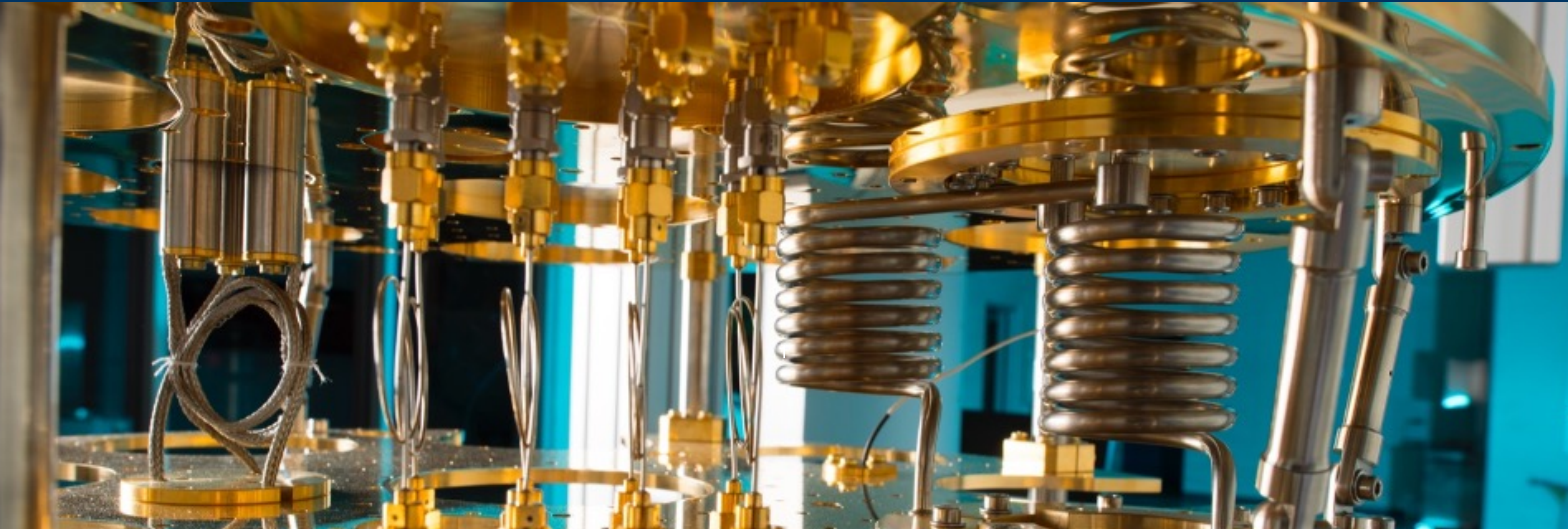
Impact of Radioactivity on Quantum Circuits: European Laboratories

Laura Cardani, INFN

Low Radioactivity Techniques, 1-4 October 2024, Kraków, Poland

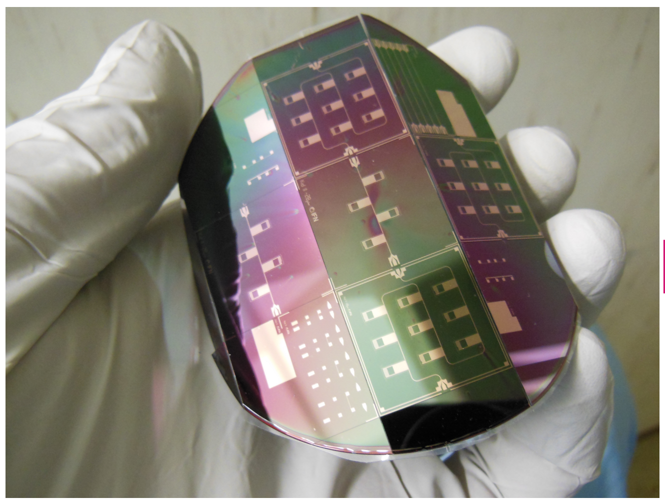


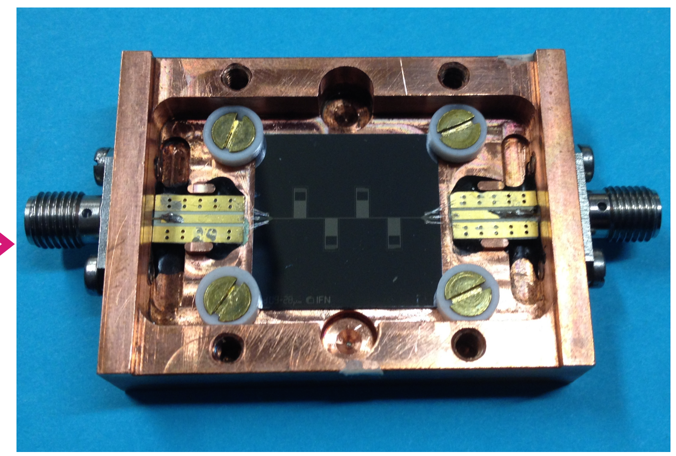
Motivation

Superconducting qubits should be **isolated** from environment

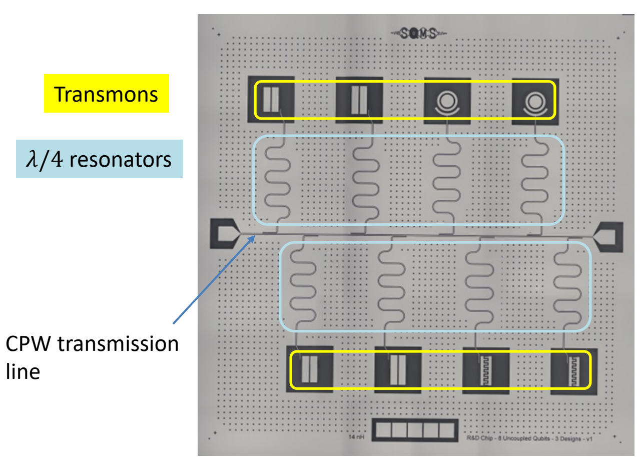
But they look a lot like particle detectors

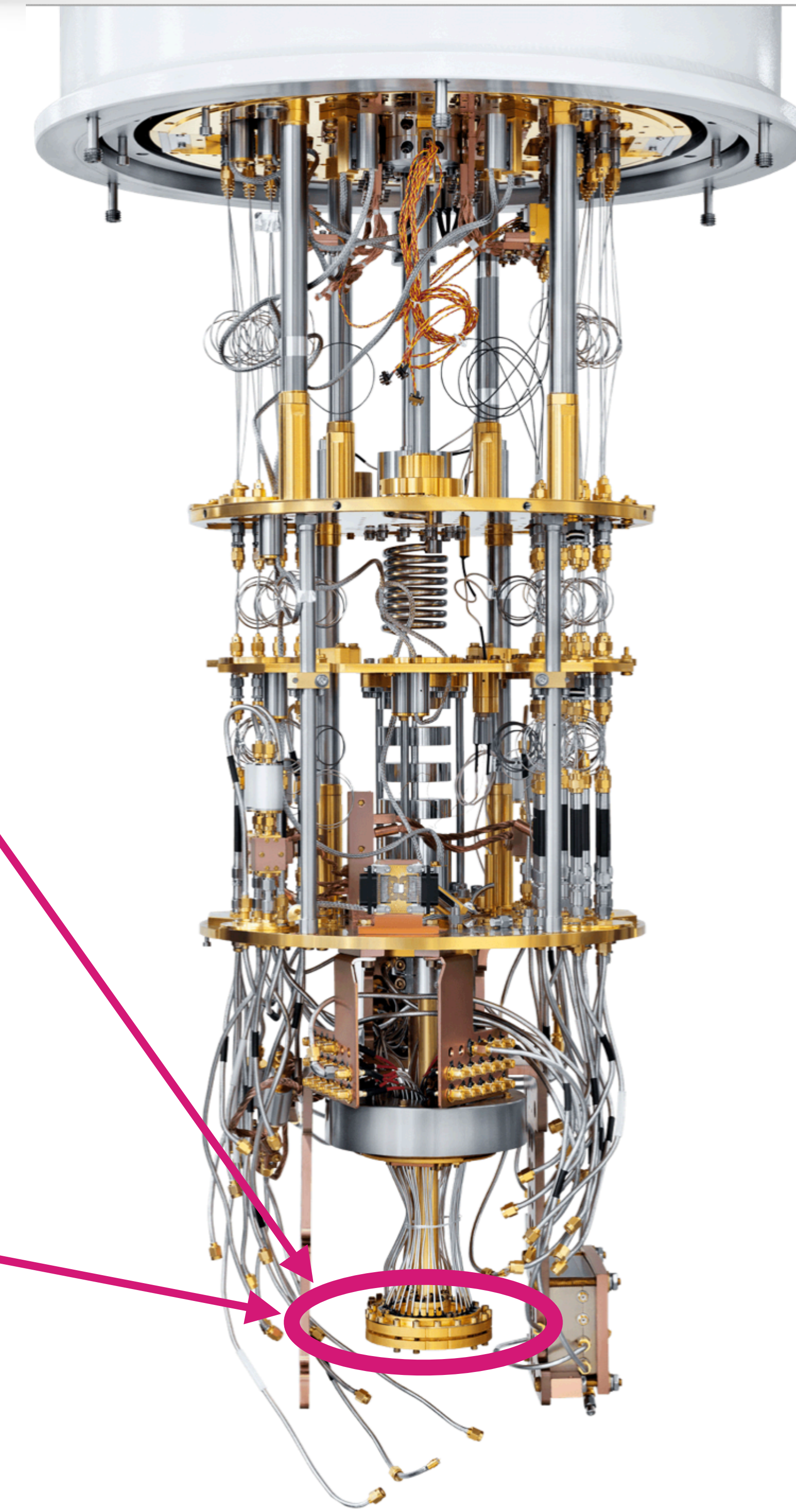
CALDER light detector prototype





FNAL 8 qubit prototype

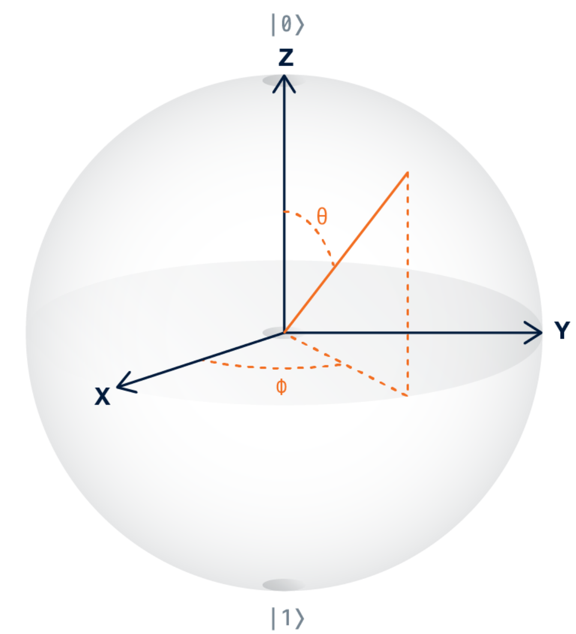


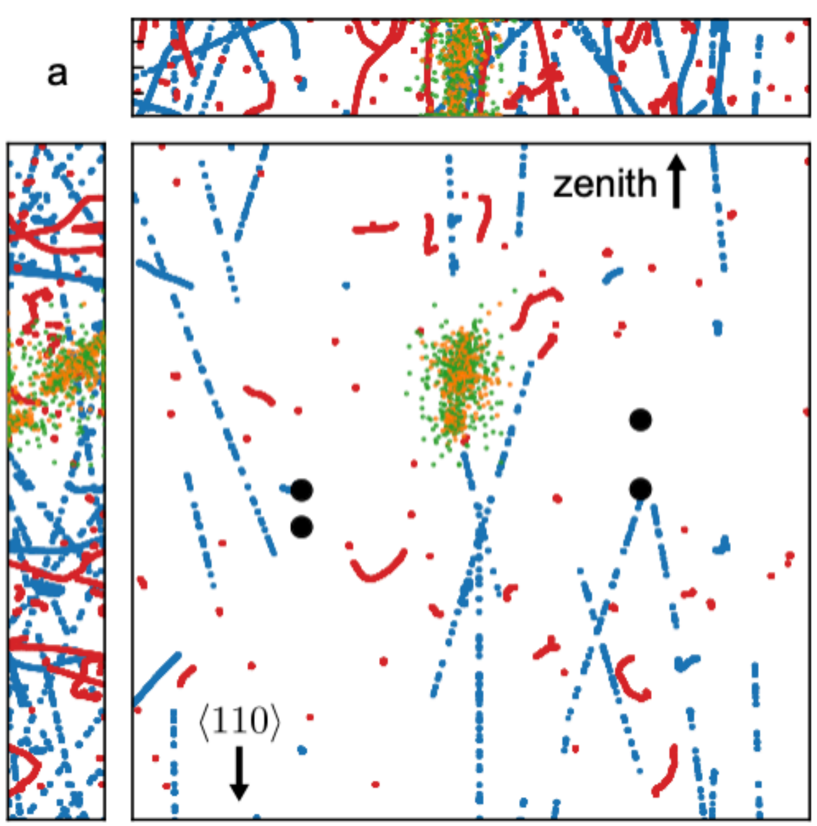


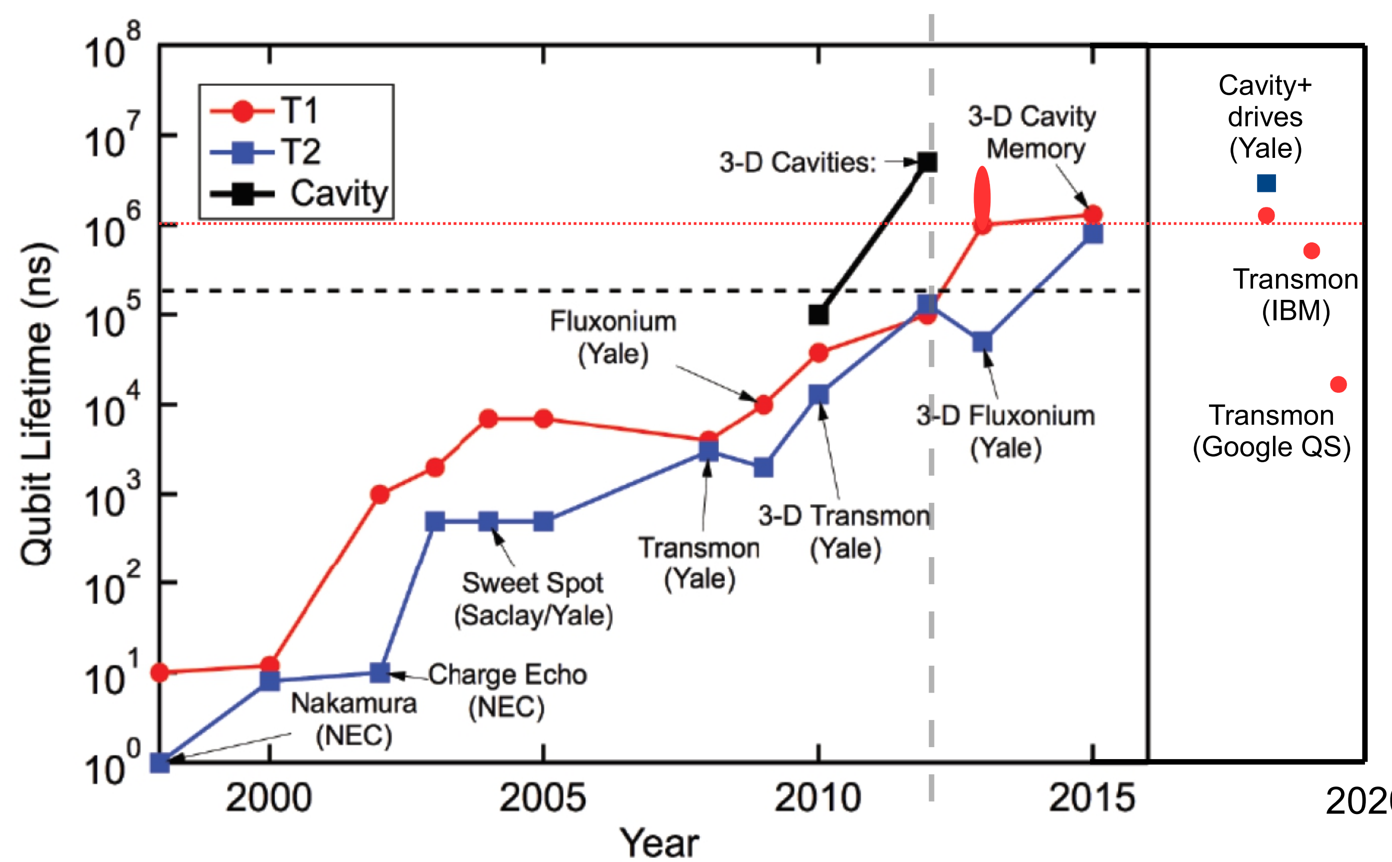
Energy deposit in the chip —> charges/phonons —> break Cooper pairs in sensor/qubit

In this Talk

- Effects of Radioactivity in Superconducting Qubits;
- Sources of Radioactivity;
- Mitigation strategies;
- Perspectives;

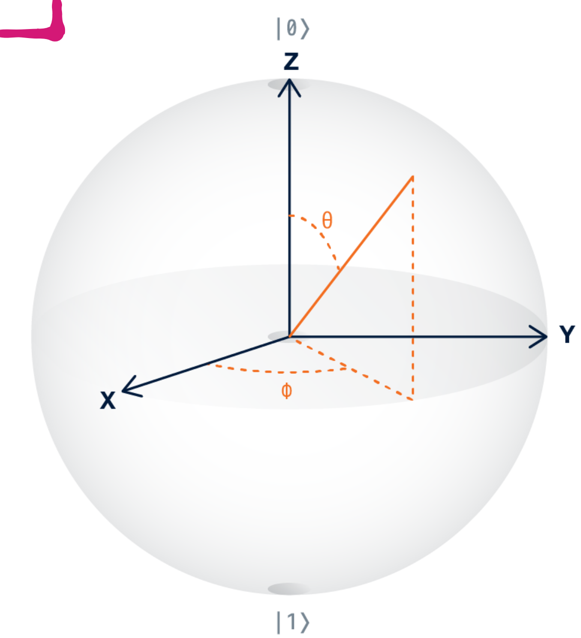


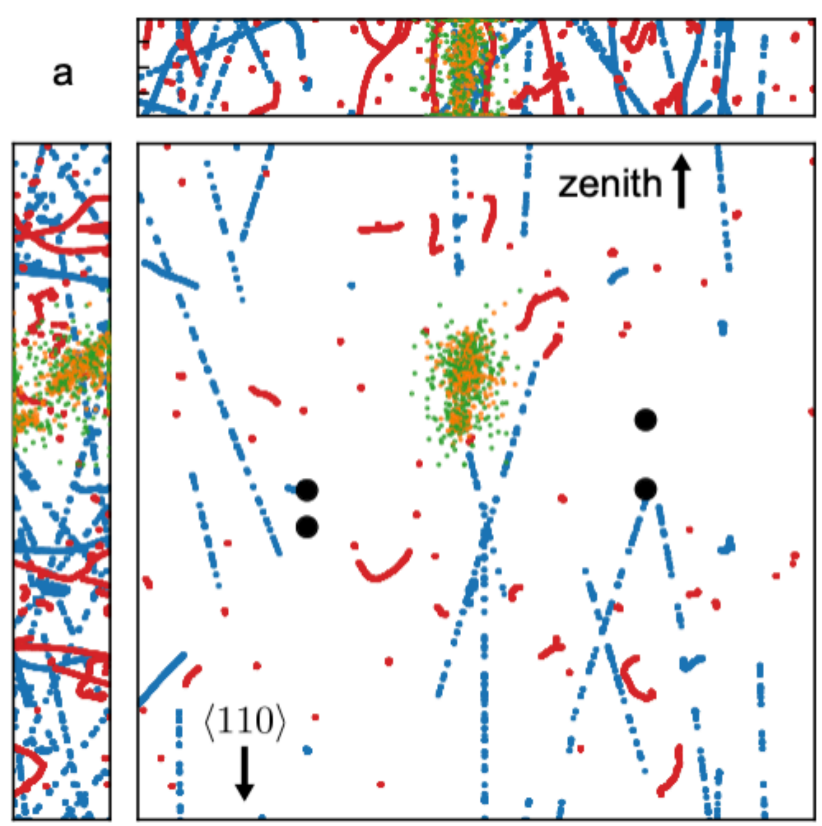


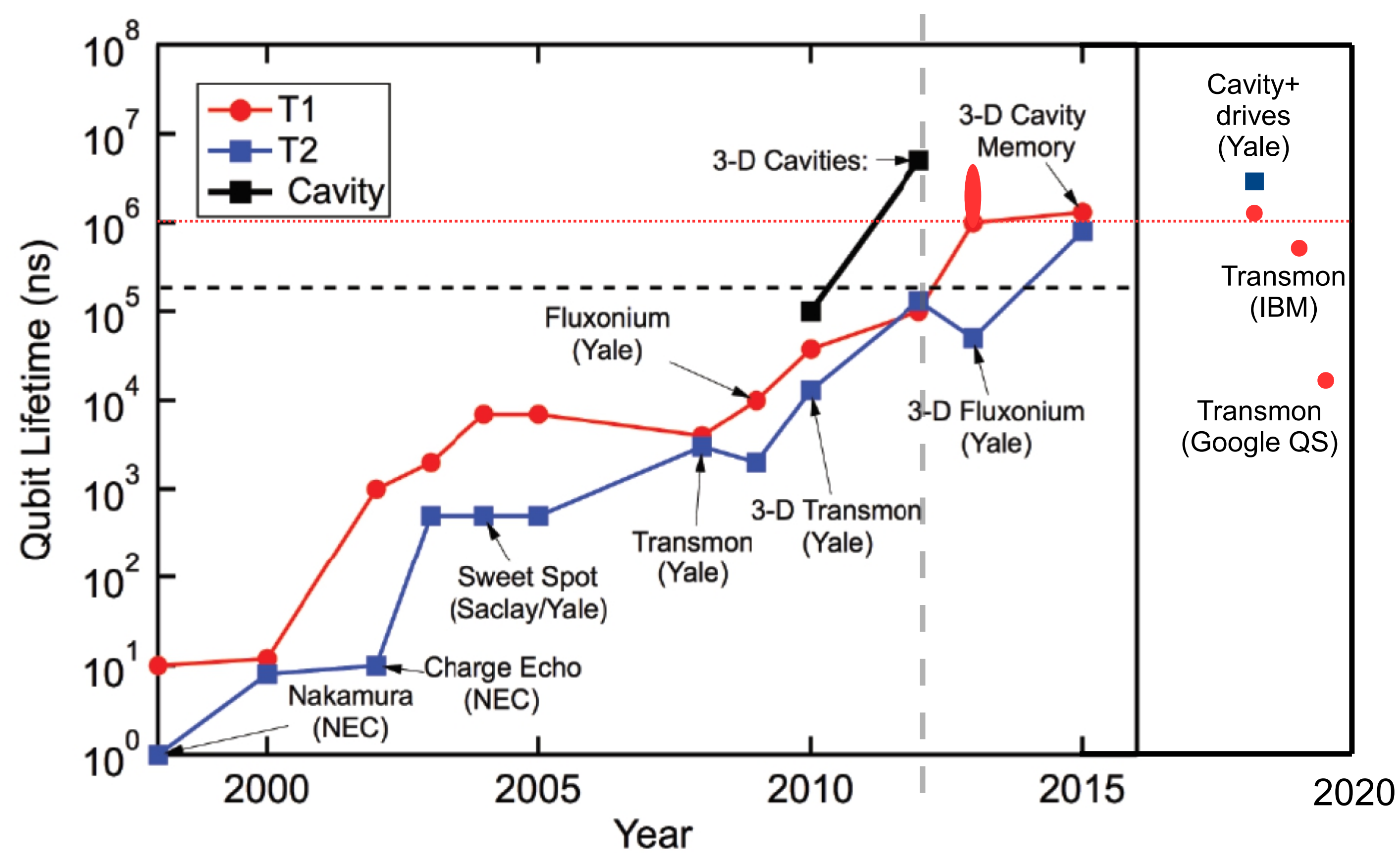


In this Talk

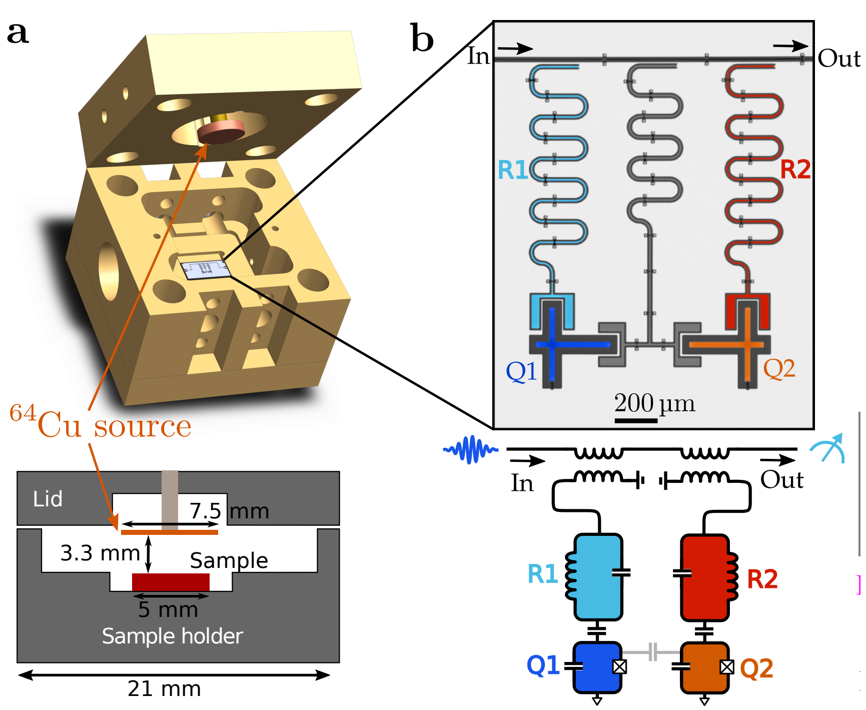
- Effects of Radioactivity in Superconducting Qubits;
- Sources of Radioactivity;
- Mitigation strategies;
- Perspectives;





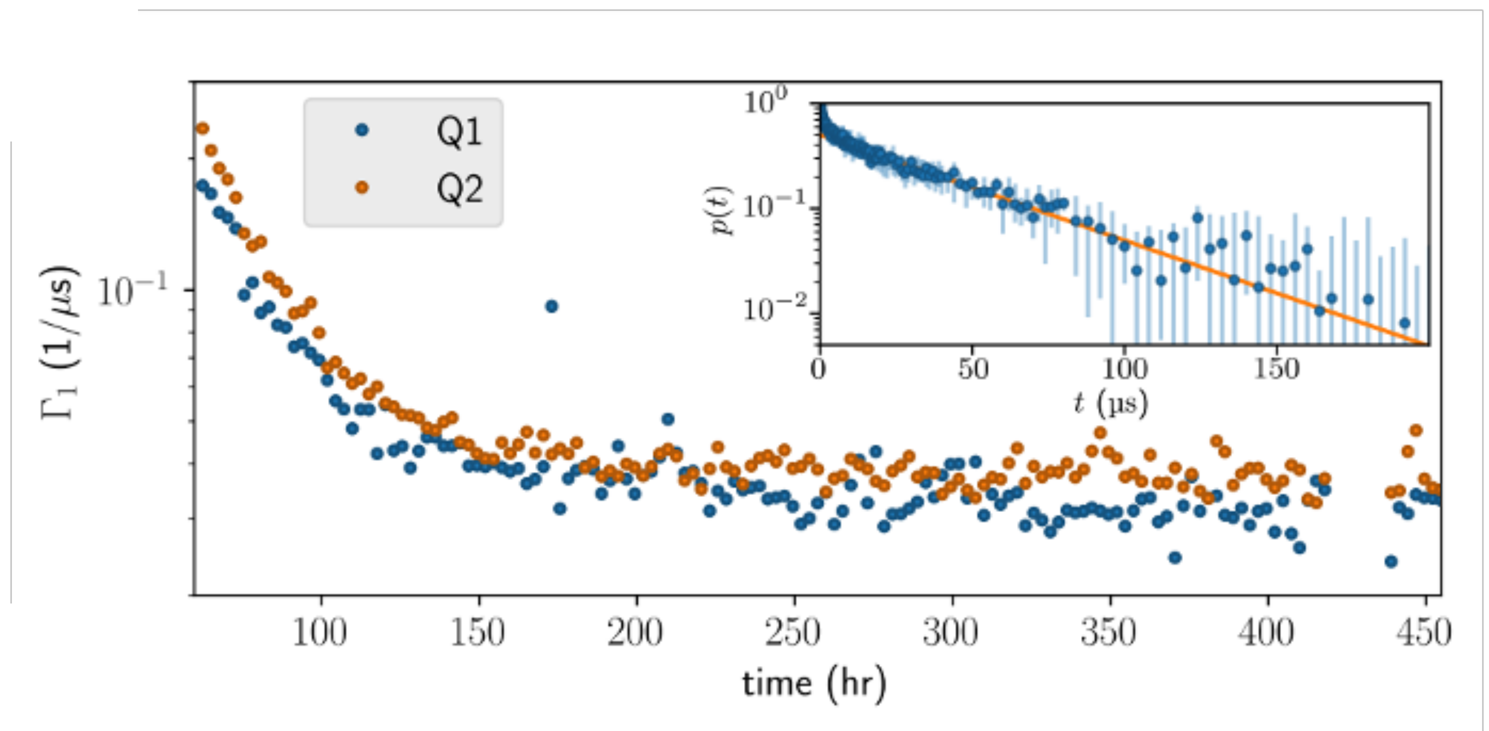


Radioactivity impacts Coherence



Vepsäläinen et al, Nature 2020

- Faced a qubit to a fast-decaying source
- Lifetime of qubit increases when source decays



Conclusion:

The quasiparticle background induced by radioactivity is $x_{QP} \sim 7\text{x}10^{-9}$

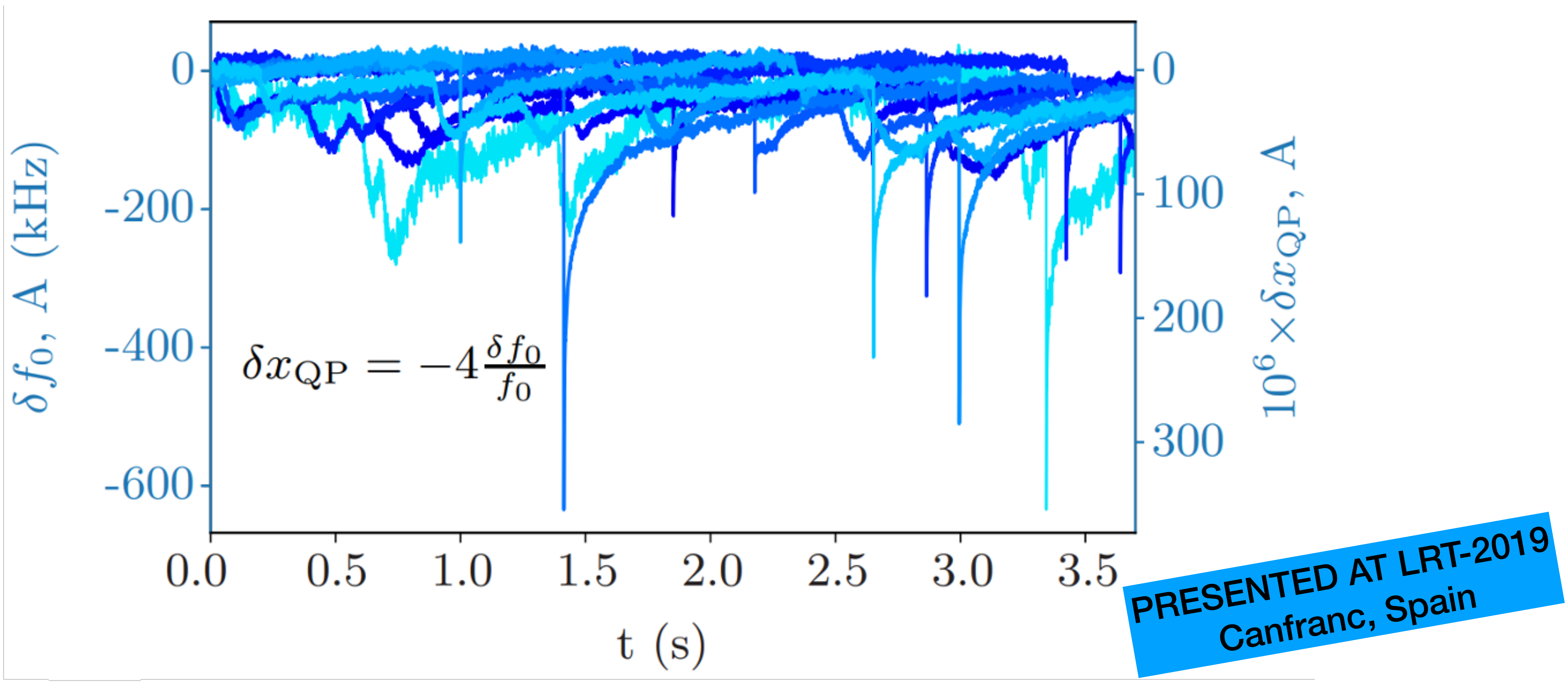
Radioactivity will limit the performance of qubits with lifetime > 1 millisec

Note: qubit of this study had T1~ 30-40 µs of but today 0.5 millesec proved

Is it so simple?

Radioactivity produces "pulses" and not an "average" QP pollution.

During the "pulse", the level of QP can reach 10^{-4} (well above the 10^{-9})

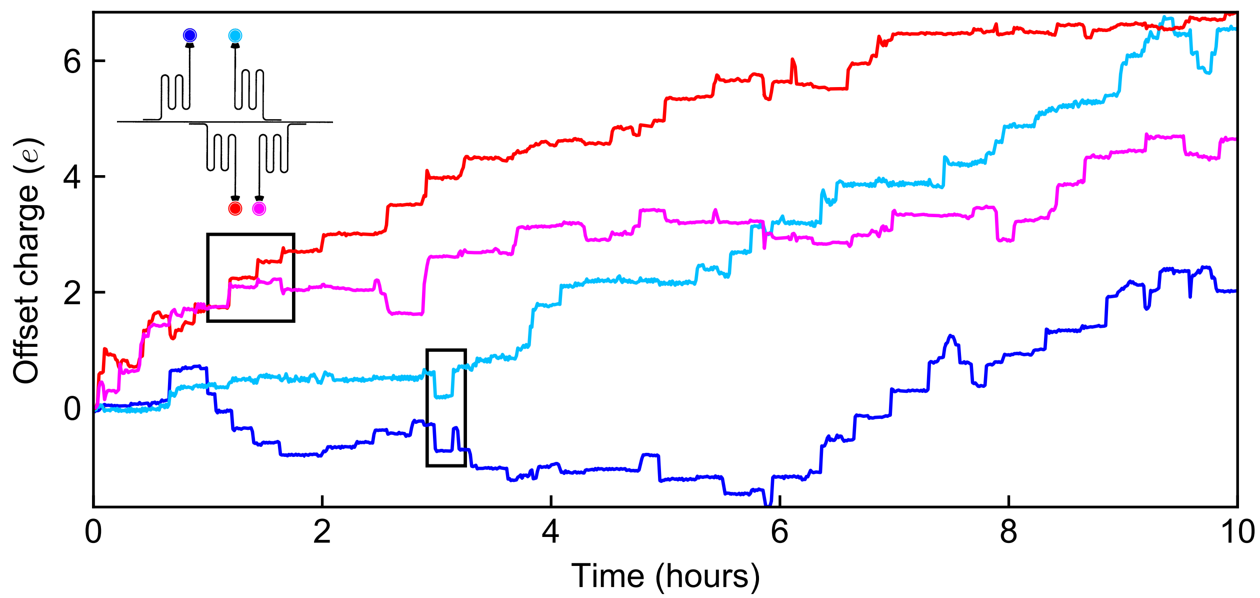


L. Cardani et al, Nature Comm. 2021

Radioactivity produced Correlated Errors

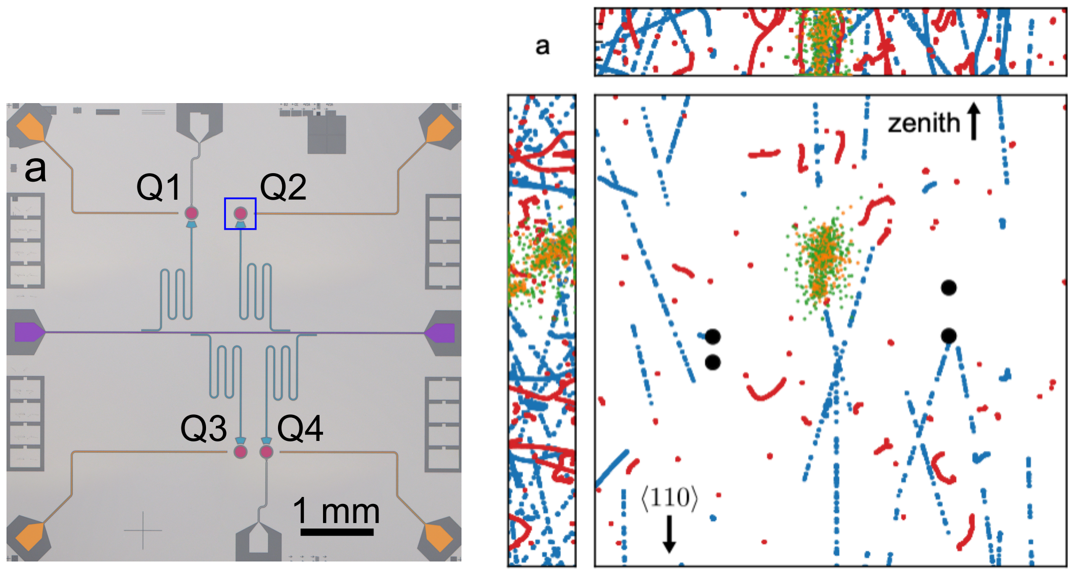
- Measurement of an array with 4 qubits performed by the groups of R. McDermott
- Charge jumps for single qubit: 1 / (75 sec)*
- Simultaneous jumps in 2-qubits:
  - 54% correlation prob. for ΔL = 340 μm
  - 46% correlation prob. for ΔL = 640 μm
  - For ΔL = 3 mm random coincidences
- Consistent with rate of impacts from μ and γ's

Wilen et al., Nature 594, 369-373 (2021)



* I changed unit compared to the original paper for consistency in the talk

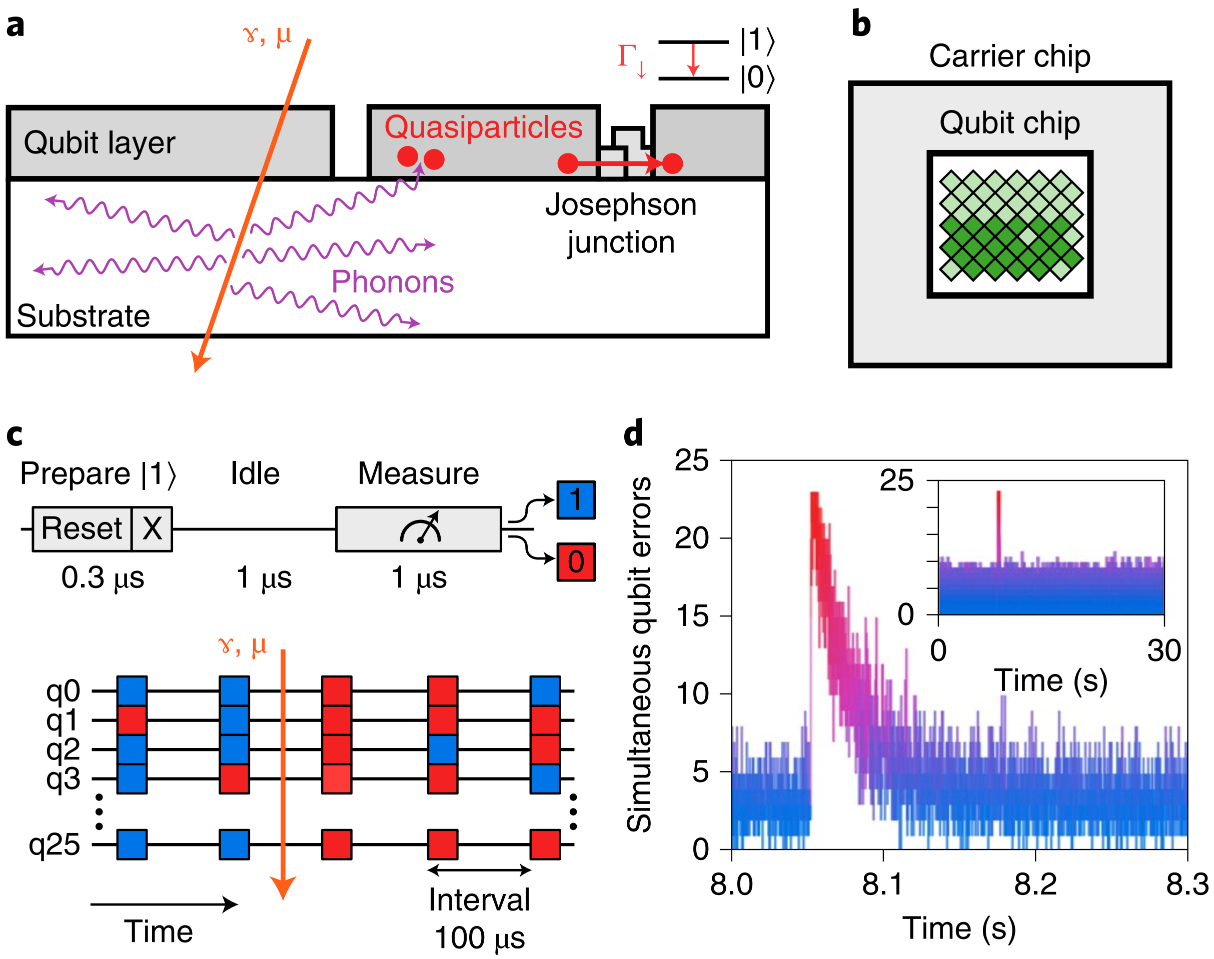
PRESENTED AT LRT-2022
South Dakota, US

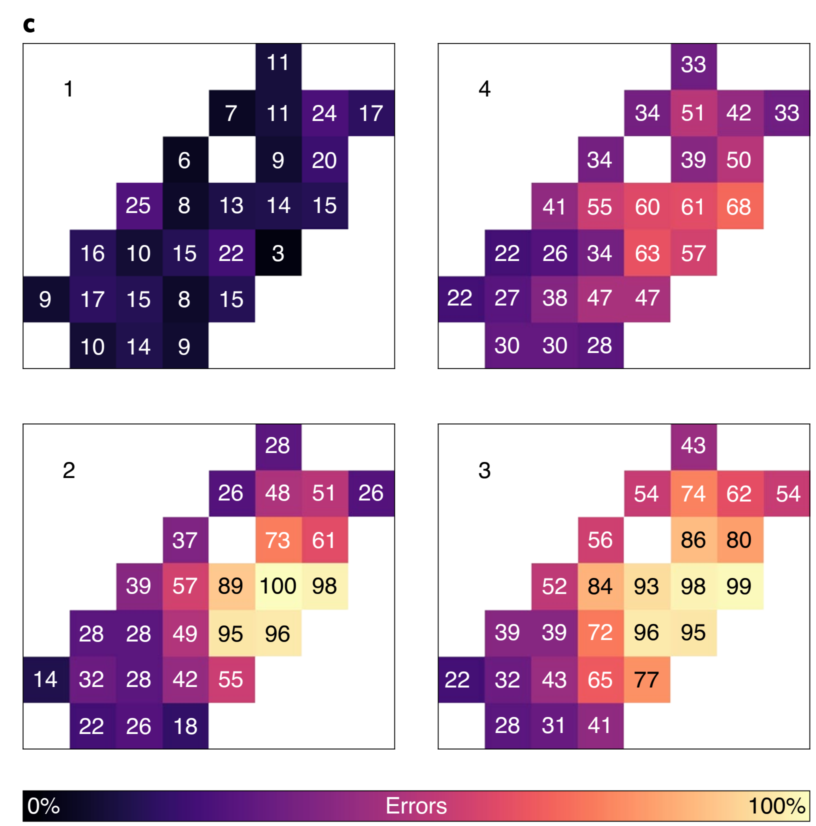


Validation

Google group performed a similar measurement on a "real" quantum processor (sycamore)

Developed a protocol for qubits operation that allowed to monitor errors "online"





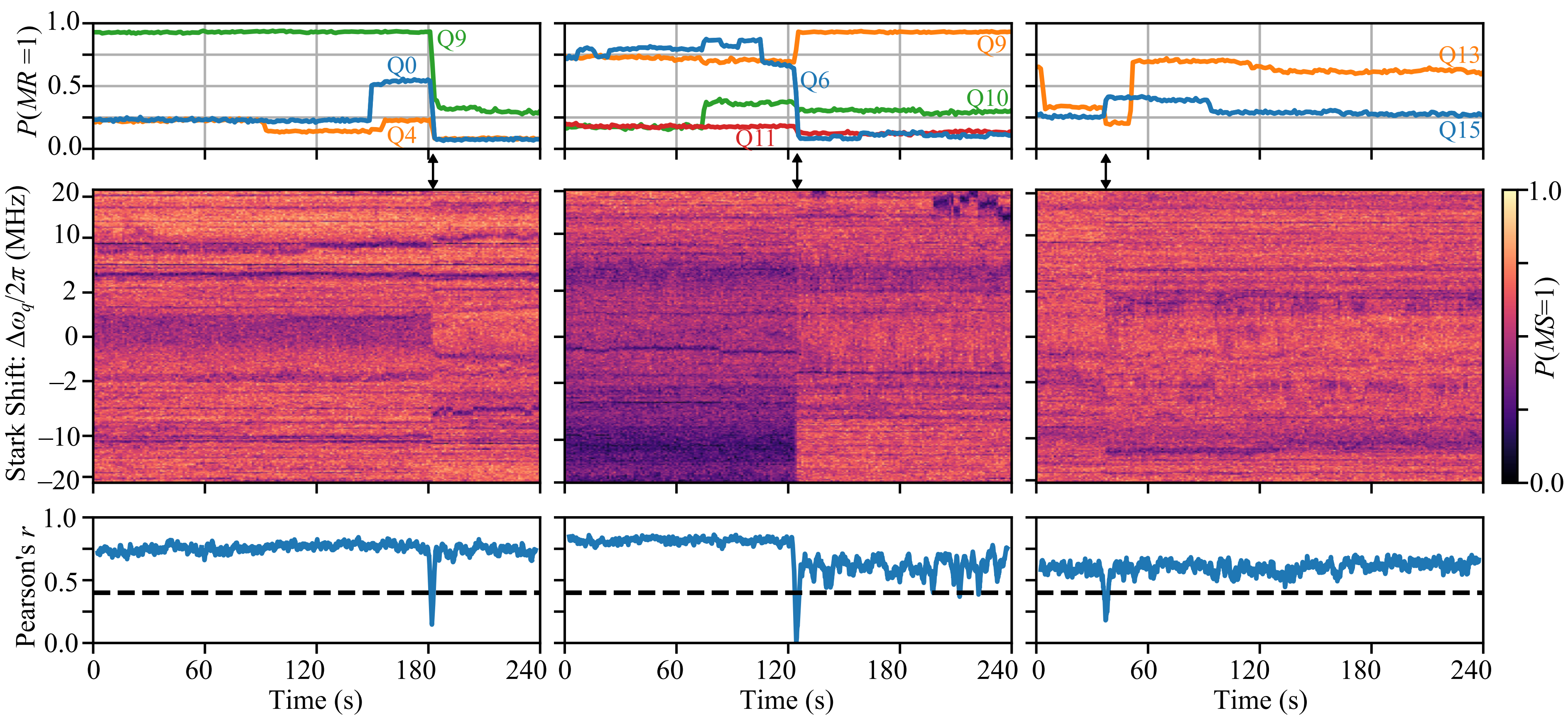
Mc Ewen et al, Nature Physics 18 107-111 (2022)

Confirmed importance of mitigation of radioactive impacts

Also…

Two Level System (TLS): dominant loss mechanism in qubits (more dangerous than radioactivity)

Destabilises qubits on a ~hour timescale

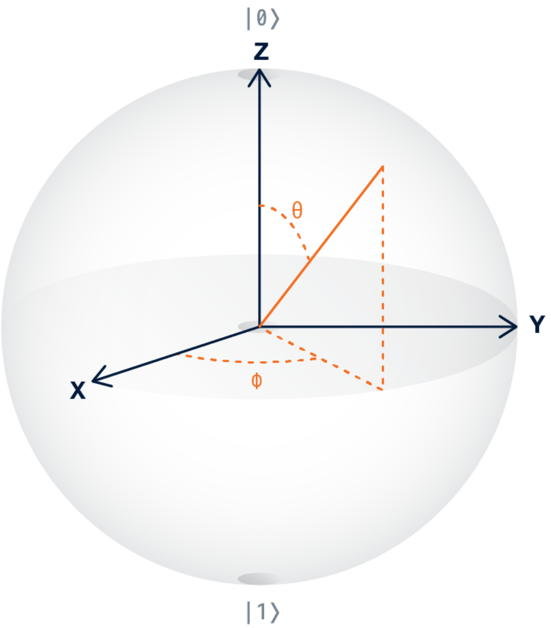


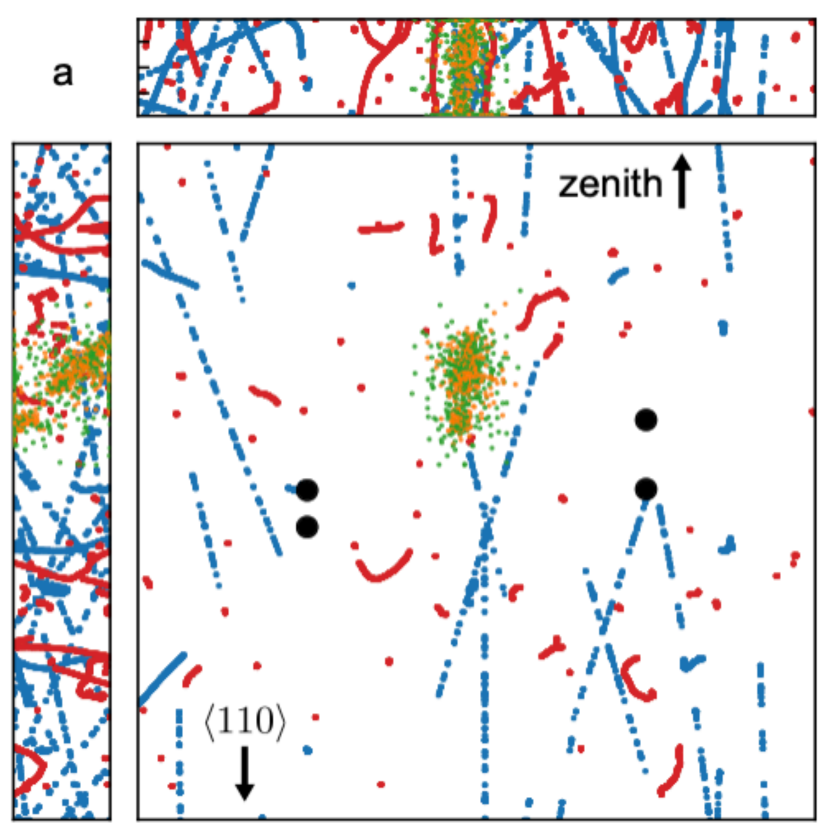
[Thorback et al, 2023]

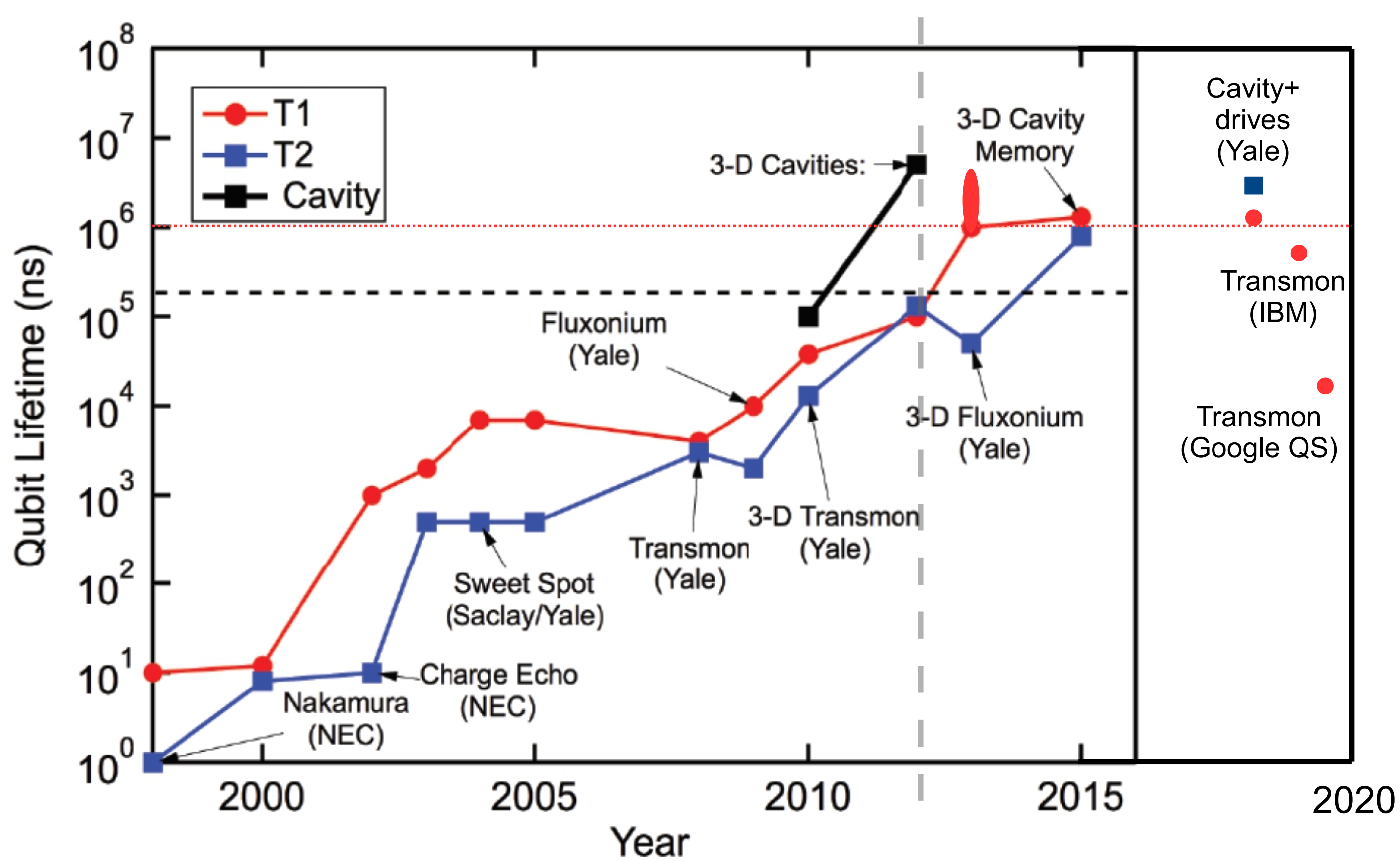
Radioactivity causes TLS “scrambling” —> radiation makes multiple TLSs jump in frequency and couple (or decouple) to qubit, increasing/decreasing its half-life

In this Talk

- Effects of Radioactivity in Superconducting Qubits;
- Sources of Radioactivity;
- Mitigation strategies;
- Perspectives;



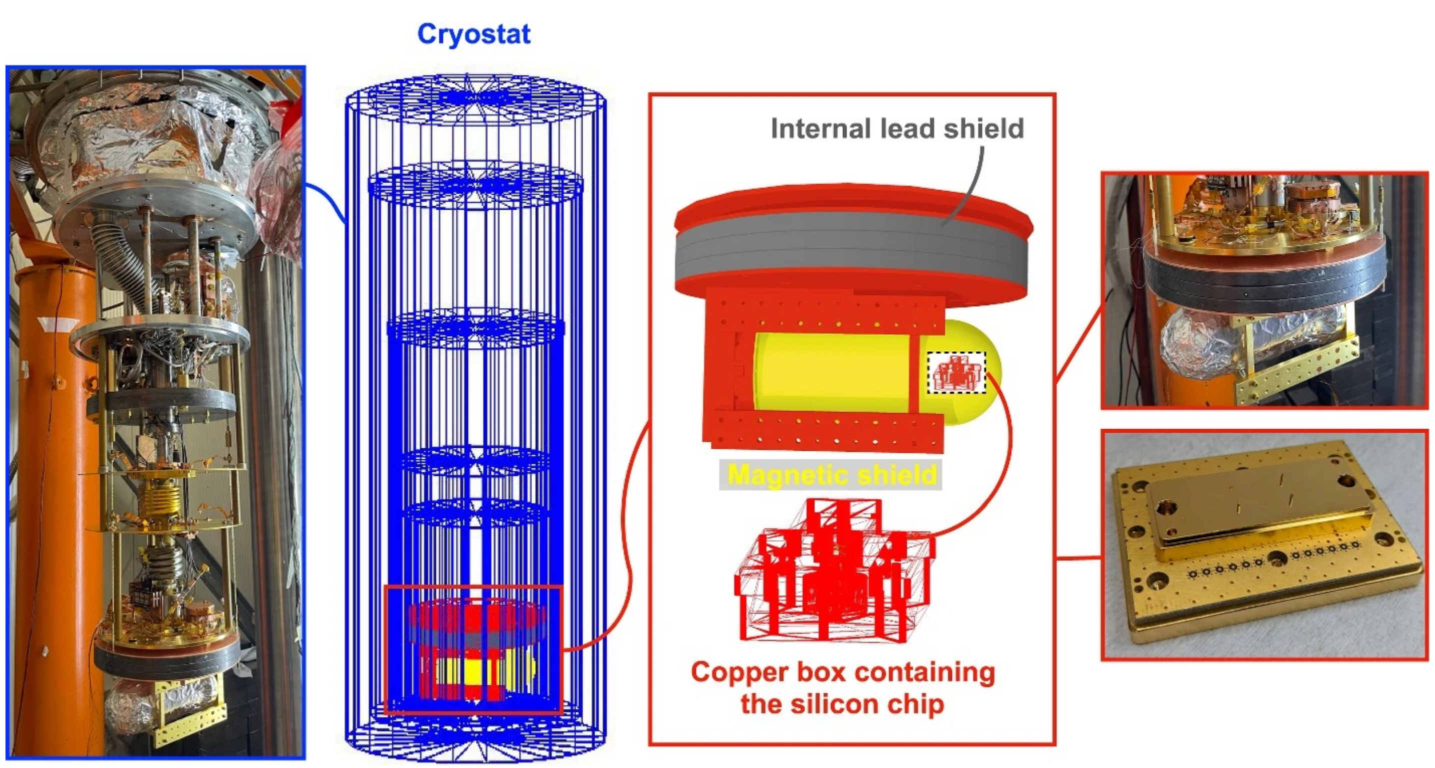


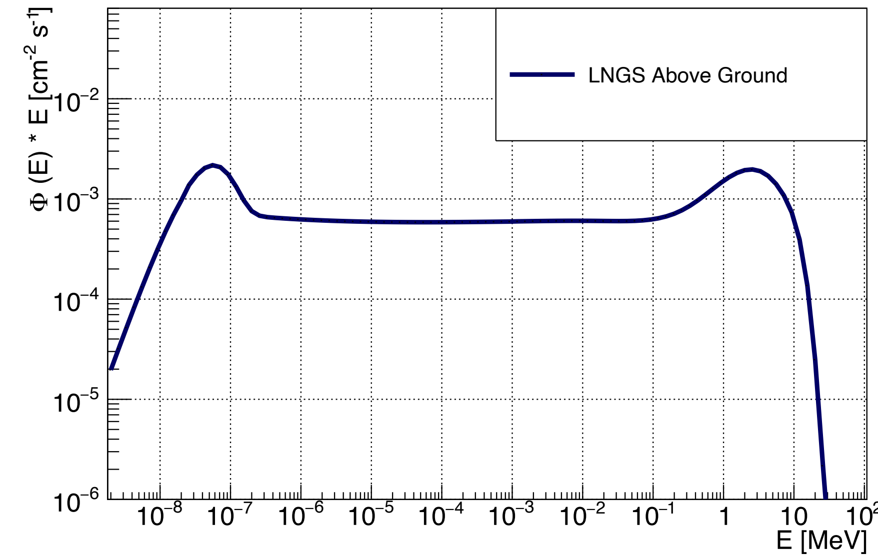


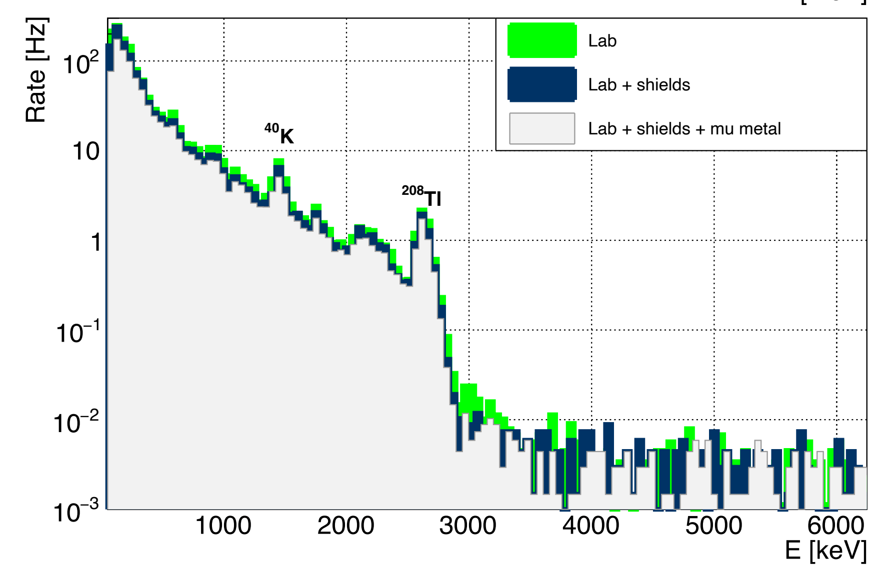
Origin of Radioactivity in Qubits

Measurement of all possible sources of radioactivity, from environment to components

Component	^{232}Th [mBq/kg]	^{238}U [mBq/kg]	^{235}U [mBq/kg]	^{40}K [mBq/kg]	^{137}Cs [mBq/kg]
PCB	(18000 ± 1000)	(11500 ± 400)	(710 ± 110)	(12000 ± 1000)	< 30
Box	(5410 ± 330)	(4200 ± 200)	(230 ± 50)	(4200 ± 500)	< 40
Holder	< 1.5	< 1.2	< 4	< 9	< 0.6
Magnetic Shield	< 8.4	< 8.3	< 8.4	< 35	< 2.7
SMA	(46 ± 13)	(42 ± 10)	(70 ± 30)	(240 ± 90)	< 10
Cu coax cables	(54 ± 12)	(44 ± 11)	(34 ± 17)	(740 ± 130)	< 12
Cryogenic switch	(1880 ± 100)	(1340 ± 60)	(130 ± 30)	(2200 ± 300)	< 11.2
Circulator	< 310	< 330	< 410	< 2000	< 60
Dual-junct. circulator	< 250	< 380	< 380	< 2600	< 60
Triple-junct. isolator	< 190	< 240	< 220	< 2000	< 50
Attenuators	< 52	(200 ± 20)	< 47	< 140	< 13
Low Pass Filters	(23 ± 4)	< 9.1	(60 ± 10)	< 100	< 1.9
NbTi cables	< 750	< 1000	< 380	< 7000	< 230
Cryogenic amplifier	< 890	< 1000	< 850	< 10000	< 210
Cu-Be cables	(240 ± 40)	< 78	(350 ± 90)	< 500	< 20
Stycast glue	(53 ± 4)	(9400 ± 900)	(350 ± 30)	(290 ± 40)	< 2.2
Cryogenic Grease	< 10	< 11	< 4.5	< 87	< 5







L. Cardani et al,
Eur. Phys. Journ C 83,
n.o 94 (2023)

Origin of Radioactivity in Qubits (2)

Source	"Standard"	LNGS + Shield
Lab γ rays	1 / (50 sec)	1 / (1000 sec)
Muons	1 / (100 sec)	0
Materials	1 / (200 sec)	1 / (200 sec)
Neutrons	1 / (2 hours)	0

* I changed unit compared to the paper for consistency in the presentation

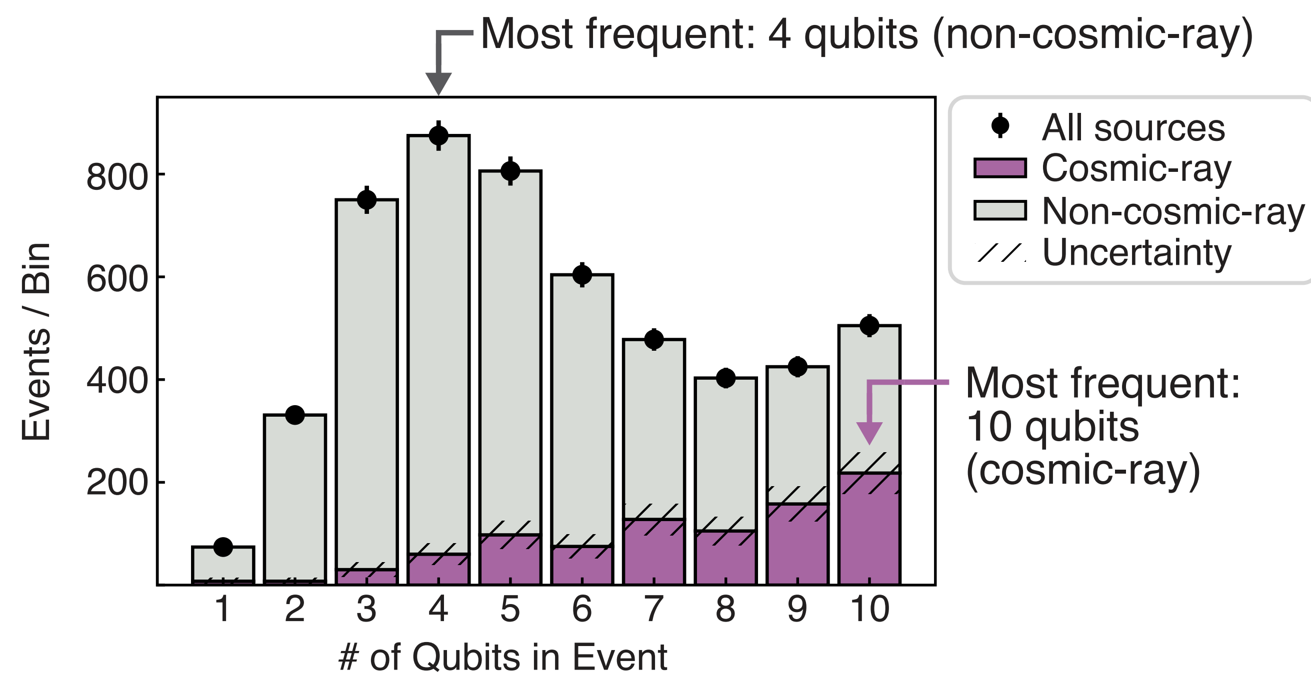
← **Almost entirely dominated by the PCB**

- More recent works of radio-assay and simulations-Canfranc, PNLL and NIST
- No surprises :)

Validation

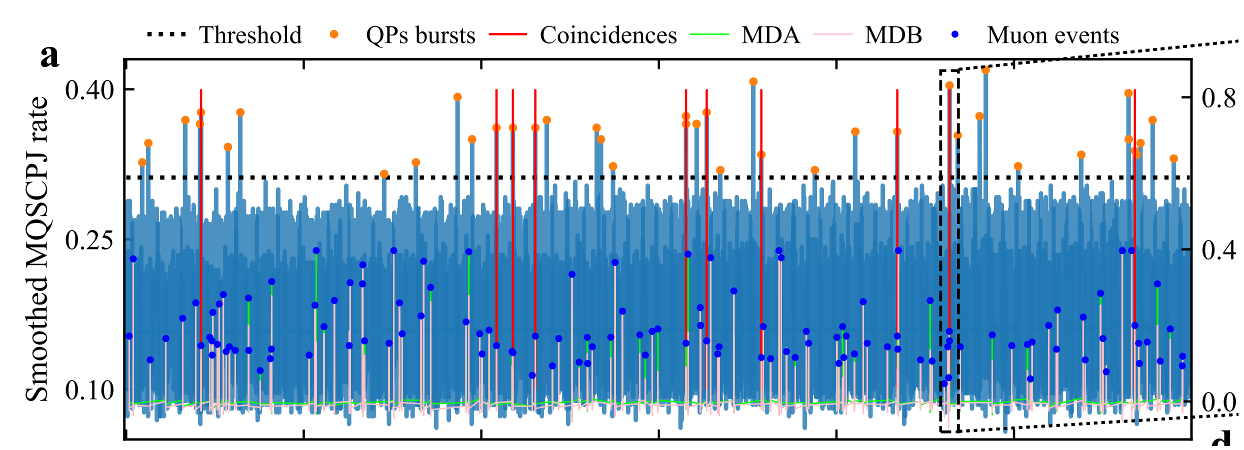
P. M. Harrington et al

- Correlated errors: 1 / (100 sec)
- Only 17% of correlated errors come from cosmic rays
- Cosmic rays affect all a large number of qubits



Xue-Gang Li et al

- Cosmic rays account for 19% of the events
- Correlated errors: 1 /(12.3 sec)
- With minimal lead shield: 1/ (16.7 sec)

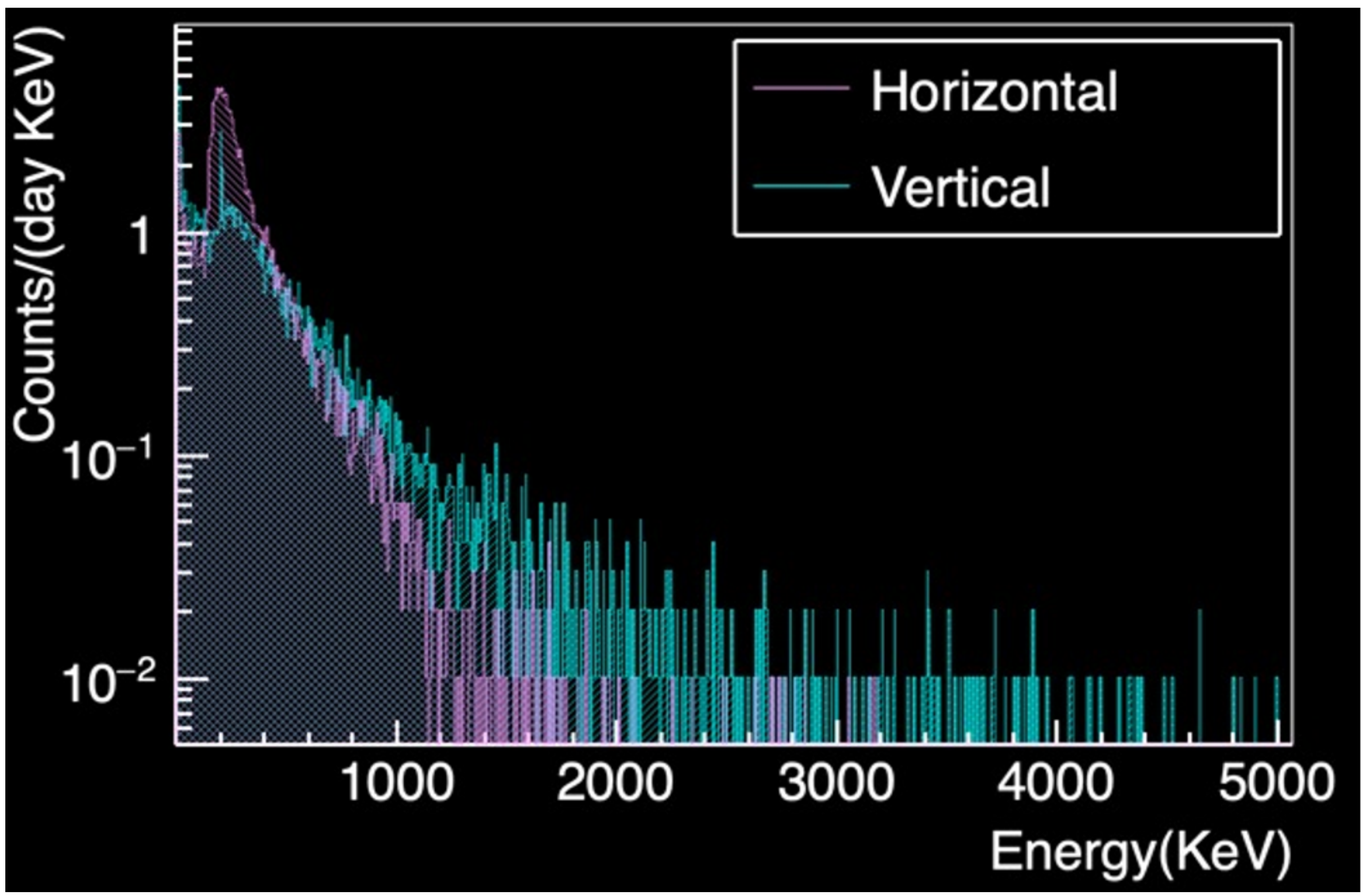


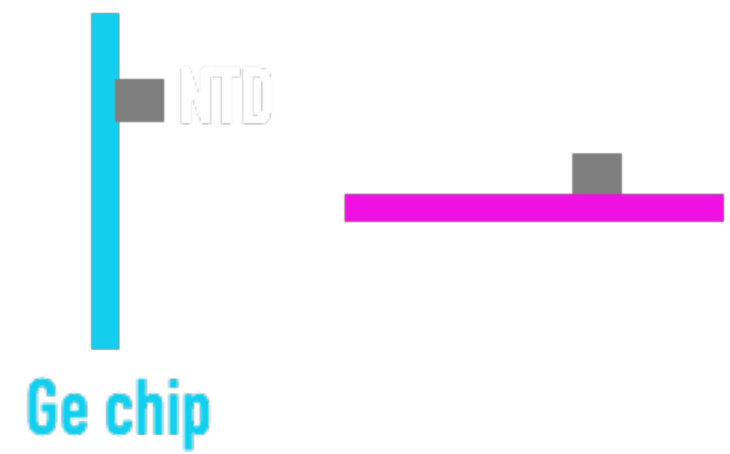
- *Evacuation time* of 20-40 µs, 2 orders of magnitude faster w.r.t. Google (Tantalum?)

Validation (2)

INFN Istituto Nazionale di Fisica Nucleare

- ICRQ (Interaction of Cosmic Rays with Qubits) project, funded by Spain (Pol Forn-Diaz)
- Measurement of two Ge light detectors (45x45x0.3 mm) with NTD Ge thermistor
- One chip vertical, one chip horizontal, simultaneous measurement





	VERTICAL	HORIZONTAL	
100-500 keV	~ 5900	~ 12200	cts per h per keV
> 500 keV	~ 3150	~ 1870	cts per h per keV
Total (>100 keV)	~ 9050	~ 14070	

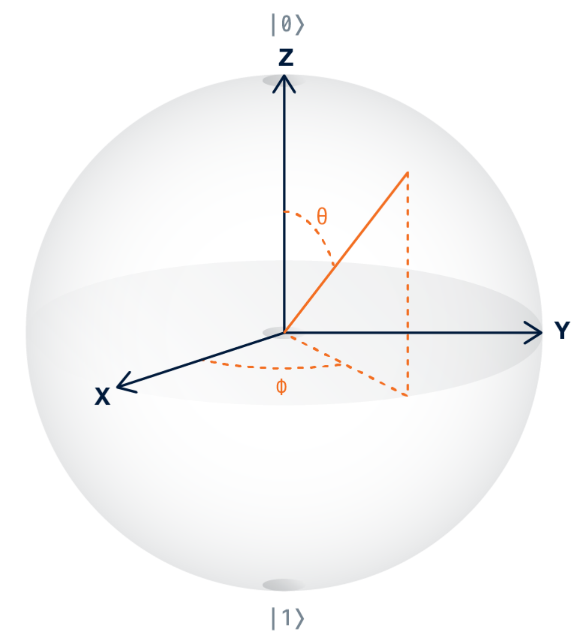
PRELIMINARY

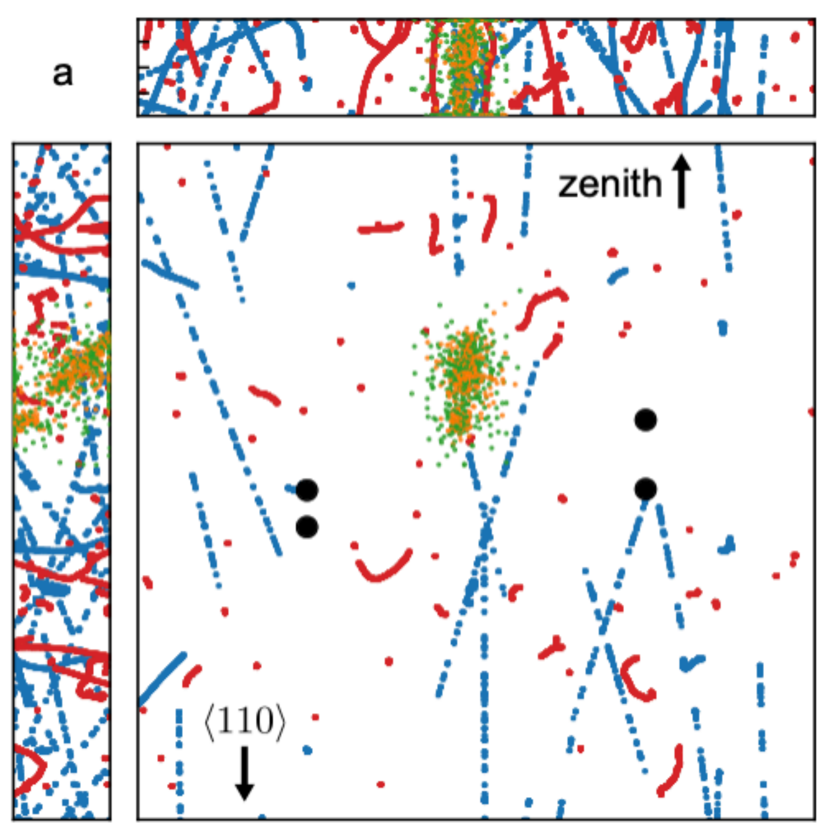
Institut de Física d'Altes Energies

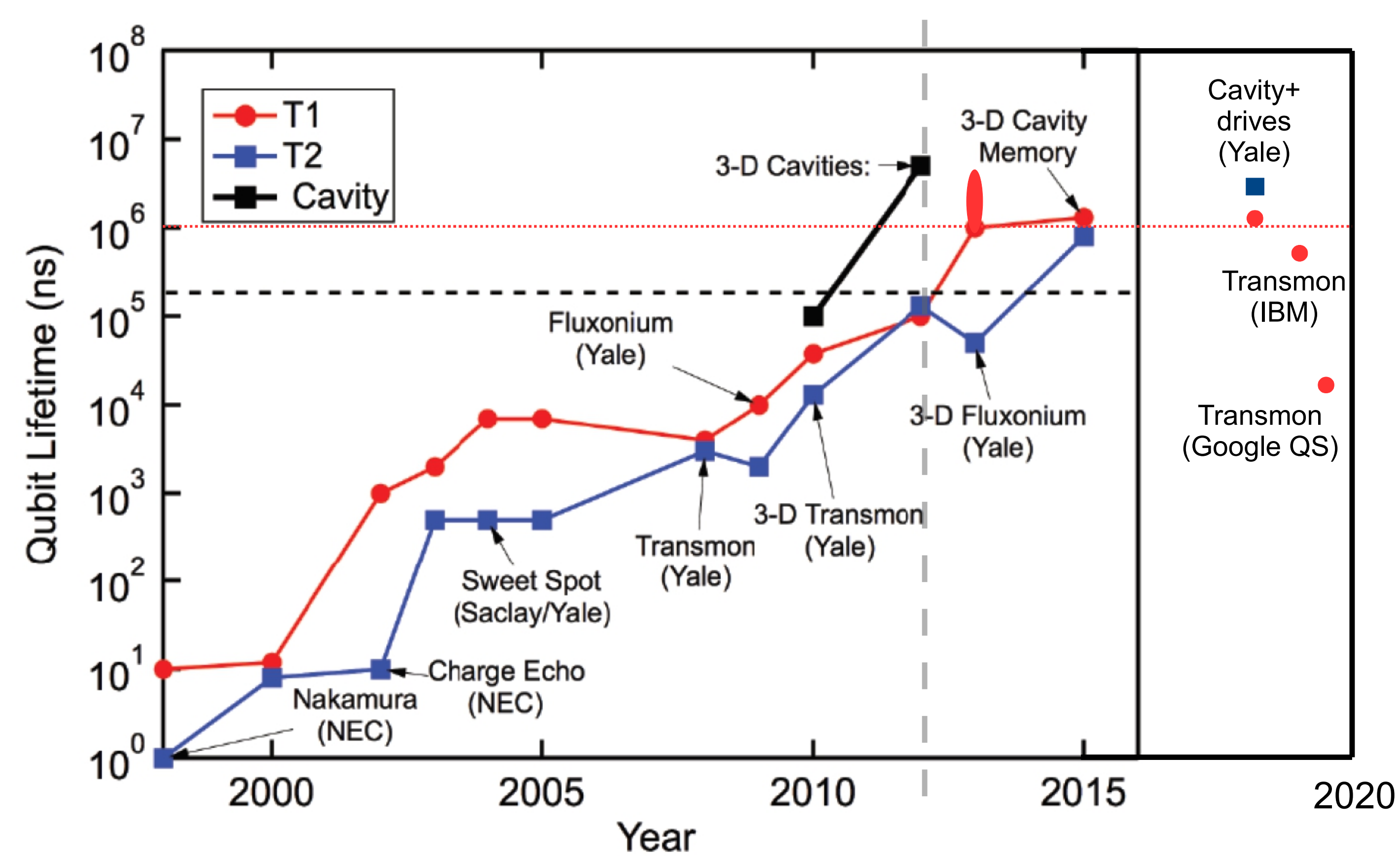
From E. Bertoldo's talk at the RISQ workshop - May 2024

In this Talk

- Effects of Radioactivity in Superconducting Qubits;
- Sources of Radioactivity;
- Mitigation strategies;
- Perspectives;



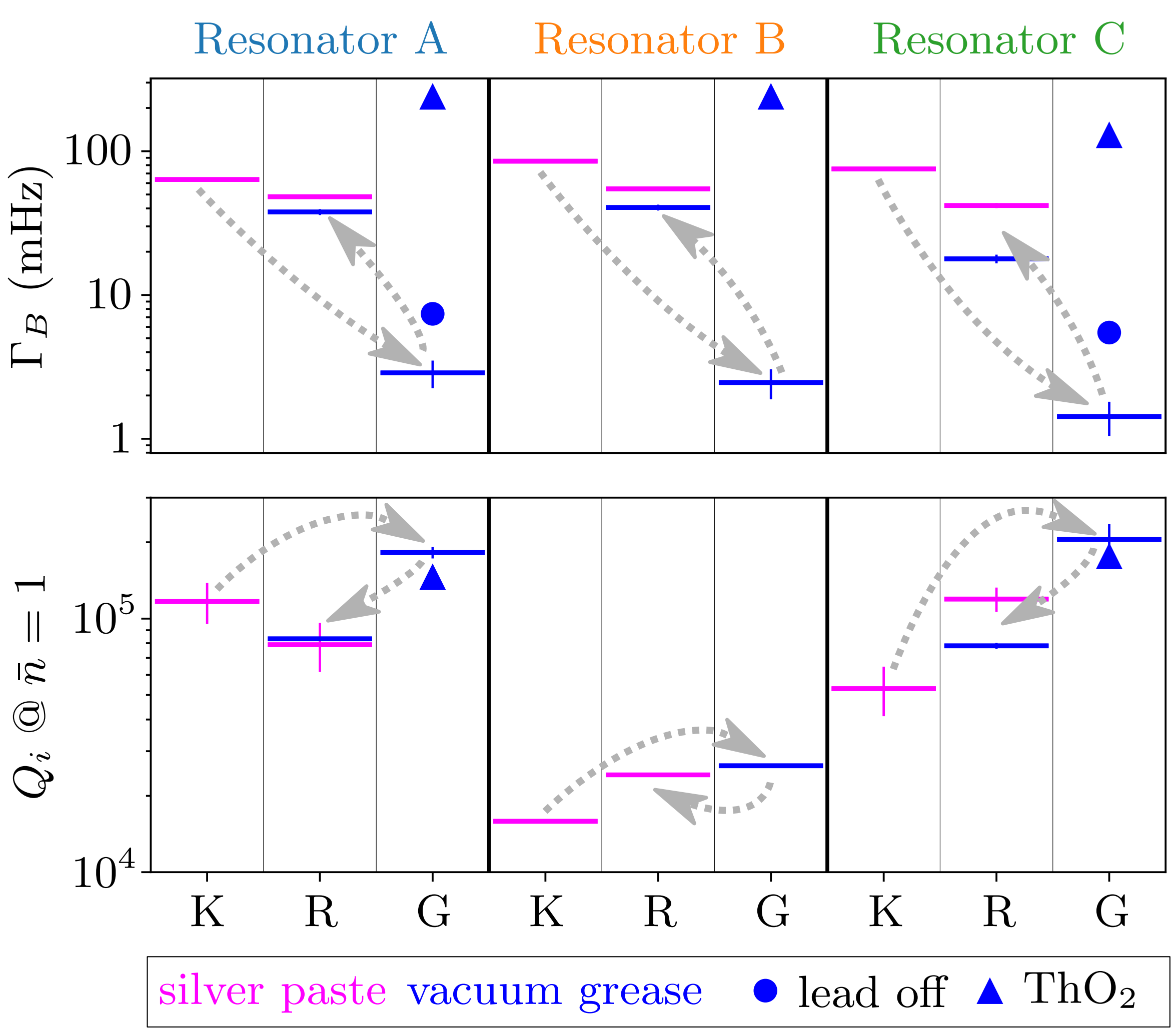




Encouraging Results

Superconducting resonators at LNGS

Improvement of int. quality factor x 2-3

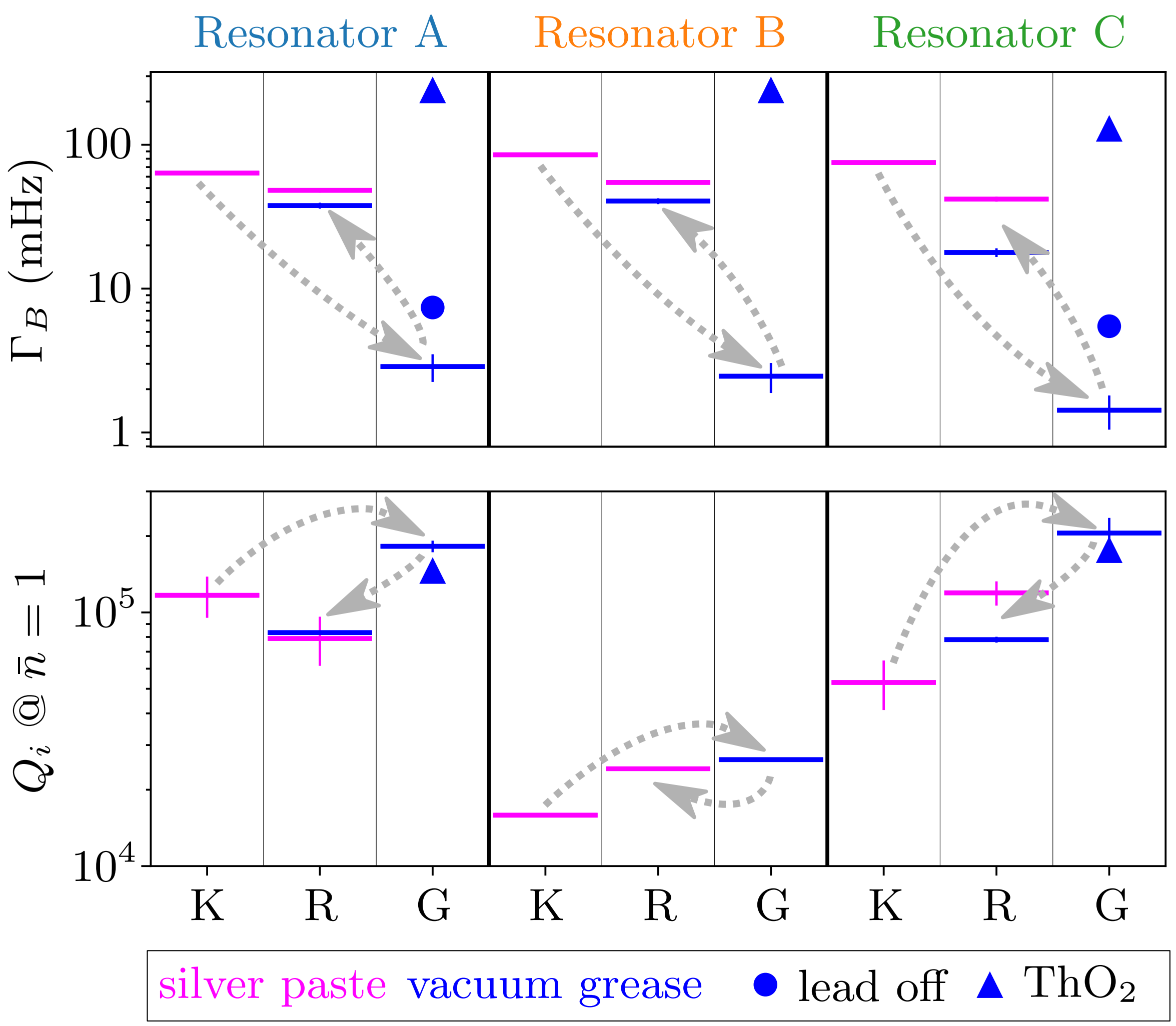


L. Cardani et al, Nature Comm. 2021

Encouraging Results

Superconducting resonators at LNGS

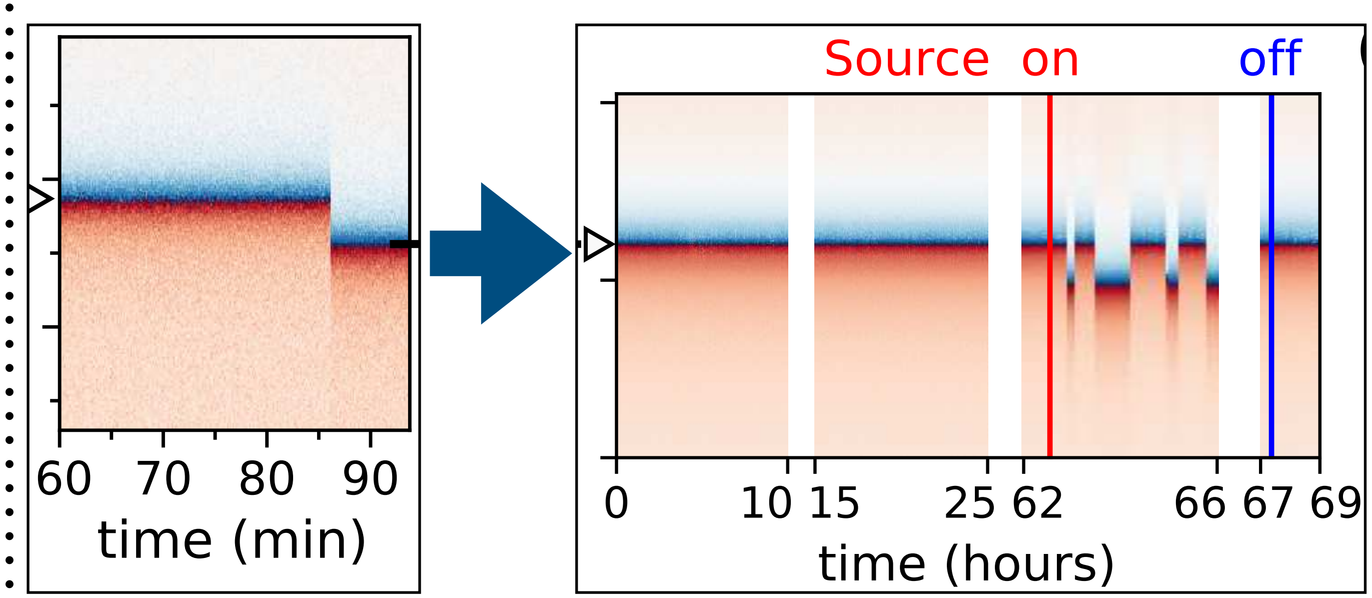
Improvement of int. quality factor x 2-3



L. Cardani et al, Nature Comm. 2021

(gradiometric) fluxonium at LNGS:

Tremendous improvement of frequency locking at the sweet spot

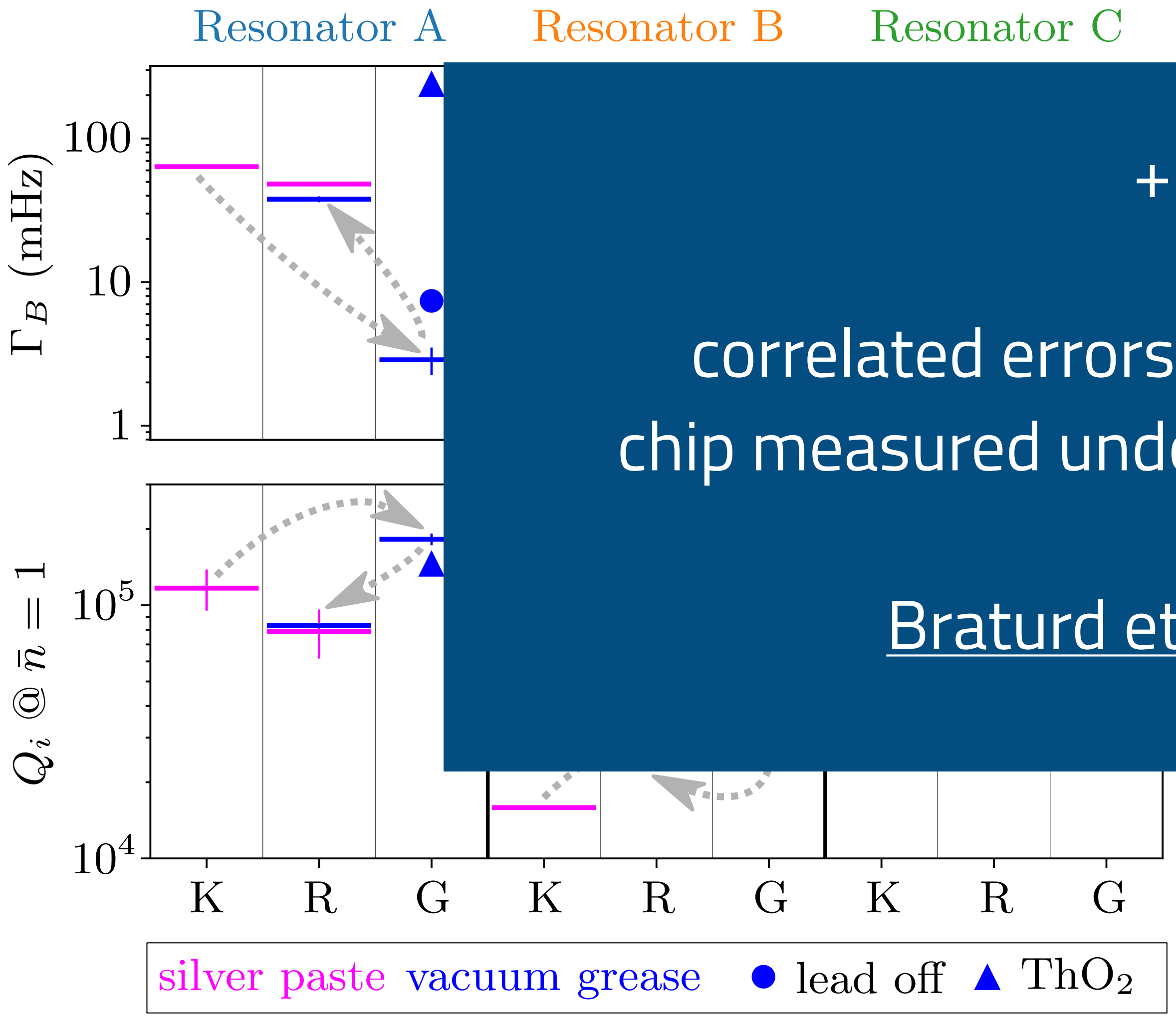


D. Gusenkova et al,
Appl. Phys. Lett 120 054001 (2022)

Encouraging Results

Superconducting resonators at LNGS

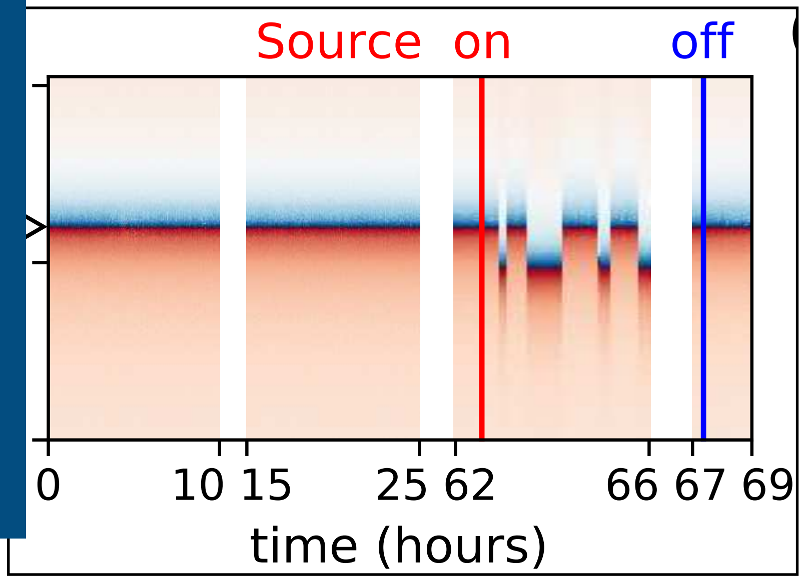
Improvement of int. quality factor x 2-3



L. Cardani et al, Nature Comm. 2021

(gradiometric) fluxonium at LNGS:

Tremendous improvement of frequency locking at the sweet spot



D. Gusenkova et al,
Appl. Phys. Lett 120 054001 (2022)

+

correlated errors diminish when chip measured underground @ FNAL

Braturd et al 2024

Is suppression of radioactivity the holy grail?

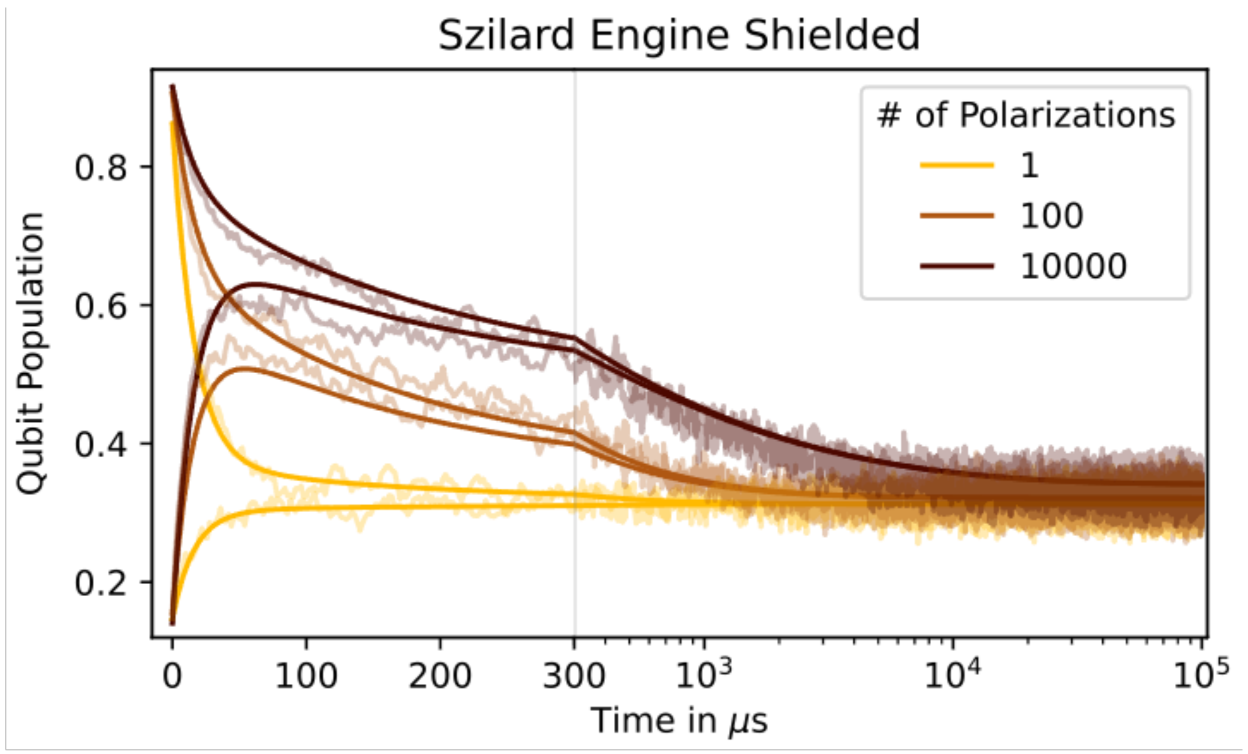
Not (yet)

Less encouraging results

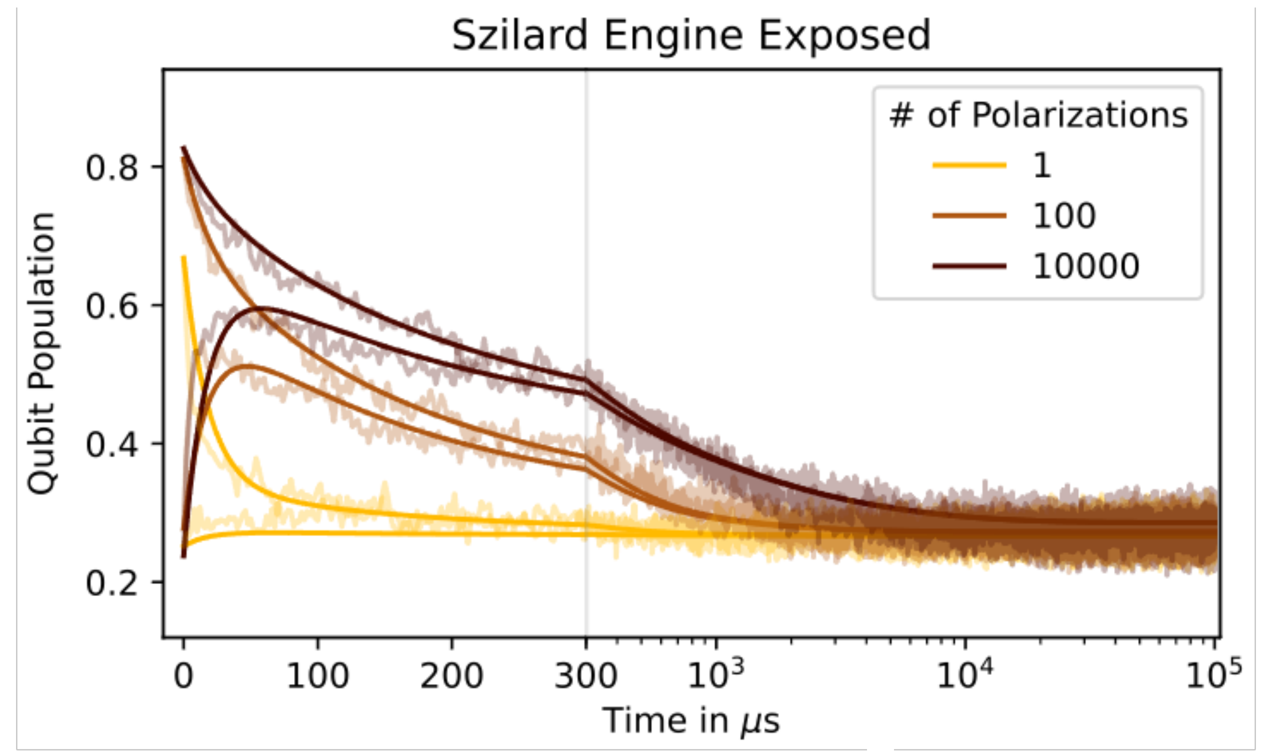
Plots from N. Gosling (KIT)

GrAl qubit already measured above ground

Characterization at LNGS in shielded configuration w.r.t exposed to a strong Th sources



$$\Gamma_q = \Gamma_1 - \sum_k \Gamma_{qt}^k \approx 1/90\,\mu s$$



$$\Gamma_q = \Gamma_1 - \sum_k \Gamma_{qt}^k \approx 1/91\,\mu s$$

$$\Gamma_t \leq 1/50\,ms$$

The TLS environment is not affected by underground operation

Karlsruhe Institute of Technology

GeQCoS

HELMHOLTZ ASSOCIATION

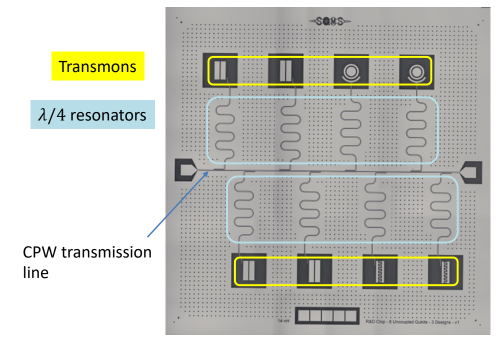
INFN Istituto Nazionale di Fisica Nucleare

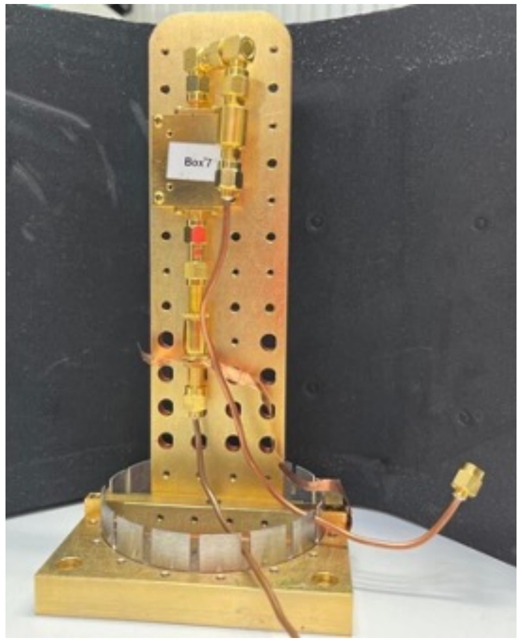
Less encouraging results

Chip with 8 transmon qubits

Operated at LNGS and at the SQMS Quantum Garage

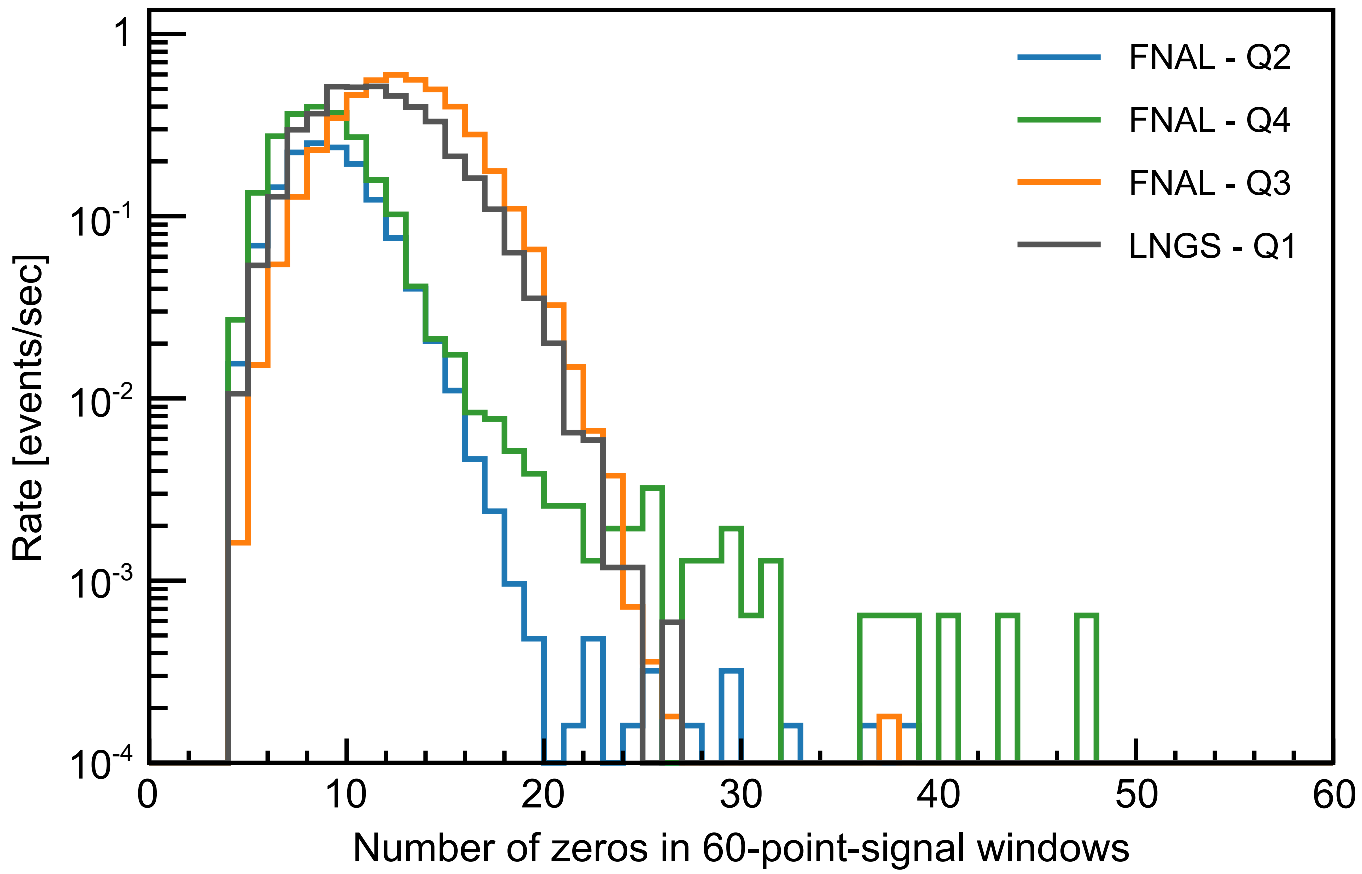
Counted the number of errors in a *single* transmon





INFN Istituto Nazionale di Fisica Nucleare

SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER



Going underground does not have a major impact on the performance of a single transmon

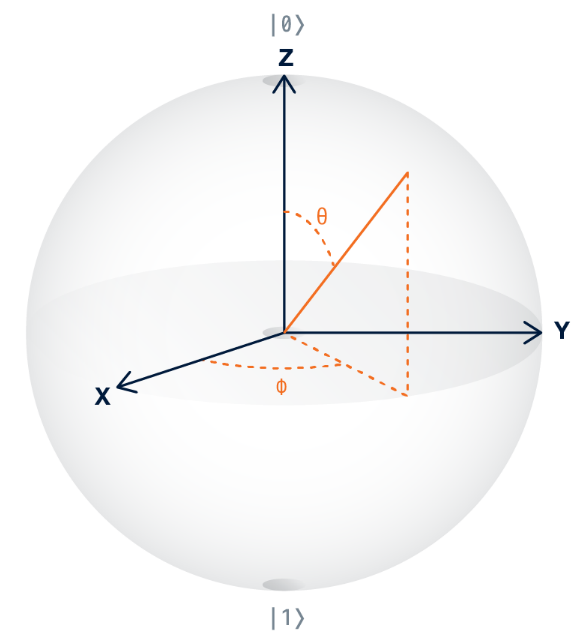
Another source of particle-like events is dominating

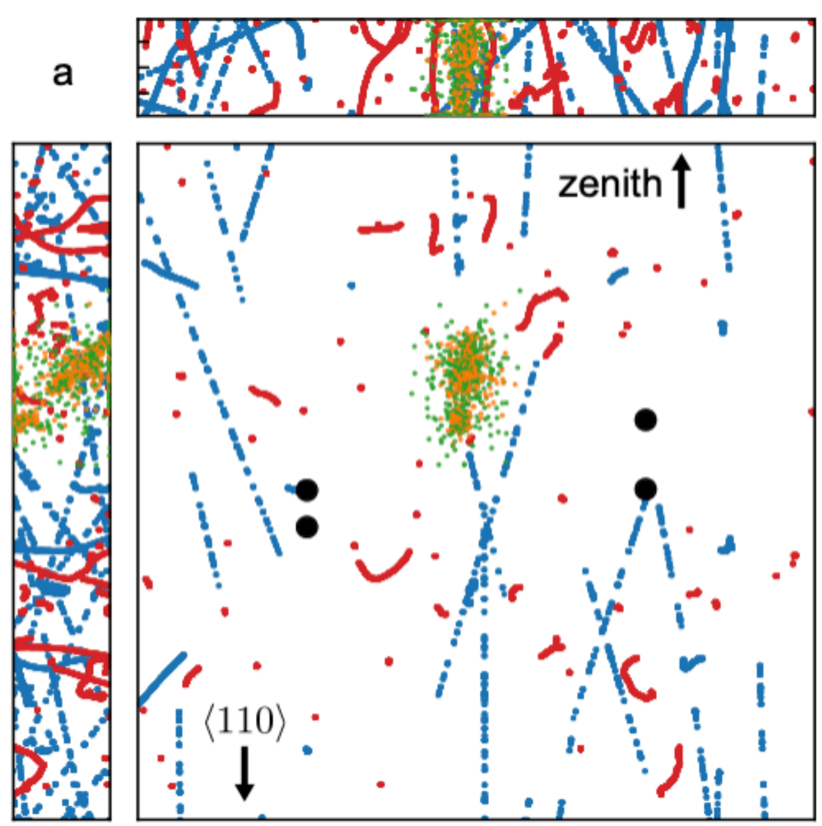
New synergy quantum/particle physics: EXCESS?

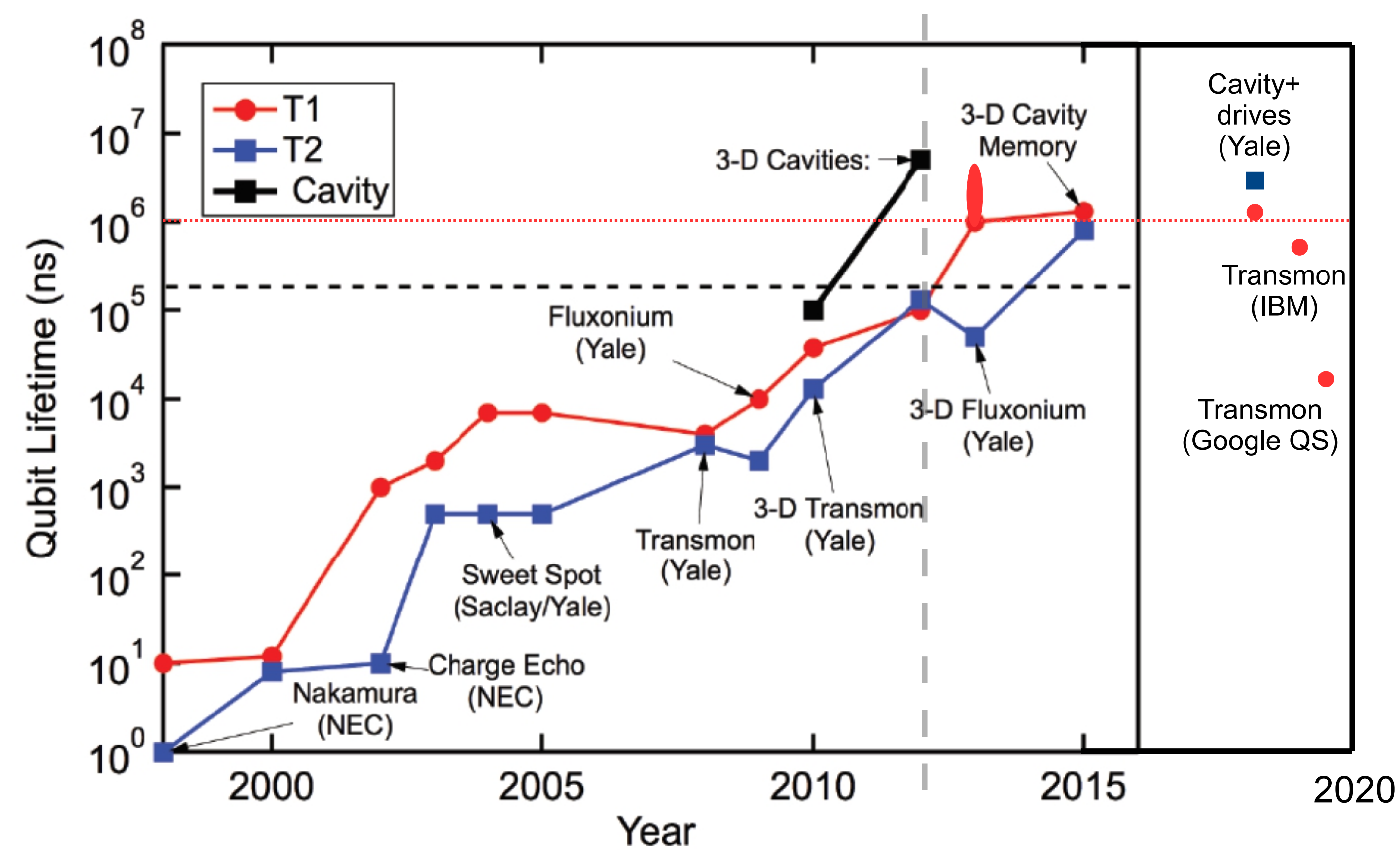
De Dominicis et al, 2024

In this Talk

- Effects of Radioactivity in Superconducting Qubits;
- Sources of Radioactivity;
- Mitigation strategies;
- Perspectives;

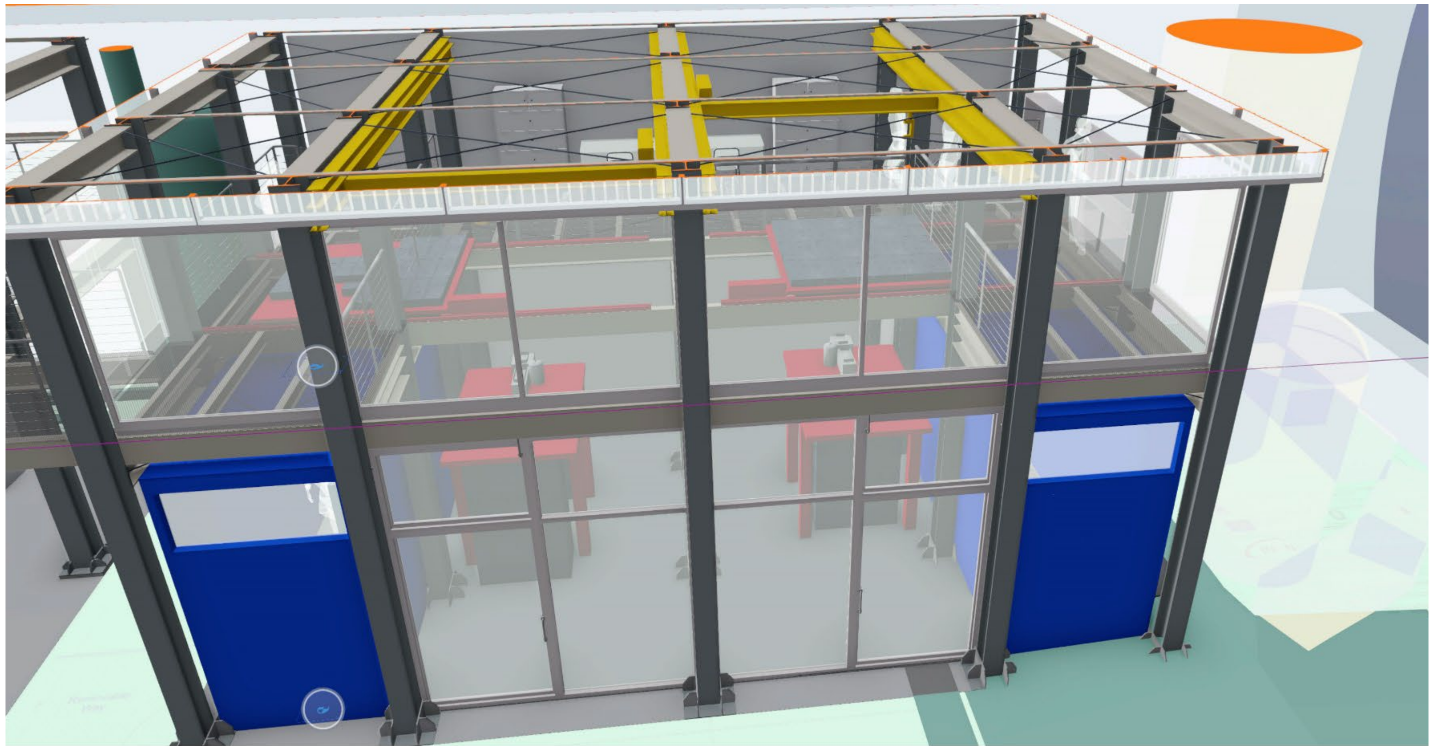


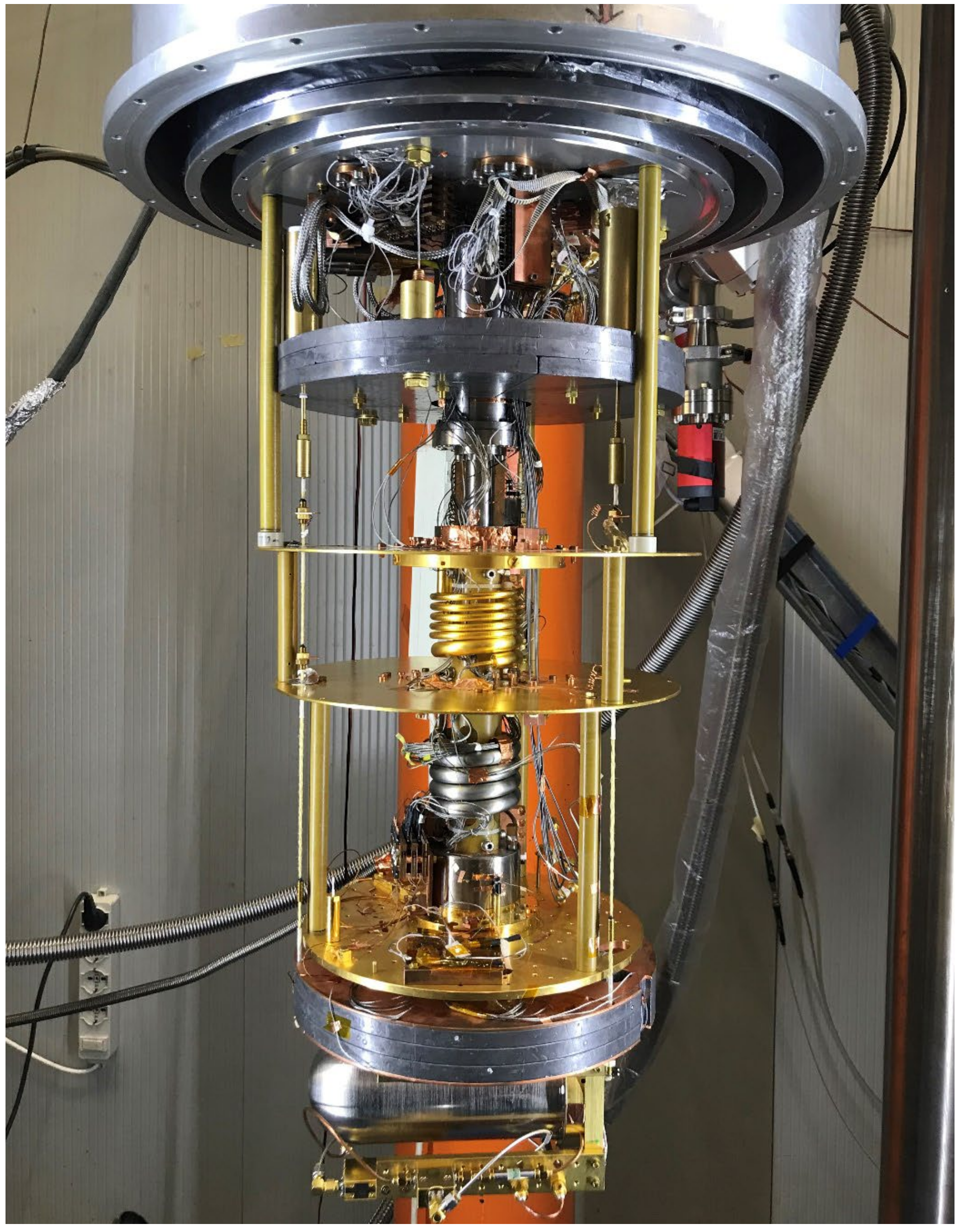




Advancing Quantum Science in EU: labs

- LNGS: partnership with SQMS center + external users
  - “Ieti" Cryostat already equipped and available
  - New Cryoplatform in construction



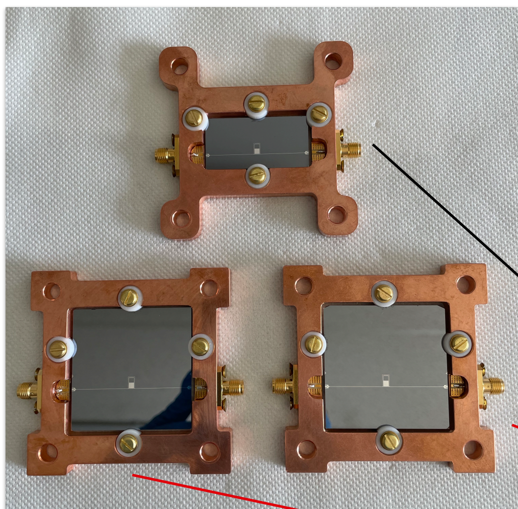


- Roma ULTRA Lab: new facility with lead shielding and cryogenic muon veto
- LSC: measurements in the CROSS fridge + installation of a fridge dedicated to qubits

Advancing Quantum Science in EU (2)

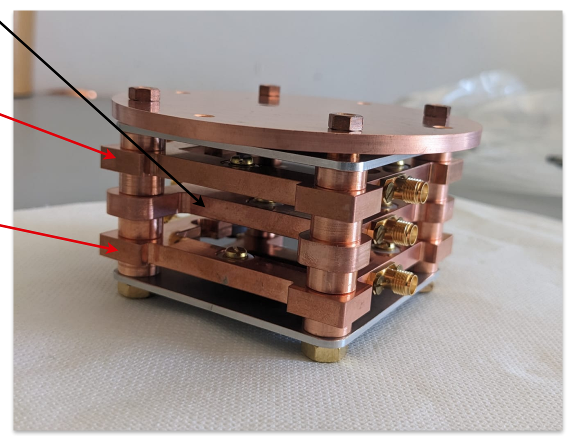
- ACE-SuperQ (PI: A. Mariani, 2024–2026)

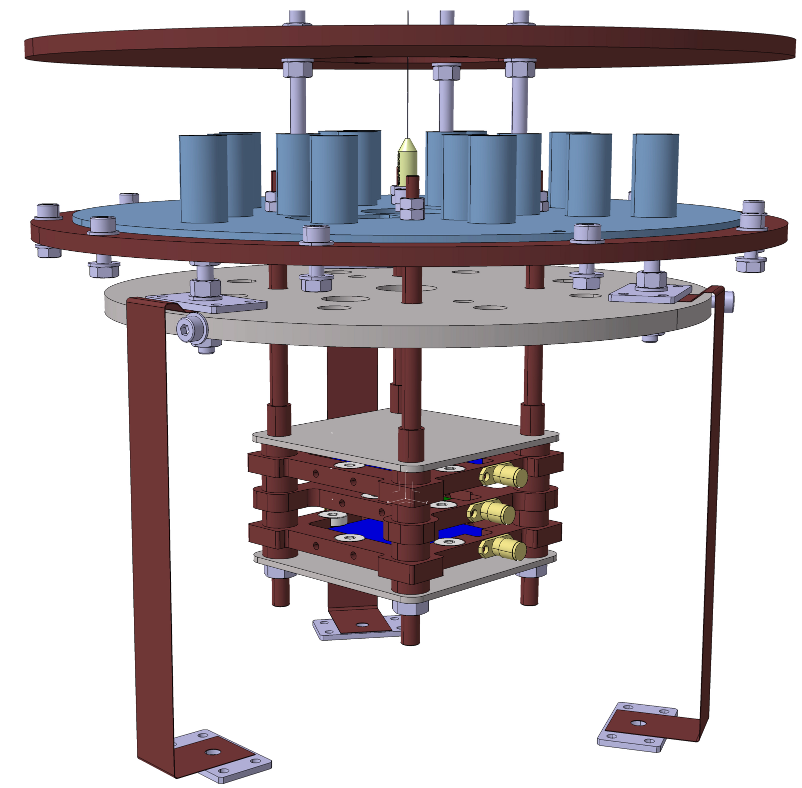
- Develop a cryogenic muon veto with >90% efficiency and < 1% dead-time

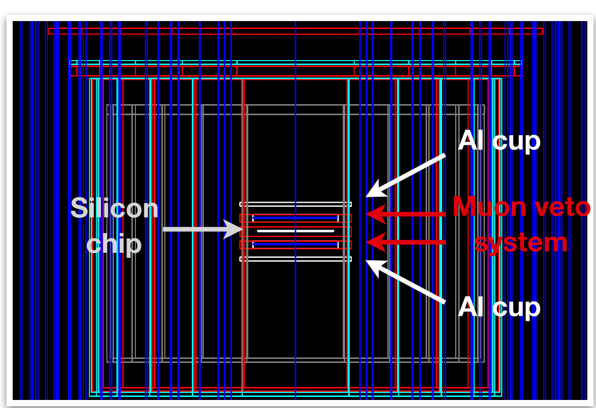


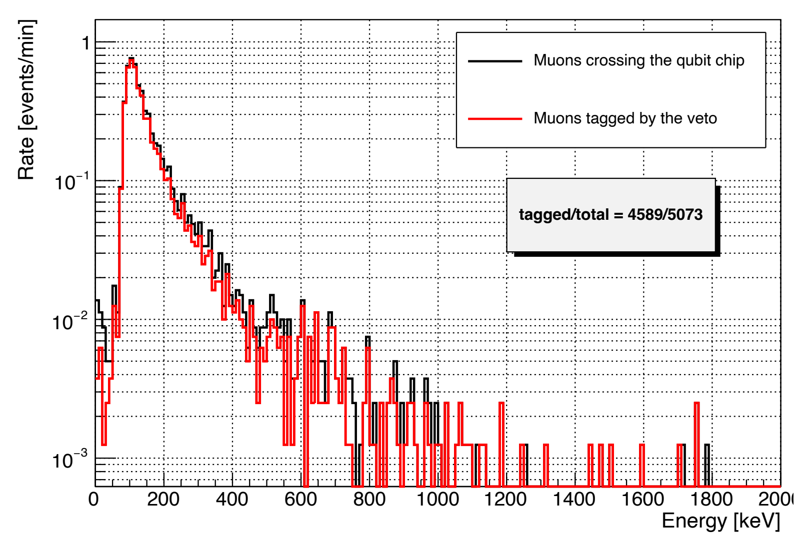
Smaller KID (2x4 cm^2) used as a **central detector** in our first prototype (it will be replaced by a superconducting quantum chip)

KIDs used **for** the **muon veto system**



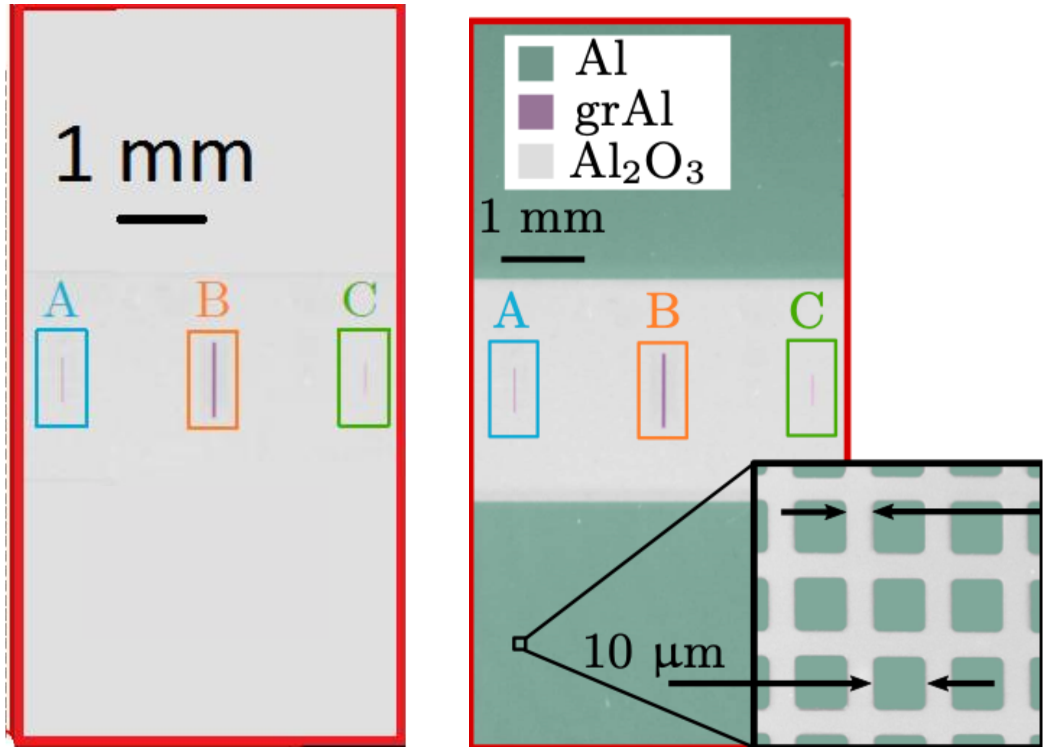






Advancing Quantum Science in EU (3)

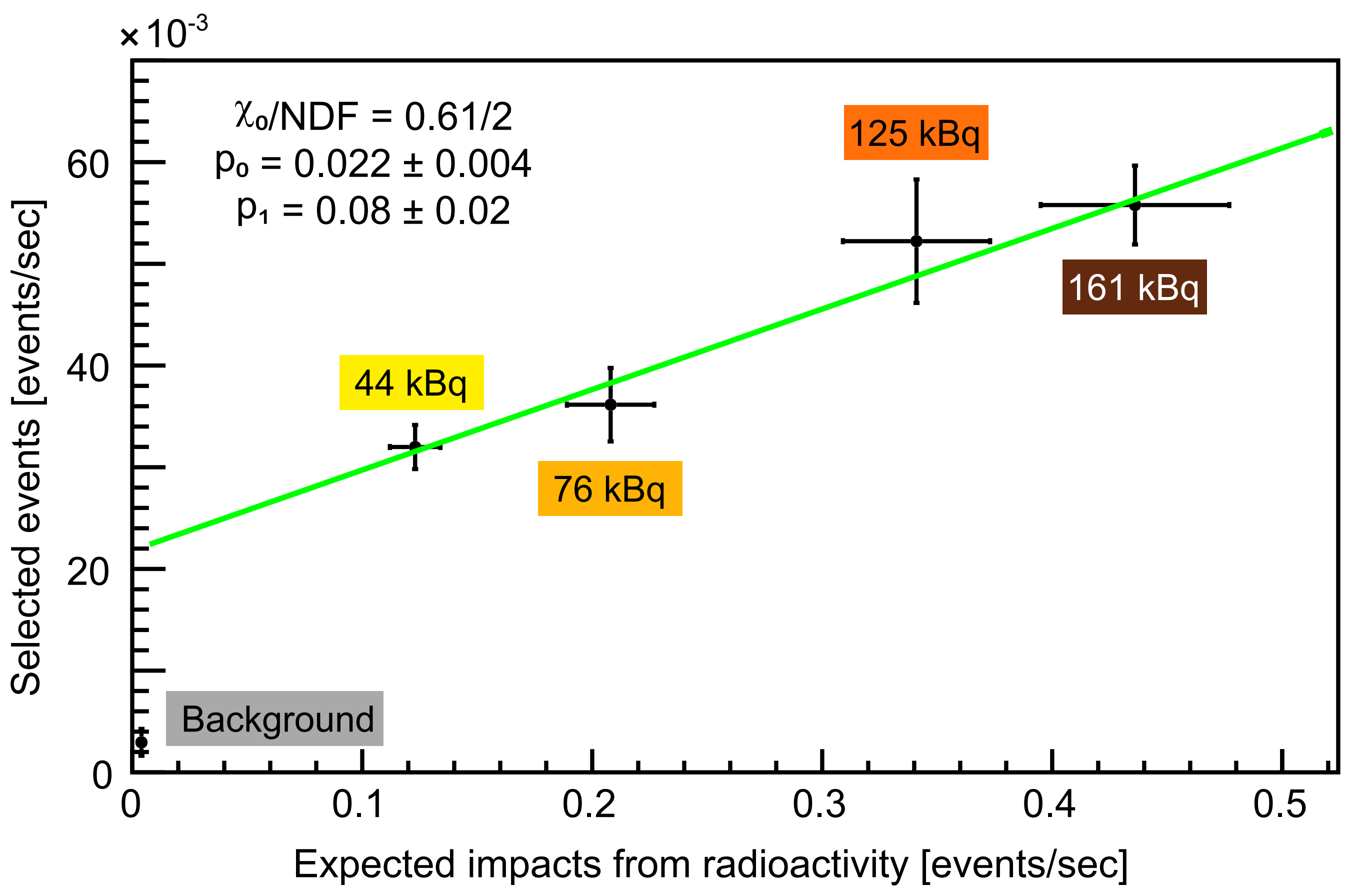
- COLD project (funded by Italian Ministry of Education~ 800 keuro, PI: S. Di Domizio)
- Mitigate phonon propagation through traps (Henriques 2019, Karatsu 2019, Iaia 2022…)
- Widely demonstrated with microwave resonators
- First evidence with qubits using copper traps
- COLD is investigating superconductors to replace copper



- Procured 4 commercial qubits chip
- Cryogenic test of Ti deposition: done
- Measurements planned by the end of 2024

Advancing Particle Physics

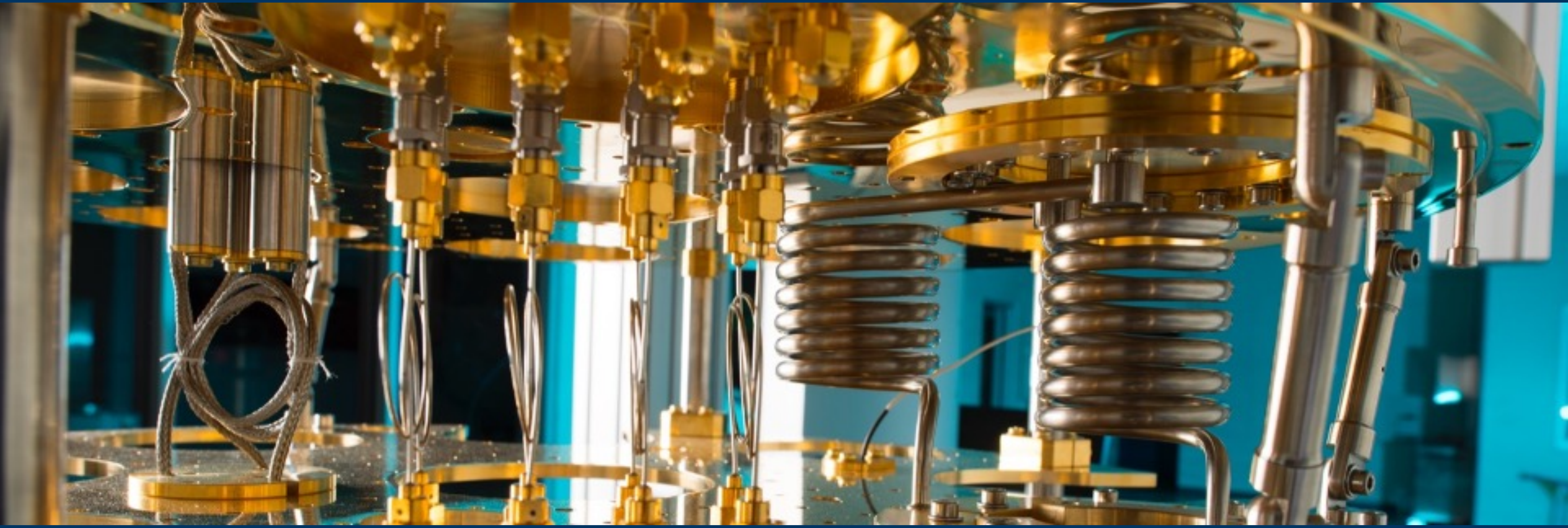
- Qubits are very sensitive to radioactivity
- Can we turn this into an advantage?
- Exposed qubits to a gamma source with increasing intensity: errors increased linearly



- With rudimental algorithms for data reconstruction, efficiency of ~10%
- Large room for improvement
  - Qubit design
  - Qubit operation
  - Analysis algorithms

De Dominicis et al, 2024

WE WELCOME NEW COLLABORATORS!



Thanks for the attention

Other Interesting Works

The quantum community is working also on “on-chip” mitigation strategies

- On-chip mitigation strategies:
    - Phonon traps (Henriques 2019, Karatsu 2019. De Visser 2021, Patel 2017, Iaia 2022...)
    - Gap engineering (Yamamoto 2006, Catalan 2022, McEwan 2024,...)
    - Structures around the qubit (Martinis 2021, ...)
    - Qubit on different dices (Gold 2021, ...)
    - Algortithms (Chubb 2021, Xu 2022, Sane 2023, Fowler 2023, Baireuther 2023, ...)

Other Interesting Works

- Since ~2017 intense "cross-pollination" between the community of qubits and of particle physics: now we speak the same language :)
- Intense effort in modelling/measuring the effects of radioactivity on qubits
    - Li et al: arXiv: 2402.04245 (23 feb 2024)-> direct measurements of μ in qubits
    - McEwen et al: arXiv:2402.15644 (23 feb 2024) -> gap engineering to protect qubits
    - Yelton et al: arXiv:2402.15471 (23 feb 2024) -> G4CMP modeling of phonon-QP poisoning
    - Harrington et al: arXiv: 2402.03208 (5 feb 2024) -> synchronous measurements of μ in qubits
    - Thorback et al, PRX Quantum 4, 020356 2023 -> effects of radioactivity on TLS
    - And many others (phonon traps, ...)