DETECTING RARE EVENTS WITH SUPERCONDUCTING QUBITS

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Institut de Física d'Altes Energies (IFAE)

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

THE QCT GROUP AT IFAE

The Quantum Computing Technology group (est. 2019)


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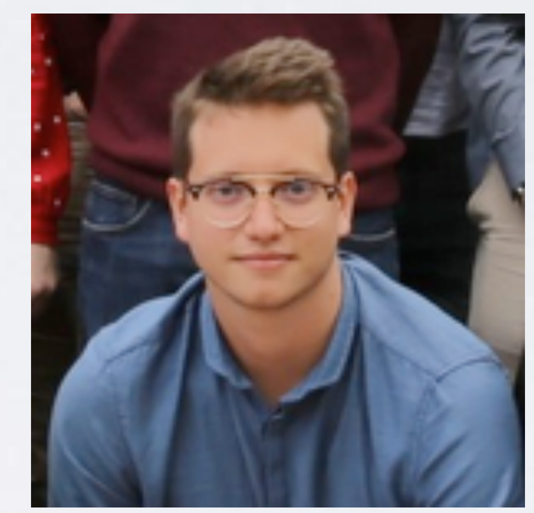
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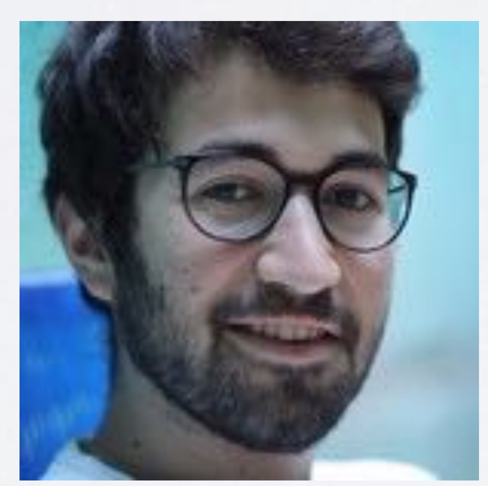
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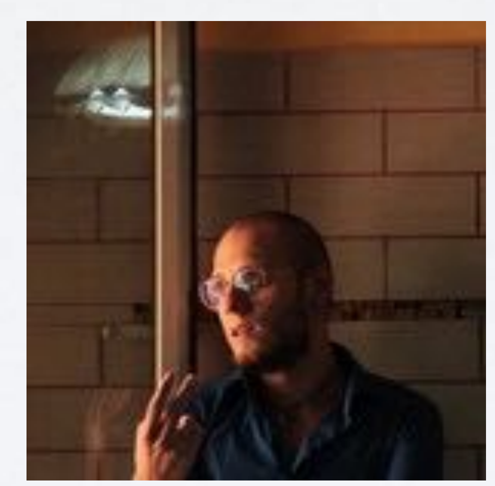
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The QCT-Qilimanjaro lab at IFAE


IFAE's quantum spin-off

QILIMANJARO QUANTUM · TECH

https://qilimanjaro.tech

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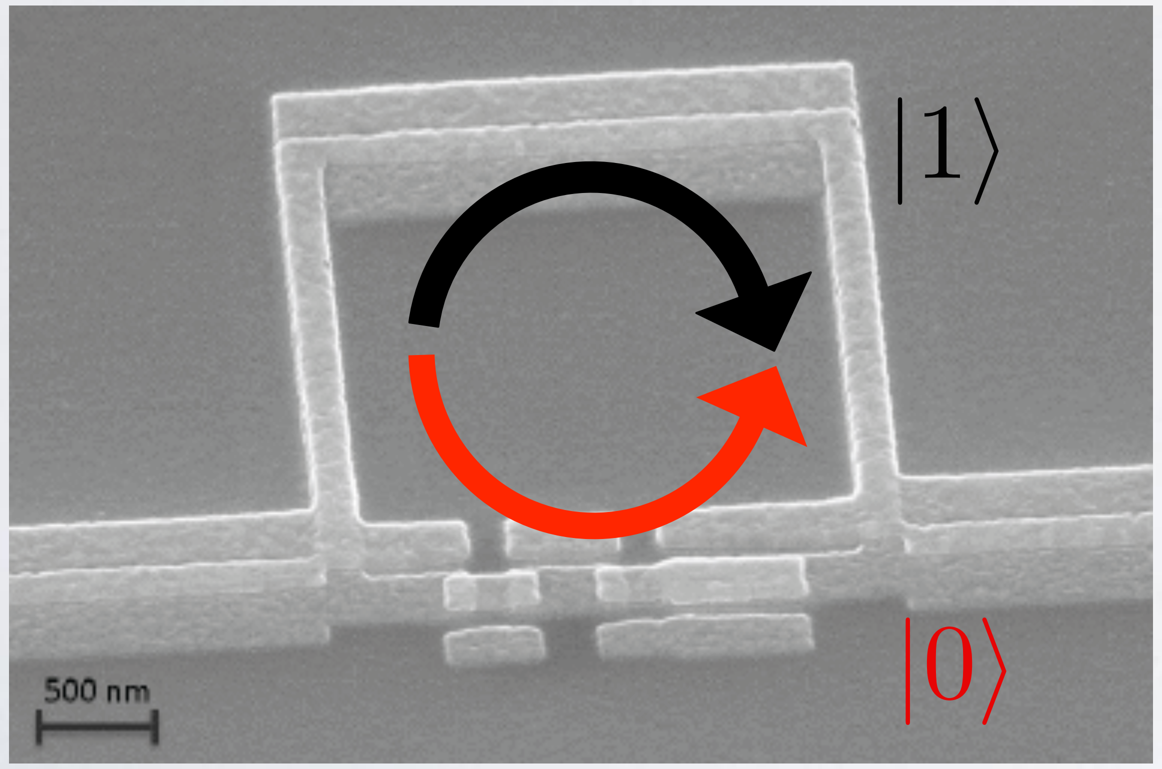
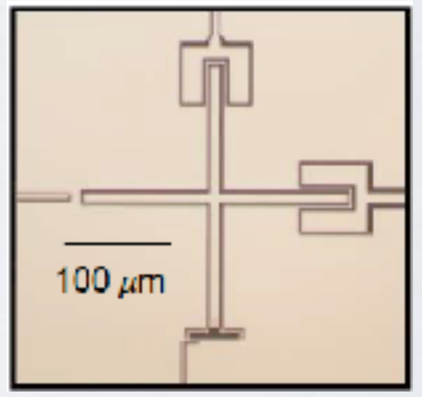
SUPERCONDUCTING QUBITS

Why superconducting qubits?

- Long coherence times: qubit "memory" longer than operation times
- Initialization: Qubits prepared in their ground state with cryogenic systems
- Readout: Strong electromagnetic interactions due to large footprint
- Scalability: Largest quantum system built and manipulated to date (Google, China)



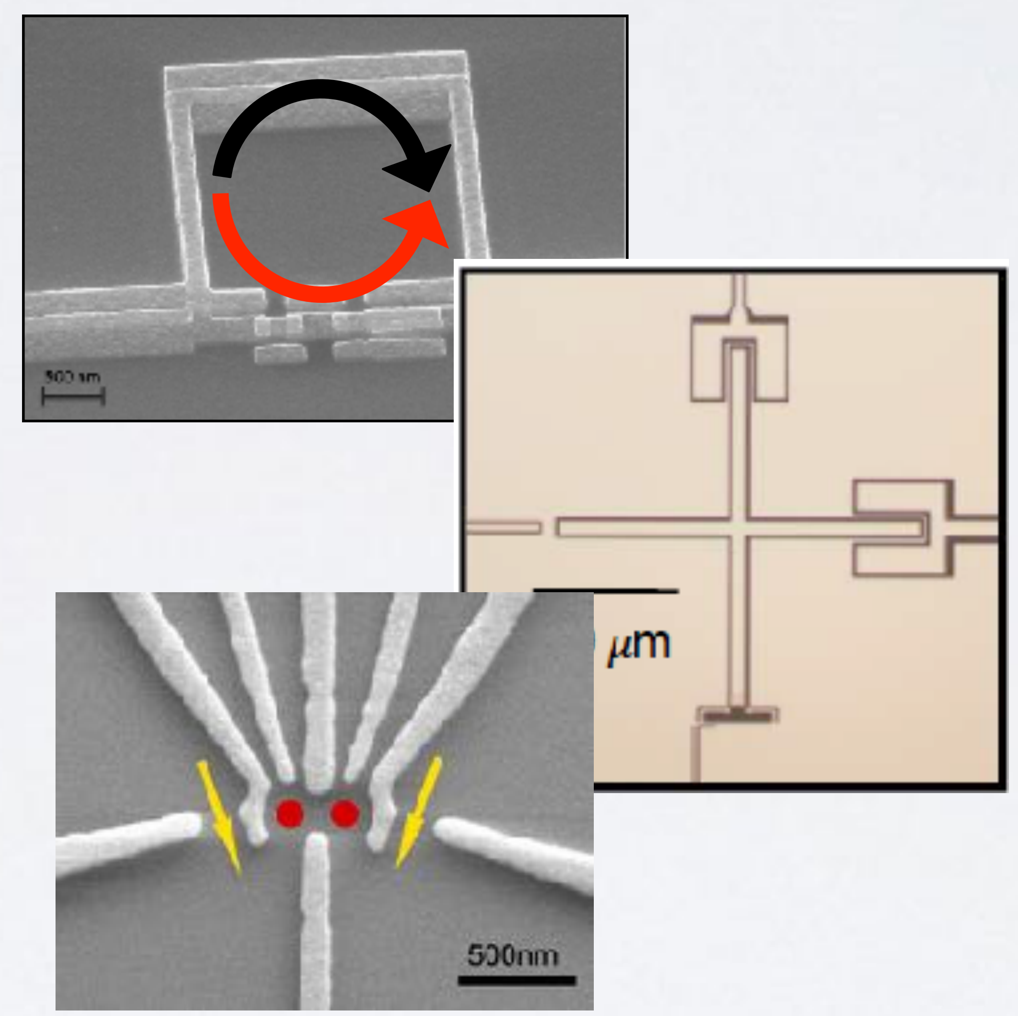


SUPERCONDUCTING QUBITS

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

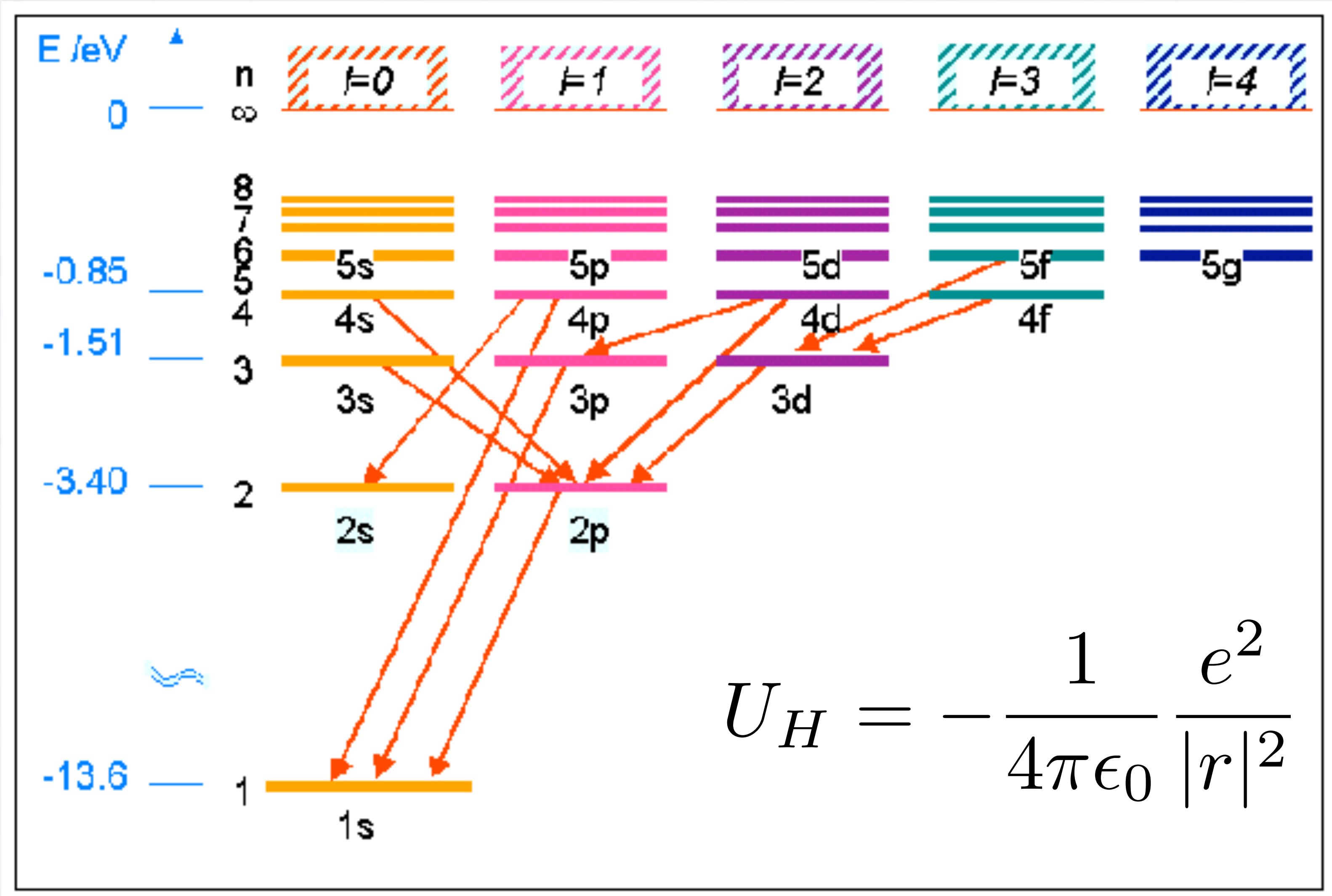
$$\vec{F} = m\vec{a}$$

SUPERCONDUCTING QUBITS

Requirements to operate a qubit

1.Communication: Energy scale + addressability

- Example: H atom



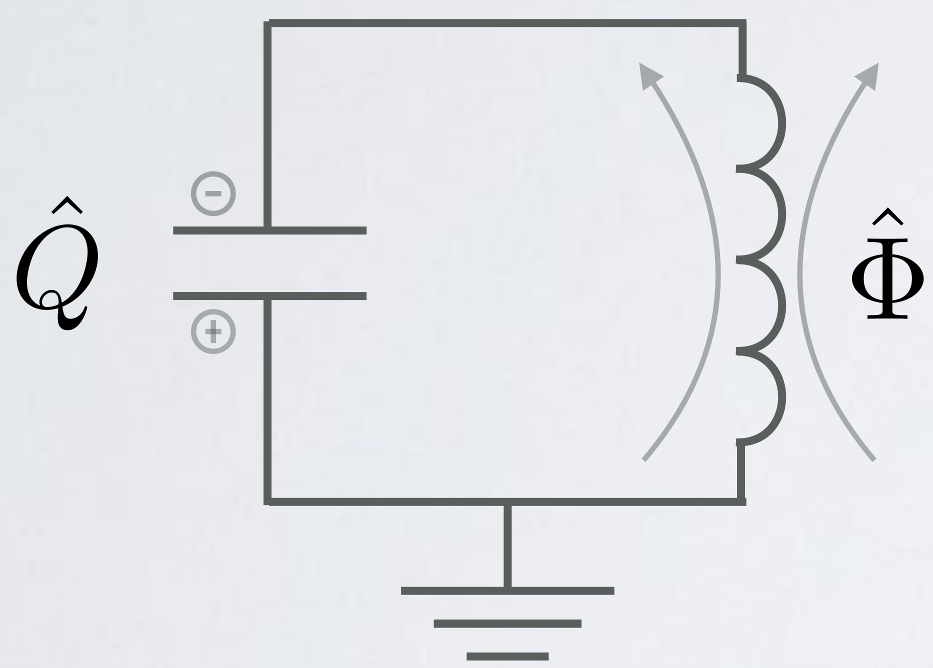
- Atomic spectra intrinsically anharmonic
- All transitions addressable by external radiation

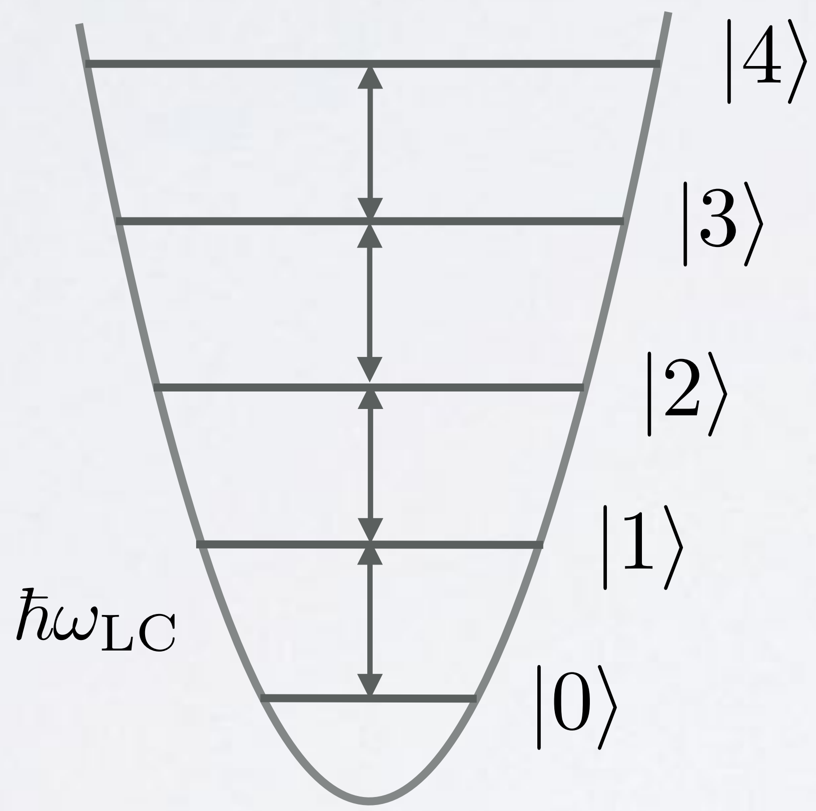
SUPERCONDUCTING QUBITS

Requirements to operate a qubit

1.Communication (language): Energy scale + addressability

- Harmonic oscillator

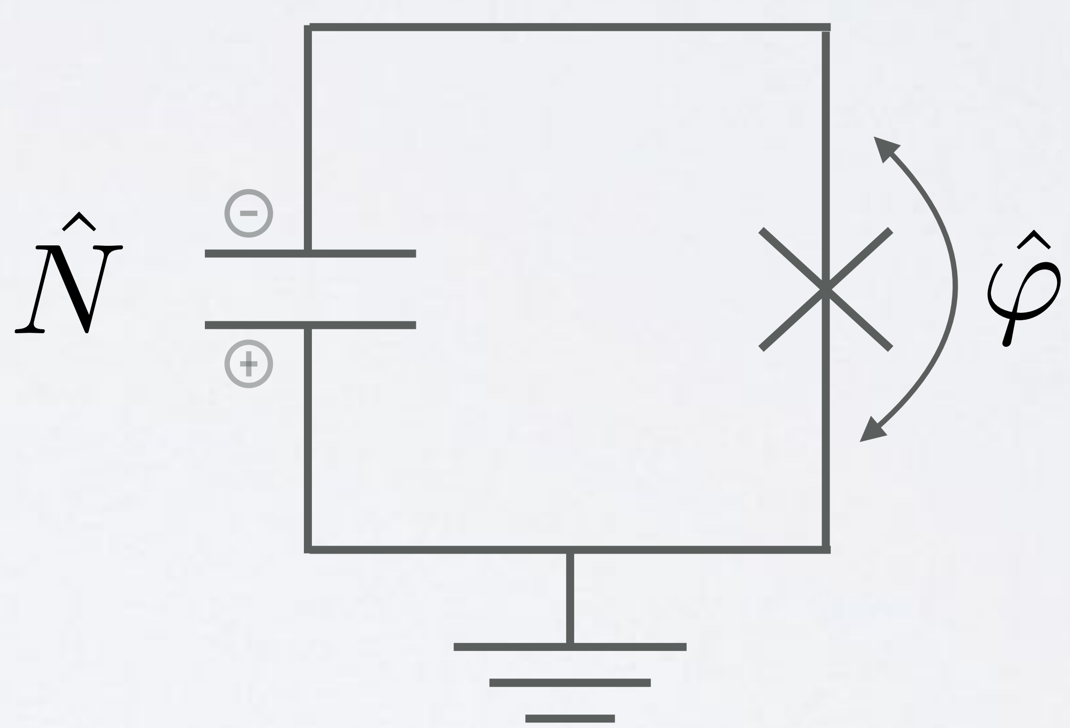


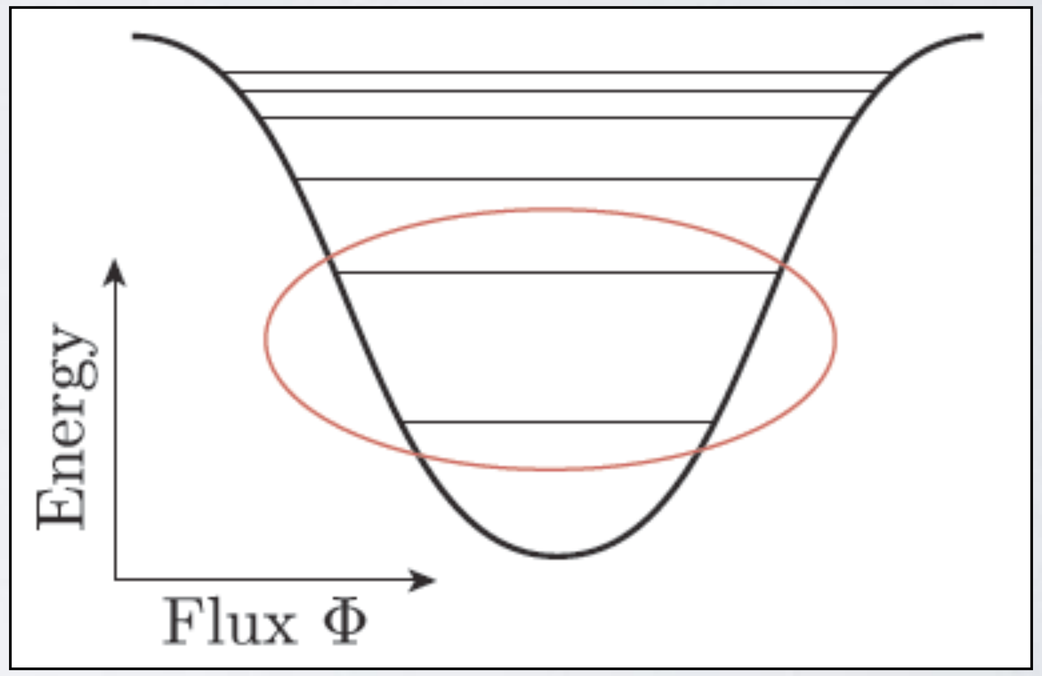


- Spectra intrinsically **harmonic**
- **No** transitions addressable by external radiation

- Anharmonic oscillator (aka Josephson junction qubit)

Transmon





- Spectra designed **anharmonic**
- Transitions designed addressable by external radiation in the **microwave range**

Vool, Devoret, IJCTA - Special Issue on Quantum Circuits

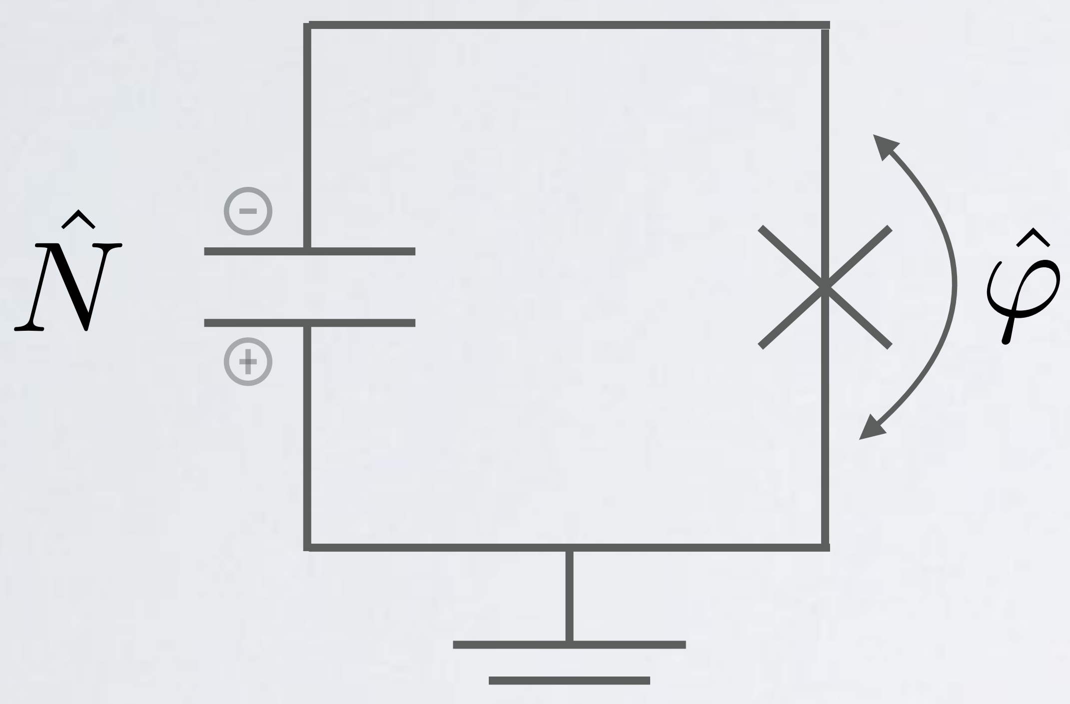
Koch et al. PRA 76, 042319 (2007)

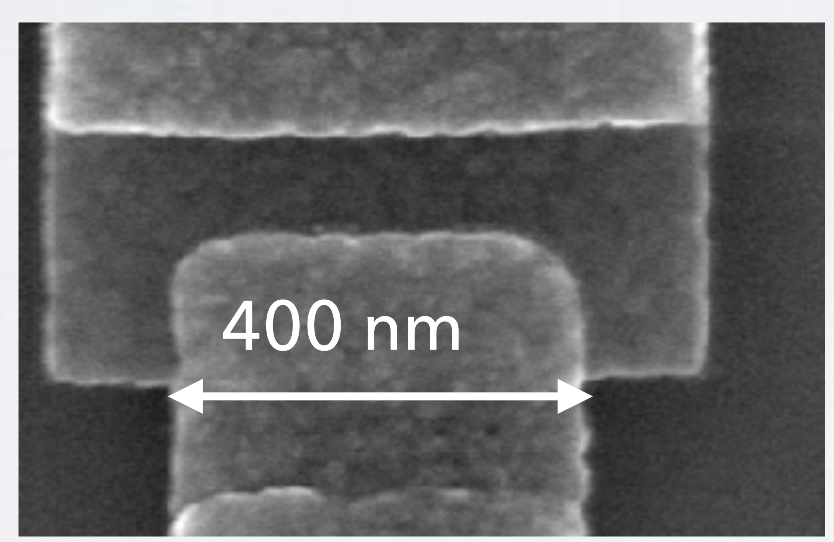
SUPERCONDUCTING QUBITS

Requirements to operate a qubit

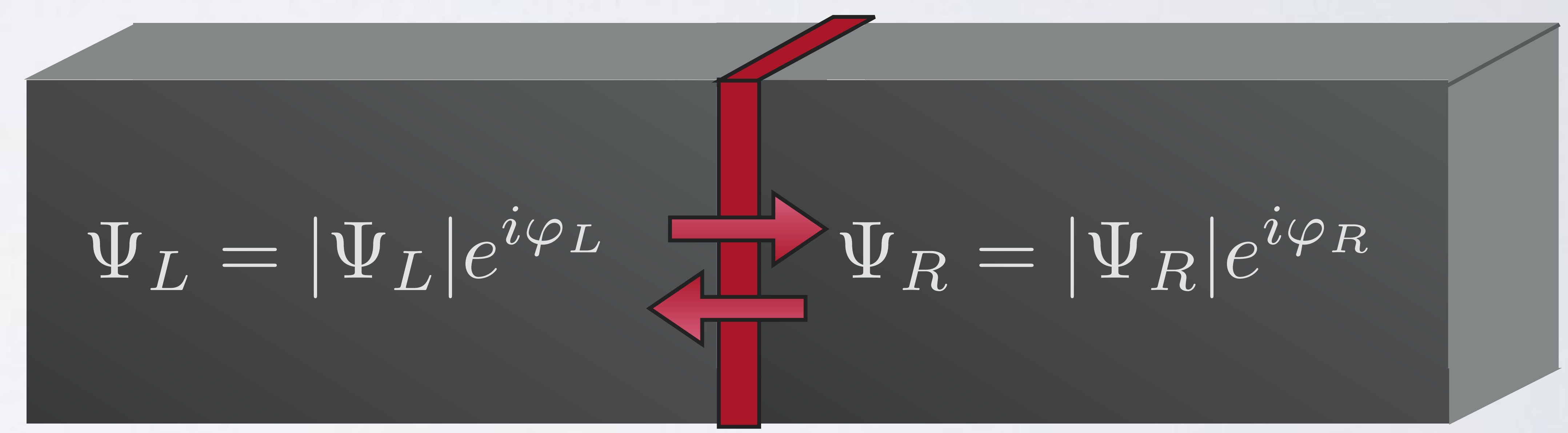
1. Communication (language): Energy scale + addressability

- Josephson junction: nonlinear, non-dissipative inductance





SEM micrograph



Electrical circuits symbol

Constituent relation:

$$\frac{dI}{dt} = V\frac{2\pi I_C}{\Phi_0}\sqrt{\frac{I_C^2 - I^2}{I_C^2}} \equiv V/L_J(I)$$

Josephson inductance

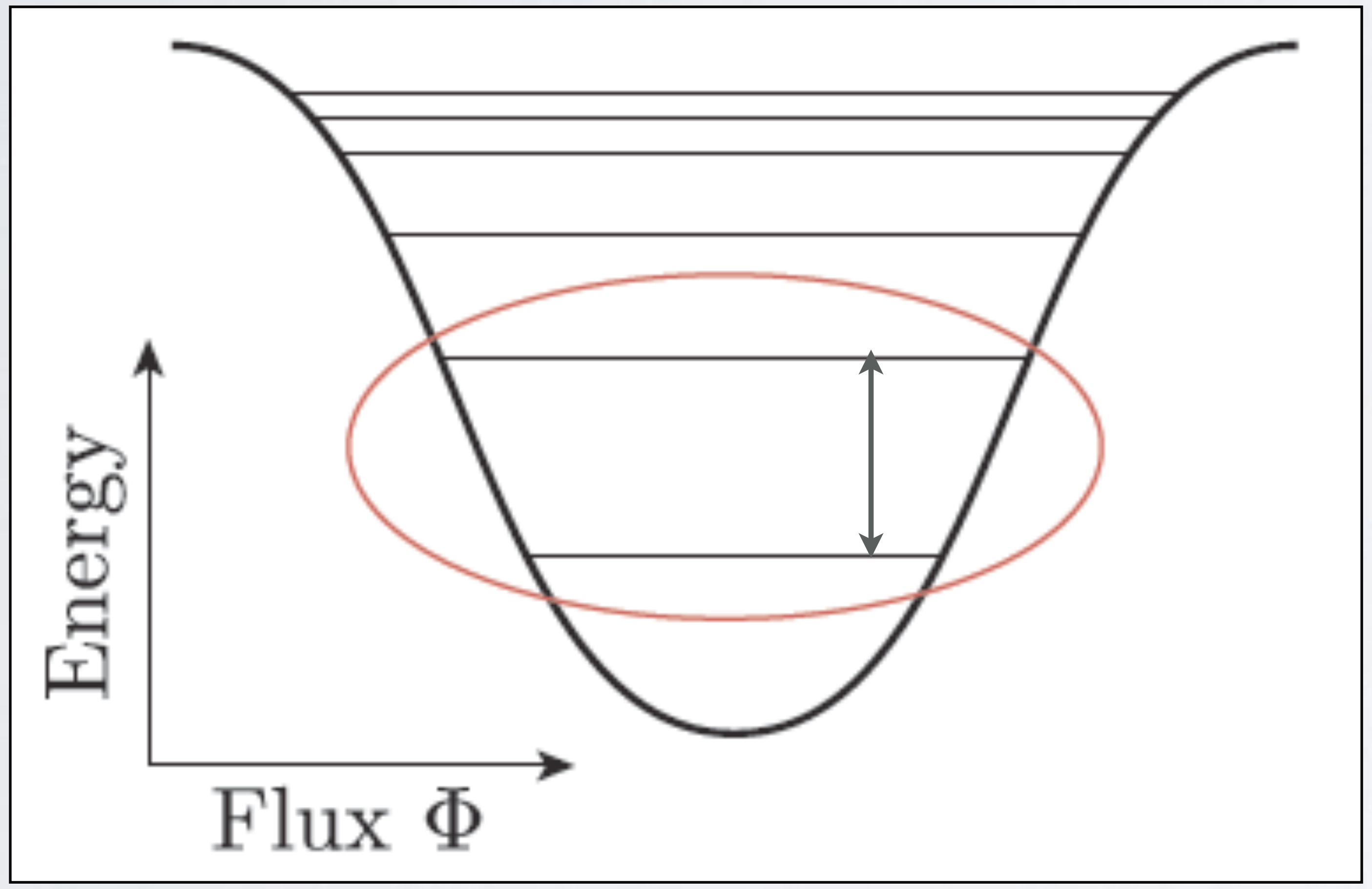
Orlando, Delin.
Foundation of applied superconductivity

SUPERCONDUCTING QUBITS

Requirements to operate a qubit

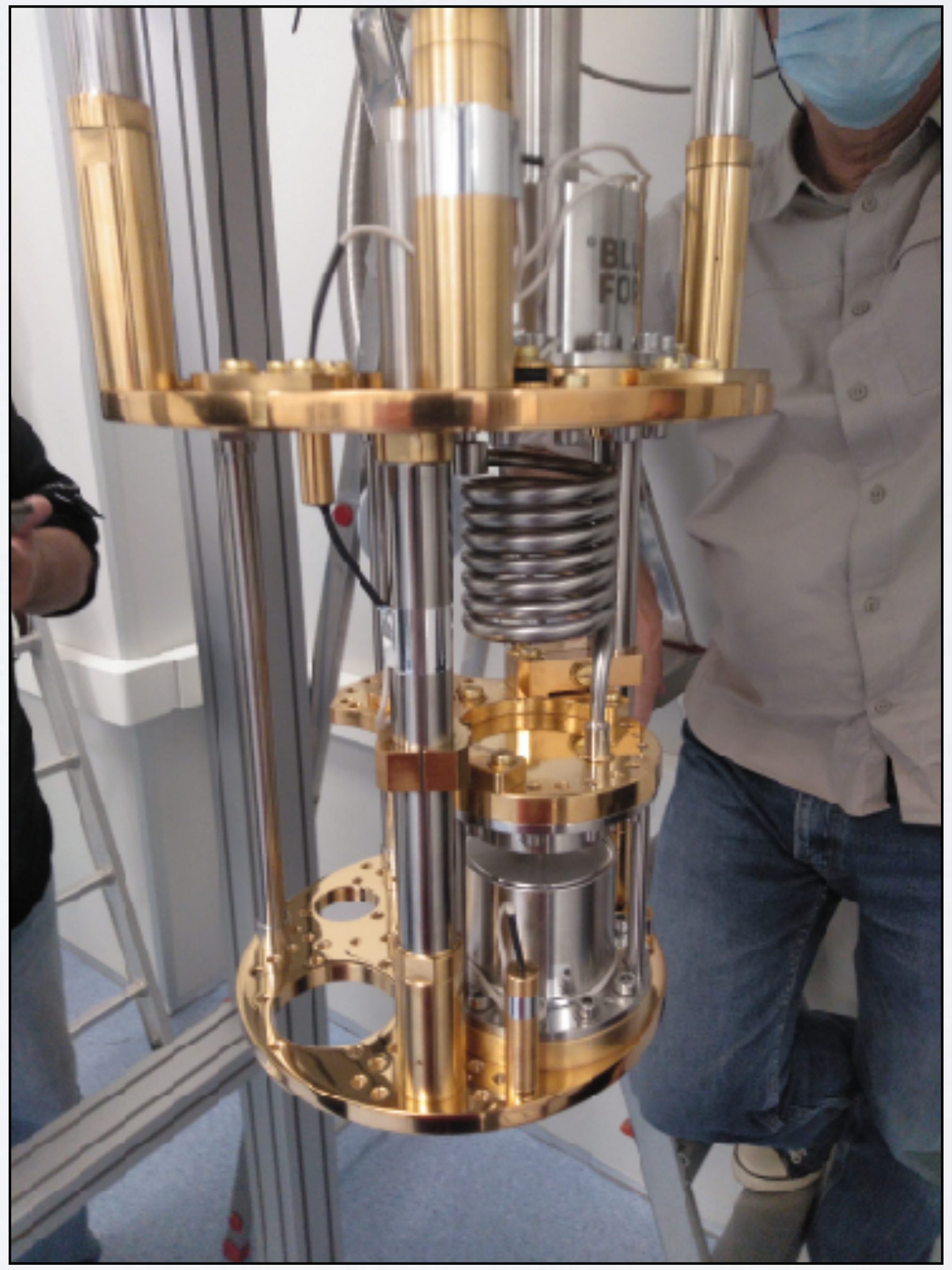
2. Initialization: Control qubit physics

- Microwave energies ~ millikelvin temperatures



- Gigaherz frequency transitions

- Dilution refrigerator



T = 0.01 K (-273.13 C)

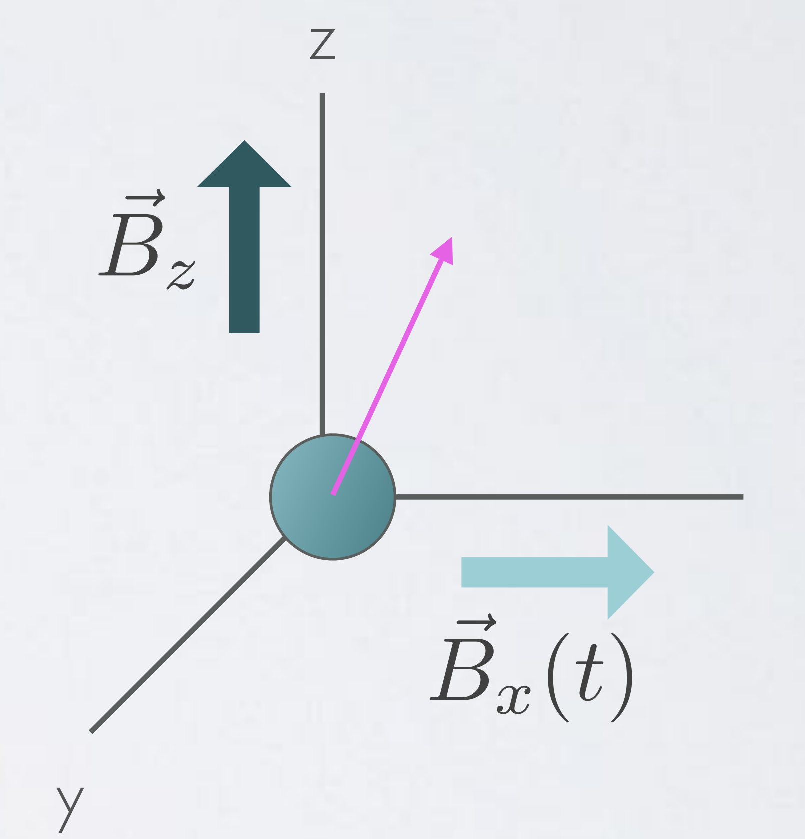
- Commercially available
- Compact, robust
- Stable
- Qubit-compatible

SUPERCONDUCTING QUBITS

Requirements to operate a qubit

2. Manipulation (dialogue): Pulse engineering

Analogy with spin-1/2



Rabi formula

$$P_{0\to1} = \frac{\Omega_R^2}{\Delta^2 + \Omega_R^2} \sin^2\left(\sqrt{(\Delta^2 + \Omega_R^2)} t/\hbar\right)$$

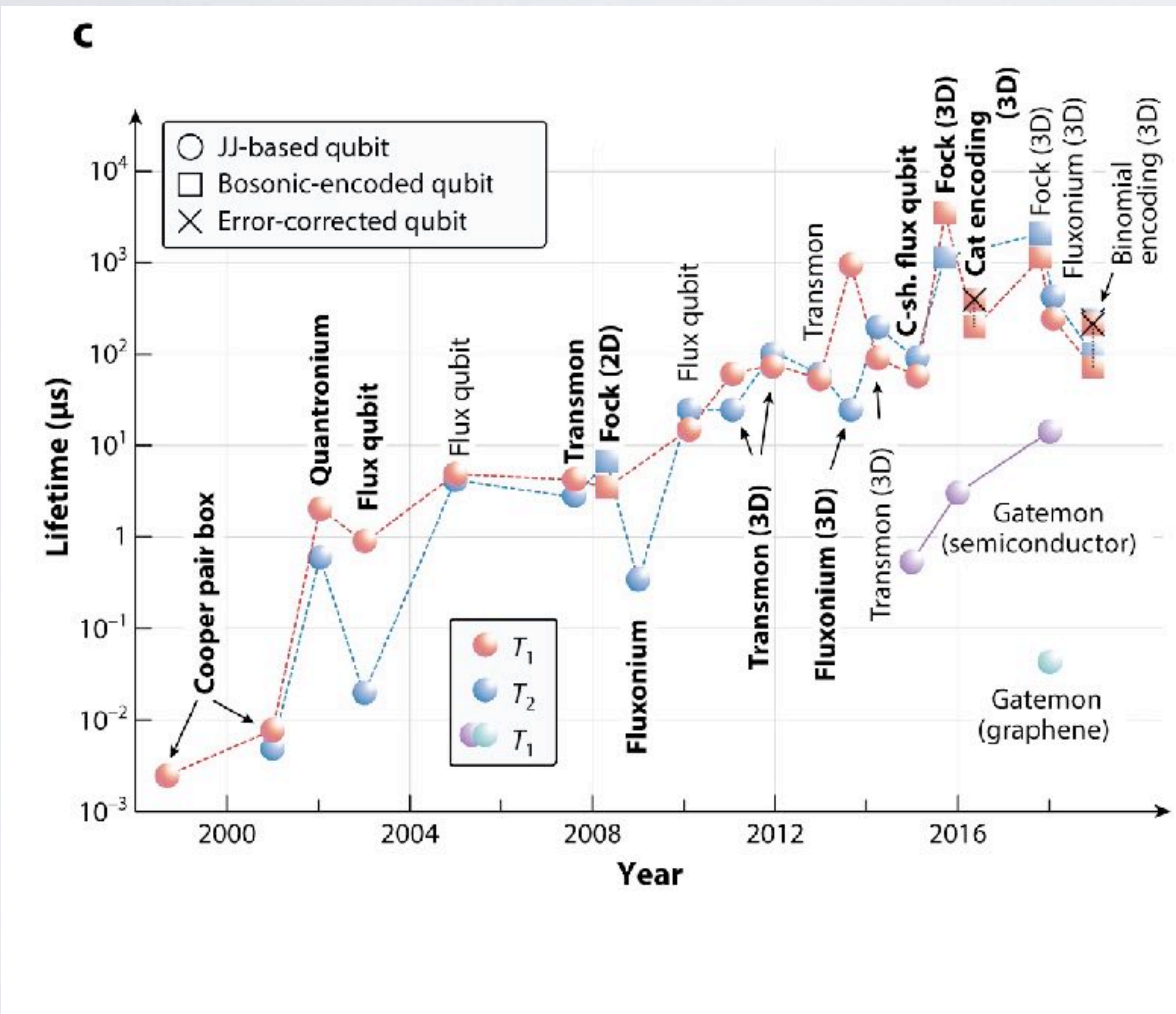
Ω_R Rabi frequency "bare"

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

Import all NMR techniques for qubit state control…

SUPERCONDUCTING QUBITS

Qubit coherent properties



Qubit coherence increase by 6 orders of magnitude in 20 years!

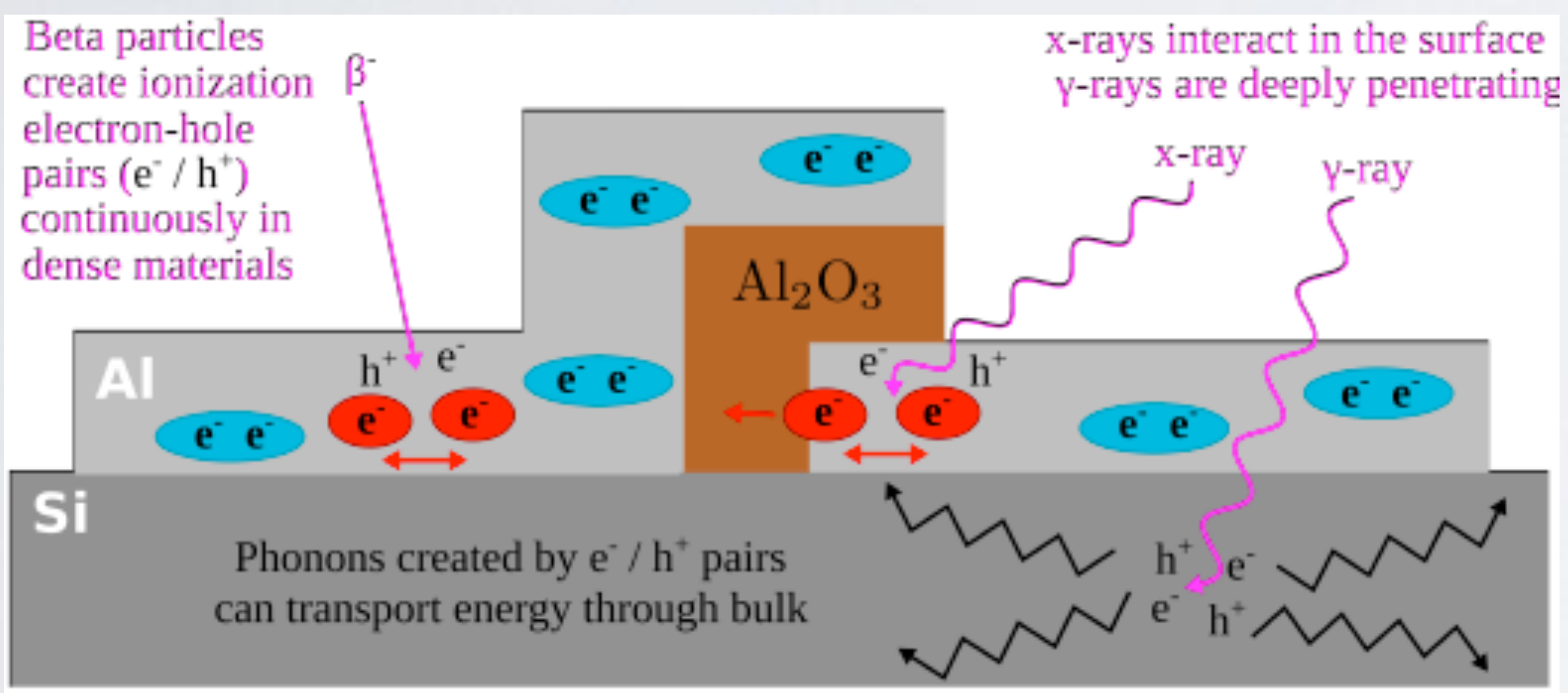
Still, some decoherence mechanisms exist:
-Dielectric noise
-Quasiparticle noise
-Non-thermal radiation
-Ionizing radiation

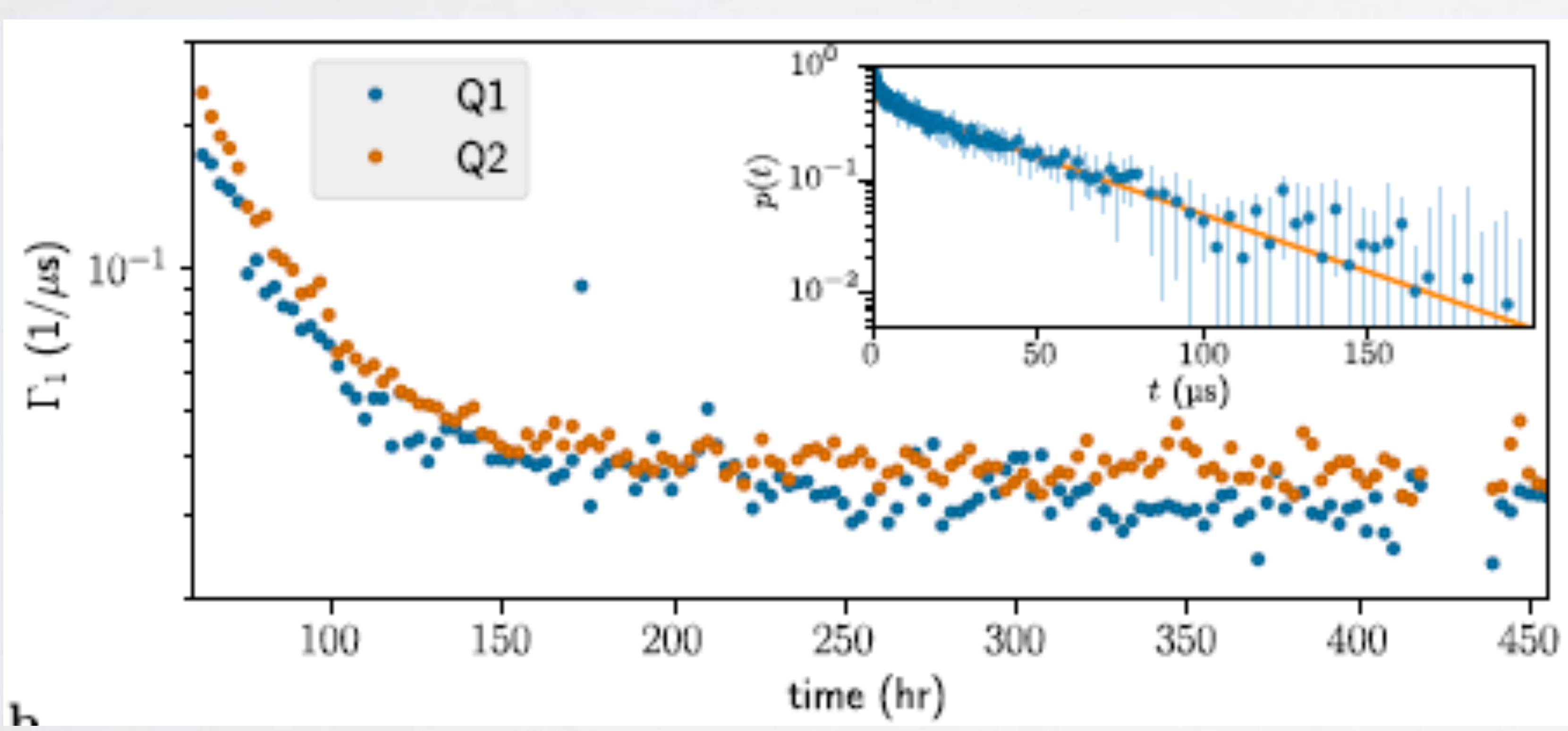
Kjaergaard et al., Annu. Rev. Condense. Matt. Phys. 11: 369-95 (2020)

SUPERCONDUCTING QUBITS

Qubit coherent properties

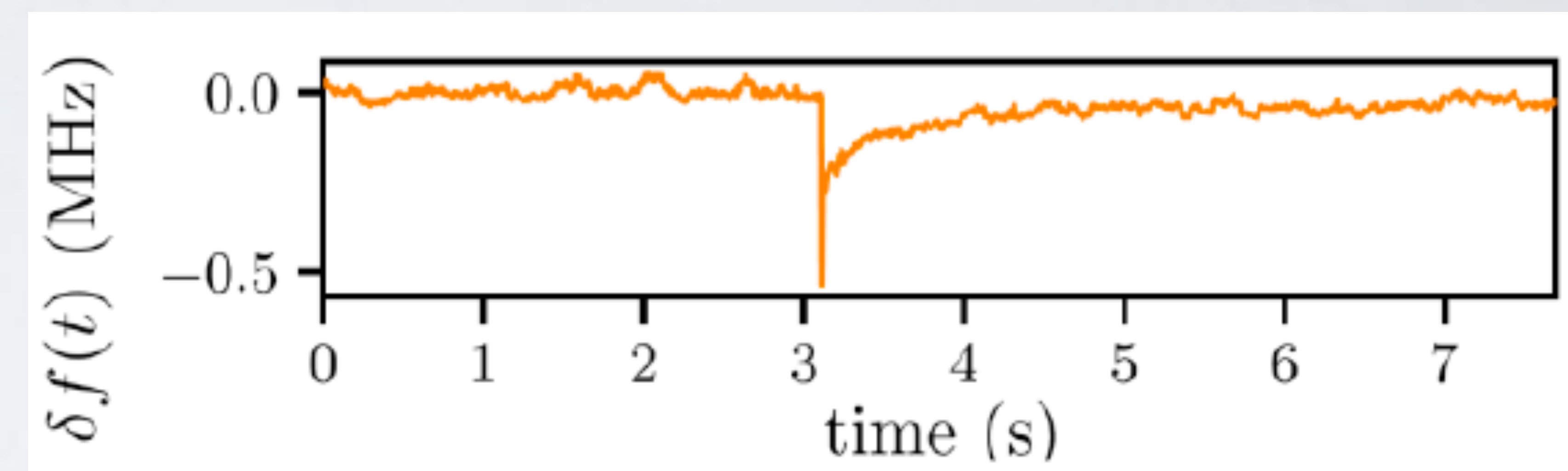
Initial evidence of effect of radioactive source on qubit

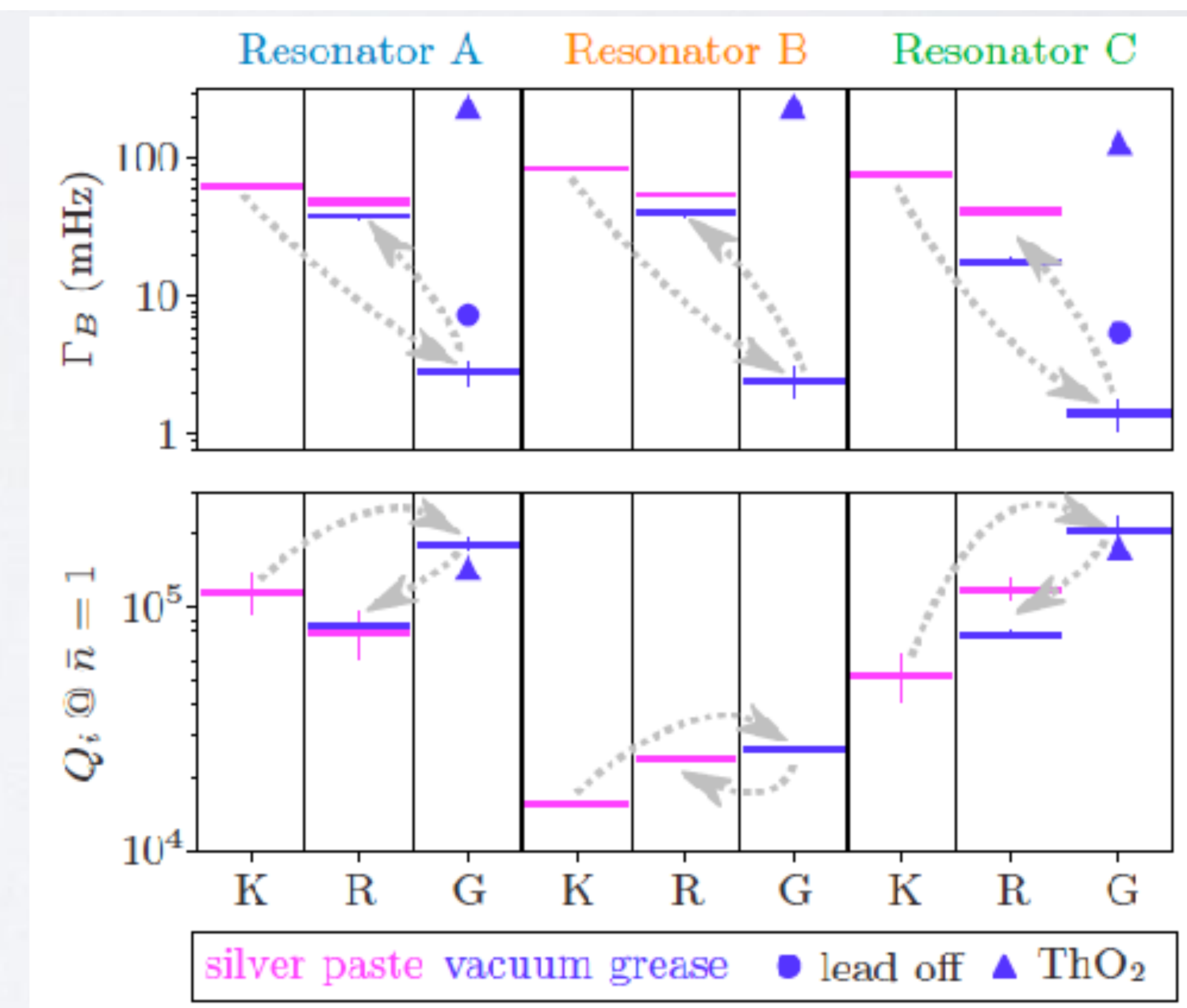




A. P. Vepsäläinen *et al.*, Nature 584, 551-556 (2020)

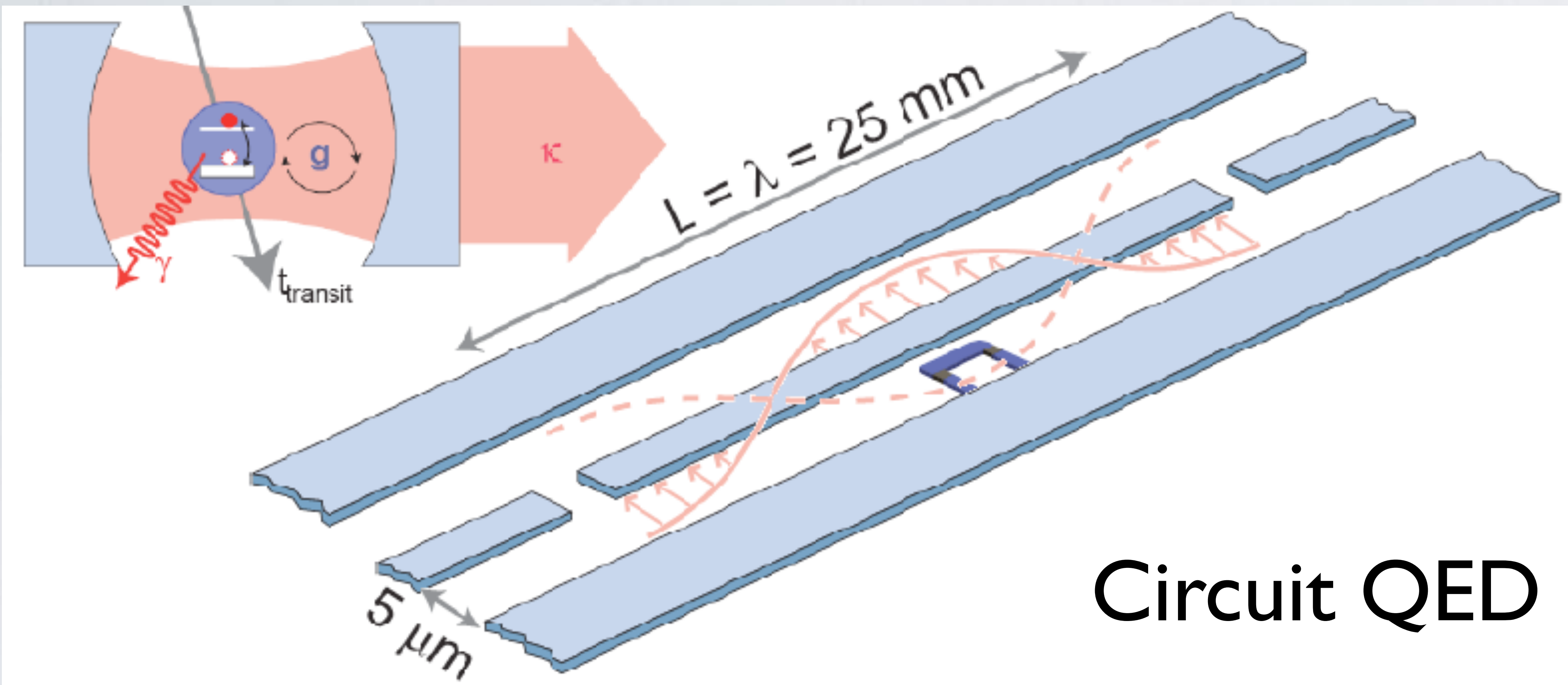
Initial evidence of effect of underground shielding





L. Cardani *et al.*, Nat. Commun. 12, 2733 (2021)

DETECTION BY QUBITS



$E_{0,\mathrm{rms}} \approx 0.2\,\mathrm{V/m}$

for $\omega_r/2\pi \approx 6\,\mathrm{GHz}$

$\times 10^6$ larger than E_0 in 3D microwave cavity

Jaynes-Cummings model

$$\mathcal{H}_{\mathrm{JC}}/\hbar = \frac{\omega_q}{2}\sigma_z + \omega_r\left(a^\dagger a + \frac{1}{2}\right) + g(a^\dagger\sigma^- + a\sigma^+)$$

Qubits are **ideal quantum spectrometers**. In addition, qubits may **interact very strongly with photons** in superconducting resonators exhibiting pristine quality factors. The result is an **incredibly sensitive** device that is able to sense the presence of photons inside the resonator with unprecedented accuracy over a certain space of parameters.

Dispersive limit: $g \ll \Delta \equiv \omega_q - \omega_r$

$$\mathcal{H}_{\mathrm{JC}}/\hbar \approx \left(\omega_r + \frac{g^2}{\Delta}\sigma_z\right) a^\dagger a + \frac{1}{2}\left(\omega_q + \frac{g^2}{\Delta}\right)\sigma_z$$

Stark shift   Lamb shift

Resonator frequency depends on qubit state

Nondestructive readout, as operators commute

As there is no energy exchange: dispersive readout

Atomic physics and quantum optics using superconducting circuits, JQ You, F. Nori, Nature 474, 589

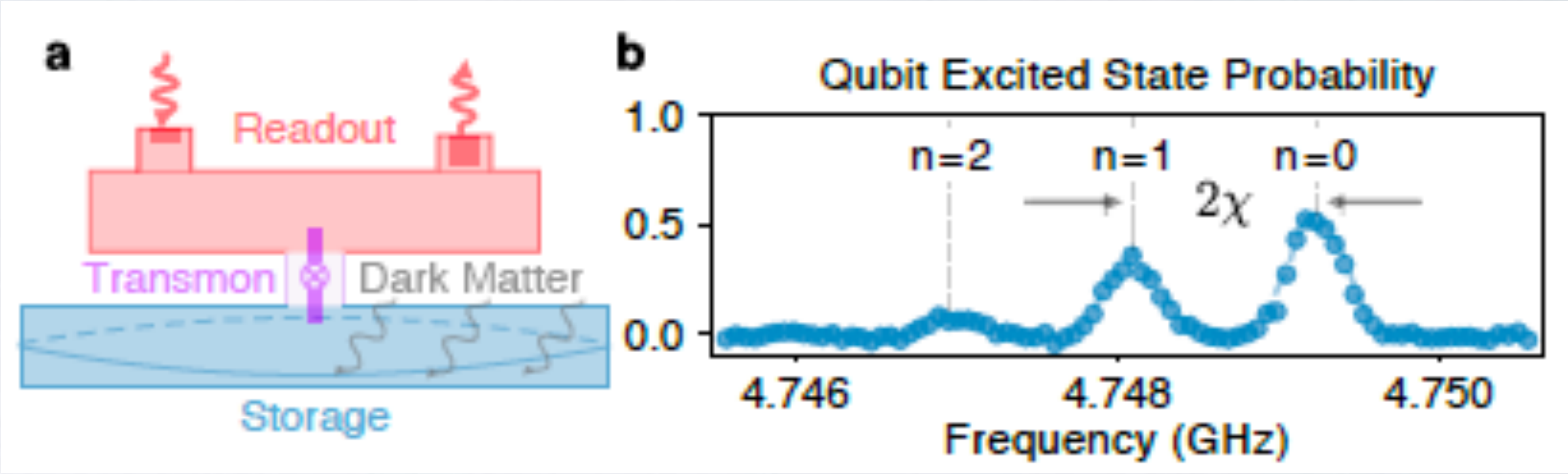
A. Blais et al., PRA 69, 062320 (2004)

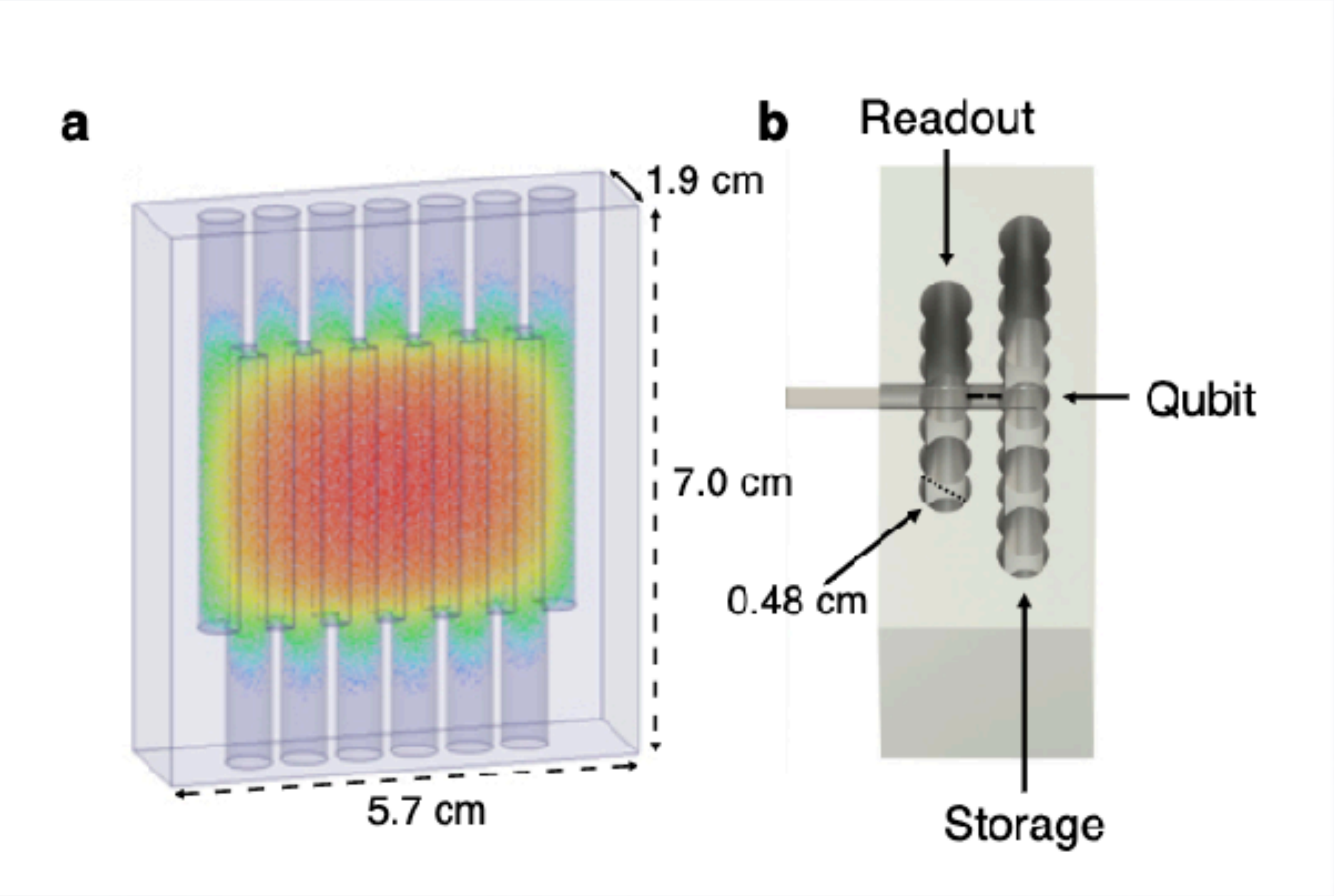
R. Barends et al., Nature 508, 500 (2014)

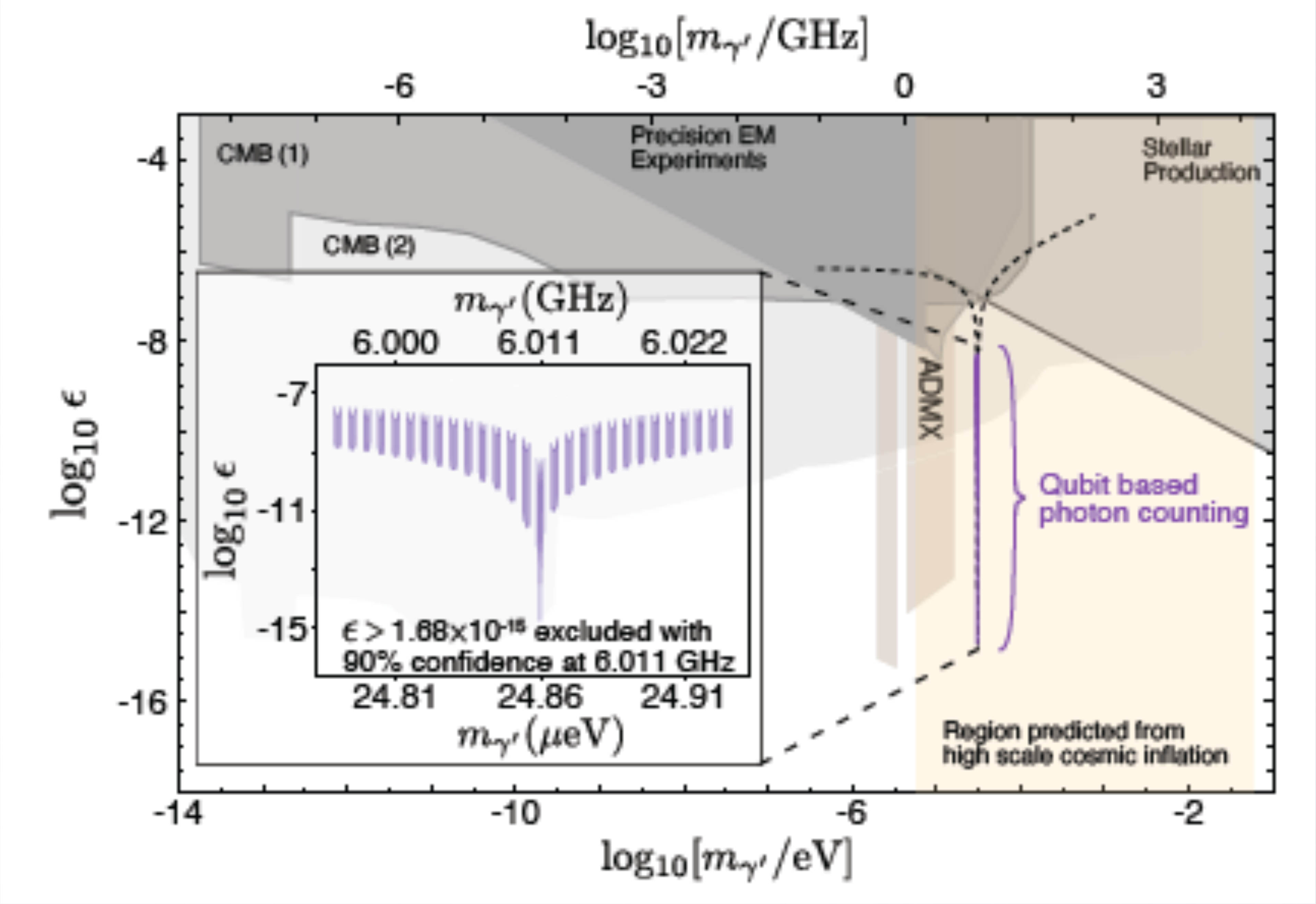
DETECTION BY QUBITS

Proposals have already been put forward to use qubits combined with cavities to **detect potential dark matter signals**, including axions and dark photons.

Initial experiments are already being established in the **US** through **Fermilab**, and in **Italy at INFN**. **IFAE** is starting a collaboration with **LSC in Spain** to carry out first measurements with qubits underground.







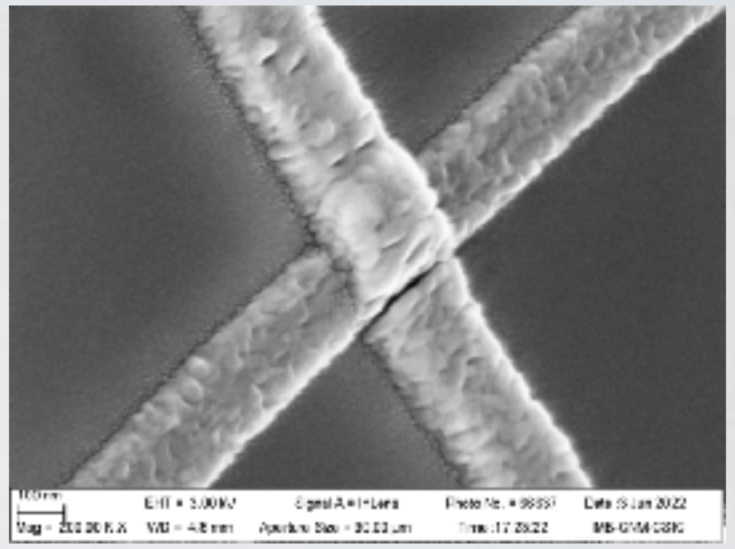
Searching for Dark Matter with a Superconducting Qubit. Akash V. Dixit, Srivatsan Chakram, Kevin He, Ankur Agrawal, Ravi K. Naik, David I. Schuster, and Aaron Chou. Phys. Rev. Lett. 126, 141302

Project ICRQ

Project relevant details

- Execution dates: 01/09/2022-31/08/2025

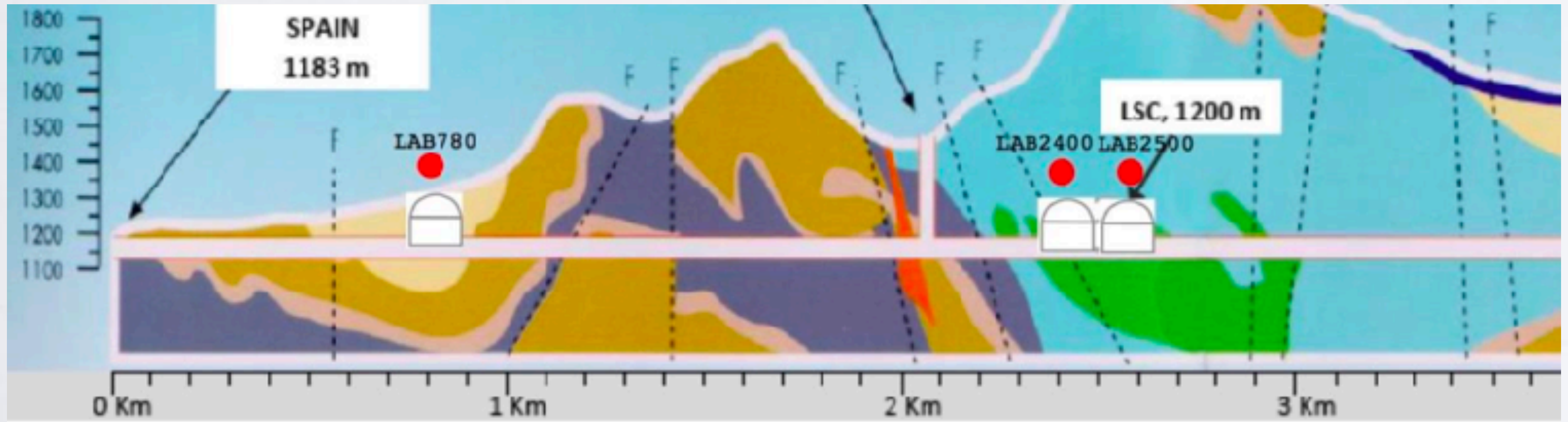
- Main project goals:



1. Assert the **viability of above-ground qubit stations** for quantum computing applications in relation to the impact of highly **ionizing radiation** and ionizing cosmic particles.

2. Provide insights on the **noise mechanisms** at the microscopic scale induced by ionizing radiation and cosmic particles in superconducting qubits using underground sites.

3. Implement advanced **on-chip mitigation** techniques that reduce the impact of ionizing radiation and particles on the performance of superconducting qubit devices.



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PhD positions open!

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European Commission | Horizon 2020 European Union funding for Research & Innovation

Thank you!

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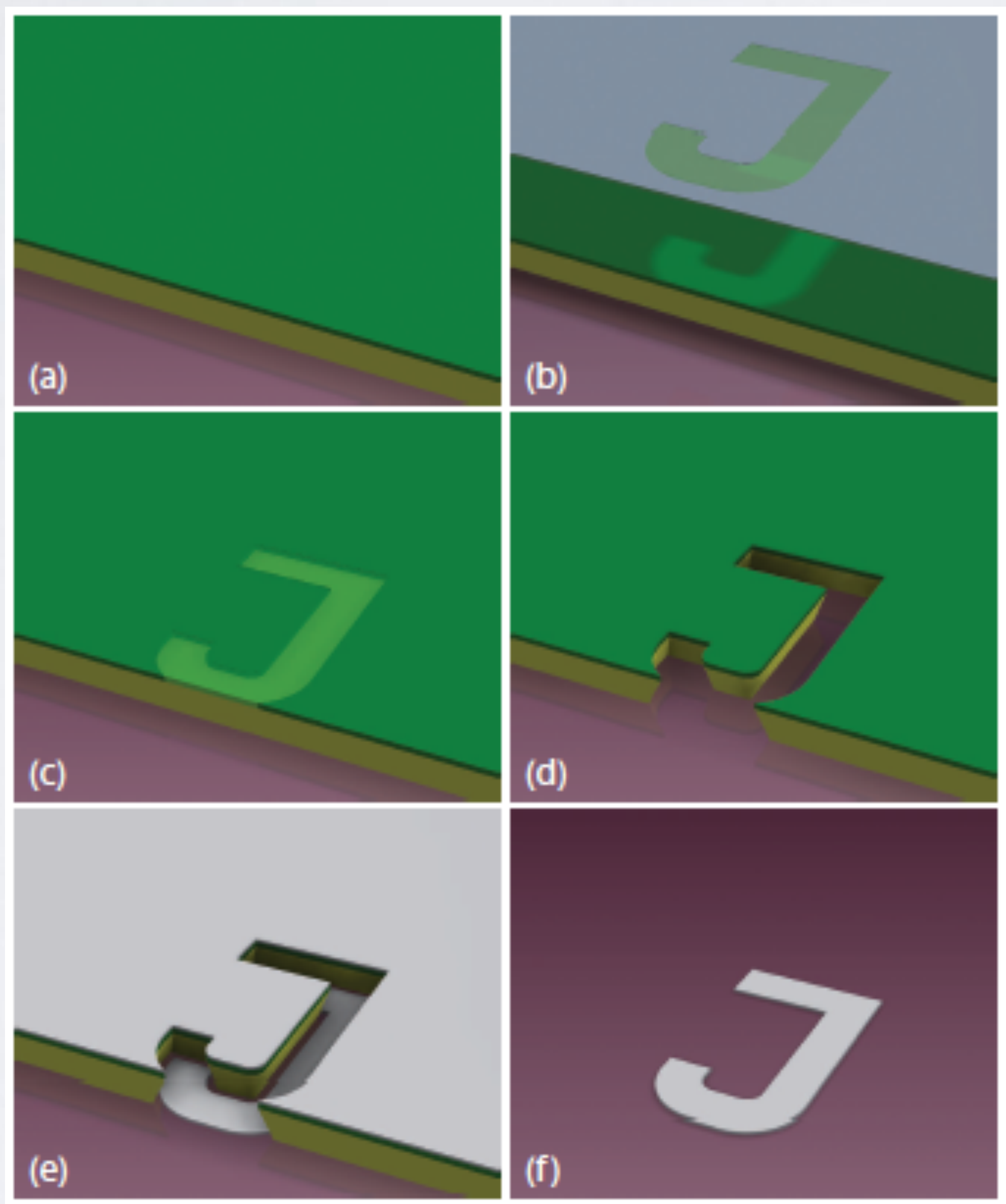
BACKUP

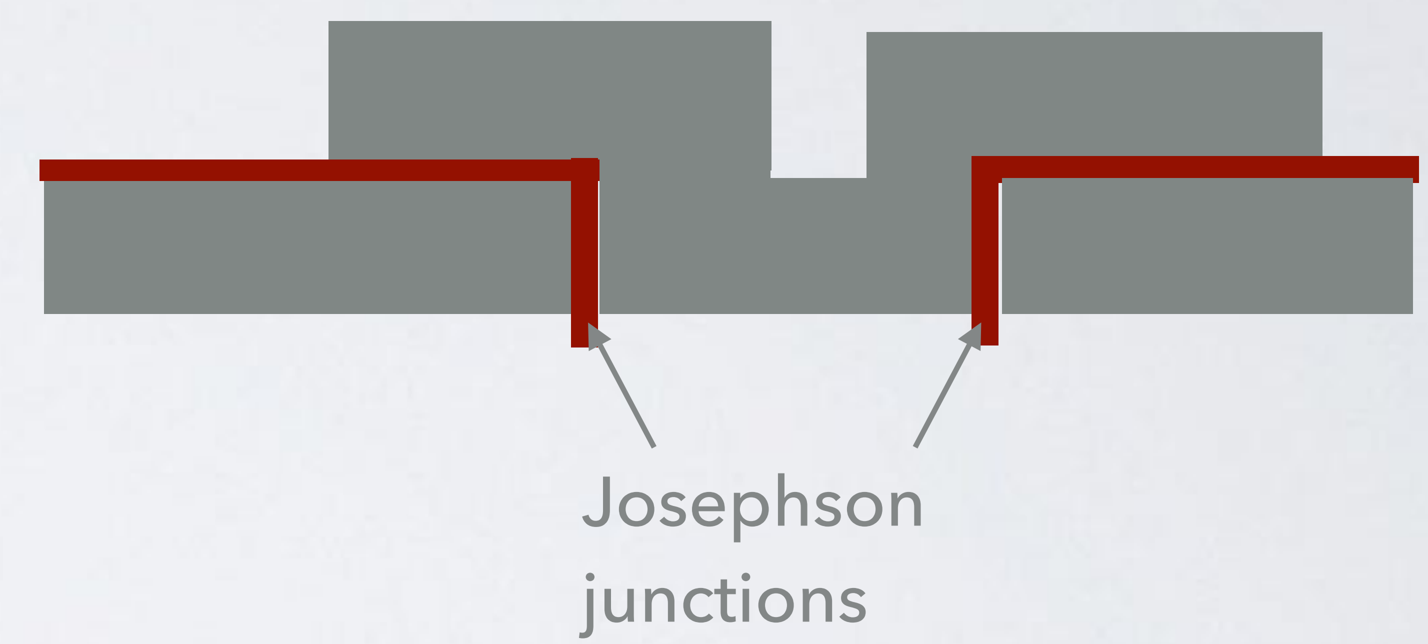
CIRCUIT QUANTIZATION

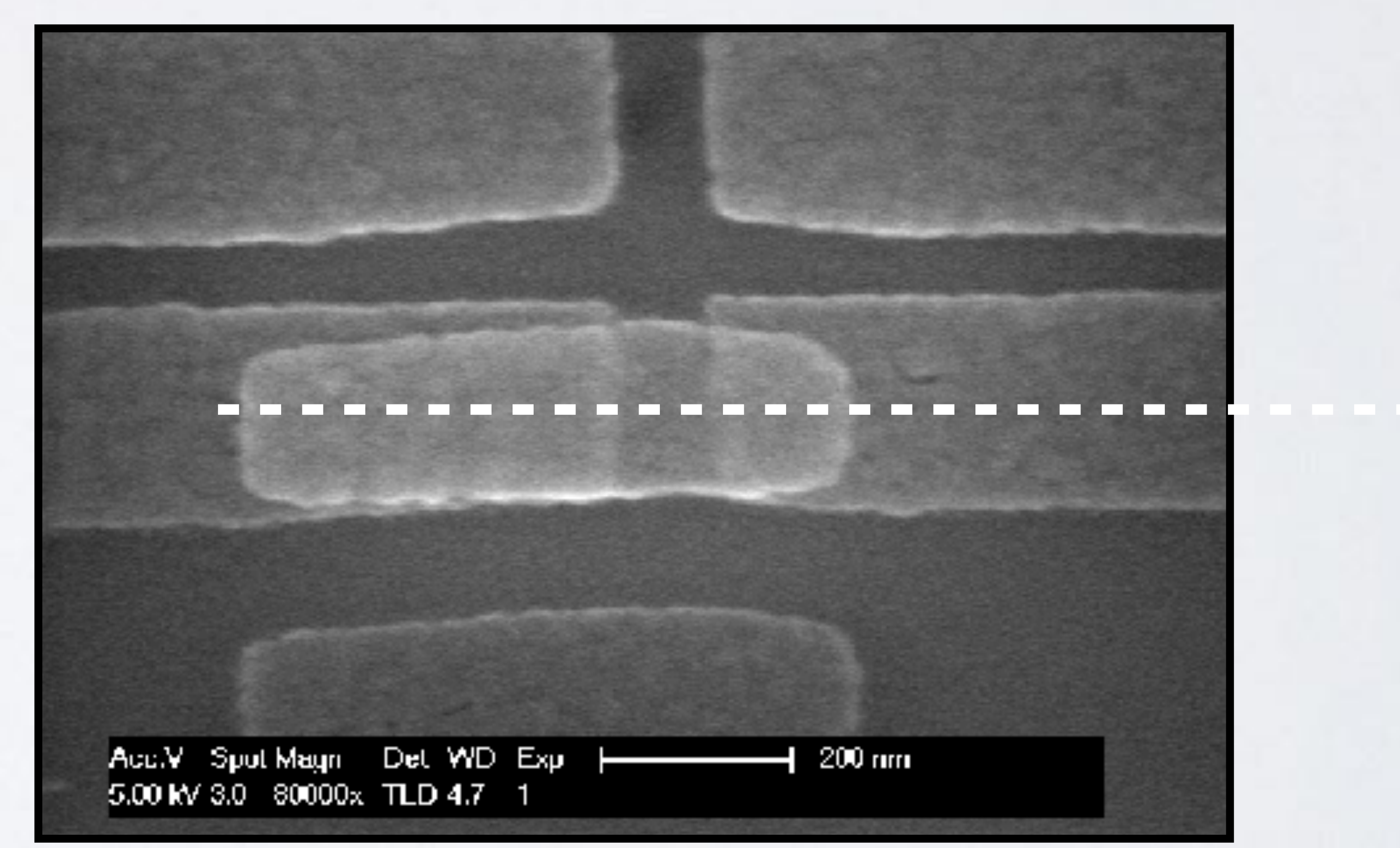
Junction fabrication

Electron beam lithography



Shadow angle evaporation





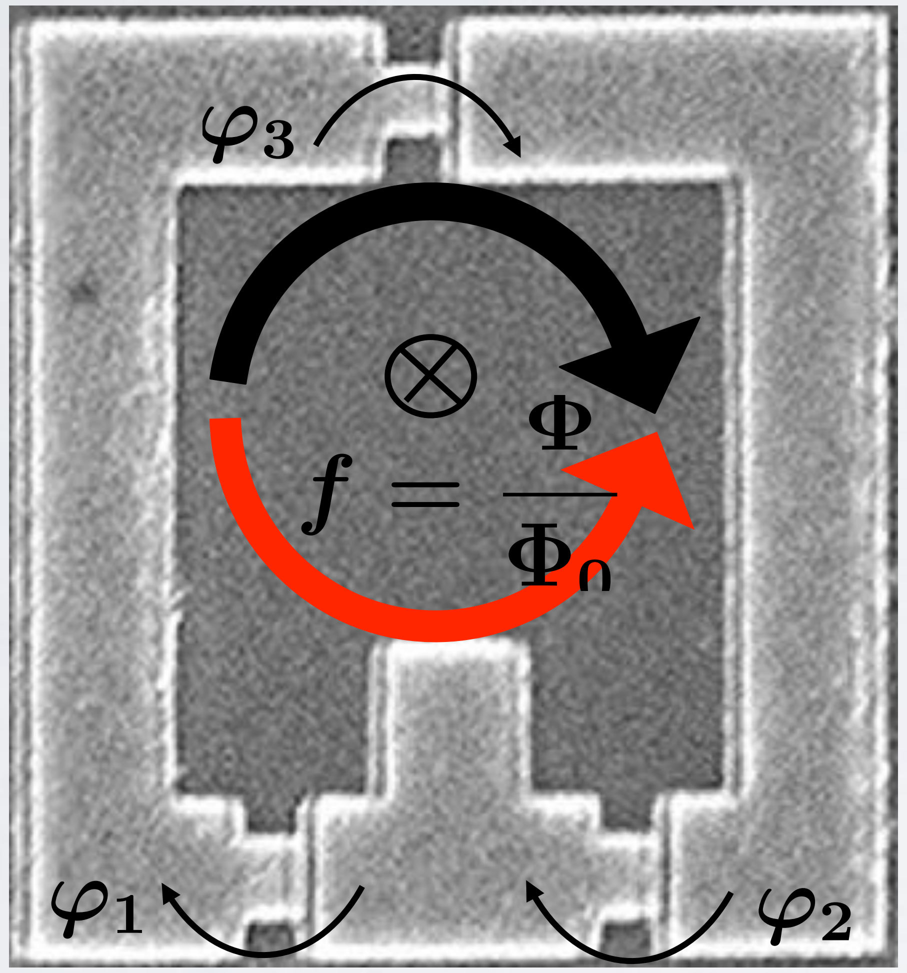
Scanning electron microscope (SEM)

M. Simoen (Chalmers), PhD Thesis 2016

SUPERCONDUCTING QUBITS

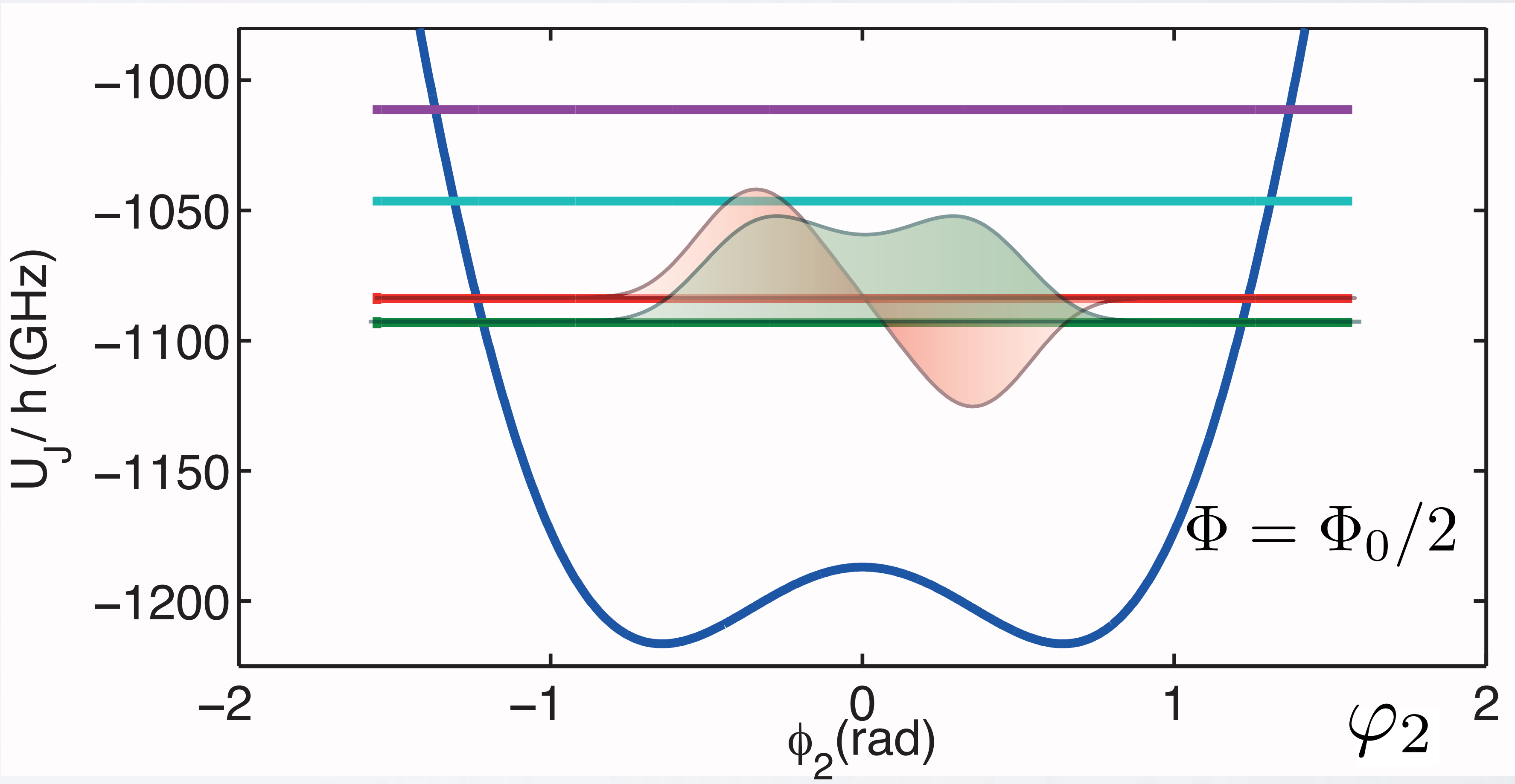
Persistent current qubit

Aluminum loop with 3 Josephson junctions

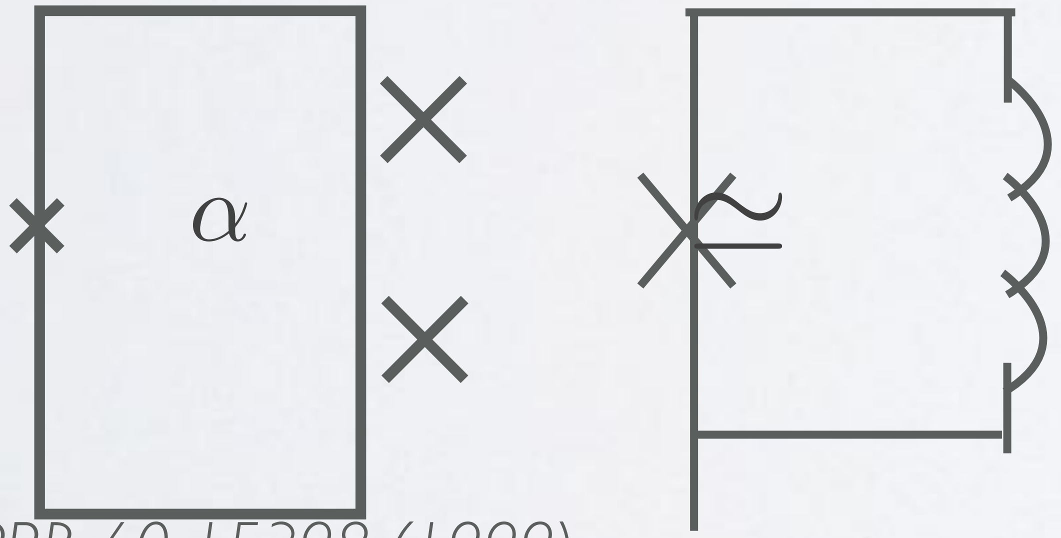


Circuit Hamiltonian:

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



Circuit diagram:



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

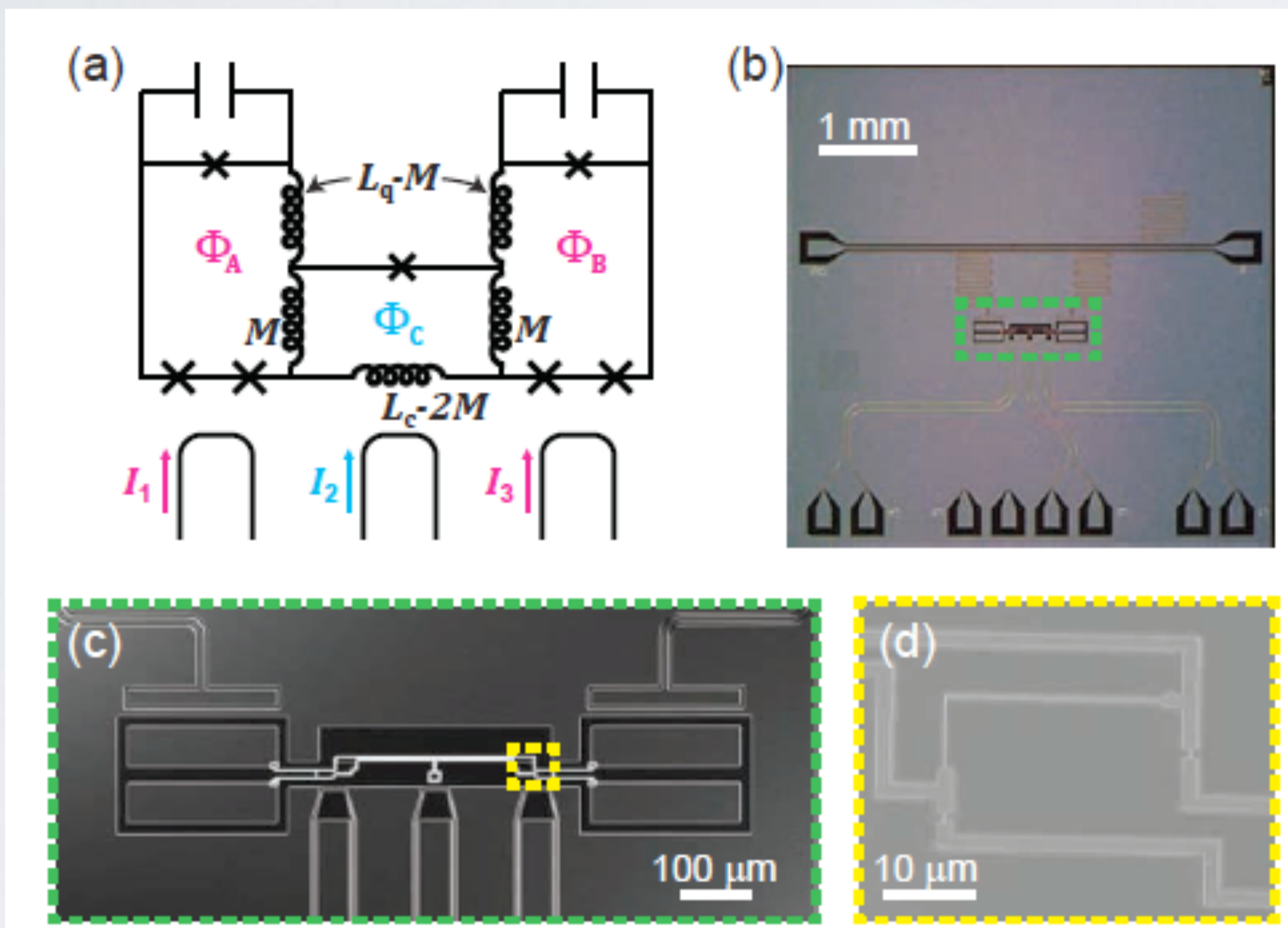
T. P. Orlando, et al. PRB 60 15398 (1999)

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

QUBIT STATE CONTROL

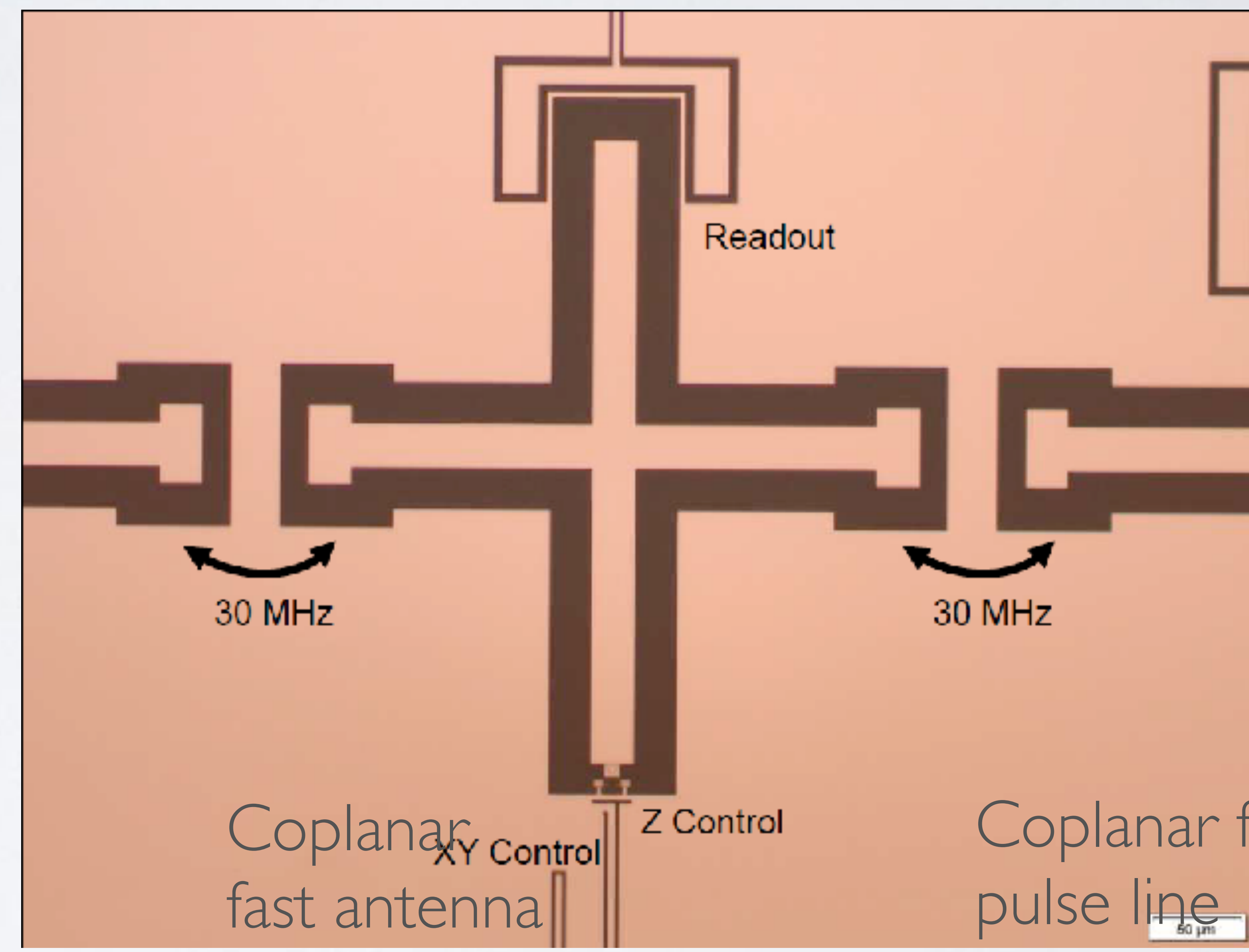
Local control lines

Flux qubit



Coplanar flux bias lines x-y-z control

Transmon qubit



Coplanar fast antenna

Coplanar flux pulse line

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

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

QUBIT STATE CONTROL