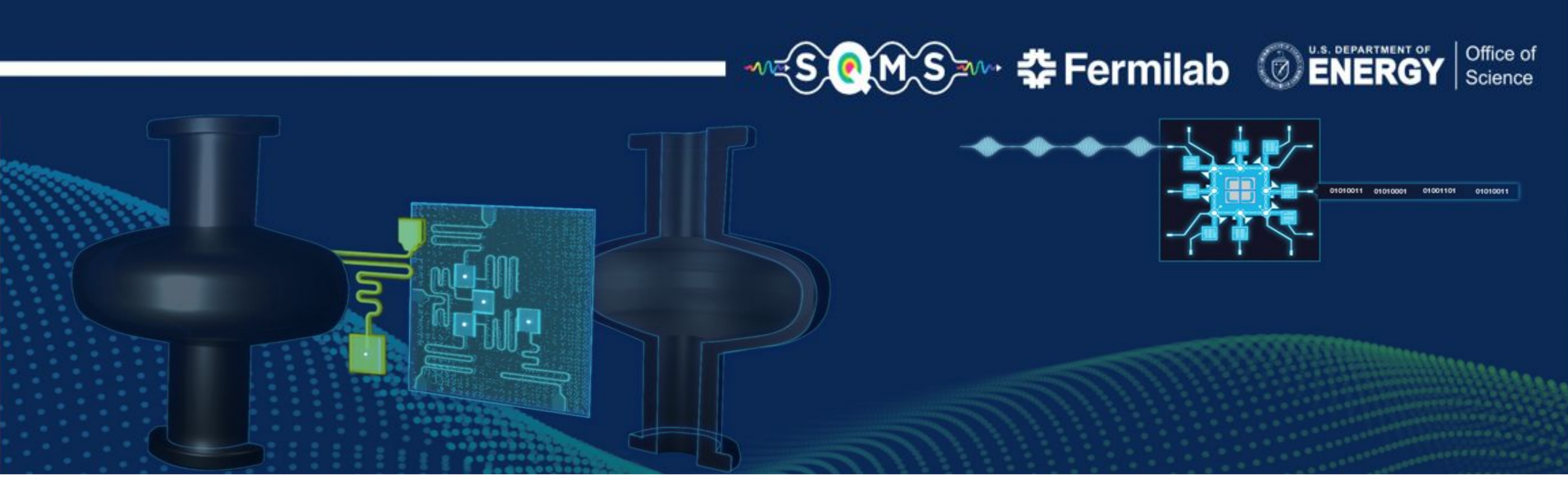


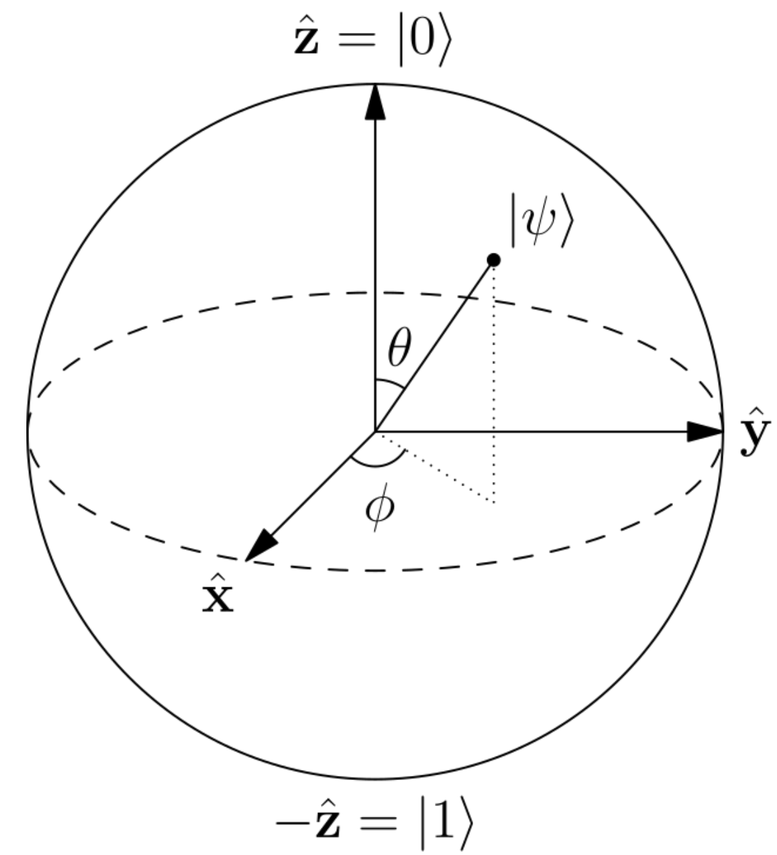

# Impact of environmental and materials radioactive contamination in superconducting quantum bits

Giulia D'Imperio for the DEMETRA and SQMS collaborations


15/06/2022 LRT workshop
South Dakota Mines

INFN
Istituto Nazionale di Fisica Nucleare

# Qubits




- Unit of quantum information
- Superposition of |0> and |1> states of a two-level quantum system
- n entangled qubits → $2^n$ possible states

Ideal Features:

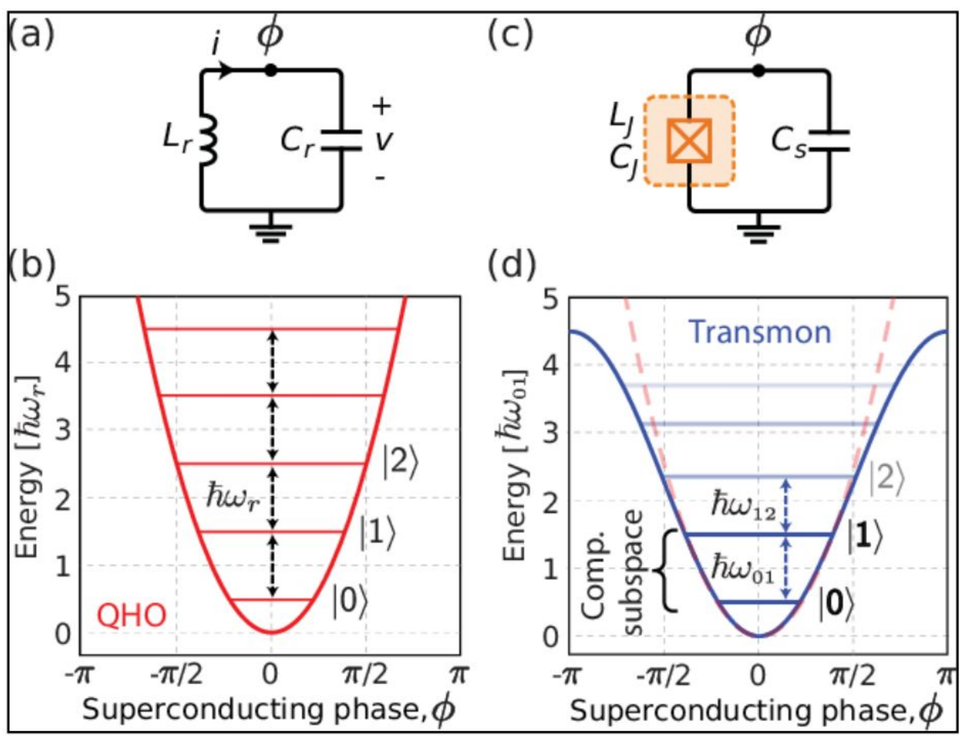
1. Strongly coupled to other qubits → **entanglement**
2. Decoupled from the world → **quantum coherence**

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

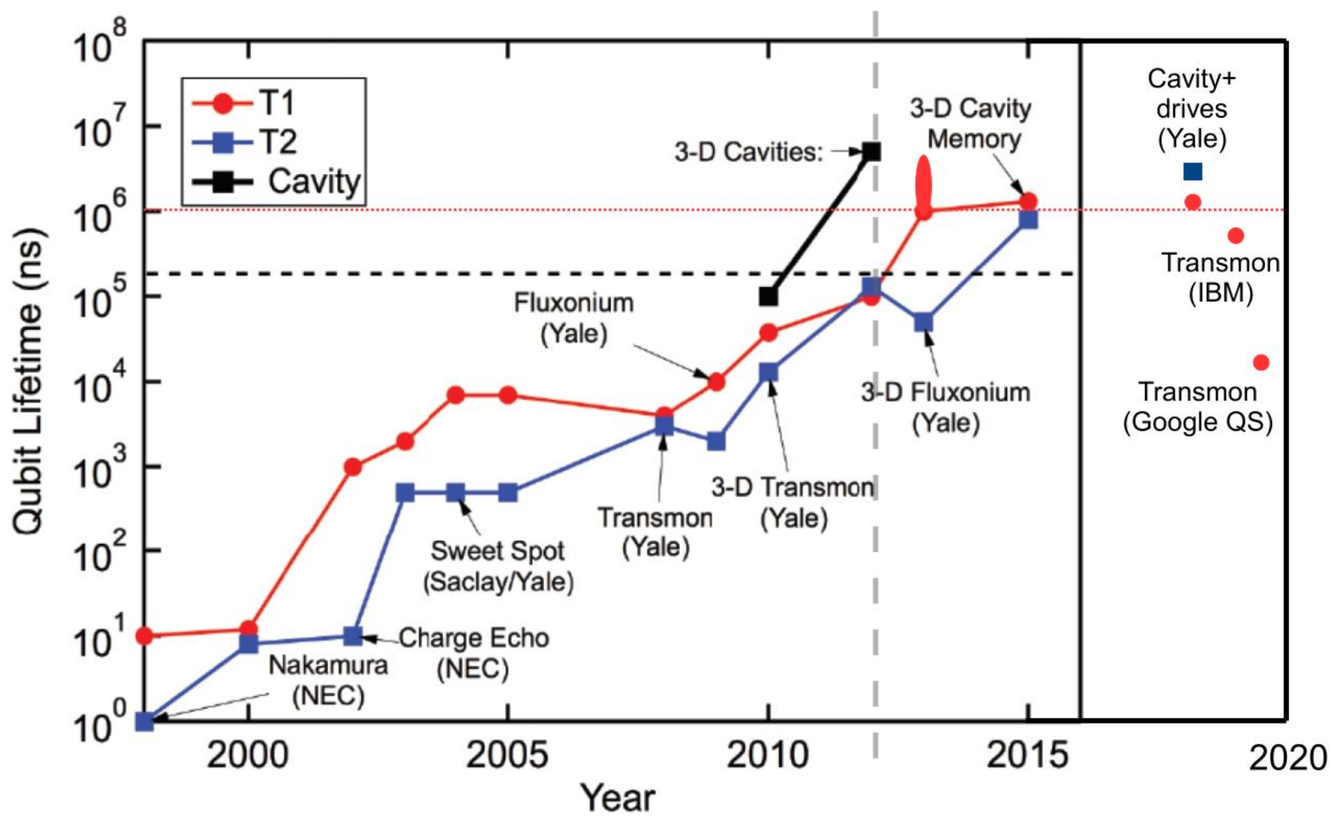
**Pros** 👍 Scalable (reached up to 100 qubits: Sycamore, Aspen-9, Zu Chongzhi, IBM,...)

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

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

# Coherence

- The longer the better
- Coherence time >> gate  operation time
- Goal: **millisecond** scale and beyond → present status  **~10-100 µs**

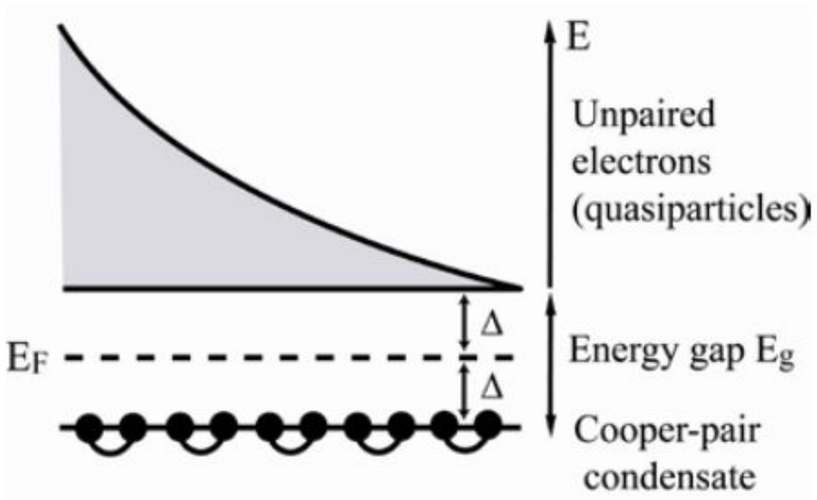



Original plot (up to 2012): [ M.H. Devoret & R.J. Schoelkopf, Science 339, 1169 (2013) ]
Extension (up to 2015): [ M. Reagor, PhD thesis (Yale) ]

# Quasiparticles

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

- Many mechanisms can break Cooper pairs into quasiparticles ($\Delta_0$ ~ 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]



# 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)*.

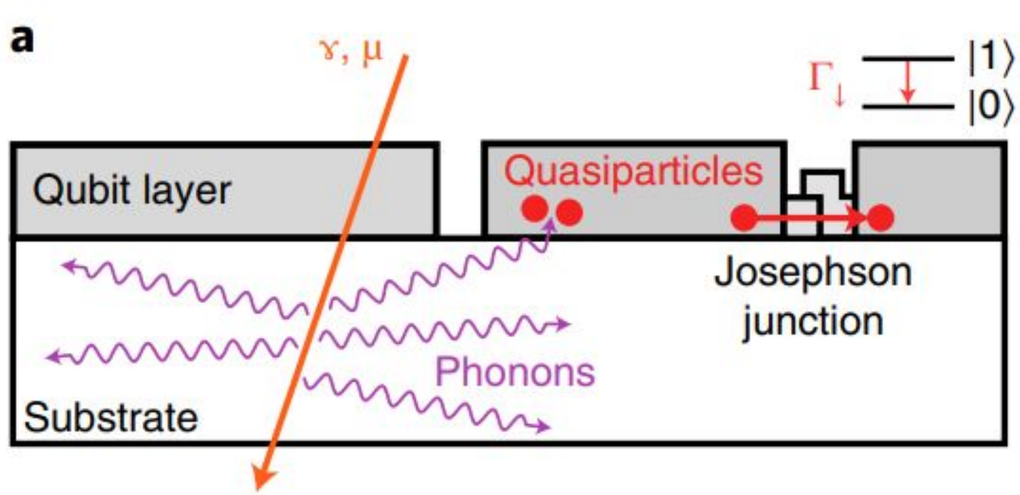
2. Radioactivity **limits quantum error correction** in a matrix of qubits [mainly Wisconsin Univ., INFN-Roma, Fermilab, Google]: *Wilen et al, Nature (2021), McEwen et al., Nature Physics (2022)*

3. **Suppressing radioactivity improves the performance of quantum circuits** [mainly INFN-Roma and LNGS, KIT]: *Cardani et al, Nature Communications (2020), Gusenkova et al., Appl. Phys. Lett. 120, 054001 (2022)*

# Radioactivity vs qubits

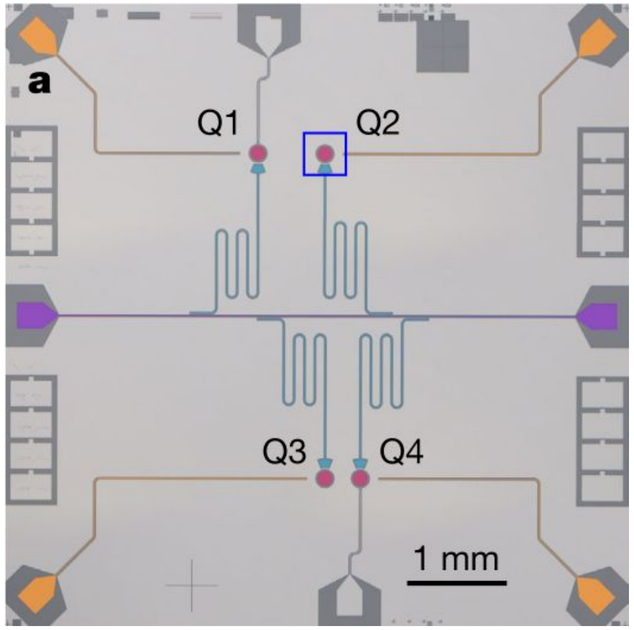
- **Direct interaction** in the qubit unlikely (qubit dimension < 100 μm)
- **Indirect interaction**: radioactivity deposits energy in **substrate** (typically ~$cm^2$ area x 300 μm thickness ), **O(100) keV energy** deposits
- **Charges** and **phonons** are produced and diffuse in the substrate
- Phonons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

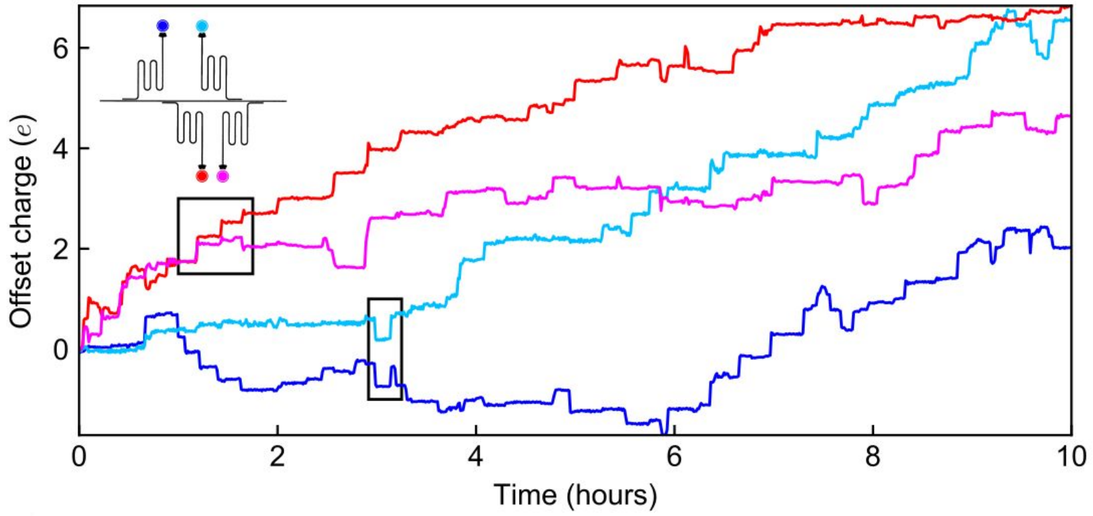
J.**Low Temp**.Phys. 199 (2020) 475



# Quantum error correction

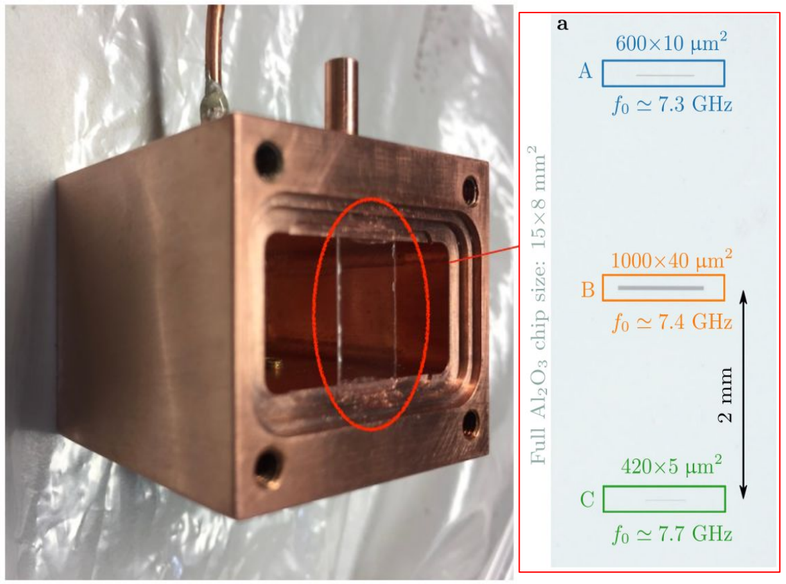
- Most popular idea for quantum error correction: encode quantum information in a **matrix of qubits**
- Key assumption: errors across the qubits belonging to this matrix are **uncorrelated in space and time**
- Radioactivity in the substrate can simultaneously affect more qubits



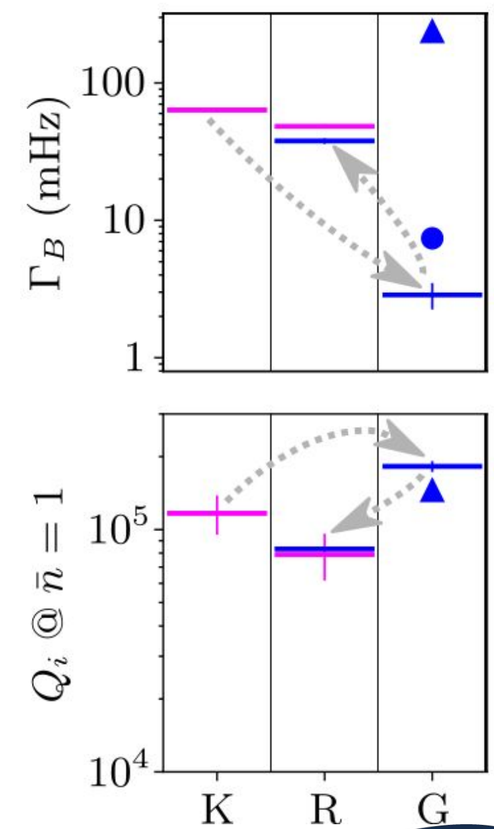

*Wilen et al, Nature (2021)*

# 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 "Q" decreases with QP burst rate




- 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

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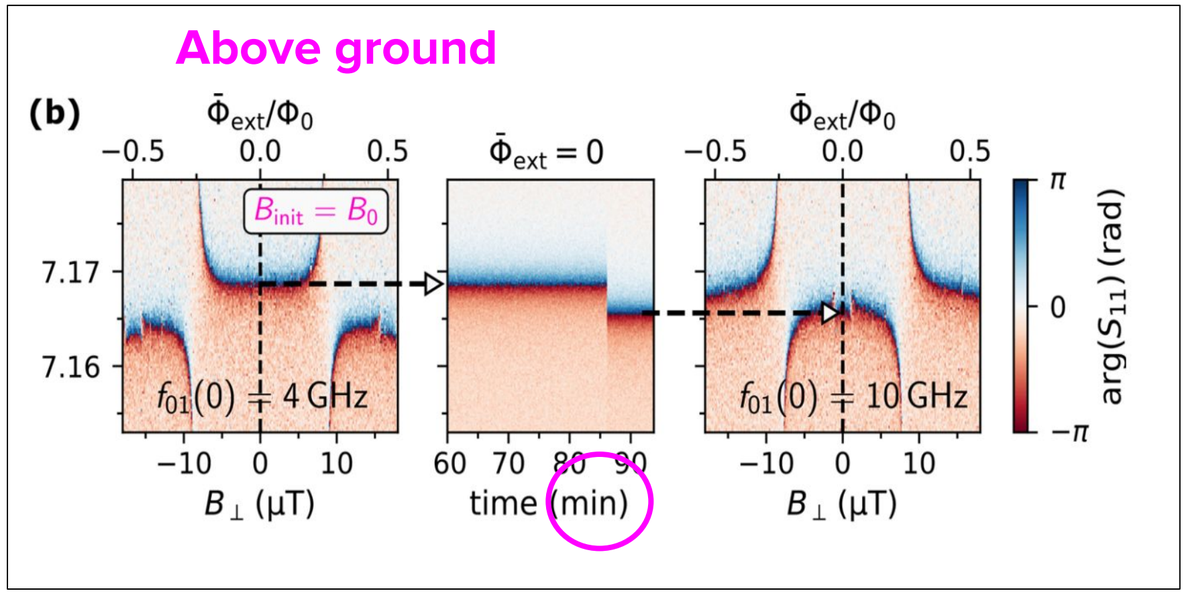
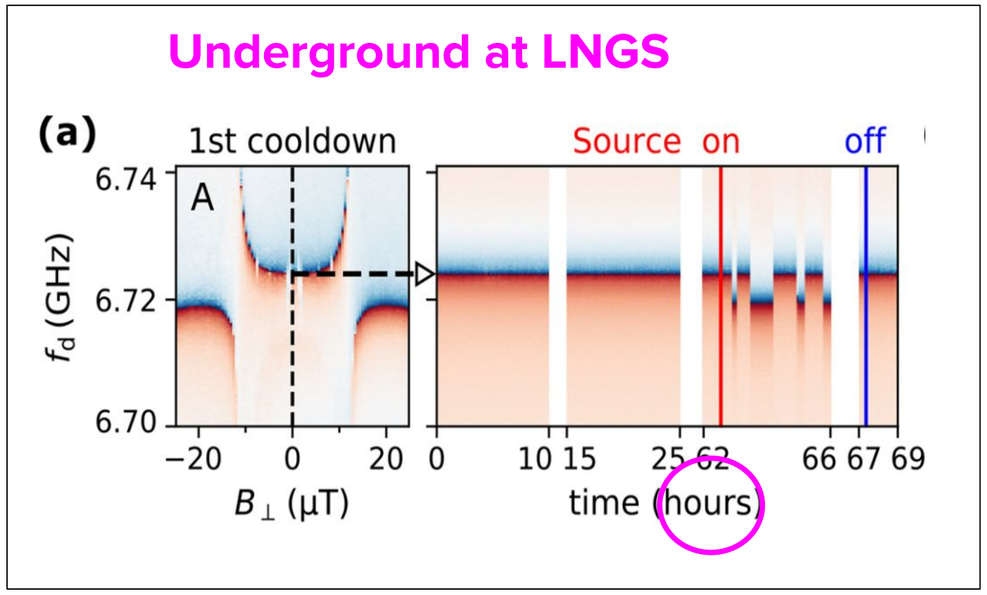
# Qubits (fluxonium) in underground setup

- Readout line at LNGS recently upgraded
- Measurements of fluxonium qubit instead of resonators

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



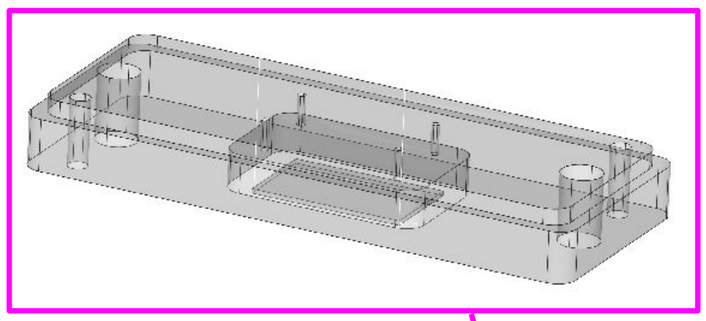



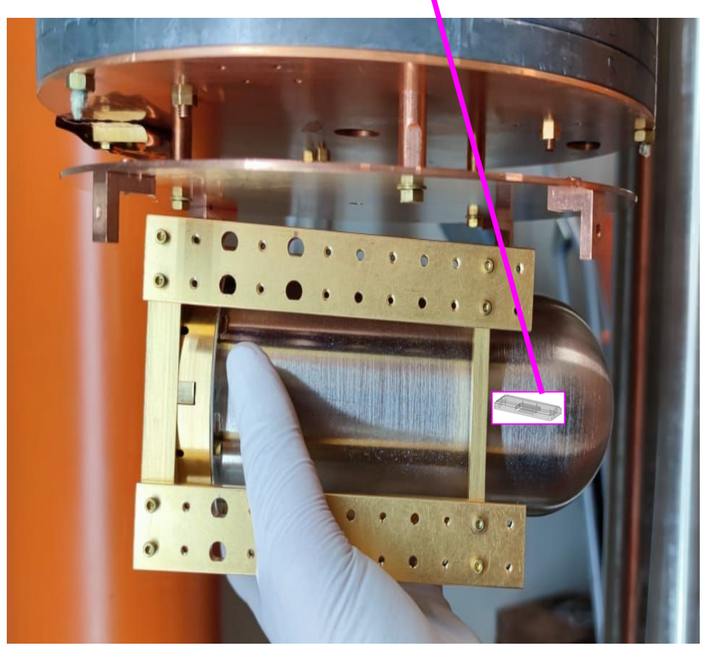

- Large **improvement of frequency stability**

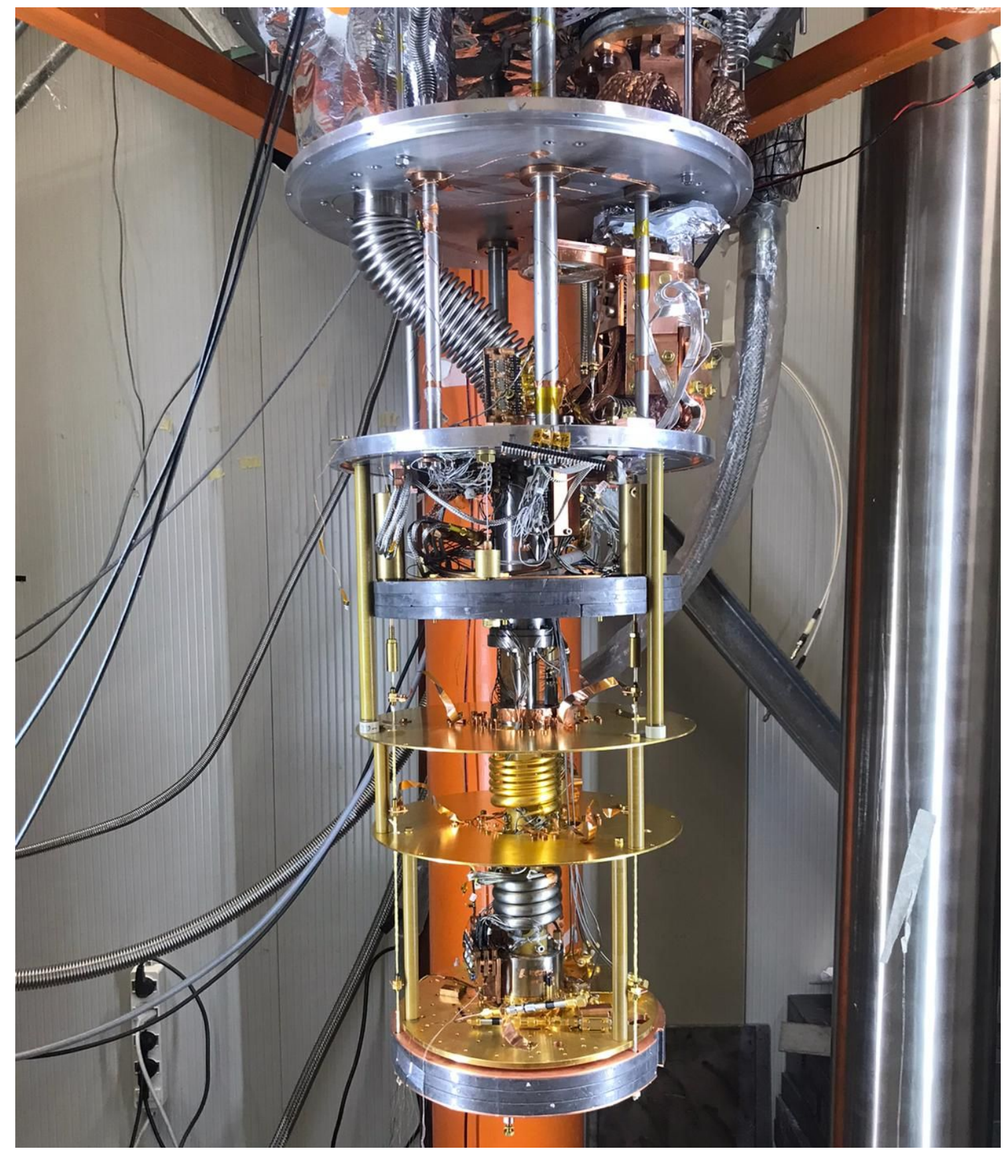
Soon measurements with more performing fluxonium and transmon qubits

# 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 (underground)





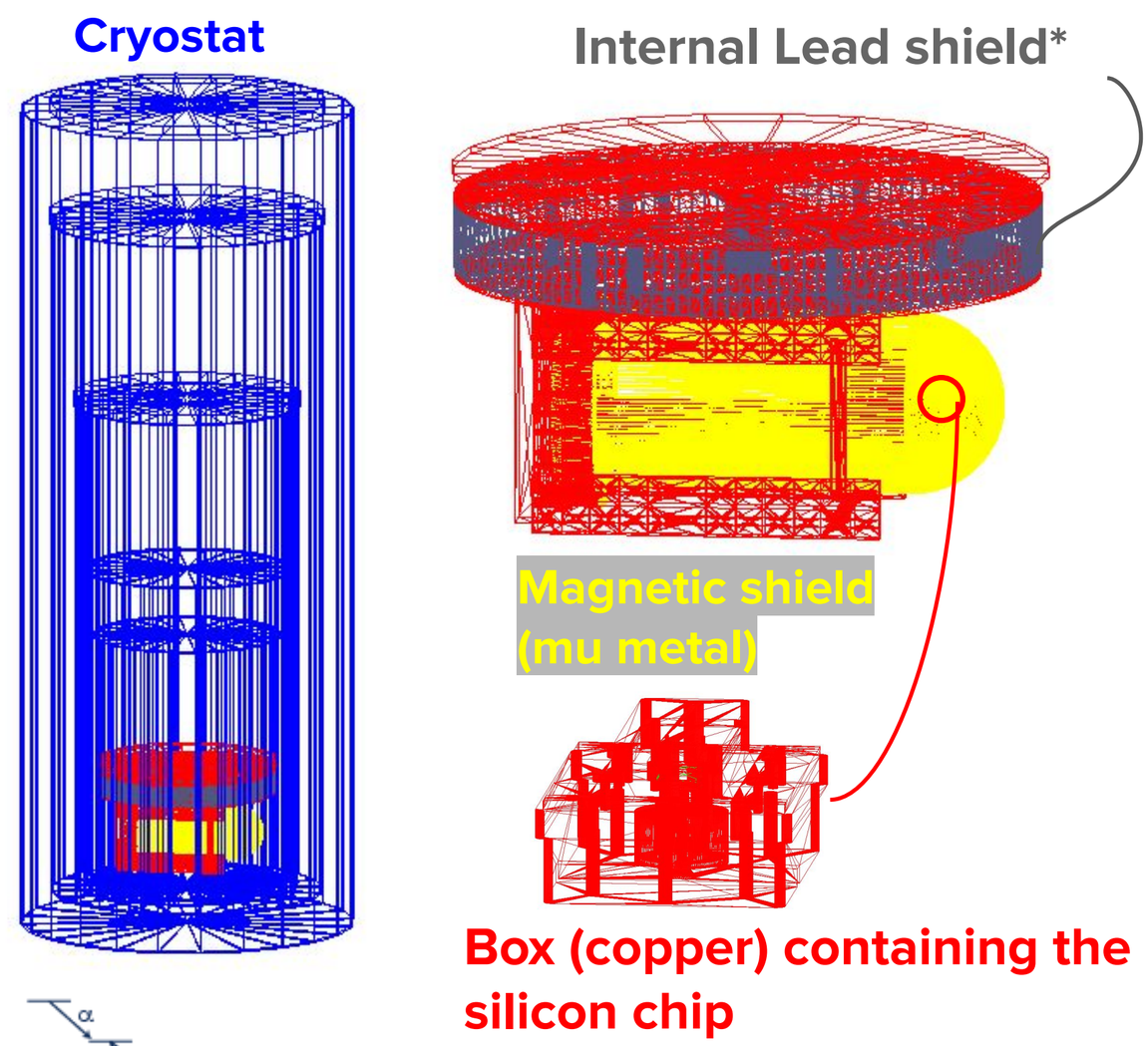


Pictures from the setup @LNGS

# Monte Carlo simulations

Geant-4 based simulation, using the following inputs:

- geometry of the chip + setup: box, holder, shieldings, cryostat
- flux of μ , γ, neutrons (measurements + literature)
- radioactivity of setup materials (measurements @LNGS HPGe facility)



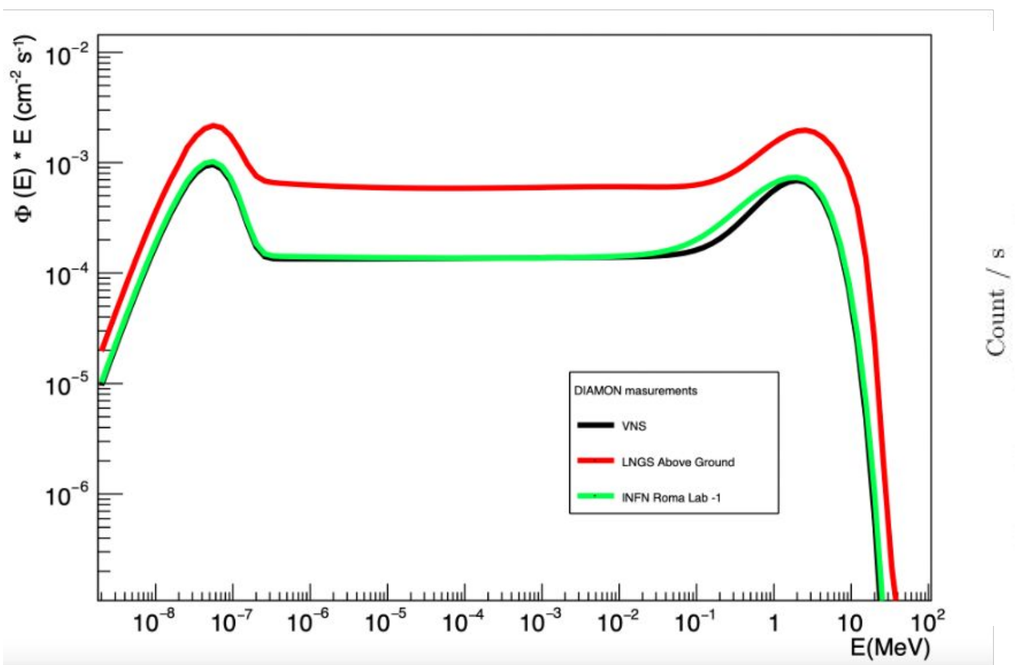

Simulations are an important tool to

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

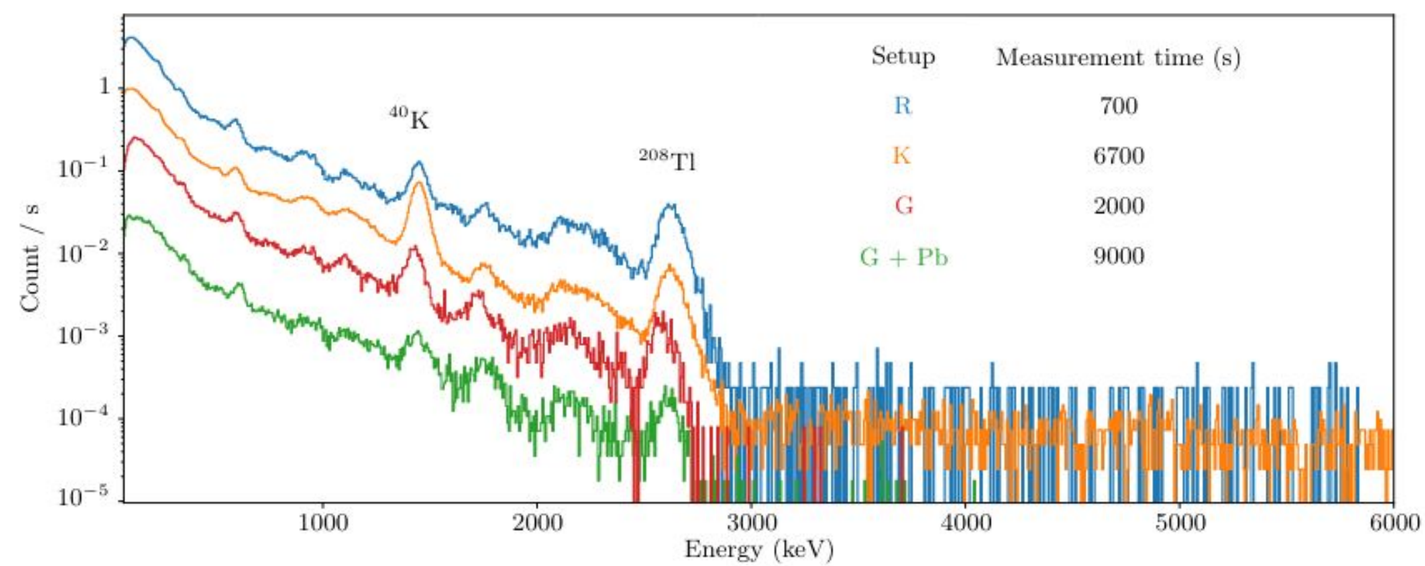
# Radioactivity measurements

Radioactivity measurements of “external sources”

- **Gammas** ➔ measurements with NaI(Tl) detector in several laboratories, above ground and underground
- **Neutrons** ➔ measurements with DIAMON spectrometer (**negligible underground**)
- **Muons** ➔ literature [IJMP A Vol. 33, No. 30, (2018)], **negligible underground**




Neutron measurements performed in several locations so far with fluxes from $10^{-3}$ to $10^{-2}$ n/cm$^2$/s




Simulations work allowed to reconstruct the flux that would produce these spectra in a 3” NaI spectrometer:

- Flux at Rome: ~15 γ/cm$^2$/sec
- Flux at LNGS ~1 γ/cm$^2$/sec

# Radioactivity measurements

Radioactivity of the materials “close” to the chip:

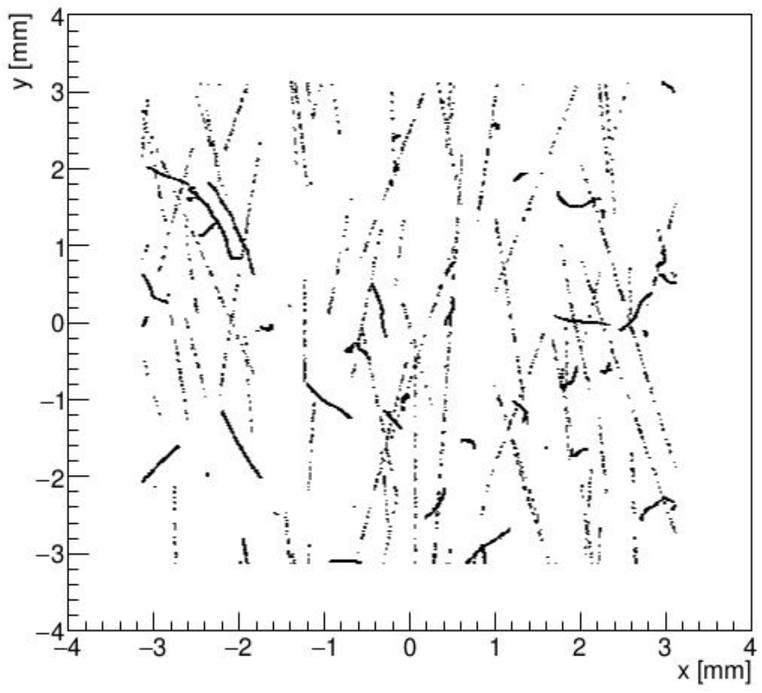
- all materials of the setup have been measured with HPGe @LNGS (M. Laubenstein & L. Pagnanini)

| | Component | $^{232}$Th [mBq/kg] | $^{238}$U [mBq/kg] | $^{235}$U [mBq/kg] | $^{40}$K [mBq/kg] | $^{60}$Co [mBq/kg] |
|---|---|---|---|---|---|---|
| COPPER FINGER | $A$ | $< 1.5$ | $< 25$ | $< 4$ | $< 9$ | $(0.6 \pm 0.3)$ |
| MAGNETIC SHIELD | $B$ | $< 8.4$ | $< 8.3$ | $< 8.4$ | $< 35$ | $< 3.7$ |
| SINGLE-JUNCT CIRCULATORS | $C$ | $< 190$ | $< 330$ | $< 410$ | $< 2000$ | $< 50$ |
| DUAL-JUNCT CIRCULATORS | $D$ | $< 240$ | $< 380$ | $< 380$ | $< 2600$ | $< 70$ |
| TRIPLE-JUNCT CIRCULATORS | $E$ | $< 0.19$ | $< 0.24$ | $< 0.22$ | $< 2.0$ | $< 0.04$ |
| ATTENUATORS | $F$ | $< 52$ | $< 2100$ | $< 69$ | $< 200$ | $< 6$ |
| SMA CONNECTORS | $G$ | $< 48$ | $(1800 \pm 600)$ | $(70 \pm 30)$ | $(240 \pm 90)$ | $(51 \pm 8)$ |
| COPPER COAX CABLES | $H$ | $(54 \pm 12)$ | $(1500 \pm 400)$ | $(34 \pm 17)$ | $(740 \pm 130)$ | $< 5$ |
| NbTi COAX CABLE | $I$ | $< 750$ | $< 1000$ | $< 380$ | $< 7000$ | $< 230$ |
| RADIALL SWITCH | $J$ | | measurements in progress | | | |
| CRYO AMPLIFIER | $K$ | $< 890$ | $< 12000$ | $< 850$ | $< 10000$ | $< 260$ |
| CuBe CABLES | $L$ | $(240 \pm 40)$ | $(8000 \pm 3000)$ | $(350 \pm 90)$ | $< 500$ | $< 31$ |

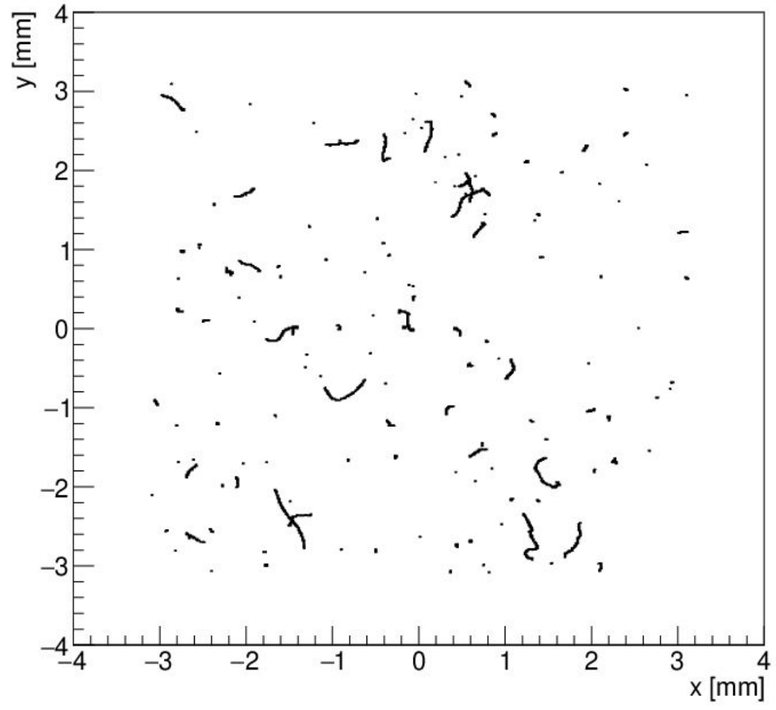
# Simulated energy deposits

- Output of Geant-4 simulations ➔ position of “hits” and energy deposits in the silicon chip  (x,y,z,dE)
- Different particles leave different “tracks” in the chip and deposit different amount of energy

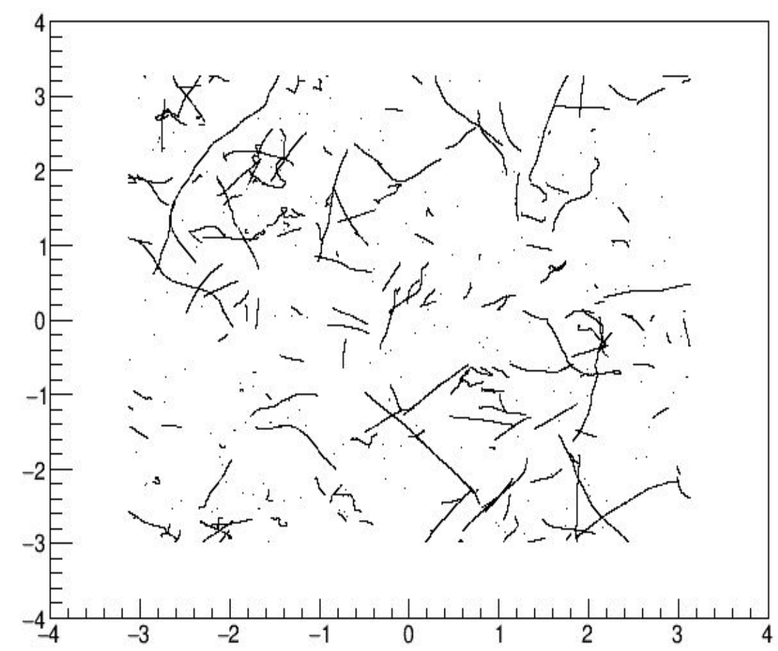
**Muons**



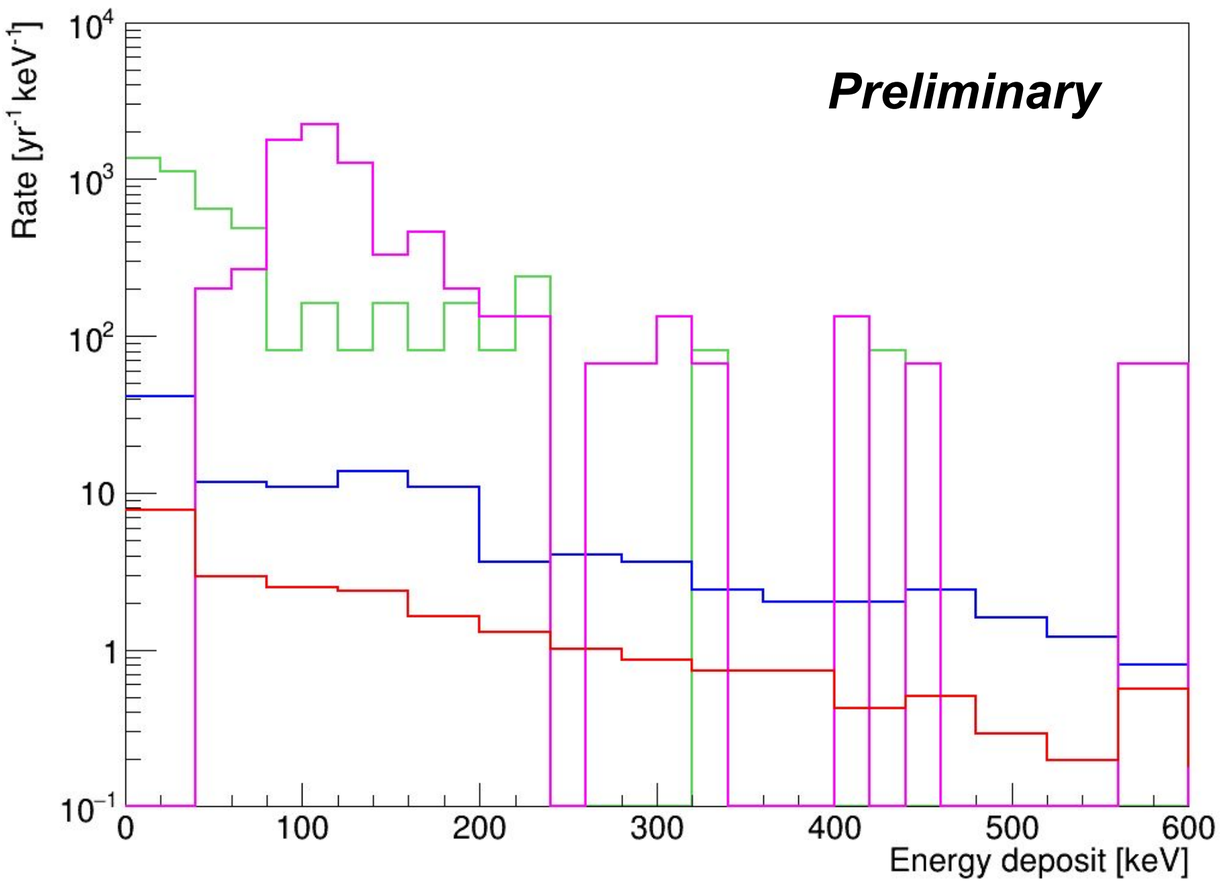

**Gammas**




**Neutrons**



# MC results for Round Robin




- Expected rate from **muons** in the silicon chip: **5 mHz** (avg 140 keV)
- Expected rate from **gammas** in the silicon chip: **6 mHz** (avg 70 keV)
- Expected rate from **neutrons** in the silicon chip: **0.15 mHz** (avg 150 keV)
- Expected rate from **close sources** in the silicon chip: **0.03 mHz** (avg 150 keV)

- At LNGS **underground** labs **muons** and **neutrons** are **negligible**
- Internal lead shield (3 cm thick) improves gamma rate of factor ~2
- An external lead shield can further improve gamma rate
- Comparison with the measurements of same qubit at FNAL will help us to study the performance of qubits in extremely clean environment

Low Radioactivity Techniques

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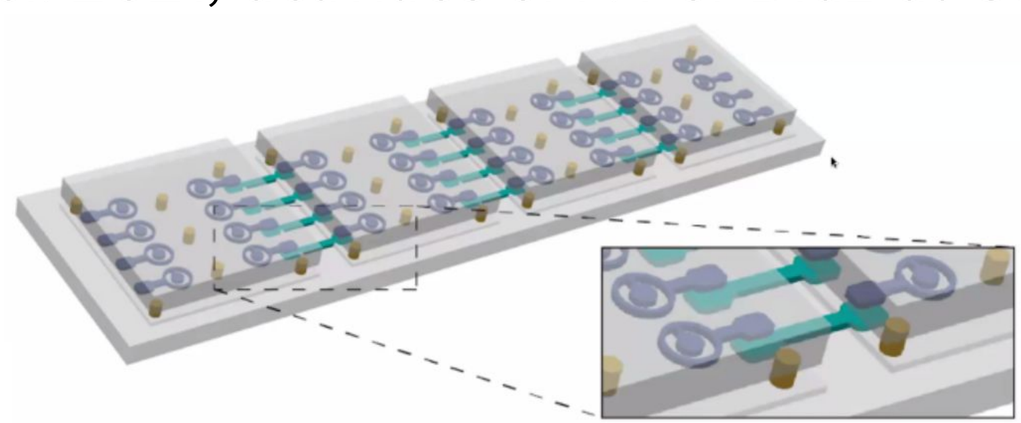
# Strategies for reducing radioactivity impact

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

- **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**
- At LNGS underground laboratories we will measure **qubits in an extremely radiopure environments** ➔ help us to understand better the impact on qubit performance

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

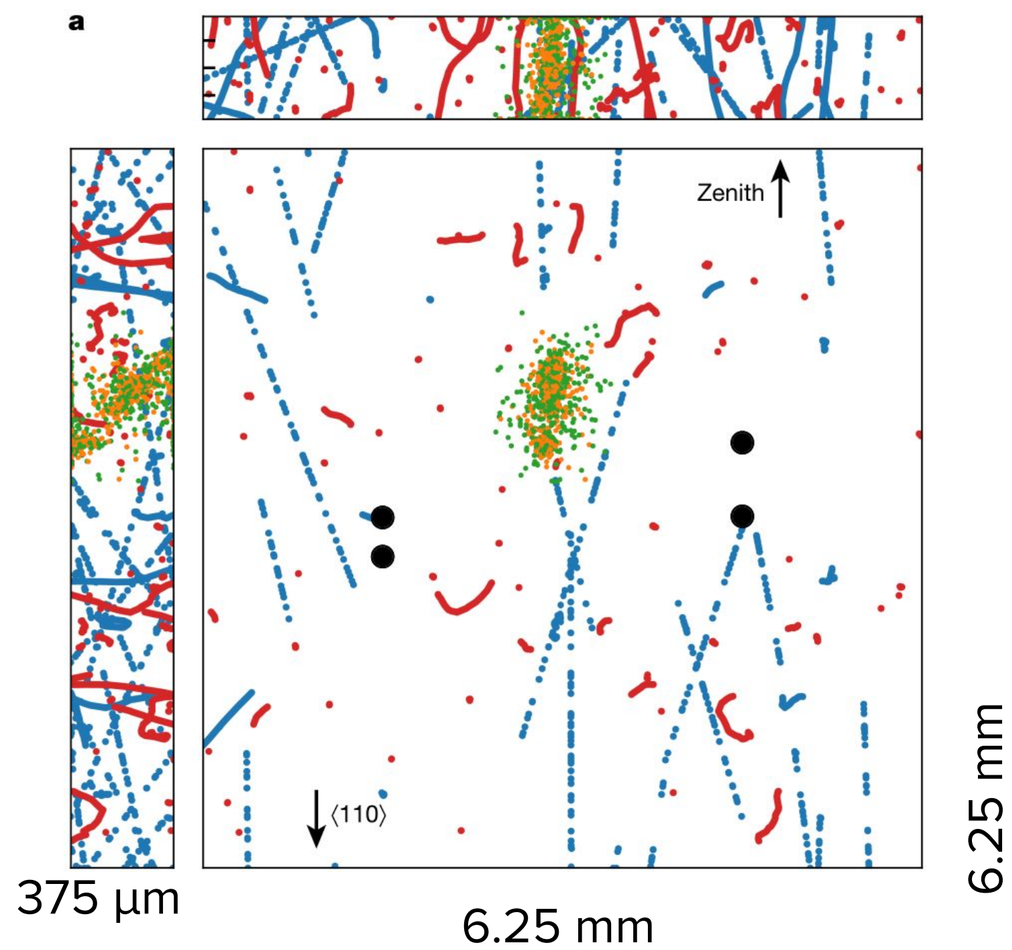
# Backup

# 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: correlated errors

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

Footprints of charges are <mm scale, phonons diffuse to all the chip size (~cm)