Quantum Supremacy and Noisy Intermediate Scale Quantum Computing

Michael J. Hartmann

FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

Google AI Quantum

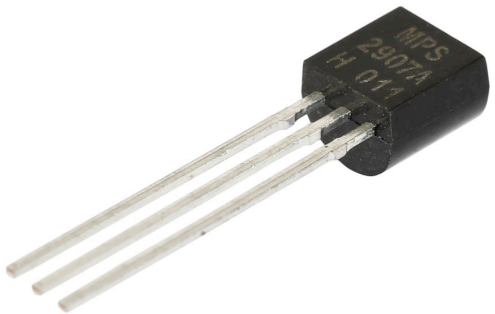
Classical Computers

represent numbers as binaries:

$0 \rightarrow 0$
$1 \rightarrow 1$
$2 \rightarrow 10$
$3 \rightarrow 11$
$4 \rightarrow 100$
$5 \rightarrow 101$
$6 \rightarrow 110$
$7 \rightarrow 111$
$8 \rightarrow 1000$
$9 \rightarrow 1001$

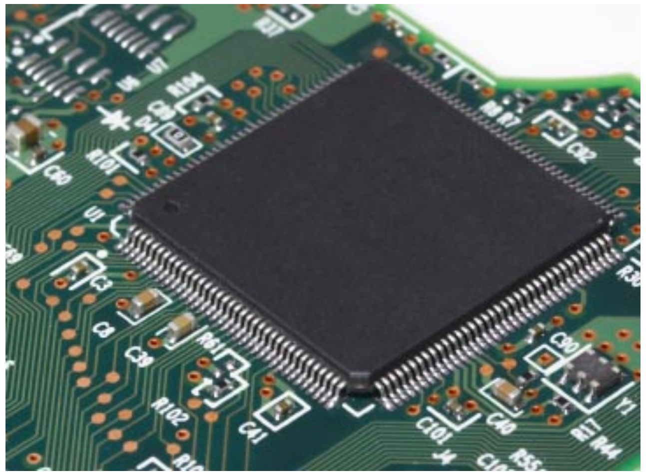
1: high voltage
0: low voltage
← bit

logical operations:
transistors



voltage in one wire controls
voltage on other wires

many transistors integrated
in chip of modern processor
e.g. iPhone 11 Pro:
8,500,000,000 transistors



How many transistors in this room?

Quantum Mechanics

dynamics: $$\frac{\partial}{\partial t}\psi(x,t) = -\frac{i}{\hbar}\mathcal{H}(x)\,\psi(x,t)$$ Schrödinger equation

$|\psi(x,t)|^2$ probability to find object at position x (at time t)

linear equation → $$\frac{\psi(x,t)+\phi(x,t)}{\sqrt{2}}$$ is also possible

superposition

boundary conditions → discrete basis for wave functions

2 dimensions: $\rightarrow |0\rangle$

quantum bit or qubit $\rightarrow |1\rangle$

Many Quantum Bits

1 qubit: $|\psi\rangle = c_0|0\rangle + c_1|1\rangle$ 2 coefficients

2 qubits: $|\psi\rangle = c_{00}|00\rangle + c_{01}|01\rangle + c_{10}|10\rangle + c_{11}|11\rangle$

4 coefficients

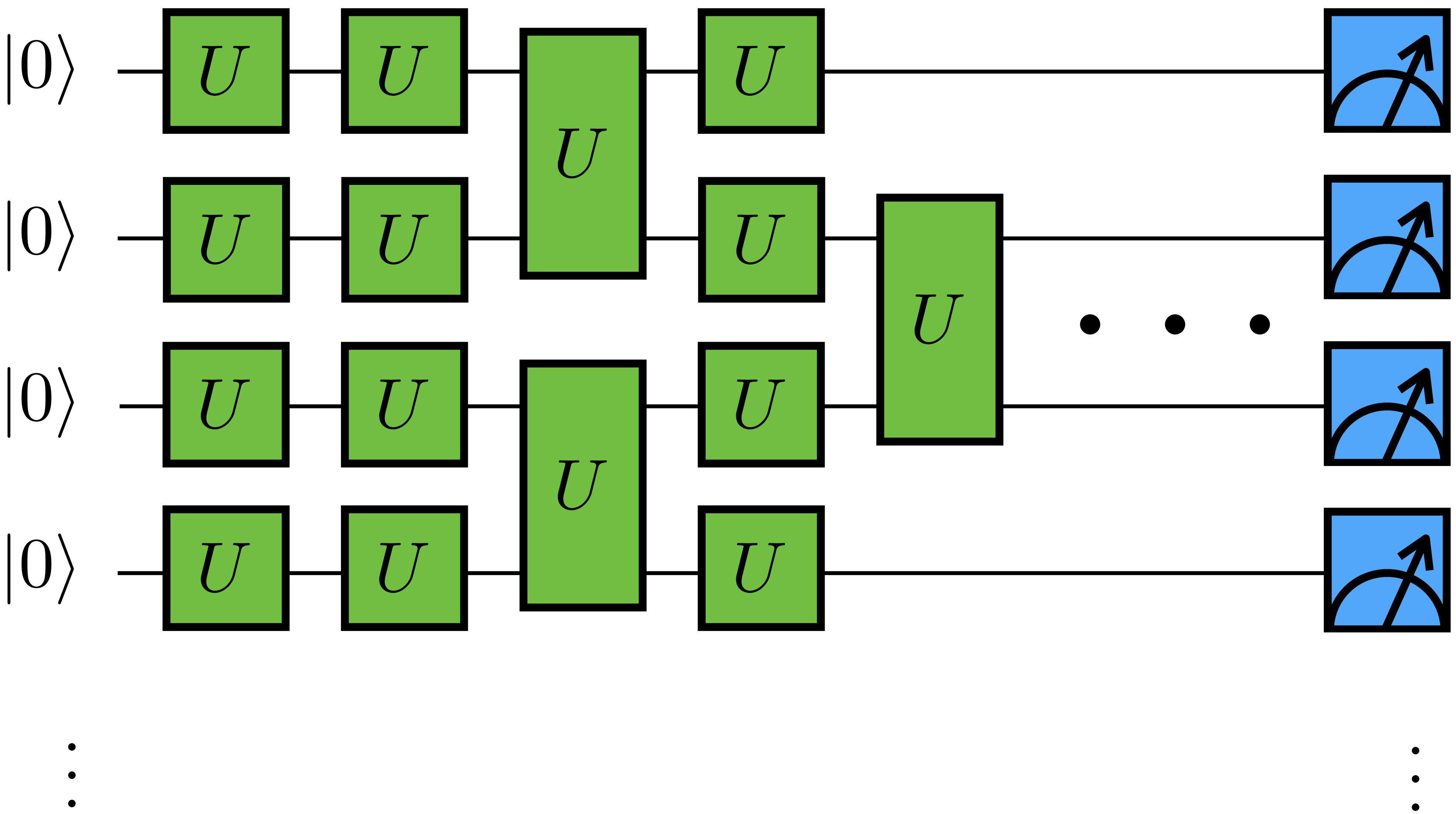
3 qubits: $$|\psi\rangle = c_{000}|000\rangle + c_{001}|001\rangle + c_{010}|010\rangle + c_{011}|011\rangle + c_{100}|100\rangle + c_{101}|101\rangle + c_{110}|110\rangle + c_{111}|111\rangle$$

8 coefficients

add 1 qubit $\rightarrow$ number of coefficients doubles

53 qubits: $2^{53} \approx 10^{16}$ coefficients

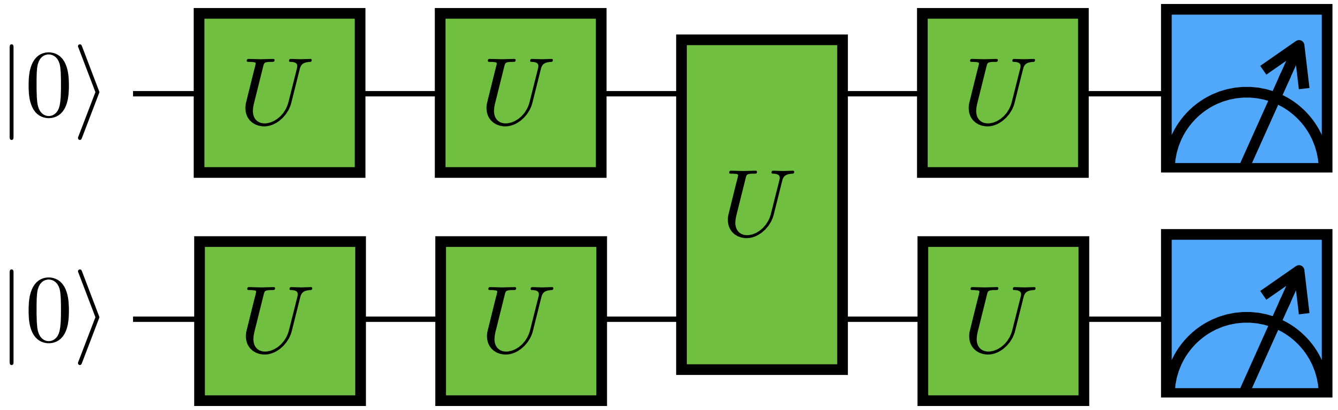
Quantum Computer

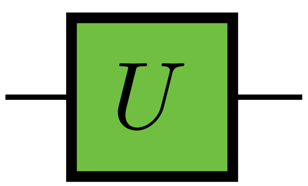


input $|\psi_i\rangle \longrightarrow |\psi_f\rangle$ output

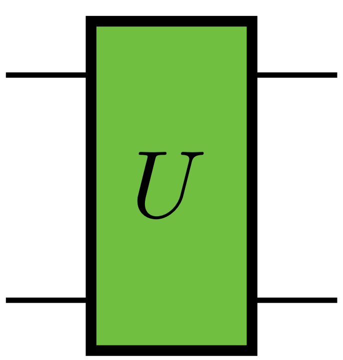
e.g.: 10110001…

Gates





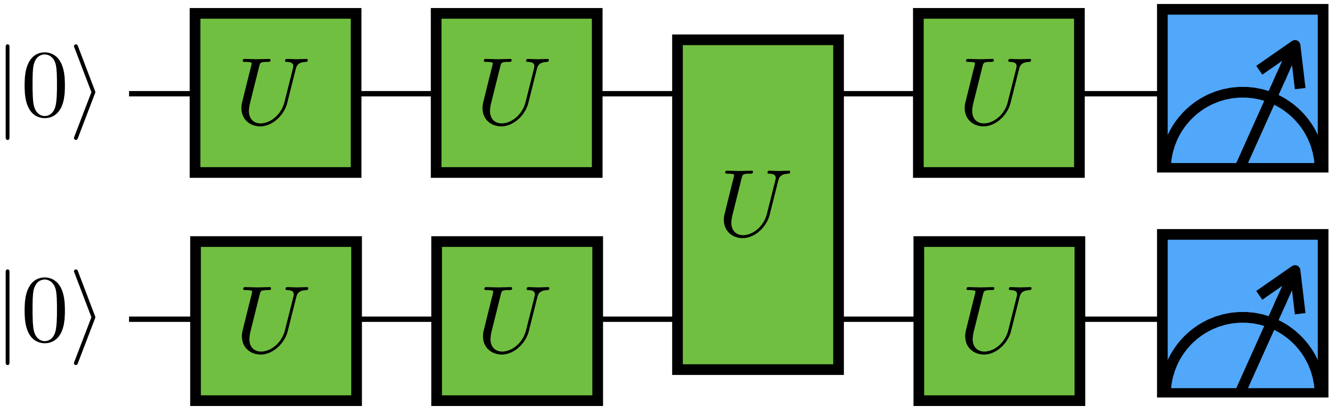
for 1 qubit: $|\varphi_j\rangle \rightarrow |\varphi'_j\rangle$

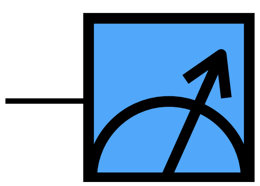


for 2 qubits:

$|\psi_{j,l}\rangle \rightarrow |\psi'_{j,l}\rangle$

Measurements





$$|\varphi\rangle = c_0 |0\rangle + c_1 |1\rangle \rightarrow \begin{cases} |0\rangle & \text{measurement outcome } \mathbf{0} \text{ occurs with probability } |c_0|^2 \\ |1\rangle & \text{measurement outcome } \mathbf{1} \text{ occurs with probability } |c_1|^2 \end{cases}$$

for multiple qubits → outcome: bit string, e.g. 10110001…

Power of Quantum Computers

input $|\psi_i\rangle \longrightarrow |\psi_f\rangle$ output

N quantum bits: $|\psi\rangle = \sum_{j_1,\ldots,j_N=0}^{1} c_{j_1,\ldots,j_N} |j_1, j_2, \ldots j_N\rangle$

sum of $\underbrace{2 \times 2 \times 2 \times \cdots \times 2}_{N \text{factors}} = 2^N$ terms

can process 2^N bit strings of length N in parallel

every additional quantum bit doubles computational power

$\rightarrow$ quantum computers are very powerful

$\rightarrow$ large quantum systems $\rightarrow$ materials

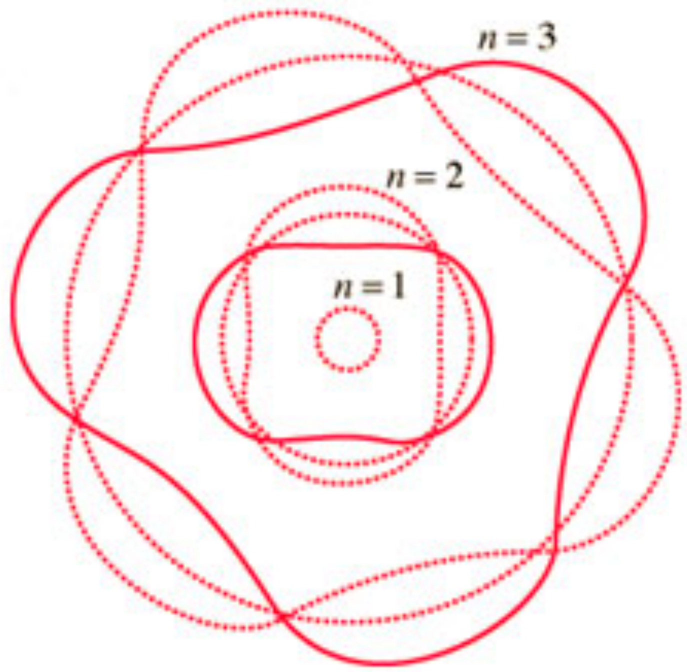
$\rightarrow$ optimization problems, machine learning

Hardware?

Qubits

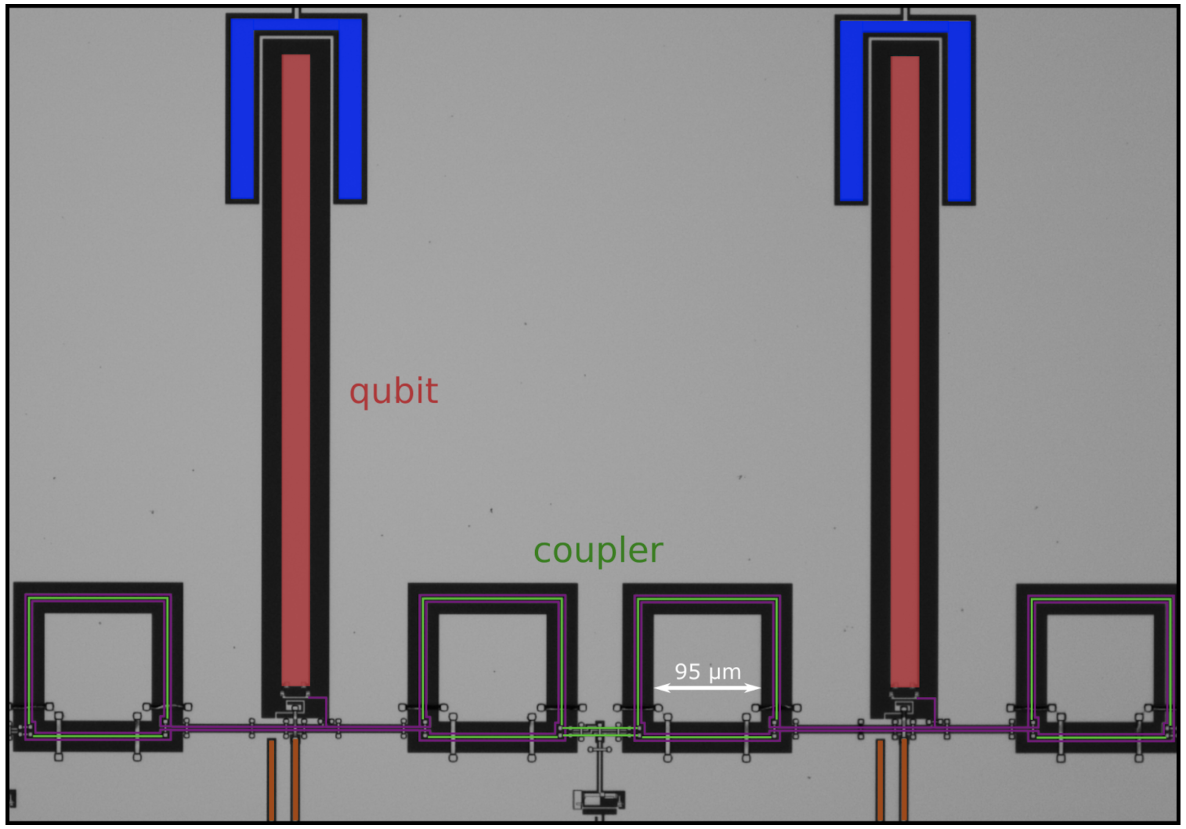
candidates for qubits:

natural atom:

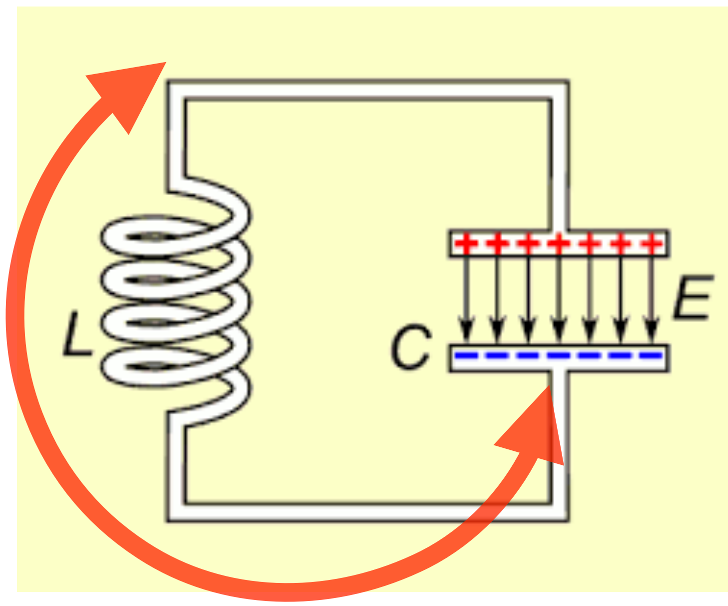


→ ion traps

@ Google: artificial atoms
superconducting qubits

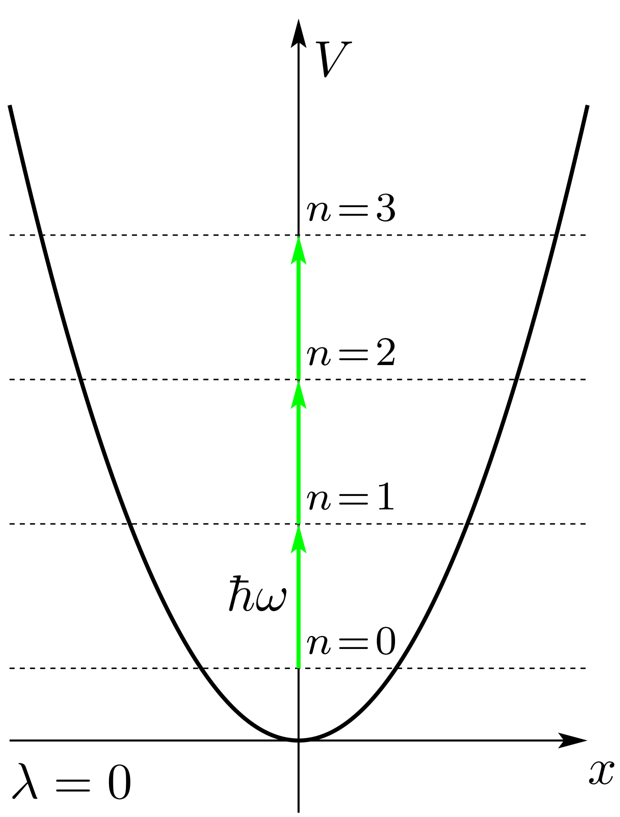


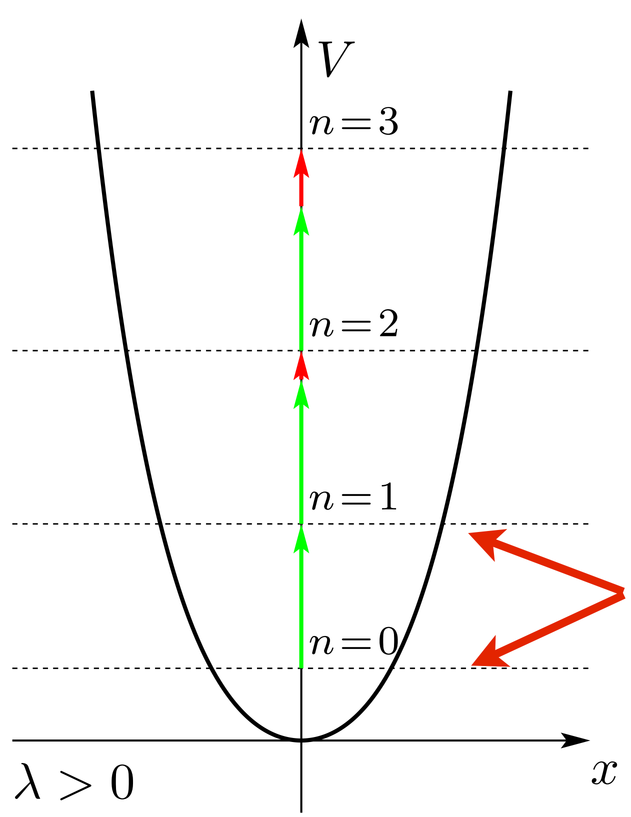
Superconducting Quantum Bits



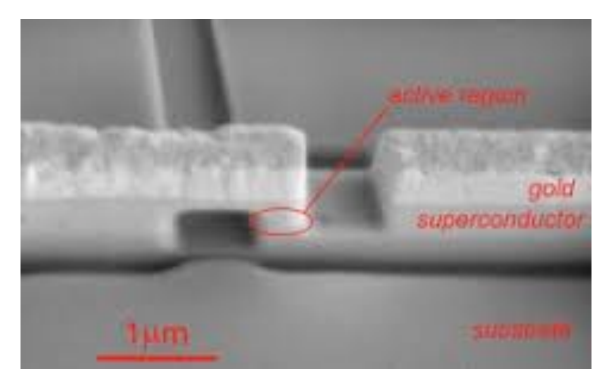
oscillation of electrical current
➡ use motional state of electrons as quantum bit

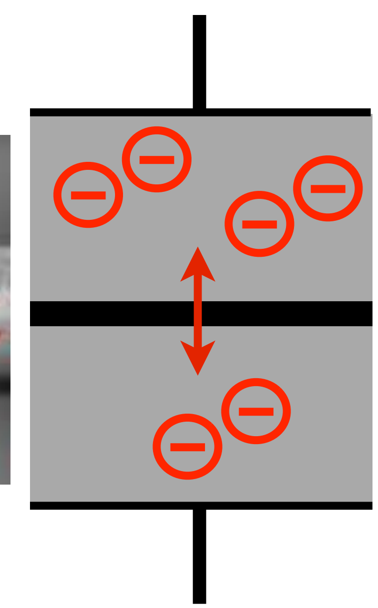
losses and perturbations
- ➡ oscillating electrons emit microwaves
- ➡ electrical resistance → superconductor





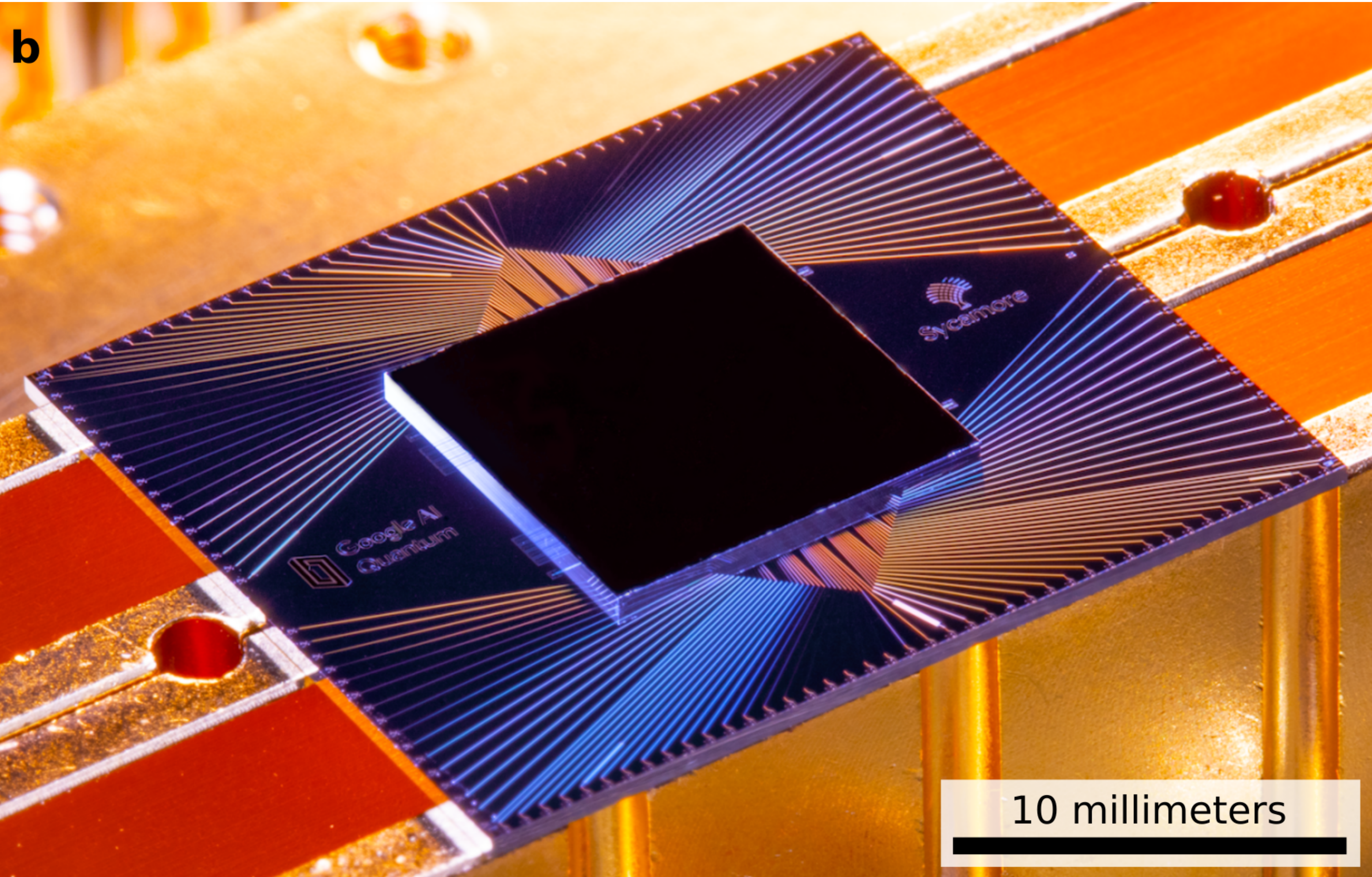
individually addressable



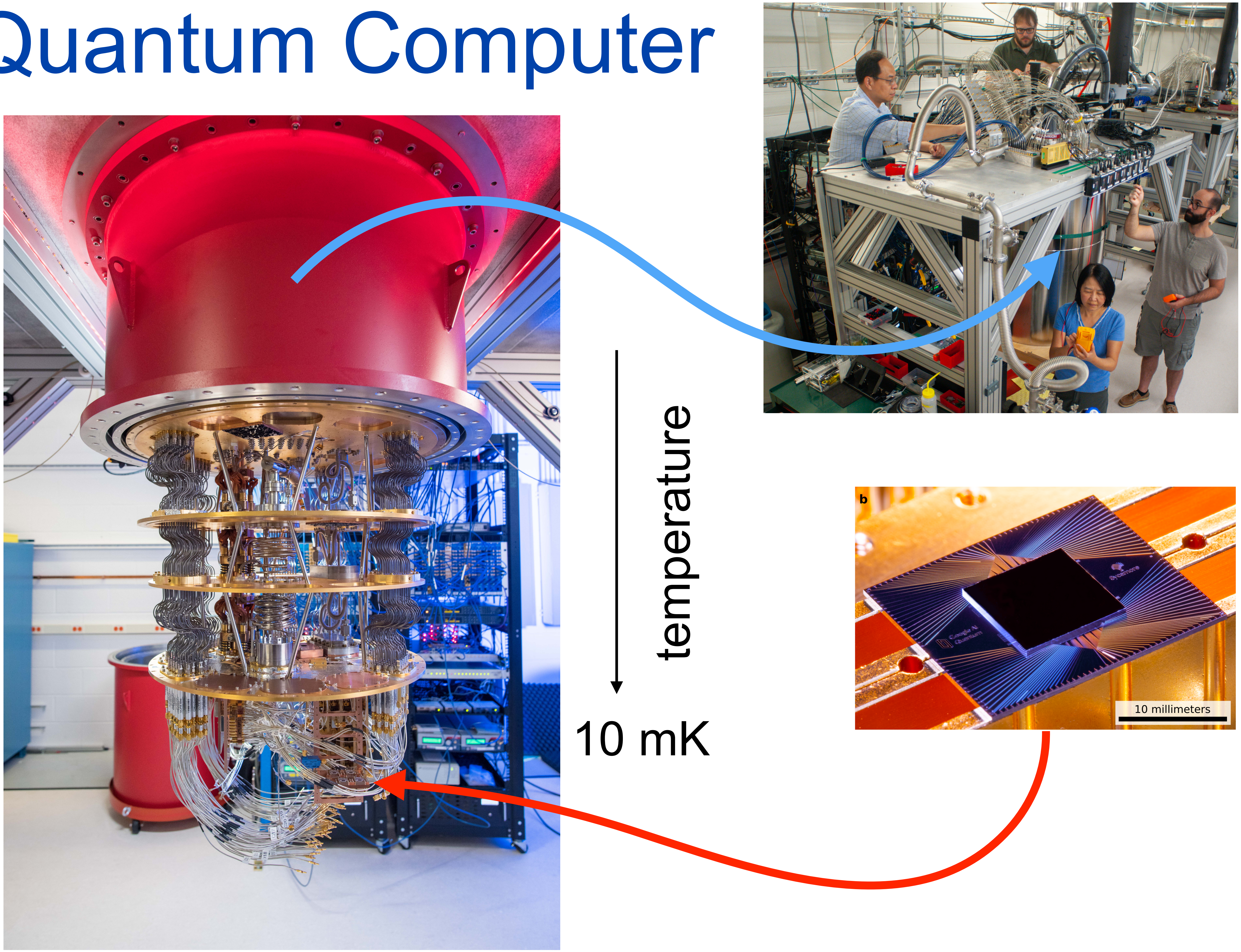


Josephson junction

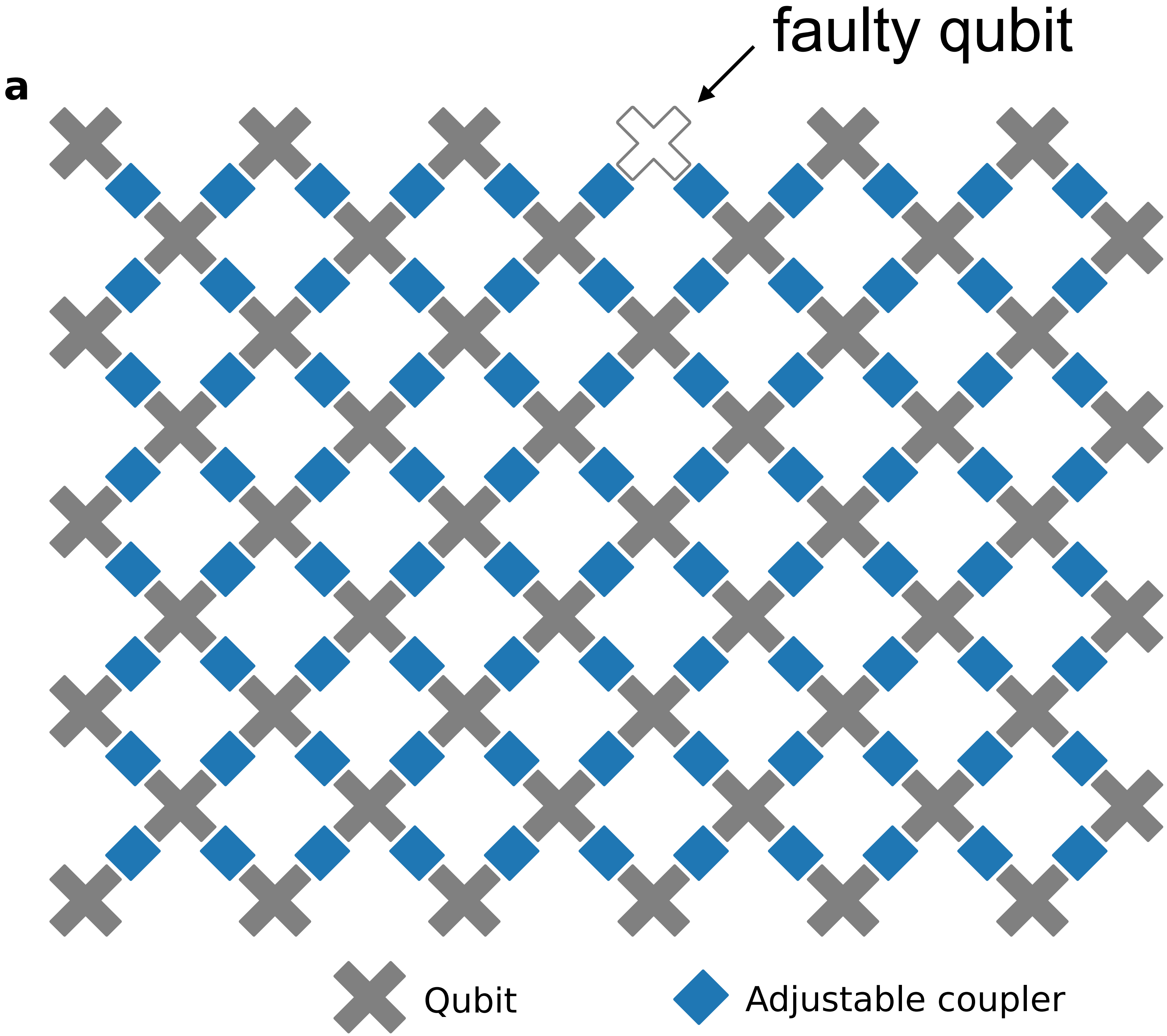
Sycamore



Quantum Computer



Sycamore Layout



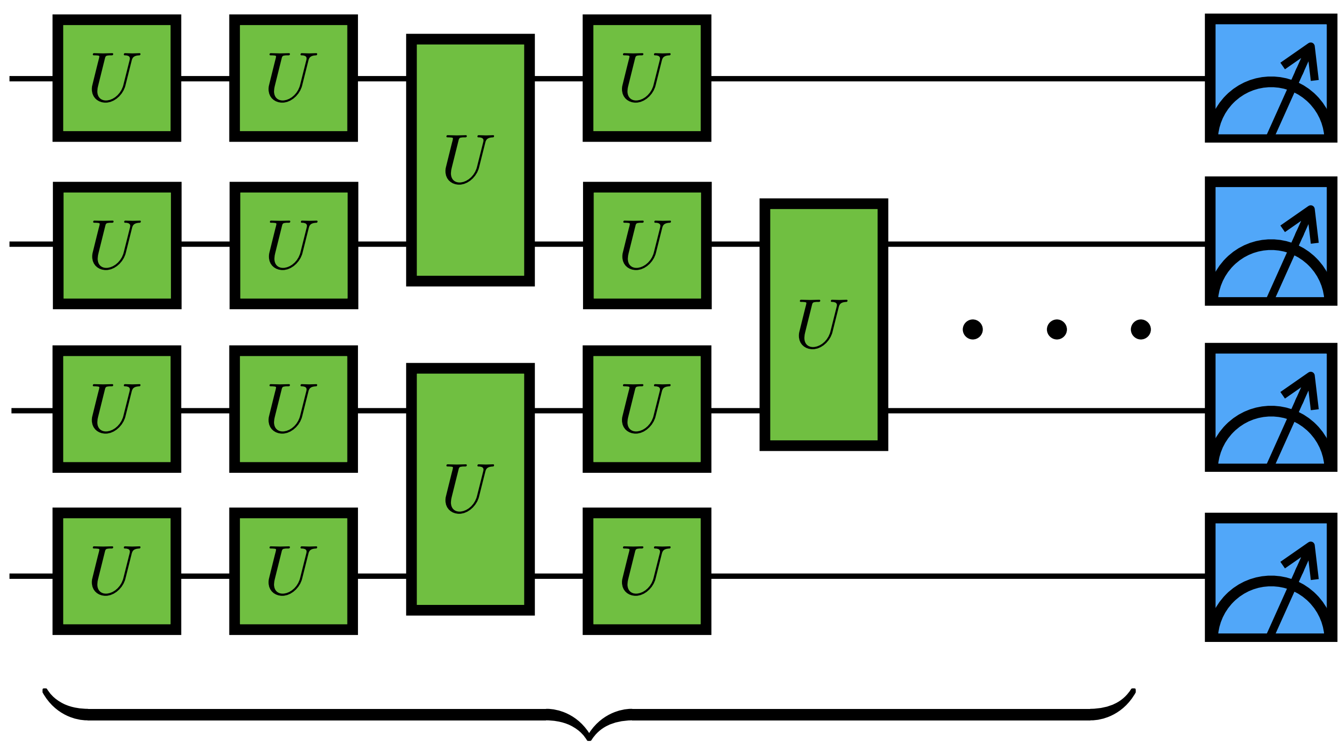
54 qubits

86 couplers

Quantum Supremacy Experiment

goal: run well defined computational problem on quantum computer that classical computing can no longer solve (in tolerable time)

computational problem: sample from output of random circuit

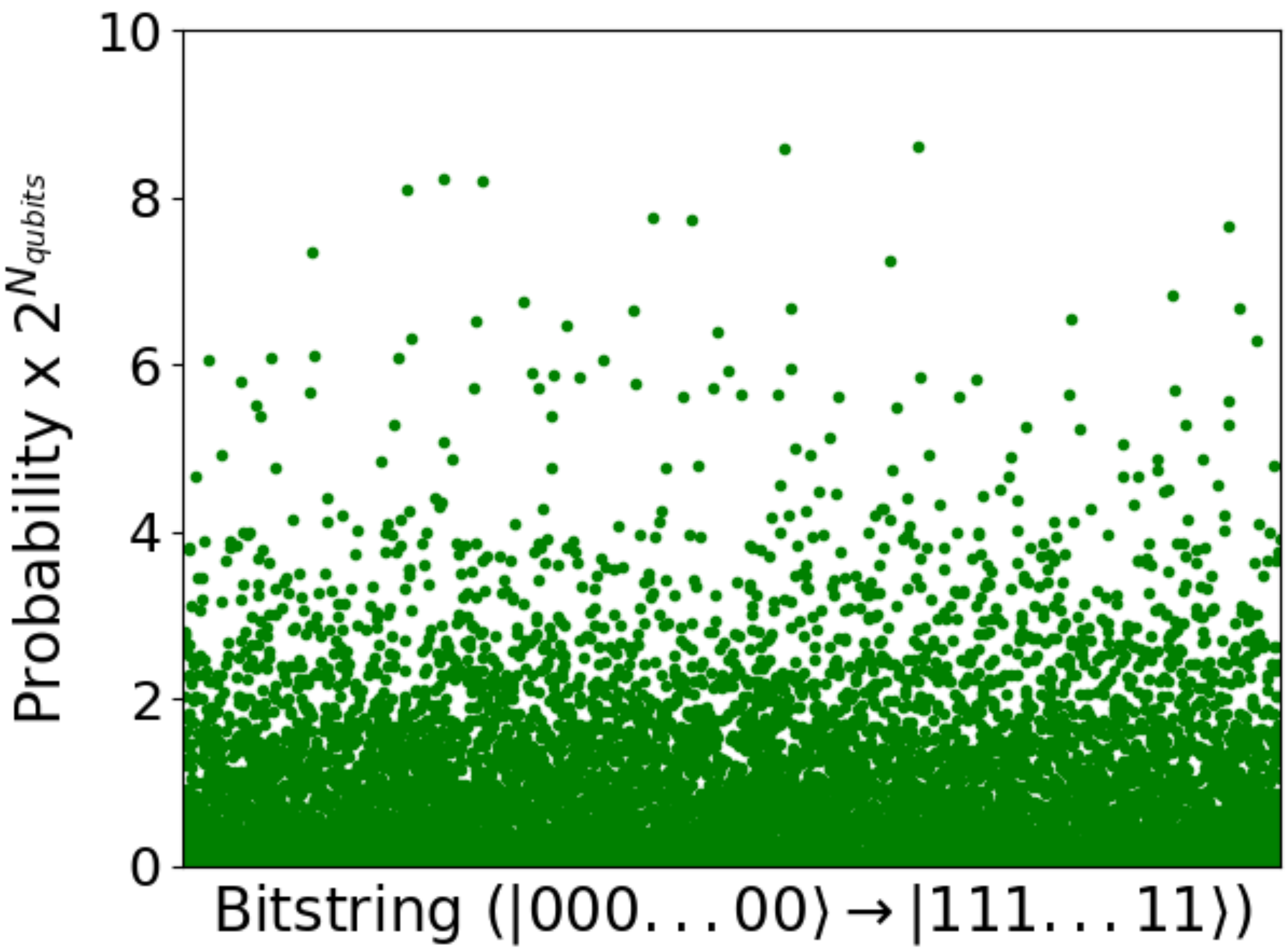


random gate sequence

measurement outcomes: bit-strings
0011010111
0101001100
…

run very often
→ distribution of bit-strings

Output Distribution



some bit-strings much more likely than others

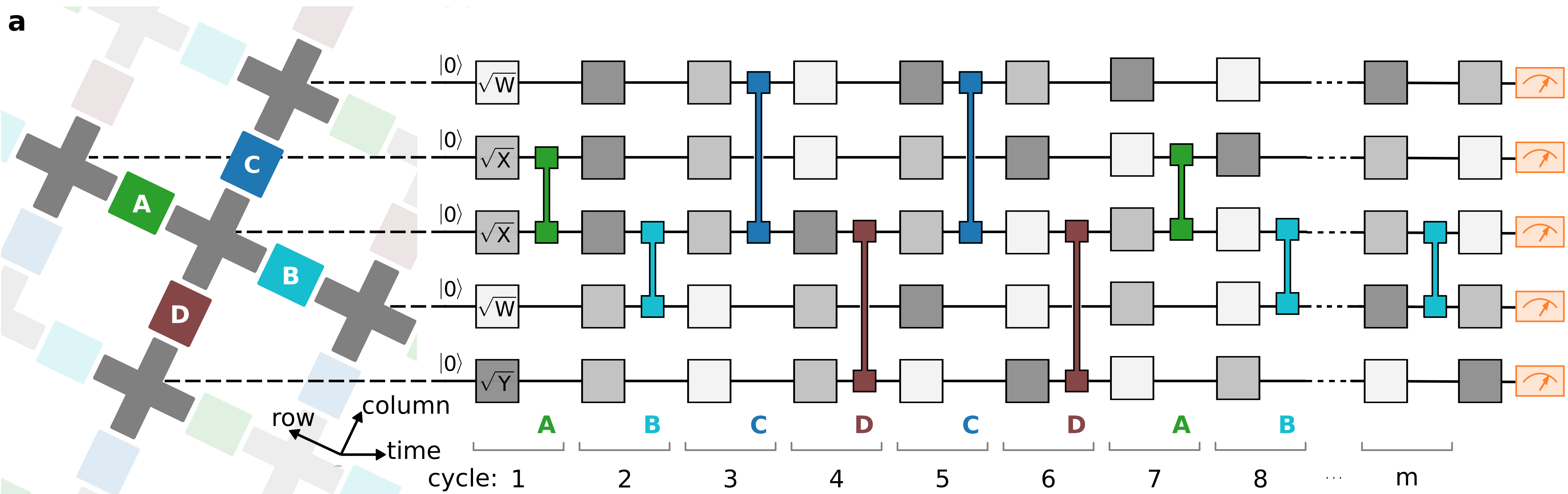
→ will be measured much more often

→ can test this with 10^6 measurements even though there are 10^{16} possible bit-strings

errors in computation destroy this signal!

Experimental Gate Sequence

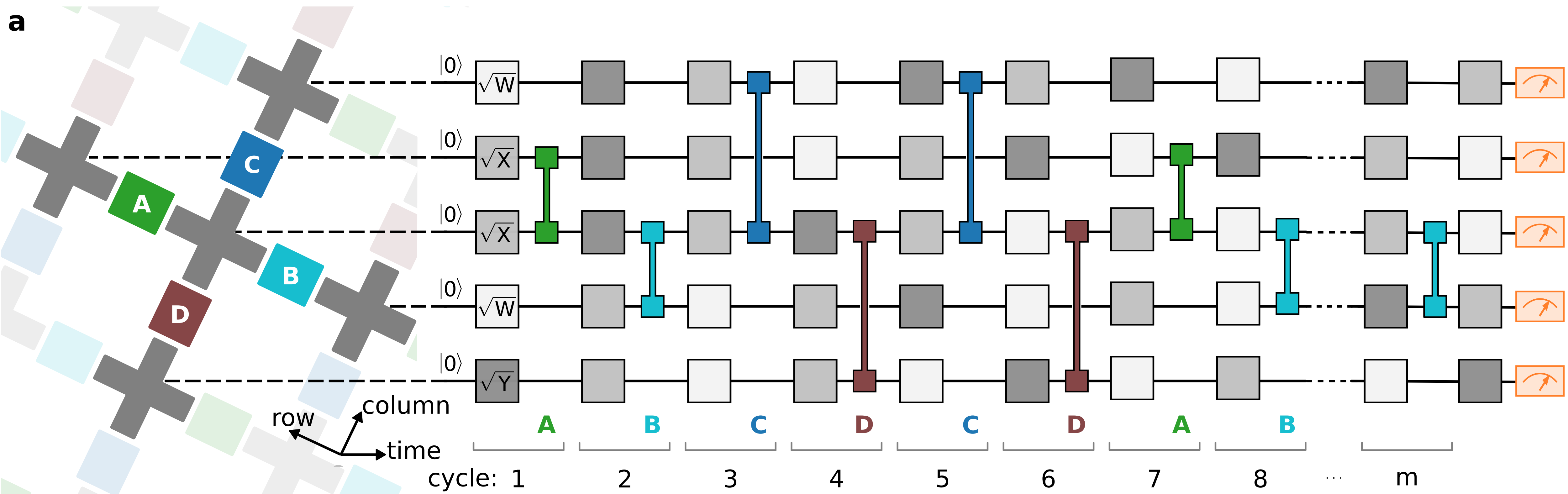
only one fixed two qubit gate
many single qubit gates → randomly chosen



classically reproducing output statistics requires simulation of circuit
→ increasingly cumbersome as number of cycles grows

Experimental Gate Sequence

only one fixed two qubit gate
many single qubit gates → randomly chosen



there are circuits that can be simulated classically
and there are circuits that cannot (would take too long)

→ use the easier circuits to check that the quantum computer works correctly (number of gates is the same)

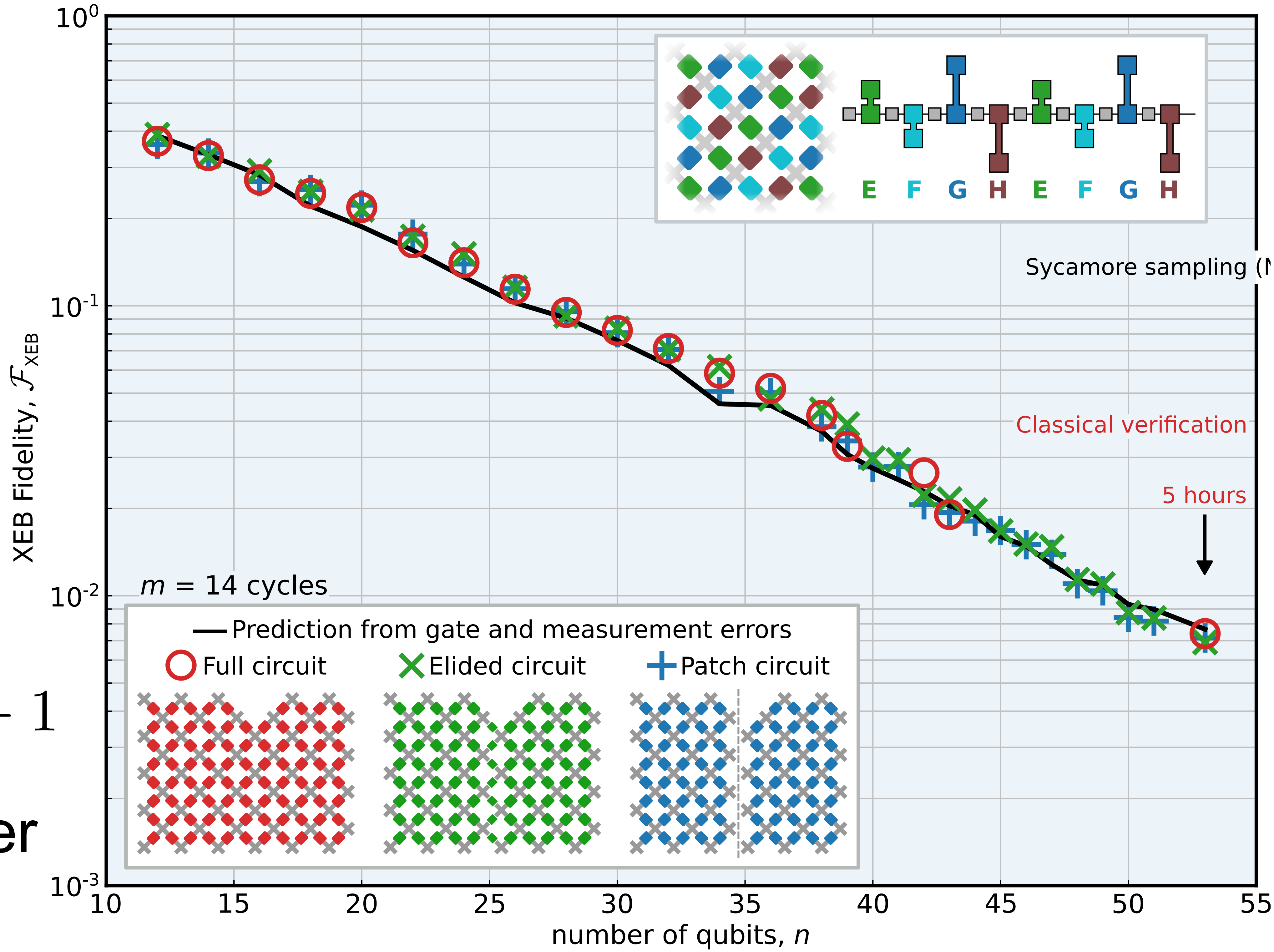
Classically Verifiable Regime

how close
to expected
distribution

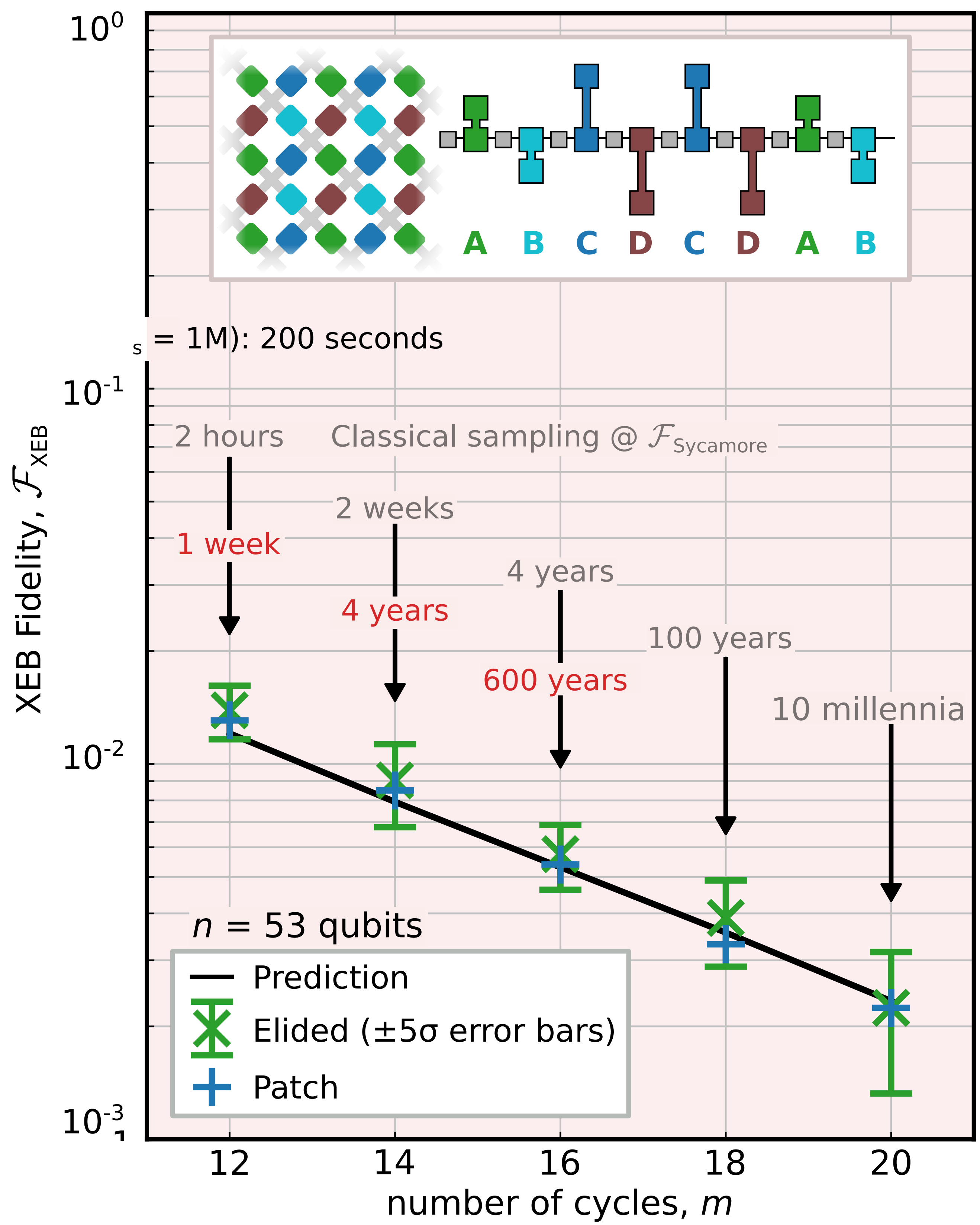
estimated
probability
for bit-string

$$\mathcal{F}_{XEB} =$$
$$= 2^n \langle P(z_j) \rangle - 1$$

average over
observed
bit-strings



Supremacy Regime

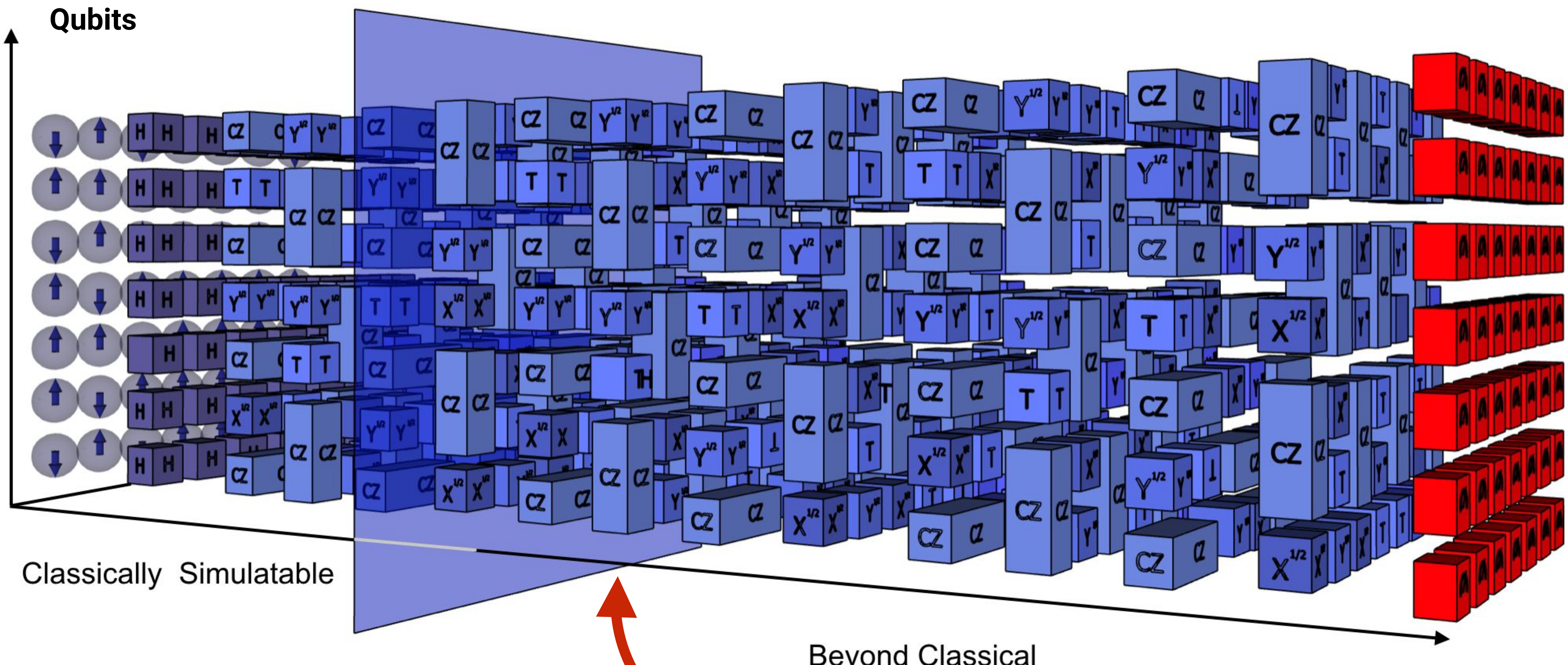


- 0.2% of all circuits run correctly
- errors of individual gates predict fidelity correctly

➡ can run computations that are too difficult for classical computers

➡ can scale technology up, there are no new complications

Quantum Supremacy Frontier



we are here

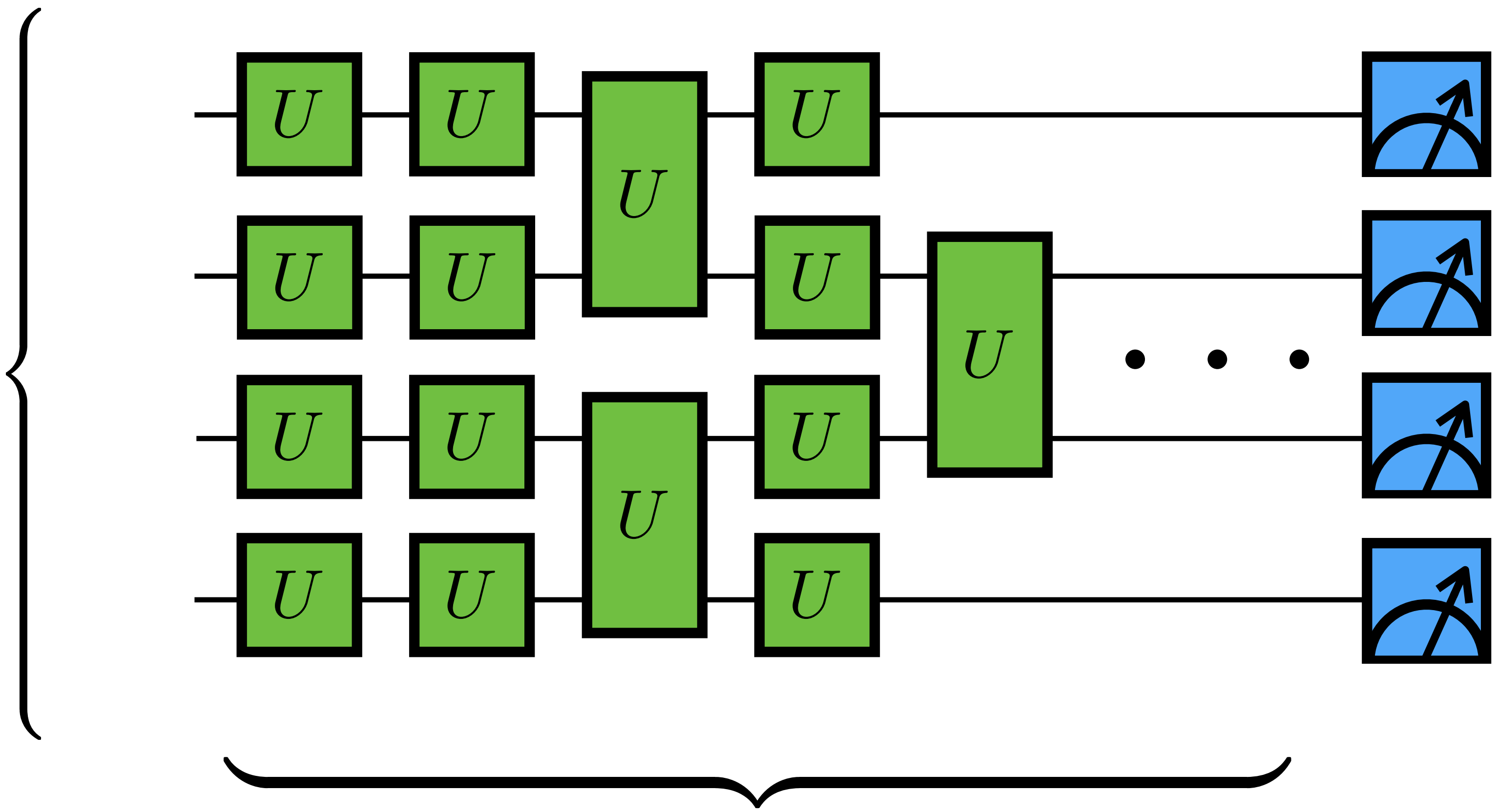
but the gates are not perfect!

→ algorithms with moderate depth

→ algorithms that don’t need perfect gates

What can we do with it?

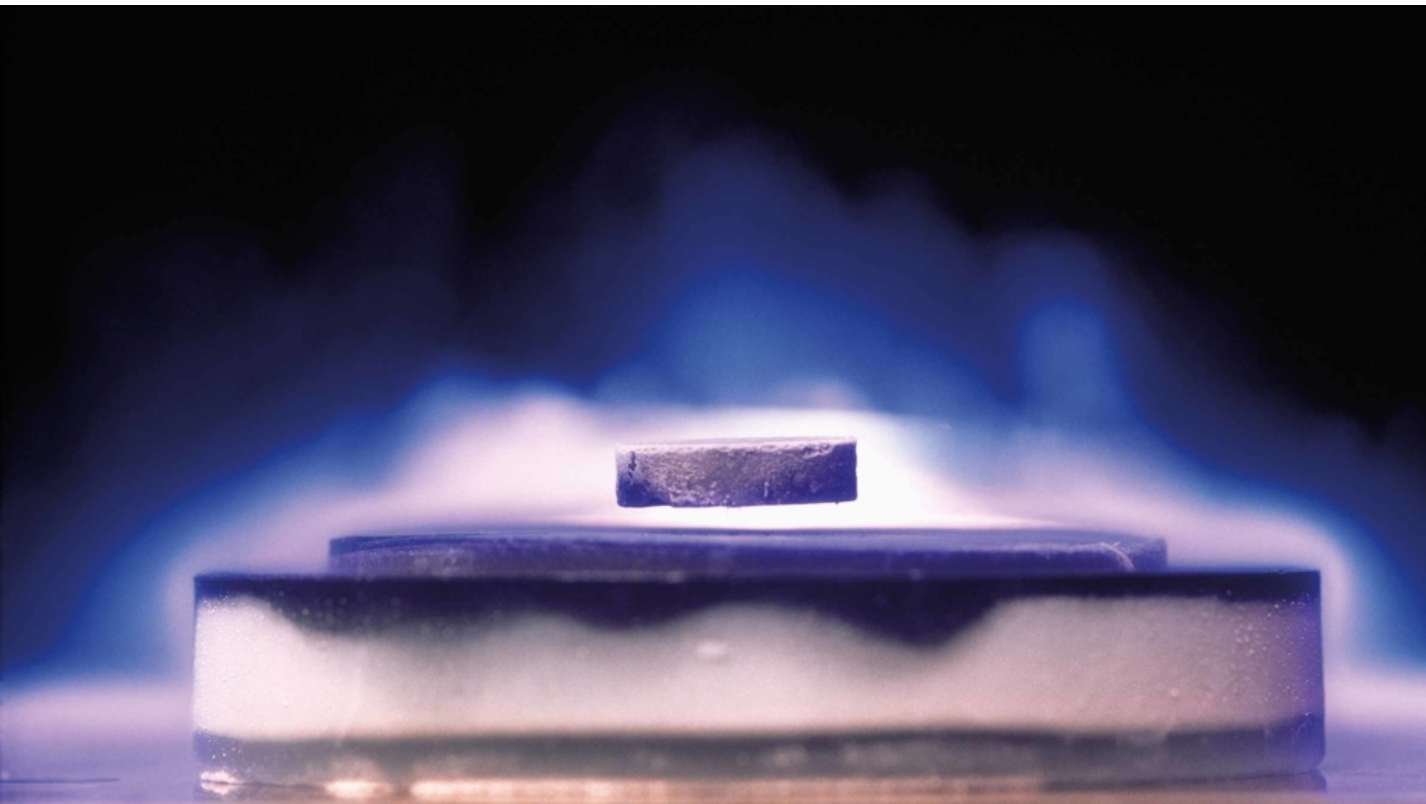
50 - 100 qubits

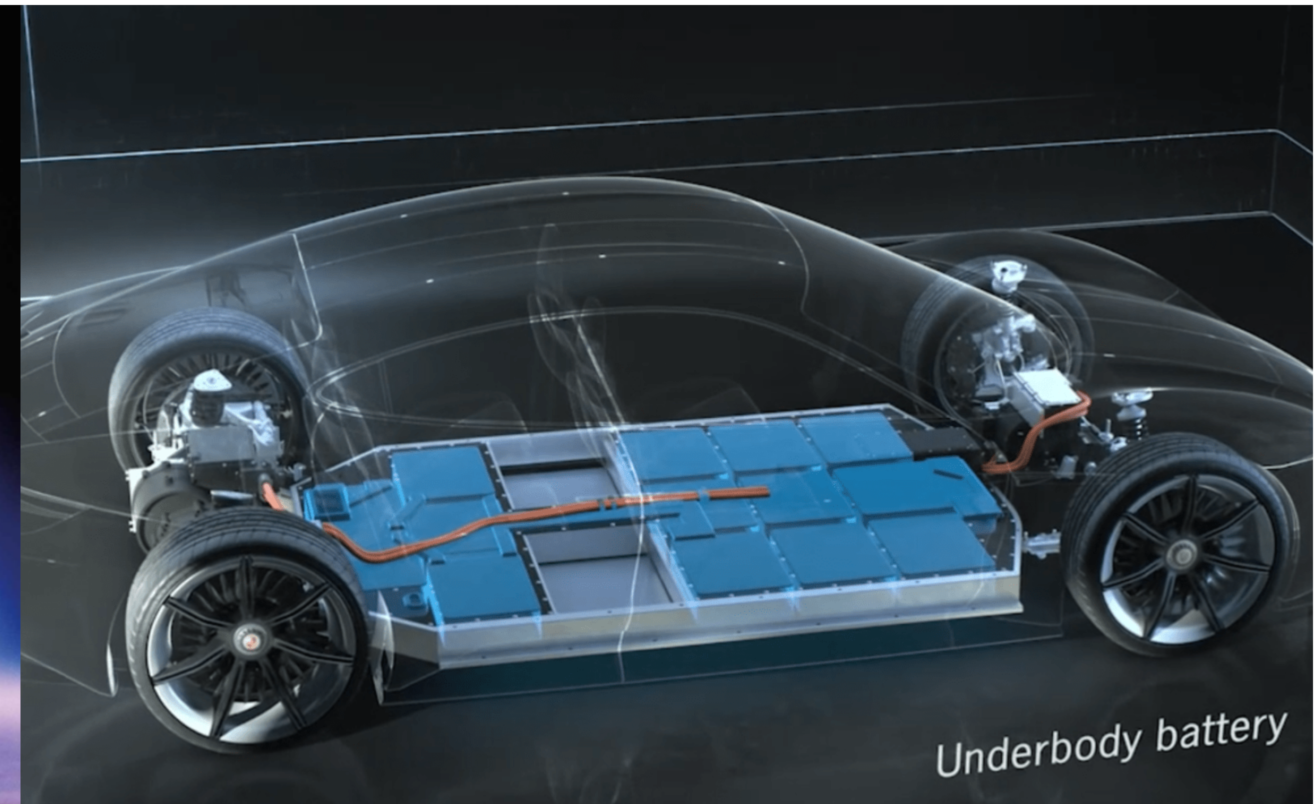


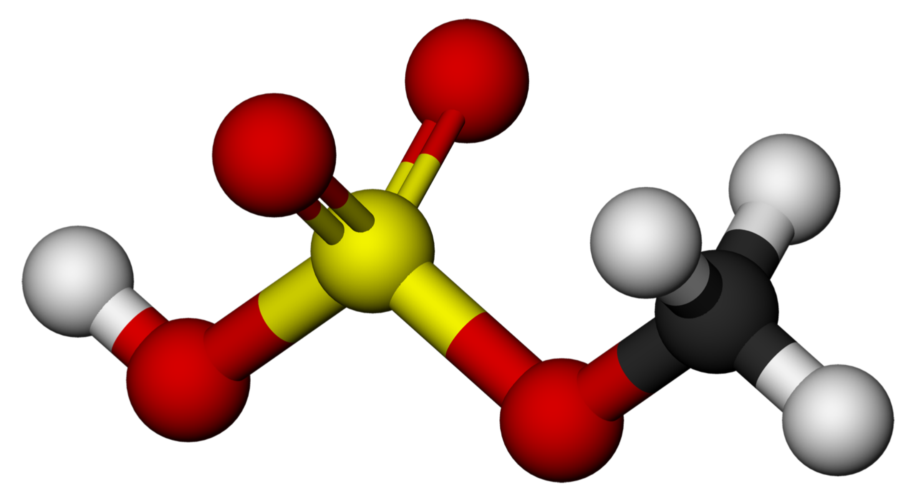
20 - 100 cycles of gates at 0.5% error/gate

- random circuit sampling not very useful
  - one application certified random numbers
- prominent algorithms like Shore’s require prefect gates

Quantum Materials/Chemistry







- find stable configurations
- find low energy states

Quantum Optimization

expect early use cases in optimization and logistics

→ write cost function as quantum Hamiltonian

E.g. Boolean MaxSat problem: $(x_0 \vee x_1) \wedge (x_0 \vee \neg x_1) \wedge \ldots$

$$H = \sum_{\alpha} C_{\alpha}(Z_1, Z_2, \ldots, Z_N)$$

$$Z_j = |0_j\rangle\langle 0_j| - |1_j\rangle\langle 1_j|$$

→ solution: configuration with lowest energy

challenges:

- need many qubits
- high connectivity

Summary

- Quantum computations can no longer be simulated classically
- Next goal: Find a useful application that can be run now
  → condensed matter systems
- Quantum computing is still a long term bet


Thanks for listening.
Google AI
Quantum
Sycamore