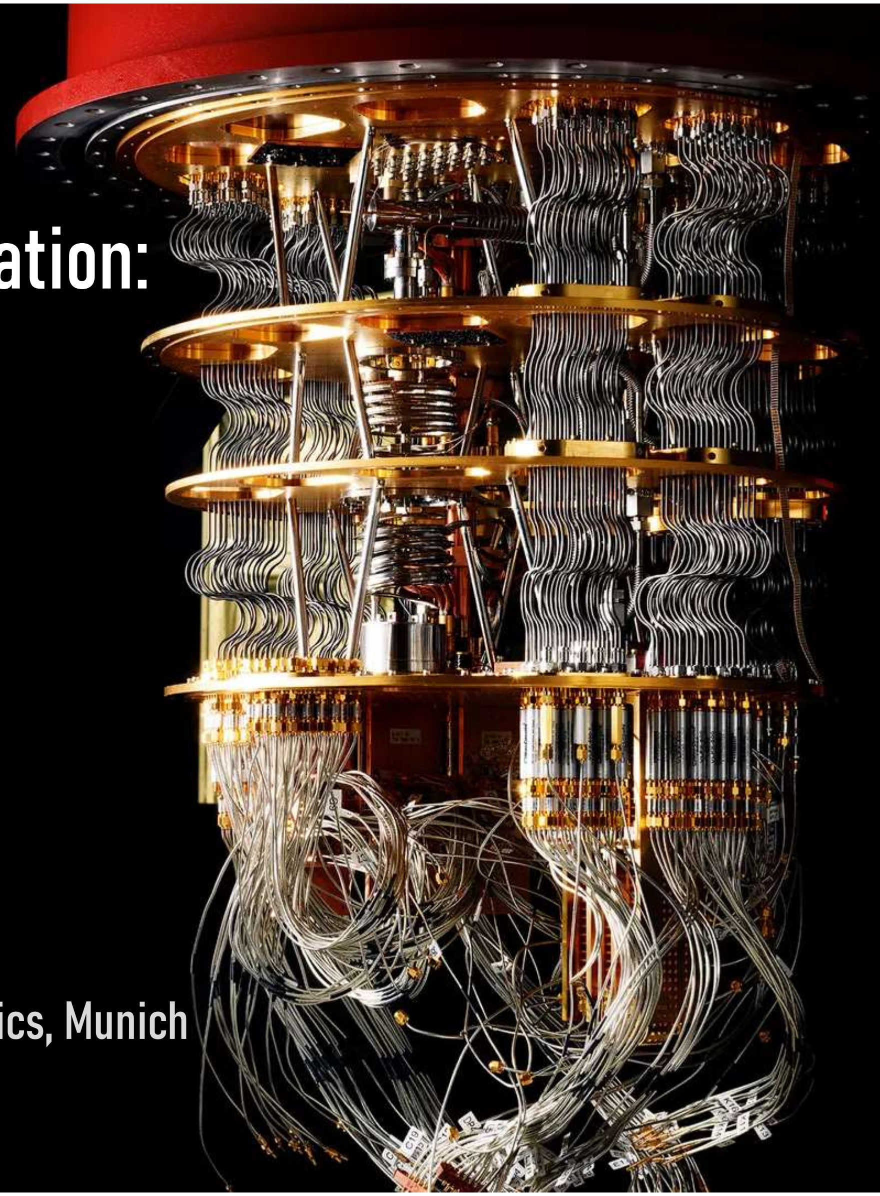
Superconducting qubits and ionizing radiation: open challenges and future opportunities



Institut de Física d'Altes Energies

Elia Bertoldo [ebertoldo@ifae.es]

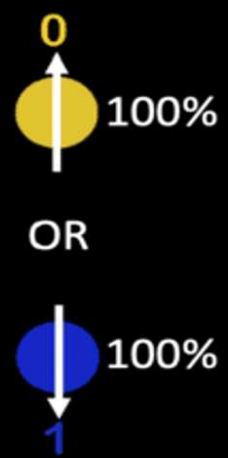
Seminar at Max Planck Institute for Physics, Munich

8th April 2024

Quantum Computing

In 1982, Richard Feynman proposed using **quantum mechanical phenomena to perform calculations** that would be impractical or impossible using classical computers. Quantum computer requires a **full rethinking of the basics of computing.**

Classical Computing - Bit



Quantum Computing - Qubit

What is a qubit?

A qubit is a **two-state quantum mechanical system.**

This means that the are **many practical ways to create a qubit:**

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

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

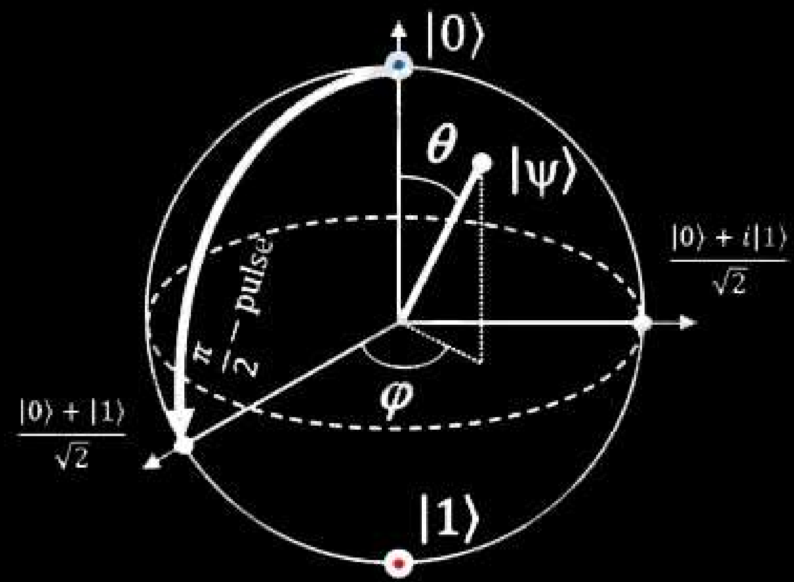
Silicon quantum dots
These "artificial atoms" are made by adding an electron to a small piece of pure silicon. Microwaves control the electron's quantum state.

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

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

Superposition of States

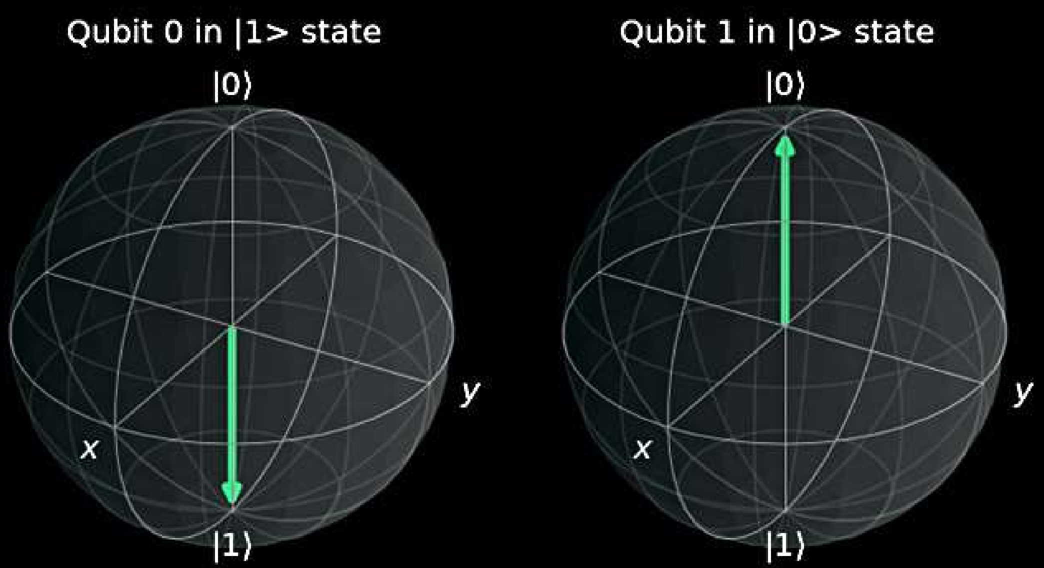
The **qubit** can be described with a **geometrical representation** called **Bloch Sphere**.
The state of this quantum system is the **superposition** of the two basis vectors |0> & |1>.



$$|\psi\rangle = cos\frac{\theta}{2}|0\rangle + e^{i\varphi} sin\frac{\theta}{2}|1\rangle$$

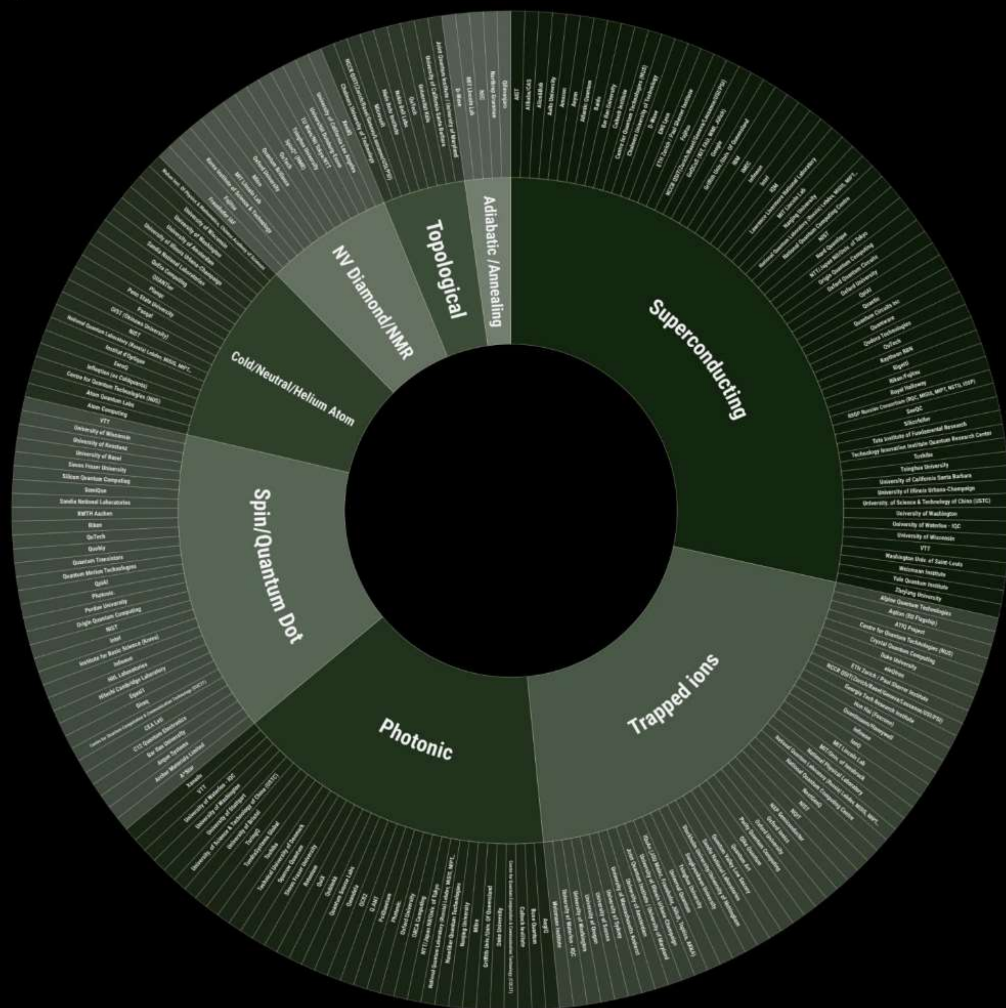
Bloch Sphere

The **classical bits** (0/1) are a **special case in the Bloch Sphere** used for the qubits, conventionally picked as the two poles of the z axis.

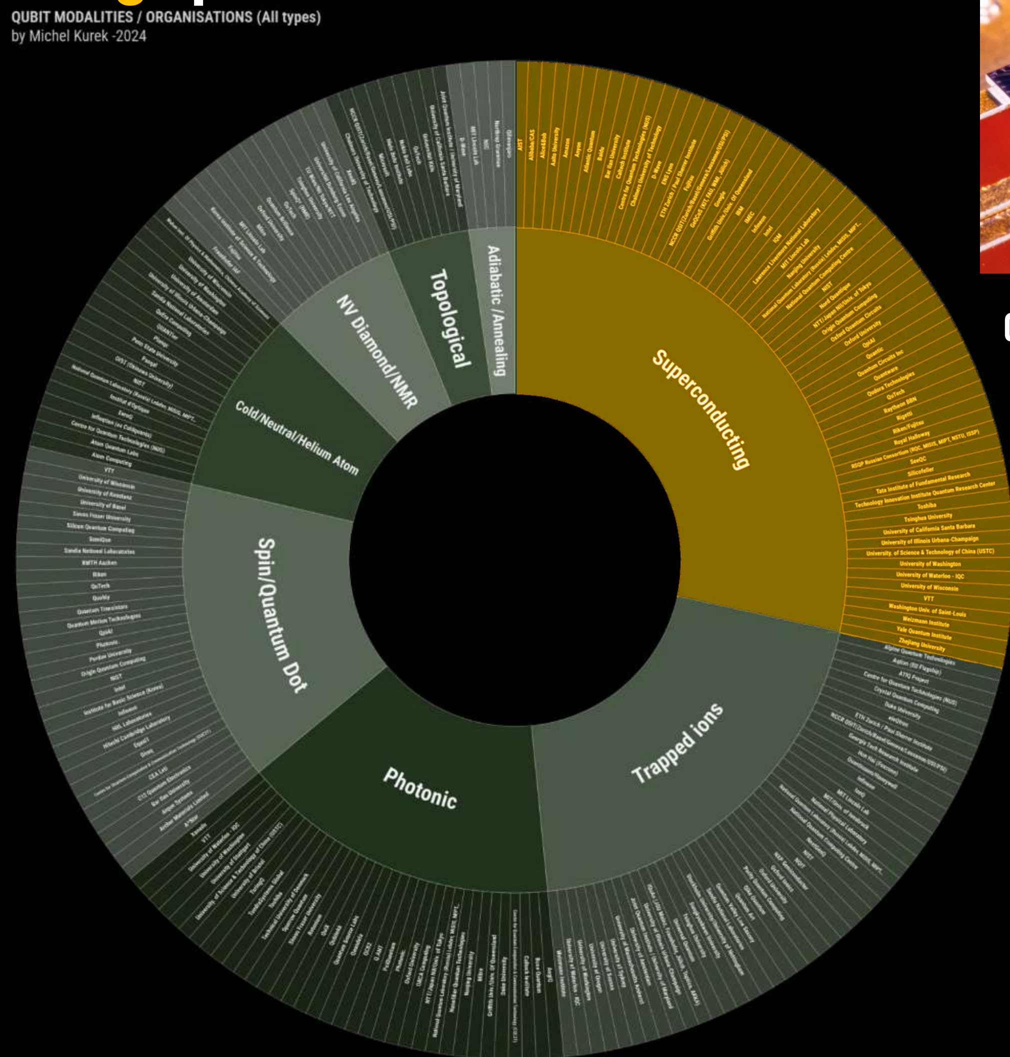


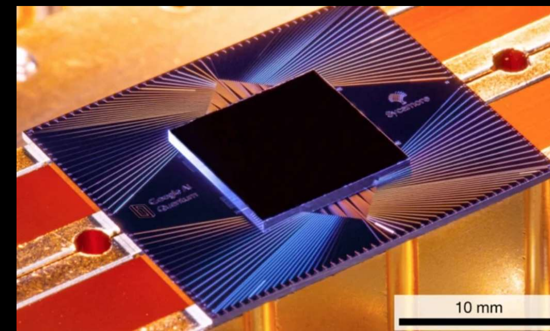
Quantum Hardware

QUBIT MODALITIES / ORGANISATIONS (All types)
by Michel Kurek -2024



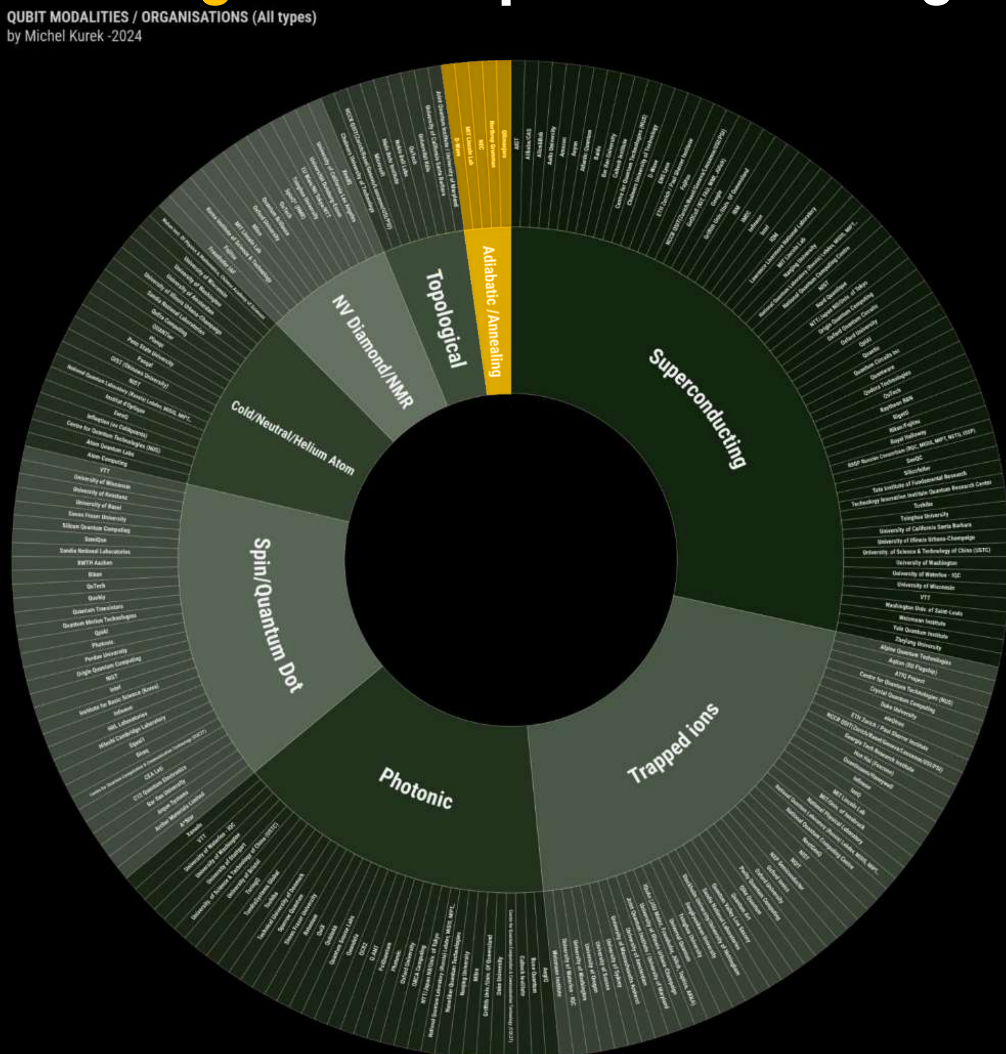
Superconducting qubits

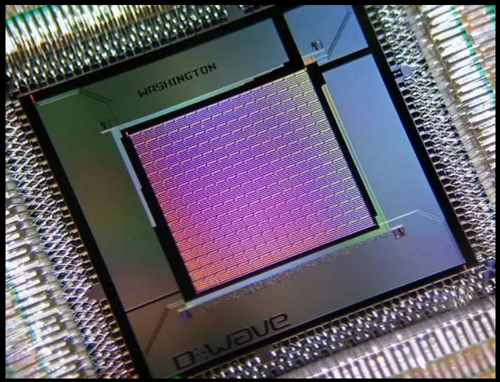




Google Sycamore Processor (**53 Qubits**)
Gate-Based Quantum Computing

Quantum Annealing with Superconducting Qubits

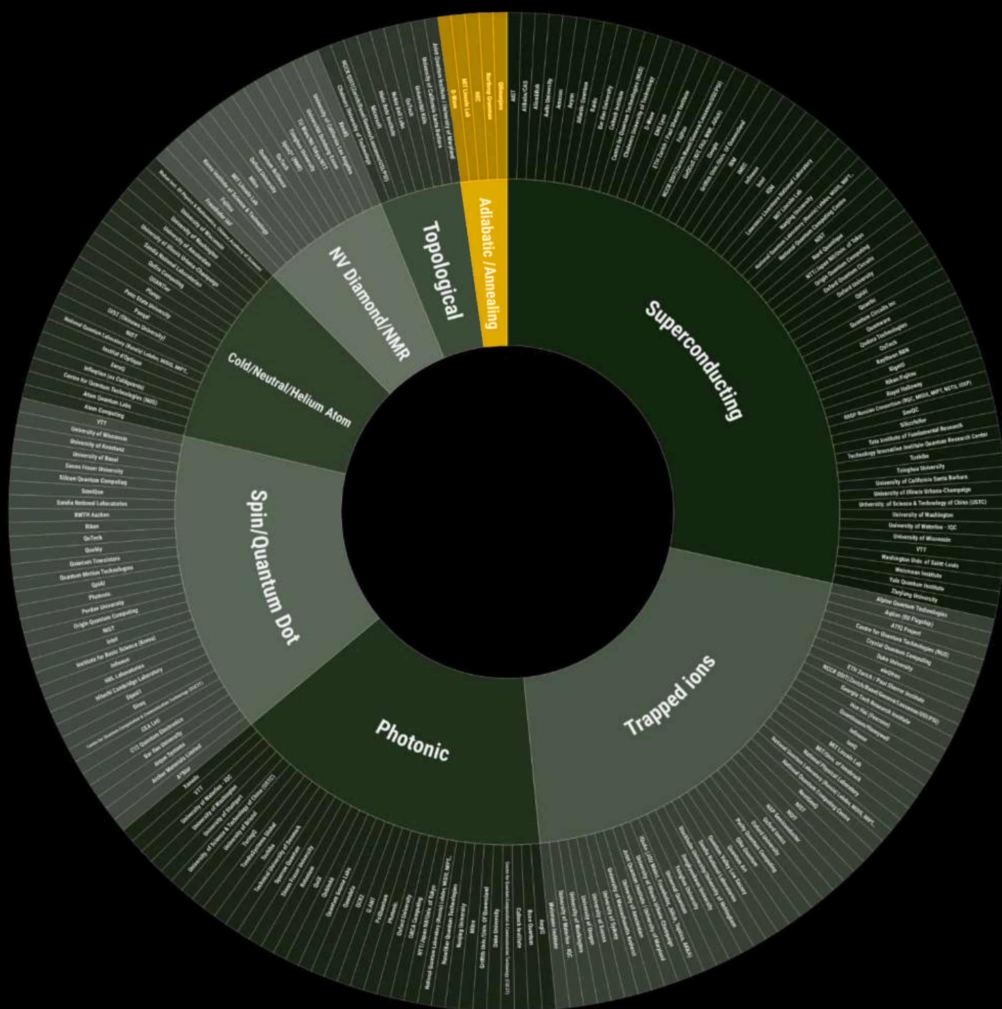




D-Wave Processor (**2048 Qubits**)
Quantum **Annealing**

Quantum Annealing with Superconducting Qubits

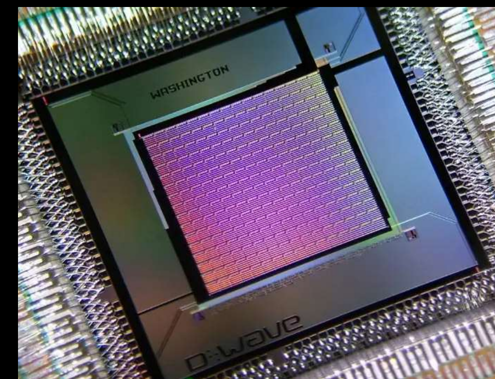
QUBIT MODALITIES / ORGANISATIONS (All types)
by Michel Kurek -2024



AVaQus

IFAE
Institut de Física
d'Altes Energies

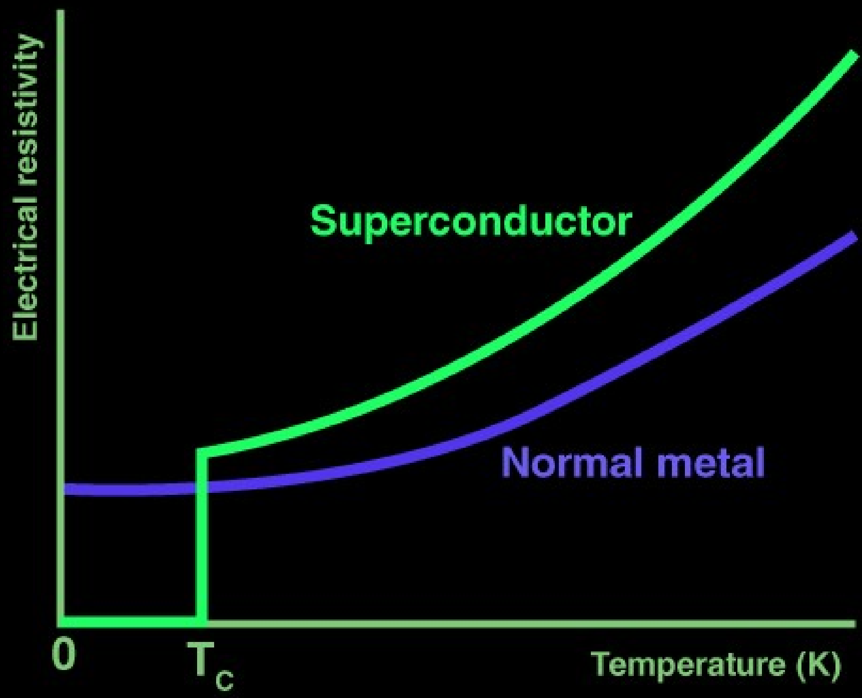
QILIMANJARO
QUANTUM TECH



D-Wave Processor **(2048 Qubits)**
Quantum **Annealing**

Superconducting qubits

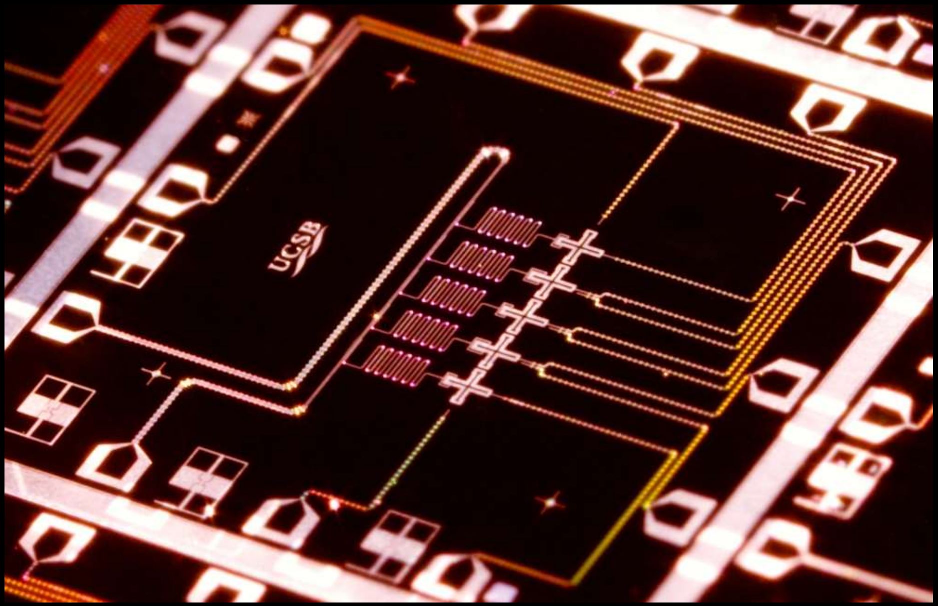
A **superconductor** is a material which cooled below a certain temperature has **no electrical resistance** and **expels magnetic fields**.



Superconducting materials

Typical elements **of superconducting qubits** are **Al**, **Nb**, **Ta**, and **Ti**.

These elements are used to produce **thin films** (~10-100 nm thickness) on **silicon or sapphire wafers**, with similar techniques employed for the fabrication of semiconductor chips.

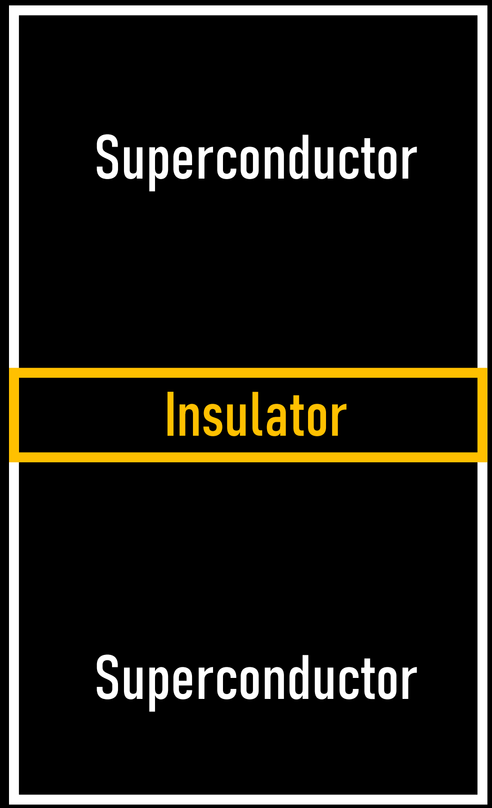


Josephson Junction

The Josephson Junction is a simple yet effective way to force a **relatively macroscopic object to behave like a two level quantum system.**

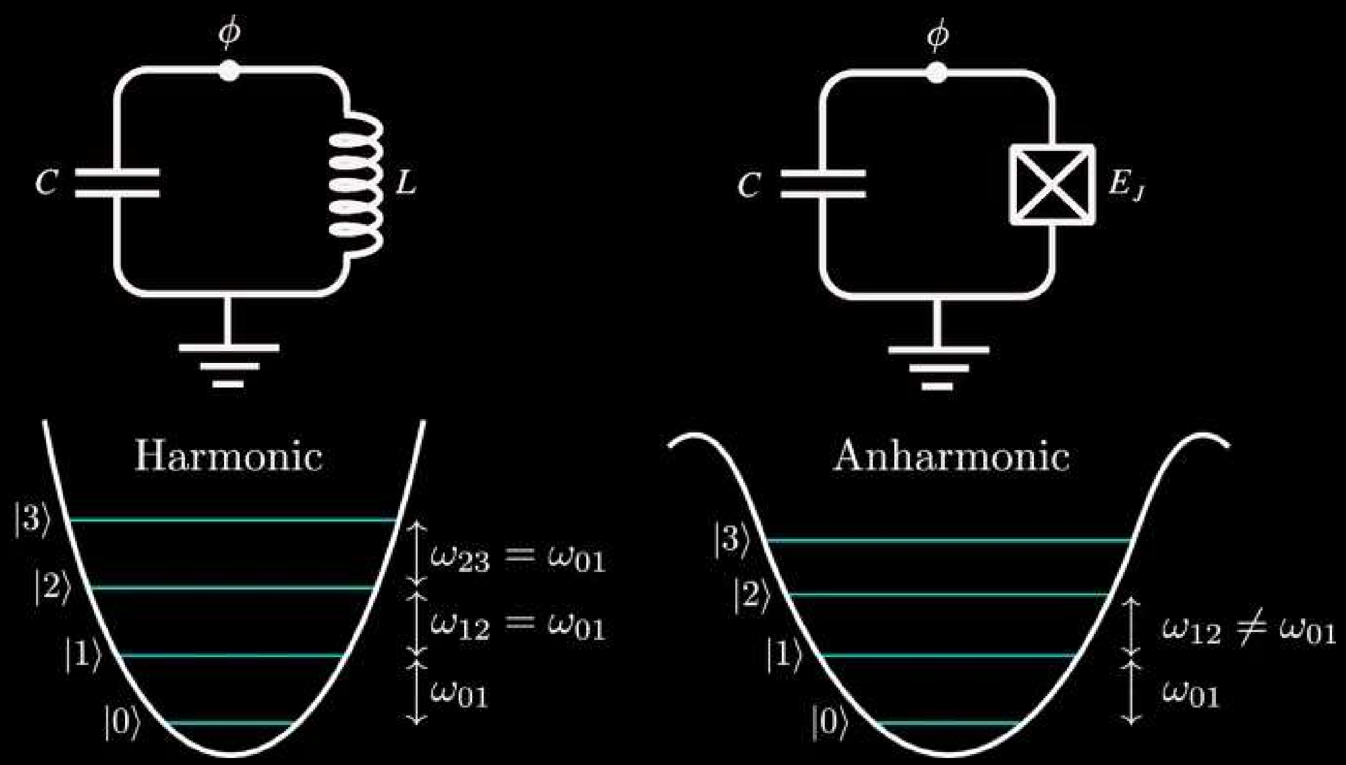
It is simply a sandwich comprised of **two superconducting layers** (usually Al) **with an insulating barrier** (usually AlOx) between them.

It serves a **comparable role as the transistor in classical computers**, being the **fundamental basic element of a superconducting quantum processor**.



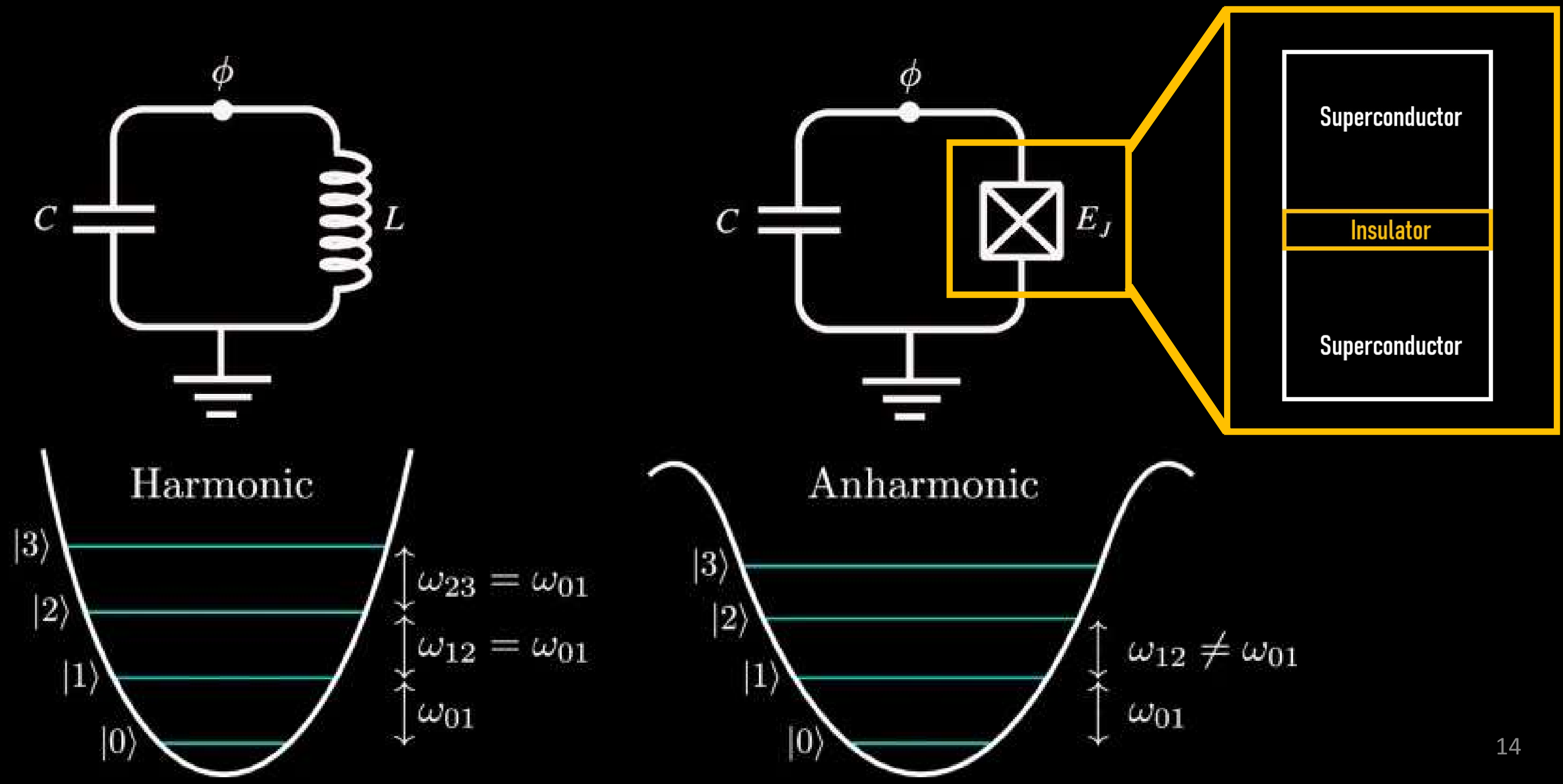
Josephson Junction

The Josephson Junction behaves as a **nonlinear inductor**. The nonlinearity makes possible to **address the qubit separately**, since the energy it takes to excite the system from **|0>** to **|1>** is different from the one required from **|1>** to **|2>**.



Josephson Junction

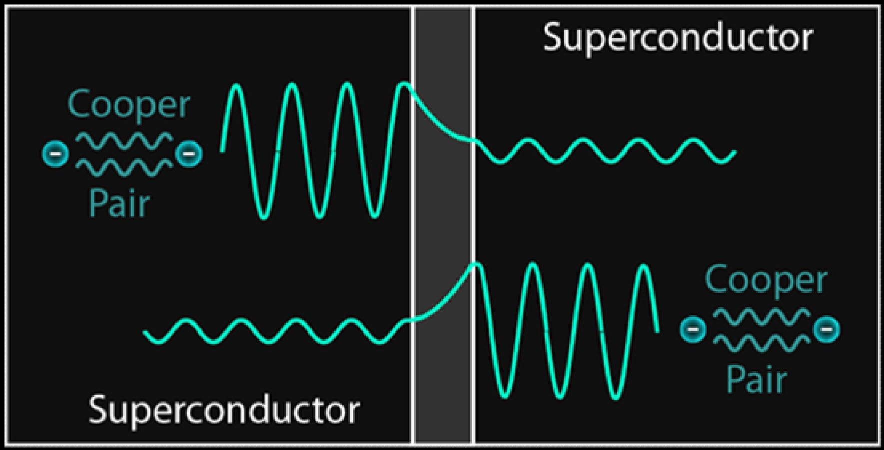
The Josephson Junction behaves as a **nonlinear inductor.** The nonlinearity makes possible to **address the qubit separately,** since the energy it takes to excite the system from **|0>** to |1> is different from the one required from |1> to |2>.



Josephson Effect

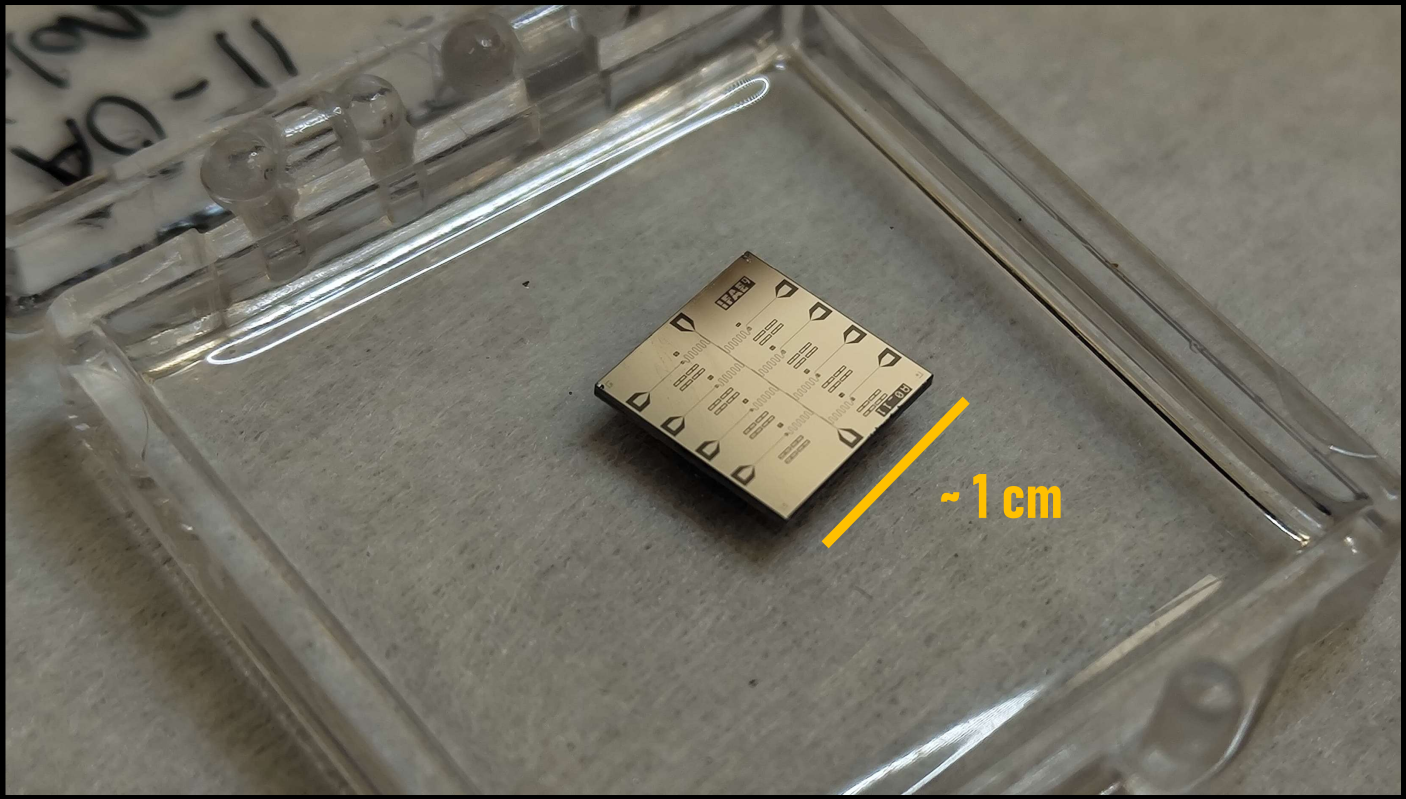
The **Josephson Effect is a macroscopic quantum phenomenon**: a current, known as a supercurrent, flows continuously across the Josephson Junction without any voltage applied.

Microscopically it is enabled by the **tunneling of Cooper pairs** (paired electrons).

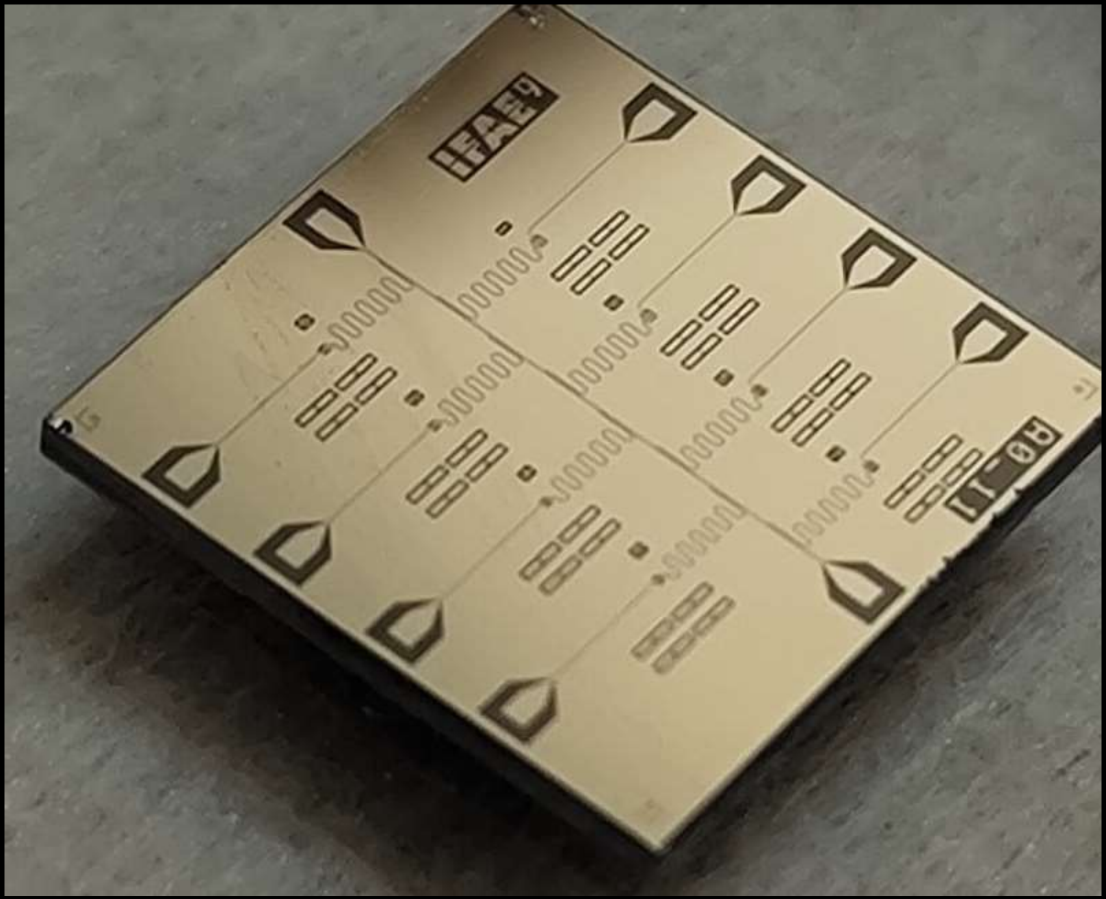


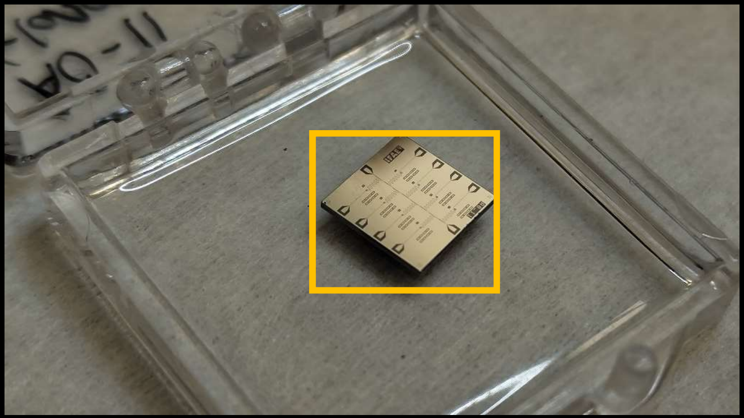
Where is the Josephson Junction?

A journey to understand what *relatively macroscopic object* means.

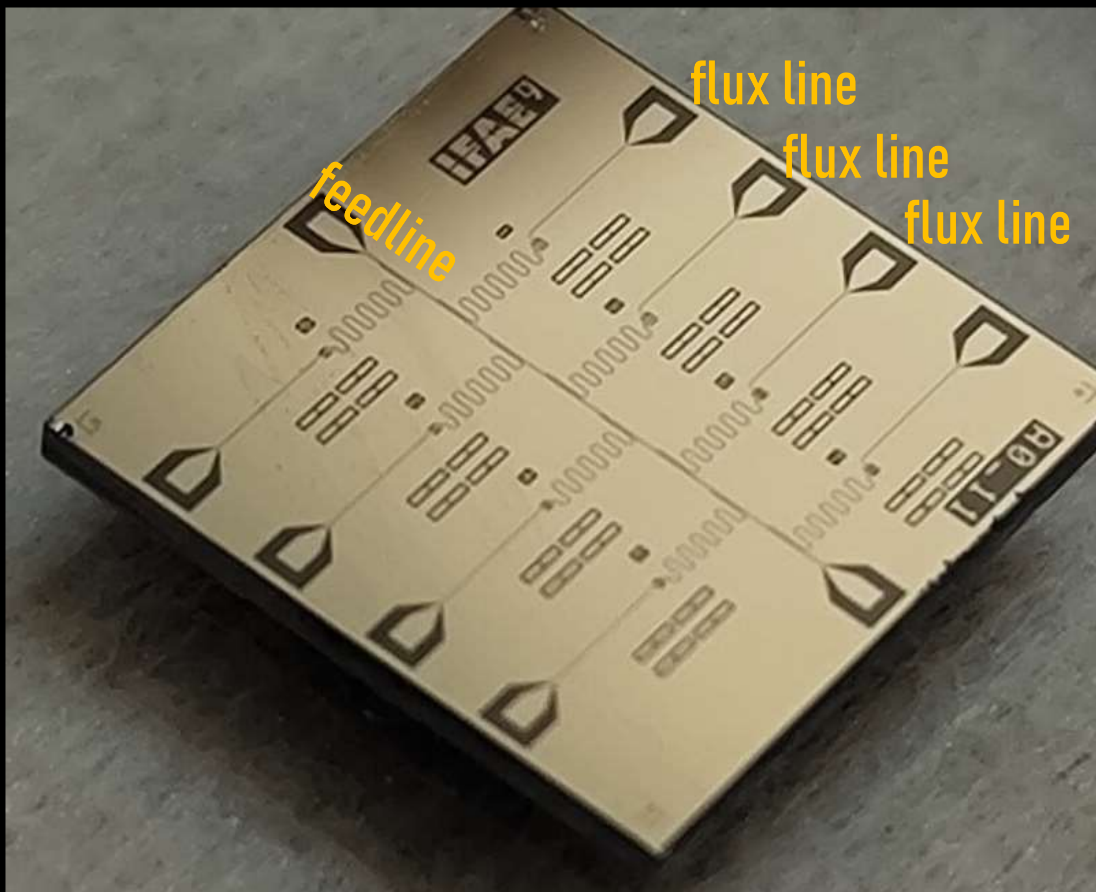


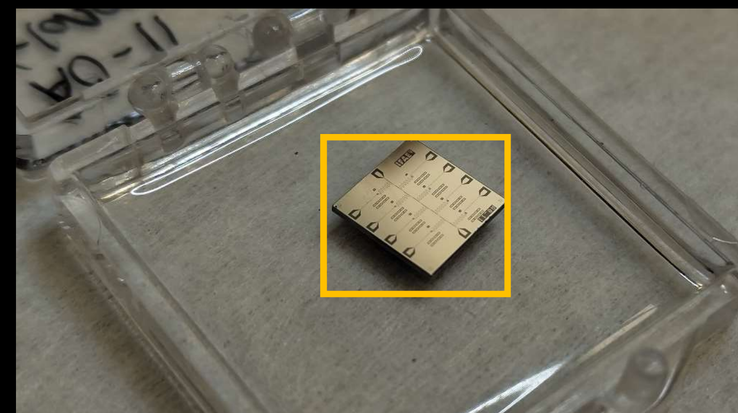
Where is the Josephson Junction?





Where is the Josephson Junction?

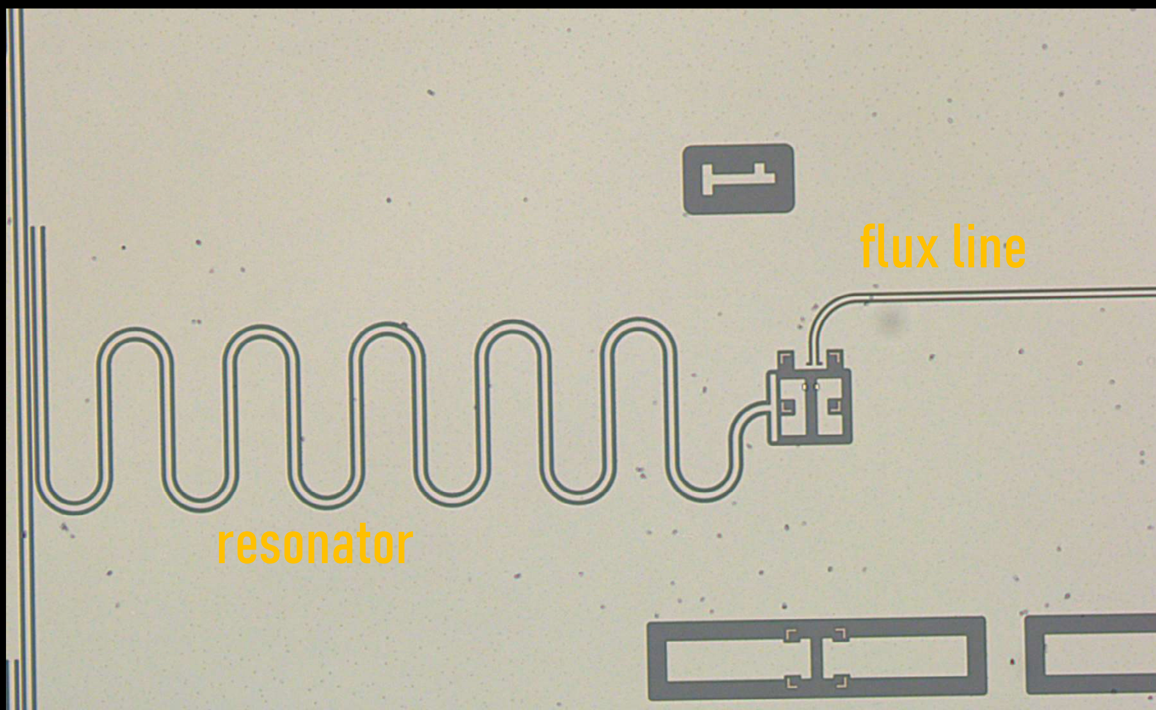


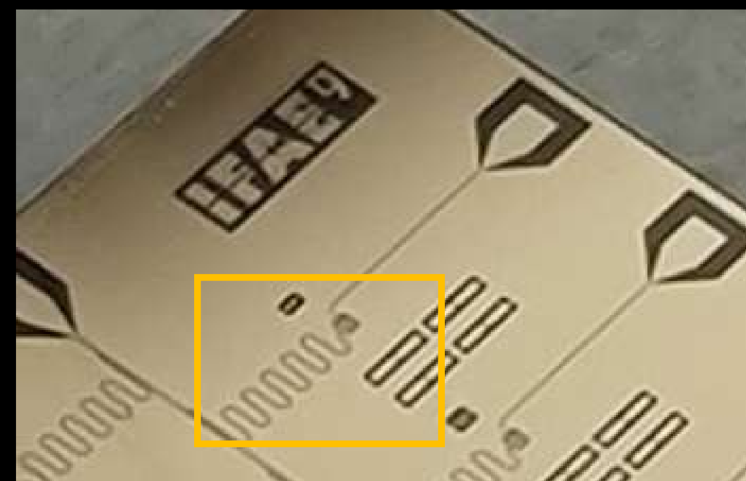


Where is the Josephson Junction?

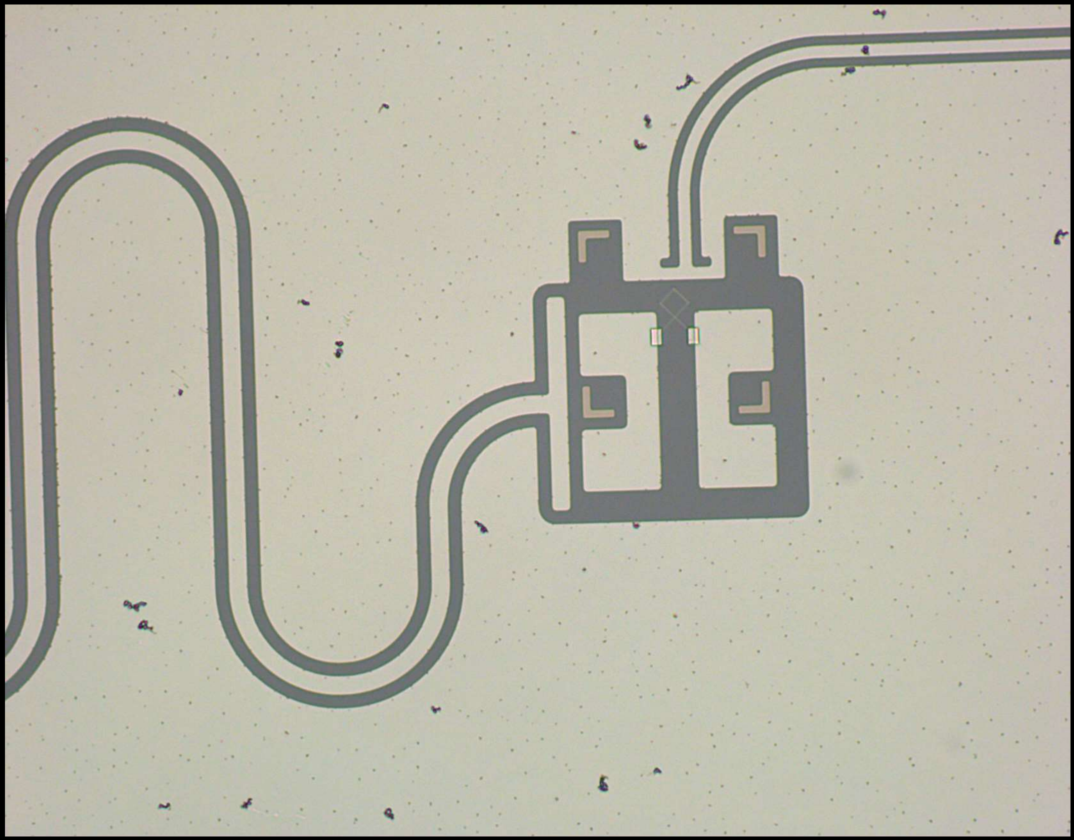
Where is the Josephson Junction?

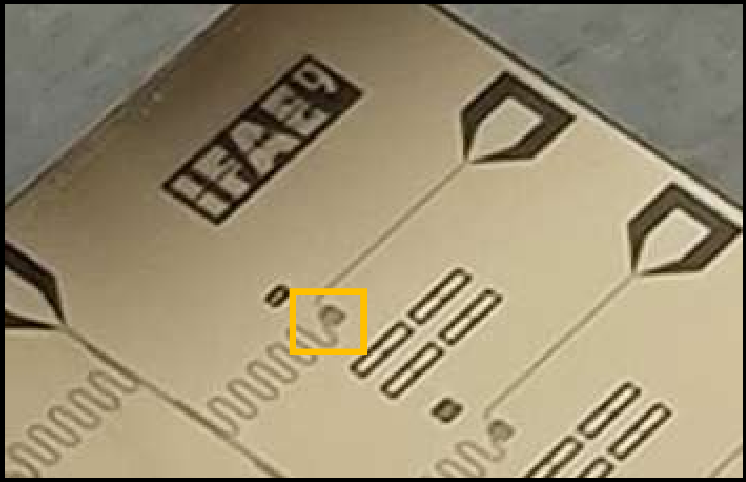
feedline

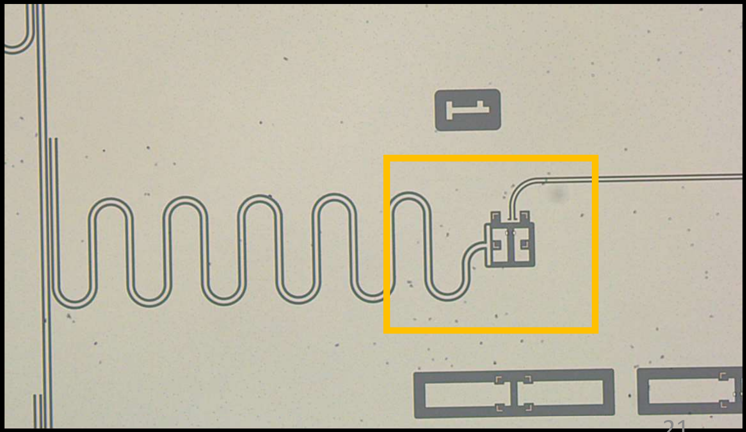




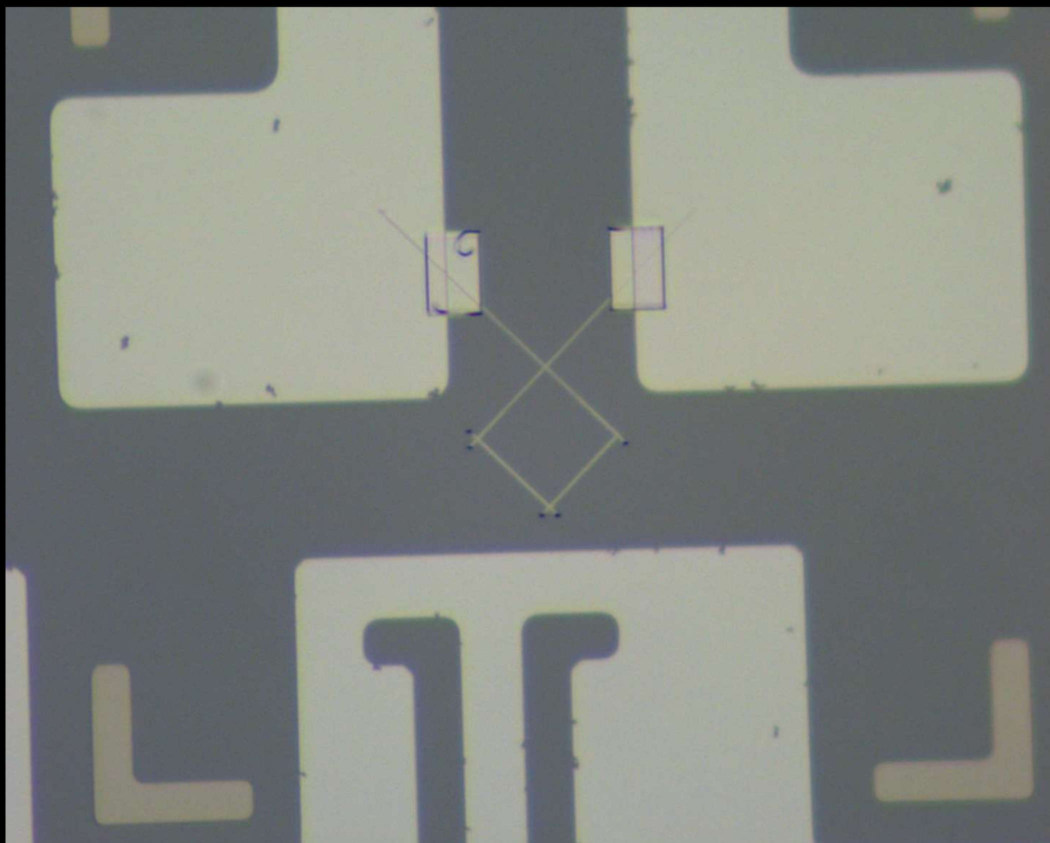
Where is the Josephson Junction?

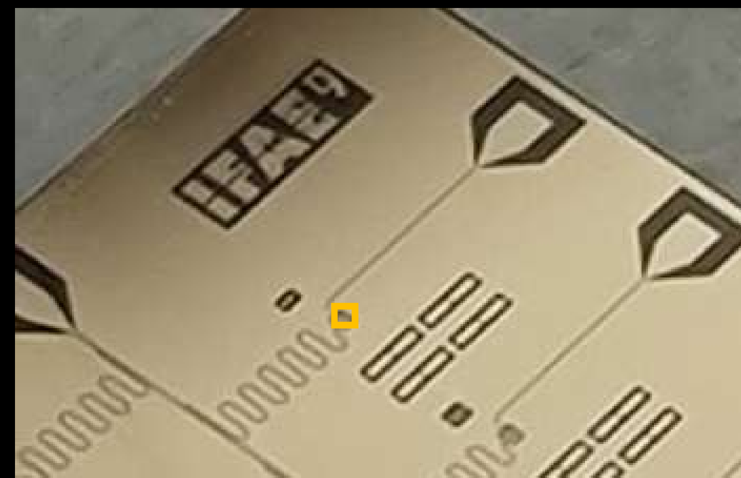


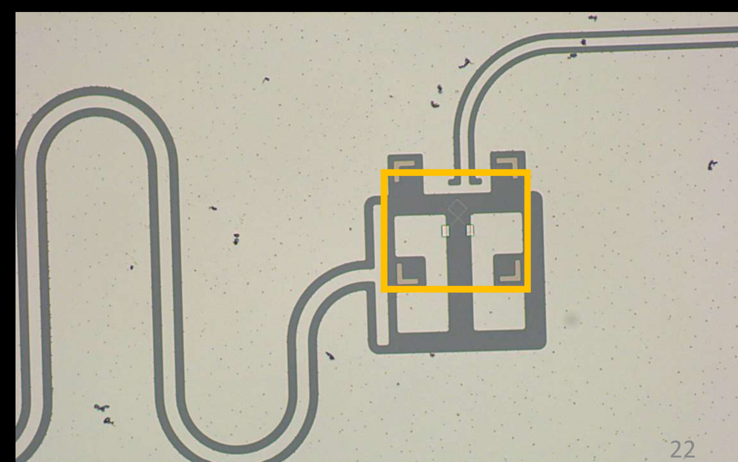




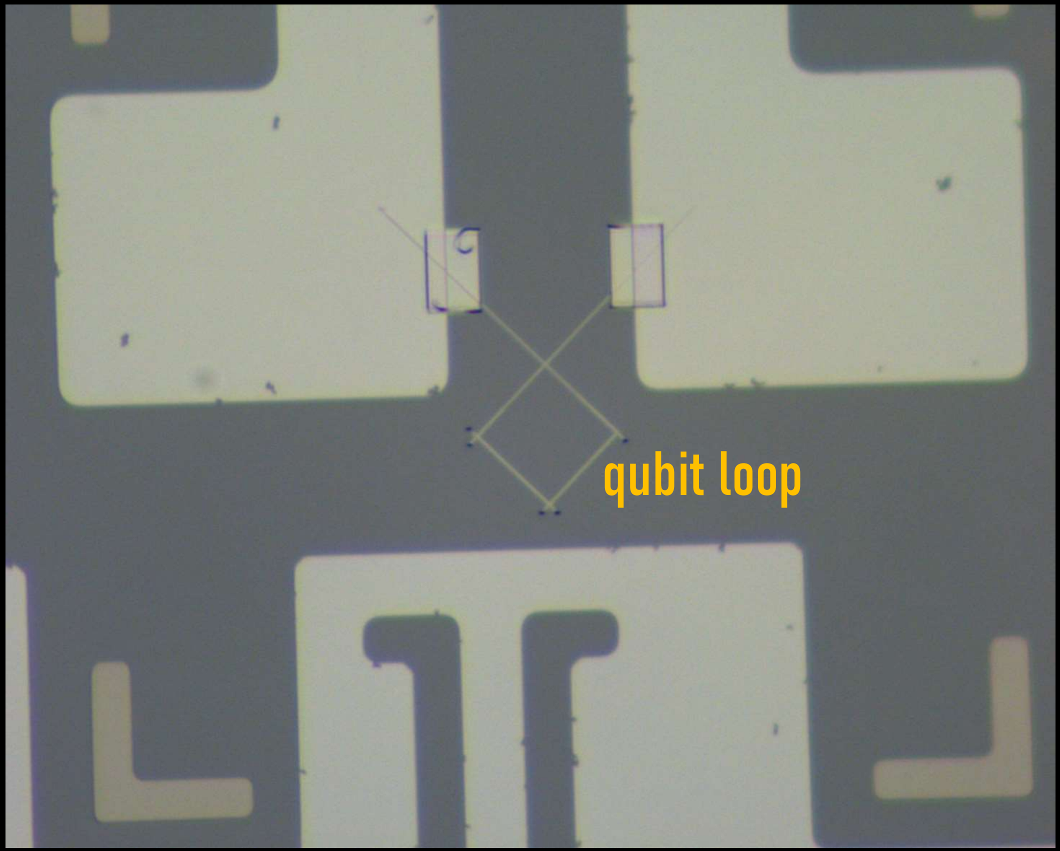
Where is the Josephson Junction?

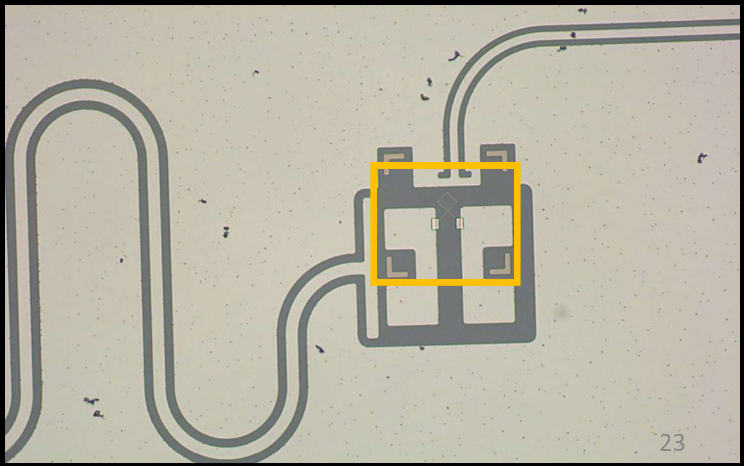




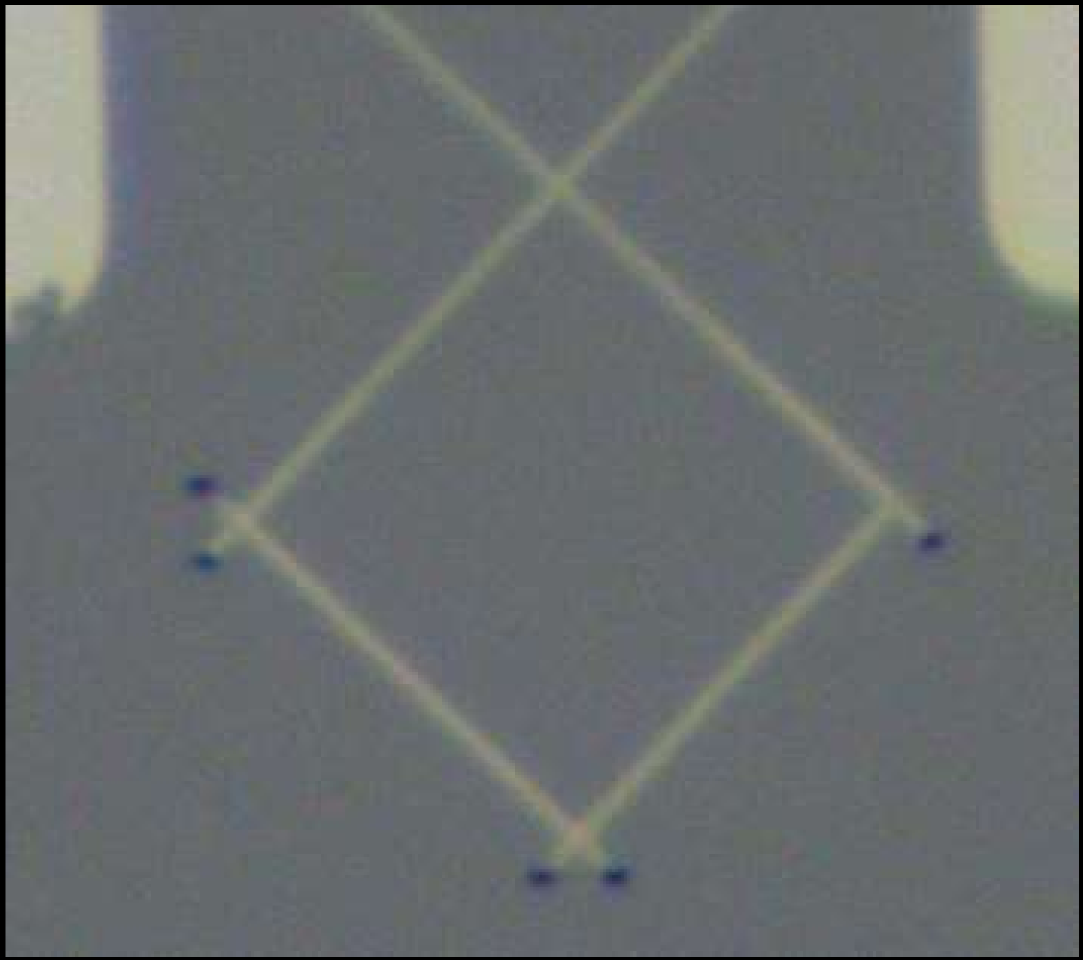


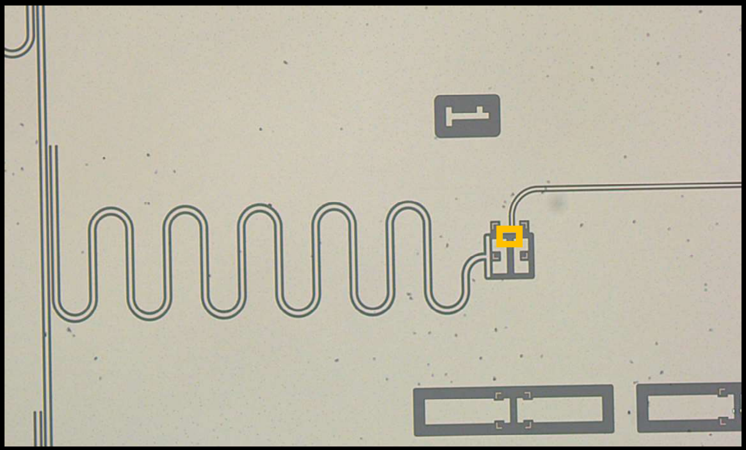
Where is the Josephson Junction?

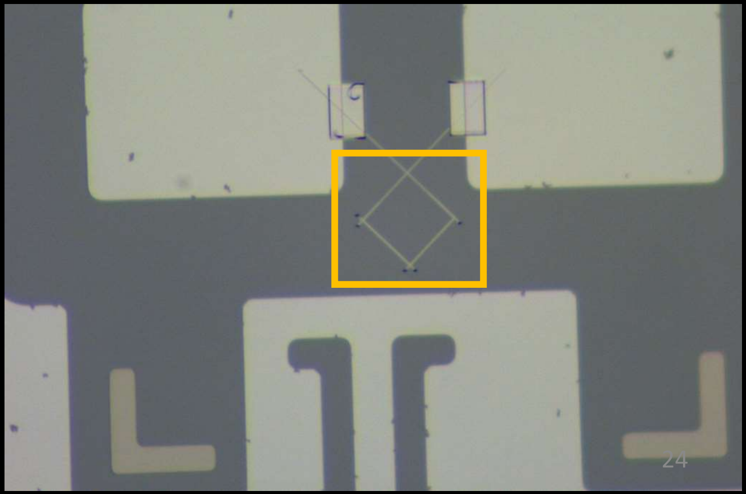




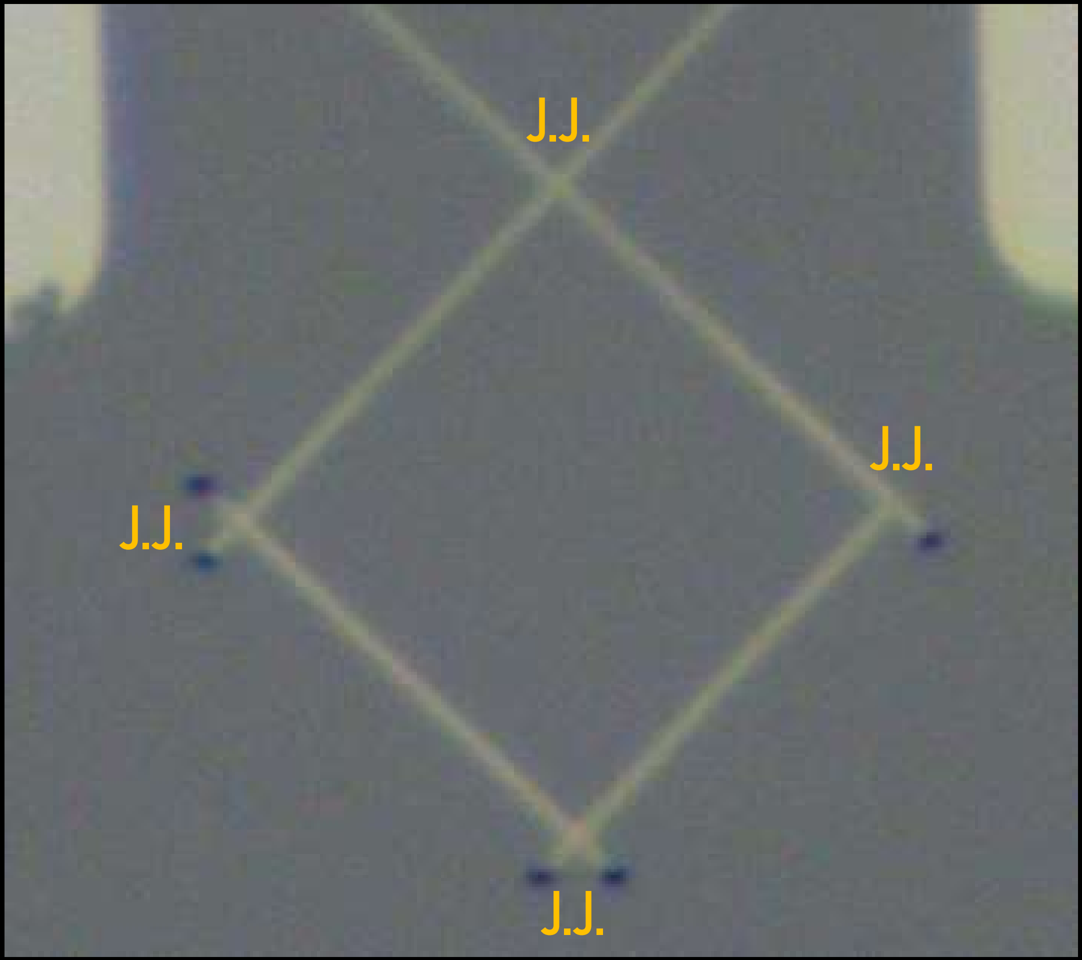
Where is the Josephson Junction?

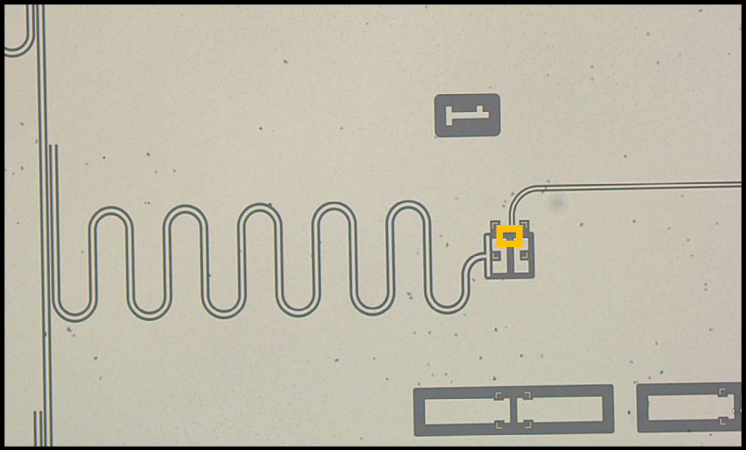


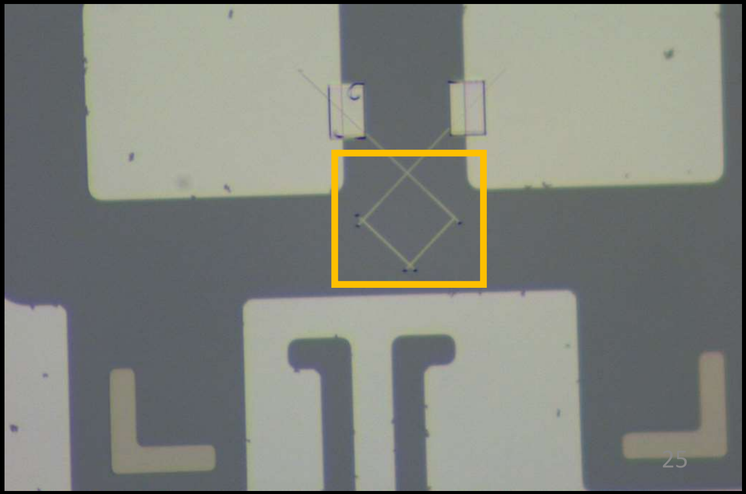




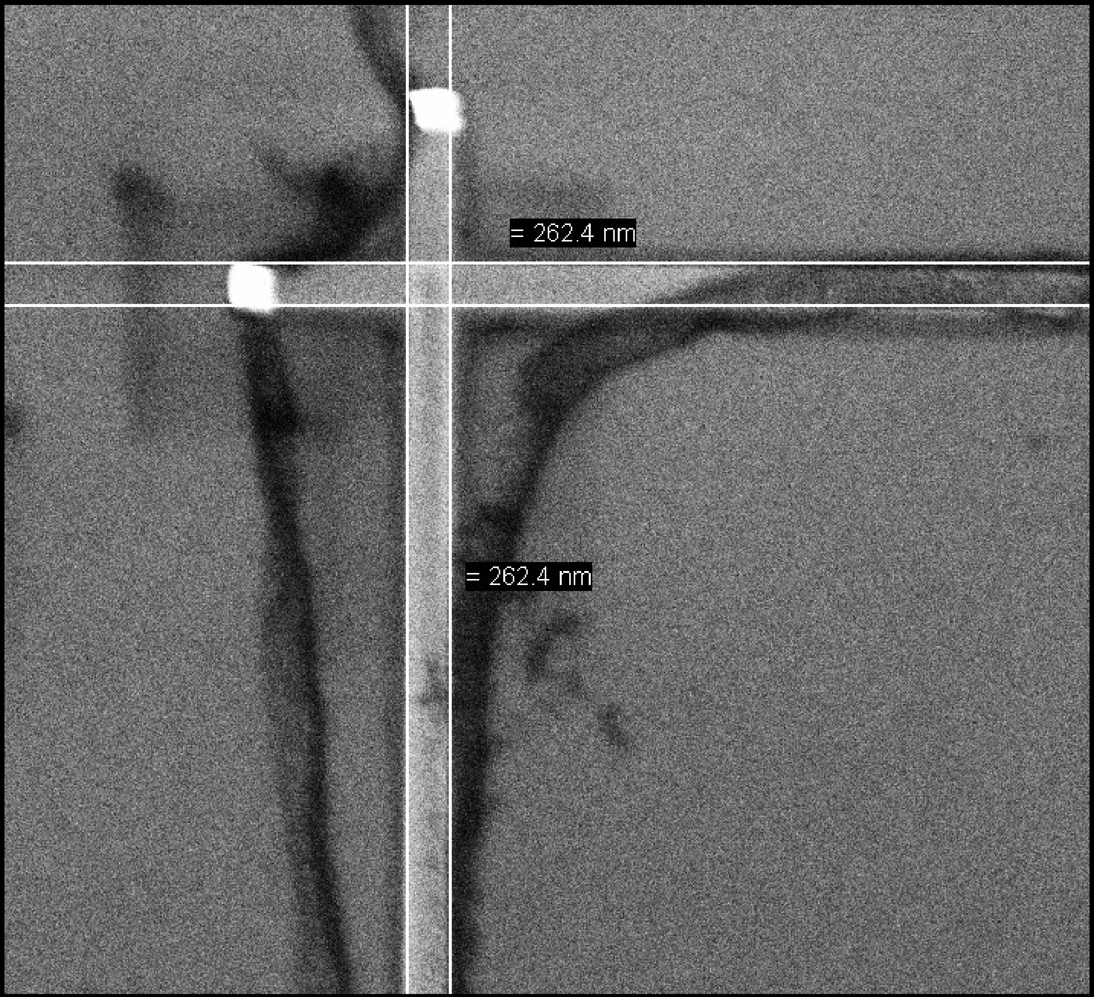
Where is the Josephson Junction?

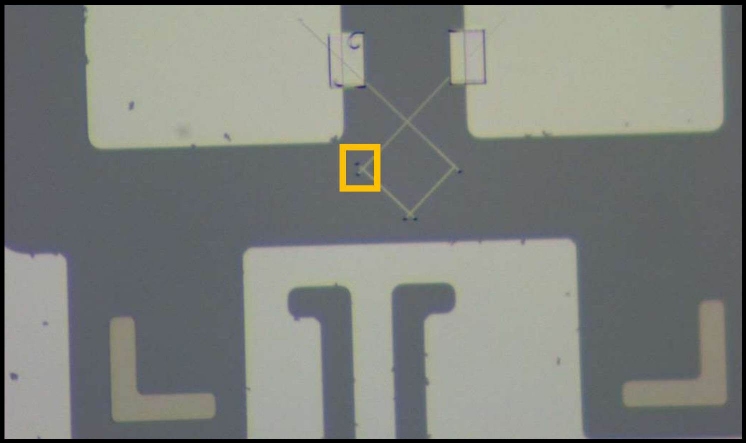


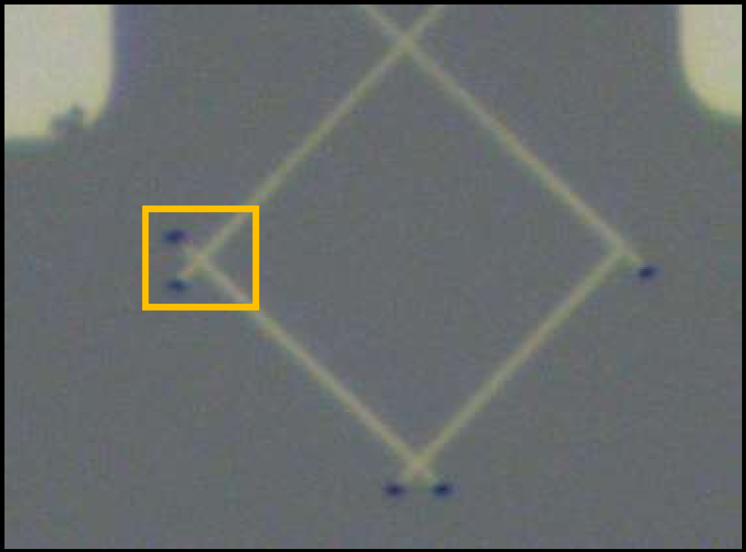




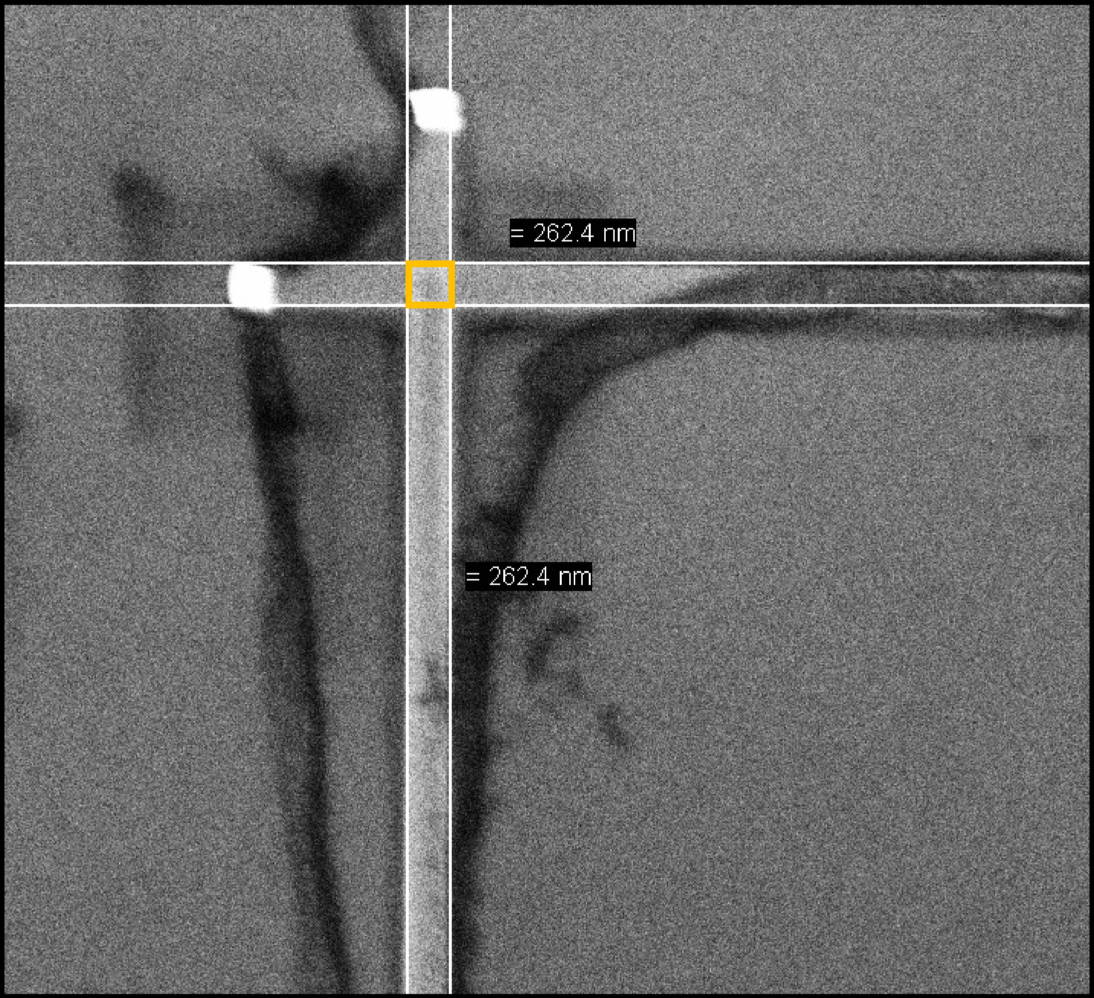
Where is the Josephson Junction?

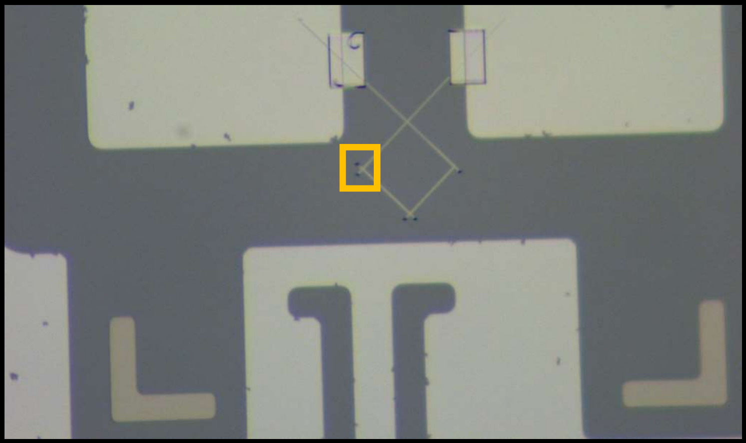


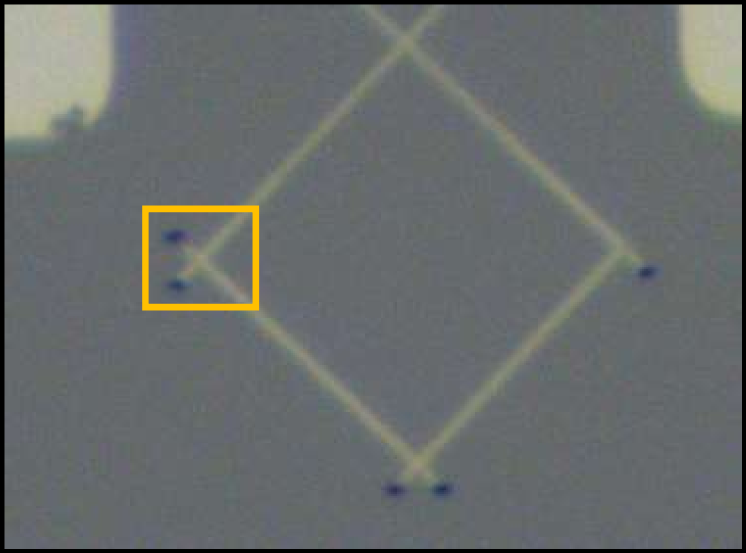




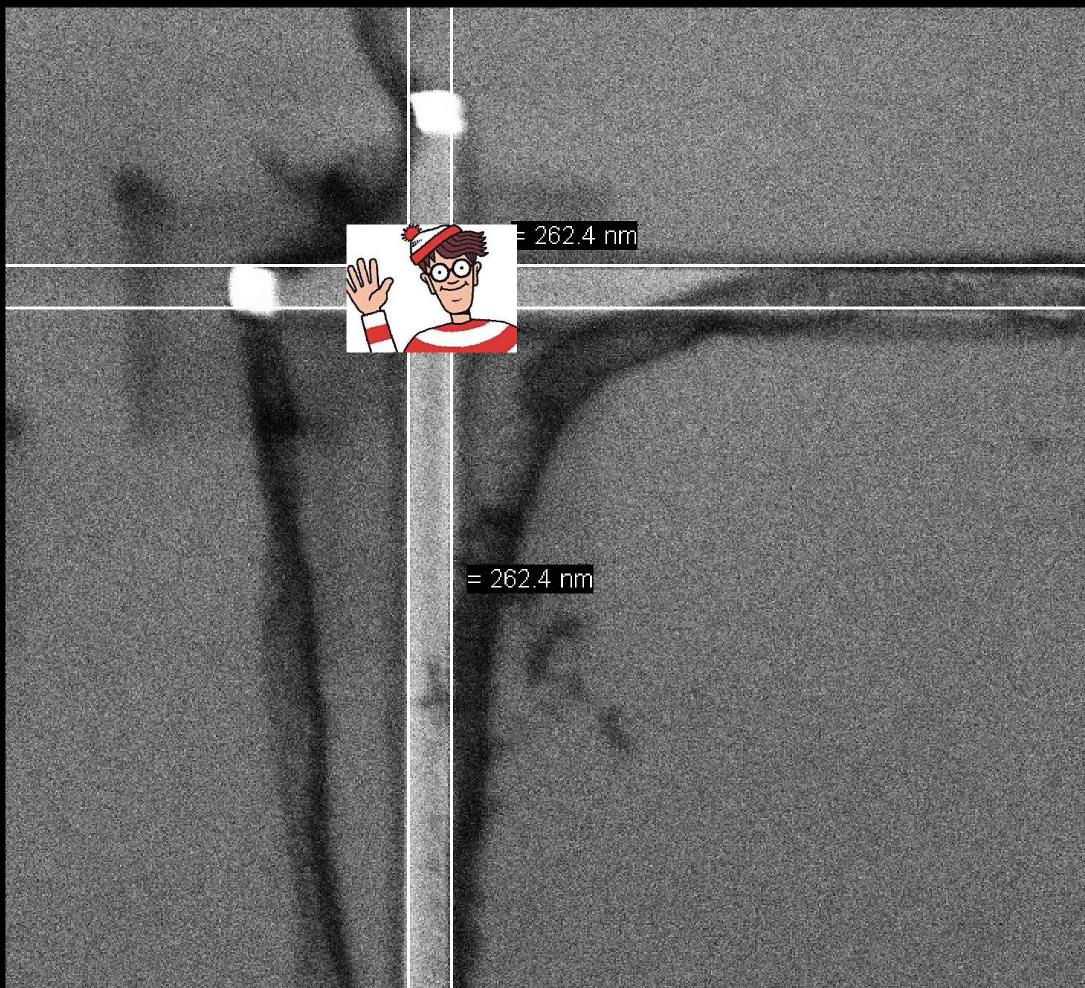
Where is the Josephson Junction?

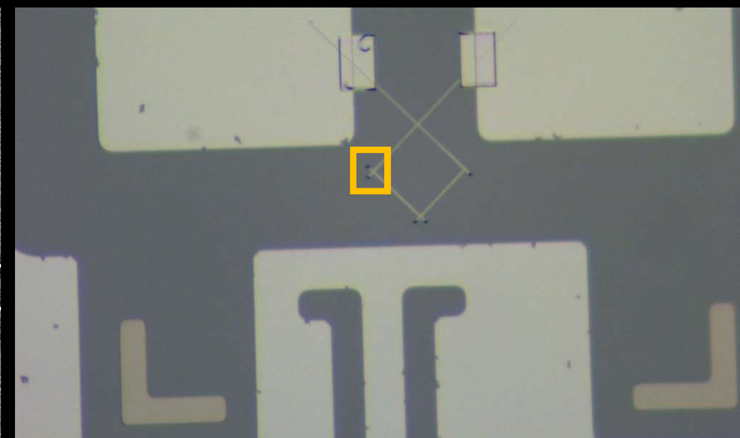


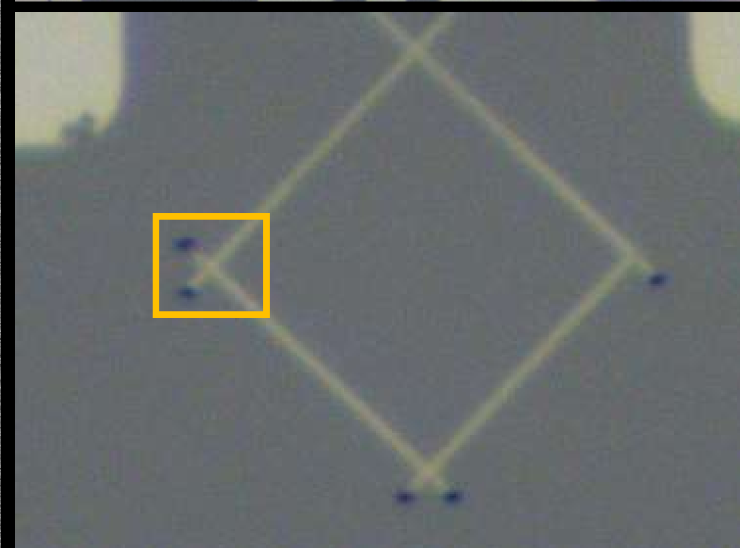




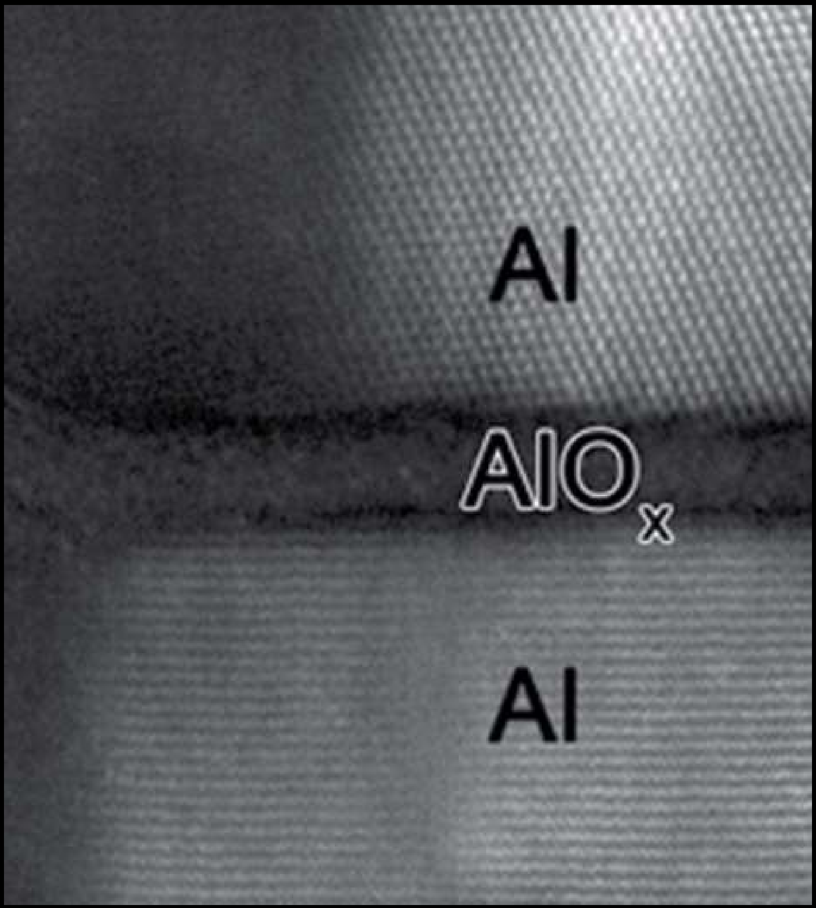
Where is the Josephson Junction?

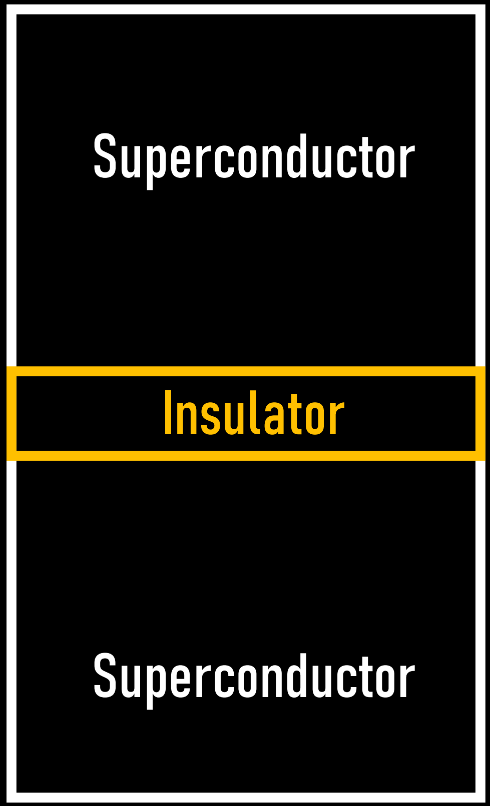






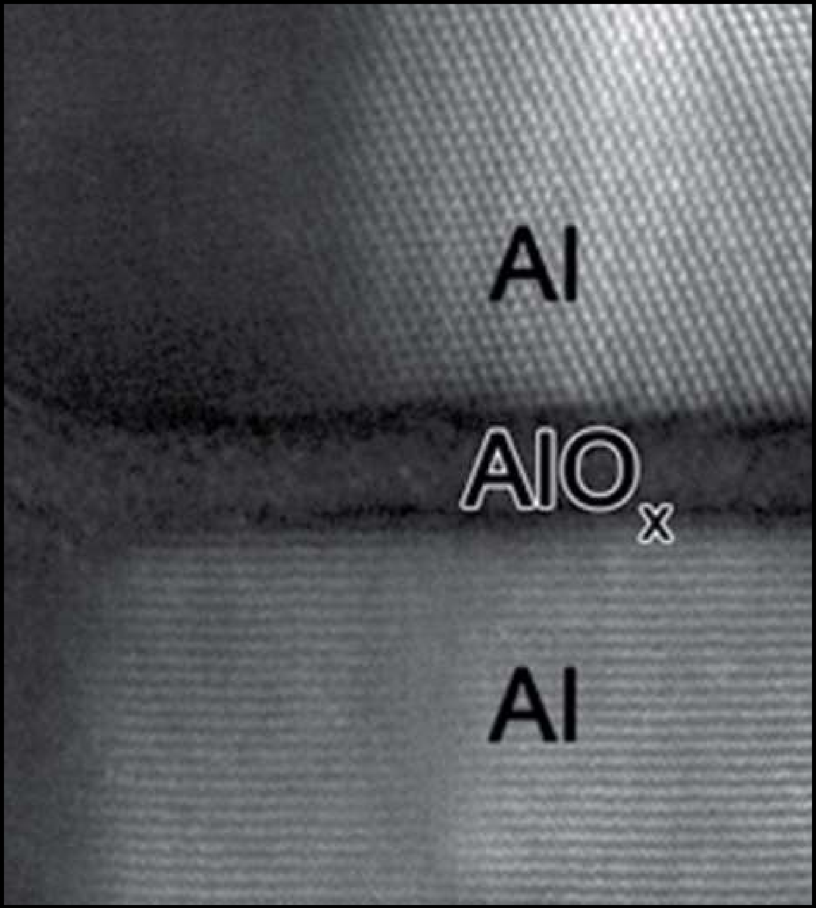
Tridimensionality of the Josephson Junction





- arXiv:1407.0173v1

Tridimensionality of the Josephson Junction



~ 10 nm

› arXiv:1407.0173v1

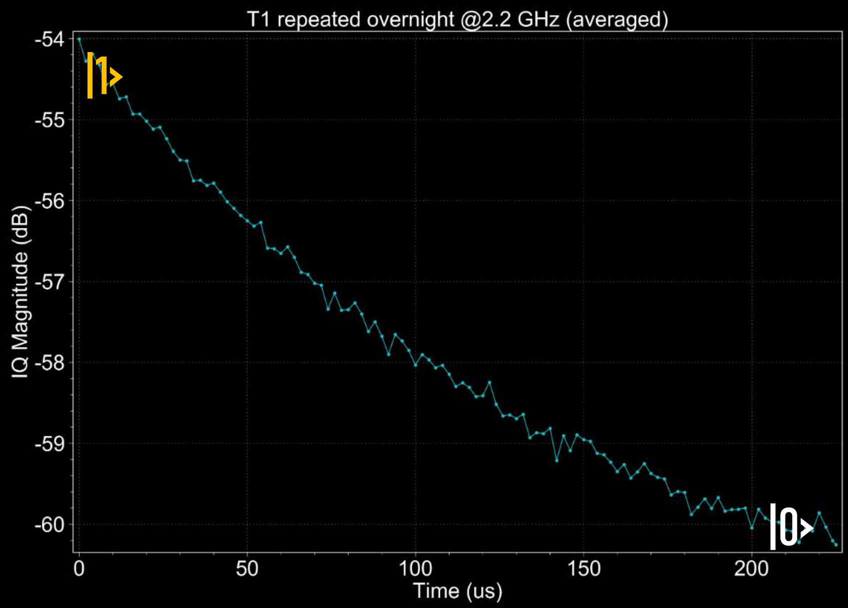
As a comparison, the **Al atom** has an atomic radius of 0.143 nm.
~10 nm is ~30 atoms.

The smoothness of the Al-AlOx interfaces, the precision of the dimensions of the oxide layer and its homogeneity are some of the strongest limitations of superconducting qubits, which means that **our fabrication techniques have to manipulate materials close to the atomic scale.**

Quantum Decoherence

Usually a **classical bit** that is in the state **0** or **1**, **maintains its state.**
This is **not true for a qubit.**

Quantum decoherence can be understood as the **loss of information to the environment.**

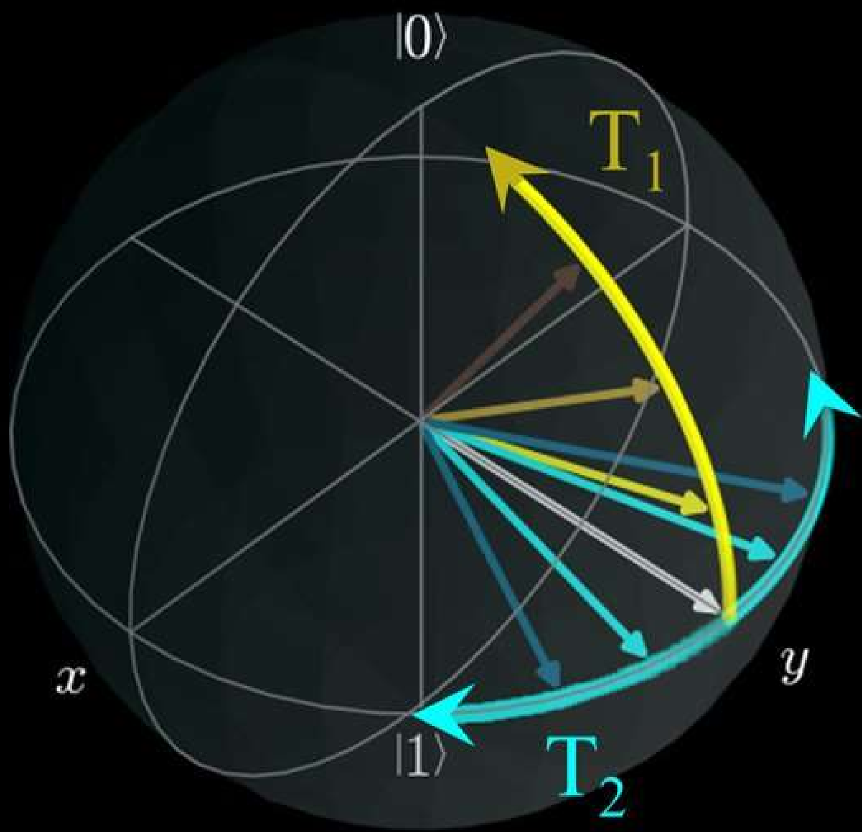


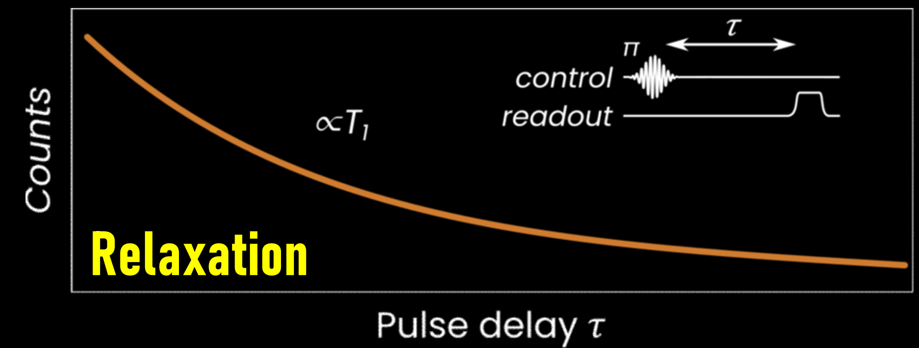
COHERENCE IS GENERALLY SHORT!

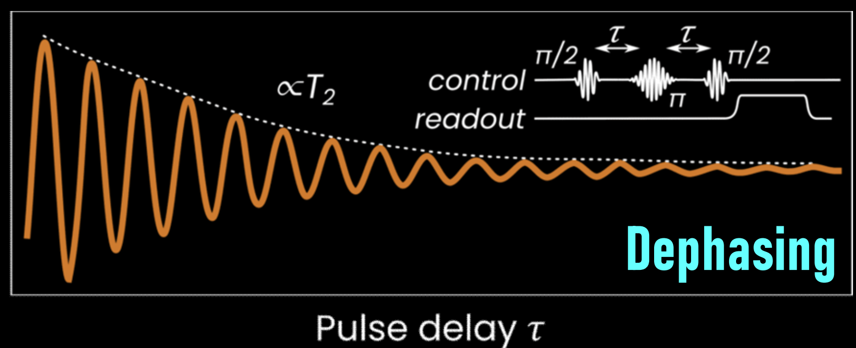
Some sources of decoherence:

- Two Level Systems (TLS)
- Electronic noise
- Thermal fluctuations
- Ionizing radiation

Quantum Decoherence



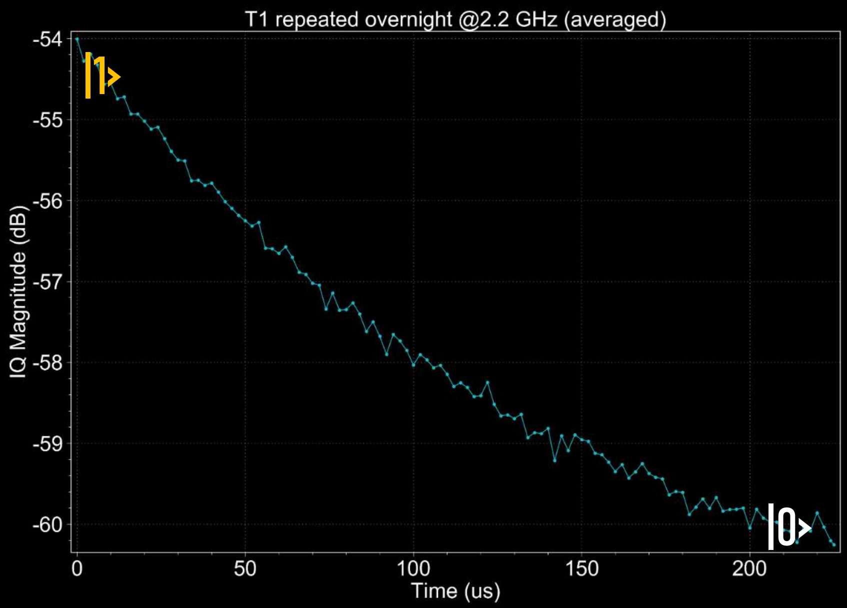




Quantum Decoherence

Usually a **classical bit** that is in the state **0** or **1**, **maintains its state.**
This is **not true for a qubit.**

Quantum decoherence can be understood as the **loss of information to the environment.**



Some sources of decoherence:

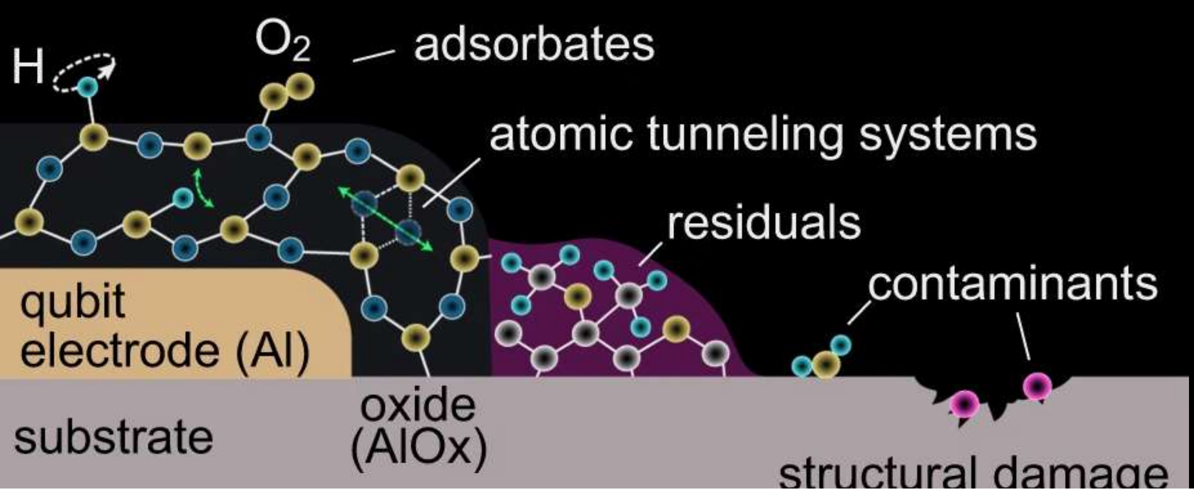
- Two Level Systems (TLS)
- Electronic noise
- Thermal fluctuations
- Ionizing radiation

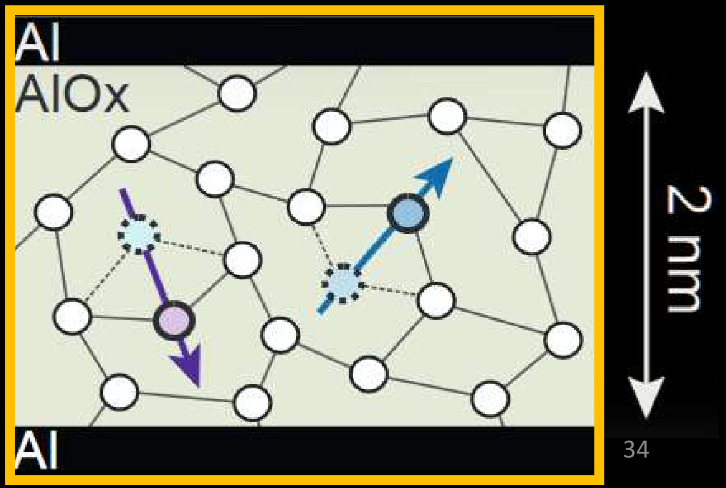
TLSs (Two Level Systems)

> arXiv:1705.01108v3 > arXiv:1909.09749v2 > arXiv:1503.03681v1

The main limiting factor for single qubit coherence.

Still not fully understood, but generally they are **defects within interfaces or materials** (tunneling atoms, trapped electrons, magnetic impurities, dangling bonds, hydroxide defects…).

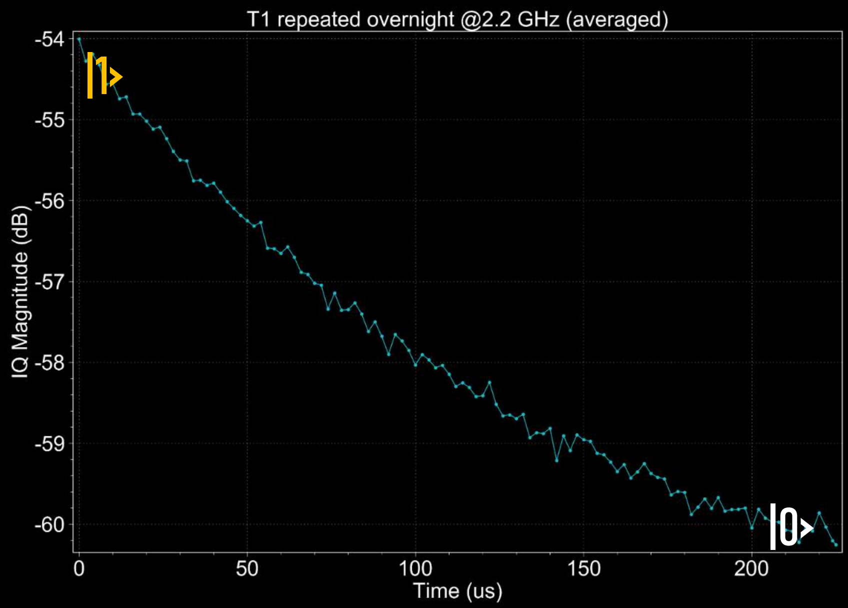




Quantum Decoherence

Usually a **classical bit** that is in the state **0** or **1**, **maintains its state.**
This is **not true for a qubit.**

Quantum decoherence can be understood as the **loss of information to the environment.**



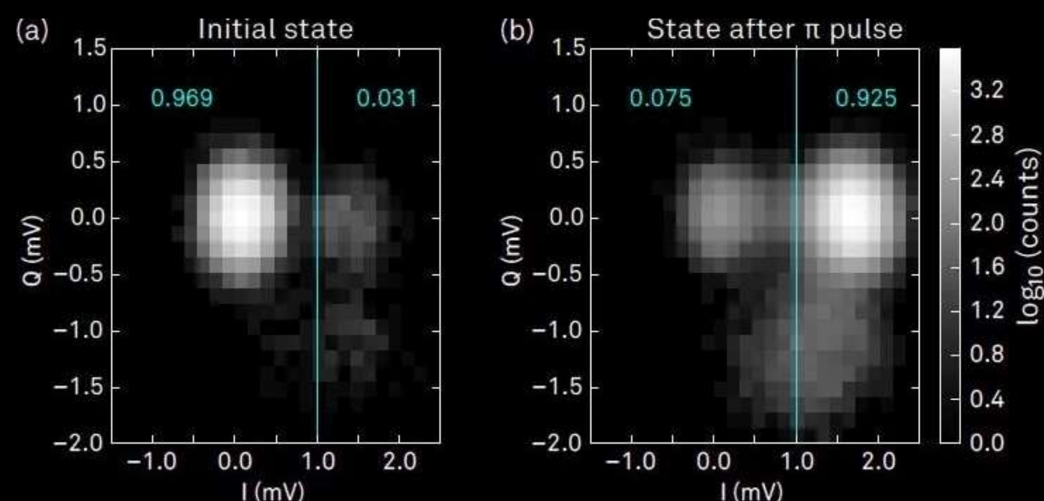
Some sources of decoherence:

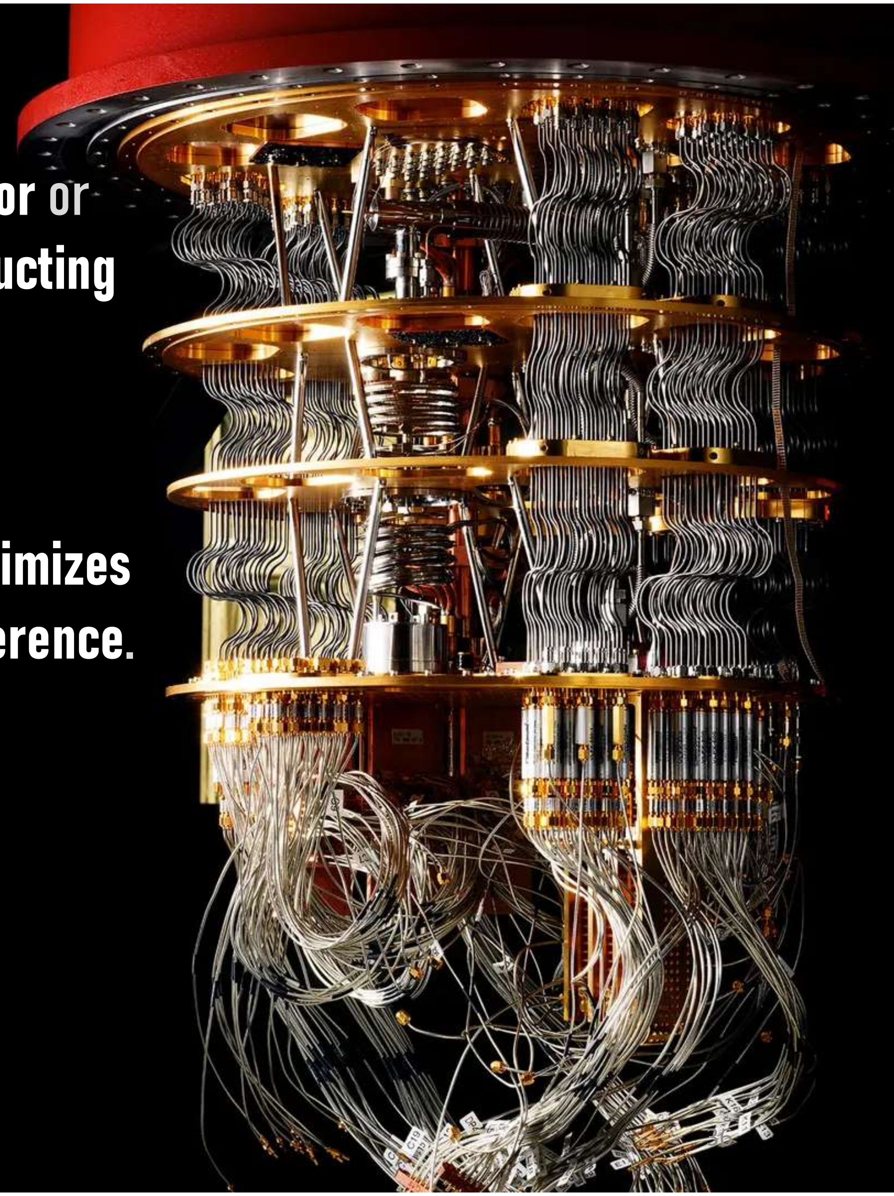
- Two Level Systems (TLS)
- Electronic noise
- Thermal excitation
- Ionizing radiation

Thermal Excitation

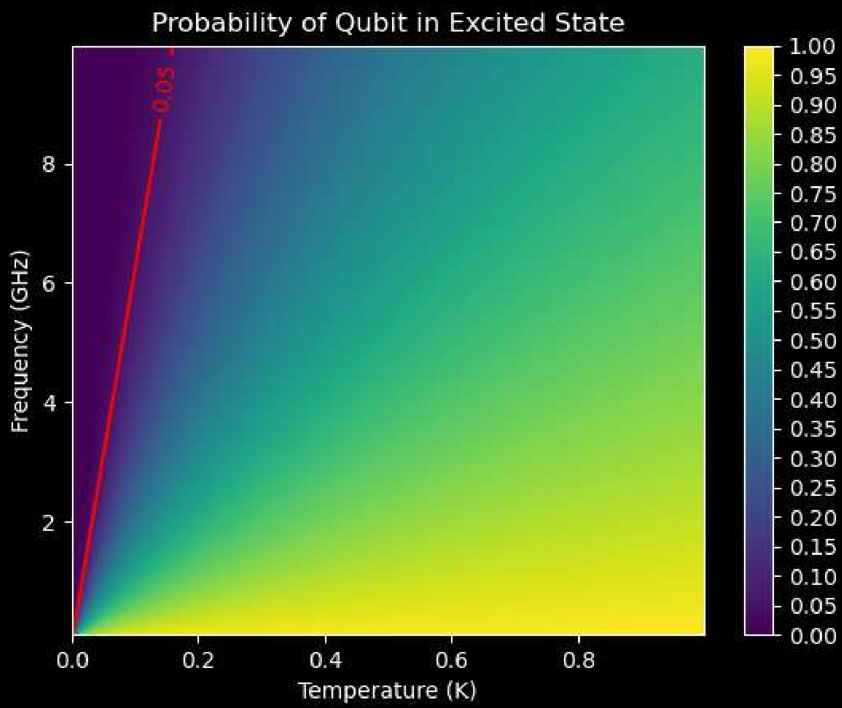
An essential role is played by the **dilution refrigerator** or **cryostat**. This instrument **cools down the superconducting circuits below their critical temperature** (T_c).

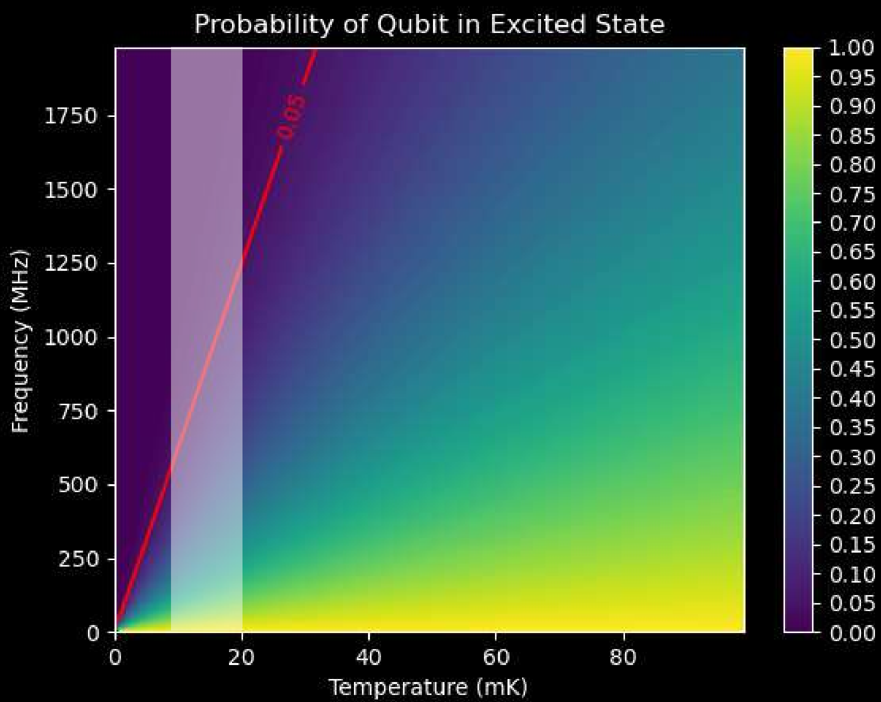
Current cryostats reach consistently **10-20 mK**: a temperature much lower than T_c (Al = 1.2 K) also **minimizes thermal excitations that can destroy the qubits coherence.**





Minimizing thermal excitations



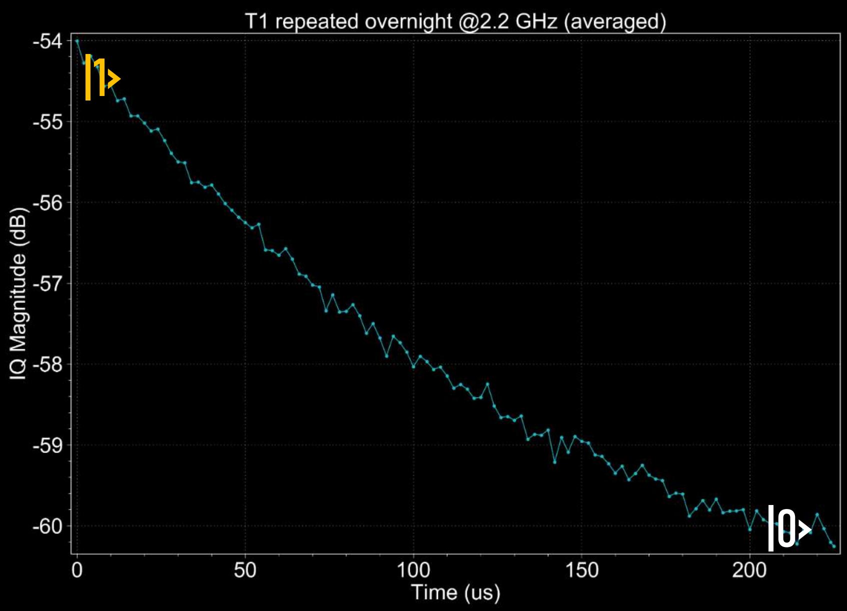


State of the art **dilution refrigerators** reach 10-20 mK consistently, allowing the operation of qubits with minimum energies of ~1 GHz (**~4 μeV**).

Quantum Decoherence

Usually a **classical bit** that is in the state **0** or **1**, **maintains its state.**
This is **not true for a qubit.**

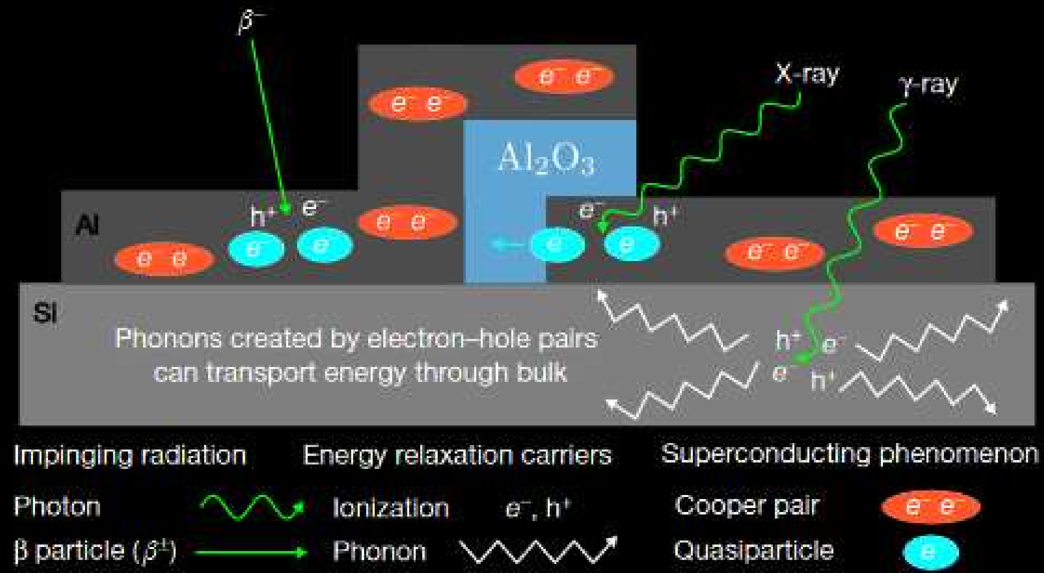
Quantum decoherence can be understood as the **loss of information to the environment.**



Some sources of decoherence:

- × Two Level Systems (TLS)
- × Electronic noise
- × Thermal fluctuations
- × Ionizing radiation

Ionizing Radiation and Superconducting Qubits



To **break a Cooper Pair** we need an **energy > 2Δ**, where Δ is the superconducting gap.

$\Delta(0K) = 1.764\ k_B\ T_C$

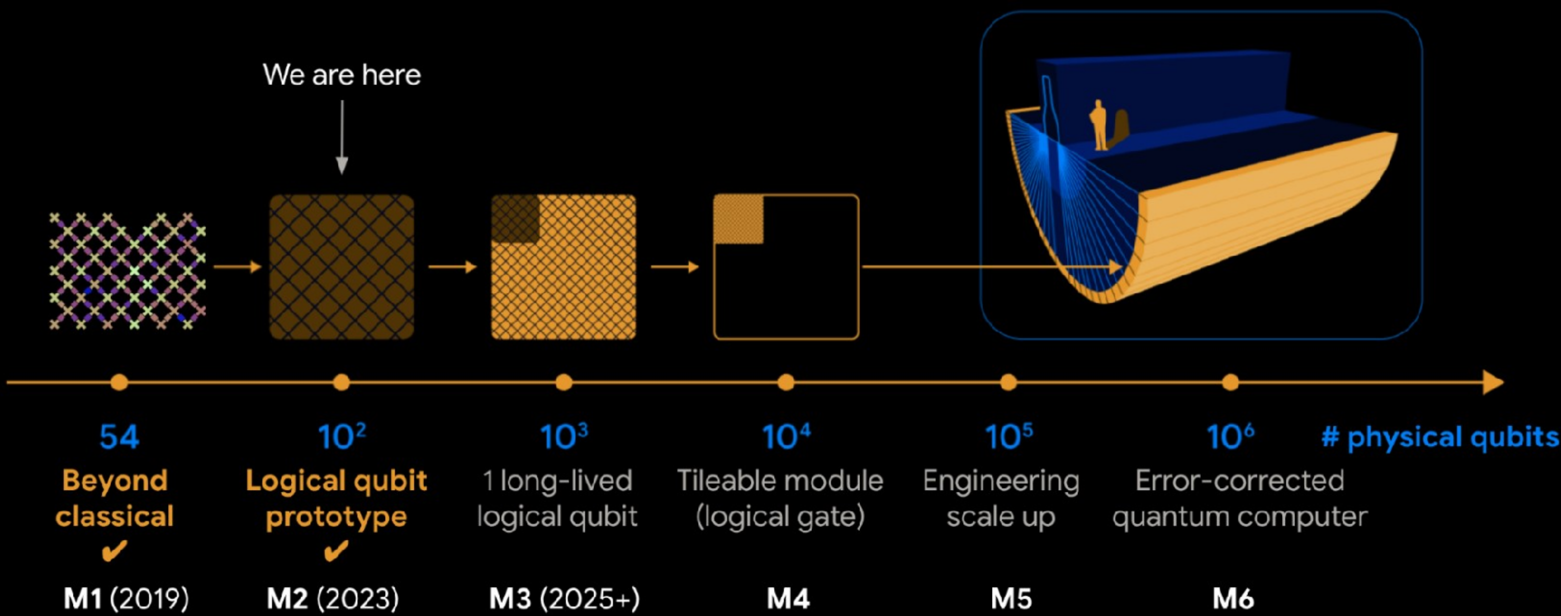
For **Aluminum 2Δ = 340 μeV**

The **effect of ionizing radiation on superconducting qubits** is still **partially understood.**

Ionizing radiation causes quantum decoherence but its detrimental effects are even more pervasive, posing a **serious threat to quantum error correction**.

QEC (Quantum Error Correction)

- Used in **Gate-Based Quantum Computing**
- In order to work it **assumes that the errors of the single qubits are uncorrelated**

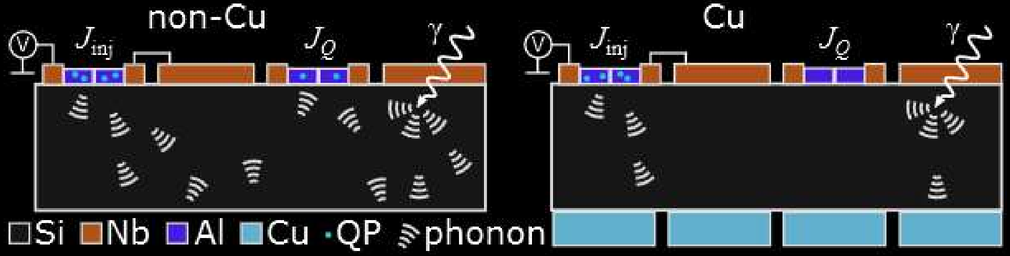


Mitigation Strategies

On-chip solutions:

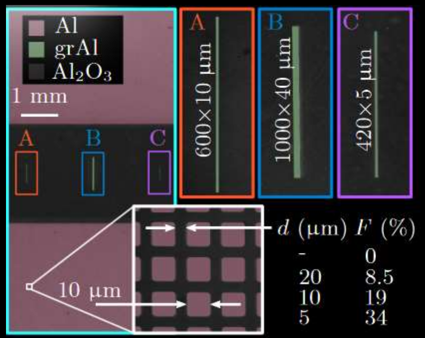
-Phonon traps with normal metals:

› arXiv:2203.06586



-Superconducting phonon traps:

› arXiv:1908.04257

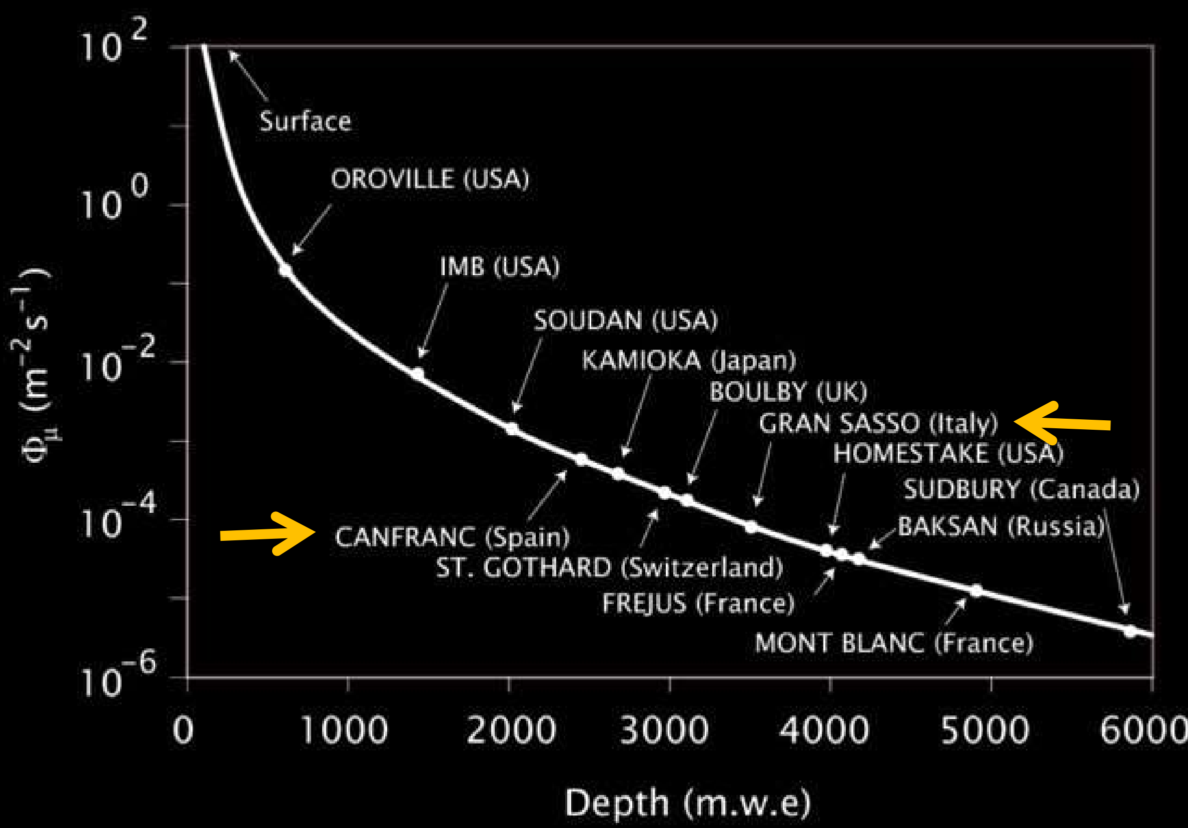


-Normal-metal quasiparticle traps:

› arXiv:1606.04591

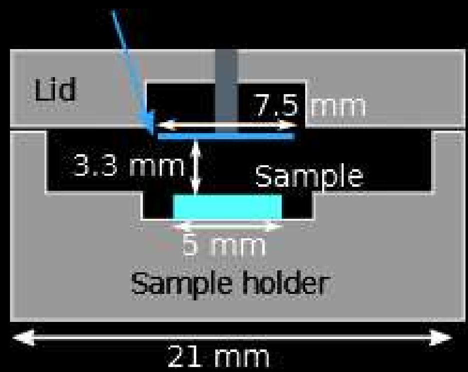
Underground Laboratories

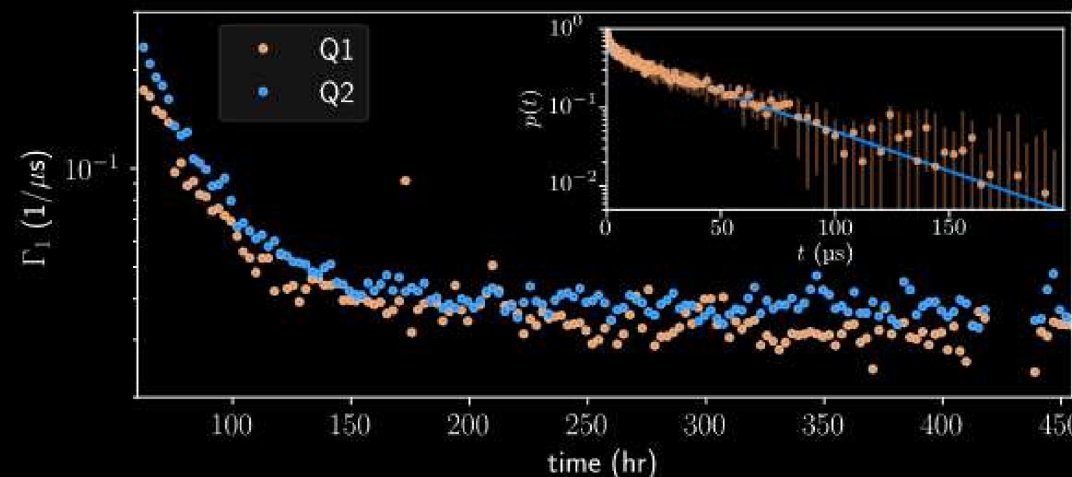
Reducing the background: we can shield the experiment from environmental radioactivity, but the only way to drastically **reduce the muon flux** is to move the experiment **underground.**



[2020] **Impact of ionizing radiation on superconducting qubit coherence** › arXiv:2001.09190

^{64}Cu radioactive source (**half-life 12.7 hours**) installed close to 2 transmon qubits



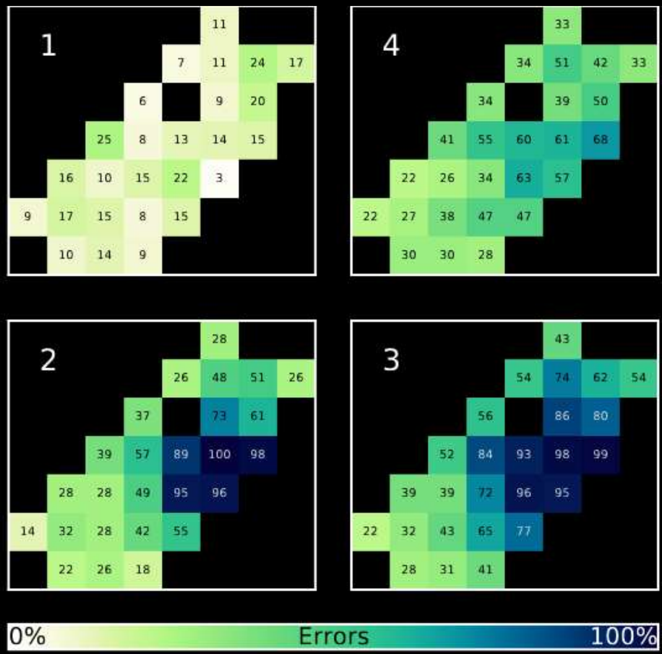


From this measurement they inferred they would be **limited to T_1 ~ 4 ms by radiation levels** in their laboratory.

[2021] Resolving catastrophic error bursts from cosmic rays in large arrays of superconducting qubits

Employed a **26 qubit** subset of **Google Sycamore** processor.
Observed "catastrophic" correlated errors in multiple qubits.

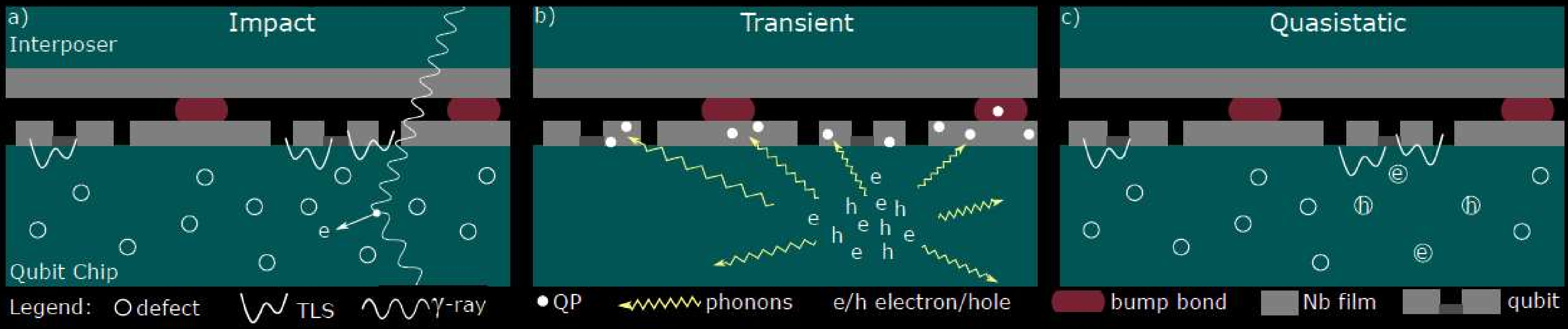
"Scalable quantum computing can become a reality with error correction, provided [...] that physical errors can remain both small and sufficiently uncorrelated as devices scale, so that logical error rates can be exponentially suppressed. Our results [...] **highlight the necessity of mitigation to enable quantum computing to scale.**" › arXiv:2104.05219



Evolution of error rates after a cosmic ray interaction:
(1) at -100 µs, (2) +10 µs,
(3) +1.5 ms, (4) +10 ms

[2022] TLS Dynamics in a Superconducting Qubit Due to Background Ionizing Radiation

- arXiv:2210.04780v1



A **27-qubit IBM Quantum Falcon R6 processor** is used in its usual conditions to:

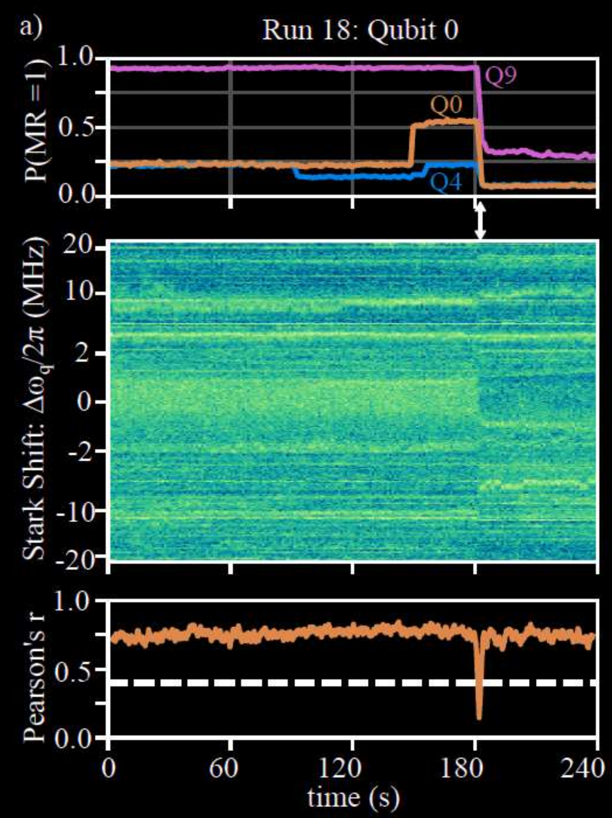
- **Detect the impact of radiation** on the chip
- **Monitor TLSs** dynamics

Given the findings it will propose a **link between radiation and TLSs dynamics (TLSs scrambling).**

[2022] TLS Dynamics in a Superconducting Qubit Due to Background Ionizing Radiation

- arXiv:2210.04780v1

- **Sudden T_1 changes** of individual qubits were observed **after multi-qubit jumps**
- **T_1 would then stabilize** on the new level (either higher or lower)
- This is attributed to **TLSs scrambling: radiation simultaneously change the frequency of several TLSs**. When a TLS is brought in resonance with the qubit, T_1 decreases. T_1 increases instead if the TLS is brought out of resonance with the qubit.

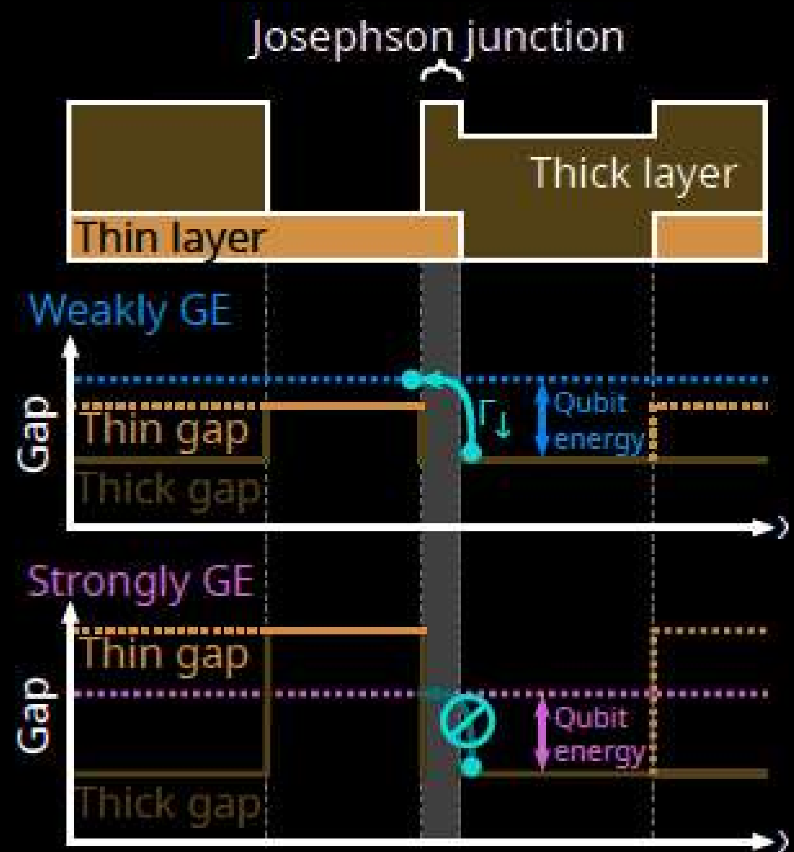


[2024] Resisting high-energy impact events through gap engineering in superconducting qubit arrays › arXiv:2402.15644v1

Ionizing radiation has the potential to **break Cooper pairs creating quasiparticles** which tunnel the Josephson Junction causing decoherence.

The **two superconducting layers** of the Josephson Junction can **be fabricated with a different thickness to create an energy barrier for quasiparticles.**

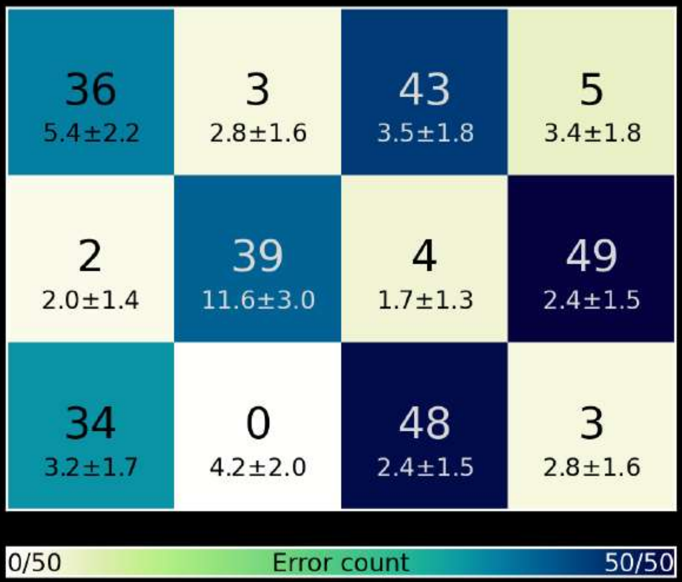
Weakly GE:
Thick Layer 100 nm, Thin Layer 30 nm, **Barrier = 5 GHz**
Strongly GE:
Thick Layer 100 nm, Thin Layer 15 nm, **Barrier = 12 GHz**

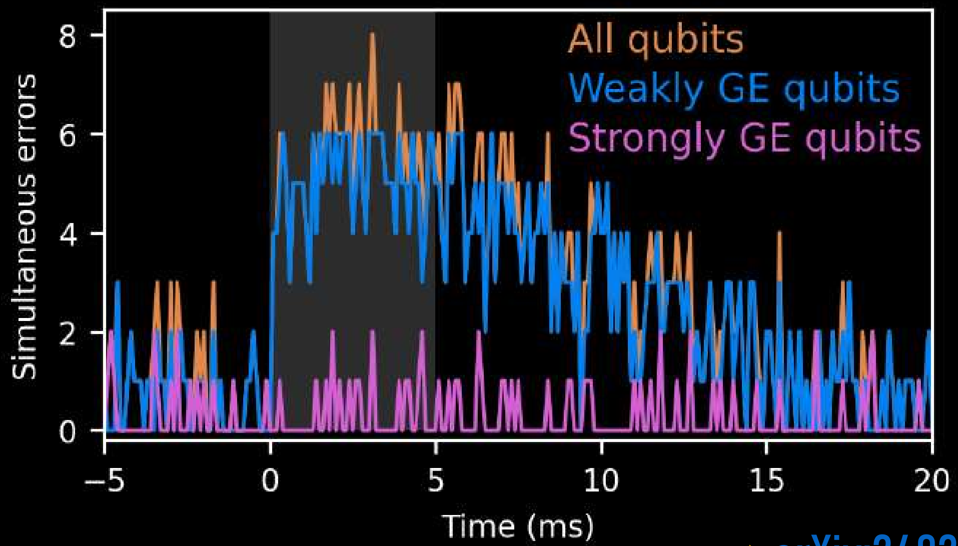


Qubit ~ 7 GHz

The Gap Engineering is a robust method to suppress correlated errors of qubits.

However, the **scrambling of TLSs** due to ionizing radiation **is still present**, inducing instability of coherence times.



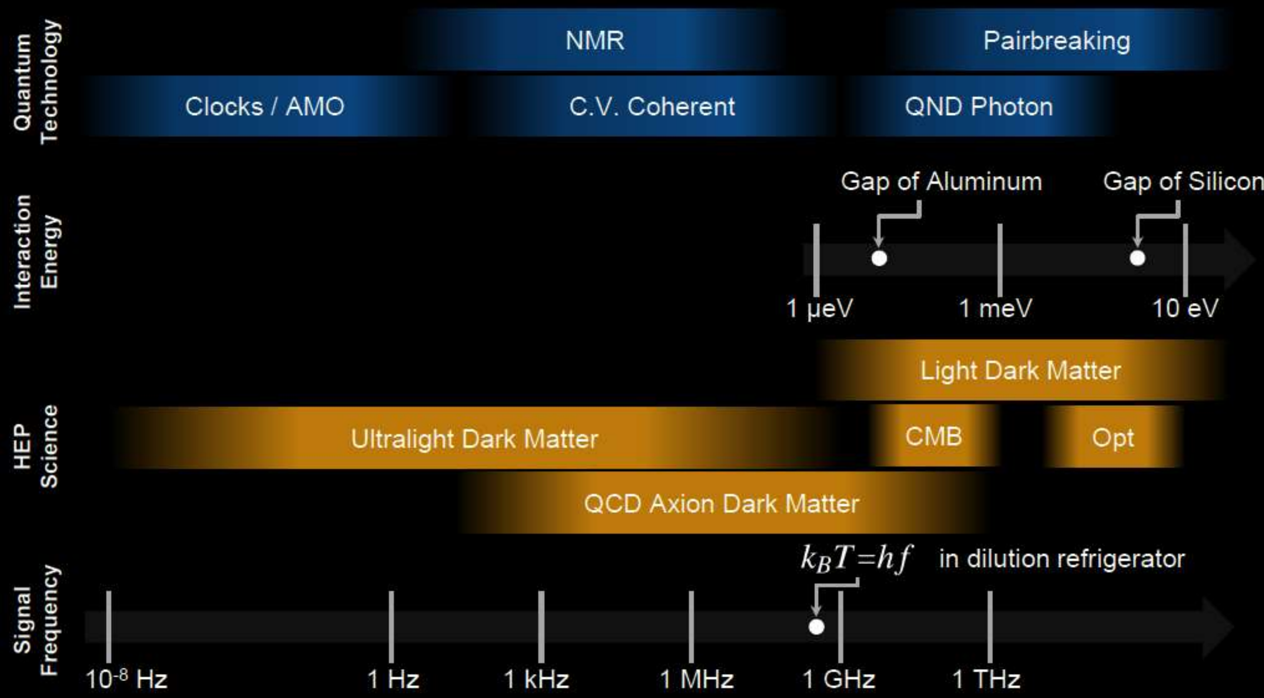


› arXiv:2402.15644v1

Detection of particles with superconducting qubits

A matter of energy:

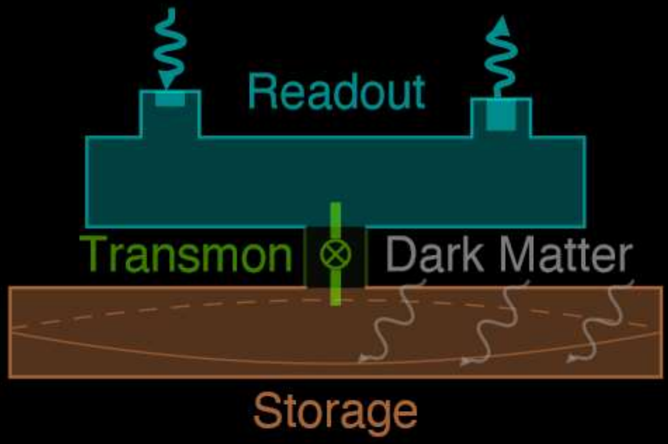
- arXiv:2311.01930v1

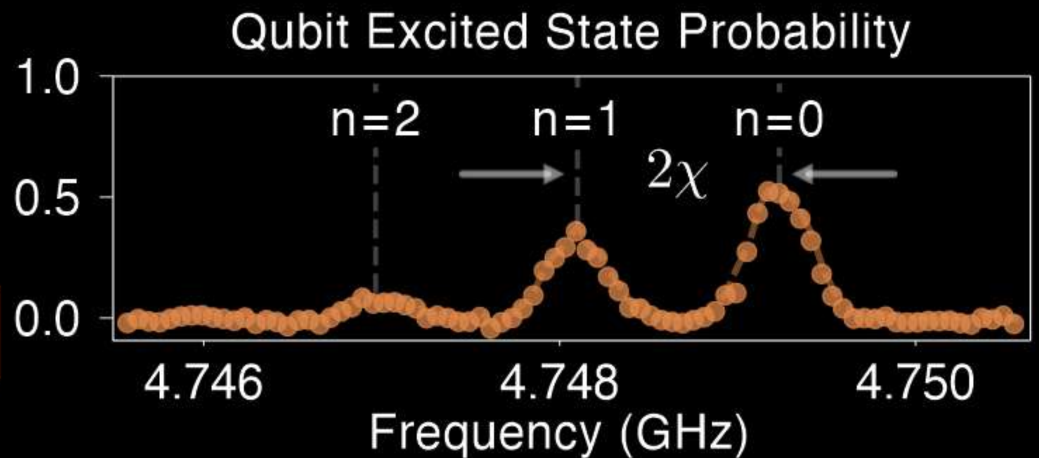


Present day **superconducting qubits** are **excellent single photon detectors** with an attractive energy range of operation (1-30 GHz or **4-120 µeV**).

Axion Experiments

› arXiv:2008.12231v3 [2020]





A **storage cavity** with resonant frequency 6.011 GHz is **used as a "target" for axion interactions of a specific mass** (the resonance frequency is tuned to the mass of the axion).
A **transmon qubit** (4.749 GHz) bridges the storage cavity and a **readout cavity** (8.052 GHz).

If a photon (or more) is deposited in the storage cavity, there is a shift in the qubit frequency.

Axion Experiments

› arXiv:2008.12231v3 [2020]

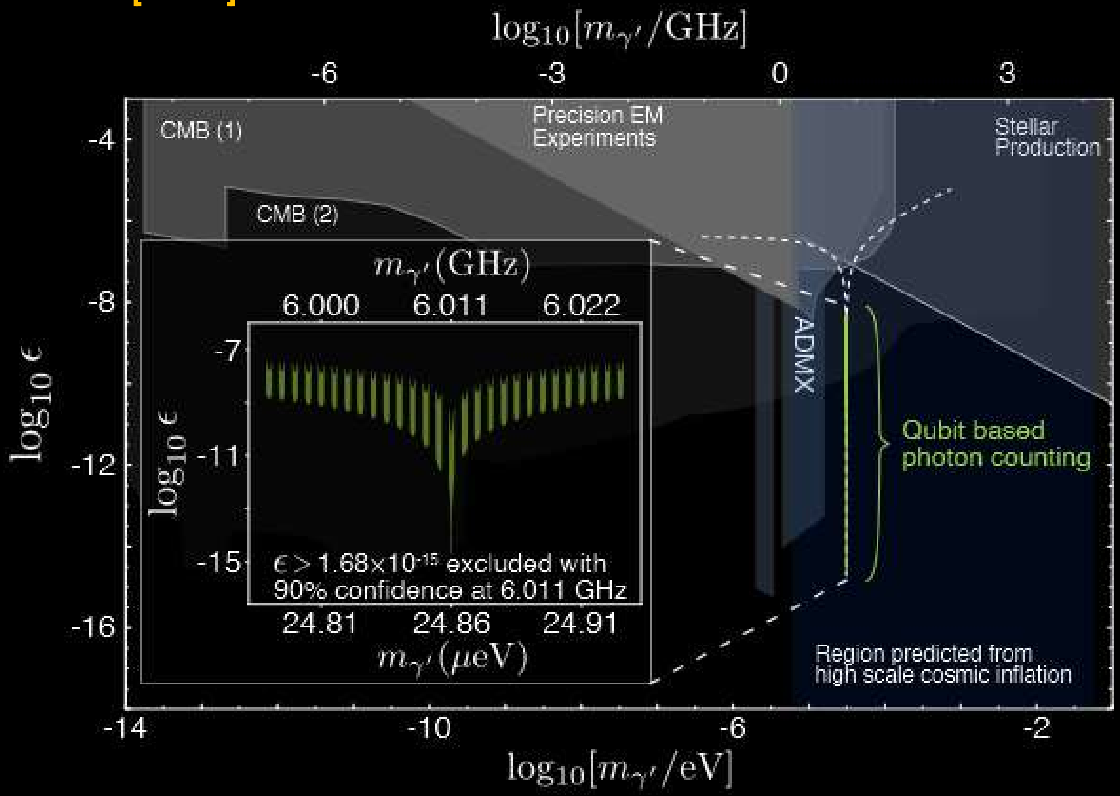
Limitations:

- × The **error rate** of current **transmon qubits** (1-10%) is still too high to perform a competitive experiment
- × The **mass range** of this kind of experiment is **narrow** and dictated by the storage cavity frequency (tunable cavities)
- × **Challenging** to work with qubits/cavities in **magnetic fields**

Future Experiments: **DarkQuantum** (funded in late 2023 with 13M by ERC Synergy Grant, Babette Döbric's Group at **MPP** involved) + **QRADES** (QCT Group at **IFAE** involved).

Hidden Photon Experiments

› arXiv:2008.12231v3 [2020]



The same experiment can be used to search for hidden photons.

Charge Noise

› arXiv:cond-mat/0703002v2 [2007]

Quantum Computing with Superconducting Qubits and Particle Detection with Superconducting Qubits are not necessarily going in the same direction.

Most of the modern **quantum processors** employ **"charge insensitive" transmon qubits**. These devices are **insensitive to liberated charge quasiparticles** which tunnel the Josephson Junction and change the parity of the superconducting island.

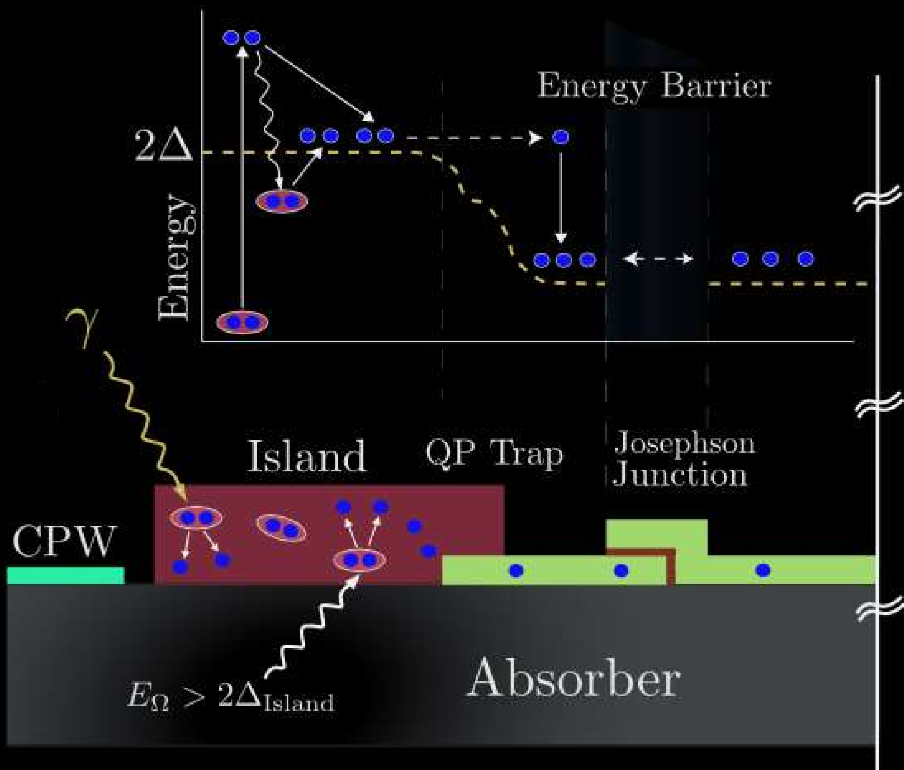
But, liberated charges (broken Cooper Pairs) are **also signaling an energy deposition within the device.**

Inevitably, **new qubit designs** should be explored **for Particle Detection.**

SQUAT Qubit

› arXiv:2310.01345v2 [2023]

New design proposed, the **Superconducting Quasiparticle-Amplifying Transmon.**



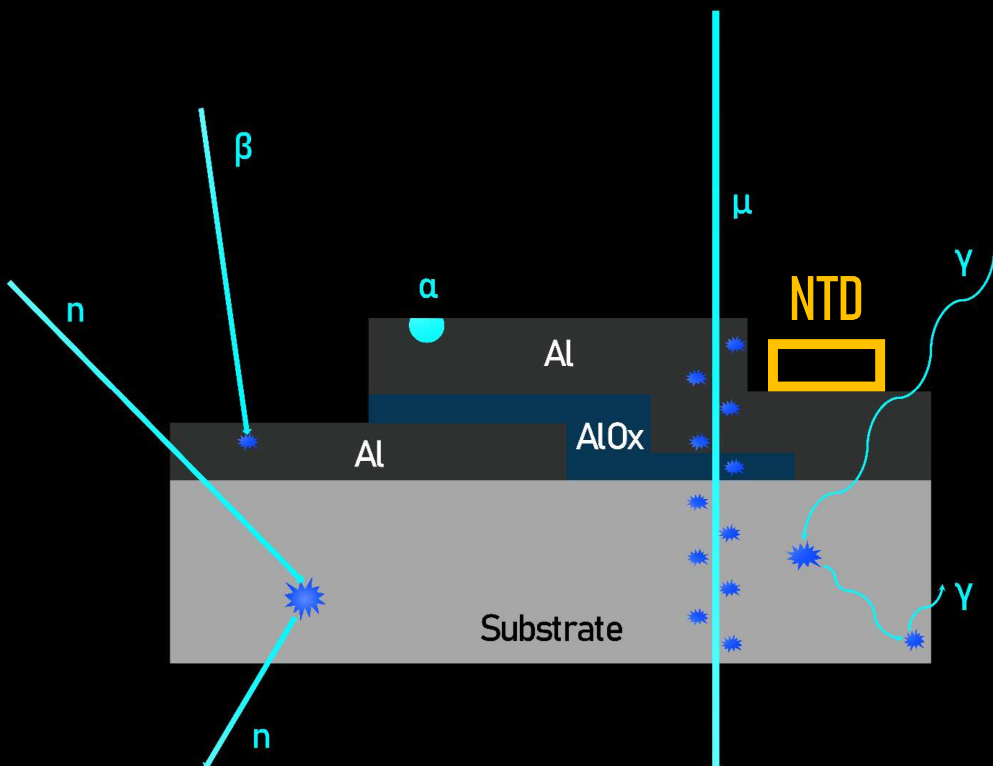
Design which **maximizes the signal by collecting as many quasiparticles in a trap.**

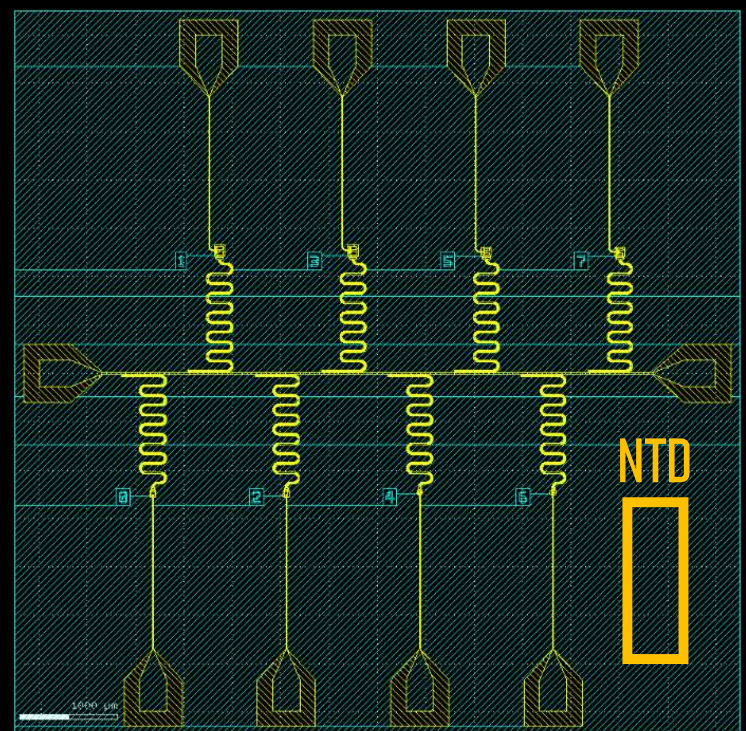
The trap is fabricated using a material with a **lower energy gap**, resulting in an **amplification of quasiparticles.**

Each quasiparticle **tunneling is a signal.**

Hybrid Devices

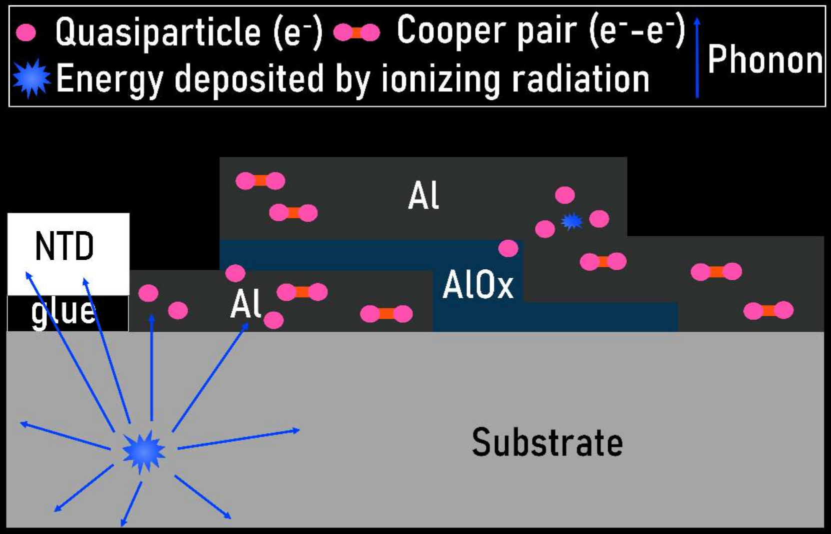
My idea is to perform an experiment with a **qubit chip equipped with a cryogenic particle sensor** (NTD). We plan to install and test this hybrid device in a cryostat **above ground** (IFAE) and subsequently **underground at LSC Canfranc.**





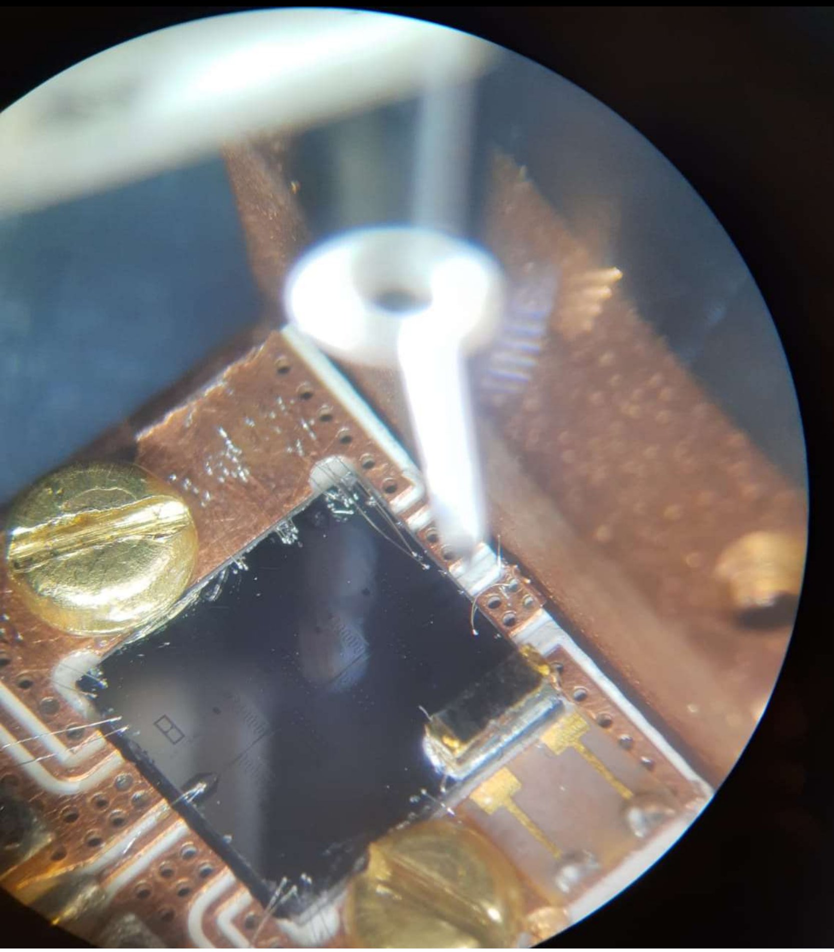
Hybrid Devices

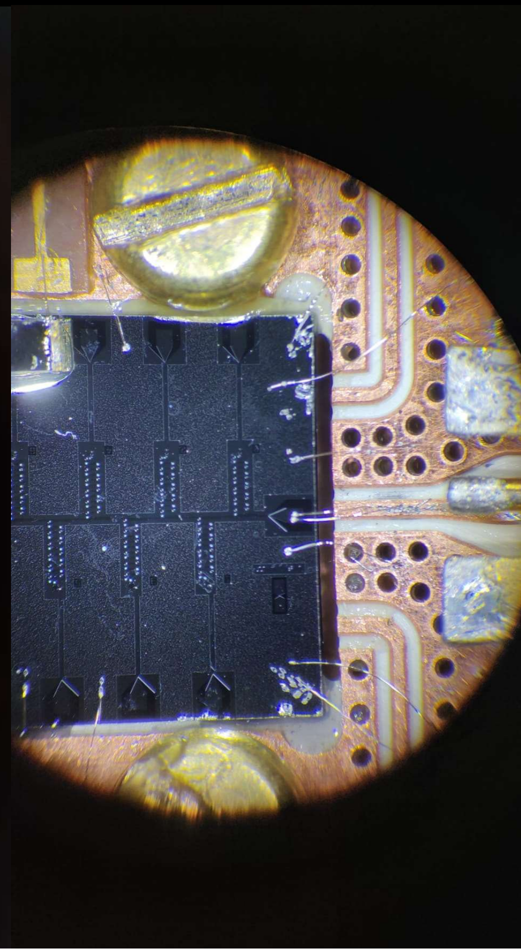
The **NTD provides the timestamp and the energy of a particle interaction** within the chip. The range of energies covered is potentially large (~1 keV – 10 MeV).
The **qubit coherence time is constantly measured** and then we can draw more informed conclusions on the reduction of performances caused by particle interactions and eventually a way to extend the detection of particles below the threshold of the NTD.

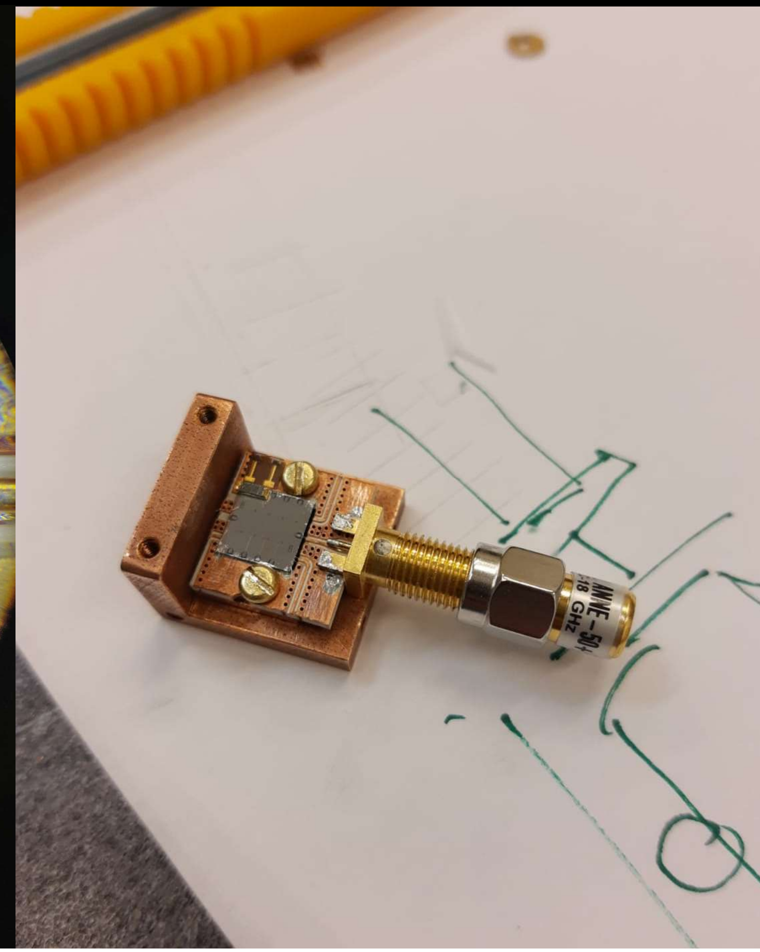


Hybrid Device

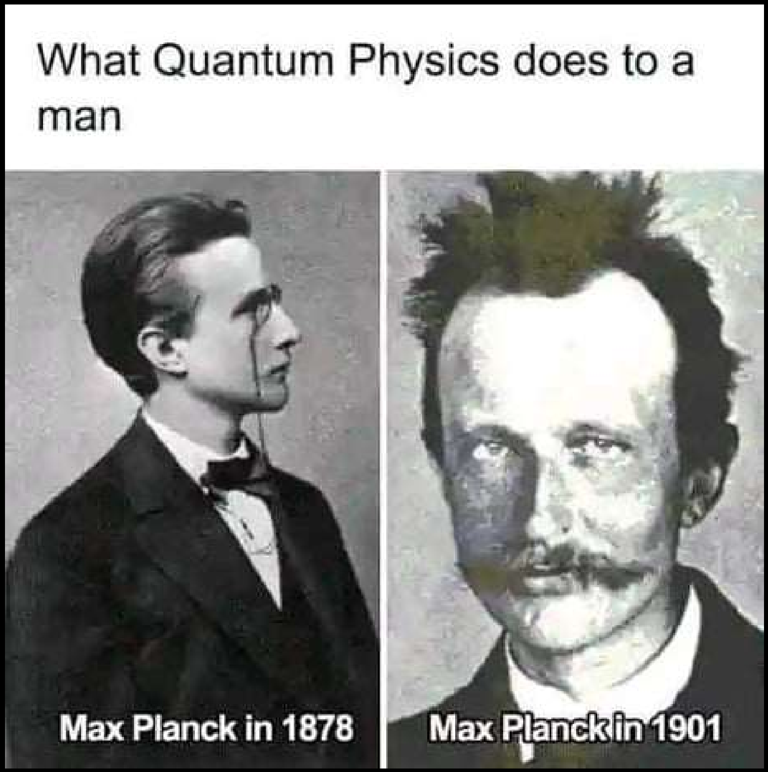
First (failed) attempt. A new prototype will be prepared at IFAE.







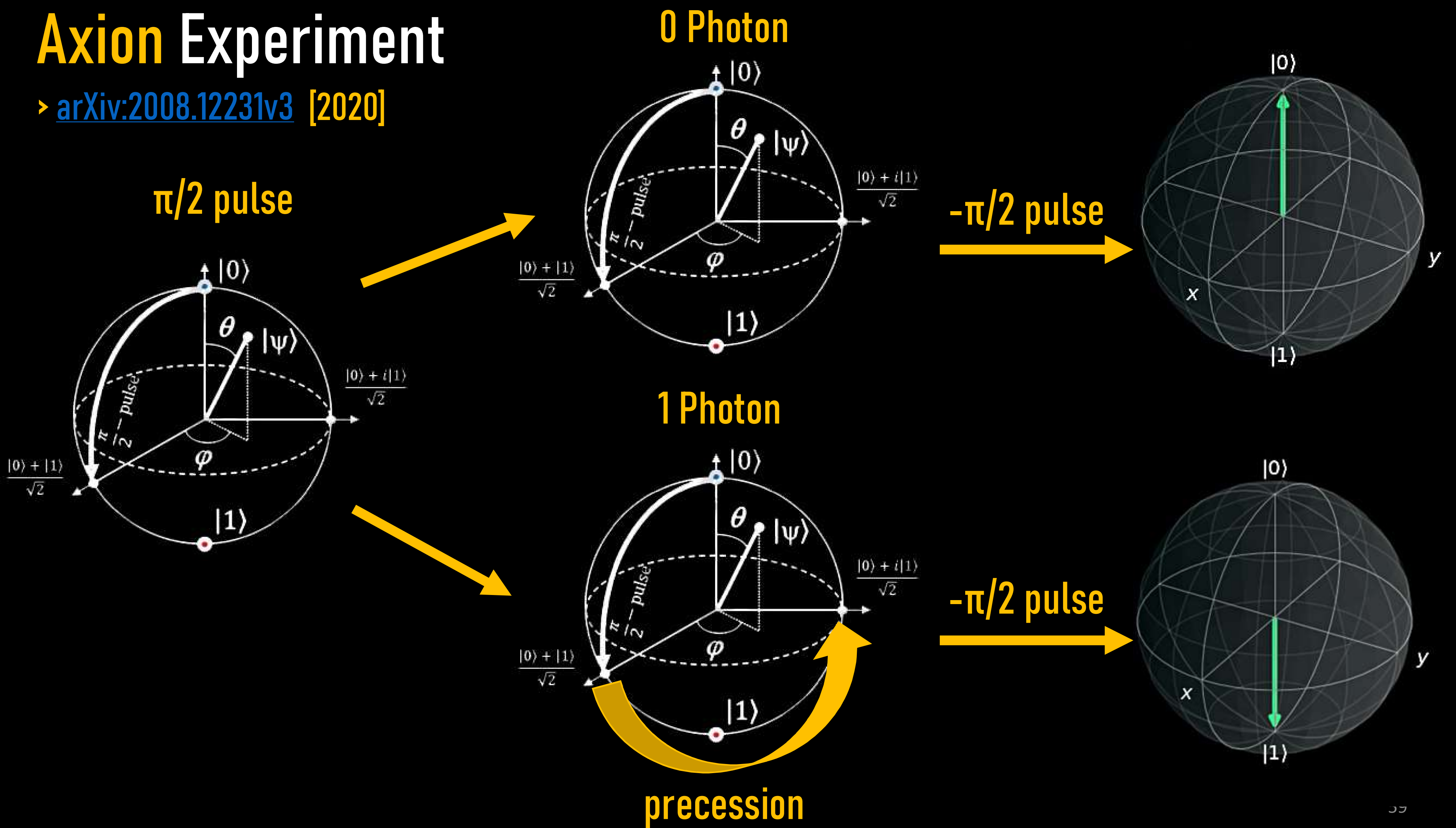
Thank You!



https://qct.ifae.es/

Axion Experiment

› arXiv:2008.12231v3 [2020]



Axion Experiments

Theoretical framework:

- arXiv:1110.5871v2 [2011]

If strong external electric and magnetic fields $\vec{E}$ and $\vec{B}$ are present, then the axion couples as follows:

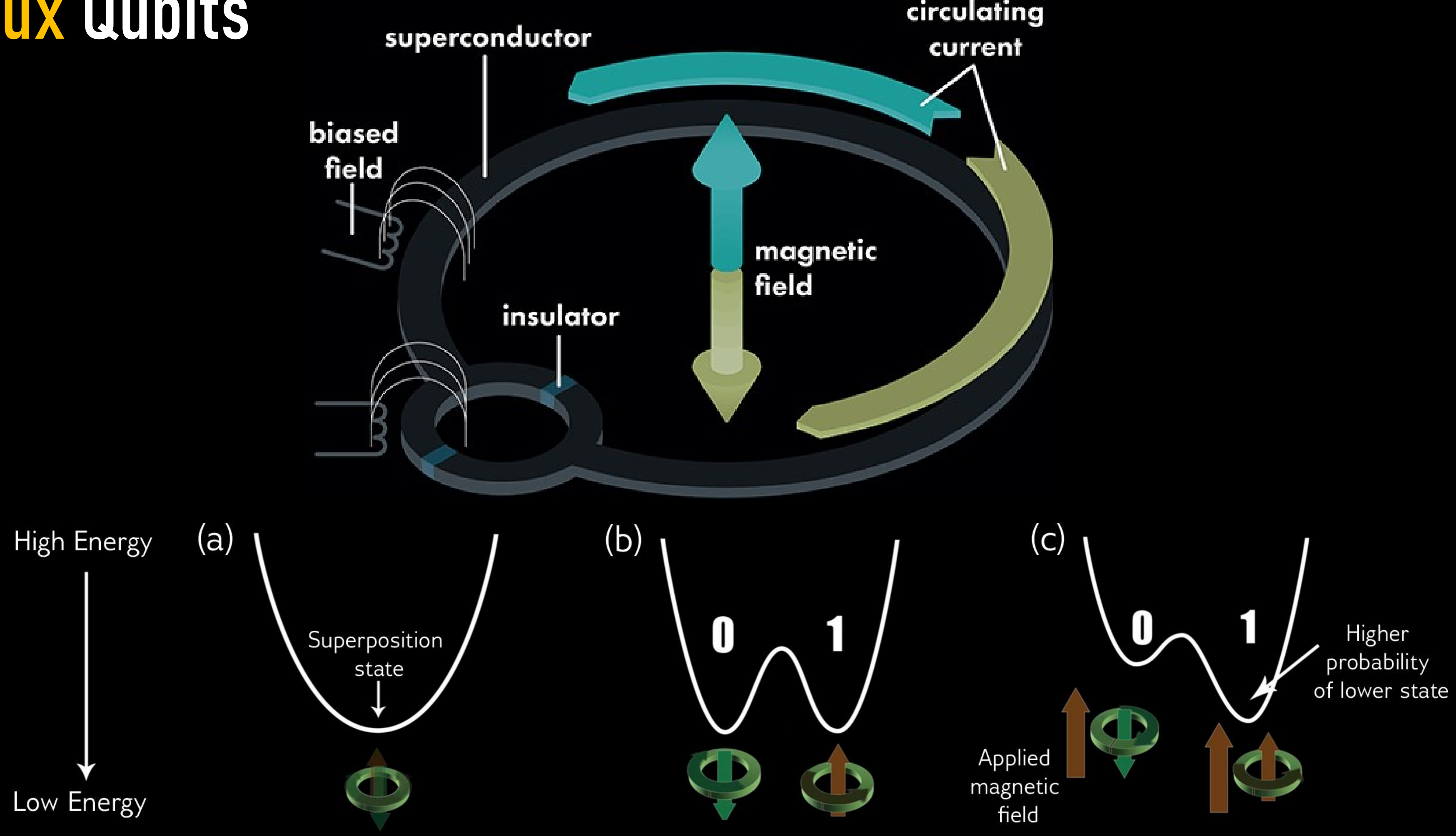
$$\ddot{\theta} + 3H\dot{\theta} + \frac{m_a^2 c^4}{\hbar^2} \sin\theta = \frac{g_\gamma}{\pi} \frac{1}{f_a^2} c^3 e^2 \vec{E}\vec{B}. \qquad (2)$$

If a bias current I is applied to the junction by maintaining a voltage difference V between the two superconducting electrodes, then the equation of motion becomes

$$\ddot{\delta} + \frac{1}{RC}\dot{\delta} + \frac{2eI_c}{\hbar C} \sin\delta = \frac{2e}{\hbar C} I. \qquad (8)$$

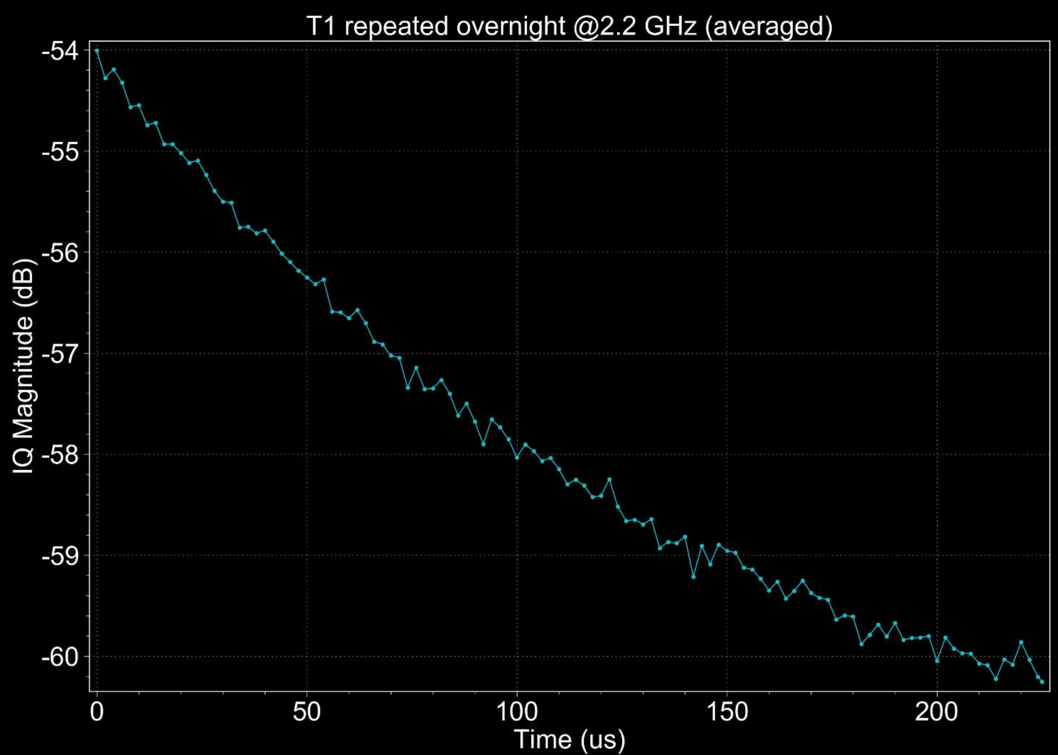
By decreasing/increasing the RC term (shunt resistor and shunt capacity of the circuit) one can simulate axion cosmology at a different time (i.e. before/after QCD phase transition).

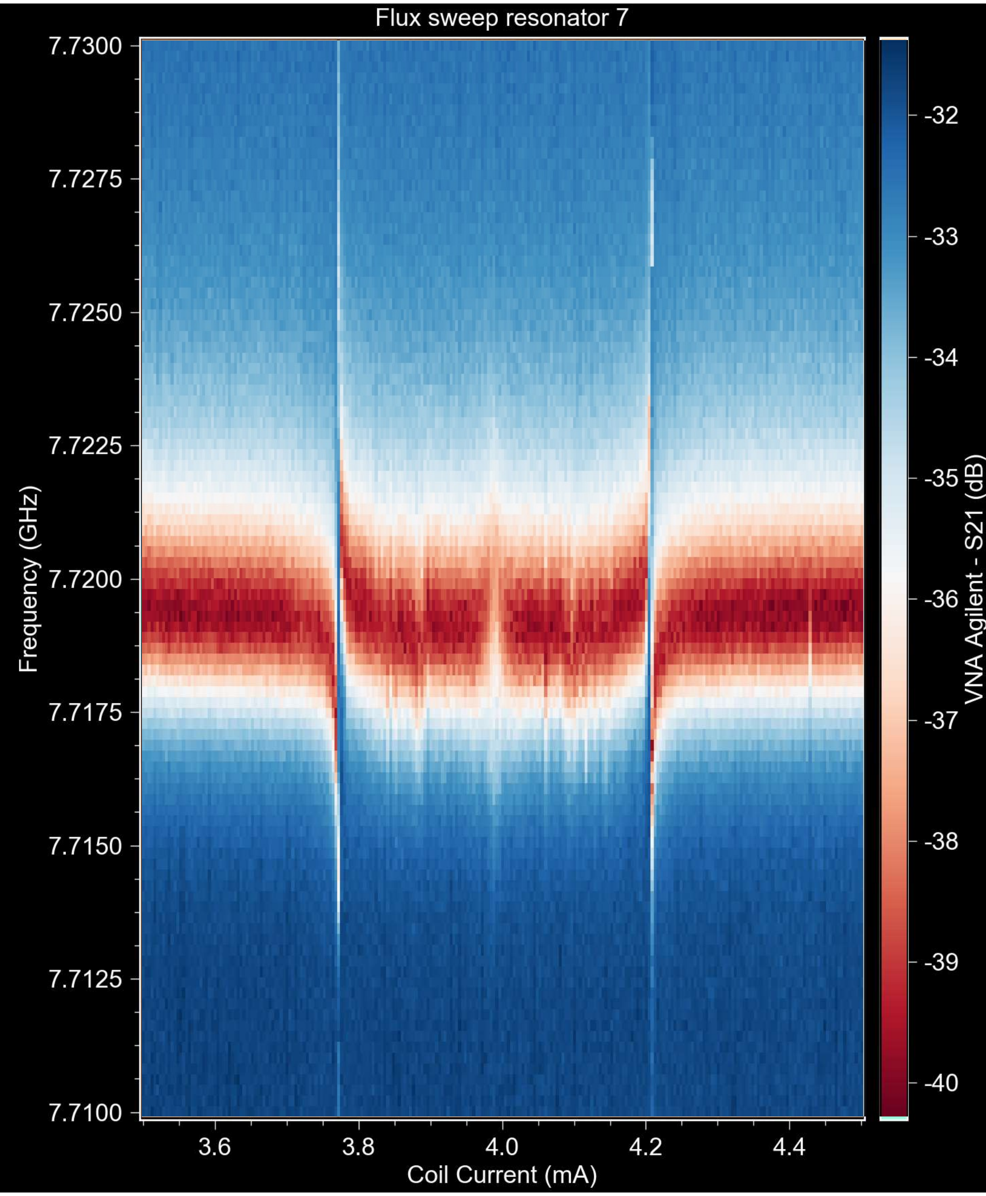
Flux Qubits



superconductor
circulating current
biased field
magnetic field
insulator
High Energy
Low Energy
(a)
Superposition state
(b)
0
1
(c)
0
1
Higher probability of lower state
Applied magnetic field

Measuring Flux Qubits





Rabi Oscillations