Cycle Error Reconstruction on a Trapped Ion Quantum Computer

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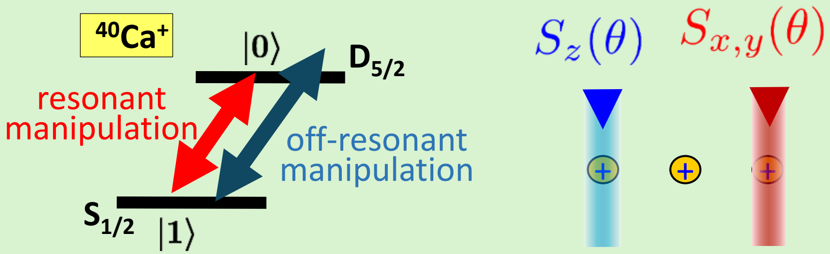
AQTION

Pogorelov, PRX Quantum 2, 020343 (2021)

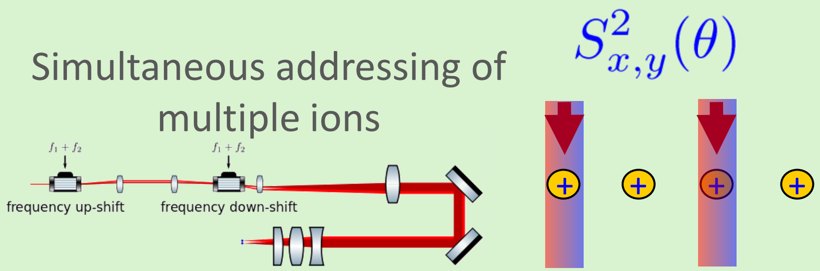
Individual (and parallel) local operations



τ = 20µs
F > 99%

Local Mølmer- Sørensen entangling gate

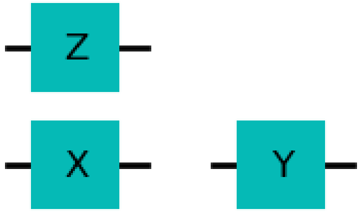
Simultaneous addressing of multiple ions

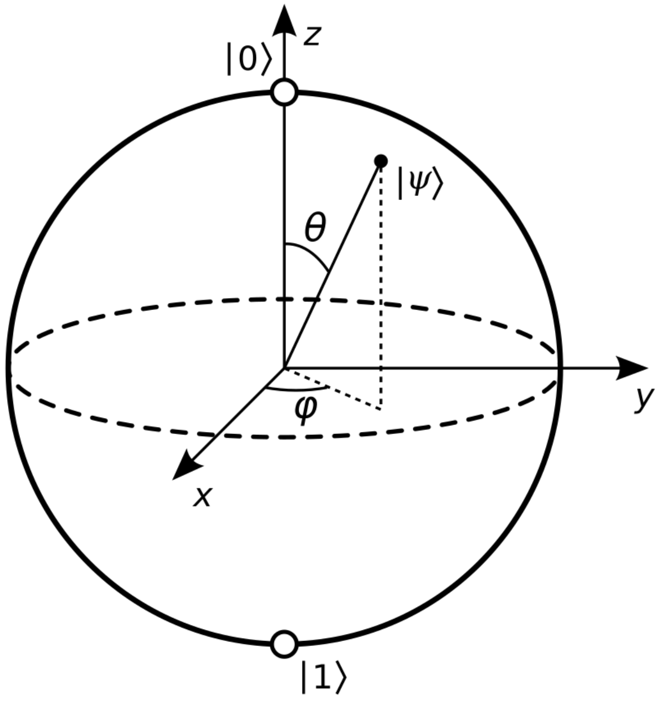


τ = 200µs
F ~ 99%

Single qubit errors e. g.:

- Dephasing (detuning)
- Over/Underrotations





Challenge

- How large are the errors for one gate?
- Where do the errors come from?
- 16 qubit register

Little information

Few measurements

All information

Many measurements

Outline

1. Characterization of Errors
    - Randomized benchmarking
    - Quantum Process Tomography
2. Noise
    - Description
    - Characterization
3. Cycle Error reconstruction
    - Method
    - Results
4. Summary and Outlook

Characterization of Errors

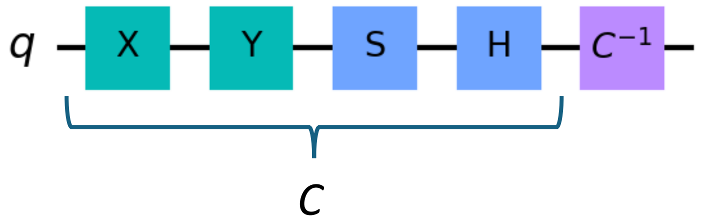
Knill, Phys. Rev. A 77, 012307 (2008)

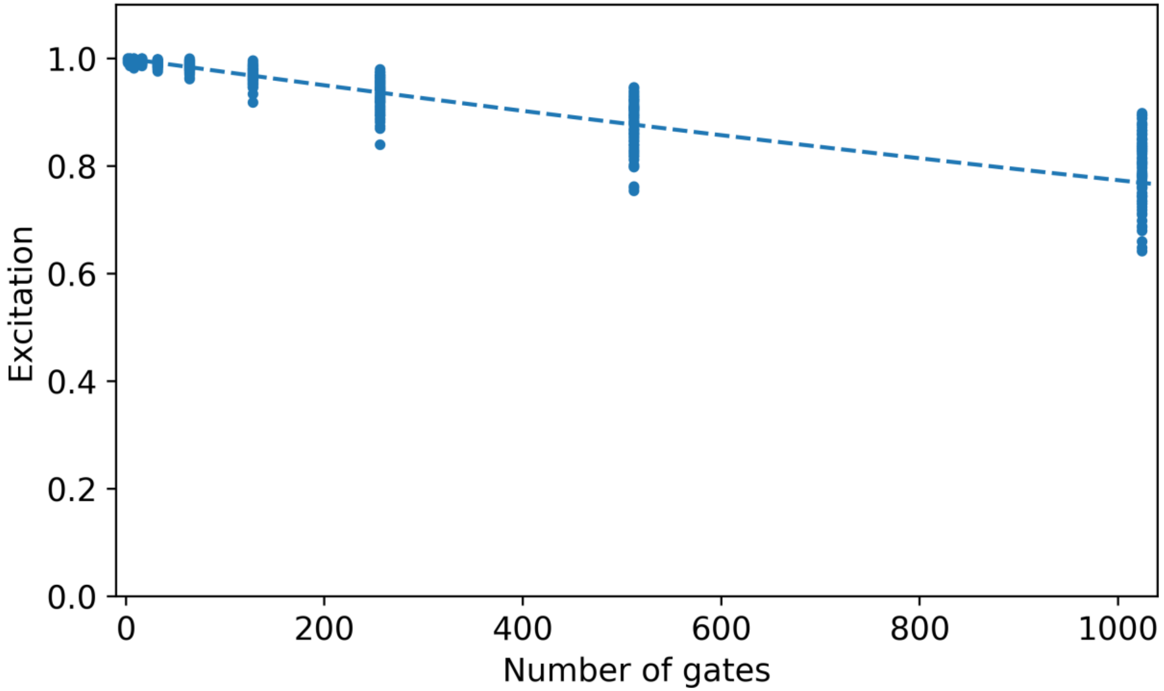
Randomized Benchmarking:

- Magnify error by repetitions
- Draw random Clifford gates
- Robust to SPAM
- Around 100 measurements per length

Disadvantages:

- Extract average error per Clifford gate
- No information about origin
- N-qubit Clifford gates needs to decompose into 2-qubit gates

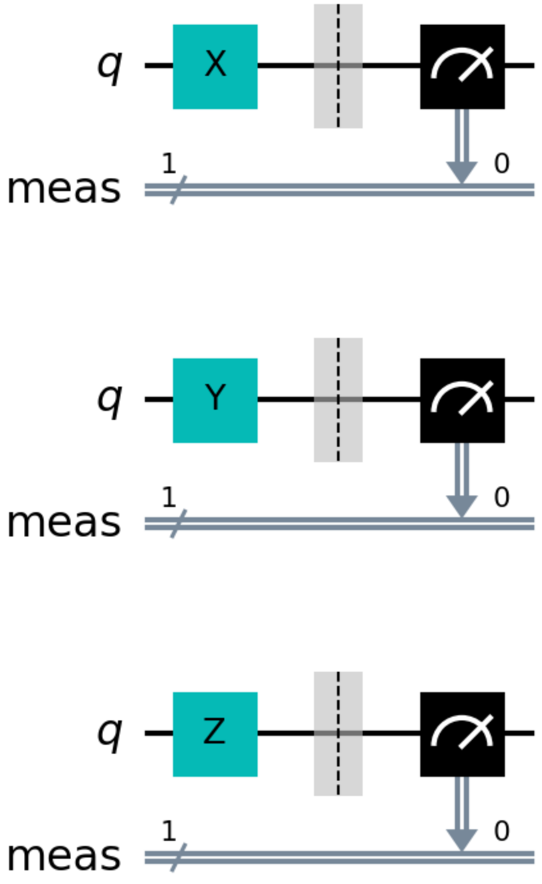




Characterization of Errors

Quantum Process Tomography:

- Determine state after process for each basis state
- Extract full information



Disadvantages:

- Measurements $\propto \exp(N)$
- Not feasible for more than 3 qubits
- Not robust to SPAM

Noise

Completely-positive trace-preserving (CPTP) maps:

$$\rho \rightarrow \varepsilon(\rho)$$

Written in Pauli transfer matrix:

$$\varepsilon(\rho) = S_\varepsilon \, |\rho\rangle\rangle \qquad \text{with} \qquad |\rho\rangle\rangle = \begin{pmatrix} 1 \\ < X > \\ < Y > \\ < Z > \end{pmatrix}$$

Examples:

$$S_H = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix} \qquad S_X = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix} \qquad S_Z = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}$$

Noise

Arbitrary single-qubit pauli channel:

$$S = (1 - p_x - p_y - p_z)S_I + p_x S_X + p_y S_Y + p_z S_z$$

$$S = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 - 2p_x - 2p_y & 0 & 0 \\ 0 & 0 & 1 - 2p_y - 2p_z & 0 \\ 0 & 0 & 0 & 1 - 2p_z - 2p_x \end{bmatrix}$$

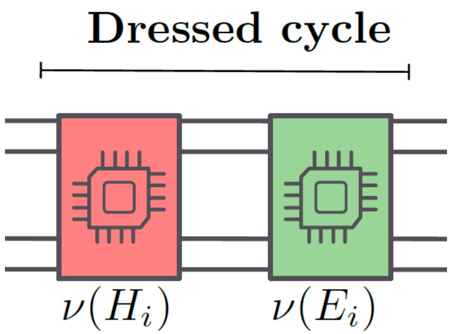
$$\lambda_{P_i} = \sum_j (-1)^{\omega(P_i, P_j)} p_j$$

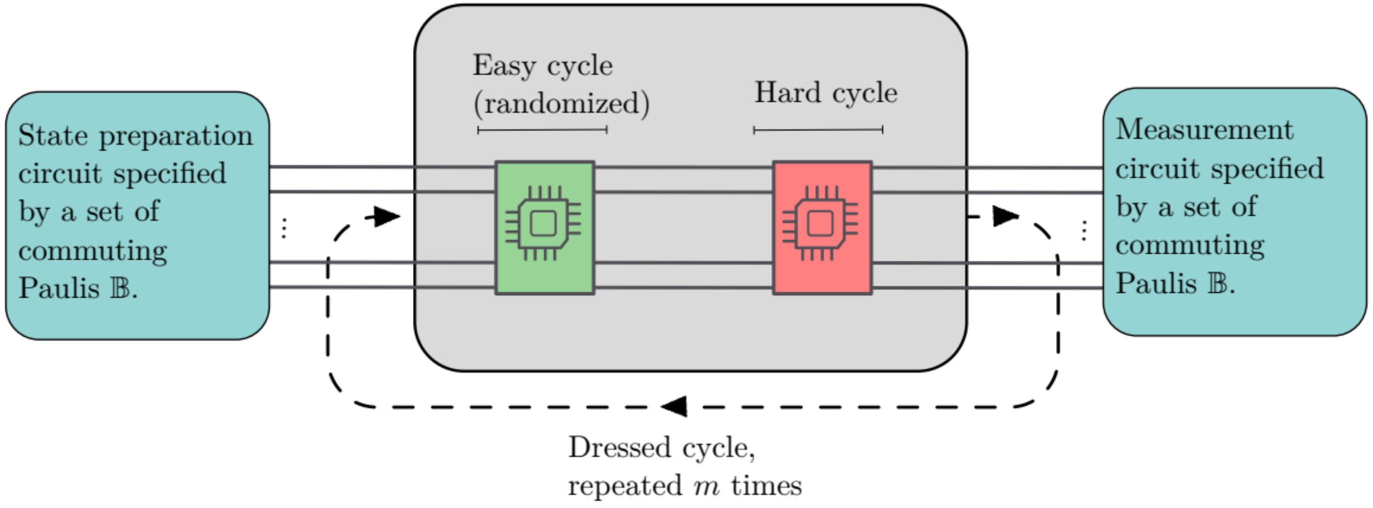
Three initial states needed to extract p_x, p_y, p_z.

Cycle Error Reconstruction

Carignan-Dugas et al, arXiv: 2303.17714

- Randomized compiling transforms arbitrary noise channel to Pauli error channel
- Robust to state preparation and measurement errors (SPAM)
- Magnify error rate of hard cycle by repititons

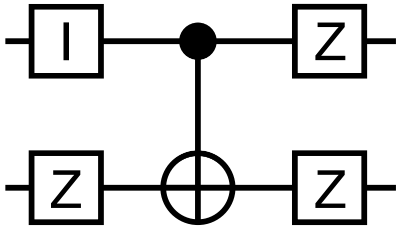




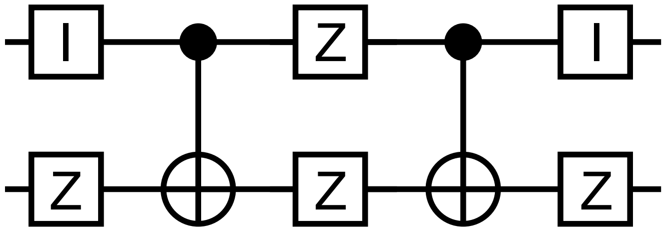
Cycle Error Reconstruction

Repetition comes with a drawback: Orbits

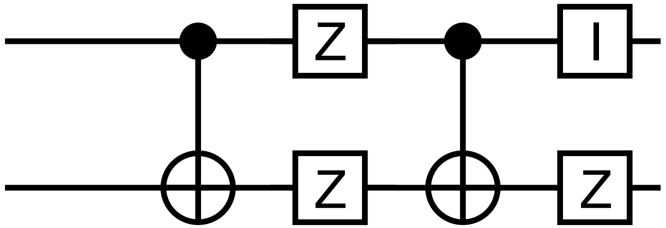
IZ turns to ZZ



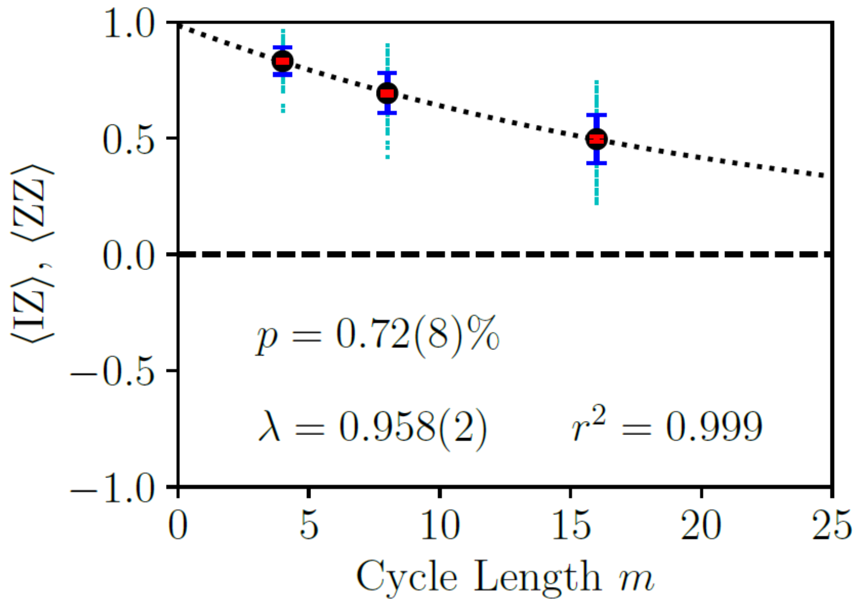
Same result from



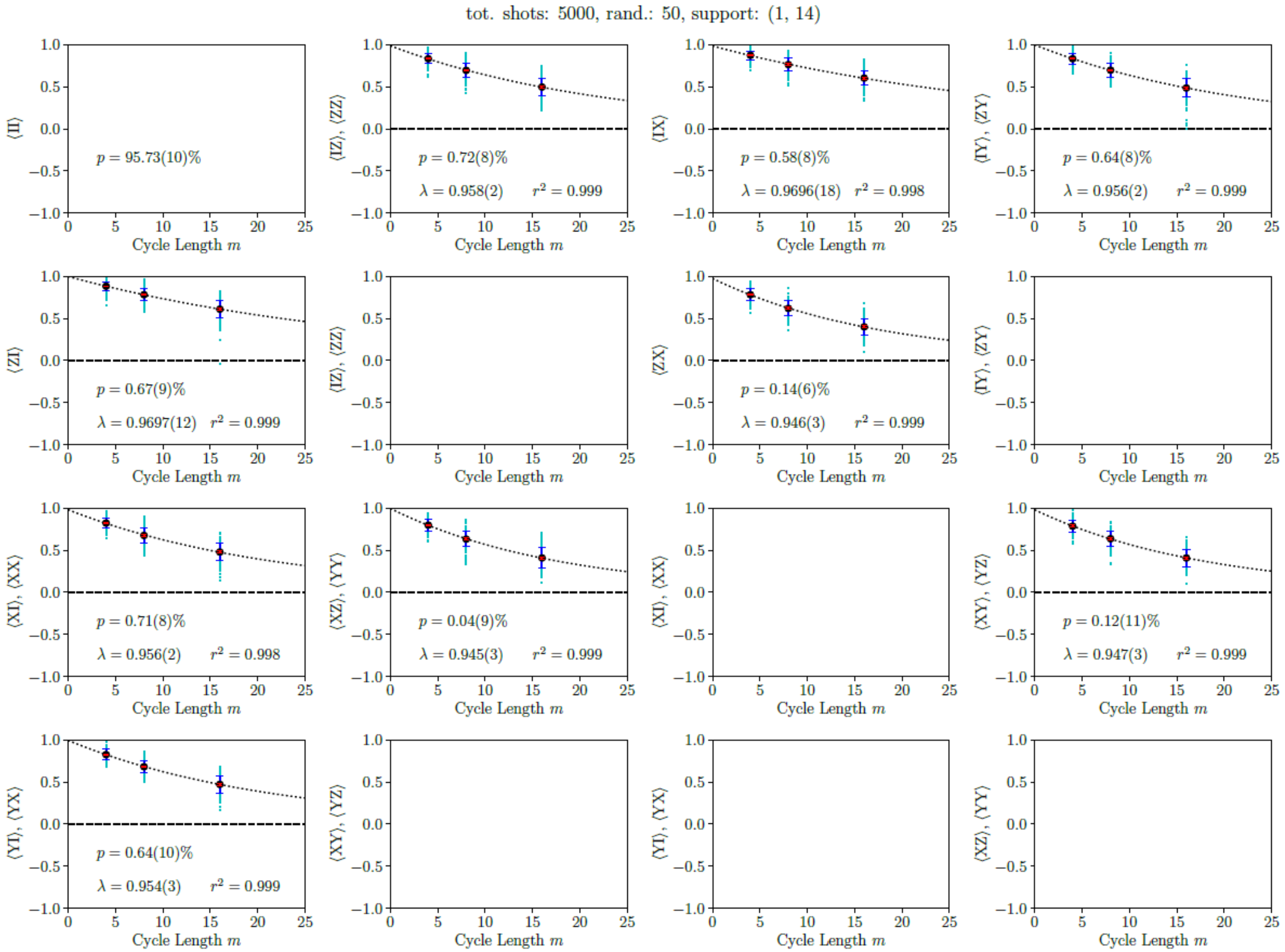
Instead of



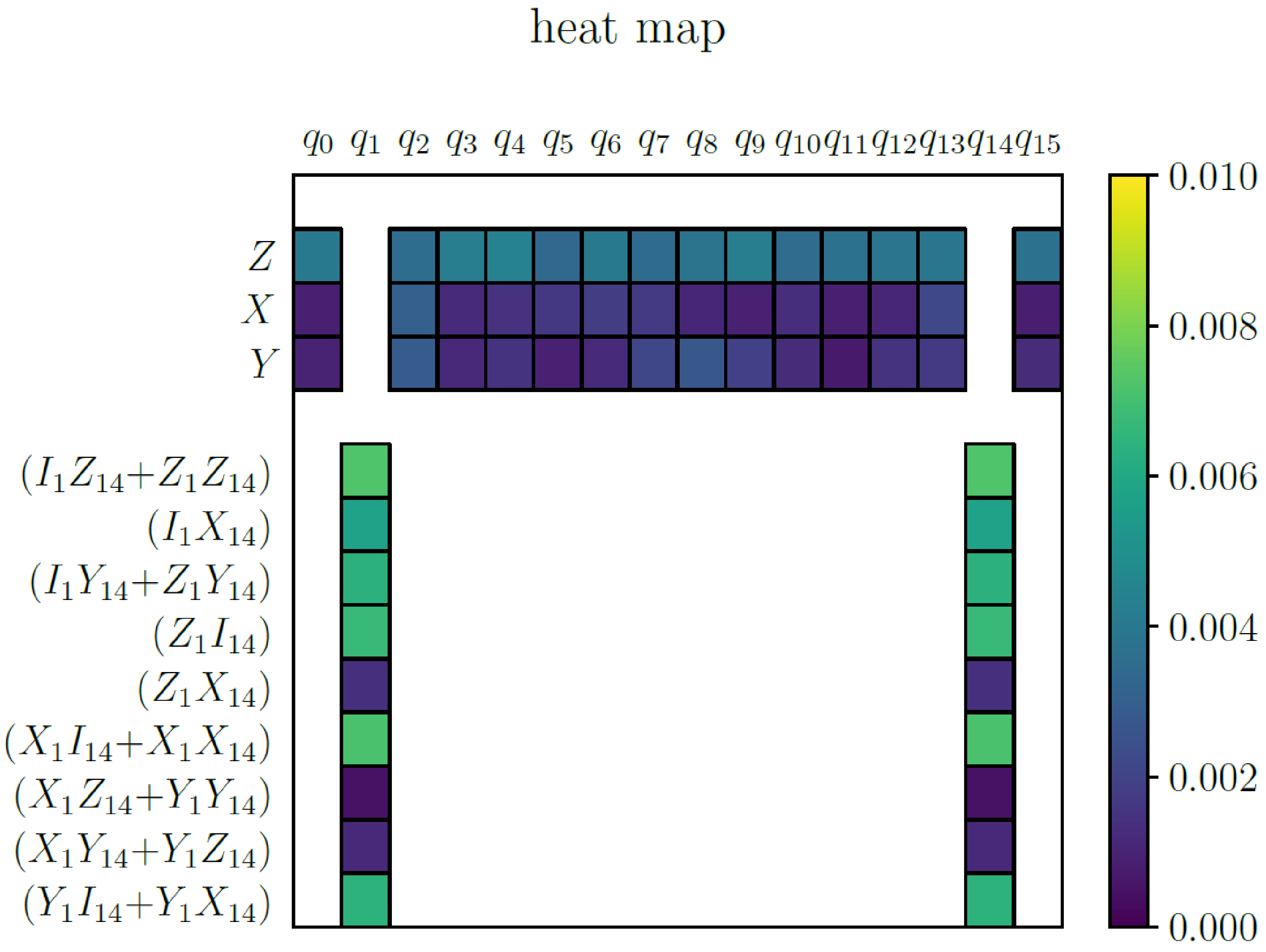
Marginal per orbit:



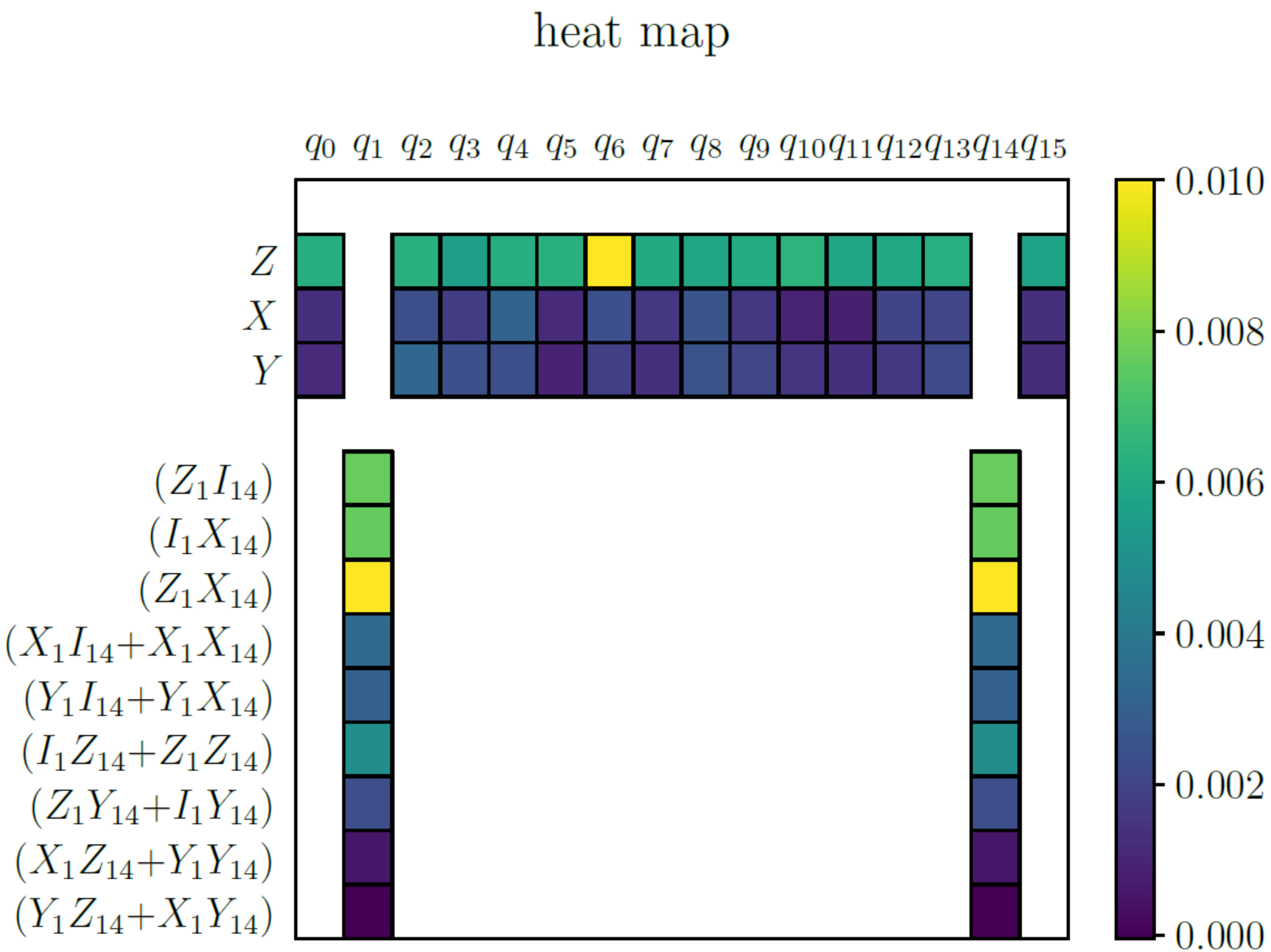
Cycle Error Reconstruction



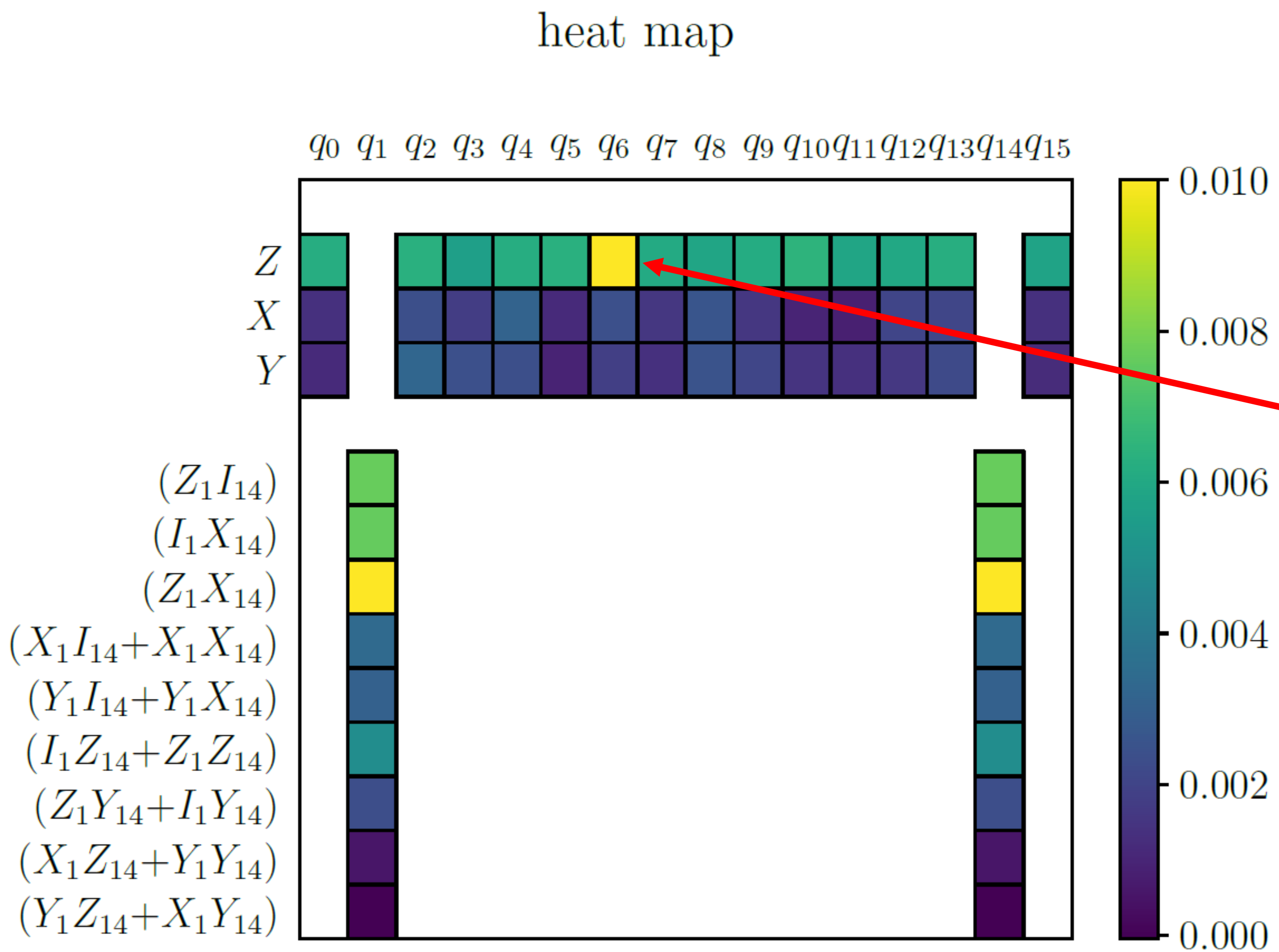
Cycle Error Reconstruction

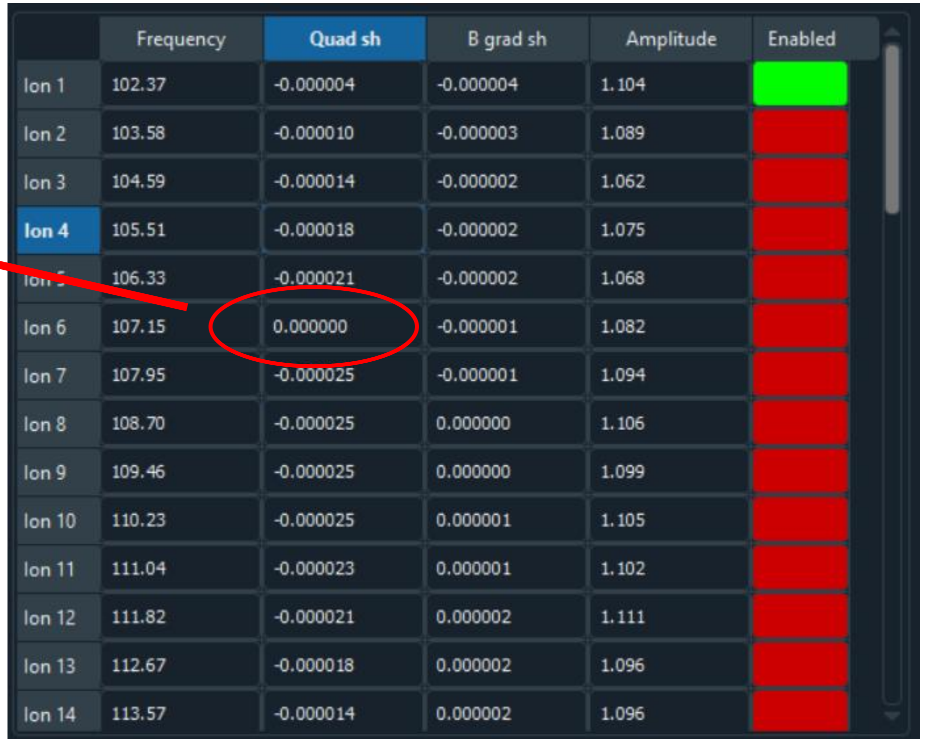


Cycle Error Reconstruction



Cycle Error Reconstruction





	Frequency	Quad sh	B grad sh	Amplitude	Enabled
Ion 1	102.37	-0.000004	-0.000004	1.104	
Ion 2	103.58	-0.000010	-0.000003	1.089	
Ion 3	104.59	-0.000014	-0.000002	1.062	
Ion 4	105.51	-0.000018	-0.000002	1.075	
Ion 5	106.33	-0.000021	-0.000002	1.068	
Ion 6	107.15	0.000000	-0.000001	1.082	
Ion 7	107.95	-0.000025	-0.000001	1.094	
Ion 8	108.70	-0.000025	0.000000	1.106	
Ion 9	109.46	-0.000025	0.000000	1.099	
Ion 10	110.23	-0.000025	0.000001	1.105	
Ion 11	111.04	-0.000023	0.000001	1.102	
Ion 12	111.82	-0.000021	0.000002	1.111	
Ion 13	112.67	-0.000018	0.000002	1.096	
Ion 14	113.57	-0.000014	0.000002	1.096	

Summary and Outlook

- Advantages of CER over QPT and RB
- Characterization of CNOT including crosstalk (16 qubits)
- Showed utility of CER to determine origin of errors

- Characterize gadgets:
    - 7 CNOTs and 14 qubits
    - CER: around 6000 different sequences
- How do errors scale from 1 CNOT to N-CNOTs?

Towards FT gadget benchmarking

Aim: Benchmark FT gadgets and circuit

A suitable method should:

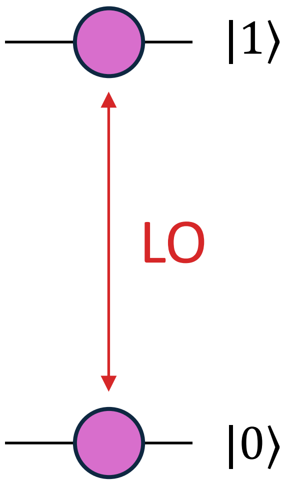
- Not scale (poorly) with the physical gadget size
- Provide contextual information including crosstalk
- Provide diagnostic utility to identify important error channels

RB

QPT, GST

Little information ⟷ All information

Why?



- Quantum Computing
- Oscillator influences fidelity P:

$$P = \frac{1}{2}[1 + e^{-\chi}]$$

$$\chi = \frac{1}{\pi}\sum_j \int_0^\infty \frac{S_j(\omega)}{\omega^2} F_j(\omega)\, d\omega$$

- Spectral density $S_j(\omega)$ and filter function $F_j(\omega)$ for process j

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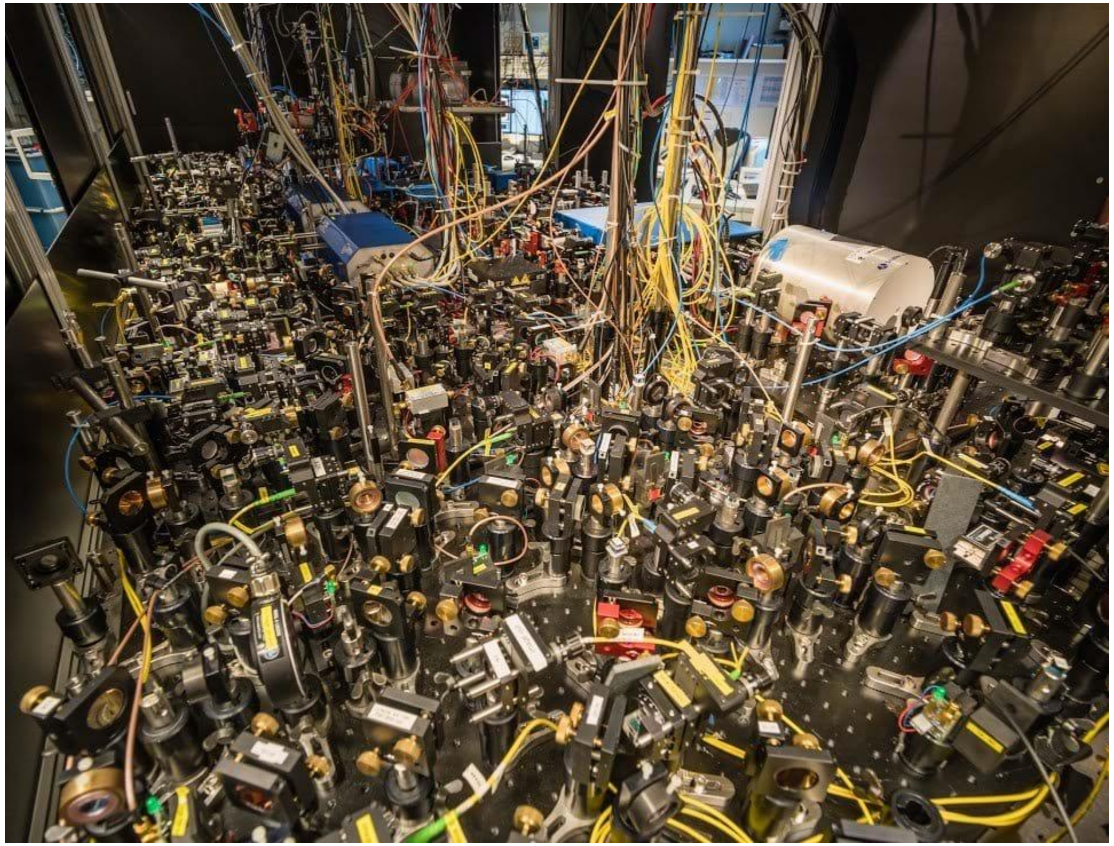
Pogorelov, PRX Quantum 2, 020343 (2021)



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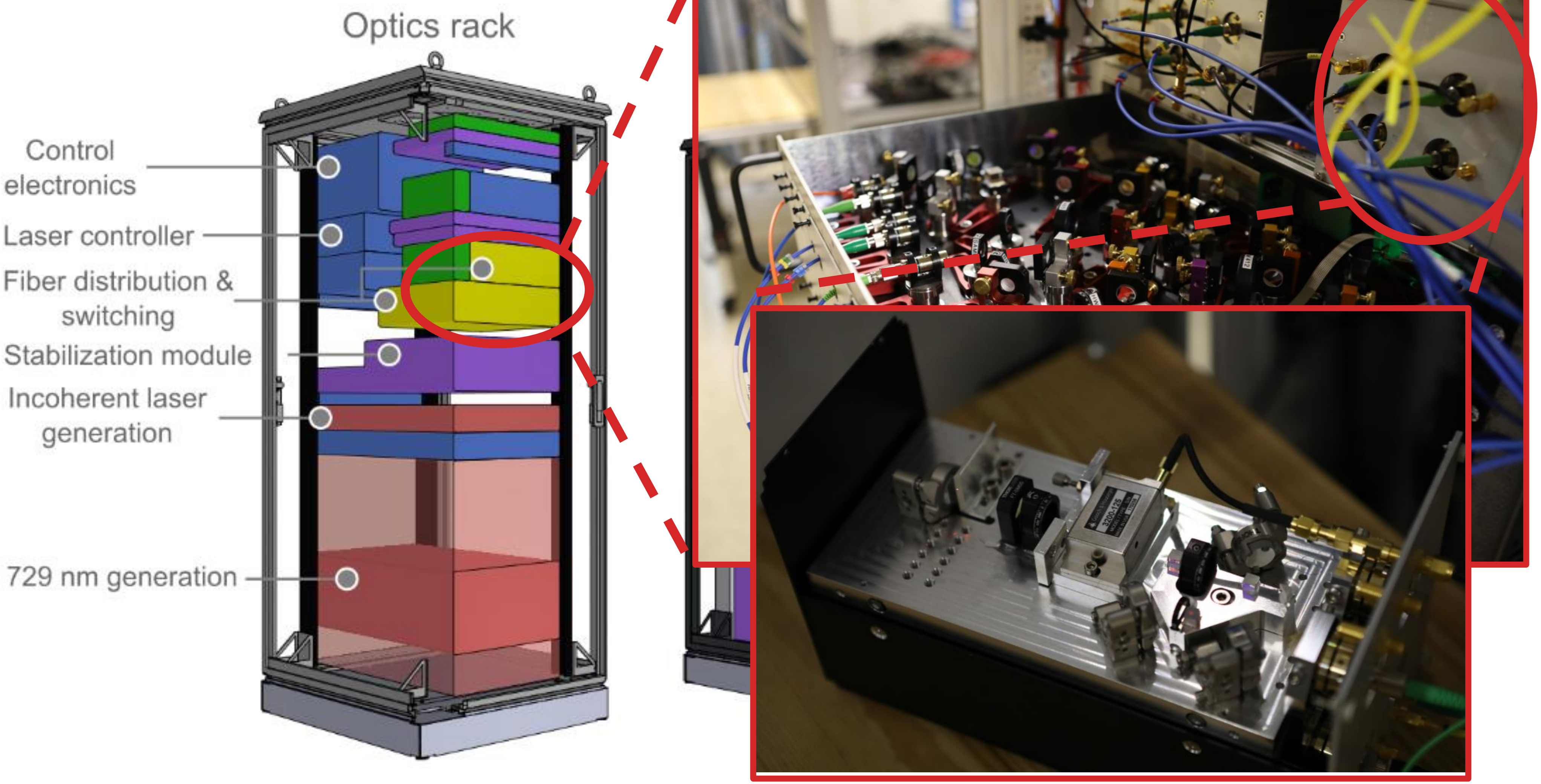

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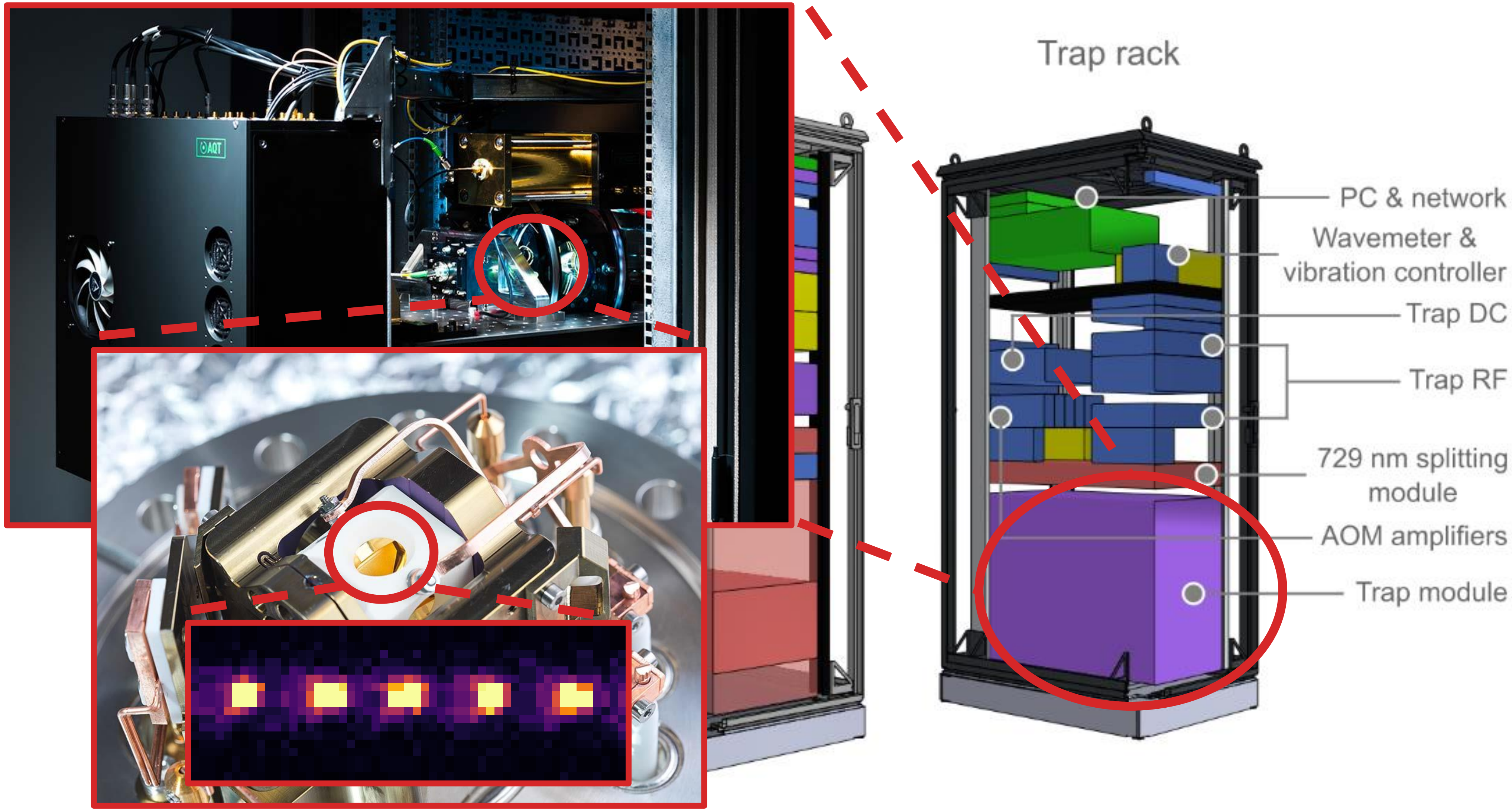
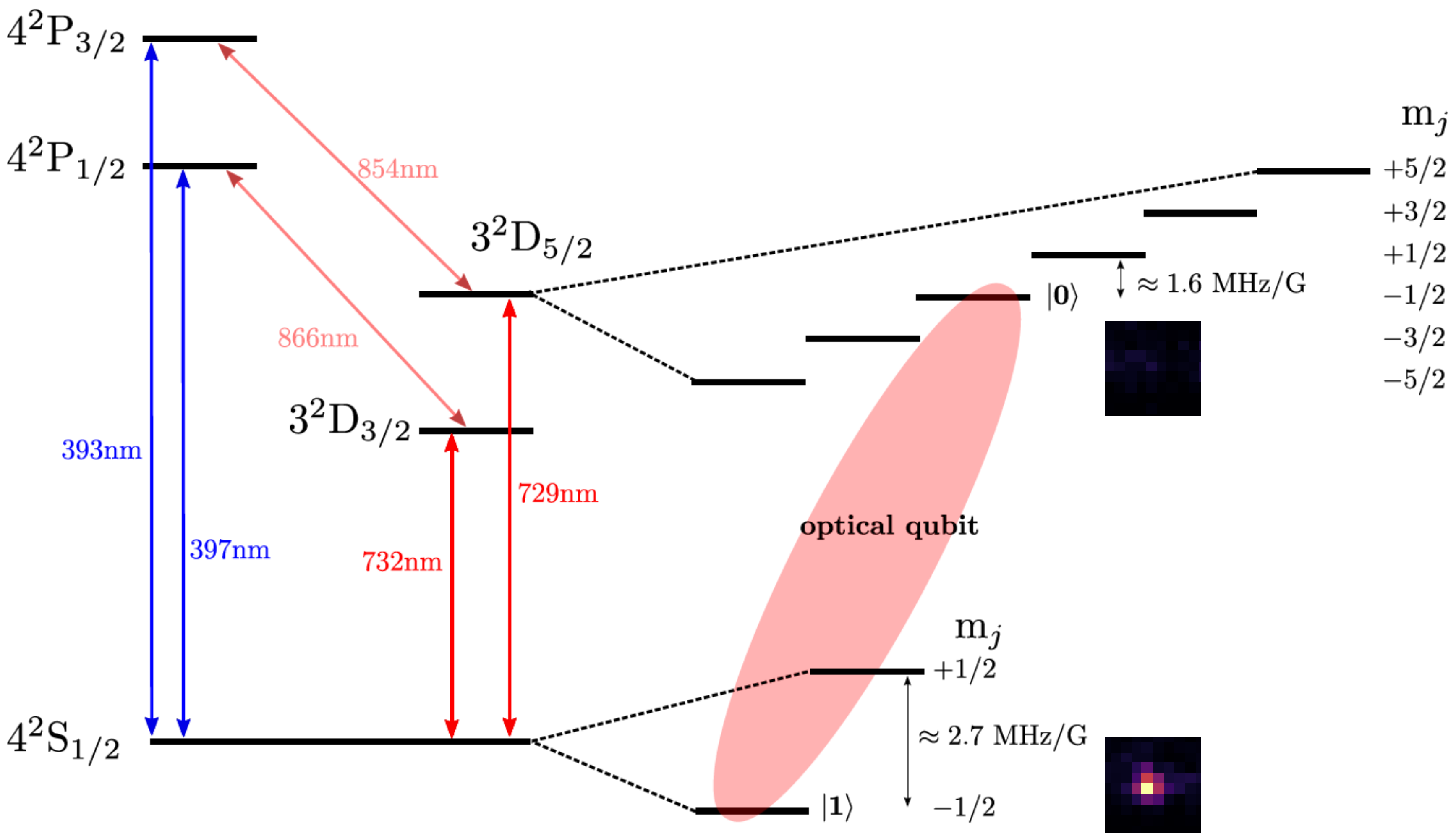


$^{40}Ca^{+}$



Qubit types:

- **Optical**
- Zeeman
- Hyperfine

Errors

General quantum operators are written in completely-positive trace-preserving (CPTP) maps:

Uncoherent Errors:

- sth