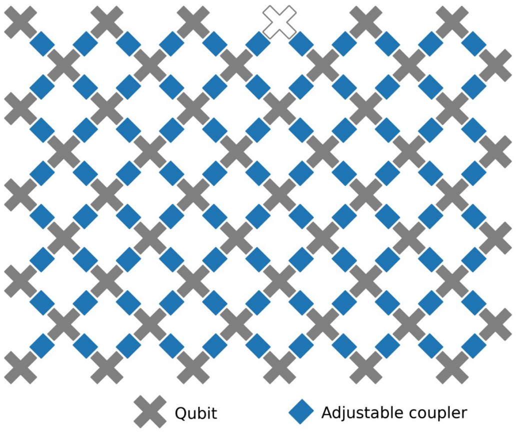
Quantum Computation & Quantum Supremacy

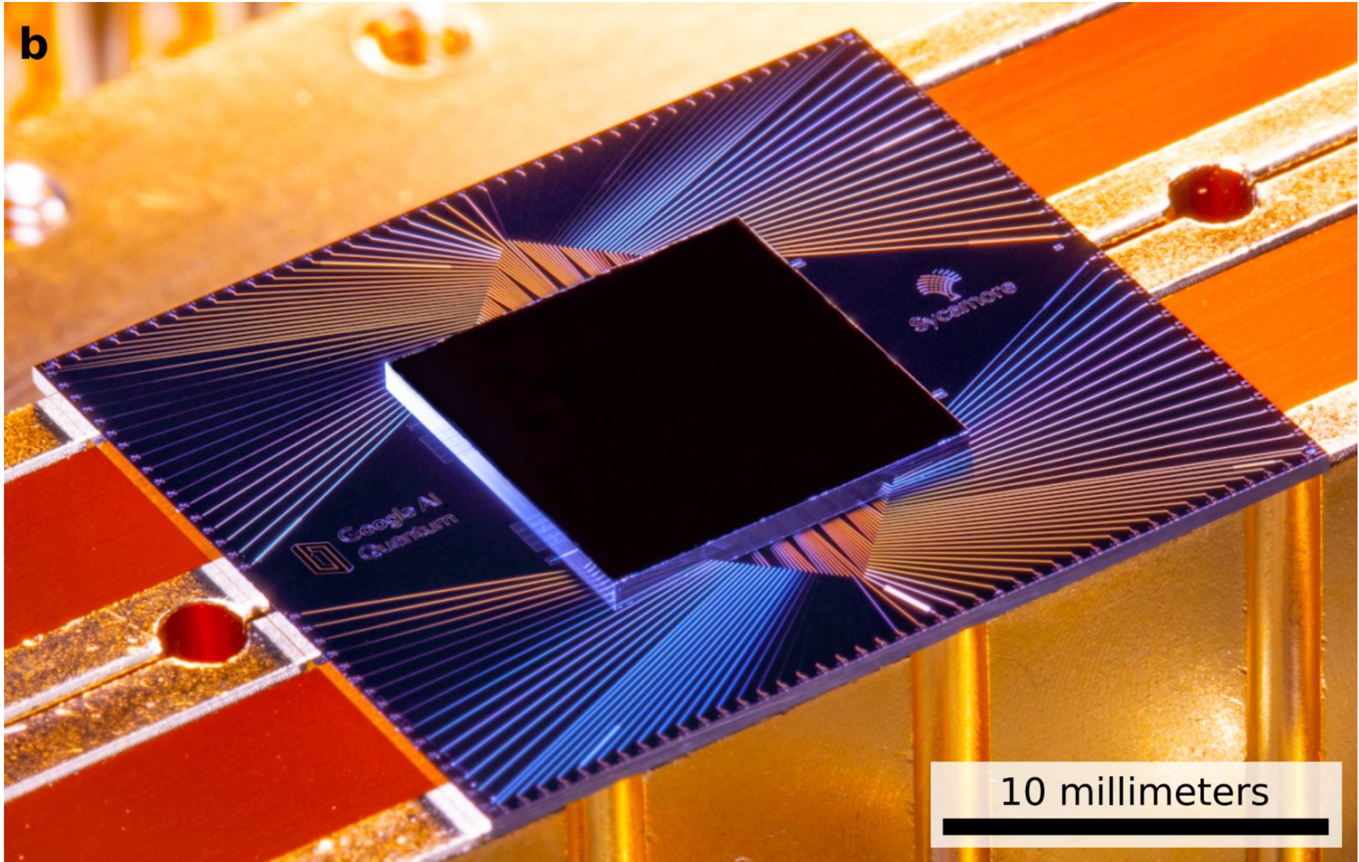
John Martinis
UCSB & (Google)

- Powerful computation paradigm
- Superconducting qubits
- Quantum supremacy achieved
  - 200s quantum computer, checked 10k yr

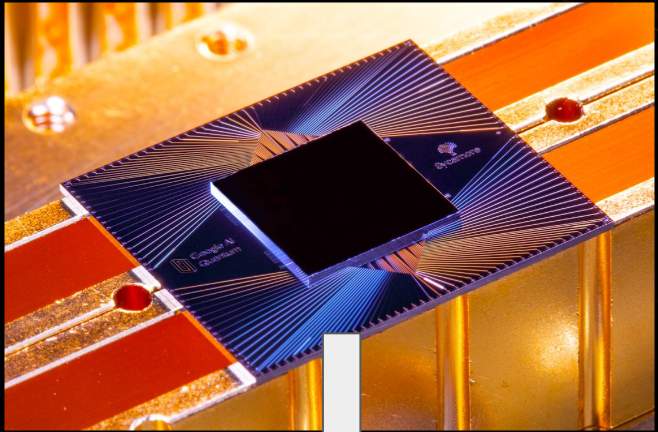
Sycamore Processor: 54 qubits



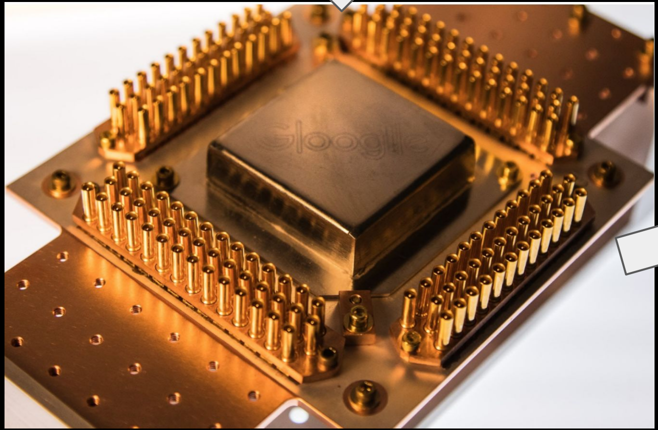
4-NN: Forward compatible SC error correction

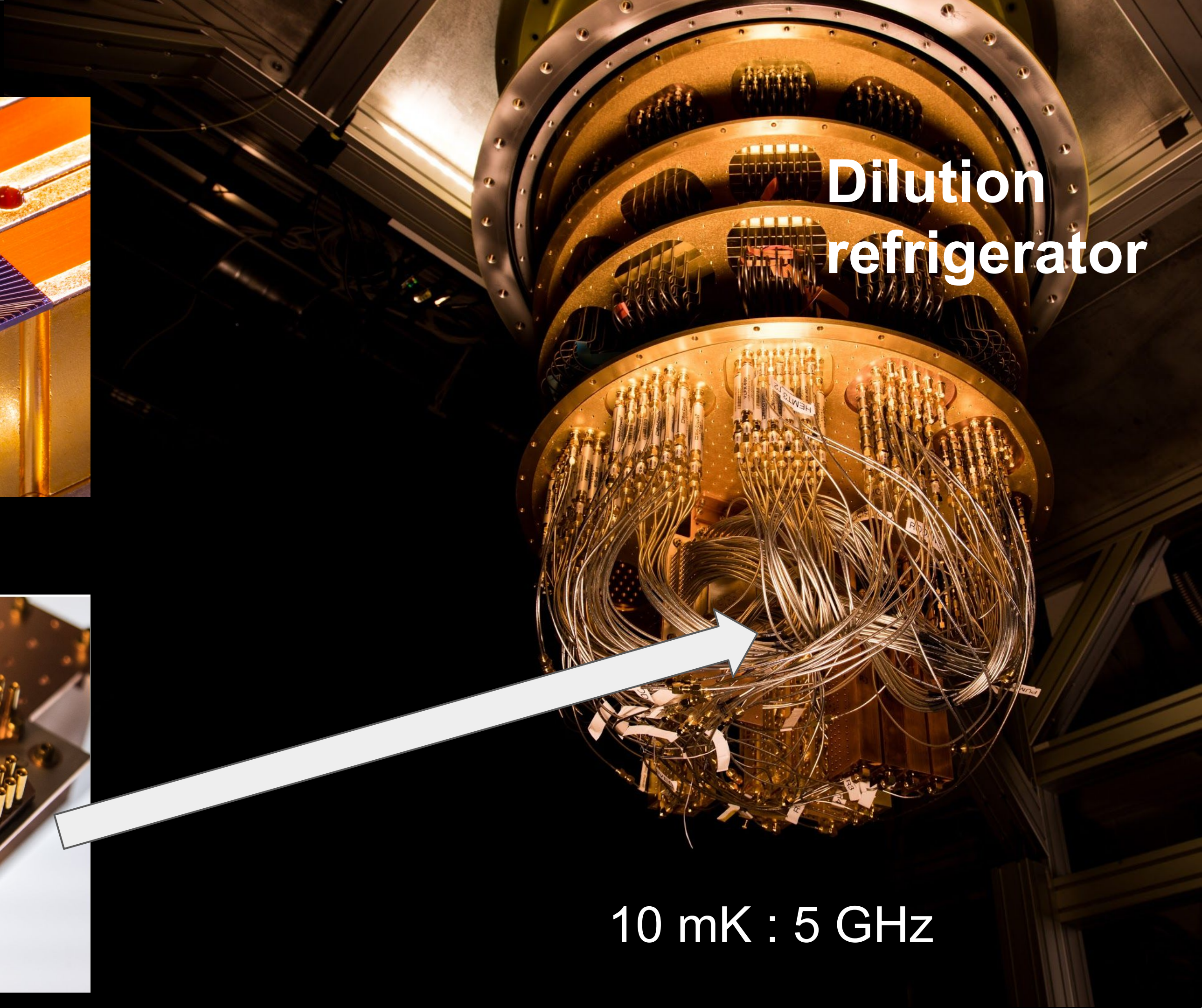


Fabrication

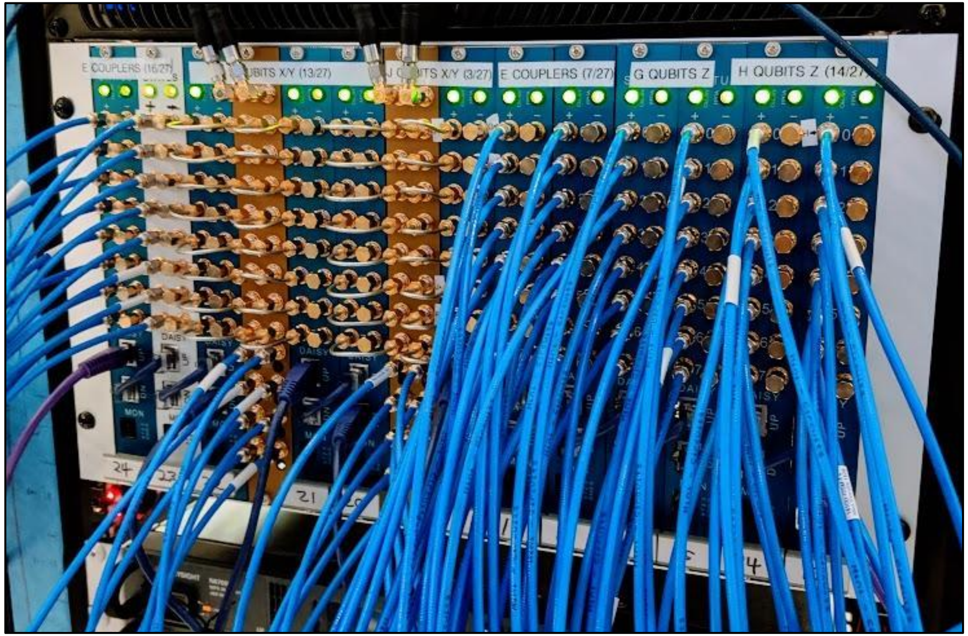


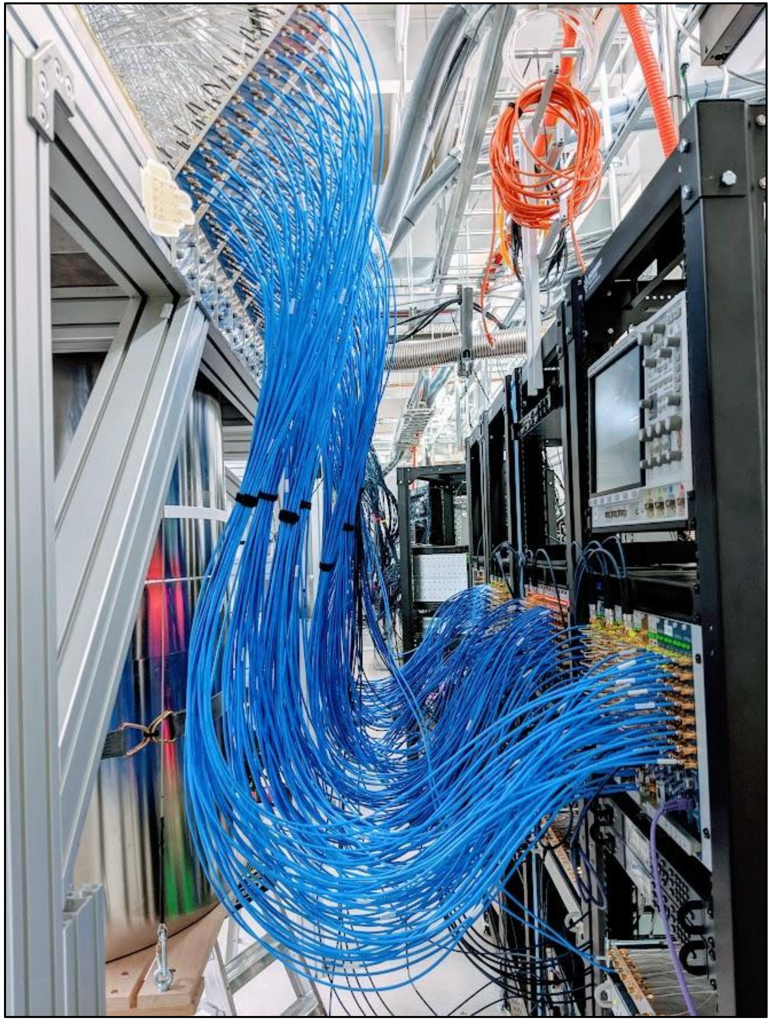
Packaging





Control Hardware

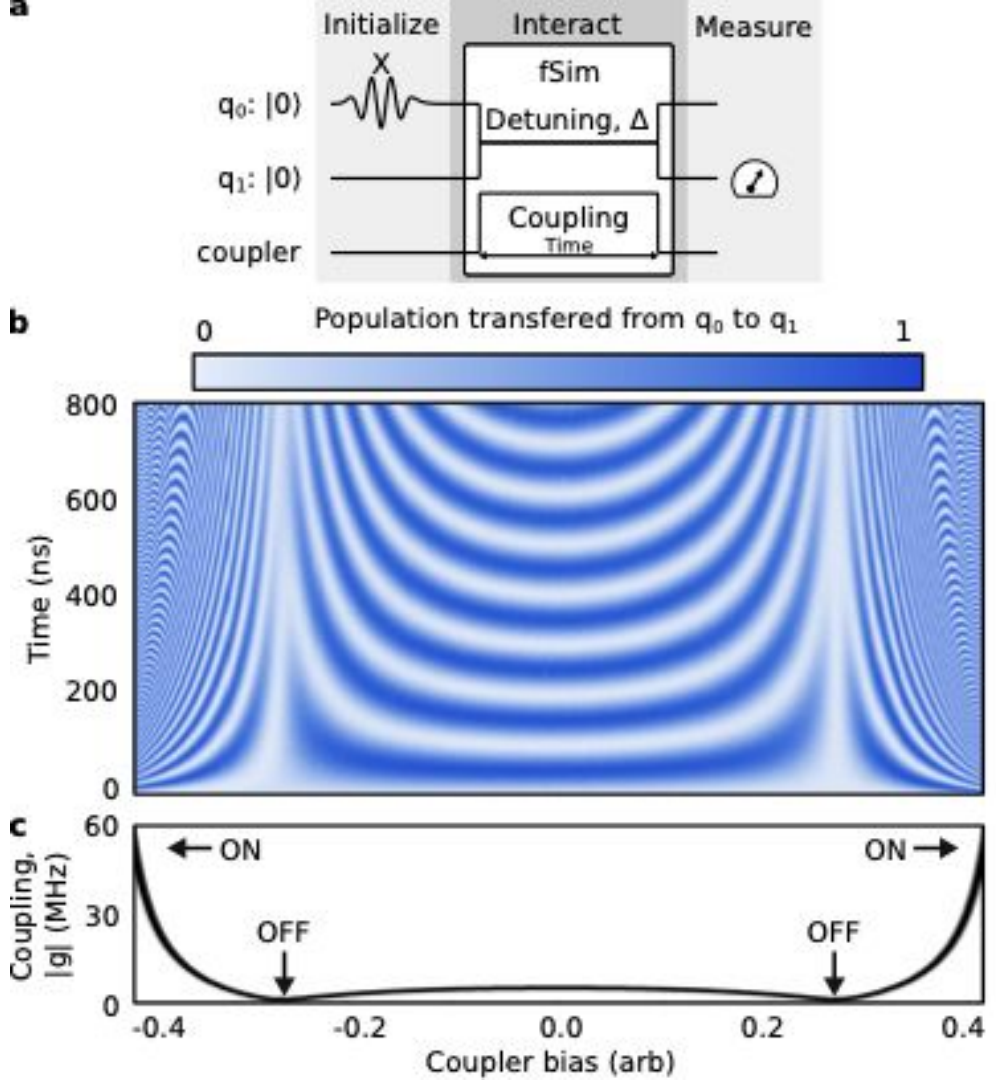


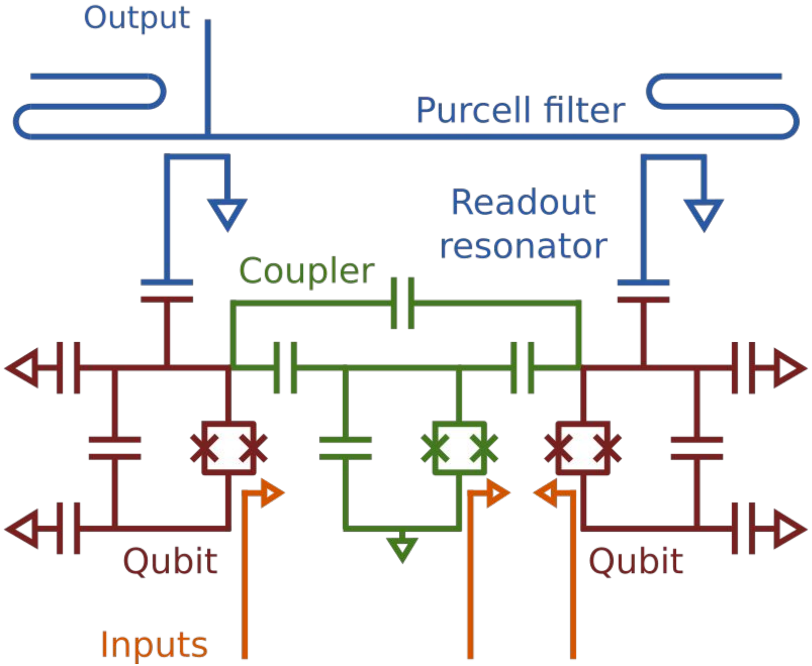


Custom built
High speed
High precision

Google AI
Quantum

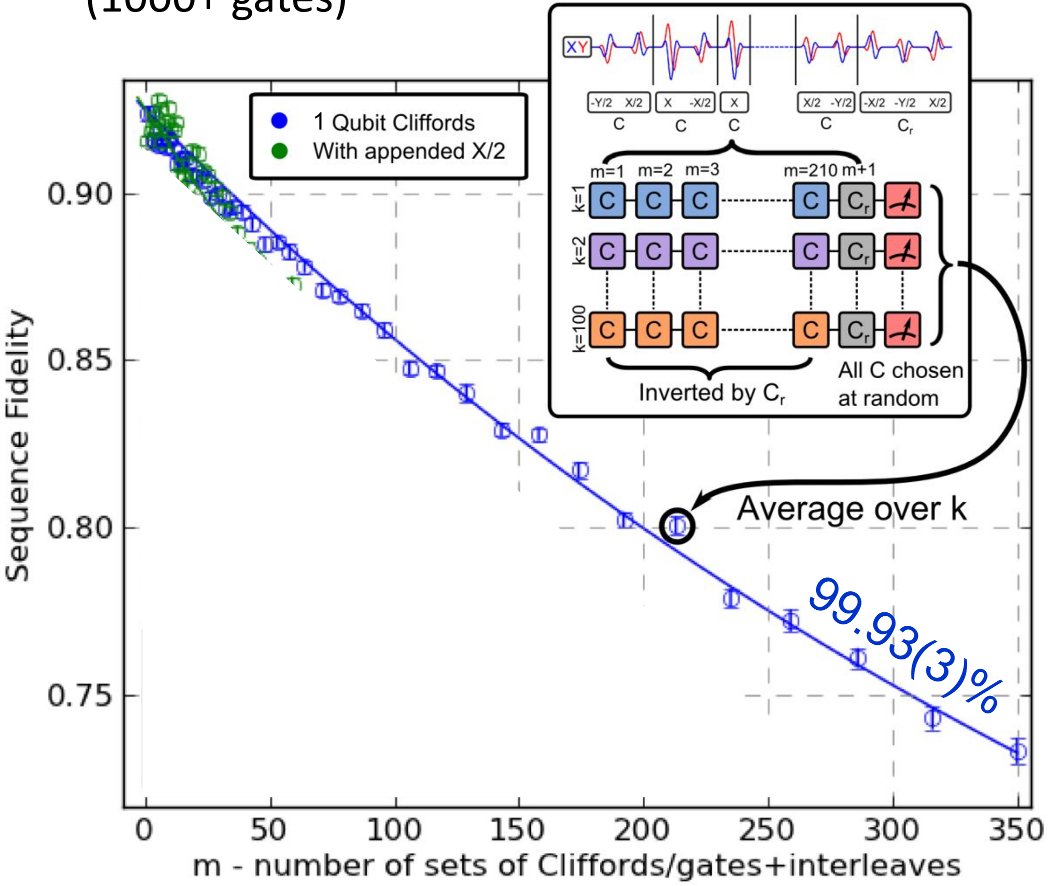
2-qubit Swap Calibration

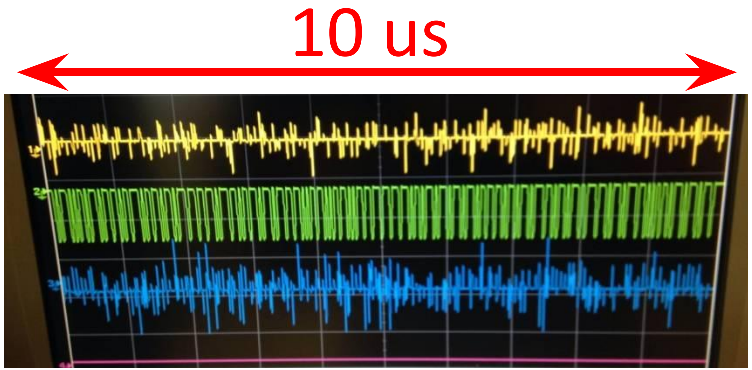




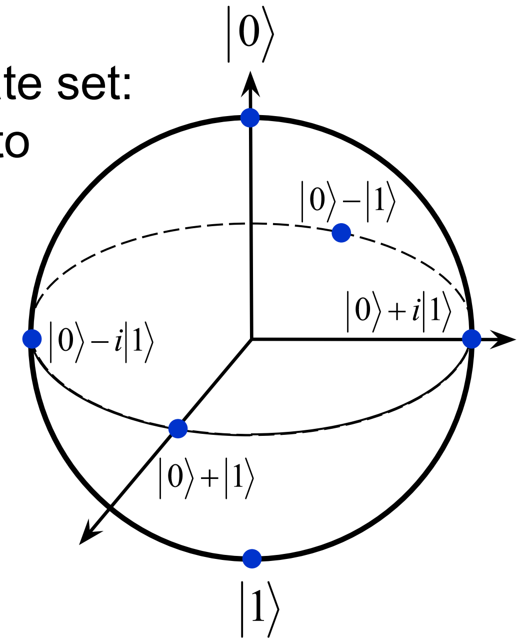
Randomized Benchmarking*

Realistic multi-qubit test of ***long*** algorithm
(1000+ gates)

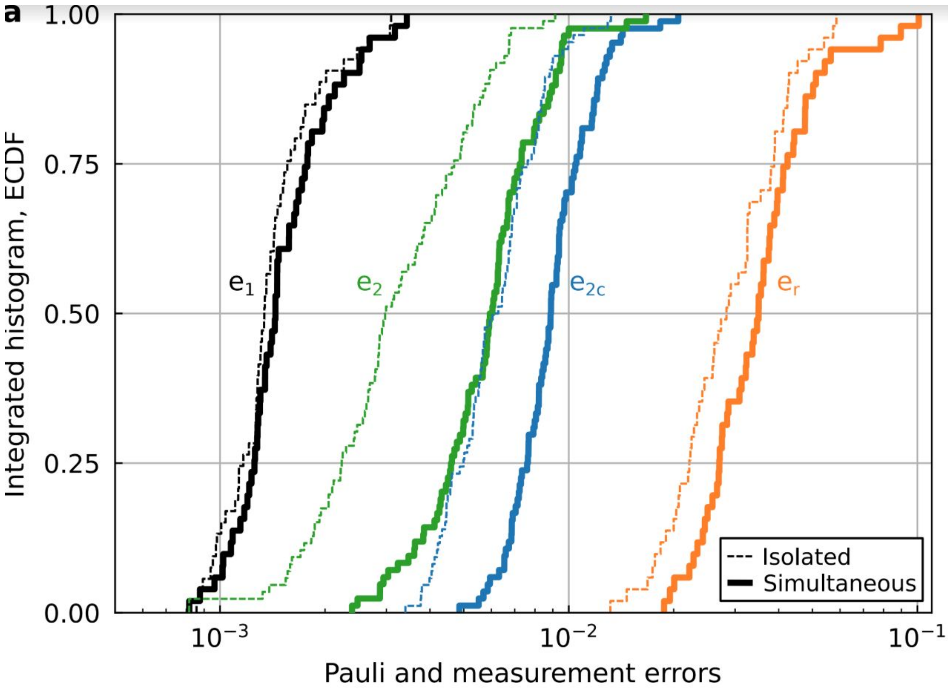




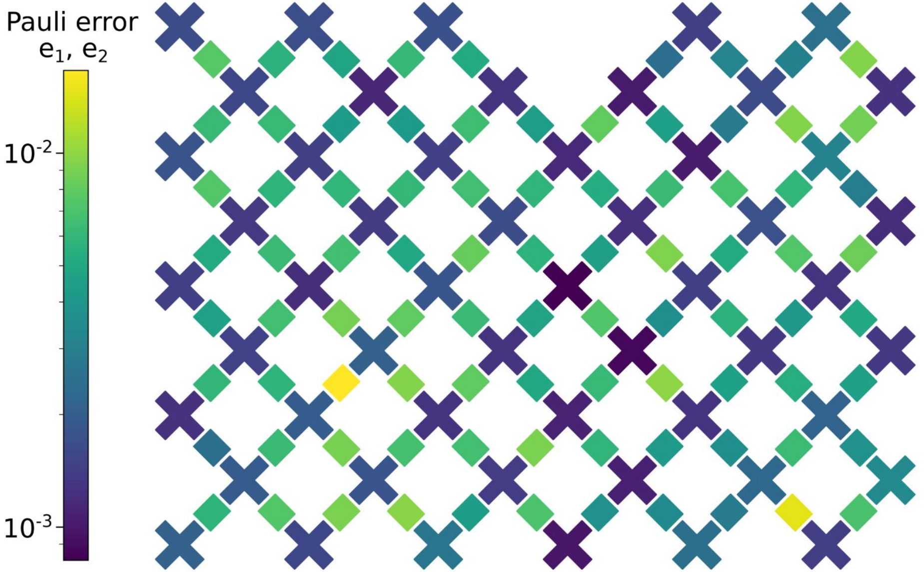
Clifford gate set:
"rotation" to
6 states



Low Errors using Fast 2-Qubit Gates (12 ns)



Average error	Isolated	Simultaneous
Single-qubit (e_1)	0.15%	0.16%
Two-qubit (e_2)	0.36%	0.62%
Two-qubit, cycle (e_{2c})	0.65%	0.93%
Readout (e_r)	3.1%	3.8%



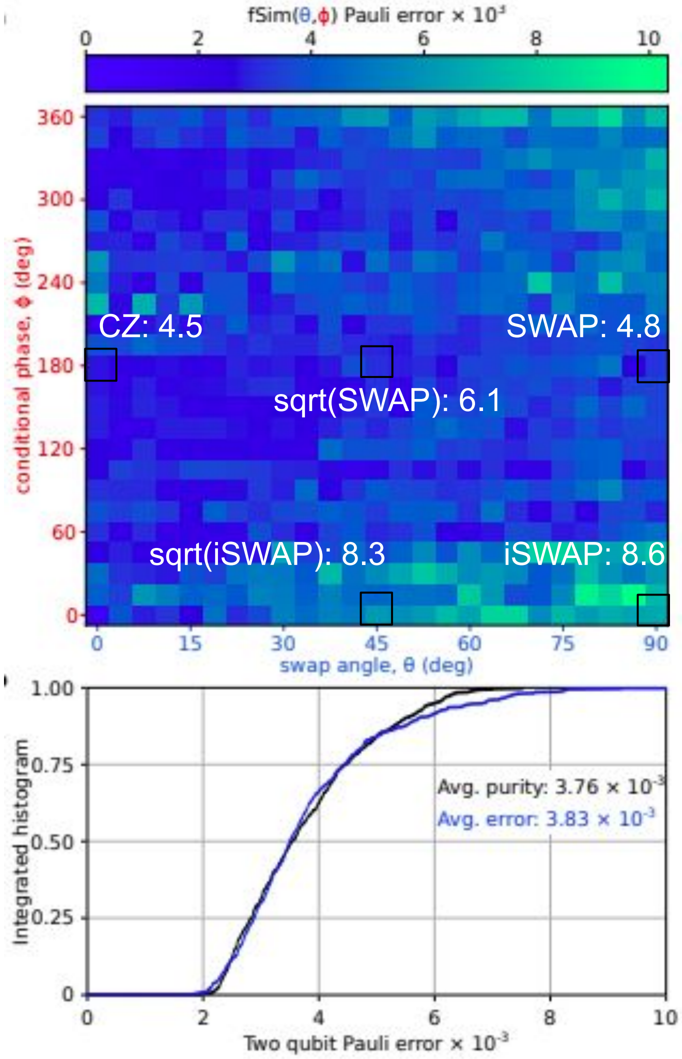
Need to quote:
All qubits
Average and **Simultaneous**

Low Errors for Arbitrary 2-qubit Gates

Excitation preserving unitary
(Fermionic simulation for NISQ)

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\theta) & -i\sin(\theta) & 0 \\ 0 & -i\sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 0 & e^{i\varphi} \end{pmatrix}$$

CZ/CNOT for $\varphi = \pi$



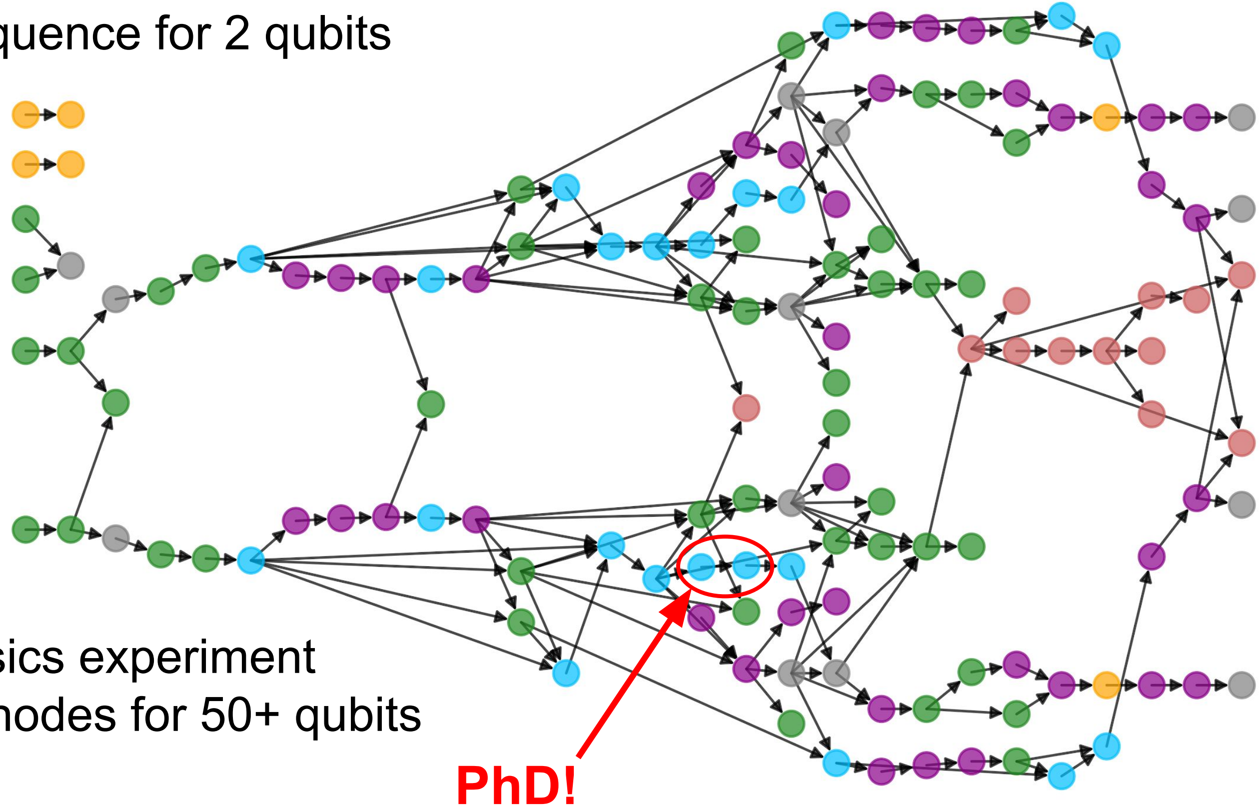
Google AI Quantum

Brooks Foxen, ArXiv 2001.08343

Calibration - Learning how to execute quantum logic

Calibration sequence for 2 qubits

- → Dependency
- Electronics
- Device parameters
- Single qubit gates
- Readout
- Waypoint
- Two qubit gates

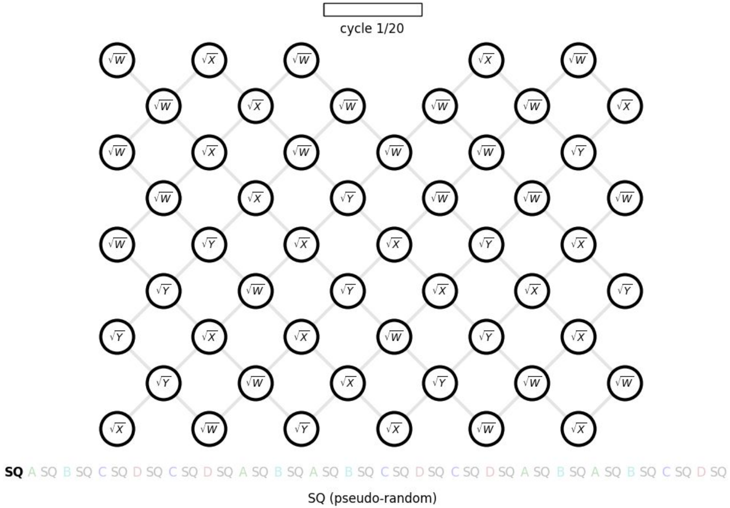


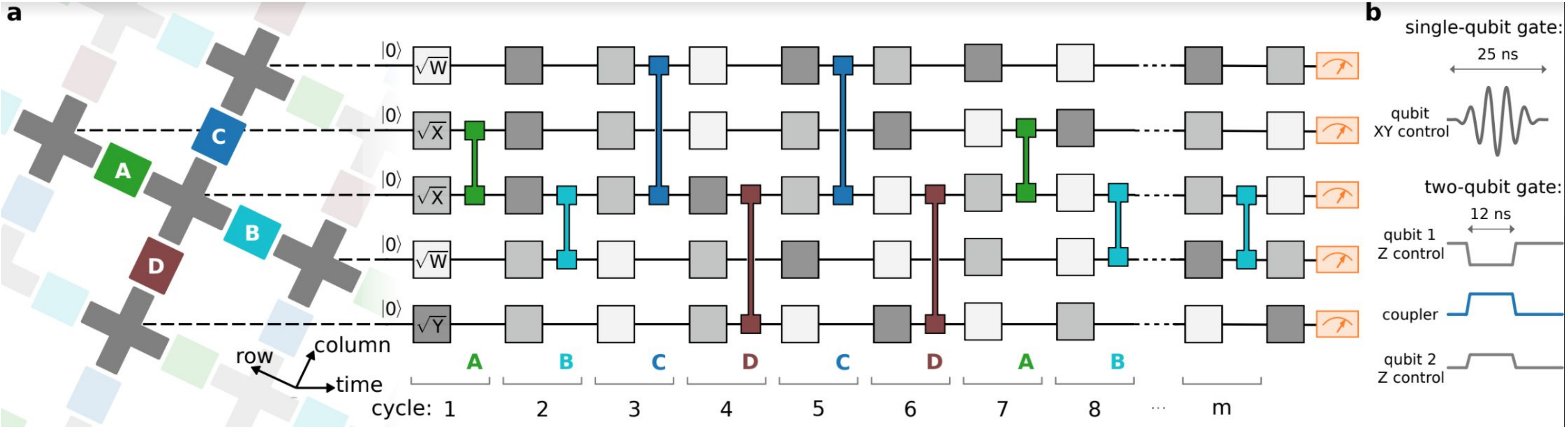
1 node = 1 physics experiment

Thousands of nodes for 50+ qubits

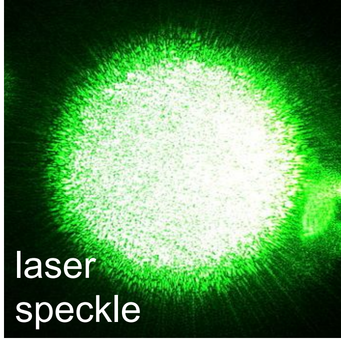
Control Sequence

- General purpose algorithm
  - Cycle with 1- and 2-qubit gates
- Simultaneous gates all qubits
- Simplest circuit for quantum supremacy
  - Pseudo-random 1-qubit gates

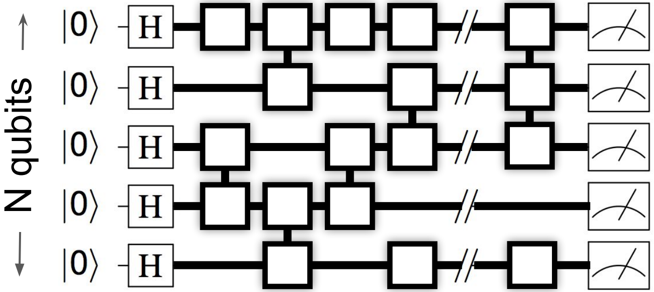


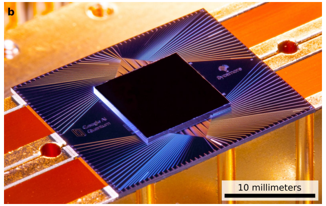


Validation Algorithm for Quantum Supremacy



- Checks general-purpose circuit
- Randomly chosen gates: qubit speckle
  - Sensitive to single qubit errors
  - Complex & difficult to simulate





$\{x_1 \ldots, x_i\}$

$\{p(1)\ldots,p(2^N)\}$

$$F = \langle 2^N p(x_i) - 1 \rangle_i$$

= 1 perfect match

= 0 any error

Google AI Quantum

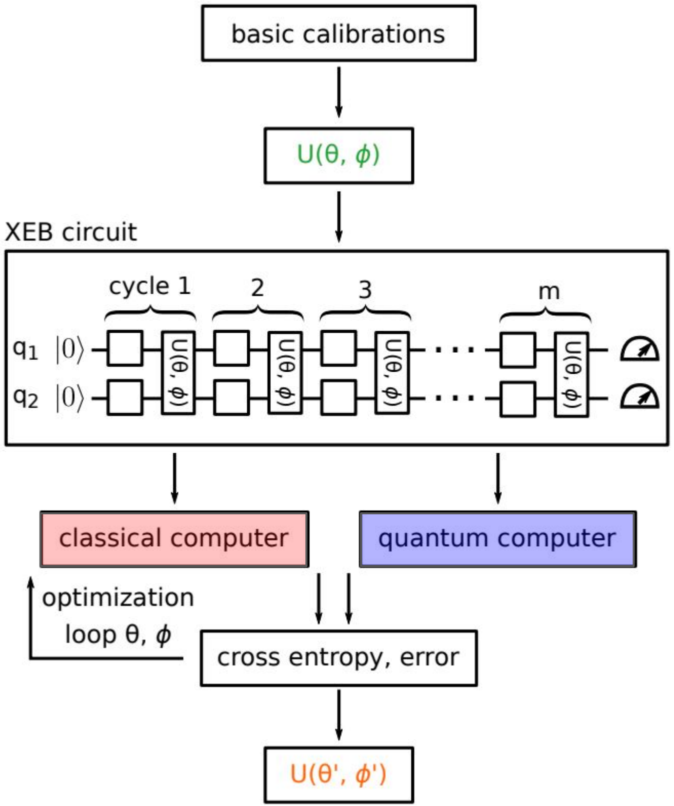
Cross entropy fidelity is useful:

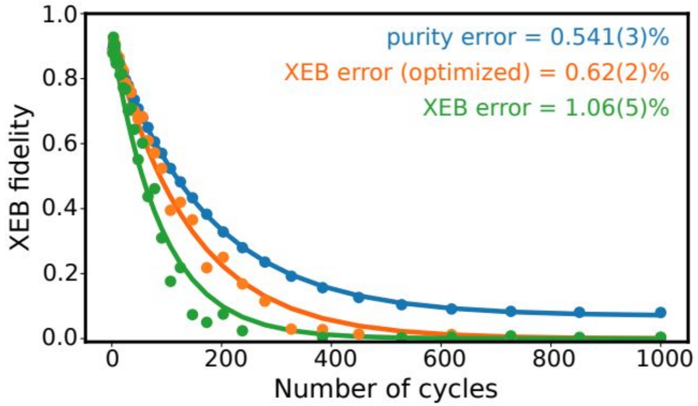
- System validation
- Learn control map

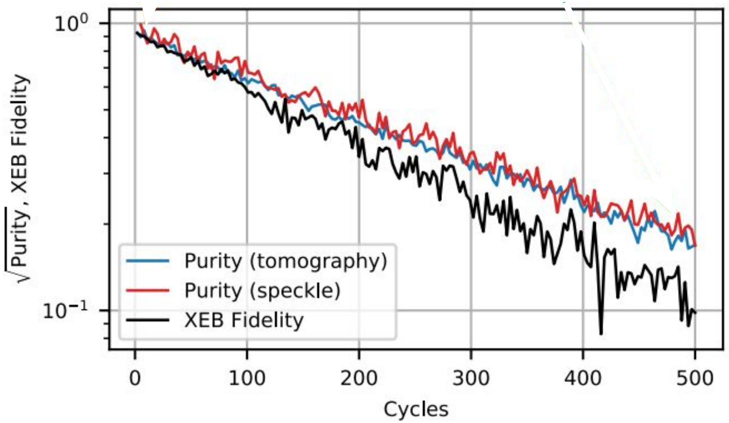
Cross-Entropy Benchmarking (Calibrate & Validate)

$$F = \langle 2^N p(x_i) - 1 \rangle_i$$

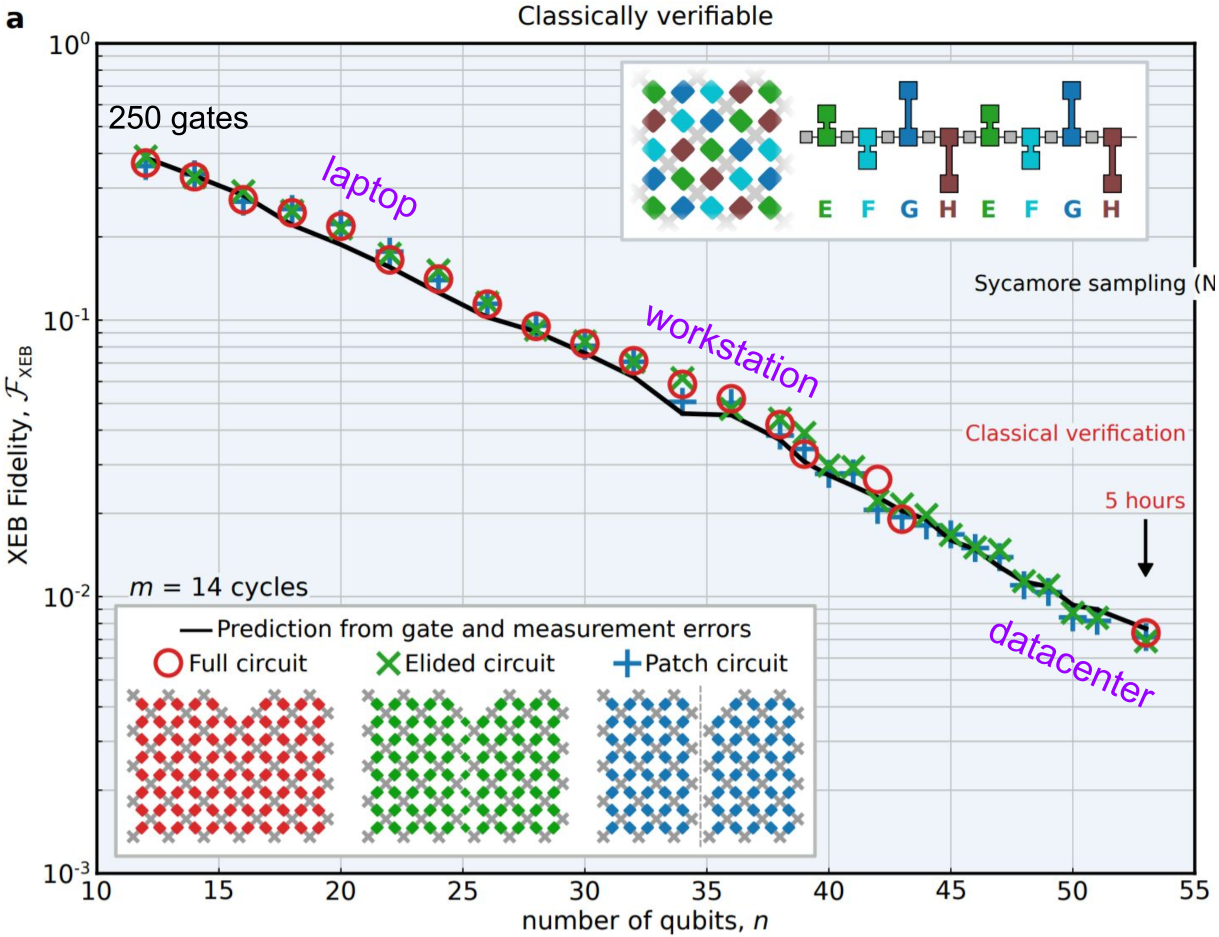
Need to calibrate physical gates: non-Clifford
XEB: measure fidelity, purity (only decoh.), optimize



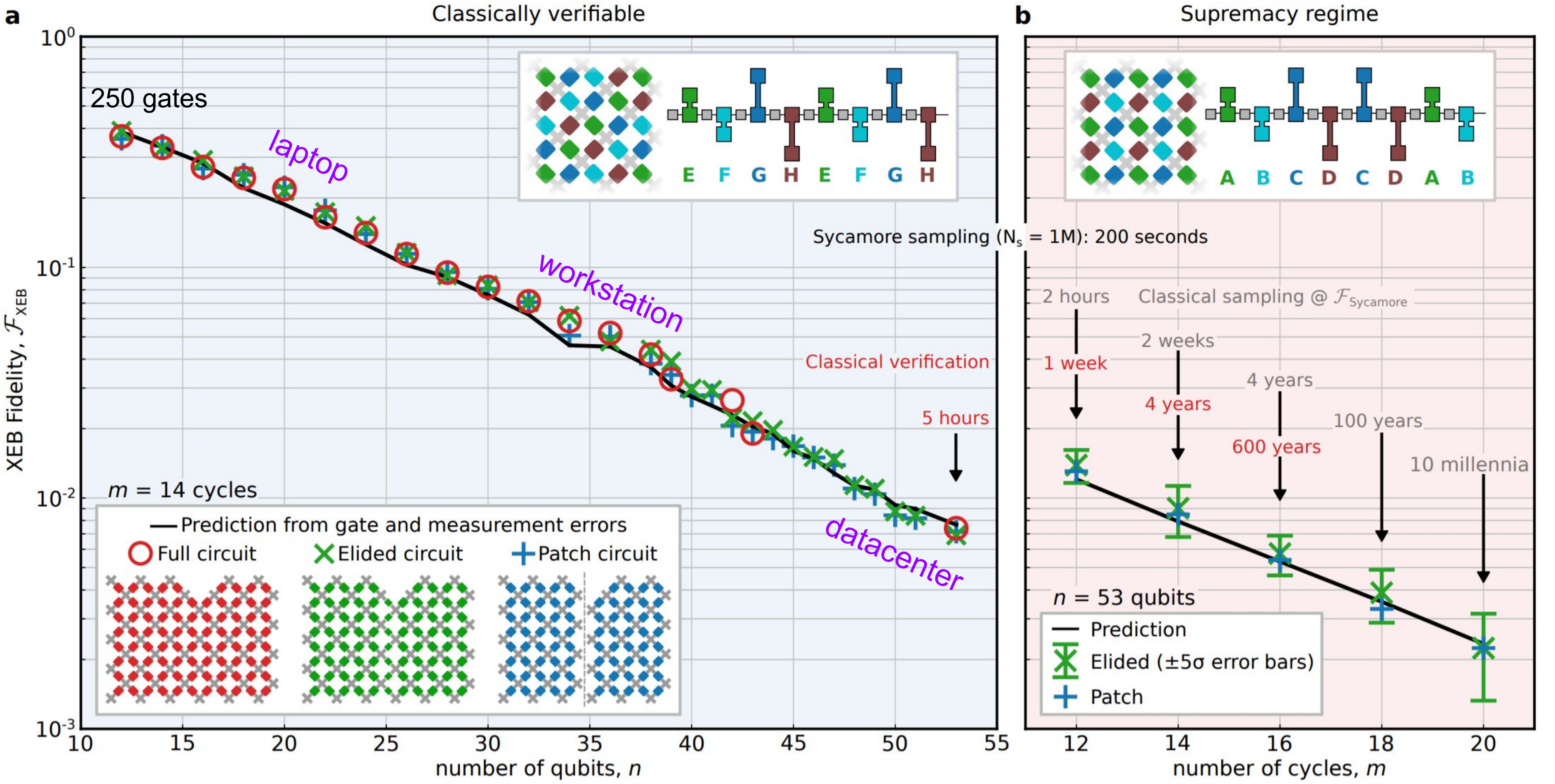




Quantum Supremacy Data



Quantum Supremacy Data



Quantum Science Results

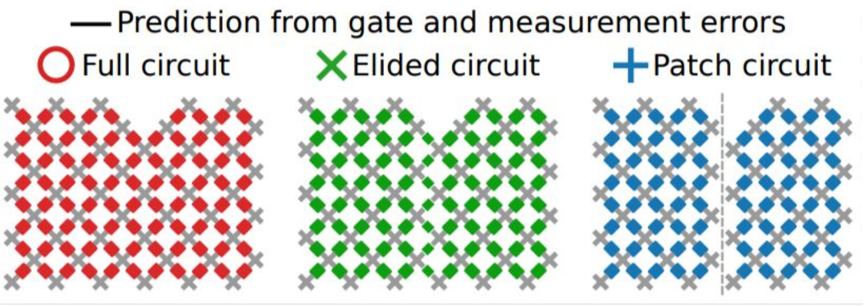
1) Same fidelity: full, elided, patch, predicted
   Errors NOT depend on entanglement
   and computation complexity!

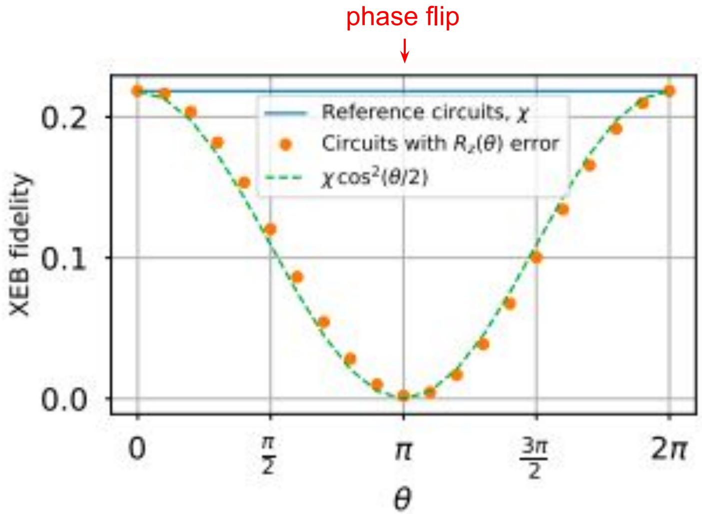
2) No new decoherence physics:
   Probability prediction, Fidelity = $\Pi_i\,(1\text{-}e_i)$
   Error correction should work

3) Quantum works at $2^{53} = 10^{16}$ Hilbert space
   Previously tested to $\sim 10^3$

4) Test model of digitized errors
   One error gives zero fidelity
   Consistent with error probability
   Tests **each** gate (of ~500)

5) Qubit = Quantum + Noise
   complex ampl. simple prob.





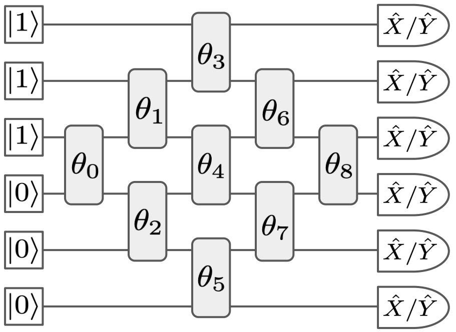
Why No Additional Errors?

1) Low crosstalk design

2) XEB algorithm uses random $NOT^{1/2}$
   a) Equivalent to “slow” spin echos / Dyn. Dec.
   b) Decorrelates noise, especially 1/f drift
   c) (Smallish & uncorrelated noise between qubits)

3) General purpose algorithm might be sensitive to phase
   a) Randomized compiling (gauge transformation)
   b) Add echos

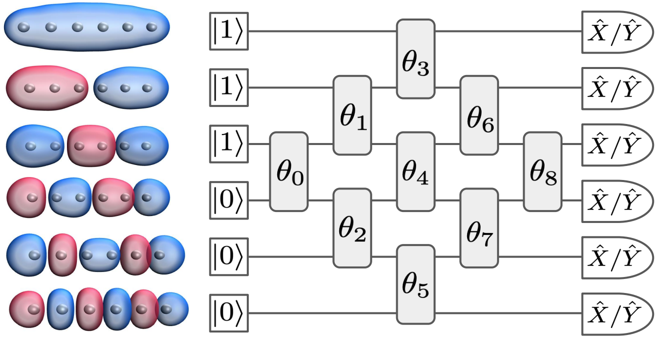
4) Some algorithms can’t echo (e.g. quantum chemistry)
   a) Photon conservation used for post-select
   b) Performance improvement with special calibration e.g phase estimation



Q-Chemistry on Sycamore

1. Compile chemistry to qubits
   a. Hartree-Fock
   b. Fermionic operators, 2nd quant.
   c. Coupling sequence (swaps)
   d. Suite of measurements, ...
2. Run quantum circuit for swap θ's

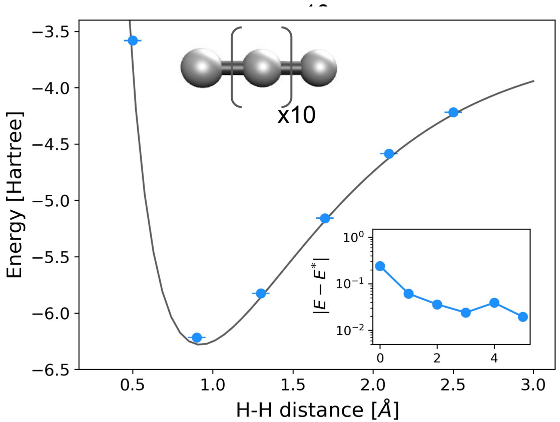
H_6



3. Correct imperfections, to F~99%
   b. Excitation loss
   c. Measurement bias, …
4. Variational optimization of θ's

Google AI Quantum

H_{12} dissociation (Sycamore)

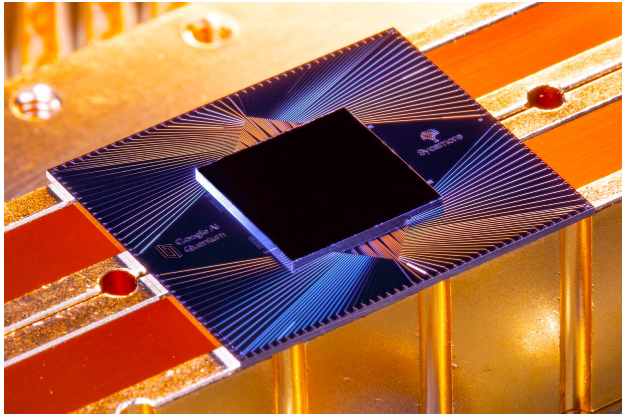


- Double the qubits/electrons as prior largest chemistry simulation
- More than 10X the number of gates

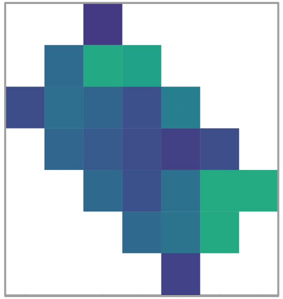
OpenFermion + Cirq +

Google's 23 qubit processor accomplishments

Experiment	# qubits	# gates	Depth of circuit	Gate set
Hartree-Fock	12	204	38	sqrt(iSWAP)
QAOA	23	3,281	153	sycamore
OTOC	17	1,500	45	sqrt(iSWAP)
Fermi-Hubbard	16	5,059	491	sqrt(iSWAP)
CRNG	23	457	29	sycamore



Architecture	Sycamore
Processor	rainbow
Qubits	23



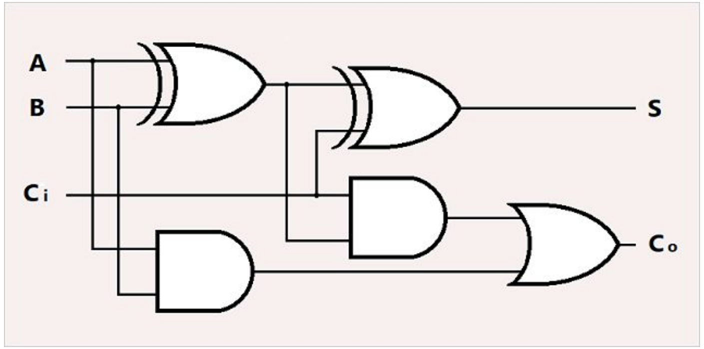
Quantum Volume-ish
1000's of gates

Google AI Quantum

Programing with Circuits, Errors

Classical (CMOS)

space

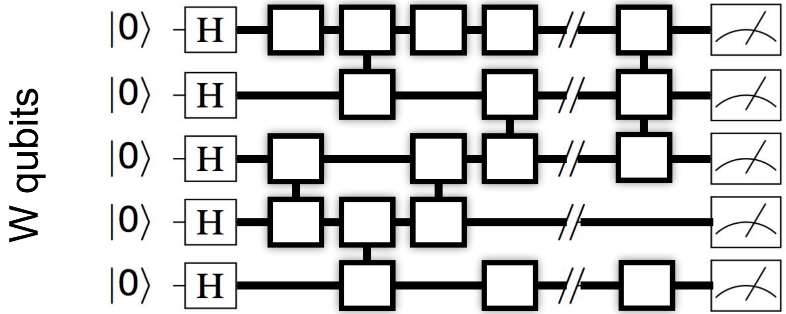


$N_{logic} \sim 1/err_{logic}$

1960's: err = 10^{-3} TTL
2020: err = 10^{-11} M1

Quantum

time (depth D)



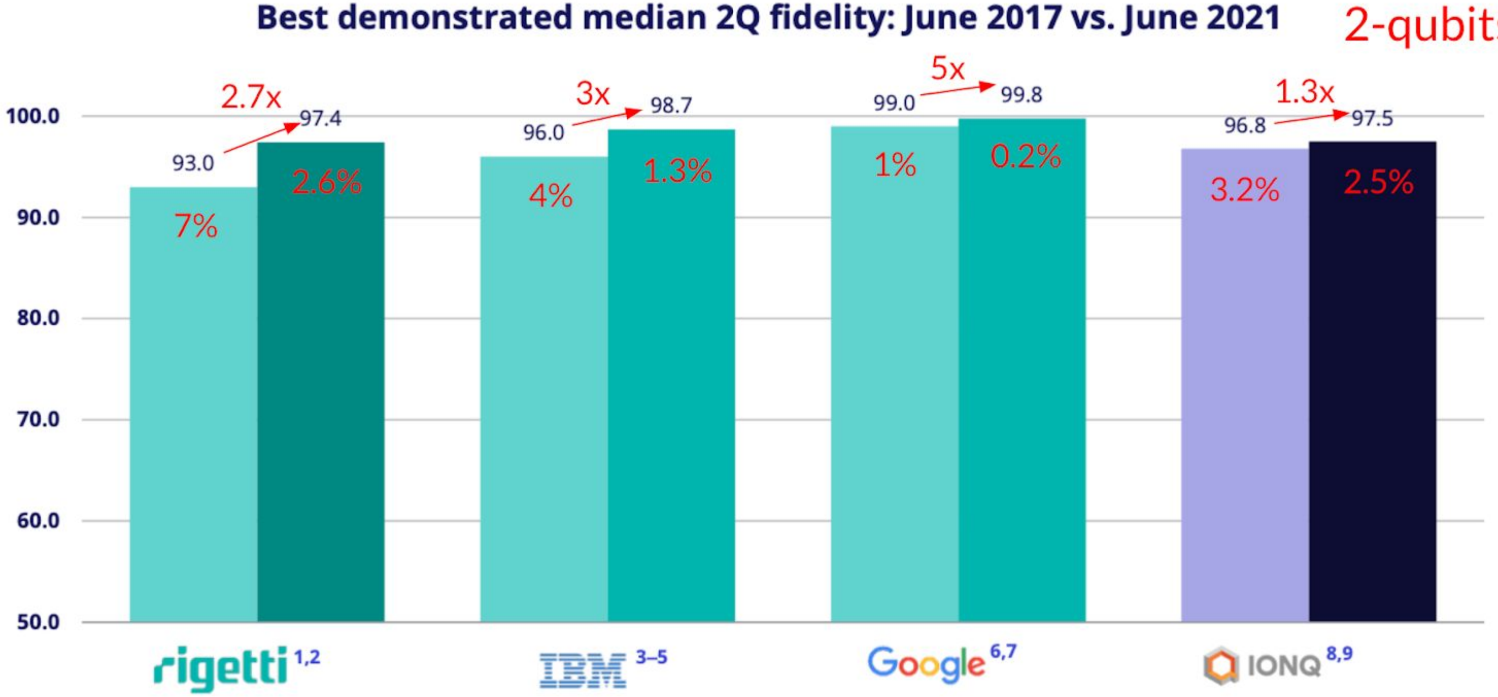
$W\,D \sim 1/err_{gate}$ = coherence time / gate time

W = 100	err = 10^{-2}	D ~ 1
	err = 10^{-4}	D ~ 100

Showstopper: Large Errors for Leading Projects

~~Fastest~~ rate of progress on increasing fidelity

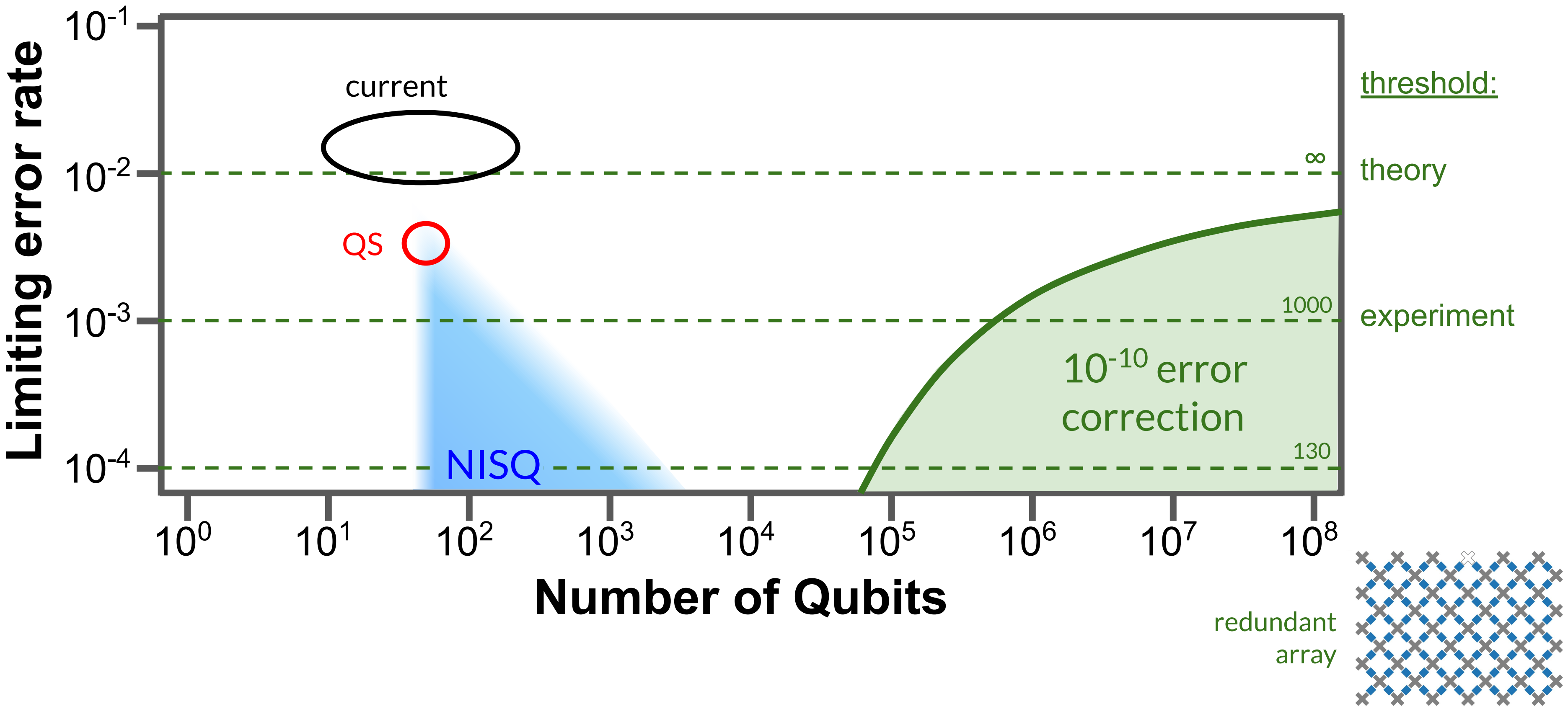
Fake News: best result, 2-qubits

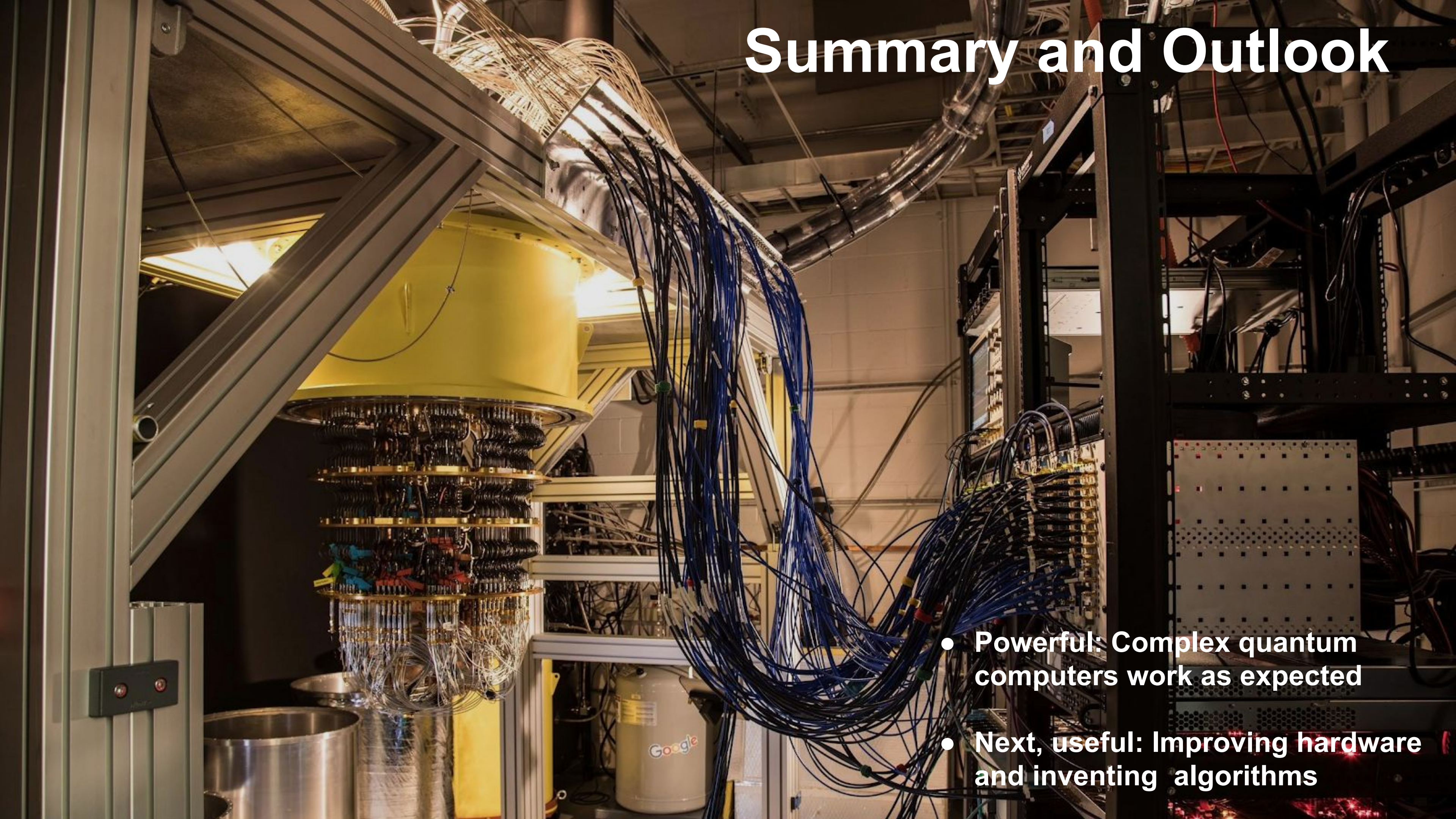


1 Reagor, M., et al. "Demonstration of Universal Parametric Entangling Gates on a Multi-Qubit Lattice." Science Advances, vol. 4, no. 2, Feb. 2018, p. eaao3603. arXiv.org, doi:10.1126/sciadv.aao3603. 2 Rigetti internal data, March 4, 2021 3 "A Quantum Experience at Maker Faire." IBM Research Blog, 19 May 2017. 4 Wang, Yuanhao, et al. "16-Qubit IBM Universal Quantum Computer Can Be Fully Entangled." Npj Quantum Information, vol. 4, no. 1, Sept. 2018, pp. 1–6. www.nature.com, doi:10.1038/s41534-018-0095-x. 5 Zhang, Eric J., et al. "High-Fidelity Superconducting Quantum Processors via Laser-Annealing of Transmon Qubits." ArXiv:2012.08475 [Quant-Ph], Dec. 2020. arXiv.org. 6 Kelly, J., et al. "State Preservation by Repetitive Error Detection in a Superconducting Quantum Circuit." Nature, vol. 519, no. 7541, Mar. 2015, pp. 66–69. www.nature.com, doi:10.1038/nature14270. 7 Arute, Frank, et al. "Quantum Supremacy Using a Programmable Superconducting Processor." Nature, vol. 574, no. 7779, Oct. 2019, pp. 505–10. www.nature.com, doi:10.1038/s41586-019-1666-5. 8 Debnath, S., et al. "Demonstration of a Small Programmable Quantum Computer with Atomic Qubits." Nature, vol. 536, no. 7614, Aug. 2016, pp. 63–

rigetti

Qubit Quantity and Quality Matter (+ others)





Summary and Outlook

- **Powerful: Complex quantum computers work as expected**
- **Next, useful: Improving hardware and inventing algorithms**

The Team