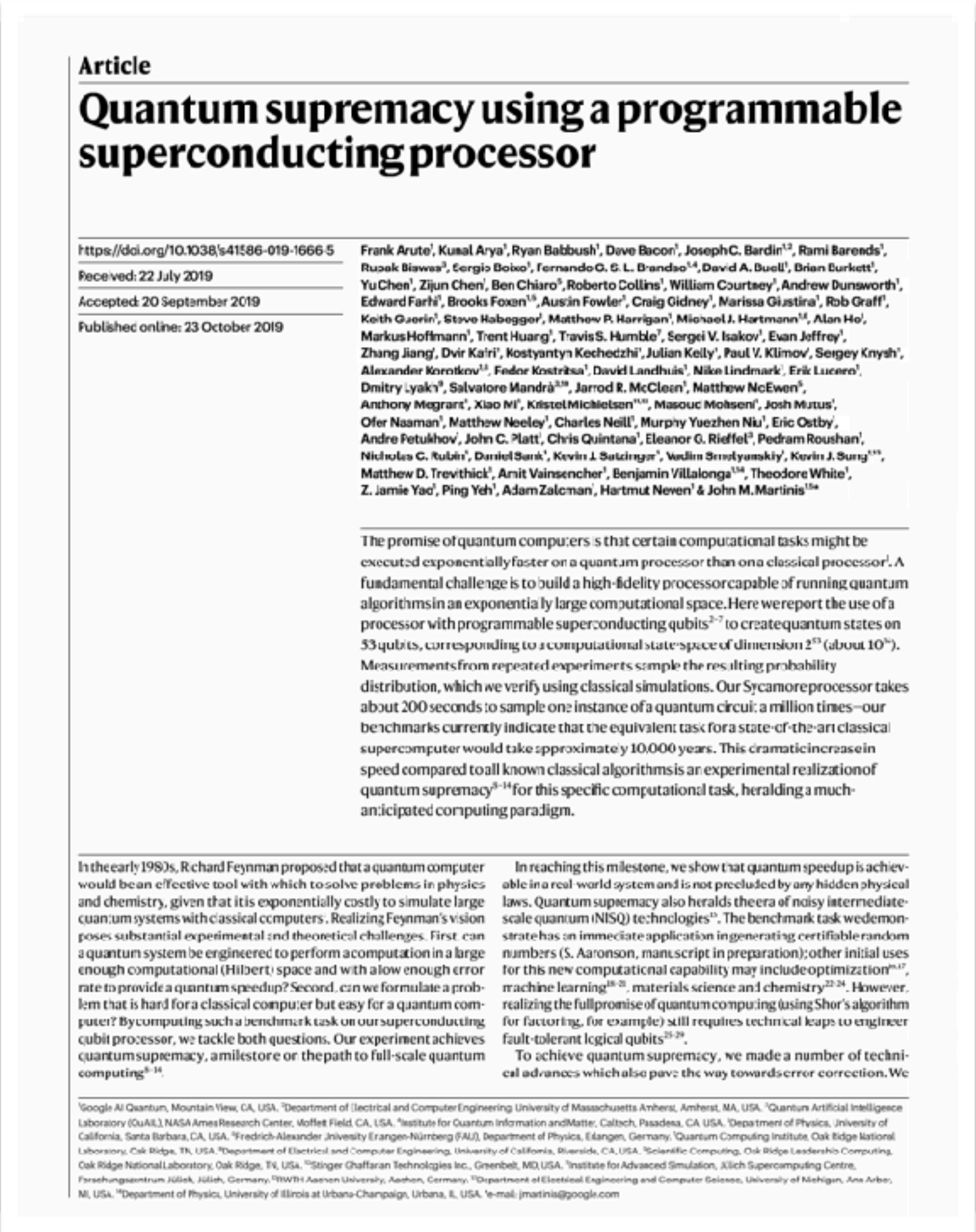
Quantum supremacy



Article

Quantum supremacy using a programmable superconducting processor

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The promise of quantum computers is that certain computational tasks might be executed exponentially faster on a quantum processor than on a classical processor[1]. A fundamental challenge is to build a high-fidelity processor capable of running quantum algorithms in an exponentially large computational space. Here we report the use of a processor with programmable superconducting qubits[2–7] to create quantum states on 53 qubits, corresponding to a computational state-space of dimension 2^{53} (about 10^{16}). Measurements from repeated experiments sample the resulting probability distribution, which we verify using classical simulations. Our Sycamore processor takes about 200 seconds to sample one instance of a quantum circuit a million times—our benchmarks currently indicate that the equivalent task for a state-of-the-art classical supercomputer would take approximately 10,000 years. This dramatic increase in speed compared to all known classical algorithms is an experimental realization of quantum supremacy[8–14] for this specific computational task, heralding a much-anticipated computing paradigm.

In the early 1980s, Richard Feynman proposed that a quantum computer would be an effective tool with which to solve problems in physics and chemistry, given that it is exponentially costly to simulate large quantum systems with classical computers[1]. Realizing Feynman's vision poses substantial experimental and theoretical challenges. First, can a quantum system be engineered to perform a computation in a large enough computational (Hilbert) space and with a low enough error rate to provide a quantum speedup? Second, can we formulate a problem that is hard for a classical computer but easy for a quantum computer? By computing such a benchmark task on our superconducting qubit processor, we tackle both questions. Our experiment achieves quantum supremacy, a milestone on the path to full-scale quantum computing[8–14].

In reaching this milestone, we show that quantum speedup is achievable in a real-world system and is not precluded by any hidden physical laws. Quantum supremacy also heralds the era of noisy intermediate-scale quantum (NISQ) technologies[15]. The benchmark task we demonstrate has an immediate application in generating certifiable random numbers (S. Aaronson, manuscript in preparation); other initial uses for this new computational capability may include optimization[16,17], machine learning[18–21], materials science and chemistry[22–24]. However, realizing the full promise of quantum computing (using Shor's algorithm for factoring, for example) still requires technical leaps to engineer fault-tolerant logical qubits[25–29].

To achieve quantum supremacy, we made a number of technical advances which also pave the way towards error correction. We

[1]Google AI Quantum, Mountain View, CA, USA. [2]Department of Electrical and Computer Engineering, University of Massachusetts Amherst, Amherst, MA, USA. [3]Quantum Artificial Intelligence Laboratory (QuAIL), NASA Ames Research Center, Moffett Field, CA, USA. [4]Institute for Quantum Information and Matter, Caltech, Pasadena, CA, USA. [5]Department of Physics, University of California, Santa Barbara, CA, USA. [6]Friedrich-Alexander University Erlangen-Nürnberg (FAU), Department of Physics, Erlangen, Germany. [7]Quantum Computing Institute, Oak Ridge National Laboratory, Oak Ridge, TN, USA. [8]Department of Electrical and Computer Engineering, University of California, Riverside, CA, USA. [9]Scientific Computing, Oak Ridge Leadership Computing, Oak Ridge National Laboratory, Oak Ridge, TN, USA. [10]Stinger Ghaffarian Technologies Inc., Greenbelt, MD, USA. [11]Institute for Advanced Simulation, Jülich Supercomputing Centre, Forschungszentrum Jülich, Jülich, Germany. [12]RWTH Aachen University, Aachen, Germany. [13]Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, MI, USA. [14]Department of Physics, University of Illinois at Urbana-Champaign, Urbana, IL, USA. e-mail: jmartinis@google.com

NISQ-era

Noisy Intermediate- Scale Quantum. Here “intermediate scale” refers to the size of quantum computers which will be available in the next few years, with a number of qubits ranging from 50 to a few hundred. ***50 qubits*** is a significant milestone, because that’s beyond what can be simulated by brute force using the most powerful existing digital supercomputers. ***“Noisy”*** emphasizes that we’ll have imperfect control over those qubits; the noise will place serious limitations on what quantum devices can achieve in the near term.

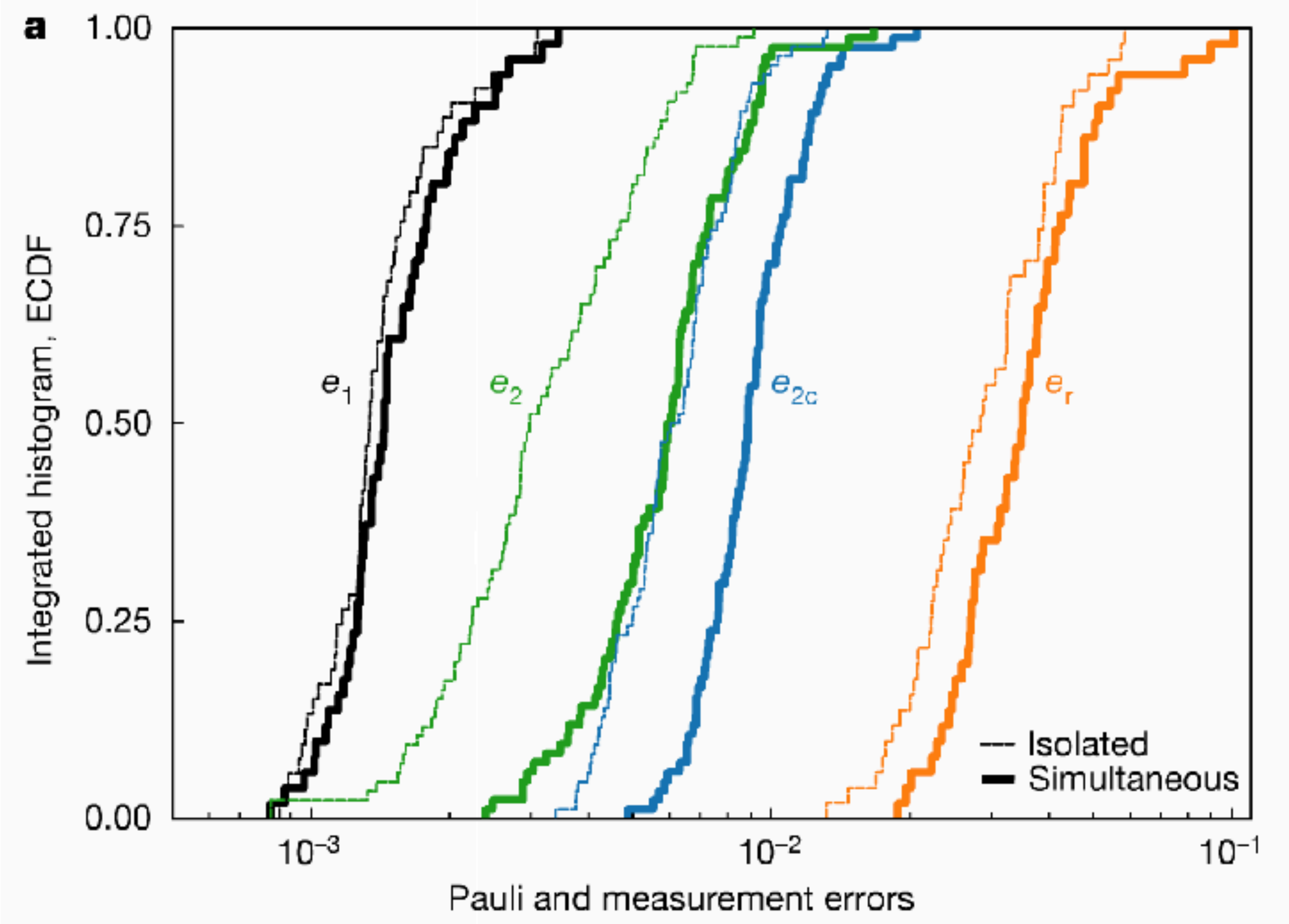
Quantum Computing in the NISQ era and beyond

John Preskill

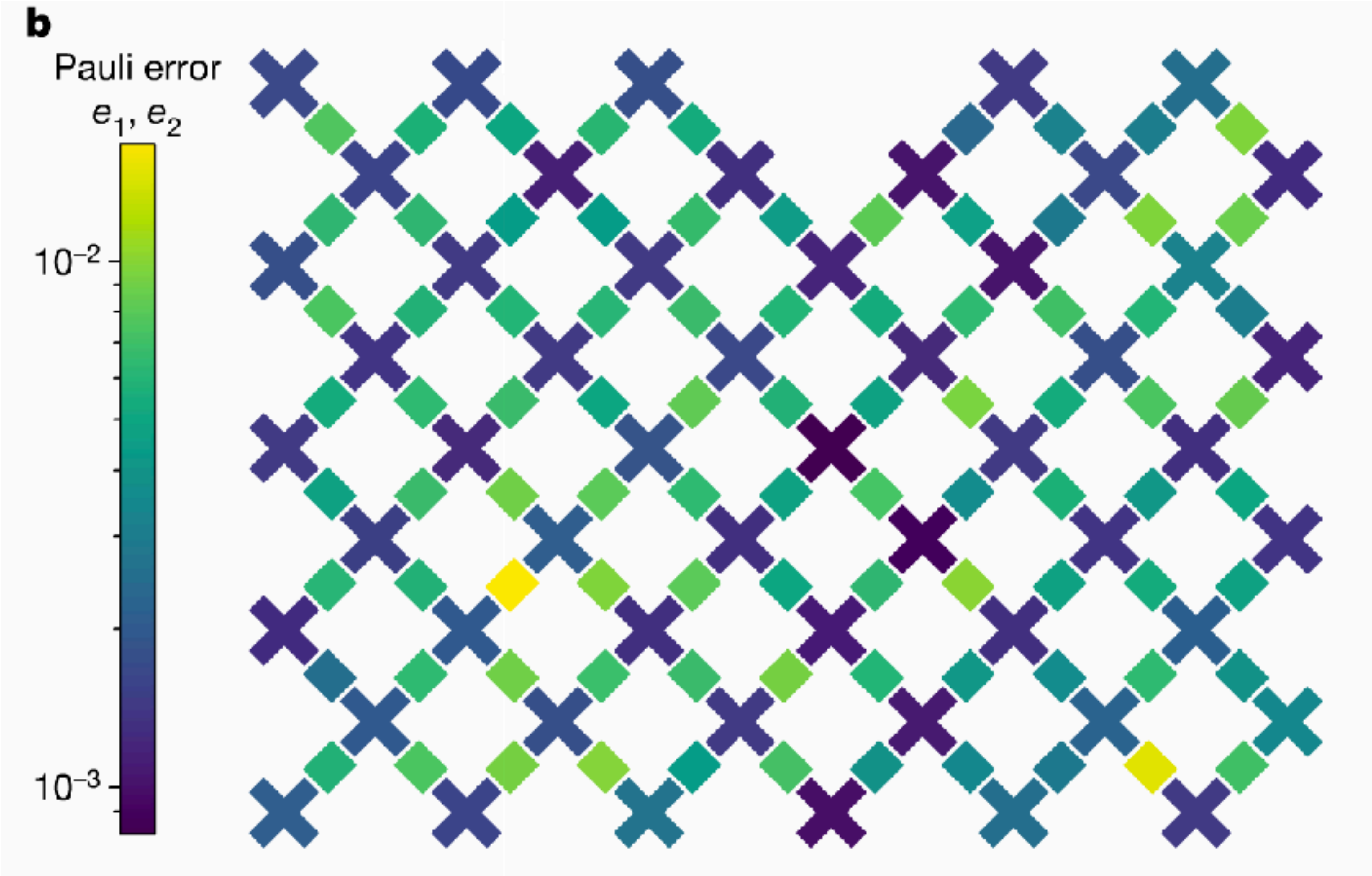
Institute for Quantum Information and Matter and Walter Burke Institute for Theoretical Physics,
California Institute of Technology, Pasadena CA 91125, USA

30 July 2018

Errors!

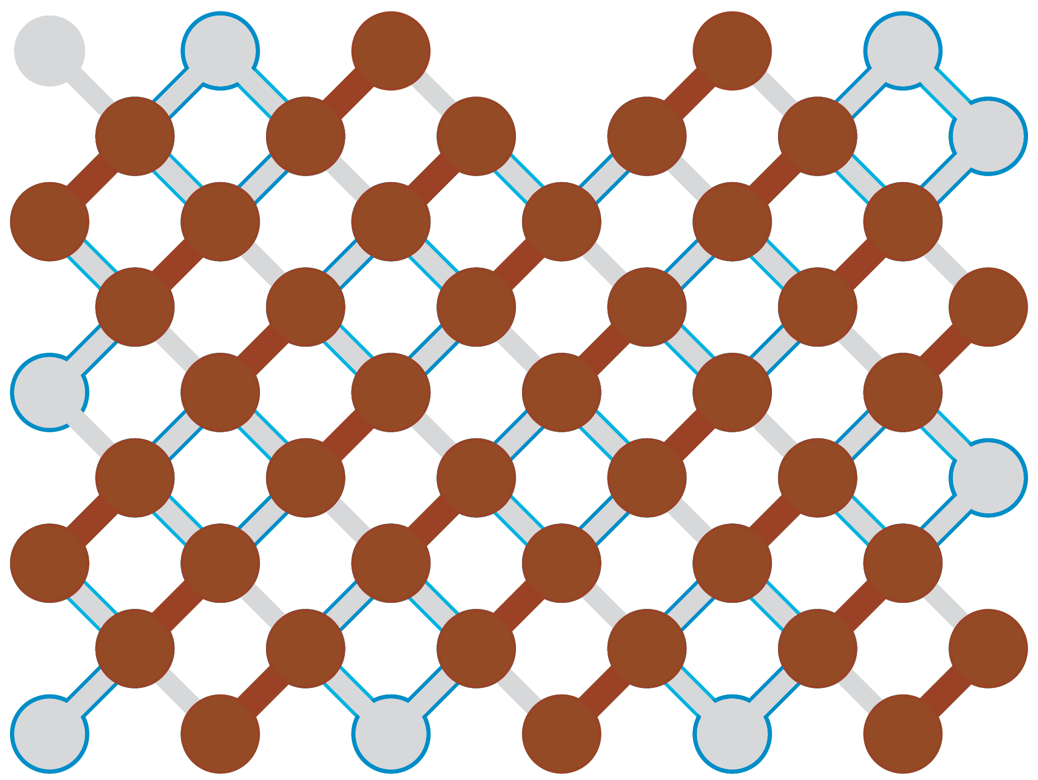


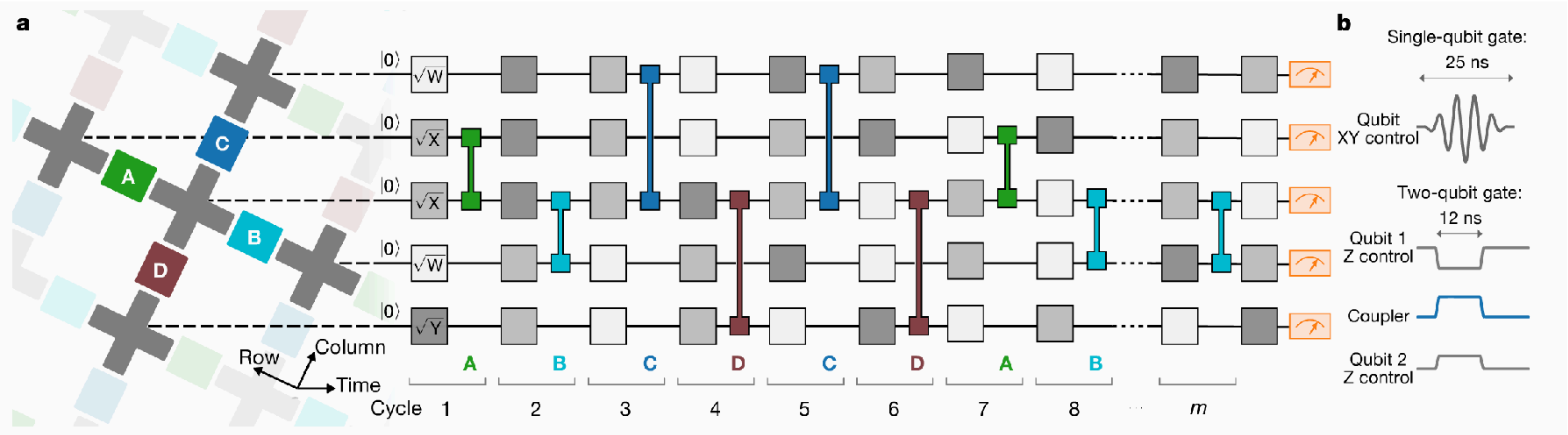
Average error	Isolated	Simultaneous
Single-qubit (e_1)	0.15%	0.16%
Two-qubit (e_2)	0.36%	0.62%
Two-qubit, cycle (e_{2c})	0.65%	0.93%
Readout (e_r)	3.1%	3.8%



Control Sequence for Quantum Supremacy

- Simultaneous gates all qubits
- General purpose algorithm
  - Cycle with 1- and2-qubit gates



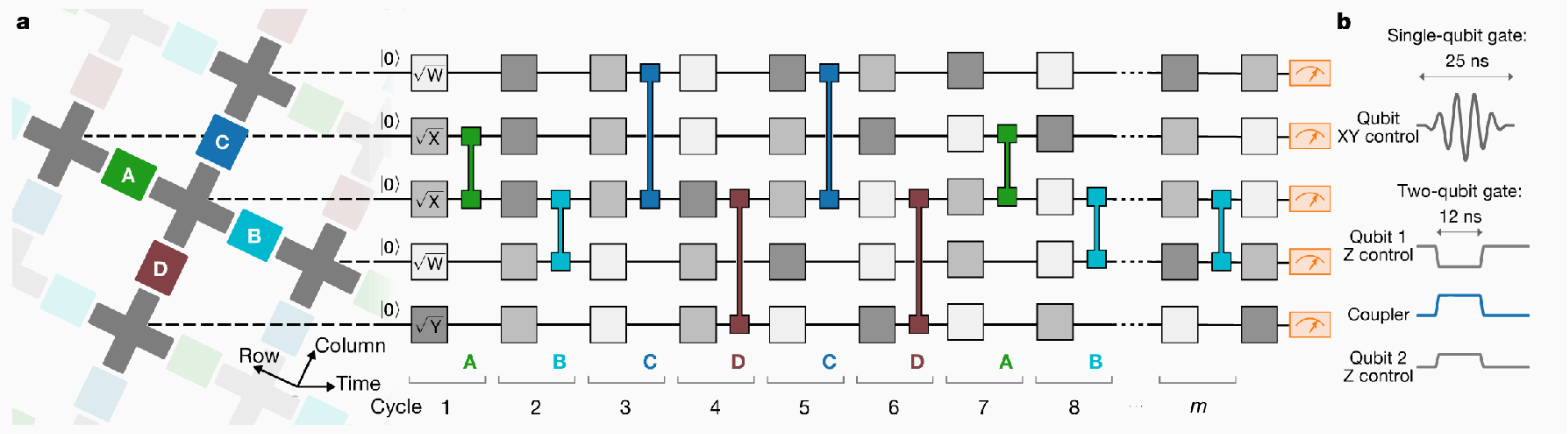


Control Sequence for Quantum Supremacy

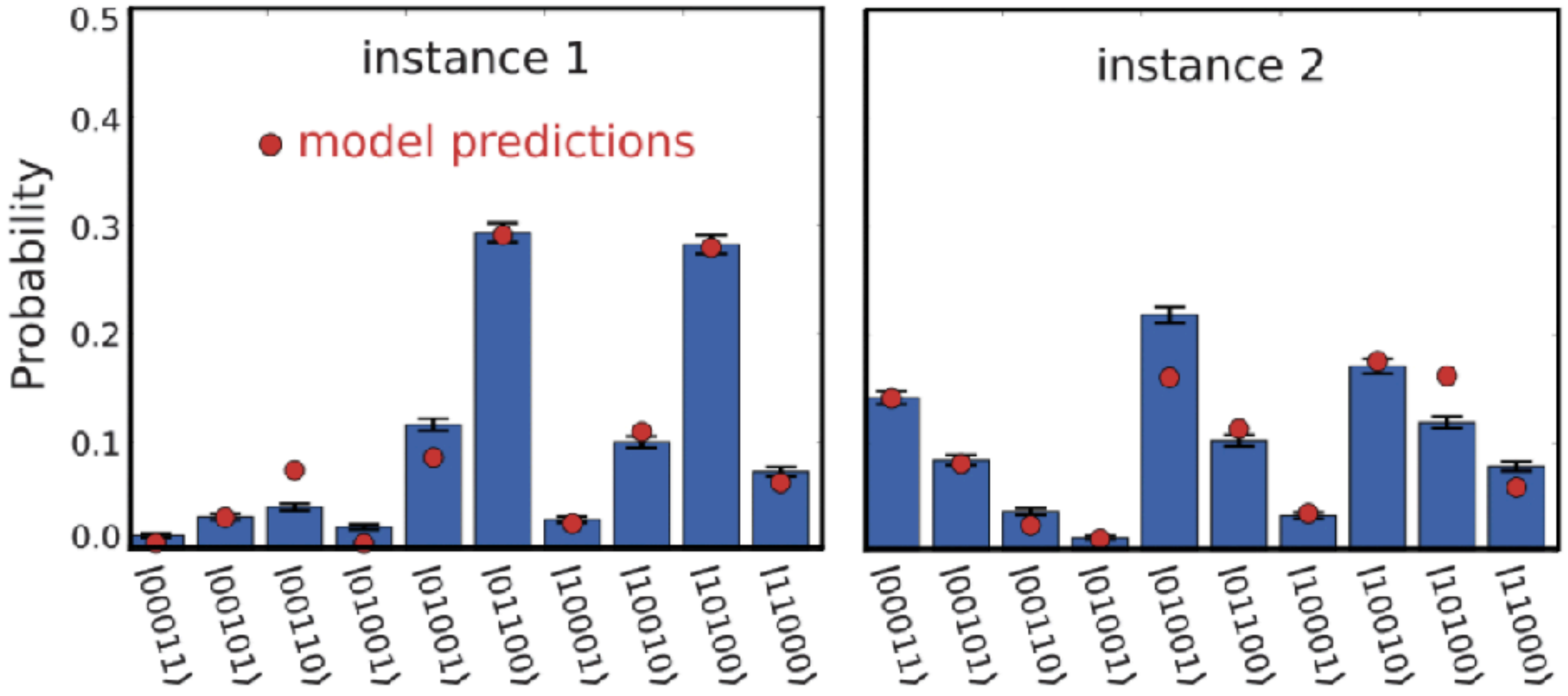
- Simultaneous gates all qubits
- General purpose algorithm
  - Cycle with 1- and2-qubit gates

$$X^{1/2} \equiv R_X(\pi/2) = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & -i \\ -i & 1 \end{bmatrix},$$
$$Y^{1/2} \equiv R_Y(\pi/2) = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix},$$
$$W^{1/2} \equiv R_{X+Y}(\pi/2) = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & -\sqrt{i} \\ \sqrt{-i} & 1 \end{bmatrix}$$

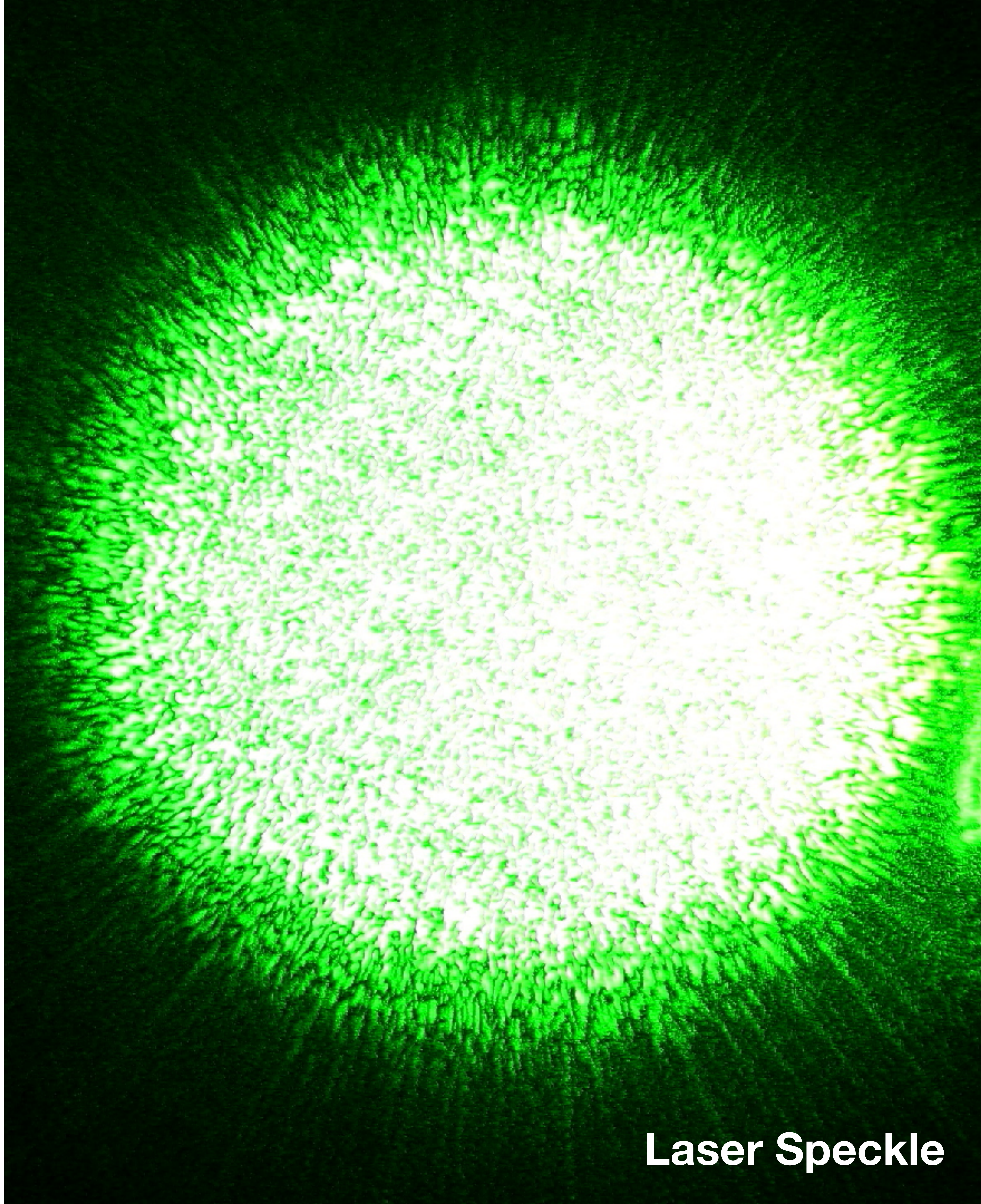
$$\mathrm{fSim}(\theta, \phi) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\theta) & -i\sin(\theta) & 0 \\ 0 & -i\sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 0 & e^{-i\phi} \end{bmatrix}$$



Qubit Speckle



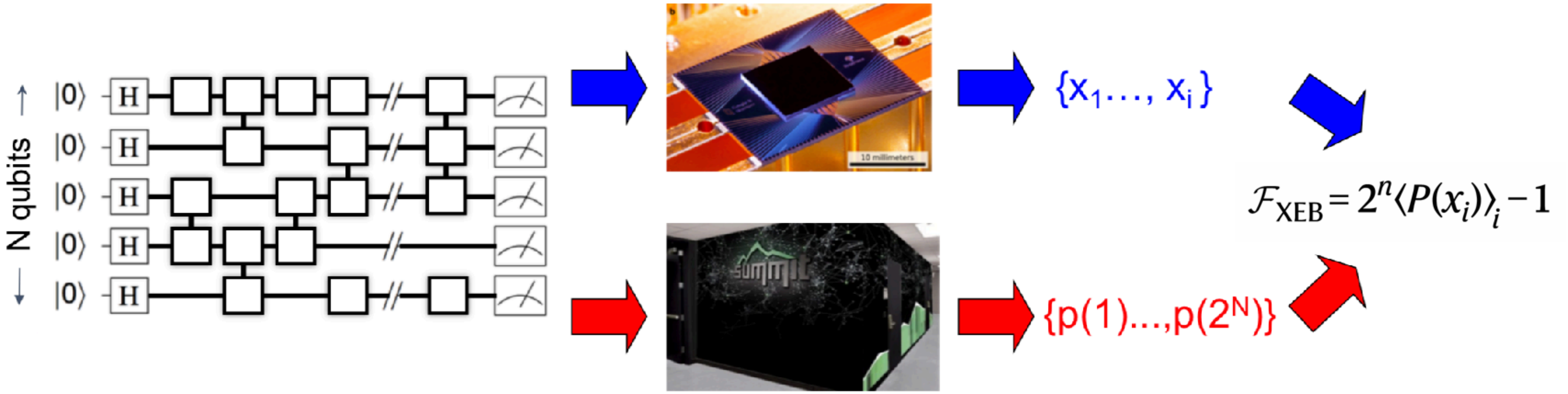
N.Charles et al., *Science* **360**, no. 6385 (2018): 195-199



Laser Speckle

Validation Algorithm for Quantum Supremacy

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



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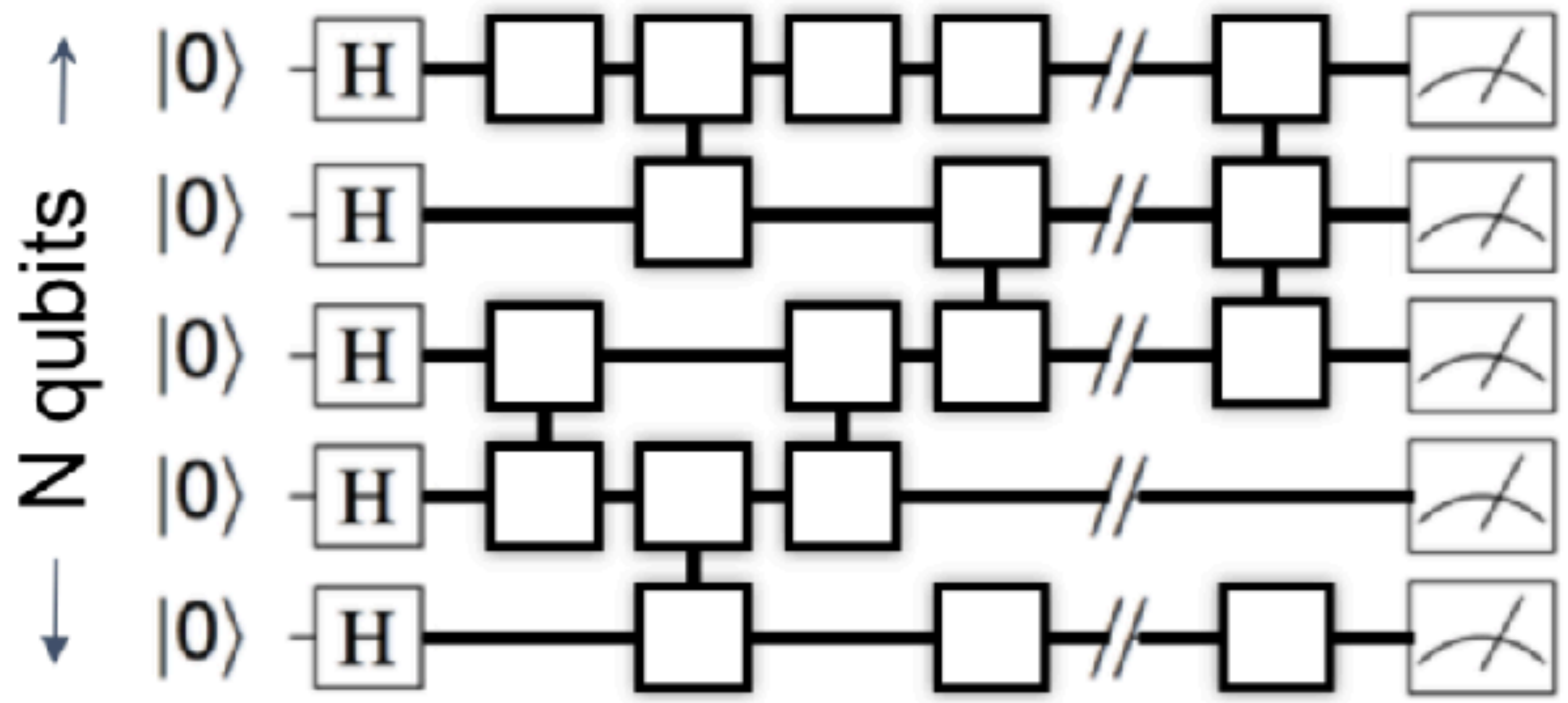
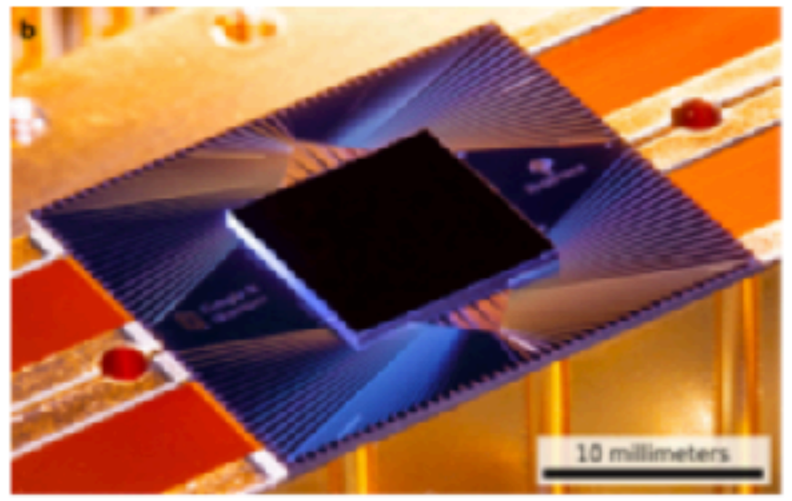




$\{x_1, \ldots, x_i\}$

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

$$\mathcal{F}_{\mathrm{XEB}} = 2^n \langle P(x_i) \rangle_i - 1$$

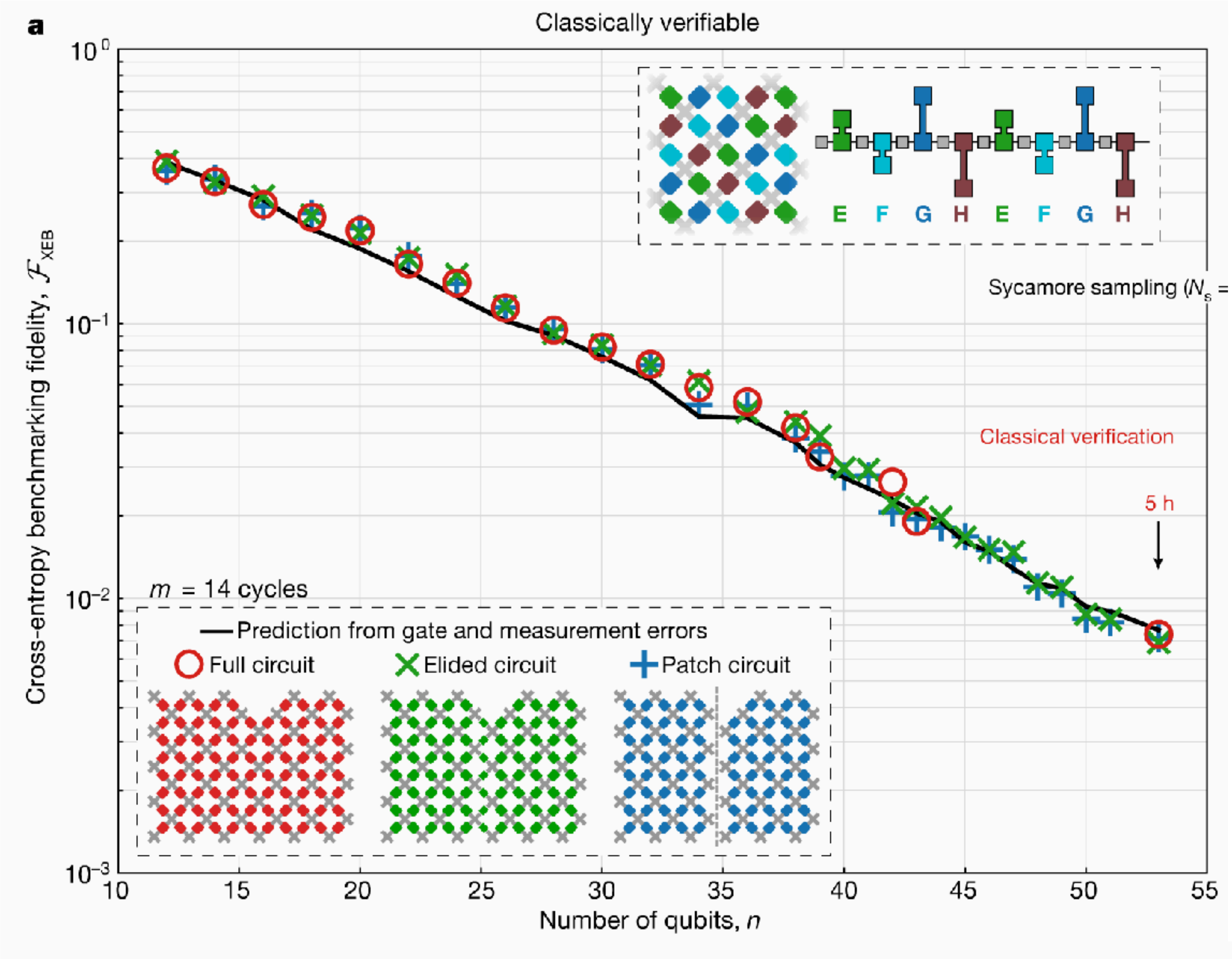
= 1 perfect match

= 0 error

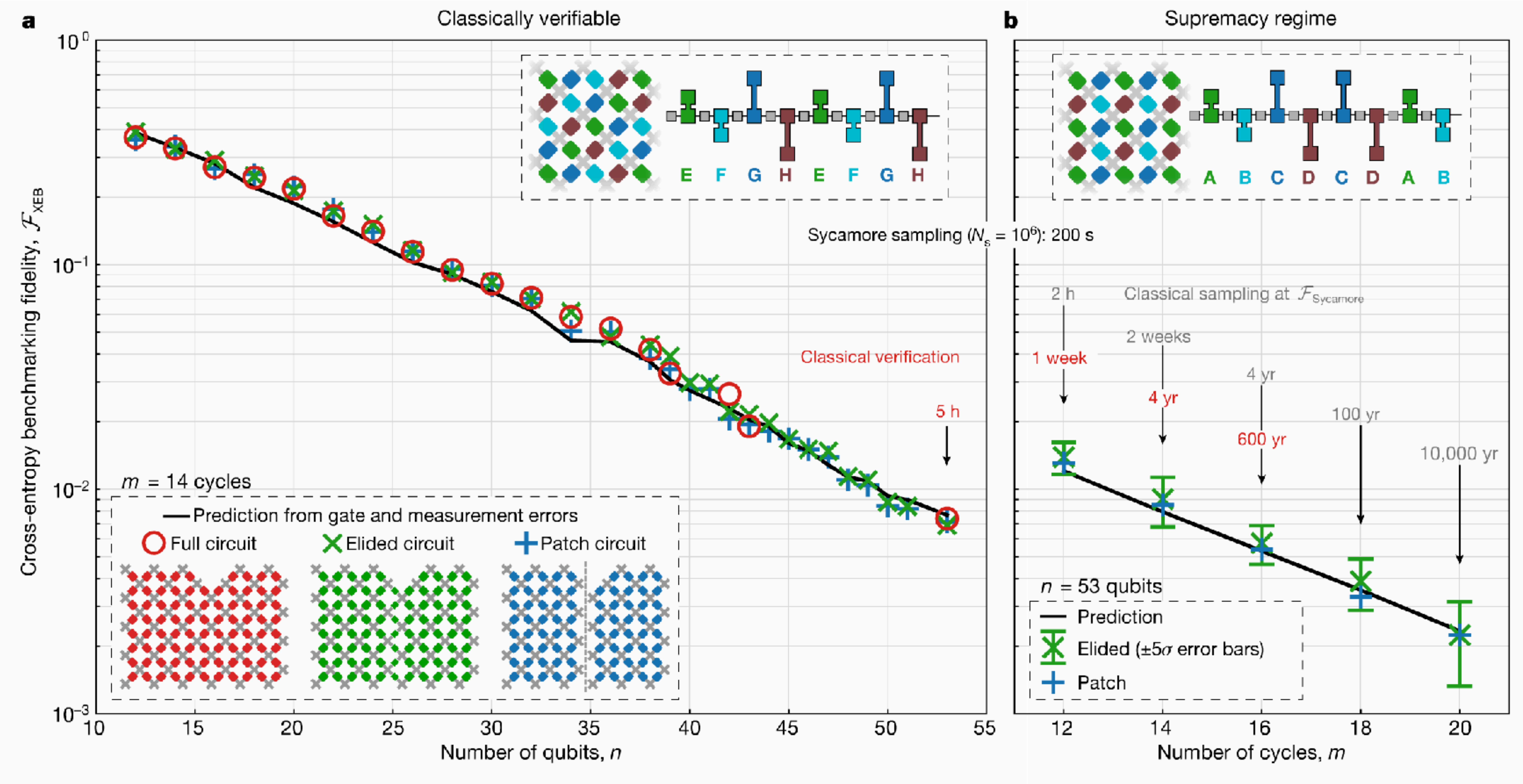
Cross entropy fidelity is useful:

- System validation
- Learn control map

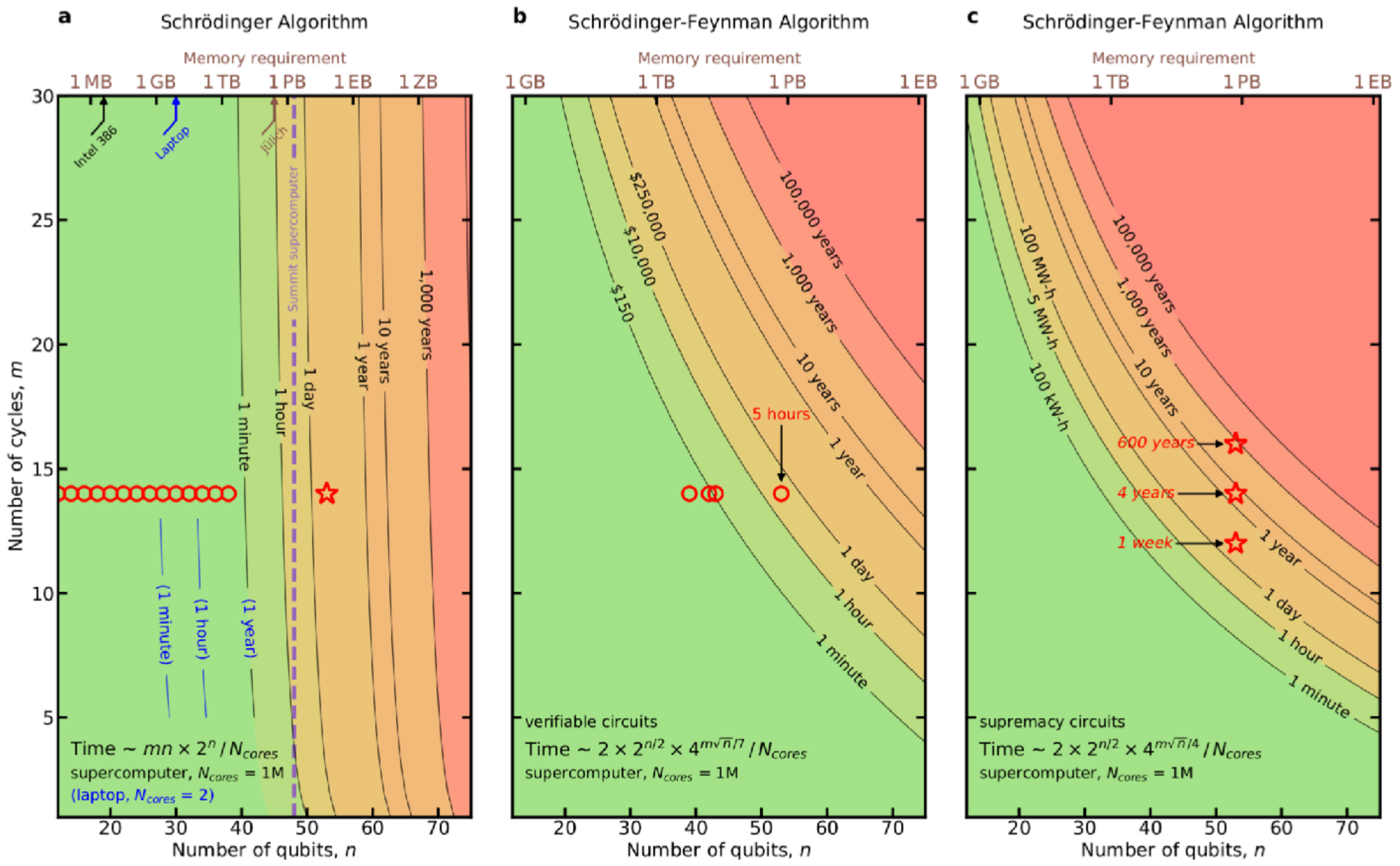
Quantum Supremacy Data



Quantum Supremacy Data



Computational Cost



Quantum supremacy

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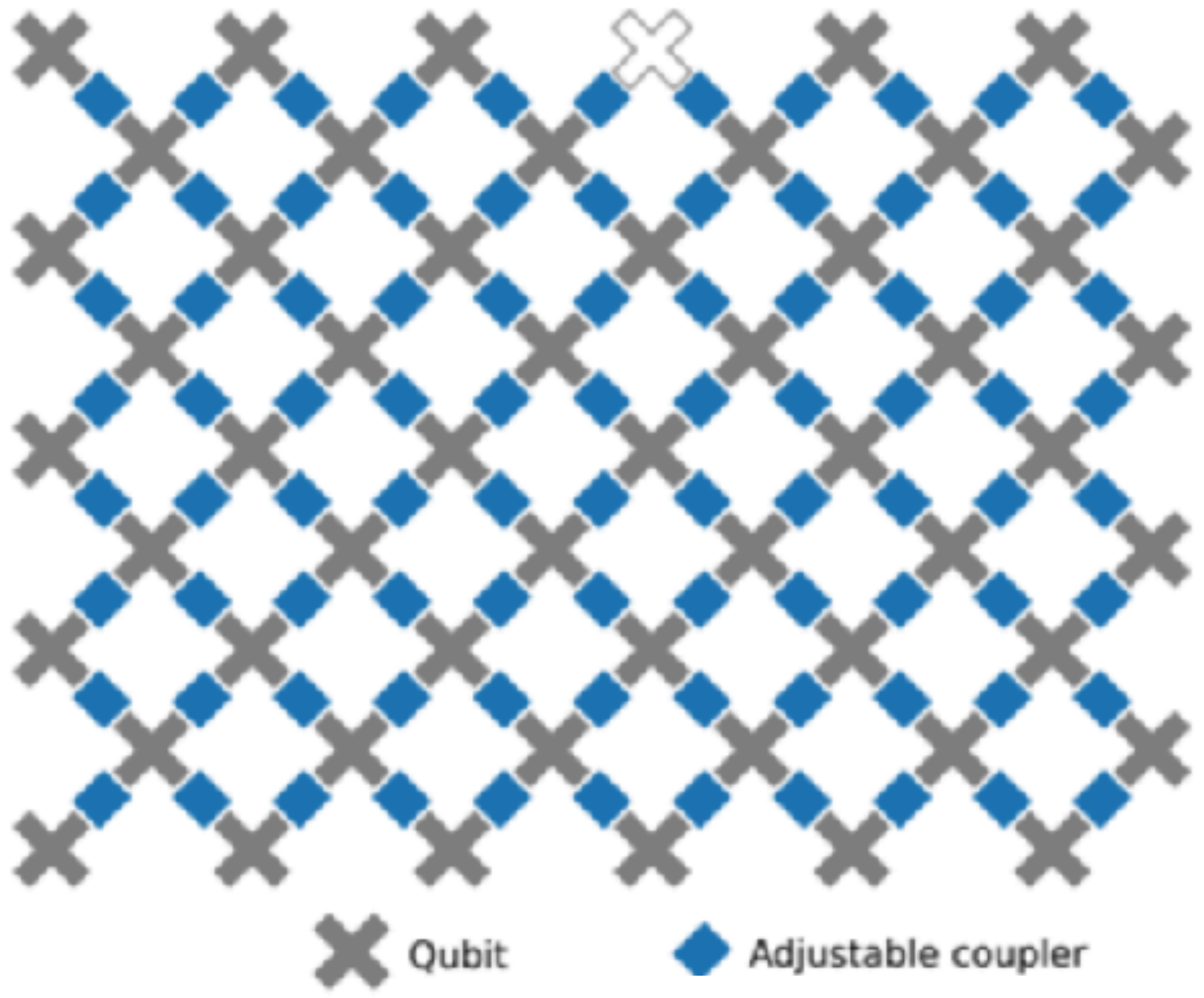
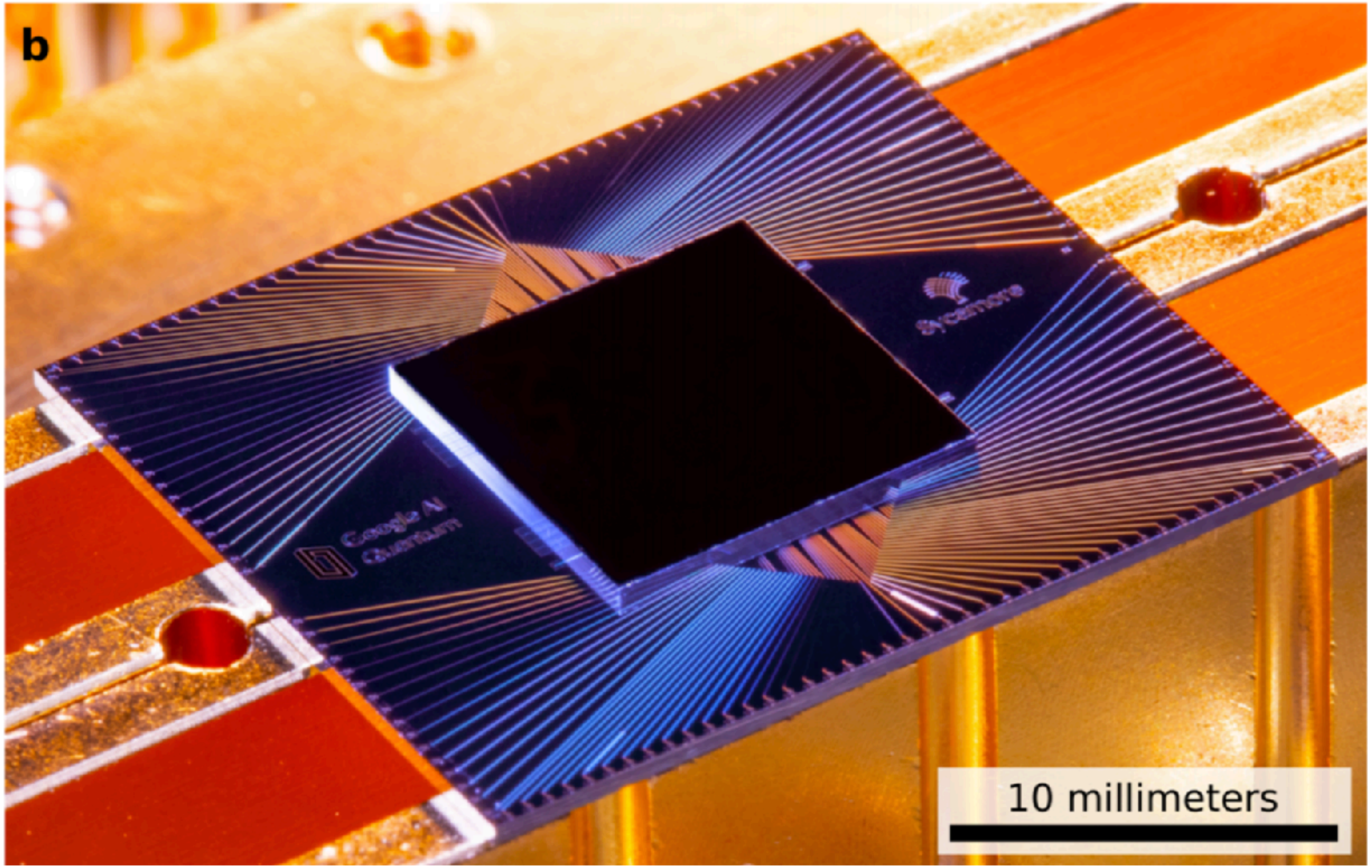
Sycamore Processor: 53 qubits

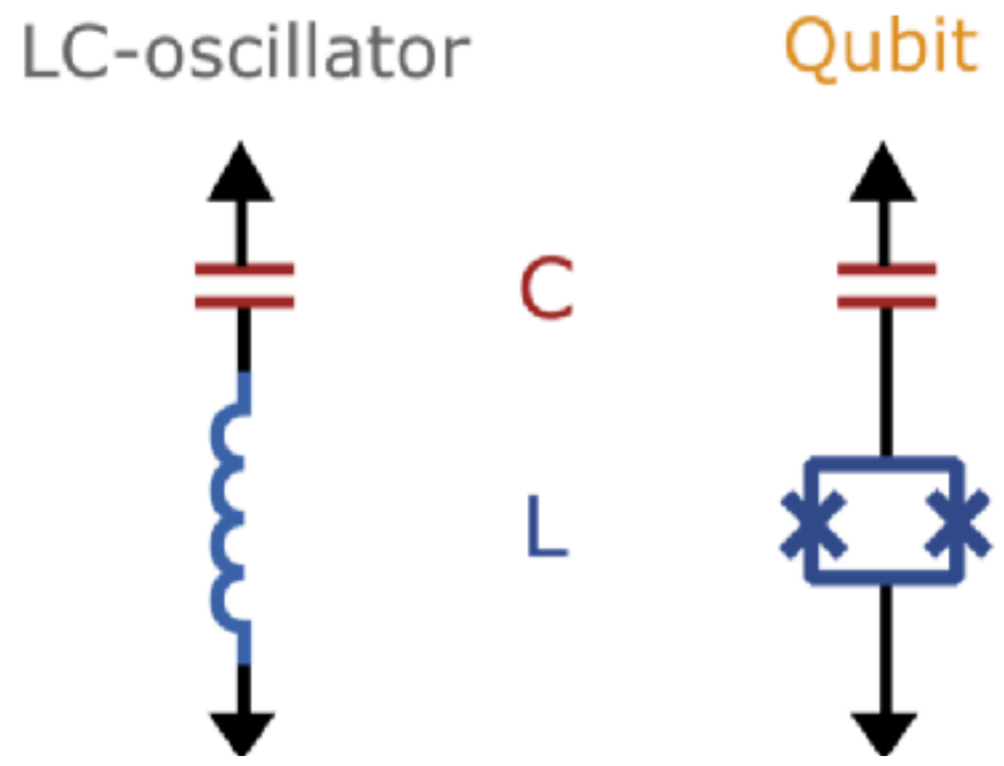


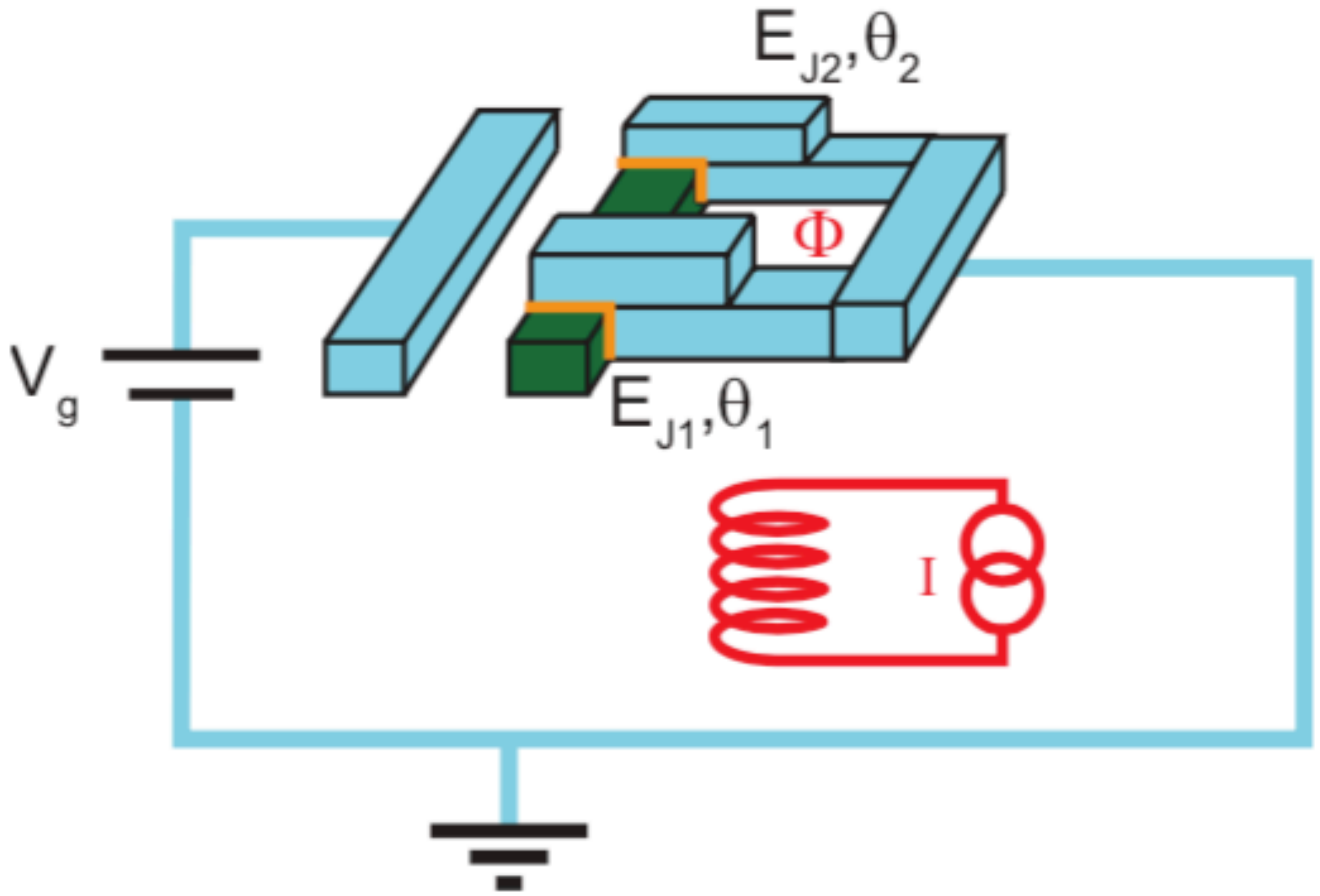


Superconducting qubits

$$\hat{H} = \frac{1}{2C}\hat{Q}^2 + \frac{1}{2}C\omega^2\hat{\Phi}^2$$

$$\hat{H} = \hbar\omega\left(\hat{a}^\dagger\hat{a} + \frac{1}{2}\right)$$





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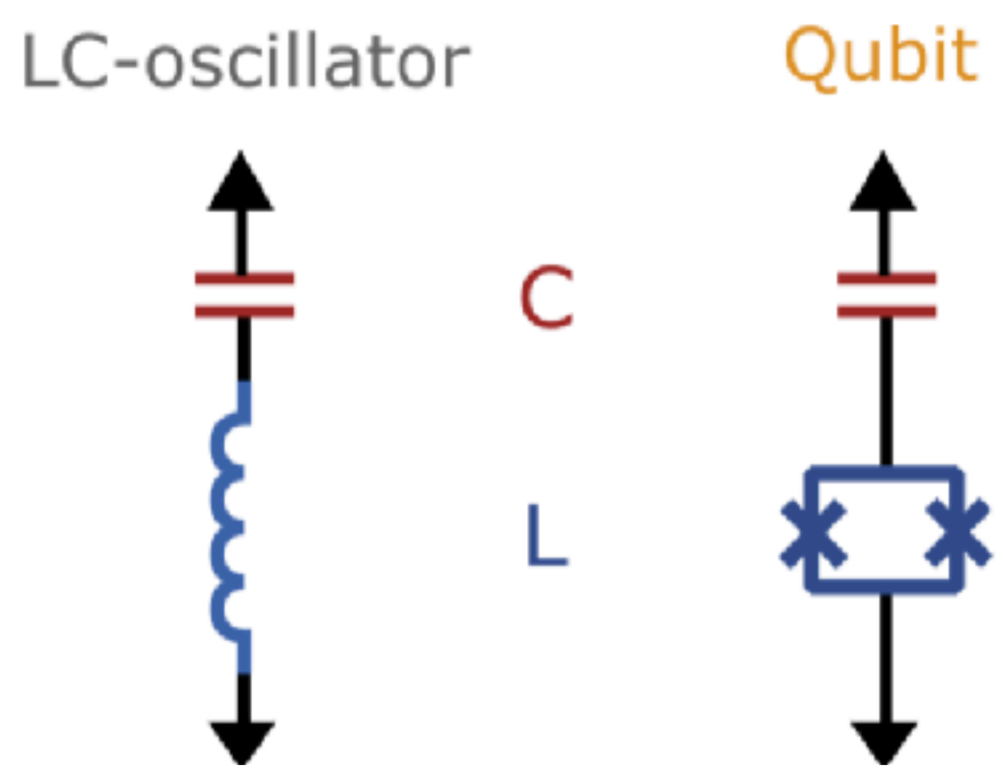
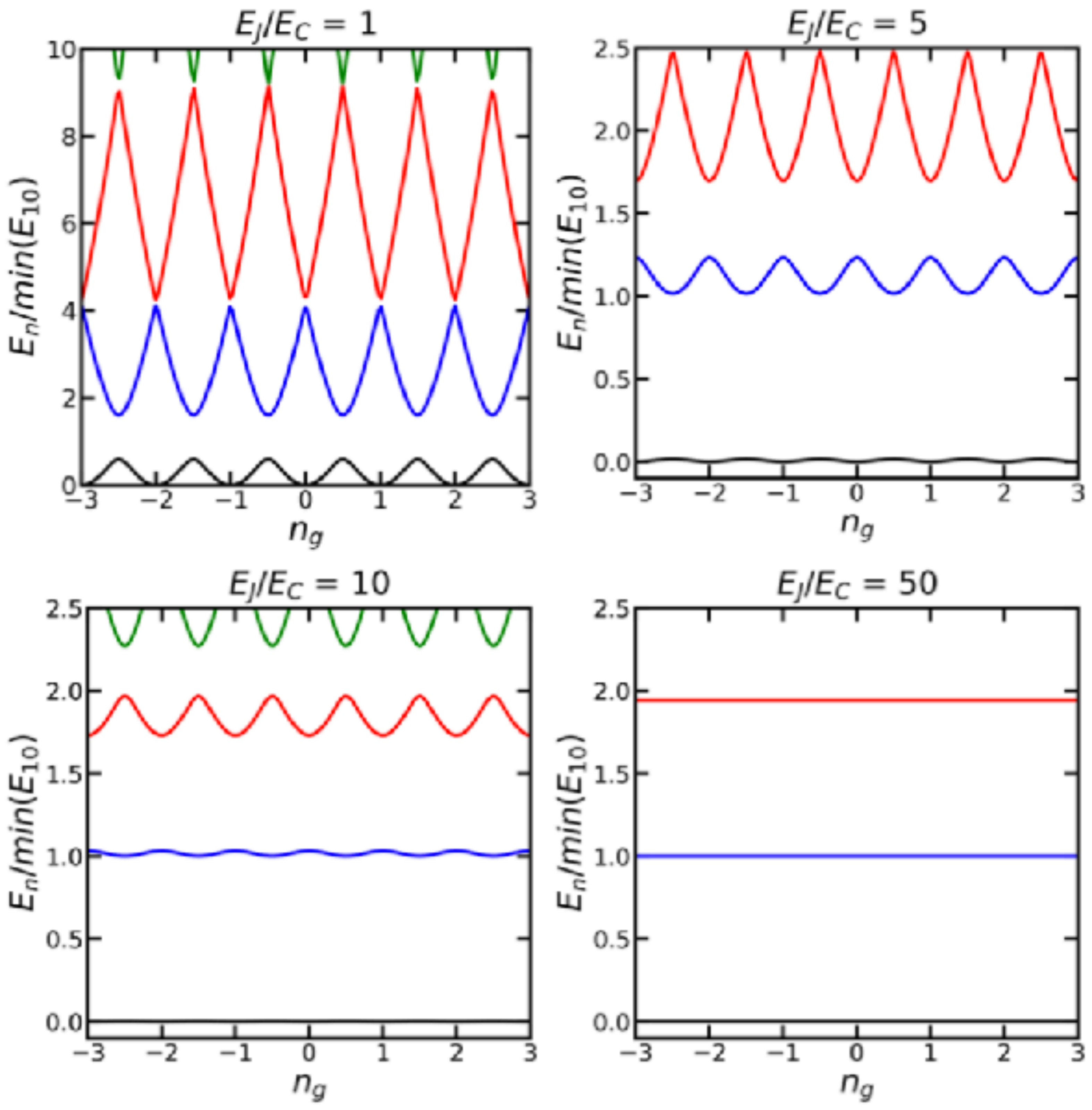
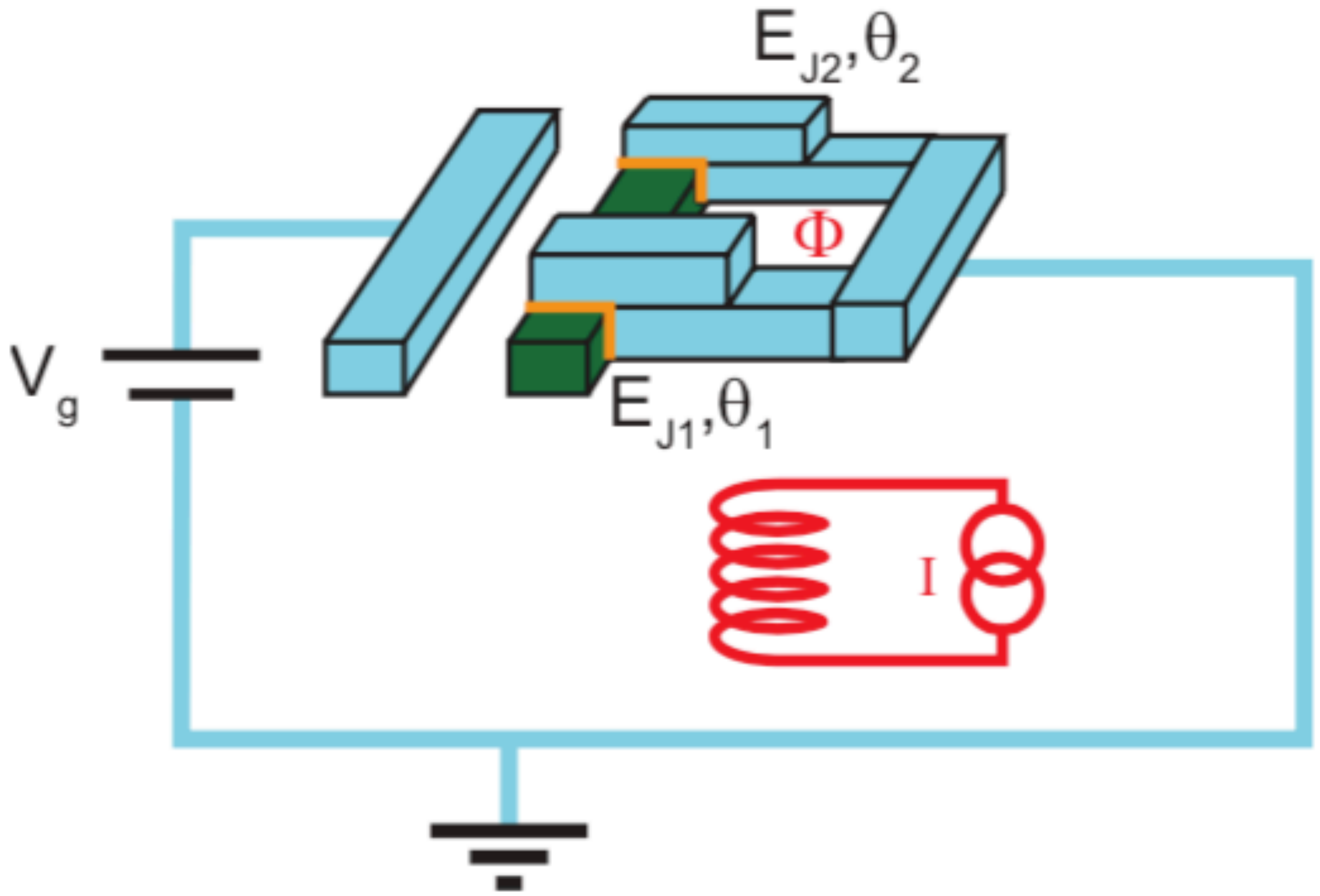


$$\hat{H}_{CPB} = 4E_c(\hat{n} - n_g)^2 - E_J\cos\hat{\phi}$$

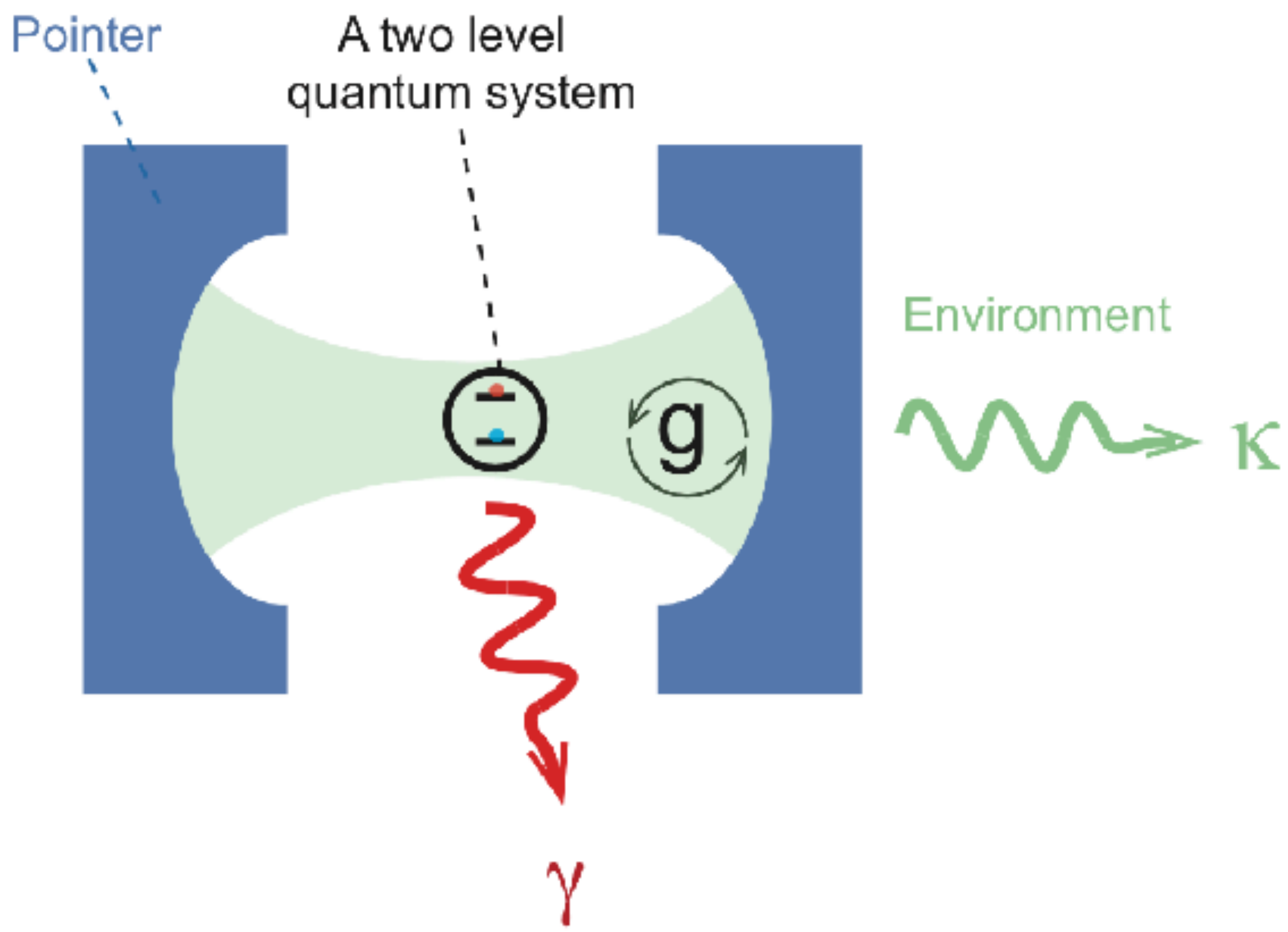




$$E_J \to E_J^{\Sigma}\cos\left(\frac{\pi\Phi}{\Phi_0}\right)\sqrt{1 + d^2\tan^2\left(\frac{\pi\Phi}{\Phi_0}\right)}, \qquad d \simeq \frac{E_{J1}-E_{J2}}{E_{J1}+E_{J2}}$$

cQED

circuit Quantum ElectroDynamics

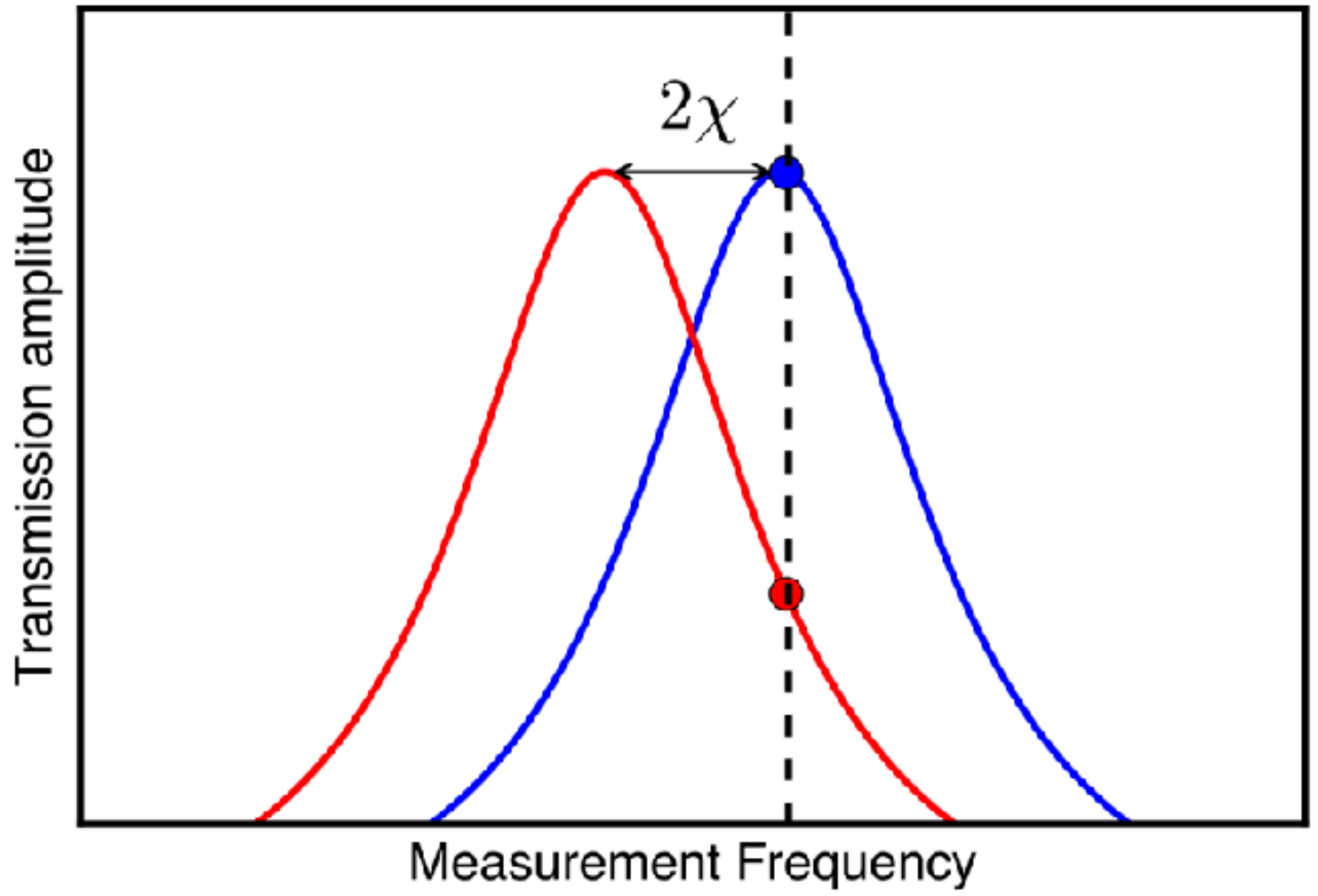


Janes-Cumming Hamiltonian

$$\hat{H}_{JC} = \frac{\hbar\omega_q}{2}\hat{\sigma}_z + \hbar\omega_c\hat{a}^\dagger\hat{a} + \hbar g(\hat{a}^\dagger + \hat{a})(\sigma_+ + \sigma_-)$$

dispersive regime

$$\hat{H}_{JC} \approx \hbar\left[\omega_c + \frac{g^2}{\Delta}\hat{\sigma}_z\right](\hat{a}^\dagger\hat{a} + \frac{1}{2}) + \frac{\hbar}{2}\omega_q\hat{\sigma}_z$$



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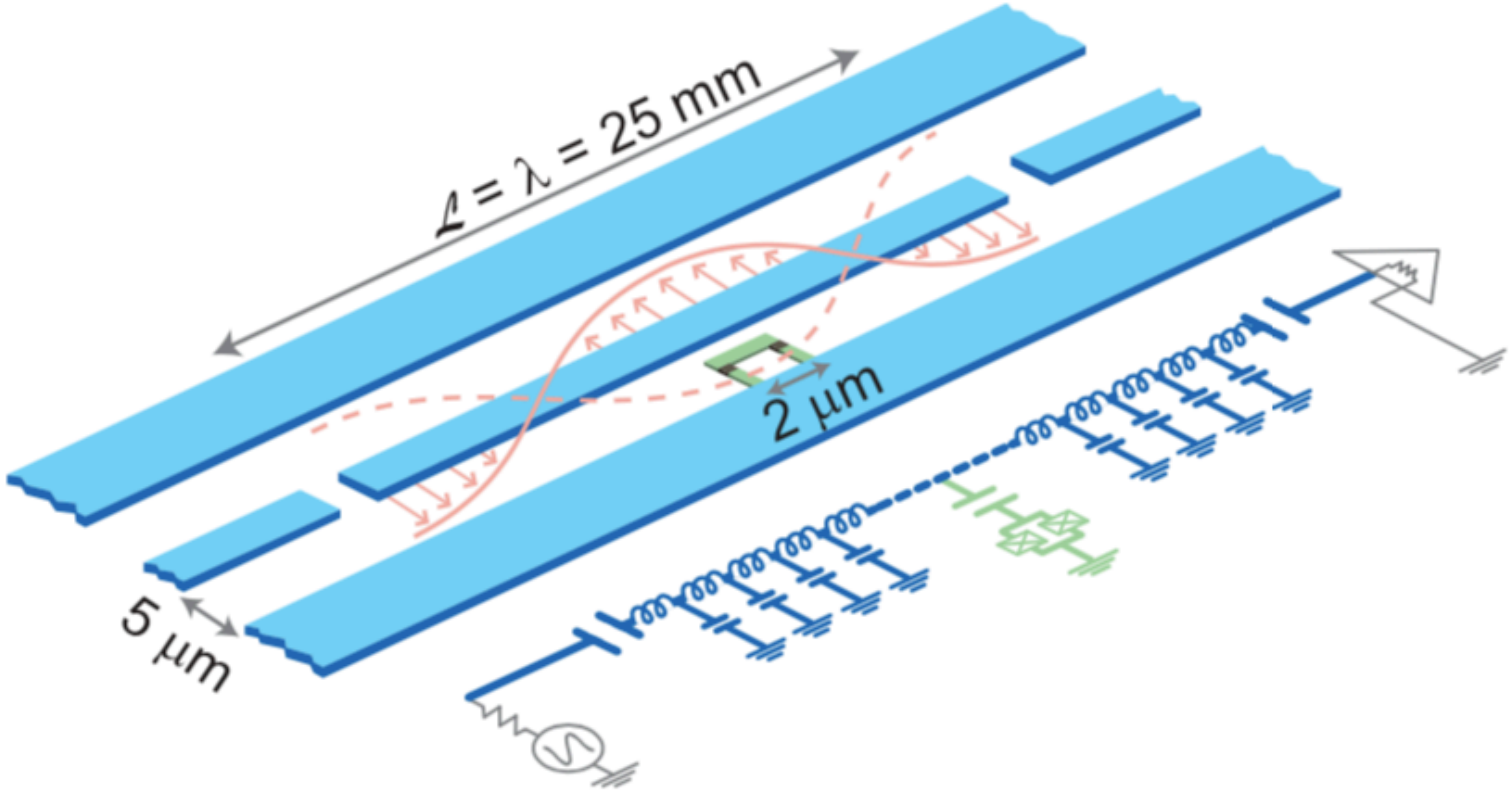
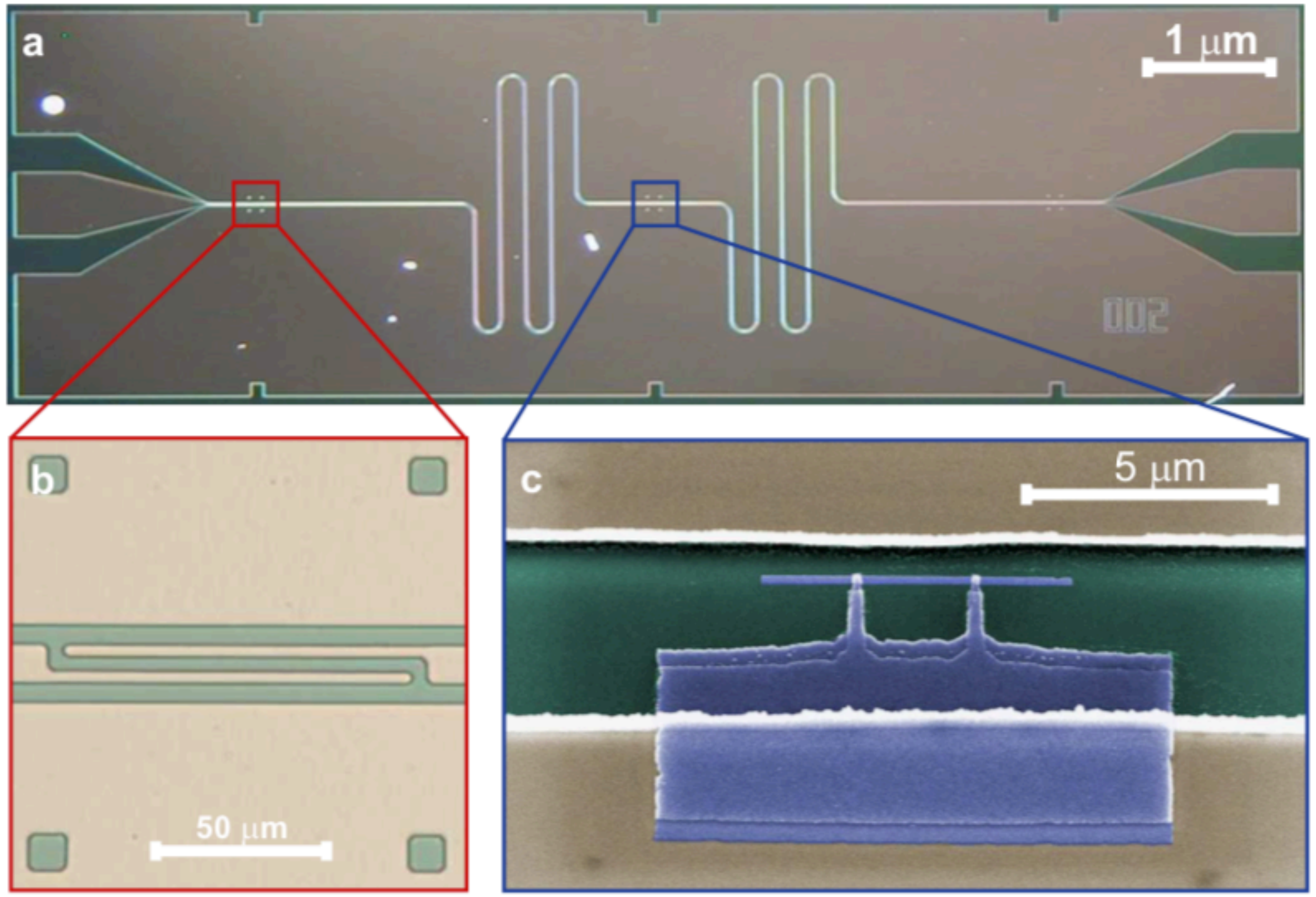
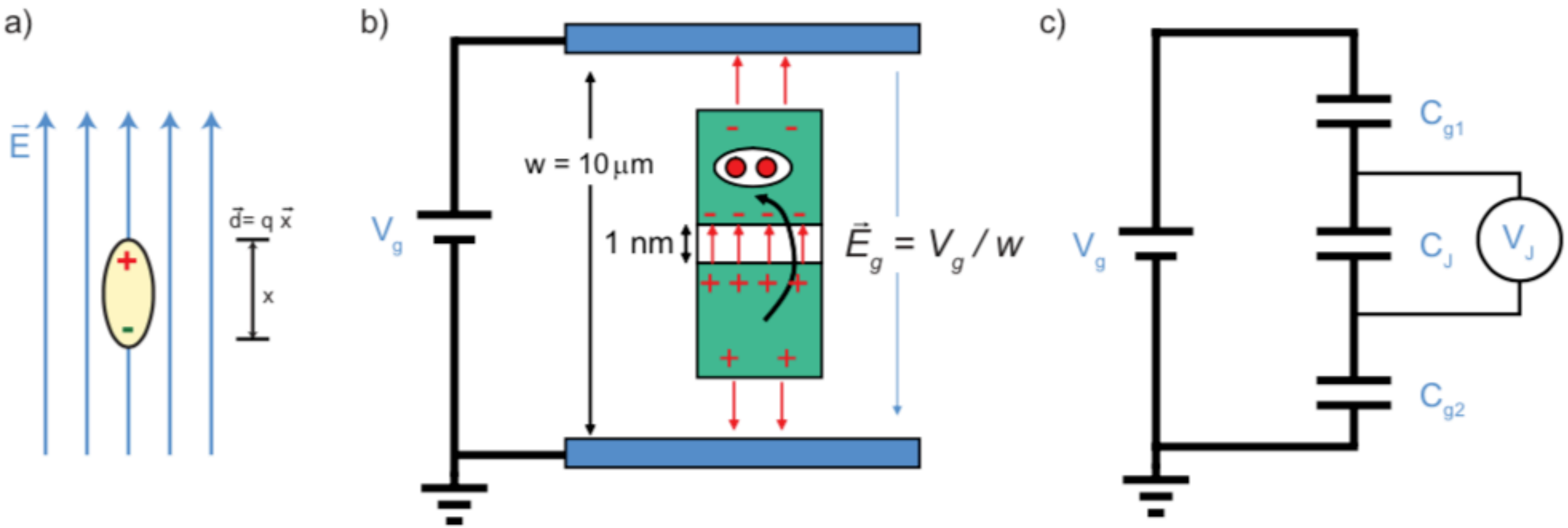
circuit Quantum ElectroDynamics





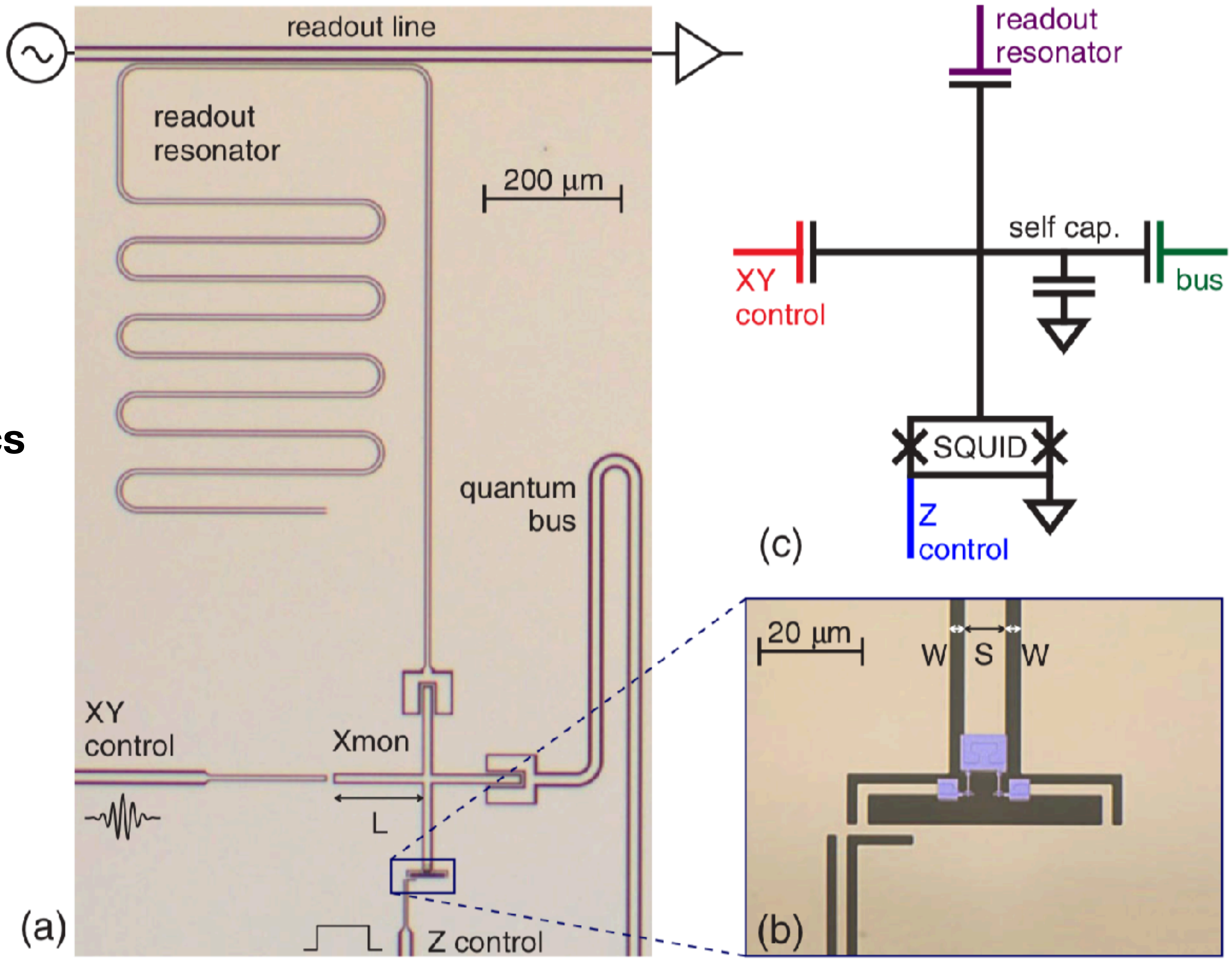
cQED

circuit Quantum ElectroDynamics



cQED

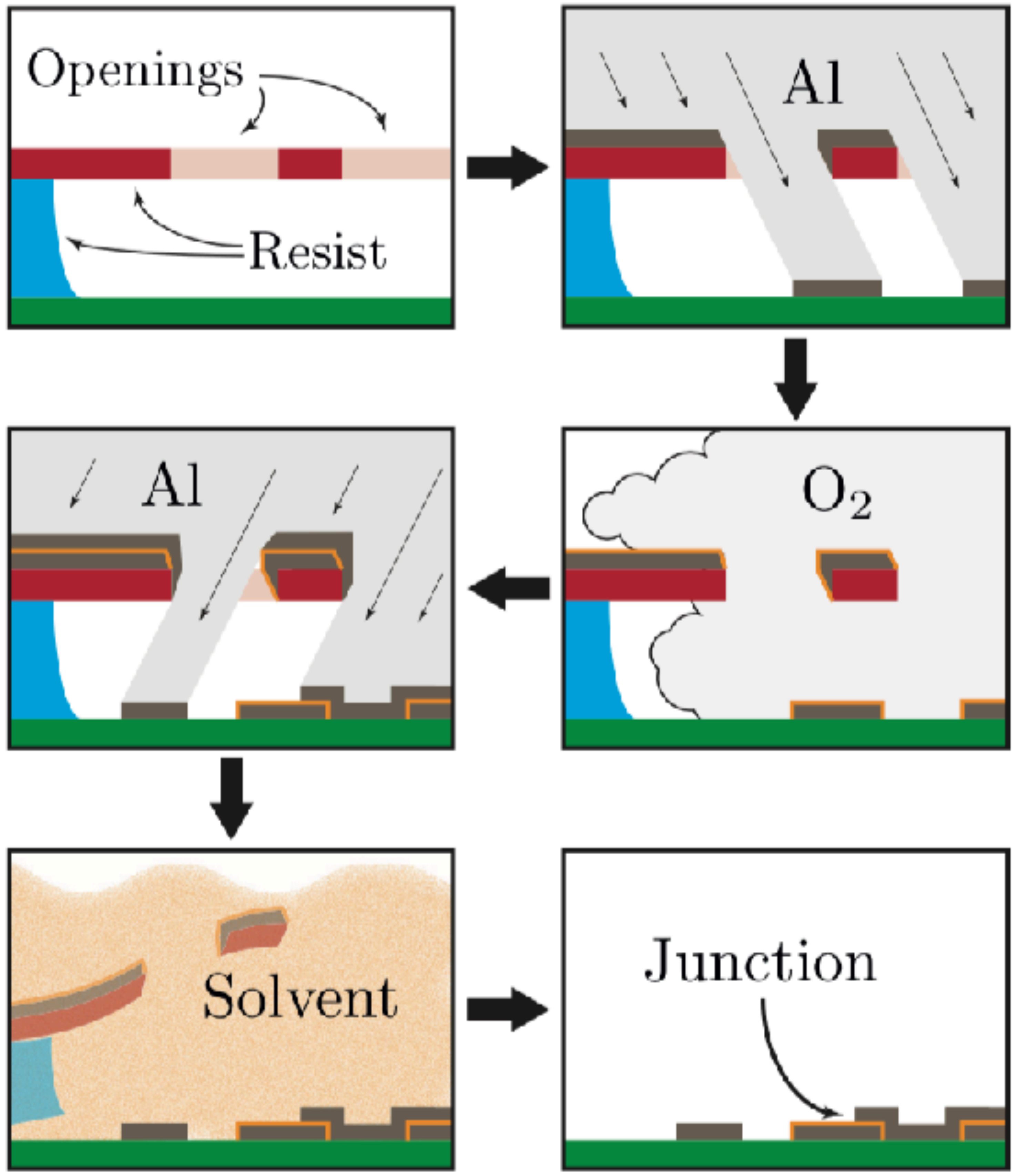
circuit Quantum ElectroDynamics on Google's device

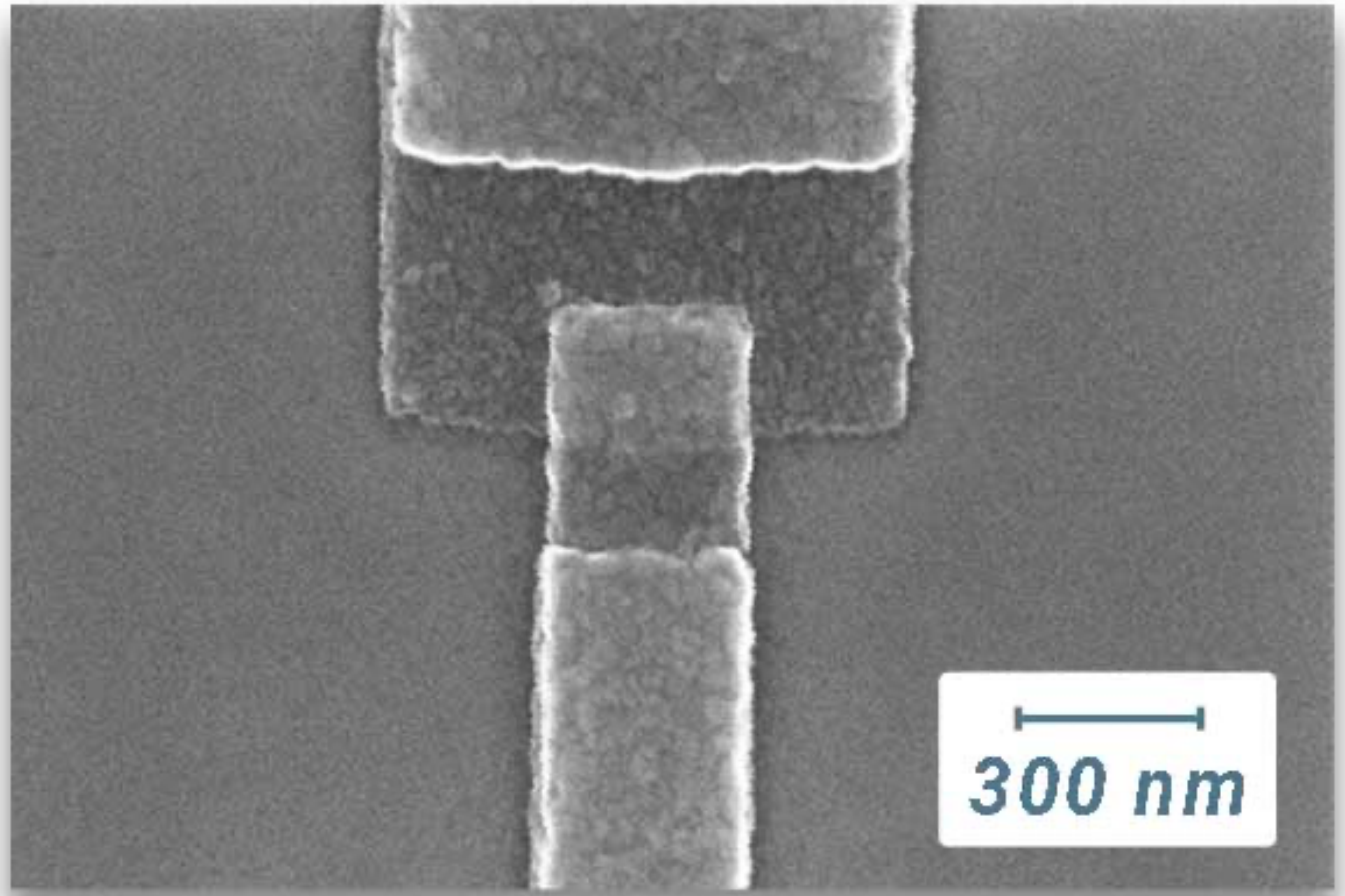


Josephson junctions

fabrication

shadow evaporation

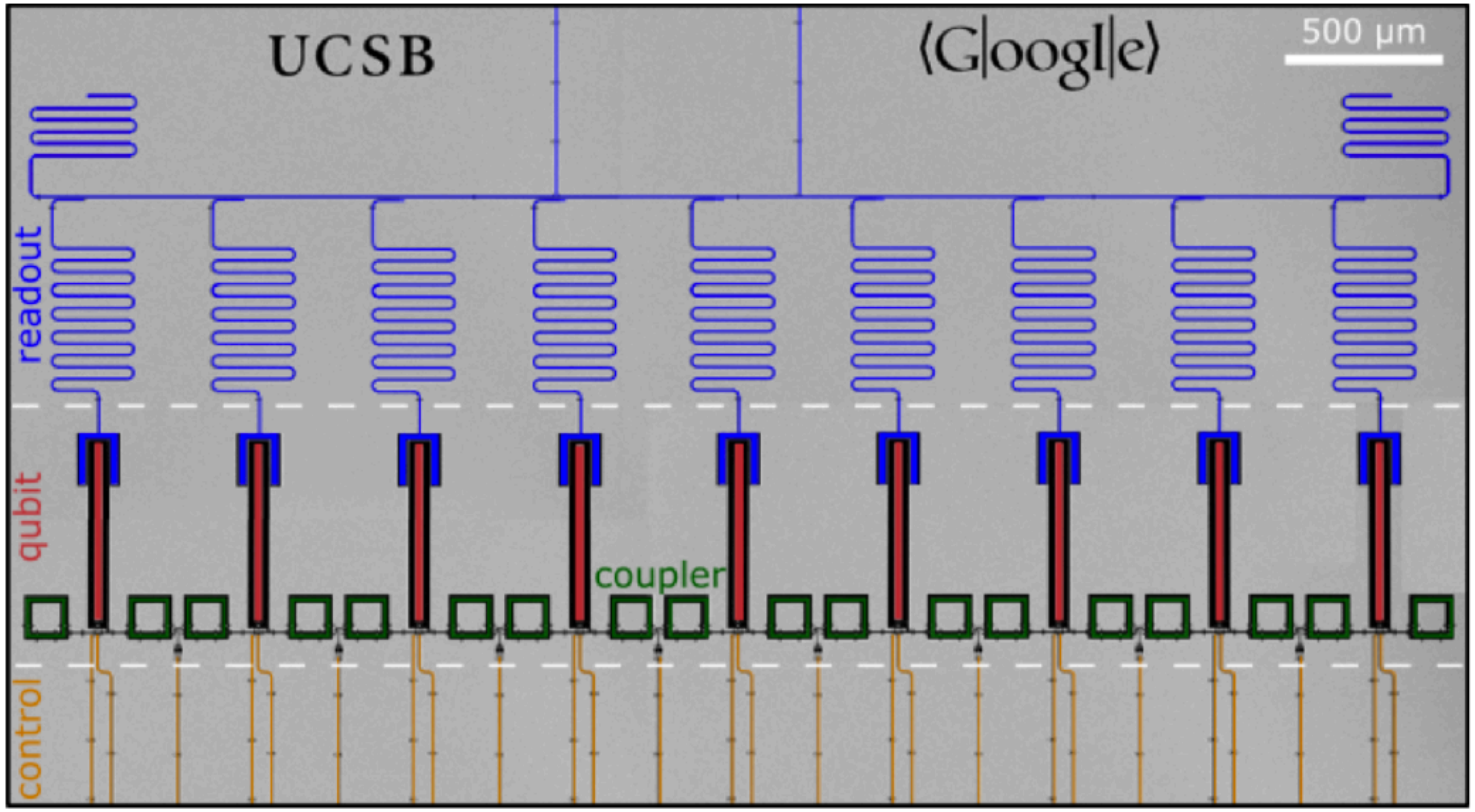


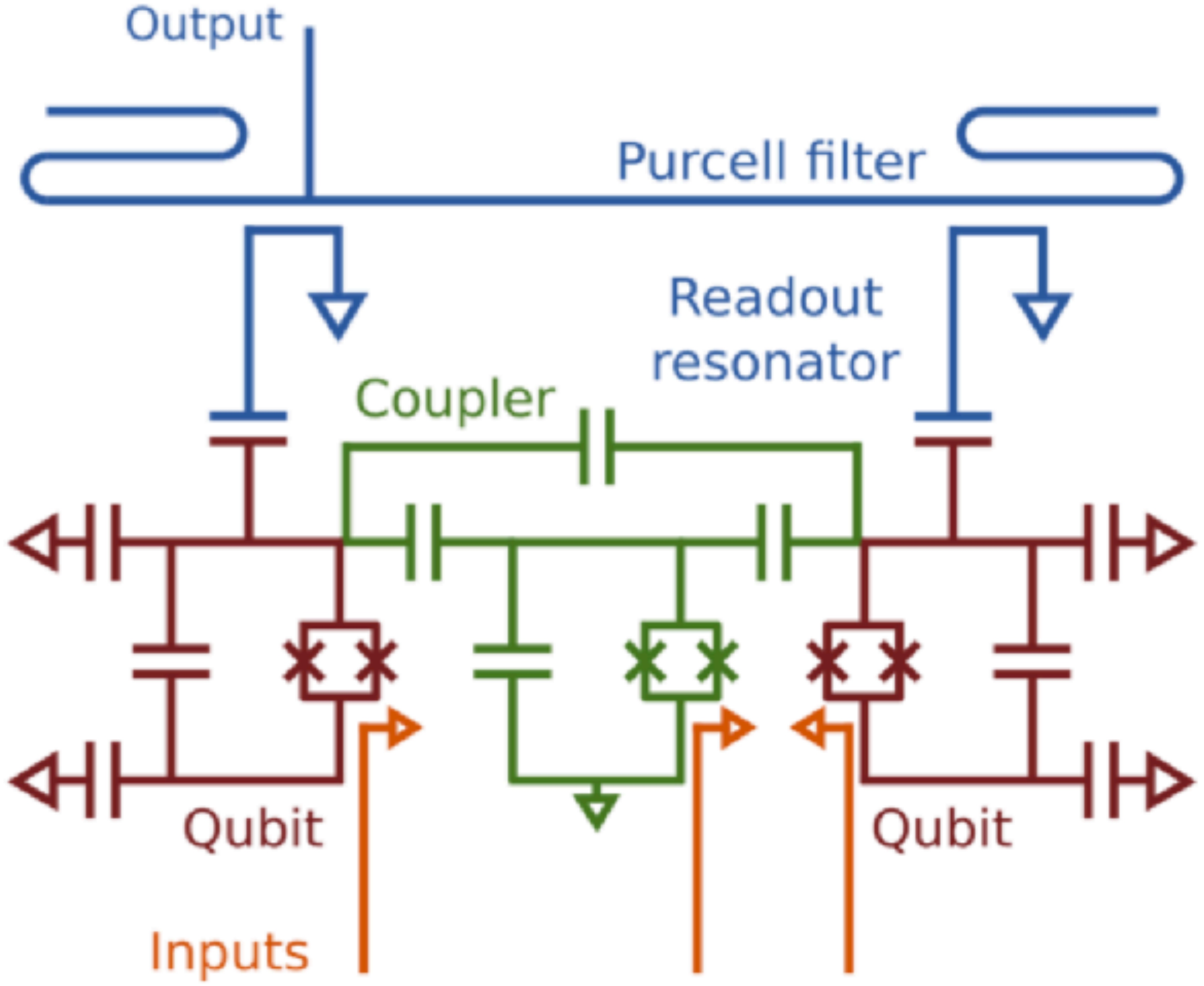


SEM image courtesy of the Institute for Quantum Computing (IQC) at the University of Waterloo

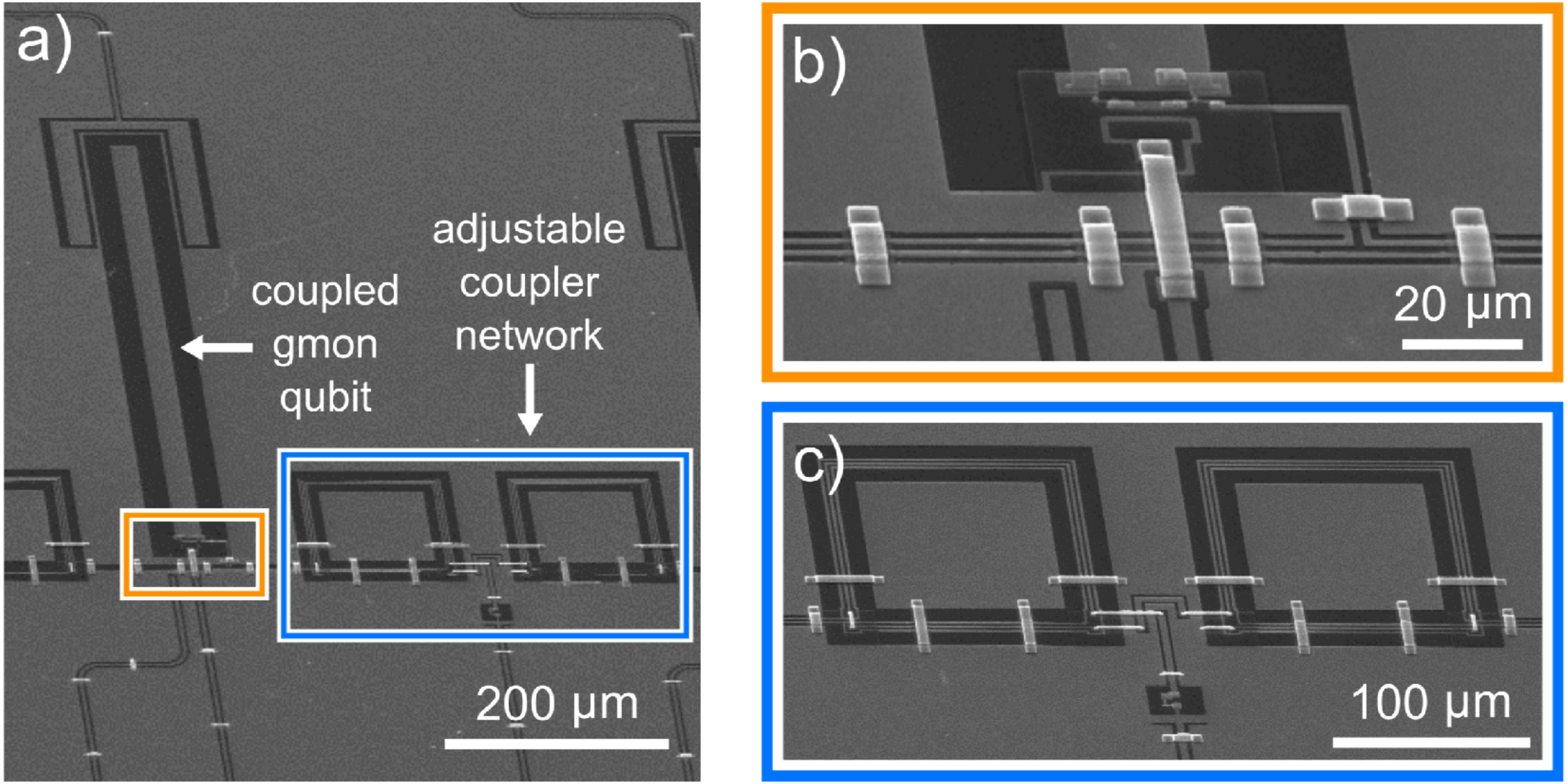
Sycamore architecture

(early prototypes)

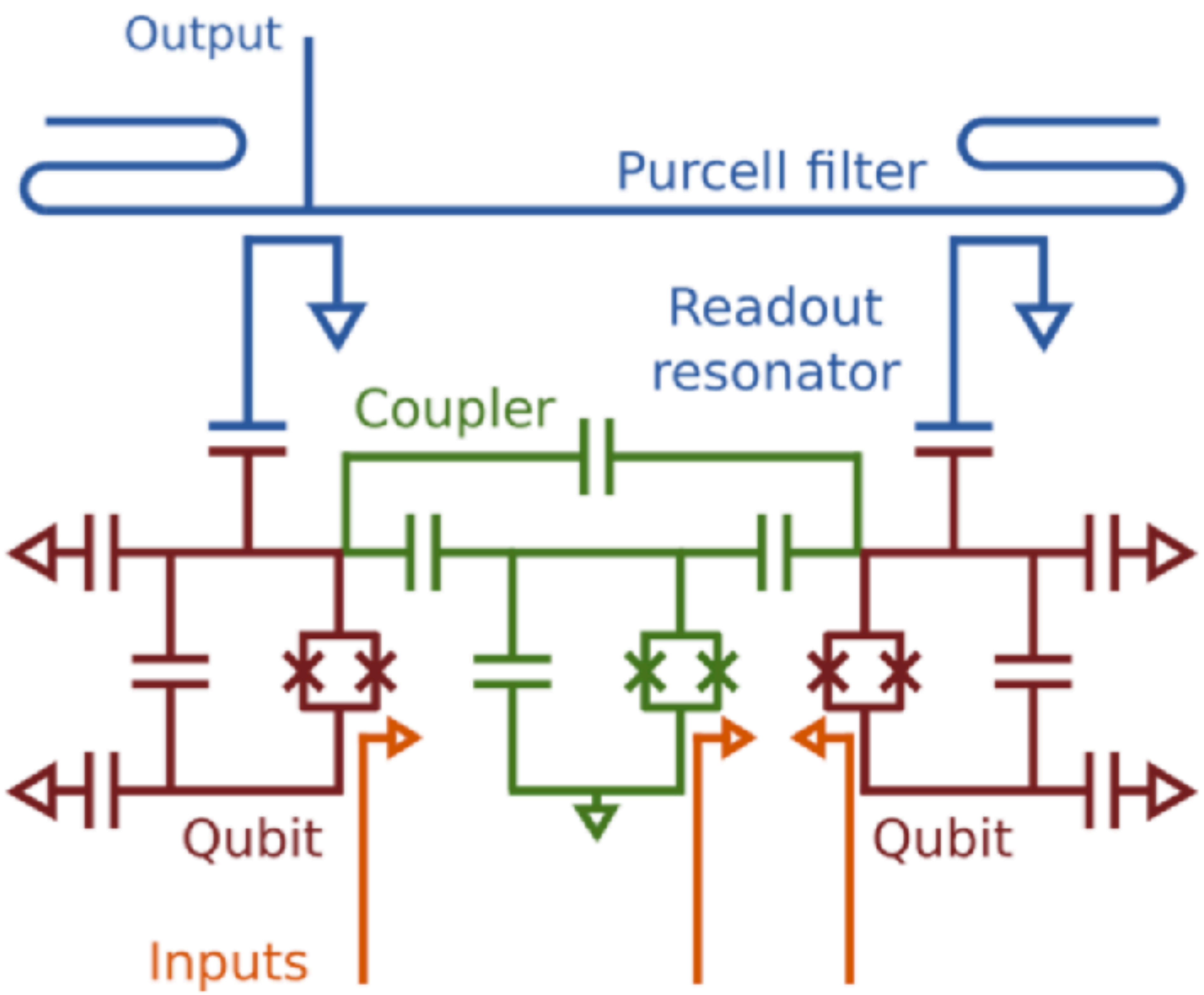


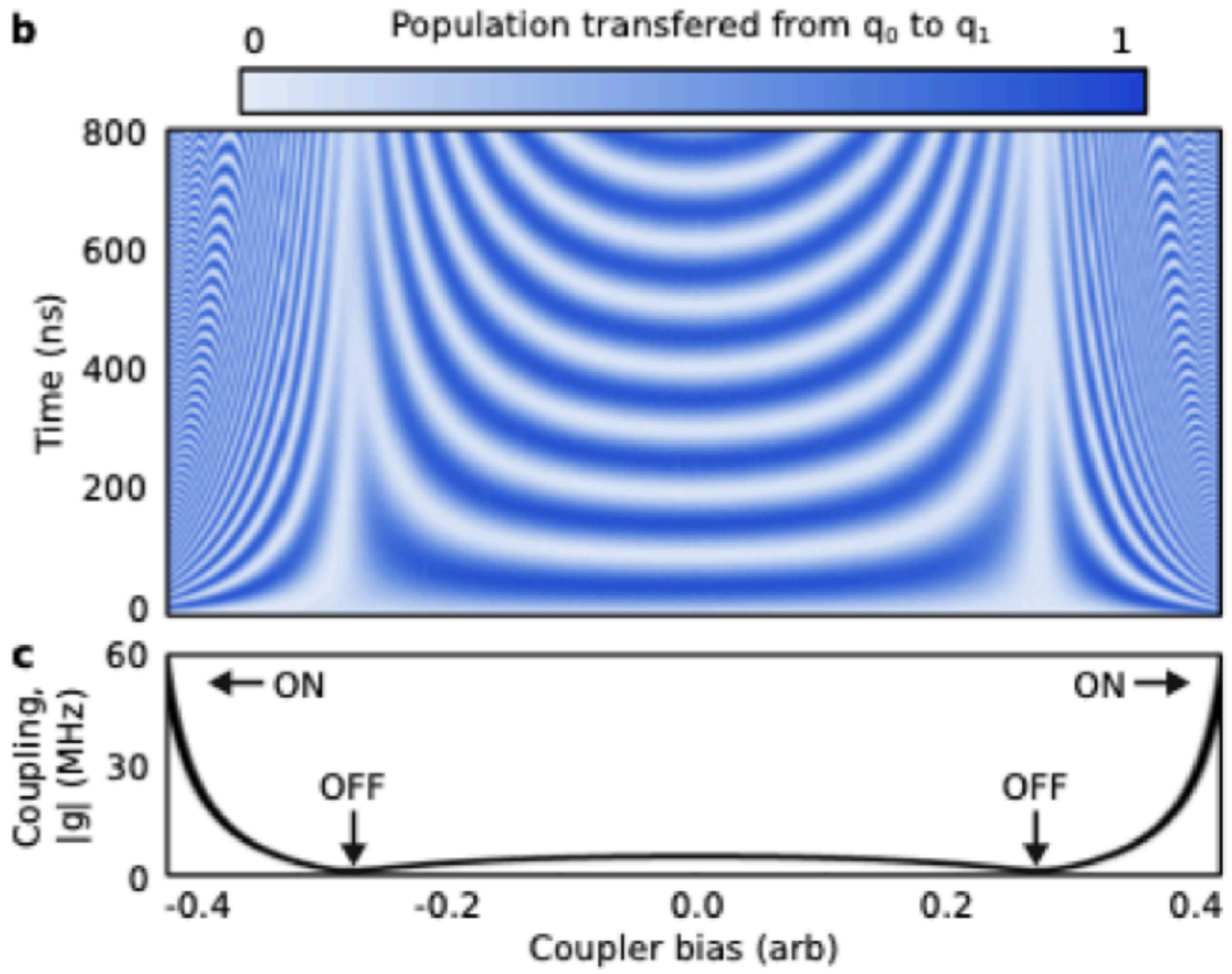


Sycamore architecture fab

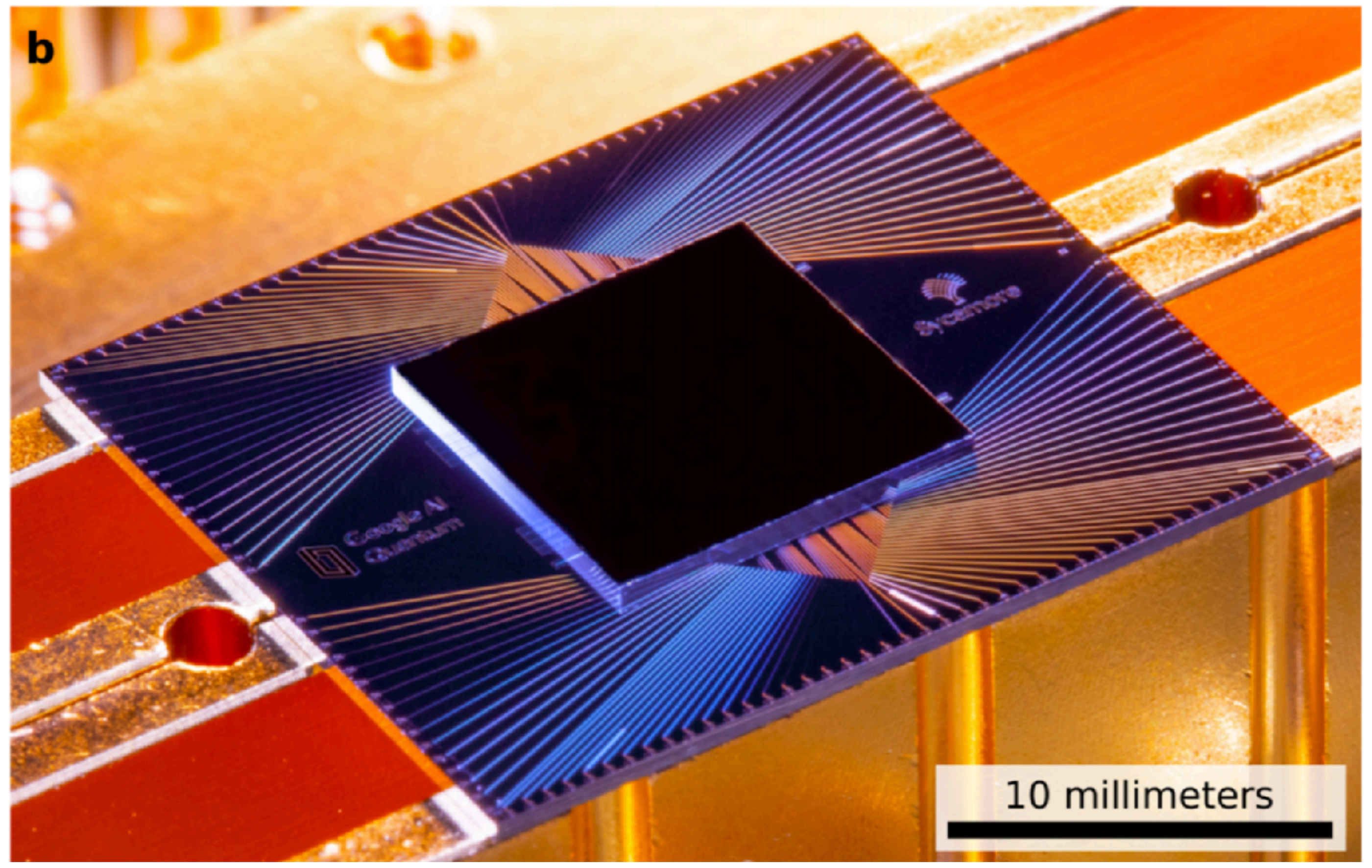


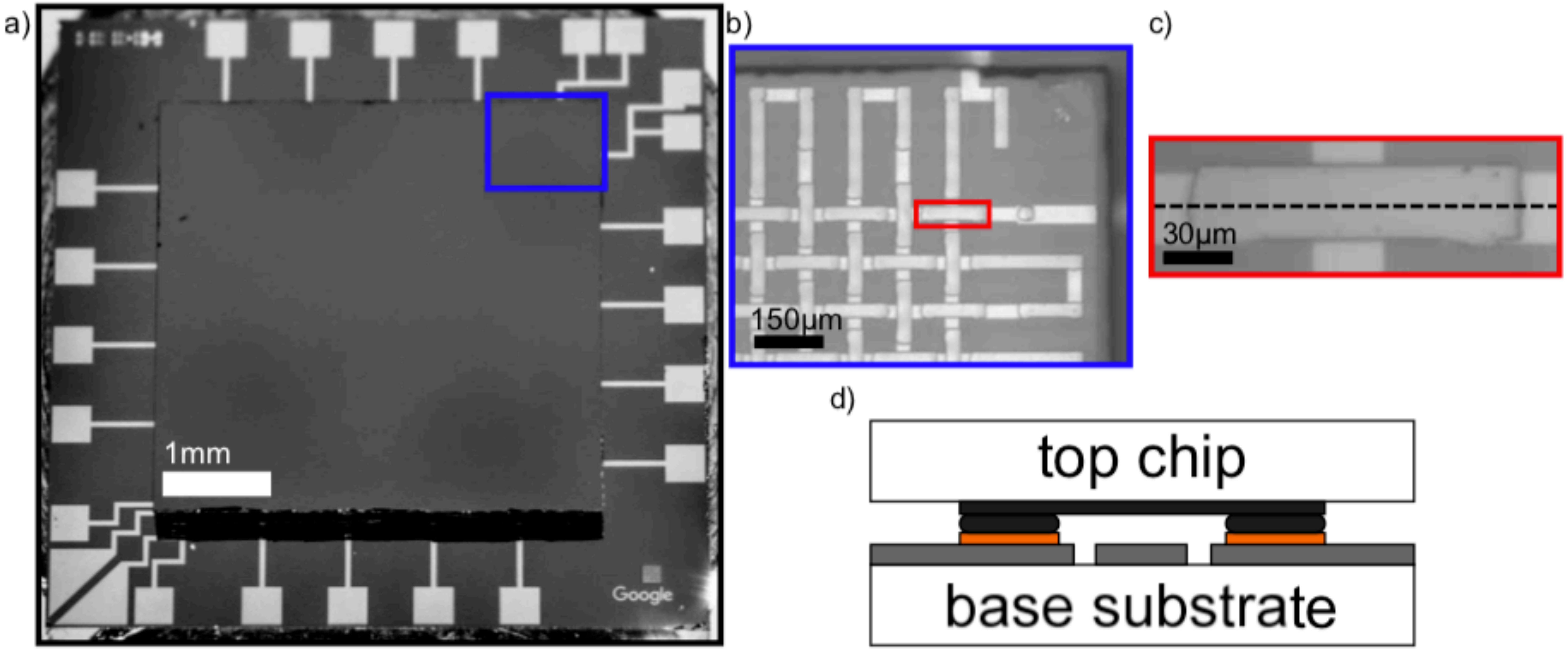
Qubit couplers



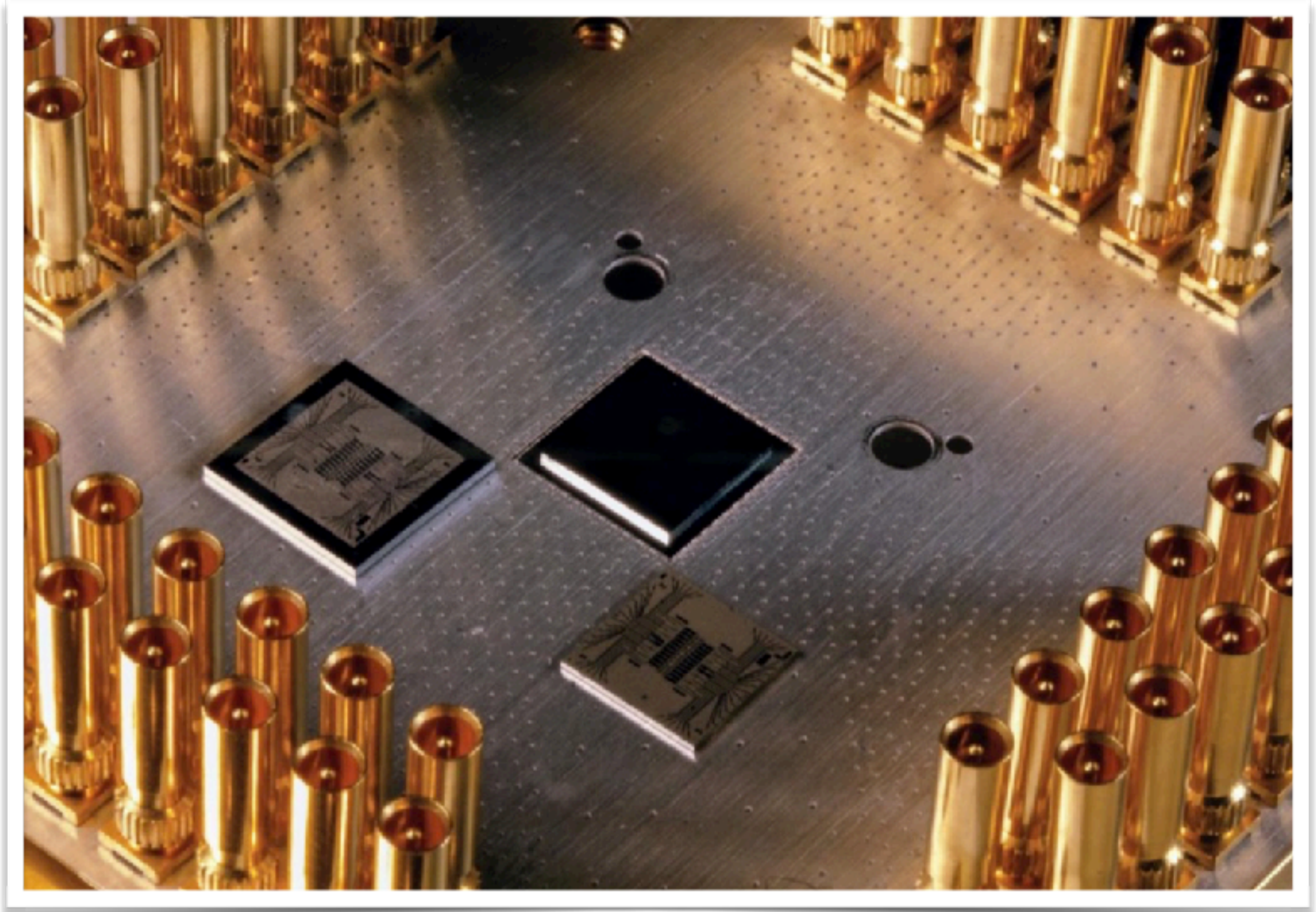


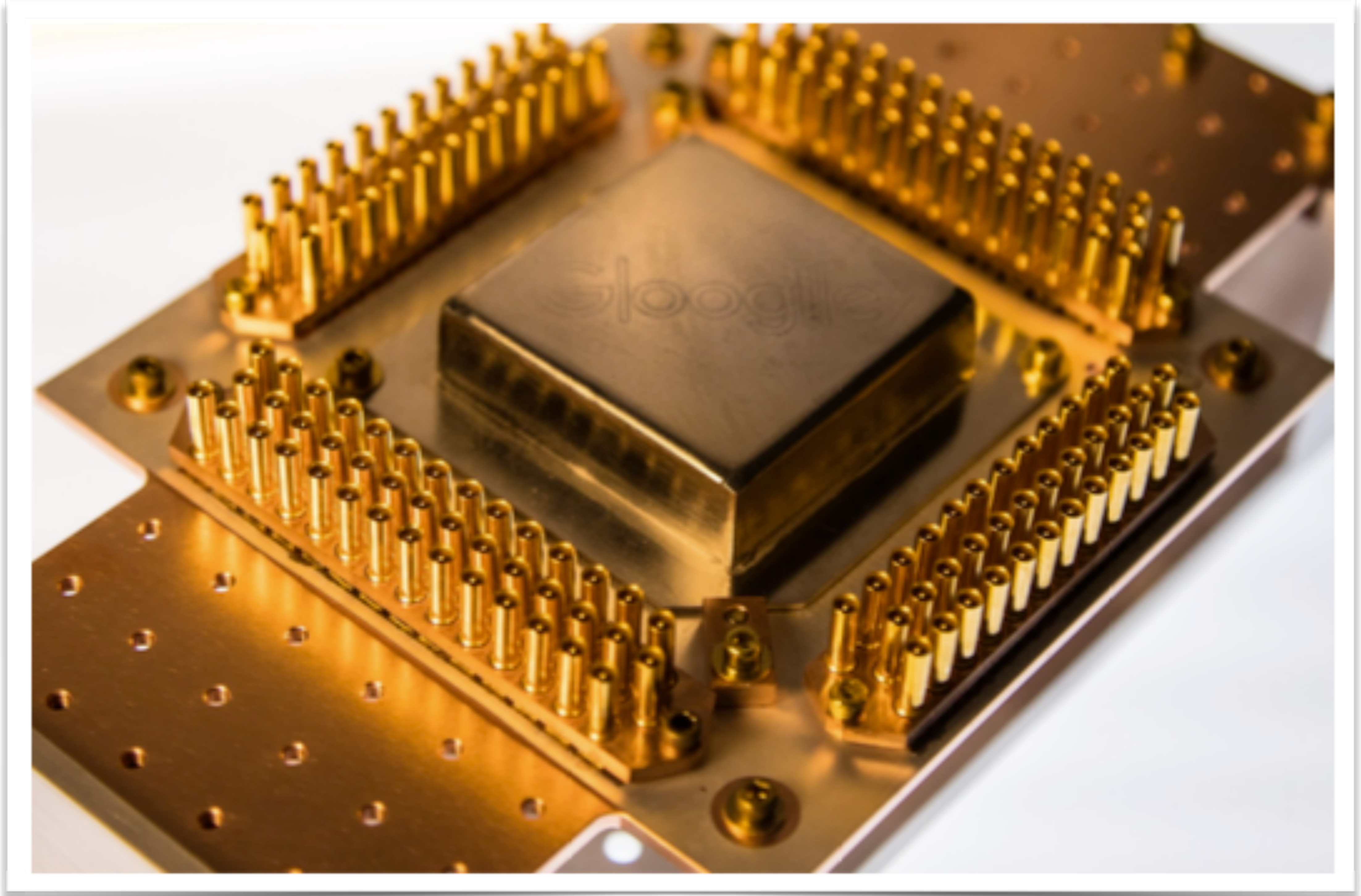
Wire connectivity



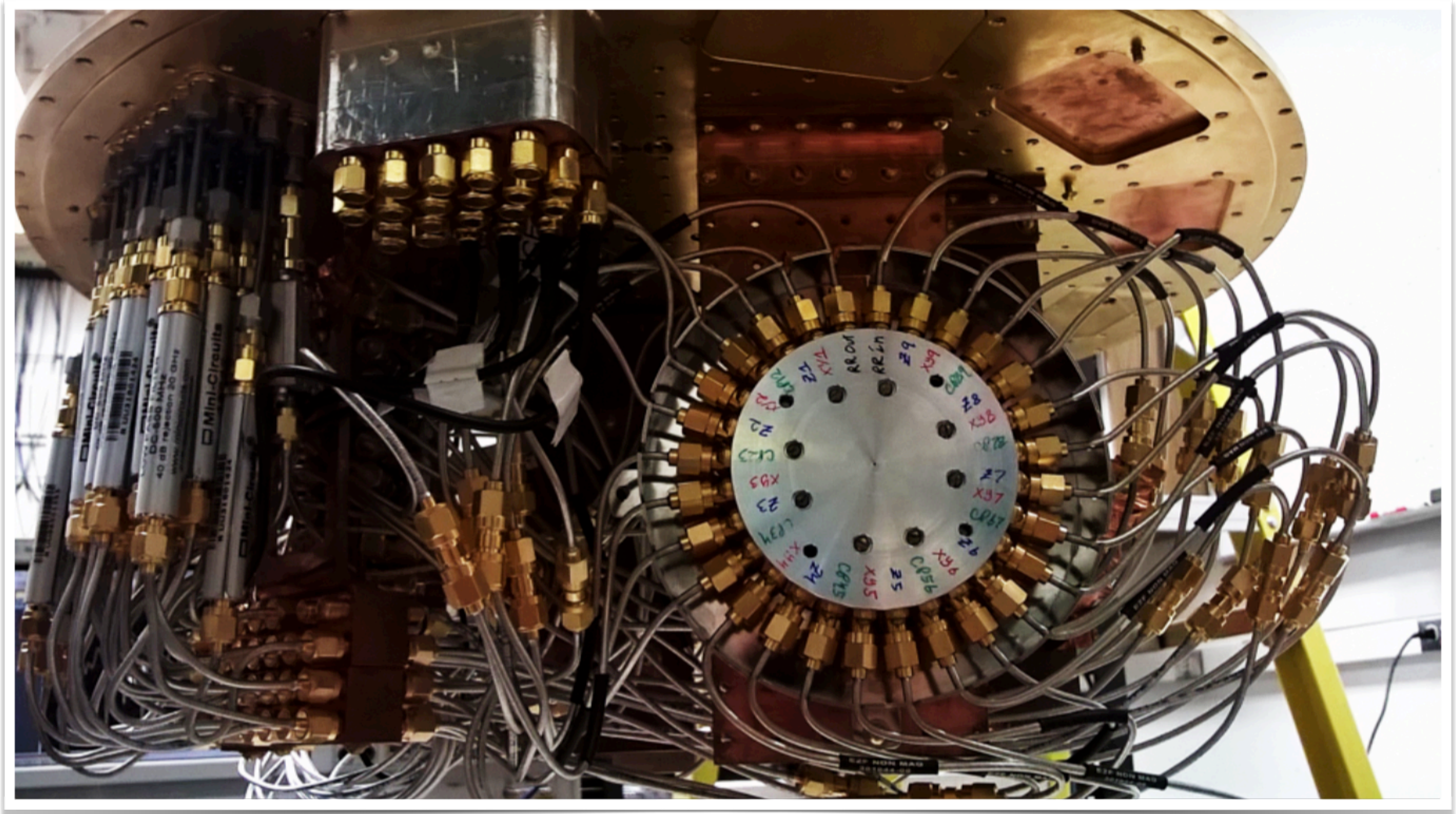


Chip packaging

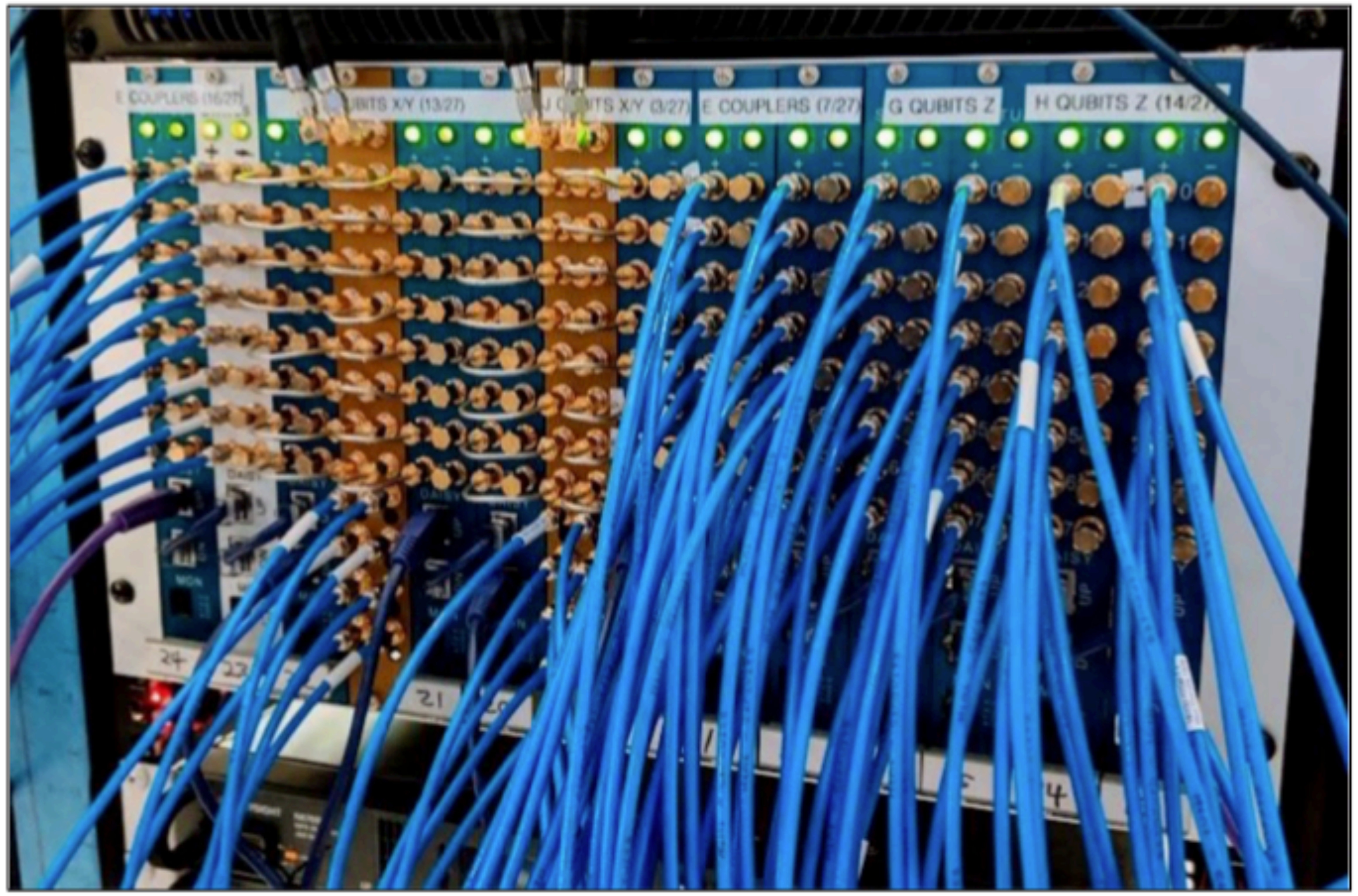




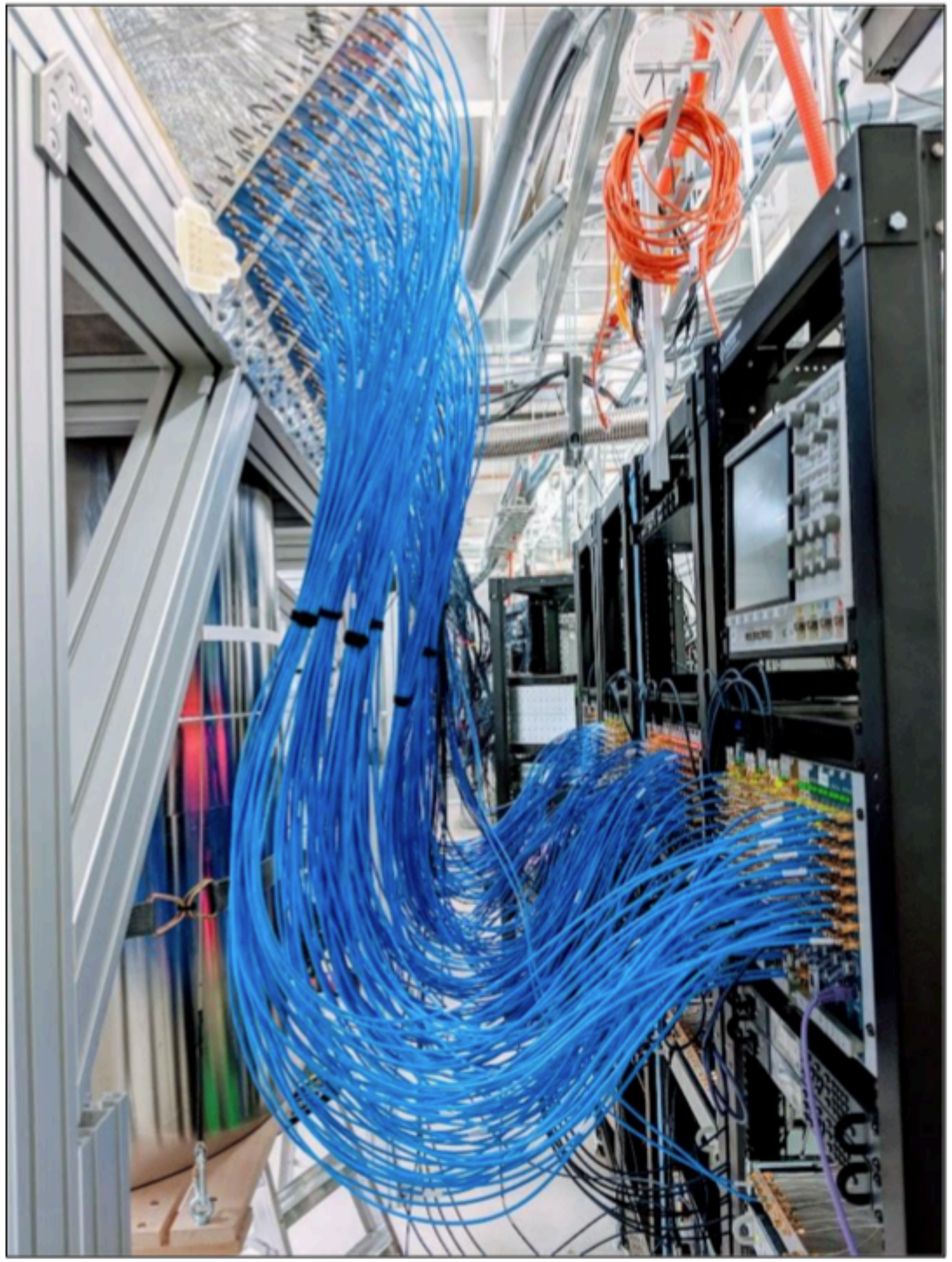
Inside the dilution fridge

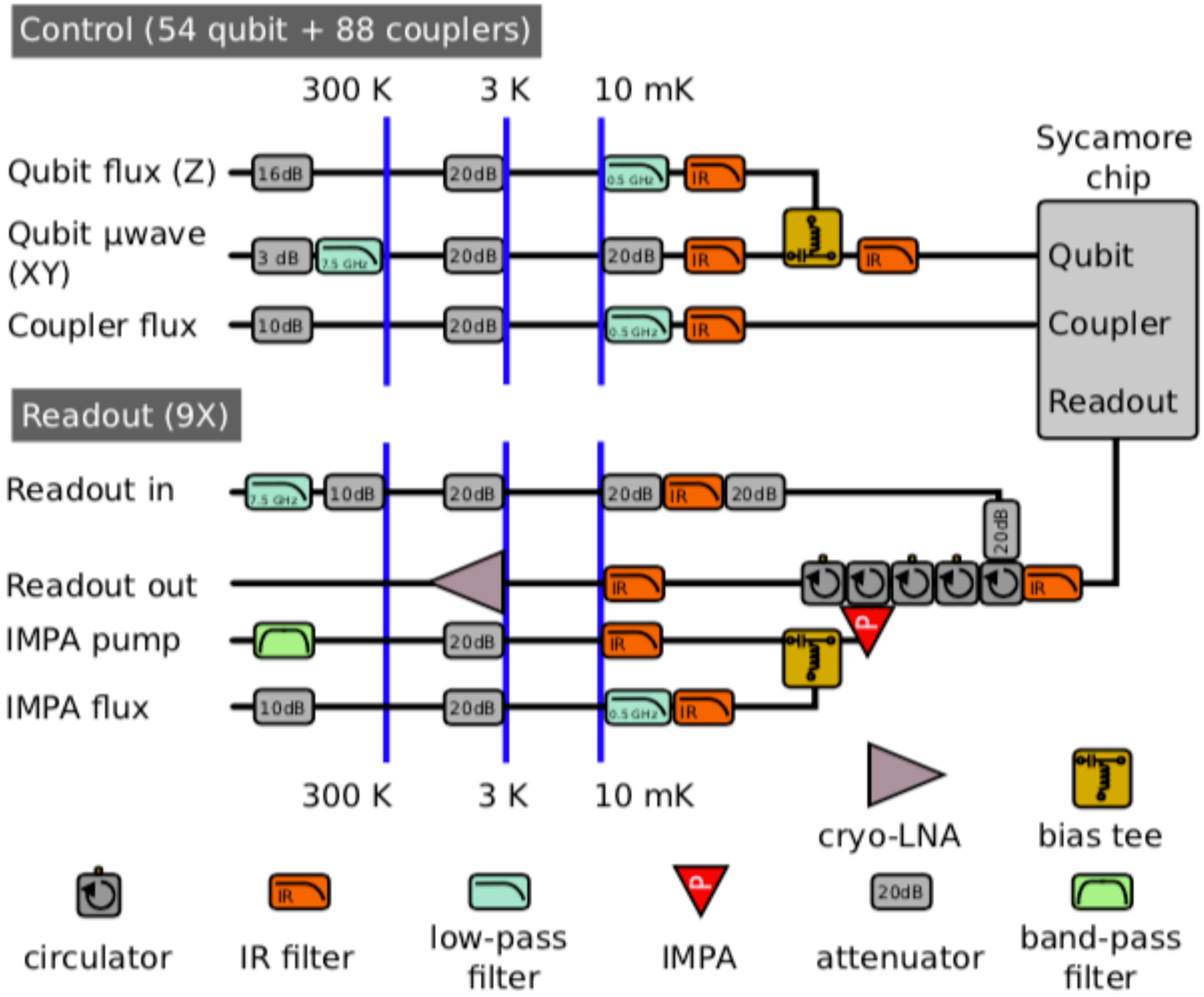


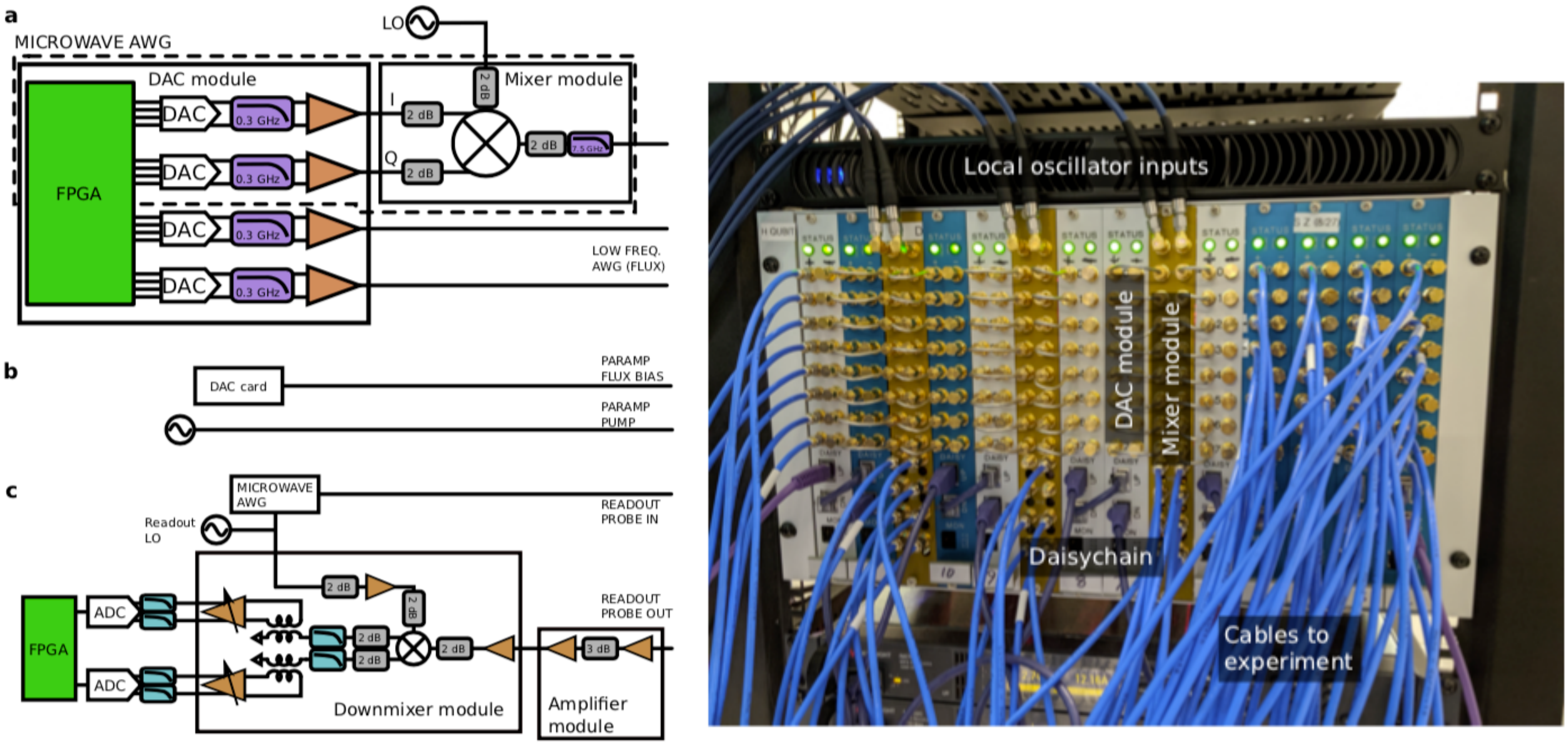
Control Hardware



Custom built
High speed
High precision




Control (54 qubit + 88 couplers)
300 K
3 K
10 mK
Qubit flux (Z)
Qubit µwave (XY)
Coupler flux
Sycamore chip
Qubit
Coupler
Readout
Readout (9X)
Readout in
Readout out
IMPA pump
IMPA flux
16dB
20dB
3 dB
10dB
IR
300 K
3 K
10 mK
cryo-LNA
bias tee
circulator
IR filter
low-pass filter
IMPA
attenuator
band-pass filter


a
MICROWAVE AWG
LO
DAC module
Mixer module
FPGA
DAC
0.3 GHz
I
Q
2 dB
7.5 GHz
LOW FREQ.
AWG (FLUX)
b
DAC card
PARAMP
FLUX BIAS
PARAMP
PUMP
c
MICROWAVE
AWG
Readout
LO
READOUT
PROBE IN
READOUT
PROBE OUT
ADC
FPGA
3 dB
Downmixer module
Amplifier
module
Local oscillator inputs
DAC module
Mixer module
Daisychain
Cables to
experiment

Susceptance at Resonance