Quantum Supremacy using a Programmable Superconducting Processor

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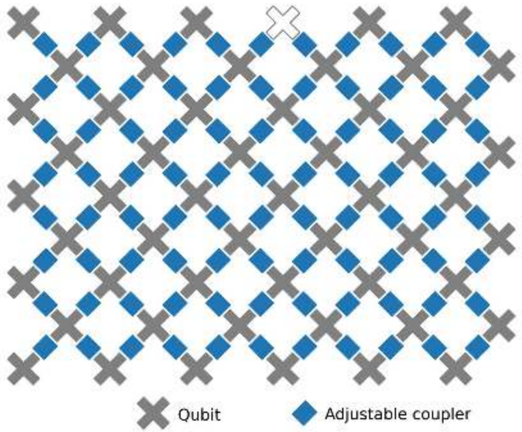
Google & UCSB

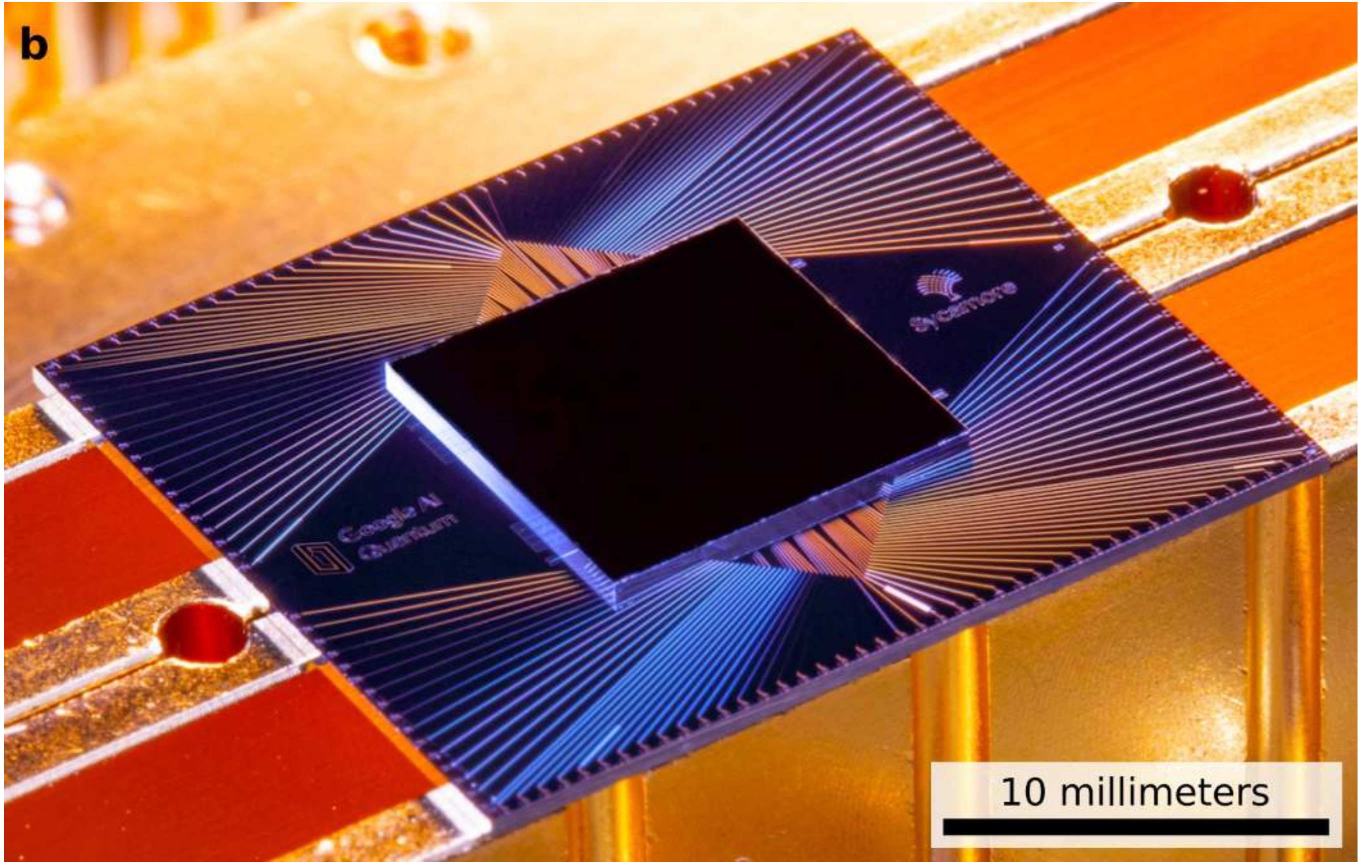
- New design, scalable and low 1&2 qubit errors
- Quantum supremacy achieved
    - 200s quantum computer, checked 10k yr
- Computation on 10^{16} state (Hilbert) space
- Fidelity validated with 1&2 qubit errors
    - No additional decoherence physics when scaled
- First useful application: certified random numbers
- Beginning of NISQ era with powerful processors

Sycamore Processor: 54 qubits

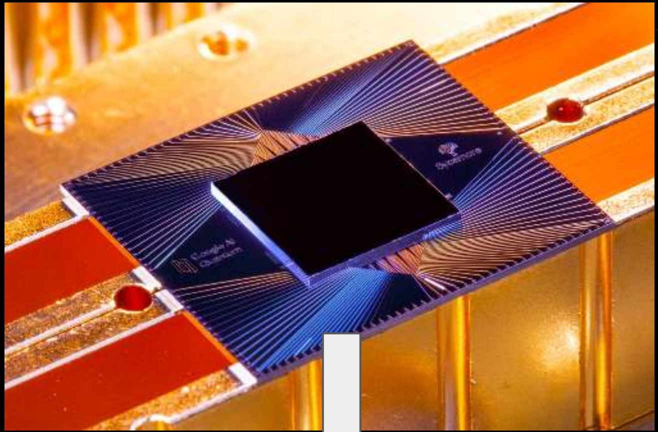


New

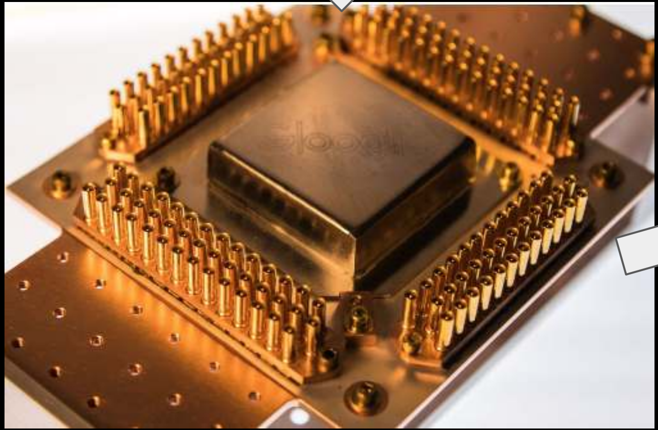
fast
low errors

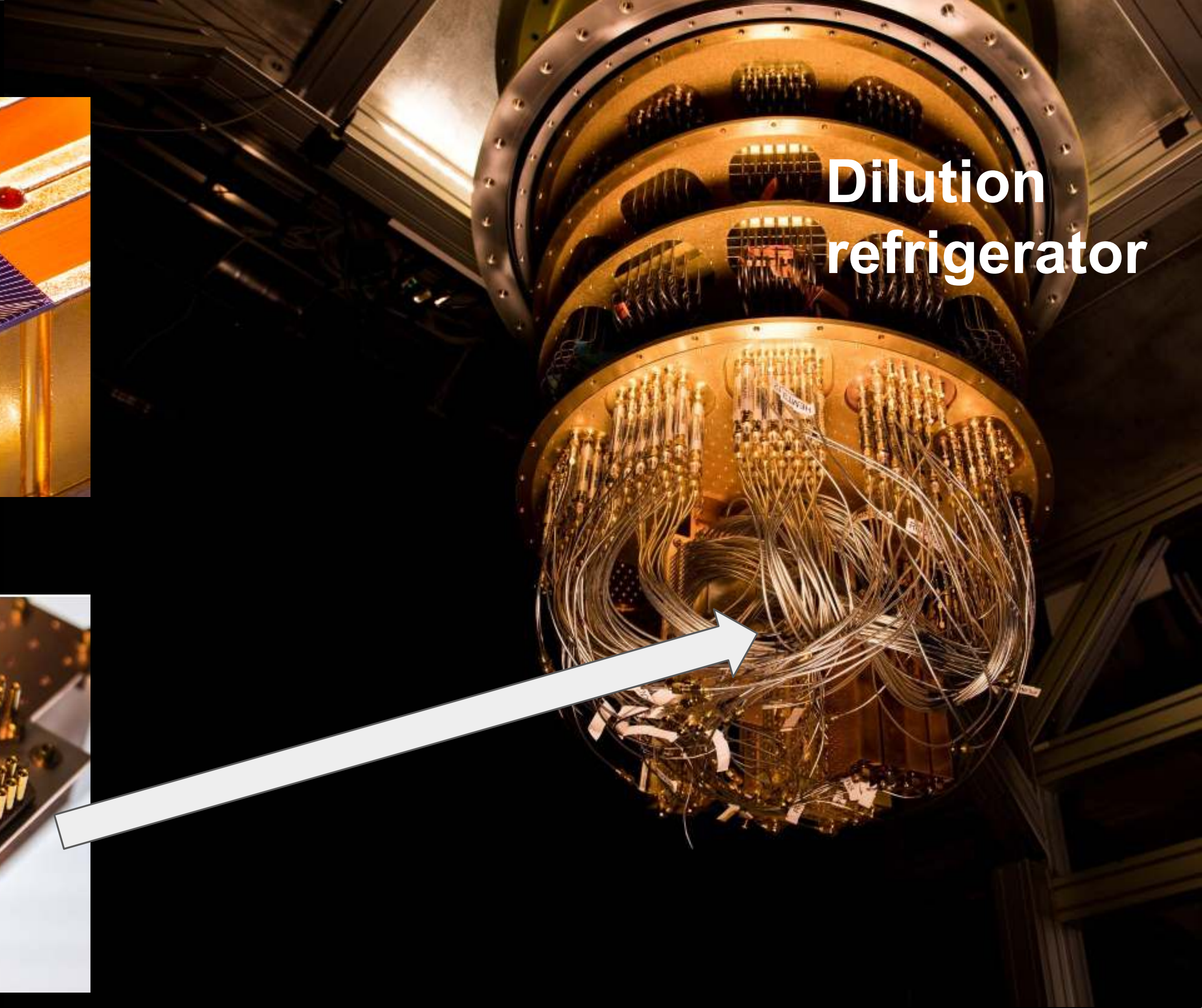


Fabrication



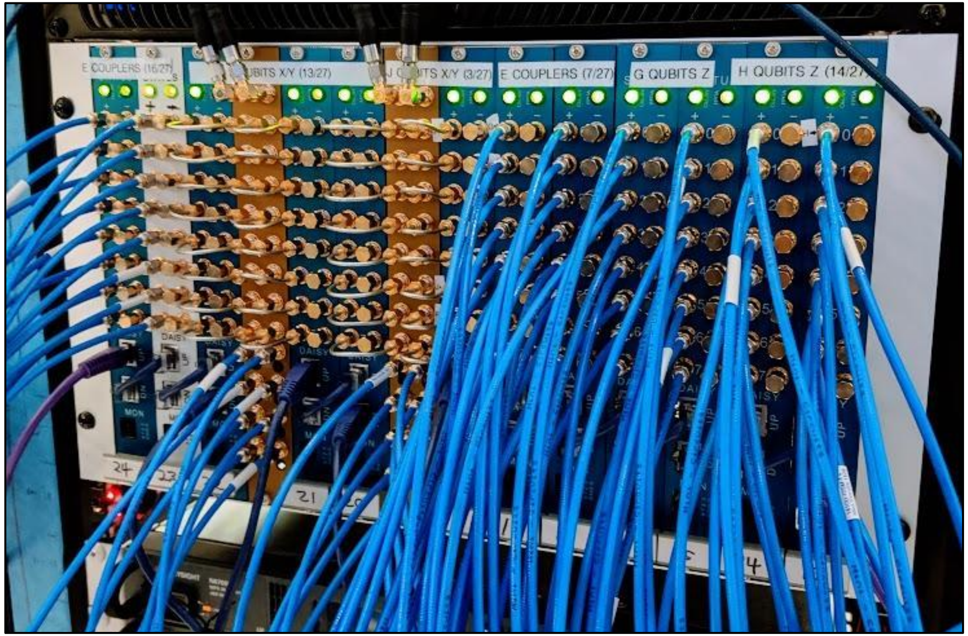
Packaging



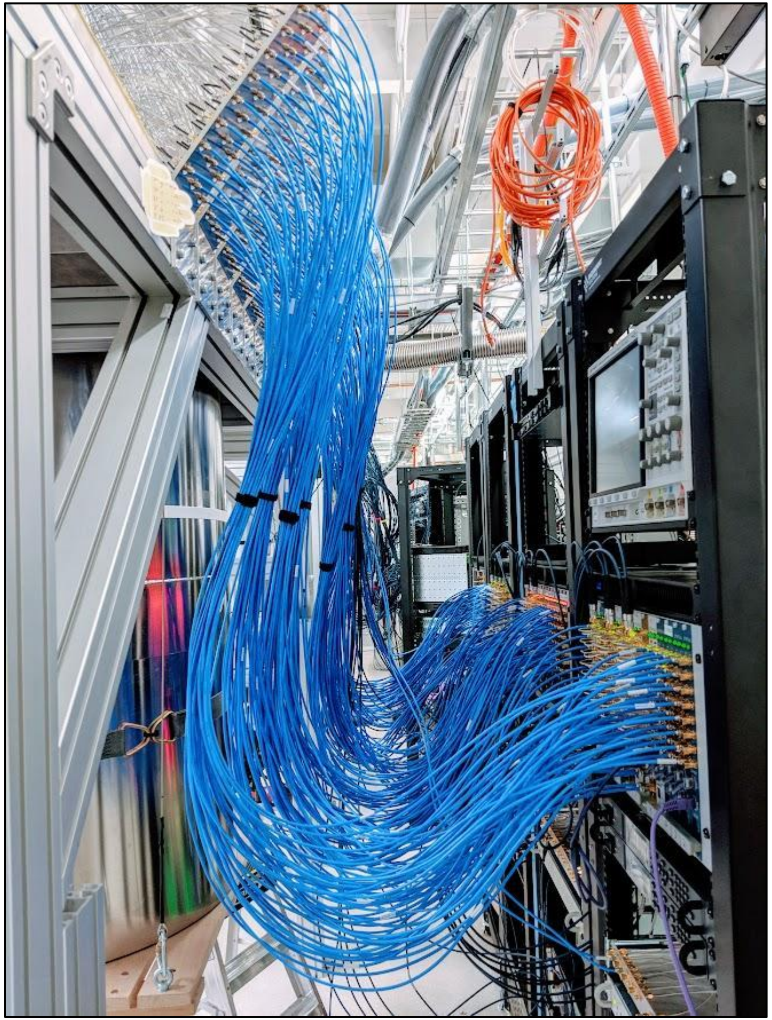


Dilution refrigerator

Control Hardware



Custom built
High speed
High precision



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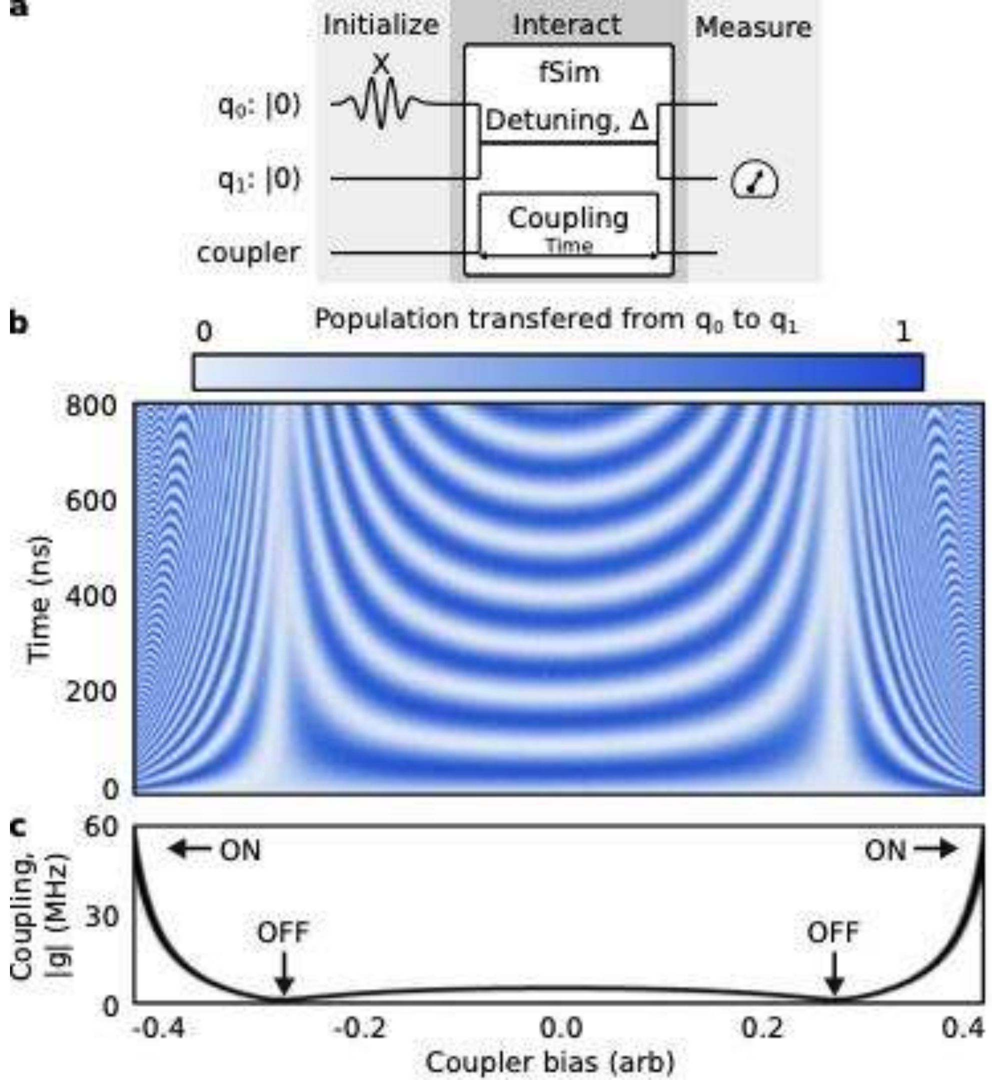
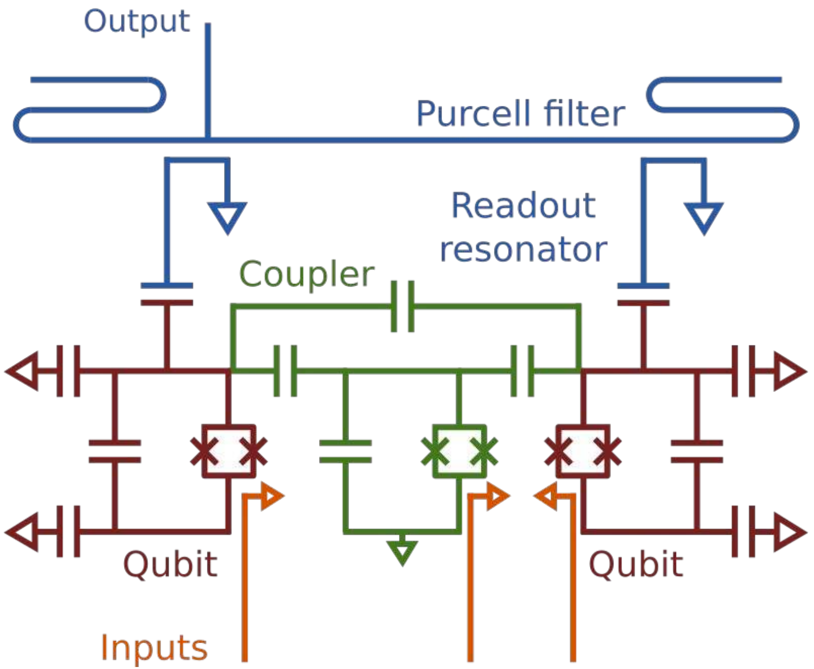
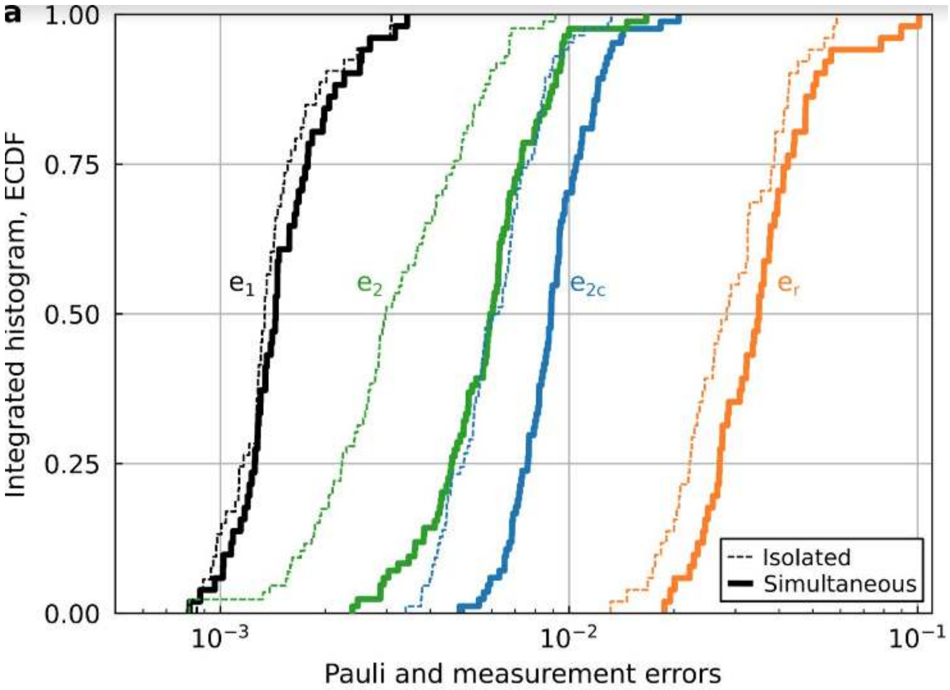
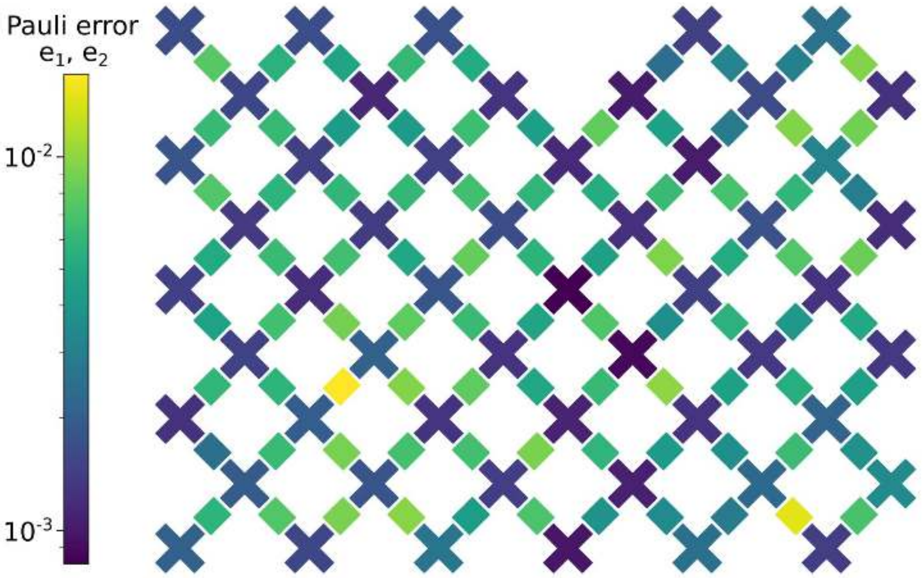
2-qubit Swap Calibration





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%

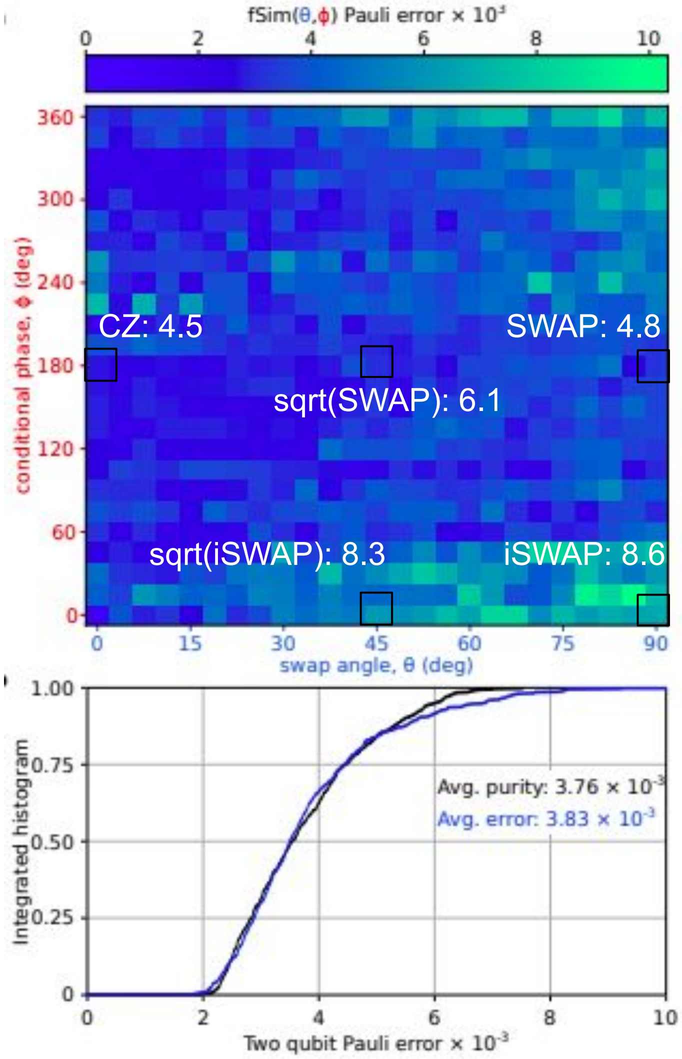
Need to quote
Average and **Simultaneous**

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 $\varphi = \pi$



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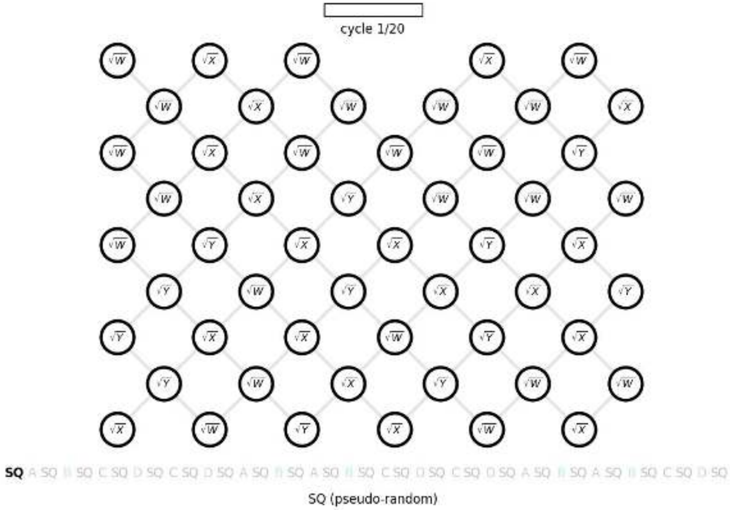
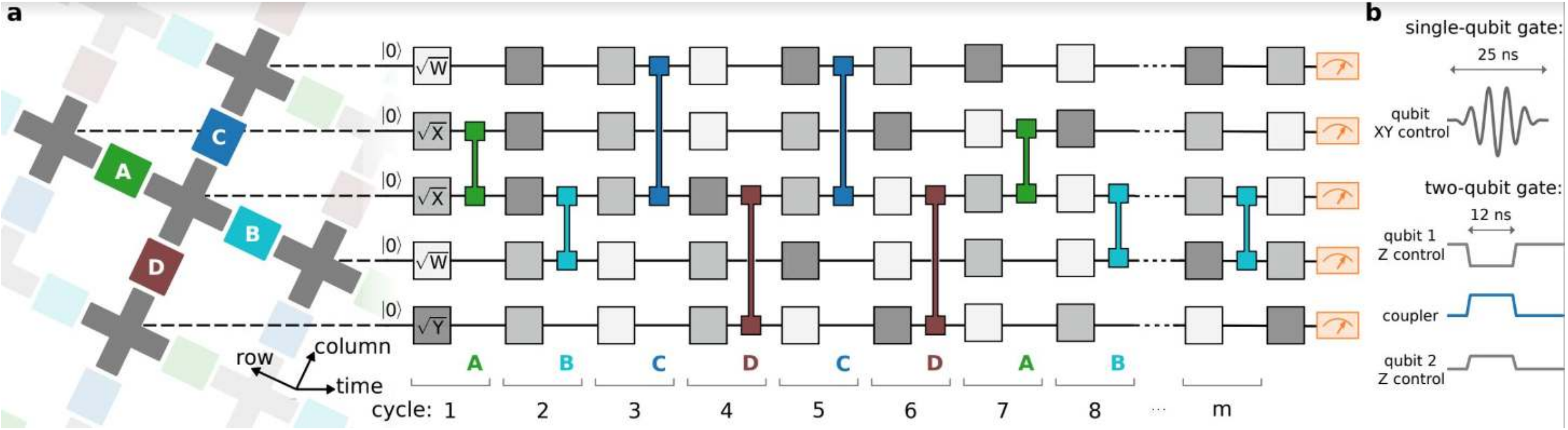
Brooks Foxen, ArXiv 2001.08343

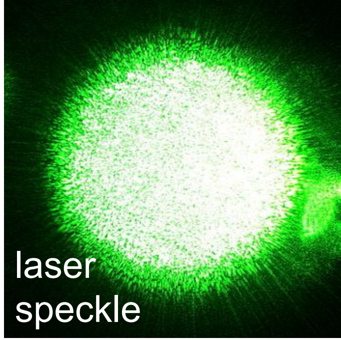
Control Sequence

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

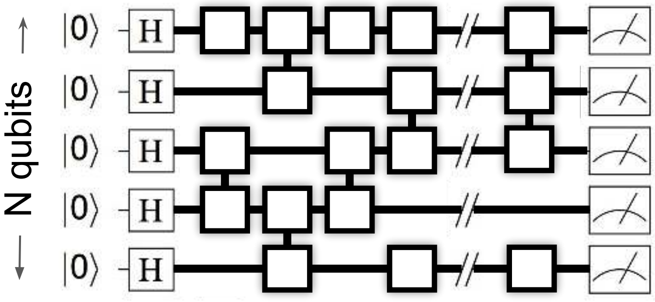


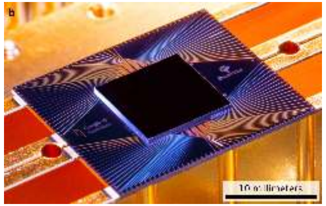


Validation Algorithm for Quantum Supremacy



- 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

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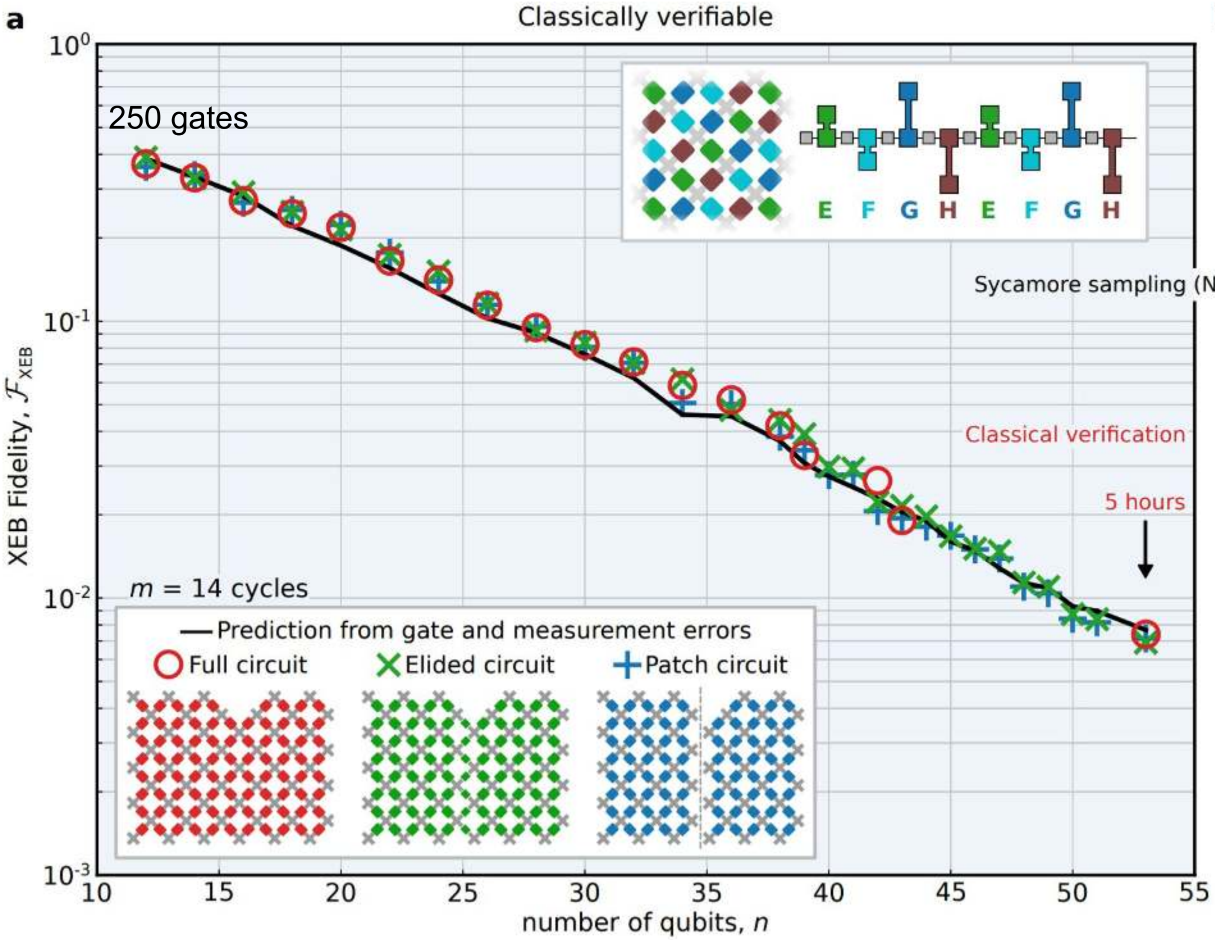
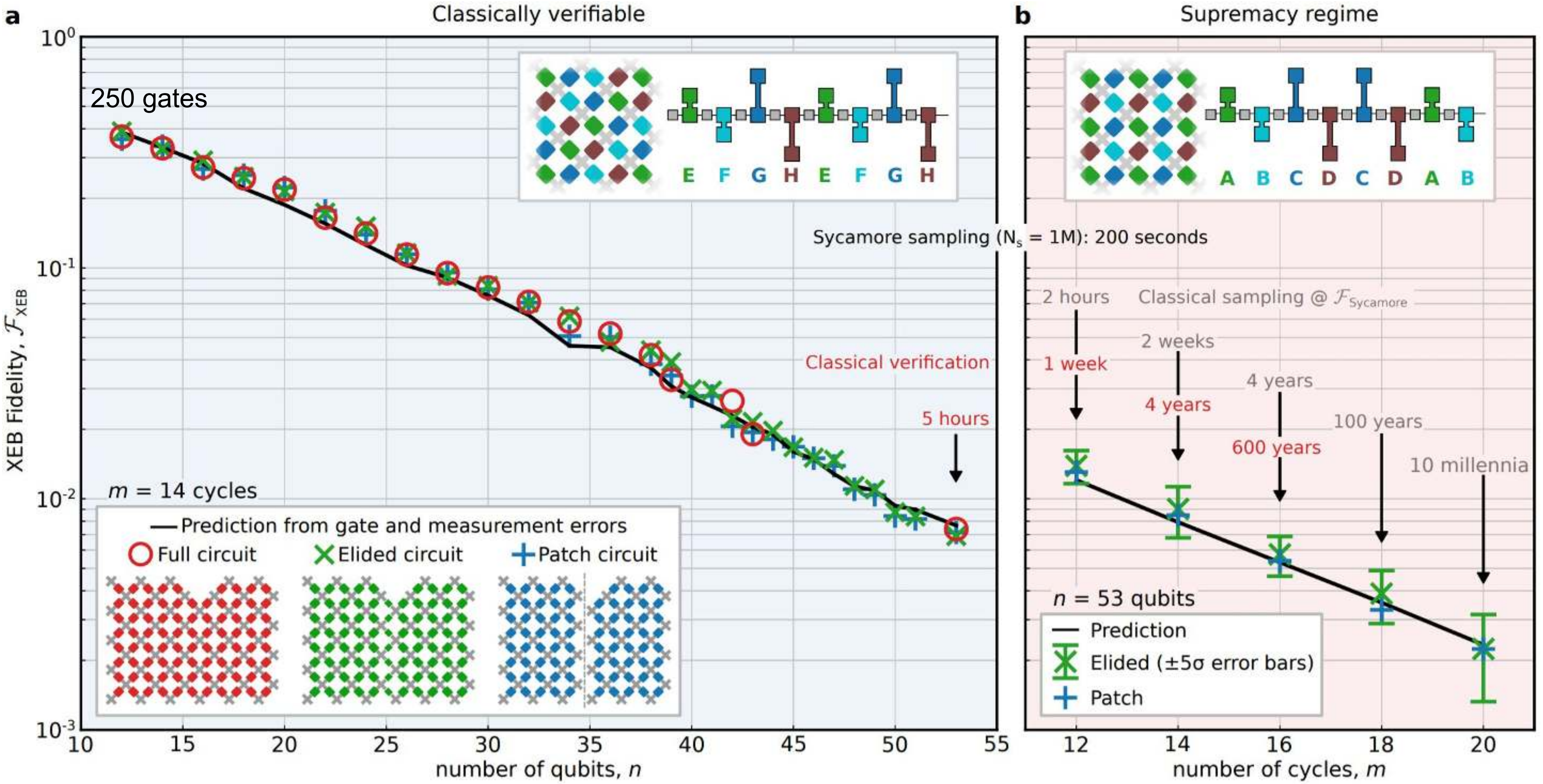
Cross entropy fidelity is useful:

- System validation
- Learn control map

Quantum Supremacy Data



Quantum Supremacy Data



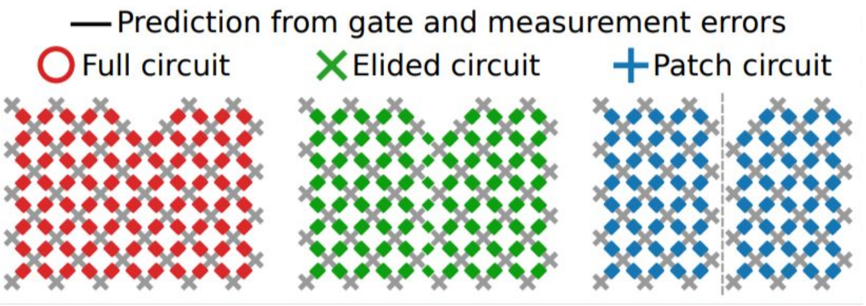
Quantum Science Results

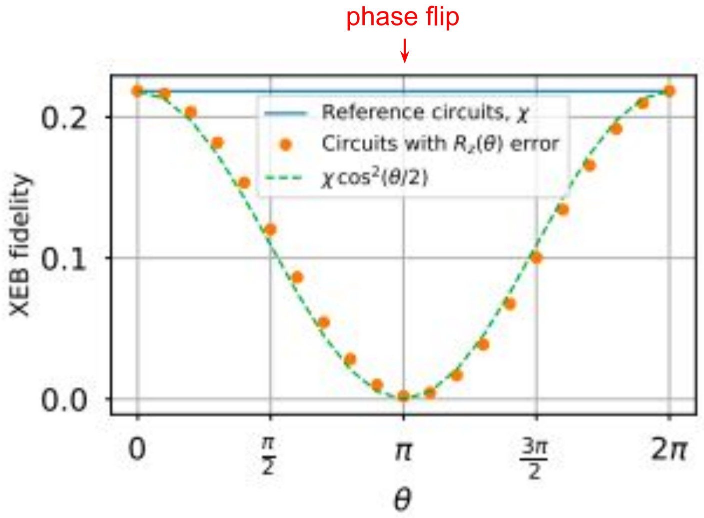
1) Same fidelity: full, elided, patch, predicted
   Errors NOT depend on entanglement
   and computation complexity!

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

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

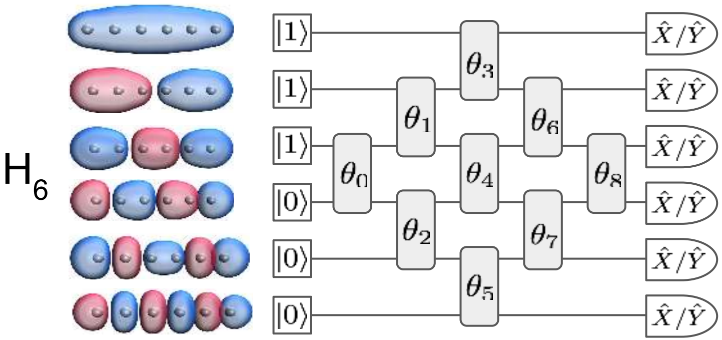
1) Test model of digitized errors
   One error gives zero fidelity
   Consistent with error probability
   Tests **each** gate (of ~500)





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



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

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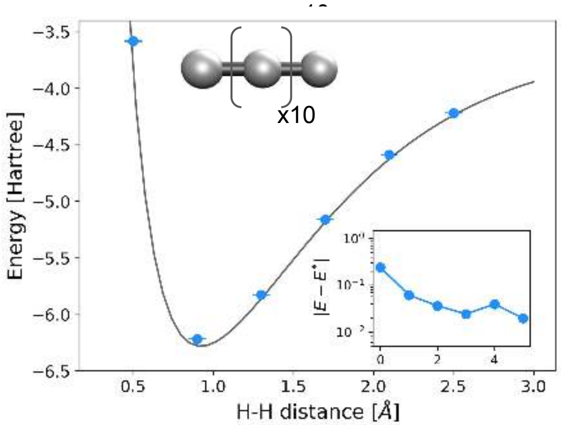
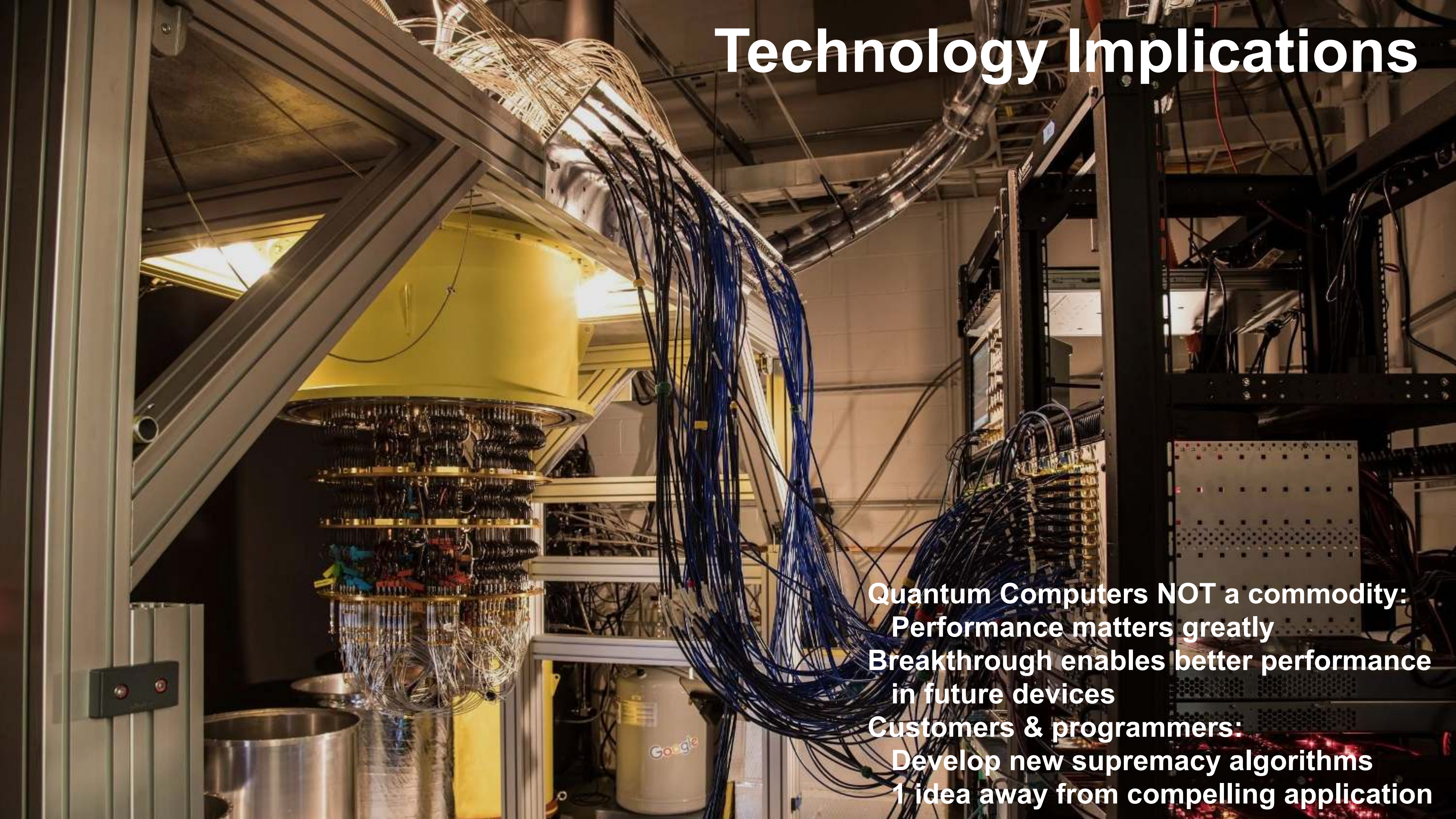
H_{12} dissociation (Sycamore)



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

OpenFermion + Cirq +

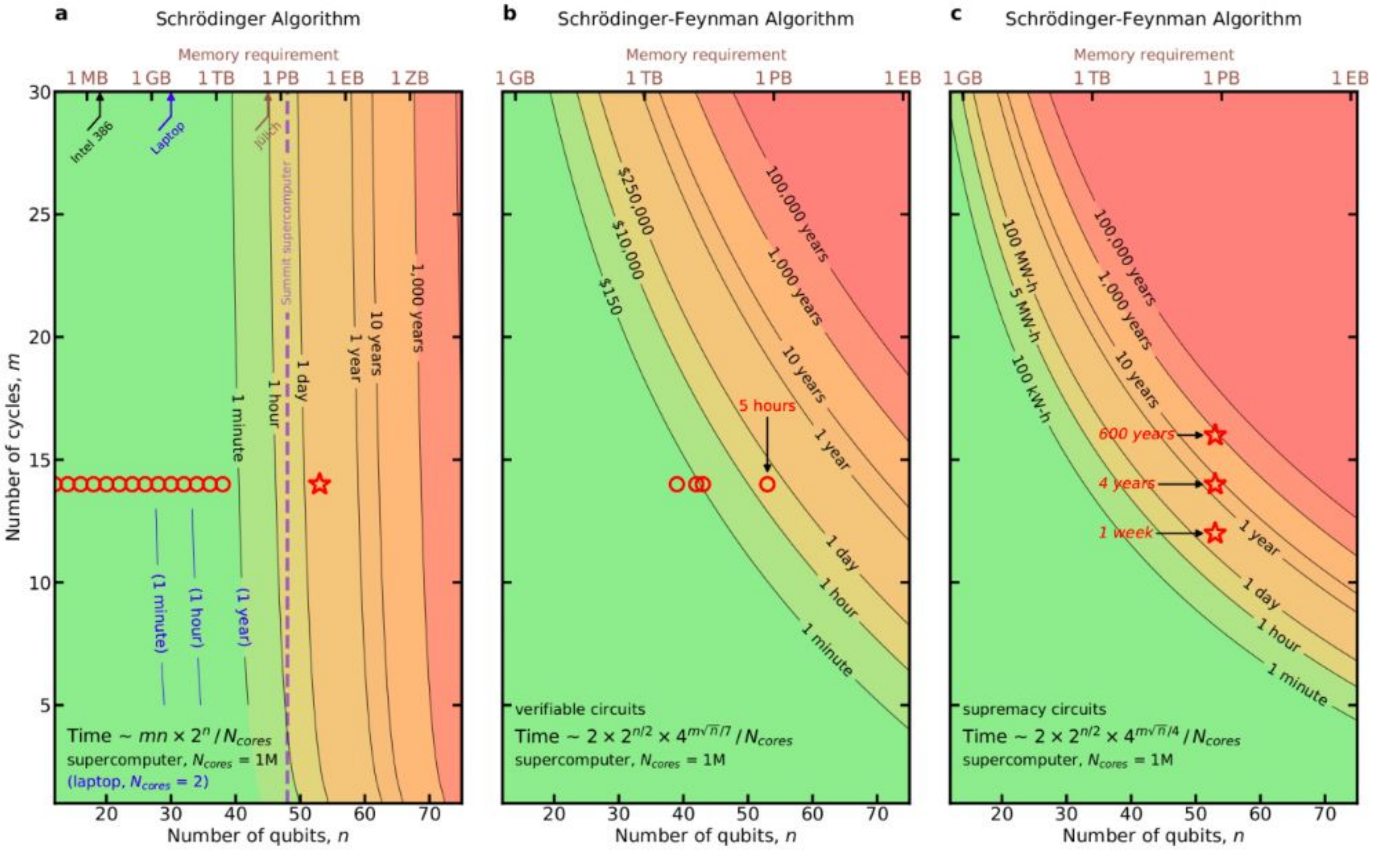
Technology Implications



- Quantum Computers NOT a commodity:
  - Performance matters greatly
- Breakthrough enables better performance in future devices
- Customers & programmers:
  - Develop new supremacy algorithms
  - 1 idea away from compelling application

The Team

Simulation Cost

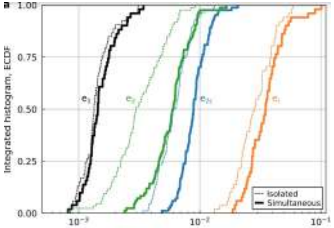


Improving Computer Simulation

- “We expect that lower simulation costs than reported here will eventually be achieved, but we also expect that they will be consistently outpaced by hardware improvements on larger quantum processors.”

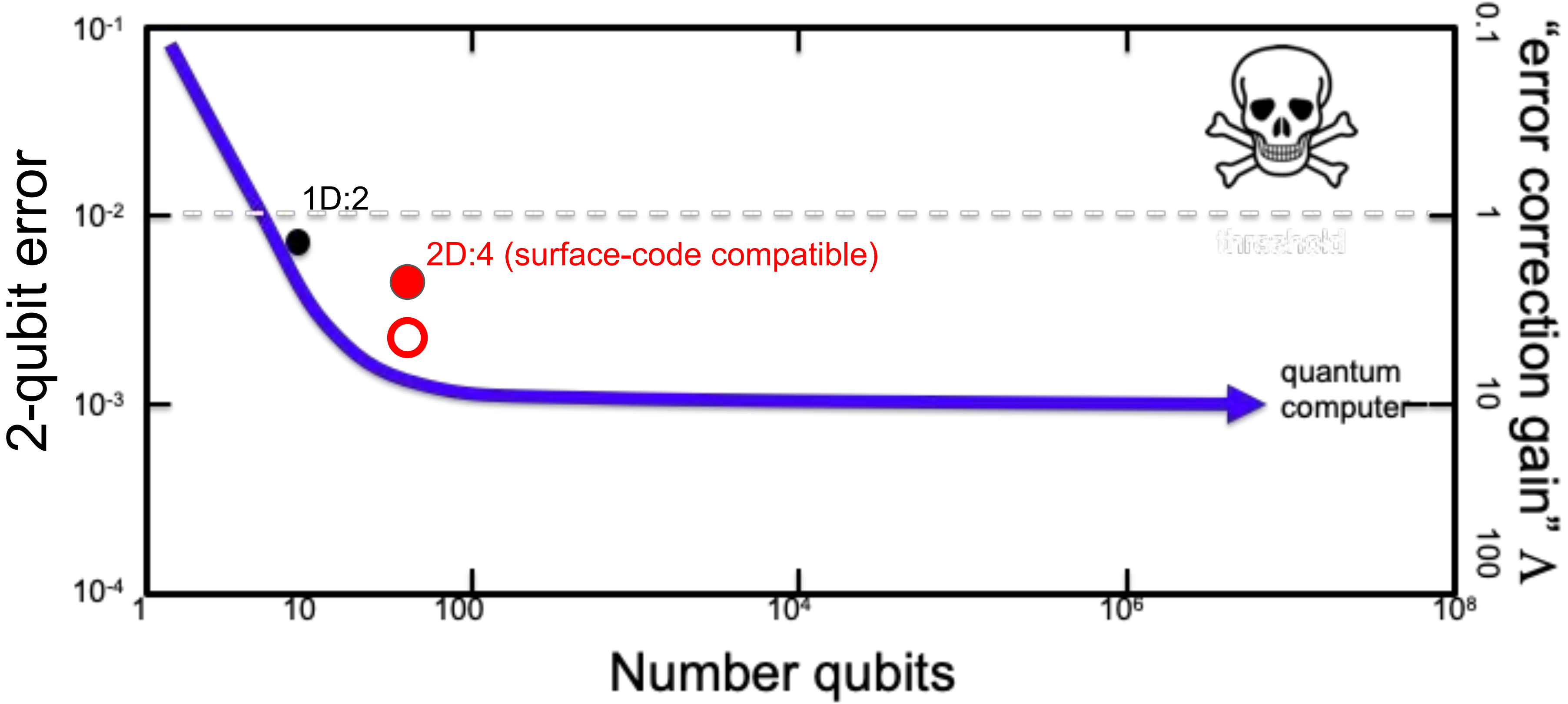
- Strongly support **running** validation programs
  - Tricky to write efficient supercomputer code, failures
  - IBM: non-standard use of disk memory
  - All data posted for checking

- Absolutely guarantee a 57+ qubit Sycamore processor
  - First processor successful
  - Did not collapse over finish line



- Distraction from real issue: quantum-hardware performance

Progress Towards Error Correction



In same device:
more qubits and connectivity, lower errors