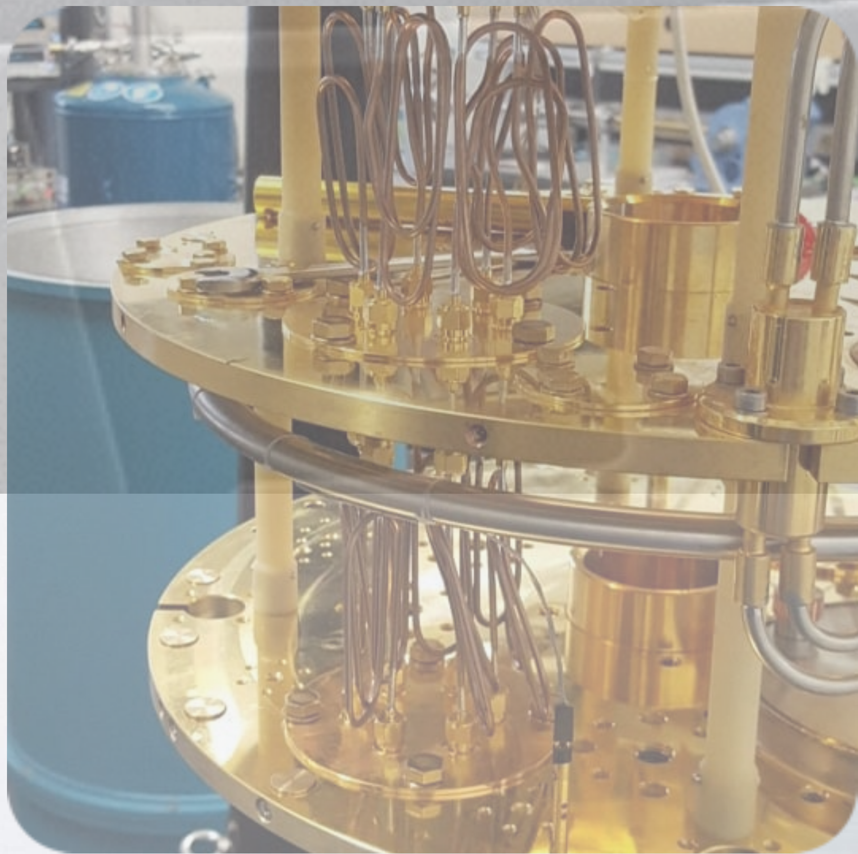
SUPERCONDUCTING QUANTUM PROCESSORS

Pol Forn-Díaz

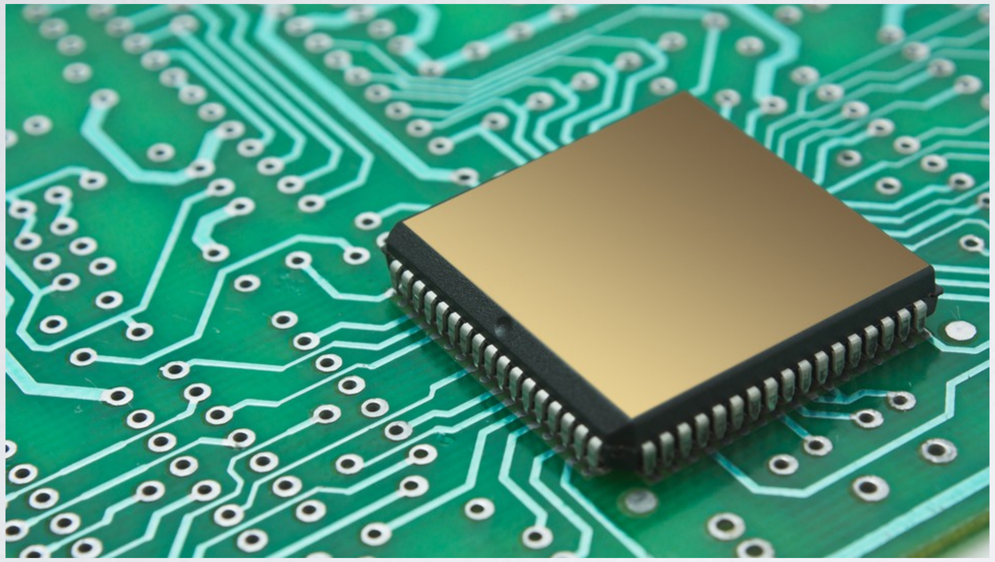
Colloquium IFAE
11/03/2019



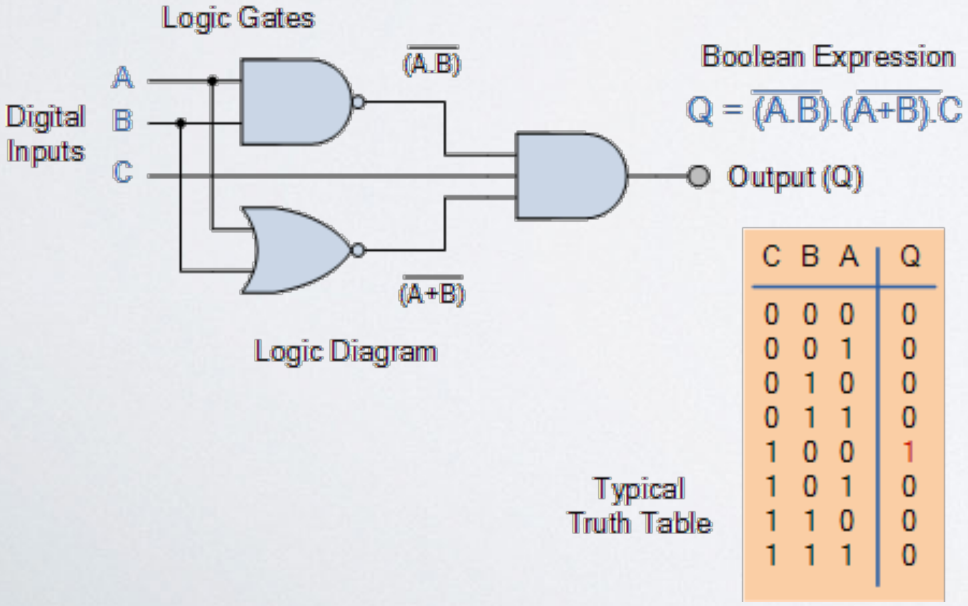
OUTLINE

- **Q**uantum computation
- Superconducting qubits
- Qubit state control
- A superconducting quantum computer

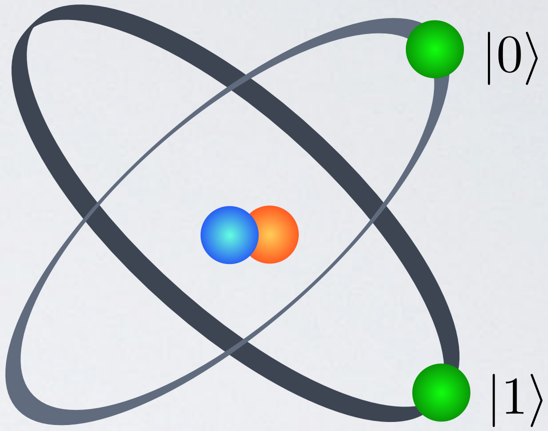
QUANTUM COMPUTATION



Classical systems can store information in classical variables (usually voltage).
Classical bit = minimal classical information unit with either of 2 options



C	B	A	Q
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	0
1	0	0	1
1	0	1	0
1	1	0	0
1	1	1	0



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

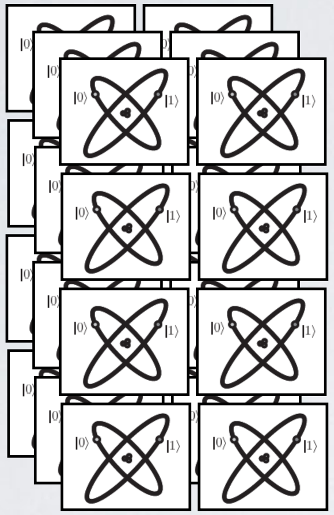
$$|\psi\rangle = \frac{|0\rangle + |1\rangle}{\sqrt{2}}$$

Qubit can live in a superposition of 0 **and** 1

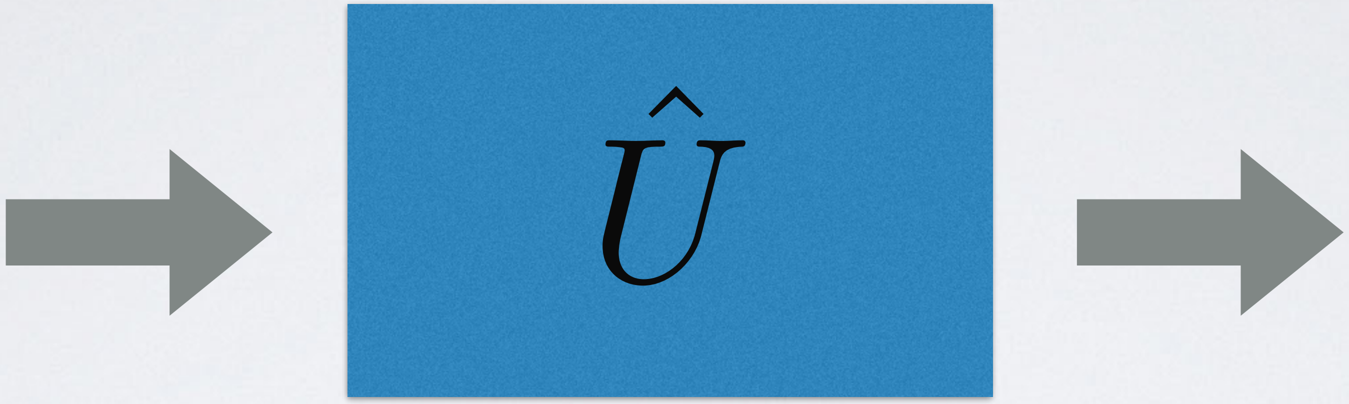
$$|\psi_N\rangle = \frac{1}{N^{1/2}} \prod_{i=1}^{N} (|0_i\rangle + |1_i\rangle)$$

QUANTUM COMPUTATION

$|\Psi(0)\rangle$

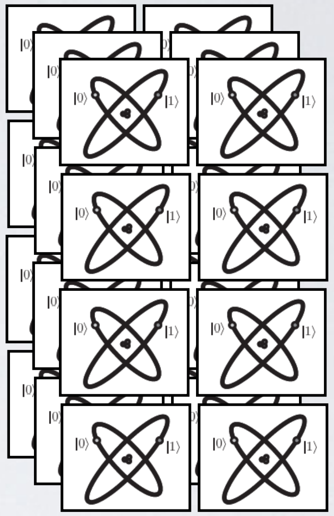


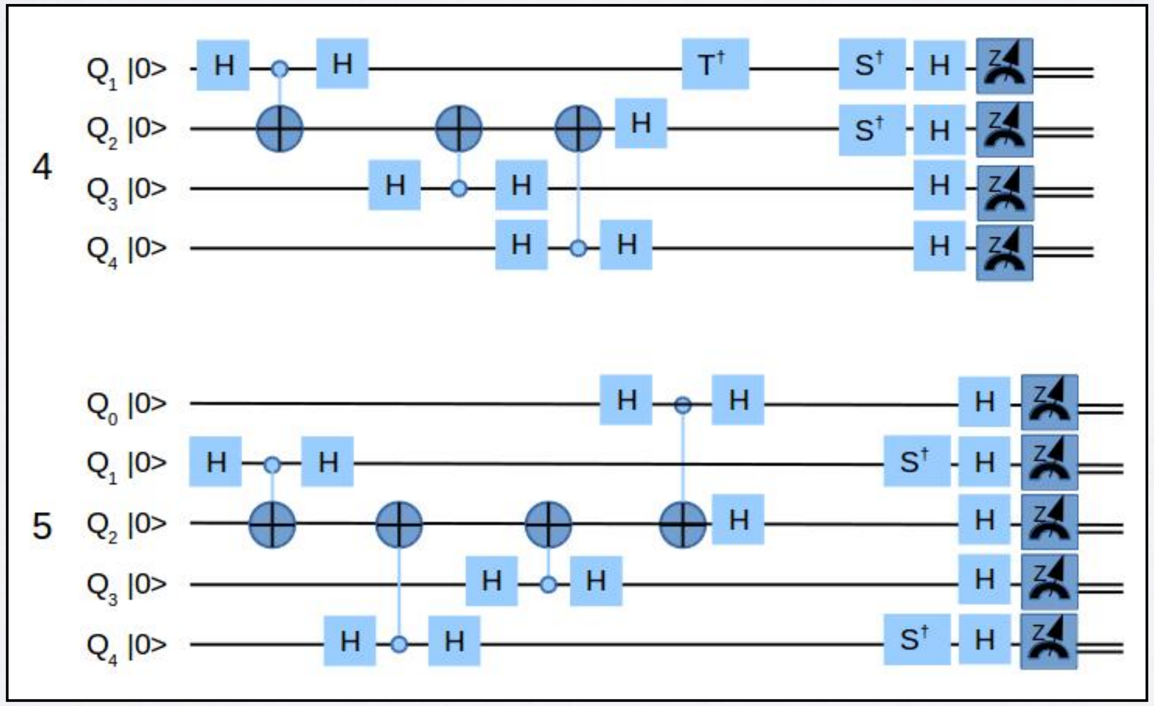
Universal Quantum Computer



$\hat{U}$

$|\Psi(t)\rangle$





Quantum gates circuit

Processing 2^N states simultaneously

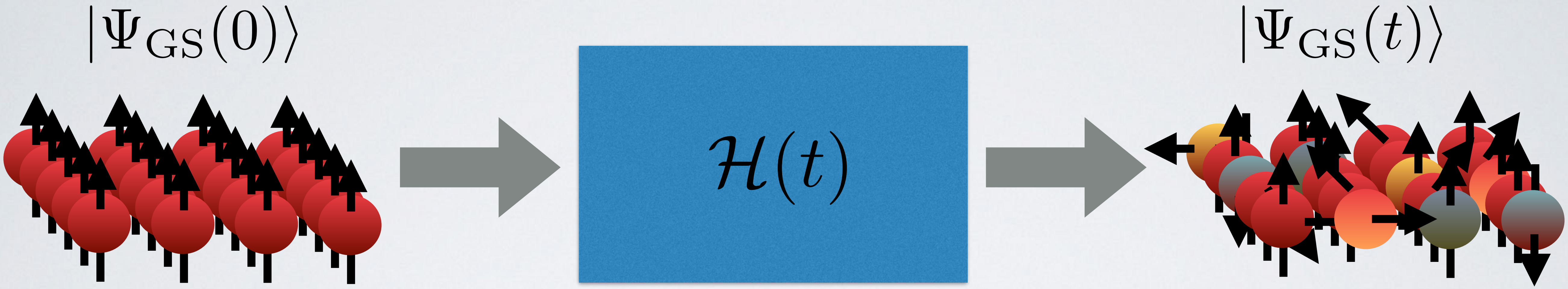
PROS:
Applicable to any quantum algorithm

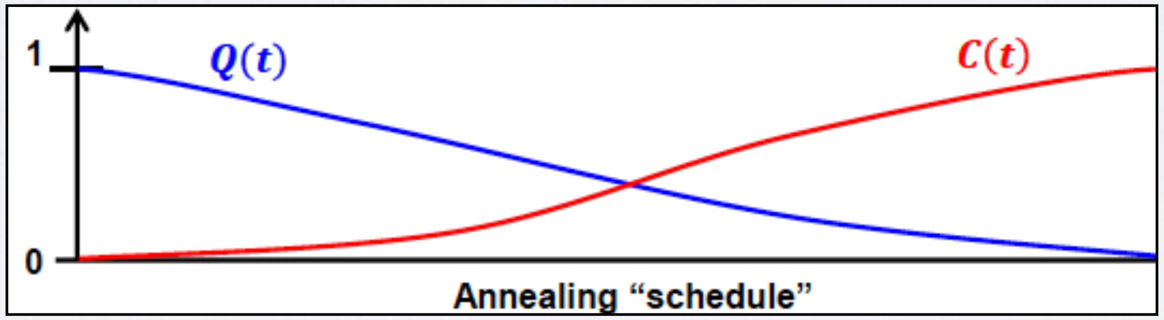
CONS:
Requires quantum error correction: ~10^6
Long-term

Nielsen and Chuang, Quantum computation and Quantum information

QUANTUM COMPUTATION

Adiabatic Quantum Computer





Final complex ground state maps into solution of optimization problem

$$\mathcal{H}(t) = Q(t)\mathcal{H}_D + C(t)\mathcal{H}_P$$

Trivial

Problem

PROS:
Does not require quantum error correction.
Near-term applications

CONS:
Non universal processor, only optimization problems

Adiabatic Quantum Computation, T. Albash and D. Lidar, Rev. Mod. Phys. 90, 015002 (2018)

QUANTUM COMPUTATION

Why do we need Quantum Computers?

MareNostrum 4, Barcelona Supercomputing Center

390 TB ~ 51 qubits

Quantum supremacy (US)

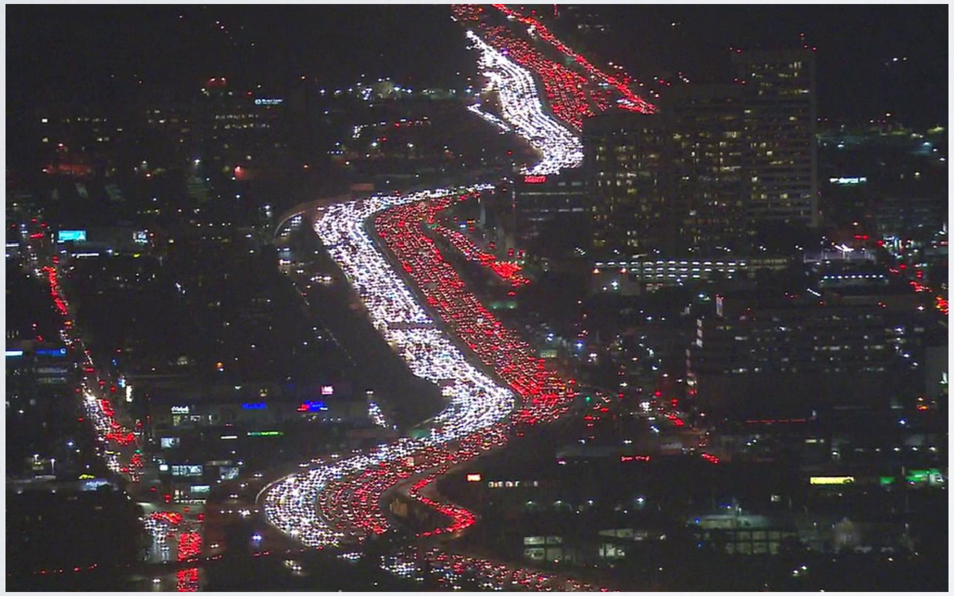
Quantum advantage (EU): outperforming classical computation

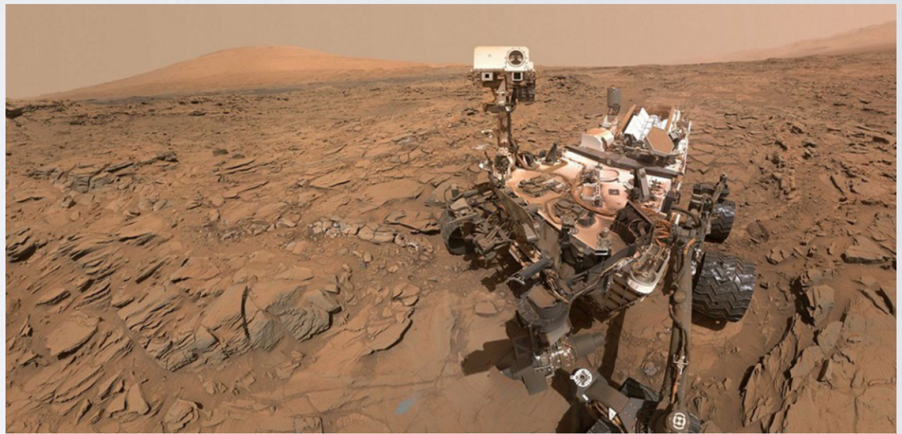
QUANTUM COMPUTATION

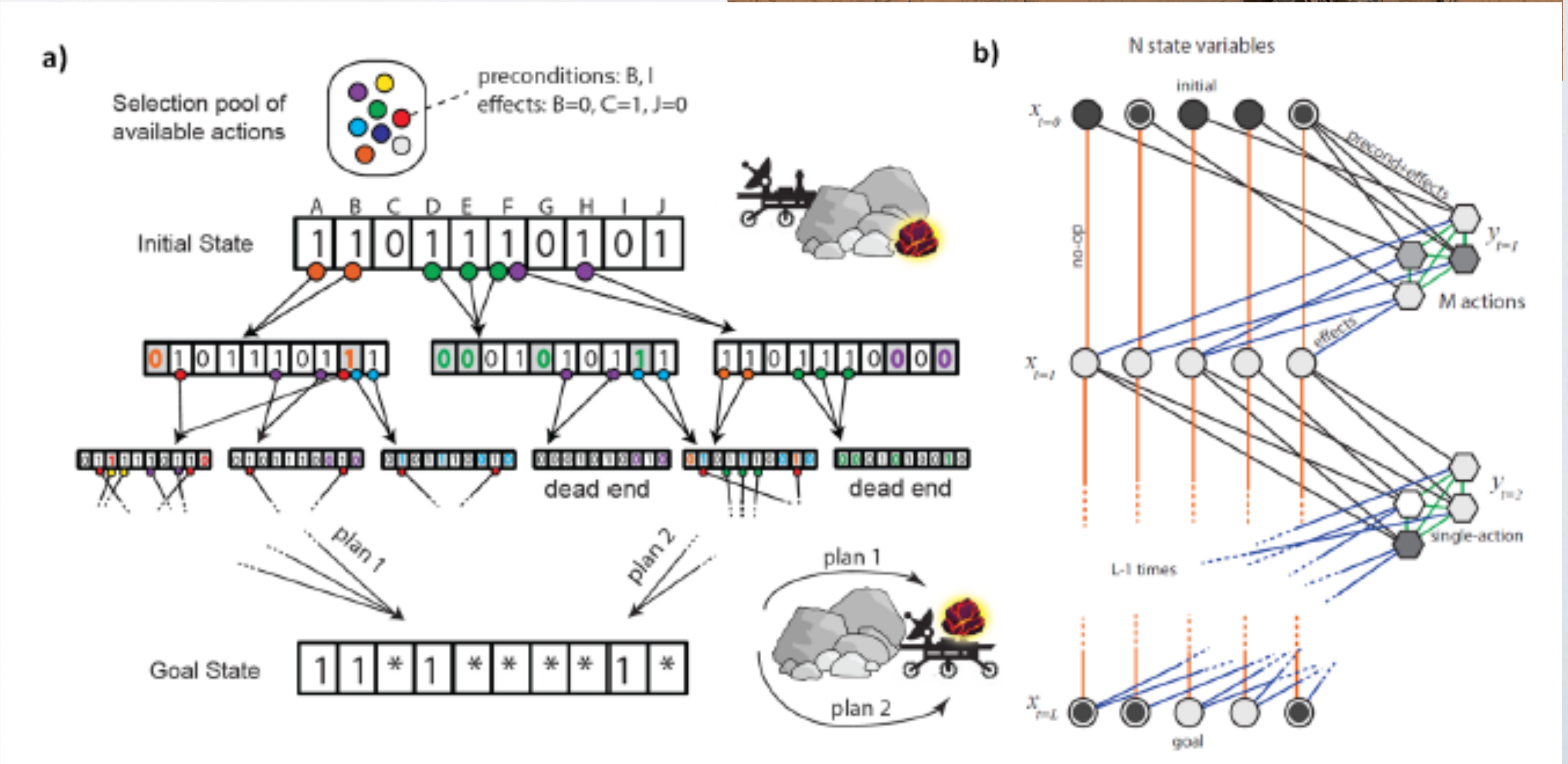
Why do we need small Quantum Computers?

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

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





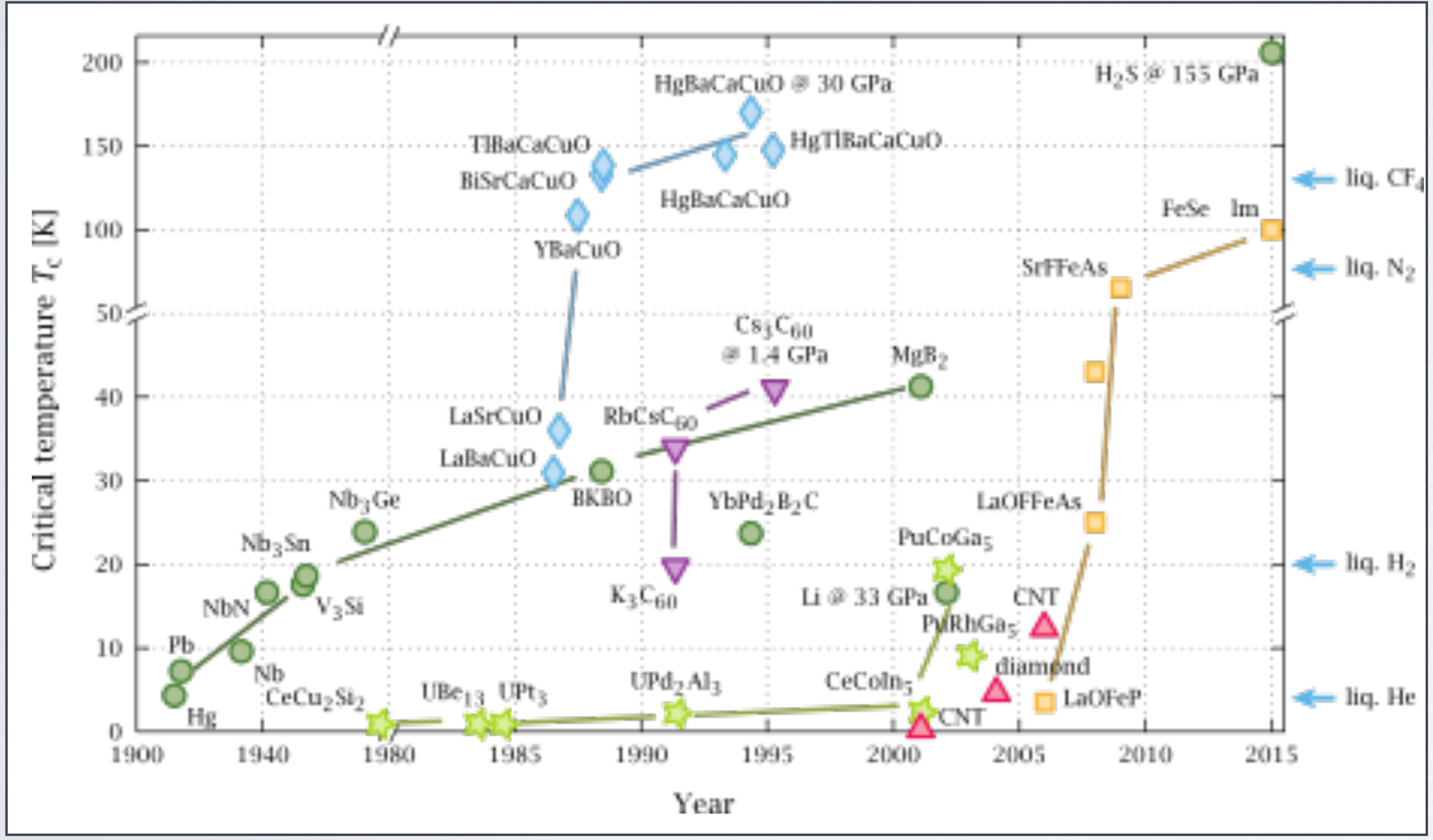


QUANTUM COMPUTATION

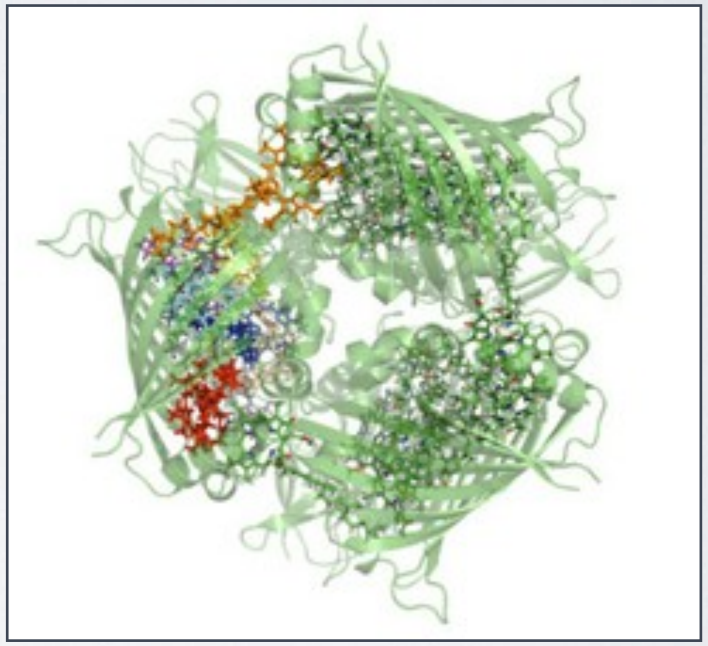
Why do we need larger Quantum Computers?

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

2. Simulation: new materials, high energy physics, quantum chemistry, stock options, etc.



Simulate higher-Tc superconductors



FMO complex, light energy harvesting

But also new fertilizers, gases to capture CO2, improve balance portfolios…

QUANTUM COMPUTATION

Why do we need large-scale Quantum Computers?

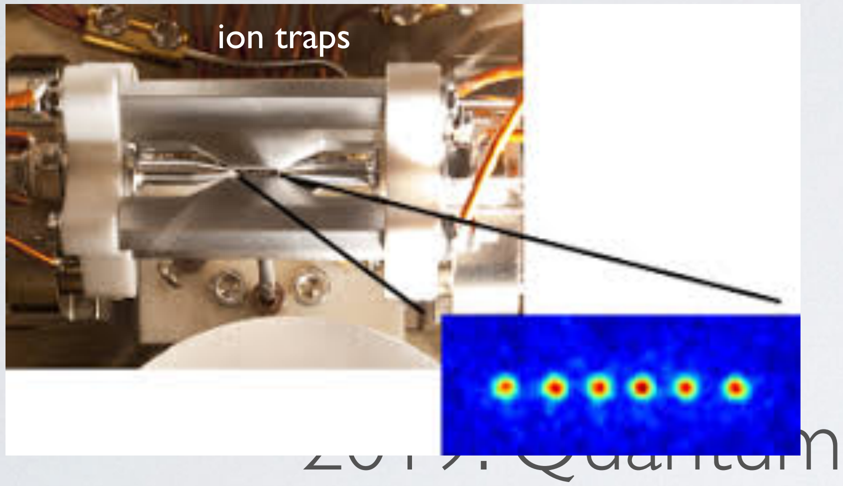
- Applications for universal quantum computers:

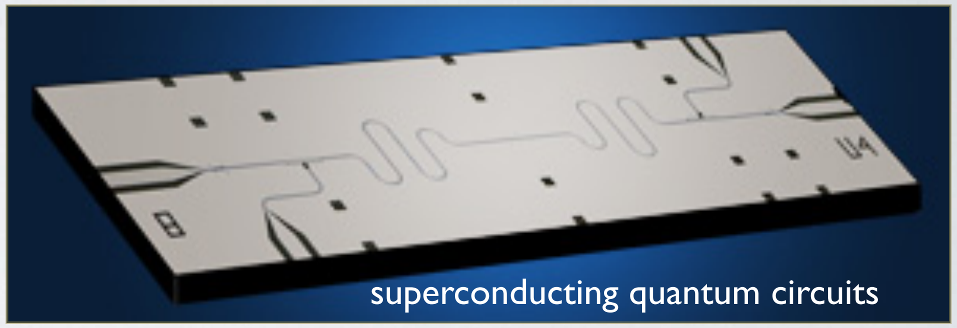
  1. Breaking RSA encryption codes
  2. Efficient search in massive data sets,
  3. Inversion of giant matrices
  4. …

…and so much we do not know!

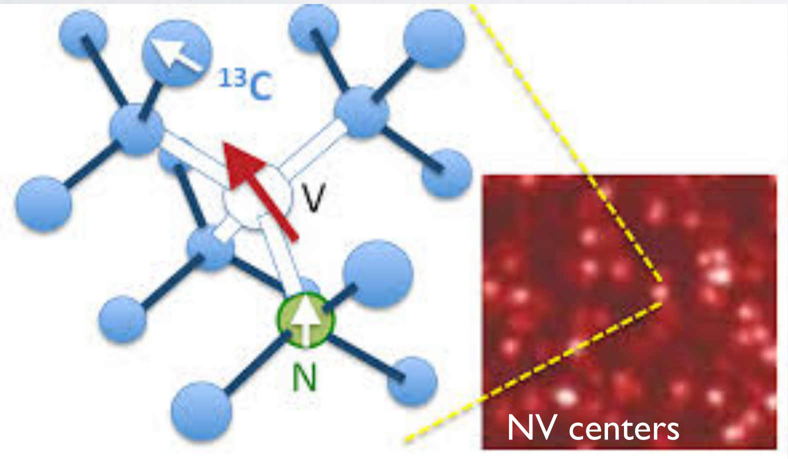
QUANTUM COMPUTATION

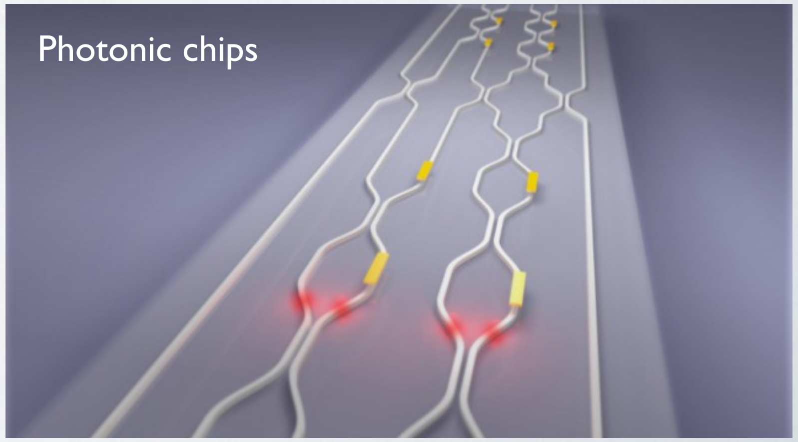
But how close are we to all this?





- 2019: Quantum supremacy: outperforming classical computation
- 2024: Noisy Intermediate Scale quantum processors
- 2030: Universal quantum computers





OUTLINE

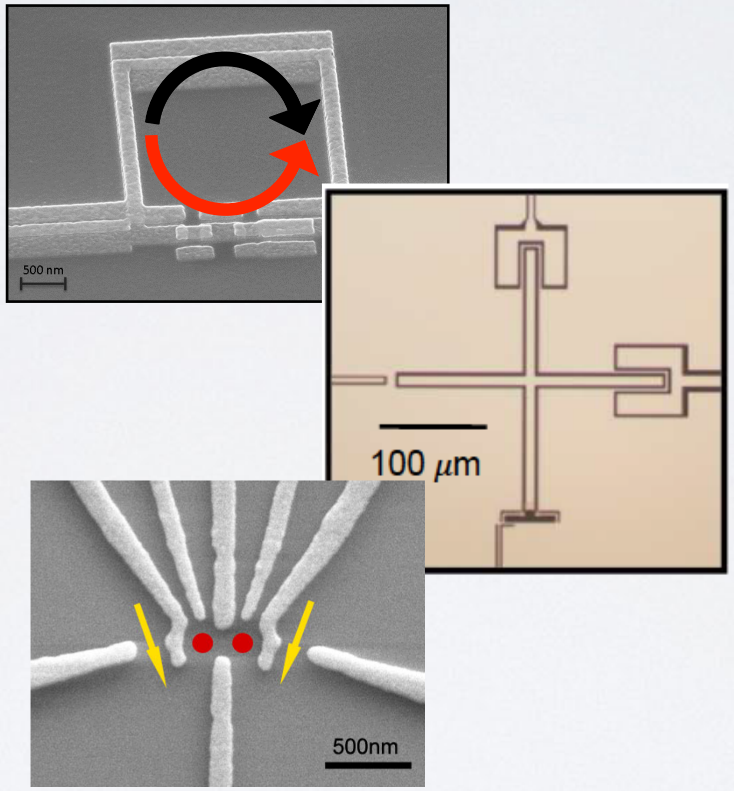
- Quantum computation
- **S**uperconducting qubits
- Qubit state control
- A superconducting quantum computer

SUPERCONDUCTING QUBITS

Microscopic

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

Mesoscopic

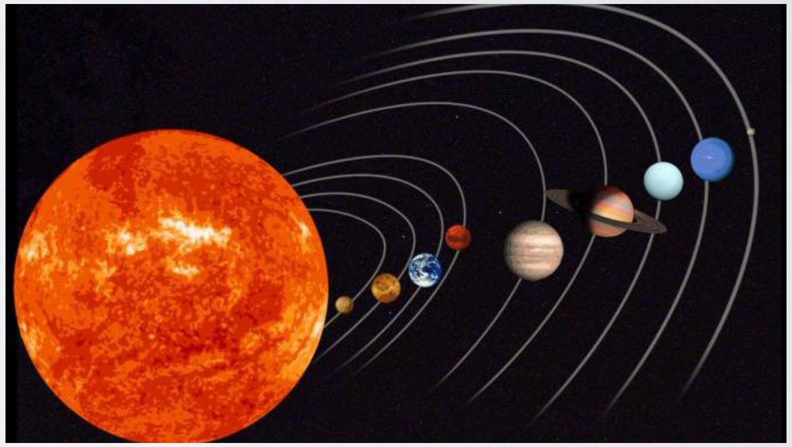


Large number of particles

Artificial, man-made

Quantum collective degrees of freedom

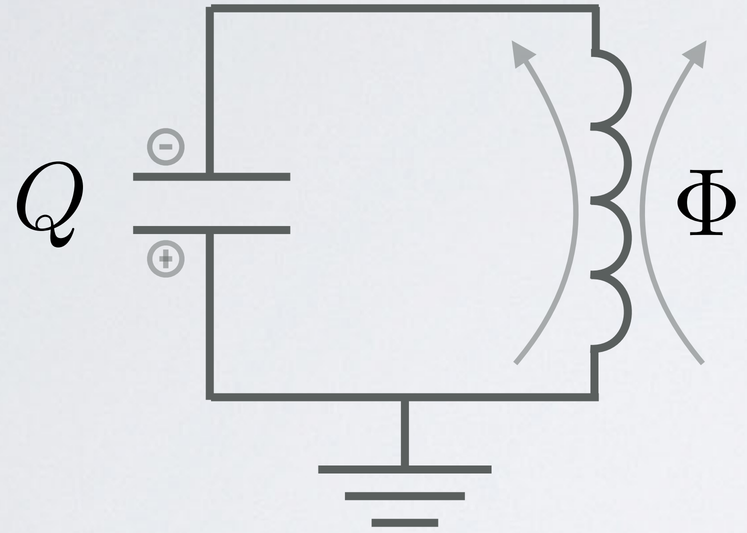
Macroscopic



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

SUPERCONDUCTING QUBITS

What corresponds to these collective degrees of freedom?



Quantum regime $k_B T \ll \hbar\omega_{\mathrm{LC}}$

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

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

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

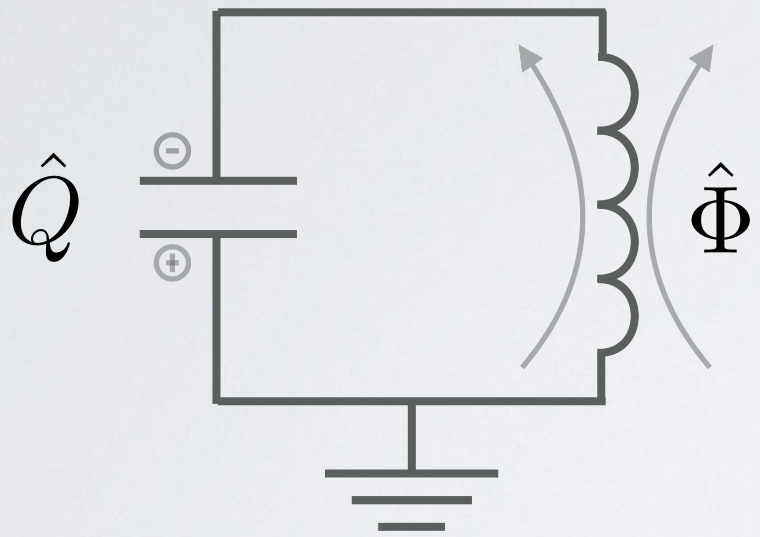
Quantum fluctuations of collective d.o.f.!

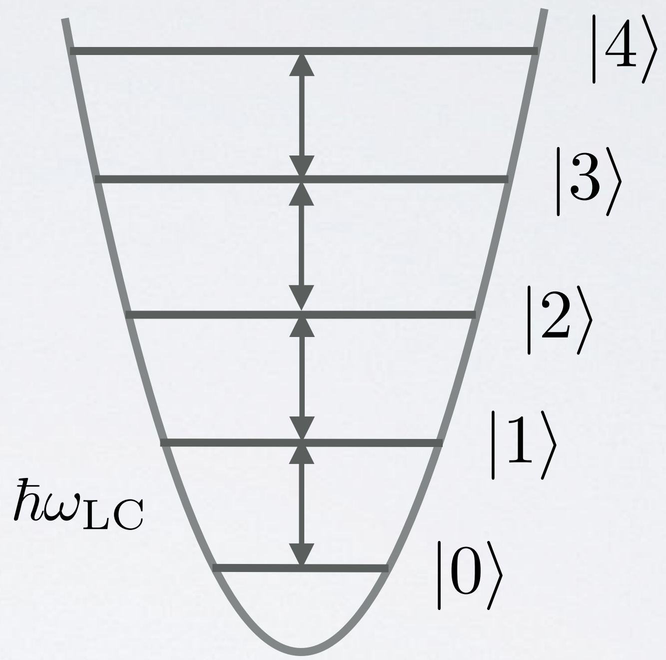
Analogous to mechanical oscillator

Vool, Devoret, IJCTA - Special Issue on Quantum Circuits

SUPERCONDUCTING QUBITS

Quantum circuit spectrum and energy levels





$$Q \gg 1$$

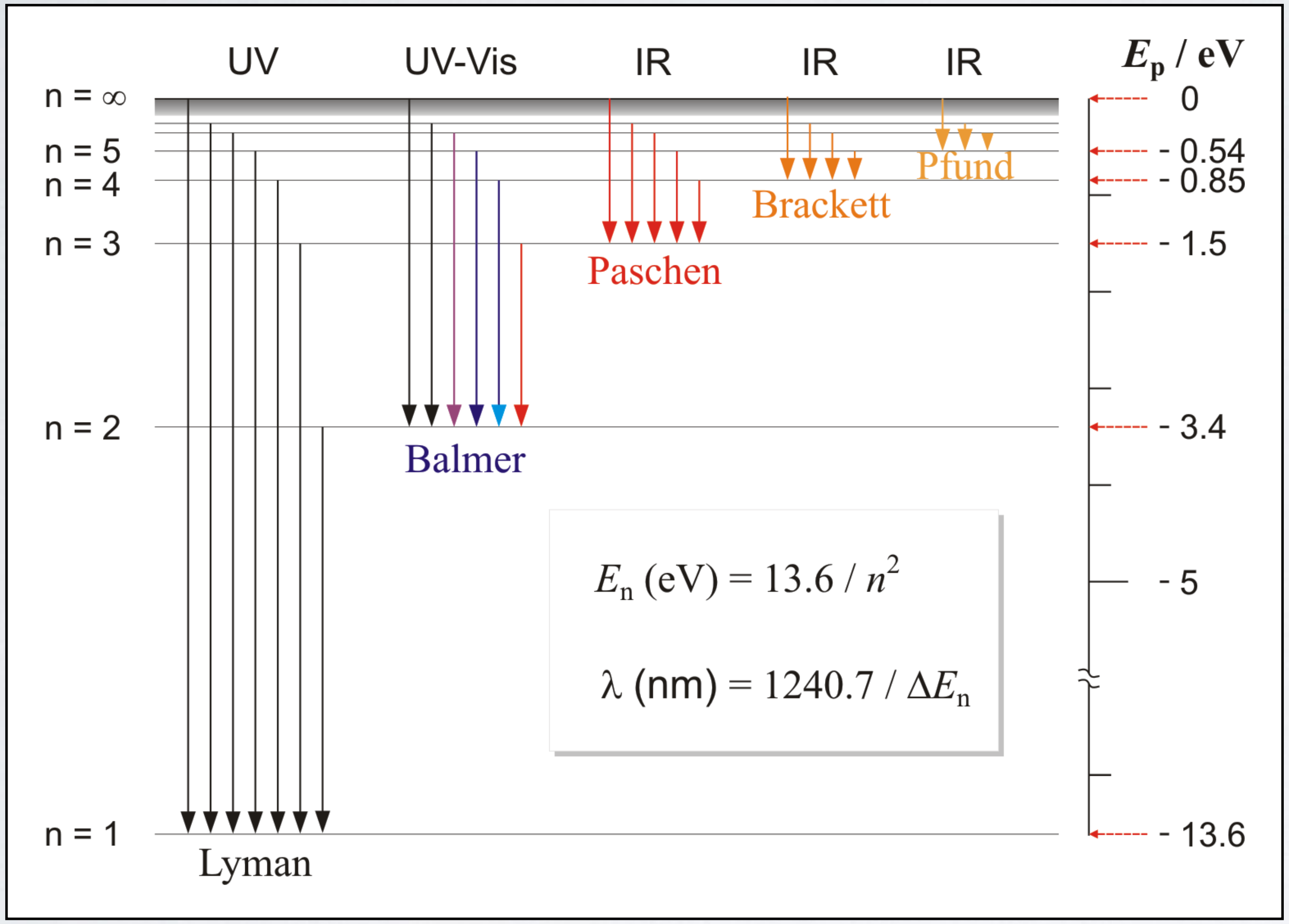
Superconducting circuit

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

Vool, Devoret, IJCTA - Special Issue on Quantum Circuits

SUPERCONDUCTING QUBITS

Hydrogen atom spectrum



E_n (eV) = 13.6 / n^2

λ (nm) = 1240.7 / ΔE_n

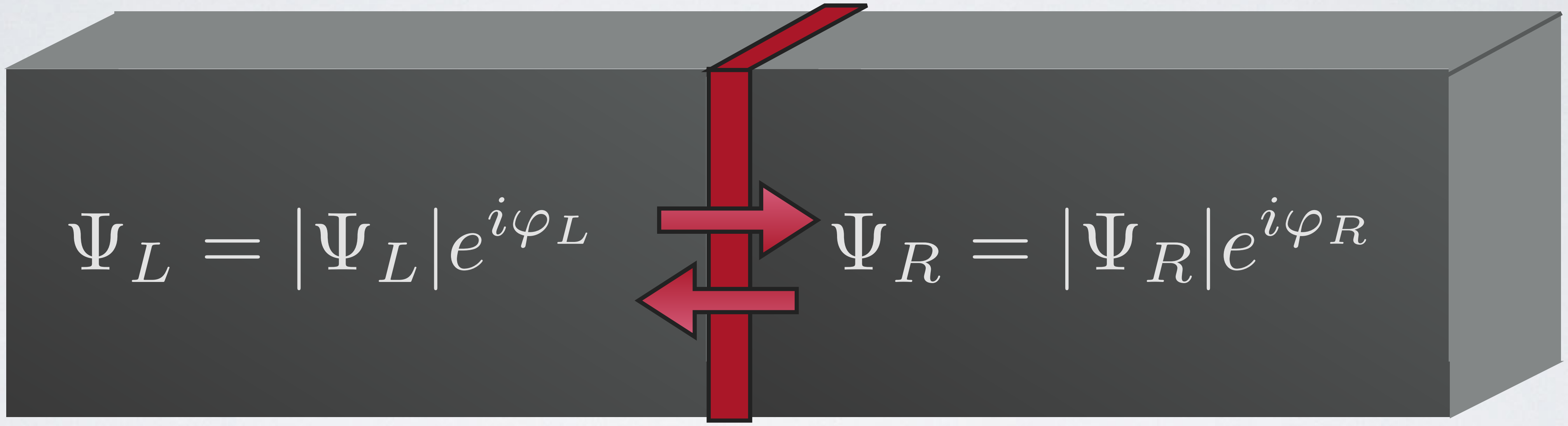
Source: https://glossary.periodni.com

Need nonlinear circuit element to alter circuit spectrum…

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

SUPERCONDUCTING QUBITS

Josephson junctions: a macroscopic quantum effect



$\Psi_L = |\Psi_L| e^{i\varphi_L}$

$\Psi_R = |\Psi_R| e^{i\varphi_R}$

Constituent relation:

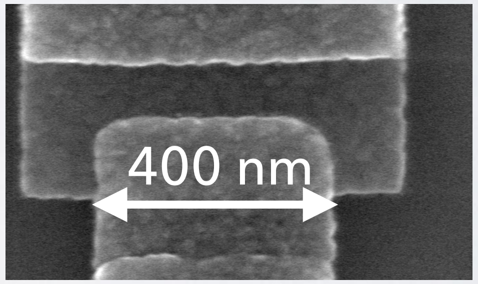
$$\frac{dI}{dt} = V \boxed{\frac{2\pi I_C}{\Phi_0} \sqrt{\frac{I_C^2 - I^2}{I_C^2}}}$$

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

Josephson inductance

Electrical circuits symbol

- Nonlinear circuit element
- Lossless



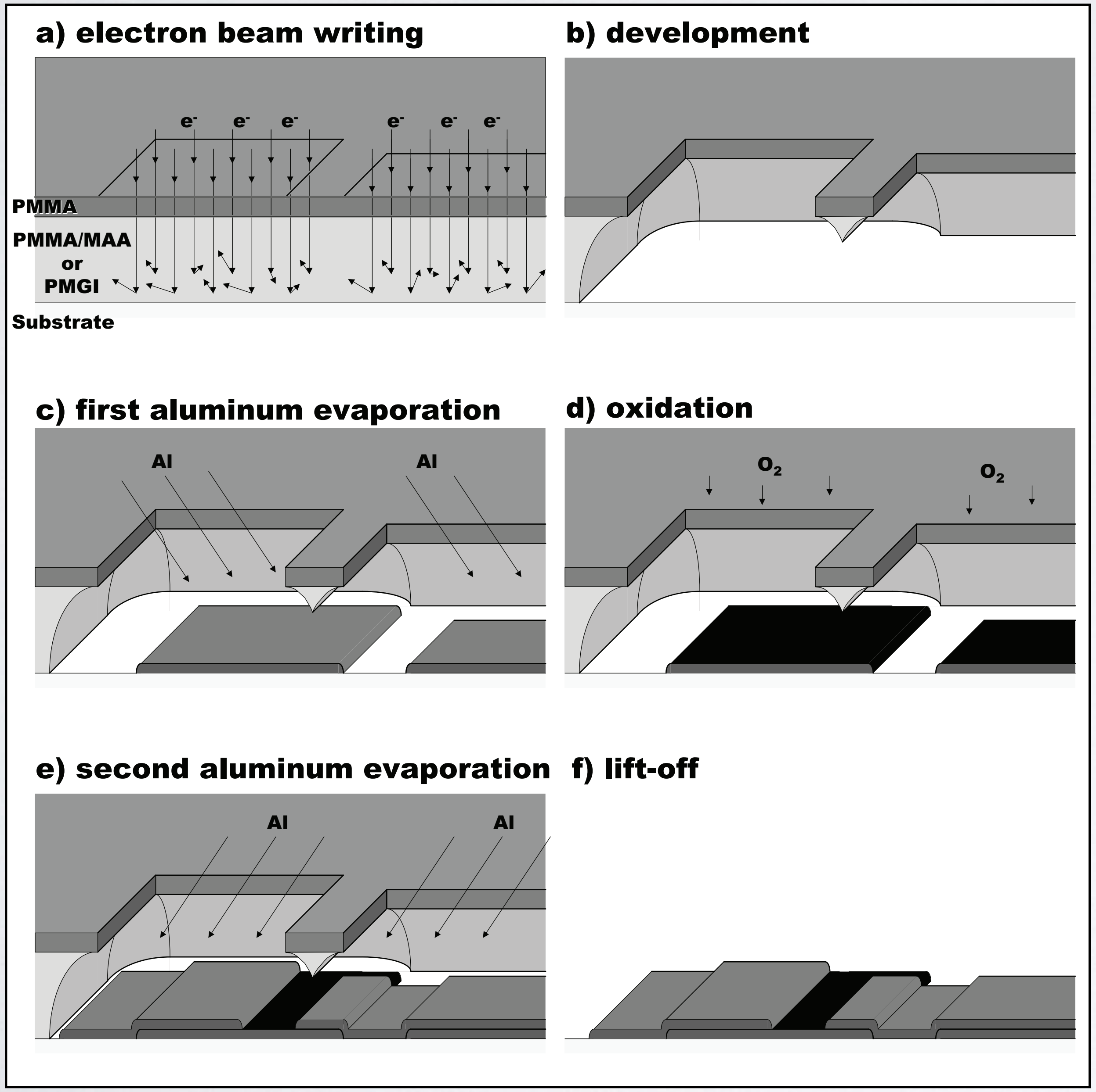
SEM micrograph

Orlando, Delin.
Foundation of applied superconductivity

SUPERCONDUCTING QUBITS

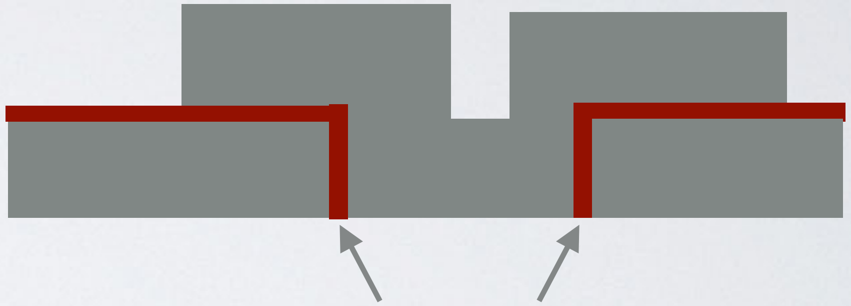
Junction fabrication

Electron beam lithography

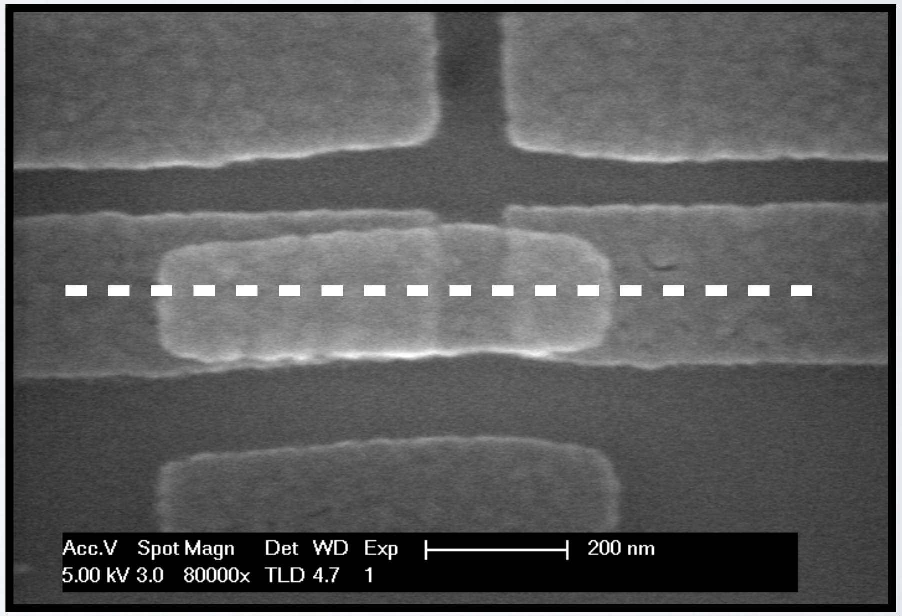


J. Majer (Delft), PhD Thesis 2002

Shadow angle evaporation



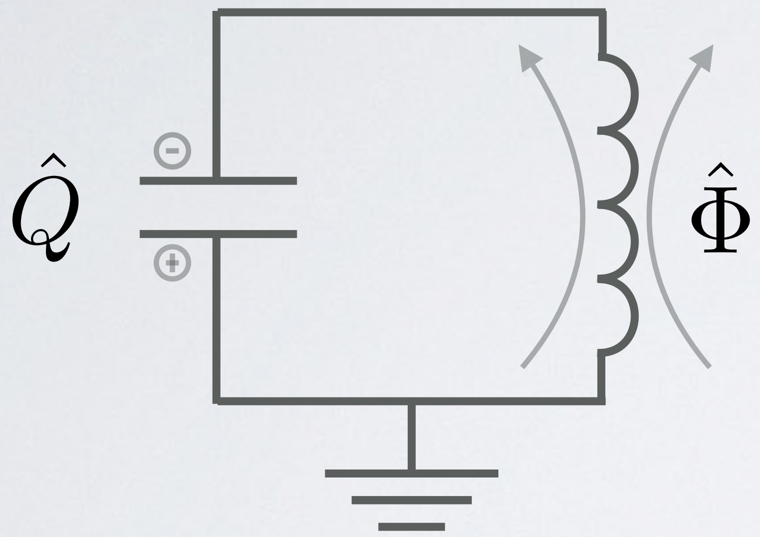
Josephson
junctions



Scanning electron microscope (SEM)

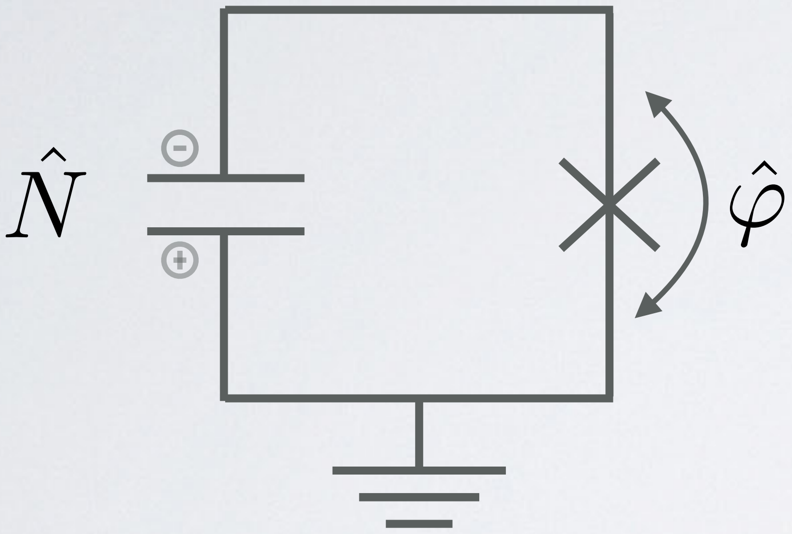
SUPERCONDUCTING QUBITS

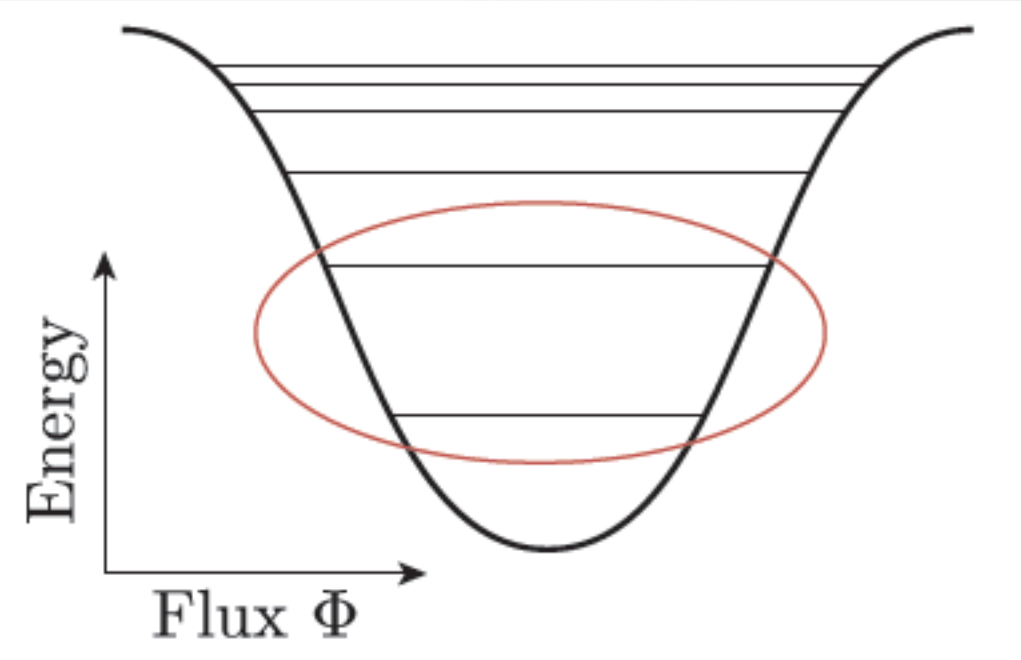
The hydrogen atom of superconducting qubits



SUPERCONDUCTING QUBITS

The hydrogen atom of superconducting qubits





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

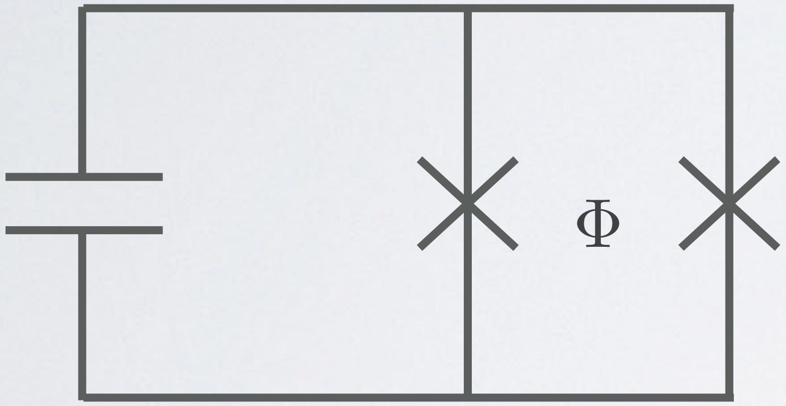
$$\simeq E_C \hat{N}^2 - E_J \left(-\frac{\hat{\varphi}^2}{2} + \frac{\hat{\varphi}^4}{4!} \right) - E_J$$

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

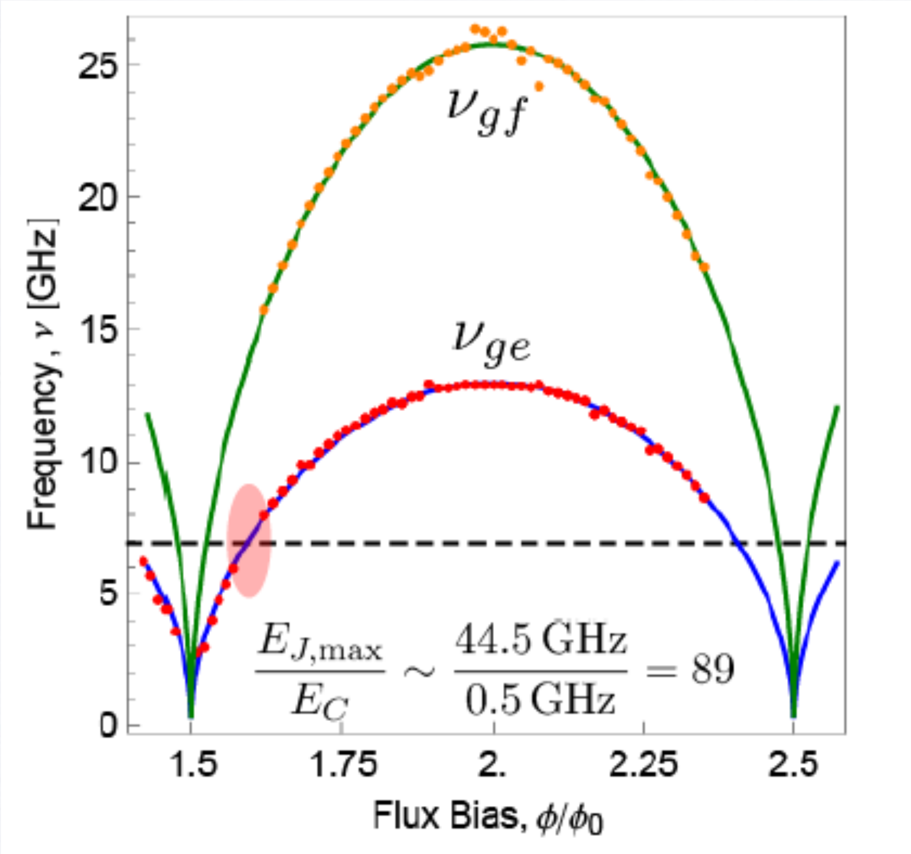
Koch et al. PRA 76, 042319 (2007)

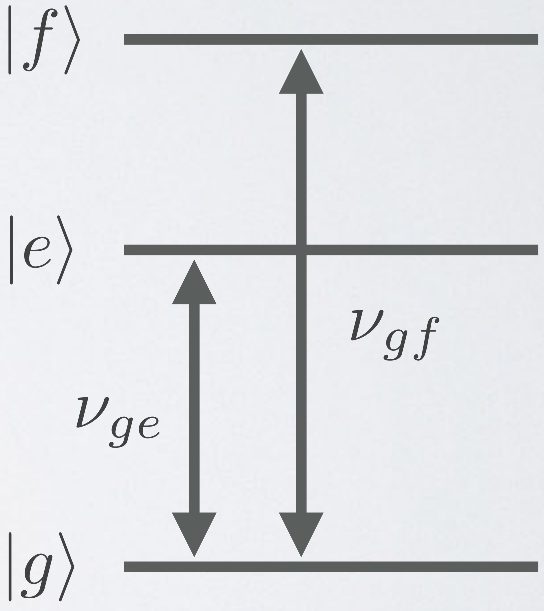
SUPERCONDUCTING QUBITS

Transmon qubit



Flux dependence of energy levels



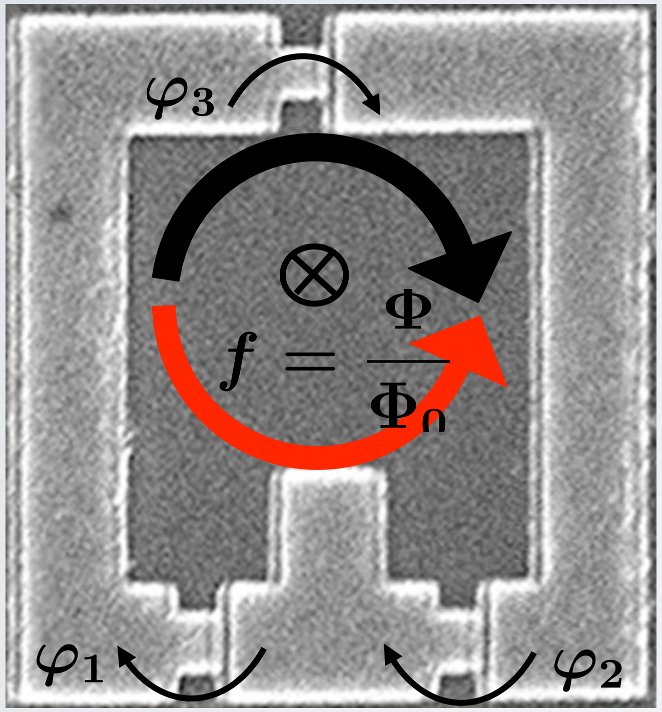


J. Fink et al., Nature 454, 315 (2008)

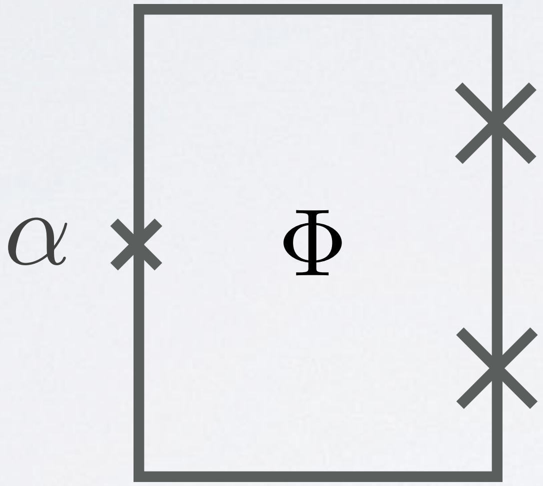
SUPERCONDUCTING QUBITS

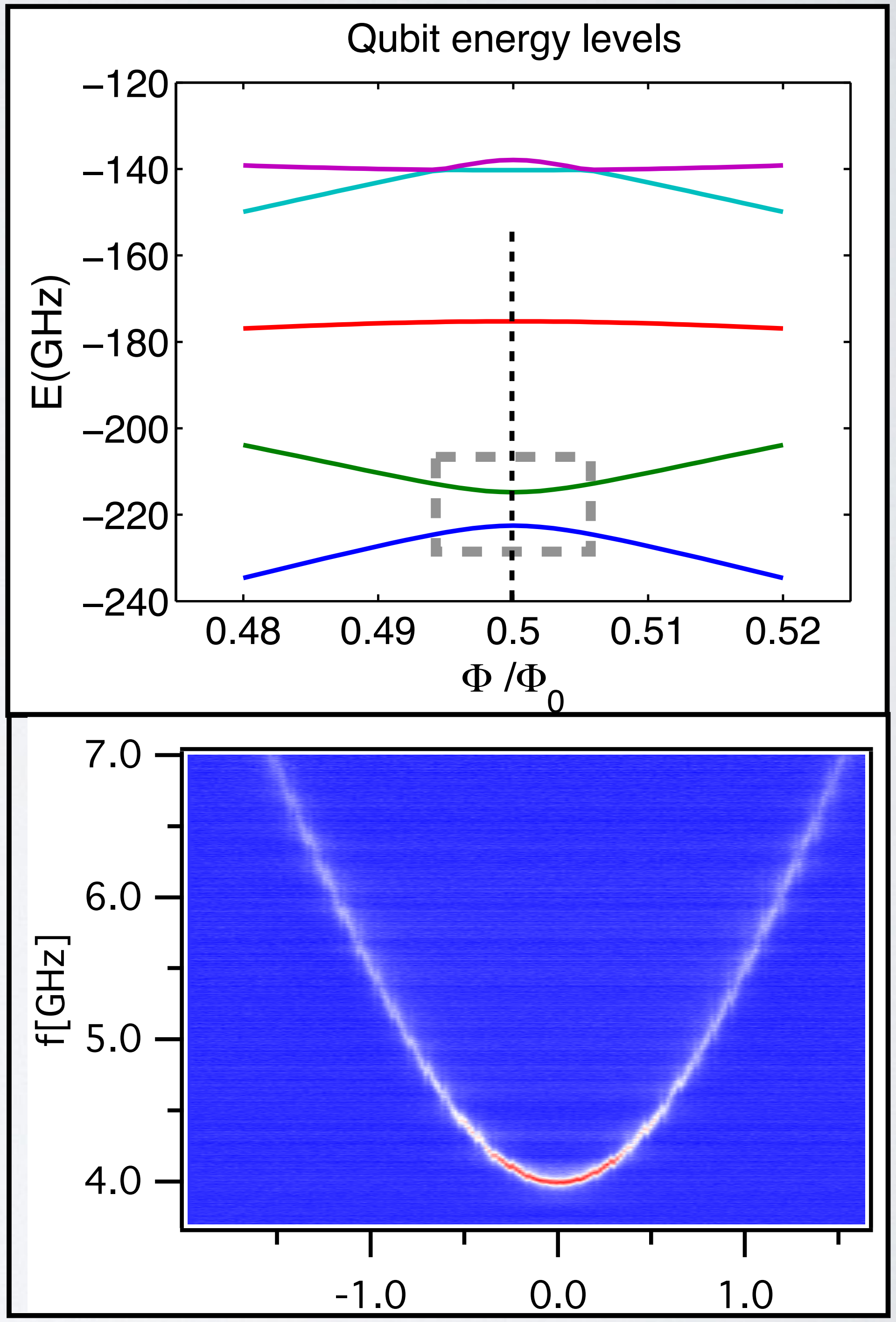
Persistent current/Flux qubit

Aluminum loop with 3 Josephson junctions



Circuit diagram:





Highly **tuneable**: ideal for quantum annealing

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

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

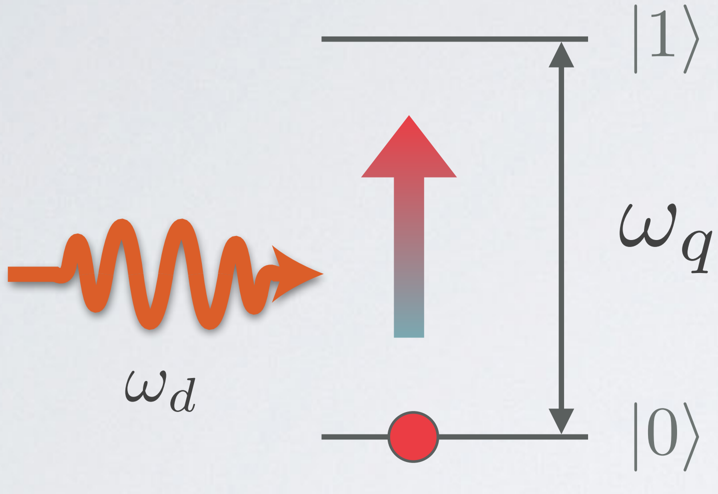
Forn-Díaz et al., *Nature Physics 13, 39 (2017)*

OUTLINE

- Quantum computation
- Superconducting qubits
- **Q**ubit state control
- A superconducting quantum computer

QUBIT STATE CONTROL

Single qubit microwave driving



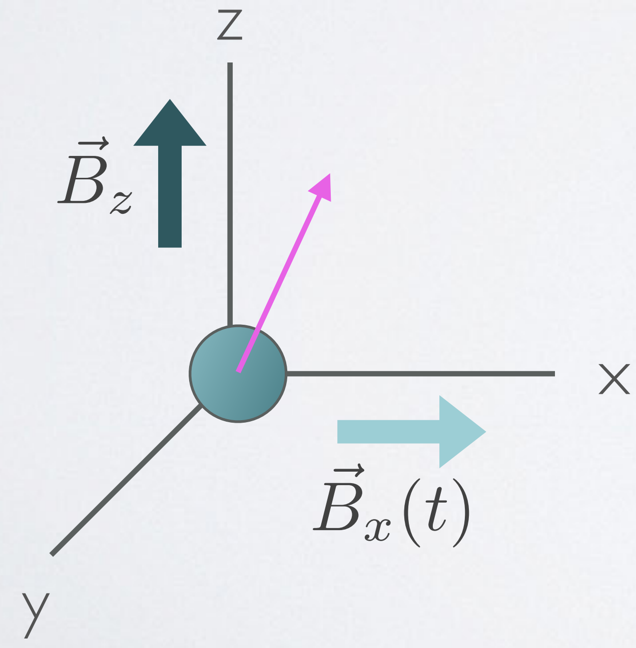
Rabi formula

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

Ω_R Rabi frequency "bare"

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

Analogy with spin-1/2



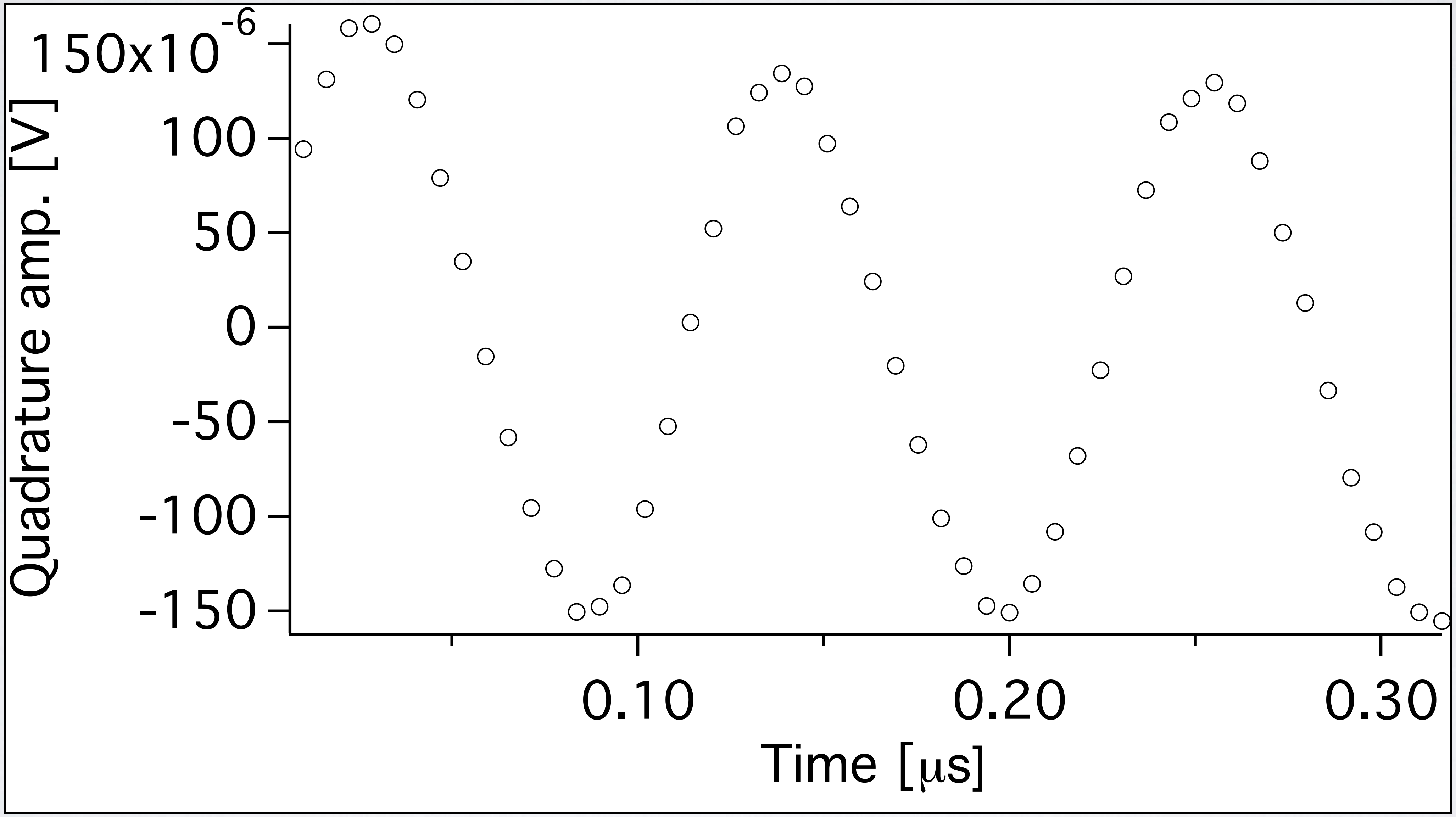
Import all NMR techniques
for qubit state control…

Quantum Mechanics, C. Tannoudji

Nielsen and Chuang, Quantum computation and Quantum information

QUBIT STATE CONTROL

In a real experiment…

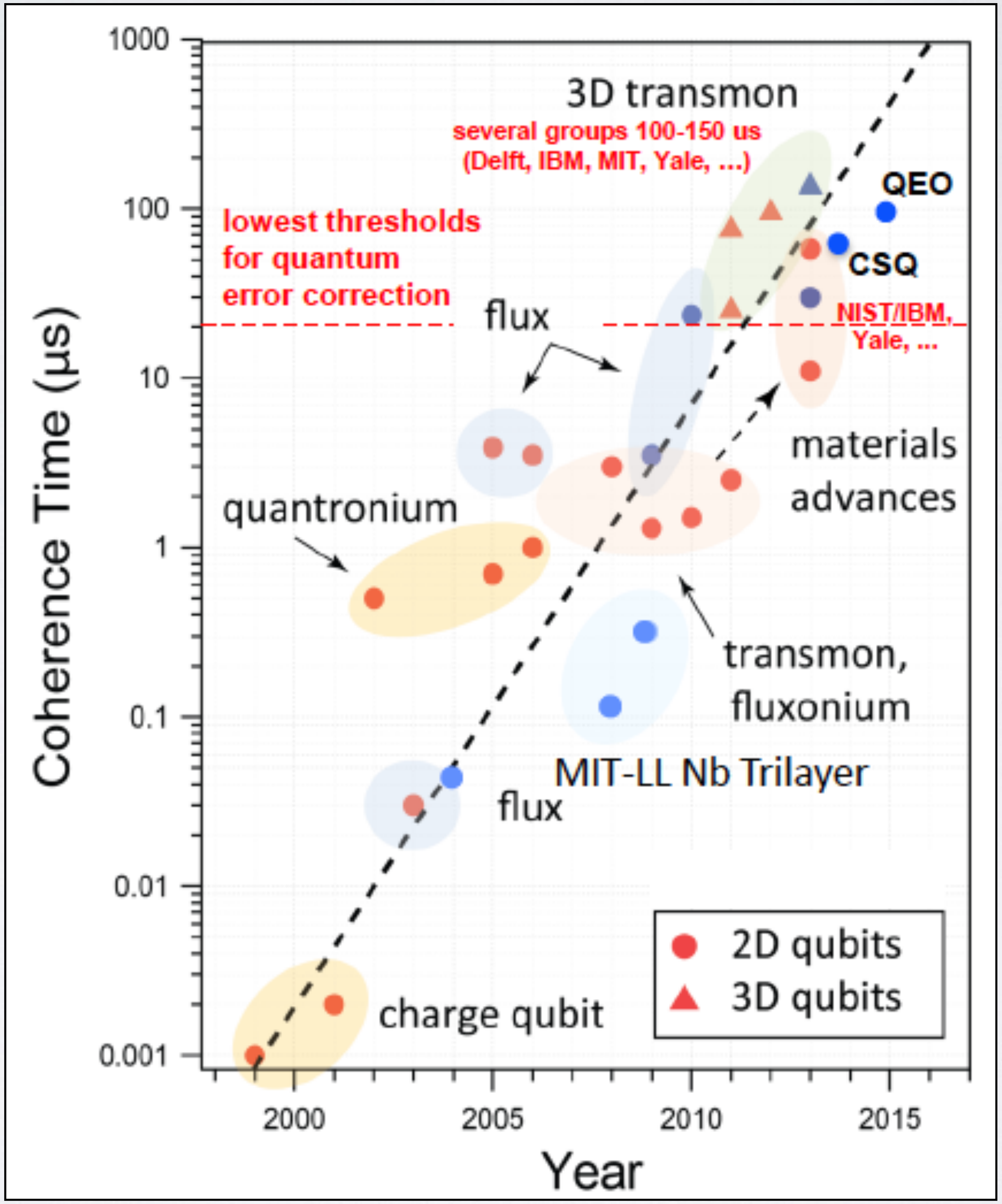


…it decays!

Forn-Díaz et al., Physical Review Applied 8 (5), 054015 (2017)

QUBIT STATE CONTROL

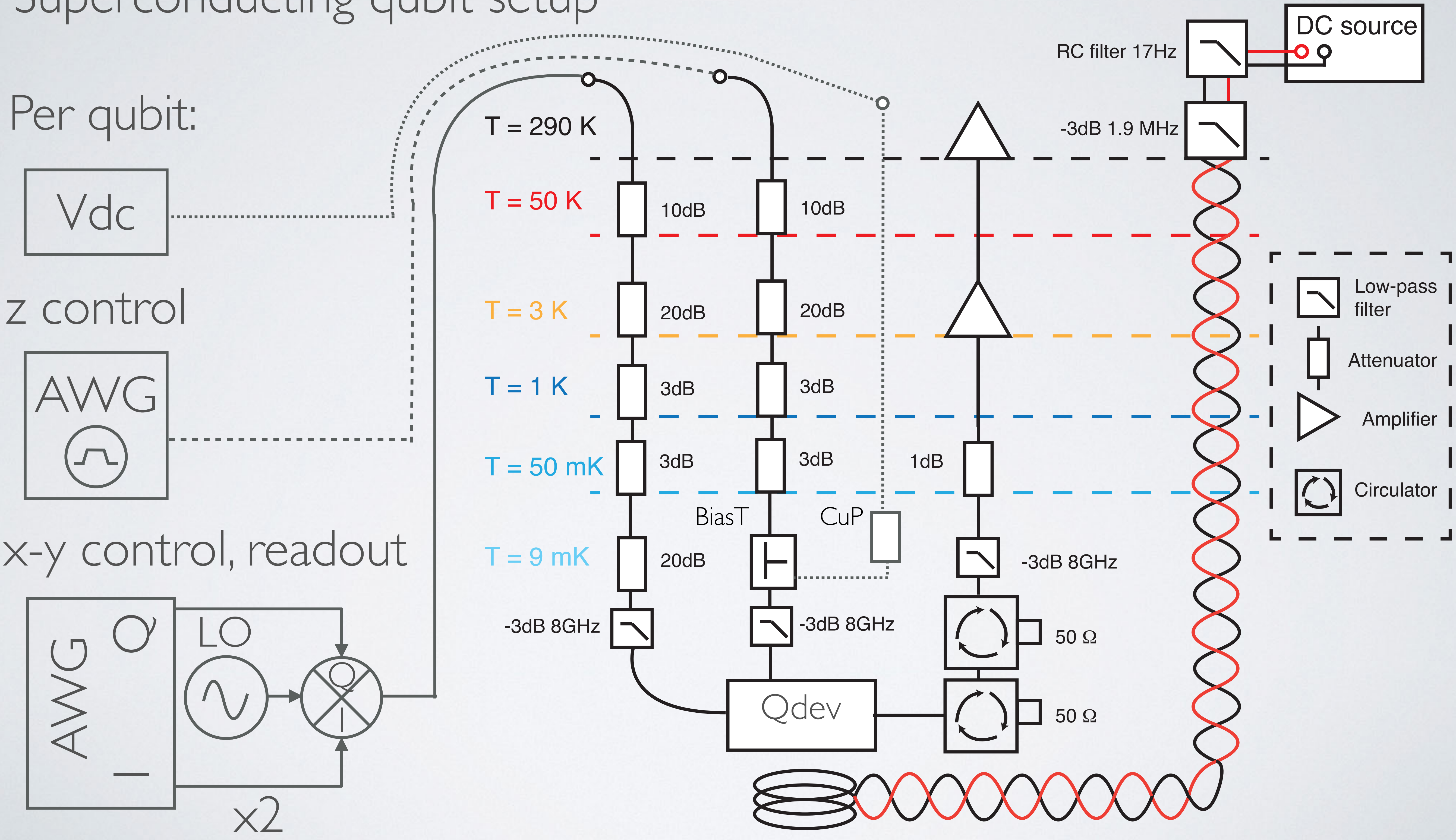
A Moore's-like law



W. Oliver & Welander, MRS Bulletin (2013)

QUBIT STATE CONTROL

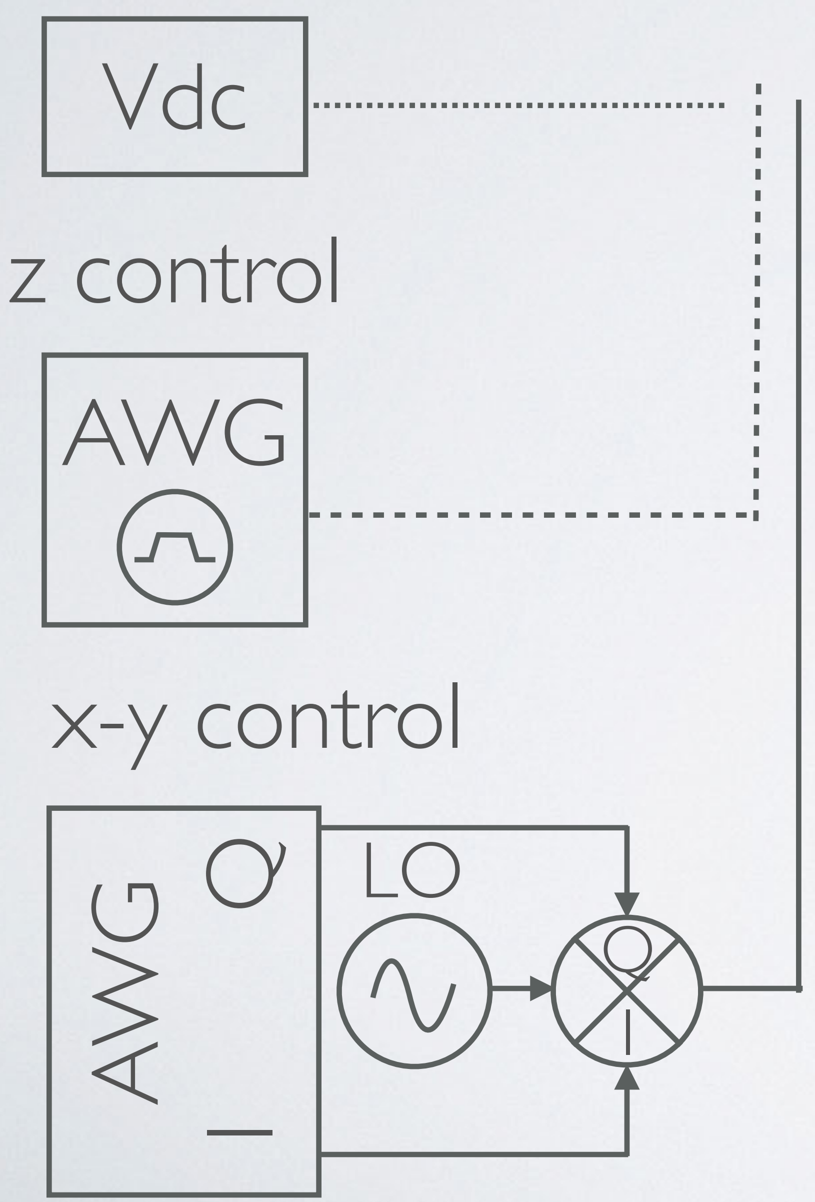
Superconducting qubit setup



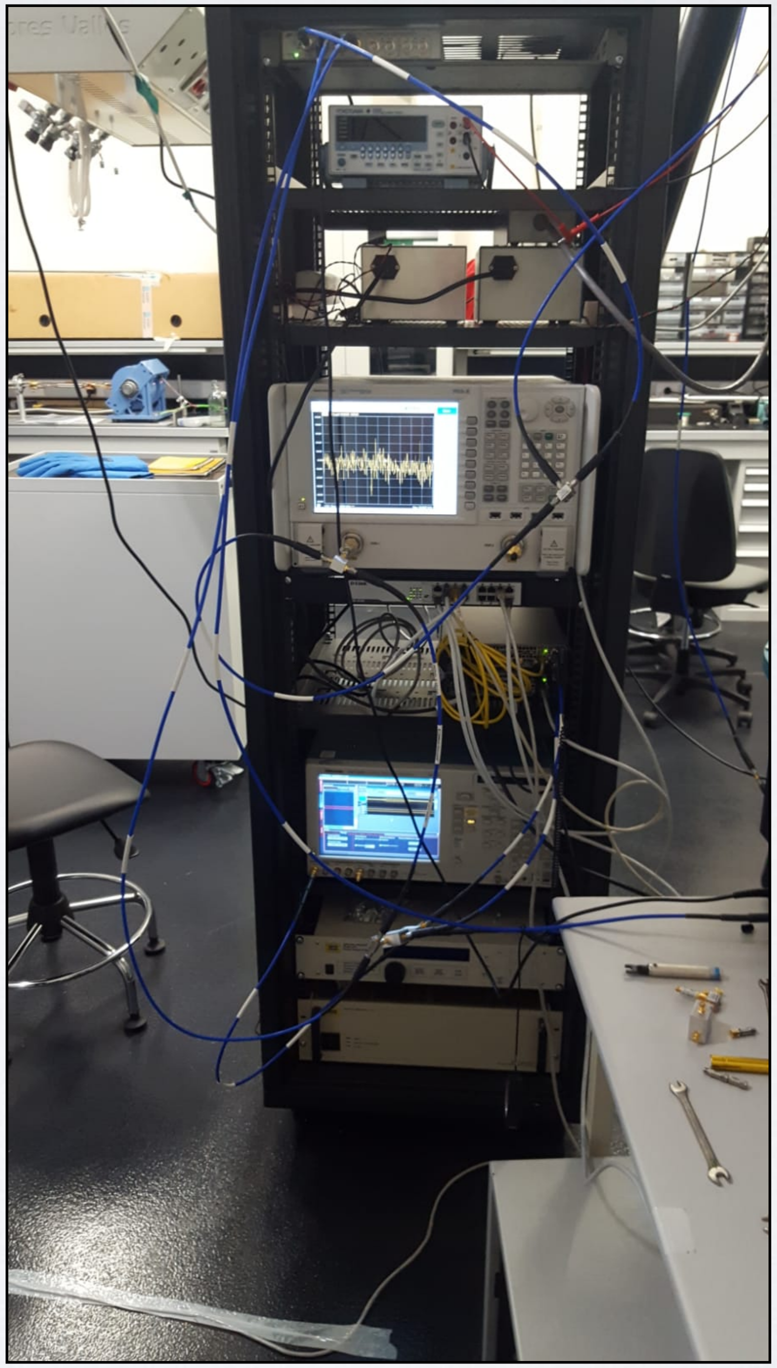
QUBIT STATE CONTROL

Setup

Per qubit:

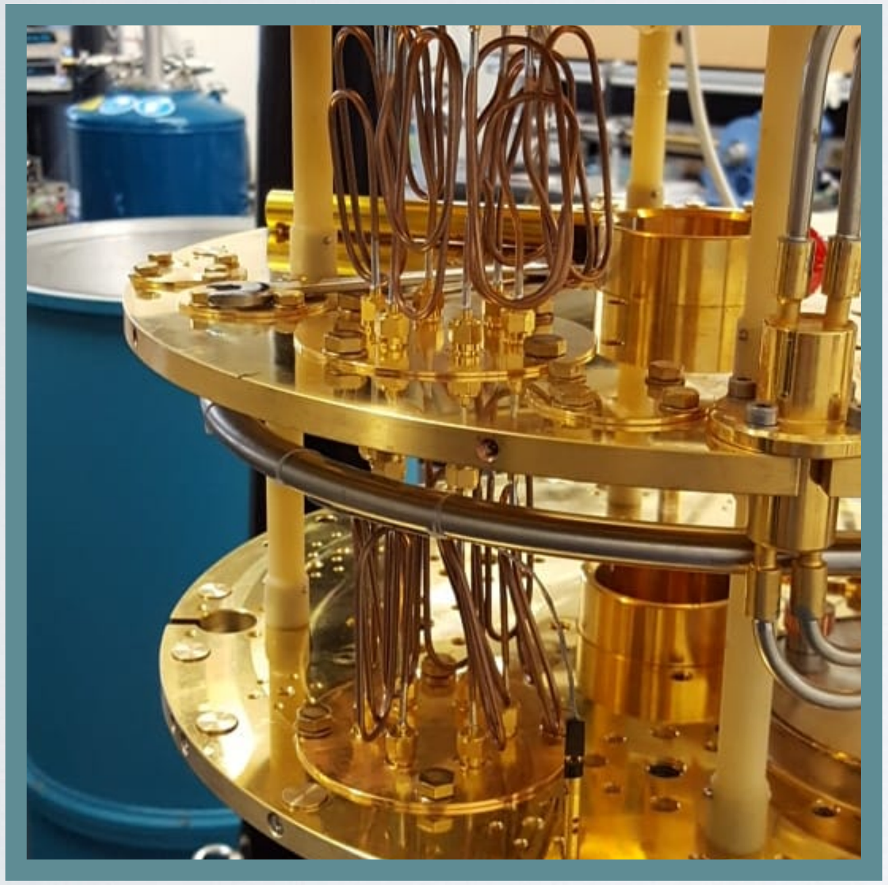


ICN2 setup

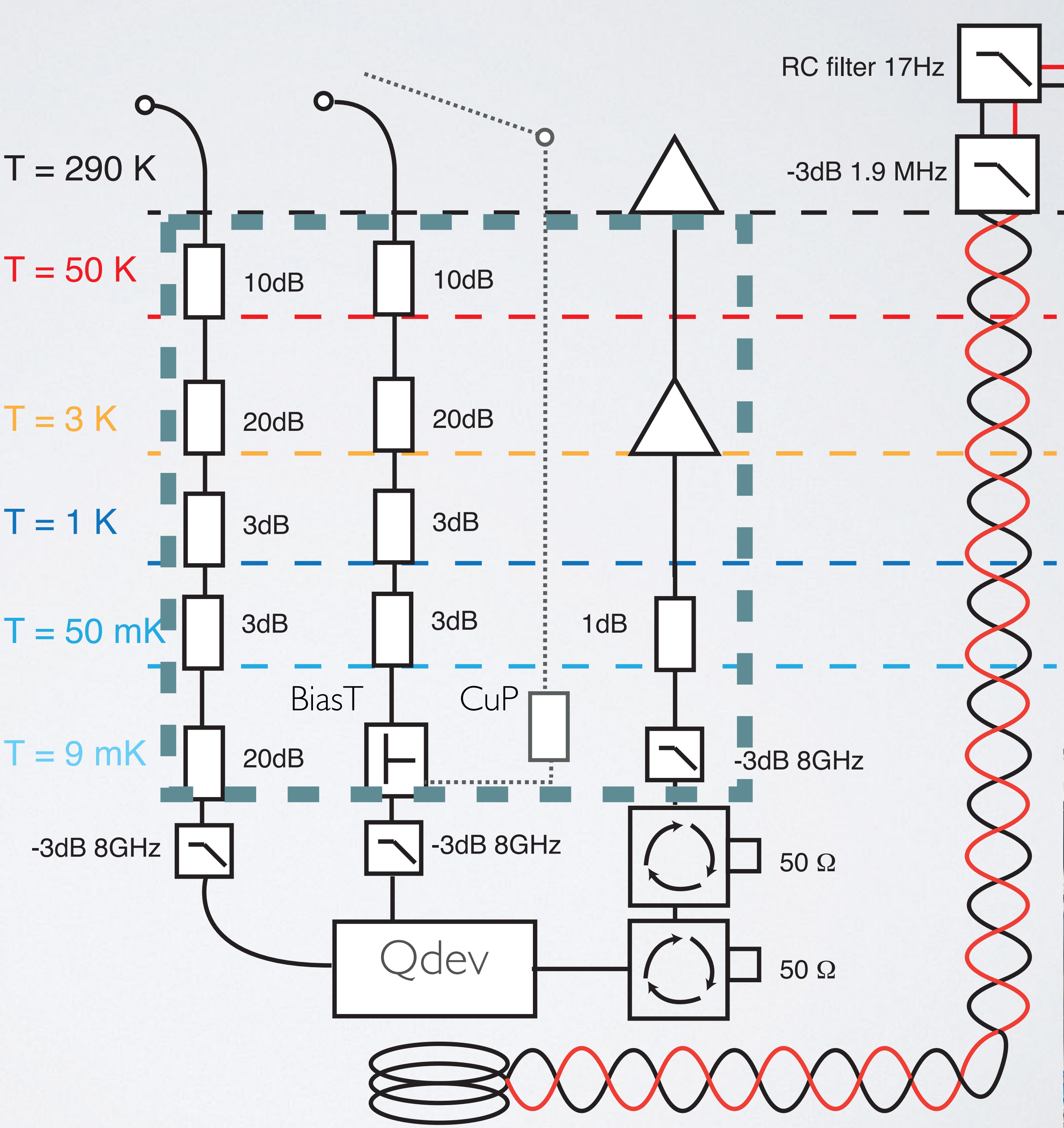


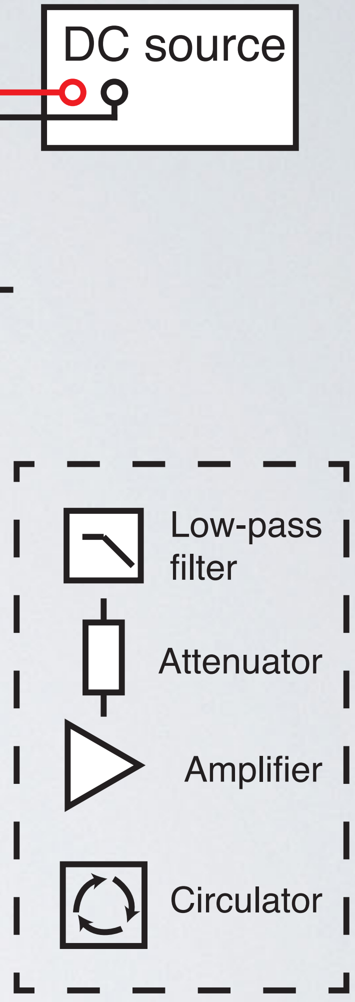
QUBIT STATE CONTROL

Coaxial wiring
dilution fridge

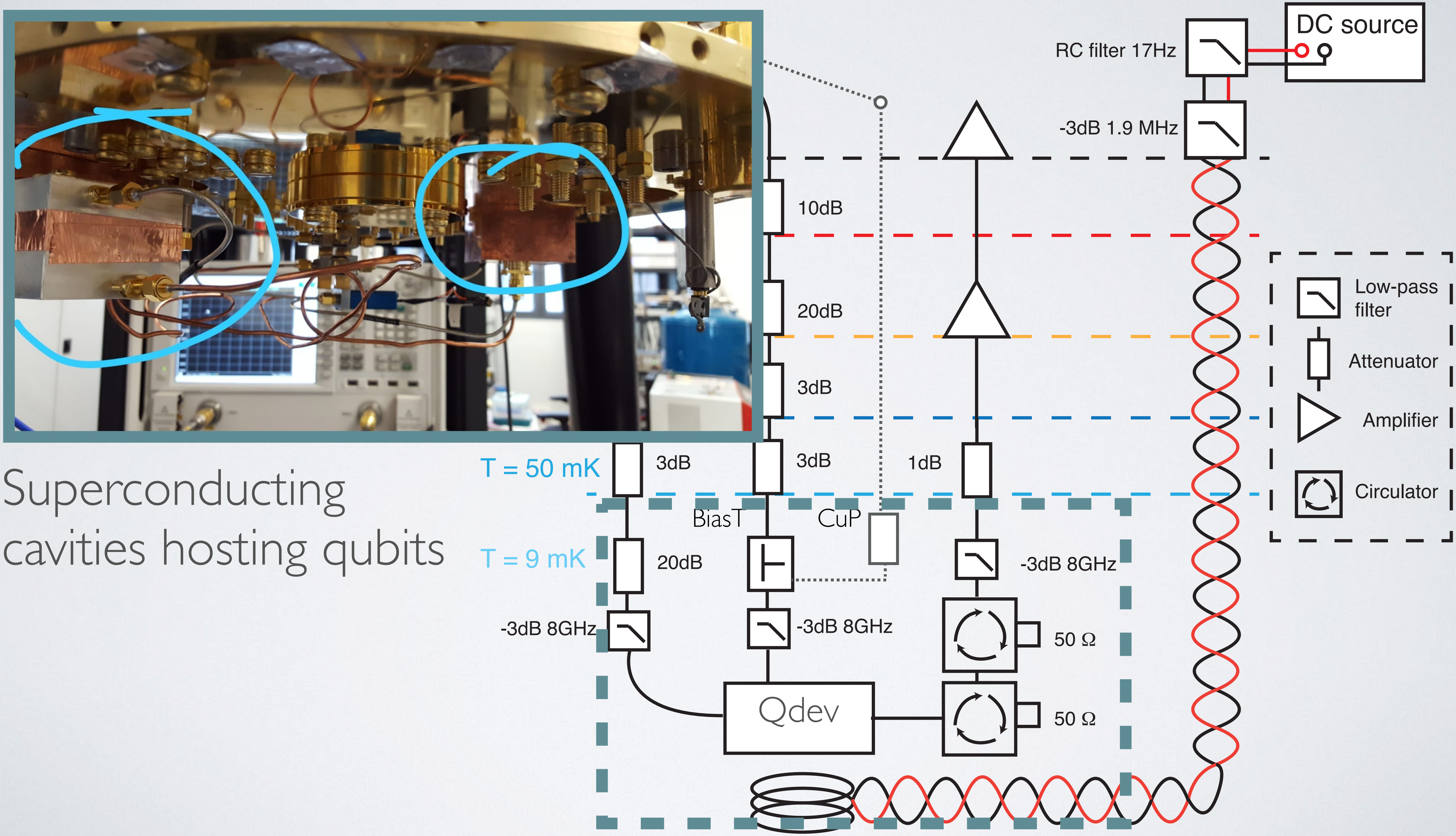


$$T = 10\ \mathrm{mK}$$





QUBIT STATE CONTROL



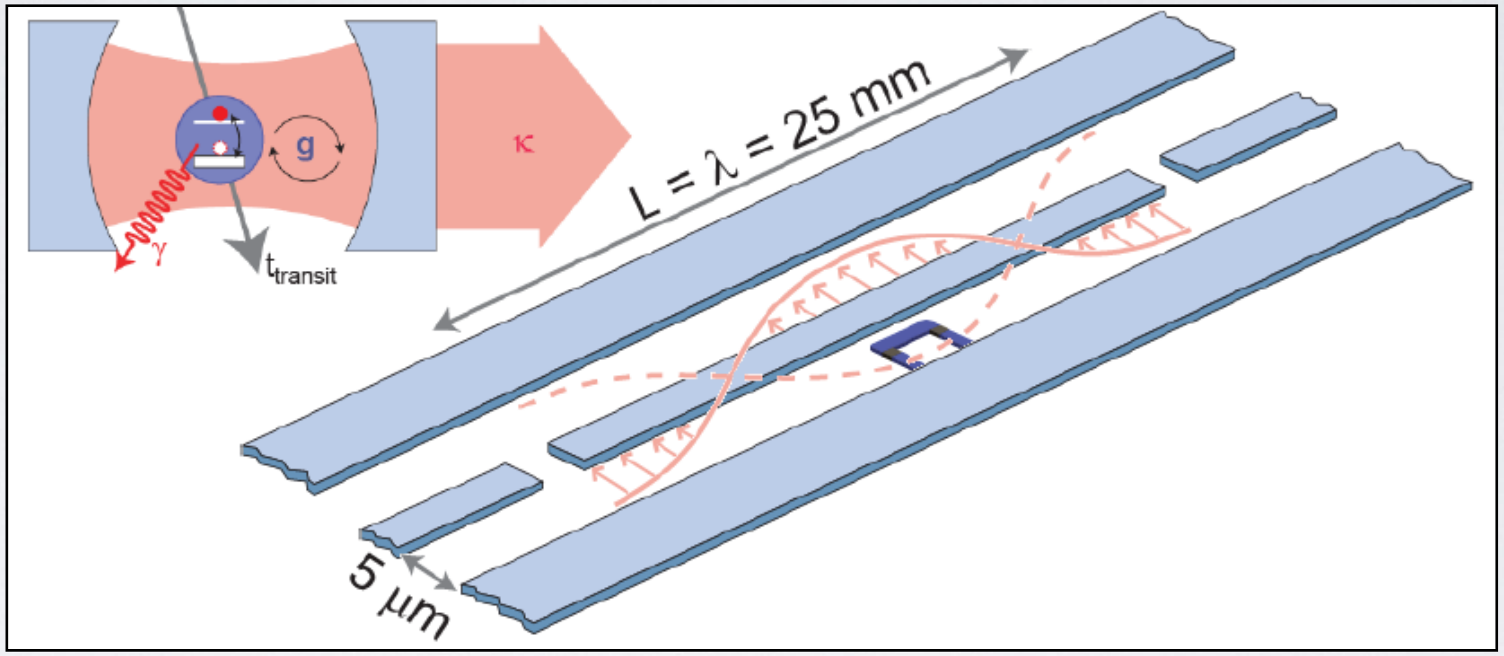
Superconducting cavities hosting qubits

OUTLINE

- Quantum computation
- Superconducting qubits
- Qubit state control
- **A** superconducting quantum computer

QUBIT STATE CONTROL

Wiring quantum chips: circuit QED



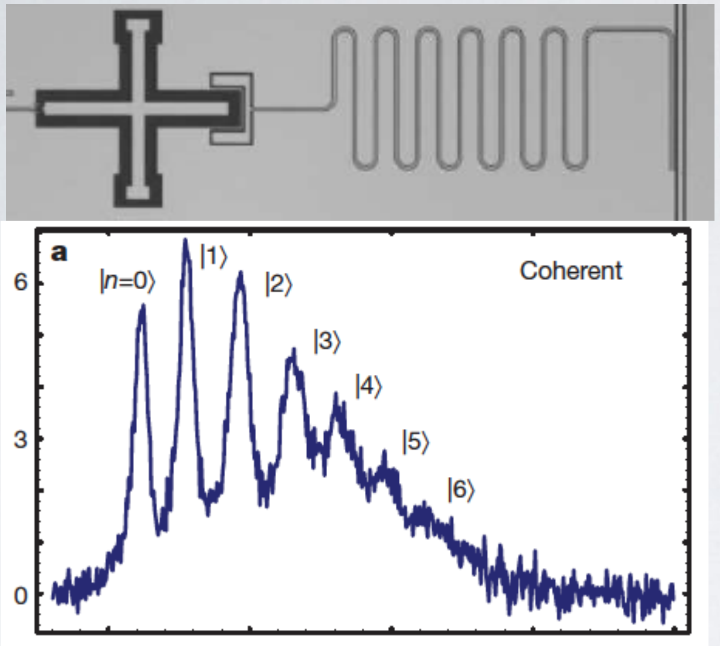
Quantum optics
on a chip

	Photon propagation	Frequency range (Hz)	Two-level systems	Photon storage	Cavity lifetime	Atom dipole	Coupling strength
Optics	Free space, fibers	10^{14}	atoms	cavities	10 ns	1 a.u.	MHz
Microwave	Transmission lines	10^{9}	qubits	resonators	100 us	10^{4} a.u.	GHz

A. Wallraff et al., Nature 431, 162 (2004)

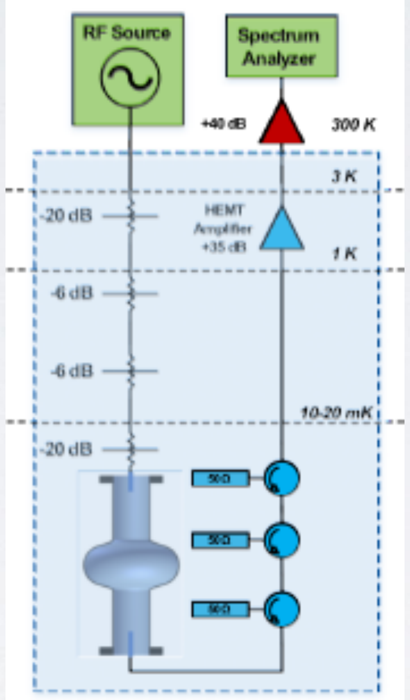
QUBIT STATE CONTROL

Dispersive qubit/resonator readout



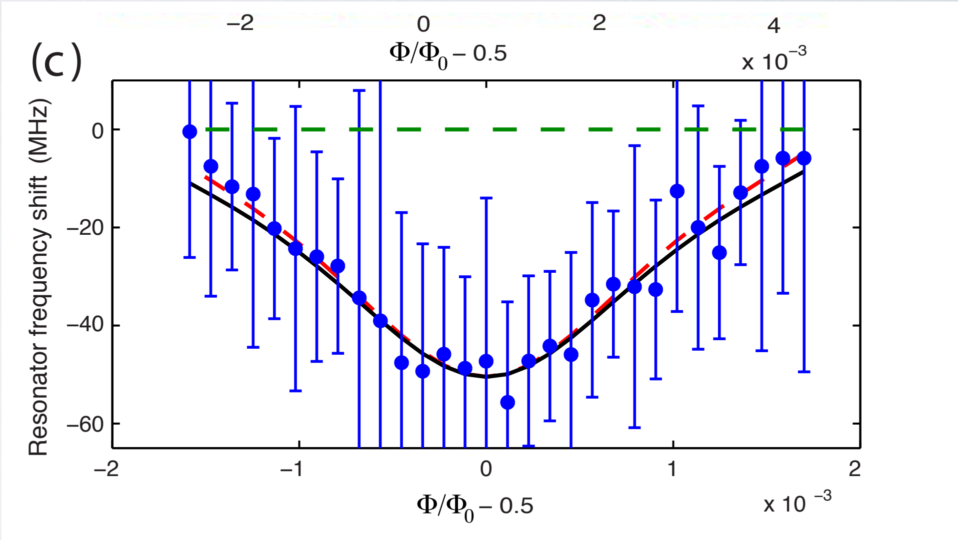
D. Schuster et al., Nature 445, 515 (2007)

@Fermilab



arxiv:1810.03703

Beyond QO: Ultrastrong couplings



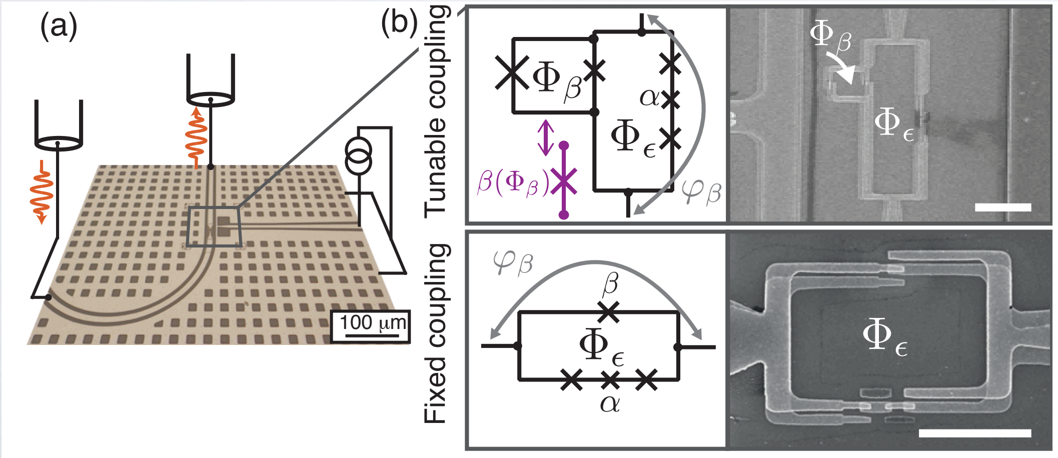
Forn-Díaz et al., PRL 105, 237001 (2010)

Quantum simulation of HEP

Garziano et al., Phys. Rev. A 90, 043817 (2014)

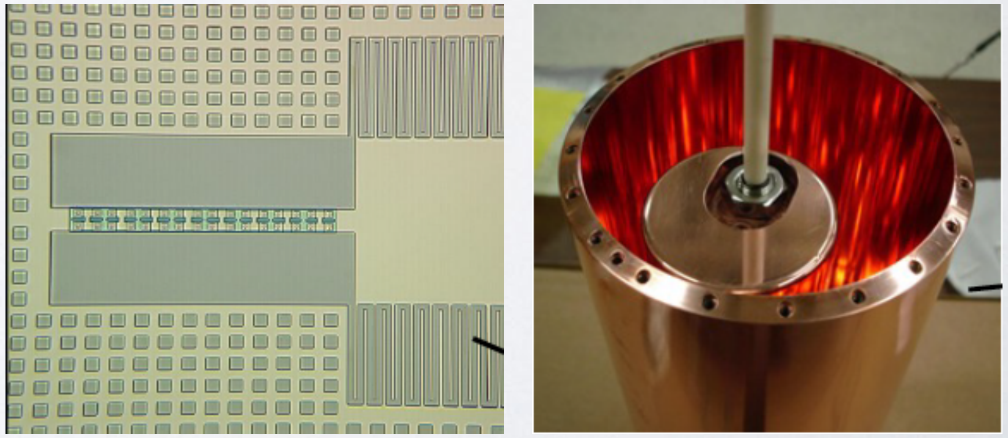
D. Marcos et al., Phys. Rev. Lett. 111, 110504 (2013)

Waveguide QED: Propagating photons



Forn-Díaz et al., Nature Phys. 13, 39 (2017)

Axion detection with JPAs *arxiv:1611.07123*



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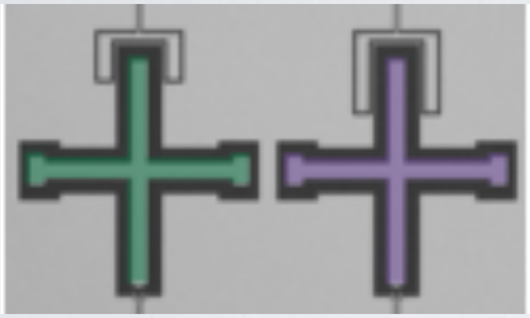
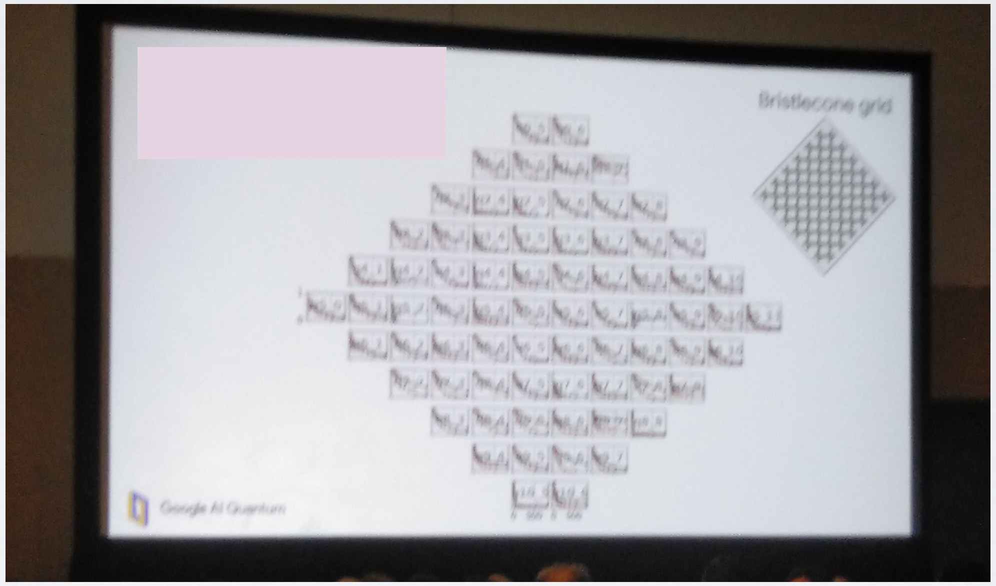
Direct qubit-qubit coupling



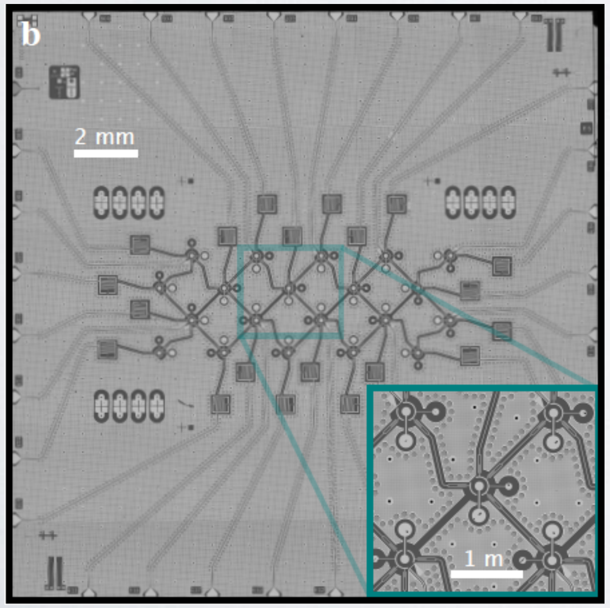
Nature 508, 500-503 (2014)

72-qubit (2019) *Google/UCSB group*



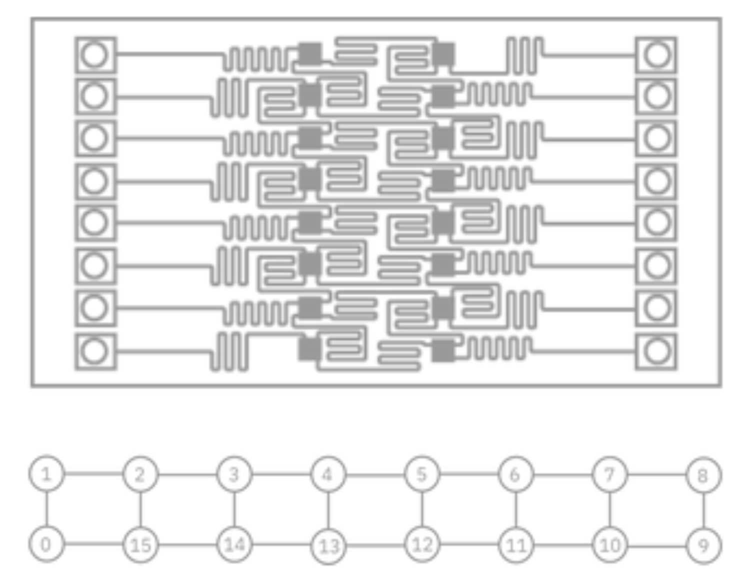
Large enough device to demonstrate quantum supremacy/ advantage

Rigetti, 19 qubits (2017)



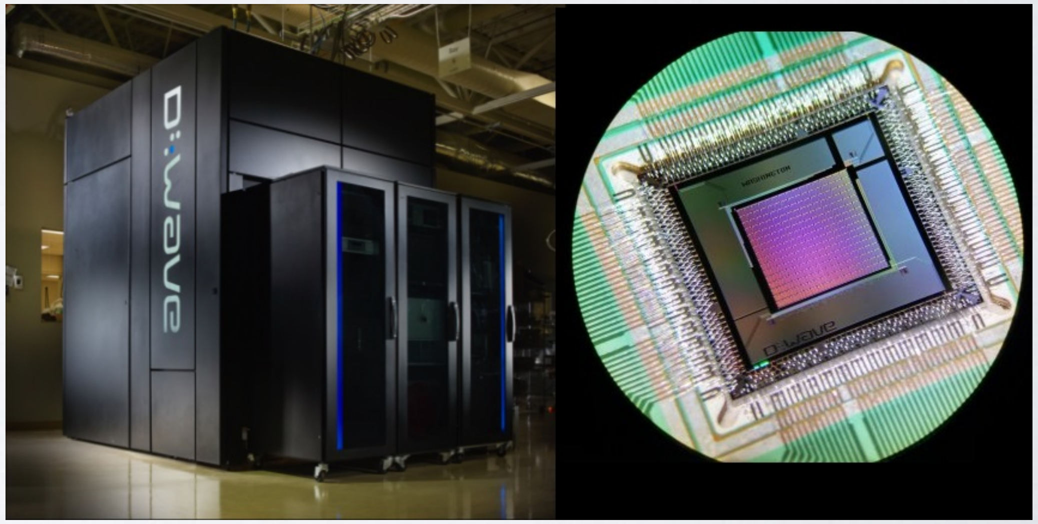
Machine learning

IBM, 20 qubits (2018)



IBM Quantum experience
Online free access

D-Wave, 2000Q (2017)



Quantum annealing, simulators

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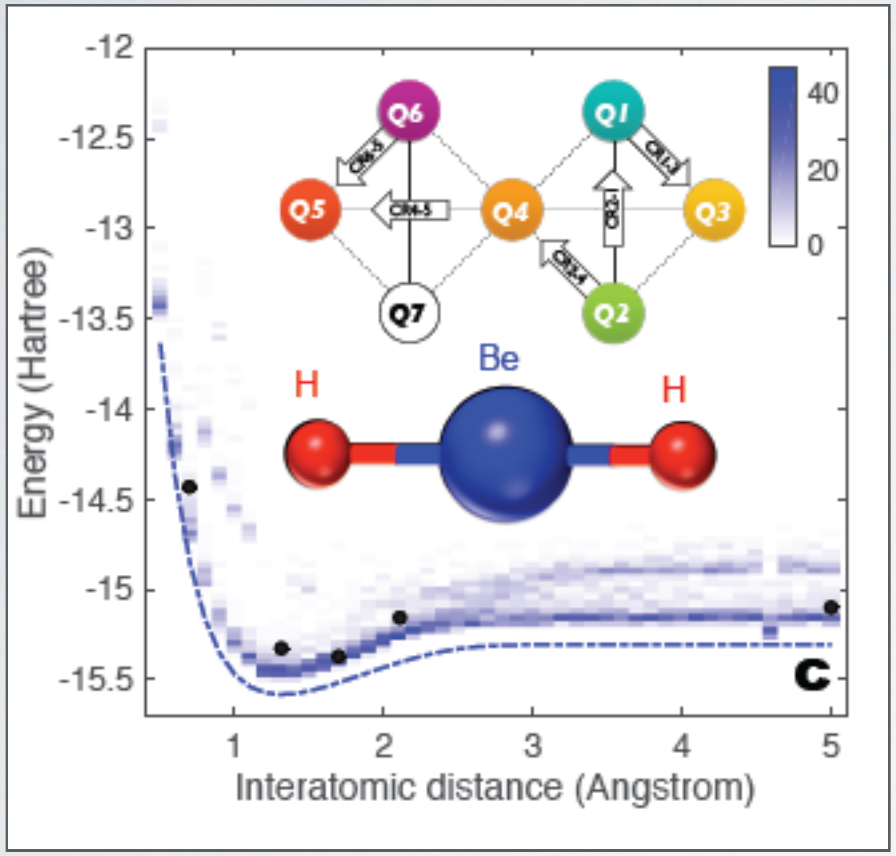
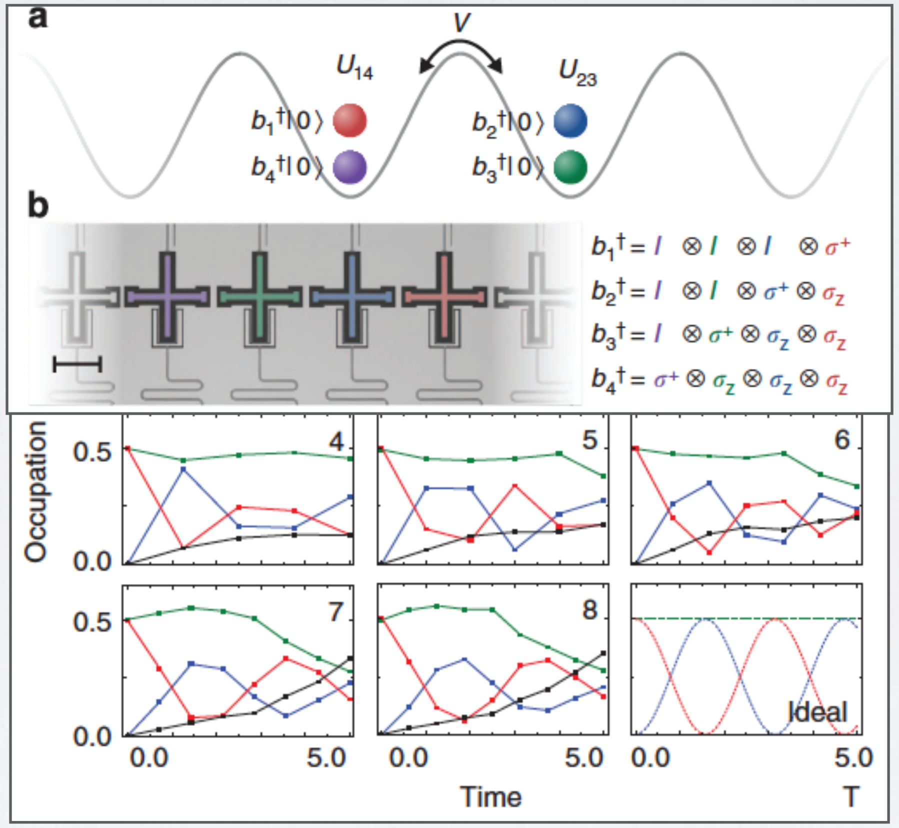
Hybrid classical-quantum algorithms: Variational quantum eigensolvers

Digital quantum simulation of fermion-fermion scattering

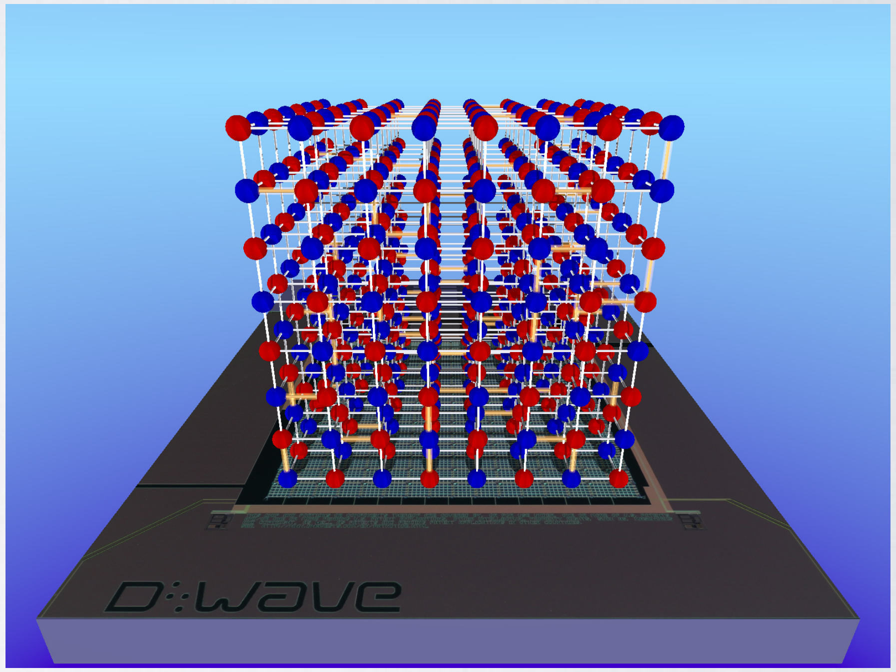
Analog simulator of cubic spin lattice



IBM



Google



D-Wave

A. Kandala et al., Nature 549, 242 (2017) *R. Barends et al., Nat. Comm. 6, 7654 (2015)* *R. Harris et al., Science 361, 162 (2018)*

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BUT…

- Available gate-based algorithms **far** from producing usable applications
- Scalability of qubit number marks **slow** pacing

STILL, ALTERNATIVES EXIST

- Develop quantum algorithms for **small-scale** processors w/o QEC
- Parallel dedicated efforts in **more resilient** quantum technologies with **shorter-term** potential, such as coherent **Quantum Annealing.**

CONCLUSIONS

- **Q**uantum computers will disrupt our society
- **S**uperconducting qubits are one of the most promising platforms
- **M**ulti-qubit circuits already in operation
- **I**n the next few years, quantum computers will become a reality

Thank you!

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