Fault-tolerant measurement-free quantum error correction with multiqubit gates

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Mark Saffman, and Robert Joynt

Phys. Rev. A **108**, 062426 (2023)

Infleqtion

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Motivation for measurement-free quantum error correction with neutral atoms:

Mid-circuit measurements ***were*** not ideal:

fidelity ~95%

Data qubit idling fidelity during ancilla measurement ~97%

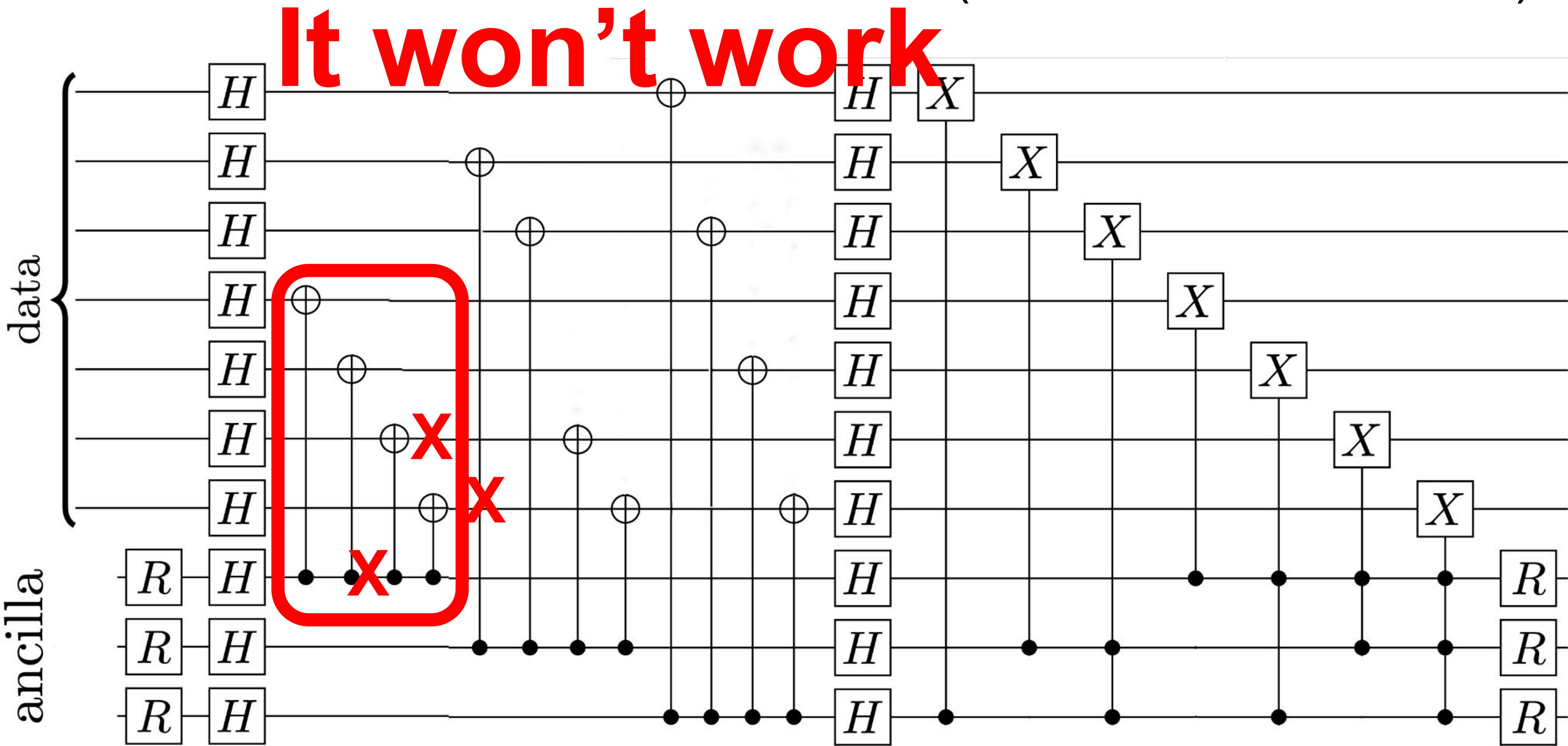
Phys. Rev. X **13**, 041051 (2023)

Parallel 2-qubit gate fidelity ~99.5%

Nature 622, 268-272 (2023)

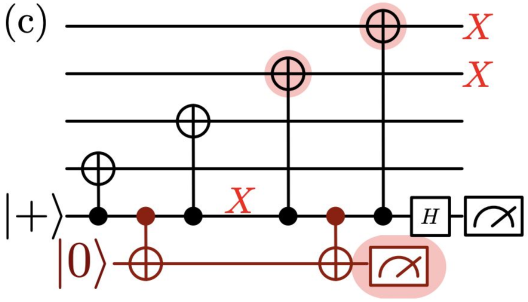
We studied measurement-free Steane code:

Naive measurement-free Steane code (X correction subcircuit)



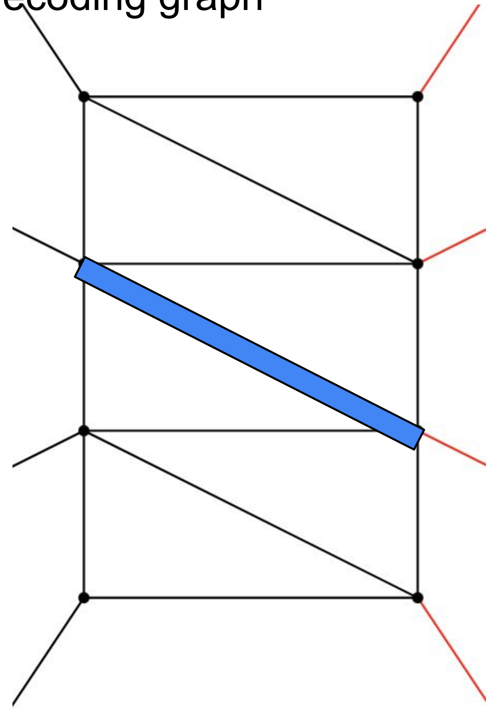
Fault-tolerance of syndrome extraction

1) Flag qubits

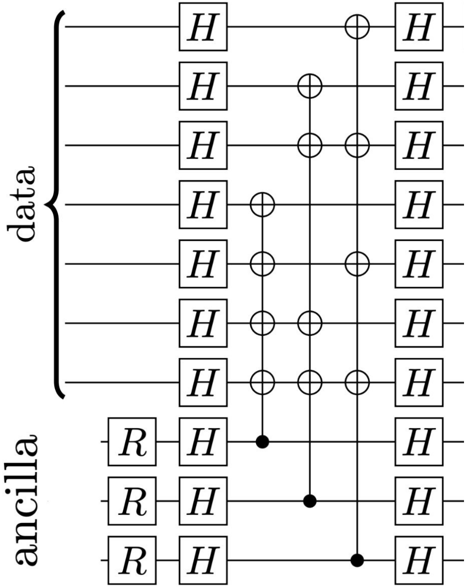


PRX Quantum **1**, 010302 (2020)

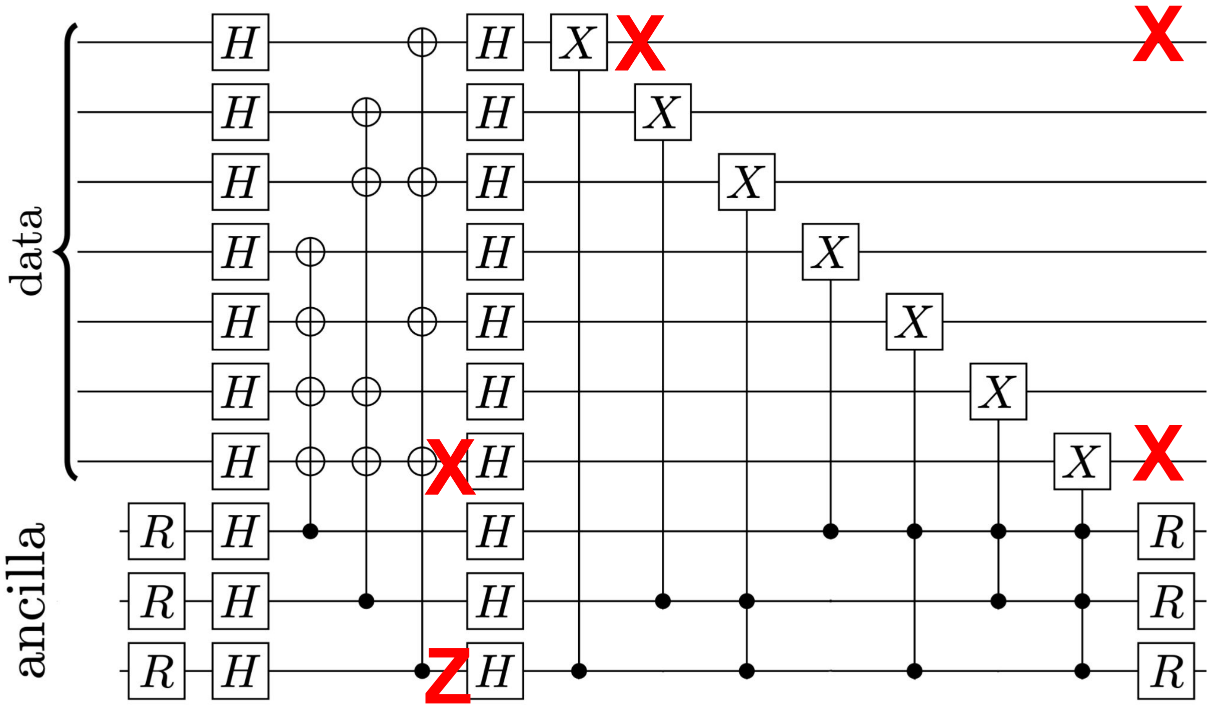
2) Space-and-time edge in decoding graph



3) (Assuming no weight-2 error on target qubits)
Single-control-multi-target gates

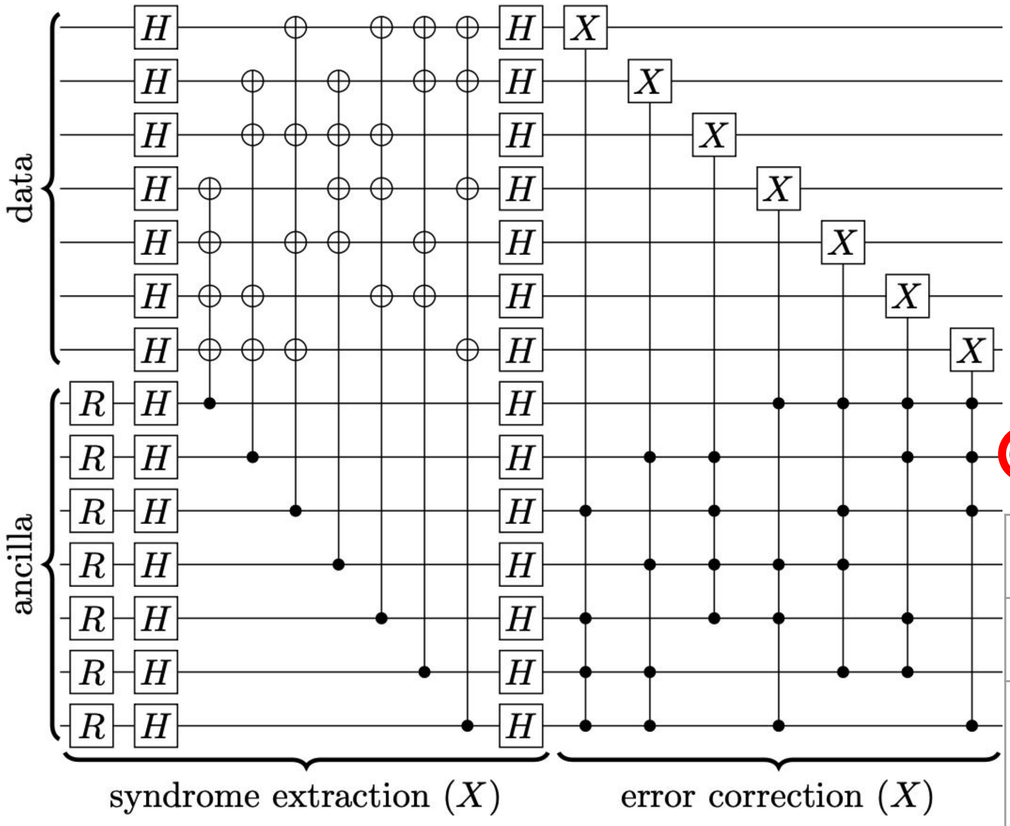


circuit still fragile!



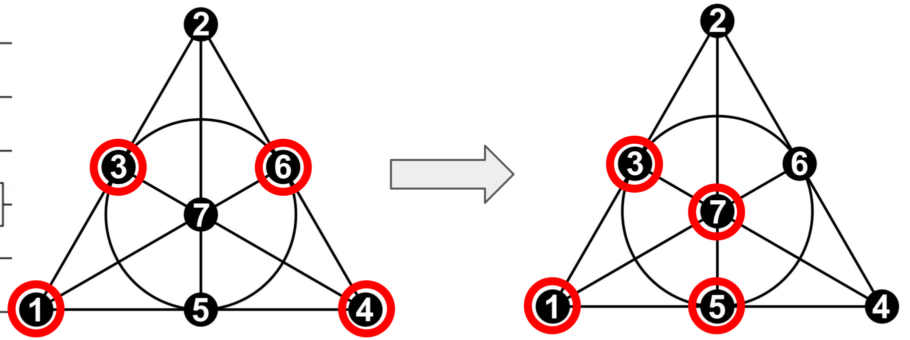
Weight-1 data qubit error +
ancilla error

Ingredient 2: Redundant syndrome



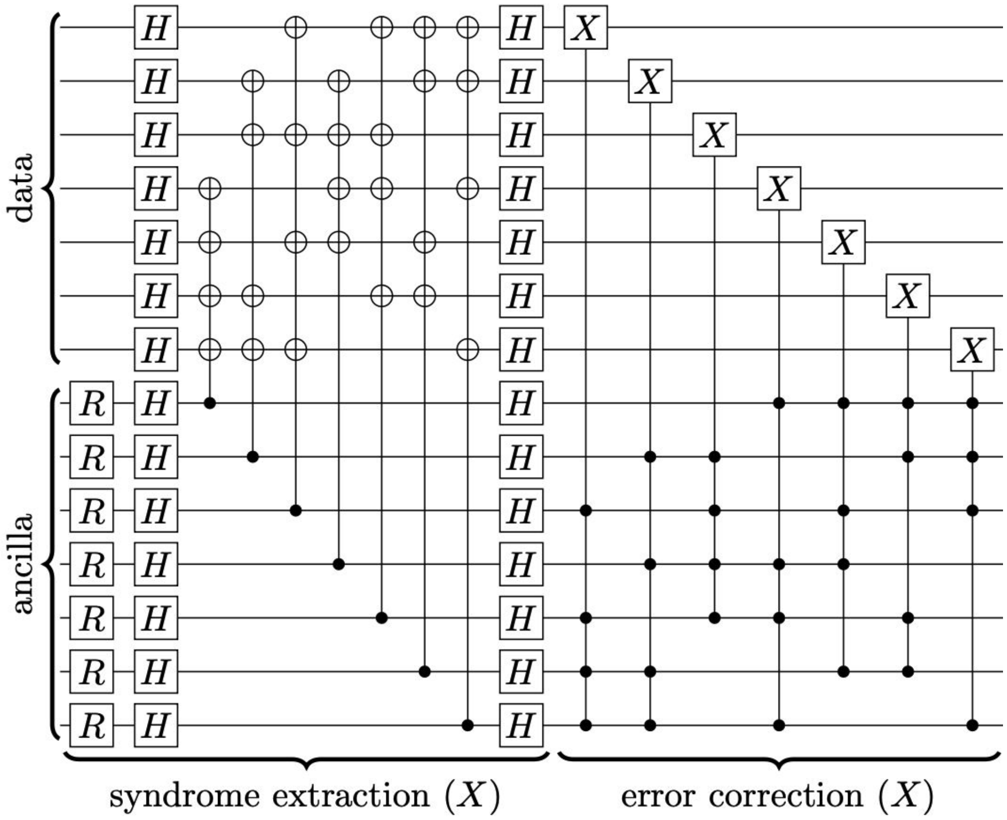
Design-Based-Redundancy (DBR) from combinatorial theory

Quantum Inf Process Vol 20, 84, (2021)



	Original	DBR
Stabilizer qubits	2 x 3	2 x 7
Syndrome hamming distance	1	2 (C_4X) (studied) 4 (C_6X)

Strong circuit! But how can we simulate it?



**14 qubits,
multi-qubit gates
are non-clifford**

For measurement based quantum error correction simulation:

Stim doesn't do Tableau simulation repeatedly. It does Pauli frame simulation against a reference shot.

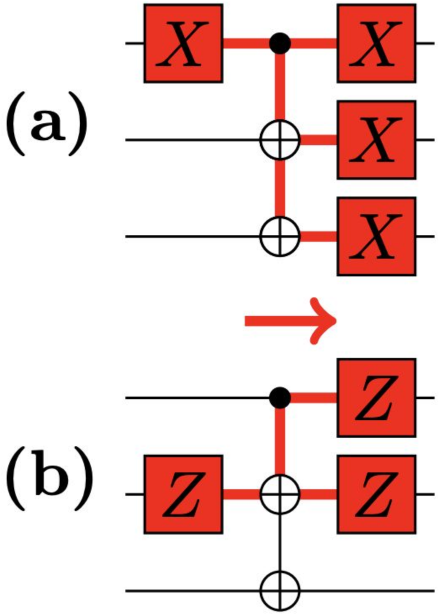
Quantum 5, 497 (2021).

For measurement based quantum computing simulation:

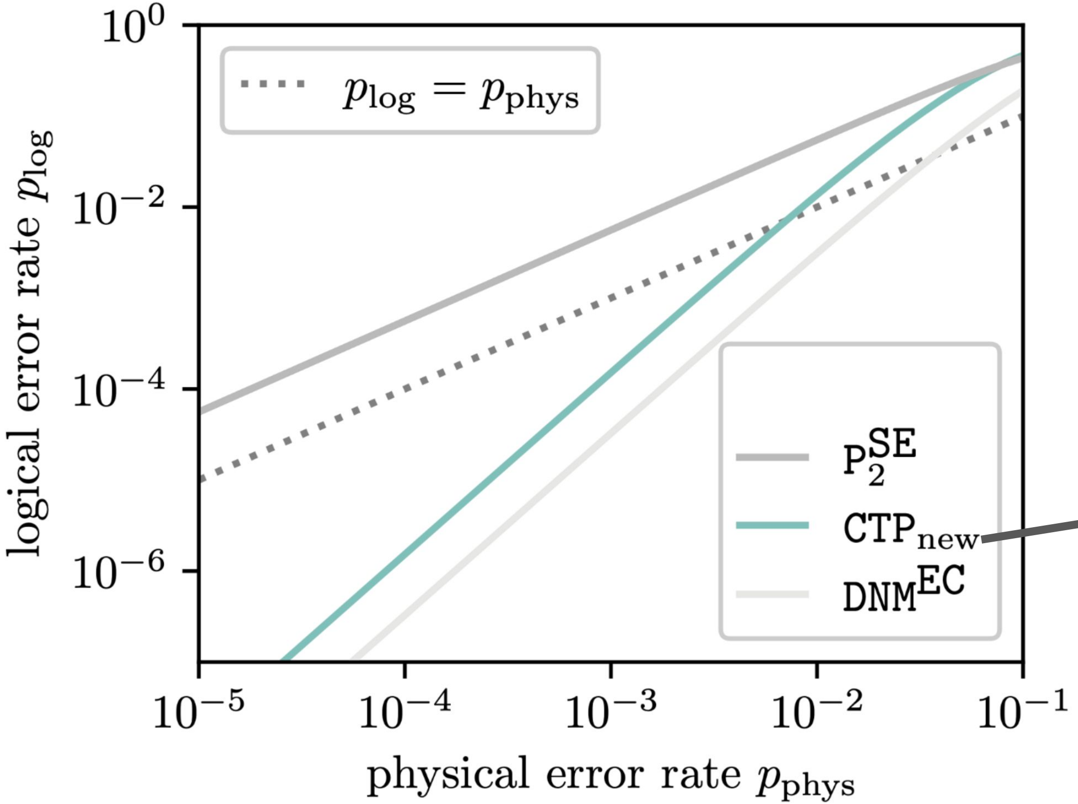
Stim doesn't do Tableau simulation repeatedly. It does Pauli frame simulation against a reference shot.

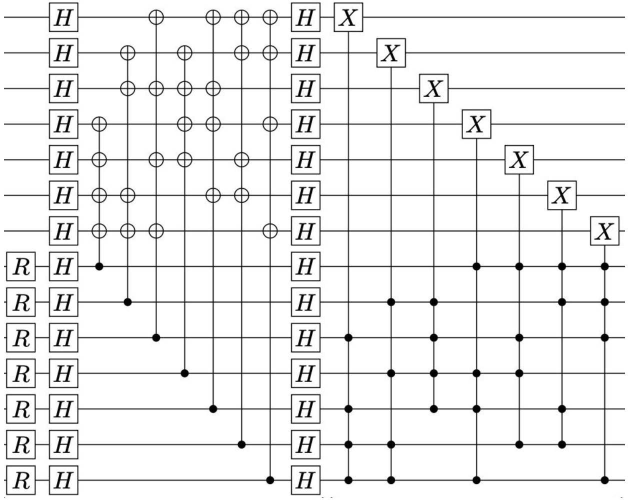
Quantum 5, 497 (2021).

We similarly use propagation rules for Pauli error to track the effect of error



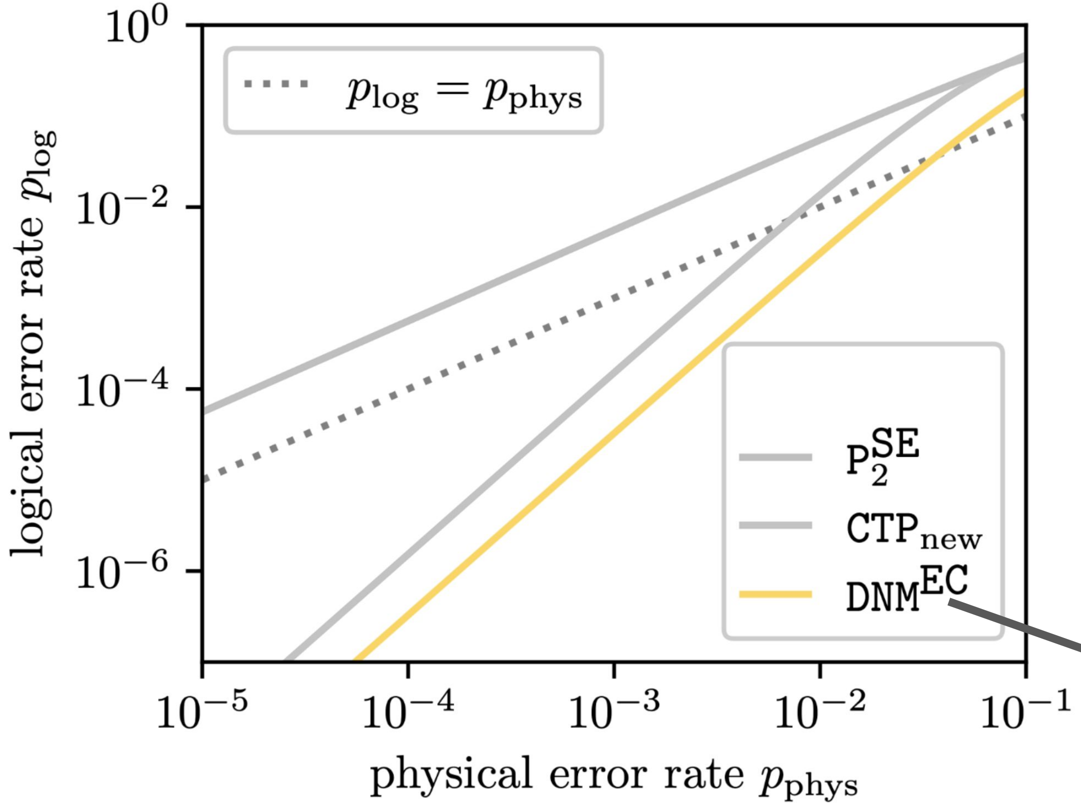
Logical error rates with different multi-qubit gate noise models: noise model 1

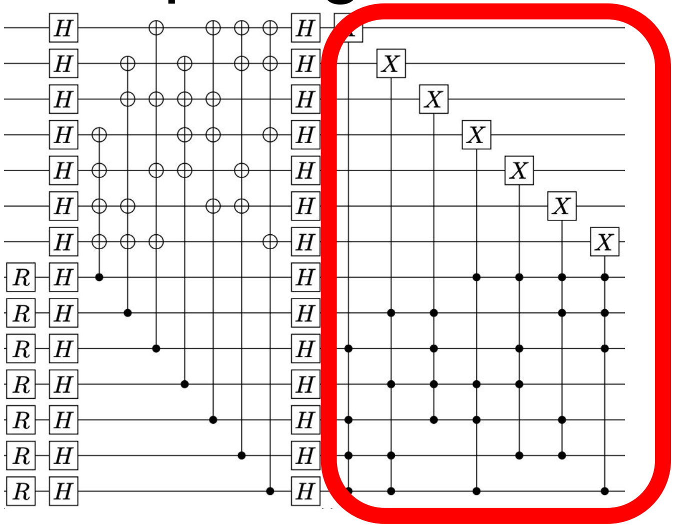




For any CX4, a single 2-qubit depolarization on one of the four **C**ontrol-**T**arget **P**airs

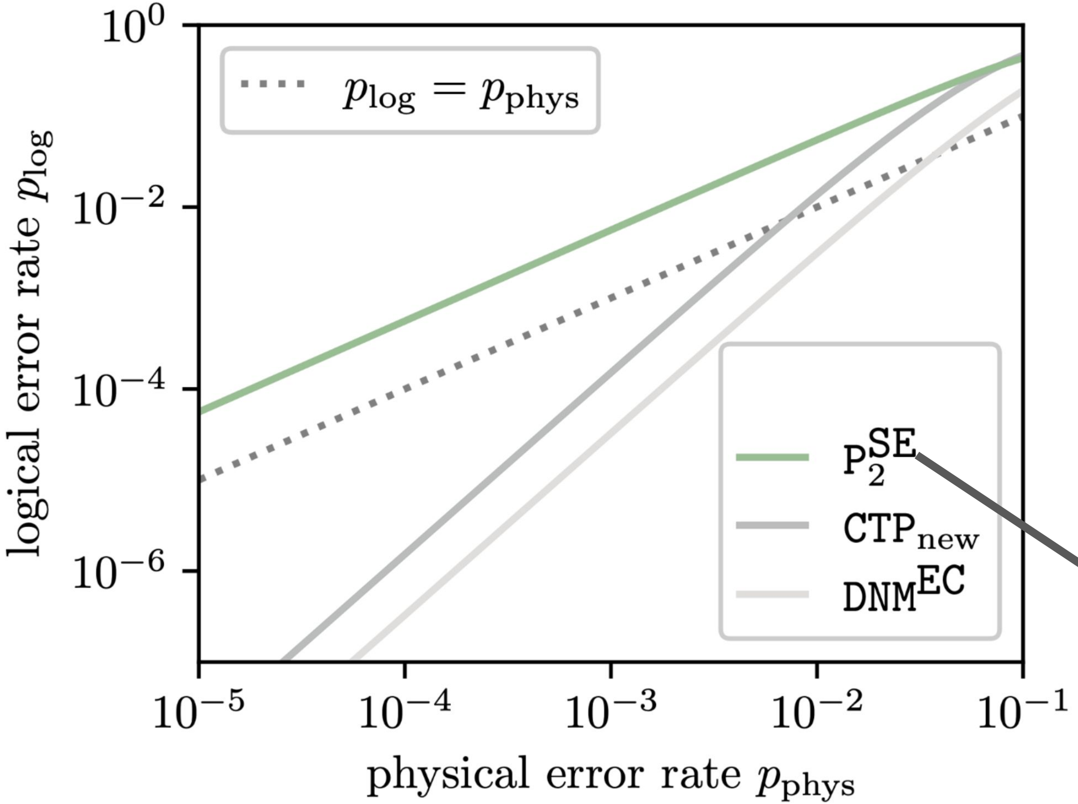
Logical error rates with different multi-qubit gate noise models: noise model 2

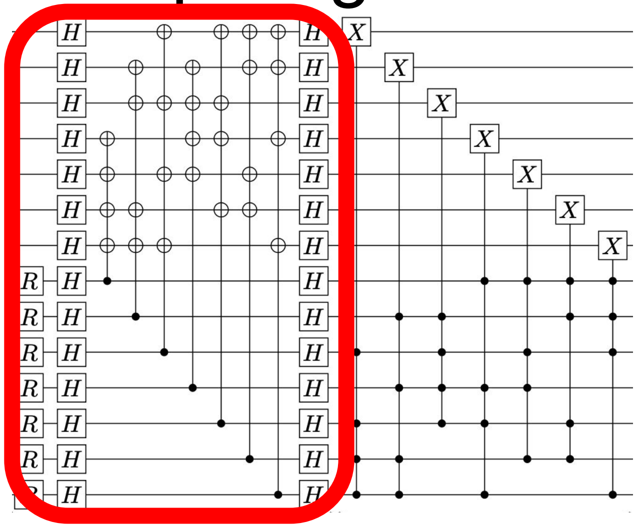




Deplolarizing **N**oise **M**odel: Any Pauli strings on the five qubits, only the **E**rror **C**orrection subcircuit is noisy

Logical error rates with different multi-qubit gate noise models: noise model 3





2-qubit **P**auli errors on any pair of qubits,
only the **S**yndrome **E**xtraction subcircuit is noisy

Finding gate implementation

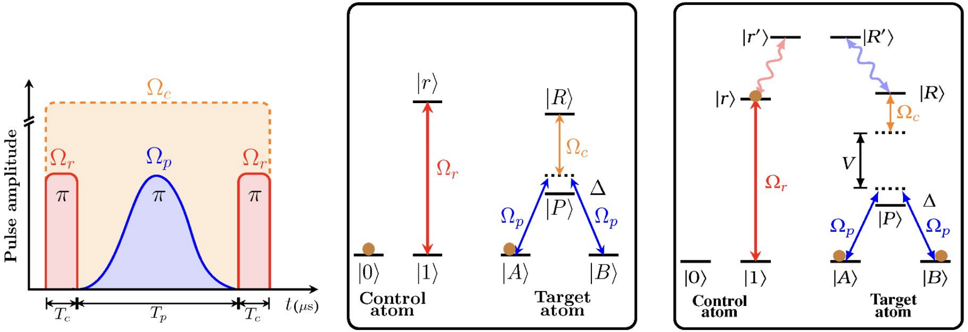
Target-target coupling can be suppressed, via:

1) Heteronuclear architecture

Photonics **2023**, *10*(11), 1280

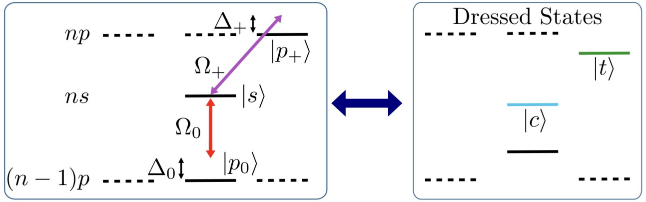
2) Microwave dressing to cancel target-target interaction

Phys. Rev. Lett. **127**, 120501 (2021)



(**a**) Sequence of pulses (**b**) No transfer scheme (**c**) Transfer scheme

Photonics **2023**, *10*(11), 1280



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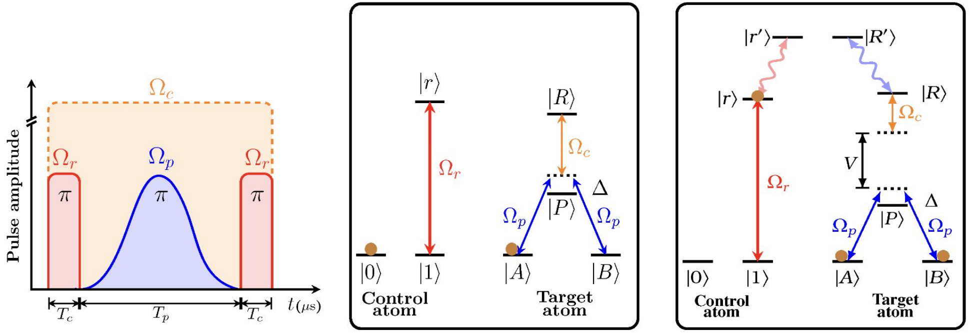


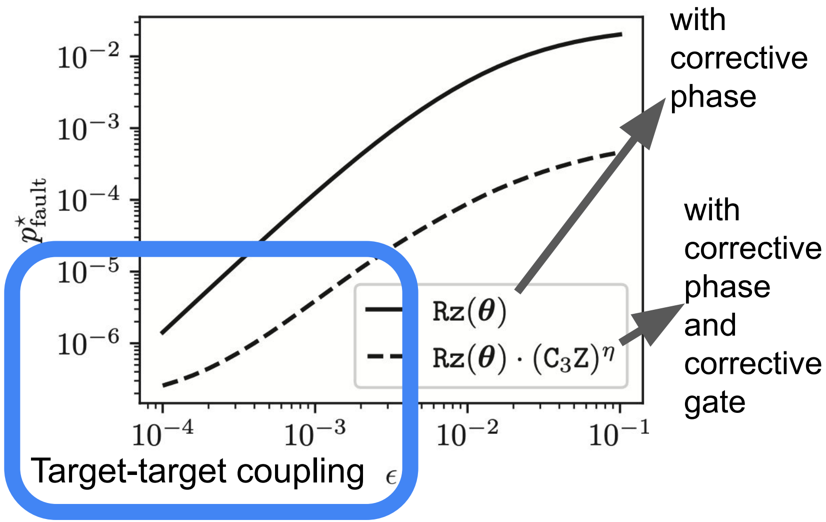
(**a**) Sequence of pulses (**b**) No transfer scheme (**c**) Transfer scheme

Photonics **2023**, *10*(11), 1280

We simulated this protocol

Phys. Rev. Lett. **127**, 120501 (2021)

Critical fault (XX/ZZ) probability as a function of target-target coupling



Might be good enough

Pauli error probability approximated from a channel:

$$\mathbb{E}_{a,b} \langle a | (\mathcal{P} \circ \mathcal{U} \circ \mathcal{U}_0^{-1})(|a\rangle\langle b|) | b \rangle$$

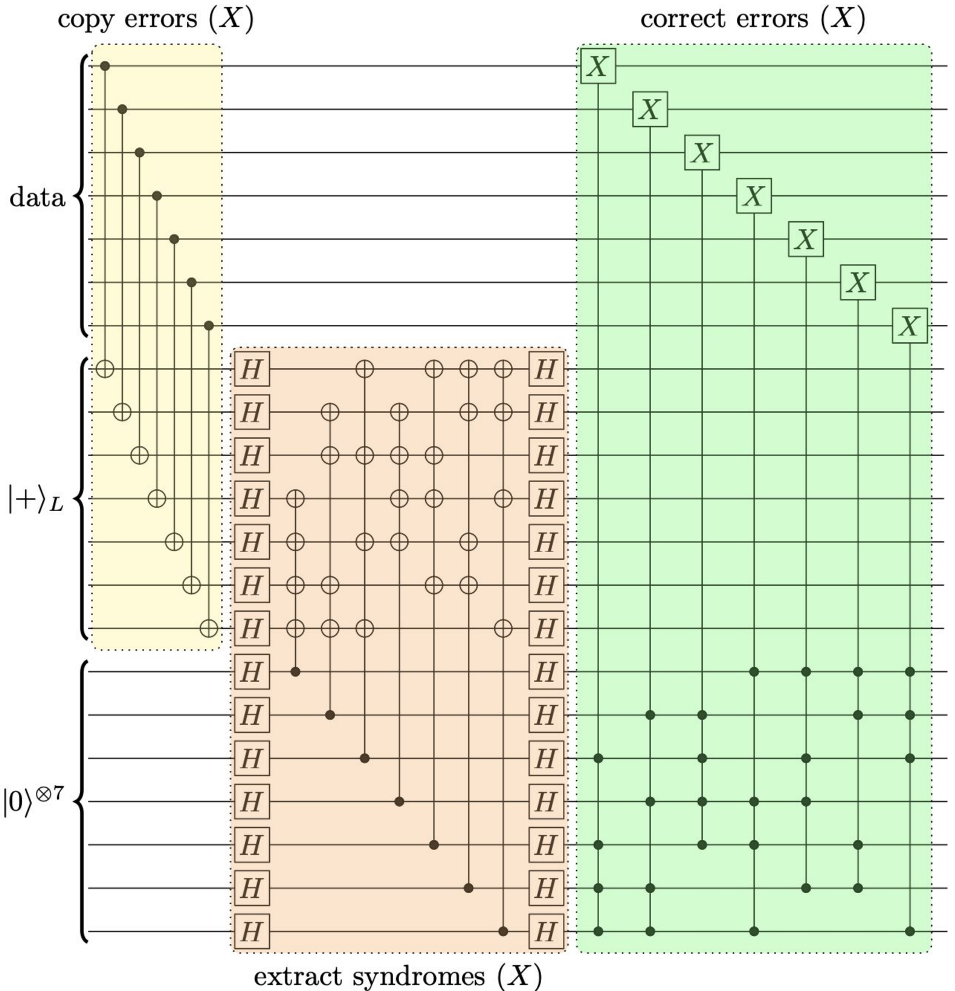
A short note on effective Pauli noise models
Michael A. Perlin
arXiv:2311.09129

With weight-2 error, logical X(Z) gate to “copy” X(Z) error to logical ancilla can restore FT

pseudothreshold ~0.1%

“copy” first proposed in

PRX Quantum **5**, 010333 (2024)



Conclusion:

Measurement free QEC with good threshold with realistic gateset

Outlook:

Measurement-free single-shot fault-tolerance ?