# Scalable Classical Shadow Tomography with Shallow Circuits and Quantum Dynamics


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[1] H.-Y. Hu, Y.-Z. You. arXiv:2102.10132

[2] H.-Y. Hu, S. Choi, Y.-Z. You. arXiv:2107.04817

[3] A. A. Akhtar, H.-Y. Hu, Y.-Z. You. arXiv:2209.02093


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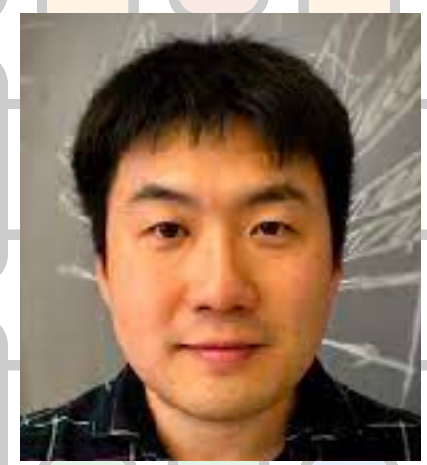


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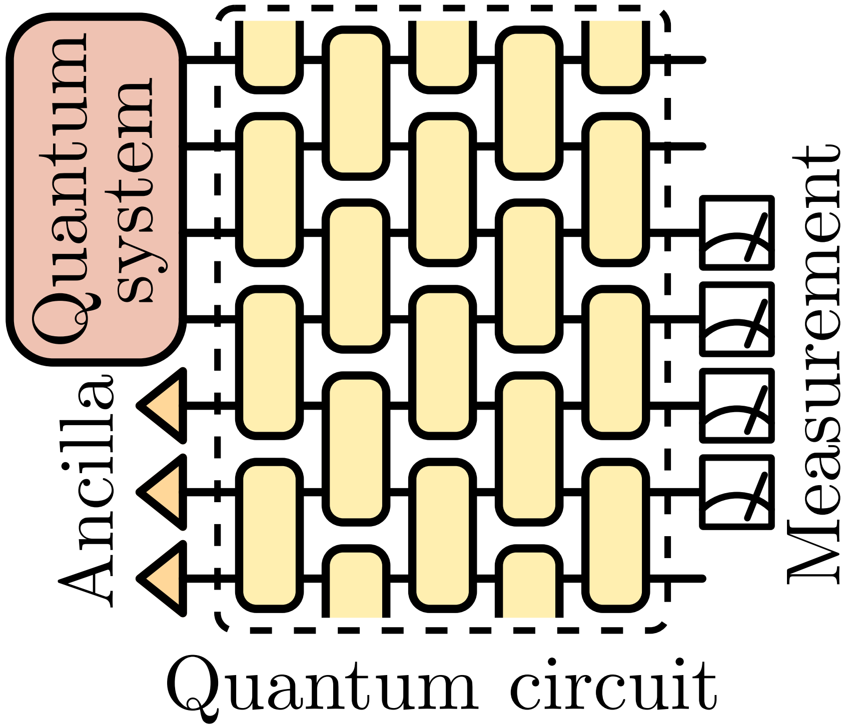
# Quantum Dynamics meets Shadow Tomography

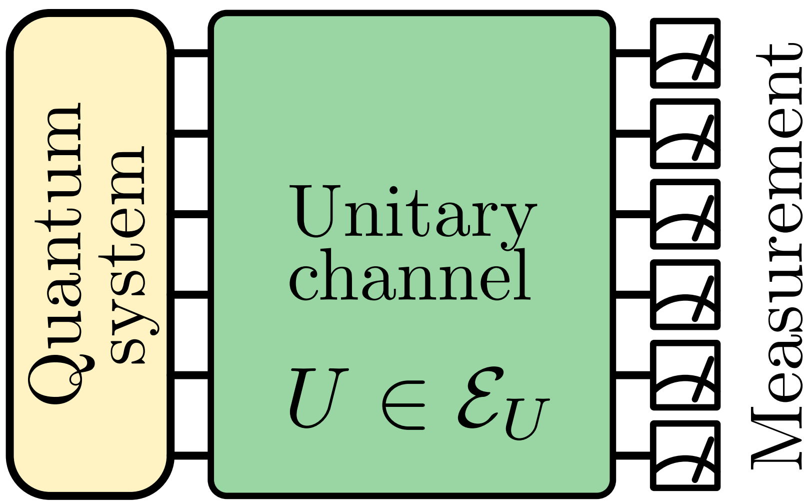
- The goal of this program is “to explore connections between NISQ devices and quantum dynamics.”
- Classical shadow tomography is one such example.
  - What do we study in quantum dynamics?
    A quantum many-body system (+ ancilla) under unitary evolution and measurements
  - Is the **randomized measurement** tomographically complete?
  - How to reconstruct the quantum information from measurements?
  - What is the sample complexity for different tasks?
  - How to optimize tomography efficiency on NISQ devices?

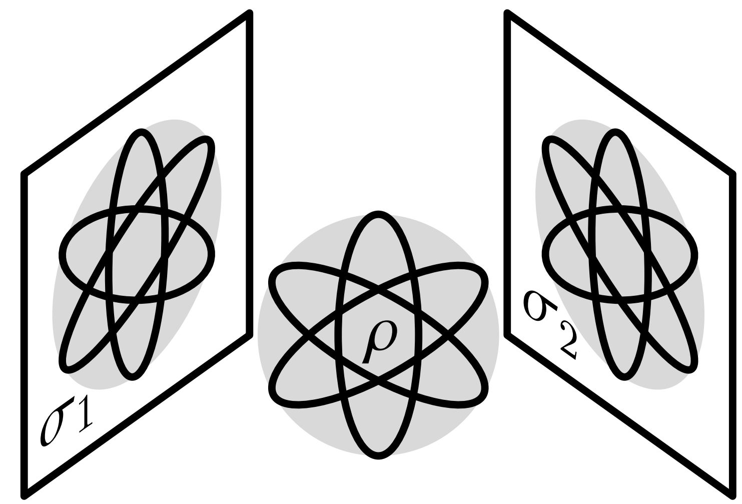



Review: Elben, Flammia, Huang, Kueng, Preskill, Vermersch, Zoller. arXiv:2203.11374 (2022)

# Randomized Measurement Protocol

- Randomized measurement
  = random unitary + computational basis measurement




- Step 1 (Random scrambling): $\rho \to \rho' = U\rho U^\dagger$
- Step 2 (Z-basis measurement): $\rho' \to |b\rangle\langle b|$
- Step 3 (Collect classical snapshot): $\hat{\sigma}_{U,b} = U^\dagger |b\rangle\langle b| U$

(Stored classically)

- Probability to obtain a classical snapshot

$$P(\hat{\sigma}_{U,b}|\rho) = P(b|\rho, U)P(U) = \mathrm{Tr}(\hat{\sigma}_{U,b}\rho)P(U)$$

# Ensembles of Classical Snapshots

- Classical snapshot states $\hat{\sigma}$ form two types of ensembles:
  - Posterior snapshot ensemble:

$$\mathcal{E}_{\sigma|\rho} = \{\hat{\sigma}_{U,b} \mid P(\hat{\sigma}_{U,b}|\rho) = \mathrm{Tr}(\hat{\sigma}_{U,b}\rho)P(U)\}$$

  - Prior snapshot ensemble:

$$\mathcal{E}_{\sigma} = \{\hat{\sigma}_{U,b} \mid P(\hat{\sigma}_{U,b}) = 2^{-N}P(U)\}$$

    - As if $\rho = \mathbb{1}/2^N$ is maximally mixed (without any knowledge about the quantum system)
    - The prior ensemble $\mathcal{E}_\sigma$ only depends on the random unitary ensemble $\mathcal{E}_U = \{U|P(U)\}$ (encodes statistical features of the randomized measurement scheme)

# Measurement Channel and Reconstruction Map

- **Measurement channel**: a quantum channel mapping from observed quantum state $\rho$ to average classical snapshot $\sigma$

$$\sigma \equiv \mathop{\mathbb{E}}_{\hat{\sigma} \in \mathcal{E}_{\sigma|\rho}} \hat{\sigma} = \mathop{\mathbb{E}}_{\hat{\sigma} \in \mathcal{E}_{\sigma}} \hat{\sigma} \, \mathrm{Tr}(\hat{\sigma}\rho) 2^N = \mathcal{M}[\rho]$$

  - Assuming the measurement basis is topographically complete → the measurement channel $\mathcal{M}$ is invertible (the inverse map $\mathcal{M}^{-1}$ exists)

- **Reconstruction map**: the inverse map from average classical snapshot $\sigma$ to observed quantum state $\rho$

$$\rho = \mathcal{M}^{-1}[\sigma] = \mathop{\mathbb{E}}_{\hat{\sigma} \in \mathcal{E}_{\sigma|\rho}} \mathcal{M}^{-1}[\hat{\sigma}]$$

Not a physical channel

  - $\mathcal{M}^{-1}$ is the key! It specifies how to post-process the classical data $\sigma$ to make predictions.

# Measurement Channel and Reconstruction Map

- **Reconstruction map**: the inverse map from average classical snapshot $\sigma$ to observed quantum state $\rho$

$$\rho = \mathcal{M}^{-1}[\sigma] = \mathop{\mathbb{E}}_{\hat{\sigma} \in \mathcal{E}_{\sigma|\rho}} \mathcal{M}^{-1}[\hat{\sigma}]$$

  - $\mathcal{M}^{-1}$ is the key! It specifies how to post-process the classical data $\sigma$ to make predictions.
  - Examples: predict physical properties about $\rho$

$$\langle O \rangle_\rho = \mathop{\mathbb{E}}_{\hat{\sigma} \in \mathcal{E}_{\sigma|\rho}} \mathrm{Tr}(O \mathcal{M}^{-1}[\hat{\sigma}])$$ (Linear property)

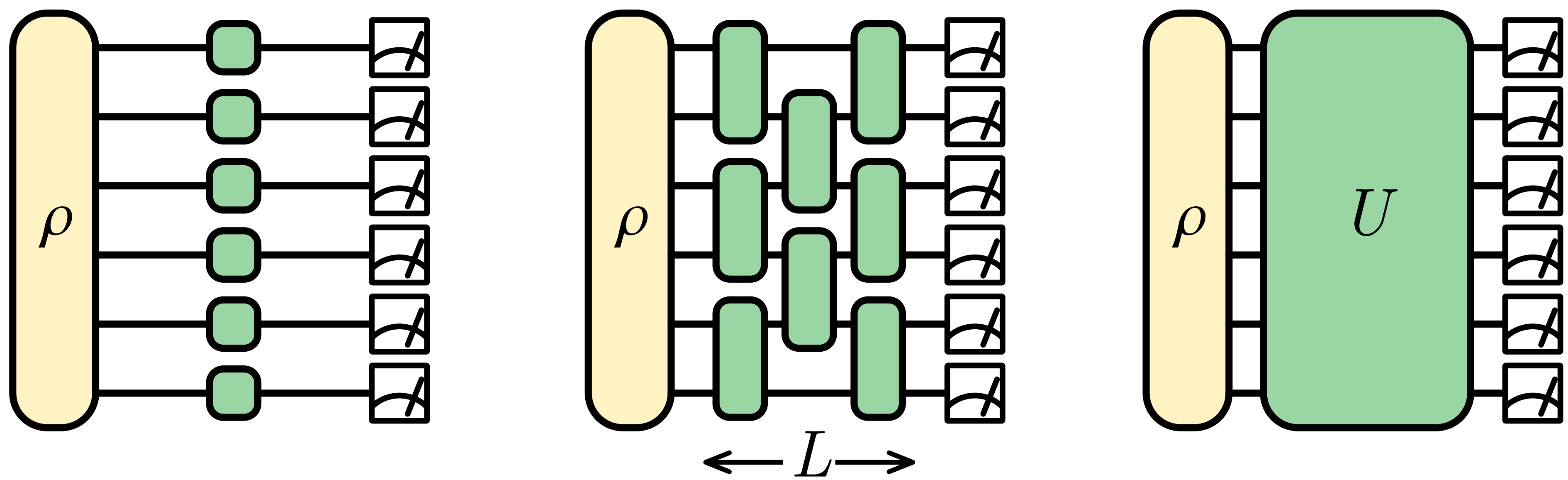
$$e^{-S_\rho^{(2)}(A)} = \mathop{\mathbb{E}}_{\hat{\sigma}, \hat{\sigma}' \in \mathcal{E}_{\sigma|\rho}} \mathrm{Tr}_A \left( \mathrm{Tr}_{\bar{A}} \mathcal{M}^{-1}[\hat{\sigma}] \, \mathrm{Tr}_{\bar{A}} \mathcal{M}^{-1}[\hat{\sigma}'] \right)$$

(Nonlinear property)

- However, known results about $\mathcal{M}$ and $\mathcal{M}^{-1}$ were limited to random Pauli and Clifford measurements previously.

# Local v.s. Global Scrambling

- Pauli Measurement
- Clifford Measurement




$$\mathcal{M}^{-1}[\sigma] = \bigotimes_i (3\sigma_i - \mathbb{1})$$

???

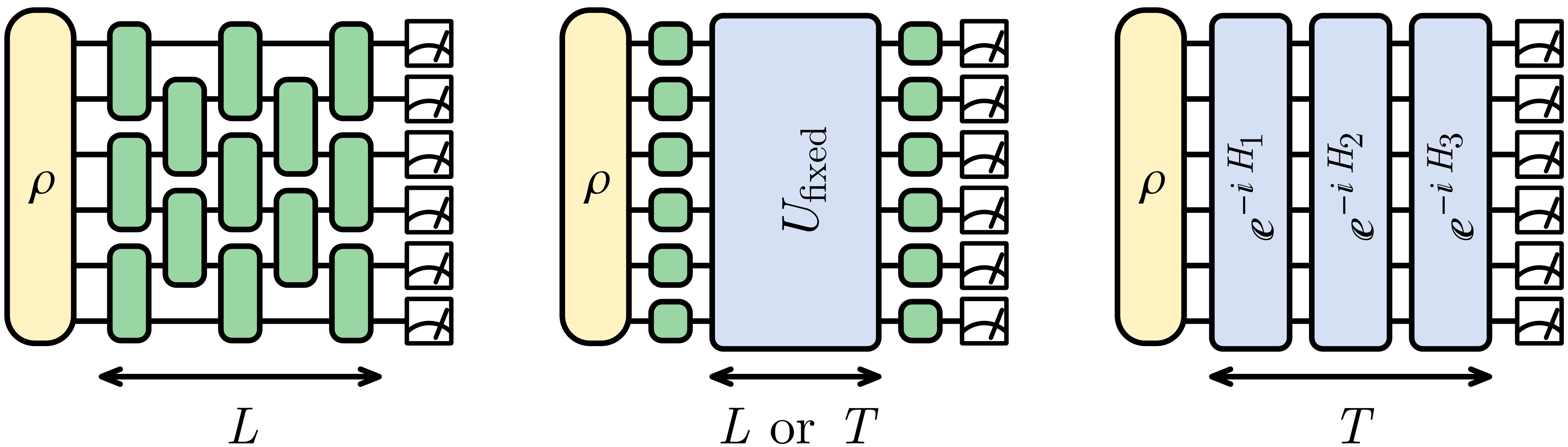
$$\mathcal{M}^{-1}[\sigma] = (2^N + 1)\sigma - \mathbb{1}$$

- Efficient for local observables (e.g. local Hamiltonian, two-point correlation)
- Low circuit complexity

- Efficient for low-rank observables (e.g. fidelity estimation)
- High circuit complexity

# Main Result

- We made progress in formulating the reconstruction map $\mathcal{M}^{-1}$ for a large class of randomized measurements based on locally scrambled quantum dynamics/circuits




$$\rho = \mathcal{M}^{-1}[\sigma] = \sum_A r_A \sigma_A$$

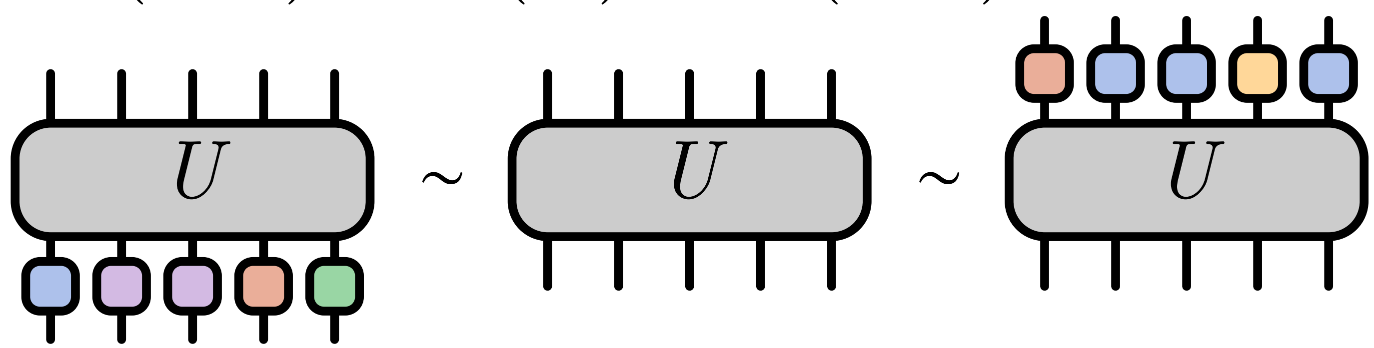
H.-Y. Hu, S. Choi, Y.-Z.You. arXiv:2107.04817 (2021)

- The key is to understand the entanglement dynamics under different scrambling unitaries.

# Locally Scrambled Quantum Dynamics

- A random unitary ensemble $\mathcal{E}_U$ is locally scrambled iff

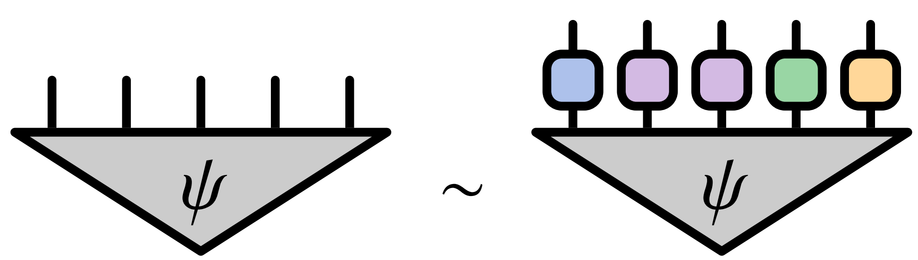
$$\forall V = \prod_i V_i : P(VU) = P(U) = P(UV)$$




  - Refined from Haar (globally scrambled) random unitary
  - Can be constructed by assembling locally scrambled unitary gates (e.g. random Clifford circuits of any structure)

- A random state ensemble $\mathcal{E}_\sigma$ is locally scrambled iff

$$\forall V = \prod_i V_i : P(\sigma) = P(V^\dagger \sigma V)$$




For pure state
$\sigma = |\psi\rangle\langle\psi|$

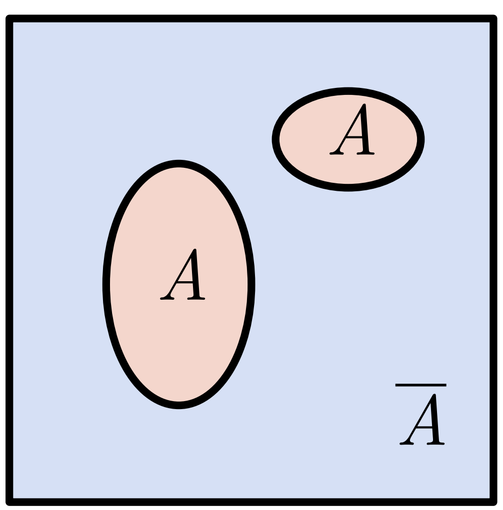
# Locally Scrambled Random States

- Classical snapshots collected from locally scrambled randomized measurements are also locally scrambled!
- Only local-basis invariant information matters
  → All such information are **entanglement features** (EF)

You, Gu (2018); Kuo, Akhtar, Arovas, You (2019)

$$W^{(n)}_{\mathcal{E}_\sigma, g} = \operatorname{Tr} \sigma^{\otimes n} g \qquad (g \in S_n^{\times N})$$

- At the 2-replica level, EF is just the purity in all possible subsystems




$$\begin{aligned} W^{(2)}_{\mathcal{E}_\sigma, A} &= \mathop{\mathbb{E}}_{\sigma \in \mathcal{E}_\sigma} \operatorname{Tr} \sigma^{\otimes 2} \mathcal{X}_A \longleftarrow \text{Swap operator} \\ &= \mathop{\mathbb{E}}_{\sigma \in \mathcal{E}_\sigma} \operatorname{Tr}_A (\operatorname{Tr}_{\bar{A}} \sigma)^2 \\ &= \mathop{\mathbb{E}}_{\sigma \in \mathcal{E}_\sigma} \mathrm{e}^{-S_\sigma^{(2)}(A)} \longleftarrow \text{Entanglement entropy} \end{aligned}$$

# Entanglement Feature Formalism

- N-qubit system: totally $2^N$ possible choices of subsystems, how to encode their entanglement features efficiently?
- Idea: use a fictitious quantum state - the **EF state**

$$|W_{\mathcal{E}_\sigma}\rangle = \sum_A W_{\mathcal{E}_\sigma, A}|A\rangle = \sum_A \mathrm{e}^{-S_\sigma(A)}|A\rangle$$

(Rényi index will be omitted)

  - Basis states are labeled by entanglement regions ~ Ising configurations

$$|A\rangle = |s_1 s_2 s_3 \cdots s_N\rangle \qquad s_i = \begin{cases} 0 & i \in \bar{A} \\ 1 & i \in A \end{cases}$$

- Every locally scrambled random state ensemble $\mathcal{E}_\sigma$ is characterized by a corresponding EF state $|W_{\mathcal{E}_\sigma}\rangle$
- Are there any fictitious operators that can act on the EF state? - Yes, the **EF operator**

Kuo, Akhtar, Arovas, You (2019)

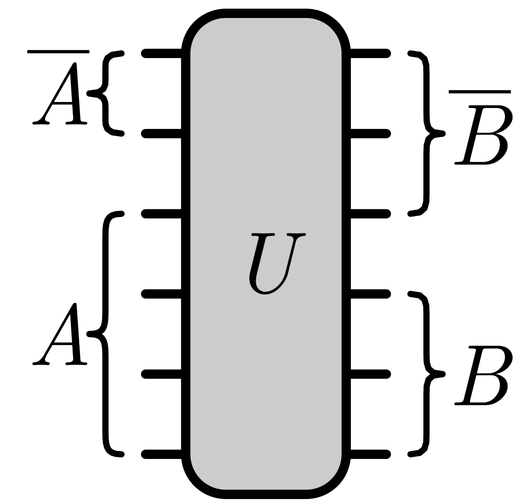
# Entanglement Feature Formalism

- Entanglement features of random unitary ensemble

$$W_{\mathcal{E}_U,A,B} = \mathop{\mathbb{E}}_{U\in\mathcal{E}_U} \operatorname{Tr} U^{\otimes 2}\mathcal{X}_A (U^\dagger)^{\otimes 2}\mathcal{X}_B$$

which define the **EF operator**

$$\begin{aligned}\hat{W}_{\mathcal{E}_U} &= \sum_{A,B} |A\rangle W_{\mathcal{E}_U,A,B}\langle B| \\ &= \sum_{A,B} |A\rangle \mathrm{e}^{-S_U(A\cup B)}\langle B|\end{aligned}$$




- *A* and *B* label the entanglement regions on the past and the future sides of the unitary.

- Every locally scrambled random unitary ensemble $\mathcal{E}_U$ is characterized by a corresponding EF operator $\hat{W}_{\mathcal{E}_U}$

Kuo, Akhtar, Arovas, You (2019)

# Entanglement Dynamics

- Unitary evolution of a locally scrambled random state by a locally scrambled random unitary

$$\sigma \to U^\dagger \sigma U \qquad (\sigma \in \mathcal{E}_\sigma, U \in \mathcal{E}_U)$$

  - The resulting state is still locally scrambled
  - Its entanglement feature evolves as

$$|W_{\mathcal{E}_\sigma}\rangle \to \hat{W}_{\mathcal{E}_U} \hat{W}_{\mathbb{1}}^{-1} |W_{\mathcal{E}_\sigma}\rangle$$

Kuo, Akhtar, Arovas, You (2019)

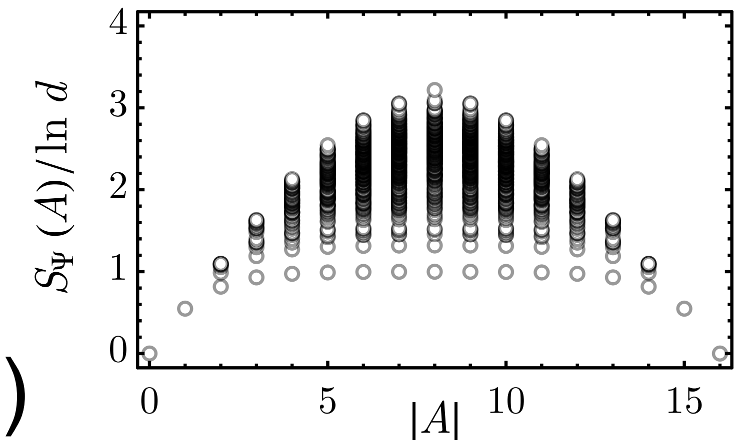
  where $\hat{W}_{\mathbb{1}}$ denotes the EF operator for the identity channel

  - Generalizable to locally scrambled quantum channels …
- **Entanglement dynamics** = time evolution of EF state.
- **Entanglement transition** = quantum phase transition of EF state.

Fan, Vijay, Vishwanath, You (2020); Akhtar, You (2020)

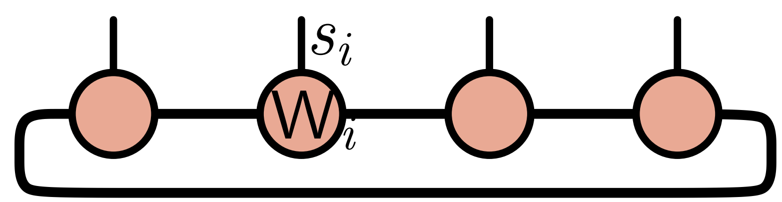
# Advantage of Entanglement Feature

- EF state $|W_{\mathcal{E}_\sigma}\rangle$: A systematic organization of all single/multi-region entanglements. **Solve it once, get them all!**

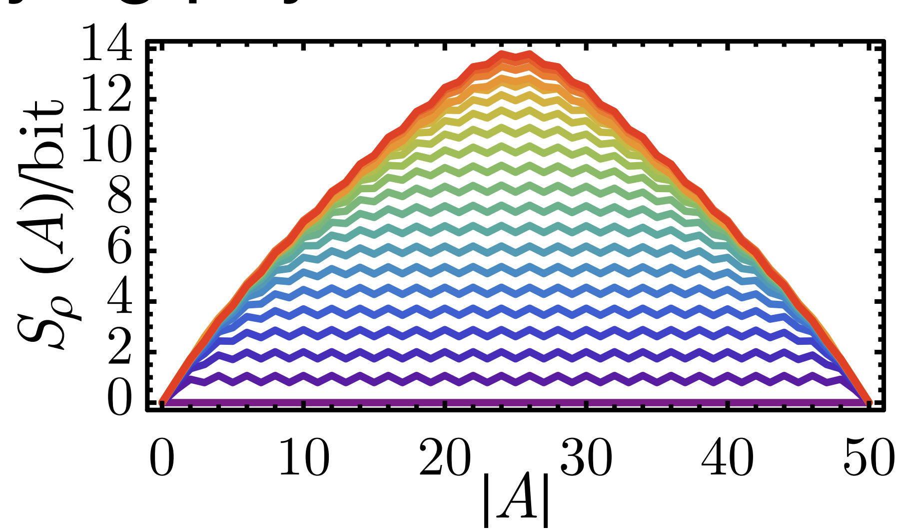



- Admits efficient matrix product state (MPS) representation Akhtar, You (2020)

$$W_{\mathcal{E}_\sigma}[s] \propto \mathrm{Tr}\left(\prod_i \mathsf{W}_i^{s_i}\right)$$




since $|W_{\mathcal{E}_\sigma}\rangle$ is *almost* always an area-law state, even if the underlying physical state $\sigma$ is highly-entangled.




Entanglement growth in random unitary circuits by TEBD method

## Other Related Works

- Relation to other approaches
  - The entanglement feature formalism is in line with the statistical mechanics / conformal field theory approach towards entanglement dynamics

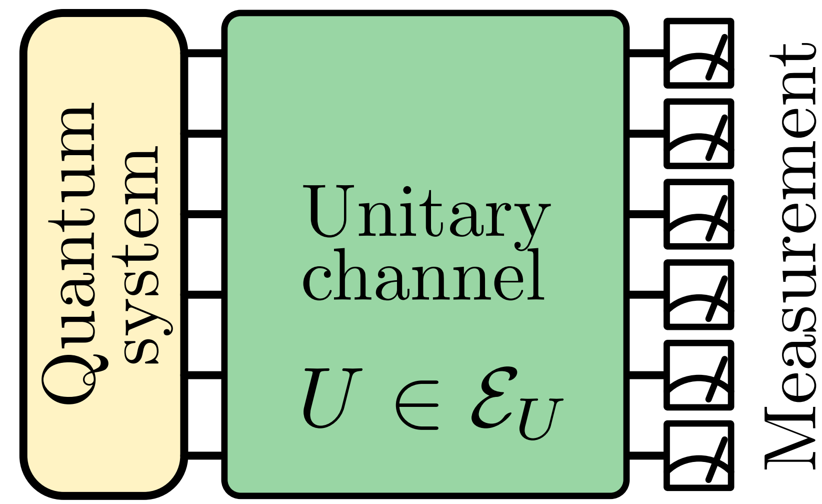
    Znidaric (2008); Hayden, Nezami, Qi, Thomas, Walter, Yang (2016); Nahum, Ruhman, Vijay, Haah (2017); Chan, Luca, Chalker (2018); Vasseur, Potter, You, Ludwig (2019); Zhou, Nahum (2019); Lensky, Qi (2019); Bao, Choi, Altman (2019); Jian et.al. (2019); Li, Chen, Ludwig, Fisher (2020) …
  - It reproduces results on random unitary circuits (RUC) and Brownian dynamics.

    Nahum, Vijay, Haah (2017); Zhou, Xiao (2019); Xu, Swingle (2019)
  - It is consistent with entanglement line tension and capillary wave theories.

    Jonay, Huse, Nahum (2018); Mezei (2018); Skinner, Ruhman, Nahum (2019); Li, Fisher (2020)

# Locally Scrambled Shadow Tomography (LSST)

- How are these useful in classical shadow tomography?
- In the randomized measurement, if the prior classical snapshots $\mathcal{E}_\sigma$ are locally scrambled, the measurement channel is given by the entanglement feature of $\mathcal{E}_\sigma$




$$\begin{aligned}
\mathcal{M}[\rho] &= \mathop{\mathbb{E}}_{\hat{\sigma}\in\mathcal{E}_\sigma} \hat{\sigma}\,\mathrm{Tr}(\hat{\sigma}\rho)2^N \\
&= \mathop{\mathbb{E}}_{V\in \mathrm{U}(2)^N} \mathop{\mathbb{E}}_{\hat{\sigma}\in\mathcal{E}_\sigma} (V^\dagger\hat{\sigma}V)\,\mathrm{Tr}(V^\dagger\hat{\sigma}V\rho)2^N \\
&= \sum_A 2^{2N-|A|}\langle A|\hat{W}_{\mathbb{1}}^{-1}|W_{\mathcal{E}_\sigma}\rangle\ \rho_A \\
&= \sum_A m_A \rho_A
\end{aligned}$$

Coefficients only depend on entanglement feature

$$\rho_A = (\mathrm{Tr}_{\bar{A}}\,\rho)\otimes(\mathbb{1}_{\bar{A}}/2^{|\bar{A}|})$$

Reduced density matrix (embedded in the full Hilbert space)

# Locally Scrambled Shadow Tomography (LSST)

- Inverting the measurement channel gives the reconstruction map

$$\sigma = \mathcal{M}[\rho] = \sum_A m_A \rho_A \quad \Leftrightarrow \quad \rho = \mathcal{M}^{-1}[\sigma] = \sum_A r_A \sigma_A$$

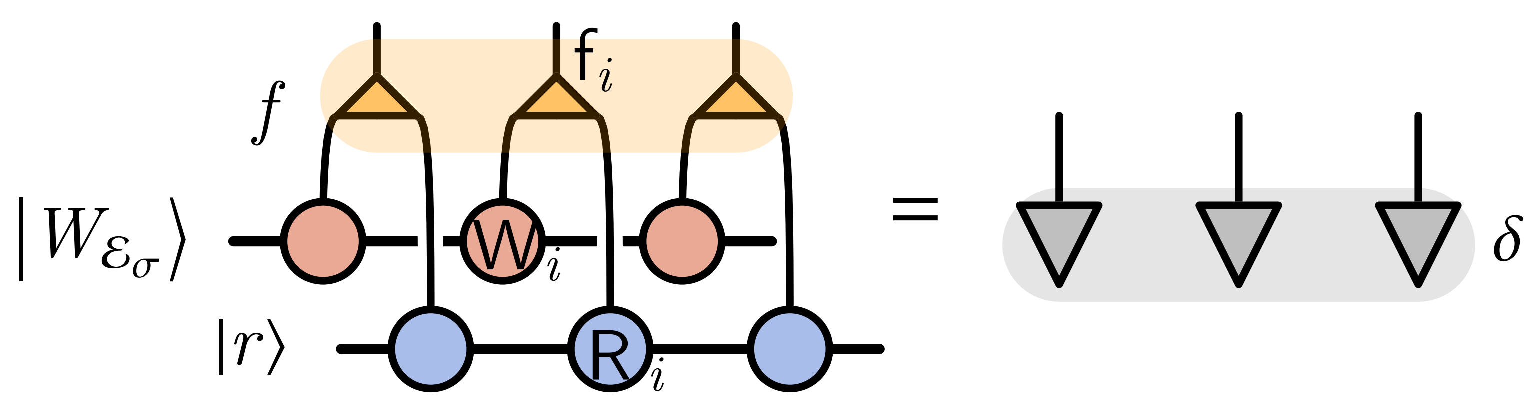
- Reconstruction coefficients given by entanglement features $W_{\mathcal{E}_\sigma}$ of the prior snapshot ensemble

$$r_A = (-1)^{|A|} \sum_{A \subseteq C} \frac{3^{|C|}}{\sum_{B \subseteq C} (-2)^{|B|} W_{\mathcal{E}_\sigma, B}}$$

Bu, Koh, Garcia, Jaffe (2022)

- These coefficients $r_A$ can be encoded as an MPS too

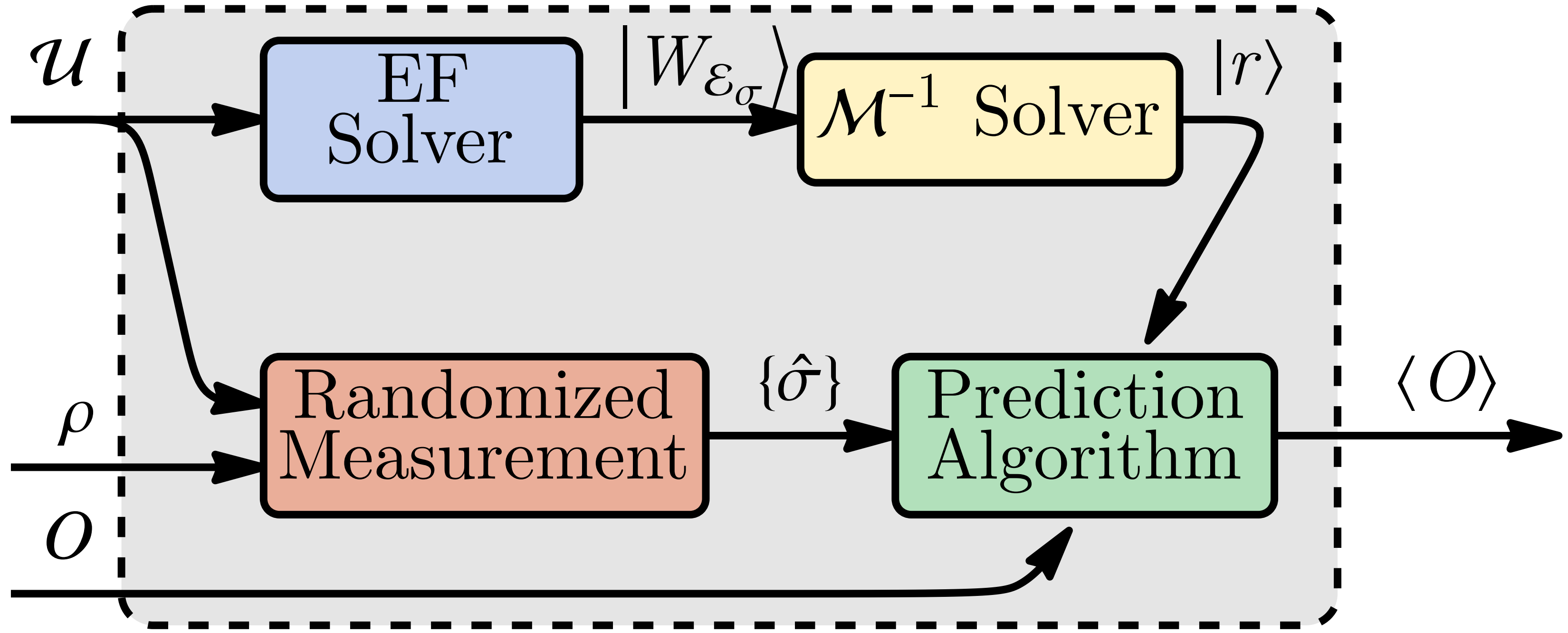
$$|r\rangle = \sum_A r_A |A\rangle$$




A.A.Akhtar, H.-Y. Hu, Y.-Z.You. arXiv:2209.02093 (2022)

## Locally Scrambled Shadow Tomography (LSST)

- Given a randomized measurement scheme, specified by the prior snapshot ensemble $\mathcal{E}_\sigma$
  - Compute $|W_{\mathcal{E}_\sigma}\rangle$ by entanglement dynamics
  - Solve reconstruction coefficients $|r\rangle$ from $|W_{\mathcal{E}_\sigma}\rangle$
- Collect posterior snapshot ensemble $\mathcal{E}_{\sigma|\rho}$ from measurement
- Predict: $\langle O\rangle_\rho = \mathop{\mathbb{E}}_{\hat{\sigma}\in\mathcal{E}_{\sigma|\rho}} \mathrm{Tr}(\mathcal{M}^{-1}[\hat{\sigma}]O) = \mathop{\mathbb{E}}_{\hat{\sigma}\in\mathcal{E}_{\sigma|\rho}} \sum_A r_A \,\mathrm{Tr}(\hat{\sigma}_A O)$




A.A.Akhtar, H.-Y. Hu, Y.-Z.You. arXiv:2209.02093 (2022)

# Locally Scrambled Shadow Norm

- In practice, the expectation value is estimated on a finite number $M$ of samples

$$\langle O\rangle = \frac{1}{M}\sum_{m=1}^{M} \mathrm{Tr}(\mathcal{M}^{-1}[\hat{\sigma}^{(m)}]O)$$

- The variance of the finite-sample mean

$$\mathrm{var}\,\langle O\rangle \lesssim \|O\|_{\mathrm{shd}}^2/M$$

Huang, Kueng, Preskill (2020)

is controlled by the operator shadow norm $\|O\|_{\mathrm{shd}}^2$ (assuming $O$ is traceless)

  - Shadow norm = single-shot variance (maximized over all possible states $\rho$)

$$\|O\|_{\mathrm{shd}}^2 = \max_{\rho} \mathop{\mathbb{E}}_{\hat{\sigma}\in\mathcal{E}_{\sigma|\rho}} (\mathrm{Tr}\,\mathcal{M}^{-1}[\hat{\sigma}]O)^2$$

# Locally Scrambled Shadow Norm

- An alternative definition: locally scrambled shadow norm

$$\|O\|^2_{\mathcal{E}_\sigma} = \mathop{\mathbb{E}}_{\hat{\sigma}\in\mathcal{E}_\sigma} (\operatorname{Tr} \mathcal{M}^{-1}[\hat{\sigma}]O)^2$$
$$= \sum_A 2^{|A|-2N} r_A (W_O)_A$$

  - Depends only on (i) the measurement scheme $r_A$ and (ii) the operator entanglement
$$(W_O)_A = \operatorname{Tr}_A(\operatorname{Tr}_{\bar{A}} O)^2.$$
  - Advantage: easy to compute (no maximization over states)
  - Given the sample number $M$, determine the typical variance of the estimation $\operatorname{var}\langle O\rangle \simeq \|O\|^2_{\mathcal{E}_\sigma}/M$
  - Given the desired prediction accuracy $\operatorname{var}\langle O\rangle \leq \epsilon^2$, roughly bound the number of experiments $M \gtrsim \|O\|^2_{\mathcal{E}_\sigma}/\epsilon^2$

A.A.Akhtar, H.-Y. Hu, Y.-Z.You. arXiv:2209.02093 (2022)

# Scalable Tomography on Clifford Circuits

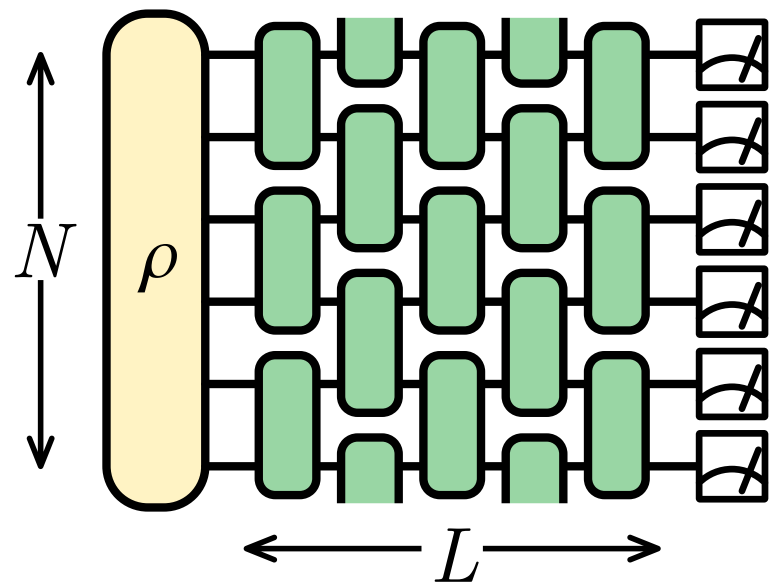
- Test states:

$$\rho_{\mathrm{GHZ}} = |\mathrm{GHZ}\rangle\langle\mathrm{GHZ}| \qquad |\mathrm{GHZ}\rangle = \frac{1}{\sqrt{2}}(|00\cdots\rangle + |11\cdots\rangle)$$

$$\rho_{\mathrm{ZXZ}} = |\mathrm{ZXZ}\rangle\langle\mathrm{ZXZ}| \qquad Z_{i-1}X_iZ_{i+1}|\mathrm{ZXZ}\rangle = |\mathrm{ZXZ}\rangle$$

(Cluster state)

- Randomized measurement scheme:



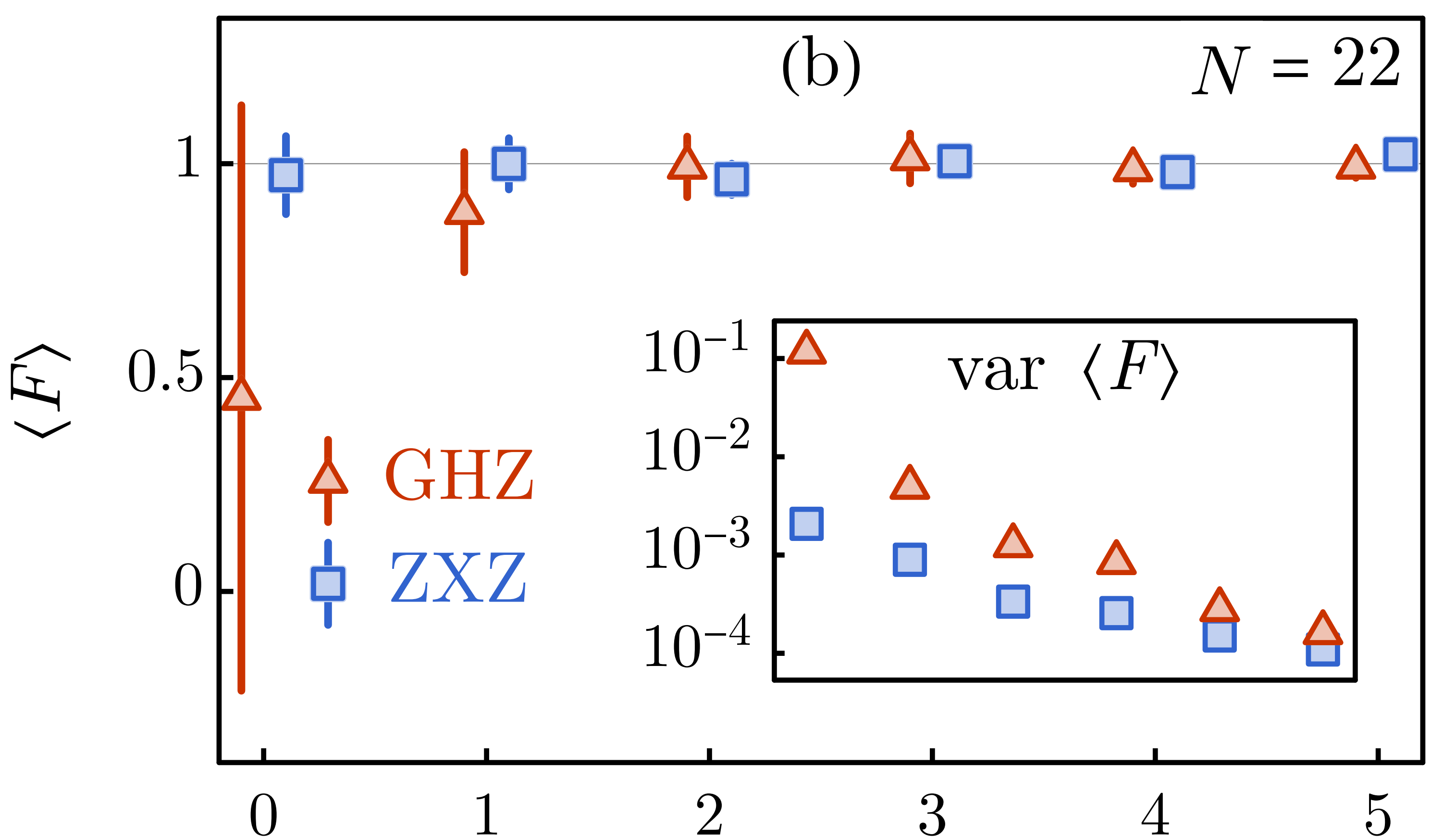

  - Brick-wall arrangement of 2-qubit random Clifford gates
  - Width (number of qubits): $N$
  - Depth (number of layers): $L$

A.A.Akhtar, H.-Y. Hu, Y.-Z.You. arXiv:2209.02093 (2022)

# Fidelity Estimation

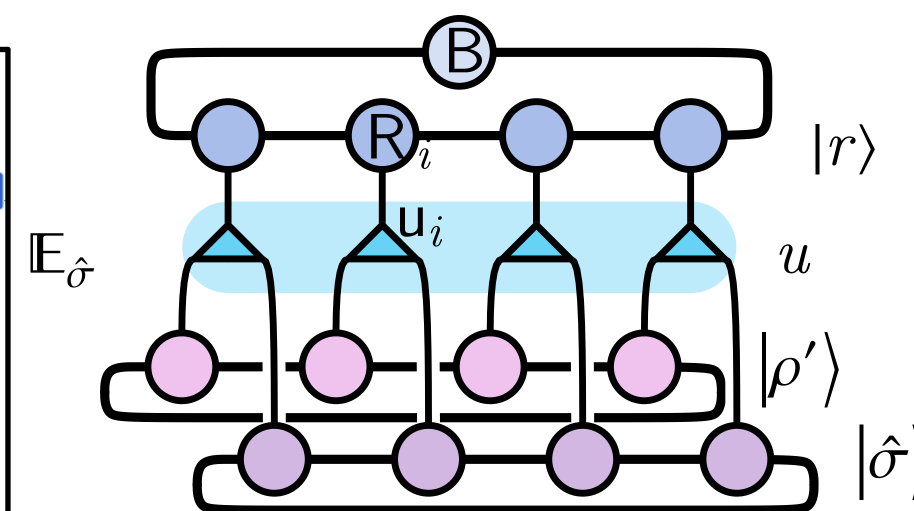
- Task 1: Estimate the fidelity (state overlap) between the reconstructed state and the original state

$$F(\rho, \rho') = \mathrm{Tr}(\rho\rho') \qquad \text{(For pure states)}$$




Pauli measurement

$L$ (Circuit depth)




Efficient MPS-based post-processing

A.A.Akhtar, H.-Y. Hu, Y.-Z.You. arXiv:2209.02093 (2022)

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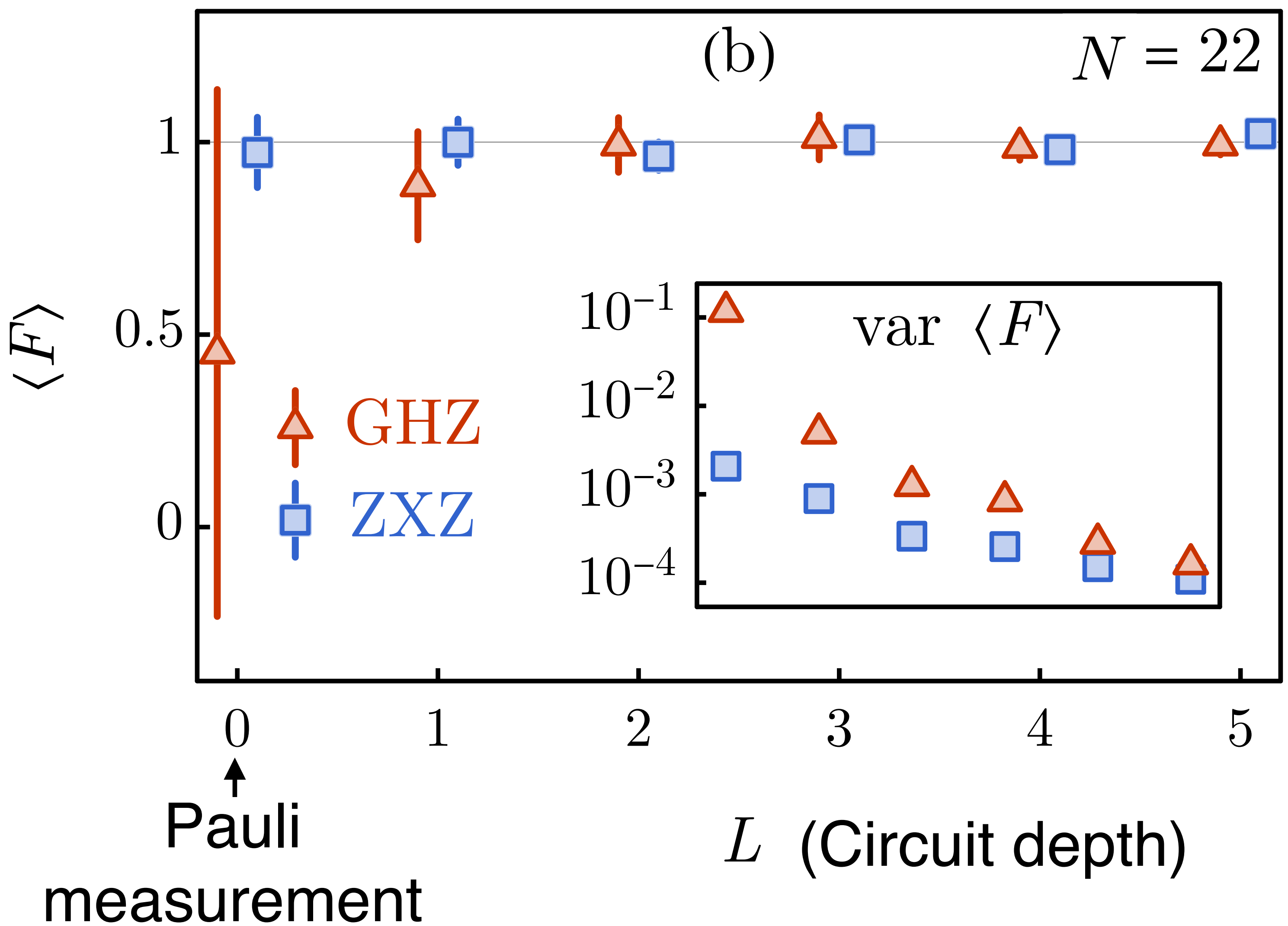


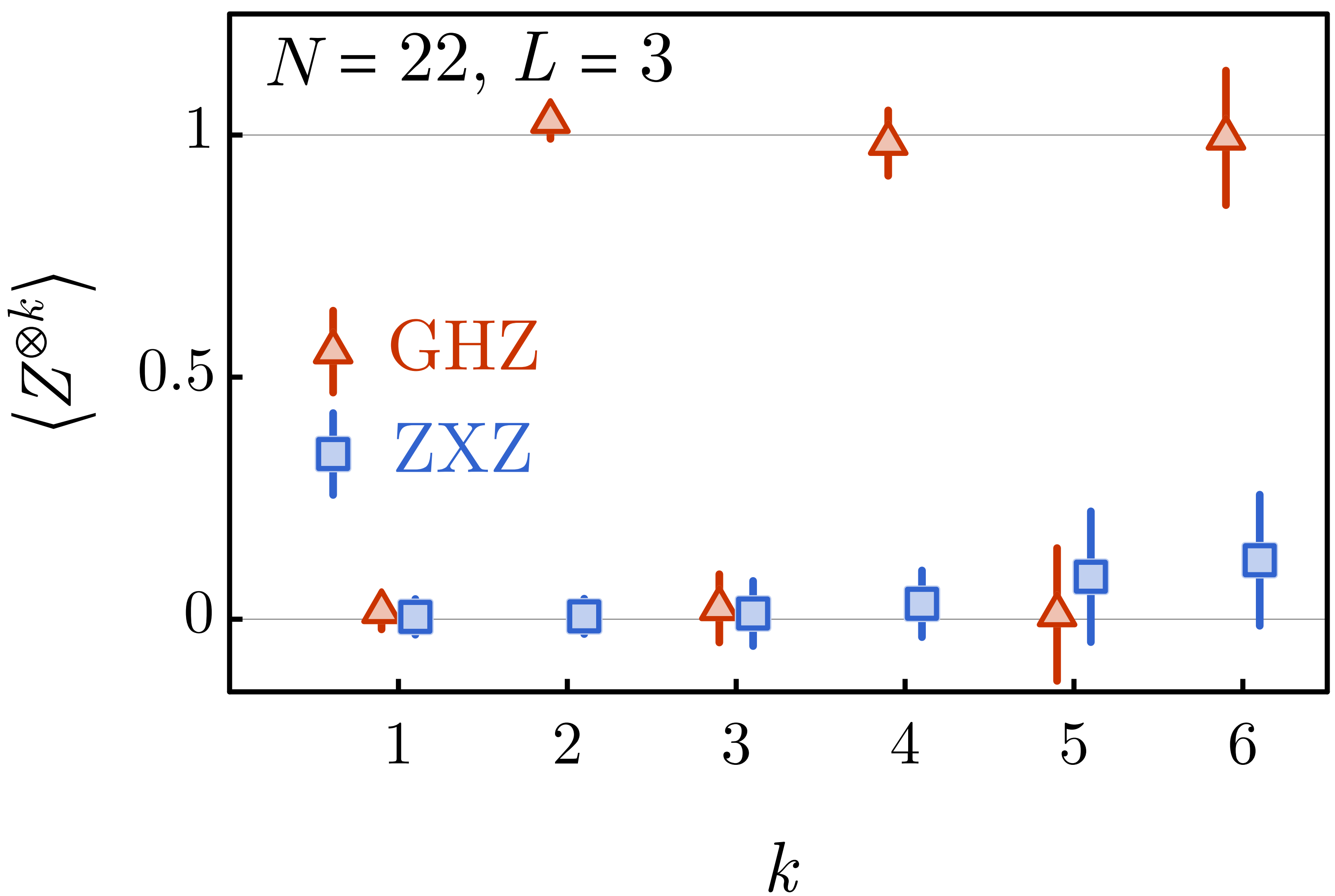

- Scalability (22 qubits)
- Reconstruction is unbiased for all circuit depth
- $M = 50\mathrm{k}$ samples: variance is reduced for deeper circuits — quantum information scrambling helps!

A.A.Akhtar, H.-Y. Hu, Y.-Z.You. arXiv:2209.02093 (2022)

# Pauli Operator Estimation

- Task 2: Estimate the expectation value of a Pauli string operator

$$Z^{\otimes k} := \prod_{i=1}^{k} Z_i$$




- Estimations are unbiased (converge to the ground truth)
- Variance (shadow norm) increases with the weight (size) of the Pauli string
  - Note: For Pauli measurements ($L = 0$)

$$\|Z^{\otimes k}\|^2_{\mathcal{E}_\sigma} \sim 3^k$$

A.A.Akhtar, H.-Y. Hu, Y.-Z.You. arXiv:2209.02093 (2022)

# Pauli Operator Estimation

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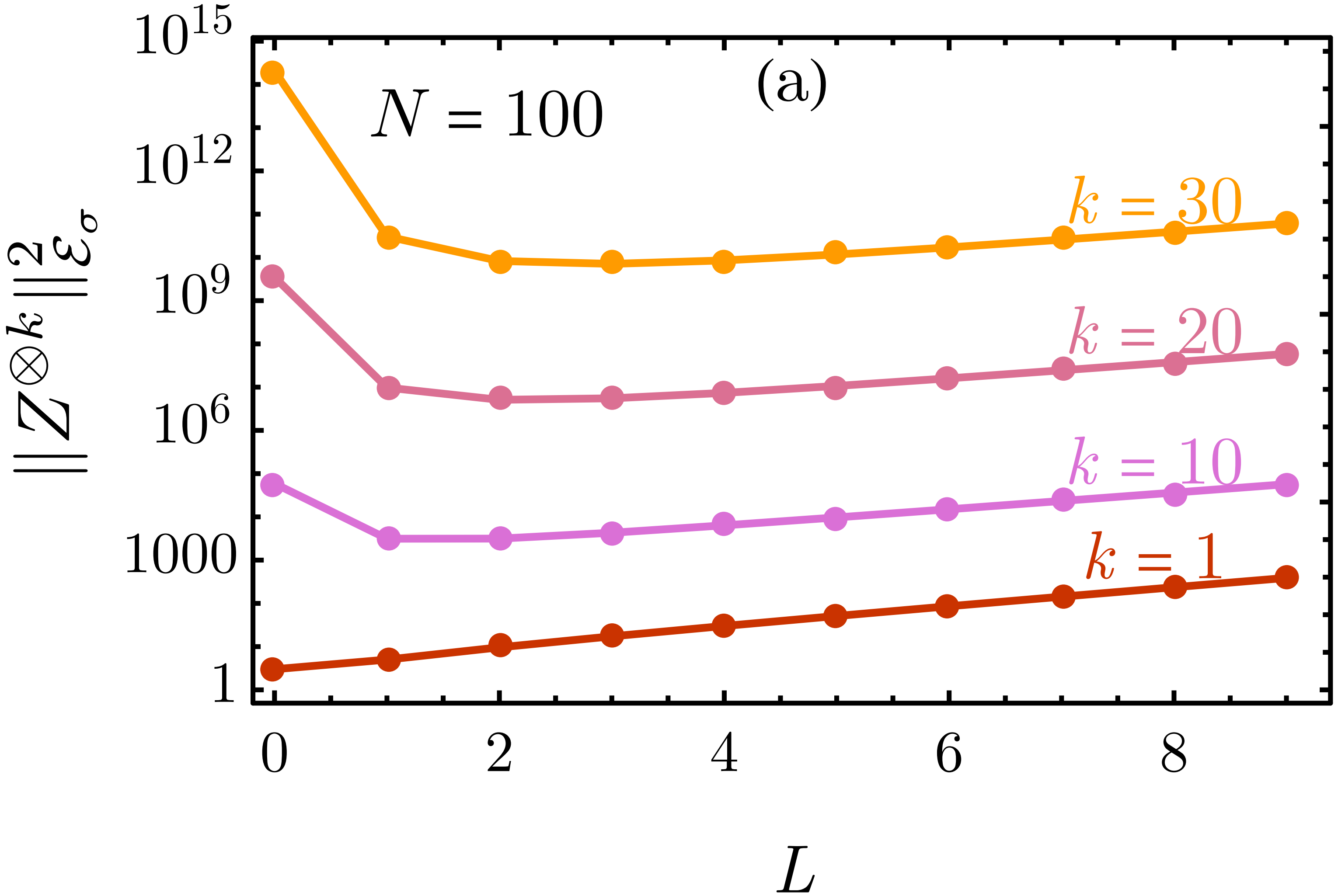


- Given the size $k$ of the Pauli string, there is an optimal circuit depth $L^*$ minimizing the shadow norm (sample complexity)

A.A.Akhtar, H.-Y. Hu, Y.-Z.You. arXiv:2209.02093 (2022)

# Pauli Operator Estimation

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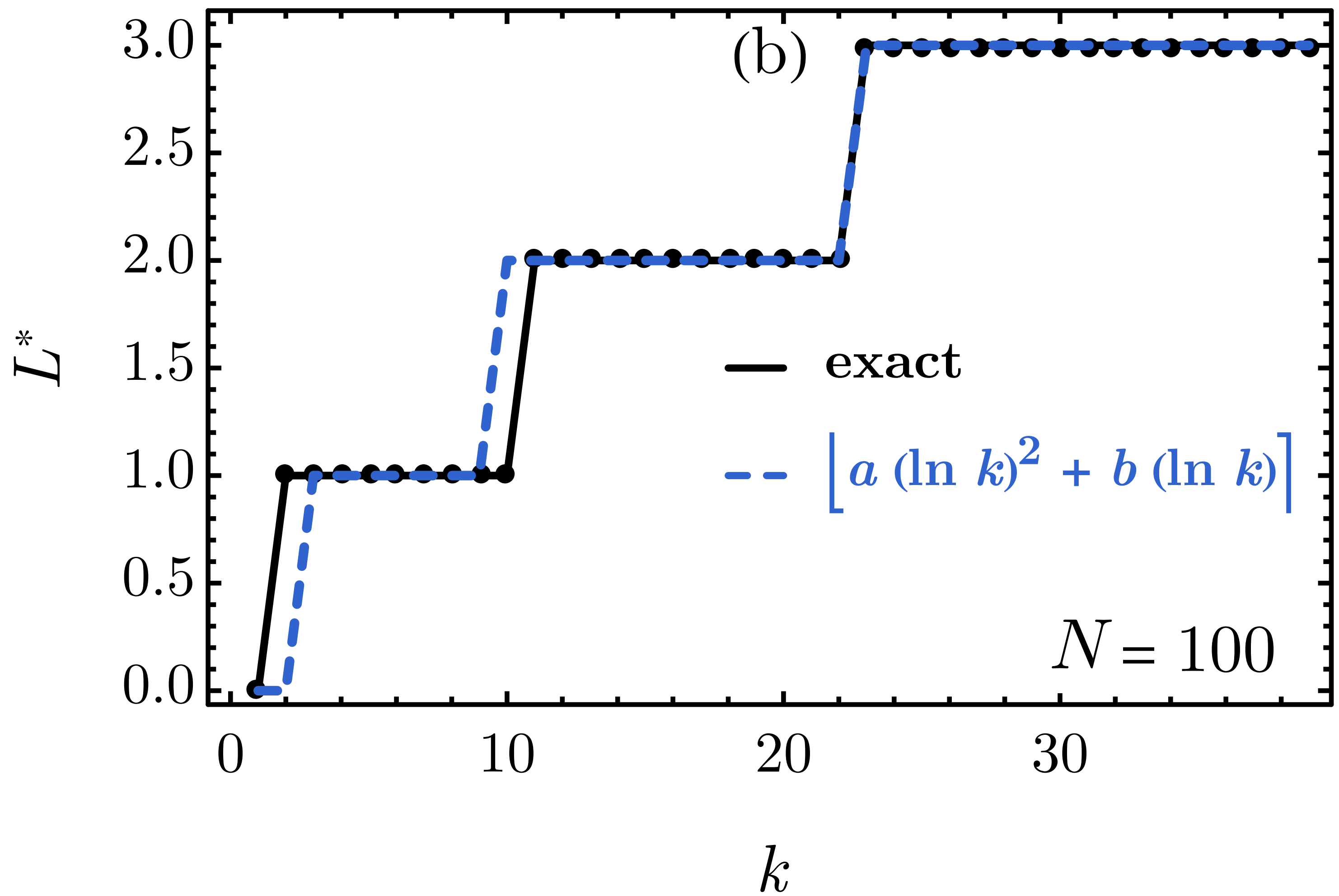


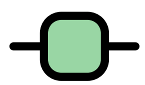

- The optimal circuit depth $L^*$ scales with $k$ poly-logarithmically

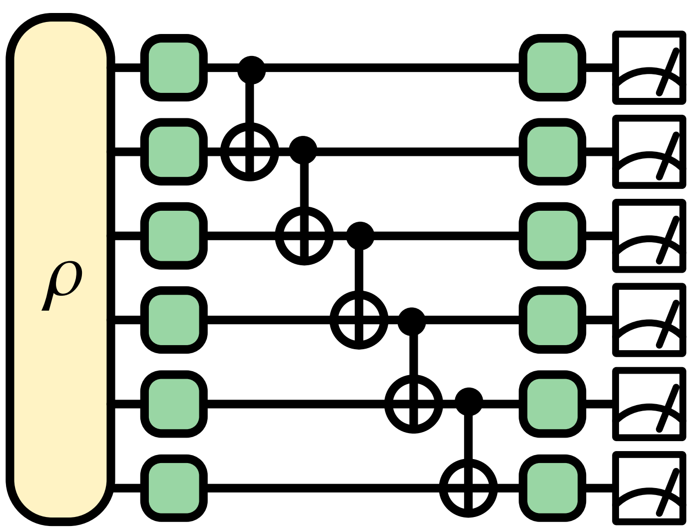
$$L^* \sim a(\ln k)^2 + b \ln k$$

A.A.Akhtar, H.-Y. Hu, Y.-Z.You. arXiv:2209.02093 (2022)

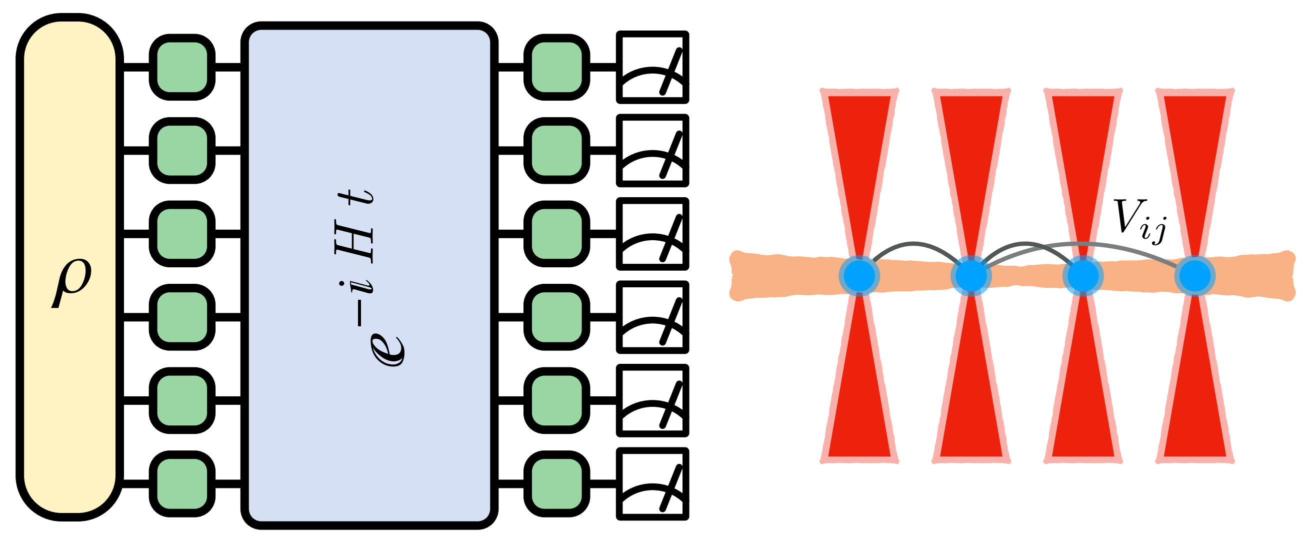
# Classical Shadow Tomography on NISQ Devices

- Random Clifford gate may still be challenge for noisy intermediate-scale quantum (NISQ) devices
- Our approach enables very flexible design of randomized measurement protocol
  - Wrap any circuit / quantum dynamics with local scramblers → Locally scrambled unitary ensemble

 = single-qubit random Clifford gate




Locally scrambled CNOT circuit

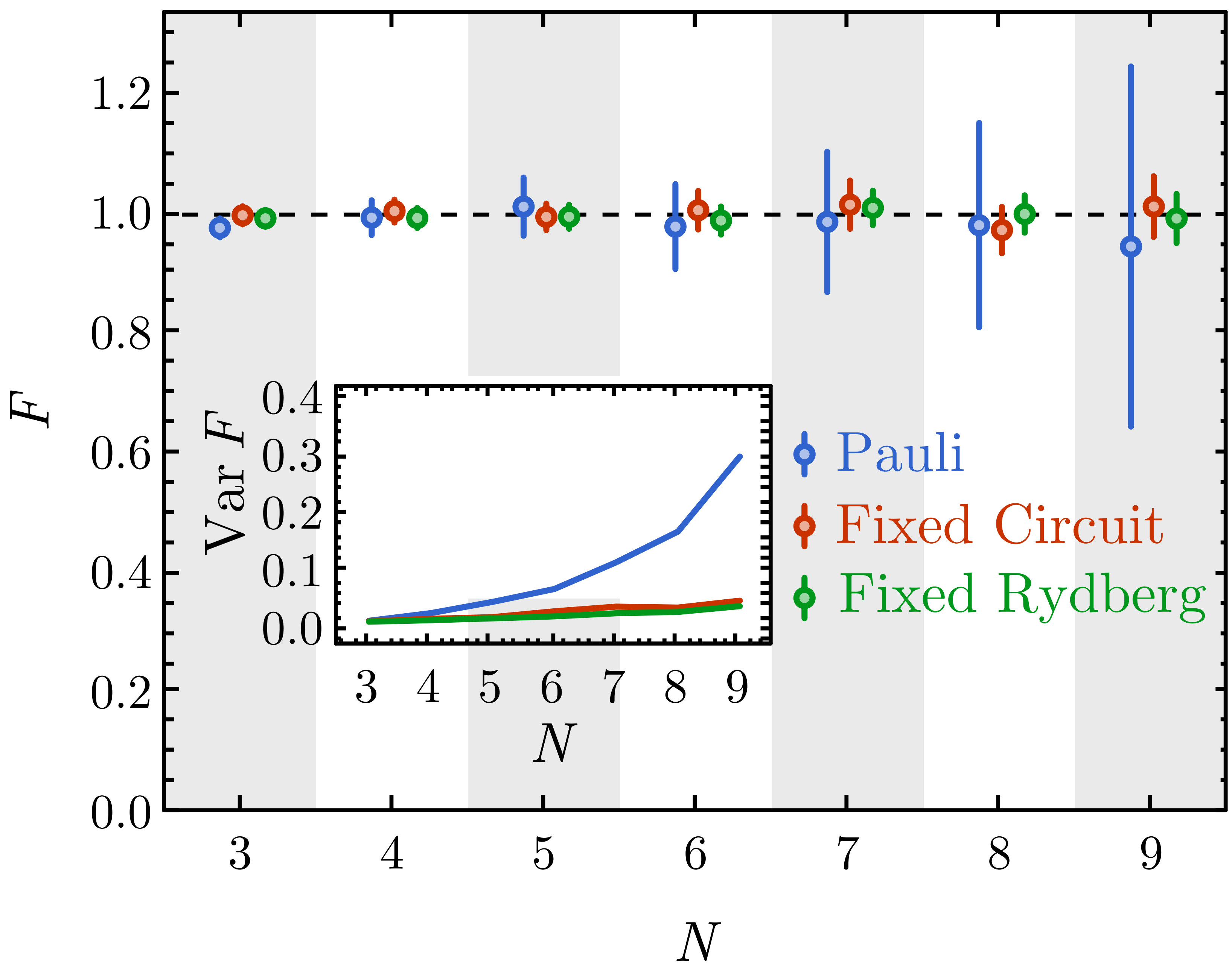



Locally scrambled Hamiltonian dynamics

H.-Y. Hu, S. Choi, Y.-Z.You. arXiv:2107.04817 (2021)

# Classical Shadow Tomography on NISQ Devices

- They can just achieve the same effect in reducing the estimation variance as a shallow random circuit!

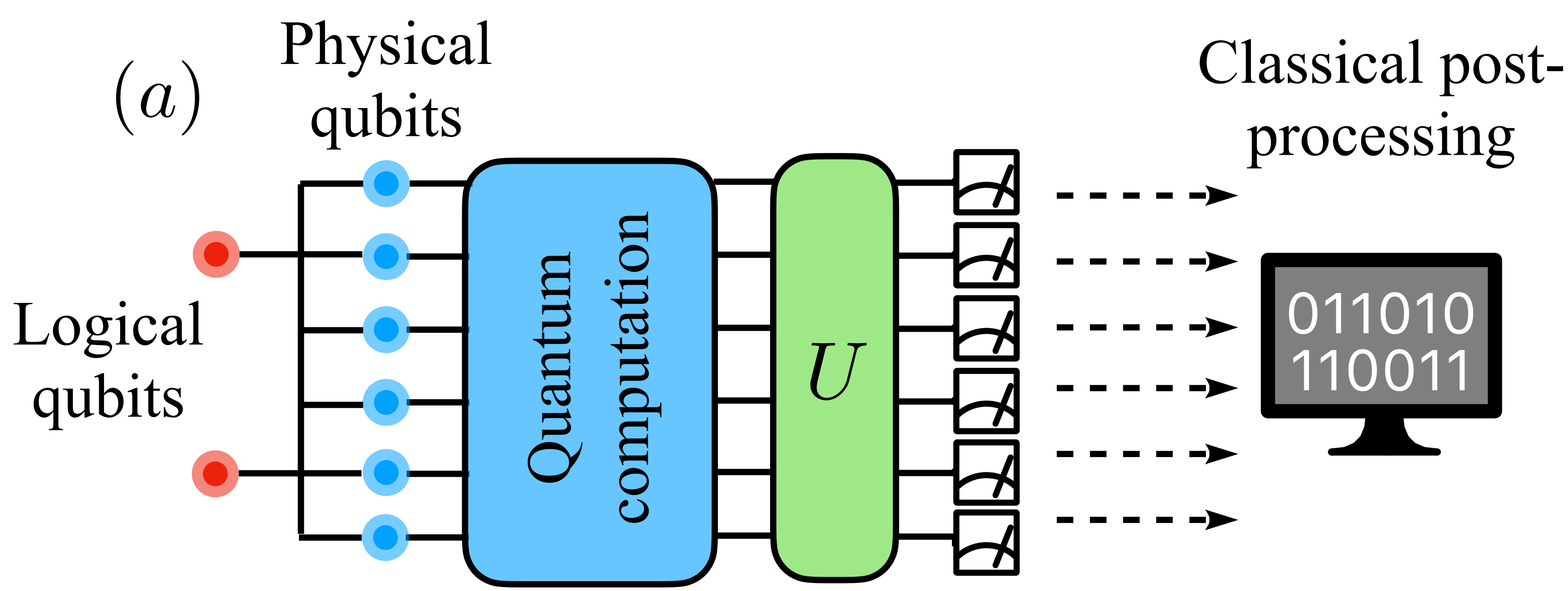



H.-Y. Hu, S. Choi, Y.-Z.You. arXiv:2107.04817 (2021)

# LSST for Quantum Error Mitigation

- Classical shadow tomography has many amazing applications, one example is to implement code subspace projection in **quantum error mitigation** (QEM)

Hu, LaRose, You, Rieffel, Wang (2022); Seif, Cian, Zhou, Chen, Jiang (2022)

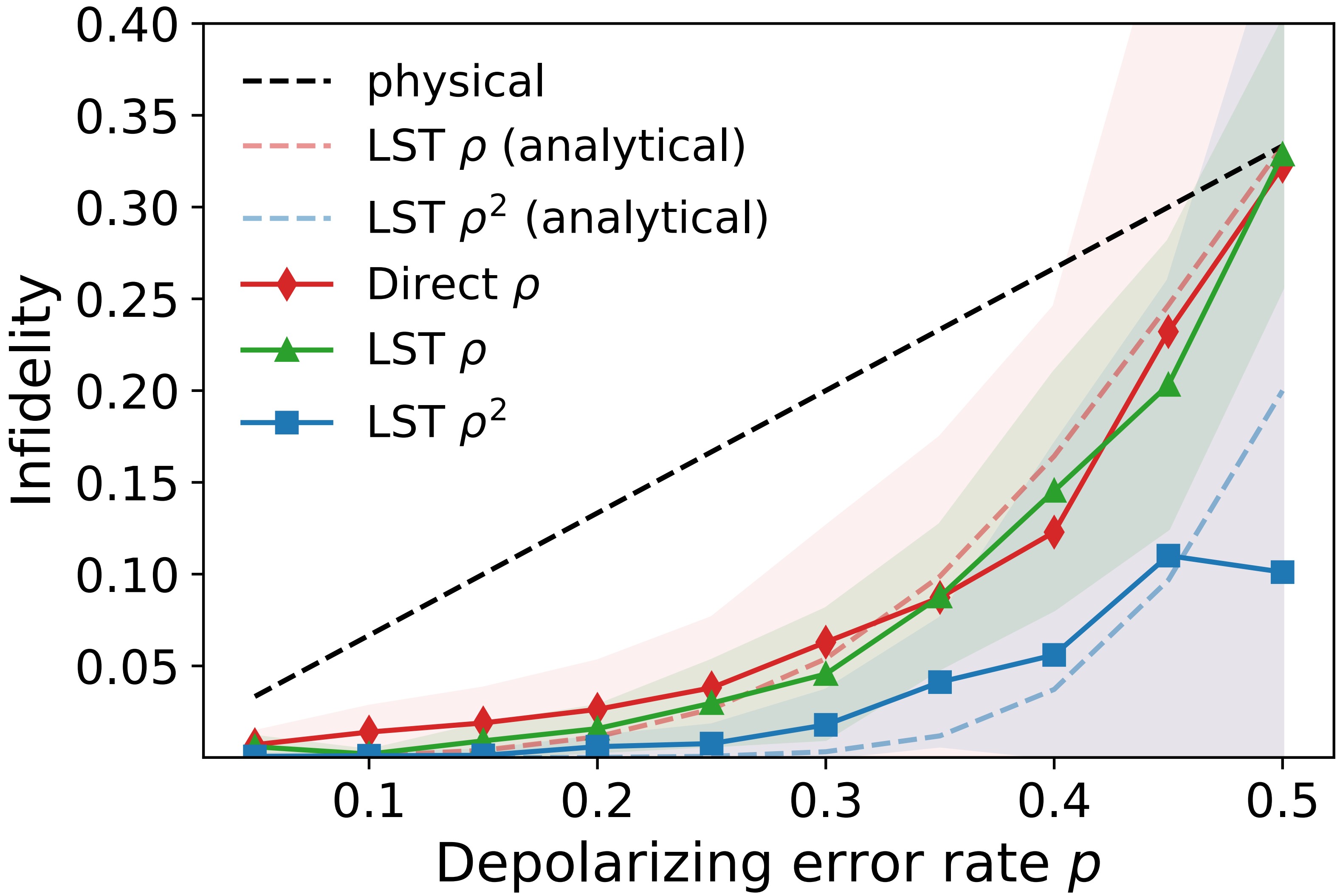



$$\langle O \rangle_{\mathrm{QEM}} = \frac{\mathrm{Tr}(\Pi \rho \Pi^\dagger O)}{\mathrm{Tr}(\Pi \rho \Pi^\dagger)}$$

$$\mathrm{Tr}(\Pi \rho \Pi^\dagger O) = \mathop{\mathbb{E}}_{\hat{\sigma} \in \mathcal{E}_{\sigma|\rho}} \sum_A r_A \, \mathrm{Tr}(\hat{\sigma}_A \Pi^\dagger O \Pi)$$

# LSST for Quantum Error Mitigation

- Assume each physical bit is subject to depolarization error
- QEM can reduce the infidelity when the error rate is small
- Logical shadow tomography (LST) demonstrates superior sample efficiency (small variance)




H.-Y. Hu, R. LaRose, Y.-Z. You, E. Rieffel, Z. Wang. arXiv:2203.07263 (2022)

# Summary

- Combining the quantum entanglement dynamics and classical shadow tomography, we introduce the **locally scrambled shadow tomography** (LSST), which is
  - Scalable (efficient classical post-processing)
  - Flexible (arbitrary circuit structure / quantum dynamics)
  - NISQ friendly (shallow circuits, simple gates, available devices)
- We expect our approach to have broad applications in many quantum information processing tasks (e.g. quantum error mitigation)

Thanks for your attention!