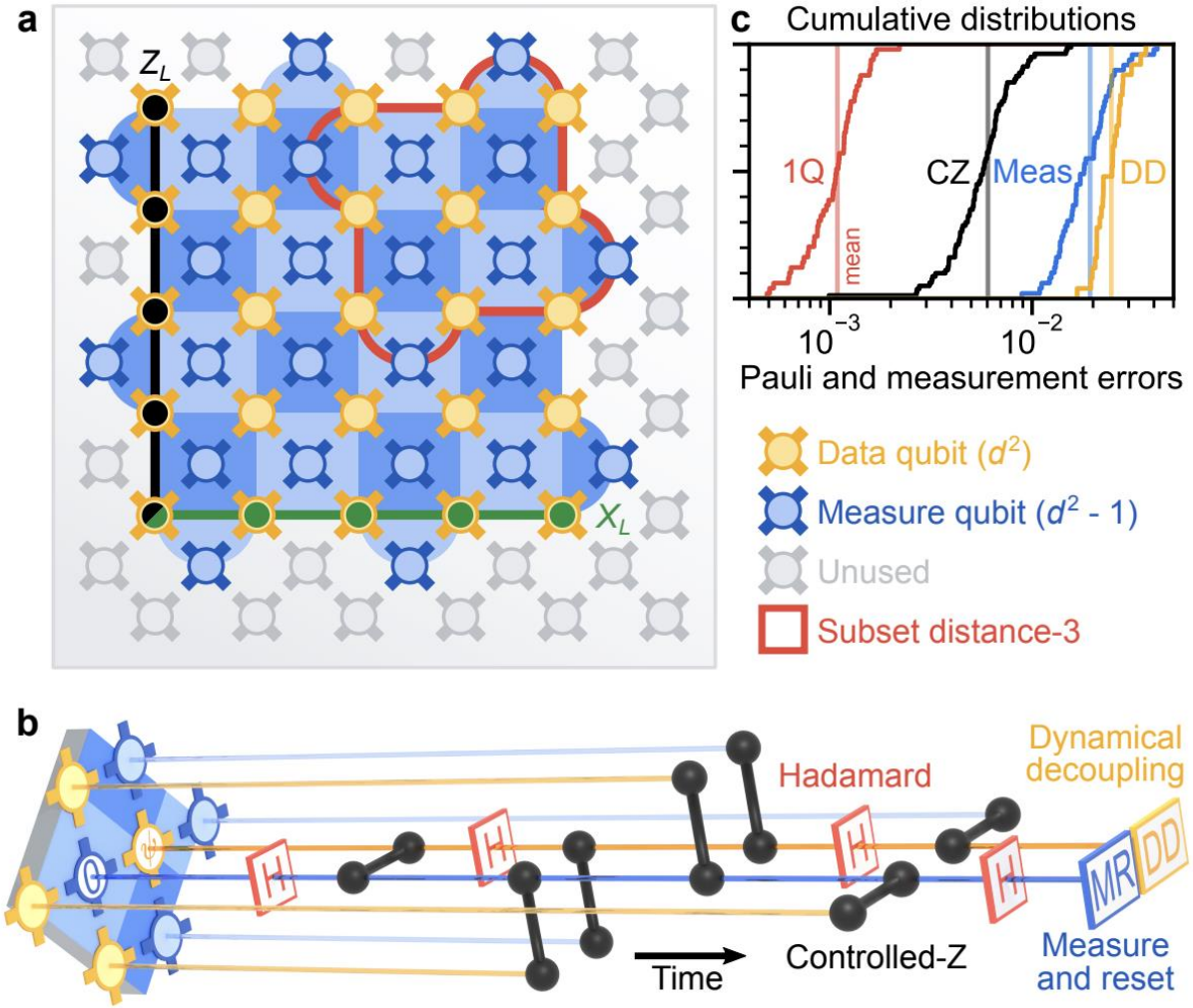


Google Quantum AI, arXiv:2207.06431 (2022)

2023 Sievert Lectures

Quantum Computing in Practice

Daniel Weiss
Yale Quantum Institute

Review of previous lecture

- Gate-model quantum computing

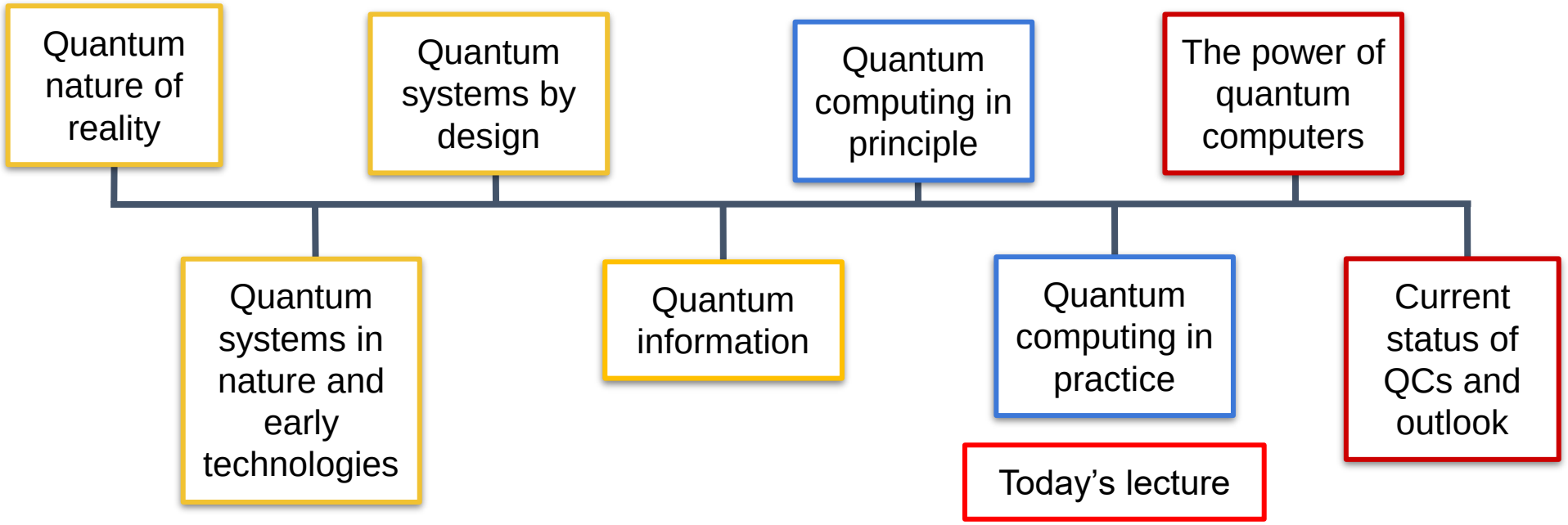
superposition states

quantum algorithms

15 = 3 x 5!!!!

https://www.reddit.com/r/xkcd/n33728/quantum_computing_papers/

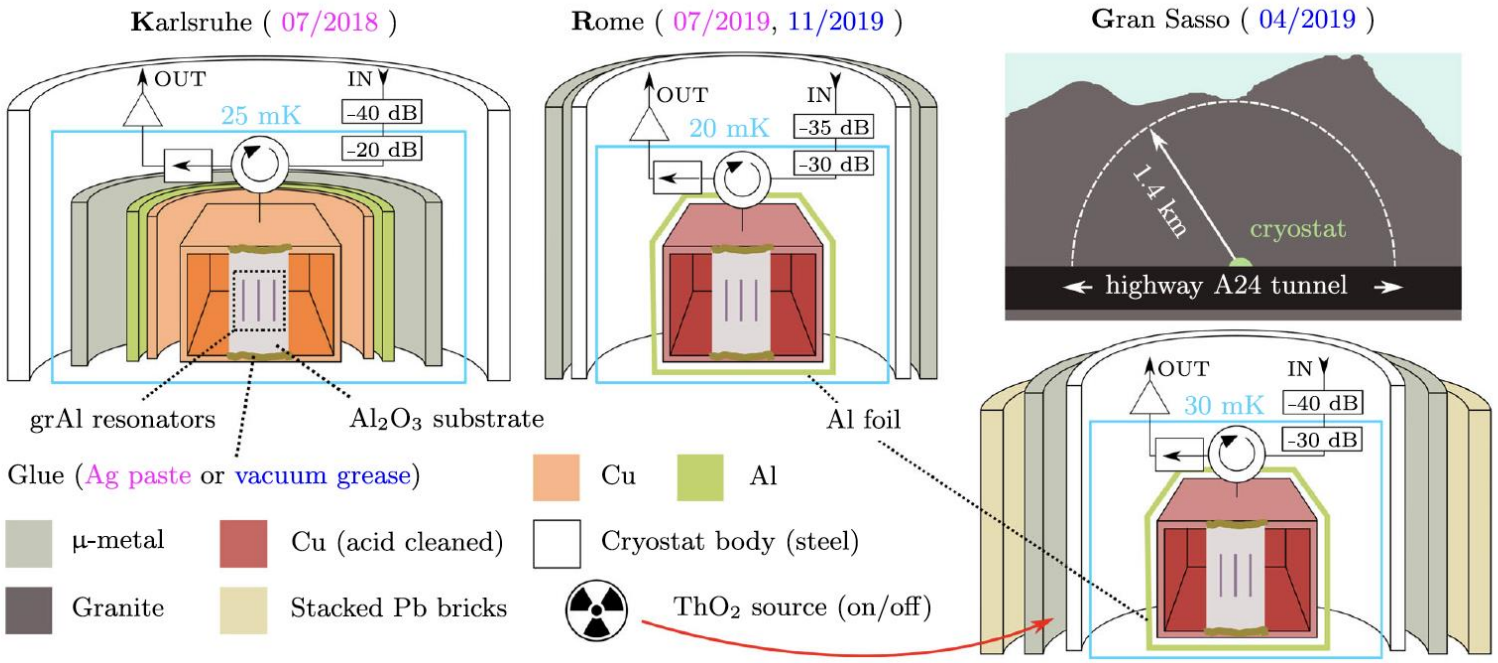
Roadmap


Quantum nature of reality
Quantum systems by design
Quantum computing in principle
The power of quantum computers
Quantum systems in nature and early technologies
Quantum information
Quantum computing in practice
Current status of QCs and outlook
Today's lecture

Decoherence

- Real systems experience decoherence!

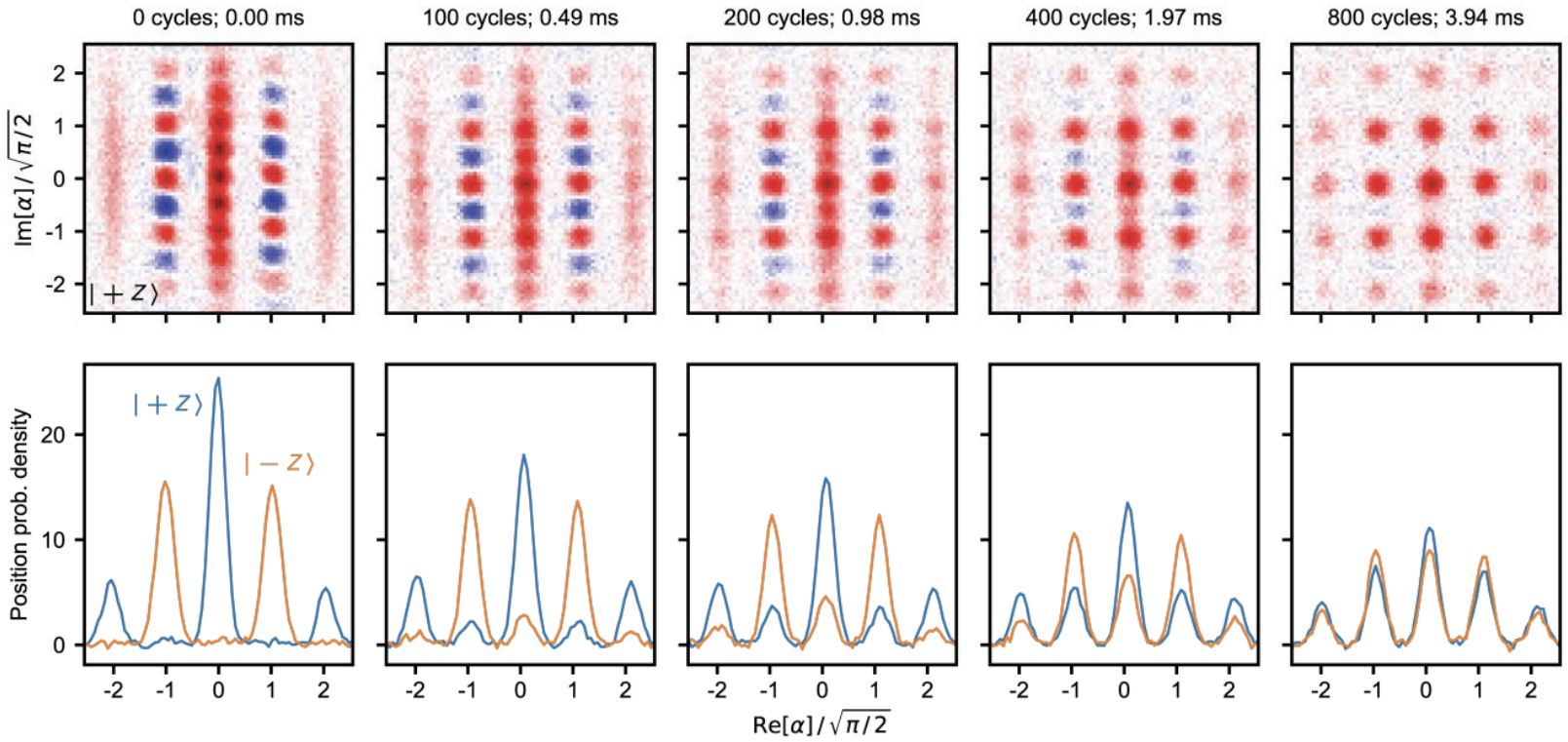
- Name of the game: reducing *unwanted* interactions w/ env. while maintaining *control*



L. Cardani *et al.,* Reducing the impact of radioactivity on quantum circuits in a deep-underground facility, Nature Communications, **12**, 2733 (2021)

Decoherence

- Consequence of decoherence?
  - Destroy *superposition* states and *entanglement*



- blue spots represent “quantumness”

V. V. Sivak *et al.,* Real-time quantum error correction beyond break even, arXiv:2211.09116 (2022)

Classical error correction

- Repetition code

lossy channel! majority vote!

$$0 \to 000 \rightsquigarrow 010 \to 0$$
$$1 \to 111 \rightsquigarrow 110 \to 1$$

- Phonetic alphabet

https://tinyurl.com/3463e7p6

Quantum error correction

- Quantum system: more ways for errors to occur!
  - Classically, only have bit flips
- Still have bit flips $|0\rangle \rightarrow |1\rangle$
- Now also phase flips $|0\rangle + |1\rangle \rightarrow |0\rangle - |1\rangle$

- No-cloning theorem: cannot copy an arbitrary quantum state

$$(a|0\rangle + b|1\rangle)|0\rangle|0\rangle \nrightarrow (a|0\rangle + b|1\rangle)(a|0\rangle + b|1\rangle)(a|0\rangle + b|1\rangle)$$

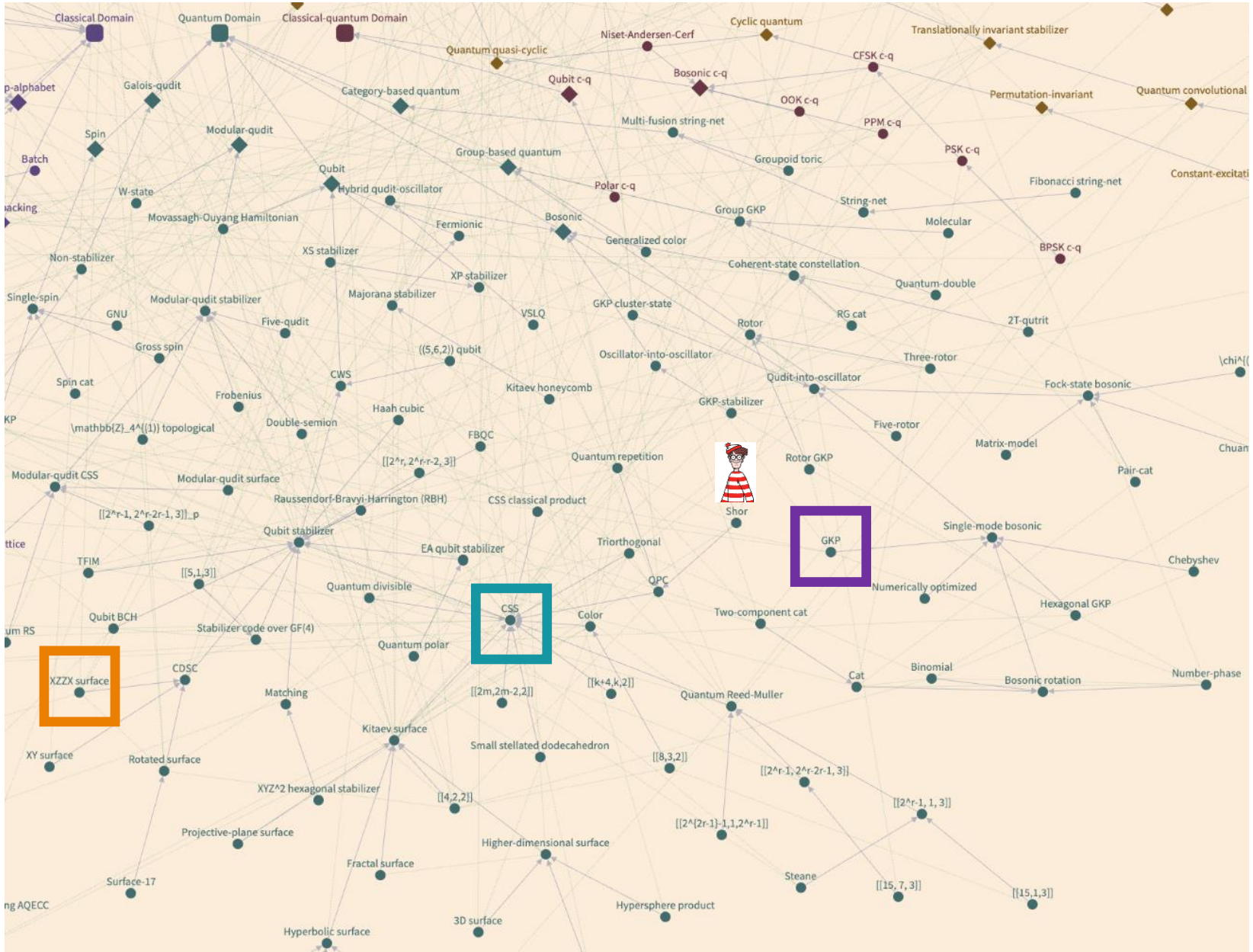
- Solution (Shor): use highly entangled states of multiple qubits to encode a single qubit

$$(a|0\rangle + b|1\rangle)|0\rangle|0\rangle \rightarrow a|0\rangle|0\rangle|0\rangle + b|1\rangle|1\rangle|1\rangle$$

- This corrects for bit flips: correcting for phase slips only a slight generalization!

P. W. Shor, PRA **52**, 2493 (1995)

Quantum error correction zoo!



different strengths and weaknesses!

qubits amenable to a grid layout?
CSS surface code!

biased-noise qubits?
XZZX surface code!

qubits encoded in harmonic oscillators?
GKP code!

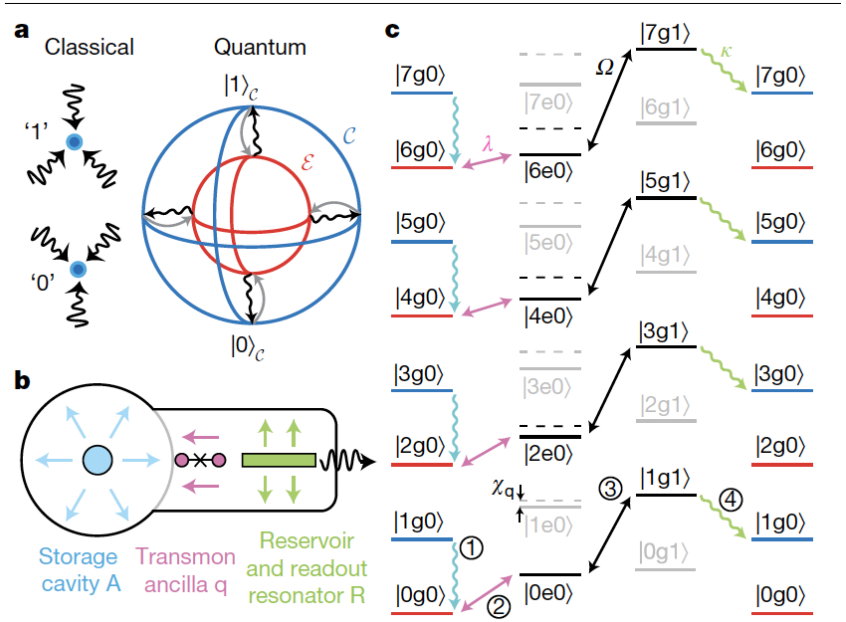
can you spot the original Shor code?

https://errorcorrectionzoo.org/

Experimental realizations of QEC

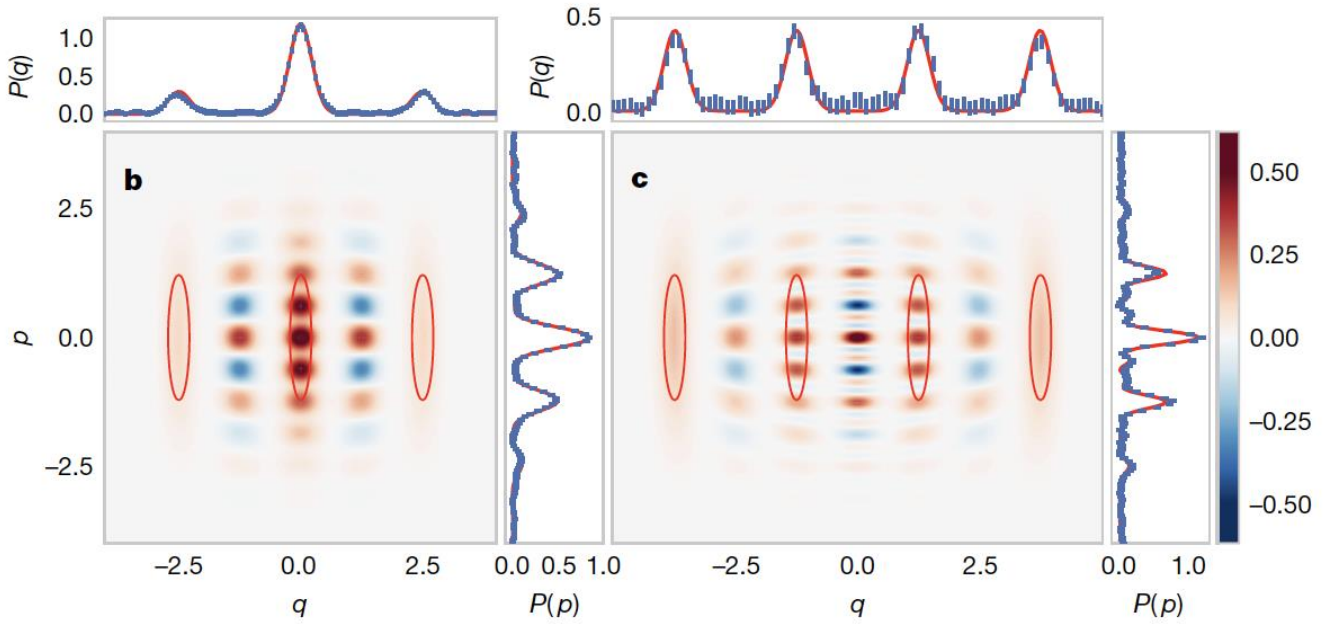
autonomous bosonic error correction (sc circuits)

J. Gertler *et al.*, Nature **590**, 243 (2021)



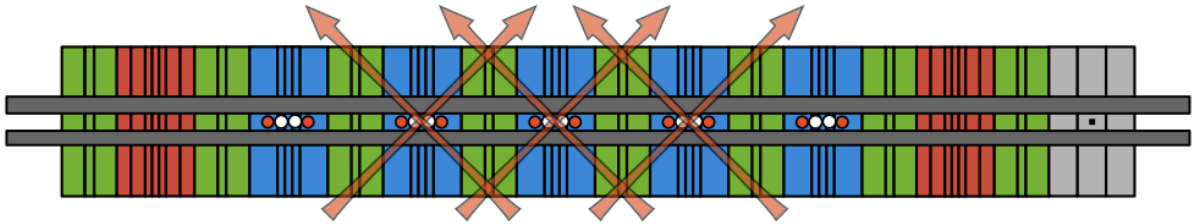
GKP code (trapped ions)

Flühmann *et al.*, Nature **566**, 513 (2019)



Color code (trapped ions)

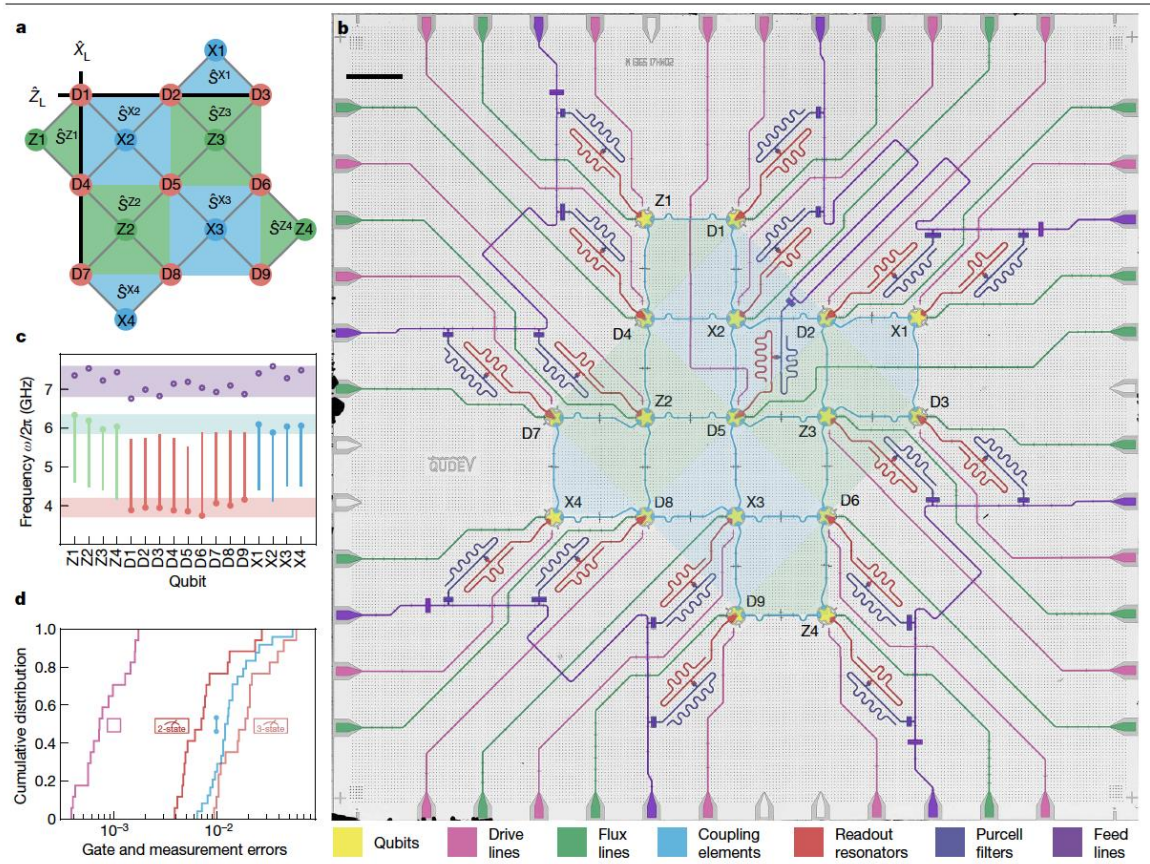
C. Ryan-Anderson *et al.*, PRX **11**, 041058 (2021)



Experimental realizations of QEC

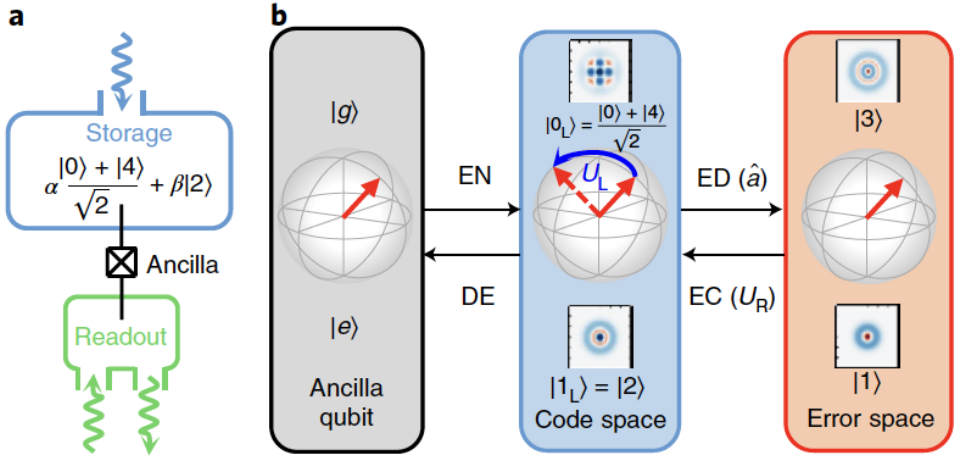
distance 3 surface code (sc circuits)

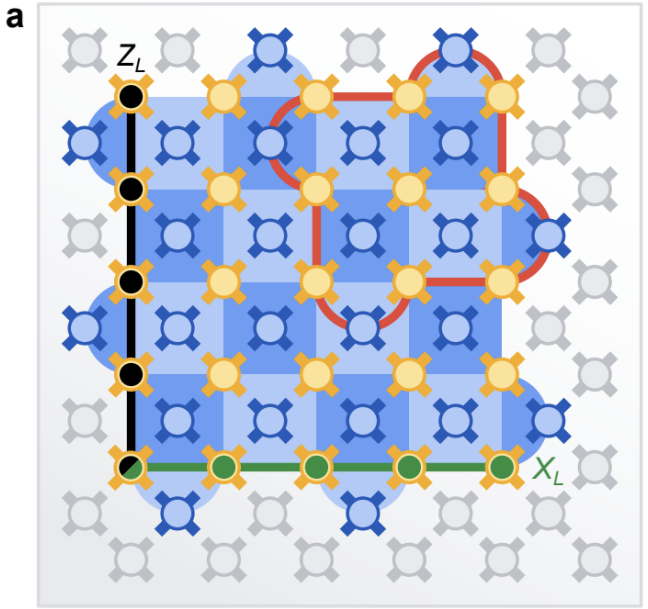
S. Krinner *et al.*, Nature 605, 669 (2022)



binomial code (sc circuits)

L. Hu *et al.*, Nature physics **15**, 503 (2019)



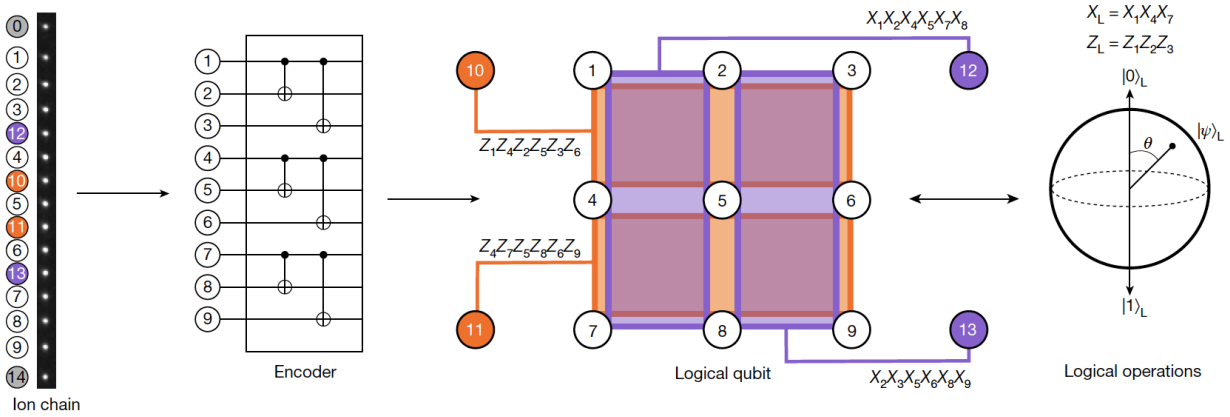


distance 5 surface code (sc circuits)

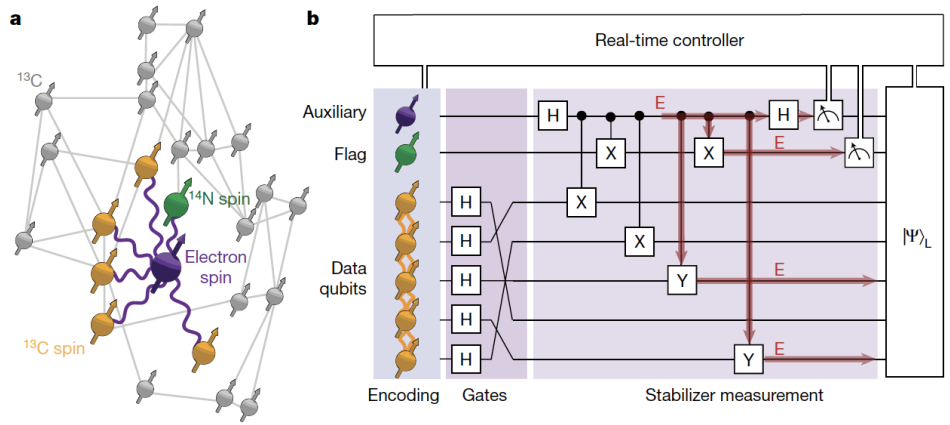
Google Quantum AI, arXiv:2207.06431 (2022)

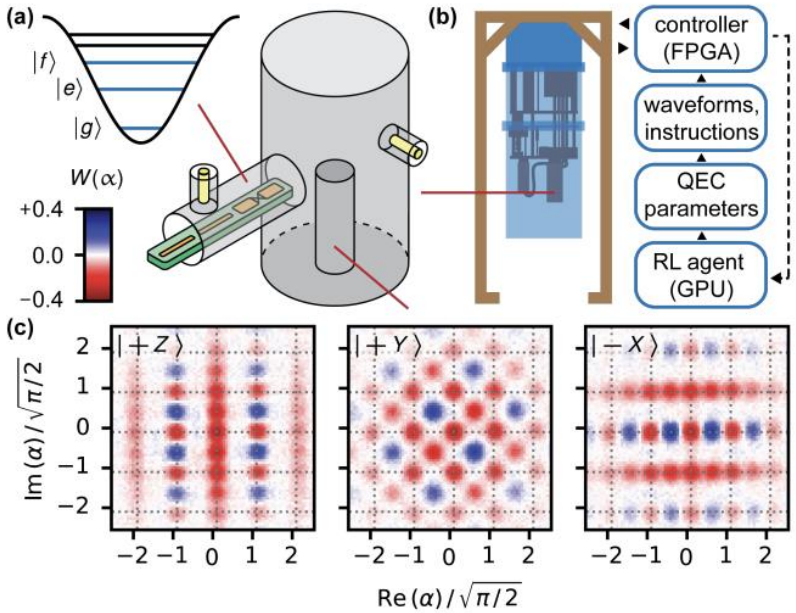
Experimental realizations of QEC

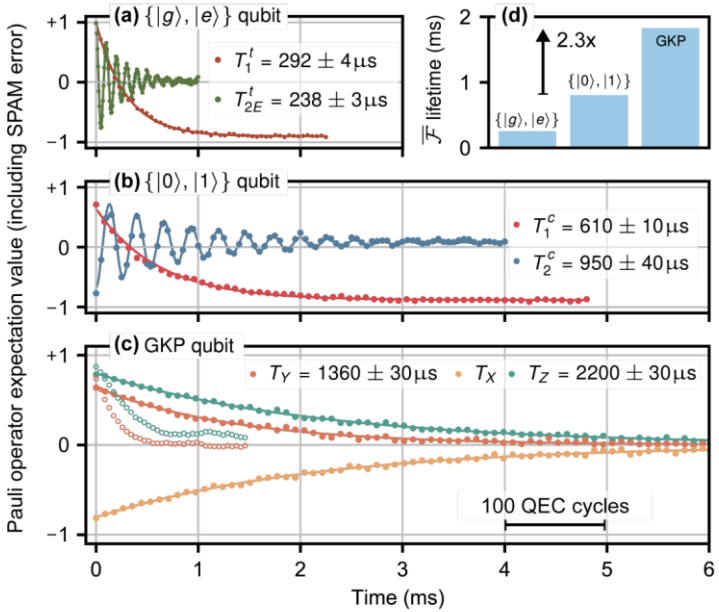
Bacon-Shor code (trapped ions)
L. Egan *et al.*, Nature **598**, 281 (2021)



5-qubit code (NV centers in diamond)
M. H. Abobeih *et al.*, Nature **606**, 884 (2022)



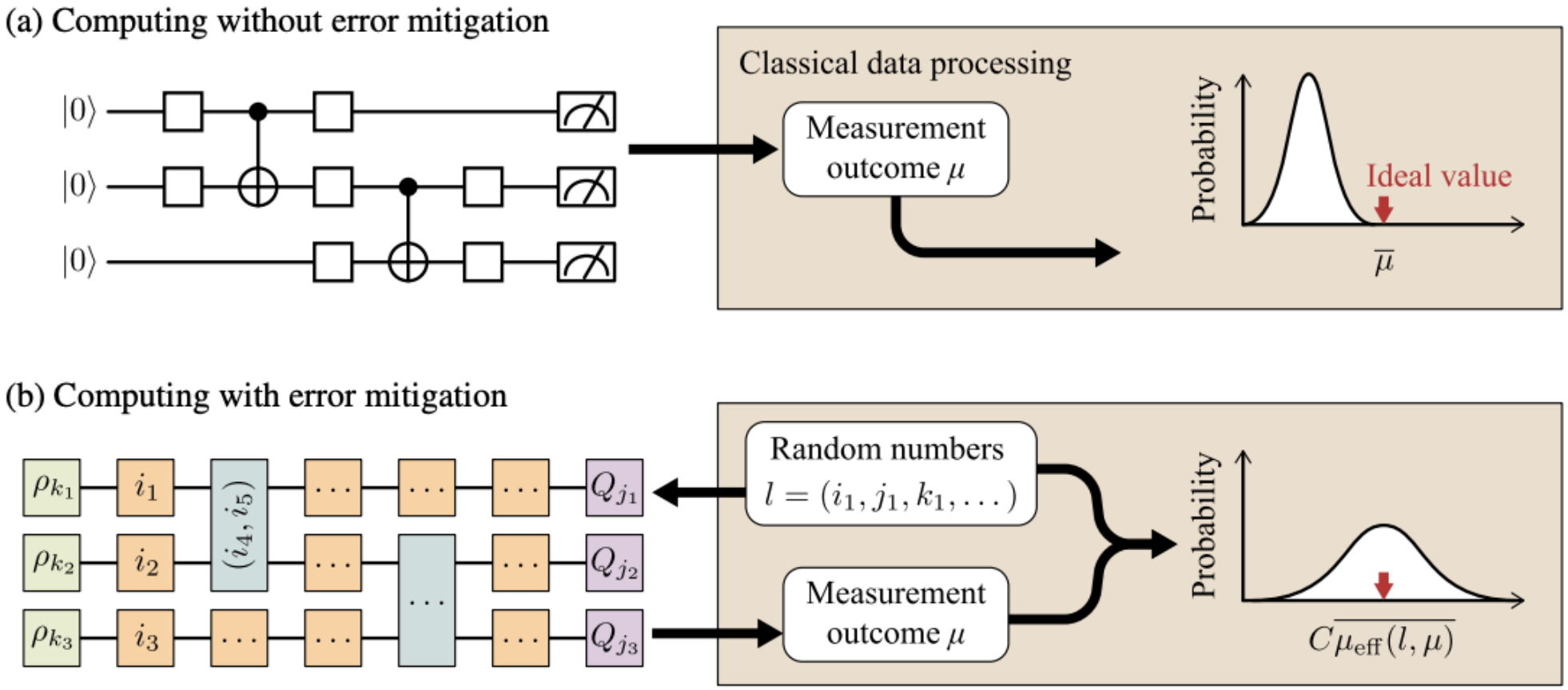




GKP code (sc circuits)
V. V. Sivak *et al.*,
arXiv:2211.09116

Near term: quantum error *mitigation*

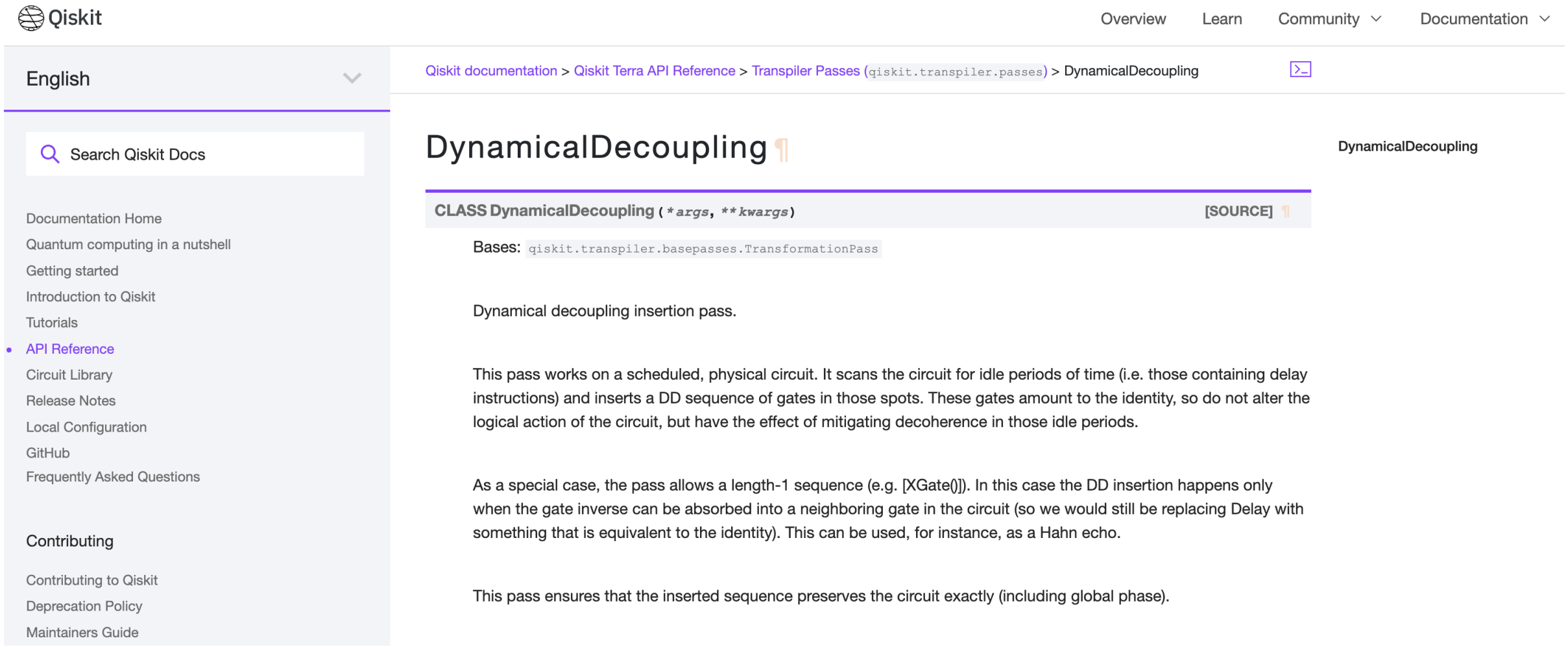
- Idea: if we can *understand* the kinds of errors that occur, we can *unbias* our results!



S. Endo *et al.*, PRX **8**, 031027 (2018)

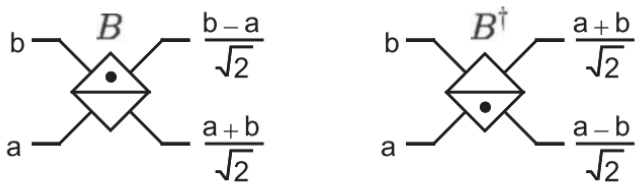
Near term: quantum error *suppression*

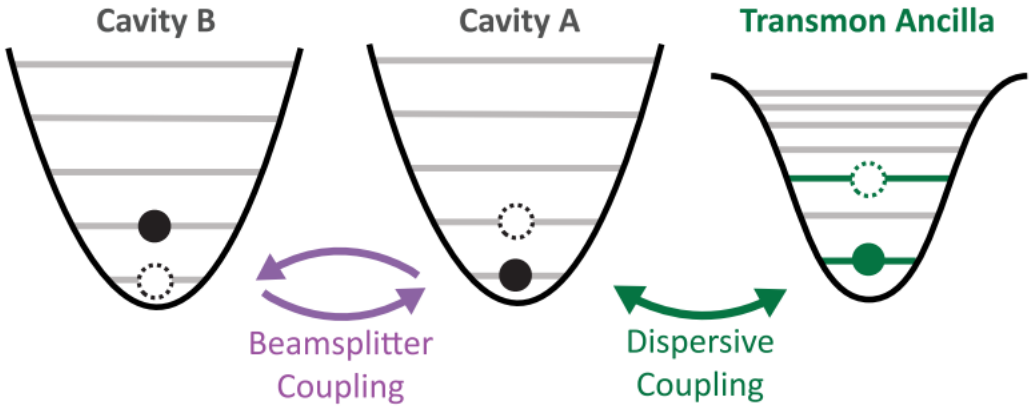
- Dynamical decoupling: continuously flip your qubits when they are idle!

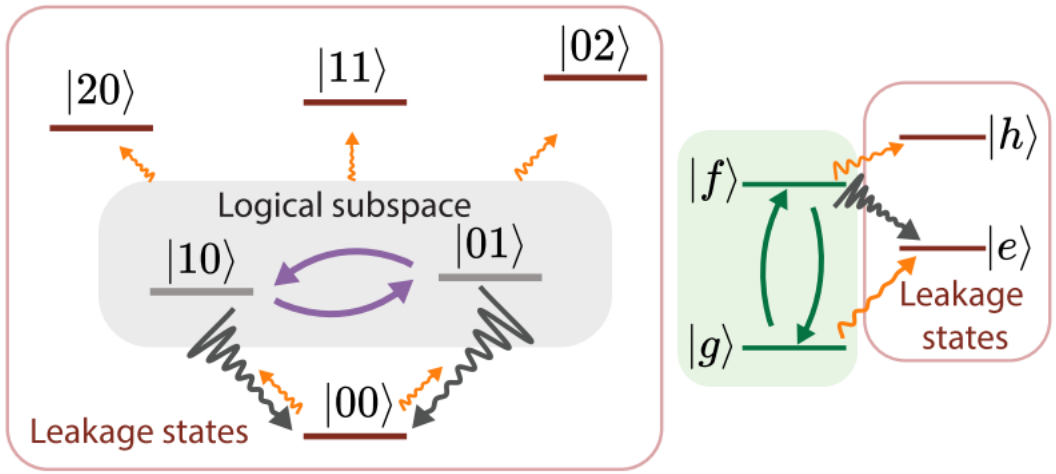


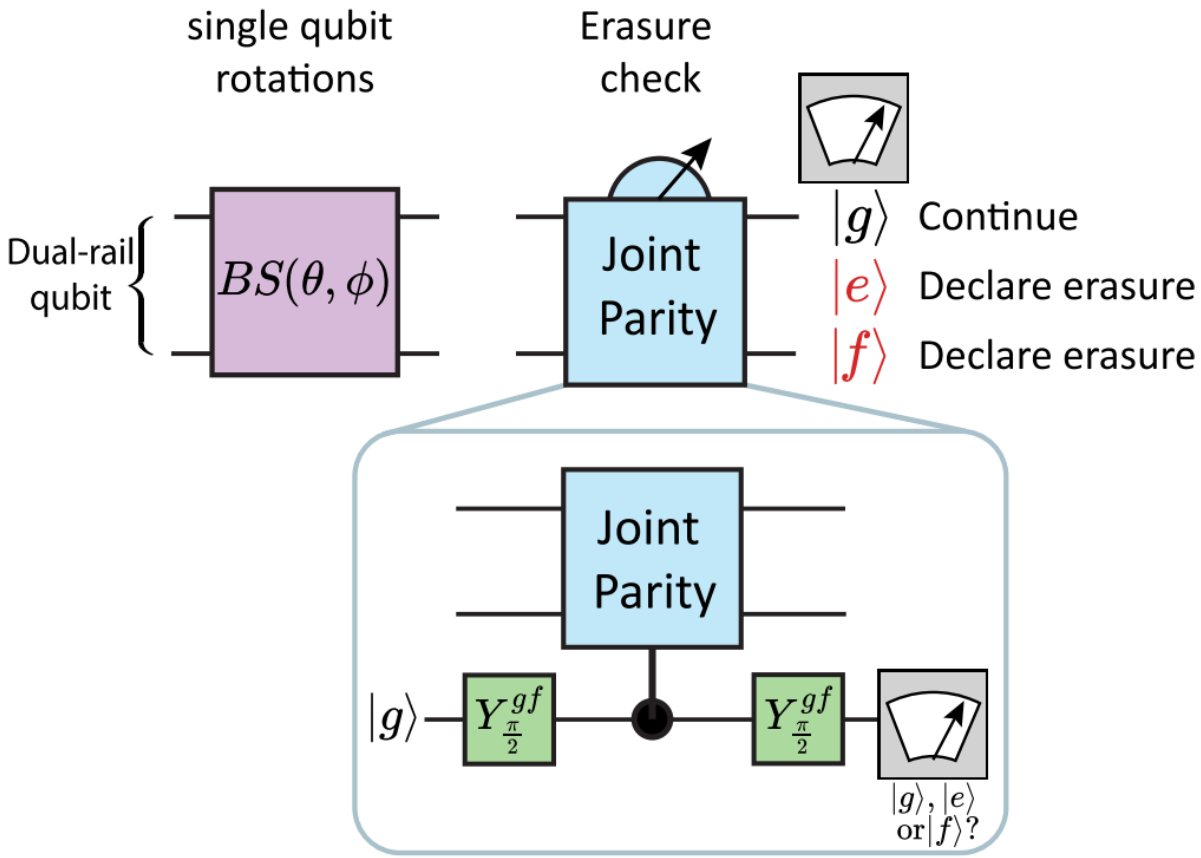
Near term: quantum error *detection*

- Dual-rail qubits: old idea, new system!



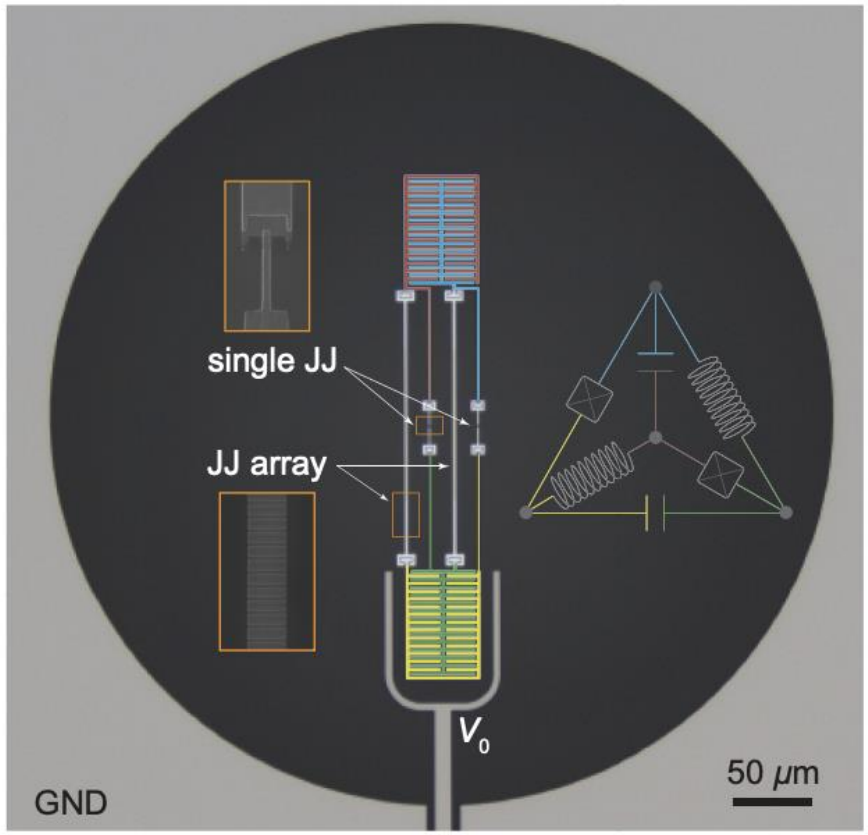




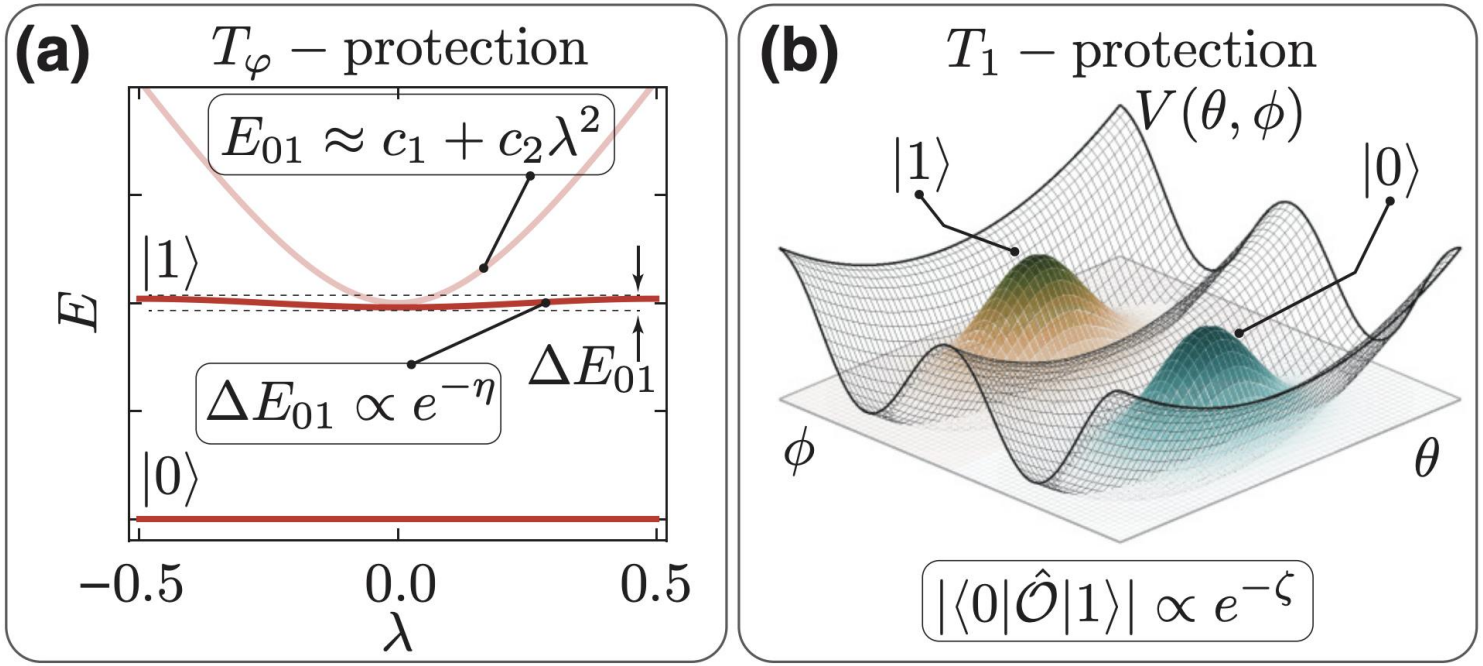


Mike and Ike
J. D. Teoh *et al.*, arXiv:2212.12077

Near term: *protected* physical qubits



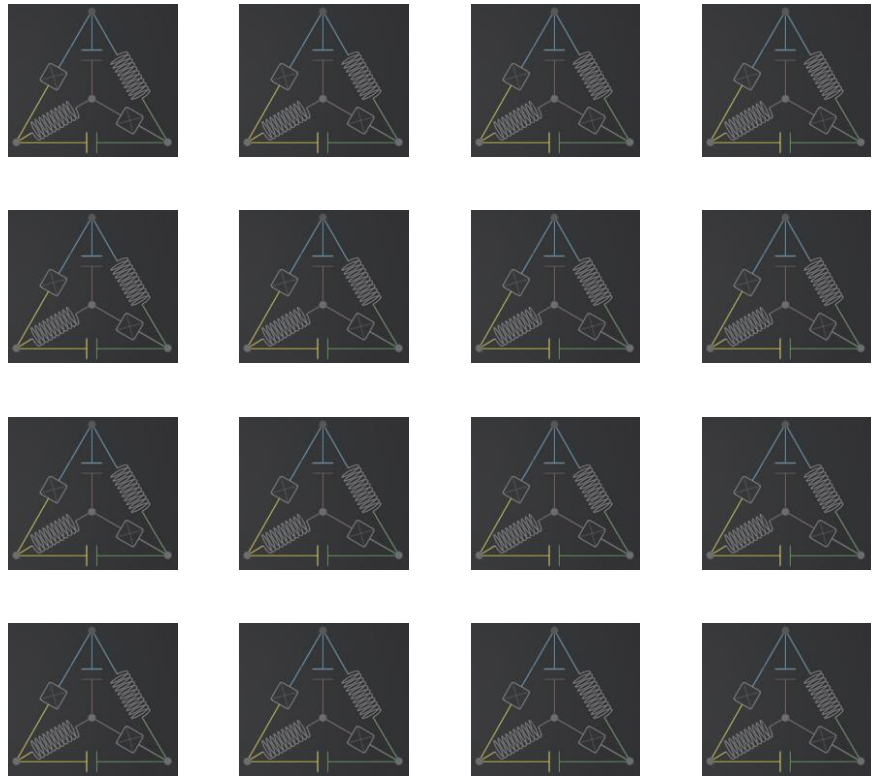
A. Gyenis *et al.*, PRX Quantum **2**, 010339 (2021)



A. Gyenis *et al.,* PRX Quantum 2, 030101 (2021)

Far term: fault-tolerant quantum computation

- Multiple layers:



protected qubits

Far term: fault-tolerant quantum computation

- Multiple layers:

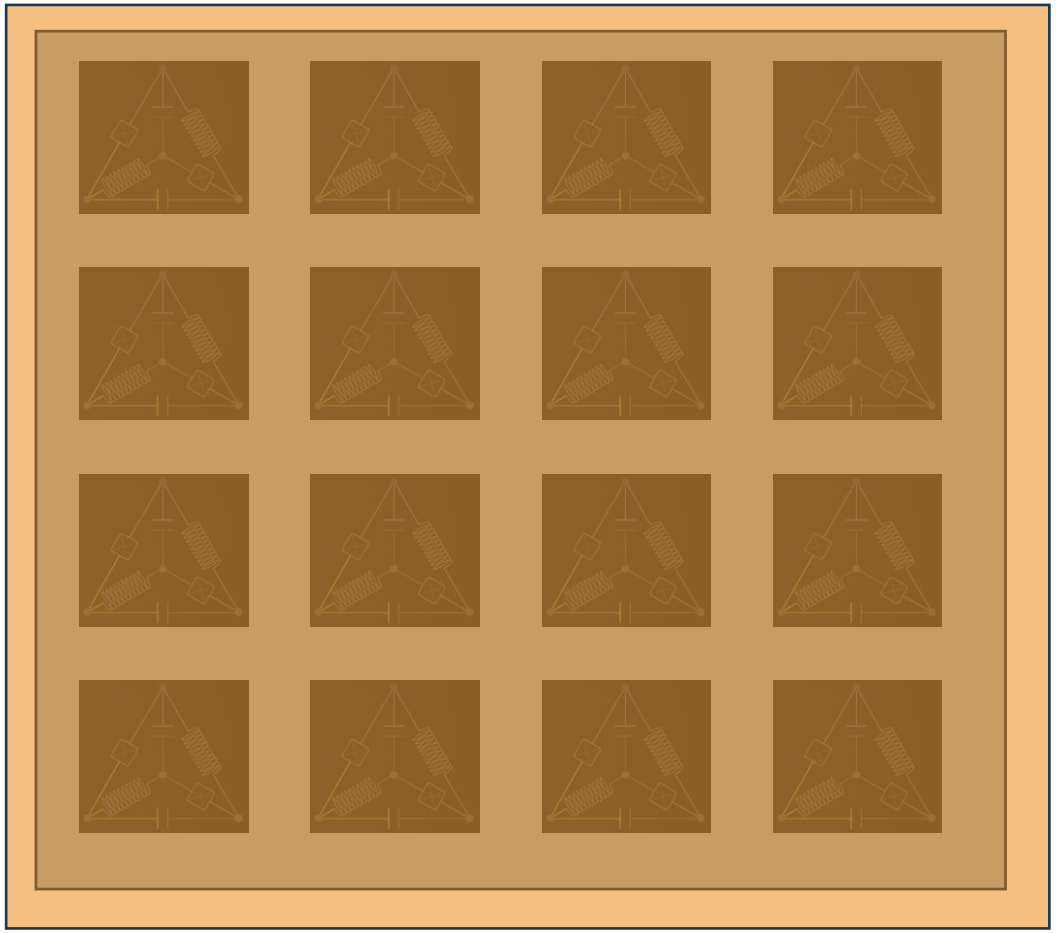
protected qubits

error mitigation

Far term: fault-tolerant quantum computation

- Multiple layers:

error suppression

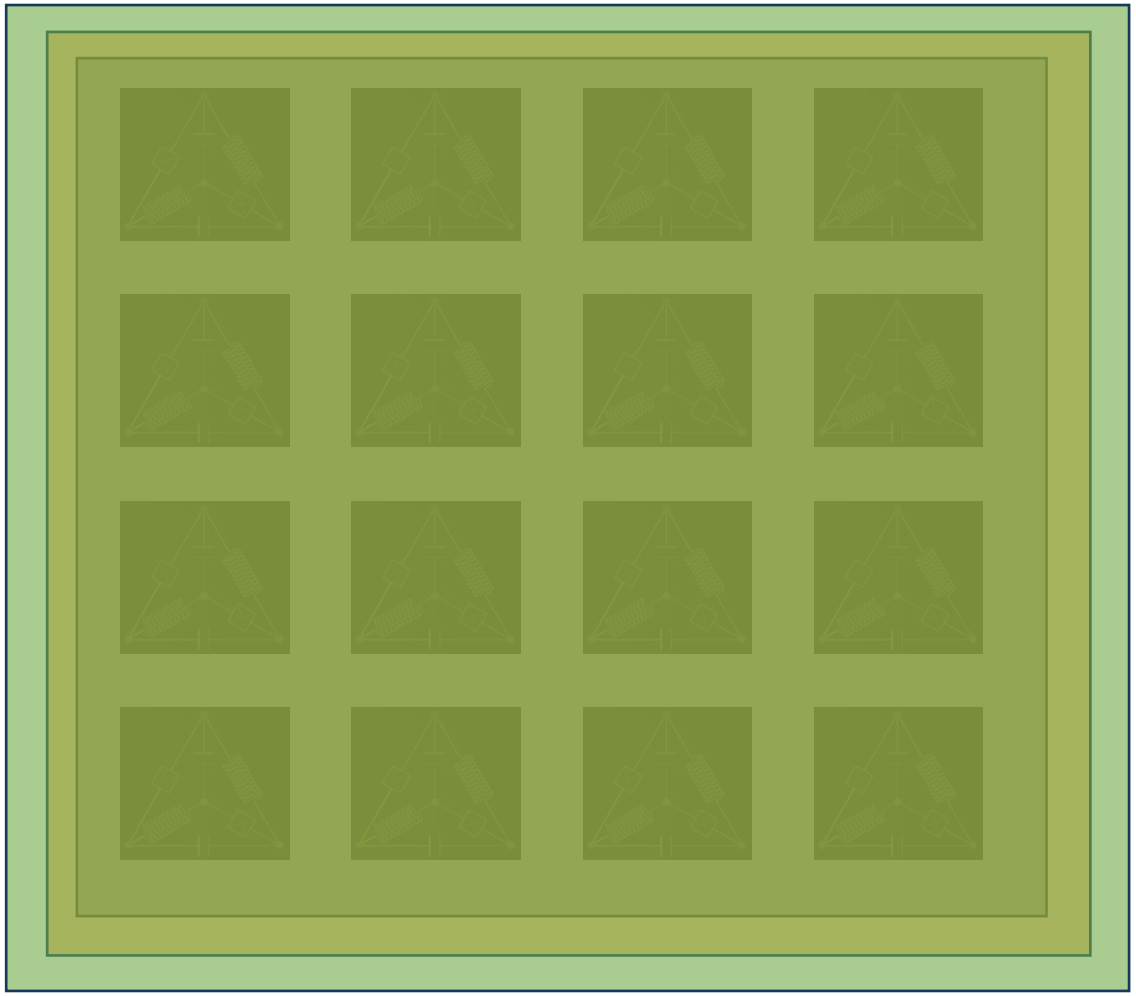


protected qubits

error mitigation

Far term: fault-tolerant quantum computation

- Multiple layers:



error detection

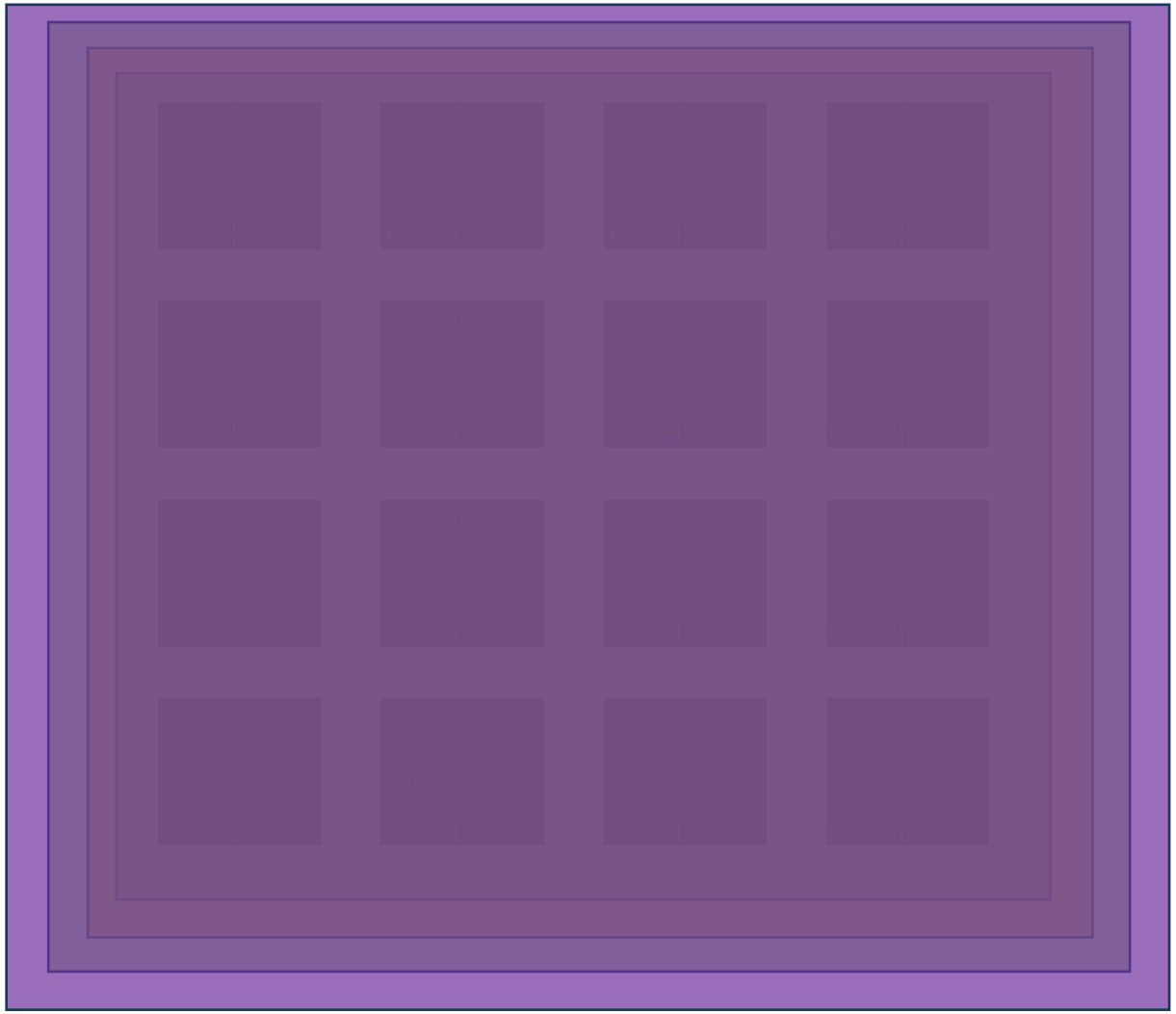
error suppression

protected qubits

error mitigation

Far term: fault-tolerant quantum computation

- Multiple layers:



error detection

error suppression

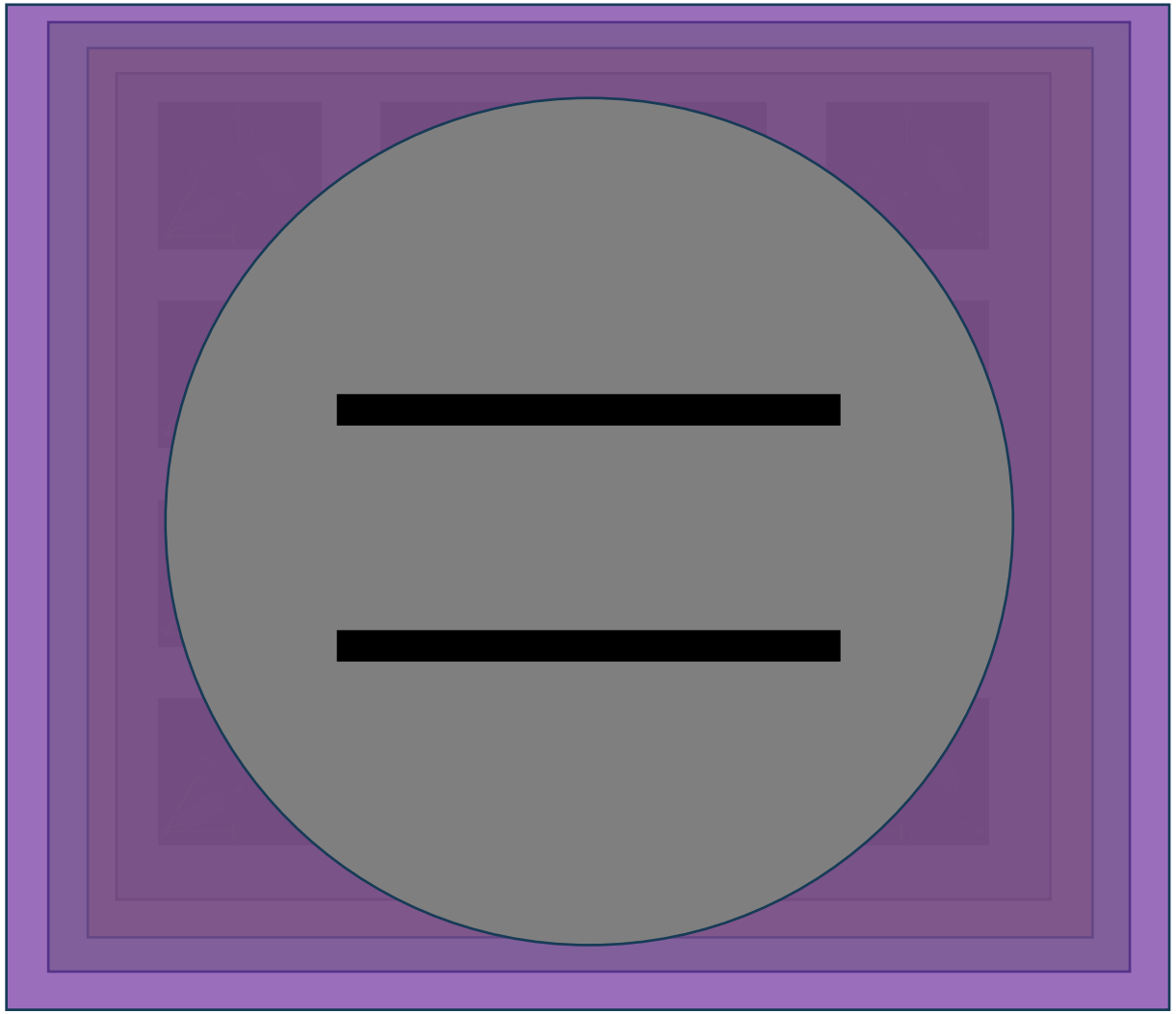
error correction

protected qubits

error mitigation

Far term: fault-tolerant quantum computation

- Multiple layers:



error detection

error suppression

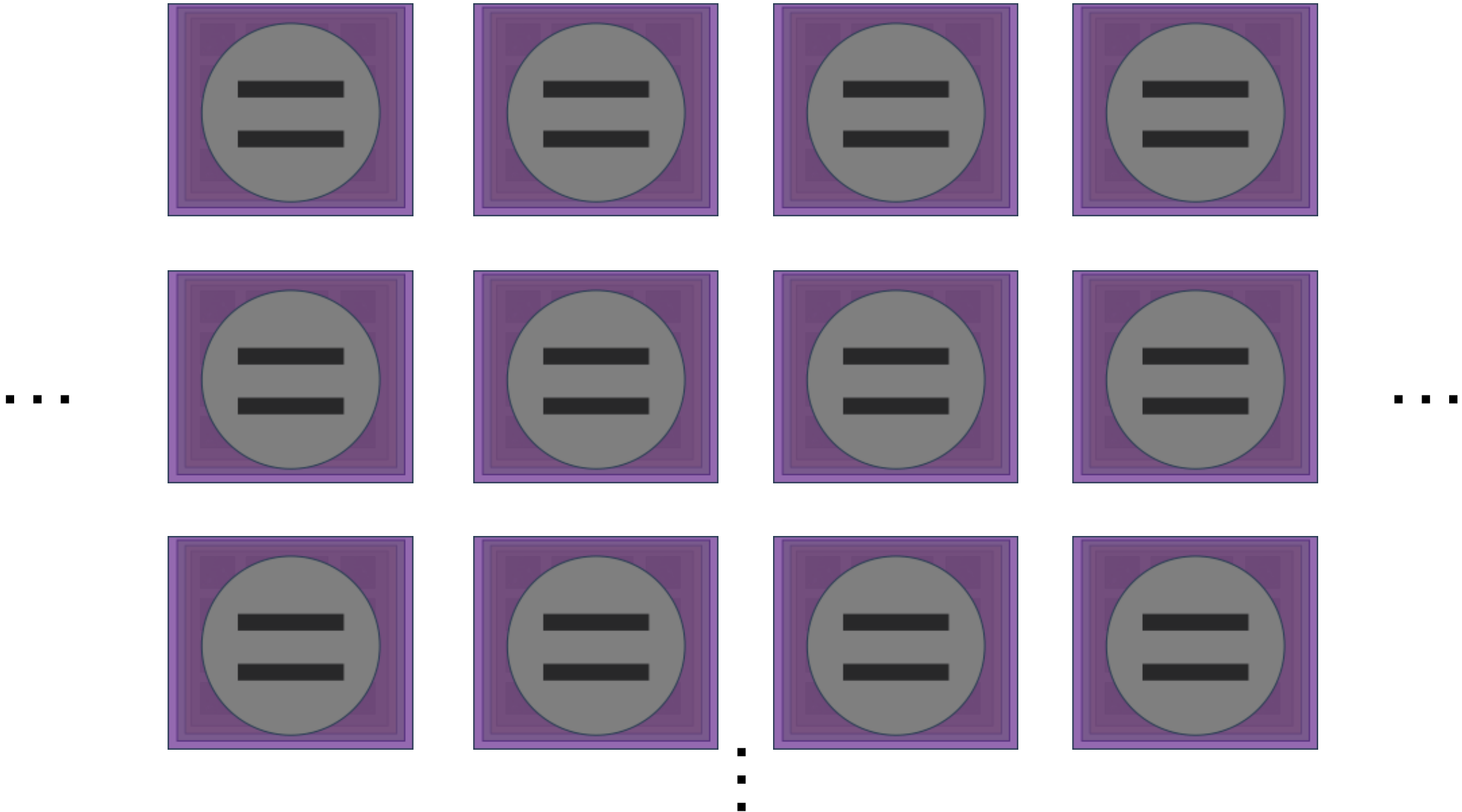
error correction

one logical qubit!

protected qubits

error mitigation

Far term: fault-tolerant quantum computation



Scaling up!

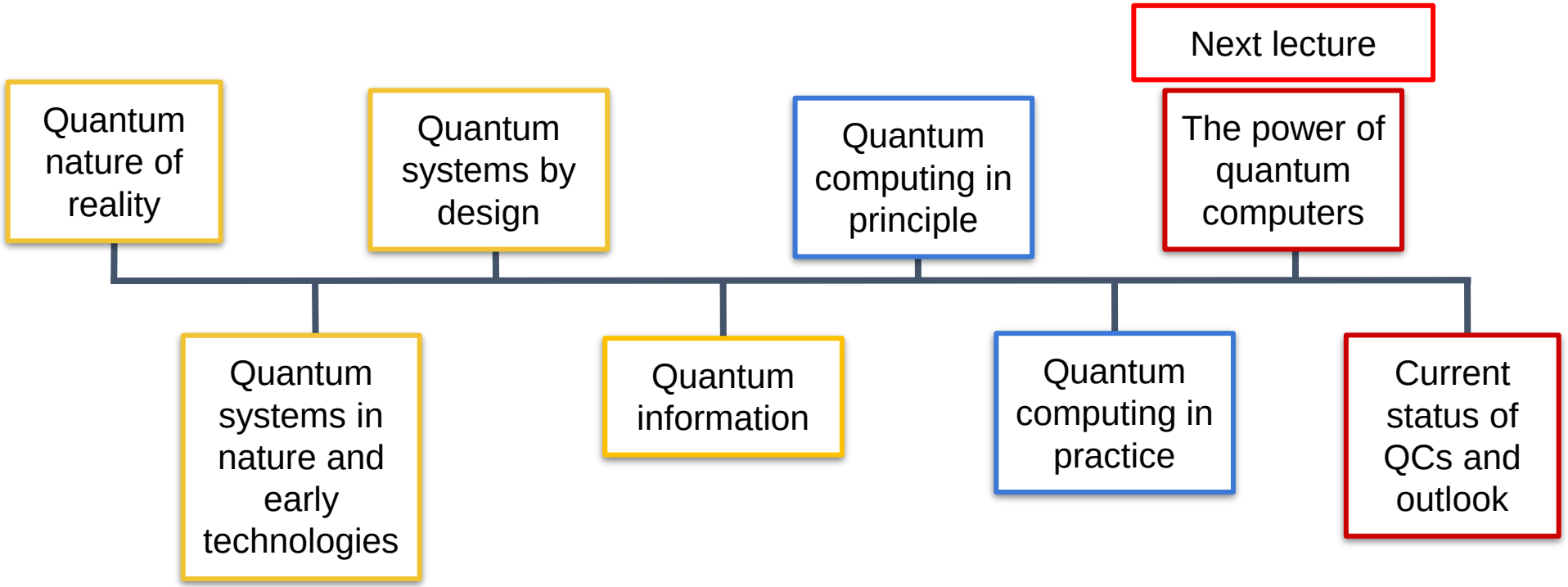
IBM fridge “Goldeneye” (1,000 - 4,000 qubits)

https://spectrum.ieee.org/ibms-envisons-the-road-to-quantum-computing-like-an-apollo-mission

Wallraff group linking two fridges

P. Magnard *et al.,* Phys. Rev. Lett., **125**, 260502 (2020)

Roadmap


Next lecture
Quantum nature of reality
Quantum systems by design
Quantum computing in principle
The power of quantum computers
Quantum systems in nature and early technologies
Quantum information
Quantum computing in practice
Current status of QCs and outlook

Summary and outlook

- Noise destroys superpositions and entanglement
- Combat with quantum error mitigation, detection, suppression, correction, (insert fun jargony word here)
- Recent years have seen an EXPLOSION of progress on the feasibility of QEC