EPFL

MICRO-435 Quantum and Nanocomputing

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Quantum Computing Syllabus (Week 1-7)

- Fundamentals of quantum computing
- **Qubit realization & control**
- Cryo-CMOS components
- Scalable quantum computers
- Quantum communication, sensing, and metrology

Qubit Realization & Control

- Background
- Quick superconductivity recap
- Superconducting qubits
- Transmon control
- Qubit readout
- Relaxation and dephasing
- Control system

Background

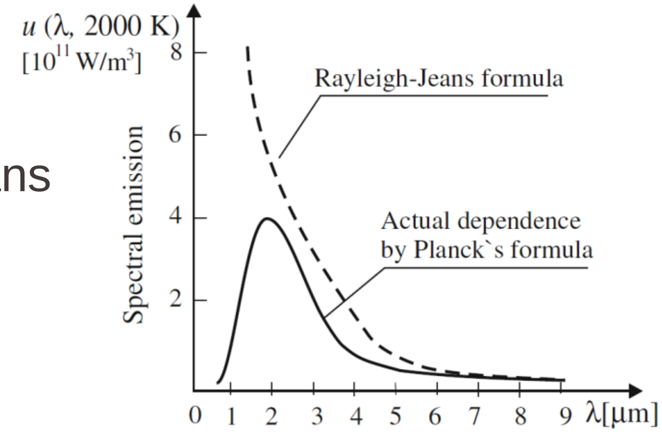
The Birth of Quantum Mechanics: Planck's Intuition

- The development of quantum mechanics was preceded by the discovery by Max Planck (in 1900).
- Planck's assumption was that energy was exchanged in a noncontinuous manner between particles and radiation, and emitted in quanta proportional to a constant ($h = 6.626 \times 10^{-34}$ Js – Planck constant) and the radiation frequency f:

$$E = hf$$

- Planck law of spectral emission was then formulated, and with respect to the Rayleigh-Jeans formula that diverged at high frequencies, gave more stable and experimentally valid values:

$$u(f,T) = \frac{4hf^3}{c^3}\frac{1}{\exp\left(\frac{hf}{k_B T}\right) - 1}$$



Schrödinger's Equations

- The Schrödinger equation was formulated in 1926 on the speculative basis by analogy with the then known descriptions of waves and particles.
- The Schrödinger equation describes the state of an elementary particle and features a function referred to as state function or wave function Ψ, and expresses its complex dependence on time and position coordinates of the particles:

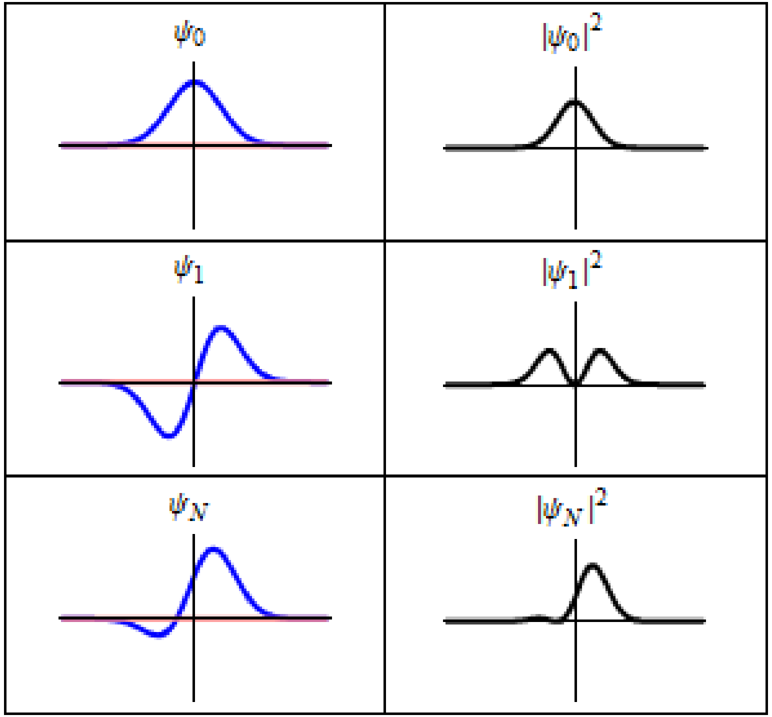
$$-\frac{\hbar^2}{2m}\nabla^2\Psi + A\Psi = j\hbar\frac{\partial\Psi}{\partial t}$$

- The Schrödinger equation can be also written in terms of the Hamiltonian operator $\hat{H}$ as

$$\hat{H}|\Psi(t)\rangle = j\hbar\frac{\partial}{\partial t}|\Psi(t)\rangle$$

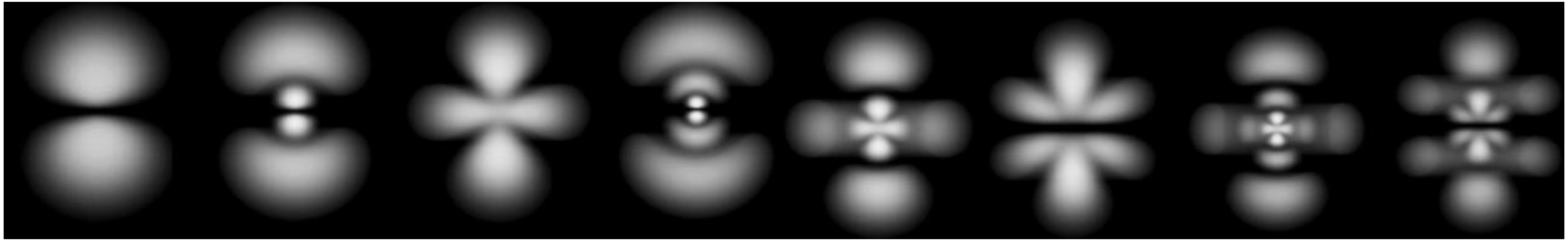
W. Nawrocki, *Introduction to Quantum Metrology: Quantum standards and instrumentation*, 1st ed., 2015, Chap 1.2

Examples of Wave Functions



Wave functions satisfying the time-dependent Schrödinger equation for harmonic oscillations. Source: Wikipedia.

3-D Wave Functions



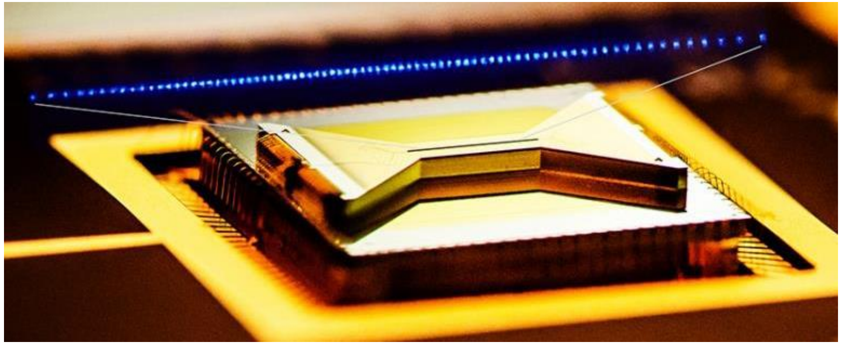
Wave functions for orbitals in atoms

A Physical interpretation of the wave function was first proposed by Max Born in 1926: the wave function describes the probability that the particle is present within a certain region, specifically in a volume dV. The probability density is proportional to the square of the module of the wave function:

$$P = k|\Psi|^2 dV$$

The Concept of Artificial Atoms

- Feynman’s intuition* was to use physics systems to compute.
- This required the creation of qubits in real physical systems
- One could use the wave function of an atom to represent a qubit, but this would require to keep an atom in isolation, to read it out (destructively or non-destructively) and to control it.
- The closest realization to this idea is that of creating trapped ions.

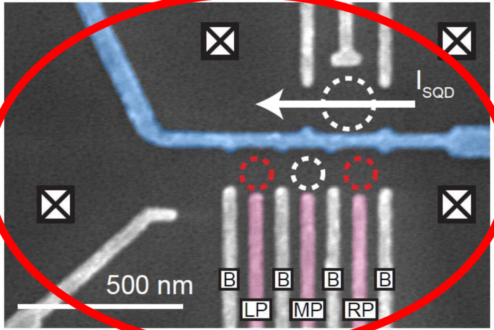


Source: Chris Monroe, Univ. of Maryland

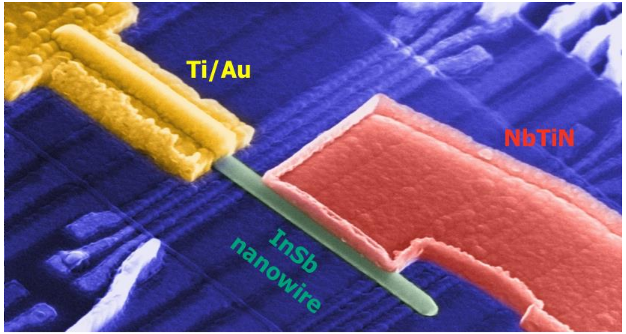
*) R.P. Feynman, “Simulating physics with computers,” *International Journal of Theoretical Physics*, vol. 21, pp. 467–488, June 1982.

Solid-State Qubits

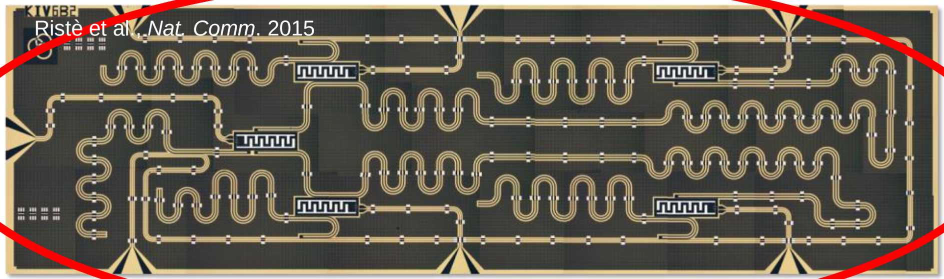
- In alternative to trapped ions, several have been made to achieve solid-state qubits.

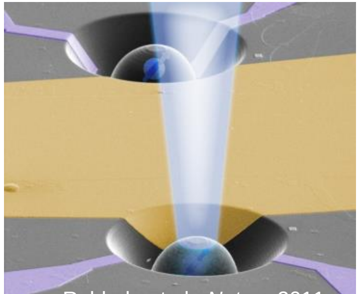


Semiconductor quantum dots



Semiconductor-superconductor hybrids


Ristè et al., *Nat. Comm.* 2015
Superconducting circuits


Robledo et al., *Nature* 2011
Impurities in diamond or silicon

Source: L. Vandersypen, 2017

Principle of Superposition

- The most powerful property of quantum systems, however, relies in the principle of superposition of states. In a quantum system where two states $|0\rangle$ and $|1\rangle$ are state vectors solutions of the Schrödinger equation, due to the linear nature of the equation, also all linear combinations of these states, i.e.

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle,$$

are solution of the Schrödinger equation, hence possible states.

- The coefficients α^2 and β^2 satisfy the condition $\alpha^2 + \beta^2 = 1$ and represent the probability for the quantum system to be in either $|0\rangle$ or $|1\rangle$ states respectively.

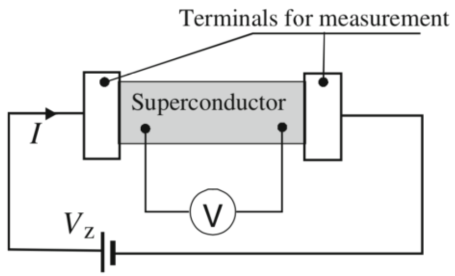
W. Nawrocki, *Introduction to Quantum Metrology: Quantum standards and instrumentation*, 1st ed., 2015

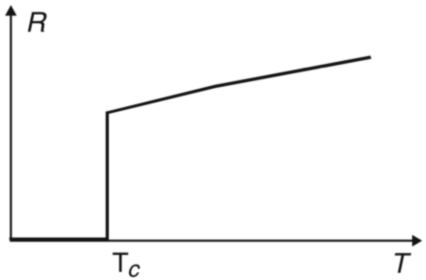
Quick Superconductivity Recap

Superconductivity & Josephson Effect

- Quantum voltage standards use the effect of voltage quantization in Josephson junctions. A necessary condition for a Josephson junction to operate is the superconducting state of its electrodes.
- The transition to the superconducting phase occurs at a specific temperature referred to as critical temperature T_C.
- Common superconducting materials are:

<u>Metals:</u> Mercury (1911, $T_c = 4.15$ K), Niobium ($T_c = 9.3$ K), Lead ($T_c = 7.2$ K), Vanadium ($T_c = 5.4$ K)
<u>Binary Alloys:</u> Nb_3Ge ($T_c = 23.2$ K), V_3Si ($T_c = 17.1$ K), MgB_2 (2001, $T_c = 39$ K)
<u>Ceramics:</u> $La_2Sr_4CuO_4$ (1986, $T_c = 36$ K), $YBaCu_3O_7$ ($T_c = 91$ K)





W. Nawrocki, *Introduction to Quantum Metrology: Quantum standards and instrumentation*, 1st ed., 2015

Theory of Superconductivity

- In 1957 Leon Cooper (USA), a Ph.D. student under supervision of John Bardeen, proposed to explain the zero electrical resistance by the occurrence of electron pairs (referred to as Cooper pairs) in the superconducting phase.
- Each Cooper pair includes two strongly correlated electrons with opposite orientation of momentum and spin. In a superconducting material Cooper pairs form a coherent quantum condensate (fluid) and are all described by a single wave function fulfilling the Schrödinger equation:

$$\Psi = \Psi_0 \exp\left[-\frac{j}{\hbar}(Et - \boldsymbol{p}\boldsymbol{x})\right], \qquad \rho = \Psi \times \Psi^* = \Psi_0^2$$

W. Nawrocki, *Introduction to Quantum Metrology: Quantum standards and instrumentation*, 1st ed., 2015

Theory of Superconductivity (2)

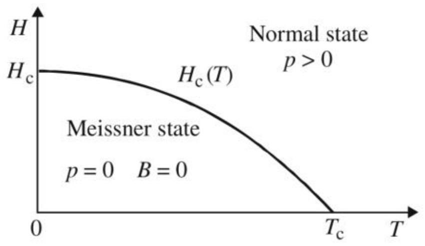
- Setting in motion one electron from a Cooper pair brings about a response of the other electron. As this response involves no energy loss, a number of electrons can move without dissipating any energy to produce a zero-resistance electric current.

- Developed by Bardeen, Cooper and Schrieffer, the theory based on Cooper pairs is commonly referred to as the BCS theory.

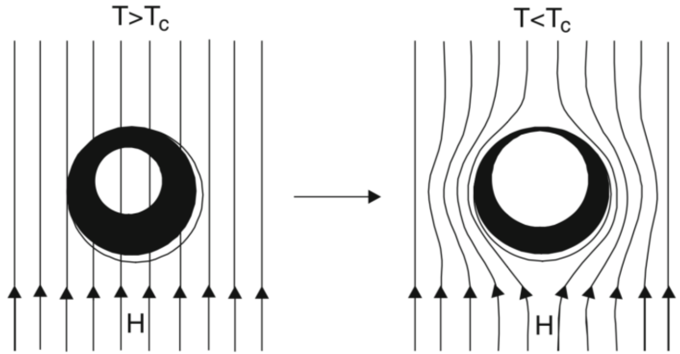
W. Nawrocki, *Introduction to Quantum Metrology: Quantum standards and instrumentation*, 1st ed., 2015

Superconductivity and Magnetic Fields

- In a sufficiently strong magnetic field the superconductor will quit the superconducting state to return to its normal state.
- The minimum value of magnetic field necessary to destroy superconductivity is known as the critical magnetic field H_c. The critical magnetic field H_c increases with decreasing temperature of the sample.

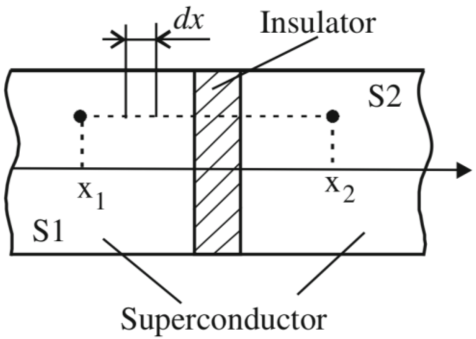


- Discovered in 1933 by German physicists Walter Meissner and Robert Ochsenfeld, is the expulsion of magnetic field from the interior of superconductors, which therefore act as ideal diamagnetic materials. This expulsion of magnetic field by superconductors is referred to as the Meissner effect.



Josephson Effect

- In 1962 Brian D. Josephson, 22 years old graduate student in Cambridge, studied a junction consisting of two superconductors separated by an insulating layer with 0.1–1 nm thickness.
- The wave functions of Cooper pairs in two separated superconductors S1 and S2 are independent. However, if the distance between the superconductors is small (0.1–1 nm), Cooper pairs cross the potential barrier between superconductors due to the tunneling effect.



- Let Ψ_A and Ψ_B be the wave functions of Cooper pairs in superconductors S1 and S2, respectively:

$$\psi_A = \sqrt{n_A} e^{i\phi_A} \qquad \psi_B = \sqrt{n_B} e^{i\phi_B}$$

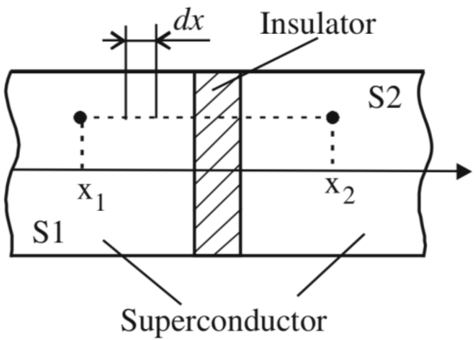
where n_A is the charge carrier density and ϕ_i is the phase of Ψ_i

Josephson Junction

- When the distance between the superconductors is small, their wave functions are correlated due to Cooper pair exchange. The correlation of both wave functions can be expressed as:

$$i\hbar\frac{\partial}{\partial t}\begin{pmatrix}\sqrt{n_A}e^{i\phi_A}\\ \sqrt{n_B}e^{i\phi_B}\end{pmatrix}=\begin{pmatrix}eV & K\\ K & -eV\end{pmatrix}\begin{pmatrix}\sqrt{n_A}e^{i\phi_A}\\ \sqrt{n_B}e^{i\phi_B}\end{pmatrix}$$

where K is the superconductor coupling coefficient.



W. Nawrocki, *Introduction to Quantum Metrology: Quantum standards and instrumentation*, 1st ed., 2015

Josephson Junction

- To solve the above equation, first calculate the time derivative of the order parameter in superconductor A:

$$\frac{\partial}{\partial t}(\sqrt{n_A}e^{i\phi_A}) = \dot{\sqrt{n_A}}e^{i\phi_A} + \sqrt{n_A}(i\dot{\phi}_A e^{i\phi_A}) = (\dot{\sqrt{n_A}} + i\sqrt{n_A}\dot{\phi}_A)e^{i\phi_A}$$

- Define $\varphi = \phi_B - \phi_A$
- The Schrödinger equation becomes:

$$\dot{\sqrt{n_A}} + i\sqrt{n_A}\dot{\phi}_A = \frac{1}{i\hbar}(eV\sqrt{n_A} + K\sqrt{n_B}e^{i\varphi})$$

- And its complex conjugate:

$$\dot{\sqrt{n_A}} - i\sqrt{n_A}\dot{\phi}_A = \frac{1}{-i\hbar}(eV\sqrt{n_A} + K\sqrt{n_B}e^{-i\varphi})$$

Josephson Junction

- Add the two conjugate equations together to eliminate $\dot{\phi}_A$:

$$2\sqrt{\dot{n}_A} = \frac{1}{i\hbar}\left(K\sqrt{n_B}e^{i\varphi} - K\sqrt{n_B}e^{-i\varphi}\right) = \frac{K\sqrt{n_B}}{\hbar} \cdot 2\sin\varphi.$$

- Using: $\sqrt{\dot{n}_A} = \dfrac{\dot{n}_A}{2\sqrt{n_A}}$

$$\dot{n}_A = \frac{2K\sqrt{n_A n_B}}{\hbar}\sin\varphi$$

- Knowing that the $\dot{n}_A$ is proportional to the current when $n_A = n_B$ we can write:

$$I(t) = I_c \sin(\varphi(t))$$

Josephson Junction

- Add the two conjugate equations together to eliminate $\dot{\phi}_A$:

$$2\dot{\sqrt{n_A}} = \frac{1}{i\hbar}\left(K\sqrt{n_B}e^{i\varphi} - K\sqrt{n_B}e^{-i\varphi}\right) = \frac{K\sqrt{n_B}}{\hbar}\cdot 2\sin\varphi.$$

- Using: $\dot{\sqrt{n_A}} = \frac{\dot{n}_A}{2\sqrt{n_A}}$

$$\dot{n}_A = \frac{2K\sqrt{n_A n_B}}{\hbar}\sin\varphi$$

- Knowing that the $\dot{\mathrm{n}}_{\mathrm{A}}$ is proportional to the current when $n_{\mathrm{A}} = n_{\mathrm{B}}$we can write:

$$I(t) = I_c \sin(\varphi(t))$$ First Josephson equation

Josephson Junction

- Subtract the two conjugate equations together to eliminate $\sqrt{\dot{n}_A}$:

$$2i\sqrt{n_A}\dot{\phi}_A = \frac{1}{i\hbar}\left(2eV\sqrt{n_A} + K\sqrt{n_B}e^{i\varphi} + K\sqrt{n_B}e^{-i\varphi}\right)$$

$$\dot{\phi}_A = -\frac{1}{\hbar}\left(eV + K\sqrt{\frac{n_B}{n_A}}\cos\varphi\right)$$

- For superconductor B: $\dot{\phi}_B = \frac{1}{\hbar}\left(eV - K\sqrt{\frac{n_A}{n_B}}\cos\varphi\right)$

- Using $\dot{\varphi} = \dot{\phi}_B - \dot{\phi}_A$, we obtain

$$\frac{\partial\varphi}{\partial t} = \frac{2eV(t)}{\hbar}$$

Second Josephson equation

Josephson Junction

- From both Josephson equations, we get the following relationships:

$$I = I_C \sin\phi\,, \qquad V = \frac{\Phi_0}{2\pi}\dot{\phi}$$

from which we can obtain the Josephson inductance and energy

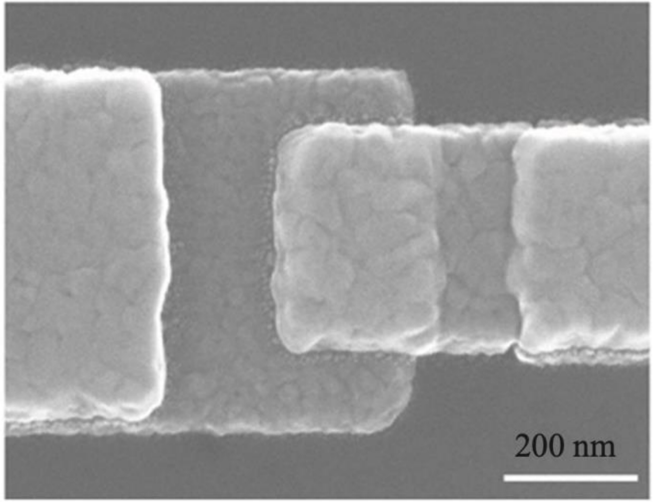
$$V = \frac{\Phi_0}{2\pi}\dot{\phi} = \frac{\Phi_0}{2\pi I_C}\frac{1}{\cos\phi}\dot{I} = L_J\dot{I}$$

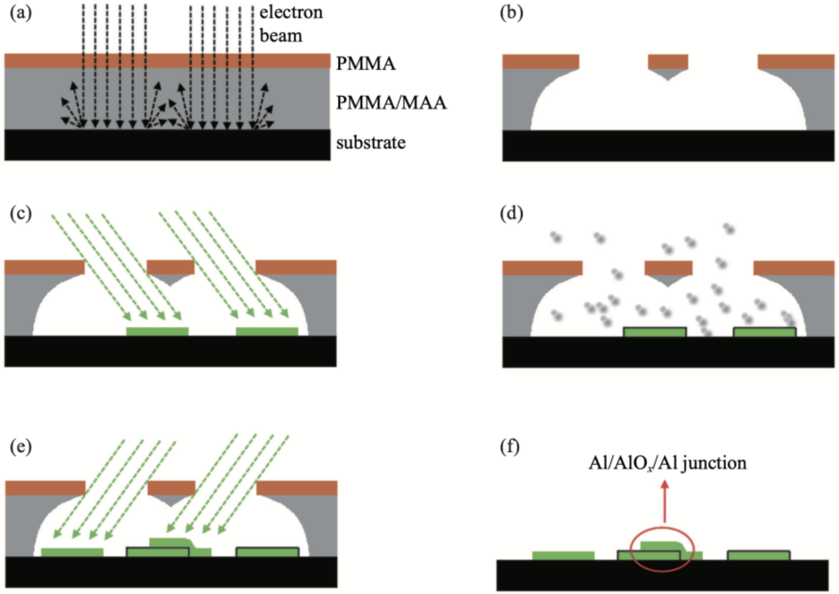
$$E_J = \int VI\,dt = \frac{\Phi_0 I_C}{2\pi}(1-\cos\phi)$$

with $\Phi_0 = h/2e$ being the single flux quantum and $\phi = \phi_A - \phi_B$ the Josephson phase

Josephson Junction Fabrication

- Josephson junctions are fabricated using shadowing depositions such as the Manhattan or Dolan Bridge techniques.

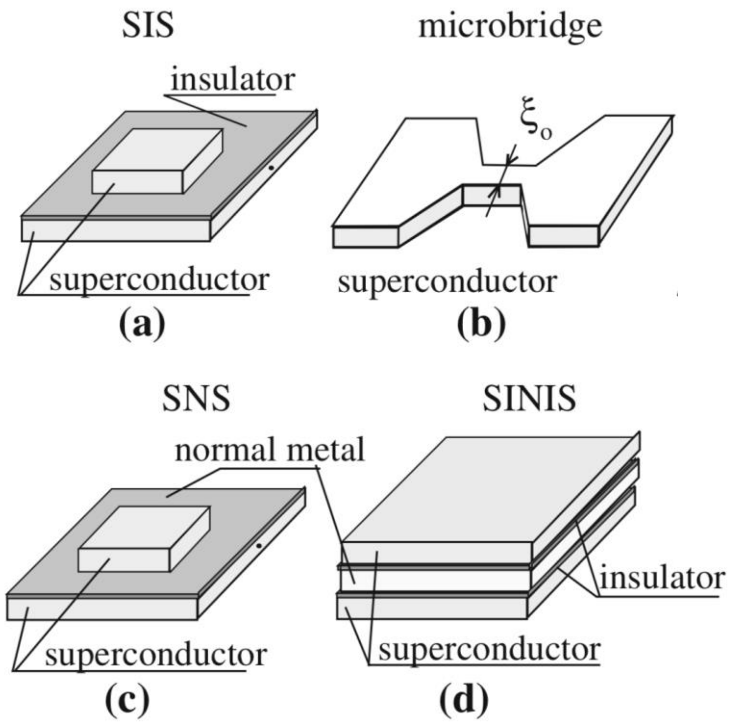




W. Yu-Lin et al., *Fabrication of Al/AlO$_x$/Al Josephson junctions and superconducting quantum circuits by shadow evaporation and a dynamic oxidation process*, Chin. Phys. B Vol. 22, No. 6 (2013)

Josephson Junction Summary

Type of junction	–	SIS	SINIS	SNS
Material	–	Nb-Al/ AlO_x-Nb	Nb-Al/AlO_x/Al/ AlO_x/Al-Nb	Nb-Nb_xSi_{1-x}-Nb with $x \approx 10$ %
Number of Josephson junctions N	–	13 924	69 632	69 632
Number of microstrips	–	4	128	128
Number of JJs in one microstrip N_m	–	3481	136–562	136–562
Junction length l	μm	20	15	6
Junction width w	μm	50	30	20
Current density j	A cm^{-2}	10	750	3000
Critical current I_c	mA	0.1	3.5	3.5
Normal state resistance R_n	Ω	15 at 1.5 mV	0.04 at I_c	0.04 at I_c



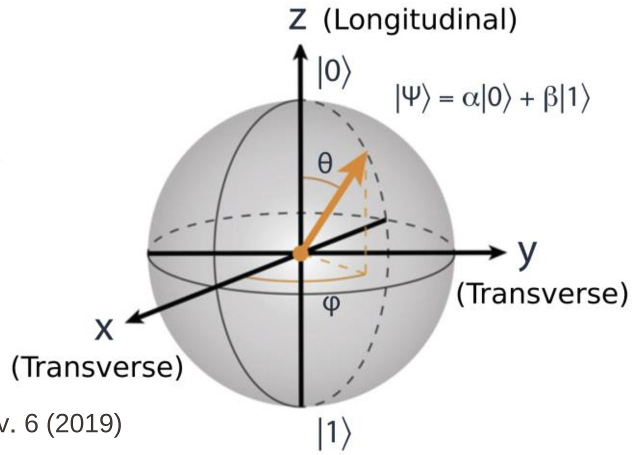
W. Nawrocki, *Introduction to Quantum Metrology: Quantum standards and instrumentation*, 1st ed., 2015, Chap 4.3

Superconducting Qubits

What is a qubit?

- A qubit is a quantum system, hence governed by the rules of quantum mechanics, which can be approximated to a two-levels system (a 0 and a 1 states "only").

- According to the Di Vincenzo criteria, a qubit needs to be easy to initialize and should have long coherence time compared to the gating times.



P. Krantz et al., *A quantum engineer's guide to superconducting qubits*, Appl. Phys. Rev. 6 (2019)

A.Blais et al., Circuit Quantum electrodynamics, Rev. Mod. Phys. 93, 025005(2021)

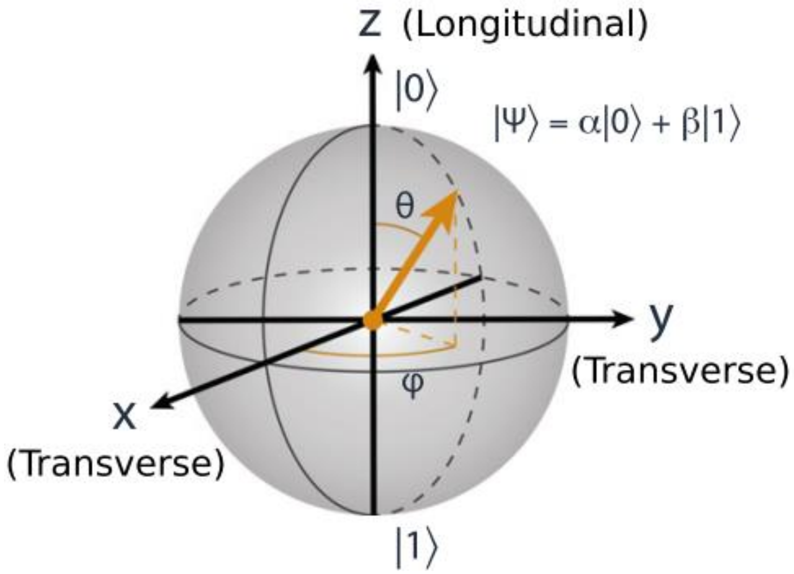
What is a qubit?

- The evolution of the quantum system is determined by a time dependant Schrödinger equation:

$$\hat{H}(t)|\psi(t)\rangle = j\hbar\frac{\partial|\psi(t)\rangle}{\partial t}$$

- Single qubit Hamiltonian is:

$$H = -\frac{\omega_q}{2}\sigma_z$$



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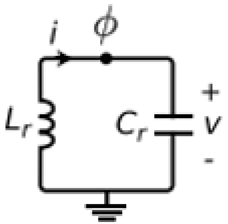
Quantum harmonic oscillator



$$E(t) = \int_{-\infty}^{t} V(t')I(t')dt' \quad (1)$$

$$\Phi(t) = \int_{-\infty}^{t} V(t')dt' \quad (2)$$

$$V = L\,dI/dt, \quad I = C\,dV/dt$$

From 1 and 2 we can write energy for capacitor and inductor

$$\mathcal{T}_C = \frac{1}{2}C\dot{\Phi}^2$$

$$\mathcal{U}_L = \frac{1}{2L}\Phi^2$$

Lagrangian is defined as:

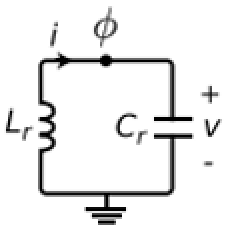
$$\mathcal{L} = \mathcal{T}_C - \mathcal{U}_L = \frac{1}{2}C\dot{\Phi}^2 - \frac{1}{2L}\Phi^2$$

Classical Hamiltonian is defined as:

$$Q = \frac{\partial \mathcal{L}}{\partial \dot{\Phi}} = C\dot{\Phi}$$

$$H = Q\dot{\Phi} - \mathcal{L} = \frac{Q^2}{2C} + \frac{\Phi^2}{2L} \equiv \frac{1}{2}CV^2 + \frac{1}{2}LI^2$$

Quantum harmonic oscillator



Classical Hamiltonian

$$H = Q\dot{\Phi} - \mathcal{L} = \frac{Q^2}{2C} + \frac{\Phi^2}{2L} \equiv \frac{1}{2}CV^2 + \frac{1}{2}LI^2$$

Promoting classical coordinates to quantum operators which satisfy the commutation relation

$$\left[\hat{\Phi}, \hat{Q}\right] = \hat{\Phi}\hat{Q} - \hat{Q}\hat{\Phi} = i\hbar$$

$$H = 4E_C n^2 + \frac{1}{2}E_L \phi^2$$

$$\phi \equiv 2\pi\Phi/\Phi_0$$

$$n = Q/2e$$

$$E_C = e^2/(2C)$$

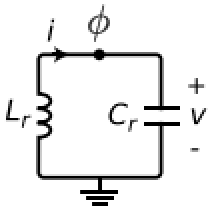
$$E_L = (\Phi_0/2\pi)^2/L$$

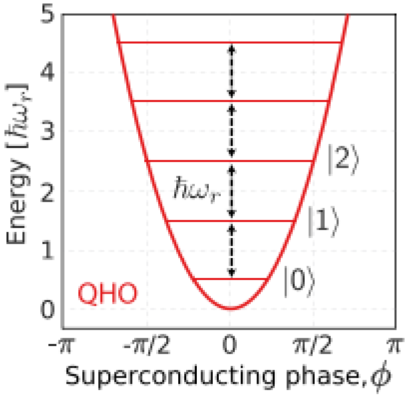
Solving the eigen value problem:

$$\omega_r = \sqrt{8E_L E_C}/\hbar = 1/\sqrt{LC}$$

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

Role of cryogenic temperatures





$$\omega_r = \sqrt{8E_L E_C}/\hbar = 1/\sqrt{LC}$$

- At room temperature (*T=300K*) the thermal energy is high enough to excite multiple states
- The system will be in a statistical mixture of states and not a pure quantum state

$$\frac{kT}{\hbar\omega_r} = 1250$$

- Thermal energy at least 10 times smaller than energy level difference

$$\hbar\omega_r \gg kT$$

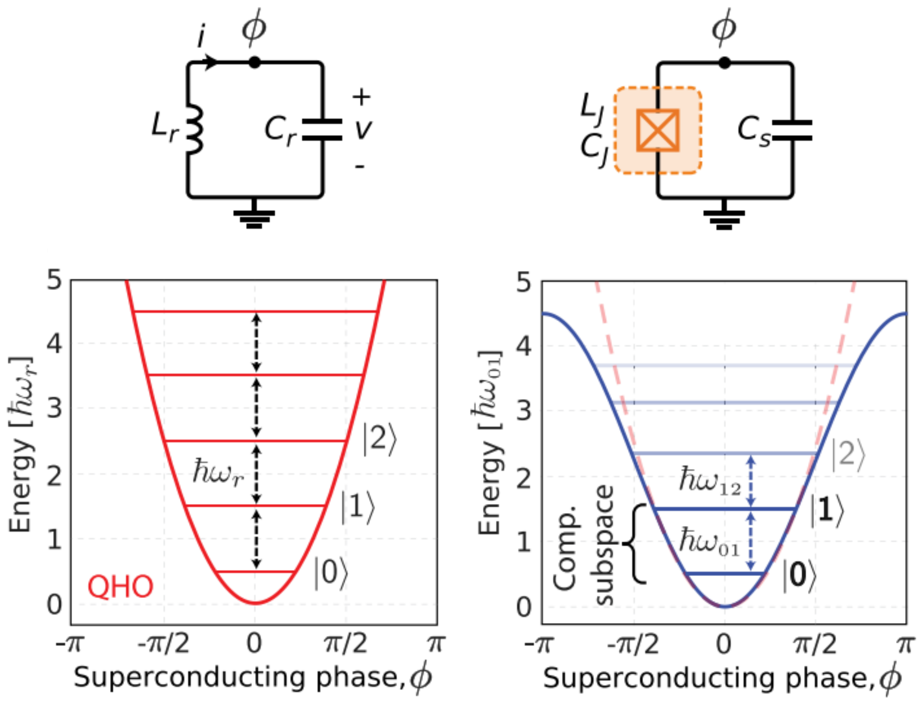
10GHz≈500mK

10-20mK

QHO vs. Qubit

- The necessary nonlinearity that breaks the equidistance of the levels is introduced by replacing the inductor with a Josephson junction

$$\hat{H} = 4E_C(\hat{n} - n_g)^2 - E_J \cos \hat{\varphi}$$

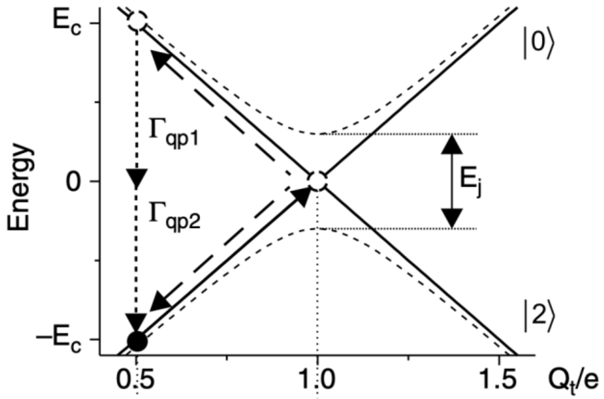


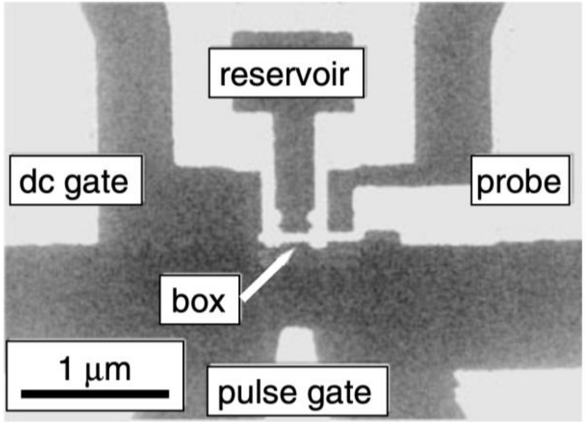
The superconducting qubits: the Cooper Pair Box

- First type of superconducting qubit. It was made in Japan in 1999.

- Very nonlinear due to the large charge energy-to-Josephson energy ratio. For the same reason, it was also extremely susceptible to electrical noise, which caused the characteristic lifetime of the qubit to be very low (order of tens of ns).

- The states |0⟩ and |2⟩ represent presence or absence of a cooper pair in the box.

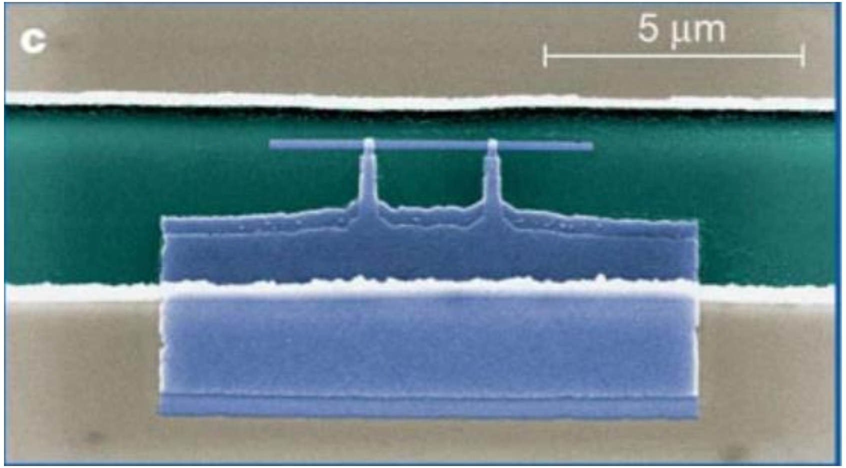


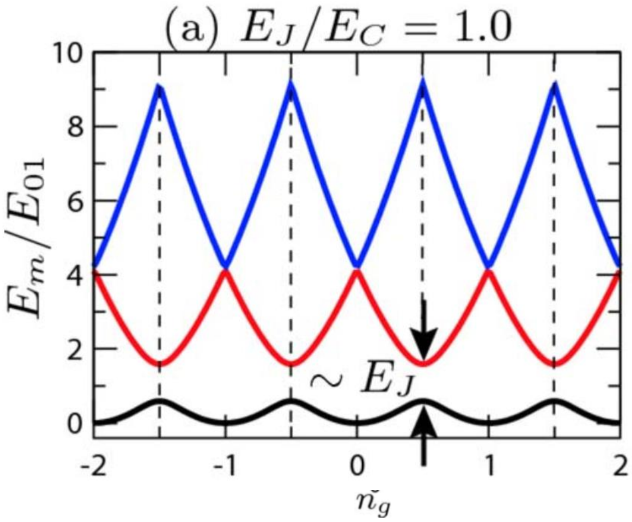


Y. Nakamura et al., *Coherent control of macroscopic quantum states in a single-Cooper-pair box*, Nature 398 (1999)

Cooper Pair Box

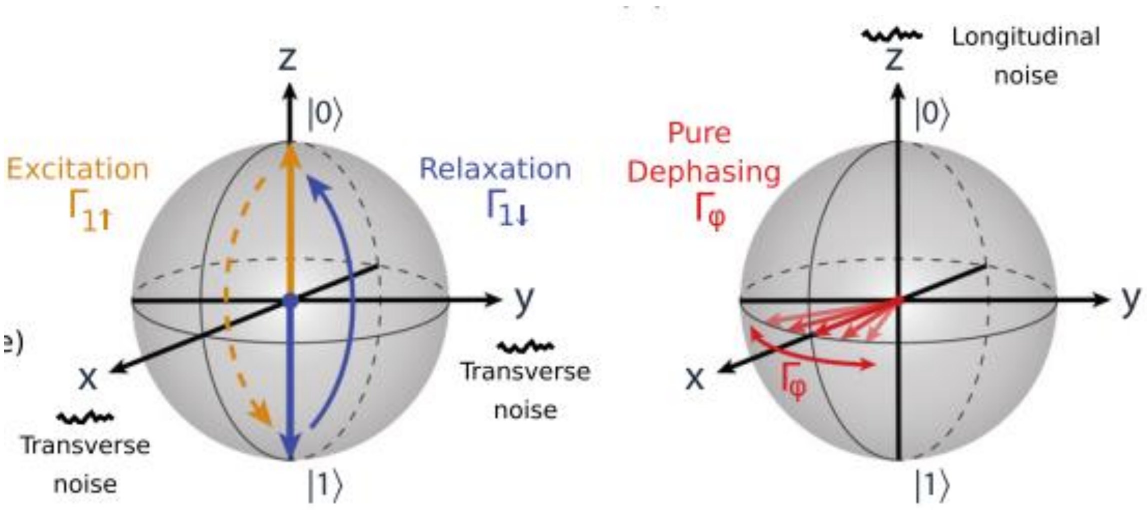
- While the nonlinearity is very large, CPB is susceptible to charge fluctuations.
- This energy fluctuation affects the coherence time of the qubit.





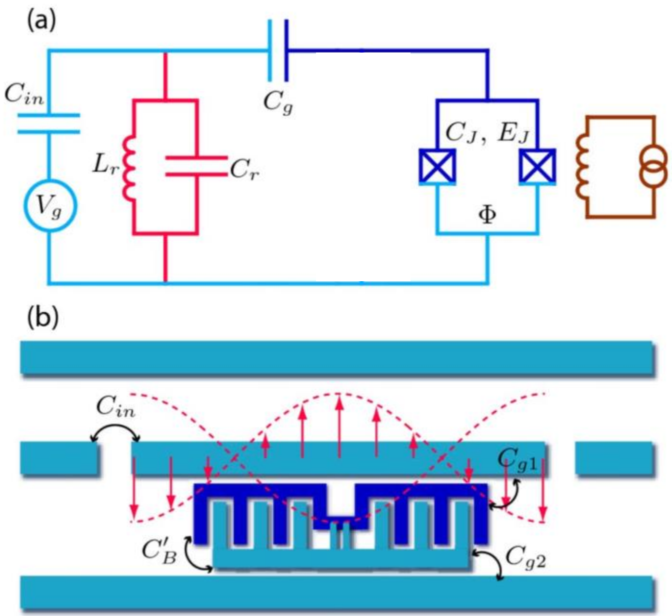
J. Koch et al., *Charge-insensitive qubit design derived from the Cooper pair box, Phys. Rev. A 76, 042319 (2007)*
A. Wallraff, et al. *Strong coupling of a single photon to a superconducting qubit using circuit quantum electrodynamics. Nature 431, (2004)*

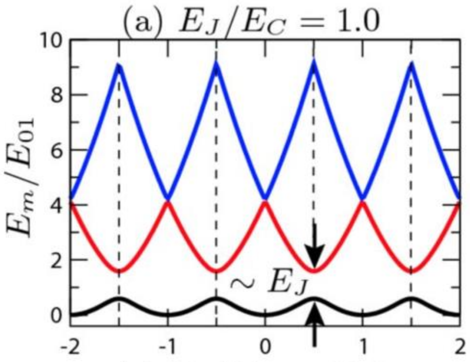
Bloch sphere representation of decoherence



P. Krantz et al., *A quantum engineer's guide to superconducting qubits*, Appl. Phys. Rev. 6 (2019)

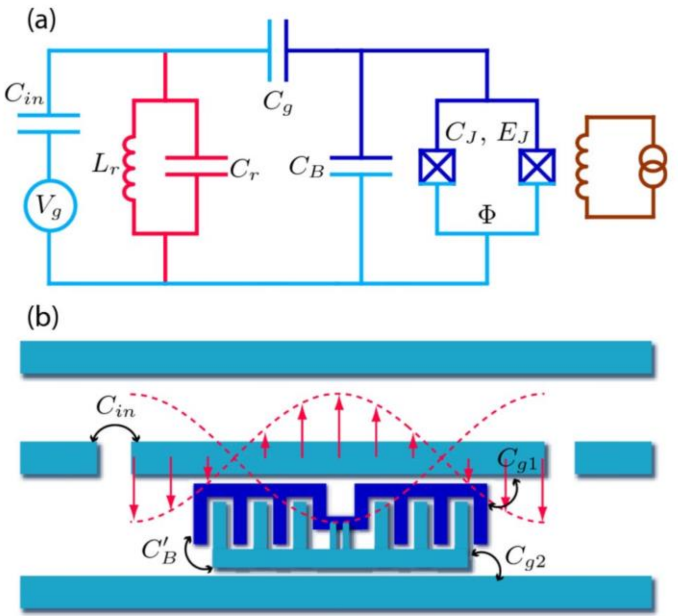
From the CPB to the Transmon regime

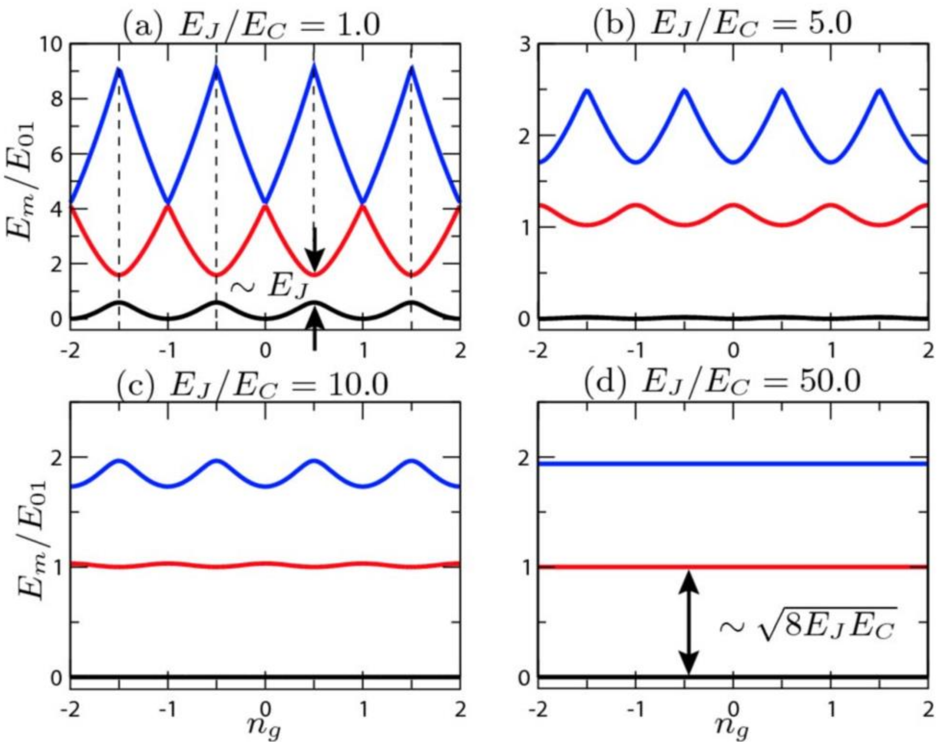




J. Koch et al., *Charge-insensitive qubit design derived from the Cooper pair box*, Phys. Rev. A 76, 042319 (2007)

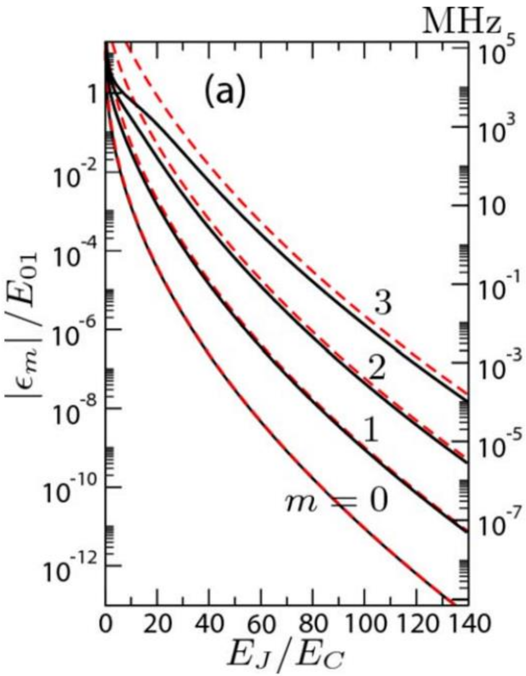
From the CPB to the Transmon

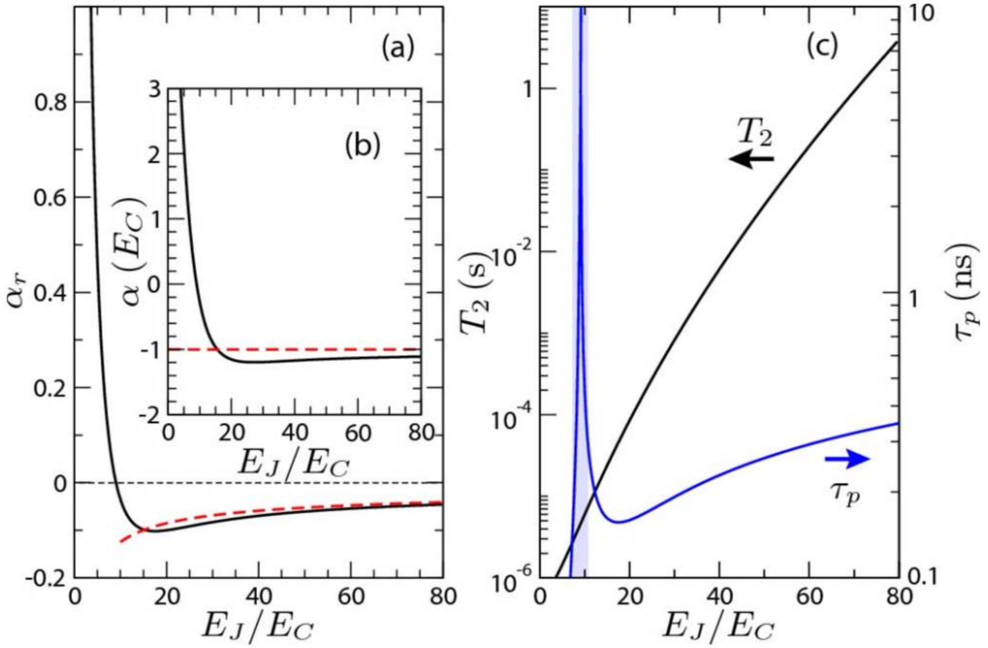




J. Koch et al., *Charge-insensitive qubit design derived from the Cooper pair box*, Phys. Rev. A 76, 042319 (2007)

Transmon regime

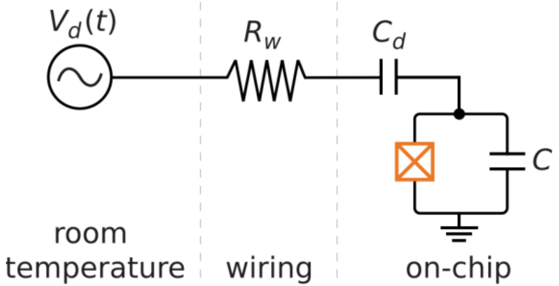




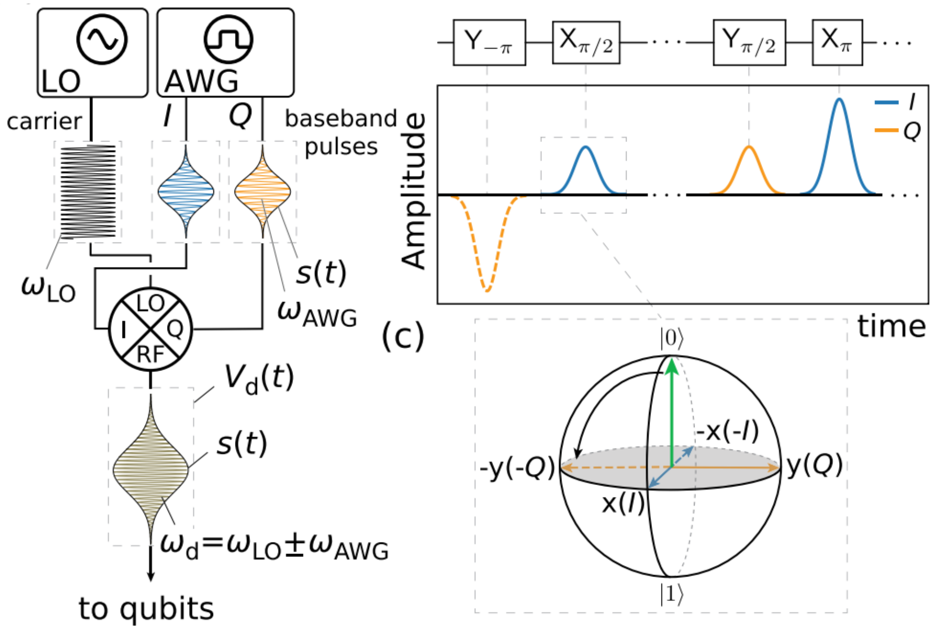
J. Koch et al., Phys. Rev. A 76, 042319 (2007)

- Charge dispersion is exponentially suppressed with Ej/Ec
- Anharmonicity is reduced as a weak power law of Ej/Ec

Transmon control



$$\hat{H} = 4E_C(\hat{n} - n_g)^2 - E_J \cos \hat{\varphi}$$



After diagonalization qubit Hamiltonian can be written as:

$$\mathrm{H} = \omega_q a^\dagger a + \frac{\alpha}{2} a^\dagger a^\dagger a a$$

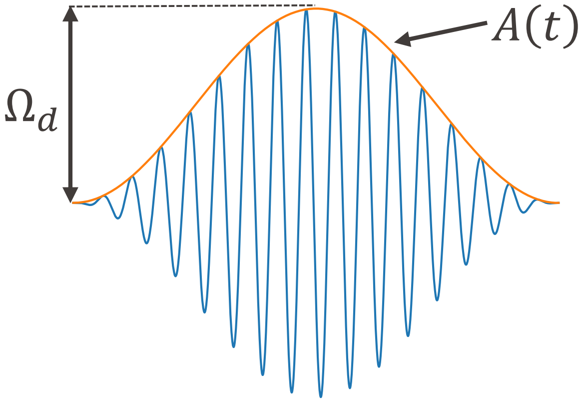
$$\mathrm{H} = (a^\dagger - a)\ \Omega_d A(t)\cos(2\pi f_d t + \phi)$$ Driving Hamiltonian

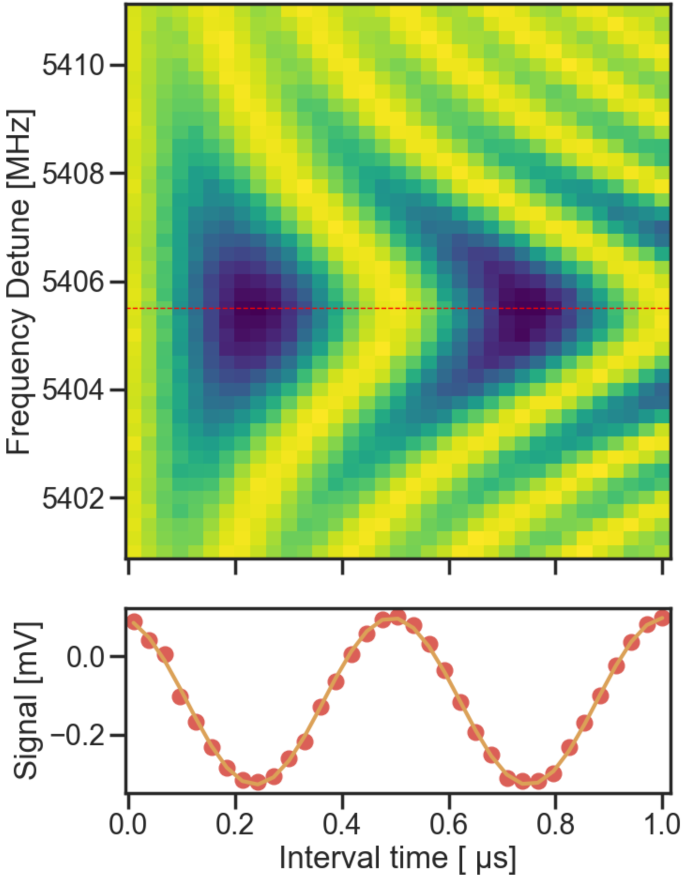
P. Krantz et al., *A quantum engineer's guide to superconducting qubits*, Appl. Phys. Rev. 6 (2019)

Rabi Oscillations and qubit pulse calibration

- Coherent population swapping between the two states while driving at qubit frequency
- Enables calibration of the pulse durations, amplitudes and qubit frequency

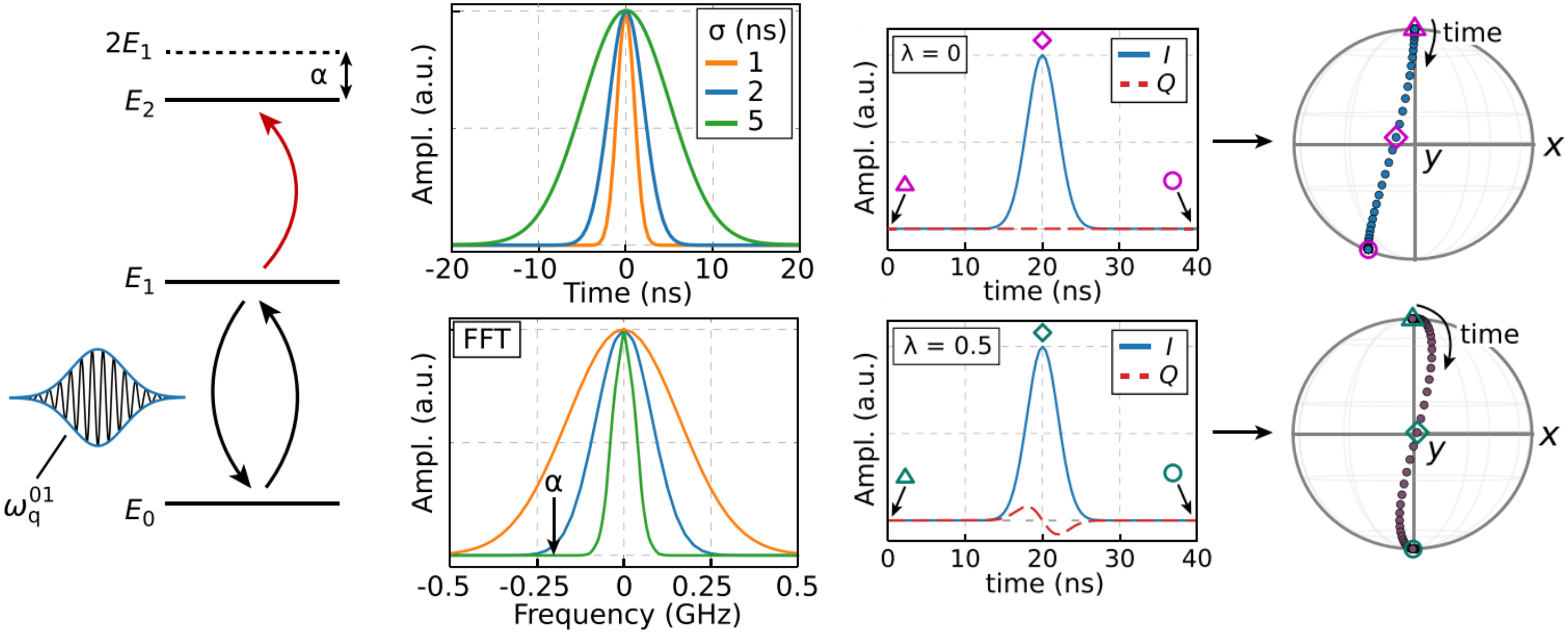
$$\theta = |\langle 0|n|1\rangle| \int_0^{t_g} A(t)dt$$





Gate speed limit

- Small anharmonicity of transmon (100-300 MHz) limits the gate speed
- Improved by special pulse shaping and applying simultaneous drive on both quadratures (DRAG)



P. Krantz et al., *A quantum engineer's guide to superconducting qubits*, Appl. Phys. Rev. 6 (2019)

Gate fidelity

- Gate performance is determined by the gate fidelity metric:

$$F_{avg}(U_{ideal}, U_{real}) = \frac{|\,Tr\left(U_{ideal}^{\dagger} U_{real}\right)|^2}{d^2}$$

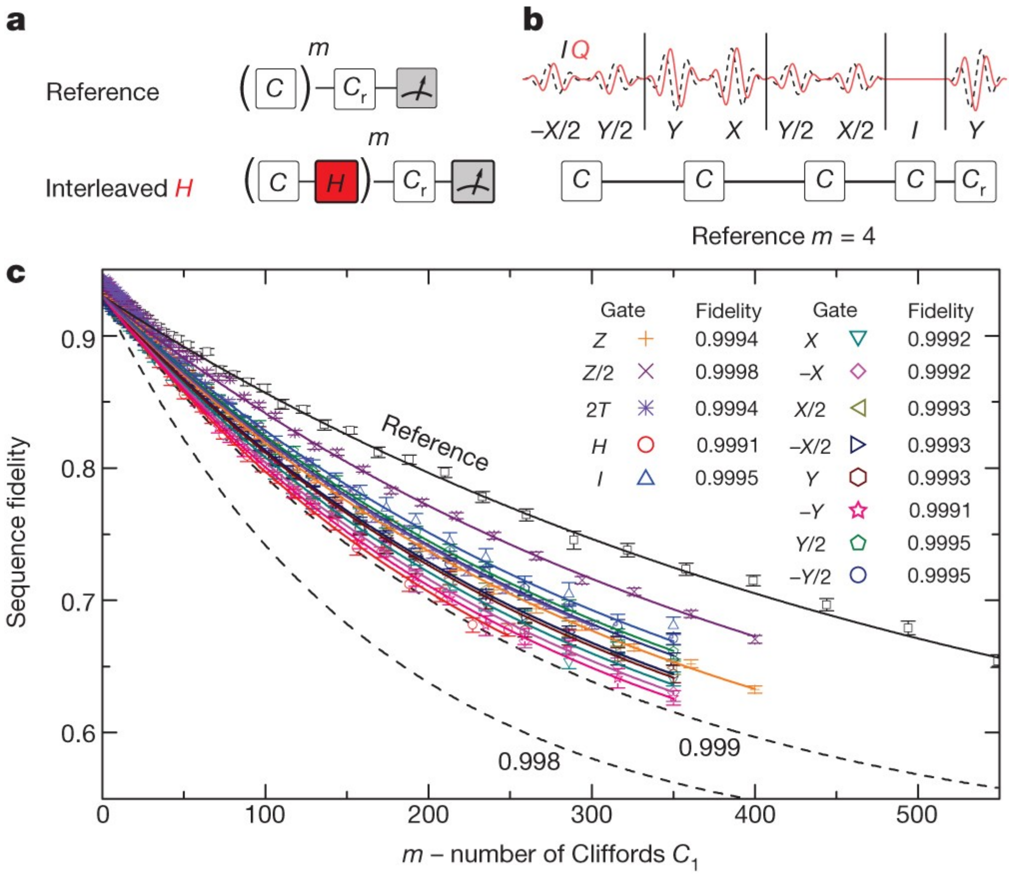
- Where d is the number of states involved d=2 for a qubit
- Gate duration, amplitude, pulse shape need to be tuned to optimize gate fidelity
- Incoherent errors linked to depolarization and decoherence and coherent errors coming from pulse non-idealities
- Expression can be calculated theoretically,
- Experimentally usually measured through randomized bechmarking technique

Randomized benchmarking

$$F_{\text{ref}} = A p_{\text{ref}}{}^{m} + B$$

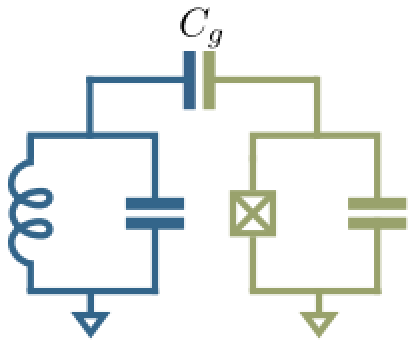
$$r_{\text{ref}} = (1 - p_{\text{ref}})(d-1)/d$$

$$r_{\text{gate}} = (1 - p_{\text{gate}}/p_{\text{ref}})(d-1)/d$$



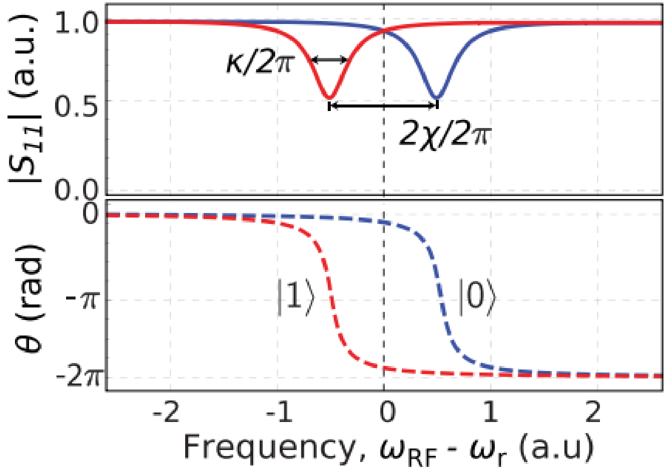
R. Barends et al., *Superconducting quantum circuits at the surface code threshold for fault tolerance*, Nature 508, 500-503 (2014)

Qubit readout



- Superconducting qubits are read out using a microwave resonator
- Resonator can be capacitively coupled to a qubit
- System is described by a Jaynes-Cummings Hamiltonian

$$H_{\mathrm{JC}} = \omega_r\left(a^\dagger a + \frac{1}{2}\right) + \frac{\omega_{\mathrm{q}}}{2}\sigma_z + g\left(\sigma_+ a + \sigma_- a^\dagger\right),$$



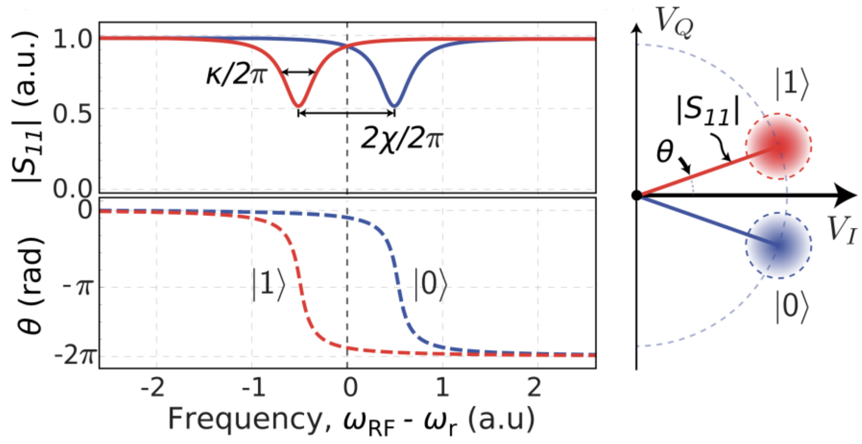
- In the dispersive limit $\Delta \gg \kappa, g$ J.C Hamiltonian simplifies to :

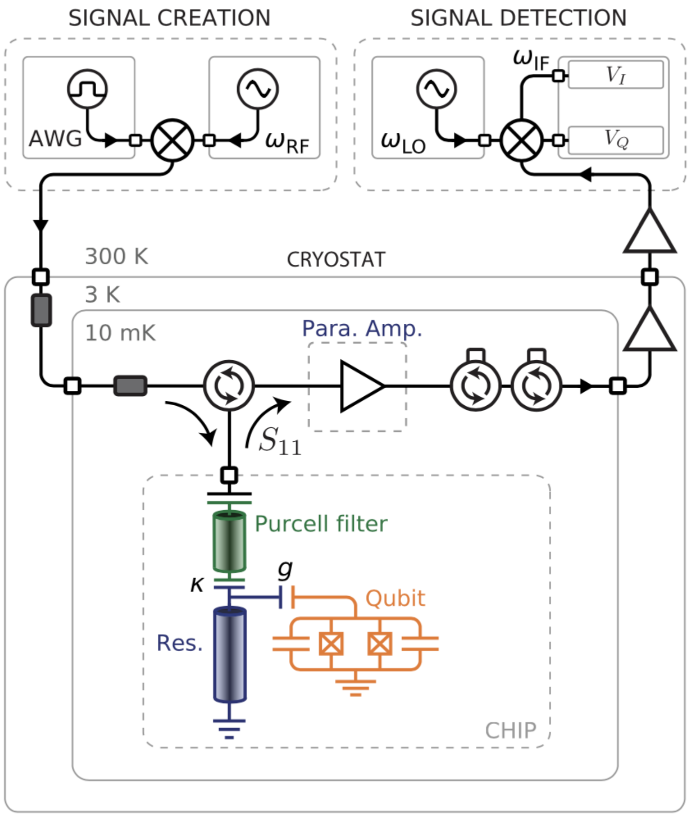
$$H_{\mathrm{disp}} = (\omega_r + \chi\sigma_z)\left(a^\dagger a + \frac{1}{2}\right) + \frac{\tilde{\omega}_{\mathrm{q}}}{2}\sigma_z$$

$$\chi = \frac{g^2}{\Delta} \longrightarrow \text{dispersive shift}$$

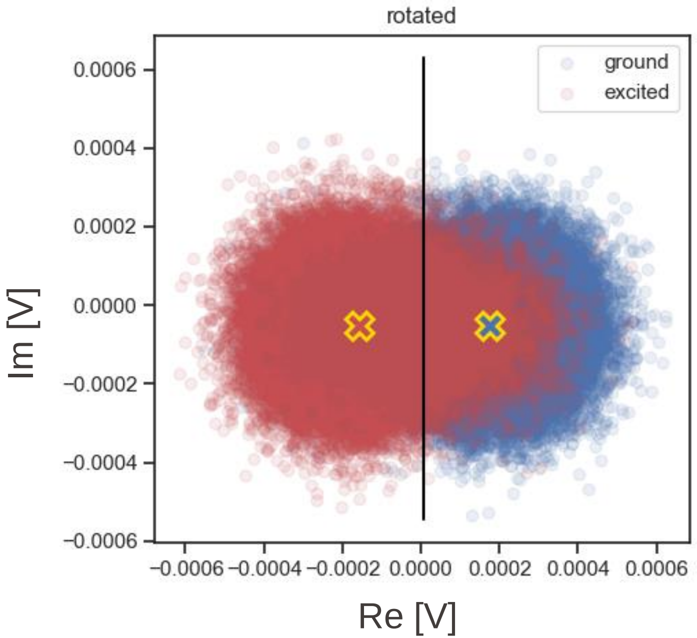
Qubit readout

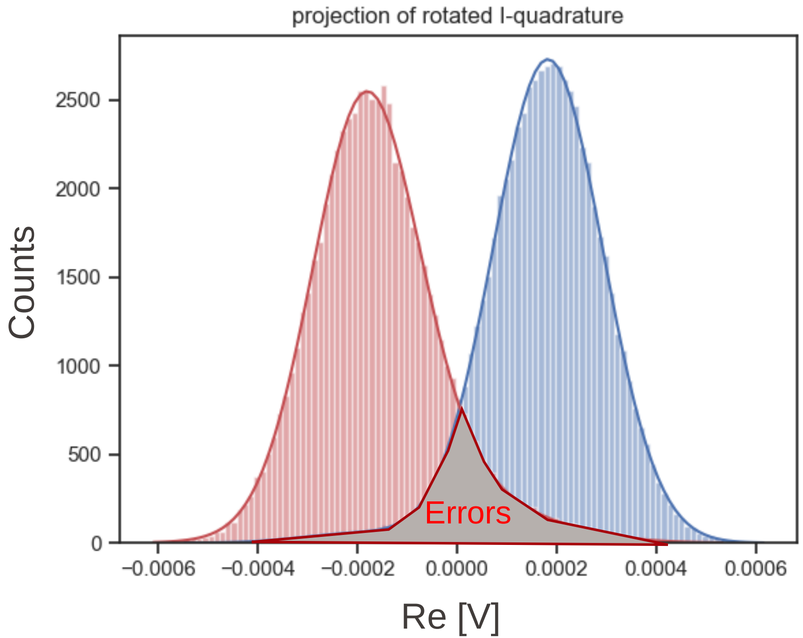
- The resonator is probed at ω_{RF}
- Received signal is demodulated and converted to a point in the IQ plane on the detection side
- Resonator response in the IQ plane is dependant on the qubit state





Qubit readout





$$\mathrm{SNR}^2(t) \equiv \frac{|\langle \hat{M}(t)\rangle_e - \langle \hat{M}(t)\rangle_g|^2}{\langle \hat{M}_N^2(t)\rangle_e + \langle \hat{M}_N^2(t)\rangle_g}$$

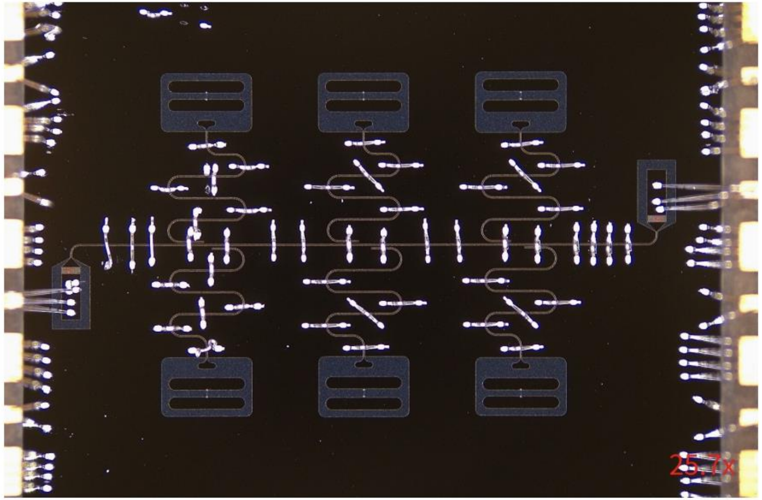
$$\mathrm{SNR}(\tau_m \to \infty) \simeq (2\varepsilon/\kappa)\sqrt{2\kappa\tau_m}\,|\sin 2\phi|$$

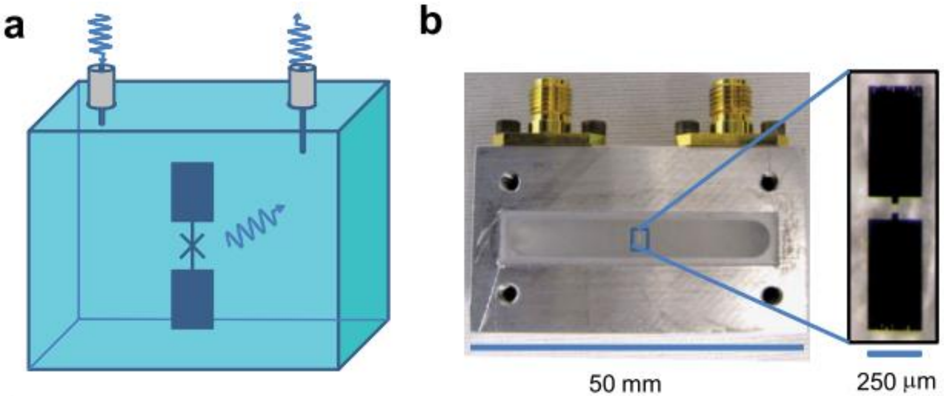
$$F_m = 1 - [P(e|g) + P(g|e)] \equiv 1 - E_m,$$

$$F_m = 1 - \mathrm{erfc}(\mathrm{SNR}/2)$$

Qubit readout

- Readout resonator can be realized on chip (2D coplanar waveguide resonators)
- Coupling between a qubit and a resonator is determined by the mutual capacitance between them
- Alternatively qubit can be capacitively coupled to a mode of a 3D microwave cavity

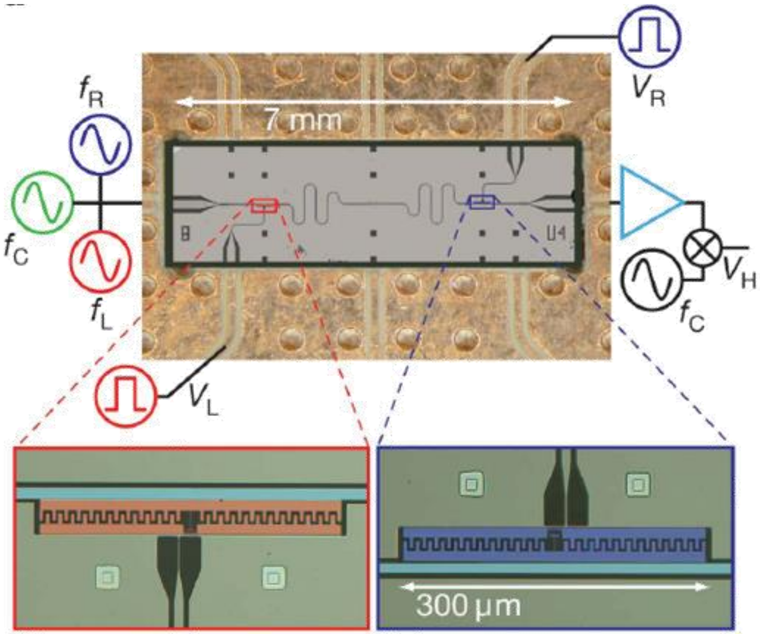


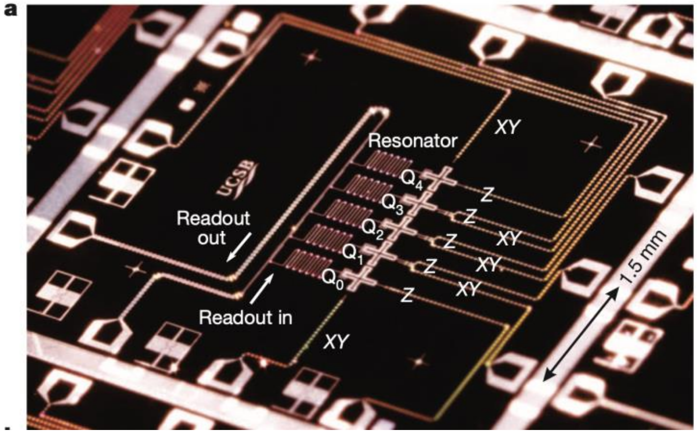


M. P. Bland et al. arxiv.org/abs/2503.14798

Paik, H., et al., 2011, Phys. Rev. Lett. 107, 240501

Transmon Qubit Design



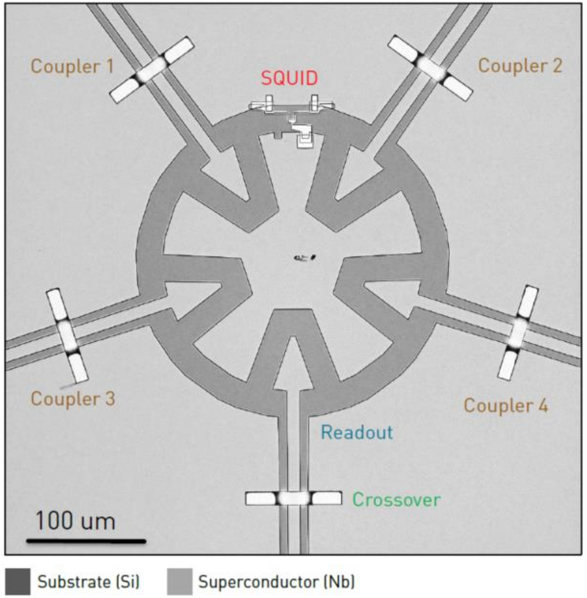


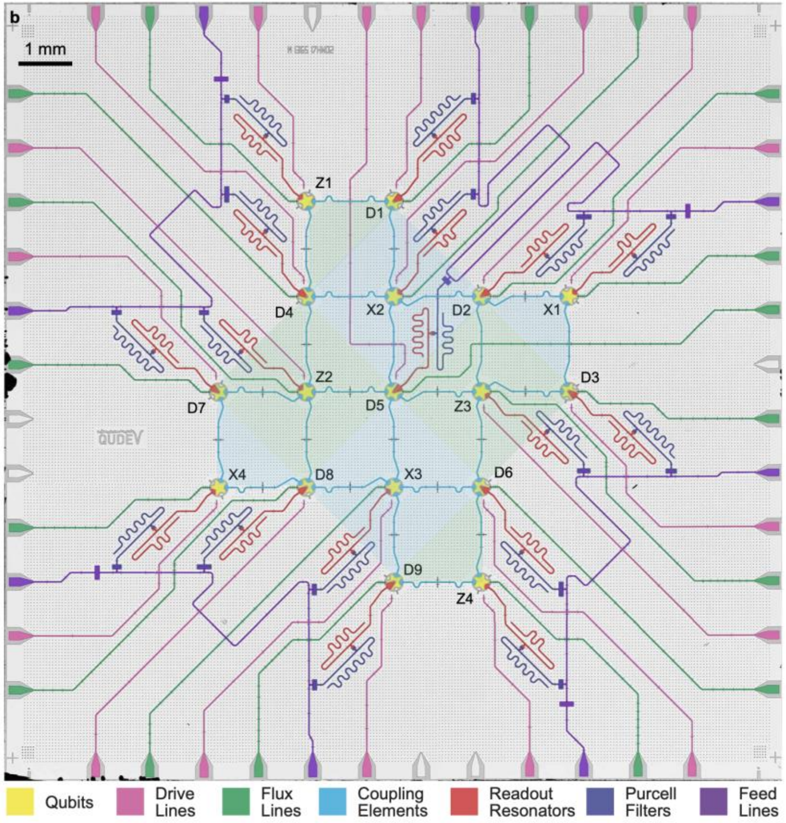
- Different capacitance shapes are used to optimize:
  - Field distribution
  - Loss
  - Coupling to readout or neighbouring qubits

Courtesy: L. Di Carlo

R. Barends et al., *Superconducting quantum circuits at the surface code threshold for fault tolerance*, Nature 508, 500-503 (2014)

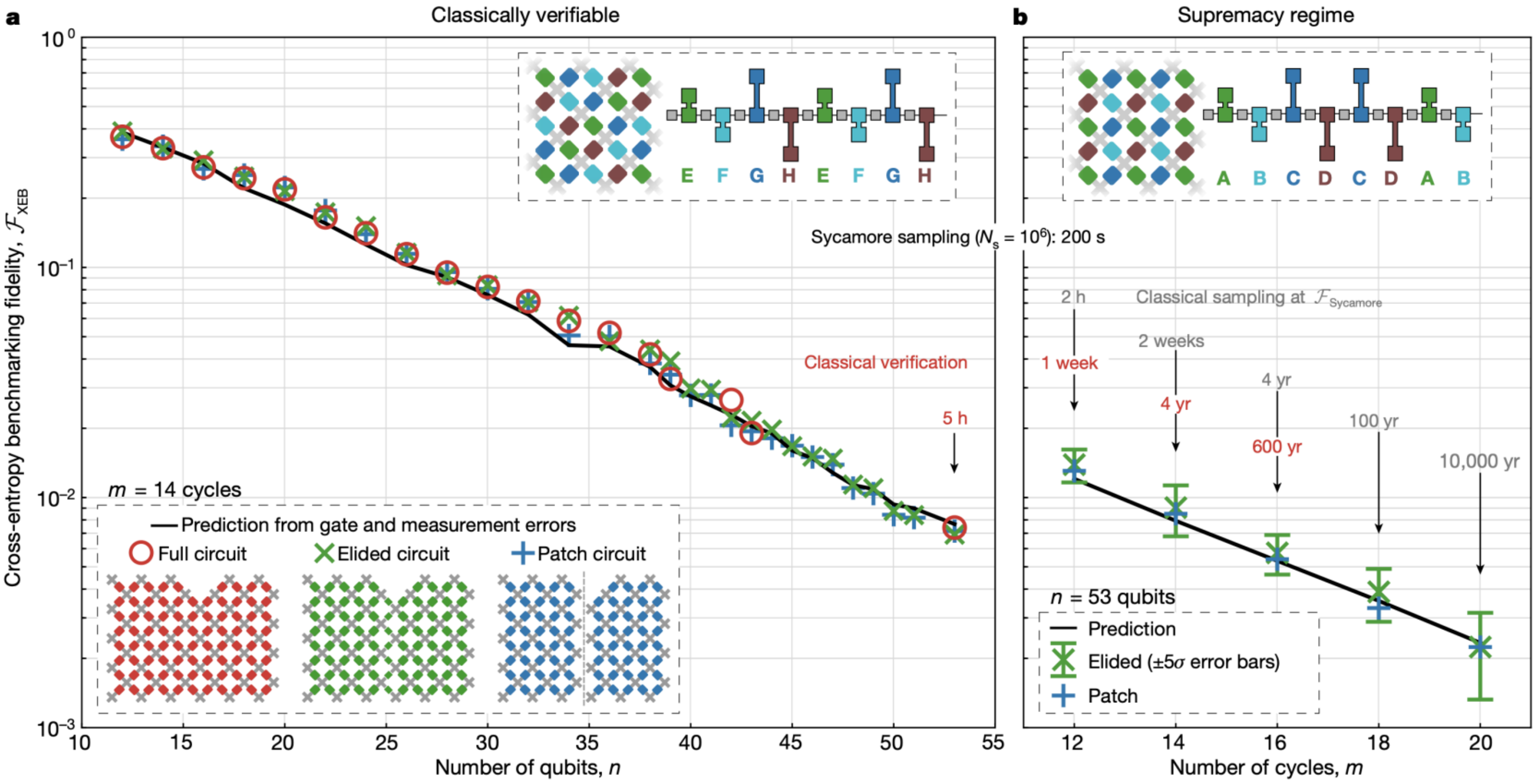
Transmons in literature





S. Krinner et al., *Realizing repeated quantum error correction in a distance-three surface code*, Nature 605, 669–674 (2022)

Transmons in literature

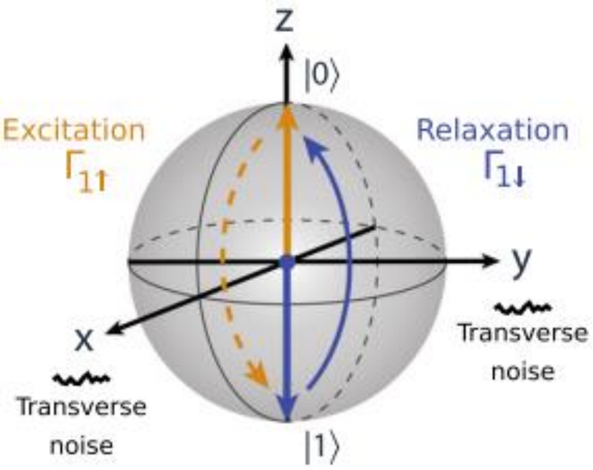


F. Arute et al., *Quantum supremacy using a programmable superconducting processor*, Nature 574, 505-510 (2019)

Qubit relaxation

- Relaxation caused by transverse noise on σ_x or σ_y
- Energy exchange with the environment leading to the qubit transitioning between ground and excited state

$$\Gamma_1 = \frac{1}{T_1} = \Gamma_{1\uparrow} + \Gamma_{1\downarrow} - \text{longitudinal relaxation rate}$$



- From Boltzmann equilibrium and detailed balance equations in steady state rates are given by:

$$\Gamma_{1\uparrow} = \Gamma_{1\downarrow}\, e^{-\frac{\hbar\omega}{k_B T}} = 3 \cdot 10^{-7}\, \Gamma_{1\downarrow}$$

P. Krantz et al., *A quantum engineer's guide to superconducting qubits*, Appl. Phys. Rev. 6 (2019)

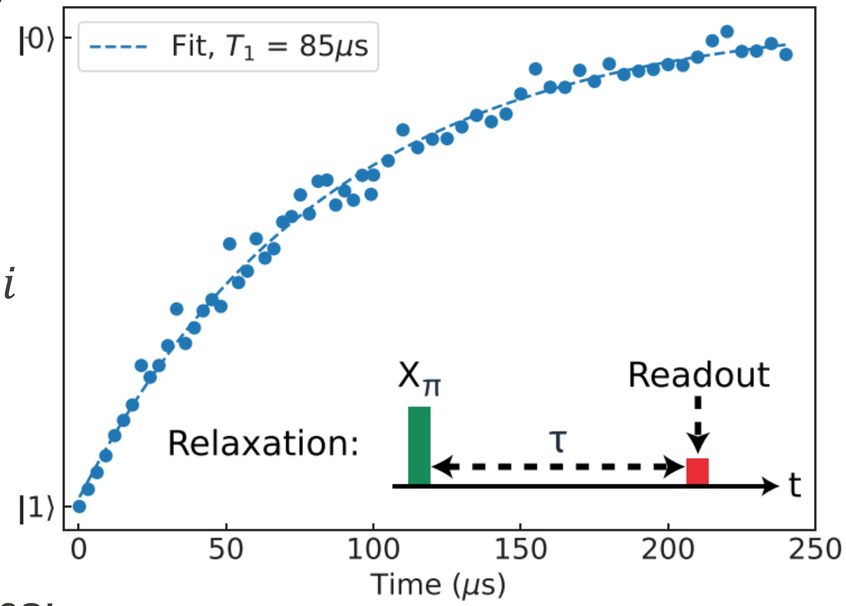
Qubit relaxation

Relaxation can be calculated using Fermi's Golden rule:

$$\Gamma_{01} = \frac{1}{\hbar^2}\left|\left\langle 0\left|\frac{dH}{d\lambda}\right|1\right\rangle\right|^2 S(\omega_{ij})$$

Where Γ_{ij} is transition rate between states i and j, $\frac{dH}{d\lambda}$ represents sensitivity to a certain noise source operator and $S(\omega_{ij})$ is noise spectral density at the transition frequency

Measurement protocol and example of a result



Most common relaxation sources in transmons:

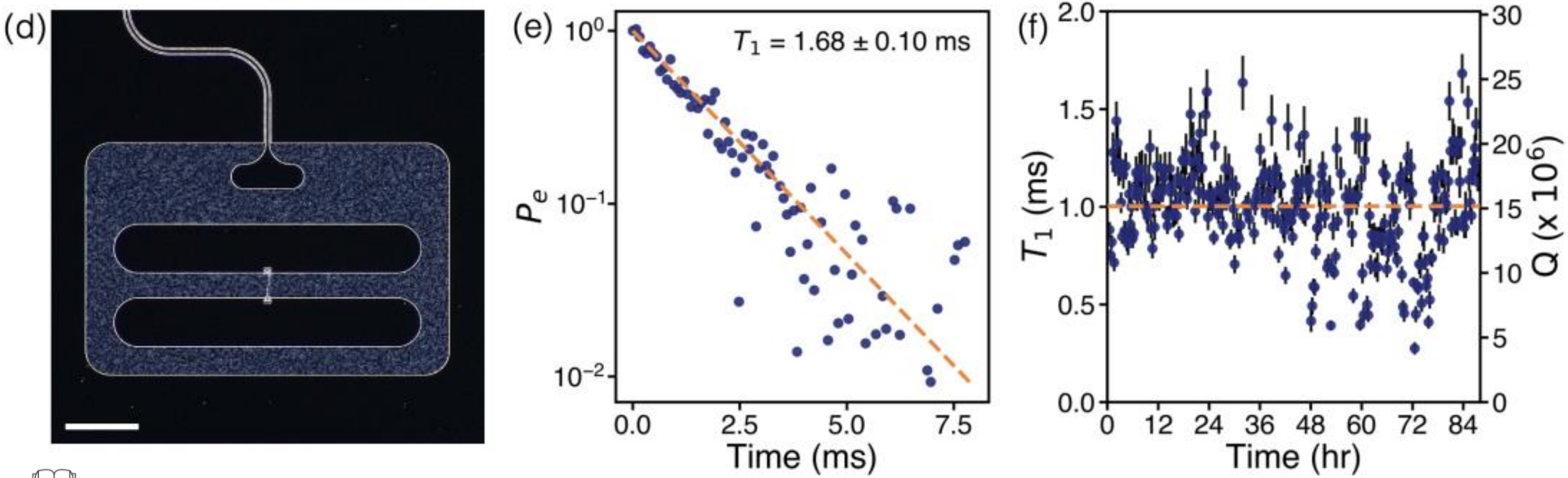
- Capacitive noise (dielectric quality factor)
- Purcell decay
- Quasi-particle noise

Dielectric loss

$$\Gamma_1 = \frac{1}{T_1} = \frac{32\pi Ec|\langle 0|\hat{n}|1\rangle|^2}{Q_{diel}}$$

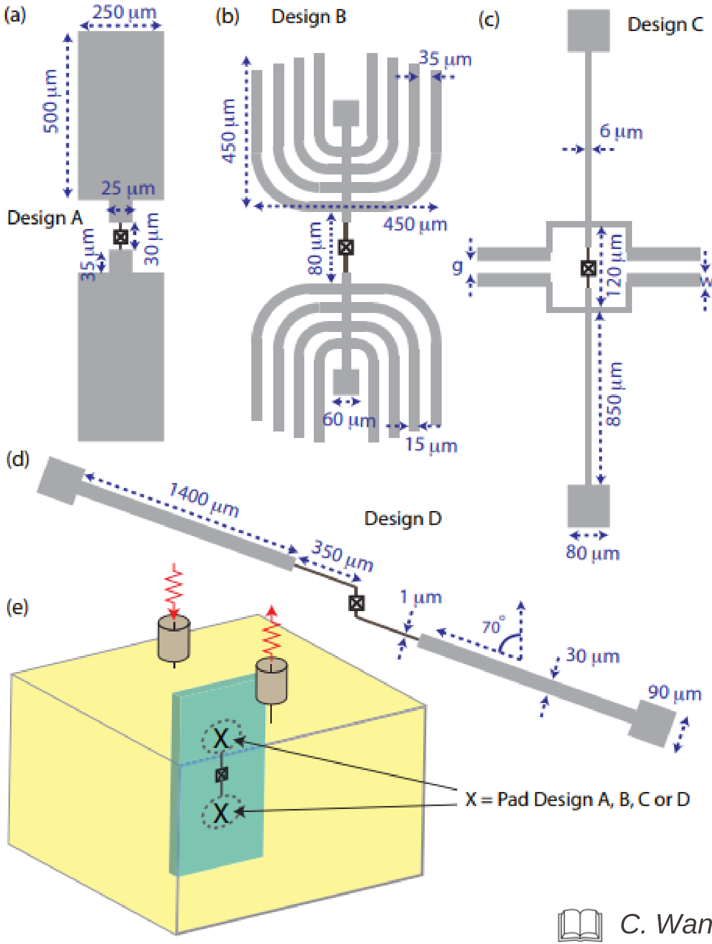
- Associates the qubit decay to an imperfect dielectric linked to the qubit capacitor
- Common limiting factor of the state of the art qubits
- Highlights the importance of fabrication process, capacitance materials, substrates, electric field distribution (surface participation ratios)
- Commonly used materials for capacitances Al, Nb, Ta

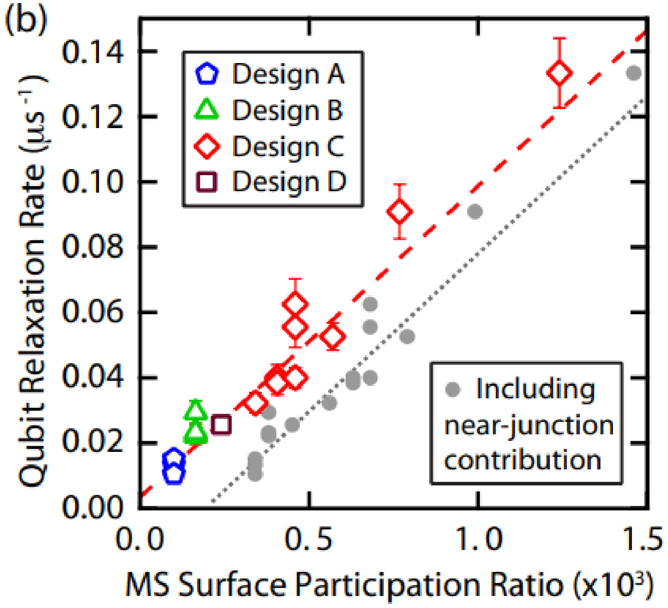
Current record T1 in transmon qubits



M. P. Bland et al. arxiv.org/abs/2503.14798
C. Wang et al. Appl. Phys. Lett. 107, 162601 (2015)

Participation ratio and dielectric loss





$$\frac{1}{T_1} = \frac{\omega}{Q} = \omega \sum_i \frac{p_i}{Q_i} + \Gamma_0$$

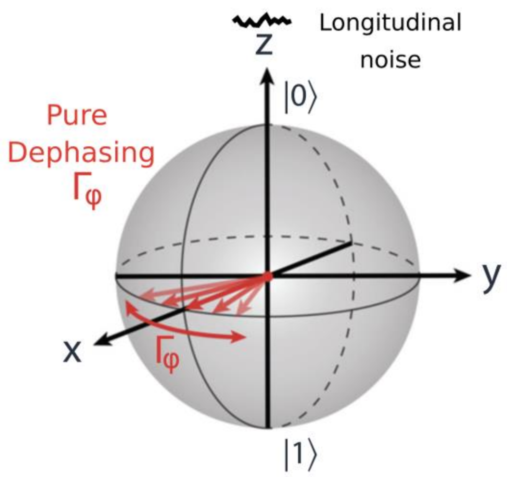
$$p_{i,\mathrm{int}} = t \iint_{\mathrm{int}} \frac{\epsilon}{2} |\mathbf{E}_i(x,y)|^2 dxdy / U_{\mathrm{tot}}$$

C. Wang et al. Appl. Phys. Lett. 107, 162601 (2015)

Dephasing in Transmon Qubits

- Pure dephasing rate Γ_ϕ is associated to noise which causes the qubit's frequency to fluctuate, hence inducing a precession along the z-axis of the state vector.

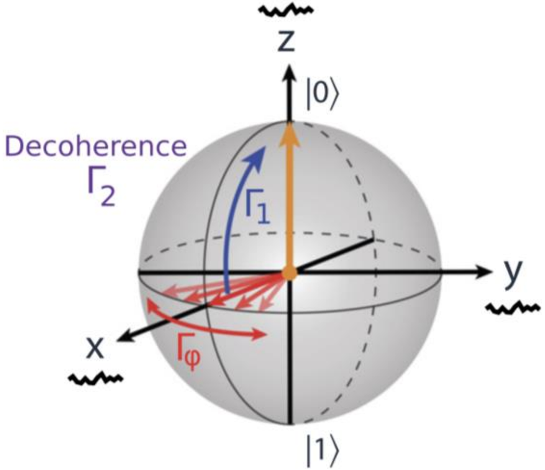
- Dephasing is represented as noise along the z-axis of the Bloch sphere. When averaging the position of the state in the Bloch sphere, noise along z causes the overall length of the state vector to be less than 1.

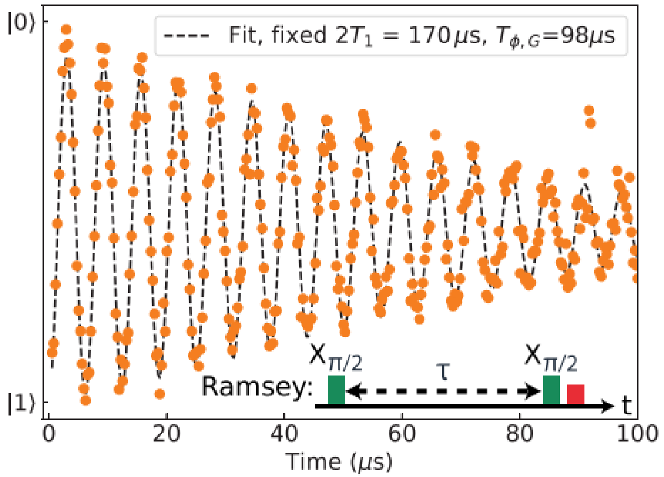


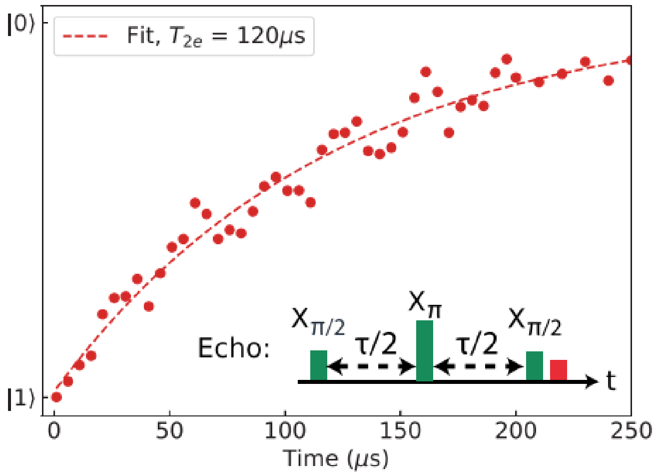
P. Krantz et al., *A quantum engineer's guide to superconducting qubits*, Appl. Phys. Rev. 6 (2019)

Decoherence in Transmon Qubits

- Decoherence is a combination of both relaxation and dephasing effects.
  Decoherence rate is defined as $\Gamma_2 = \frac{\Gamma_1}{2} + \Gamma_\phi$.
- There are mainly two measurements protocols used to estimate T_2, the Ramsey protocol and the Spin Echo protocol.







P. Krantz et al., *A quantum engineer's guide to superconducting qubits*, Appl. Phys. Rev. 6 (2019)

Dephasing

Similarly to relaxation dephasing can be described by:

$$\Gamma_{\varphi} = \frac{1}{T_{\varphi}} = \left|\frac{\delta\omega_{01}}{\delta\lambda}\right|^2 S(\omega \longrightarrow 0)$$

Important difference is that the noise now is not only evaluated around the qubit frequency, not a resonant phenomenon. Dephasing can be undone with refocusing techniques.

Dephasing sources:

- 1/f charge noise (exponentially suppressed for transmon)
- 1/f flux noise for flux sensitive qubits
- Photon shot noise
- Dispersively coupled two level systems (TLS)

Photon shot noise

- Adding the readout resonator coupling in the Hamiltonian:

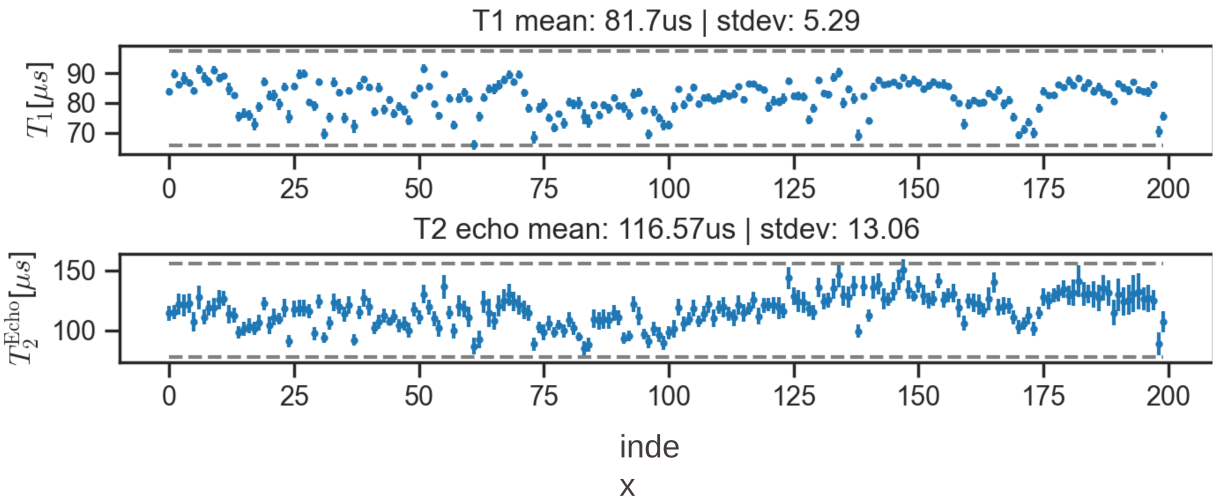
$$H_{\text{disp}} = (\omega_r + \chi\sigma_z)\left(a^\dagger a + \frac{1}{2}\right) + \frac{\tilde{\omega}_q}{2}\sigma_z$$

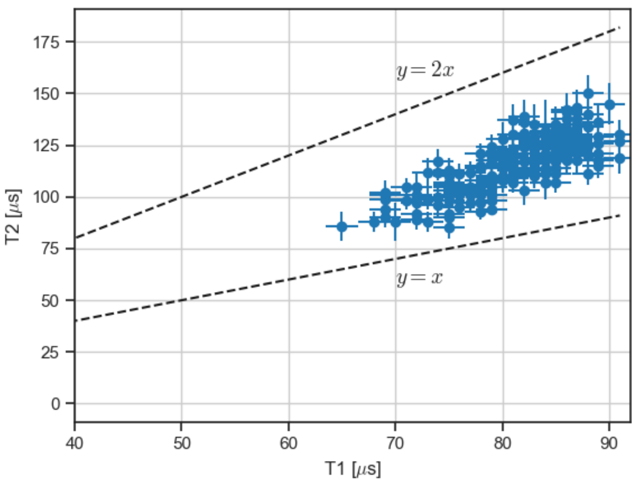
$$H_{\text{disp}} = \omega_r\left(a^\dagger a + \frac{1}{2}\right) + \frac{1}{2}\left(\omega_q + \underbrace{\frac{g^2}{\Delta}}_{\text{Lamb shift}} + \underbrace{\frac{2g^2}{\Delta}a^\dagger a}_{\text{ac-Stark shift}}\right)\sigma_z$$

$$\Gamma_\varphi = \frac{n_{th}\chi_{01}^2\kappa \cdot 2\pi}{\kappa^2 + \chi_{01}^2}, \qquad n_{th} = \frac{1}{\exp\left(\frac{hfr}{k_B T_{eq}}\right) - 1}$$

- Nth is the thermal photon population coming from environment temperature that the resonator sees T_{eq}
- Assuming Boltzman distribution can be solved for T_{eq}, state of the art $\sim 40\ mK$

Our results

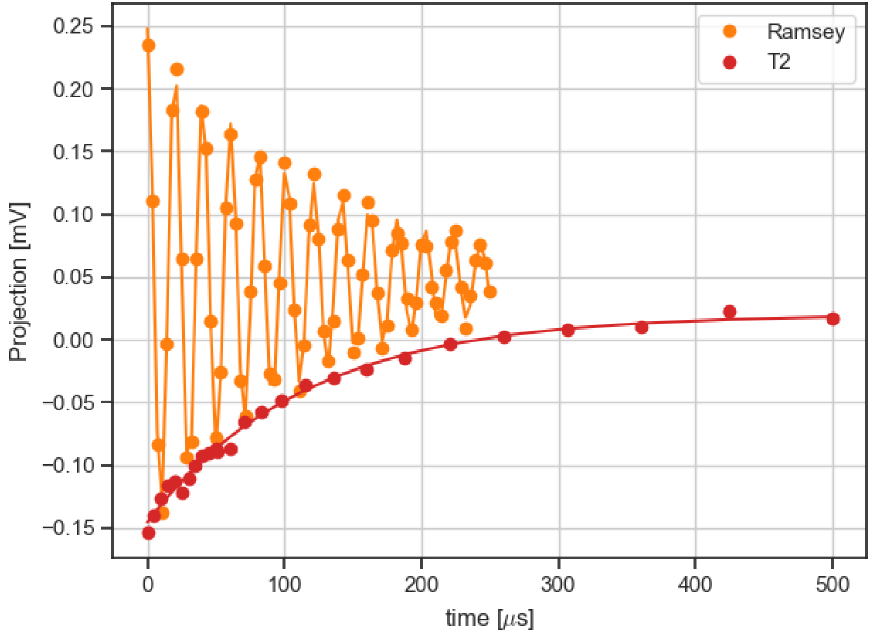




$$Tcavity = 49 \pm 2\ mK$$

Our results

$$T_1 \sim 81.7\ \mu s \quad T_2 \sim 116.6\ \mu s \quad T_2^* \sim 115\ \mu s$$

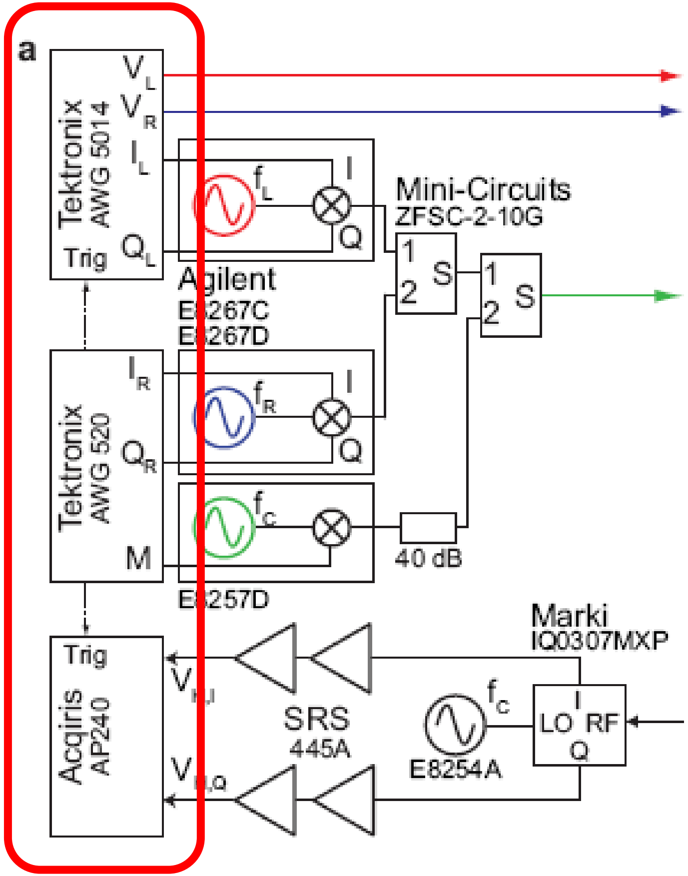


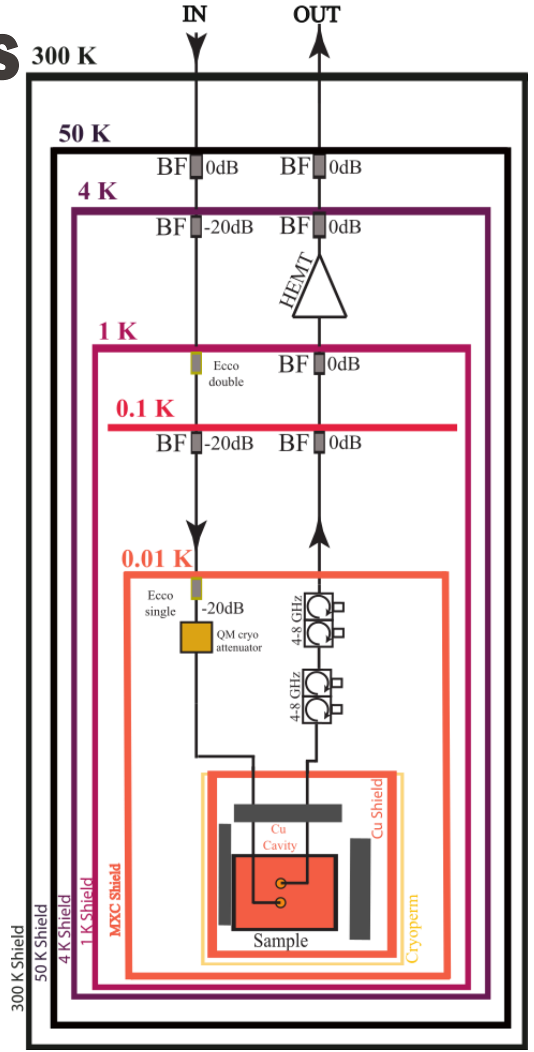
- T2*=T2echo suggests photon shot noise limit

EPFL

Cryogenic setup and RT electronics

FPGA + ADC + DAC





Setup Requirements

- Frequency synthesizers
  - Modulated in phase and amplitude
  - Controlled digitally
- Bias signal generators
  - Programmable
  - With coarse and fine voltage control

DACs

- Measurement of output voltages

ADCs

- Digital Feedback control
  - Controllers
  - Programmable e.g. in an FPGA
- High frequency up/down-converters

FPGA

Classical ASICs

Some current research directions

- Readout

P. D. Kurilovich et al. arxiv.org/abs/2501.09161, T.Connolly et al. arxiv.org/abs/2506.05306

- Control

D. A. Rower et al.PRX Quantum 5, 040342, V. Pešić et al. 10.1109/QCE60285.2024.00093

- Coherence and relaxation

M. P. Bland et al. arxiv.org/abs/2503.14798

- Multi qubit gates and couplers

*S. Vallés-Sanclemente arxiv.org/abs/*2503.13225

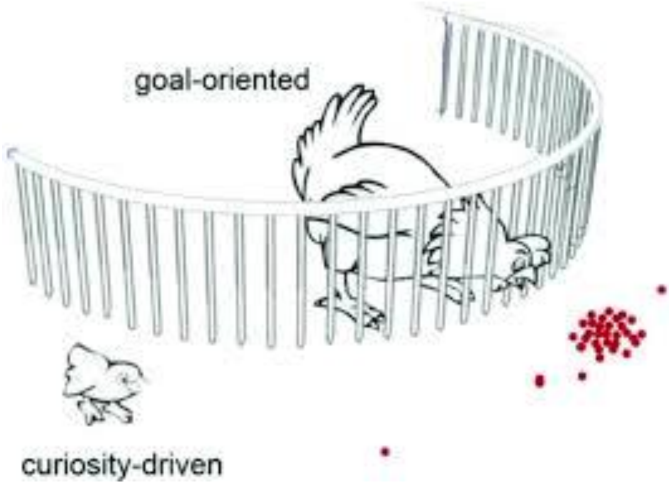
- Error correction and algorithms on hardware

S. Krinner et al., Nature 605, 669–674 (2022), Marques, J.F et al. Nat. Phys. 18, 80–86 (2022), Google Quantum AI, IBM

- Novel qubits

A.Gyenis et al.PRX Quantum 2, 010339, L.Nguyen et al.,Phys. Rev. X 9, 041041, I.V. Pechenezhskiy et al. Nature 585, 368–371 (2020)

Thank you



T. Haensch