Probing Quantum Phases of Matter on Quantum Processors

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Quantum AI


QUANTINUUM

DFG TRR 360 FOR 5522 MCQST erc EQUAHUMO Efficient Quantum Algorithms for the Hubbard Model | Munich Quantum Valley

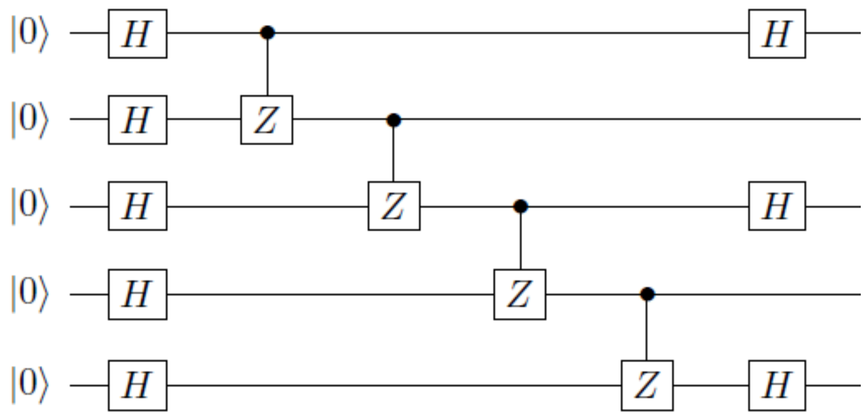
Advanced School and Conference on Quantum Matter
ICTP Trieste, Dec. 3 2025

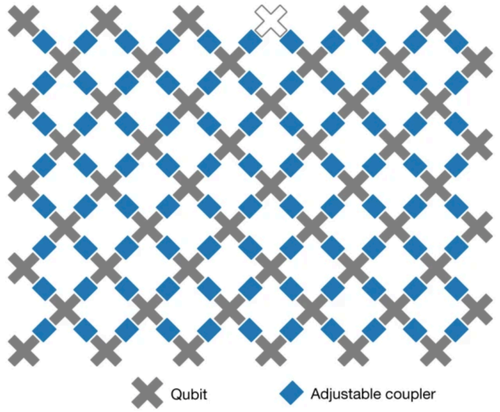
Simulate Quantum Matter on Quantum Processors

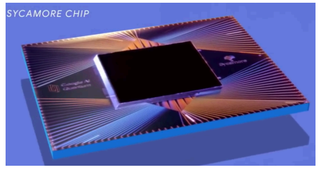
Quantum algorithms to generate entangled quantum many-body states

$$H|\psi_0\rangle = E_0|\psi_0\rangle \qquad |\psi_t\rangle = e^{-iHt}|\psi_i\rangle$$

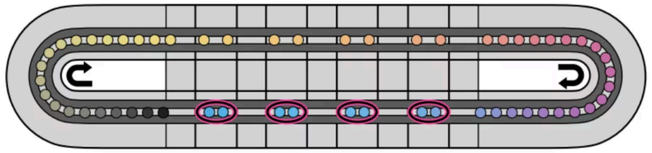
$$|\psi\rangle =$$

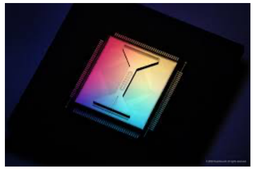






SC qubits





Ion traps

- "NISQ" devices: Limited circuit depth and connectivity, readout errors, …
- Identify problems that are **hard on classical computers but doable on near term NISQ devices:** Potential exponential speedup!

Outline

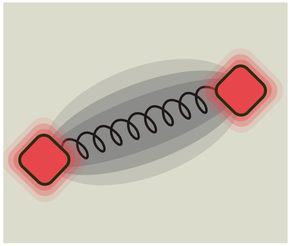
Realization of topological ordered ground states

- Topological entanglement
- Anyonic quasi-particles



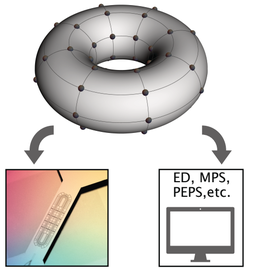
Dynamics of the confinement transition

- Tuning away from the fixed point
- Dynamics of quasi particles



Digital quantum magnets

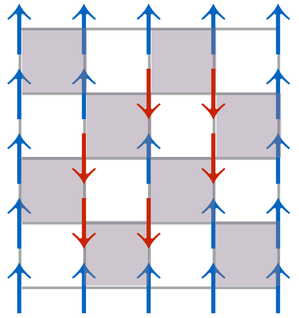
- Simple realization of thermal magnetic states



Toric code model

$$\hat{H} = -\sum_{\{\square\}} \underbrace{\hat{\sigma}^z\hat{\sigma}^z\hat{\sigma}^z\hat{\sigma}^z}_{A} - \sum_{\{\square\}} \underbrace{\hat{\sigma}^x\hat{\sigma}^x\hat{\sigma}^x\hat{\sigma}^x}_{B}$$

[Kitaev '97]



Ground state: All terms in H commute $\rightarrow$ Eigenvalue $+1$ on all plaquettes

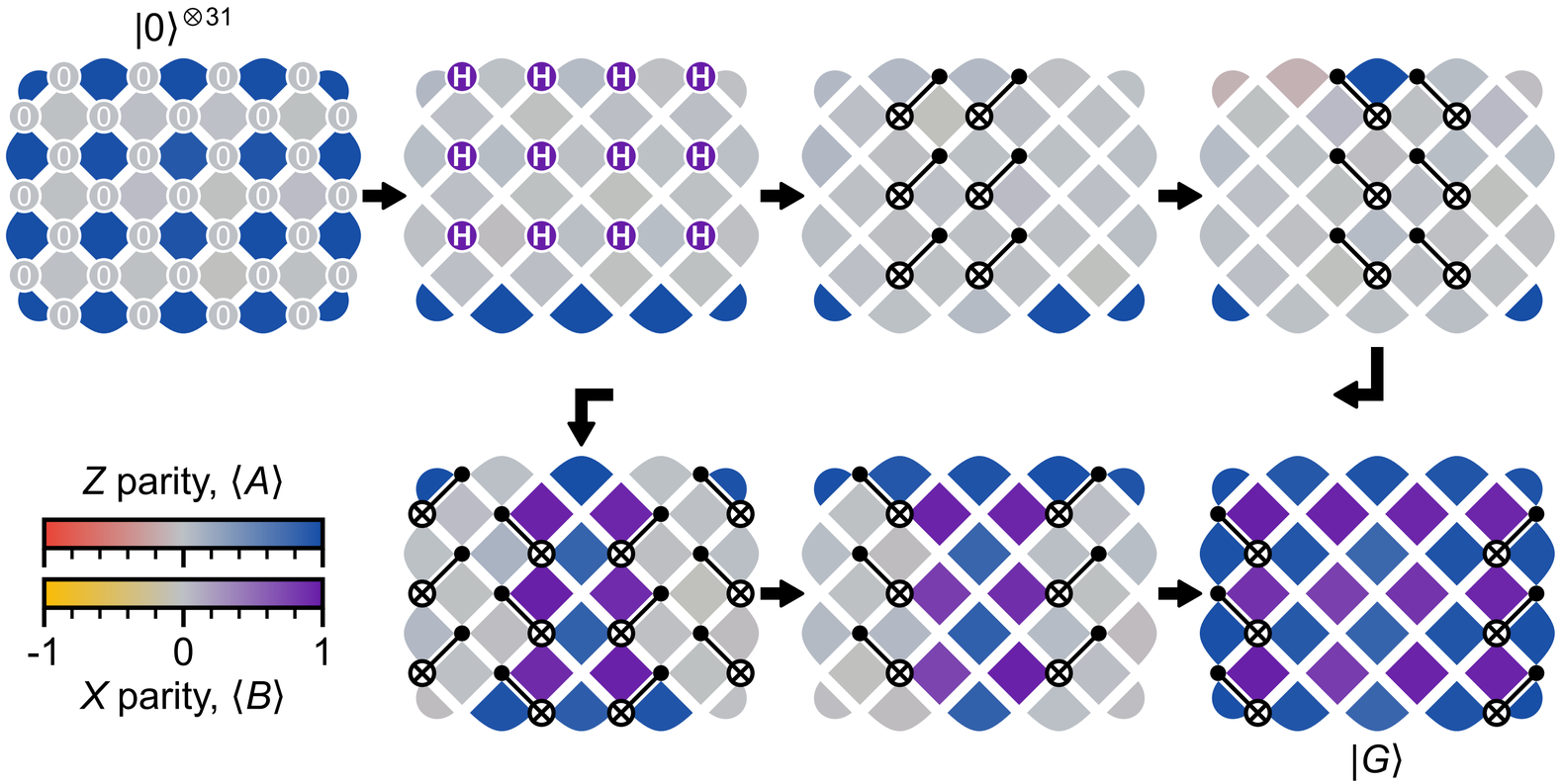
$$|\psi_0\rangle = \left|\ \right\rangle = \frac{1}{\mathcal{N}}\left(\left|\ \right\rangle + \ldots + \left|\ \right\rangle\right)$$

"Quantum Spin Liquid (QSL)": No symmetry breaking!

Hidden structure: Topological order and non-local entanglement! [Wen '90]

Realizing a QSL on a Quantum Processor

Generate the **Toric code** ground state using a quantum circuit



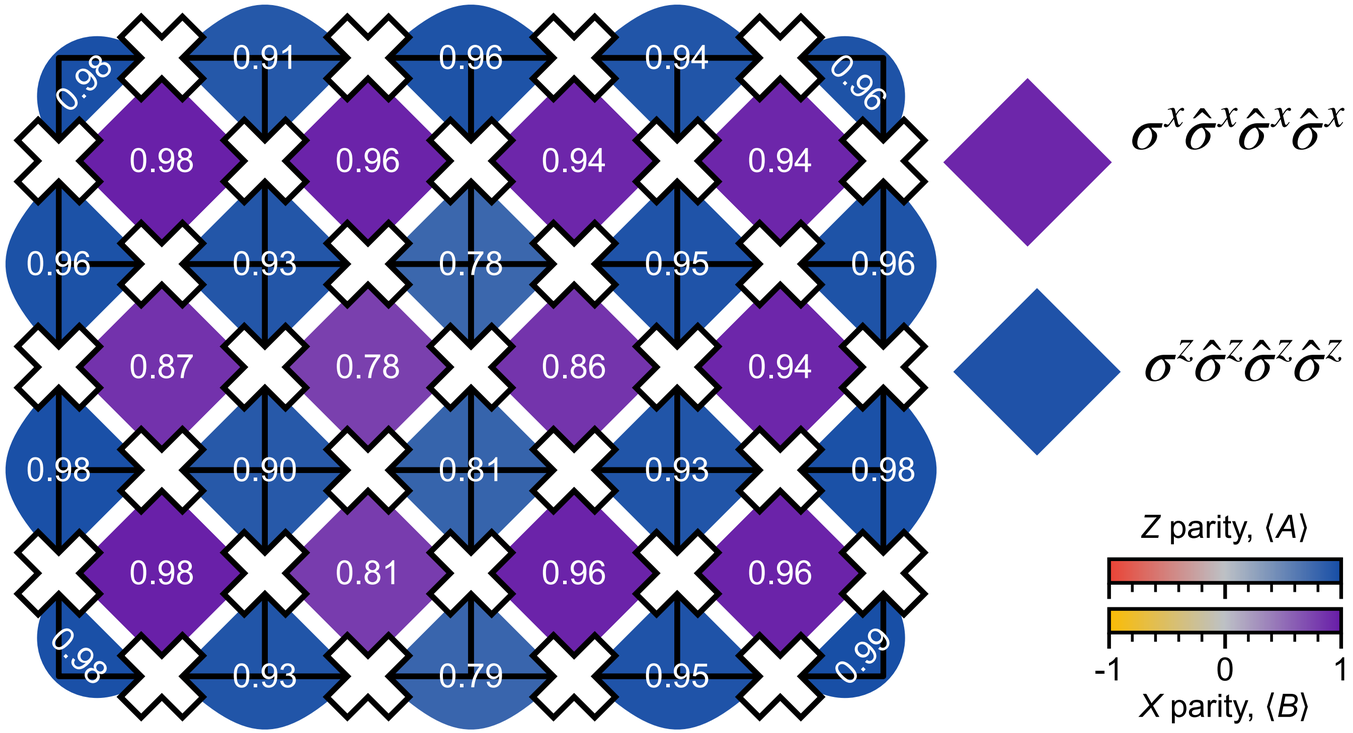
- Linear depth to generate $|\psi_0\rangle$

[Satzinger, Liu, Smith et al., Knap, FP, Roushan Science **374**, 1237 (2021)]

Realizing a QSL on a Quantum Processor

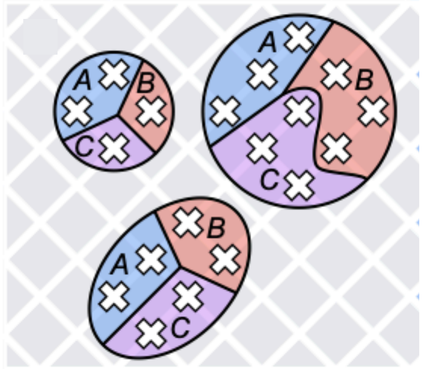
Toric code ground state: Topological entanglement entropy $S_{\text{topo}} = -\ln 2$

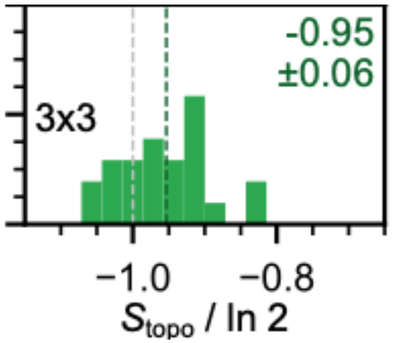
[Kitaev and Preskill '06, Levin and Wen '06]



$\sigma^x \hat{\sigma}^x \hat{\sigma}^x \hat{\sigma}^x$

$\sigma^z \hat{\sigma}^z \hat{\sigma}^z \hat{\sigma}^z$

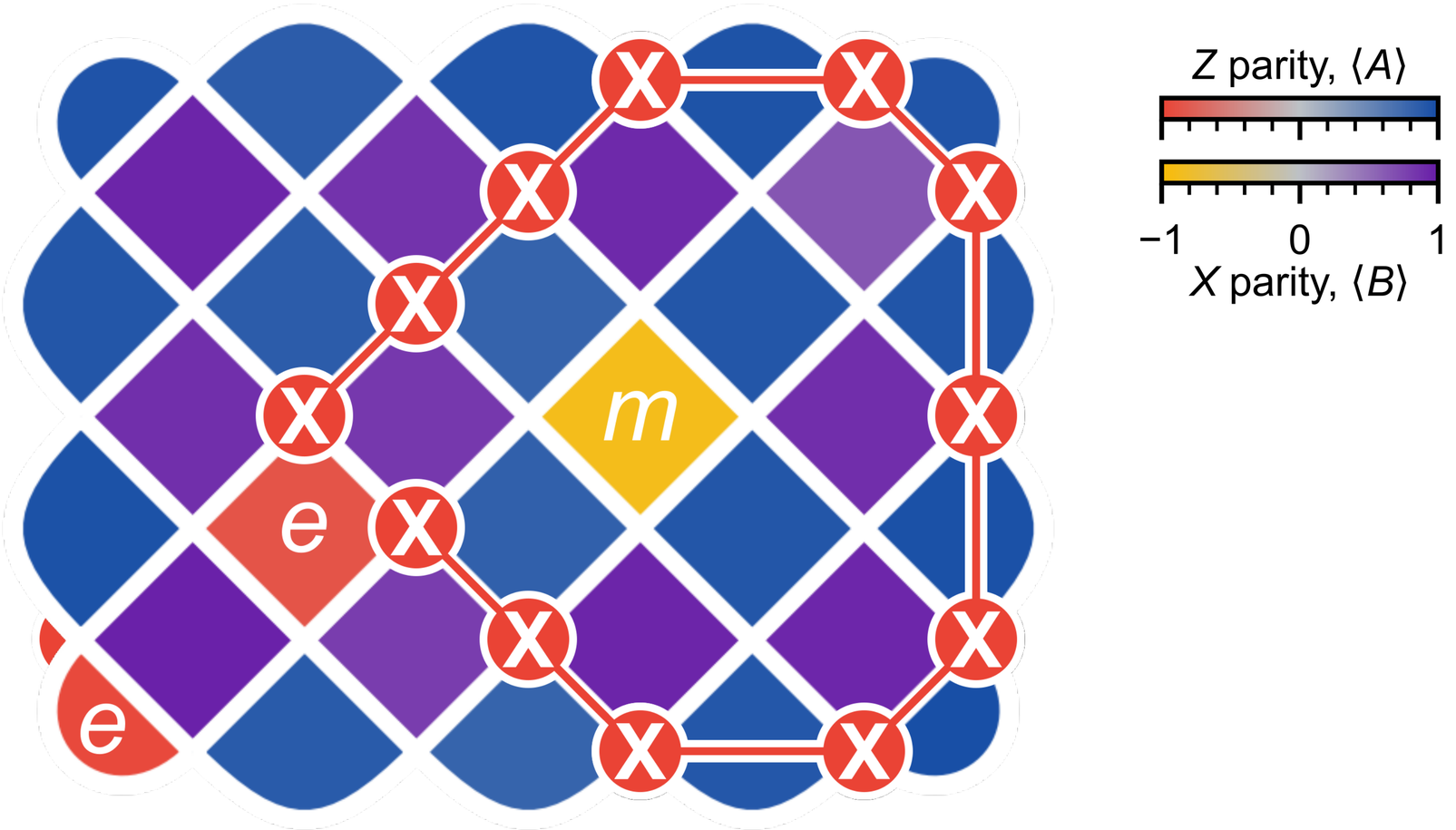




31 qubits, average stabilizer fidelity 0.92 ±0.06

[Satzinger, Liu, Smith et al., Knap, FP, Roushan Science **374**, 1237 (2021)]

Anyonic Statistics on a Quantum Processor



[Satzinger, Liu, Smith et al., Knap, FP, Roushan Science **374**, 1237 (2021)]

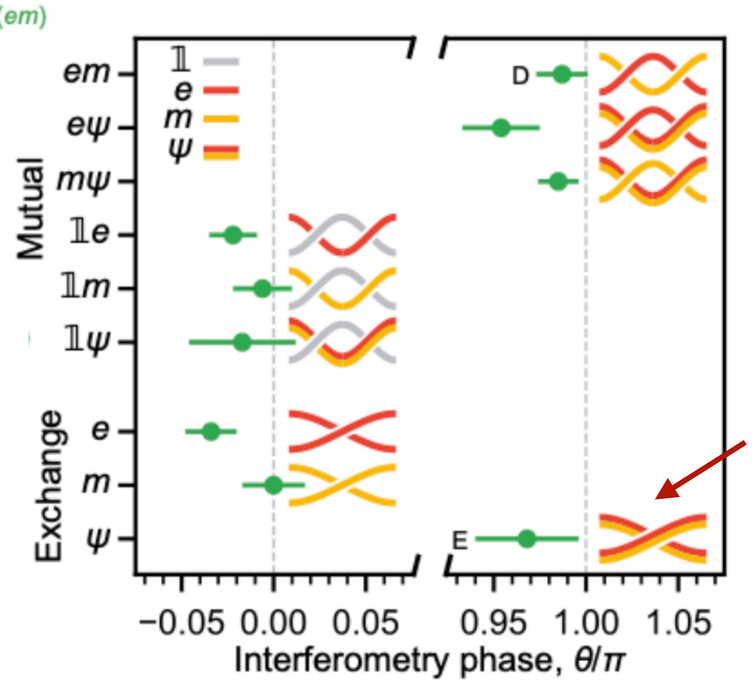
Anyonic Statistics on a Quantum Processor



[Jiang et al. '08]







Emergent Fermion!

[Satzinger, Liu, Smith et al., Knap, FP, Roushan Science **374**, 1237 (2021)]

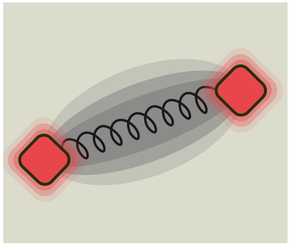
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- Topological entanglement
- Anyonic quasi-particles

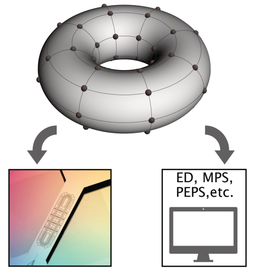
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- Tuning away from the fixed point
- Dynamics of quasi particles



Digital quantum magnets

- Simple realization of thermal magnetic states

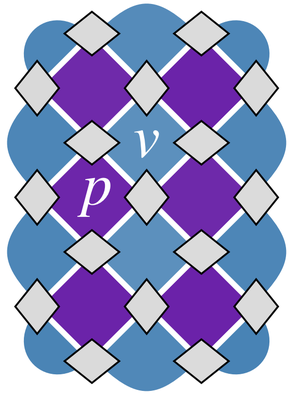


Beyond the fixed point: Confinement transition

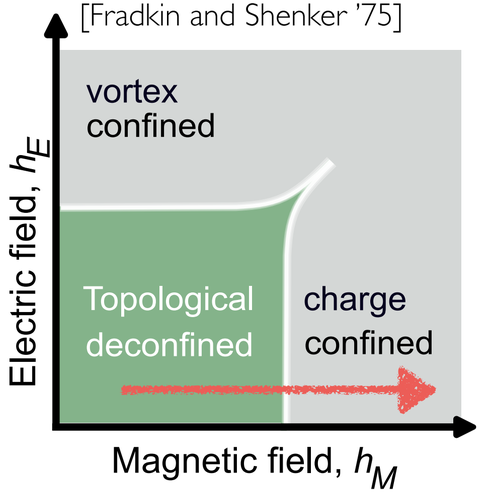
Toric code in a field

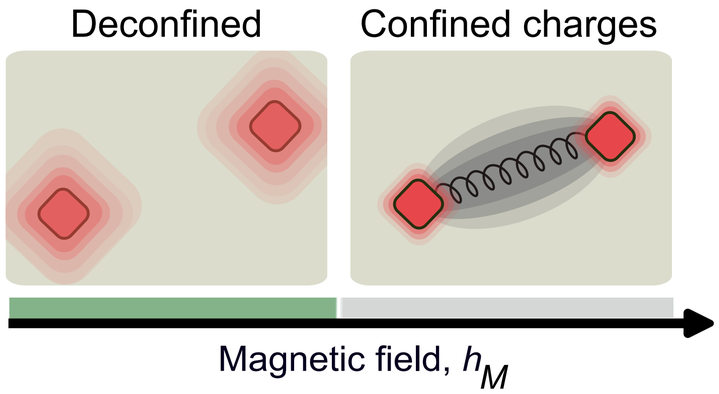
$$H = -J\sum_{v} A_v - J\sum_{p} B_p - h_M\sum_{l} Z_l - h_E\sum_{l} X_l$$

with $A_v = \prod_{i\in v} Z_i$ and $B_p = \prod_{i\in p} X_i$



[Fradkin and Shenker '75]





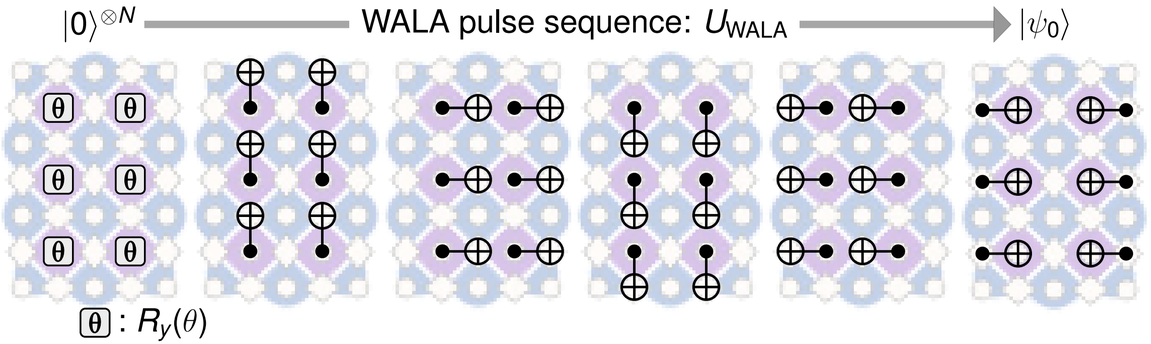
- Condensation of magnetic fluxes and confinement of electric charges

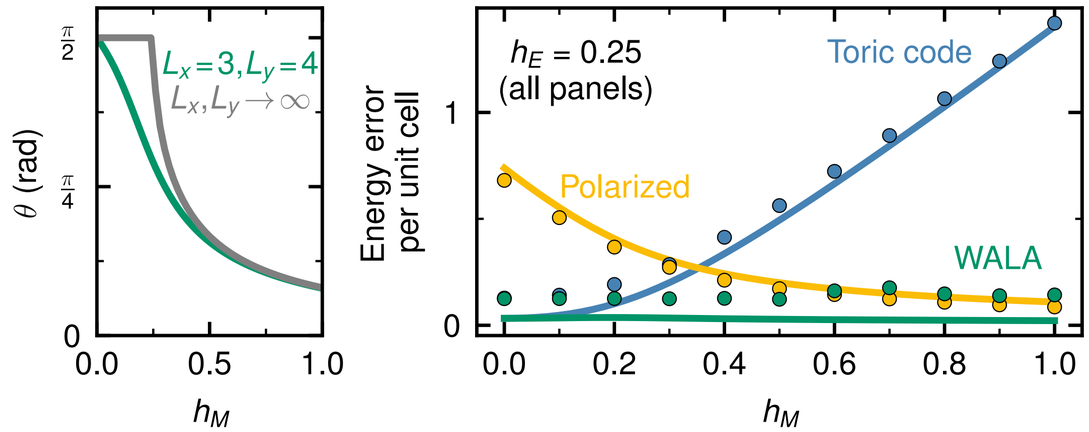
Beyond the fixed point: Confinement transition

Weight Adjustable Loop Ansatz (WALA):

$$|\psi\rangle = \prod_p \left(\cos\left(\tfrac{\theta}{2}\right)\mathbb{1} + \sin\left(\tfrac{\theta}{2}\right) B_p\right)|0\rangle$$

[Dusuel and Vidal '15, Sun et. al '23]

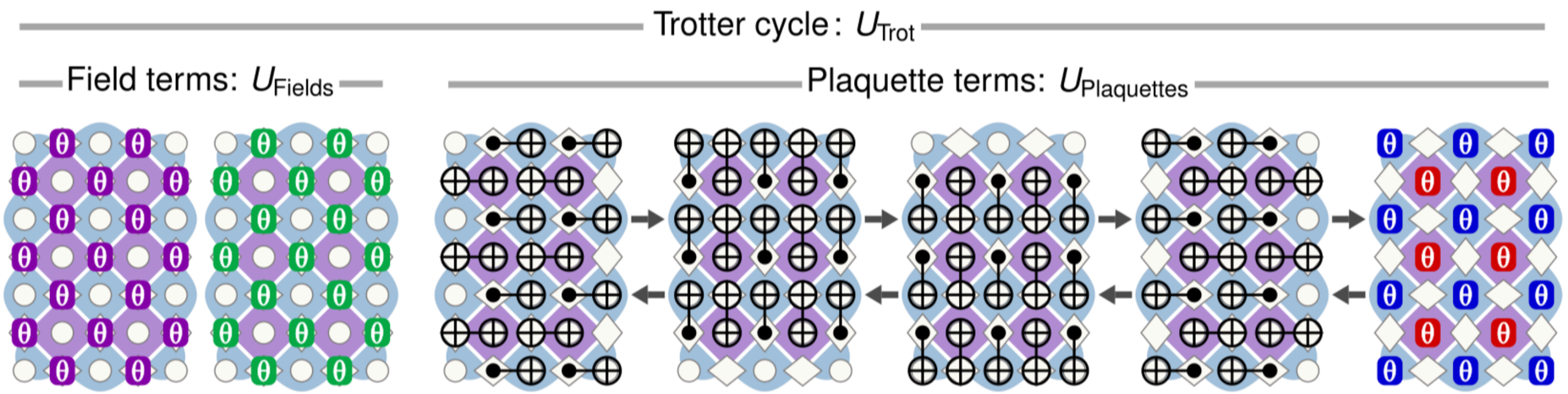




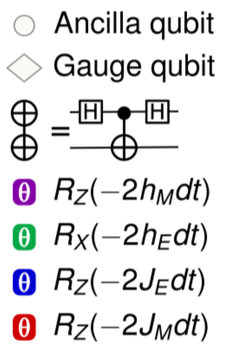
- Variational WALA state is simple to prepare and has low energy density

[Cochran, Jobst, et al., Smith, FP, Knap, Roushan, Nature **642**, 315 (2025)]

Suzuki-Trotter evolution circuit

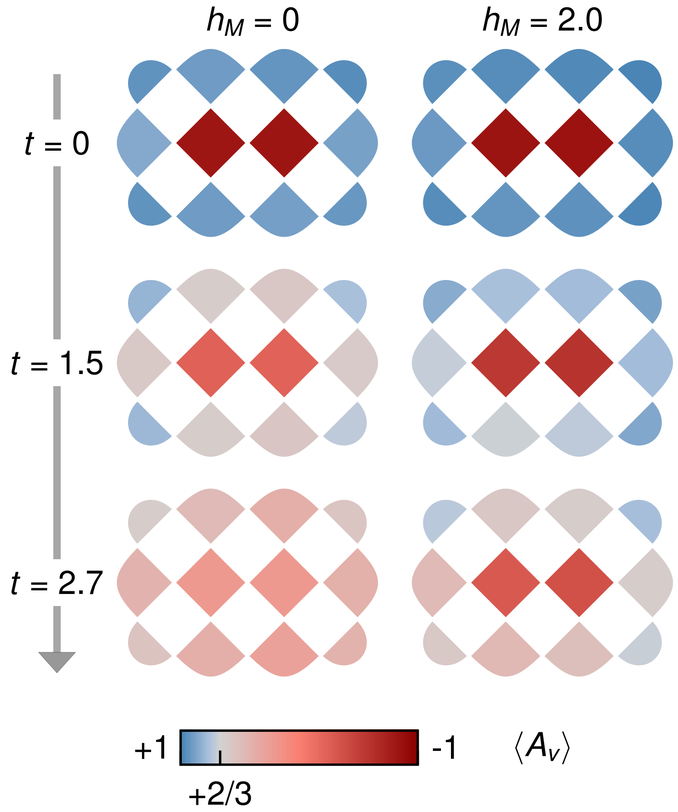


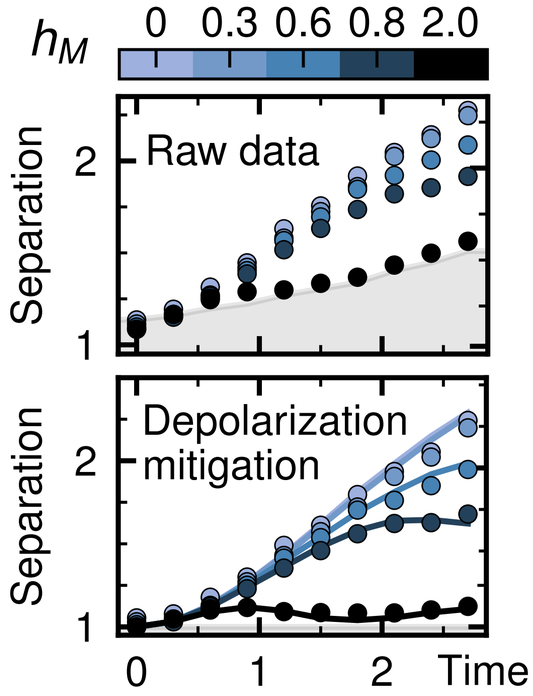
- Efficient Suzuki-Trotter using ancilla qubits
  (116 CZ gates per time step for the grid of 35 qubits)
- Post-select the measured data on the
  ancilla $|0\rangle$ state to mitigate decoherence



[Cochran, Jobst, et al., Smith, FP, Knap, Roushan, Nature **642**, 315 (2025)]

Confinement dynamics of electric charges

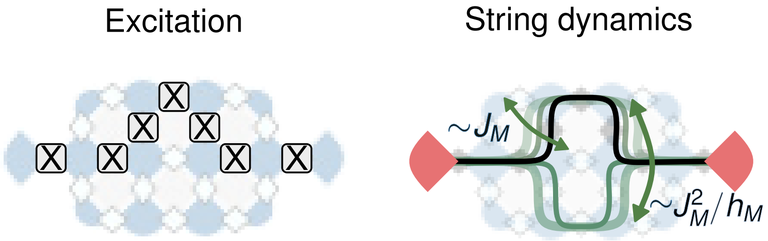


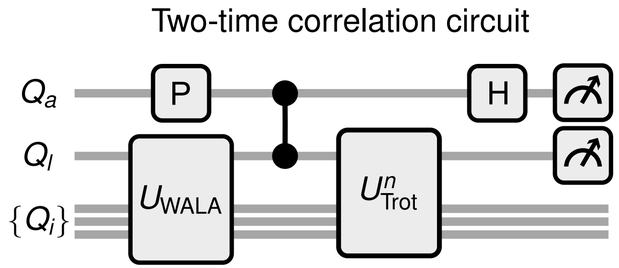


- Qualitatively distinct dynamical signatures as the magnetic field is tuned

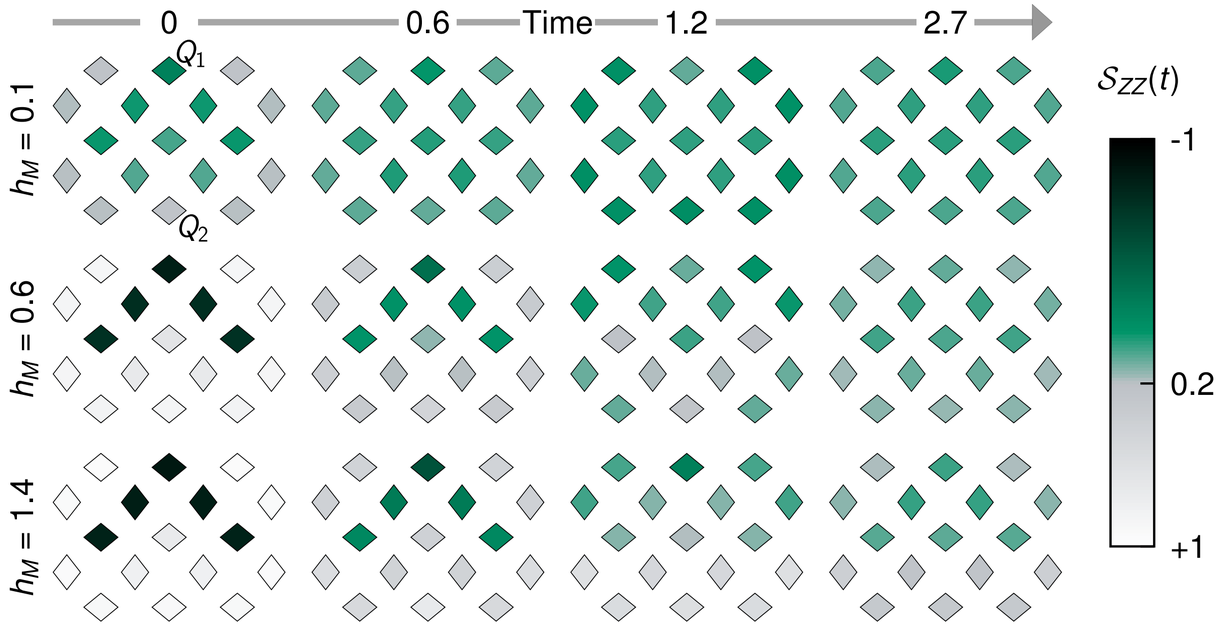
[Cochran, Jobst, et al., Smith, FP, Knap, Roushan, Nature **642**, 315 (2025)]

String Dynamics of two localized electric charges





$$\mathcal{S}_{ZZ}(t) = \mathrm{Re}[\langle Z(t)Z(0)\rangle] \times \langle Z(0)\rangle$$





Equilibrium: [Lüscher, 1981; Hasenfratz^3, 1981]

[see also Xu, Knap, FP, PRL 135, 036503 (2025)]

[Cochran, Jobst, et al., Smith, FP, Knap, Roushan, Nature **642**, 315 (2025)]

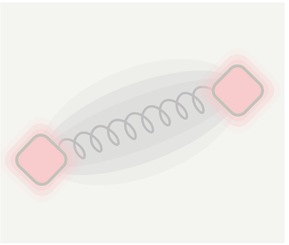
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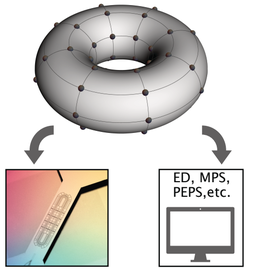
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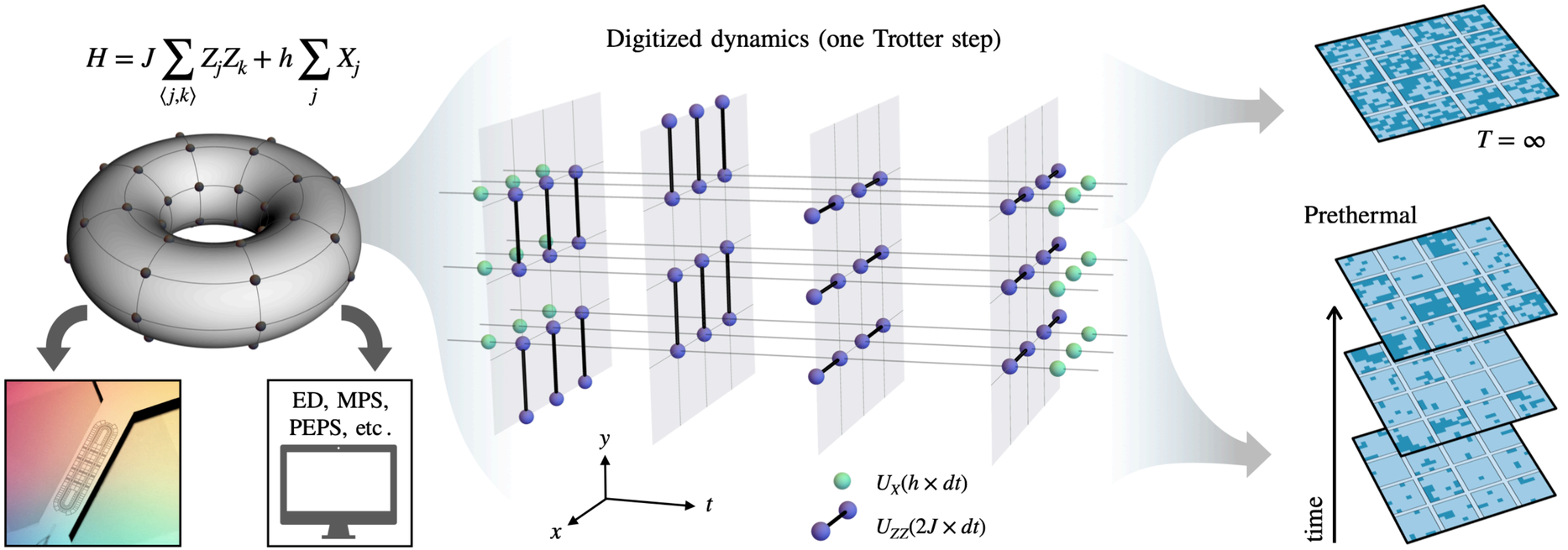
Digital quantum magnets

- Simple realization of thermal magnetic states



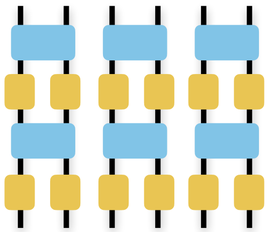
Digital quantum magnets

Periodic dynamics of 2D transverse-field Ising model



Effective Hamiltonian governs the evolution of one cycle

$$\hat{U}(T) = e^{-iH_{ZZ}}e^{-iH_X} \equiv e^{-i\hat{H}_F}$$



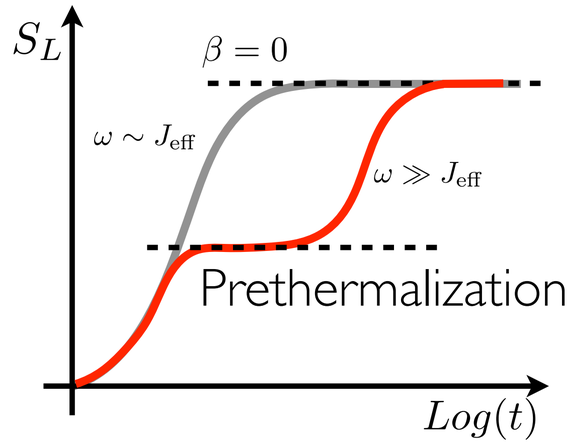
[Haghshenas, Chertkov, Mills, Kadow, … FP, Knap, Dreyer, Foss-Feig, arXiv:2503.20870]

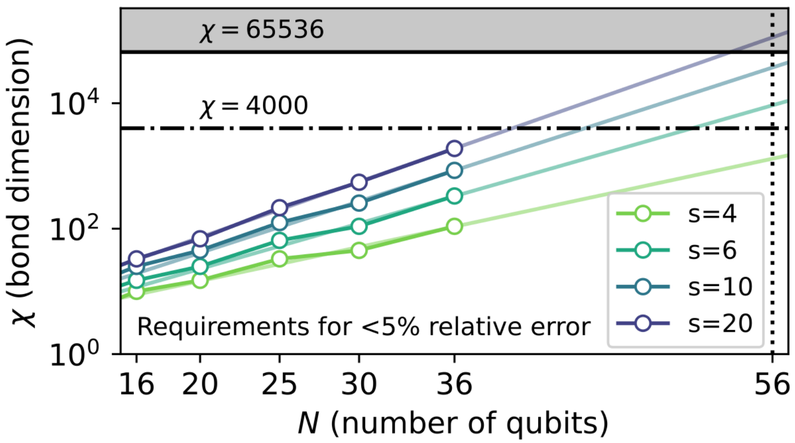
Floquet Pre-thermalization

For high drive frequencies stable intermediate regime appears

[Bukov, Gopalakrishnan, MK, Demler, PRL '15, Kuwahara, et al. '16, Abanin et al. '16, Weidinger, MK '17, Heyl et al. '19, Yang et al. '23]

- Dynamics governed by effective Hamiltonian $\hat{H}_F = \hat{H}_{\text{eff}} + O(\omega^{-n})$ to long time scales $t \sim e^{\omega/J}$
- Effective pre-thermal ensemble $\hat{\rho}_{\text{eff}} \sim e^{-\beta_{\text{eff}}\hat{H}_{\text{eff}}}$, with β_{eff} set by $|\psi_i\rangle$
- Prethermal states are difficult to simulate classically





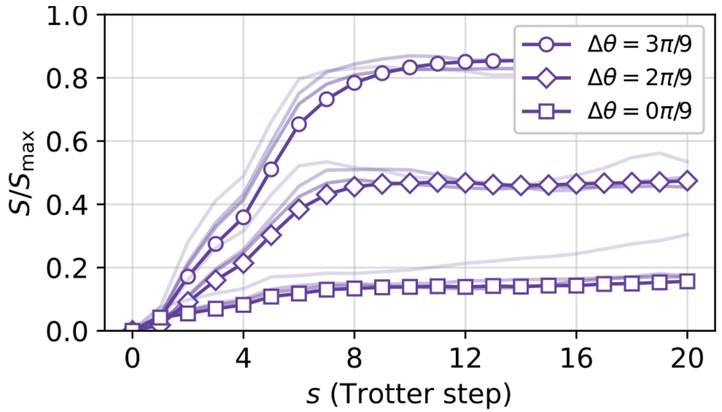
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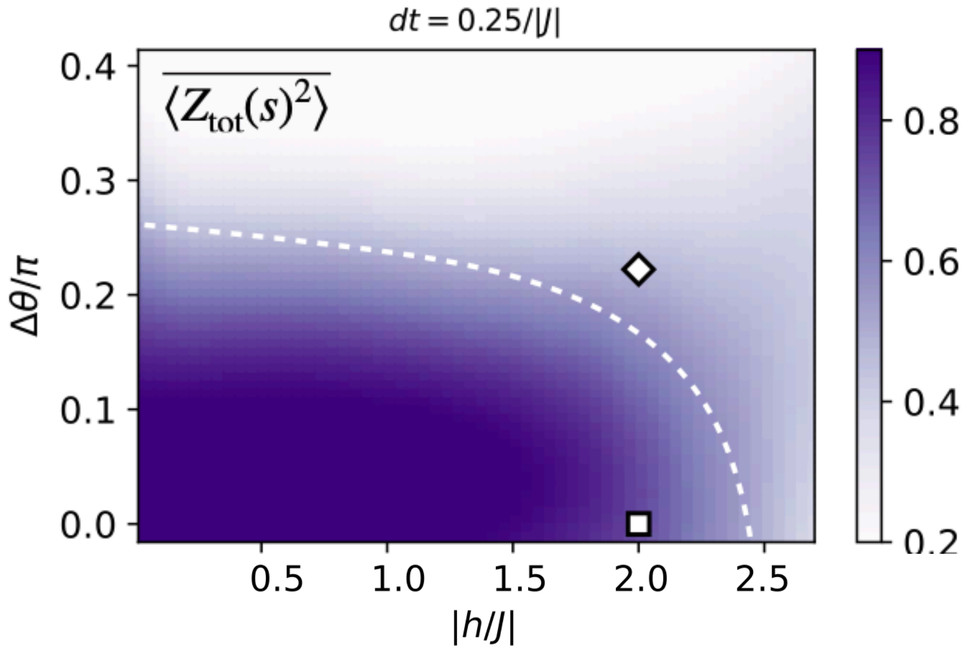
How to control the pre-thermal state?

Tune "simple" initial state: $|\Psi(\theta)\rangle = \bigotimes_j (\cos(\theta_j/2)|0\rangle_j + \sin(\theta_j/2)|1\rangle_j)$

Deviations from mean field solution $\theta_j = \theta_{\text{mf}} + \Delta\theta$

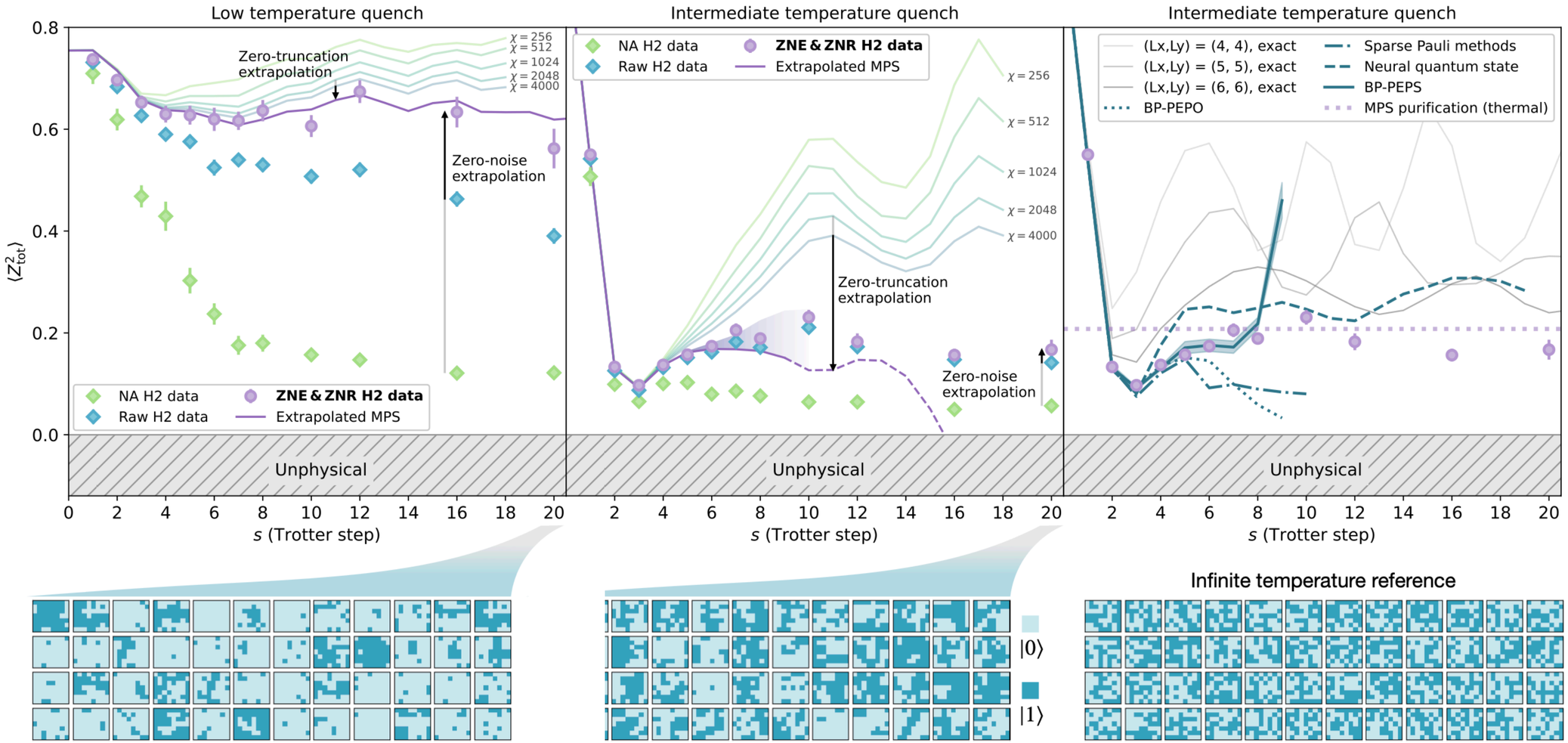
- Large $\Delta\theta$: Hight-T (numerically hard)
- Large $\Delta\theta$: Low-T (numerically simpler)

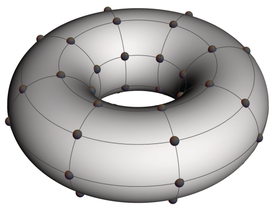




[Haghshenas, Chertkov, Mills, Kadow, … FP, Knap, Dreyer, Foss-Feig, arXiv:2503.20870]

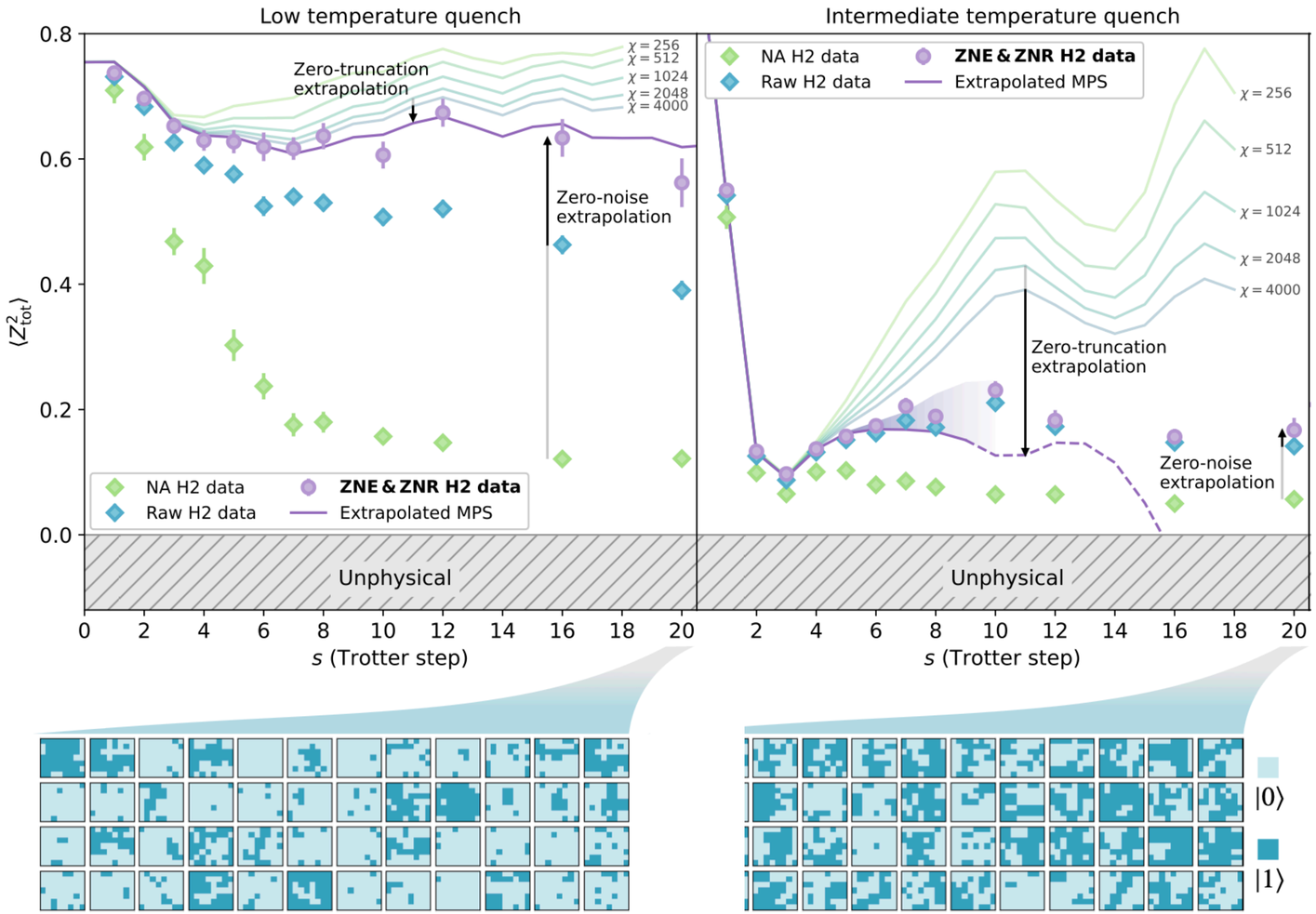
Pre-thermalization dynamics: 56 qubit square lattice

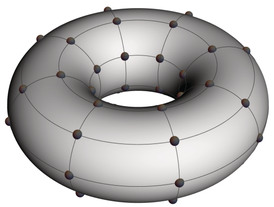




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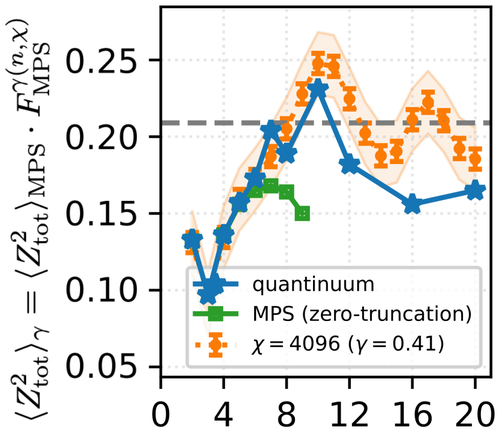
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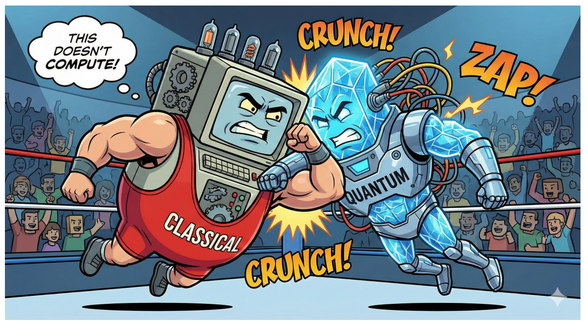




Heuristic MPS Simulation

[Mandra et al. arXiv:2511.23438]

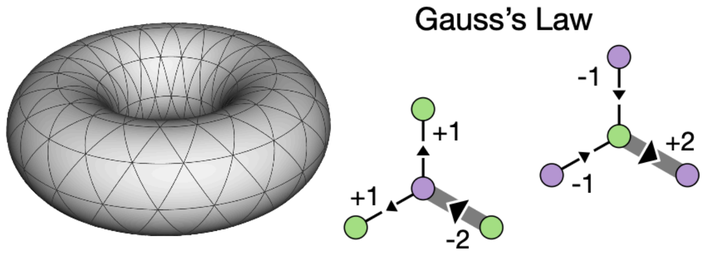


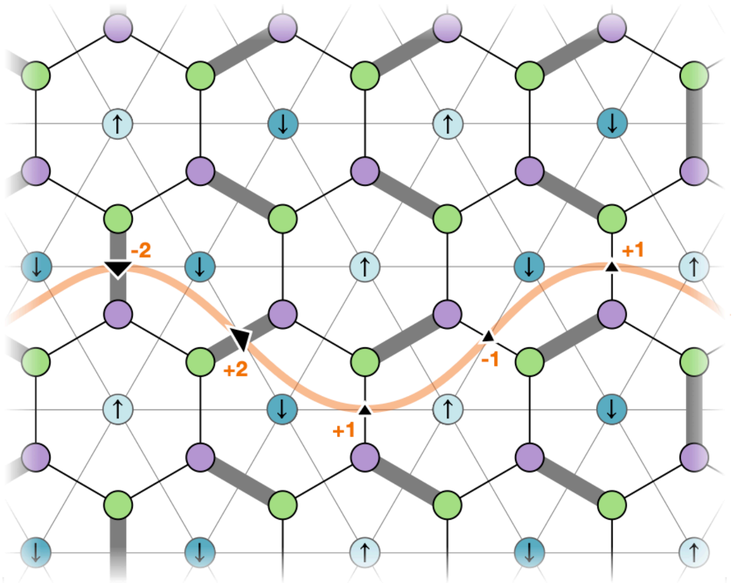


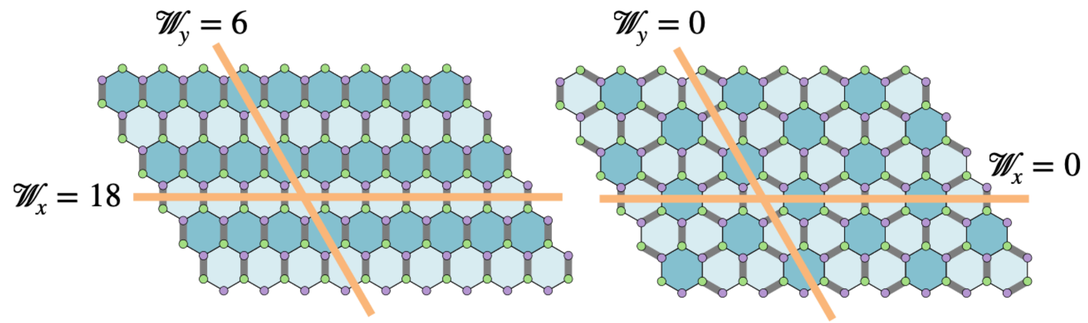
[Nano Banana]

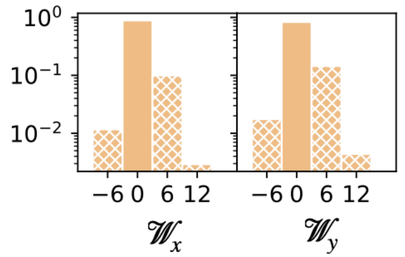
[Haghshenas, Chertkov, Mills, Kadow, … FP, Knap, Dreyer, Foss-Feig, arXiv:2503.20870]

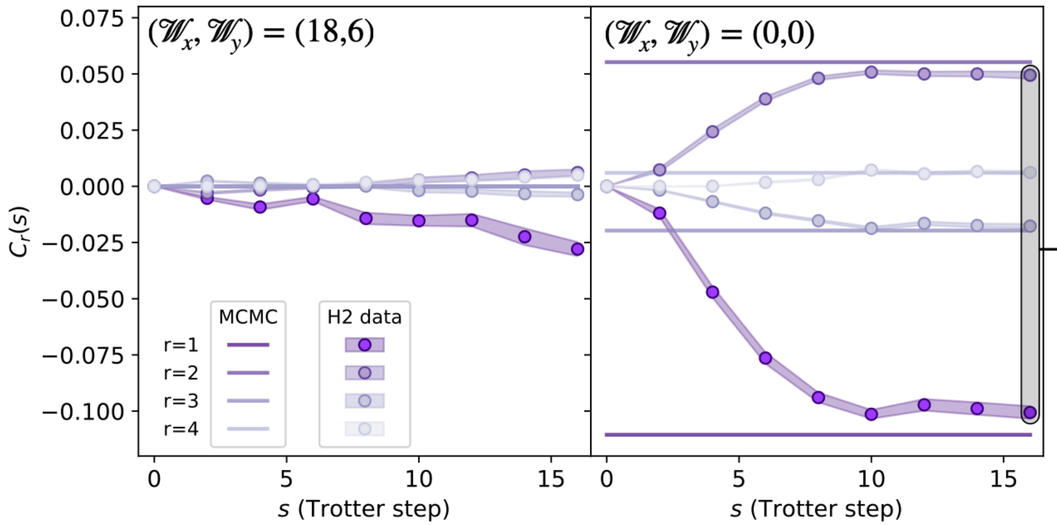
Prethermalization dynamics: 48 qubit triangular lattice

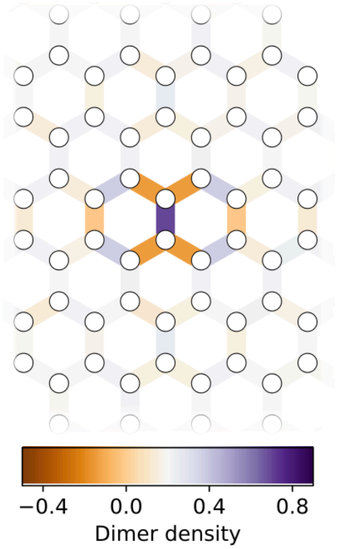












[Haghshenas, Chertkov, Mills, Kadow, … FP, Knap, Dreyer, Foss-Feig, arXiv:2503.20870]

Conclusions

Realization of topological ordered ground states

Topological entanglement

Anyonic quasi-particles

[Satzinger, Liu, Smith et al., Knap, FP, Roushan Science **374**, 1237 (2021)]

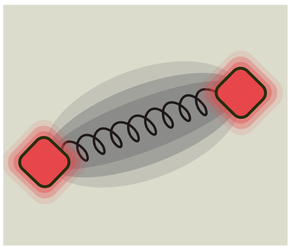


Dynamics of the confinement transition

Tuning away from the fixed point

Dynamics of quasi particles

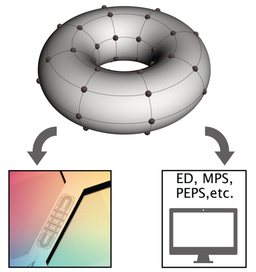
[Cochran, Jobst, et al., Smith, FP, Knap, Roushan, Nature **642**, 315 (2025)]



Digital quantum magnets

Simple realization of thermal magnetic states

[Haghshenas, Chertkov, Mills, Kadow, … FP, Knap, Dreyer, Foss-Feig, arXiv:2503.20870]




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