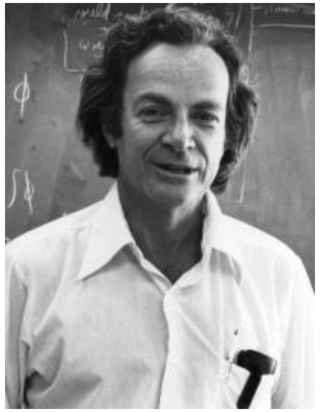
Digital quantum magnetism at the frontier of classical simulations

Eli Chertkov

Unitary Foundation Werqshop, 7/17/2025

arXiv:2503.20870

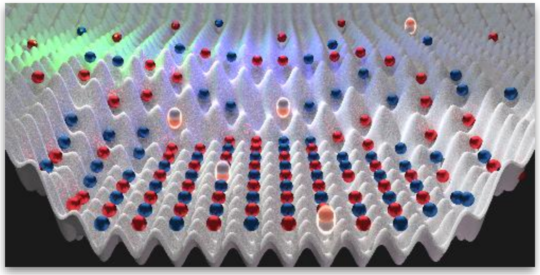
Digital quantum simulation



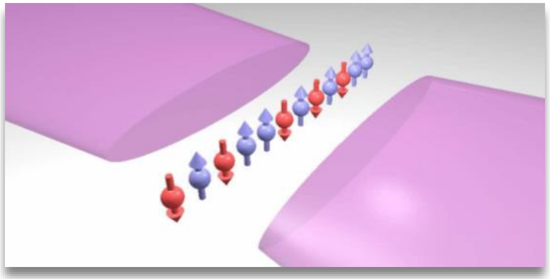
1982

40 years later, this dream remains largely unrealized

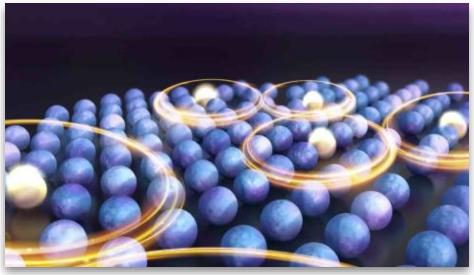
- Analog machines have made impressive progress on quantum simulation of a few simple models



C. Chiu / Harvard



G. Pagano / Rice

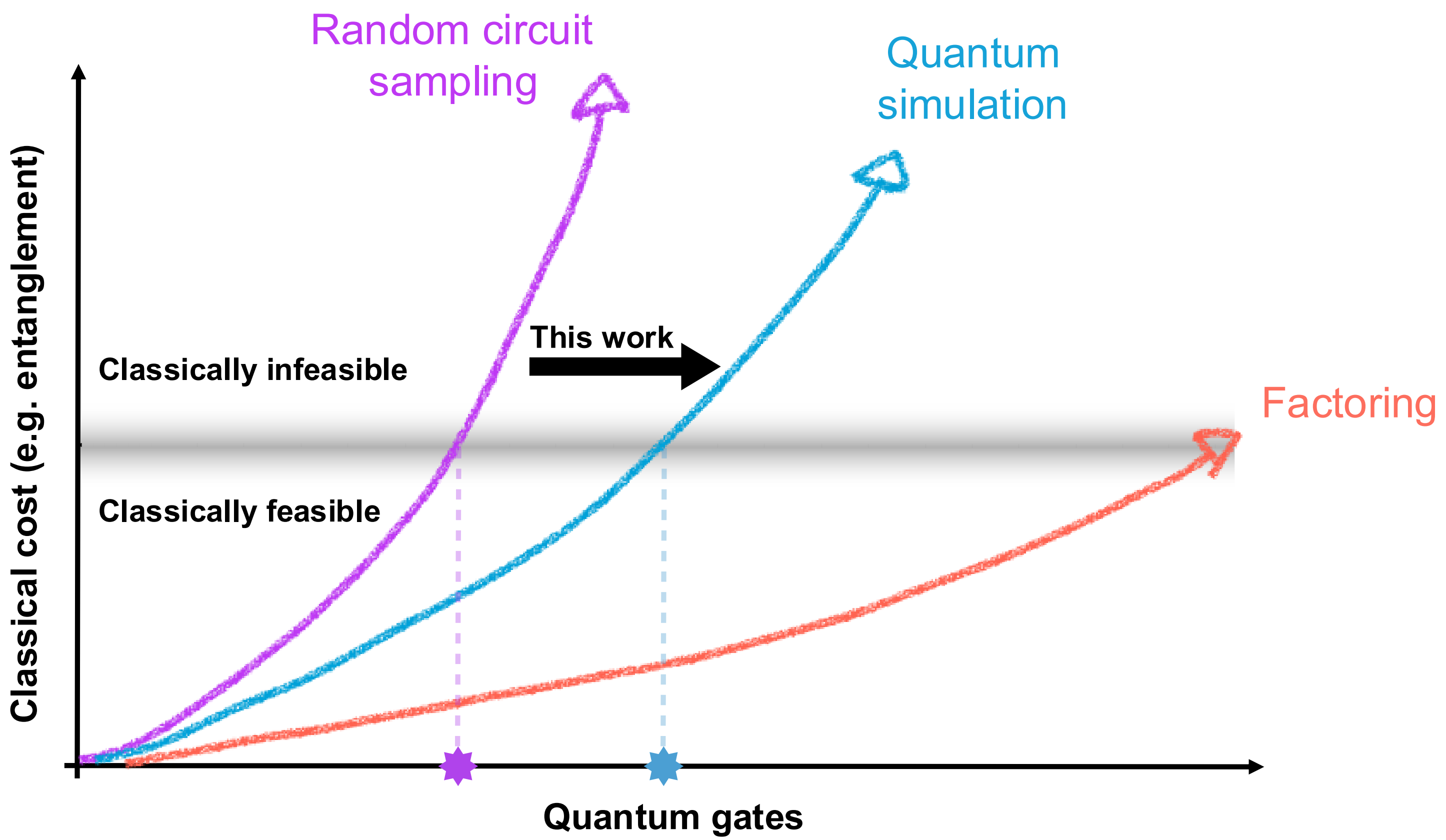


LMU Quantum Optics Group

- Universal digital machines promise more flexibility, but have so far only made small-scale demonstrations

Quantum advantage on useful problems

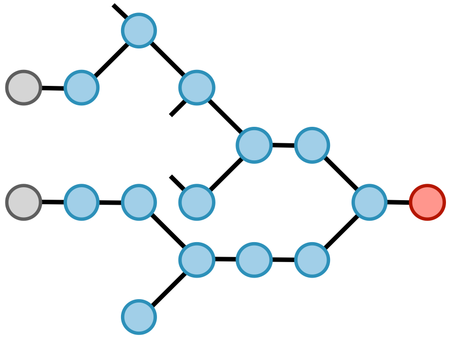
- Quantum algorithms for solving useful problems generally impose **limited entanglement/classical cost per quantum gate**



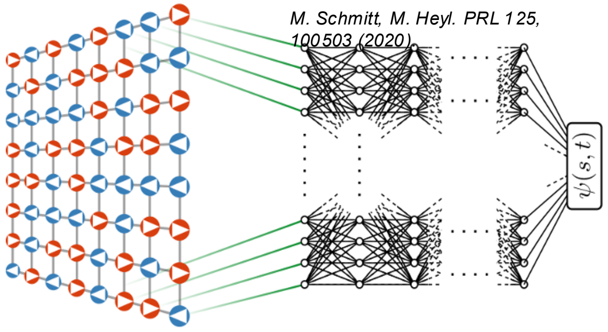
Quantum advantage on useful problems

- Quantum algorithms for solving useful problems generally impose **limited entanglement/classical cost per quantum gate**
- Useful problems have structure that often enables **high-performance classical algorithms** with much lower cost than exact circuit simulation

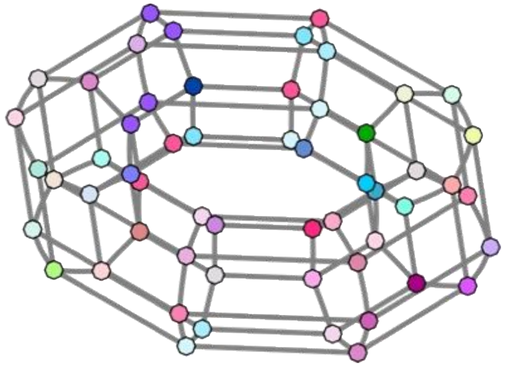
Sparse Pauli methods



Variational wave functions



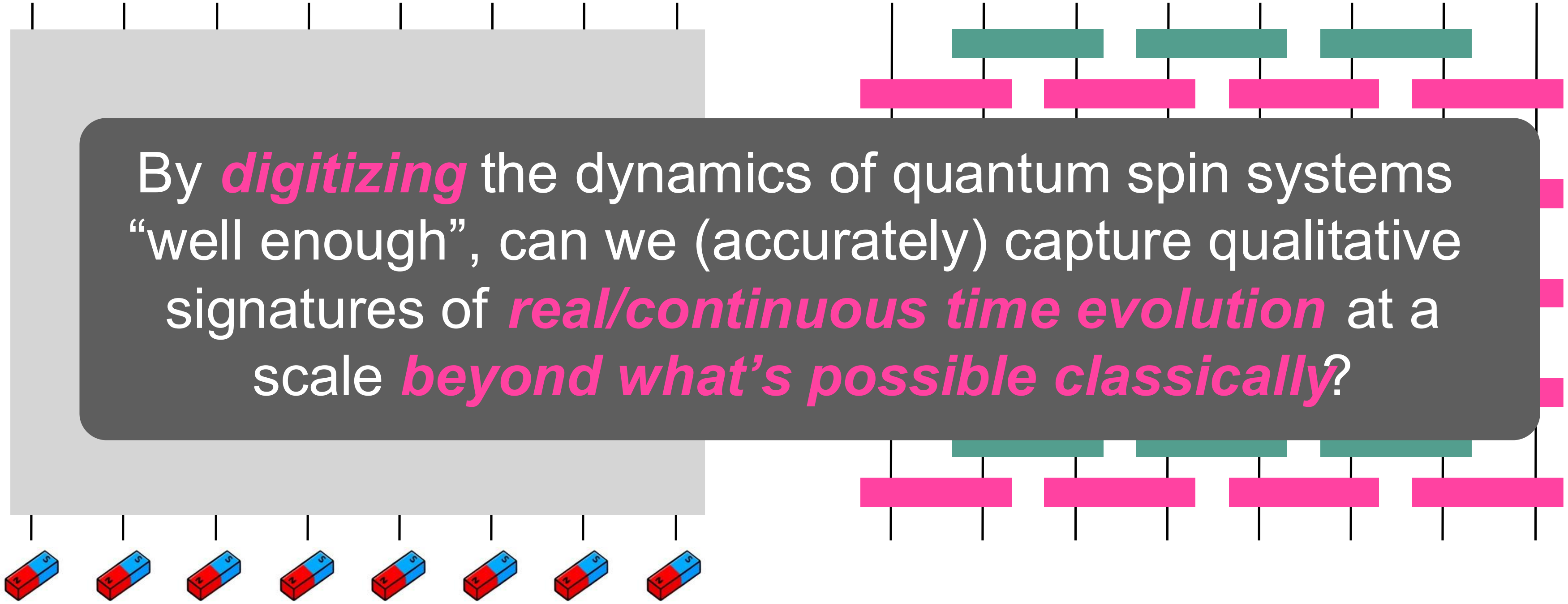
Limited-entanglement methods



Digital quantum magnetism

Where to start: **Dynamics of magnetic systems**

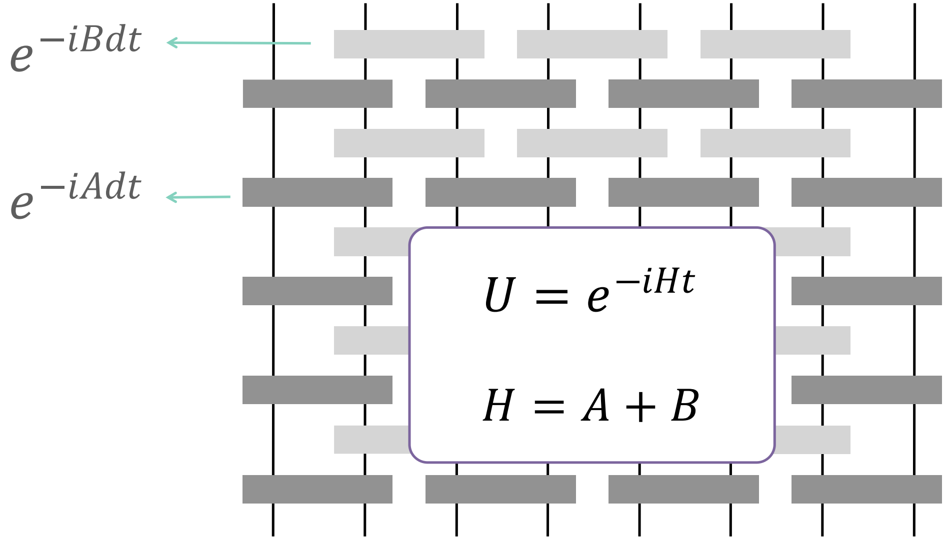
- Very qubit native, but entanglement per gate is limited by the need to approximate continuous time evolution:

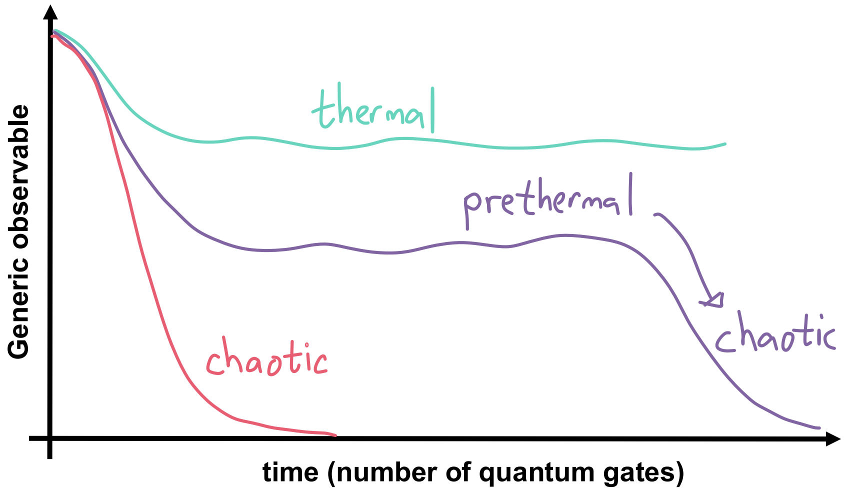


By ***digitizing*** the dynamics of quantum spin systems "well enough", can we (accurately) capture qualitative signatures of ***real/continuous time evolution*** at a scale ***beyond what's possible classically***?

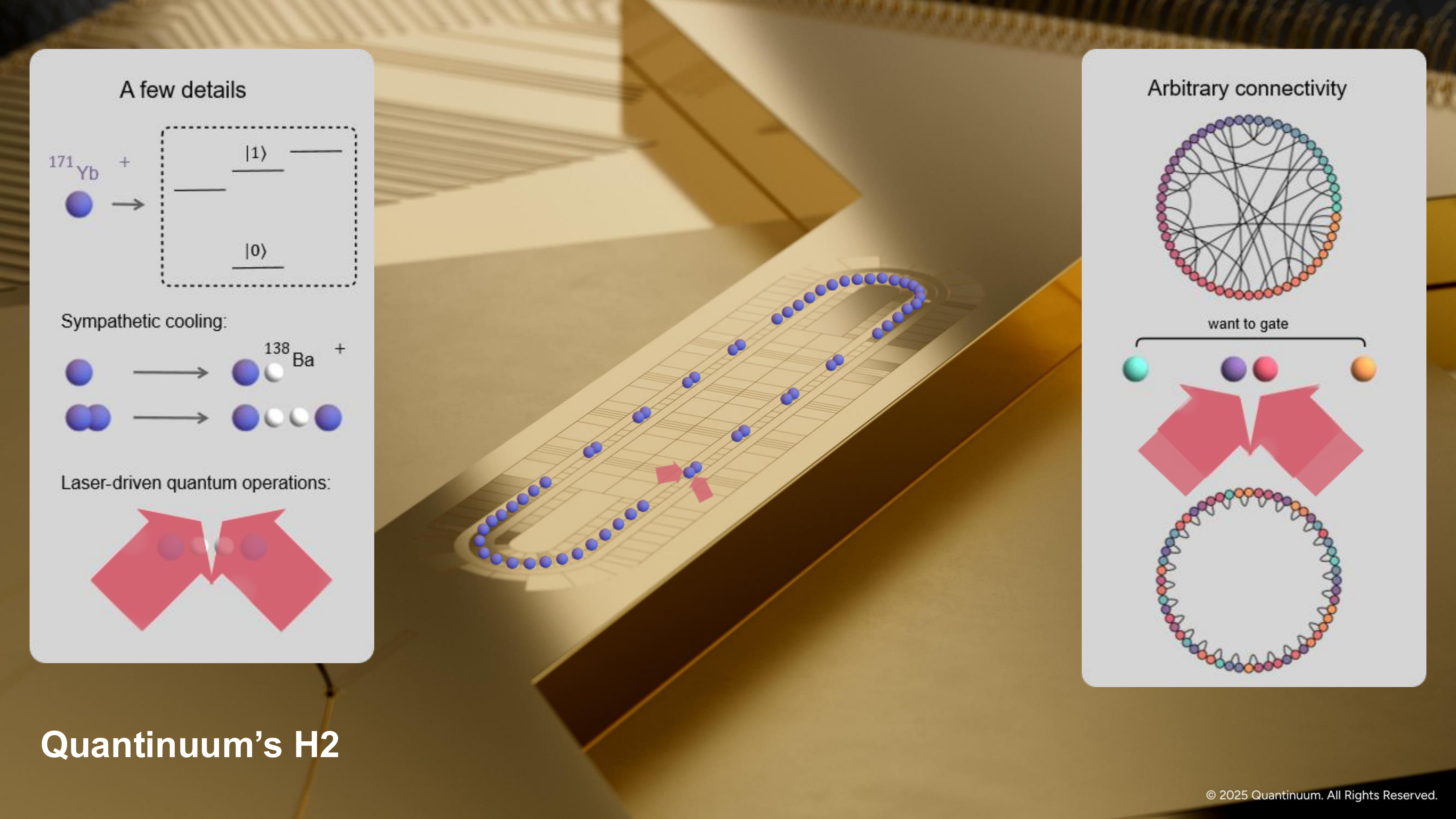
Digital quantum magnetism

- Quantum circuits implementing time evolution **break continuous time translation symmetry** (i.e., do not conserve energy)





- Even though late-time states look **infinite temperature / chaotic**, at intermediate times they can reach a **prethermal** regime when time step dt is small enough.


A few details
171 Yb +
|1⟩
|0⟩
Sympathetic cooling:
138 Ba +
Laser-driven quantum operations:
Arbitrary connectivity
want to gate
Quantinuum’s H2
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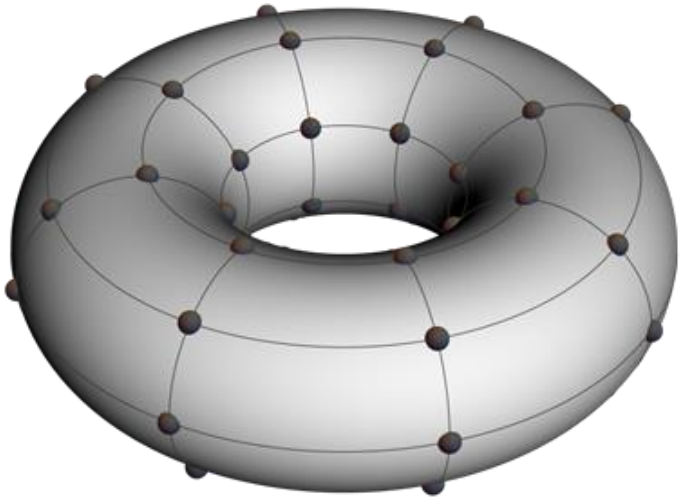
Magnetic simulations on Quantinuum's H2

Transverse-field Ising model

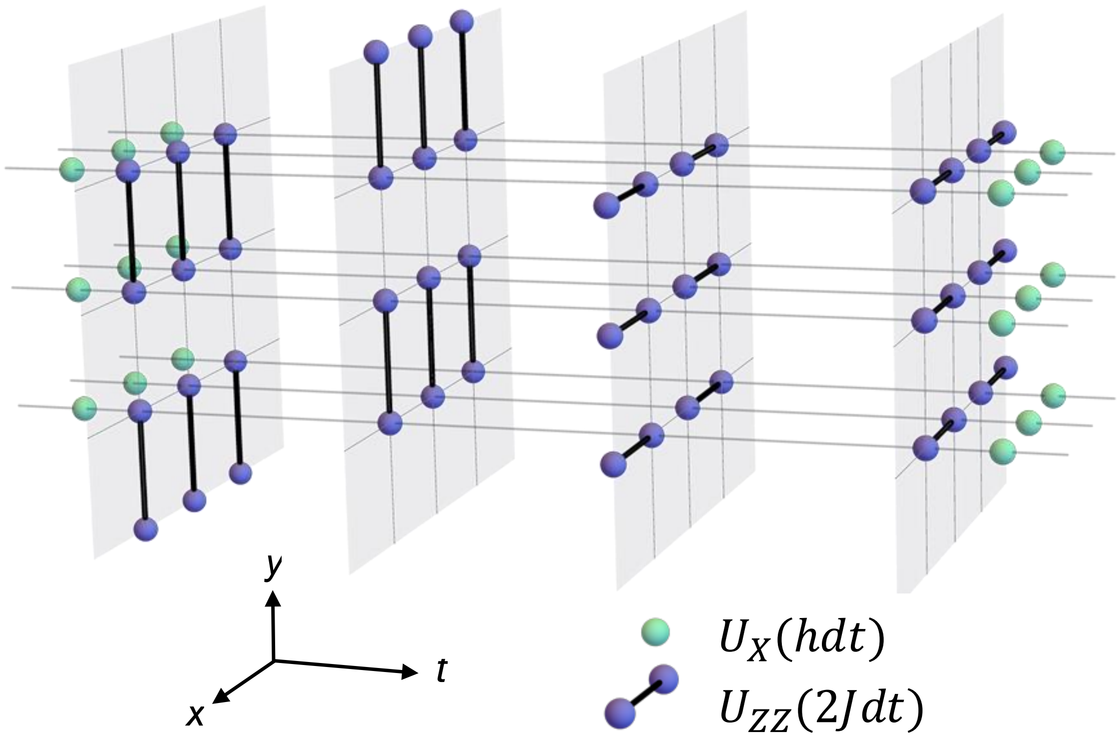
$$H = J \sum_{\langle ij \rangle} Z_i Z_j + h \sum_i X_i$$



56 qubits (7x8 lattice)

Digitized dynamics

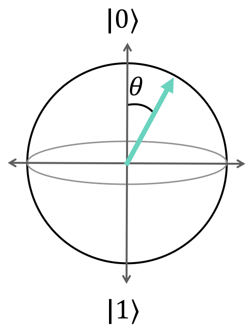
$$e^{-iHdt} \approx$$



- Periodic boundary conditions minimize finite-size effects (easy on H2)
- **Minimal model with non-trivial physics and no exact solution**

(Pre) Thermal physics from dynamics

- If the time step is small enough, the dynamics reveals a thermal phase diagram
- **We can effectively tune the temperature by changing our initial state**

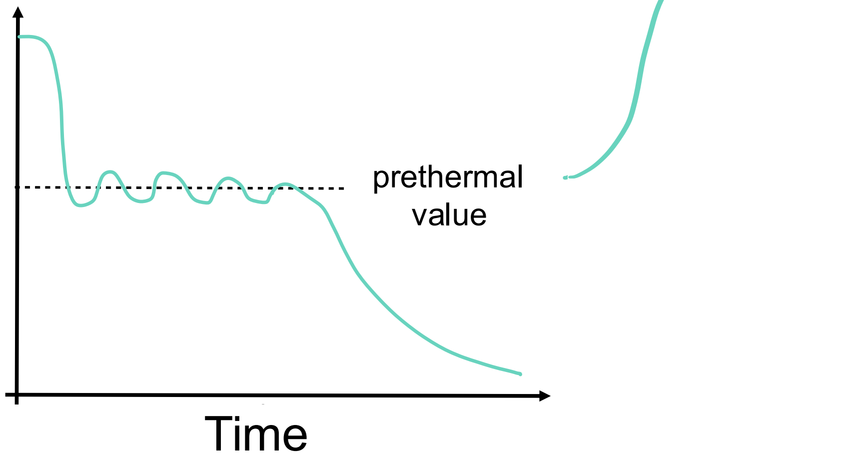


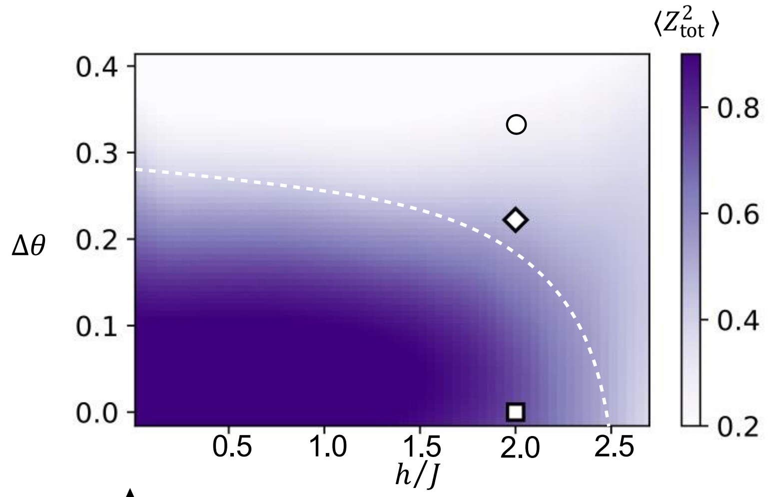
Initial product state

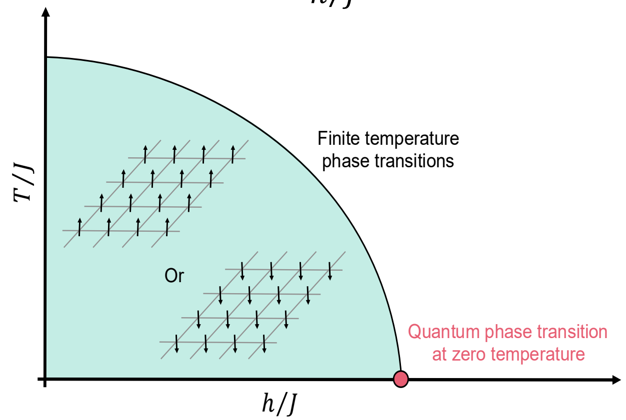
$$\prod_j (\cos\theta/2\,|0\rangle_j + \sin\theta/2\,|1\rangle_j)$$

Observable

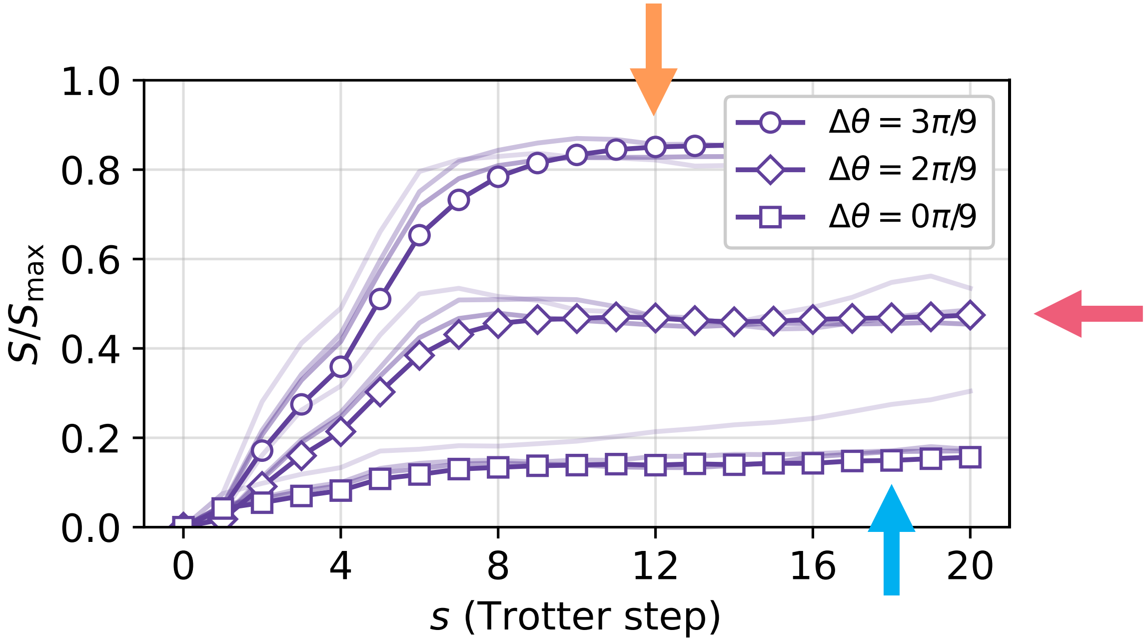
$$\langle Z_{\text{tot}}^2\rangle = \frac{1}{N^2}\sum_{ij}\langle Z_i Z_j\rangle$$

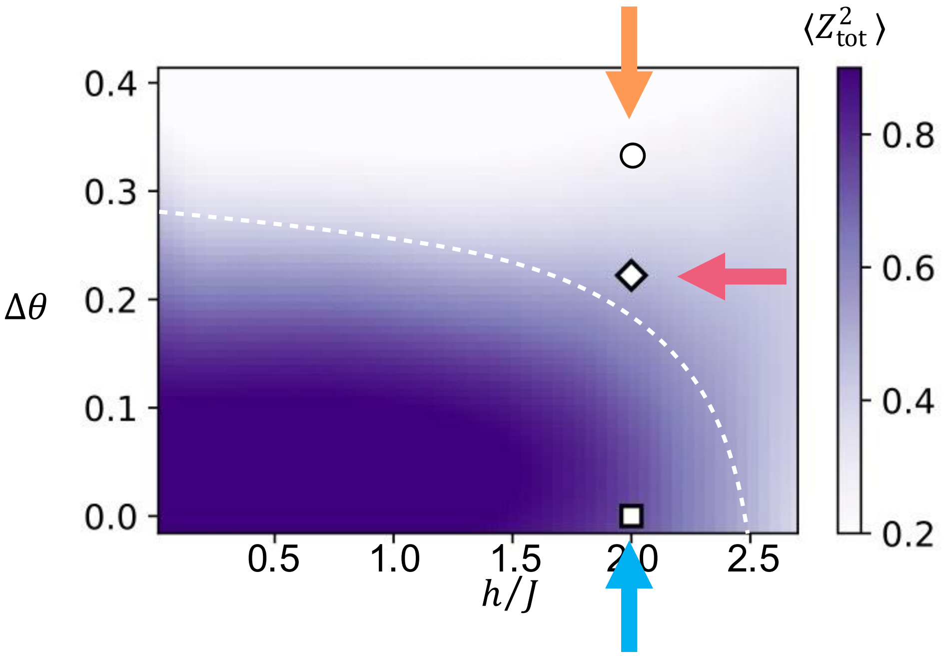






Where can a quantum computer help?





□ **Too cold:** Low entanglement, tensor networks effective

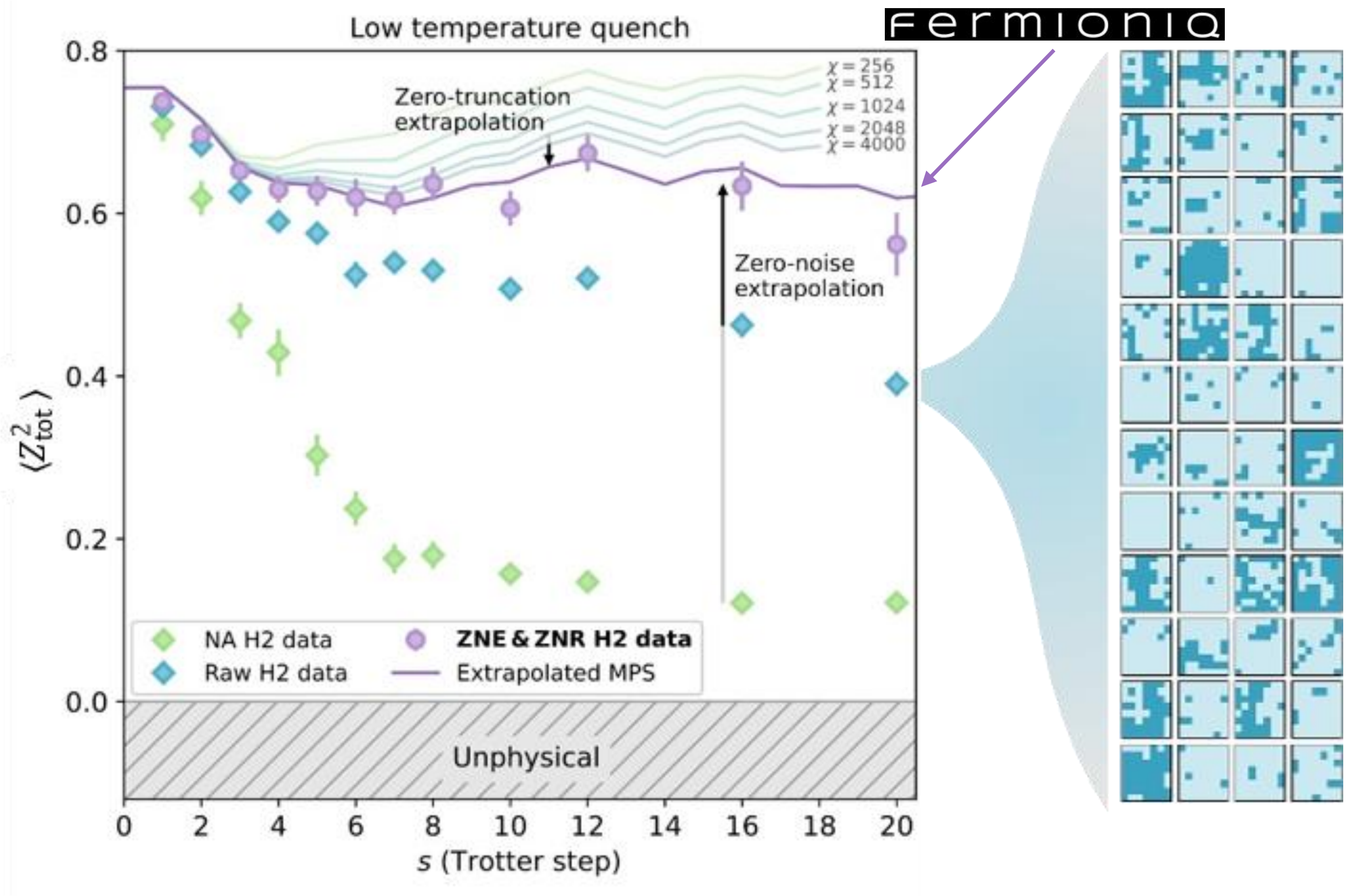
○ **Too hot:** Weak correlations, low signal

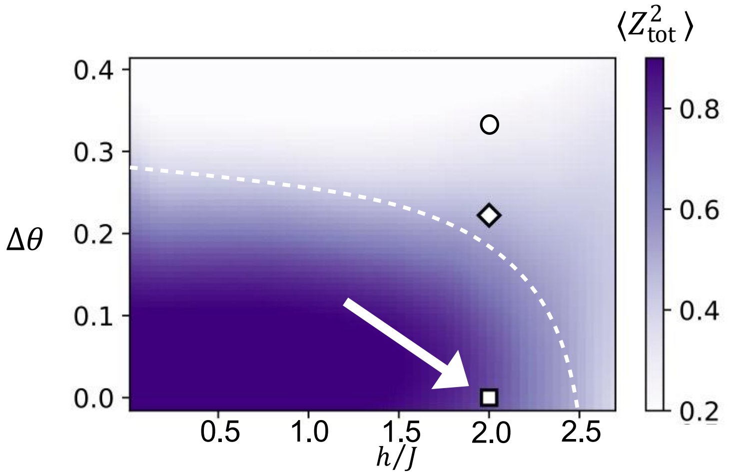
◇ **Just right:** High entanglement and strong correlations

arXiv:2503.20870

Benchmarking machine performance at low temperature

- We use the low-temperature quench (where classical MPS simulations are barely manageable) to benchmark the quantum data and error mitigation techniques





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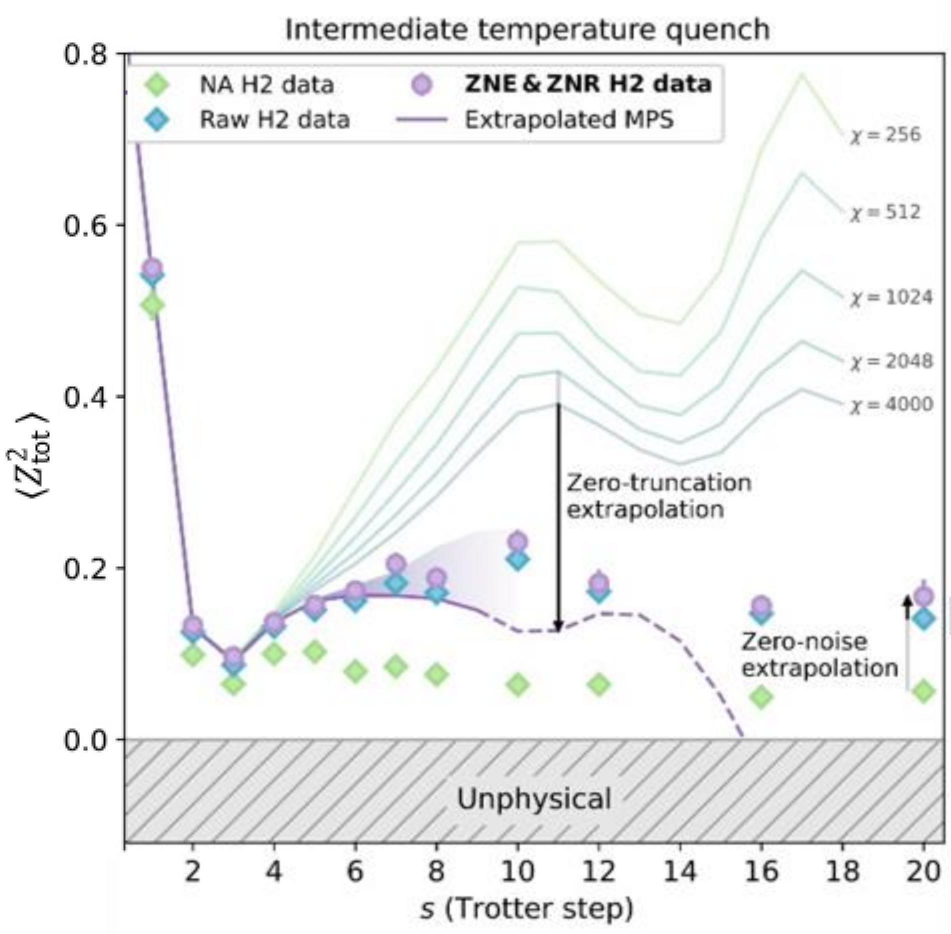
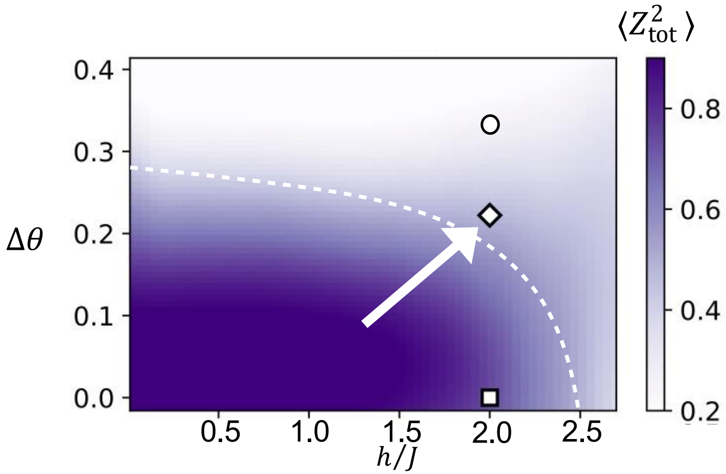
Classically difficult dynamics at intermediate temperature

- By raising the temperature, we can observe (pre)thermalization in a regime with too much entanglement for accurate MPS simulations



Largest circuits had 2350 two-qubit gates!



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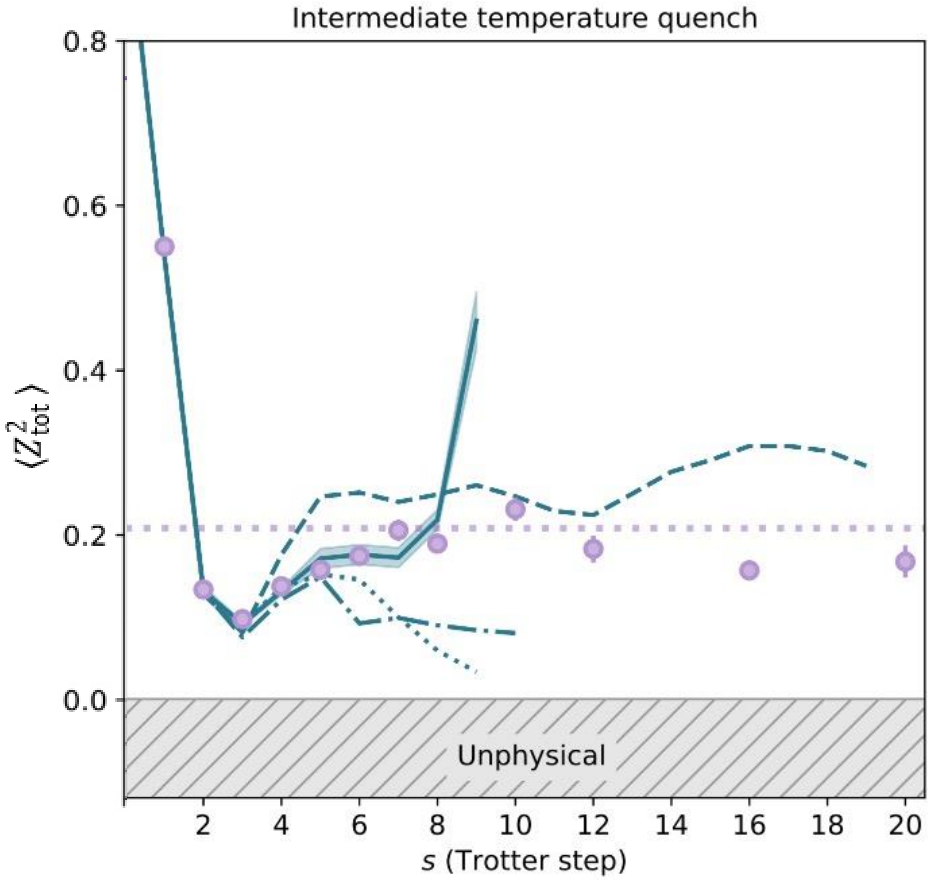
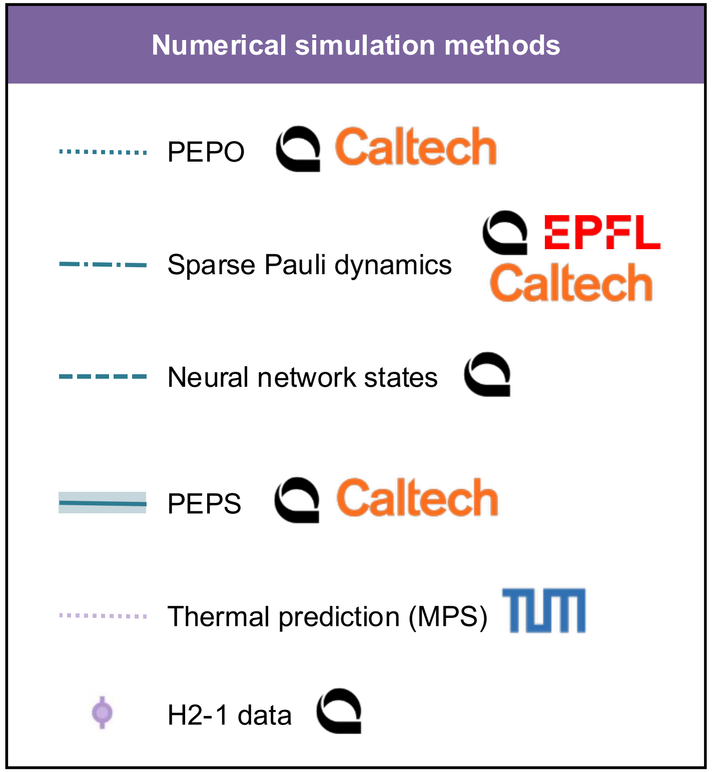
Classically difficult dynamics at intermediate temperature

- Dynamics at this scale seriously challenges many state-of-the-art classical simulation methods





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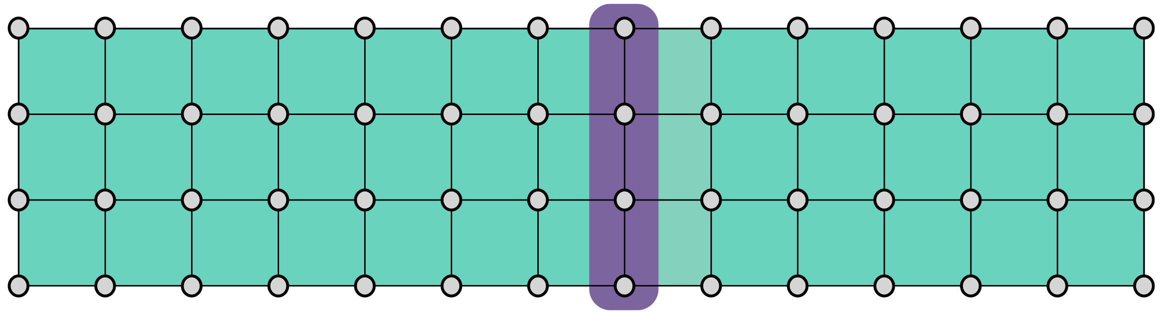
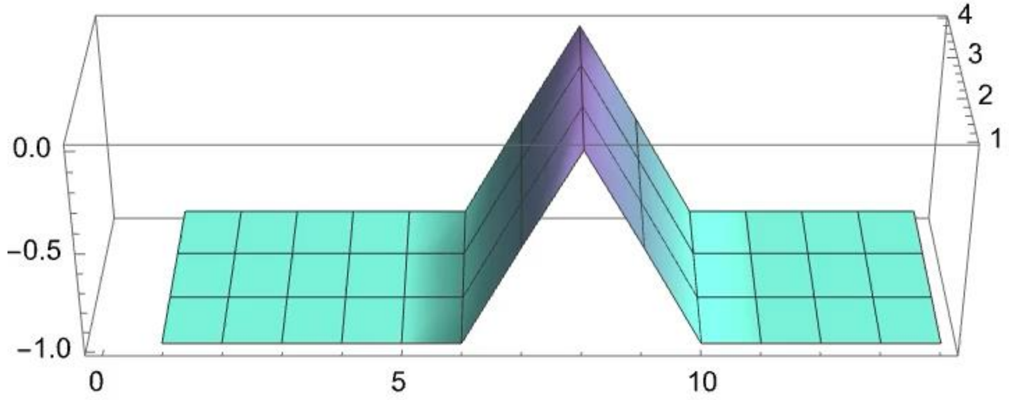
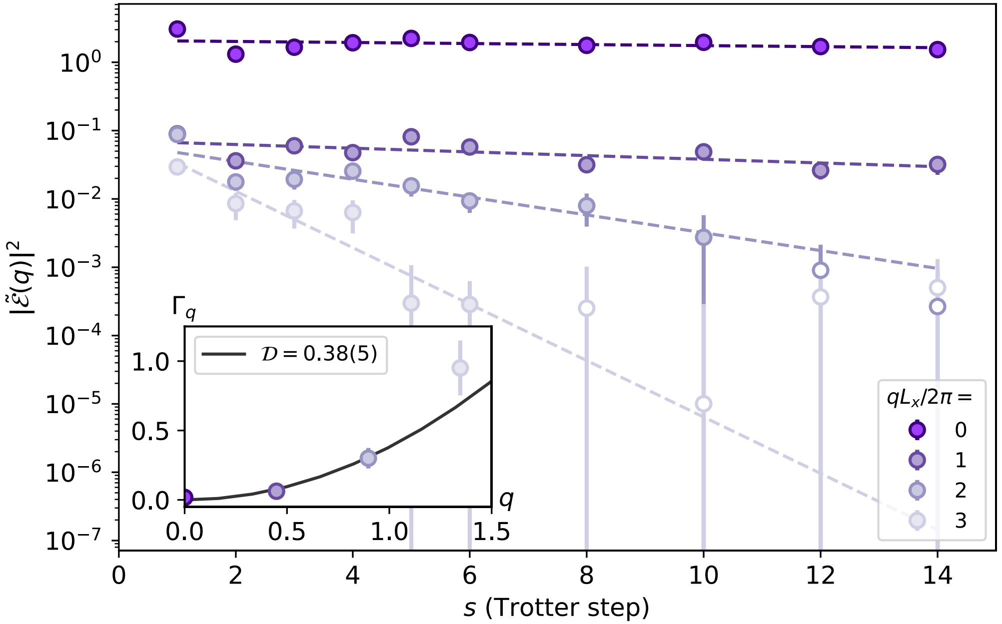
Experimental observation of hydrodynamic behavior

- By inserting energy locally and watching the relaxation, we observe an emergent hydrodynamic behavior







$\mathcal{E}(x) = \frac{J}{4}\sum_{j\in\langle i\rangle}\langle Z_i Z_j\rangle$ ~ "energy density" $\quad \widetilde{\mathcal{E}}(q) = \frac{1}{\sqrt{L_x}}\sum_x e^{iqx}\mathcal{E}(x)$

- By Fourier transforming the diffusion equation, we expect $\Gamma_q \sim \mathcal{D}q^2$.
- We observe and measure the diffusion constant $\mathcal{D}$, a (potentially) classically difficult-to-compute quantity.

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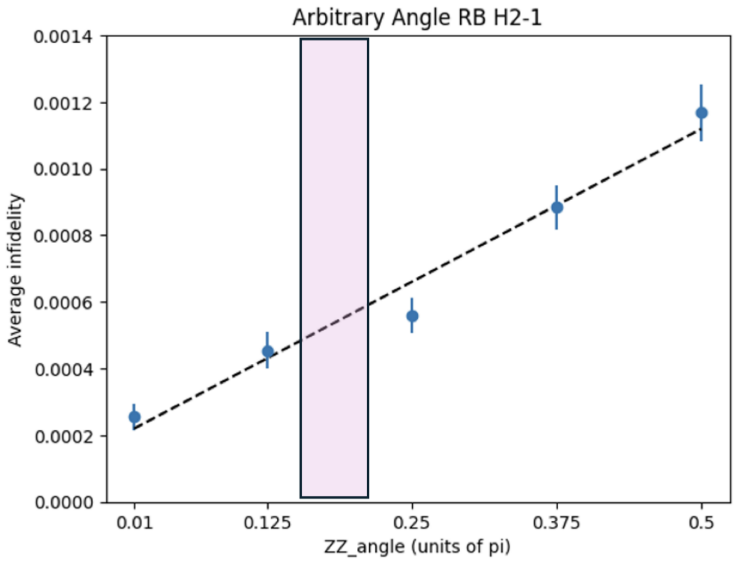
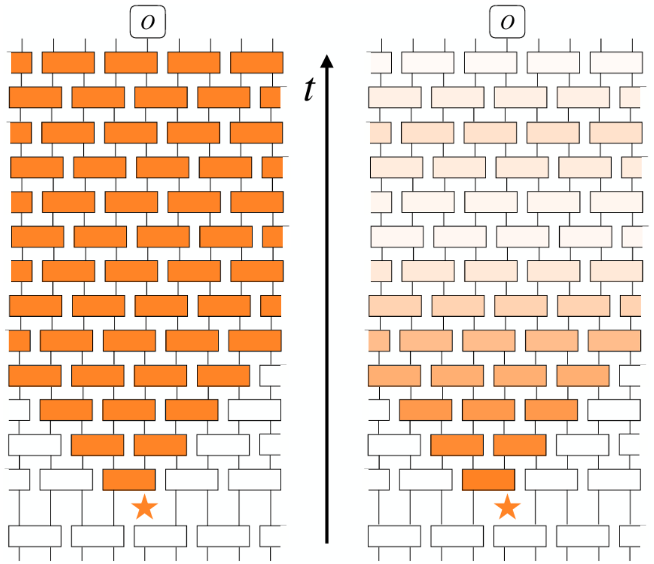
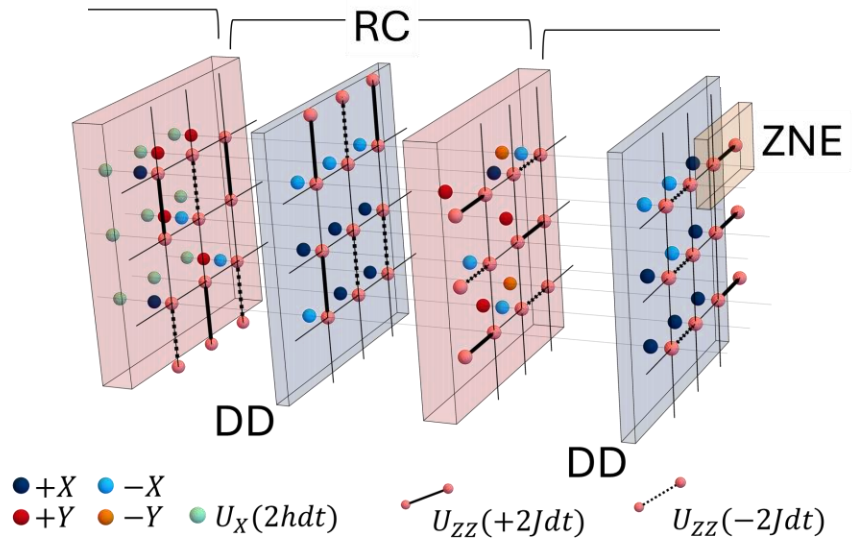
How did we get good results?







Our native arbitrary-angle 2Q gates improve with decreasing gate angle

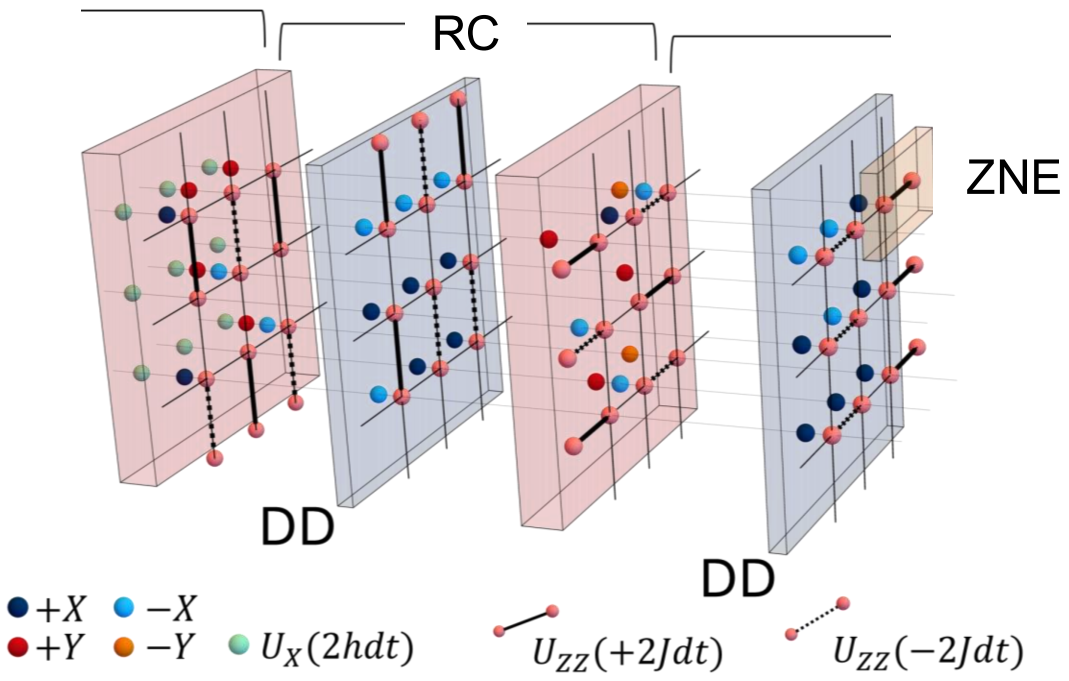
- Our maximum-angle 2Q gate infidelity $\sim 1 \times 10^{-3}$ is already state-of-the-art.
- For the $e^{-i(0.25)ZZ}$ gate in our experiments it is 6×10^{-4}.

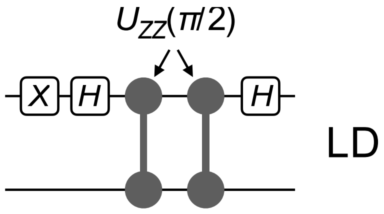
Dynamics simulations near thermal equilibrium are inherently robust to errors!

- Y. Yang et. al., PRX Quantum 4, 030320 (2023).
- E. Granet and H. Dreyer, PRX Quantum 6, 010333 (2025)
- EC, Y.-H. Chen, M. Lubasch, D. Hayes, M. Foss-Feig, arXiv:2410.10794 (2024).

Error mitigation

Circuit-level error mitigation



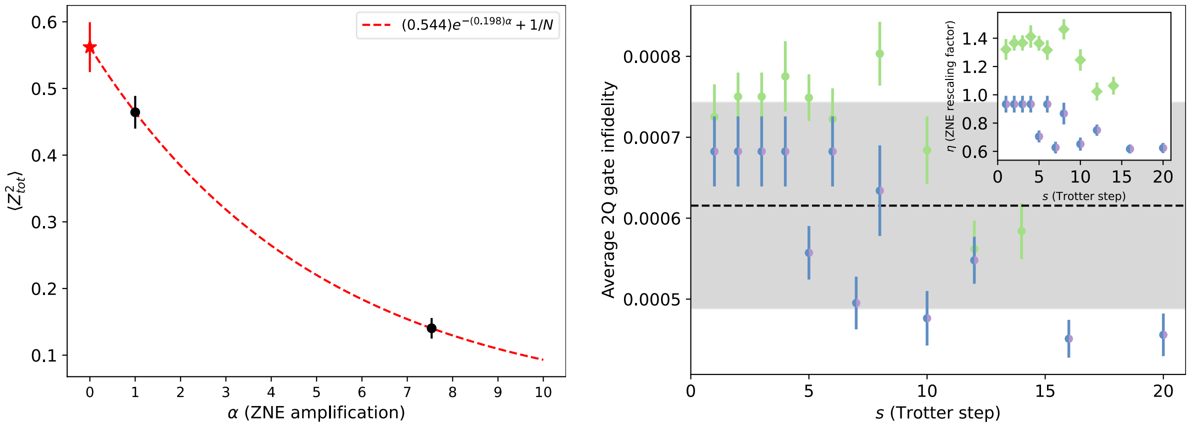


- Dynamical decoupling (DD) to cancel coherent memory errors
- Randomized compiling (RC) to make errors incoherent
- Zero noise extrapolation (ZNE) to estimate noise-less observable
- Leakage detection (LD) gadget to mitigate leakage errors

Using classical compute functionality on our machines we could compile once and generate a different random circuit in each shot.

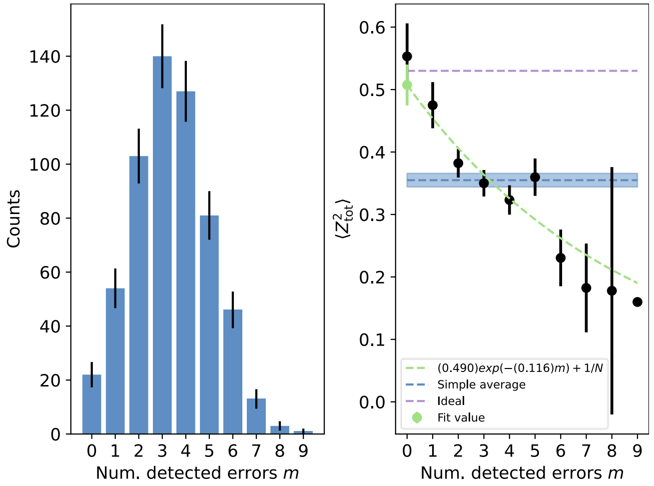
Post-processing error mitigation

Zero-noise extrapolation (ZNE)



- We performed ZNE on our 2Q gate error by learning the error model and randomly inserting Paulis.
- We used two points and an exponential decaying fit.
- We optimally chose the amplification factor and the number of shots to allocate between the two points.
- Using benchmarking circuits, we kept track of the two-qubit gate fidelity to adjust our ZNE fits.

Zero-noise regression (ZNR)



(synthetic data to illustrate the method)

See also: R. Nigmatullin et al. Nature Physics (2025).

- We performed ZNR on our leakage error.
- Using the LD gadget, we recorded how many leakage errors were detected in each shot.
- We binned observables by numbers of errors and performed a fit to obtain the zero-error result.
- Improved error bar compared with post-selection.
- Can be used with **quantum error detection**.

Outlook

- Digital quantum computers, aided by error mitigation methods, have finally achieved a level of accuracy where they can compete with the best classical methods on scientifically useful problems.
- The main limiting factor in this work was system size!

	2020	2023	2025	2027	2029
SYSTEMS:	SYSTEM MODEL H1	SYSTEM MODEL H2	QUANTINUUM HELIOS	QUANTINUUM SOL	QUANTINUUM APOLLO
PHYSICAL QUBITS:	20	56	96	192	1000's
PHYSICAL 2-QUBIT GATE ERROR:	1×10^{-3}	1×10^{-3}	$< 5 \times 10^{-4}$	$< 2 \times 10^{-4}$	1×10^{-4}
LOGICAL QUBITS:		> 12	~ 50	~ 100	100's
LOGICAL ERROR RATES:		1×10^{-3}	$< 10^{-4}$	$\sim 10^{-5}$	1×10^{-5} to 1×10^{-10}*

This work (2023) → Coming soon (2025)

*analysis based on recent literature in new, novel error correcting codes predict that error could be as low as 1E-10 in Apollo (ref: arXiv:2403.16054, arXiv:2308.07915)

arXiv:2503.20870

Thanks!

Reza Haghshenas

Michael Mills

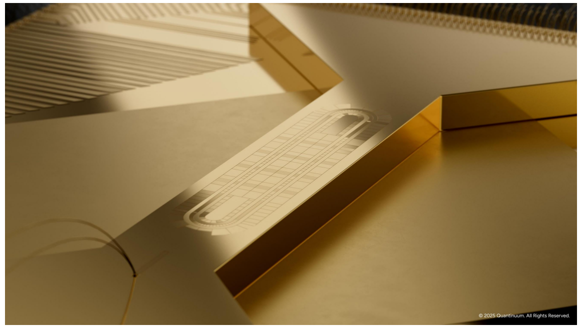
Michael Foss-Feig

Digital quantum magnetism at the frontier of classical simulations

R. Haghshenas,[1,*] E. Chertkov,[1,*] M. Mills,[1] W. Kadow,[2,3] S.-H. Lin,[4,2,3] Y. H. Chen,[1] C. Cade,[5] I. Niesen,[5] T. Begušić,[6] M. S. Rudolph,[7] C. Cirstoiu,[8] K. Hemery,[4] C. Mc Keever,[9] M. Lubasch,[9] E. Granet,[4] C. H. Baldwin,[1] J. P. Bartolotta,[1] M. Bohn,[1] J. Cline,[1] M. DeCross,[1] J. M. Dreiling,[1] C. Foltz,[1] D. Francois,[1] J. P. Gaebler,[1] C. N. Gilbreth,[1] J. Gray,[6] D. Gresh,[1] A. Hall,[1] A. Hankin,[1] A. Hansen,[1] N. Hewitt,[1] C. A. Holliman,[10] R. B. Hutson,[1] M. Iqbal,[4] N. Kotibhaskar,[1] E. Lehman,[1] D. Lucchetti,[1] I. S. Madjarov,[1] K. Mayer,[1] A. R. Milne,[9] S. A. Moses,[1,11] B. Neyenhuis,[1] G. Park,[12] B. Ponsioen,[5] M. Schecter,[1] P. E. Siegfried,[1] D. T. Stephen,[1] B. G. Tiemann,[1] M. D. Urmey,[1] J. Walker,[1] A. C. Potter,[1] D. Hayes,[1] G. K.-L. Chan,[6,13] F. Pollmann,[2,3] M. Knap,[2,3] H. Dreyer,[4] and M. Foss-Feig[1,†]

And numerous institutions contributing to this work

And many, many people responsible for H2



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