Quantum Computing Hardware & Superconducting Circuits

Olivia Lanes, PhD

North American Lead, IBM Quantum + Qiskit Community

Qiskit | Global Summer School 2023

Big Picture + Game Plan

(1) What is a REAL qubit anyway

(2) Atoms & artificial atoms

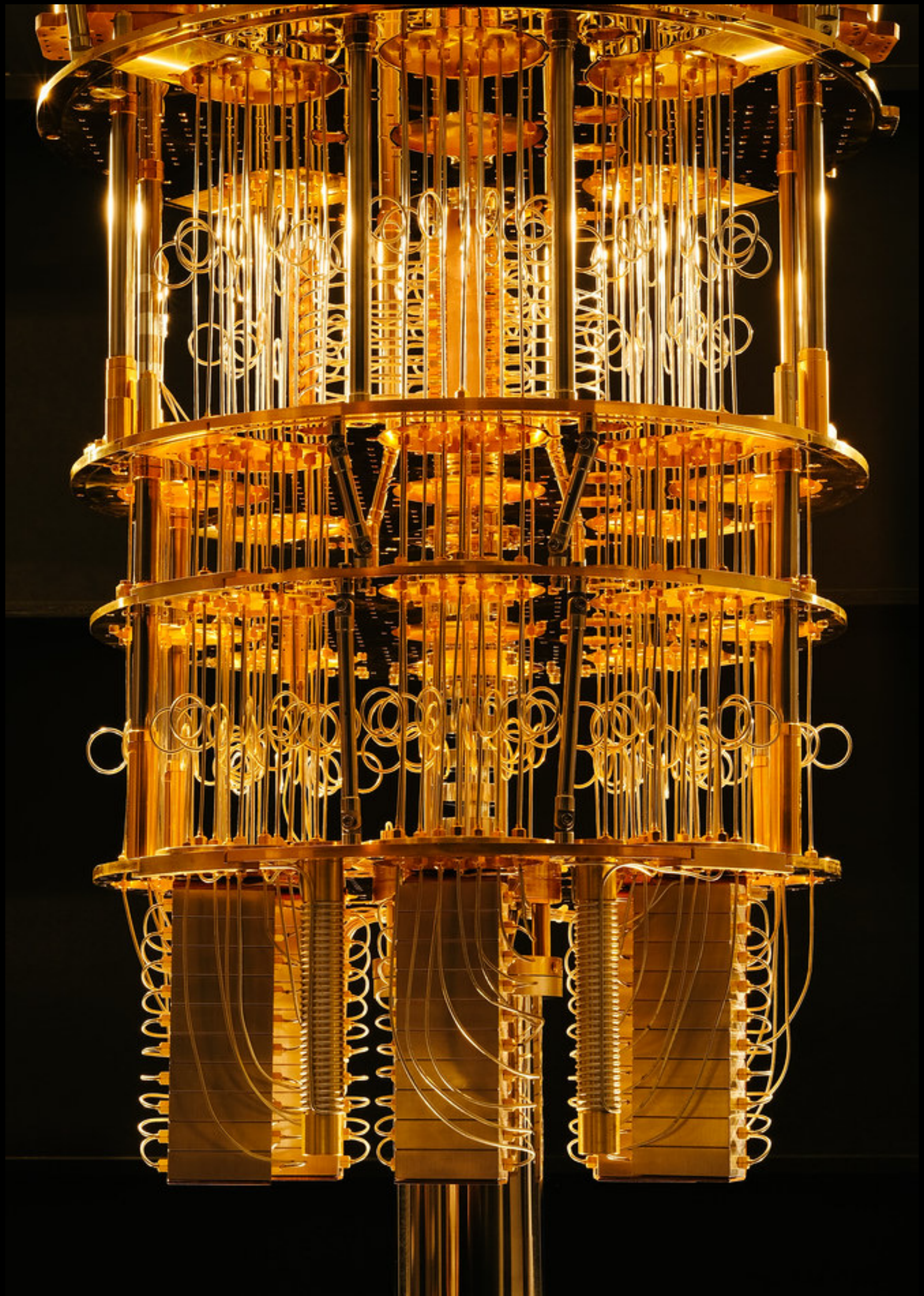
(3) DiVincenzo Criteria

(4) Classical circuits

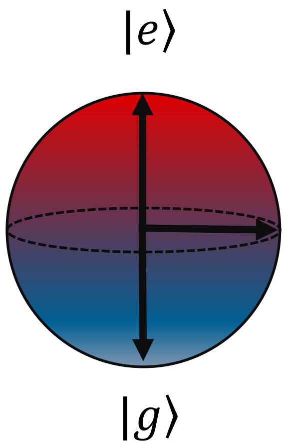
(5) Quantum Circuits and the Josephson Junction

(6) How to control & measure a transmon

Motivation



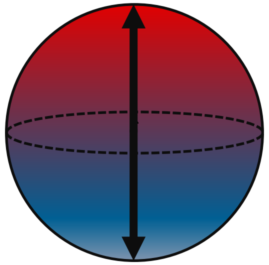
How do we build a quantum computer?

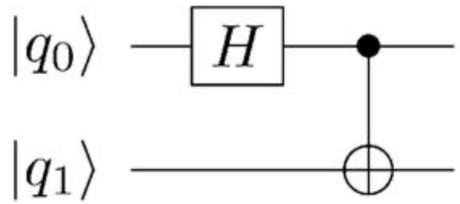


Well-behaved quantum systems

...that we can initialize into a known state

...with relatively-long coherence times





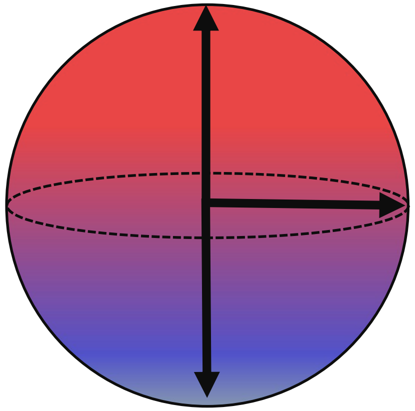
...and a universal set of quantum gates

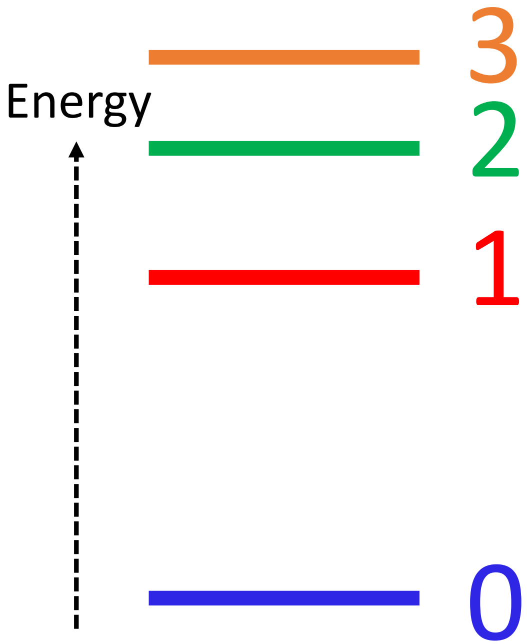
And qubit-specific measurement capability

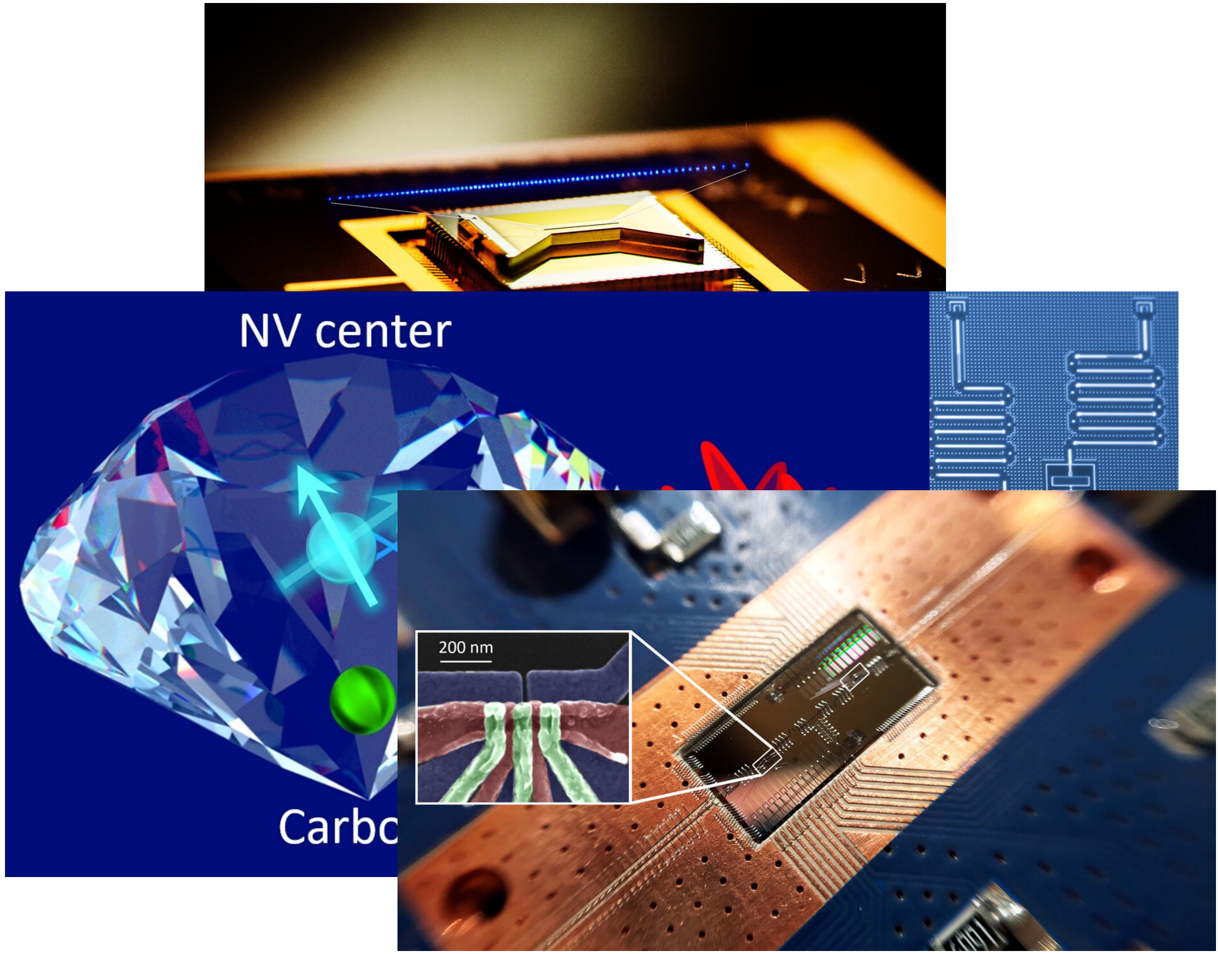
Qiskit | Global Summer School 2023

D. DiVincenzo, arXiv (2020)

What is a real qubit?







<u>Toy Model</u>

<u>Real Life</u>

Images from IonQ, IBM, Phys.org

Qubit Flavors

Superconducting loops
A resistance-free current oscillates back and forth around a circuit loop. An injected microwave signal excites the current into super-position states.

Trapped ions
Electrically charged atoms, or ions, have quantum energies that depend on the location of electrons. Tuned lasers cool and trap the ions, and put them in superposition states.

Silicon quantum dots
These "artificial atoms" are made by adding an electron to a small piece of pure silicon. Microwaves control the electron's quantum state.

Topological qubits
Quasiparticles can be seen in the behavior of electrons channeled through semi-conductor structures. Their braided paths can encode quantum information.

Diamond vacancies
A nitrogen atom and a vacancy add an electron to a diamond lattice. Its quantum spin state, along with those of nearby carbon nuclei, can be controlled with light.

Fig. Source: Michel Kurek, Feb 2021.

Quantum Origins

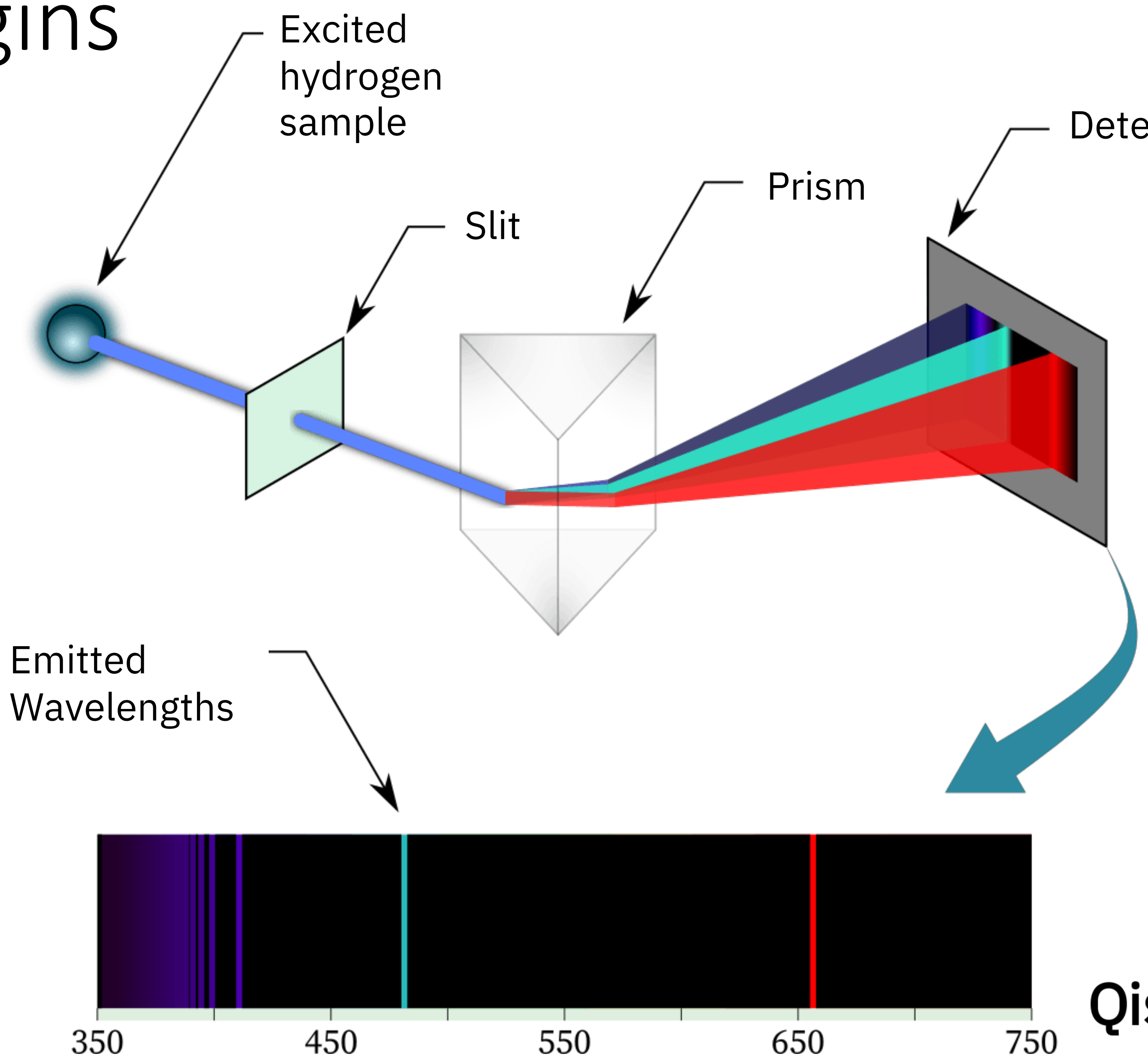


Image from chemistrygod.com

Spectral lines

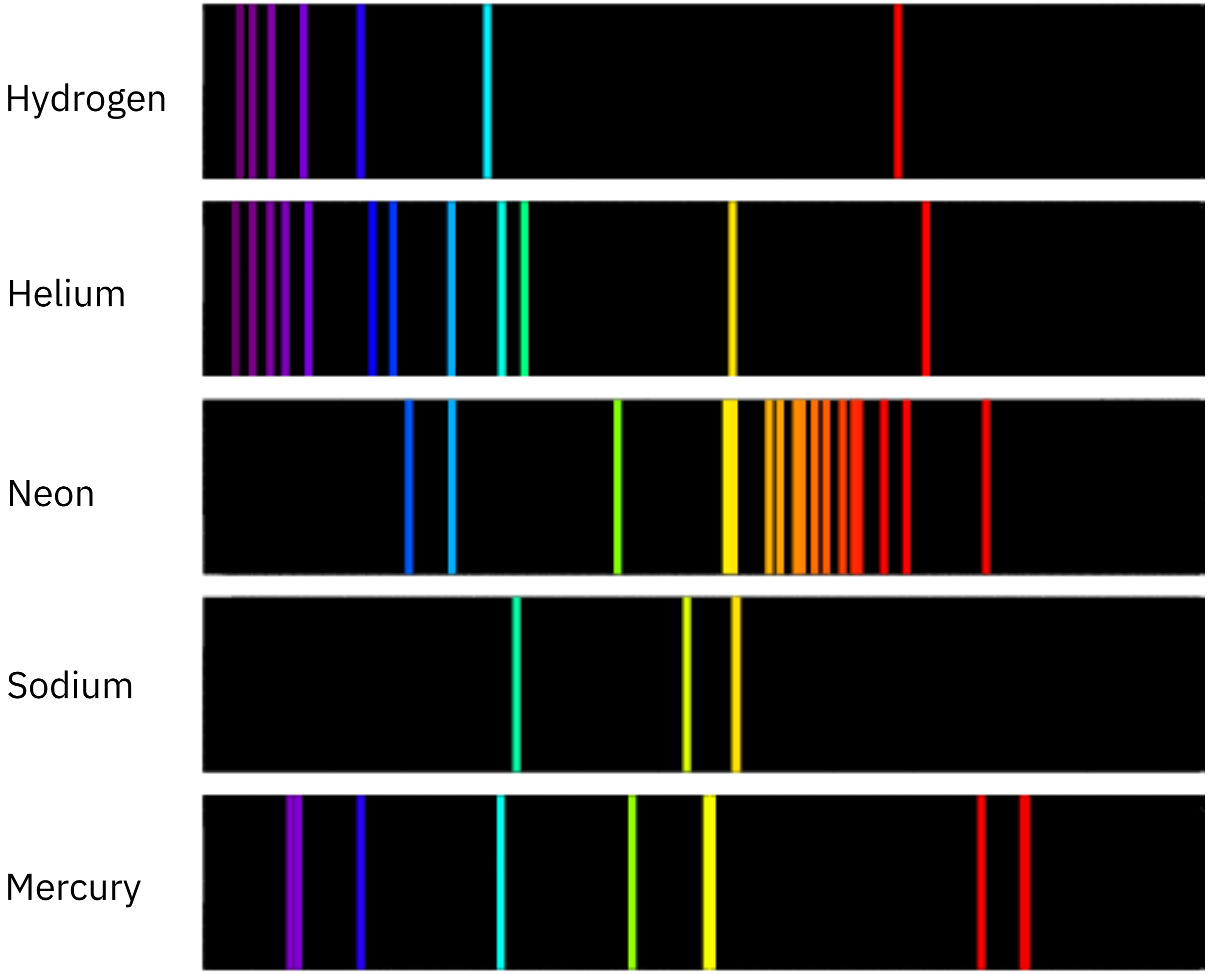
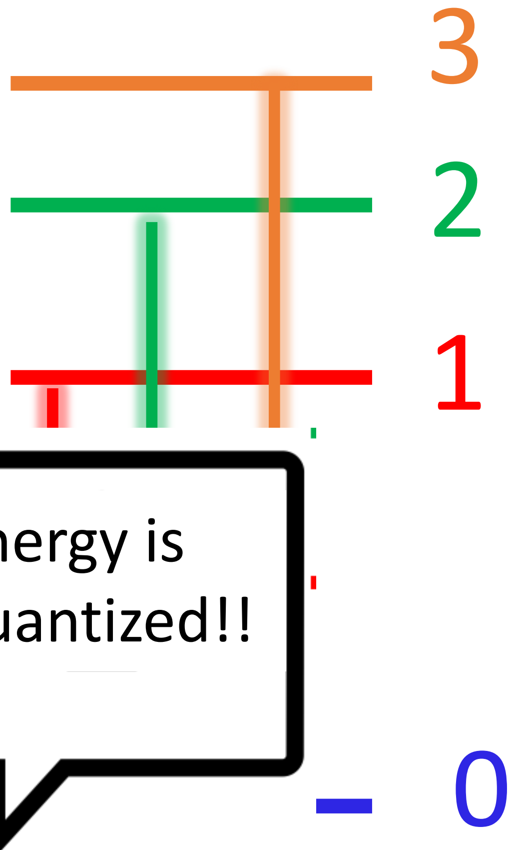
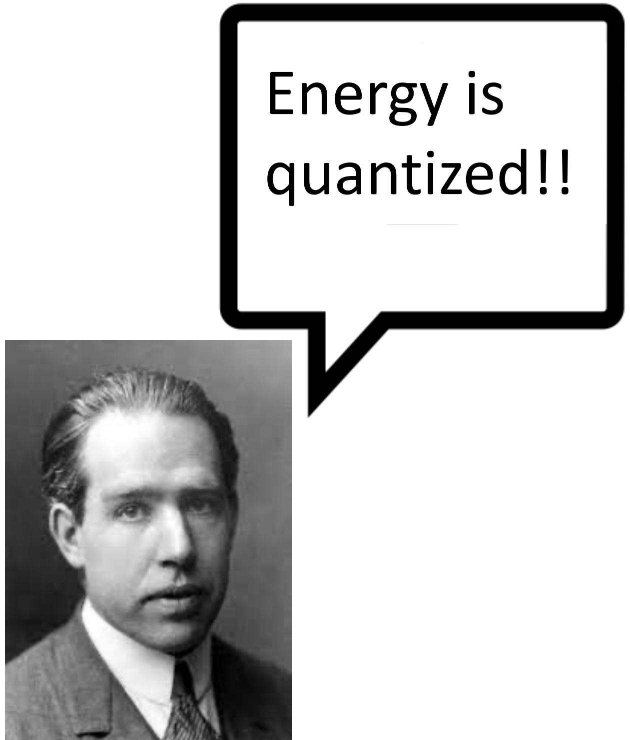
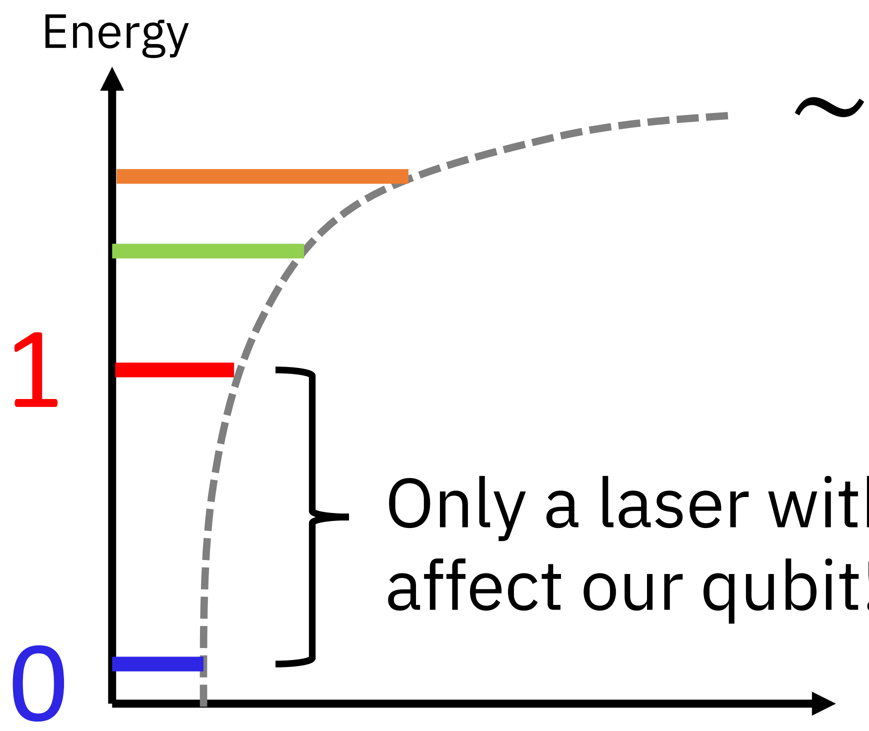


Image NMSU, N. Vogt



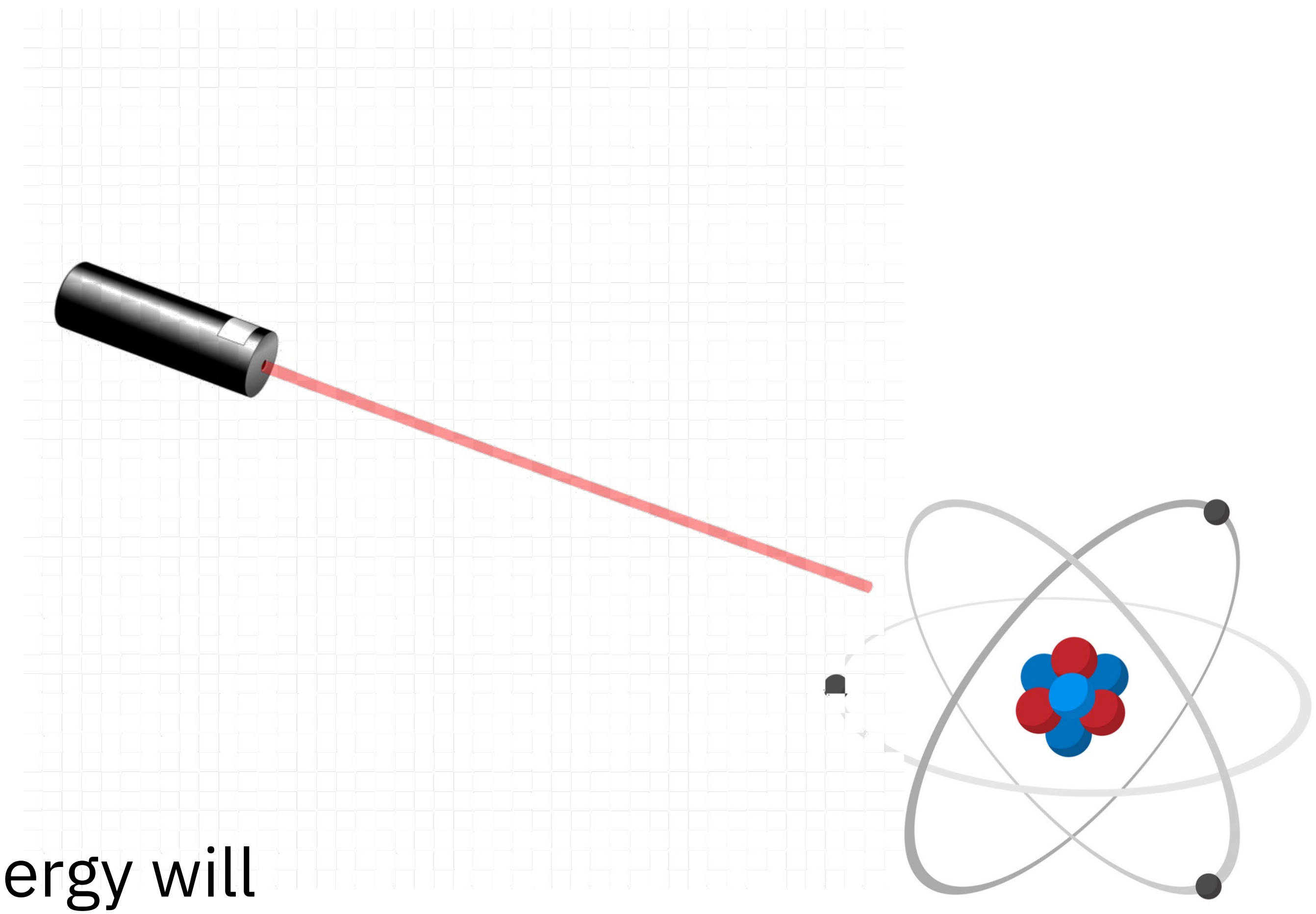


Atomic Qubits

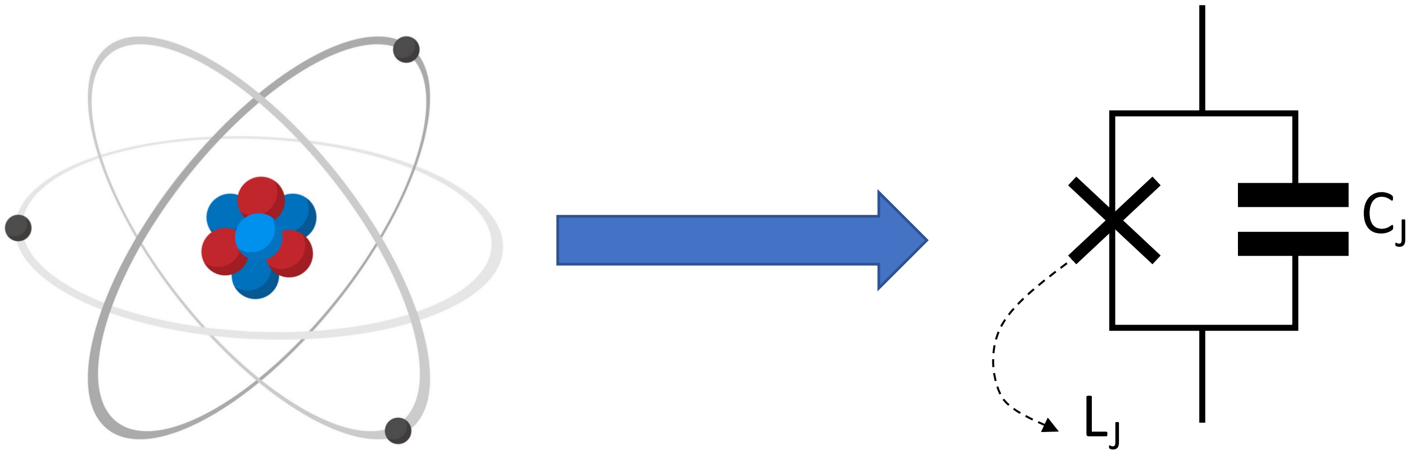


$\sim {}^{1}/_{r}$

Only a laser with this energy will affect our qubit!



Why make an artificial atom?



- Can mimic electromagnetic spectrum
- Can create “knobs” to control all elements we care about
- Can leverage semiconductor fab industry

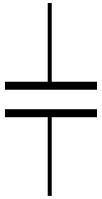
Classical electrical circuits

Toolkit:

R

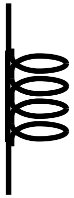
- Implements electrical resistance

C



- Stores energy in electric field

L

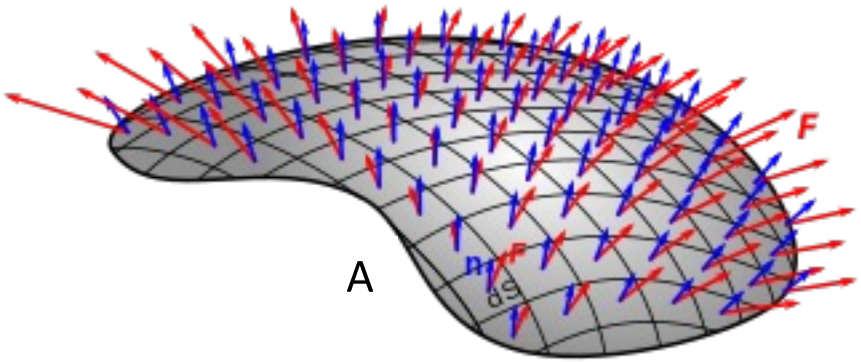


- Stores energy in magnetic field

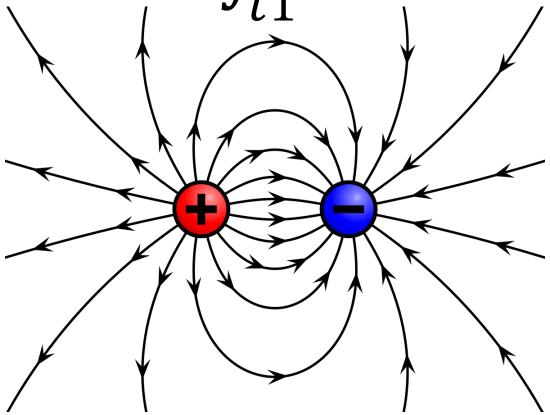
- Described by Kirchoff’s laws
- Flux and charge are continuous variables

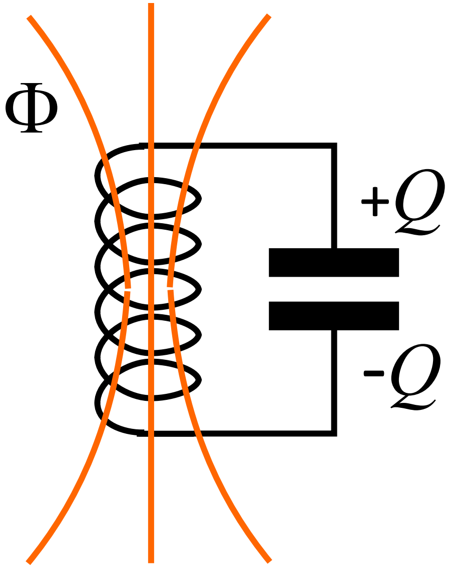
What is flux/charge

$$\Phi = BA\cos(\theta)$$



$$Q = \int_{t1}^{t2} I \cdot dt$$





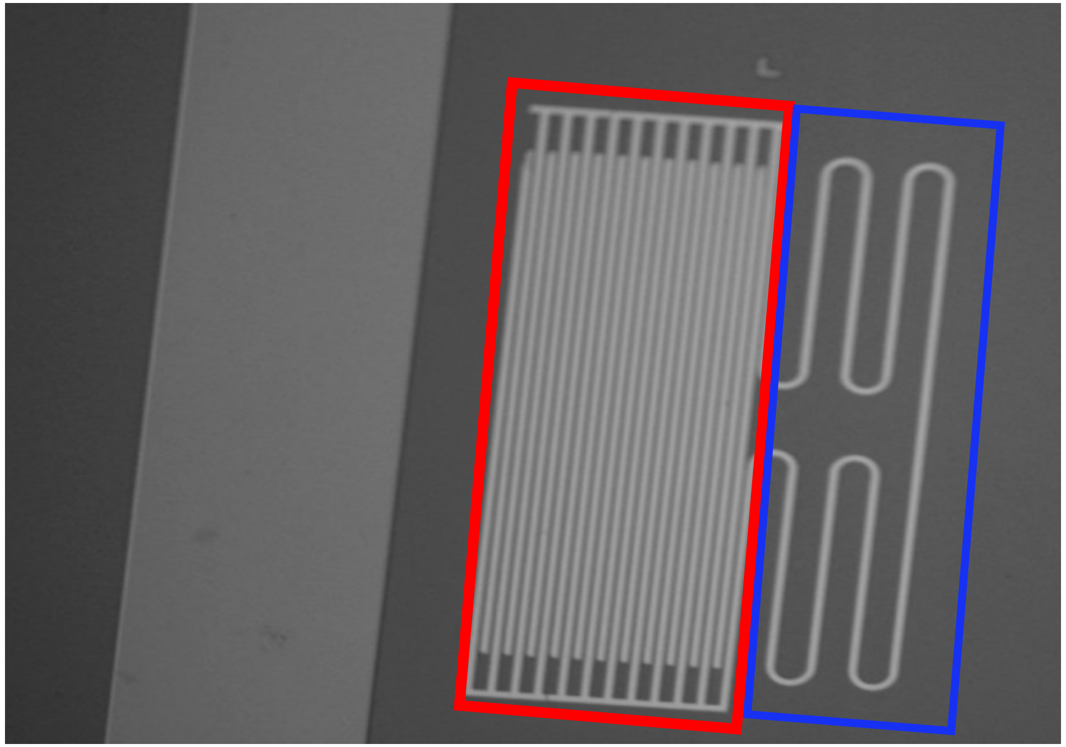
LC circuit

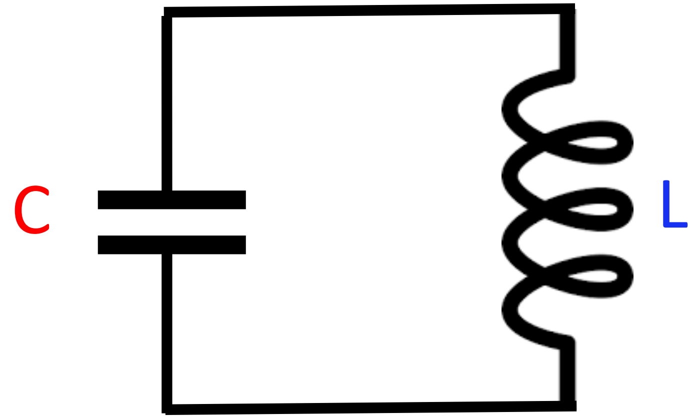
Classical Hamiltonian

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

$$\omega_0/2\pi = 1/2\pi\sqrt{LC}$$

Linear circuits





$$\overset{K}{}\qquad\overset{V}{}$$

$$H = \boxed{\frac{Q^2}{2C}} + \boxed{\frac{\phi^2}{2L}}$$

$$H = \boxed{\frac{p^2}{2m}} + \boxed{\frac{kx^2}{2}}$$

Image taken by O.Lanes @ Univ. of Pittsburgh

Quantum linear circuits

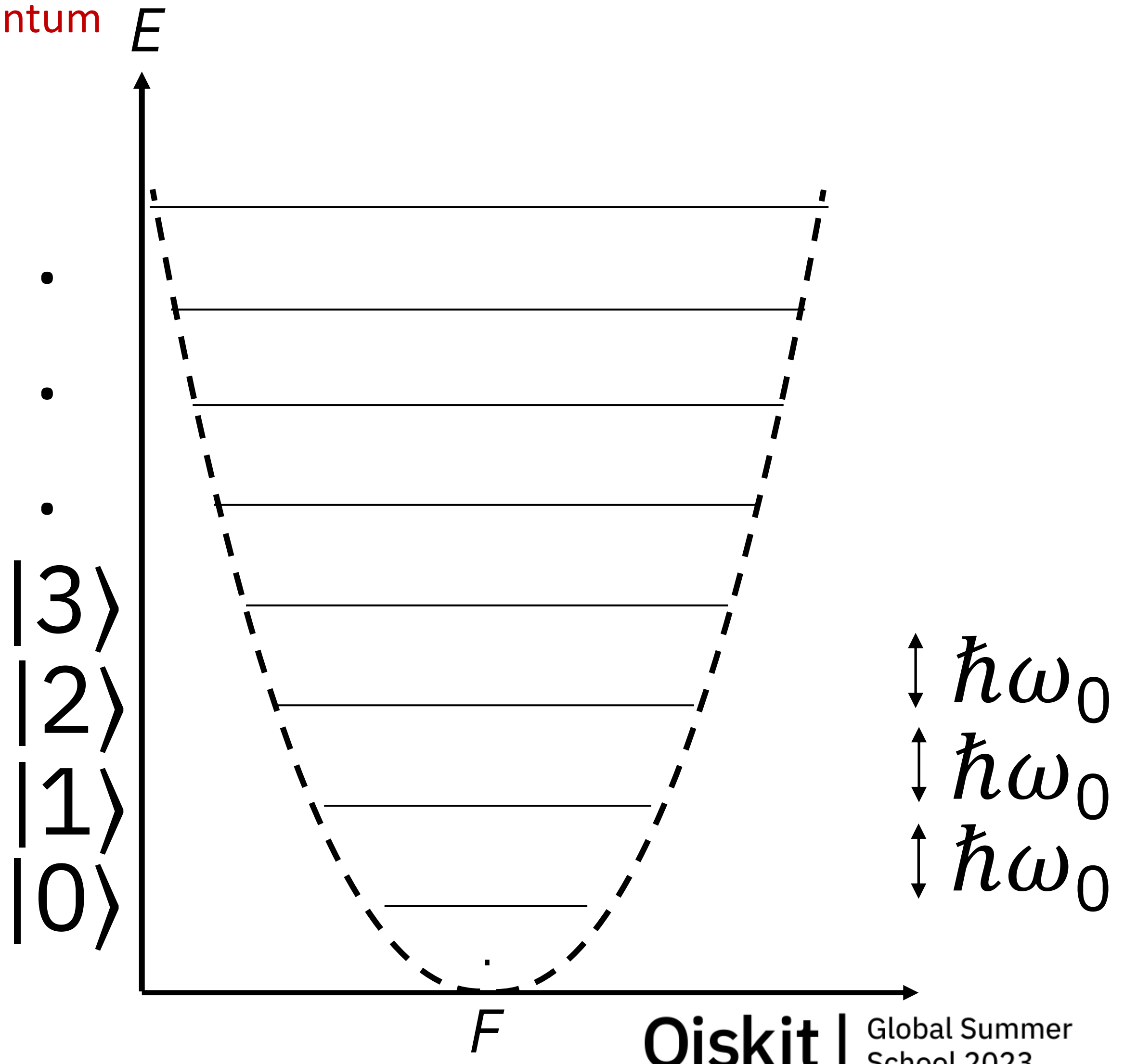
Means it's a quantum variable now

Quantum Hamiltonian

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

$$\hat{H} = \hbar\omega_0(\hat{n} + 1/2)$$

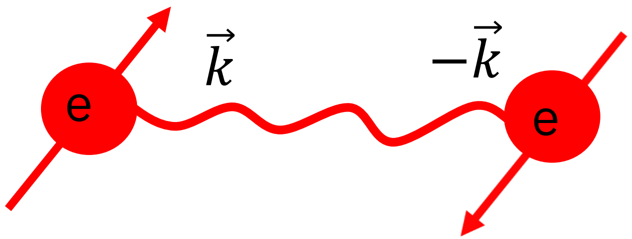
Need unique addressability for use as a qubit

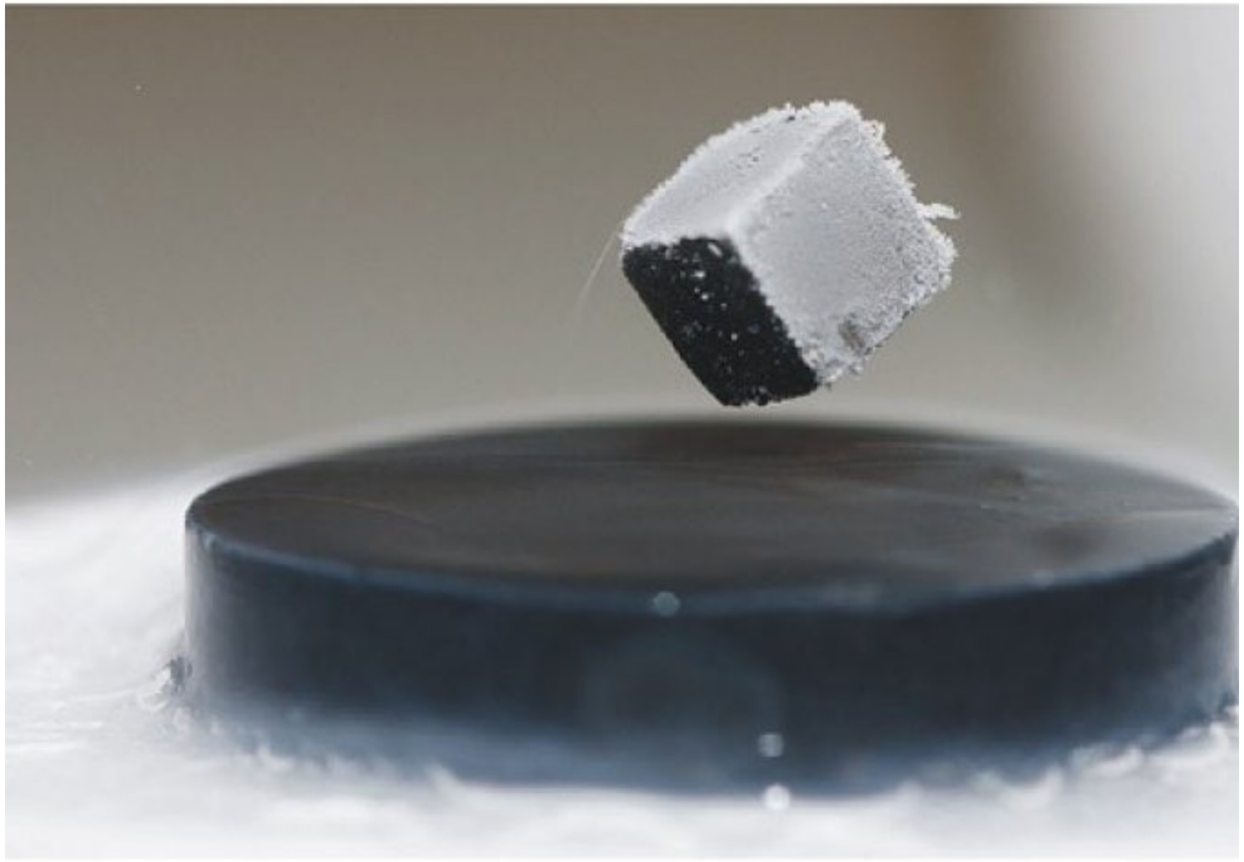


Superconductivity

- Vanishing electrical resistance. Non-dissipative

- Cooper pairs: Electrons anti-correlated in momentum. Attractive interaction mediated by the lattice

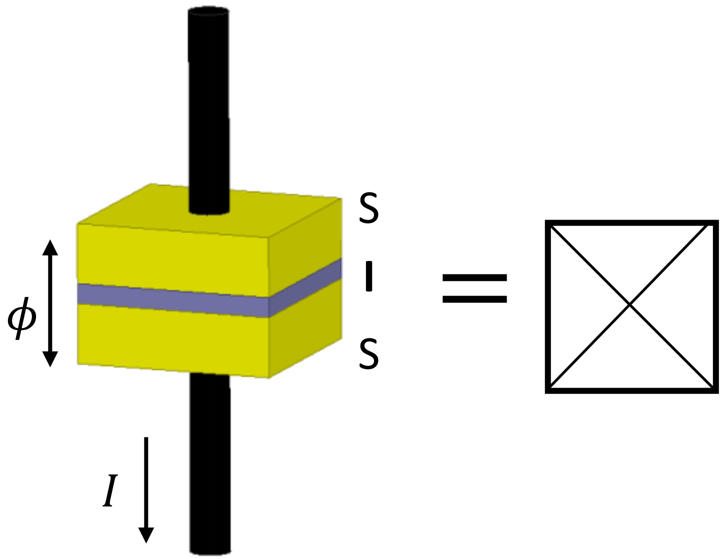


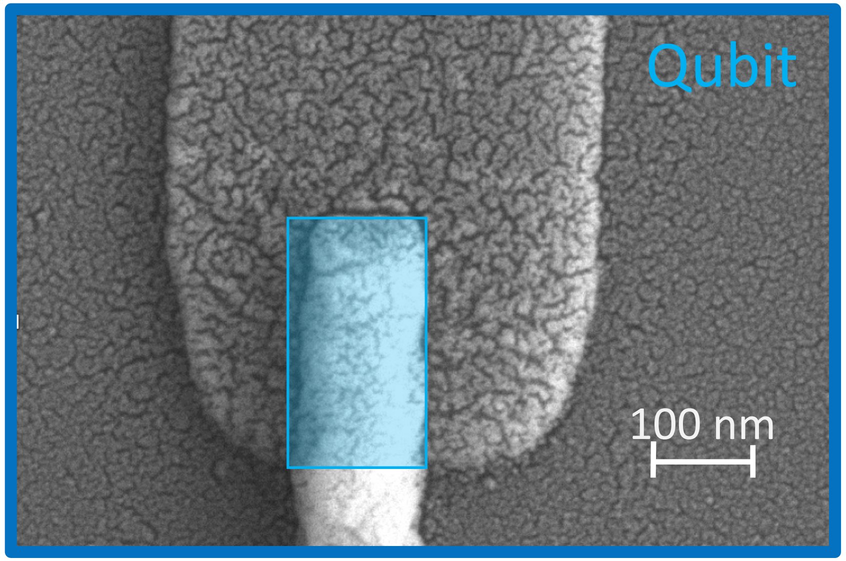


T>Tc T<Tc

Images from physicsfeed.com

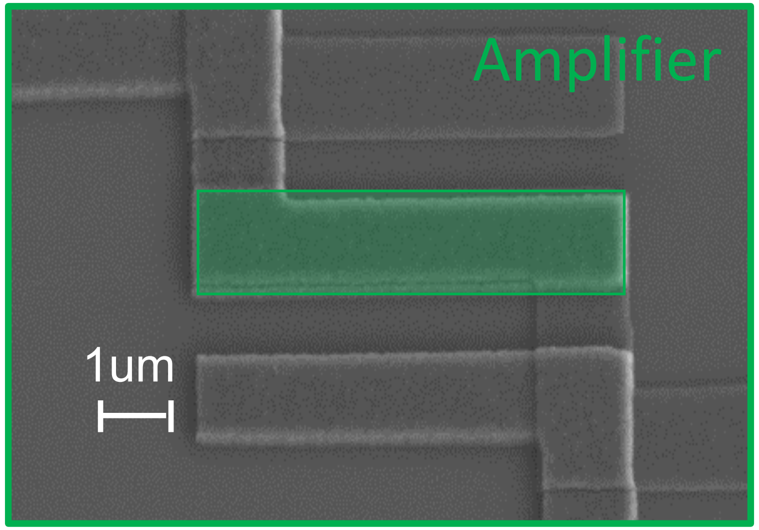
Josephson Junctions





$$I = I_0 \, sin(\phi)$$

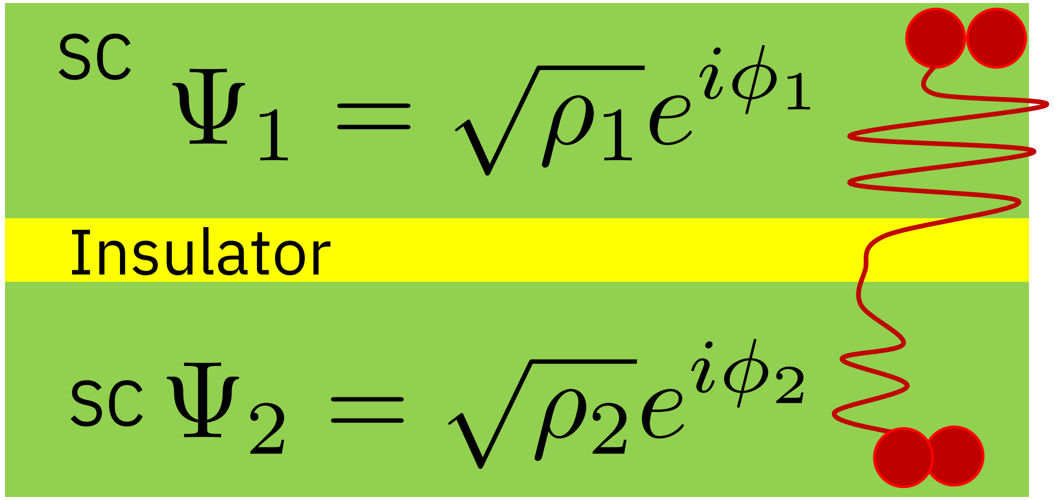
$$\mathrm{E} = E_J cos(\phi)$$

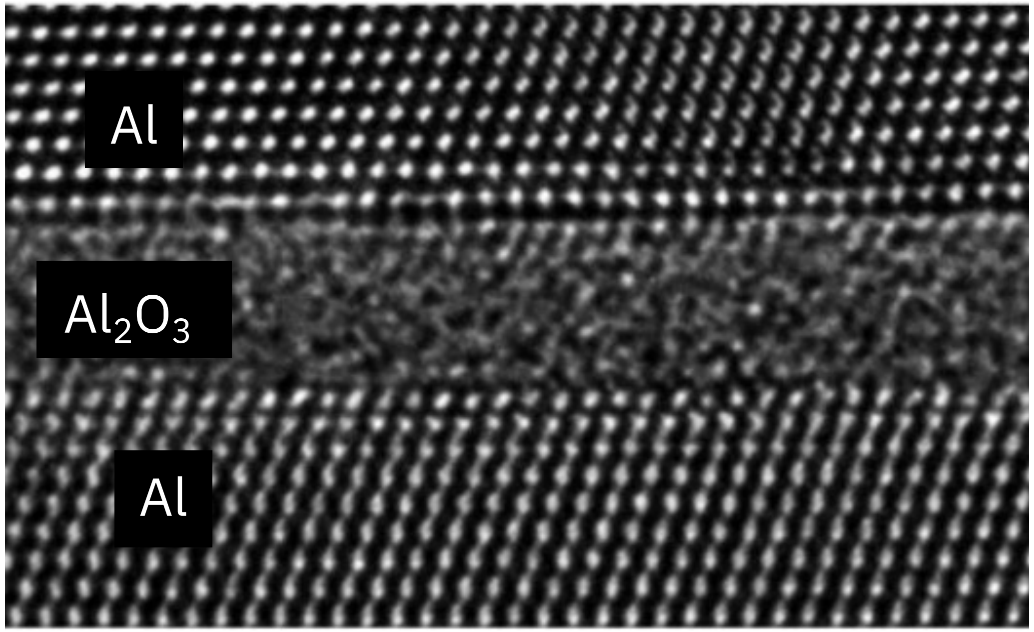


$$\phi = \frac{\Phi}{\varphi_0}, \varphi_0 = \frac{\Phi_0}{2\pi}$$

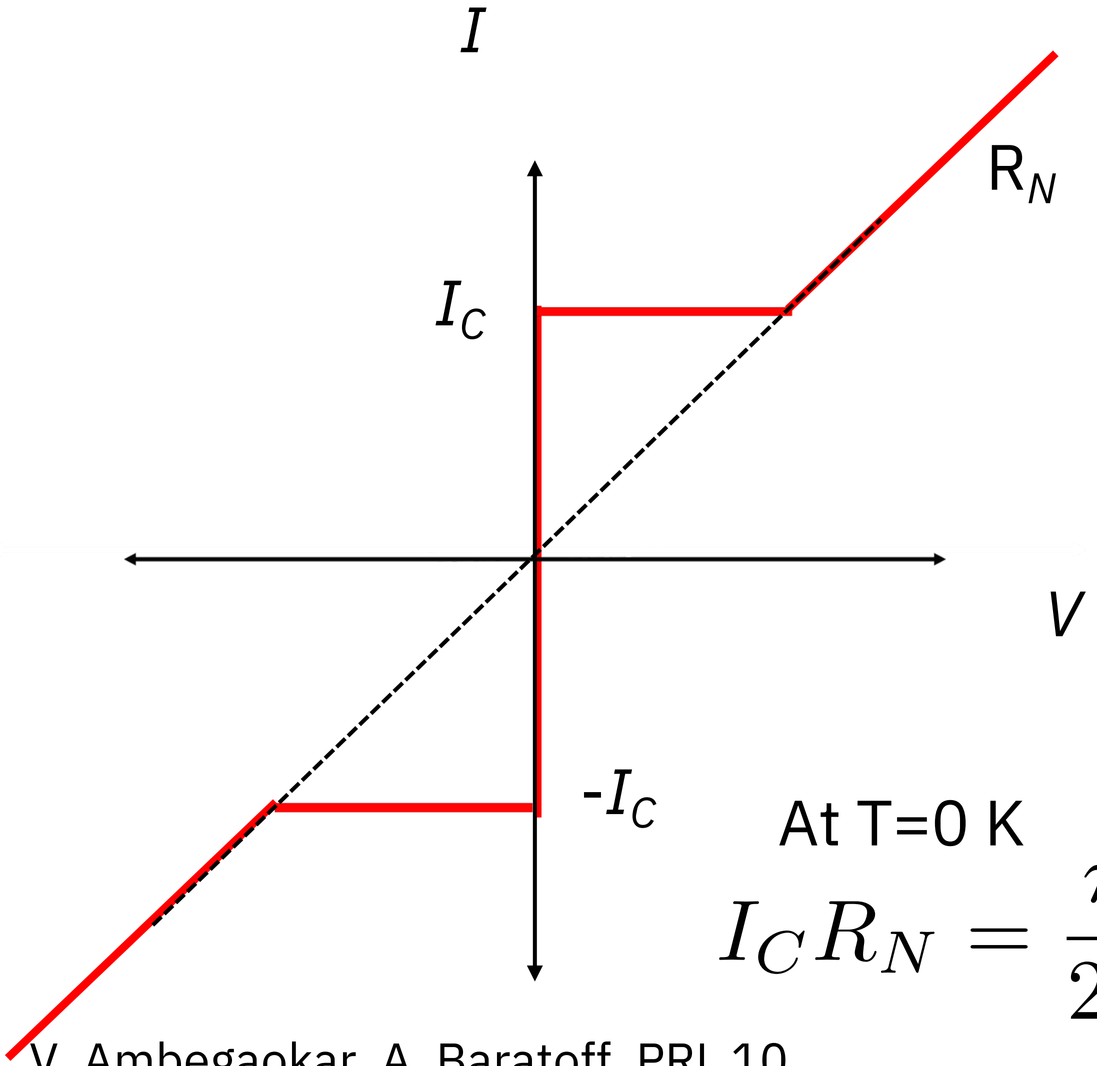
Images taken by O.Lanes @ Univ. of Pittsburgh

Quantum non-linear circuits: Josephson junction





JAP, 125(16), 165301, 2019



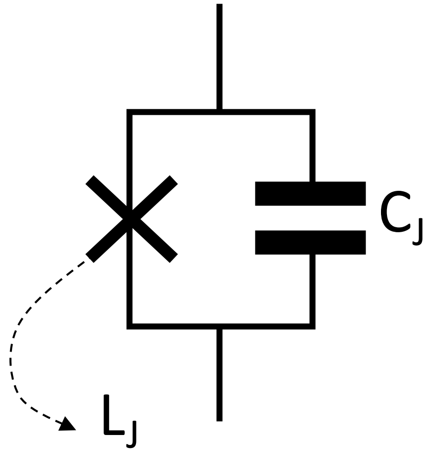
V. Ambegaokar, A. Baratoff, PRL 10, 486-489 (1963)

At T=0 K

$$I_C R_N = \frac{\pi}{2e}\Delta$$

Circuit Quantization

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



$$H = -E_J \cos\left(\frac{\Phi}{\varphi_0}\right) + \frac{Q^2}{2C_J}$$

$$\cos x = 1 - \frac{x^2}{2!} + \frac{x^4}{4!} - \frac{x^6}{6!} + \ldots$$

$$= \left[\frac{E_J}{2}\left(\frac{\Phi}{\varphi_0}\right)^2 - \underline{\frac{E_J}{4!}\left(\frac{\Phi}{\varphi_0}\right)}^4 + \cdots\right] + \frac{Q^2}{2C}$$

$$\frac{1}{L_J} = \frac{E_J}{{\Phi_0}^2}$$

Higher order perturbation

$$\hat{a} = +i\frac{1}{\sqrt{2L\hbar\Omega}}\hat{\Phi} + \frac{1}{\sqrt{2C\hbar\Omega}}\hat{Q}$$

$$\hat{a}^\dagger = -i\frac{1}{\sqrt{2L\hbar\Omega}}\hat{\Phi} + \frac{1}{\sqrt{2C\hbar\Omega}}\hat{Q}$$

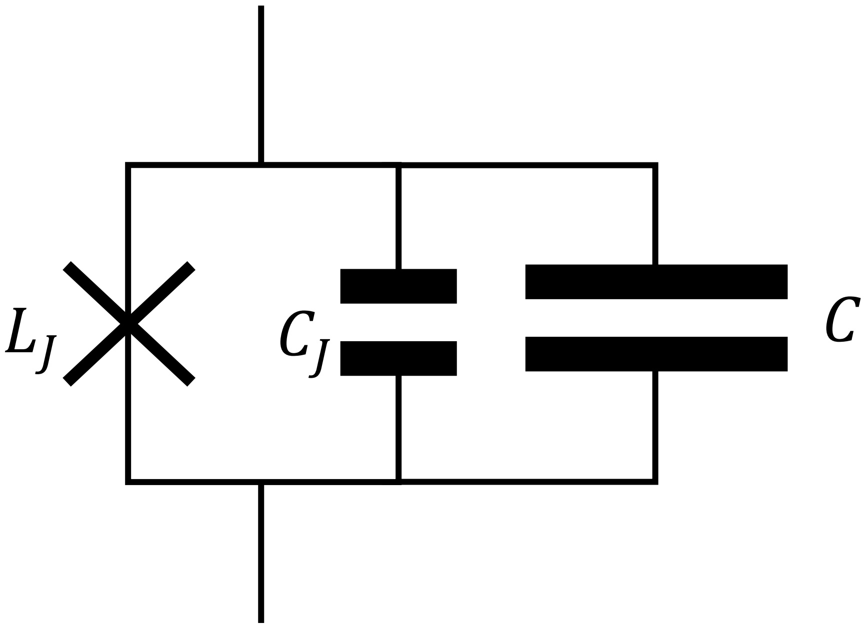
Approximate JJ Hamiltonian:

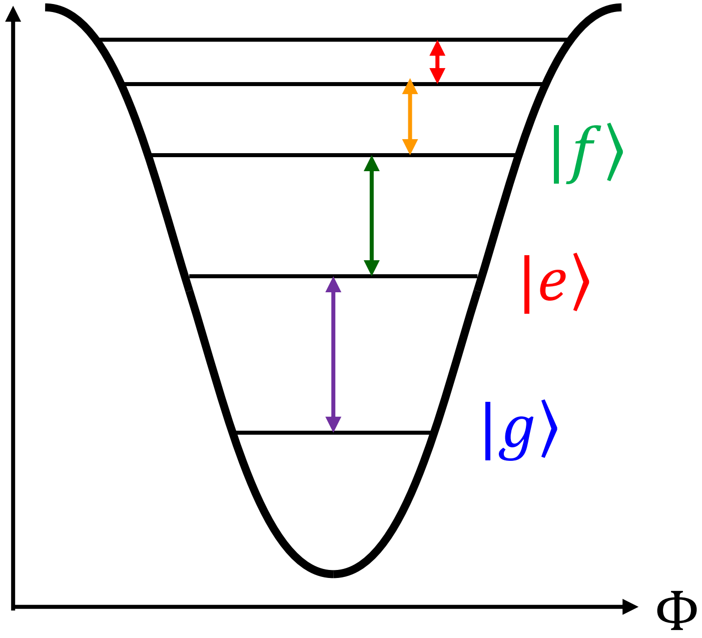
$$\boxed{\approx \hbar\omega_a a^\dagger a - \lambda\hbar \underline{a^\dagger a a^\dagger a} + \cdots}$$

For more details on this math, see Zlatko's lecture from QGSS #1

Transmon qubit

Josephson junction with shunting capacitor ➔ anharmonic oscillator



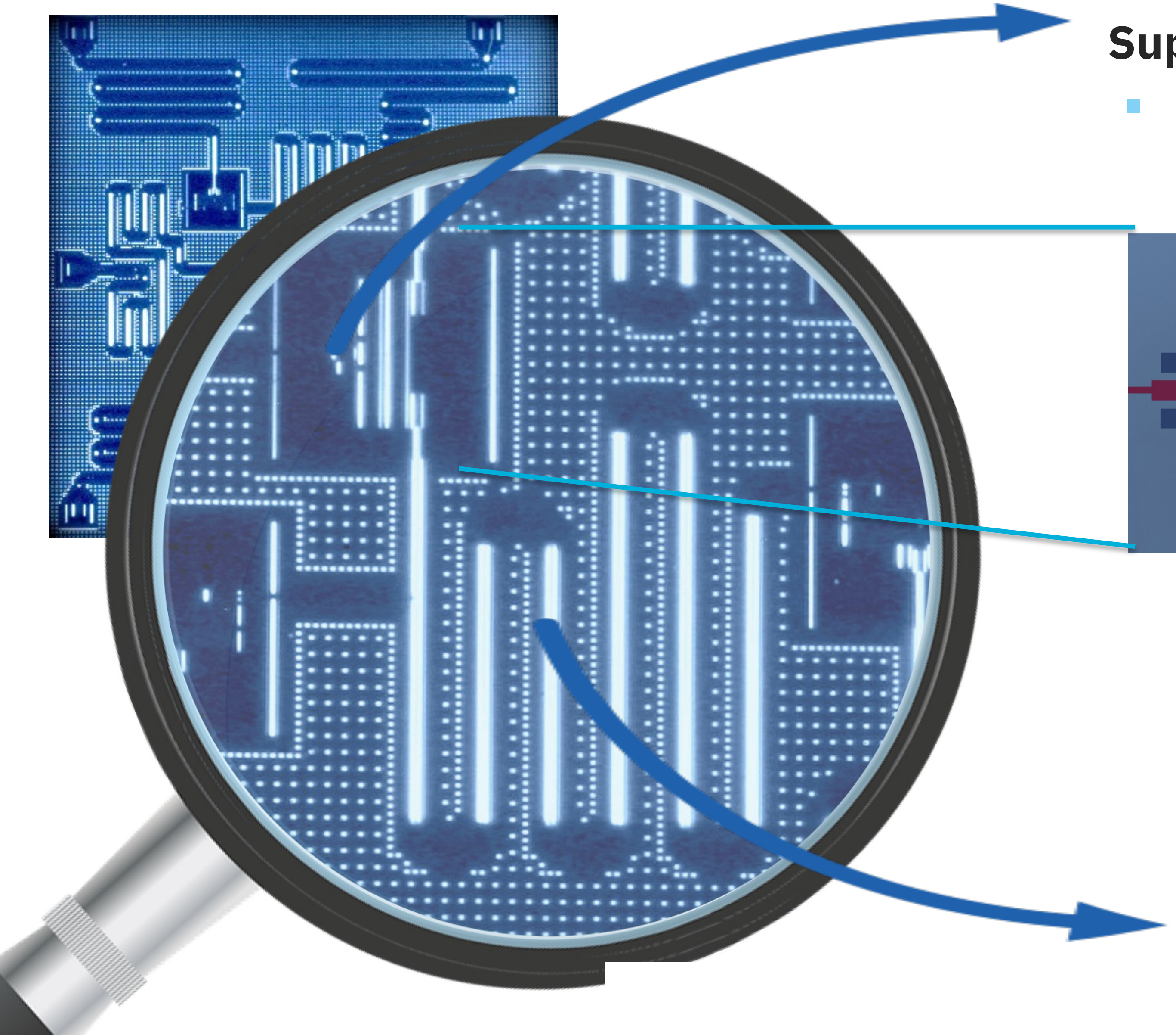


lowest two levels form qubit

f_{ge} ~ 5.0 GHz, f_{ef} ~ 4.80 GHz

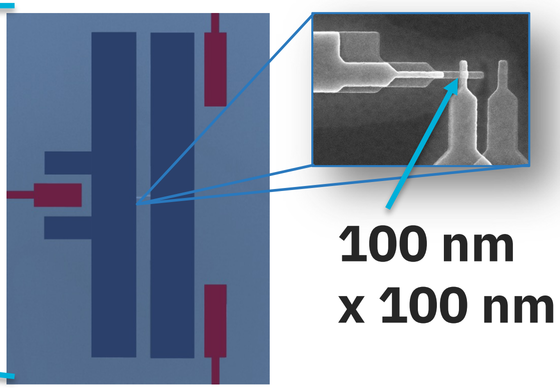
Koch, et al. Phys. Rev. A (2007)

Anatomy of an IBM transmon



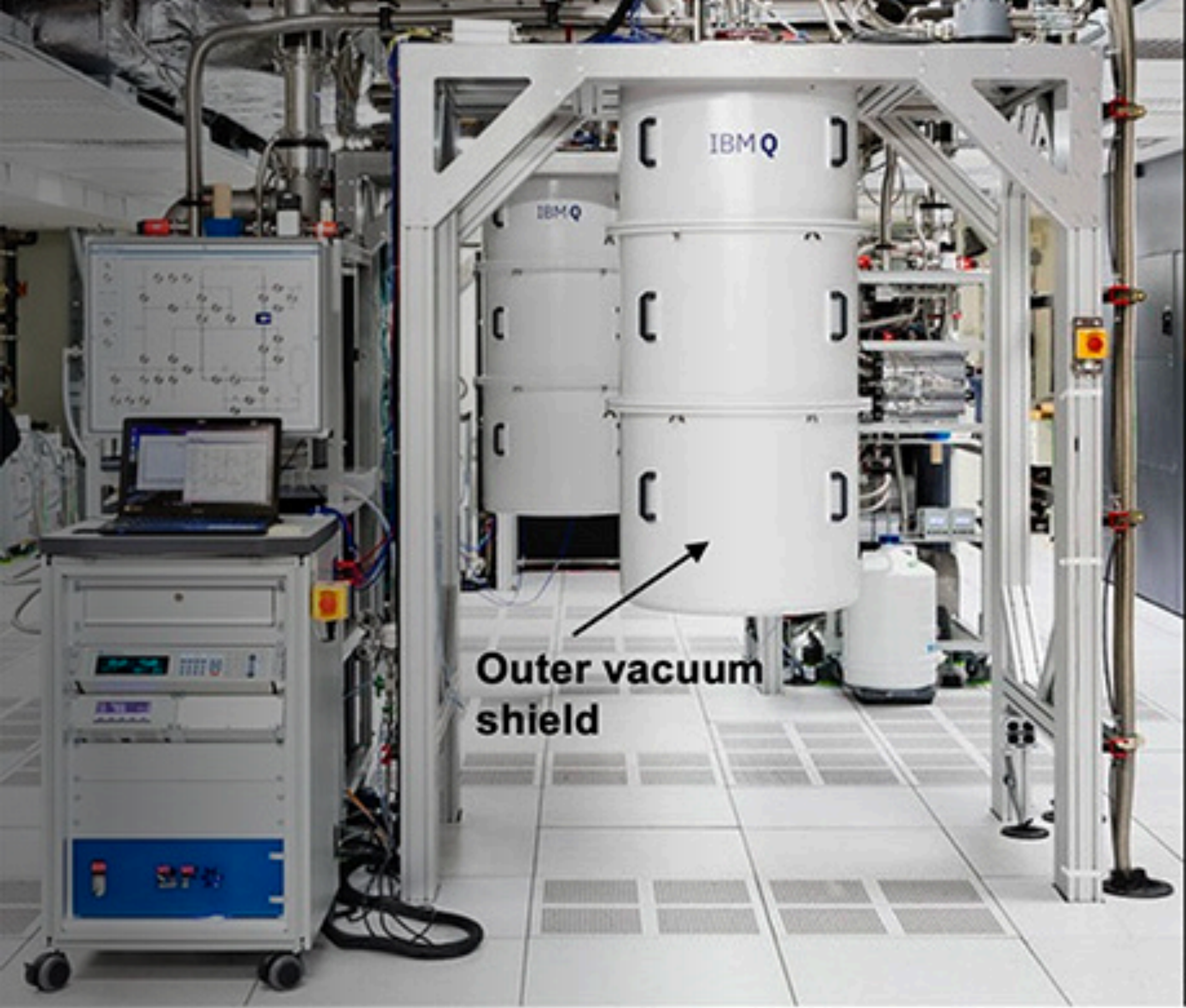
Superconducting Qubit:

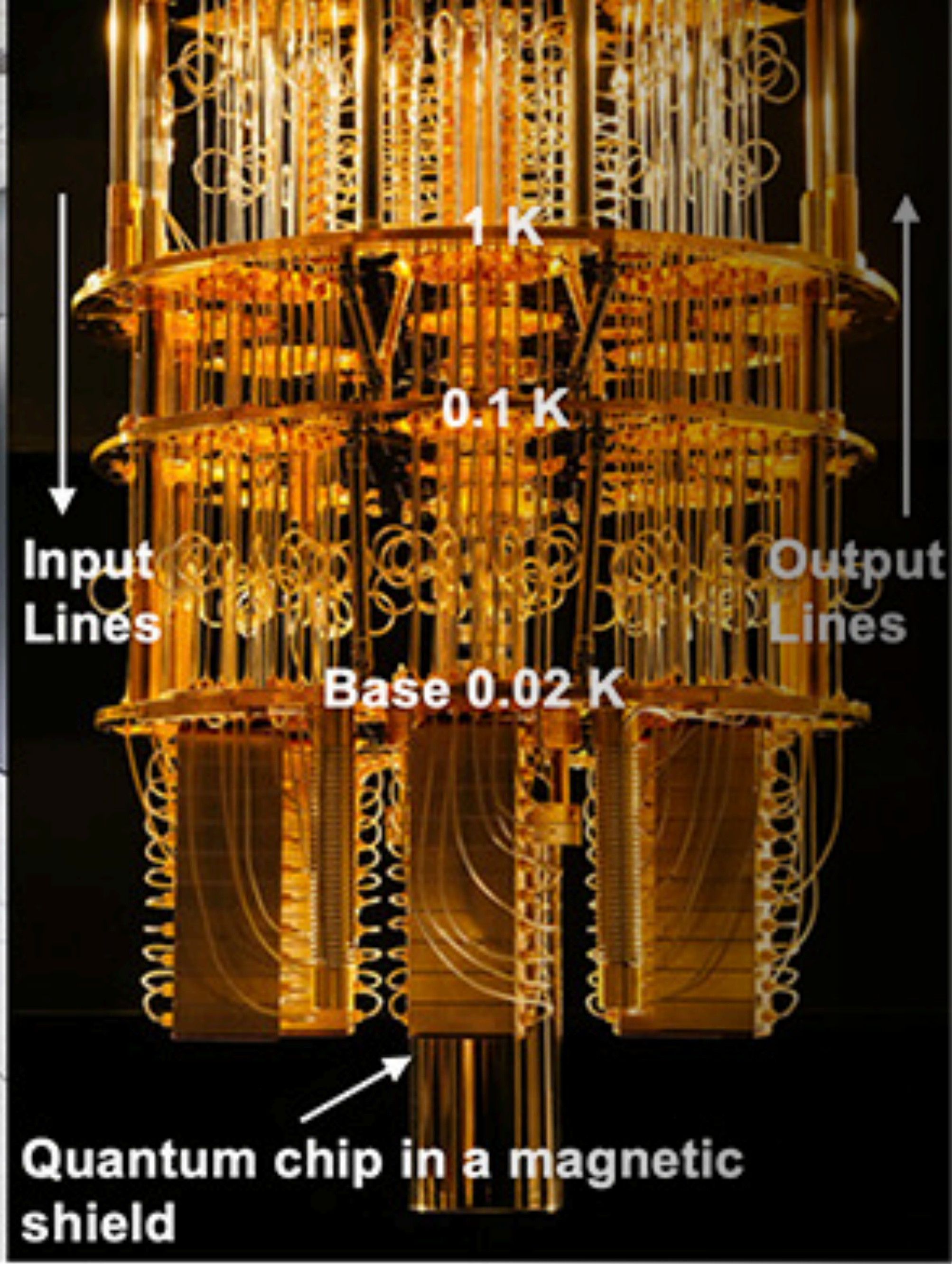
- Josephson Junction as a nonlinear inductor



Superconducting Microwave Resonators:

- read-out of qubit states
- multi-qubit quantum bus
- filters at qubit freq





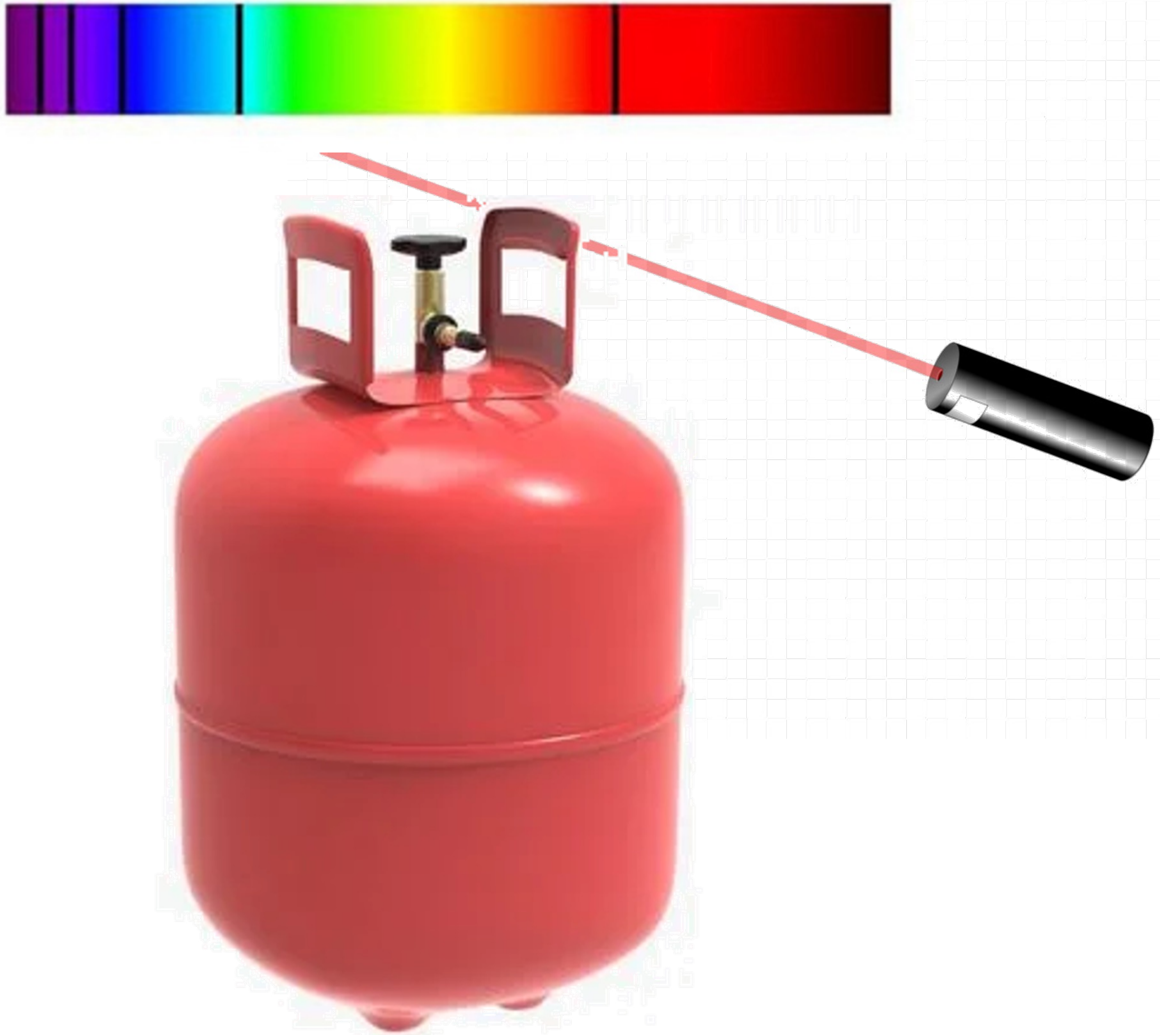
<u>Dilution fridge setup:</u> outside view

<u>Dilution fridge setup:</u> inside view

Break

Classical Non-Demolition Measurement

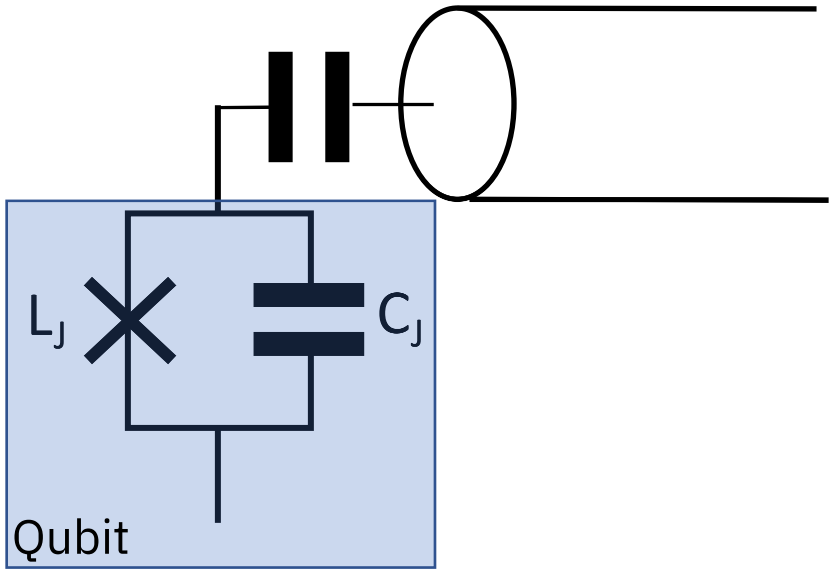
Demolition (obviously)



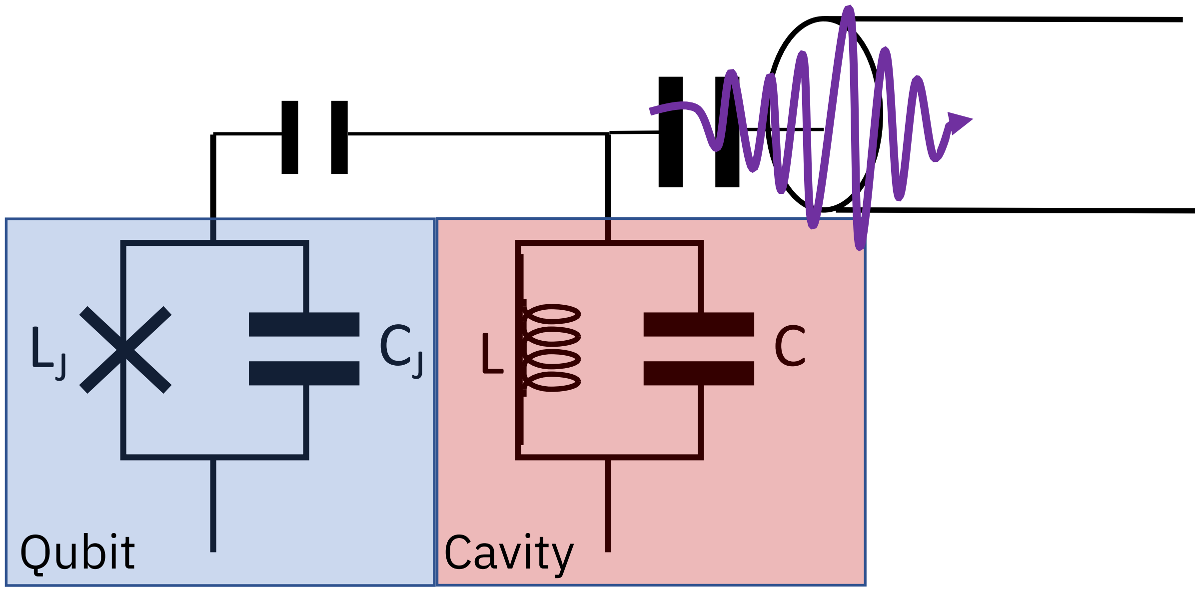
Non-demolition (yay)

Analogy from Howard Wiseman

Quantum Non-Demolition Measurement



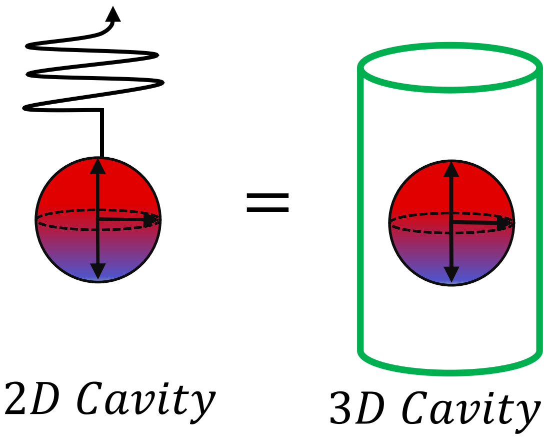
Direct observation



$$\omega_{Qubit} \neq \omega_{Cavity}$$

QND

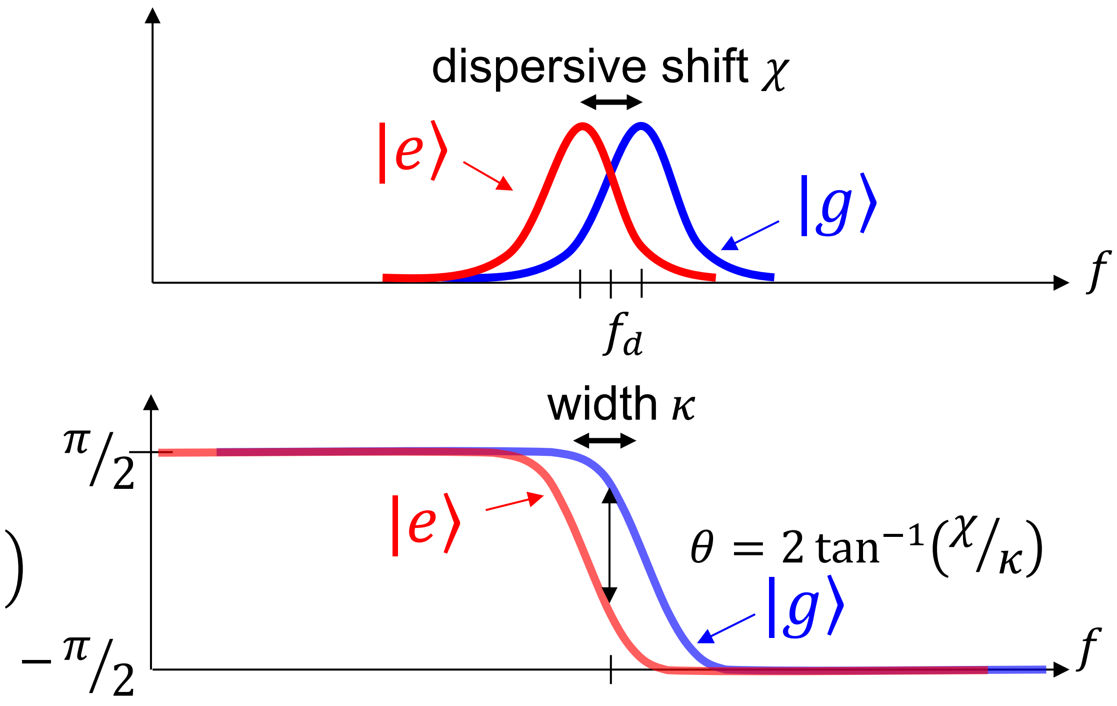
Quantum dispersive measurement

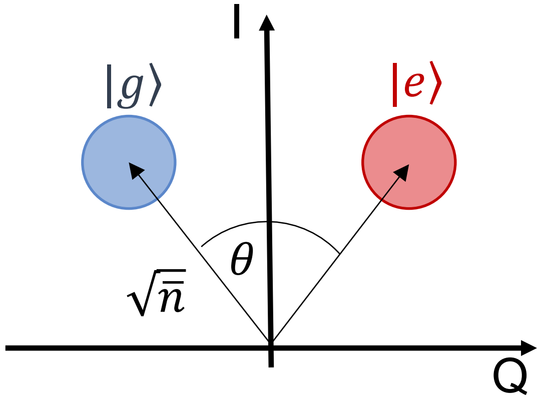


$$\frac{H}{\hbar} = \omega_q q^\dagger q + \omega_c c^\dagger c - \frac{\alpha}{2}\left(q^\dagger q\right)^2 - \chi q^\dagger q c^\dagger c$$

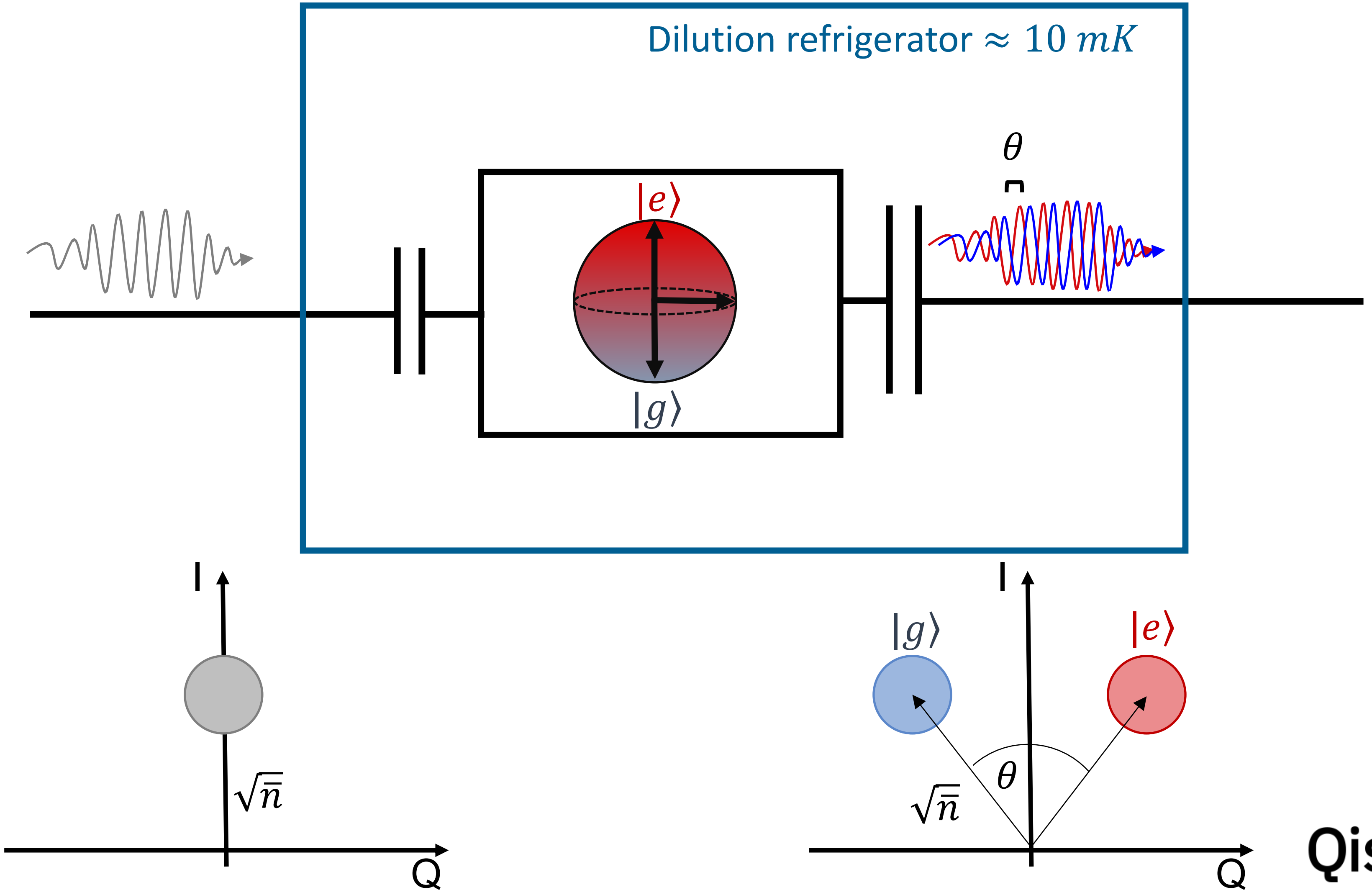
Readout amplitude $\sqrt{I_m^2 + Q_m^2}$

Readout phase $\tan^{-1}\left(Q_m/I_m\right)$

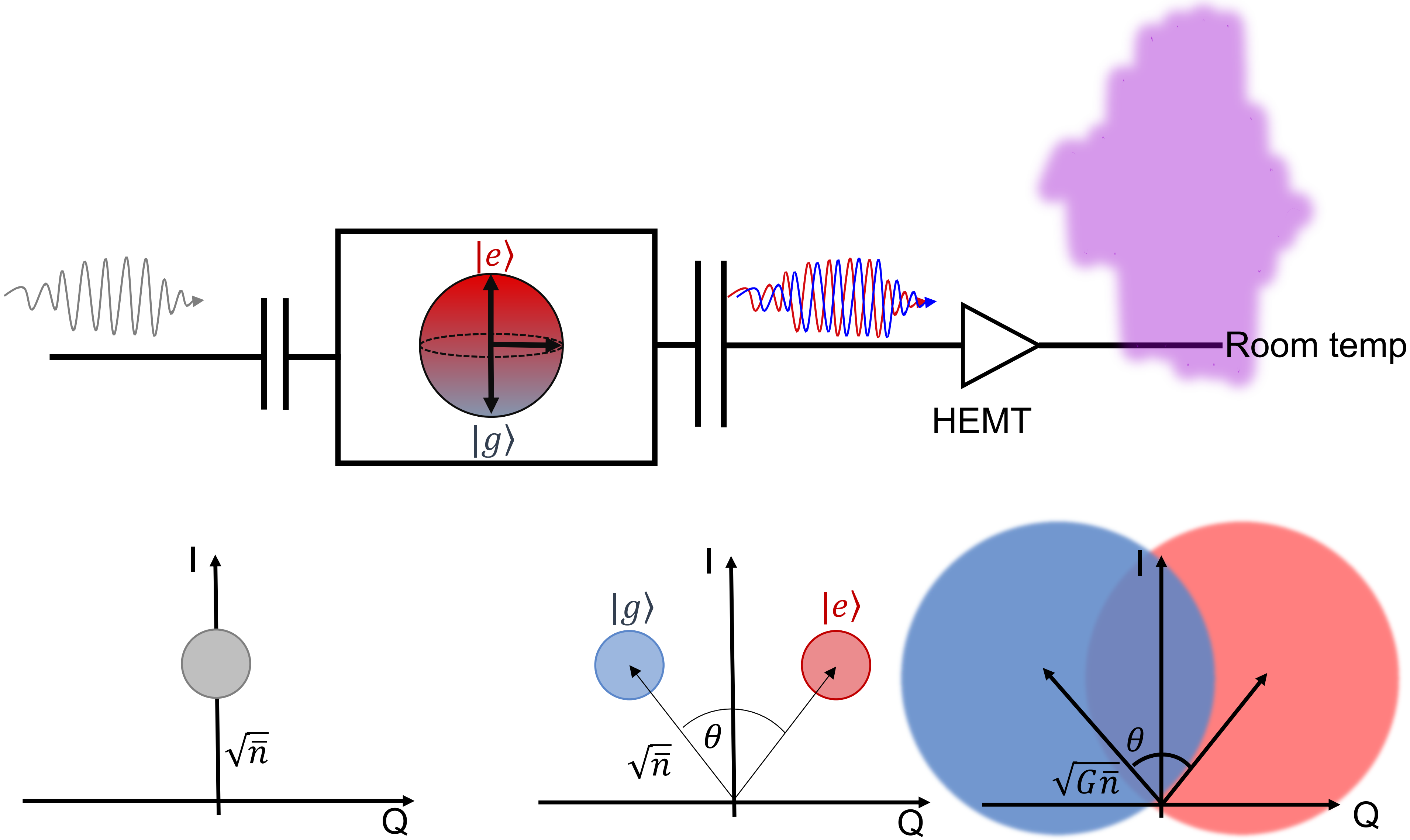




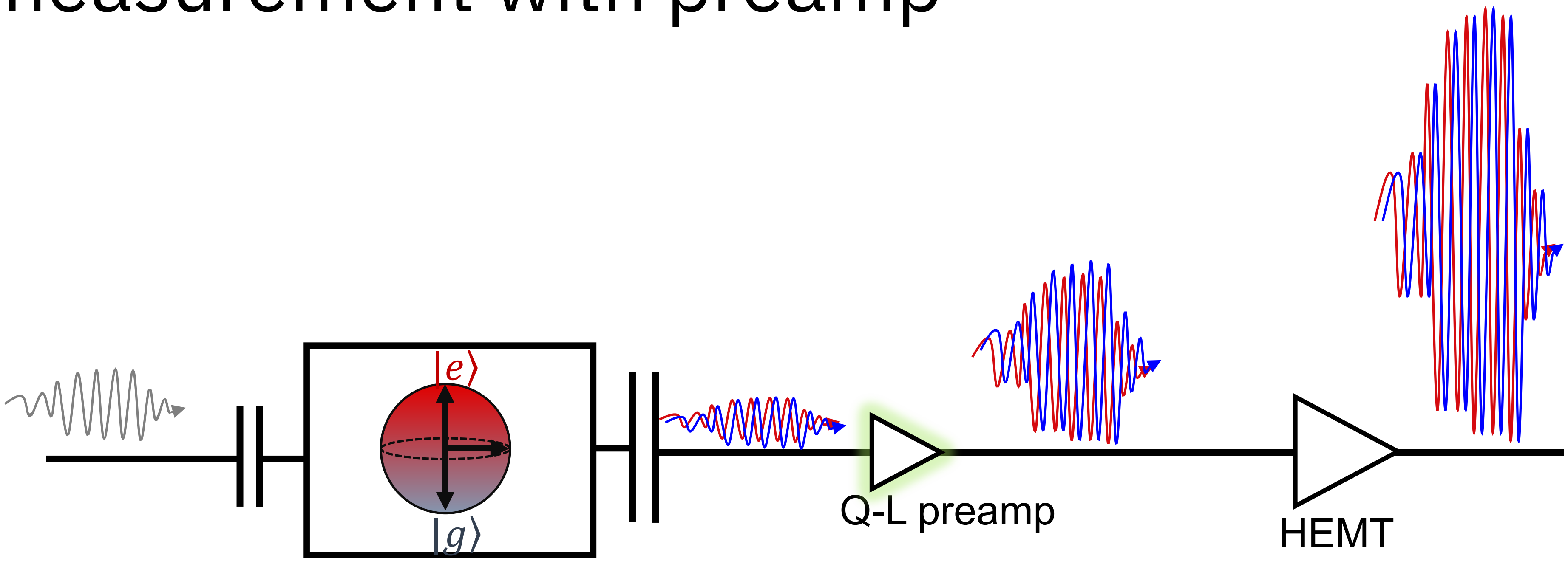
Qubit measurement, no amplifier

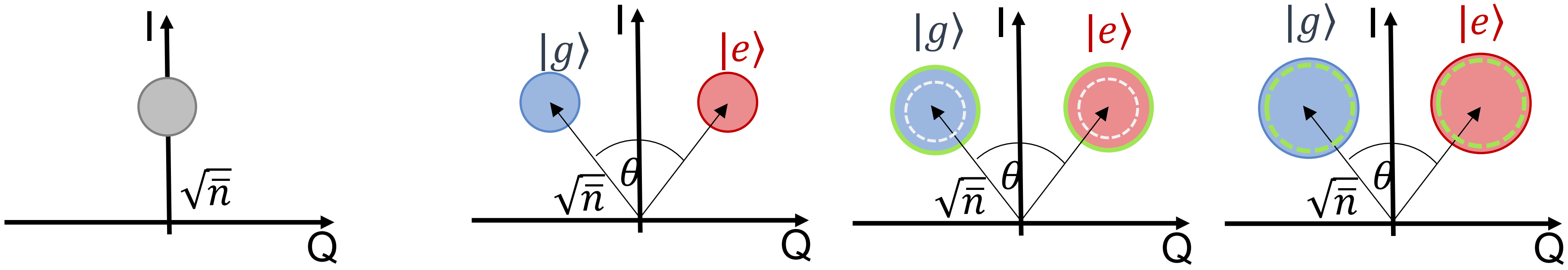


Qubit measurement, HEMT only



Qubit measurement with preamp

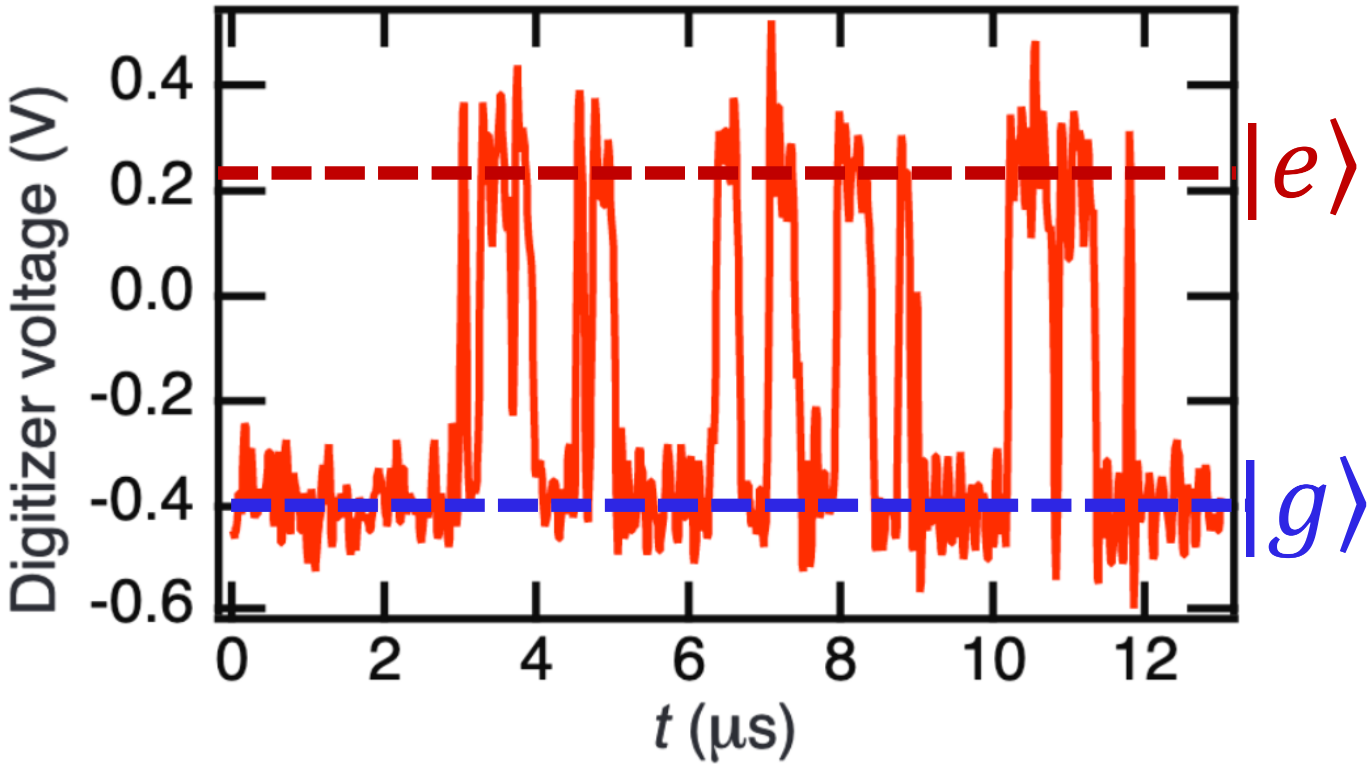




- State preparation
- msmt back-action
- error correction
- ……

C. Caves 1982

High fidelity single-shot readout



- State of the art fidelities exceed 99%
- Josephson junction based quantum limited amplifiers enable single-shot measurement

Quantum jumps
R. Vijay et al, PRL 106, 110502 (2011)

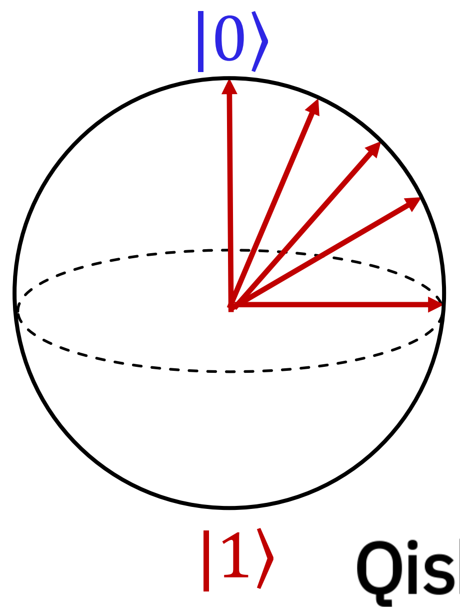
A theoretical look at gates

Pauli Matrices: $$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \quad \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Rotations about the Bloch sphere: $$R(\theta) = \exp(-i(^{\theta}/_{2})n \cdot \sigma) = I\cos(^{\theta}/_{2}) - i(n \cdot \sigma)sin(^{\theta}/_{2})$$

$$\sigma = X, Y, Z$$

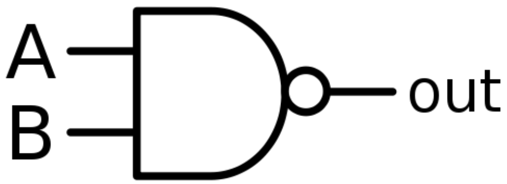
Example of X rotation: $$R_x(\theta) = \begin{pmatrix} \cos(^{\theta}/_{2}) & -i\sin(^{\theta}/_{2}) \\ -i\sin(^{\theta}/_{2}) & \cos(^{\theta}/_{2}) \end{pmatrix}$$



Classical vs. quantum gates

Classical Computers

NAND



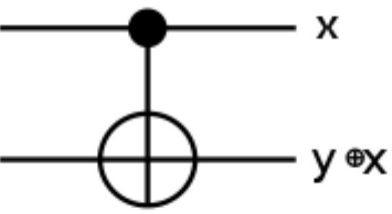
A	B	Output
0	0	1
1	0	1
0	1	0
1	1	0

NOR

A	B	Output
0	0	1
0	1	0
1	0	0
1	1	0

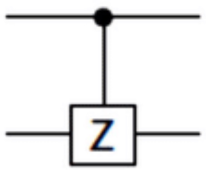
Quantum Computers

cNOT



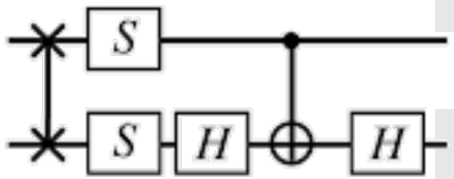
Input	Output
$\|00\rangle$	$\|00\rangle$
$\|01\rangle$	$\|01\rangle$
$\|10\rangle$	$\|11\rangle$
$\|11\rangle$	$\|10\rangle$

cPhase



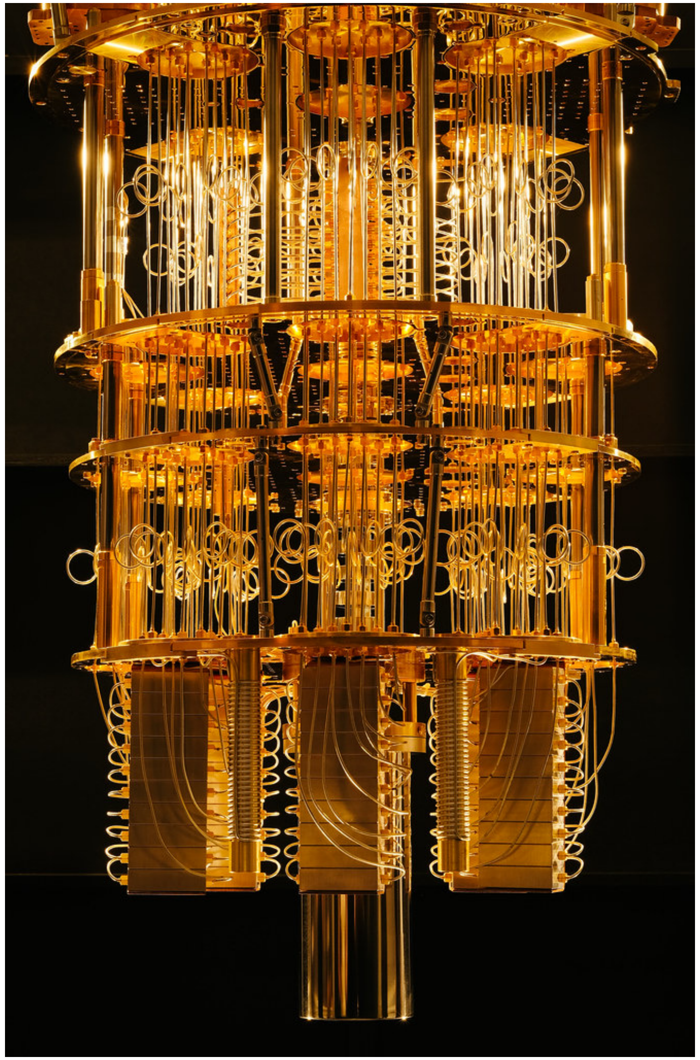
Input	Output
$\|00\rangle$	$\|00\rangle$
$\|01\rangle$	$\|01\rangle$
$\|10\rangle$	$\|10\rangle$
$\|11\rangle$	$-\|10\rangle$

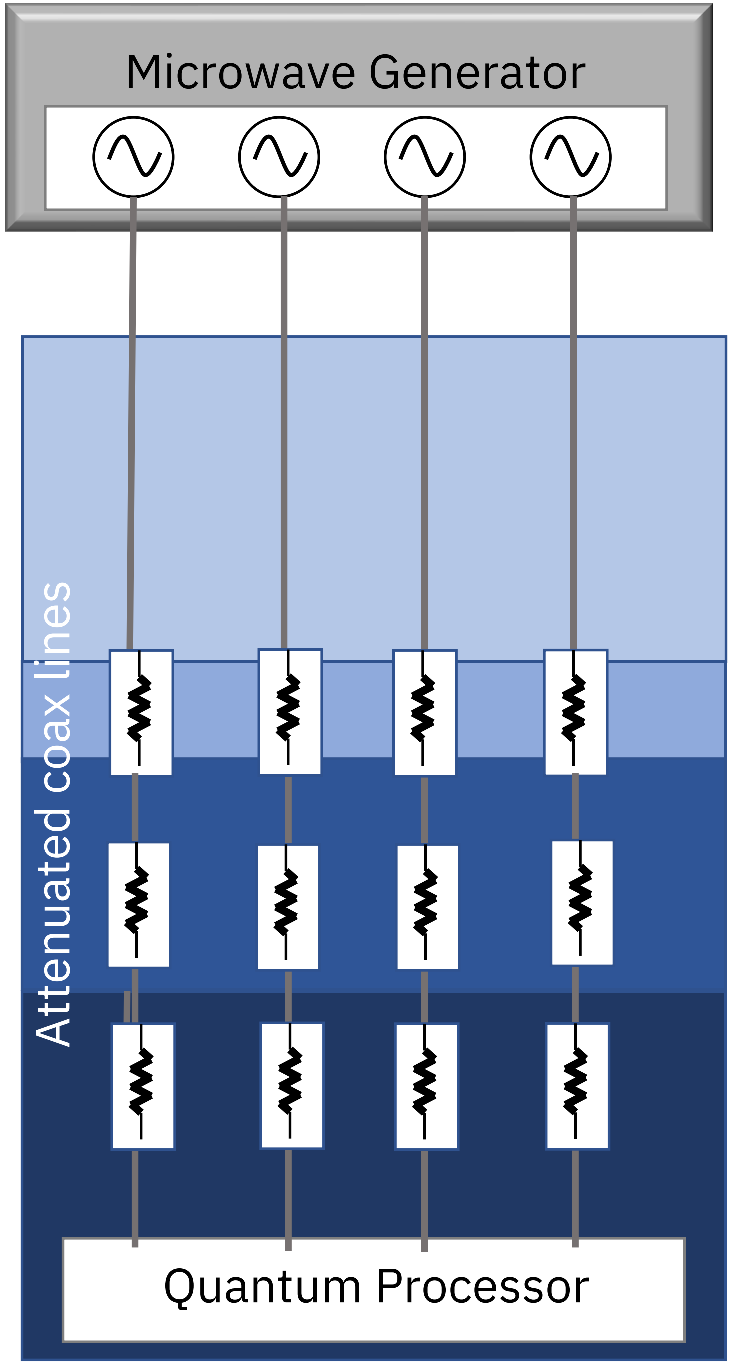
iSWAP



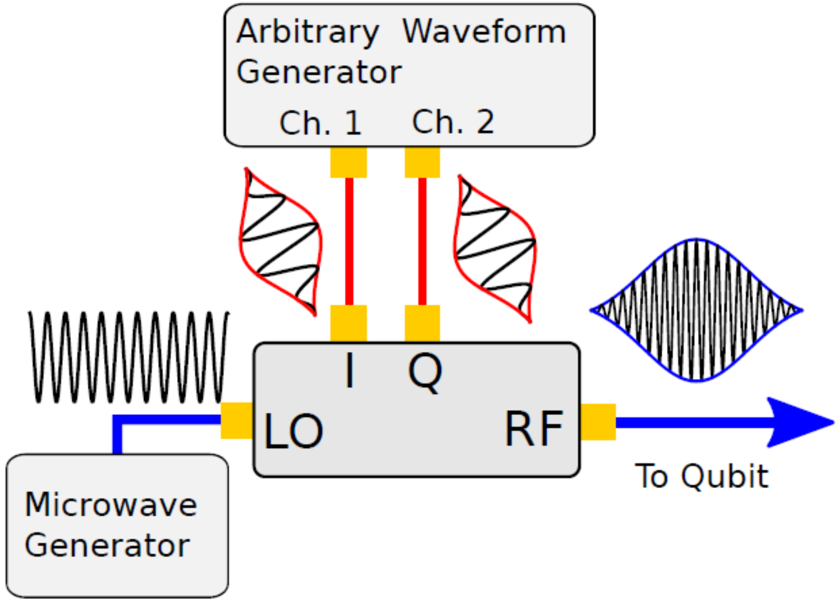
Input	Output
$\|00\rangle$	$\|00\rangle$
$\|01\rangle$	$i\|10\rangle$
$\|10\rangle$	$i\|01\rangle$
$\|11\rangle$	$\|11\rangle$

How do we interact with superconducting qubits?





Generating Shaped Microwave Pulses

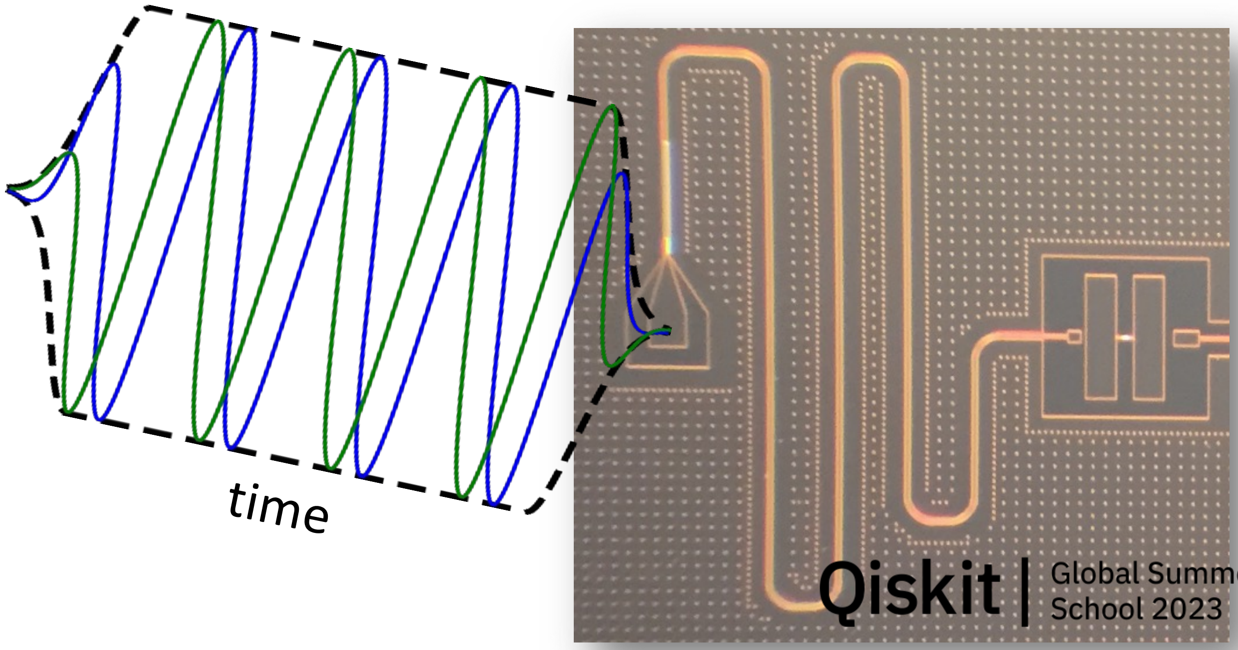


See, e.g., McKay et al, Phys. Rev. A **96**, 022330 (2017)

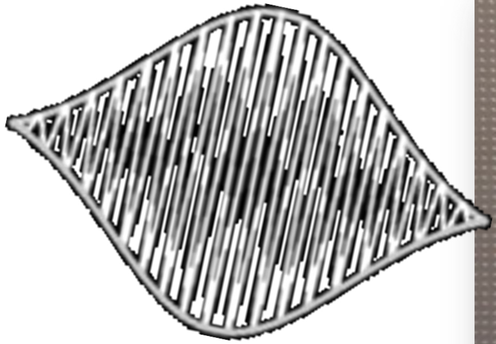
Arbitrary waveform generators (which can produce arbitrary voltages at ~1-2 GSamples/s) are used to produced shaped pulses at lower frequency which are then mixed up with an IQ mixer to the qubit frequency

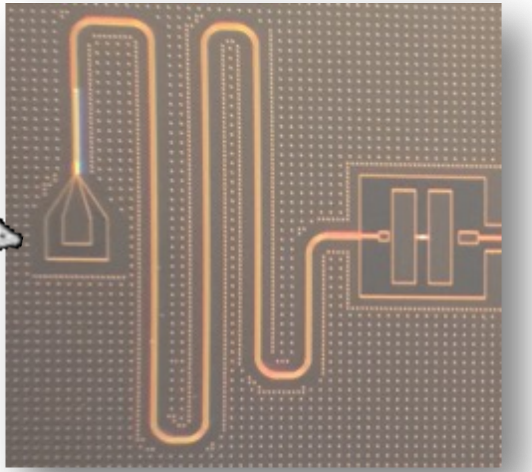
$$H = \omega_Q \hat{a}^\dagger \hat{a} + \frac{\alpha}{2}\hat{a}^\dagger \hat{a}(\hat{a}^\dagger \hat{a} - 1) + \underbrace{\Omega(\hat{a}^\dagger + \hat{a})\cos(\omega_D t + \phi)}$$

This term is physically generated by applying an oscillating voltage (microwave pulse) at the qubit

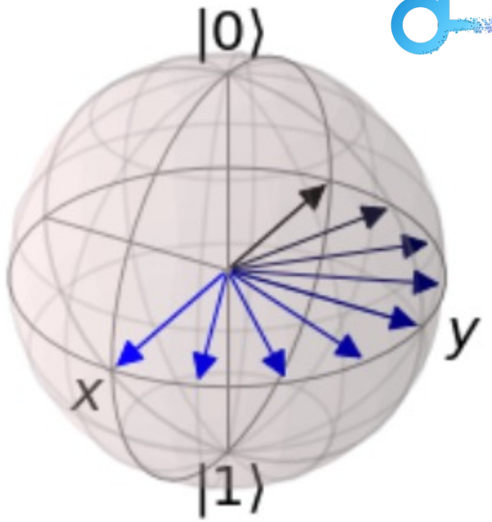


Single Qubit Control

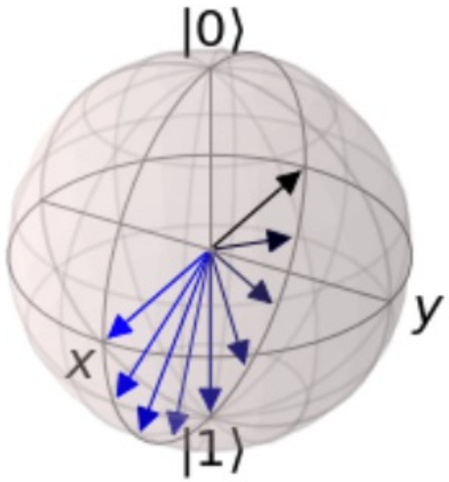


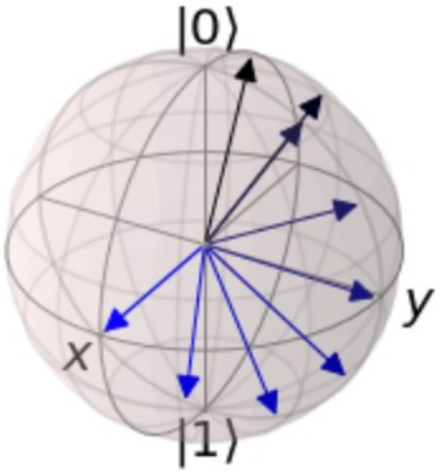


Z Rotations



Axis of rotation in Bloch sphere depends on phase





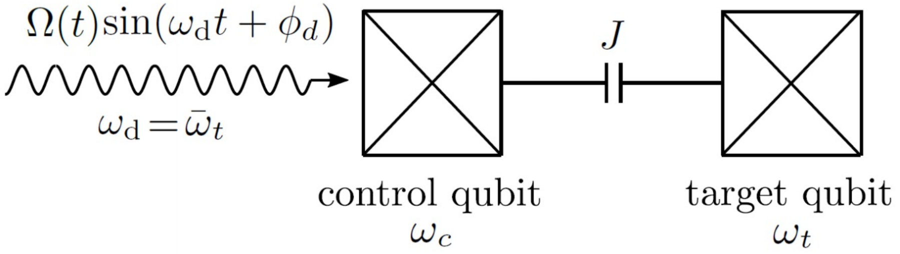
Rotations come for free:

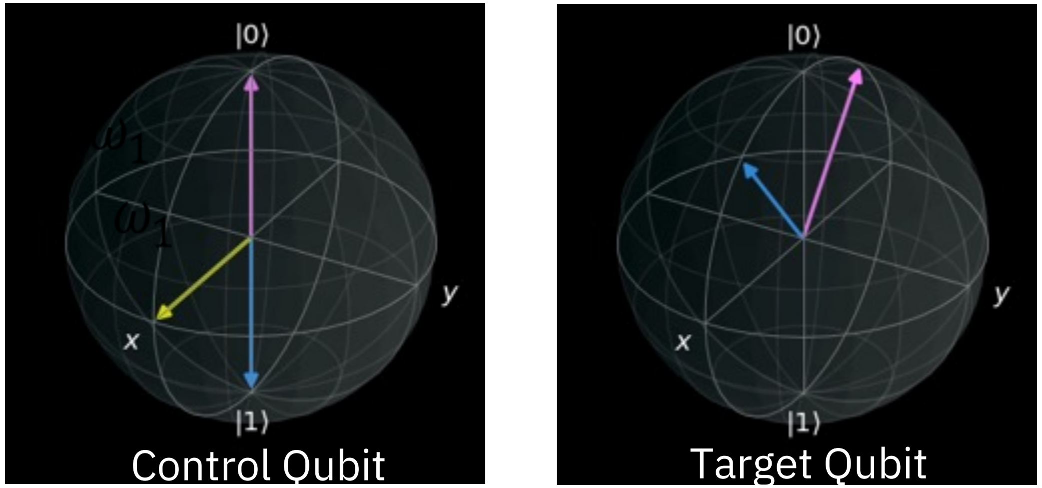
Just shift phase of subsequent pulses

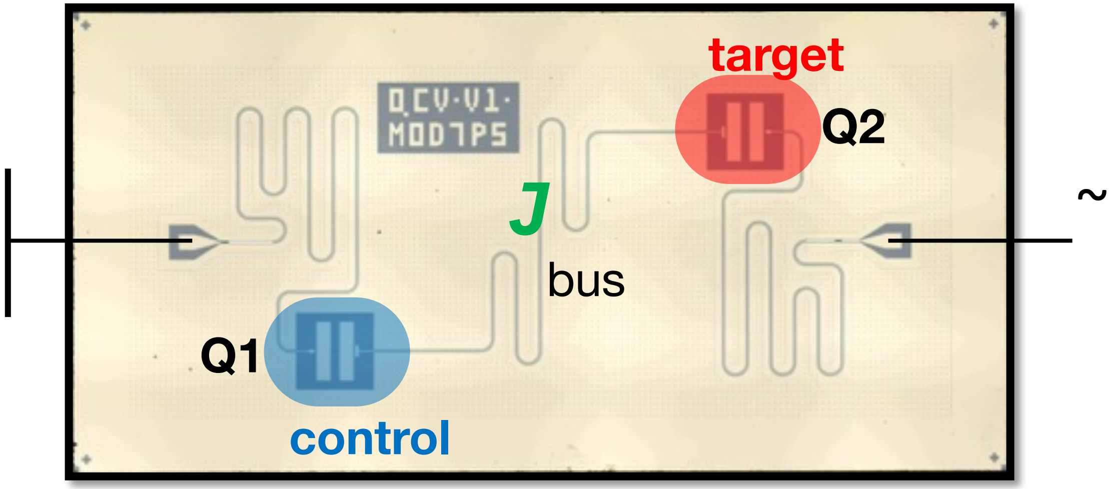
Two Qubit Gates

Cross Resonance: *ZX* Operation

Rotation of Target Qubit depends on state of Control Qubit

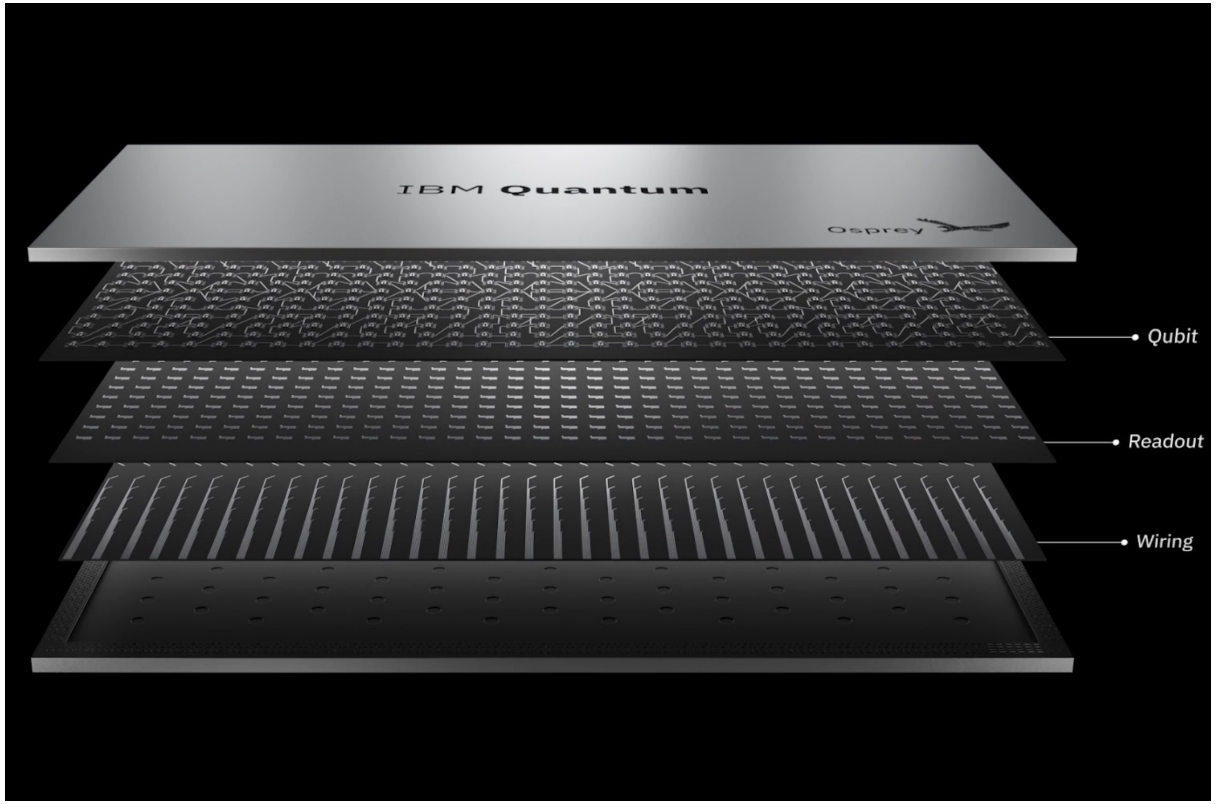




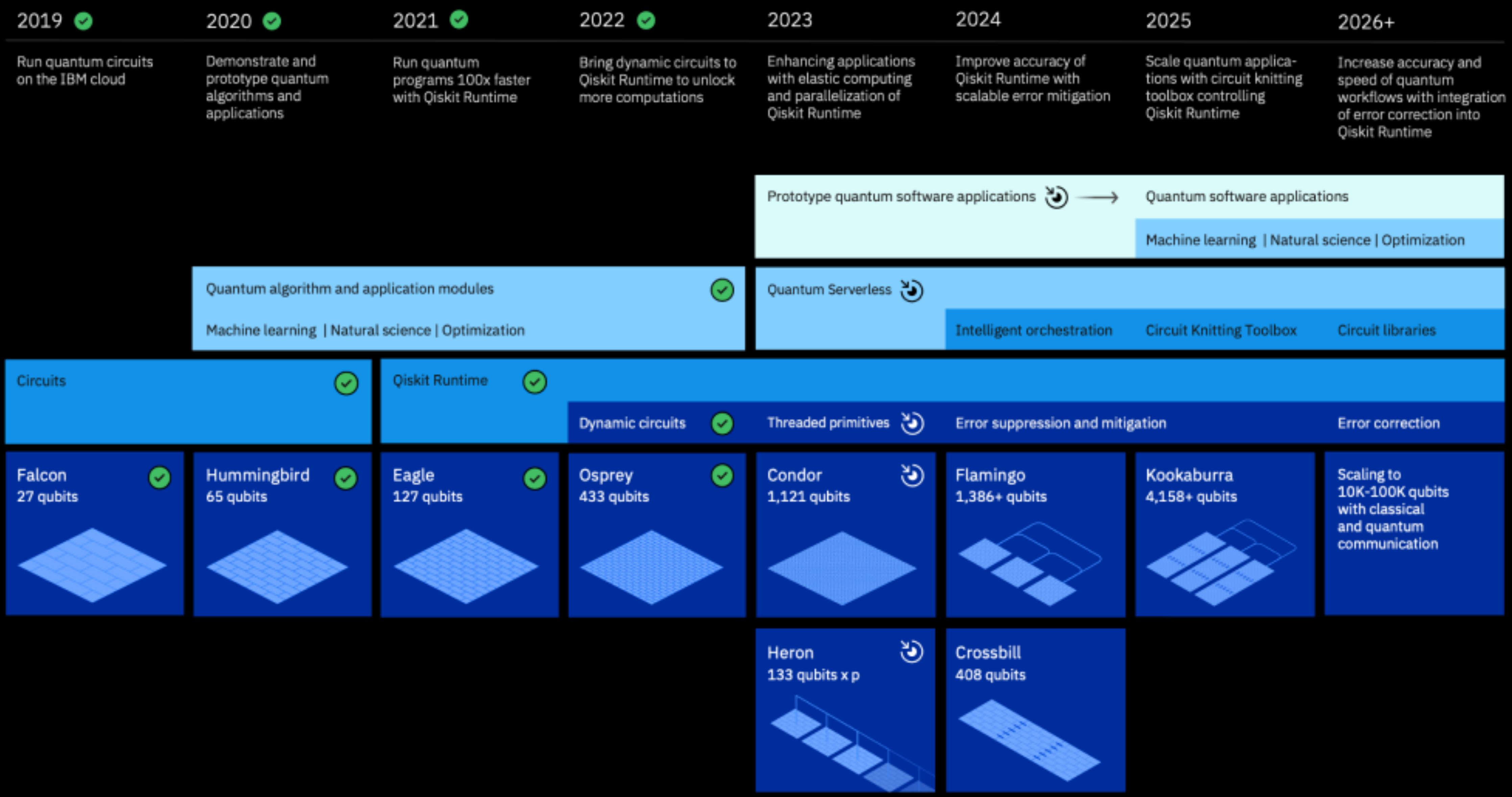


[C Rigetti et al, PRB (2010)] [JM Chow et al, PRL (2011)]

Large Processor Development

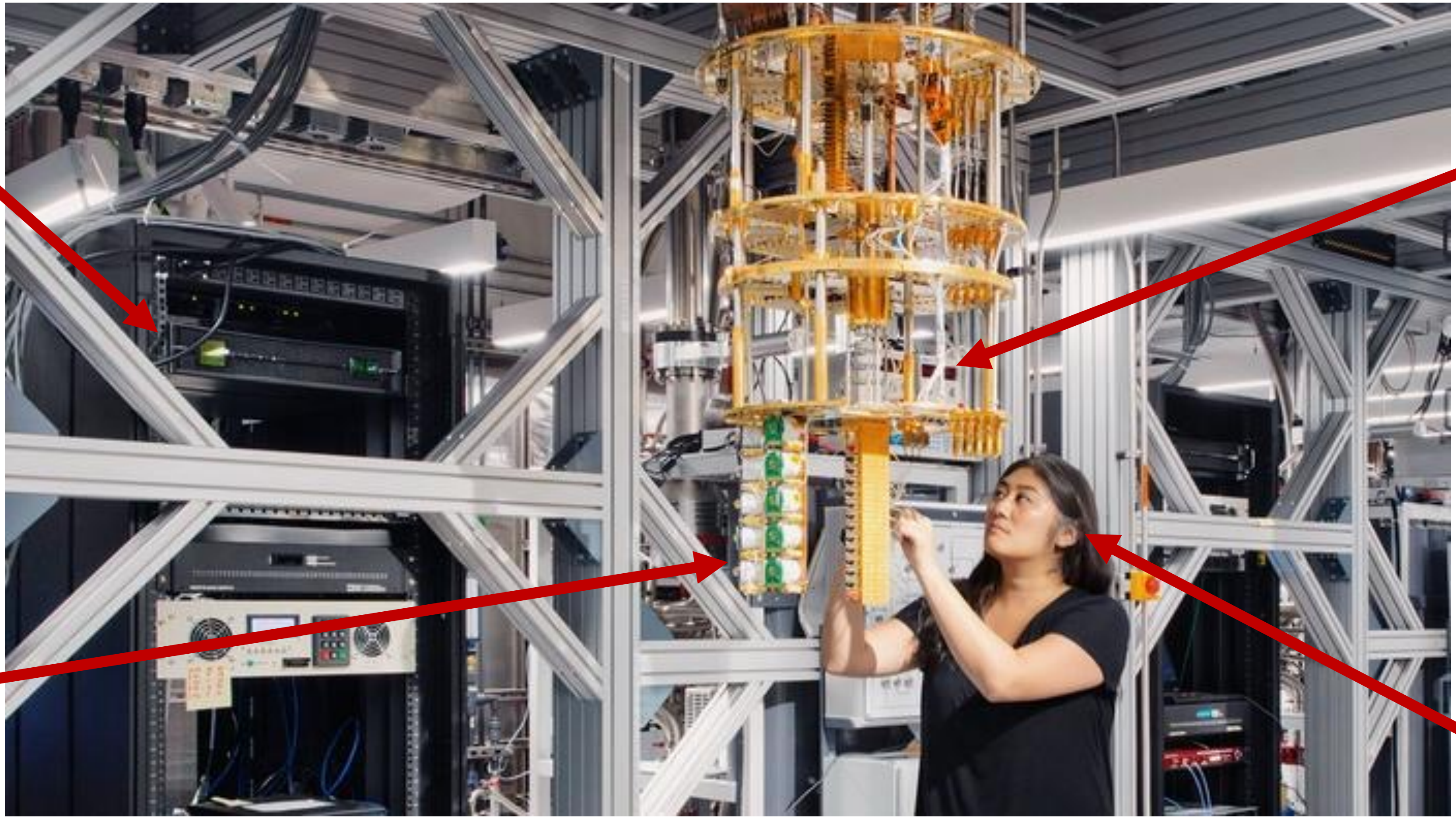


Development roadmap



Putting it all together

Room temp control electronics



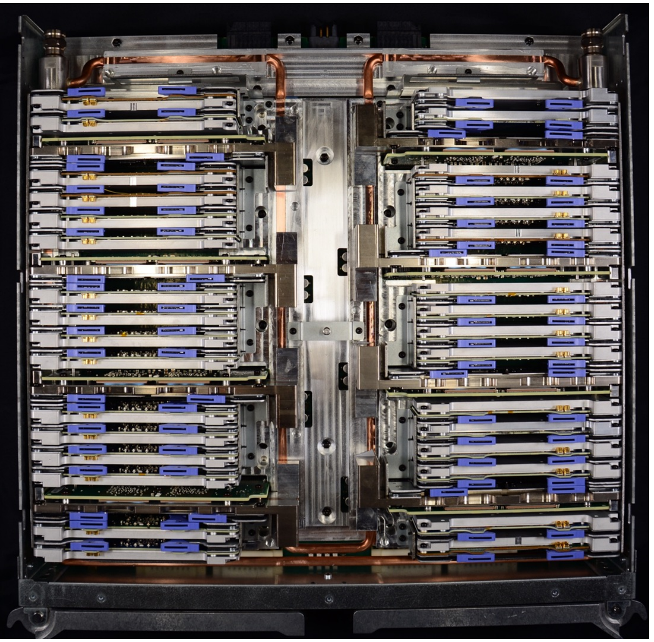
Radio-frequency (RF) cables

Qubits + cryo amplifiers

Maika ☺

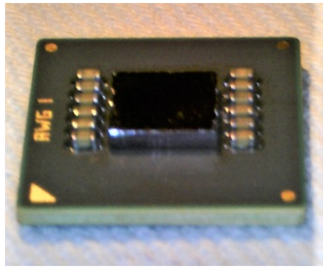
Quantum Hardware Challenges

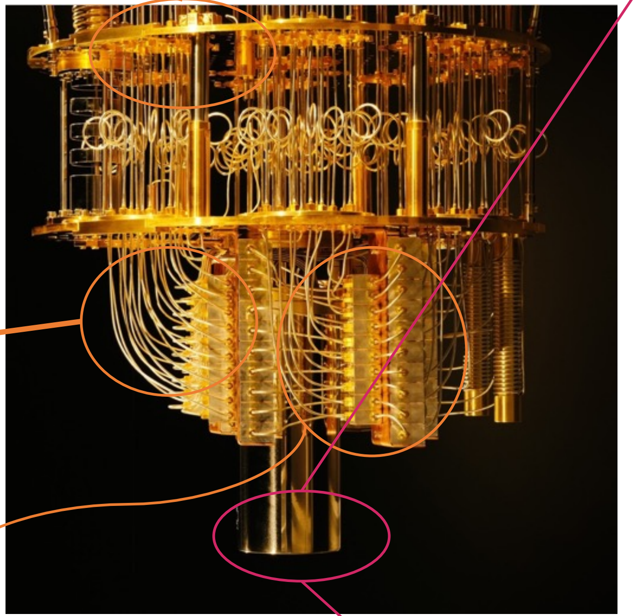
Room temp electronics
(stable, low-noise, cost)



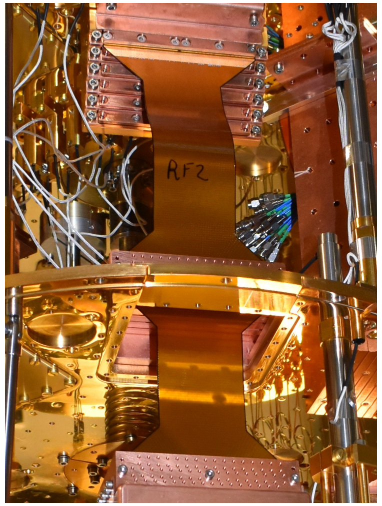
Inside the Cryo Dilution Fridge

Cryo-CMOS controls

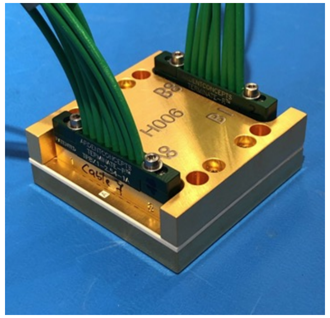




Cryo flex lines

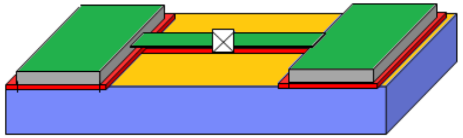


Amplifiers, Attenuators, Isolators

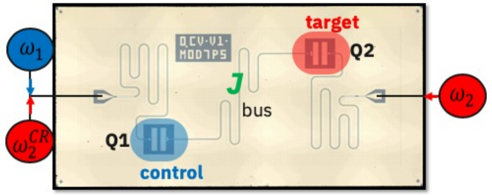


Processor, device development

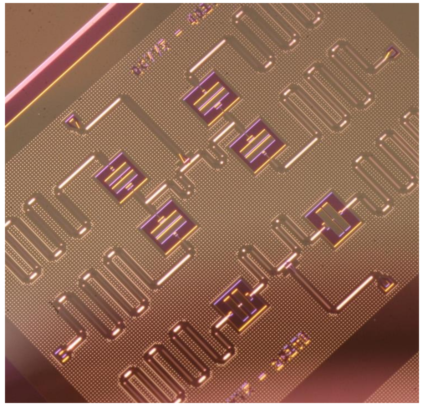
Coherence, junctions, materials



Better two-qubit gates

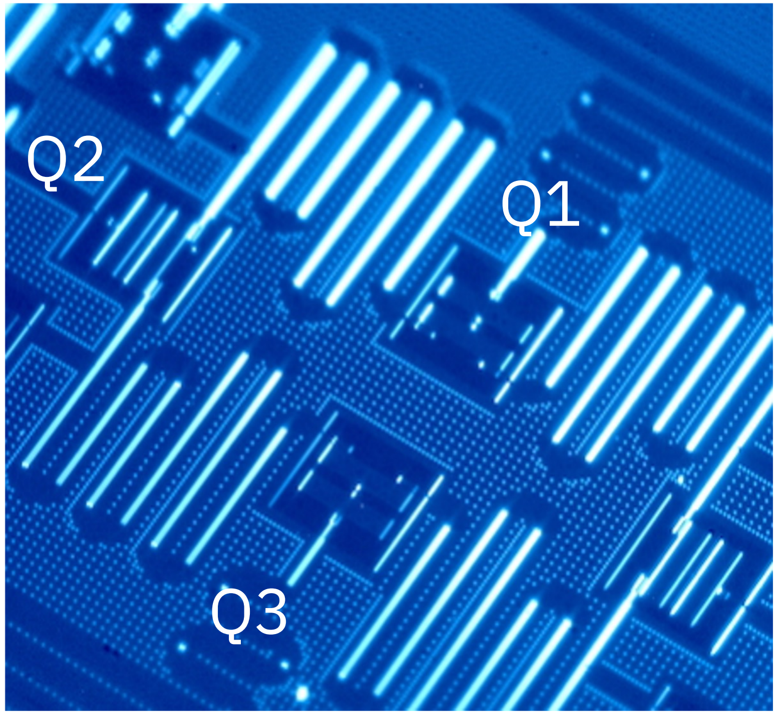


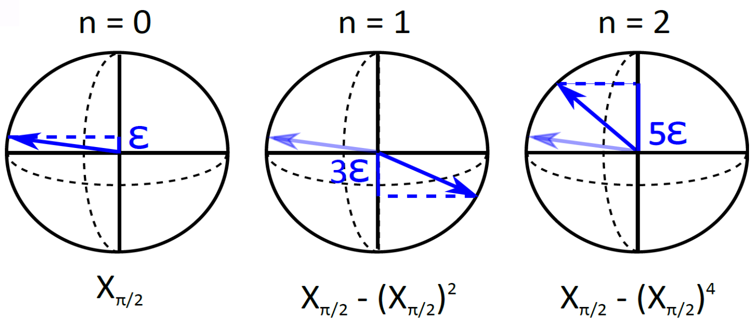
Novel qubit couplers

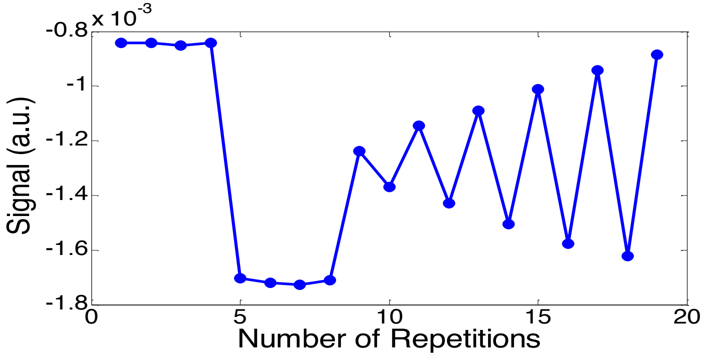


Coherent errors

$$U_{CNOT} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix} \qquad U_{Exp} = \begin{bmatrix} 0.995 & 0.1j & 0 & 0 \\ -0.1j & 0.995 & 0 & 0 \\ 0 & 0 & -0.1 & 0.995 \\ 0 & 0 & 0.995 & -0.1 \end{bmatrix}$$







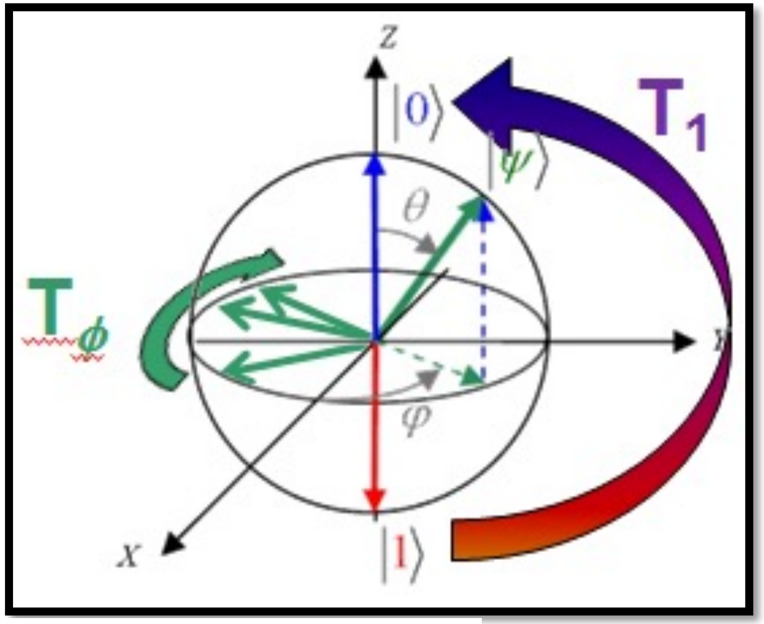
- Always-on interactions
- Spectators (Quantum cross-talk)
- Frequency collisions

- Coherent over/under rotations
- Calibration of pulses by error amplification

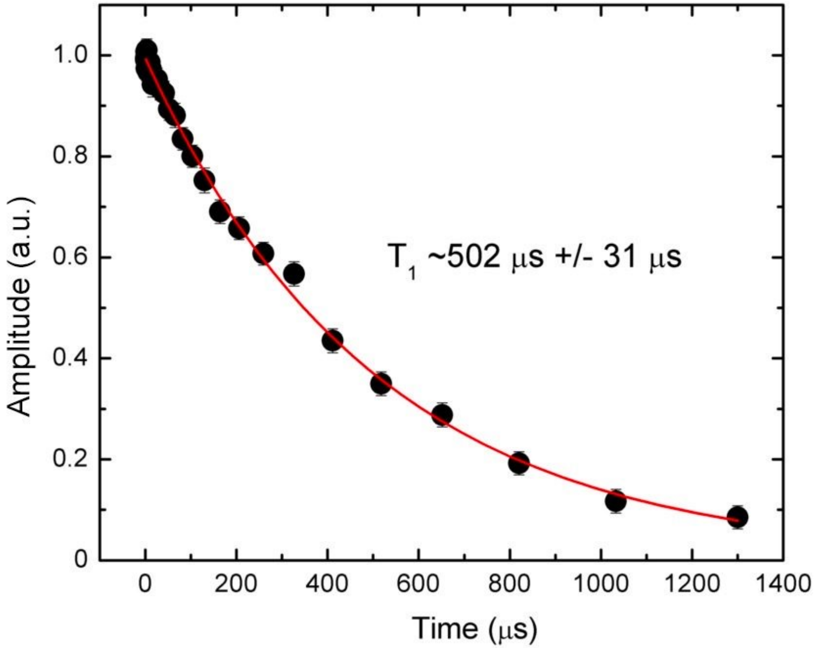
- Incomplete understanding of drive Hamiltonian

Incoherent errors

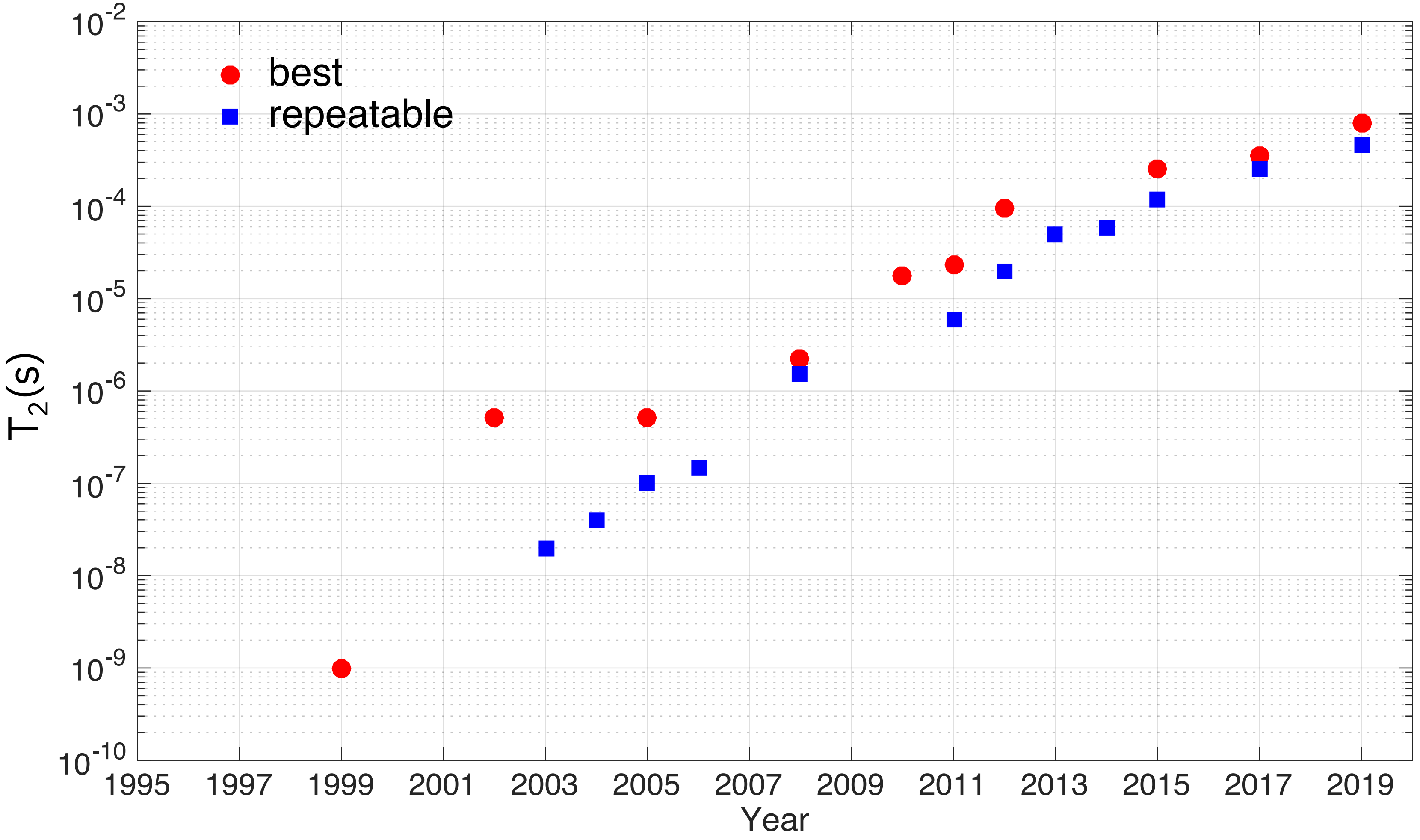
- **Qubit decoherence** (loss of quantum information)
  - T_1: relaxation time (decay from |1> to |0>)
  - T_ϕ: dephasing time (randomization of ϕ)
  - T_2: overall decoherence time (both T_1 and T_ϕ)



$$\frac{1}{T_2} = \frac{1}{2T_1} + \frac{1}{T_\phi}$$



Superconducting qubits coherence timeline



– Understand charge noise e.g. [1]

– 3D transmon [5]

– IR Shielding [6,7],

– Cold cavities & cold qubits [8]

– High Q cavities [9]

– Materials e.g. [2,10]

– Design and geometries [4,10]

– Microwave environment [3]

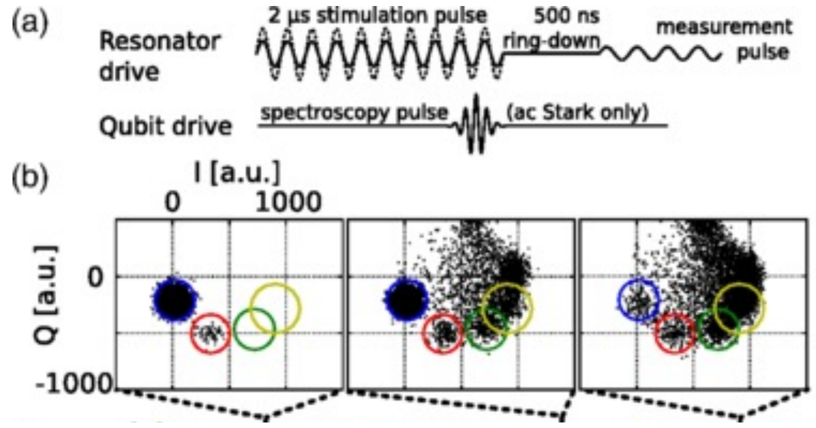
[1] Koch et. al. PRA 76, 04319 (2007)
[2] J. Martinis et al., PRL 95 210503 (2005)
[3] Houck et. al. PRL 101, 080502 (2008)
[4] K. Geerlings et al., APL 100, 192601 (2012)
[5] H. Paik et al., PRL 107, 240501 (2011)
[6] R. Barends et al., APL 99, 113507 (2011)
[7] A. Corcoles et al., APL 99, 181906 (2011)
[8] C. Rigetti et al., PRB 86, 100506 (2012)
[9] M. Reagor et al., APL 102, 192604 (2013)
[10] J. Chang et al. APL 103, 012602 (2013)

Sources of Leakage

- Single qubit gates
- Readout
- Two qubit gates
- Reset

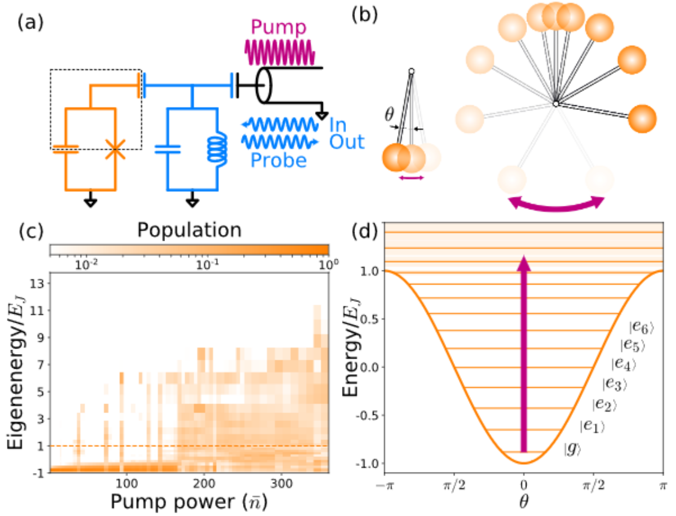
- Bandwidth of fast pulse excites e-f transitions.

- Readout signal can excite multiphoton transitions to states well above |f>



Sank, PRL 2016.

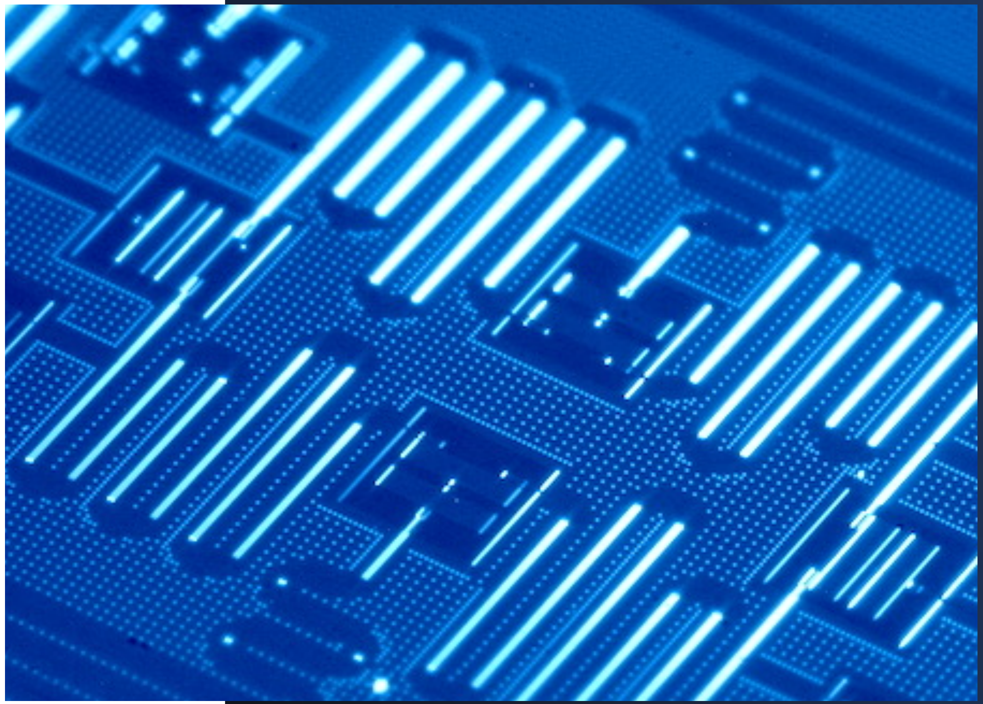
- Depends on implementation
- CR requires very strong drive tones
- We know to avoid certain collision frequencies to avoid leakage
- Ongoing research



Verney, PRApp (2019)

Summary & Take-Aways

- You now know what a real superconducting qubit looks like, and the components that make it
- A little something about classical circuits and quantum circuits
- Why Josephson Junctions are *key*
- How to measure and control a qubit
- Key challenges in the field of hardware research



Thank you