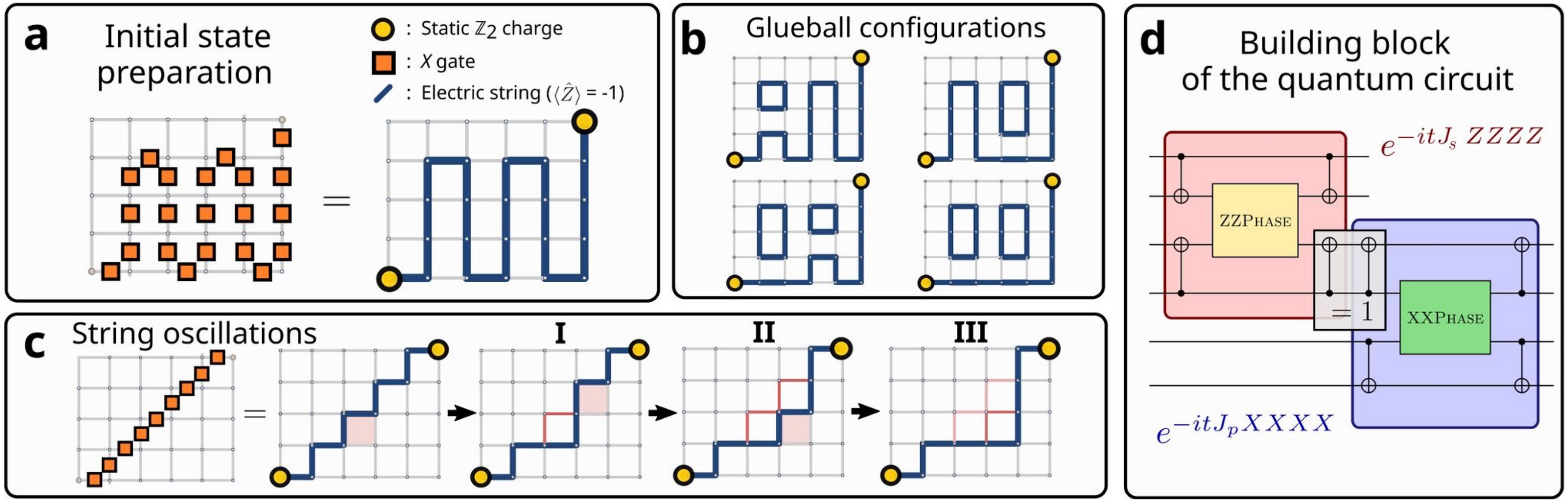
Quantum simulation of $2+1$D $\mathbb{Z}_2$ and U(1) Lattice Gauge Theories on Trapped-Ion Quantum Computers

Jad C. Halimeh



Previous quantum simulation experiments in 1 + 1D

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Observation of gauge invariance in a 71-site Bose–Hubbard quantum simulator

Bing Yang, Hui Sun, Robert Ott, Han-Yi Wang, Torsten V. Zache, Jad C. Halimeh, Zhen-Sheng
Philipp Hauke & Jian-Wei Pan

Nature **587**, 392–396 (2020) | Cite this article

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REPORT | QUANTUM SIMULATION

Thermalization dynamics of a gauge theory on a
tum simulator

ZHAO-YU ZHOU, GUO-XIAN SU, JAD C. HALIMEH, ROBERT OTT, HUI SUN, PHILIPP HAUKE, BING YANG, ZHEN-SHENG YUAN,
AND JIAN-WEI PAN Authors Info & Affiliations

SCIENCE • 14 Jul 2022 • Vol 377, Issue 6603 • pp. 311-314 • DOI: 10.1126/science.abl6277

nature physics

Article https://doi.org/10.1038/s41567-024-02702-x

Observation of microscopic confinement dynamics by a tunable topological θ-angle

Received: 29 March 2024

Accepted: 8 October 2024

Published online: 20 December 2024

Wei-Yong Zhang[1,11], Ying Liu[1,11], Yanting Cheng[2,11], Ming-Gen He[1], Han-Yi Wang[1], Tian-Yi Wang[1], Zi-Hang Zhu[1], Guo-Xian Su[1], Zhao-Yu Zhou[1], Yong-Guang Zheng[1], Hui Sun[1], Bing Yang[3], Philipp Hauke[4,5], Wei Zheng[1,6,7], Jad C. Halimeh[8,9,10] ✉, Zhen-Sheng Yuan[1,6,7] ✉ & Jian-Wei Pan[1,6,7] ✉

nature physics

Article https://doi.org/10.1038/s41567-024-02723-6

Confinement in a $\mathbb{Z}_2$ lattice gauge theory on a quantum computer

Received: 5 May 2022

Accepted: 30 October 2024

Julius Mildenberger[1,2] ✉, Wojciech Mruczkiewicz[3], Jad C. Halimeh[1,4,5], Zhang Jiang[3] & Philipp Hauke[1,2] ✉

Confinement

nature physics

Article

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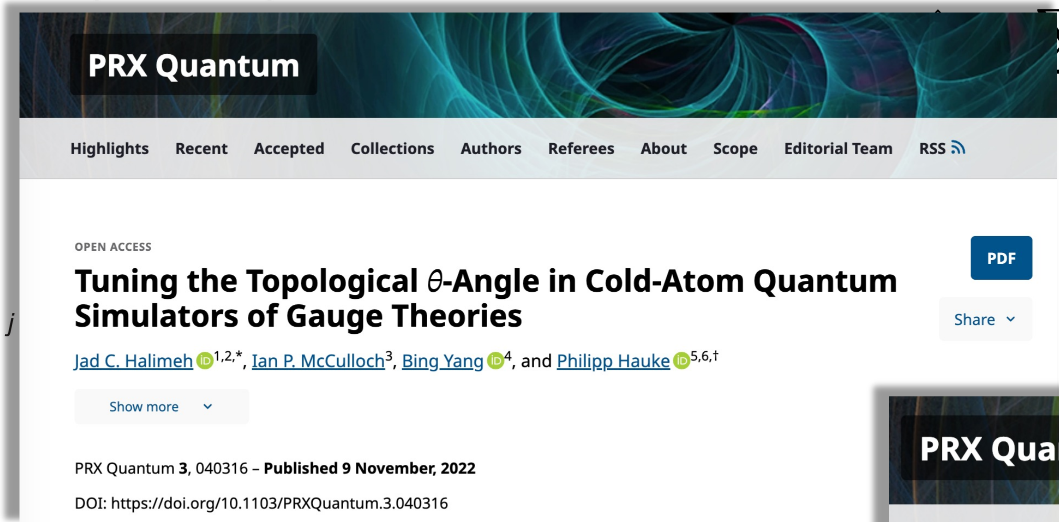
The topological θ-angle is central to several gauge theories in condensed-matter and high-energy physics. For example, it is responsible for the strong CP problem in quantum chromodynamics and can emerge in effective theories of electrodynamics in topological insulators. Although analogue quantum simulators potentially offer a venue for realizing and controlling the θ-angle, doing so has hitherto remained an outstanding

Confinement

Experimental implemetation

$$\sum_\ell \left[\frac{\kappa}{2}\left(\hat\sigma^+_\ell \hat S^+_{\ell,\ell+1}\hat\sigma^-_{\ell+1} + \text{H.c.}\right) + \frac{m}{2}(-1)^\ell \hat\sigma^z_\ell + \chi \hat S^z_{\ell,\ell+1}\right]$$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Tuning the Topological θ-Angle in Cold-Atom Quantum Simulators of Gauge Theories

Jad C. Halimeh[1,2,*], Ian P. McCulloch[3], Bing Yang[4], and Philipp Hauke[5,6,†]

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PRX Quantum **3**, 040316 – **Published 9 November, 2022**

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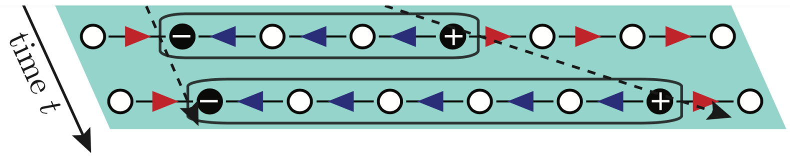
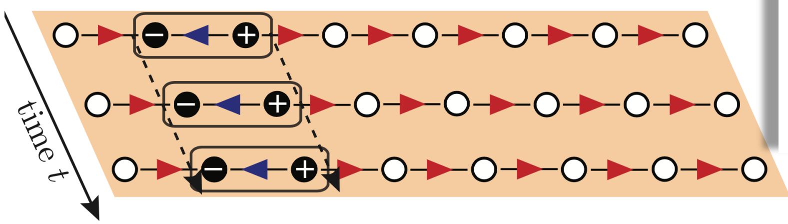
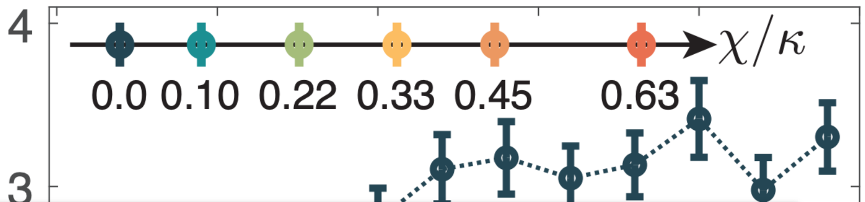


Confined $(\chi > 0)$



Experimental results

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Tunable Confinement-Deconfinement Transition in an Ultracold-Atom Quantum Simulator

Yanting Cheng[1], Shang Liu[2], Wei Zheng[3,4], Pengfei Zhang[5], and Hui Zhai[6,*]

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DOI: https://doi.org/10.1103/PRXQuantum.3.040317

JCH *et al.*, PRX Quantum **3**, 040316 (2022)
Zhang *et al.* (JCH), Nature Physics **21**, 155-160 (2025)

Microscopic collision dynamics on a quantum simulator


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Cold-Atom Particle Collider

Guo-Xian Su[1,2,*,‡], Jesse J. Osborne[3,‡], and Jad C. Halimeh[4,5,6,7,†]

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PRX Quantum **5**, 040310 – **Published 22 October, 2024**

DOI: https://doi.org/10.1103/PRXQuantum.5.040310

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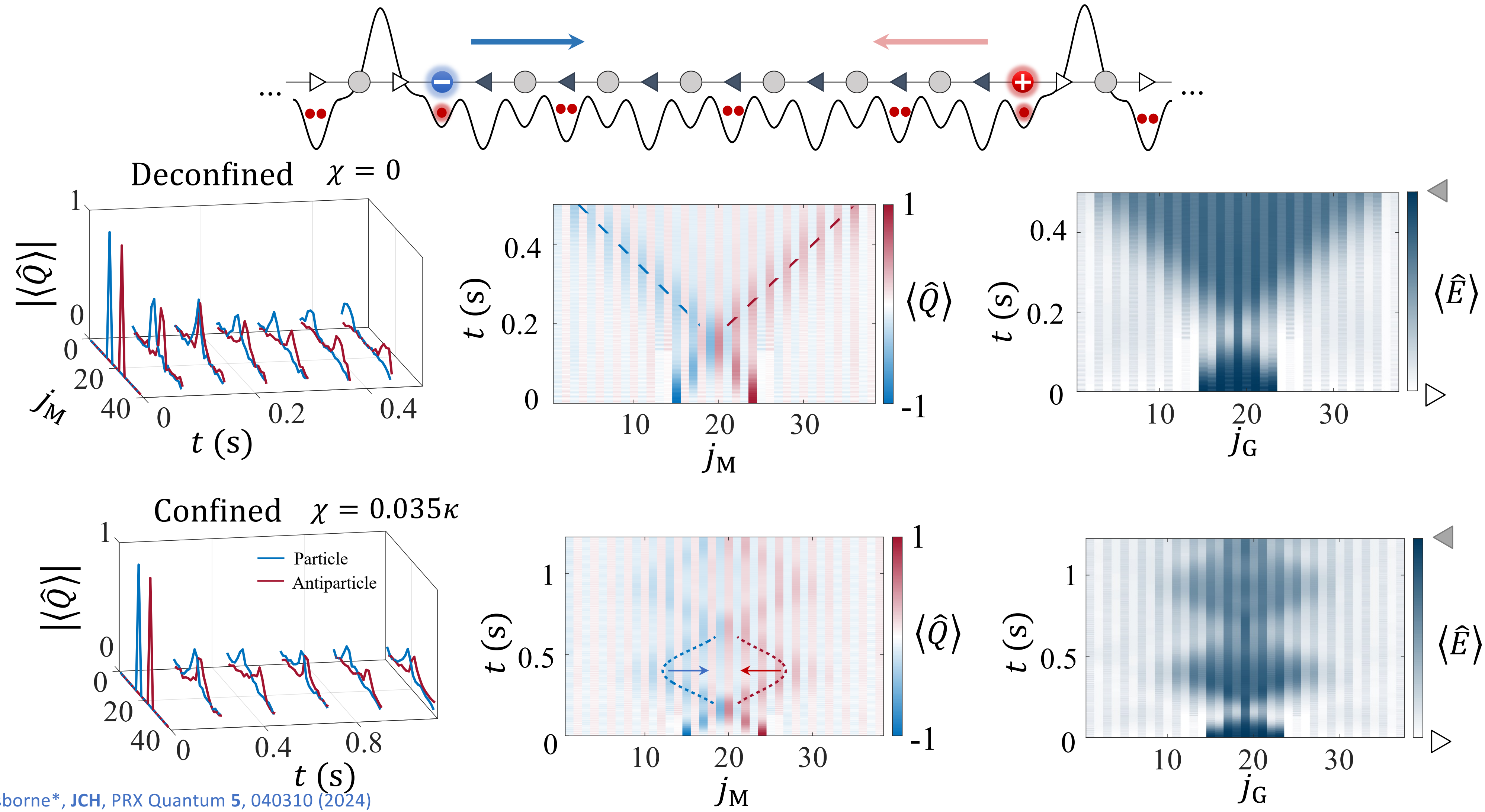
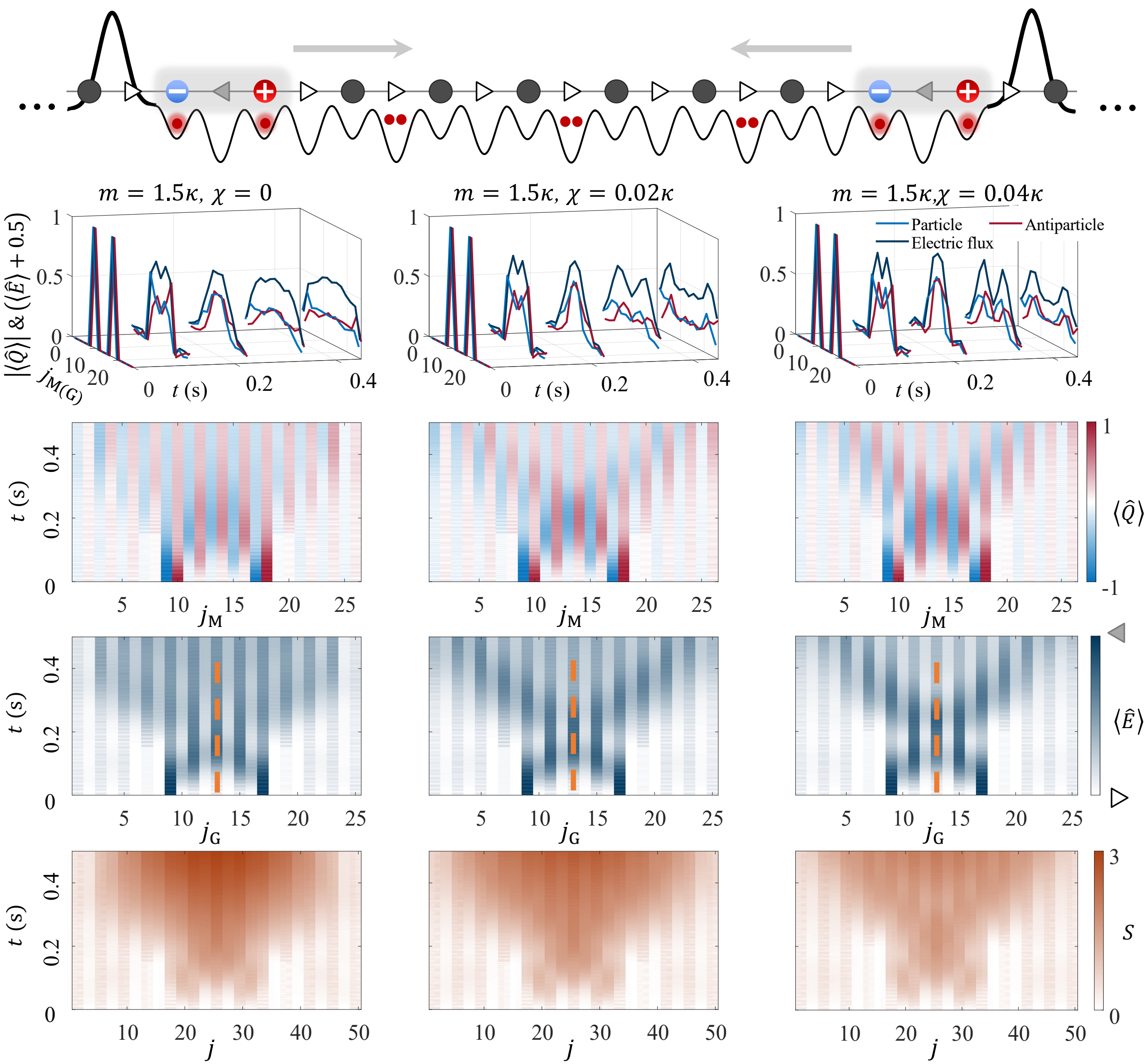
$$\hat{H}_0 = \sum_{\ell}\left[\frac{\kappa}{2}\left(\hat{\sigma}^{+}_{\ell}\hat{S}^{+}_{\ell,\ell+1}\hat{\sigma}^{-}_{\ell+1} + \text{H.c.}\right) + \frac{m}{2}(-1)^{\ell}\hat{\sigma}^{z}_{\ell} + \chi\hat{S}^{z}_{\ell,\ell+1}\right]$$

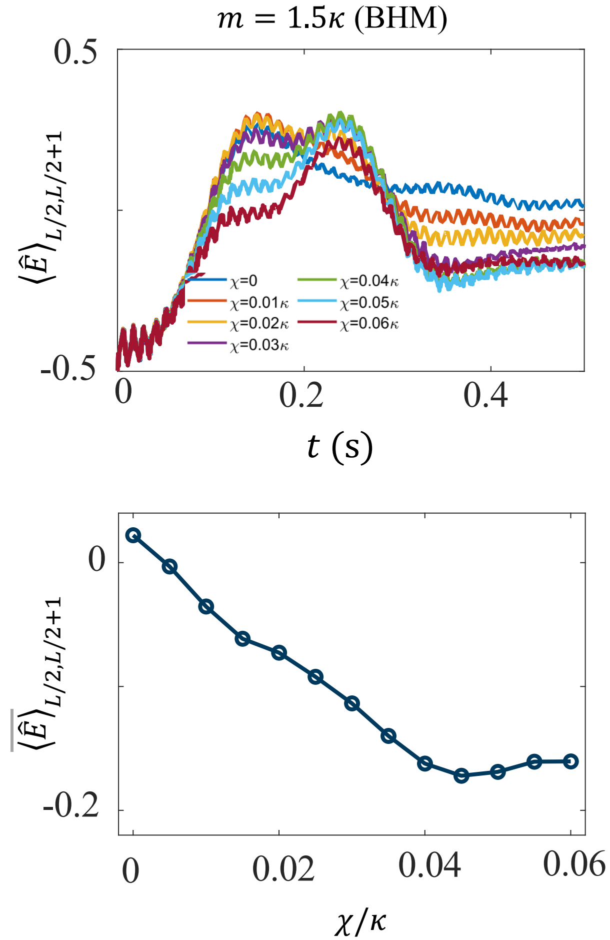
Su*, Osborne*, **JCH**, PRX Quantum **5**, 040310 (2024)

Microscopic collision dynamics on a quantum simulator



Su*, Osborne*, **JCH**, PRX Quantum **5**, 040310 (2024)



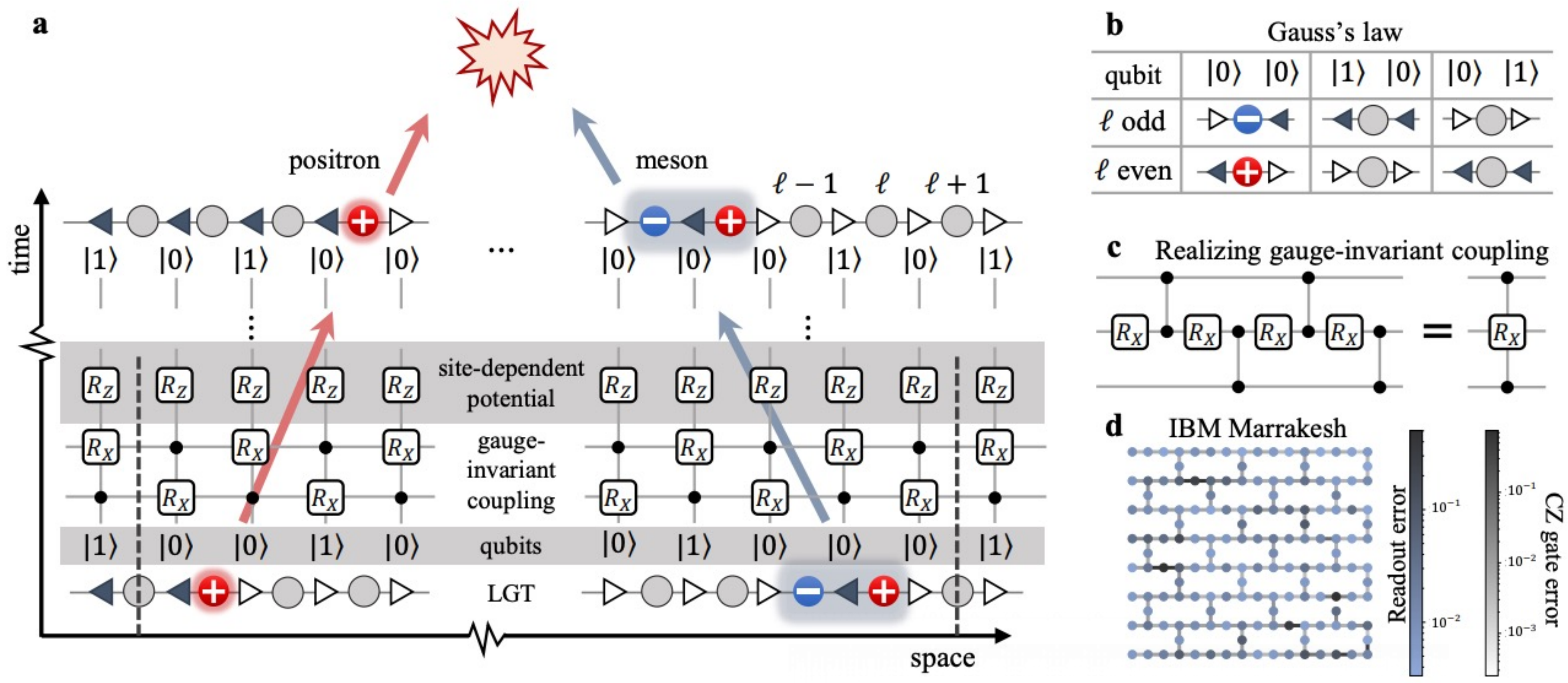


Su*, Osborne*, **JCH**, PRX Quantum **5**, 040310 (2024)

Experimental observation of scattering dynamics in an LGT

Observation of hadron scattering in a lattice gauge theory on a quantum computer

Julian Schuhmacher[1,2] Guo-Xian Su[3] Jesse J. Osborne[4,5]
Anthony Gandon[1,6] Jad C. Halimeh[4,7,5,*] and Ivano Tavernelli[1,†]

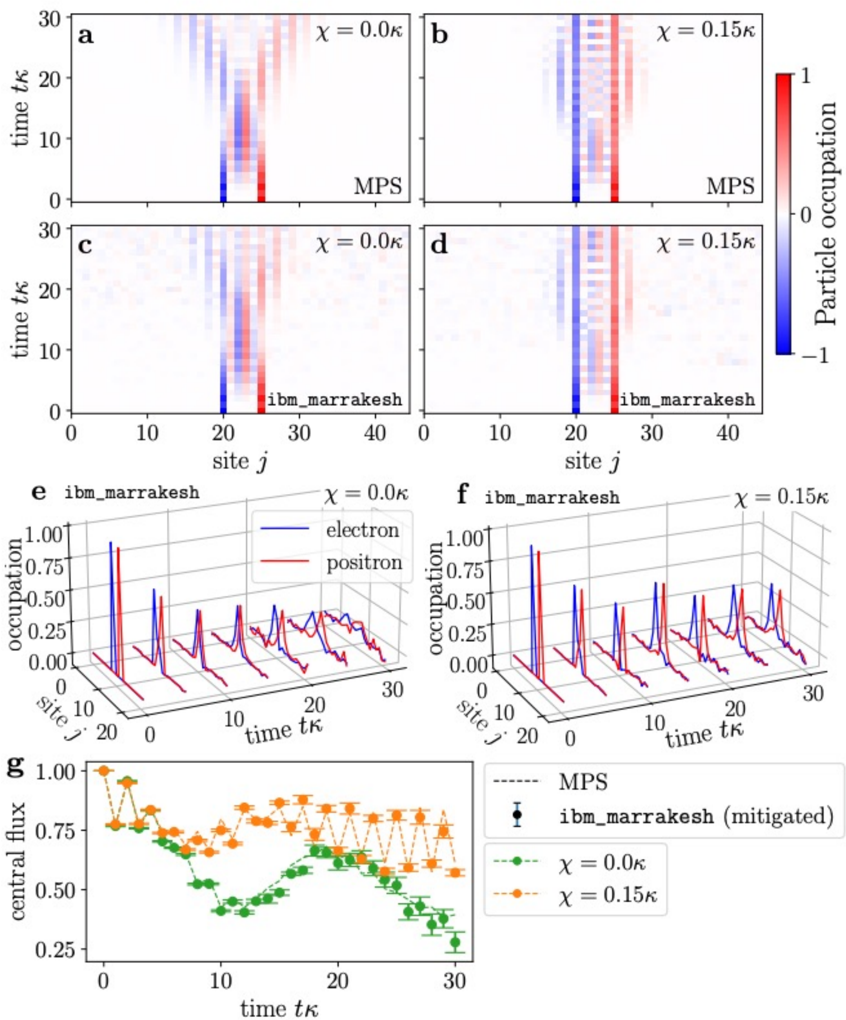


Schuhmacher, Su, Osborne, Gandon, **JCH**, Tavernelli, arXiv:2505.20387

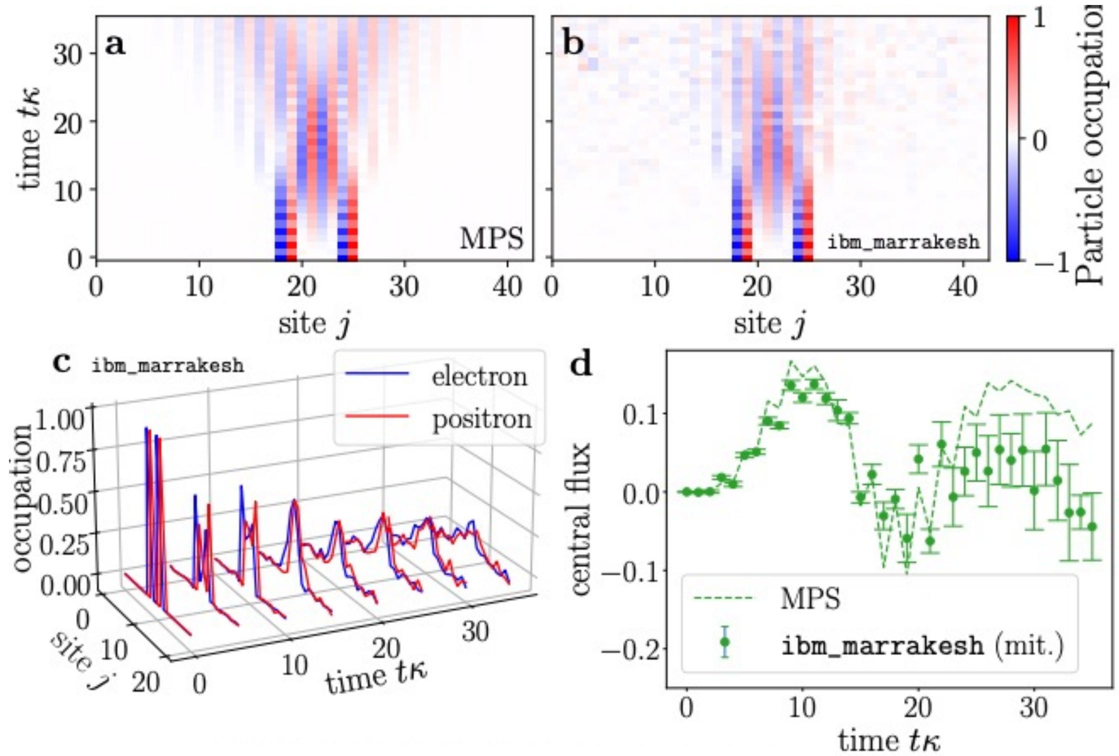
IBM **Quantum**

Experimental observation of scattering dynamics in an LGT

Electron-positron scattering



Meson-meson scattering



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Schuhmacher, Su, Osborne, Gandon, **JCH**, Tavernelli, arXiv:2505.20387

Theory proposal for $2 + 1$D LGT in cold atoms

communications physics — Article

A Nature Portfolio journal

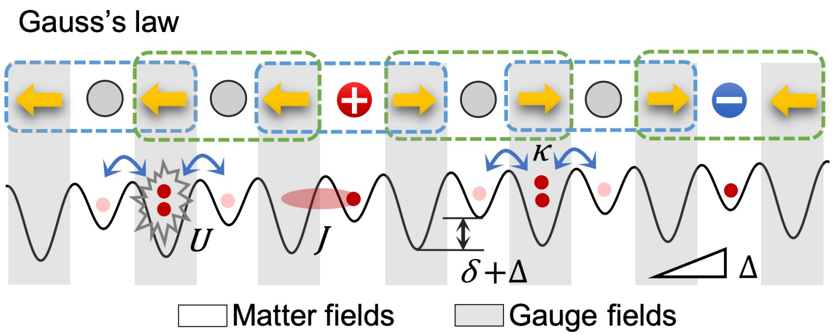
https://doi.org/10.1038/s42005-025-02144-8

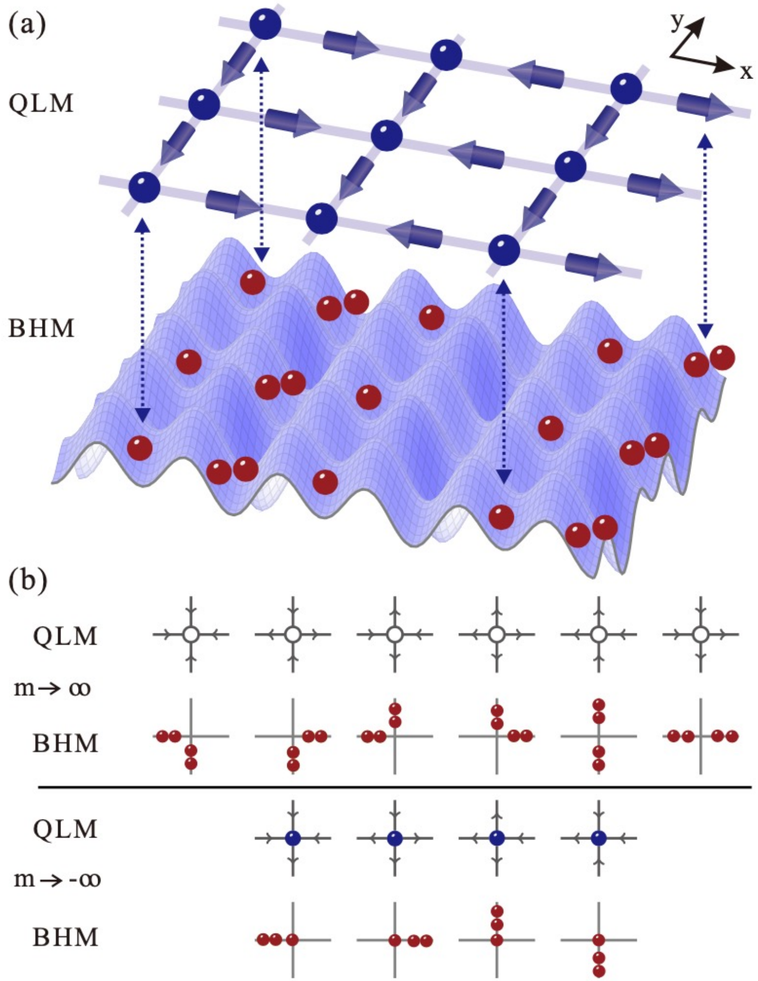
Large-scale $2 + 1$D U(1) gauge theory with dynamical matter in a cold-atom quantum simulator

Check for updates

Jesse J. Osborne[1,2,3], Ian P. McCulloch[1], Bing Yang[4], Philipp Hauke[5,6] & Jad C. Halimeh[2,3,7]

$$\hat{H}_{\mathrm{BHM}} = \sum_{\mathbf{j}} \Big[J \sum_{\nu=x,y} \Big(\hat{b}_{\mathbf{j}}^{\dagger} \hat{b}_{\mathbf{j}+\mathbf{e}_{\nu}} + \mathrm{H.c.} \Big) + \frac{U_{\mathbf{j}}}{2} \hat{n}_{\mathbf{j}} \Big(\hat{n}_{\mathbf{j}} - 1 \Big) + \Big(\boldsymbol{\gamma}^{\top} \mathbf{j} - \delta_{\mathbf{j}} - \eta_{\mathbf{j}} \Big) \hat{n}_{\mathbf{j}} \Big]$$





Osborne, McCulloch, Yang, Hauke, **JCH**, Commun. Phys. **8**, 273 (2025)

Confinement on a digital quantum computer

nature physics

Article https://doi.org/10.1038/s41567-024-02723-6

Confinement in a $\mathbb{Z}_2$ lattice gauge theory on a quantum computer

Received: 5 May 2022

Accepted: 30 October 2024

Published online: 13 January 2025

Check for updates

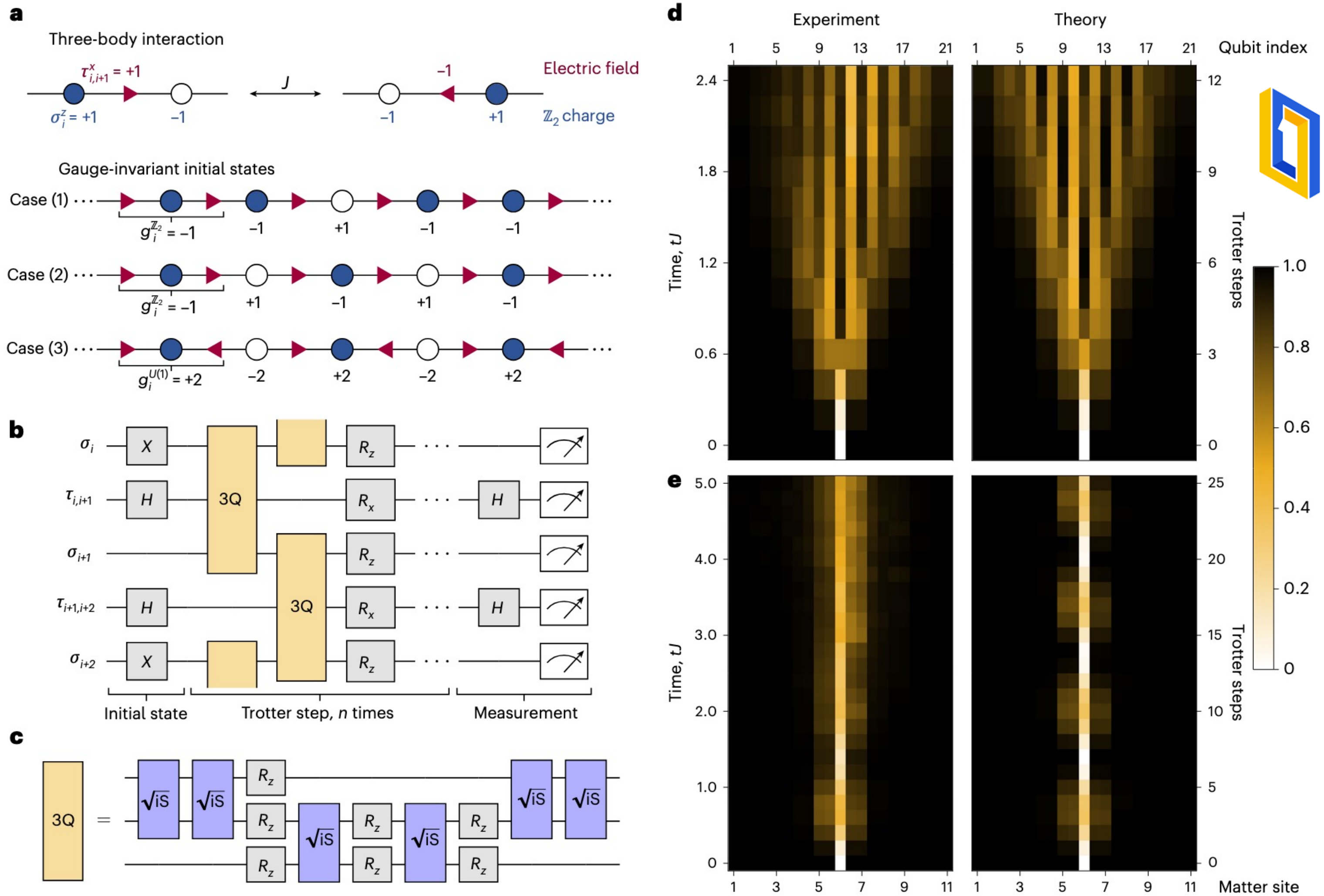
Julius Mildenberger [1,2] ✉, Wojciech Mruczkiewicz [3], Jad C. Halimeh [1,4,5], Zhang Jiang [3] & Philipp Hauke [1,2] ✉

Gauge theories describe the fundamental forces in the standard model of particle physics and play an important role in condensed-matter physics. The constituents of gauge theories, for example, charged matter and electric gauge field, are governed by local gauge constraints, which lead to key phenomena such as the confinement of particles that are not fully understood. In this context, quantum simulators may address questions that are challenging for classical methods. Although engineering gauge constraints is highly demanding, recent advances in quantum computing are beginning to enable digital quantum simulations of gauge theories. Here

Google Quantum AI

Mildenberger *et al.* (**JCH**), Nature Physics **2025**

$\mathbb{Z}_2$ lattice gauge theories: confinement



Google Quantum AI

Mildenberger *et al.* (**JCH**), Nature Physics **2025**

Experimental observation of (non)thermal dynamics in a 2 + 1D LGT

Observation of disorder-free localization using a (2+1)D lattice gauge theory on a quantum processor

Google Quantum AI and Collaborators †

Disorder-induced phenomena in quantum … ystems pose significant challenges for analytical methods and numerical simulati… e and system scales. To reduce the cost of disorder-sampling, we investigate … ed in states tunable to superpositions over all disorder configurations. … lattice gauge theory (LGT), these states can be interpreted as a s… s. We observe localization in this LGT in the absence of disorder i… erturbations fail to diffuse despite fully disorder-free evolution and in… nyi entropy measurements reveal that superposition-prepared states fundam… hose obtained by direct disorder sampling. Leveraging superposition, we propose a… ith a polynomial speedup in sampling disorder configurations, a longstanding challenge … -body localization studies.

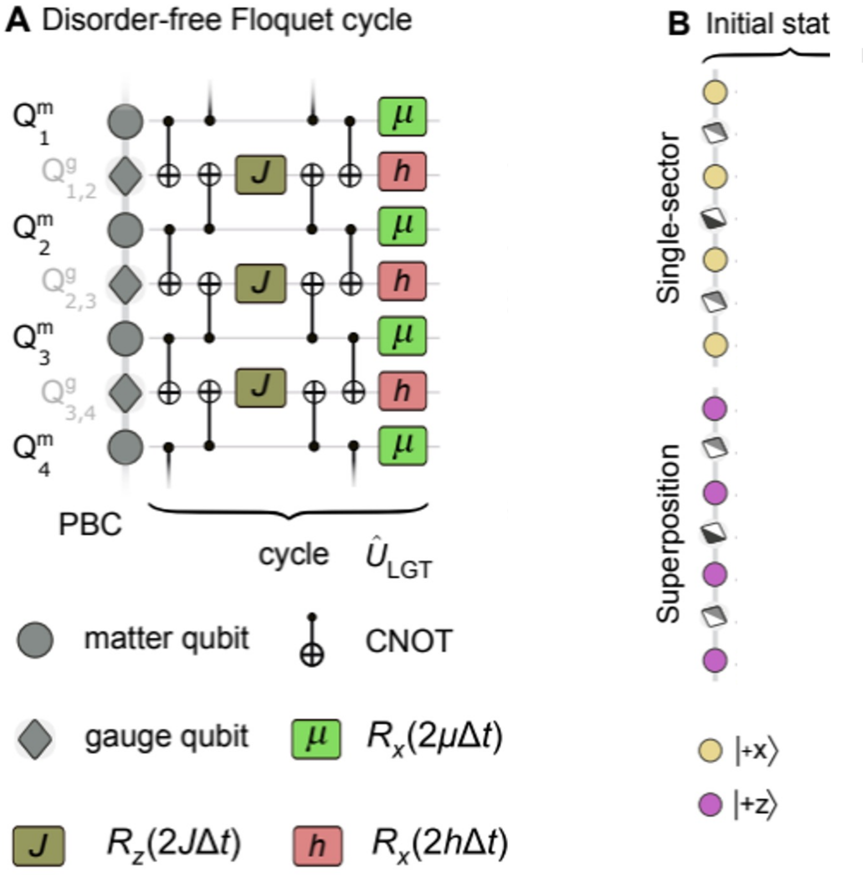
Accepted in Science

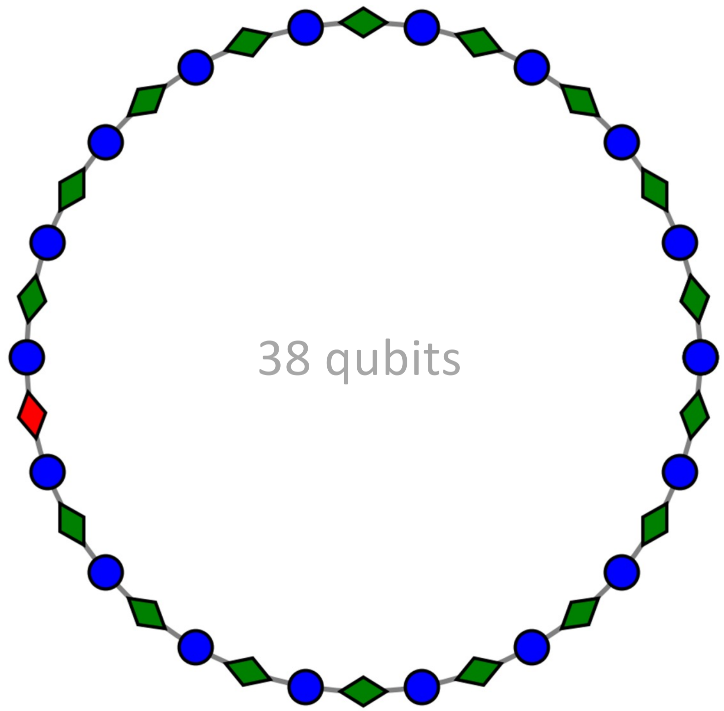
Google Quantum AI

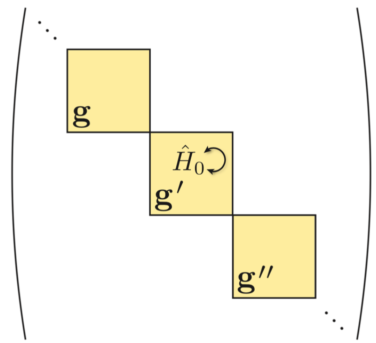
Google Quantum AI and collaborators (**JCH**), arXiv:2410.06557

Local perturbation in a translation-invariant ring

$$\mathcal{H} = \mu \sum_i \sigma_i^x + h \sum_{\langle ij \rangle} X_{ij} + J \sum_{\langle ij \rangle} \sigma_i^z Z_{ij} \sigma_j^z$$







Local perturbation in a translation-invariant ring

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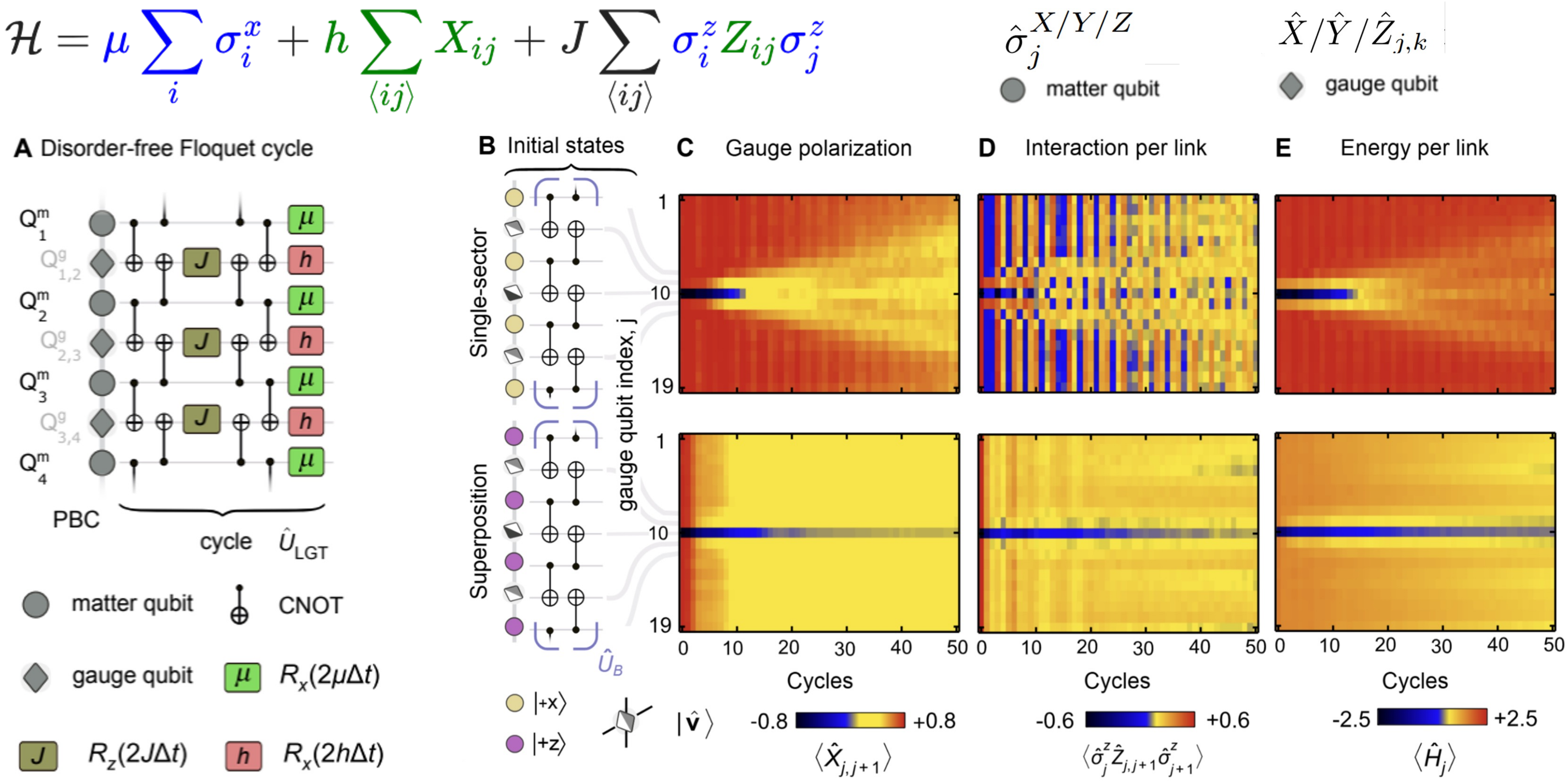
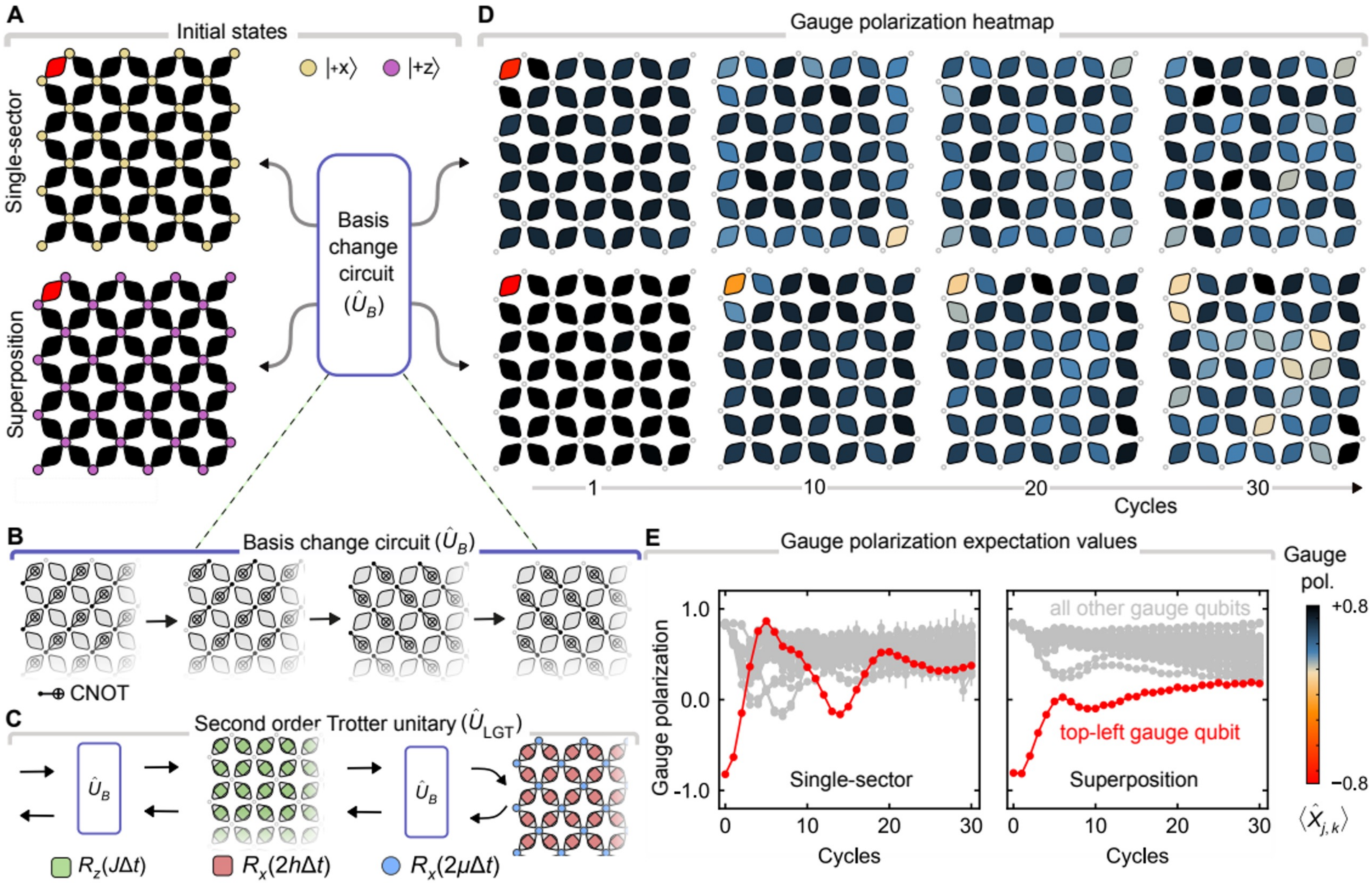
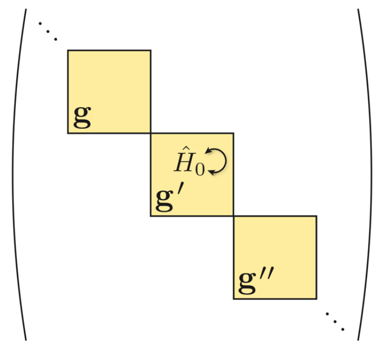


Experimental observation of localization dynamics in a 2 + 1D LGT





Google Quantum AI and collaborators (**JCH**), arXiv:2410.06557

Experimental observation of localization dynamics in a 2 + 1D LGT

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Disorder-Free Localization and Fragmentation in a Non-Abelian Lattice Gauge Theory

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Giovanni Cataldi[1,2,3,4,6,*], Giuseppe Calajó[2,1], Pietro Silvi[1,2,3], Simone Montangero[1,2,3], and Jad C. Halimeh[4,5,6,†]

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Phys. Rev. Lett. **136**, 170401 – **Published 30 April, 2026**

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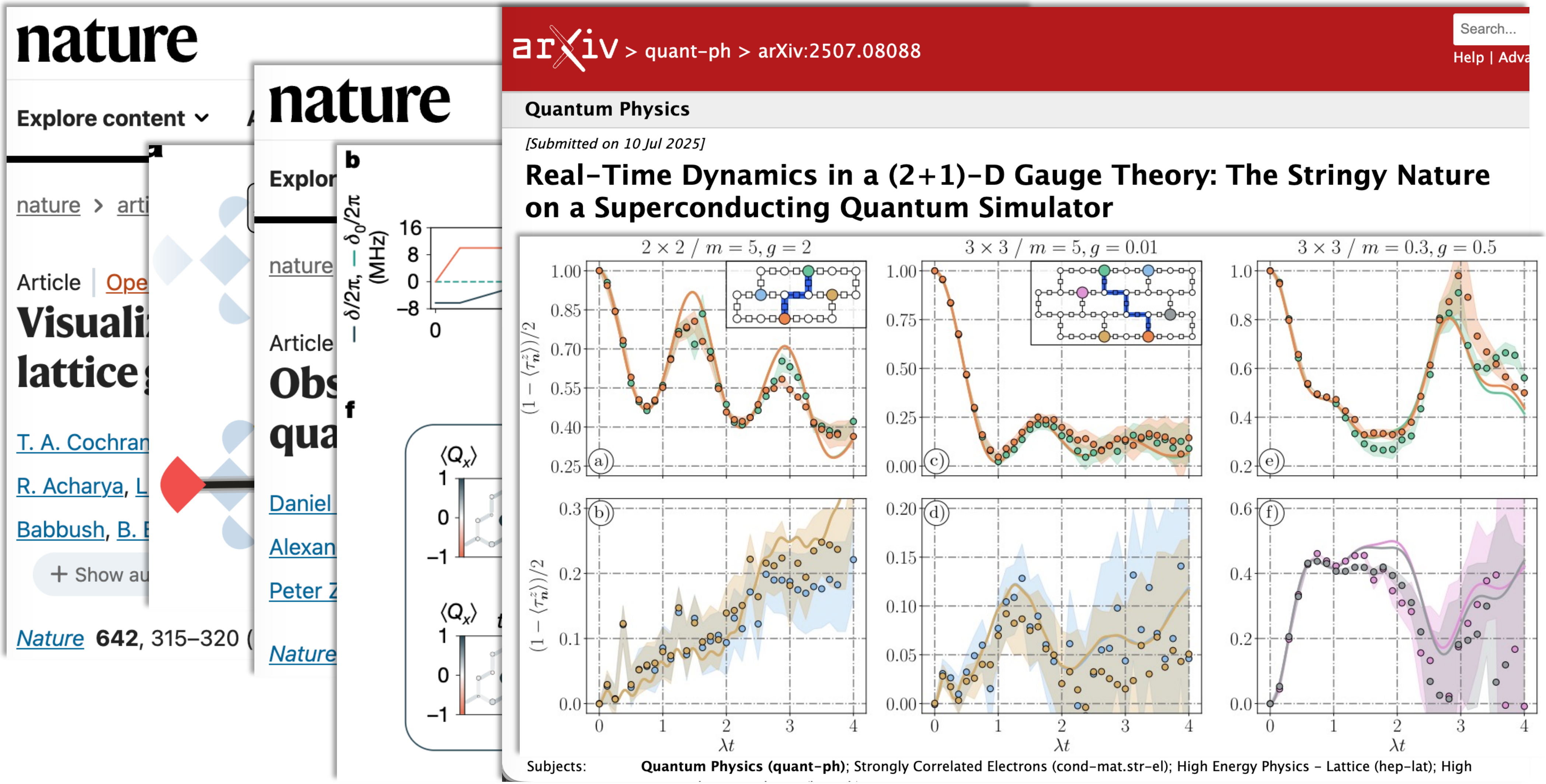
Google Quantum AI and collaborators (**JCH**), arXiv:2410.06557

Recent experiments of string dynamics in 2 + 1D



State-of-the-art tensor-network results: Electric flux strings in 2 + 1D

Borla, Osborne, Moroz, **JCH**, arXiv:2501.17929

Xu, Borla, Moroz, **JCH**, arXiv:2507.01950

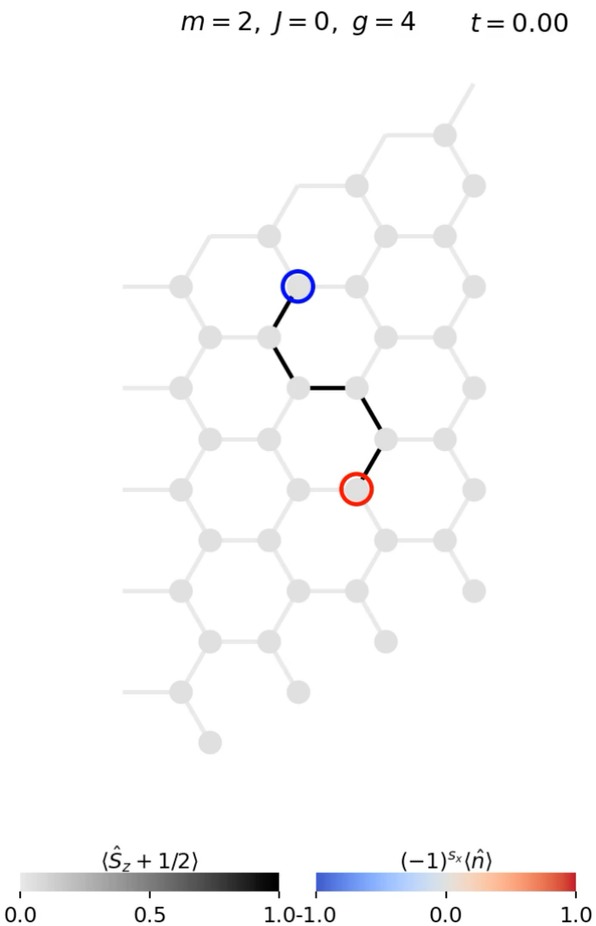
Tian, Srivatsa, Xu, Osborne, Borla, **JCH**, arXiv:2508.05736

Cataldi, Orlando, **JCH**, arXiv:2509.08868

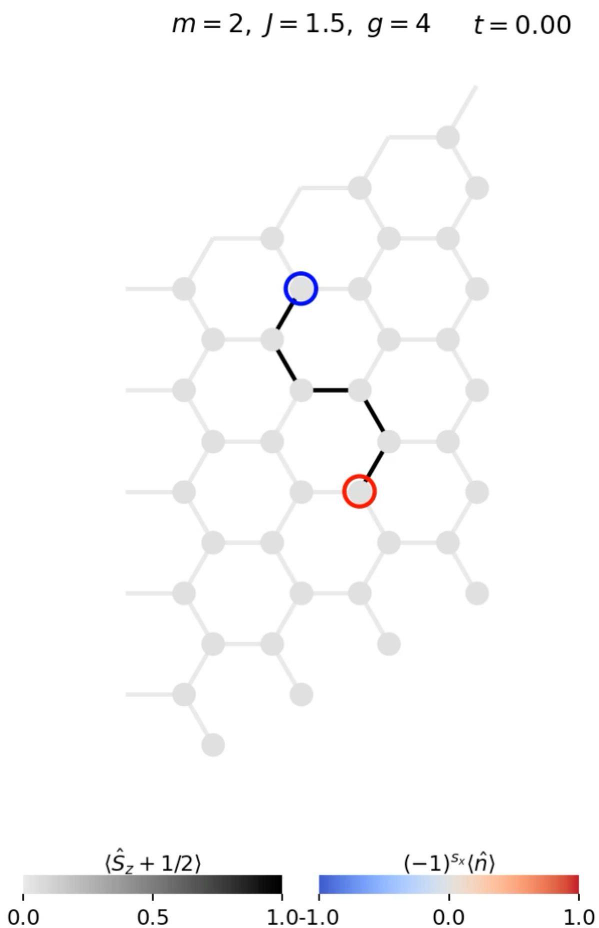
Cao, Joshi, Tian, Srivatsa, **JCH**, arXiv:2601.16166

QuEra experiment not genuine 2 + 1D string dynamics

No plaquette (QuEra)

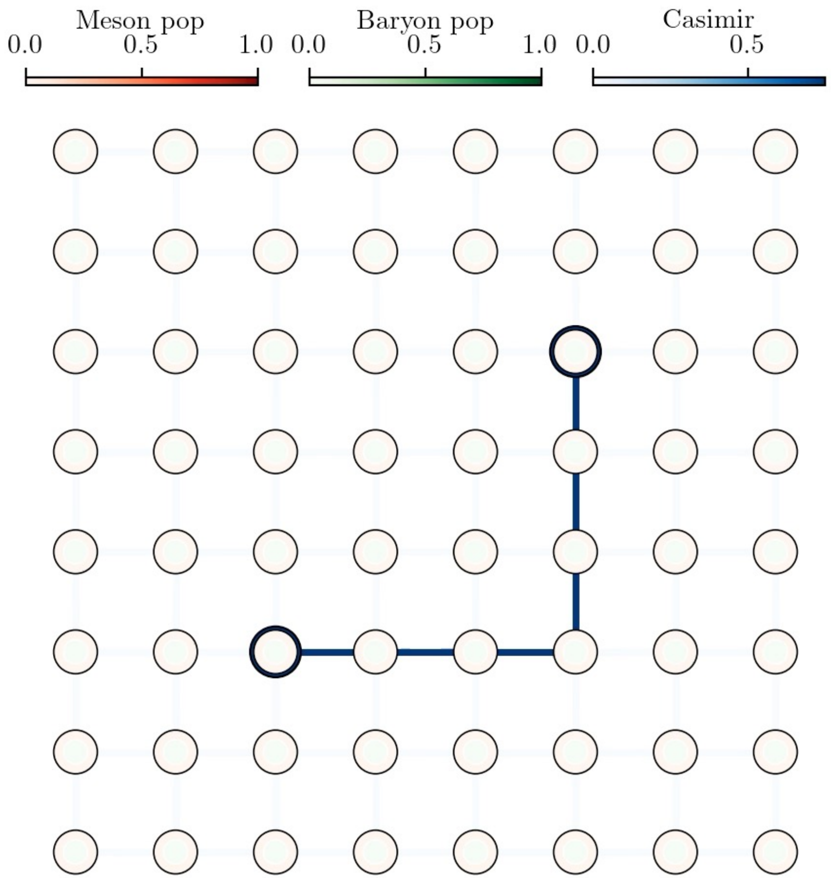


With plaquette

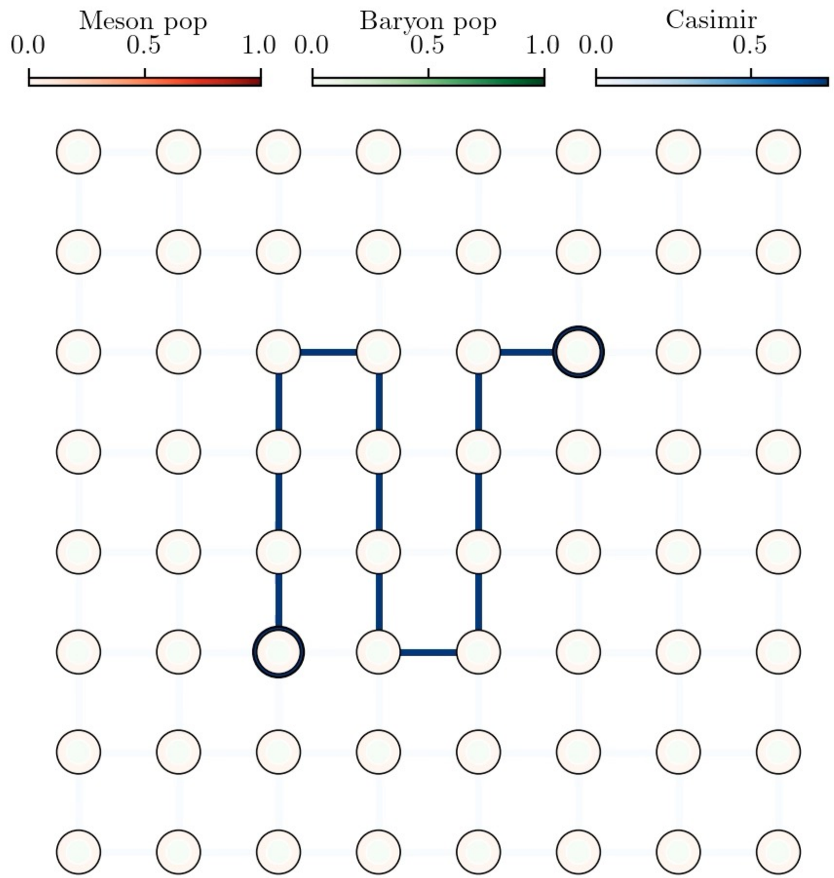


Tian, Srivatsa, Xu, Osborne, Borla, **JCH**, arXiv:2508.05736

String breaking and glueball formation in a 2 + 1D non-Abelian LGT



$(g_E = 50, m = 18.75, g_B = 1, w = 1, t = 0.00)$
Minimal SU(2) $j = \frac{1}{2}$ string breaking



$(g_E = 50, m = 50, g_B = 1, w = 1, t = 0.00)$
Maximal SU(2) $j = \frac{1}{2}$ string fluctuations

Cataldi, Orlando, **JCH**, arXiv:2509.08868

State-of-the-art quantum simulation experiments: Electric flux strings in 2 + 1D

QUANTINUUM

Observation of glueball excitations and string breaking in a $2+1$D $\mathbb{Z}_2$ lattice gauge theory on a trapped-ion quantum computer

Kaidi Xu,[1,2,3,*] U
Henrik Dreyer
[1] *Max Planck*
[2] *Department of Physic*
Ludwig Maxi
[3] *Munich Center for Qua*
[4] *Quant*
[5] *Quantinuum, P*
[6] *RIKEN Center for Qua*
[7] *School of Mathematical Sciences*
[8] *Department of Physics, Co*

A major goal of the qua
nonperturbative far-from-eq
in quantum chromodynami
and glueballs, both essentia
important step towards this
plaquette term on a `Quanti`
shallow depth-6 Trotter circ
execute over 1000 entangling
we quench across a range of
of gauge-invariant closed-lo
breaking accompanied by sp
the system displays genuine
be trivially mapped to $1+$
nonequilibrium dynamics in
accessible setting for pheno

Observation of genuine $2+1$D string dynamics in a U(1) lattice gauge theory with a tunable plaquette term on a trapped-ion quantum computer

Rohan Joshi,[1,2,3,*] Yizhuo Tian,[2,3,*] Kevin Hemery,[4] Kaidi Xu,[1,2,3] N. S. Srivatsa,[1,2,3] Jesse J. Osborne,[1,2,3] Henrik Dreyer,[4] Enrico Rinaldi,[5,6,7] and Jad C. Halimeh[2,1,3,8,†]

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[4] *Quantinuum, Leopoldstr. 180, 80804 Munich, Germany*
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[8] *Department of Physics, College of Science, Kyung Hee University, Seoul 02447, Republic of Korea*

(Dated: April 10, 2026)

Quantum simulations of high-energy physics in $2+1$D can probe dynamical phenomena nonexistent in one spatial dimension and access regimes that are challenging for existing classical simulation methods. For string dynamics—relevant to hadronization—a plaquette term is required to realize genuine $2+1$D behavior, as it endows the gauge field with dynamics and enables the propagation of photon-like excitations. Here, we realize a U(1) quantum link model of quantum electrodynamics in two spatial dimensions with a tunable plaquette term on a `Quantinuum System Model H2` quantum computer. We implement, to our knowledge, the largest quantum simulation of string-breaking dynamics reported to date, on a 5×4 matter-site square lattice using 51 qubits. The simulation uses a shallow circuit design with a two-qubit gate depth of 28 per Trotter step and up to 1540 entangling gates. Starting from far-from-equilibrium string configurations, we measure the probability for the string to propagate within the lattice plane and find signatures of genuine $2+1$D dynamics only when the plaquette term is present. In a resonant regime, we observe the annihilation of string segments accompanied by the production of electron–positron pairs that screen them. We further find that, only with a nonzero plaquette term, matter creation extends across the lattice plane rather than remaining confined to the initial string path. These results experimentally realize string breaking and demonstrate the emergence of dynamical gauge fields in two spatial dimensions, establishing a route to photon-like propagation in programmable quantum simulators of gauge theories.

Xu *et al.*, … , **JCH**, arXiv:2604.07435

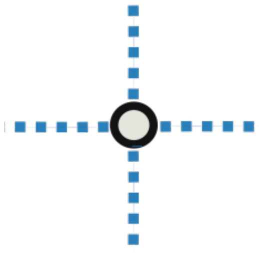
Joshi *et al.*, … , **JCH**, arXiv:2604.07436

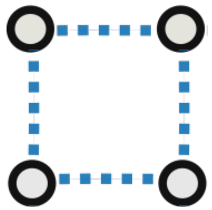
First experiment: 2 + 1D $\mathbb{Z}_2$ Lattice Gauge Theory

$$\hat{H} = -J_s \sum_s Q_s \hat{A}_s - J_p \sum_p \hat{B}_p - \sum_i \left(h_E \hat{Z}_i + h_M \hat{X}_i \right)$$

matter field | magnetic field (plaquette term) | electric field | gauge field

$$\hat{A}_s = \prod_{i \in s} \hat{Z}_i \qquad \hat{B}_p = \prod_{i \in p} \hat{X}_i$$





Generator of $\mathbb{Z}_2$ gauge symmetry

$$\hat{G}_s = \hat{A}_s \hat{\tau}_s^z$$

$$\hat{G}_s |\Psi\rangle = Q_s |\Psi\rangle$$

$Q_s = +1$ everywhere except at static-charge sites where $Q_s = -1$

Xu *et al.*, … , **JCH**, arXiv:2604.07435

First experiment: 2 + 1D $\mathbb{Z}_2$ Lattice Gauge Theory

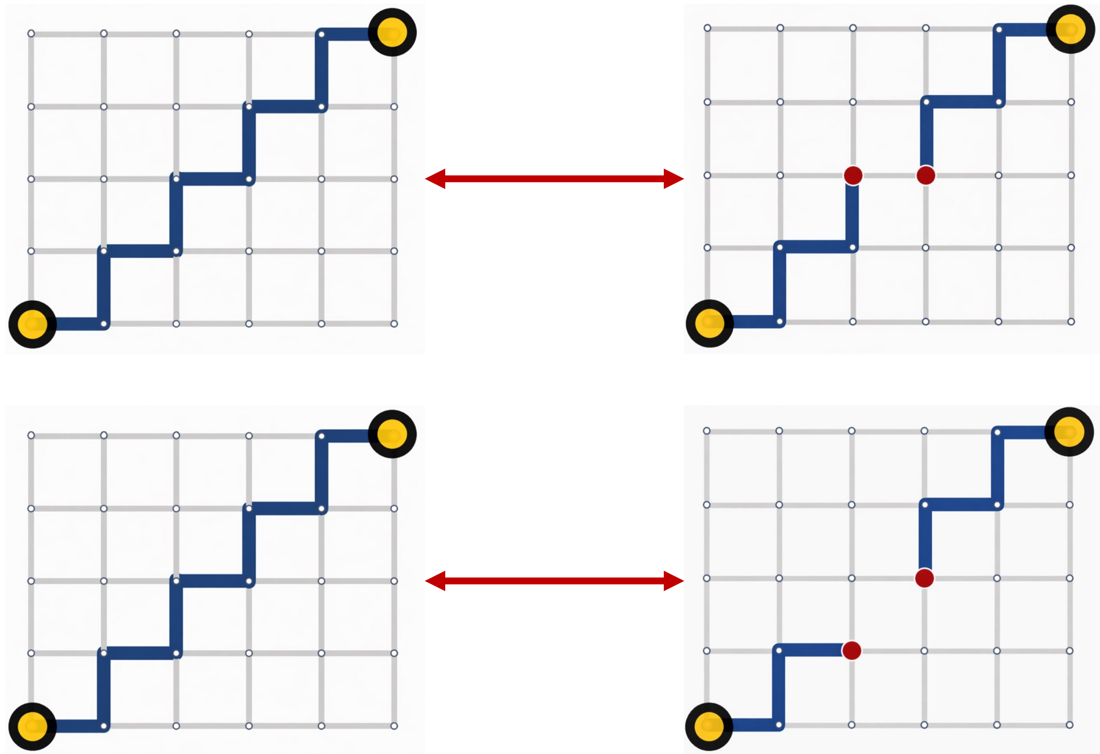
$$\hat{H} = -J_s \sum_s Q_s \hat{A}_s - J_p \sum_p \hat{B}_p - \sum_i \left(h_E \hat{Z}_i + h_M \hat{X}_i\right)$$

First-order resonance

$$h_E = 2J_s$$

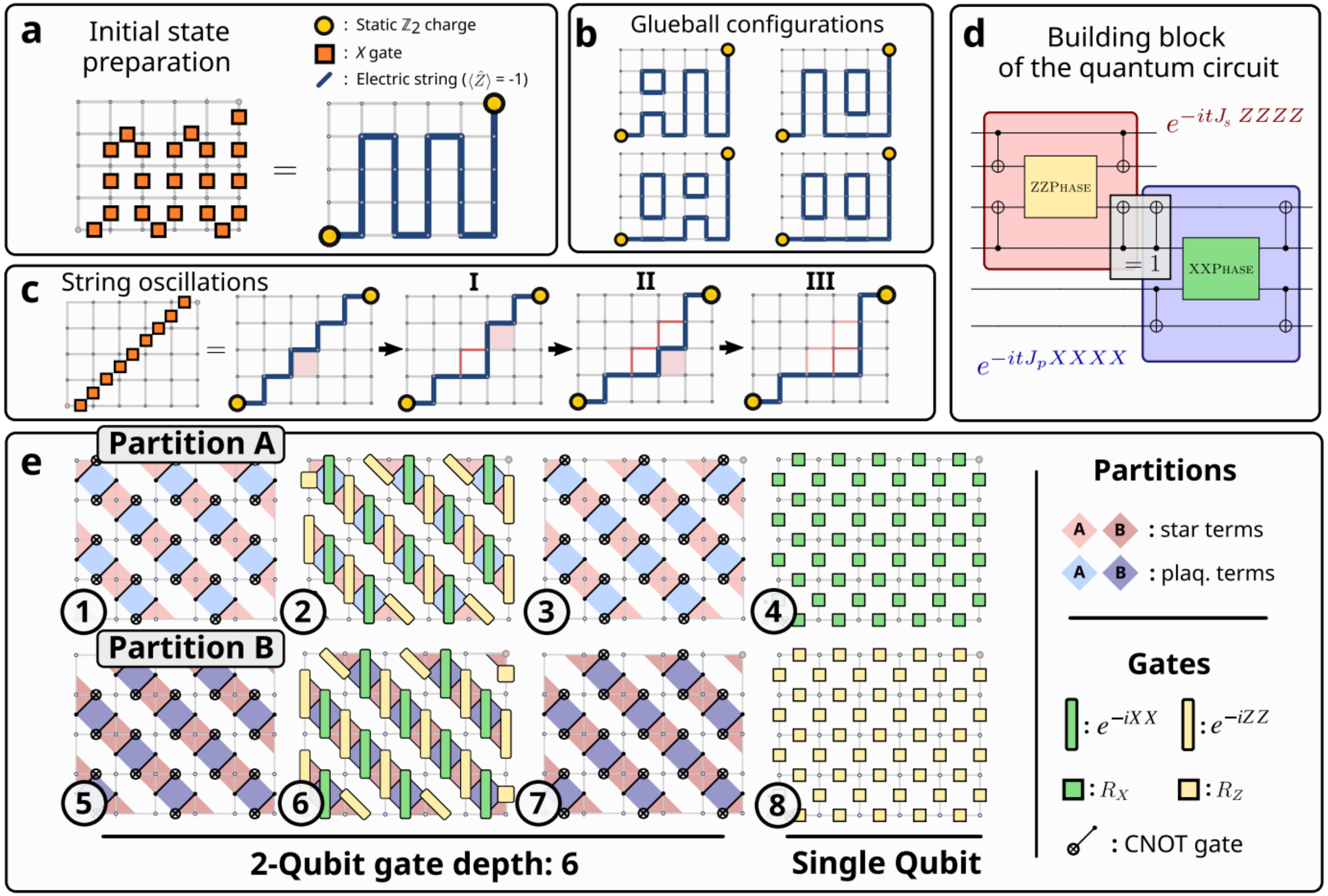
Second-order resonance

$$h_E = J_s$$



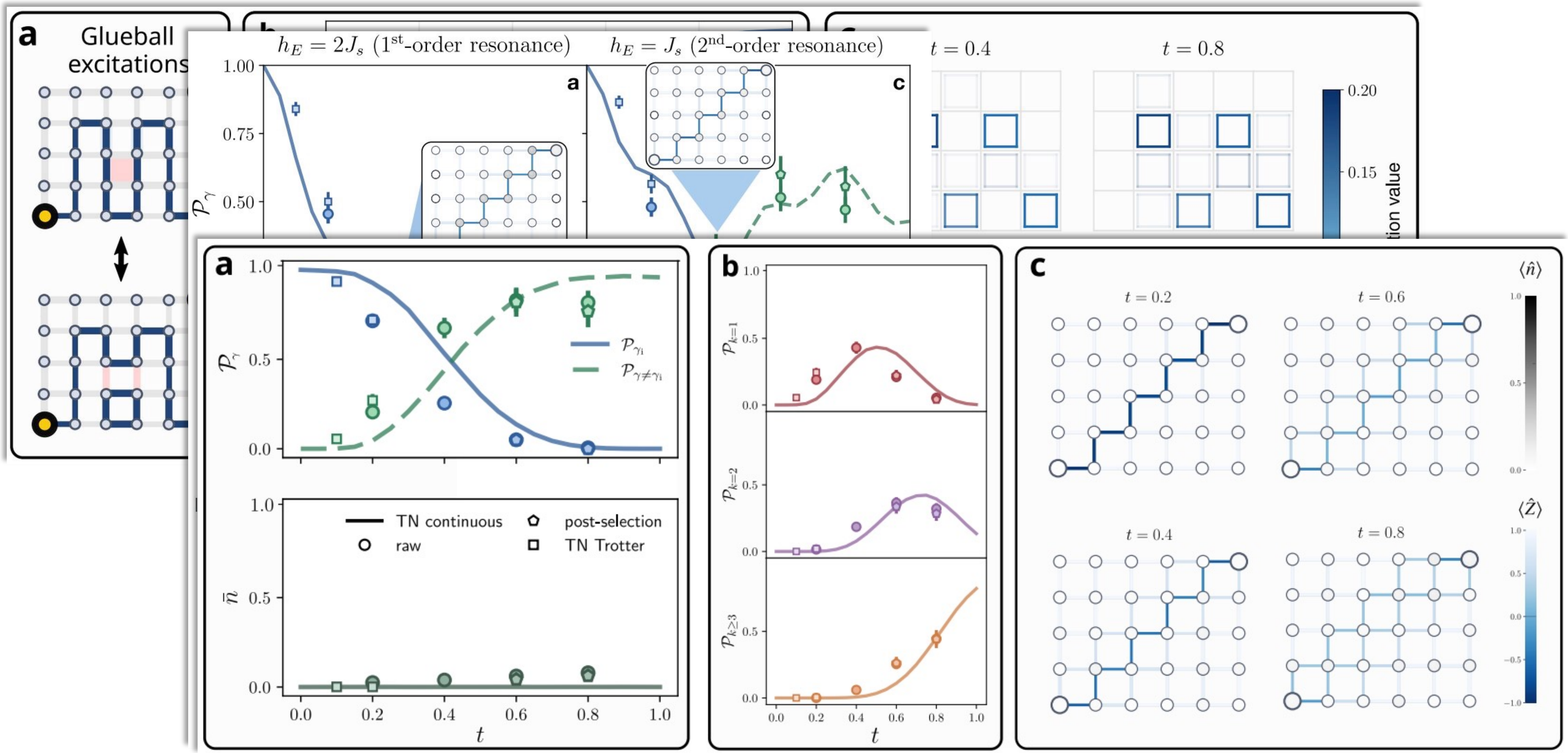
Xu *et al.*, … , **JCH**, arXiv:2604.07435

First experiment: $2+1\mathrm{D}\ \mathbb{Z}_2$ Lattice Gauge Theory



Joshi *et al.*, … , **JCH**, arXiv:2604.07436

First experiment: $2+1\text{D}\ \mathbb{Z}_2$ Lattice Gauge Theory



Xu *et al.*, … , **JCH**, arXiv:2604.07435

Second experiment: 2 + 1D U(1) Lattice Gauge Theory

$$\hat{H} = -\kappa \sum_{\mathbf{j},\mu} \left(s_{\mathbf{j},\mathbf{e}_\mu} \hat{\phi}^\dagger_{\mathbf{j}} \hat{S}^+_{\mathbf{j},\mathbf{e}_\mu} \hat{\phi}_{\mathbf{j}+\mathbf{e}_\mu} + \mathrm{H.c.} \right) + m \sum_{\mathbf{j}} s_{\mathbf{j}} \hat{\phi}^\dagger_{\mathbf{j}} \hat{\phi}_{\mathbf{j}} - g \sum_{\mathbf{j},\mu} \hat{S}^z_{\mathbf{j},\mathbf{e}_\mu} + J \sum_{\square} \left(\hat{U}_\square + \hat{U}^\dagger_\square \right)$$

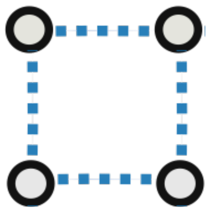
gauge field

matter field

electric field

magnetic field
(plaquette term)

$$\hat{U}_\square = \hat{S}^+_{\mathbf{j},\mathbf{e}_x} \hat{S}^+_{\mathbf{j}+\mathbf{e}_x,\mathbf{e}_y} \hat{S}^-_{\mathbf{j}+\mathbf{e}_y,\mathbf{e}_x} \hat{S}^-_{\mathbf{j},\mathbf{e}_y}$$



$$\hat{G}_{\mathbf{j}} = \hat{\phi}^\dagger_{\mathbf{j}} \hat{\phi}_{\mathbf{j}} - \frac{1-(-1)^{j_x+j_y}}{2} - \sum_{\mu} \left(\hat{S}^z_{\mathbf{j},\mathbf{e}_\mu} - \hat{S}^z_{\mathbf{j}-\mathbf{e}_\mu,\mathbf{e}_\mu} \right)$$

$$\hat{G}_{\mathbf{j}} |\Psi\rangle = q_{\mathbf{j}} |\Psi\rangle \qquad q_{\mathbf{j}} = 0,\ \forall \mathbf{j},\ \text{except at static-charge sites: } q_{\mathbf{j}_{\mathrm{o(e)}}} = \pm 1$$

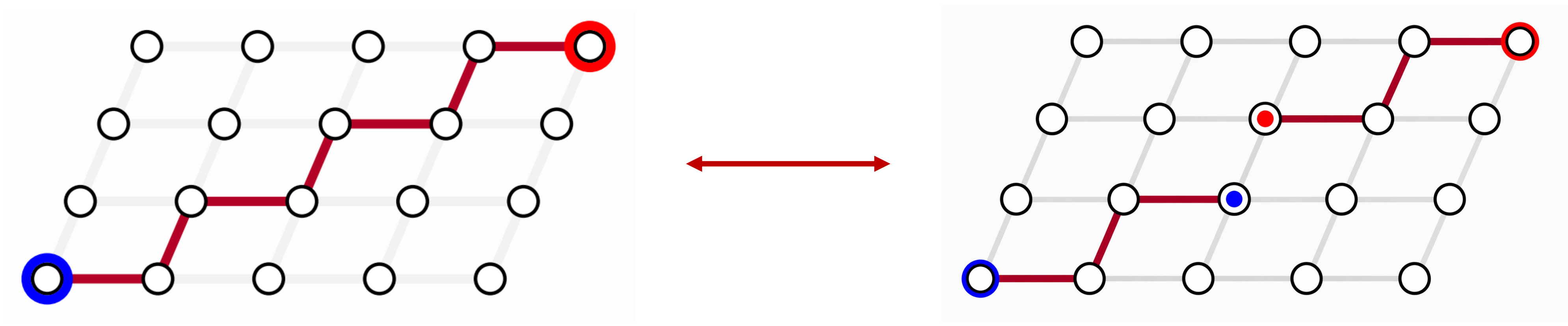
Joshi *et al.*, … , **JCH**, arXiv:2604.07436

Second experiment: 2 + 1D U(1) Lattice Gauge Theory

$$\hat{H} = -\kappa \sum_{\mathbf{j},\mu} \left(s_{\mathbf{j},\mathbf{e}_\mu} \hat{\phi}^\dagger_{\mathbf{j}} \hat{S}^+_{\mathbf{j},\mathbf{e}_\mu} \hat{\phi}_{\mathbf{j}+\mathbf{e}_\mu} + \text{H.c.} \right) + m \sum_{\mathbf{j}} s_{\mathbf{j}} \hat{\phi}^\dagger_{\mathbf{j}} \hat{\phi}_{\mathbf{j}} - g \sum_{\mathbf{j},\mu} \hat{S}^z_{\mathbf{j},\mathbf{e}_\mu} + J \sum_{\square} \left(\hat{U}_\square + \hat{U}^\dagger_\square \right)$$

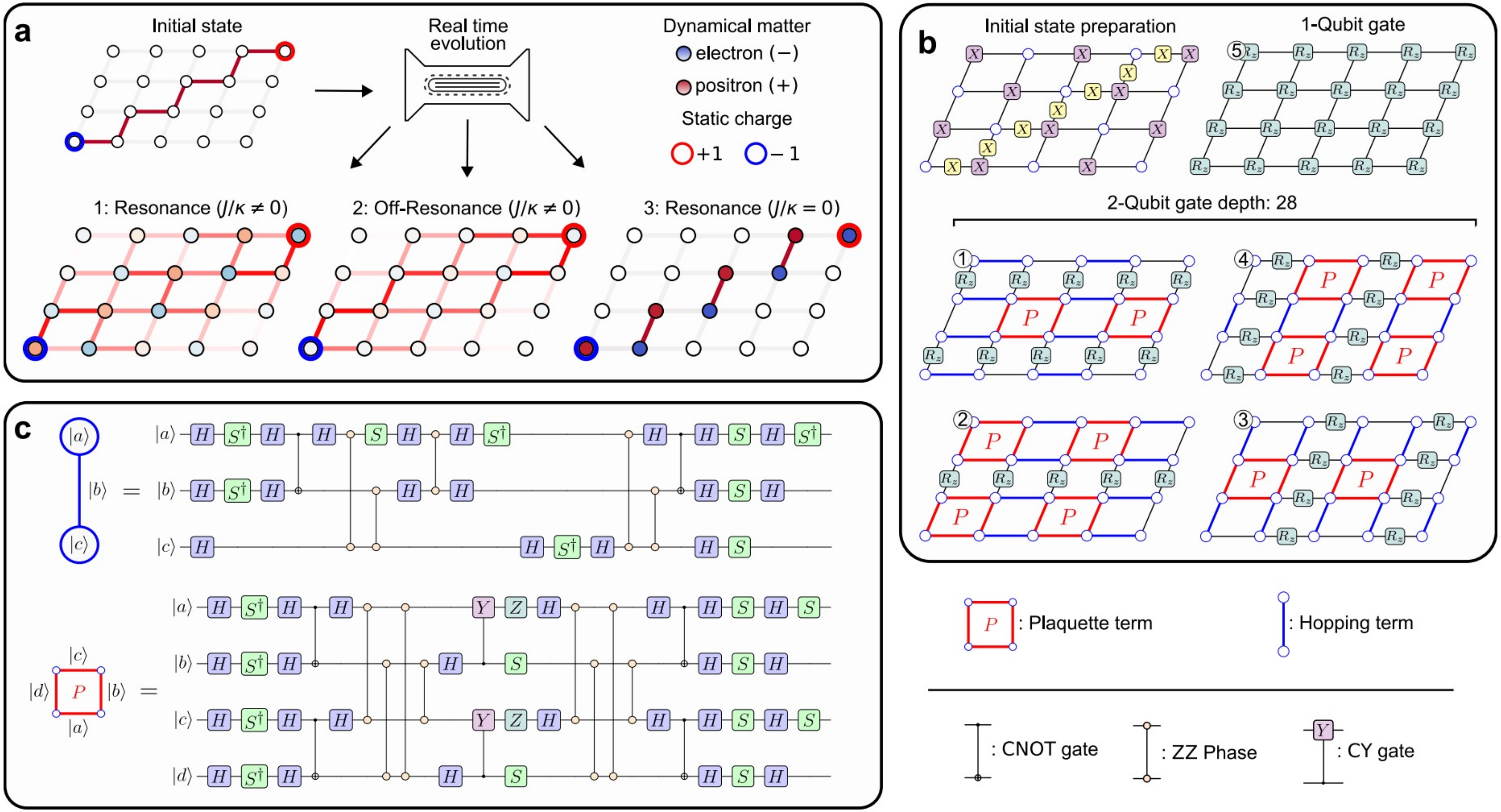
String breaking resonance

$$2m = g$$



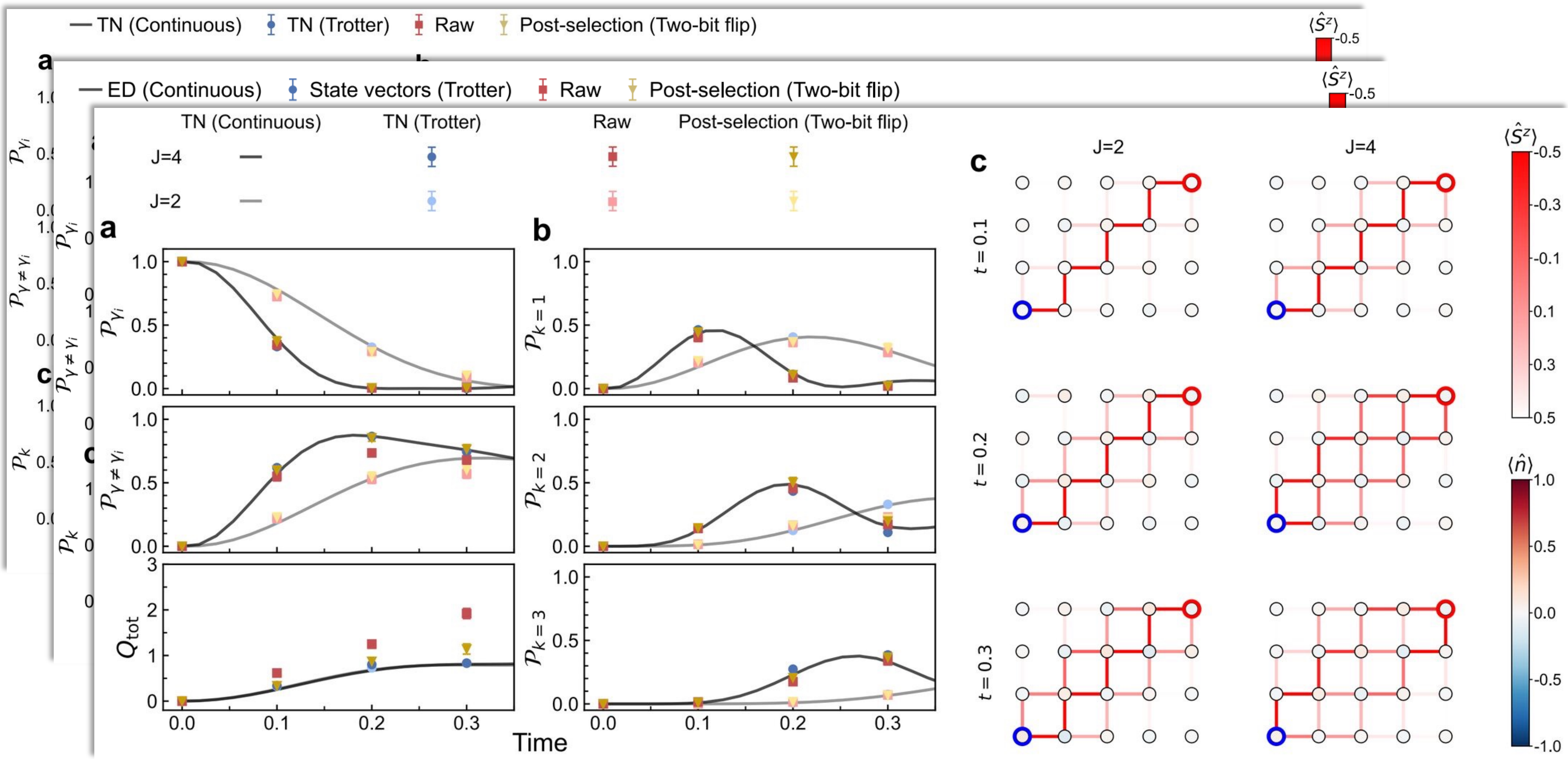
Joshi *et al.*, … , **JCH**, arXiv:2604.07436

Second experiment: 2 + 1D U(1) Lattice Gauge Theory



Joshi *et al.*, … , **JCH**, arXiv:2604.07436

Second experiment: $2 + 1\mathrm{D}\ \mathrm{U}(1)$ Lattice Gauge Theory



Joshi *et al.*, … , **JCH**, arXiv:2604.07436

QC4HEP (CERN +DESY+IBM) roadmap paper

PRX Quantum

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

PDF

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Alberto Di Meglio[1,*], Karl Jansen[2,3,†], Ivano Tavernelli[4,‡], Constantia Alexandrou[3,5], Srinivasan Arunachalam[6], Christian W. Bauer[7], Kerstin Borras[8,9], Stefano Carrazza[1,10], Arianna Crippa[2,11] *et al.*

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Abstract

Quantum computers offer an intriguing path for a paradigmatic change of computing in the natural sciences and beyond, with the potential for achieving a so-called quantum advantage—namely, a significant (in some cases exponential) speedup of numerical simulations. The rapid development of hardware devices with various realizations of qubits enables the execution of small-scale

Di Meglio *et al.* (**JCH**), PRX Quantum **5**, 037001 (2024)

Review paper

nature physics

Review article

https://do

Cold-atom quantum simulators of gauge theories

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Check for updates

Jad C. Halimeh [1,2,3] ✉, Monika Aidelsburger [1,3,4], Fabian Grusdt [2,3], Philipp Hauke [5,6] & Bing Yang [7] ✉

Gauge theories constitute the basis of the Standard Model and provide useful descriptions of various phenomena in condensed matter. Realizing gauge theories on tunable tabletop quantum devices such as cold-atom quantum simulators offers the possibility to study their dynamics from

JCH *et al.*, Nature Physics **21**, 25-36 (2025)

Overarching review

REVIEWS OF MODERN PHYSICS

Quantum simulation of out-of-equilibrium dynamics in gauge theories

Jad C. Halimeh*†,[1,2,3,4] Niklas Mueller*,[5,6] Johannes Knolle,[7,3,8] Zlatko Papić,[9] and Zohreh Davoudi†[10,11,12]

Recent advances in quantum technologies have enabled quantum simulation of gauge theories—some of the most fundamental frameworks of nature—in regimes far from equilibrium, where classical computation is severely limited. These simulators, primarily based on neutral atoms, trapped ions, and superconducting circuits, hold the potential to address long-standing questions in nuclear, high-energy, and condensed-matter physics, and may ultimately allow first-principles studies of matter evolution in settings ranging from the early universe to high-energy collisions. Research in this rapidly growing field is also driving the convergence of concepts across disciplines and uncovering new phenomena. In this Review, we highlight recent experimental and theoretical developments, focusing on phenomena accessible in current and near-term quantum simulators, including particle production and string breaking, collision dynamics, thermalization, ergodicity breaking, and dynamical quantum phase transitions. We conclude by outlining promising directions for future research and opportunities enabled by available quantum hardware.

JCH, Mueller, Knolle, Papić, Davoudi, arXiv:2509.03586

The String Breakers

Kaidi Xu

Rohan Joshi

Yizhuo Tian

Umberto Borla

Jesse Osborne

Srivatsa NS

Henrik Dreyer

Enrico Rinaldi

Kevin Hemery

THANK YOU

Halimeh Group

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