INFN
Istituto Nazionale di Fisica Nucleare

Impact of environmental and materials radioactive contamination in superconducting quantum bits

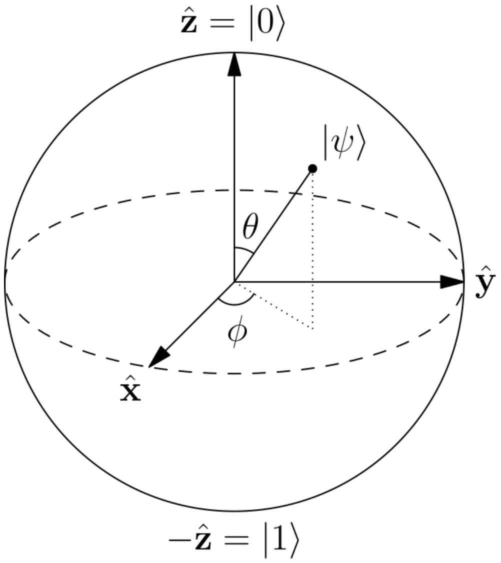
Giulia D'Imperio for the DEMETRA and SQMS collaborations

02/05/2022
ICRM-LLRMT conference, LNGS

LNGS 2022
ICRM - LLRMT

Qubits

- Two-level quantum-mechanical system
  - n classical bits ➔ string with n [0,1]
  - n entangled qubits ➔ 2^n possible states

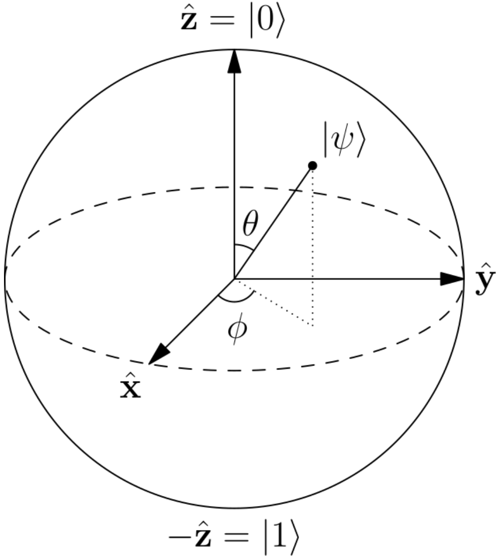


Ideal Features:

1. Strongly coupled to other qubits ➔ **entanglement**
2. Decoupled from the world ➔ **quantum coherence**

Qubits

- Two-level quantum-mechanical system
  - n classical bits ➔ string with n [0,1]
  - n entangled qubits ➔ 2^n possible states



Ideal Features:

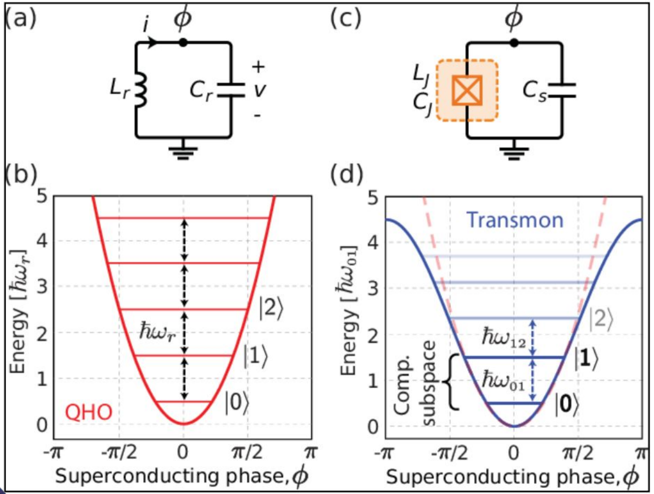
1. Strongly coupled to other qubits ➔ **entanglement**
2. Decoupled from the world ➔ **quantum coherence**

Any two-level QM system can be used as a qubit:

- Trapped Ions
- Photons (lasers)
- ...
- Superconducting circuits

Superconducting qubits

A superconductive circuit with a non-linear inductance (**Josephson junction**) can be used as a qubit



https://arxiv.org/pdf/1904.06560.pdf

Pros 👍 Scalable (reached up to 100 qubits: Sycamore, Aspen-9, Zu Chongzhi, IBM,...)

Cons 👎 Several effects can limit the **coherence**:

- affected by **two-level system noise**
- affected by **quasiparticles (QP)**

Coherence time goal for quantum computers: **millisecond** and beyond
➔ present status ~10-100 μs

Quasiparticles

Superconductors: electrons bound into **Cooper pairs** (**no dissipation**)

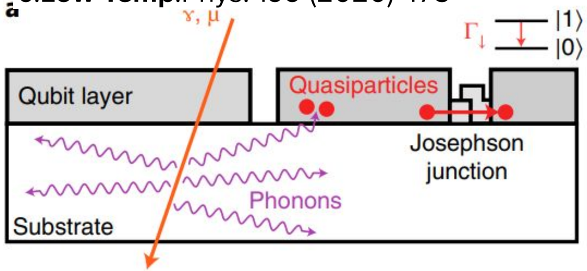
- Many mechanisms can break Cooper pairs into quasiparticles (Δ_0 ~ 0.1 meV)
- **Quasiparticles** are **dissipative** (in contrast to Cooper pairs)
- Sources: any energy dissipation
  - Infrared radiation
  - Thermal stress
  - ...
  - Cosmic rays and environmental radioactivity [**DEMETRA** project, INFN grant 2018]

J.**Low Temp**.Phys. 199 (2020) 475

Radioactivity vs qubits

- **Direct interaction** in the qubit unlikely (qubit dimension < 100 μm)
- **Indirect interaction**: radioactivity deposits energy in **substrate** (typically ~cm^2 area x 300 μm thickness)
- **Charges** and **phonons** are produced and diffuse in the substrate
- Phonons break Cooper pairs and produce **quasiparticles (QP)**

J.**Low Temp**.Phys. 199 (2020) 475



Recent experimental results

1. Radioactivity will be (or already is) the **ultimate limit the coherence of qubits** [mainly MIT and PNNL]: *Vepsäläinen et al, Nature (2020).*

2. Radioactivity **limits quantum error correction** in a matrix of qubits [mainly Wisconsin Univ., INFN-Roma, Fermilab, Google]: *Wilen et al, Nature (2021), McEwen et al., Nature Physics (2022)*

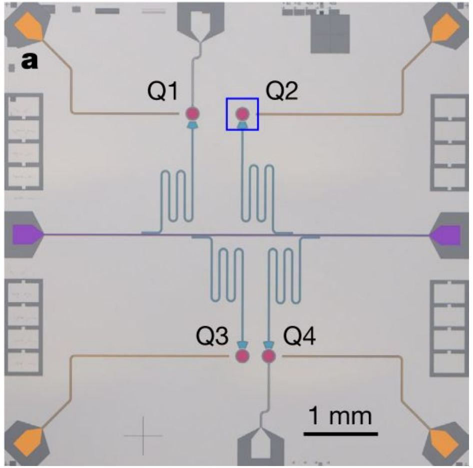
3. **Suppressing radioactivity improves the performance of quantum circuits** [mainly INFN-Roma and LNGS, KIT]: *Cardani et al, Nature Communications, Gusenkova et al., Appl. Phys. Lett. 120, 054001 (2022)*

Quantum error correction

- Most popular idea for quantum error correction: encode quantum information in a **matrix of qubits**

- Key assumption: errors across the qubits belonging to this matrix are **uncorrelated in space and time**

- Radioactivity in the substrate can simultaneously affect more qubits

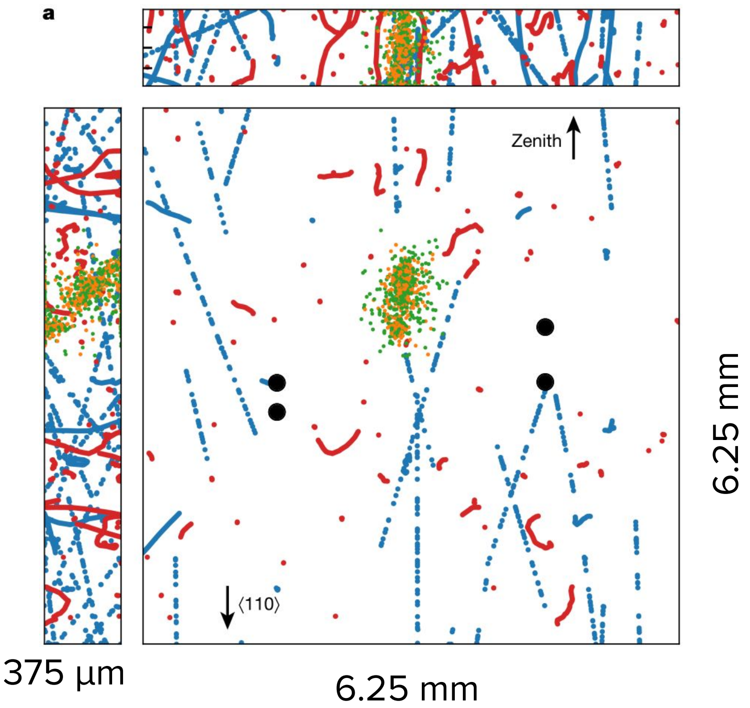


Simulations on a 4-qubits array

1. Energy deposits in Si chip:
   a. **Muons** (blue): 0.5 mHz
      ~500 keV in substrate
   b. **Gammas** from lab (red): 8 mHz
      ~100 keV in substrate

2. Creation of **e/h pairs** (3.8 eV each ➔ 10^4)

3. Charges diffuse creating **phonons**

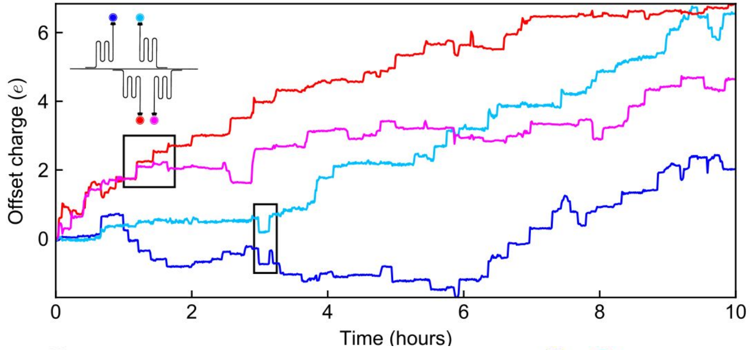


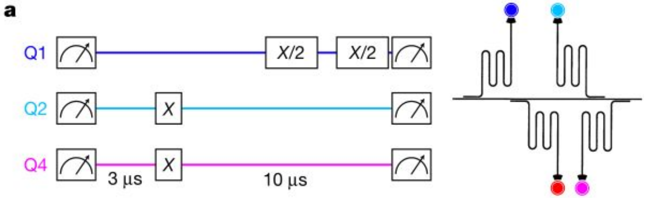
Wilen et al, Nature (2021)

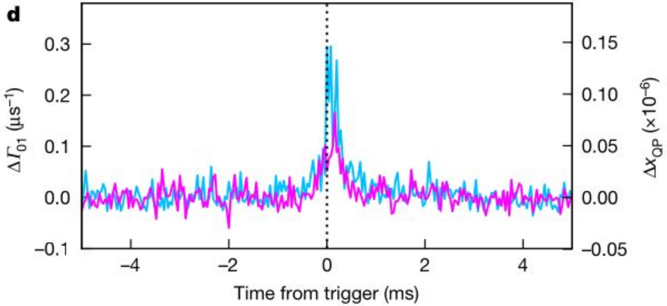
Experimental results

1. Ramsey tomography on 4 qubits (Q1-Q2 ΔL= 640 µm, Q3-Q4 ΔL=320 µm)
   ➔ Many simultaneous charge jumps in pairs
   - **54%** correlation prob for **ΔL= 320 µm**
   - **46%** correlation prob for **ΔL= 640 µm**
   - **no correlation** for **ΔL= 3 mm**

2. Separate measurement:
   - Q1 trigger for charge event
   - measure **Q2-Q4 state (ΔL=3 mm)** ➔ **simultaneous change**
   - **relaxation time ~130 µs** compatible with phonons diffusion in the chip

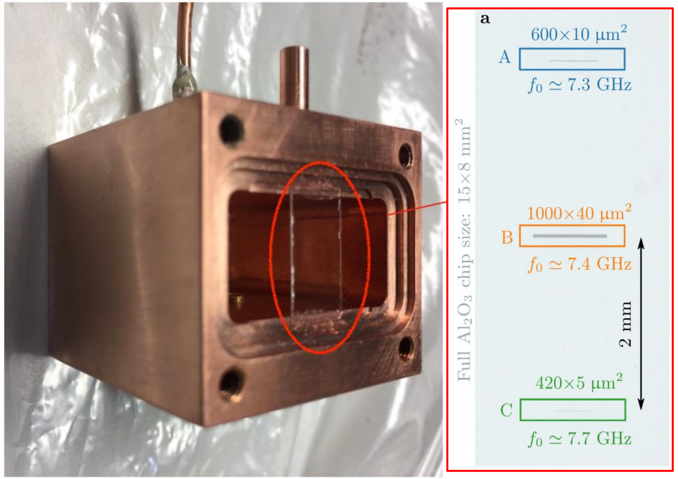






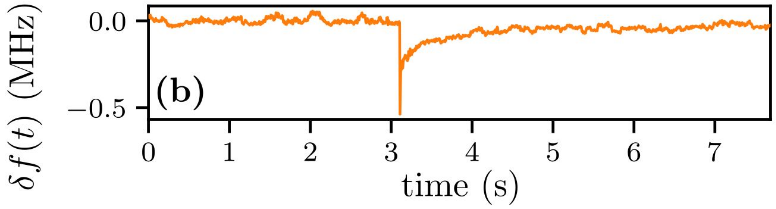
LNGS 2022 ICRM - LLRMT

Resonators in underground setup



Cardani et al., Nature Communications 2021

- 3 high kinetic inductance superconducting **resonators** (KIDs)
- 1.2 cm^2 x 330 µm thick sapphire substrate
- QP burst ➔ shift in frequency of resonators



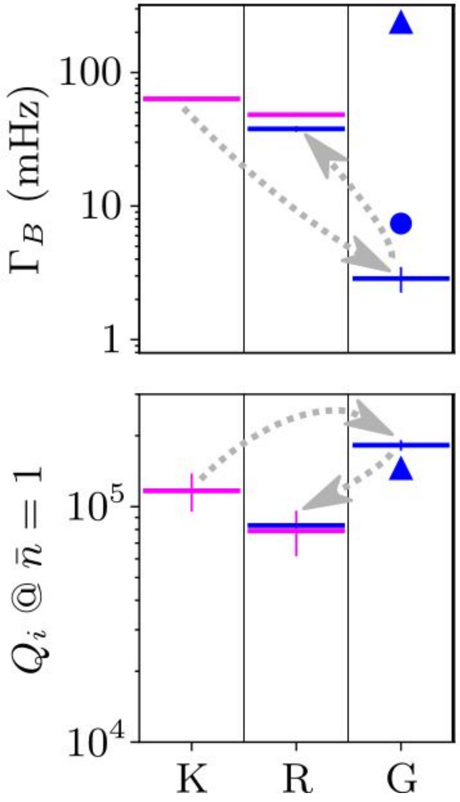
- Quality factor of the resonators anti-correlated with rate of QP bursts

Resonators in underground setup

- Measured in 3 setups:
  - "Standard" Karlsruhe (**K**)
  - **Underground** setup at Gran Sasso + 10cm lead **shielding** (**G**)
  - Crosscheck above ground in Roma (**R**)

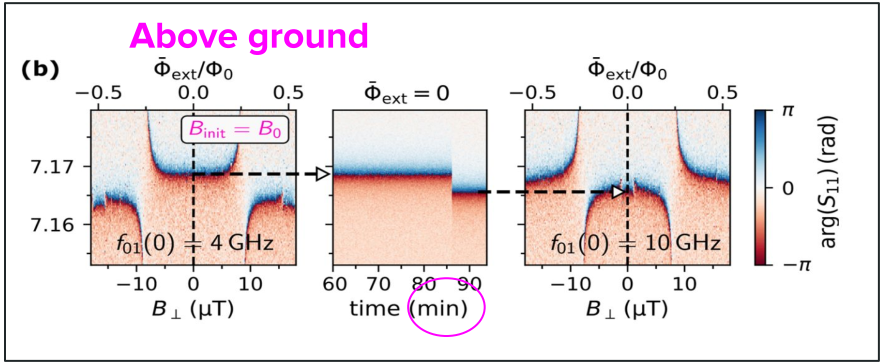
- **Rate of QP** bursts reduced by **factor ~30** from 70 → 2.5 mHz in G

- **Quality factor** improved up to **factor 2-3** in G

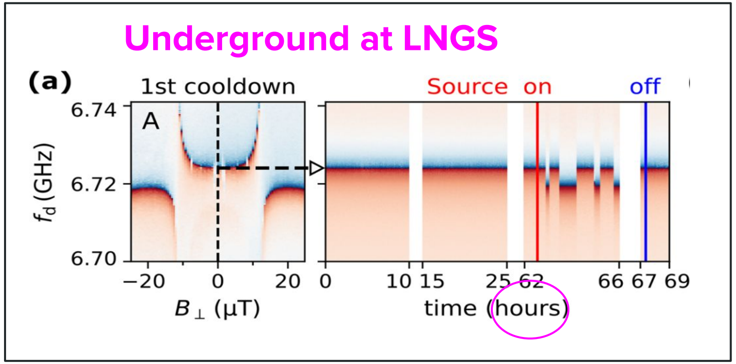


Qubits (fluxonium) in underground setup

- Readout line at LNGS upgraded
- Fluxonium qubit instead of resonators



Appl. Phys. Lett. 120, 054001 (2022)

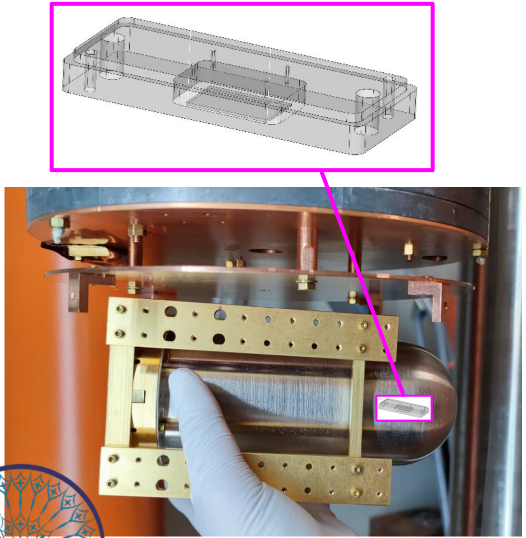


- Large **improvement of frequency stability**

Soon measurements with more performing fluxonium and transmon qubits

Round robin

- Rigetti round robin qubit for SQMS center
- 325 µm-thick, 11.9×7 mm^2 silicon wafer hosting 16 transmon qubits
- Will be measured in multiple facilities: Boulder, Fermilab, Rigetti and LNGS



Rate from “far” radioactive sources

- 1 gamma/min from laboratory in absence of shield (~70 keV on avg)
- 1 neutron/hour (150 keV on avg)
- <1 muon/day (500 keV on avg)

Radioactivity of the materials “close” to the chip

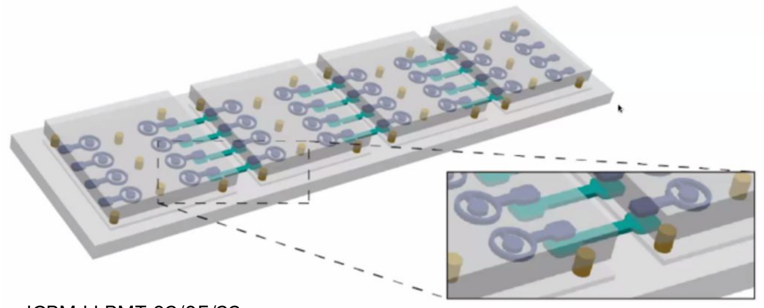
Component	^{232}Th [mBq/kg]	^{238}U [mBq/kg]	^{235}U [mBq/kg]	^{40}K [mBq/kg]	^{60}Co [mBq/kg]
COPPER FINGER	< 1.5	< 25	< 4	< 9	(0.6 ± 0.3)
MAGNETIC SHIELD	< 8.4	< 8.3	< 8.4	< 35	< 3.7
SINGLE-JUNCT CIRCULATORS	< 190	< 330	< 410	< 2000	< 50
DUAL-JUNCT CIRCULATOR	< 240	< 380	< 380	< 2600	< 70
TRIPLE-JUNCT CIRCULATOR	< 0.19	< 0.24	< 0.22	< 2.0	< 0.04
ATTENUATORS	< 52	< 2100	< 69	< 200	< 6
SMA CONNECTORS	< 48	(1800 ± 600)	(70 ± 30)	(240 ± 90)	(51 ± 8)
COPPER COAX CABLES	$4 \pm 12)$	(1500 ± 400)	(34 ± 17)	(740 ± 130)	< 5
NbTi COAX CABLE	< 750	< 1000	< 380	< 7000	< 230
RADIALL SWITCH	< 1.0	< 1.0	< 1.0	< 1.0	< 0.0
CRYO AMPLIFIER	< 890	< 12000	< 850	< 10000	< 260
CuBe CABLES	$40 \pm 40)$	(8000 ± 3000)	(350 ± 90)	< 500	< 31

Simulations in progress:
➜ rate ~1 evt/day

Strategies for reducing radioactivity impact

- Low radioactivity:
  - underground laboratory, shieldings,...
  - improve radiopurity of setup materials, cleaning, etc...

- Novel chip design
  - phonon traps in the substrate (*F. Henriques et al. Appl. Phys. Lett. 2019, J. Martinis npj Quantum Information 2021*)
  - decouple chips as much as possible from common substrate (*J. Orrell and B. Loer Phys. Rev. Appl. 2021, activities of P. For Diaz at Canfranc, ...*)



Conclusions

- Radioactivity will be the ultimate limit for coherence of qubits
- Severely affects quantum error correction ➔ **correlated noise**
- Evidence that **suppressing radioactivity improves the qubits**

Since 2018: a lot of progress, new bridges between communities

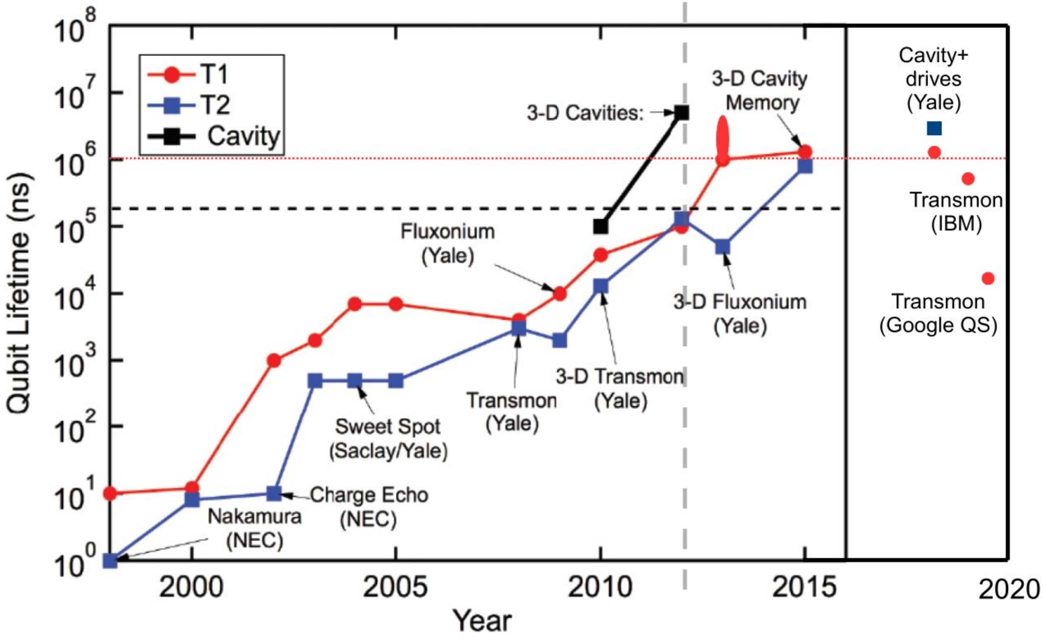
- **Astro-particle physics** has knowledge/expertise that would significantly advance the comprehension and performance of these devices
- **Particle physicists** are getting excited: quantum sensing to search for dark photons, axions, … but also technological breakthroughs for other applications

LNGS 2022 ICRM - LLRMT

Backup

Coherence

- The longer the better
- Coherence time >> gate operation time
- Goal: **millisecond** scale and beyond



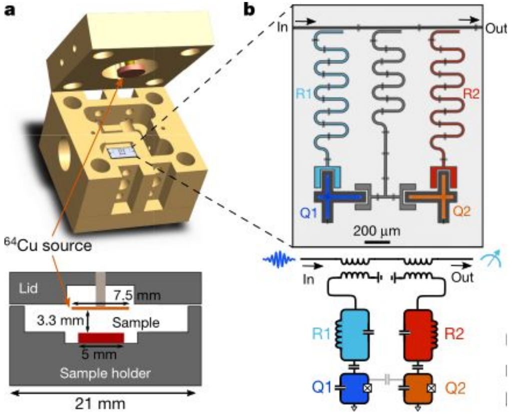
Original plot (up to 2012): M.H. Devoret & R.J. Schoelkopf, Science 339, 1169 (2013)
extension (up to 2015): M. Reagor, PhD thesis (Yale)

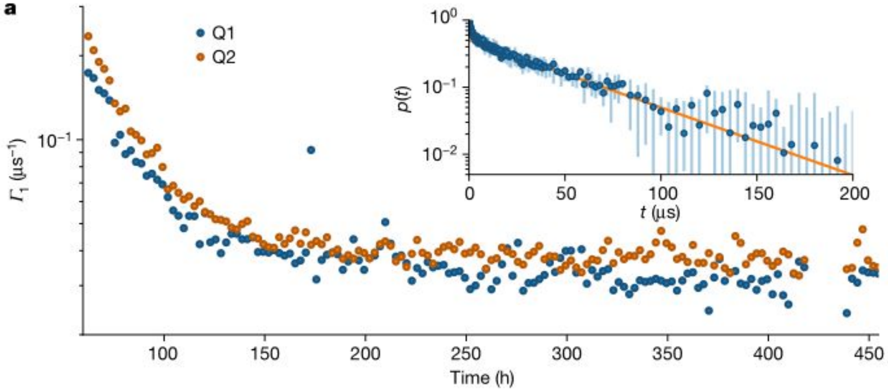
Qubit vs radioactive source

- Qubit faced to a fast-decaying source (Copper-64, half-life 12.7 h)
- Coherence of qubit increases while the source decays
- Radioactivity limits the coherence time of superconducting qubits to **~ms**

Reducing impact of radioactivity will be critical for realizing fault-tolerant superconductive quantum computers

Vepsäläinen et al, Nature 2020



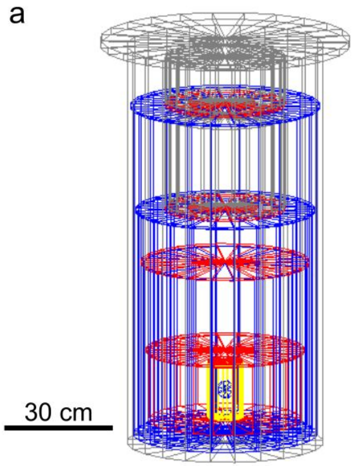


ICRM - LLRMT LNGS 2022

Monte Carlo simulations

Simulations are an important tool to

- **predict the impact** of radioactivity in a given setup
- find the elements that have the **most important contributions**
- **optimize** geometry, cleaning protocols, etc… to minimize the rate



Input:

- geometry of the chip + setup: box, holder, shieldings, cryostat
- flux of μ , ɣ, neutrons
- radioactivity of materials

Output ➔ Energy deposits in the chip (x,y,z,dE)

ICRM - LLRMT LNGS 2022