Dissipative preparation of thermal states on quantum computers

Preparing thermal states of frustrated quantum spin systems using 139 qubits
ArXiv: 2605.26245

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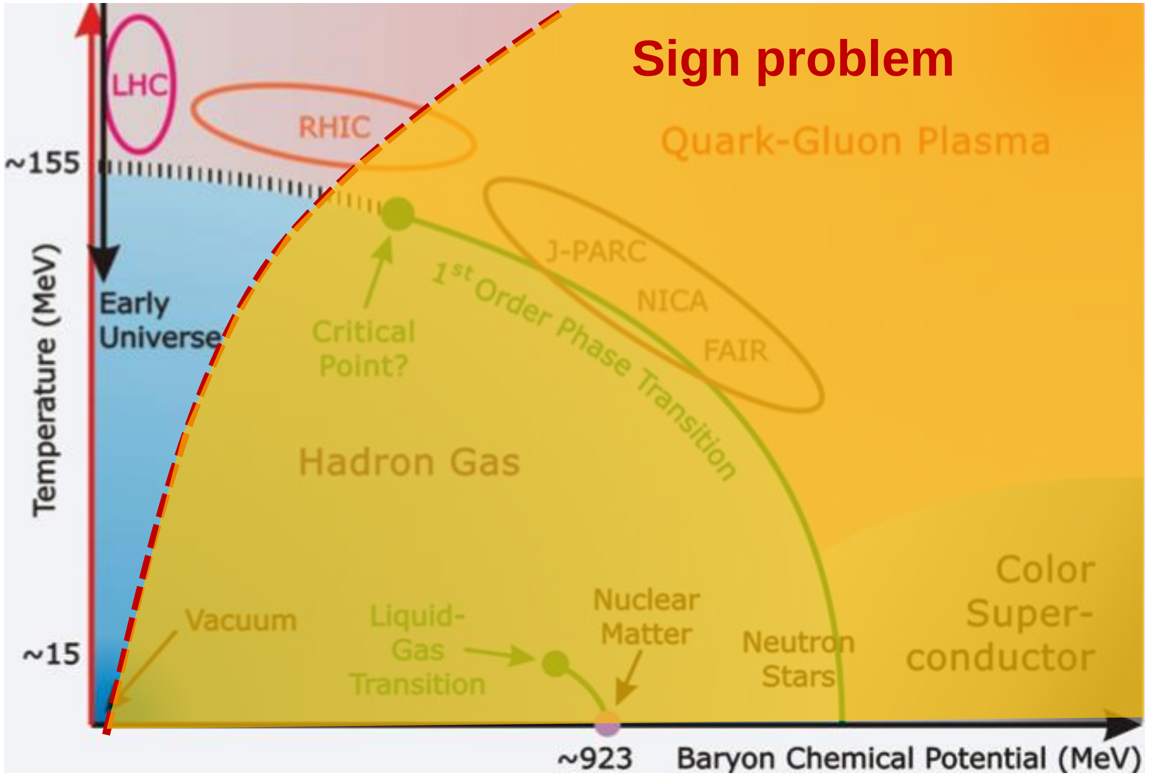
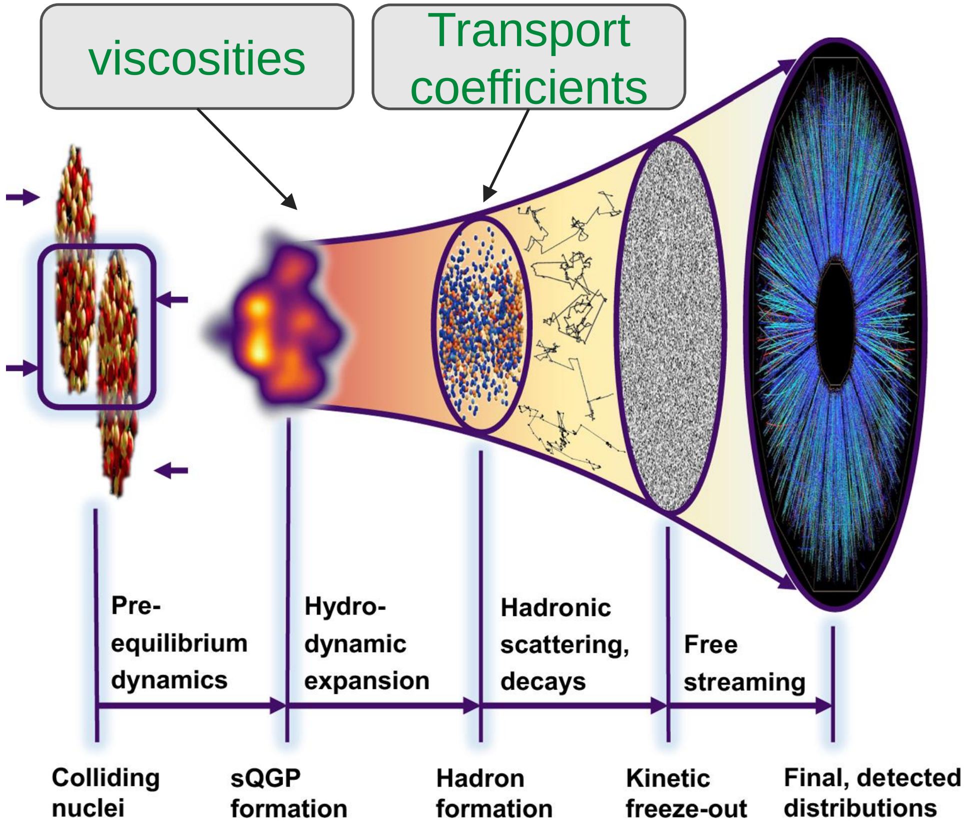
Applications of thermal state preparation

Equilibrium observables and phase structure



https://www.gsi.de/

Real-time observables



D. Kincses, M. Nagy, and M. Csanád, Commun Phys **8**, 55 (2025).

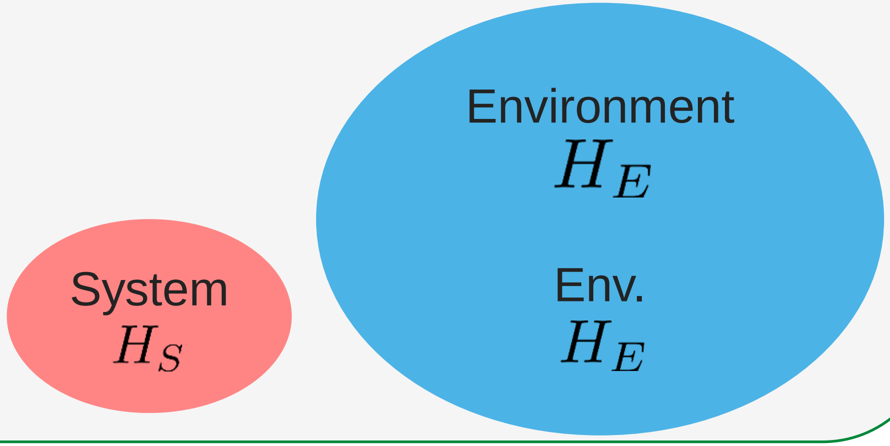
Beyond HEP: Condensed matter physics, quantum chemistry, …

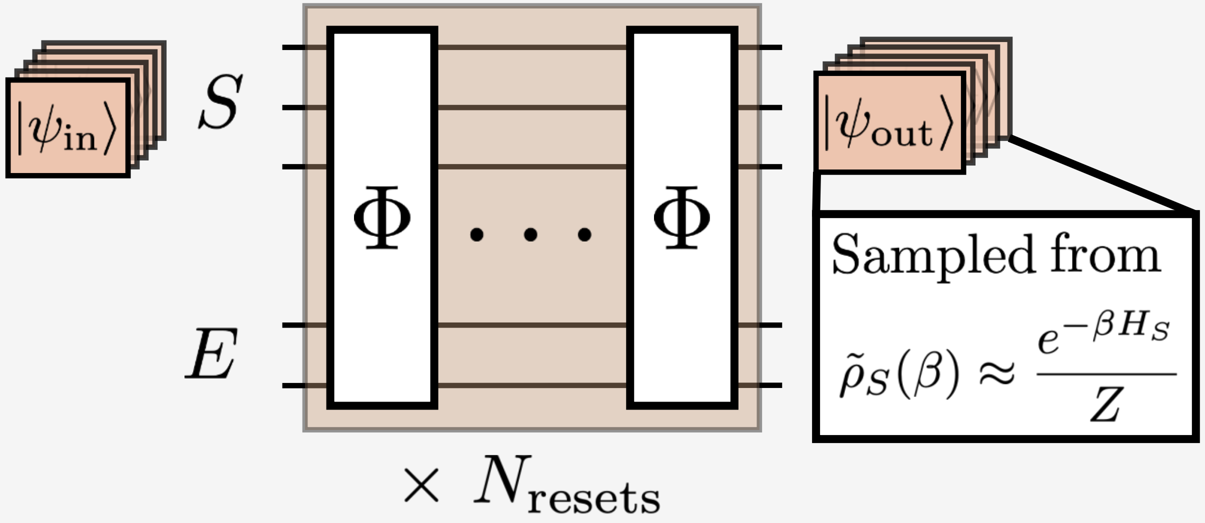
Dissipative Thermal State Preparation

Goal: Sample from Gibbs state

$$\rho(\beta) = \frac{e^{-\beta H}}{Z} = \sum_i p_i |\psi_i\rangle\langle\psi_i|$$

Idea: Engineered dissipation





Design quantum channel with approximately thermal steady state

$$\Phi[\tilde{\rho}_{\mathrm{S}}(\beta)] = \tilde{\rho}_{\mathrm{S}}(\beta)$$

$$||\tilde{\rho}_{\mathrm{S}}(\beta) - \rho(\beta)|| < \epsilon$$

F. Verstraete, M. M. Wolf, and J. Ignacio Cirac, Nature Phys **5**, 633 (2009).

Z. Ding, C.-F. Chen, and L. Lin, Phys. Rev. Res. **6**, 033147 (2024).

Towards an efficient algorithm for thermal state preparation

Previous results: Analytic guarantee[1][2][3]

Convergence to an approximate thermal state upon repeated application of Φ

How many times do we need to apply Φ ?

Previous results: Simple models (Analytic)[4][5][6]

Here: Frustrated spin systems (Numerical)

Will Φ have a steady state in the presence of device noise?

Here: Hardware runs on `ibm_boston`

Verification that steady state in the presence of noise is approximately thermal

Here: Comparison to Quantum Monte Carlo

[1] D. Hahn, S. A. Parameswaran, and B. Placke, 2505.22816(2026).
[2] J. Lloyd and D. A. Abanin, 2506.21318 (2026).
[3] Z. Ding *et al.*, 2508.05703 (2025).
[4] C. Rouzé, D. S. França, and Á. M. Alhambra, Nat. Phys.(2026).
[5] Š. Šmíd *et al.*, Nat Commun **16**, 10736 (2025).
[6] Á. Capel, C. Rouzé, and D. S. França, 2009.11817 (2021).

End-to-End Efficient Quantum Thermal and Ground State Preparation[1]

Randomly sampled Bohr frequencies

Environment: $H_\mathrm{E} = -\sum_{i_\mathrm{E}} \omega_{i_\mathrm{E}} Z_{i_\mathrm{E}}/2$

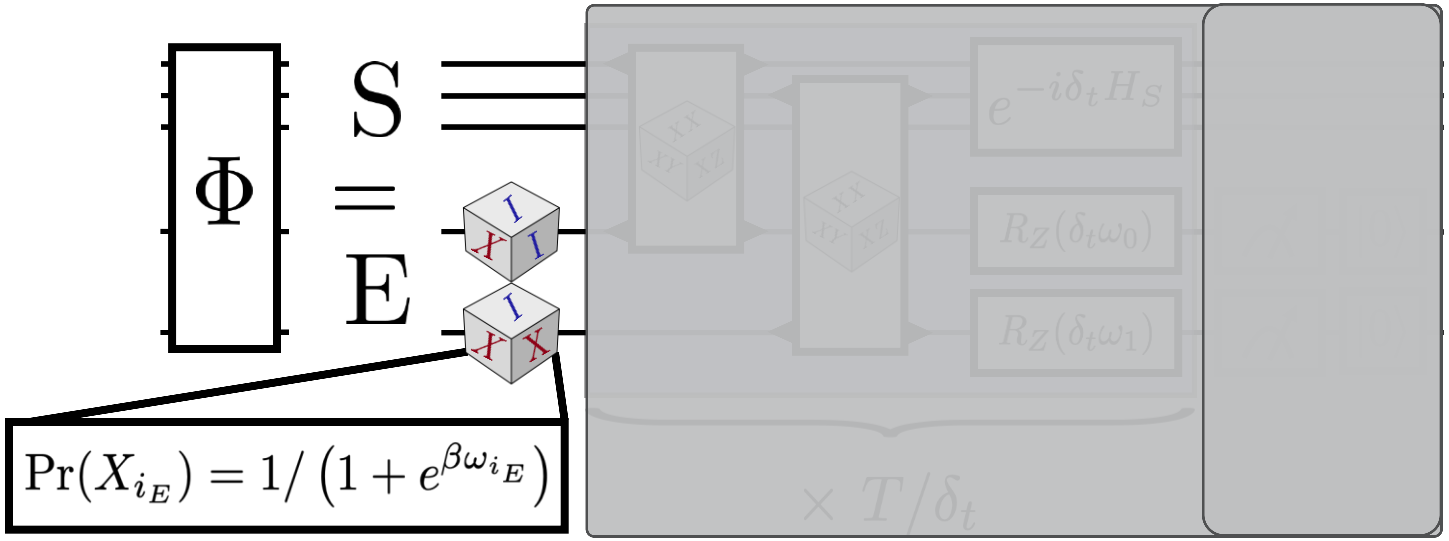
System-Environment Interaction: $H_{SE} = \sum_{\langle i_S, i_E \rangle} O_{i_S} \otimes X_{i_E}$

Randomly sampled operators

1. Prepare environment in thermal state
2. Do joint time evolution for time T:

$$H(t) = H_S + H_E + \alpha f(t) H_{SE}$$

3. Reset environment qubits

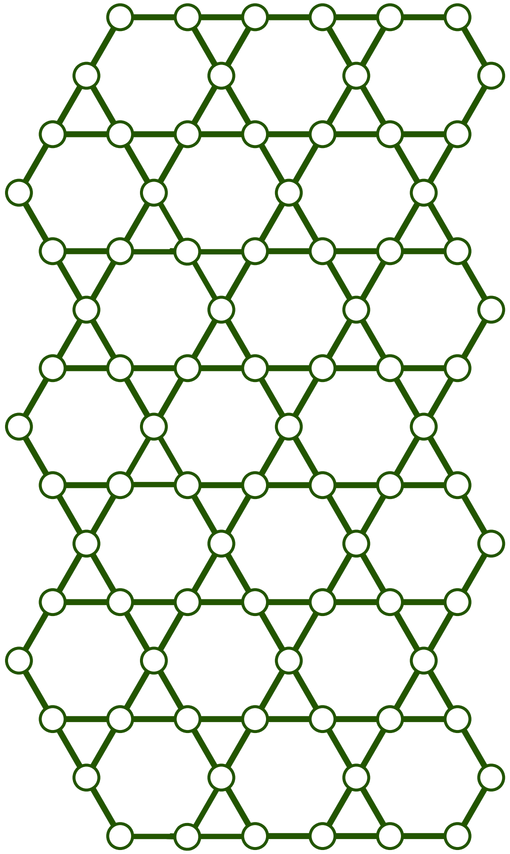


Guaranteed to reach approximate thermal steady state. But How many applications of the channel are required to reach the steady state?

[1] Z. Ding *et al.*, 2508.05703 (2025).
See also: D. Hahn, S. A. Parameswaran, and B. Placke, 2505.22816(2026). & J. Lloyd and D. A. Abanin, 2506.21318 (2026).

Frustrated spin systems – a testing ground

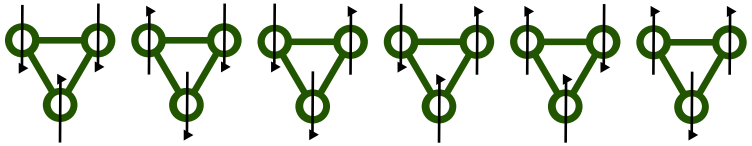
Kagome lattice



Geometric frustration

Antiferromagnetic mixed field Ising model

$$H_{\mathrm{AFIM}} = \sum_{\langle i_S, j_S\rangle} Z_{i_S} Z_{j_S} + \sum_{i_S} (g_x X_{i_S} + g_z Z_{i_S})$$



Exponentially many states clustered in energy around the ground state energy. **Spin ice**

Challenging to simulate classically. Current frontier from QMC $\beta \approx 10$ [1],[2]

Antiferromagnetic Heisenberg model

$$H_{\mathrm{AFHM}} = \sum_{\langle i_S, j_S\rangle} (X_{i_S} X_{j_S} + Y_{i_S} Y_{j_S} + Z_{i_S} Z_{j_S})$$

numerical sign problem

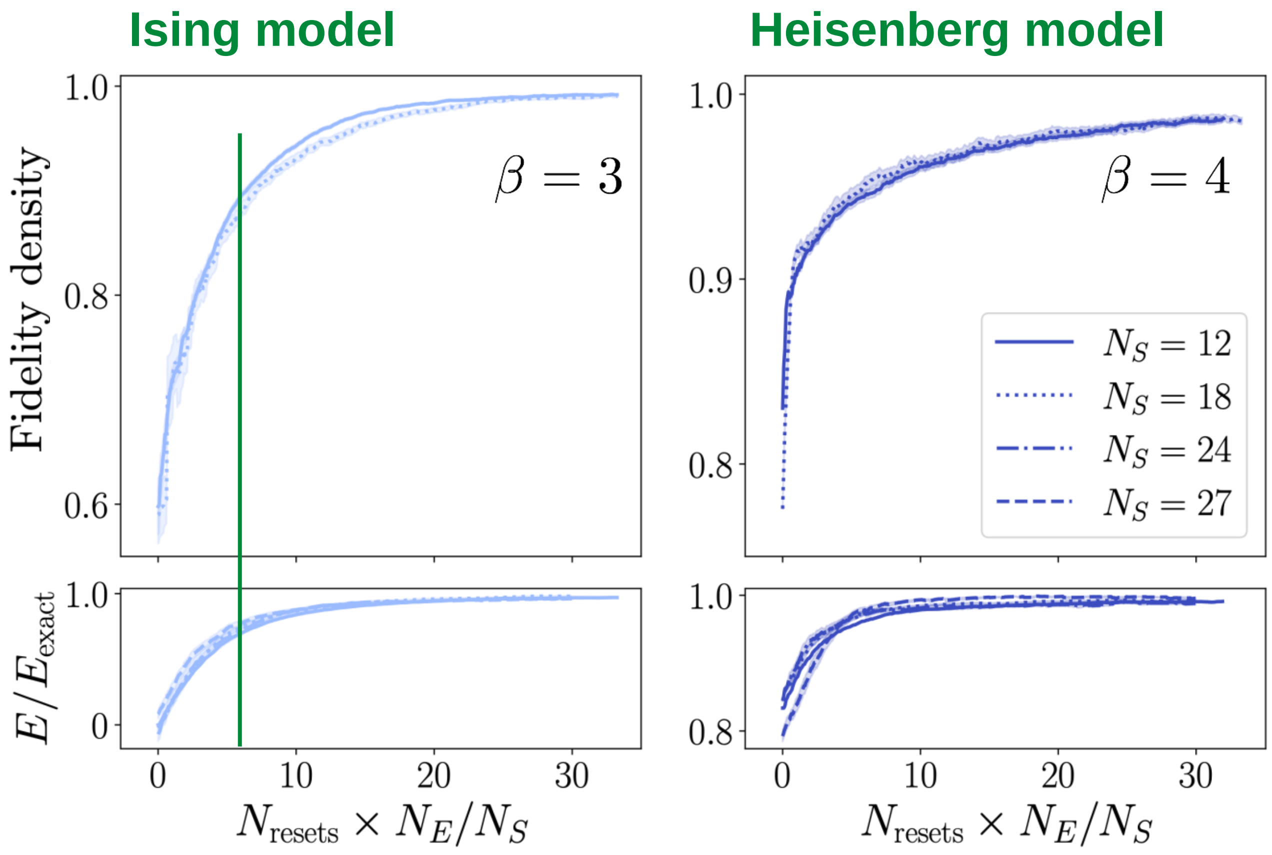
Current frontier from High temperature expansions with Padé resummation $\beta \approx 2.5$ [3]

Low temperature properties still debated.

[1] Y. Wang, S. Humeniuk, and Y. Wan, Phys. Rev. B **101**, 134414 (2020).
[2] P. Narasimhan *et al.*, Phys. Rev. B **110**, 054432 (2024).
[3] B. Bernu *et al.*, Phys. Rev. B **101**, 140403 (2020).

Classical state-vector simulations 1: Scaling with system size

Noiseless simulations with Trotterization and periodic boundary conditions

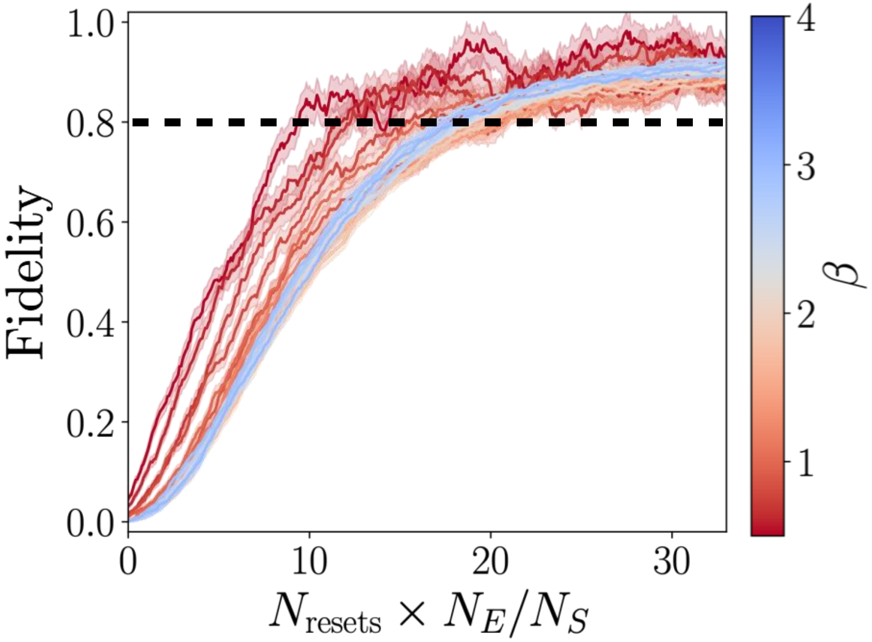


Few resets are enough to reach good fidelities and energy accuracies. Reasonable to put on hardware.

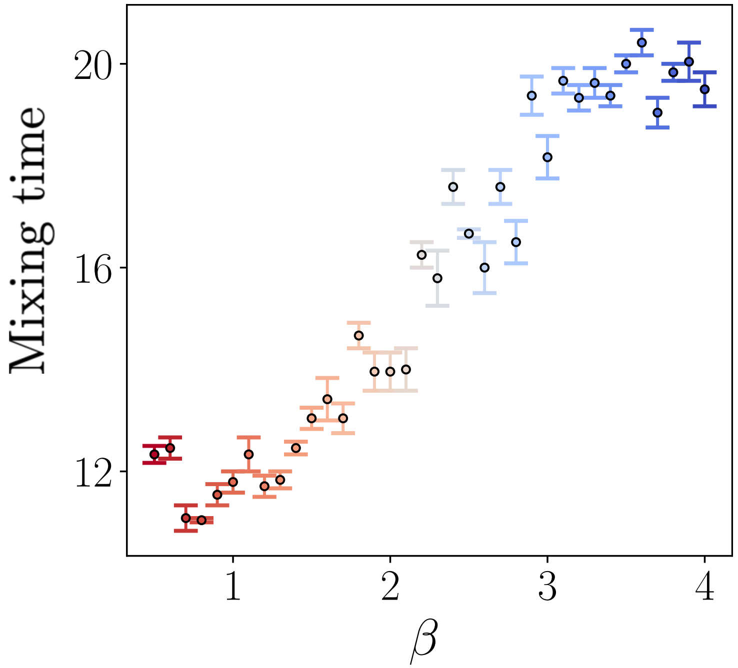
Mixing time is independent of system size. **Indicator for rapid mixing**

Classical state-vector simulations 2: Scaling with temperature

Ising model



Heisenberg model

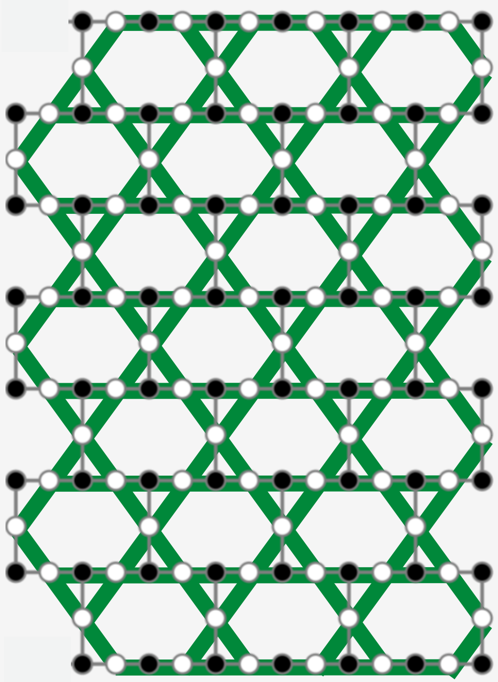


Here: Mixing time = resets needed to reach threshold fidelity

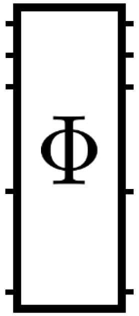
Starting state $\beta = 0$ ➡ faster mixing for high temperatures.
Peak in mixing time around cross-over.

Linear scaling with β
Vs. need of **exponentially** many samples in QMC

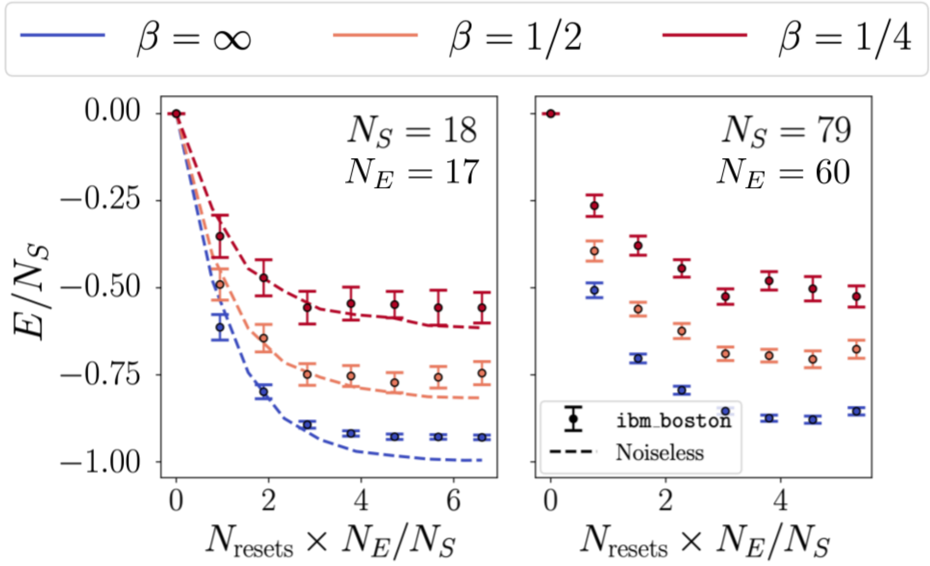
Hardware runs for the Ising model on *ibm_boston*



Kagome lattice fits on heavy hex with bath qubits spread throughout the system[1]

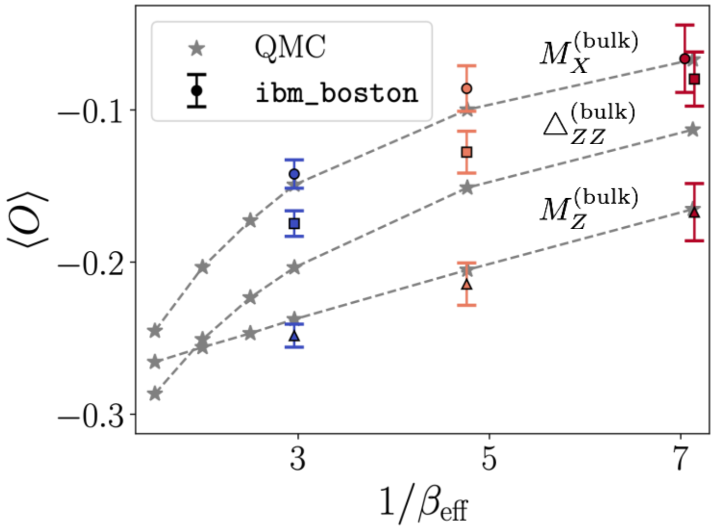


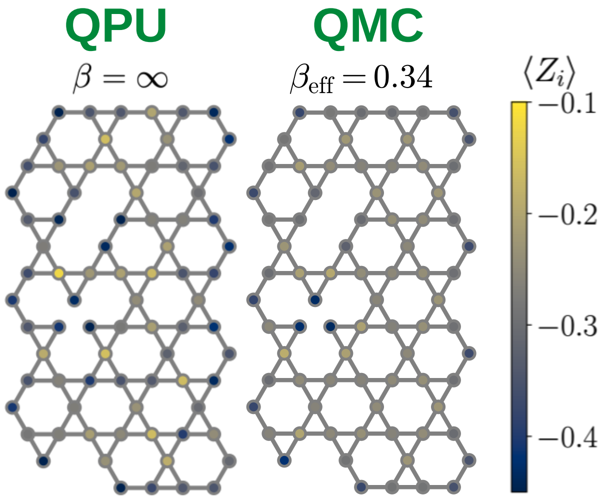
3 trotter steps per reset cycle. Total of 55 2-qubit gate depth for one cycle



Without rapid mixing this would not be possible

Use QMC to find β_{eff} such that the thermal energy matches the experiment





[1] K. Shinjo, K. Seki, and S. Yunoki, 2510.13577 (2026).

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Conclusion

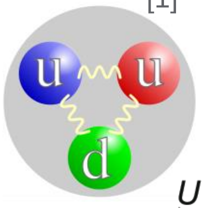
Summary

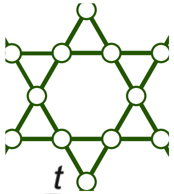
Using classical and quantum computers we found evidence for rapid mixing in frustrated spin systems.

Actual device noise drives the system to a new stable steady state with approximate thermal properties.

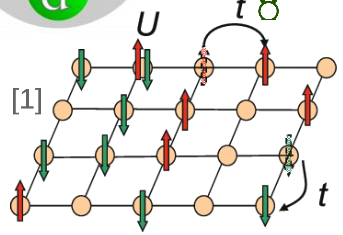
Outlook

[1]

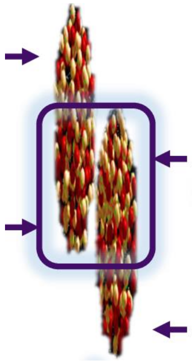




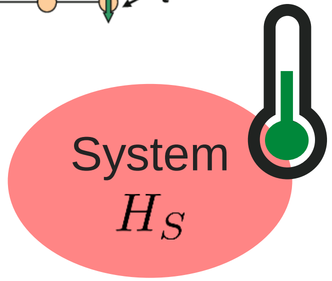
[1]



Put model with sign problem on quantum hardware



Combine thermal state preparation with real time evolution



Verify equilibration/temperature beyond comparison to classical methods

[1] https://www.wikipedia.org/

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Thank you for your attention!

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Check out our preprint:
2605.26245

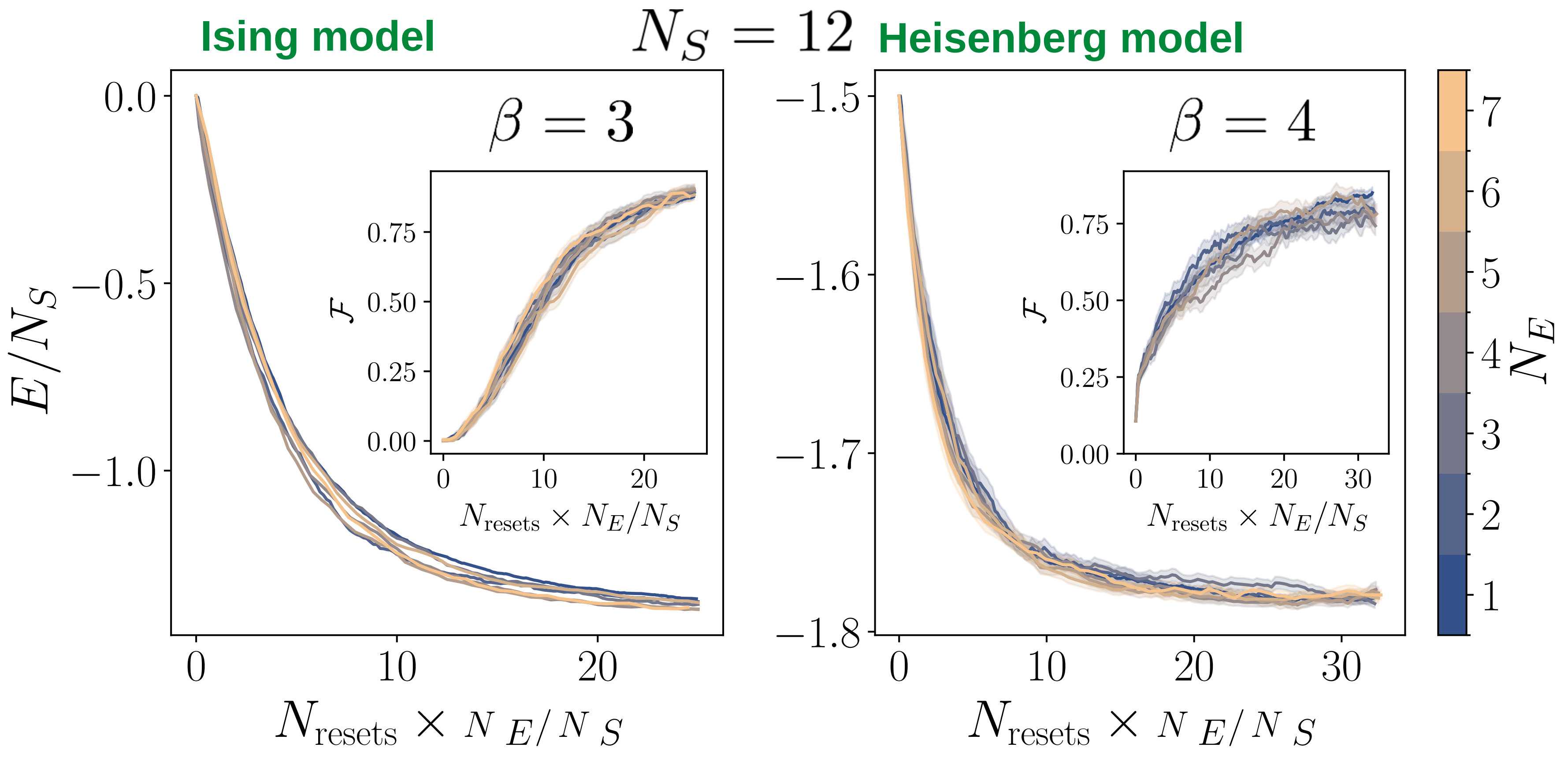
Preparing thermal states of frustrated quantum spin systems using 139 qubits

Backup

Scaling of resets with number of environment qubits

Ising model

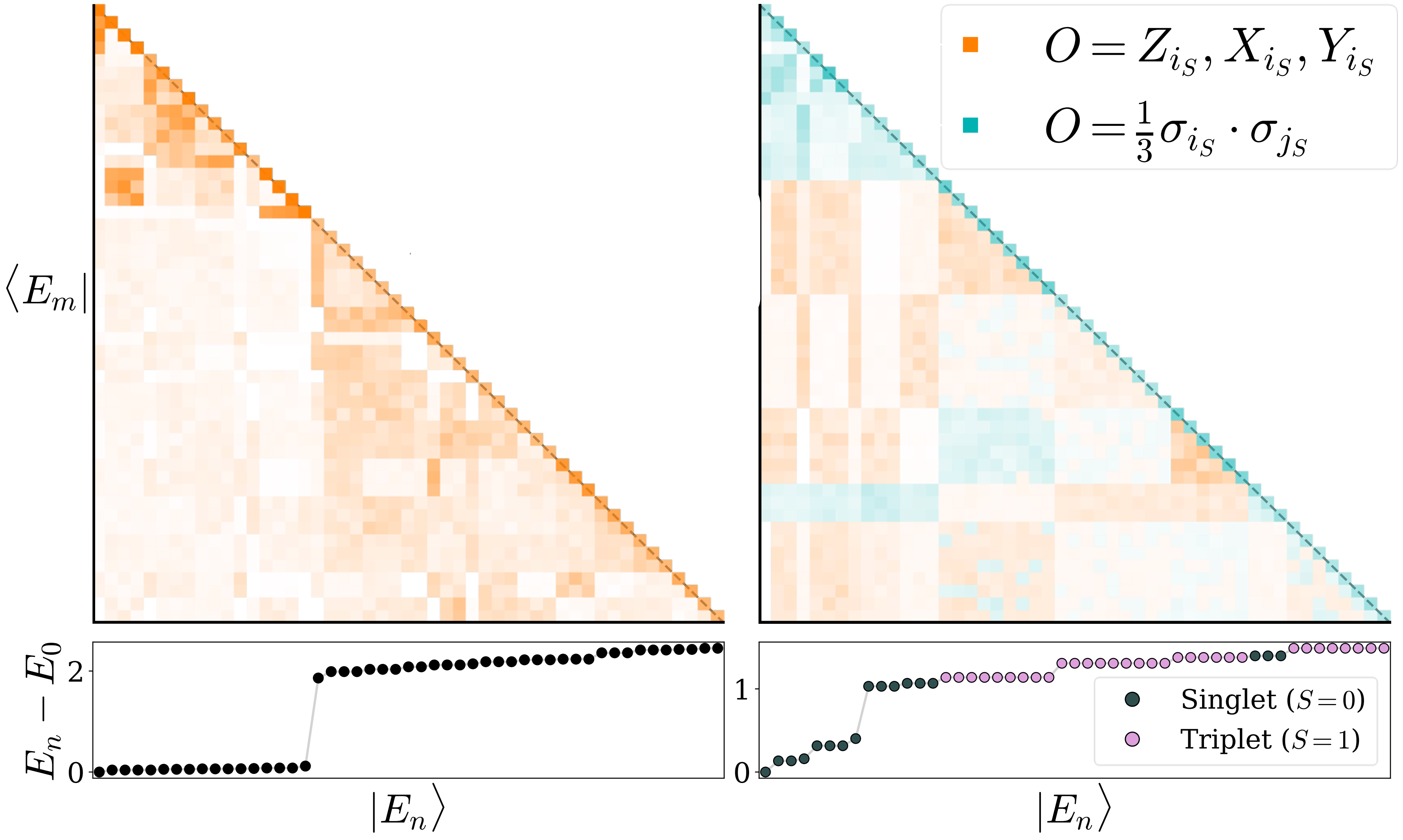
Heisenberg model



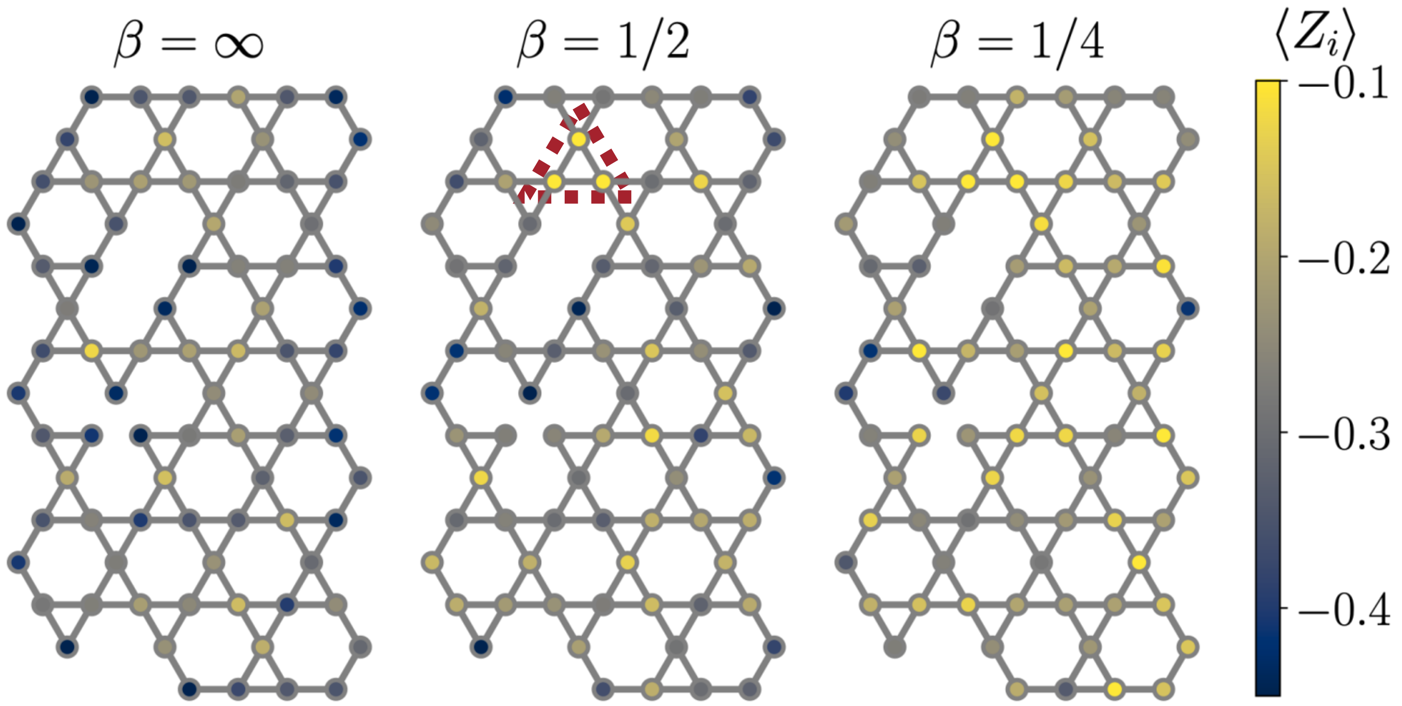
Jump Operators

Ising model

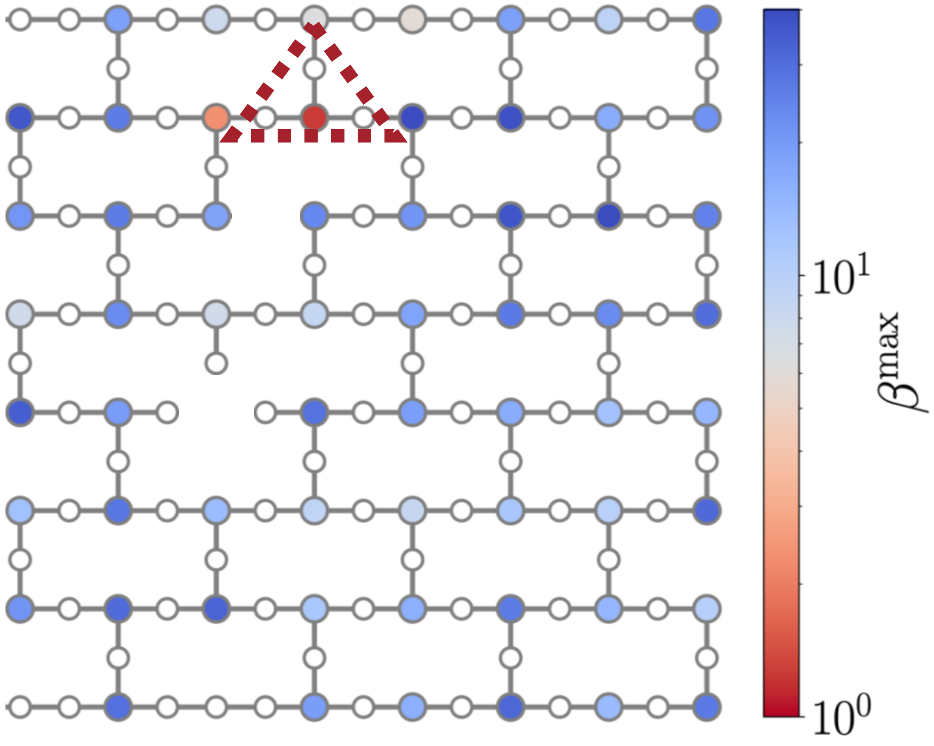
Heisenberg model



Qubit reset error



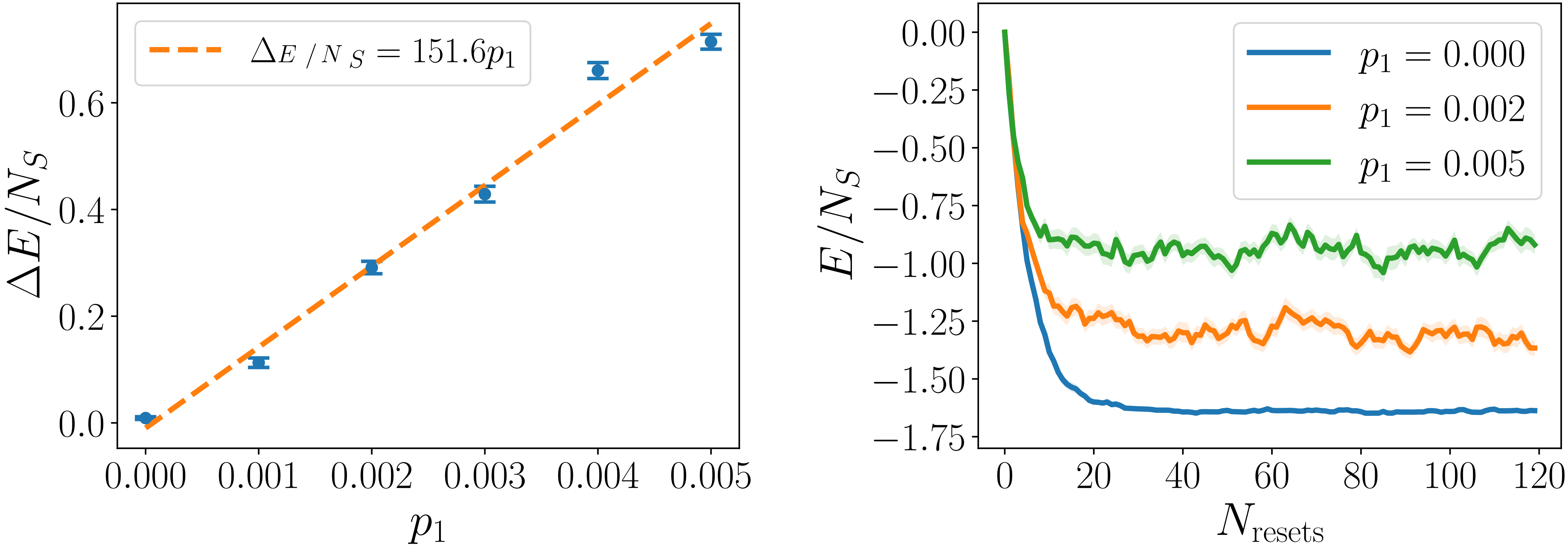
Reset errors:



Reset errors lead to „hot“ bath qubits

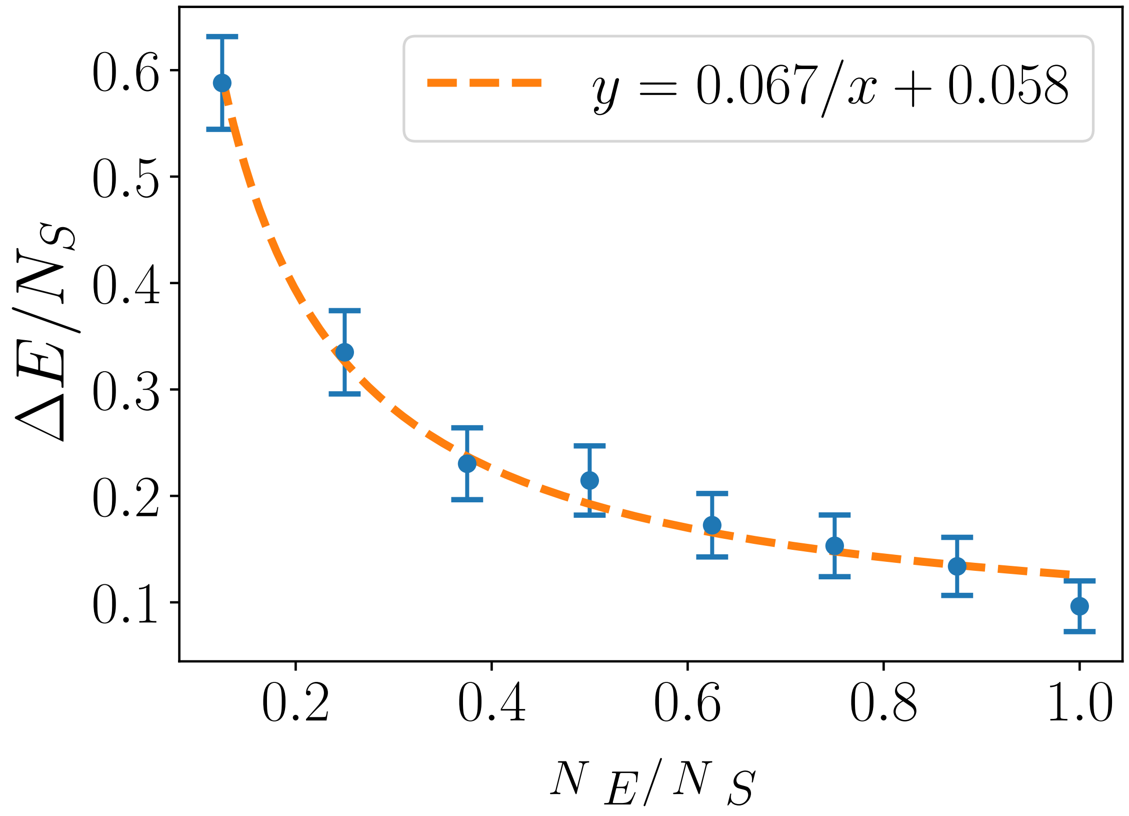
$$\beta^{\max} = \log 2 / (\epsilon_{\text{reset}} \omega_{\max})$$

Scaling with noise classical simulations

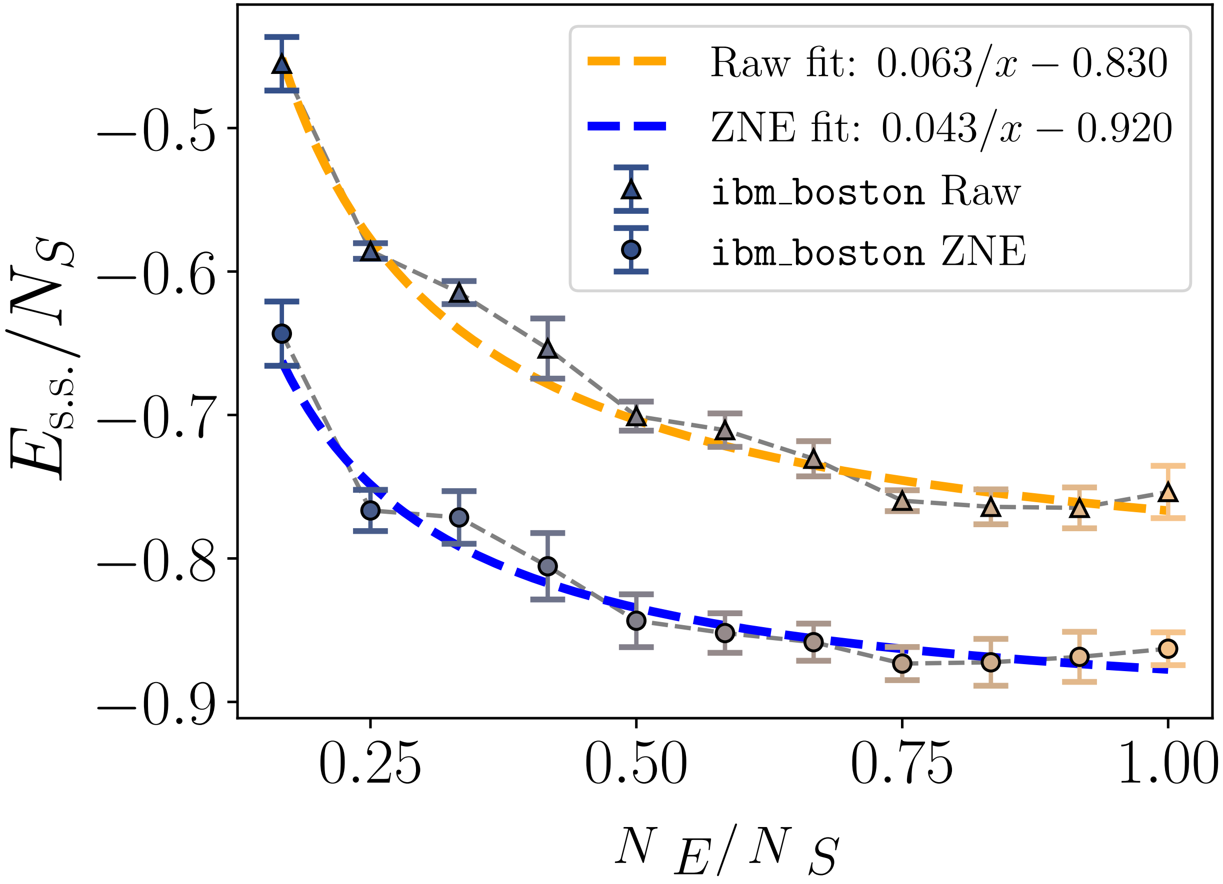


Steady state scaling with environment qubits

Classical simulations



Actual device data



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