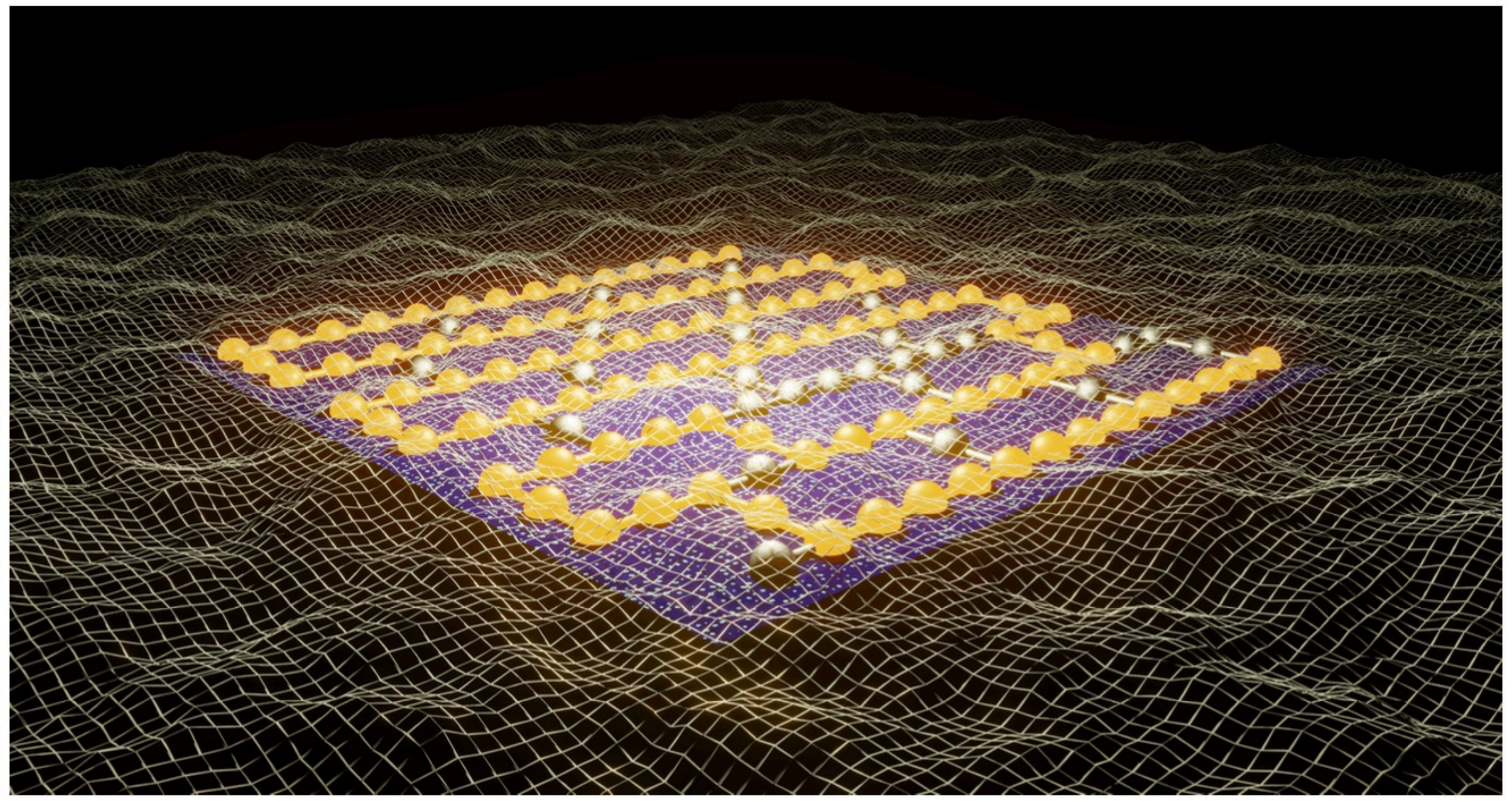
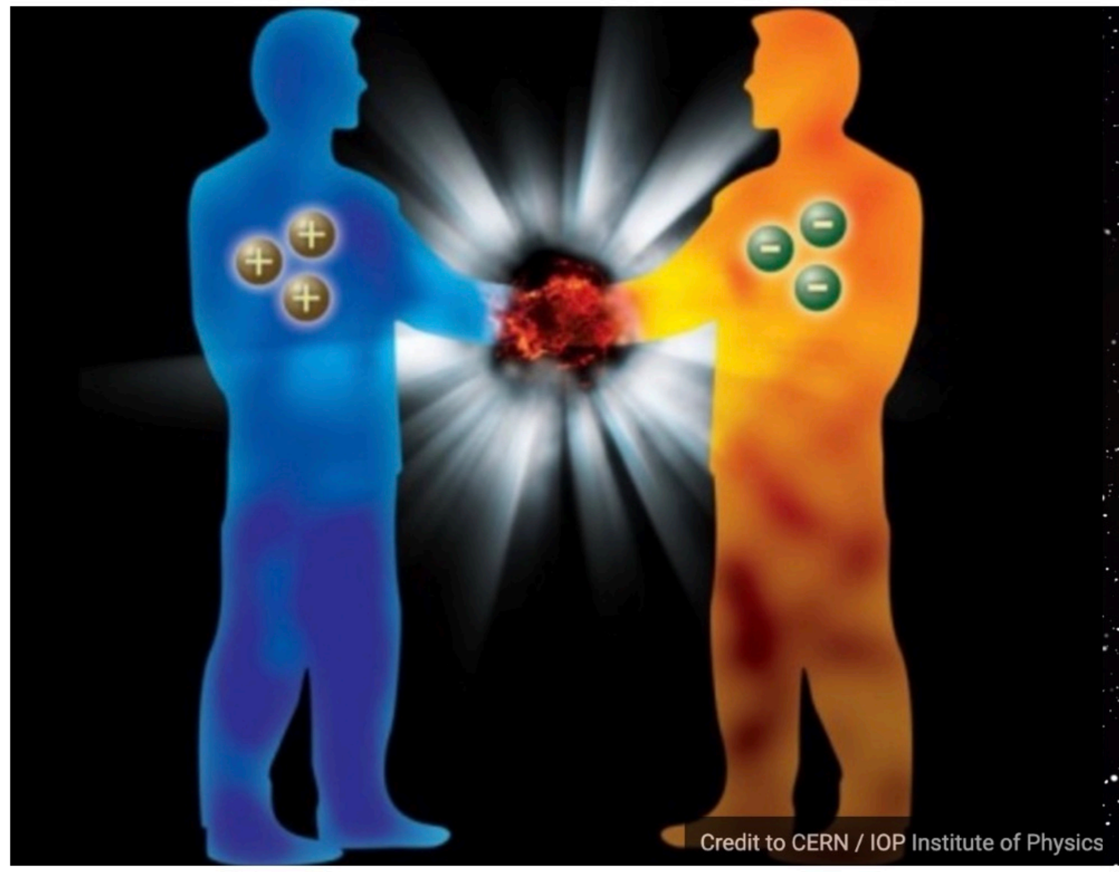
Quantum Simulation of Fundamental Physics





Progress and Thoughts
ECT*, Trento, September 1, 2025

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

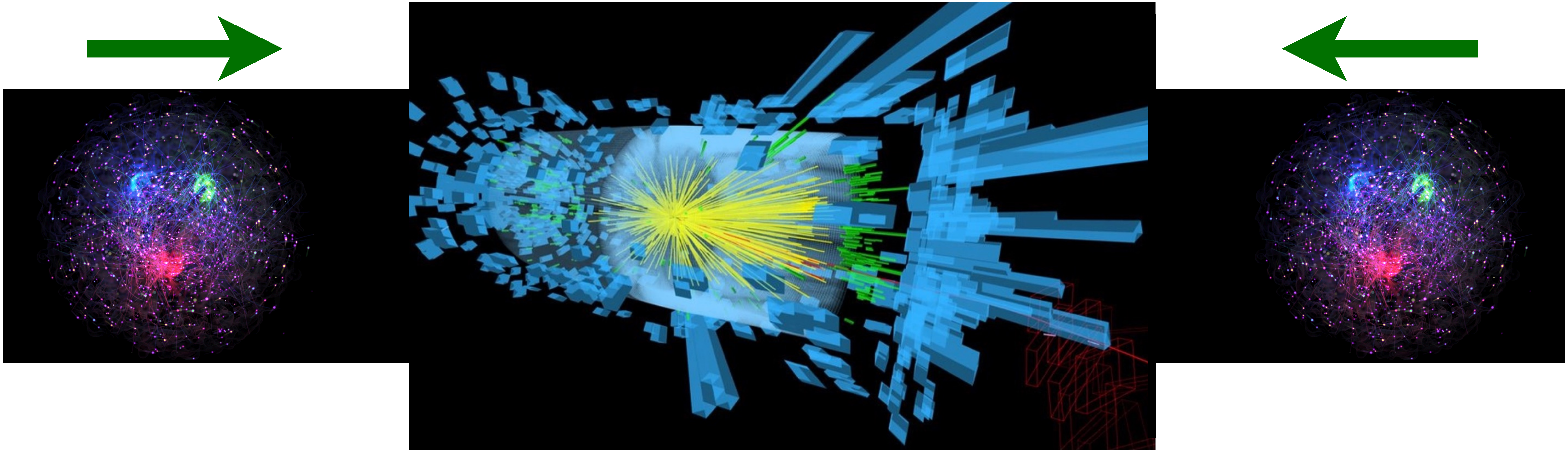
IQuS
https://iqus.uw.edu/

QUANTUM SCIENCE CENTER

Office of Science
U.S. Department of Energy

Oak Ridge National Laboratory

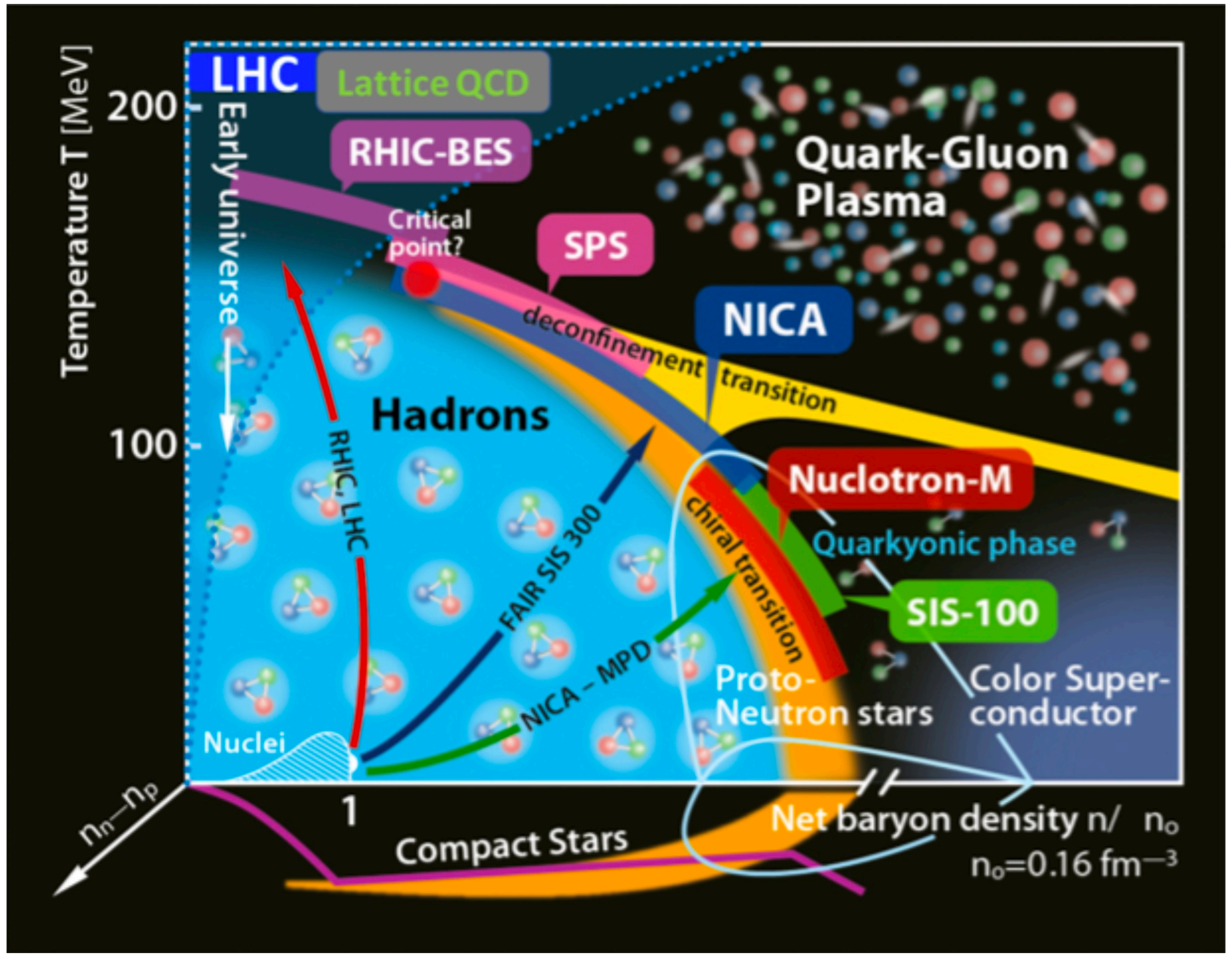
High-Energy Collisions

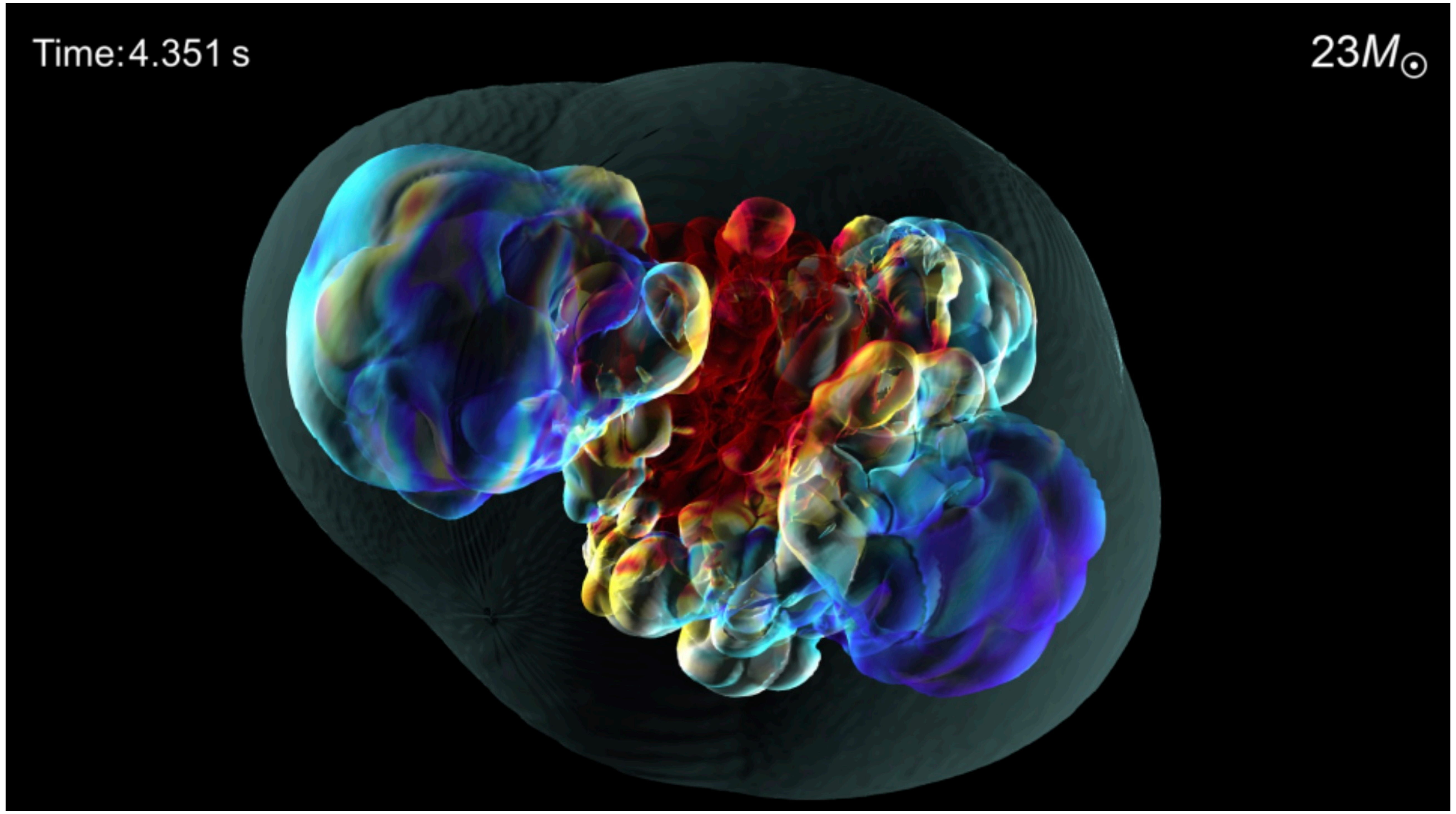


There is a lot of physics that takes place in collisions of matter

- Production of new particles, e.g., Higgs
- Collisions of nuclei with satellites, energy loss with materials - quantification
- Properties and thermalization of quark-gluon plasma/liquid
- Fragmentation, hadronization, confinement - QCD is now the background
- Transport in strongly interacting, correlated non-equilibrium matter - open quantum system(s)
- Neutrino interactions with matter and properties

Hot and Dense Non-Equilibrium Matter





Possible early universe signals in proton collisions at the Large Hadron Collider

Raghunath Sahoo[1,2,*] and Tapan Kumar Nayak[2,3]
[1]*Department of Physics, Indian Institute of Technology Indore, Simrol, Indore 453552, India*
[2]*CERN, CH 1211, Geneva 23, Switzerland and*
[3]*School of Physical Sciences, National Institute of Science Education and Research, HBNI, Jatni-752050, India*

(Dated: January 4, 2022)

Next-Generation 3D Core-Collapse Supernova Simulations

PI Adam Burrows, Princeton University
CO-PI David Vartanyan, University of California Berkeley
Matt Coleman, Princeton University
Chris White, Princeton University

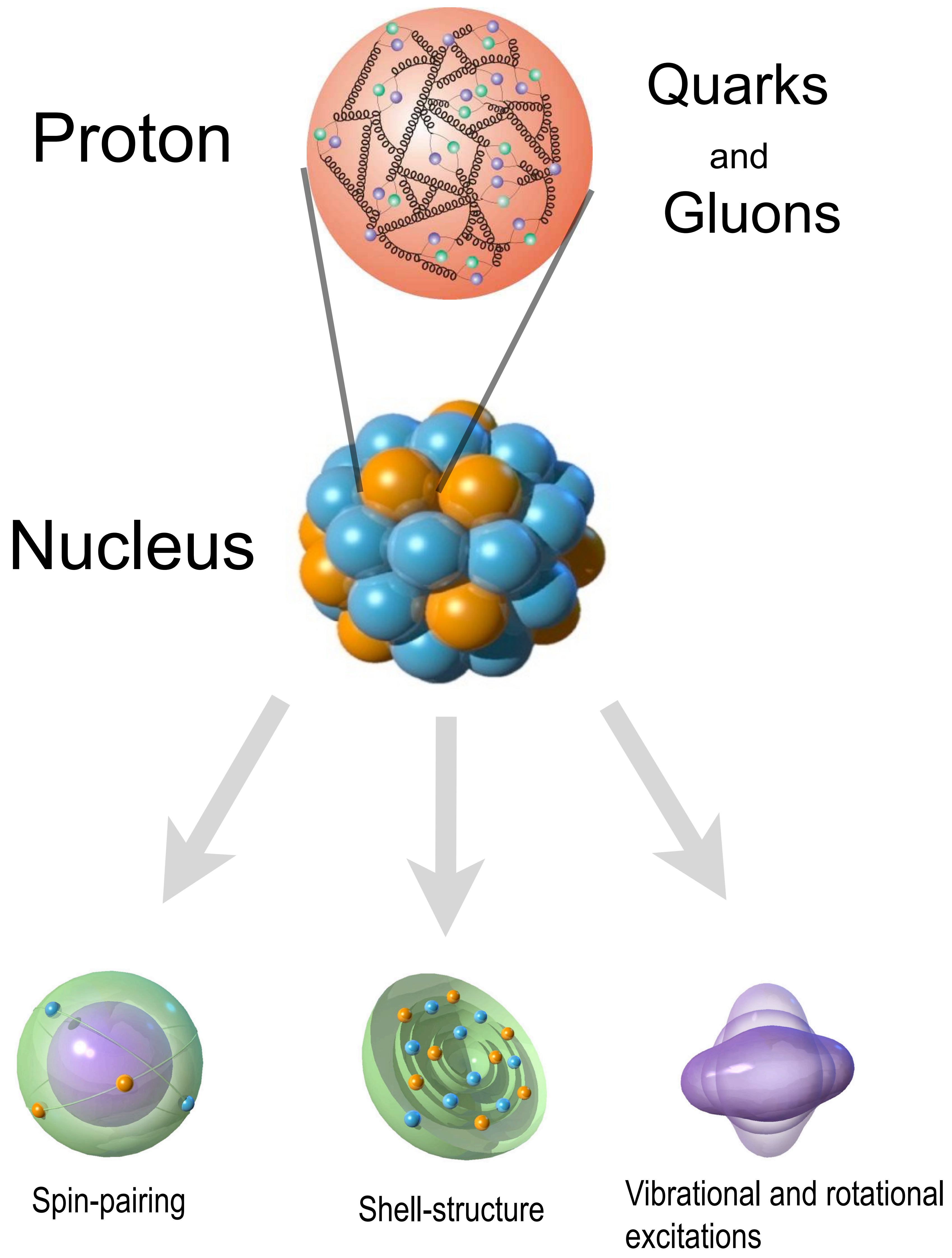
Perspective | Published: 21 June 2023

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

Ordinary Matter



$$\Lambda_{\mathrm{QCD}}$$

$$\frac{m_u}{\Lambda_{\mathrm{QCD}}} \quad \frac{m_d}{\Lambda_{\mathrm{QCD}}} \quad \frac{m_s}{\Lambda_{\mathrm{QCD}}}$$

$$\alpha_e$$

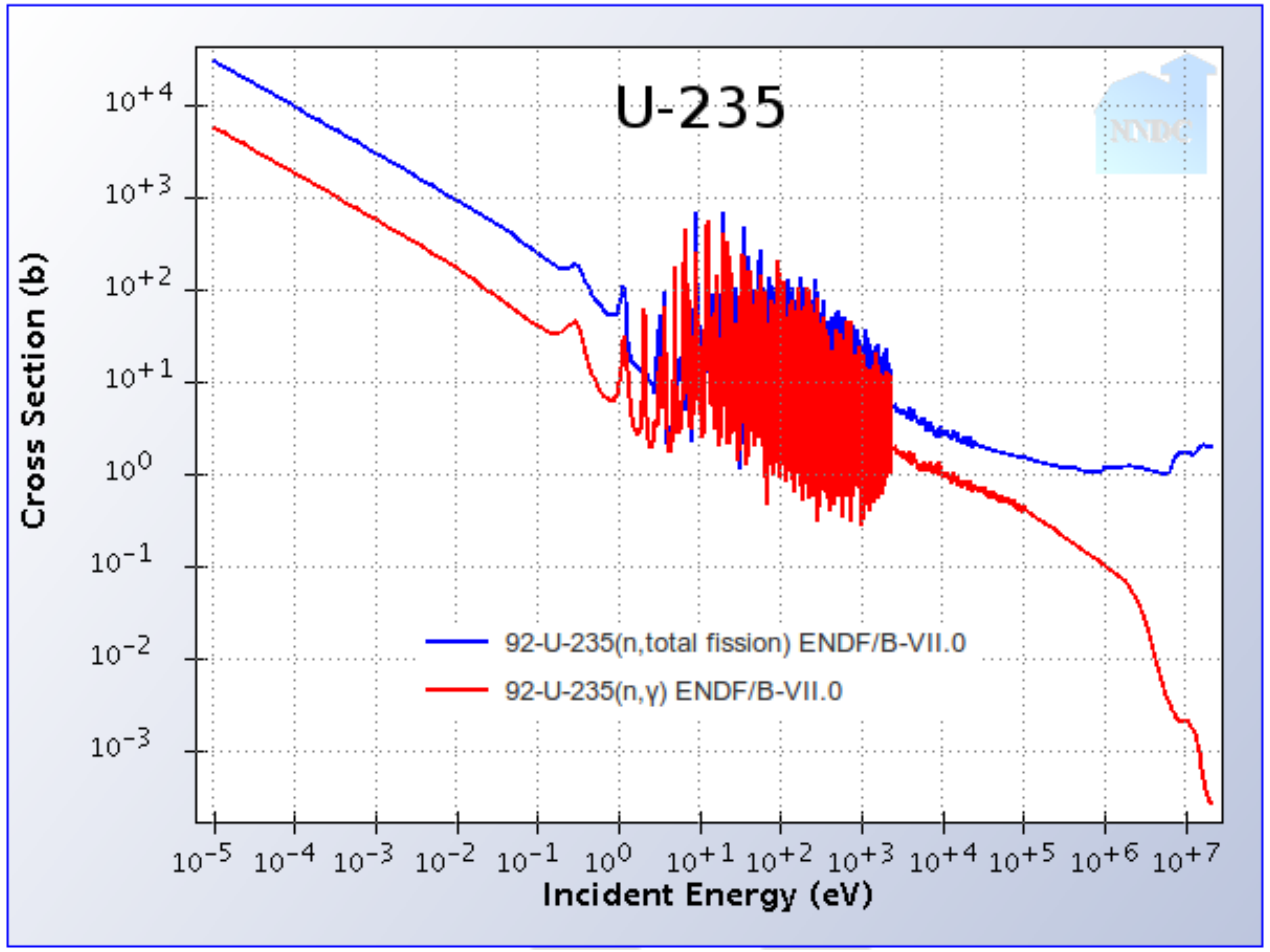
Small number of input parameters responsible for all of strongly interacting matter

Dimensionless plus a scale

LQCD - dimensionless

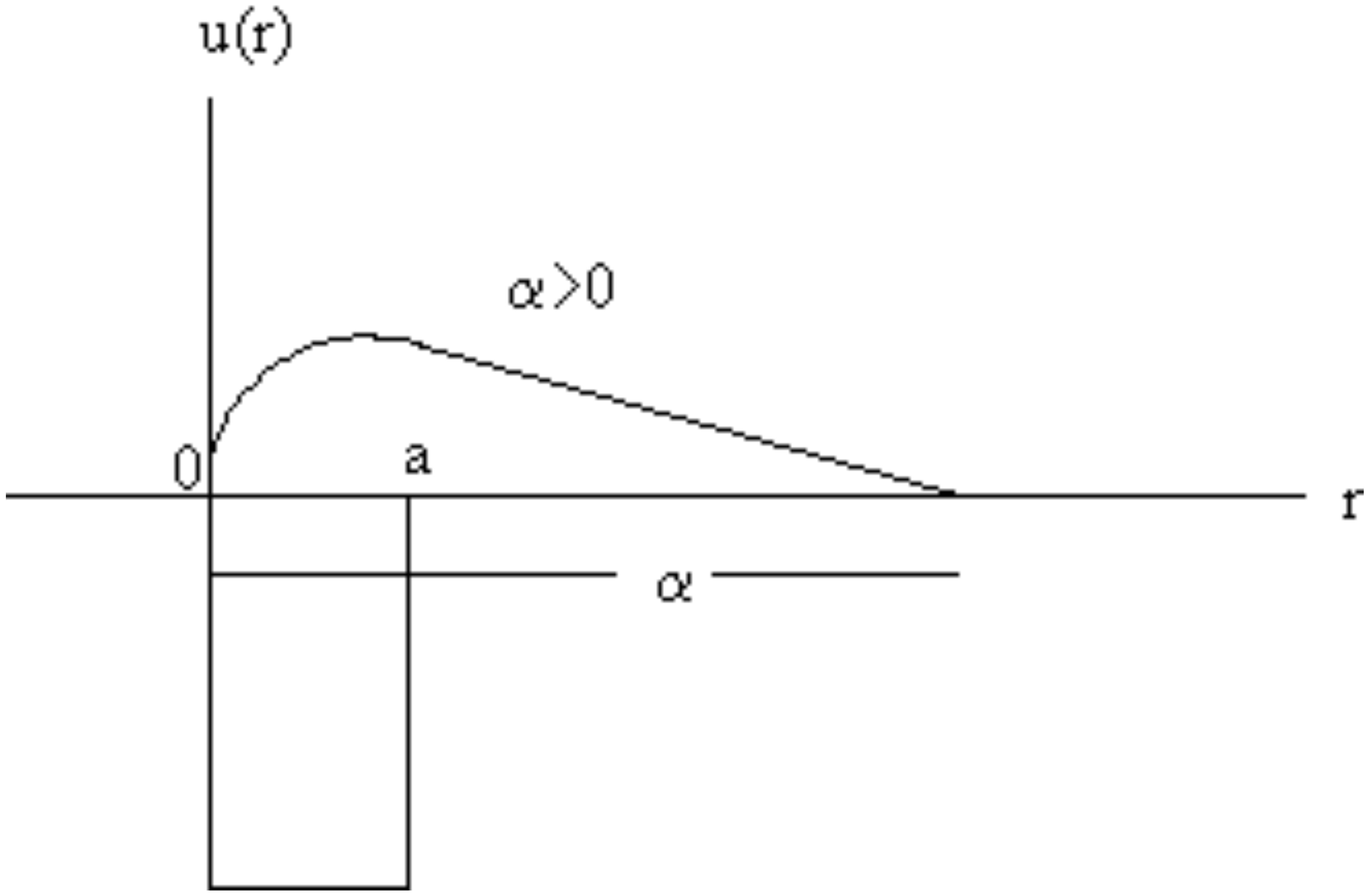
Hierarchies

Neutron-Induced Fission



Mass ^{235}U ~ 220 900 MeV

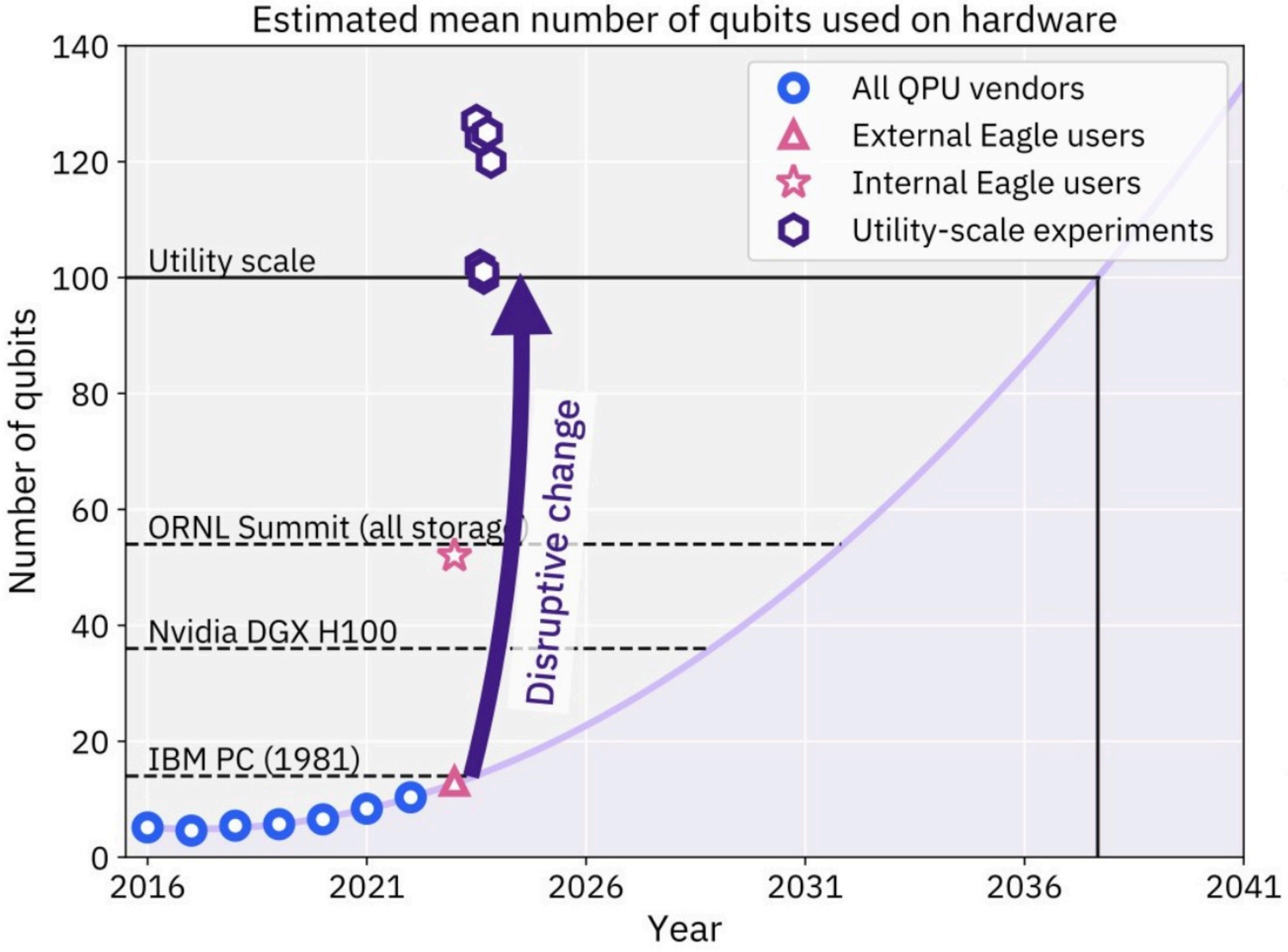
NN wavefunction at E=0



IBM Quantum Summit - NYC December 2023

Utility-scale experiments

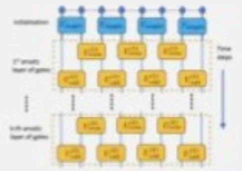
With quantum systems composed of 100+ qubits, researchers are beginning to explore algorithms and applications at scales beyond brute-force classical computation using IBM Quantum systems.



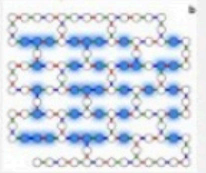
IBM **Quantum**

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

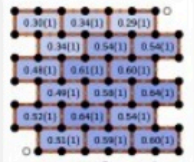
Simulating large-size quantum spin chains on cloud-based superconducting quantum computers
102 qubits / 3186 CX gates — arXiv:2207.09994



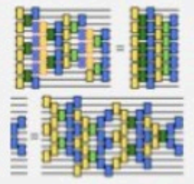
Uncovering Local Integrability in Quantum Many-Body Dynamics
124 qubits / 2641 CX gates — arXiv:2307.07552



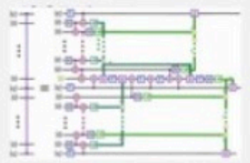
Realizing the Nishimori transition across the error threshold for constant-depth quantum circuits
125 qubits / 429 gates + meas. — arXiv:2309.02863



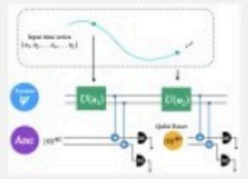
Scalable Circuits for Preparing Ground States on Digital Quantum Computers: The Schwinger Model Vacuum on 100 Qubits
100 qubits / 788 CX gates — arXiv:2308.04481



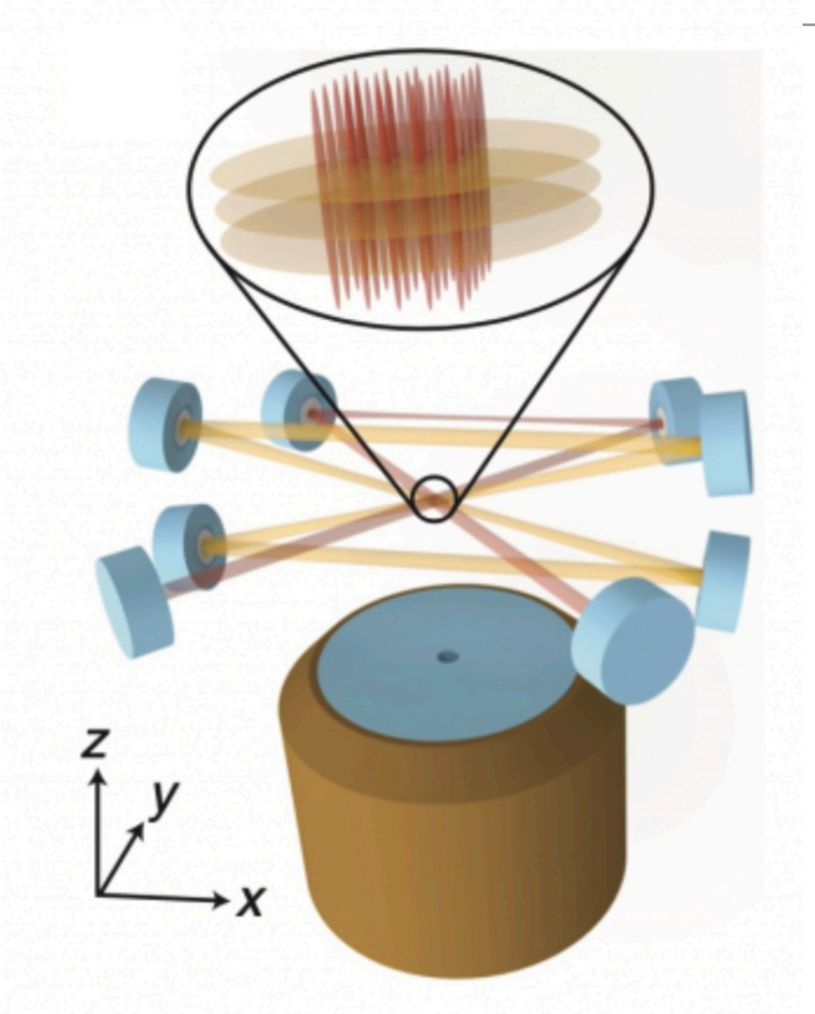
Efficient Long-Range Entanglement using Dynamic Circuits
101 qubits / 504 gates + meas. — arXiv:2308.13065



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)

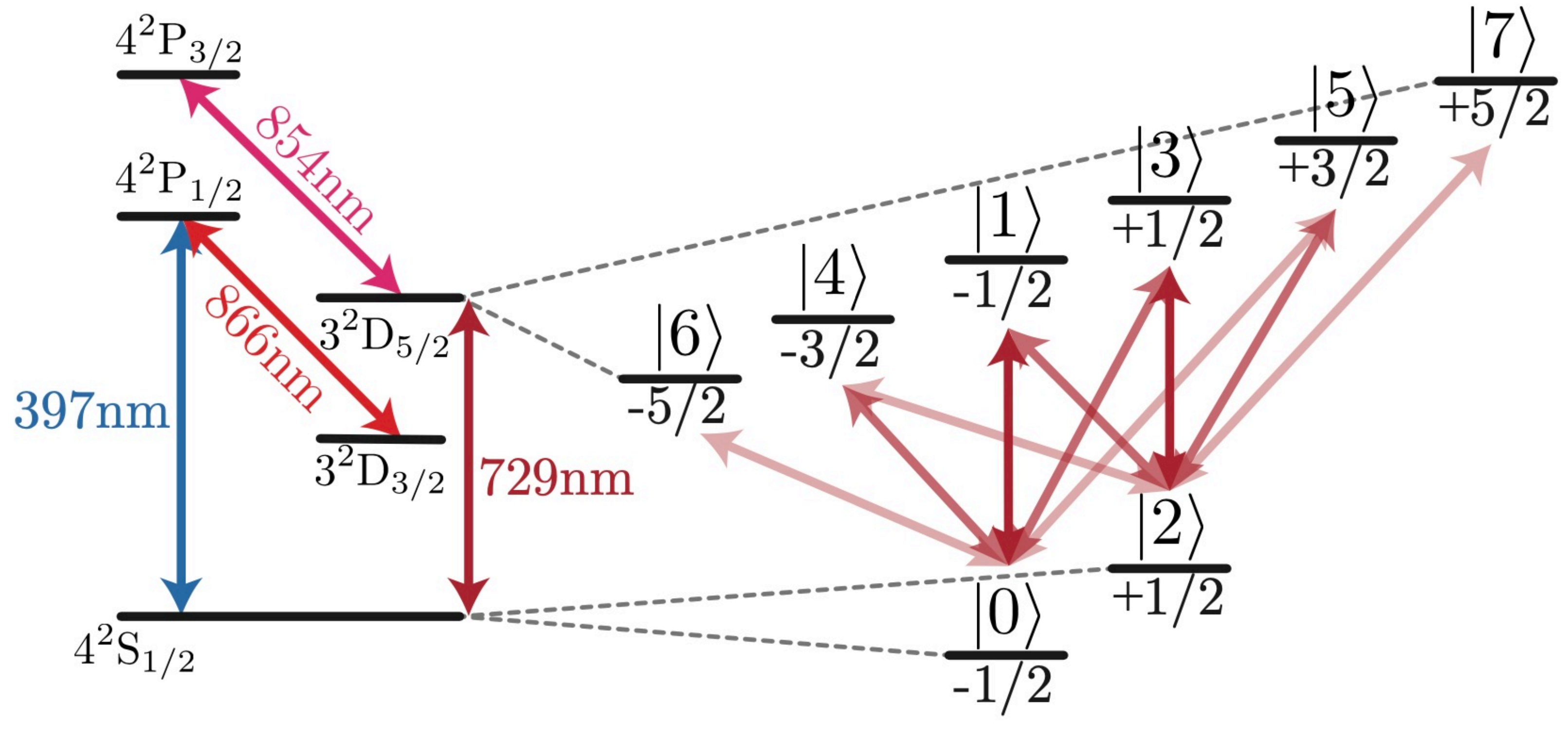
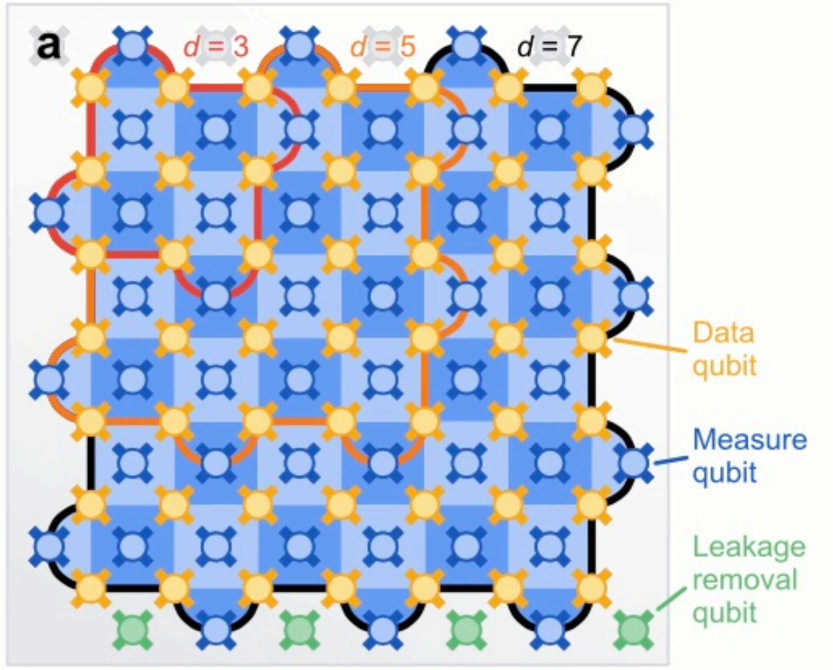
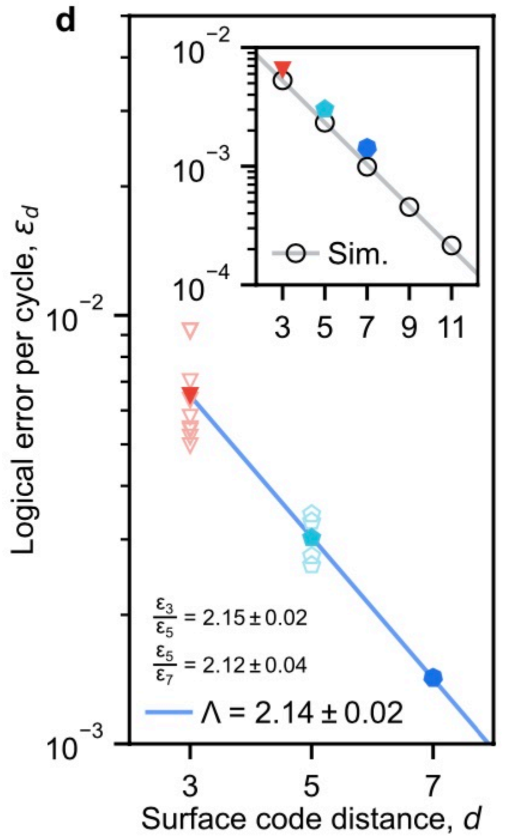


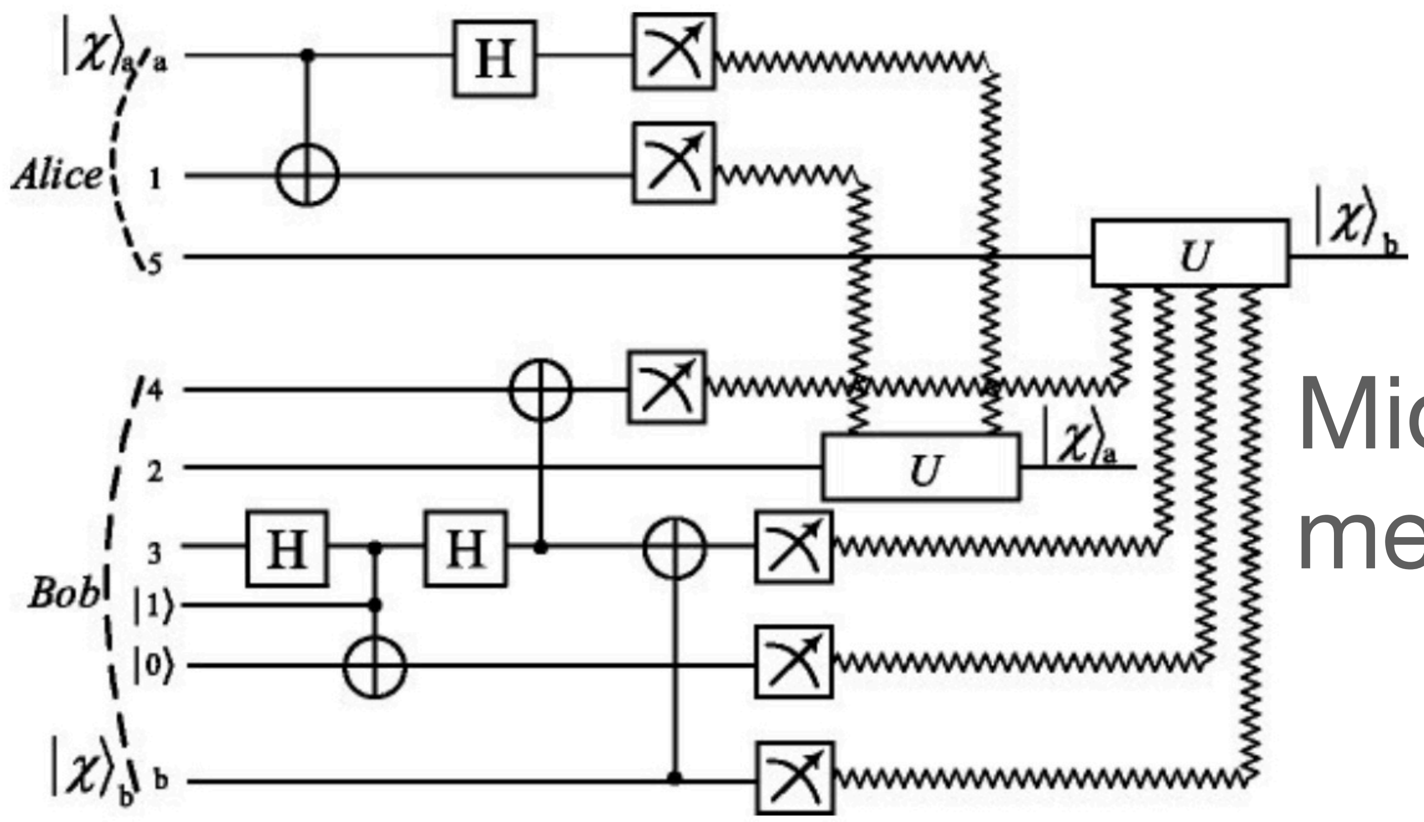
FIG. 1. **Level scheme of the $^{40}Ca^{+}$ ion.**

Qudits with trapped ions





Surface code
>100 superconducting qubits

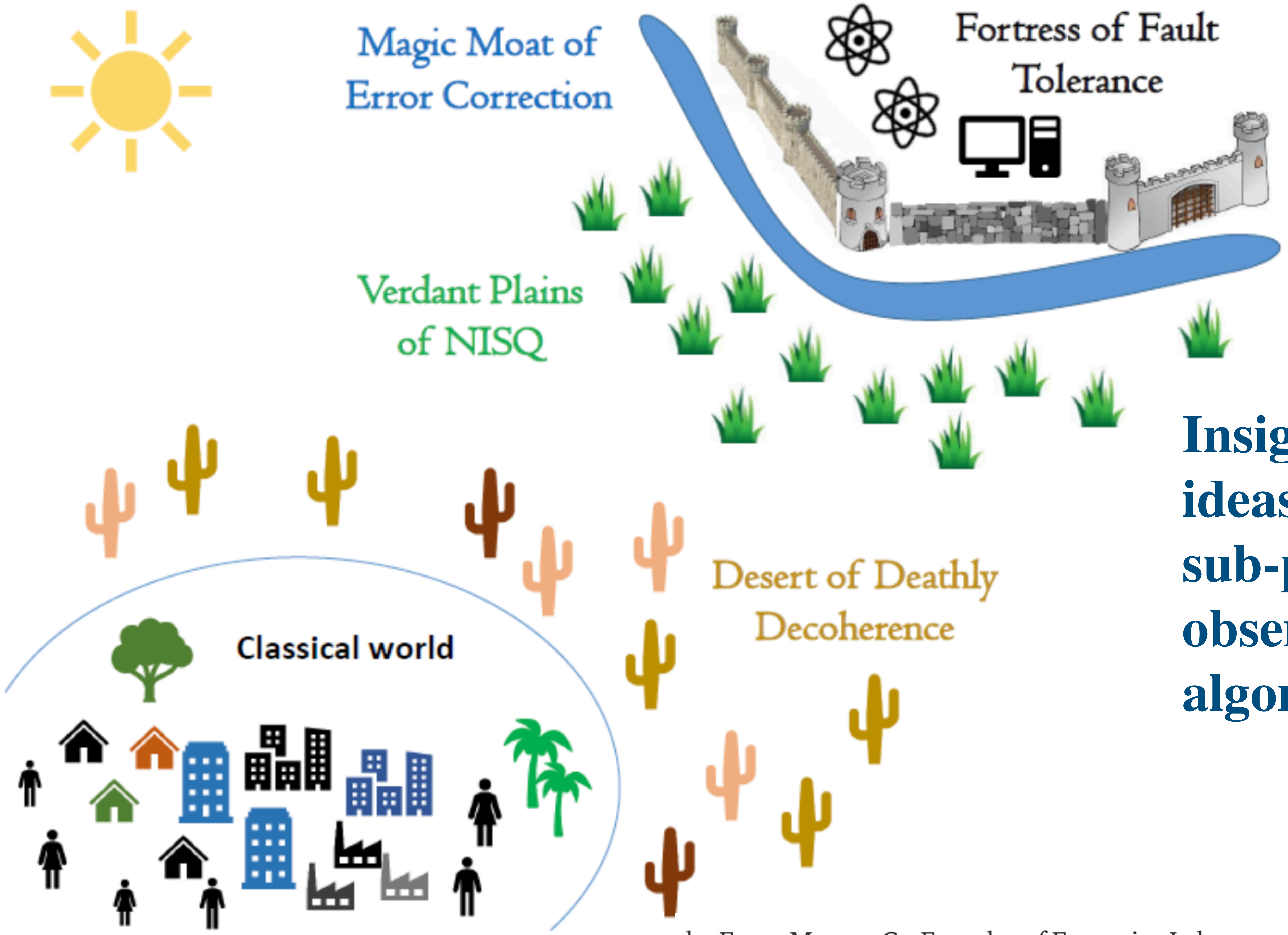


Mid-circuit measurements

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

From Classical to Error-Corrected Quantum Computing

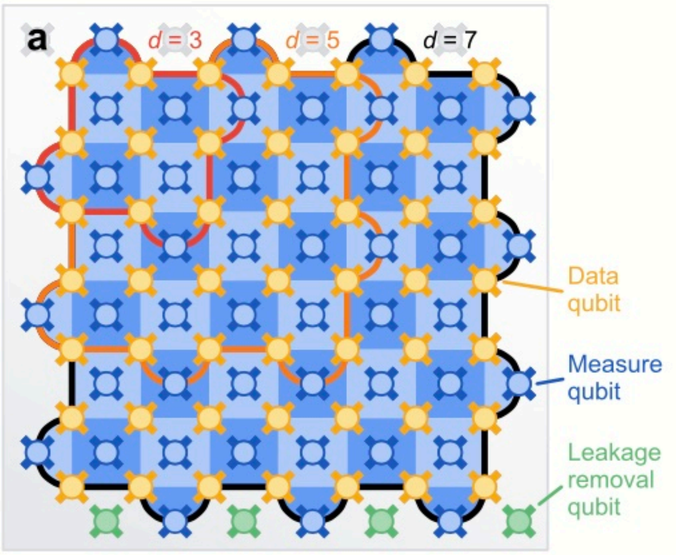
Precision simulations

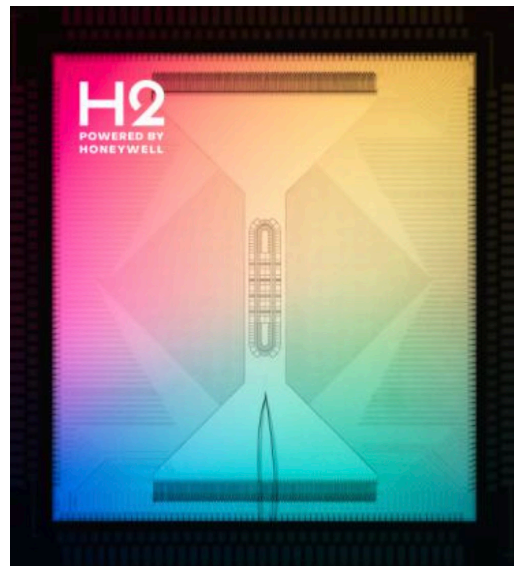


by Ewan Munro, Co-Founder of Entropica Labs.

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

Insights, ideas, sub-parts, observables, algorithms





Logical Qubits

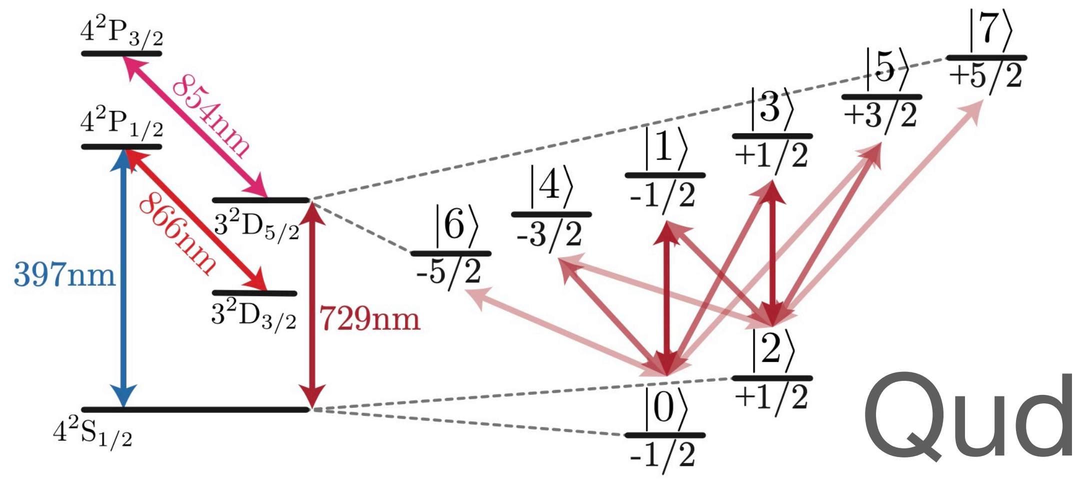
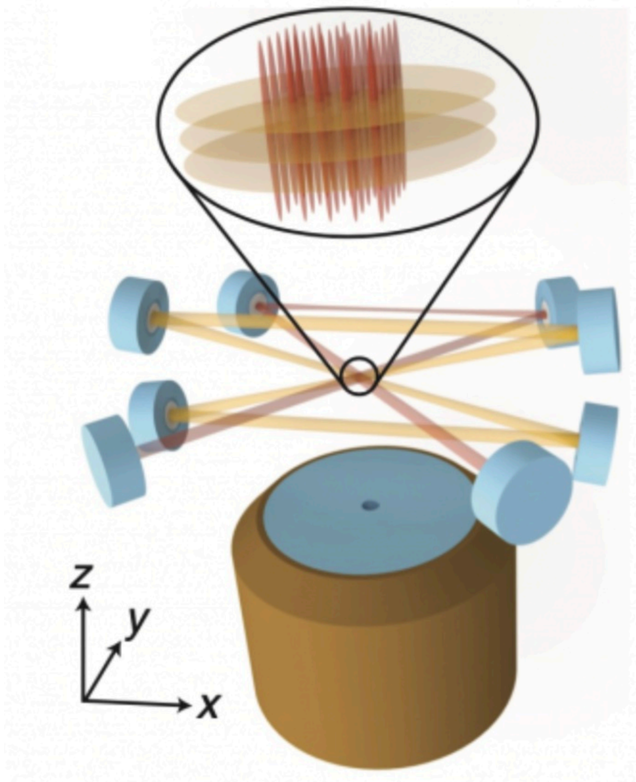


FIG. 1. **Level scheme of the $^{40}Ca^+$ ion.**

Qudits



Cold Atoms

Physics Output Optimization

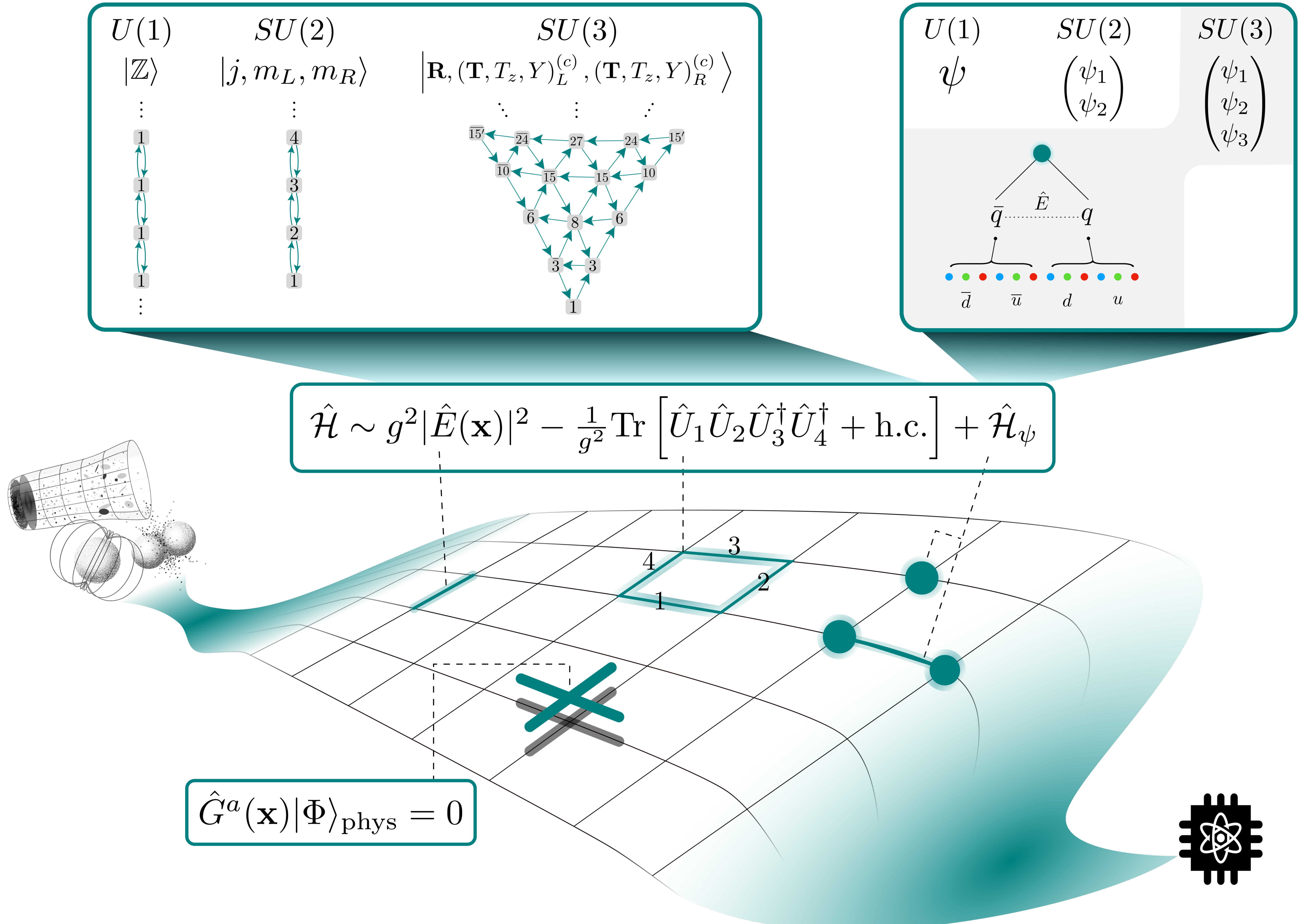
Simulating Lattice Gauge Field Theories

Hamiltonian
Kogut-Susskind
1970's

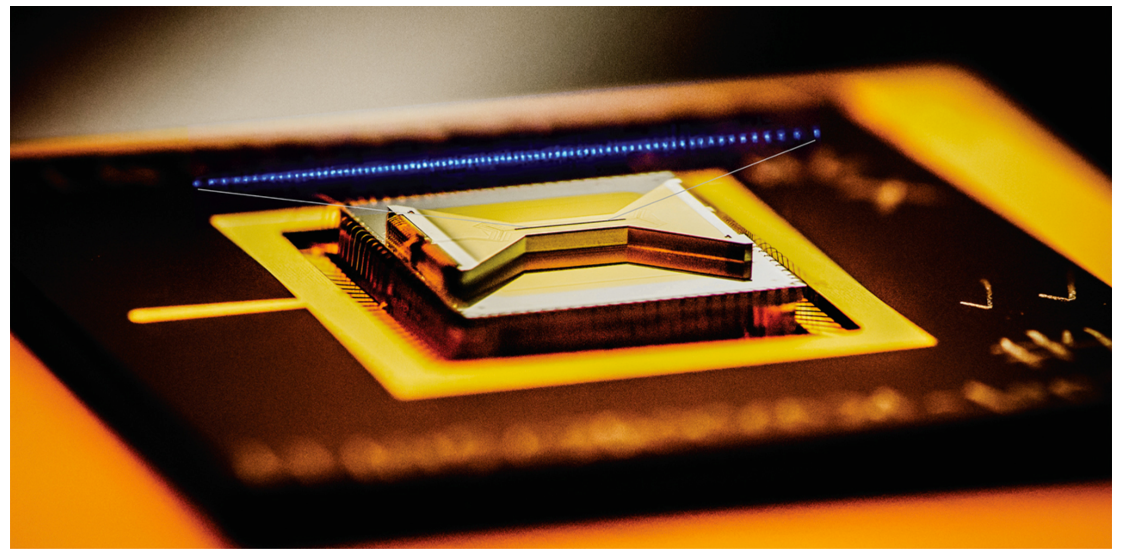
Yang-Mills:
Byrnes-Yamamoto
2005

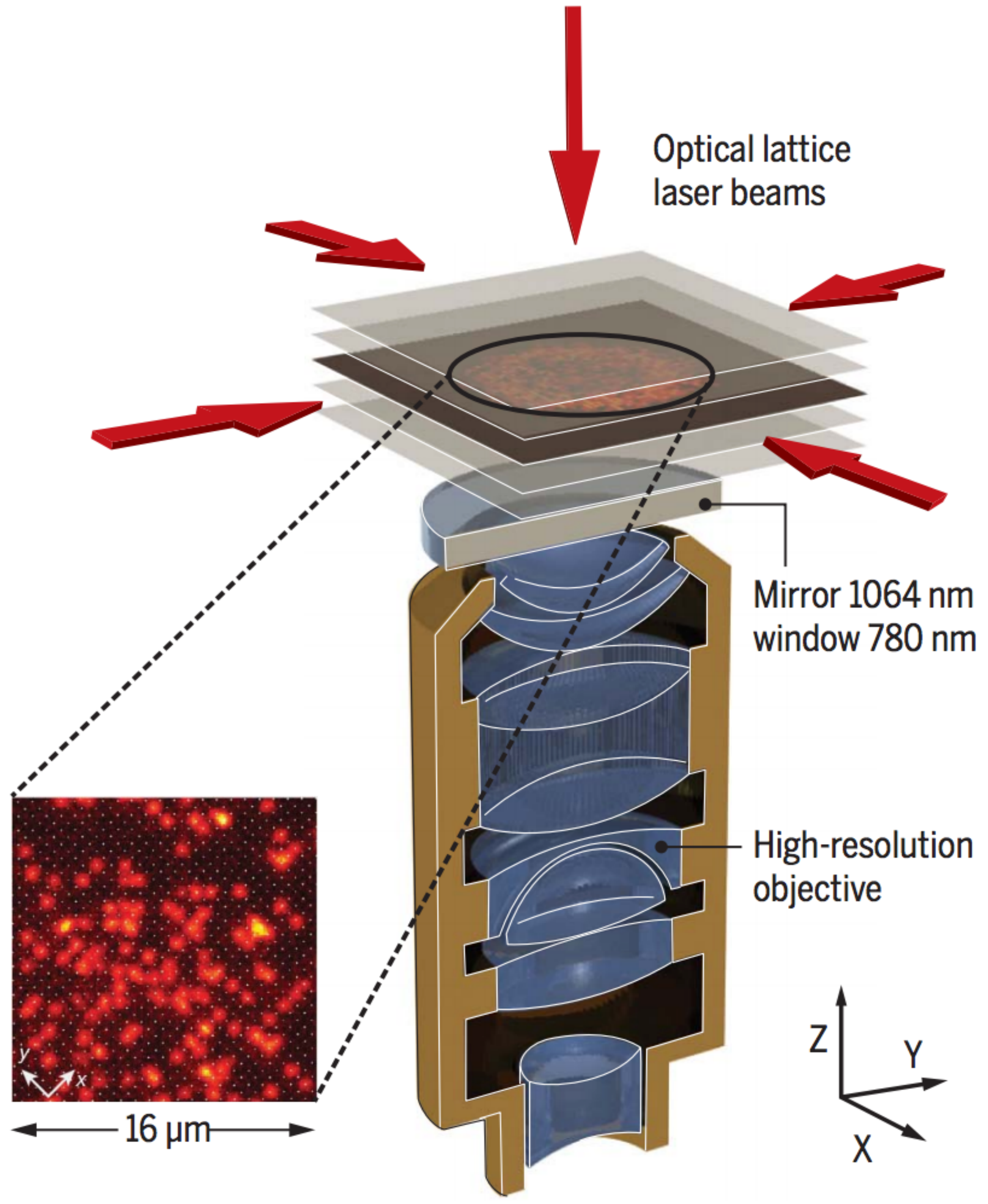
SU(N):
Zohar et al
(2013)

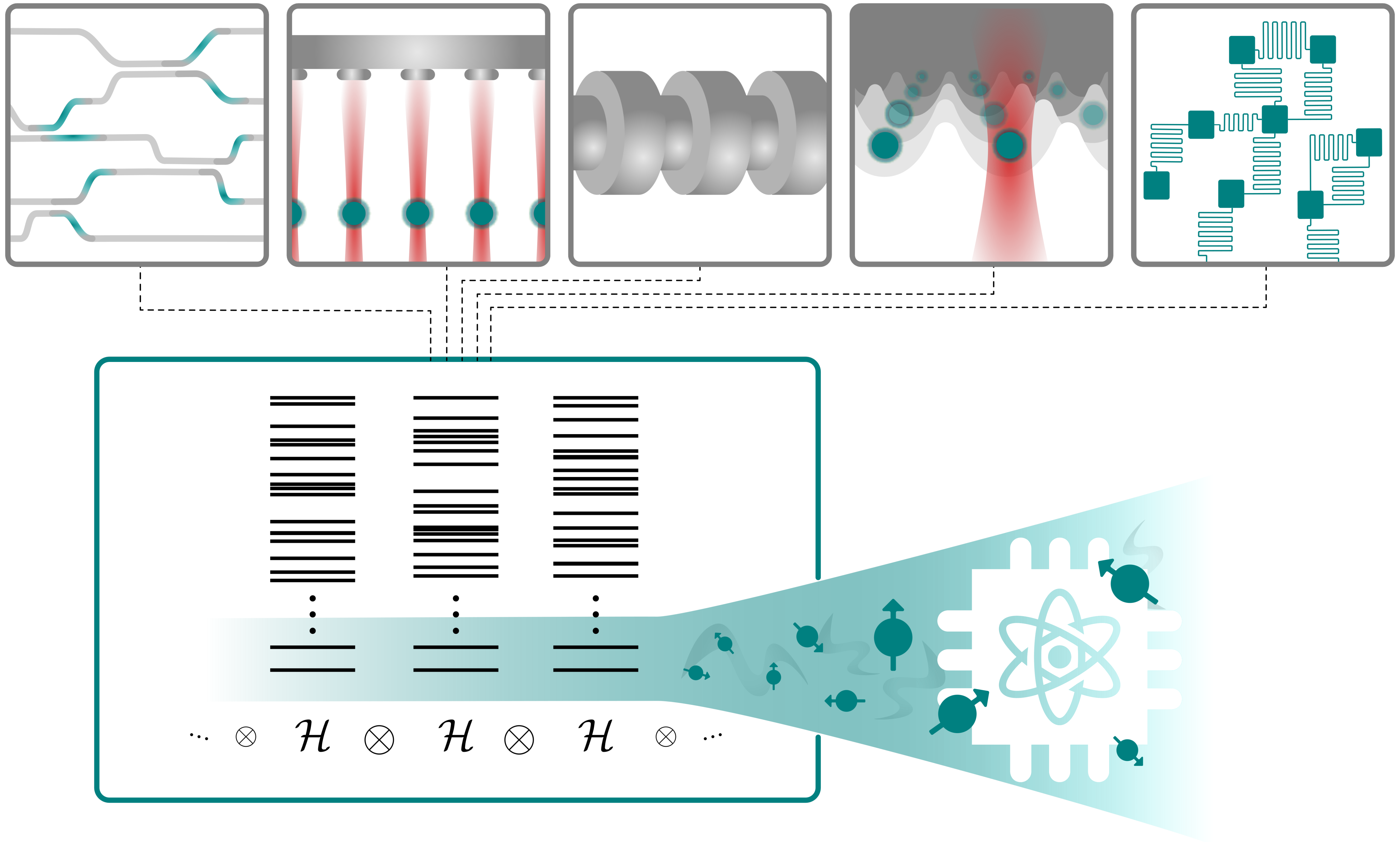
QLM
Banerjee et al
Tagliacozzo et al
(2013)

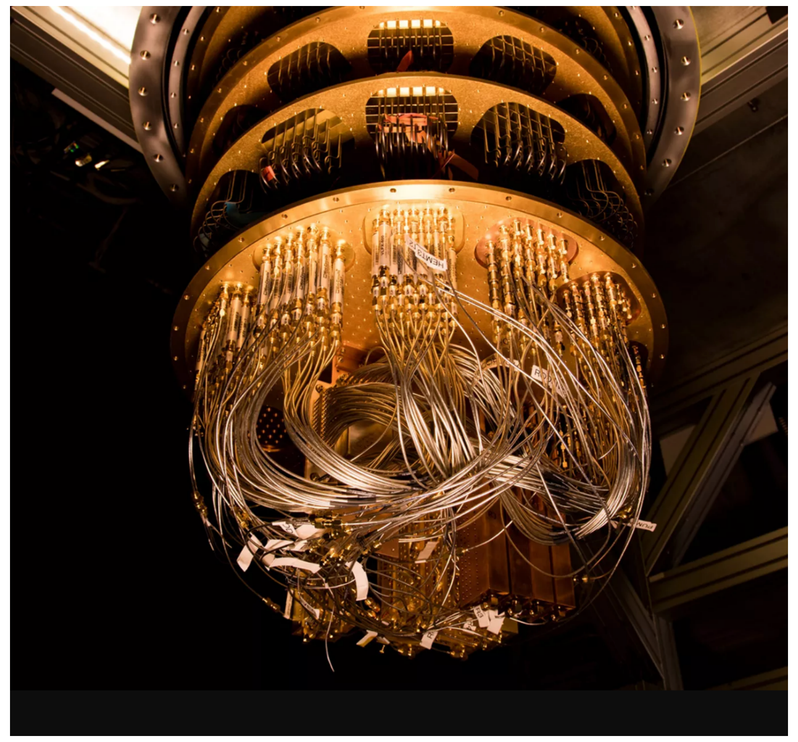


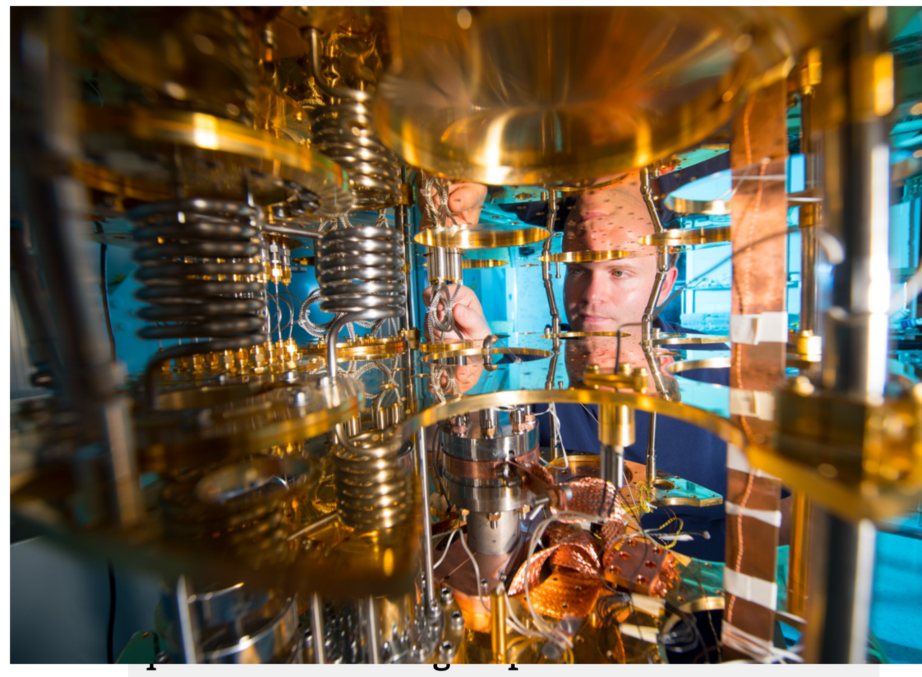
Encoding Systems in Multi-Hilbert Spaces Embedded in Large HPC systems

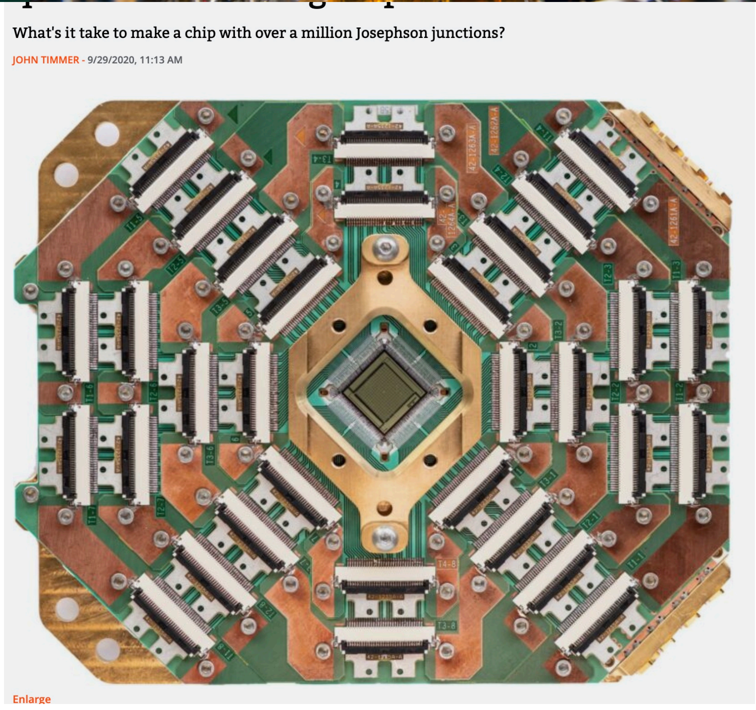












Map scalar, fermion and vector systems

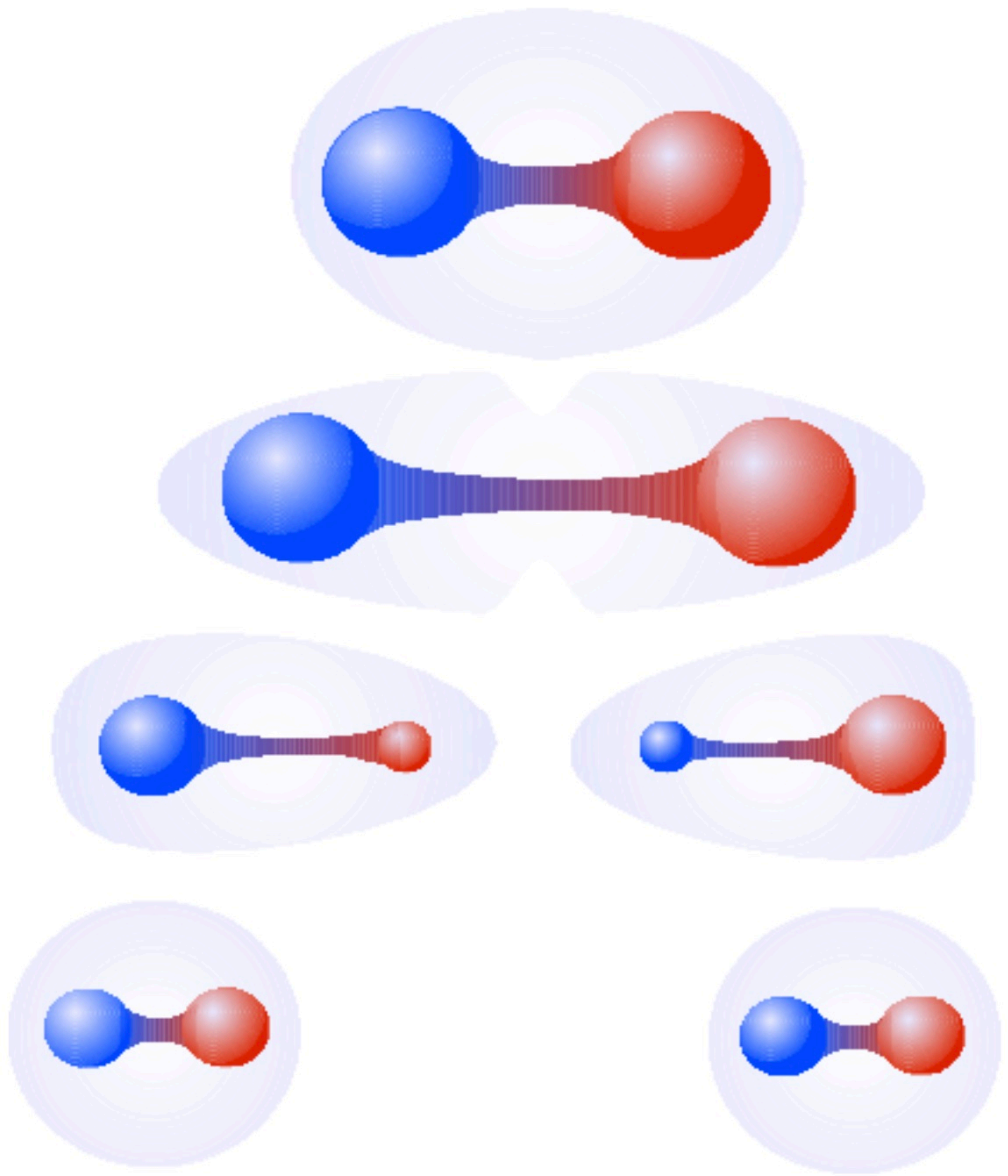
Optimize for target observables - Physics Aware

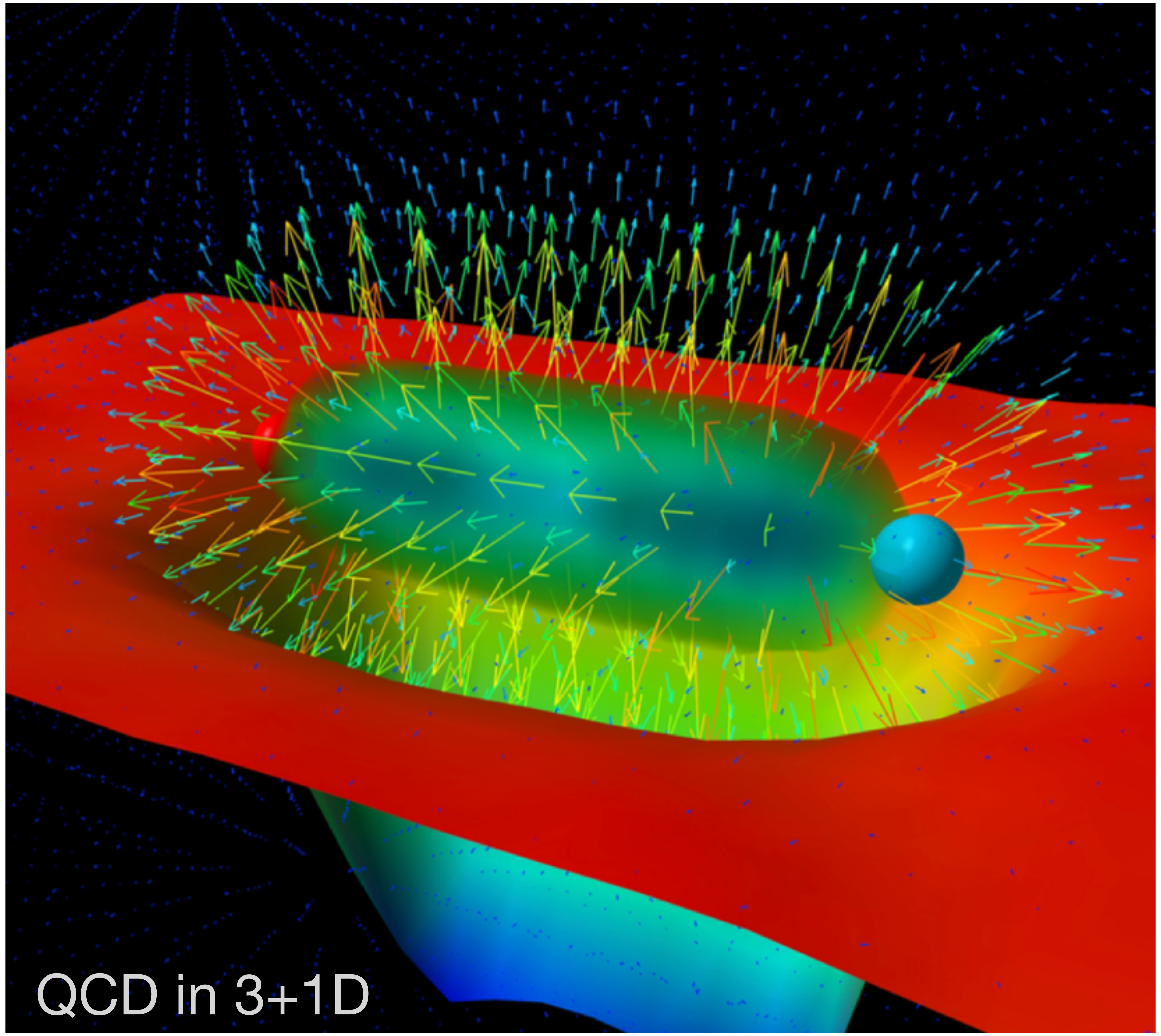
Human-intensive co-design exploration

Low-Dimensional Models:

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

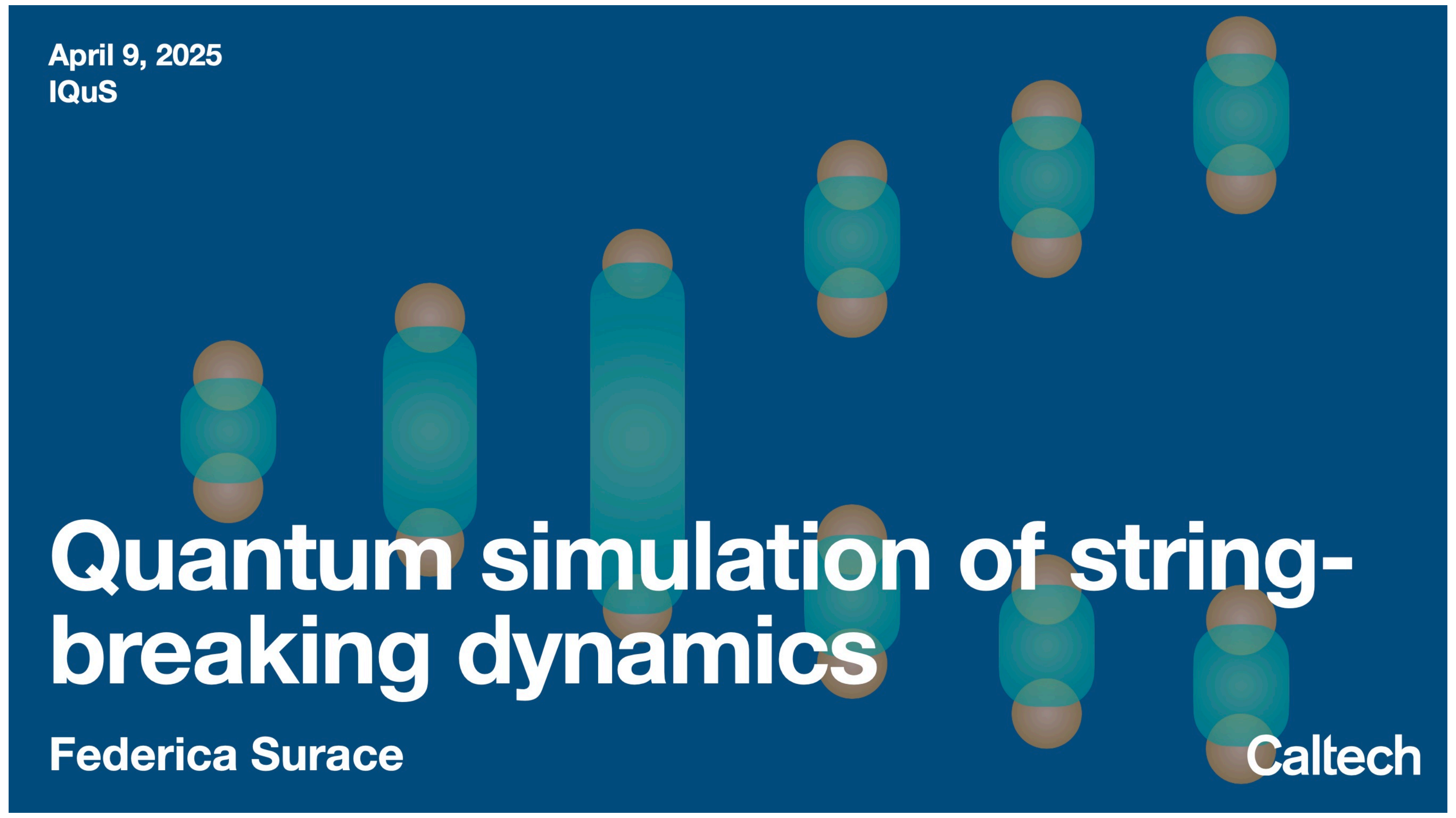
2+1D simulations are starting - Zn-like

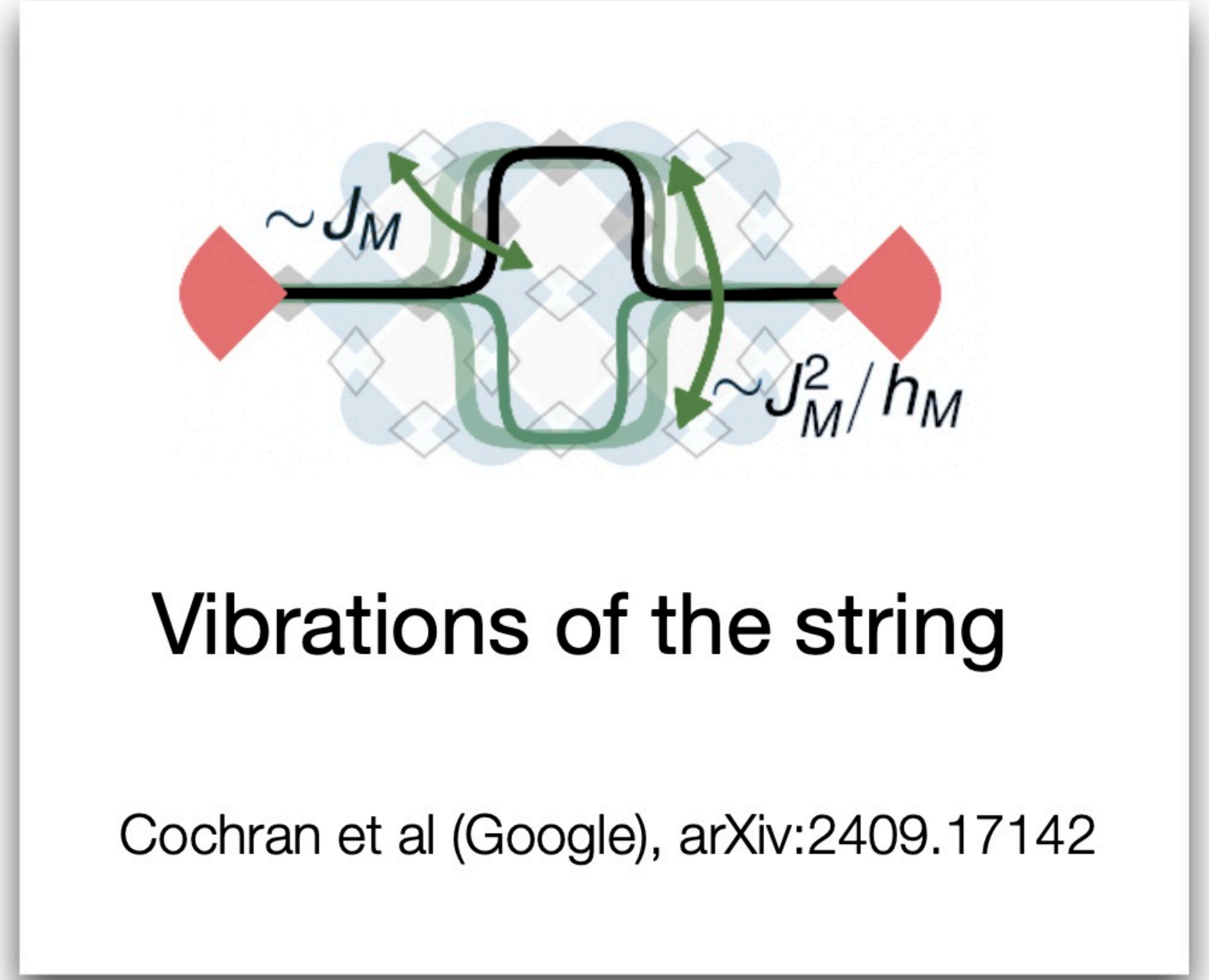




This model is being used by several groups pursuing quantum simulations

String Breaking as an Example





Quantum simulation of string breaking: summary

<u>Models</u>

1+1D

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

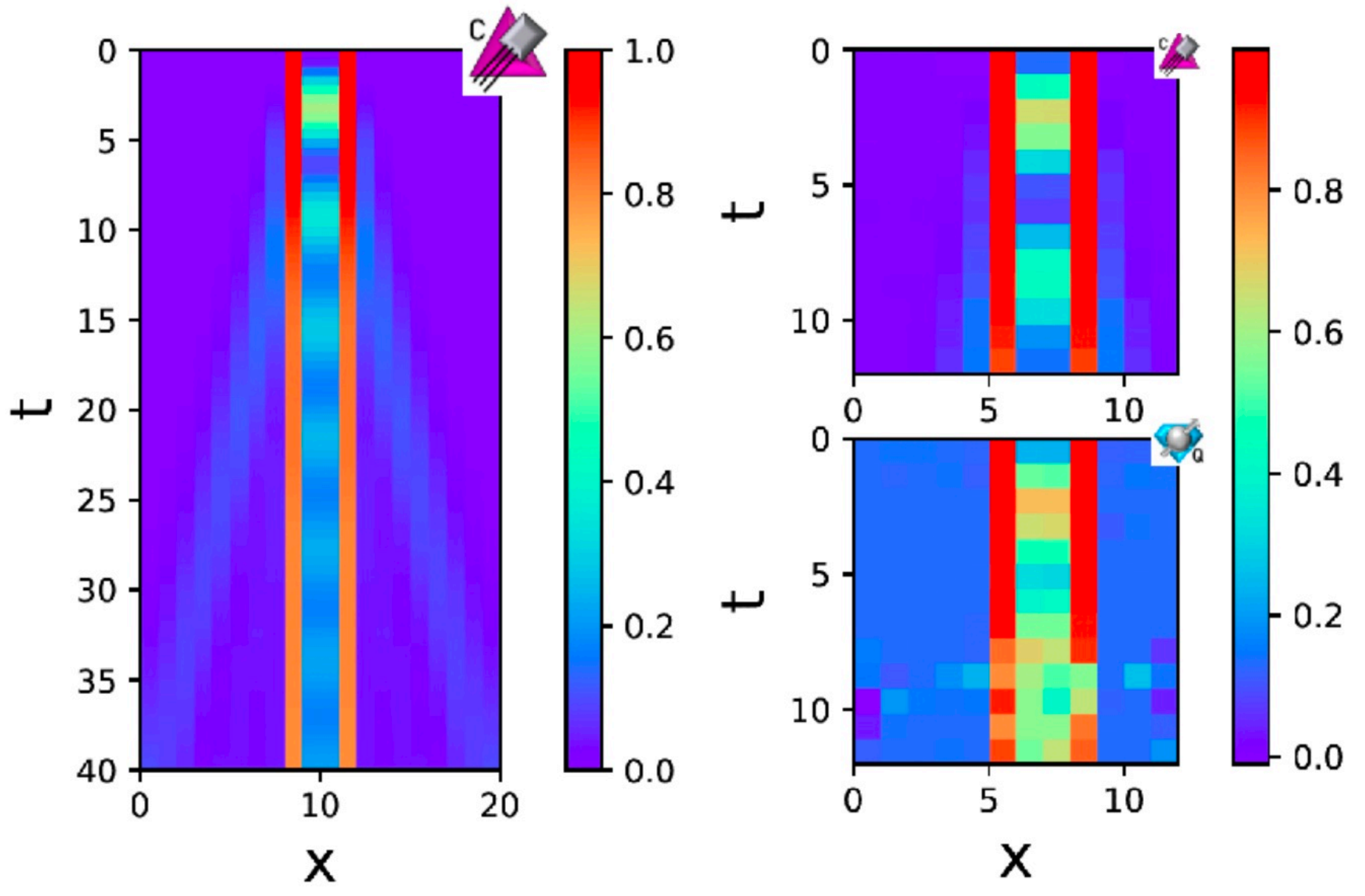
2+1D

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

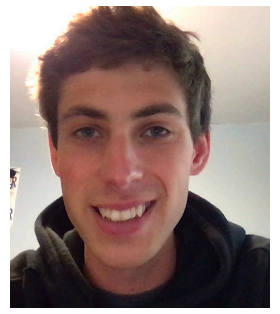
<u>Phenomenology</u>

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

SU(2) lattice gauge theory 1+1D



Ciavarella, arXiv:2411.05915



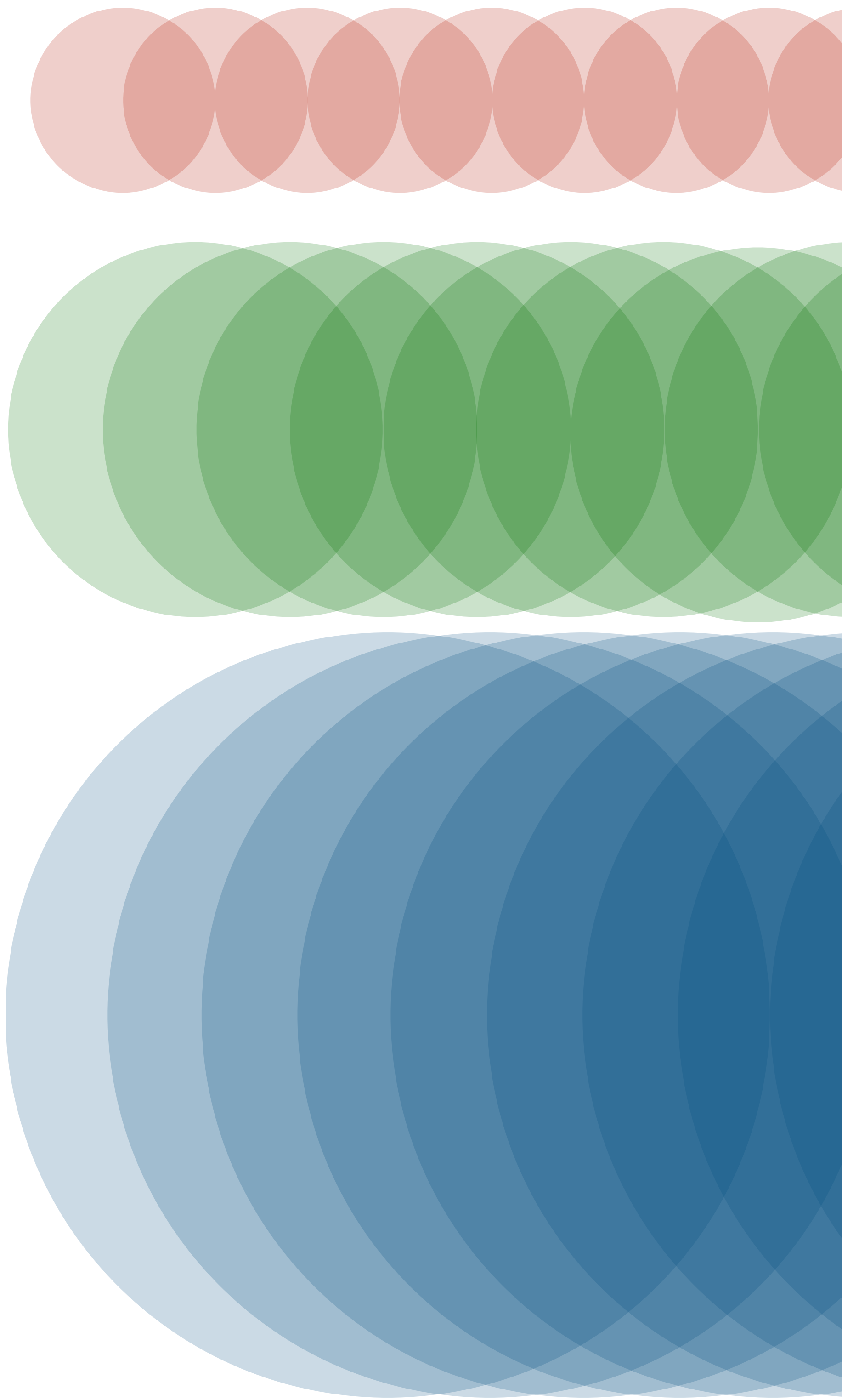
Confinement and Scalable Circuits

(2023-)

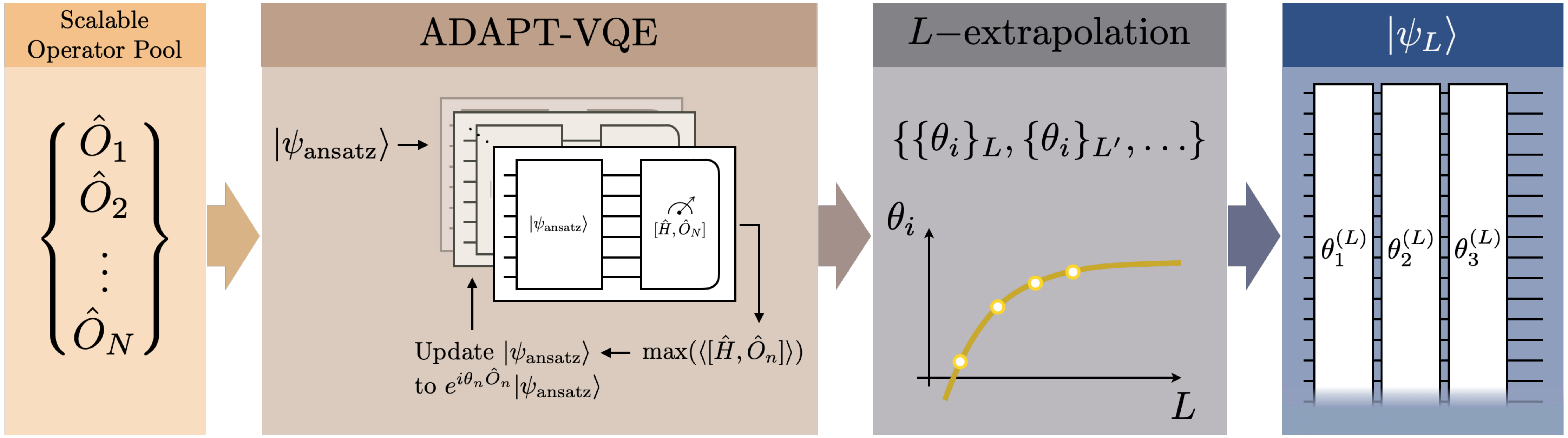
Roland Farrell, Marc Illa,
Anthony Ciavarella and MJS

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

Local | Nearest Neighbor | Non-local



Symmetries and Confinement | **Classical** Extrapolations



Classical Optimization | **Quantum** Implementation

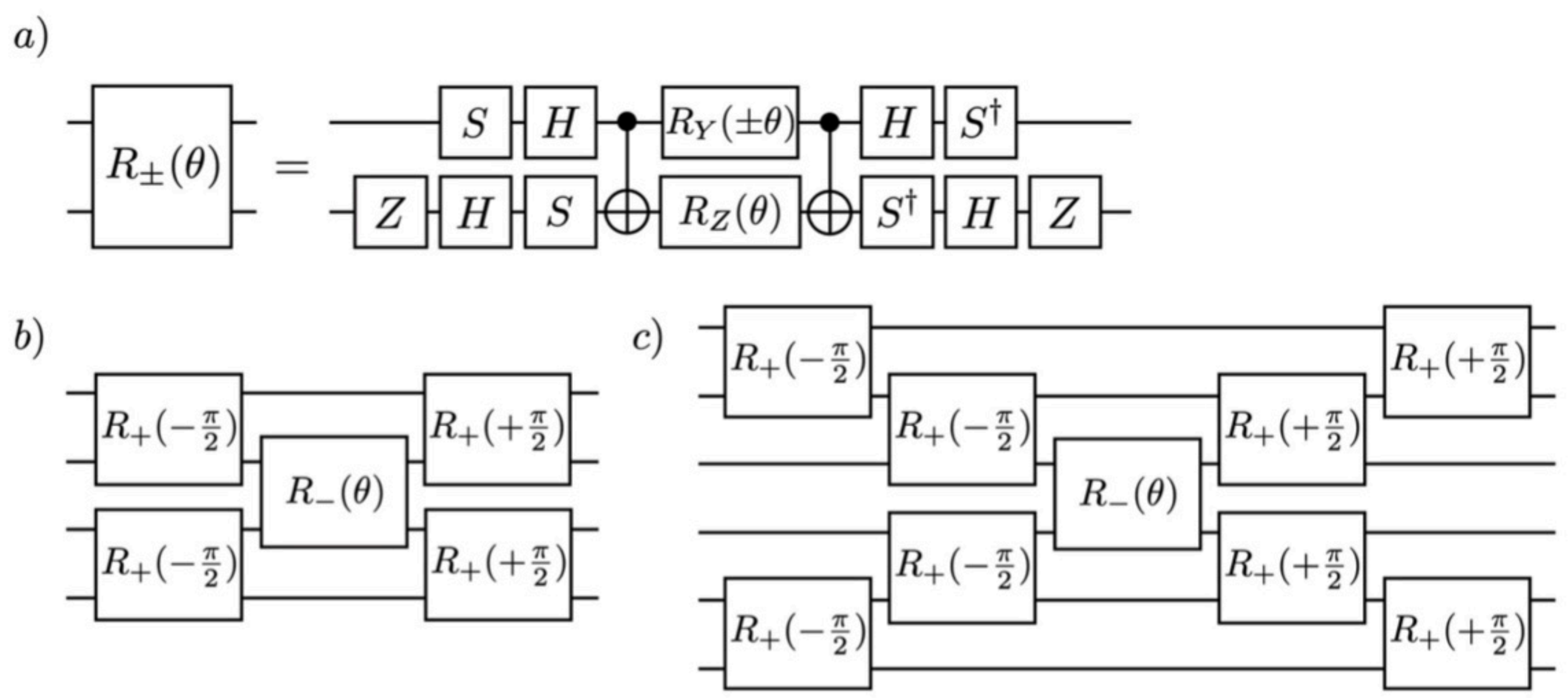
Scalable Circuits for Preparing Ground States on Digital Quantum Computers: The Schwinger Model Vacuum on 100 Qubits
Roland C. Farrell, Marc Illa, Anthony N. Ciavarella, and Martin J. Savage
PRX Quantum **5**, 020315 – Published 18 April 2024

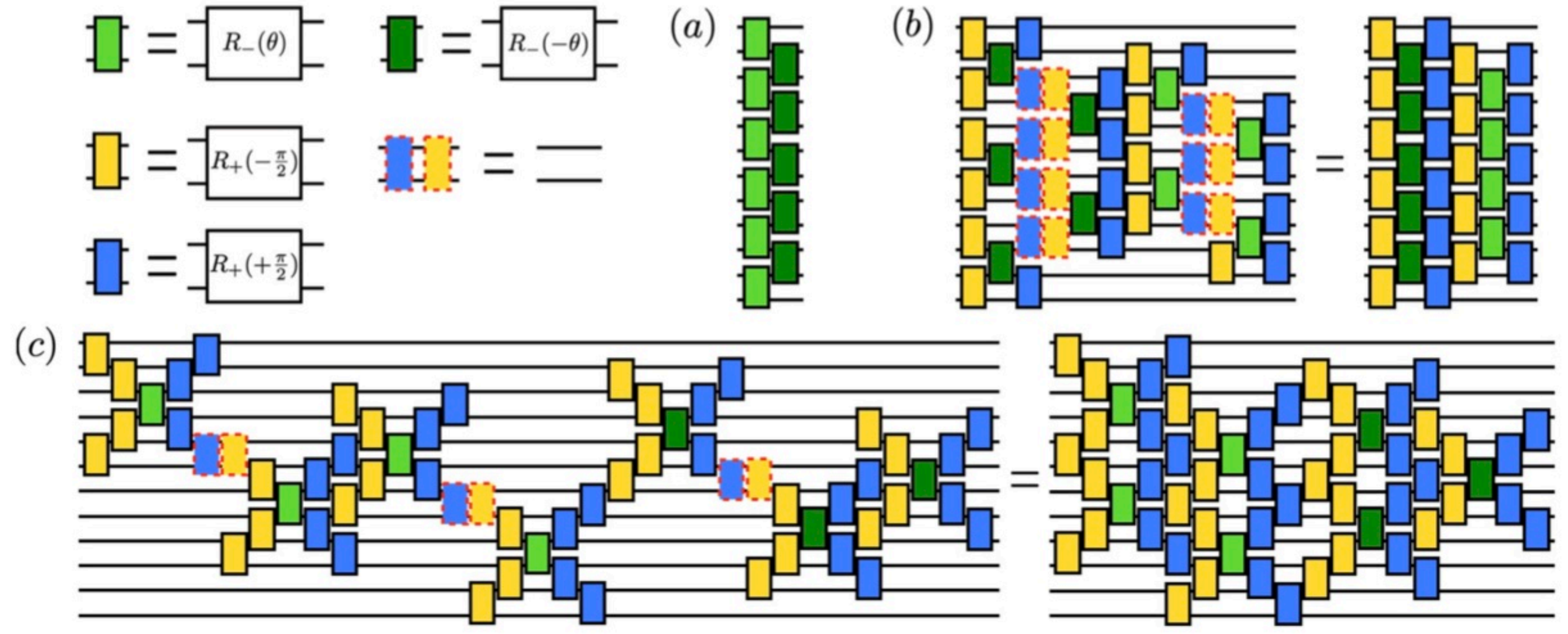
Quantum simulations of hadron dynamics in the Schwinger model using 112 qubits
Roland C. Farrell, Marc Illa, Anthony N. Ciavarella, and Martin J. Savage
Phys. Rev. D **109**, 114510 – Published 10 June 2024

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

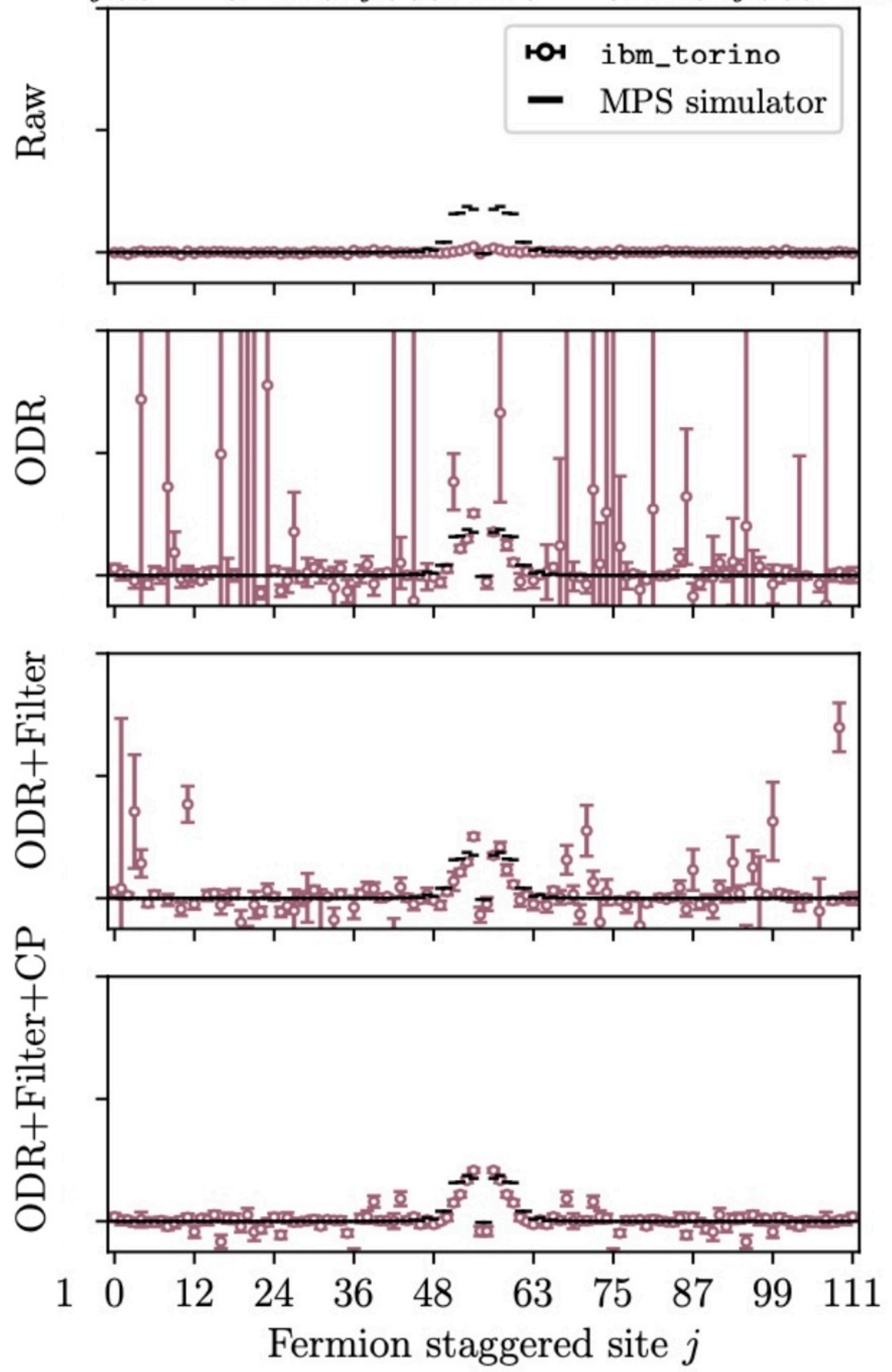
Production using IBM's QPU Torino

(The largest quantum simulation that had been performed)





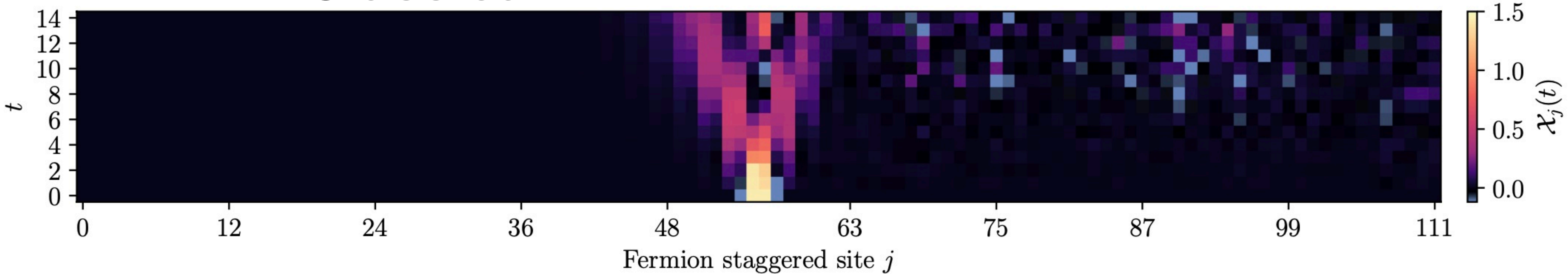
$\mathcal{X}_j(t) = \langle\psi_{\rm WP}|\hat{\chi}_j(t)|\psi_{\rm WP}\rangle - \langle\psi_{\rm vac}|\hat{\chi}_j(t)|\psi_{\rm vac}\rangle$



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

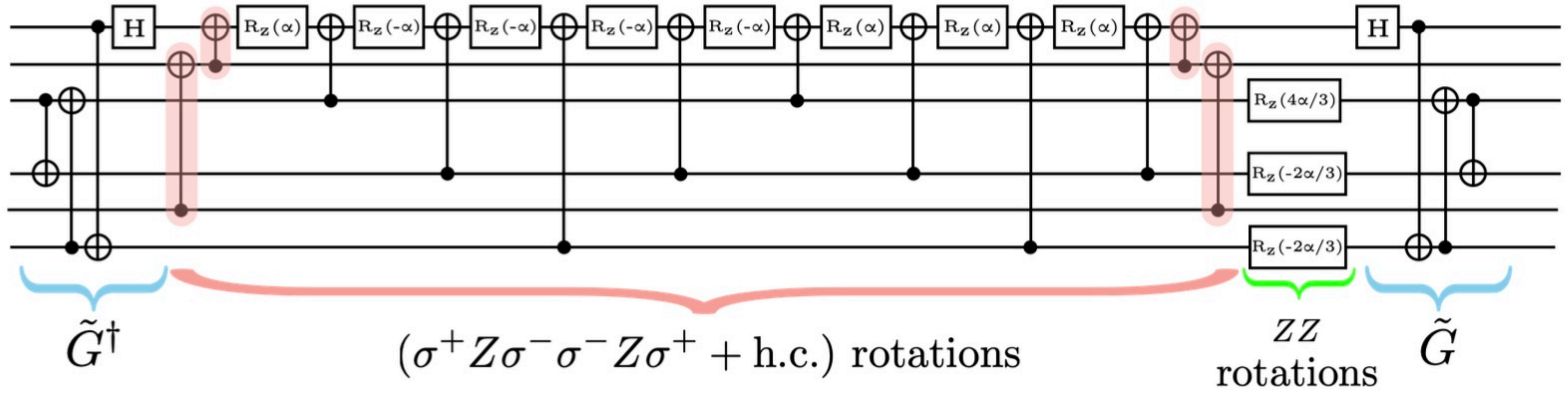
Sarmed A Rahman, Randy Lewis, Emanuele Mendicelli, and Sarah Powell
Department of Physics and Astronomy, York University, Toronto, Ontario, Canada, M3J 1P3

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

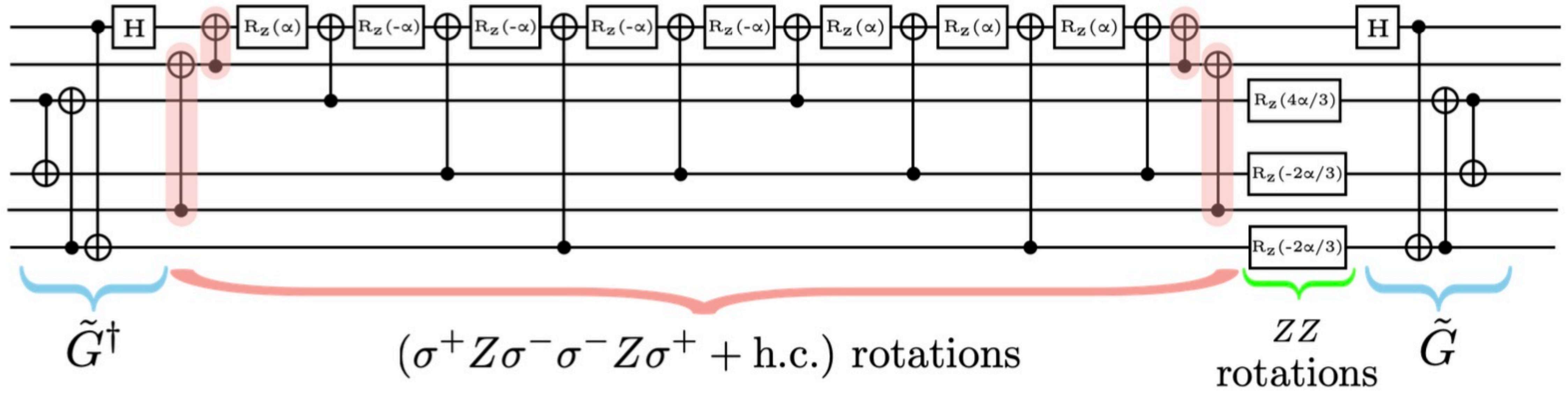
The device is approaching a classical, depolarized set of qubits as time goes by.

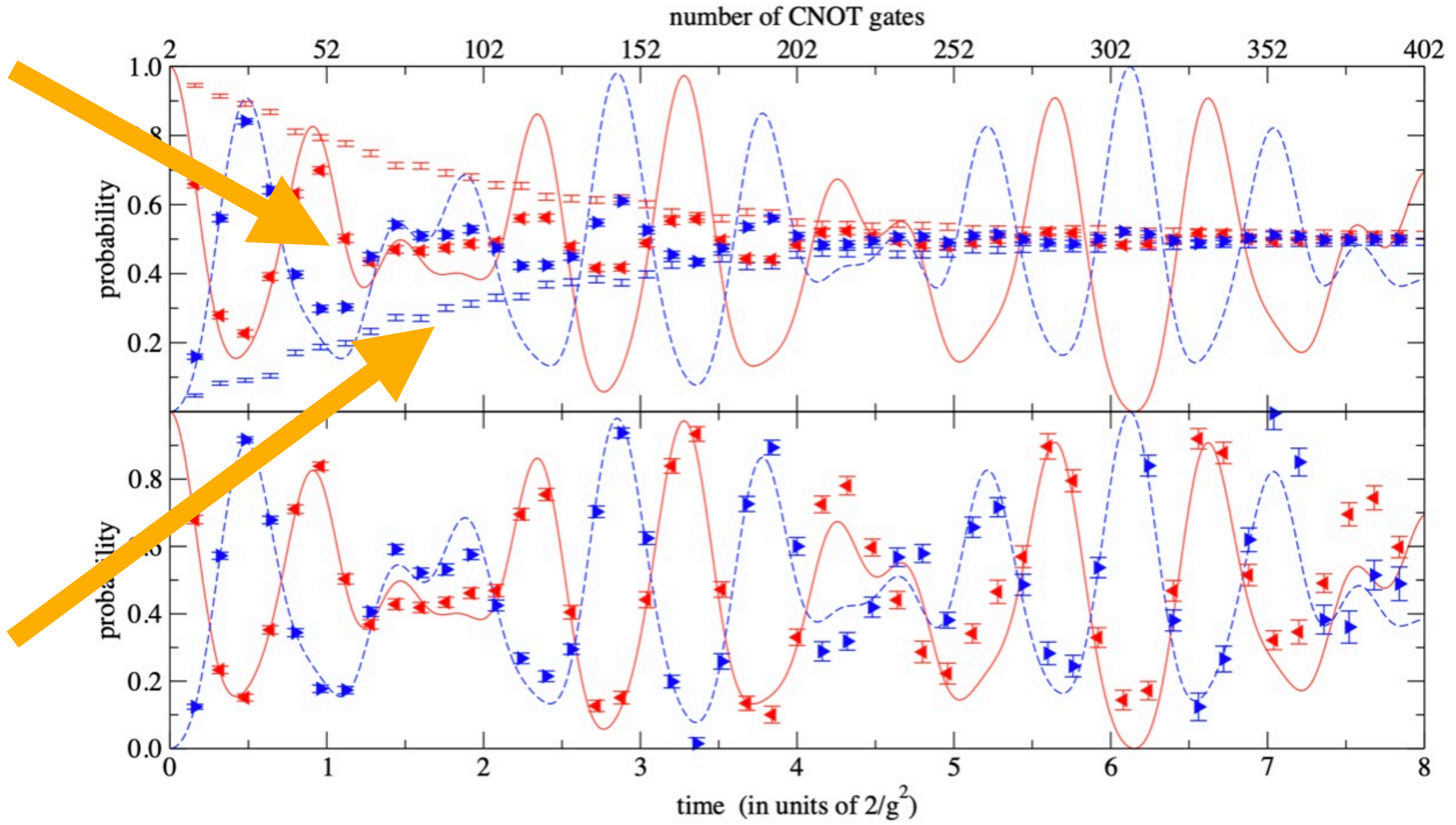
Mitigation methods are essential and effective

"Physics circuit"



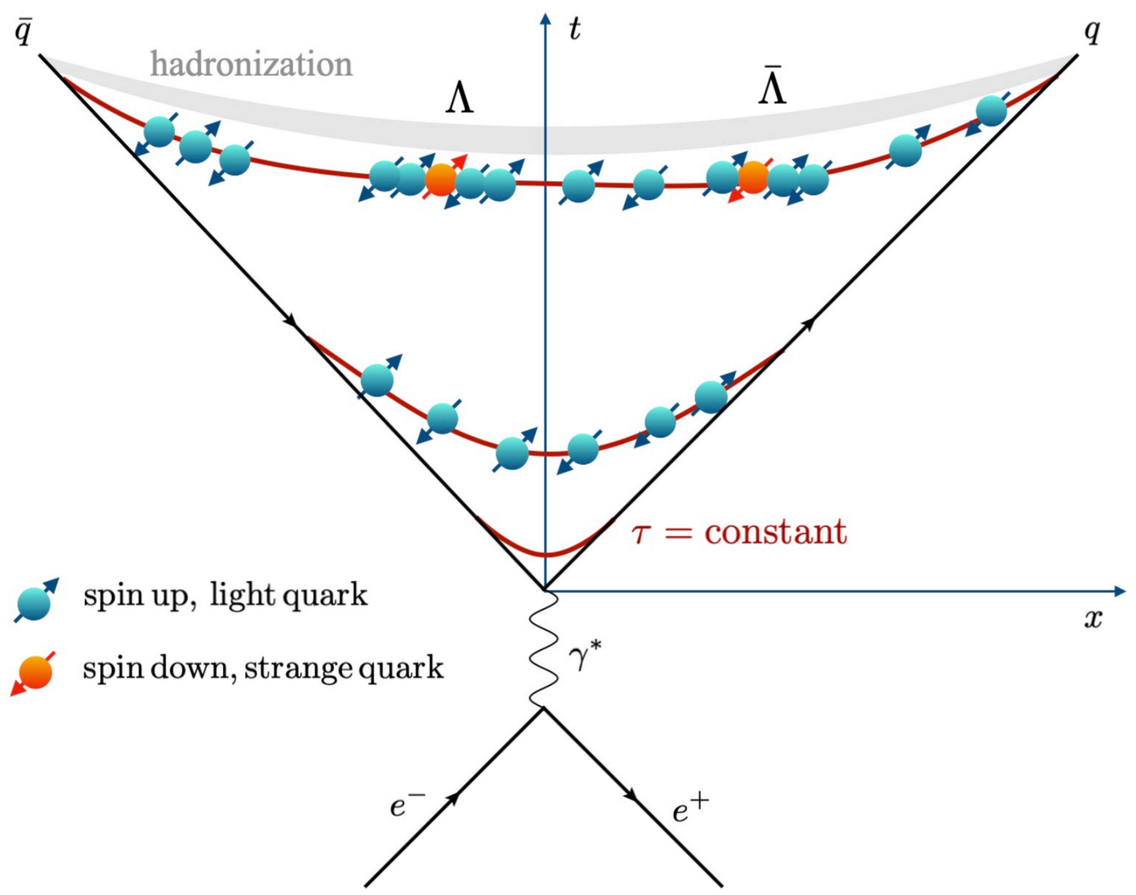
"Mitigation circuit" - all angles set to zero (e.g.)



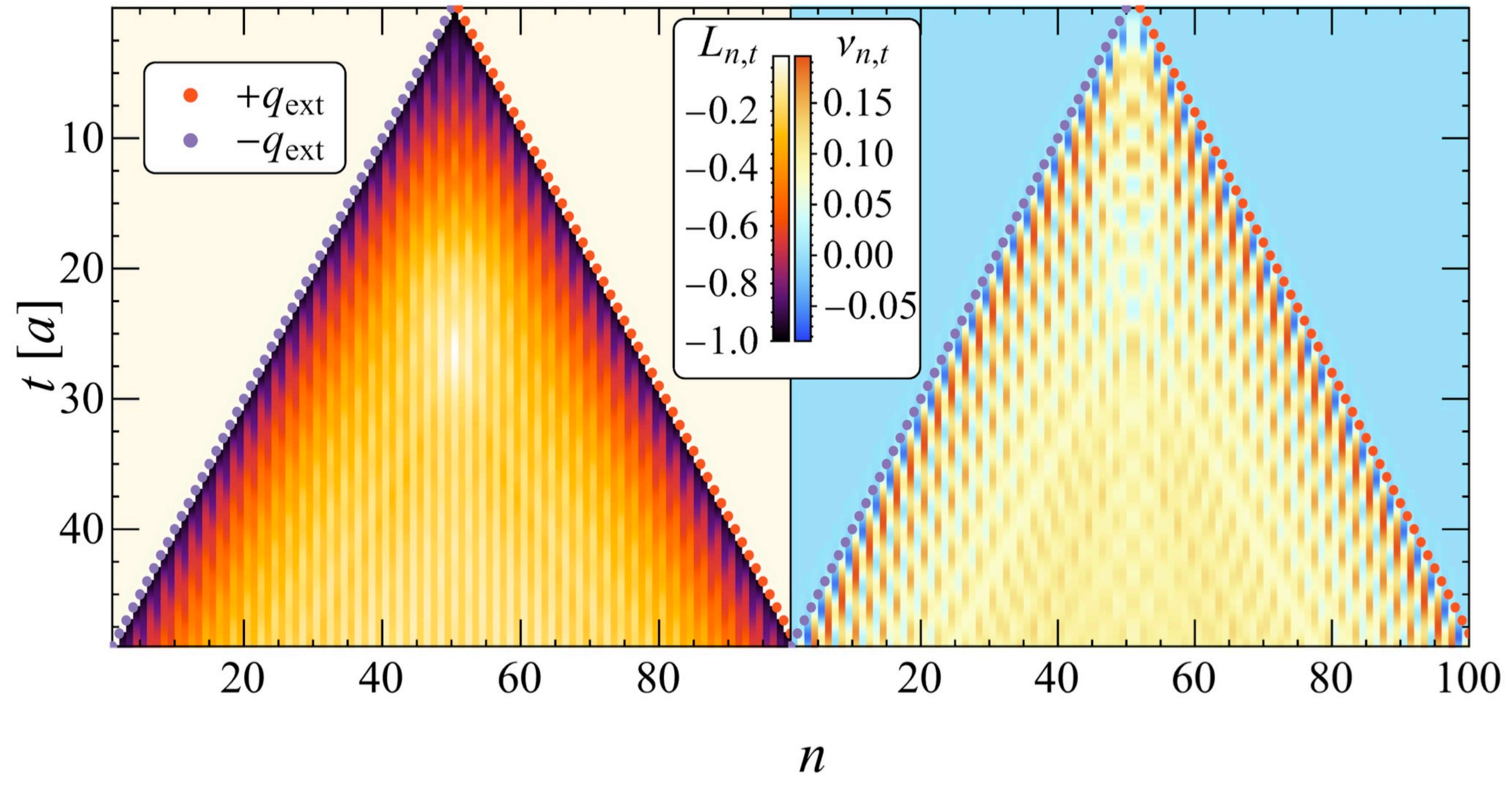


Hadronization and Fragmentation

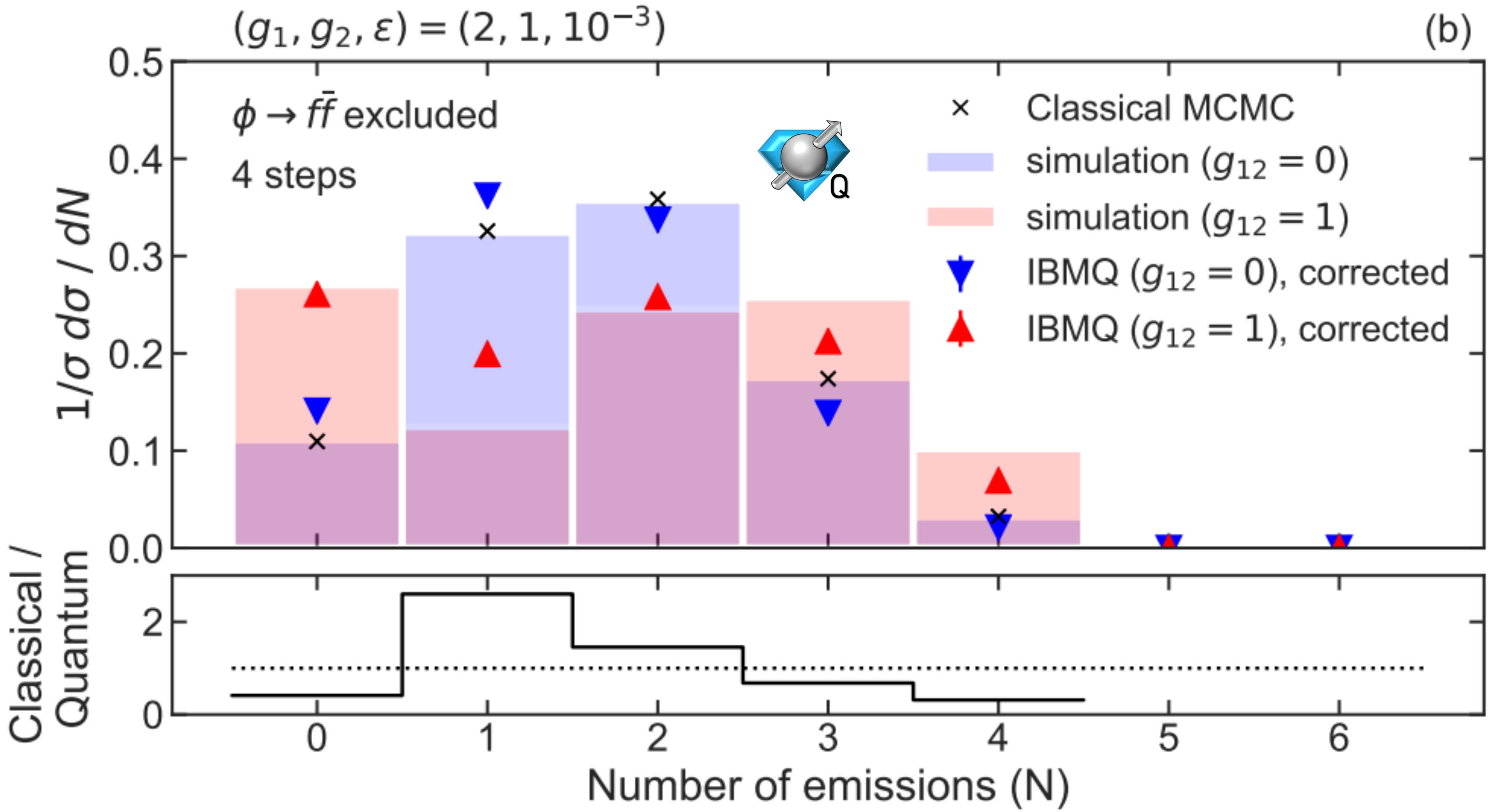
Baryon Entanglement, Barata *et al*, Gong *et al*



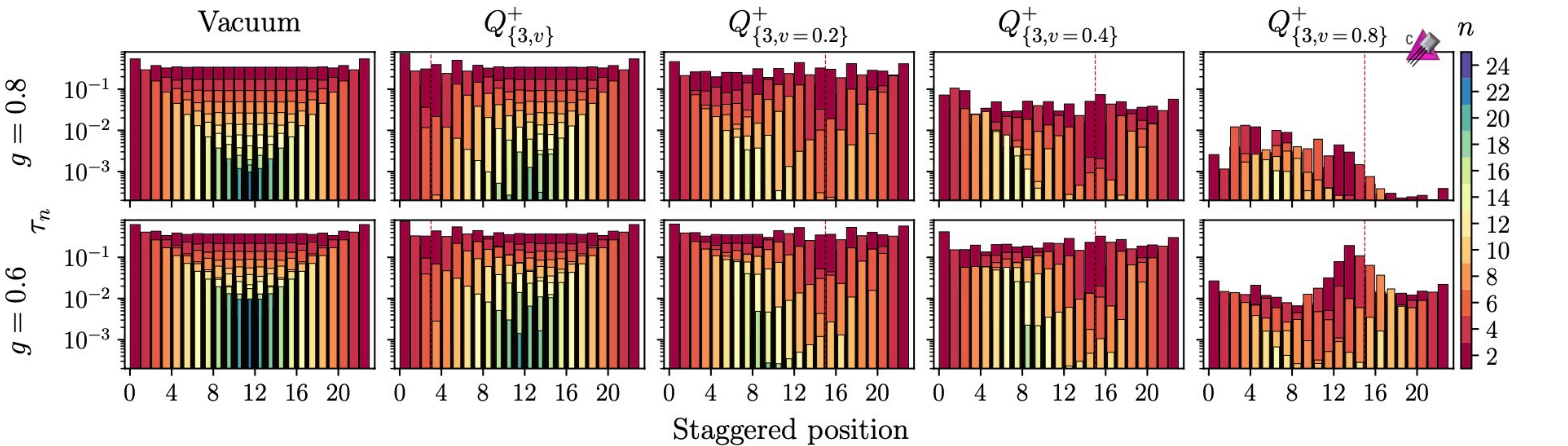
Hadronization, Florio *et al*



Fragmentation, Bauer *et al*

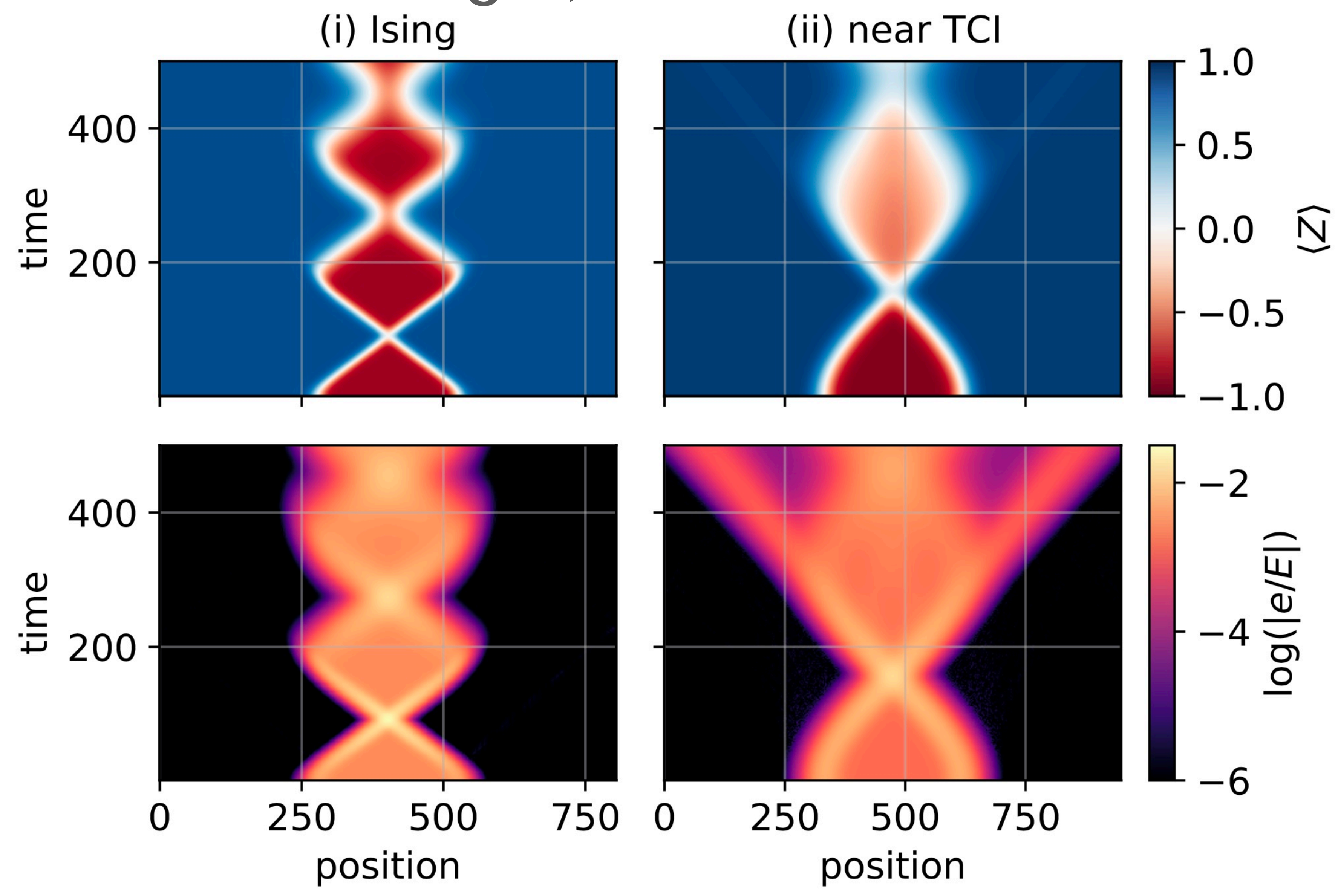


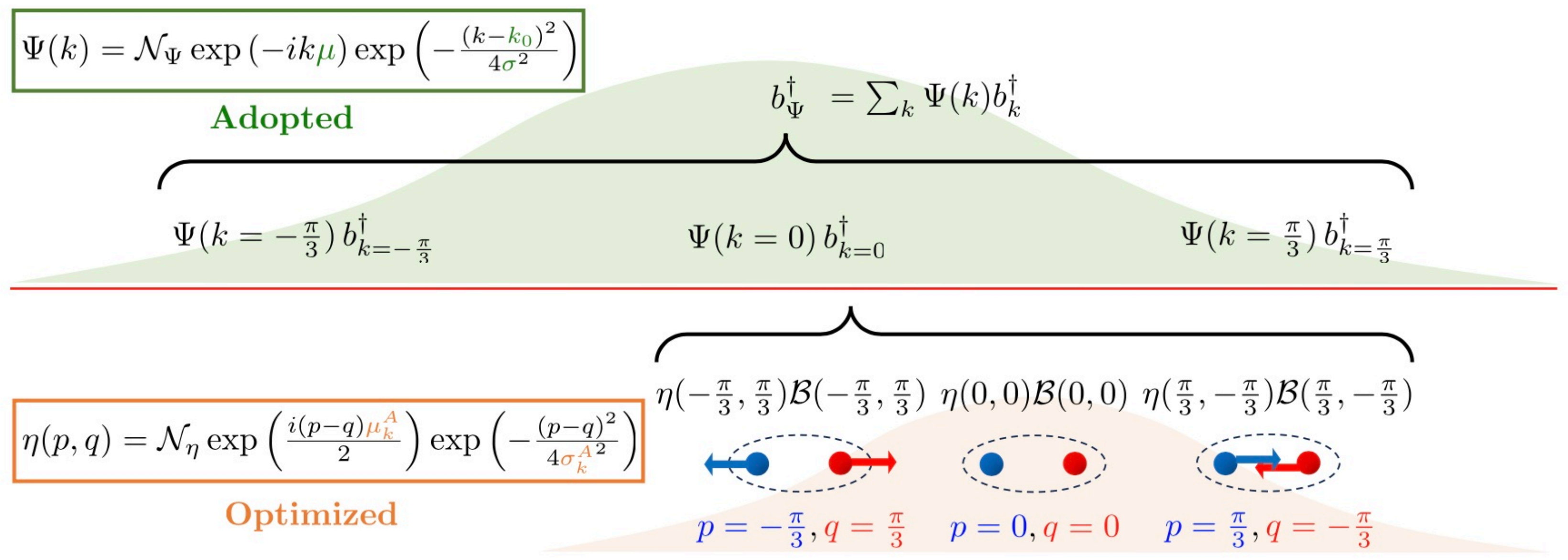
Energy Loss and Multi-partite Entanglement, Farrell *et al*



1+1D Preparing for the Future

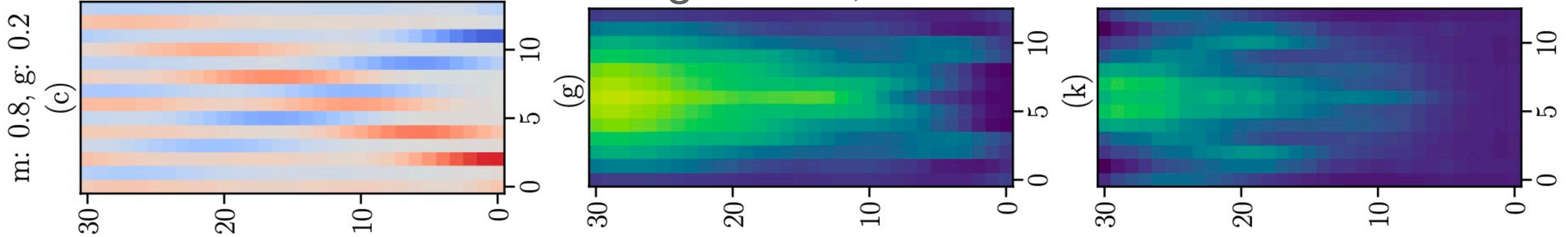
Ising+ , Milsted et al

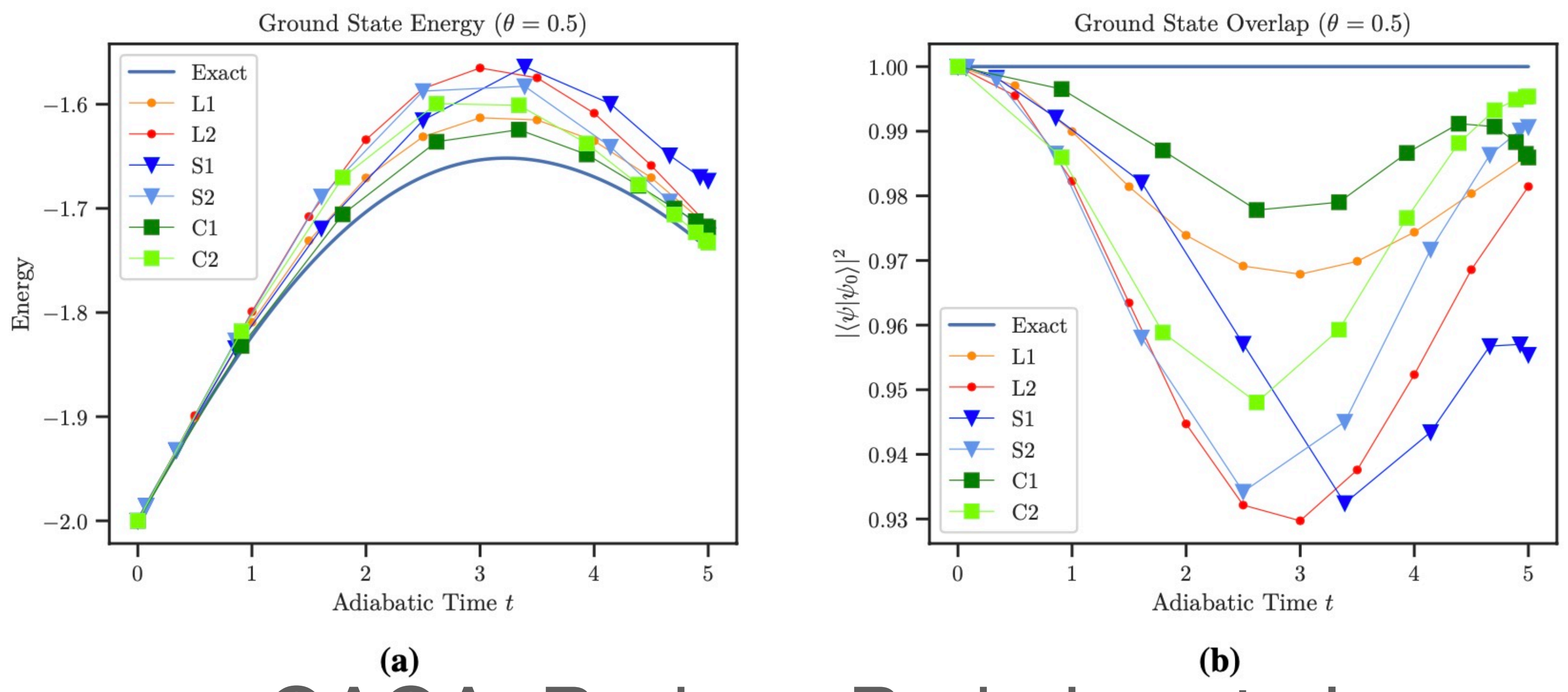




Wavepackets , Davoudi et al

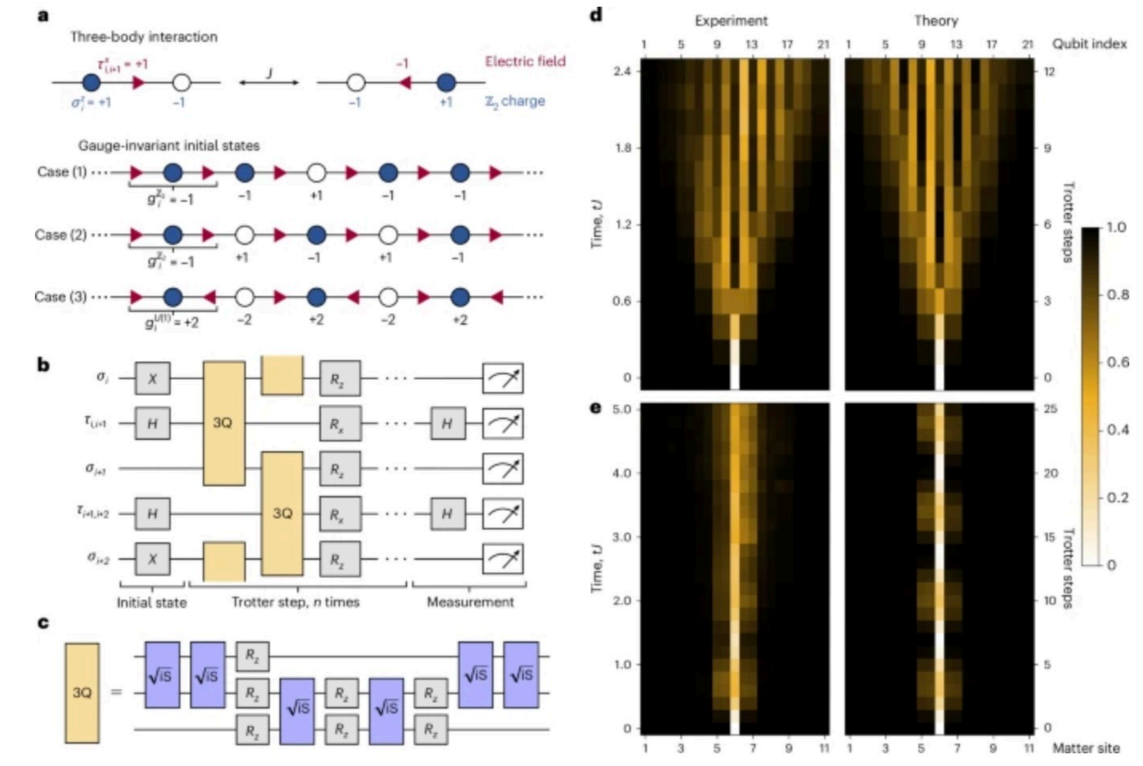
Thirring model , Chai et al



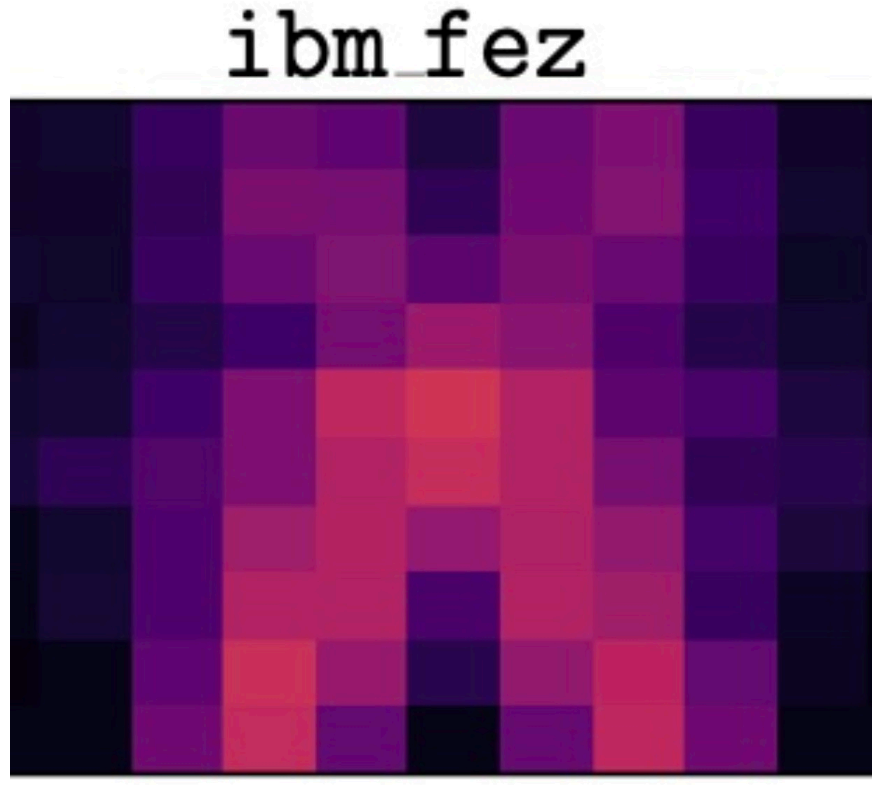


QAOA, Rodeo , Pederiva et al

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



Confinement in Z2, Mildenberger et al



Scalar FT, Zemlevskiy

Error Correction in Gauge Theories

Abelian Z_n models

Quantum error correction with gauge symmetries

Abhishek Rajput, Alessandro Roggero & Nathan Wiebe

npj Quantum Information **9**, Article number: 41 (2023) | Cite this article

Fault-tolerant simulation of Lattice Gauge Theories with gauge covariant codes

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Dipartimento di Fisica, University of Trento, via Sommarive 14, I–38123, Povo, Trento, Italy and INFN-TIFPA Trento Institute of Fundamental Physics and Applications, Trento, Italy

Nathan Wiebe‡
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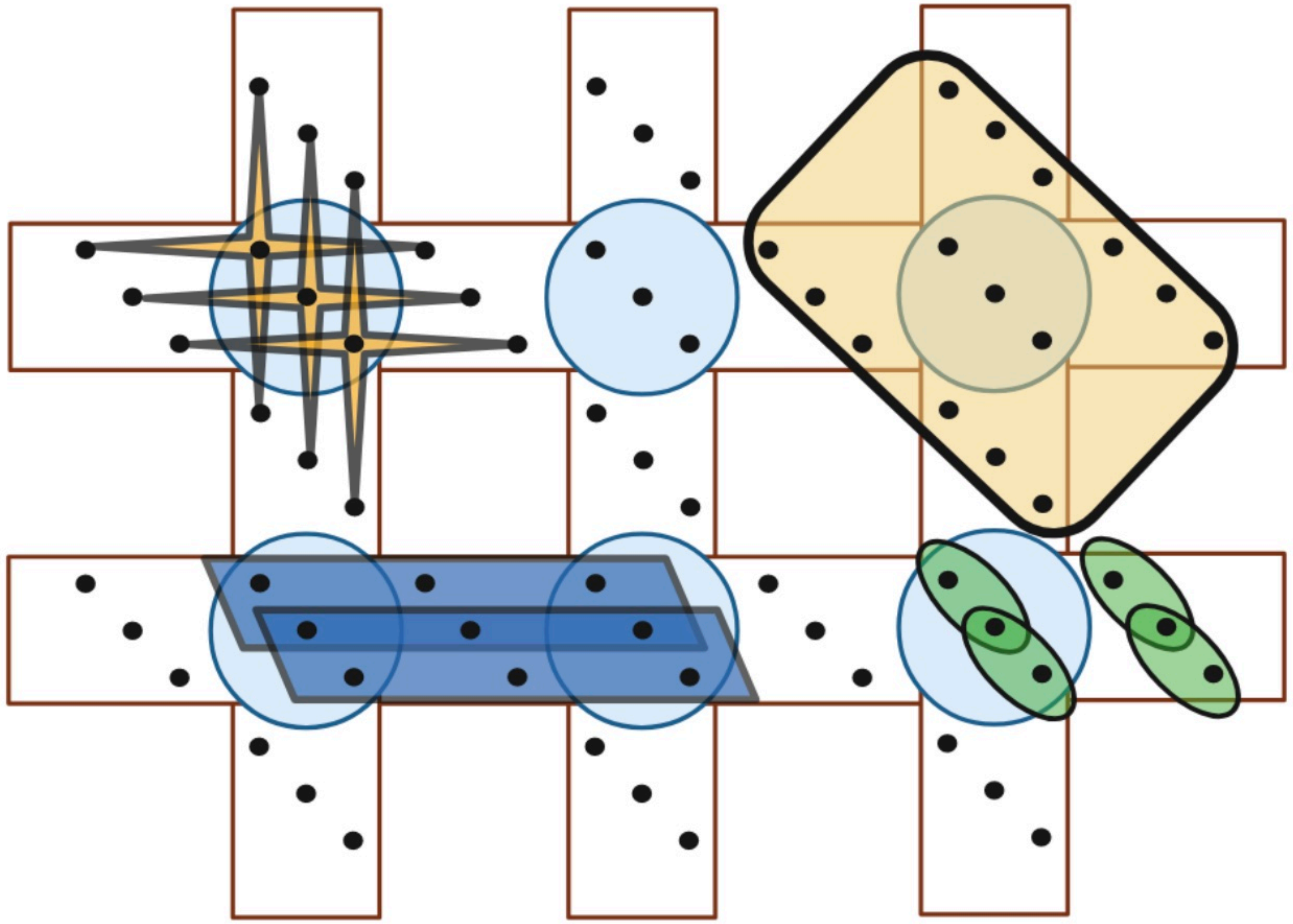
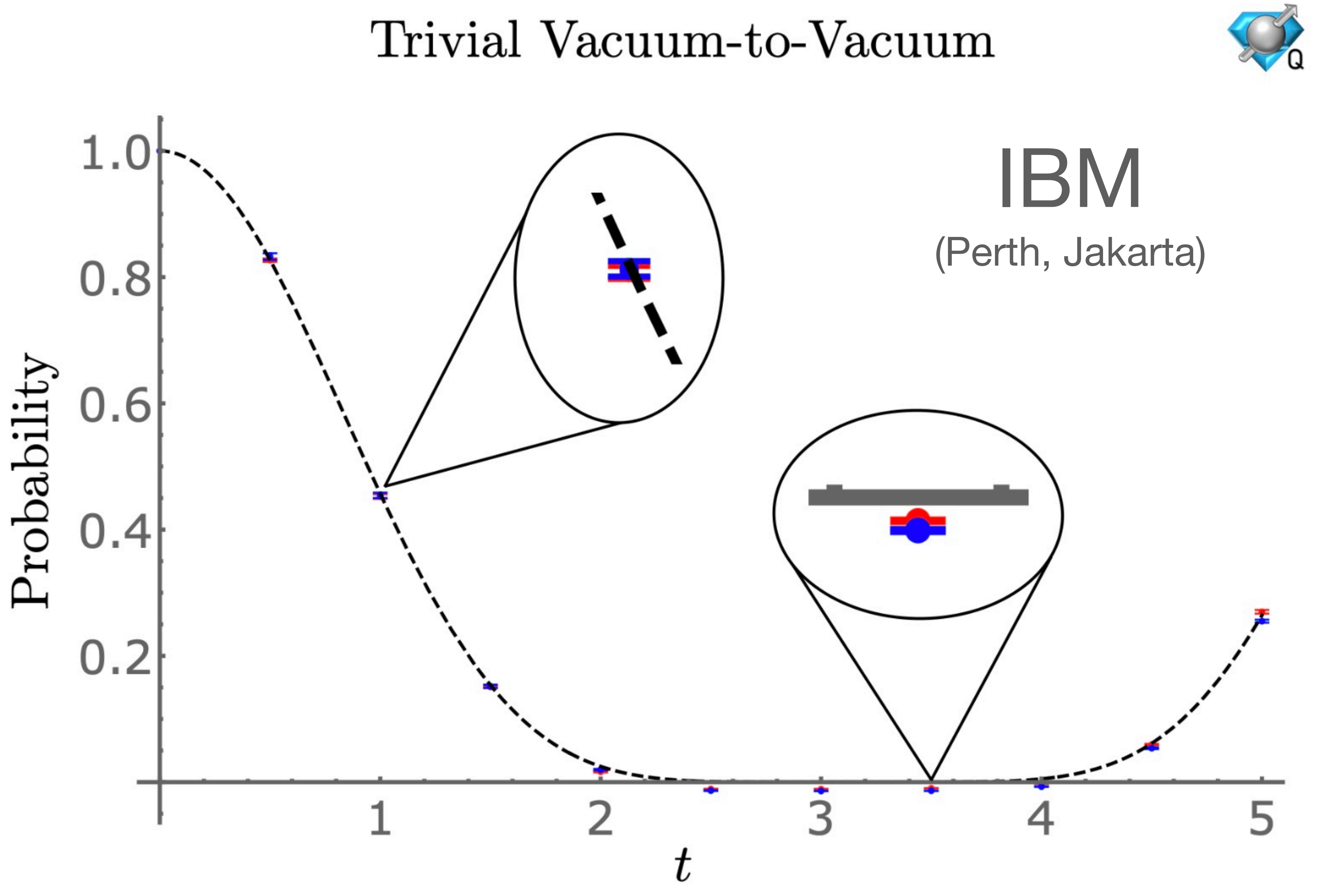
Pacific Northwest National Laboratory, Richland, WA 99354, USA and
Department of Physics, University of Washington, Seattle, WA 98195, USA
(Dated: October 7, 2024)



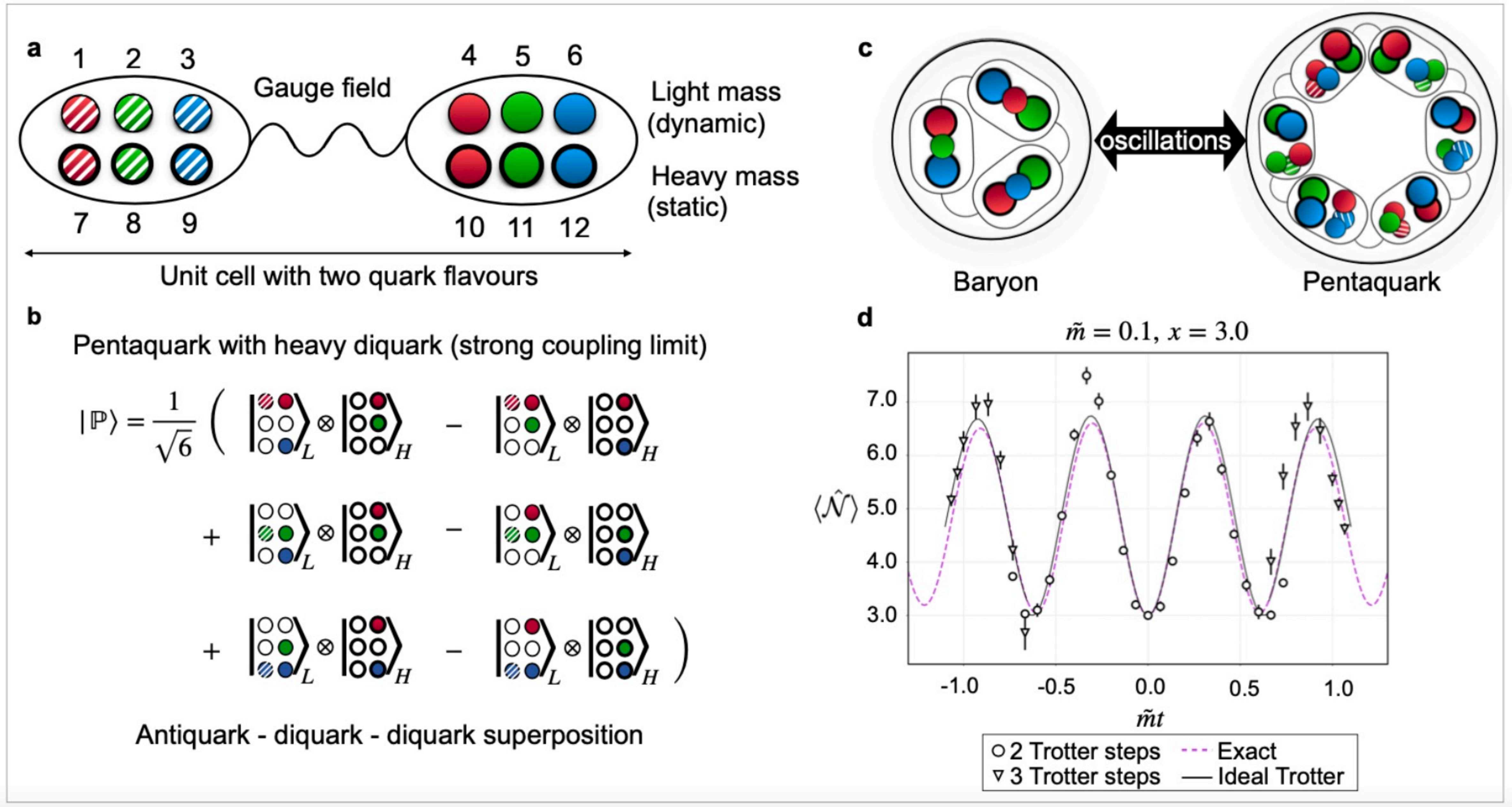
Gauss's law → Stabilizers

1+1D Quantum Chromodynamics



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



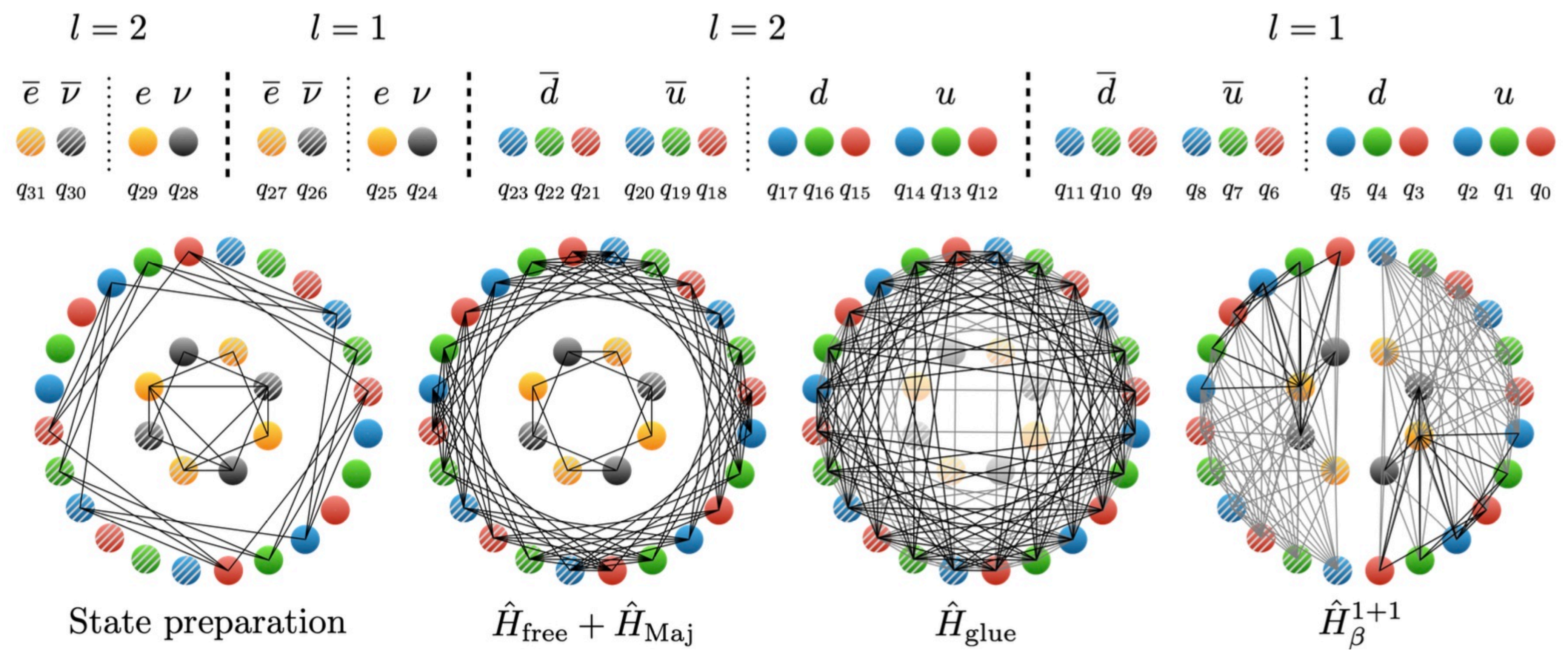
Simulating one-dimensional quantum chromodynamics on a quantum computer: Real-time evolutions of tetra- and pentaquarks

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]

SU(3) and higher is quite different from U(1) and SU(2)

Pathfinding Quantum Simulations of Neutrinoless Double-β Decay

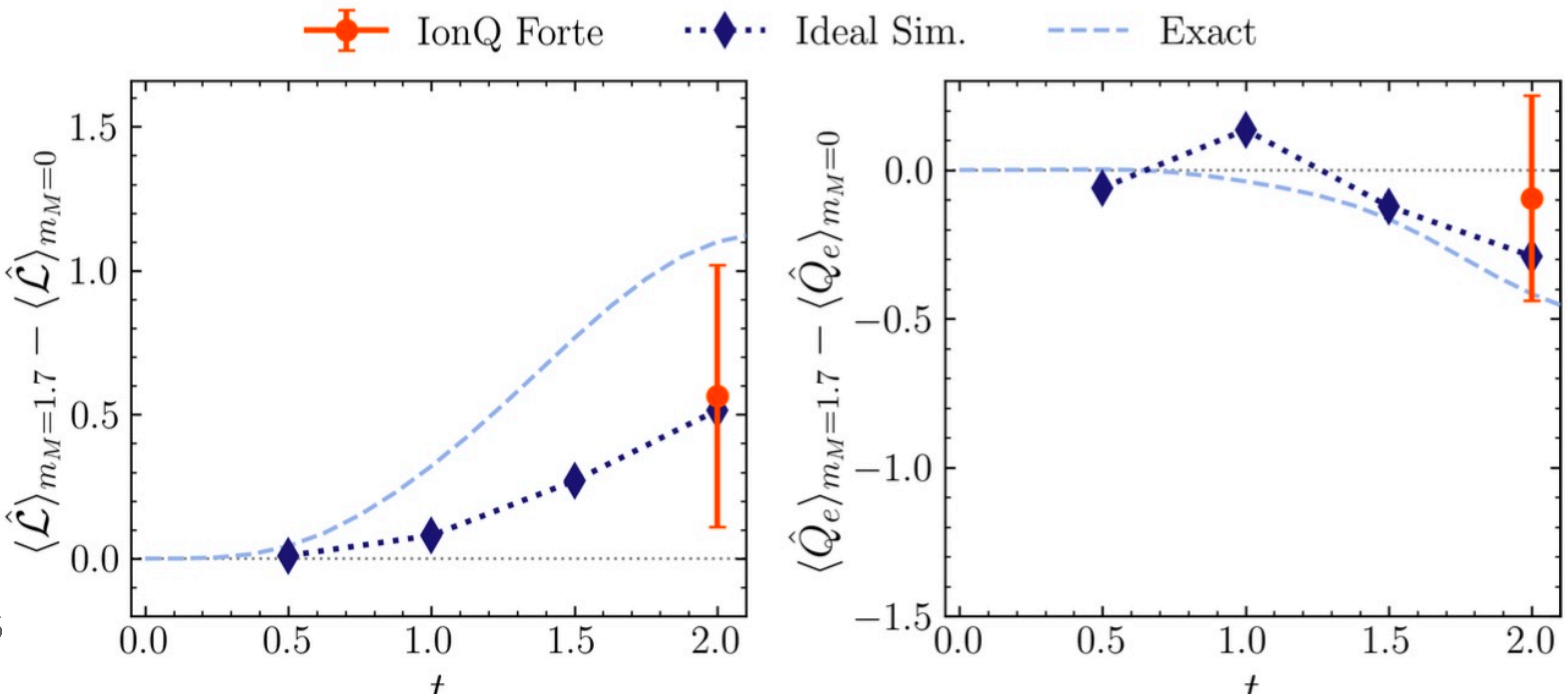
Ivan A. Chernyshev,[1] Roland C. Farrell,[2] Marc Illa,[3] Martin J. Savage,[3,*] Andrii Maksymov,[4] Felix Tripier,[4] Miguel Angel Lopez-Ruiz,[4] Andrew Arrasmith,[4] Yvette de Sereville,[4] Aharon Brodutch,[4] Claudio Girotto,[4] Ananth Kaushik,[4] and Martin Roetteler[4,†]



$$\hat{H}_{\beta}^{1+1} = \frac{G}{\sqrt{2}} \sum_{\text{spatial sites}} \left(\overline{\psi}_u \gamma^\mu \psi_d \, \overline{\psi}_e \gamma_\mu \mathcal{C} \psi_\nu + \text{h.c.}\right)$$

$$\approx \frac{G}{\sqrt{2}} \sum_{n \text{ even}} \left(\phi_n^{(u)\dagger} \phi_n^{(d)} \phi_n^{(e)\dagger} \phi_{n+1}^{(\nu)} + \text{h.c.}\right) ,$$

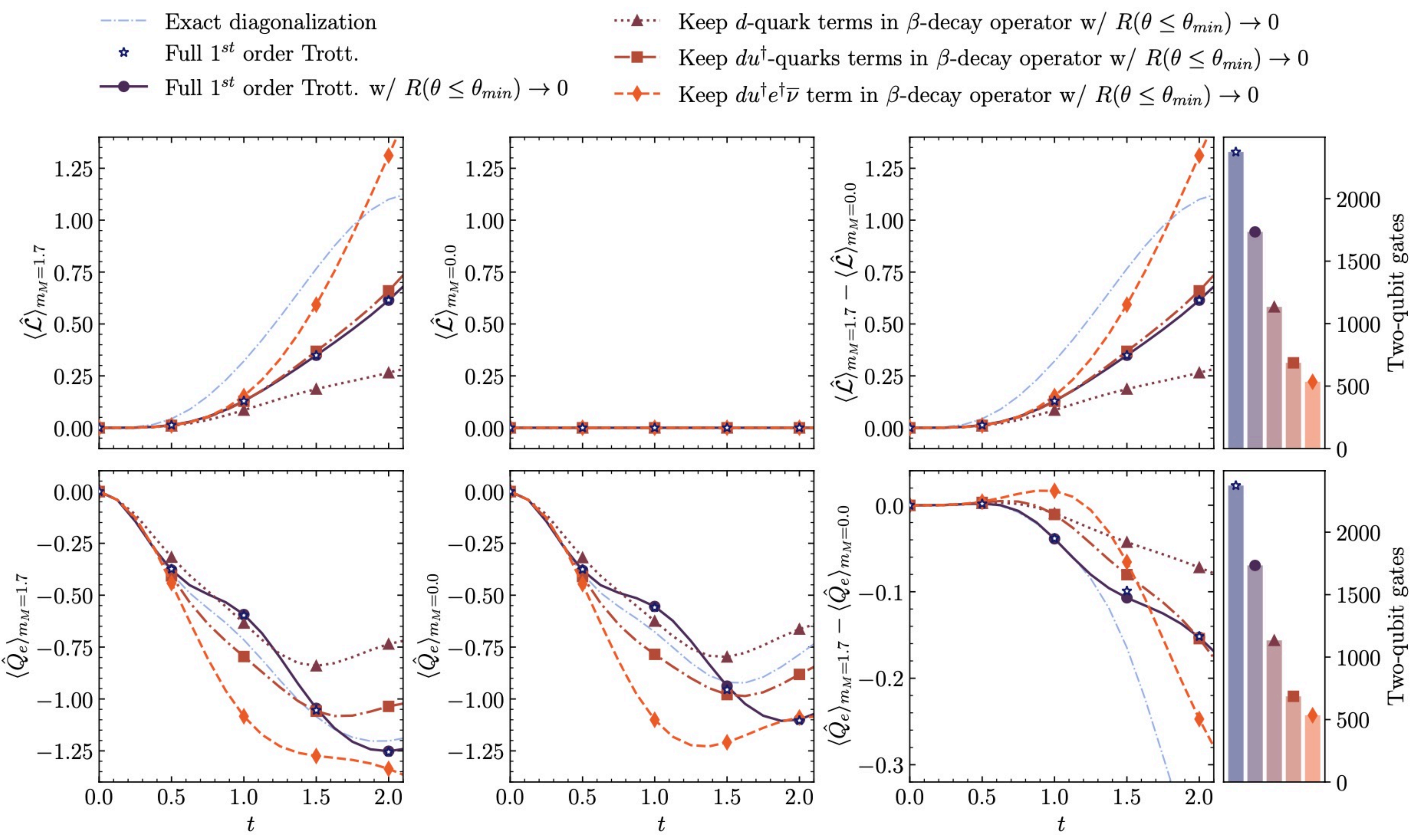
$$\hat{H}_{\text{Maj}} = \frac{1}{2} m_M \sum_{n \text{ even}} \left(\phi_n^{(\nu)} \phi_{n+1}^{(\nu)} + \text{h.c.}\right)$$

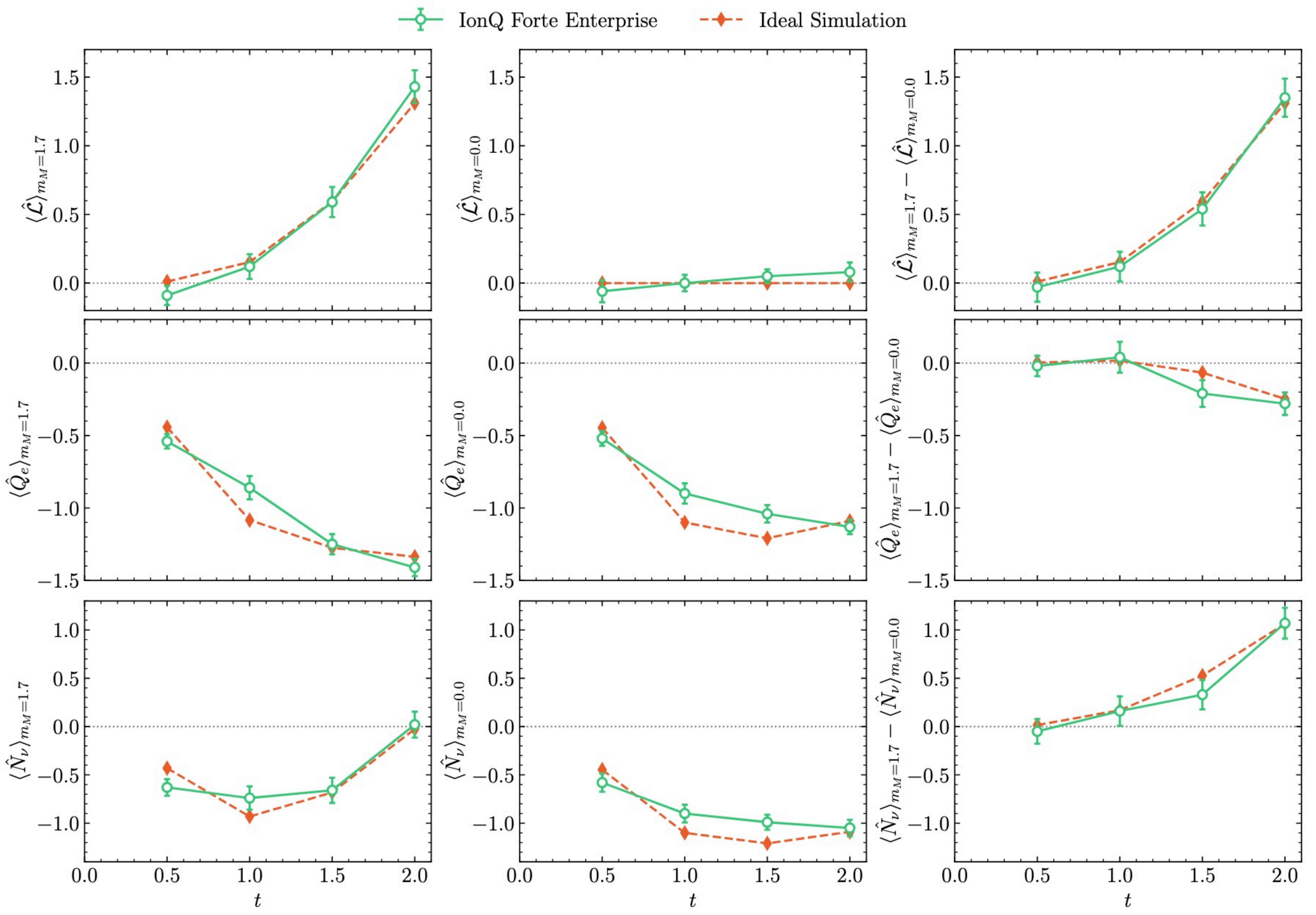


>2300 entangling gates

Pathfinding Quantum Simulations of Neutrinoless Double-β Decay

Ivan A. Chernyshev,[1] Roland C. Farrell,[2] Marc Illa,[3] Martin J. Savage,[3,*] Andrii Maksymov,[4] Felix Tripier,[4] Miguel Angel Lopez-Ruiz,[4] Andrew Arrasmith,[4] Yvette de Sereville,[4] Aharon Brodutch,[4] Claudio Girotto,[4] Ananth Kaushik,[4] and Martin Roetteler[4,†]





>450 entangling gates

Dynamical Quantum Phase Transitions

2018

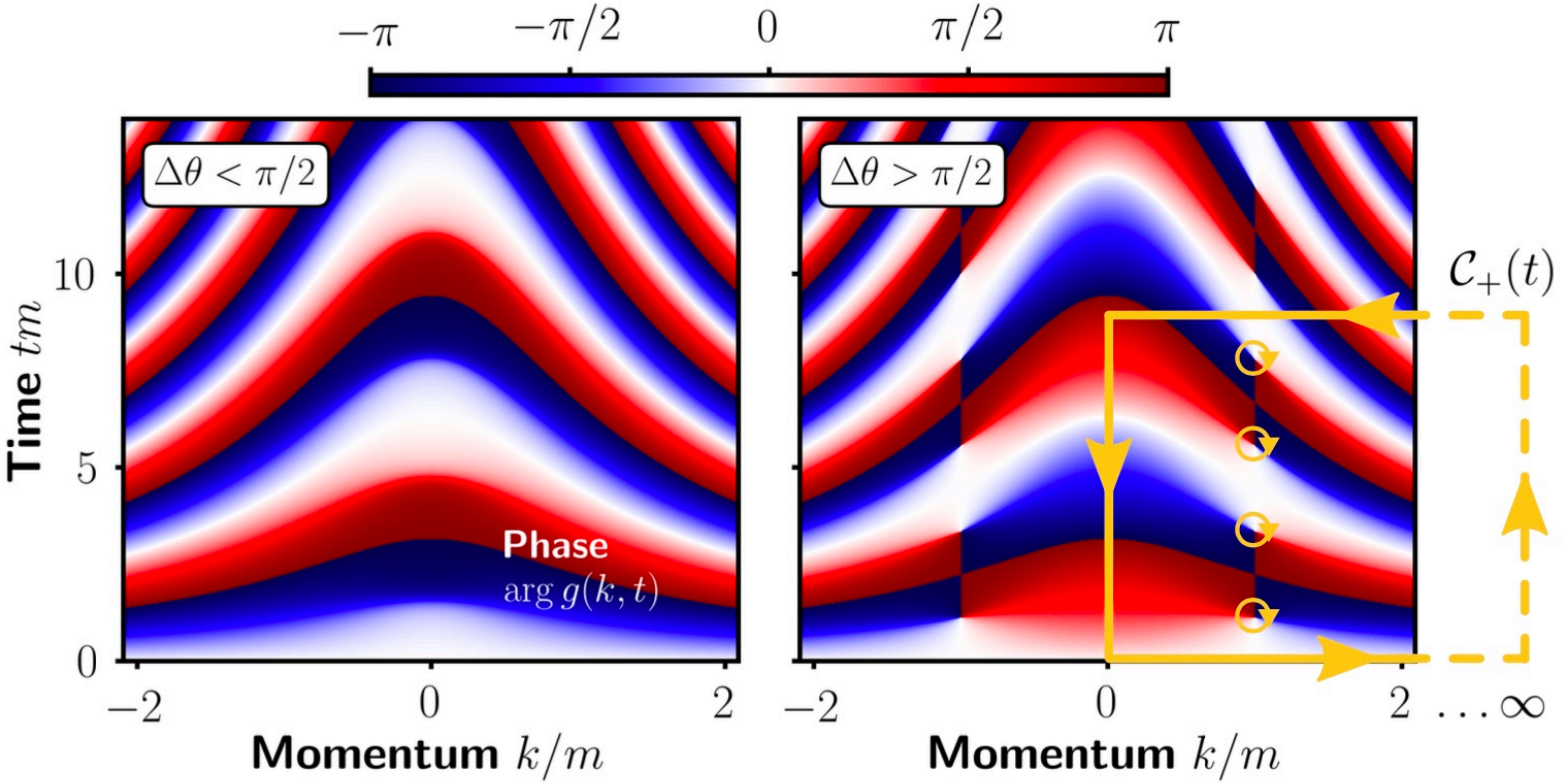
Dynamical topological transitions in the massive Schwinger model with a θ-term

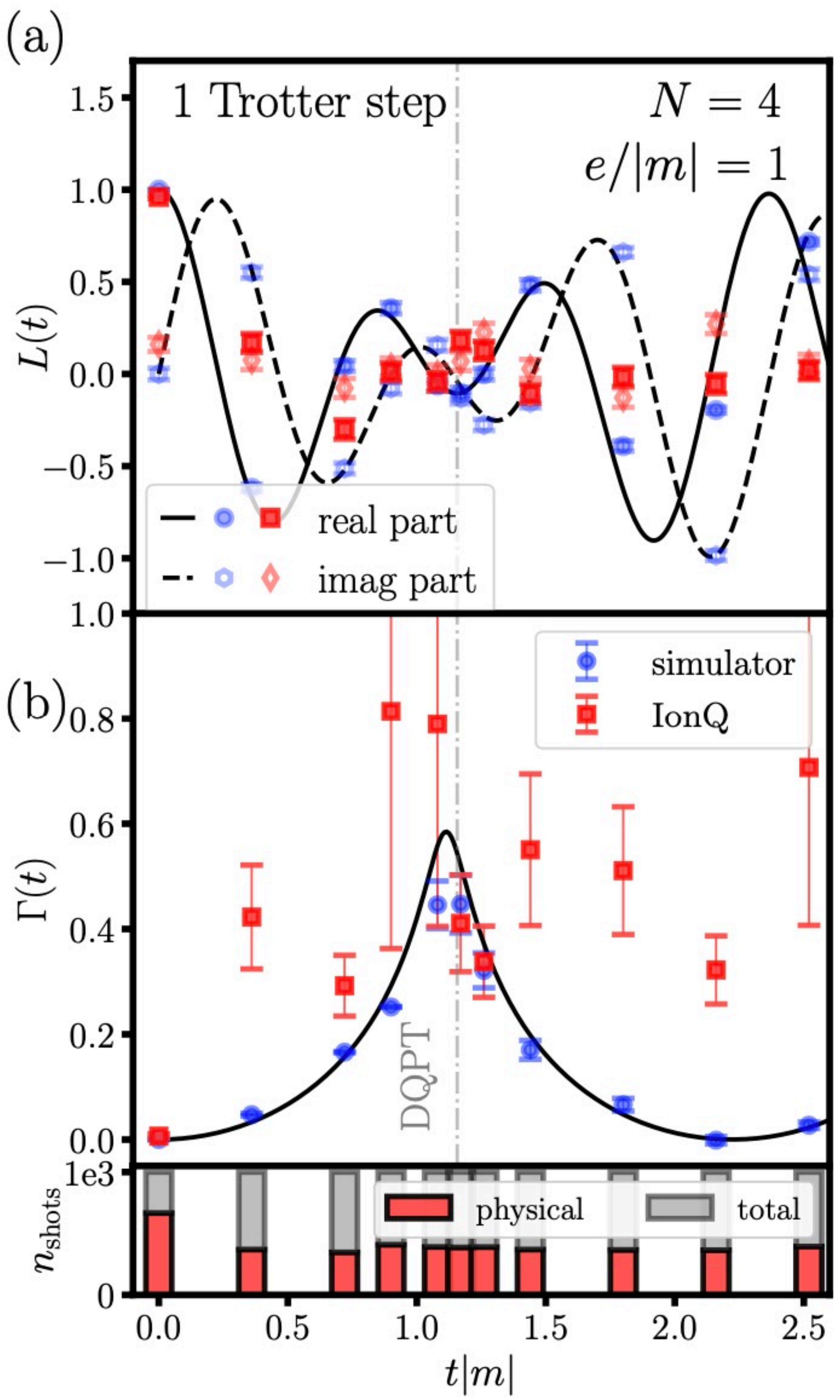
T. V. Zache,[1,*] N. Mueller,[2] J. T. Schneider,[1] F. Jendrzejewski,[3] J. Berges,[1] and P. Hauke[1,3]

2023

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

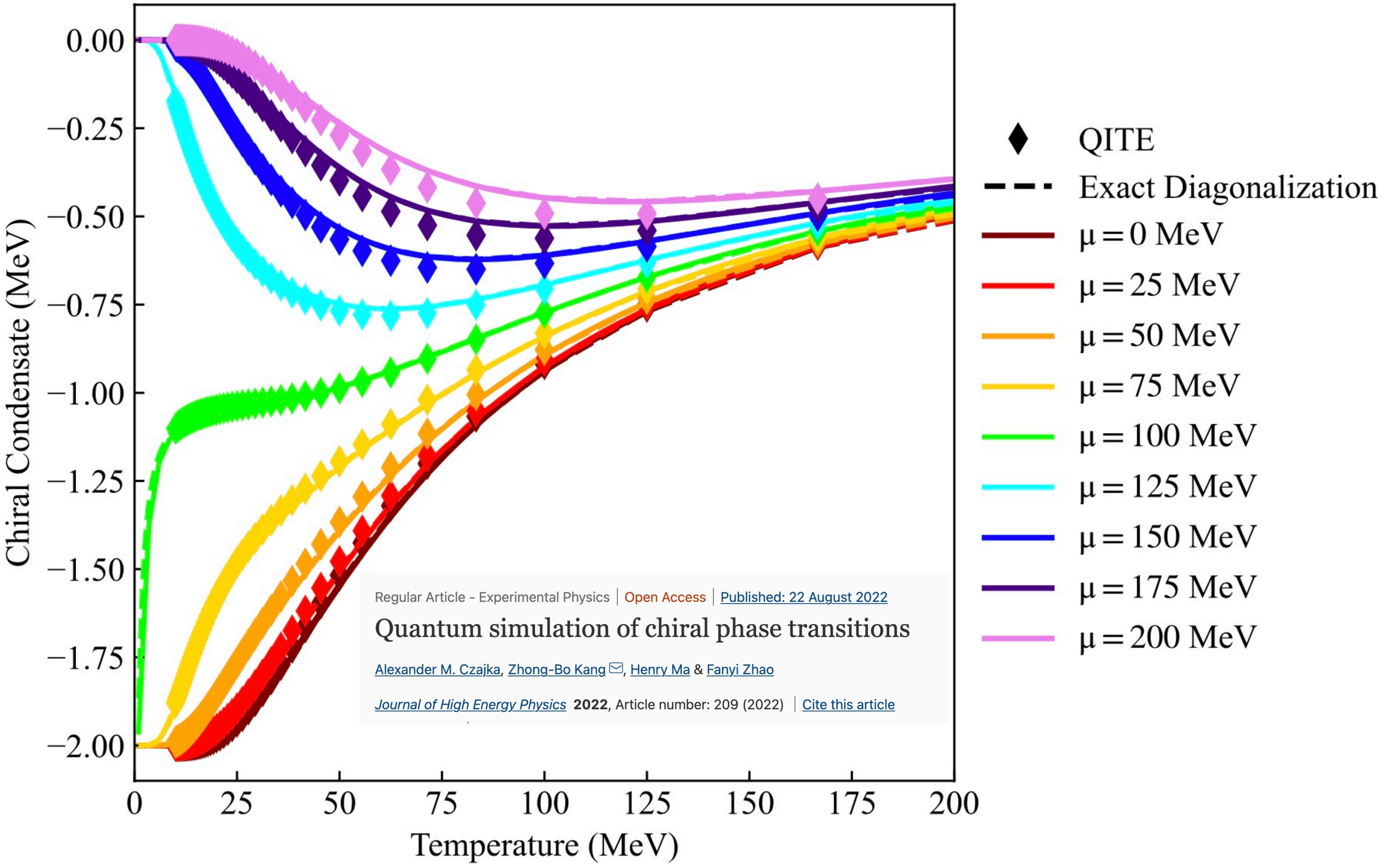
Niklas Mueller,[1,2,3,*] Joseph A. Carolan,[4] Andrew Connelly,[5]
Zohreh Davoudi,[1,6,†] Eugene F. Dumitrescu,[7,‡] and Kübra Yeter-Aydeniz[8]





Modeling the QCD Phase Diagram

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

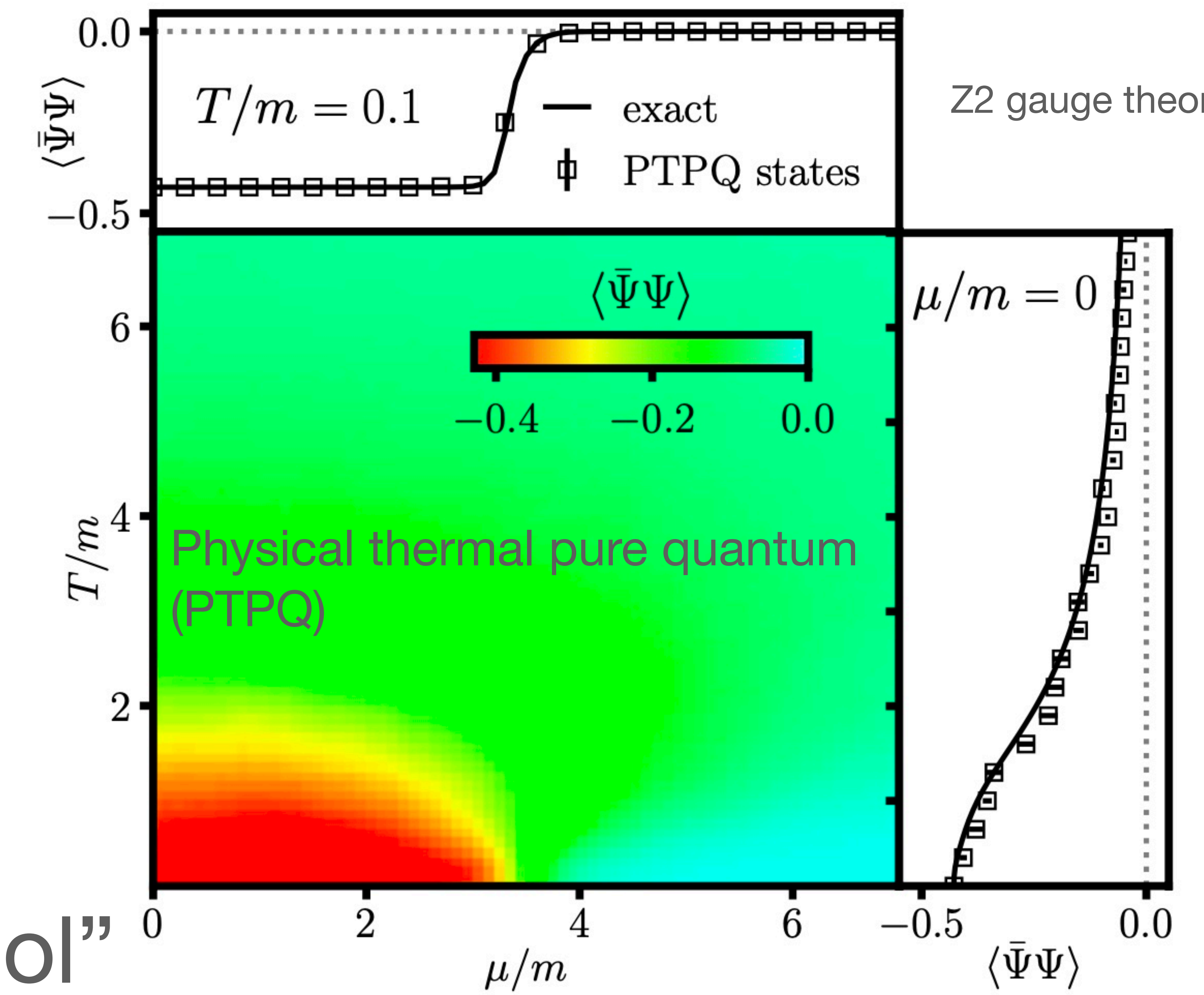


Toward Quantum Computing Phase Diagrams of Gauge Theories with Thermal Pure Quantum States

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*

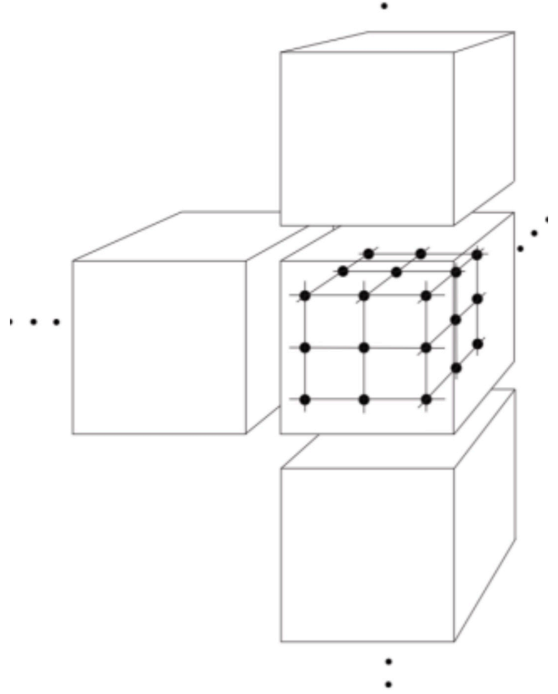
Phys. Rev. Lett. **131**, 081901 – Published 21 August 2023



Z2 gauge theory

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 ....

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

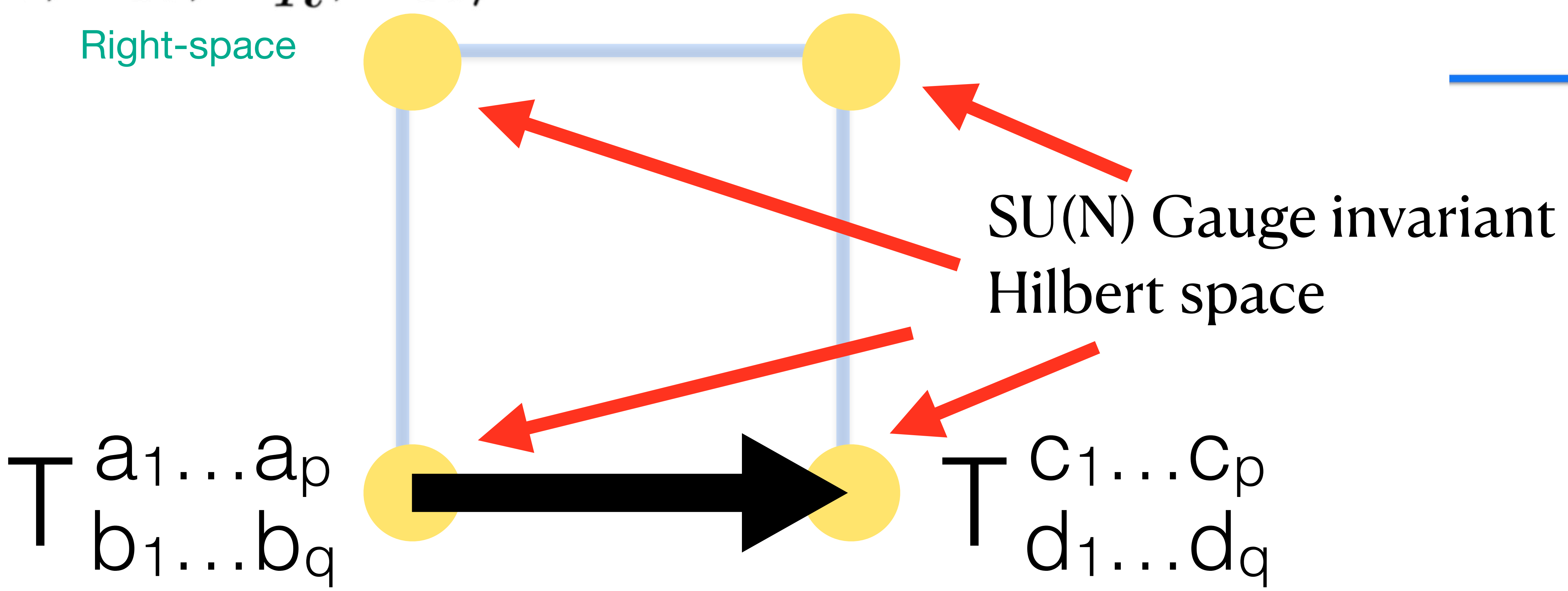
Electric Field Casimir operator

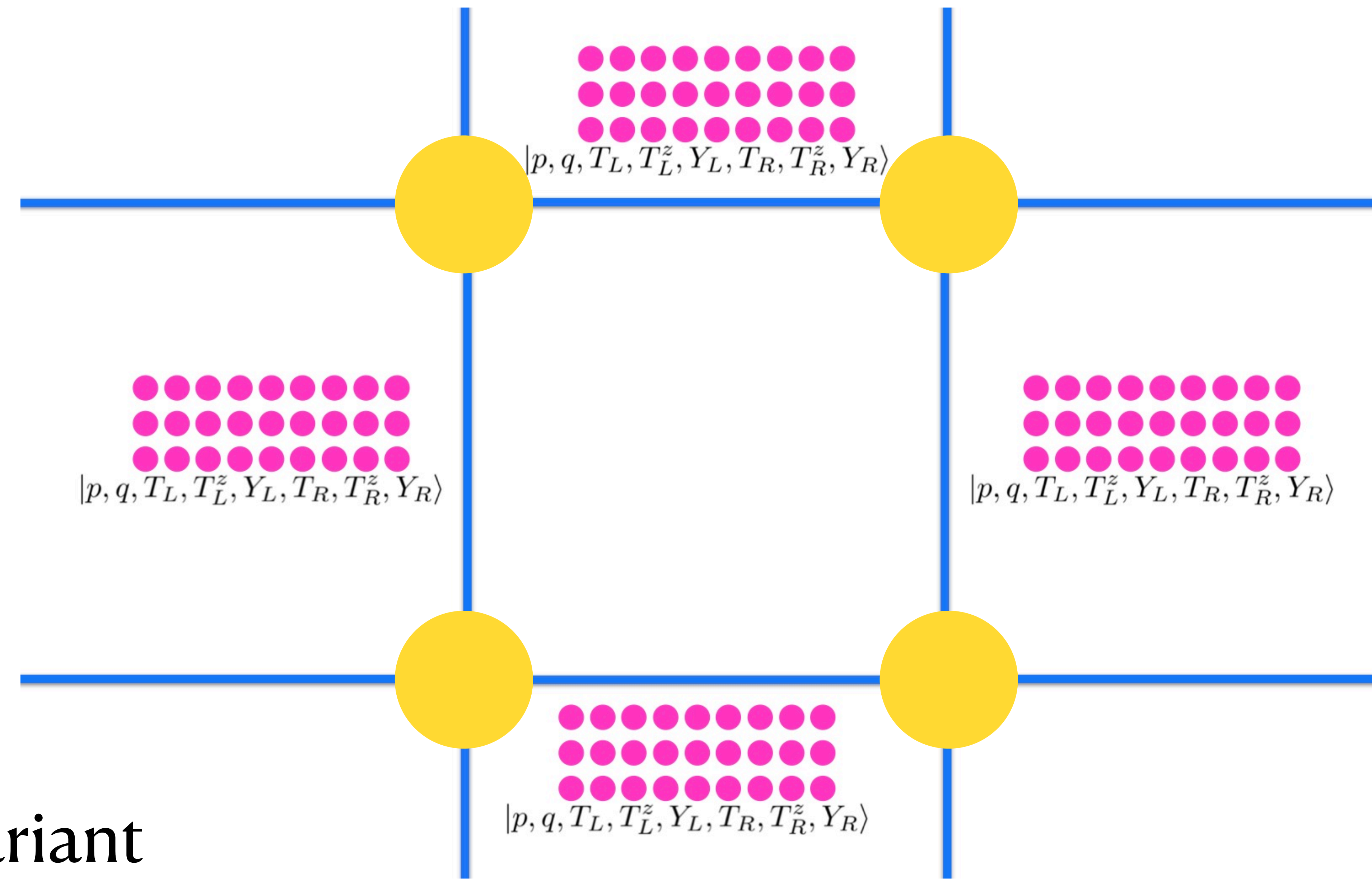
$|p, q, T_L, T_L^z, Y_L, T_R, T_R^z, Y_R\rangle$

Irrep Left-space Right-space

Magnetic Field operator

Off-diagonal on electric basis

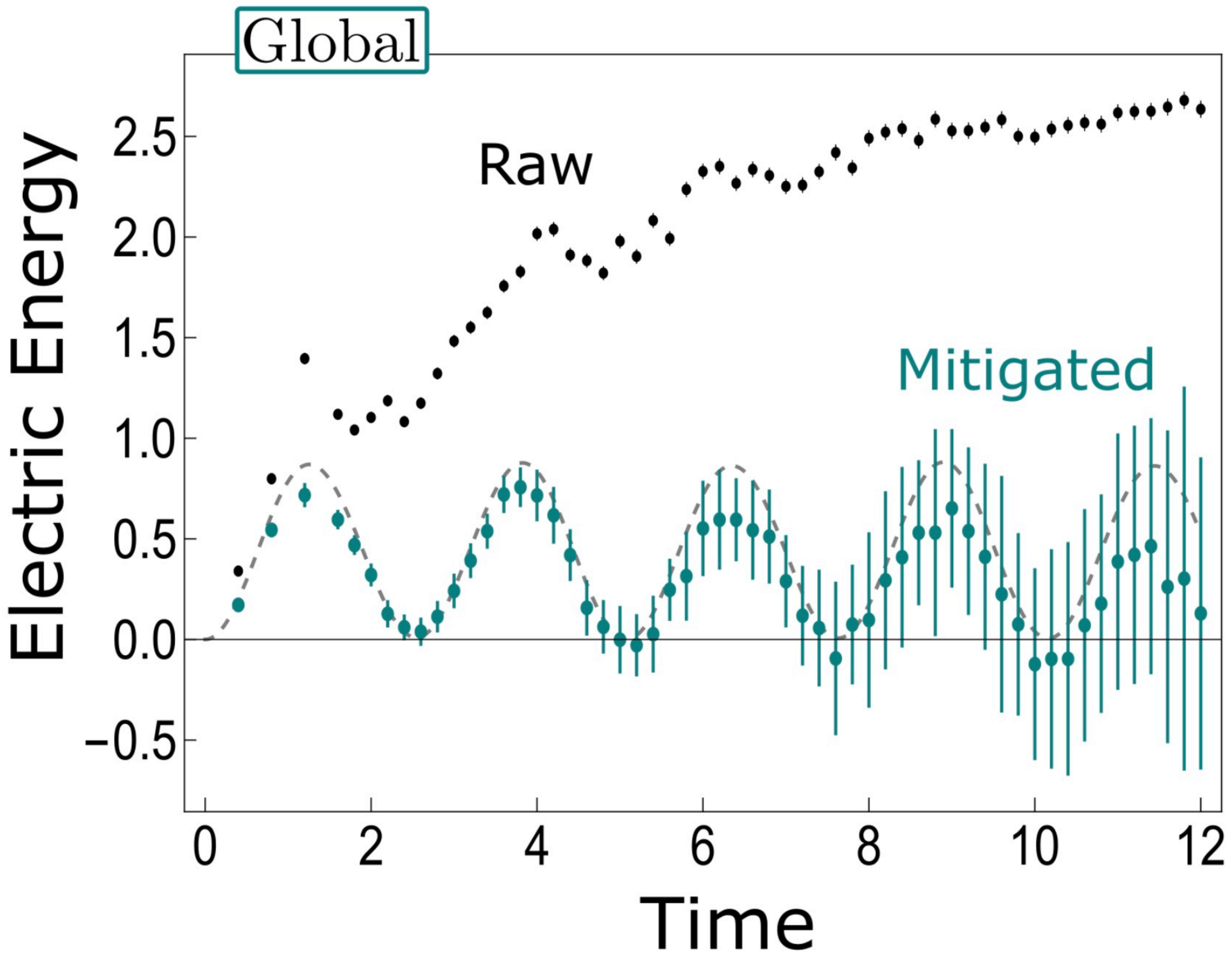


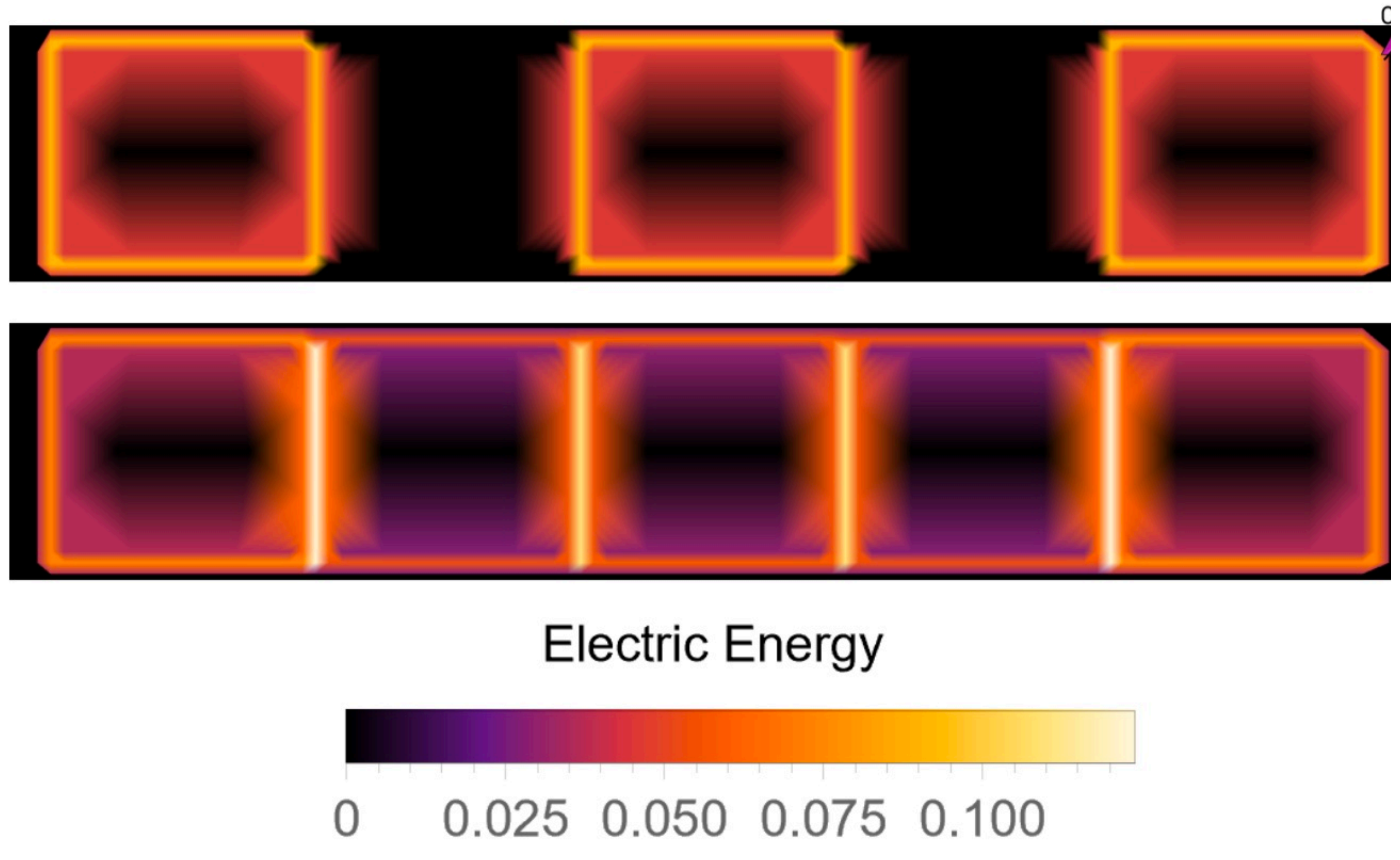


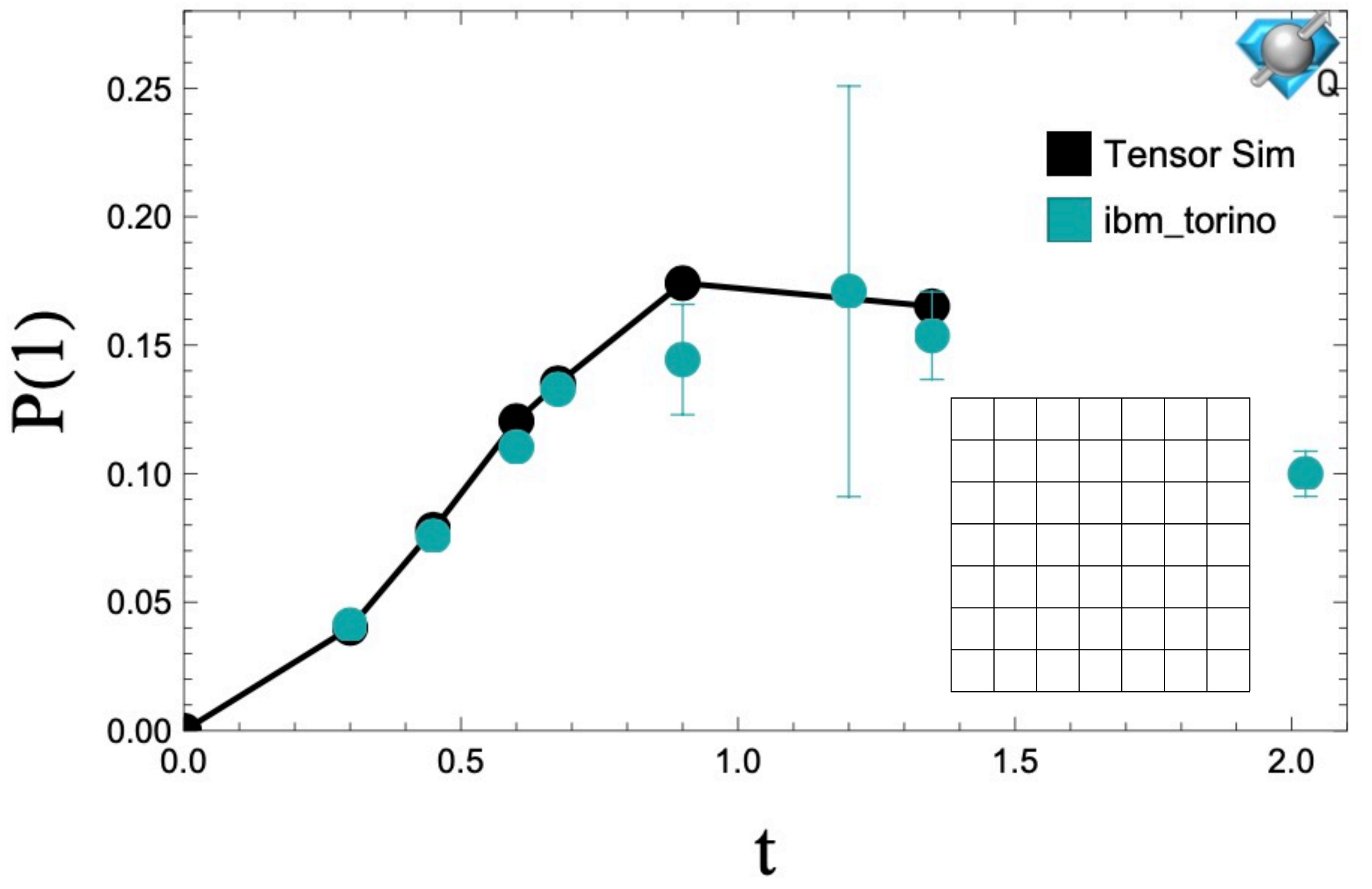
Truncations in irrep space !!!!!

SU(3) Yang-Mills Plaquettes

IBM







One Plaquette

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,‡]

Quantum Circuits for SU(3) Lattice Gauge Theory

Praveen Balaji[1], Cianán Conefrey-Shinozaki[1], Patrick Draper[*1], Jason K. Elhaderi[1], Drishti Gupta[1], Luis Hidalgo[1], Andrew Lytle[1], and Enrico Rinaldi[2]

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

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

Hot Starts

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

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

Perturbative Expansions
and
Effective Field Theories

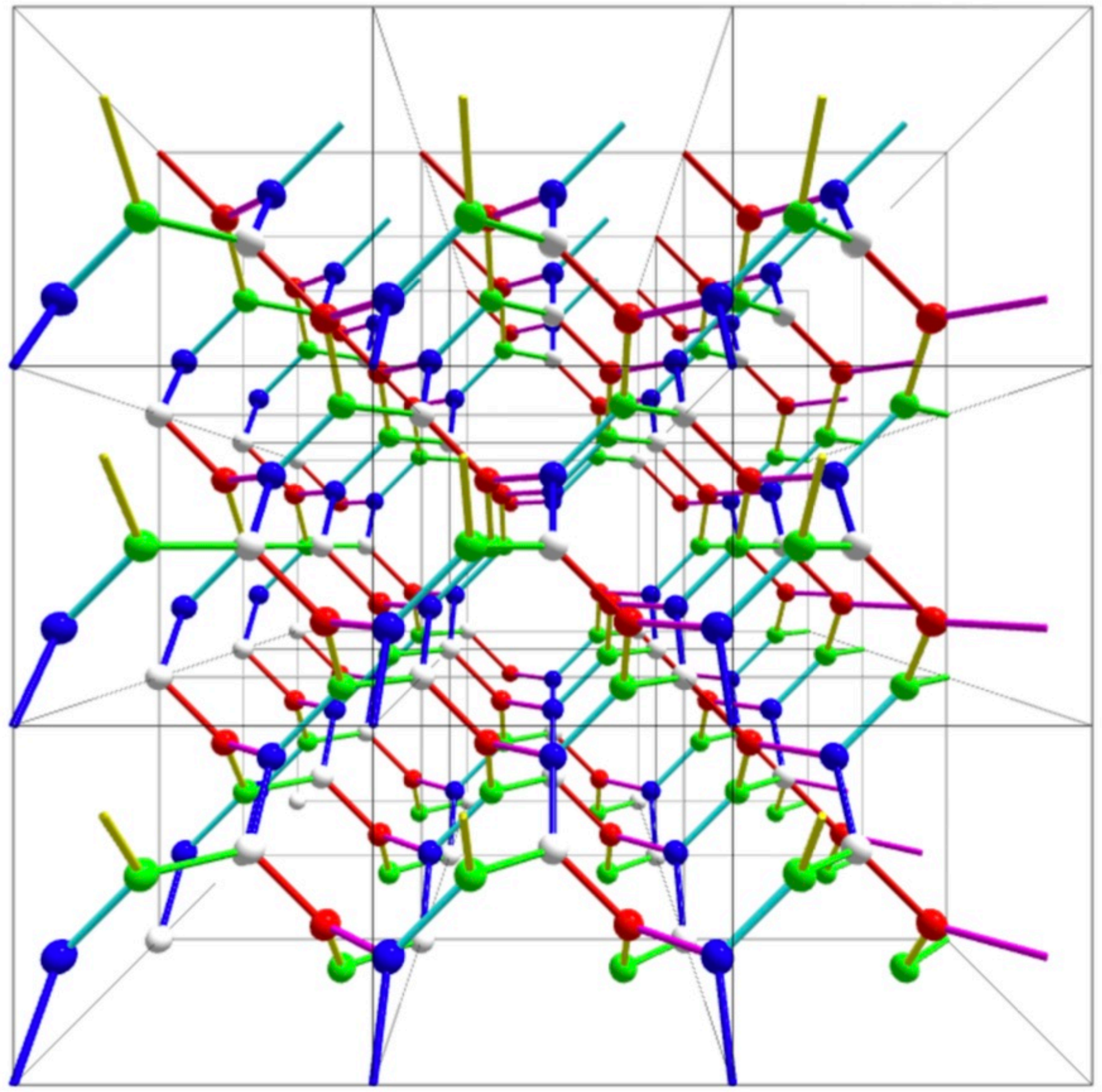
Reducing Group Space Overheads in non-Abelian LGT

reducing the number of links per vertex

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

Ali H. Z. Kavaki* and Randy Lewis†

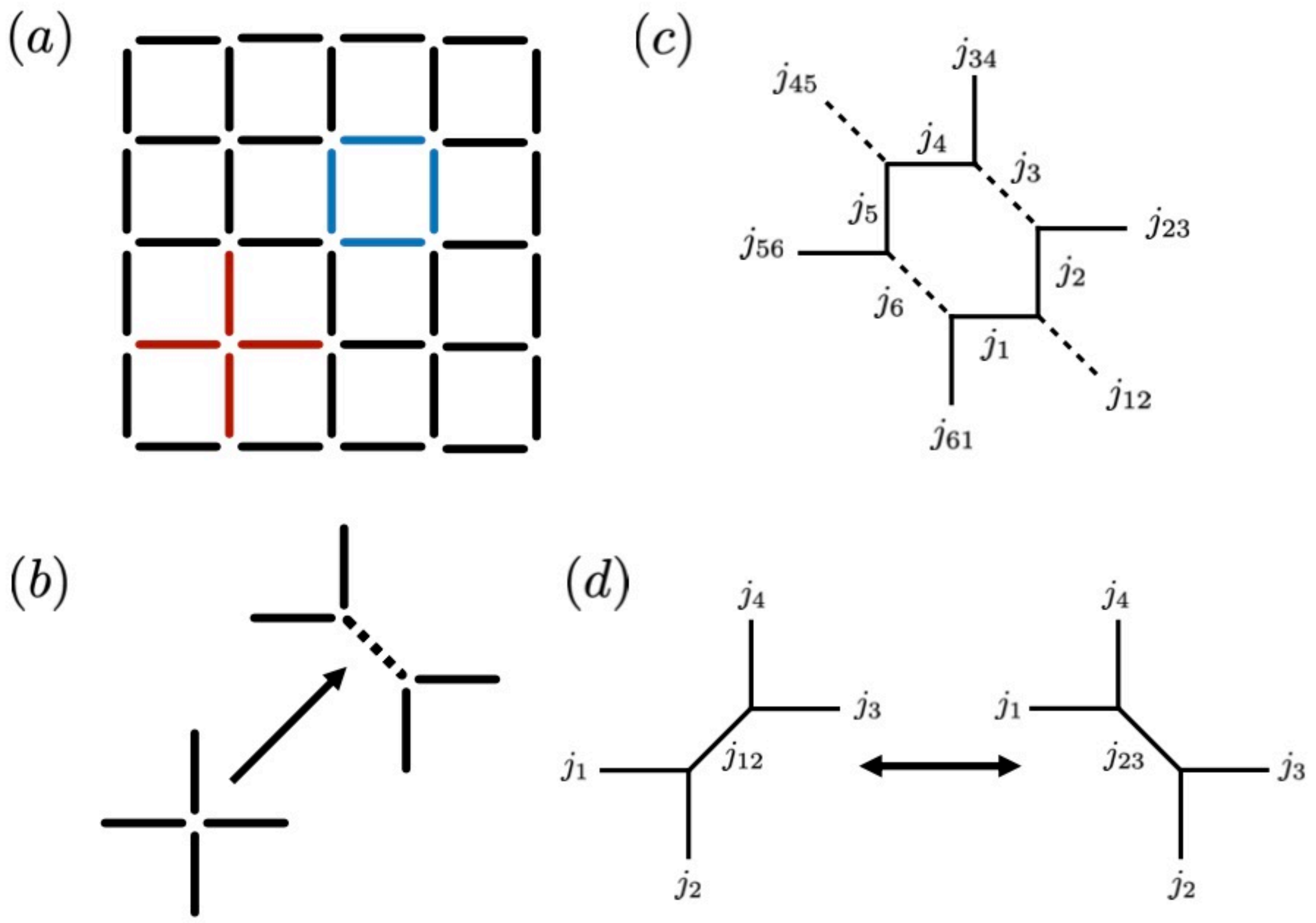
2024



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

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

2023



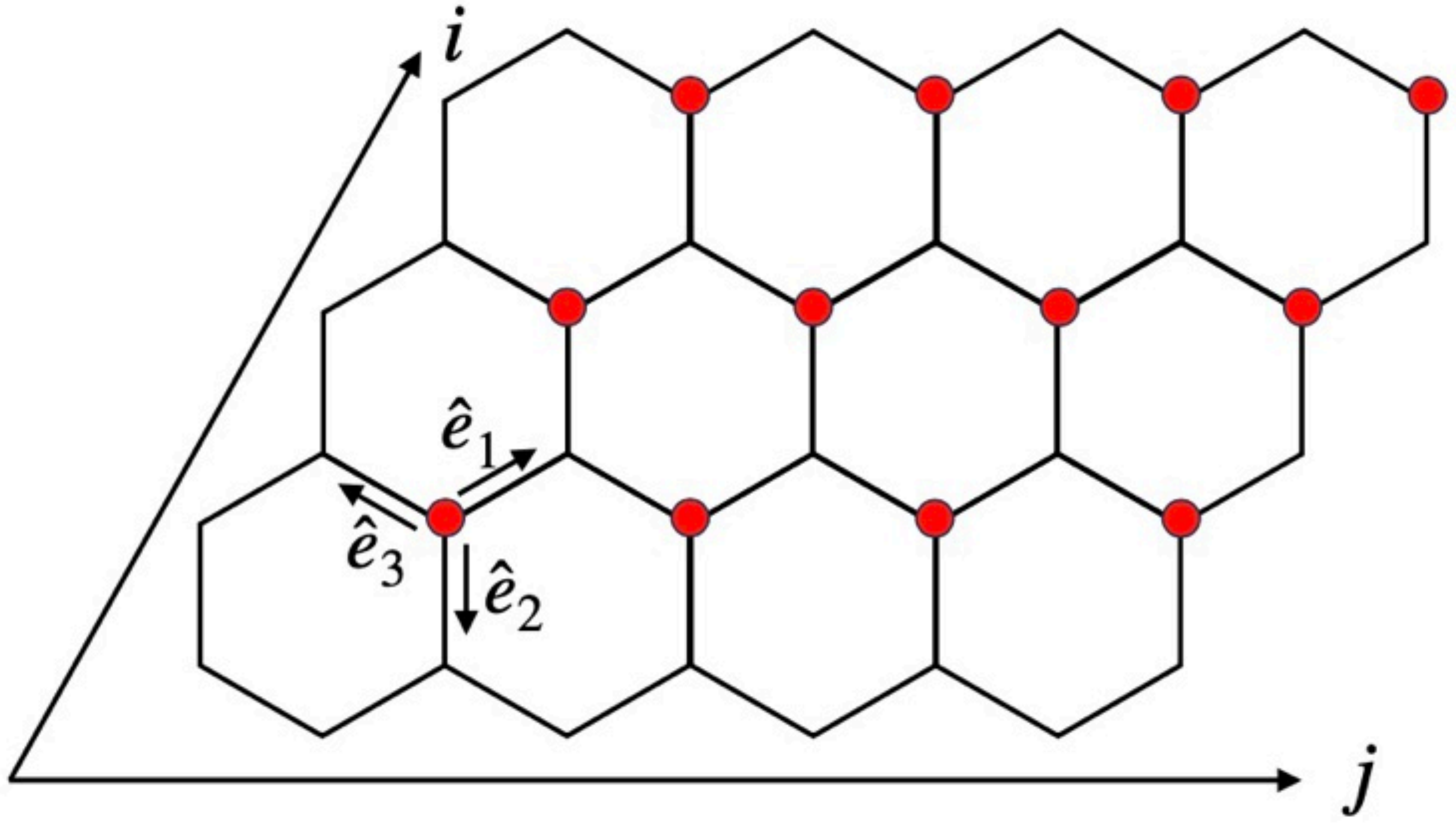
Transport Properties
Shear Viscosity in 2+1D SU(2)

Editors' Suggestion | Open Access

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

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

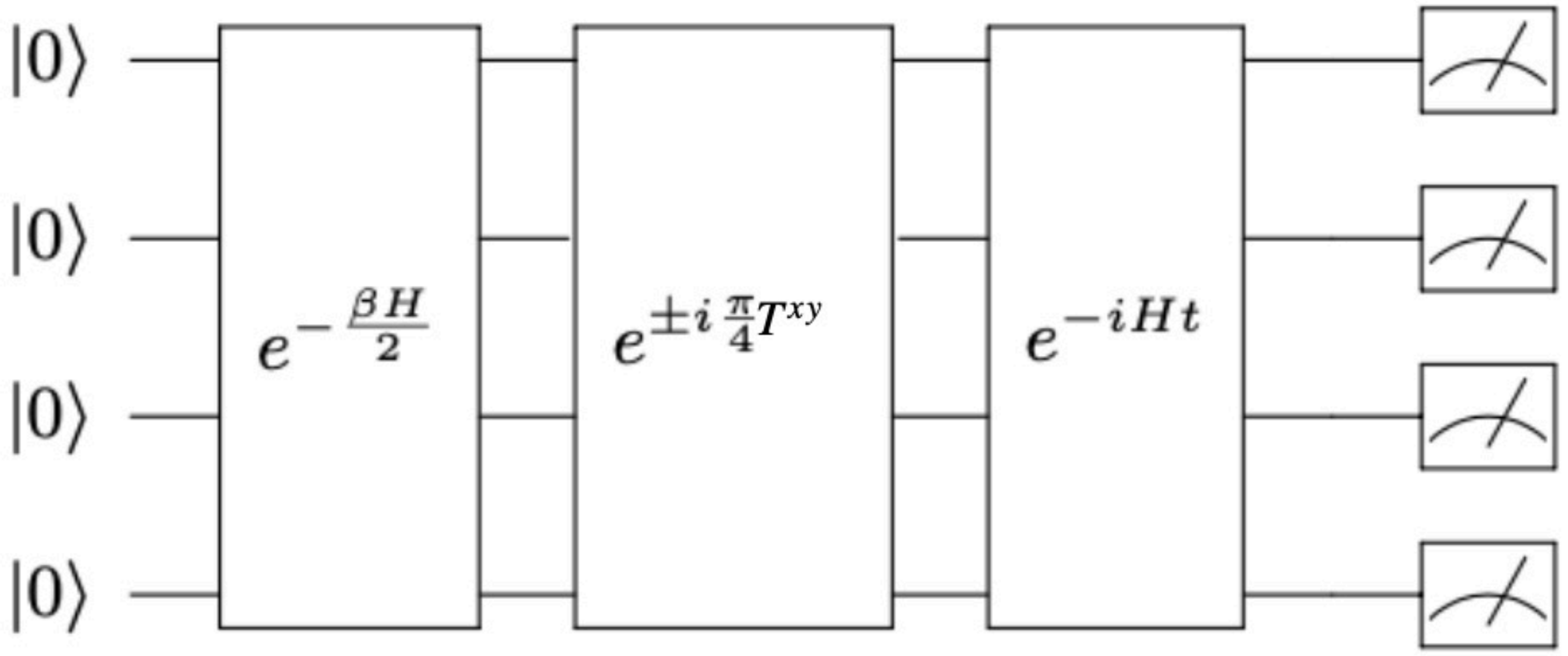
Berndt Mueller and Xiaojun Yao



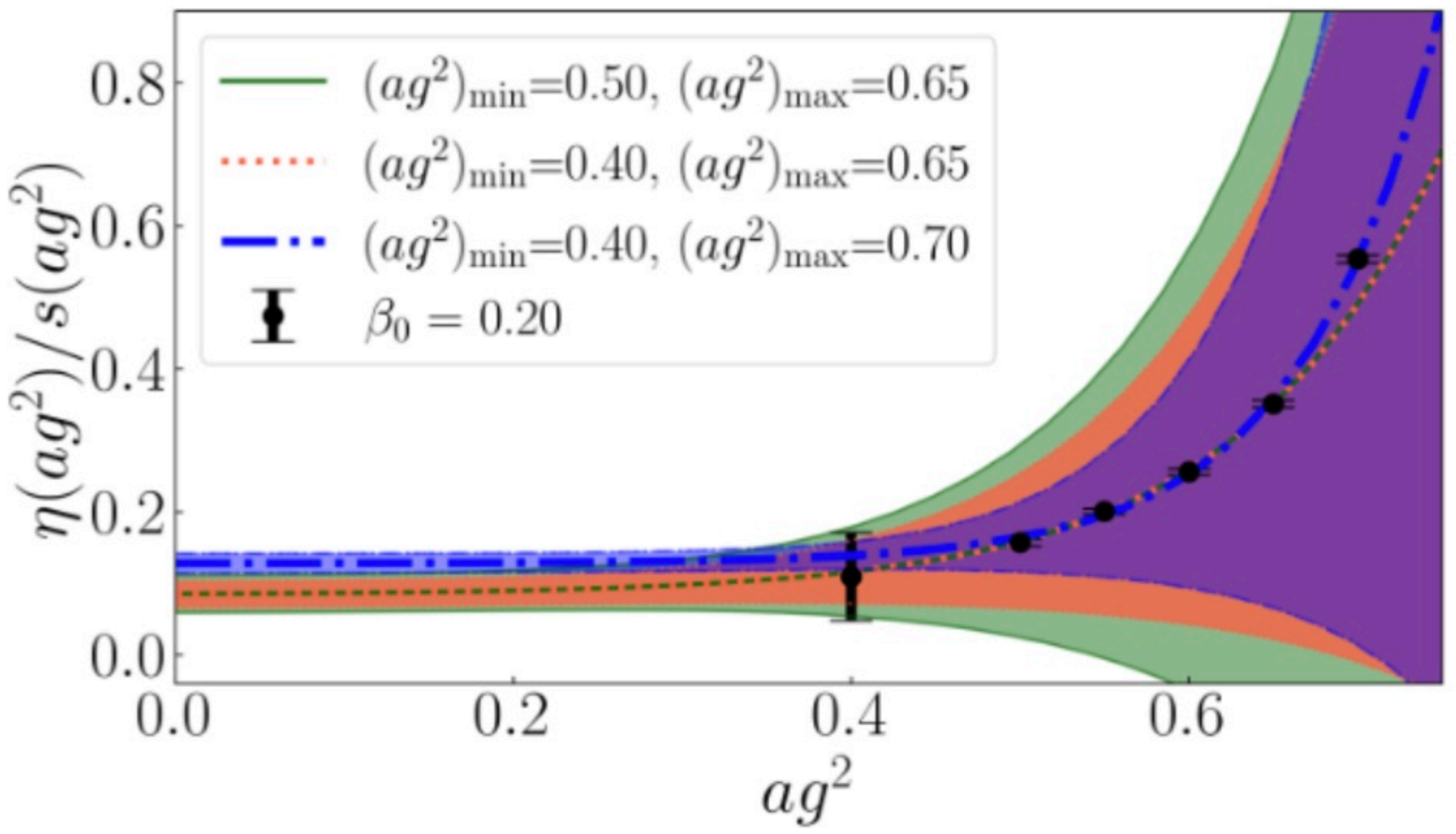
$$H = \frac{3\sqrt{3}g^2}{4}\sum_{\text{links}} E_i^a E_i^a - \frac{4\sqrt{3}}{9g^2a^2}\sum_{\text{plaqs}} \hexagon$$

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

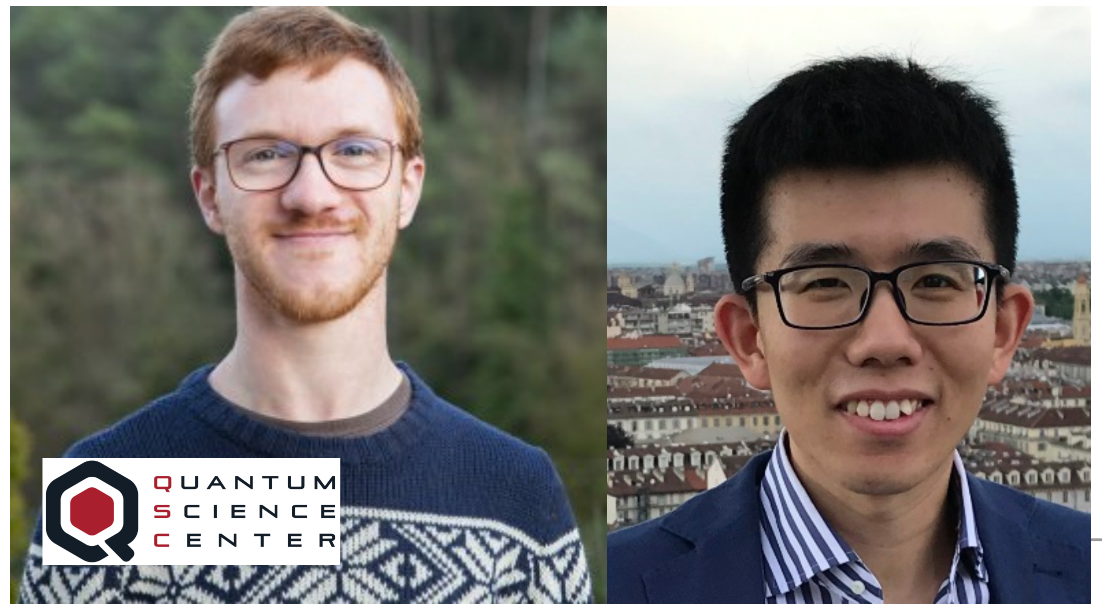
Quantum algorithm for G_r^{xy}



On 4×4 lattice w/ $j_{\max} = 0.5$



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



Improved Hamiltonian for Honeycomb lattices non-Abelian LGTs in 2+1

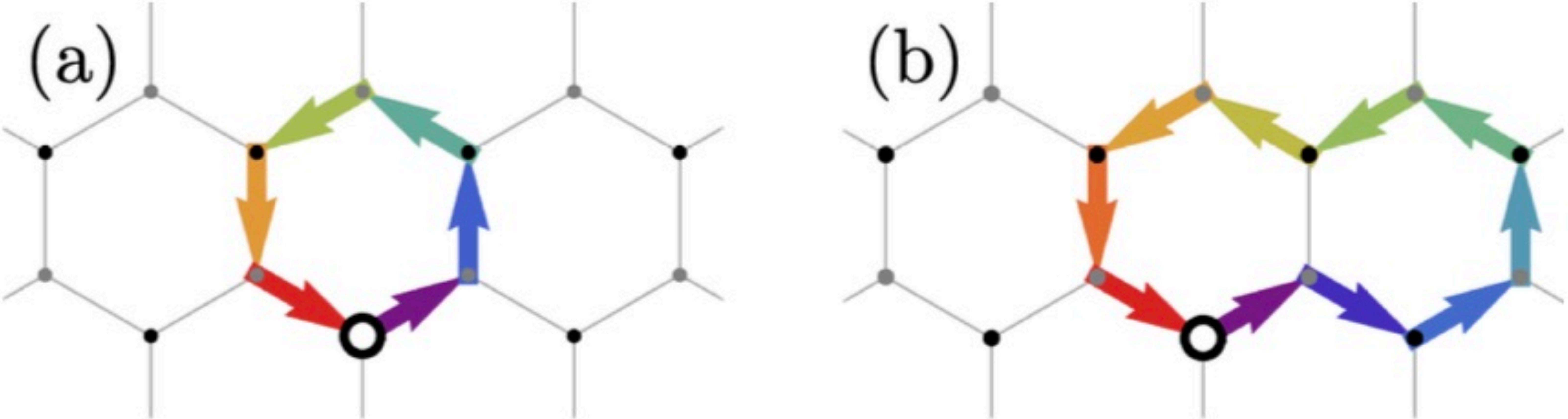
Improved honeycomb and hyperhoneycomb lattice Hamiltonians for quantum simulations of non-Abelian gauge theories

Marc Illa[*], Martin J. Savage[†,‡], and Xiaojun Yao[§]

Show more

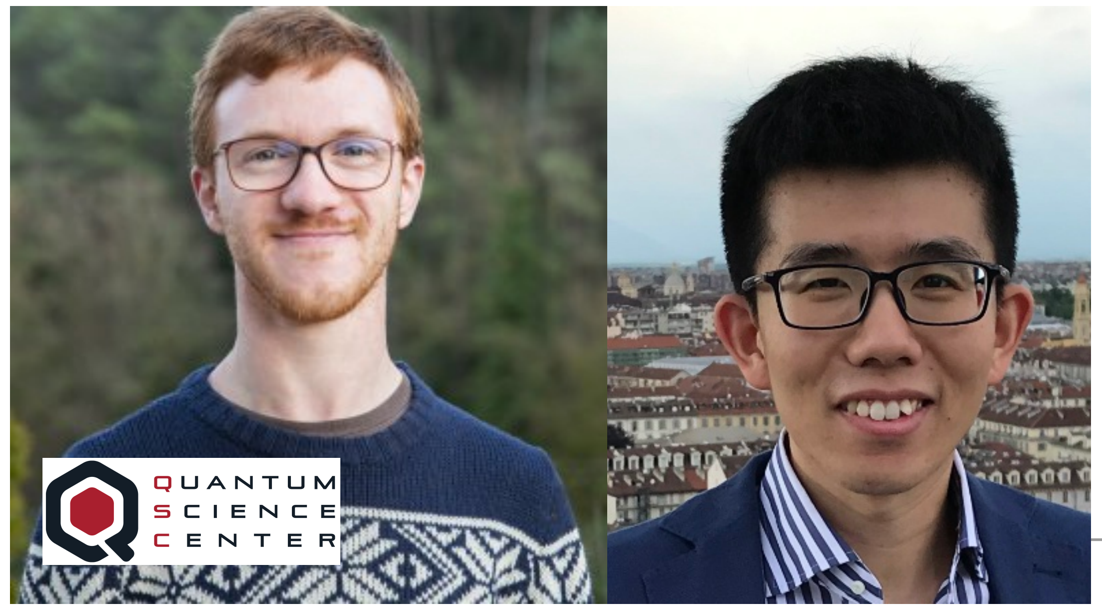
Phys. Rev. D **111**, 114520 – **Published 26 June, 2025**

DOI: https://doi.org/10.1103/3rwf-f844



$$\Gamma^{(\mathrm{HC})}_{6,10} = \frac{14}{9}\Gamma^{(\mathrm{HC})}_{6} - \frac{5}{36}\Gamma^{(\mathrm{HC})}_{10} = \frac{g^2}{4} S^2_{\hexagon} \sum_a [B^a(\boldsymbol{x})]^2 + \mathcal{O}(b^7)$$

Improved Hamiltonian for Hyper-Honeycomb lattices non-Abelian LGTs in 3+1



Improved honeycomb and hyperhoneycomb lattice Hamiltonians for quantum simulations of non-Abelian gauge theories

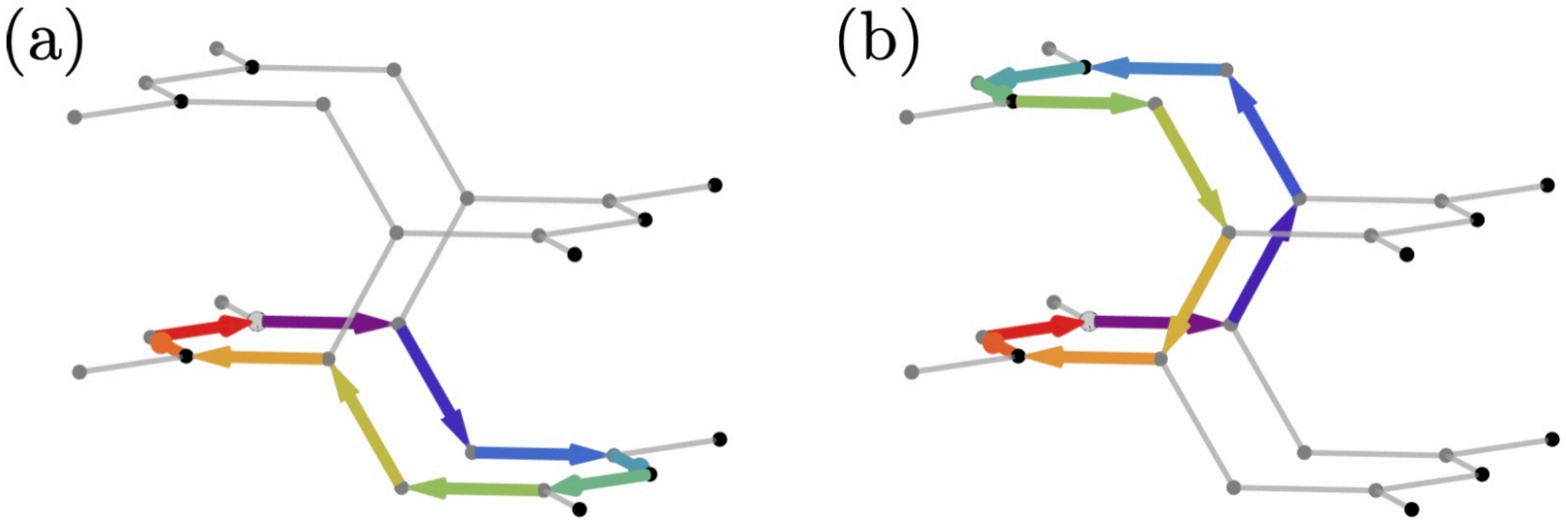
Marc Illa[*], Martin J. Savage[†,‡], and Xiaojun Yao[§]

Show more

Phys. Rev. D **111**, 114520 – **Published 26 June, 2025**

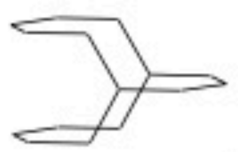
DOI: https://doi.org/10.1103/3rwf-f844

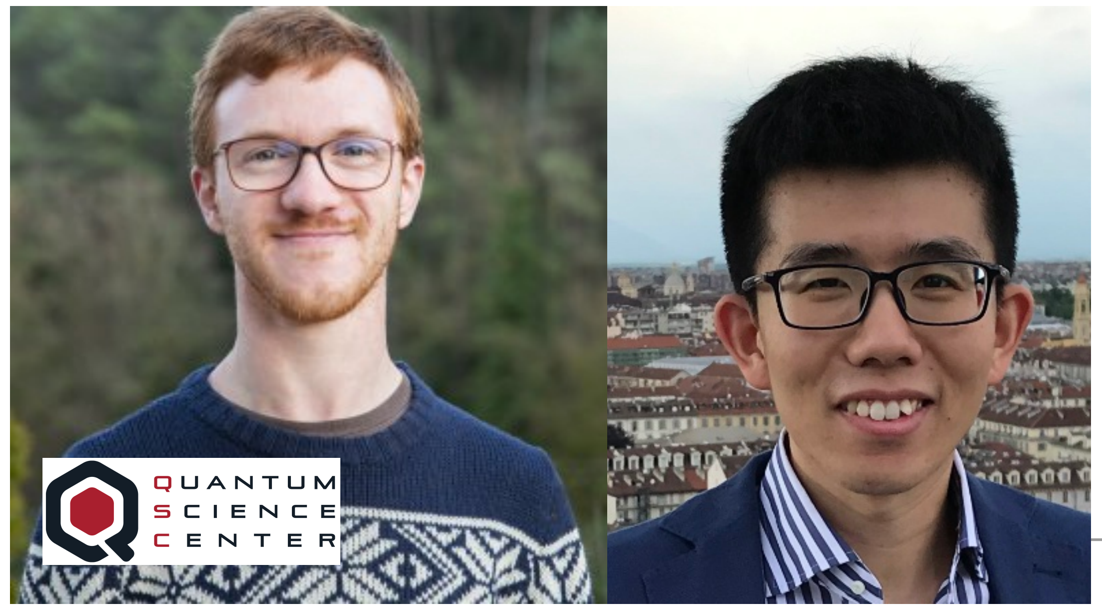
Exp



Defines Leading-Order Magnetic Contribution

$$\Gamma^{(\mathrm{HHC})}_{10,12} = \Gamma^{(\mathrm{HHC})}_{10} + \frac{5}{4}\Gamma^{(\mathrm{HHC})}_{12} = \frac{3g^2bV}{8}\sum_{a,i}[B_i^a(\boldsymbol{x})]^2 + \mathcal{O}(b^6)$$





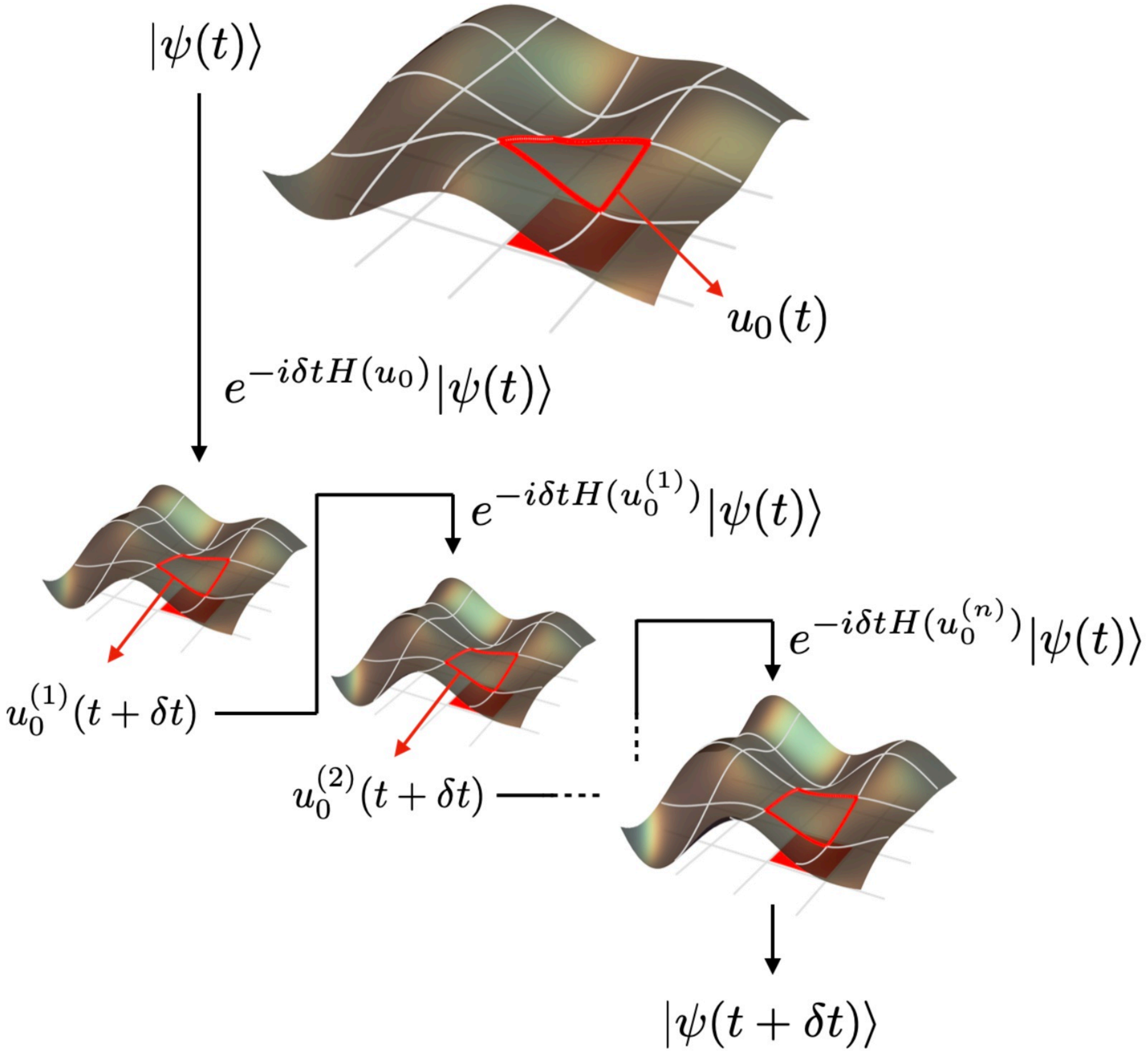
Improved Hamiltonian - Tadpoles

Dynamical Local Tadpole-Improvement in Quantum Simulations of Gauge Theories

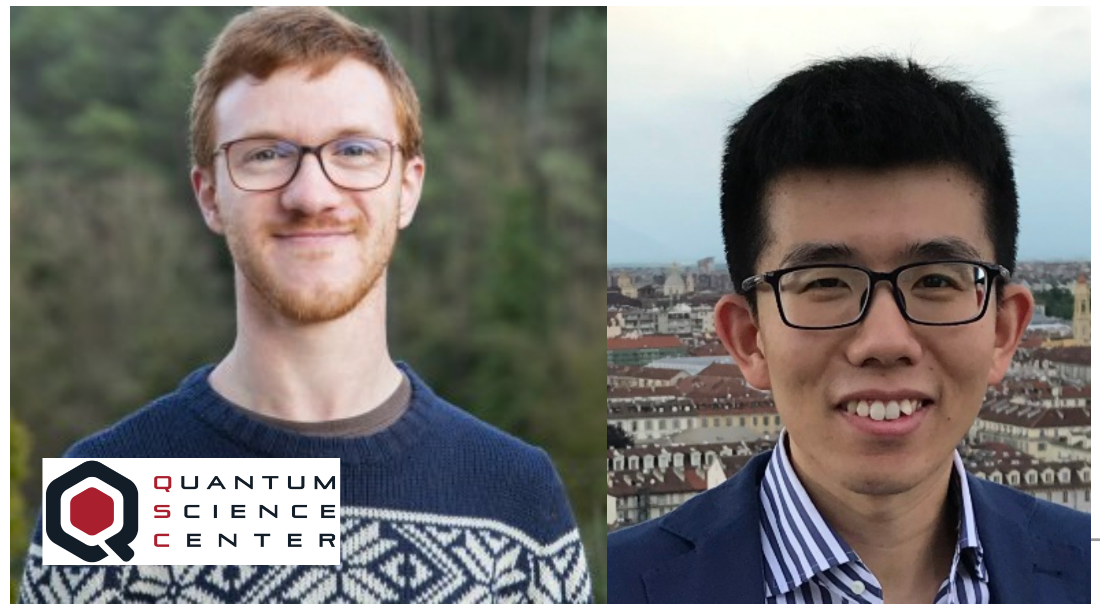
Marc Illa,* Martin J. Savage,† and Xiaojun Yao‡

Space-time dependent tadpole corrections

$$\hat{H} = \frac{g^2}{2a^{d-2}} \sum_{b,\text{links}} |\hat{\boldsymbol{E}}^{(b)}|^2 + \frac{1}{2a^{4-d}g^2} \sum_i \left[2N_c - \frac{1}{u_{0,i}^4} \left(\hat{\Box}_i + \hat{\Box}_i^\dagger \right) \right]$$



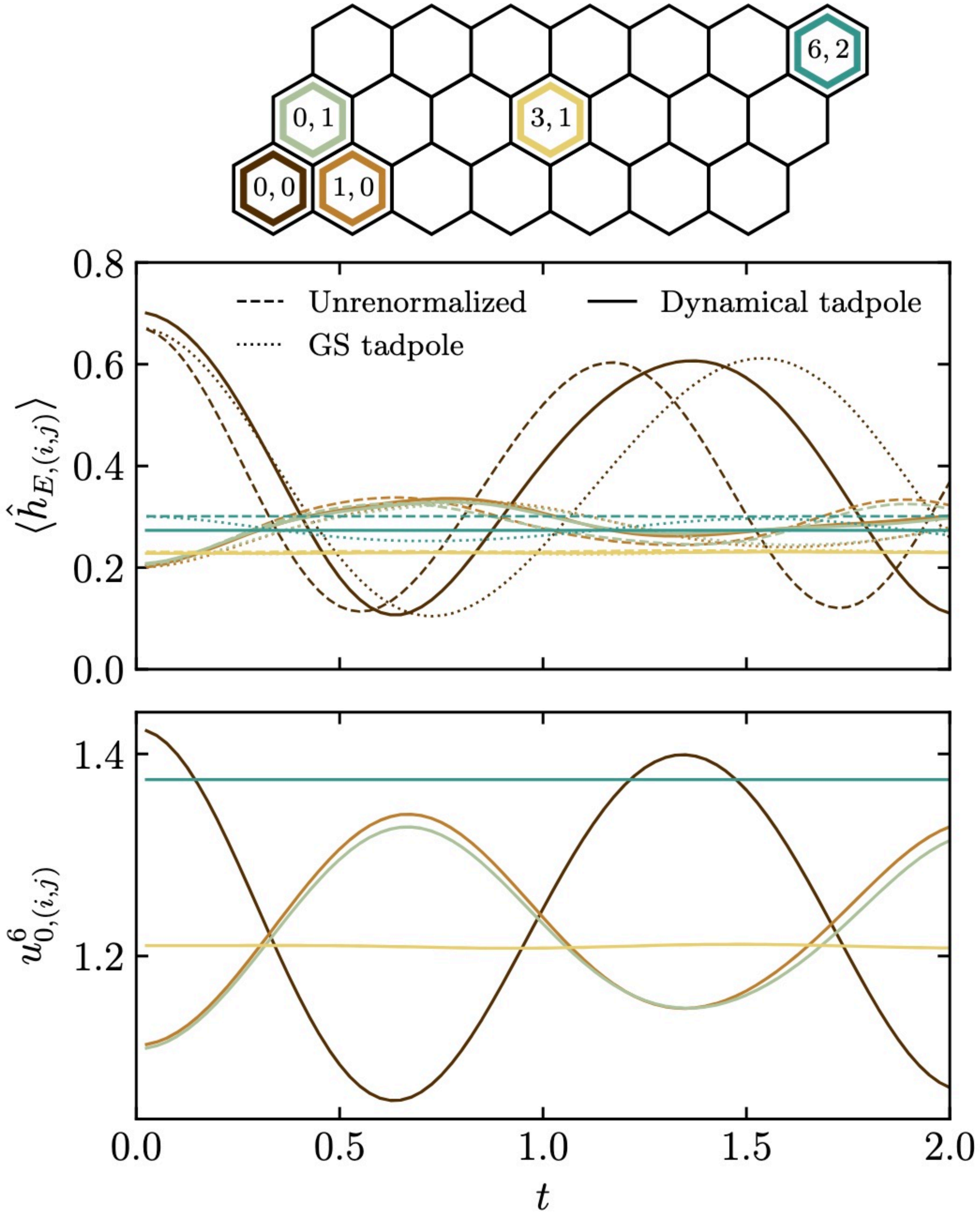
$$u_{0,i} = \left(1 + \frac{1}{2N_c} \langle \psi | \hat{\Box}_i + \hat{\Box}_i^\dagger | \psi \rangle \right)^{1/4}$$



Improved Hamiltonian - Tadpoles

Dynamical Local Tadpole-Improvement in Quantum Simulations of Gauge Theories

Marc Illa,[*] Martin J. Savage,[†] and Xiaojun Yao[‡]



Scalar Field Theory with bounded, smooth wave packet on interacting vacuum

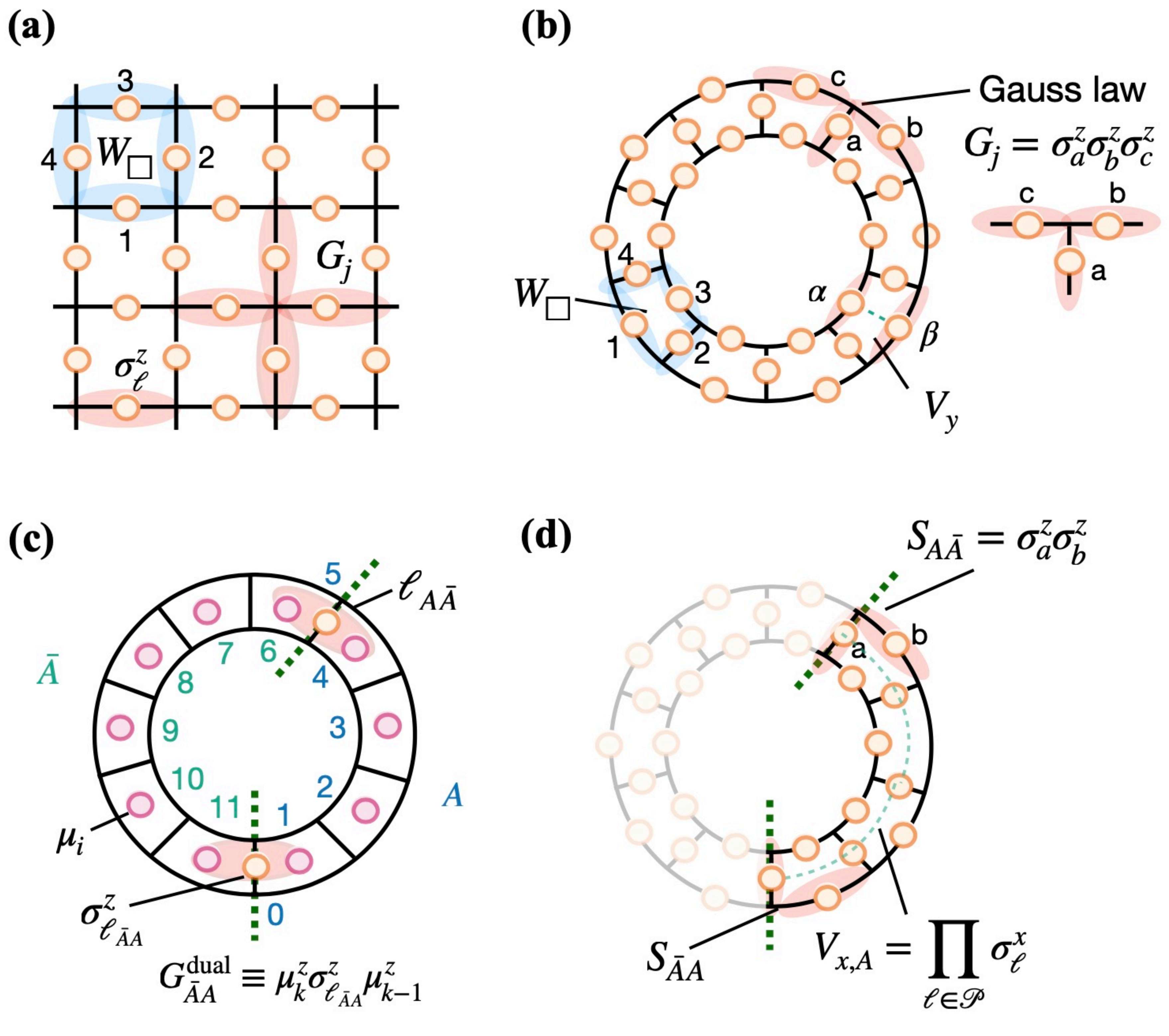
$$\langle\Psi|\,\phi_\alpha^2\,|\Psi\rangle \to \frac{1}{L}\sum_k \frac{1}{2E_k} + \left|\sum_k \frac{g_k V_{k\alpha}}{\sqrt{E_k}}\right|^2$$

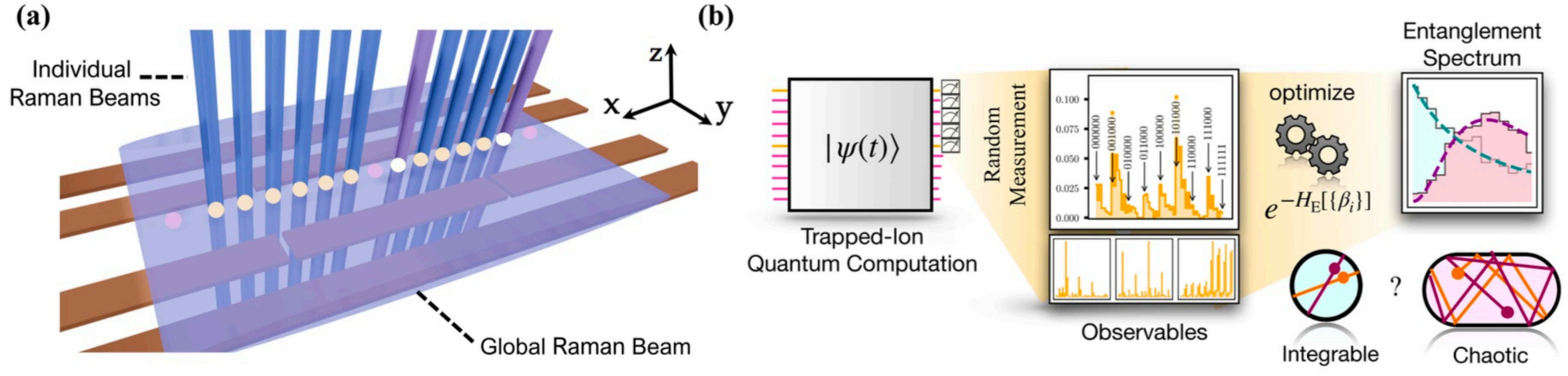
Vacuum tadpole correction plus Lattice spacing finite density term

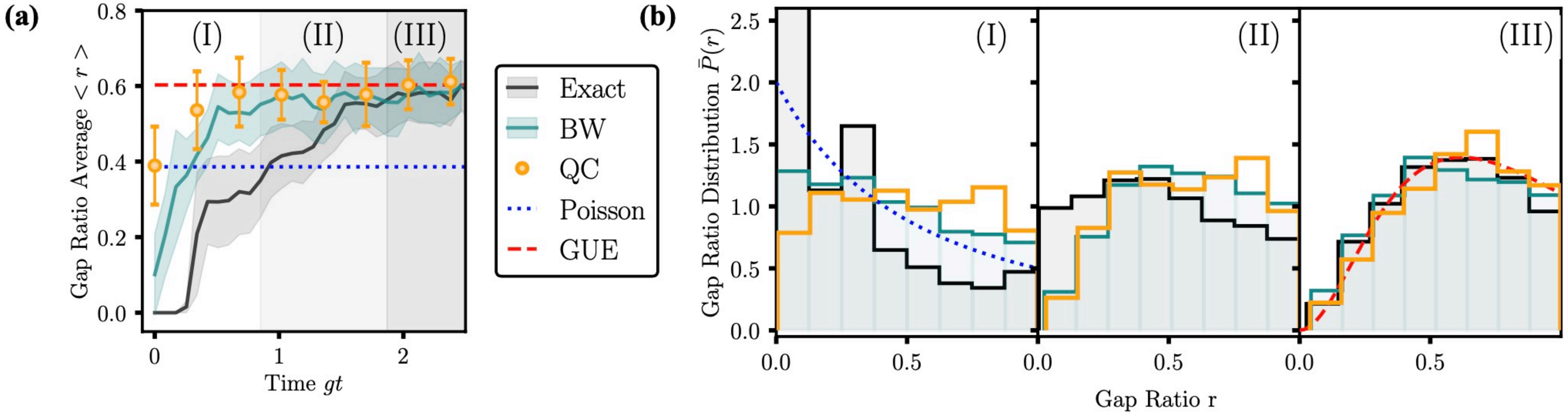
Entanglement and Thermalization

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

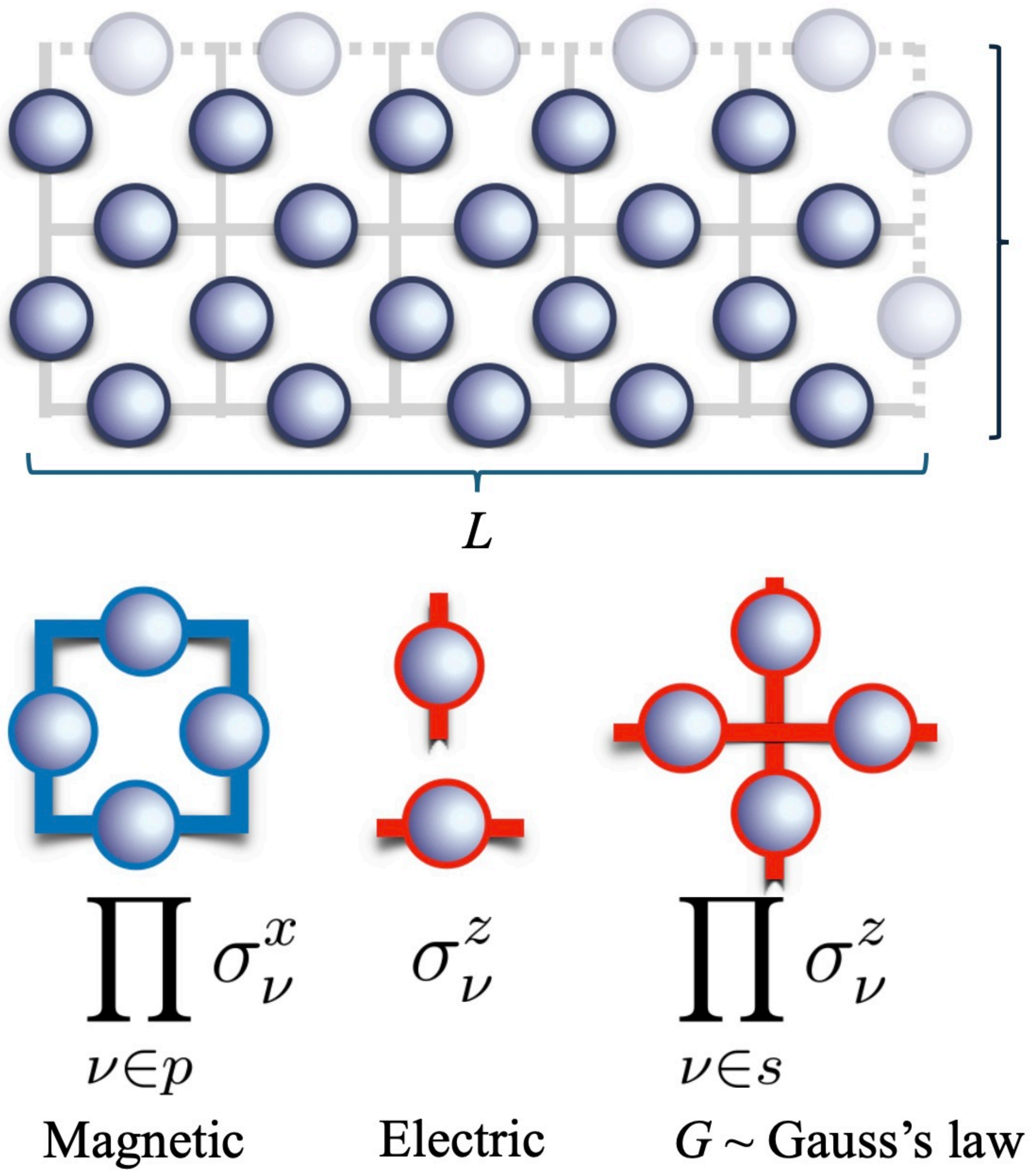
Niklas Mueller,[1,*] Tianyi Wang,[2,3,4] Or Katz,[3,5,6] Zohreh Davoudi,[7,8,4,9] and Marko Cetina[2,3,5,4]

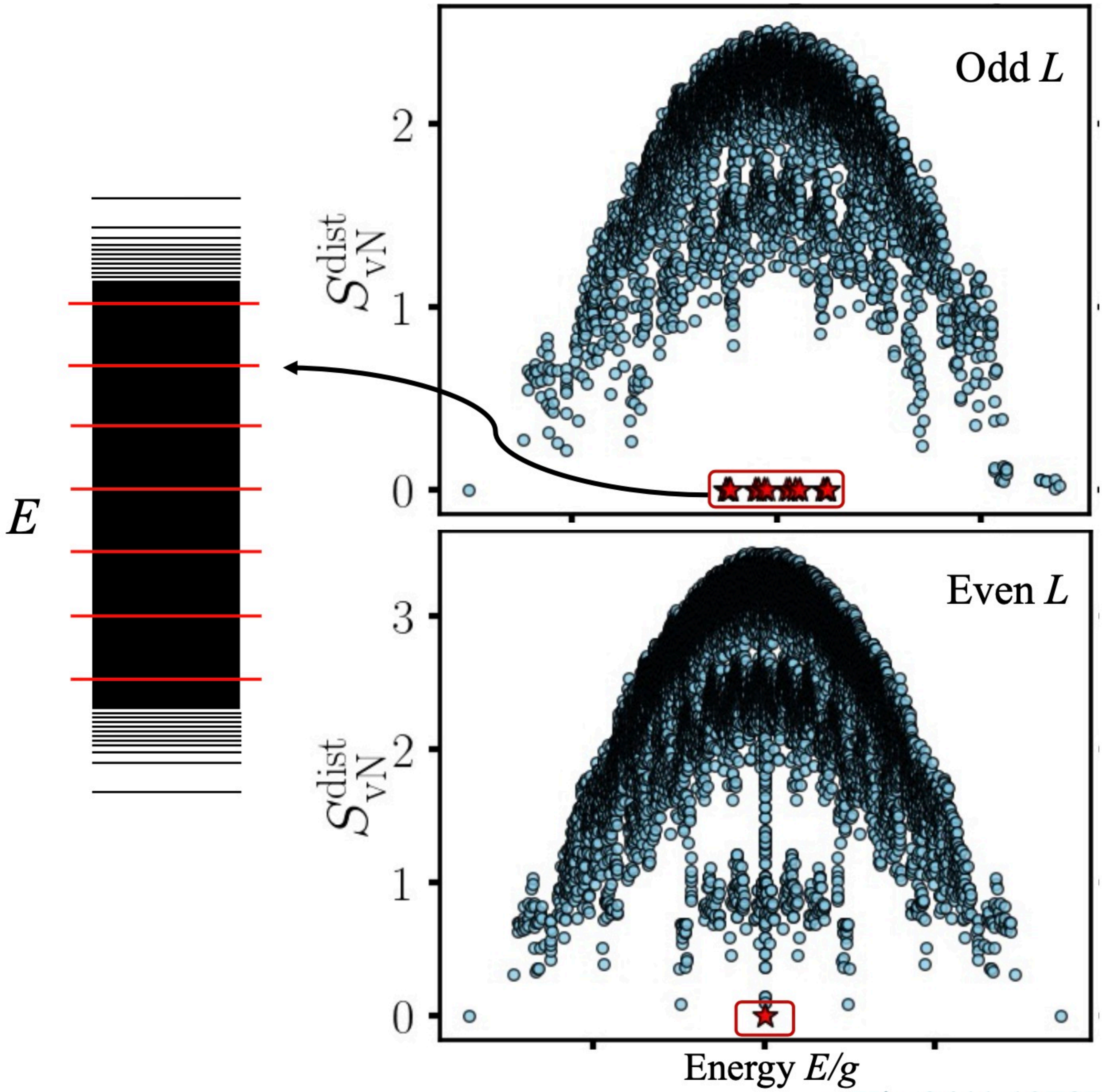






Entanglement and Thermalization
Stabilizer Scars



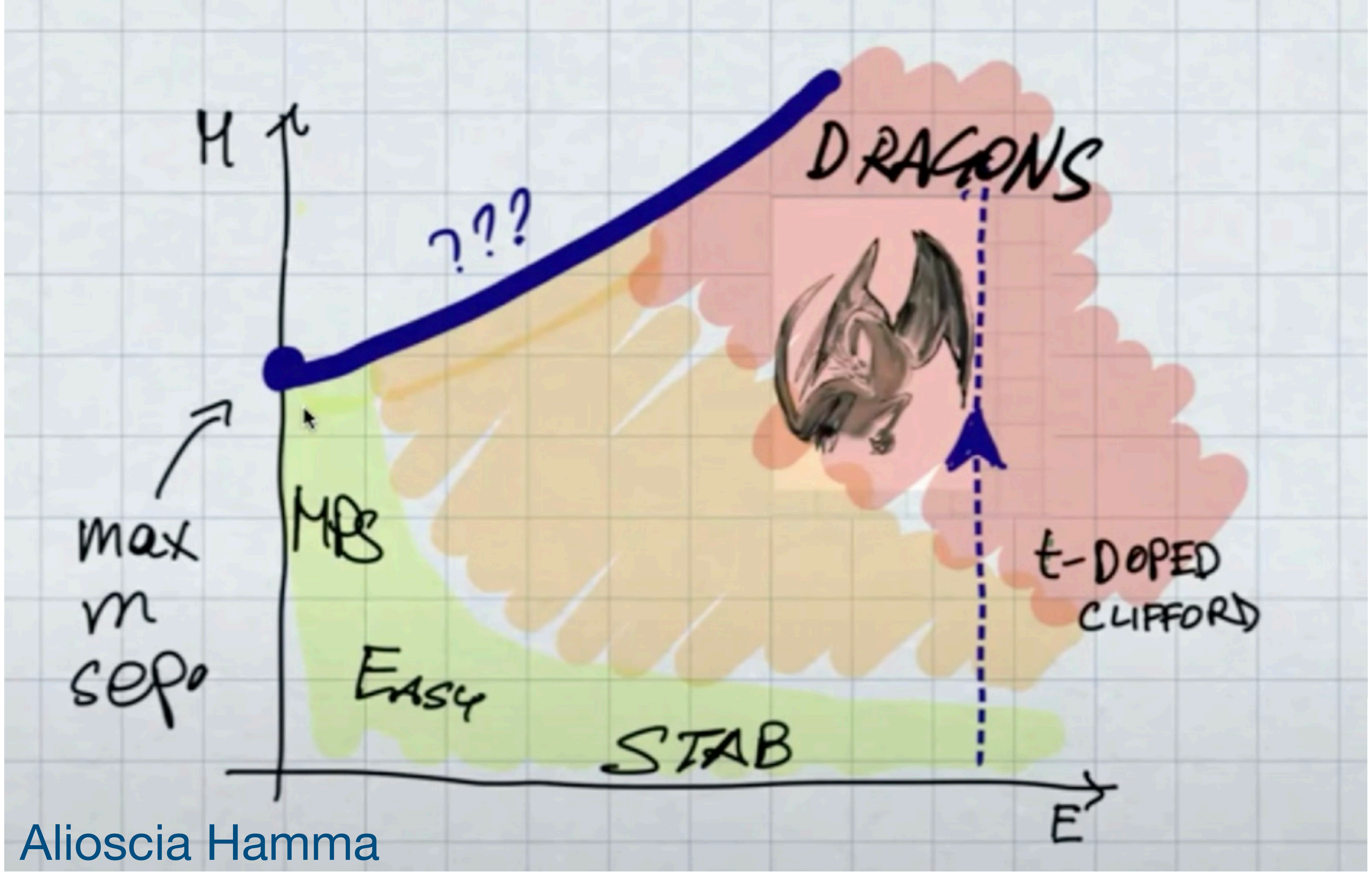


arXiv:2411.12797

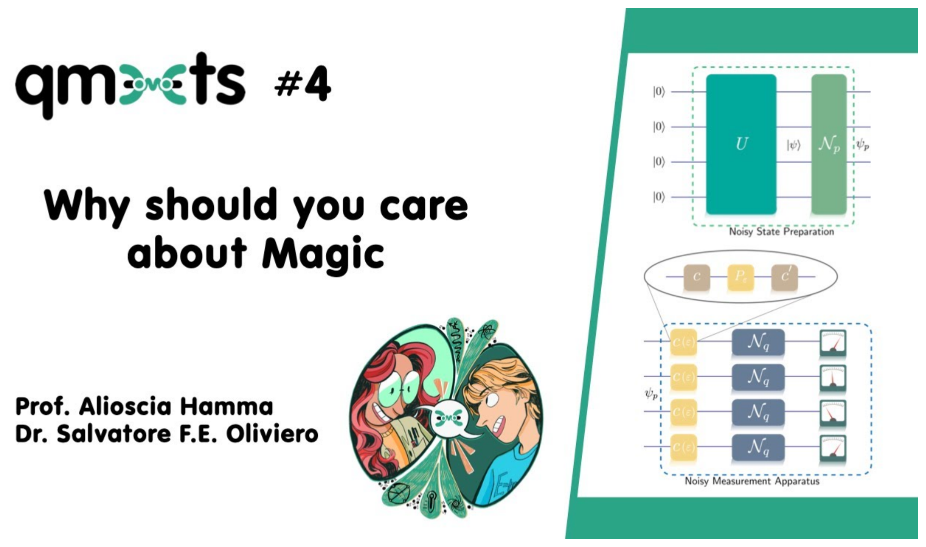
When is a Quantum Computer Required?

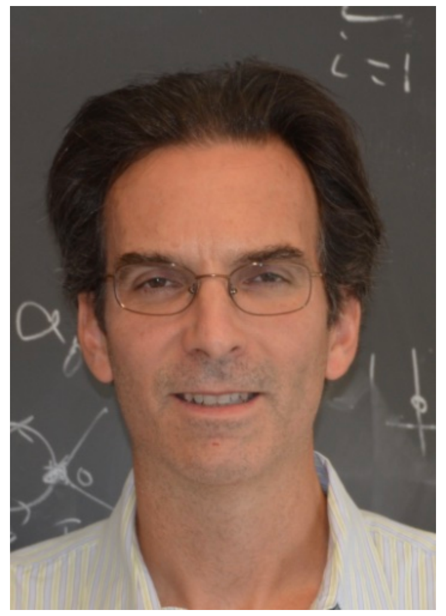
Quantum Complexity of Physical Systems?

Magic



Entanglement

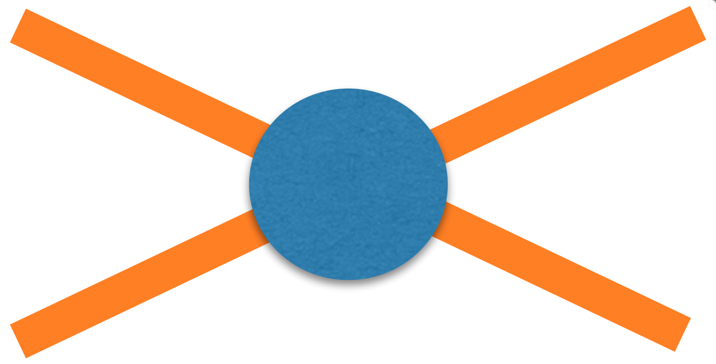




Entanglement Suppression and Emergent Symmetries of Strong Interactions

Silas R. Beane, David B. Kaplan, Natalie Klco, and Martin J. Savage

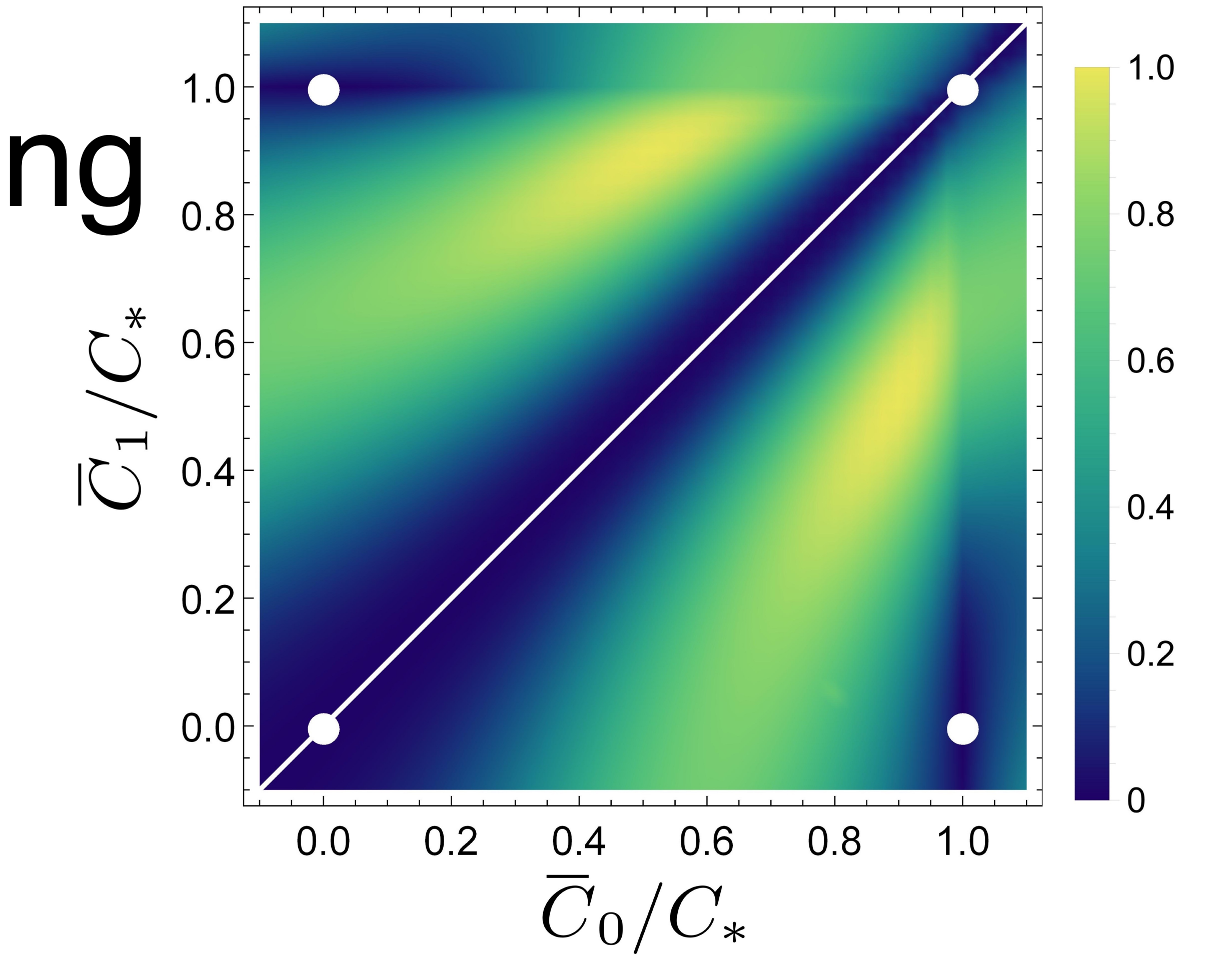
Phys. Rev. Lett. **122**, 102001 – Published 14 March 2019



Low-energy QCD: NN and YN S-Wave Scattering

$$\hat{\mathbf{S}}_\sigma = \frac{1}{4}\left(3e^{i2\delta_3} + e^{i2\delta_1}\right)\hat{\mathbf{1}} + \frac{1}{4}\left(e^{i2\delta_3} - e^{i2\delta_1}\right)\hat{\boldsymbol{\sigma}}\cdot\hat{\boldsymbol{\sigma}}$$

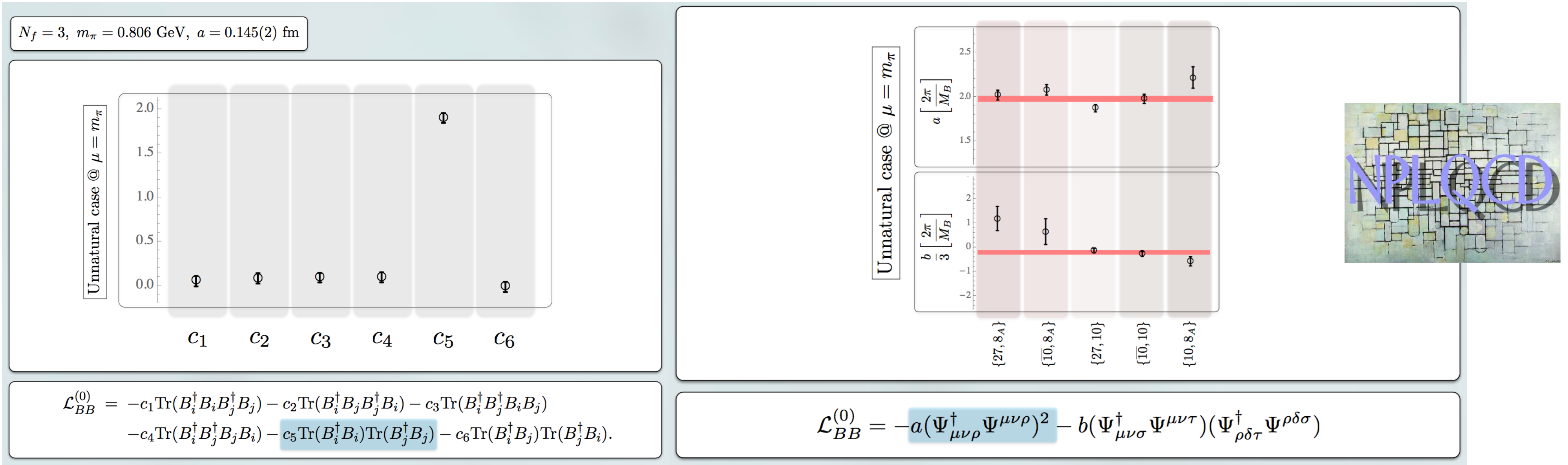
$$e_p(\hat{A}) \longrightarrow \mathcal{E}(\hat{\mathbf{S}}_\sigma) = \frac{1}{6}\sin^2\left(2(\delta_3 - \delta_1)\right)$$




conformal points

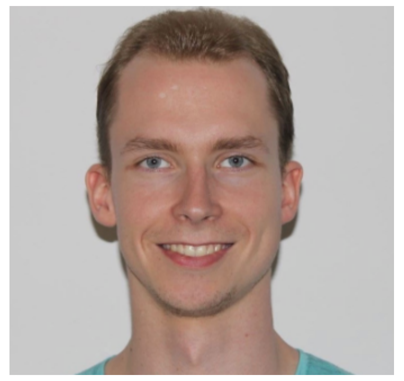

Wigner symmetry

SU(4) for 2 flavors and **SU(16)** for 3 flavors
- more symmetry than large-Nc, [SU(4) and SU(6)]

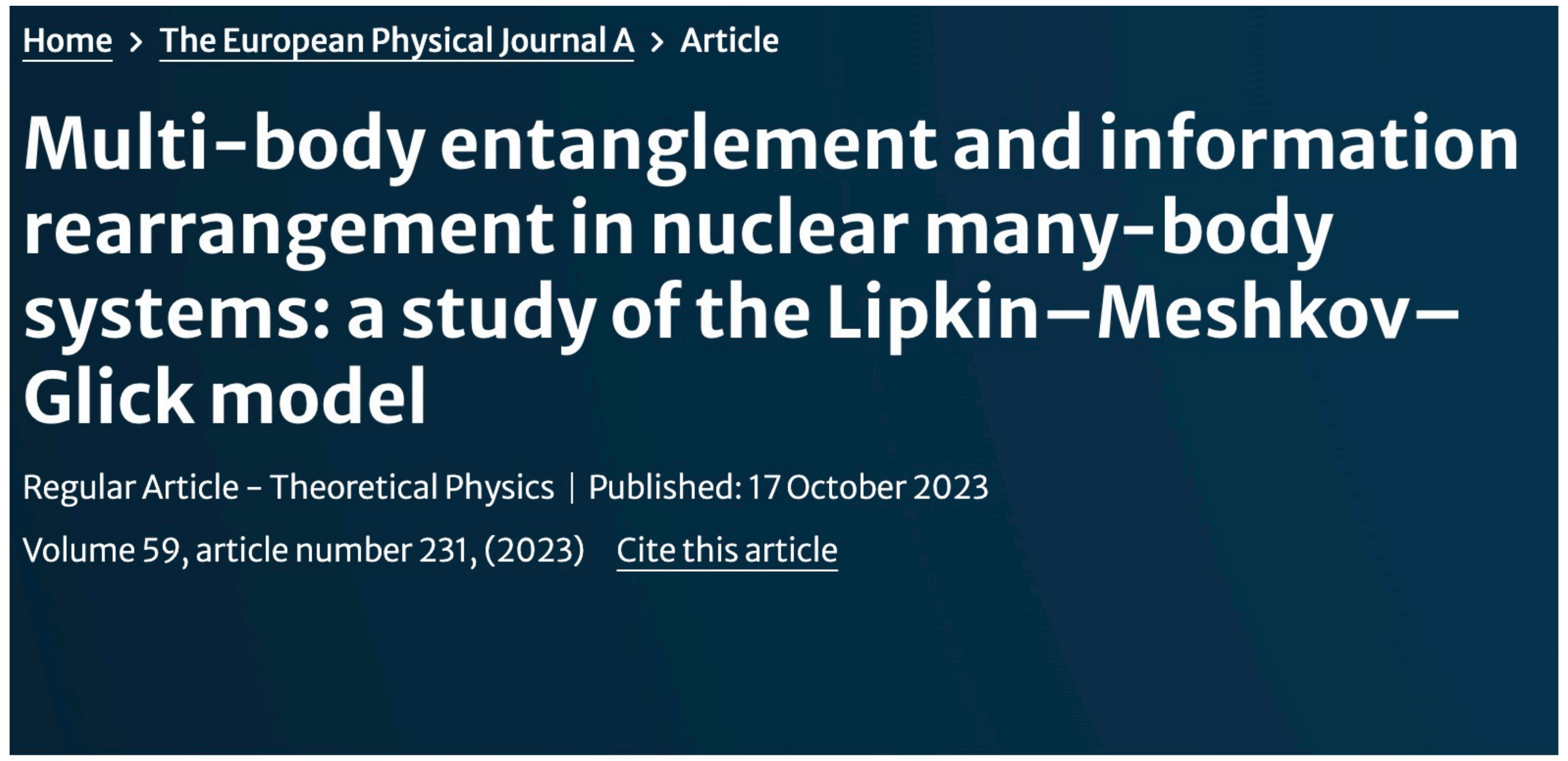


Emergent approximate symmetries in nuclear systems ⟷ Suppressed fluctuations in entanglement

Suppressed sign problems in classical simulations

Entanglement Rearrangment, Effective Model Spaces and Symmetries

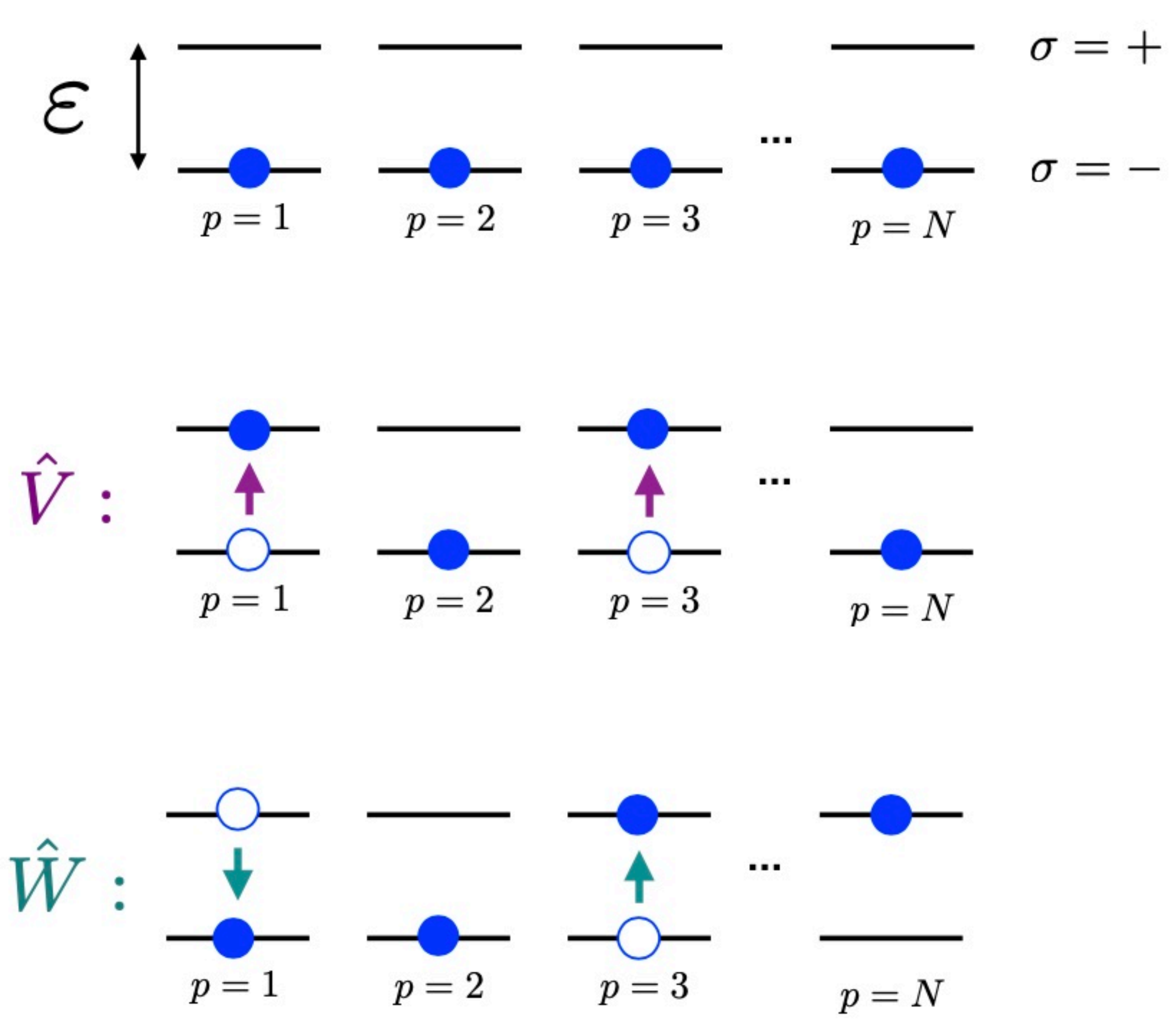

Home > The European Physical Journal A > Article

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

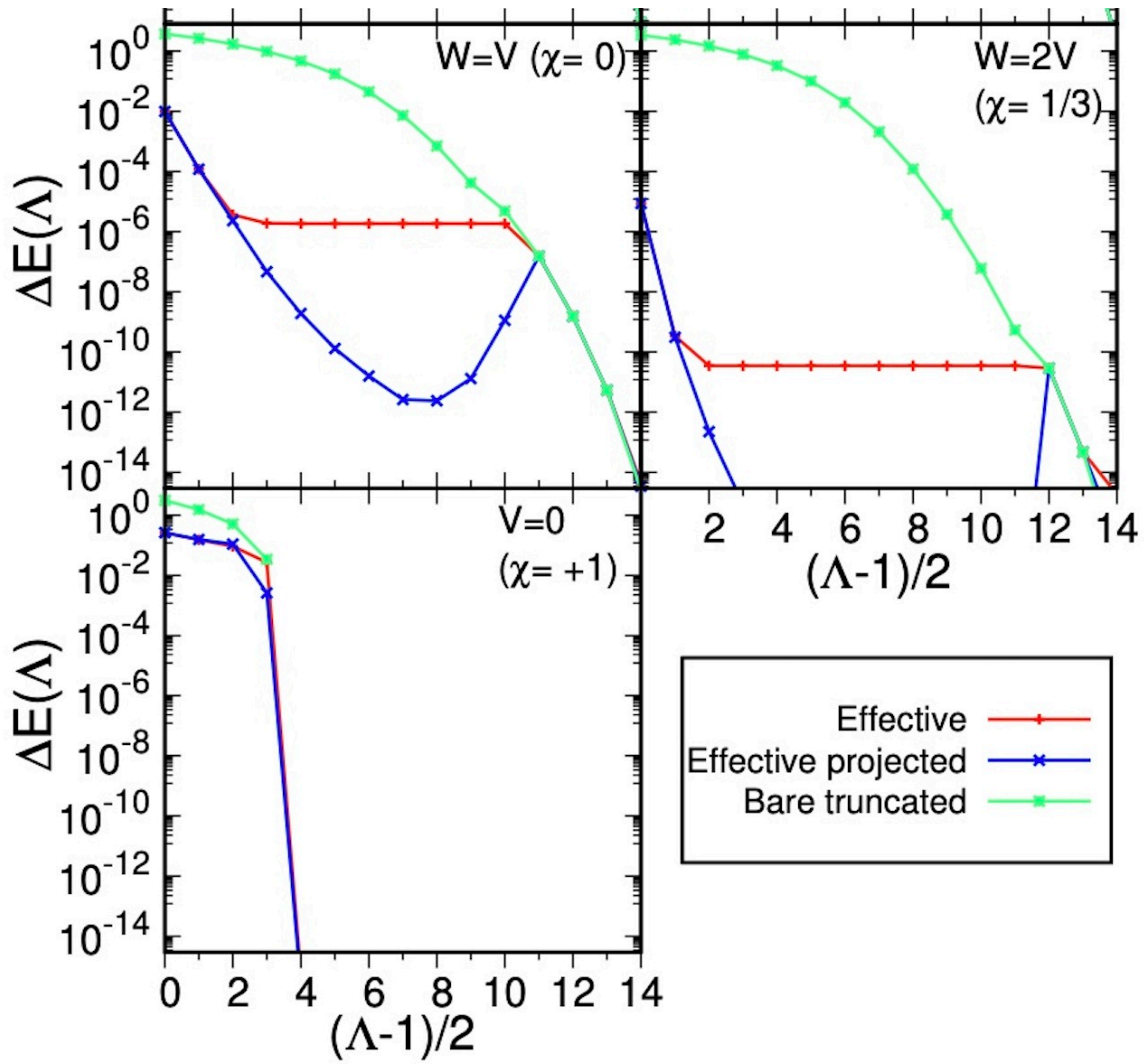
Regular Article – Theoretical Physics | Published: 17 October 2023

Volume 59, article number 231, (2023) Cite this article

S. Momme Hengstenberg, Caroline E. P. Robin & Martin J. Savage



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



$$\hat{H} = \frac{\varepsilon}{2}\sum_{\sigma p} \sigma \hat{c}^\dagger_{p\sigma}\hat{c}_{p\sigma} - \frac{V}{2}\sum_{pq\sigma} \hat{c}^\dagger_{p\sigma}\hat{c}^\dagger_{q\sigma}\hat{c}_{q-\sigma}\hat{c}_{p-\sigma} - \frac{W}{2}\sum_{pq\sigma} \hat{c}^\dagger_{p\sigma}\hat{c}^\dagger_{q-\sigma}\hat{c}_{q\sigma}\hat{c}_{p-\sigma} ,$$

$$= \varepsilon \hat{J}_z - \frac{V}{2}\left(\hat{J}_+^2 + \hat{J}_-^2\right) - \frac{W}{2}\left(\hat{J}_+\hat{J}_- + \hat{J}_-\hat{J}_+ - \hat{N}\right)$$

The Magic Power of the S-Matrix - Fluctuations in Magic

$$\overline{\mathcal{M}}(\hat{\mathbf{S}}) \equiv \frac{1}{\mathcal{N}_{ss}} \sum_{i=1}^{\mathcal{N}_{ss}} \mathcal{M}\left(\hat{\mathbf{S}}\,|\Psi_i\rangle\right)$$

arXiv > nucl-th > arXiv:2405.10268

Nuclear Theory

[Submitted on 16 May 2024 (v1), last revised 20 May 2024 (this version, v2)]

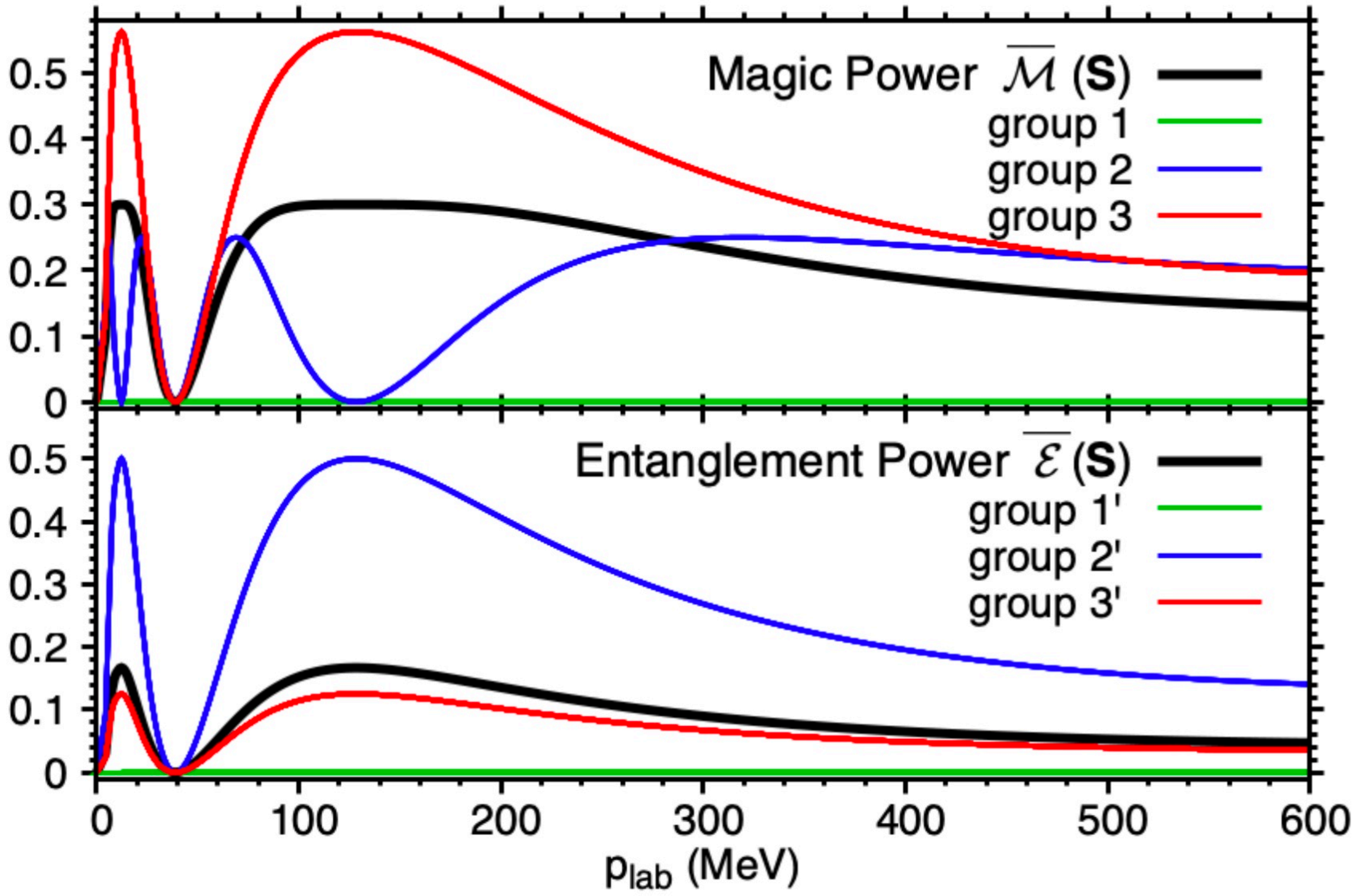
The Magic in Nuclear and Hypernuclear Forces

Caroline E. P. Robin, Martin J. Savage

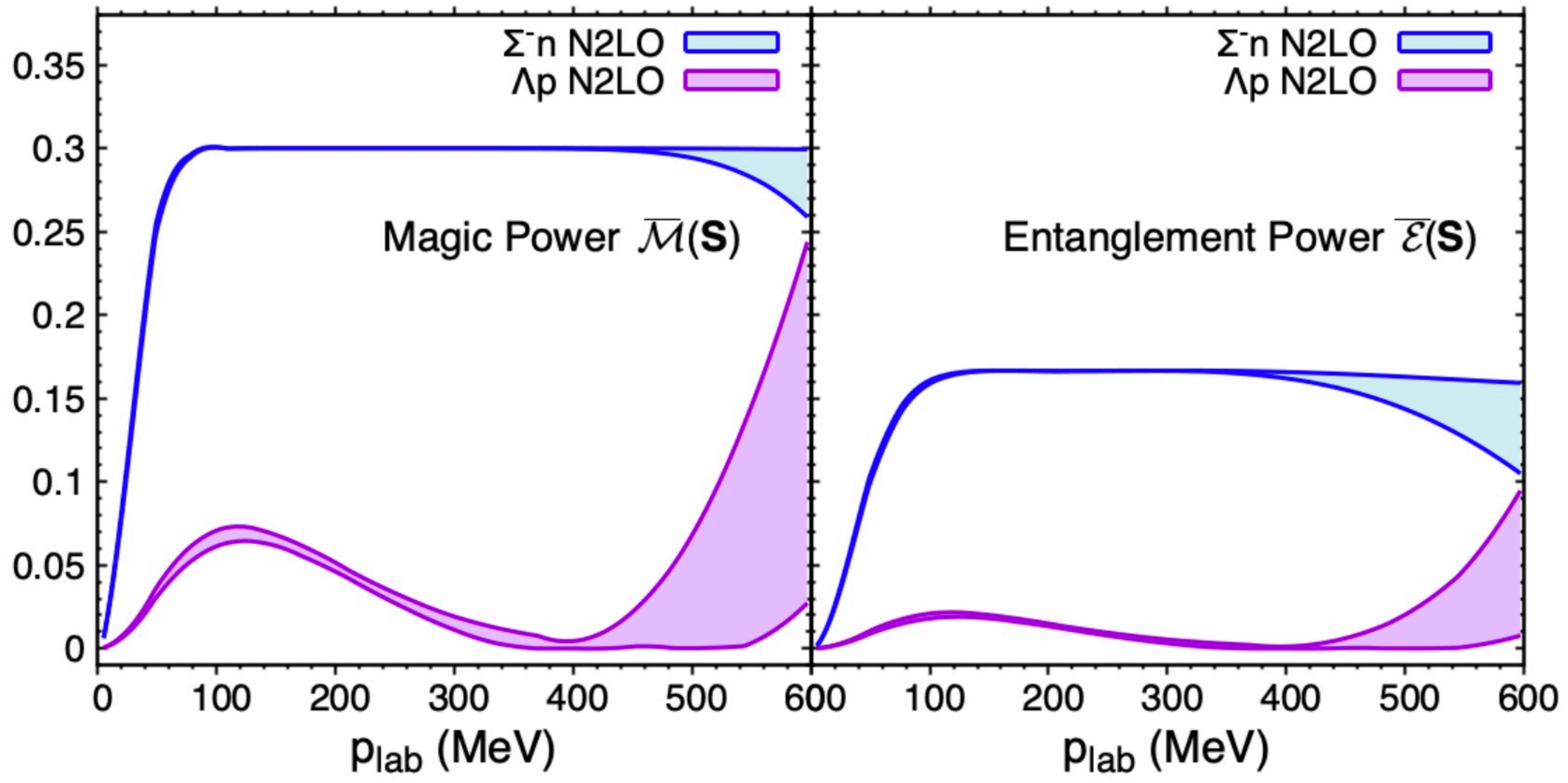
$$\hat{\mathbf{S}}_\sigma = \frac{1}{4}\left(3e^{i2\delta_3} + e^{i2\delta_1}\right)\hat{\mathbf{1}} \;+\; \frac{1}{4}\left(e^{i2\delta_3} - e^{i2\delta_1}\right)\hat{\boldsymbol{\sigma}}\cdot\hat{\boldsymbol{\sigma}}$$

$$\overline{\mathcal{M}}(\hat{\mathbf{S}}) = \frac{3}{20}\left(3+\cos(4\,\Delta\delta)\right)\sin^2(2\,\Delta\delta)\,,$$

$$\overline{\mathcal{E}}(\hat{\mathbf{S}}) = \frac{1}{6}\sin^2(2\,\Delta\delta)\,,$$



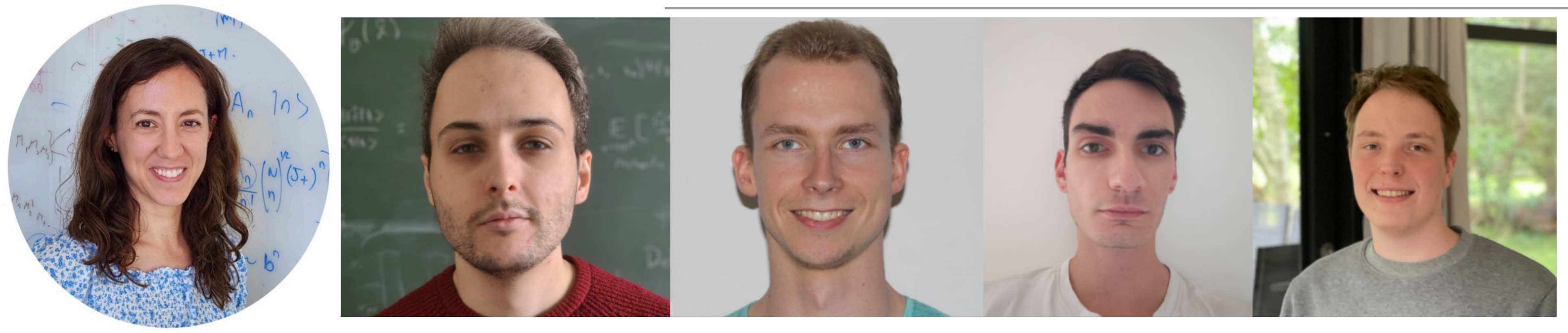
Neutron-Proton



Hyperon-Nucleon

Indicates the fluctuations in quantum magic due to nuclear forces

Magic and Multi-Partite Entanglement in Nuclei



Quantum magic and multipartite entanglement in the structure of nuclei

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

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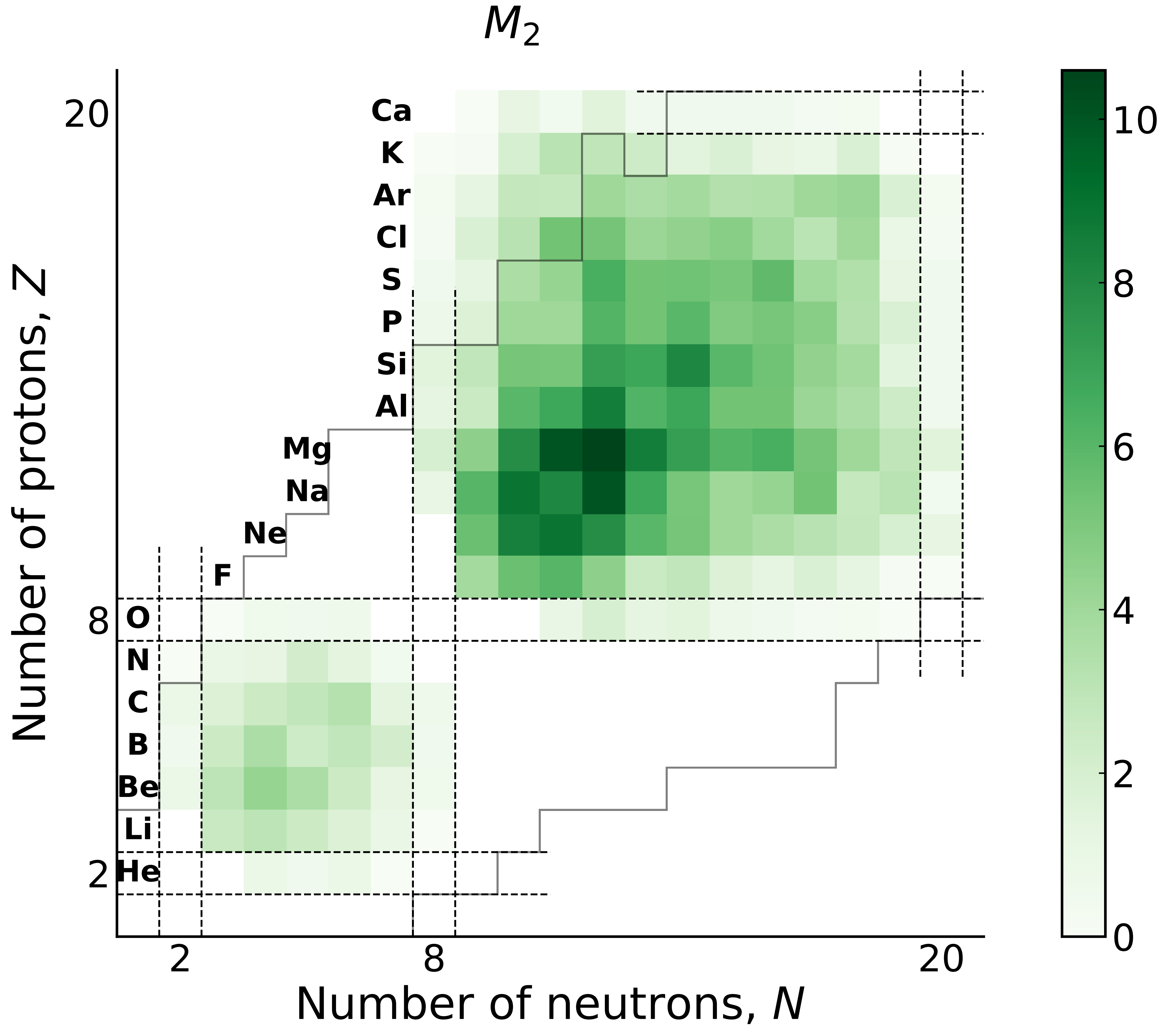
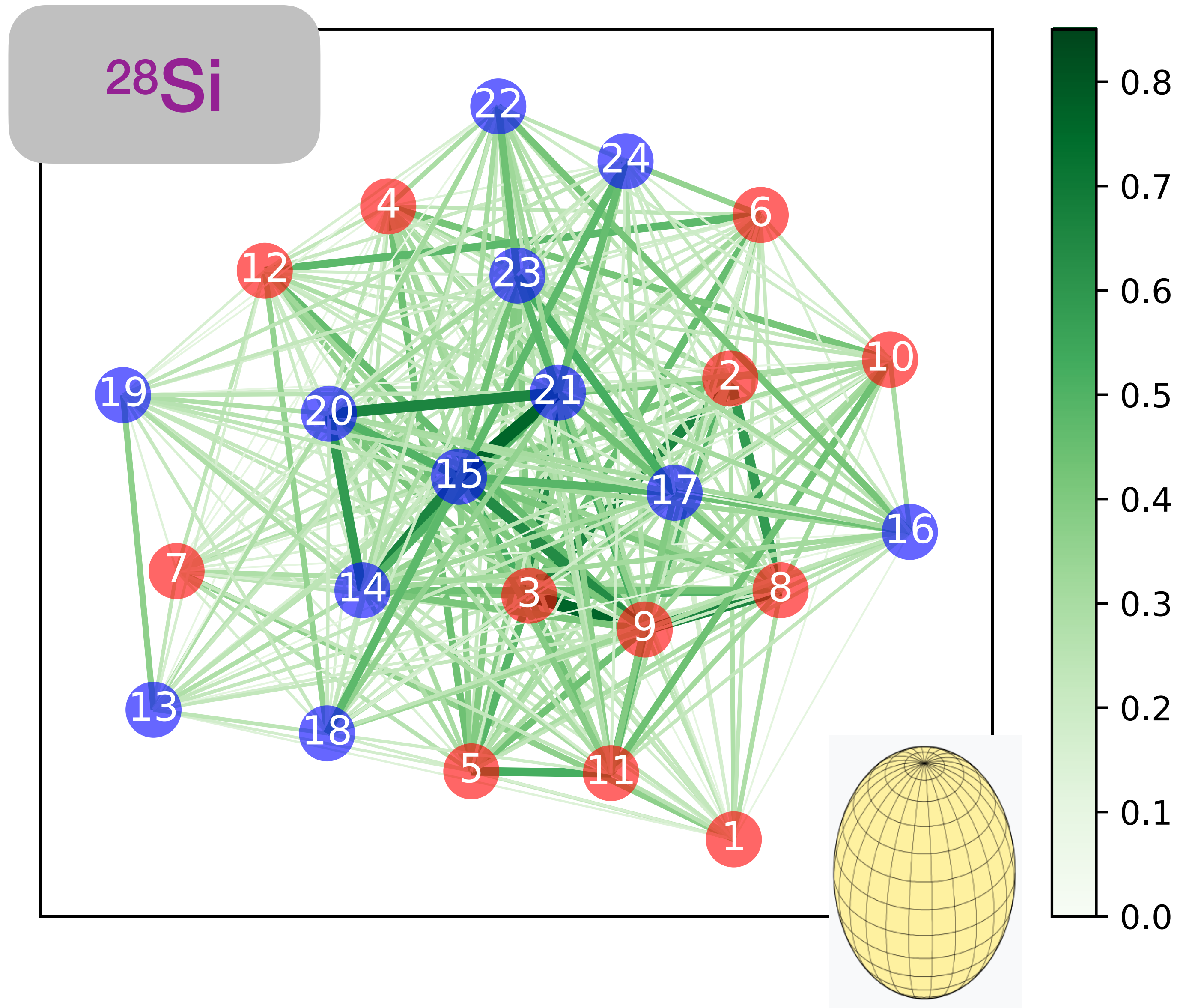
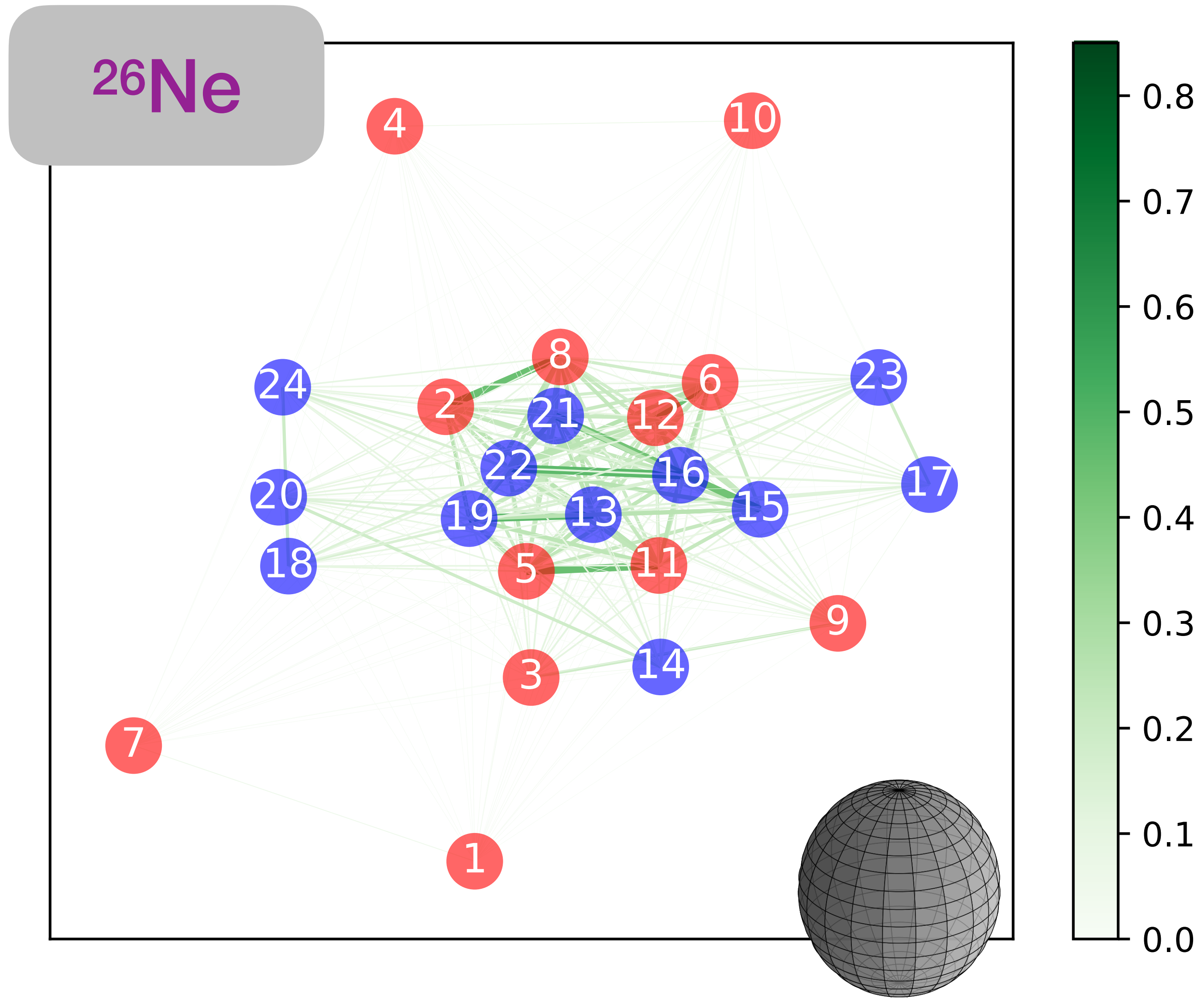
Phys. Rev. C **111**, 034317 – **Published 11 March, 2025**

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

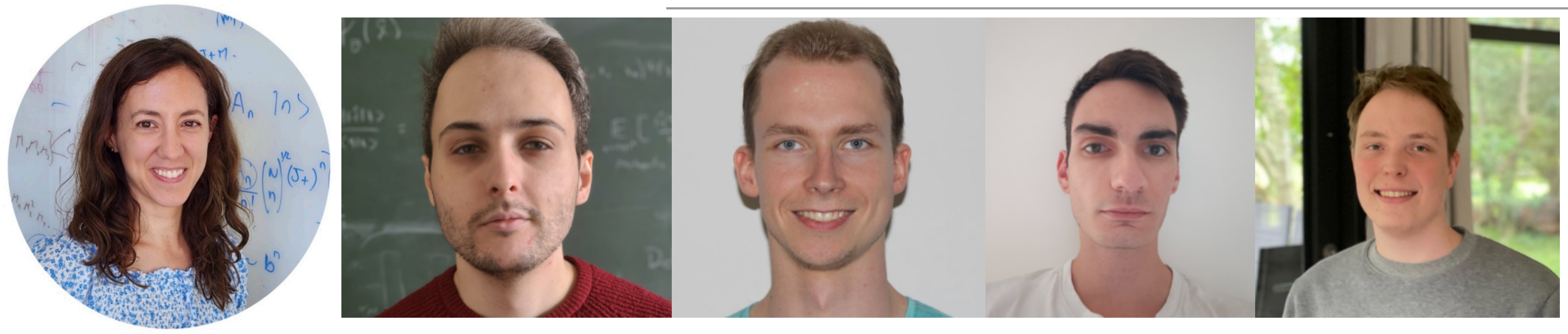






8-tangles

Magic and Multi-Partite Entanglement in Nuclei



Quantum magic and multipartite entanglement in the structure of nuclei

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

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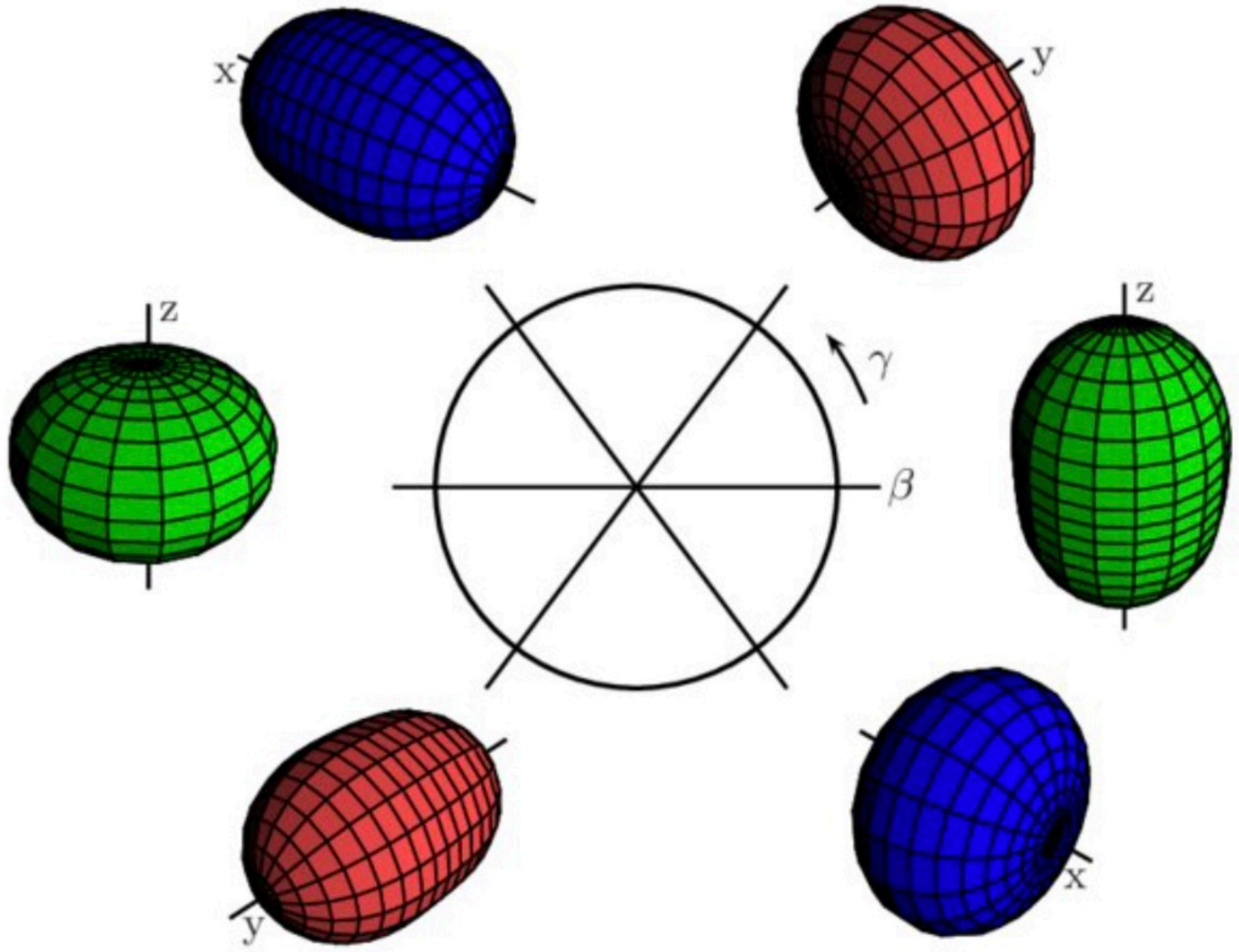
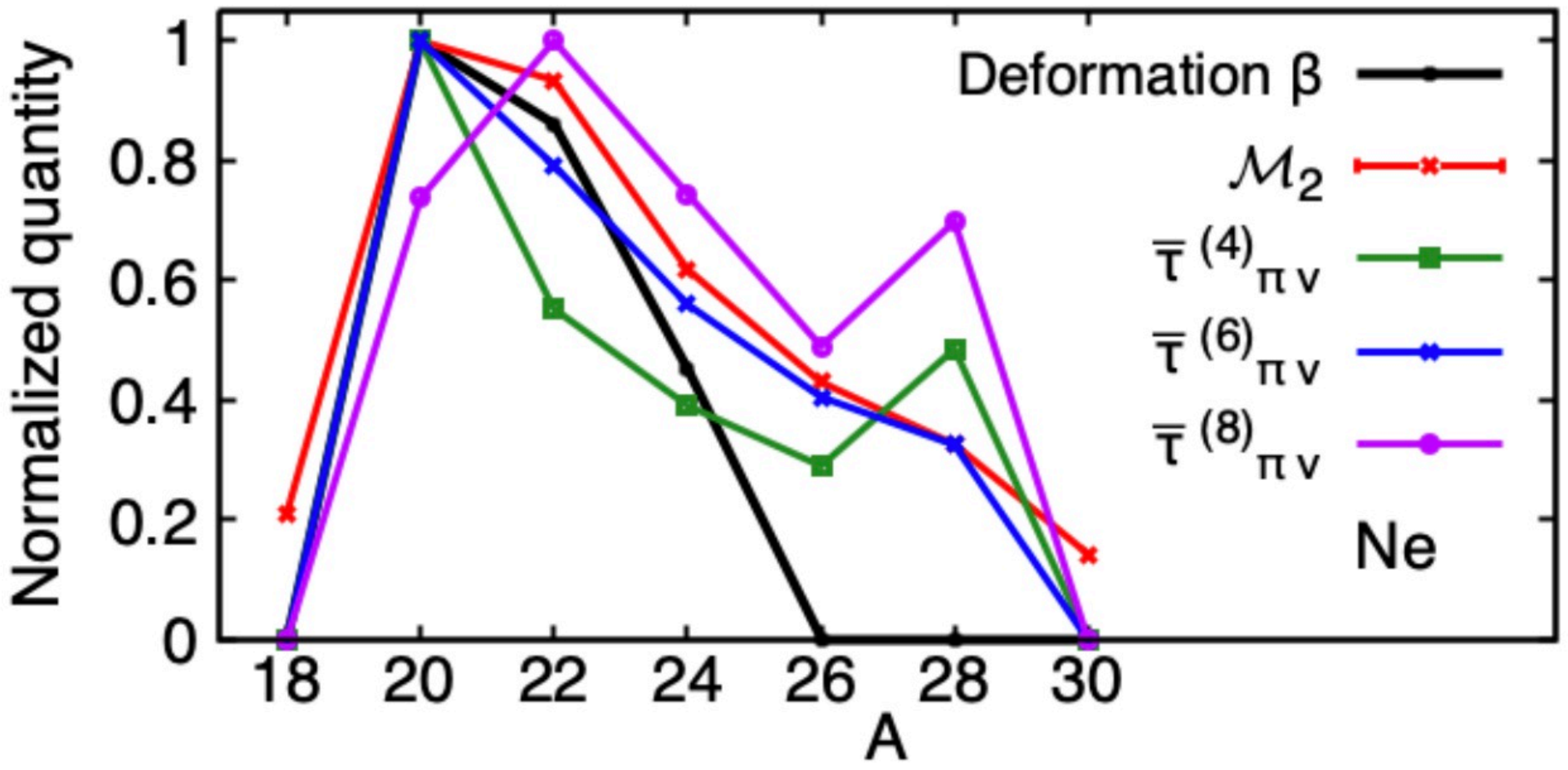
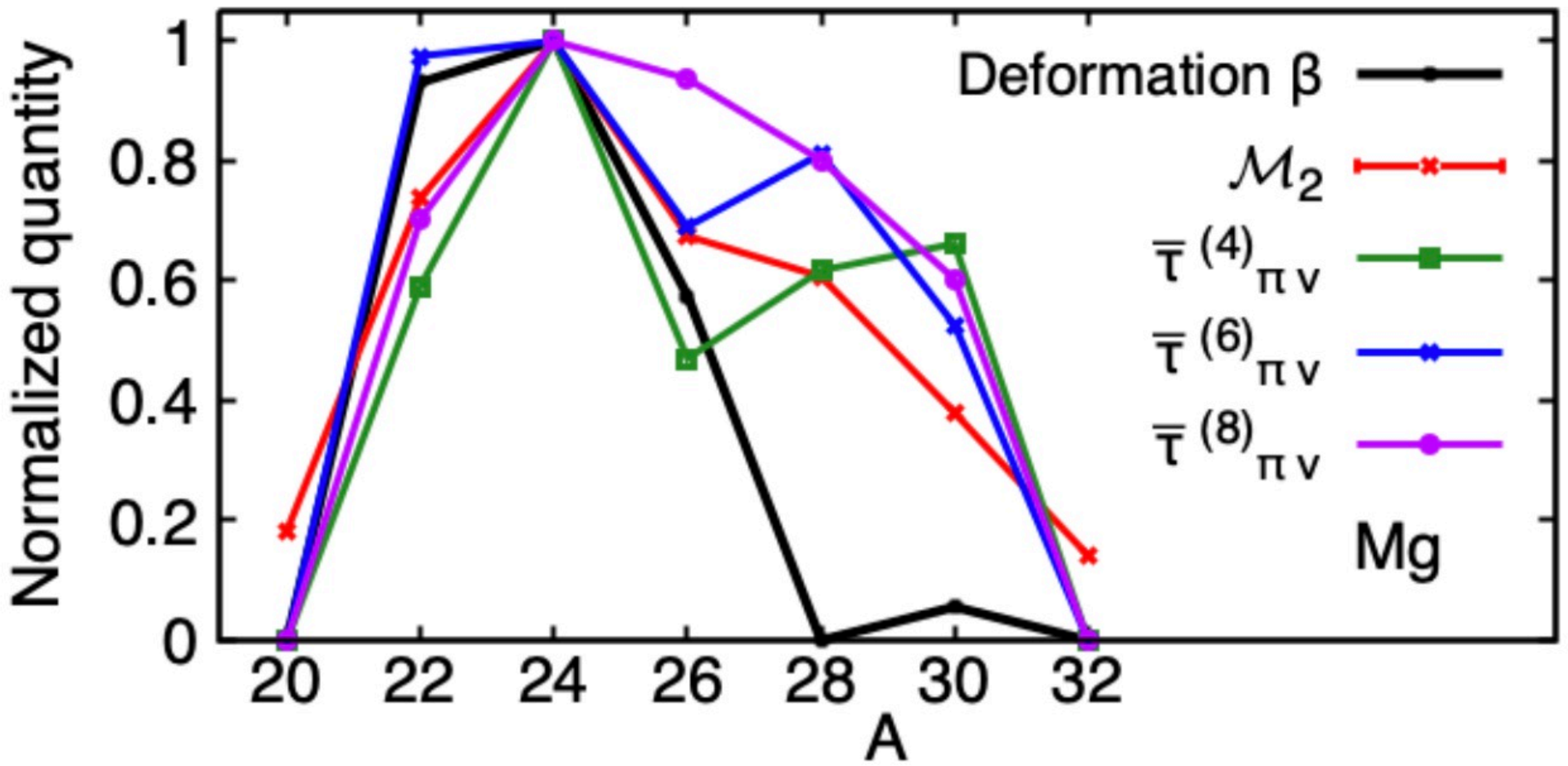


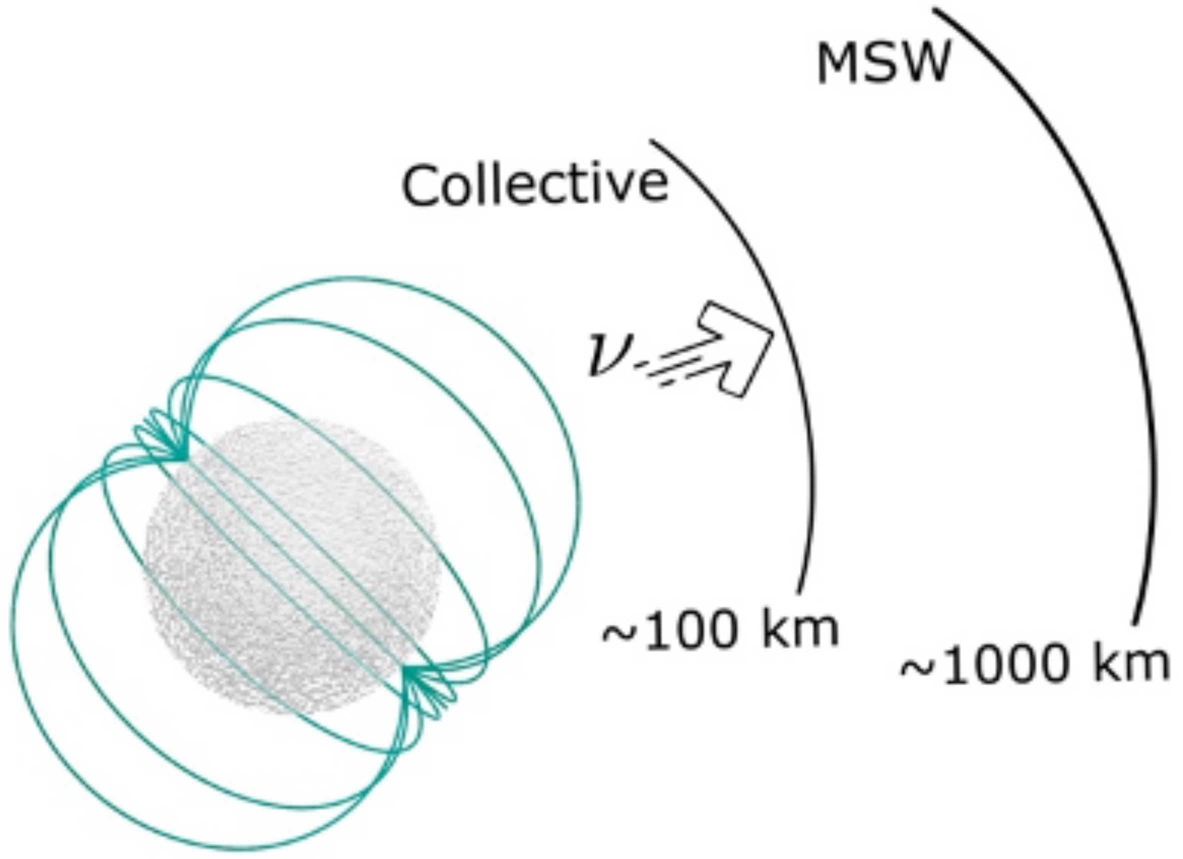


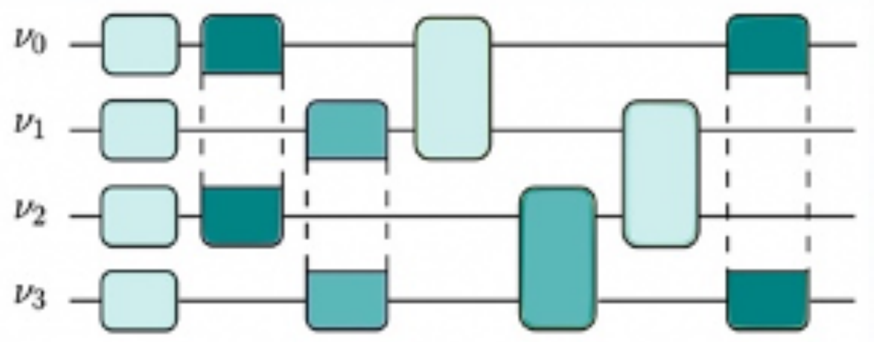


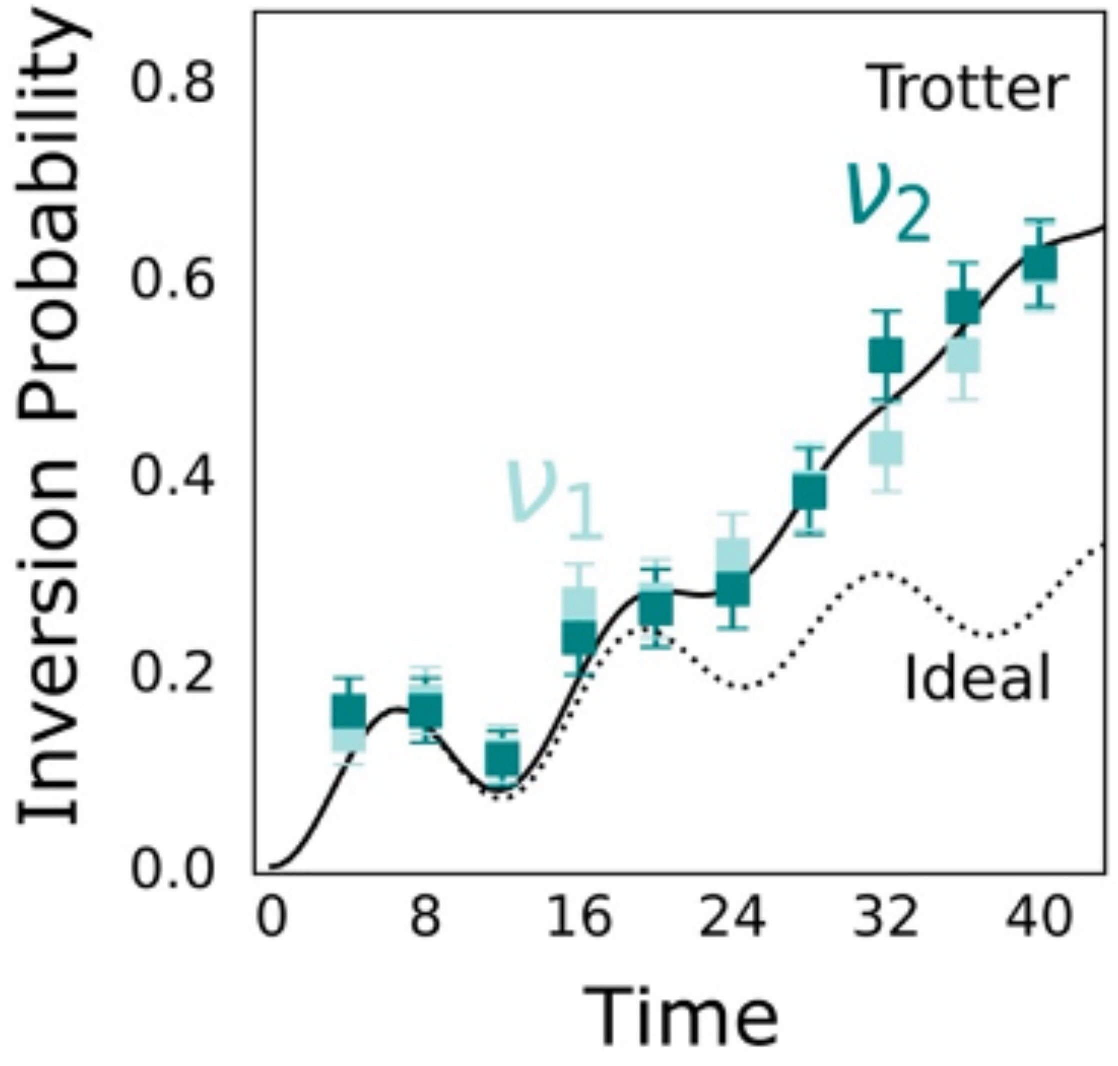
$$H_{FS} = -\sum_{k=1}^{N} \frac{\omega_k}{2}\sigma_k^z + \frac{\mu}{2N}\sum_{i<j}^{N} \mathcal{J}_{ij}\vec{\sigma}_i \cdot \vec{\sigma}_j$$

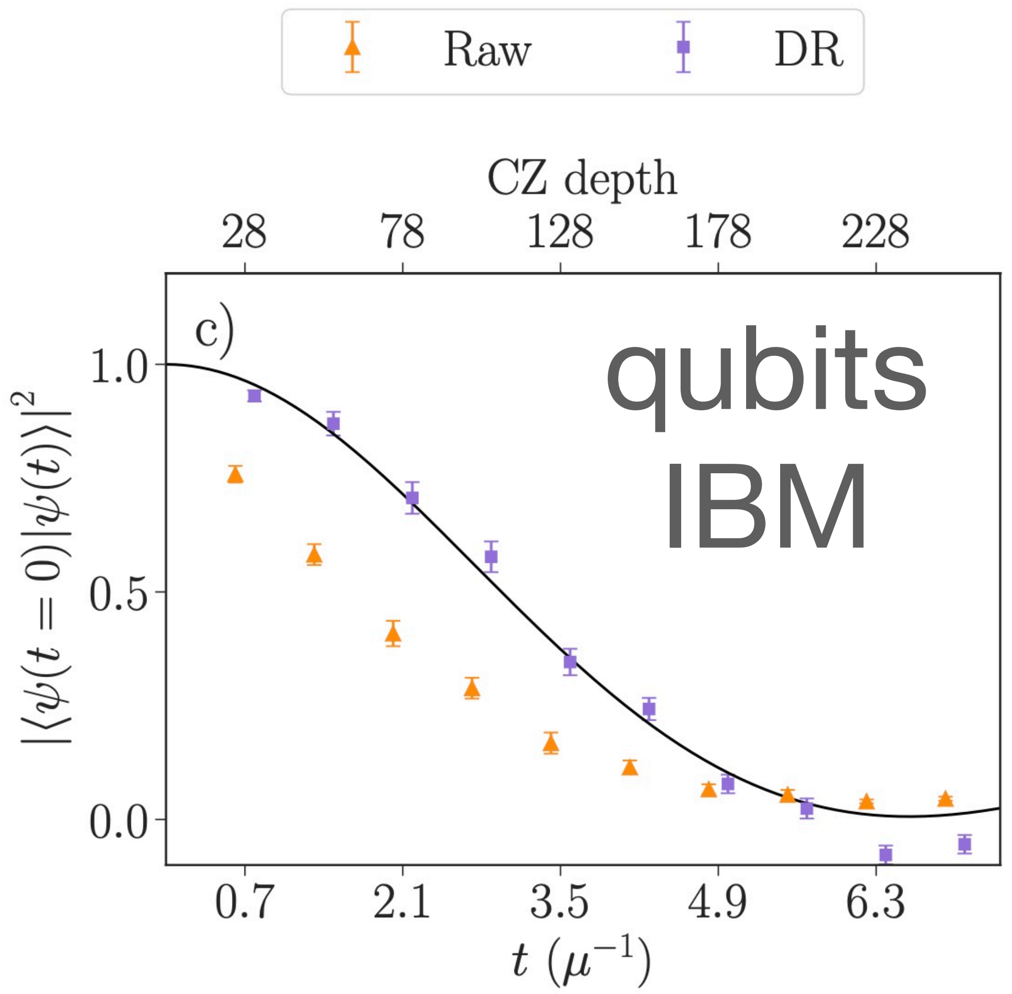
Neutrino Flavor Dynamics in Supernova

Simulations with qubits and qutrits

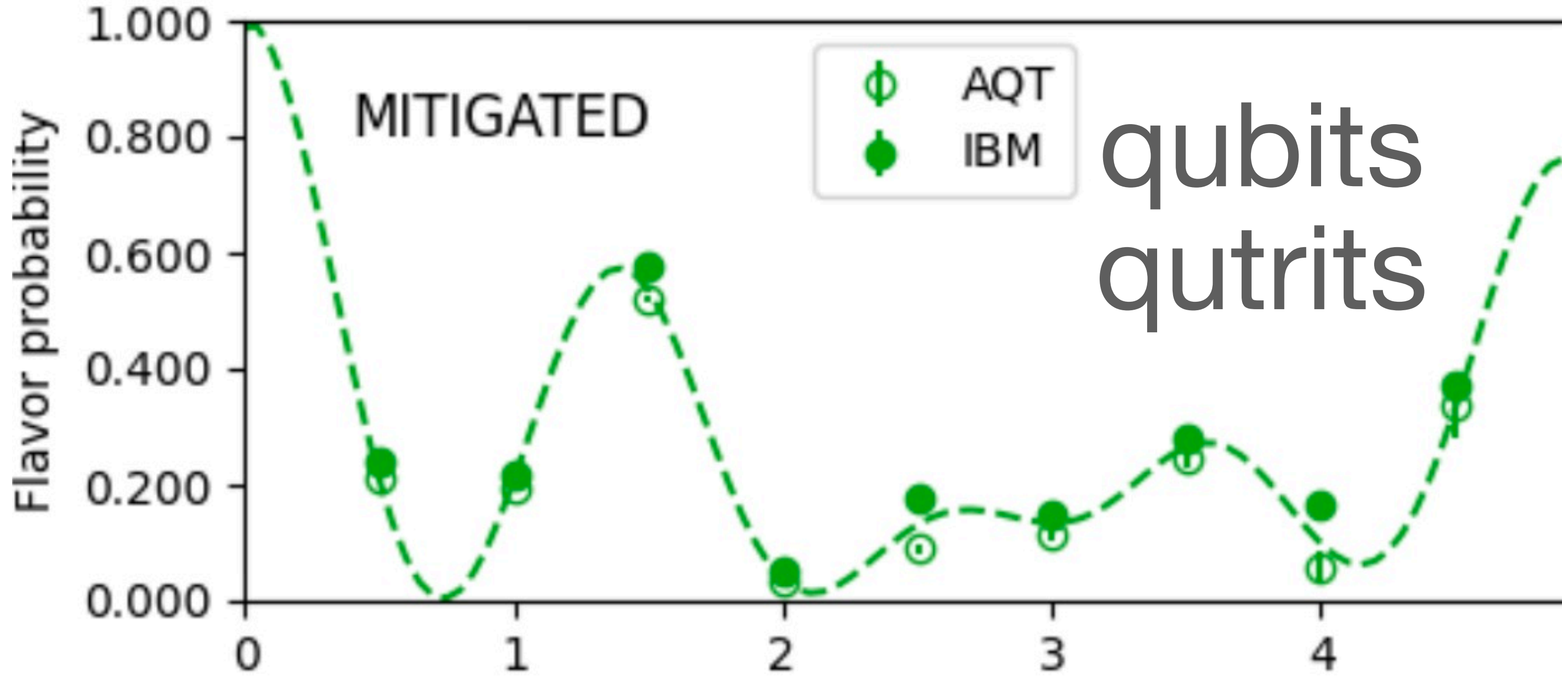








Turro et al (2024)



Spagnoli et al (2025)

Quantum Complexity in Neutrinos - Qutrits

Quantum magic and computational complexity in the neutrino sector

Ivan Chernyshev[1,*], Caroline E. P. Robin[2,3,†], and Martin J. Savage[1,‡,§]

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Phys. Rev. Research **7**, 023228 – **Published 4 June, 2025**

DOI: https://doi.org/10.1103/PhysRevResearch.7.023228

For the two-qutrit system, explicit calculation gives a maximum value of magic in a tensor-product state of $M_2 = 2$ (consistent with 2× the maximum value for a single three-flavor neutrino), while entangled states can support a maximum value of $M_2 = 2.23379$.

$$\hat{\Sigma}_i \in \{\hat{I}, \hat{X}, \hat{Z}, \hat{X}^2, \omega\hat{X}\hat{Z}, \hat{Z}^2, \omega^2\hat{X}\hat{Z}^2, \hat{X}^2\hat{Z}, \hat{X}^2\hat{Z}^2\},$$

$$\hat{X}|j\rangle = |j+1\rangle \ , \ \hat{Z}|j\rangle = \omega^j|j\rangle \ , \ \omega = e^{i2\pi/3}$$

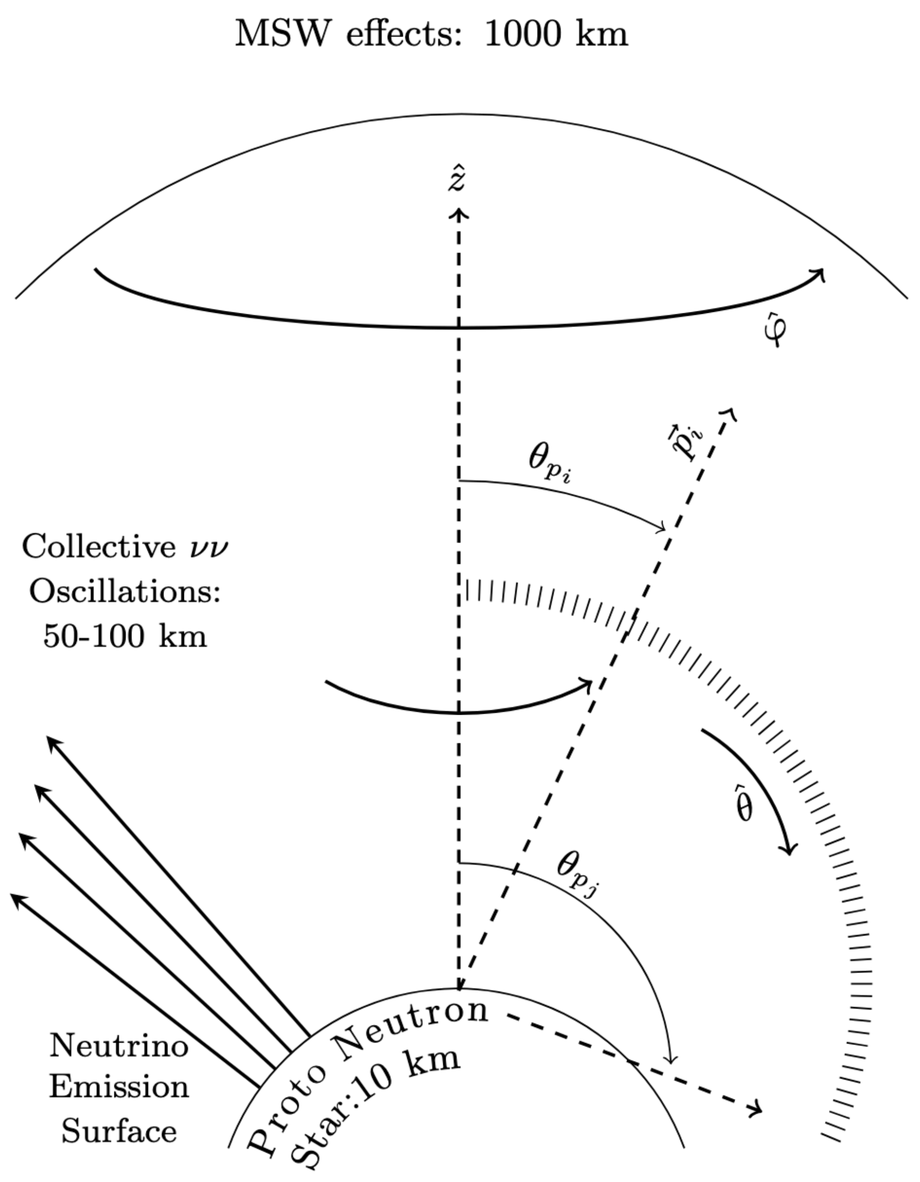
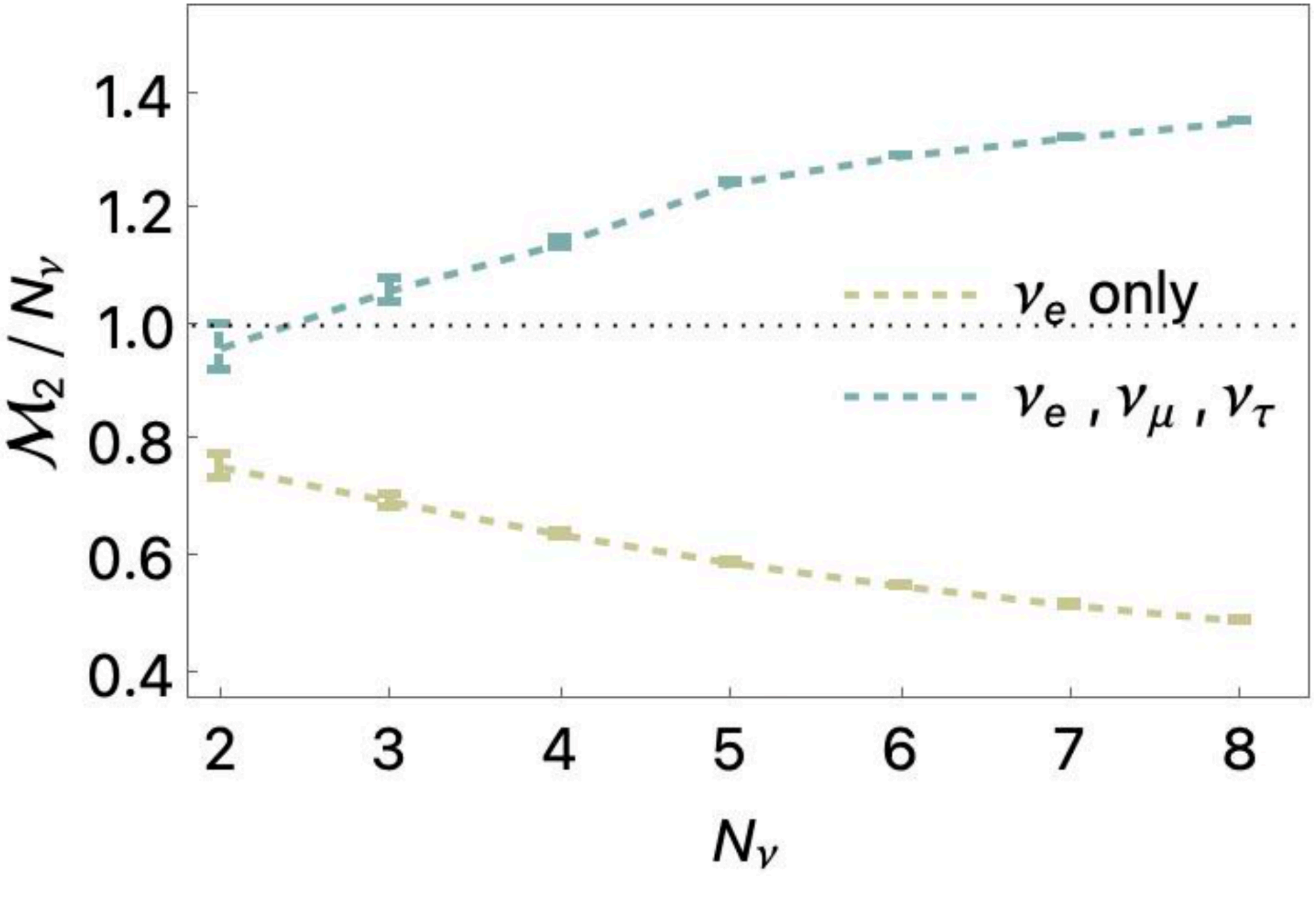
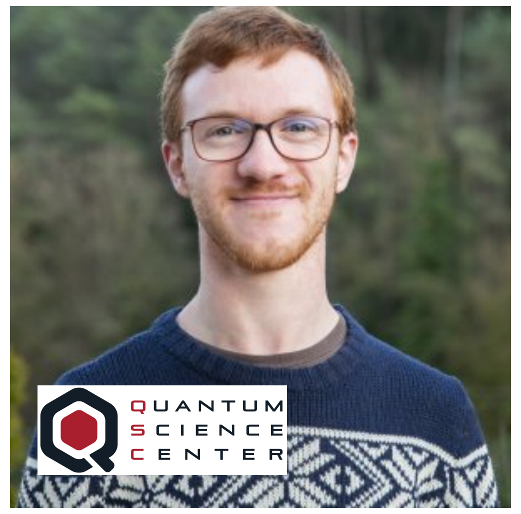


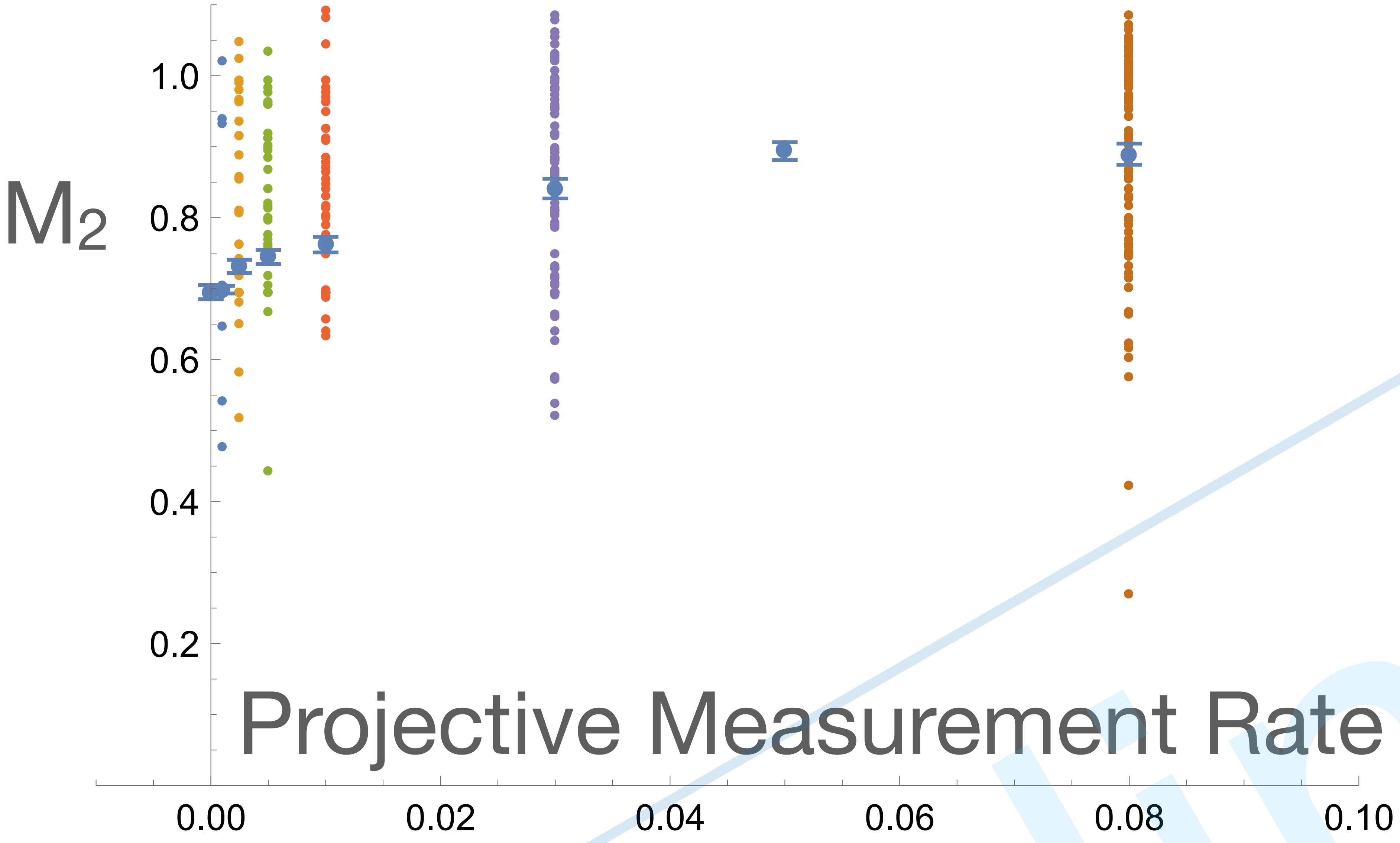
Figure created by Ramya Bhaskar

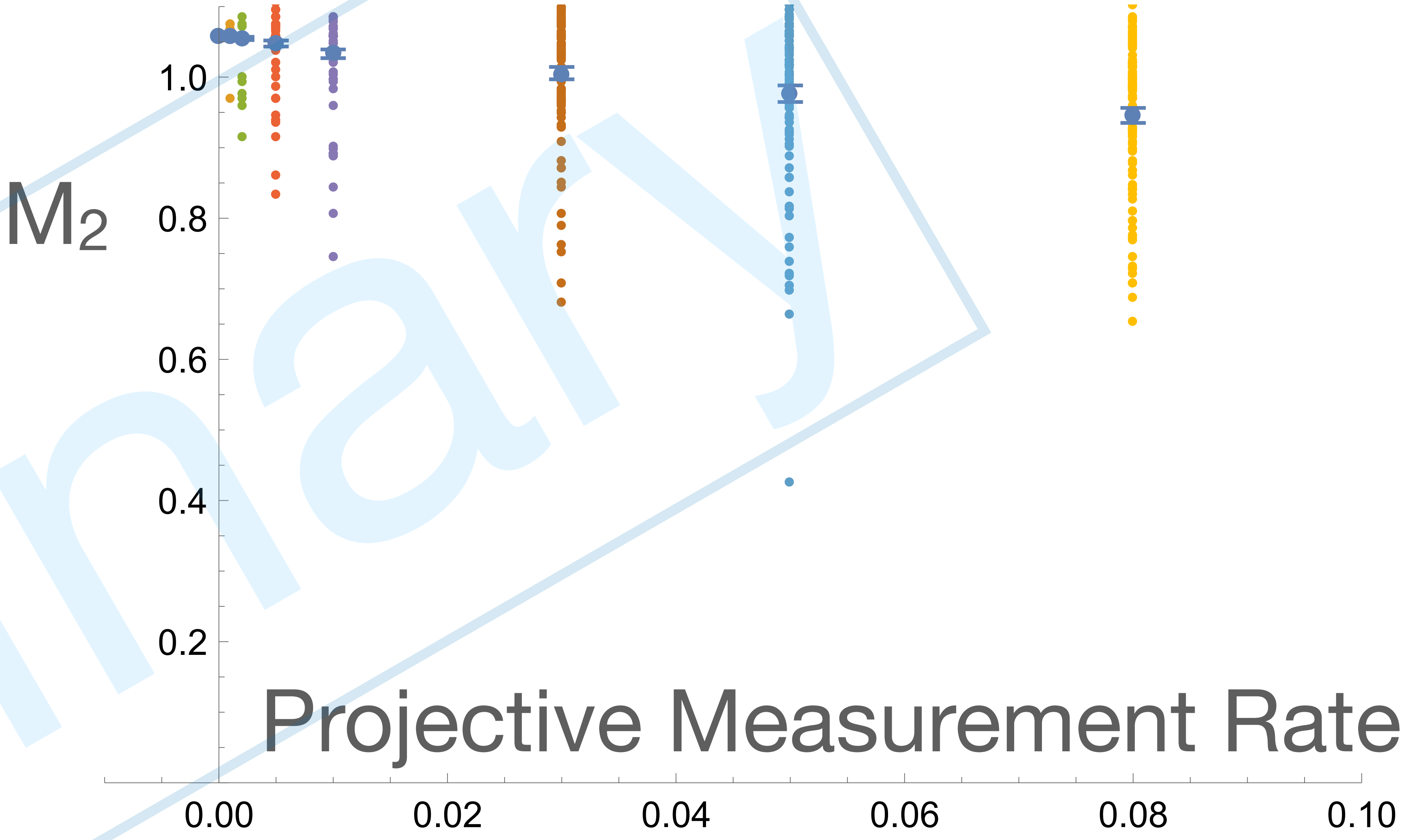


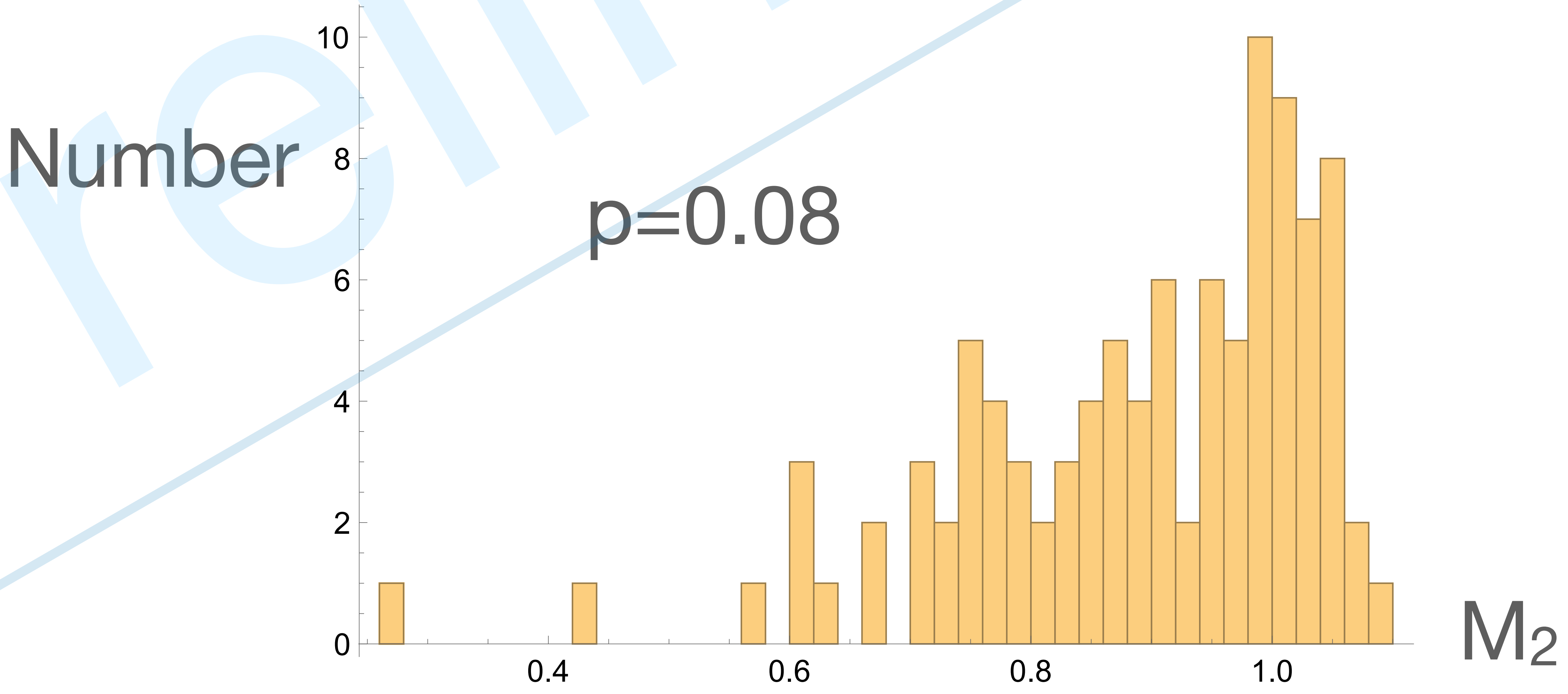
Quantum Complexity in Neutrinos

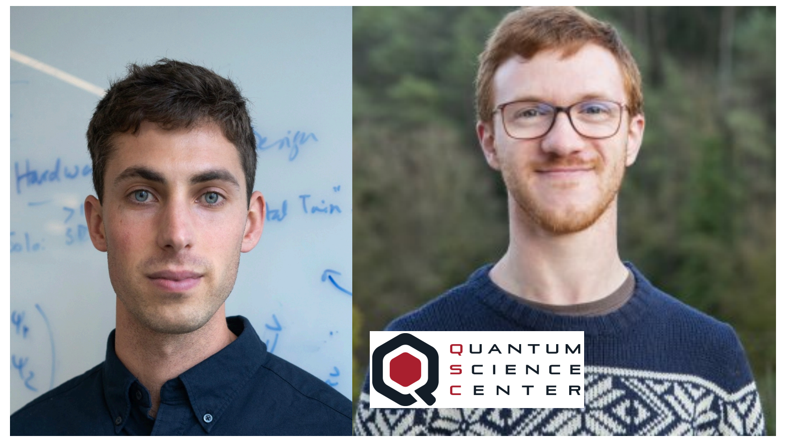


Marc Illa and Caroline Robin









Lorentz Violation by Lattice Spacing

Steps toward quantum simulations of hadronization and energy loss in dense matter

Roland C. Farrell[1,2,*], Marc Illa[1,†], and Martin J. Savage[1,‡,§]

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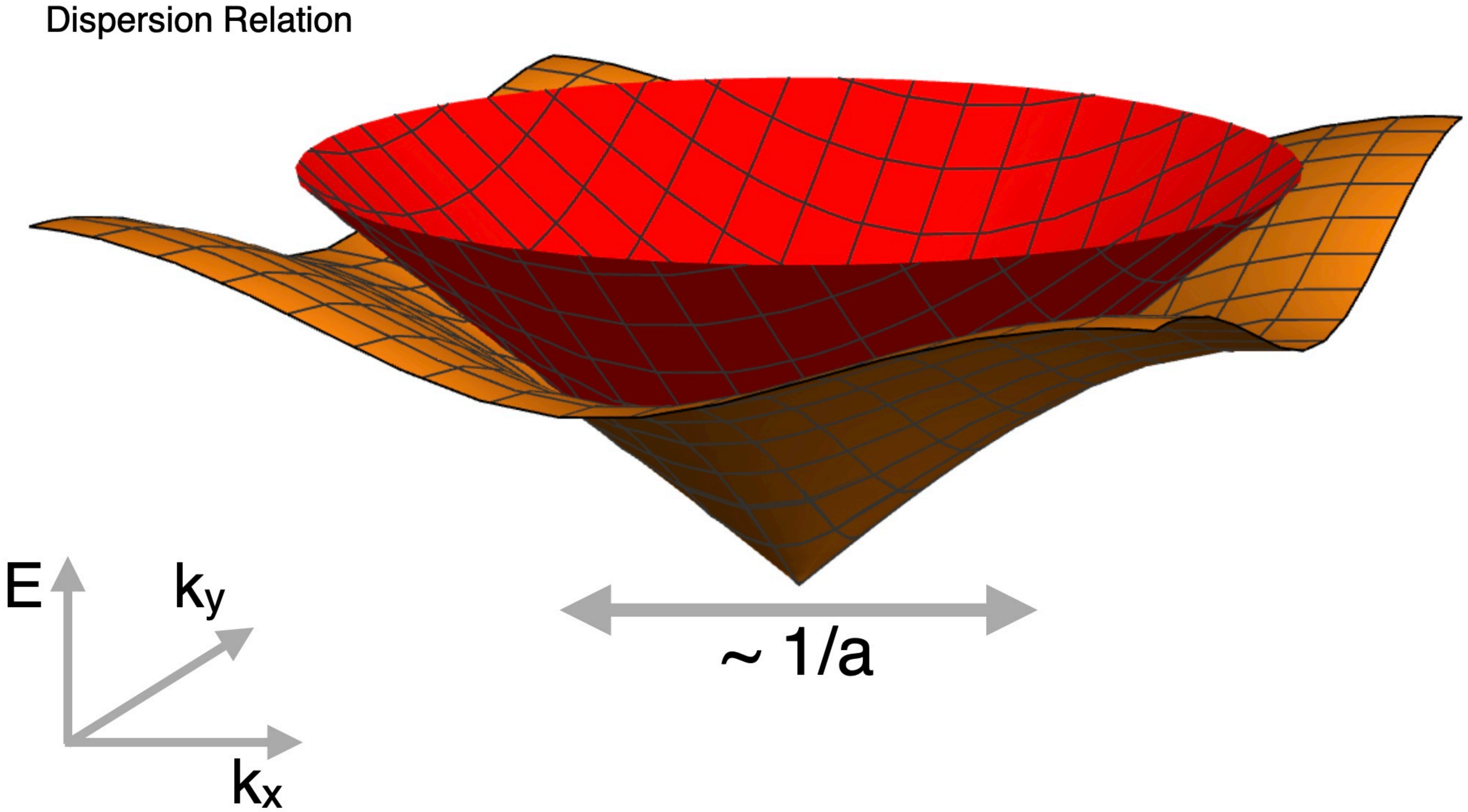
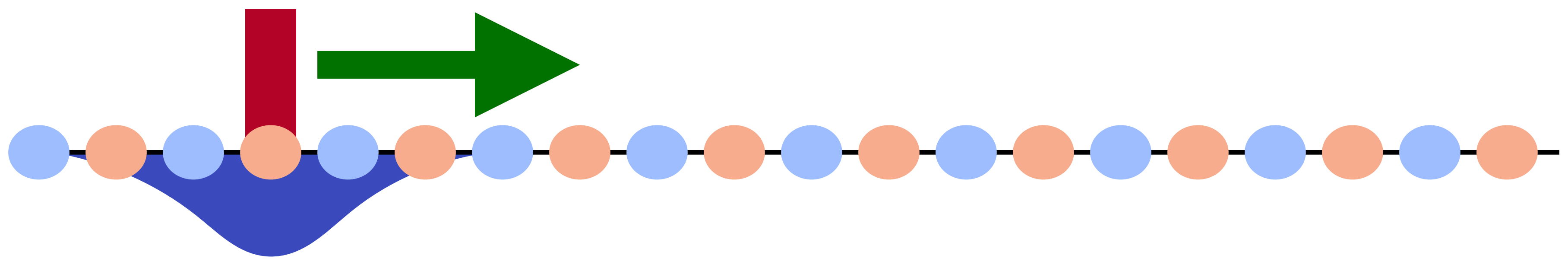
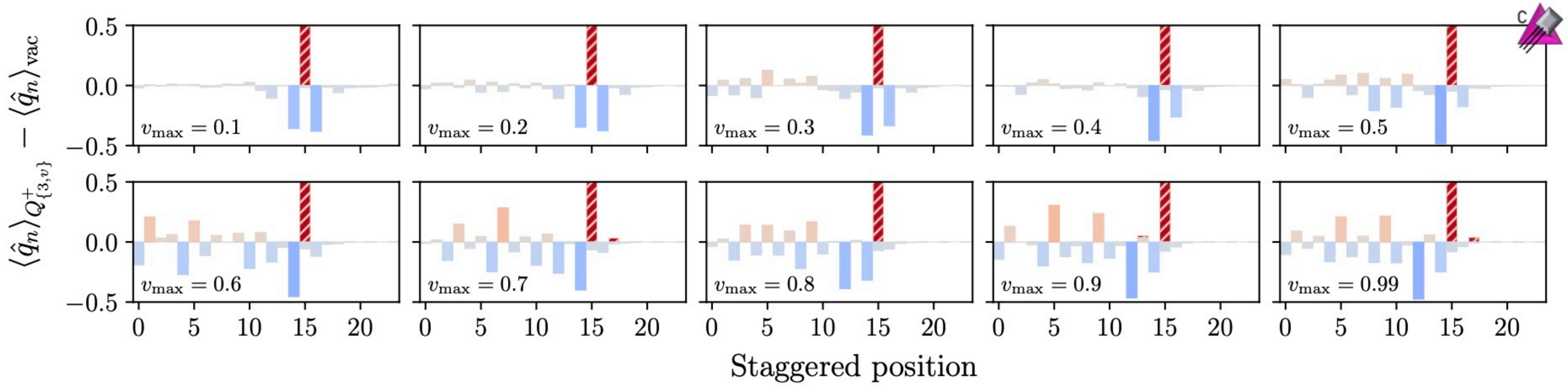
Phys. Rev. C **111**, 015202 – **Published 14 January, 2025**

DOI: https://doi.org/10.1103/PhysRevC.111.015202



Lorentz Violation by the Lattice Spacing





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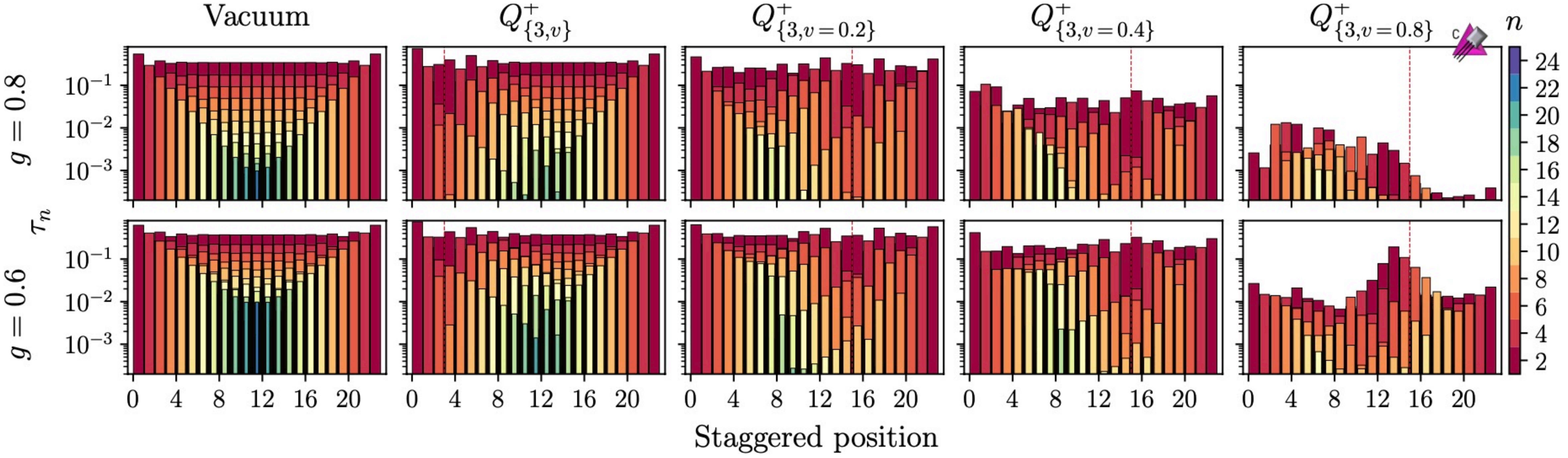
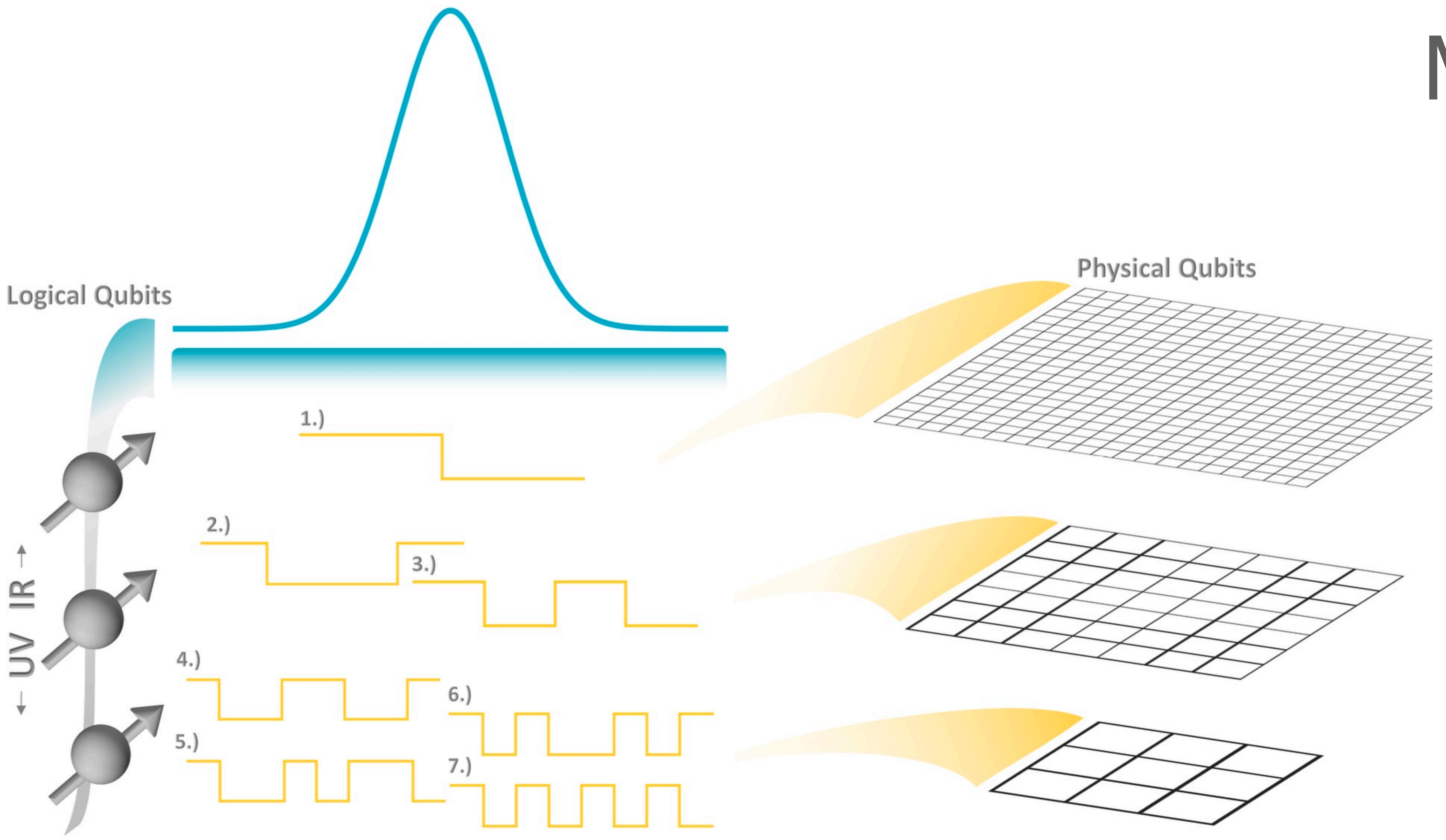
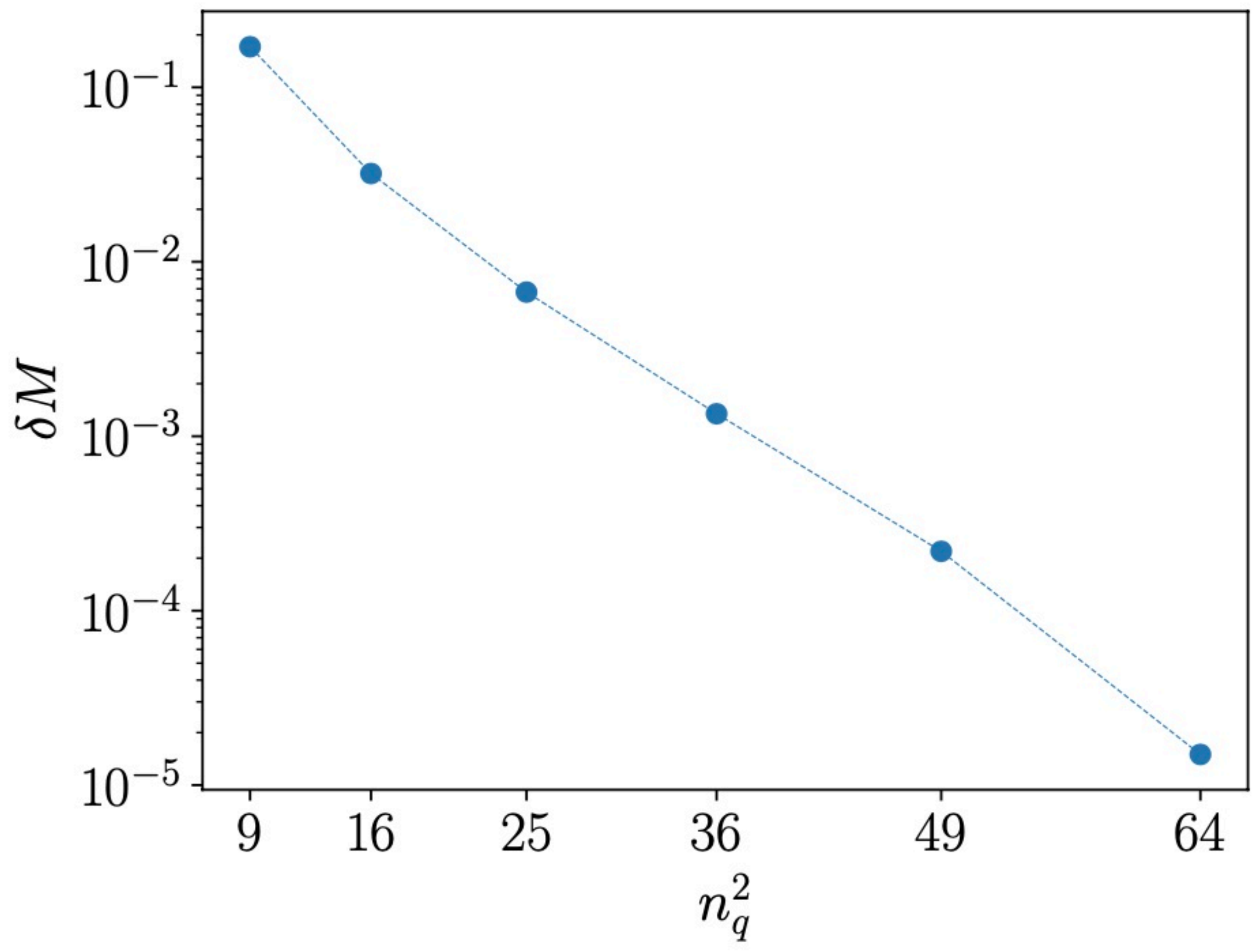


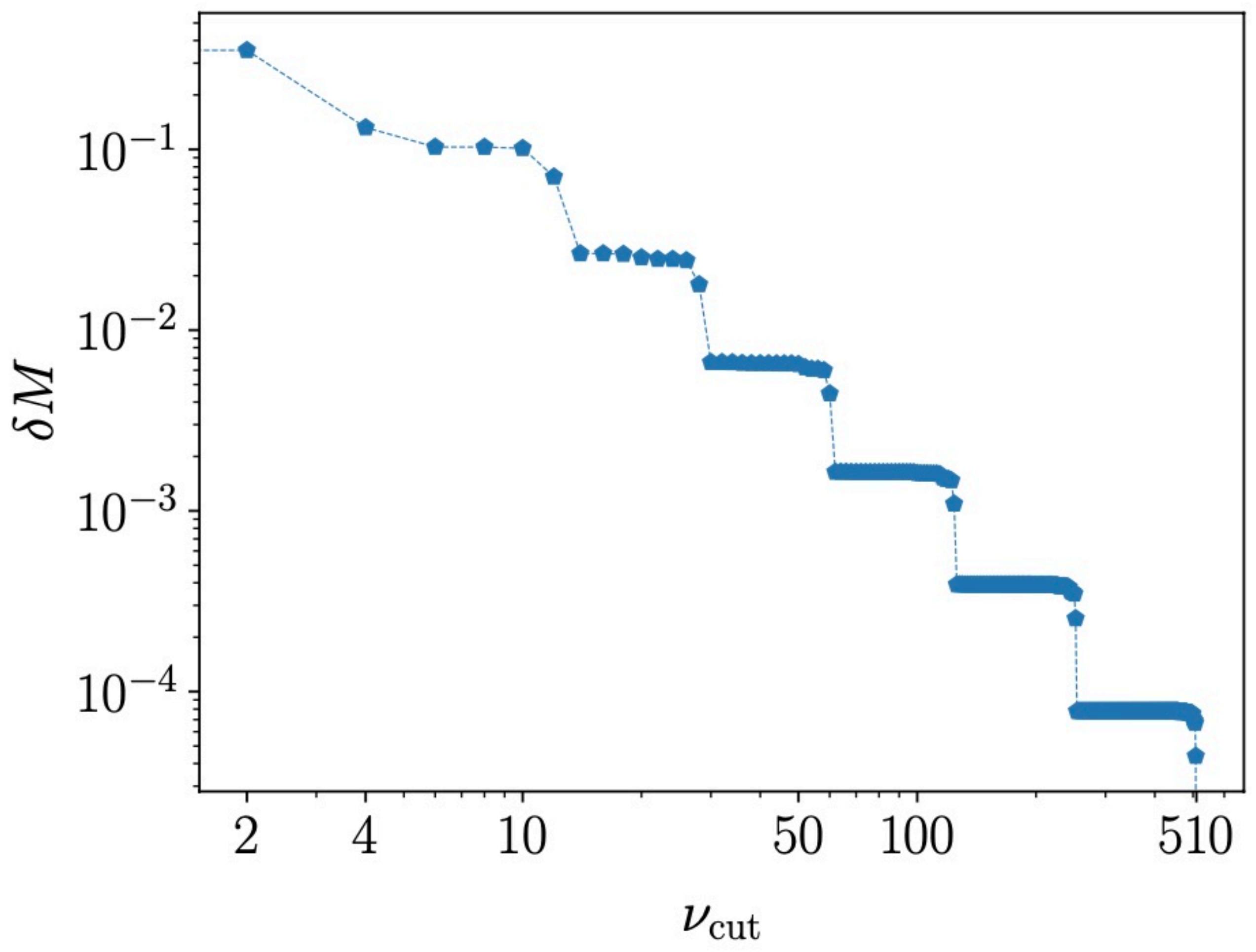
What is the Magic doing?

From NISQ to Fault Tolerant
Sequency Hierarchies

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







UV versus IR qubits

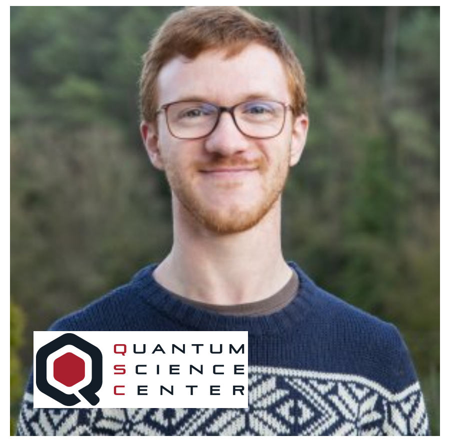

Hierarchical qubit maps and hierarchically implemented quantum error correction

Natalie Klco and Martin J. Savage

Phys. Rev. A **104**, 062425 – Published 15 December 2021

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

- e-Print: 2407.13835 [quant-ph] Zhiyao Li [*] Dorota M. Grabowska [†] and Martin J. Savage [‡]

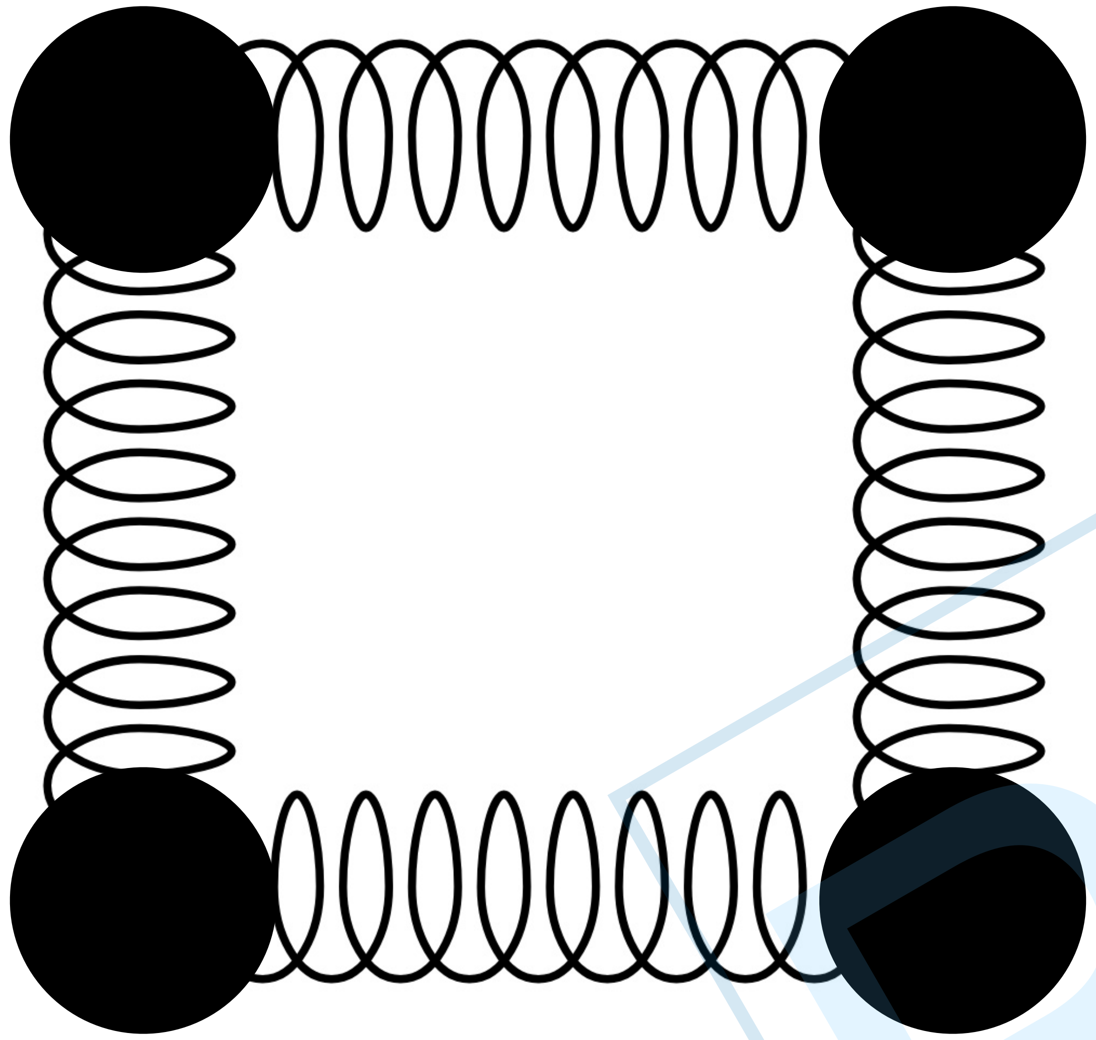


1-Plaquette of SU(2) Yang-Mills
Magic to Guide Truncations (?)

Marc Illa + MJS

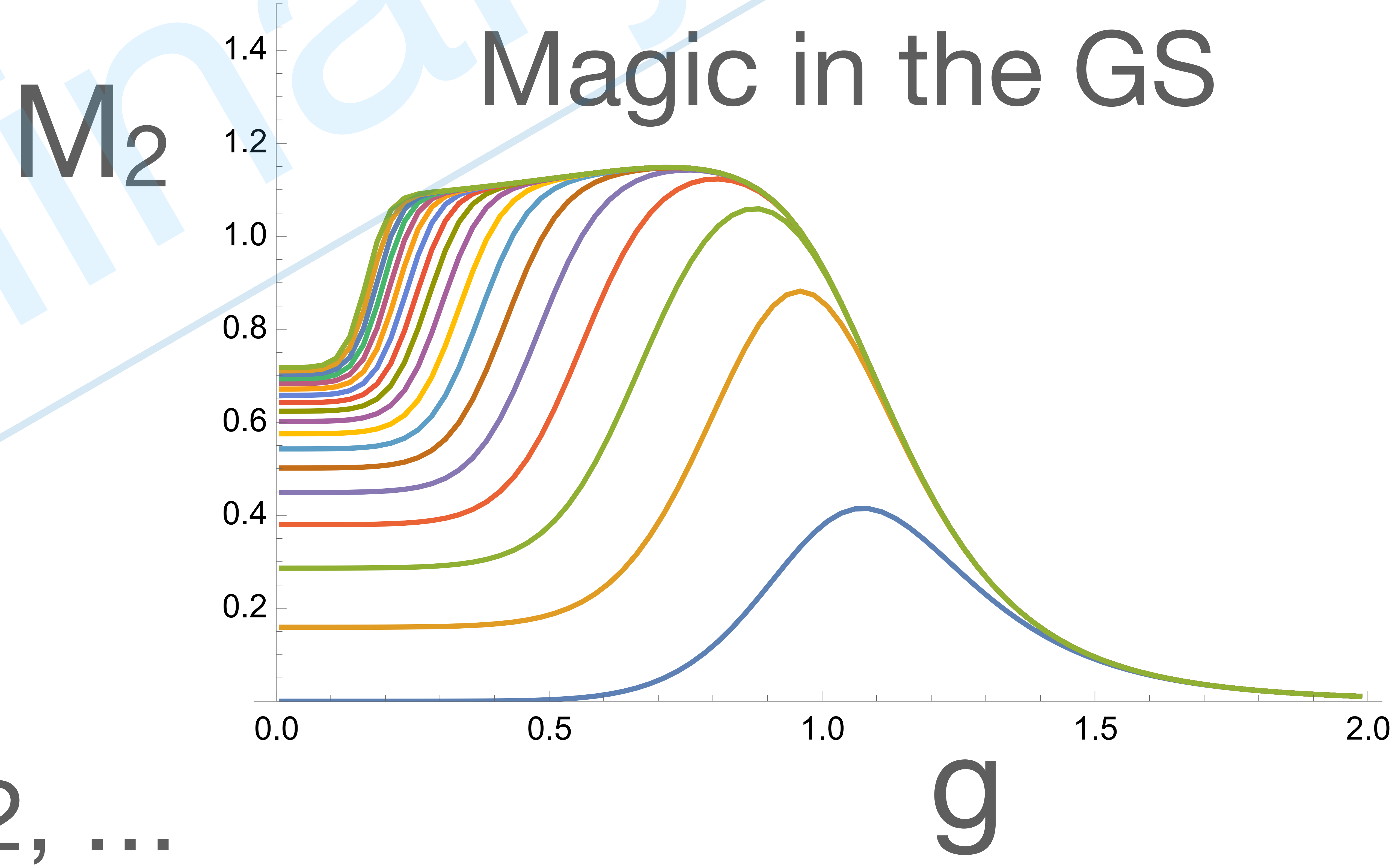
$$\hat{H} = \frac{g^2}{2} \sum_{\mathrm{a,links}} |\mathbf{E}^a|^2 + \frac{1}{2g^2} \left(4 - \hat{\Box} - \hat{\Box}^\dagger \right)$$

$$H_{j,j'} = \frac{1}{2} g^2 j(j+1)\delta_{j,j'} + \frac{1}{g^2}\left(2\delta_{j,j'} - \delta_{j+1,j'} - \delta_{j-1,j'}\right)$$



qudit

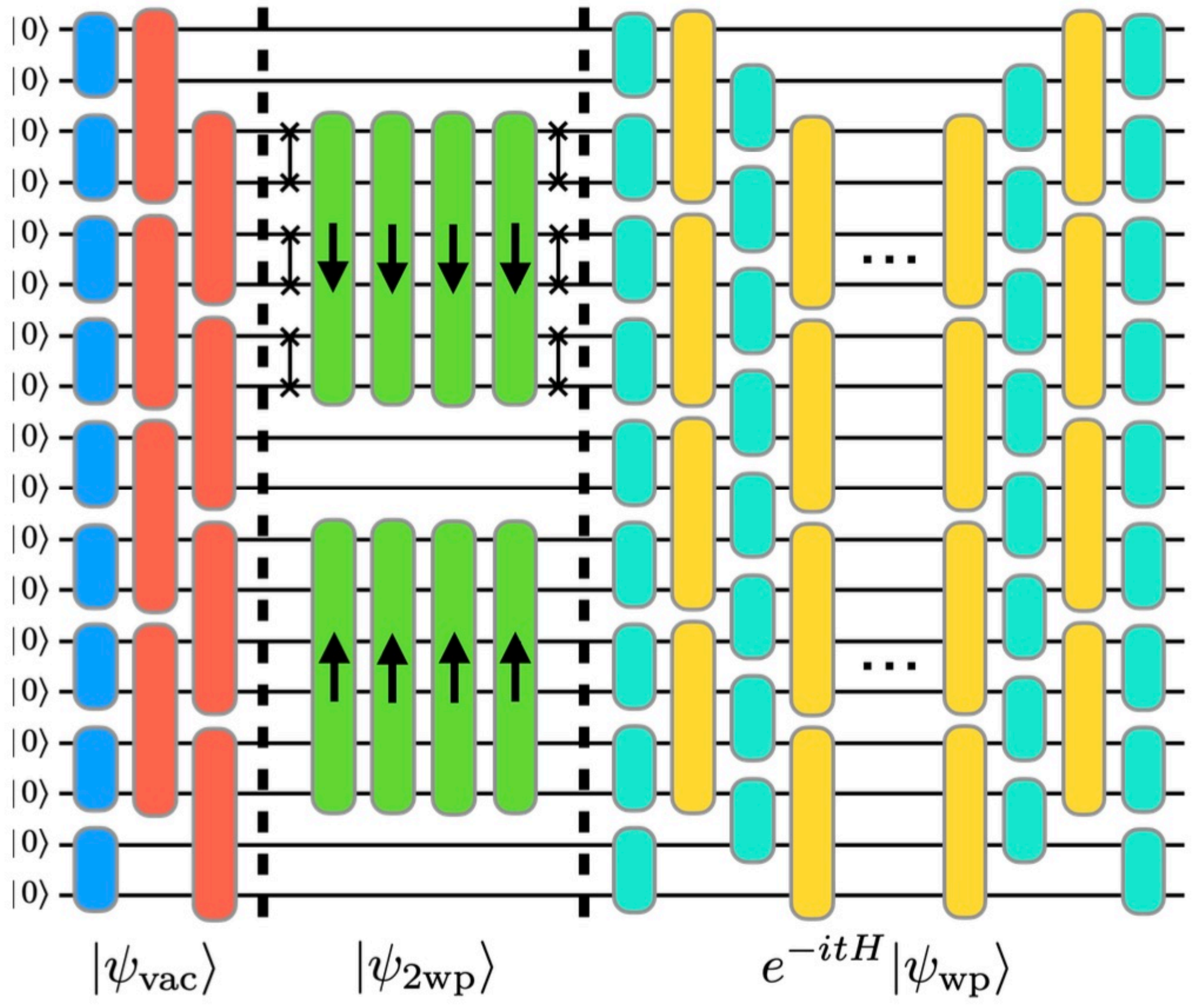
j_{Max} =1/2, 1, 3/2, 2, ...



Summary and Outlook

A unique time in the history of computing !!

Quantum simulations focused on fundamental physics are advancing



Evolution from NISQ to fault tolerant/error correcting

Understanding how to organize quantum complexity

(Multiple) focused teams with access to forefront quantum hardware are essential

IQuS

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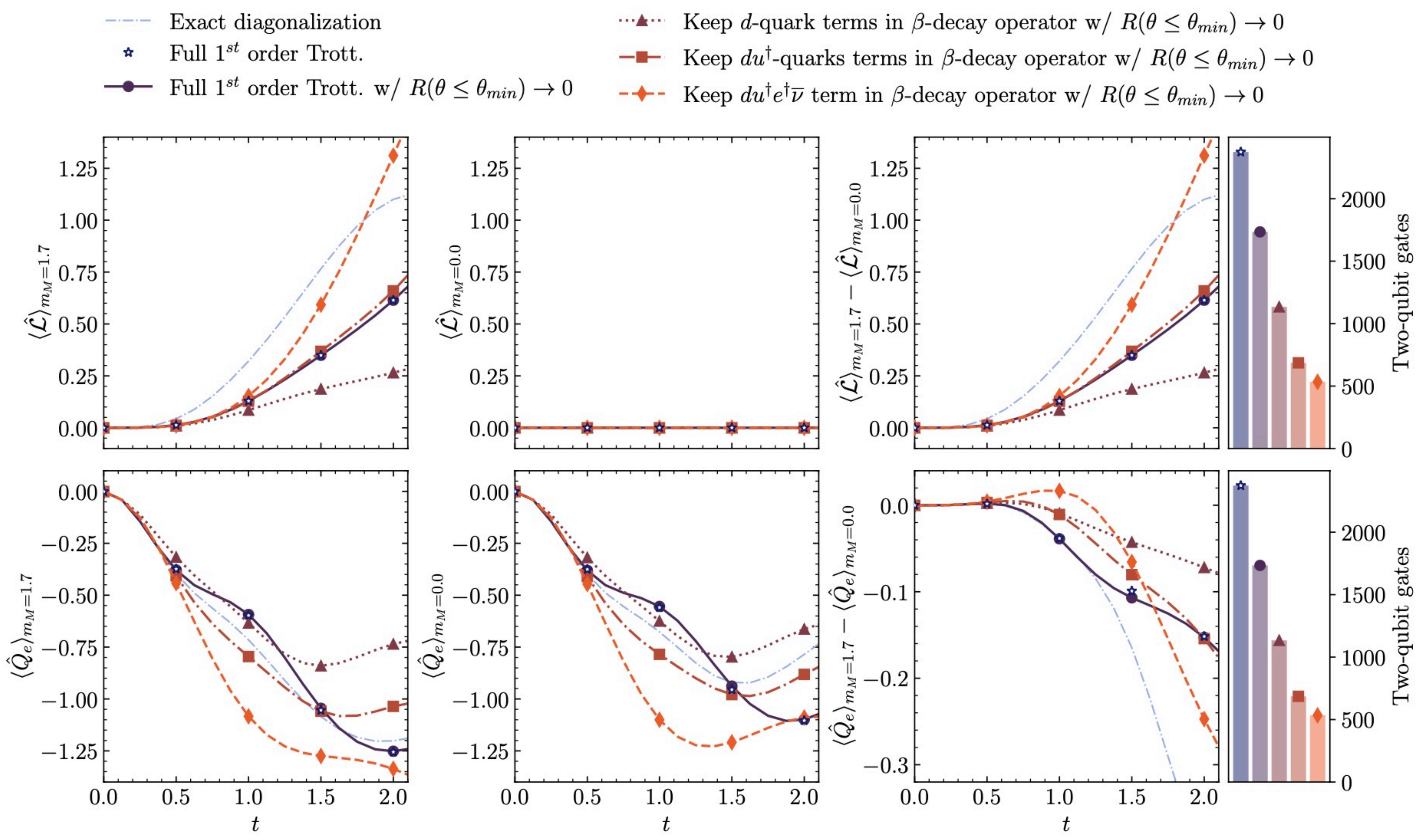
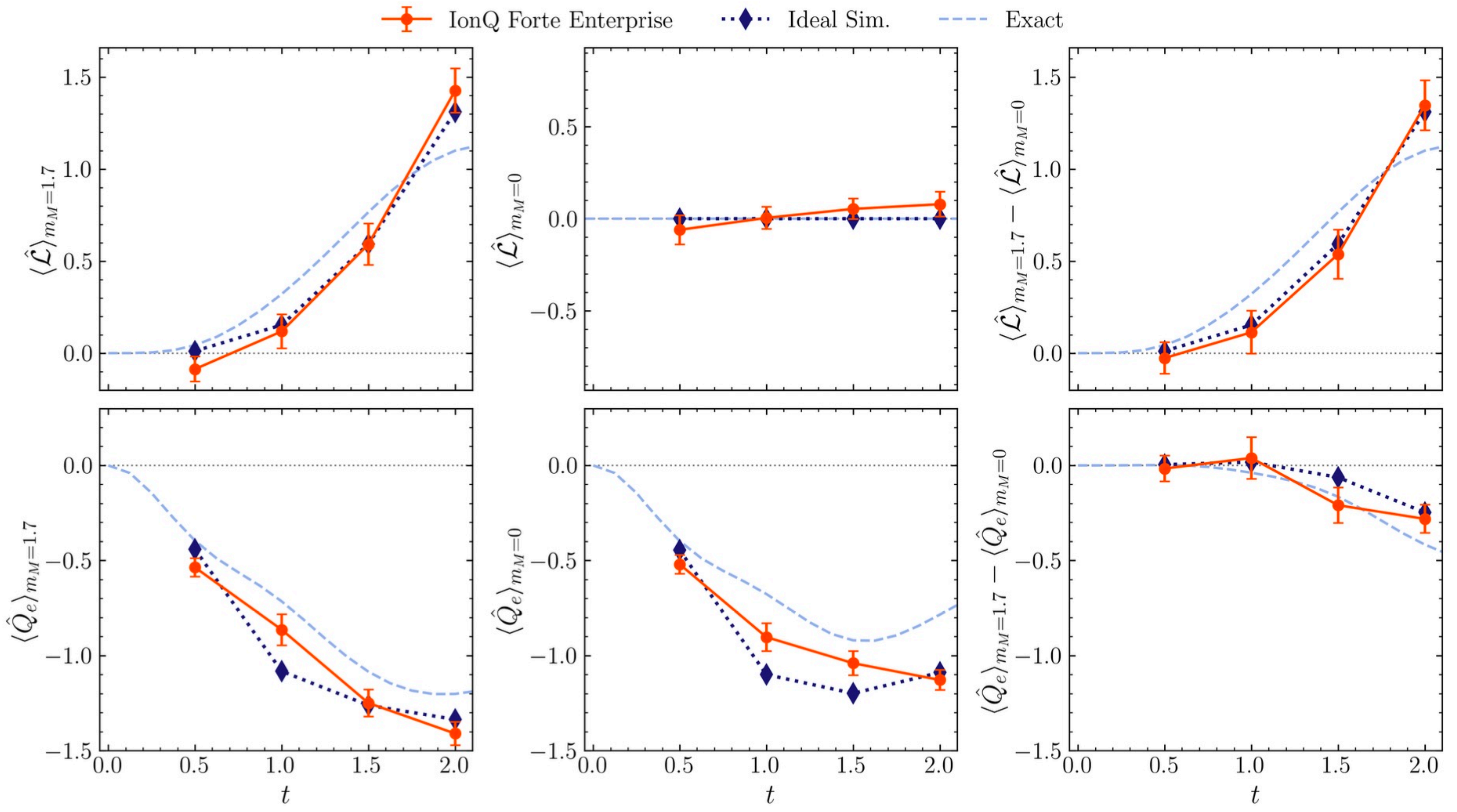
FIN

Pathfinding Quantum Simulations of Neutrinoless Double-β Decay

Ivan A. Chernyshev,[1] Roland C. Farrell,[2] Marc Illa,[3] Martin J. Savage,[3,*] Andrii Maksymov,[4] Felix Tripier,[4] Miguel Angel Lopez-Ruiz,[4] Andrew Arrasmith,[4] Yvette de Sereville,[4] Aharon Brodutch,[4] Claudio Girotto,[4] Ananth Kaushik,[4] and Martin Roetteler[4,†]





>450 entangling gates