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Leakage Mobility in Superconducting Qubits as a Leakage Reduction Unit

arXiv:2406.04083

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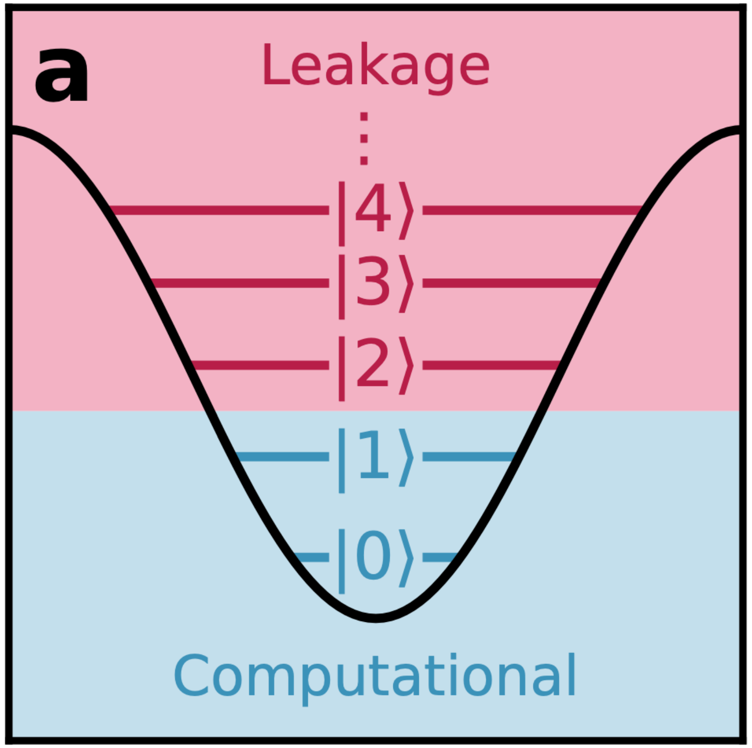
Riverlane, Cambridge, UK

ReAQCT, 20 June 2024, Budapest

Leakage



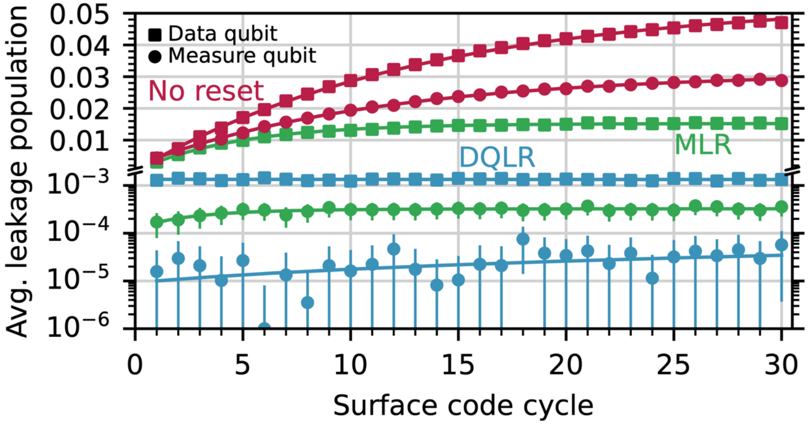
- Requires methods to force the state back into the computational space
- E.g. resetting the qubit removes leakage from it.

Leakage Reduction Units (LRUs)

Hardware-based LRU

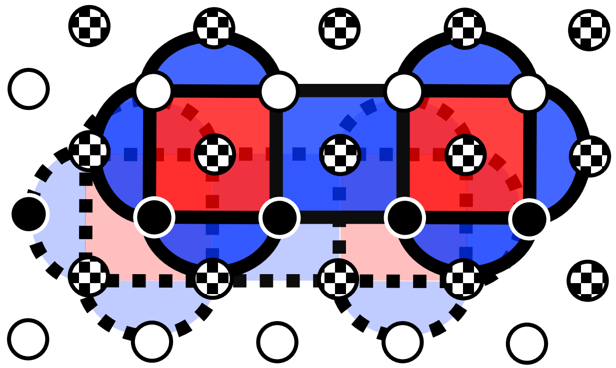
For instance,

- Multi-Level Reset (MLR).
- Data Qubit Leakage Removal (DQLR).



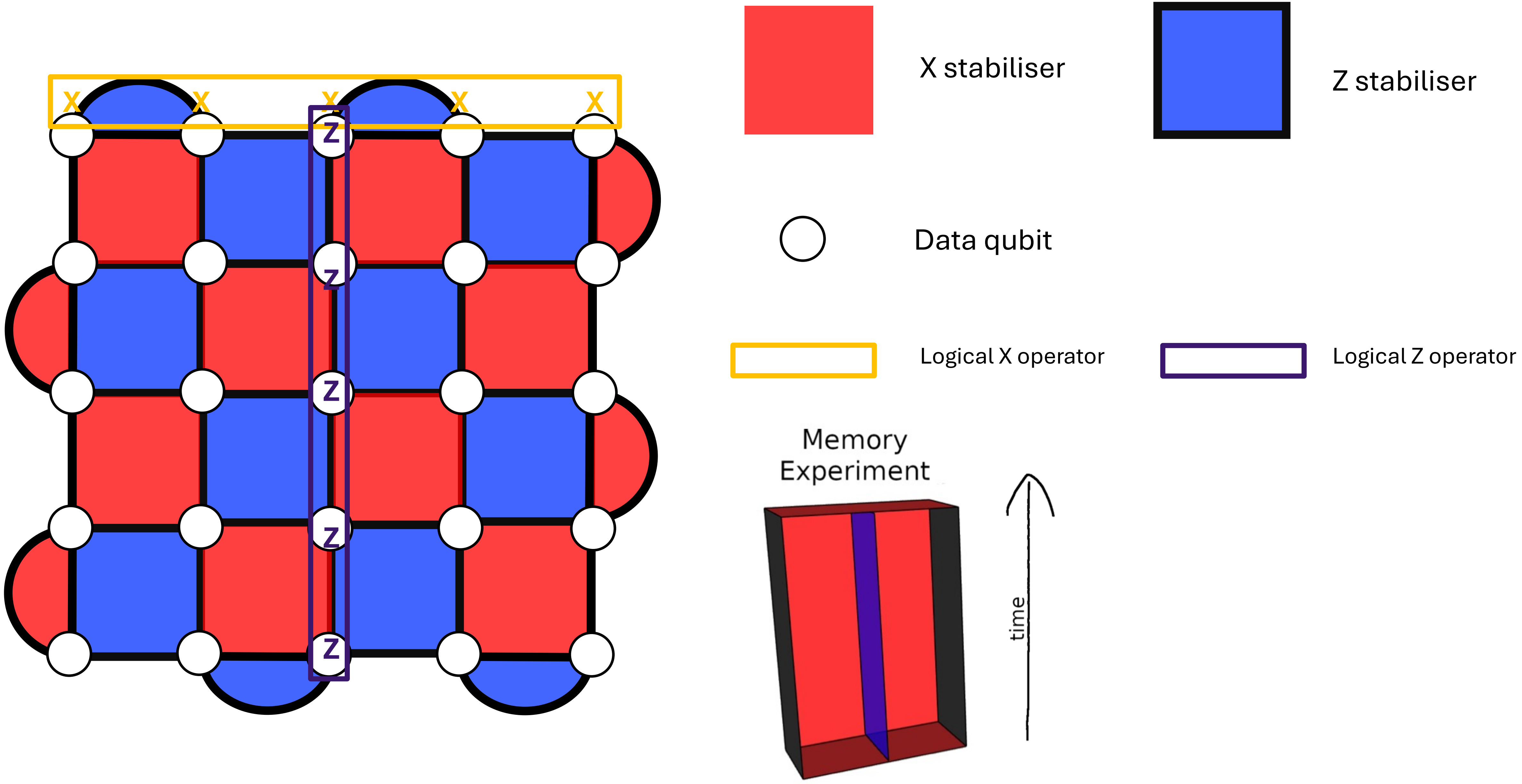
Circuit-based LRU

- Reset removes leakage from individual qubits.
- We construct circuits to measure the stabilisers that also periodically reset each qubit.

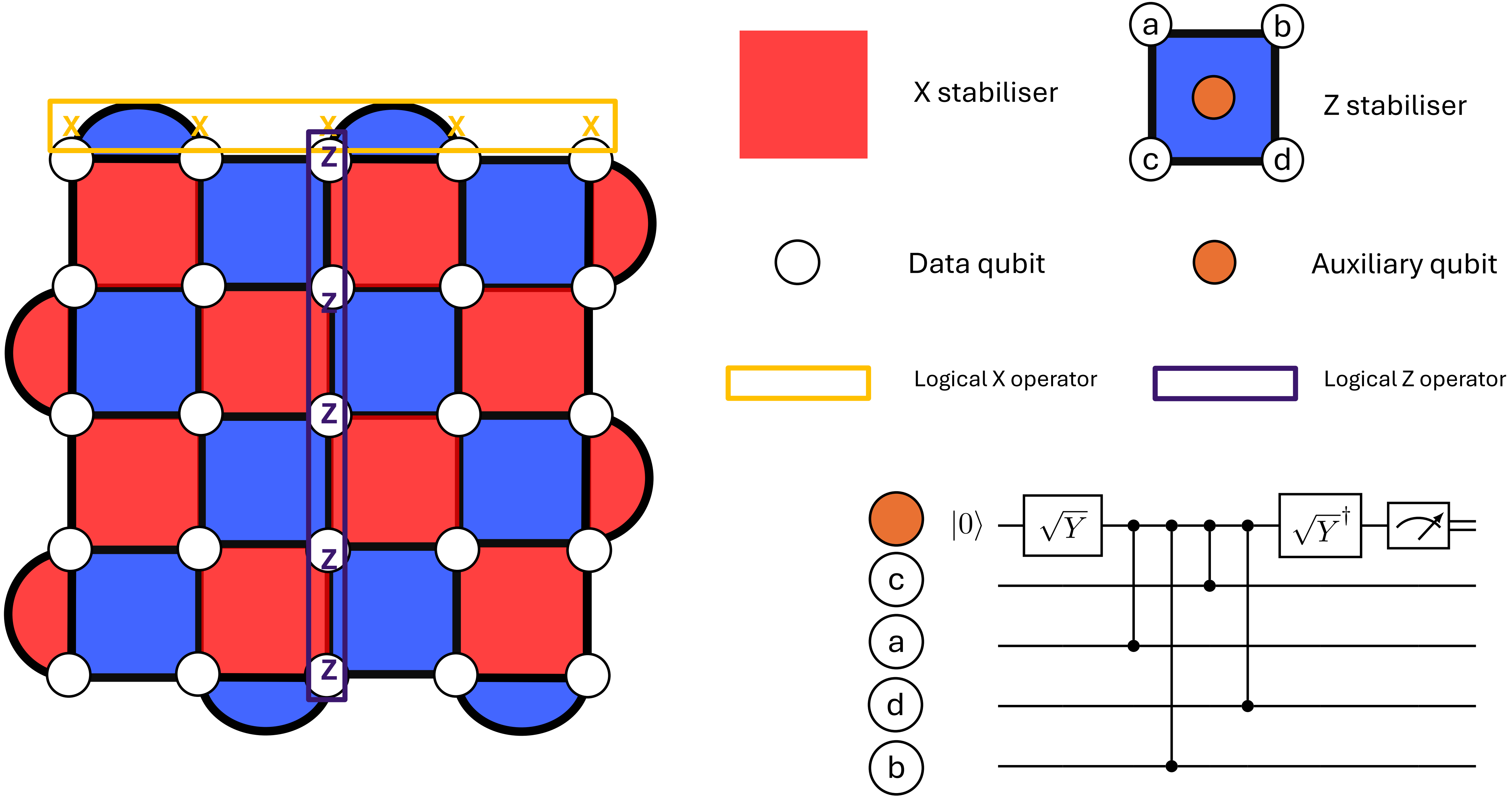


K. C. Miao et al., Nat. Phys. 19, 1780 (2023).
M. McEwen, D. Bacon, C. Gidney, Quantum 7, 1172 (2023).

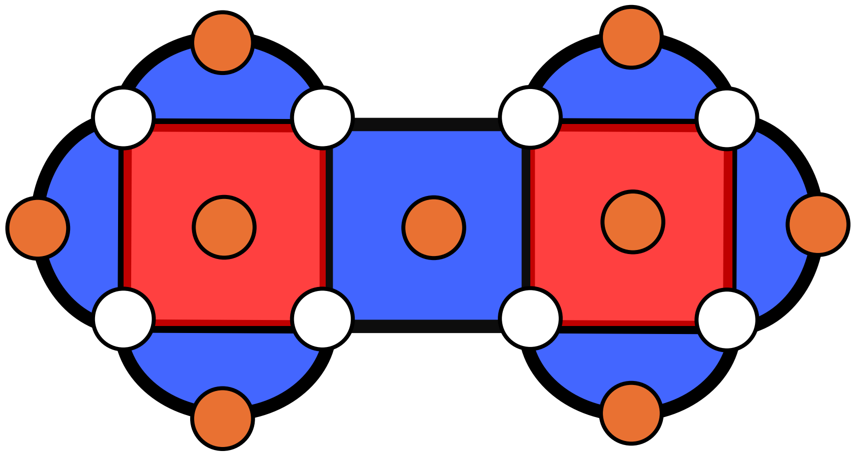
Planar code and Quantum memory



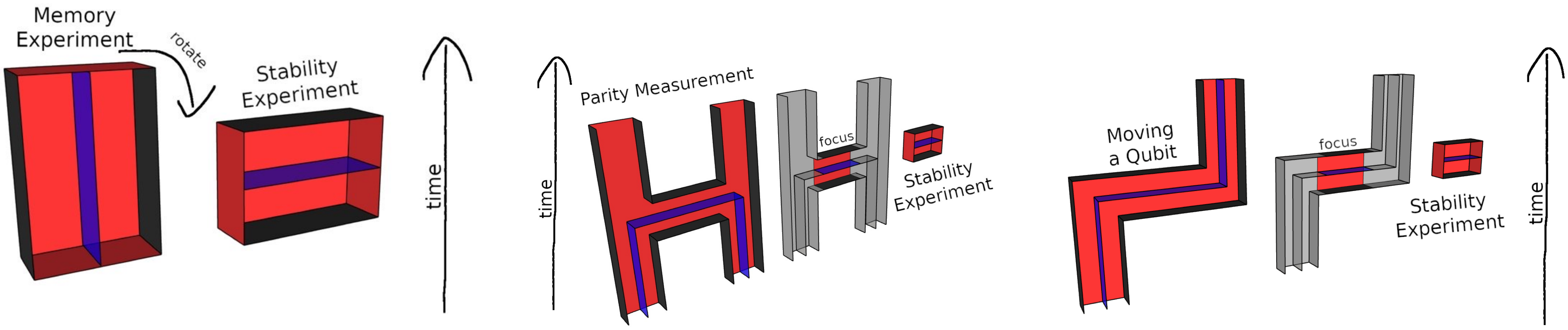
Planar code on hardware



Planar code stability experiment



	Memory	**Stability**
	Preserving an encoded state through time	Preserving encoded information through space
More qubits	Improves	Degrades
More QEC rounds	Degrades	**Improves**



C. Gidney, Quantum 6, 786 (2022).

Our goal

- Simulate realistic leakage in SC qubits, especially the effect of leakage mobility
- Evaluate its effect during FTQC
- Combine this with LRUs

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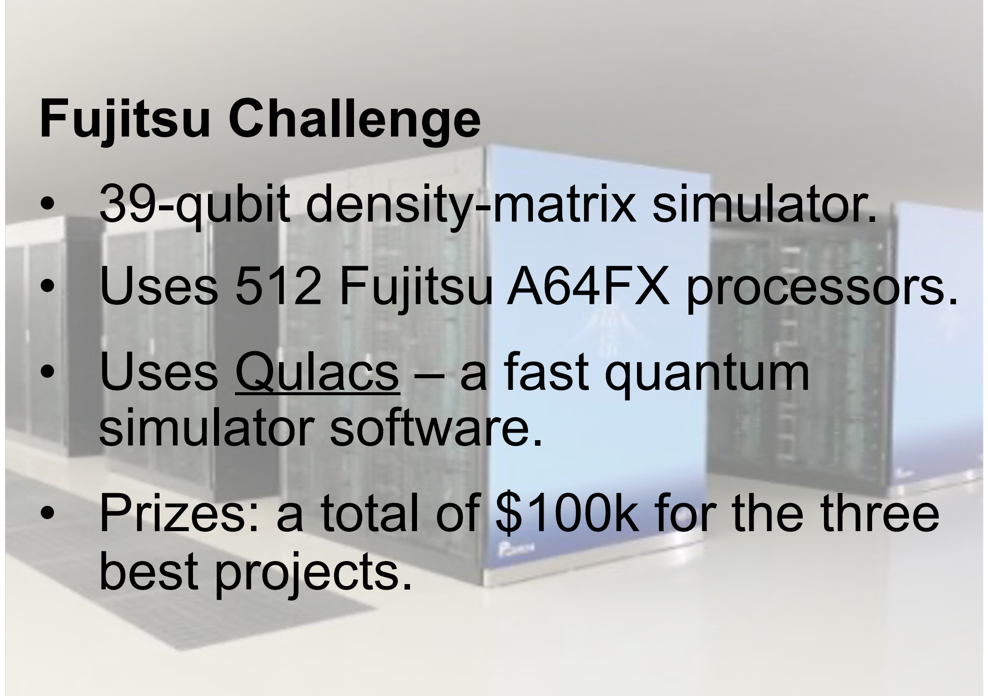

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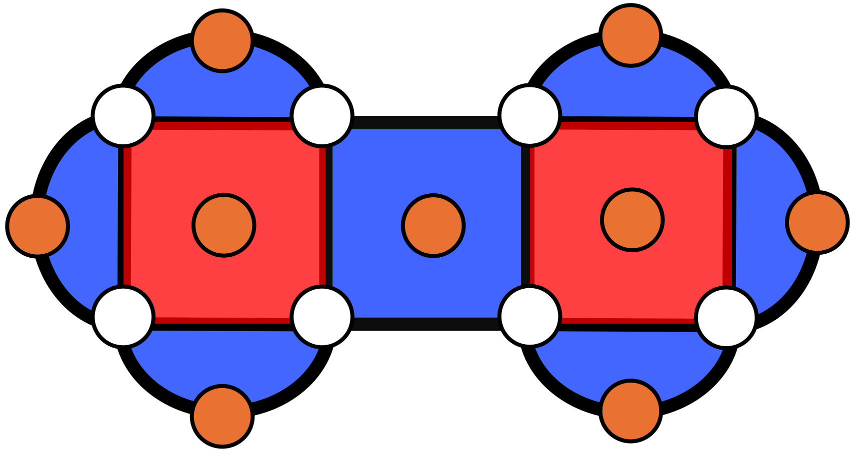

Fujitsu Challenge

- 39-qubit density-matrix simulator.
- Uses 512 Fujitsu A64FX processors.
- Uses Qulacs – a fast quantum simulator software.
- Prizes: a total of $100k for the three best projects.

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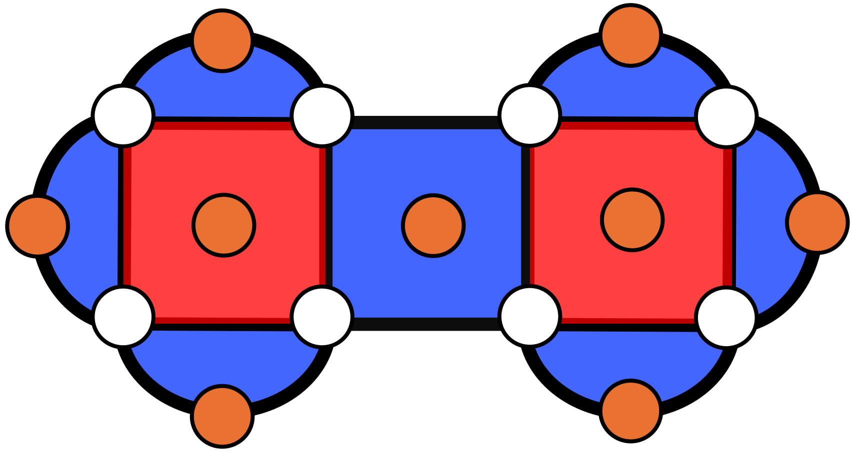

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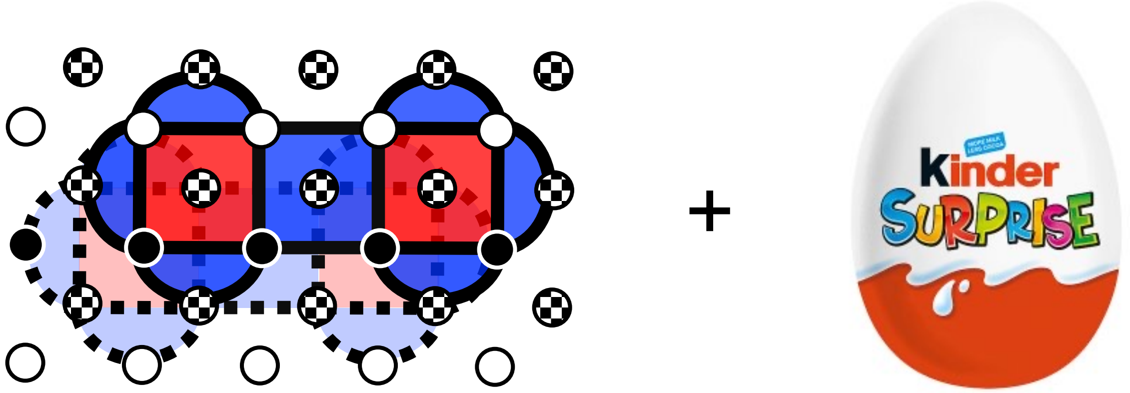

Some simulation details

- Qulacs does not support qutrits:
  $$|0\rangle \equiv |\overline{00}\rangle, |1\rangle \equiv |\overline{01}\rangle, |2\rangle \equiv |\overline{10}\rangle.$$
- Thus, we can simulate only 19 qutrits.
- Quantum memory needs increasing qubit number to show improvement in QEC performance.
- On the other hand, stability experiment has better QEC performance with increased number of rounds — unlike quantum memory.

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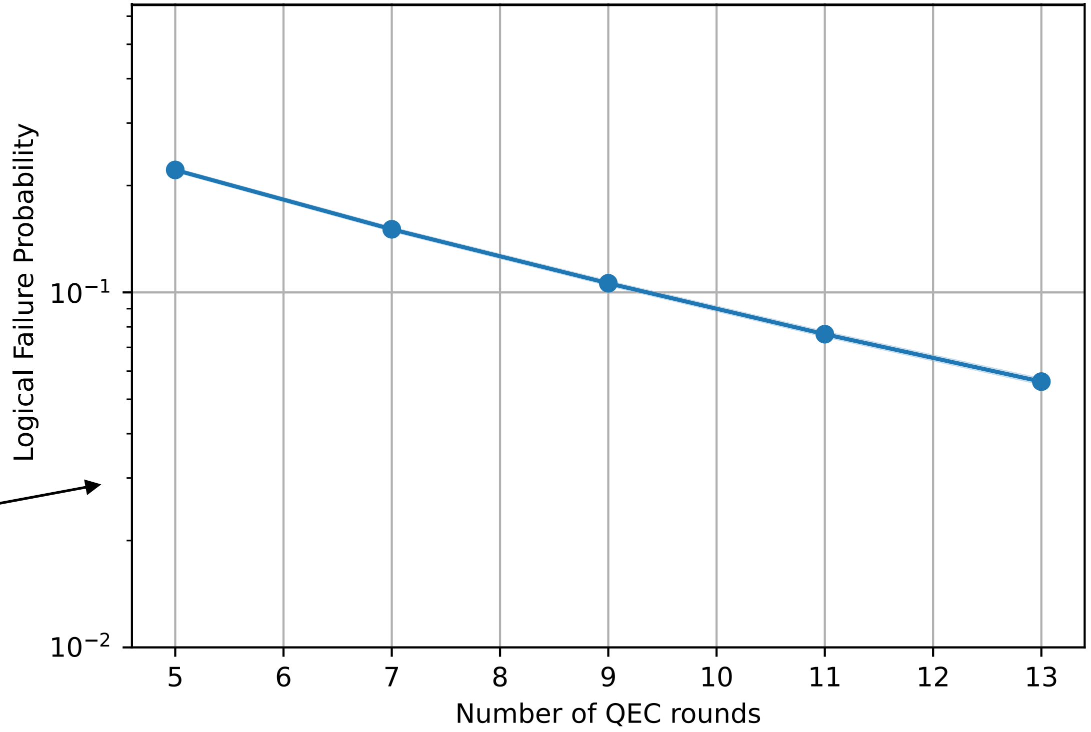
- Thus, we can simulate only 19 qutrits.
- Quantum memory needs increasing qubit number to show improvement in QEC performance.
- On the other hand, stability experiment has better QEC performance with increased number of rounds — unlike quantum memory.
- We can fix a planar code patch and simply increase simulation time for better performance.

$$P_{\text{fail}} = P_{\text{SPAM}}(\Lambda_s)^{-n_r/2}$$



Noise model — the leakage part

Leakage

$$|11\rangle \to -\sqrt{1-4L_1}\,|11\rangle + 2\sqrt{L_1}\,|02\rangle$$
$$|02\rangle \to -\sqrt{1-4L_1}\,|02\rangle - 2\sqrt{L_1}\,|11\rangle$$

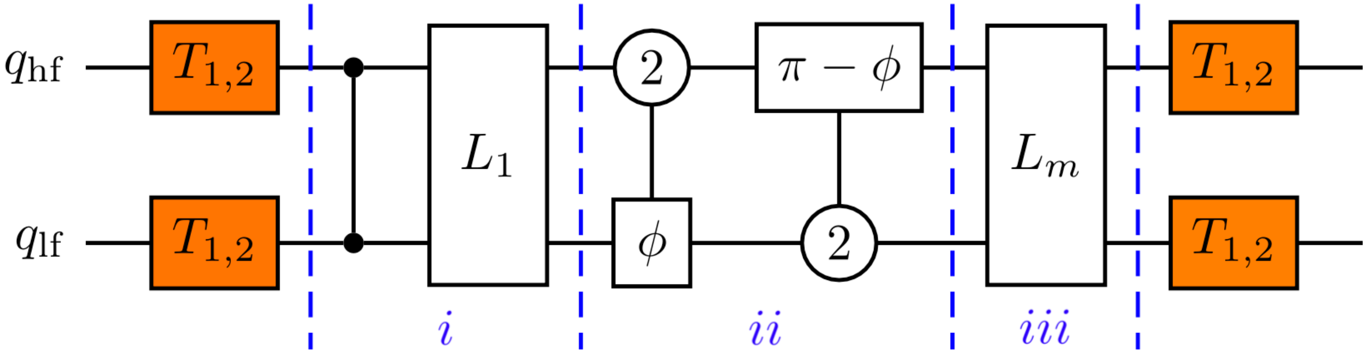
Leakage mobility

$$|21\rangle \to -\sqrt{1-4L_m}e^{+i\phi}\,|21\rangle + 2\sqrt{L_m}\,|12\rangle$$
$$|12\rangle \to -\sqrt{1-4L_m}e^{-i\phi}\,|12\rangle - 2\sqrt{L_m}\,|21\rangle$$

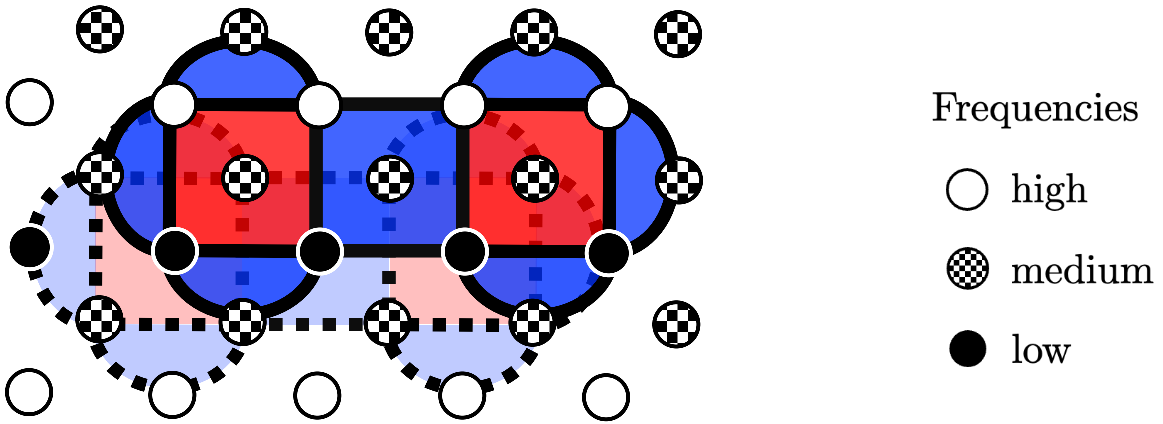
We simulated the following parameters:

- $L_1 = 0.001, 0.005$
- $L_m = 0.005, 0.025, 0.06, 0.09, 0.125$
- With and without wiggling

CZ gate



Qubit frequency arrangement



B. M. Varbanov, et al., npj Quantum Inf. 6, 102 (2020).

Exponential error suppression

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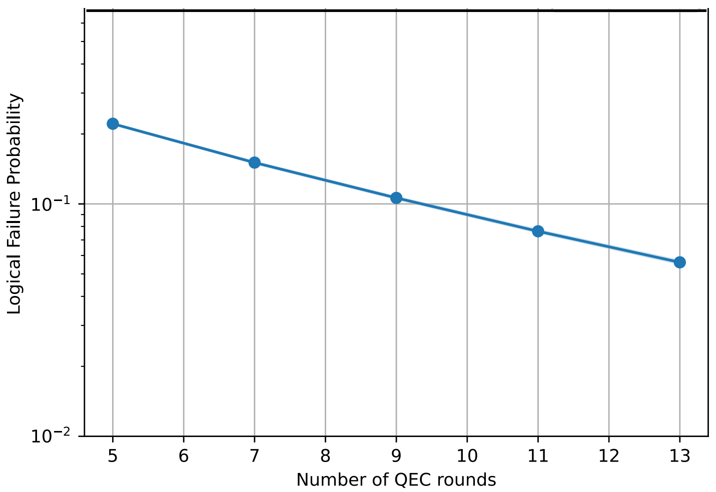


Steeper line

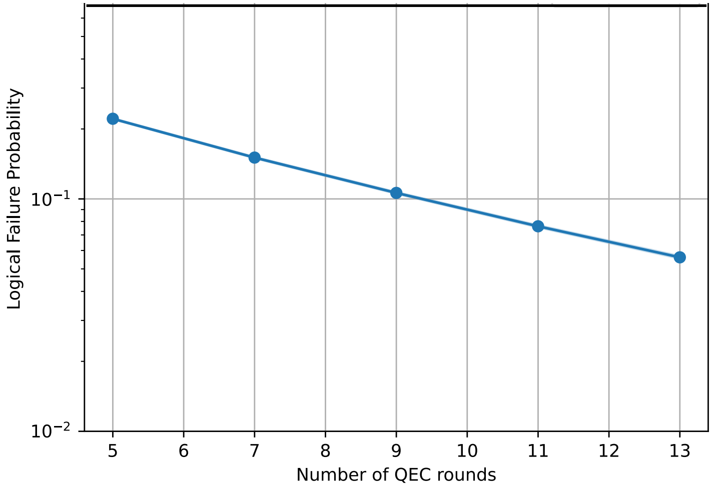
→ better error suppression

→ larger Λ_s

Exponential error suppression

- High mobility escapes wiggling
- High mobility reduces non-wiggled error

$$P_{\text{fail}} = P_{\text{SPAM}}(\Lambda_s)^{-n_r/2}$$



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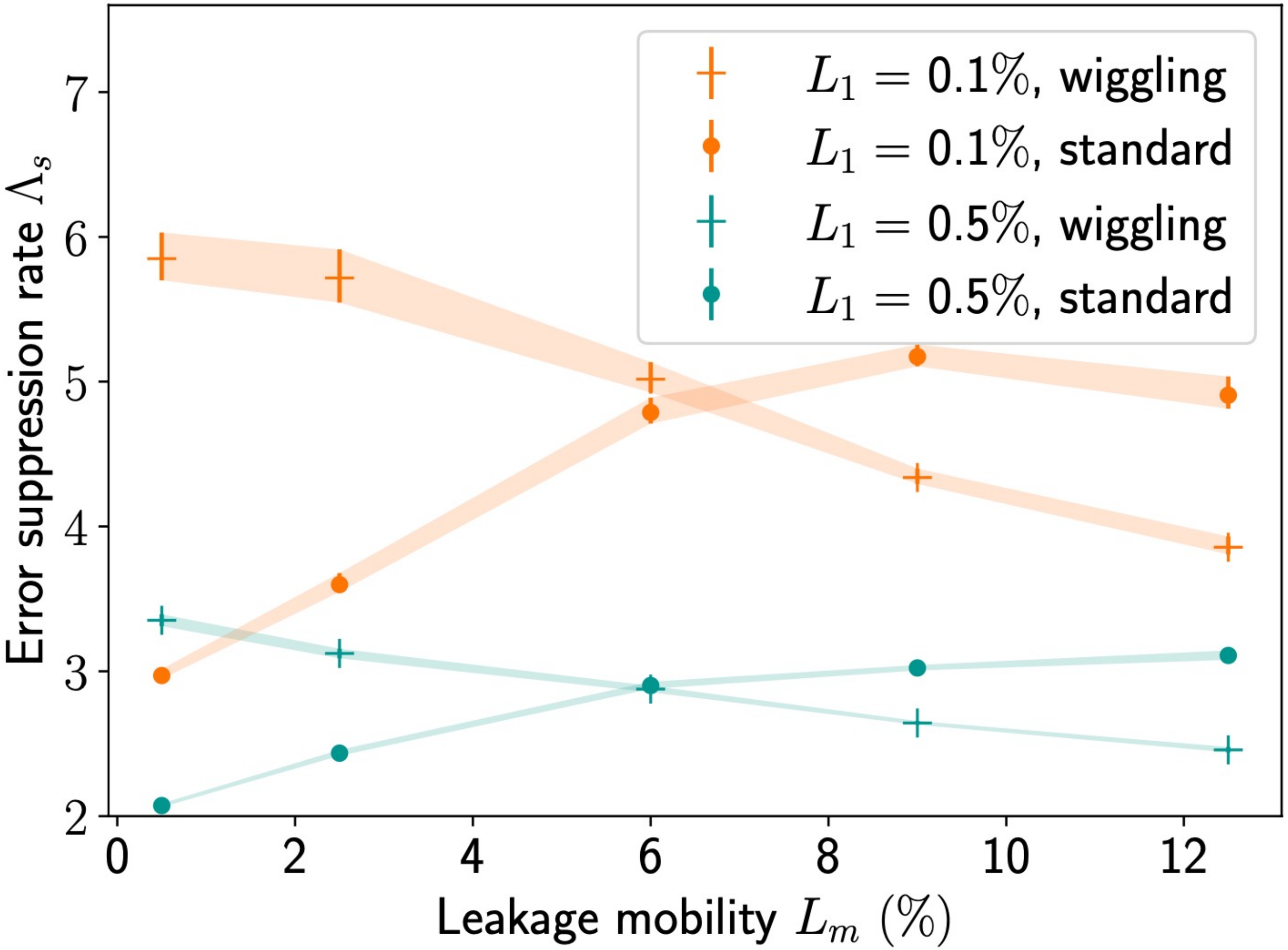

Conclusion

- Realistic simulations of stability experiments under leakage
- Leakage reduced with patch-wiggling at low leakage mobility
- Patch-wiggling is counterproductive at high mobility
- Mobility is itself can be an LRU

- The paper is available on arXiv: 2406.04083

Thank you


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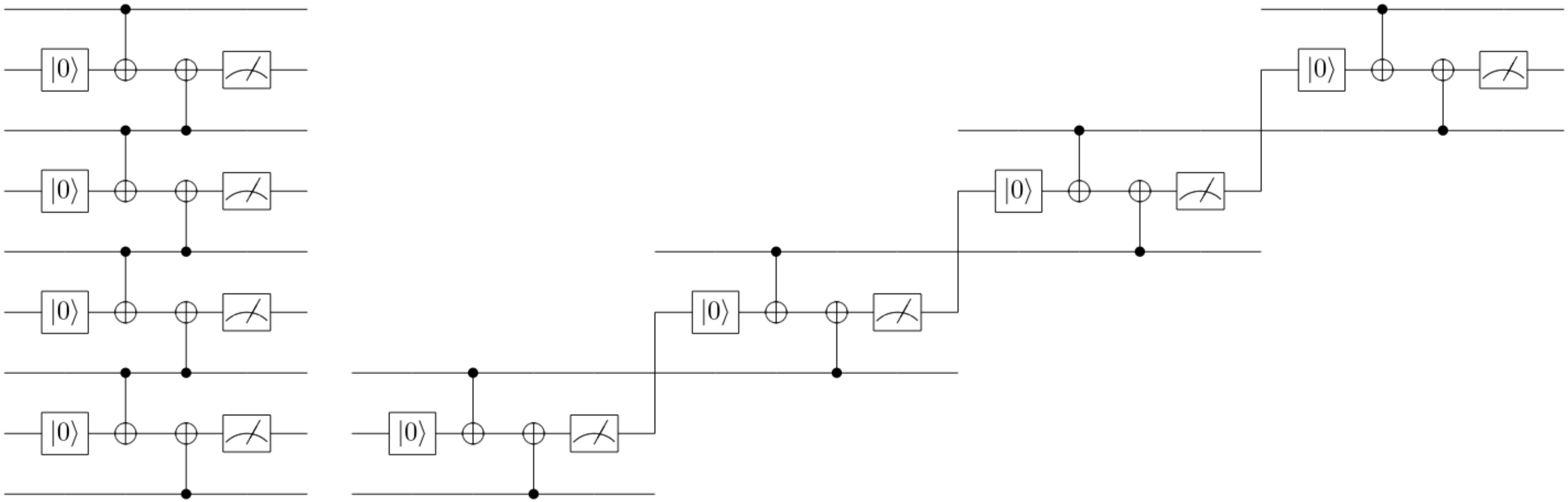
Additional slides

Qubit recycling



M Katsuda, et al., arxiv:2204.11404

Noise model — leakage-ness part

Parameter	Numerical value
Relaxation time T_1	30 μs
Dephasing time $T_2 = T_\phi/2$	30 μs
$\sqrt{Y}$, $\sqrt{Y}^\dagger$ gate duration	20 ns
CZ gate duration	40 ns
Measurement duration	600 ns
Reset duration	500 ns

$$\frac{d\rho}{dt} = -i[H,\,\rho] + \sum_j L_j \rho L_j^\dagger - \frac{1}{2}\left\{L_j^\dagger L_j,\,\rho\right\}$$

$$L_{\mathrm{amp}} = \sqrt{\frac{1}{T_1}}a = \sqrt{\frac{1}{T_1}}\begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & \sqrt{2} \\ 0 & 0 & 0 \end{pmatrix}$$

$$L_{\mathrm{deph},1} = \sqrt{\frac{4}{9T_2}}\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix}, \quad L_{\mathrm{deph},2} = \sqrt{\frac{1}{9T_2}}\begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \quad L_{\mathrm{deph},3} = \sqrt{\frac{1}{9T_2}}\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{pmatrix}$$

$$\mathcal{E}(t) = \exp\left(t\mathcal{L}\right)$$

$$\mathcal{E}(\rho) = \sum_i K_i \rho K_i^\dagger, \qquad \sum_i K_i^\dagger K_i = I.$$

Noisy gate without leakage: $T_{1,2}(t_{\mathrm{gate}}/2)\,U_{\mathrm{gate}}\,T_{1,2}(t_{\mathrm{gate}}/2)$

B. M. Varbanov, et al., npj Quantum Inf. 6, 102 (2020).

Noise model — the leakage part

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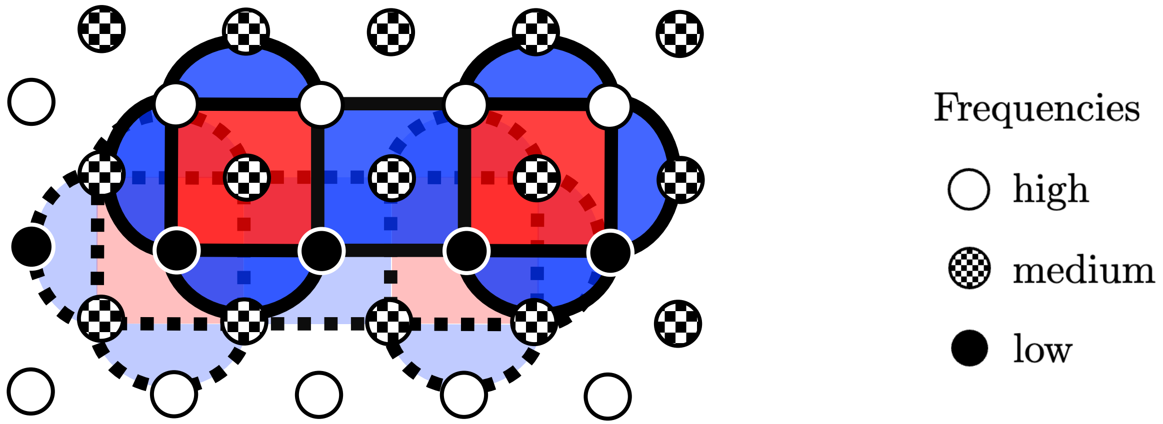
$\sqrt{Y}$, $\sqrt{Y}^\dagger$ gate duration	20 ns
CZ gate duration	40 ns
Measurement duration	600 ns
Reset duration	500 ns
Conditional phase ϕ	$\pi/10$
Variable parameters:	
Leakage L_1	0.1%, 0.5%
Leakage mobility L_m	0.5%, 2.5%, 6%, 9%, 12.5%

Qubit frequency arrangement



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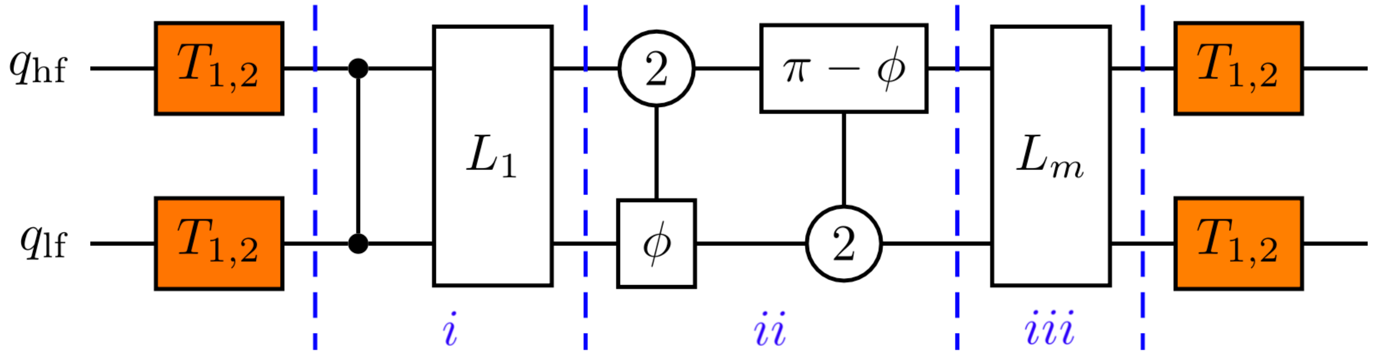

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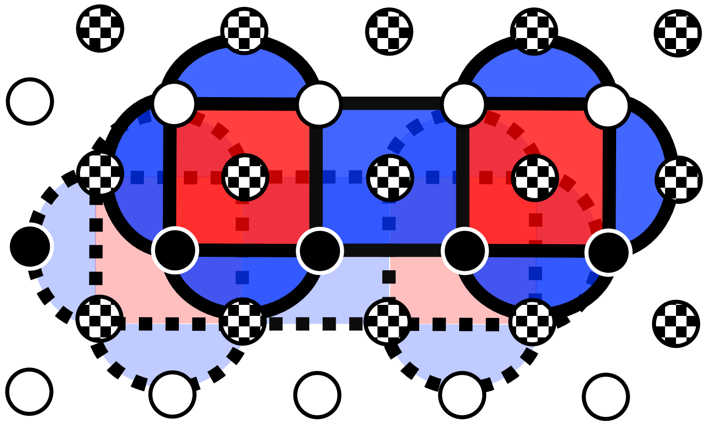
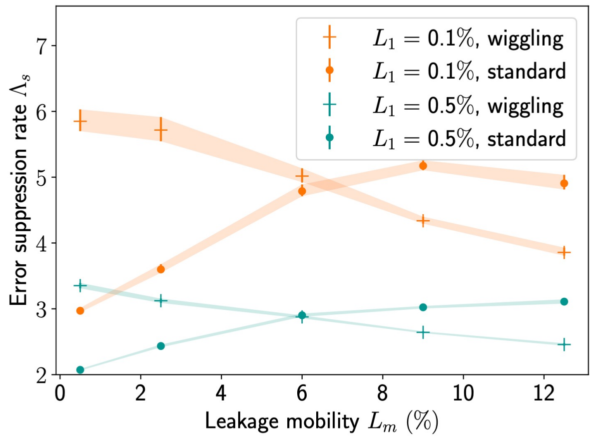
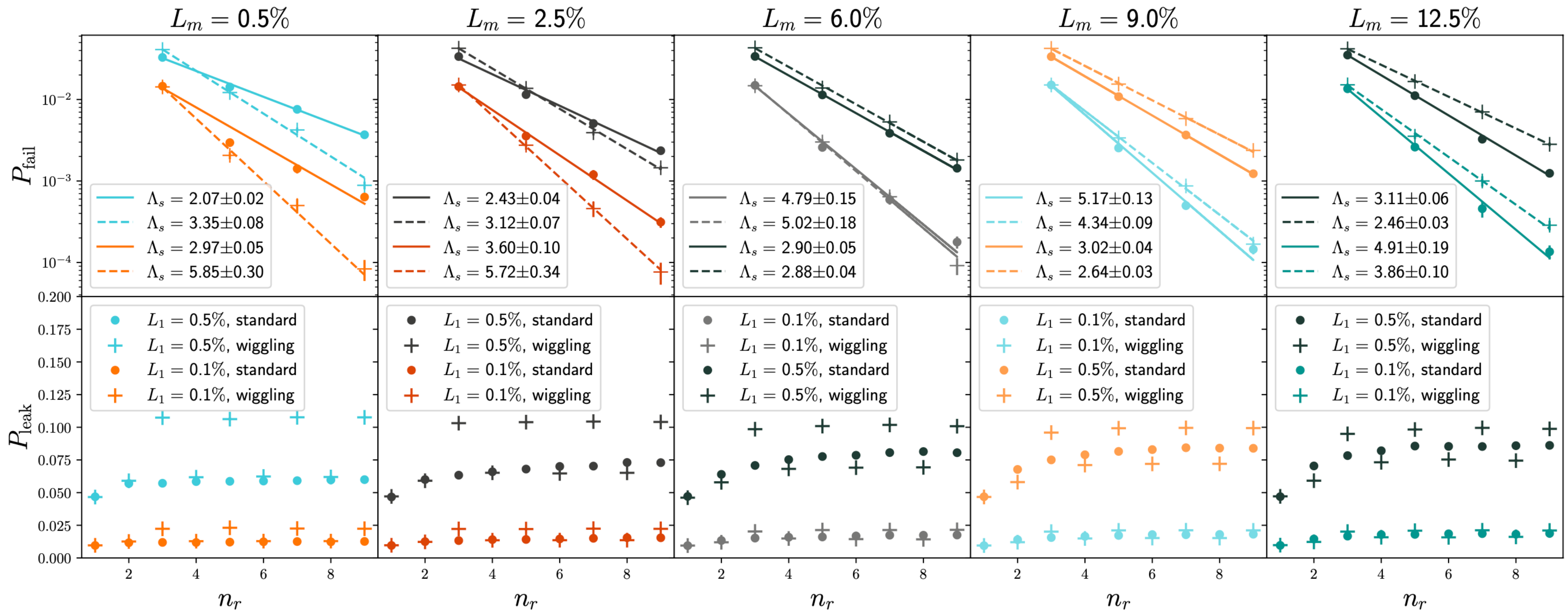
Additional results for 2x4 rotated patch







Additional results for 3x3 unrotated patch