Quantum Simulation of Gauge Theories

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December 10, 2024

``Quantum Simulation of Gauge Theories, Xmas edition'' according to *Microsoft Designer*

Outline

Motivation: why study gauge theories?

Overview of quantum platforms & early LGT implementations

State-of-the-art: selected highlights from 2024

Observation of string-breaking on a (2+1)D Rydberg simulator

Conclusion & Outlook

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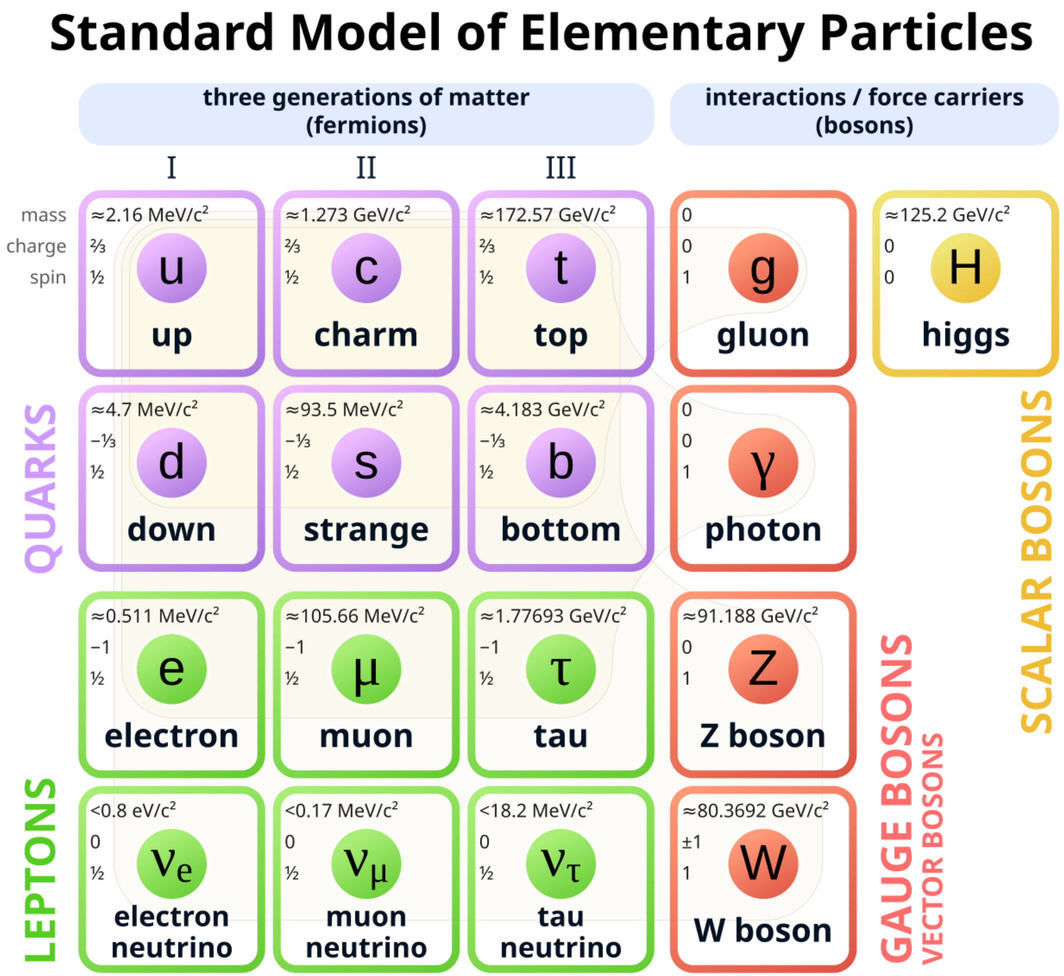
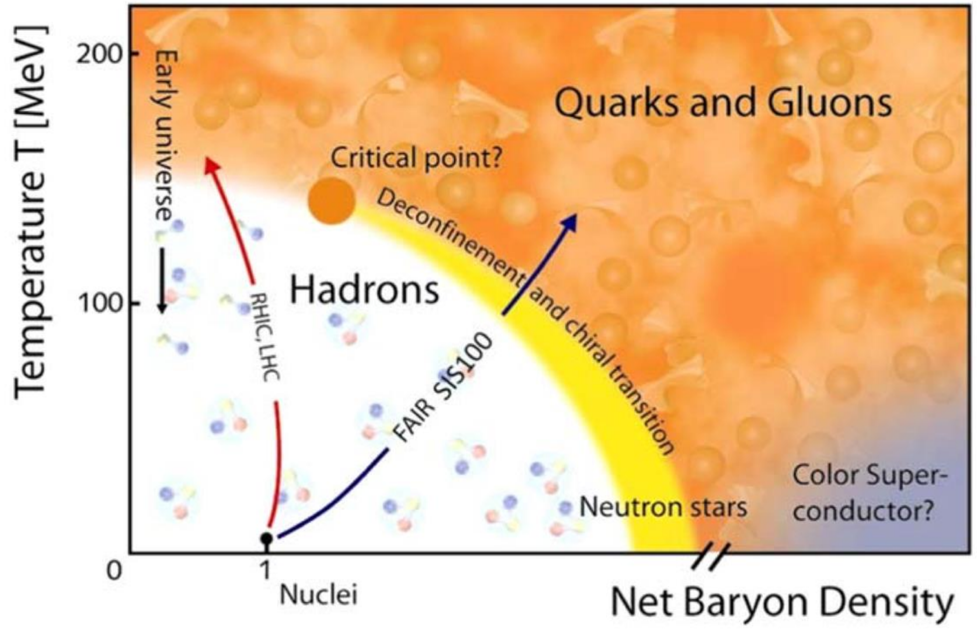
Why study Gauge Theories? (I) High-Energy Physics!



wikipedia

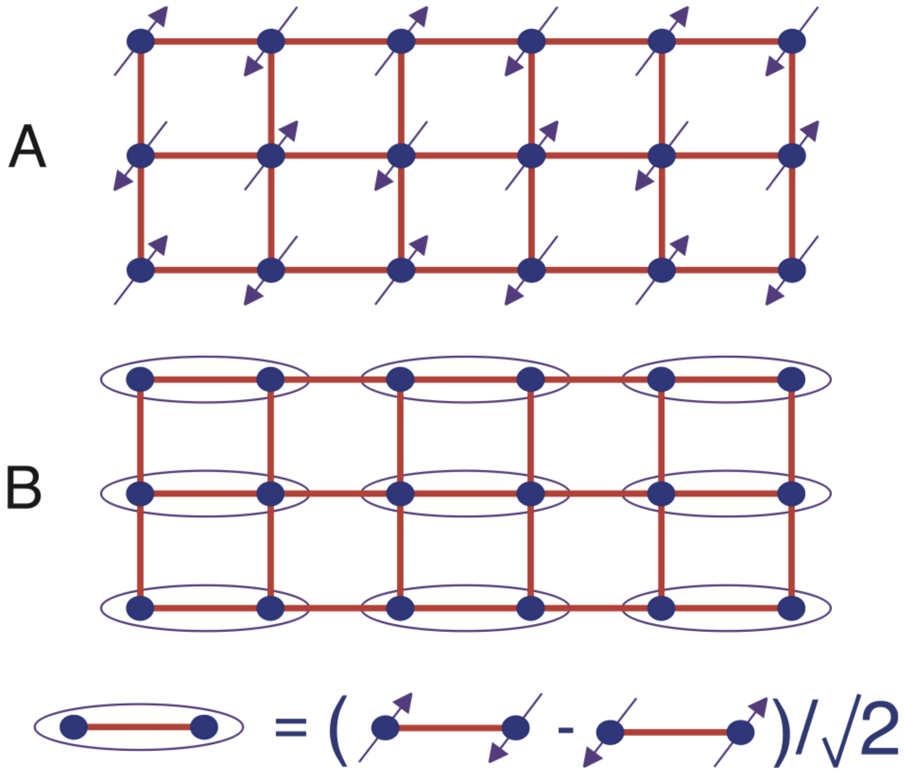
Phases of nuclear matter (QCD)?



Durante et al., Physica Scripta, 94(3), 033001 (2019)

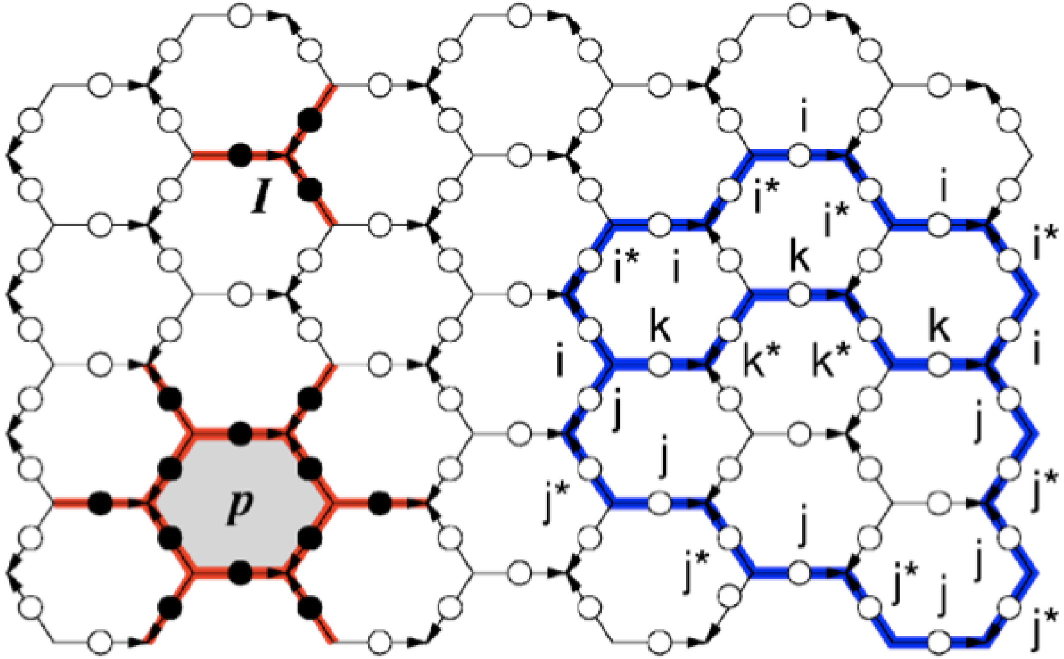
Why study Gauge Theories? (II) Condensed Matter!

Deconfined quantum criticality



Senthil, Vishwanath, Balents, Sachdev & Fisher, Science, 303, 1490 (2004)

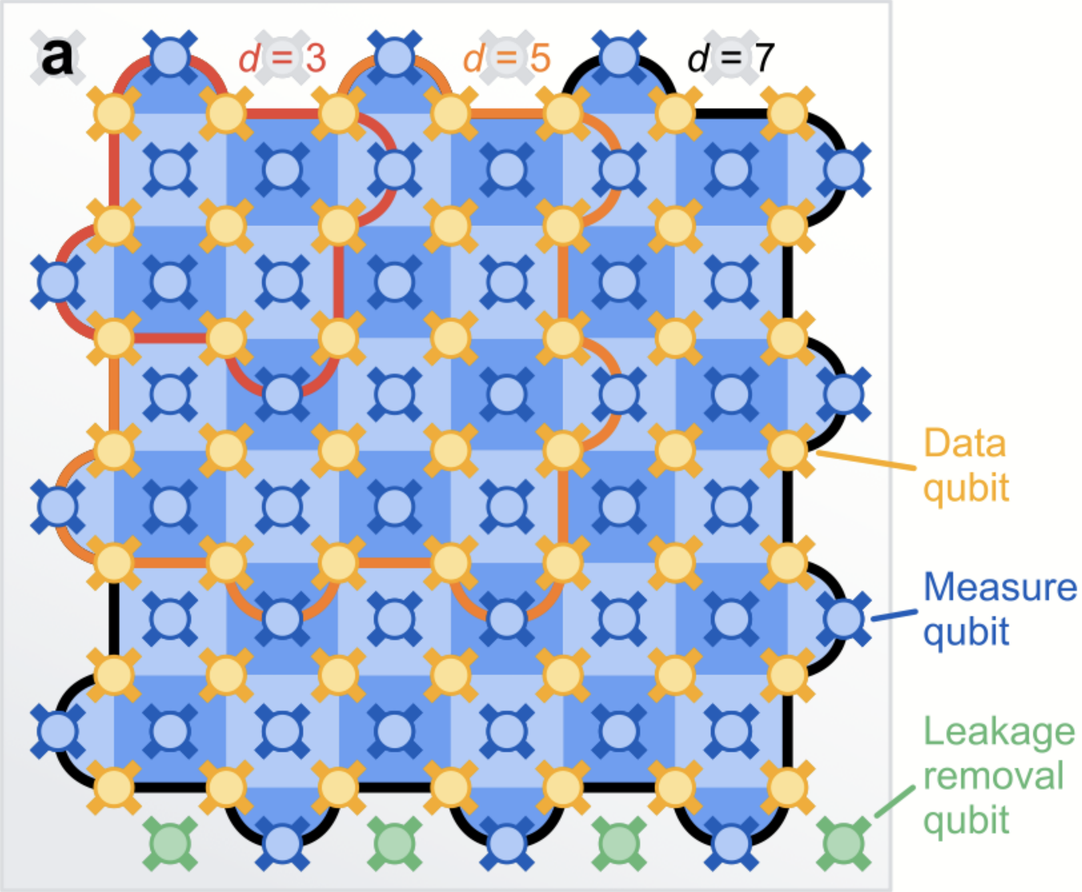
Topological order



Levin & Wen, Physical Review B, 71, 045110 (2005)

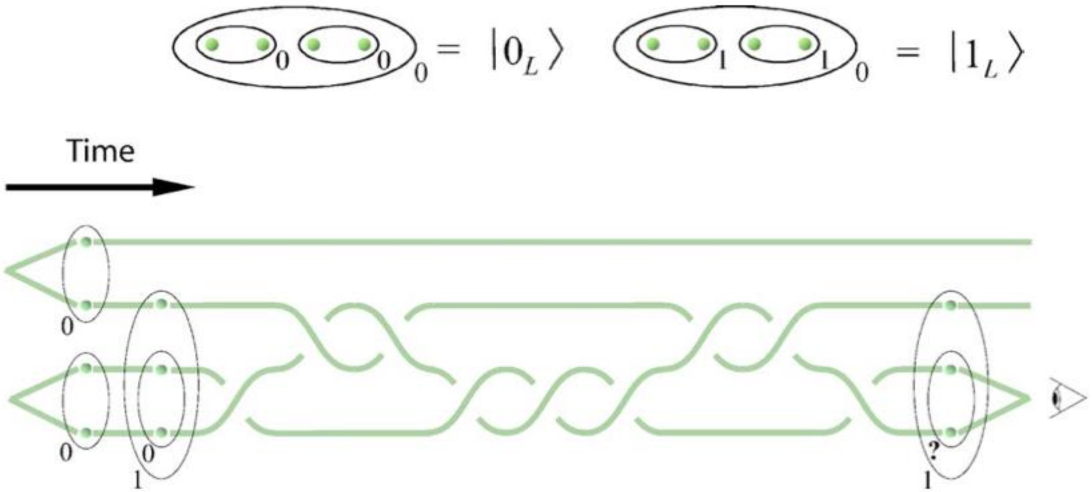
Why study Gauge Theories? (III) Quantum Info.!

Quantum Error Correcting Codes



Google Quantum AI, arXiv:2408.13687

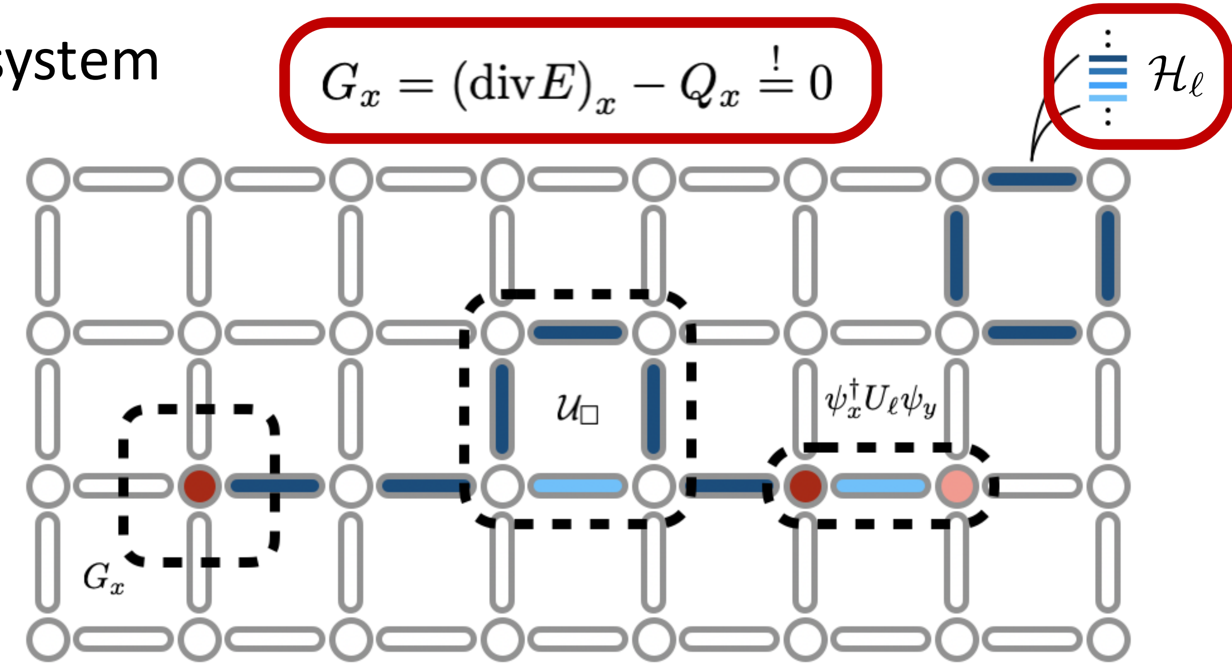
Topological Quantum Computing



Hormozi, Zikos, Bonesteel & Simon, Physical Review B, 75, 165310 (2007)

Challenges of simulating lattice gauge theories (LGTs)

- gauge invariance: constrained many-body system
- Physics in 2D / 3D: plaquette interactions
- Truncate large local Hilbert spaces!
- How to treat fermionic matter?
- eventually: continuum field theory limit



$$H = \frac{g^2}{2}\sum_\ell E_\ell^2 - \frac{1}{2g^2}\sum_\square (\mathcal{U}_\square + \text{h.c.}) + J \sum_{\langle x \ell y \rangle} (\psi_x^\dagger U_\ell \psi_y + \text{h.c.}) + \sum_x M_x \psi_x^\dagger \psi_x$$

Classical comp. "sign problem":
- Real-time dynamics
- Finite fermion density

Troyer & Wiese, Physical review letters, 94(17), 170201 (2005)

Kogut & Susskind, Physical Review D, 11(2), 395 (1975)

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The idea of quantum simulation

1982

``Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy.''

R. Feynman, 1982

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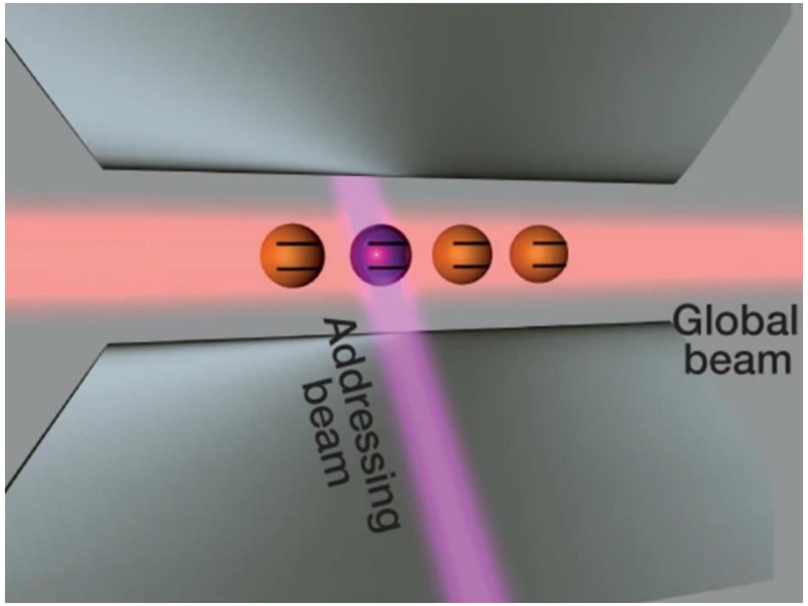
Quantum platforms: Trapped Ions

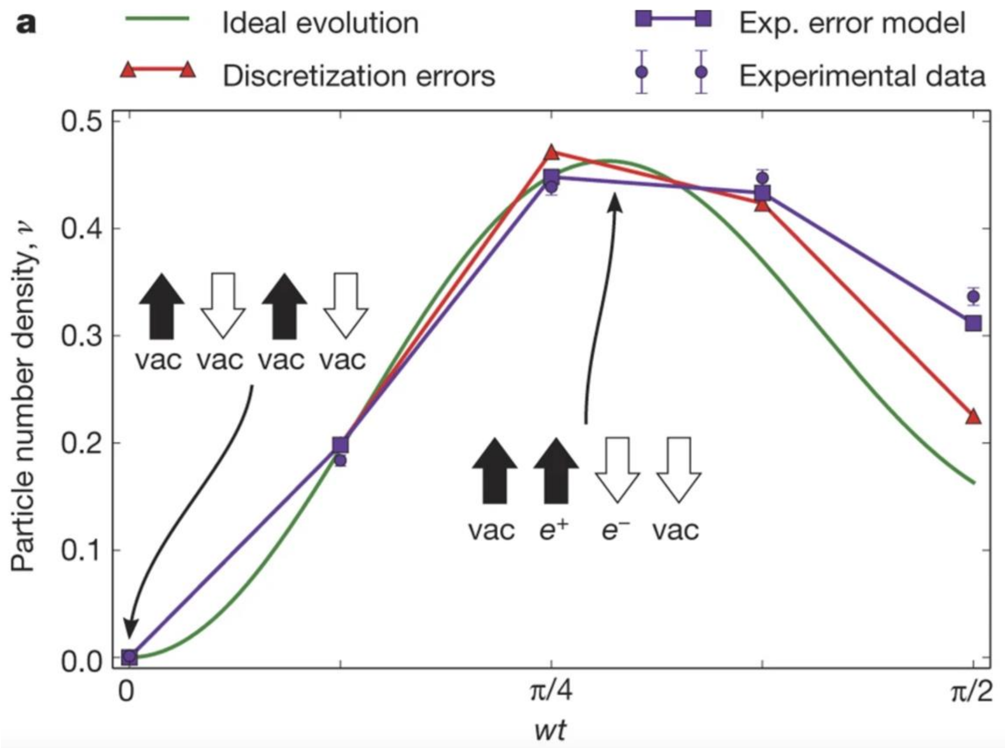
1982

First digital quantum simulation of a LGT (lattice Schwinger model)

⋮

2016





Martinez, Muschik, Schindler, Nigg, Erhard, Heyl, Hauke, Dalmonte, Zoller & Blatt, Nature, 534, 516 (2016)

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Quantum platforms: Rydberg Tweezer Arrays

1982

⋮

2016

2017

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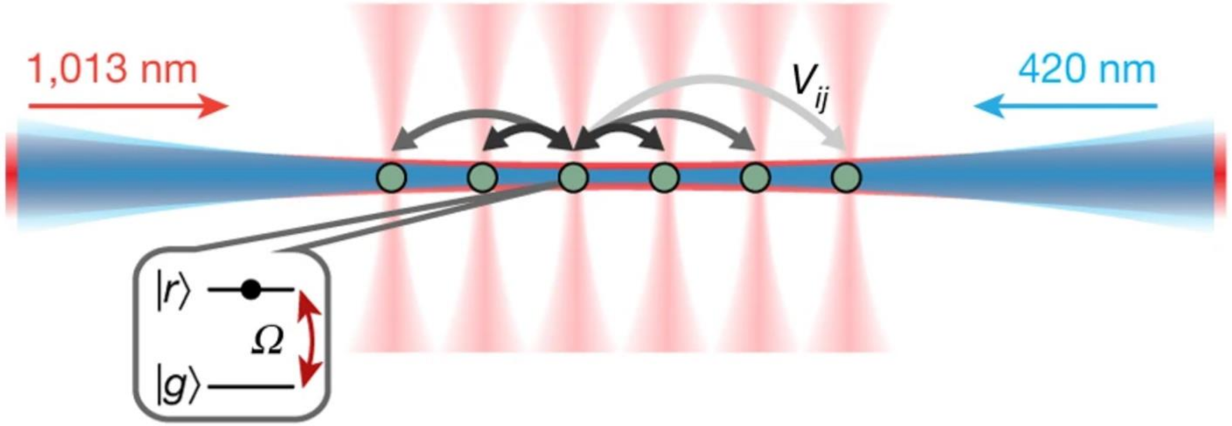
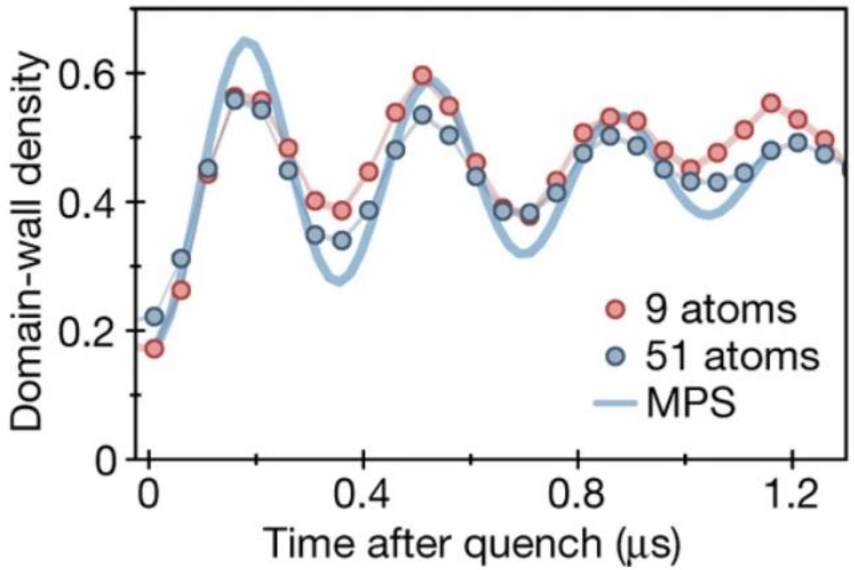
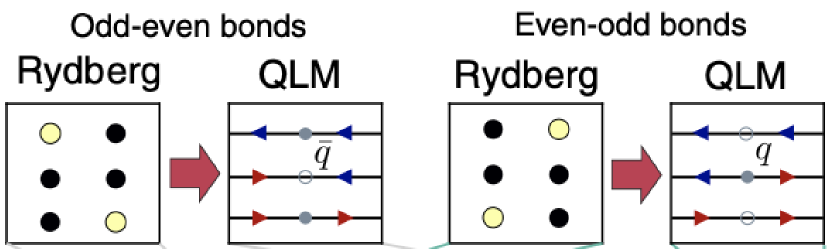
Analog quantum simulation of a U(1) quantum link model





Bernien, Schwartz, Keesling, Levine, Omran, Pichler, … & Lukin, Nature, 551, 579 (2017)



… interpreted as a gauge theory later …

Surace, Mazza, Giudici, Lerose, Gambassi & Dalmonte, Physical Review X, 10, 021041 (2020)

Quantum platforms: Superconducting Qubits

1982

⋮

2016

2017

2018

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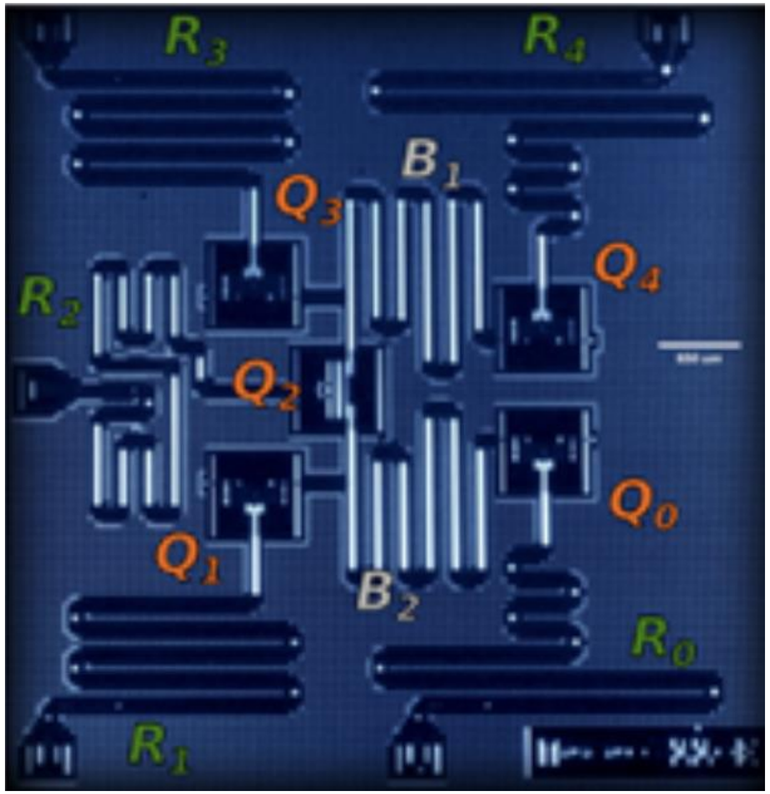
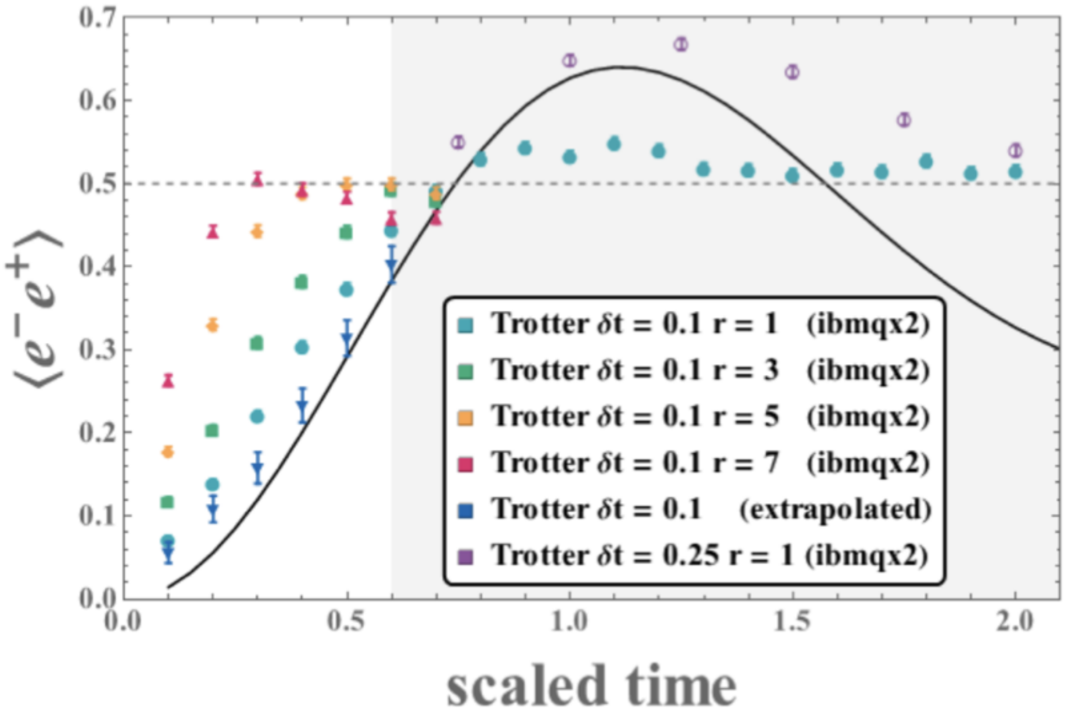
Quantum simulation of the lattice Schwinger model via IBM Q



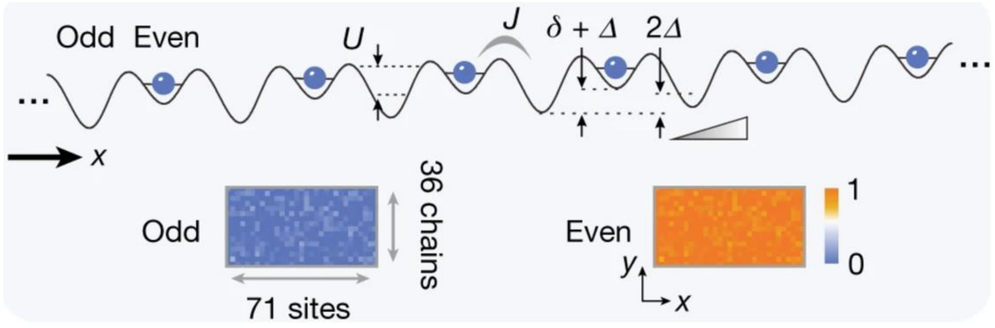
IBM Q 5 “Yorktown”

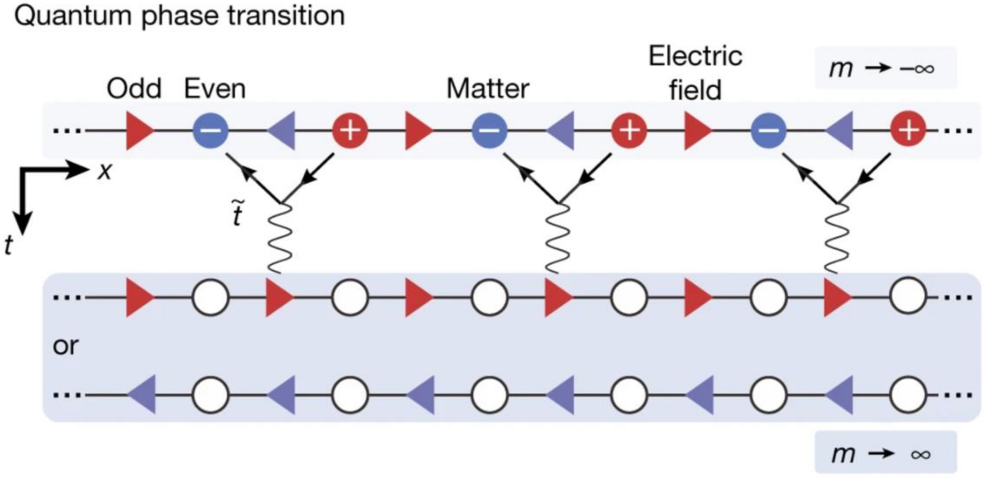


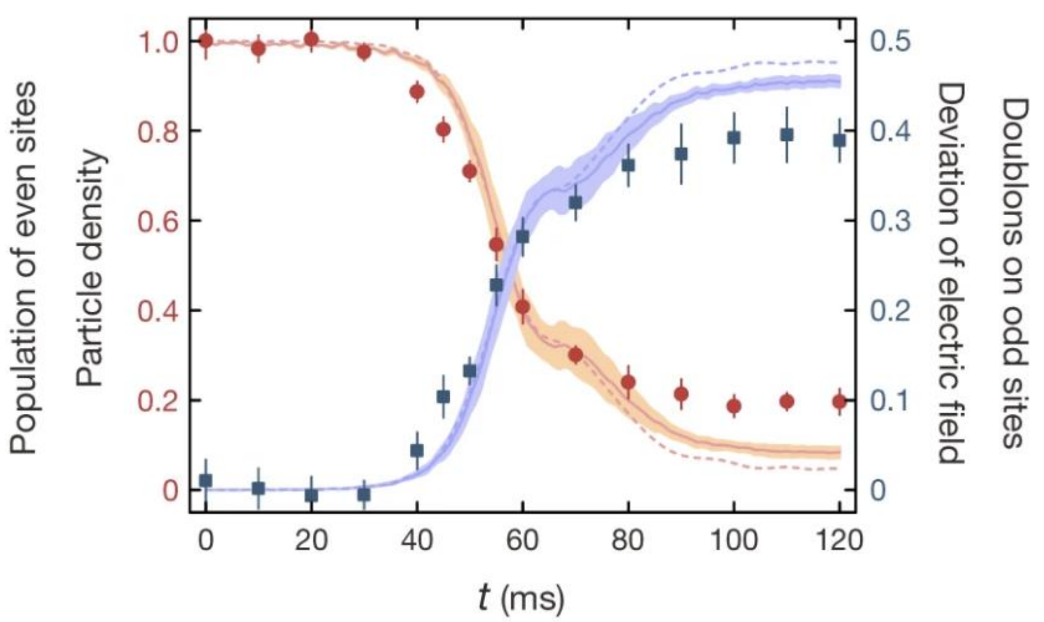
Klco, Dumitrescu, McCaskey, Morris, Pooser, Sanz, Pooser, Solano & Savage, Physical Review A, 98, 032331 (2018)

Quantum platforms: Cold Atoms in Optical Lattices

Analog quantum simulation of a U(1) quantum link model







Yang, Sun, Ott, Wang, TVZ, Halimeh, … & Pan, Nature, 587, 392 (2020)

Outline

1982

Motivation: why study gauge theories?

⋮

Overview of quantum platforms & early LGT implementations

2016

State-of-the-art: selected highlights from 2024

2017

2018

Observation of string-breaking on a (2+1)D Rydberg simulator

2020

⋮

2024

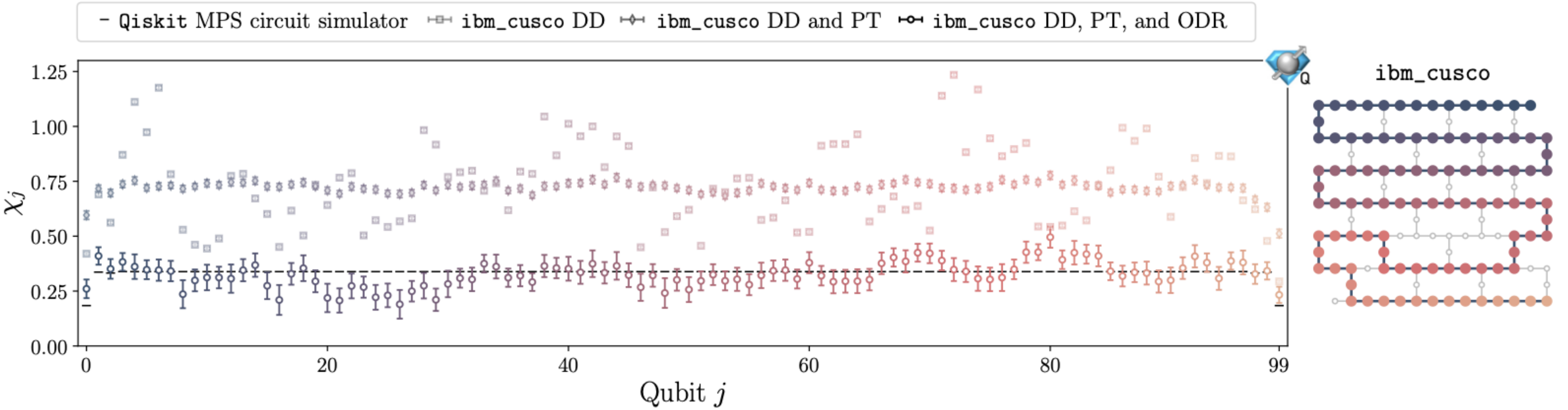
Conclusion & Outlook

t

State-of-the-art: Schwinger model >100 qubits

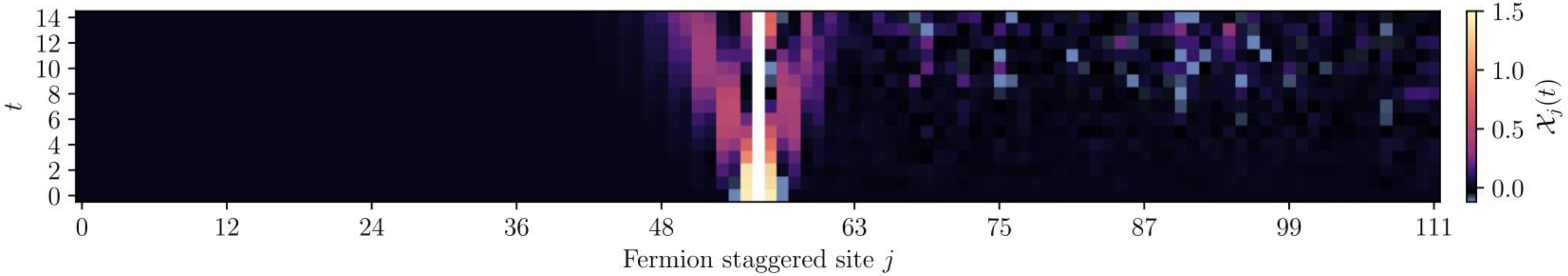
Ground state from scalable adapt-VQE

Farrell, Illa, Ciavarella & Savage,
PRX Quantum, 5, 020315 (2024)



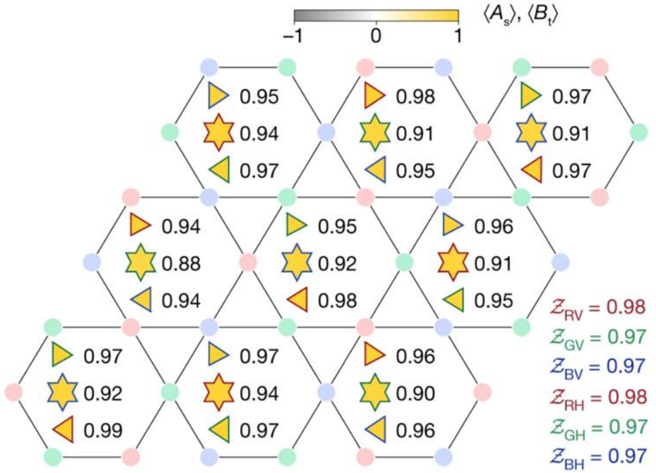
Dynamics of hadron wave-packets

Farrell, Illa, Ciavarella & Savage,
Physical Review D, 109, 114510 (2024)



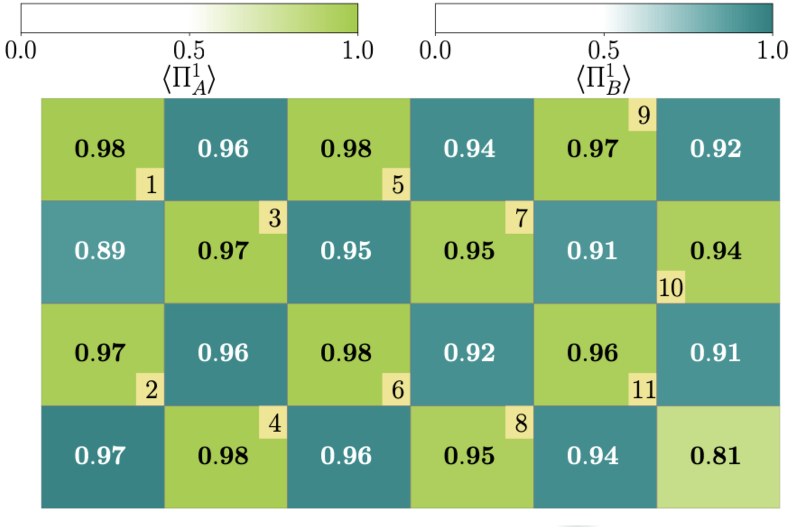
State-of-the-art: Realizing Topological Order

Iqbal et al., Nature, 626, 505 (2024)



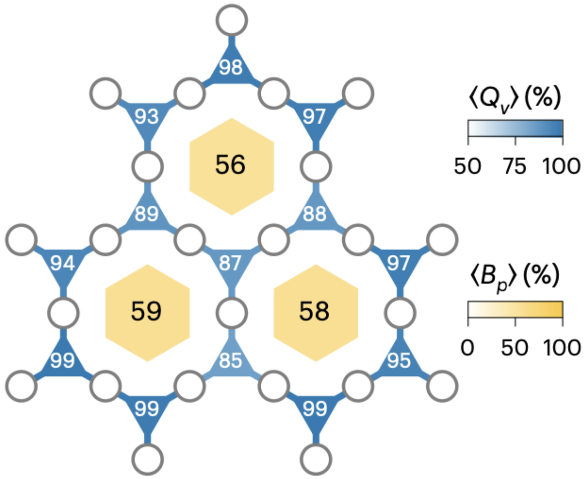
- 9 plaquettes (27 qubits)
- non-abelian D4 symmetry
- digital, trapped ions

Iqbal, et al, arXiv:2411.04185 (2024)



- 12 plaquettes (24 qutrits)
- Z3 Toric code
- digital, trapped ions

Xu et al., Nature Physics, 20, 1469 (2024)

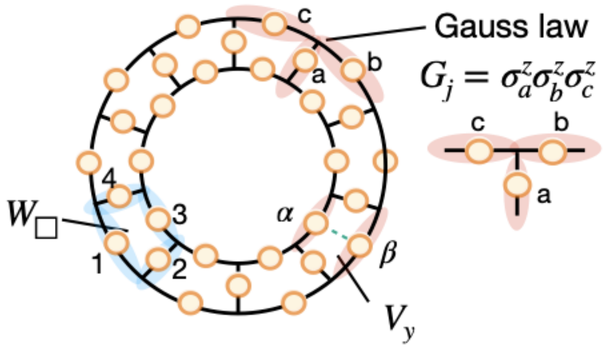


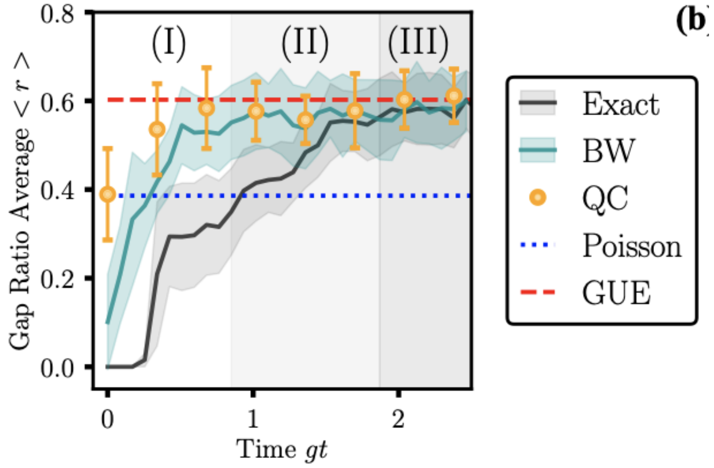
- 3 plaquettes (24 qubits)
- Fibonacci string-net
- digital, supercond. qubits

State-of-the-art: Thermalization in Plaquette Chains

Dynamics of the Entanglement Hamiltonian

- 10 plaquettes (10+2 qubits)
- dualized Z2 LGT
- digital, trapped ions

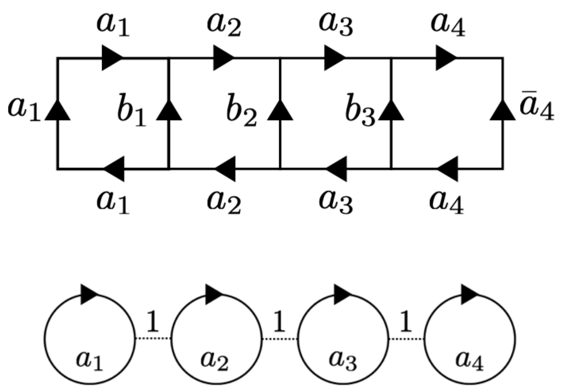


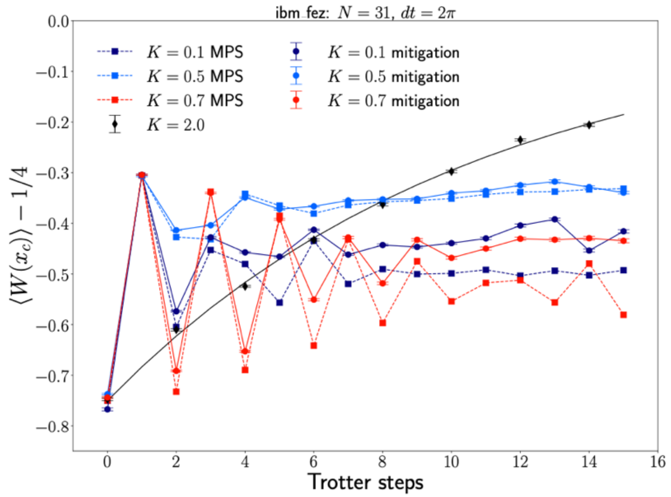


Mueller et al., arXiv:2408.00069 (2024)

Floquet (pre)thermalization

- 31 plaquettes (62 qubits)
- SU(3)_1 string-net formulation
- digital, supercond. qubits

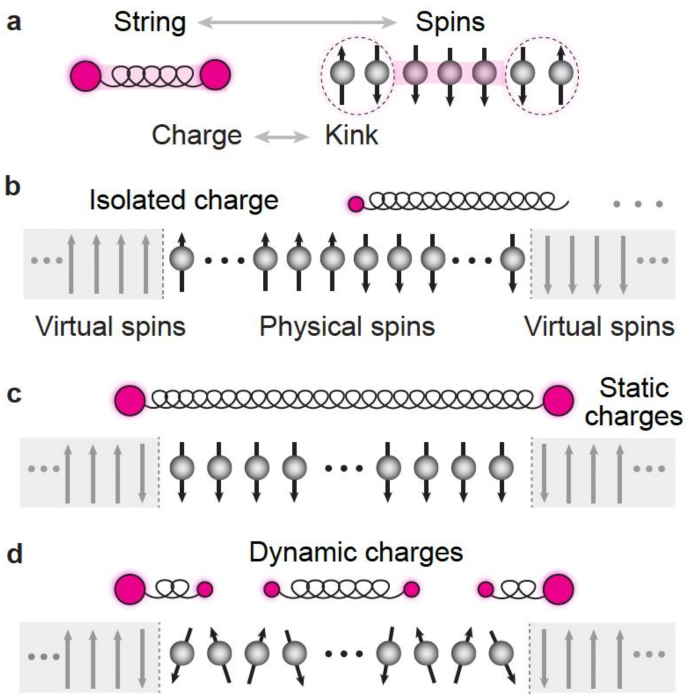




Hayata & Hidaka, arXiv:2409.20263 (2024)

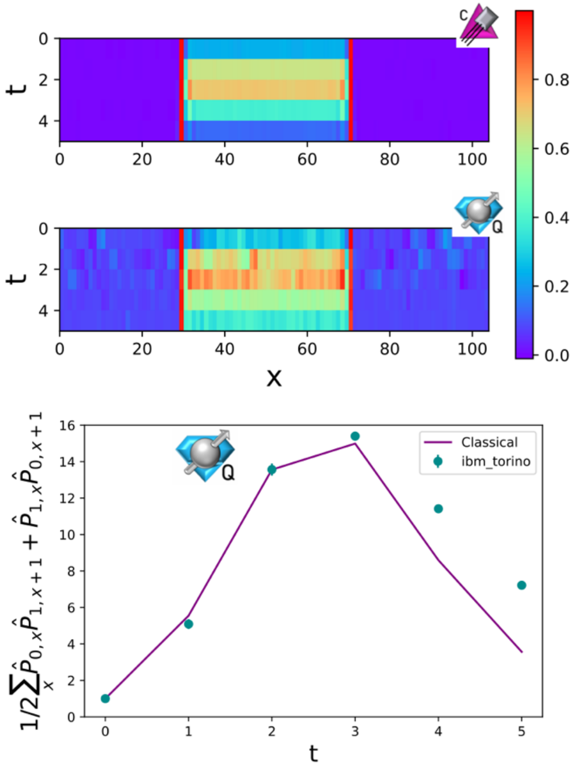
State-of-the-art: Confinement & String-Breaking in 1D

De, Lerose, Luo, Surace, Schuckert, … & Monroe, arXiv:2410.13815 (2024)



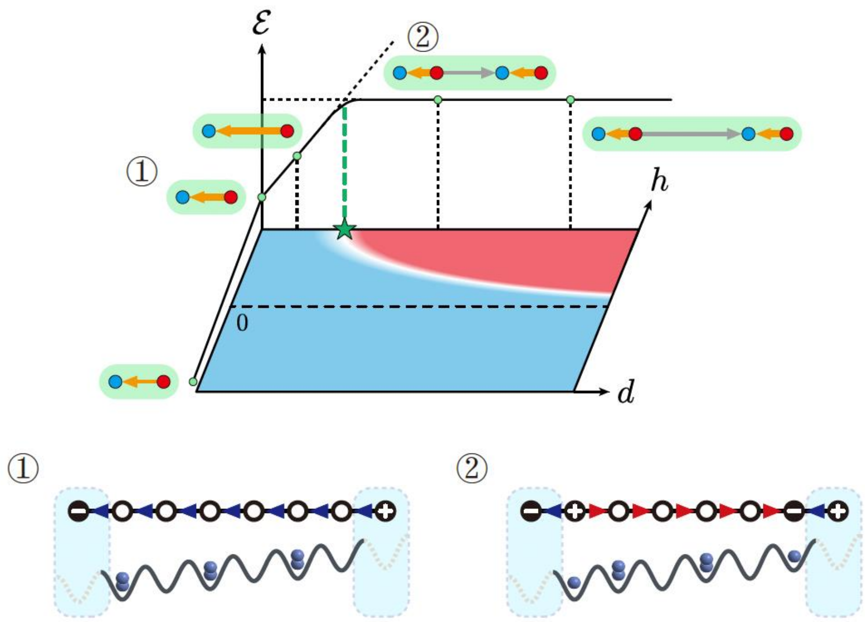
- 15 sites
- dualized Z2 LGT
- analog, trapped ions

Ciavarella, arXiv:2411.05915 (2024)



- 104 sites
- truncated SU(2), heavy quark limit
- hybrid-digital, supercond. qubits

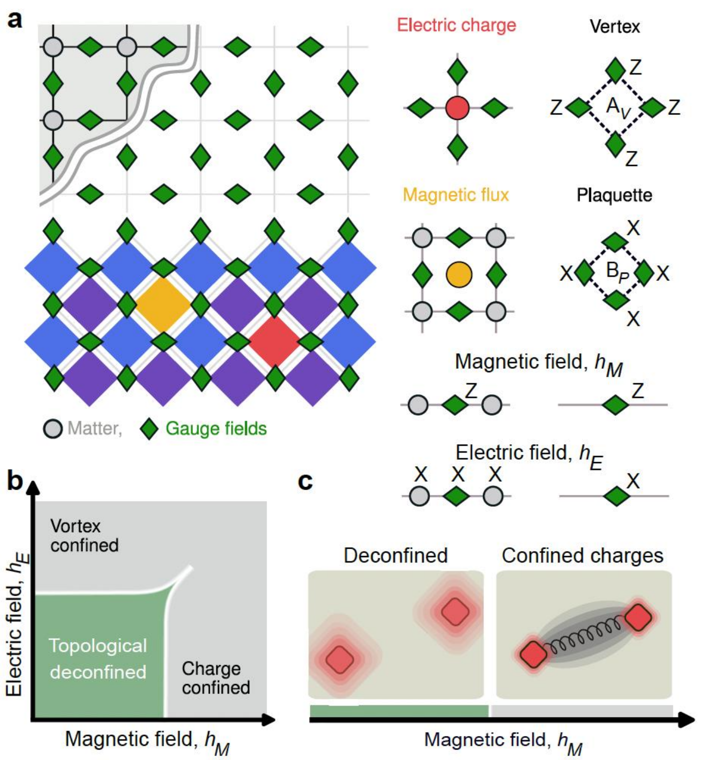
Liu, Zhang, Zhu, He, Yuan & Pan, arXiv:2411.15443 (2024)



- 10 sites
- S=1/2 U(1) QLM
- analog, cold atoms

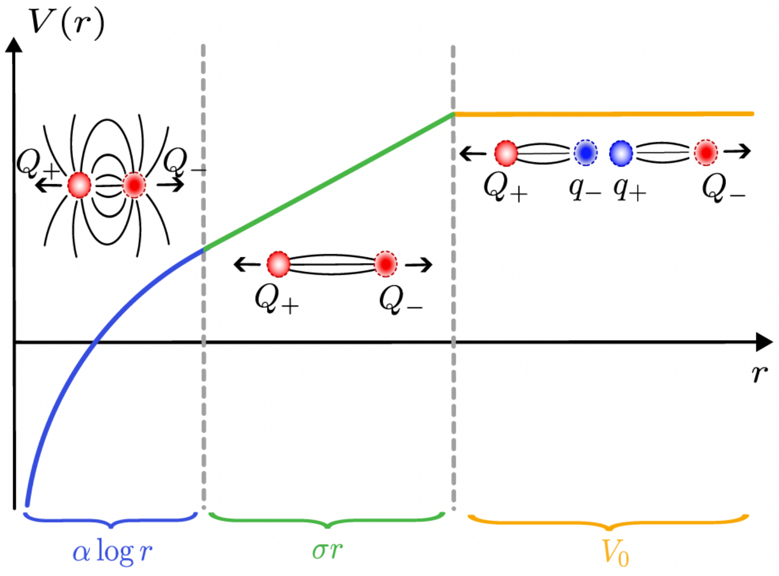
State-of-the-art: Confinement & String-Breaking in 2D

Cochran et al., arXiv:2409.17142 (2024)



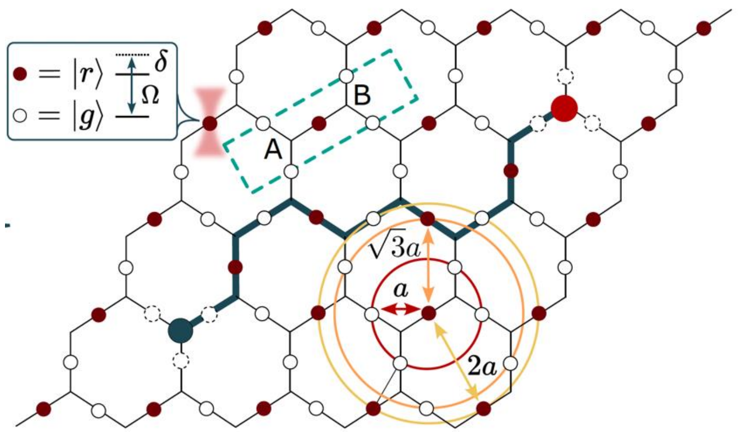
- 6 plaquettes (17+18 qubits)
- Z2 Higgs model
- hybrid-digital, supercond. qubits

Crippa, Jansen & Rinaldi, arXiv: 2411.05628 (2024)



- up to 6 plaquettes (10-20 qubits)
- truncated QED
- hybrid-digital, trapped ions

Gonzalez-Cuadra, Hamdan, TVZ, ... & Bylinskii, arXiv:2410.16558 (2024)



- 8-16 plaquettes (31-59 atoms)
- encoded U(1) QLM
- analog, Rydberg tweezer array

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Observation of string breaking on a (2+1)D Rydberg quantum simulator

IQOQI / Univ. Innsbruck:

D. González-Cuadra

→ Harvard

P. Zoller

arXiv:2410.16558

QuEra + Harvard:

M. Hamdan

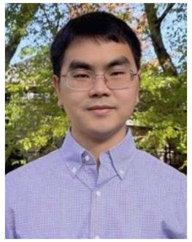
B. Braverman

→ Univ. Toronto

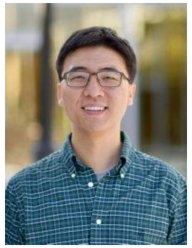
M. Kornjaca

A. Lukin

S. H. Cantu



F. Liu



S.-T. Wang

A. Keesling

M. D. Lukin

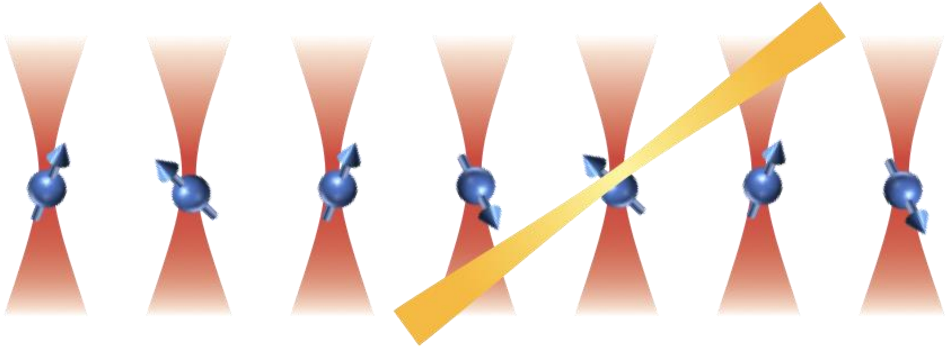
A. Bylinskii

Rydberg atom arrays

blockade = Gauss' law!

Hamiltonian: $$H_{\mathrm{Ryd}} = \frac{\Omega}{2}\sum_{\ell} X_\ell - \delta \sum_{\ell} n_\ell + \frac{1}{2}\sum_{(\ell,\ell')} V_{\ell,\ell'} n_\ell n_{\ell'}$$

Strong VdW interaction by coupling to Rydberg states: $$V_{\ell,\ell'} = \frac{C_6}{|\mathbf{r}_\ell - \mathbf{r}_{\ell'}|^6}$$



Neutral atoms trapped in tweezer array

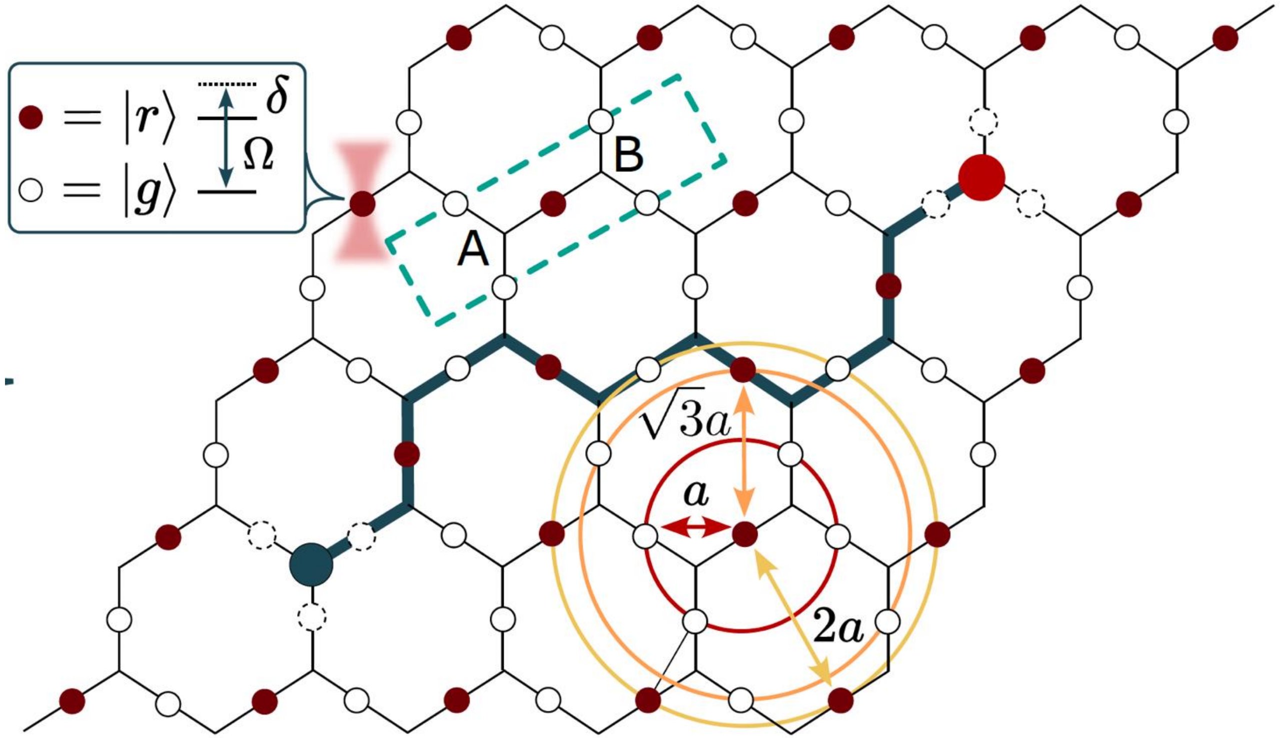
Rydberg blockade:

$$V(R_b) = \Omega \quad \Rightarrow R_b = \left(\frac{C_6}{2\Omega}\right)^{1/6}$$

Jaksch et al., Physical Review Letters 85, 2208 (2000)
Weimer, Müller, Lesanovsky, Zoller & Büchler, Nature Physics, 6(5), 382 (2010)
Browaeys & Lahaye, Nature Physics, 16(2), 132 (2020)
Surace et al., Physical Review X, 10, 021041 (2020)
Wurtz et al., arXiv:2306.11727 (2023)
Steinert et al., Physical Review Letters, 130(24), 243001 (2023)
Bluvstein et al., Nature, 626, 58 (2024)
Muniz et al., arXiv:2411.11708 (2024)
…

Analog 2D U(1) QLM with a Rydberg atom array

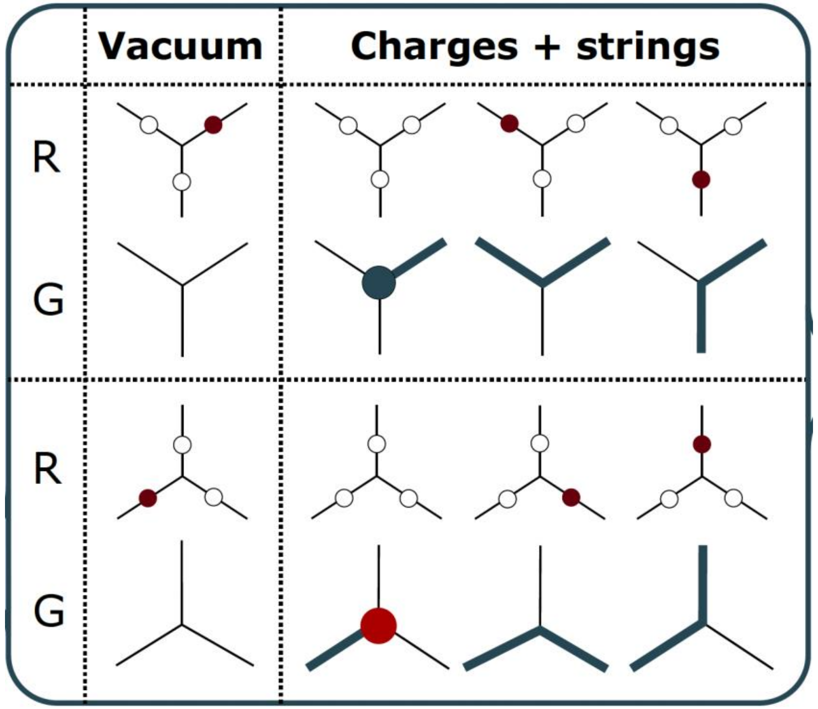
Honeycomb / Kagome lattice geometry:



$$n_\ell = |r\rangle_\ell \langle r| = \frac{1}{2} + (-1)^{s_\ell} S^z_\ell$$

Gauss' law & mapping:

$$G_x = \nabla_x S^z - Q_x \stackrel{!}{=} \frac{(-1)^{s_x}}{2}$$



Gonzalez-Cuadra, Hamdan, TVZ, Braverman, Kornjaca, Lukin, Cantu, Liu, Wang, Keesling, Lukin, Zoller & Bylinskii, arXiv:2410.16558 (2024)
See also: Samajdar et al., Proceedings of the National Academy of Sciences, 118, e2015785118 (2021)

Review of quantum link models (QLMs): Wiese, Philosophical Transactions of the Royal Society A, 380, 20210068 (2022)

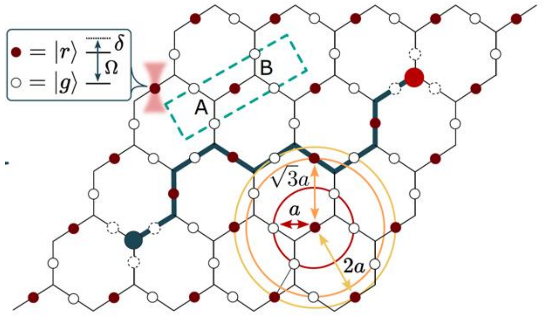
Theory expectations: confinement + string breaking

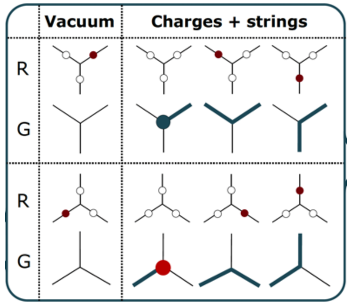
matter-gauge interaction *mass*

$$H_{\text{eff}} = \frac{\Omega}{2}\sum_{\langle x,y\rangle}\left[a_x^\dagger S^+_{\langle x,y\rangle} a_y + \text{H.c.}\right] + \frac{\delta}{2}\sum_x (-1)^{s_x} a_x^\dagger a_x$$

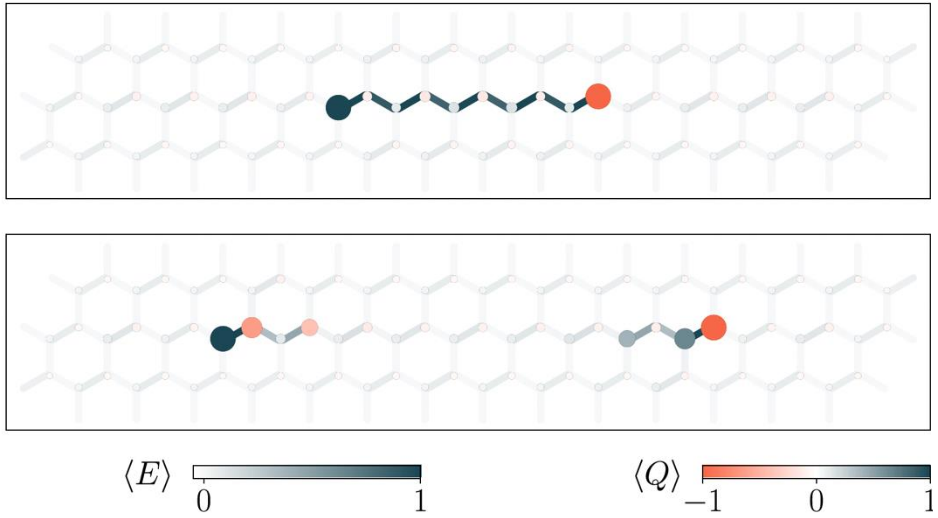
$$+ \frac{1}{2}\sum_{(\ell,\ell')\neq\langle\ell,\ell'\rangle} V_{\ell,\ell'}\left[(-1)^{s_\ell} S^z_\ell + \frac{1}{2}\right]\left[(-1)^{s_{\ell'}} S^z_{\ell'} + \frac{1}{2}\right]$$

electric energy

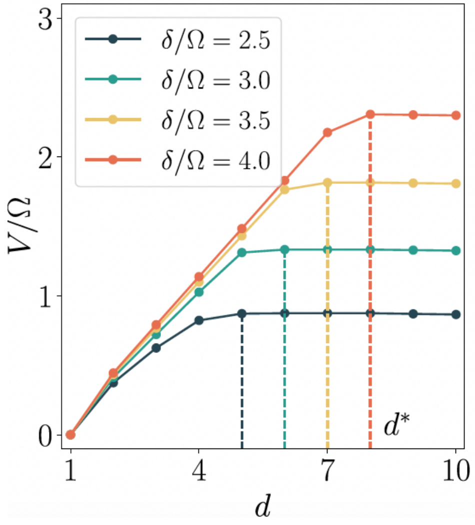




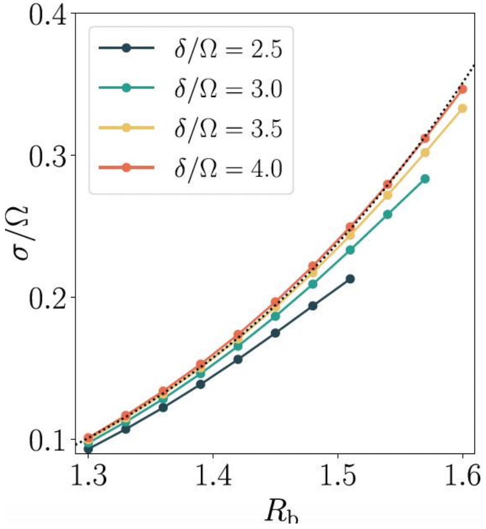
Ground state with static charges, DMRG results:



Potential

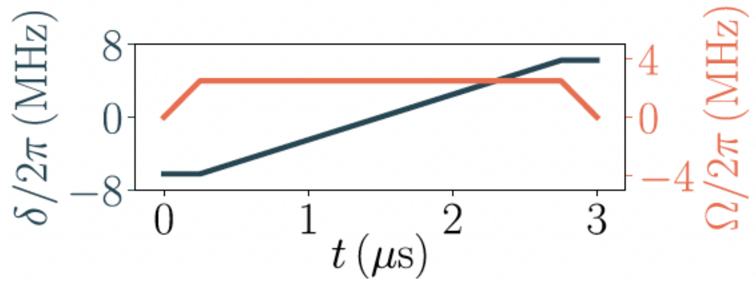


String tension

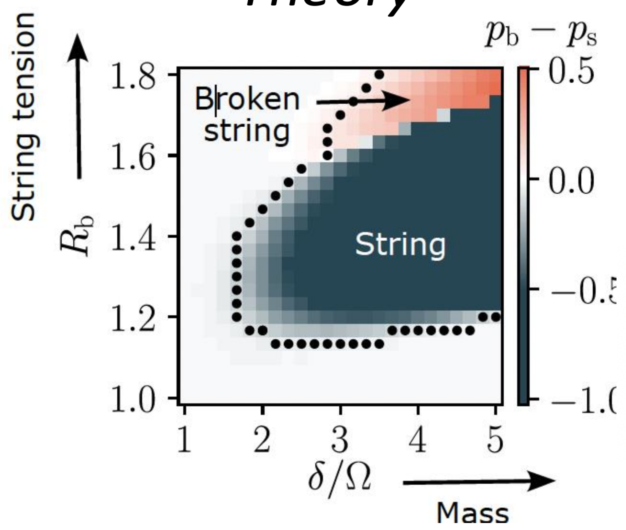


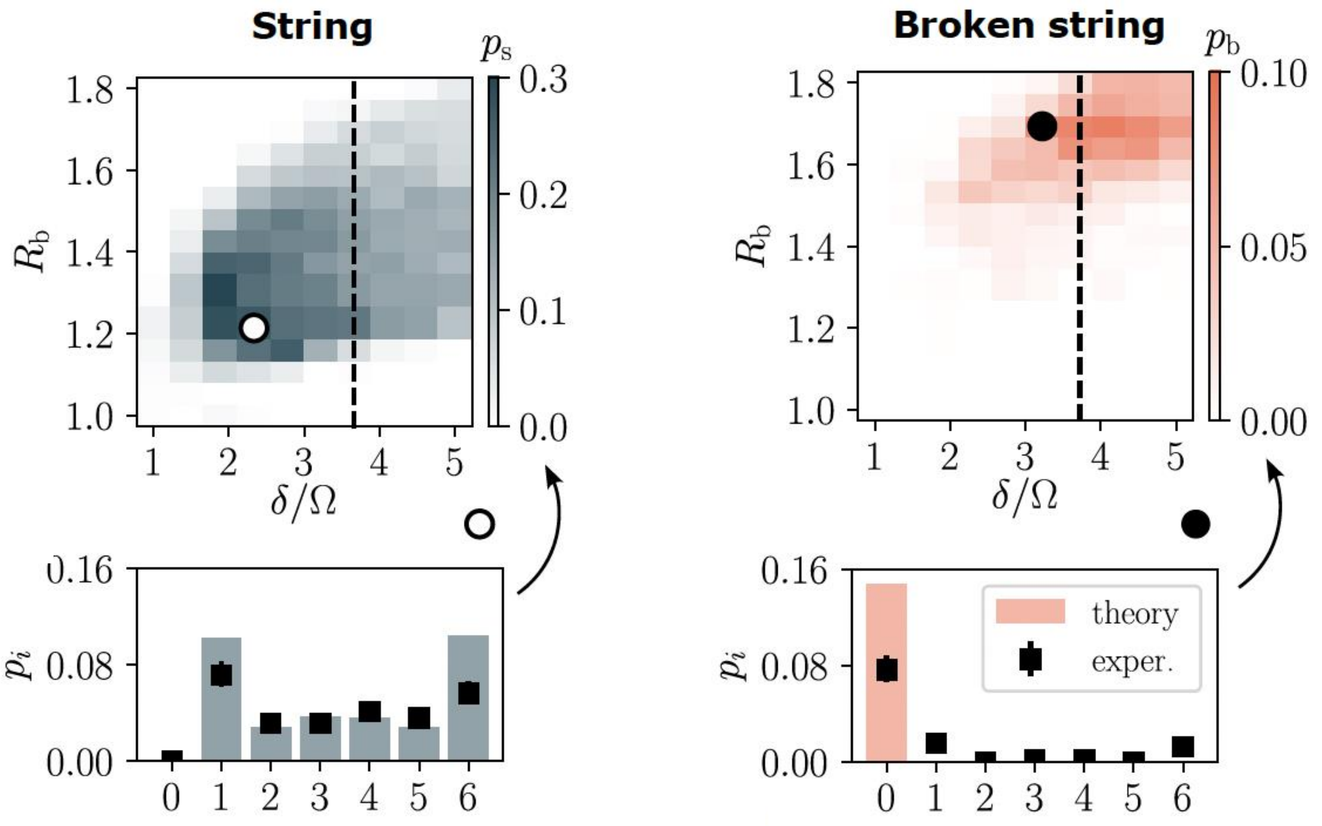
Experimental results: ground state peparation

Adiabatic state preparation on “Aquila” (QuEra)

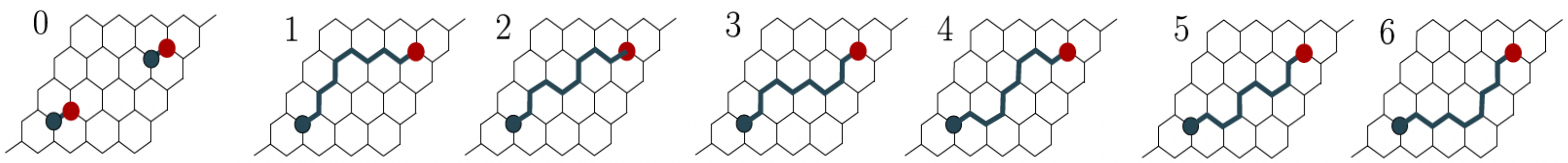


Theory





String configurations



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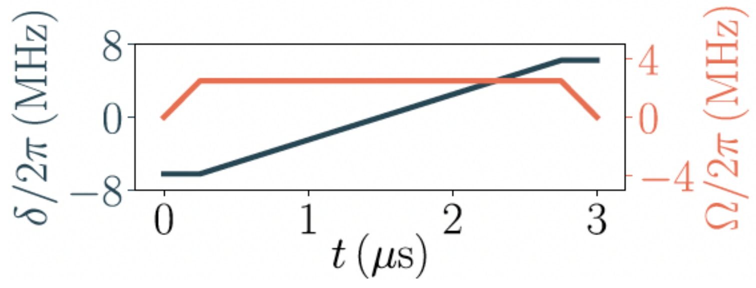
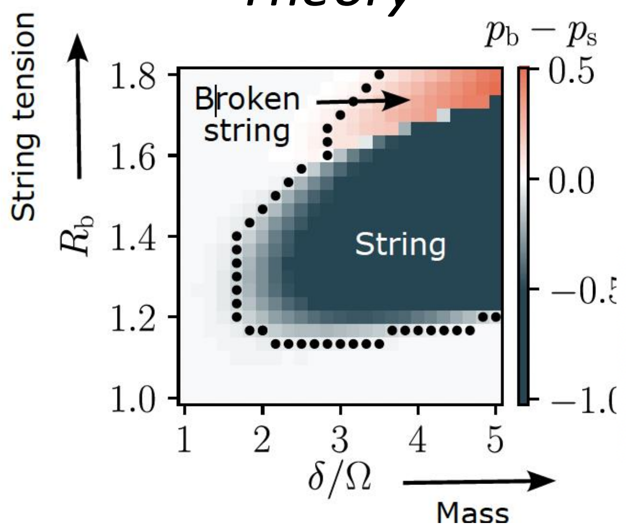
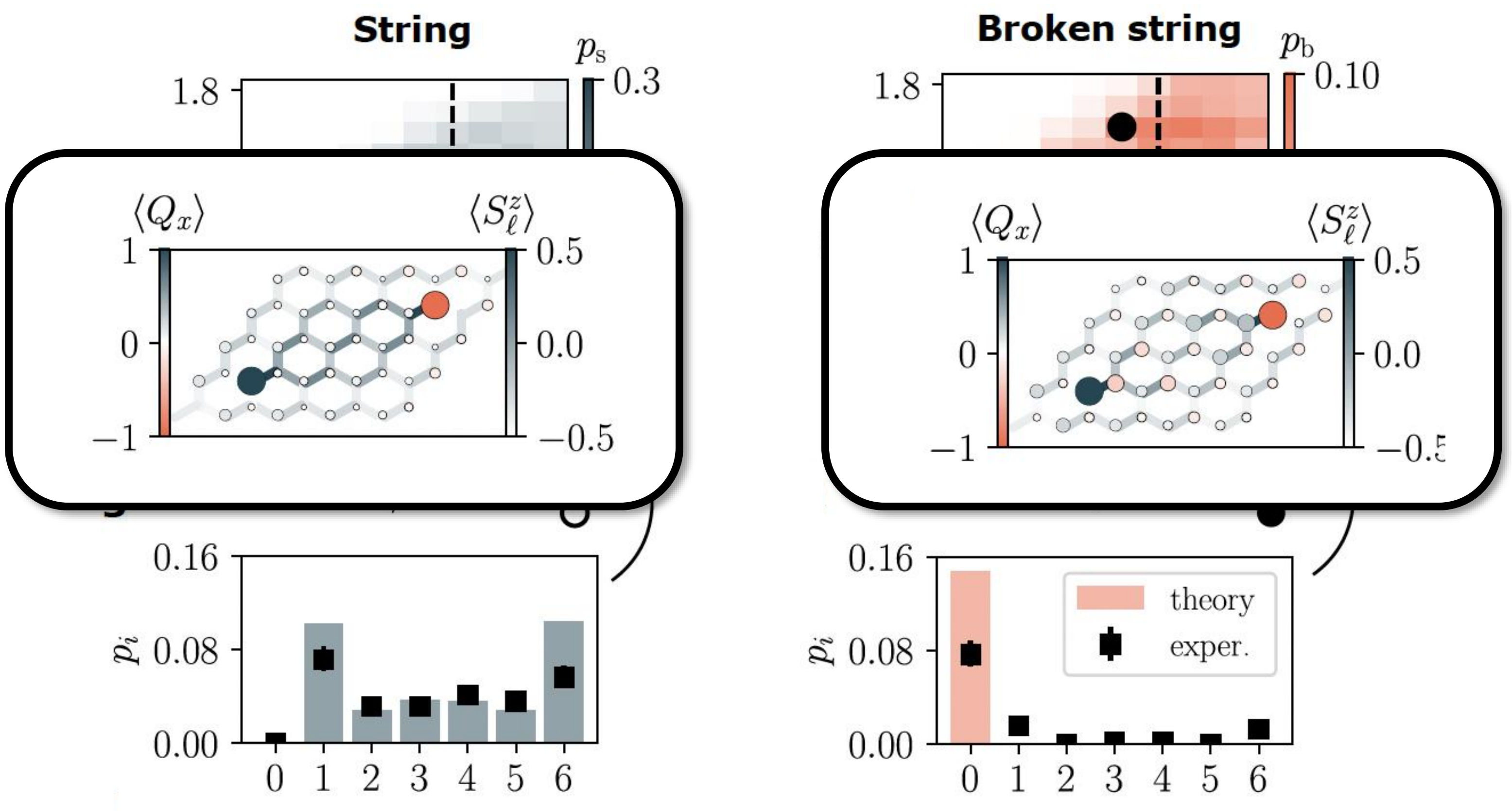
Adiabatic state preparation on “Aquila” (QuEra)

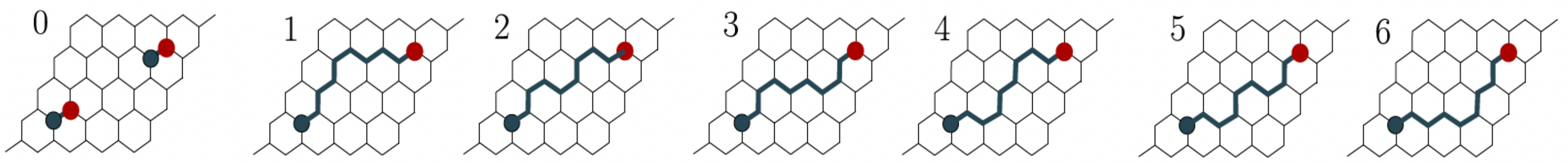


Theory

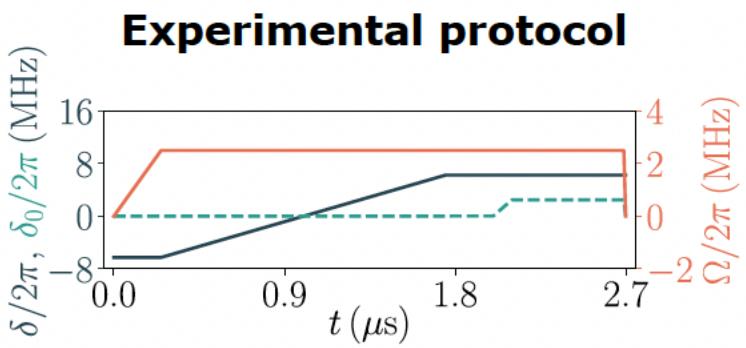




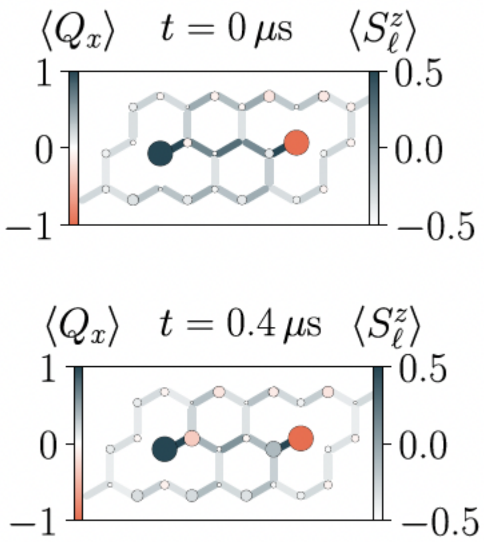
String configurations

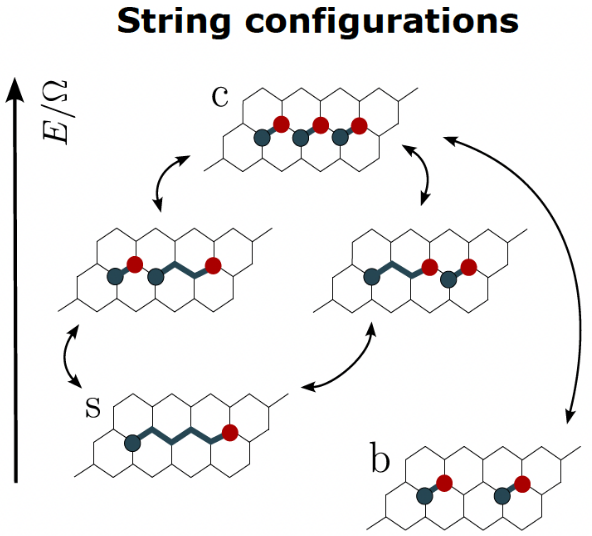


Experimental results: dynamics of a string

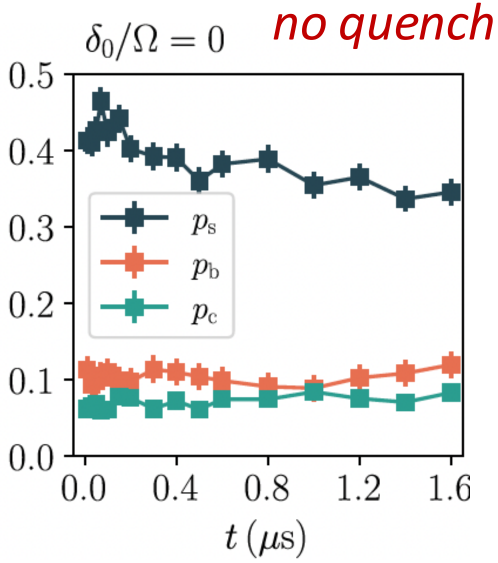


Adiabatic state prep. + local detuning quench

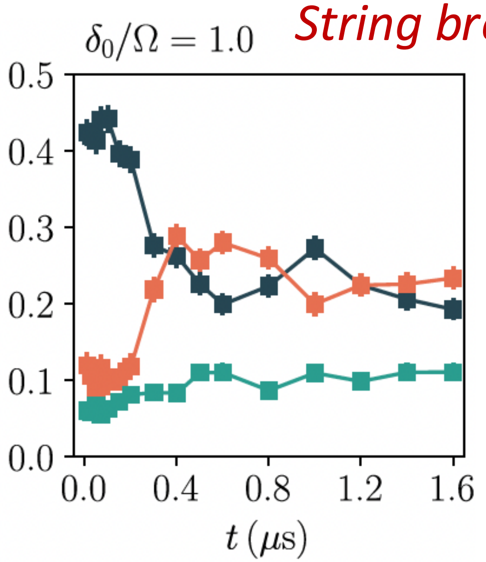




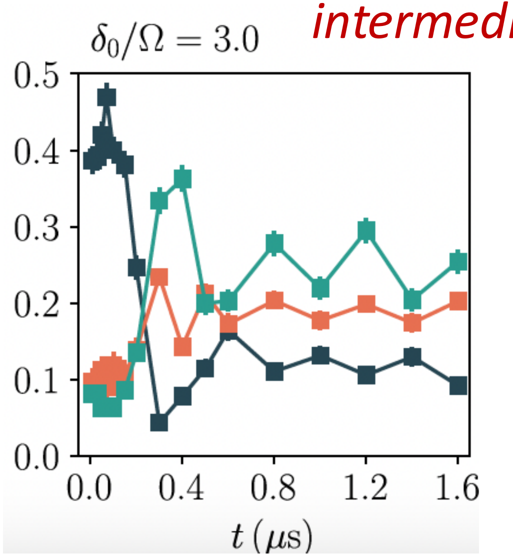
no quench



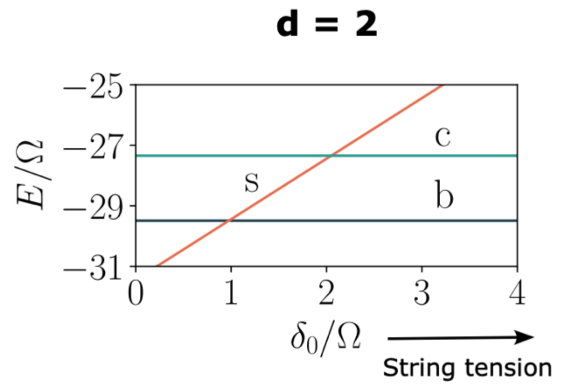
String breaking!

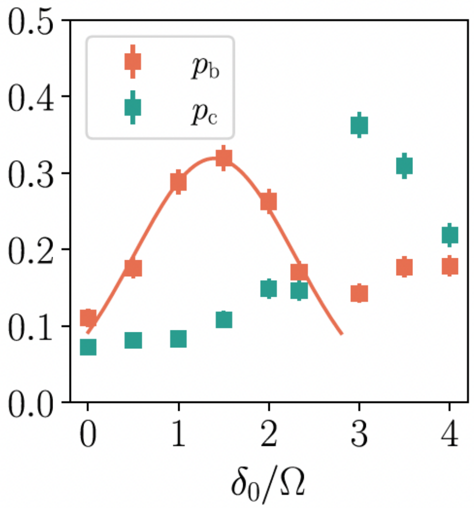


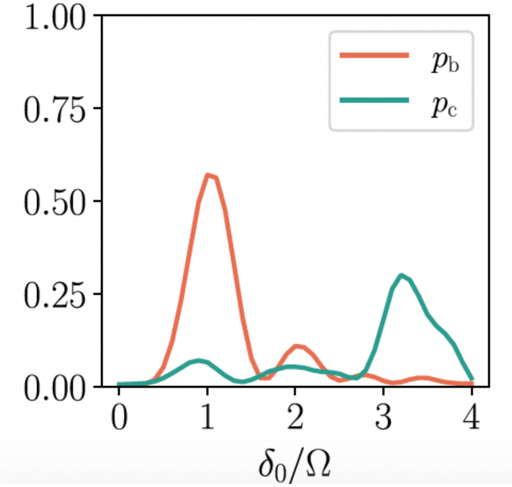
intermediate state



Experimental results: resonance of string-breaking



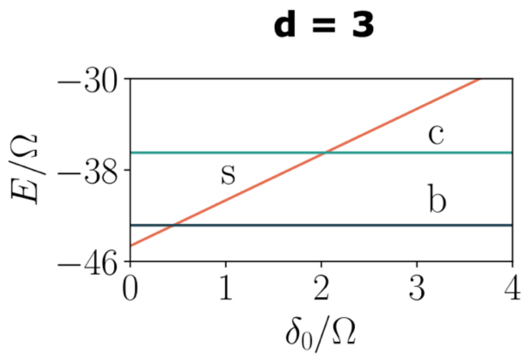


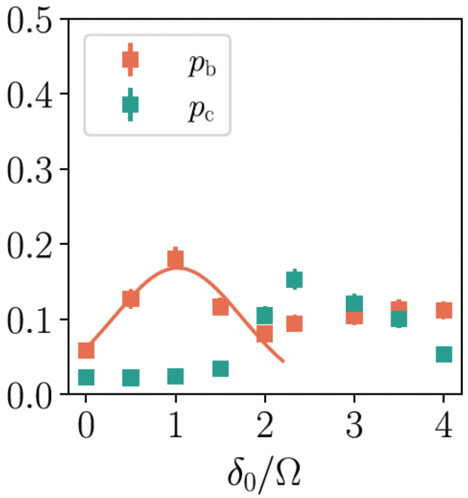


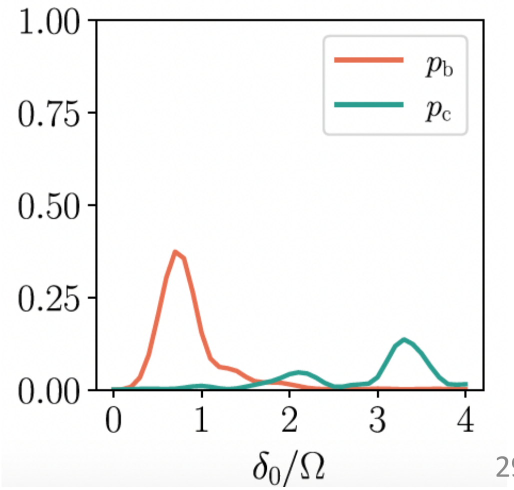
Theoretical energy levels

Experiment

Simulation







Outline

Motivation: why study gauge theories?

Overview of quantum platforms & early LGT implementations

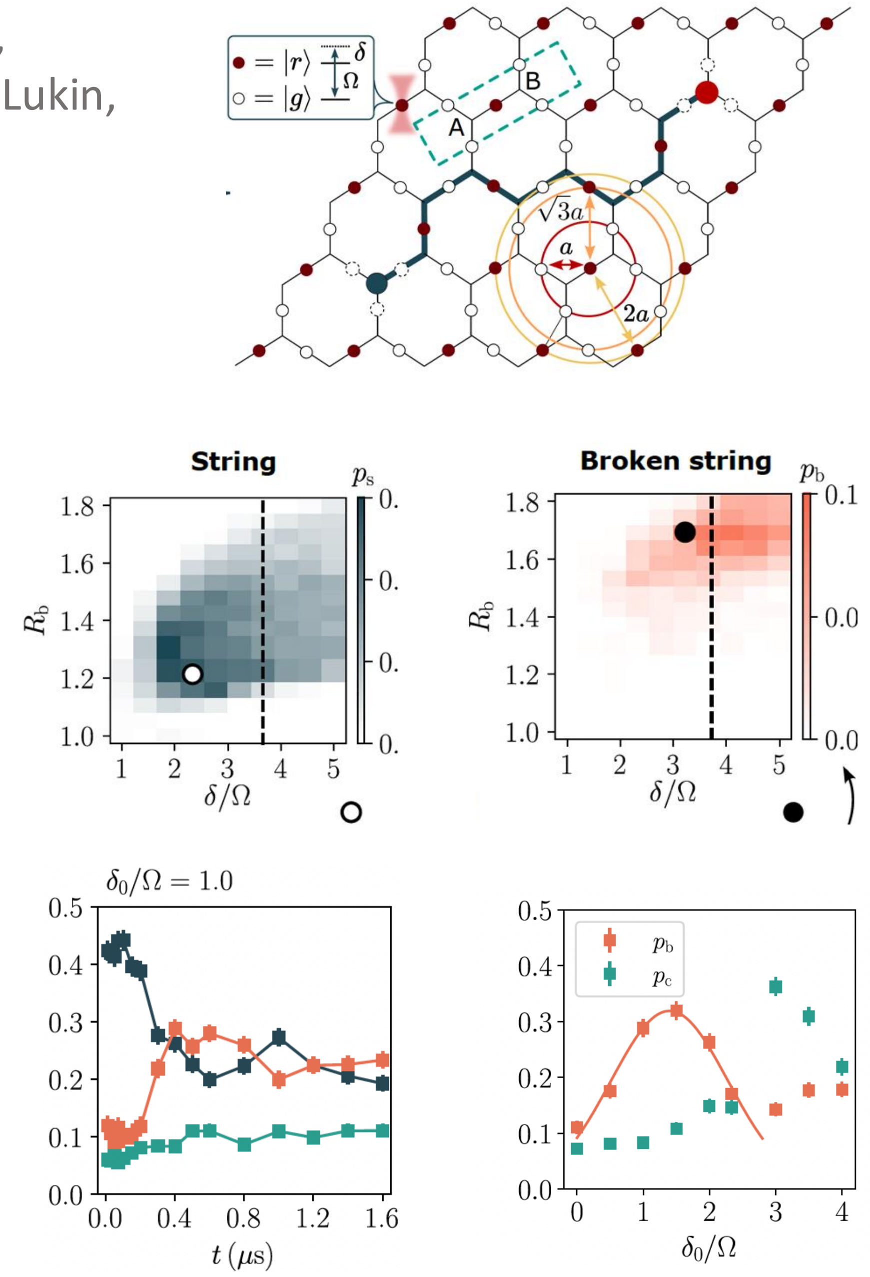
State-of-the-art: selected highlights from 2024

Observation of string-breaking on a (2+1)D Rydberg simulator

Conclusion & Outlook

Summary

Gonzalez-Cuadra, Hamdan, TVZ, Braverman, Kornjaca, Lukin, Cantu, Liu, Wang, Keesling, Lukin, Zoller & Bylinskii, arXiv:2410.16558 (2024)



- ✓Analog quantum simulator for 2D U(1) QLM with Rydberg atom array
- ✓Ground state "Phase diagram" of (un)broken strings
- ✓Real-time dynamics of resonant string-breaking
- ❖.. include plaquette interactions?!

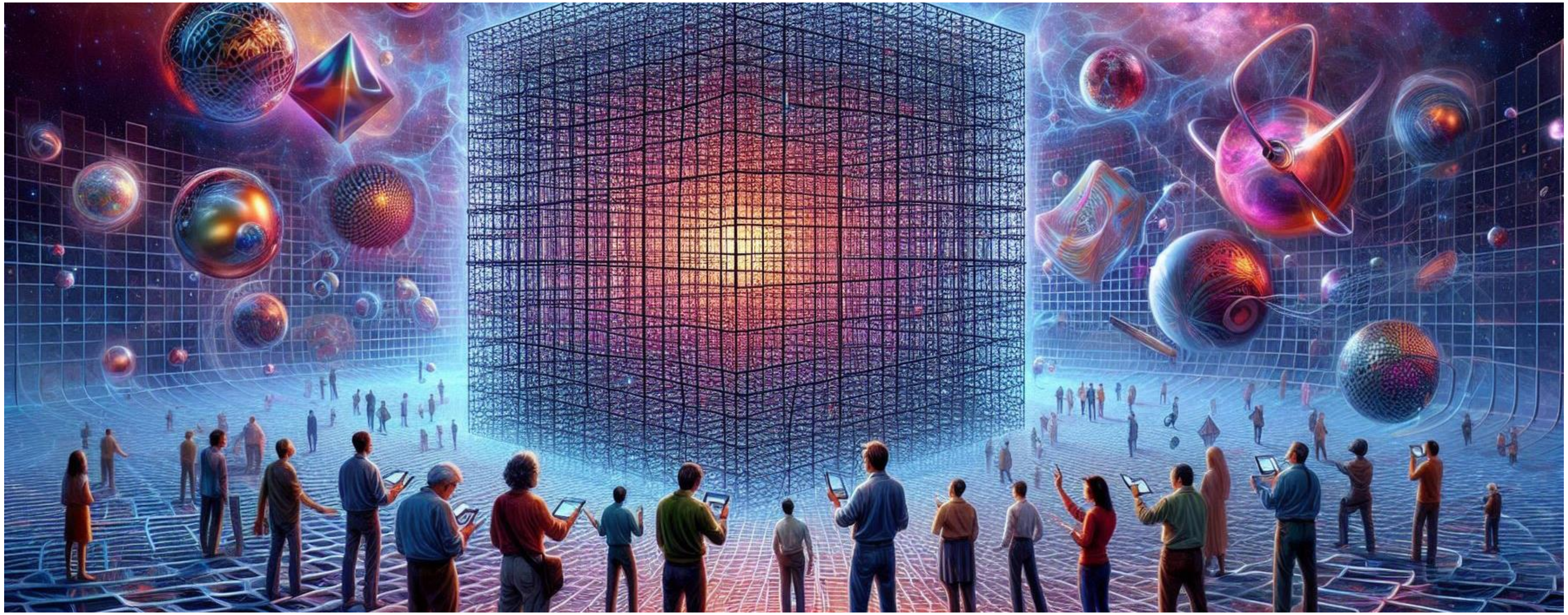
Feldmeier et al., arXiv:2408.02733 (2024)

Outlook

Will there be a quantum simulation of lattice QCD in 2025?

"While a full-fledged quantum simulation of lattice QCD at the same level of accuracy as state-of-the-art classical methods may not be fully realized by 2025, significant progress is expected, and key developments could lay the groundwork for such simulations in the coming years. **The path forward will involve a combination of quantum hardware improvements, algorithmic innovation, and hybrid approaches**."

Reply by Chat GPT4o mini



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Thanks for listening!