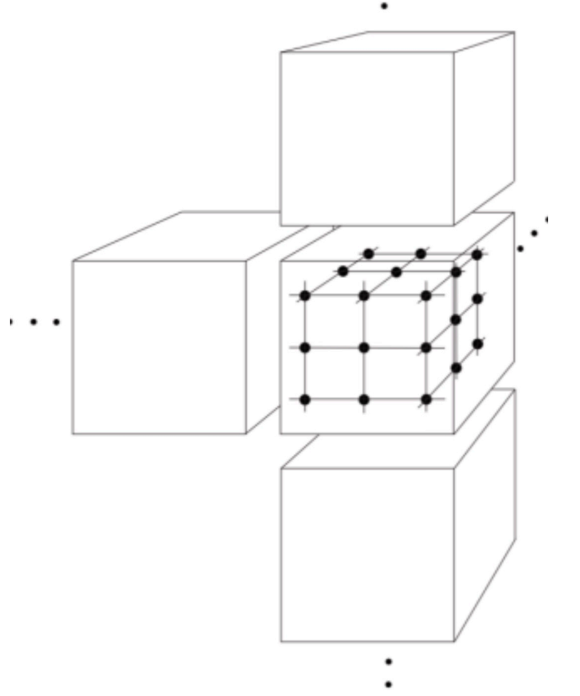
Zohreh Davoudi,[1,2,*] Niklas Mueller,[1,3,†] and Connor Powers[1,2,‡]
[1] *Maryland Center for Fundamental Physics and Department of Physics, University of Maryland, College Park, MD 20742, USA*
[2] *Institute for Robust Quantum Simulation, University of Maryland, College Park, Maryland 20742, USA*
[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 ....

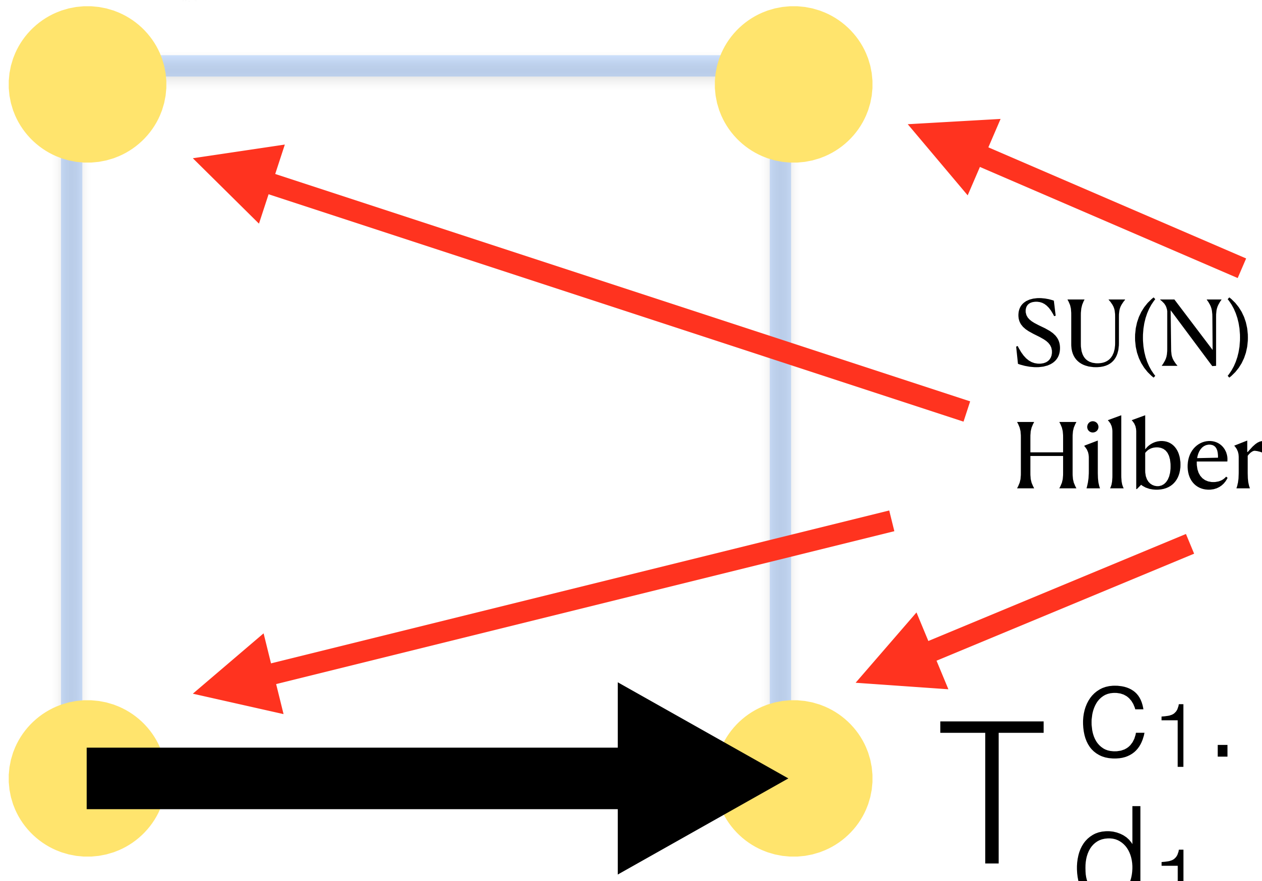
$$\hat{H} = \frac{g^2}{2}\sum_{\text{links}} \hat{E}^2 - \frac{1}{2g^2}\sum_{\Box}\left(\hat{\Box} + \hat{\Box}^\dagger\right)$$

Electric Field Casimir operator

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

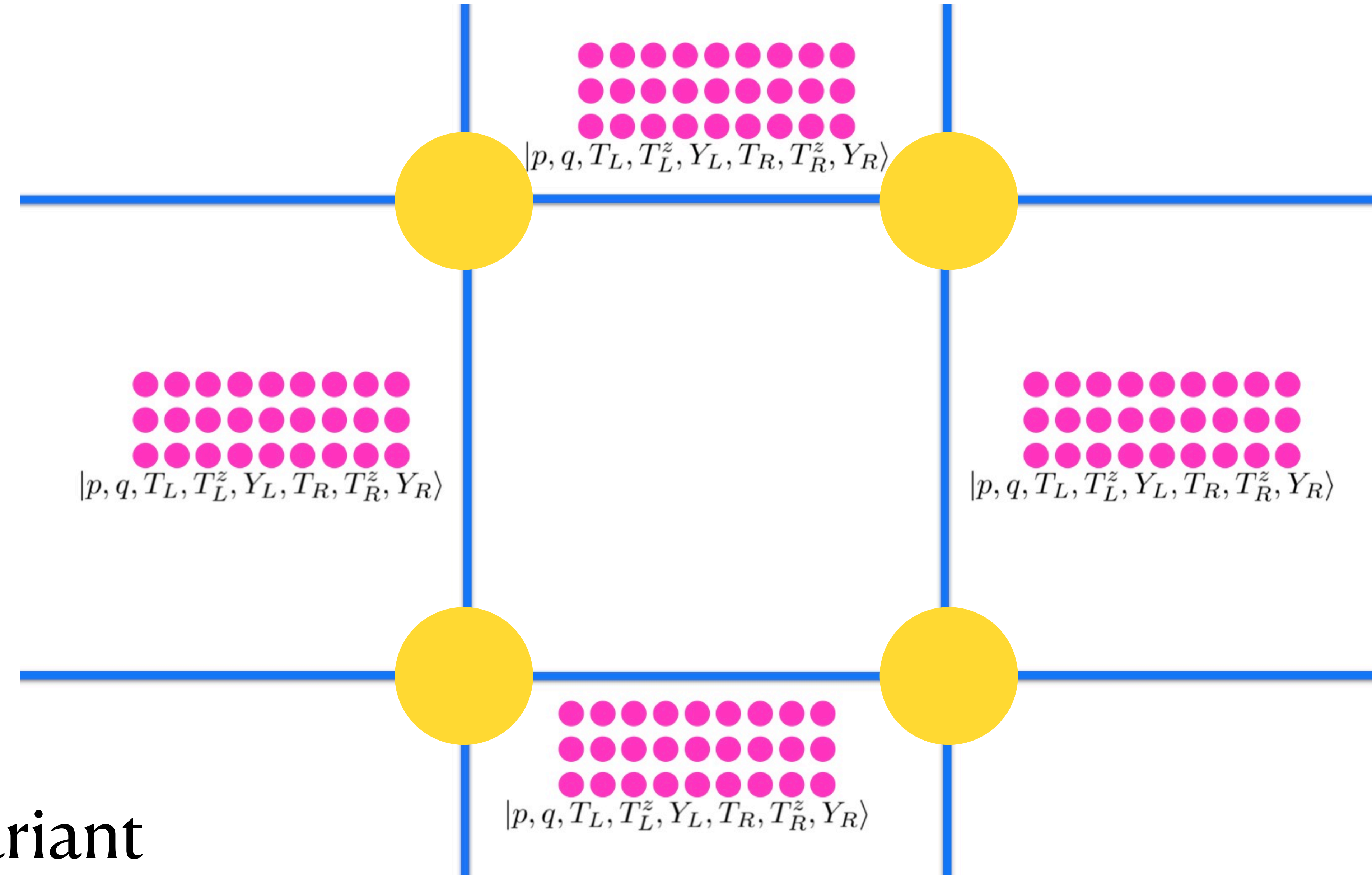
Irrep Left-space Right-space

Magnetic Field operator
Off-diagonal on electric basis



SU(N) Gauge invariant
Hilbert space

$T^{a_1 \ldots a_p}_{b_1 \ldots b_q}$ $T^{c_1 \ldots c_p}_{d_1 \ldots d_q}$

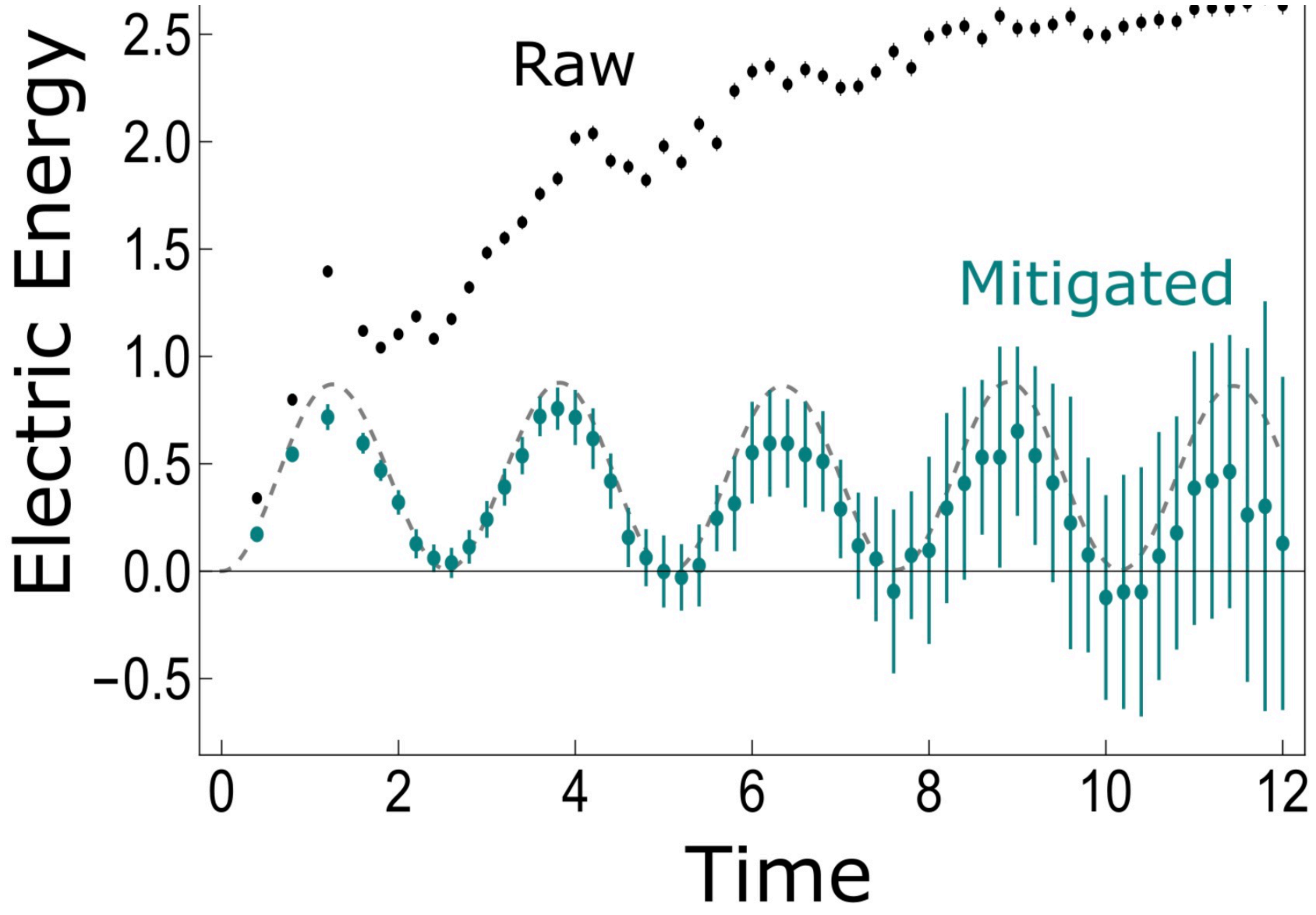


Truncations in irrep space !!!!!

SU(3) Yang-Mills Plaquettes

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

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

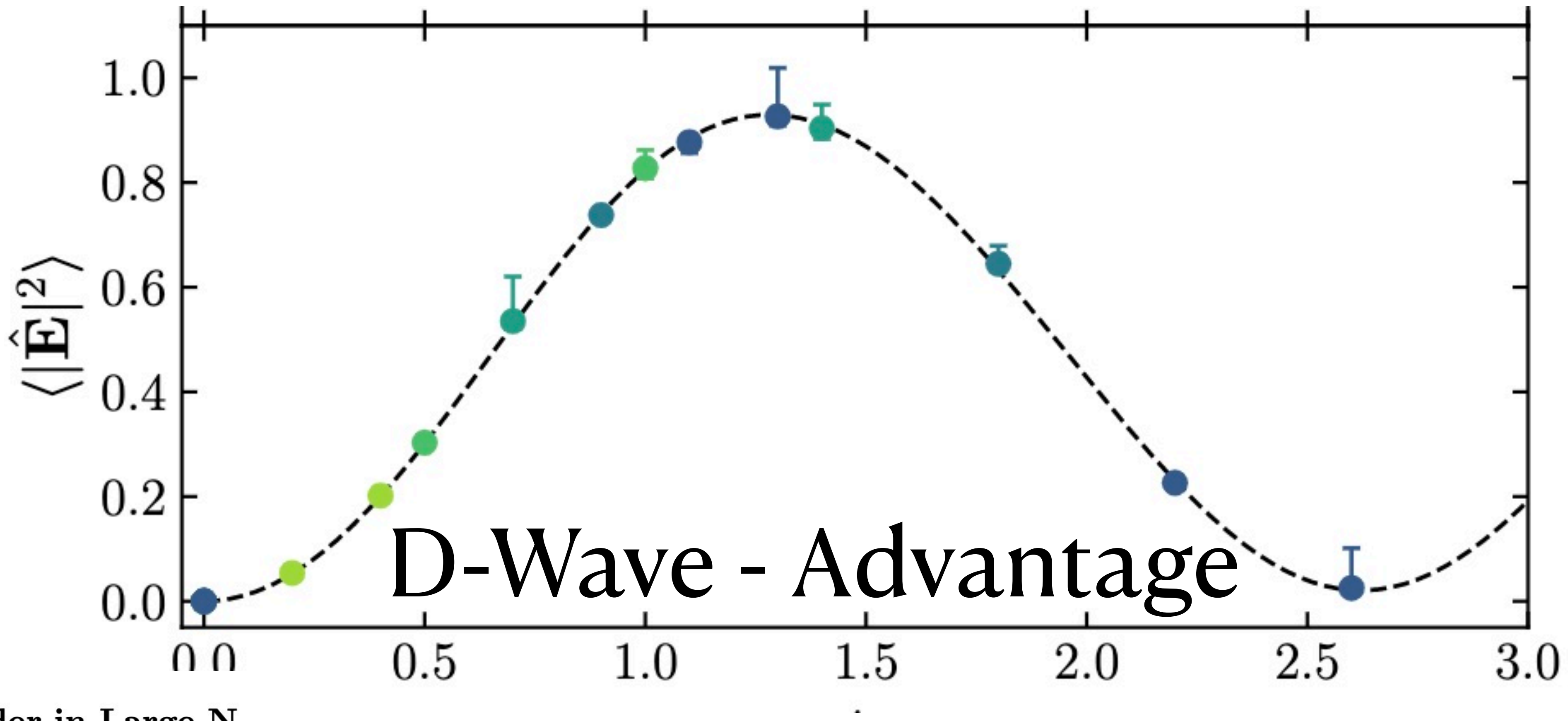


SU(2) lattice gauge theory on a quantum annealer

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

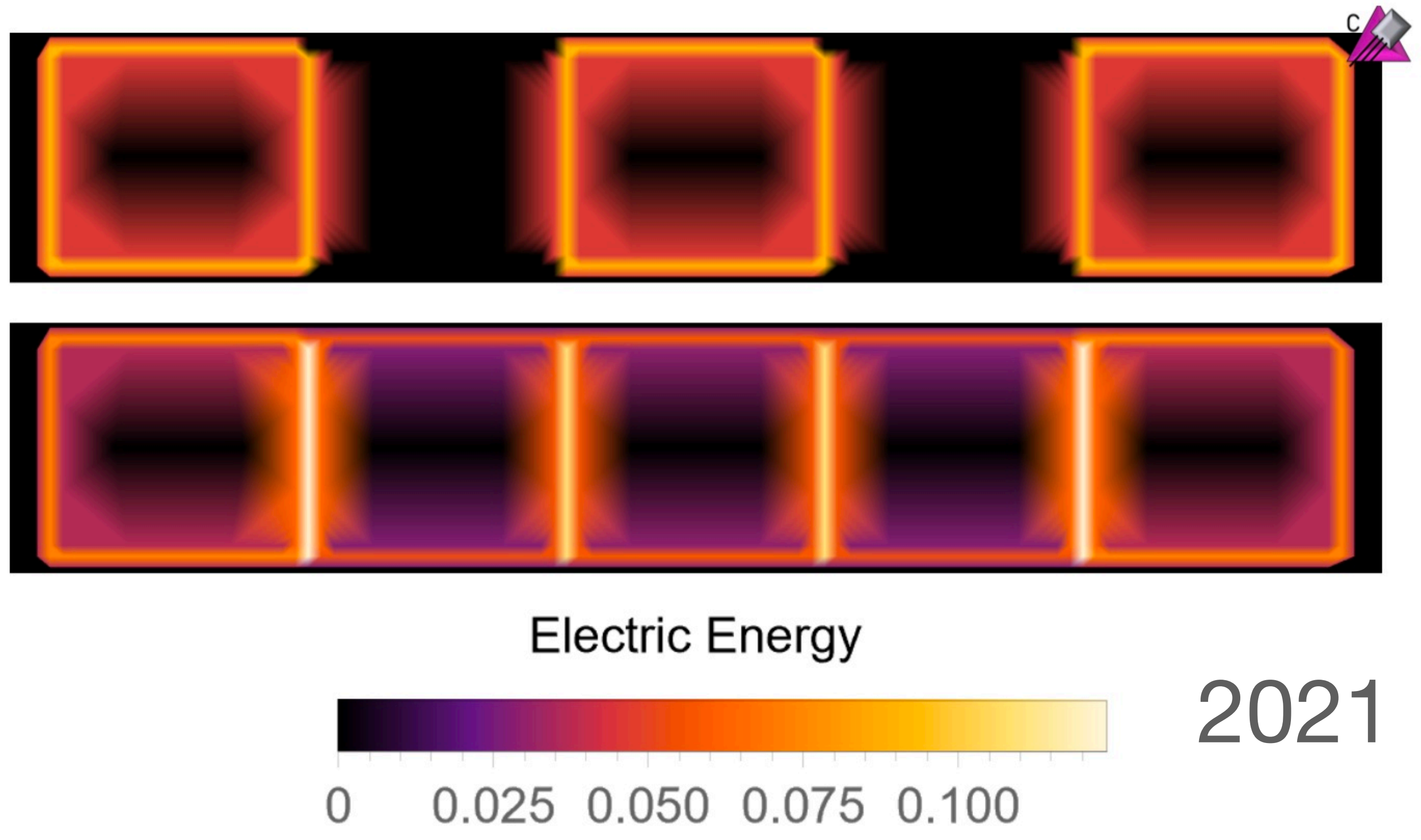
Basic Elements for Simulations of Standard Model Physics with Quantum Annealers: Multigrid and Clock States

Marc Illa[1,*] and Martin J. Savage[1,†]

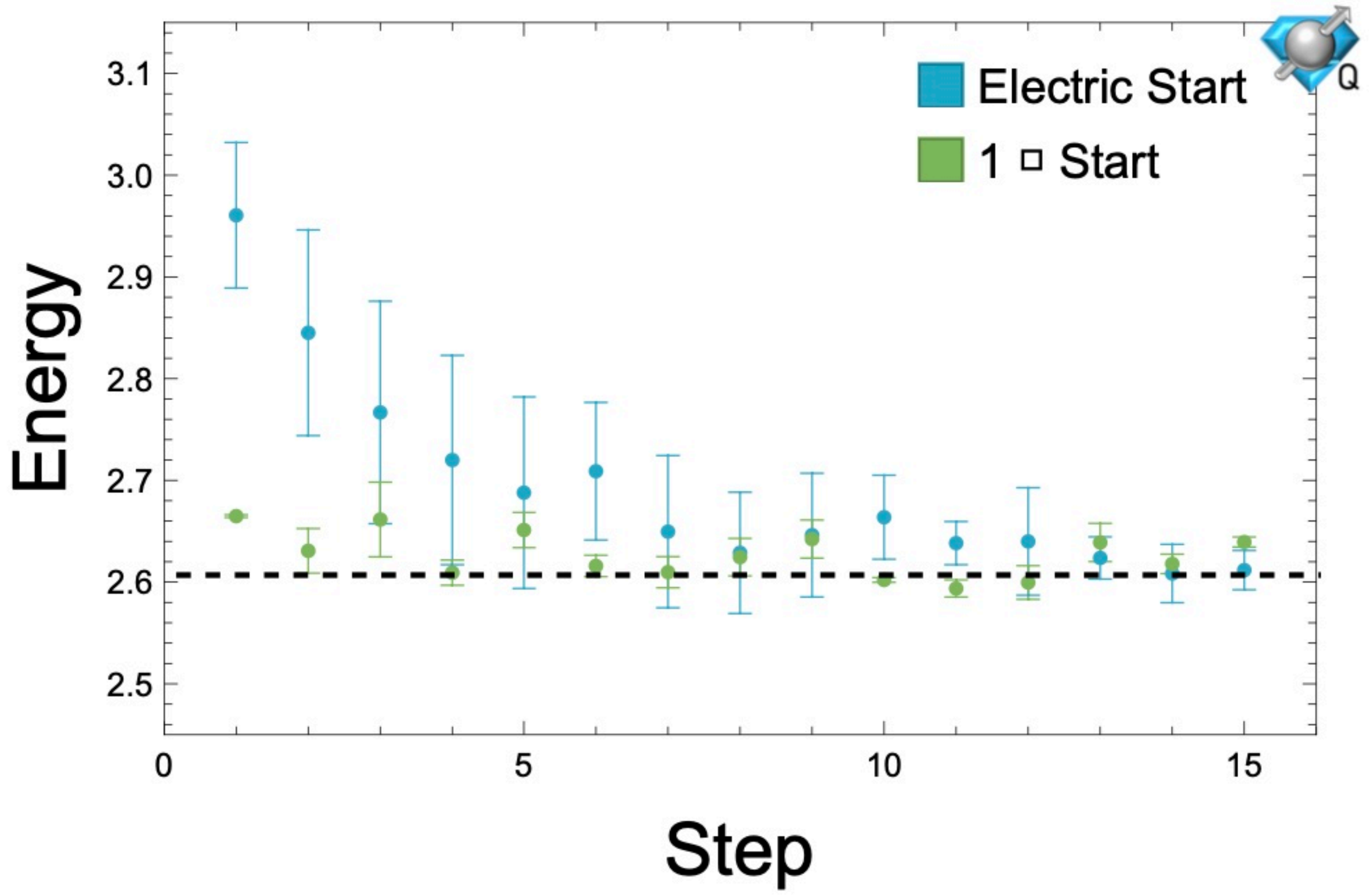


Preparation of the SU(3) Lattice Yang-Mills Vacuum with Variational Quantum Methods

Anthony N Ciavarella[1,*] and Ivan A Chernyshev[1,†]

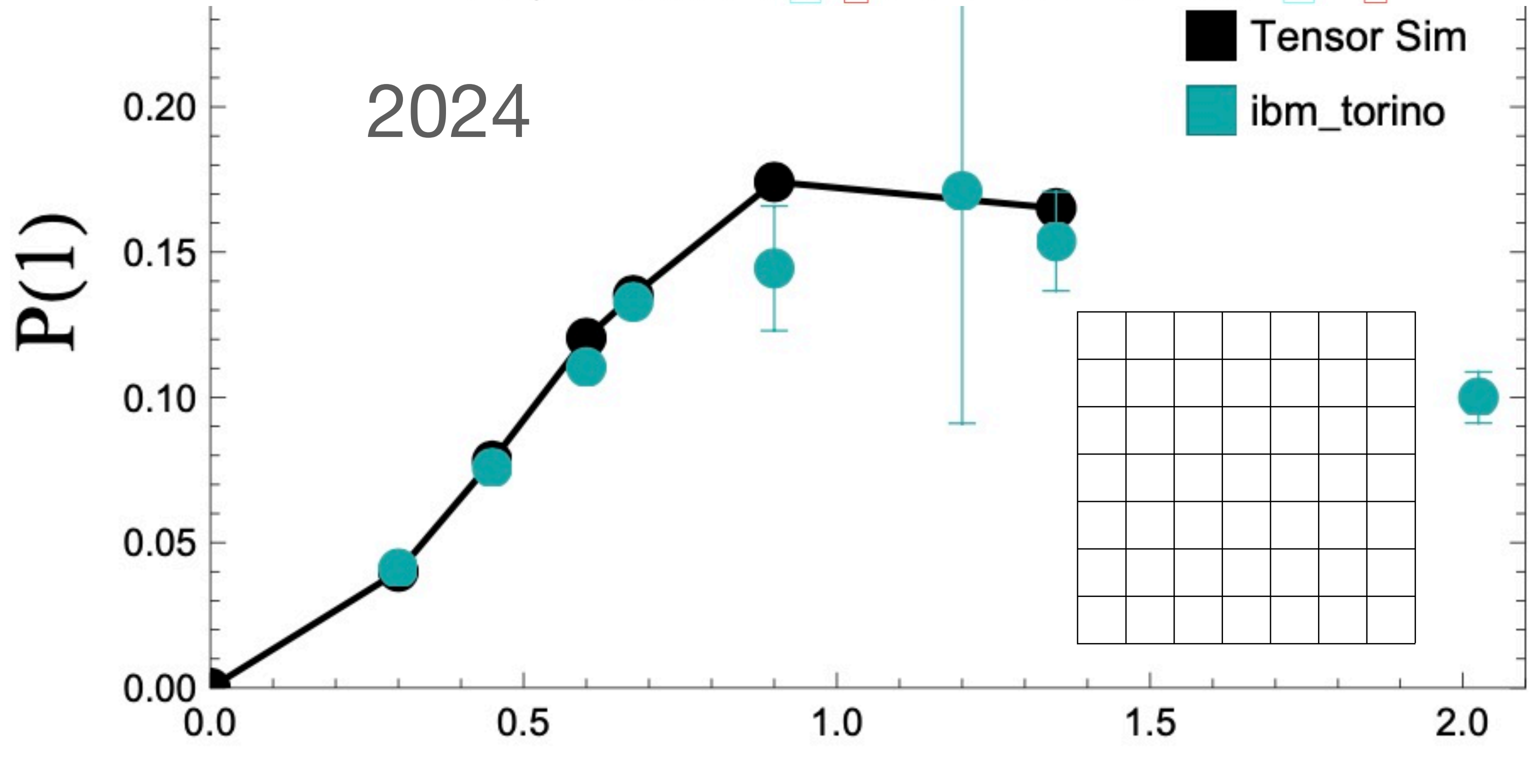


2021



Quantum Simulation of SU(3) Lattice Yang Mills Theory at Leading Order in Large N

Anthony N. Ciavarella[1,*] and Christian W. Bauer[1,2,†]



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

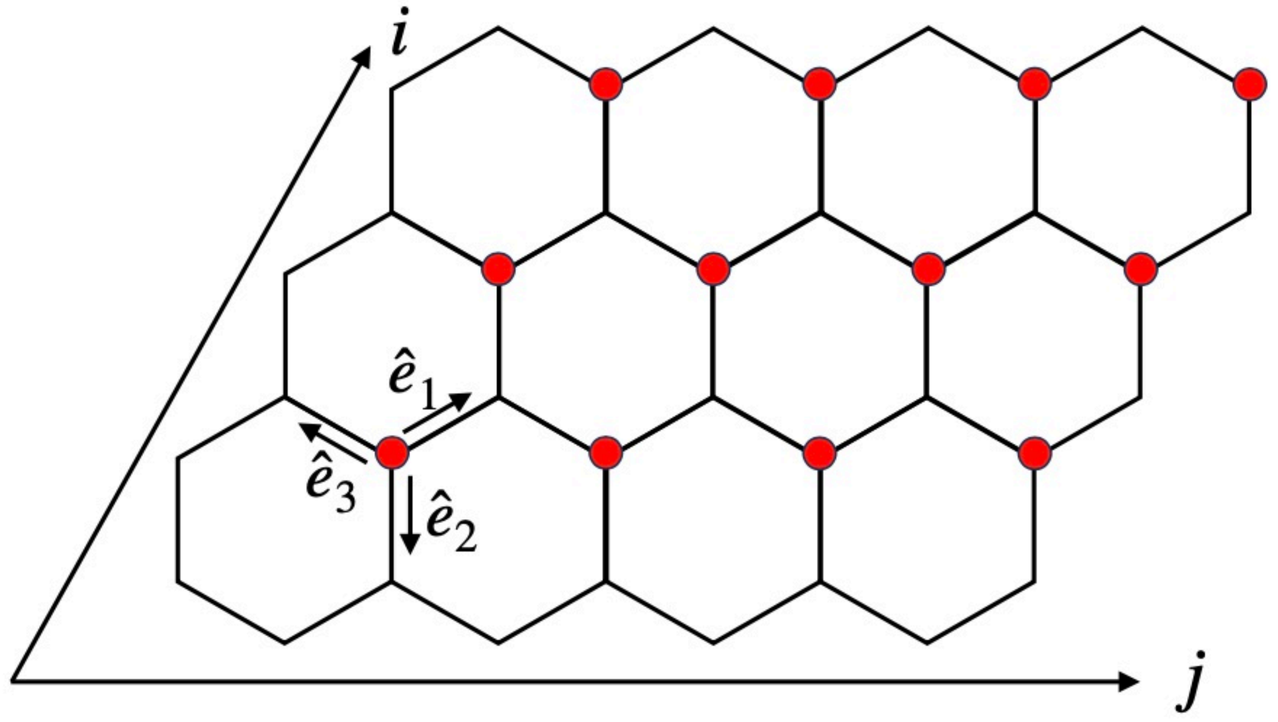
"Tree-level" Kubo formula $$\eta = \lim_{\omega \to 0} \frac{\partial}{\partial \omega} G_r^{xy}(\omega)$$

Baier, Romatschke, Son, Starinets, Stephanov, 0712.2451

$$G_r^{xy}(\omega) = \int \mathrm{d}t\, e^{i\omega t} G_r^{xy}(t) \equiv \int \mathrm{d}t\, \mathrm{d}^2x\, e^{i\omega t} G_r^{xy}(t, \boldsymbol{x})$$

$$G_r^{xy}(t, \boldsymbol{x}) \equiv \theta(t) \mathrm{Tr}\big([T^{xy}(t, \boldsymbol{x}), T^{xy}(0, \boldsymbol{0})]\rho_T\big)$$

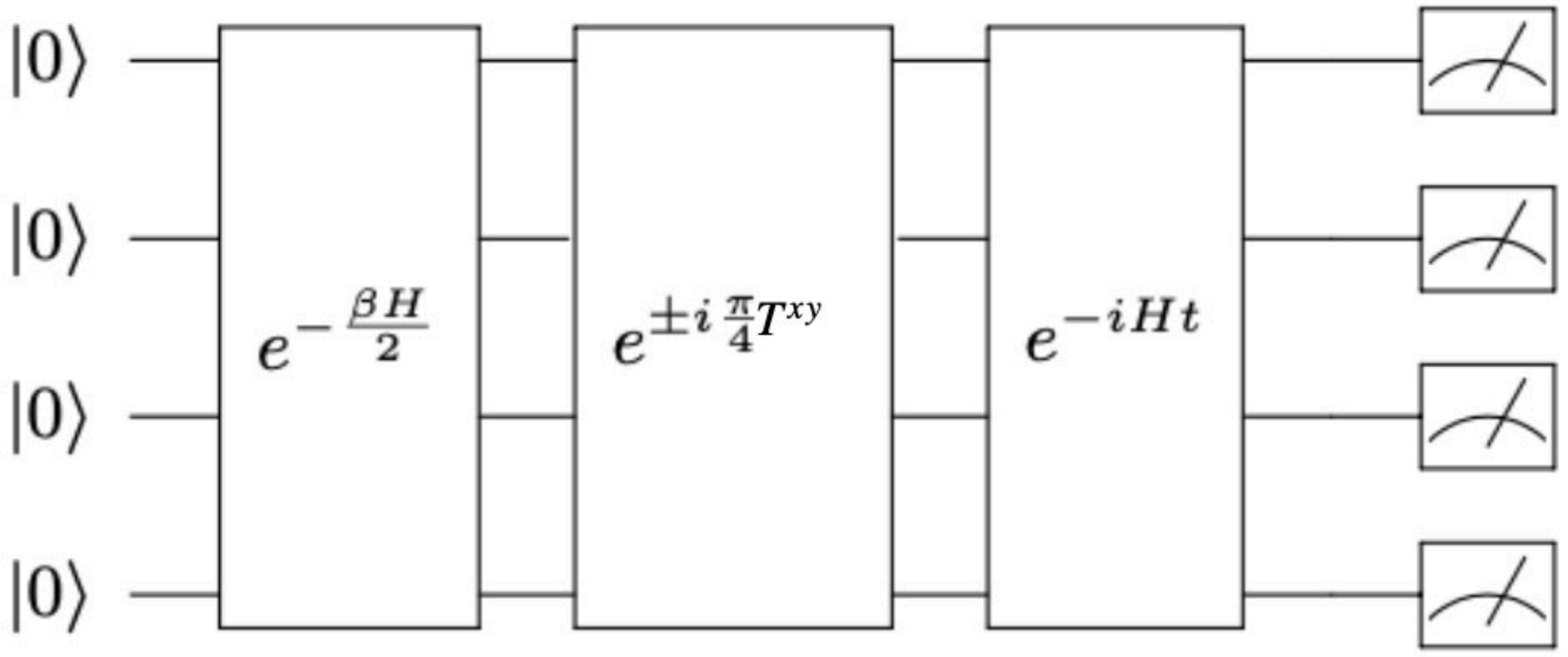
$$T^{\mu\nu} = -\frac{1}{g^2} F^{a\mu\rho} F^{a\nu}{}_{\rho} + \frac{1}{4g^2} \eta^{\mu\nu} F^{a\rho\sigma} F^{a}_{\rho\sigma}$$



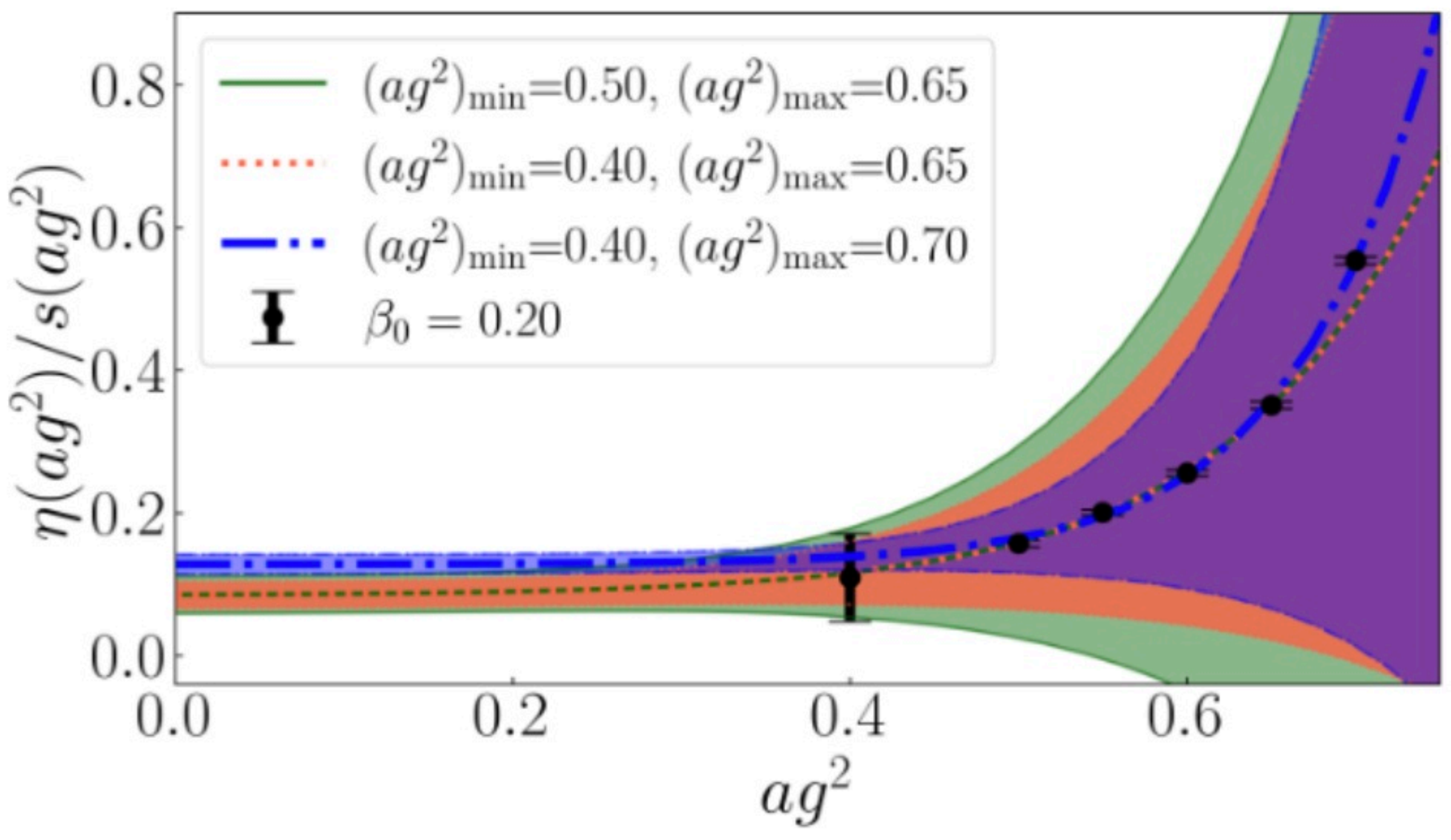
$$H = \frac{3\sqrt{3}g^2}{4} \sum_{\text{links}} E_i^a E_i^a - \frac{4\sqrt{3}}{9g^2a^2} \sum_{\text{plaqs}} \hexagon$$

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

Quantum algorithm for G_r^{xy}



On 4×4 lattice w/ $j_{\max} = 0.5$



2307.00045
Berndt Mueller and Xiaojun Yao

2402.04221
Francesco Turro, Anthony Ciavarella and Xiaojun Yao

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]

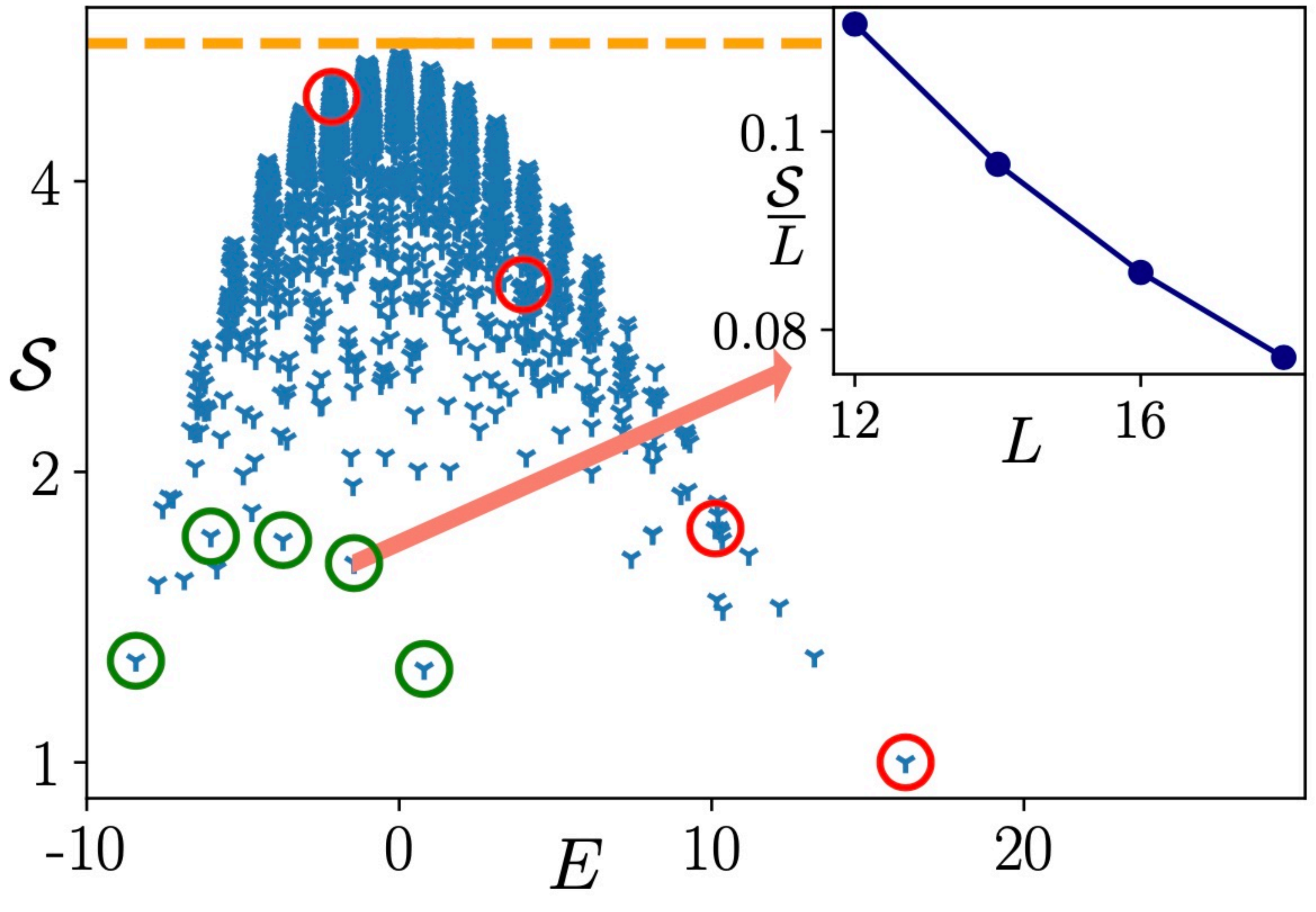
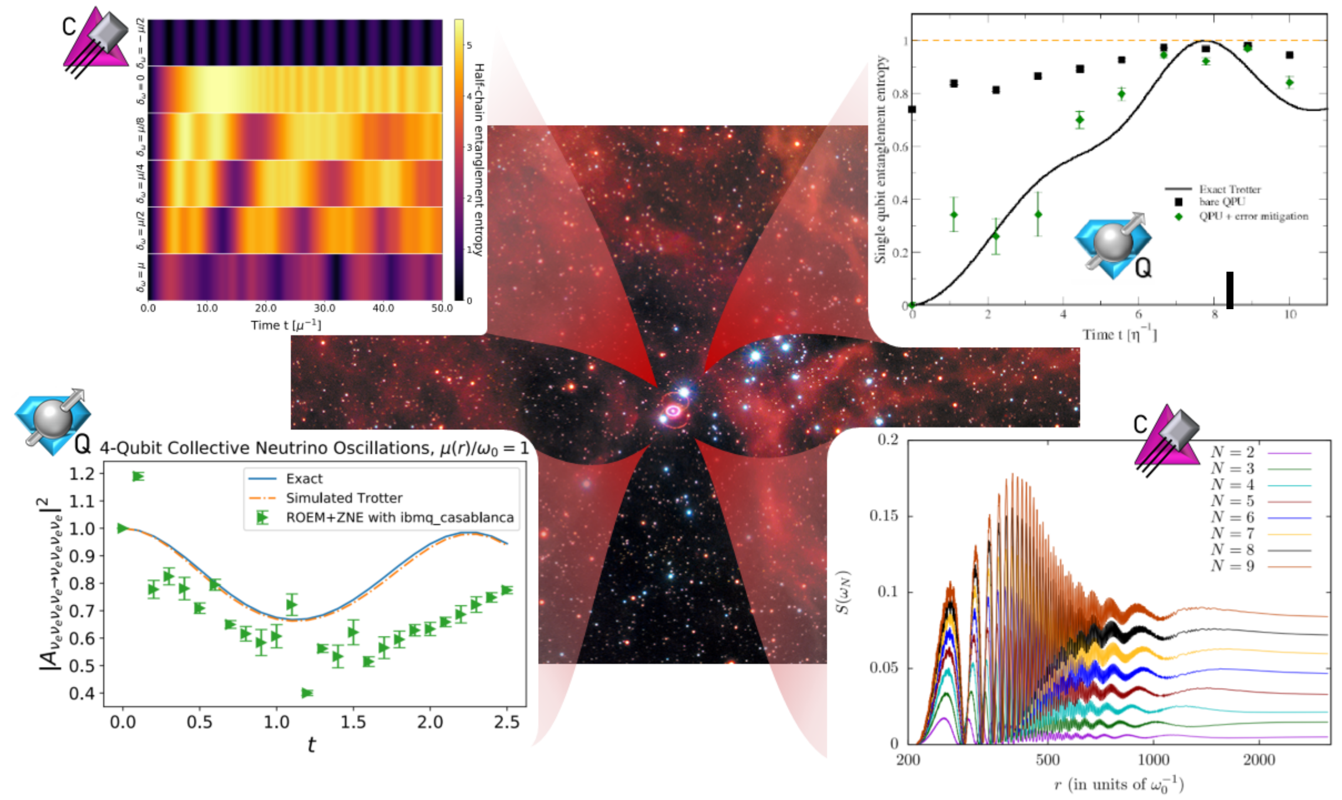


FIG. 4. The half-chain entanglement entropy($\mathcal{S}$) of all the eigenstates at $t = 0.2$, $h = 0.5$ for $L = 16$. The orange dashed line gives the $\mathcal{S}_{RMT}$ value. Circles denote different QMBS obtained via our tracking procedure. Green circles denote antimagnon-like family S_n^2 for $n = 0, 2, 4, 6, 8$ 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

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

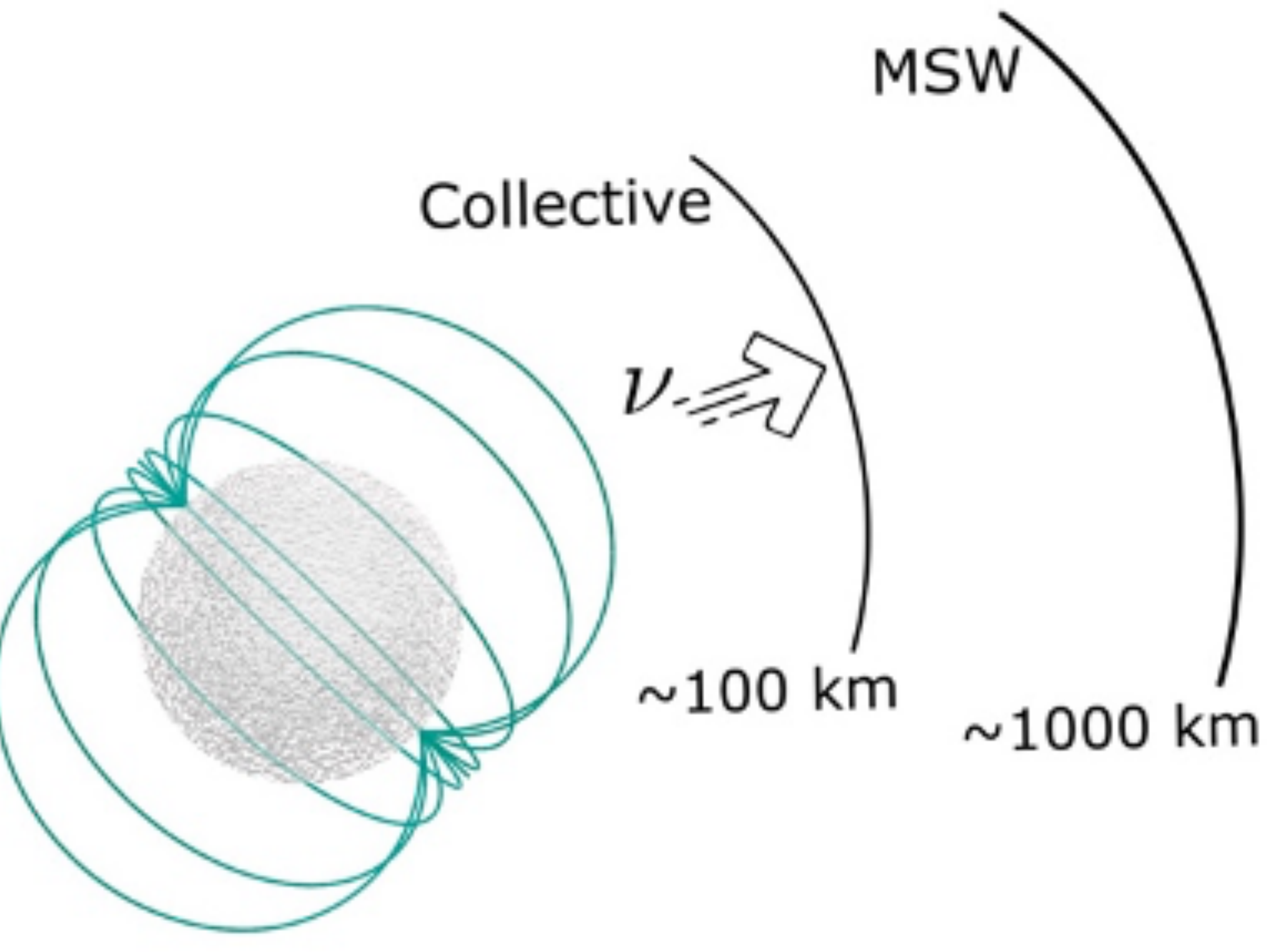
- Previously: only confining systems exhibited scars
- Shown to exist in de-confined regime
- Shown not to exist in confining regime

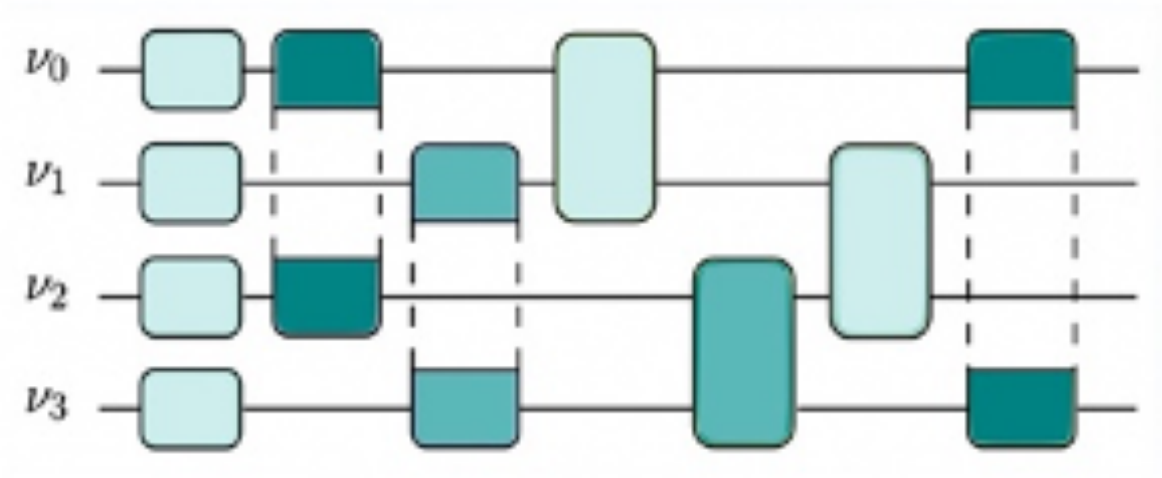


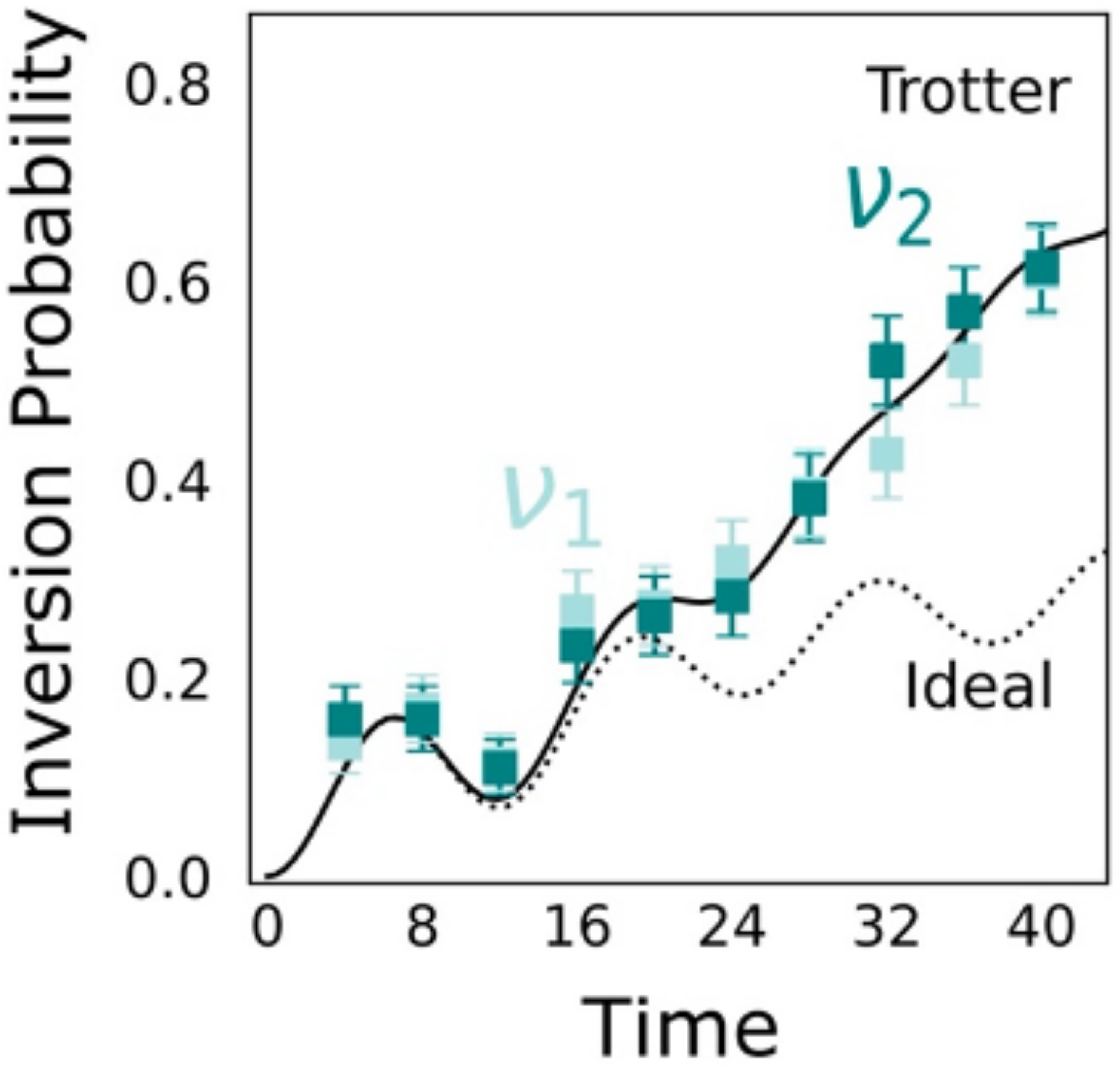
Neutrino Flavor Dynamics in Supernova

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

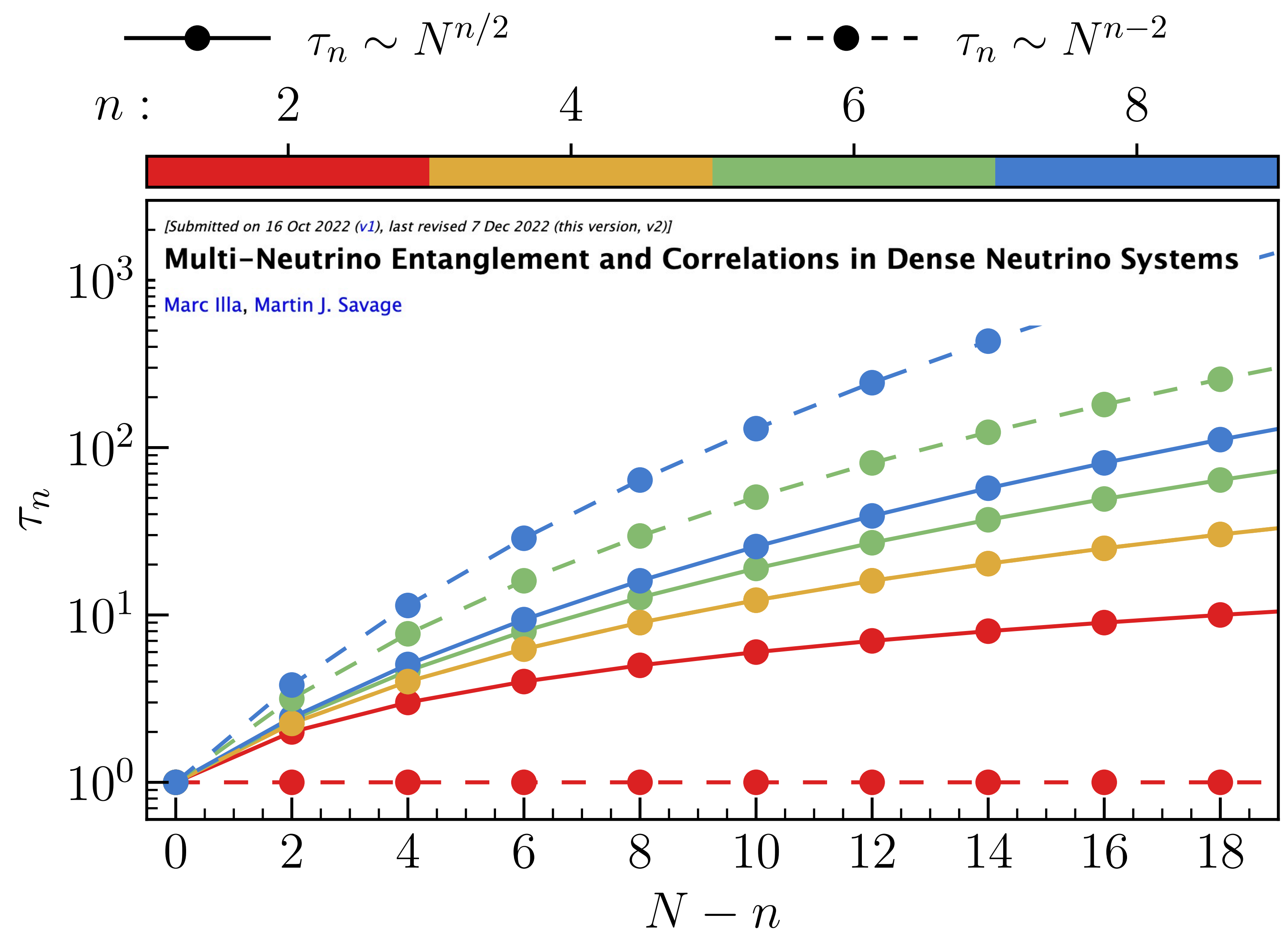
$$H_{FS} = -\sum_{k=1}^{N} \frac{\omega_k}{2}\sigma_k^z + \frac{\mu}{2N}\sum_{i<j}^{N} \mathcal{J}_{ij}\vec{\sigma}_i \cdot \vec{\sigma}_j$$







Multi-Neutrino Entanglement



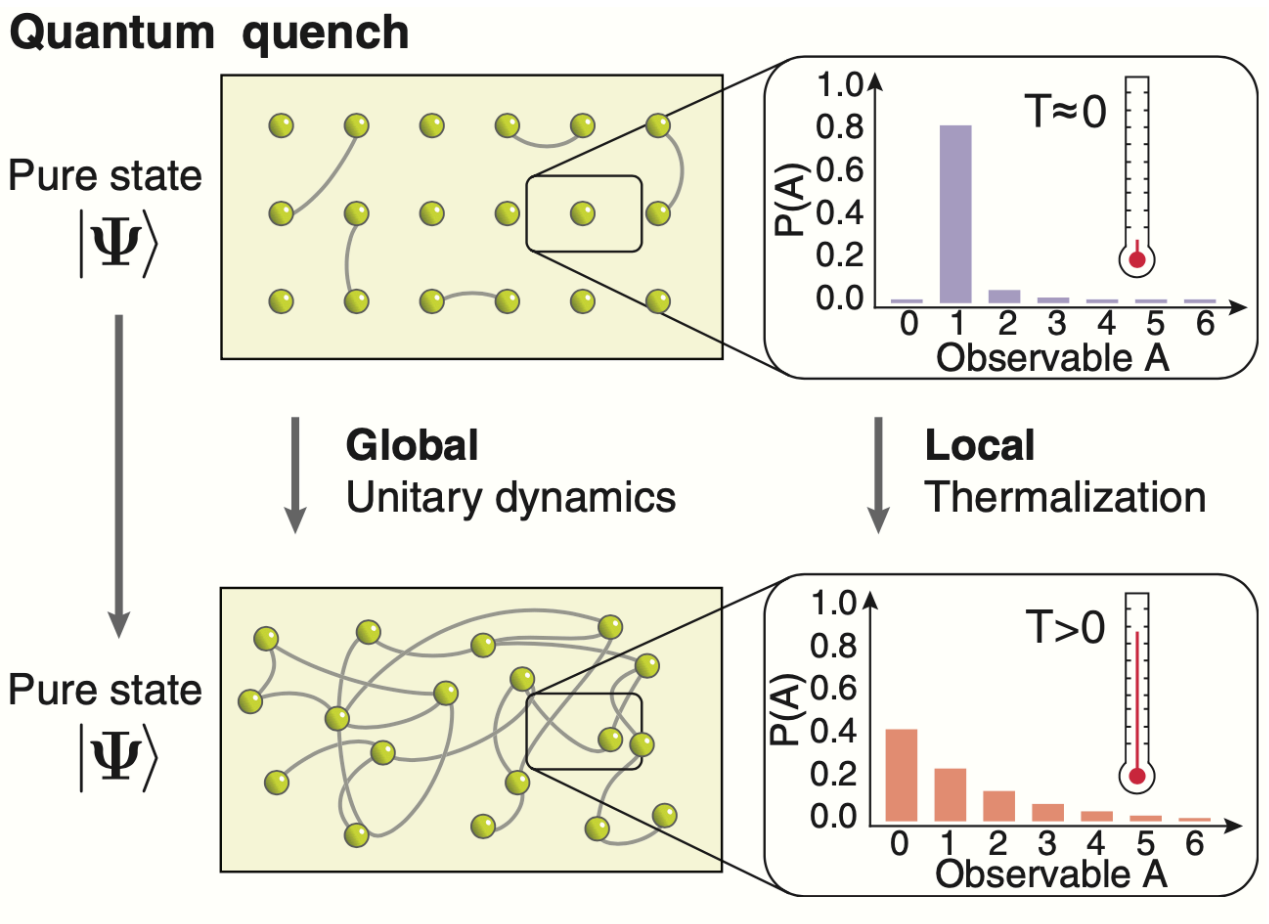
Entanglement and Thermalization

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

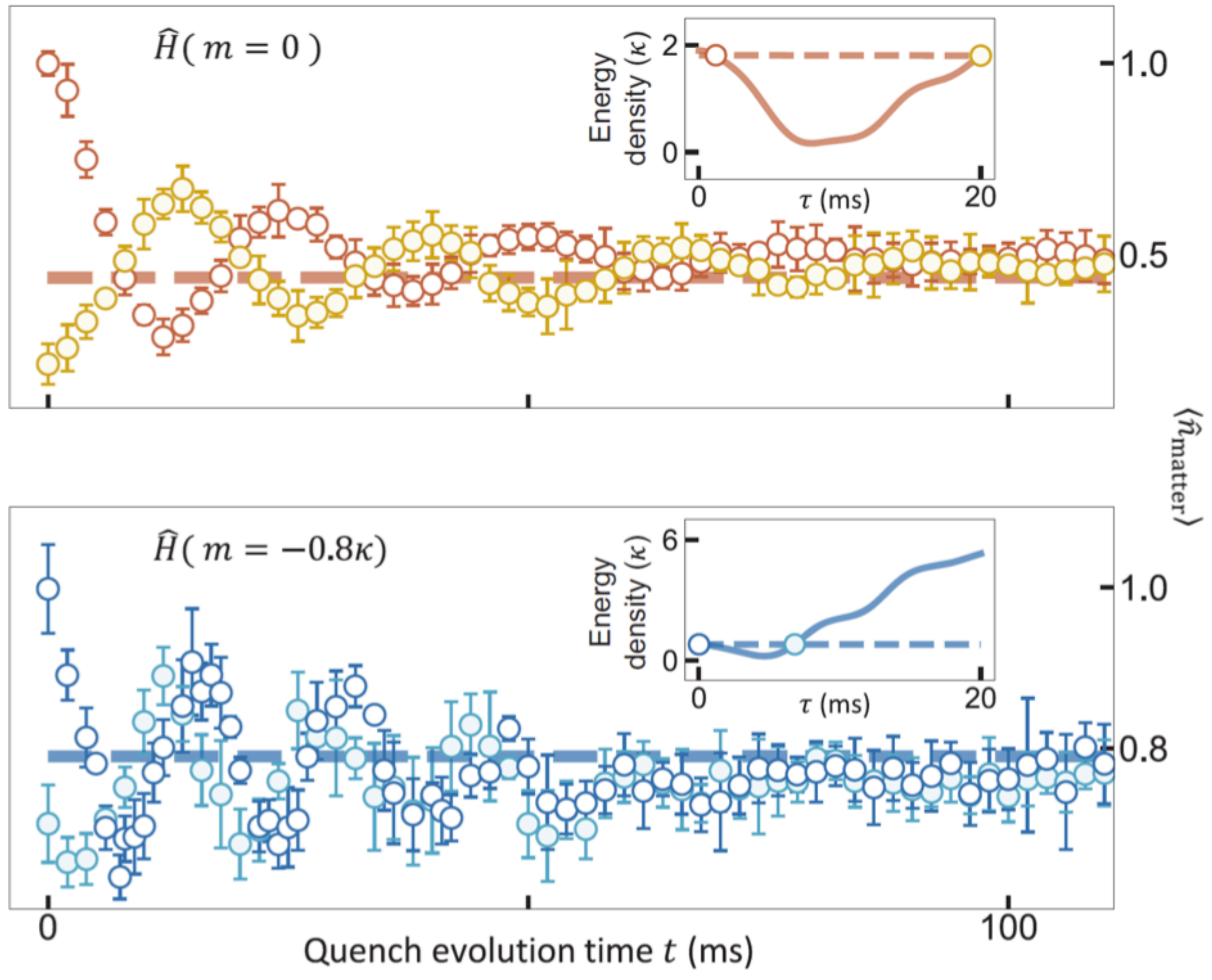
6 Rubidium atoms in an optical trap

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



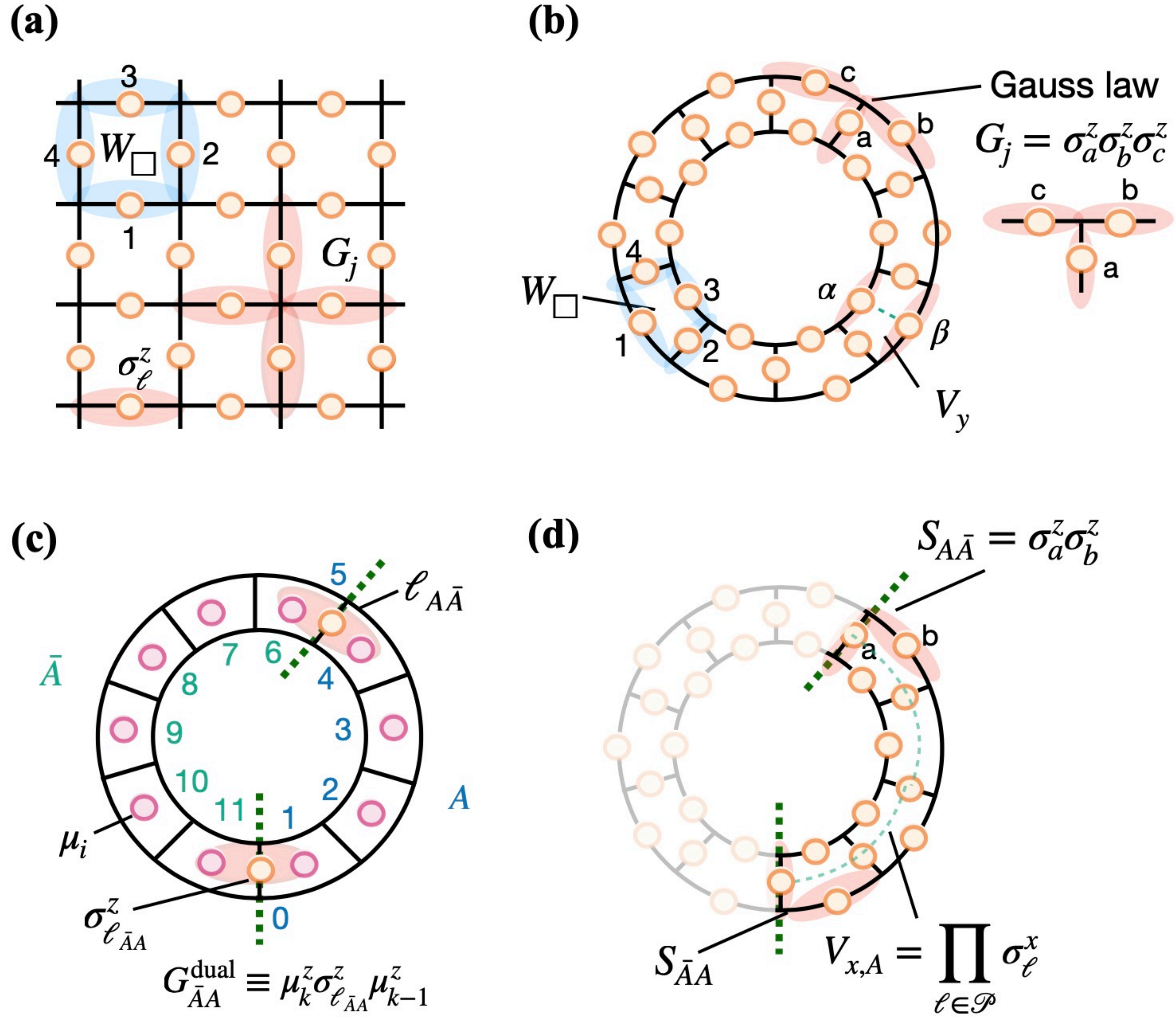
71 Rubidium atoms, U(1) Lattice Gauge Theory

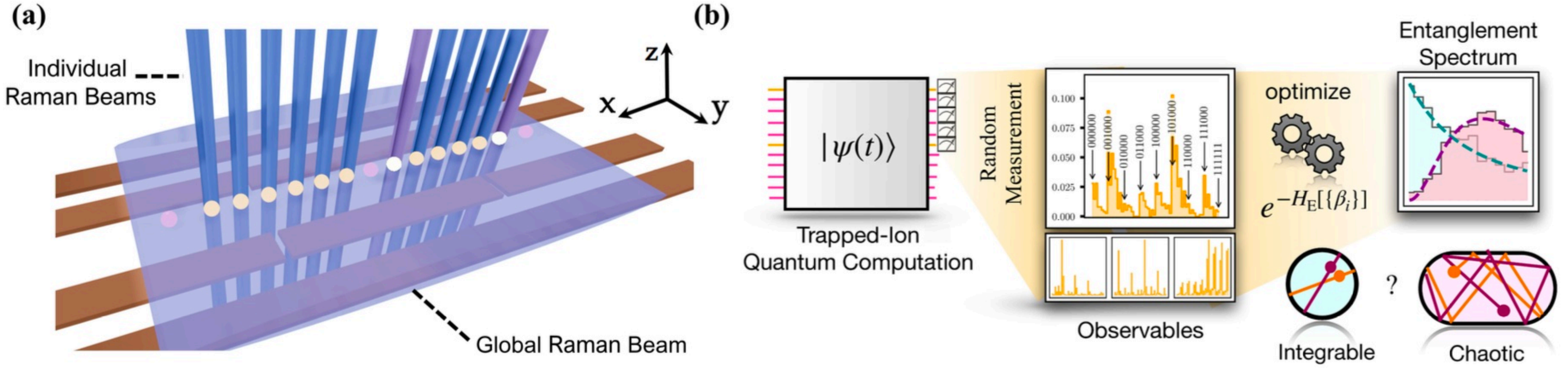
Slide content from Niklas Mueller

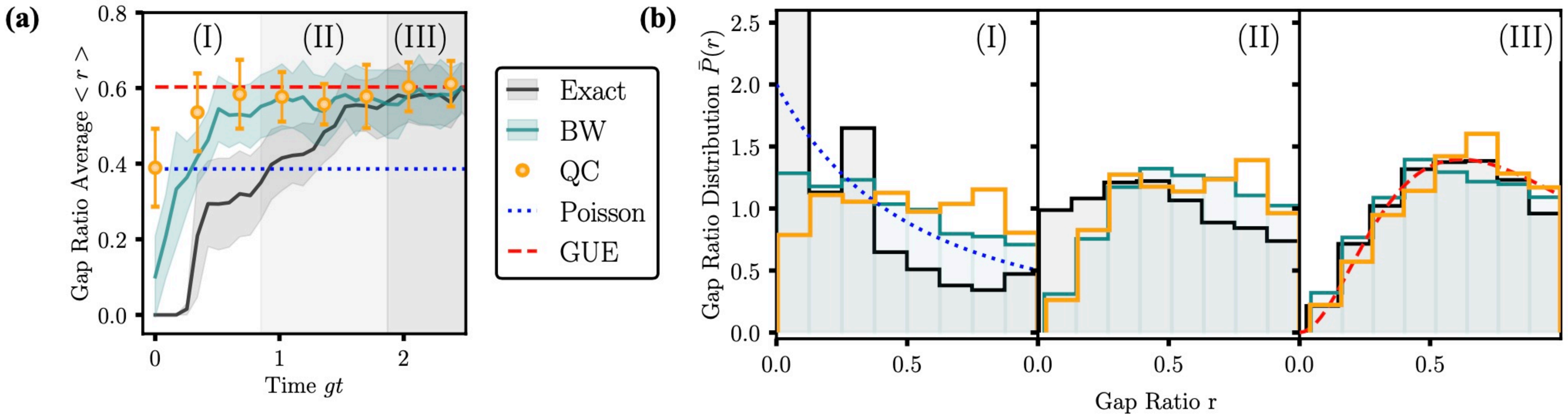
Entanglement and Thermalization

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

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

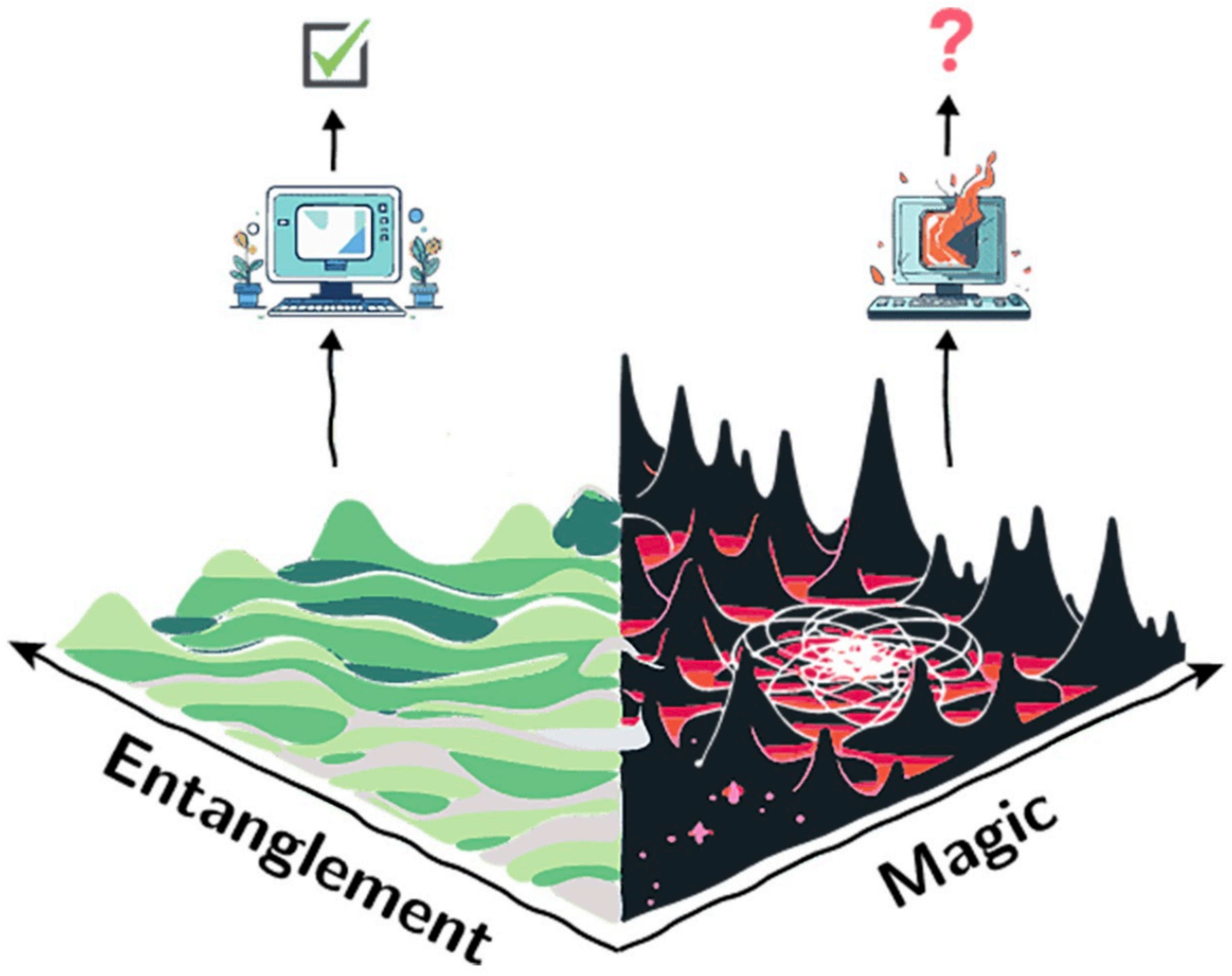
1-qubit : 6 stabilizer states
2-qubits: 60 stabilizer states
3-qubits: 1080 stabilizer states

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 are measures of non-stabilizerness

Classical computing needs scale exponentially with Magic



Magic-induced computational separation in entanglement theory

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

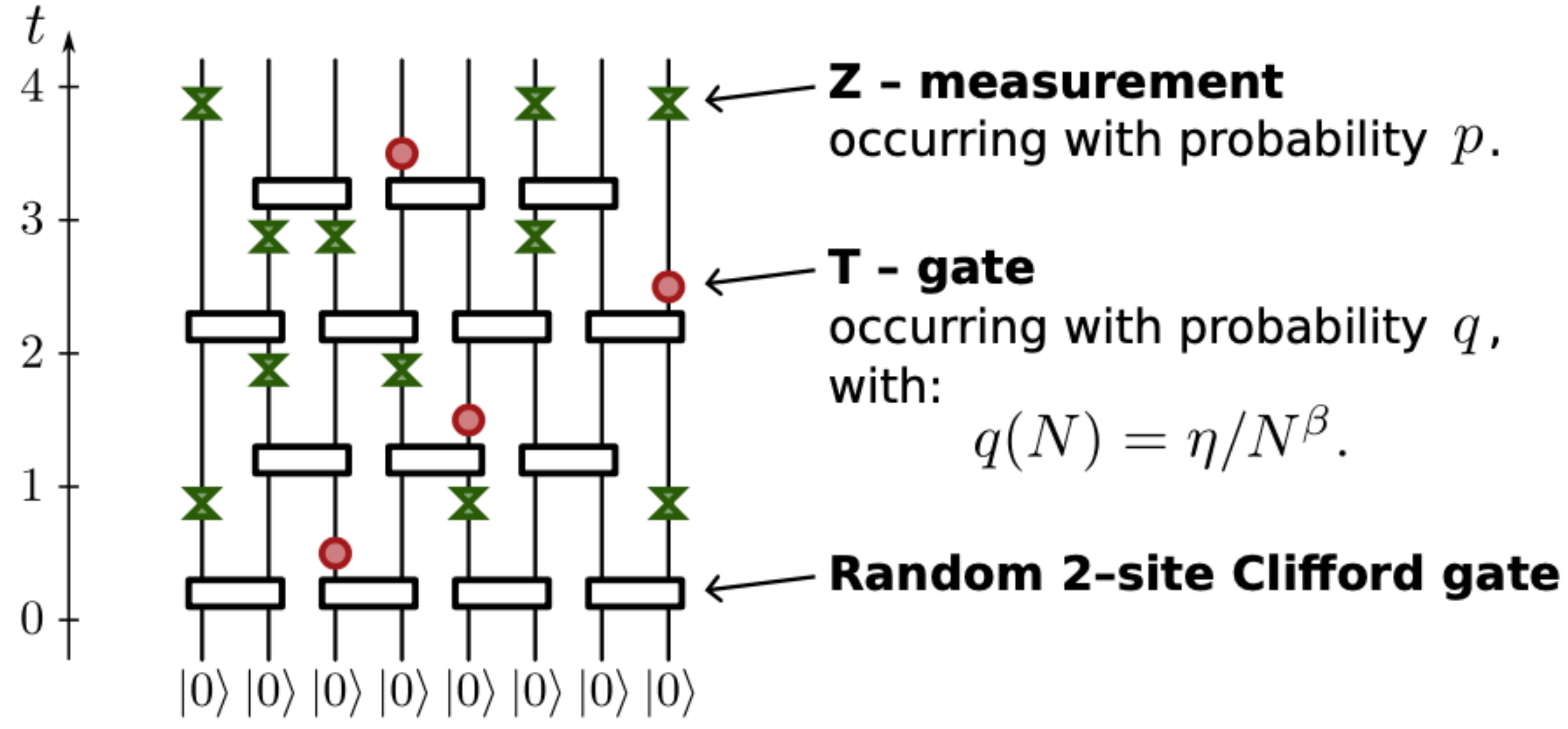
Entanglement and Magic Phase Transitions

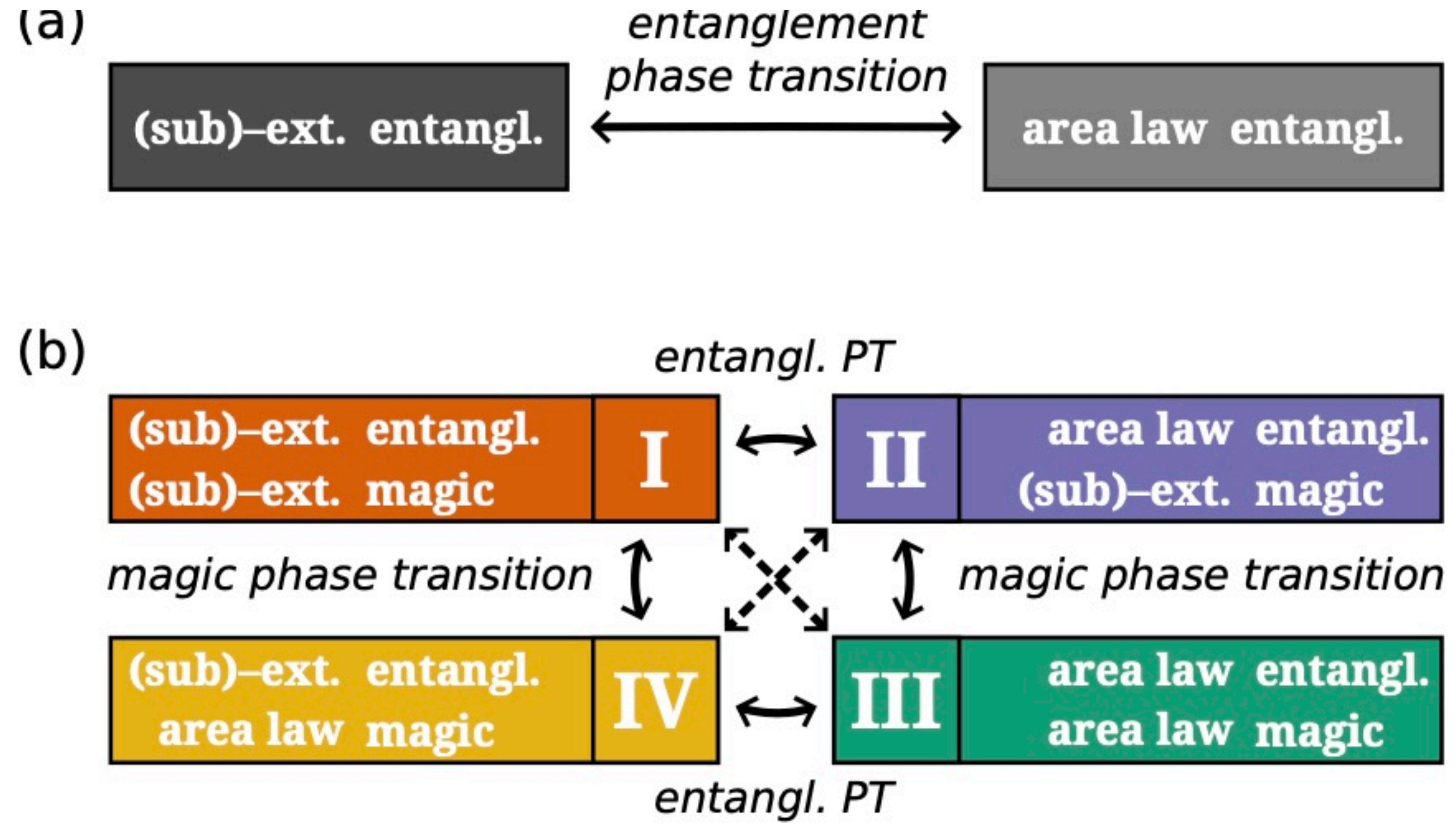
Entanglement–magic separation in hybrid quantum circuits

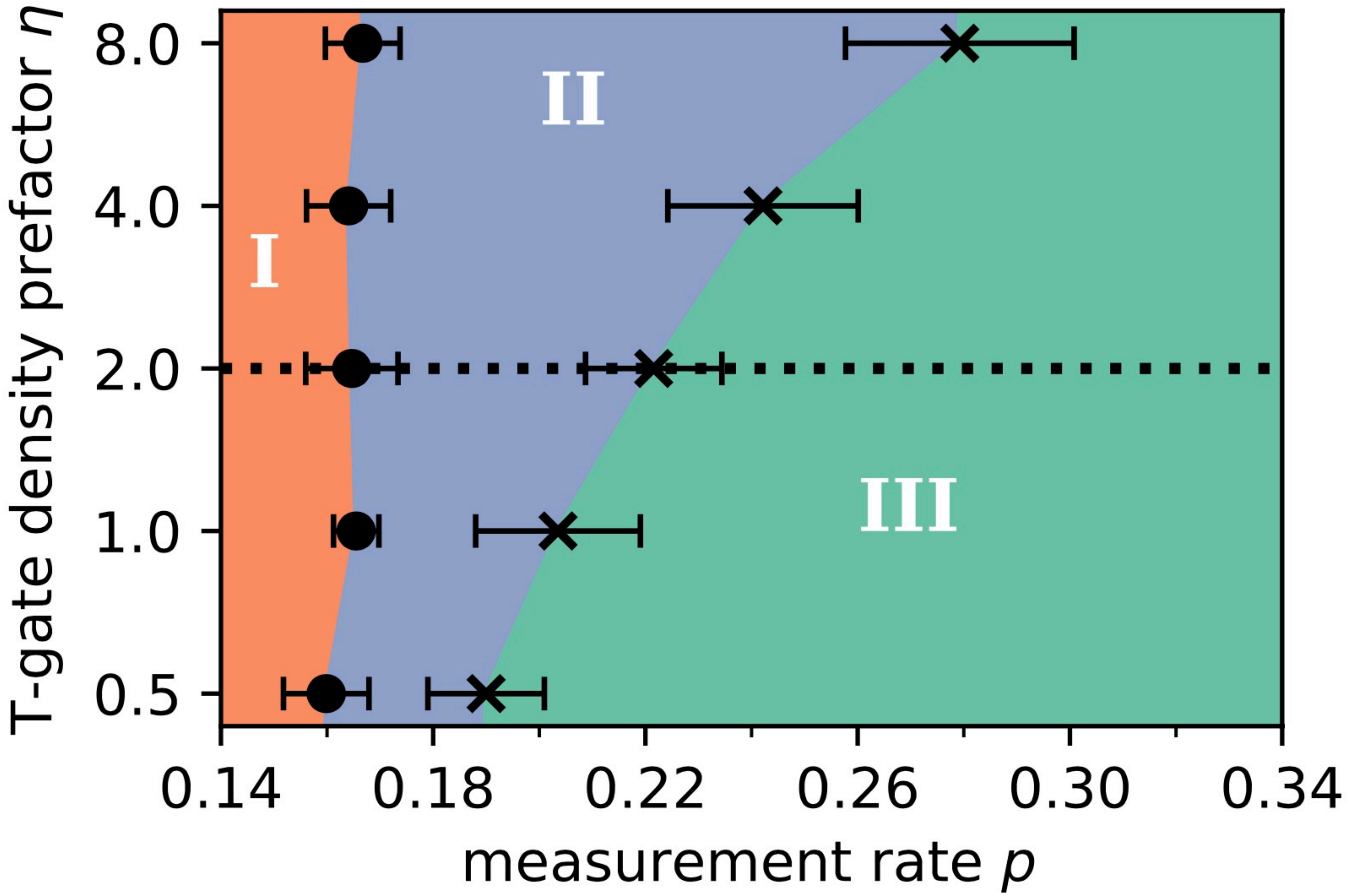
Gerald E. Fux[1] Emanuele Tirrito[1,2] Marcello Dalmonte[1,3] and Rosario Fazio[1,4]

[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*

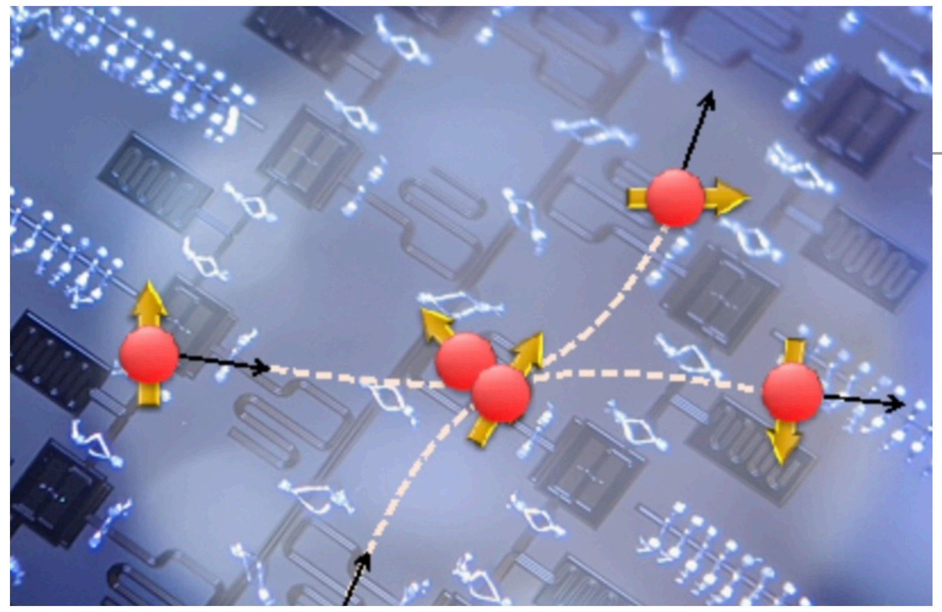
(Dated: December 12, 2023)



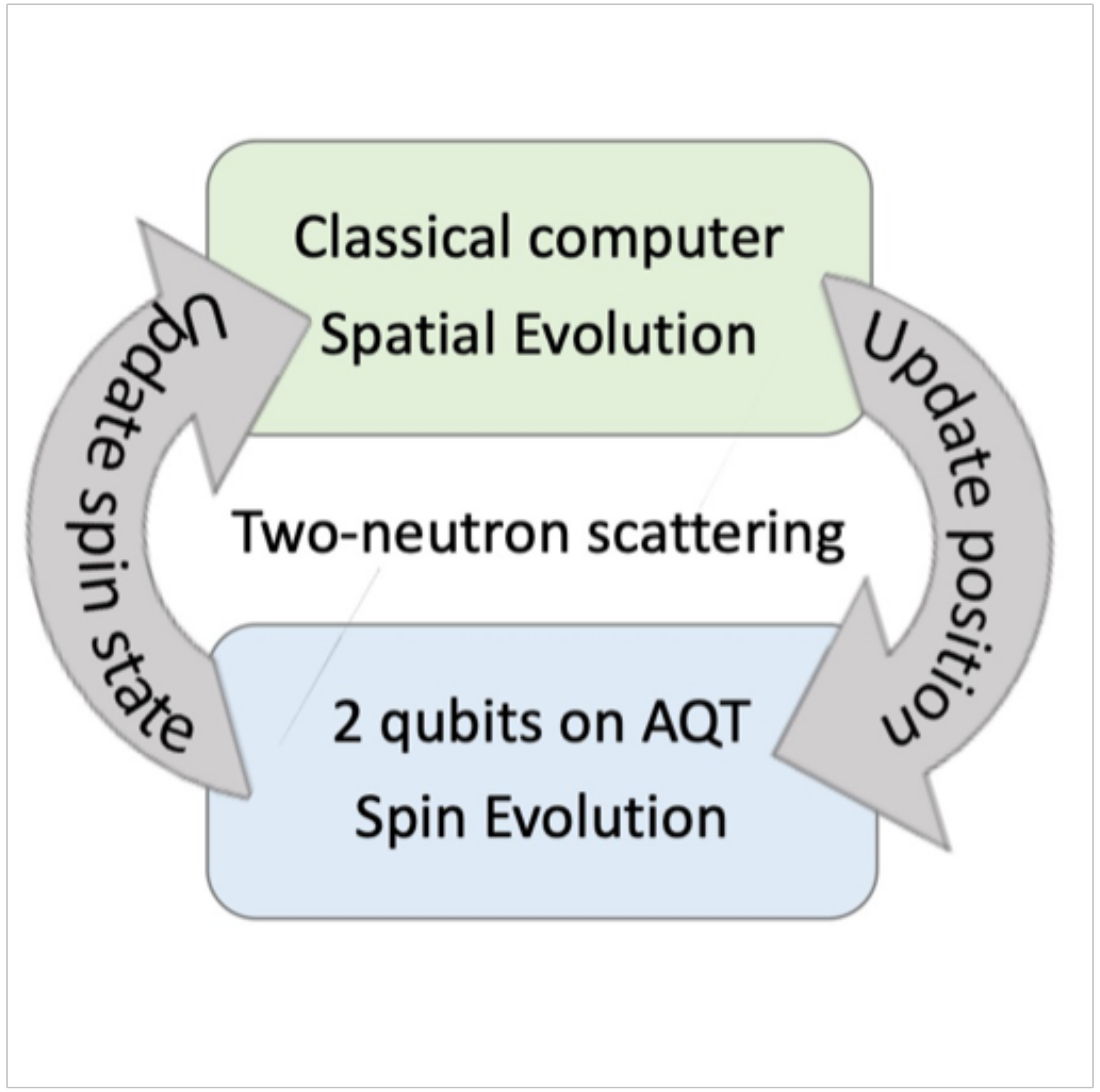


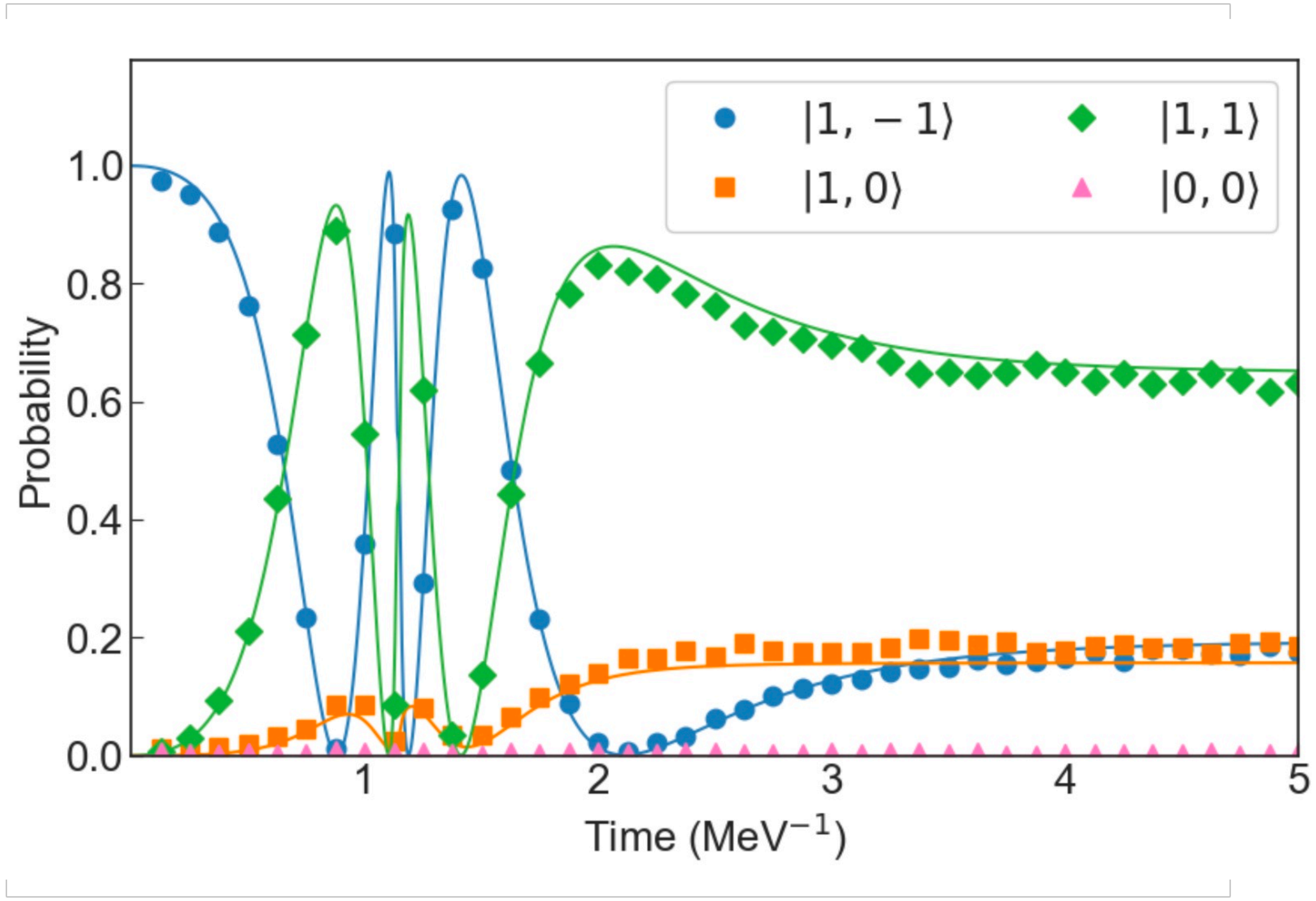


Neutron Scattering with Hybrid Quantum Simulation



LLNL+Trento

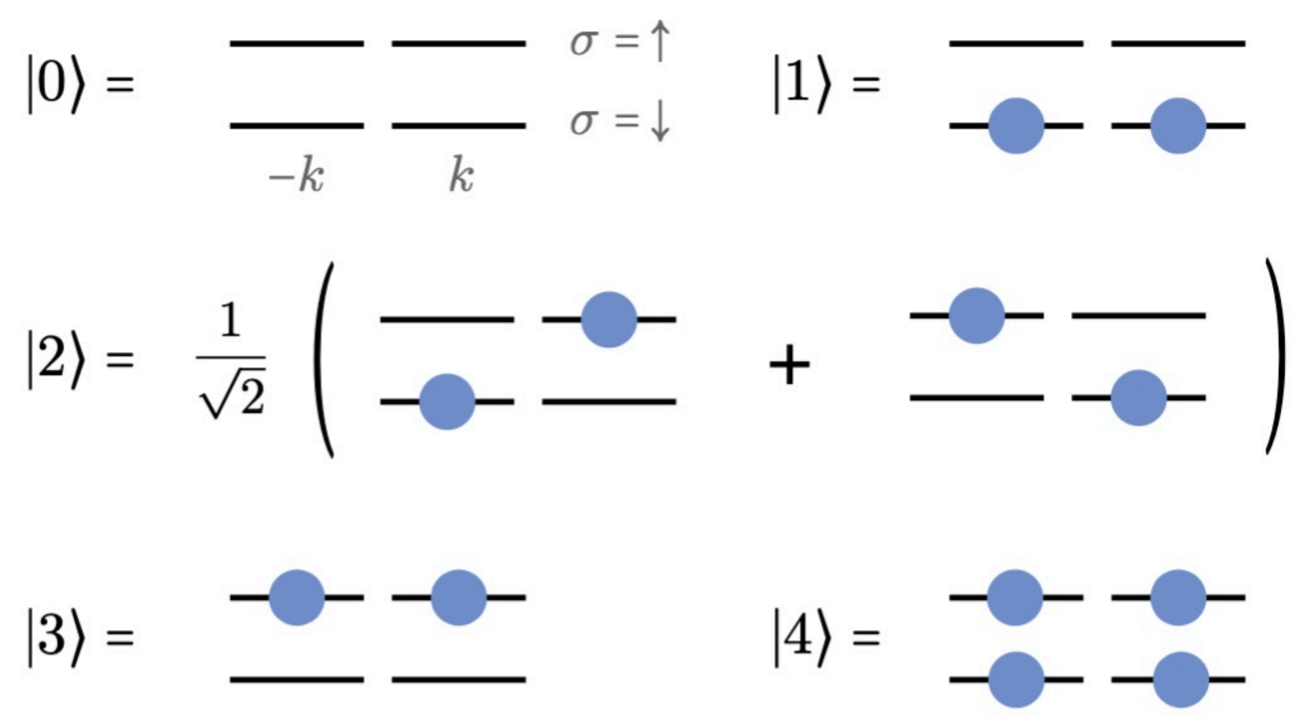


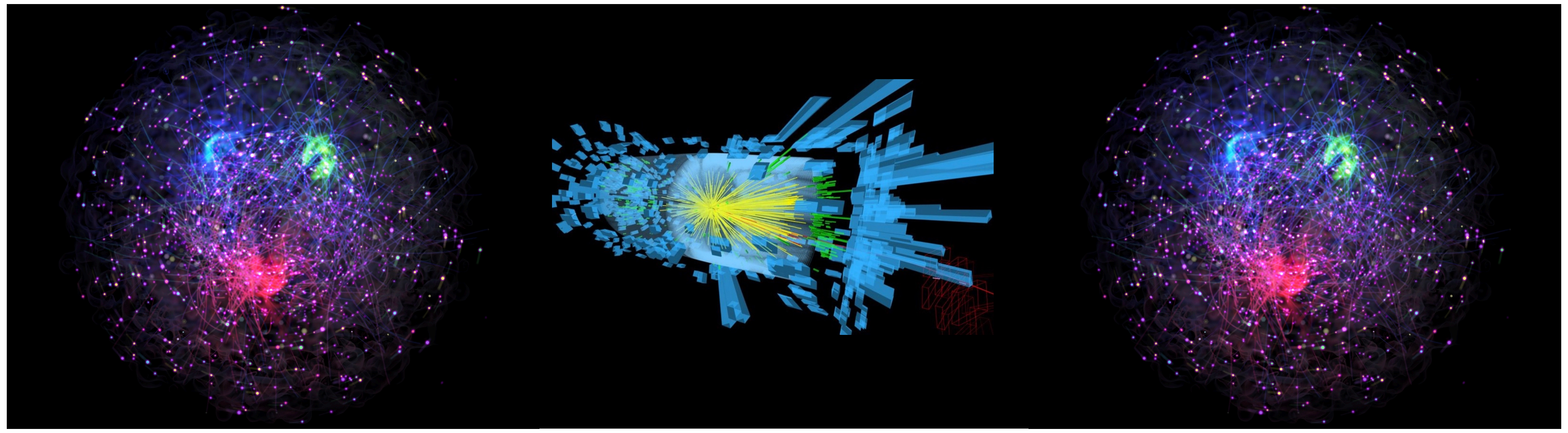


Lessons from the LMG and Agassi Models
“Sign Problems” in Evolution

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

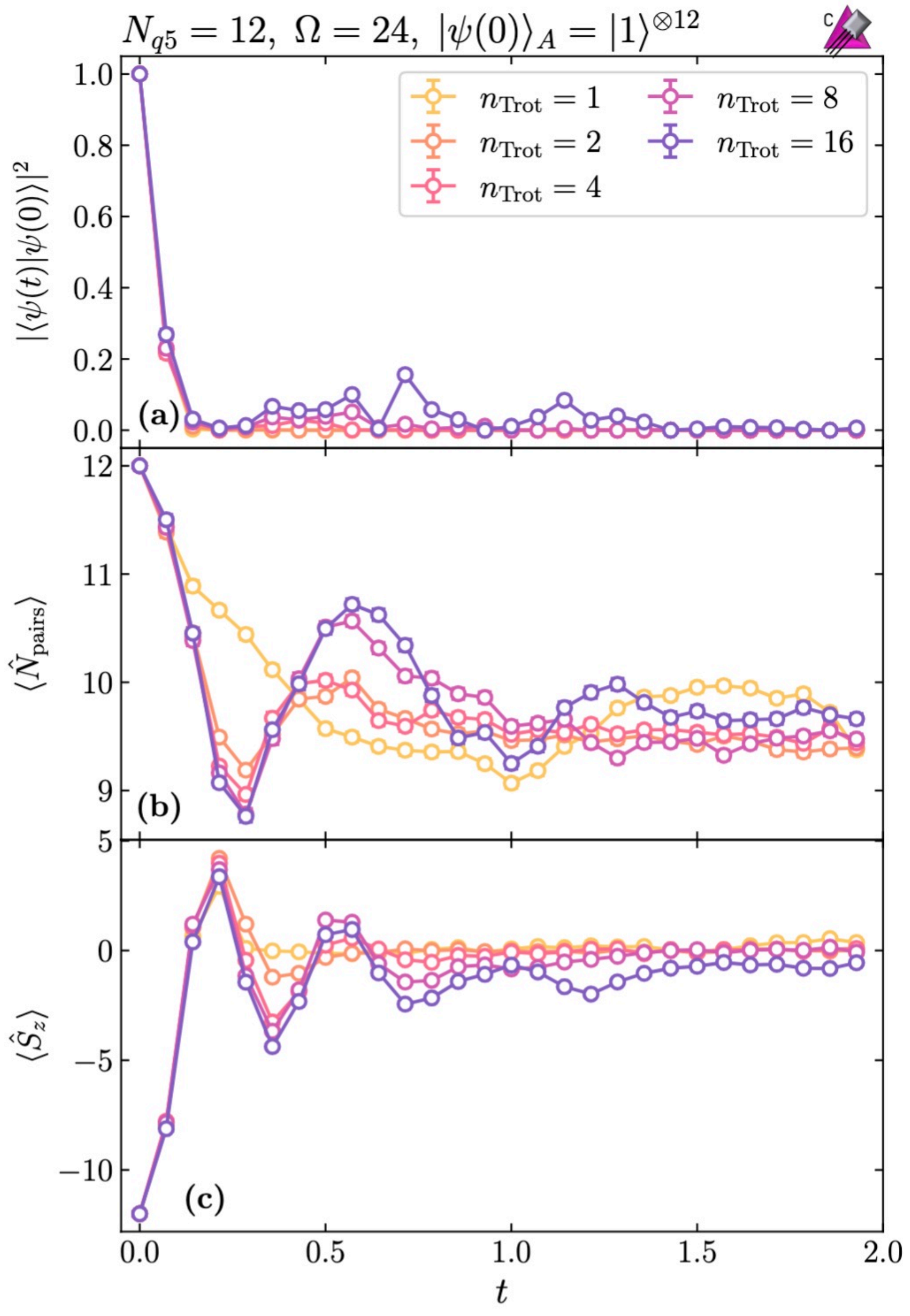
Marc Illa[1,*] Caroline E. P. Robin[2,3,†] and Martin J. Savage[1,‡]



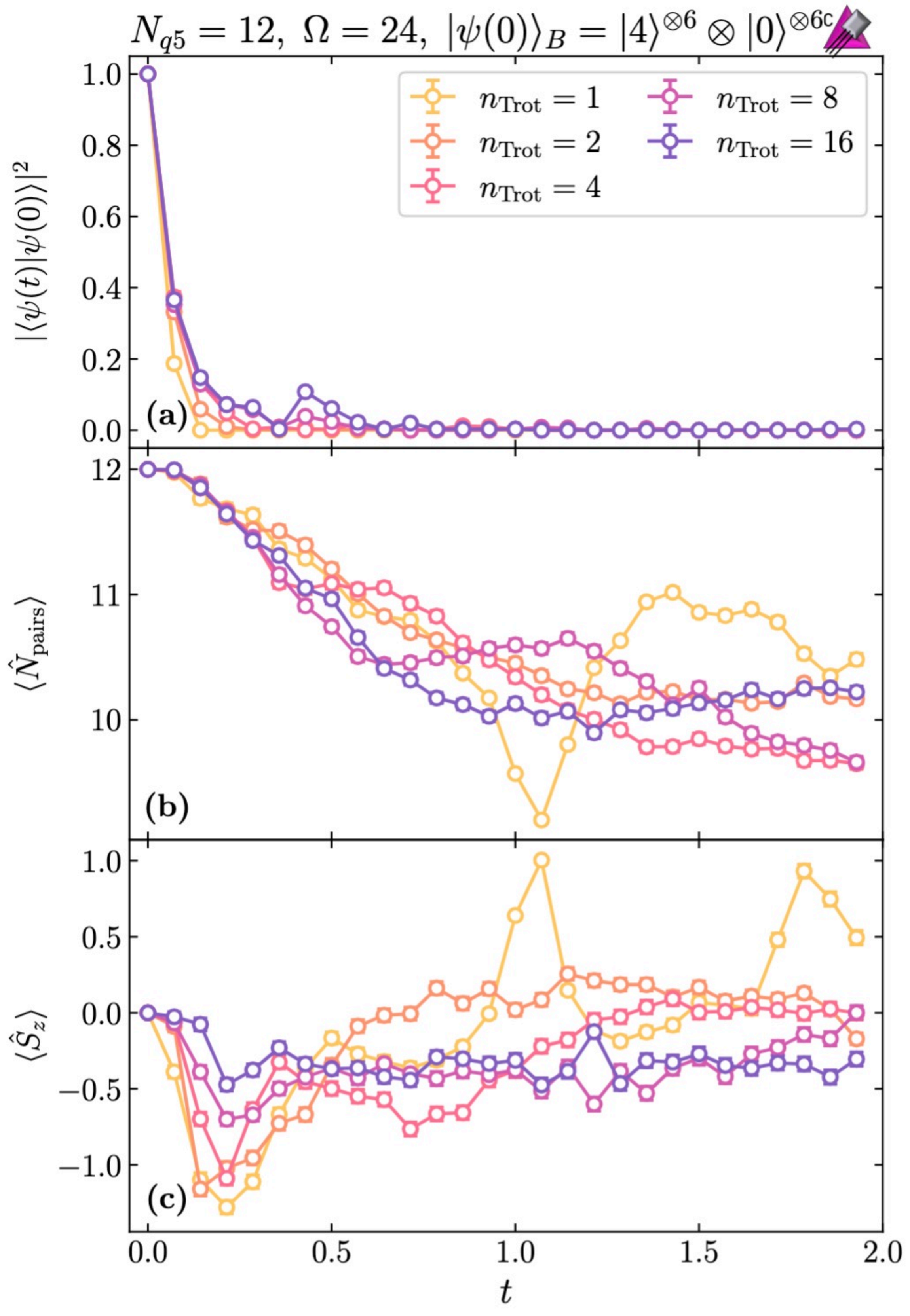


2 high-energetic energy particles collide to produce many lower energy particles

Low in spectrum



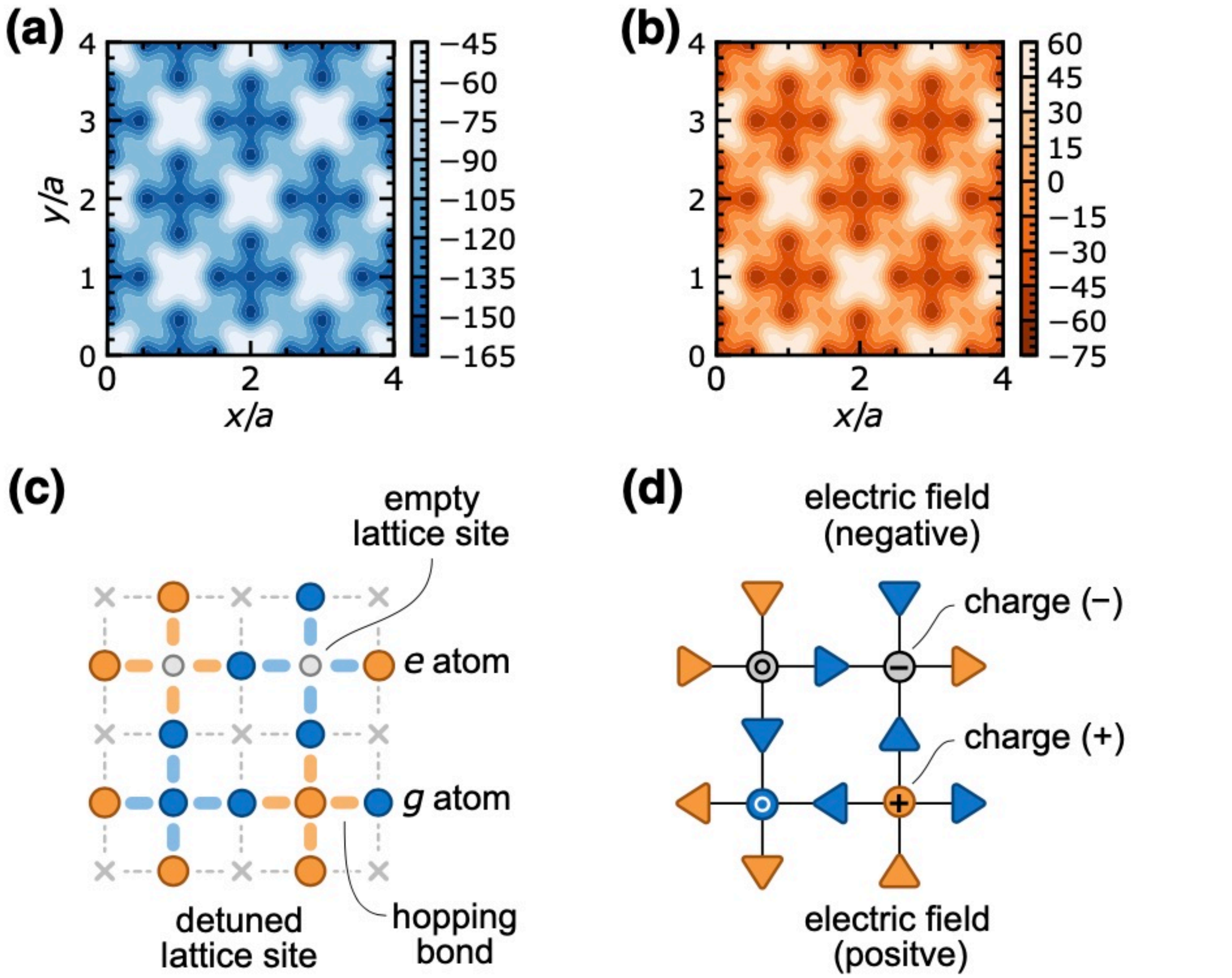
High in spectrum



Some New Directions

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

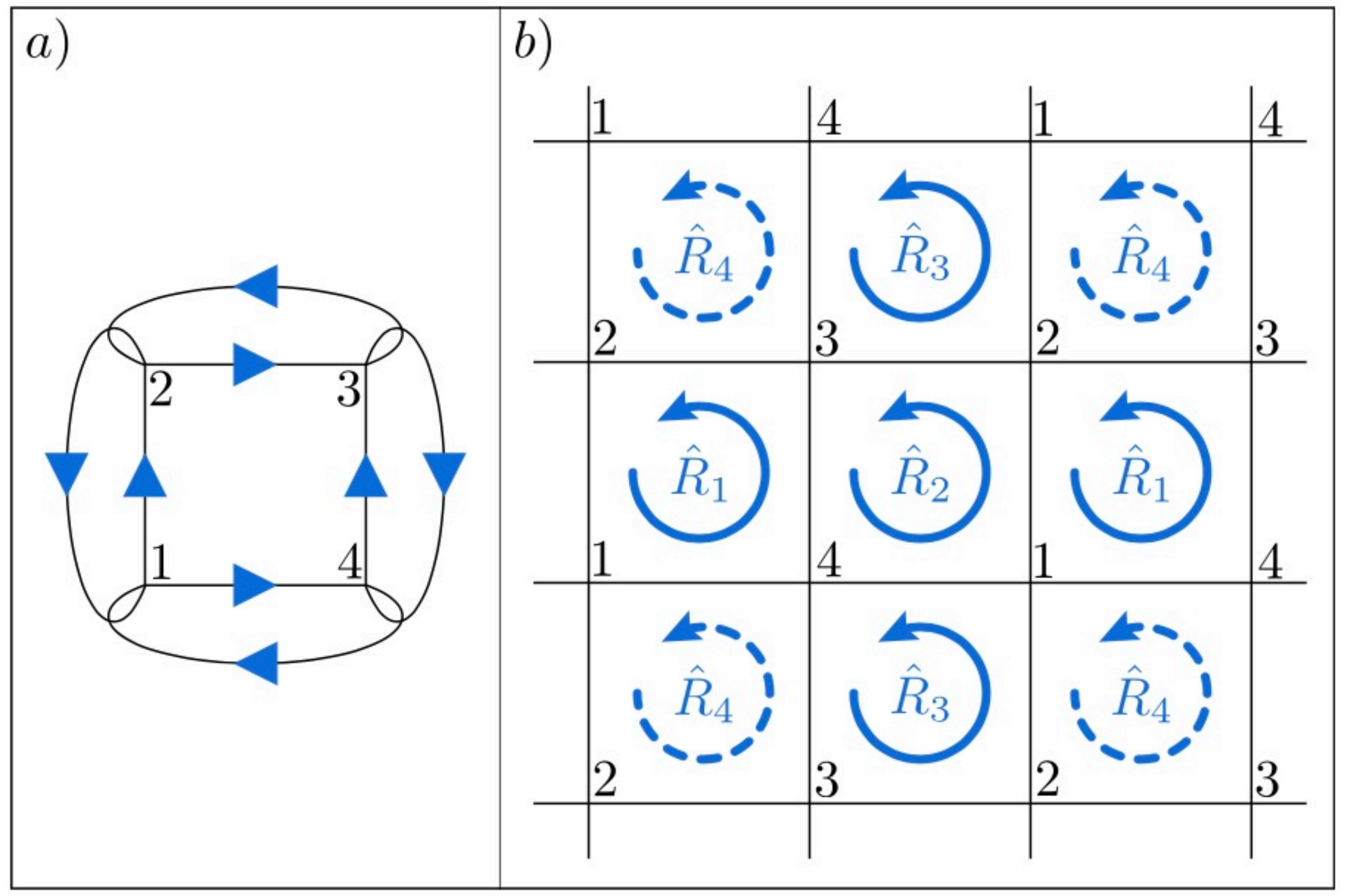
Federica Maria Surace[1,*] Pierre Fromholz[2,3,†] Nelson Darkwah Oppong[4,5,§]
Marcello Dalmonte[2,3] and Monika Aidelsburger[4,5,‡]



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

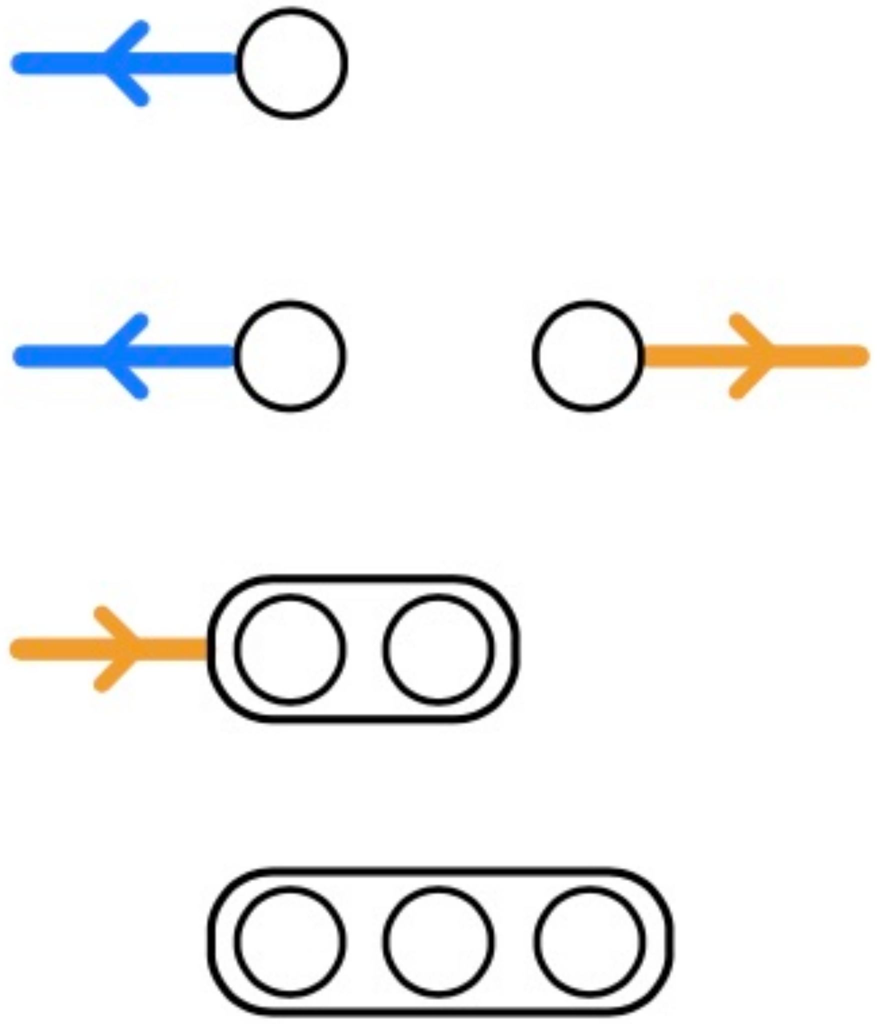
Jan F. Haase[1,2], Luca Dellantonio[1,2], Alessio Celi[3,4], Danny Paulson[1,2], Angus Kan[1,2], Karl Jansen[5], and Christine A. Muschik[1,2,6]

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,‡]



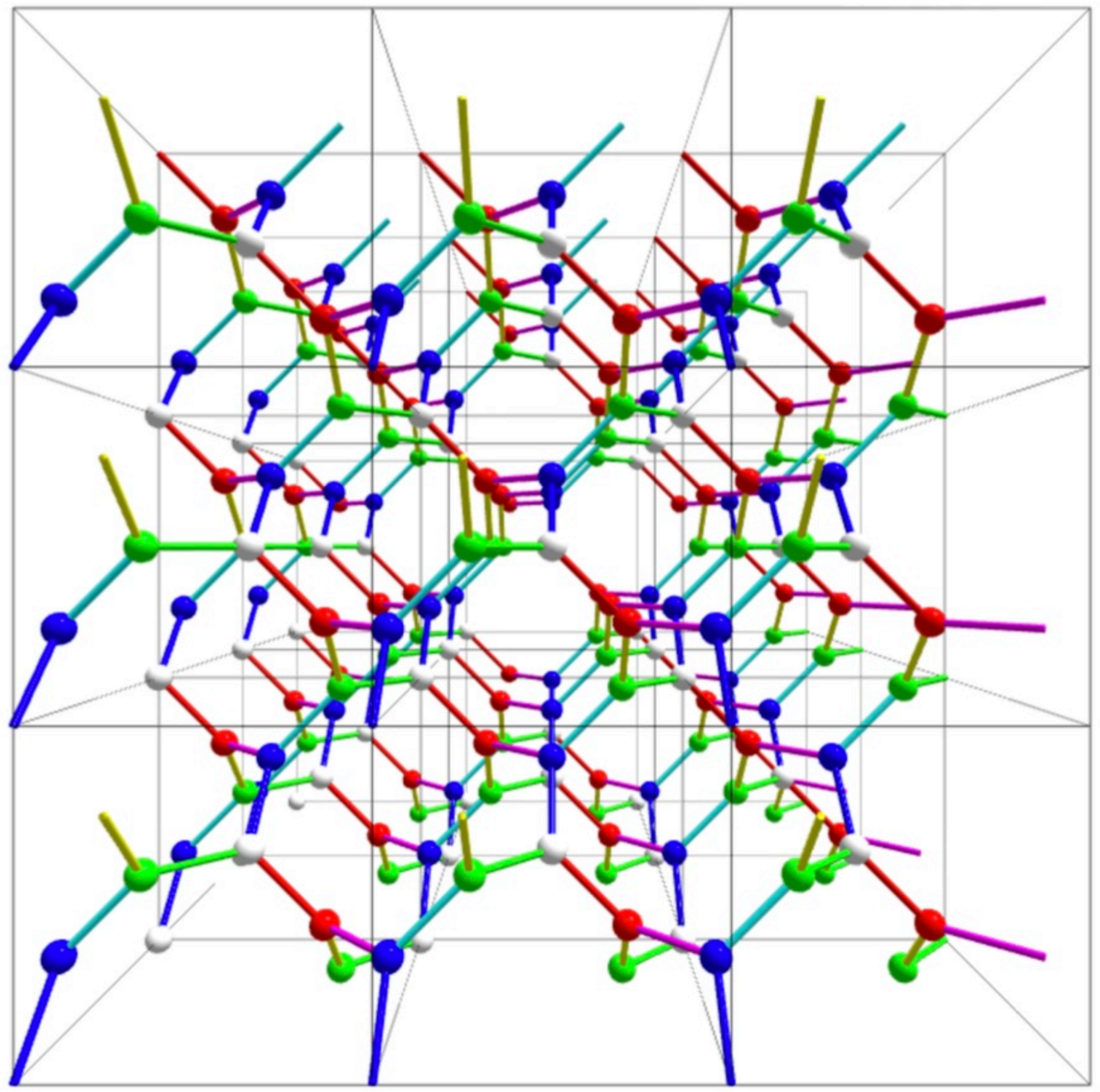
2018-2024

Some New Directions

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

Ali H. Z. Kavaki* and Randy Lewis†

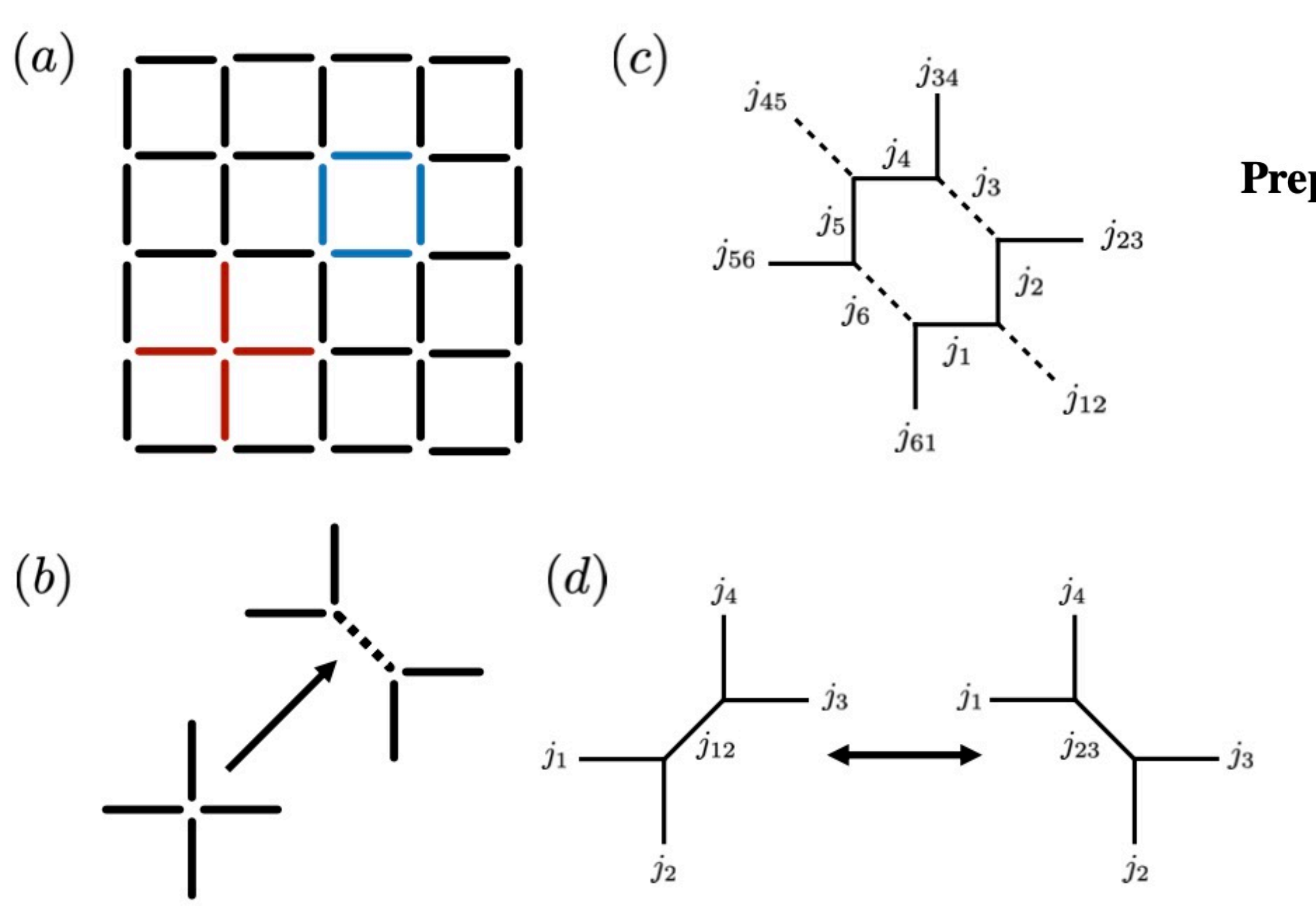
2024



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

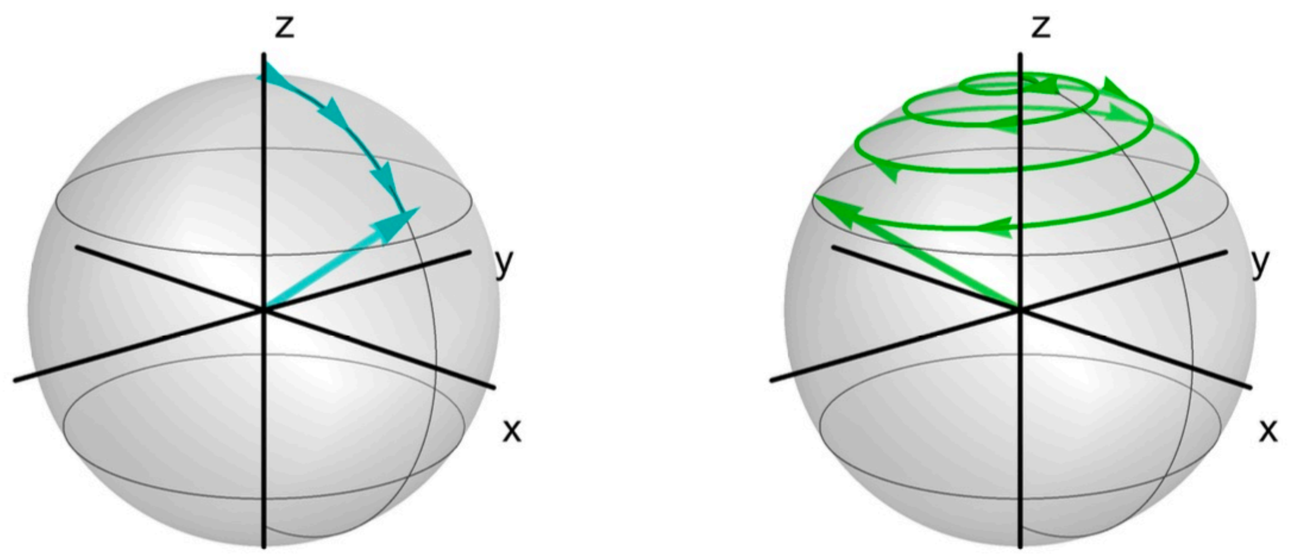
Torsten V. Zache,* Daniel González-Cuadra, and Peter Zoller

2023



State Preparation in the Heisenberg Model through Adiabatic Spiraling

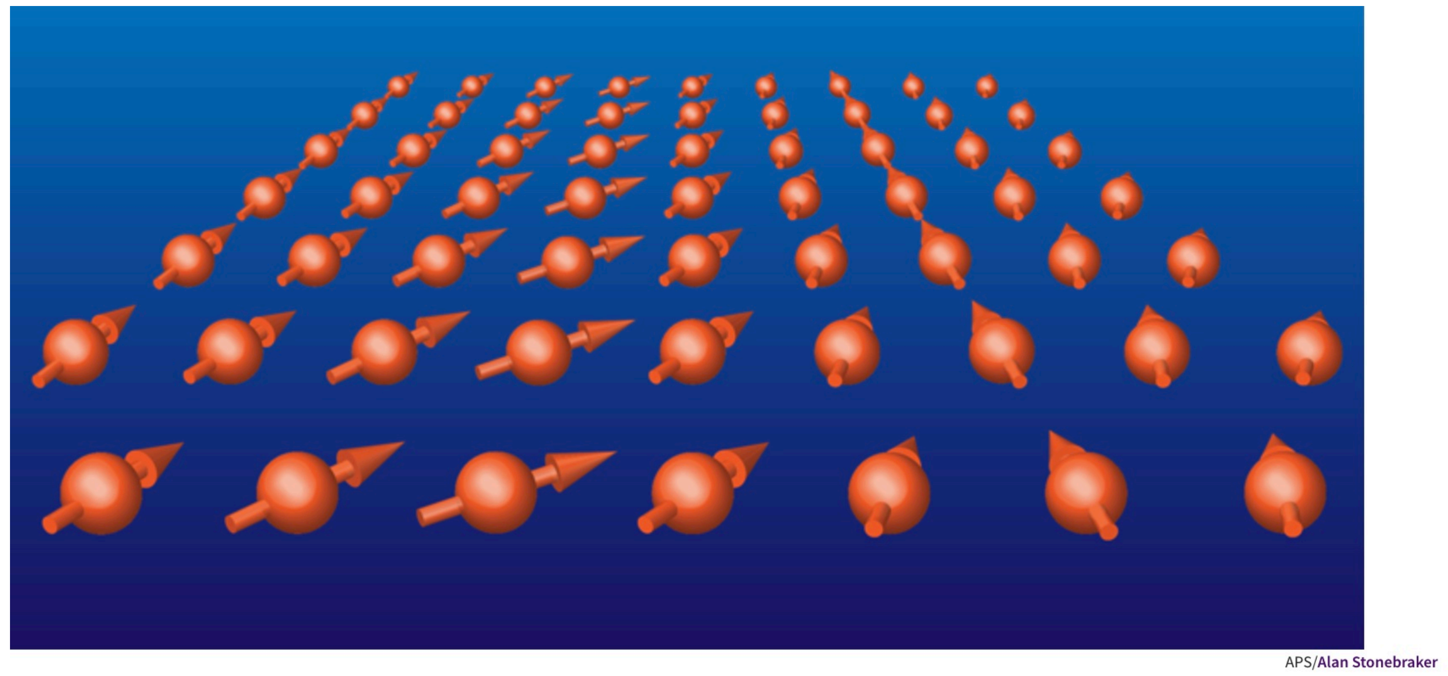
Anthony N. Ciavarella, Stephan Caspar, Marc Illa, and Martin J. Savage



(a) Laboratory (b) Interaction Picture

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

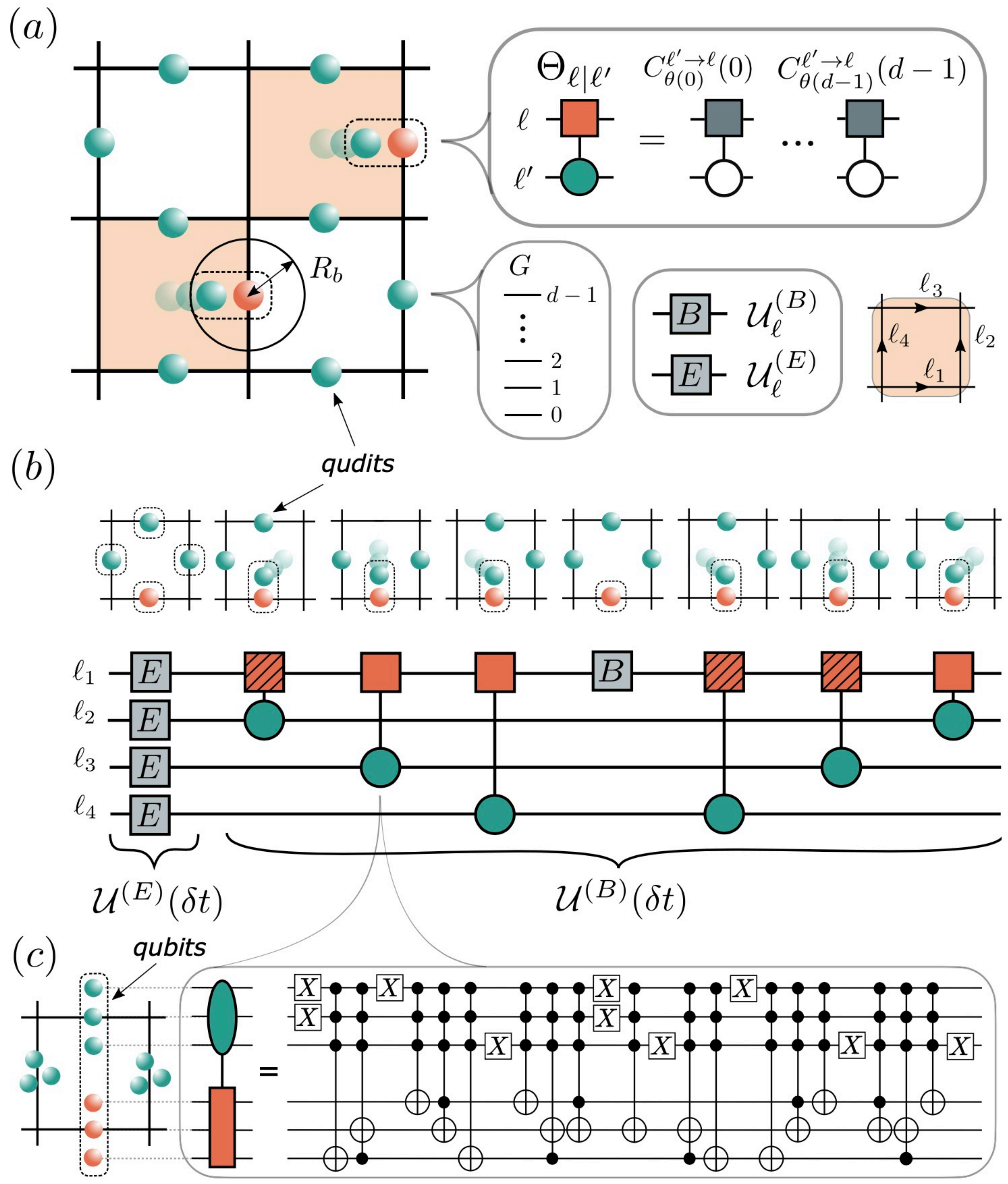
Anthony N. Ciavarella,* Stephan Caspar,† Hersh Singh,‡ and Martin J. Savage§



Qudits

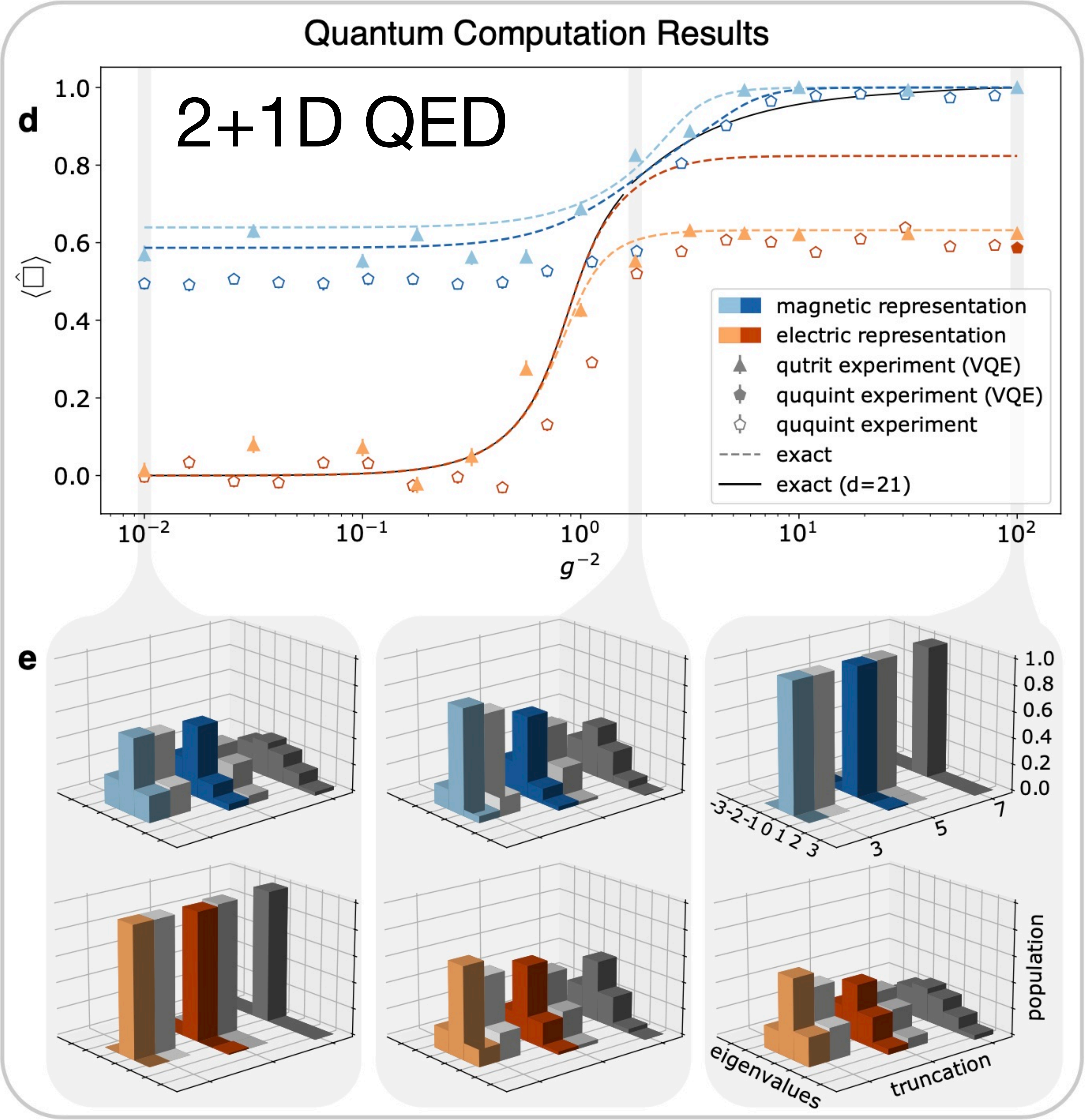
Hardware efficient quantum simulation of non-abelian gauge theories with qudits on Rydberg platforms

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]



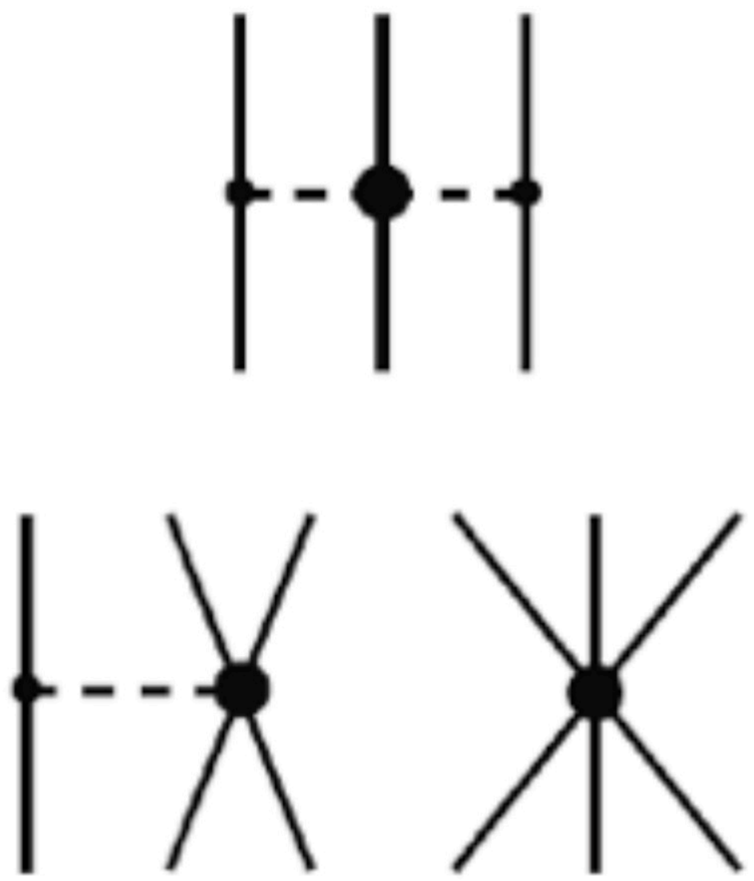
N-body Gates in Trapped Ion Systems
Co-Design in Action

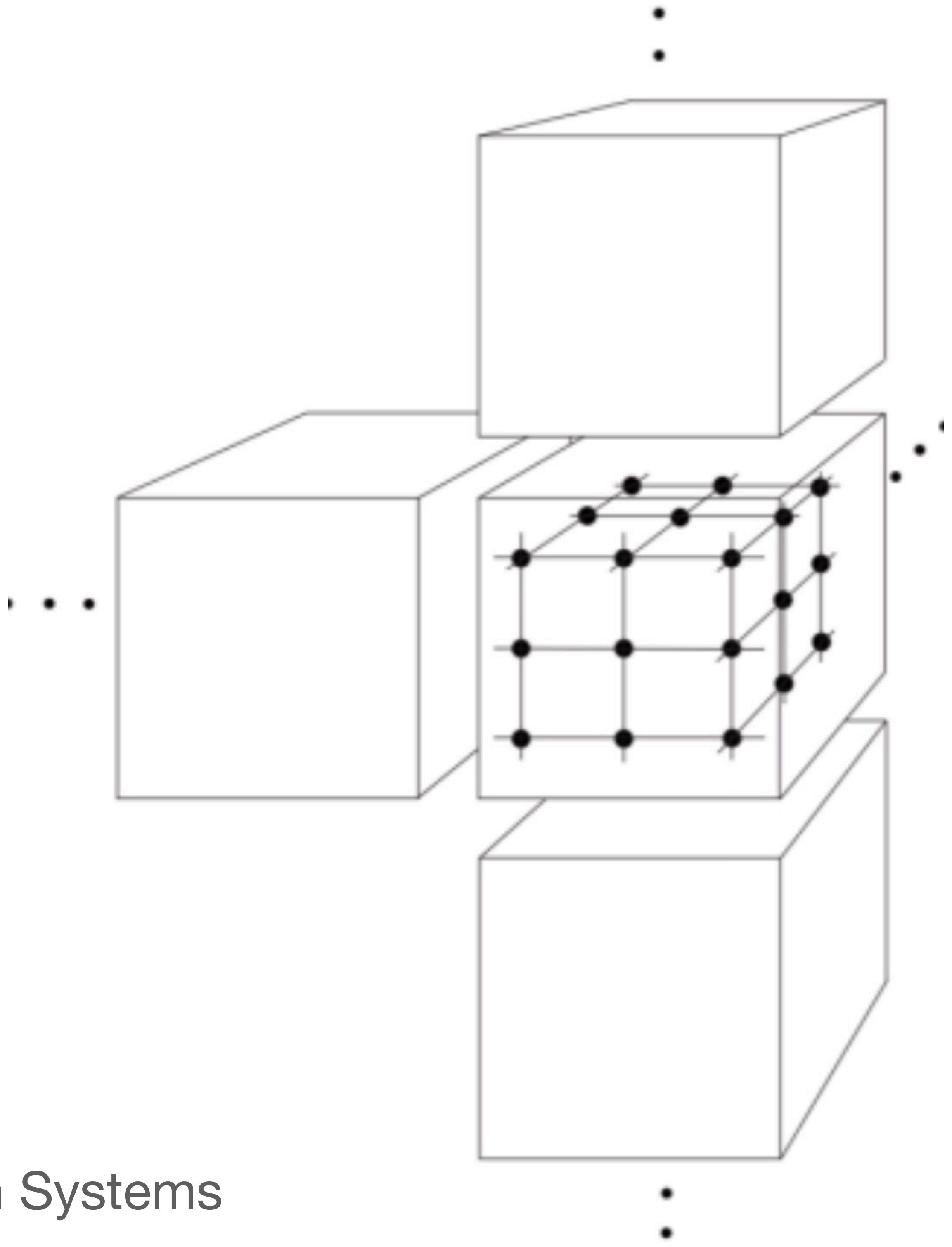
Engineering an Effective Three-spin Hamiltonian in Trapped-ion Systems for Applications in Quantum Simulation

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

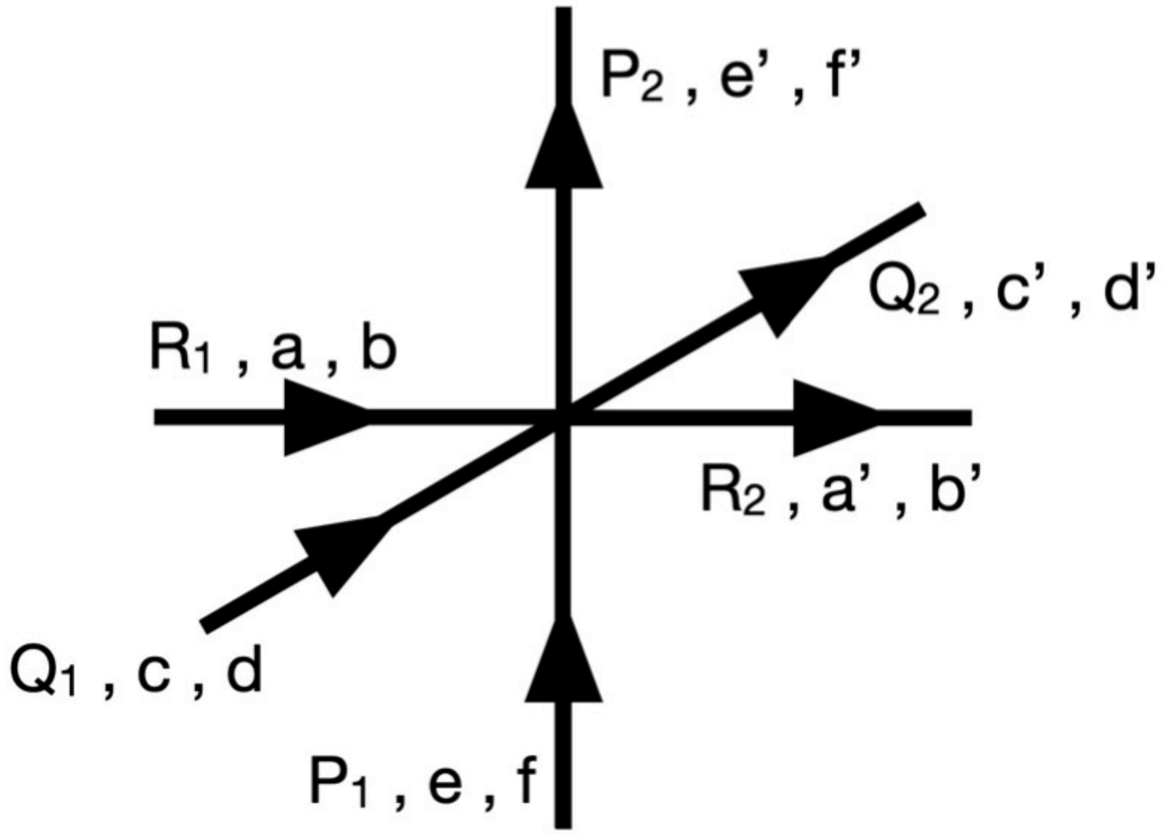
***N*-body interactions between trapped ion qubits via spin-dependent squeezing**

Or Katz,[1,2,3,*] Marko Cetina,[1,3] and Christopher Monroe[1,2,3,4]





NNEFT with Trapped Ion Systems



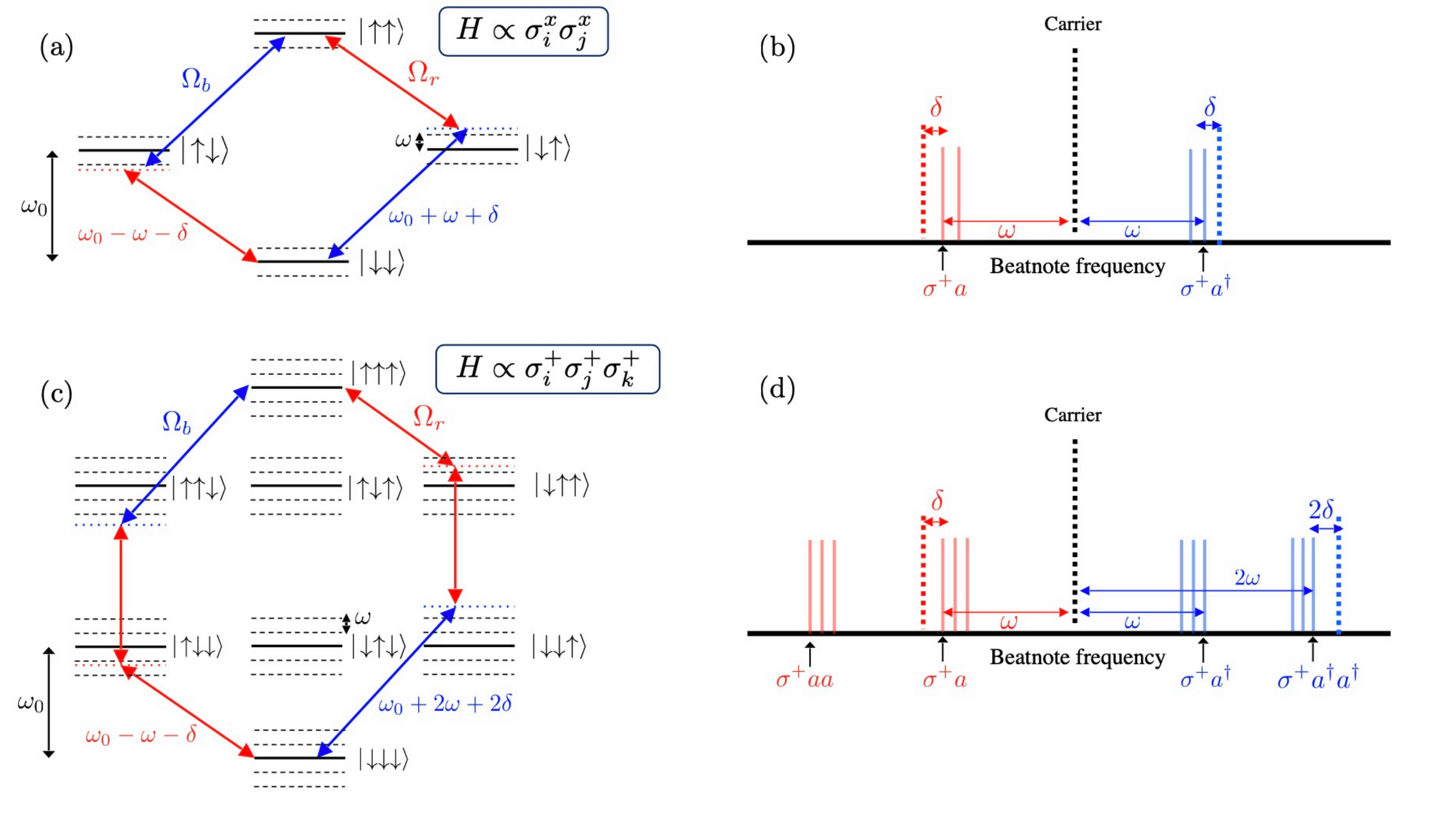
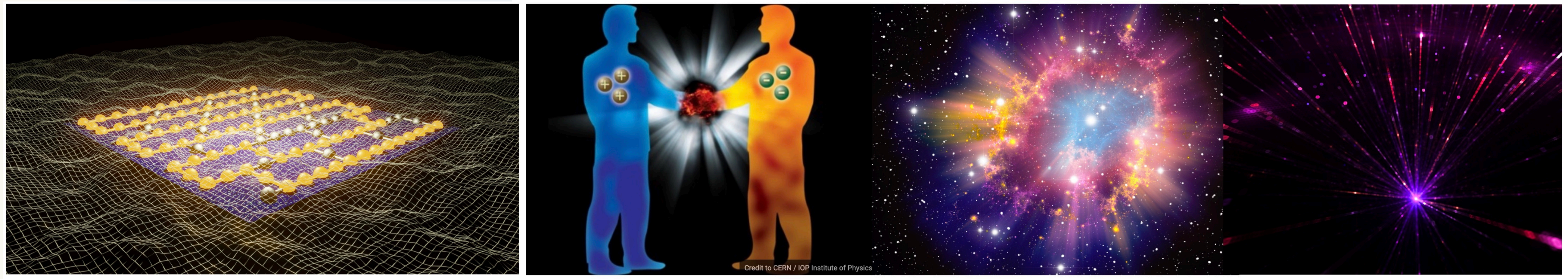


FIG. 1. (a,b) Traditional Mølmer-Sørensen scheme based on a pair of bichromatic laser beatnotes off-resonantly driving first-order spin-phonon couplings with symmetric detuning ($\pm\delta$), giving rise to an effective spin-spin interaction. The two-ion case is shown for simplicity. (c,d) Generalized 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.

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

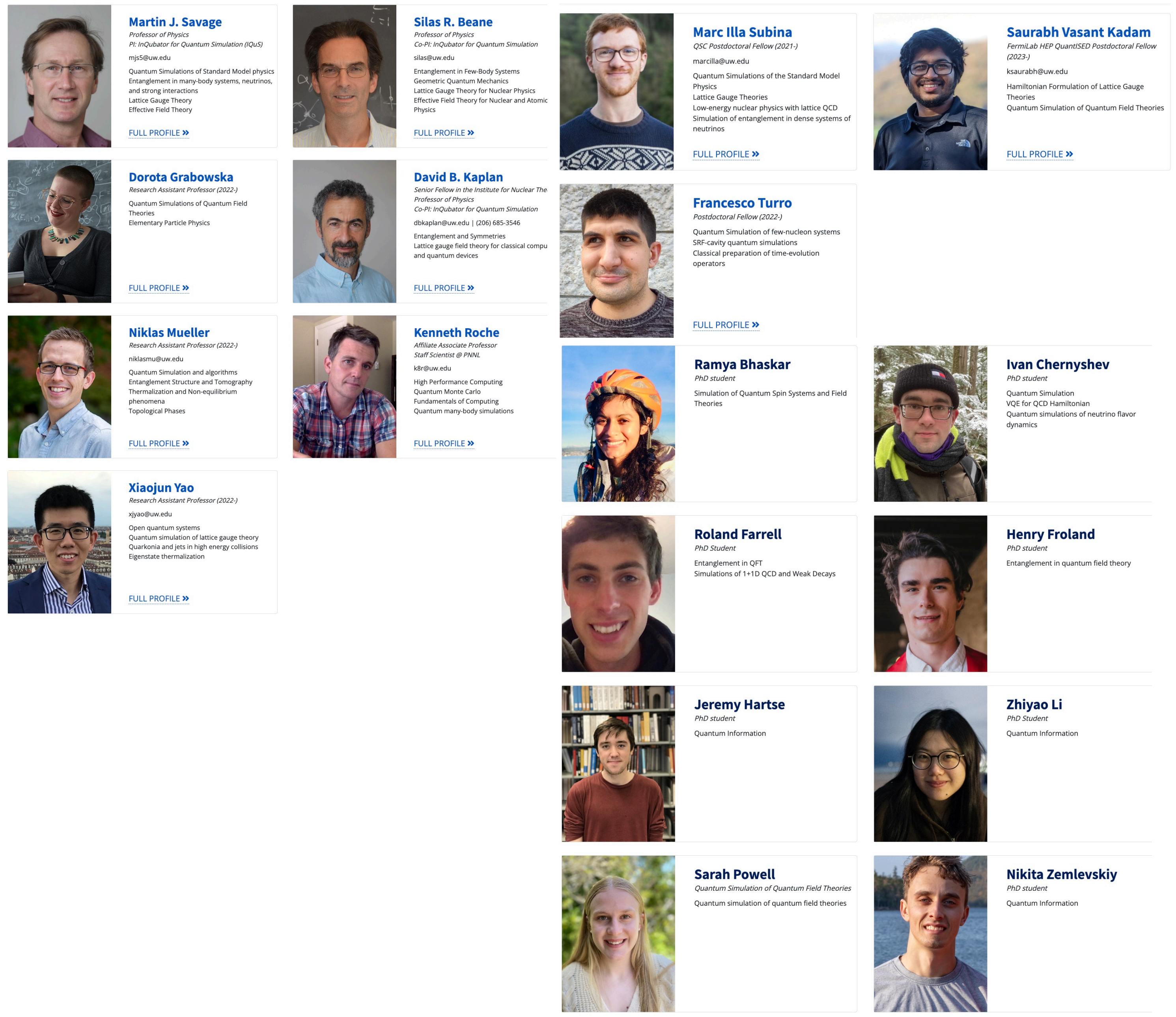
IQuS

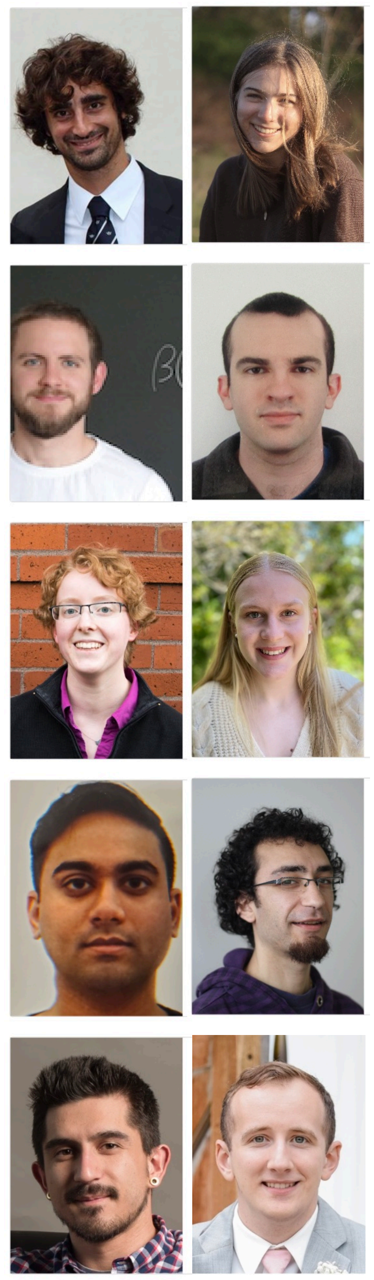
QUANTUM SCIENCE CENTER

FIN

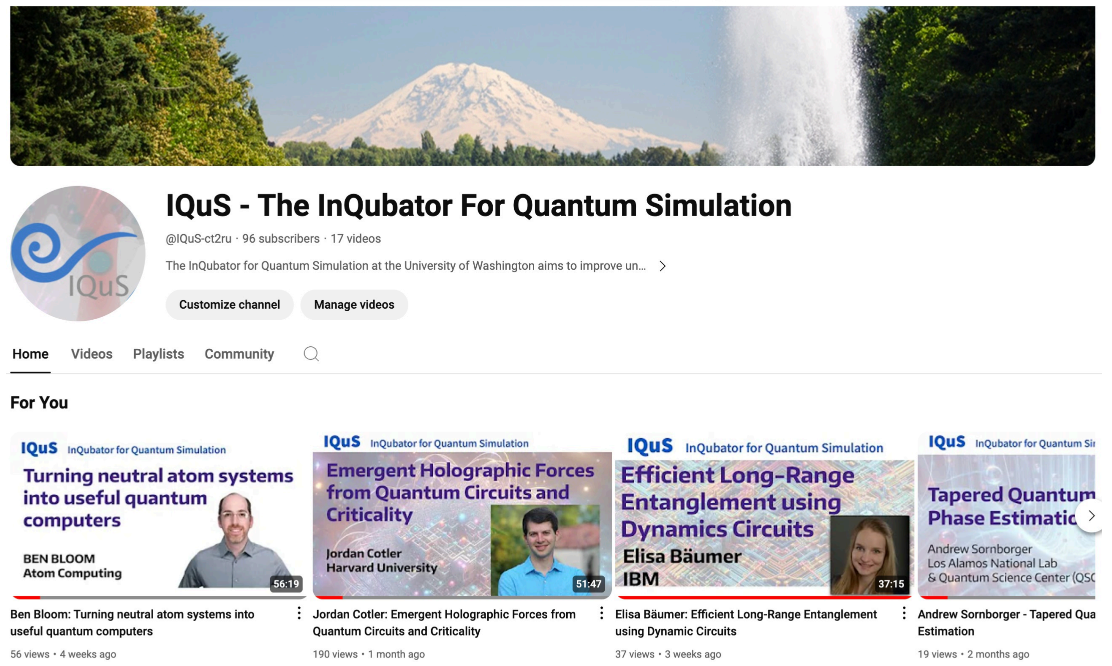
IQuS InQubator for Quantum Simulation

Workshops
Research
Visitors





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



DOE OFFICE OF NUCLEAR PHYSICS

UW DEPARTMENT OF PHYSICS

DEPARTMENT OF PHYSICS

UW COLLEGE OF ARTS & SCIENCES

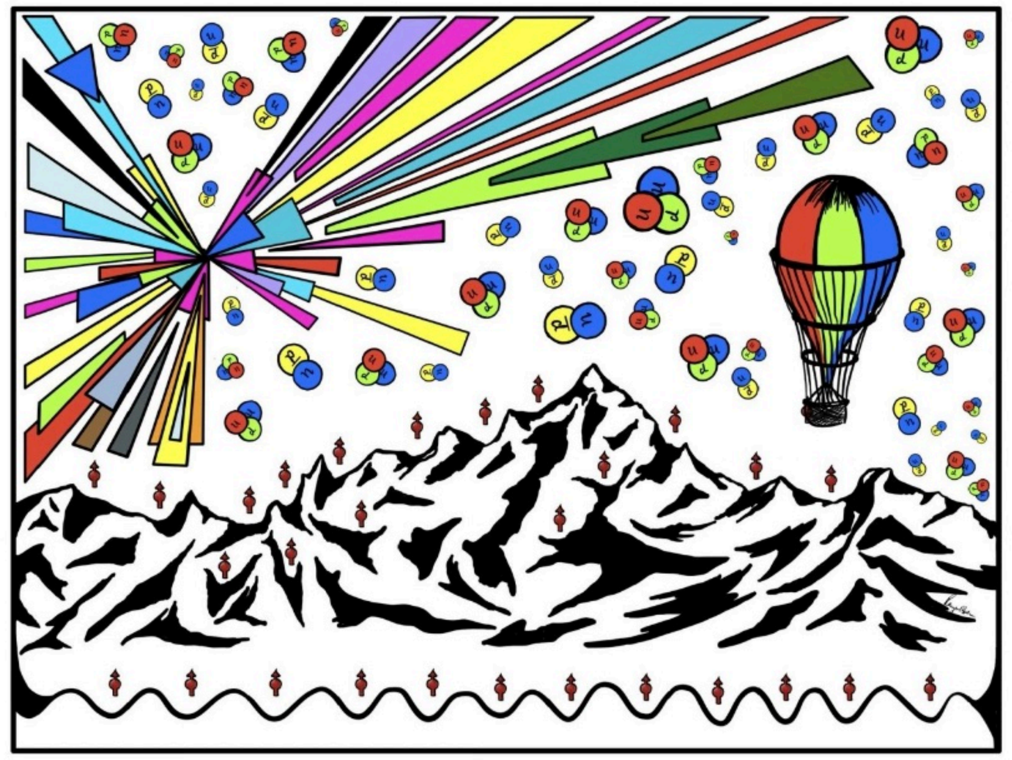
ARTS & SCIENCES

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