Detection error and fidelity benchmarking

Analyzing Ni group preliminary data

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1. Detection error

How to correct detection errors:

(Single qubit) “confusion matrix,” from estimated detection errors

$$\begin{array}{cc} & |0\rangle \to |1\rangle \\ C_0 = & \begin{pmatrix} 0.957 & 0.06 \\ 0.043 & 0.94 \end{pmatrix} \end{array}$$

Post-processing expt. data: let $\vec{p}_{\mathrm{Emp}}$ be 2^N-vector of empirical frequencies of each bitstring. Corrected frequencies:

$$\overrightarrow{f'} = {C^{-1}}^{\otimes L}\, \vec{f}$$

Estimated frequencies $\overrightarrow{f'}(z)$ will not be normalized, may be negative, and does not lie in blockaded subspace. We project onto blockaded subspace and normalize:

$$\vec{f}_{\mathrm{est}}(z) = \frac{\mathbb{P}_{\mathrm{bl}}[f'(z)]}{\sum_z \mathbb{P}_{\mathrm{bl}}[f'(z)]}$$

1. Detection error

$$C_0 = \begin{pmatrix} 0.957 & 0.06 \\ 0.043 & 0.94 \end{pmatrix}$$

Sanity check on “confusion matrix”: Checking percentage in blockaded subspace

Going the other way: With theoretical $\mathrm{p(z,t)} = |\langle \mathrm{z}|\Psi_0\rangle|^2$ (all z’s in blockaded subspace), we can compute % of measured bitstrings in blockaded subspace:

$$\%_{\mathrm{bl}} = \sum_{z\in \mathrm{bl}} (C\vec{p})\,(z)$$

Simulation (with $\boldsymbol{C_0}$): $\%_{\mathrm{bl}}^{\mathrm{sim}} = 88\%$
Experiment: $\%_{\mathrm{bl}}^{\mathrm{exp}} = 66\%$

Trying to match $\%_{\mathrm{bl}}^{\mathrm{exp}}$ with $\%_{\mathrm{bl}}^{\mathrm{sim}}$ gives $C_1 \approx \begin{pmatrix} 0.87 & 0.13 \\ 0.13 & 0.87 \end{pmatrix}$ (13% detection error), does not improve F_d scores (see below)

Important to figure out detection error confusion matrix (see 1*. for more sophisticated analysis)

1.* Looking at marginals

*(you can ignore this, just FYI)

○ Ground
● Rydberg

Probability of finding these configurations, averaged over bulk (removing 2 boundary sites)

	○○	○●	●○	●●
Data	0.37	0.27	0.27	0.08
Sim. detection err., C_0	0.42	0.28	0.28	0.02
Sim. detection err., C_1	0.39	0.27	0.27	0.07
Ideal simulation	0.42	0.29	0.29	0
Theoretical limit: inf. temp	0.44	0.28	0.28	0

1. Few-qubit marginal probabilities can be used to verify detection error model (theory tbd)
2. Marginals from data are a lot closer to C_1 than C_0 (but not perfect agreement)

$$C_0 = \begin{pmatrix} 0.94 & 0.043 \\ 0.06 & 0.957 \end{pmatrix}, \qquad C_1 = \begin{pmatrix} 0.87 & 0.13 \\ 0.13 & 0.87 \end{pmatrix}$$

13% symmetric detection error, estimated by matching blockaded subspace probabilities

3. Can in principle identify correlated detection errors
4. Bitstring distribution from chaotic evolution is close to "inf. Temp." uniform distribution over blockaded bitstrings

	○○○	○○●	○●○	○●●	●○○	●○●	●●○	●●●
Data	0.23	0.13	0.22	0.06	0.14	0.13	0.07	0.02
Sim. detection err., C_0	0.25	0.15	0.29	0.02	0.15	0.11	0.02	0.005
Sim. detection err., C_1	0.23	0.15	0.24	0.05	0.15	0.11	0.05	0.02
Ideal simulation	0.25	0.16	0.32	0	0.16	0.11	0	0
Theoretical limit: inf. temp	0.27	0.17	0.27	0	0.17	0.10	0	0

Defect distribution

data_2_8.mat

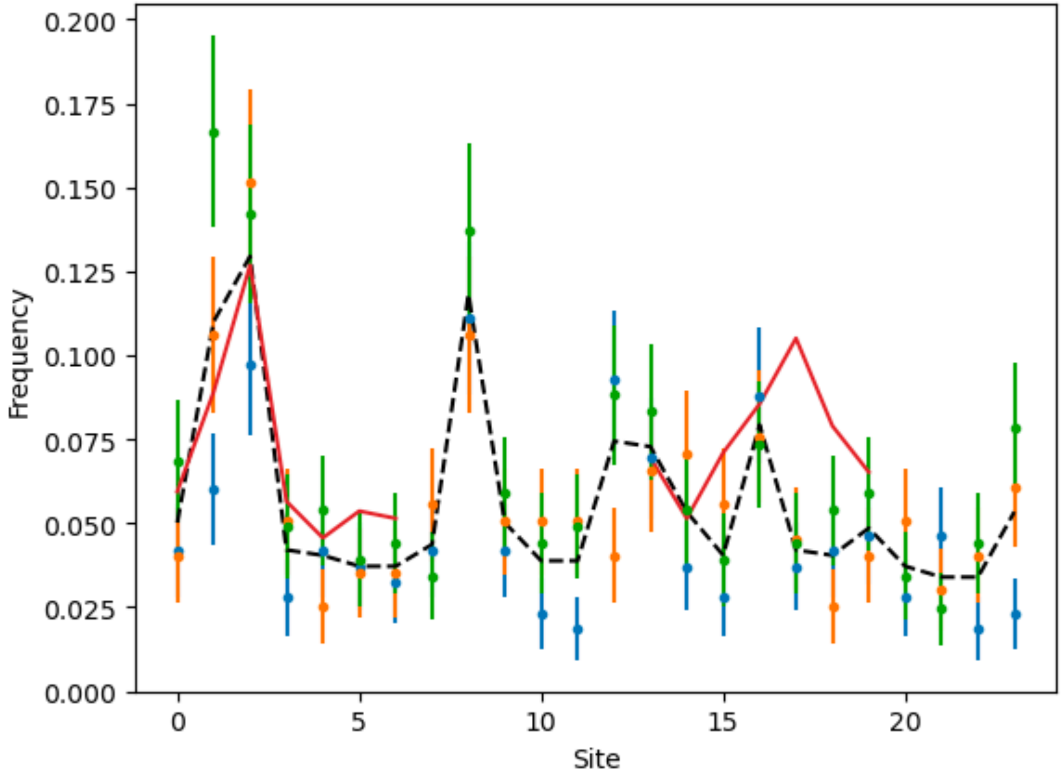
	Left	Right
2us (469)	69.3%	66.3%
3.3us (490)	68.8%	68.0%
4.62us (421)	66.3%	56.3%

data_2_8_continue.mat

	Left	Right
2us (68)	70.6%	67.6%
3.3us (87)	72.4%	72.4%
4.62us (71)	67.6%	67.6%

data_2_9.mat

	L=24, PBC
2us (216)	37.5%
3.3us (198)	34.8%
4.62us (204)	29.9%



	○○	○●	●○	●●
“2_8”	0.37	0.27	0.27	0.08
“2_9”	0.43	0.26	0.26	0.05

2. Benchmarking protocol

Benchmarking: Estimating fidelity by comparing simulated distribution $p(z,t)$ with experimental one

Expt. Data

Inverting detection error

$$\{z_i\} \to p_{\mathrm{Emp}}(z) \to \vec{p}_{\mathrm{Est}} = (C^{-1})^{\otimes L}\vec{p}_{\mathrm{Emp}}$$

Simulation

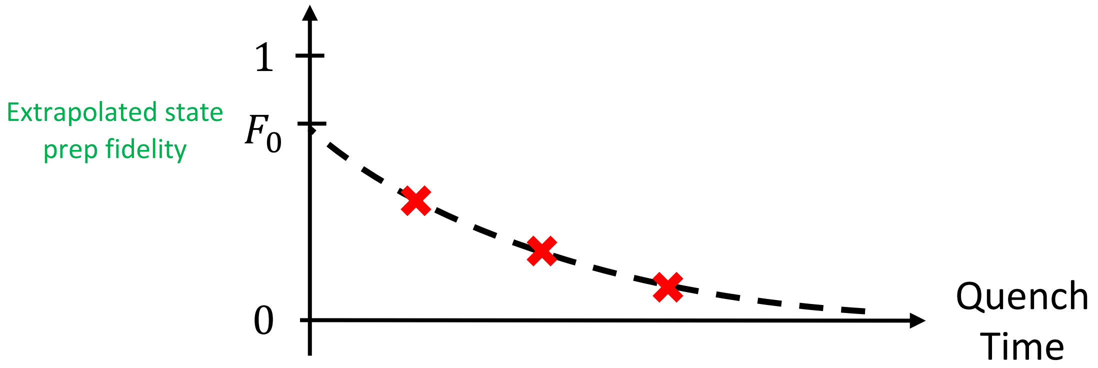
Ideal distribution $\quad p(z,t)$

Time average (technical) $\quad p_{\mathrm{avg}}(z) = \int_0^\infty p(z,t)\,dt$

Estimated many-body fidelity

$$F_d \equiv 2\frac{\sum_z p_{\mathrm{Est}}(z)p(z,t)/p_{\mathrm{avg}}(z)}{\sum_z p(z,t)^2/p_{\mathrm{avg}}(z)} - 1$$

Estimated fidelity



3. Actual data

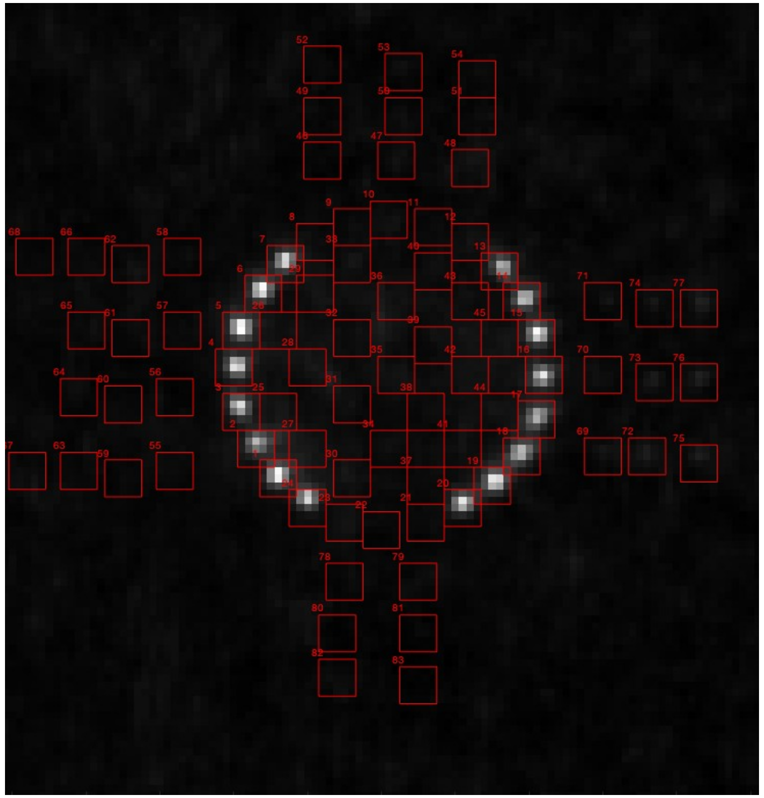
2 chains of length 8

Start from $|g\rangle^{\otimes 8}$, evolve with

$$H = \sum_j \left(-\Delta_j \hat{n}_j + \frac{\Omega_j}{2} \hat{X}_j \right) + \sum_{i<j} \frac{C_6}{|\mathbf{r}_i - \mathbf{r}_j|^6} \hat{n}_i \hat{n}_j$$

for 2us ,3.3us, 4.62us, with

$$\Delta_j \approx (2\pi) \times 0.1 \text{ MHz}$$
$$\Omega_j \approx (2\pi) \times 1.53 \text{ MHz}$$
$$C_6/a^6 \approx (2\pi) \times 10 \text{ MHz}$$



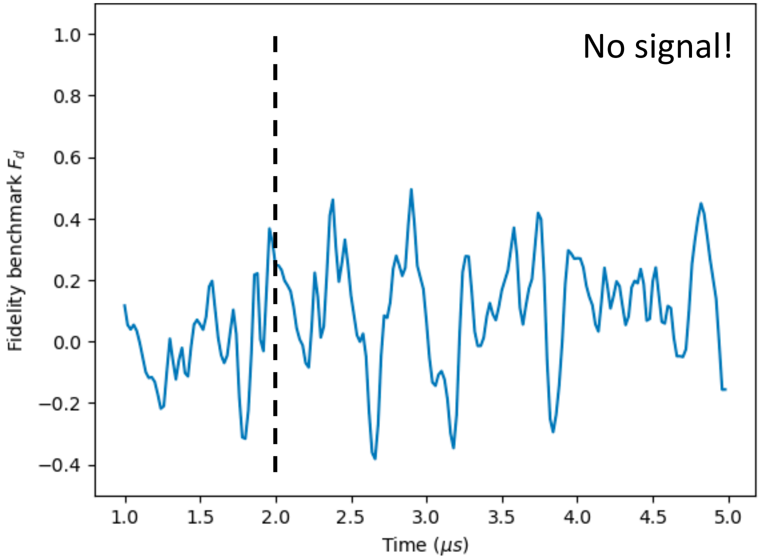
a = lattice constant

3. Benchmarking protocol: Actual data

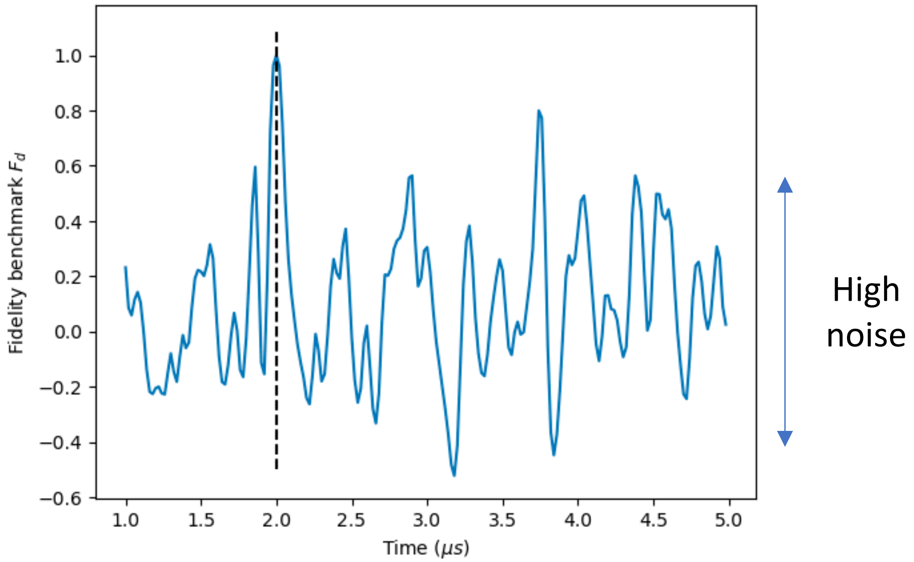
Sanity check: testing against multiple times
If model + data processing is correct, fidelity will peak at one time (2us)

Simulated data shows peak, but actual data doesn't
Likely culprit: wrong confusion matrix

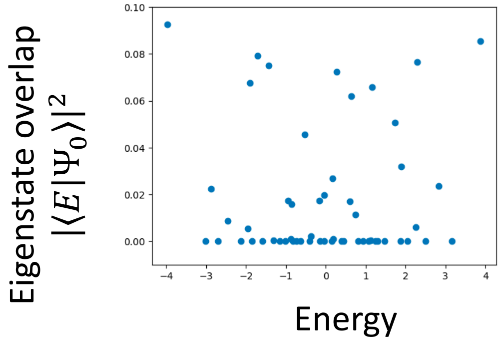
Actual data, $t = 2us$



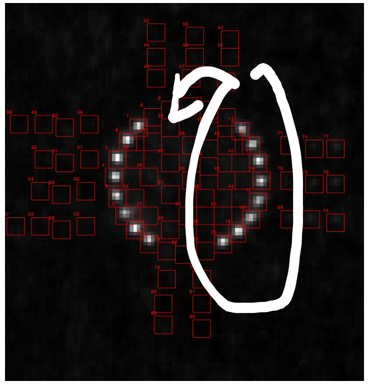
Simulated data, $t = 2us$



*Ideal simulated data still has small signal-to-noise ratio.
Cause: Scar-like physics of Hamiltonian, leads to small "effective dimension"
Solution: Go to $L = 16$ (next slide)



4. Fix for benchmarking protocol: Scaling up



1. With L = 16, effective dimension goes from $D \approx 7$ to $D \approx 50$

2. Signal to noise ratio a lot better! (dark blue curve)

3. Peak still prominent even with worst case 13% per site detection error, with 3000 samples (light blue curve). At 1000 samples, peak is less prominent