

Quantum Information and Quantum Computing for Fundamental Physics



National Nuclear Physics Summer School 2026

Seattle, WA

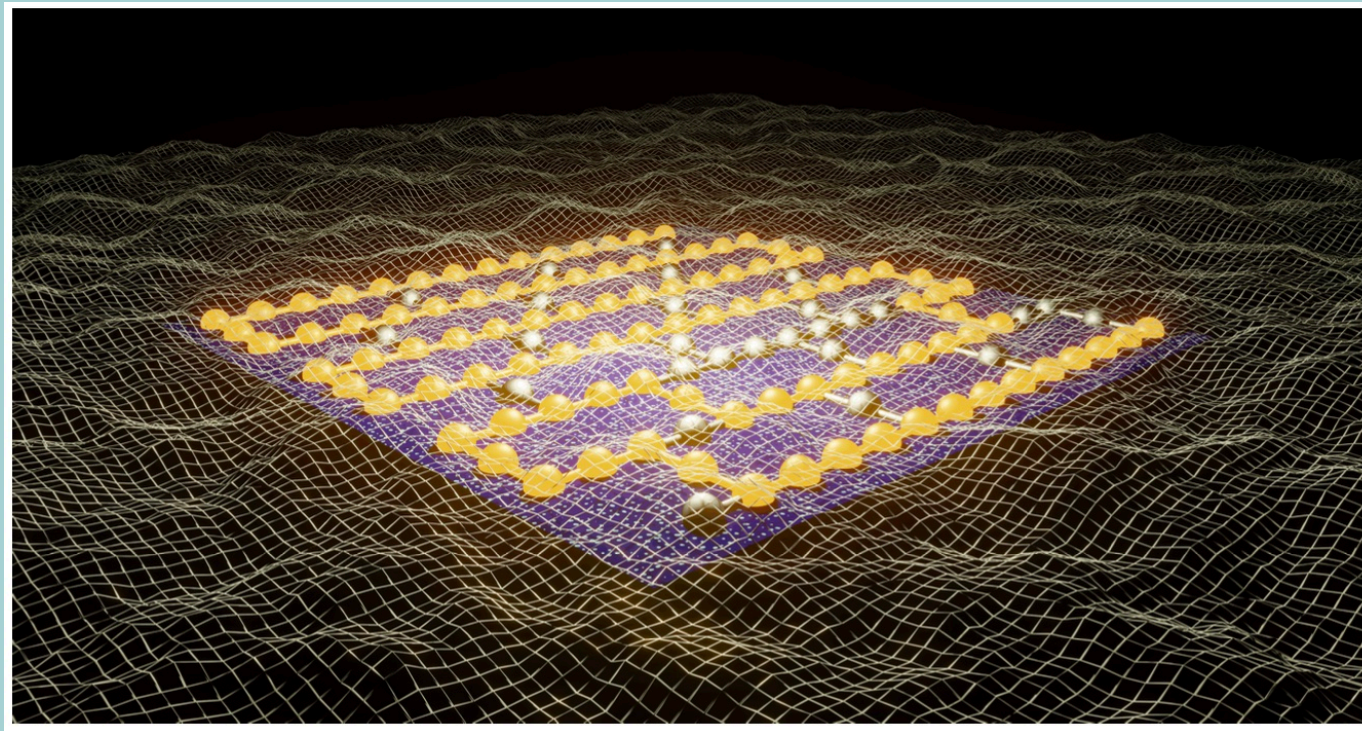
June 29 - July 11, 2026

Martin Savage
InQubator for Quantum Simulation
University of Washington

Part-4:
Fault Tolerance and Error Correction

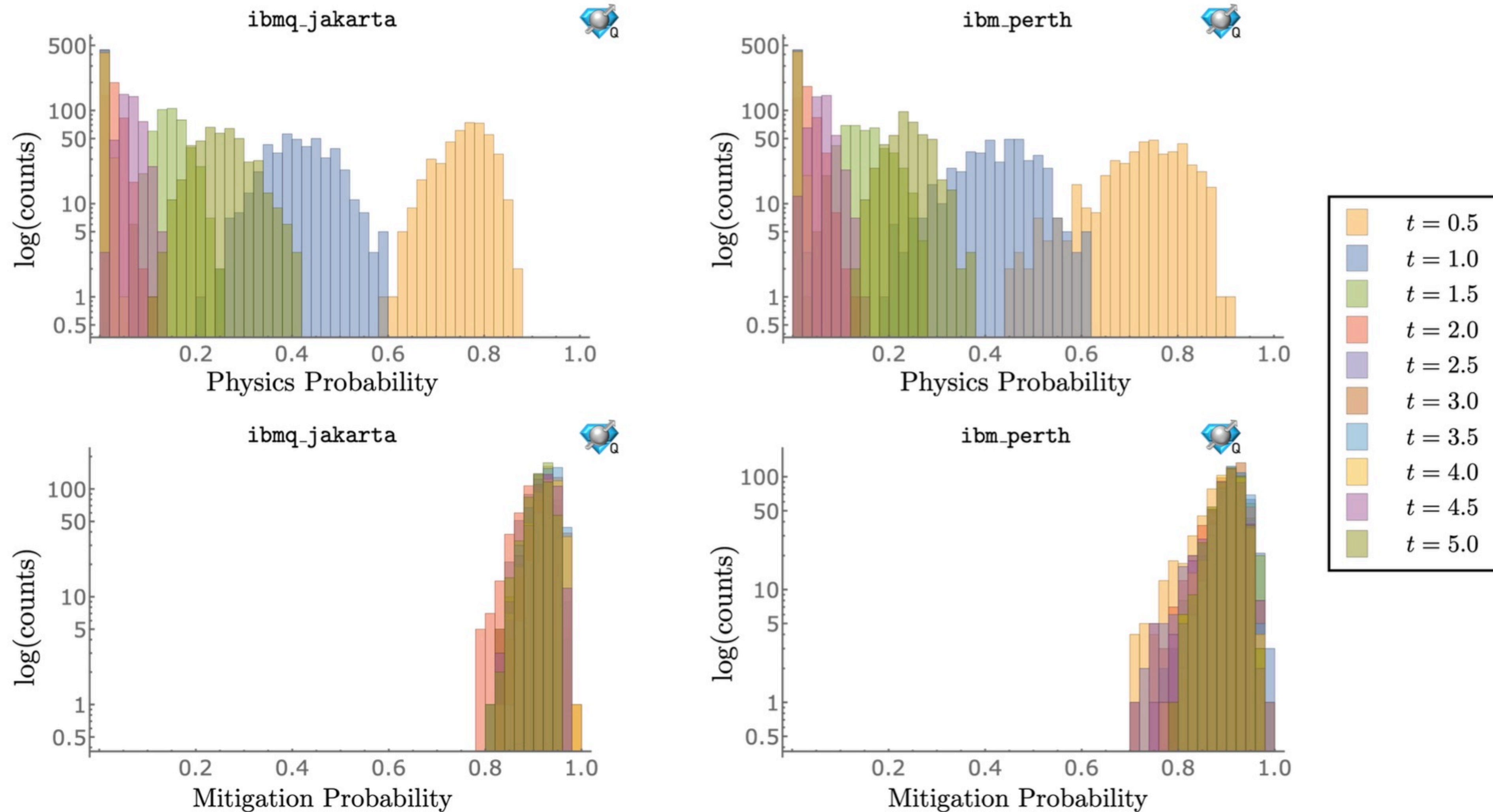
Part-3

Quantum Computing and Simulation



End of Day-2

Error Mitigation - Pauli Twirling



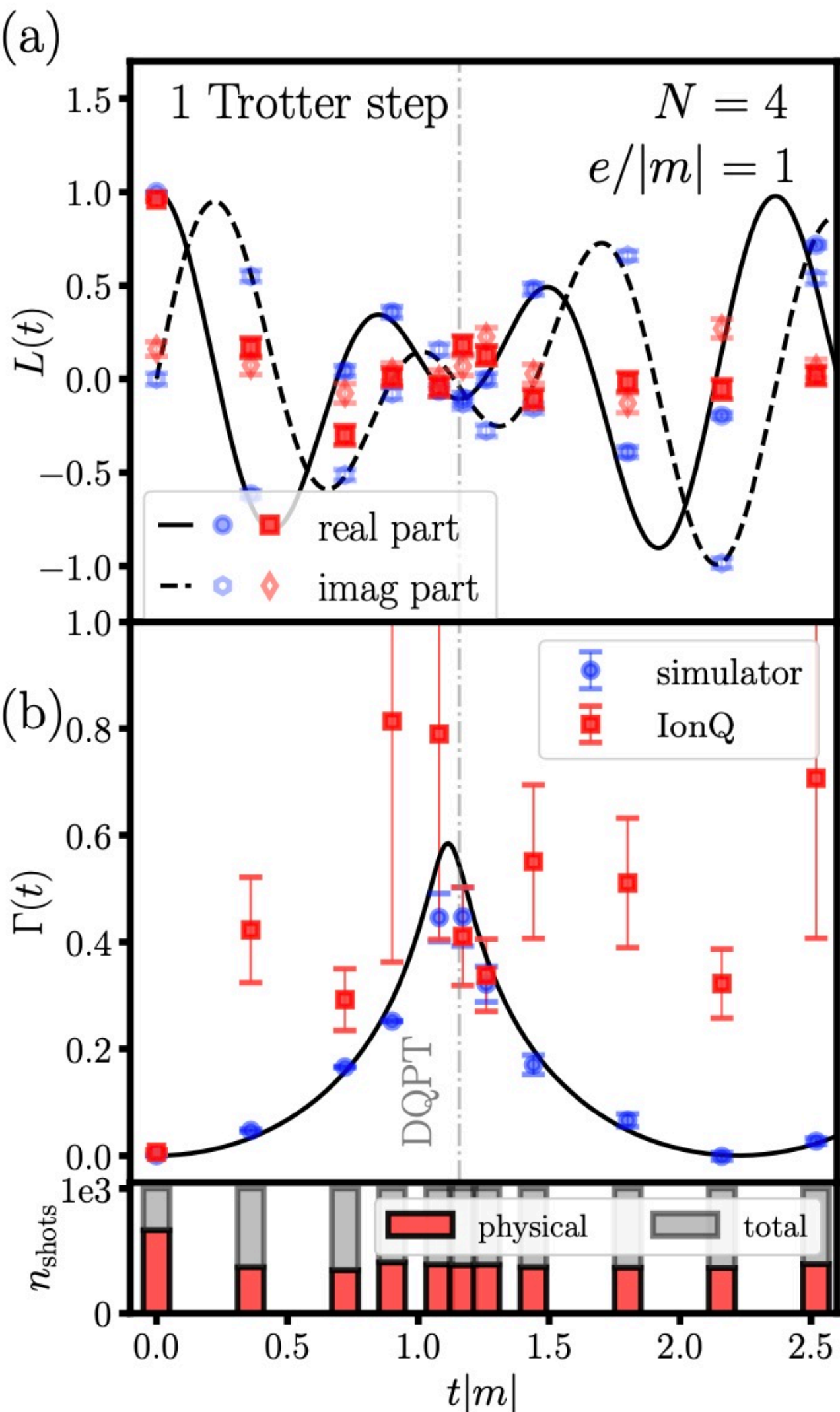
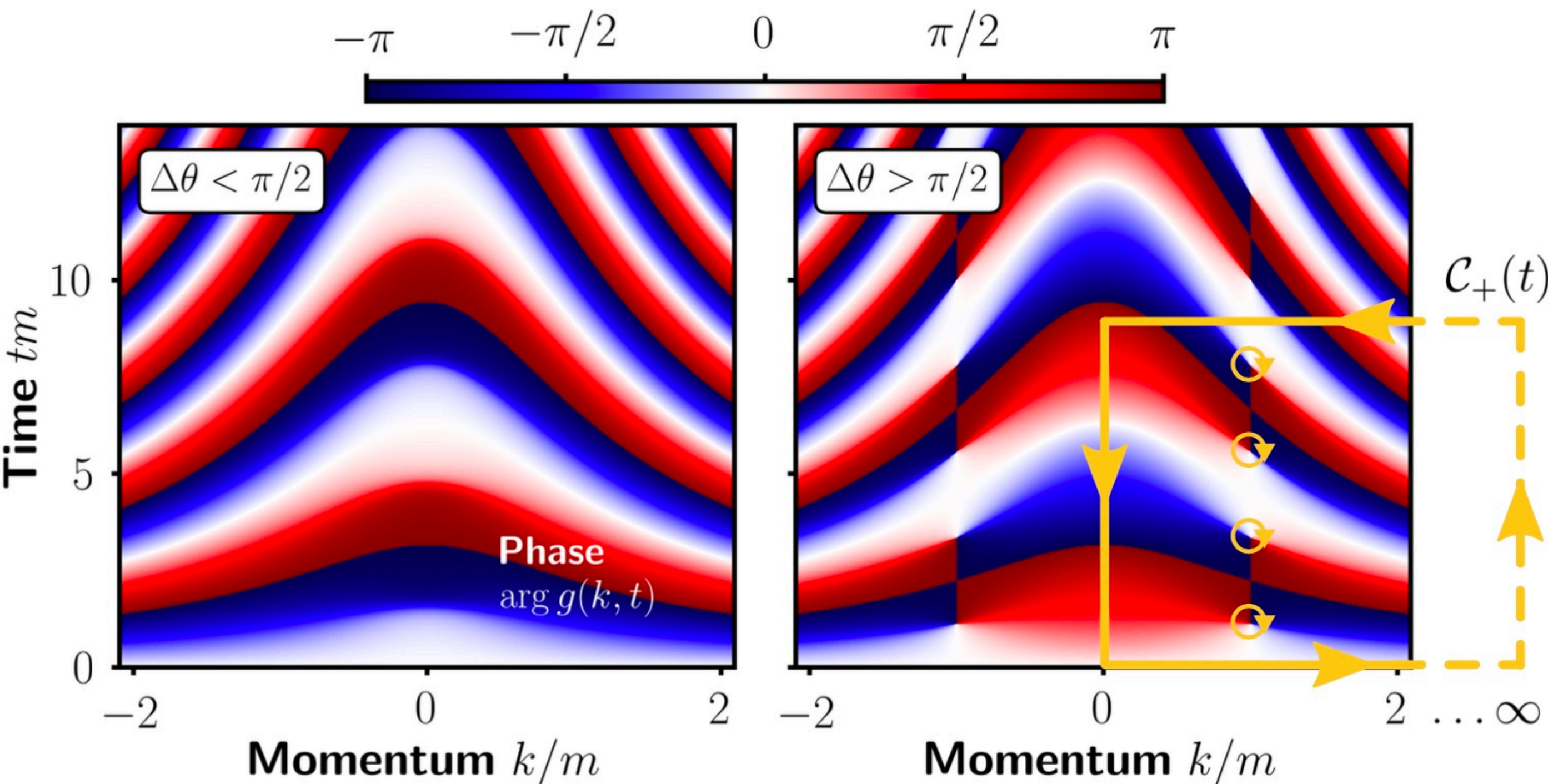
Dynamical Quantum Phase Transitions

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

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

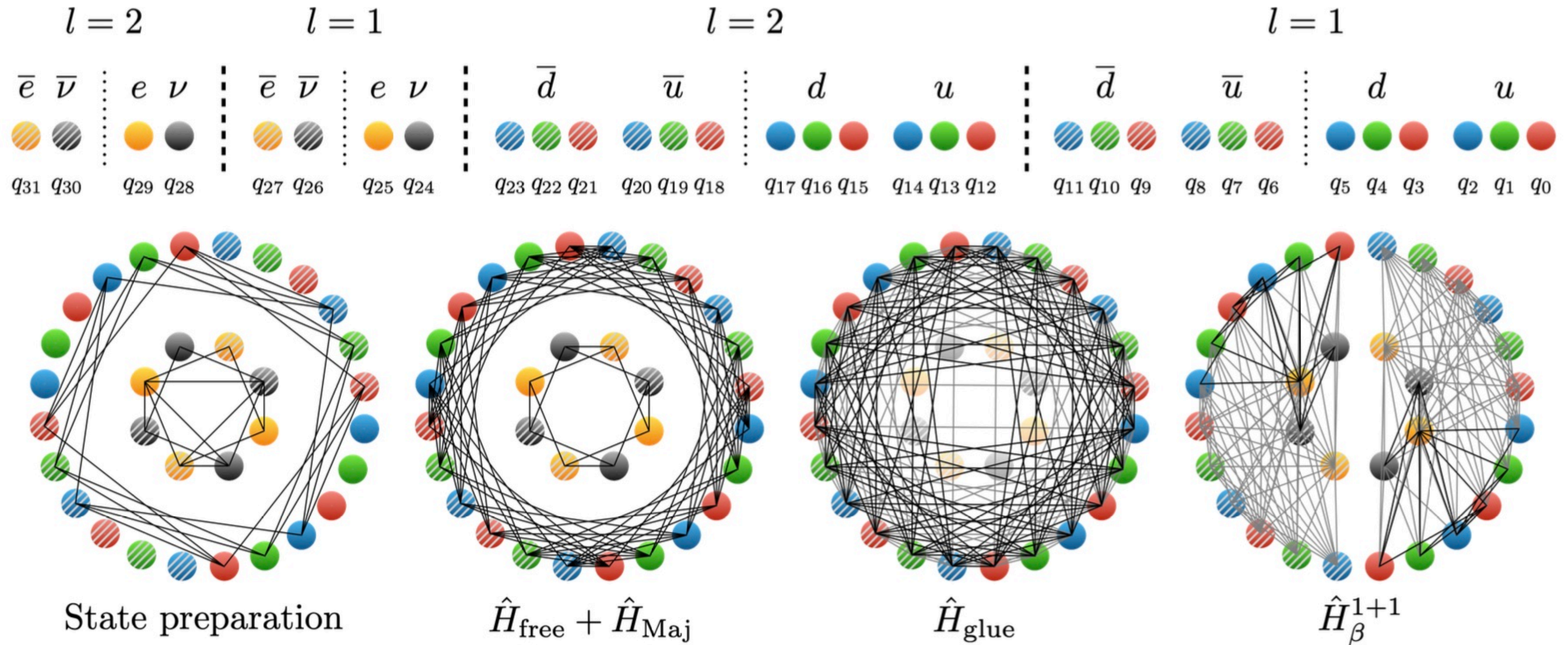
Quantum computation of dynamical quantum phase transitions and entanglement tomography in a lattice gauge theory

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



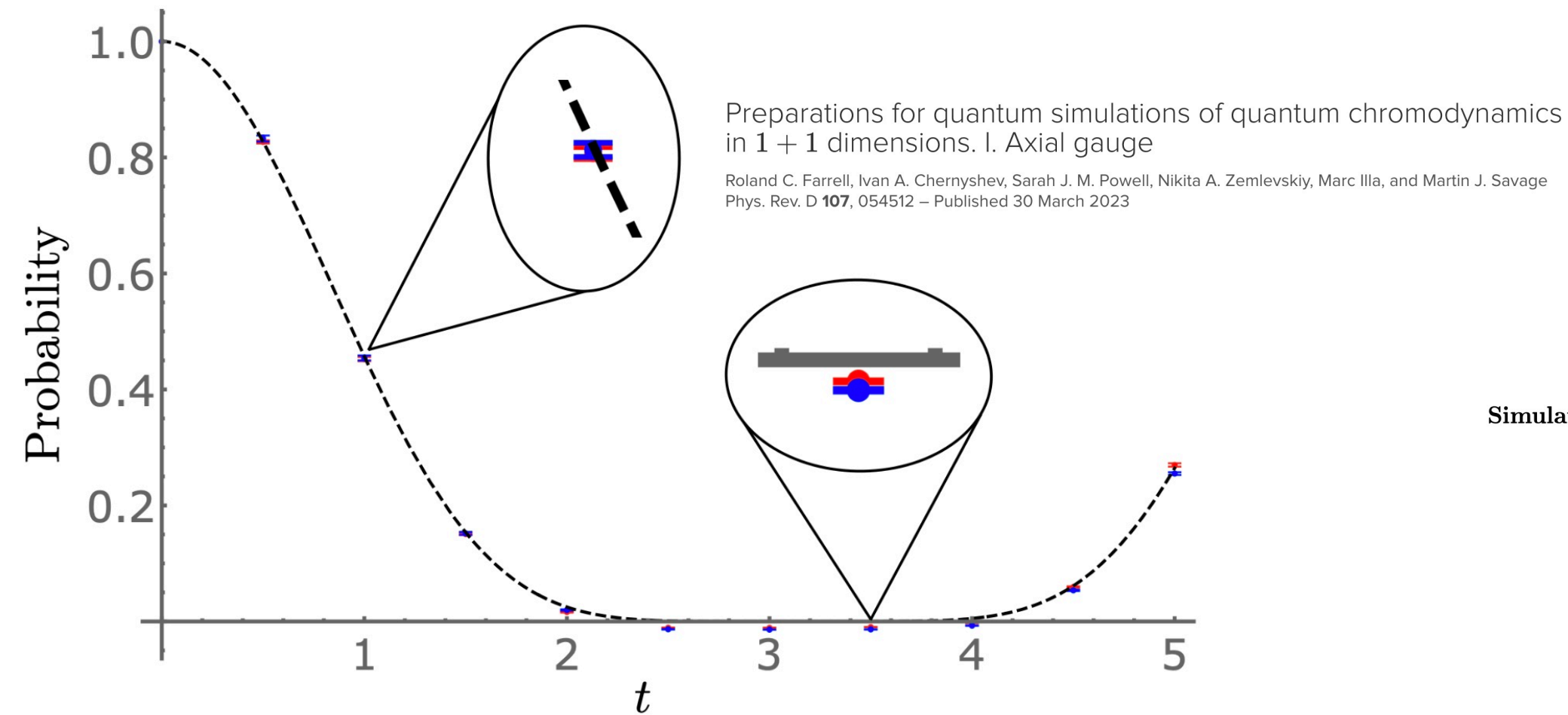
1+1D SU(N) and Quantum Chromodynamics

8



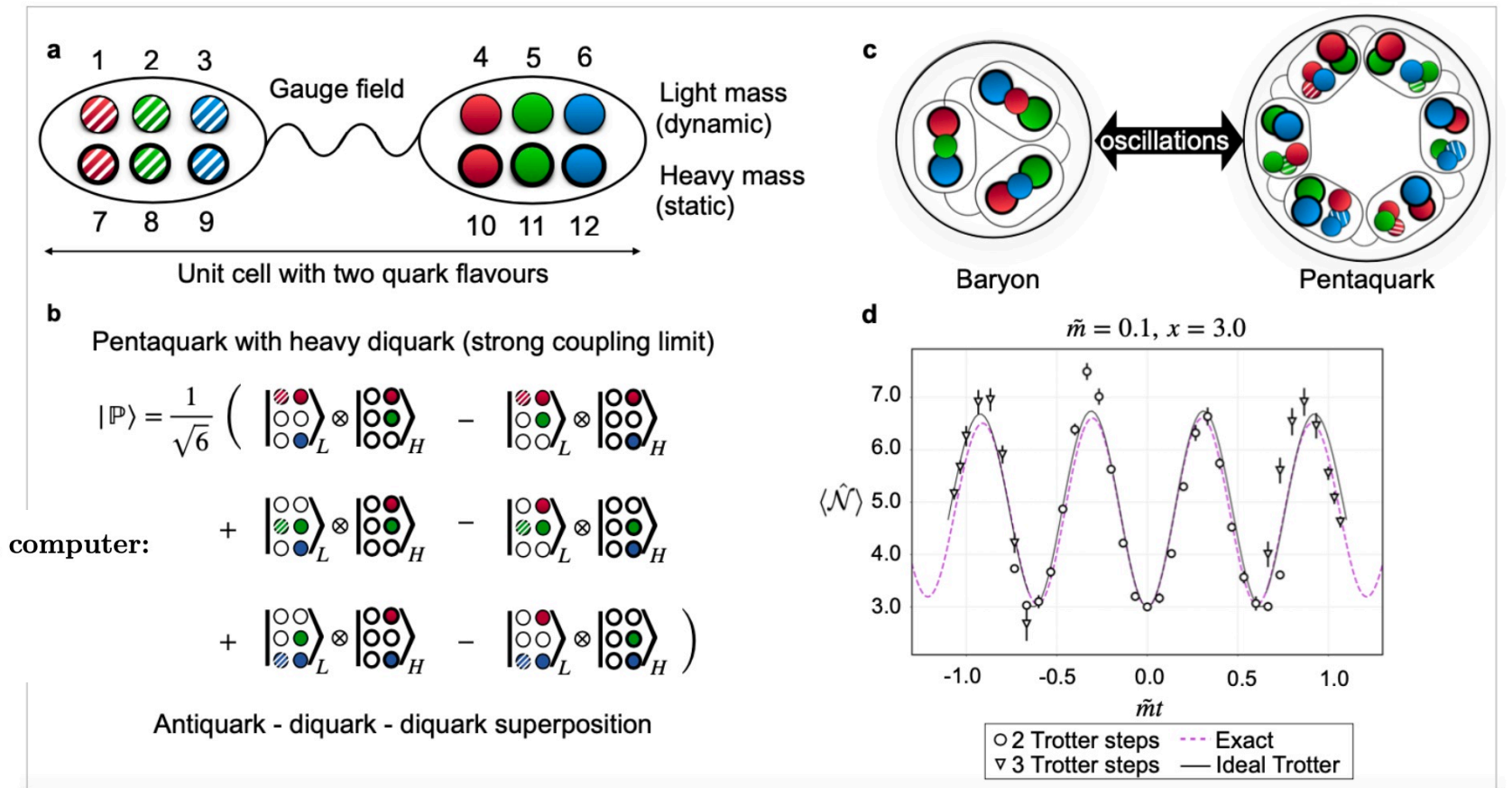
1+1D QCD and Decays

Trivial Vacuum-to-Vacuum

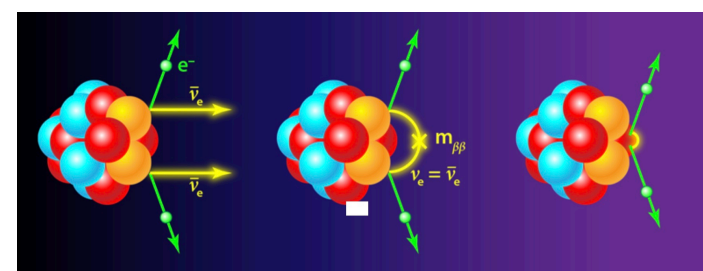
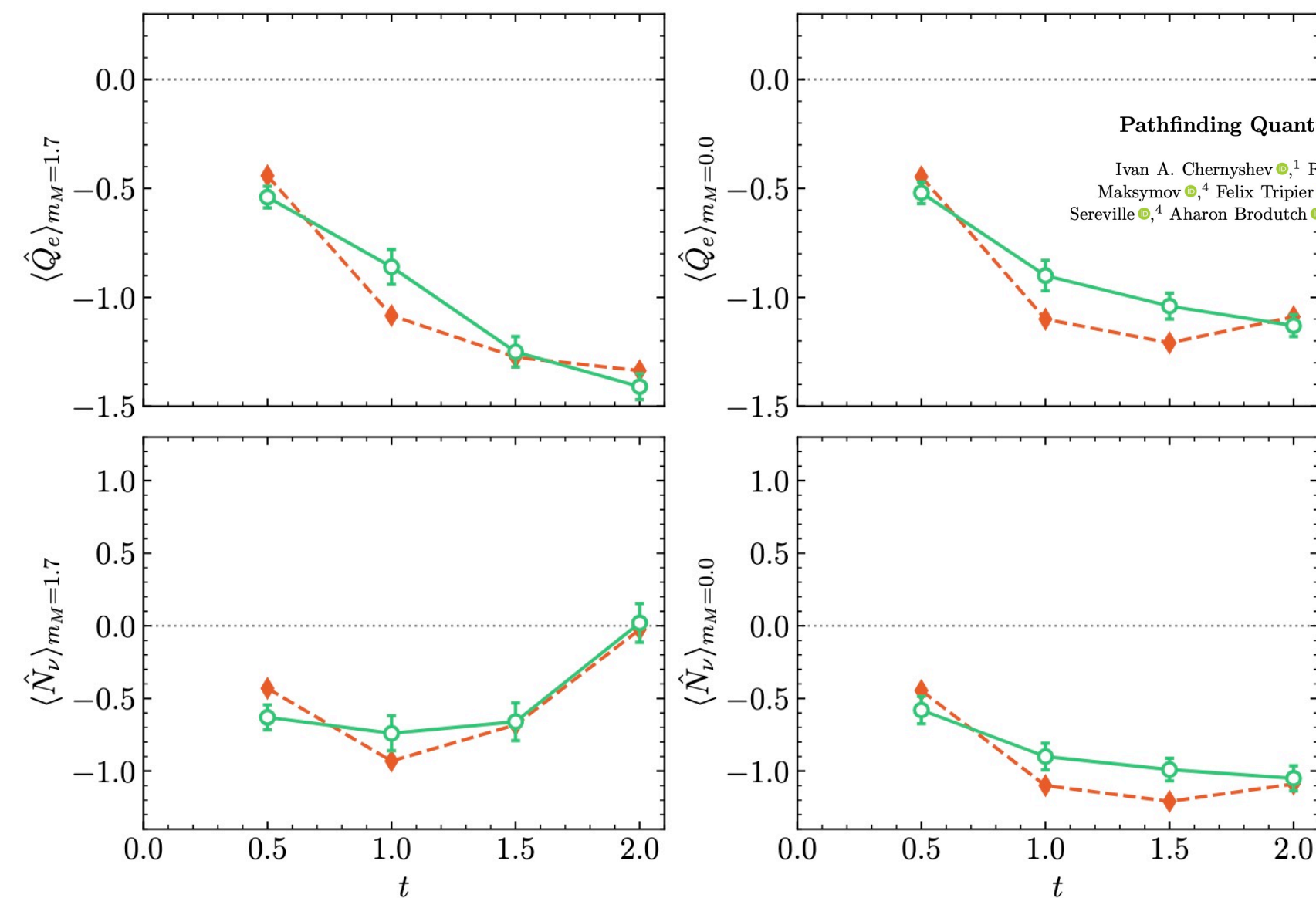
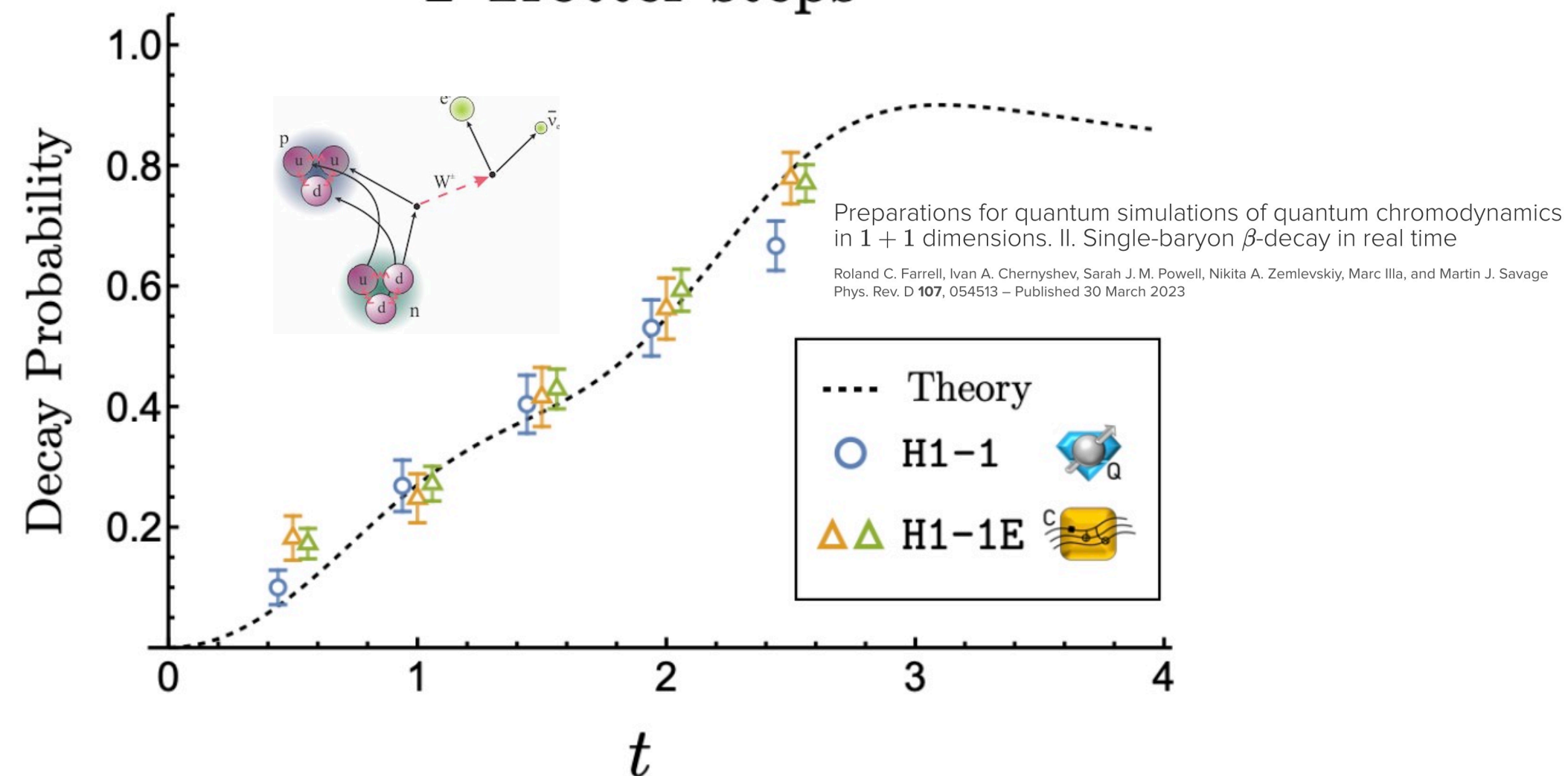


Simulating one-dimensional quantum chromodynamics on a quantum computer: Real-time evolutions of tetra- and pentaquarks

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

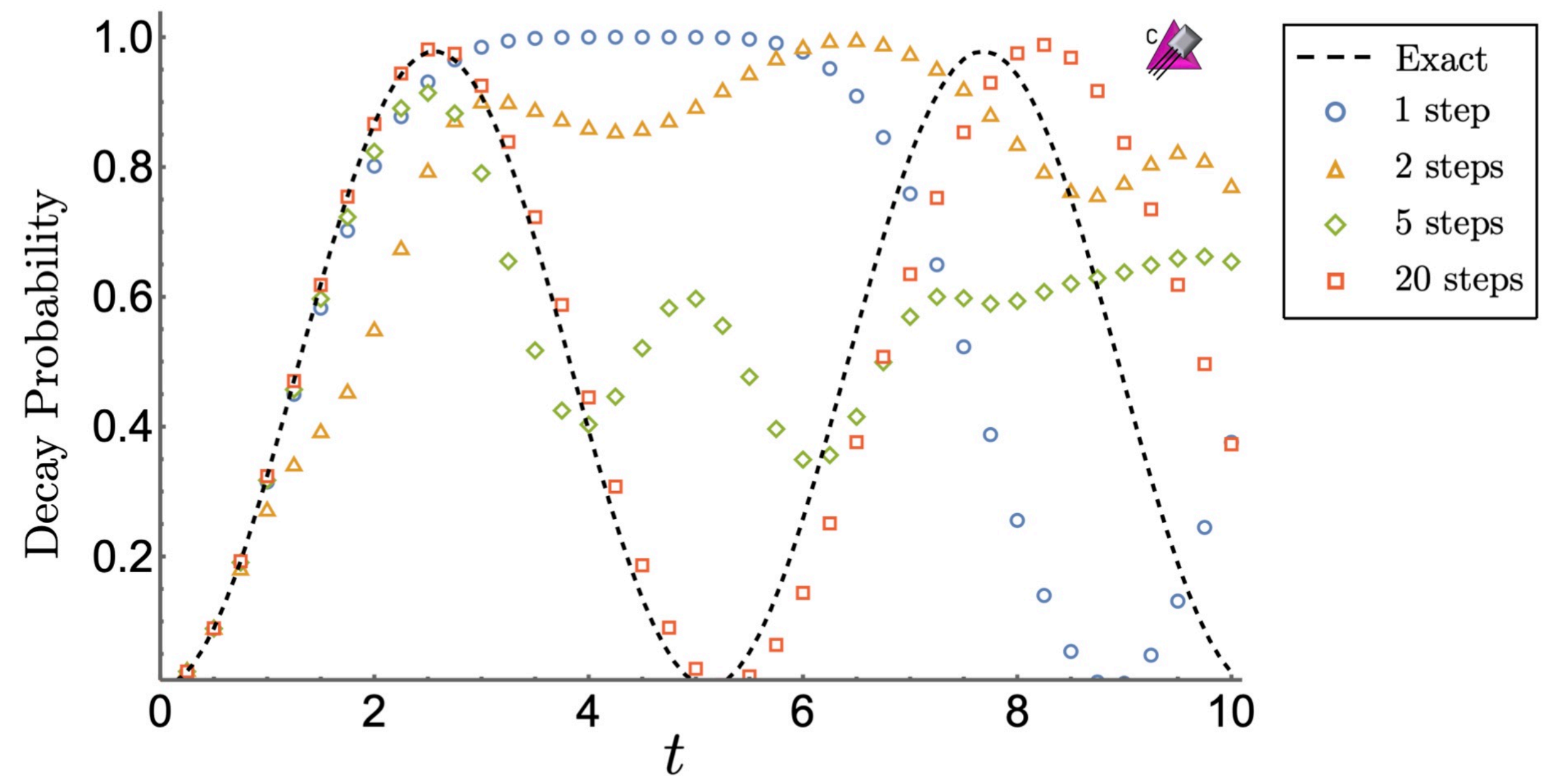


2 Trotter steps

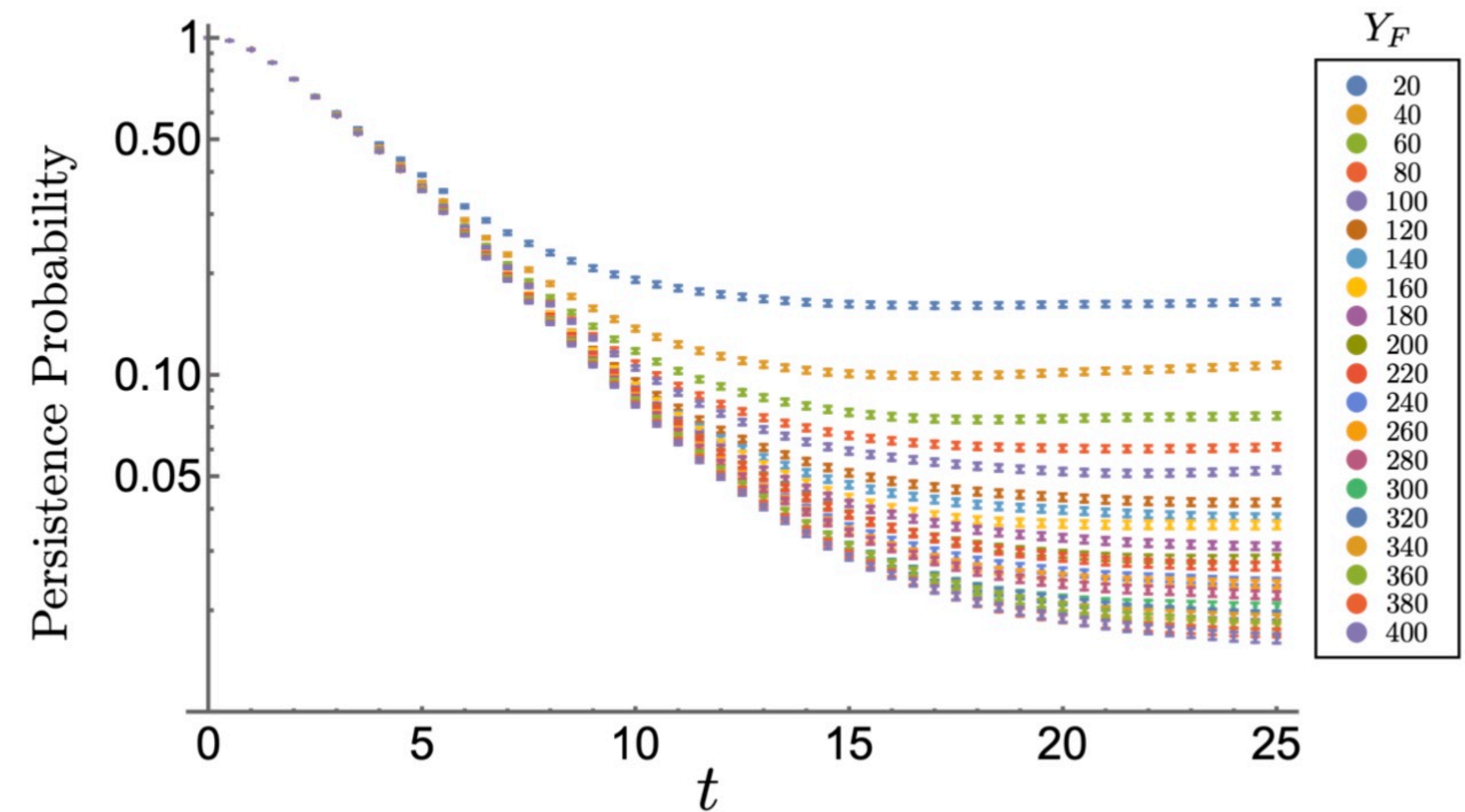


Weak Decays : Expectations

—Recovering Real-time Exponential-Decay



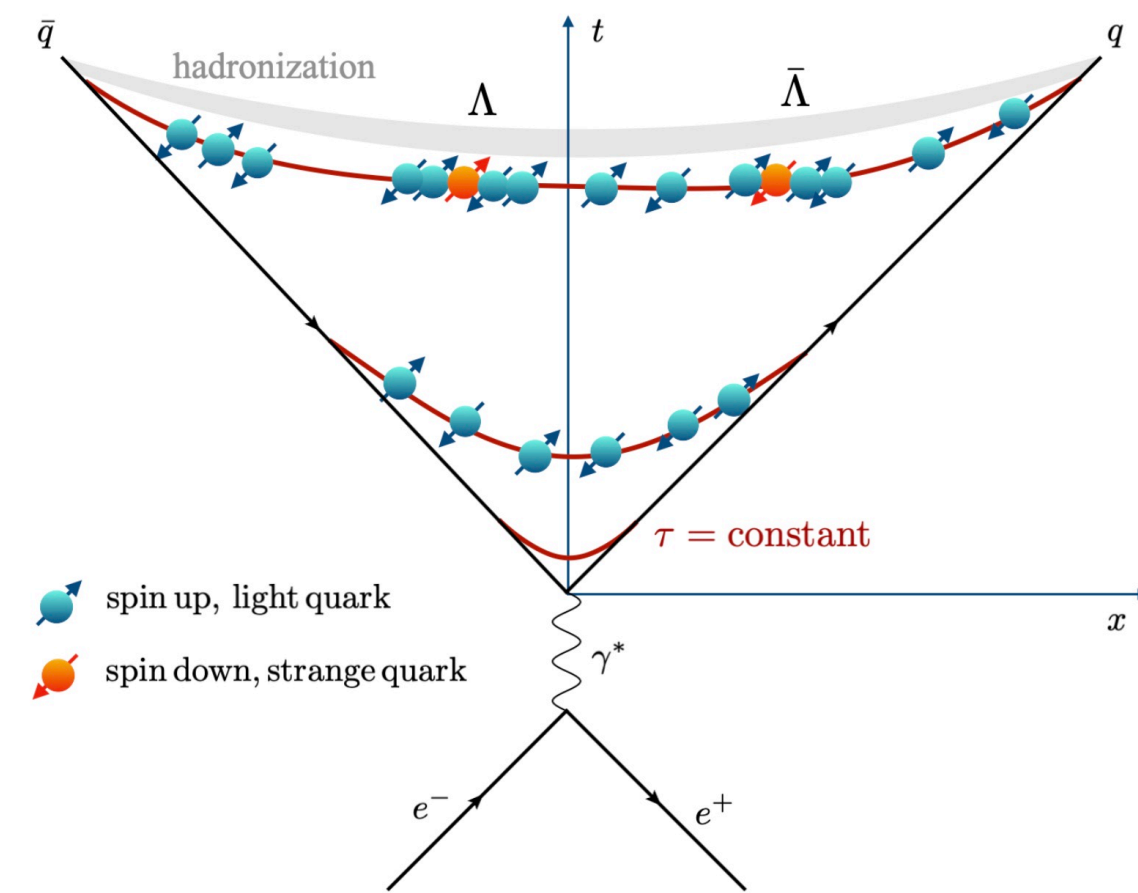
One available final state



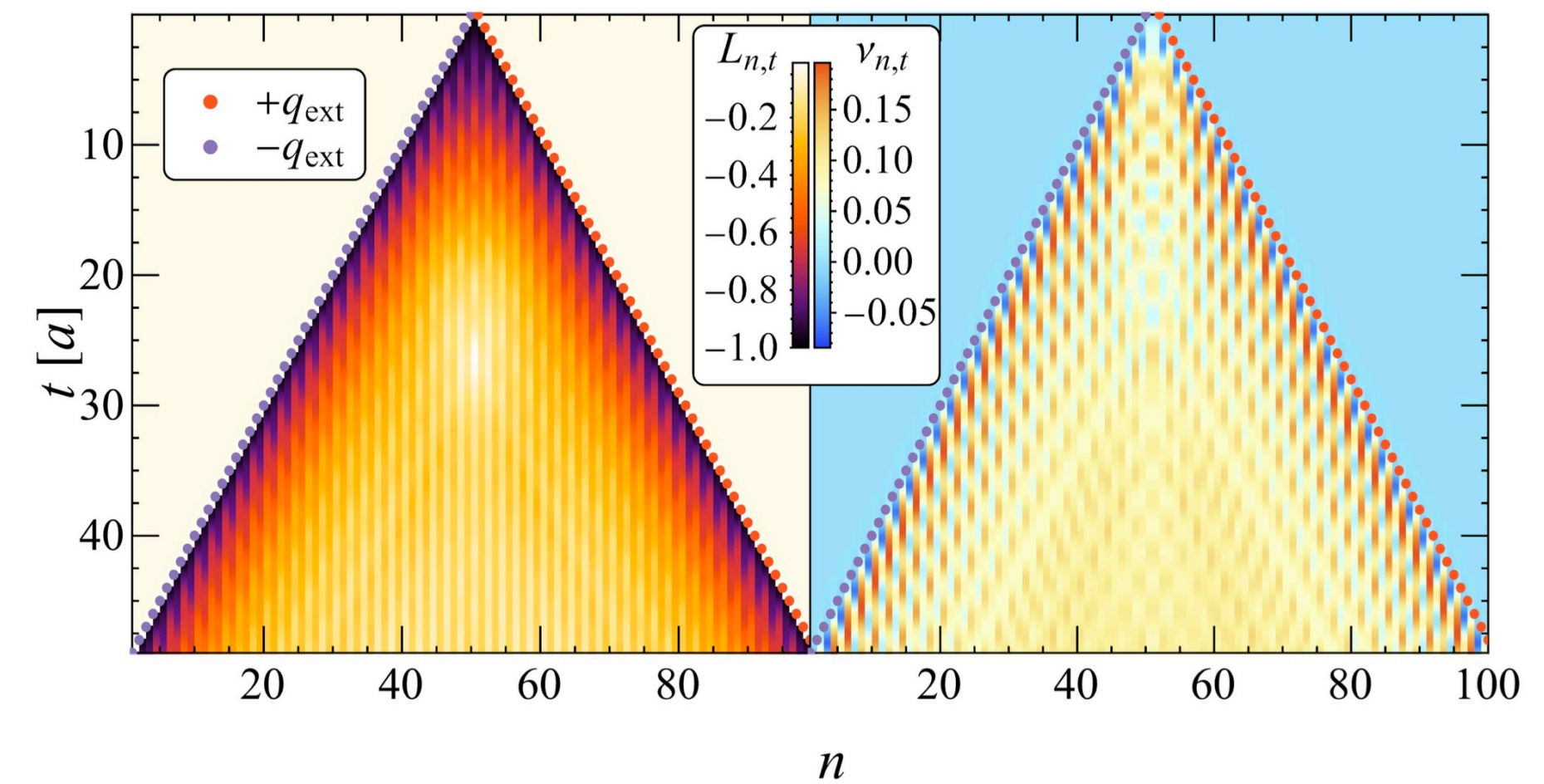
Y_F available final states

Hadronization and Fragmentation

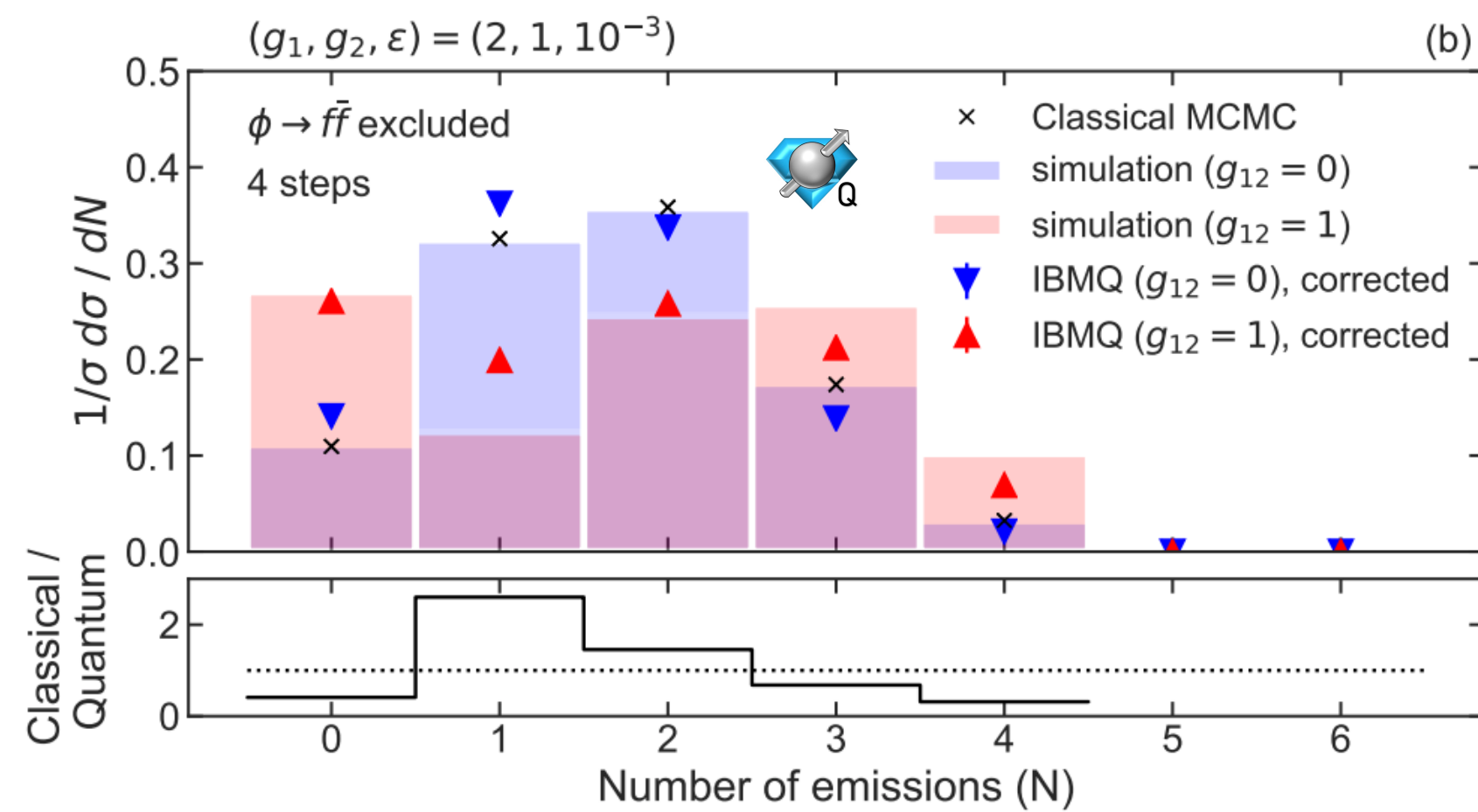
Baryon Entanglement, Barata *et al*, Gong *et al*



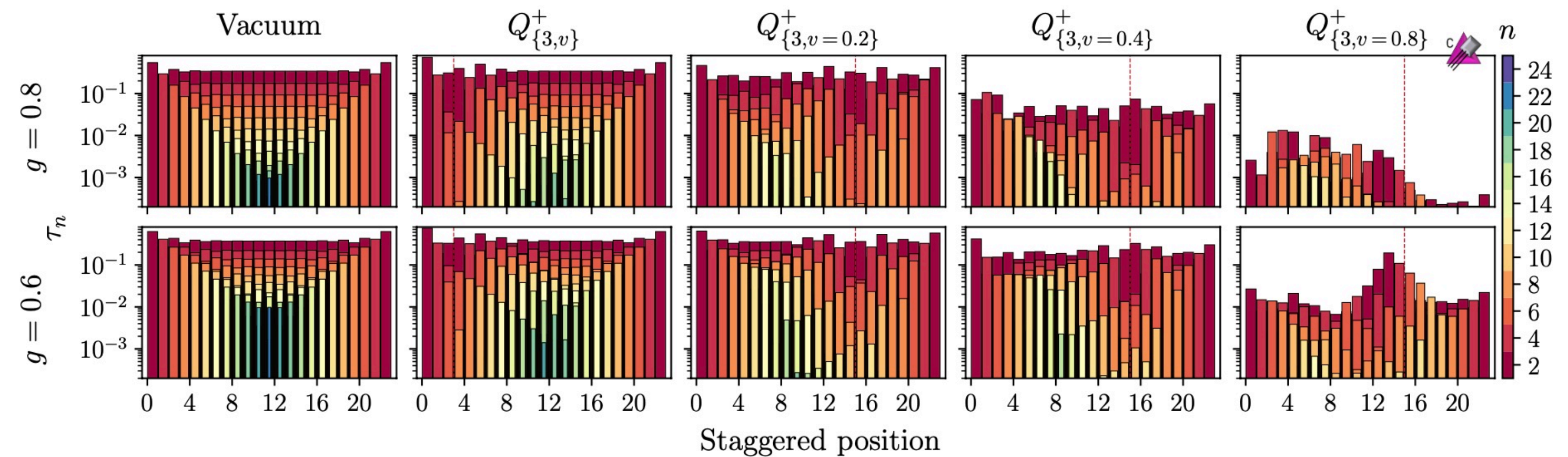
Hadronization, Florio *et al*



Fragmentation, Bauer *et al*

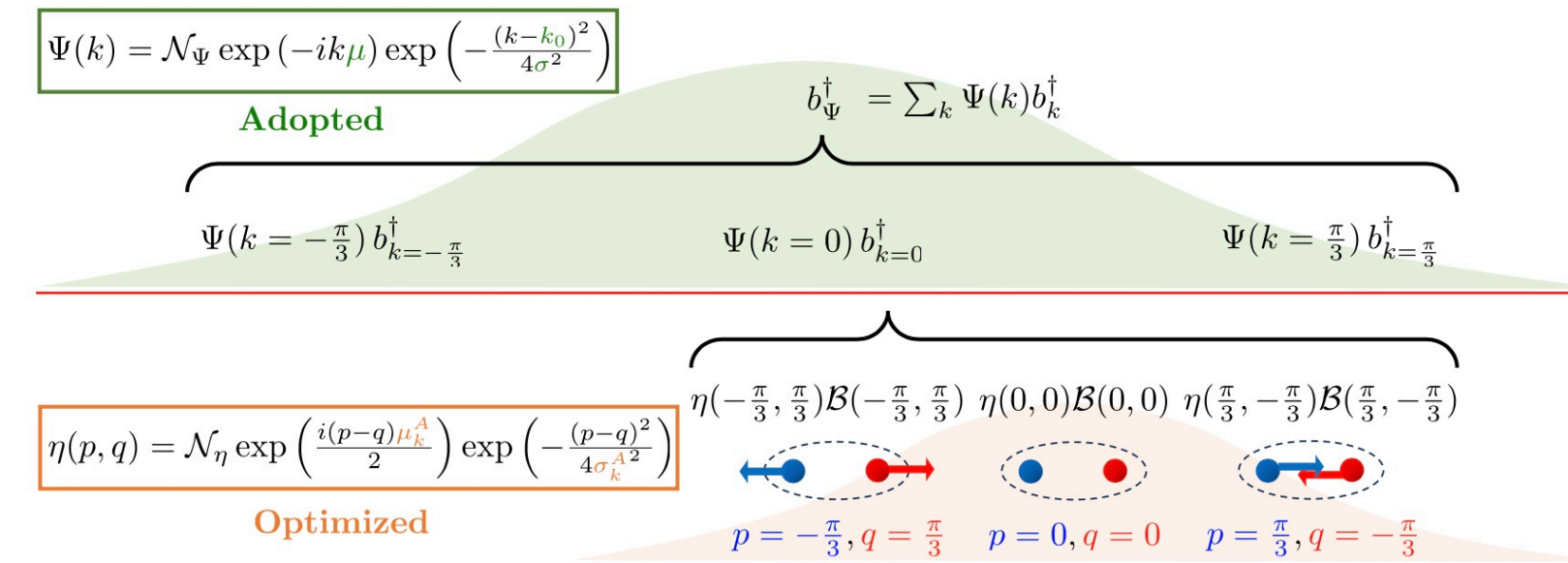
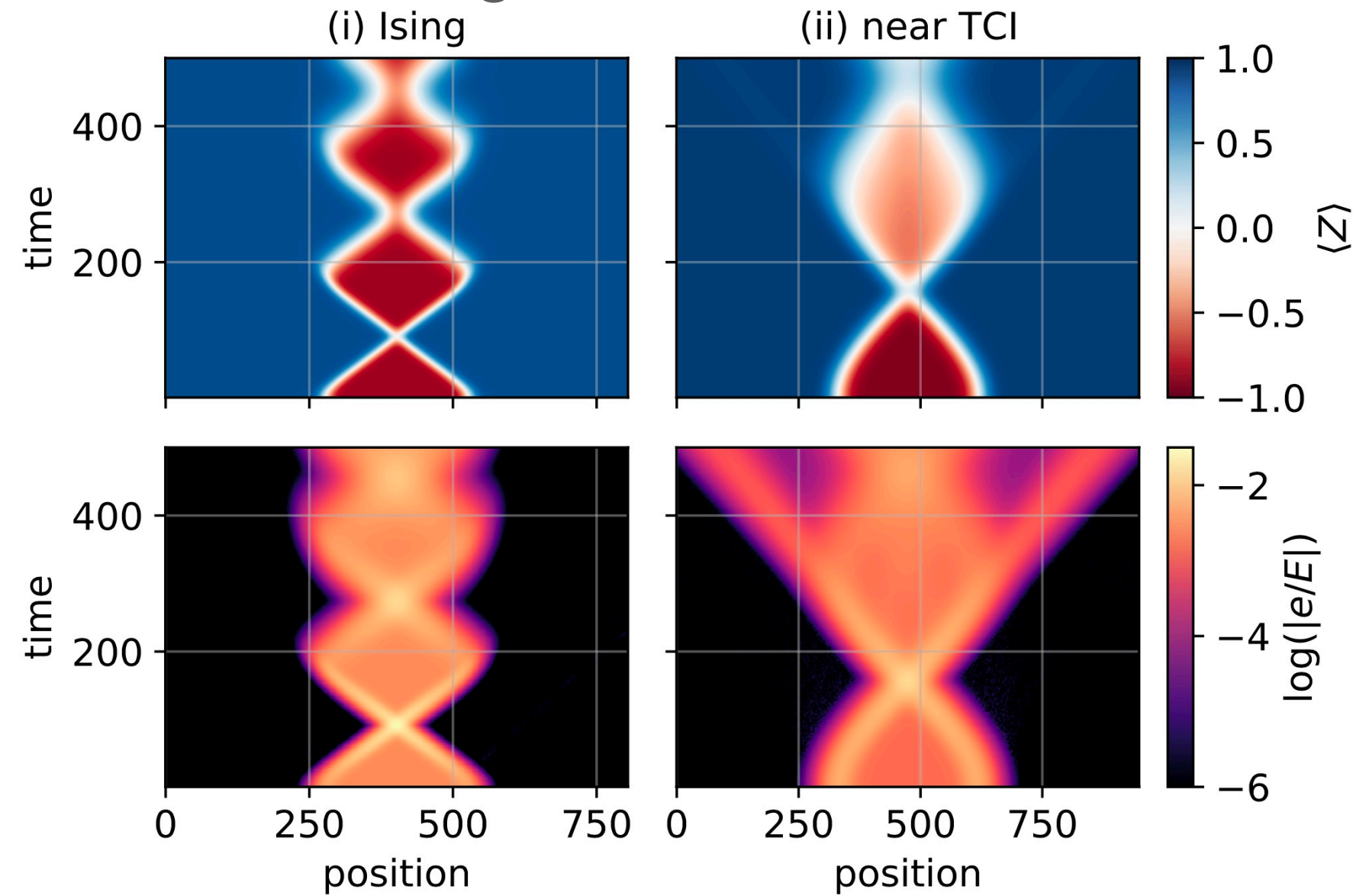


Energy Loss and Multi-partite Entanglement, Farrell *et al*



1+1D Preparing for the Future

Ising+ , Milsted et al



Wavepackets ,
Davoudi et al

Thirring model , Chai et al

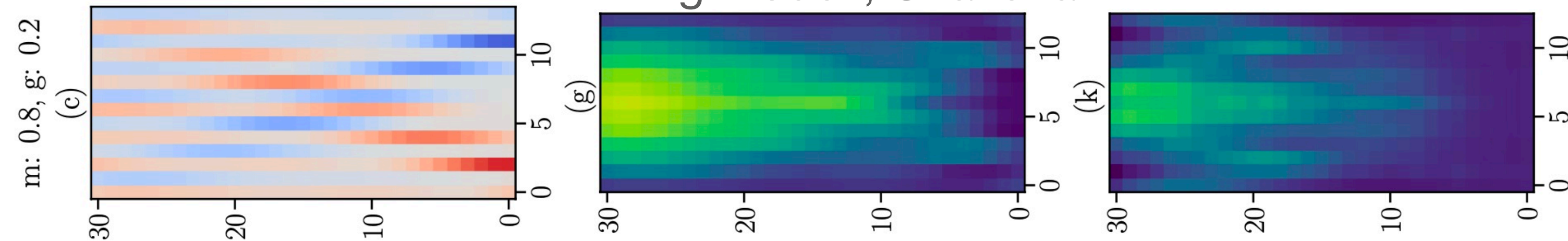
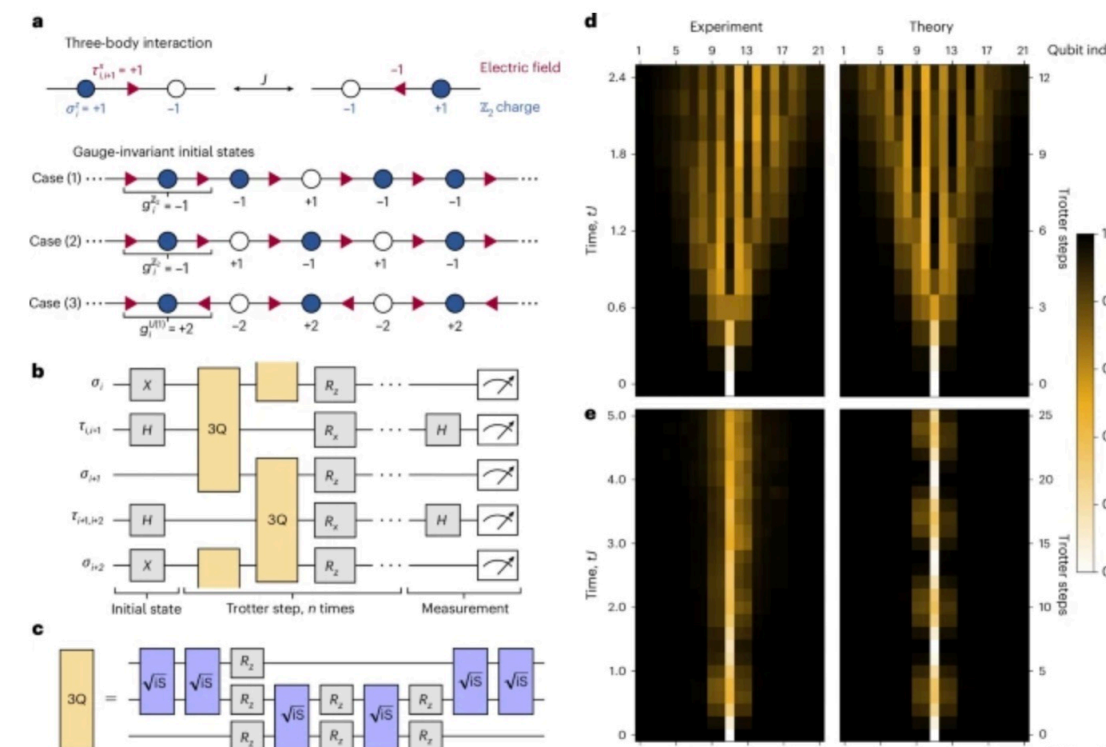
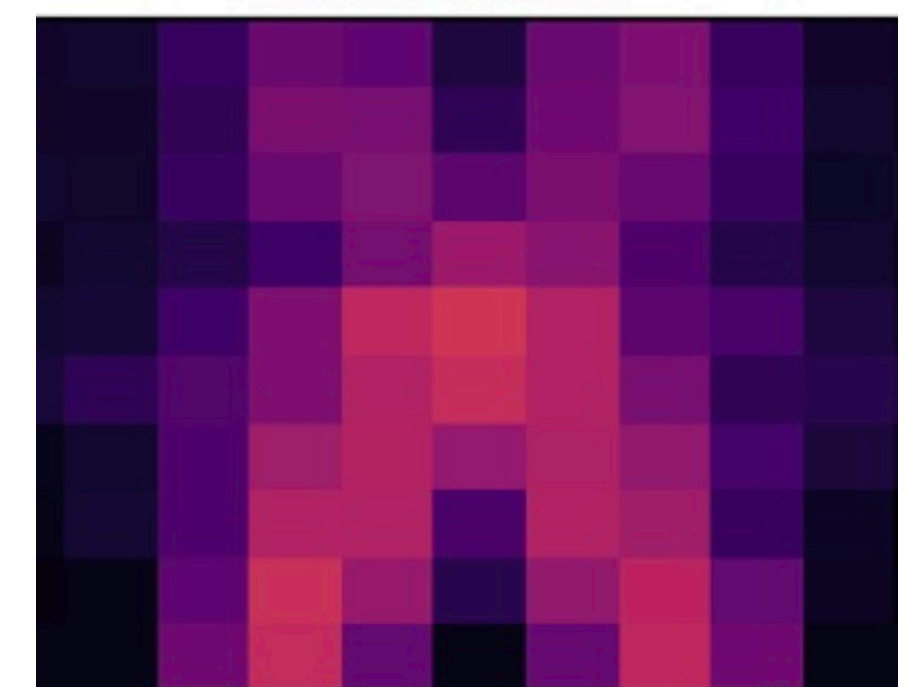


Fig. 1: Simulating confinement in a $\mathbb{Z}_2$ LGT on a digital superconducting chip.

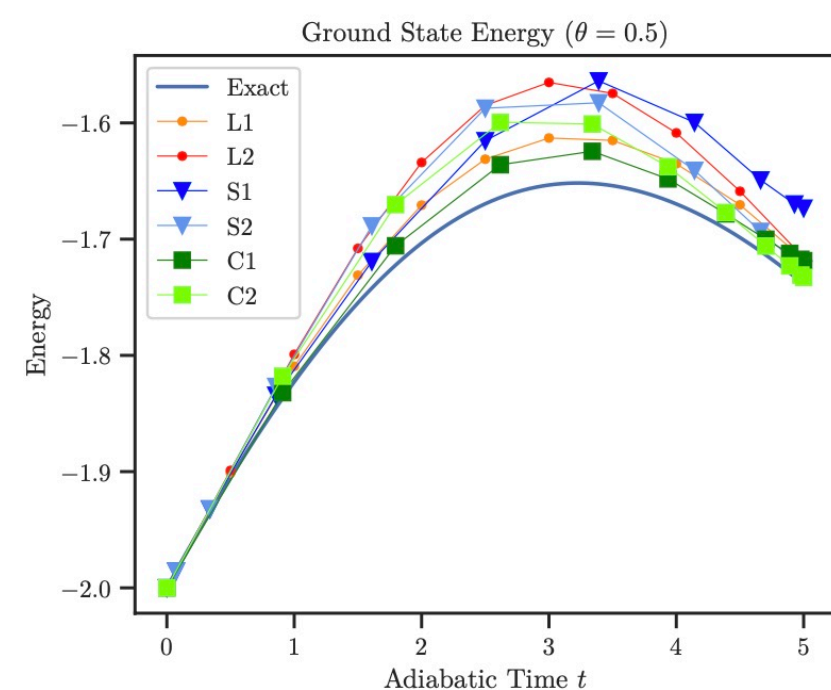


Confinement in Z2, Mildenerger et al

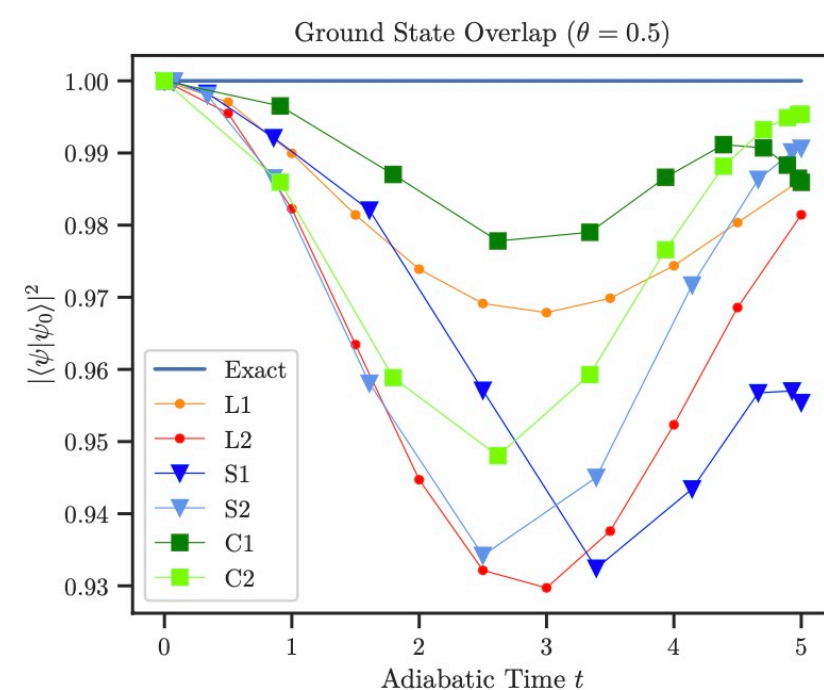
ibm fez



Scalar FT, Zemlevskiy



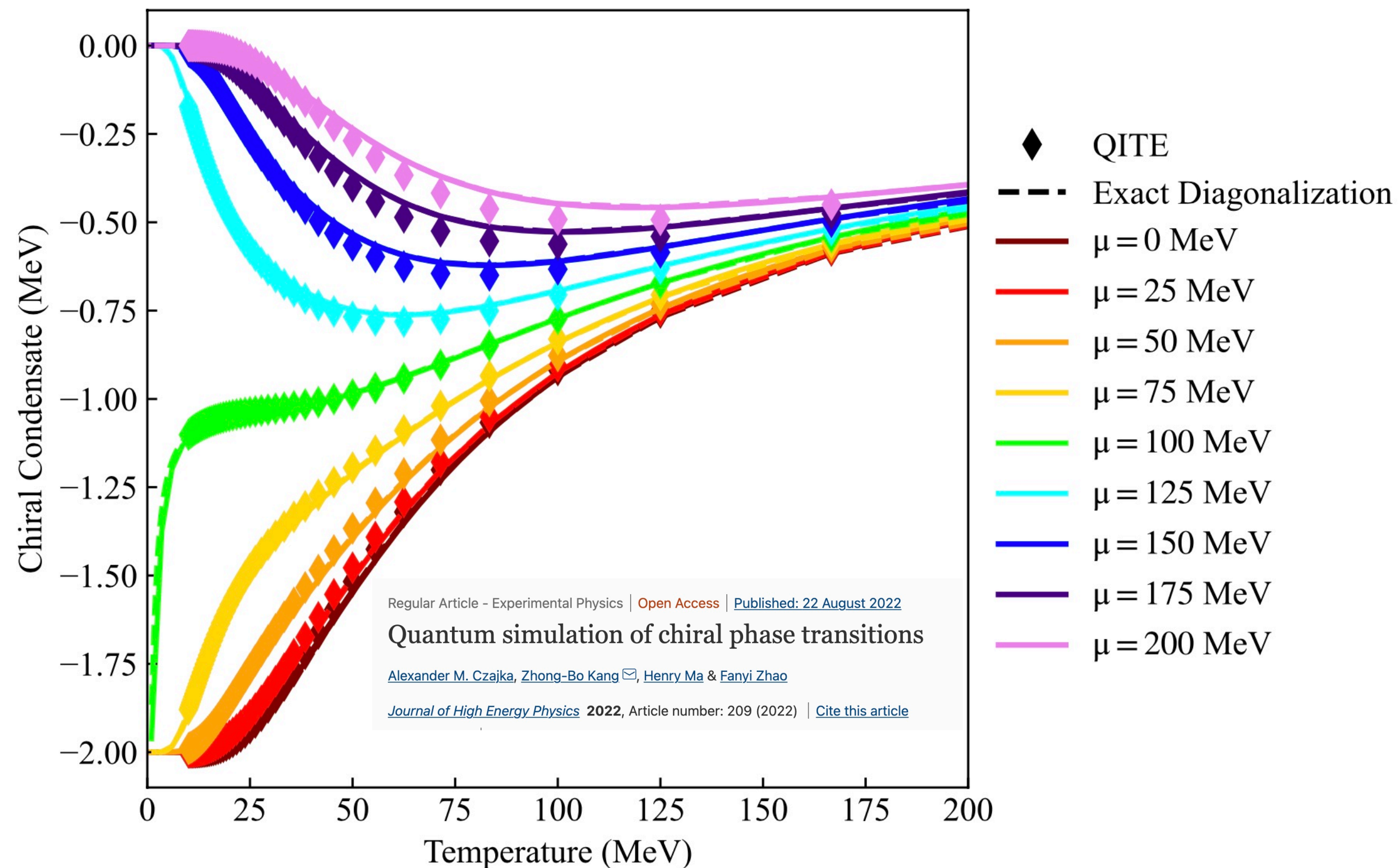
(a) QAOA, Rodeo , Pederiva et al



(b)

Modeling the QCD Phase Diagram

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



QITE algorithms to “cool”

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

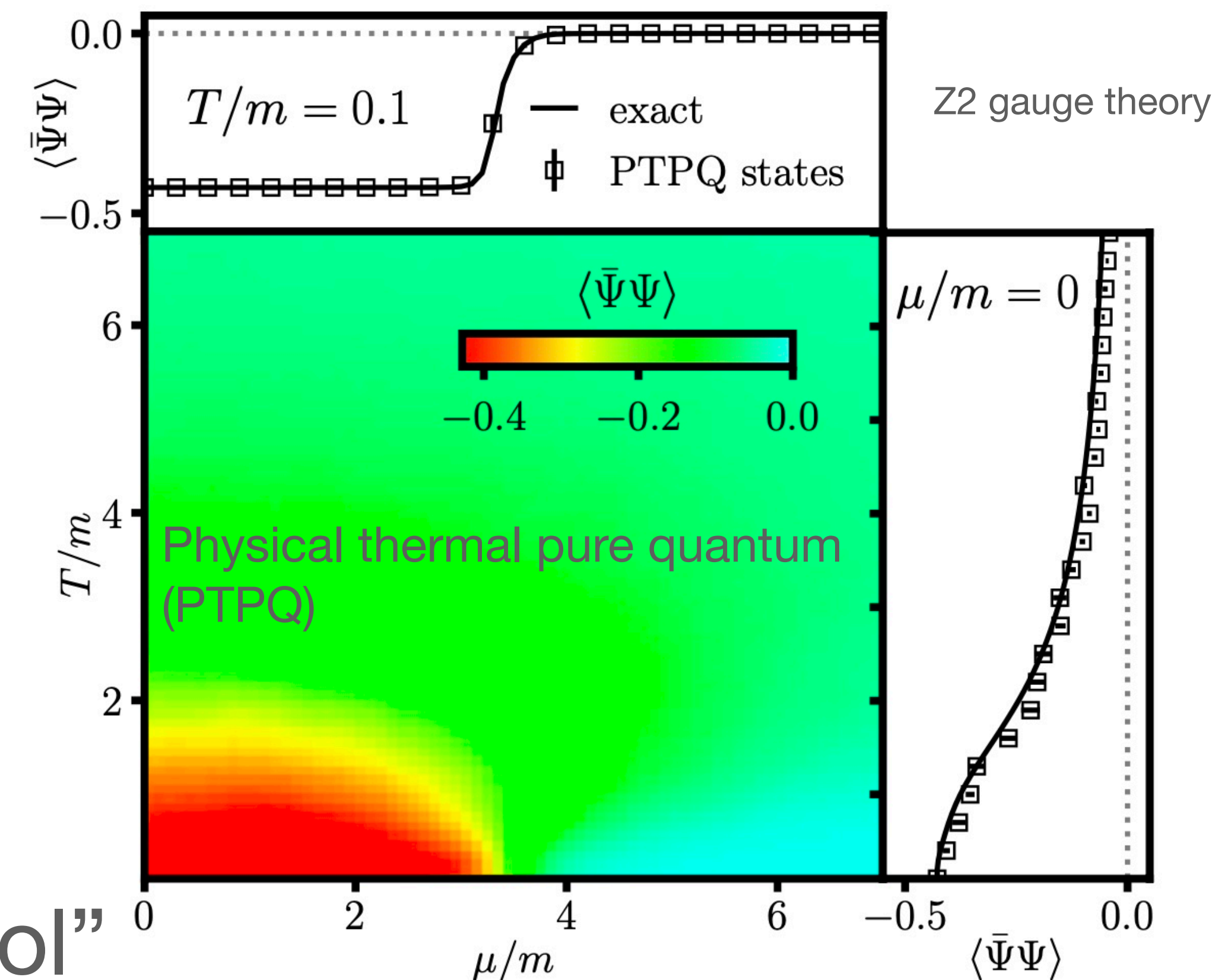
Zohreh Davoudi,^{1,2,*} Niklas Mueller,^{1,3,†} and Connor Powers^{1,2,‡}

¹Maryland Center for Fundamental Physics and Department of Physics, University of Maryland, College Park, MD 20742, USA

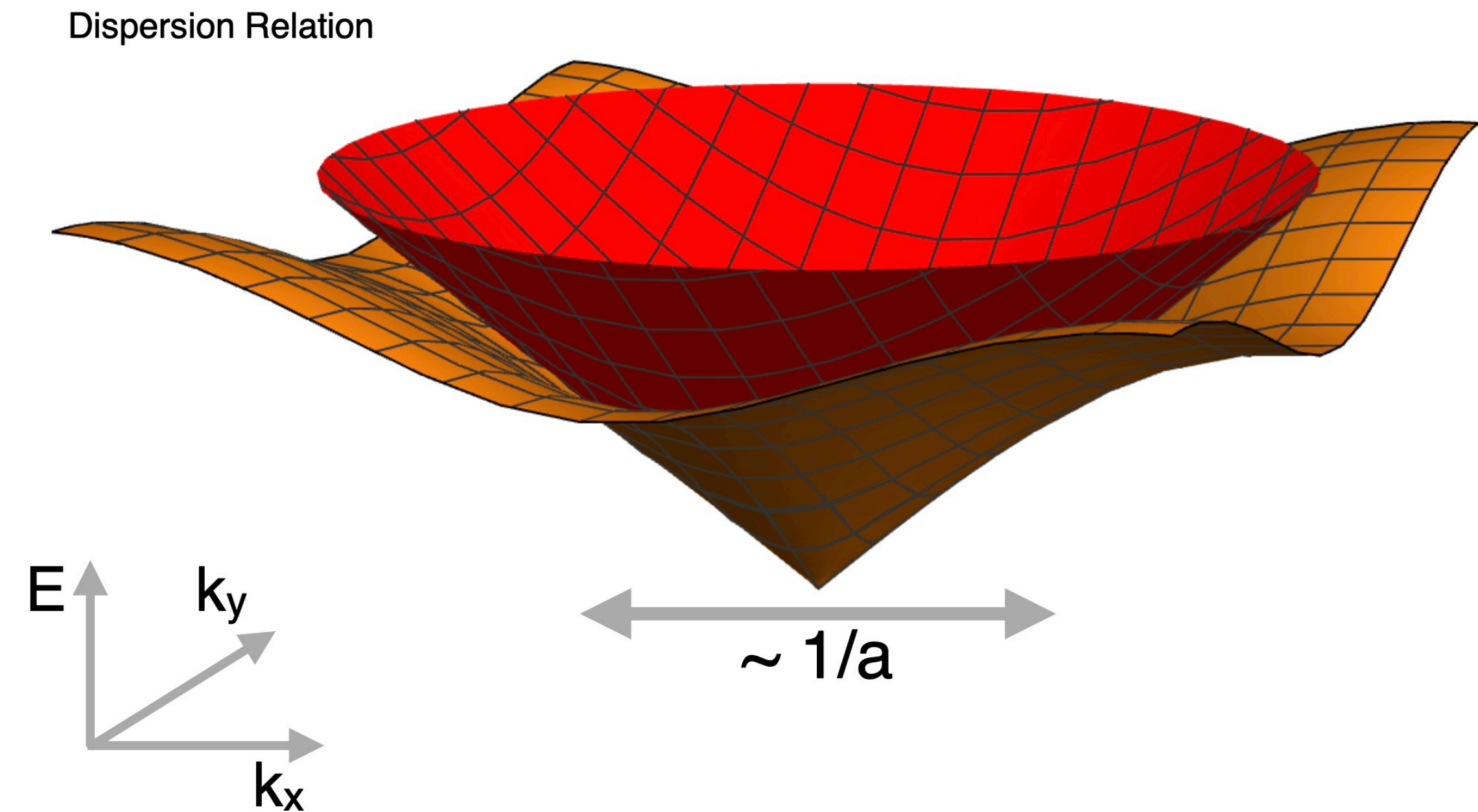
²Institute for Robust Quantum Simulation, University of Maryland, College Park, Maryland 20742, USA

³Joint Quantum Institute, NIST/University of Maryland, College Park, MD 20742, USA

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



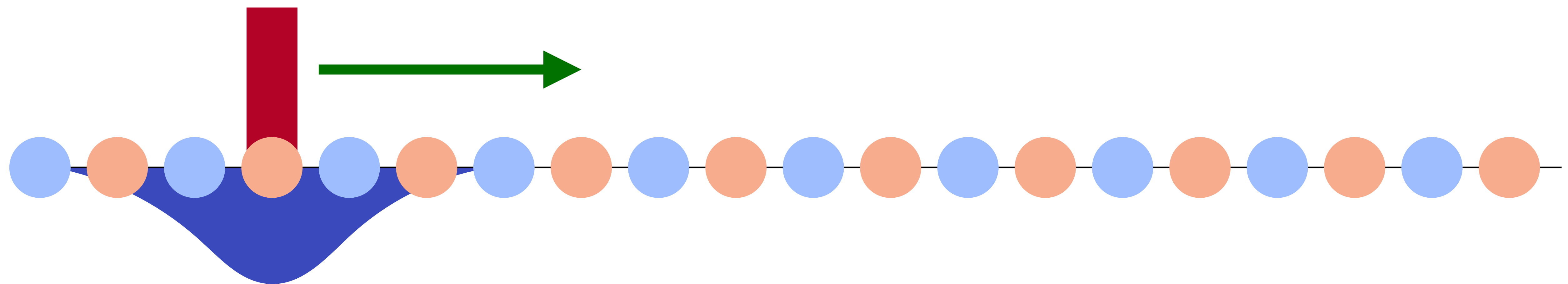
Systematics in Scattering ??



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

Abelian Gauge Theory: Moving in the Lattice Vacuum Classical Simulations

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

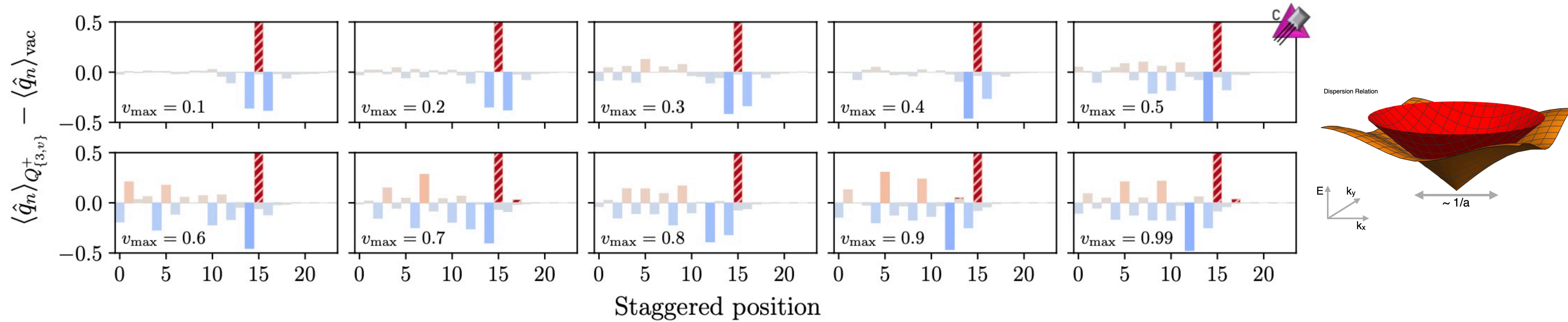


Composite Hadron
charge screening, confinement

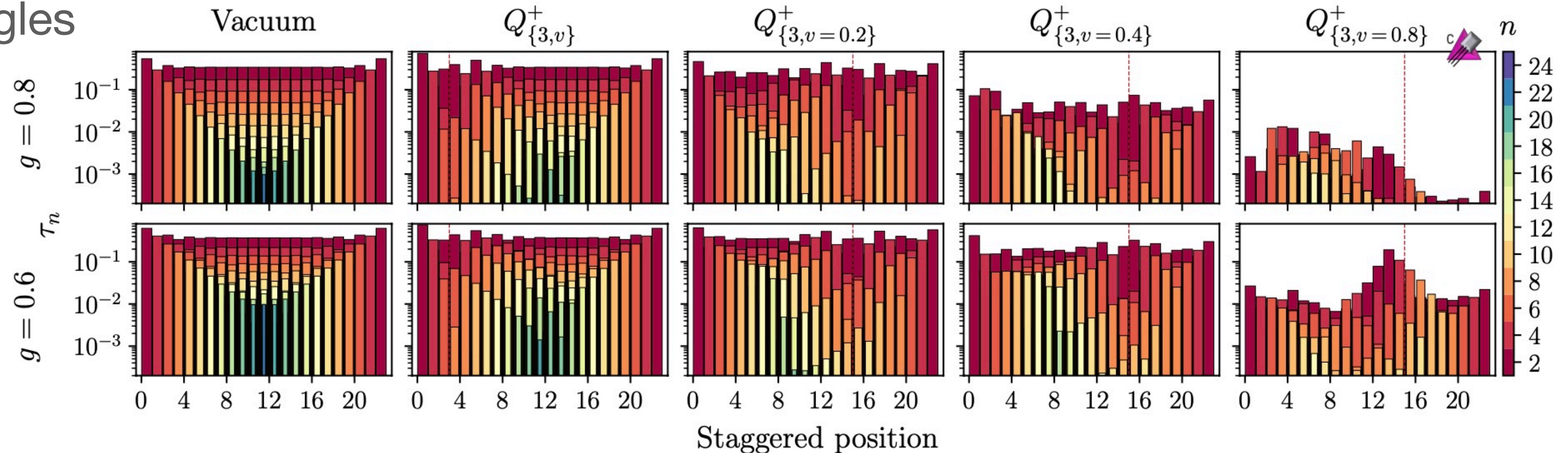
No energy-loss or hadronization in a Lorentz Invariant system (continuum)

Heavy quarks provide control for colliding partons

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

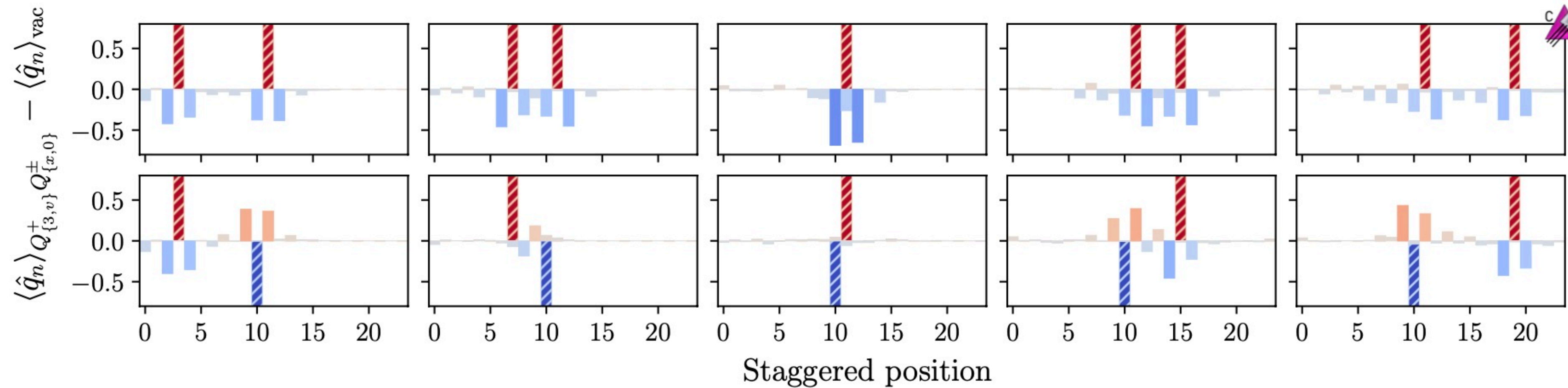


n-tangles

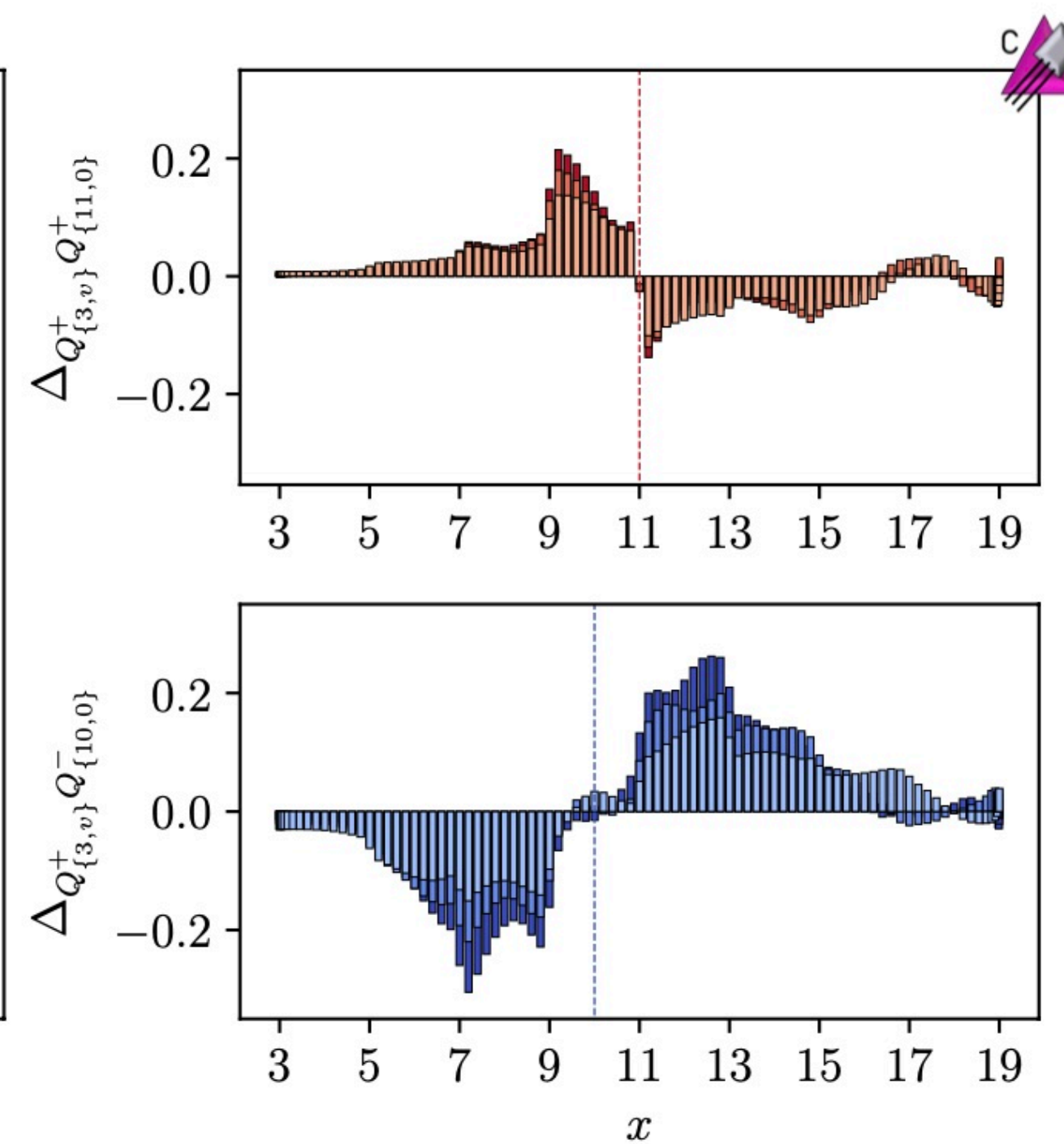
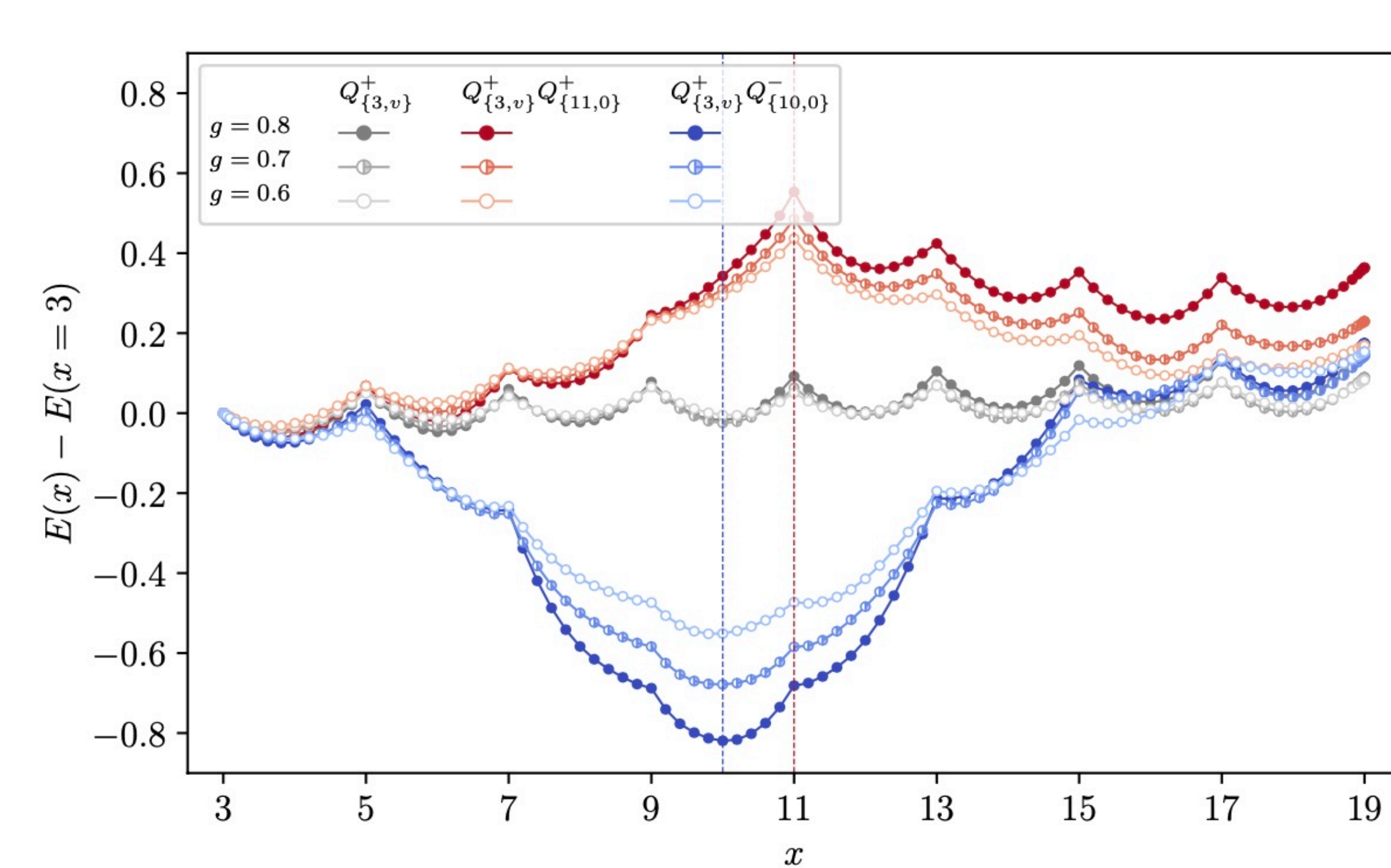


Colliding Partons

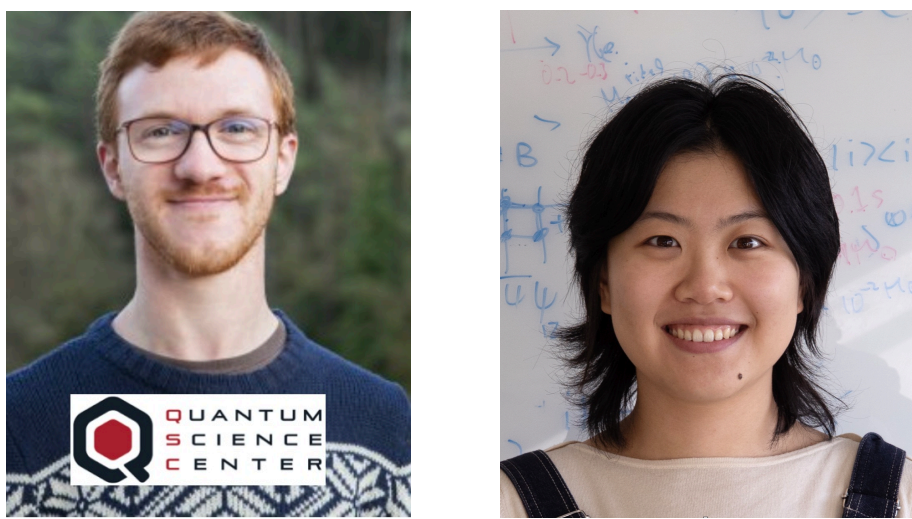
— One Static Background Heavy Quark



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

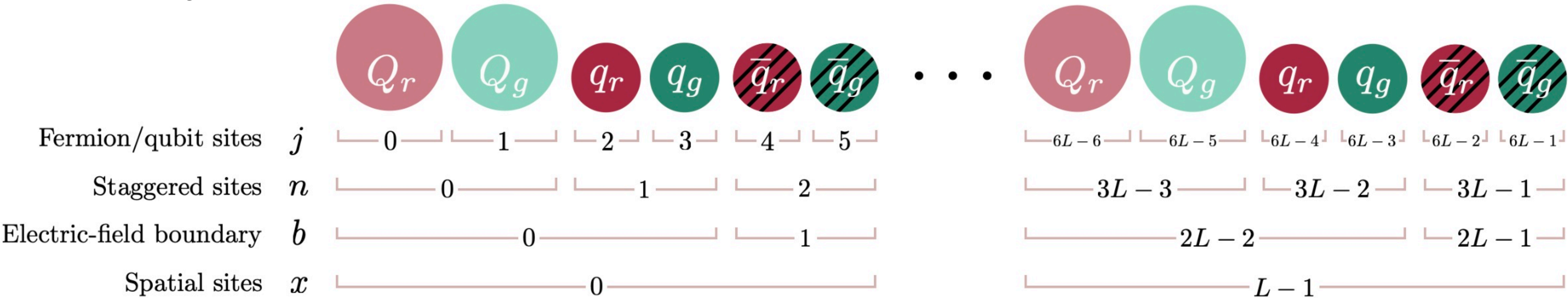


Leading parton collisions
dominate energy loss



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

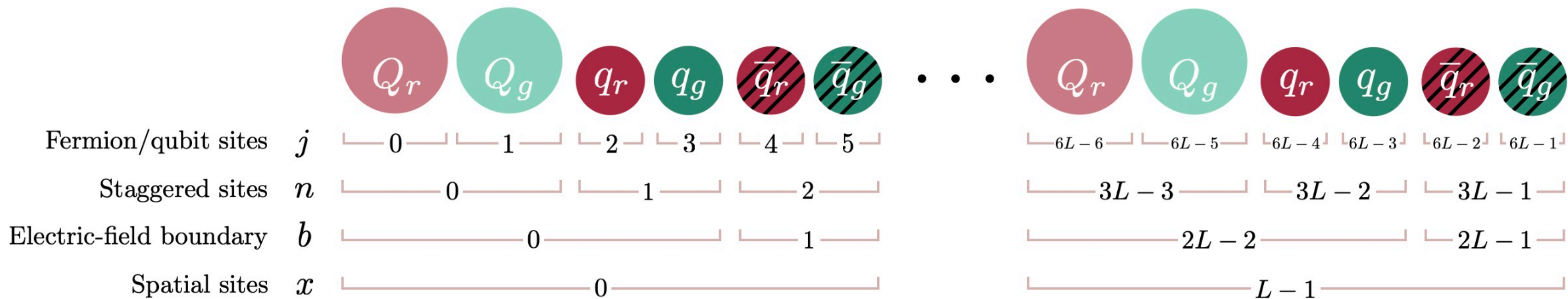
Marc Illa, Zhiyao Li



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

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

The SU(2) Hamiltonian



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

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

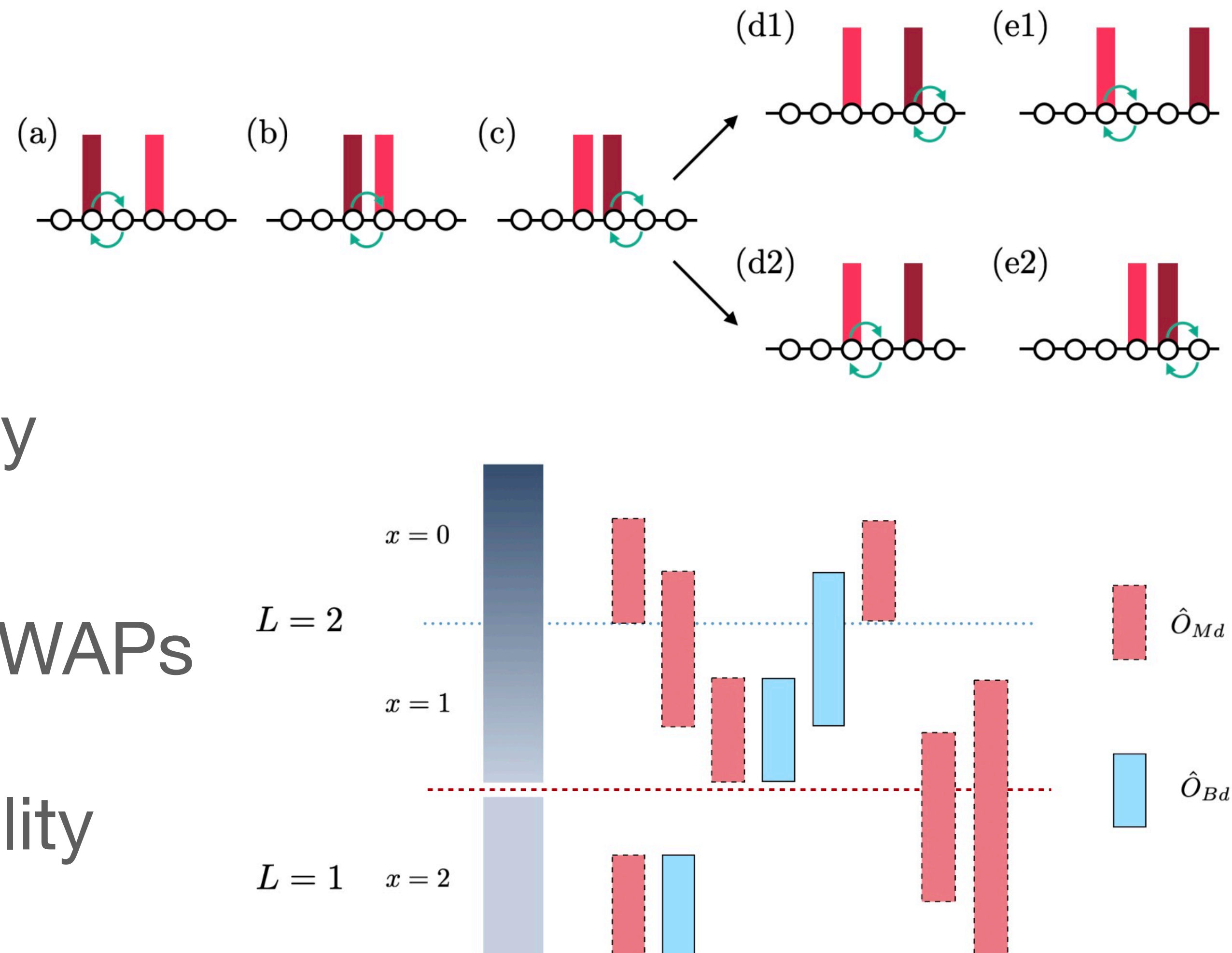
$$\hat{H}_k = -\frac{1}{2} \sum_{n \in q} \sum_{c=0,1} \left(\hat{\sigma}_{2n+c}^+ \hat{Z}_{2n+1+c} \hat{\sigma}_{2n+2+c}^- + \text{h.c.} \right) - \frac{1}{2} \sum_{n \in \bar{q}} \sum_{c=0,1} \left(\hat{\sigma}_{2n+c}^+ \hat{Z}_{2n+1+c} \hat{Z}_{2n+2+c} \hat{Z}_{2n+3+c} \hat{\sigma}_{2n+4+c}^- + \text{h.c.}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

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

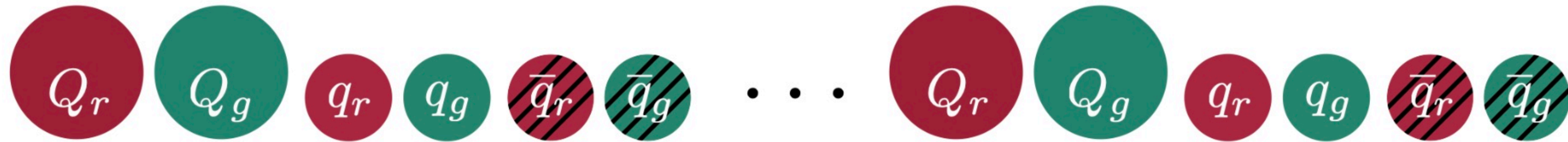
$$\hat{H}_g = \frac{g^2}{2} \sum_{a=1,2,3} \sum_{b=0}^{2L-2} \left(E_b^{(a)} \right)^2 , \quad \hat{H}_\lambda = \frac{\lambda^2}{2} \sum_{a=1,2,3} \left(E_{b=2L-1}^{(a)} \right)^2 \quad E_b^{(a)} \propto \sum_{n=0}^{b+1+\lfloor b/2 \rfloor} \hat{Q}_n^{(a)}$$

Four New Ingredients - Beyond U(1)

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

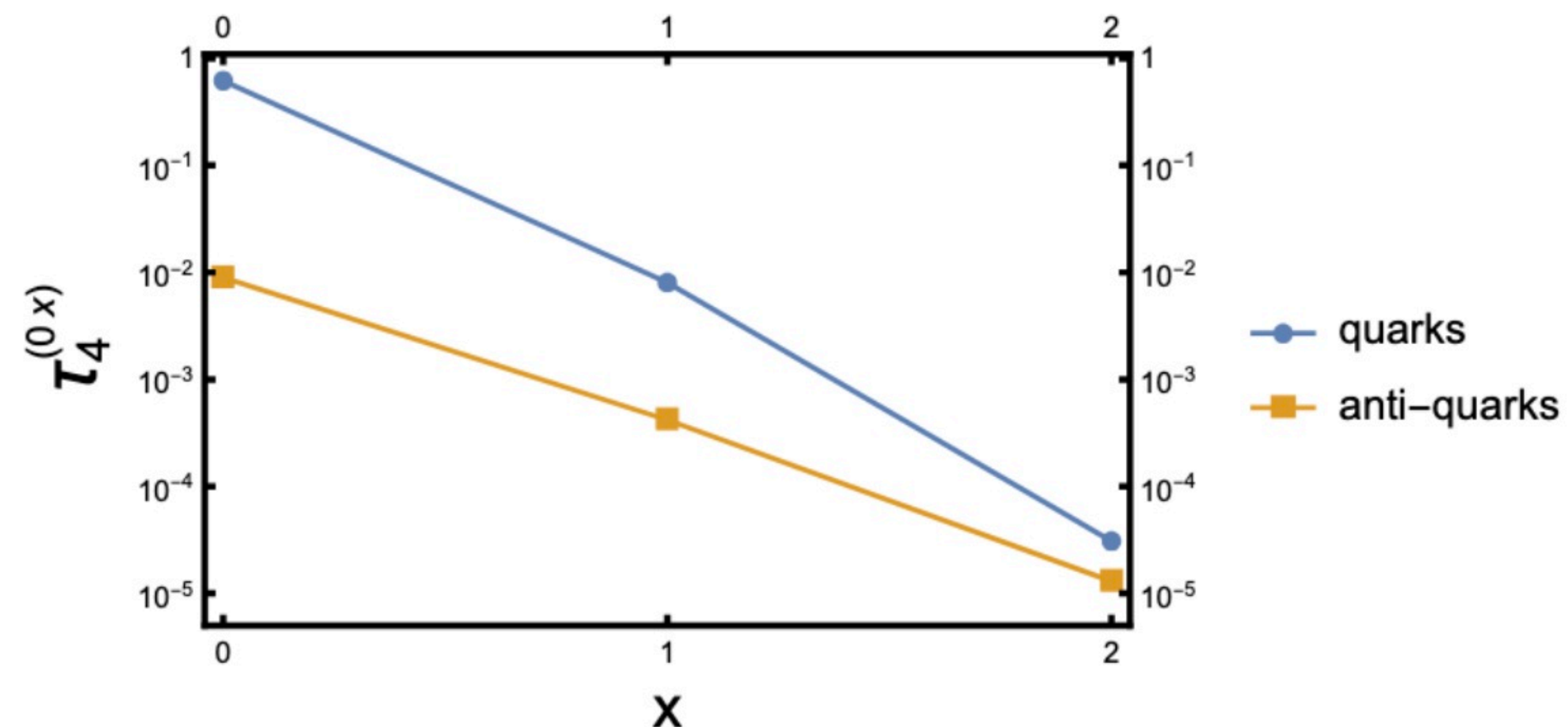


Elaboration : Color Entanglement

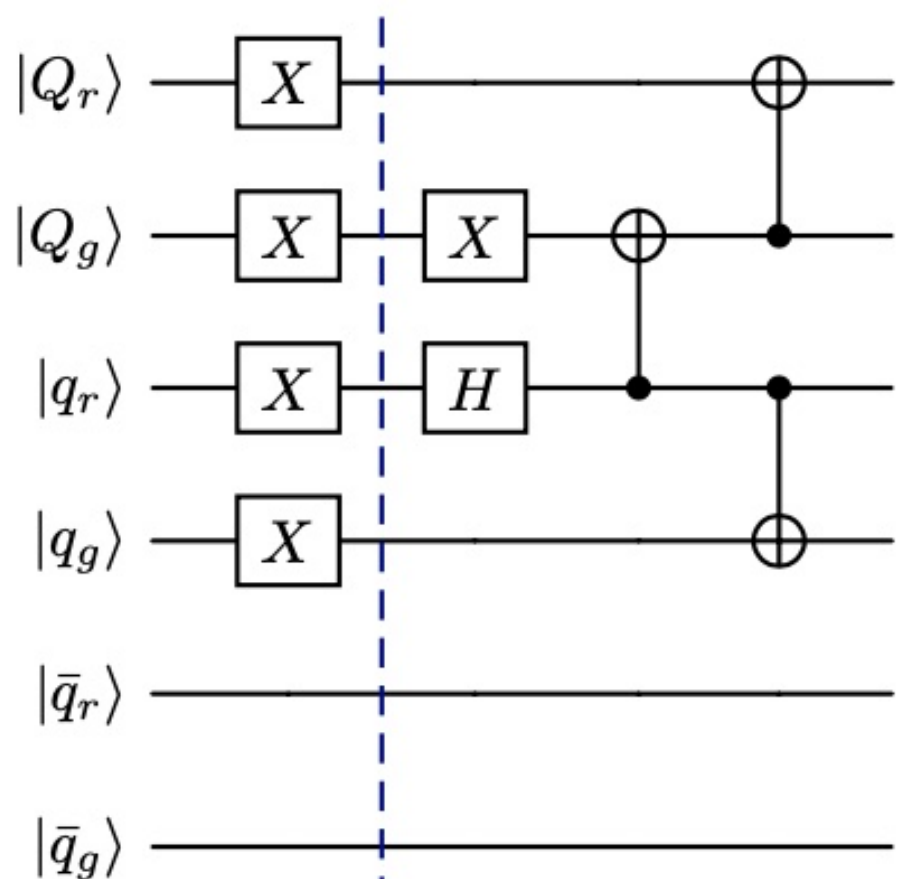


Heavy-Quark
positioned here

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



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



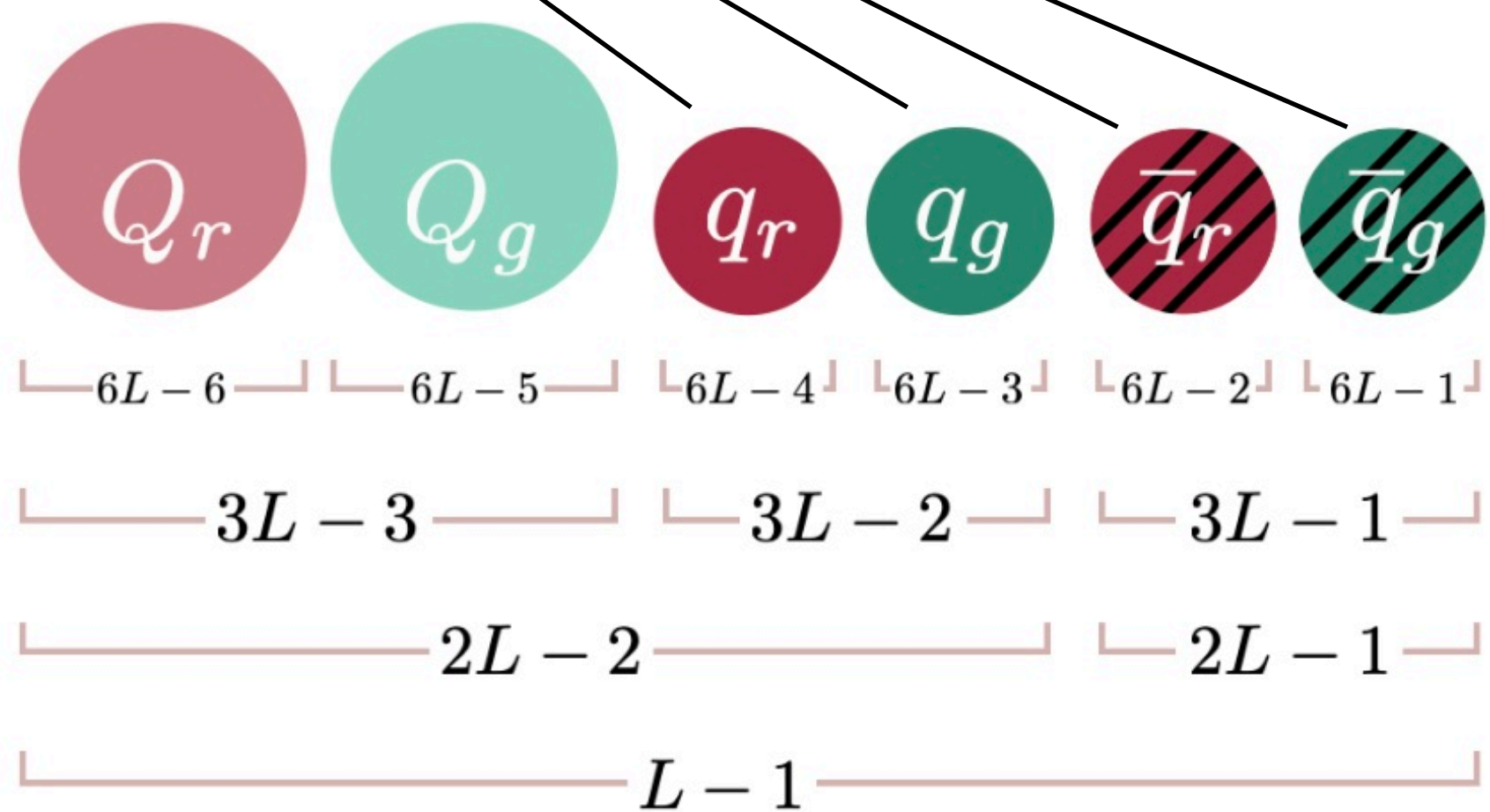
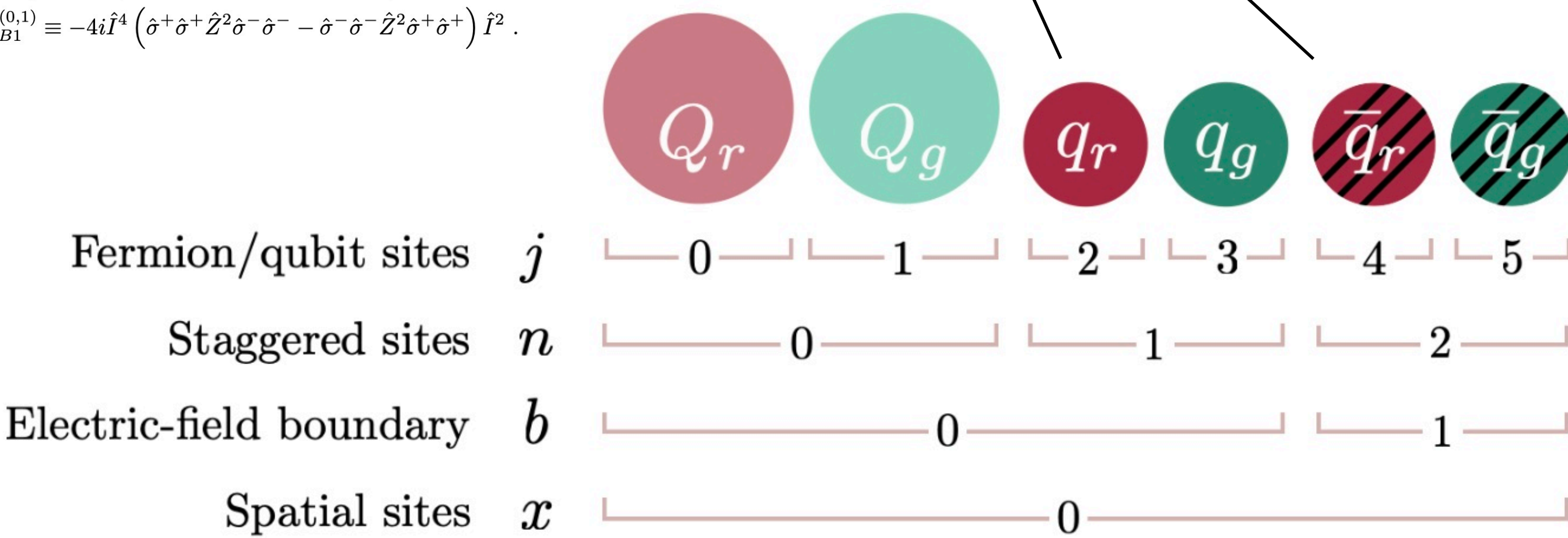
Elaboration : HPC Optimization

Color-singlet operators in the ADAPT-VQE pool

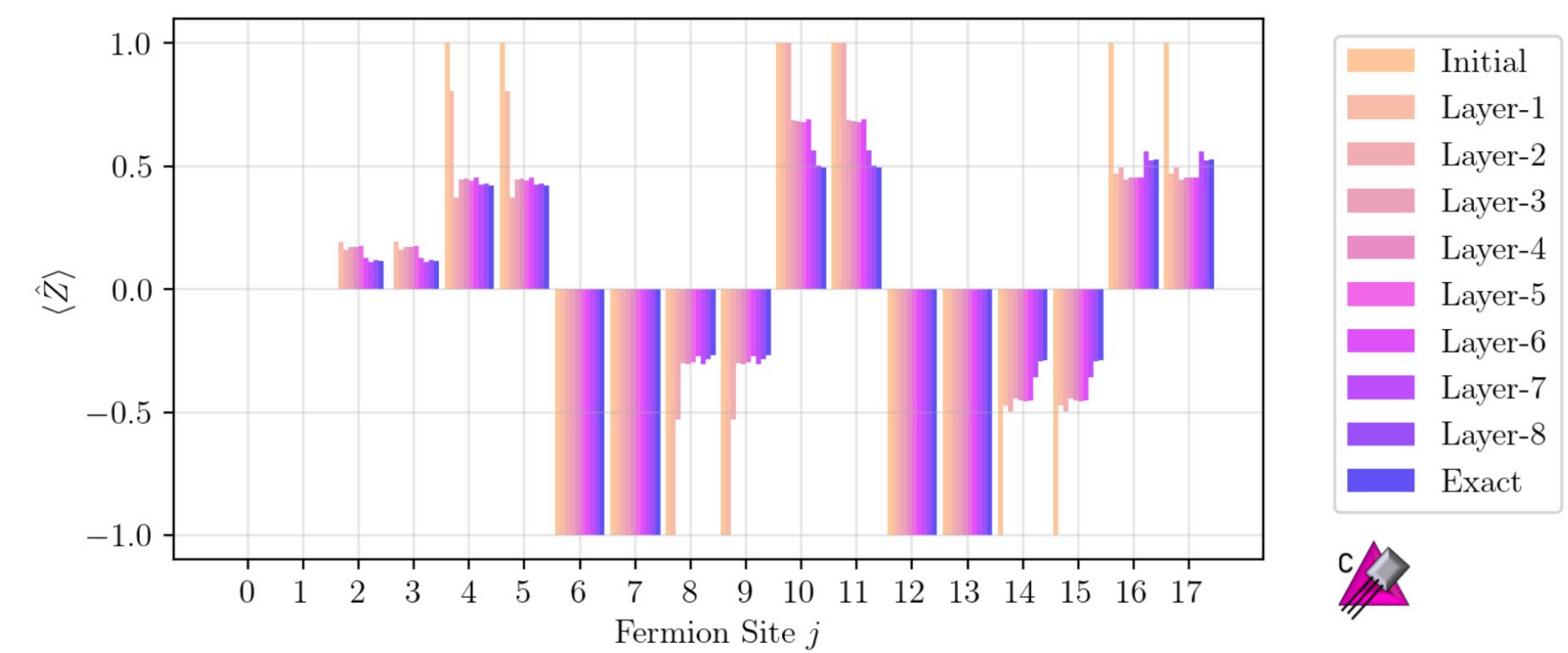
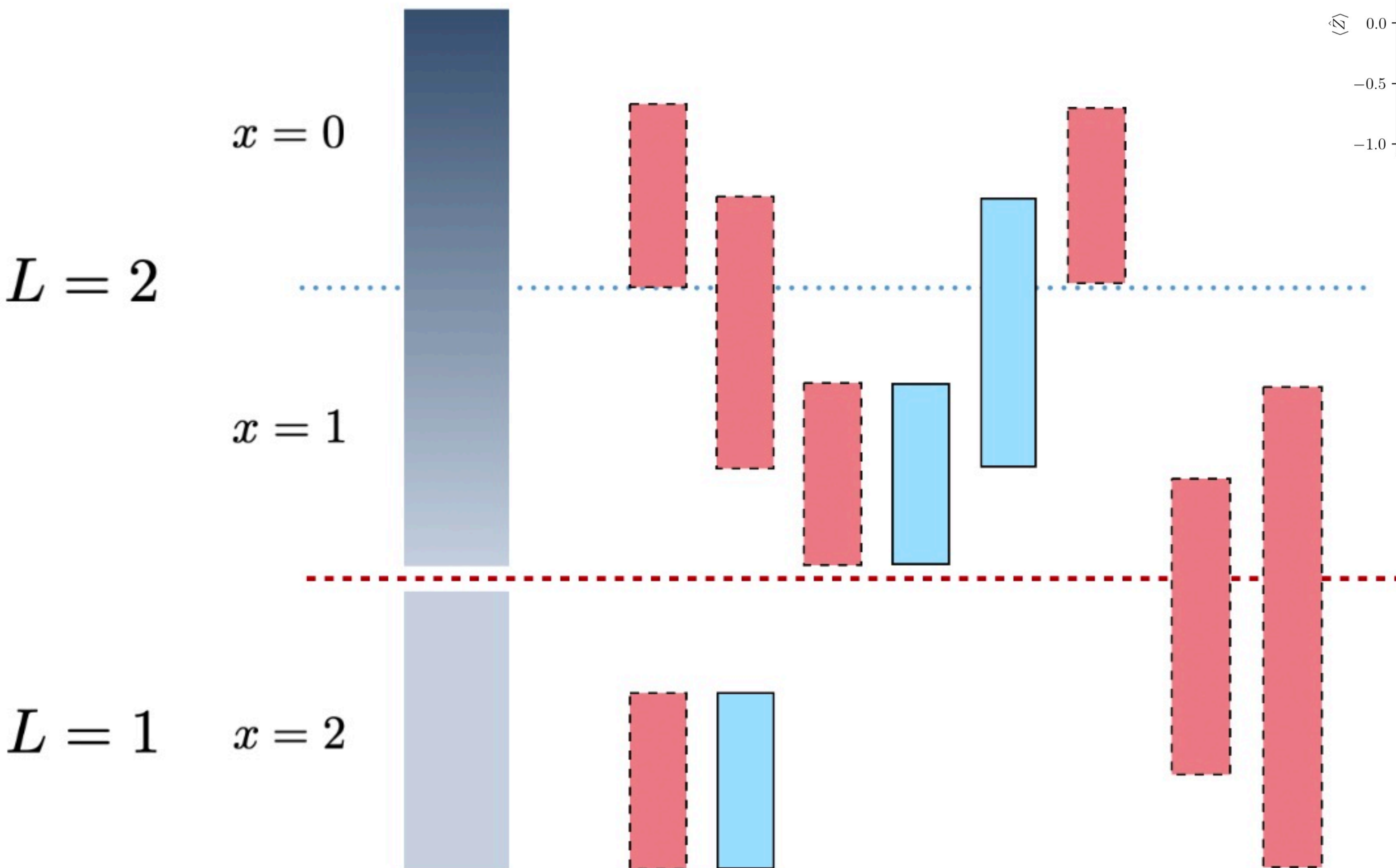
- form factors and position

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

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

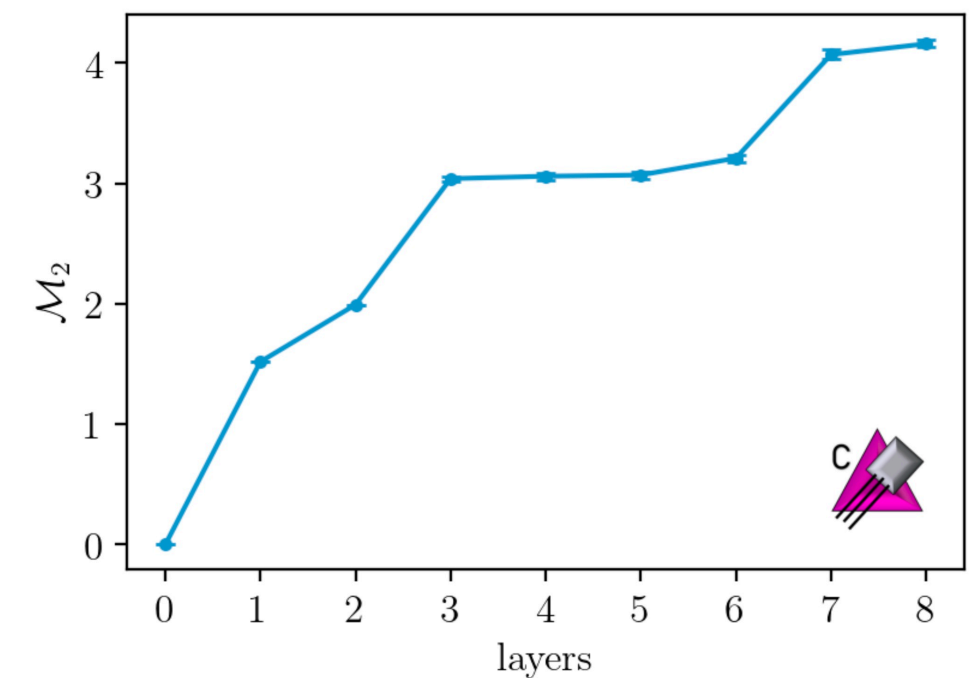


Elaboration : Domain Decomposition

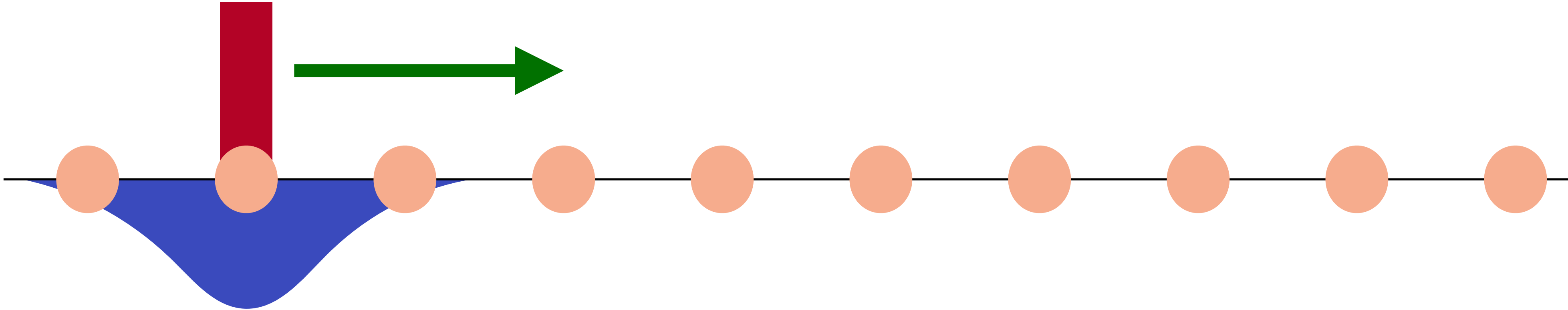


$$\hat{O}_{Md}$$

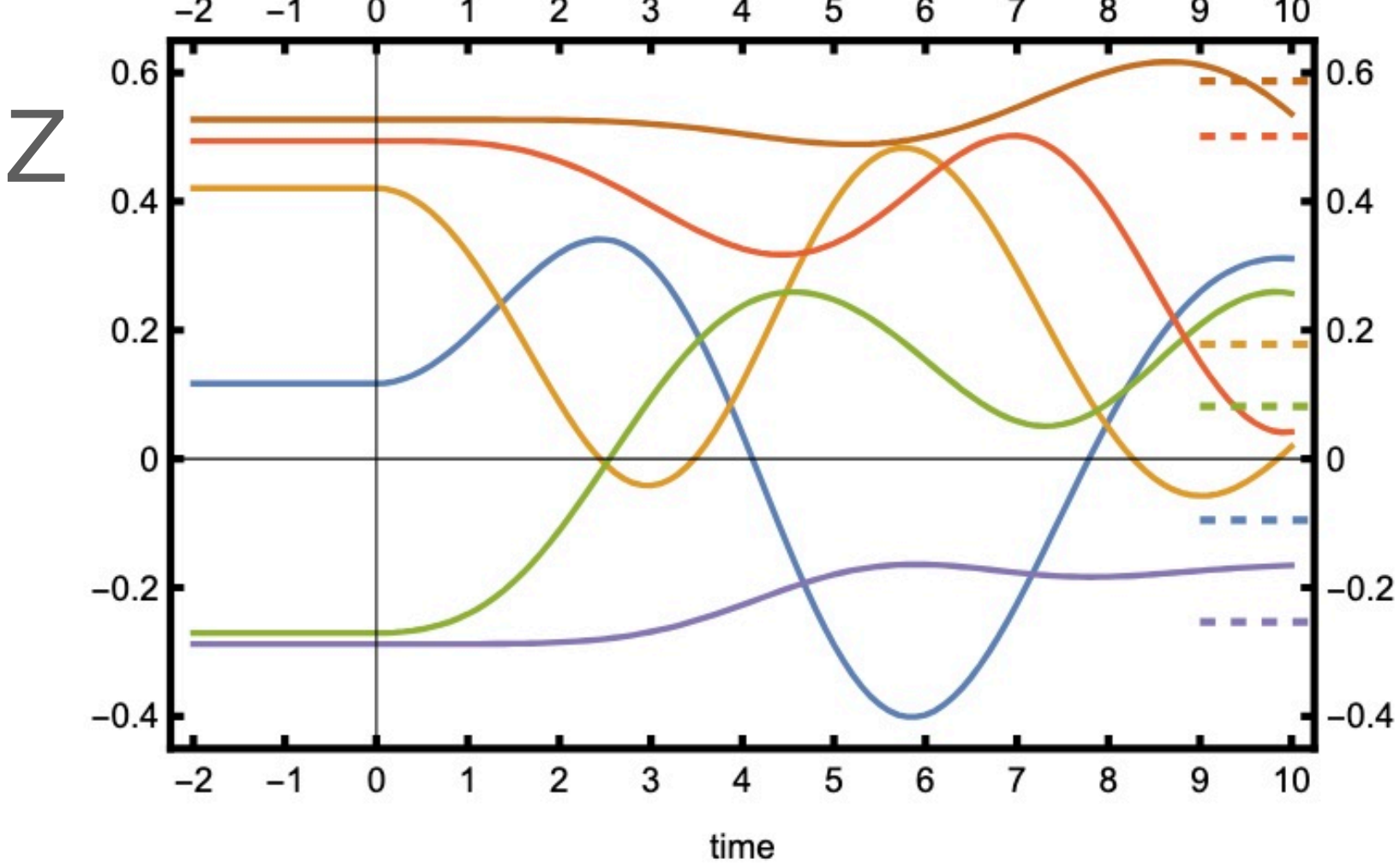
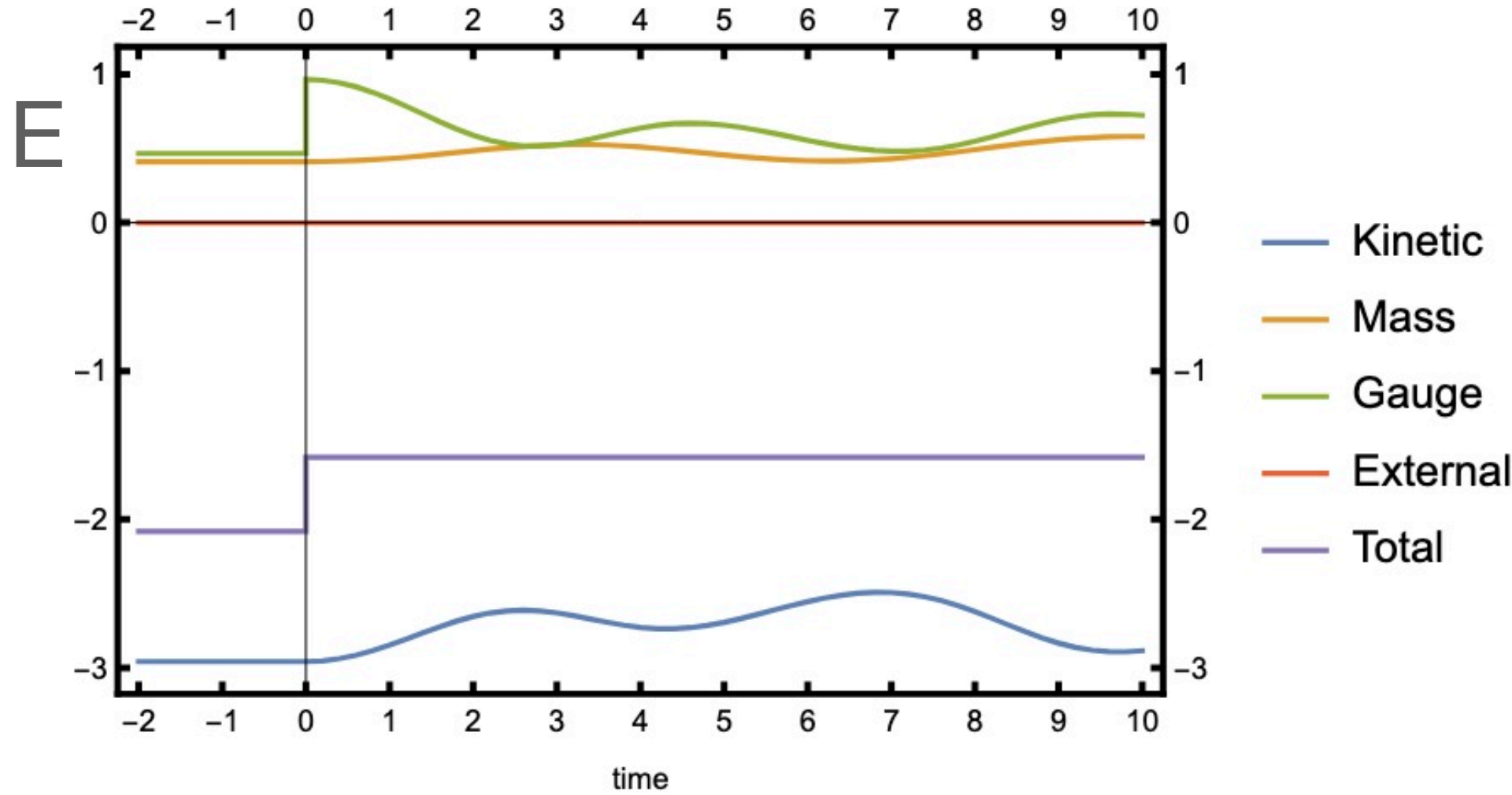
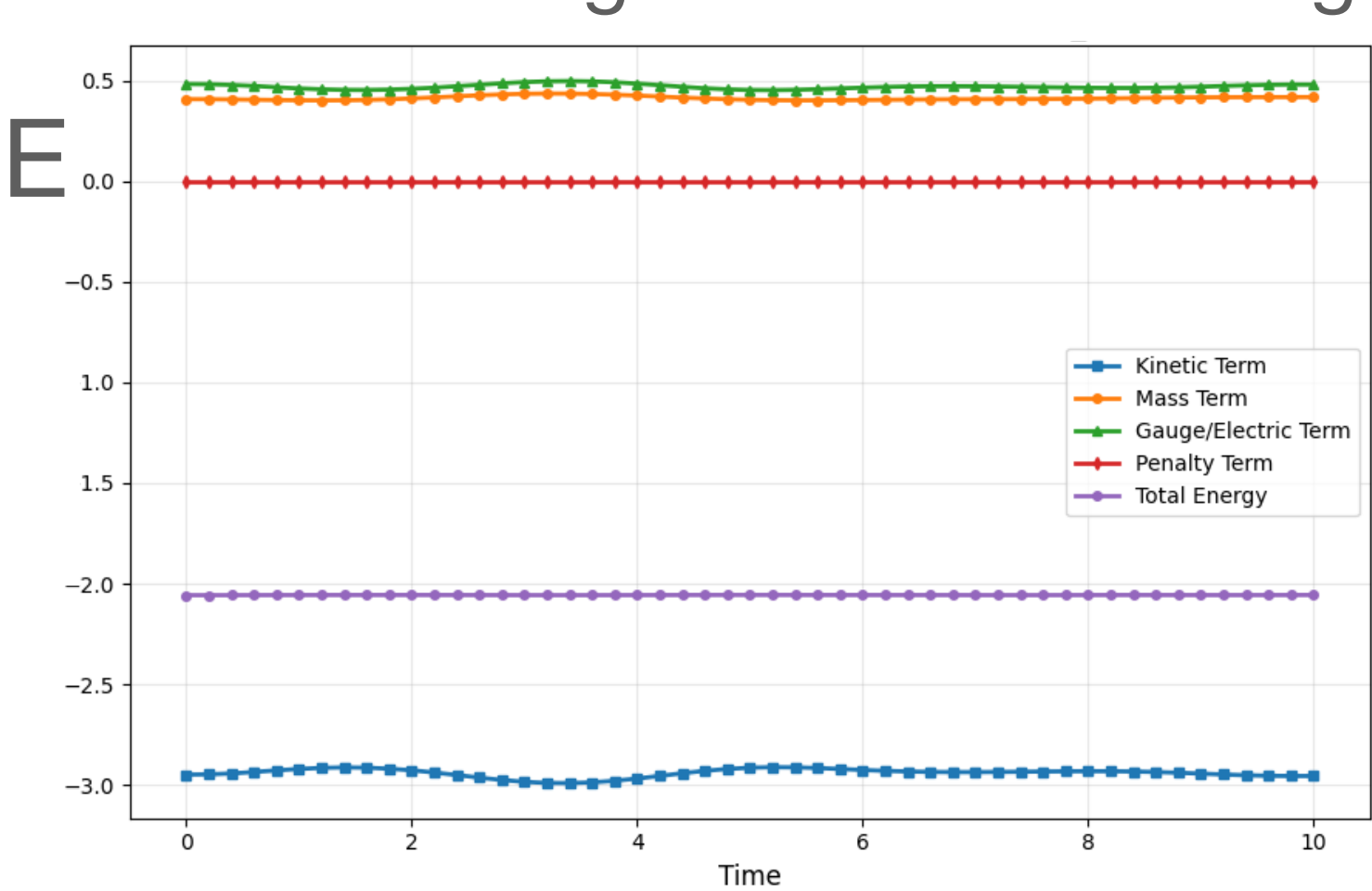
$$\hat{O}_{Bd}$$



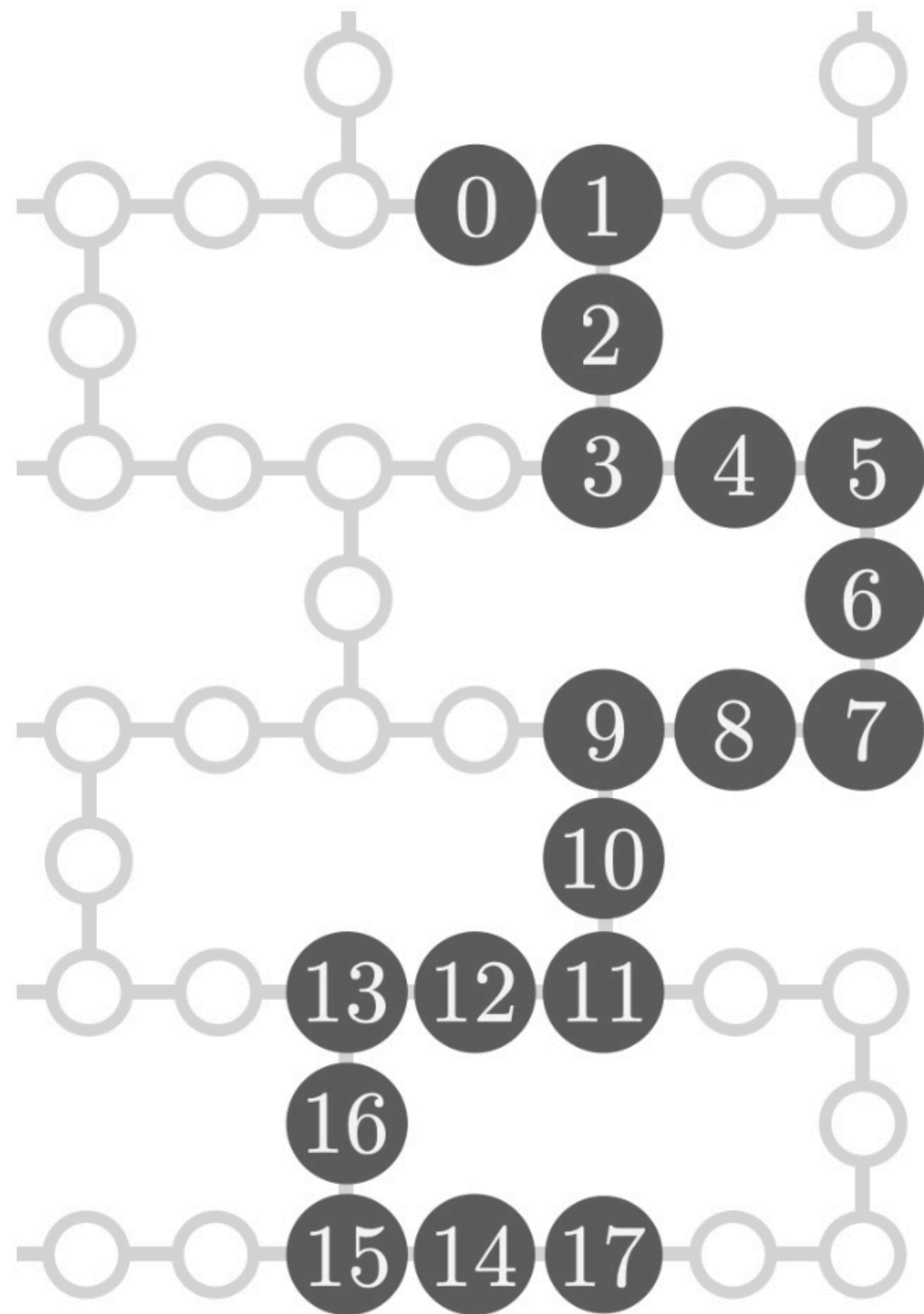
Classical Results



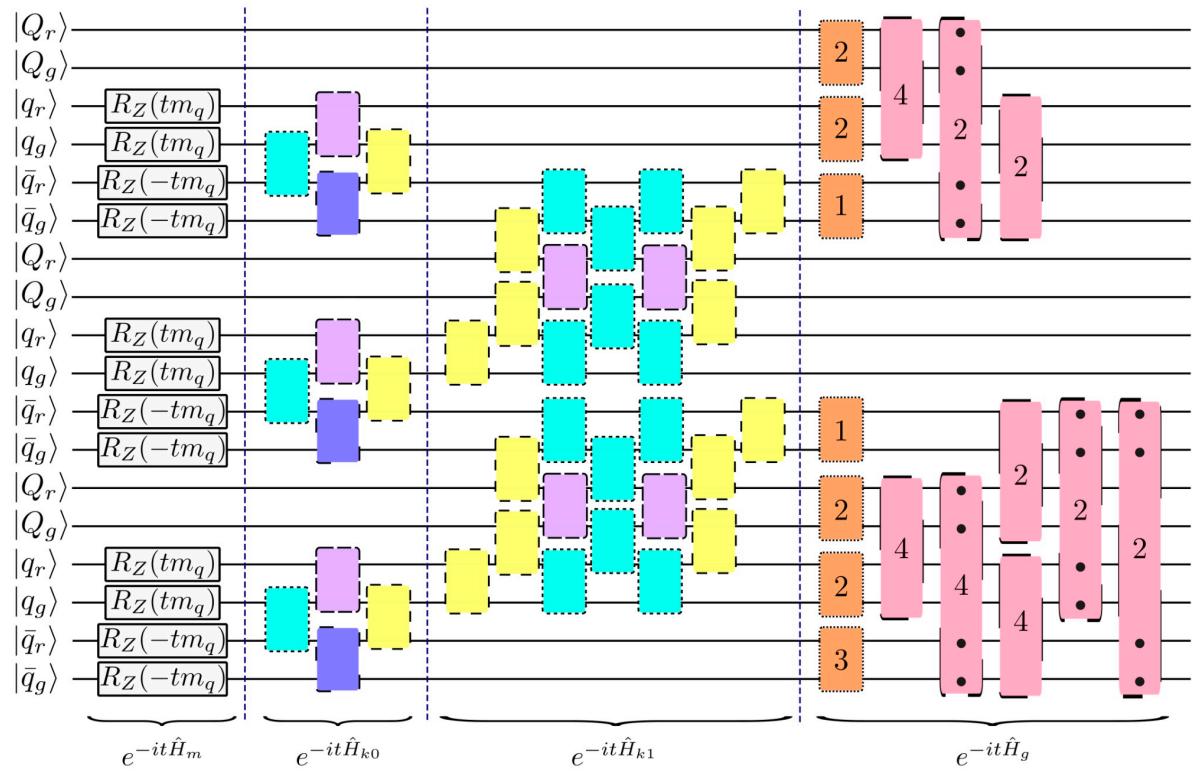
Trotterized ground state heating



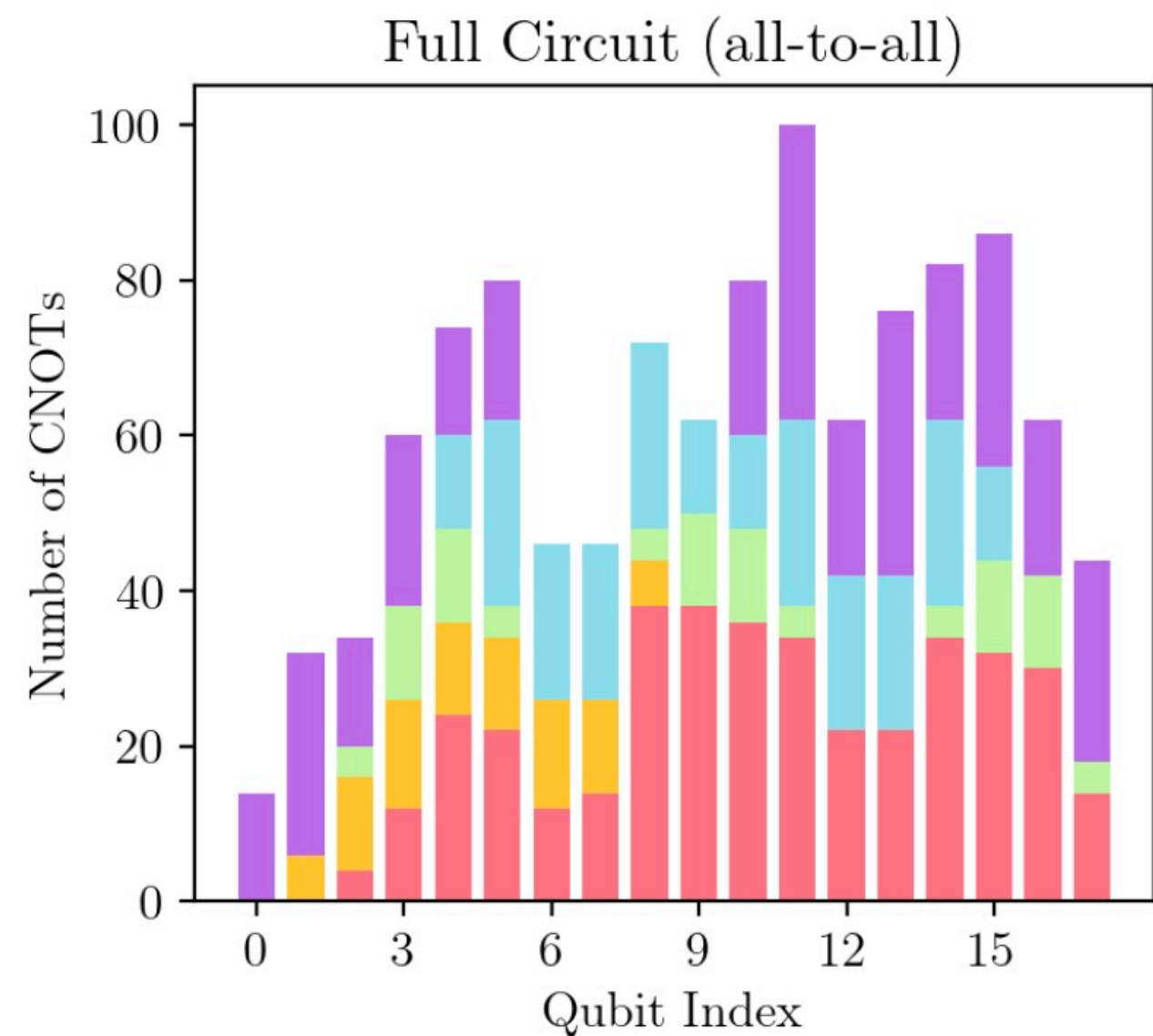
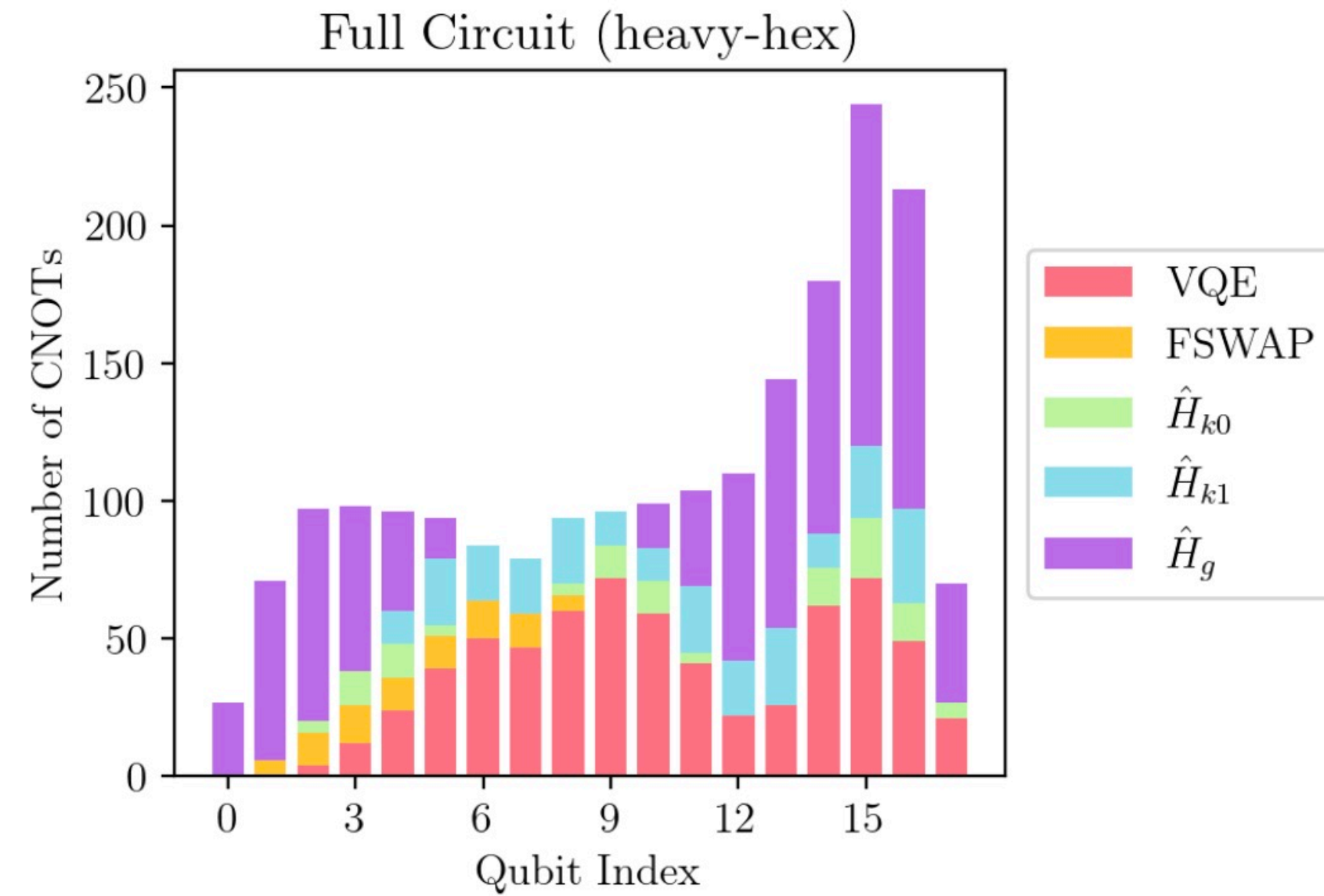
Resources and Layout for L=3



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



Production



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

- HPC optimized ADAPT-VQE (fidelity > 99.5)

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

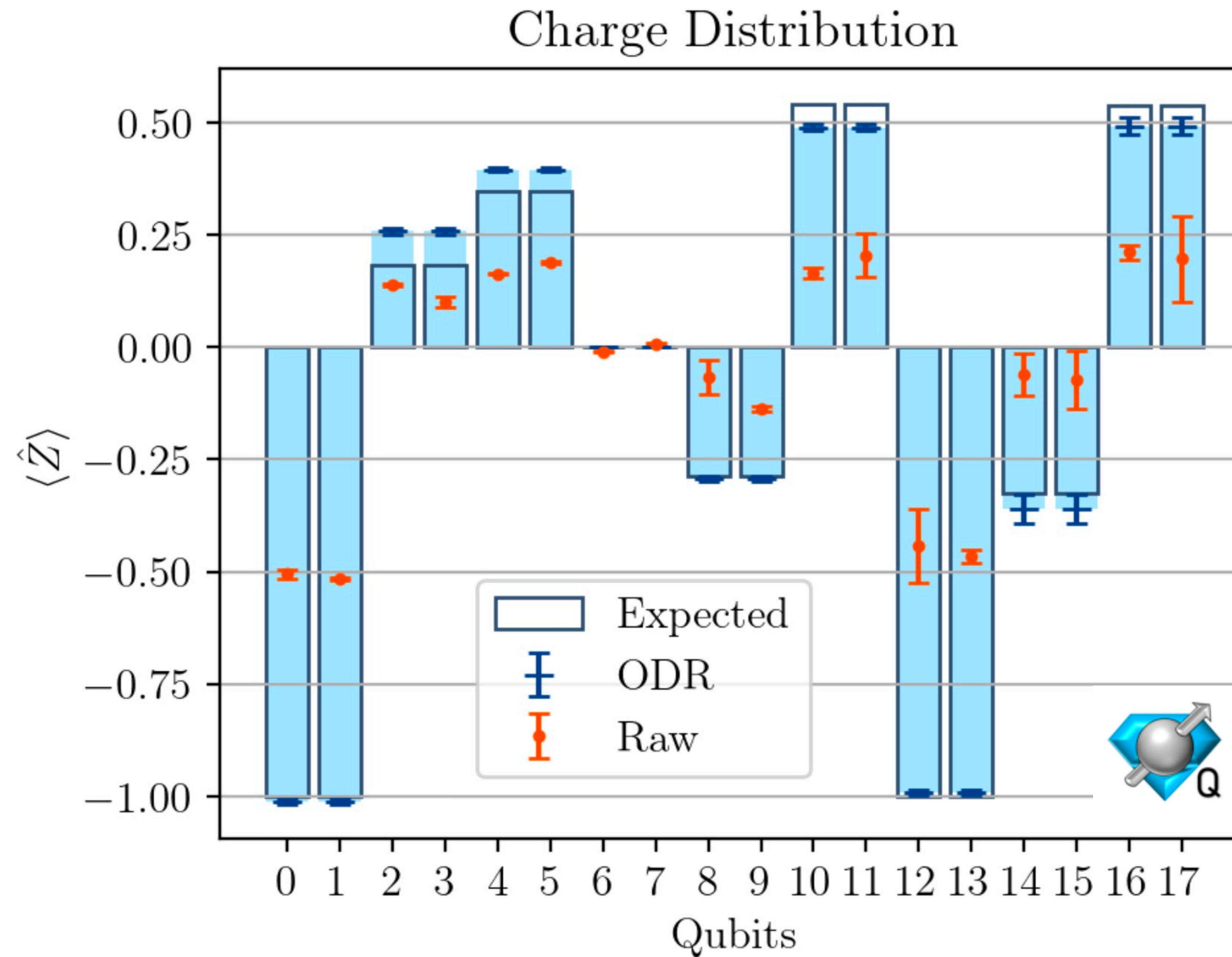
3a) One 2nd-Order Trotter step from t=0 to t=1

3b) Measure the energy in the light quarks

Total 2-Qubit Depth = 398
(after transpilation)

Charge Distribution

IBM Quantum



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

Depth: 1350

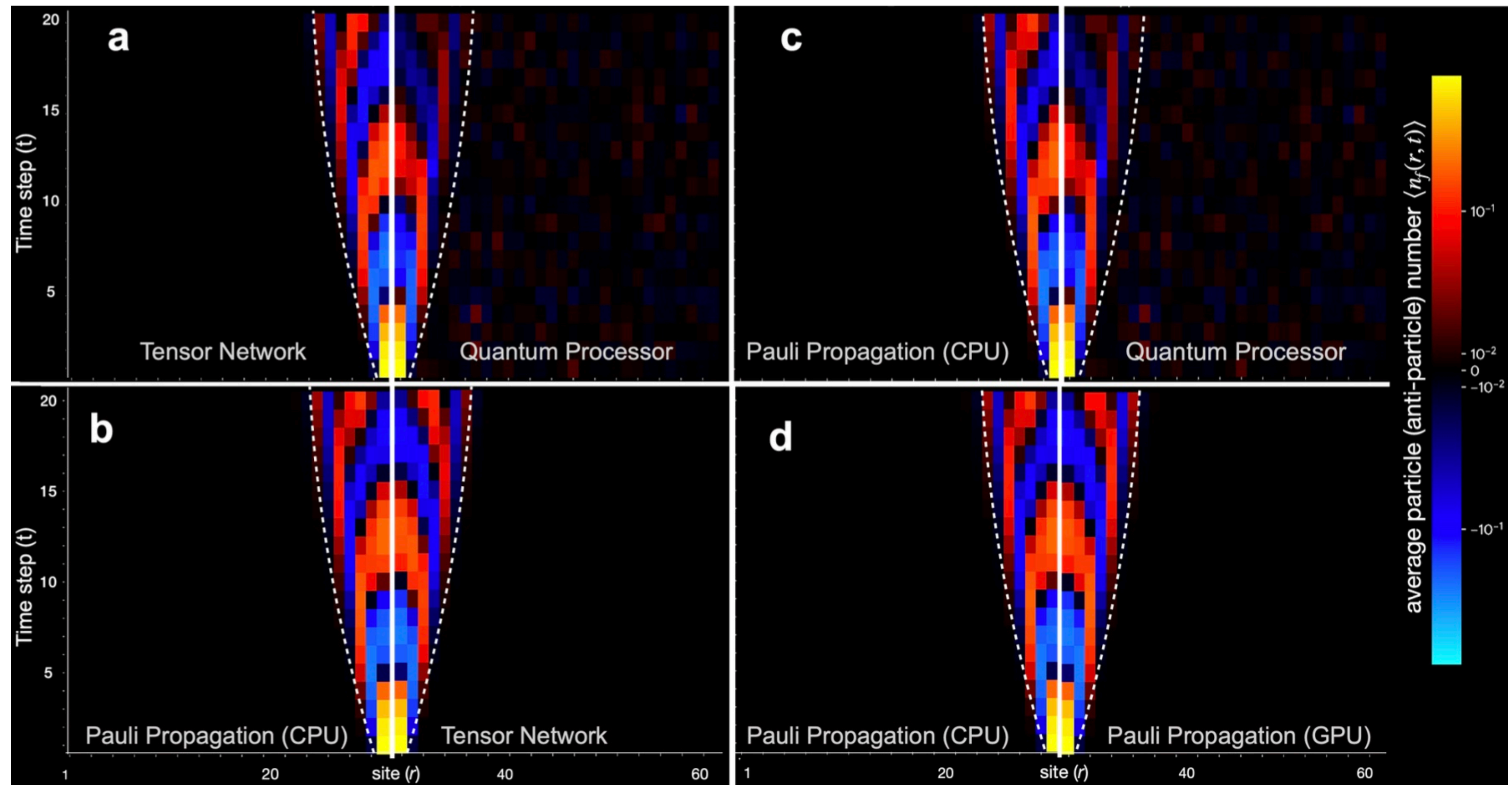
Two-qubit gate depth: 456

from an early implementation

Wavepacket Evolution in 1+1D SU(2)

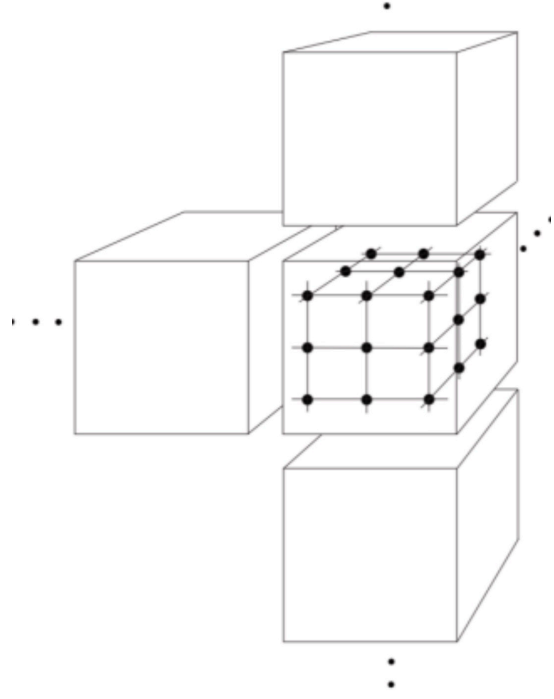
Observation of Robust and Coherent Non-Abelian Hadron Dynamics on Noisy Quantum Processors

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



Dynamical Gauge Fields - Yang-Mills

Byrnes-Yamamoto — Kogut-Susskind



Many ways to map/distribute the field(s) in the UV (lattice spacing)

Consider the Kogut-Susskind basis = electric basis

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

Electric Field Casimir operator

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

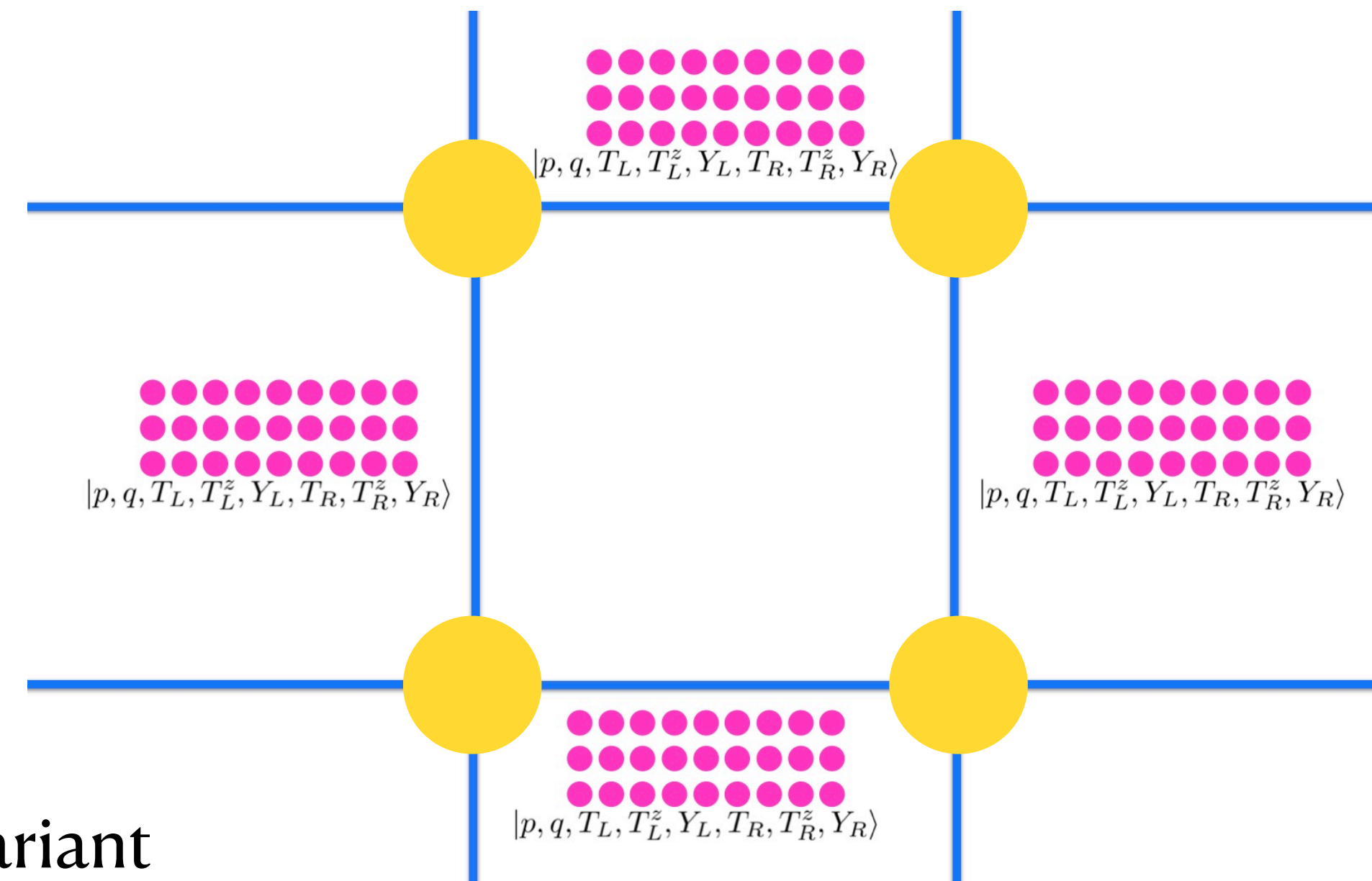
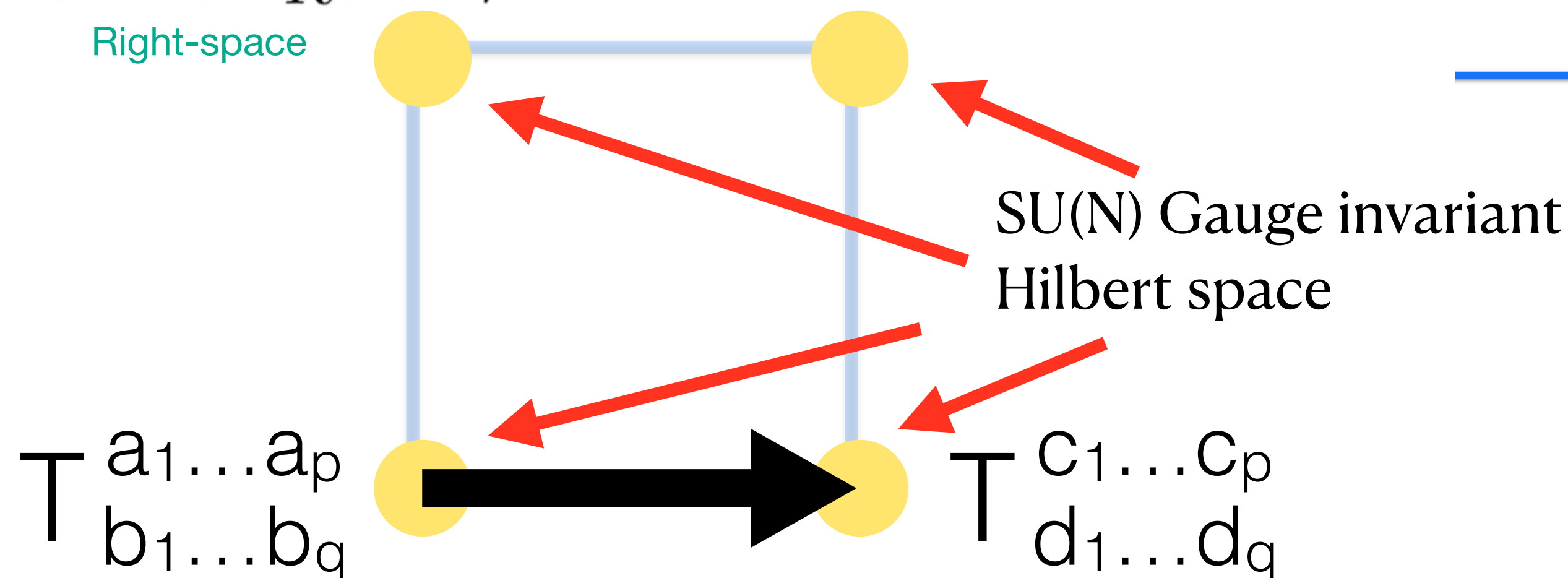
Irrep

Left-space

Right-space

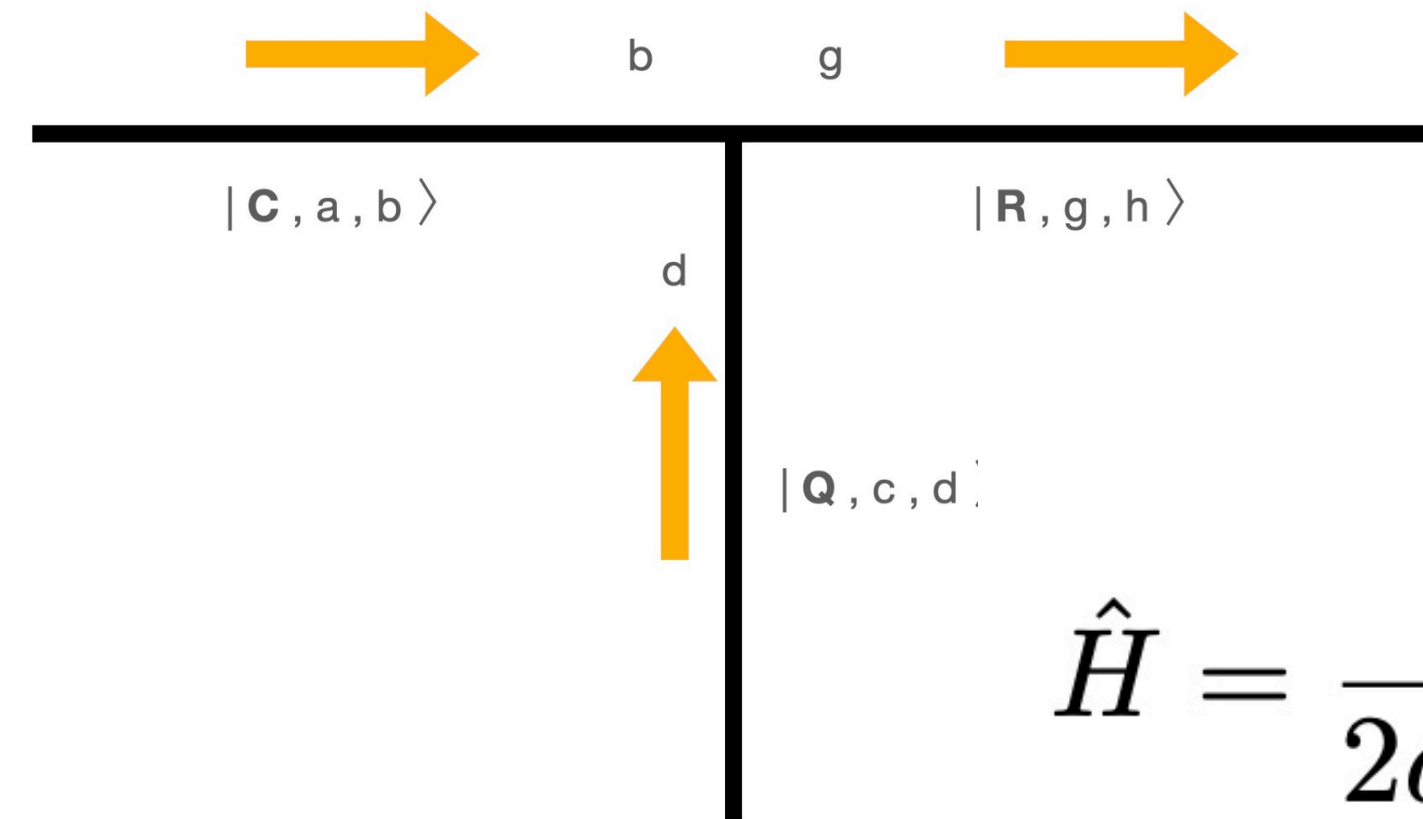
Magnetic Field operator

Off-diagonal on electric basis



Truncations in irrep space !!!!!

Why Non-Abelian is More Complex than Abelian



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

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

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

Yang-Mills

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

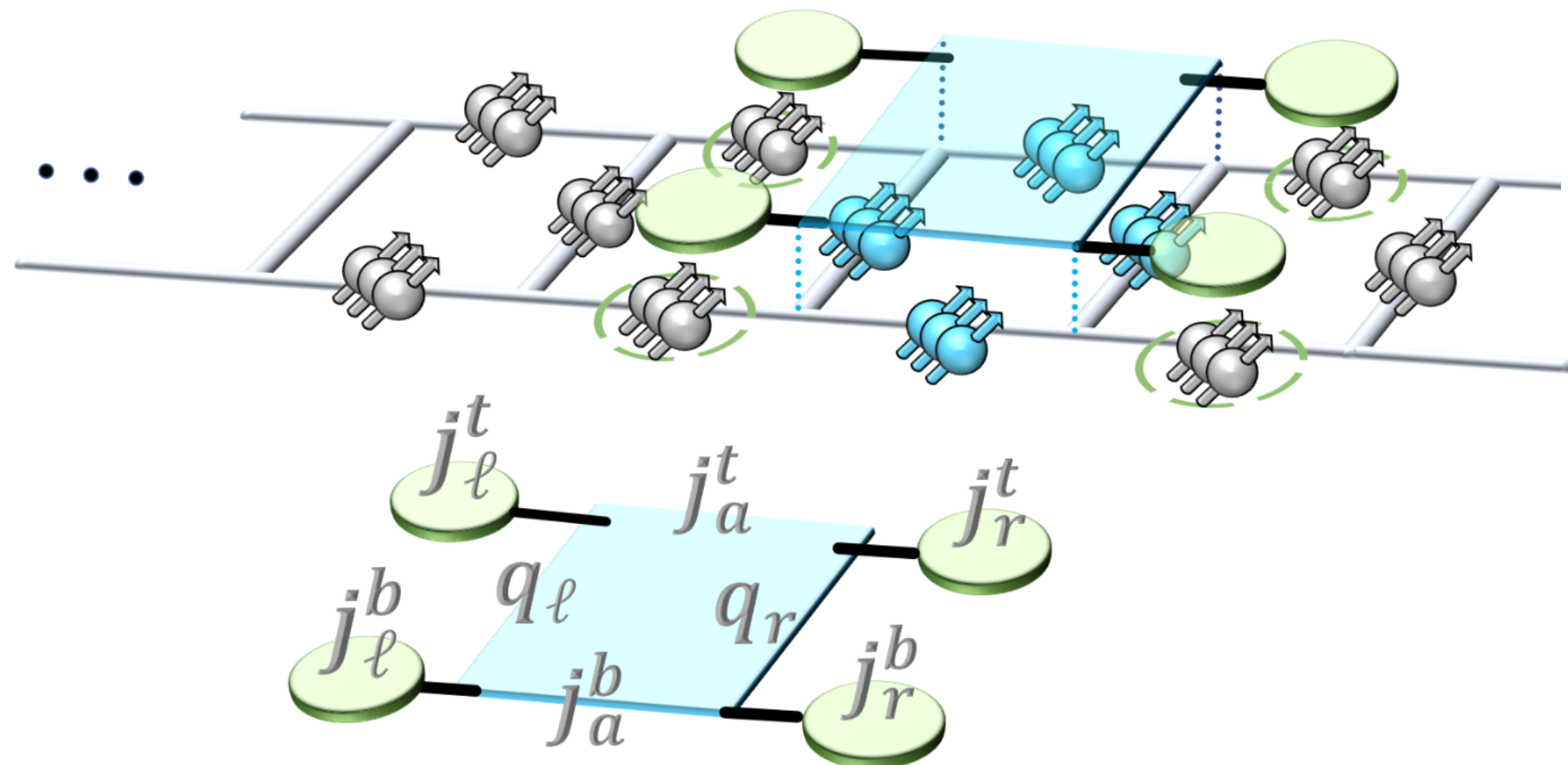
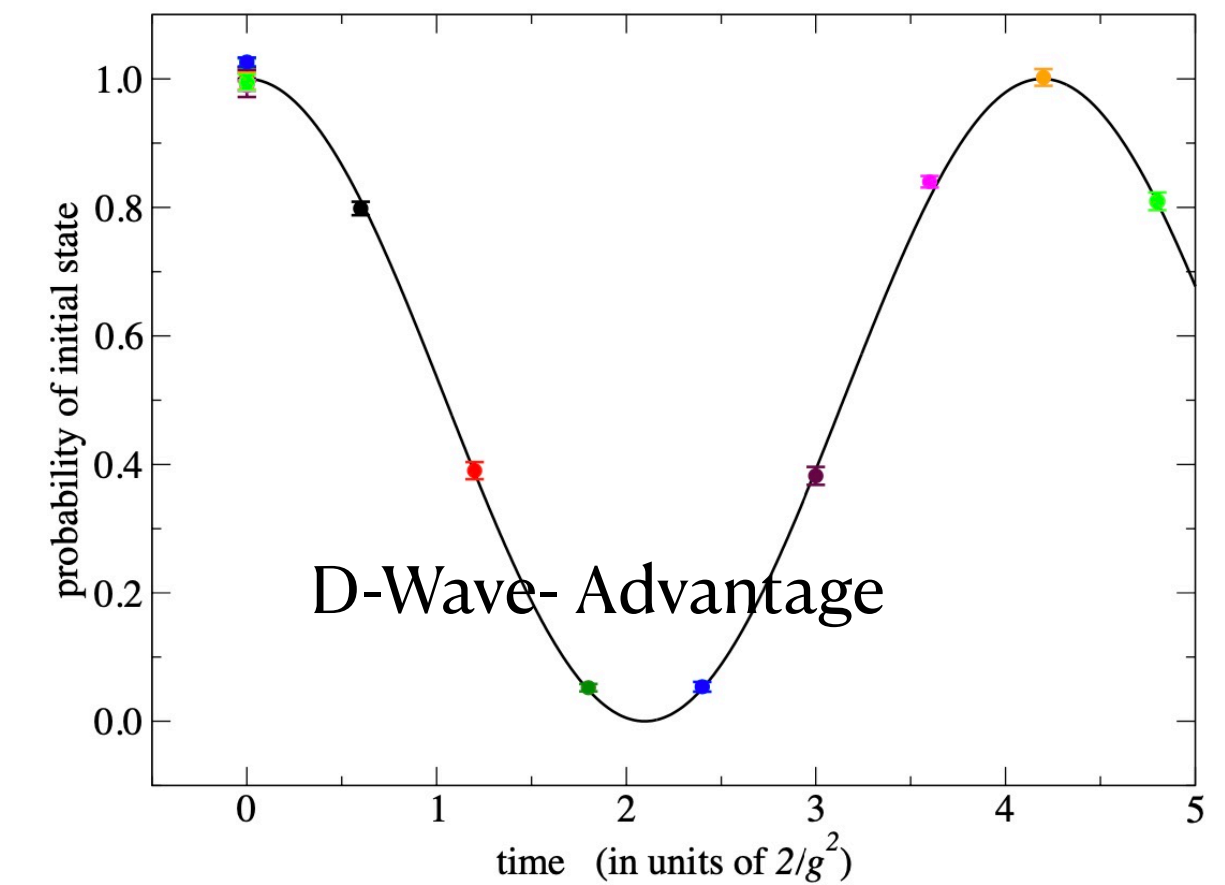
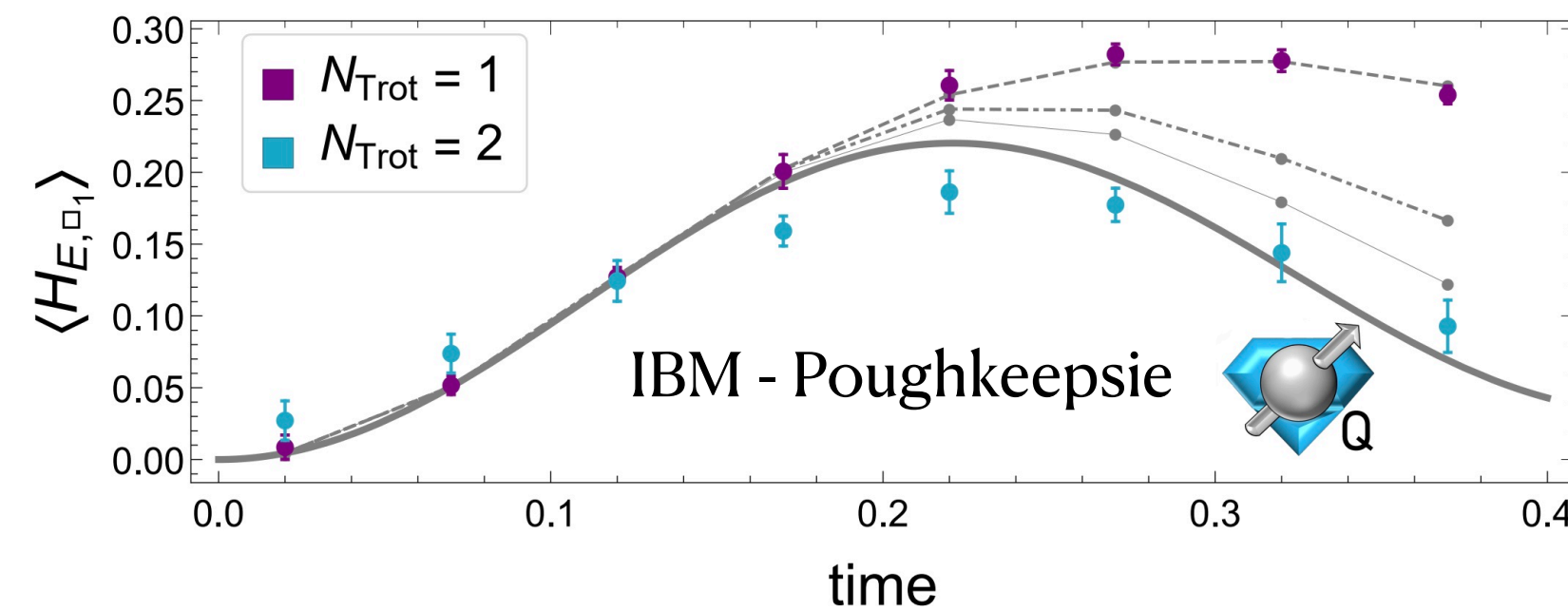


Also see Mari Carmen Banuls, Karl Jansen et al

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

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

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



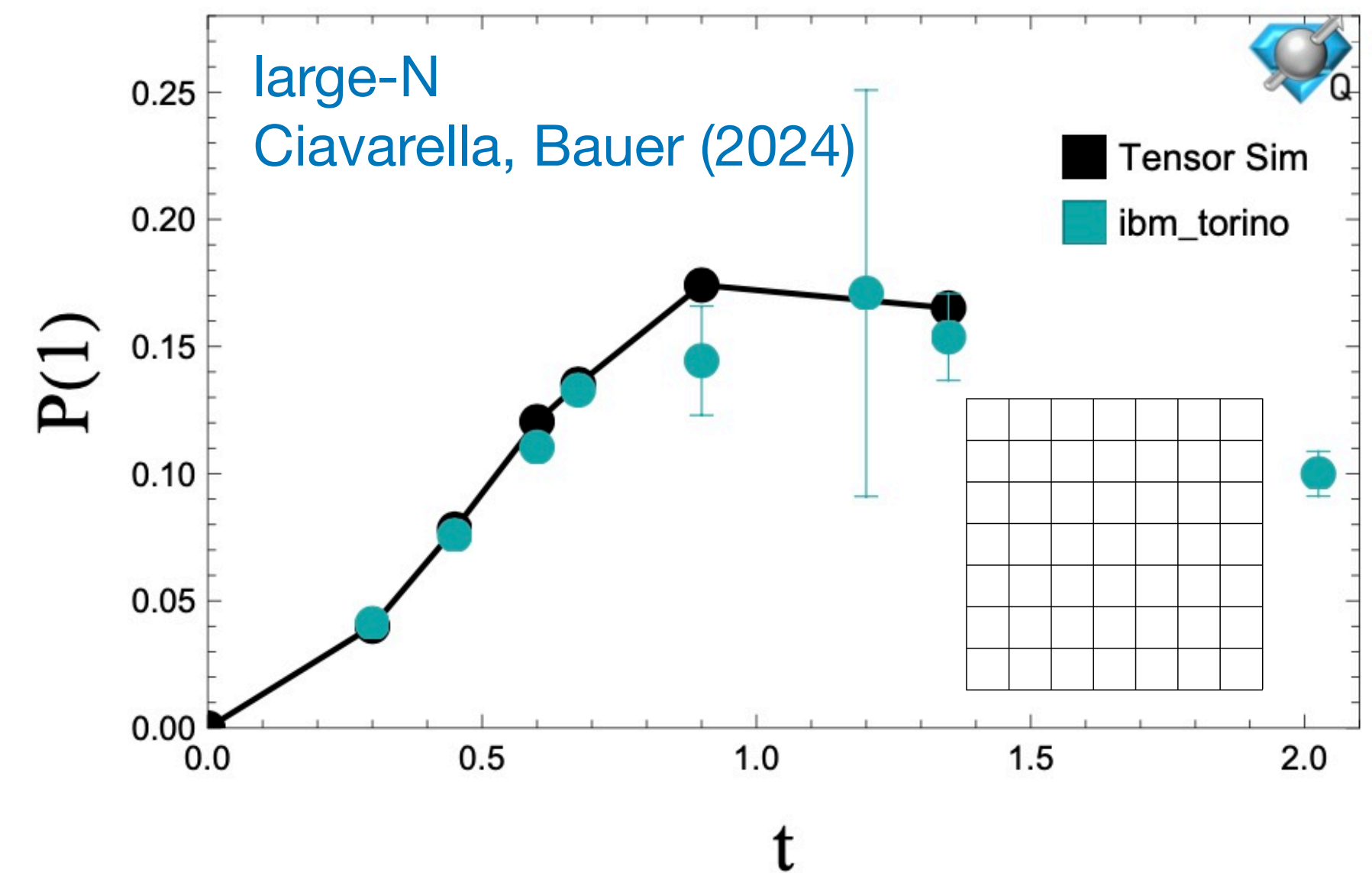
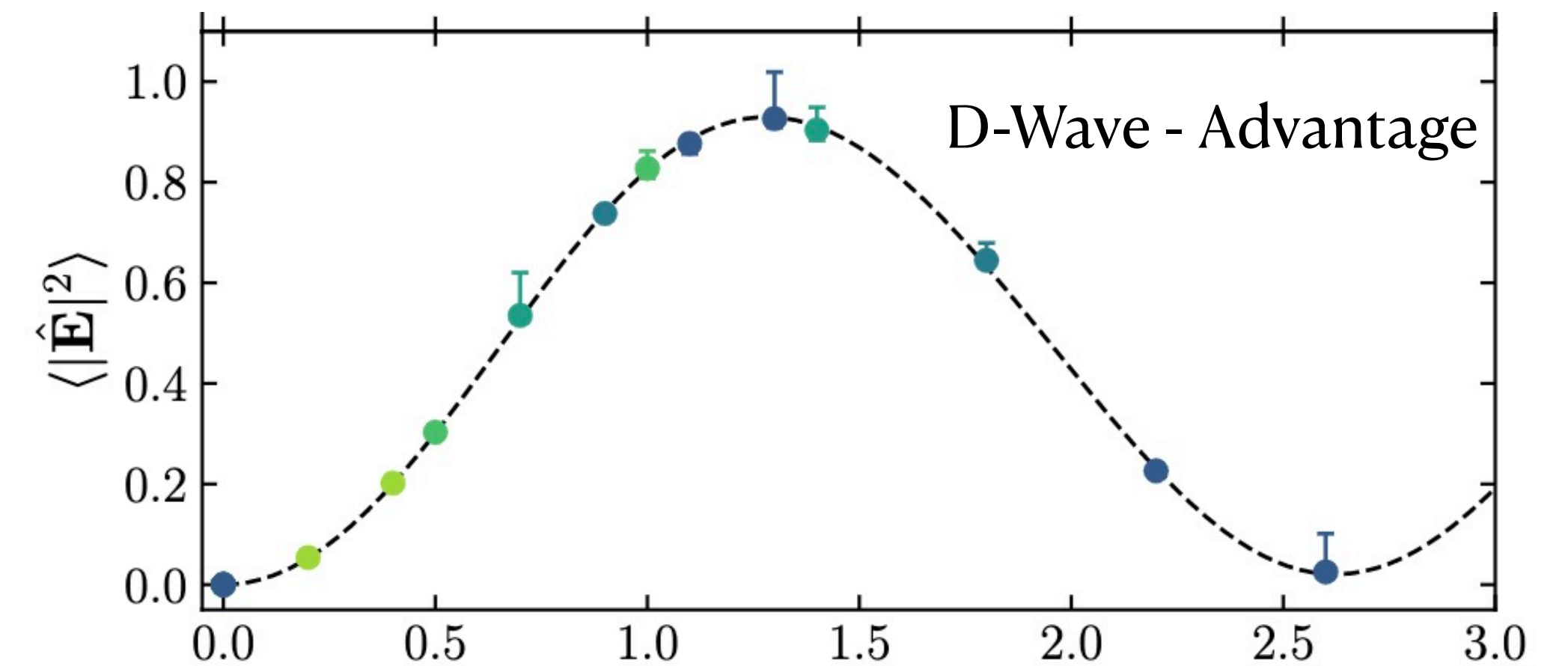
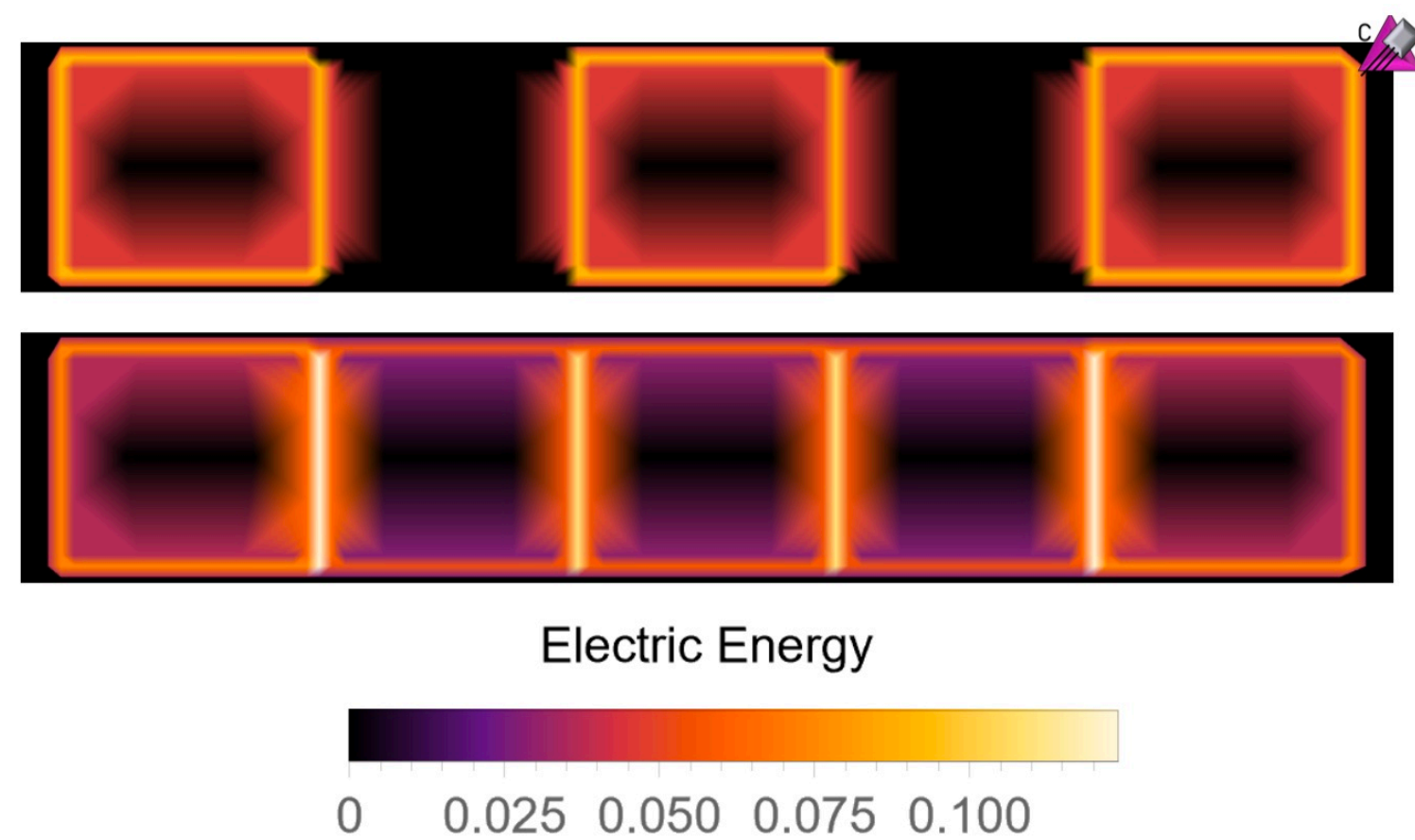
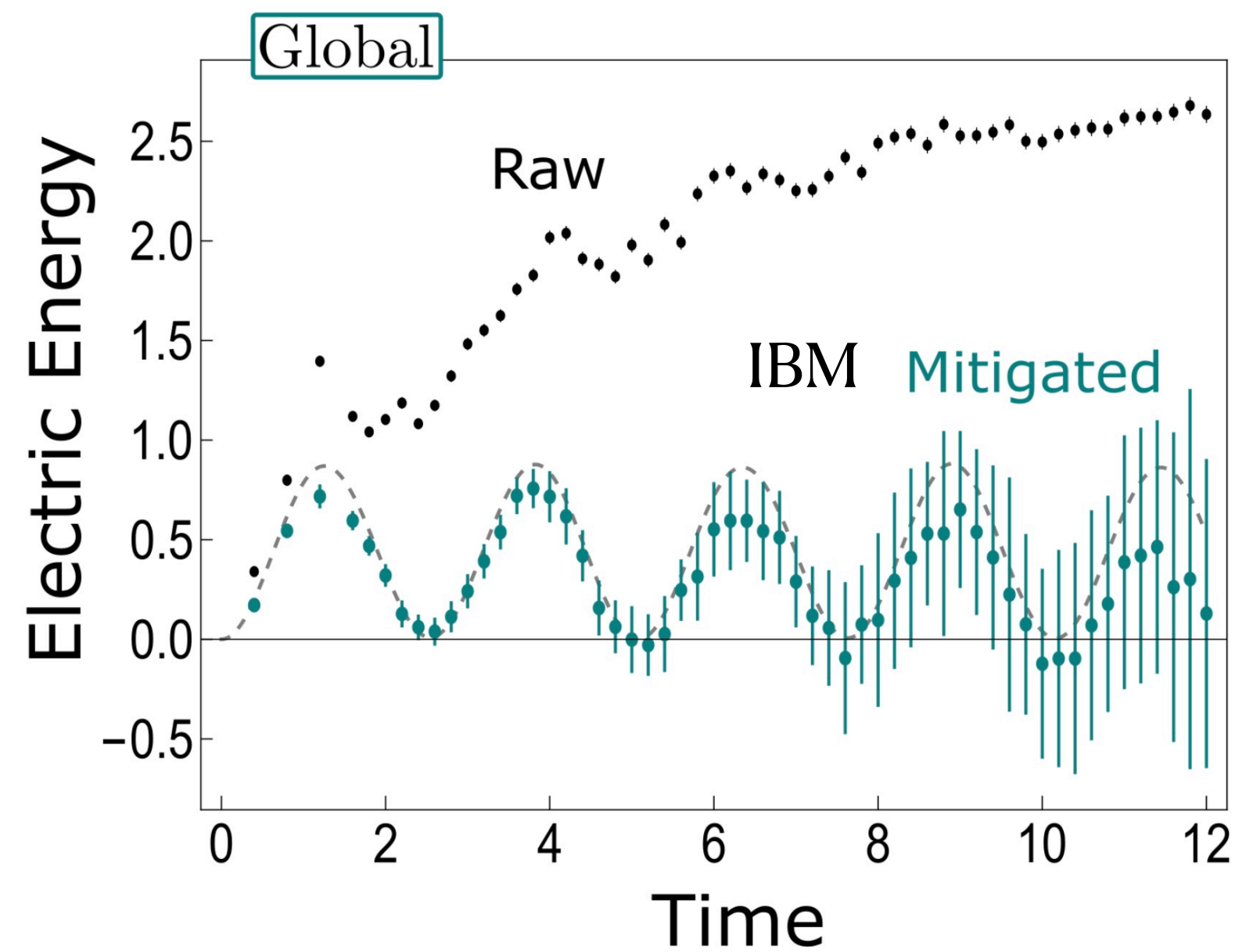
- Only dynamical gauge fields
- Gauge Variant Completions (GVC)
- Severely truncated in field space
- 2D, but really 1D

SU(2) lattice gauge theory on a quantum annealer

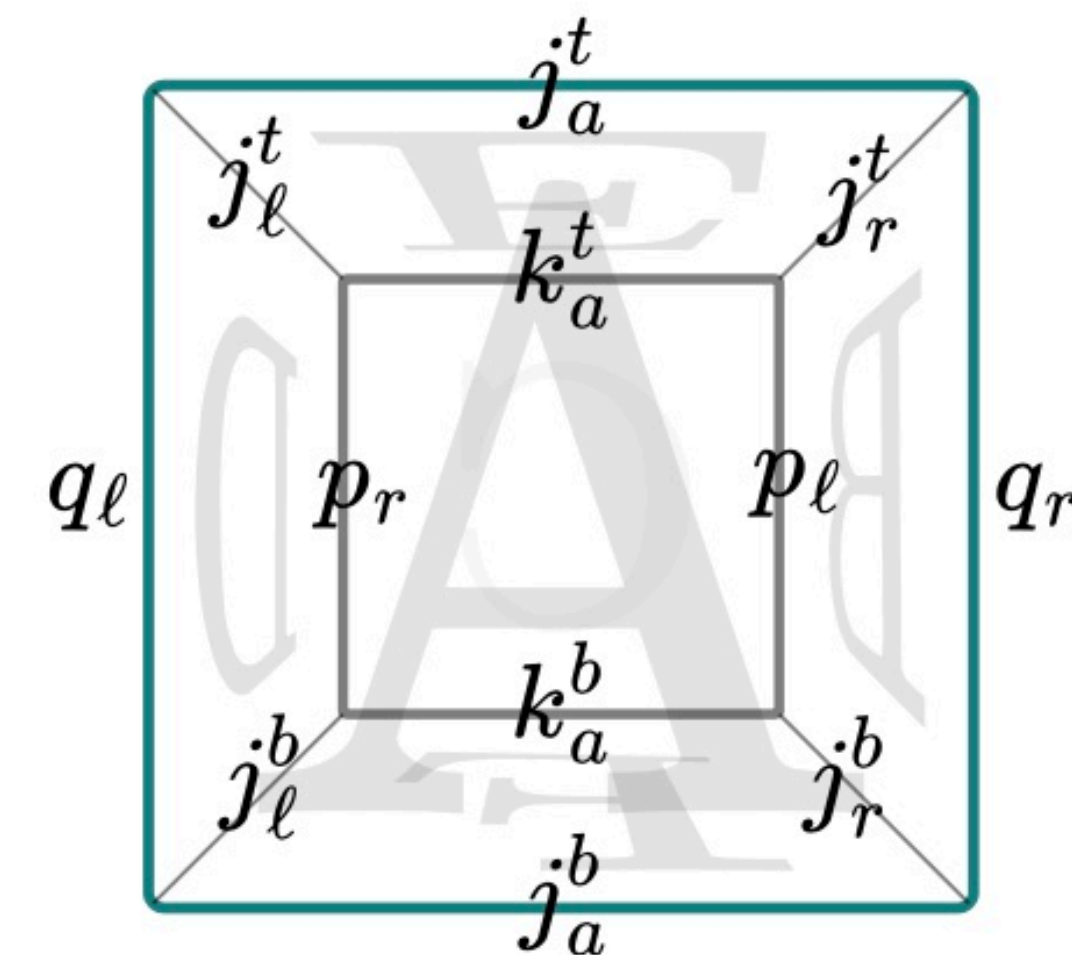
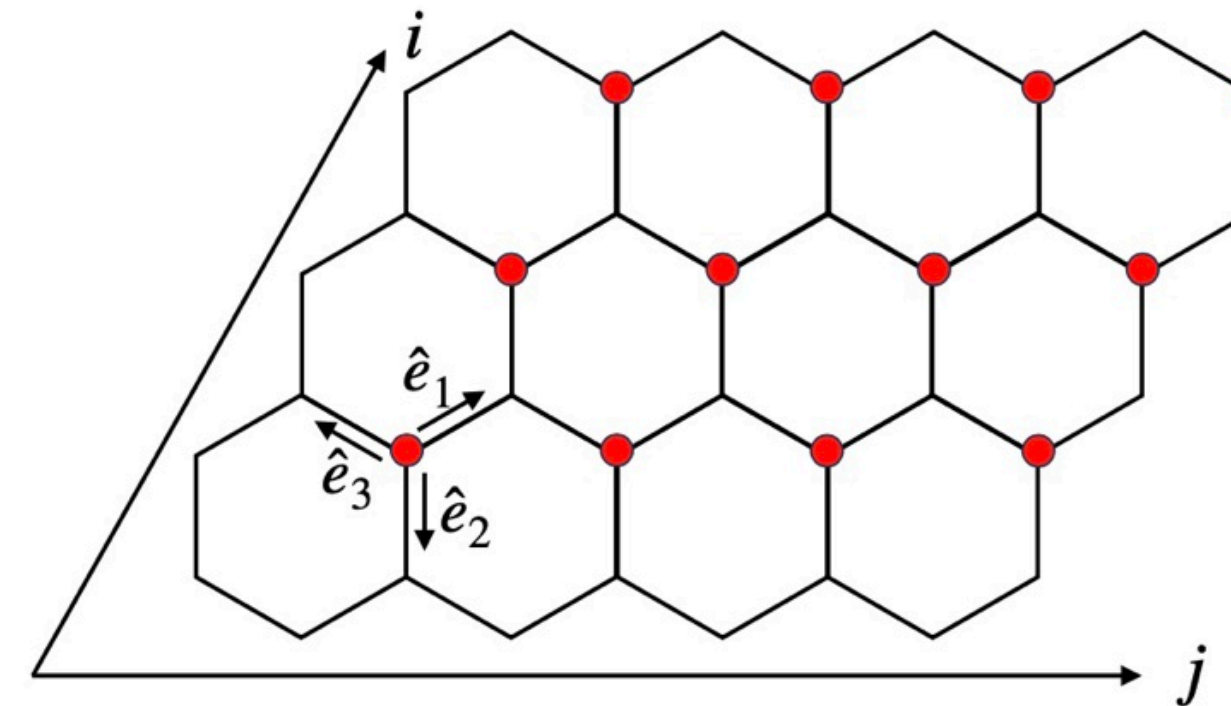
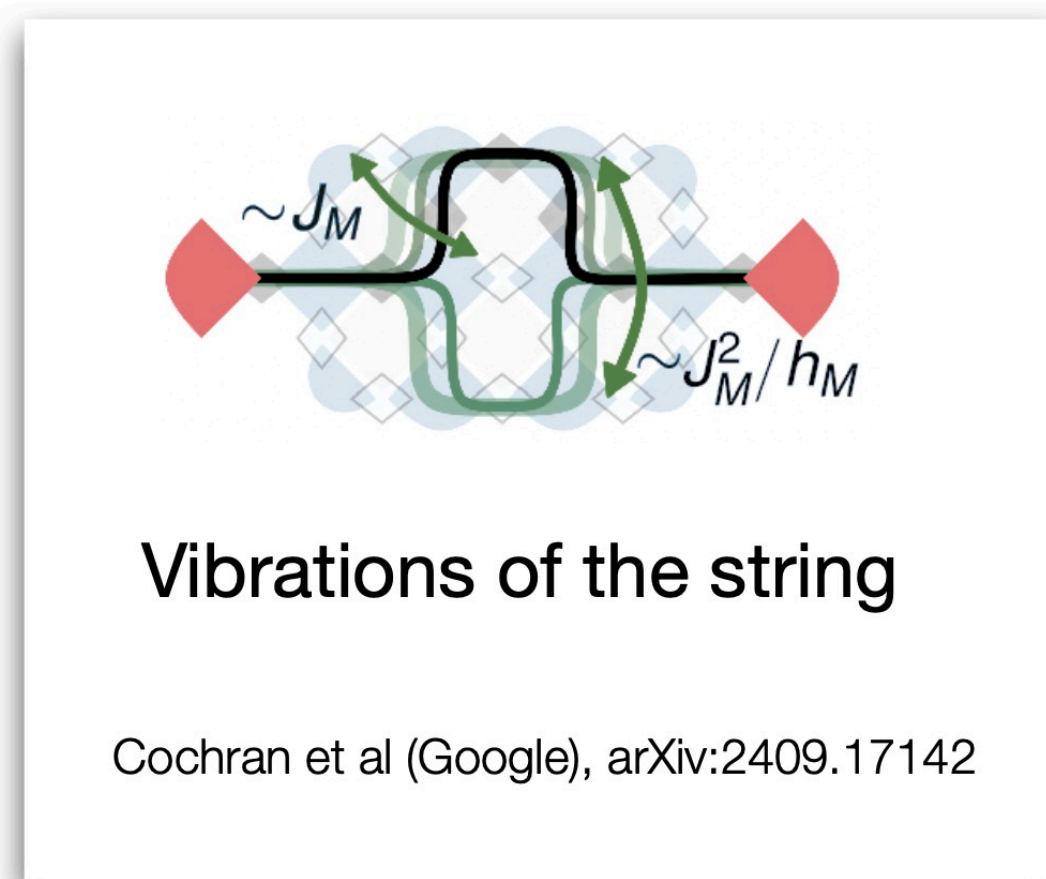
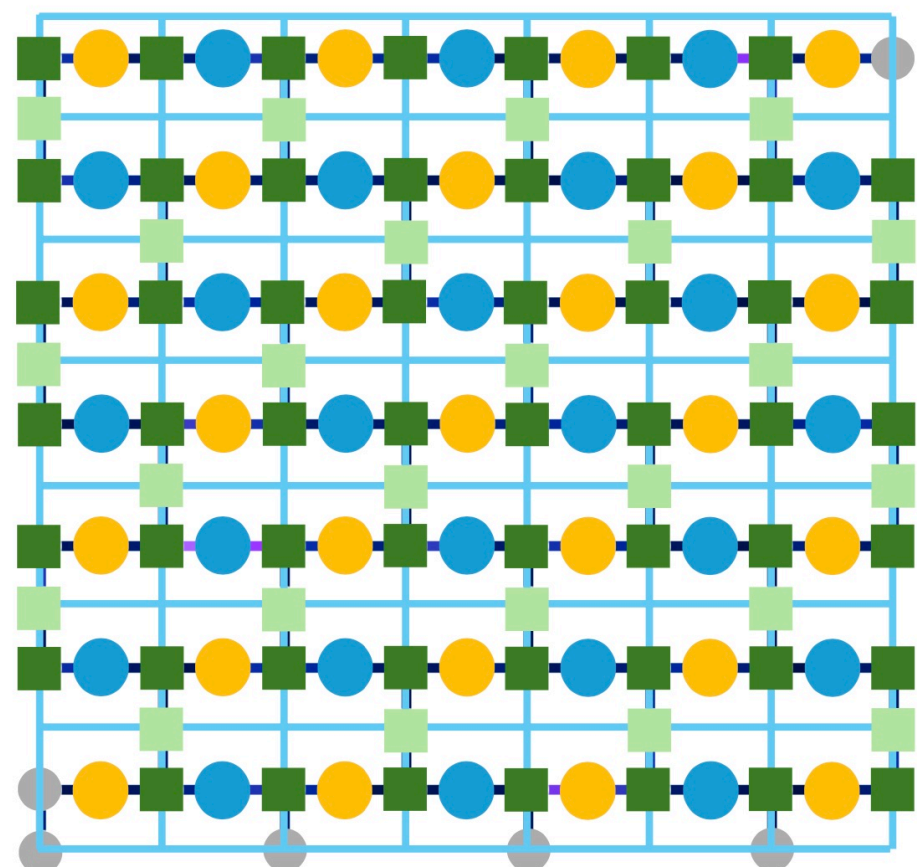
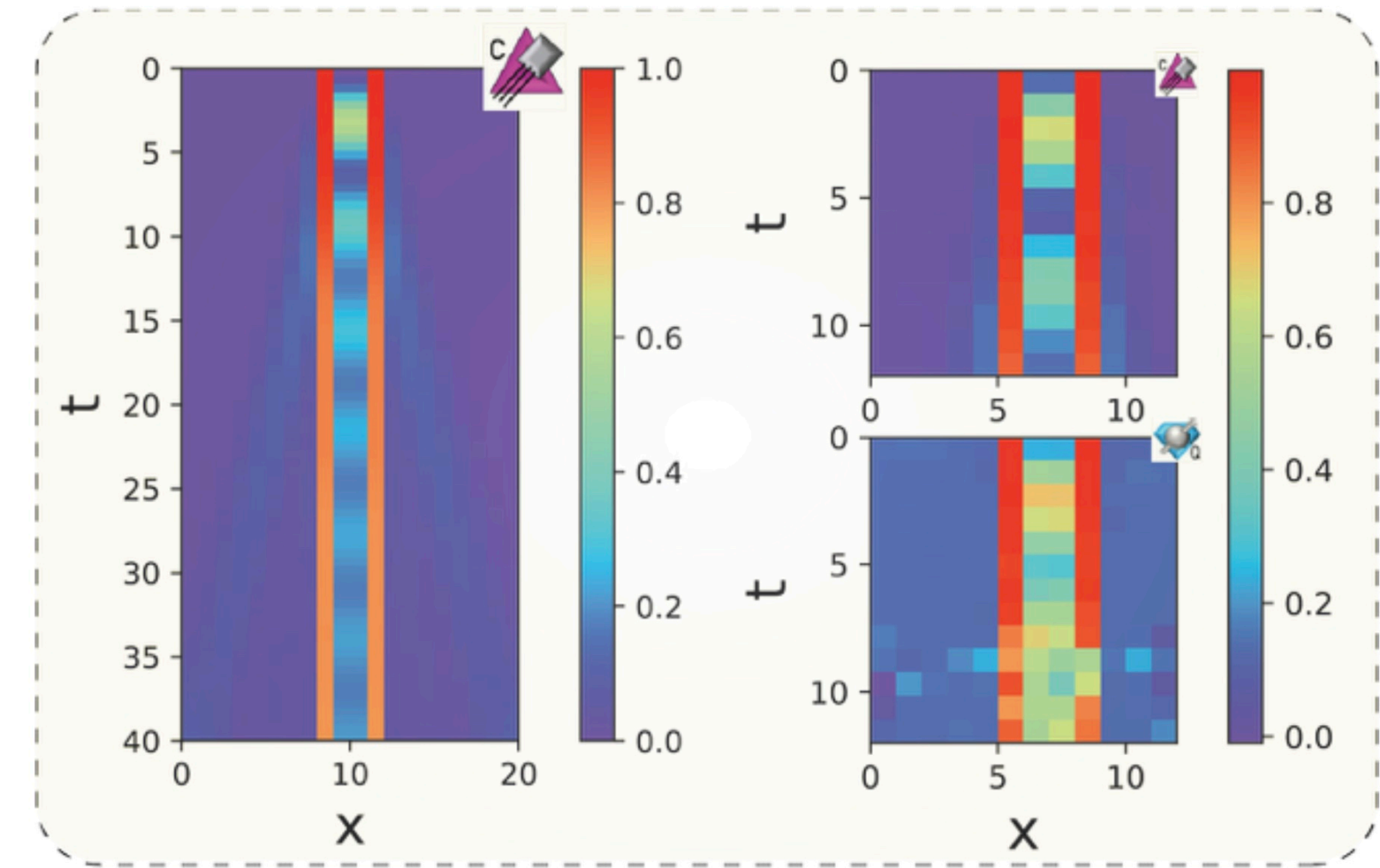
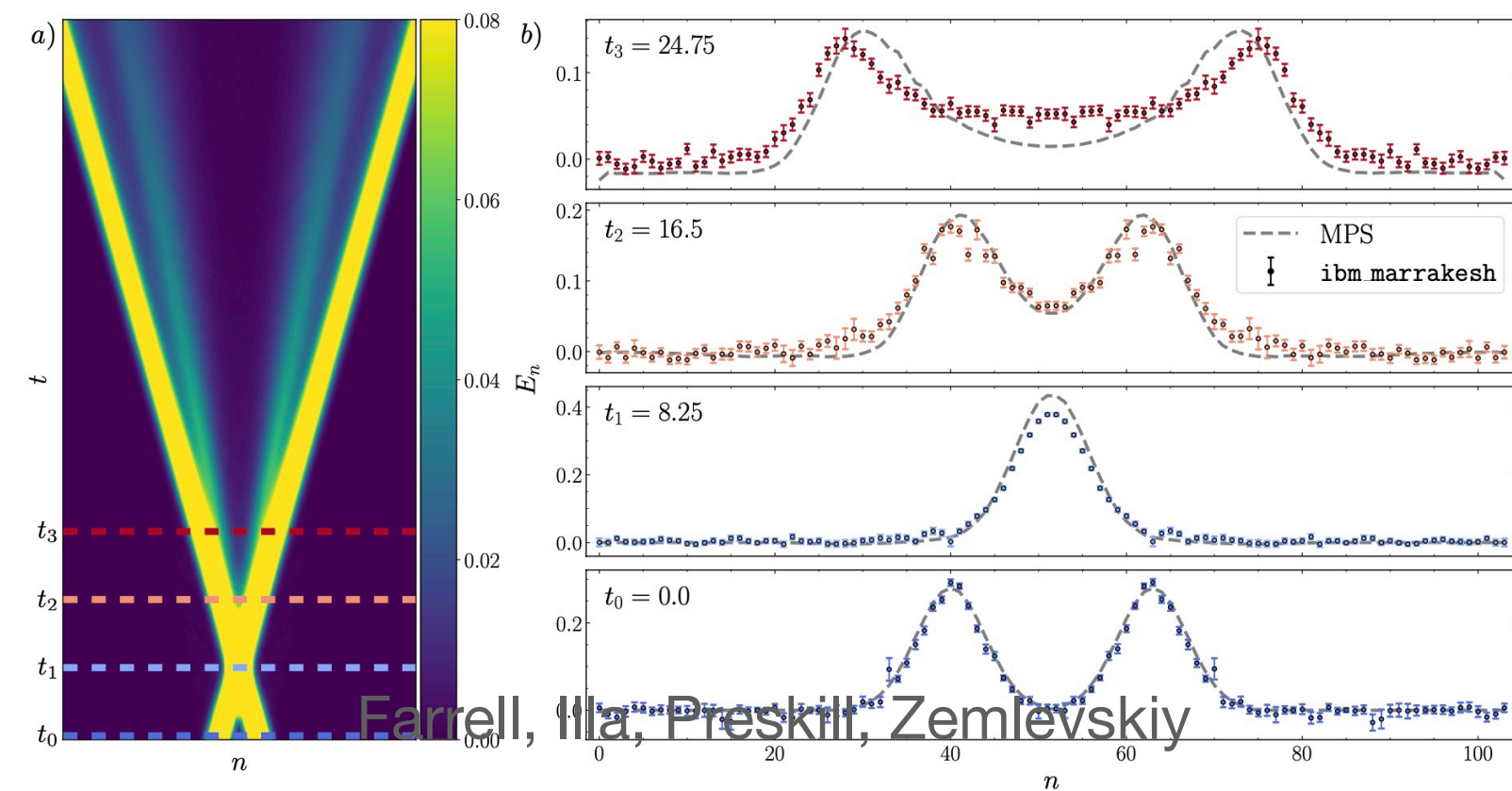
Sarmed A Rahman, Randy Lewis, Emanuele Mendicelli, and Sarah Powell
 Department of Physics and Astronomy, York University, Toronto, Ontario, M3J 1P3, Canada
 (Dated: August 3, 2021)

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

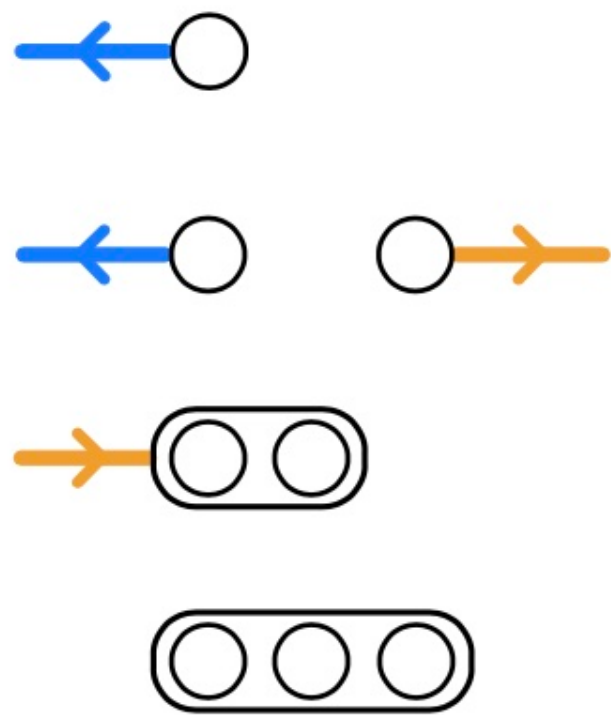
SU(3) Yang-Mills Plaquettes - Examples



Some Recent Simulation Results

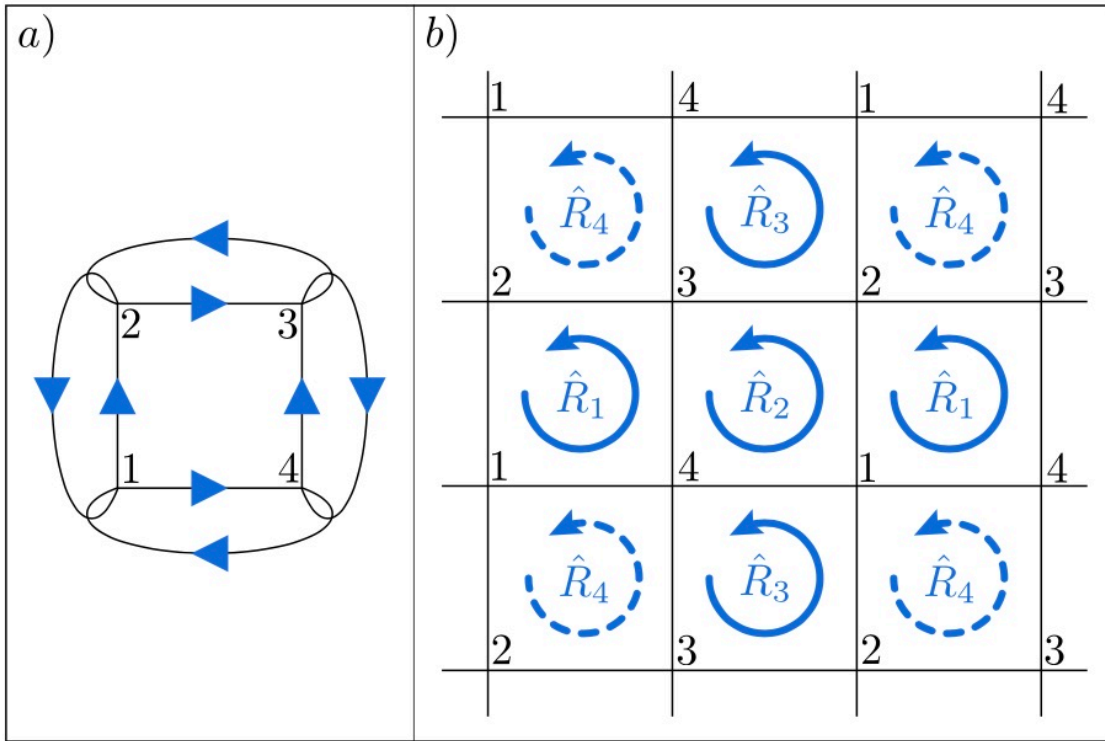


Taming Non-Abelian Gauge Space



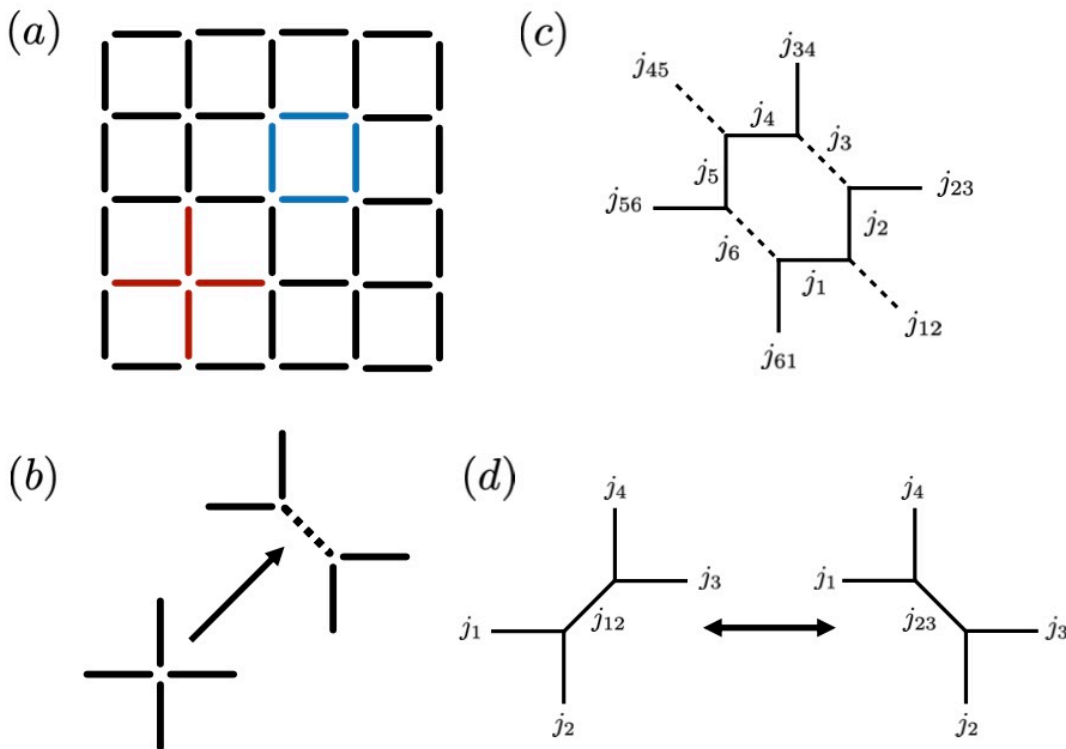
Loop-string-hadron formulation of an $SU(3)$ gauge theory with dynamical quarks

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



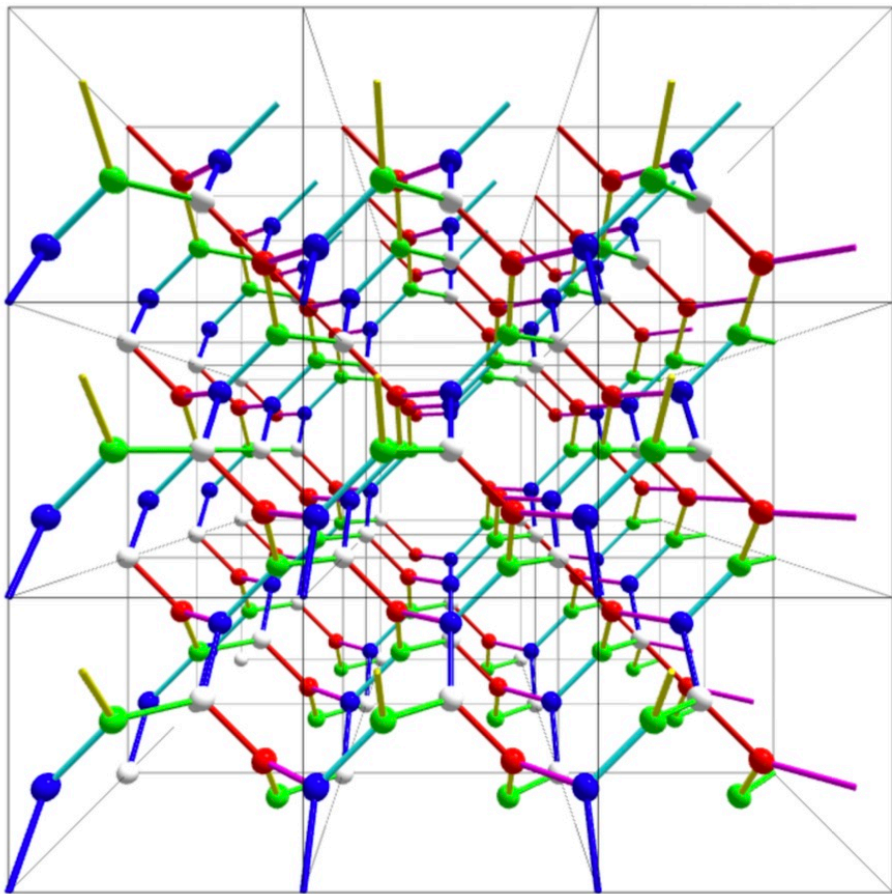
A resource efficient approach for quantum and classical simulations of gauge theories in particle physics

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



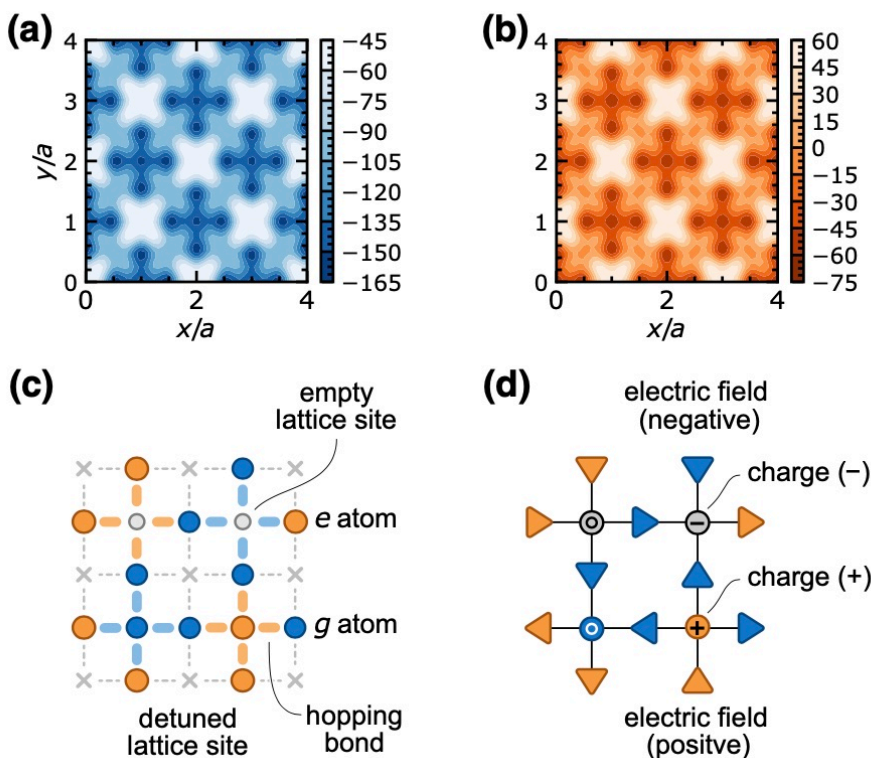
Quantum and classical spin network algorithms for q -deformed Kogut-Susskind gauge theories

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



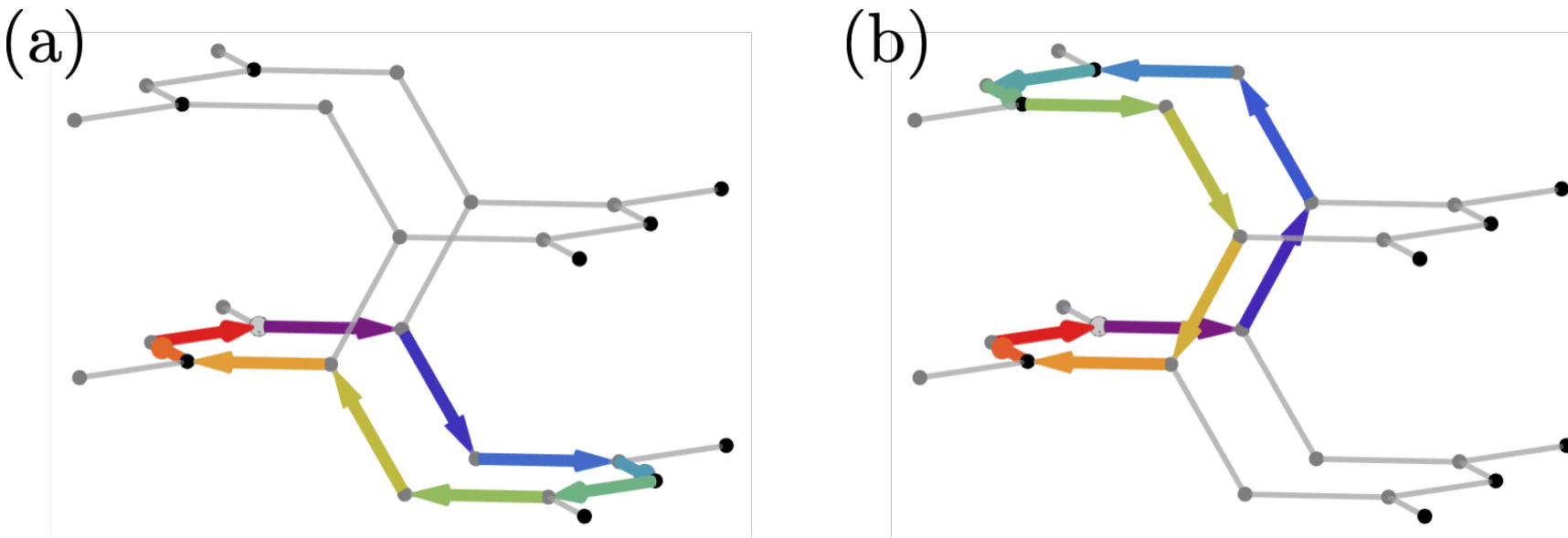
From square plaquettes to triamond lattices for $SU(2)$ gauge theory

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



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,‡}



[Submitted on 12 Mar 2025]

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

Marc Illa, Martin J. Savage, Xiaojun Yao



Transport Properties

Shear Viscosity in 2+1D SU(2)

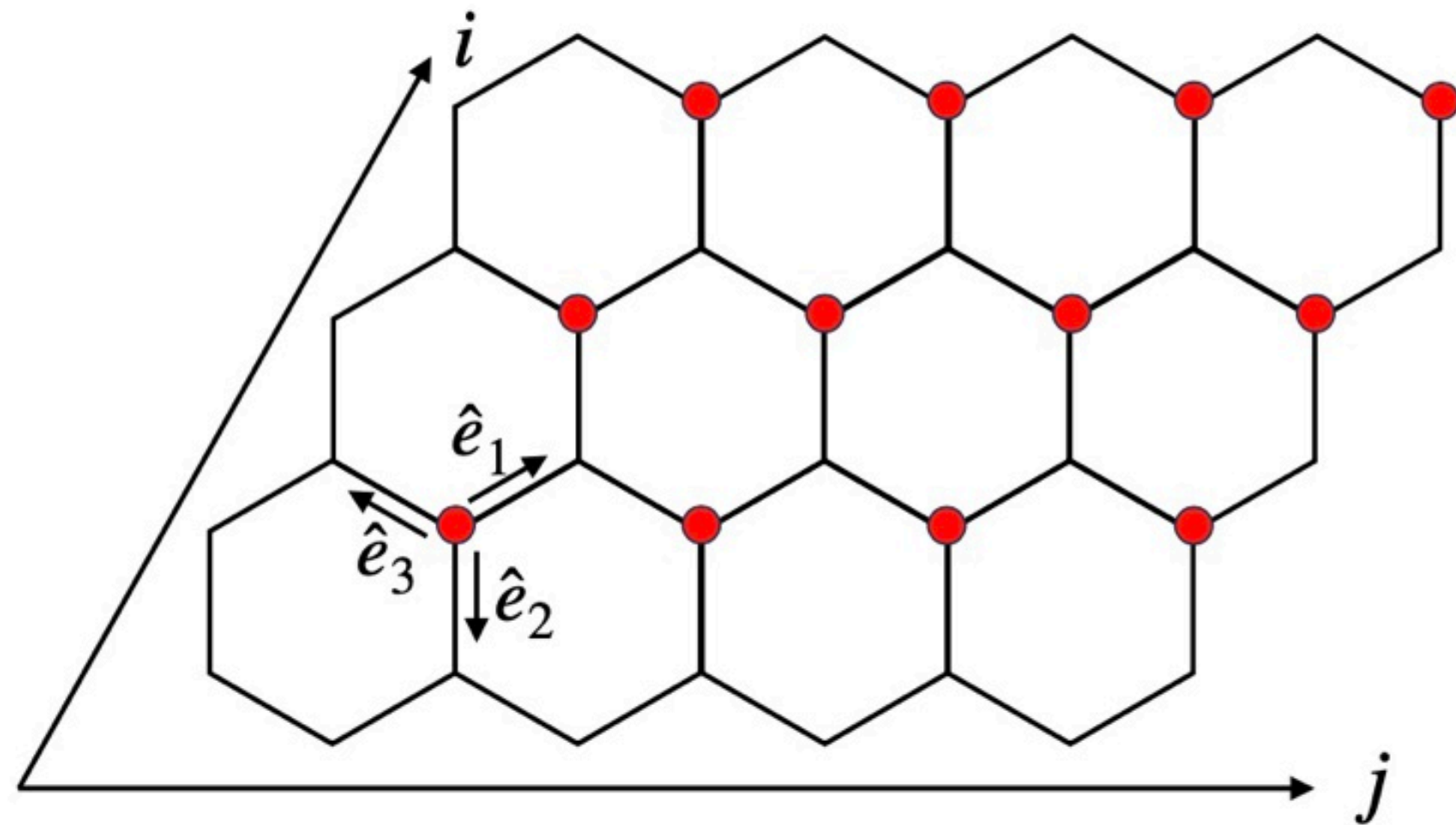
Editors' Suggestion

Open Access

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

Berndt Mueller and Xiaojun Yao

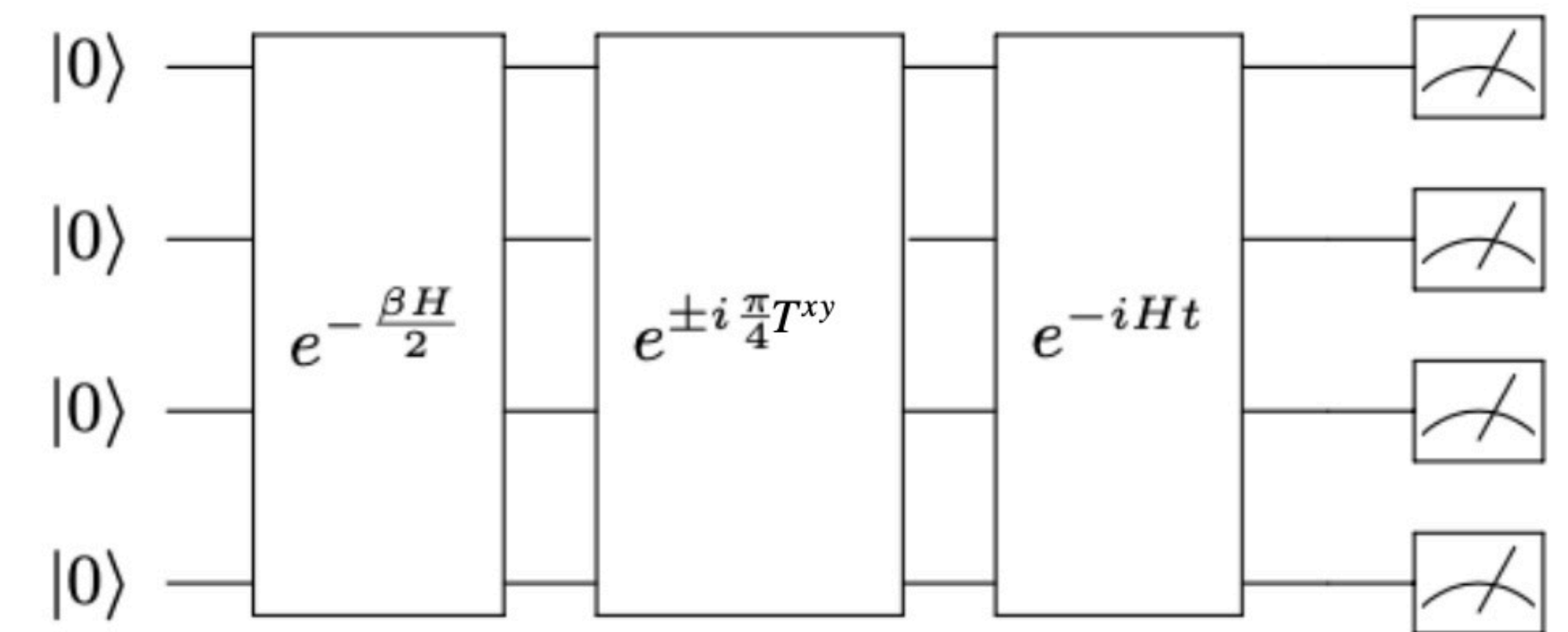
Francesco Turro, Anthony Ciavarella, and Xiaojun Yao
Phys. Rev. D **109**, 114511 – Published 13 June 2024



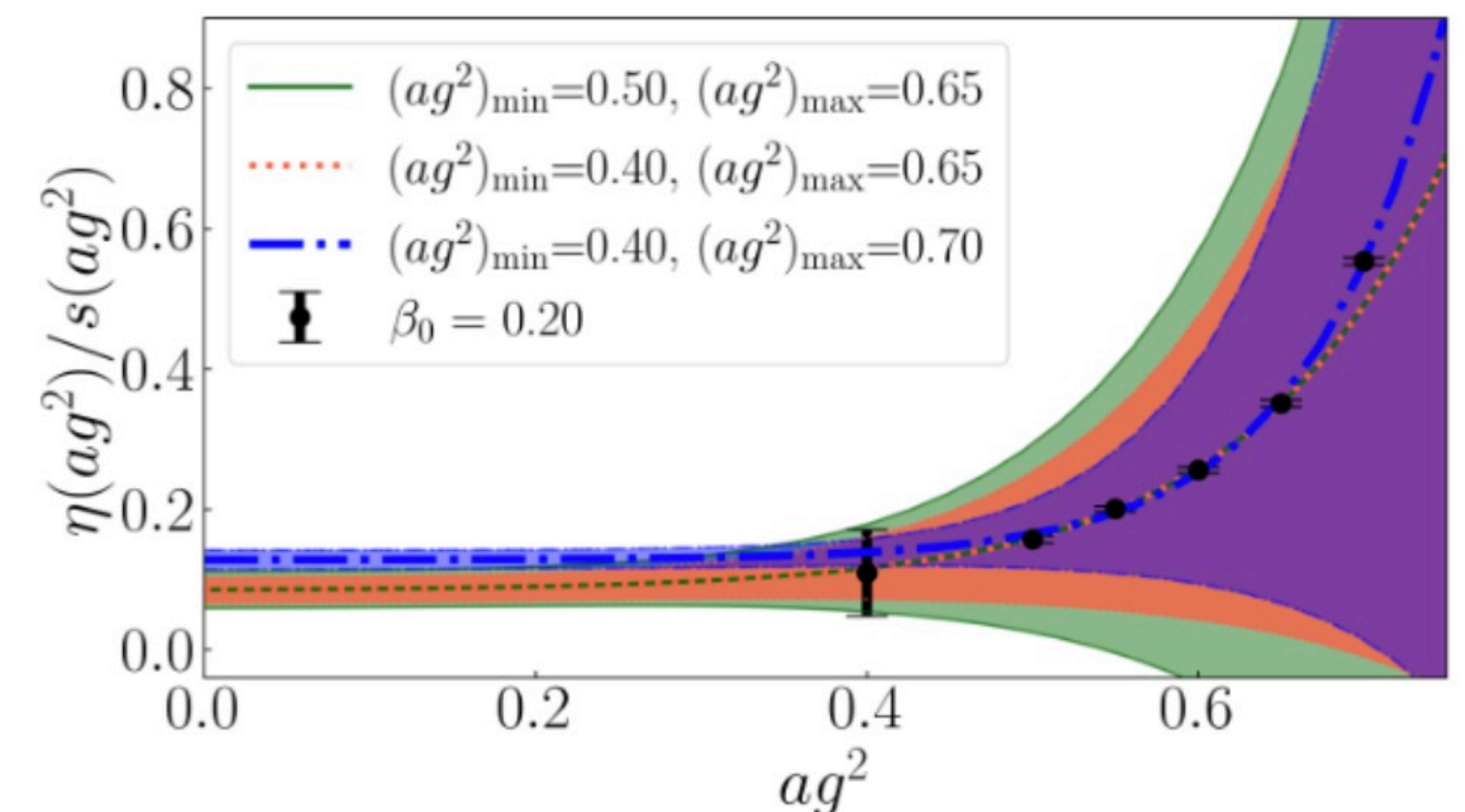
$$H = \frac{3\sqrt{3}g^2}{4} \sum_{\text{links}} E_i^a E_i^a - \frac{4\sqrt{3}}{9g^2 a^2} \sum_{\text{plaqs}} \text{Hexagon}$$

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

Quantum algorithm for G_r^{xy}



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

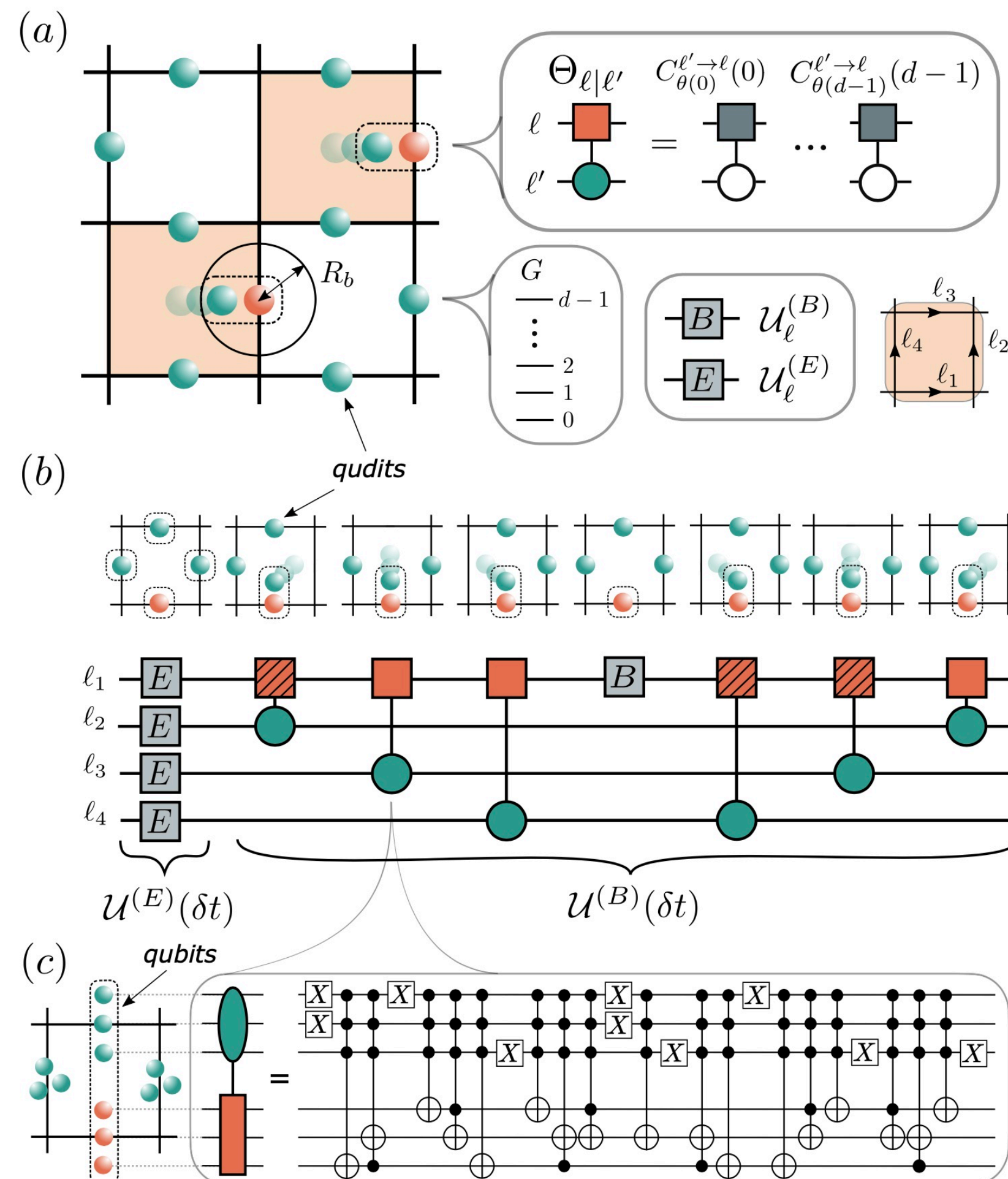


At the Quantum Limit, same as liquid created in heavy-ion collisions

Qudits

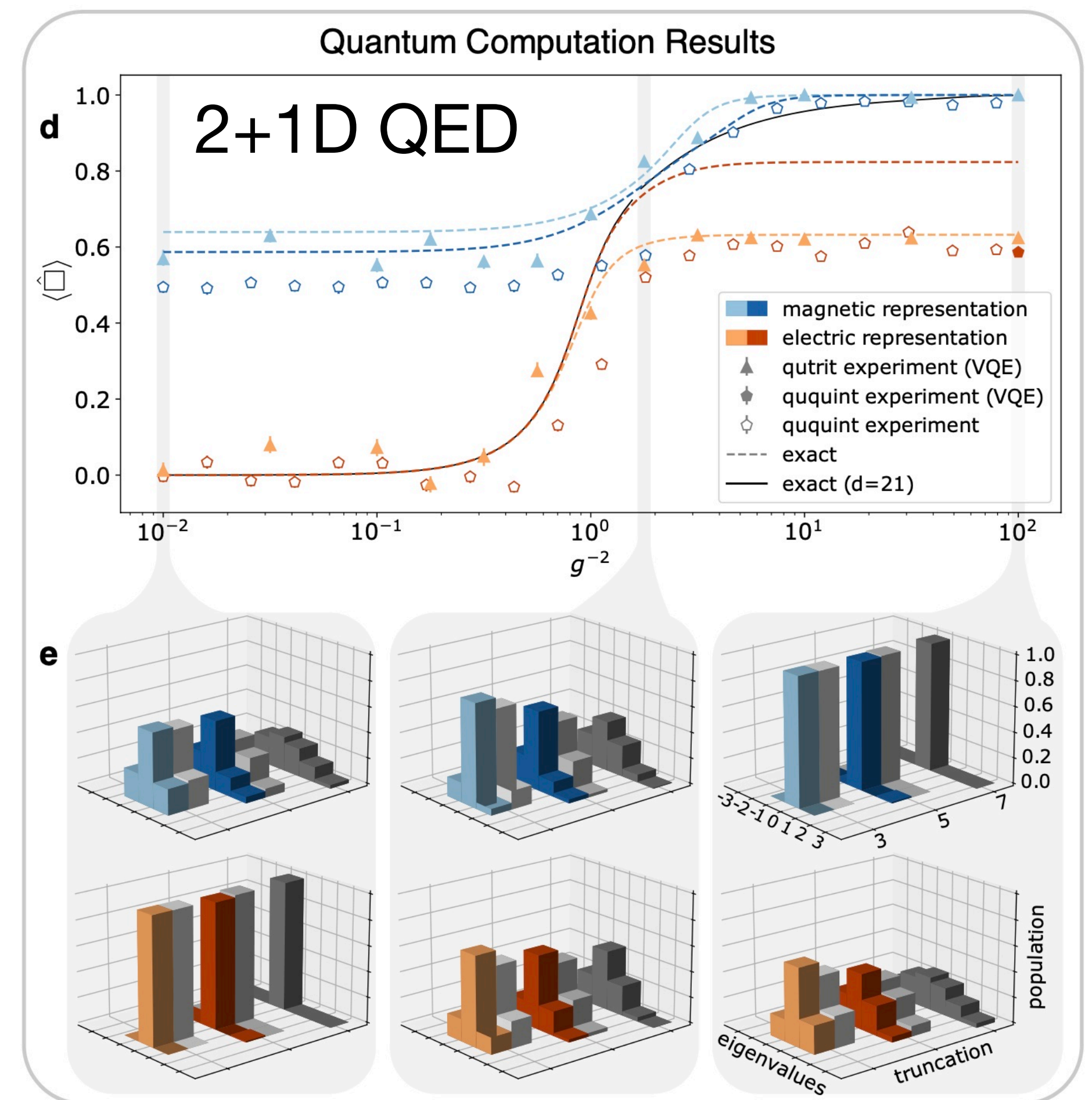
Hardware efficient quantum simulation of non-abelian gauge theories with qudits on Rydberg platforms

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

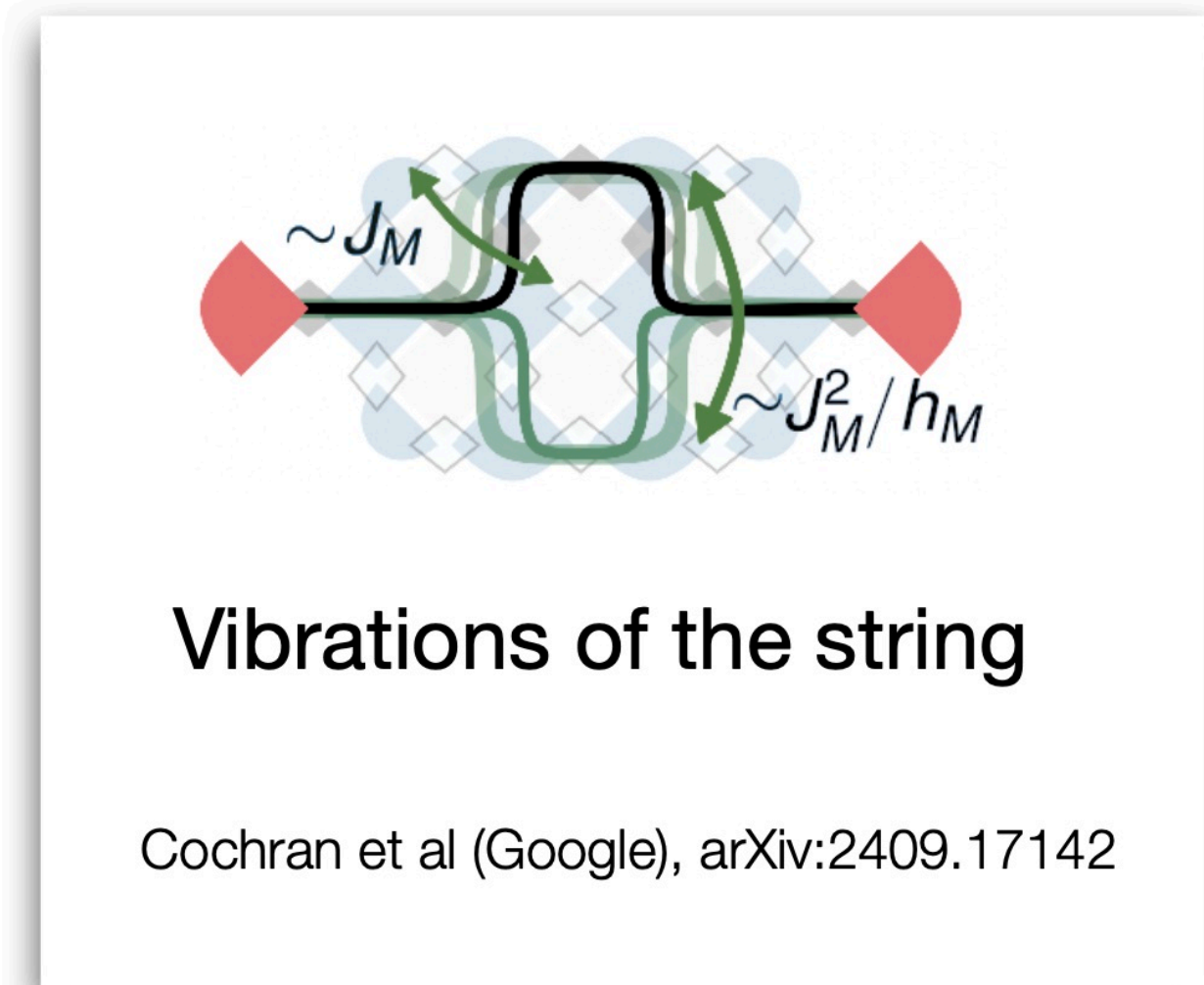
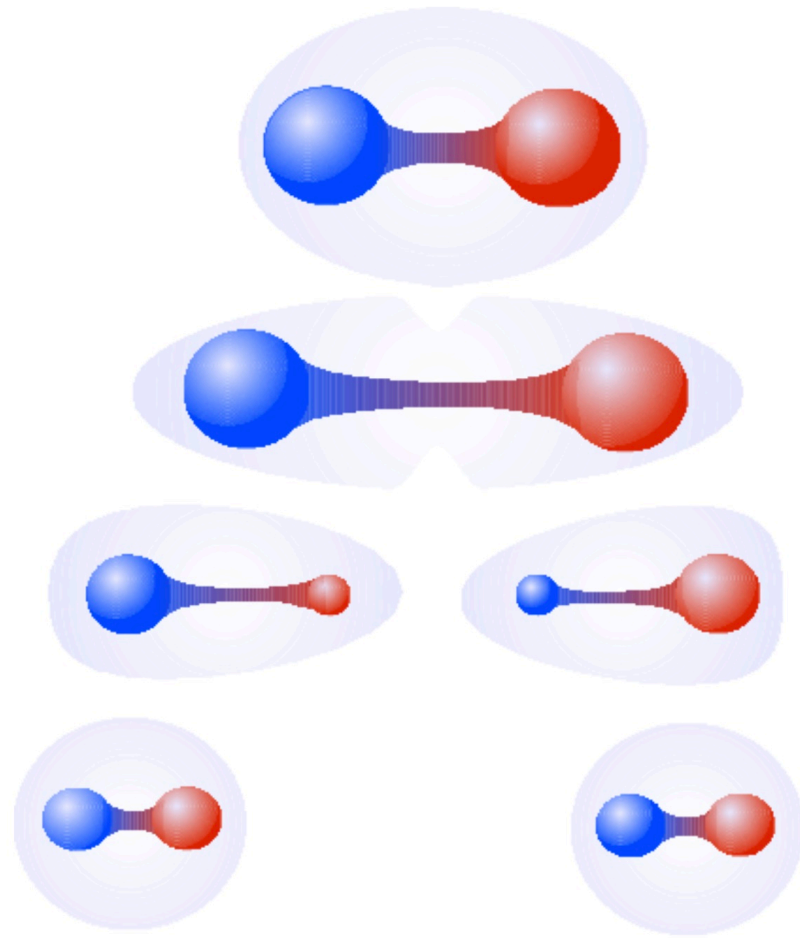


Simulating 2D lattice gauge theories on a qudit quantum computer

Michael Meth,¹ Jan F. Haase,^{2,3,4} Jinglei Zhang,^{2,3} Claire Edmunds,¹ Lukas Postler,¹ Andrew J. Jena,^{2,3} Alex Steiner,¹ Luca Dellantonio,^{2,3,5} Rainer Blatt,^{1,6,7} Peter Zoller,^{8,6} Thomas Monz,^{1,7} Philipp Schindler,¹ Christine Muschik*,^{2,3,9} and Martin Ringbauer*¹



String Breaking as an Example



Quantum simulation of string breaking: summary

Models

1+1D

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

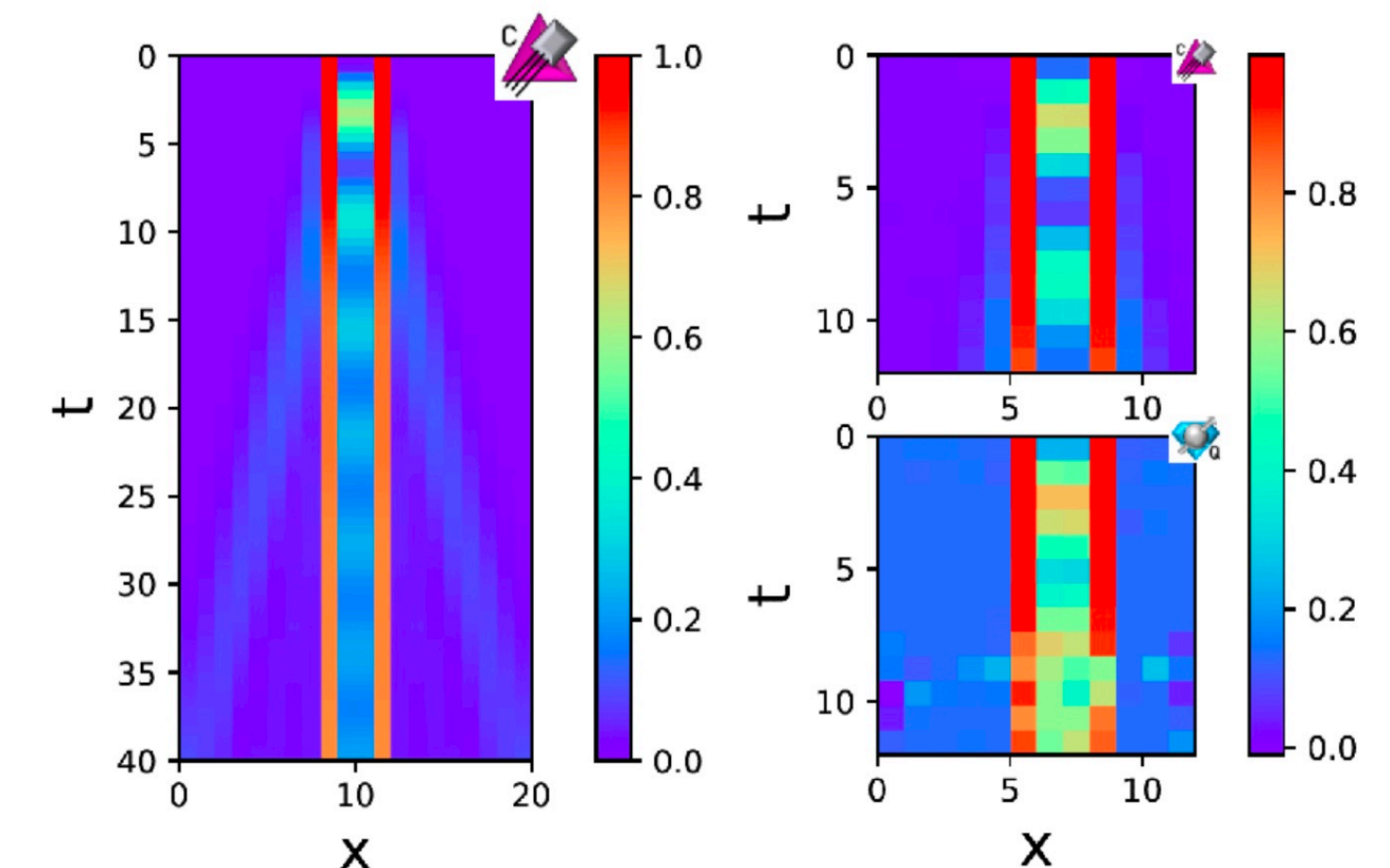
2+1D

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

Phenomenology

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

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



Entanglement in Particle Detection

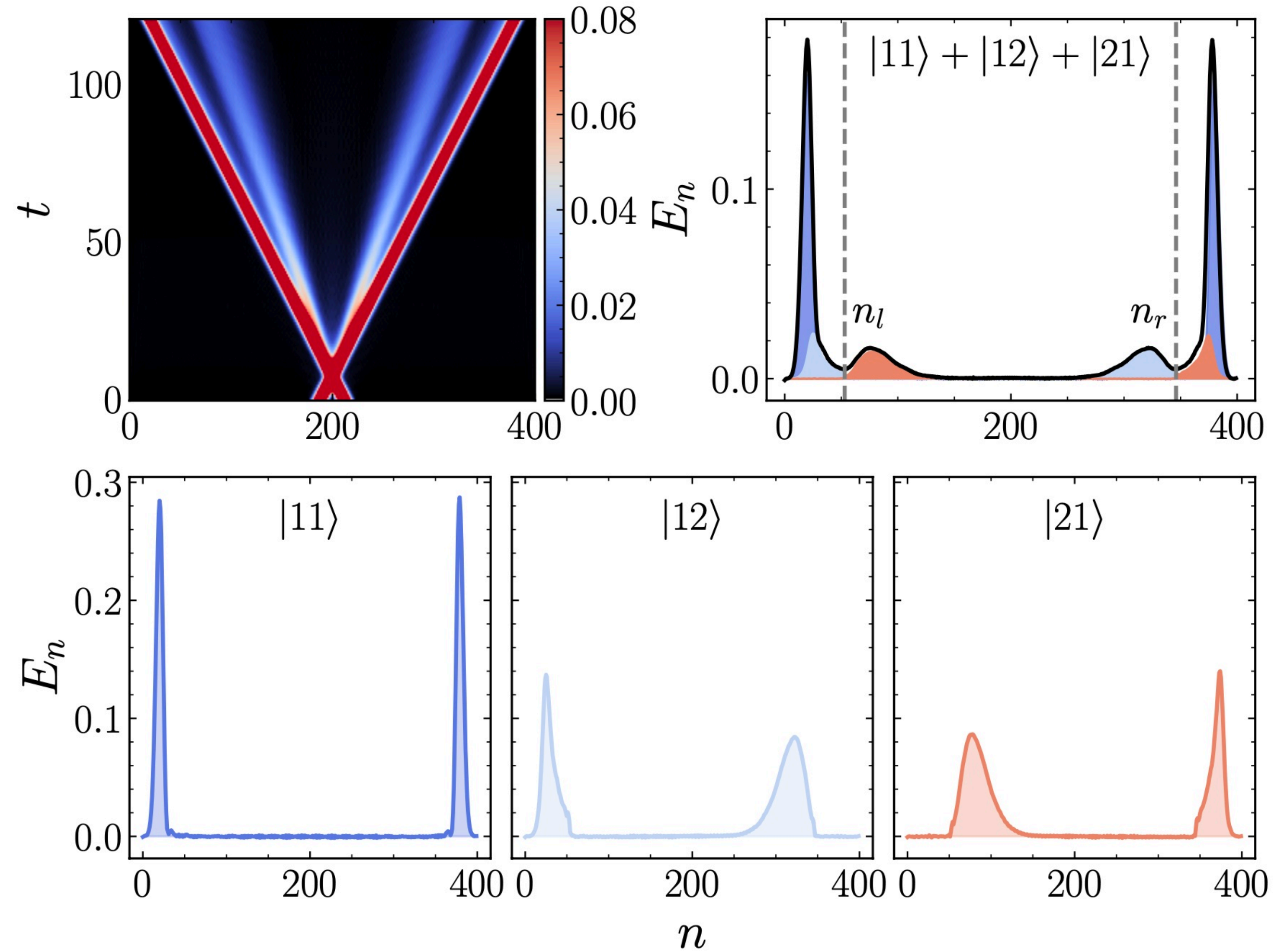
Exclusive Scattering Channels from Entanglement Structure in Real-Time Simulations

Nikita A. Zemlevskiy ^{1,*}

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

(Dated: May 21, 2026)

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



Scar States in Gauge Theories and Delayed Thermalization

March 2022

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

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

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

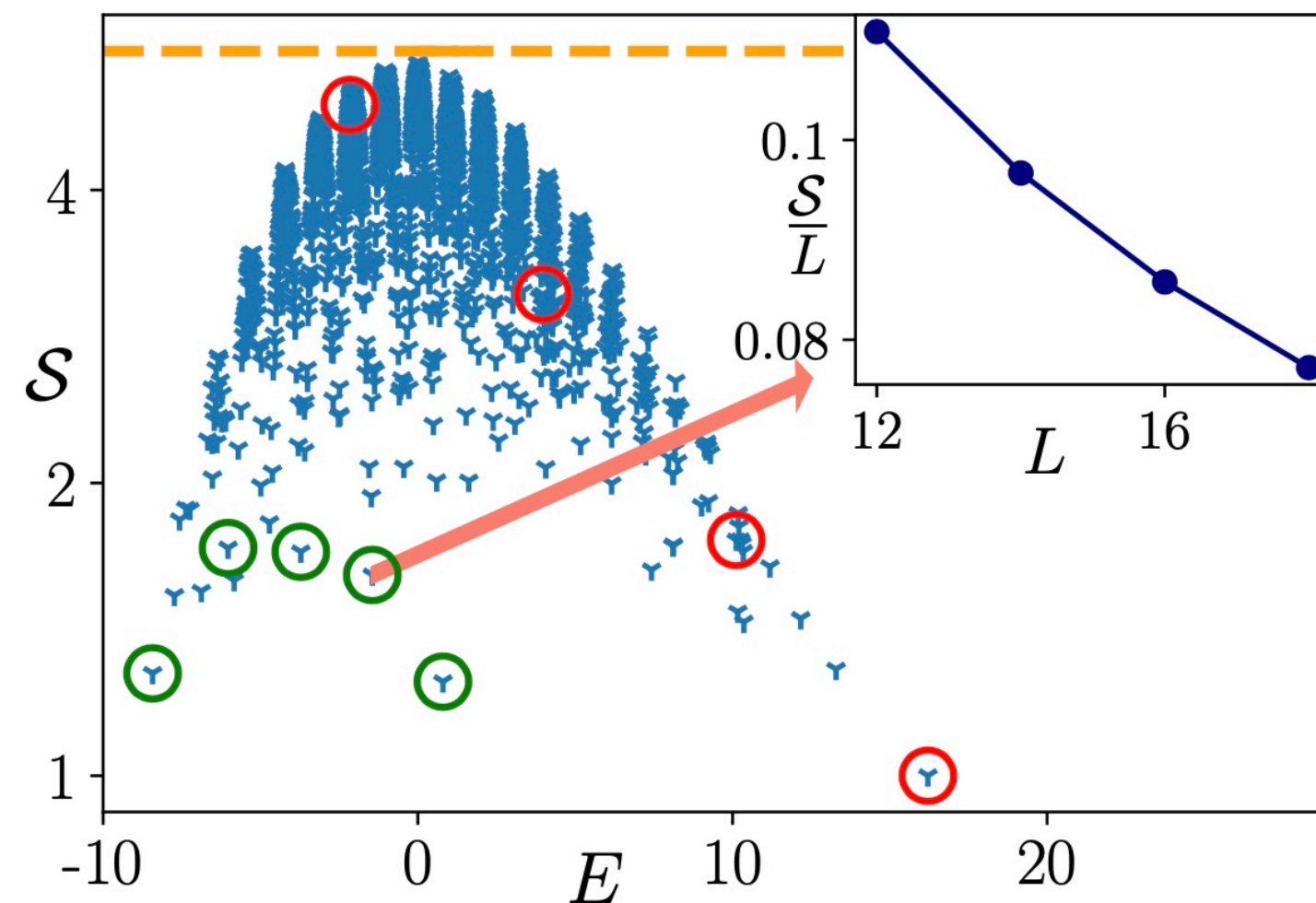


FIG. 4. The half-chain entanglement entropy($\mathcal{S}$) of all the eigenstates at $t = 0.2$, $h = 0.5$ for $L = 16$. The orange dashed line gives the $\mathcal{S}_{RMT}$ value. Circles denote different QMBS obtained via our tracking procedure. Green circles denote antimagnon-like family $\mathcal{S}_n^2$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

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

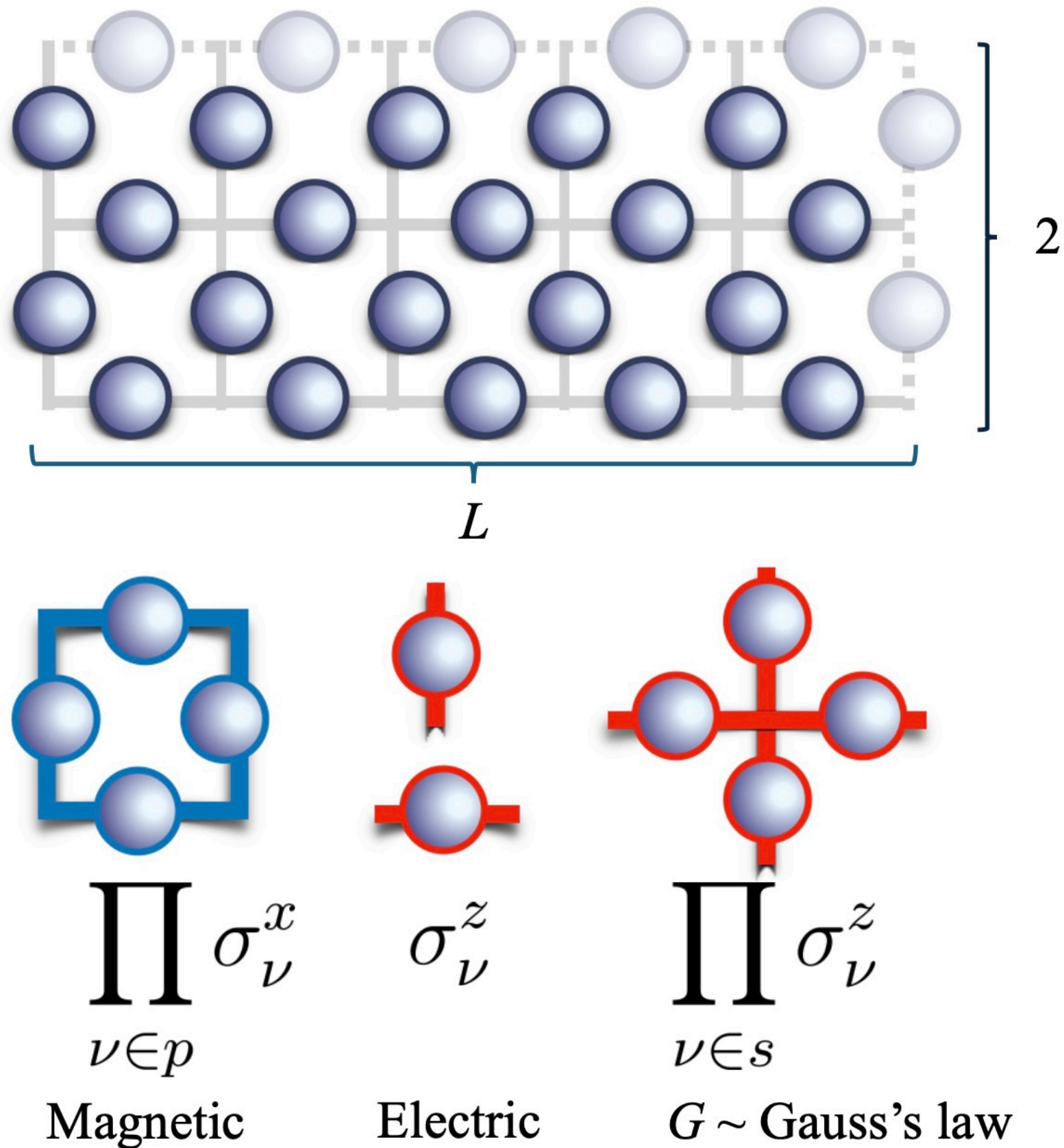
- Previously: only confining systems exhibited scars
- Shown to exist in de-confined regime
- Shown not to exist in confining regime

Stabilizer Scars

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

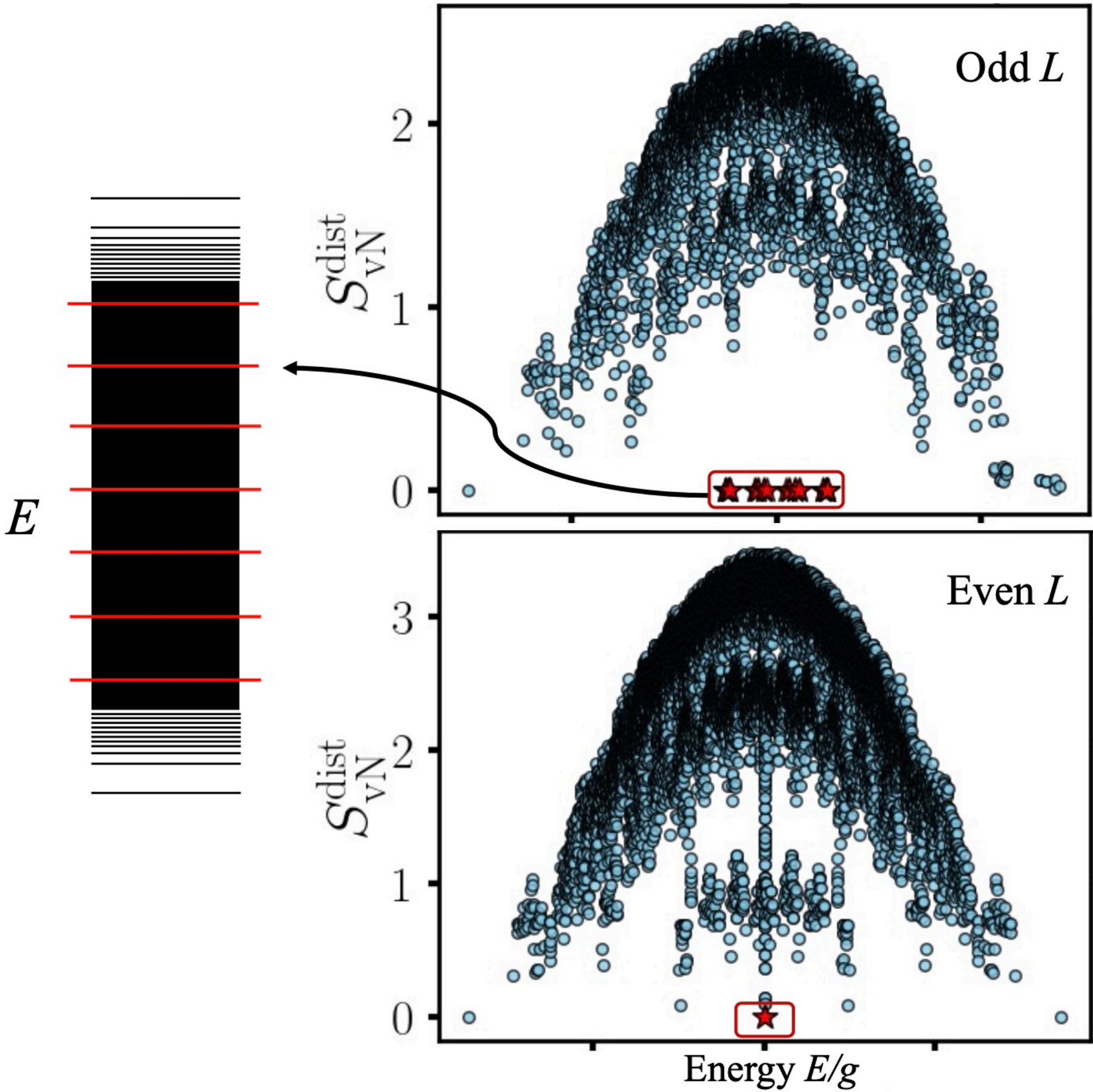
Show more ▾

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



Entanglement and Thermalization

Stabilizer Scars



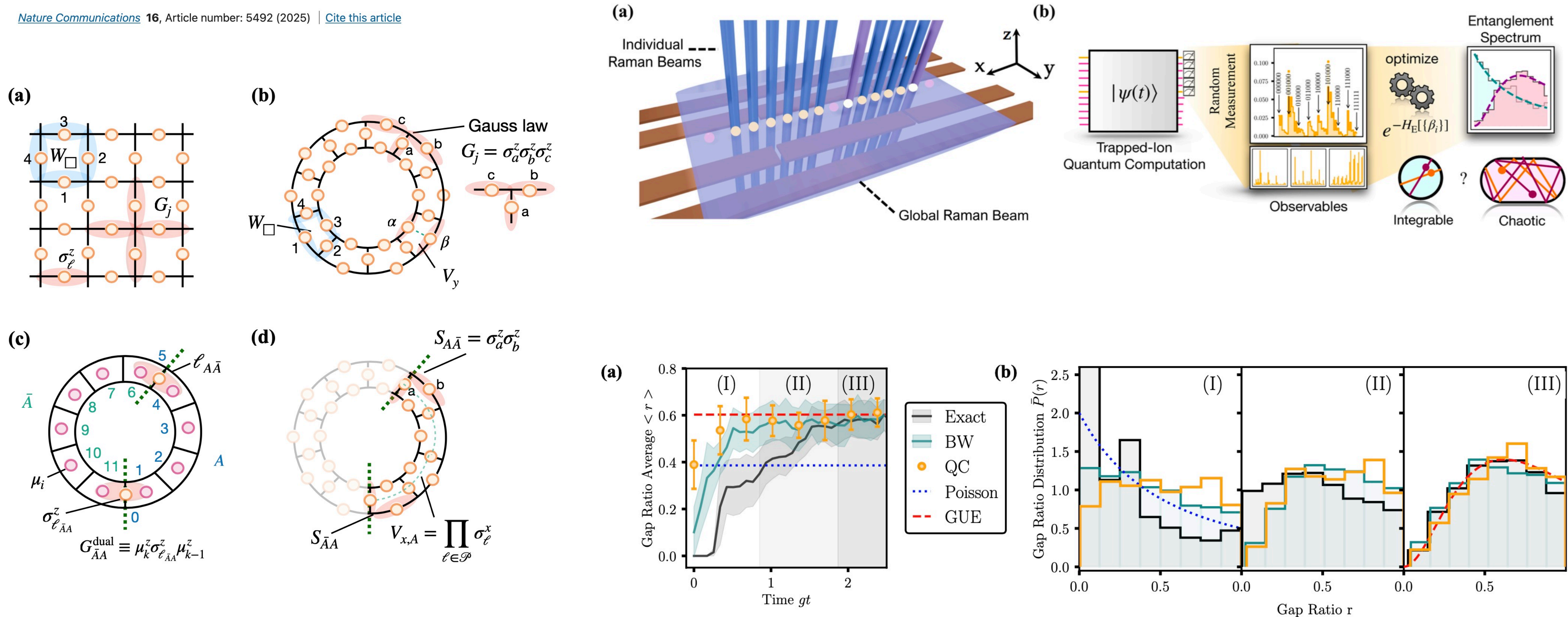
[arXiv:2411.12797](#)

Entanglement and Thermalization

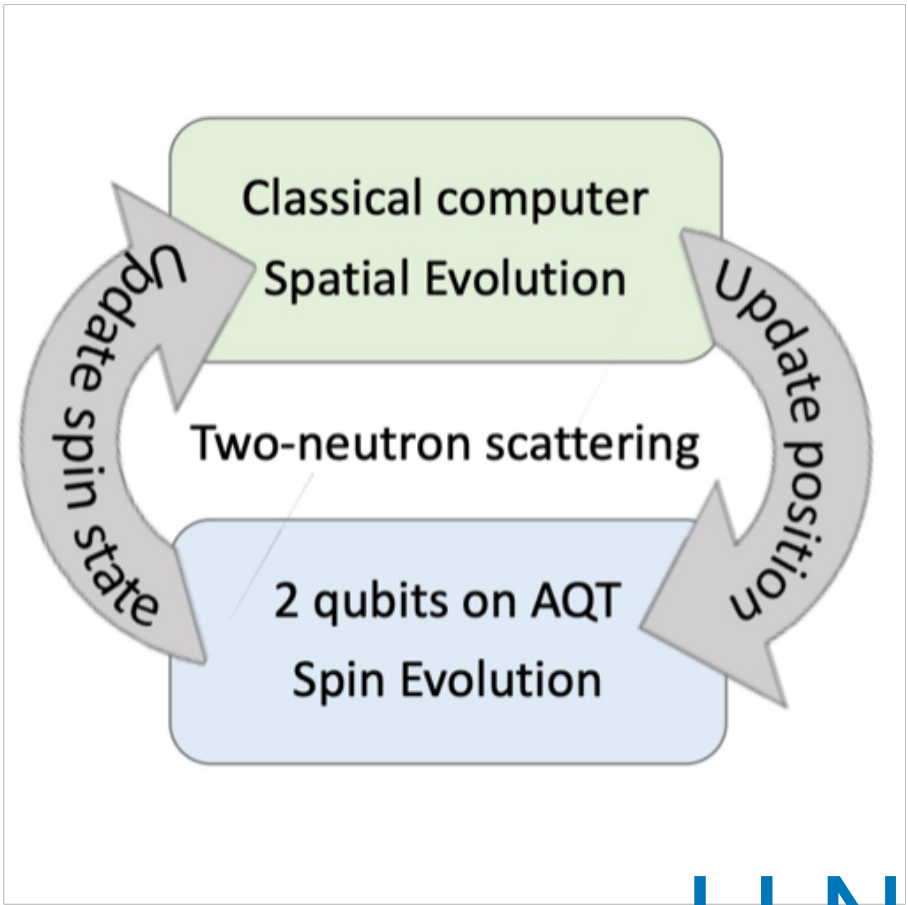
Quantum computing universal thermalization dynamics in a (2 + 1)D Lattice Gauge Theory

Niklas Mueller , Tianyi Wang, Or Katz, Zohreh Davoudi & Marko Cetina

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



Nuclear Structure and Reactions



LLNL+Trento

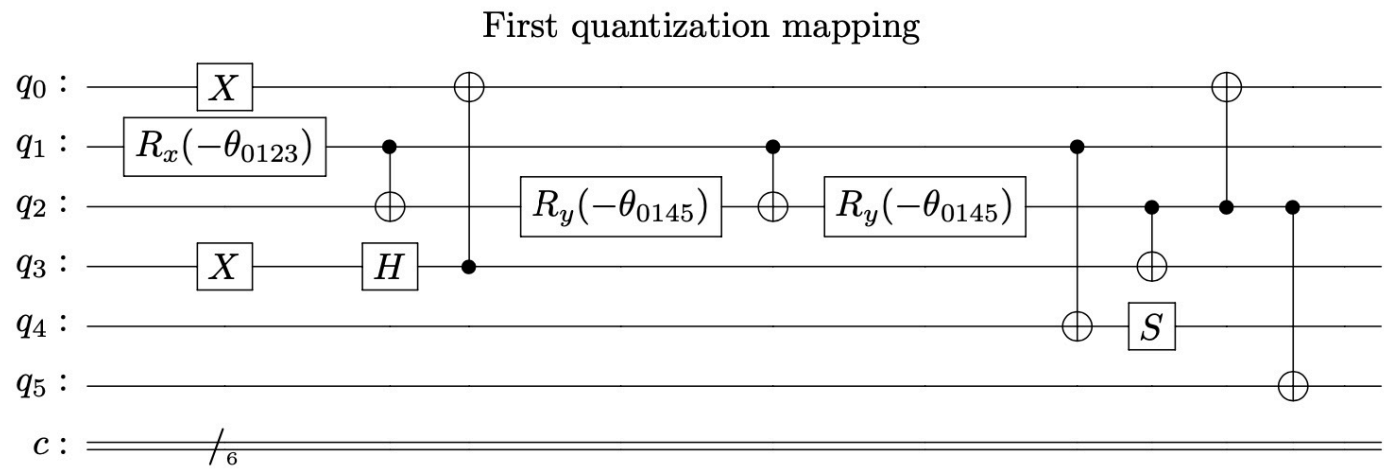
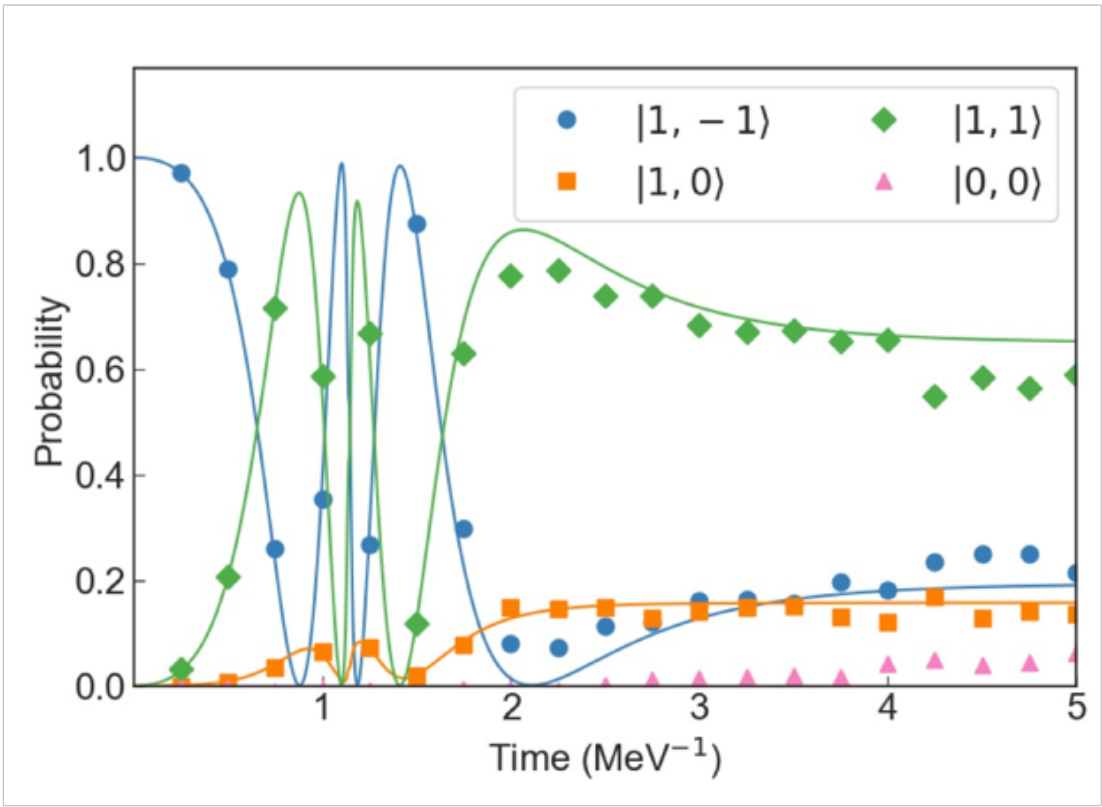
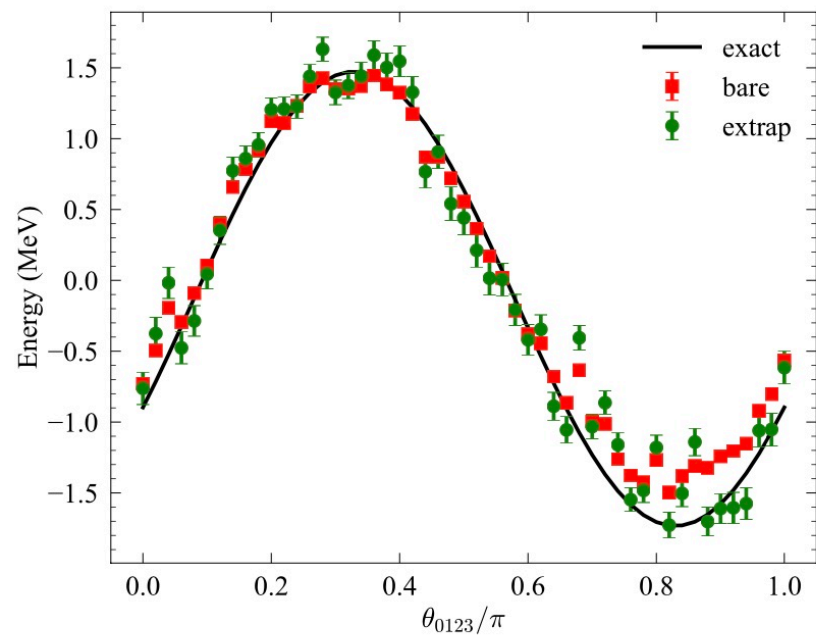
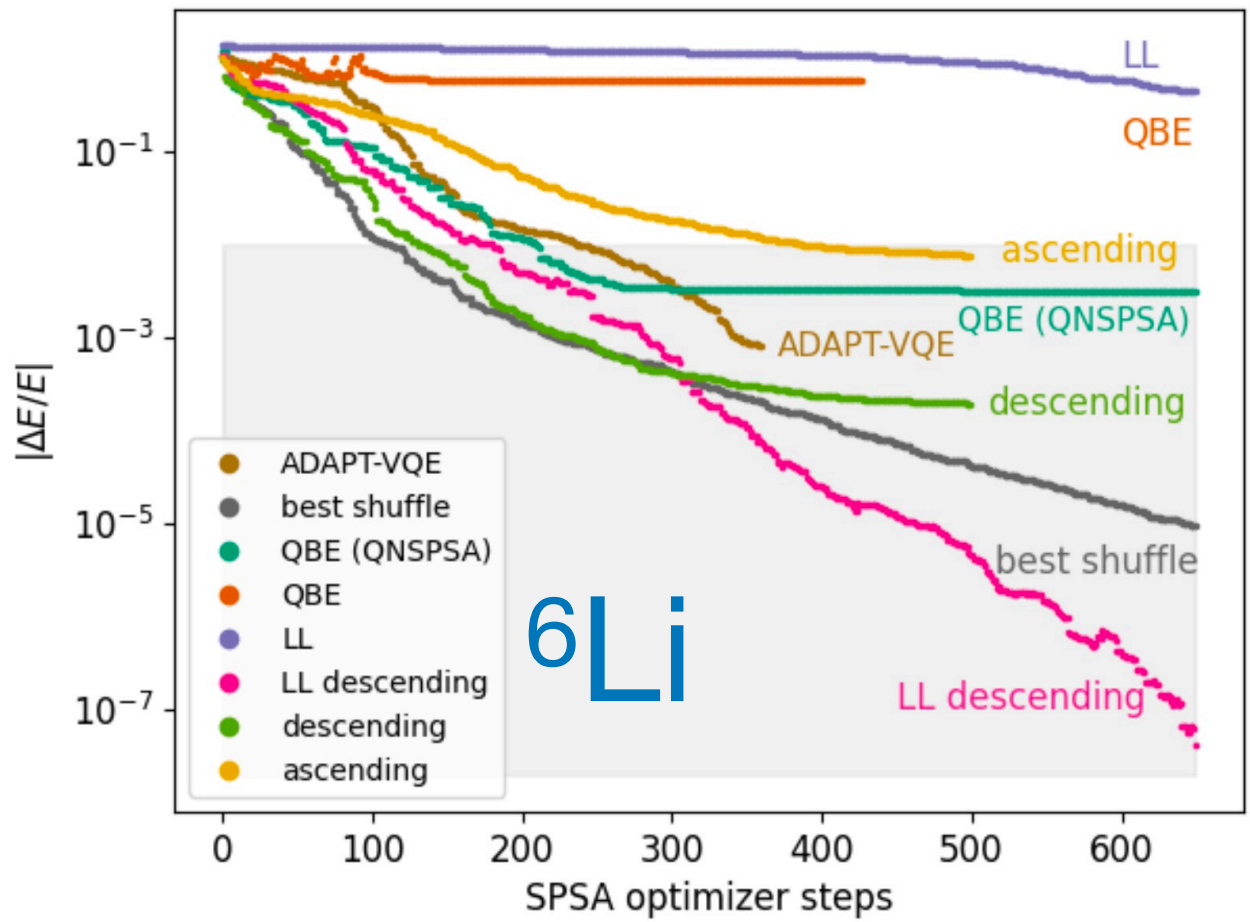


TABLE 1. Summary of the results for the ground-state energy for different systems in different

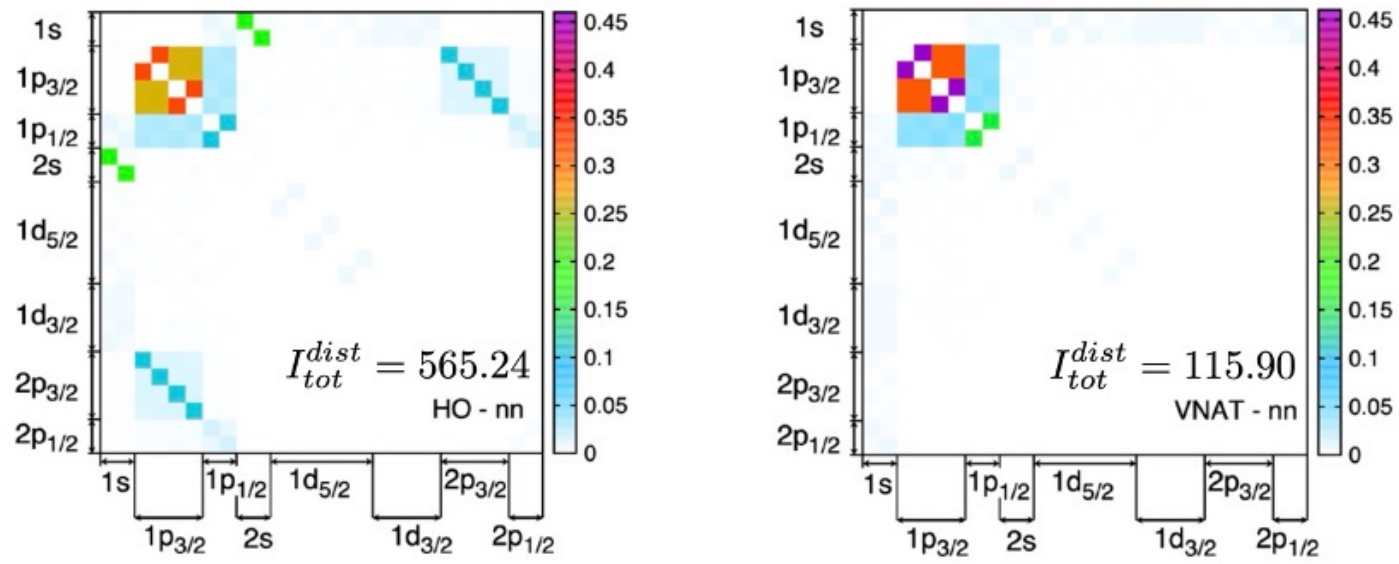
Nucleus	Model Space	E_{exact} (MeV)	E_{HF} (MeV)	$E_{\text{HF}} + \text{corr}$ (MeV)	Number paramet
${}^6\text{He}$	p	-3.91	-0.90	-3.85	2
${}^8\text{Be}$	p	-31.12	-26.12	-26.79	12
${}^8\text{Be}^*$	p	-31.12	-26.12	-29.37	76
${}^8\text{Be}^{**}$	p	-31.12	-26.12	-30.67	112
${}^{20}\text{O}$	sd	-23.93	-21.29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



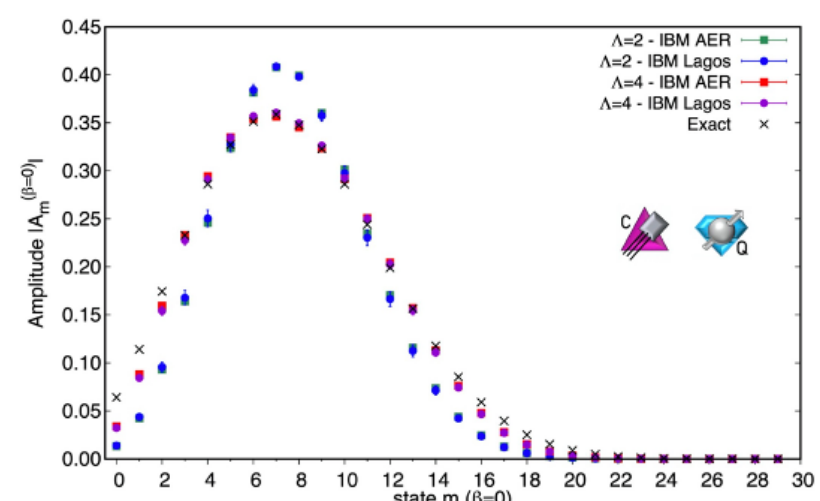
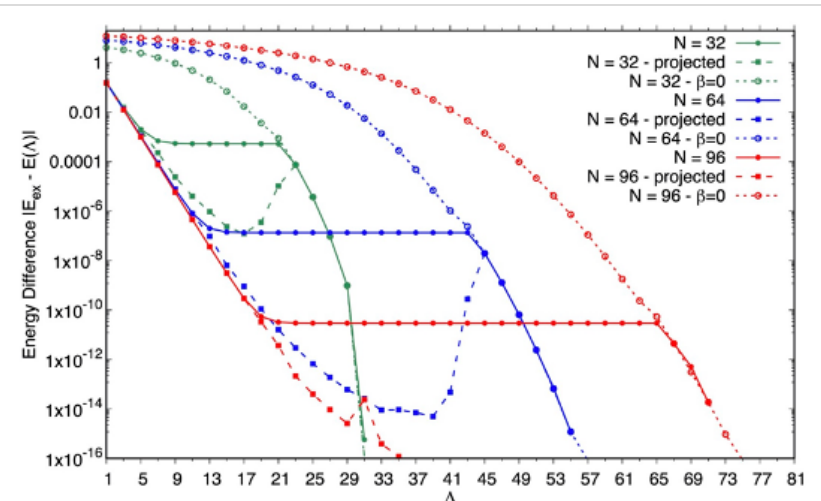
LANL



ORNL, AWS, CERN, UTK, UGeneva,



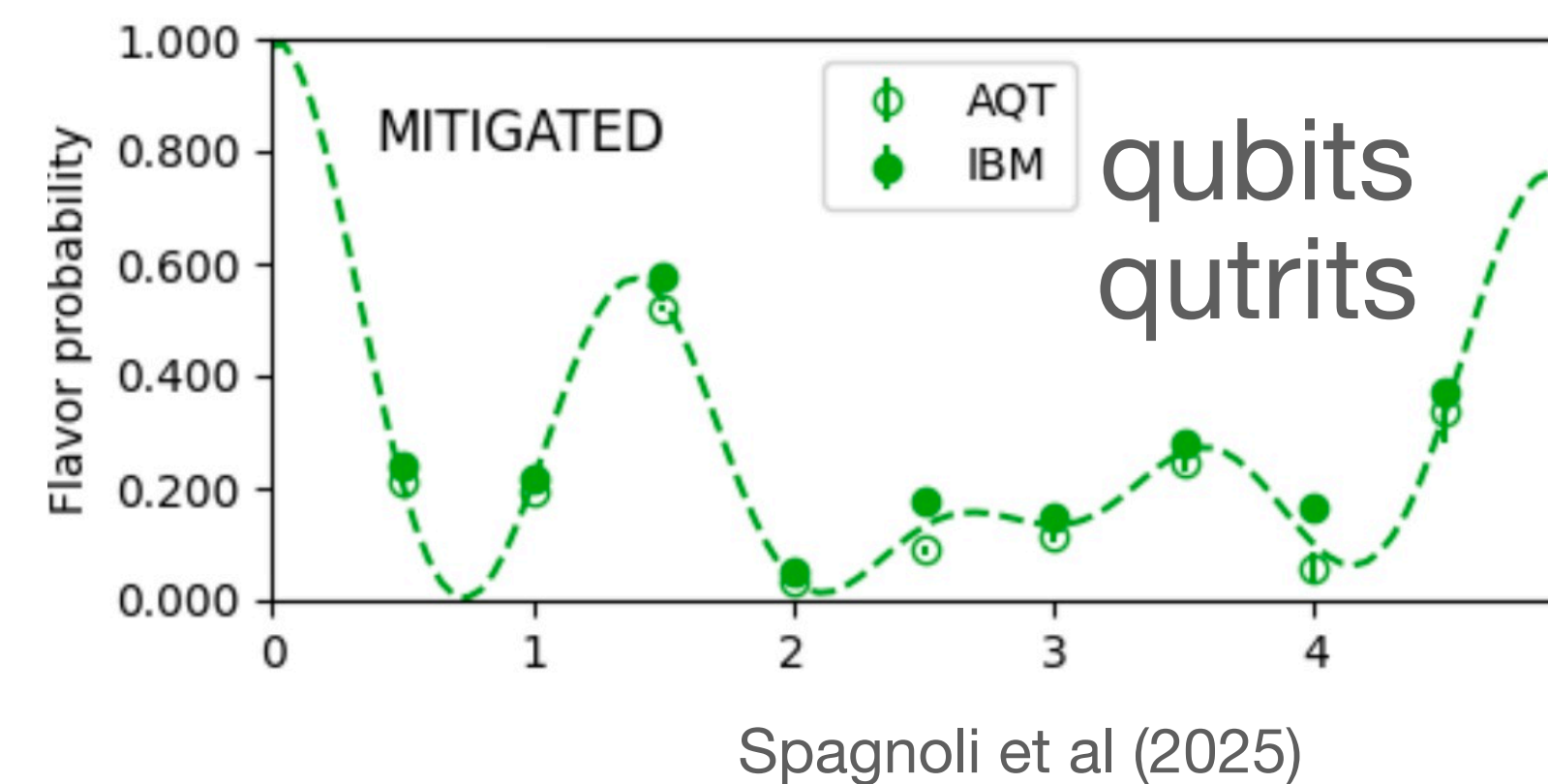
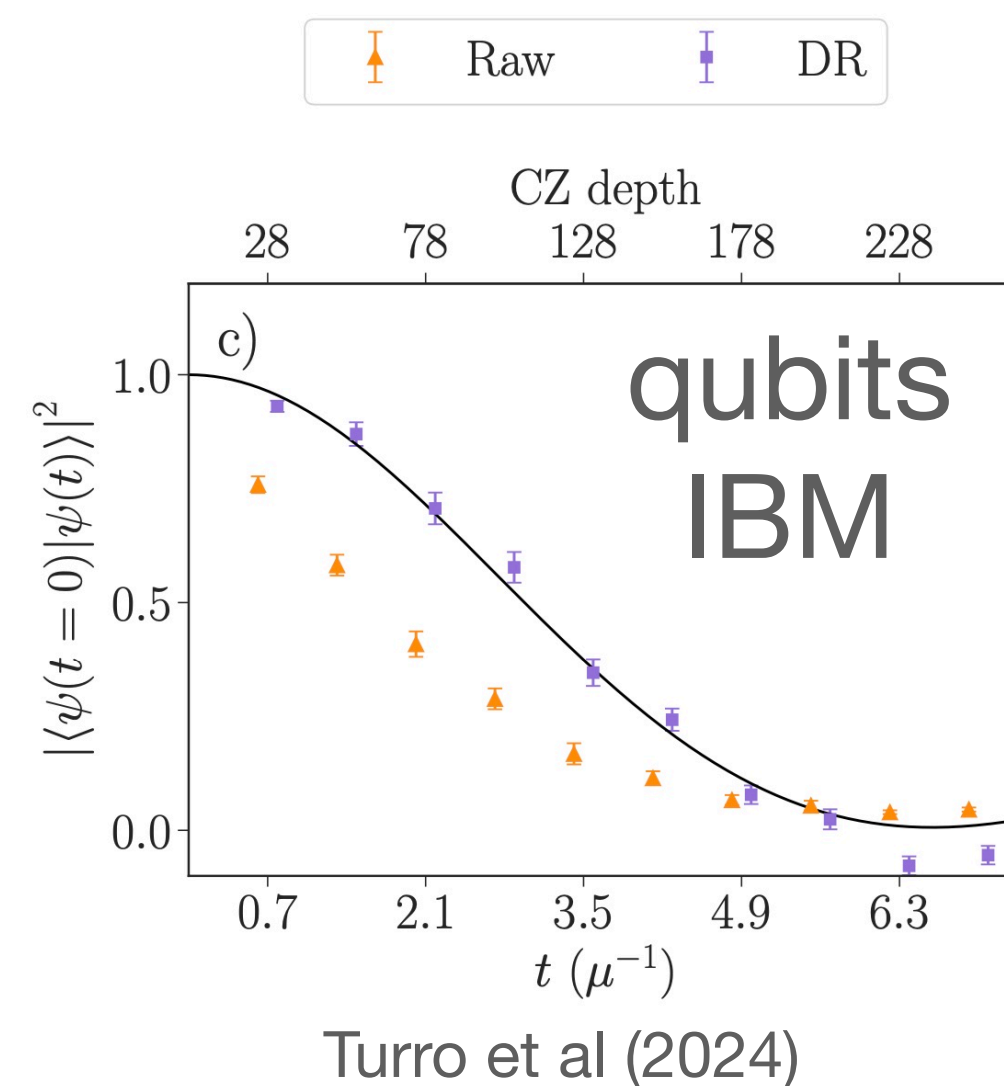
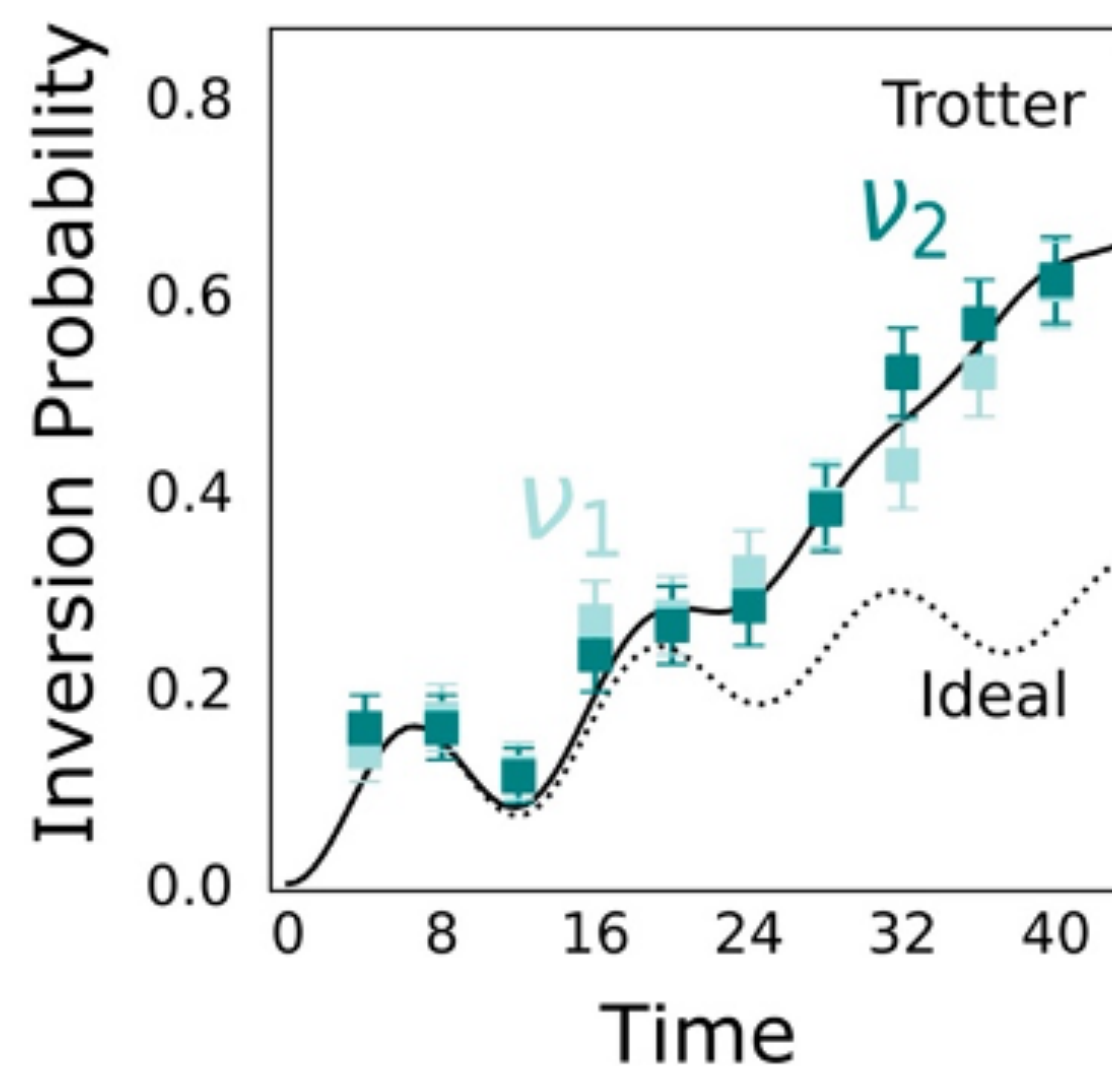
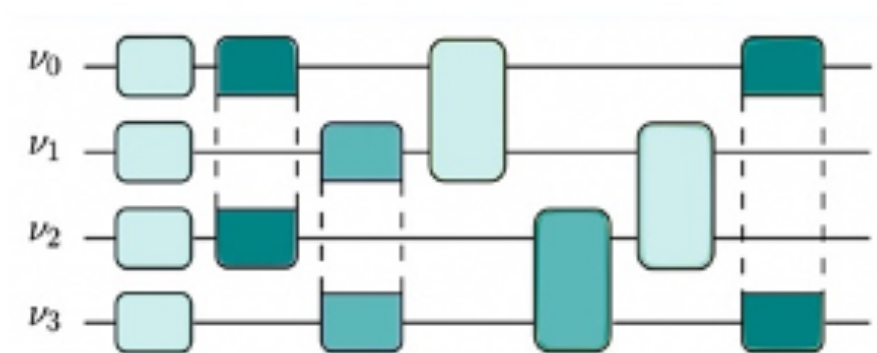
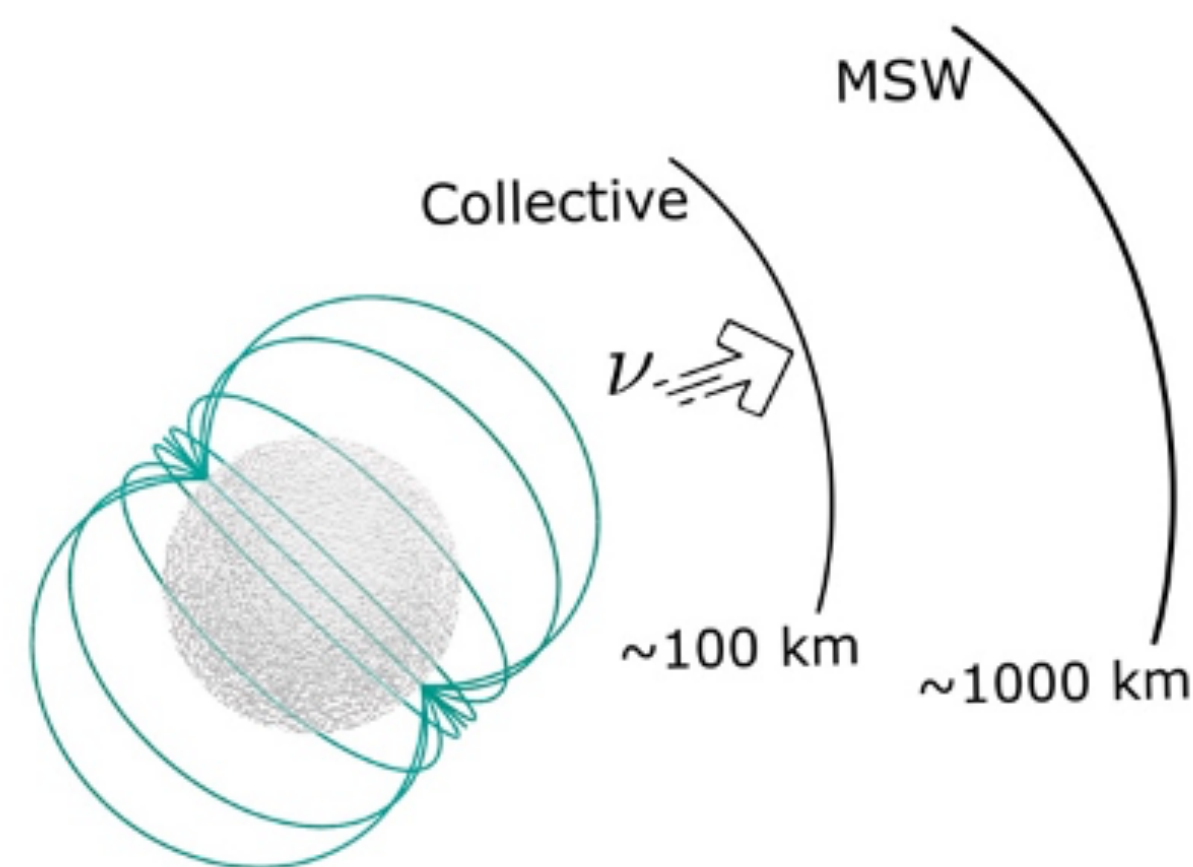
Bielefeld, IQuS



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

Neutrino Flavor Dynamics in Supernova

Simulations with qubits and qutrits



N-body Gates in Trapped Ion Systems

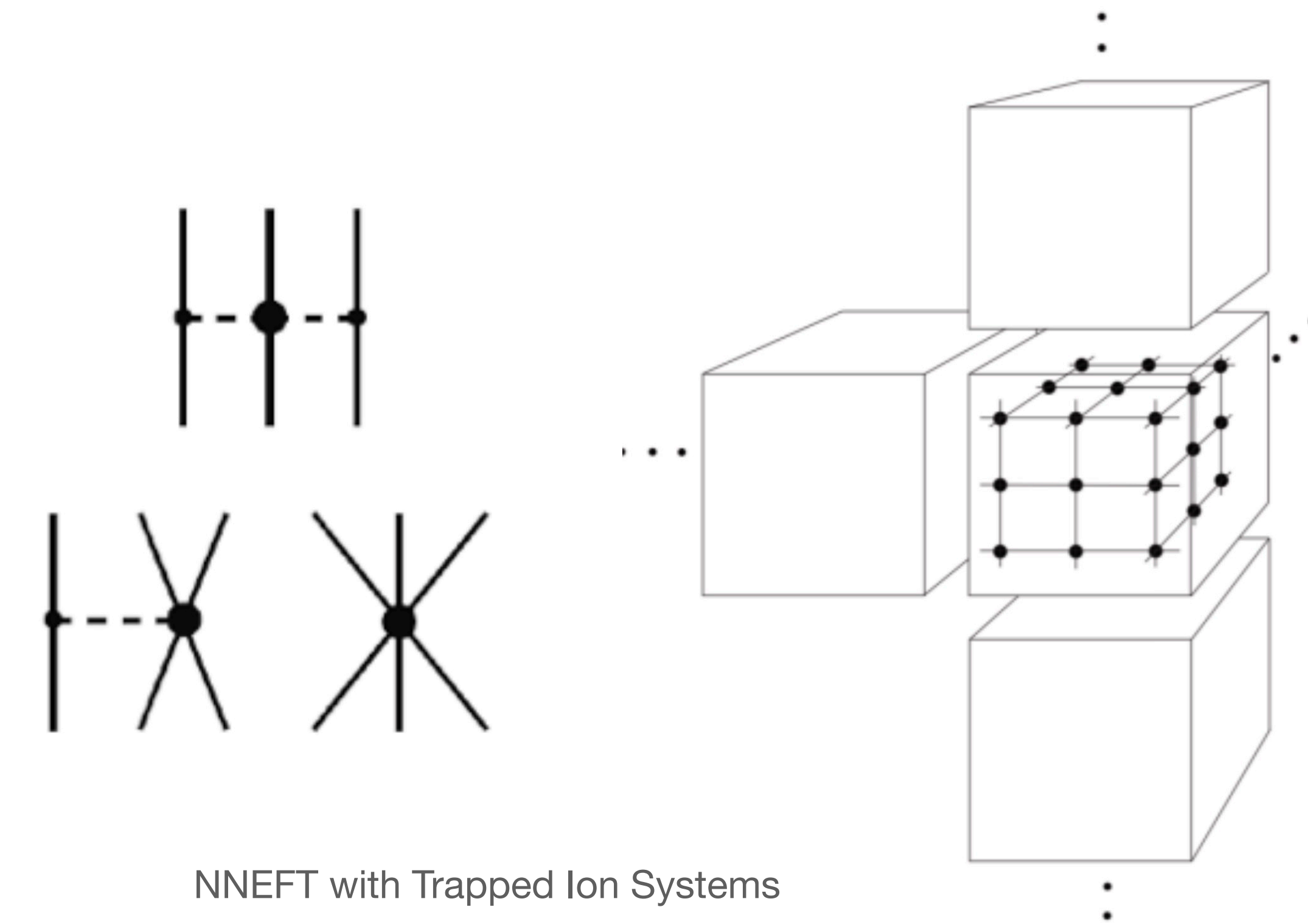
Co-Design in Action

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

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

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

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



NNEFT with Trapped Ion Systems

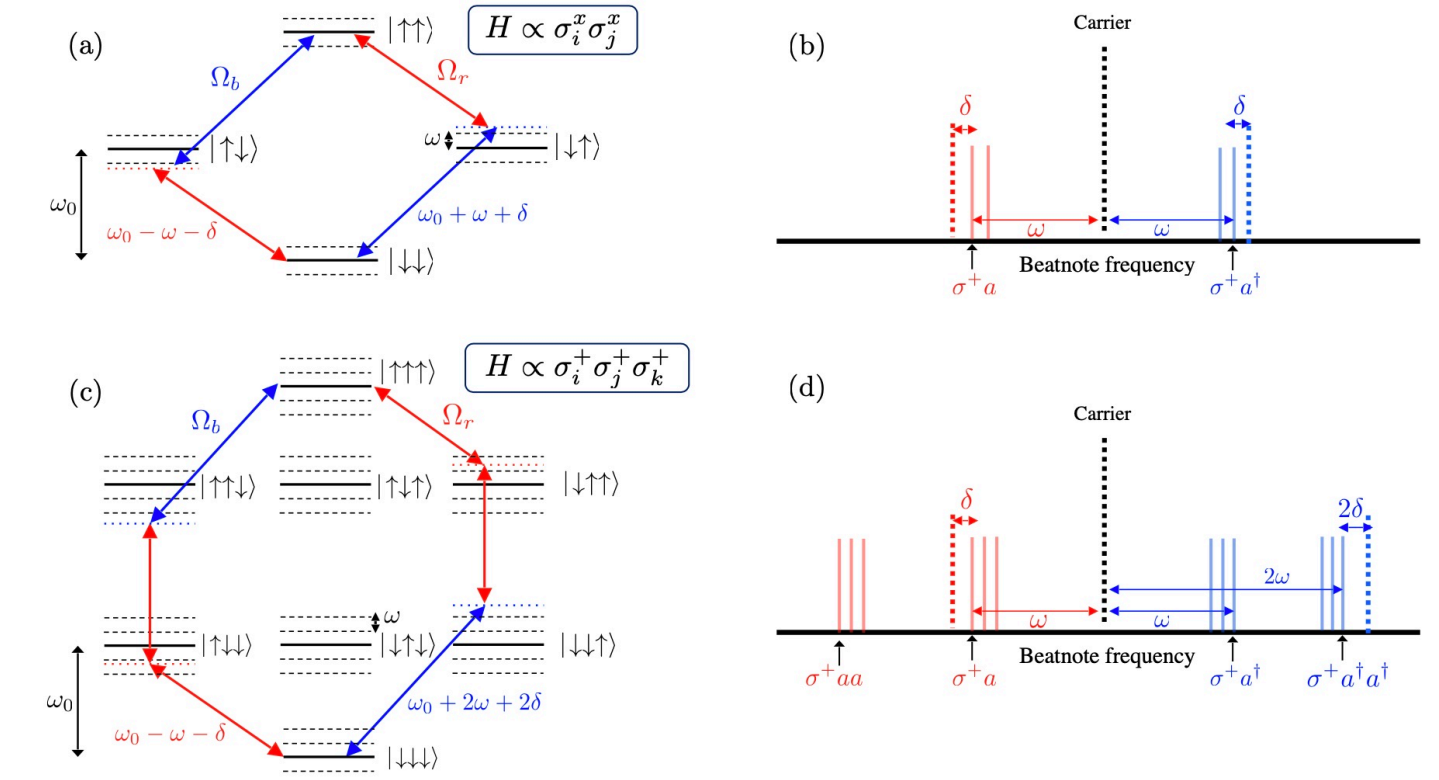
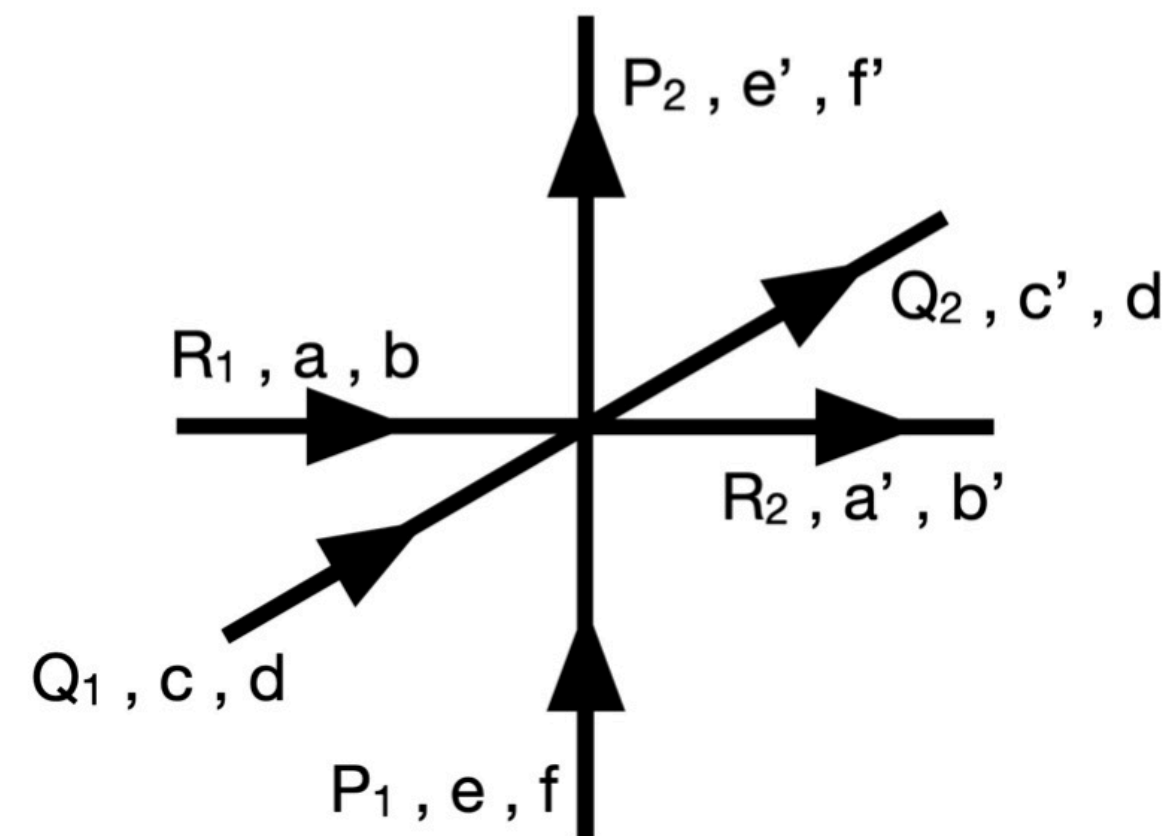
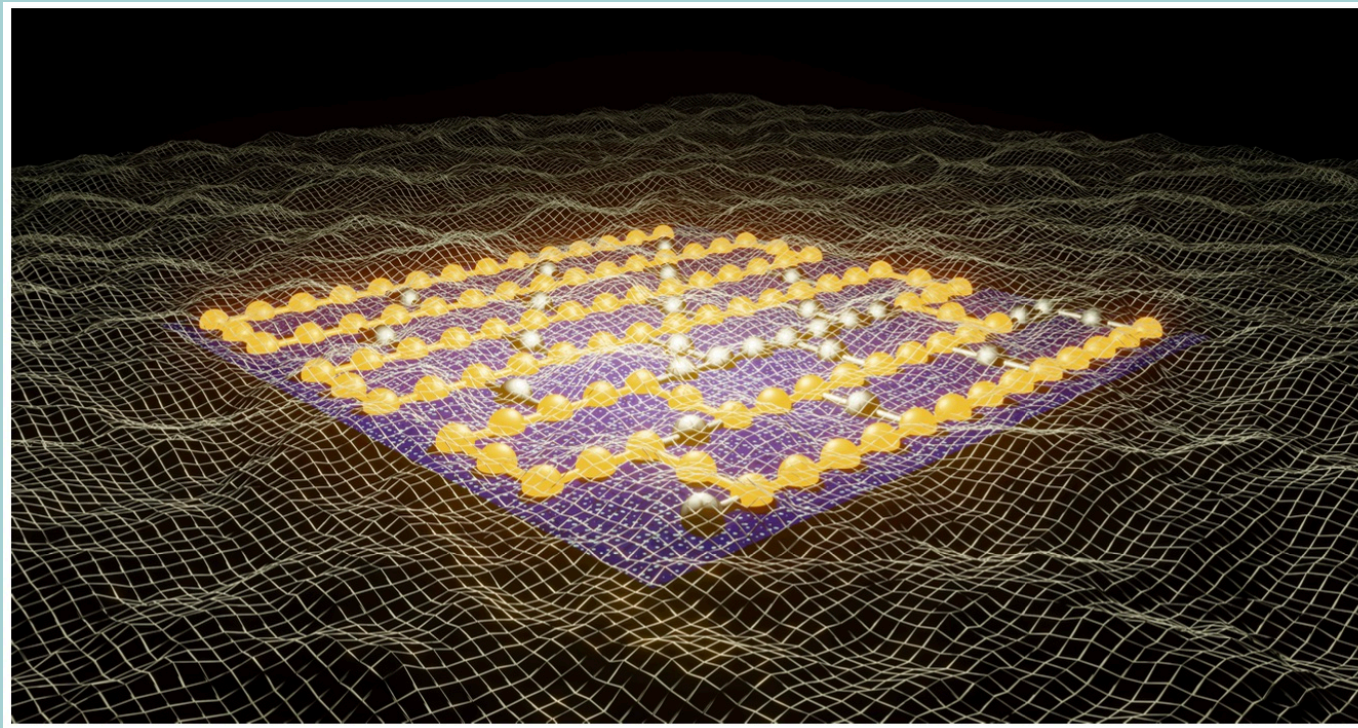


FIG. 1. (a,b) Traditional Mølmer-Sørensen scheme based on a pair of bichromatic laser beatnotes off-resonantly driving first-order spin-phonon couplings with symmetric detuning ($\pm\delta$), giving rise to an effective spin-spin interaction. The two-ion case is shown for simplicity. (c,d) Generalized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

Part-3

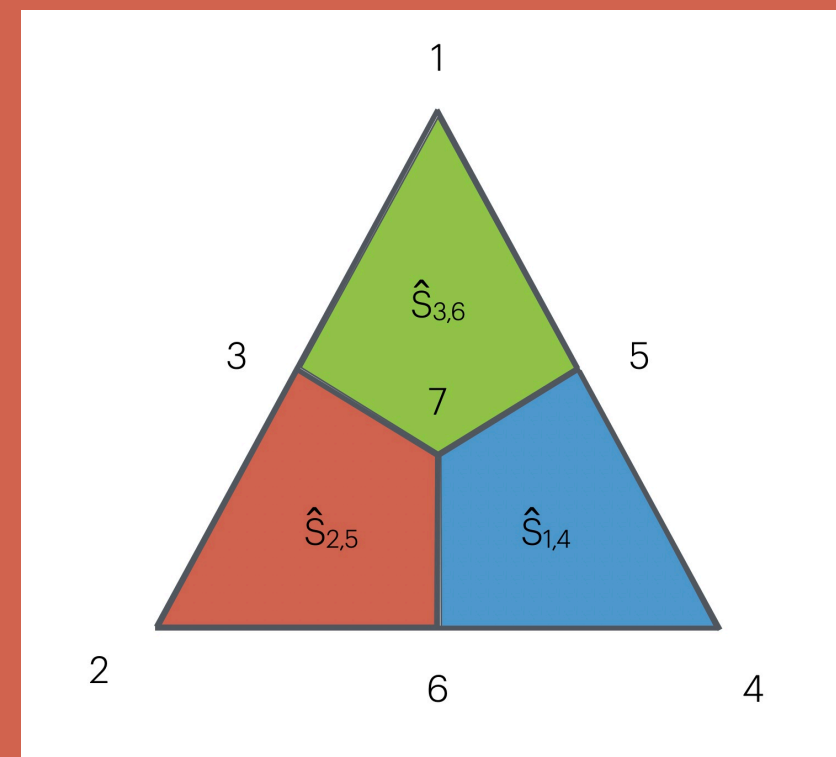
Quantum Computing and Simulation



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

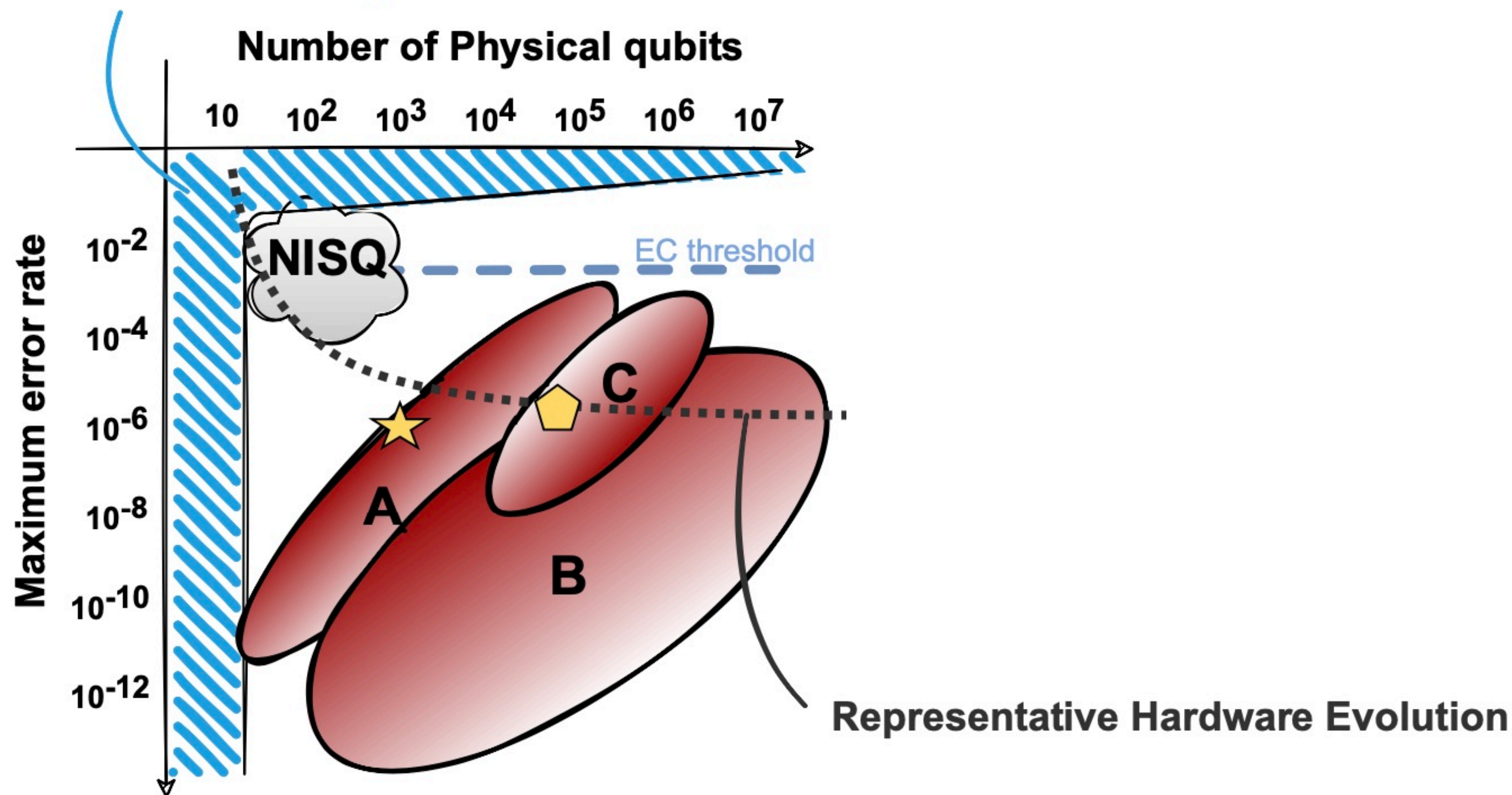
Part-4

Beyond NISQ:
FaultTolerance and Error
Correction



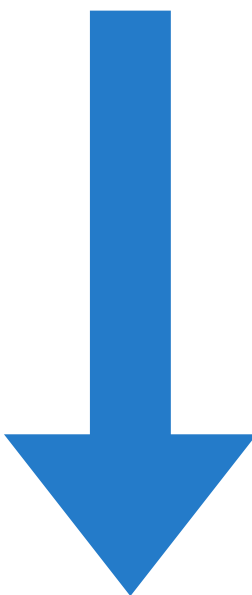
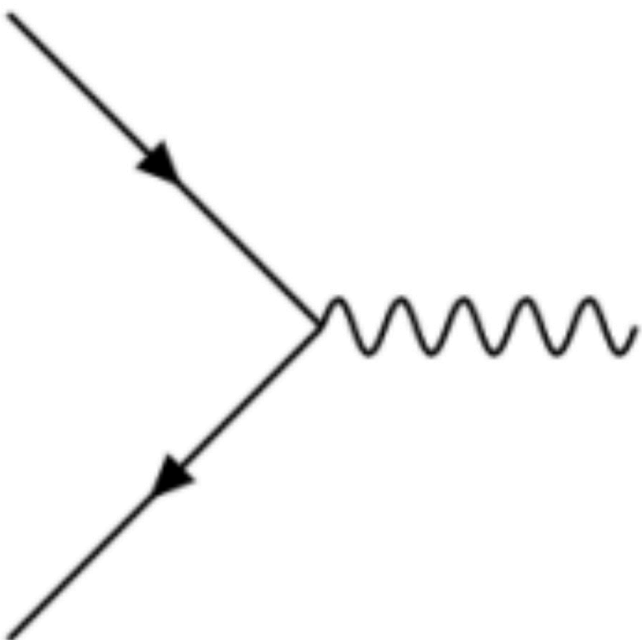
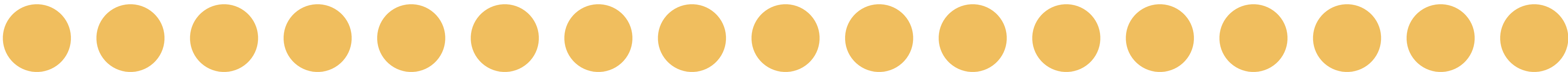
Fault Detection and Error Correction is
essential for Quantum Computers to be useful

Classical Computation

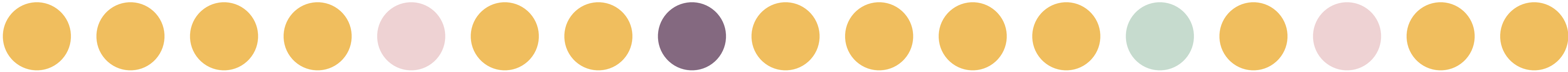


Ensemble of 1-Qubit States with Noise

Pure ensemble of single qubit states



After some time



X

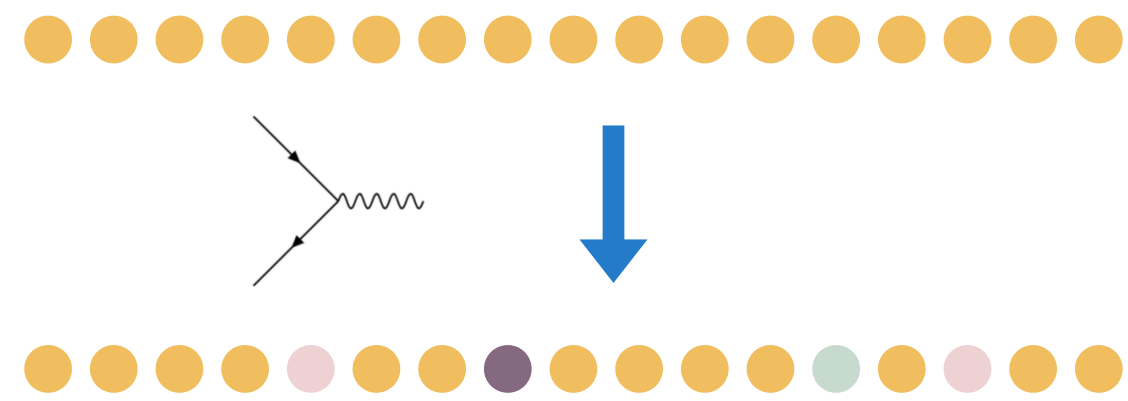
Y

Z

X

Mixed ensemble of single qubit states

Ensemble of 1-Qubit States with Noise



Interactions with environment change a pure ensemble into a mixed ensemble

An error rate per qubit leads to, after some time,

$$\{ |\psi\rangle, |\psi\rangle, |\psi\rangle, |\psi\rangle, |\psi\rangle, |\psi\rangle, |\psi\rangle, |\psi\rangle, \dots \} \rightarrow \{ |\psi\rangle, |\psi\rangle, \hat{X}|\psi\rangle, |\psi\rangle, \hat{Y}|\psi\rangle, \hat{Z}|\psi\rangle, |\psi\rangle, |\psi\rangle, \dots \}$$

For Isotropic, independent noise with probability p :

$$|\psi\rangle = c_0|0\rangle + c_1|1\rangle : 1 - p$$

$$|e_z\rangle = c_0|0\rangle - c_1|1\rangle : p/3$$

$$|e_x\rangle = c_0|1\rangle + c_1|0\rangle : p/3$$

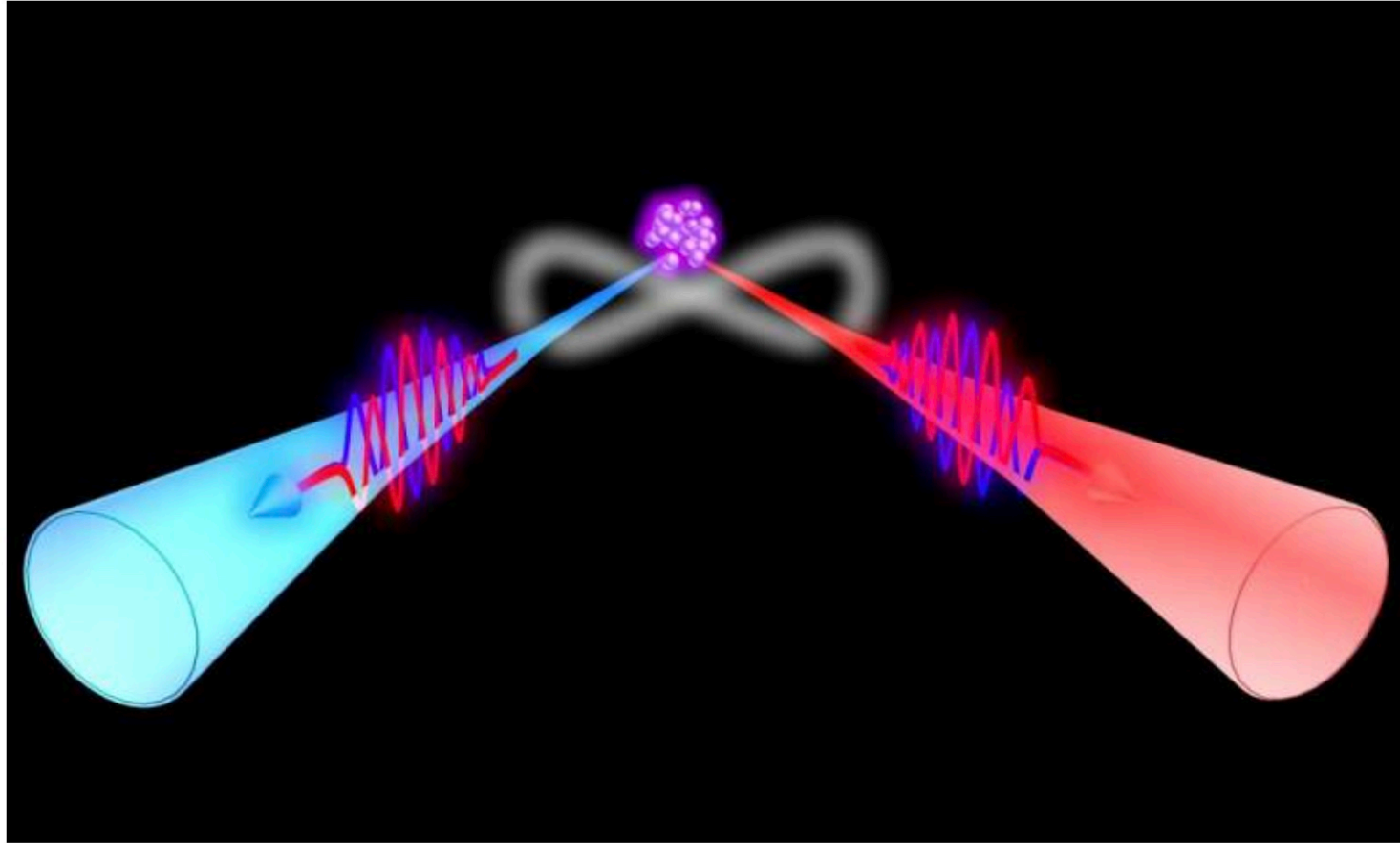
$$|e_y\rangle = ic_0|1\rangle - ic_1|0\rangle : p/3$$

$$\begin{aligned} \rho_e &= (1 - p)\rho + \frac{p}{3} \sum_i \sigma_i \rho \sigma_i \\ &= \left(1 - \frac{4}{3}p\right) \rho + p \frac{2}{3} I \end{aligned}$$

Expectation values of Paulis decrease with increasing p

2-Qubit Werner State

Mixed ensemble with Bell pairs and classically correlated pairs



Quantum entanglement. Credit: Physics Department, HKUST

$$p : |\Phi_1\rangle = \frac{1}{\sqrt{2}} [|00\rangle + |11\rangle]$$

$$\frac{1}{4}(1-p) : |00\rangle$$

$$\frac{1}{4}(1-p) : |01\rangle$$

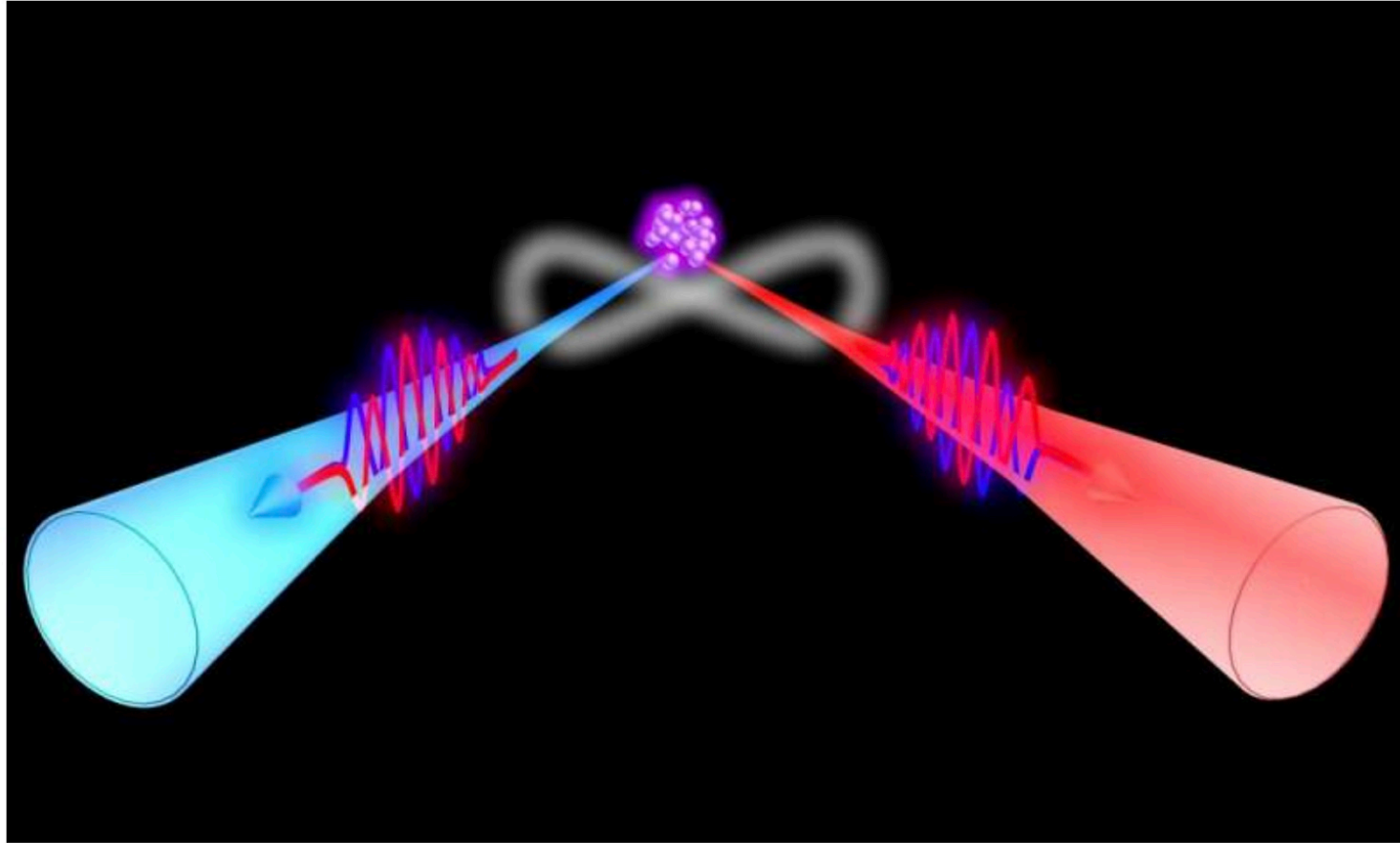
$$\frac{1}{4}(1-p) : |10\rangle$$

$$\frac{1}{4}(1-p) : |11\rangle$$

$$\hat{\rho}_{AB} = p|\Phi_1\rangle\langle\Phi_1| + (1-p)\frac{1}{4}I_4$$

$$\hat{\rho}_{AB} = \begin{pmatrix} \frac{1+p}{4} & 0 & 0 & \frac{p}{2} \\ 0 & \frac{1-p}{4} & 0 & 0 \\ 0 & 0 & \frac{1-p}{4} & 0 \\ \frac{p}{2} & 0 & 0 & \frac{1+p}{4} \end{pmatrix}$$

2-Qubit Werner State



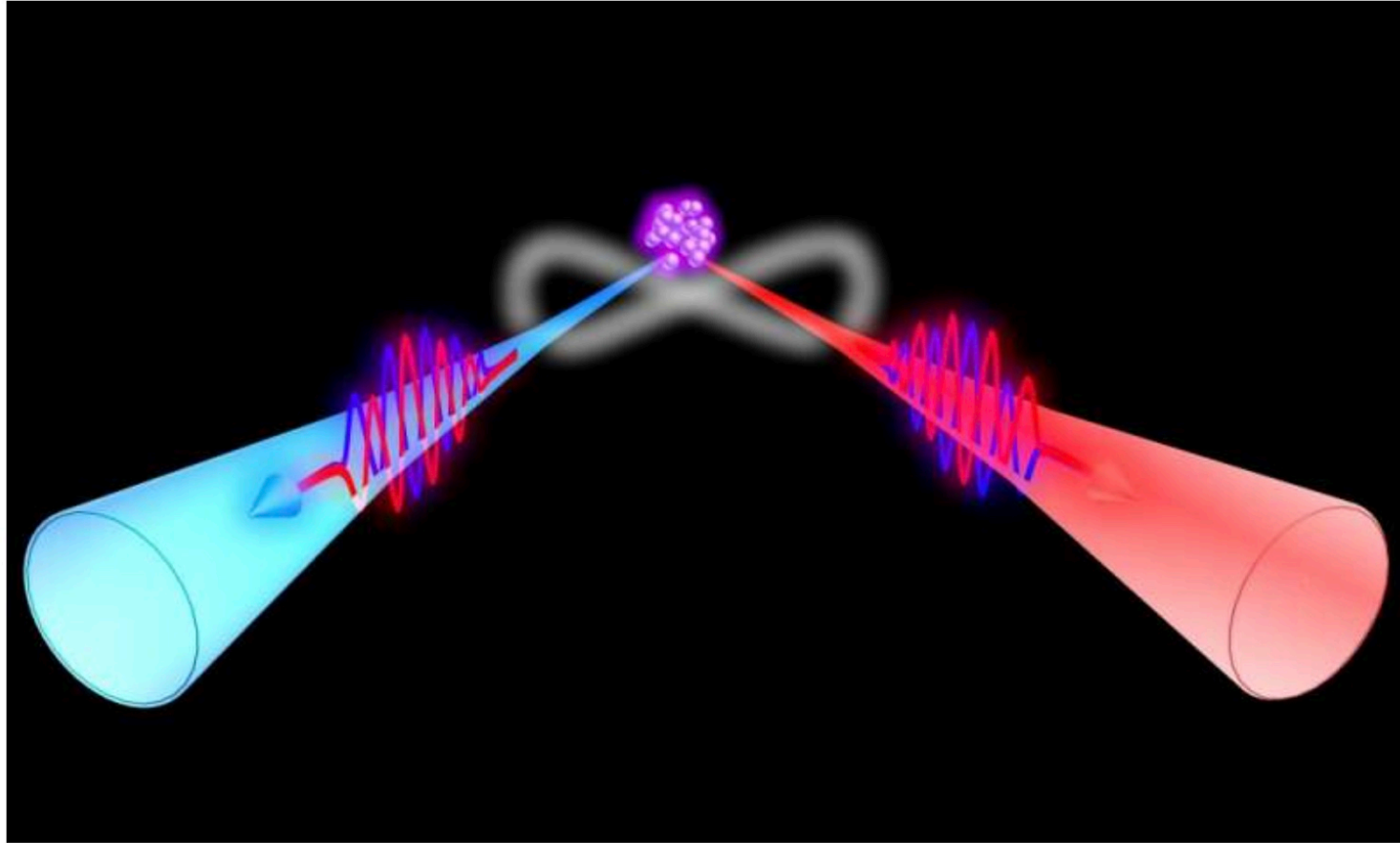
Quantum entanglement. Credit: Physics Department, HKUST

$$\hat{\rho}_{AB} = \frac{p}{2} [\rho(|++\rangle_x) + \rho(|--\rangle_x) + \rho(|+-\rangle_y) + \rho(|-+\rangle_y)] \\ + \frac{1-p}{4} (\rho(|00\rangle) + \rho(|11\rangle)) + \frac{1-3p}{4} (\rho(|01\rangle) + \rho(|10\rangle)) \\ |\pm\rangle_x = \frac{1}{\sqrt{2}} [|0\rangle \pm |1\rangle] , \quad |\pm\rangle_y = \frac{1}{\sqrt{2}} [|0\rangle \pm i|1\rangle] .$$

If $p \leq \frac{1}{3}$ separable and not distillable!!

“Quantumness” is lost

2-Qubit Werner State

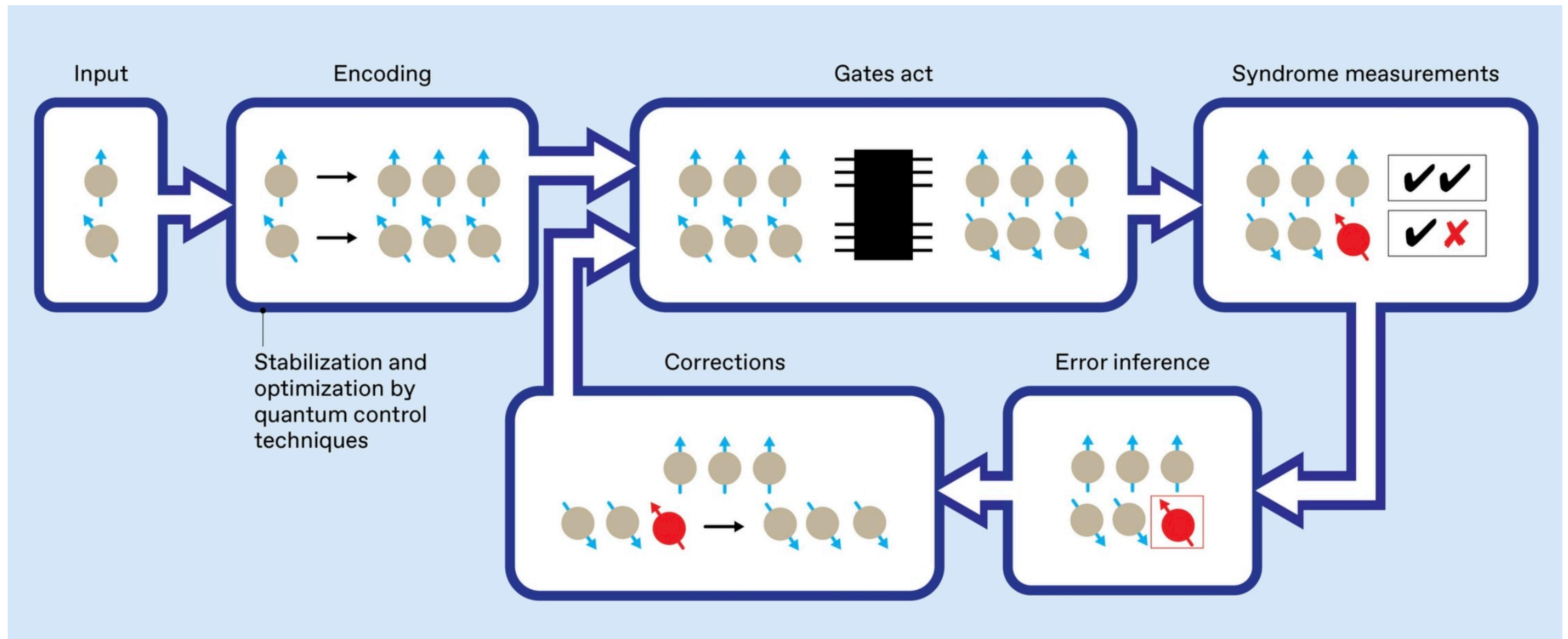


Quantum entanglement. Credit: Physics Department, HKUST

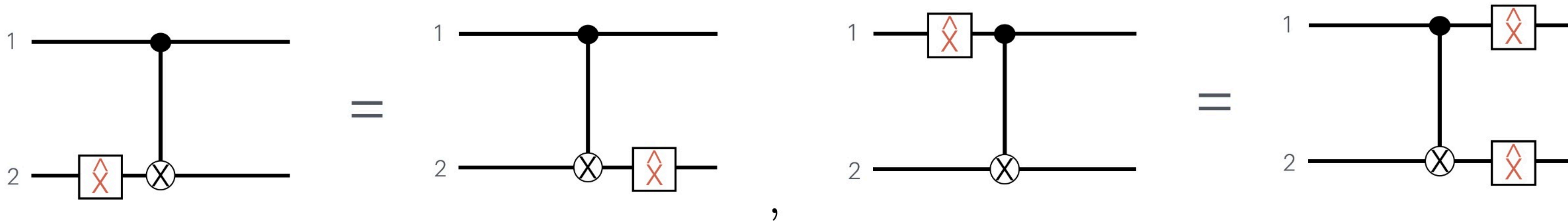
- $p = 0$: classical and separable (there are no entangled states in this mixed ensemble)
- $0 < p \leq \frac{1}{3}$: mixed ensemble containing entangled states, but the system is separable
- $p > \frac{1}{3}$: mixed ensemble containing entangled states and the system is not separable
- $p = 1$: pure state, entangled and not separable

Schematic of Error Correction

Need to be able to recover from errors over an extended period of time.



Error Propagation



$$|\psi\rangle = c_0|00\rangle + c_1|01\rangle + c_2|10\rangle + c_3|11\rangle$$

$$\hat{X}_1 |\psi\rangle = c_0|10\rangle + c_1|11\rangle + c_2|00\rangle + c_3|01\rangle$$

$$\text{CNOT}_{12} \hat{X}_1 |\psi\rangle = c_0|11\rangle + c_1|10\rangle + c_2|00\rangle + c_3|01\rangle$$

$$\text{CNOT}_{12} |\psi\rangle = c_0|00\rangle + c_1|01\rangle + c_2|11\rangle + c_3|10\rangle$$

$$\hat{X}_1 \text{CNOT}_{12} |\psi\rangle = c_0|10\rangle + c_1|11\rangle + c_2|01\rangle + c_3|00\rangle$$

$$\hat{X}_2 \hat{X}_1 \text{CNOT}_{12} |\psi\rangle = c_0|11\rangle + c_1|10\rangle + c_2|00\rangle + c_3|01\rangle$$

$$|\psi\rangle = c_0|00\rangle + c_1|01\rangle + c_2|10\rangle + c_3|11\rangle$$

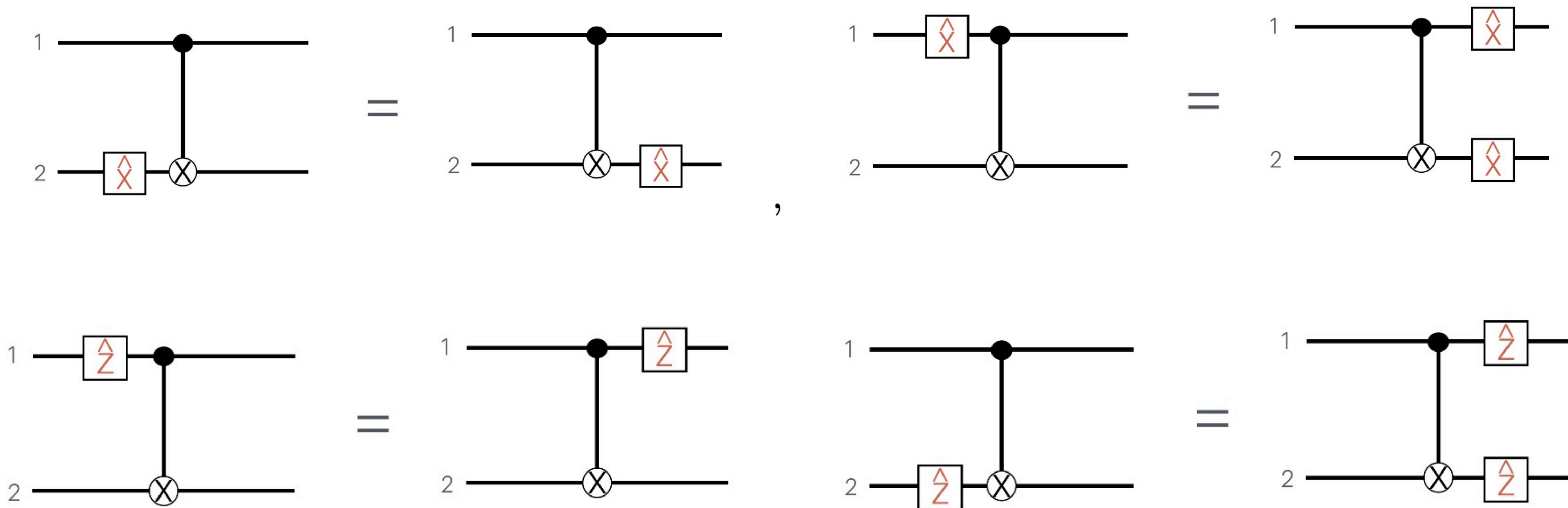
$$\hat{X}_2 |\psi\rangle = c_0|01\rangle + c_1|00\rangle + c_2|11\rangle + c_3|10\rangle$$

$$\text{CNOT}_{12} \hat{X}_2 |\psi\rangle = c_0|01\rangle + c_1|00\rangle + c_2|10\rangle + c_3|11\rangle$$

$$\text{CNOT}_{12} |\psi\rangle = c_0|00\rangle + c_1|01\rangle + c_2|11\rangle + c_3|10\rangle$$

$$\hat{X}_2 \text{CNOT}_{12} |\psi\rangle = c_0|01\rangle + c_1|00\rangle + c_2|10\rangle + c_3|11\rangle$$

Error Propagation



Design circuits that suppress/eliminate or identify and remove

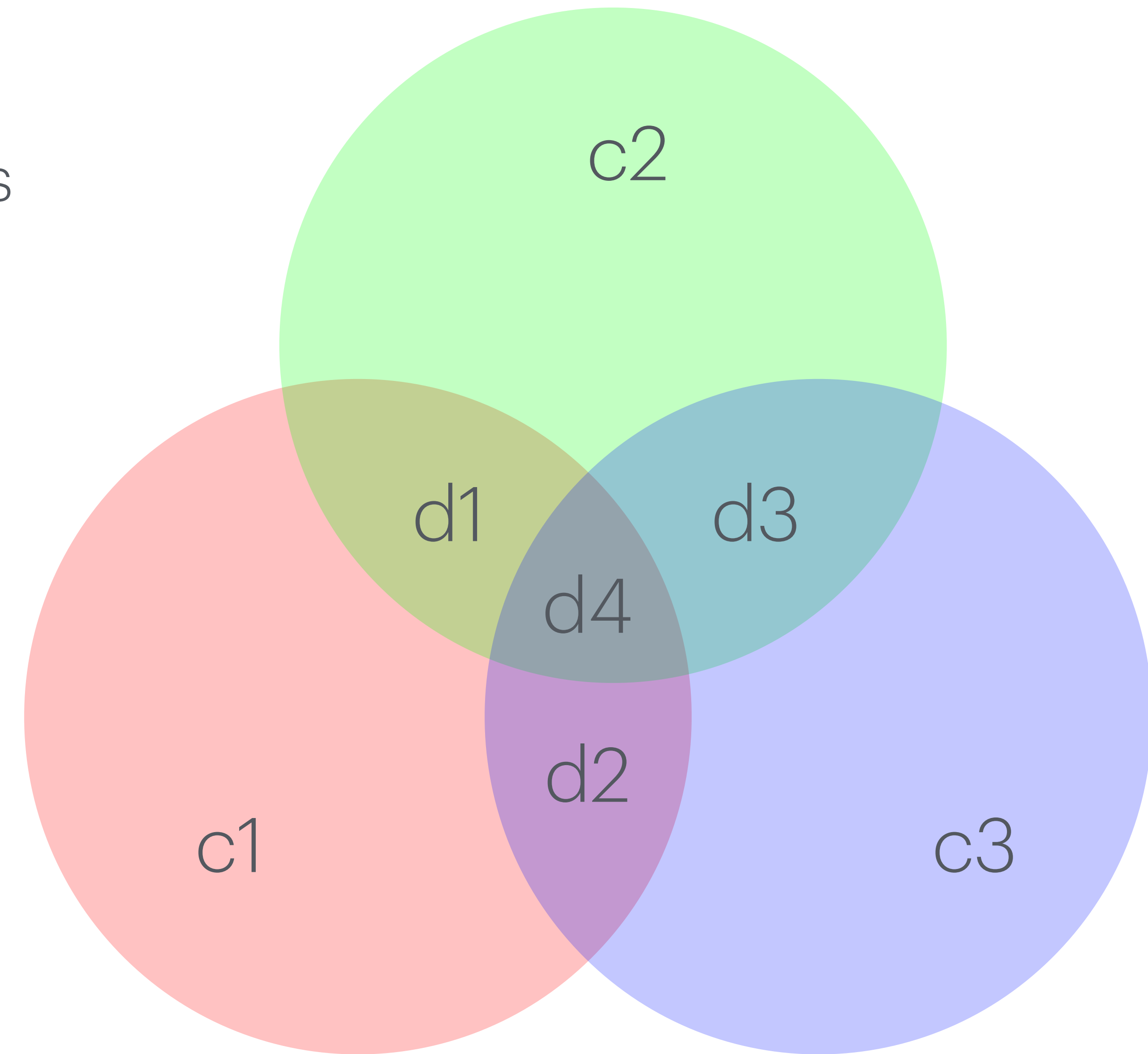
Classical Error Correction, e.g., Hamming (7,4,3)

4 classical bits embedded in 7 classical bits

Parity checks on partitions of 3 of the 4

Mod(2) math

$d_1 \ d_2 \ d_3 \ d_4 \rightarrow c_1 \ c_2 \ d_1 \ c_3 \ d_2 \ d_3 \ d_4$



$$c_1 = d_1 + d_2 + d_4, \quad c_2 = d_1 + d_3 + d_4, \quad c_3 = d_2 + d_3 + d_4$$

Classical Error Correction, e.g., Hamming (7,4,3)

$2^4 = 16$ codewords (sparsely) embedded in $2^7 = 128$ space

Need 3 bit flips to convert a codeword into another codeword

- Hamming Distance = 3
- Denoted as (7,4,3)
- 1 error can be detected and corrected
- 2 errors can be detected, but not corrected (correctly!)

Classical Error Correction, e.g., Hamming (7,4,3)

Encoding matrix

$$v_7 = \begin{pmatrix} c_1 \\ c_2 \\ d_1 \\ c_3 \\ d_2 \\ d_3 \\ d_4 \end{pmatrix}, \quad G^T = \begin{pmatrix} 1 & 1 & 0 & 1 \\ 1 & 0 & 1 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 1 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix},$$

$$H = \begin{pmatrix} 1 & 0 & 1 & 0 & 1 & 0 & 1 \\ 0 & 1 & 1 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 & 1 & 1 \end{pmatrix}, \quad R = \begin{pmatrix} 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

Syndrome matrix

Decoding matrix

Classical Error Correction, e.g., Hamming (7,4,3)

$$H = \begin{pmatrix} 1 & 0 & 1 & 0 & 1 & 0 & 1 \\ 0 & 1 & 1 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 & 1 & 1 \end{pmatrix} \quad \text{H. Codeword.} = (0,0,0)$$

$$H.e_1 = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \rightarrow 001 \rightarrow 1, \quad H.e_6 = \begin{pmatrix} 0 \\ 1 \\ 1 \end{pmatrix} \rightarrow 110 \rightarrow 6$$

H. [single error]. = location of bit flip in binary

Flip it back — error corrected - then decode

Classical Error Correction, e.g., Hamming (7,4,3)

$$H.(e_1 + e_6) = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} \rightarrow 111 \rightarrow 7 .$$

Two errors can be detected, but correction leads to wrong codeword

- 1) Detect errors and remove from ensemble, removes $O(p, p^2)$
- 2) Detect and correct errors, removes $O(p)$ without reducing ensemble

Classical Error Correction, e.g., Extended Hamming (8,4,4)

4 classical bits embedded in 8 classical bits

Parity checks on partitions of 3 of the 4

Global Parity Check

$$\begin{aligned} p_1 &= c_1 + c_2 + d_1 + c_3 + d_2 + d_3 + d_4 \\ &= d_1 + d_2 + d_4 + d_1 + d_3 + d_4 + d_1 + d_2 + d_3 + d_4 + d_2 + d_3 + d_4 \\ &= d_1 + d_2 + d_3 , \end{aligned}$$

$$v_8 = c_1 \ c_2 \ d_1 \ c_3 \ d_2 \ d_3 \ d_4 \ p_1$$

Classical Error Correction, e.g., Extended Hamming (8,4,4)

$$v_8 = \begin{pmatrix} c_1 \\ c_2 \\ d_1 \\ c_3 \\ d_2 \\ d_3 \\ d_4 \\ p_1 \end{pmatrix}, \quad G^T = \begin{pmatrix} 1 & 1 & 0 & 1 \\ 1 & 0 & 1 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 1 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 1 & 1 & 0 \end{pmatrix},$$

$$H = \begin{pmatrix} 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 & 1 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{pmatrix}, \quad R = \begin{pmatrix} 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{pmatrix}$$

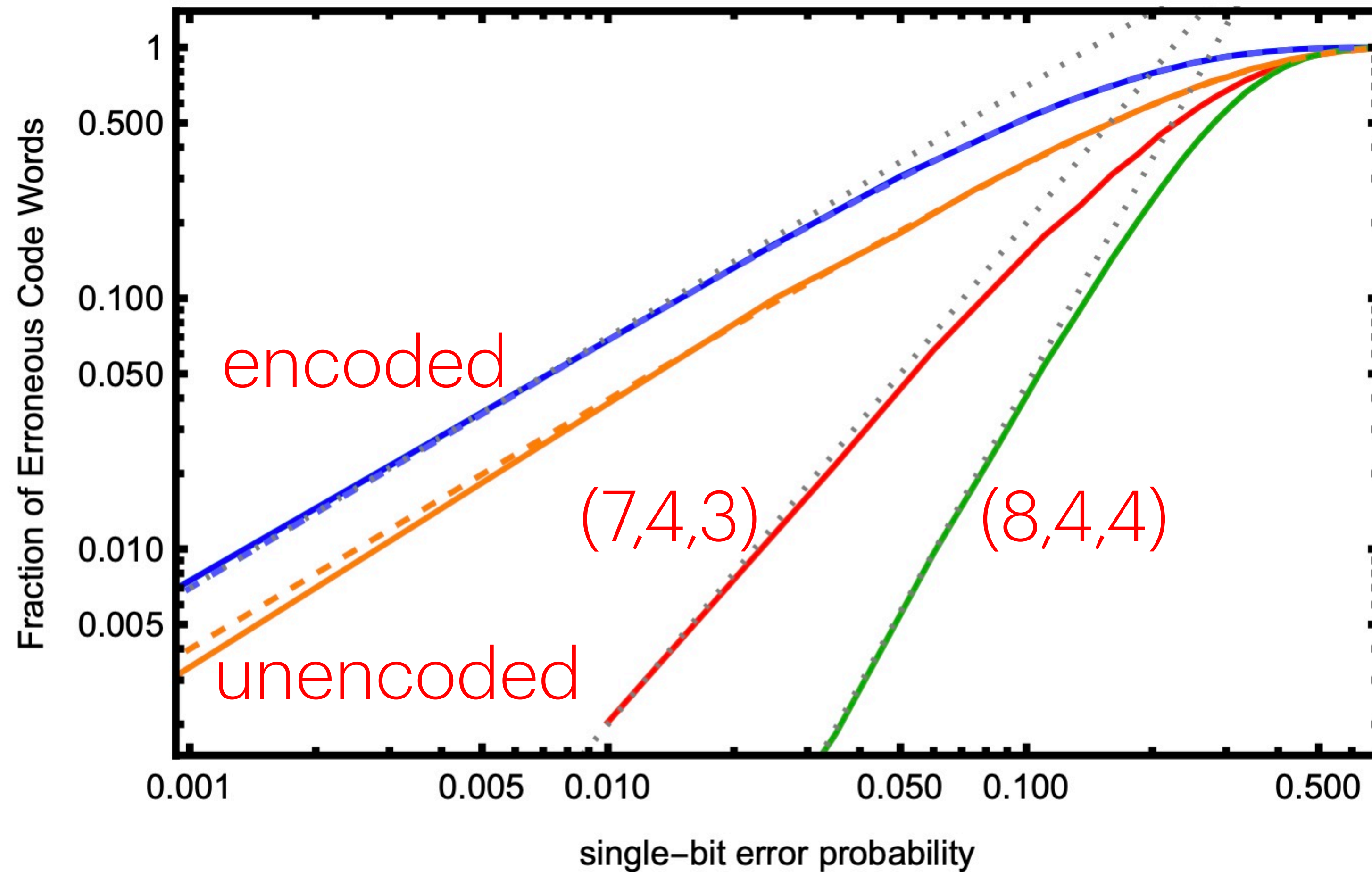
$$1 : \sum_{i=1}^3 H_i = 0 \text{ and } H_4 = 0 : 0 \text{ or } 4 \text{ or more errors, keep codeword} \quad ($$

$$2 : \sum_{i=1}^3 H_i = 0 \text{ and } H_4 = 1 : \text{error in } p_1, \text{ correct } p_4 \quad ($$

$$3 : \sum_{i=1}^3 H_i > 0 \text{ and } H_4 = 1 : 1, 3 \text{ or more errors in } c_1 \dots d_4, \text{ correct bit identified by } H$$

$$4 : \sum_{i=1}^3 H_i > 0 \text{ and } H_4 = 0 : 2 \text{ or more (unrecoverable) errors, reject codeword} \quad ($$

Classical Error Correction, e.g., Extended Hamming (8,4,4)



Quantum Error Detection and Correction

Logical qubits from multiple physical qubits

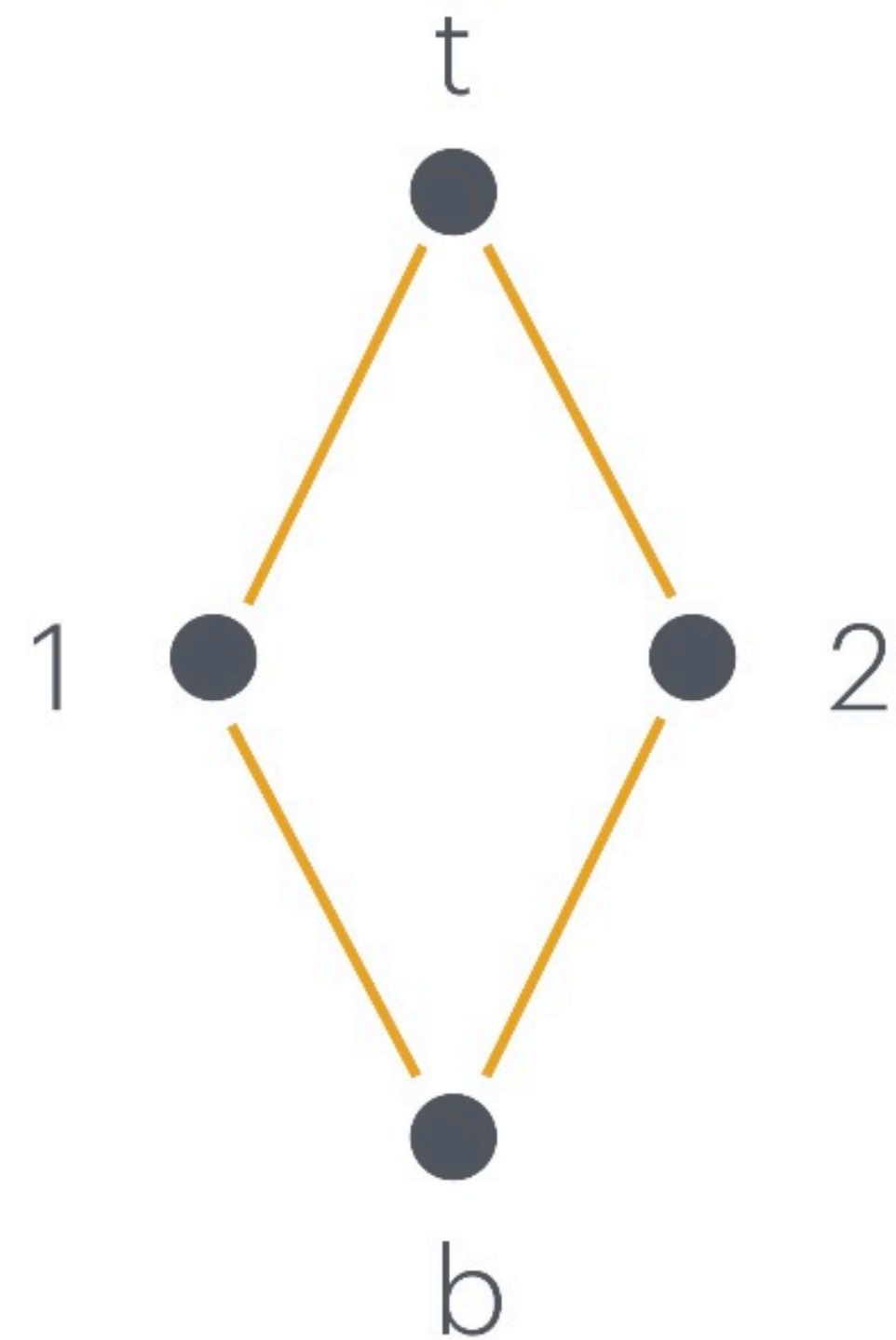
physical qubits

Hamming distance

$[[n, k, d]]$

logical qubits

Quantum Error Detection, e.g., $[[4,2,2]]$ code



$$\hat{X}_{L1} = \hat{X}\hat{X}\hat{I}\hat{I} \quad , \quad \hat{X}_{L2} = \hat{X}\hat{I}\hat{X}\hat{I}$$

$$\hat{Z}_{L1} = \hat{I}\hat{Z}\hat{I}\hat{Z} \quad , \quad \hat{Z}_{L2} = \hat{I}\hat{I}\hat{Z}\hat{Z} \quad ,$$

$$\hat{R}_{X_{Li}}(\theta) = e^{-i\frac{\theta}{2}\hat{X}_{Li}}$$

$$|0_L 0_L\rangle = \frac{1}{\sqrt{2}} [|0000\rangle + |1111\rangle] \quad , \quad |1_L 0_L\rangle = [|1100\rangle + |0011\rangle]$$

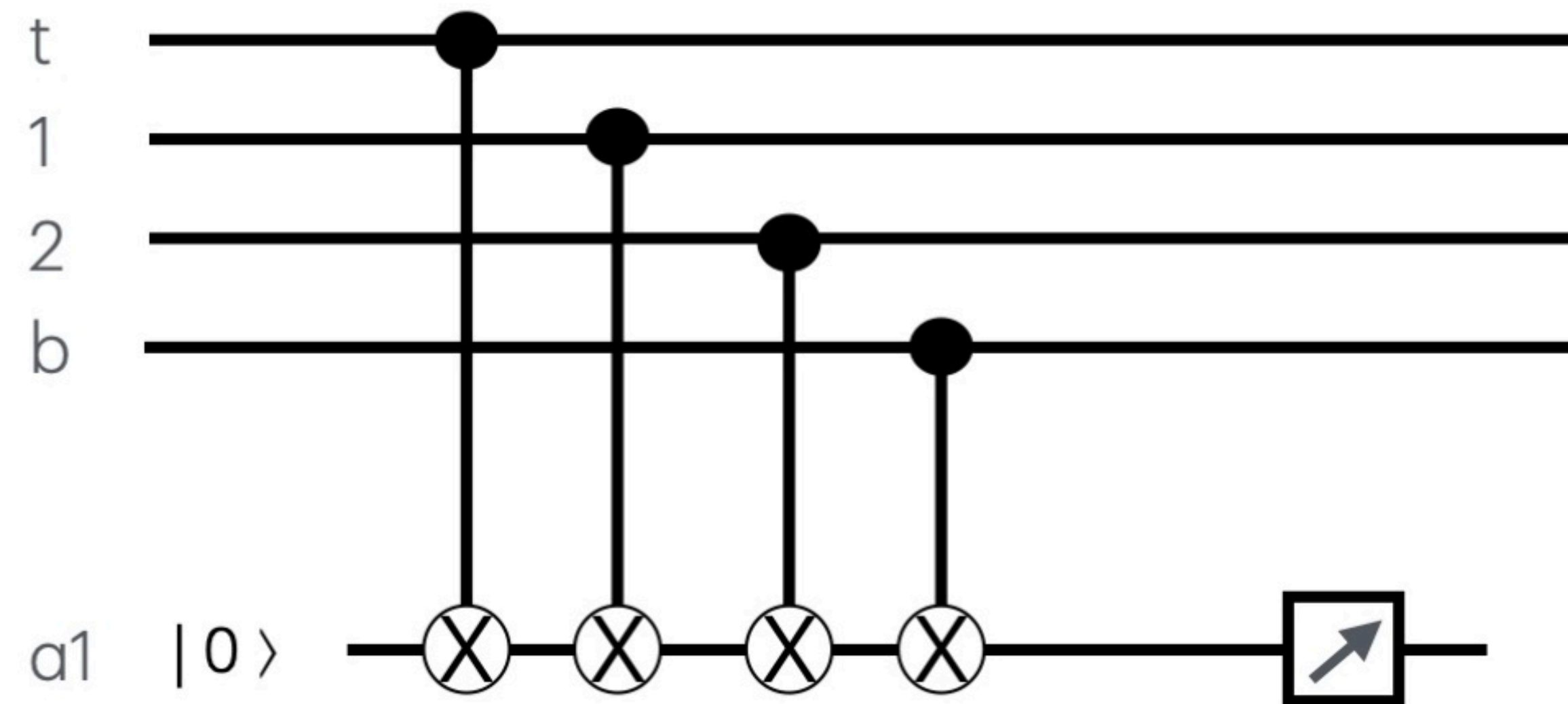
$$|0_L 1_L\rangle = \frac{1}{\sqrt{2}} [|1010\rangle + |0101\rangle] \quad , \quad |1_L 1_L\rangle = [|0110\rangle + |1001\rangle]$$

e.g., $[[4, 2, 2]]$: 4 physical, 2 logical, distance-2

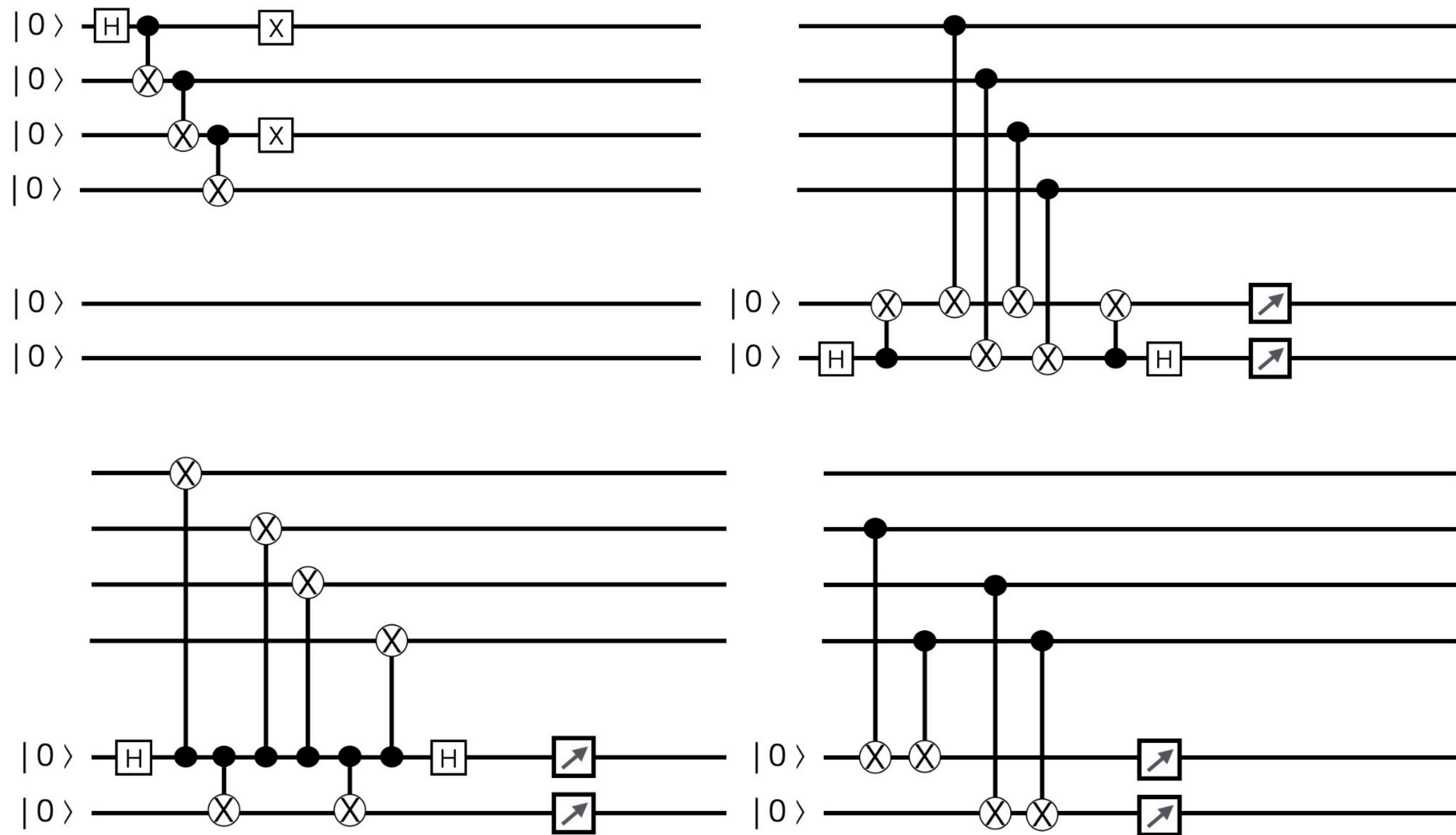
Quantum Error Detection, e.g., $[[4,2,2]]$ code

$$\hat{S}_z = \hat{Z}\hat{Z}\hat{Z}\hat{Z} \quad , \quad \hat{S}_x = \hat{X}\hat{X}\hat{X}\hat{X}$$

When acting on (all) codewords = +1



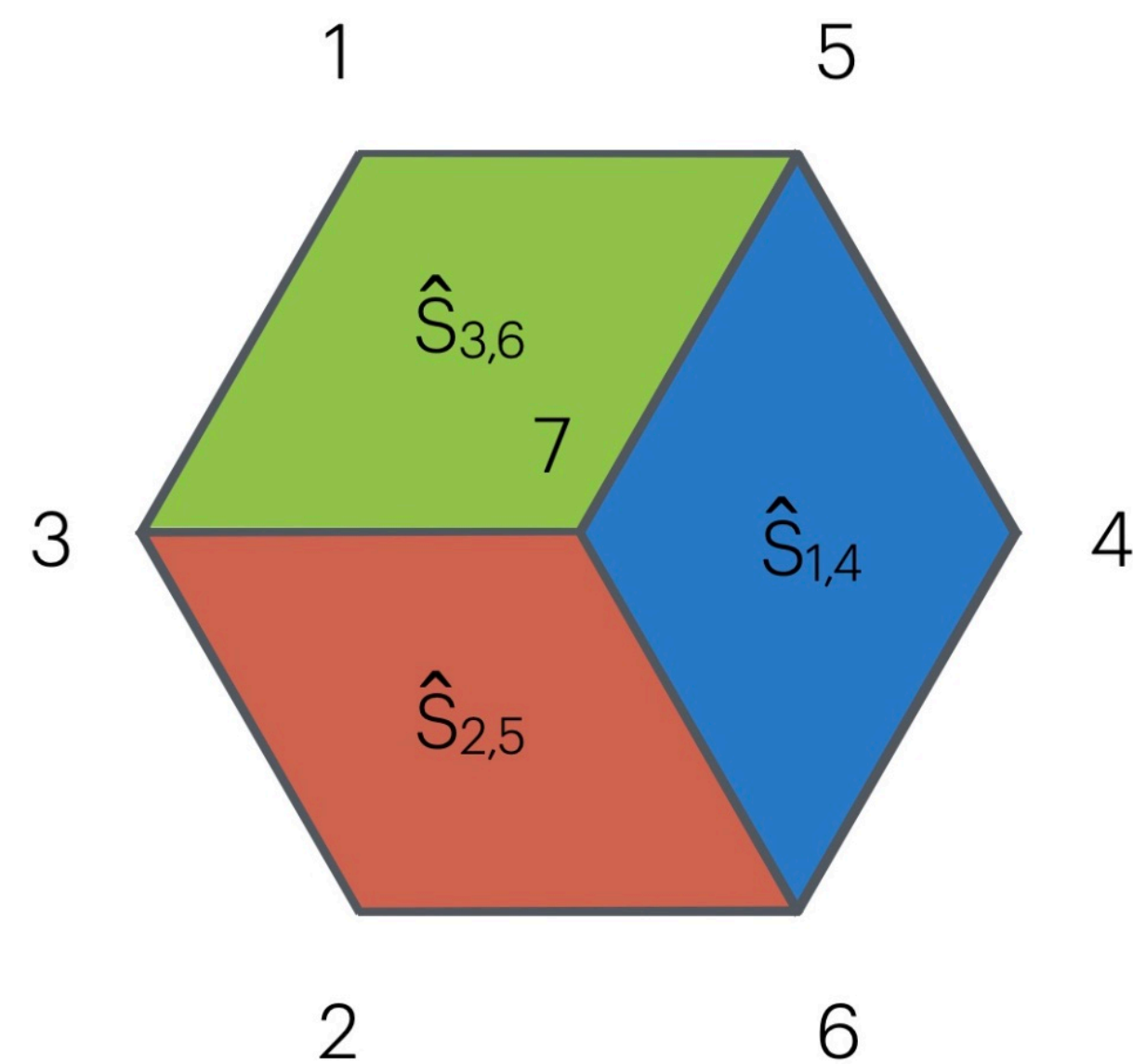
Quantum Error Detection, e.g., $[[4,2,2]]$ code



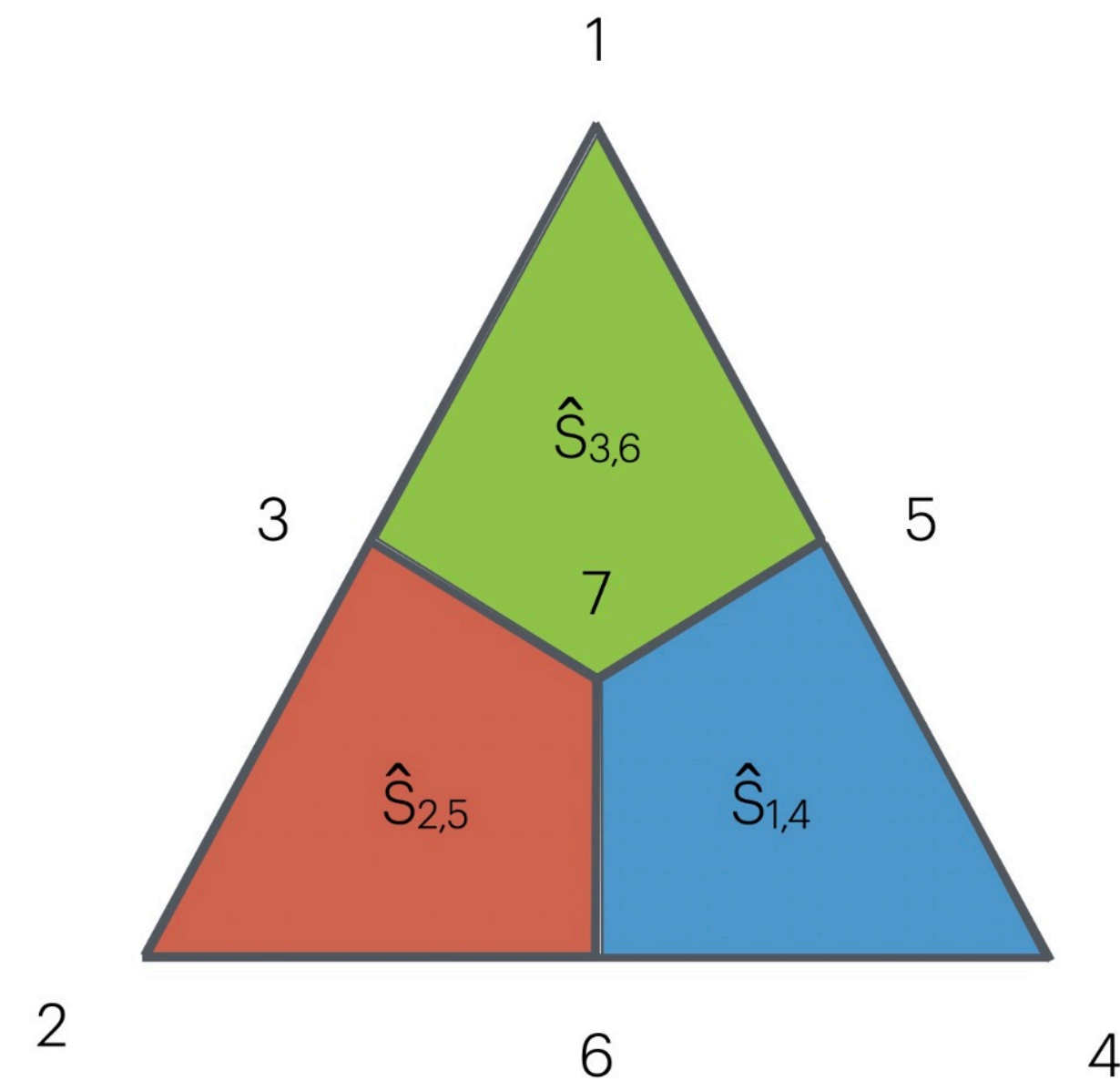
Measure the ancillary, reject states with detected faults

Quantum Error Correction, e.g., $[[7,1,3]]$ code

Quantum descendant of the (7,4,3) Hamming code



Calderbank-Shor-Steane code - CSS



$$\hat{X}_L = \hat{X}_1 \hat{X}_2 \hat{X}_3, \quad \hat{Z}_L = \hat{Z}_1 \hat{Z}_2 \hat{Z}_3$$

$$\hat{X}_L = \hat{X}^{\otimes 7}, \quad \hat{Z}_L = \hat{Z}_1 \hat{Z}_2 \hat{Z}_3$$

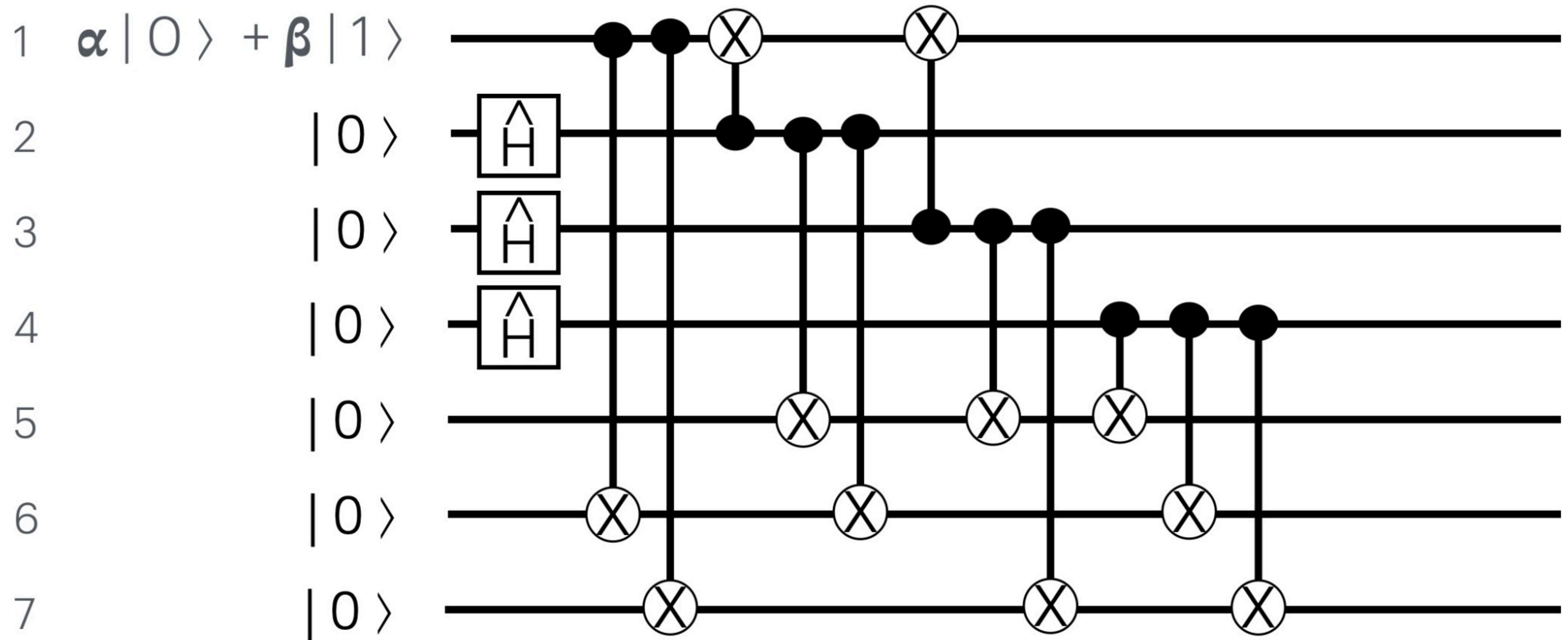
Quantum Error Correction, e.g., $[[7,1,3]]$ code

$$|0_L\rangle = \frac{1}{\sqrt{8}} [|0000000\rangle + |0001111\rangle + |0110011\rangle + |1010101\rangle \\ + |0111100\rangle + |1011010\rangle + |1100110\rangle + |1101001\rangle]$$

$$|1_L\rangle = \frac{1}{\sqrt{8}} [|1111111\rangle + |1110000\rangle + |1001100\rangle + |0101010\rangle \\ + |1000011\rangle + |0100101\rangle + |0011001\rangle + |0010110\rangle]$$

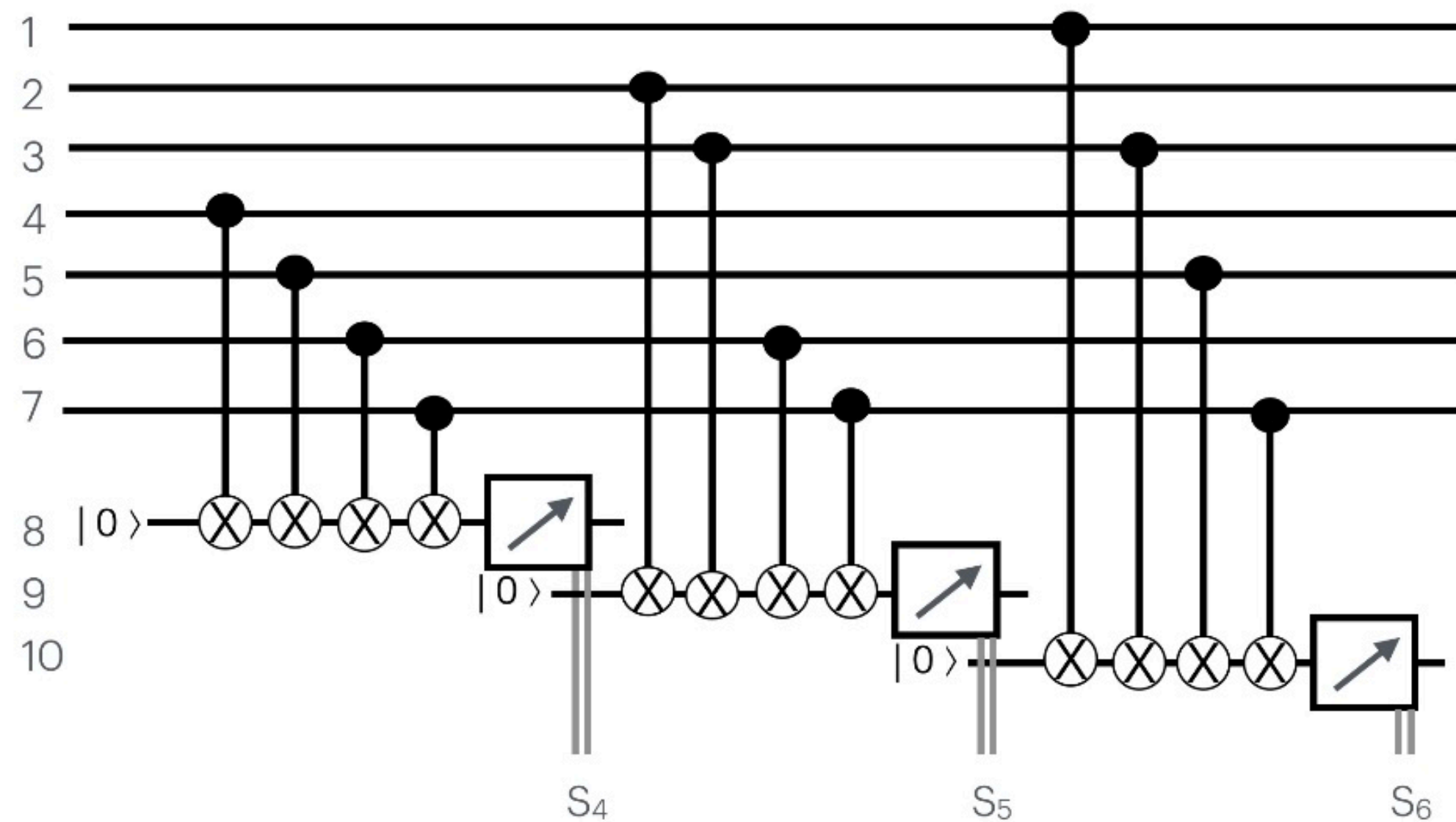
$$\hat{X}_L = \hat{X}_1 \hat{X}_2 \hat{X}_3 \ , \ \hat{Z}_L = \hat{Z}_1 \hat{Z}_2 \hat{Z}_3 \ .$$

Quantum Error Correction, e.g., $[[7,1,3]]$ code



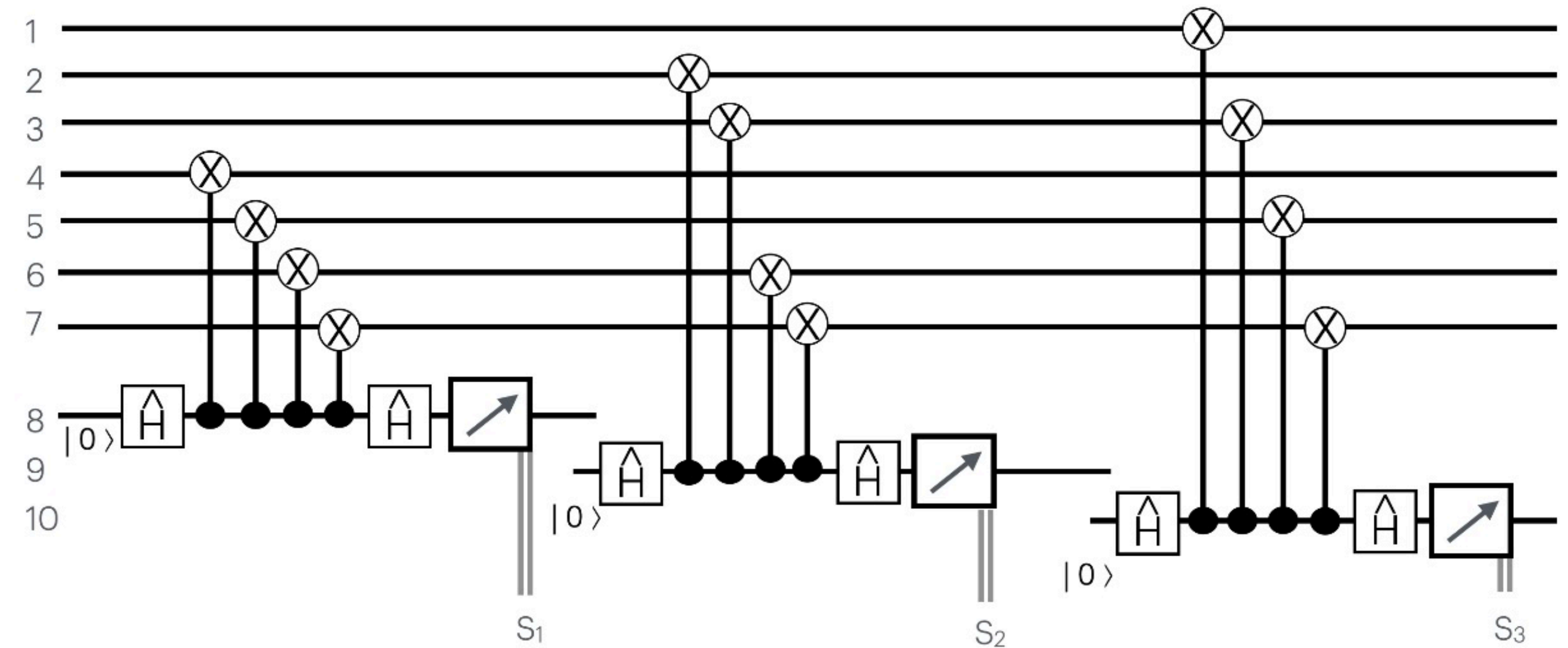
Quantum Error Correction, e.g., $[[7,1,3]]$ code

$$\begin{aligned}\hat{s}_1 &= \hat{I}^{\otimes 3} \hat{X}^{\otimes 4}, \hat{s}_2 = \hat{I} \hat{X} \hat{X} \hat{I} \hat{I} \hat{X} \hat{X}, \hat{s}_3 = \hat{X} \hat{I} \hat{X} \hat{I} \hat{X} \hat{I} \hat{X} \\ \hat{s}_4 &= \hat{I}^{\otimes 3} \hat{Z}^{\otimes 4}, \hat{s}_5 = \hat{I} \hat{Z} \hat{Z} \hat{I} \hat{I} \hat{Z} \hat{Z}, \hat{s}_6 = \hat{Z} \hat{I} \hat{Z} \hat{I} \hat{Z} \hat{I} \hat{Z},\end{aligned}$$



(S4, S5, S6)

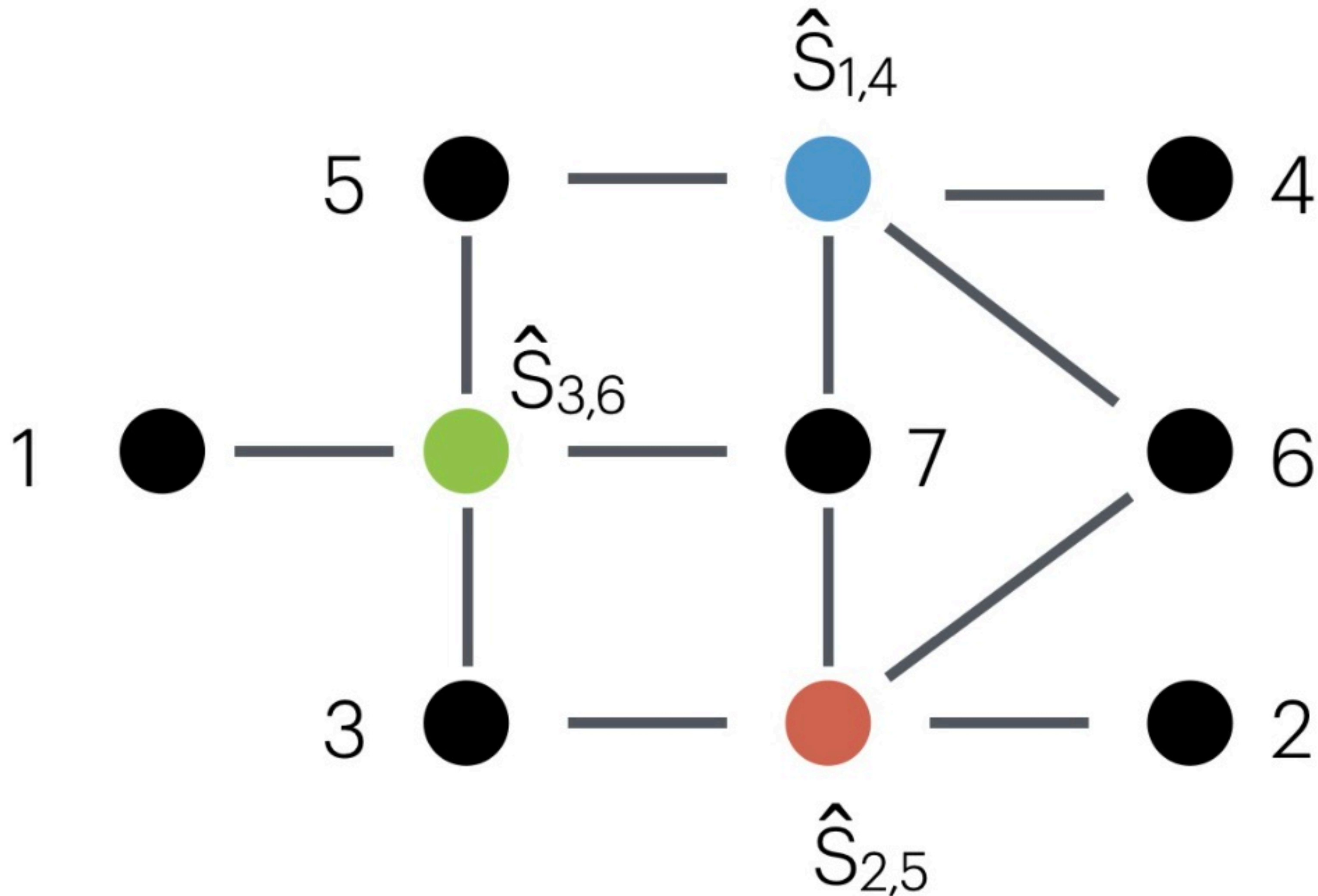
Binary location of error



(S1, S2, S3)

Quantum Error Correction, e.g., $[[7,1,3]]$ code

Qubit layout on a grid



Quantum Error Correction, e.g., [[7,1,3]] code

Is the gate set transversal?

$$\hat{H}_L |\psi_L\rangle = \alpha \frac{1}{\sqrt{2}} (|0_L\rangle + |1_L\rangle) + \beta \frac{1}{\sqrt{2}} (|0_L\rangle - |1_L\rangle) = \hat{H}^{\otimes 7} |\psi_L\rangle$$

$$\hat{H}_L = \hat{H}^{\otimes 7}, \quad \hat{S}_L = (\hat{S}^*)^{\otimes 7}, \quad \text{CNOT}_L^{(12)} = \left[\text{CNOT}^{(12)} \right]^{\otimes 7}$$

T-gate is not transversal

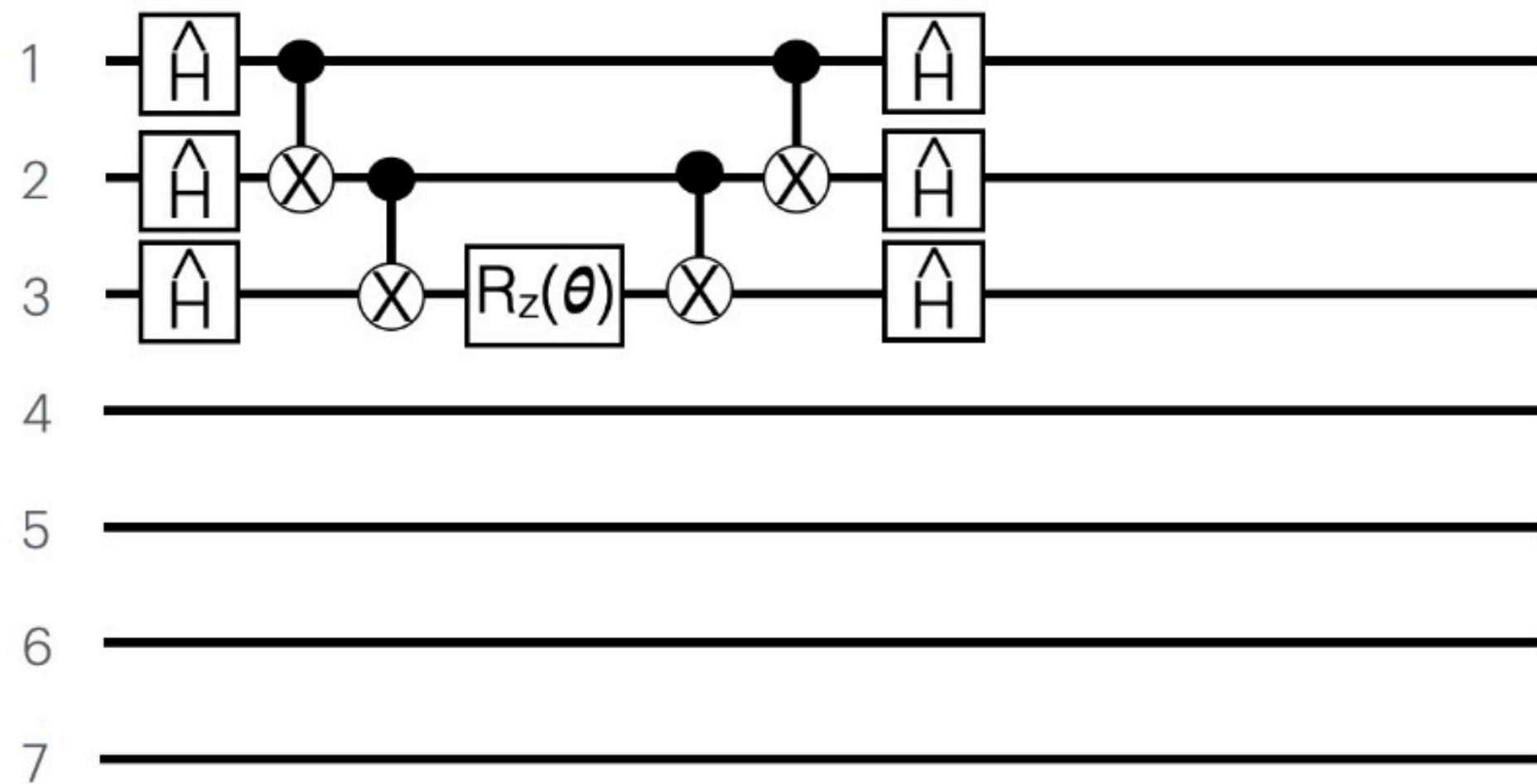
$$\begin{aligned} |0_L\rangle &= \frac{1}{\sqrt{8}} [|0000000\rangle + |0001111\rangle + |0110011\rangle + |1010101\rangle \\ &\quad + |0111100\rangle + |1011010\rangle + |1100110\rangle + |1101001\rangle] \\ &= \frac{1}{\sqrt{8}} \left| \frac{7}{2}, +\frac{7}{2} \right\rangle + \sqrt{\frac{7}{40}} \left| \frac{7}{2}, -\frac{1}{2} \right\rangle + \sqrt{\frac{7}{10}} \left| \frac{3}{2}, -\frac{1}{2} \right\rangle; \text{Fano} \rangle \\ |1_L\rangle &= \frac{1}{\sqrt{8}} [|1111111\rangle + |1110000\rangle + |1001100\rangle + |0101010\rangle \\ &\quad + |1000011\rangle + |0100101\rangle + |0011001\rangle + |0010110\rangle] \\ &= \frac{1}{\sqrt{8}} \left| \frac{7}{2}, -\frac{7}{2} \right\rangle + \sqrt{\frac{7}{40}} \left| \frac{7}{2}, +\frac{1}{2} \right\rangle + \sqrt{\frac{7}{10}} \left| \frac{3}{2}, +\frac{1}{2} \right\rangle; \text{Lines} \rangle, \end{aligned}$$

Quantum Error Correction, e.g., $[[7,1,3]]$ code

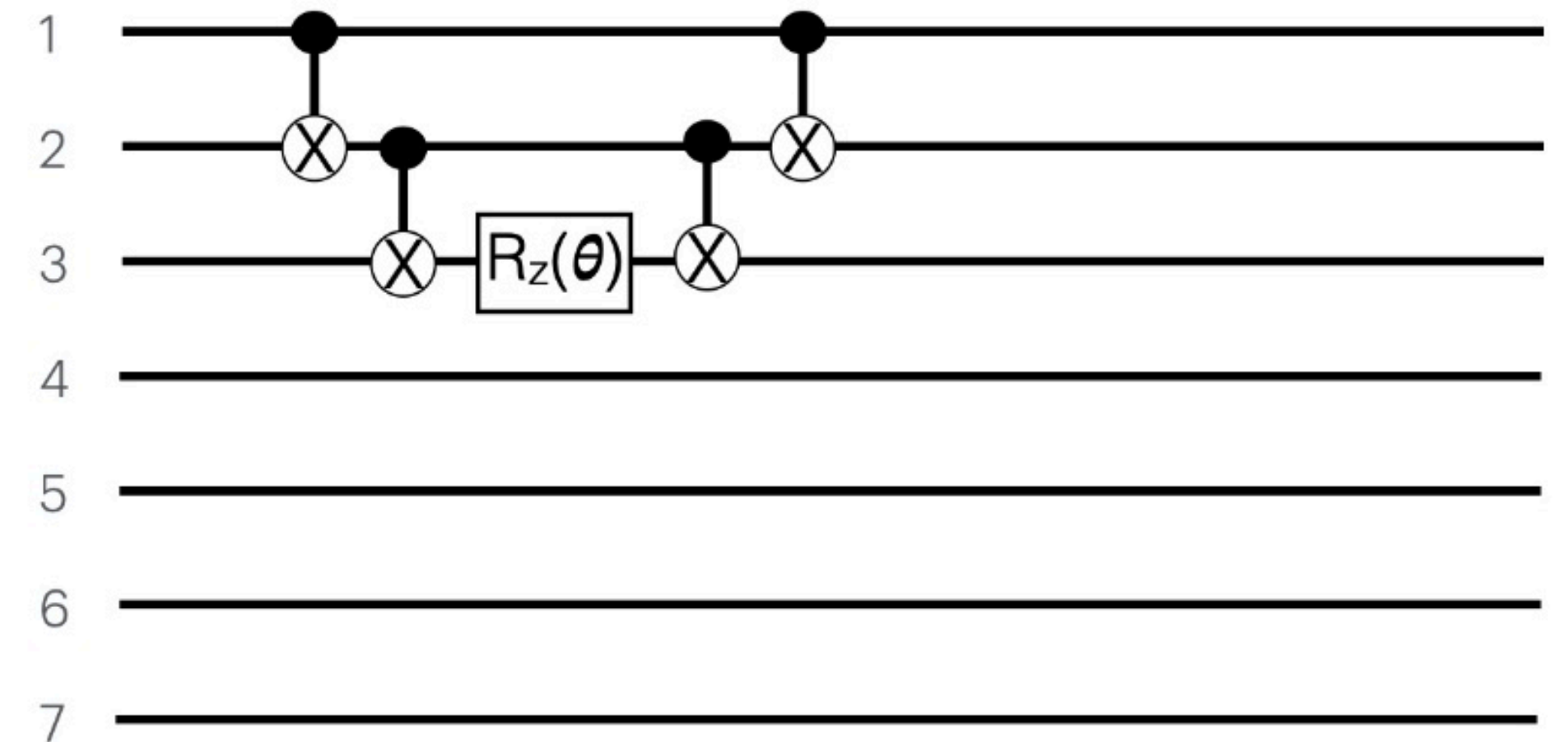
$$R_{X_L}(\theta) = e^{-i\frac{\theta}{2}\hat{X}_L} = e^{-i\frac{\theta}{2}\hat{X}_1\hat{X}_2\hat{X}_3}$$

$$R_{Z_L}(\theta) = e^{-i\frac{\theta}{2}\hat{Z}_L} = e^{-i\frac{\theta}{2}\hat{Z}_1\hat{Z}_2\hat{Z}_3},$$

$R_{XL}(\theta)$



$R_{zL}(\theta)$



Non-fault-tolerant circuitry within the code block

Error Correction in Gauge Theories

Abelian $\mathbb{Z}_n$ 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

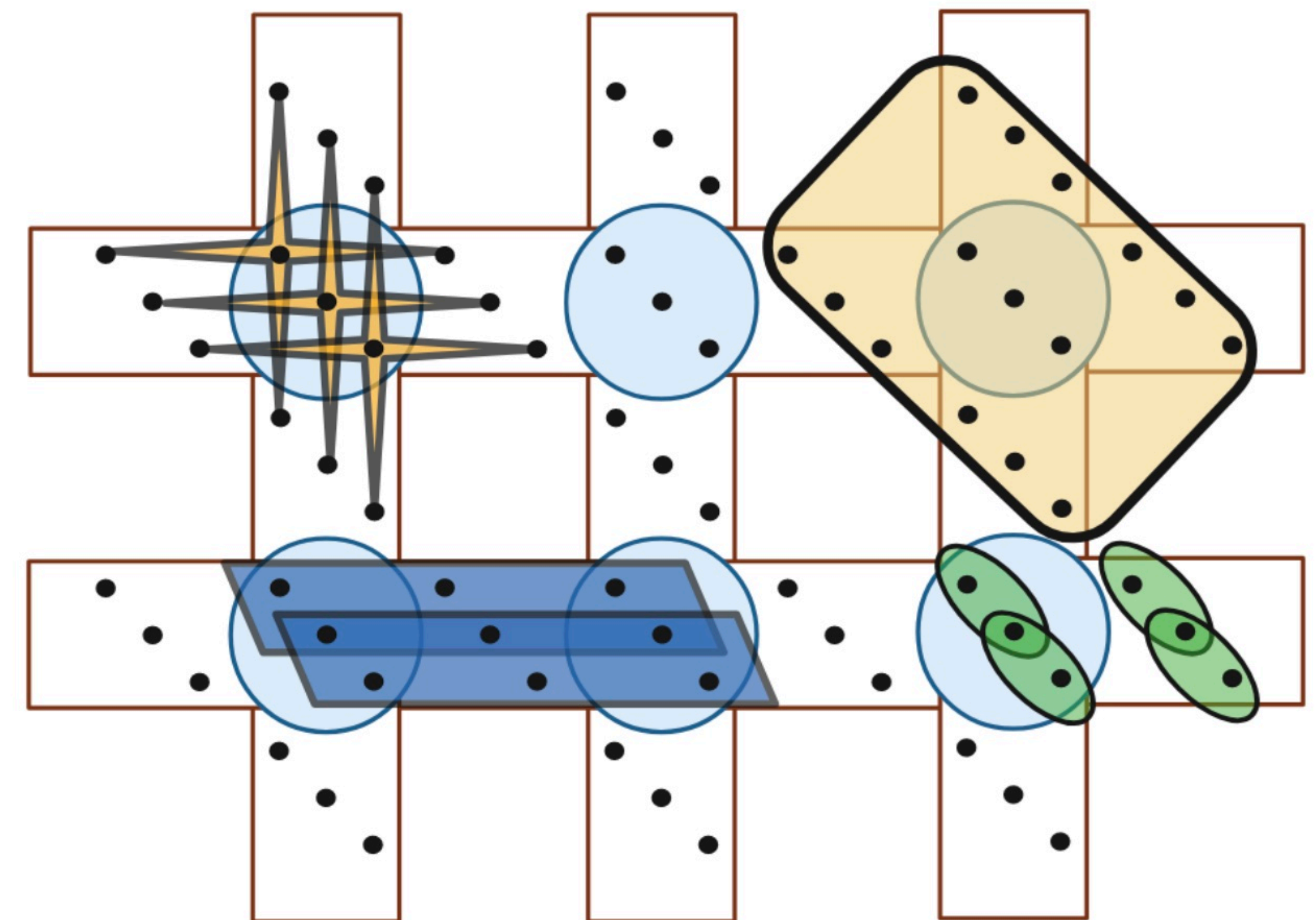
Luca Spagnoli* and Alessandro Roggero†

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INFN-TIFPA Trento Institute of Fundamental Physics and Applications, Trento, Italy*

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(Dated: October 7, 2024)

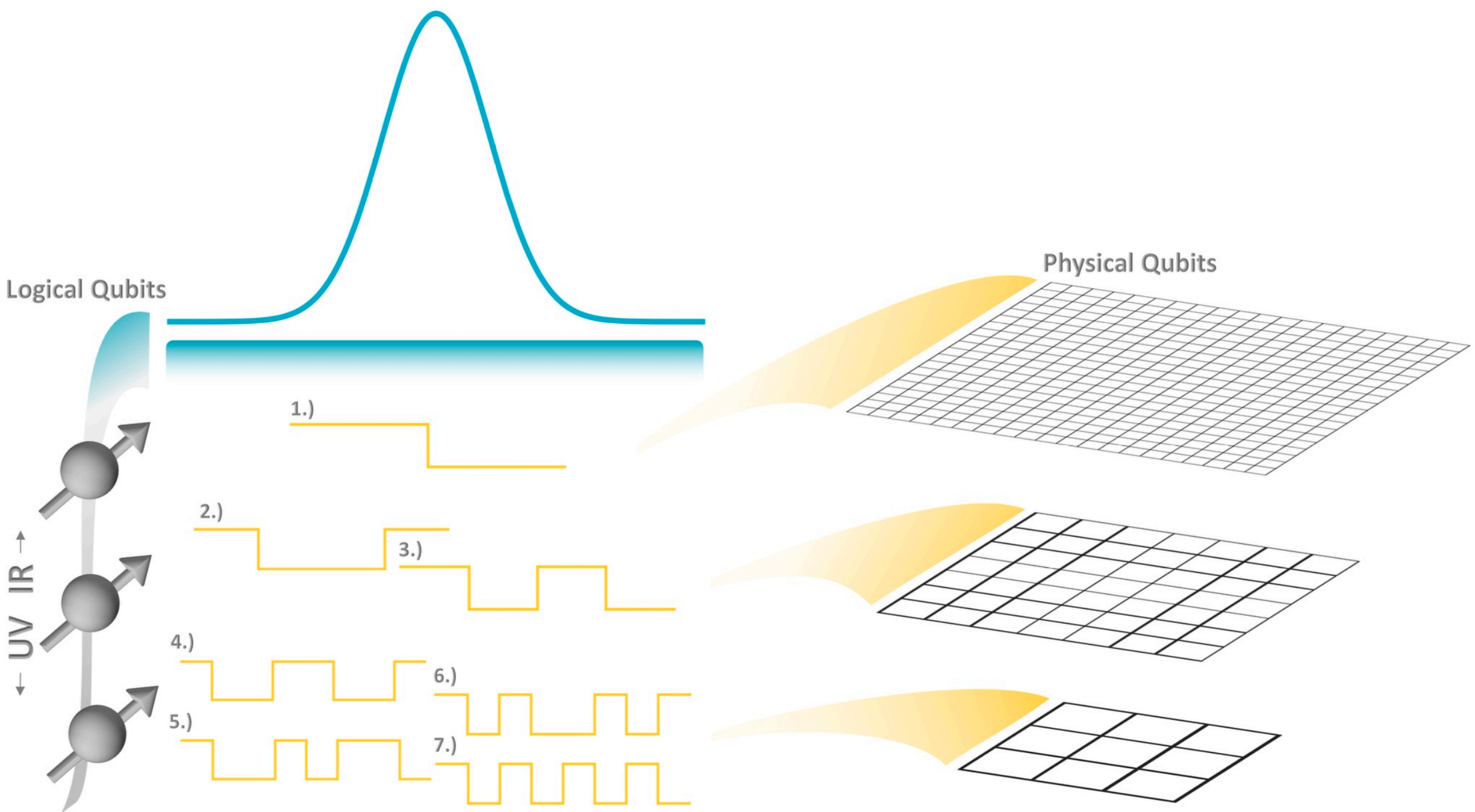


Gauss's law



Stabilizers

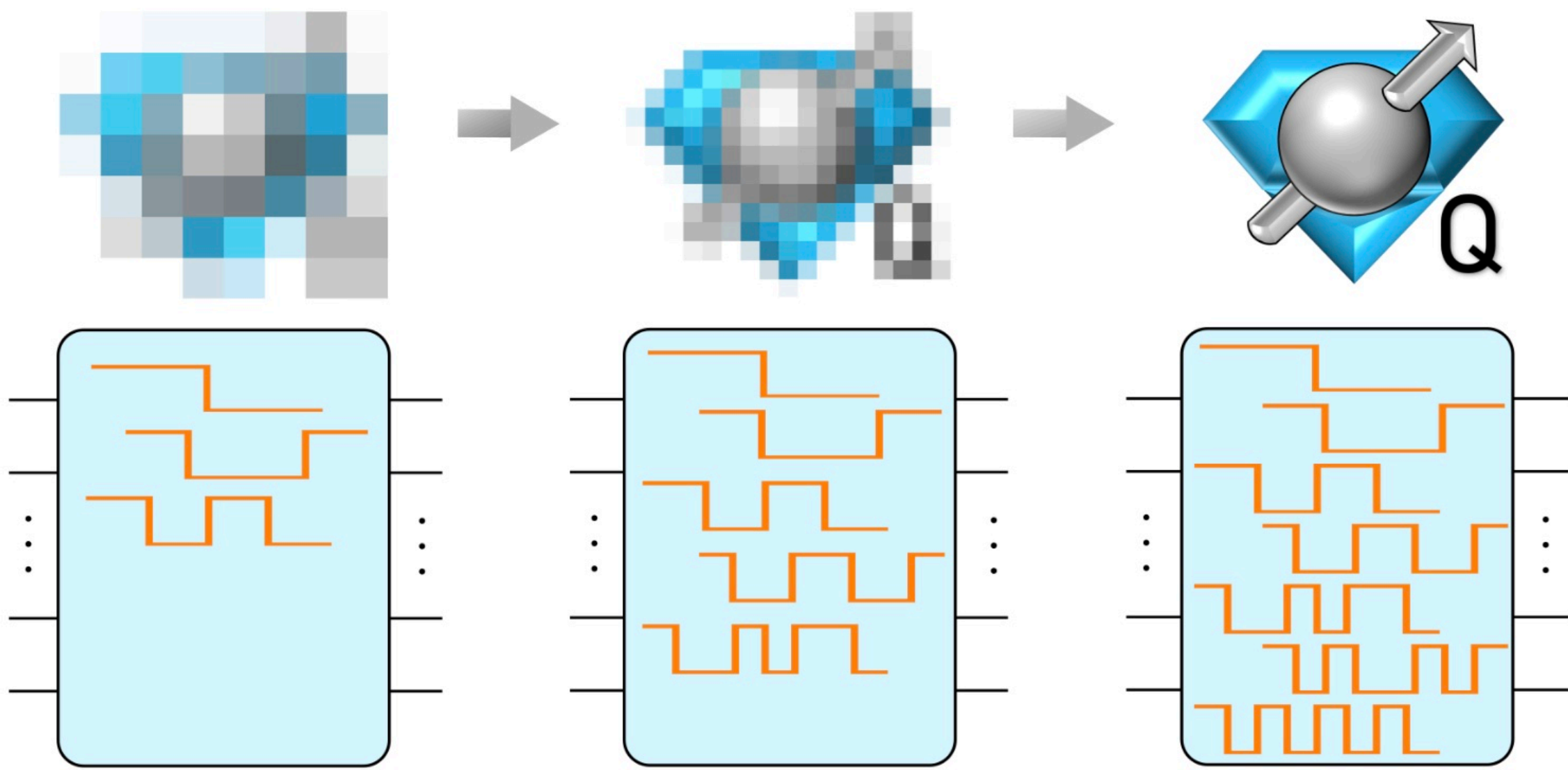
From NISQ to Fault Tolerant Physics Aware Sequency Hierarchies



UV versus IR qubits

Hierarchical qubit maps and hierarchically implemented quantum error correction

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

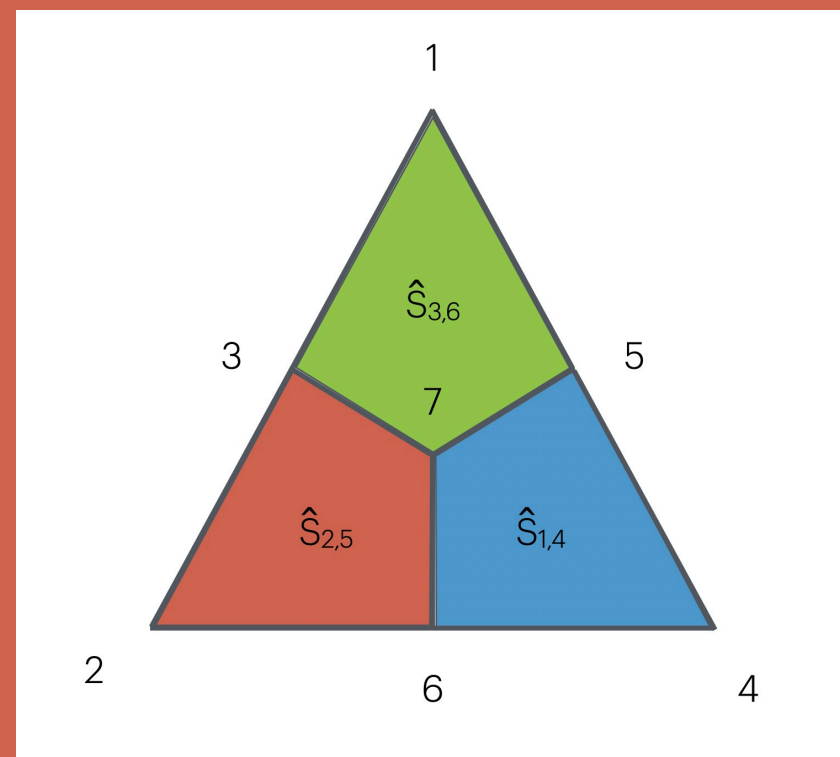


Sequency Hierarchy Truncation (SeqHT) for Adiabatic State Preparation and Time Evolution in Quantum Simulations

Zhiyao Li ,* Dorota M. Grabowska ,† and Martin J. Savage

Part-4

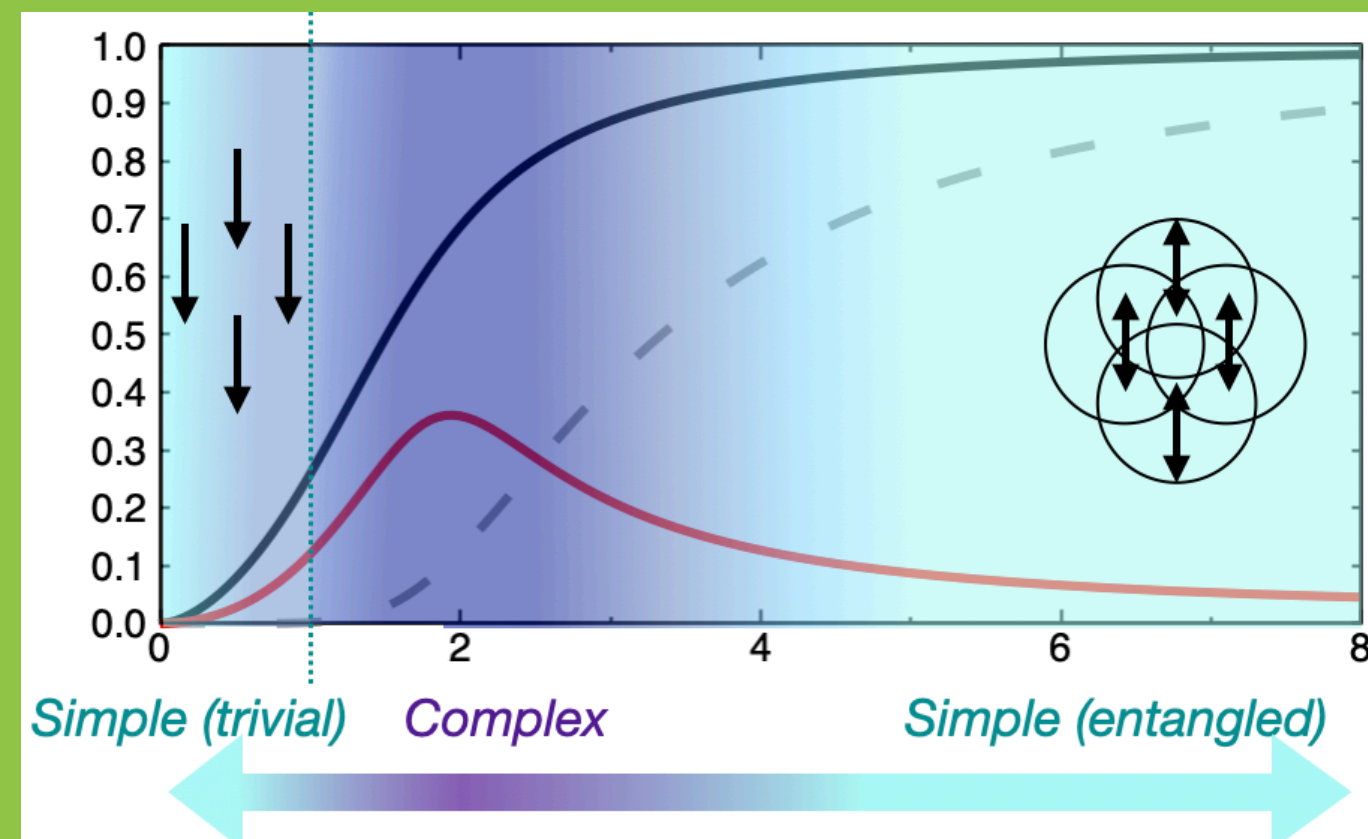
Beyond NISQ: FaultTolerance and Error Correction



- Fault Tolerance and Error Correction is essential for quantum computers to be able to perform useful tasks
- Quantum information is stabilized against environment by classical measurements and feedback
- Integration into physics simulations is now being explored

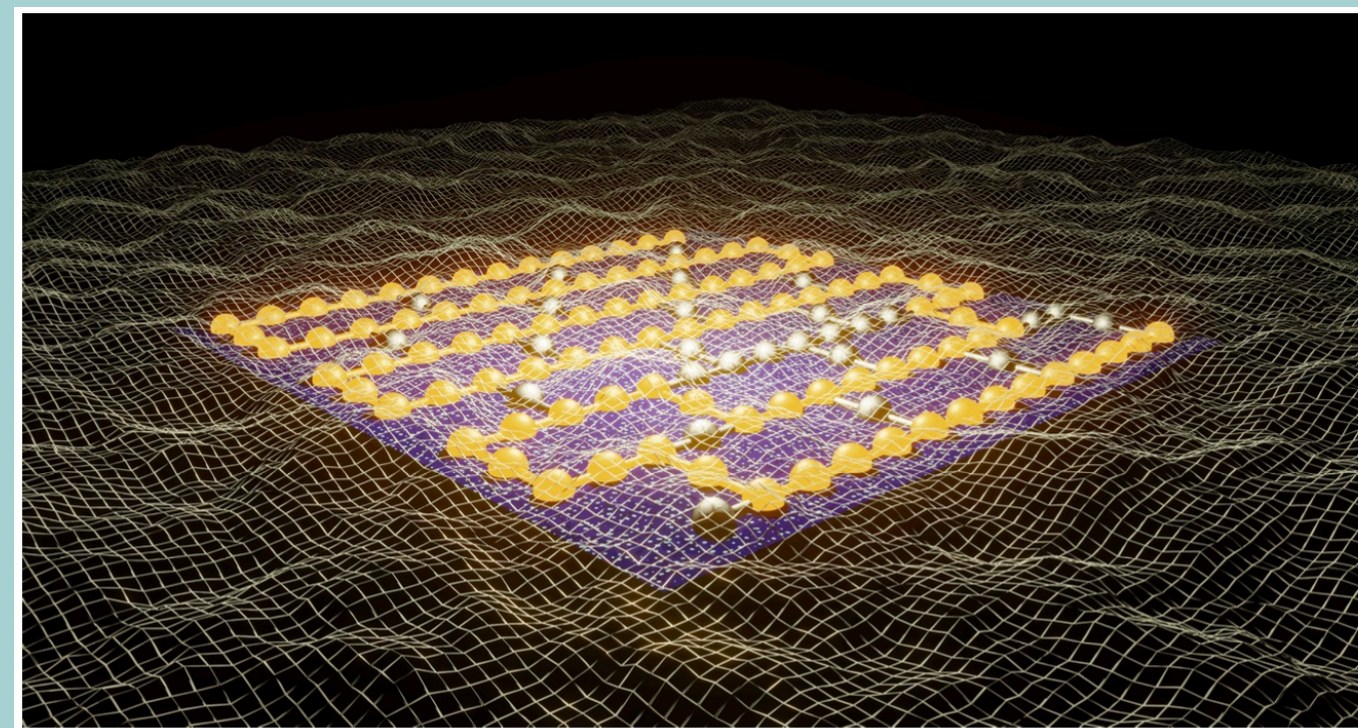
Part-2

Quantum Complexity



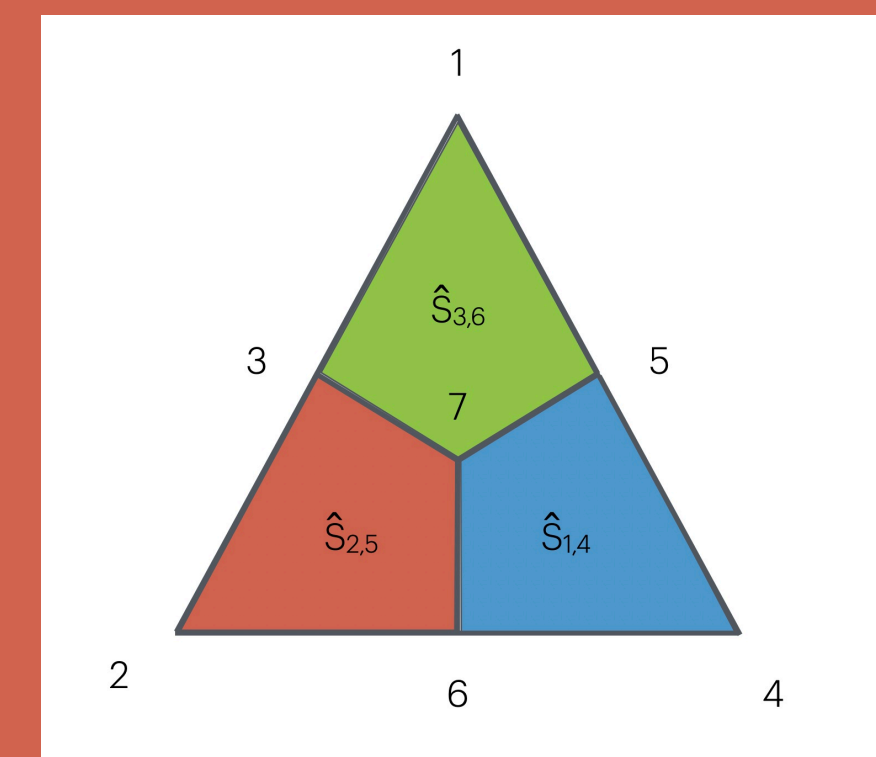
Part-3

Quantum Computing and Simulation



Part-4

Beyond NISQ: FaultTolerance and Error Correction



Quantum information science and quantum computing:

- providing new insights into quantum many-body systems
- changing how we work with quantum many-body systems
- moving toward providing predictions for fundamental physics that cannot be obtained with classical computing alone
- most effective when integrated with AI

Quantum Information and Quantum Computing for Fundamental Physics



National Nuclear Physics Summer School 2026

Seattle, WA

June 29 - July 11, 2026

Martin Savage
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