INTRODUCTION TO EXPERIMENTAL QUANTUM COMPUTATION

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Institut de Física d'Altes Energies (IFAE)

Summer School on Quantum Computing
Universidad Internacional Menéndez y Pelayo
September 3d, 2020

Institut de Física d'Altes Energies
EXCELENCIA SEVERO OCHOA
BIST Barcelona Institute of Science and Technology

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OUTLINE

Lecture I

- **Quantum computation**
- Circuit quantization
- Superconducting qubit zoo
- Qubit state control

Lecture II

- Resonators for quantum computation
- Circuit quantum electrodynamics
- Qubit-qubit couplings and 2-qubit gates
- State of the art

QUANTUM COMPUTATION

Why do we need Quantum Computation?

MareNostrum 4, Barcelona Supercomputing Center:

390 TB, 11.5 Pflops ~ 40 qubits

But also energy consumption!

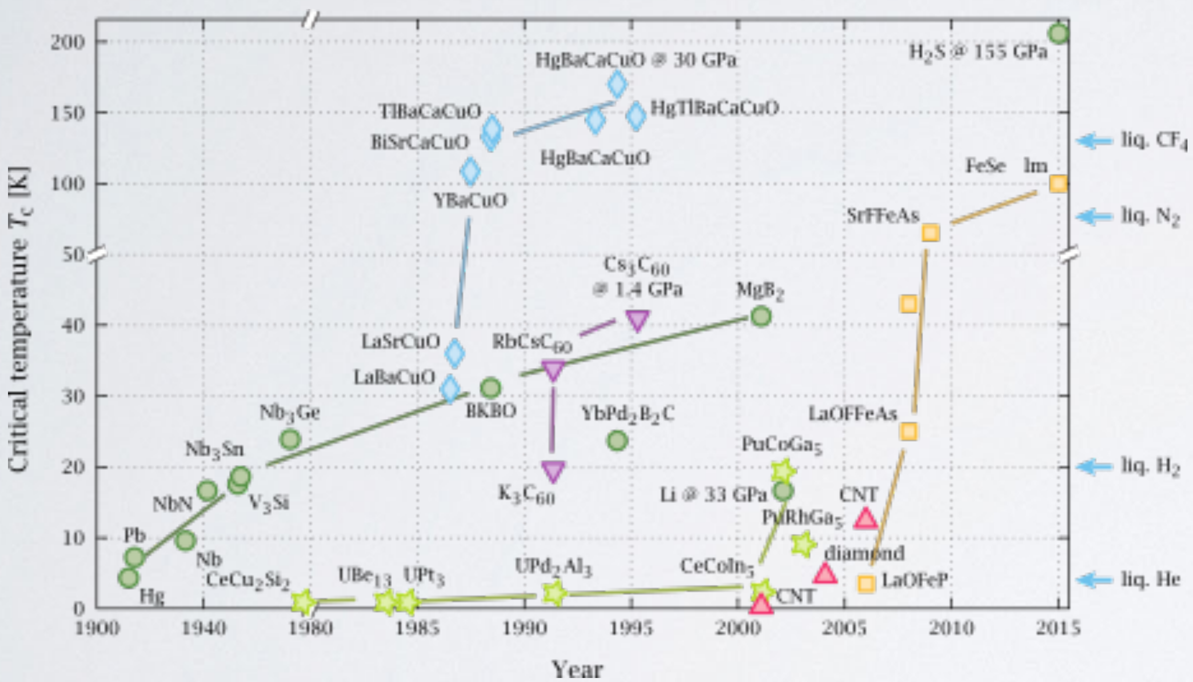
Power consumed 1.3MW

TFlop generation many MWs...

QUANTUM COMPUTATION

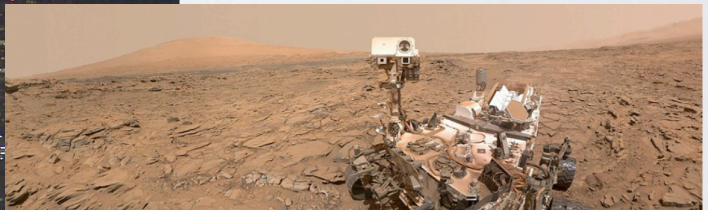
Why do we need Quantum Computation?

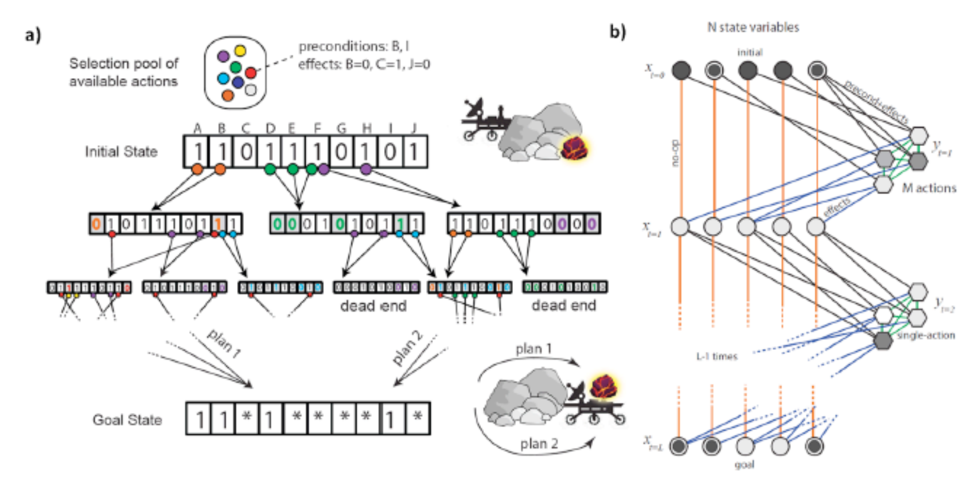
- Applications where small-sized quantum processors can outperform classical computers



Simulate higher Tc superconductor

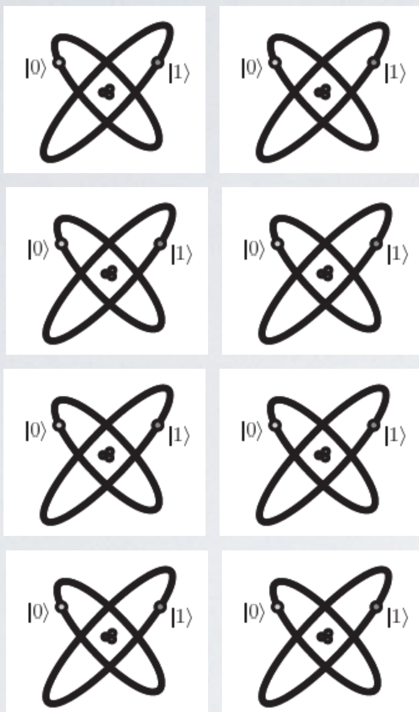
FMO complex, light energy harvesting



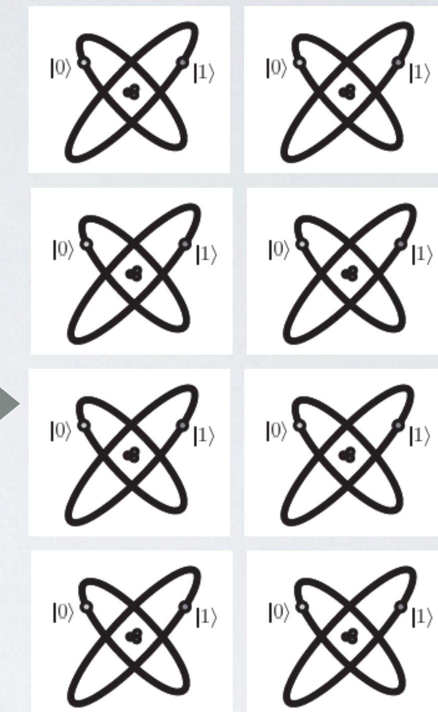


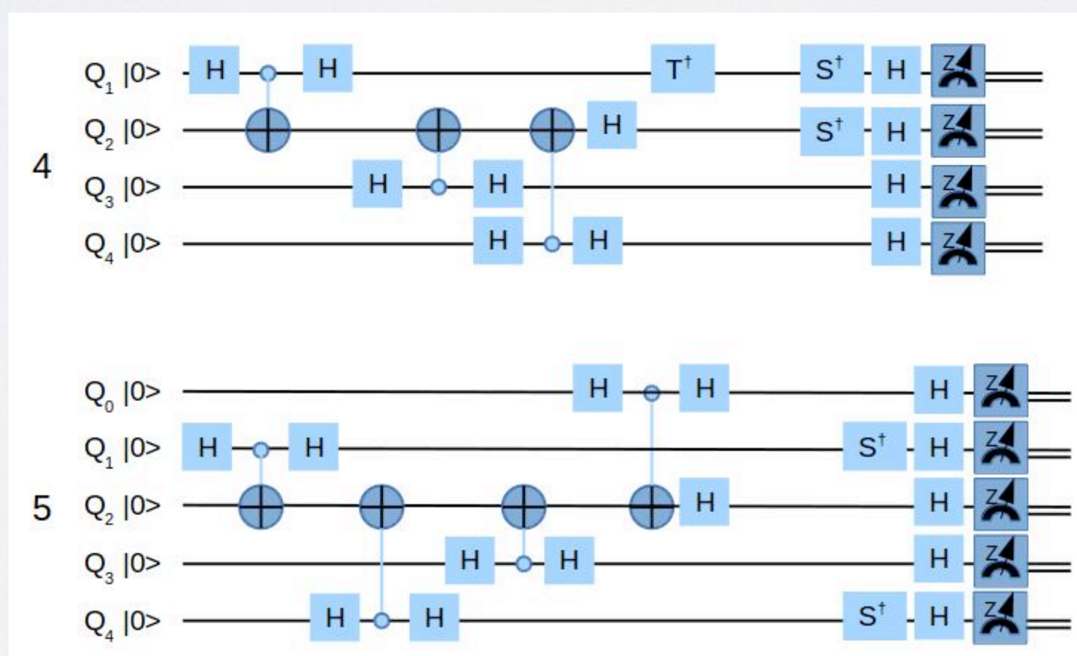
Optimization: traffic, navigation, scheduling, machine learning, etc.

QUANTUM COMPUTATION



$$\hat{U}$$

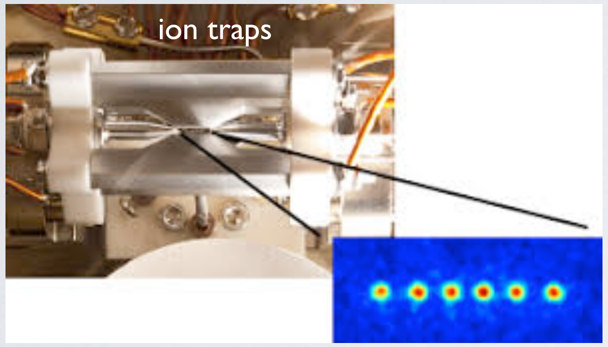


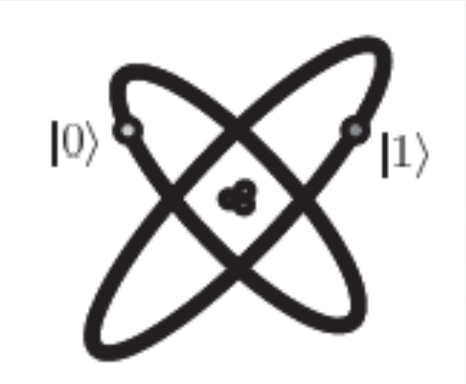


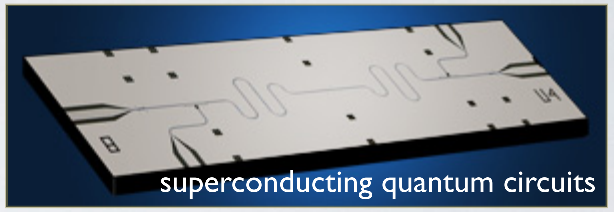
Processing 2^N states simultaneously

Nielsen and Chuang, Quantum computation and Quantum information

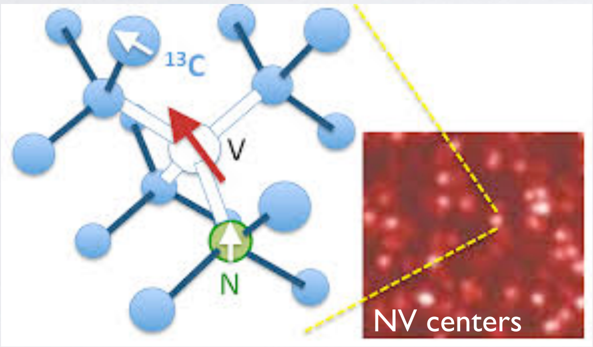
QUANTUM COMPUTATION



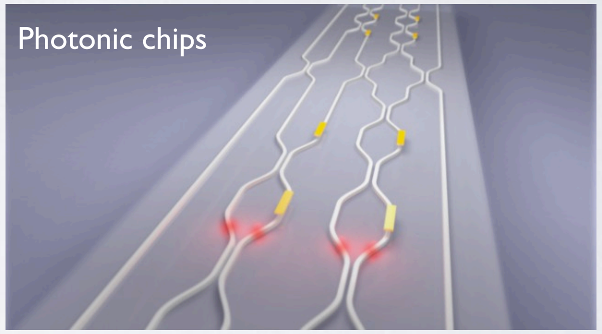


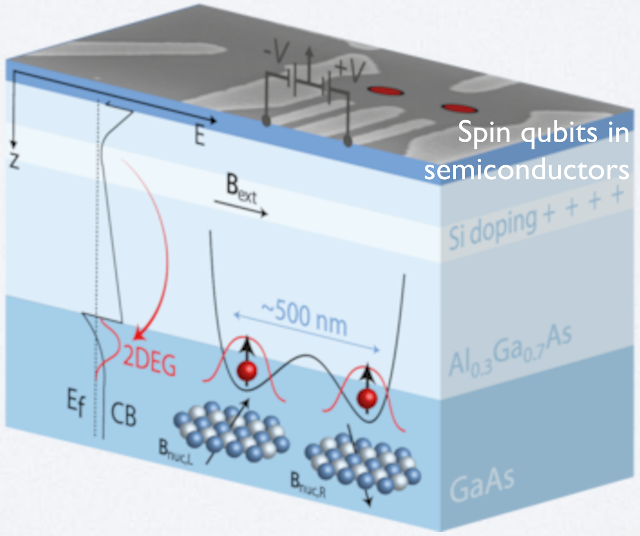


Quantum systems store information in their quantum states.
Quantum bit = qubit: minimal quantum information unit with 2 states



$$|\psi\rangle = \frac{|0\rangle + |1\rangle}{\sqrt{2}}$$





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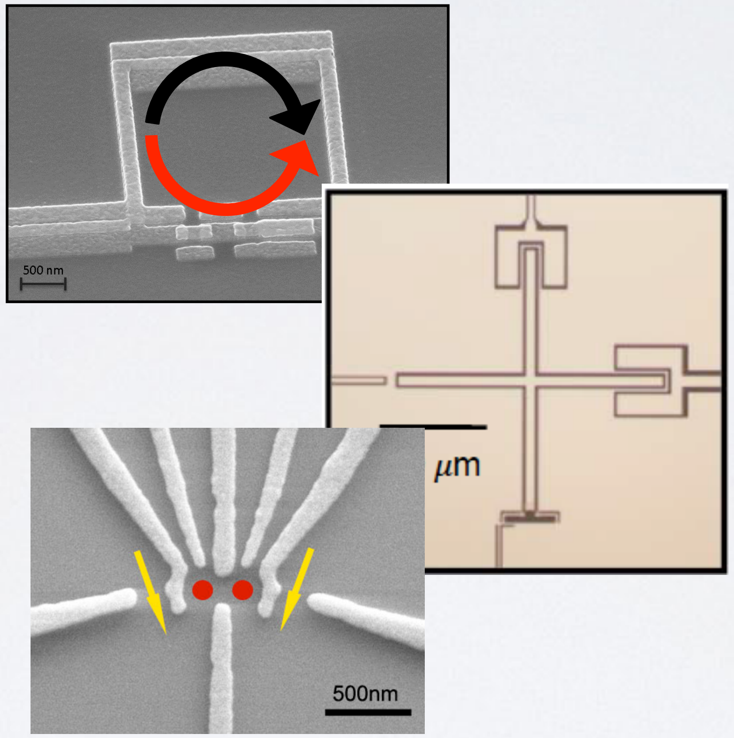
CIRCUIT QUANTIZATION

Microscopic

$$i\hbar\frac{\partial\psi(\vec{r},t)}{\partial t} = \mathcal{H}(\vec{r},t)\psi(\vec{r},t)$$

Mesoscopic

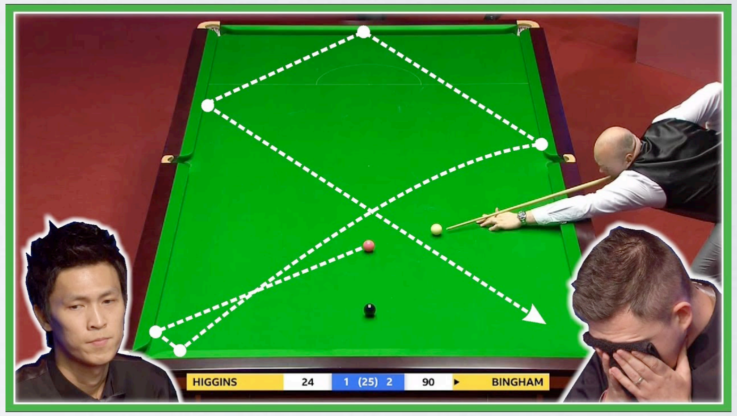


Large number of particles

Artificial, man-made

Quantum collective degrees of freedom

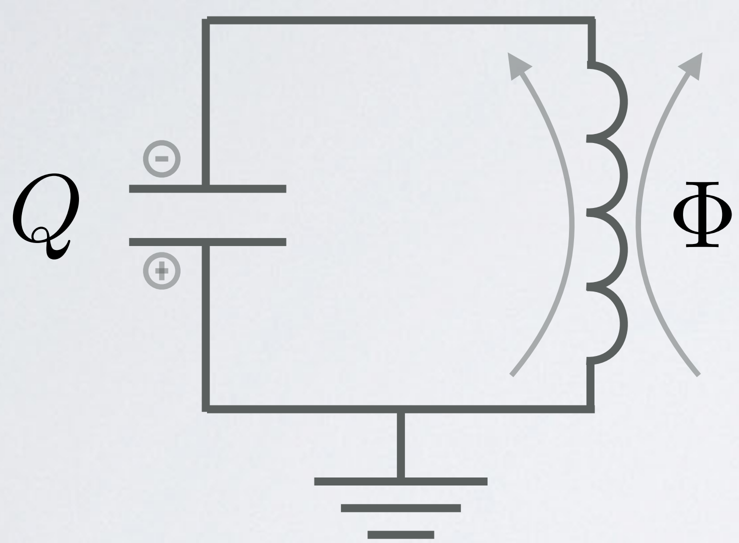
Macroscopic



$$\vec{F} = m\vec{a}$$

CIRCUIT QUANTIZATION

What corresponds to these collective degrees of freedom?



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

$$\omega_{\mathrm{LC}} = \frac{1}{\sqrt{LC}}$$

$$k_B T \ll \omega_{\mathrm{LC}}$$

$$P_e = e^{\frac{\hbar\omega_{\mathrm{LC}}}{k_B T}} \approx 6 \times 10^{-6}$$

$$\langle \hat{\Phi}^2 \rangle = \frac{\hbar Z_0}{2} \coth\left(\frac{\hbar \omega_{\mathrm{LC}}}{2 k_B T}\right)$$

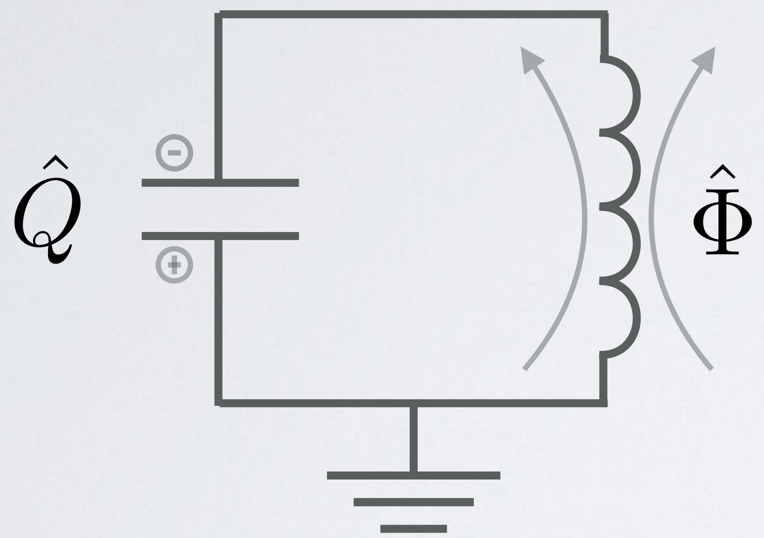
$$\begin{matrix} \Phi \\ Q \end{matrix} \Rightarrow \begin{matrix} \hat{\Phi} \\ \hat{Q} \end{matrix} \qquad [\hat{\Phi}, \hat{Q}] = i\hbar$$

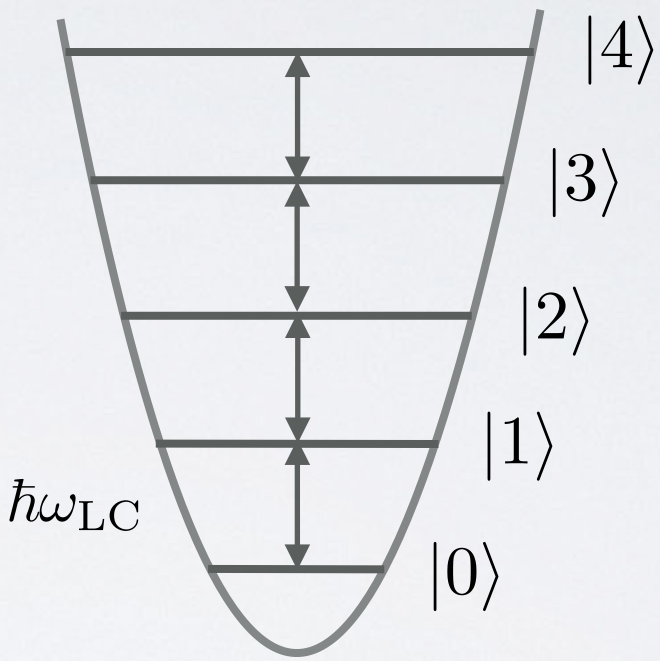
Quantum fluctuations of collective d.o.f.!

Vool, Devoret, IJCTA - Special Issue on Quantum Circuits

CIRCUIT QUANTIZATION

Quantum circuit spectrum and energy levels





$$Q \gg 1$$

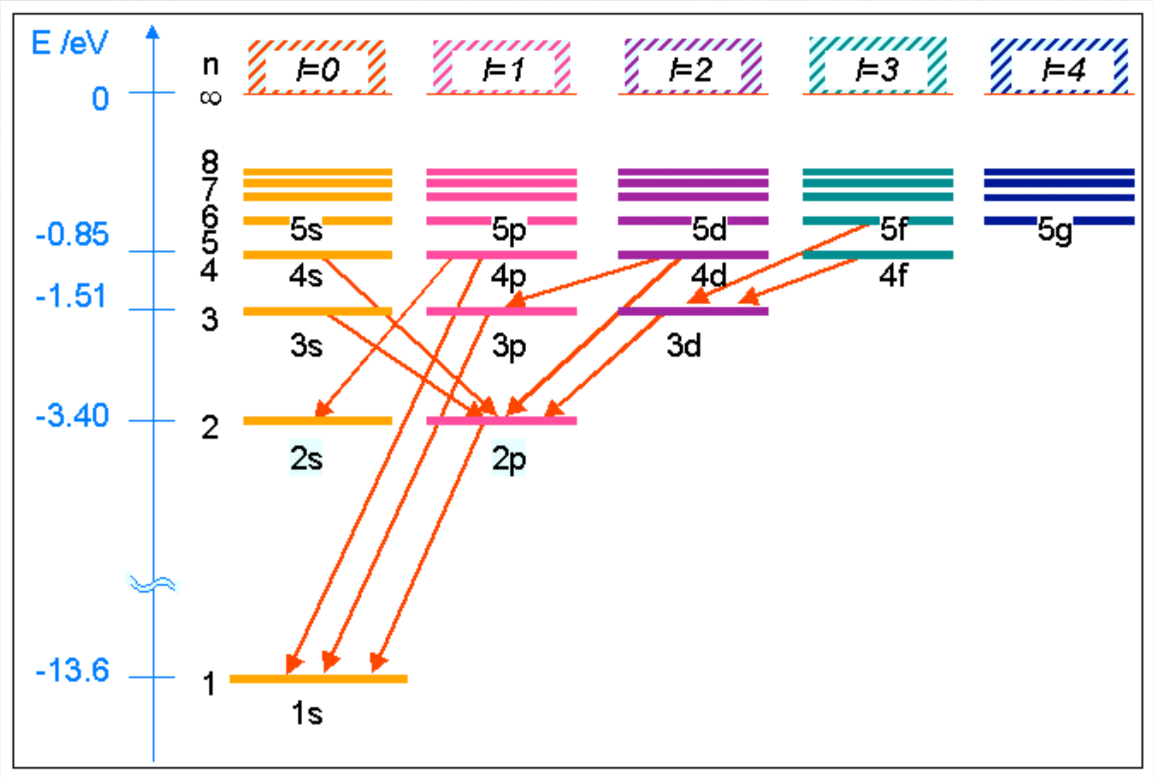
Superconducting quantum circuit!

Problems:

- We cannot single out a particular transition
- Not a proper quantum system for quantum information processing

Vool, Devoret, IJCTA - Special Issue on Quantum Circuits

CIRCUIT QUANTIZATION



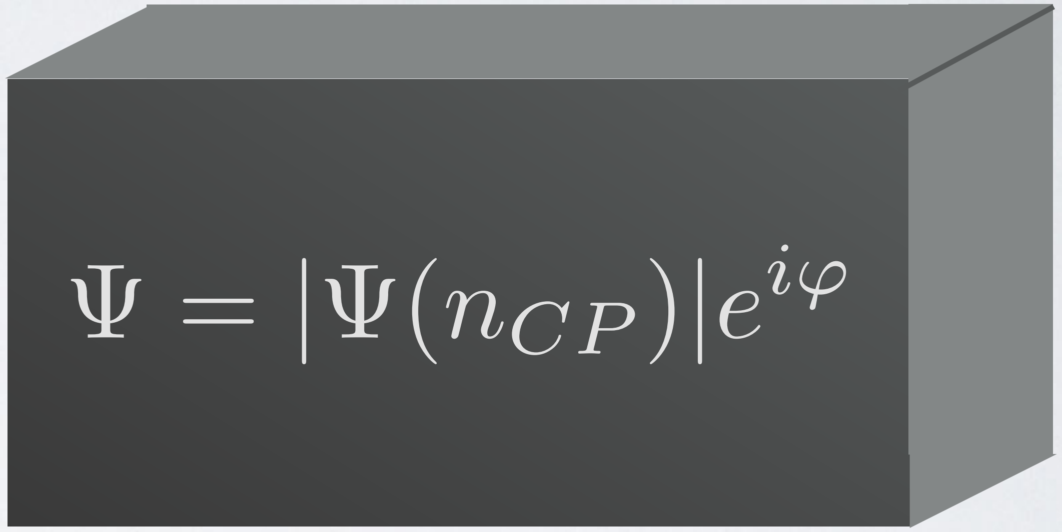
- Atomic spectra intrinsically anharmonic
- All transitions addressable by external radiation

Need nonlinear circuit element to alter circuit spectrum…

CIRCUIT QUANTIZATION

Superconductivity for qubits 101

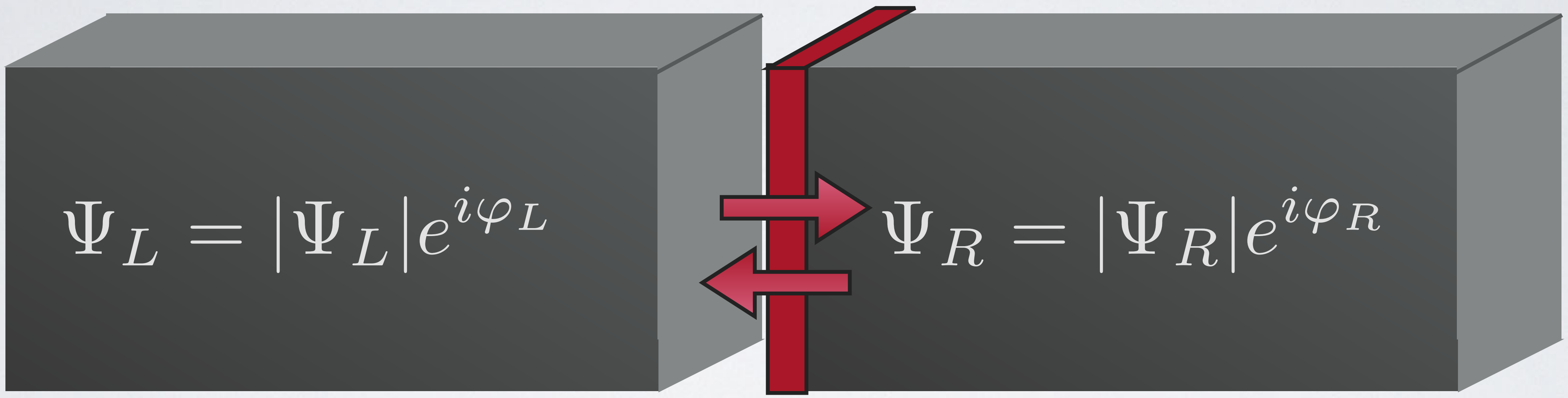
$T < T_C$



- Macroscopic quantum system with collective wave function
- No dissipation by charge transport
- Charge and phase conjugate variables: $[\hat{\varphi}, \hat{n}] = i \longleftrightarrow [\hat{x}, \hat{p}] = i\hbar$

CIRCUIT QUANTIZATION

Superconductivity for qubits 101

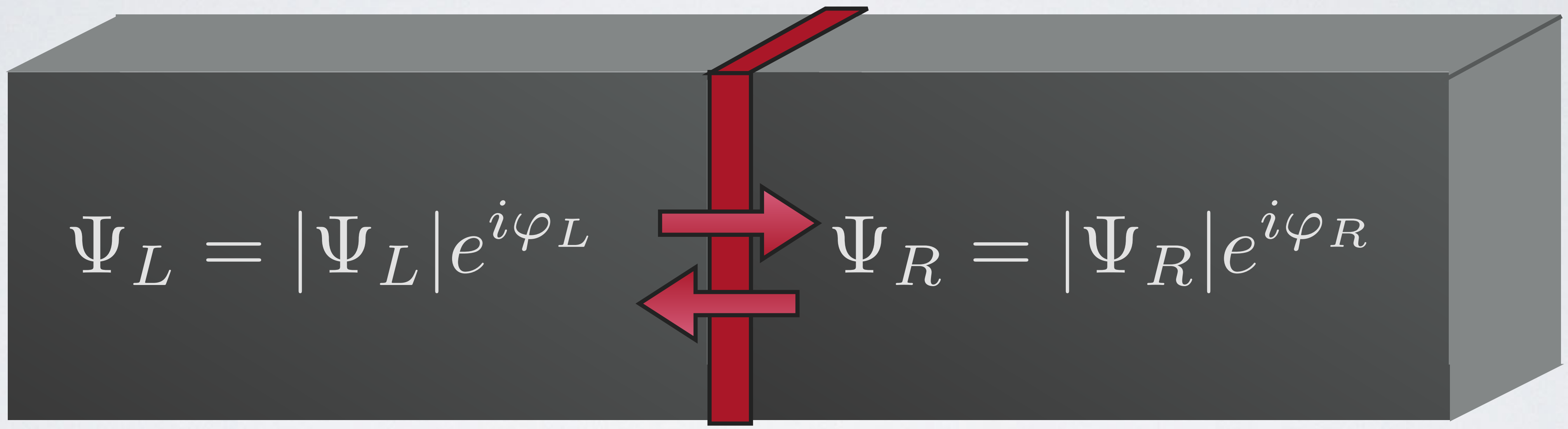


- Each block has its own wavefunction
- Perfectly isolated systems
- Insulating layer separates superconducting blocks
- Quantum tunneling is established between both sides leading to SUPERCURRENTS. It's a Josephson tunnel junction.

The Feynman lectures, vol. III

CIRCUIT QUANTIZATION

Josephson junctions: a macroscopic quantum effect



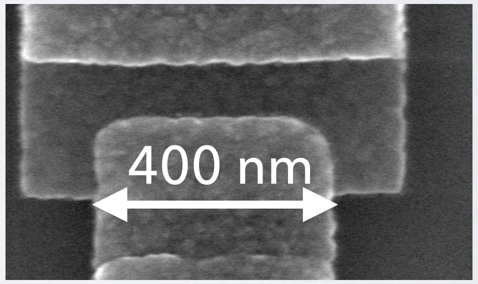
Constituent relation:

$$\frac{dI}{dt} = V \boxed{\frac{2\pi I_C}{\Phi_0} \sqrt{\frac{I_C^2 - I^2}{I_C^2}}}$$

$$\equiv 1/L_J(I)$$

Josephson inductance

Electrical circuits symbol



SEM micrograph

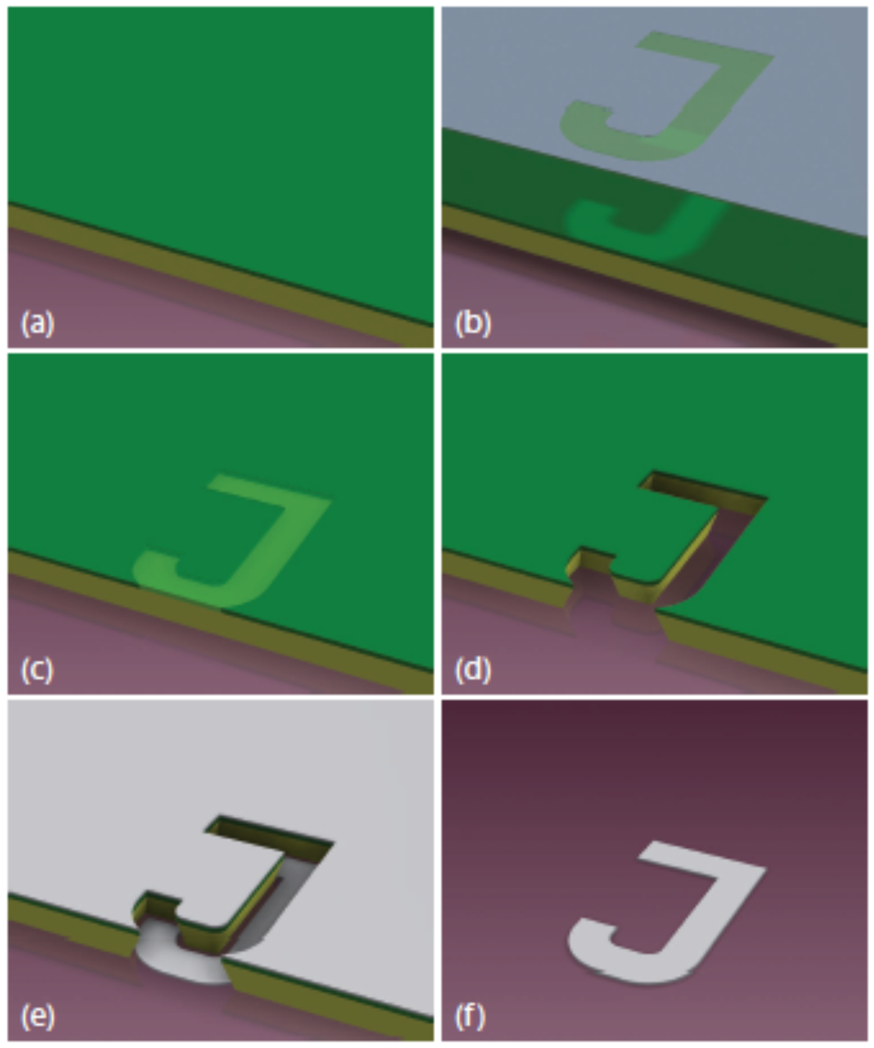
- Nonlinear circuit element
- Lossless

Orlando, Delin.
Foundation of applied superconductivity

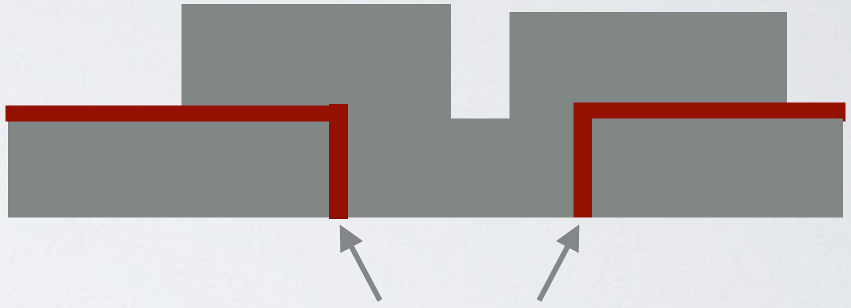
CIRCUIT QUANTIZATION

Junction fabrication

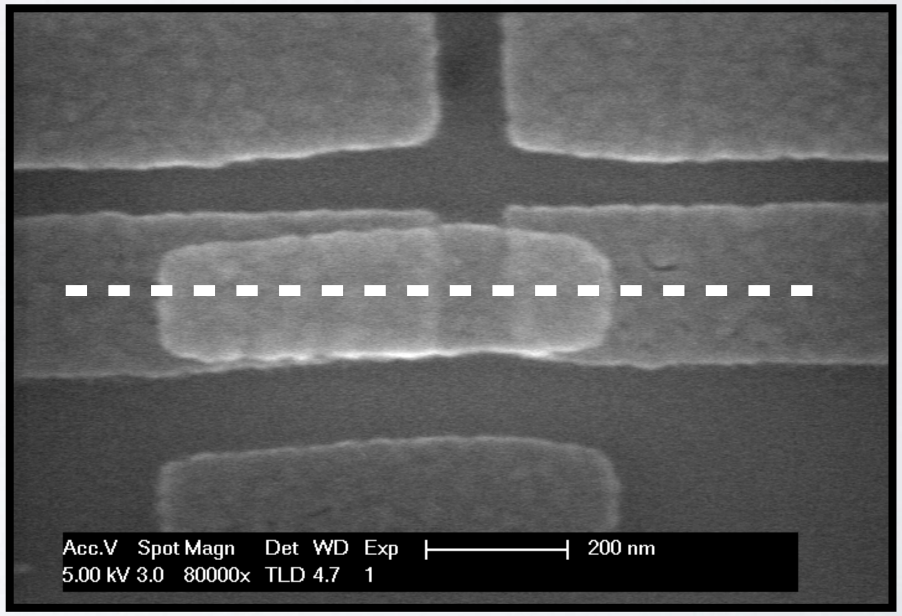
Electron beam lithography



Shadow angle evaporation



Josephson junctions



Scanning electron microscope (SEM)

M. Simoen (Chalmers), PhD Thesis 2016

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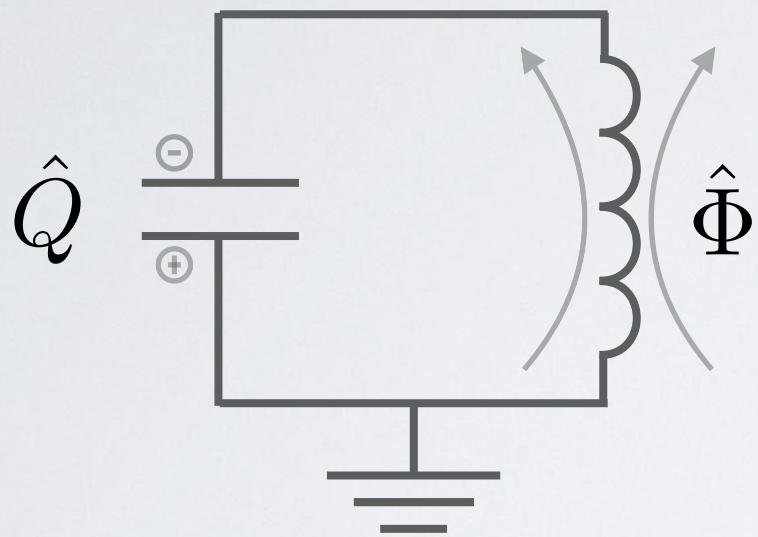
SUPERCONDUCTING QUBITS

The hydrogen atom of superconducting qubits



SUPERCONDUCTING QUBITS

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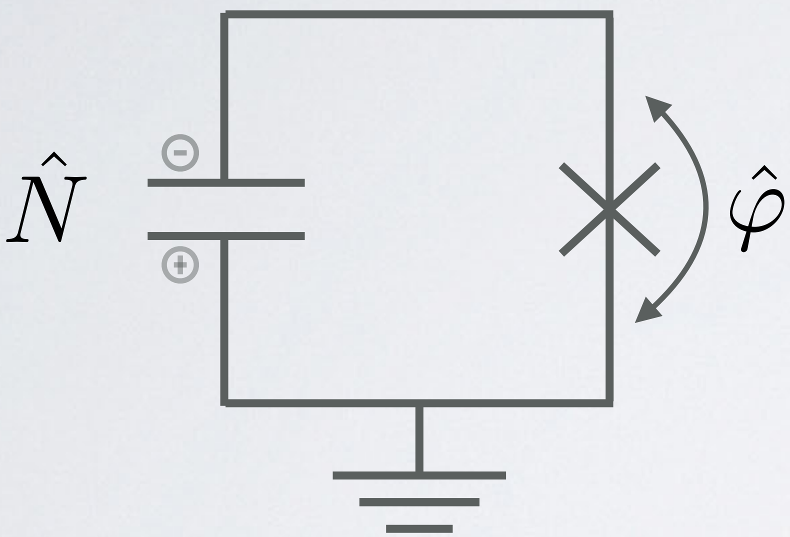
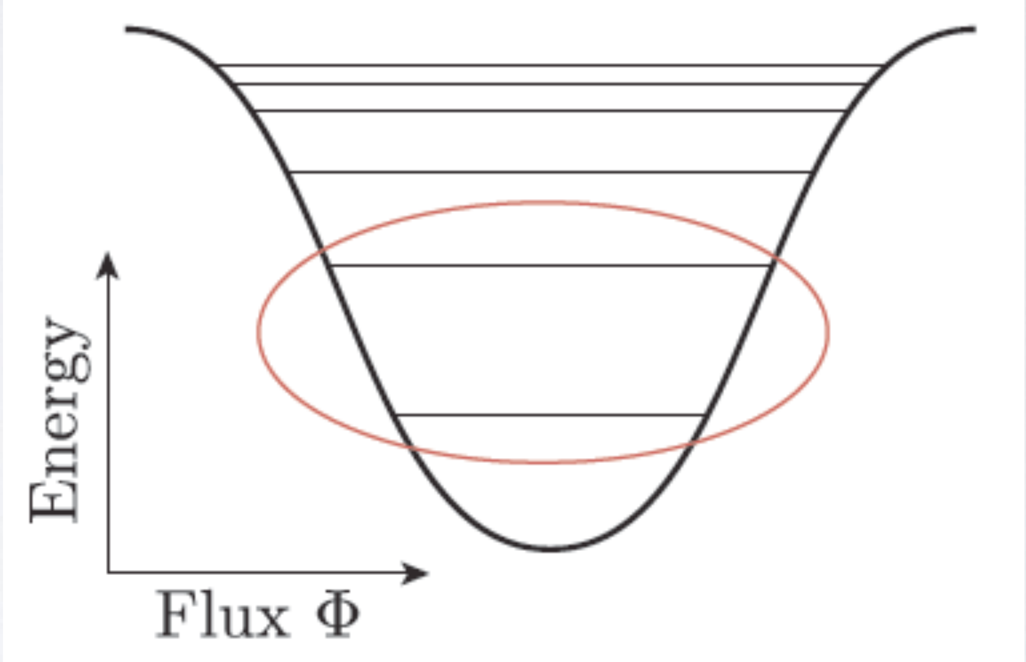




$$\hat{\mathcal{H}} = E_C \hat{N}^2 - E_J \cos(\hat{\varphi})$$

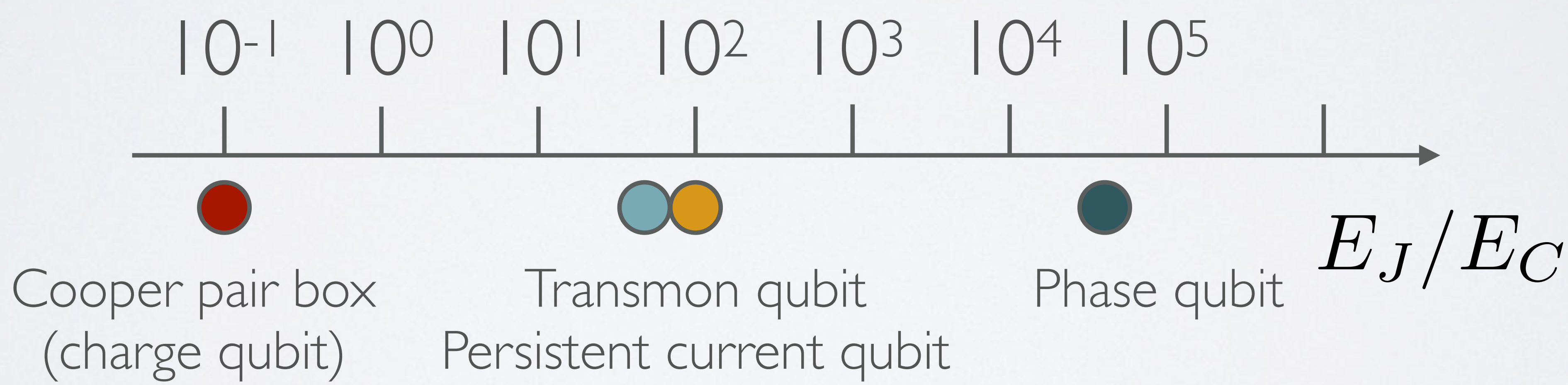
- Anharmonic spectrum
- Energy levels related to charge tunneling
- Lowest two states form a qubit

Koch et al. PRA 76, 042319 (2007)

SUPERCONDUCTING QUBITS

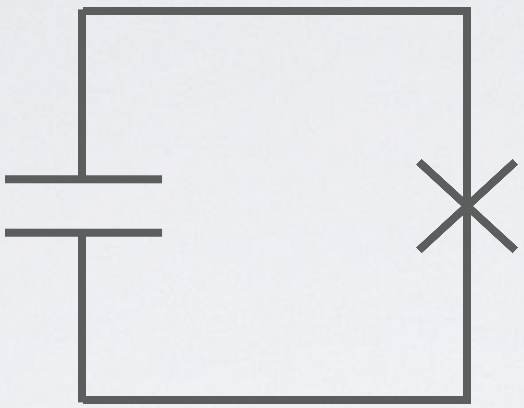
A zoo of superconducting qubits

$$\hat{\mathcal{H}} = E_C \hat{N}^2 - E_J \cos(\hat{\varphi})$$

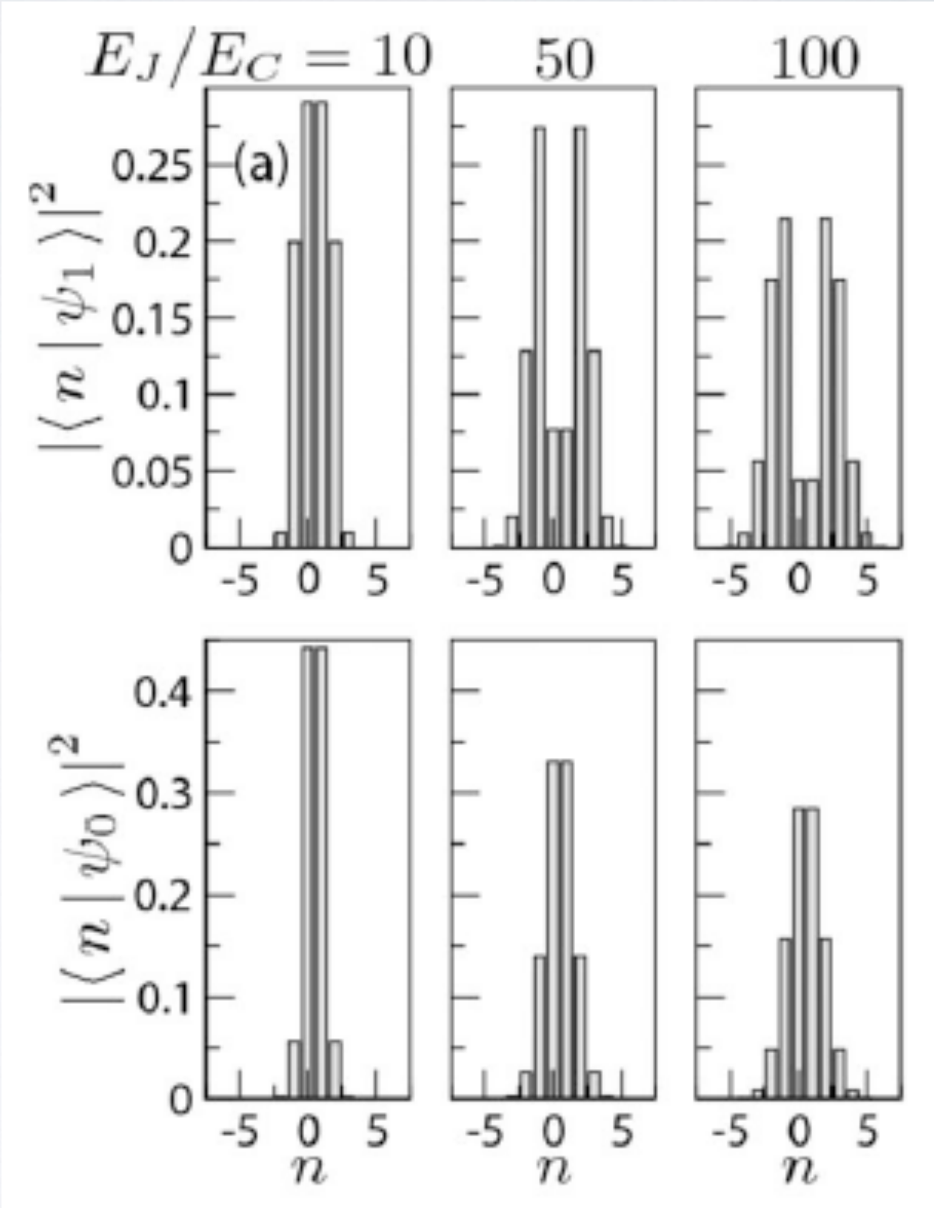


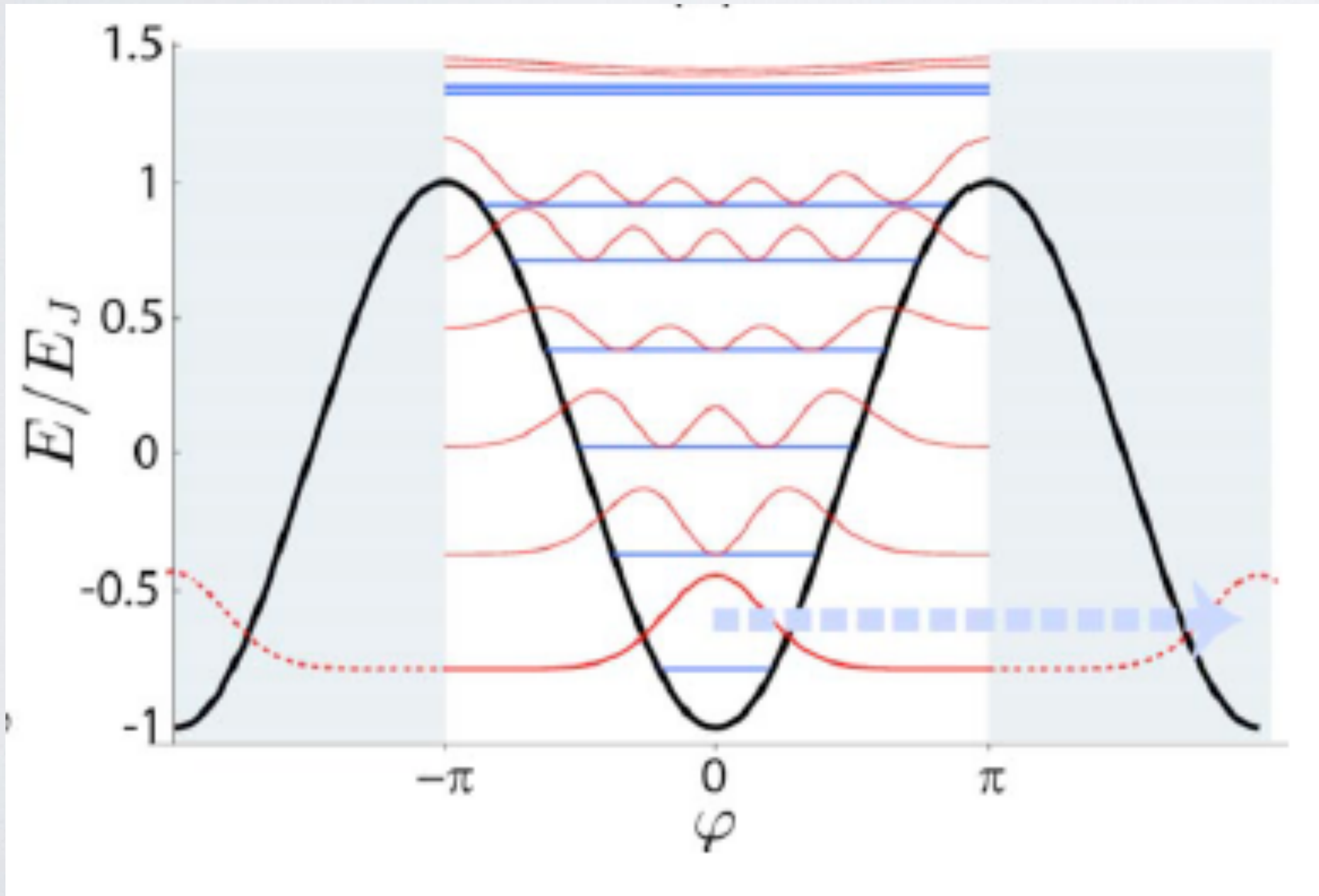
SUPERCONDUCTING QUBITS

Transmon qubit



Eigenstates: charge superposition





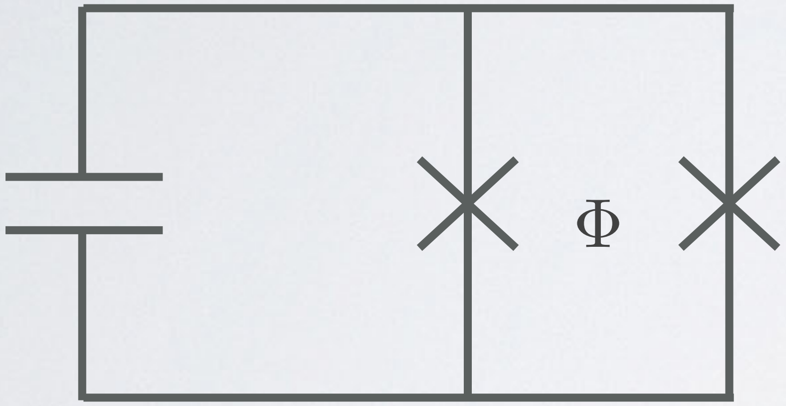
Harmonic to cosine potential

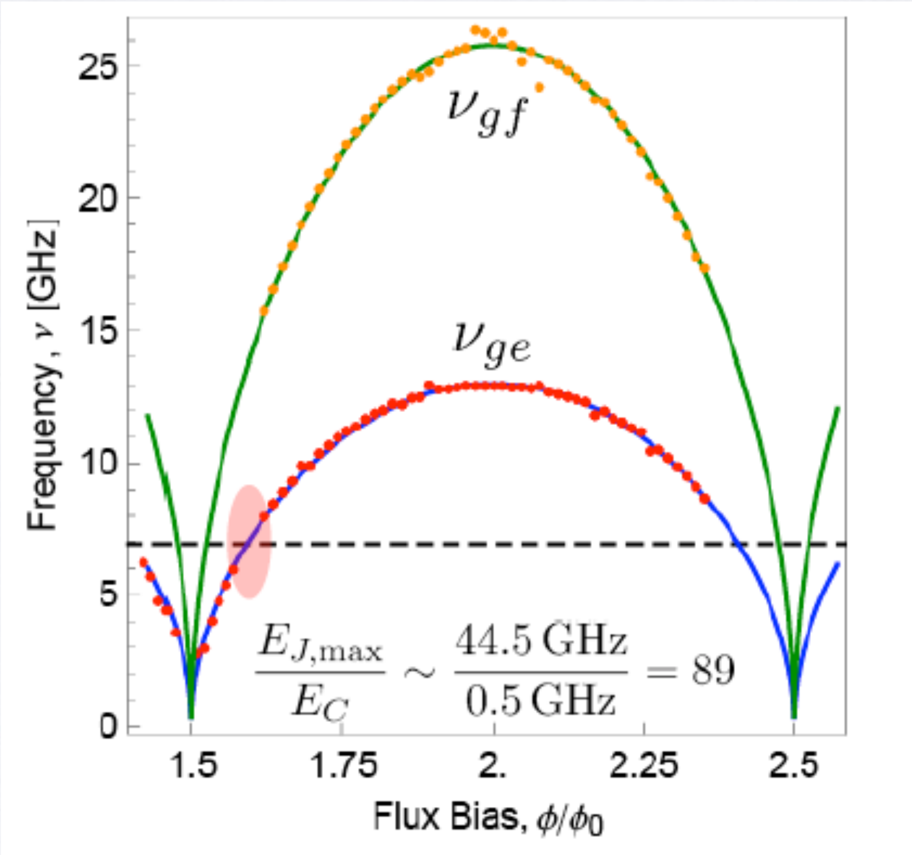
Koch et al. PRA 76, 042319 (2007)

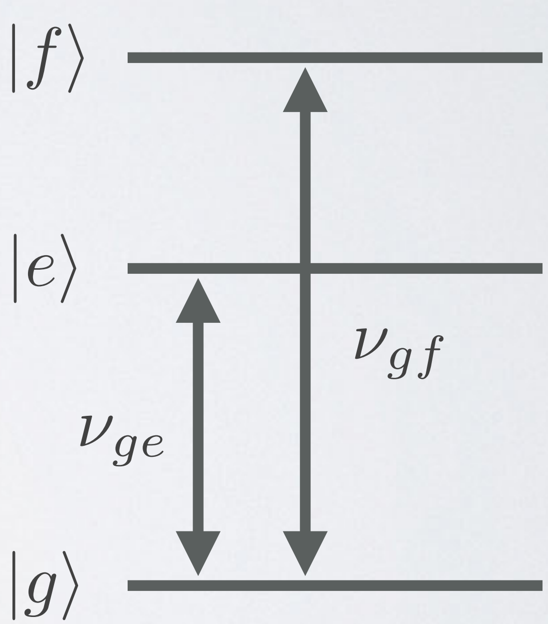
SUPERCONDUCTING QUBITS

Transmon qubit

Flux dependence of energy levels





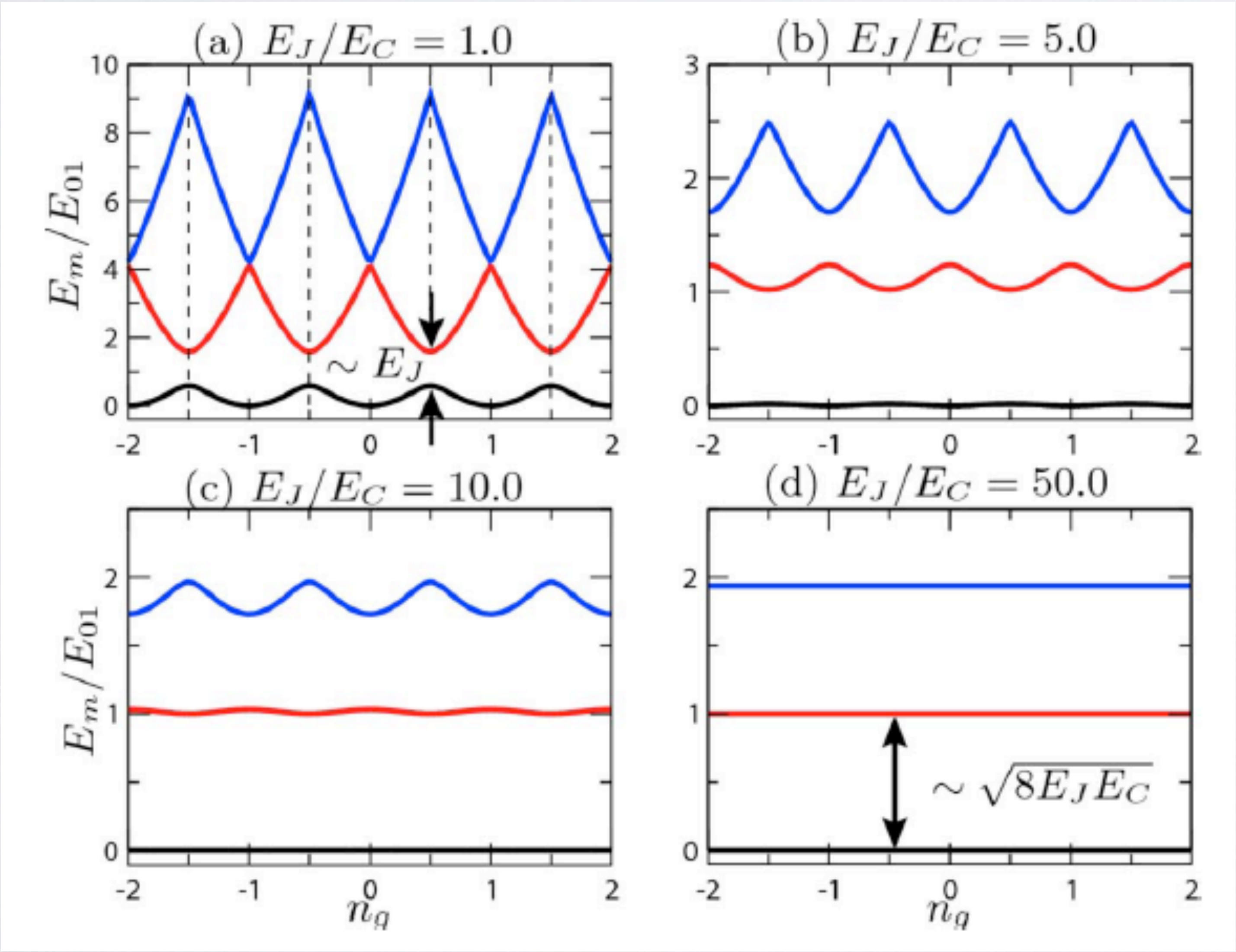


J. Fink et al., Nature 454, 315 (2008)

SUPERCONDUCTING QUBITS

Transmon qubit

Charge insensitivity of transmon from circuit design



Flat bands mean
larger insensitivity

System remains slightly
anharmonic

$$\omega_{01} - \omega_{12} = -\alpha = -E_C$$

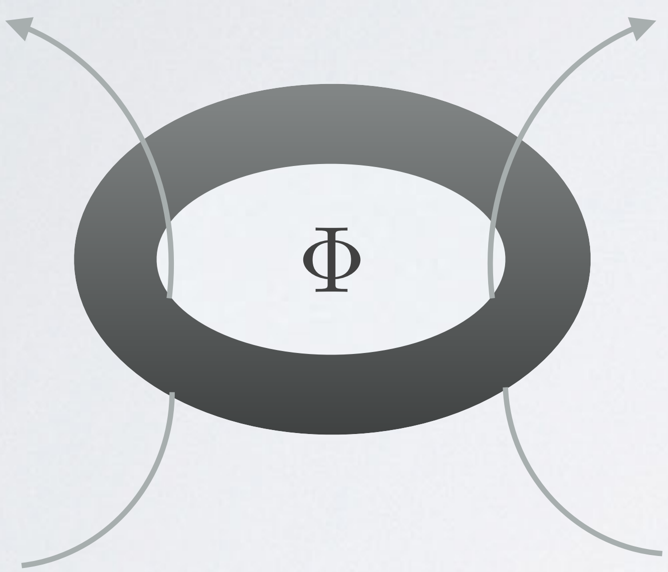
anharmonicity

Koch et al. PRA 76, 042319 (2007)

SUPERCONDUCTING QUBITS

Flux qubit

Superconducting ring: flux quantized

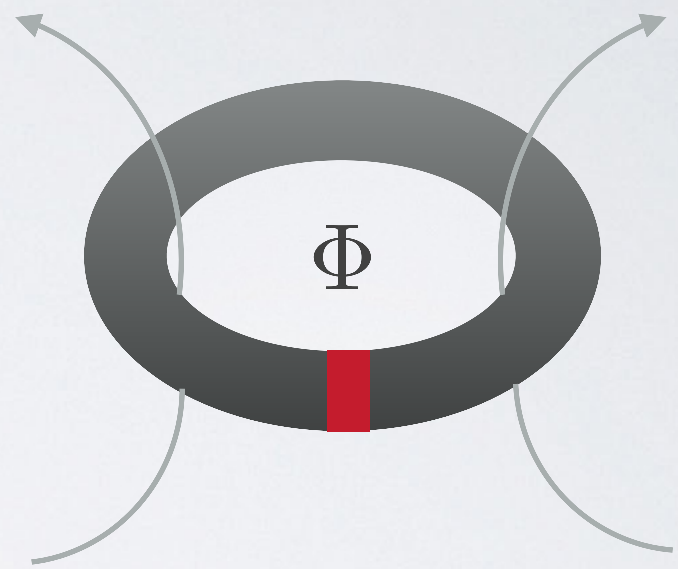


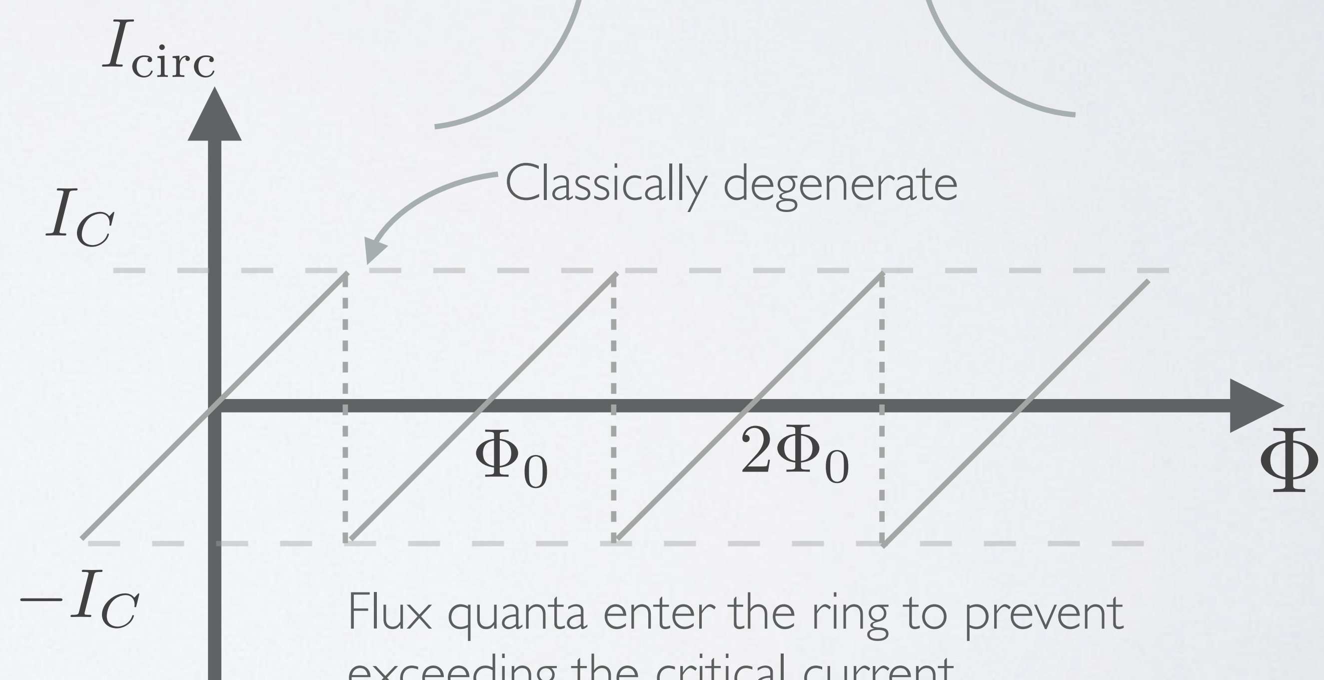
$$\Psi = |\Psi(n_{\mathrm{CP}})|e^{i\varphi}$$

$$\Delta\varphi = \varphi + 2\pi N$$

fixed upon cooldown:
Number of flux quanta trapped

Single-junction loop: rf-SQUID / Flux qubit





Flux quanta enter the ring to prevent exceeding the critical current

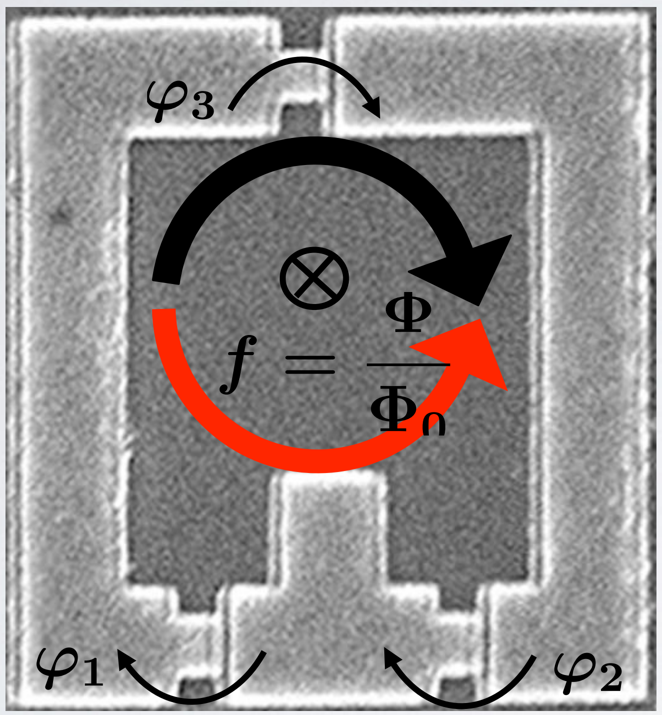
But: large loop, too sensitive to flux noise…

M. Tinkham, Introduction to Superconductivity

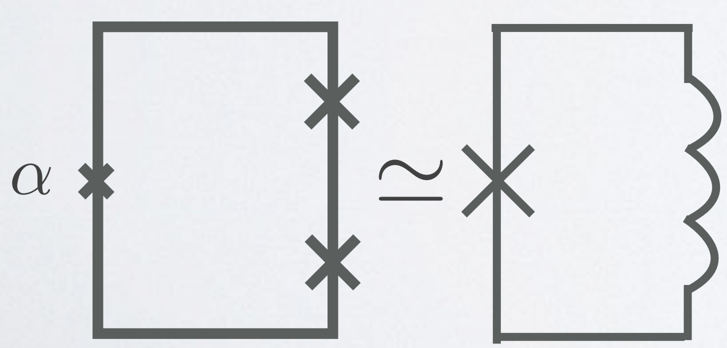
SUPERCONDUCTING QUBITS

Persistent current qubit

Aluminum loop with 3 Josephson junctions



Circuit diagram:

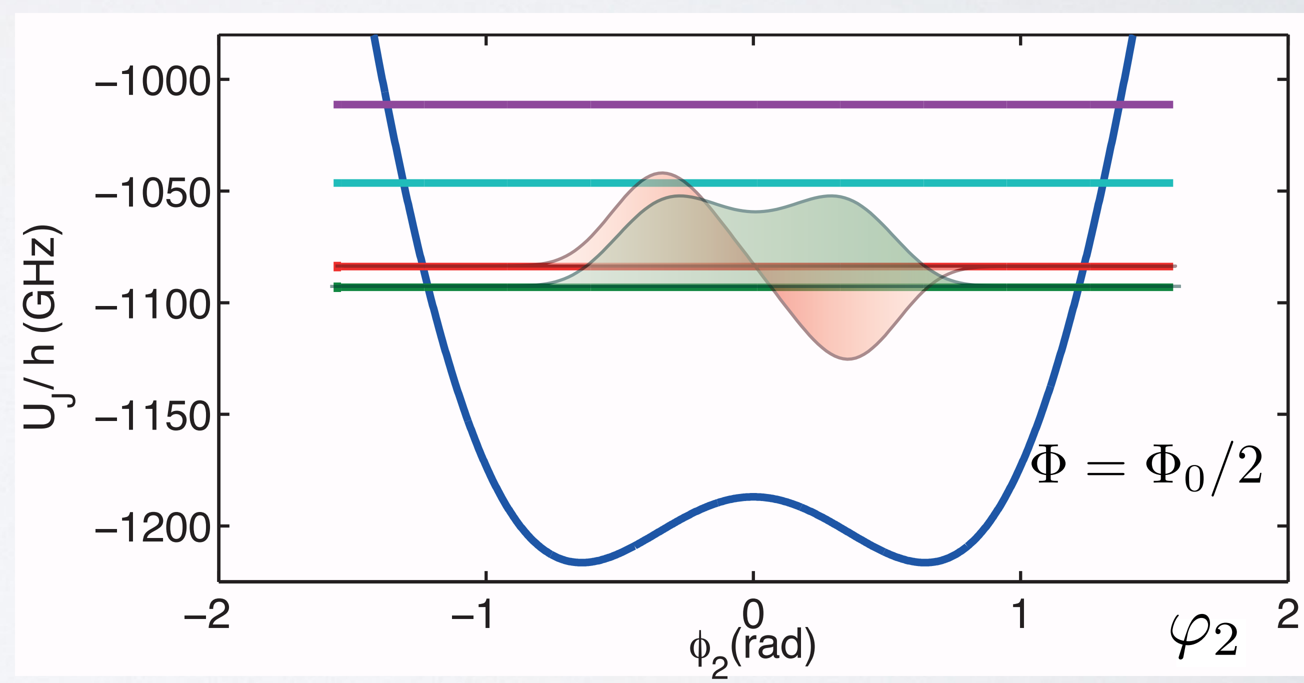


T. P. Orlando, et al. PRB 60 15398 (1999)

J. E. Mooij, et al. Science 285 1036 (1998)

Circuit Hamiltonian:

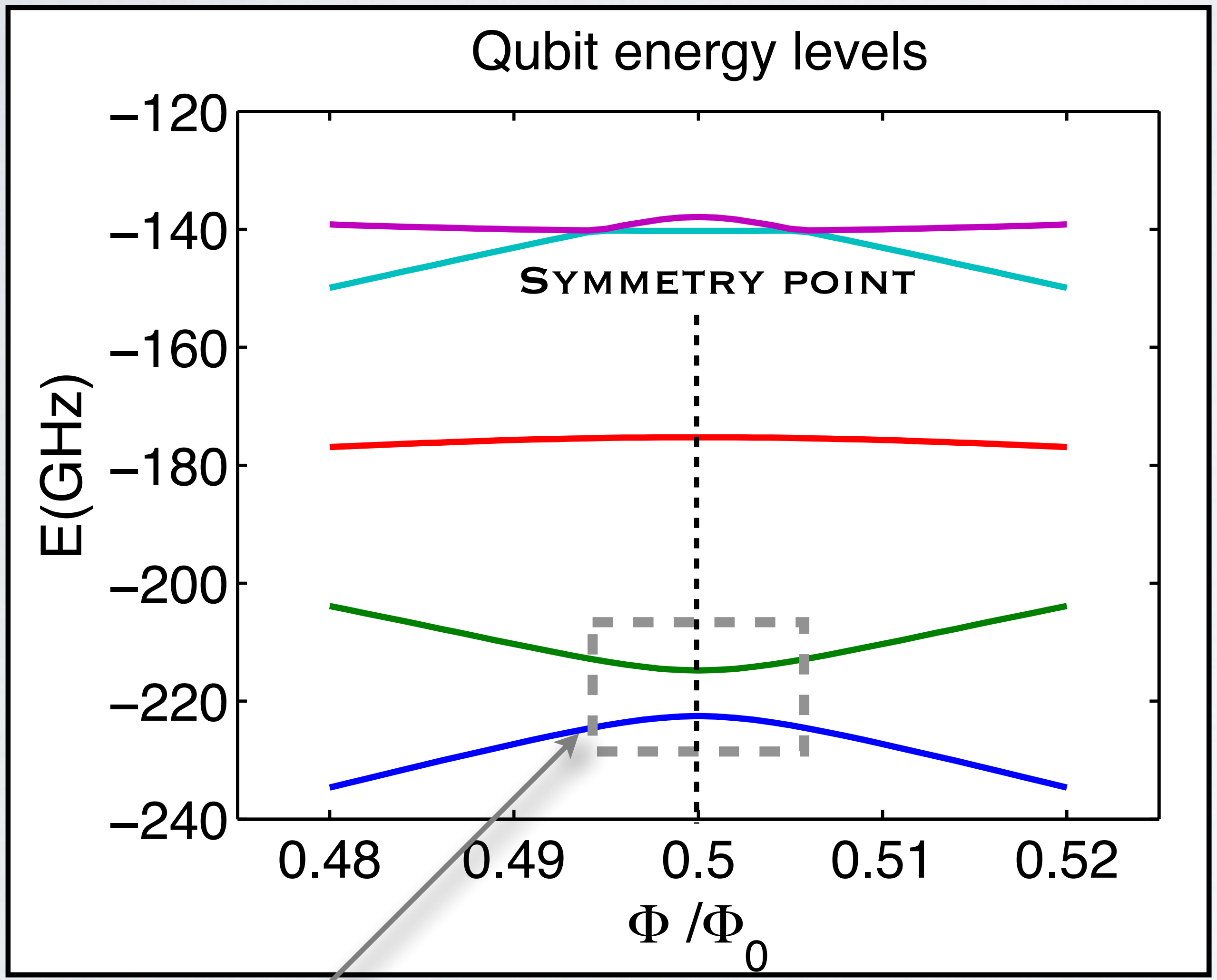
$$\mathcal{H}_{\mathrm{PCQ}} = \frac{E_C}{1+2\alpha}\left[n_1^2 - 2\alpha n_1 n_2 + (1+\alpha)n_2^2\right] +$$
$$E_J\left[\cos\varphi_1 + \cos\varphi_2 + \alpha\cos(\varphi_1 + \varphi_2 + 2\pi\Phi/\Phi_0)\right]$$

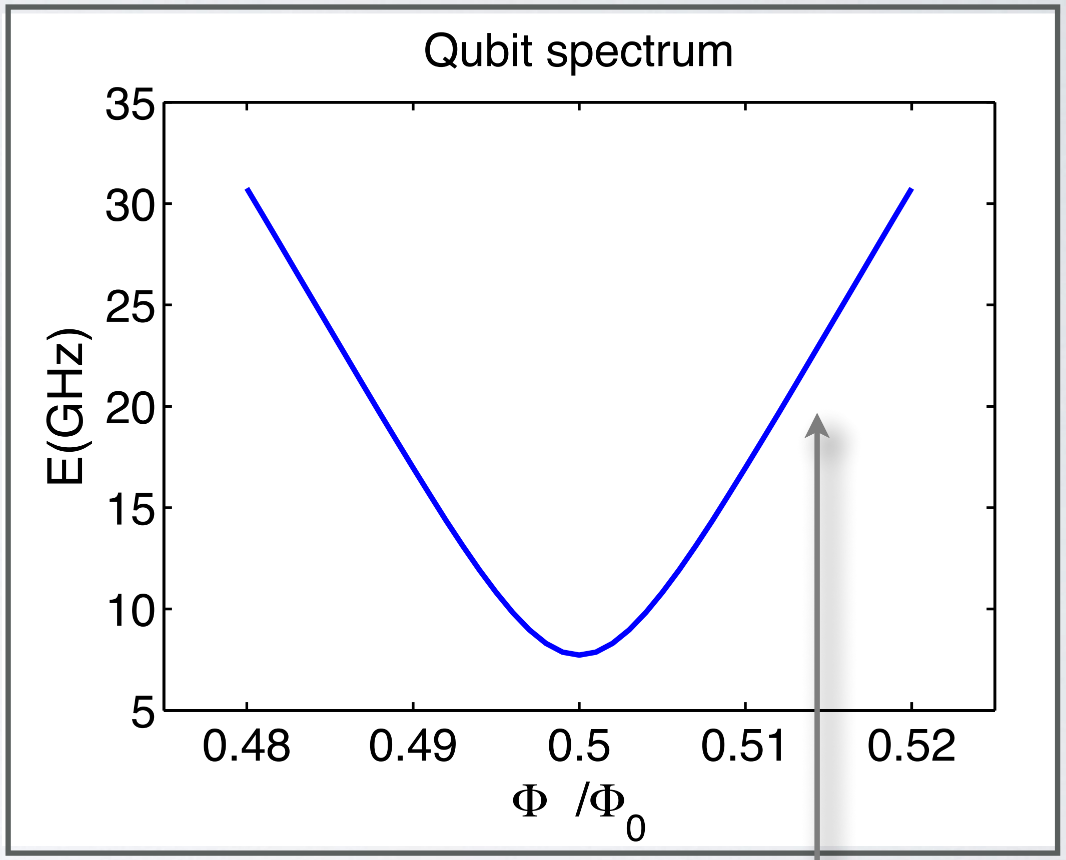


The tunneling through or over the barrier couples states into superposition of phase, hence current states

SUPERCONDUCTING QUBITS

Persistent current qubit





High sensitivity to magnetic flux*

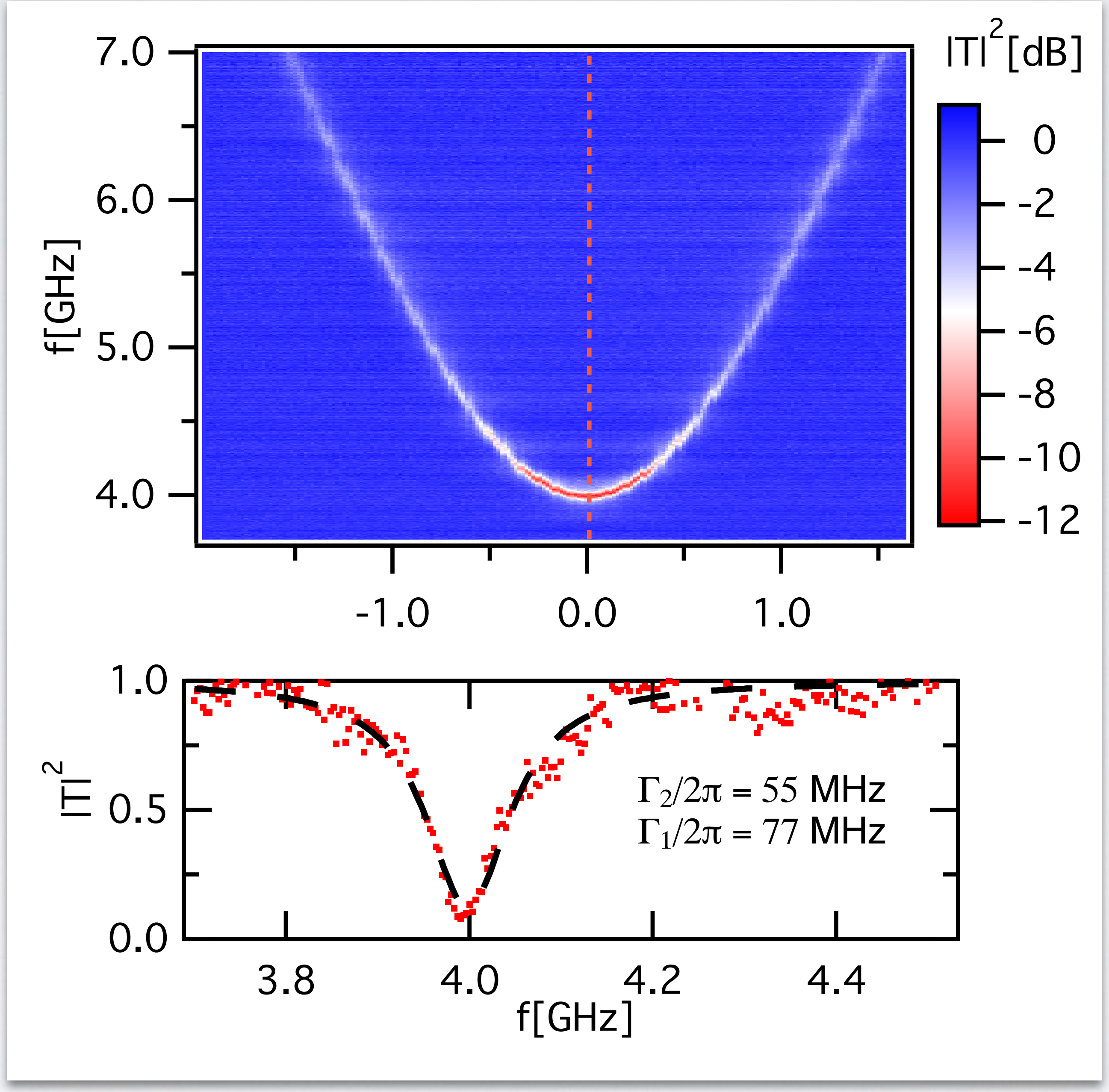
Persistent current states are degenerate in energy

*M. Bal, et al., Nat. Comm. 3, 1324 (2012)

SUPERCONDUCTING QUBITS

Persistent current qubit

Experimental signature?



Forn-Díaz et al., Nature Physics 13 (1), 39-43 (2017)

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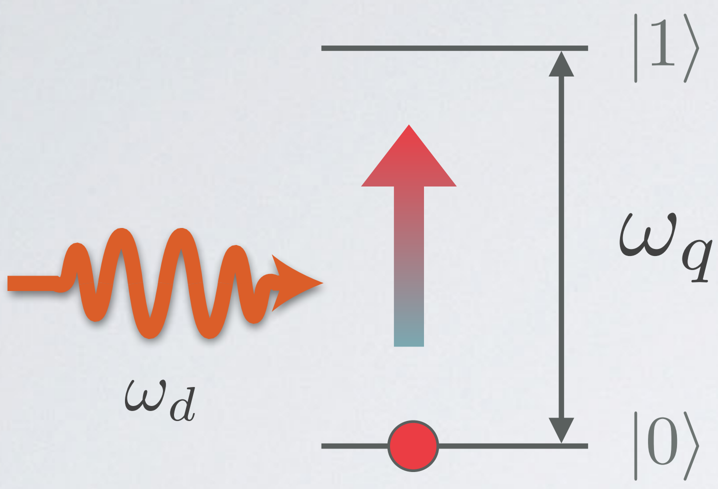
QUBIT STATE CONTROL



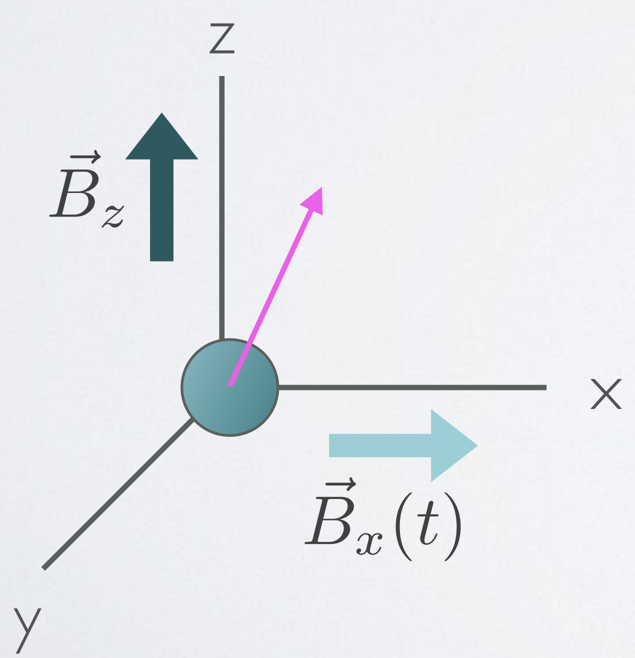
Rabi formula

$$P_{0\to 1} = \frac{\Omega_R^2}{\Delta^2 + \Omega_R^2} \sin^2\left(\sqrt{(\Delta^2 + \Omega_R^2)}t/\hbar\right)$$

Ω_R Rabi frequency "bare"

$\Delta \equiv \omega_q - \omega_d$ Detuning

Analogy with spin-1/2

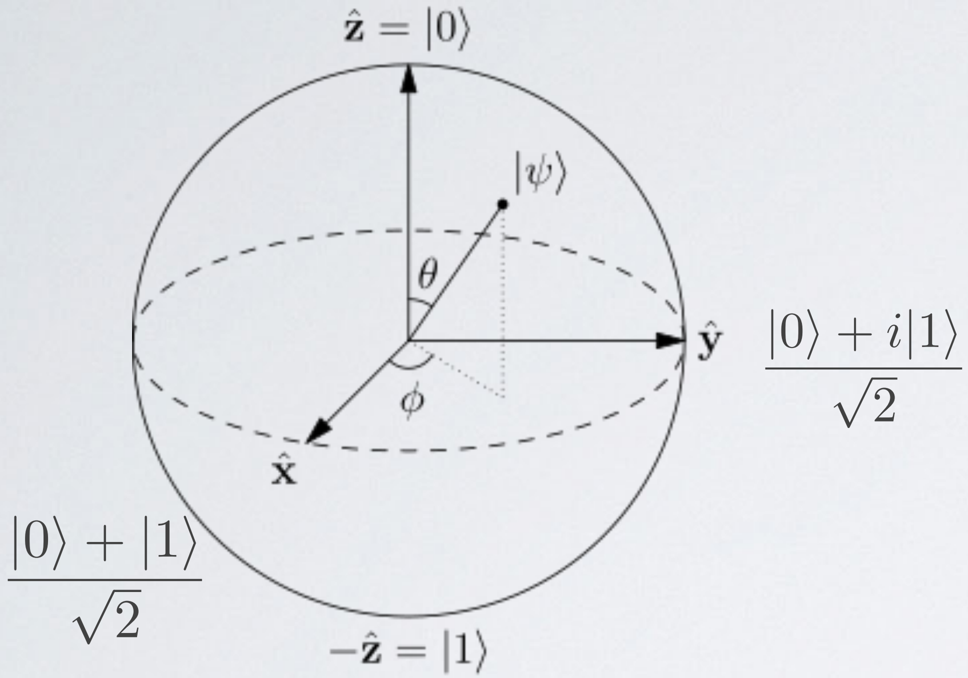


Import all NMR techniques for qubit state control…

Quantum Mechanics, C. Tannoudji

Nielsen and Chuang, Quantum computation and Quantum information

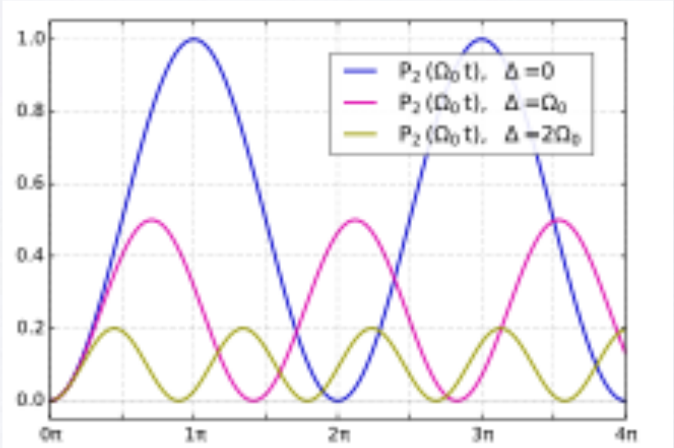
QUBIT STATE CONTROL



$$|\Psi\rangle = \cos\theta|0\rangle + \sin\theta e^{i\phi} e^{-iE_{01}t/\hbar}|1\rangle$$

In lab frame, spin precesses (Larmor frequency),
z-axis control

Rabi oscillations



Wikipedia

x-y axes control

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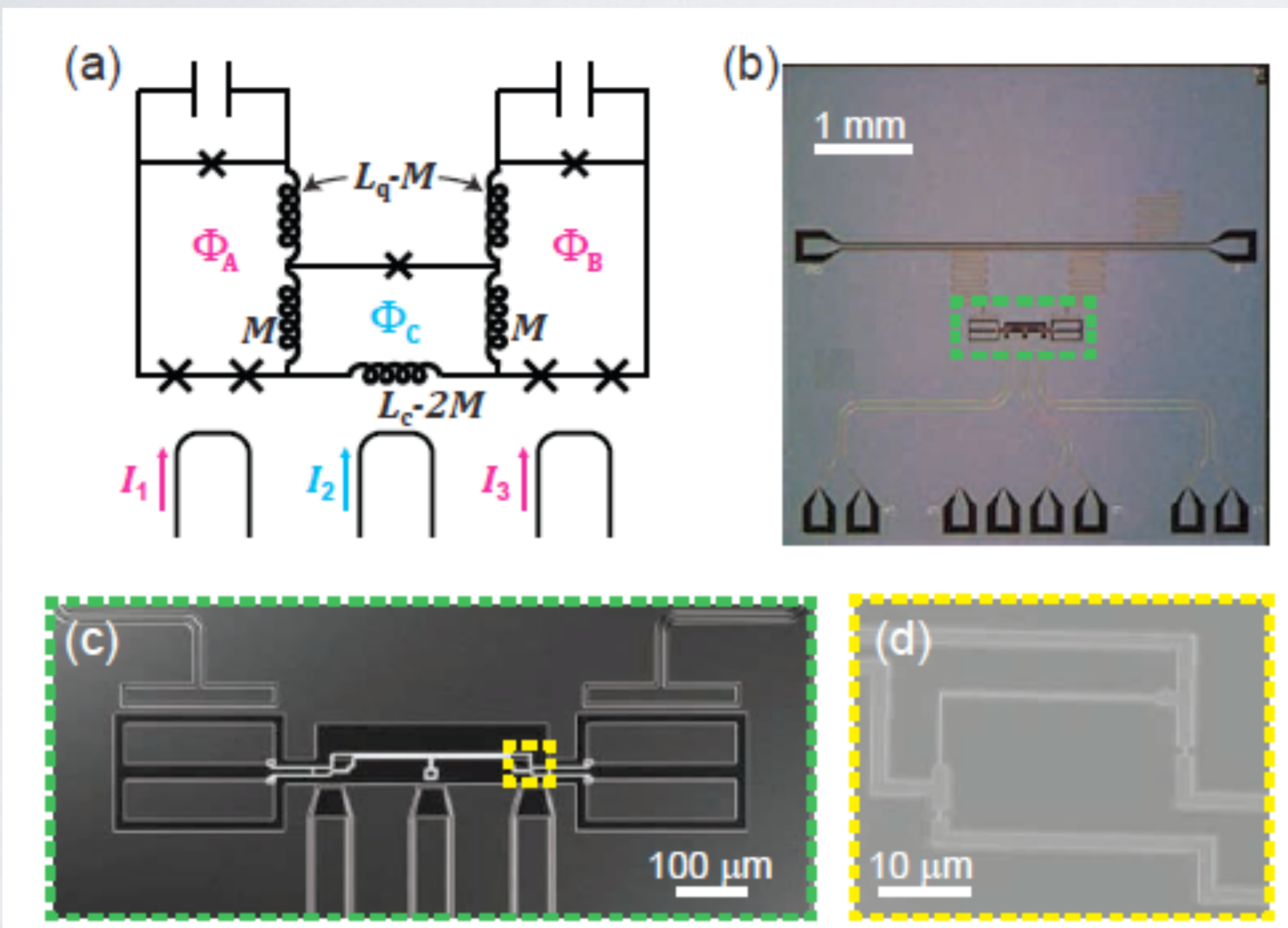
Quantum Mechanics, C.Tannoudji

Nielsen and Chuang, Quantum computation and Quantum information

QUBIT STATE CONTROL

Local control lines

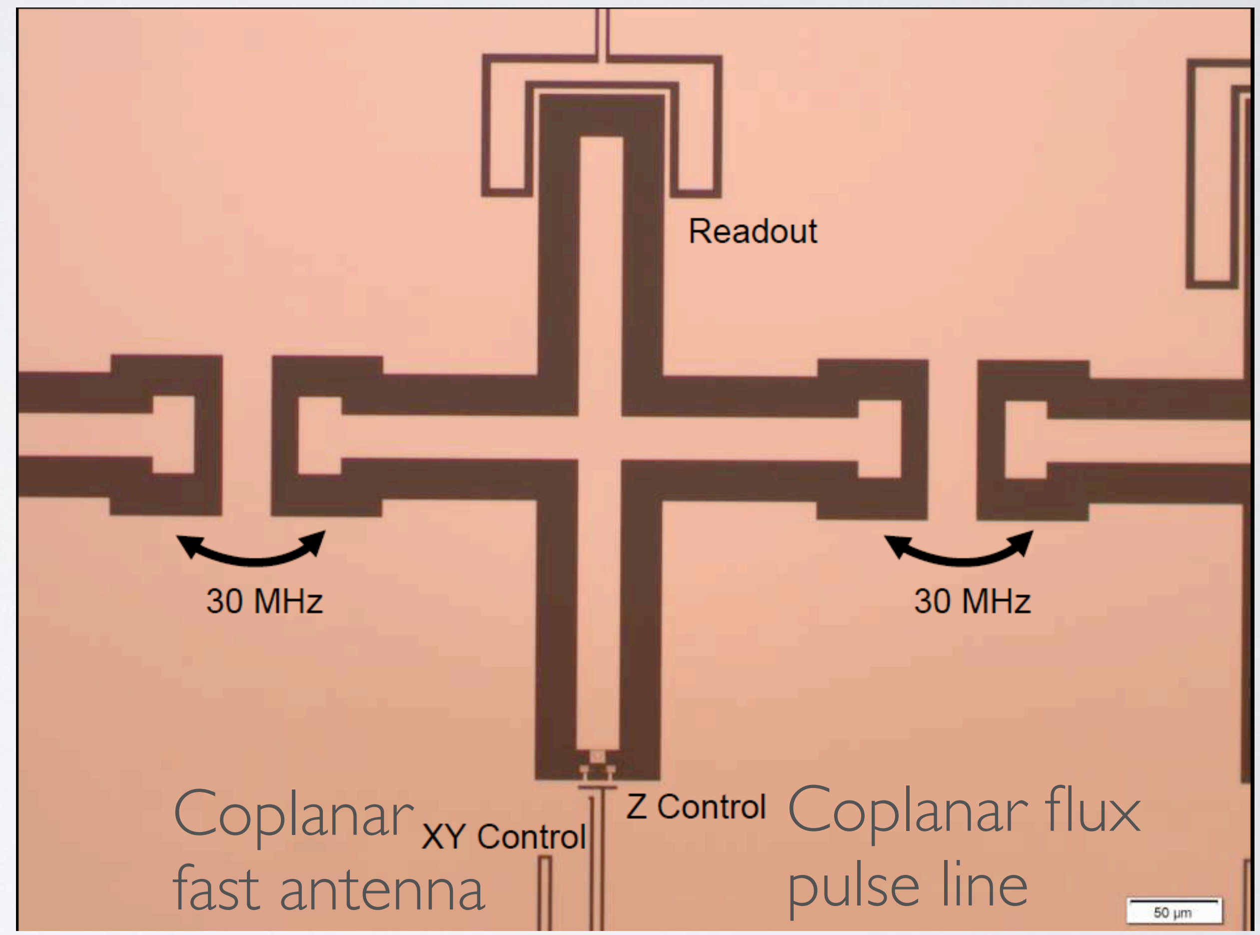
Flux qubit



Coplanar flux bias lines x-y-z control

Steven J. Weber, Phys. Rev. Applied 8, 014004 (2017)

Transmon qubit



Barends et al., PRL 111, 080502 (2013)

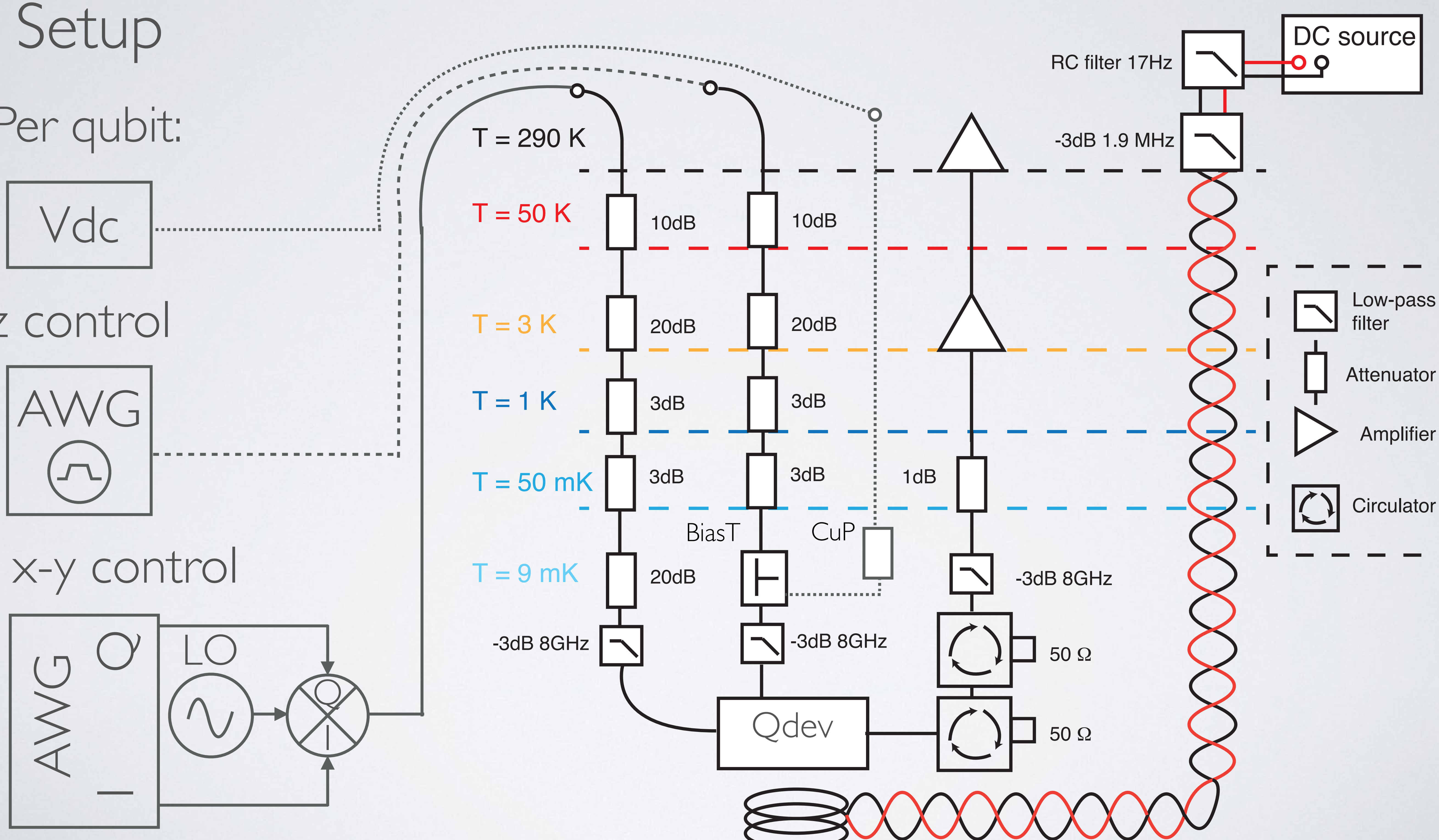
QUBIT STATE CONTROL

Setup

Per qubit:

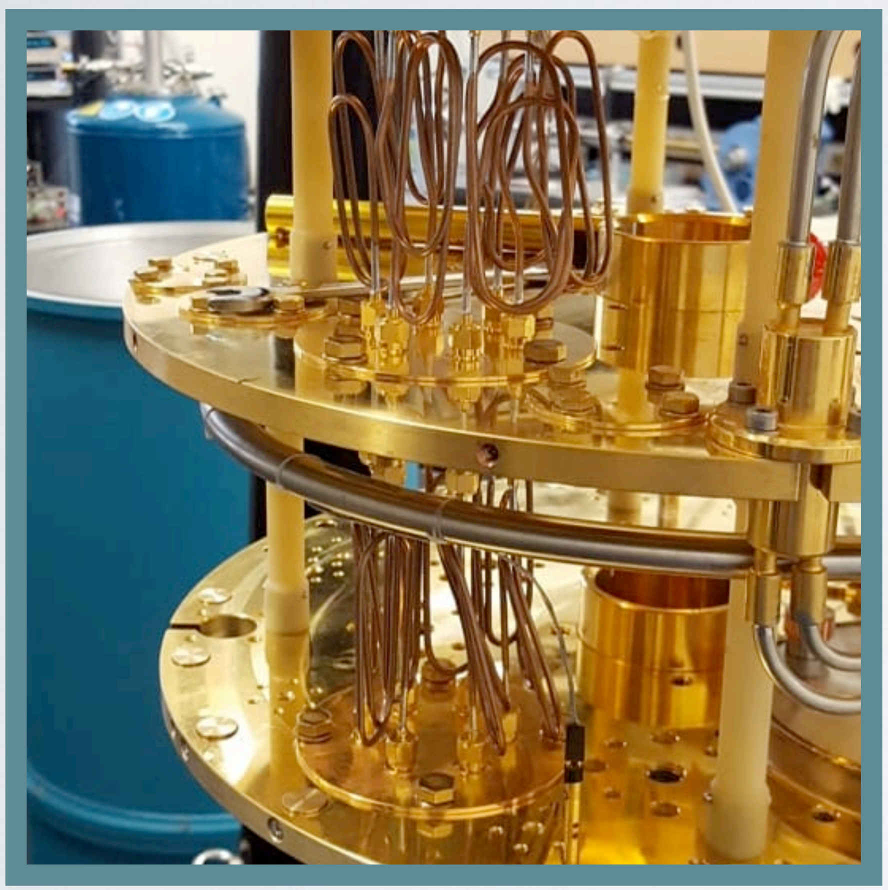
z control

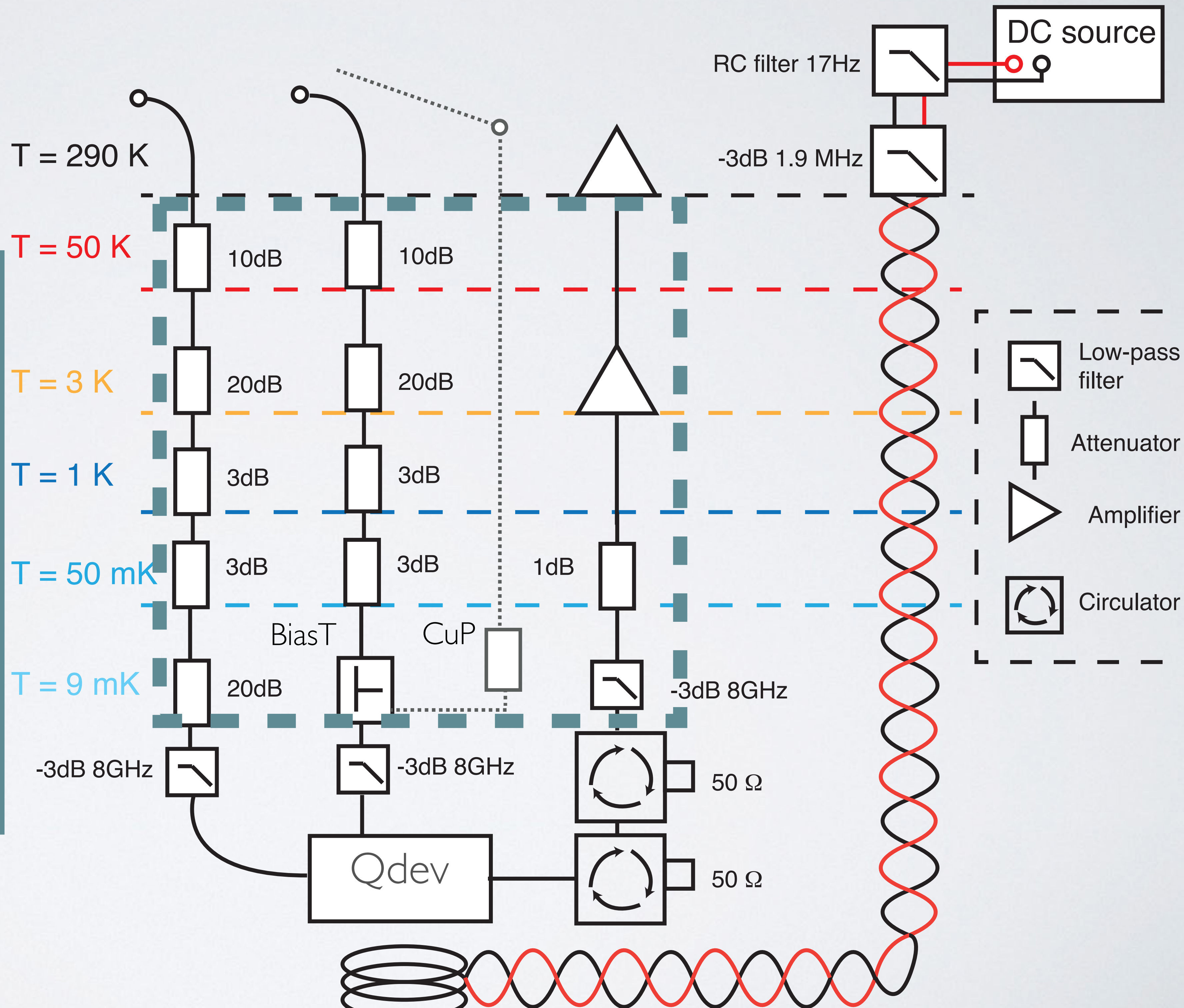
x-y control



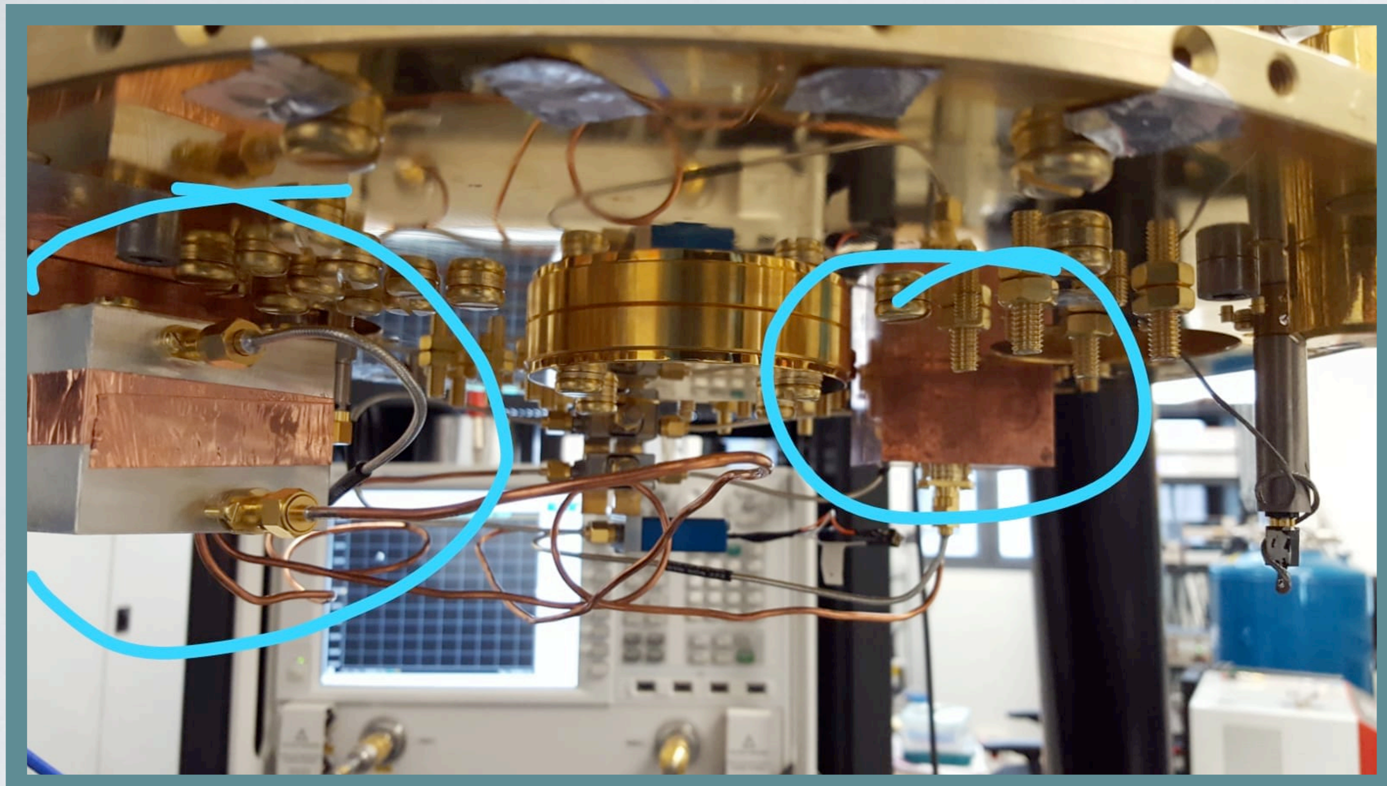
QUBIT STATE CONTROL

Coaxial wiring
dilution fridge

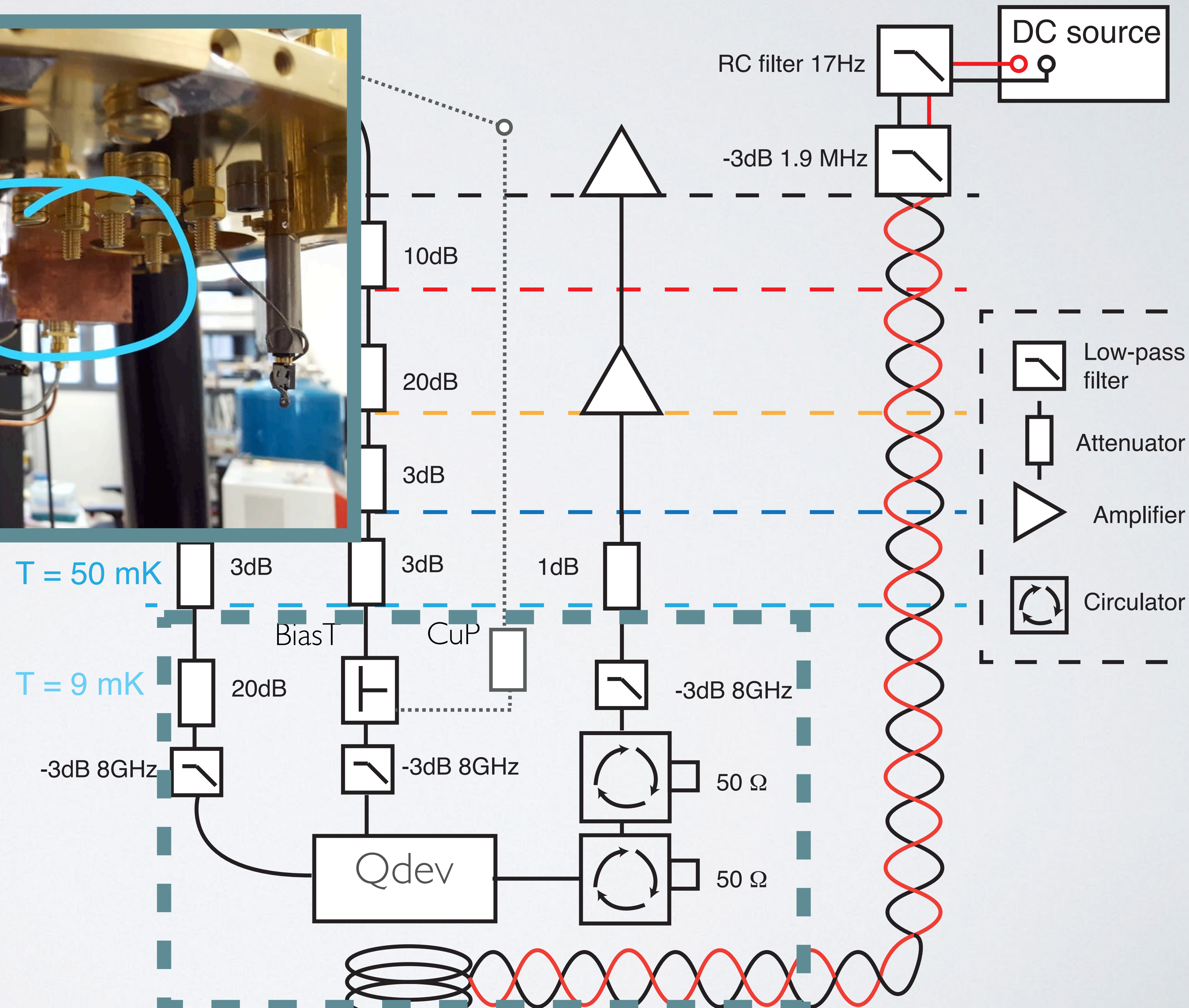




QUBIT STATE CONTROL

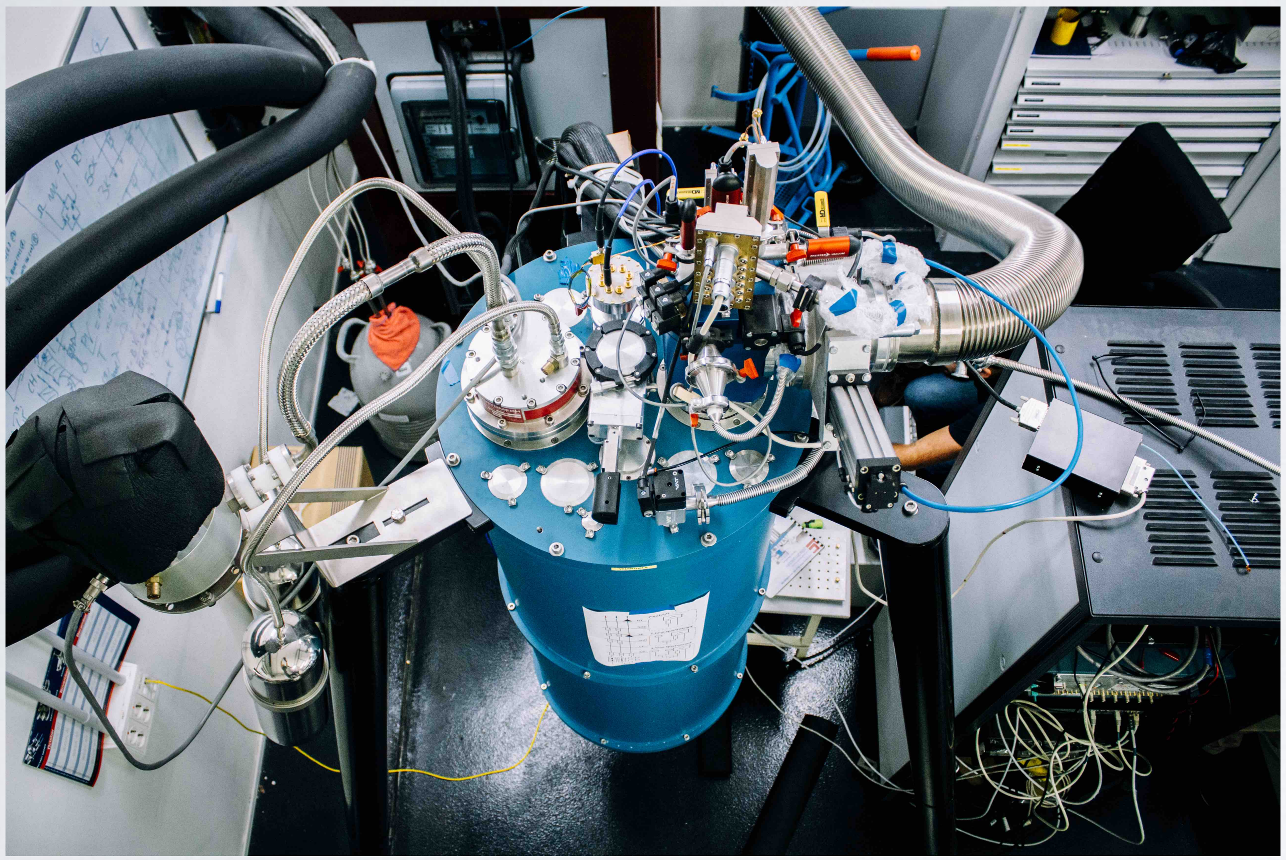


Superconducting cavities hosting qubits

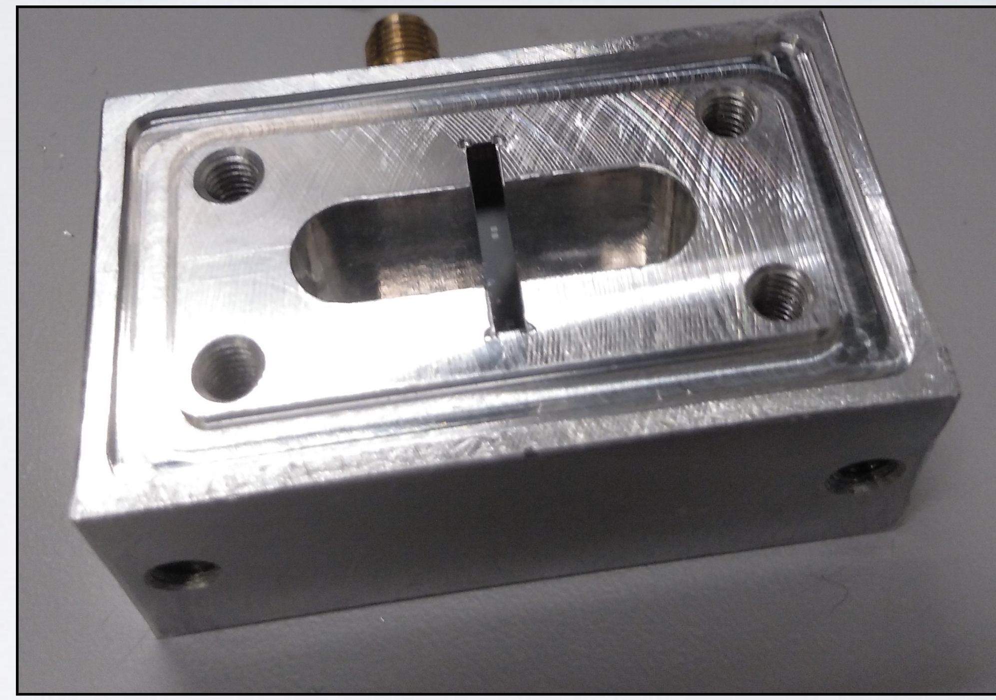


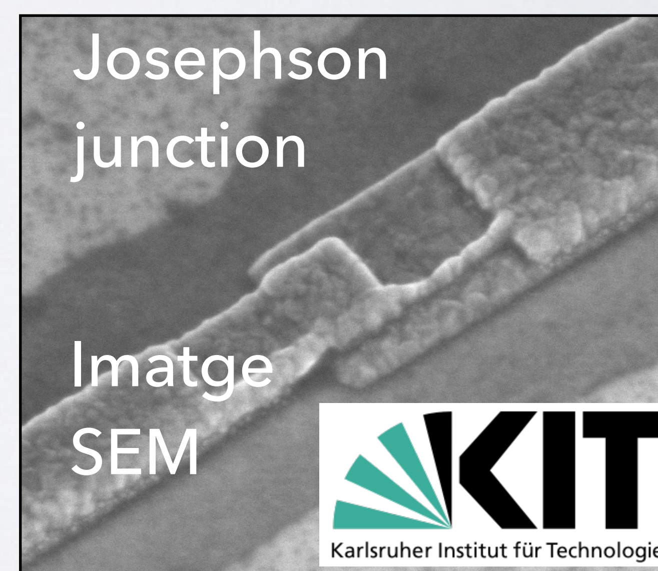
QUBIT STATE CONTROL

In a real experiment…



T = 0.01 K (-273.13 C)
Power consumption: 10kW





Currently at:

ICN2
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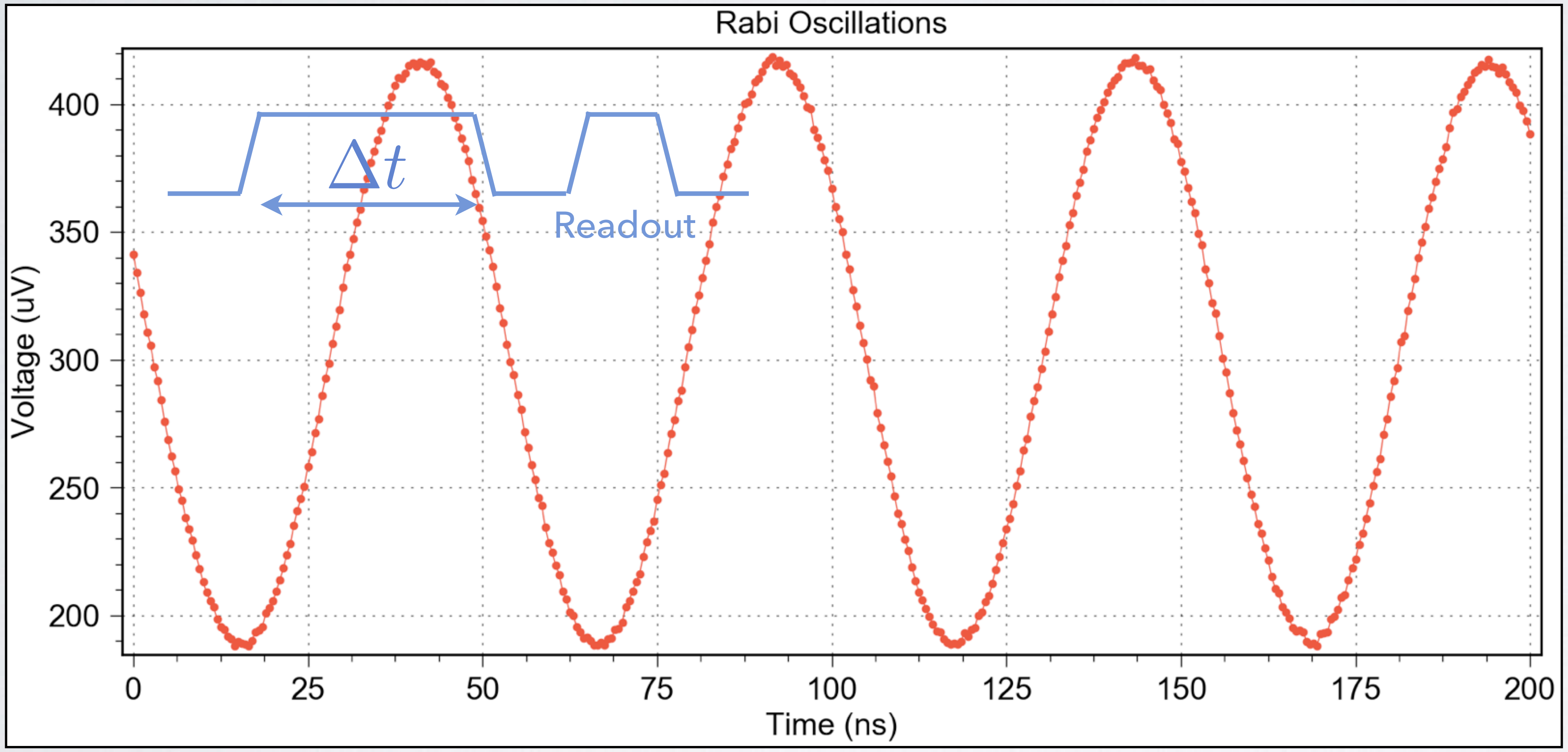
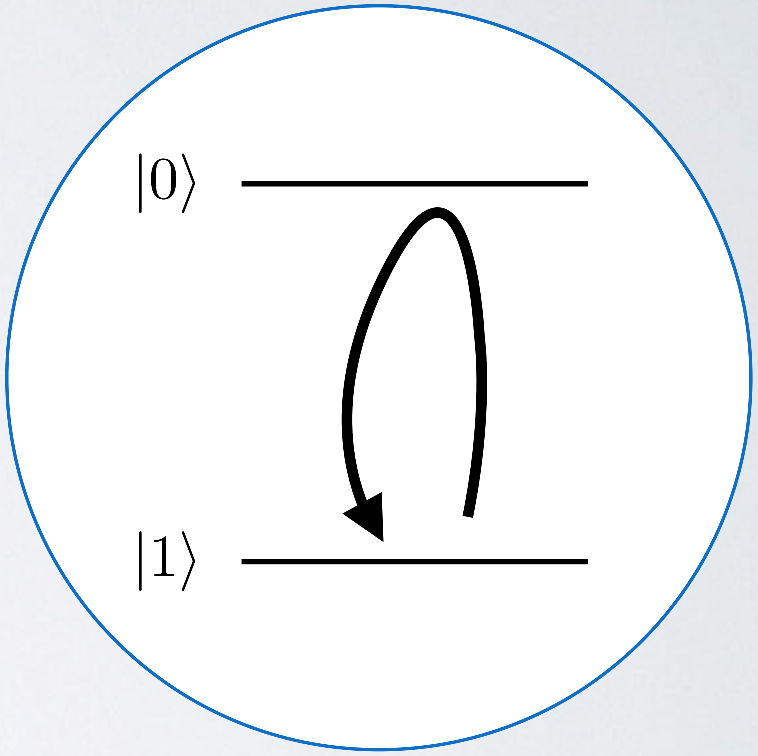
de Nanociència
i Nanotecnologia
EXCELENCIA
SEVERO
OCHOA

QUBIT STATE CONTROL

Driven, coherent Rabi oscillations of a superconducting qubit

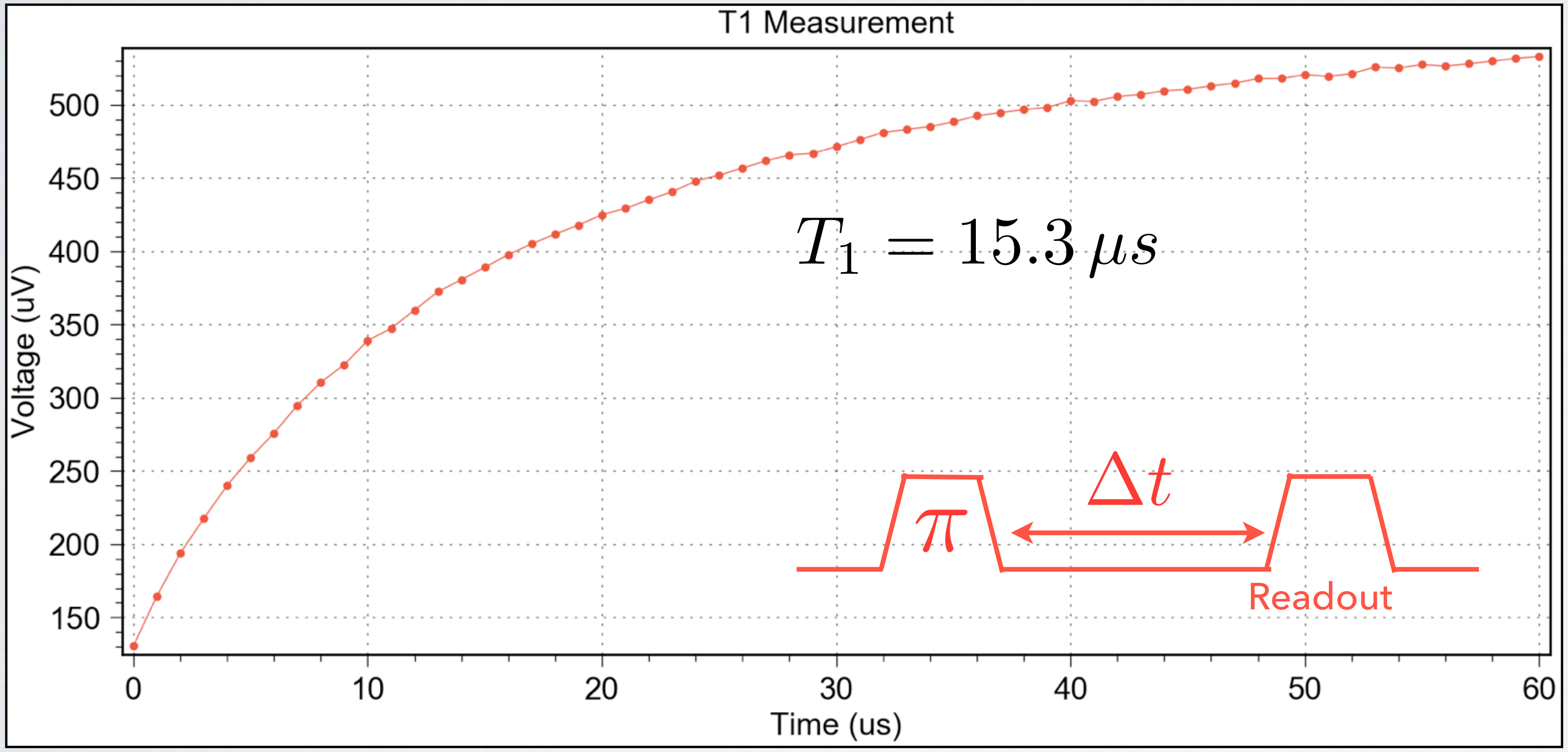


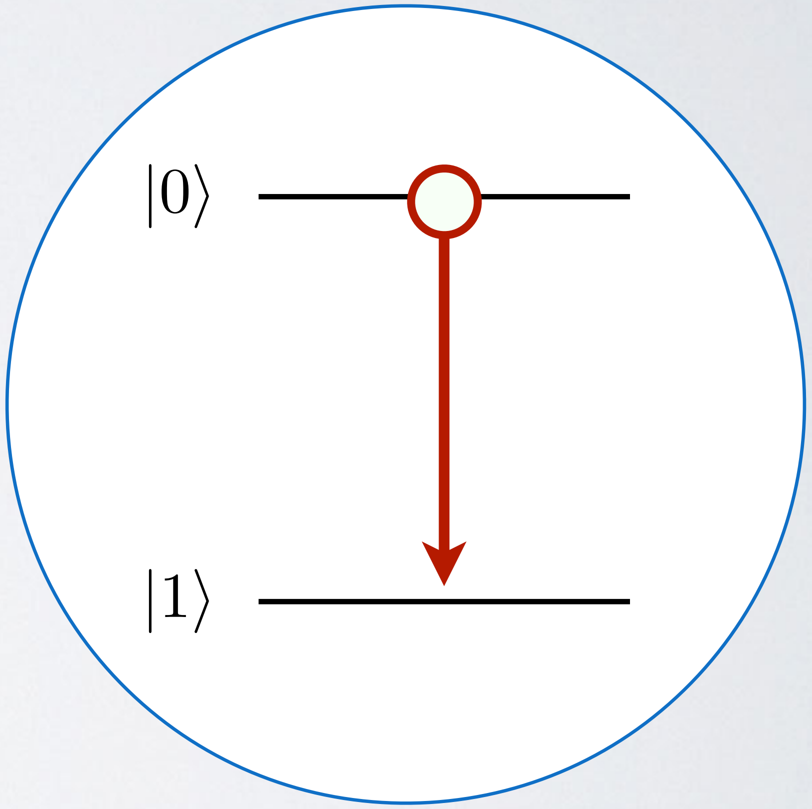


Spin-1/2-like control of qubits allows us to characterize qubit properties borrowing techniques from NMR

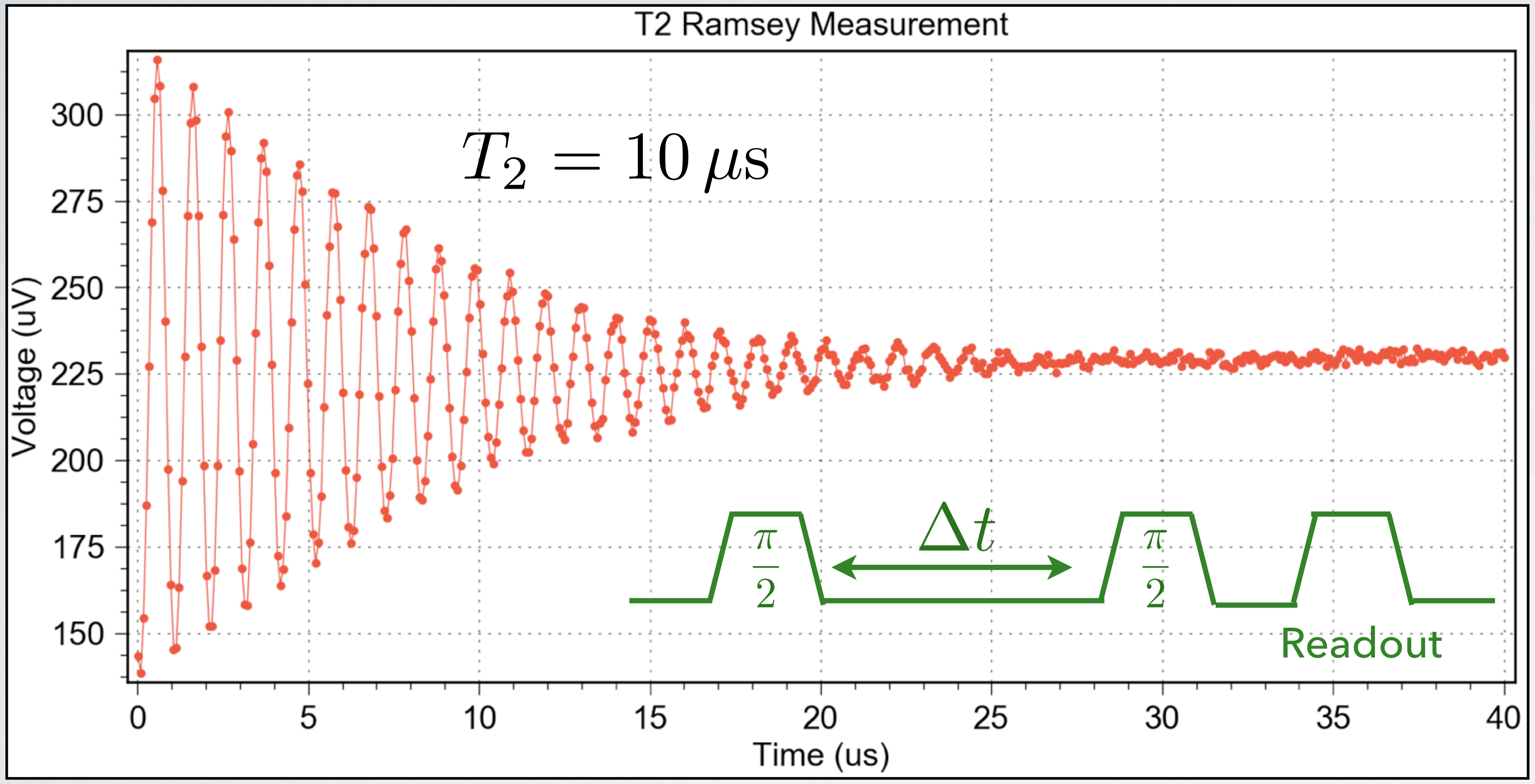
QUBIT STATE CONTROL

Energy decay of a superconducting qubit



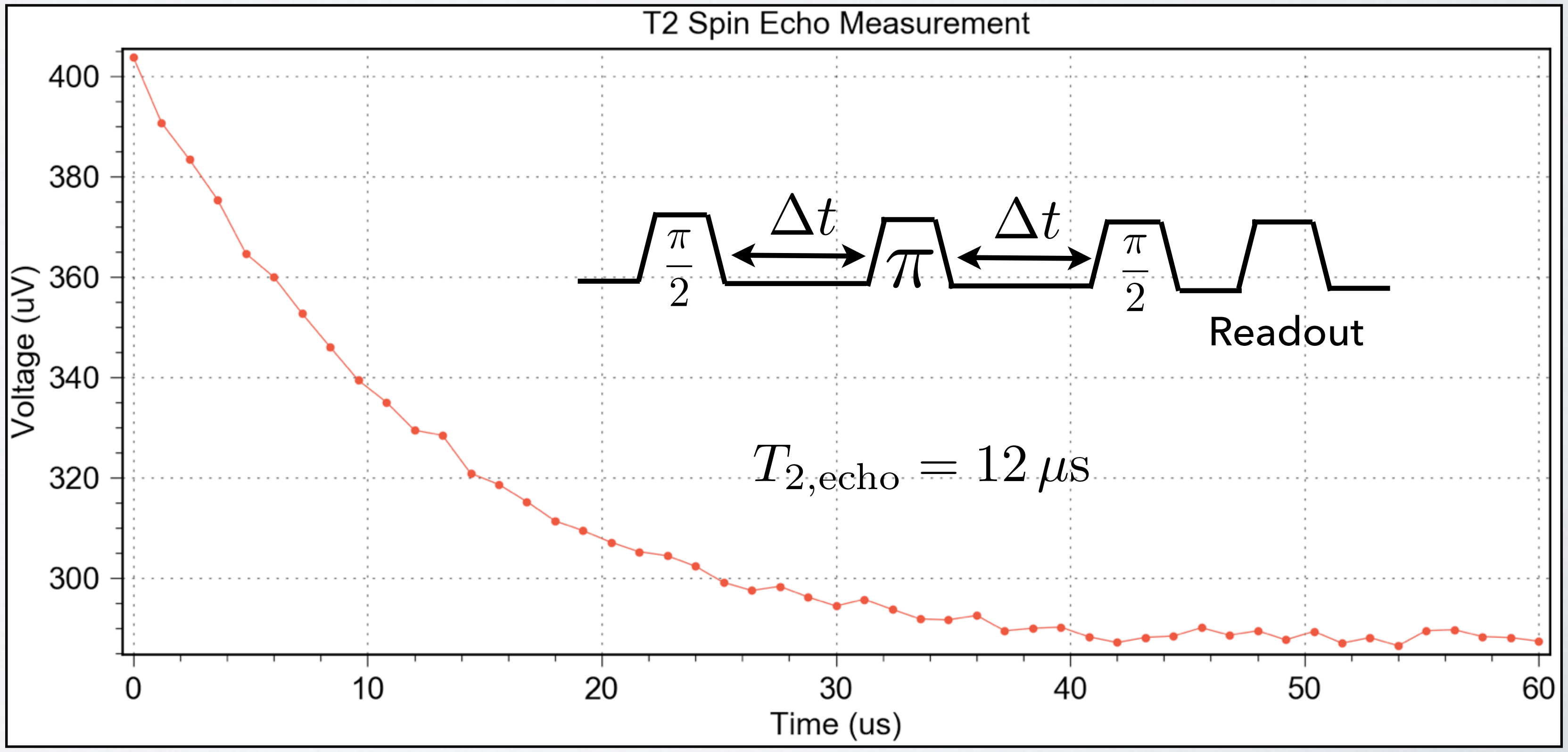


QUBIT STATE CONTROL



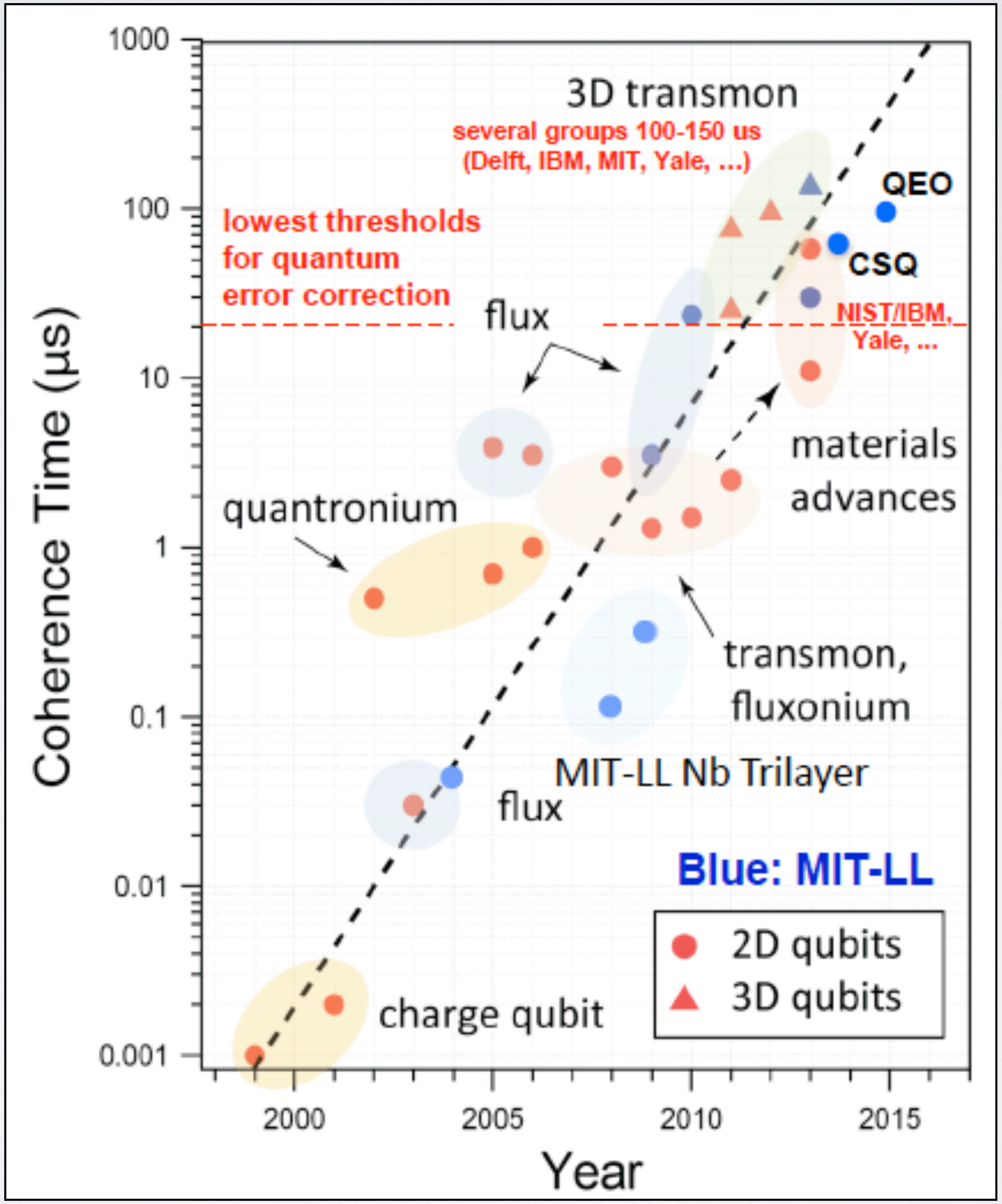
Decay of a superposition state: Ramsey fringes

Dynamical correction: Hahn spin-echo



QUBIT STATE CONTROL

A Moore's-like law



W. Oliver & Welander, MRS Bulletin (2013)

OUTLINE

Lecture I

- Quantum computation
- Circuit quantization
- Superconducting qubit zoo
- Qubit state control

End of lecture I!

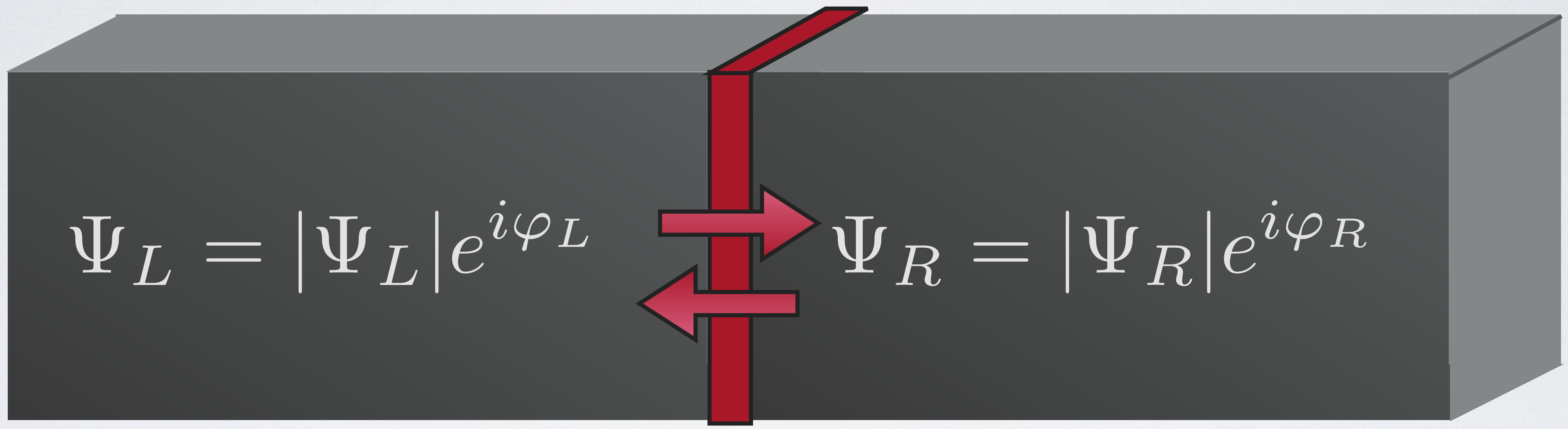
Lecture II

- Resonators for quantum computation
- Circuit quantum electrodynamics
- Qubit-qubit couplings and 2-qubit gates
- State of the art

BACKUP SLIDES

CIRCUIT QUANTIZATION

Superconductivity for qubits 101



First Josephson relation:

Critical current

$$I_{L\to R} = I_C \sin(\varphi_L - \varphi_R)$$

Second Josephson relation:

$$V = \frac{\Phi_0}{2\pi}\frac{\mathrm{d}(\varphi_\mathrm{L} - \varphi_\mathrm{R})}{\mathrm{dt}}$$

Flux quantum:

$$\Phi_0 = \frac{h}{2e} \sim 2.07 \times 10^{-15}\ \mathrm{Wb}$$

Energy stored:

$$U = -E_J \cos(\varphi_L - \varphi_R)$$

Josephson energy:

$$E_J = I_C \Phi_0 / 2\pi$$