Google AI
Quantum

Google's quantum computer and pursuit of quantum supremacy

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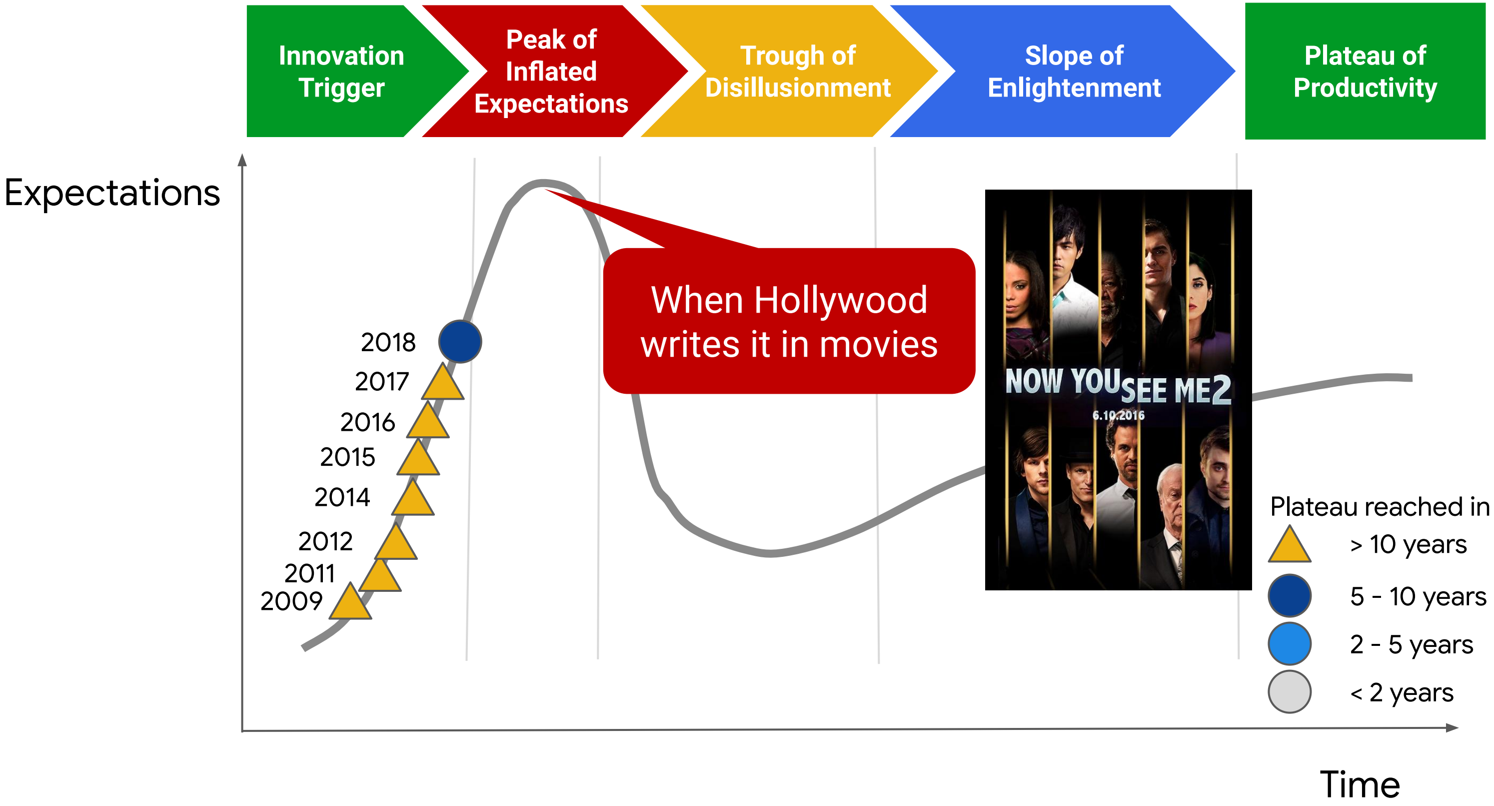
Google Santa Barbara
University of Tokyo, 2019-09-25

Quantum computing on Gartner's hype curve



Goal & timeline set by physicists

Quantum Computing Roadmap v1 (2002) and v2 (2004)

https://qist.lanl.gov/pdfs/qc_roadmap.pdf

> “ The ten-year (2012) goal would extend QC into the “architectural / algorithmic” regime, involving a quantum system of such complexity that it is beyond the capability of classical computers to simulate. ”

Coined by John Preskill as "Quantum Supremacy" in 2012.

Not yet achieved

"Temperature" of researches

Talks and posters in the March Meeting of American Physical Society, 2019.

Search word in title or abstract	Talks	Posters	Total
qubit	631	23	654
quantum comput	333	24	357
quantum simulat	81	7	88
quantum algorithm	58	2	60
quantum anneal	47	0	47
NISQ	26	1	27
adiabatic quantum	14	1	15
QAOA	10	1	11
VQE	10	1	11
Union	861	41	902
Whole meeting	10160	1204	11364
Percentage	8.5%	3.4%	7.9%

p.s. Personal counts, your counts may vary

Quantum control

Also in the roadmap:

> “ Quantum systems of ***unprecedented complexity*** will be created and ***controlled***, potentially leading to greater fundamental understanding of how classical physics emerges from a quantum world, which is as perplexing and as important a question today as it was when quantum mechanics was invented. ”

Skepticism

Dyakonov: "Prospects for quantum computing: **Extremely doubtful**"
[Int. J. of Mod. Phys. Conf. Ser. **33**, 1460357 (2014)]

Precision of control and measurement at scale

- Analog system
- Instability of nonlinear system
- Zhdanov: quantum control landscape is not "trap-free" [arXiv:1710.07753]

Free evolution of quantum states due to energy difference

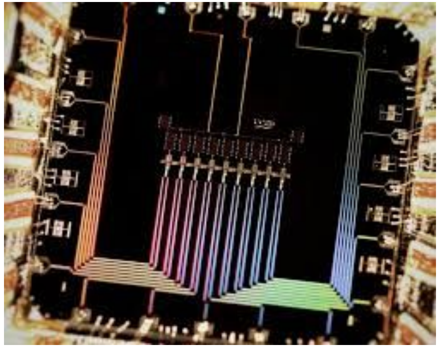
How to debug an algorithm requiring 1000 qubits (2^{1000} amplitudes)?

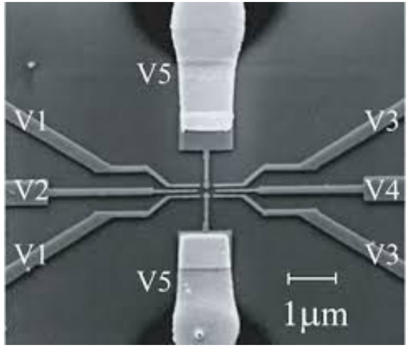
What is Quantum Computing?

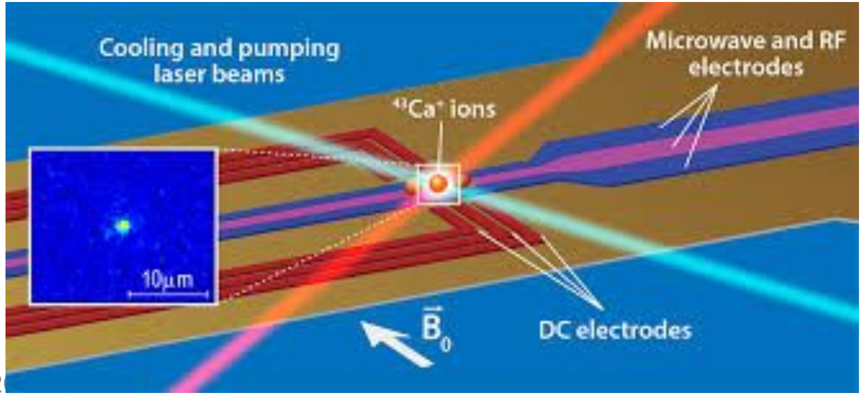
Using **2-state quantum systems** to perform computational tasks.

Some 2-state quantum systems:

- Photons
- Nuclear spins
- Trapped Ions
- Neutral Atoms
- Molecular spins
- Quantum dots
- Superconducting circuits



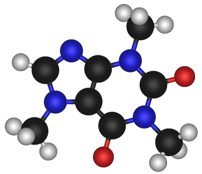


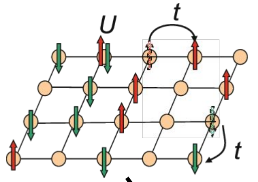


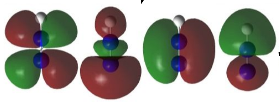
Why build a quantum computer?

Quantum simulation

Feynman's initial idea

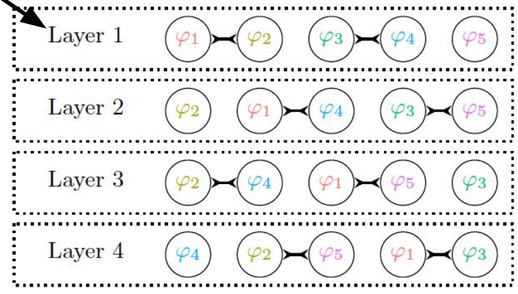


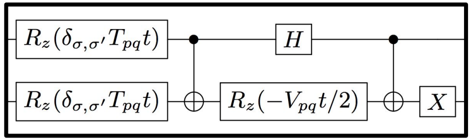




$$H = \sum_{ij} h_{ij} a_i^\dagger a_j + \frac{1}{2} \sum_{ijkl} h_{ijkl} a_i^\dagger a_j^\dagger a_k a_l$$

$$H = \sum_{p \neq q} \tilde{T}_{pq} \left(X_p Z_{p+1} \cdots Z_{q-1} X_q + Y_p Z_{p+1} \cdots Z_{q-1} Y_q \right)$$
$$+ \sum_{p \neq q} \tilde{V}_{pq} Z_p Z_q + \sum_p \tilde{U}_p Z_p$$

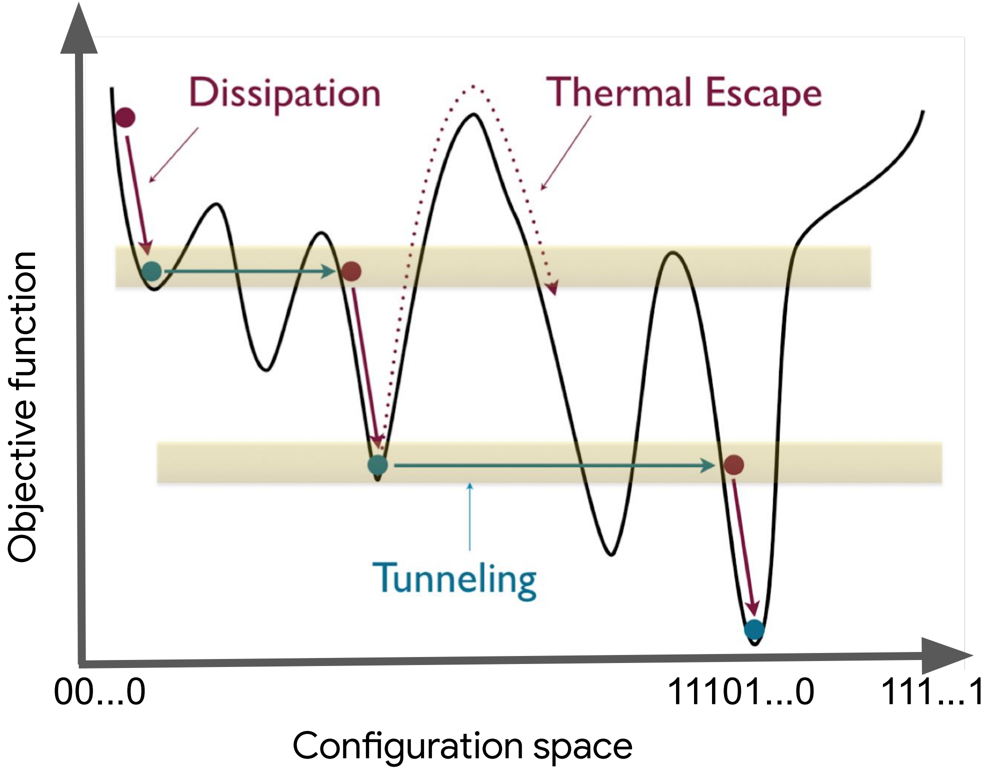




Why build a quantum computer?

Quantum simulation

Optimization



Why build a quantum computer?

Quantum simulation

Optimization

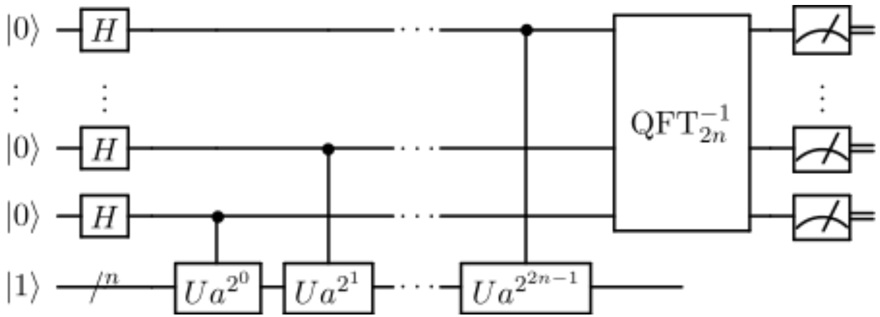
Factoring

age of universe vs. < 1 day

for n = 2048.

Classical algorithm $O\left(e^{1.9\,n^{1/3}(\log n)^{2/3}}\right)$

Shor's algorithm $O\left(n^2(\log n)(\log\log n)\right)$



Factoring

$$15 = 5 \times 3$$

Why build a quantum computer?

Quantum simulation

Optimization

Factoring

???

OpenFermion

+

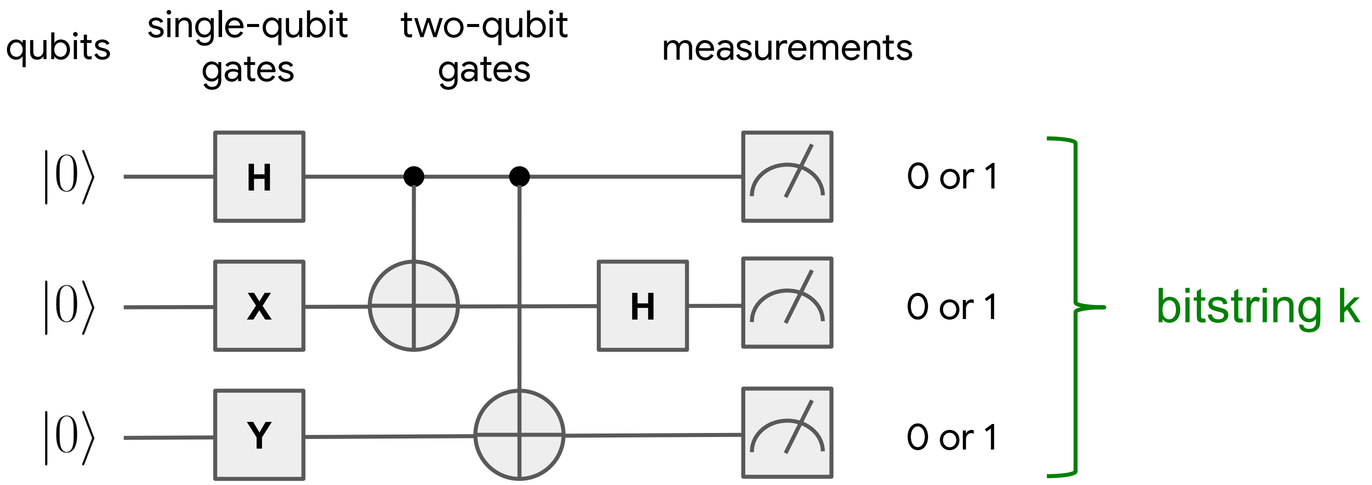
Cirq

https://www.openfermion.org/

https://github.com/quantumlib/cirq

The computation model

Turing machine ⟶ Quantum Turing machine
Alternatively: Quantum circuit

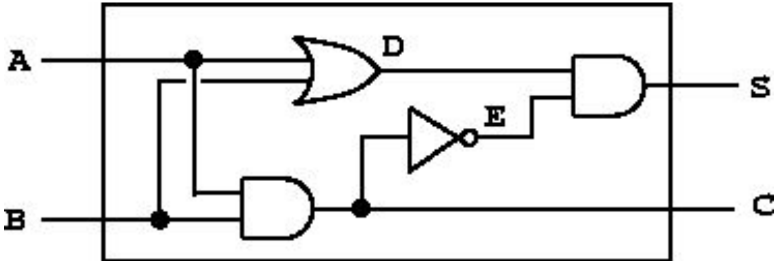


Other models: quantum annealing, adiabatic quantum computing.

Logic and quantum circuits

Classical logic circuit

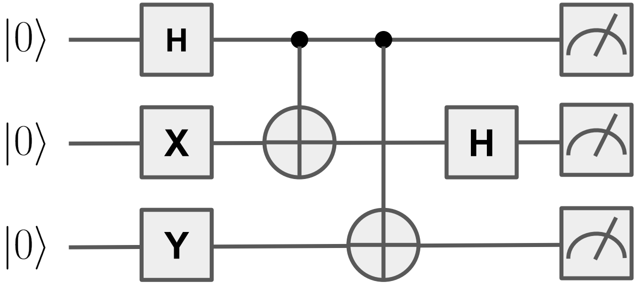
- Deterministic
- Wiring fan-out
- Universal: 1 bit NOT + 2 bit AND



Space (layout) →

Quantum circuit

- Probabilistic
- No clone theorem
- Universal: 1 qubit rotation + 2 qubit CNOT



Time (sequence) →

State of a qubit: Bloch sphere representation

Bloch sphere representation of a qubit:

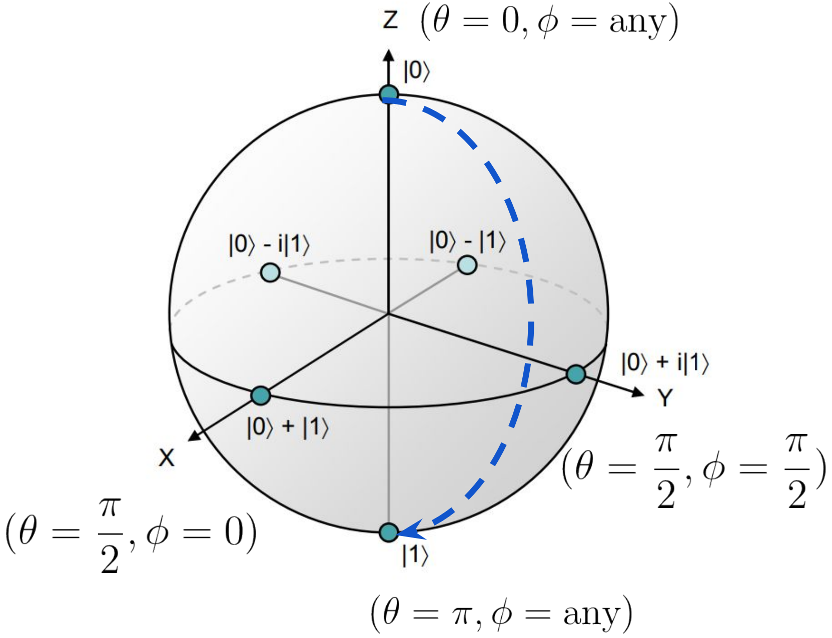
$$
\begin{aligned}
|\psi\rangle &= c_0|0\rangle + c_1|1\rangle \\
&= \cos\frac{\theta}{2}\,|0\rangle + \sin\frac{\theta}{2}\,e^{i\phi}\,|1\rangle
\end{aligned}
$$

(Global phase discarded)

A gate operation: $(\theta, \phi) \longrightarrow (\theta', \phi')$

- can be modeled as a rotation on Bloch sphere
- NOT gate = rotate around x-axis by π
- What about $\frac{\pi}{2}$ rotation?

Spherical angular coordinates (θ, ϕ)



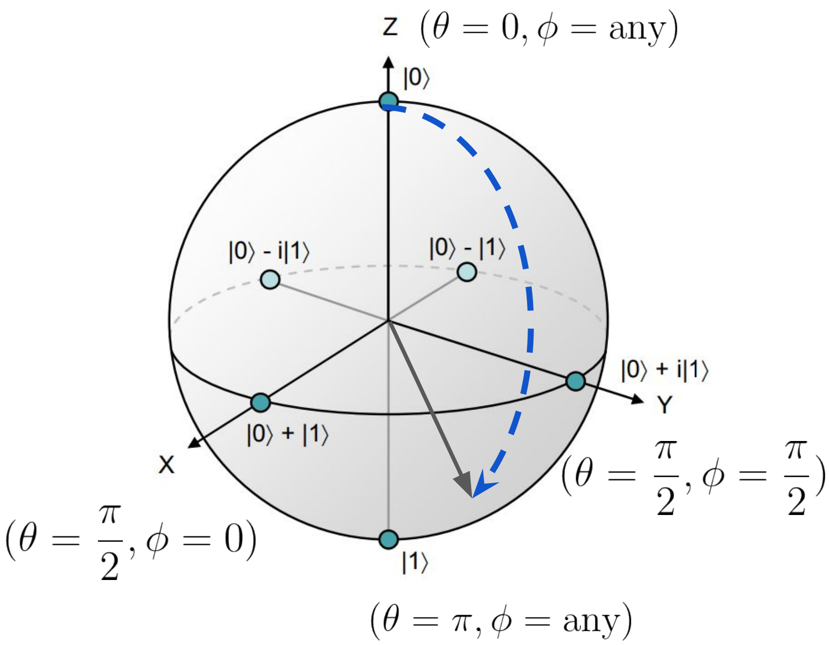
Challenge: Controlling a qubit

Analog control errors: over/under rotation, deviation of the rotation axis

Decoherence (environmental) errors: random bit flips / phase changes

Qubit error mechanisms inform nearly all design decisions

Spherical angular coordinates (θ, ϕ)



End Goal: Universal Fault-Tolerant QC

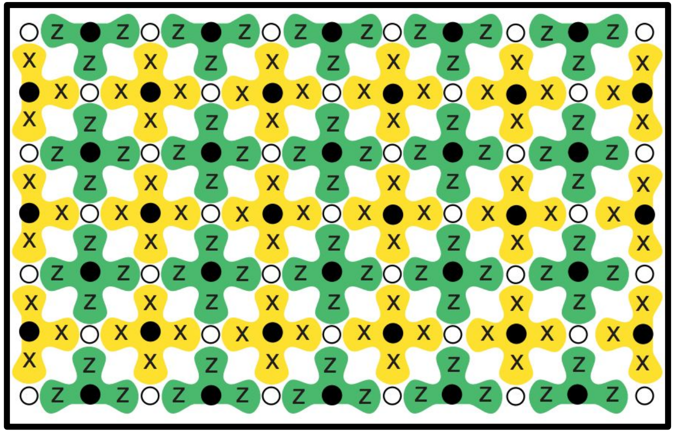
Fault tolerance via error correction

1 **logical qubit** from many **physical qubits**

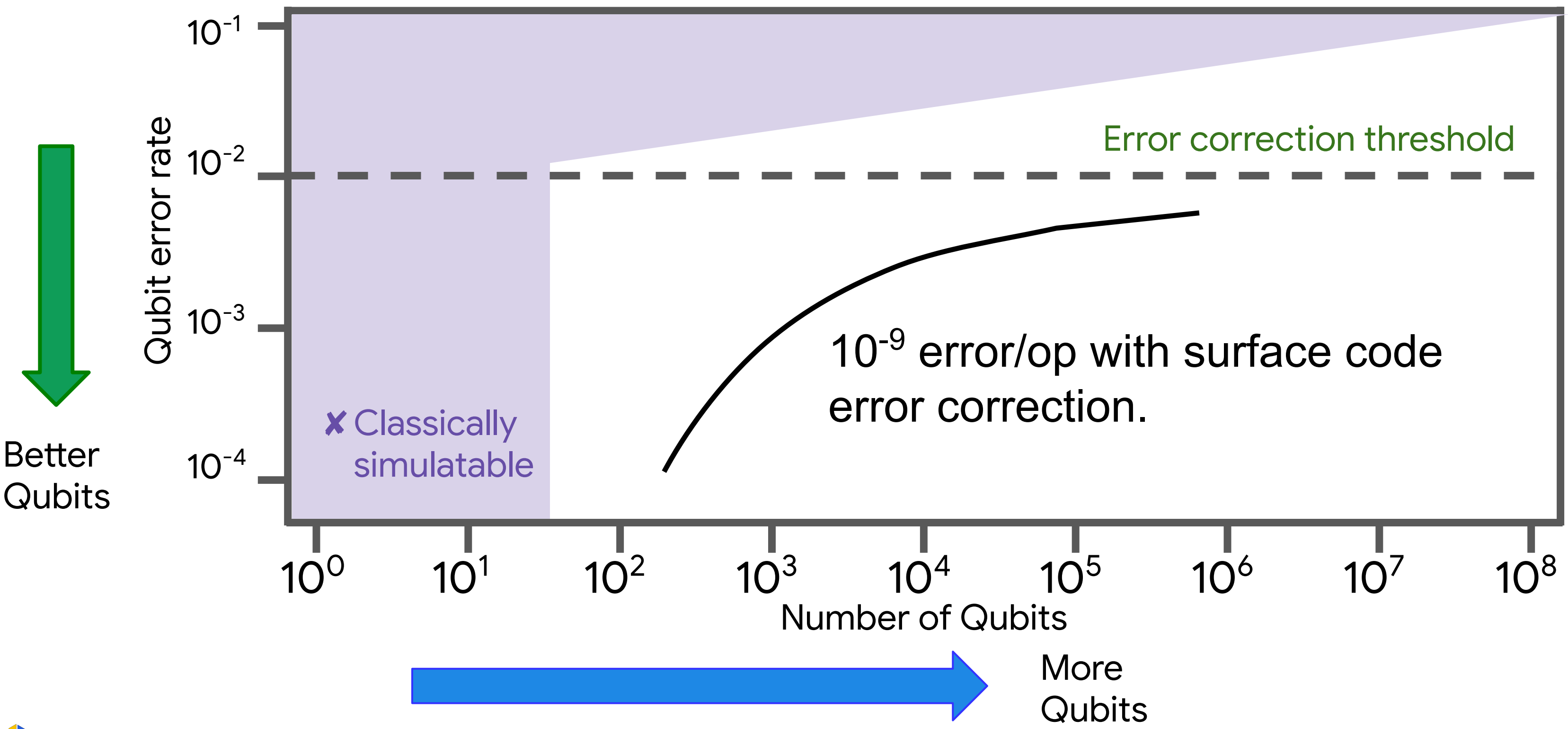
Universal QC requires error/op ~10^{-10}

Surface code error correction:

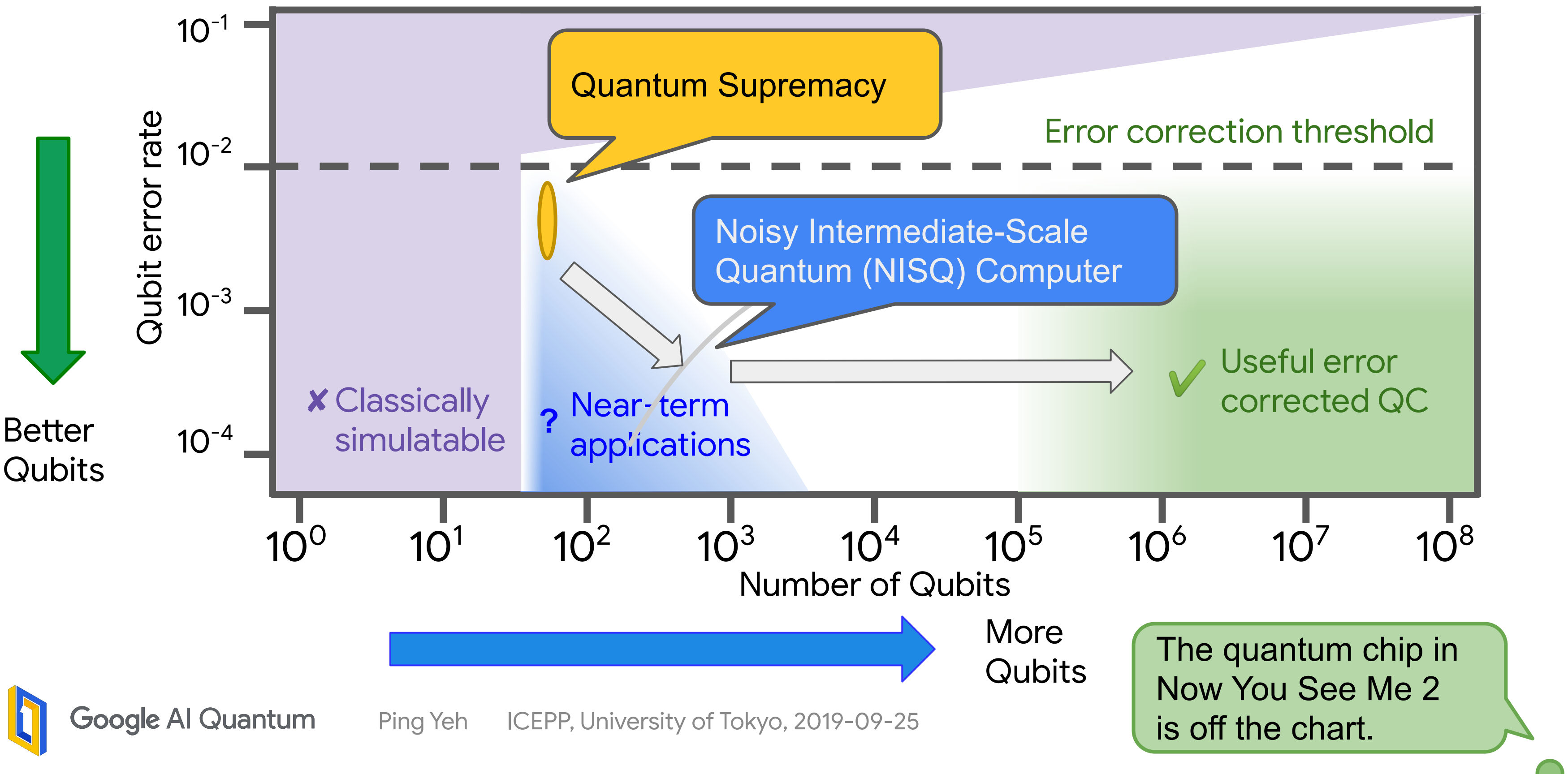
- 2D qubit array, nearest-neighbor coupling
- Error/op (physical): 10^{-2} threshold, 10^{-3} target
- Useful at 10^5-10^6 physical qubits



When is a Quantum Computer Useful?



When is a Quantum Computer Useful?



DiVincenzo Criteria for Quantum Computers

1. Scalable system of well-characterized qubits
2. Ability to initialize to a fiducial state
3. Long coherence time
4. Universal set of quantum gates
5. Capable of measuring any specific qubit

[D. P. DiVincenzo, NATO ASI Series E, Kluwer Ac. Publ., Dordrecht, 1996]; arXiv:cond-mat/9612126v2.

Two more criteria were added later for quantum communications.

Physical systems for quantum computers (2004)

	NMR	Neutral Atom	Cavity QED	Super-conductors	Trapped Ion	Photonic	Solid State
Scalable / well characterized	🔴	🟡	🟡	🟡	🟡	🟡	🟡
State preparation	🟡	🟢	🟢	🟢	🟢	🟡	🟡
Long coherence	🟡	🟡	🟡	🟡	🟡	🟢	🟡
Universal gates	🟢	🟡	🟡	🟡	🟢	🟡	🟡
Random-access measurement	🟡	🟡	🟢	🟡	🟢	🟡	🟡

🔴 No viable approach is known

🟡 Viable approach proposed, no sufficient proof of principle yet

🟢 Viable approach has been sufficiently demonstrated

QC Roadmap 2.0 (2004)
https://qist.lanl.gov/pdfs/qc_roadmap.pdf

Physical systems for quantum computers (2018)

	NMR	Neutral Atom	Cavity QED	Super-conductors	Trapped Ion	Photonic	Solid State
Scalable / well characterized	🔴	🟡	🟡	🟡🟢	🟡	🟡	🟡
State preparation	🟡	🟢	🟢	🟢	🟢	🟡🟢	🟡🟢
Long coherence	🟡	🟡🟢	🟡🟢	🟡🟢	🟡🟢	🟢	🟡🟢
Universal gates	🟢	🟡🟢	🟡	🟡🟢	🟢	🟡🟢	🟡🟢
Random-access measurement	🟡	🟡🟢	🟢	🟡🟢	🟢	🟡🟢	🟡🟢

QC Roadmap 2.0 (2004)

🔴 No viable approach is known

🟡 Viable approach proposed, no sufficient proof of principle yet

🟢 Viable approach has been sufficiently demonstrated

Peter McMahon, Q2B 2018
https://q2b2018.qcware.com/videos-presentations

Major commercial players

Company	Qubit technology	#qubits	announcement time
IonQ	trapped ion	79/160	2018-12
Rigetti	superconducting	128	2018-08
Google	superconducting	72	2018-03
Alibaba	superconducting	11	2018-03
Intel	superconducting, silicon spin qubits	49 N/A	2018-01
IBM	superconducting	50	2017-11
D-Wave	superconducting	2000	2017-01
Microsoft	topological	N/A	N/A
Others	...	...	...

quantum annealing machine

Building a Superconducting Quantum Computer

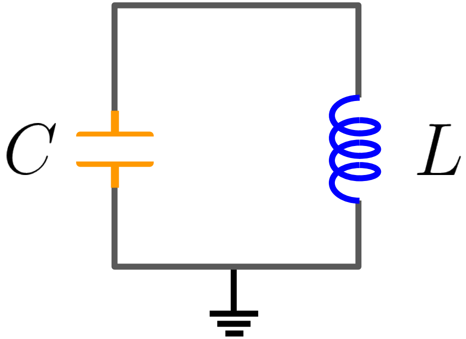
LC Circuit: Harmonic Oscillator

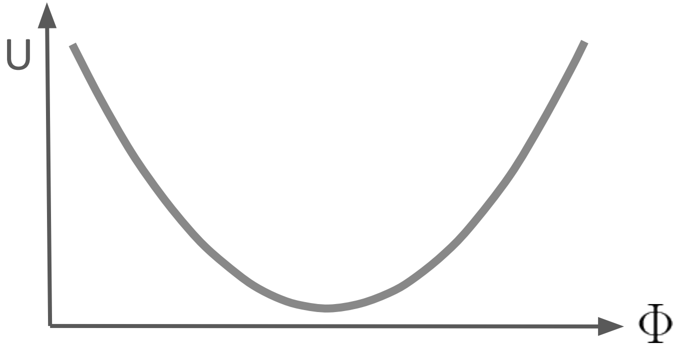
Voltages $V_L = L\frac{dI}{dt}$ $V_c = \frac{Q}{C}$

Branch flux $\Phi(t) = \int_{-\infty}^{t} V_L(\tau)d\tau$

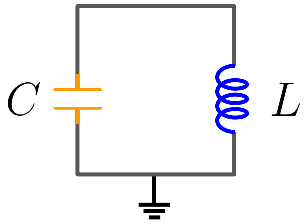
Hamiltonian $H = \frac{Q^2}{2C} + \frac{\Phi^2}{2L}$

Parabolic potential





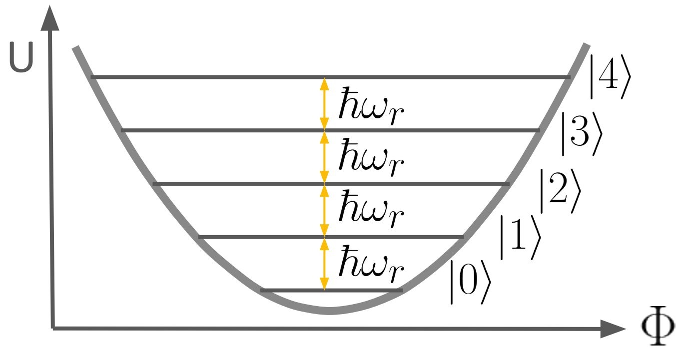
Leakage problem



Equal-spacing energy levels

$$H|n\rangle = \left(n + \frac{1}{2}\right)\hbar\omega_r|n\rangle$$

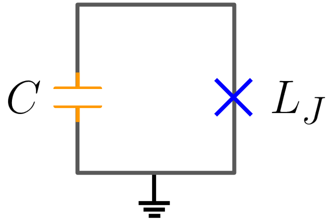
$$\omega_r = \frac{1}{\sqrt{LC}}$$



Same frequency excites $|0\rangle \rightarrow |1\rangle$, but also $|1\rangle \rightarrow |2\rangle$

Leakage out of 2-state system!

Non-linear inductor



Josephson Junction relation:

Critical current

Phase diff across junction

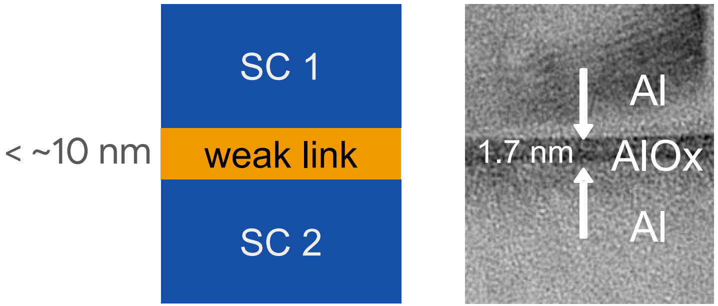
$$I = I_c \sin\phi$$

Flux quantum

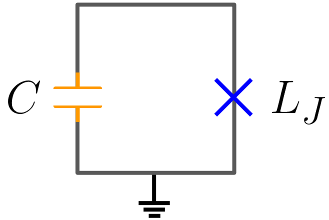
$$V = \frac{\hbar}{2e}\frac{\partial\phi}{\partial t} = \frac{\Phi_0}{2\pi}\frac{\partial\phi}{\partial t}$$

$$V = \frac{\Phi_0}{2\pi I_c \cos\phi}\frac{dI}{dt}$$

Equivalent inductance L_J

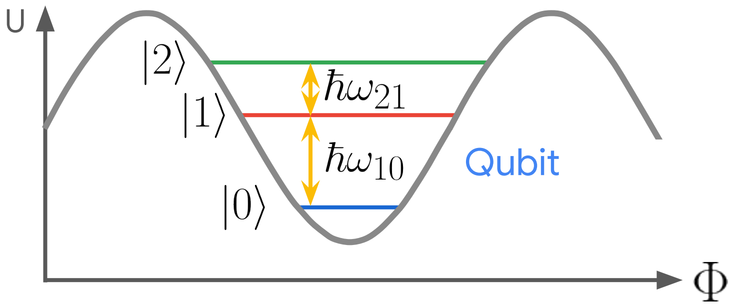


Anharmonic oscillator



Hamiltonian

$$H = \frac{Q^2}{2C} - \frac{I_c\Phi_0}{2\pi}\cos\frac{2\pi\Phi}{\Phi_0}$$



Re-written as

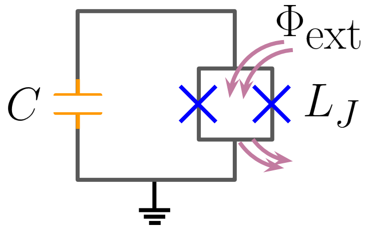
$$H = 4E_c\, n^2 - E_J \cos\varphi$$

N(Cooper pairs)

$$[\varphi, n] = 1$$

Frequency $\hbar\omega_{10}$ and other features: determined by E_C and E_J
Fixed after fabrication.

Tunable qubits with SQUID



Hamiltonian

$$H = 4E_c\, n^2 - 2E_J \left|\cos\frac{\pi\Phi_{\mathrm{ext}}}{\Phi_0}\right| \cos\varphi$$

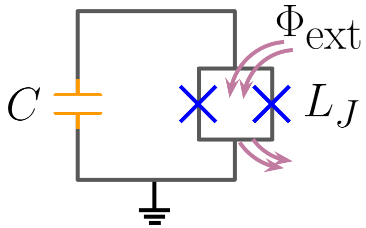
effective phase diff across SQUID

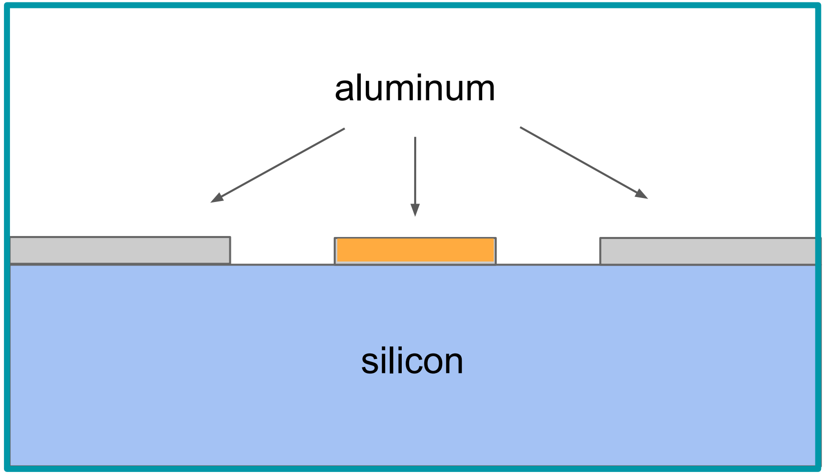
$$\varphi = \frac{\varphi_1 + \varphi_2}{2}$$

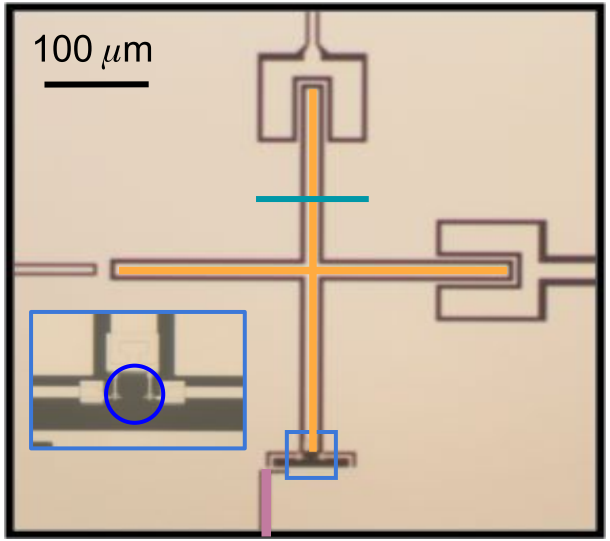
Tunable effective E_J by Φ_{ext}

Qubit frequency $\hbar\omega_{10} = \sqrt{8E_C E_J^* \left|\cos\frac{\pi\Phi_{\mathrm{ext}}}{\Phi_0}\right|} - E_C$

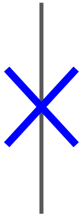
Physical layout of a transmon qubit

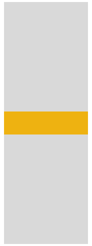


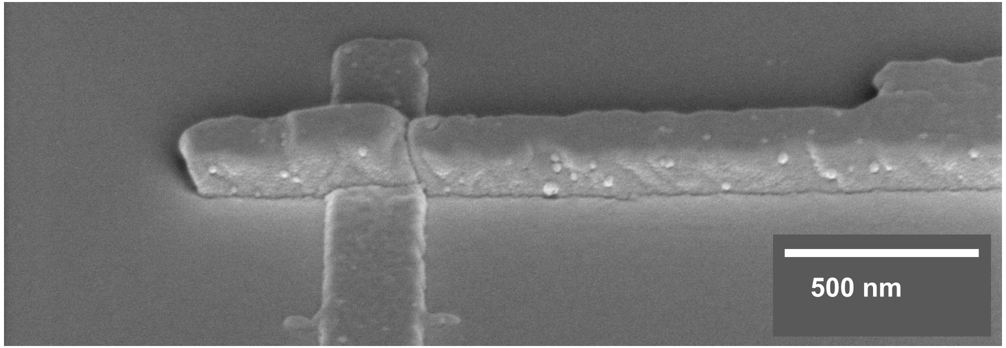


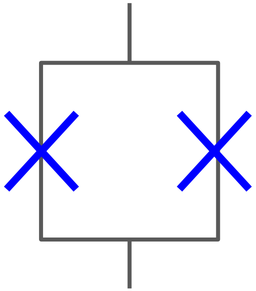


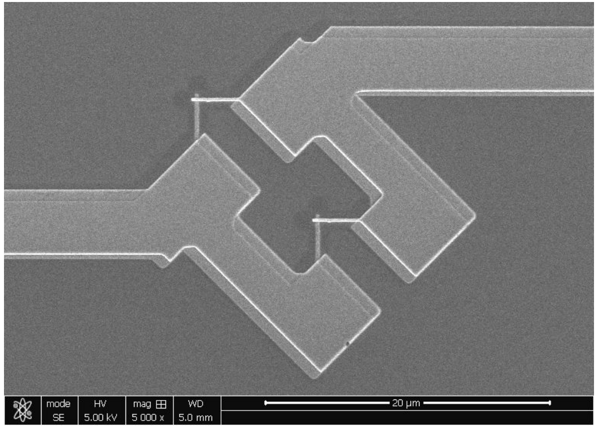
The fabricated Josephson junction







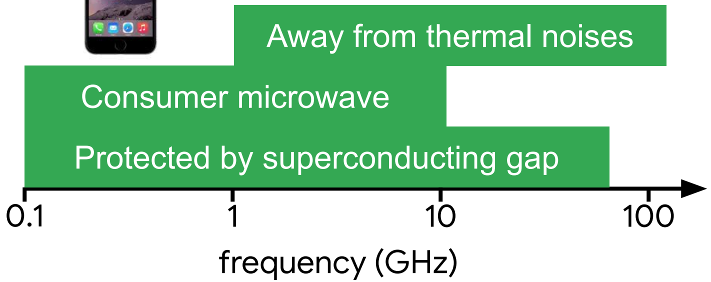




Region of Operation

Energy gap of superconducting aluminum

$$\Delta_{\mathrm{Al}} = 3.4 \times 10^{-4}\ \mathrm{eV} \approx 82\ \mathrm{GHz}$$



Consumer wireless applications (WiFi, LTE, etc.)

> 10 GHz hard/expensive to engineer

Dilution refrigerator cools to < 50 mK

Minimize thermal noises at T ~ 10 mK (~ 0.2 GHz)

Typical values (transmon):

L ≈ 8 nH, C ≈ 80 fF

$$\frac{\omega_{10}}{2\pi} = f_{10} \approx 6\ \mathrm{GHz}$$

Qubit control example: Rabi Oscillation

Driving a qubit on-resonance with a wave:

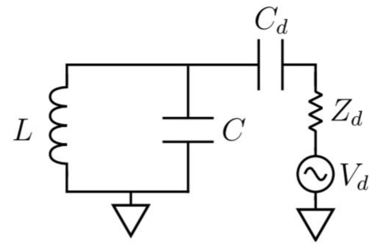
$$V(t) = V_0 \sin(\omega t + \phi)$$

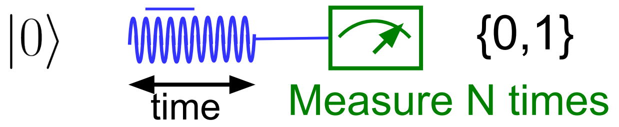
Qubit oscillates

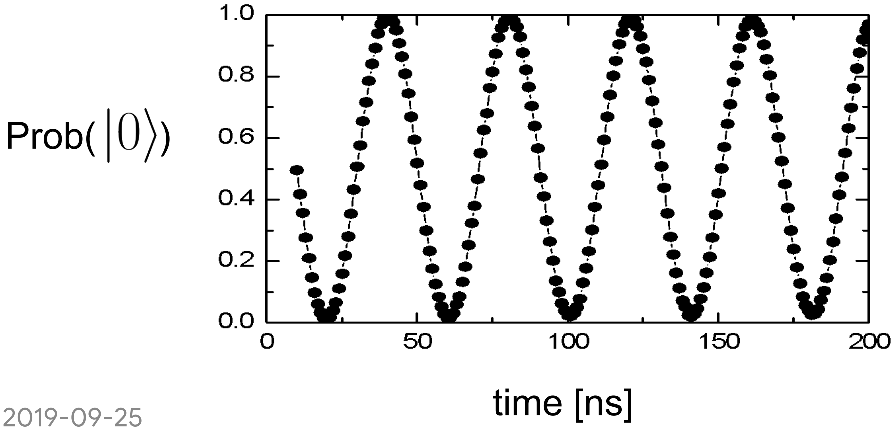
$$|\psi(t)\rangle = \cos(\tfrac{\Omega}{2}t)|0\rangle + ie^{i\phi}\sin(\tfrac{\Omega}{2}t)|1\rangle$$

with Rabi frequency

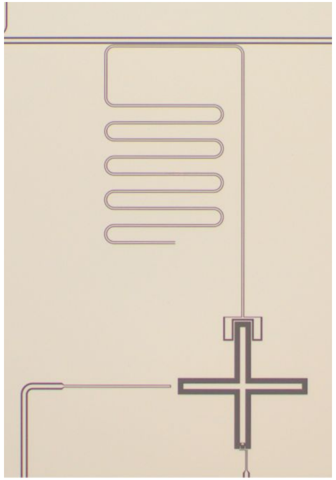
$$\Omega = \frac{C_d}{C + C_d}\frac{V_0}{\hbar}\langle 0|Q^2|0\rangle^{\frac{1}{2}}$$

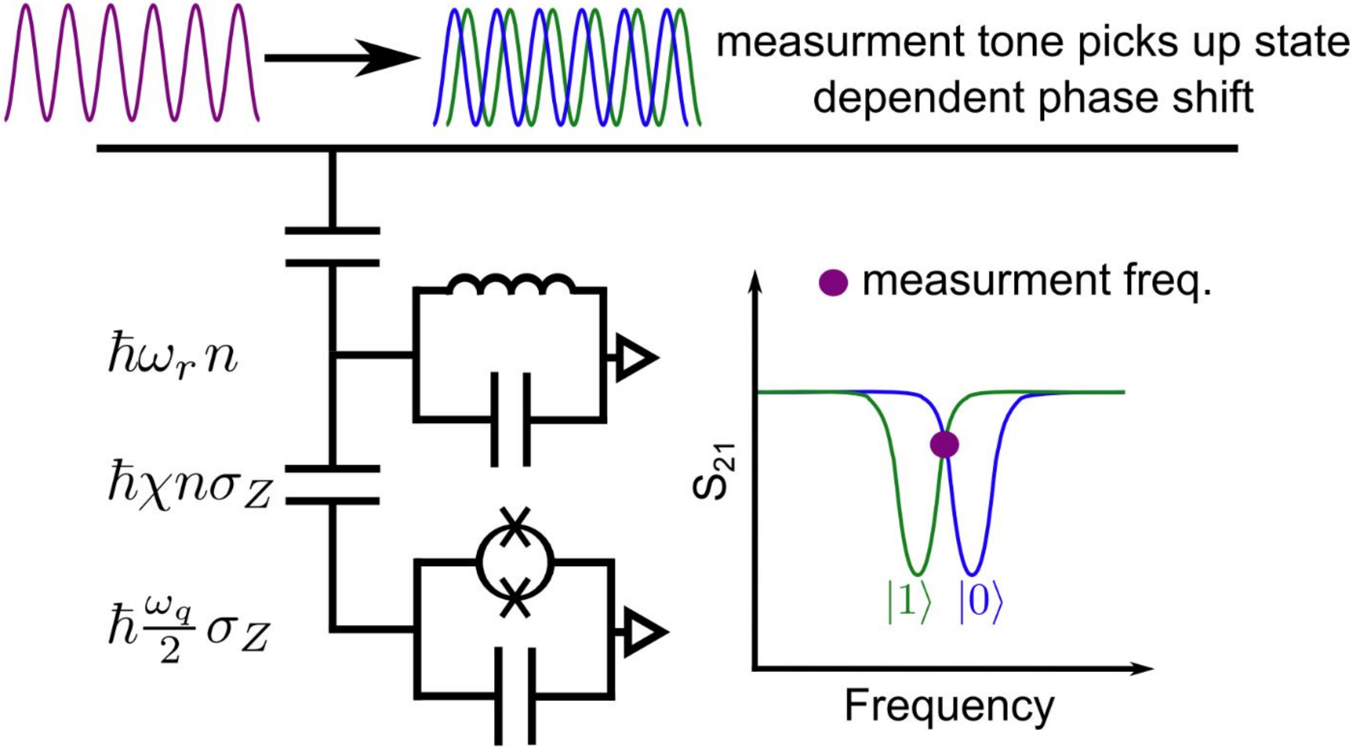




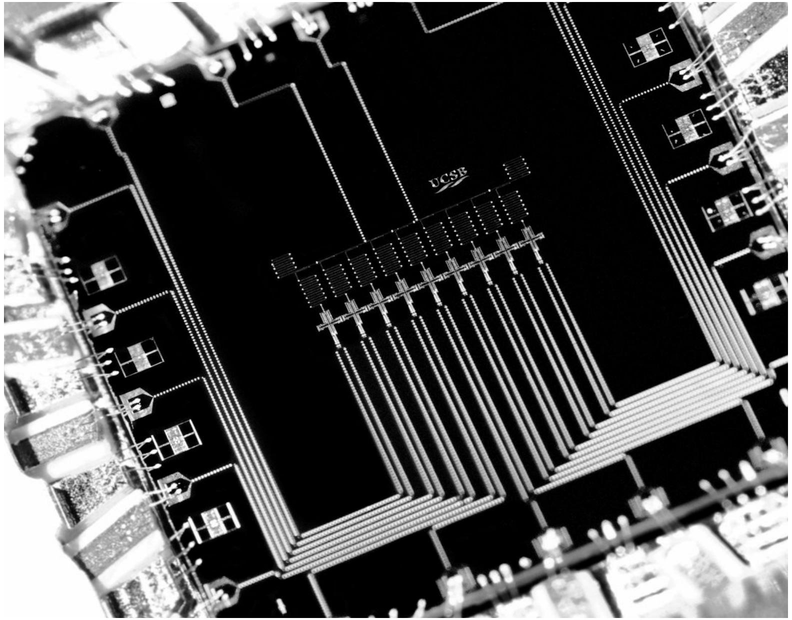


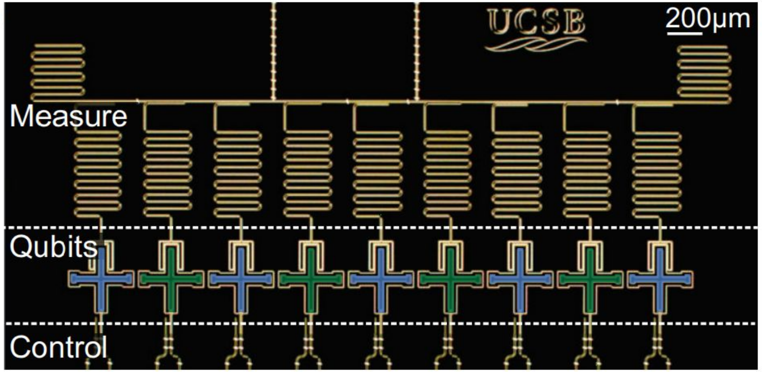
Qubit state measurement with readout resonator





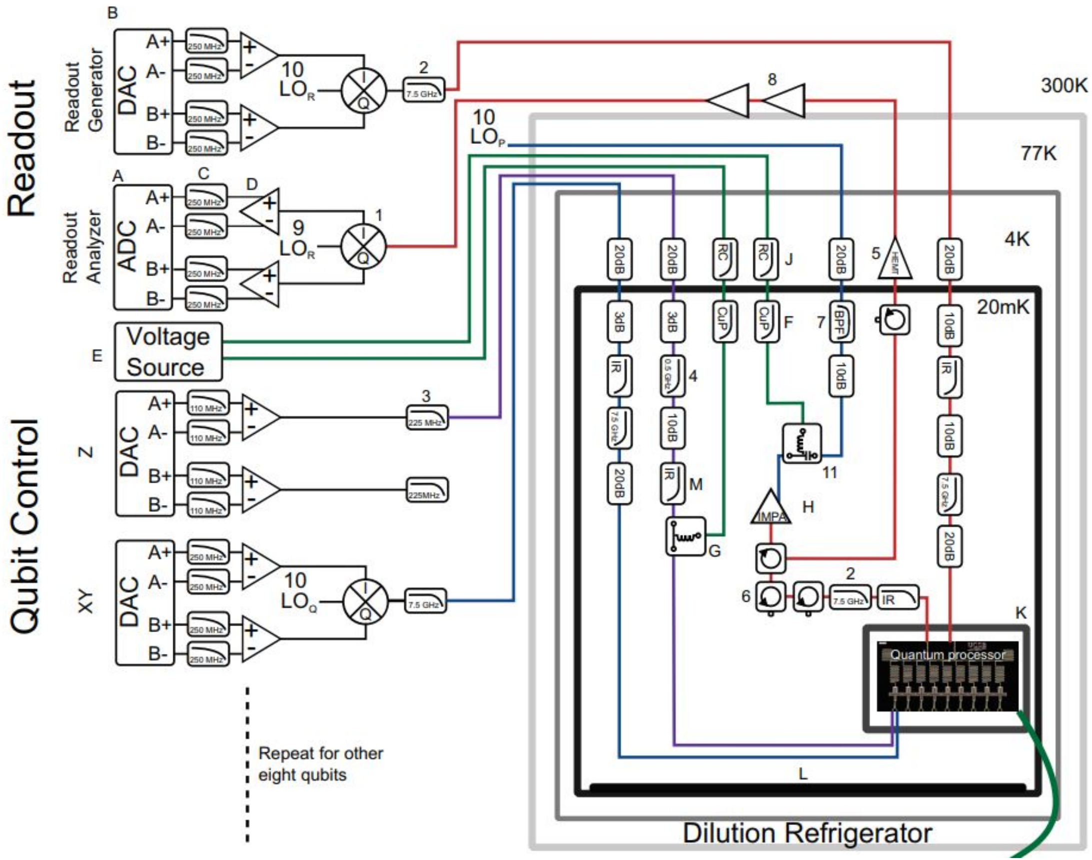
9 Qubit processor



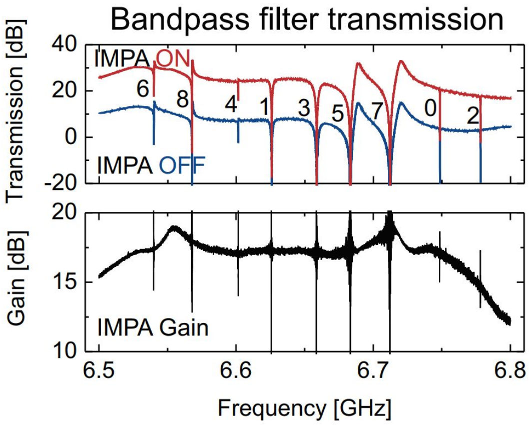


Kelly et al. Nature **519**, 66-69 (2015)
Barends et al. Nature Communications **6**, 7654 (2015)
White et al. npj Quantum Information **2**, 15022 (2016)
Barends et al. Nature **534**, 222-226 (2016)

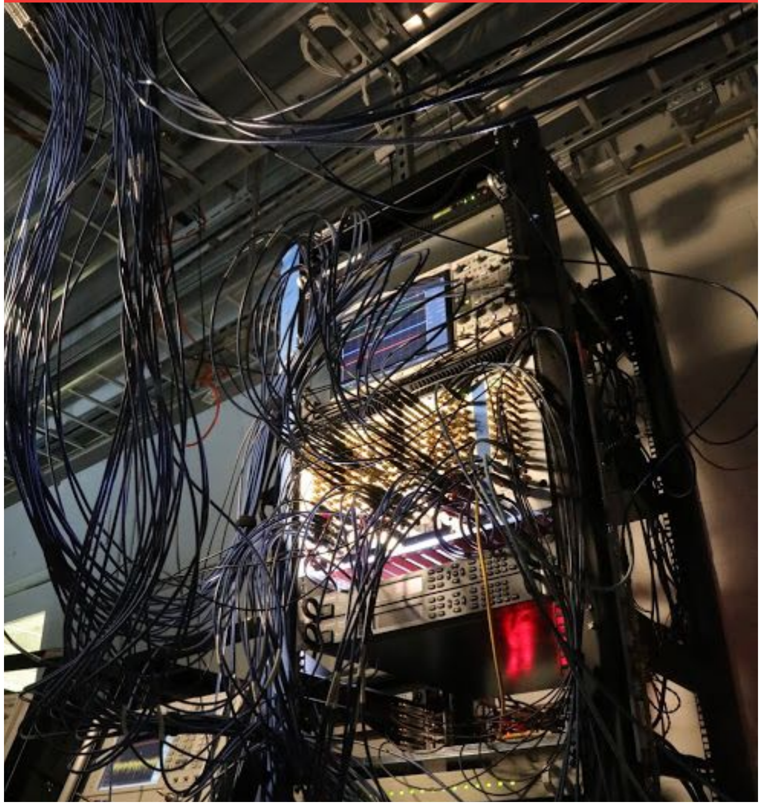
Experimental wiring and electronics

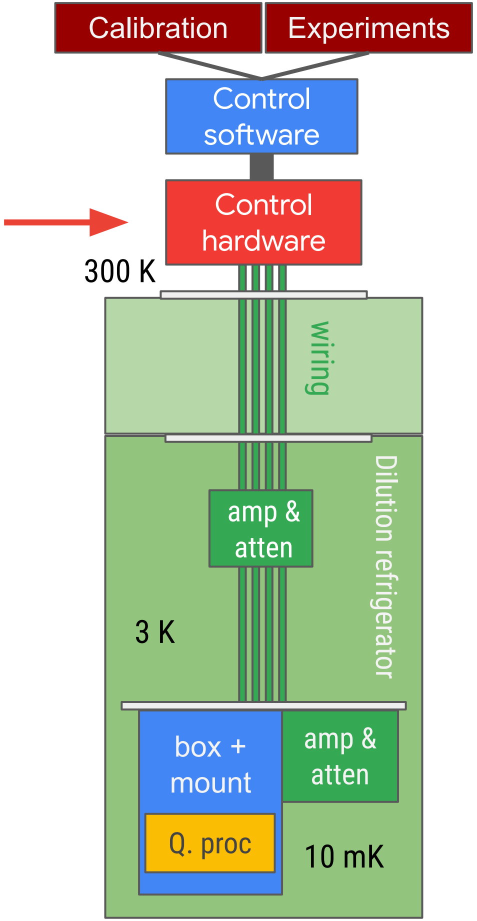


Impedance-matched parametric amplifier



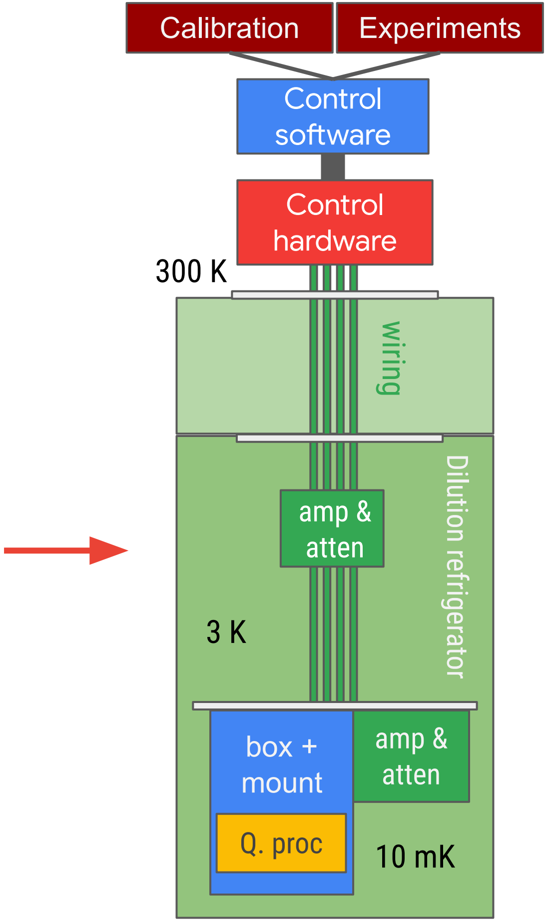
Custom Microwave Control Electronics

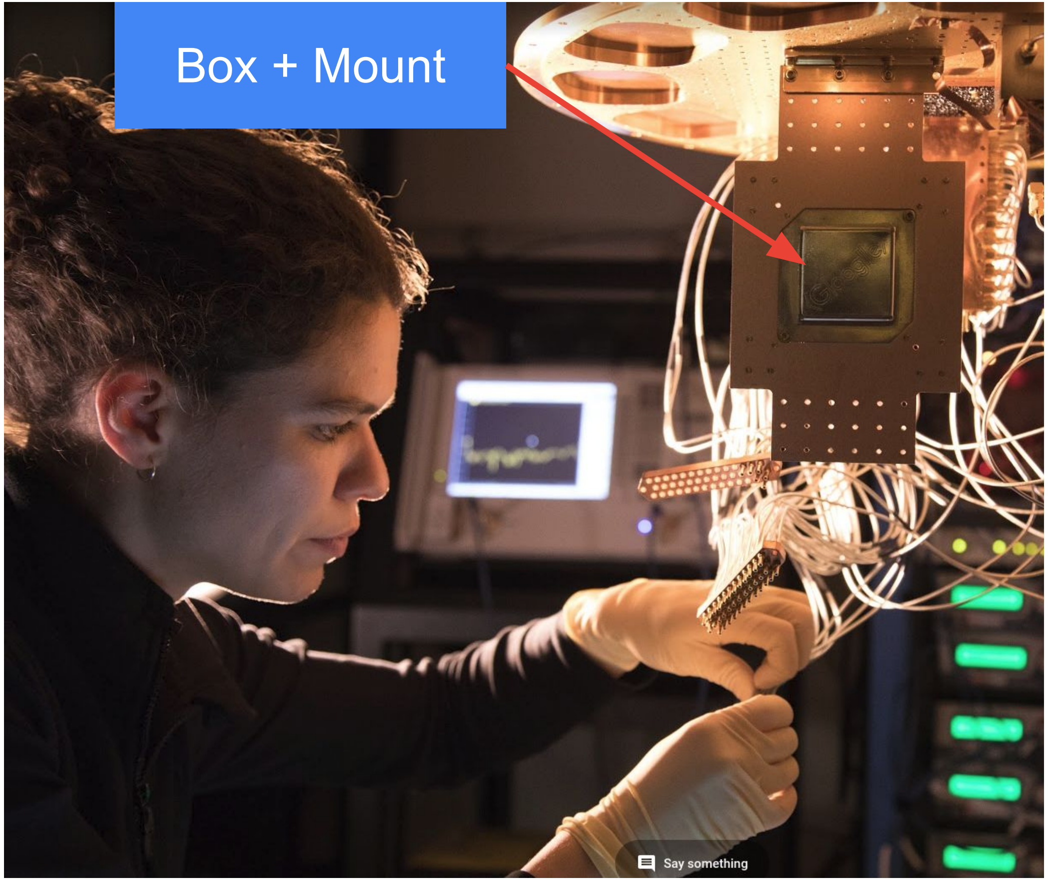




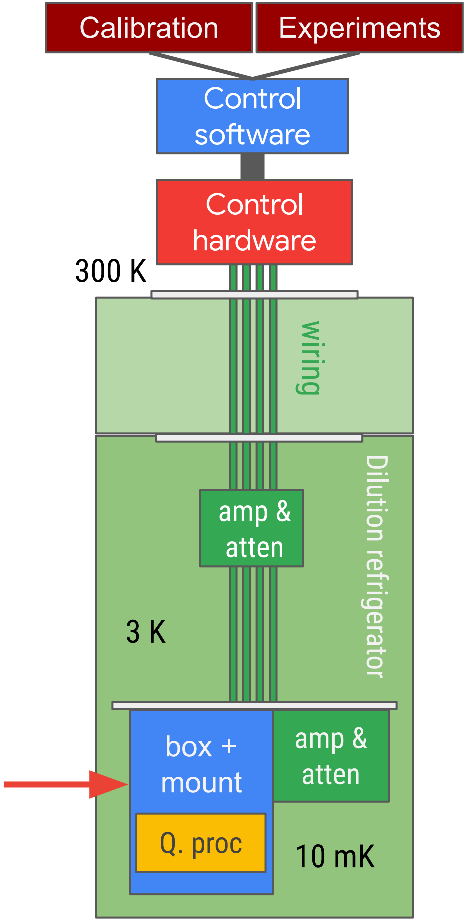
Wiring + amplifiers & filters

Dilution Refrigerator



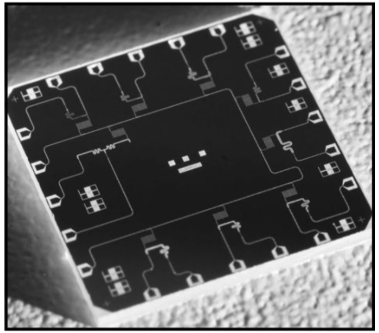


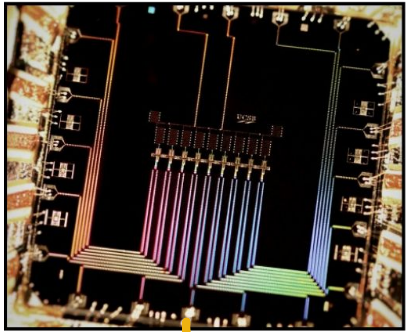
Box + Mount
Say something

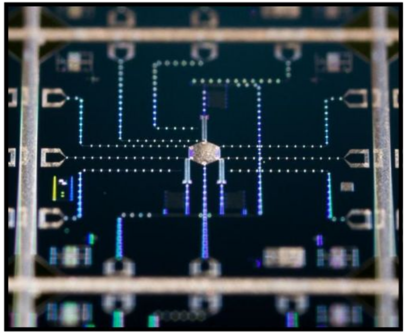


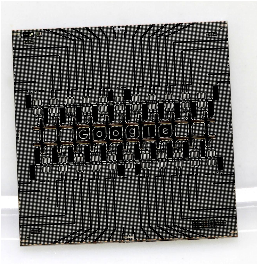
Calibration
Experiments
Control software
Control hardware
300 K
wiring
amp & atten
3 K
Dilution refrigerator
box + mount
amp & atten
Q. proc
10 mK

Fluxmon	Xmon	Gmon
- Flux qubit, tunable coupling - optimization problems	- X-shaped transmon qubit - gate-based QC	- Transmon qubit, tunable nearest-neighbor coupling



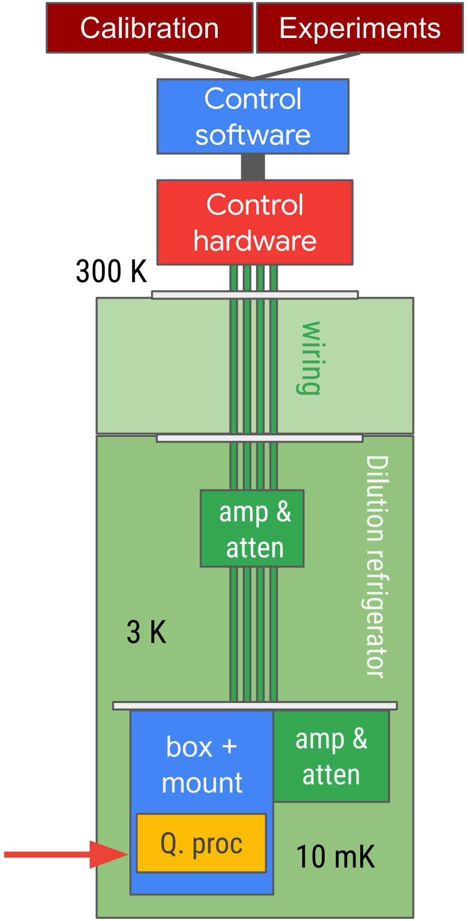




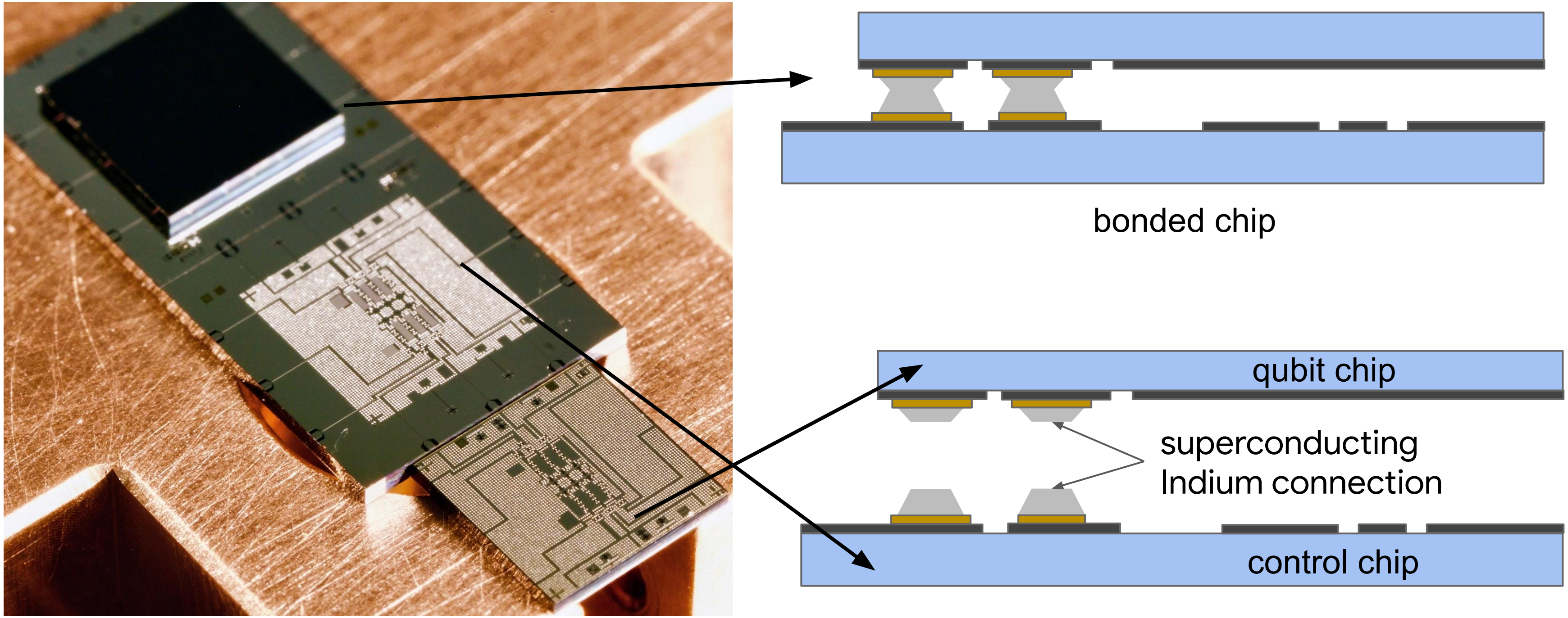


Foxtail: 22 qubits

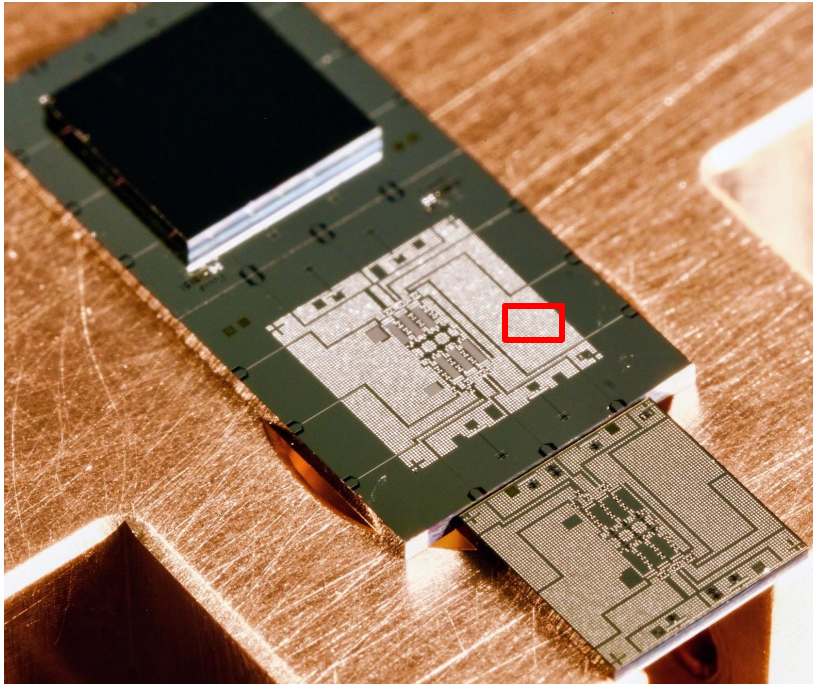
Bristlecone: 72 qubits

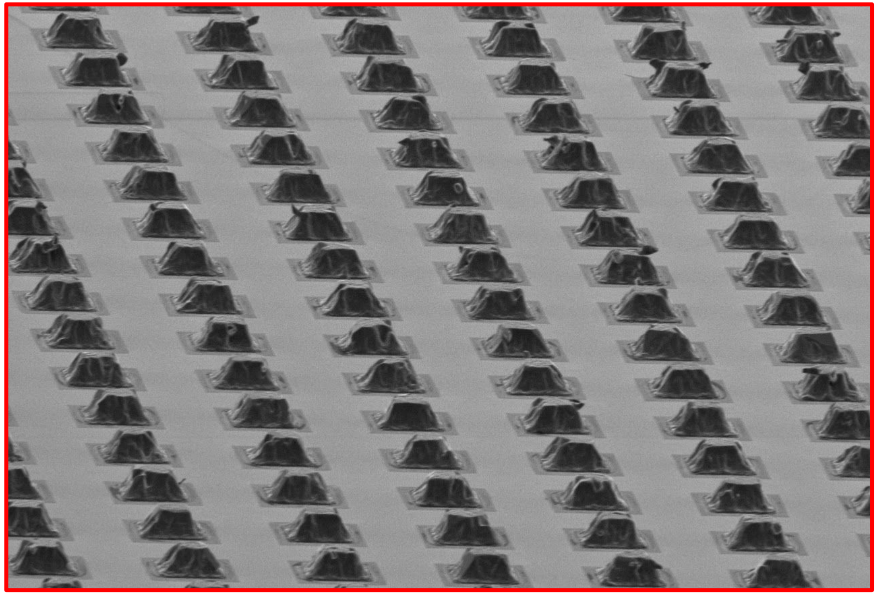


Flip chip geometry with bump bonds



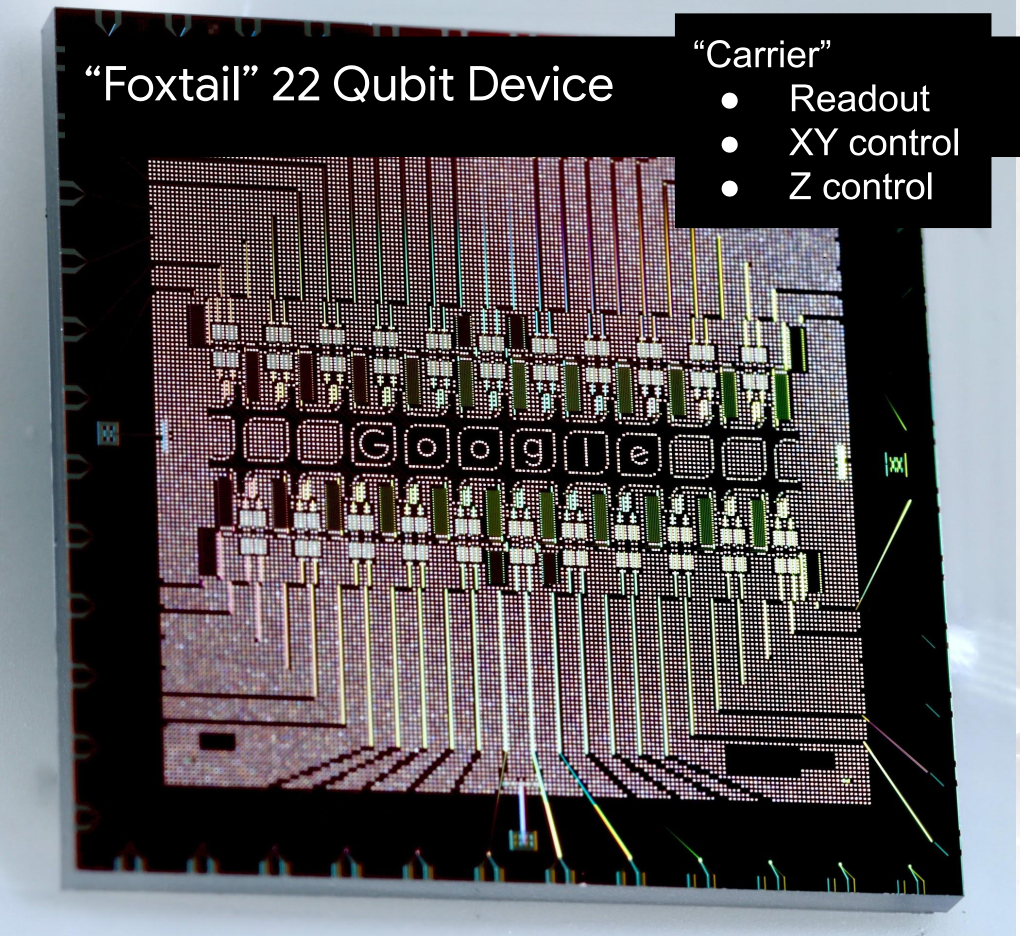
Flip chip geometry with bump bonds



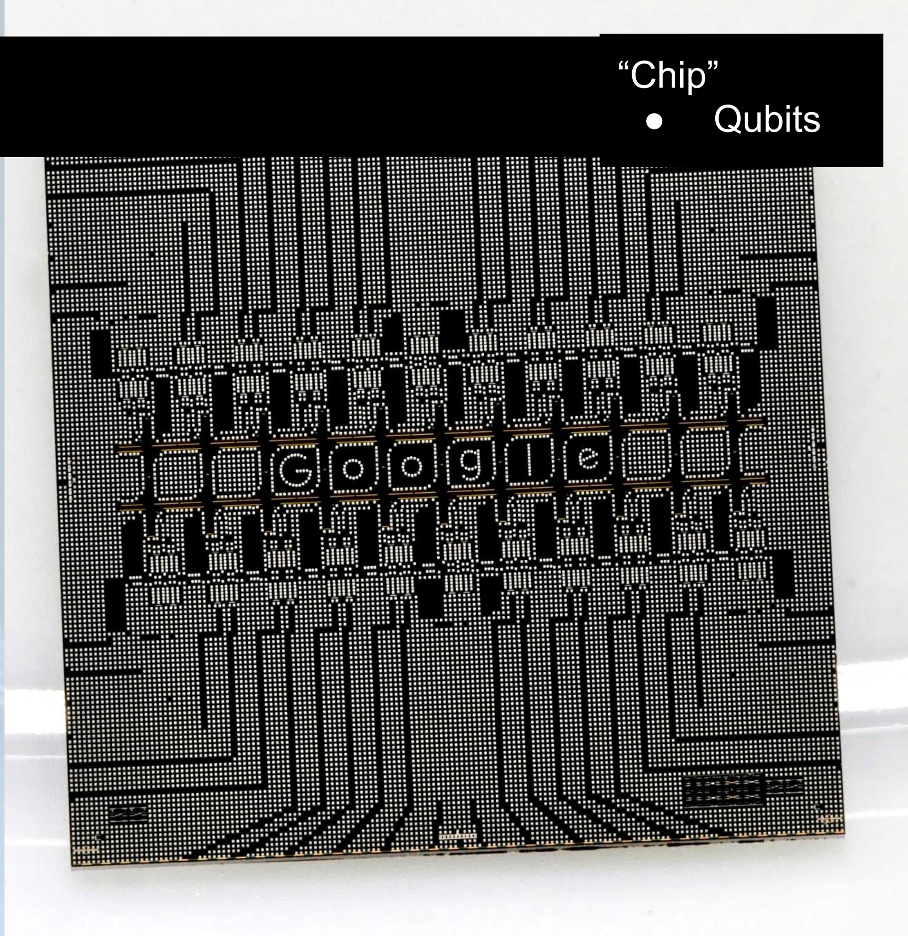


B. Foxen et al. Quantum Science and Technology, Volume 3, Number 1 (2017)

“Foxtail” 22 Qubit Device



“Carrier”
- Readout
- XY control
- Z control

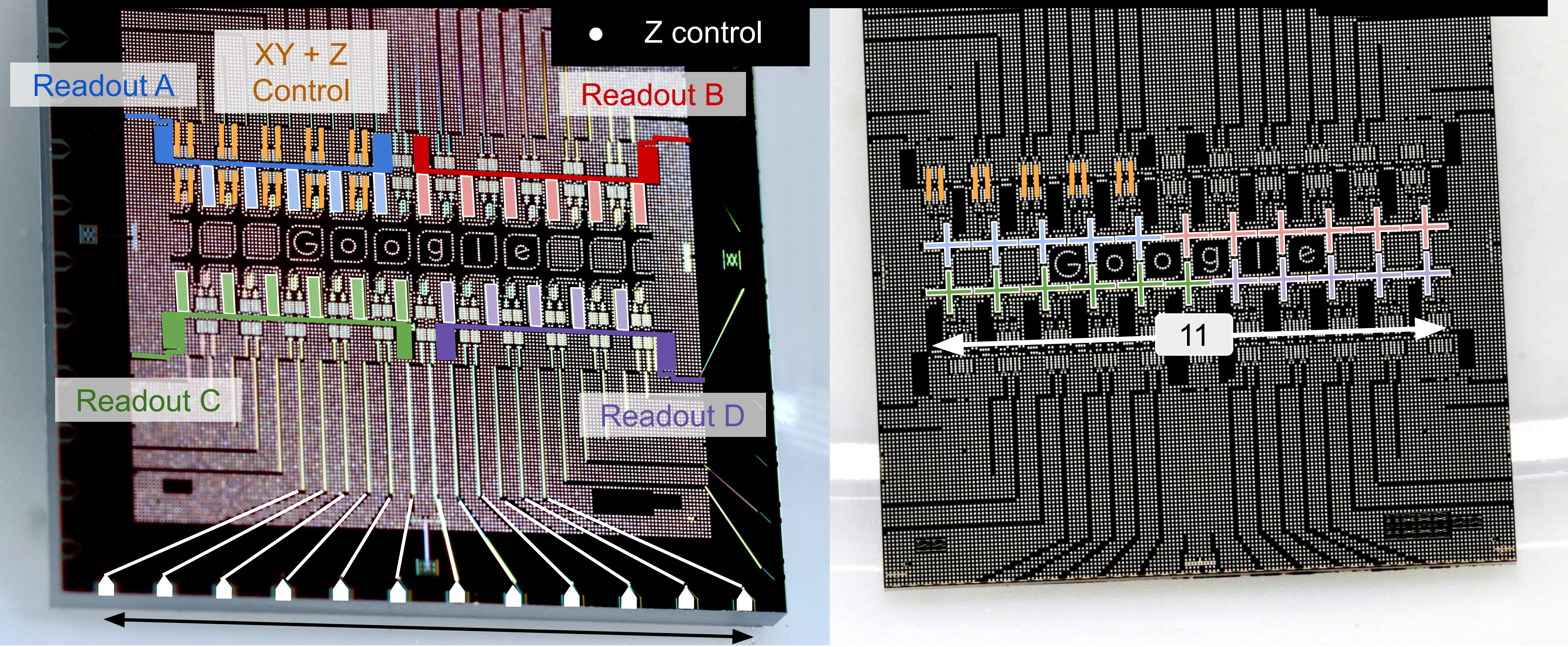


“Chip”
- Qubits

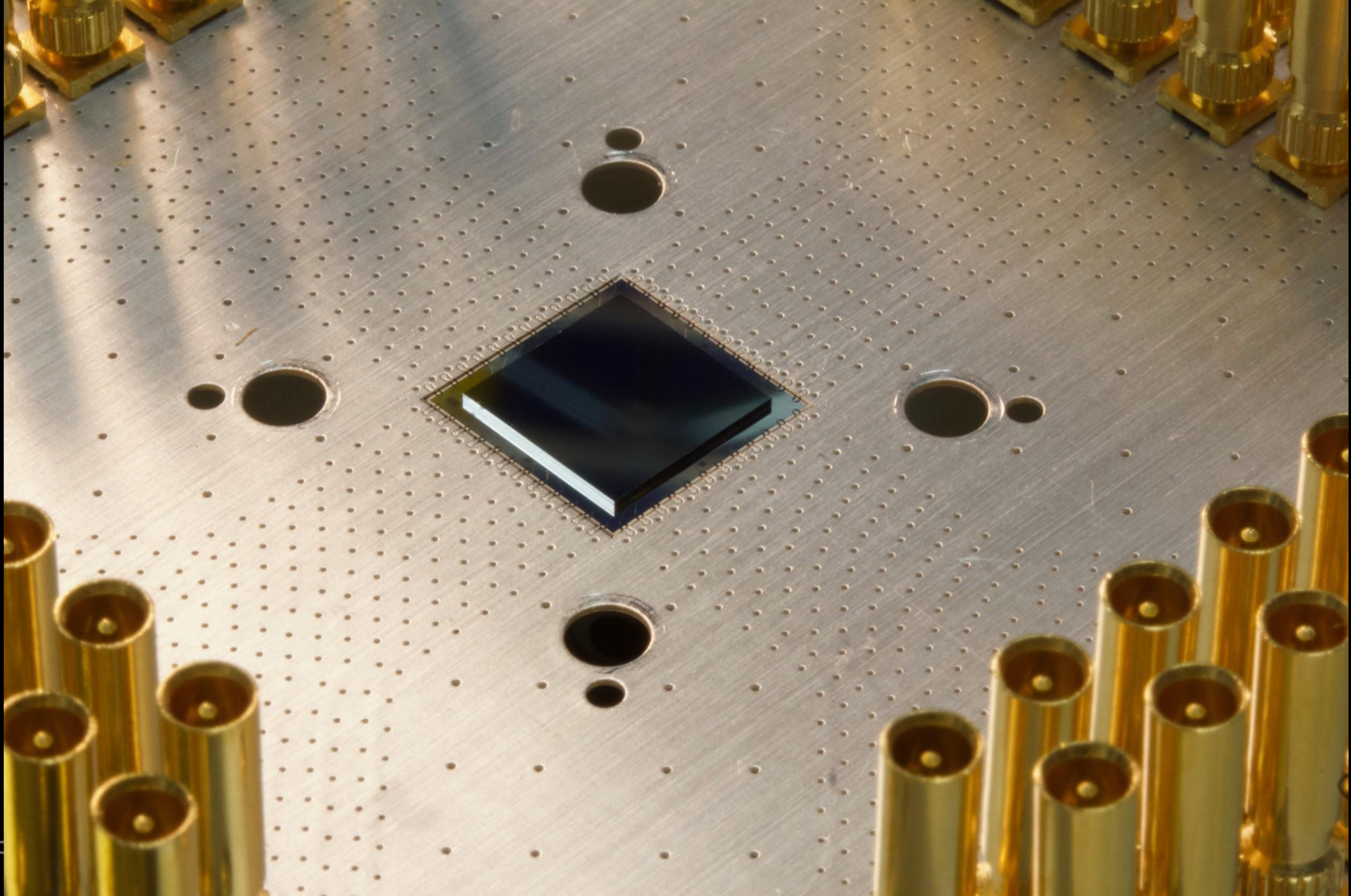
“Foxtail” 22 Qubit Device

[redacted]

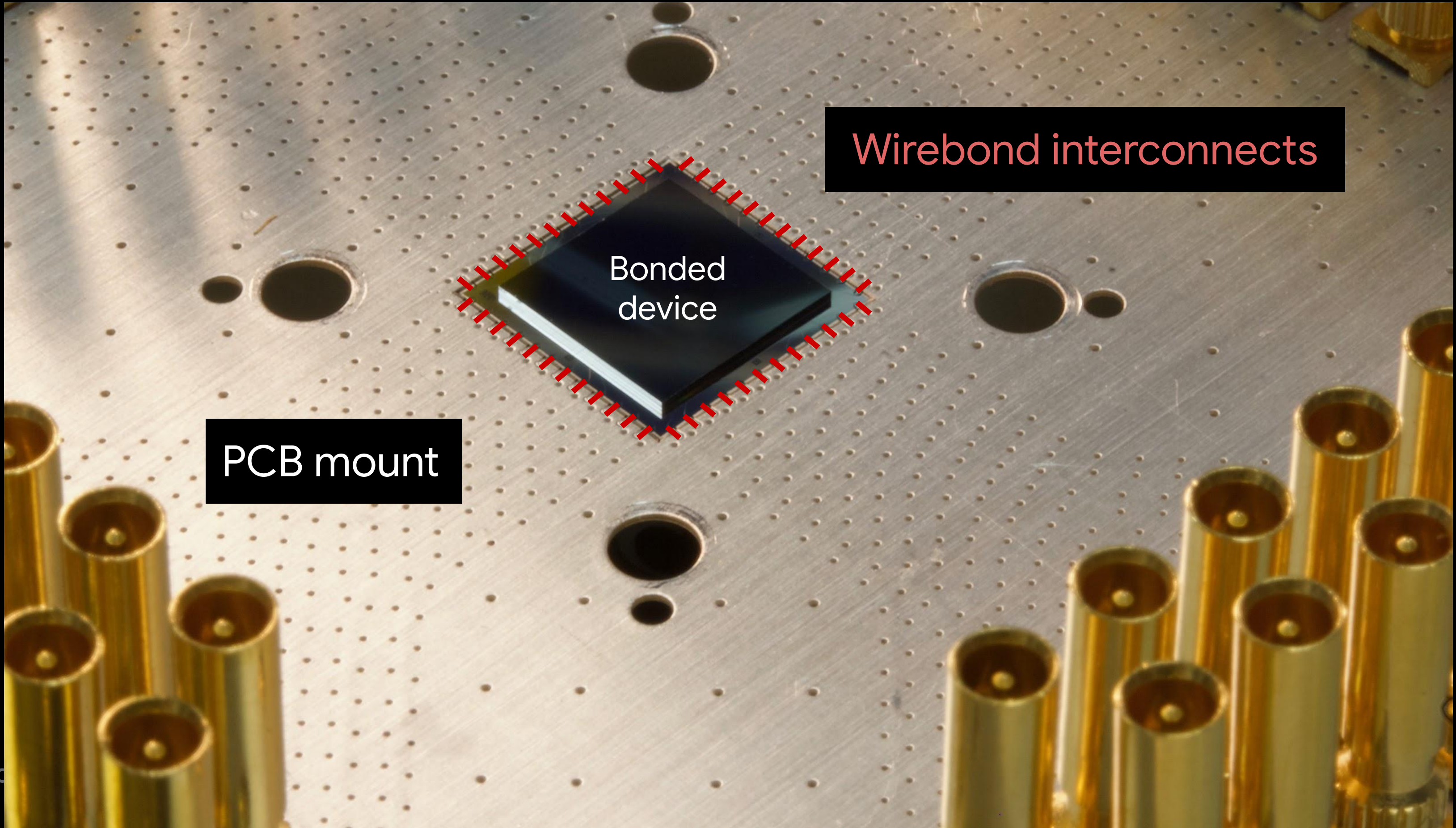
- Z control



- 2x11 grid
- 48 waveguides
- 4 readout lines
- 5-6 qubits per cell

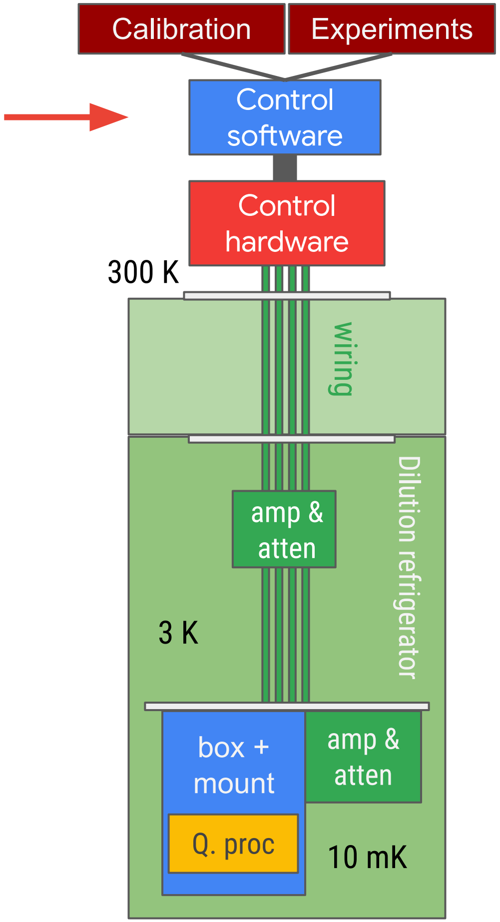


High-density coax



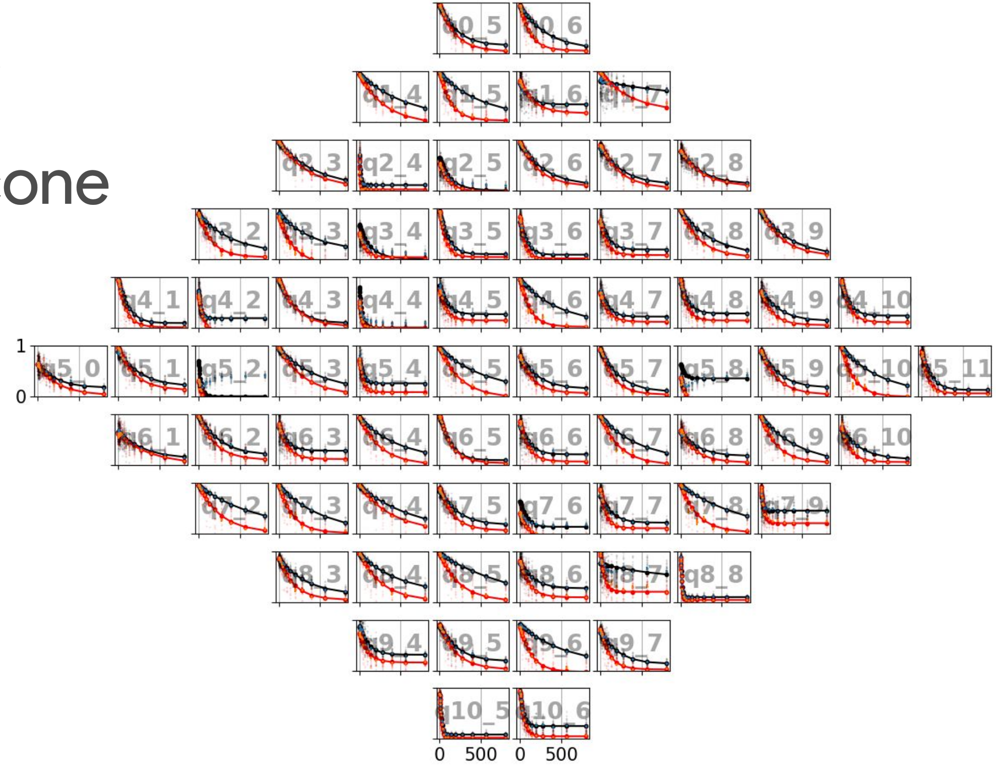
Quantum OS

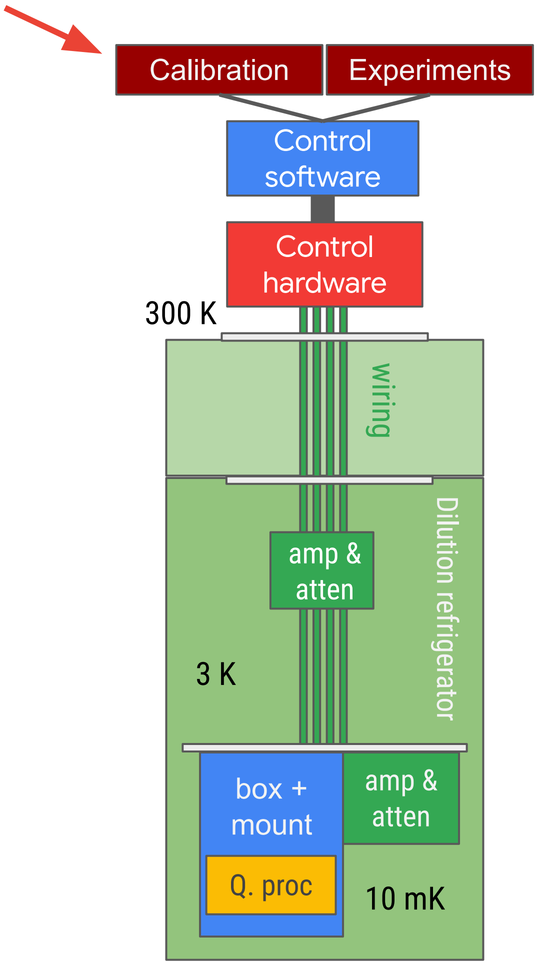
- Micro-services
  - LabRAD: service architecture / RPC
  - scheduling, gate compiler, FPGA, GPIB, etc. are servers
  - Experiments are initiated from clients
- Private github repo
  - Python + scala + rust
  - Coding styles / formatter / linter / type check
  - Code reviews / continuous integration
- Automate calibrations, experiments
  - Make hard things easy to move forward



Calibration: Key to Quality

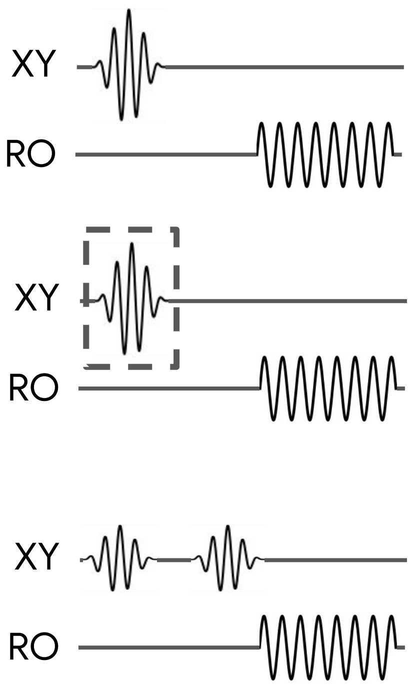
Bristlecone

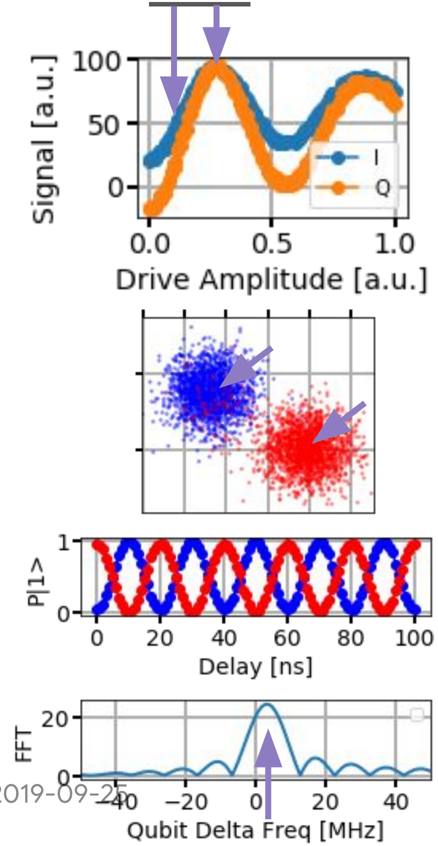




Bootstrapping

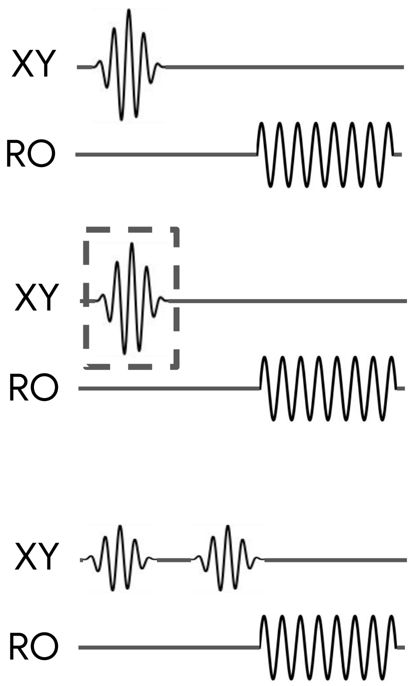
Experiment	Control Sequence	Data	Cal Value
Rabi			π amp. = 0.3 π/2 amp. = 0.15
Readout			0-state = (25, -20) 1-state = (100, 100)
Ramsey			f_{10} = 6.0 GHz +3 MHz

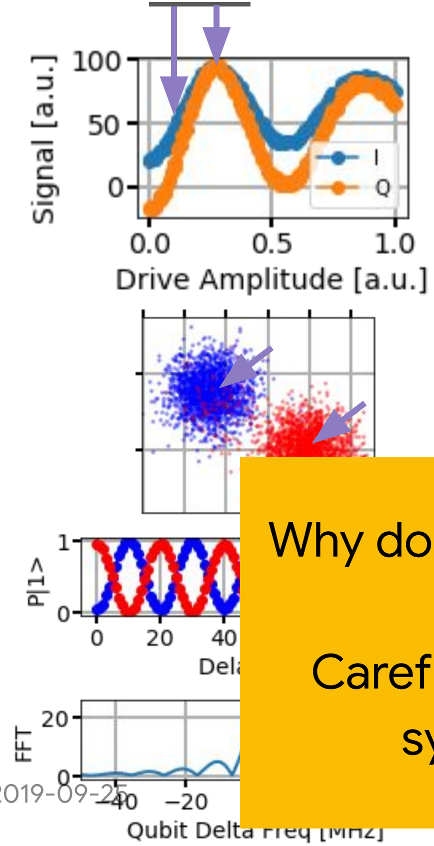




Bootstrapping

Experiment	Control Sequence	Data	Cal Value
Rabi			π amp. = 0.3 π/2 amp. = 0.15
⇩			
Readout			0-state = (25, -20) 1-state = (100, 100)
⇩			
Ramsey			



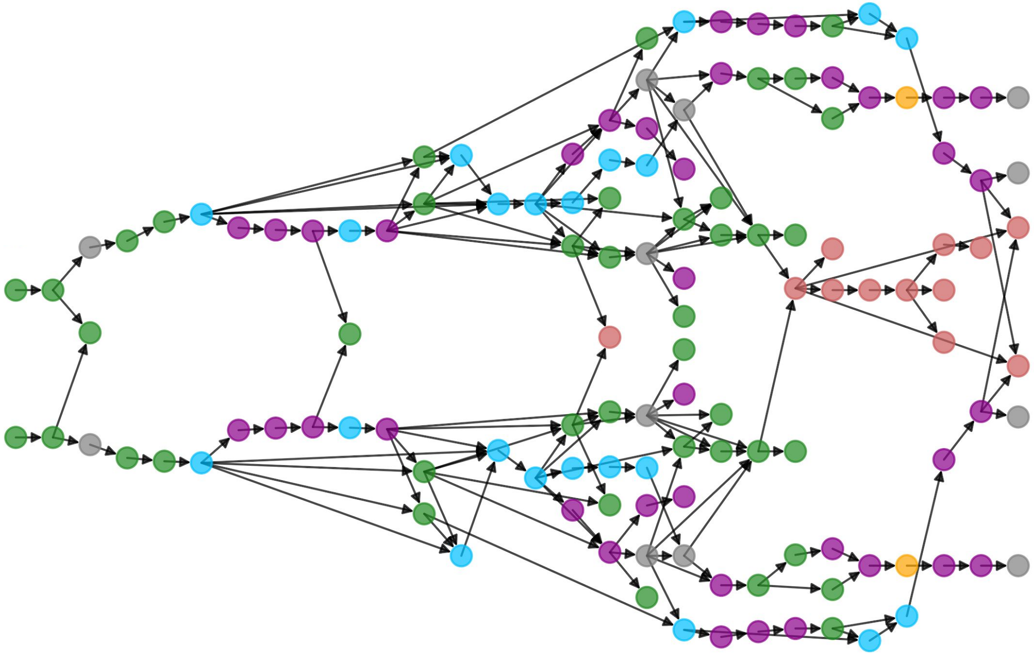


Why does this sequence work?

Careful order to **bootstrap** system knowledge

Calibration Dependency Graph

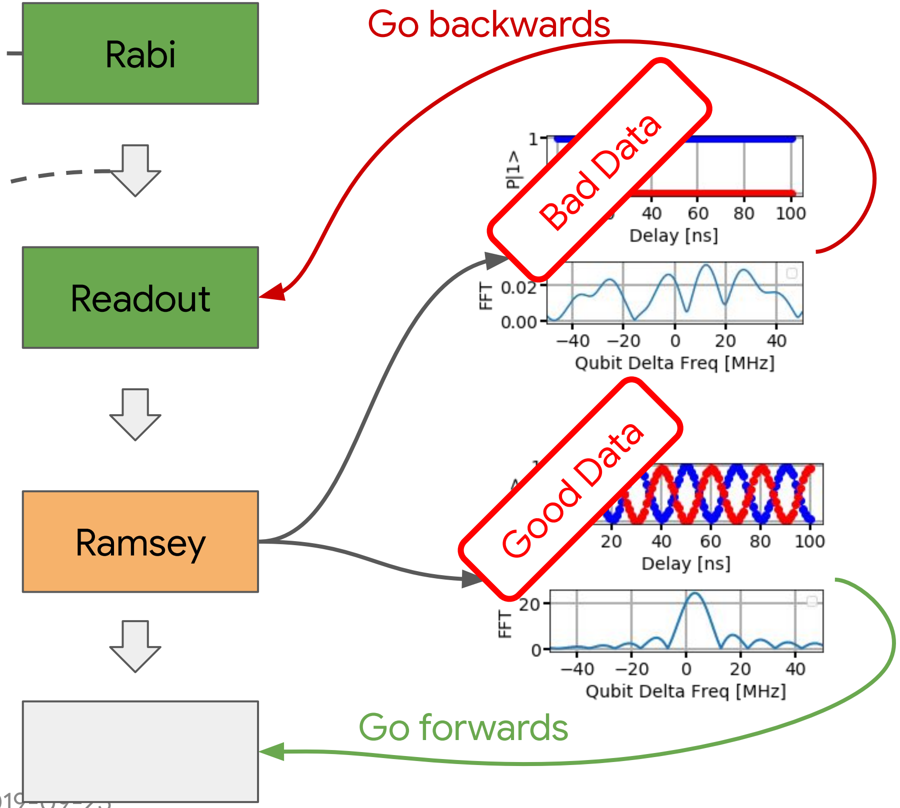
- → Dependency
- Electronics (orange)
- Device parameters (green)
- Single qubit gates (cyan)
- Readout (purple)
- Calibration waypoint (gray)
- Two qubit gates (red)



Optimus: Automatic Calibration Graph Traversal

Each cal = node in graph

Dependence = directed edge

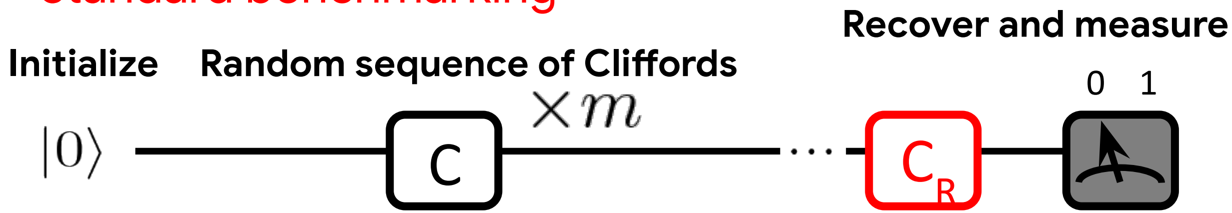


- Calibration dependences = Directed Acyclic Graph
- Each calibration makes **decisions**:
  a. Is data good?
  b. Parameter updates
- System calibration = graph traversal

Optimus white paper: [arxiv: 1803.03226]

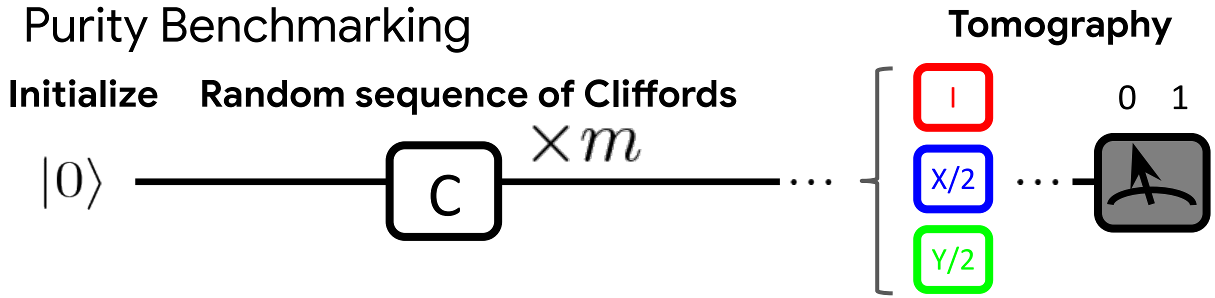
Optimization Example - Randomized Benchmarking

Standard benchmarking



Measures ***total error***

Purity Benchmarking

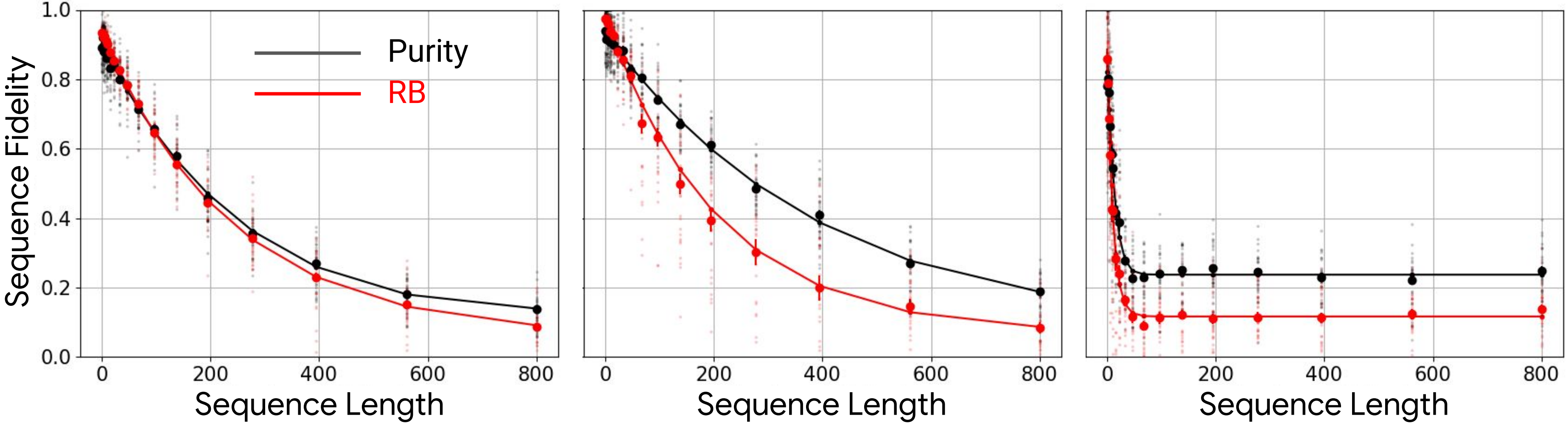


Measures ***decoherence error***

J. Wallman et al, NJP 17, 2015
G. Feng et al, PRL 117, 2016

Data: Randomized Benchmarking vs. Purity

Error = 1 - fidelity. Purity ⟶ decoherence error, RB ⟶ total error.

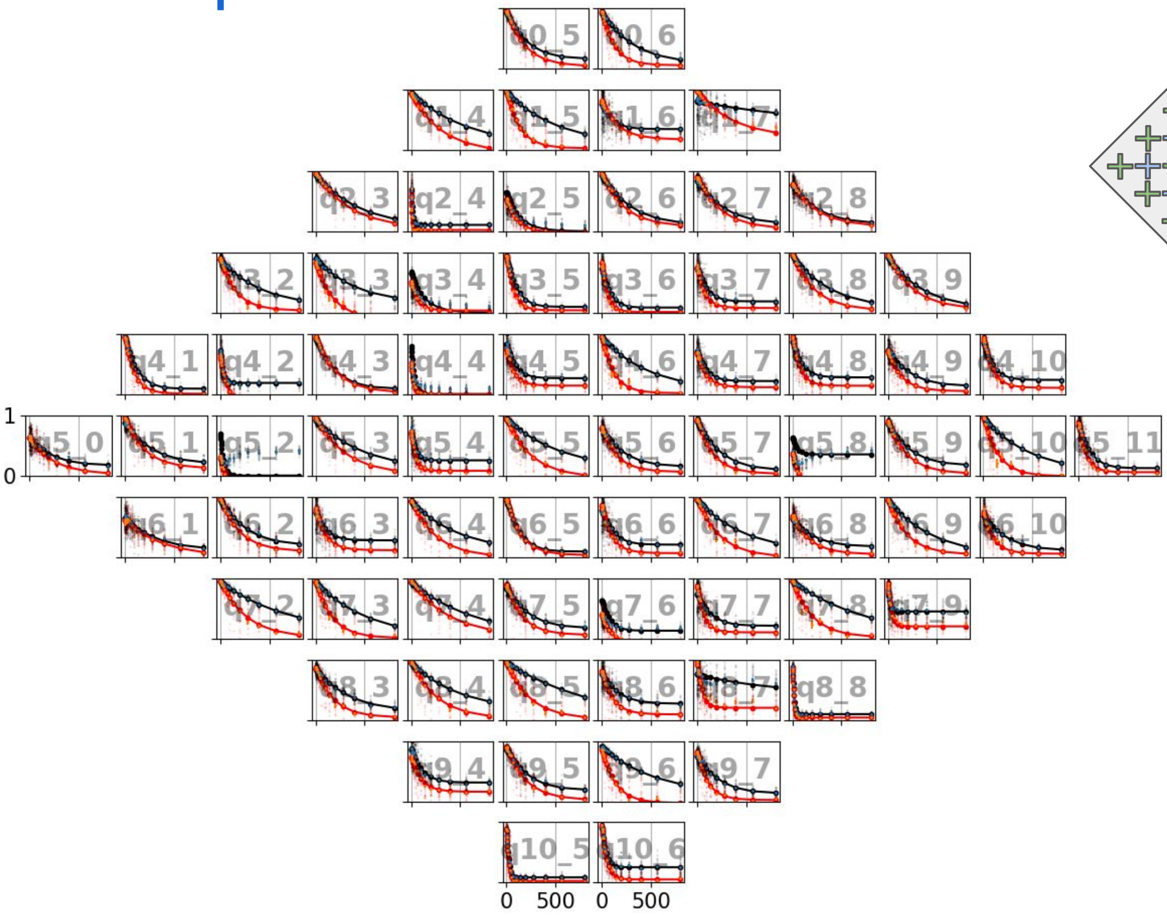


Low decoherence error
Low total error
qubit #1

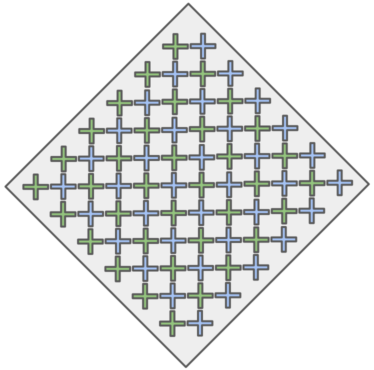
Low decoherence error
Medium total error
qubit #2

High decoherence error
High total error
qubit #3

Raw data of all qubits

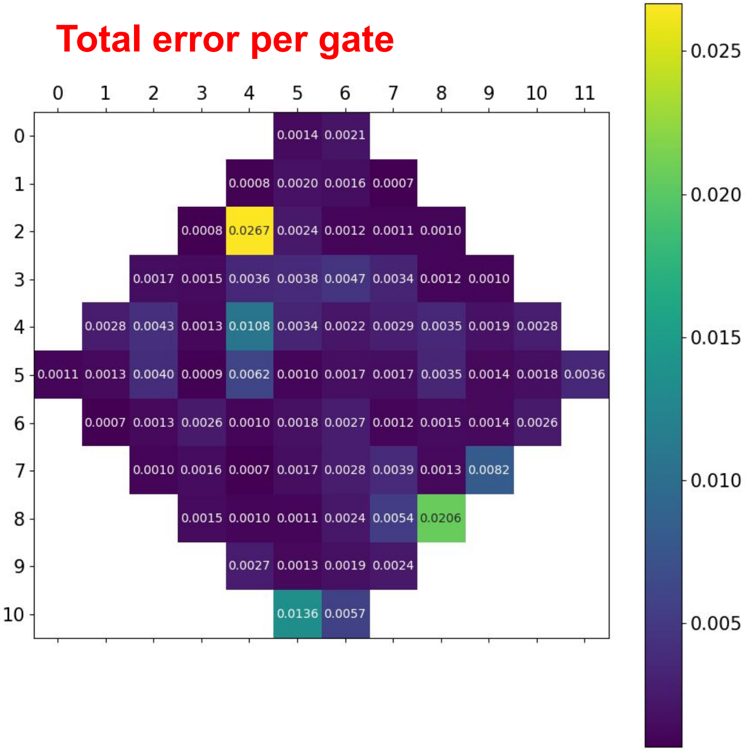


Bristlecone grid

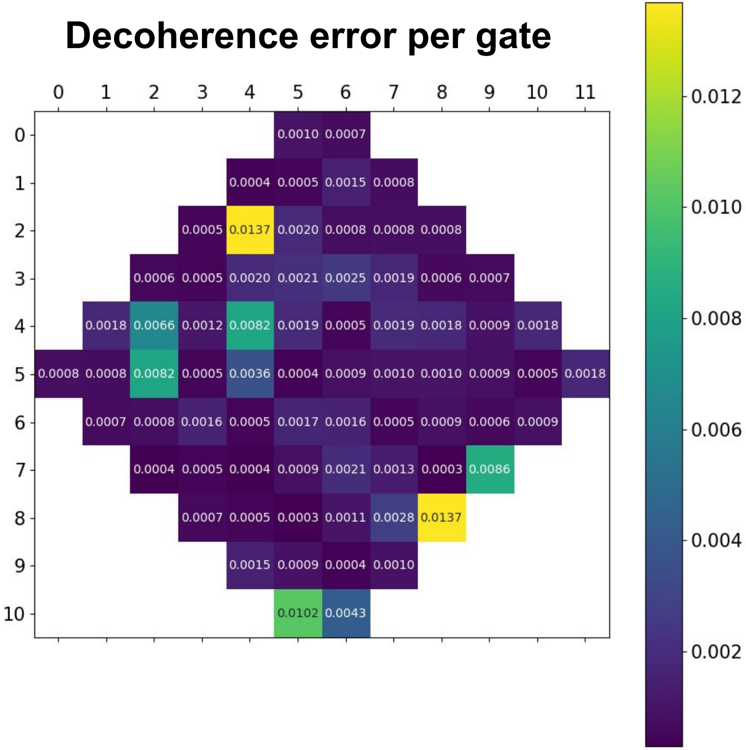


Heatmap: error vs. location

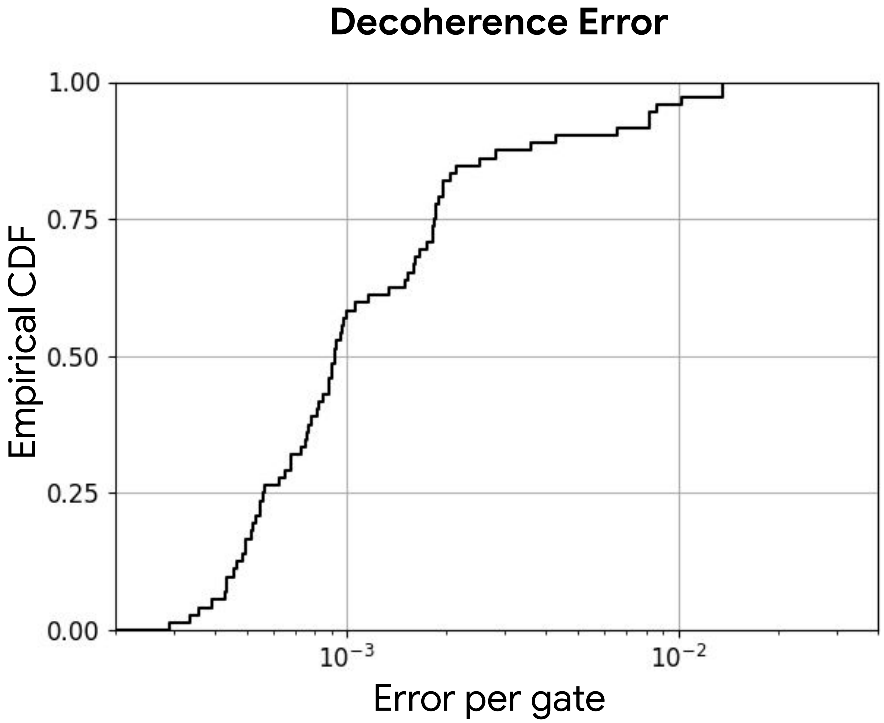
Total error per gate



Decoherence error per gate

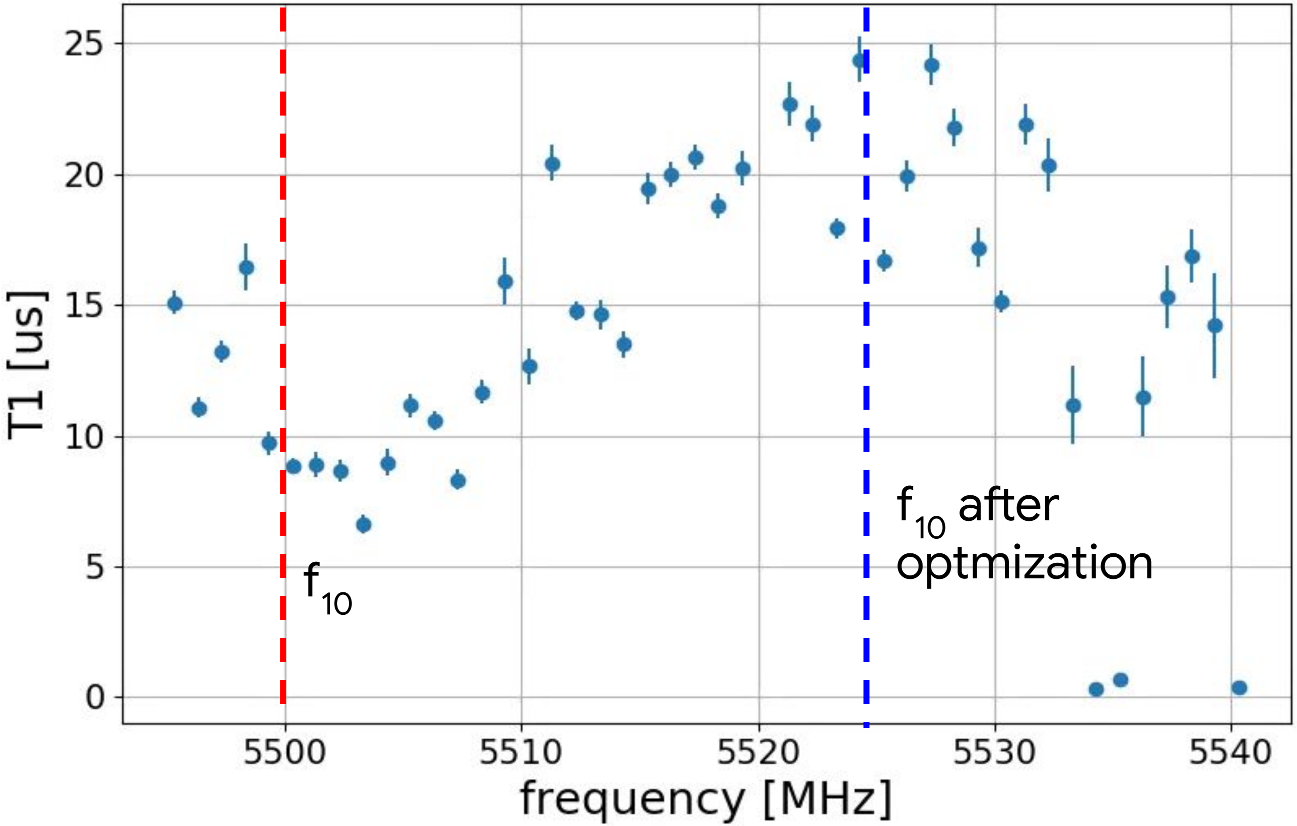


Empirical CDF: for measuring improvements



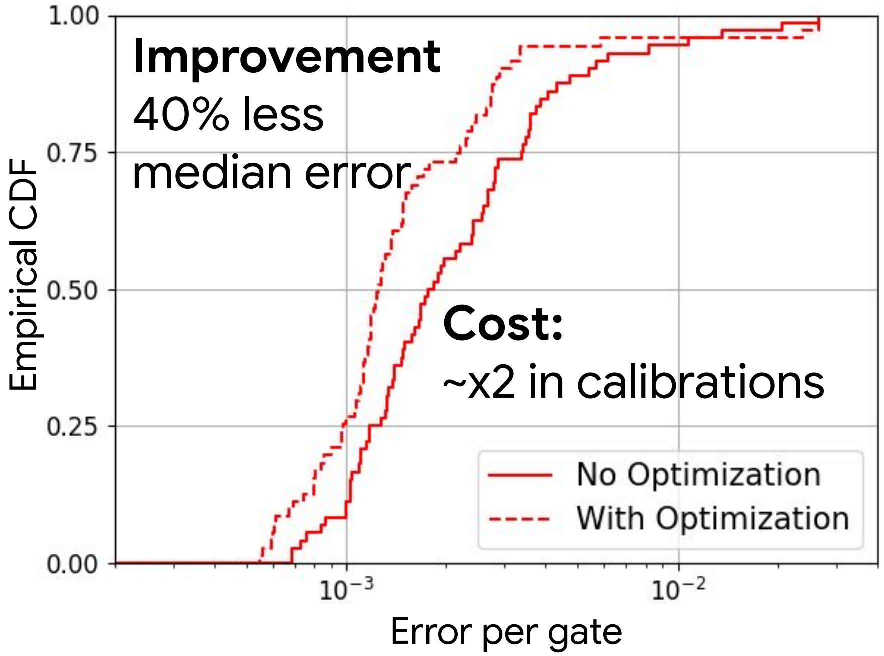
Calibration Study: Frequency Optimization

Larger
is
better

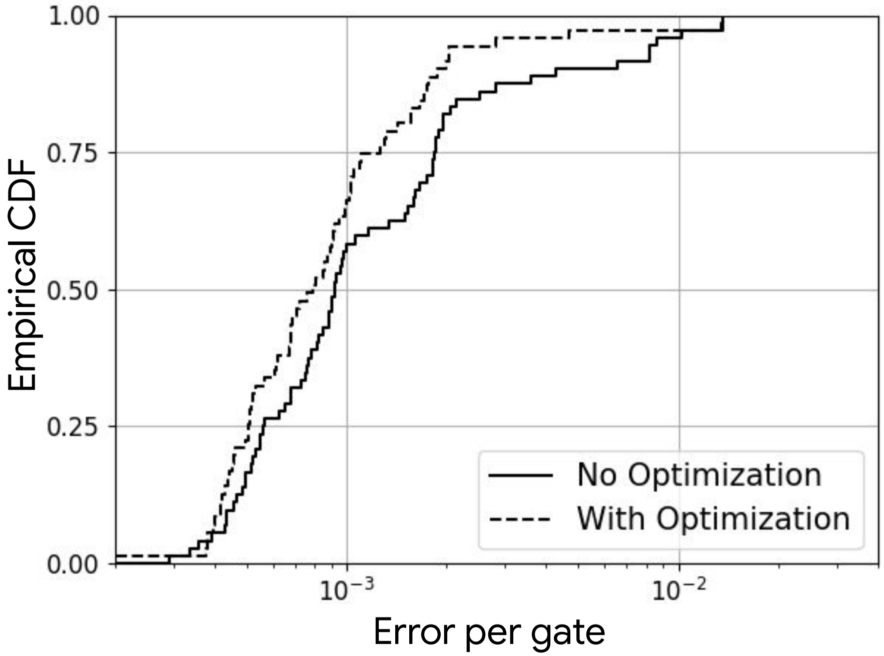


Fidelity improvements from frequency optimization

Total Error



Decoherence Error

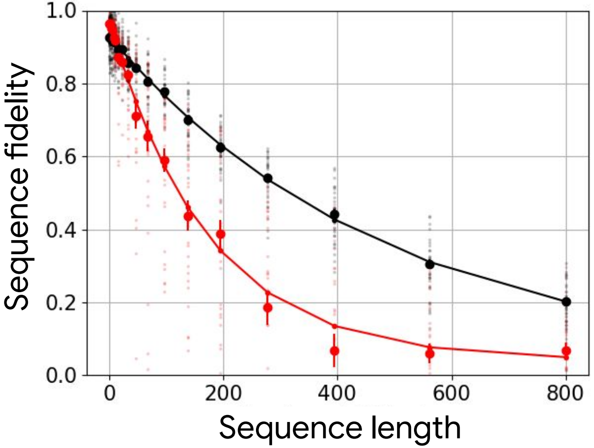


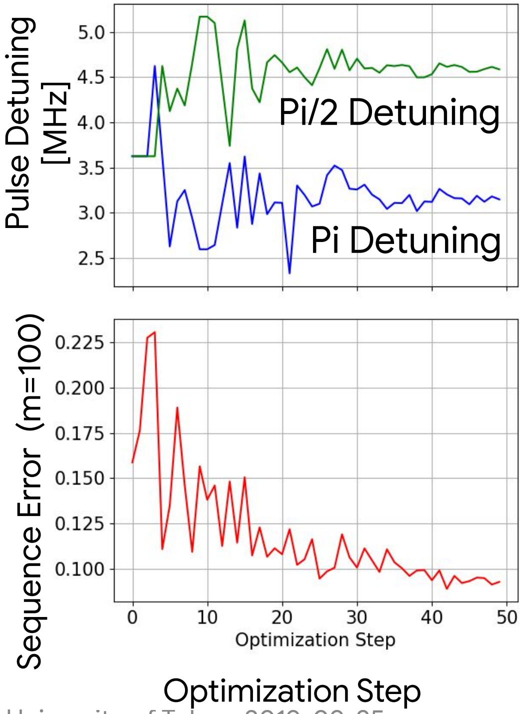
Calibration Study: ORBIT

Kelly et al, Phys. Rev. Lett. **112**, 240504 (2014)

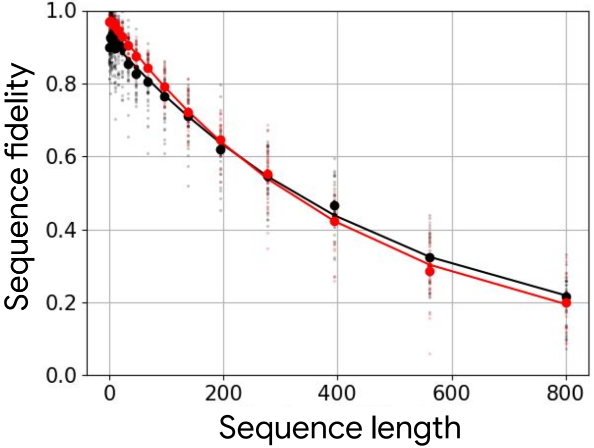
Optimize pulse parameters using RB as the objective function

Total error/gate: 2.9e-3

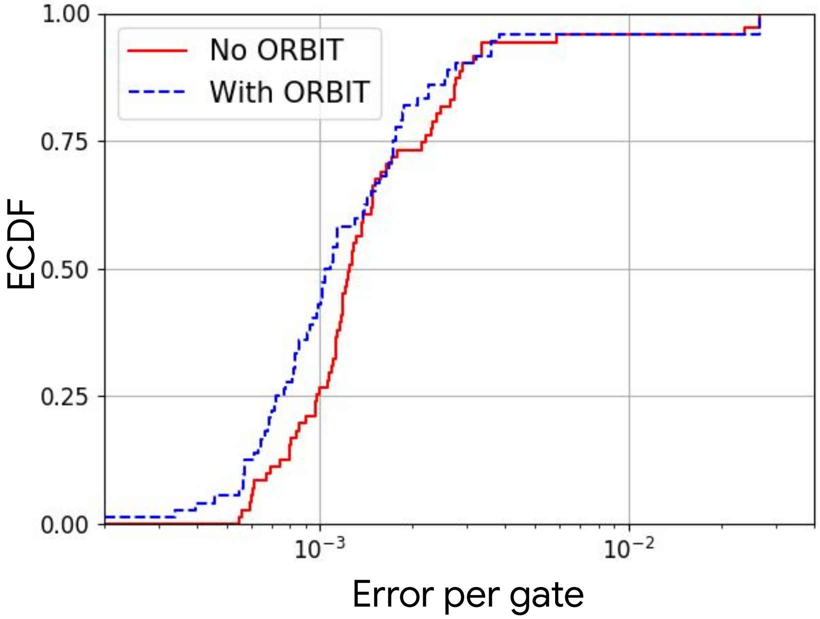




Total error/gate: 1.1e-3



Calibration Science: ORBIT



Improvement:
10% less median error

Cost:
Randomized benchmarking x 50 *per qubit*

Experiments

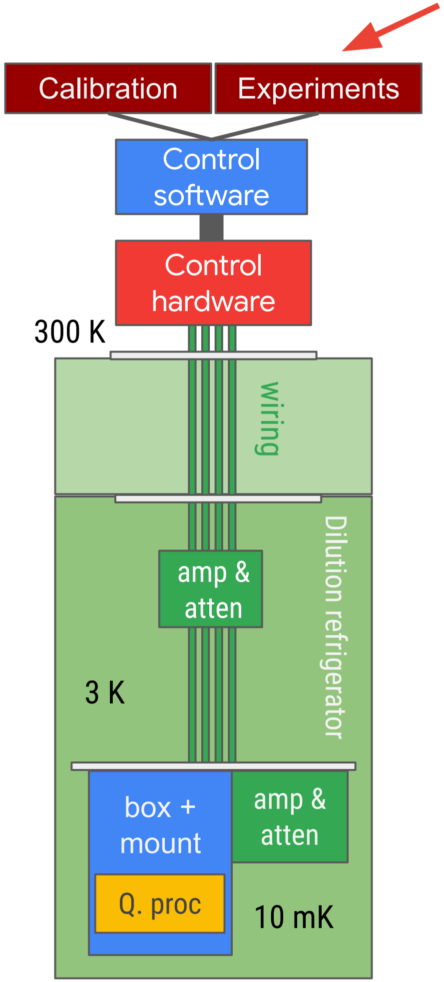
Noise study

Error/control study

Algorithm study

Sampling from random quantum circuit

etc.



Pursuit of quantum supremacy

Quantum supremacy

arXiv:1203.5813

QUANTUM COMPUTING AND THE ENTANGLEMENT FRONTIER

JOHN PRESKILL

Institute for Quantum Information and Matter
California Institute of Technology
Pasadena, CA 91125, USA

We therefore hope to hasten the onset of the era of *quantum supremacy*, when we will be able to perform tasks with controlled quantum systems going beyond what can be achieved with ordinary digital computers. To realize that dream, we must overcome the formidable enemy of *decoherence*, which makes typical large quantum systems behave classically. So another question looms over the subject:

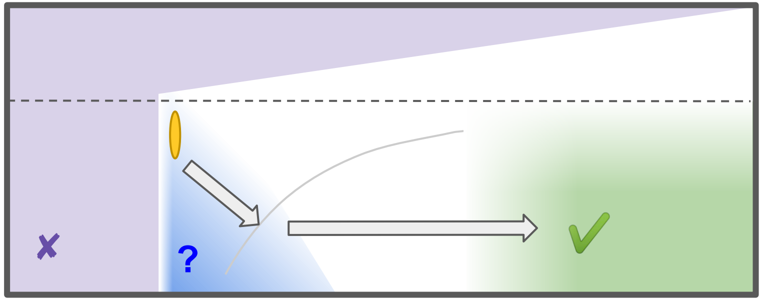
Is controlling large-scale quantum systems merely ***really, really hard****, or is it* ***ridiculously hard****?*

Quantum supremacy

Find **one** problem and demonstrate supremacy with real quantum hardware.

- A test of both quantity (number of qubits) and quality (fidelity).
- The problem itself does not need to have real world applications.

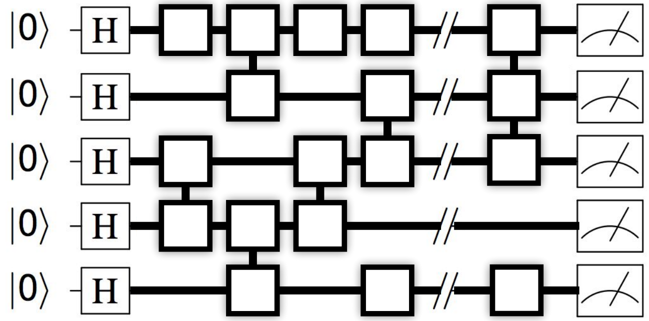
It's like a **beam test** on detectors.



My personal take: "Before claiming that you can fly, can you show that you can run instead of just walking?"

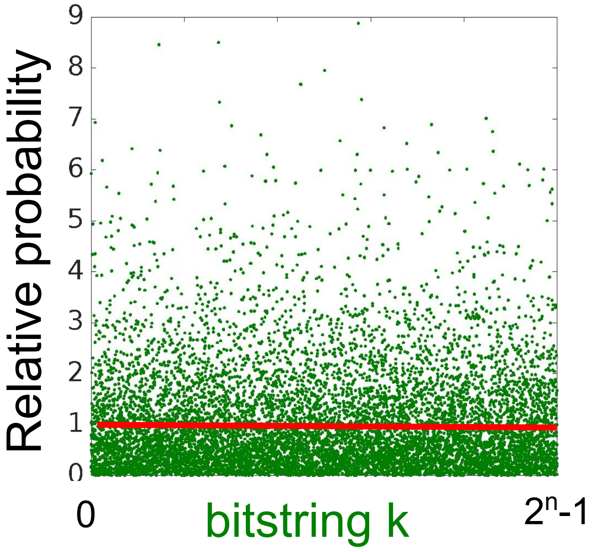
The problem Google picked: quantum sampling

Problem: Given a random quantum circuit of **n** qubits and depth **m**, sample **M** bitstrings according to the probability distribution of the final state.



$$|0\rangle^{\otimes n} \mapsto H^{\otimes n}|0\rangle^{\otimes n} = \left(\frac{|0\rangle+|1\rangle}{\sqrt{2}}\right)^{\otimes n} \mapsto U\left(\frac{|0\rangle+|1\rangle}{\sqrt{2}}\right)^{\otimes n} = \sum_{i=1}^{2^n} c_i |x_i\rangle$$

$$p_U(x_i) = |c_i|^2$$



Quantum sampling: theory

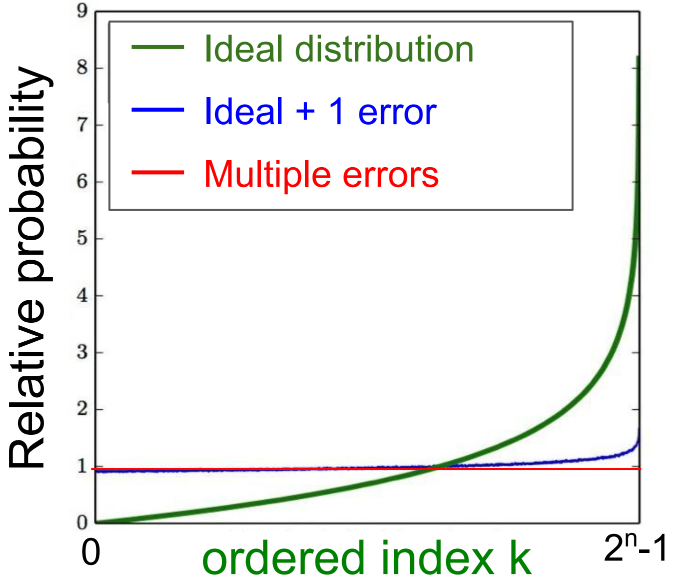
Prob(k) ~ Porter-Thomas distribution when error = 0 (ideal).

$$P(p) \propto e^{-Dp}$$

D = dimension of Hilbert space = 2^n

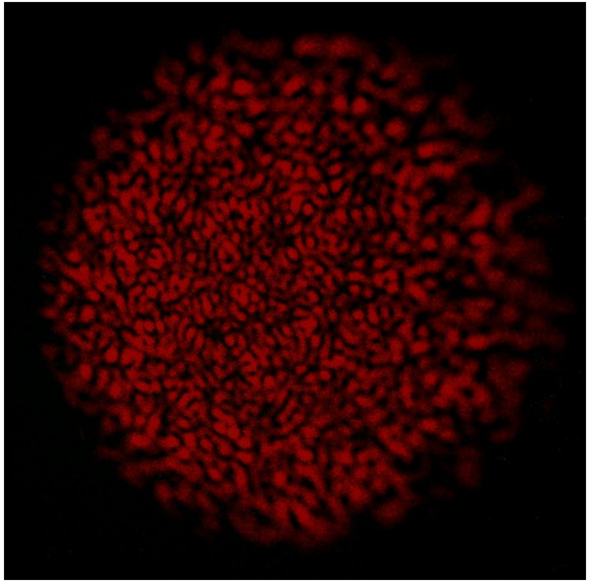
Decoherence error destroys it

~ uniform distribution



S. Boixo et al. Nature Physics **14**, 595–600 (2018), arXiv:1608.00263

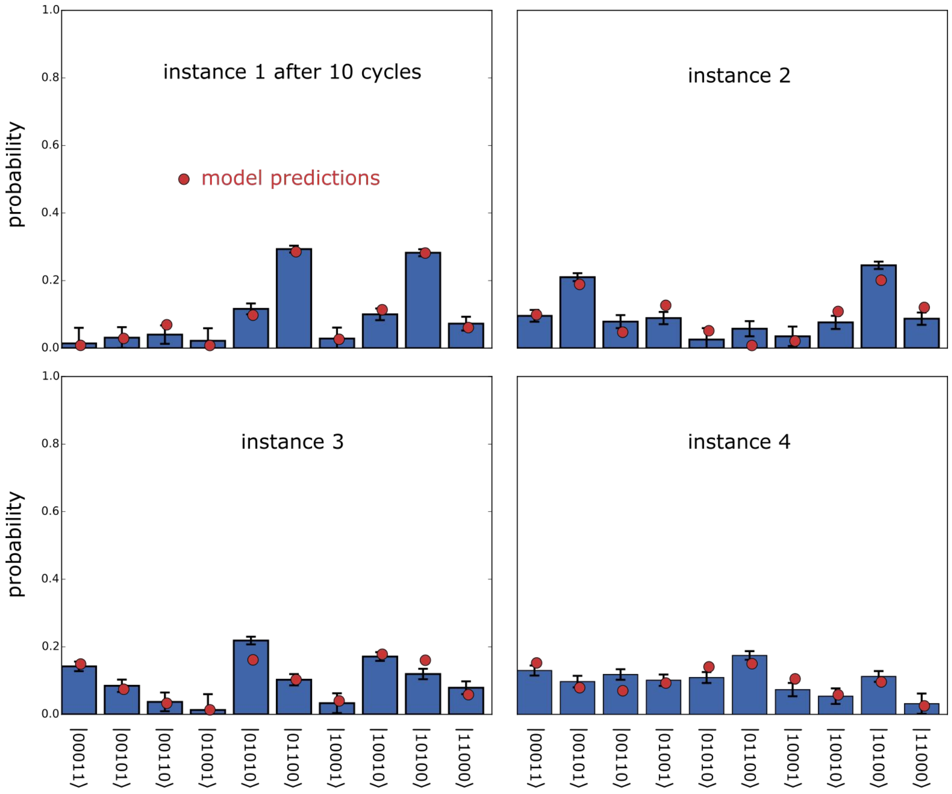
Intuition: coherence test



Coherent quantum interference: speckles

Incoherent classical light

Experimental Results with 5 qubits



Looks good qualitatively!

Quantitatively?

Cross-entropy benchmark (XEB)

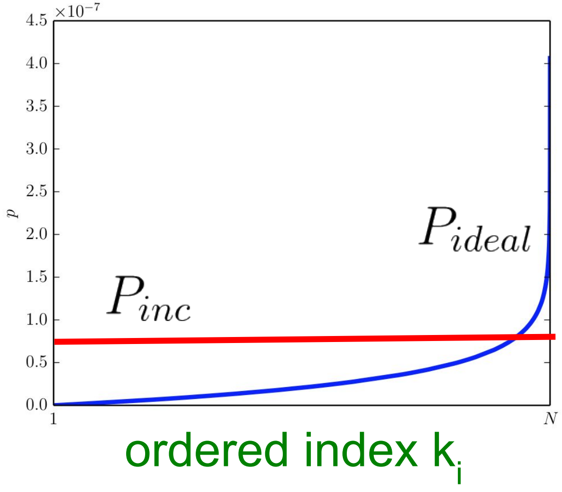
Cross entropy between 2 distributions *p* and *q*:

$$S(p(k), q(k)) \equiv -\sum_i p(k_i) \log q(k_i)$$

Fidelity $$F = \frac{S(P_{inc}, P_{ideal}) - S(P_{expt}, P_{ideal})}{S(P_{inc}, P_{ideal}) - S(P_{ideal}, P_{ideal})}$$

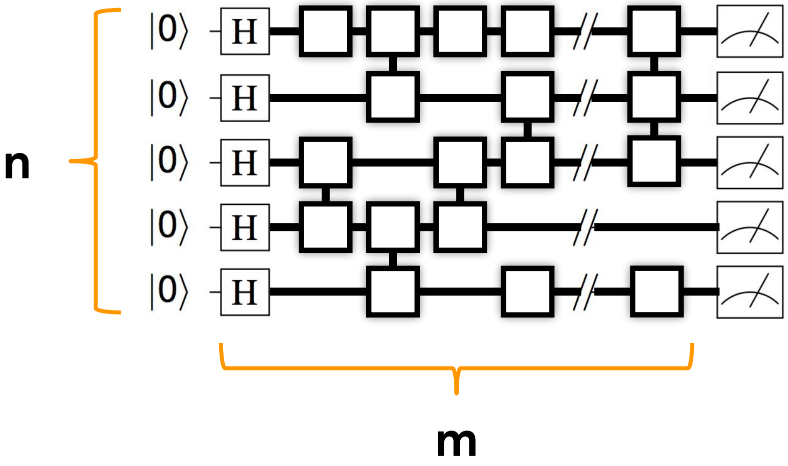
$$F = \begin{cases} 0, & \text{if } P_{expt} = P_{inc} \\ 1, & \text{if } P_{expt} = P_{ideal} \end{cases}$$

from classical simulation of ideal circuit



The quantum supremacy question

Given a random quantum circuit with **n** qubits and depth **m**, what's the amount of computation (core * hours) needed for a classical computer to sample **M** bitstrings from a quantum computer with fidelity **F**?



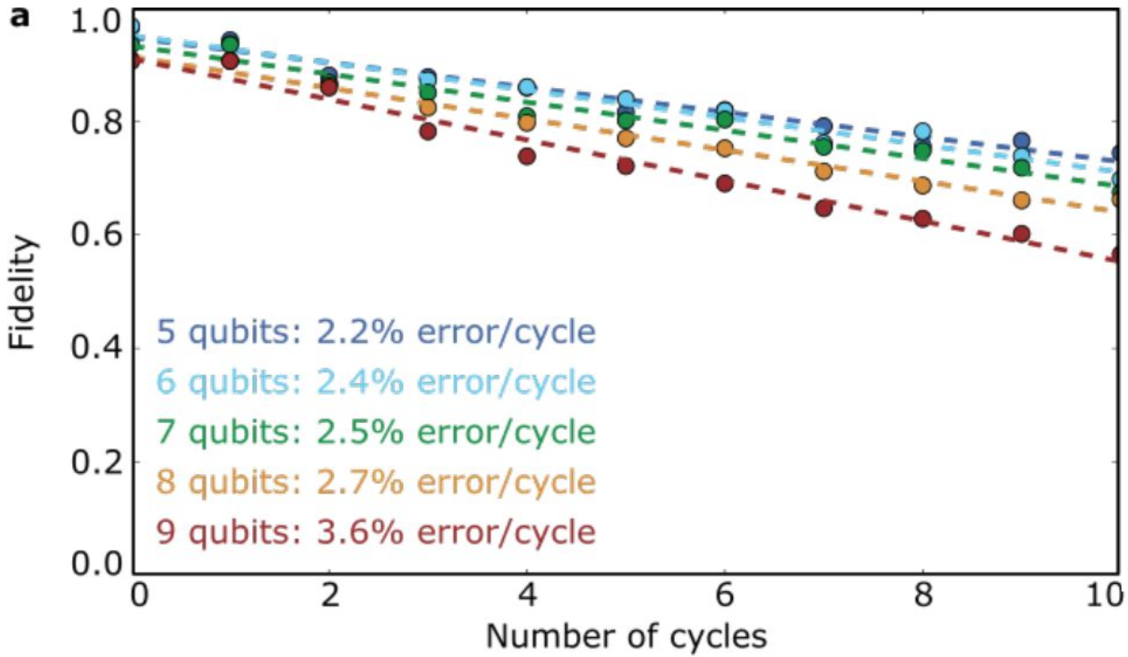
Expect:

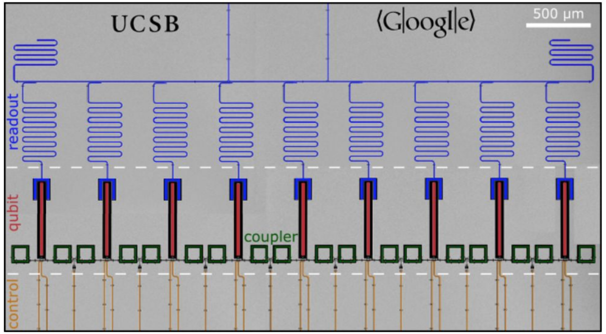
For large enough **n** and **m** with a decent **F**, this is out of reach for classical computers.

How good is your quantum computer hardware?

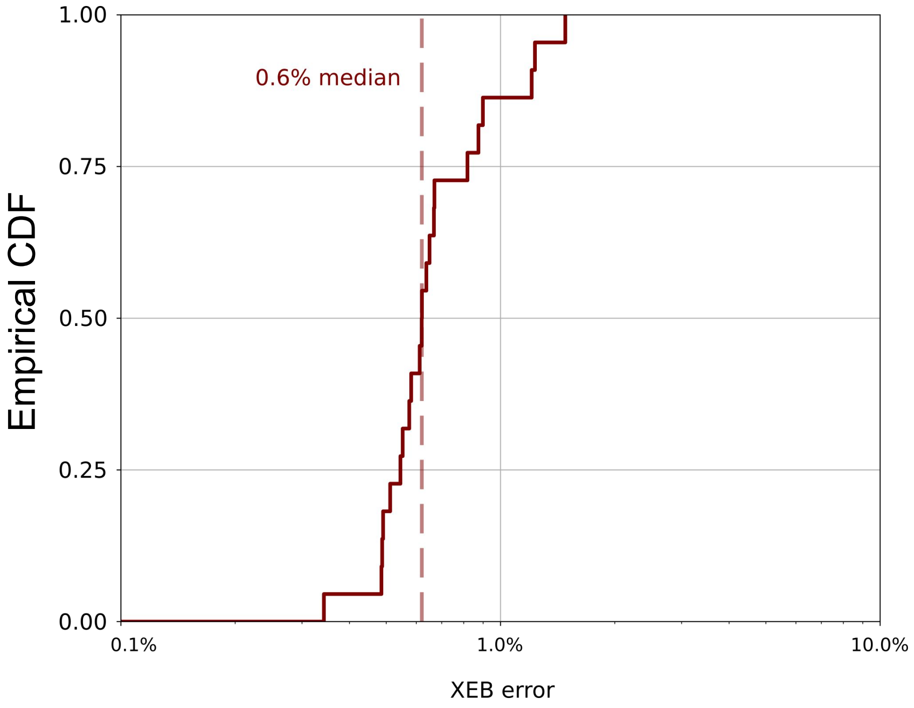
Data from 9-qubit experiments

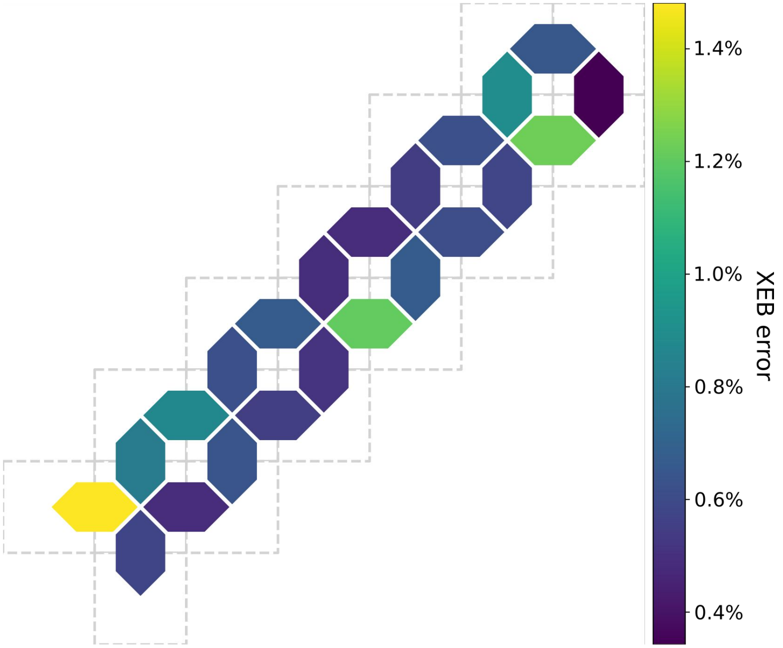
"A blueprint for demonstrating quantum supremacy with superconducting qubits", Science **13** Apr 2018 | arXiv:1709.06678



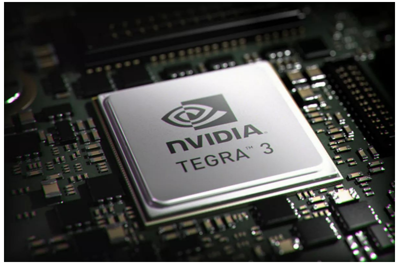


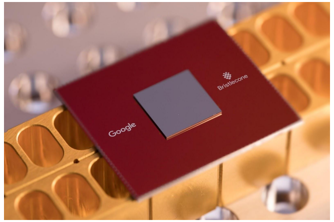
Two-qubit gate errors from an 18-qubit chip



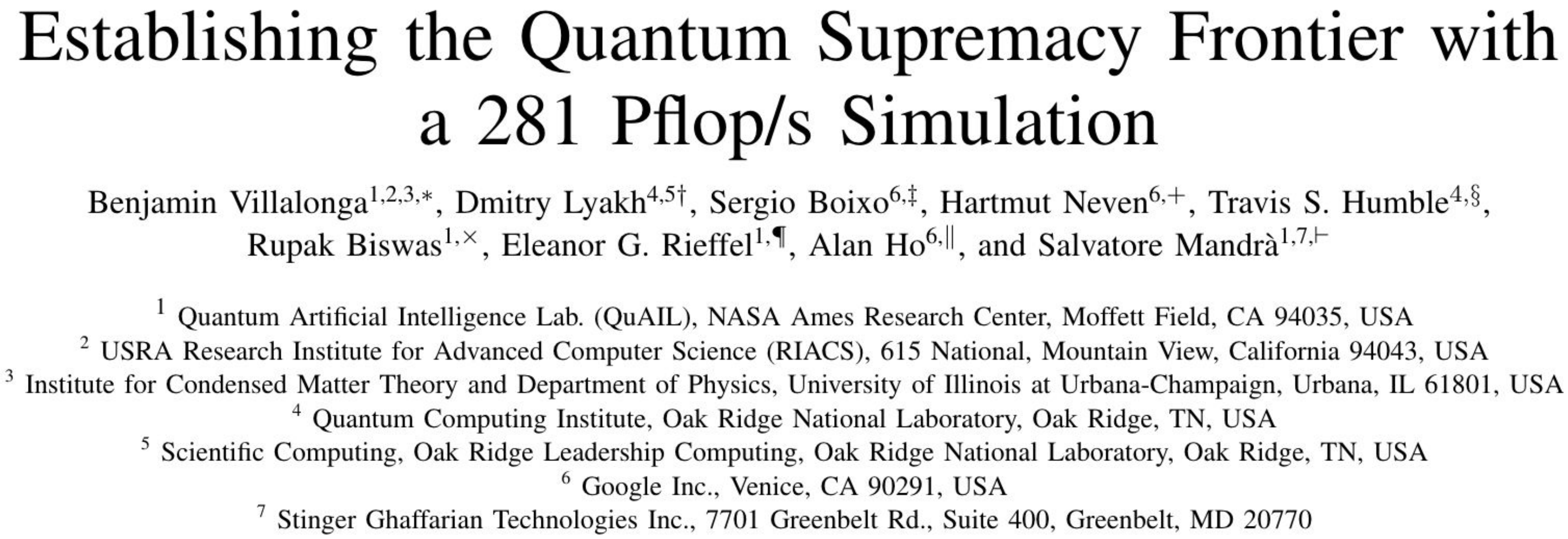


Classical computing power vs. quantum



Simulation on Summit


Establishing the Quantum Supremacy Frontier with a 281 Pflop/s Simulation

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https://arxiv.org/abs/1905.00444

Estimation for a hypothetical 49 qubit QC

		Runtime (hours)			Energy cost (MWh)		
Circuit size	Target fidelity (%)	Electra	Summit	QPU	Electra	Summit	QPU
$7 \times 7 \times (1 + 40 + 1)$	0.5	59.0	2.44	0.028	96.8	21.1	4.2×10^{-4}

49 qubits @ depth 40

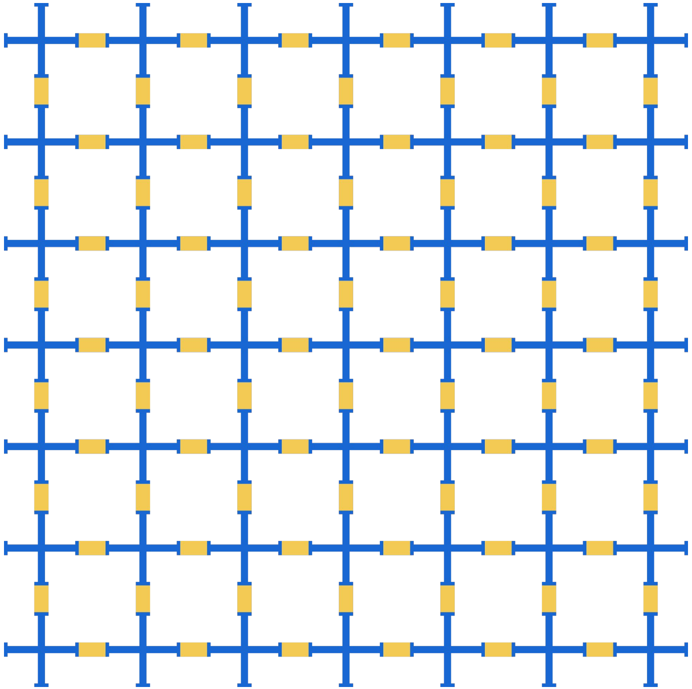
$O(10^2)$ advantage

$O(10^5)$ advantage

https://arxiv.org/abs/1905.00444

Projection for quantum supremacy

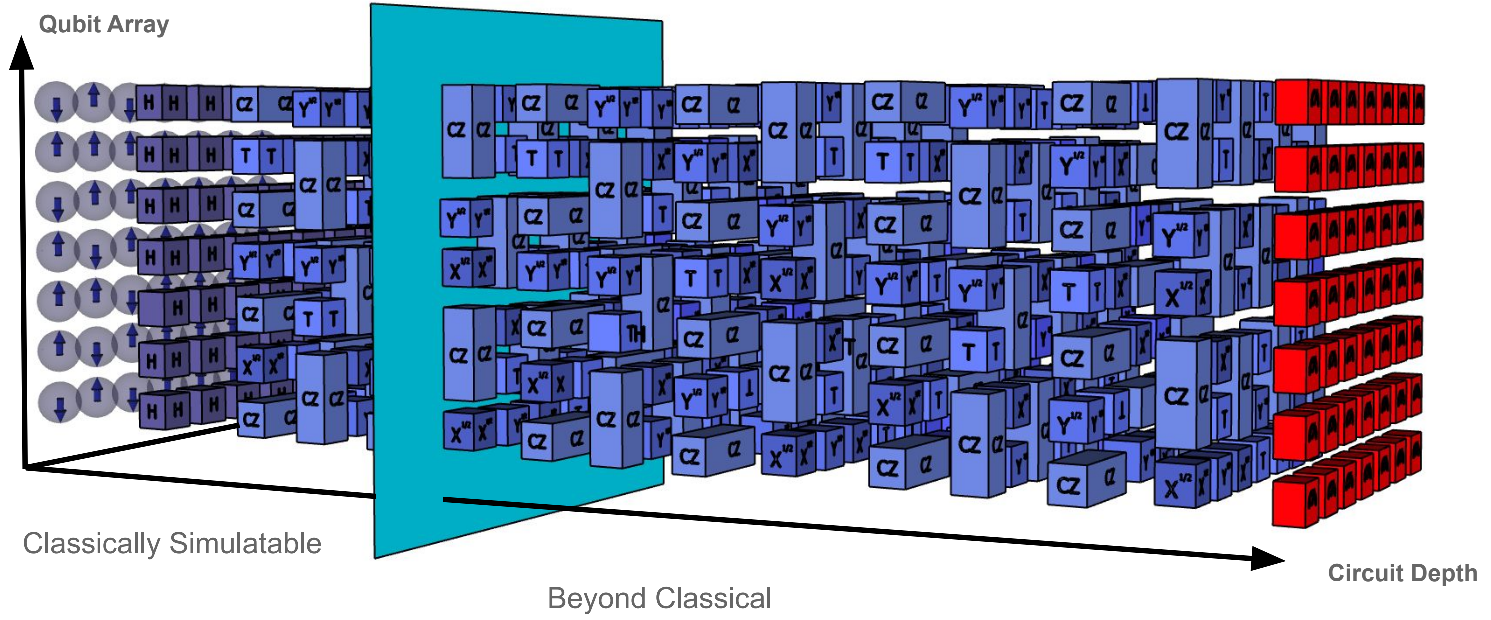
Supremacy ~49 qubits & depth ~12



		Error
1-Qubit gate fidelity	99.9%	0.1%
2-Qubit gate fidelity	99.2%	0.8%
Readout fidelity	97.0%	3%
Projected supremacy fidelity	1.6%	

Measurements needed for 5-sigma supremacy: **M** ~ 10^5

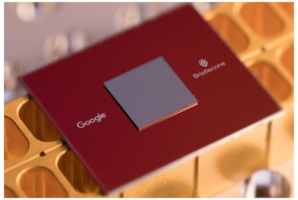
Established Frontier of Quantum Computation



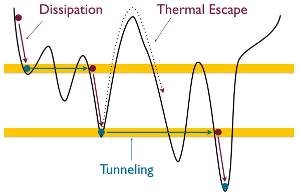
Collaboration opportunities

Google Academic Funding

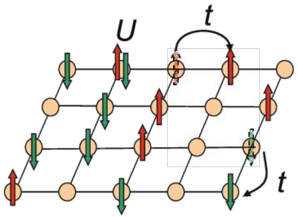
Faculty Research Awards	Focus Awards
1 year funding	2 - 3 years
1 graduate student	1+ graduate student
Collaborate with Google researchers	
Potential access to hardware	
8 awarded in 2018	
Application deadline: 10/1 5am JST	



Better hardware



Better algorithm



First applications

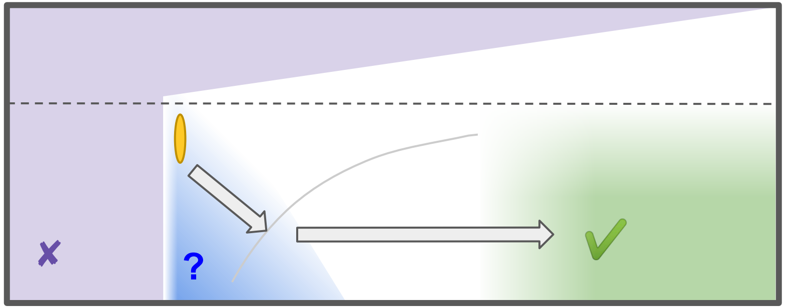
Conclusions

Quantum computing will grow as hardware becomes more capable

Google is attempting to reach quantum supremacy

Primary challenge: good coherence at larger scale / implement error correction

Collaboration opportunities




Google AI
Quantum