Error Analysis with Magic State Injections

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Project Overview

Implementation

Overview of Different Circuit Methods Used

Error Scaling

Various Scaling Laws for Errors

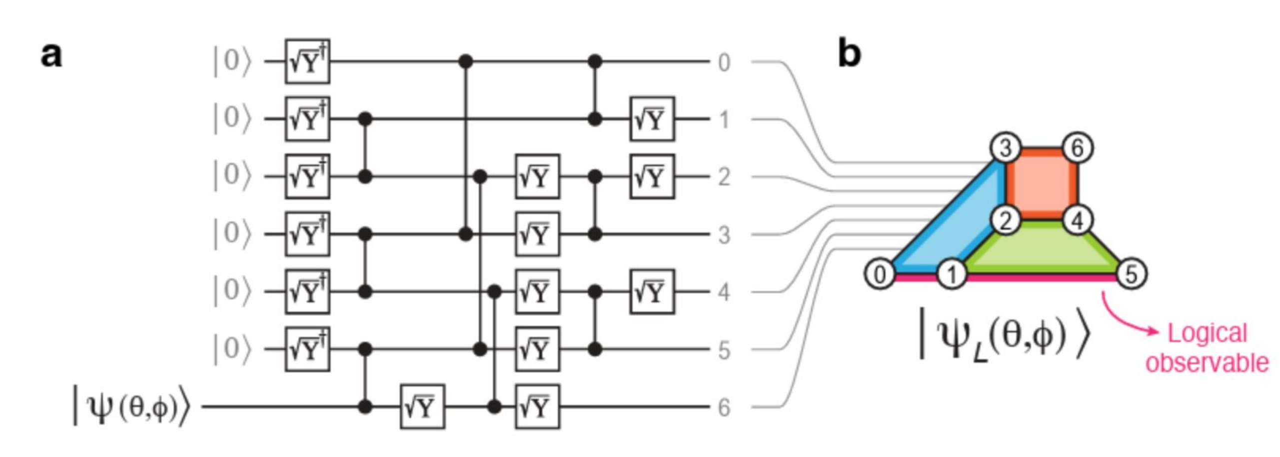
System Parameters

Comments on Error Correction, Syndrome Extraction, Noise Models

Magicness

Effects of magicness on errors

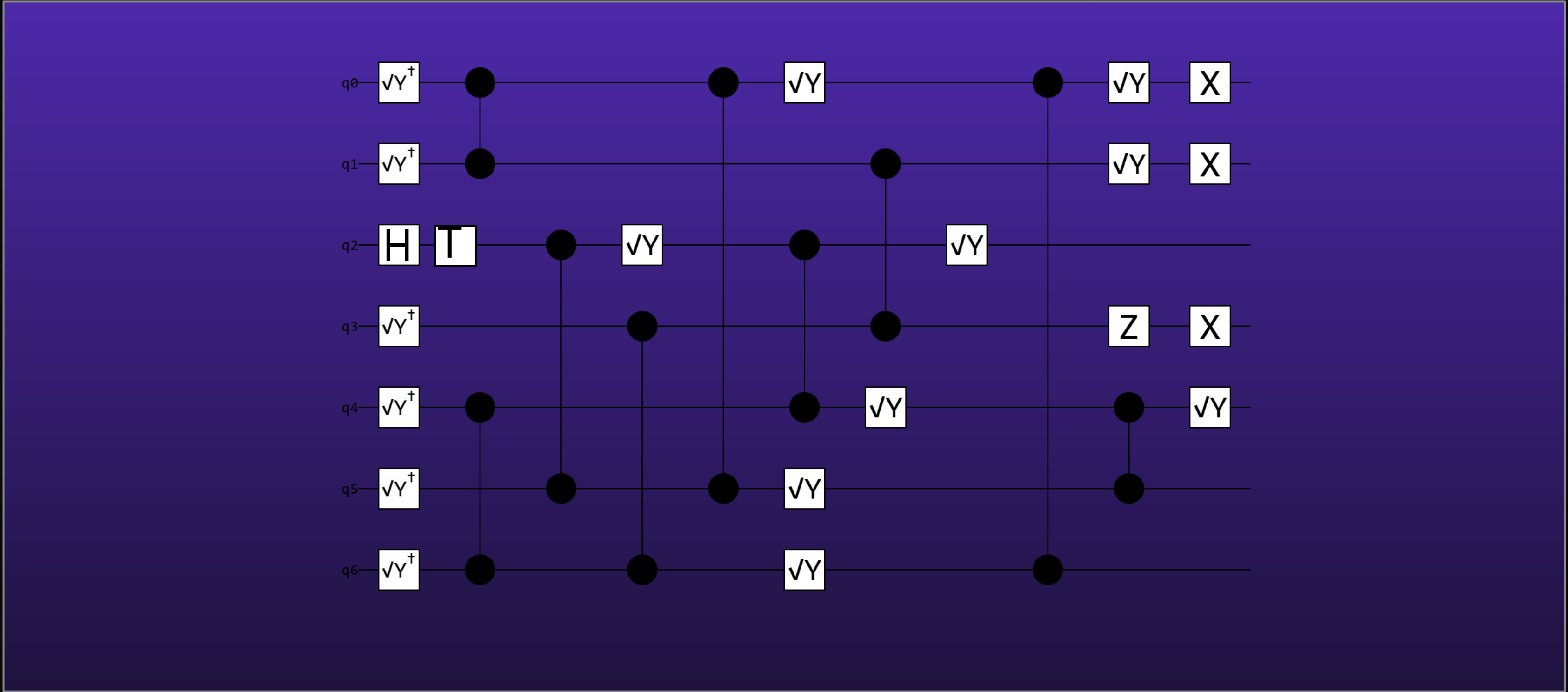
IMPLEMENTATION



Magic State Injection Circuit

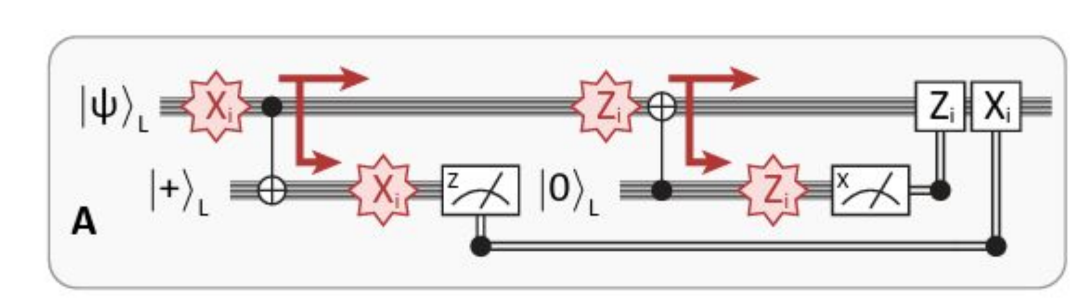
Rodriguez et al.

IMPLEMENTATION



Magic State Injection Circuit (our implementation)

IMPLEMENTATION



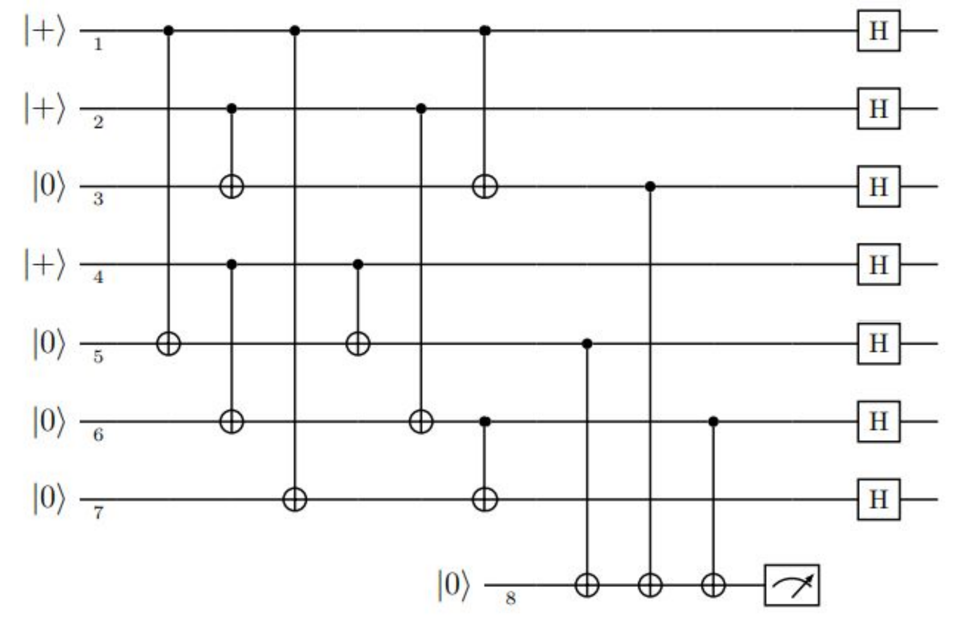
Steane Quantum Error Correction.

Magic State Distillation Procedures across both the d=3 and d=5 domains.

Circuits for Steane-type syndrome extraction in the seven-qubit color code both for A3 and A4.

from challenge

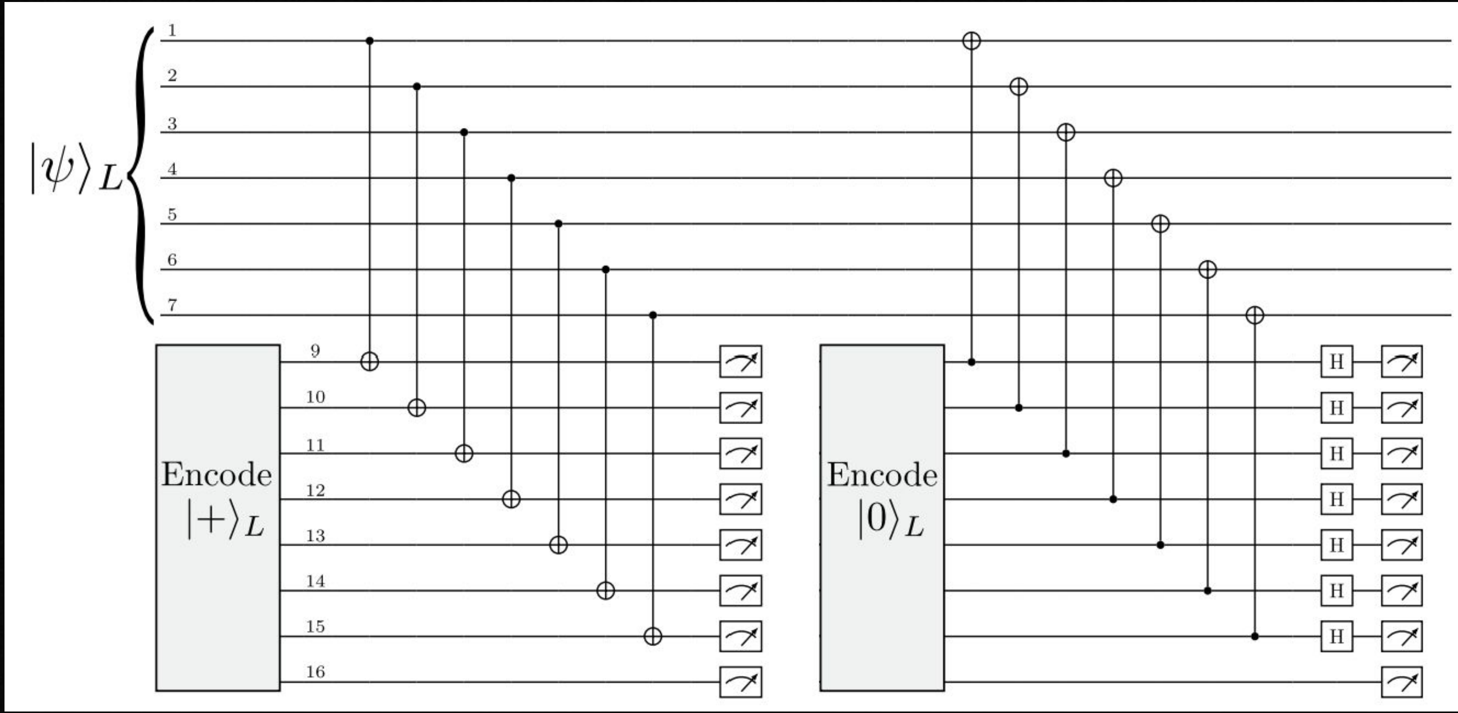
Implementation



Encoding the $|+\rangle$

Postler et. al

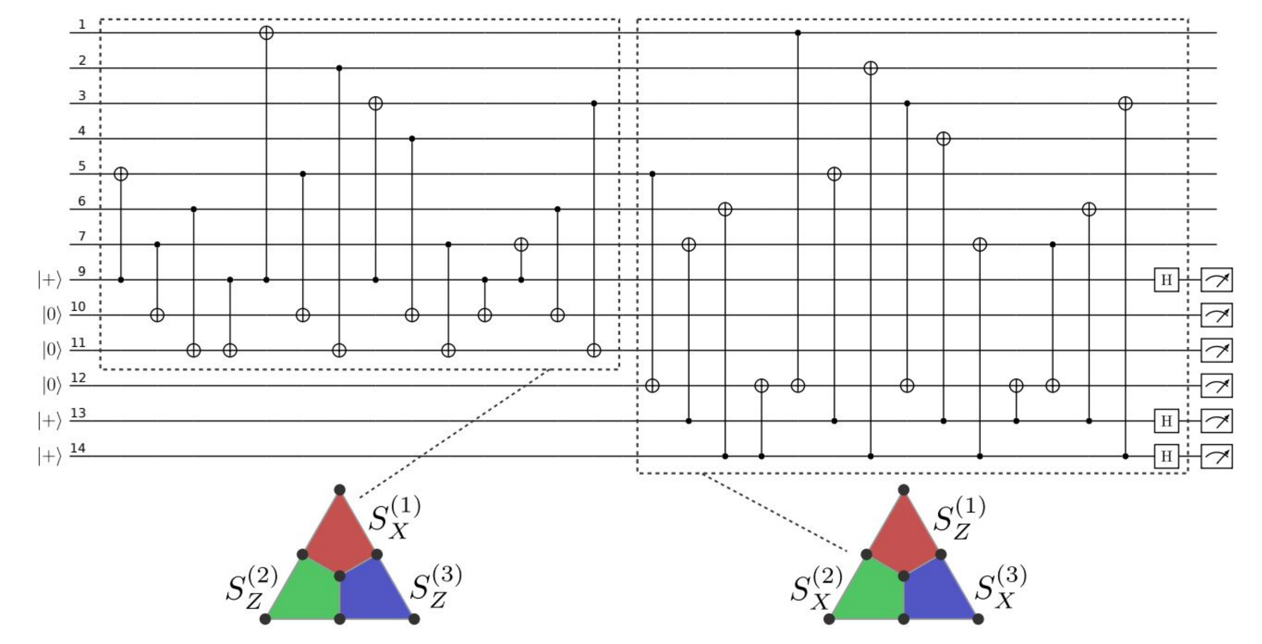
Implementation



Steane-type Syndrome Extraction Circuit: A3

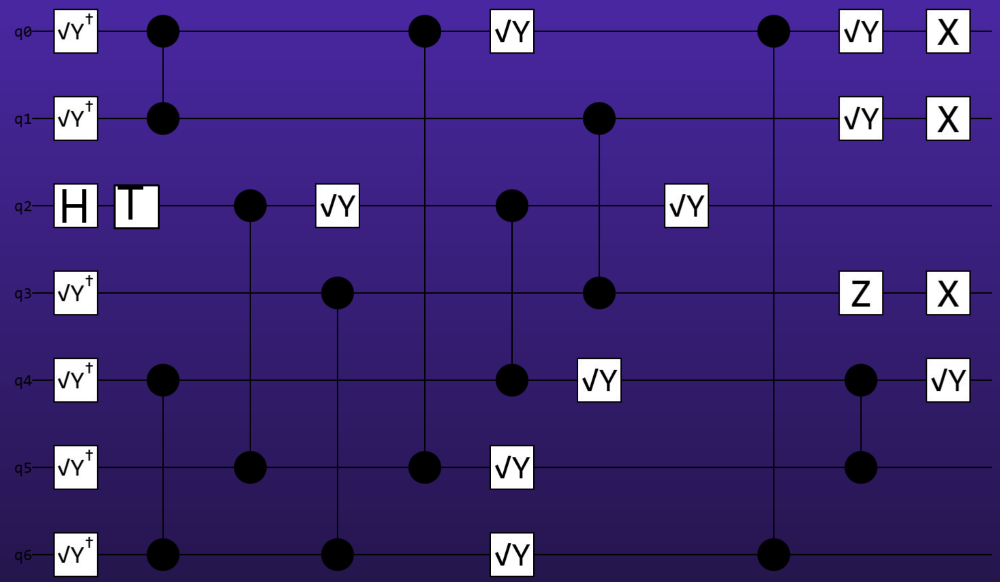
Postler et. al

Implementation



Flagged-Syndrome Readout Circuit

Postler et. al



STANDARD MAGIC STATE INJECTION

Circuit from: Rodriguez et al.

Data from our quantum circuit simulations show how loss of fidelity propagates under many different conditions. In addition, this data allow us to come to certain conclusions about our circuits, algorithms, and quantum methods in general.

Parallel Numerical Computations were performed on a consumer laptop.

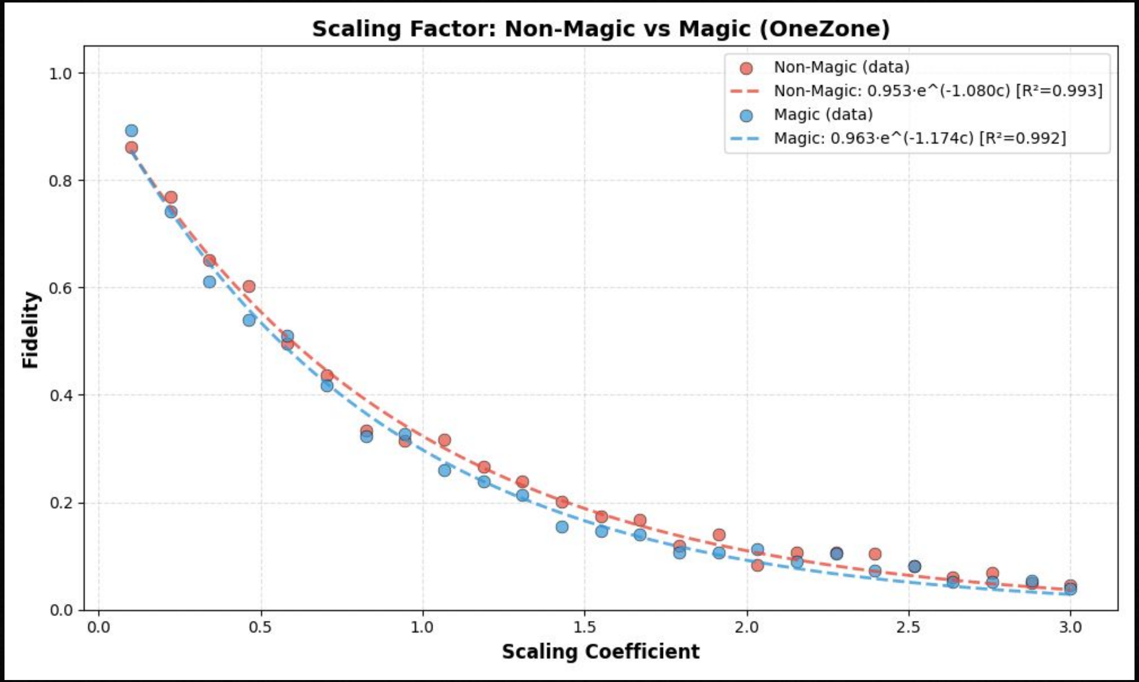
```
--------------------------------------------------------------------------------
ANALYSIS 2: Parameter Sweep Comparison (d=3 vs d=5)
--------------------------------------------------------------------------------
  Running 270 parameter tests (10 workers)...
    Progress: 20/270 (7%)
    Progress: 40/270 (15%)
    Progress: 60/270 (22%)
    Progress: 80/270 (30%)
    Progress: 100/270 (37%)
    Progress: 120/270 (44%)
    Progress: 140/270 (52%)
    Progress: 160/270 (59%)
    Progress: 180/270 (67%)
    Progress: 200/270 (74%)
    Progress: 220/270 (81%)
    Progress: 240/270 (89%)
    Progress: 260/270 (96%)
    Progress: 270/270 (100%)
```

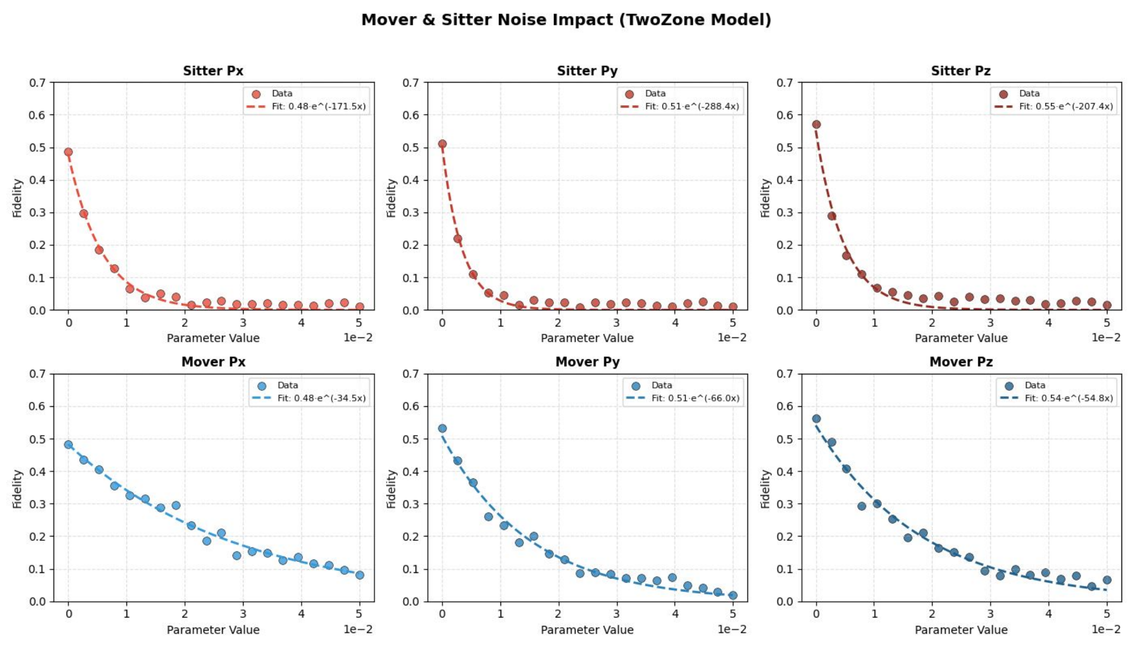
SIMULATIONS

FIDELITY CONT'D

Do "Magic States" necessarily improve fidelity? We say: No.

The added gate required to create the Magic State adds enough noise to be visible on this graph.





Moving to a two zone model for noise, we see there exists more possibilities for noise to creep in.

In this plot, notice how now “sitter” and “mover” coefficients introduce significant reductions to fidelity.

NOISY ZONES

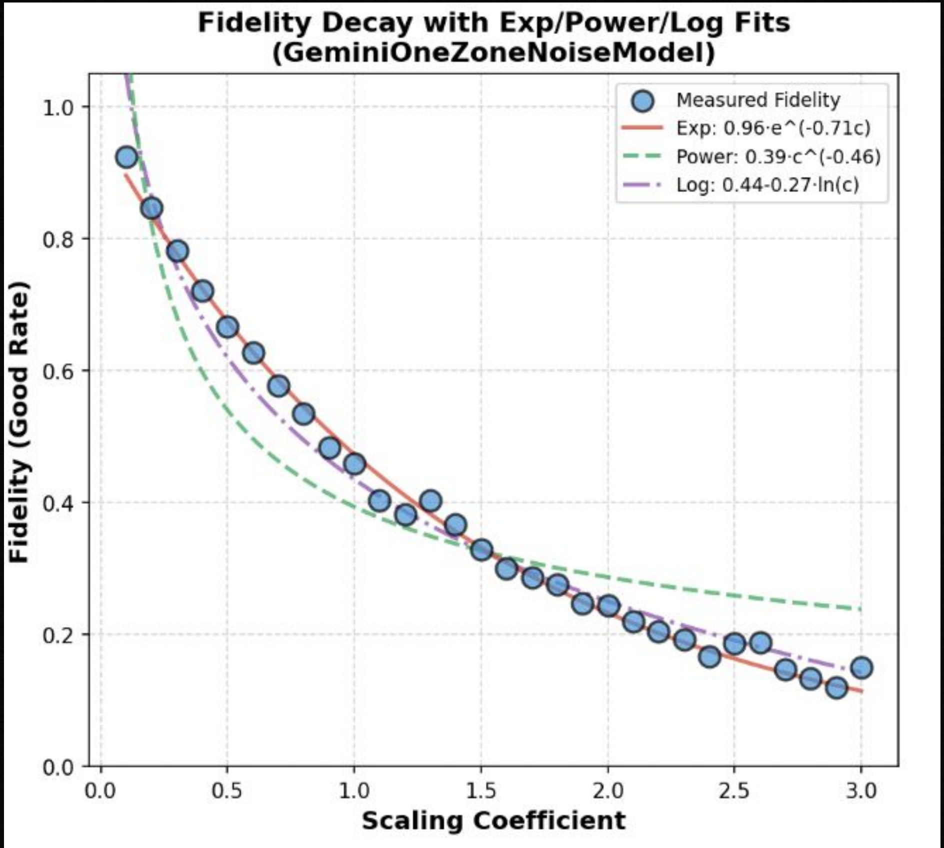
Scaling Laws of Errors

Overall Scaling

Individual Errors

Error Hierarchy

Scaling of Fidelity with Overall Errors



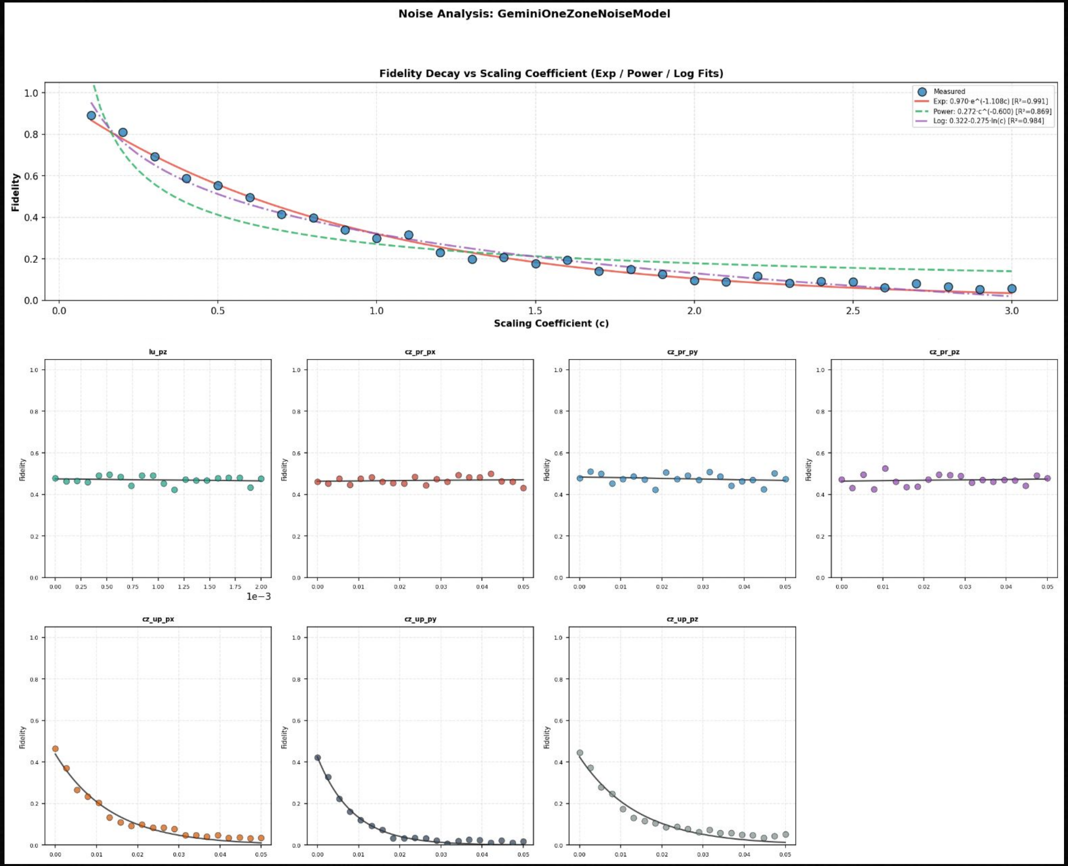
- Simulated fidelity matches expected exponential decay compared to noise, identified by a noise model "scaling coefficient"
- Best Fit: Exponential Decay

Many factors impact circuit fidelity. Let's look at a simple noise model.

Advanced One Zone Noise Analysis

In One Zone models, a significant contributor to overall errors were CZ errors.

- Fidelity comparison with Scaling Coefficient
- Comparison of the sitter/mover
- Noise comparison with fidelity

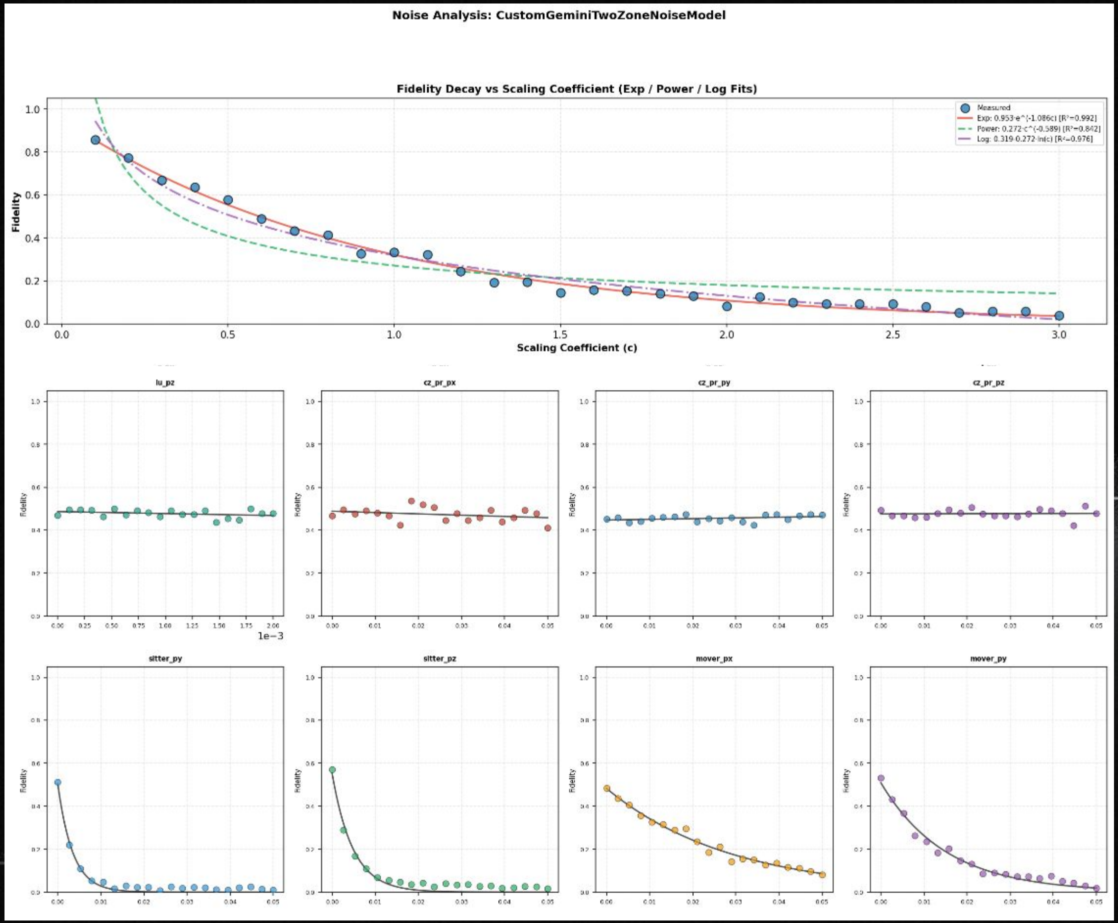


Two Noise Zone Analysis

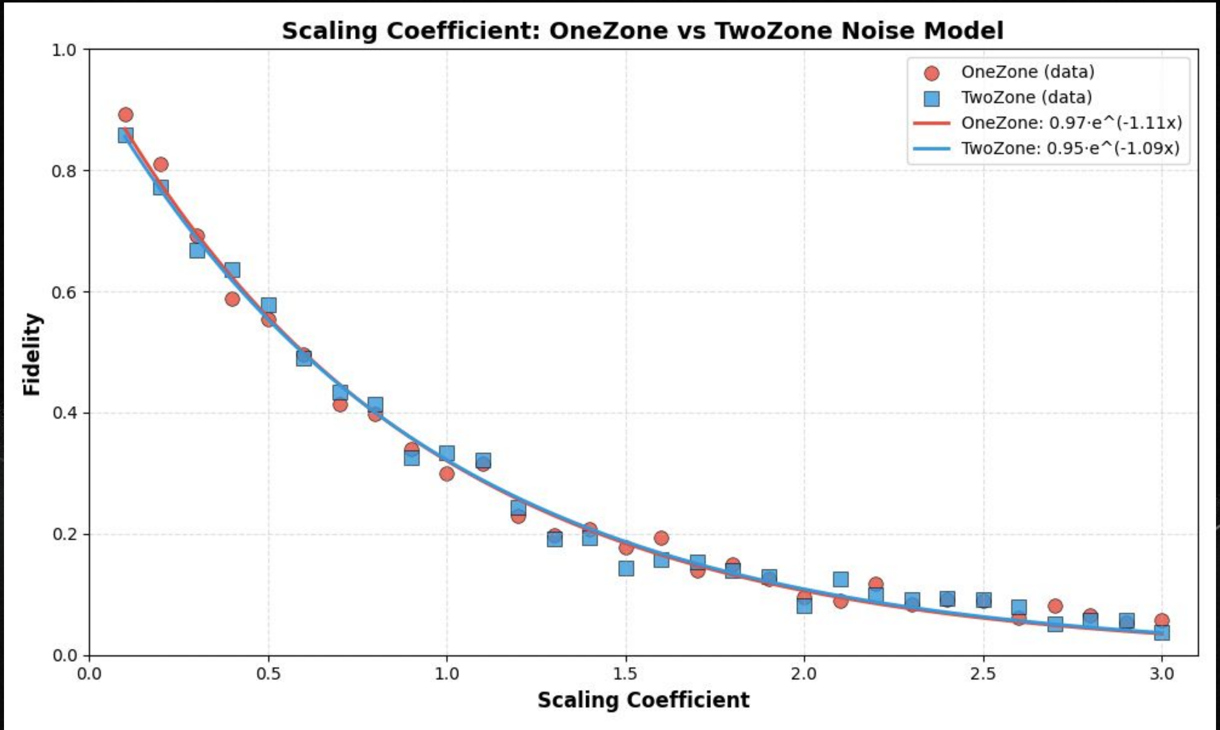
- Fidelity Comparison with Scaling Coefficient

- Comparison of the sitter/mover

- Noise comparison with fidelity



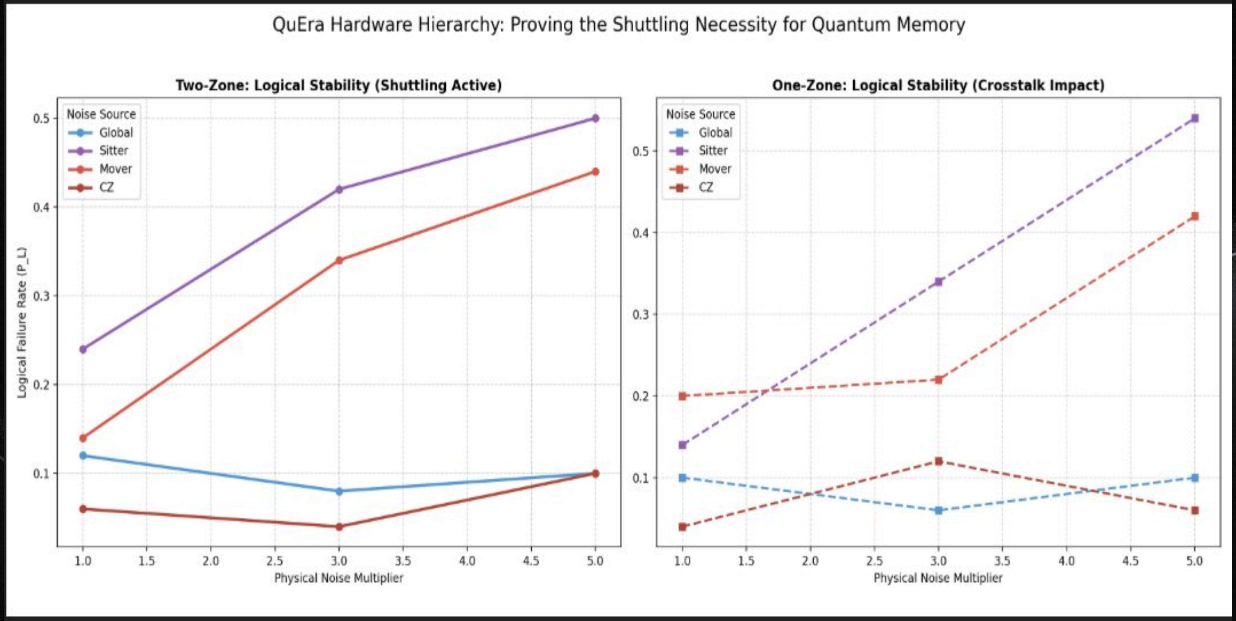
Noise Models: One-Zone versus Two-Zone



- Varying noise models did not affect overall scaling laws.

Proof of Hierarchy :

- We scaled each physical noise source independently
- The resulting mean logical failure rate induces a dominance ordering, demonstrating that the neutral-atom hardware noise hierarchy emerges at the logical level when shuttling is enabled.



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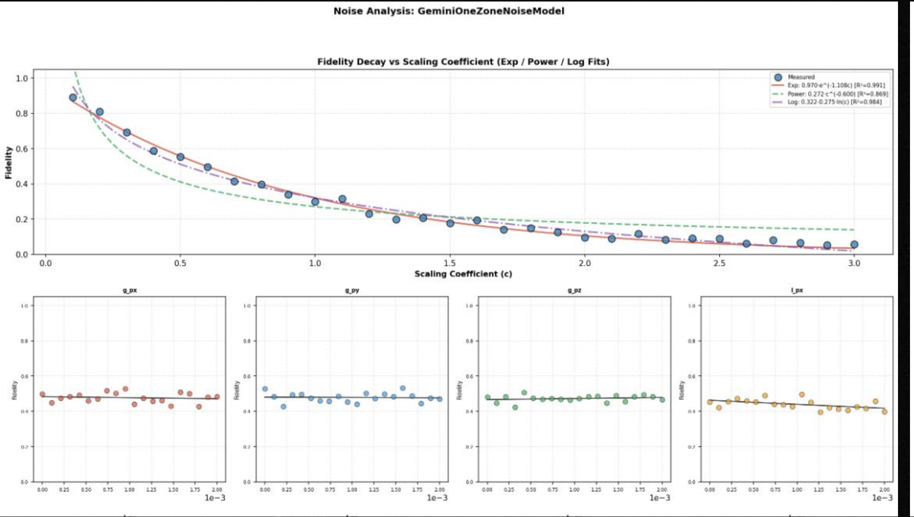
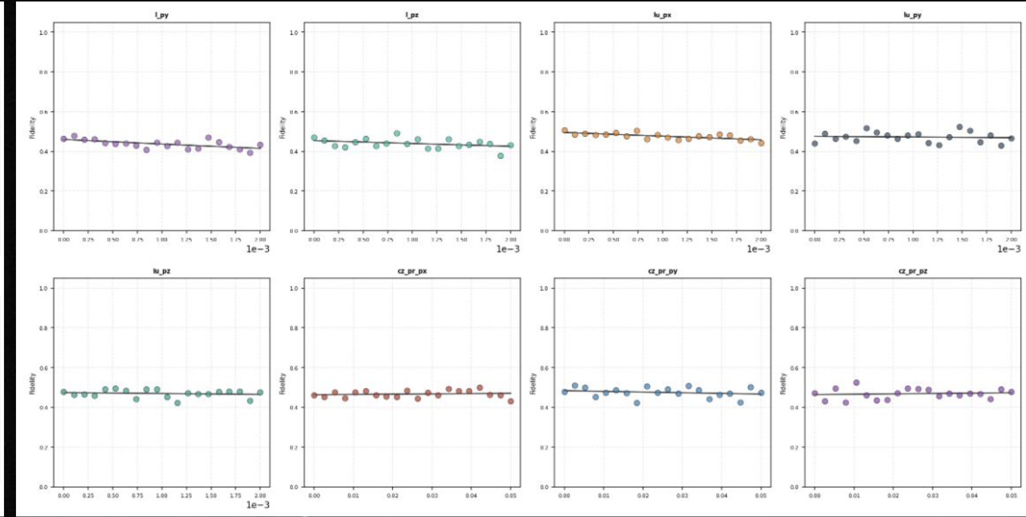
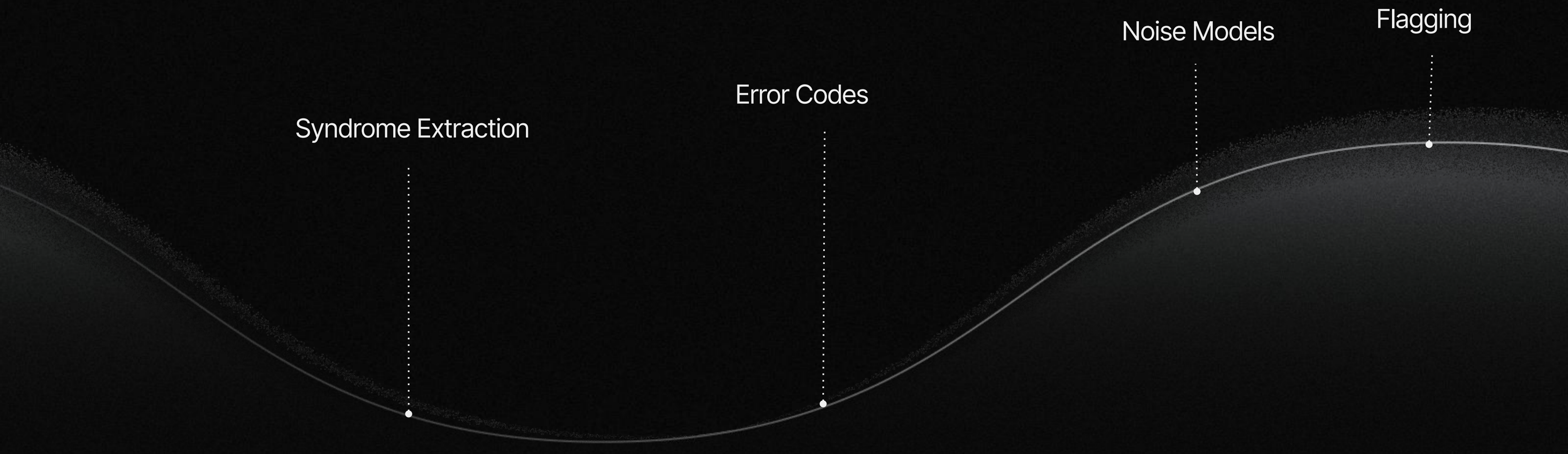




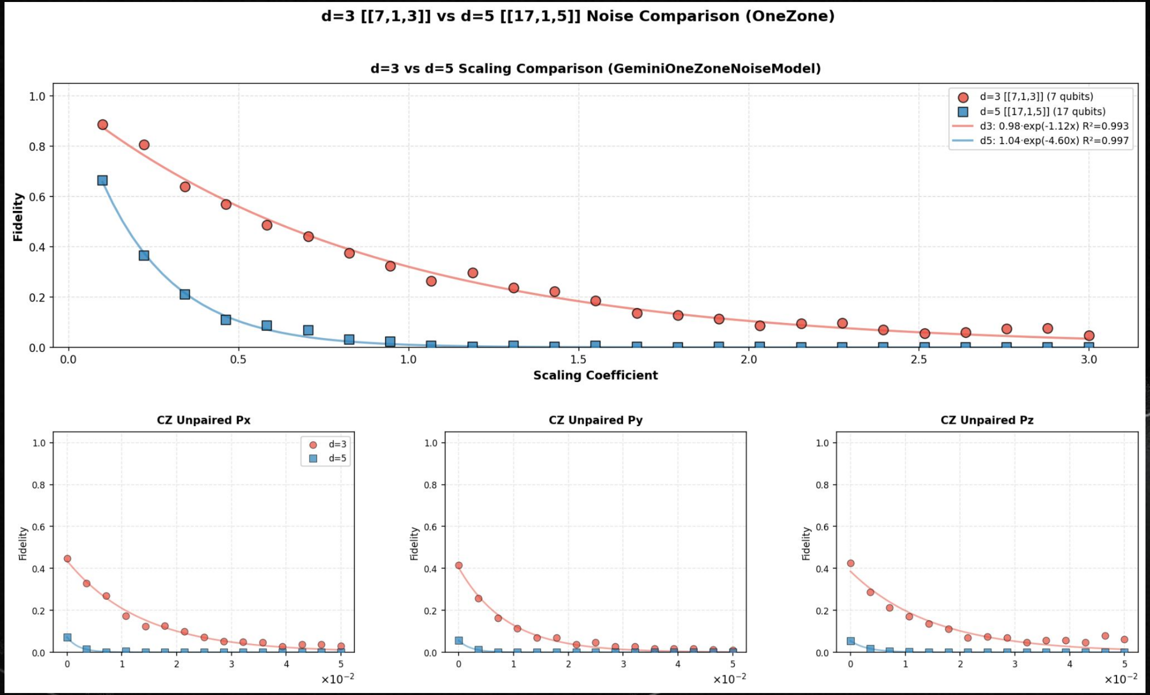
System Parameters



Fidelity Comparison for A3 and A4

- At low errors, A4 outperforms A3.

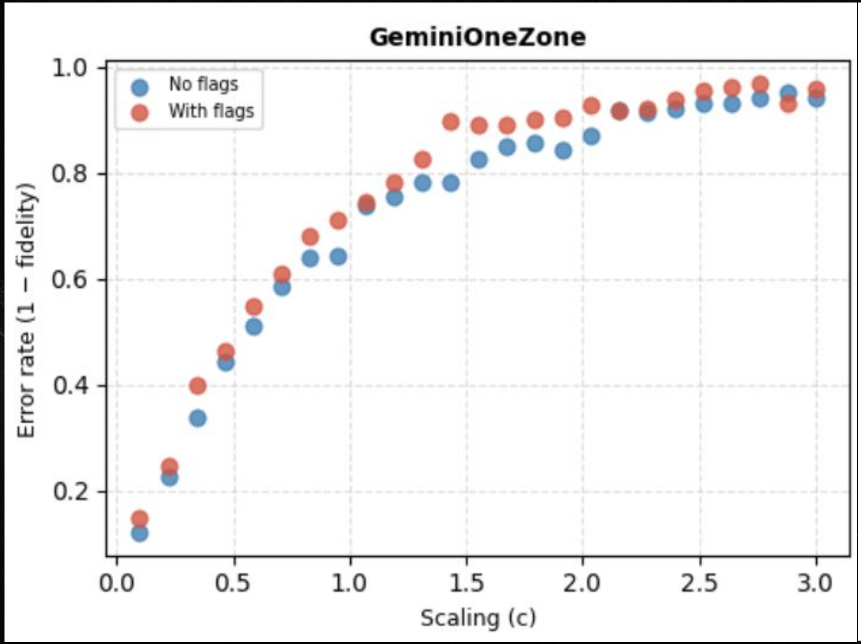
Error Codes

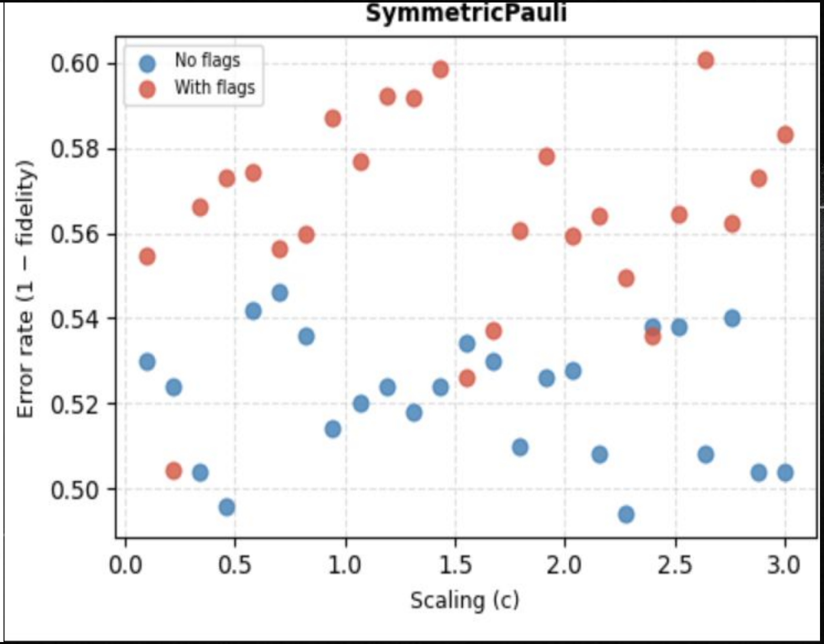


d=3 [[7,1,3]] vs d=5 [[17,1,5]] Noise Comparison (OneZone)
d=3 vs d=5 Scaling Comparison (GeminiOneZoneNoiseModel)
d=3 [[7,1,3]] (7 qubits)
d=5 [[17,1,5]] (17 qubits)
d3: 0.98·exp(-1.12x) R²=0.993
d5: 1.04·exp(-4.60x) R²=0.997
Fidelity
Scaling Coefficient
CZ Unpaired Px
CZ Unpaired Py
CZ Unpaired Pz
d=3
d=5
×10⁻²

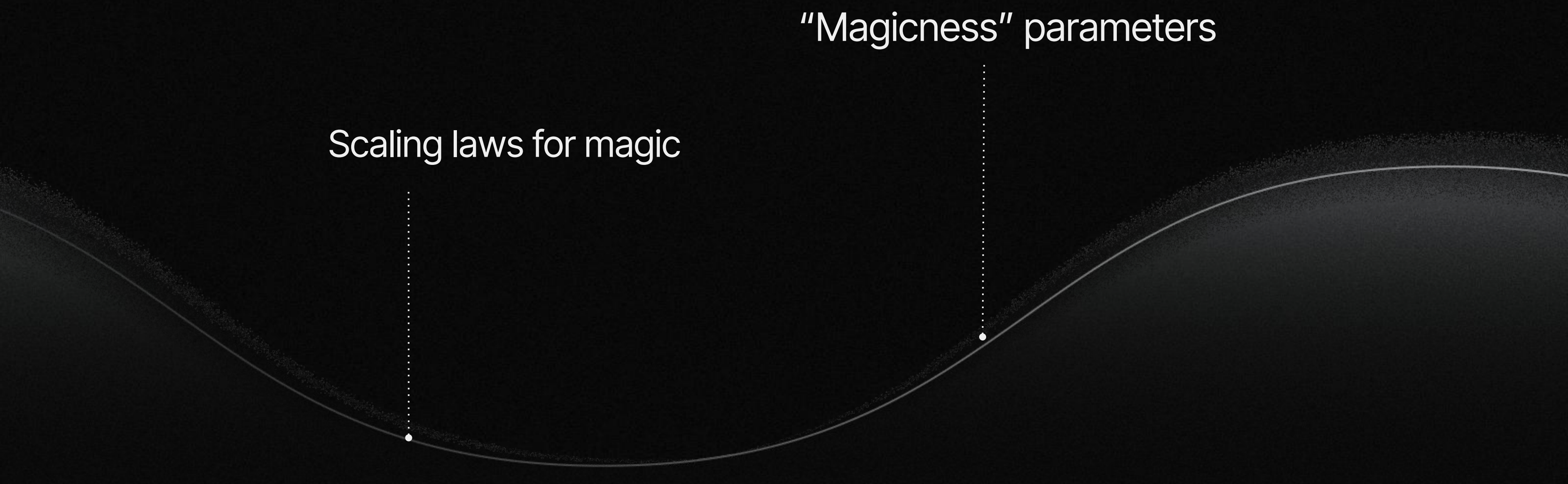
Error Rate According to Flagging

- Fixed noise model and scaling coefficient
- No flagging implemented vs. Flag Qubits

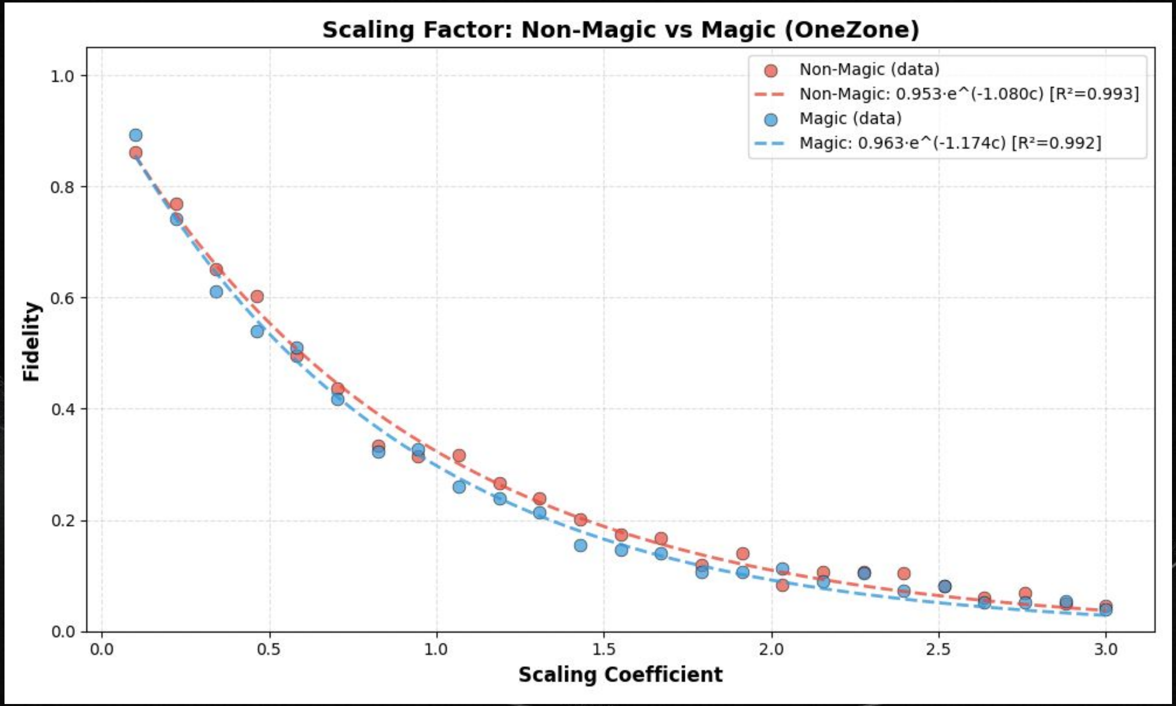




Effects of Magic



Binary Comparison: Magic vs. Non-Magic



- Non-magic States have slightly slower decay and higher fidelity.

“Magicness”

We introduced a novel topic in our analysis: “Magicness” of States

By computing the Fubini-Study metric between a traditional magic state, and the “closest non-magic state”, we get a continuum of “magicness”

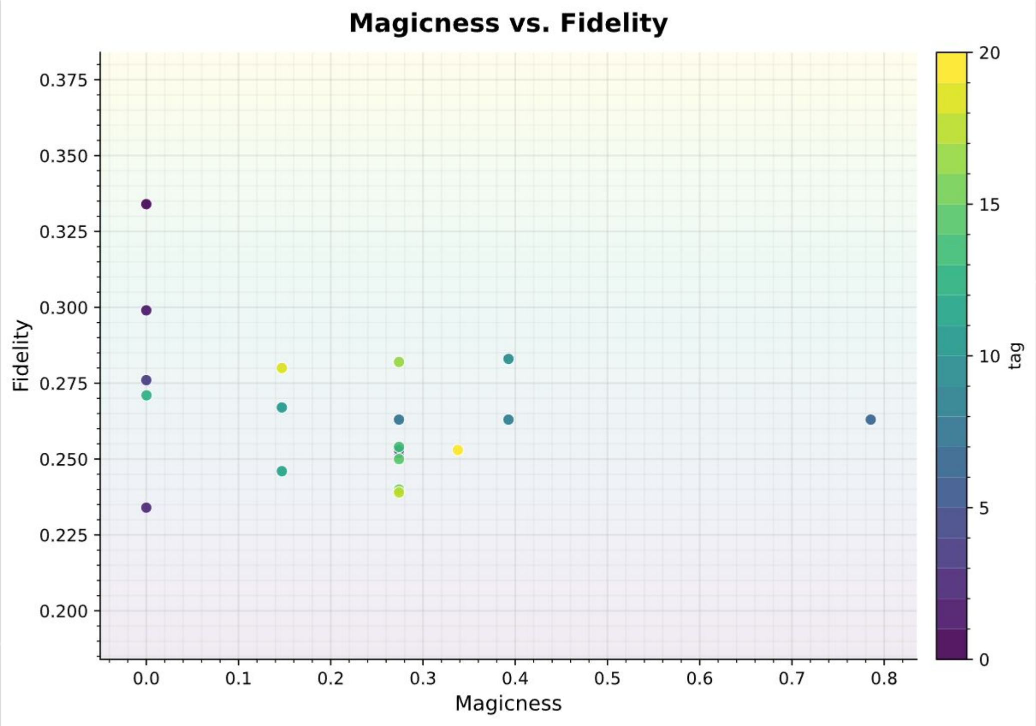
If correct, we should see varying levels of magic properties to increasingly magic-like states.

$$\arccos(|\langle \phi|\psi\rangle|)$$

Failure of Magicness

Magic-Like states do not follow expected fidelity decay curves. “Magicness” is not correlated with fidelity

This graph shows the correlation, or lack thereof, between “maginess” and fidelity of the circuit.



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Bibliography:

Postler, L., Butt, F., Pogorelov, I., Marciniak, C. D., Heußen, S., Blatt, R., Schindler, P., Rispler, M., Müller, M., & Monz, T. (2023). *Demonstration of fault-tolerant Steane quantum error correction* (arXiv:2312.09745)

Rodriguez, P. S., Robinson, J. M., Jepsen, P. N., He, Z., Duckering, C., Zhao, C., Wu, K.-H., Campo, J., Bagnall, K., Kwon, M., Karolyshyn, T., Weinberg, P., Cain, M., Evered, S. J., Geim, A. A., Kalinowski, M., Li, S. H., Manovitz, T., Amato-Grill, J., … Cantú, S. H. (2024). Experimental demonstration of logical magic state distillation. arXiv. https://doi.org/10.48550/ARXIV.2412.15165