Preparing quantum many-body scar states on quantum computers

Erik Gustafson*, Andy C. Y. Li, Abid Khan, Joonho Kim, Doga Mura Kürkçüoglu, M. Sohaib Alam, Peter P. Orth, Armin Rahmani, and Thomas Iadecola

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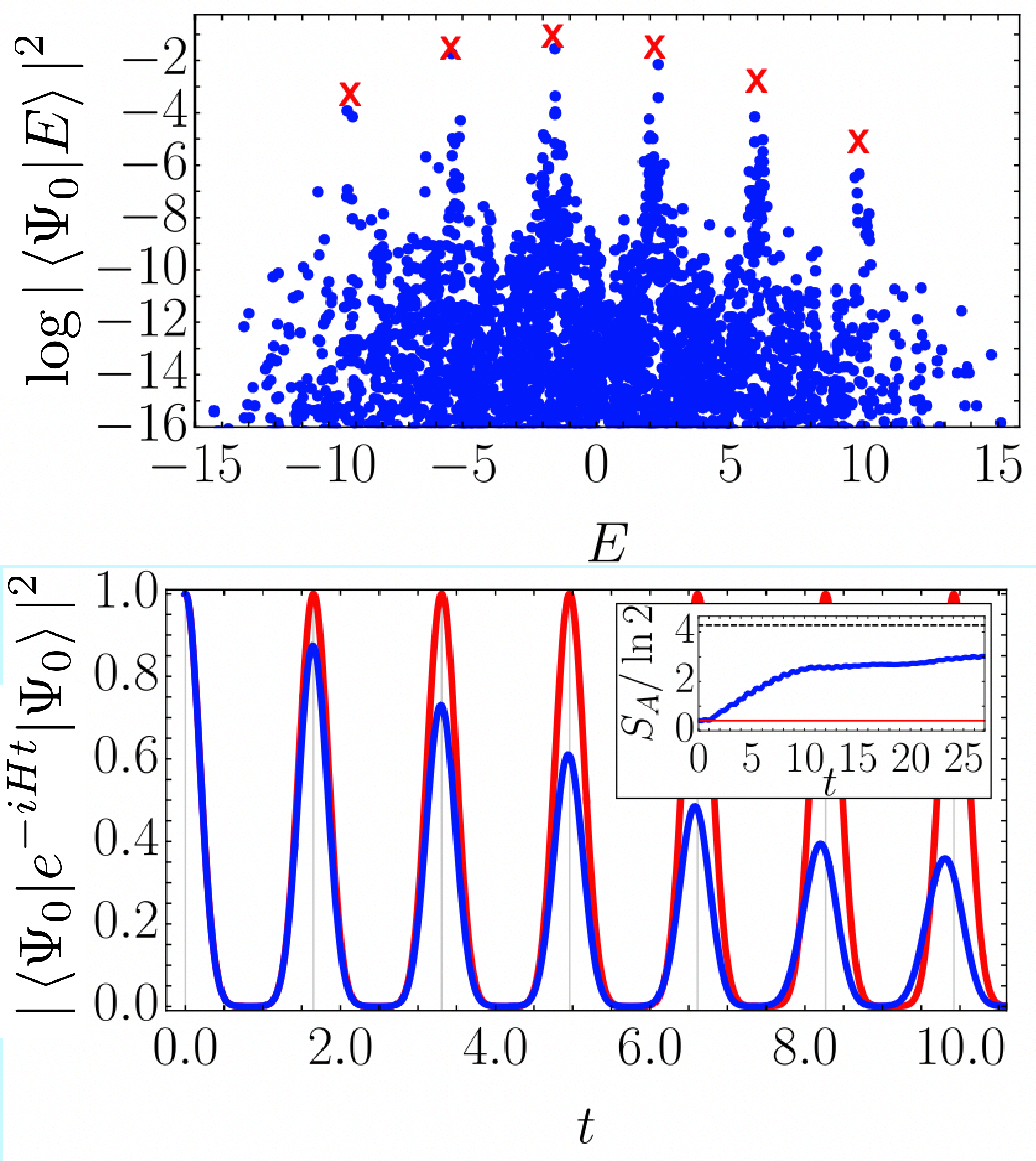
Motivation for study

- Special *highly excited* eigenstates, $|\mathcal{S}_n\rangle$, of a many body system[1]
    - **High overlap** with a particular low-entanglement state $|\Psi_0\rangle$
    - Give rise to **coherent dynamics** from $|\Psi_0\rangle$
- Have important implications for
    - Quantum statistical mechanics
    - Quantum sensing

1 Review article: Chandran, Iadecola, Khemani, and Moessner, Annual Review of Condensed Matter Physics (2023)



Iadecola and Schecter, PRB **101** 024306 (2020)

Dynamics are not well understood

- Predicting dynamics under perturbations requires evolution of **long times**
- Solving this problem requires efficient preparation of $|\Psi_0\rangle$ and $|\mathcal{S}_n\rangle$
    - Finite depth state preparation for $|\Psi_0\rangle$
    - (Quasi-) polynomial depth for $|\mathcal{S}_n\rangle$
    - Proof-of-concept demonstrations on hardware

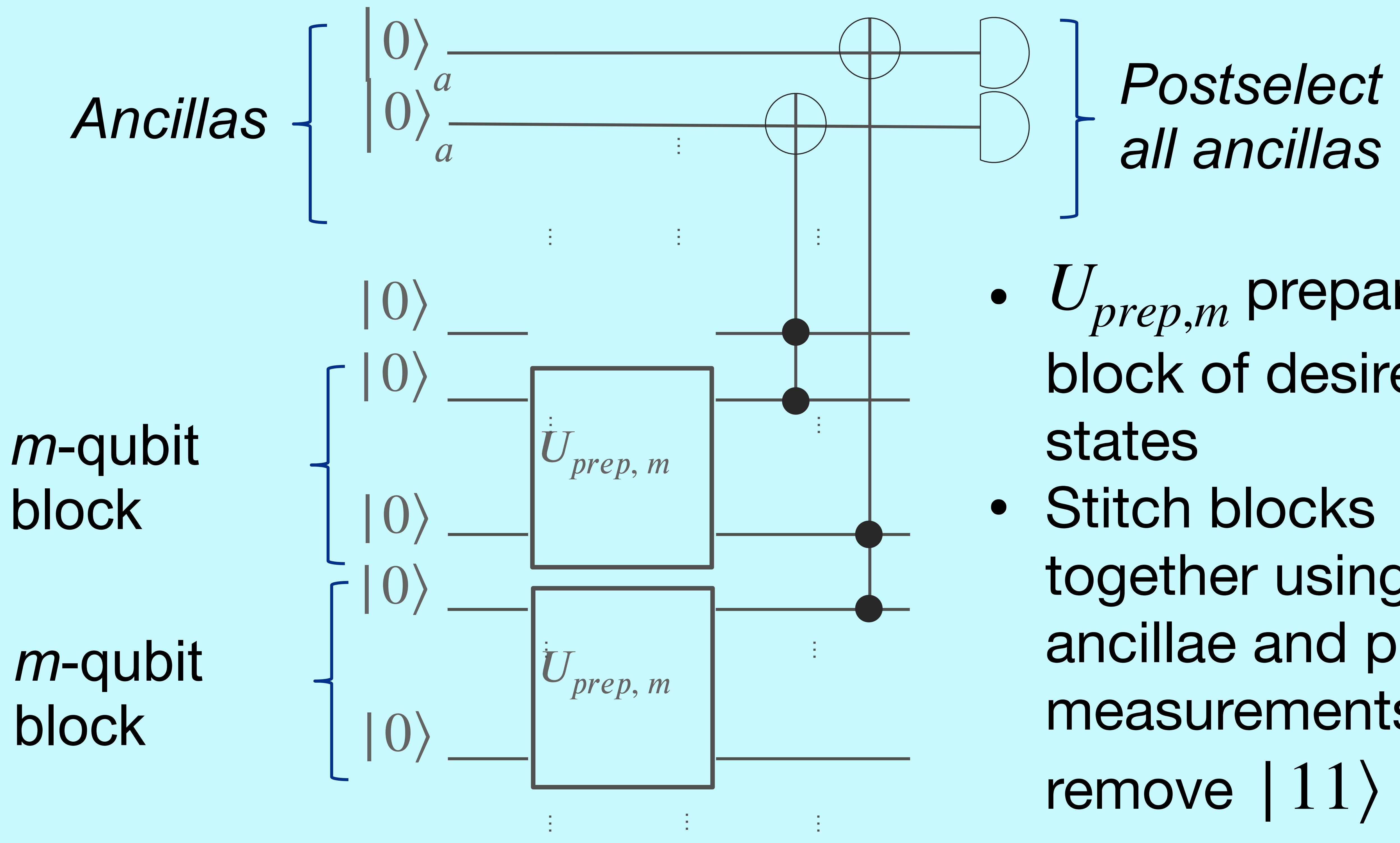
arXiv:2301.08226

$$H = H_0 + \epsilon V \qquad e^{-iHt}|\Psi_0\rangle = ?$$

$$|\Psi_0\rangle = \sum_n c_n |\mathcal{S}_n\rangle \qquad e^{-iHt}|\mathcal{S}_n\rangle = ?$$

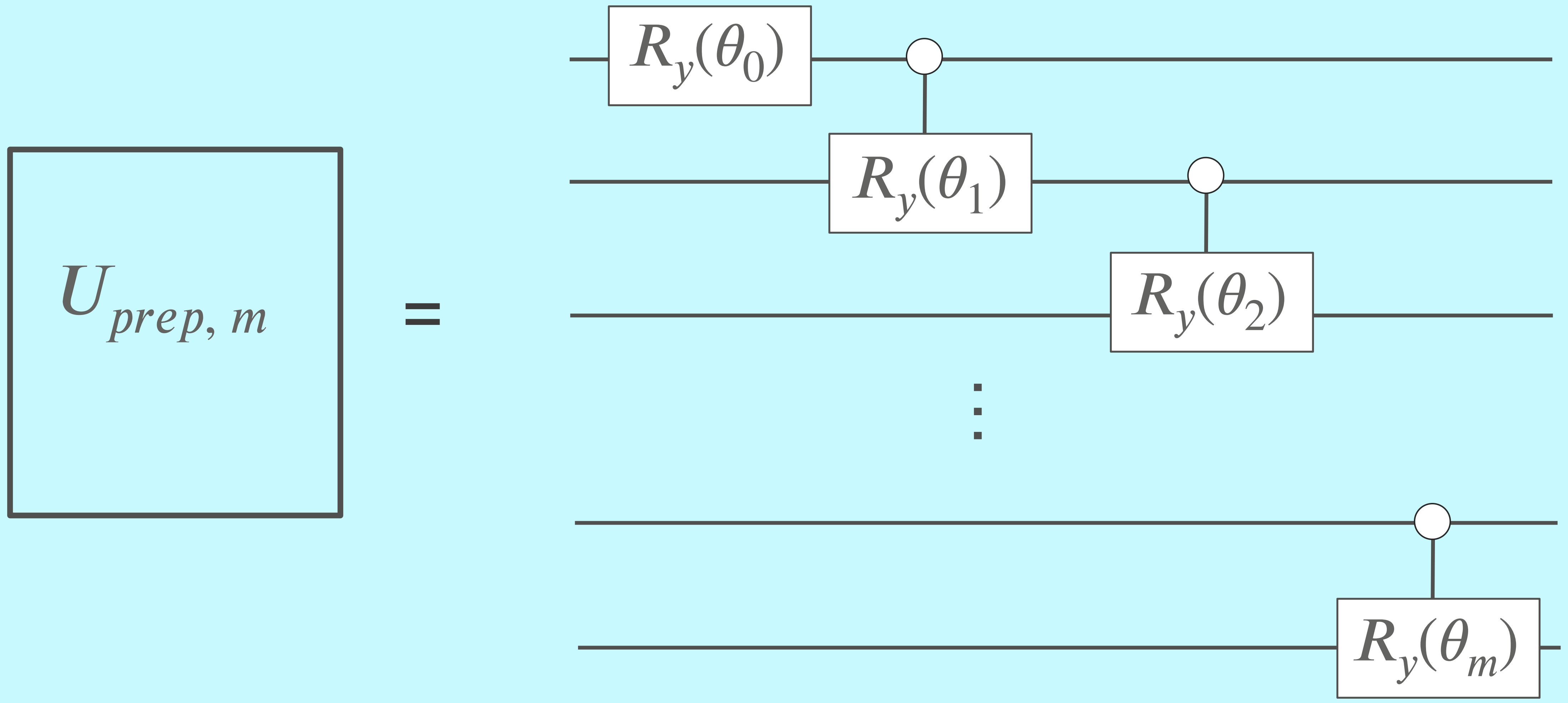
Preparing superposition state $|\Psi_0\rangle$

Finite depth circuit with measurement and post selection on ancillas



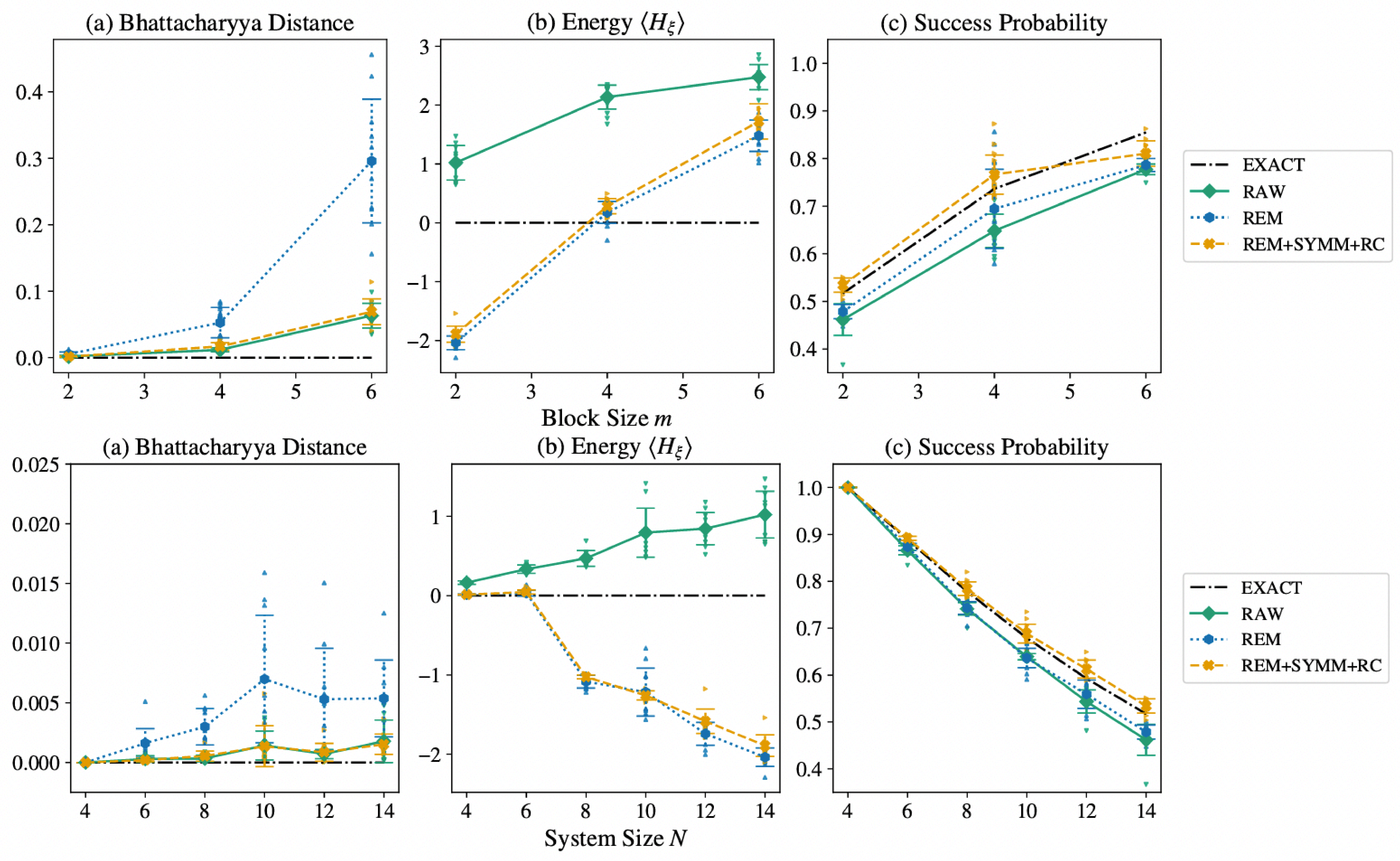
- $U_{prep,m}$ prepares block of desired states
- Stitch blocks together using ancillae and parity measurements to remove $|11\rangle$

Linear depth unitary circuit



Implementation on Aspen-M3

- Top: Benchmarks as a function of block size m
- Bottom: Benchmarks for $m = 2$
- Takeaway: Measurement and post selection offers advantage over unitary methods with current hardware

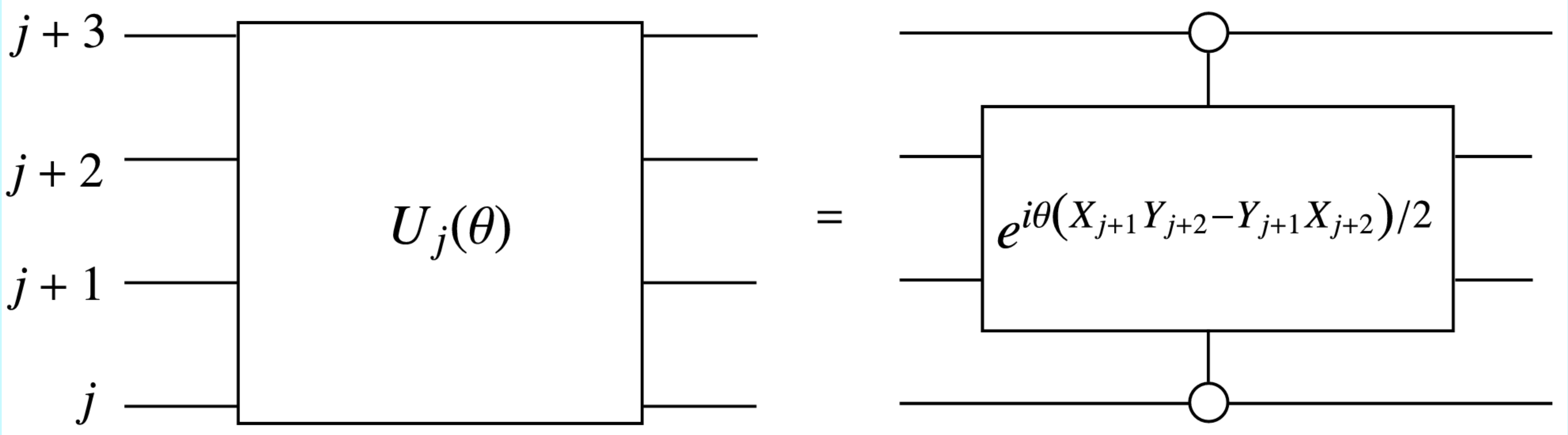


Preparing scar states $|\mathcal{S}_n\rangle$

Find a polynomial depth variational ansatz circuit to prepare these eigenstates

Basic building block:

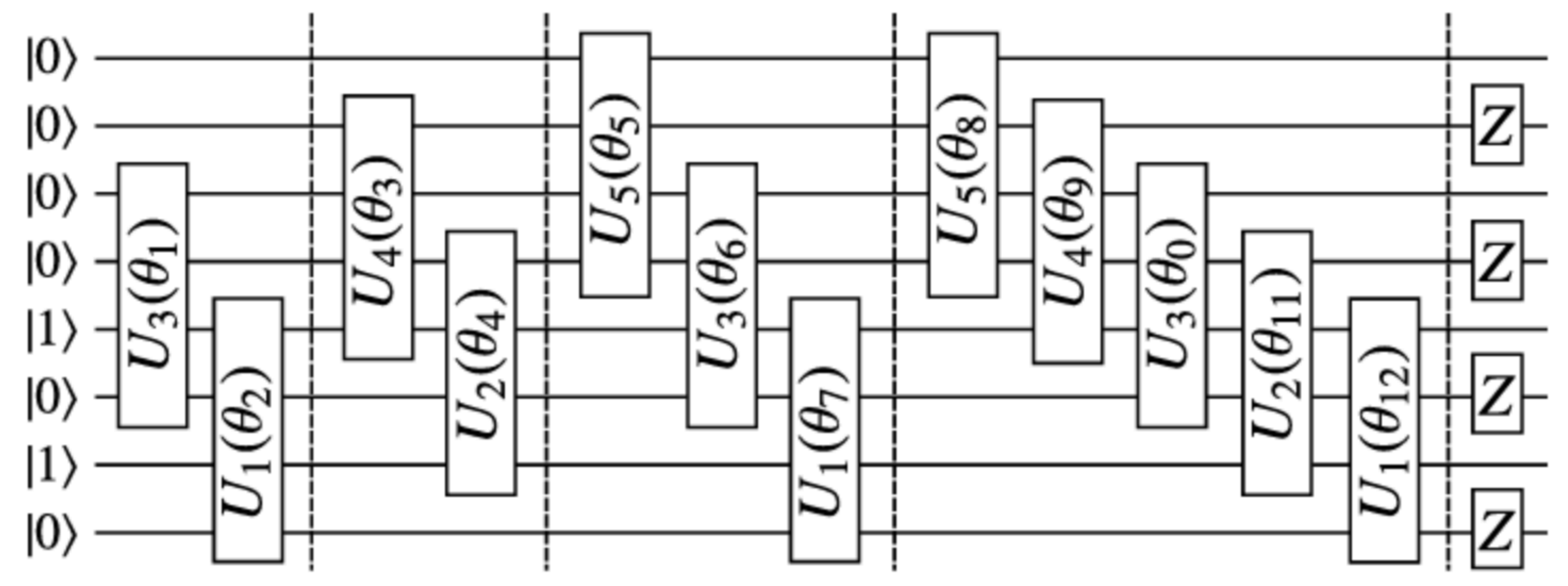
4-qubit gate



Use this to "hop" 1s around w/o letting them get too close together

Proposed circuit architecture:

Ex: N=8, n=2

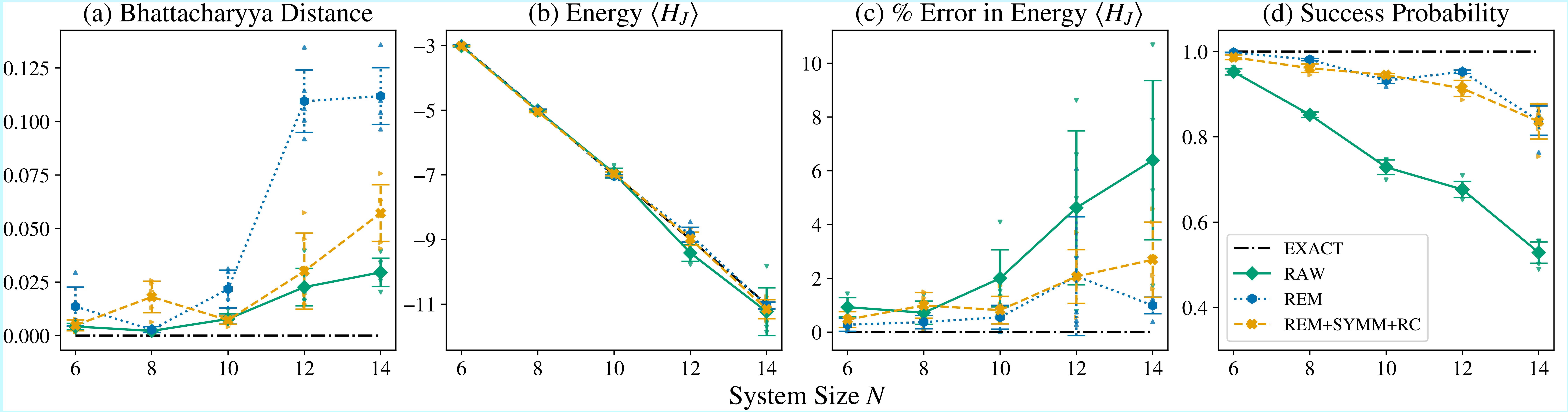


Numerical optimization of parameters gives at least 99% fidelity at all numerically accessible system sizes

Gate depth $O(N^2)$

Alternative technique: Quasipolynomial depth exact circuit from matrix product states

Implementation on Aspen-M3

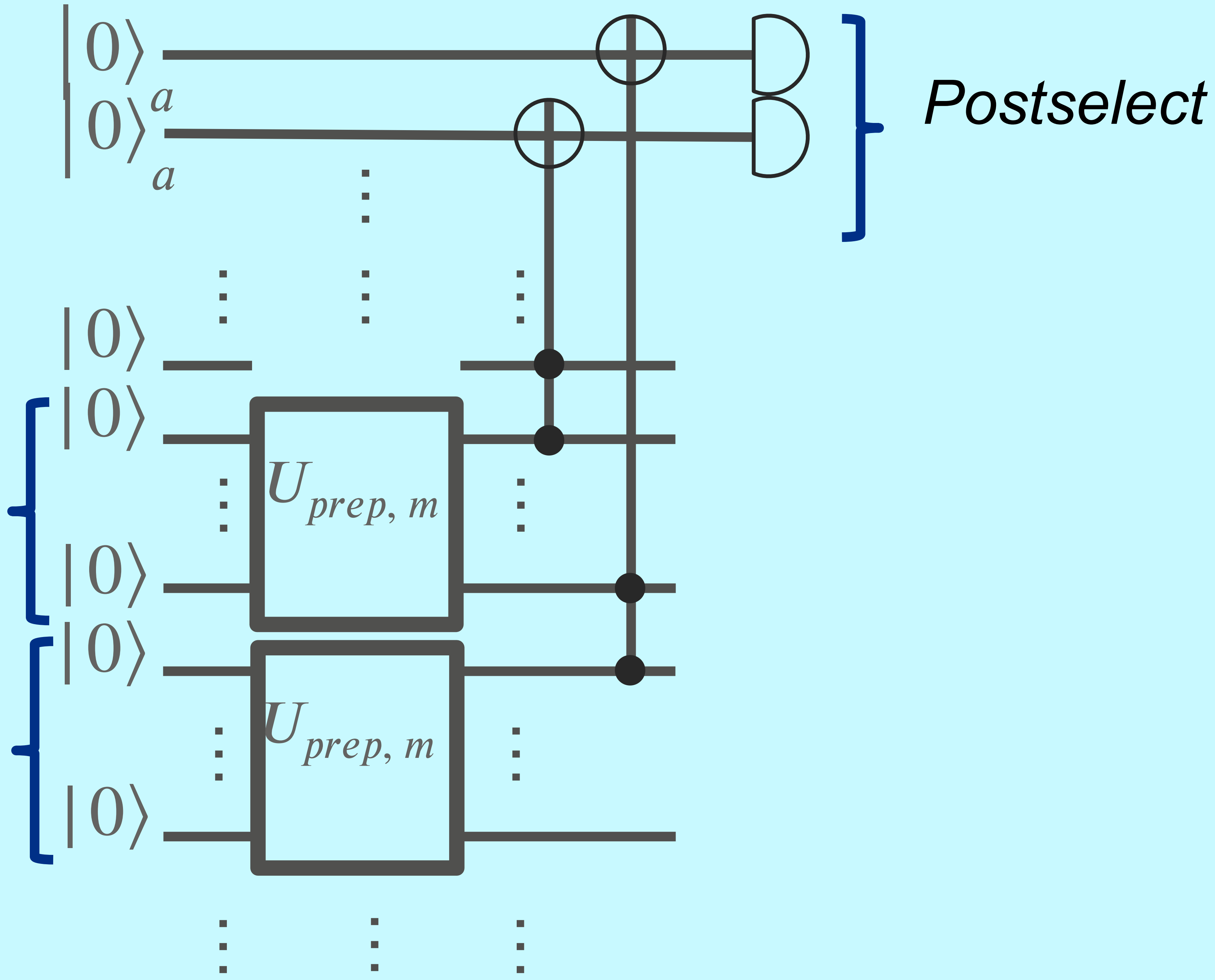


Benchmarks for preparing the $|\mathcal{S}_n\rangle$ state

Success probability decreases with system size

Future Work

- Postselection success probability for preparing $|\Psi_0\rangle$ is prohibitively small for large systems

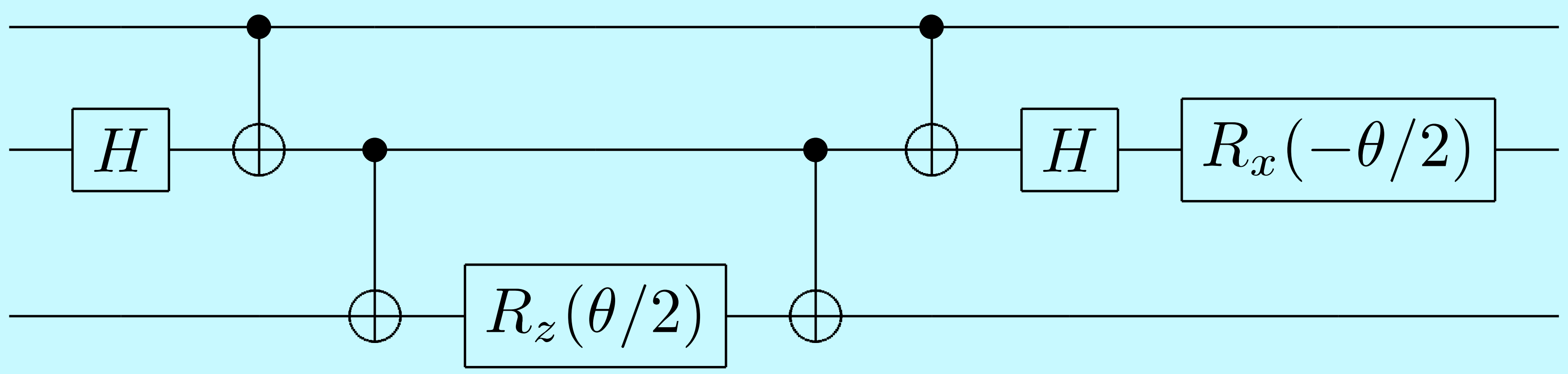


Can we feed-forward ancilla measurement results to correct “bad” outcomes?

Baby quantum error correction problem!

$$H_0 = \frac{\lambda}{2}\sum_i (X_i - Z_{i-1}X_iZ_{i+1}) + h\sum_i Z_i$$

$$e^{i\frac{\theta}{4}(X_i - Z_{i-1}X_iZ_{i+1})} =$$



- Once we have prepared the states we want, what do we need to do high fidelity time evolution over long times?

Quantum Many-Body Scars: Resource Requirements

	$\lvert\Psi_0\rangle$ state prep	$\lvert\mathcal{S}_n\rangle$ state prep
Proof of Concept (N~10 qubits)	Constant gate depth (m+1) Postselection success probability ~70% (m=2) 100% (m=8)	Gate depth ~ 200
Nontrivial Physics (N~100 qubits)	Constant gate depth (m+1) Postselection success probability ~0.4% (m=2) ~18% (m=8)	Gate depth ~ 20000
Scaling	Success prob. ~ $e^{-N/m}$	Gate depth $O(N^2)$

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