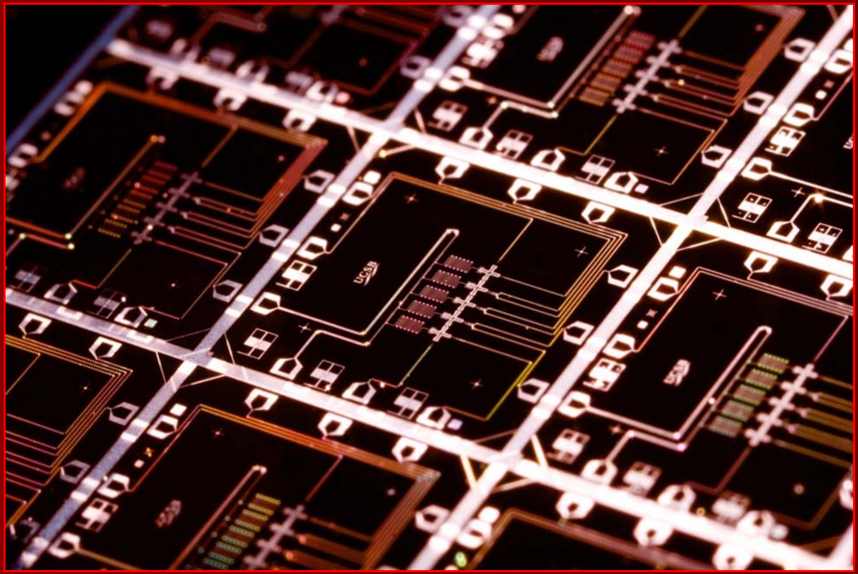
Superconducting qubits for quantum information

Symposium in honor of Paul Benioff's fundamental contributions to quantum information

Andrew N Cleland

THE UNIVERSITY OF CHICAGO | Institute for Molecular Engineering | Argonne National Laboratory

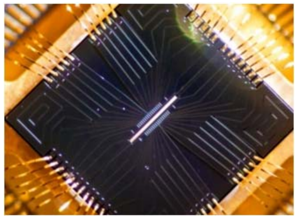
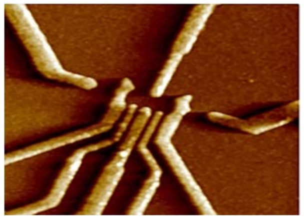
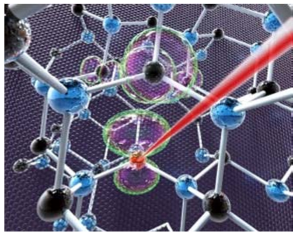
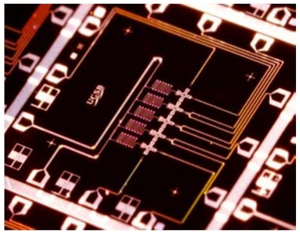


All work from UC Santa Barbara
Collaboration with: J. Martinis, M. Geller, A. Korotkov, F. Wilhelm

Argonne National Laboratory
Symposium on Quantum Computing: Beginnings to Current Frontiers
May 26 2016 3:10-4 pm

Quantum engineered systems

- Quantum computation
  - Gate-based implementation of quantum algorithms (Shor, Grover)
  - Quantum simulation of complex systems (e.g. molecular chemistry)
  - Adiabatic evolution for minimization problems (e.g. traveling salesman)
- Quantum communication
  - Quantum key distribution
  - Quantum repeaters
- Quantum sensing
  - Detection of weak fields
  - Detection of small displacements
  - Long baseline interference

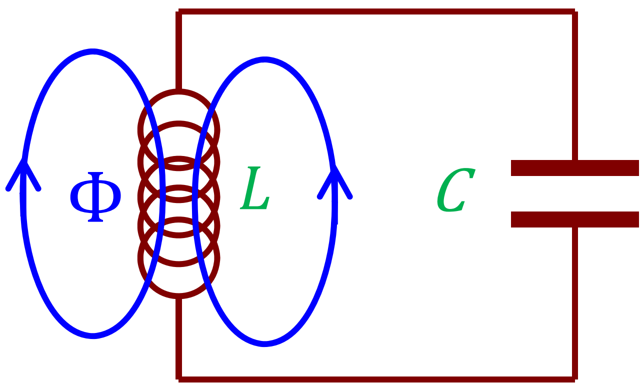
- Ions, Rydberg atoms, BECs
- Semiconductor quantum dots
- Atomic defects (NV, P in Si)
- Superconducting circuits

Superconducting circuits in the traditional semiconductor technology roadmap

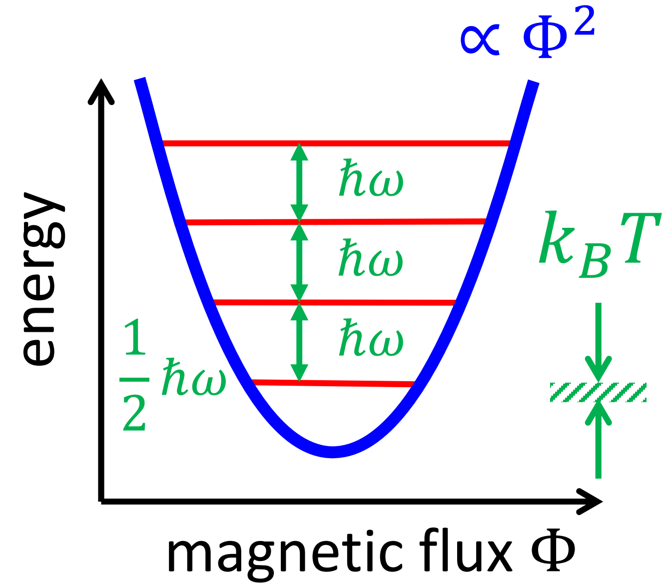
- Materials
- Device design
- Circuit design
- Interconnects
- Board level integration
- Systems integration
- Packaging

➢ Current focus of most research
➢ Tightly interconnected for engineered quantum devices/circuits

Superconducting qubits



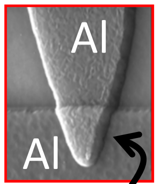
$$\omega = \frac{1}{\sqrt{LC}}$$

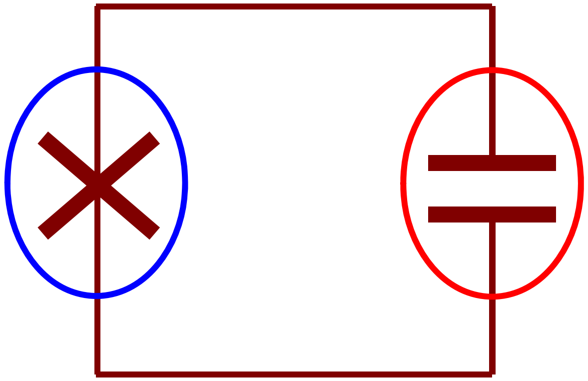


Microwave frequency circuits: $\omega/2\pi \sim 5 - 10$ GHz

- Operate at 25 mK: $k_B T \ll \hbar\omega \Rightarrow$ quantum ground state
- Need anharmonicity to enable quantum control

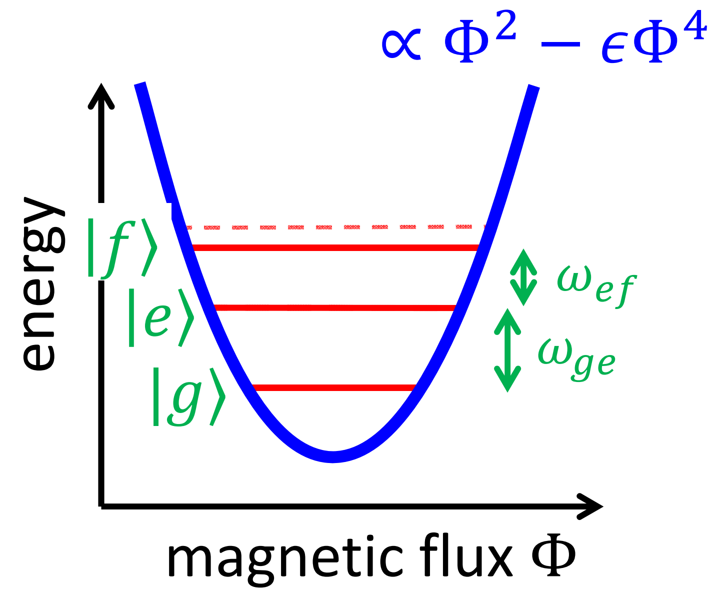
Superconducting qubits





Josephson junction:
A very nonlinear inductor

Capacitor is critical to qubit performance



- Qubit levels $|g\rangle$ and $|e\rangle$
- Qubit frequency $\omega_{ge} \sim 4 - 6$ GHz
- Anharmonicity at single photon level: $\omega_{ef} \approx 0.95\,\omega_{ge}$
- Can tune ω_{ge} & ω_{ef} by changing flux through qubit
- Qubit T_1 is determined by loss mechanisms in capacitor

Measurement:

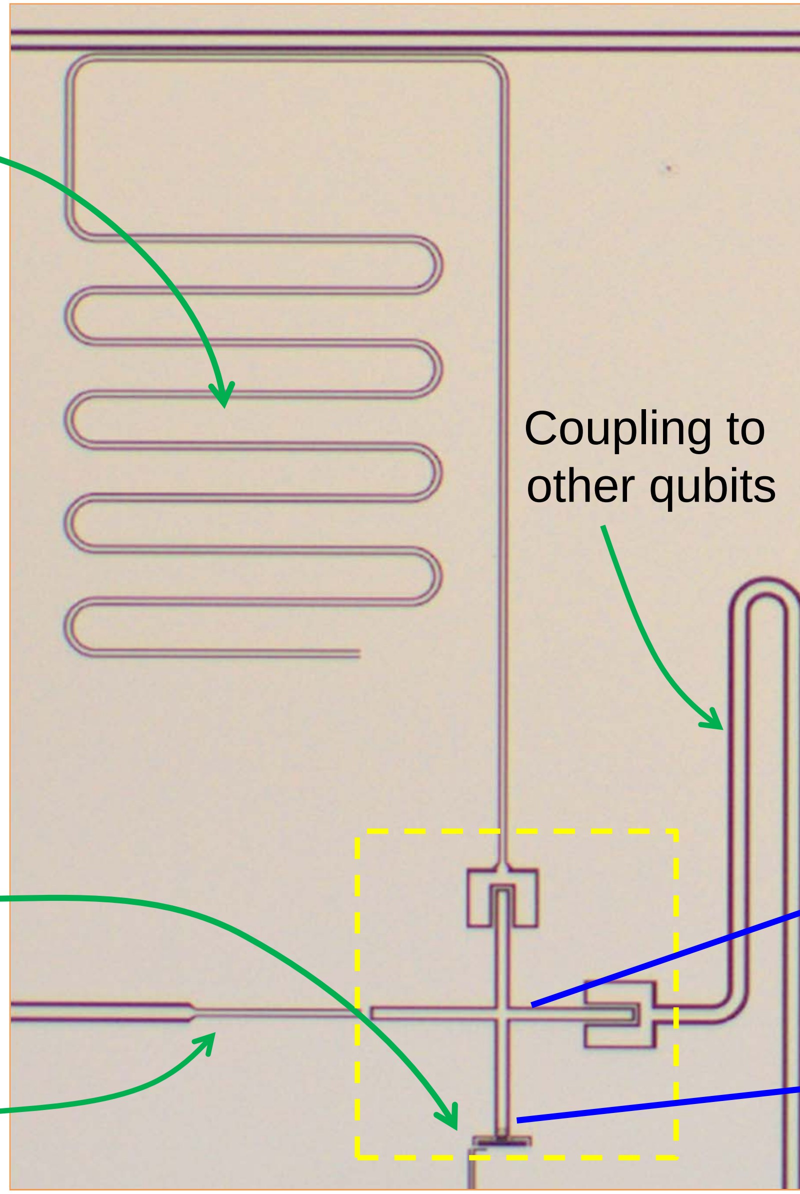
- Dispersive resonator readout
- Measure change in phase of few-photon excitation in readout resonator
- Projective & accurate

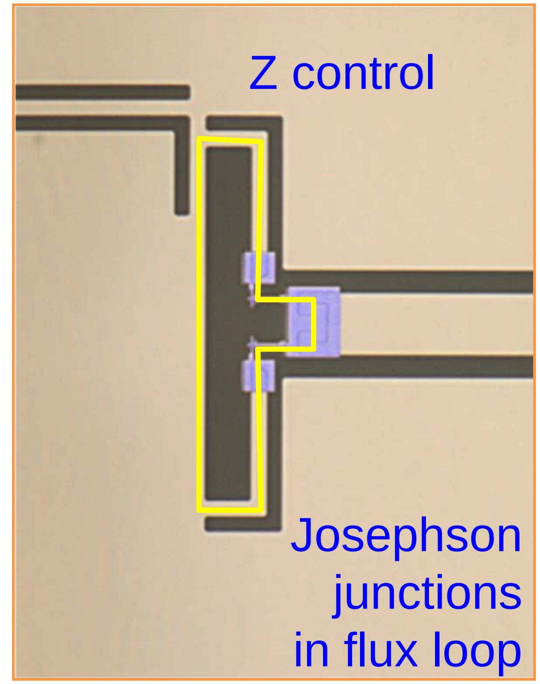
Z rotations:

- Flux tuning varies L
- Changes ω_{ge}

X and Y rotations:

- Microwaves at ω_{ge}

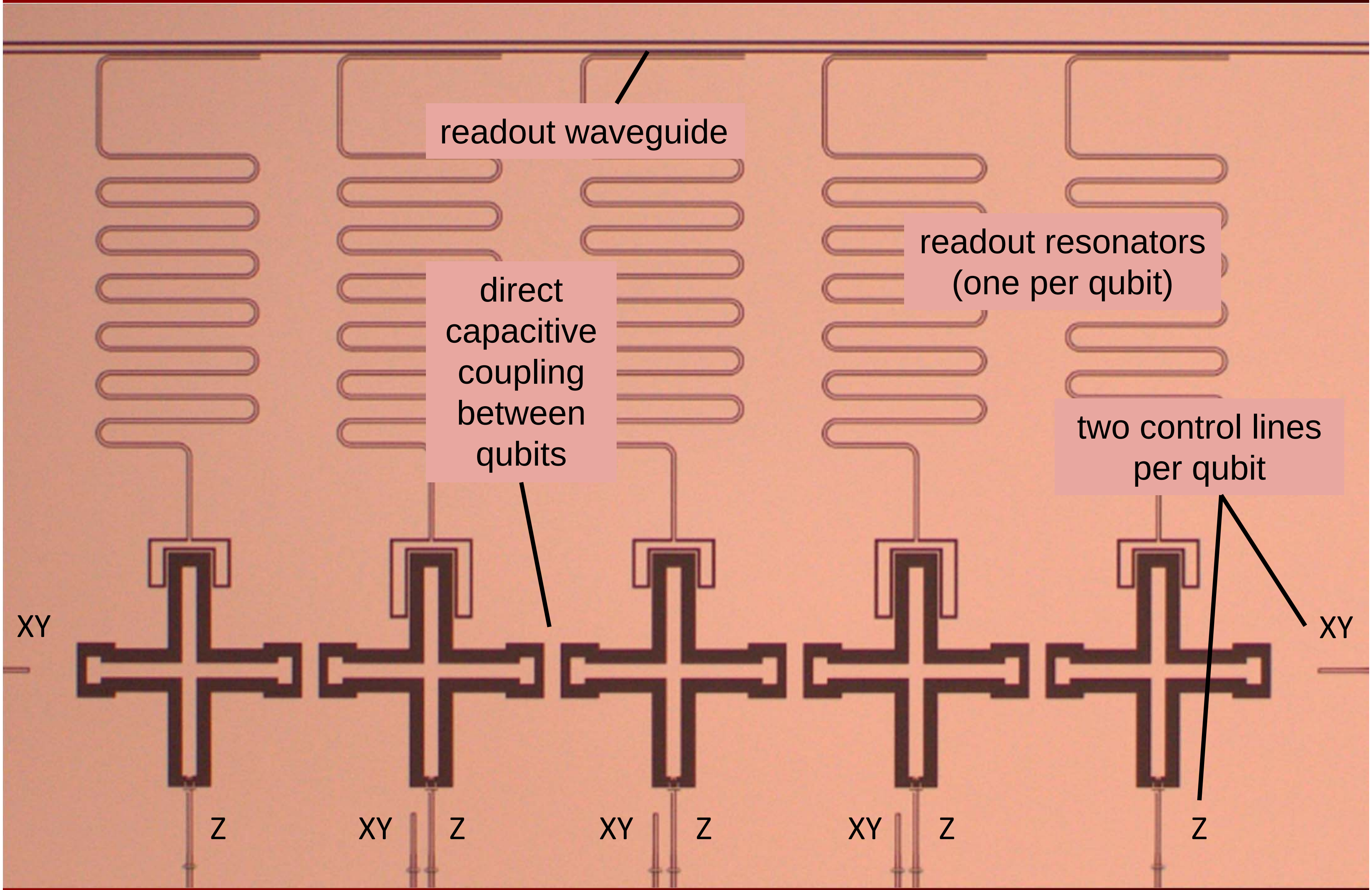


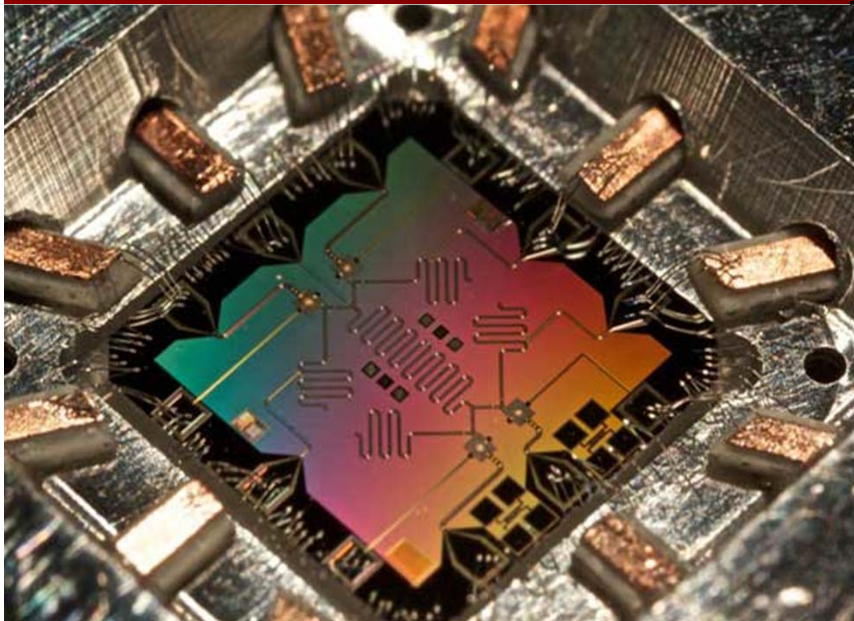


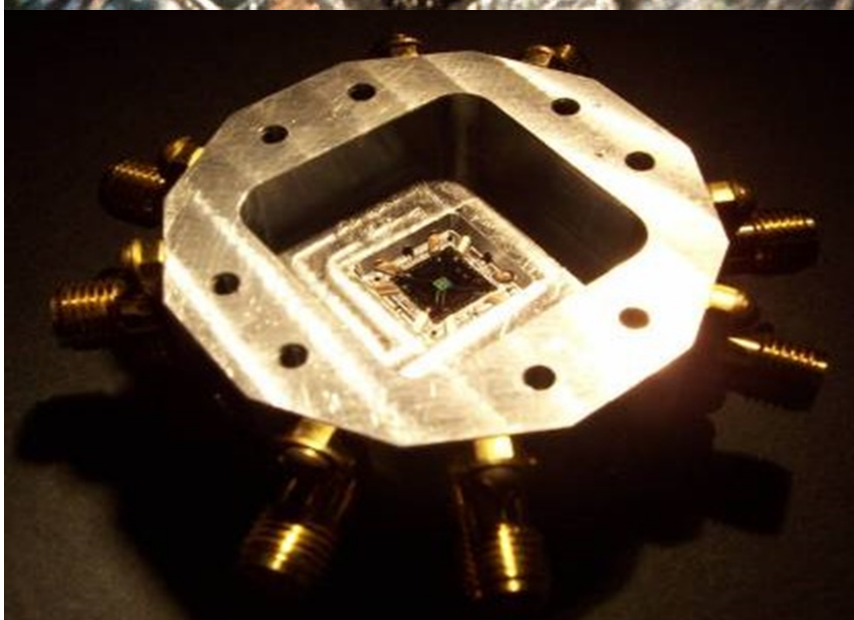
Transmon qubit (UCSB variant)

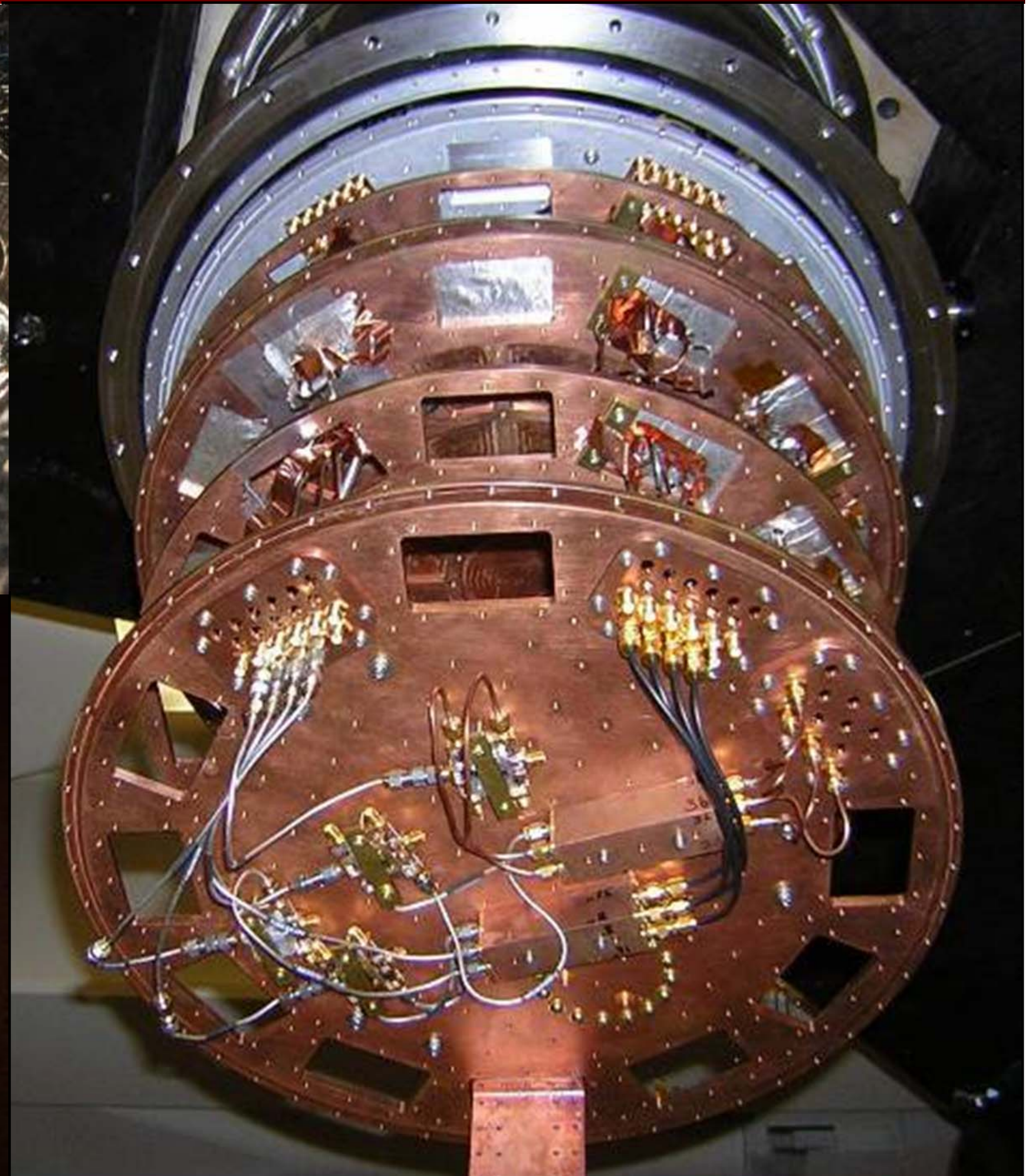
Capacitance C

Josephson junctions (inductance L)


readout waveguide
readout resonators
(one per qubit)
direct
capacitive
coupling
between
qubits
two control lines
per qubit
XY
XY
Z
XY
Z
XY
Z
XY
Z
Z







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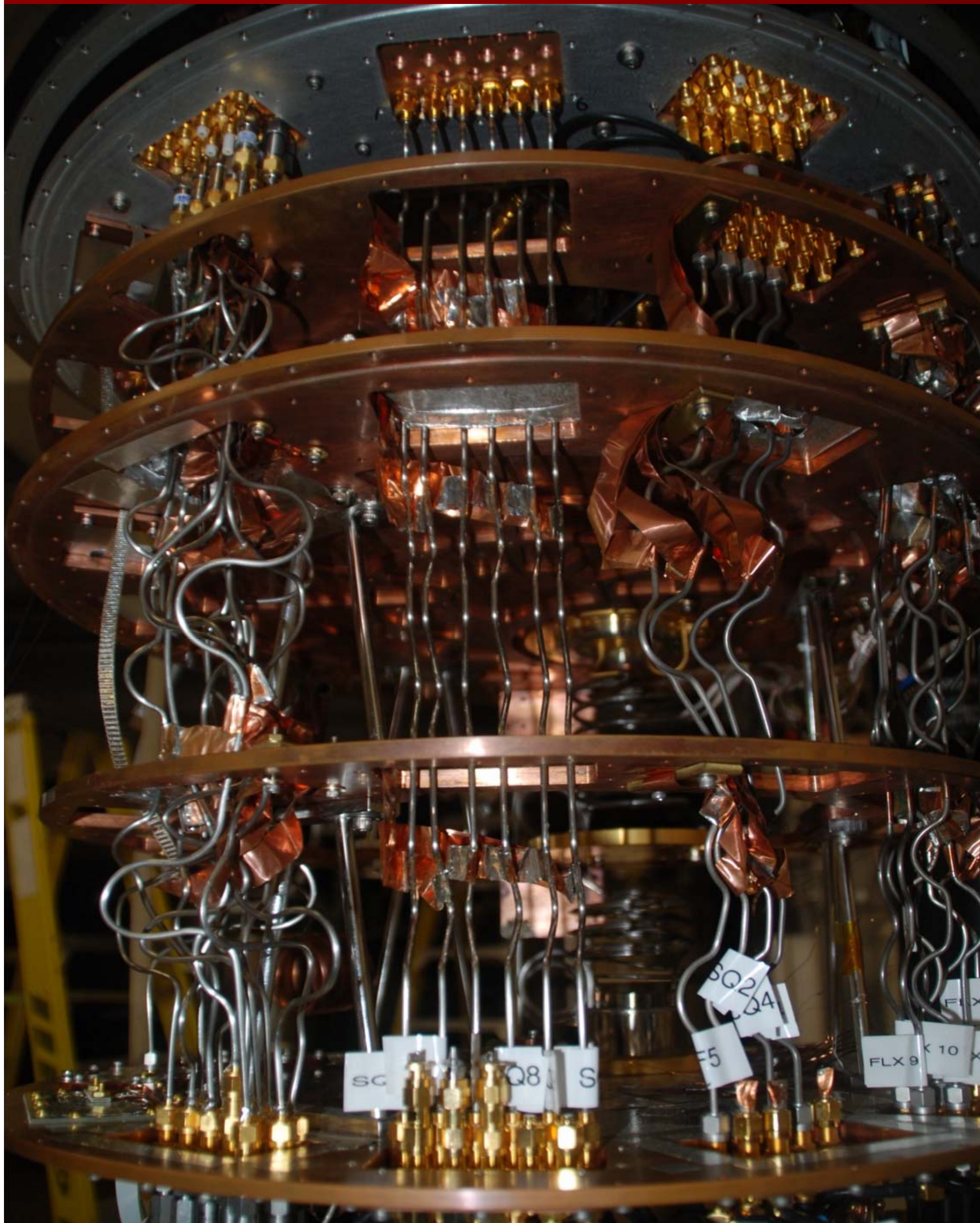

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High fidelity quantum gates

- Complete set of single qubit gates needed to execute an arbitrary quantum algorithm
- All single qubit gates operate with fidelity > 99.9% (randomized benchmarking)
- Controlled Z gate (equivalent to CNOT):
  - 40 ns execution time
  - 99.5% fidelity
- State preparation and measurement fidelity ~ 90%

How do we measure these low error rates?

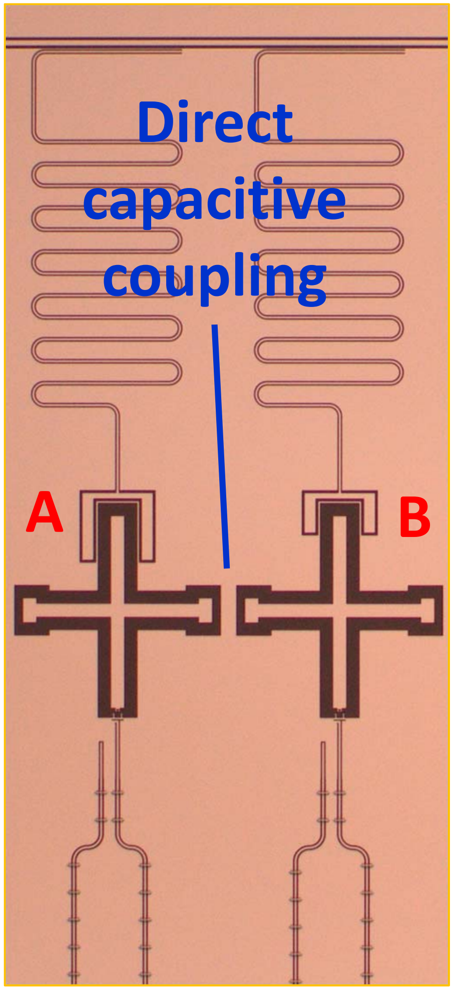
Gate	Fidelity ($\pm$0.03)
X	99.92
Y	99.92
X/2	99.93
Y/2	99.95
-X	99.92
-Y	99.91
-X/2	99.93
-Y/2	99.95
H	99.91
I	99.95
S (Z/2)	99.92
T ($e^{i\pi/4}$)	No RB method – not a Clifford

Controlled Z (CZ) gate:

$|e_A e_B\rangle \Rightarrow -|e_A e_B\rangle$

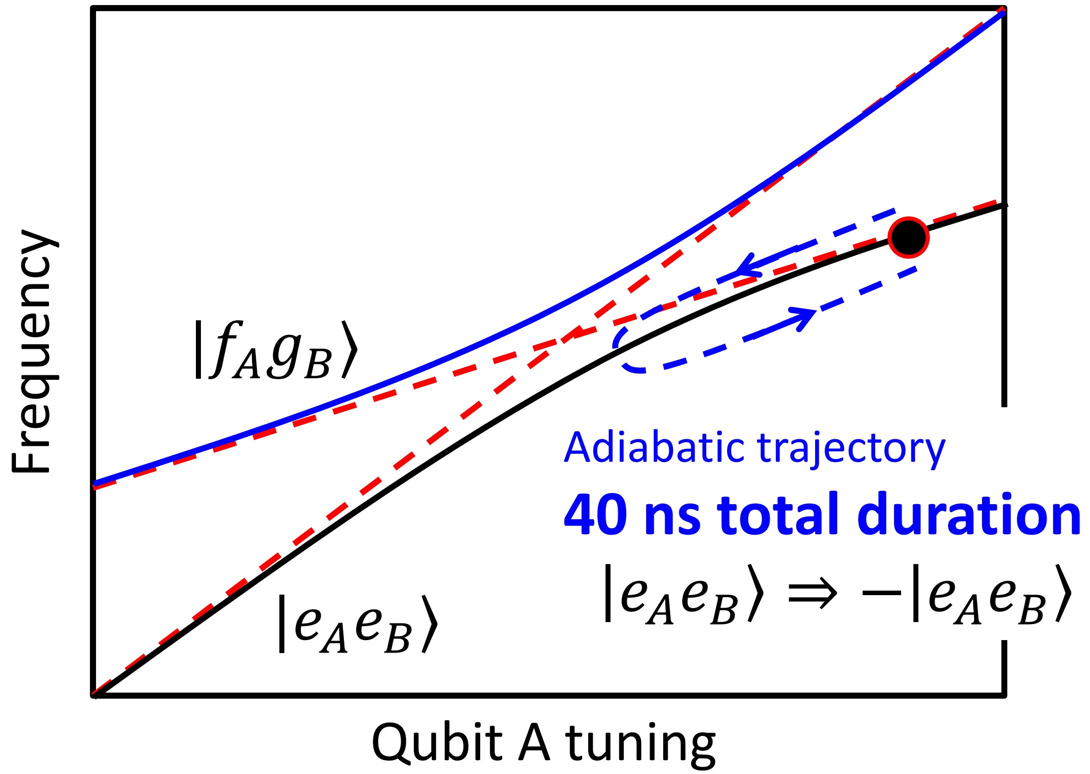
Other states left unchanged

$$U = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$



XY Z XY Z

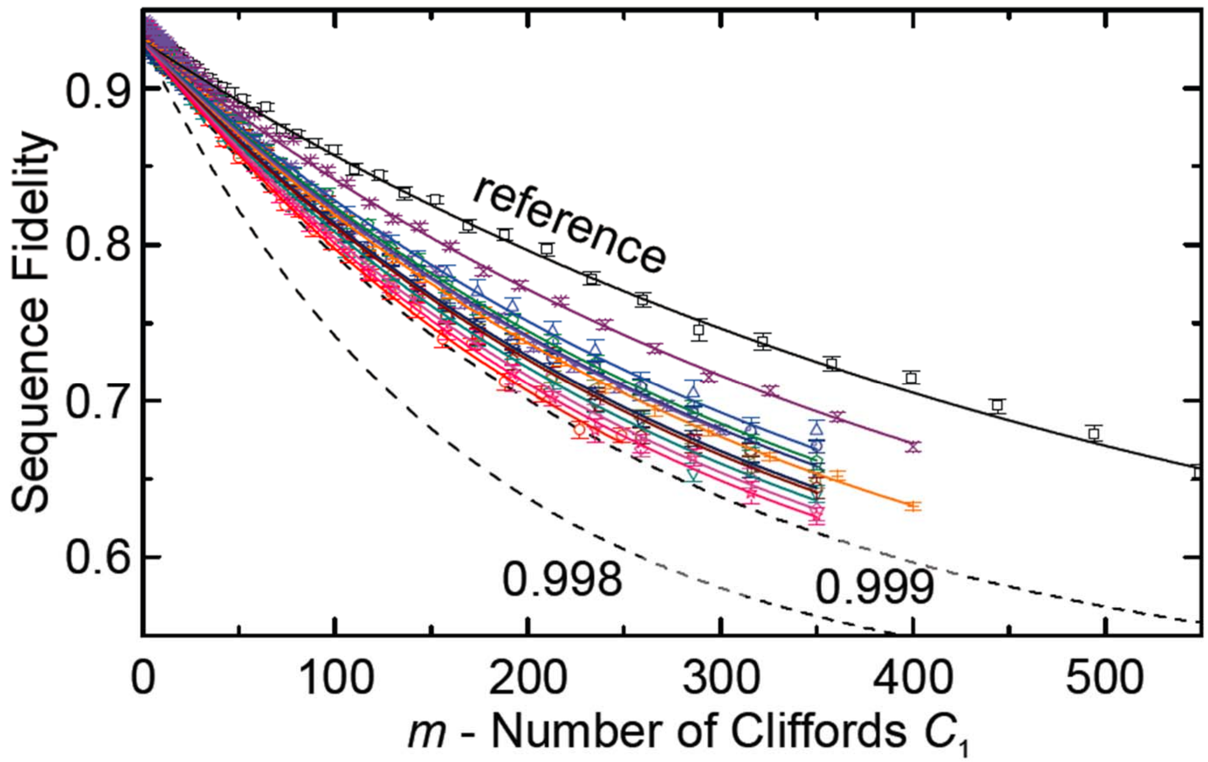
Avoided crossing $|e_A e_B\rangle - |f_A g_B\rangle$:

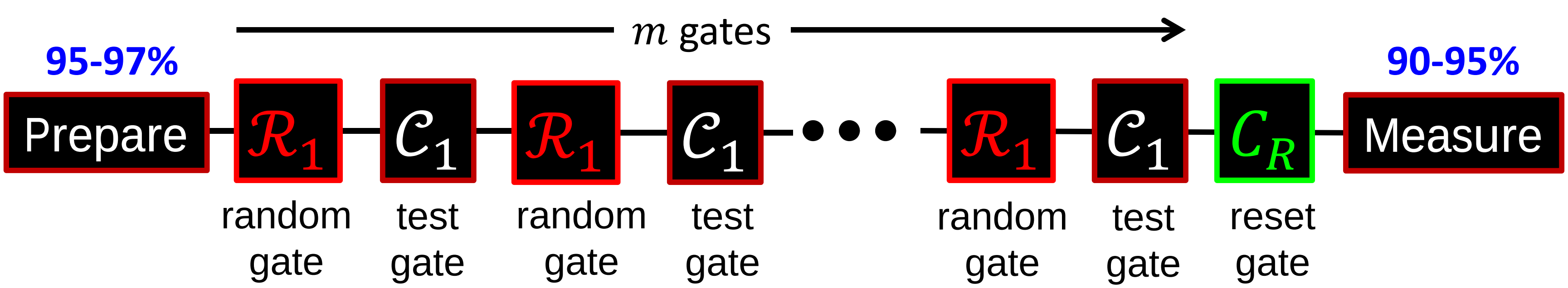


Benchmarking

- Imperfect state preparation
- Imperfect state measurement
- Individual gate errors small compared to SPAM

➢ Randomized benchmarking





High fidelity quantum gates

- Complete set of single qubit gates needed to execute an arbitrary quantum algorithm
- All single qubit gates operate with fidelity > 99.9% (randomized benchmarking)
- Controlled Z gate (equivalent to CNOT):

  40 ns execution time
  99.5% fidelity
- State preparation and measurement fidelity ~ 90%
- Measurement now 98% in 150 ns
- Dominant errors due to T_1 decay

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X	99.92
Y	99.92
X/2	99.93
Y/2	99.95
-X	99.92
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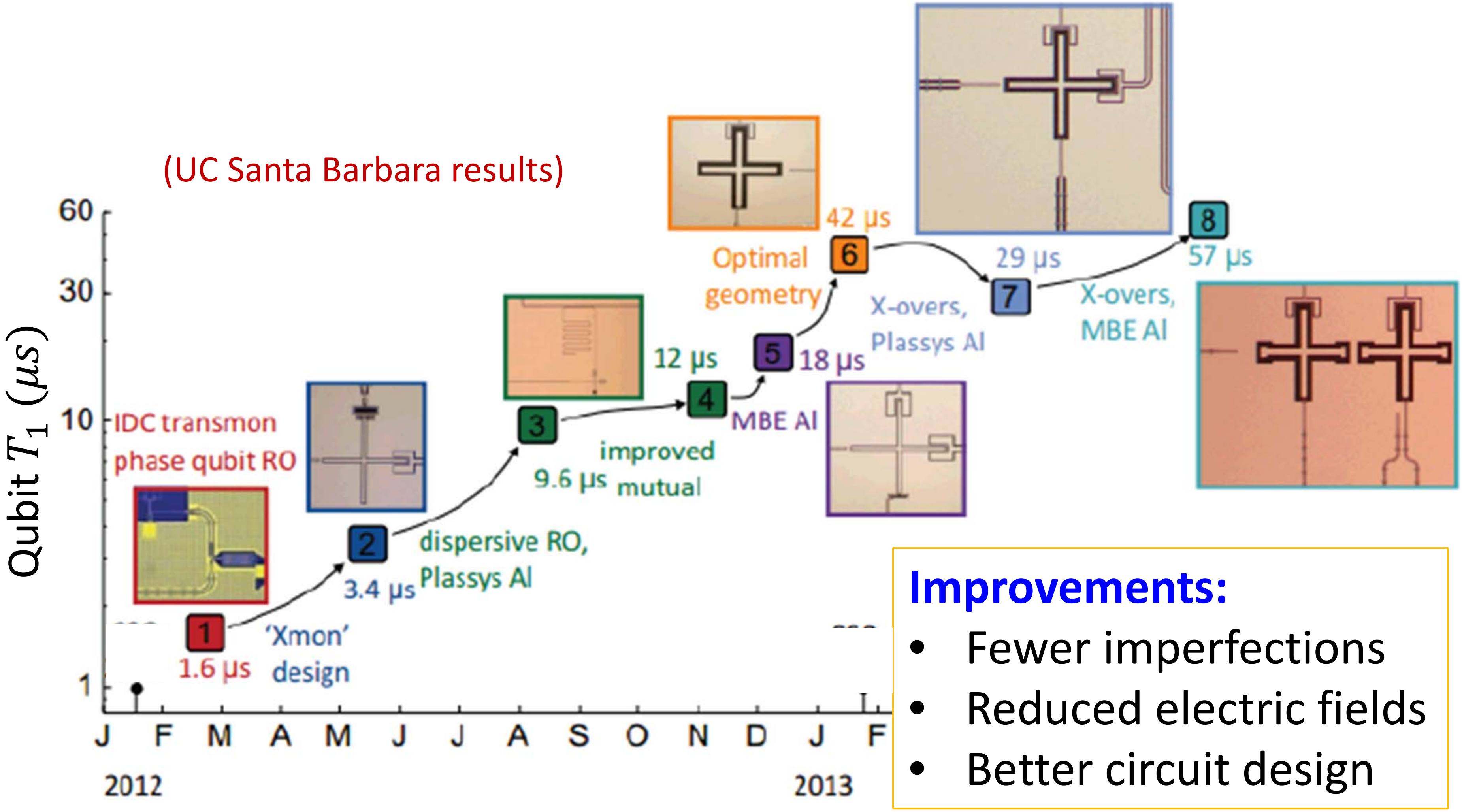
Progress in qubit T_1

(UC Santa Barbara results)

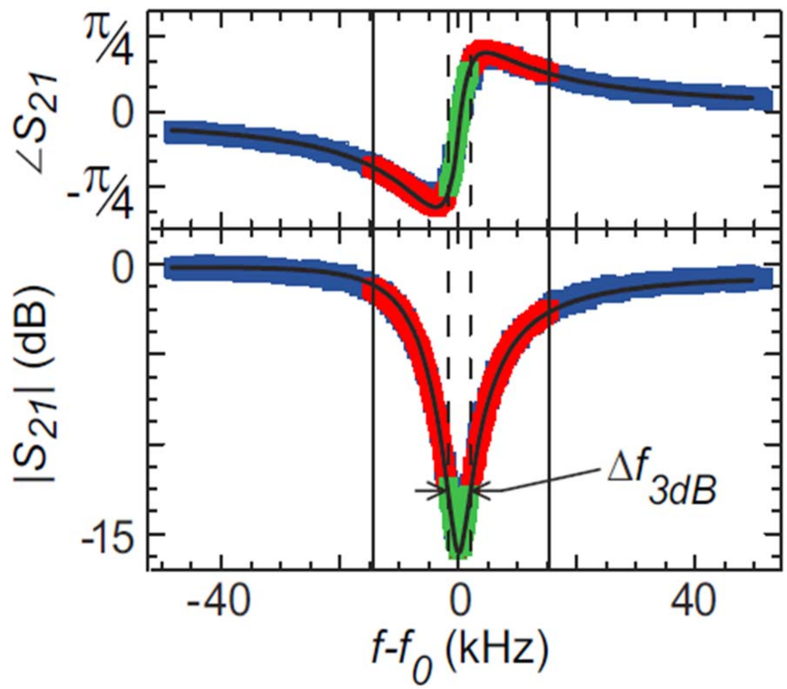


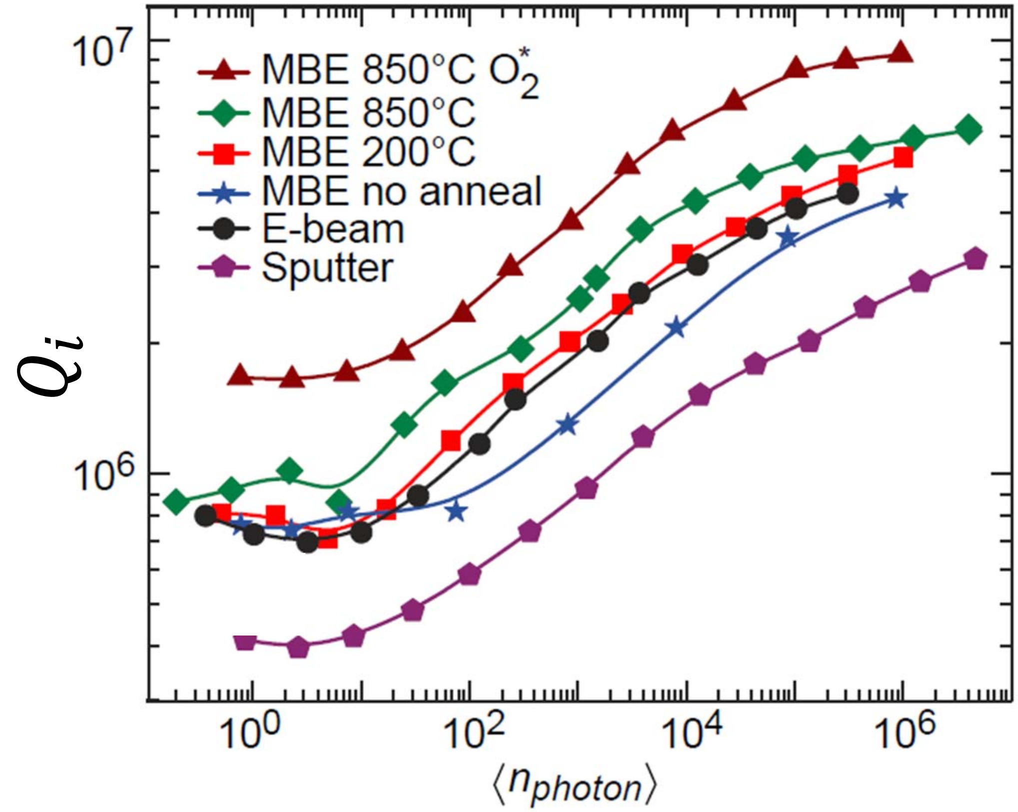
Improvements:

- Fewer imperfections
- Reduced electric fields
- Better circuit design

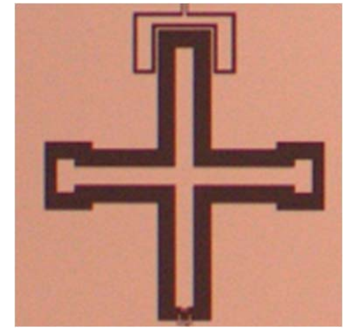
Aluminum resonators on sapphire

- MBE grown Al on annealed sapphire gives best performance
- Intrinsic Q around 2×10^6 at low power
- Film quality & substrate properties critical

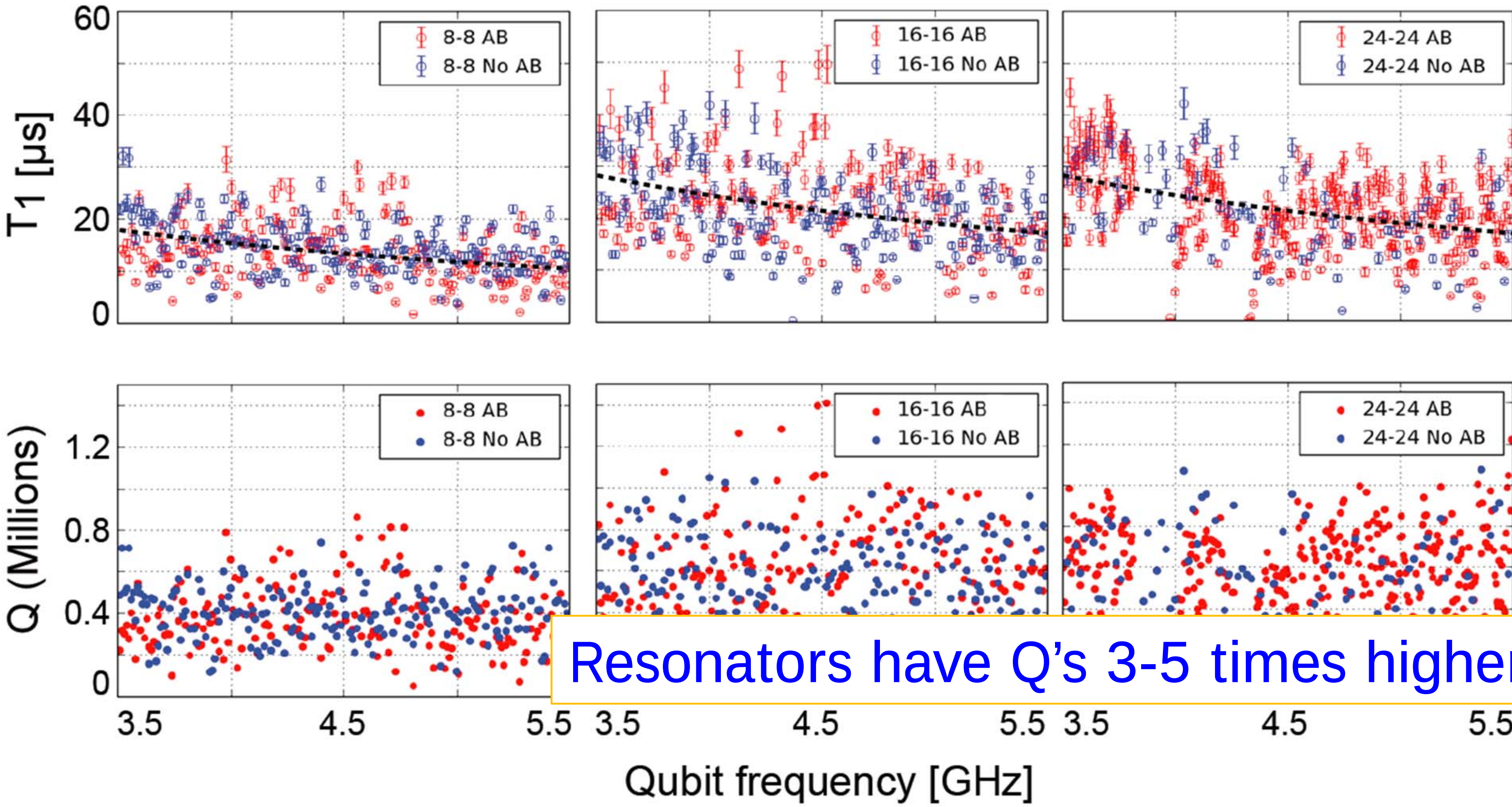




Superconducting qubits on sapphire

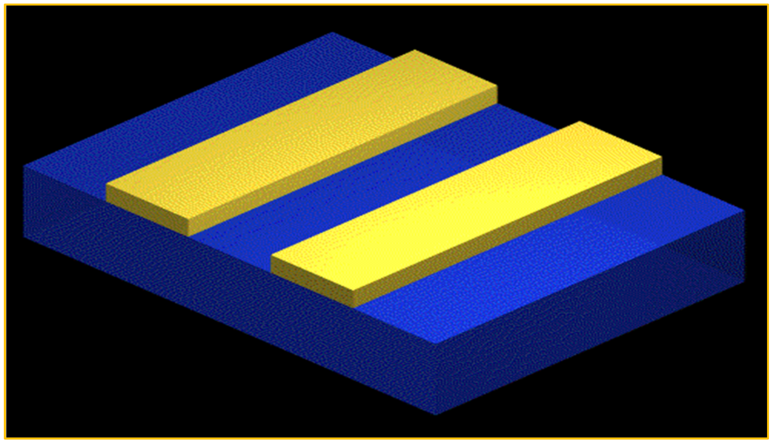


- T_1 (Q) vary strongly with frequency (repeatable)
- T_1 (Q) consistent with two-level states

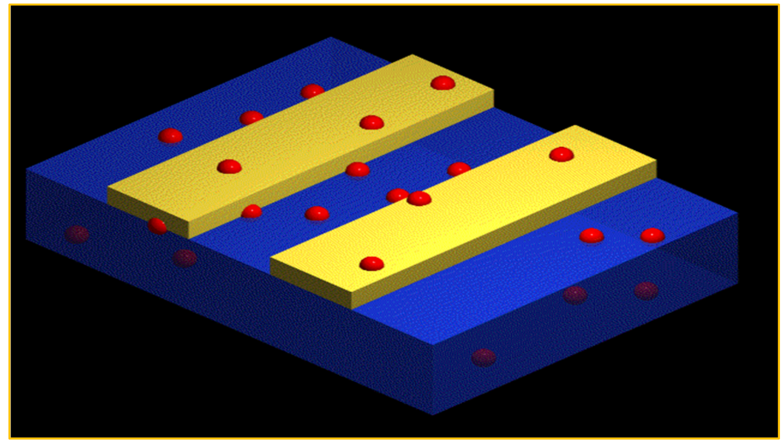


Resonators have Q's 3-5 times higher

Defects: Two-level states at GHz frequencies



SEM inspection



Microwave measurement

- GHz-frequency two-level states become active at low temperatures
- Circuits primarily sensitive to electrically active TLS
- Reduce qubit T_1 and resonator Q
- Participation strongest for aligned dipoles in strong electric fields

What are these TLS?

Where do they come from?

How do we minimize/eliminate them?

Limiting effects due to materials

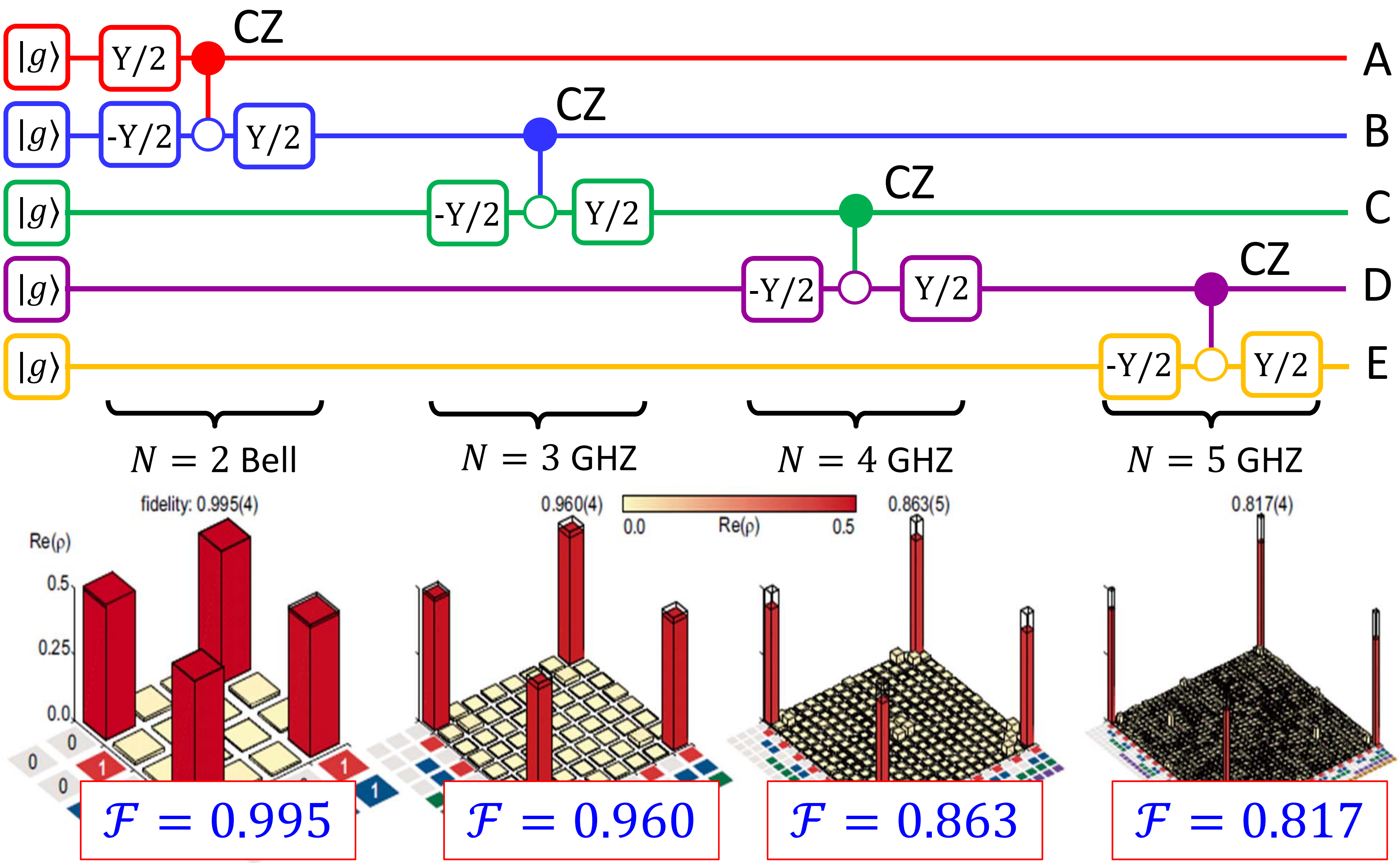
Two-level states

- Most important contributor to qubit T_1
- Resonators (single step fabrication) have 3-5 times fewer TLS
- Origin unknown
- Become active at low temperatures
- Vary with substrate and substrate preparation

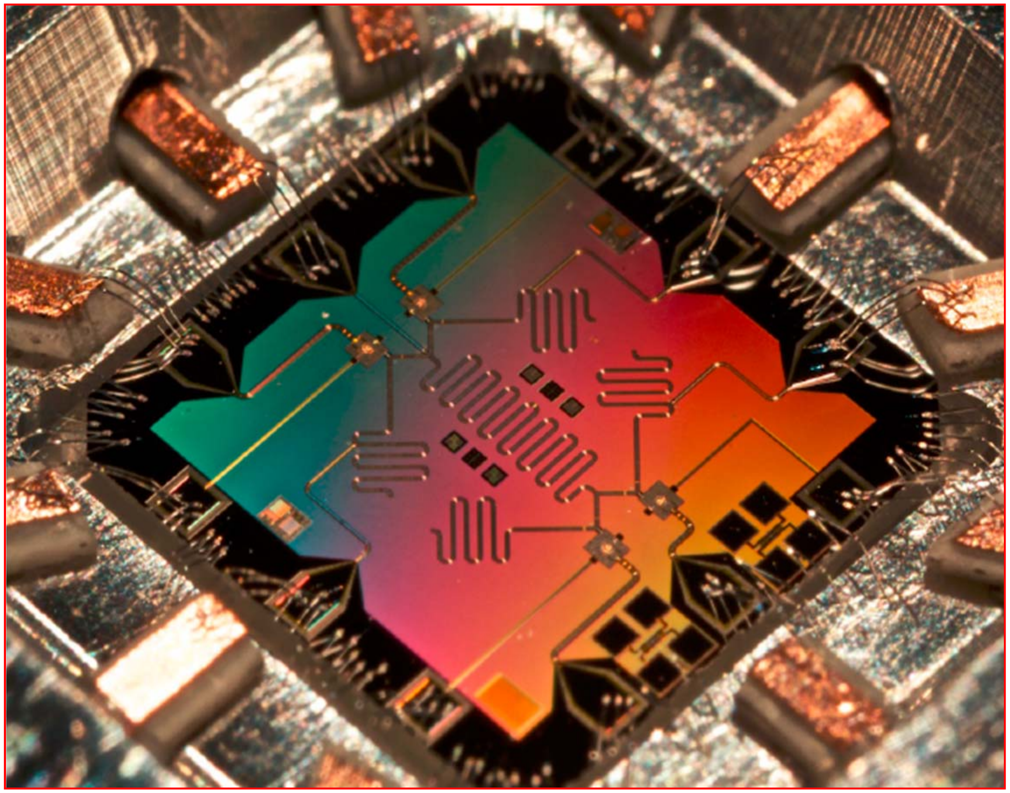
Flux noise

- Important limiting effect on qubit T_ϕ
- No apparent effect on resonators
- Origin unknown
- Investigated since 1980s in SQUIDs
- Surface density of correlated magnetic dipoles ($\sim 10^{13}/cm^2$)?

Programming a 5 qubit GHZ state $|ggggg\rangle + |eeeee\rangle$



Superconducting implementation of Shor's algorithm

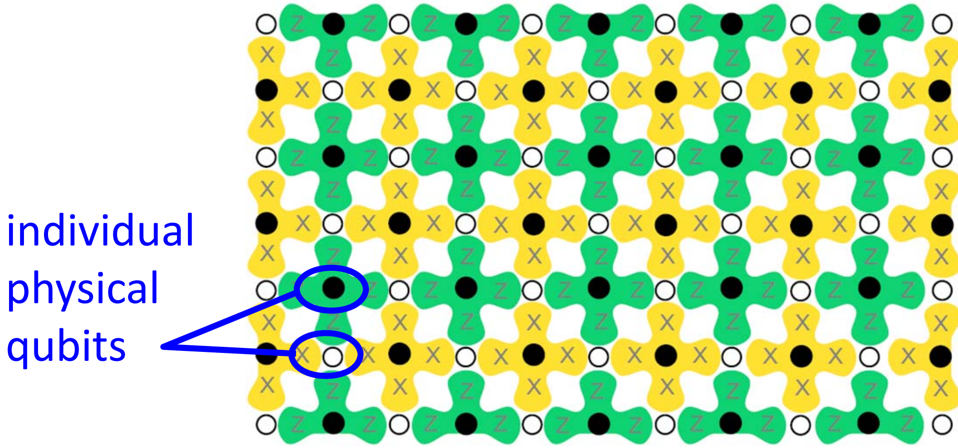


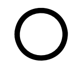
- Quantum processor with 4 qubits and 5 microwave resonators
- von Neumann architecture to factor 15 using Shor's algorithm
- Achieves correct answer 48% of attempts (best possible 50%)

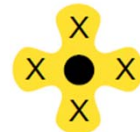
Lucero et al. *Nature Physics* (2012)

Building perfection from imperfection: The surface code

Square array of physical qubits
Only nearest-neighbor coupling



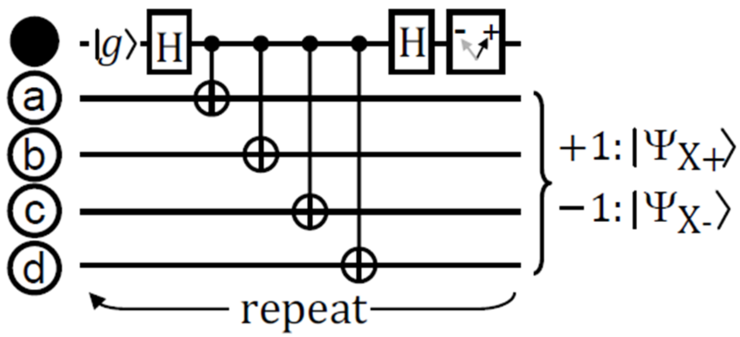

Data qubit:
Stores computational state $|\psi\rangle$



Measure-X qubit:
Stabilizes data qubits $\hat{X}\hat{X}\hat{X}\hat{X}$

Measure-Z qubit:
Stabilizes data qubits $\hat{Z}\hat{Z}\hat{Z}\hat{Z}$

Measure-X qubit cycle



Result: $\hat{X}\hat{X}\hat{X}\hat{X}$ eigenstate

Surface code $\hat{X}$ stabilizer cycle:

- Qubit state reset
- Hadamard gate
- Multiple two-qubit CNOTs
- Projective measurement

Analogous $\hat{Z}$ stabilizer

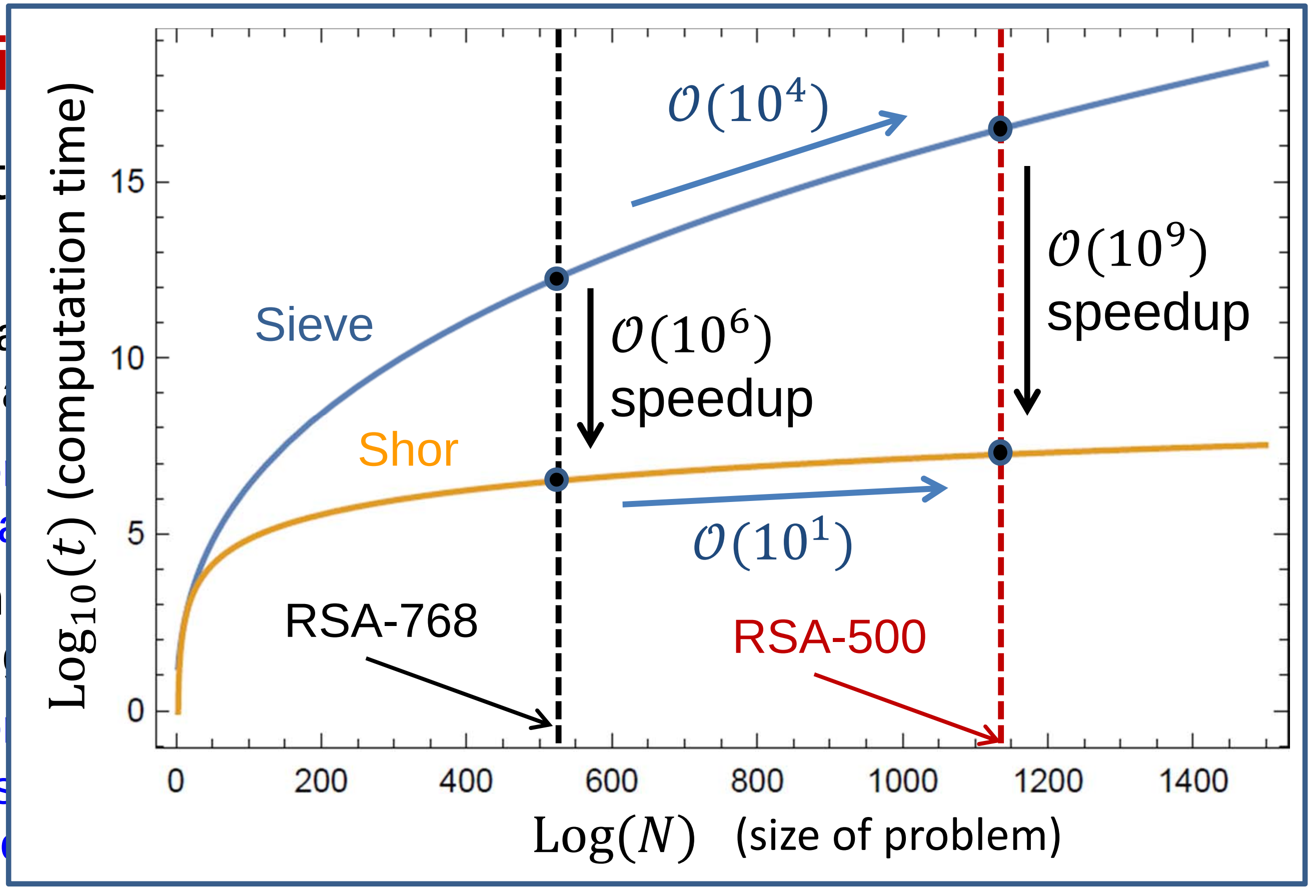
Need overall fidelity > 99.5%

Quantum algori

- Quantum ent
  algorithms
  - Deutsch-Jozsa
    N element bin

    Classical algo
    Deutsch-Jozsa
  - Grover: Given
    values, find $\vec{x}$

    Classical algo
    probability ans
    Makes brute-f



  - Shor: Find the prime factors of the integer N.

    Classical sieve algorithm: $\mathcal{O}(\exp(1.9(\log N)^{1/3}(\log\log N)^{2/3}\,))$ steps.
    Quantum Shor algorithm: $\mathcal{O}((\log N)^2(\log\log N)(\log\log\log N))$ steps
    Answer is probabilistic; assumes unlimited resources

Building perfection from imperfection: The surface code

- Assume error rate 1/10th threshold (99.95% fidelity)

Logical memory qubit from array of physical qubits

- × 1,000 smaller error rate: ~600 physical qubits
- × 1,000,000 smaller error rate: ~2,000 physical qubits
- × 1,000,000,000 smaller rate: ~4,500 physical qubits

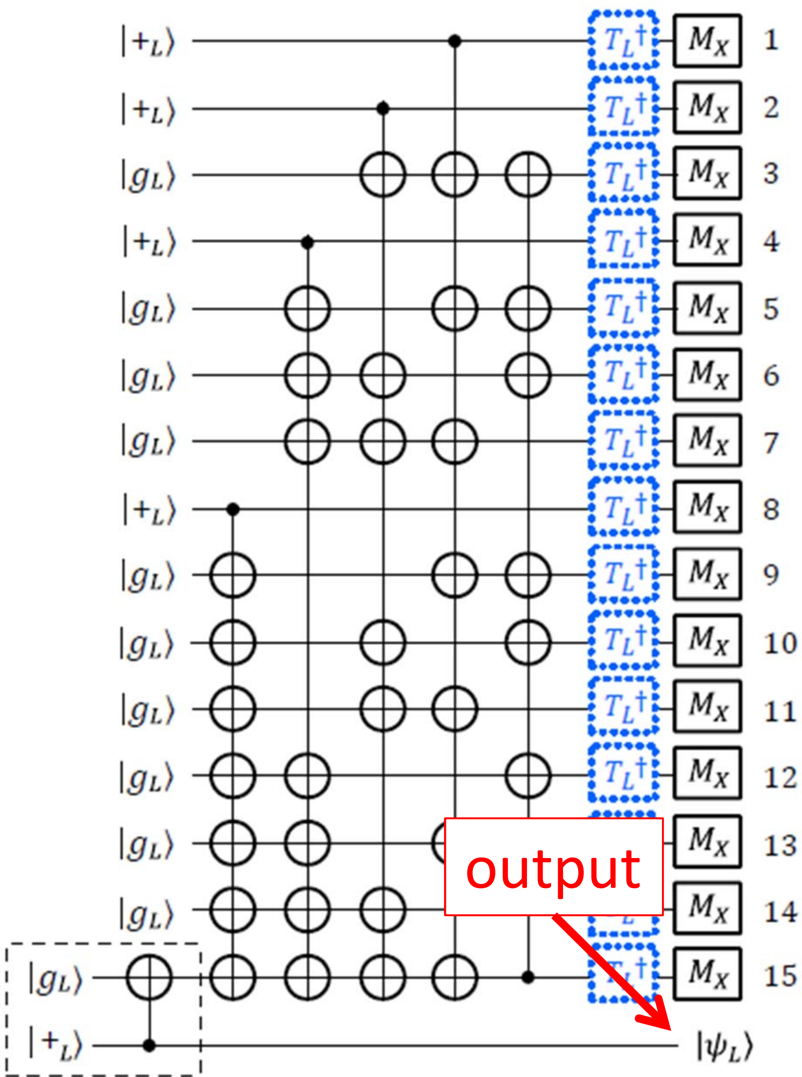
Circuit to demonstrate topological CNOT:

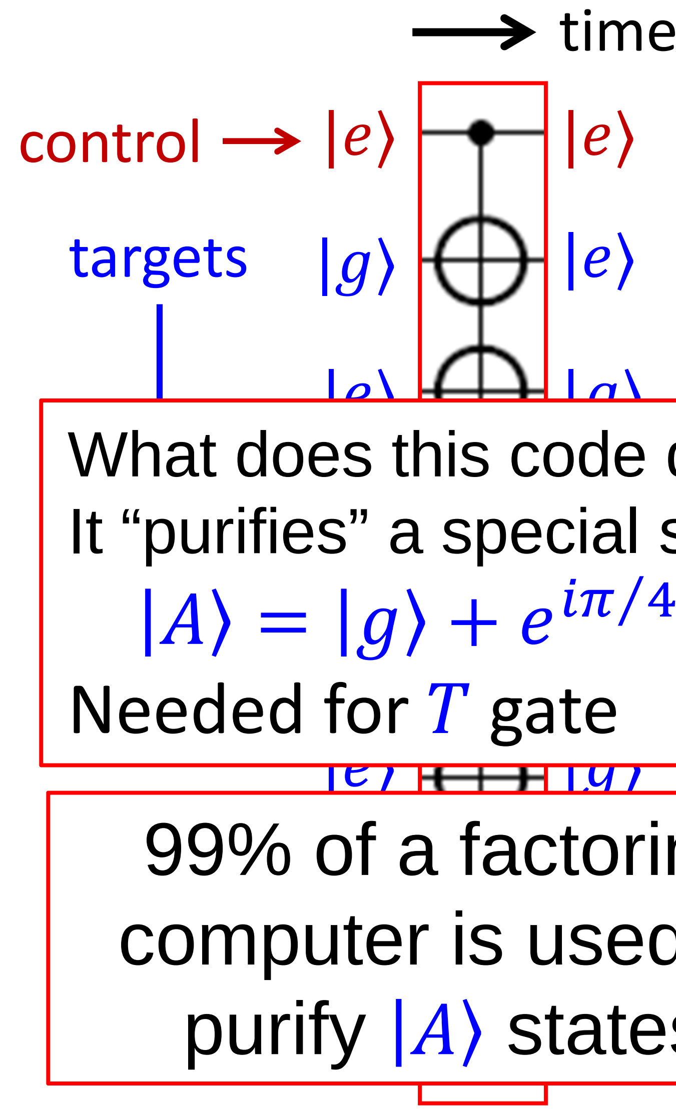
- With × 1,000 smaller error rate: ~1,800 physical qubits

Prime factoring with Shor's algorithm:

- Factor a 15 bit number (10^5): ~40,000,000 qubits
- Factor a 2000 bit number (10^{600}): ~1,000,000,000 qubits

Quantum computer circuit





What does this code do?
It "purifies" a special state:

$$|A\rangle = |g\rangle + e^{i\pi/4}|e\rangle$$

Needed for T gate

99% of a factoring computer is used to purify $|A\rangle$ states

"Gate-based" quantum computation: Challenges

- Scale-up challenge: 1D to 2D qubit circuits
- Demonstrate full quantum error correction
  Fix X, Y, Z errors caused by environment
- Demonstrate logical qubit
  Logical qubit state lifetime longer than physical qubit lifetime
- Demonstrate "large" logical qubit entanglement
- Demonstrate protected logical operations
  Logical qubit manipulations with error protection
- Scale-up challenge: 2D to 3D wiring interconnects
- Quantum simulations: Useful & interesting problems

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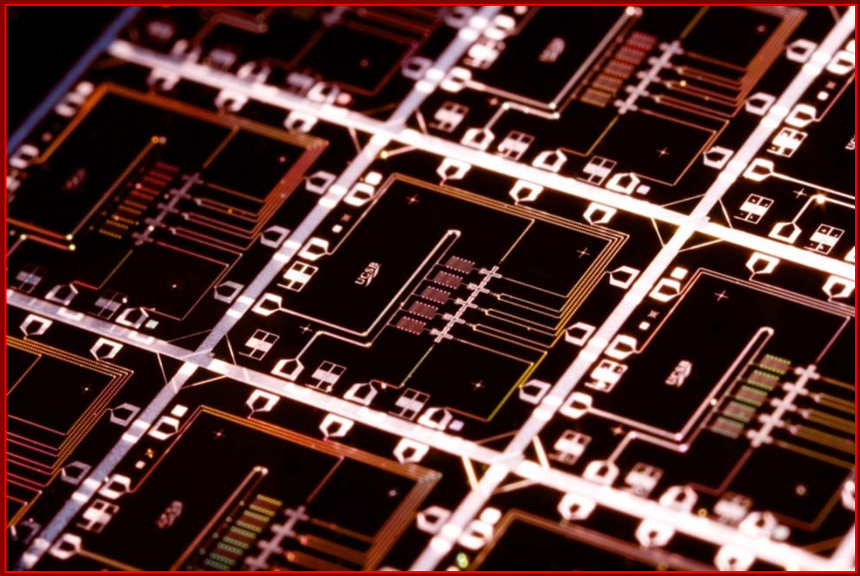

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