Study of the effects of radioactivity on superconducting quantum bits

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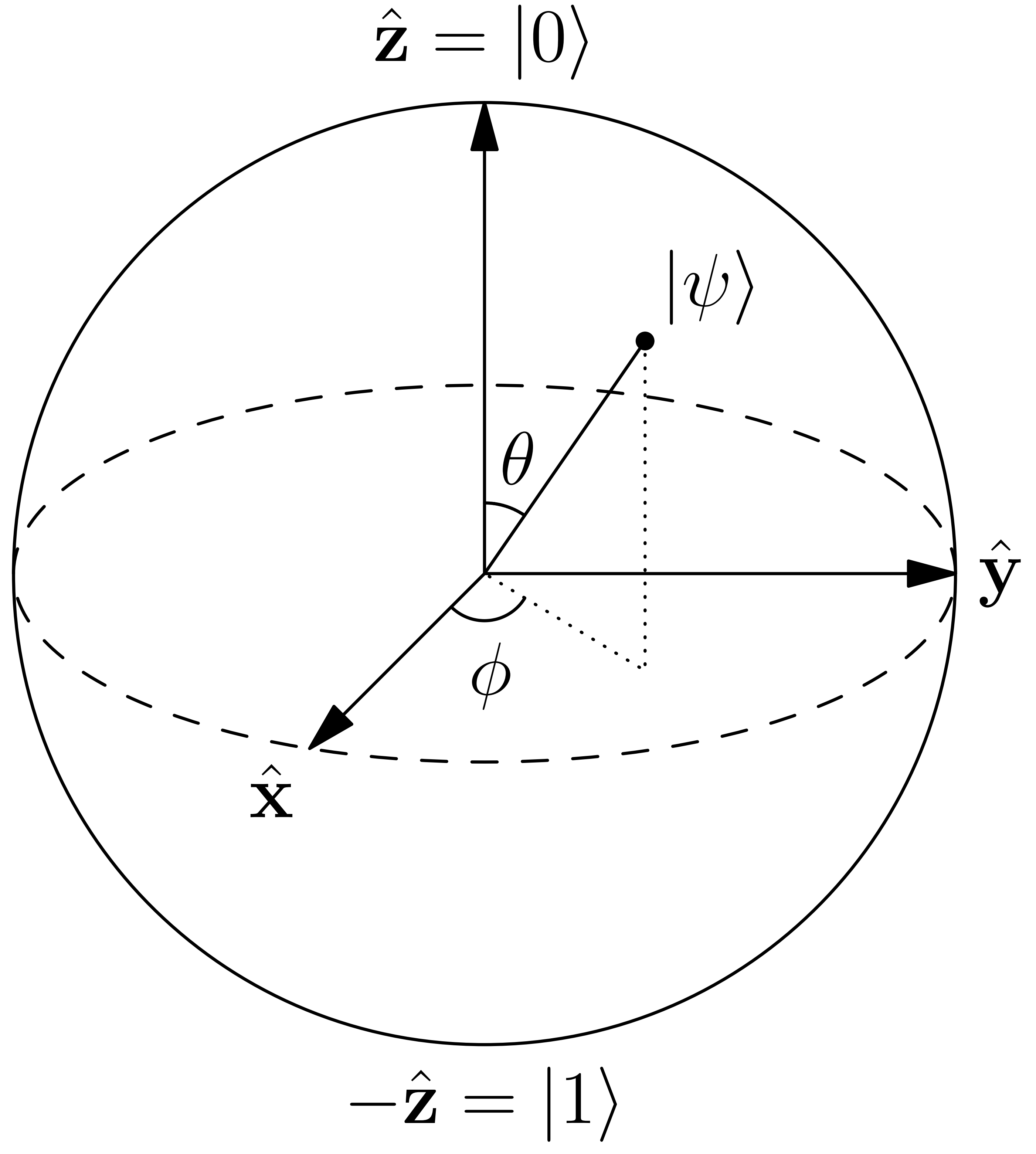
Advisors: Fernando Ferroni (GSSI), Laura Cardani (INFN)

Superconducting qubits

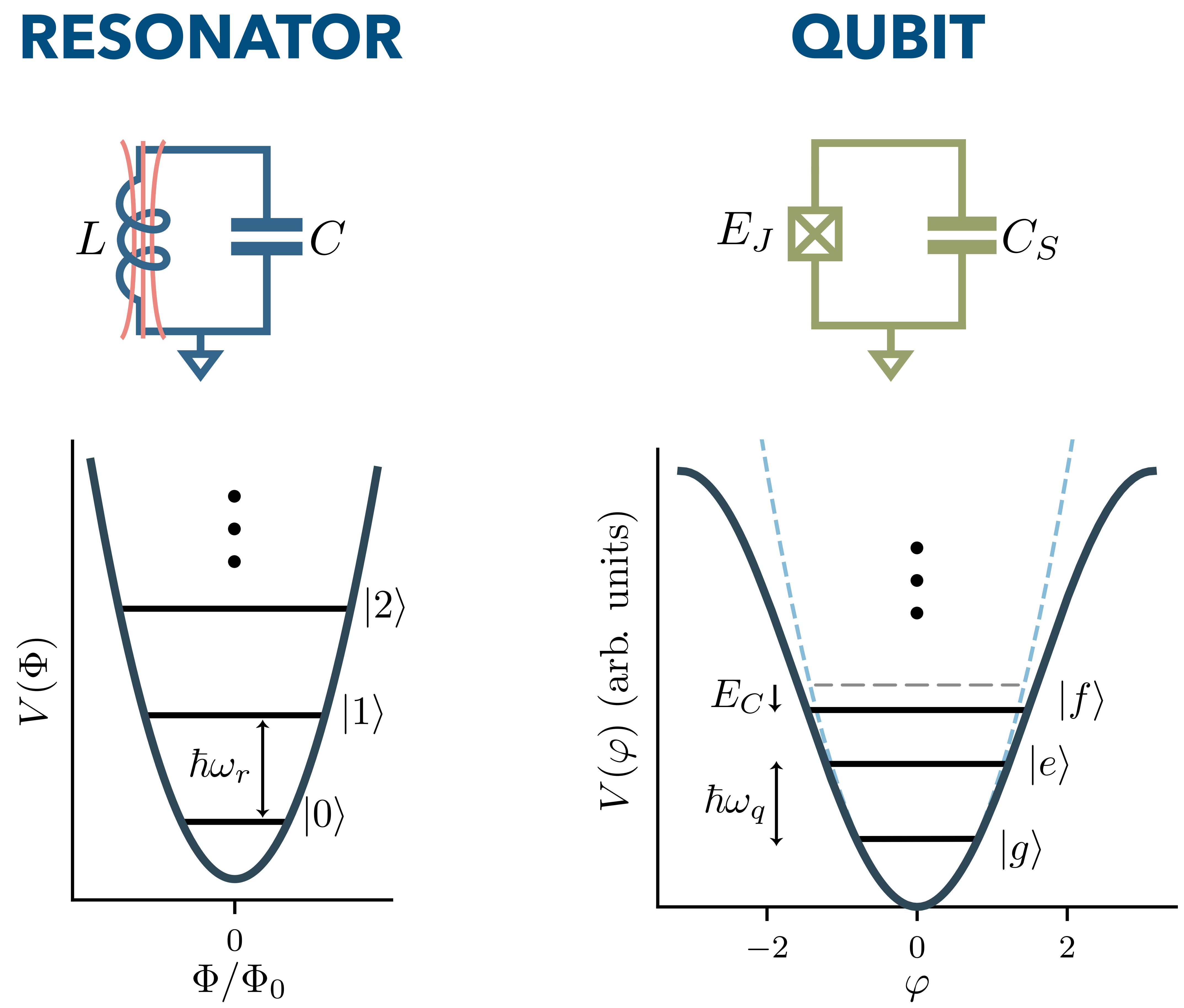
- Quantum counterpart of classical bit;
- Possibility to have superposition states $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$;
- Any two-level quantum system can be operated as a qubit;



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

Superconducting qubits

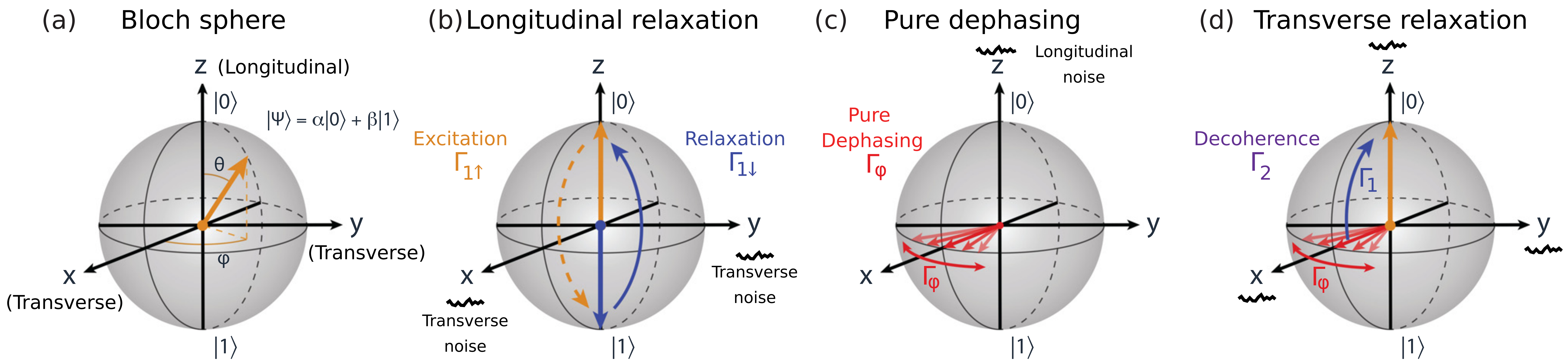
- Superconducting circuit with a Josephson Junction;
- The Josephson Junction acts as a non-linear inductor that produces an anharmonic energy spectrum;
- The anharmonic energy spectrum allows us to populate only the first two energy levels, operating the circuit as an effective qubit.



Blais et al., *Rev. Mod. Phys* **93**, 025005 (2021)

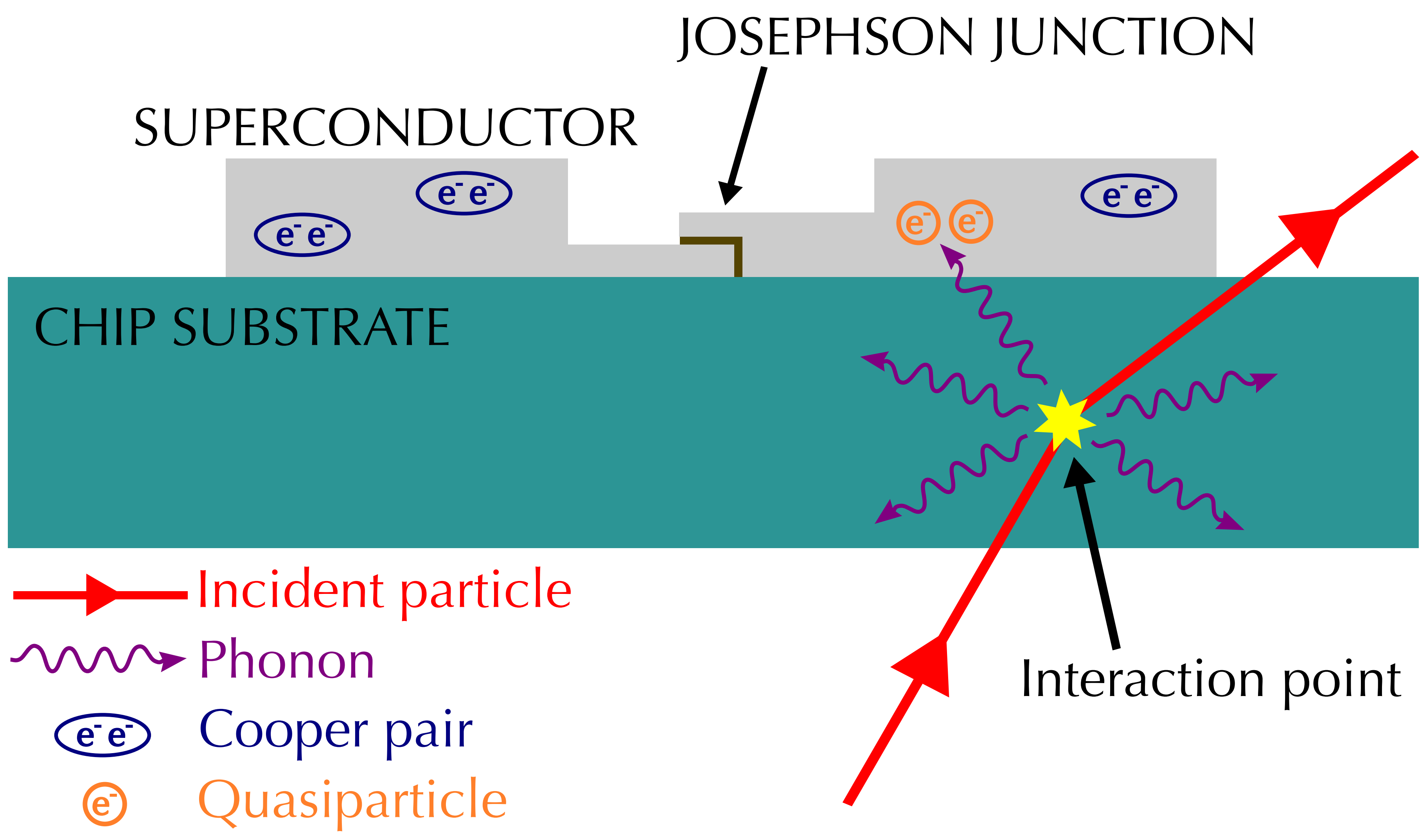
Qubit coherence

- Interactions with the environment make the qubit state change unpredictably;
- When they occur the information stored by the qubit is lost;
- This phenomenon is called **decoherence**;



Krantz et al., *Appl. Phys. Rev.* **6**, 021318 (2019)

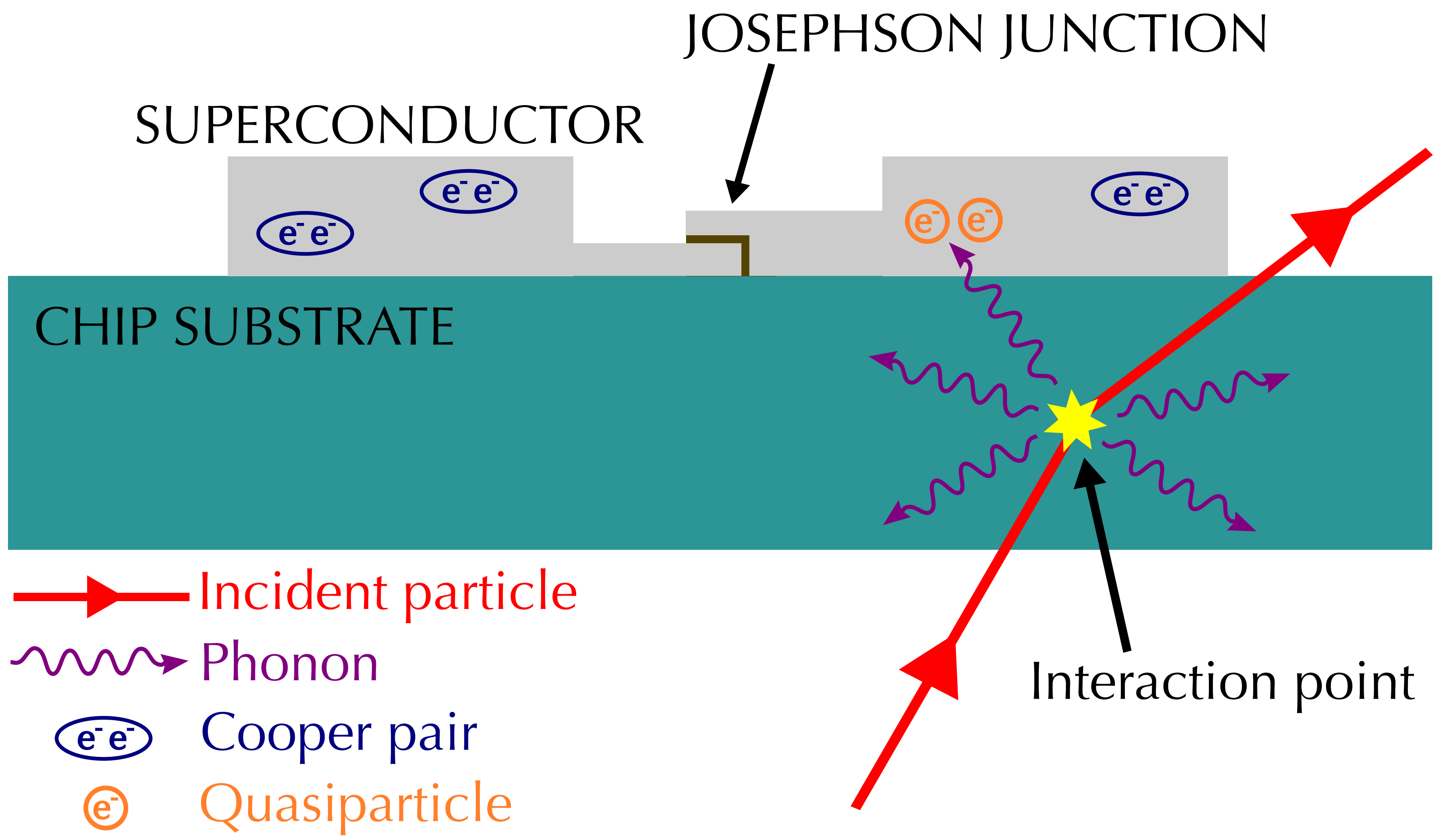
Qubits and radioactivity

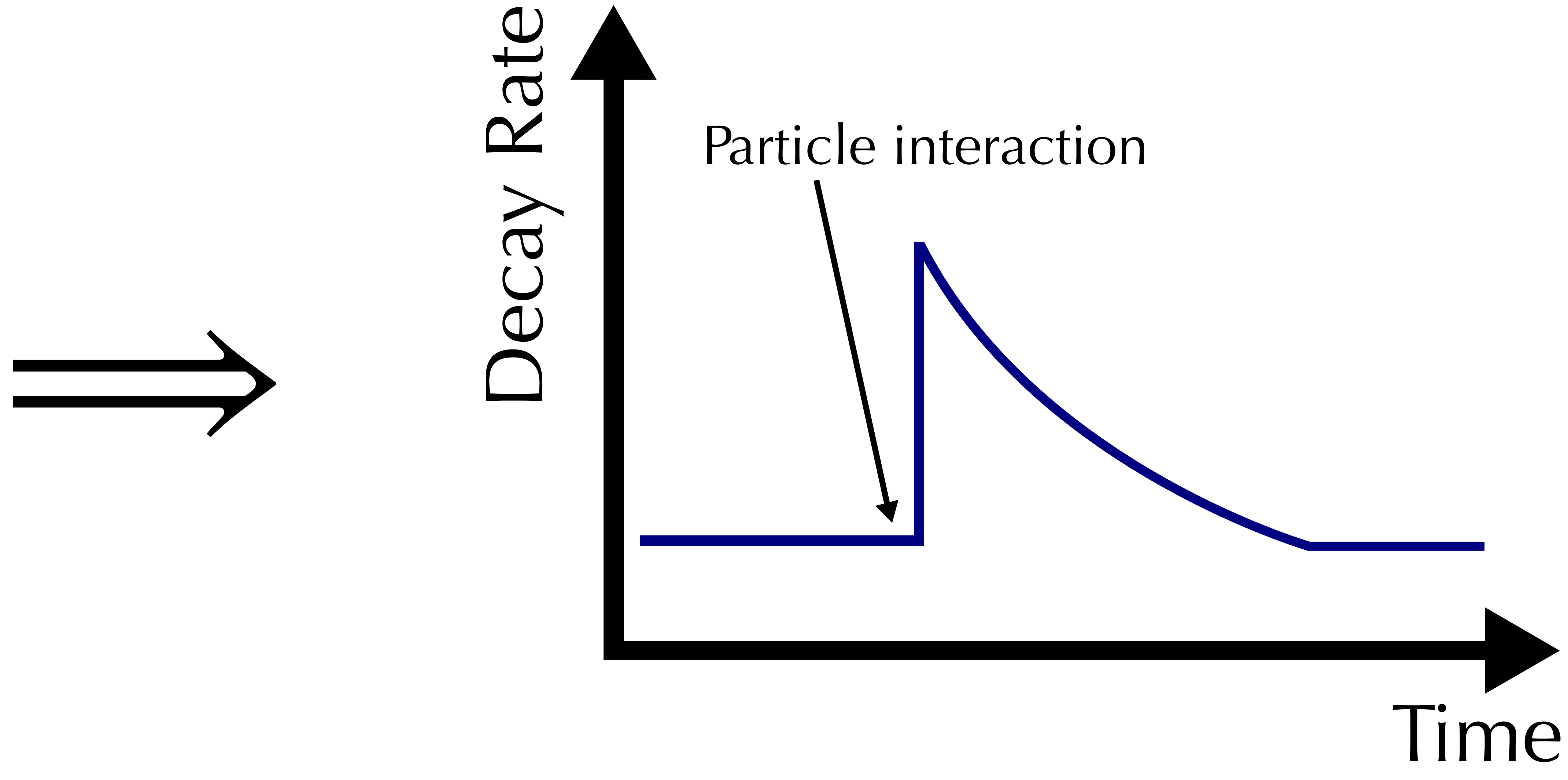


- Incident particles deposit energy in the qubit substrate;
- The phonons produced can reach the superconductor and break Cooper pairs, producing a burst of quasiparticles;
- Quasiparticles tunneling is one of the decay mechanisms of the qubit.

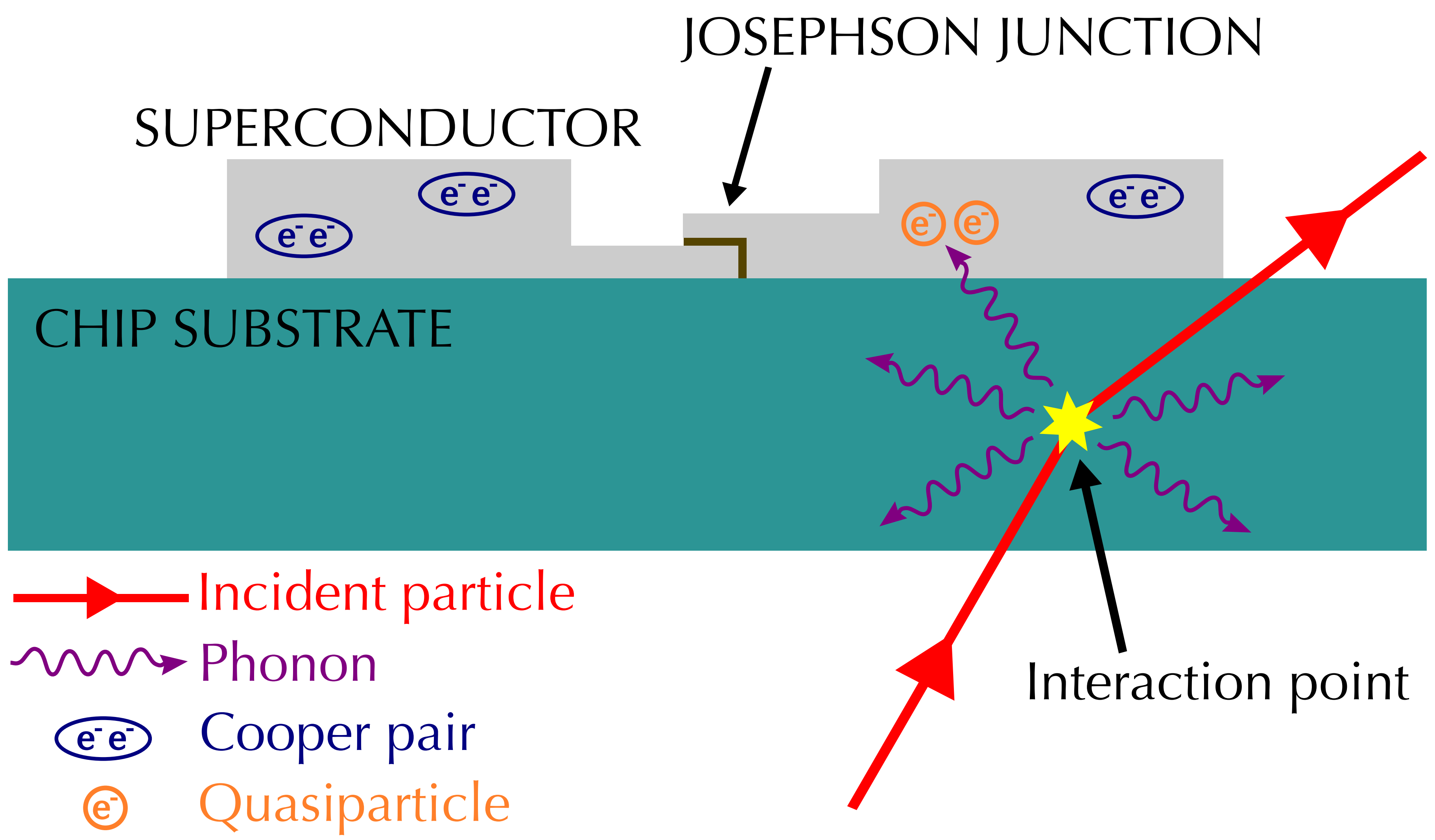
Qubits and radioactivity

- The decay rate of the qubit increases with the density of quasiparticles in the superconductor;
- When a particle impact occurs the decay rate of the qubit suddenly increases, returning to its original value as Cooper pairs are formed again;
- The entire process lasts a **few milliseconds**.





Qubits and radioactivity



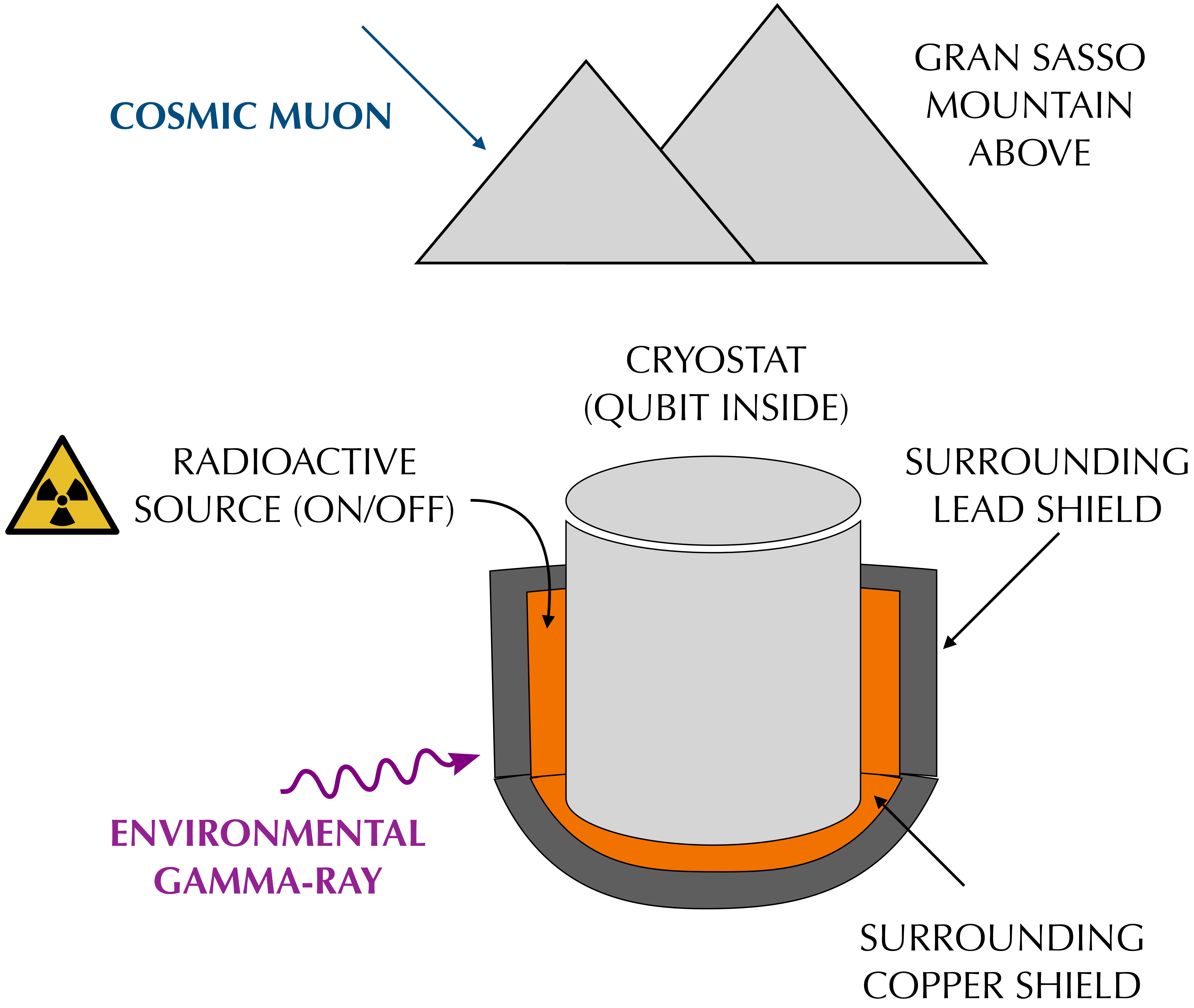
- Past researches showed that:
    - Superconducting quantum circuits are sensitive to radioactivity [Cardani et al., *Nature Communications* (2021); Vepsäiläinen et al., *Nature* (2020)];
    - Radioactivity is a source of correlated errors in multi-qubit chips [Wilen et al., *Nature* (2021), McEwen et al., *Nature Physics* (2022)];
- A quantitative study of this impact, though, was missing.

Aim of my research

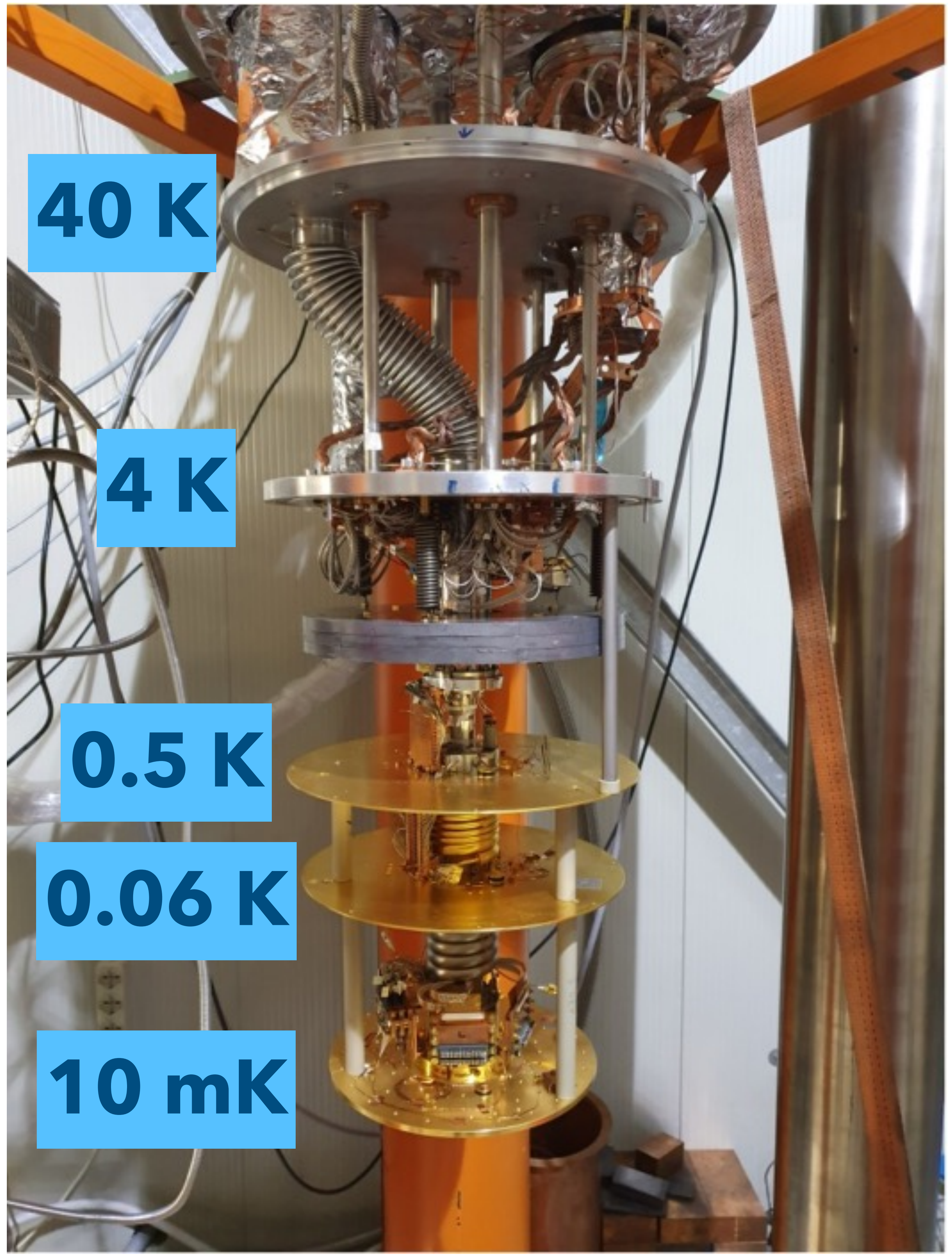
- The aim of my research is:
  - Quantify the impact of radioactivity on superconducting qubits in terms of:
    - single qubit lifetime;
    - occurrence of multi-qubit errors;
  - Assess the potential of quantum bits as particle detectors.

How to recognize ionizing radiation

- Qubit dynamics is affected by several phenomena, disentangling radioactivity from the others can be tricky;
- Our approach:
  - Characterize the qubit in a low-radioactivity environment;
  - Expose the qubit to radioactive sources with different activities and repeat the measurement;
  - Compare the results.

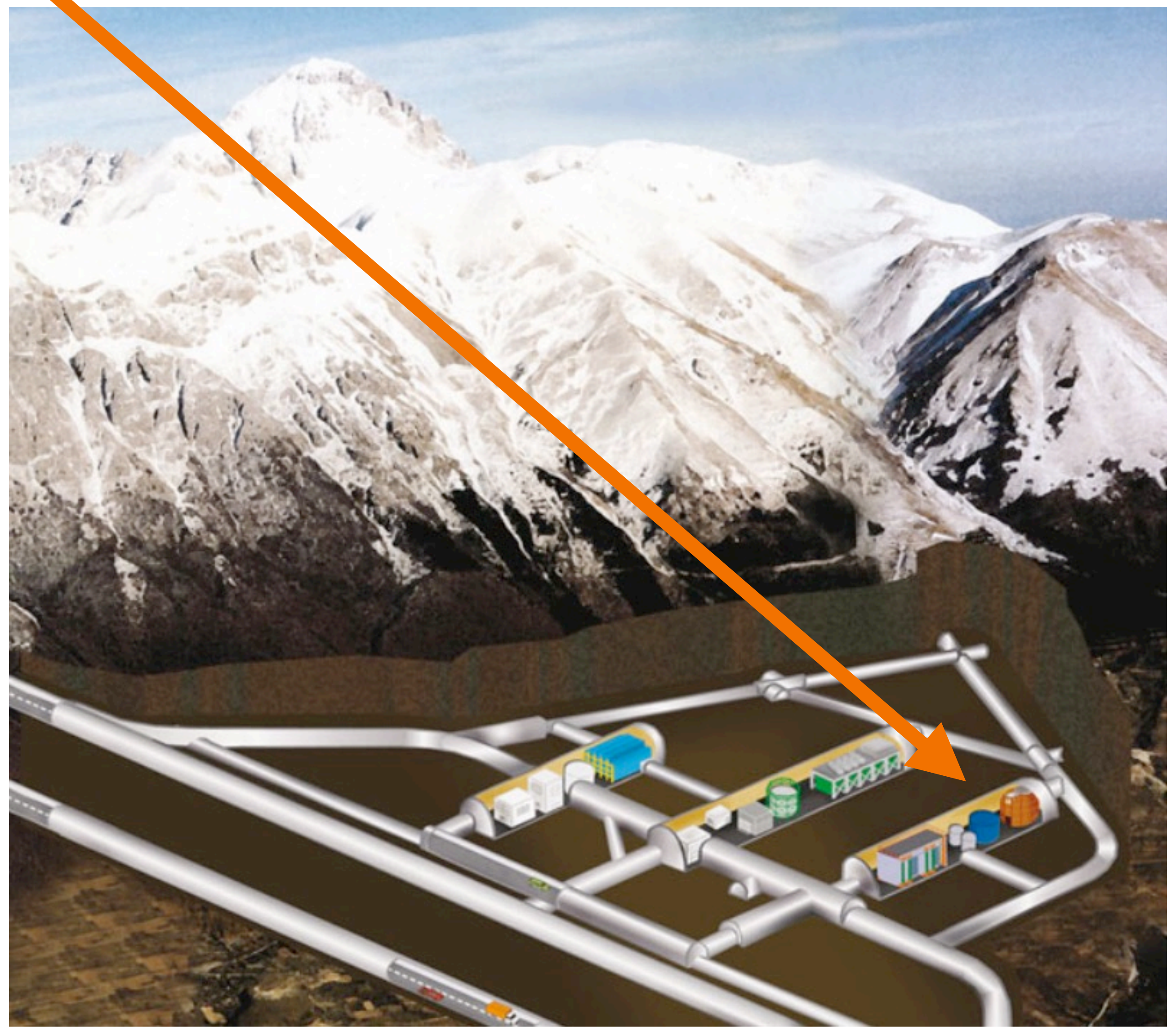


The IETI Underground Facility

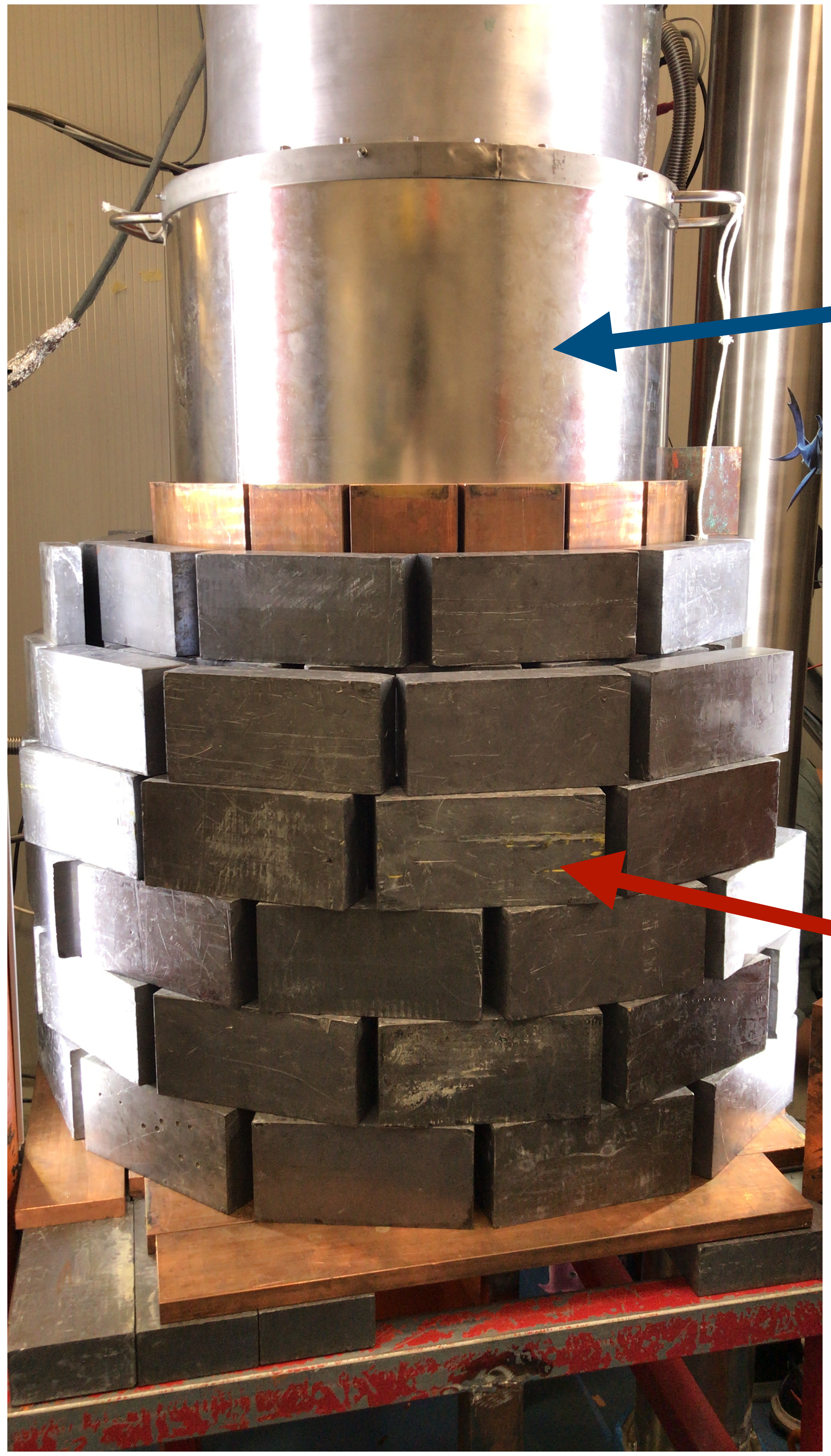


- Hall C of LNGS Underground Laboratories;
- Pulse Tube based $^3He/^4He$ dilution refrigerator;
- Originally designed for R&D of cryogenic detectors;
- Installation of qubit readout at the beginning of my PhD.

https://ieti.sites.lngs.infn.it/index.html



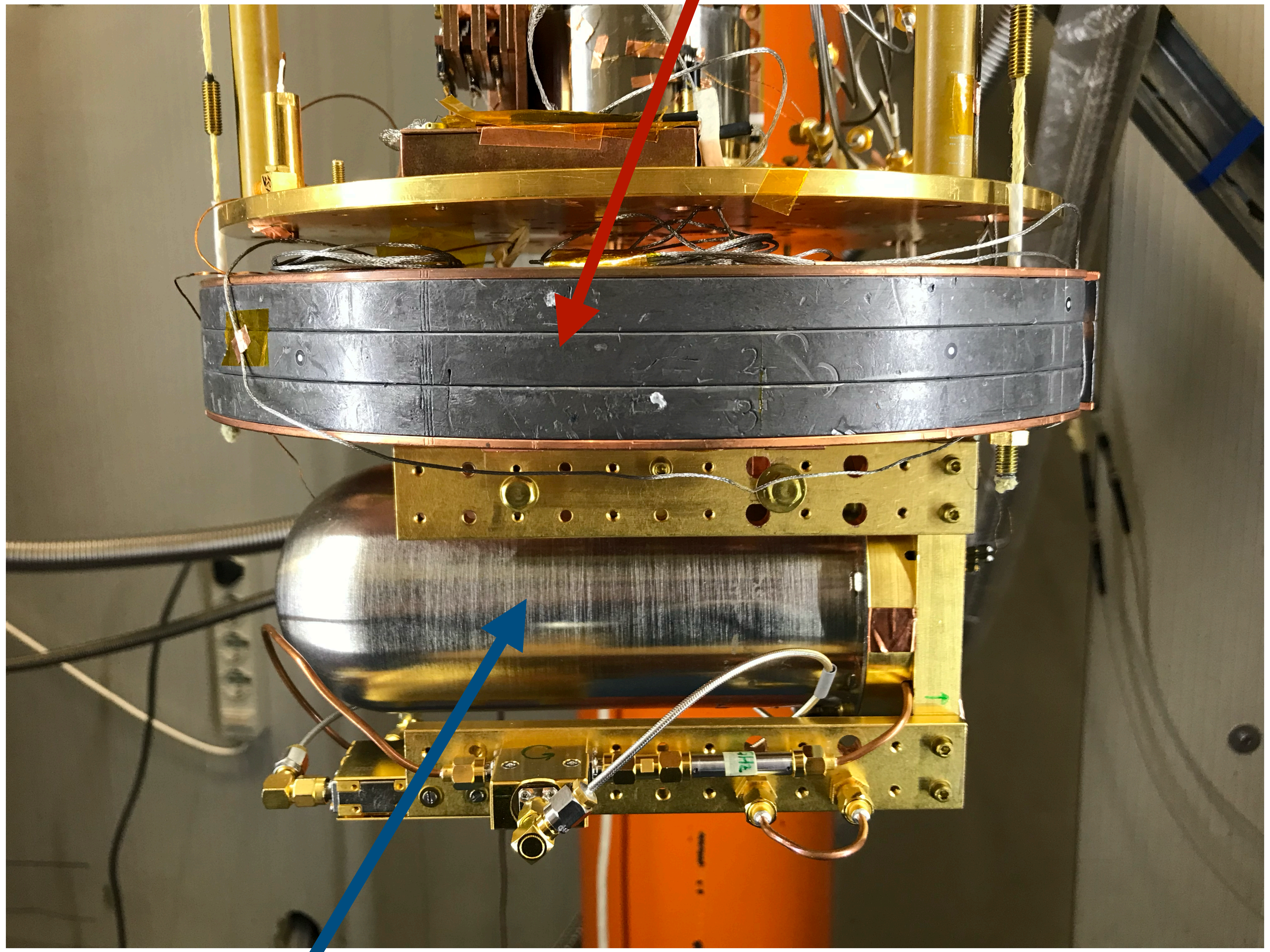
Shielding



External Magnetic Shield

External Pb+Cu Shield

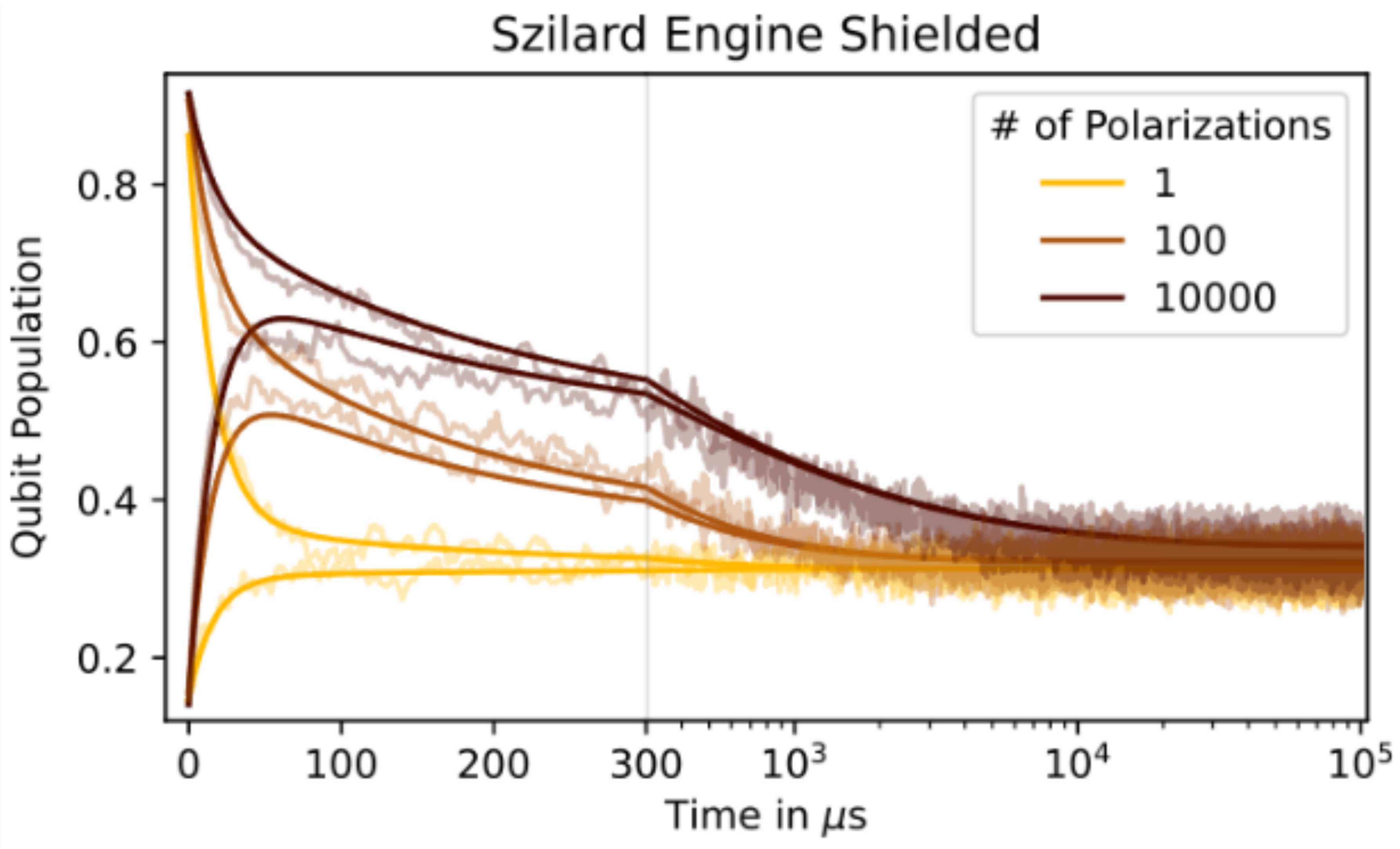
Inner Lead Shield (second shield at 4K)



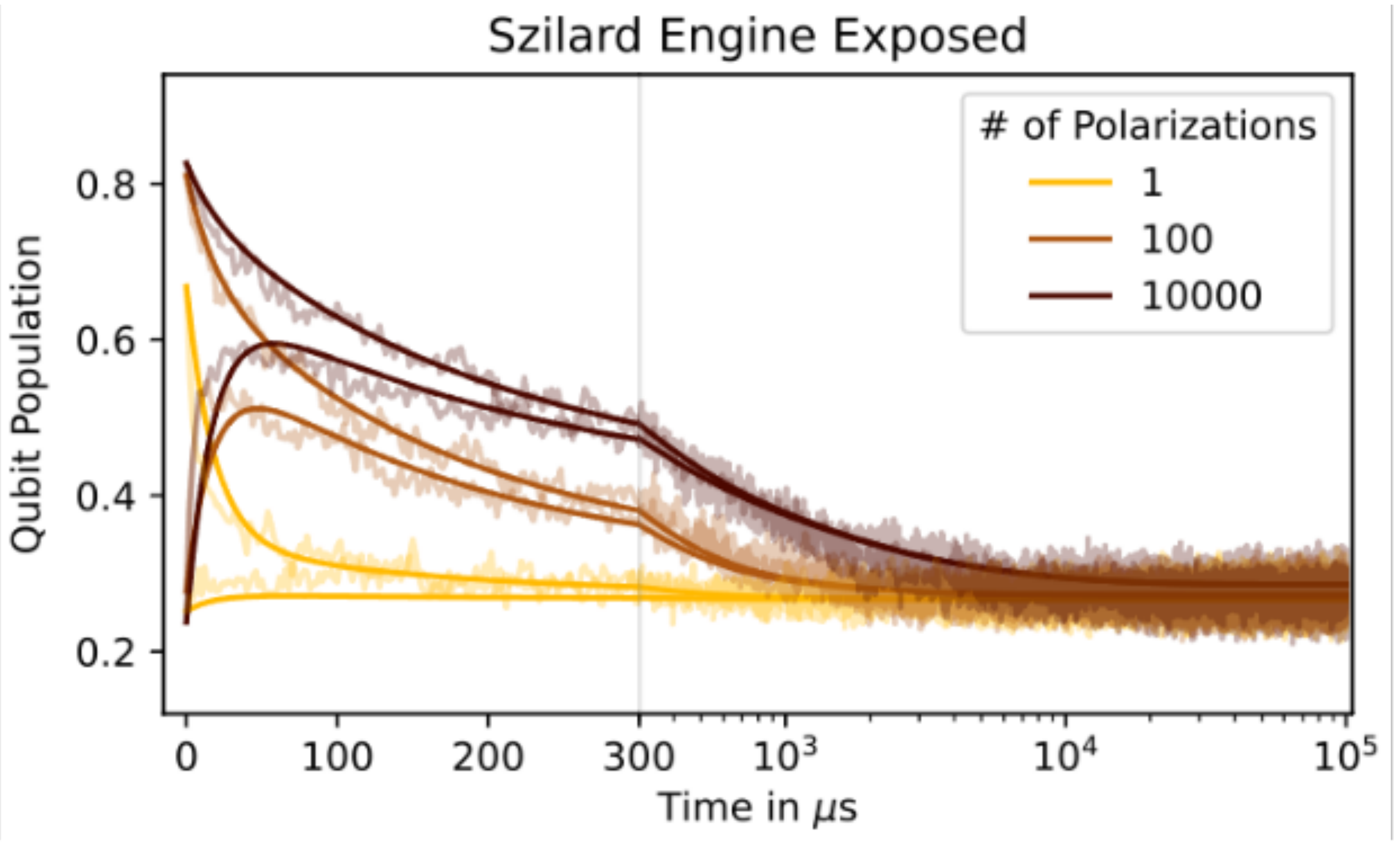
Magnetic Shield (Qubit Inside)

Is radioactivity a limit for qubits?

- Measurements of the qubit lifetime done during my second year showed no difference between the qubit shielded from radioactivity and the same qubit when exposed to a Th source to simulate radioactivity of an above-ground laboratory:



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

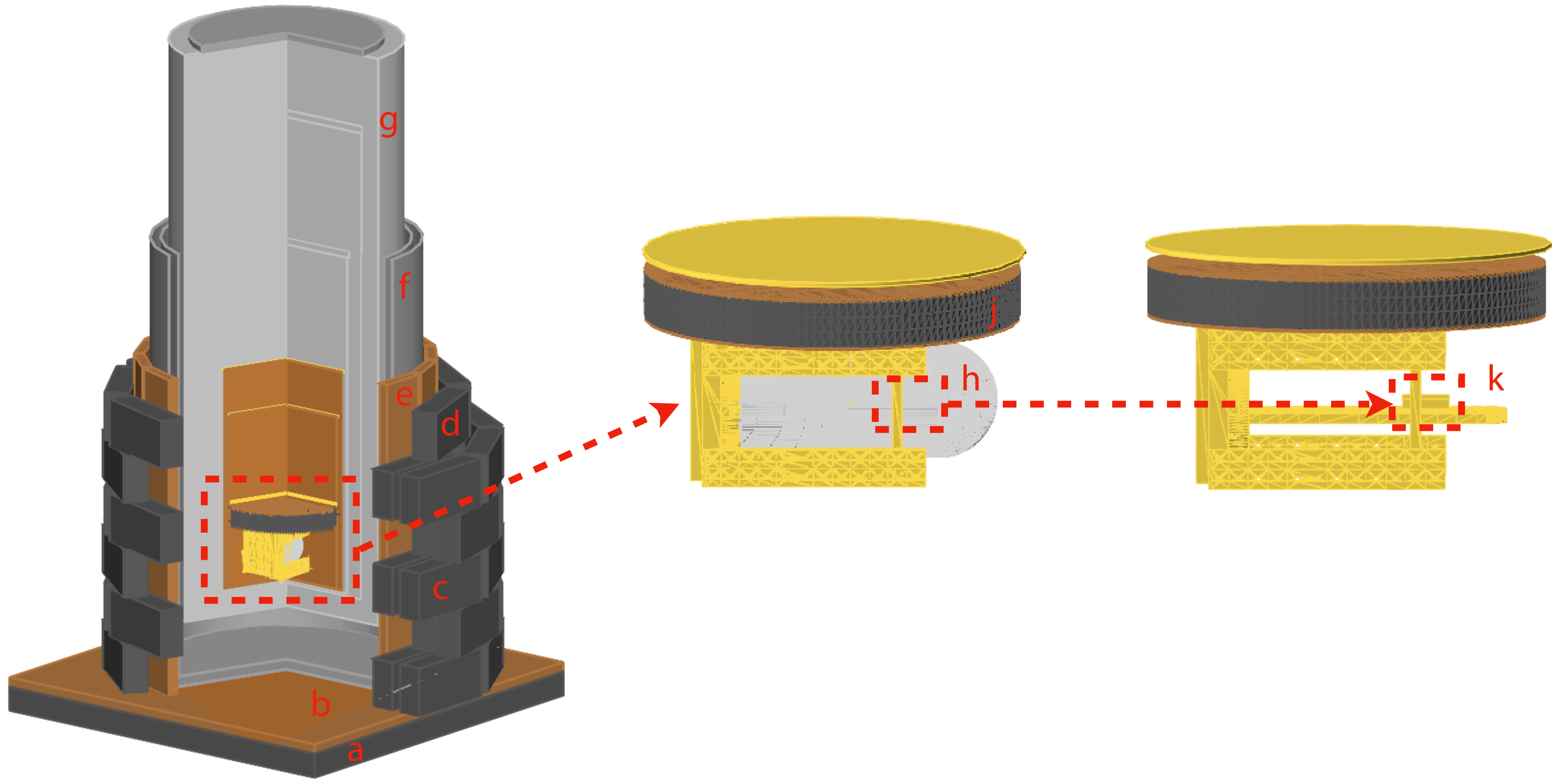


$\Gamma_q = \Gamma_1 - \sum_k \Gamma_{qt}^k \approx 1/91\,\mu s$

Expected contributions

- Setup reconstructed in a Geant4-based Monte Carlo simulation to estimate the rate of particle impacts in the chip produced by different sources of radioactivity.

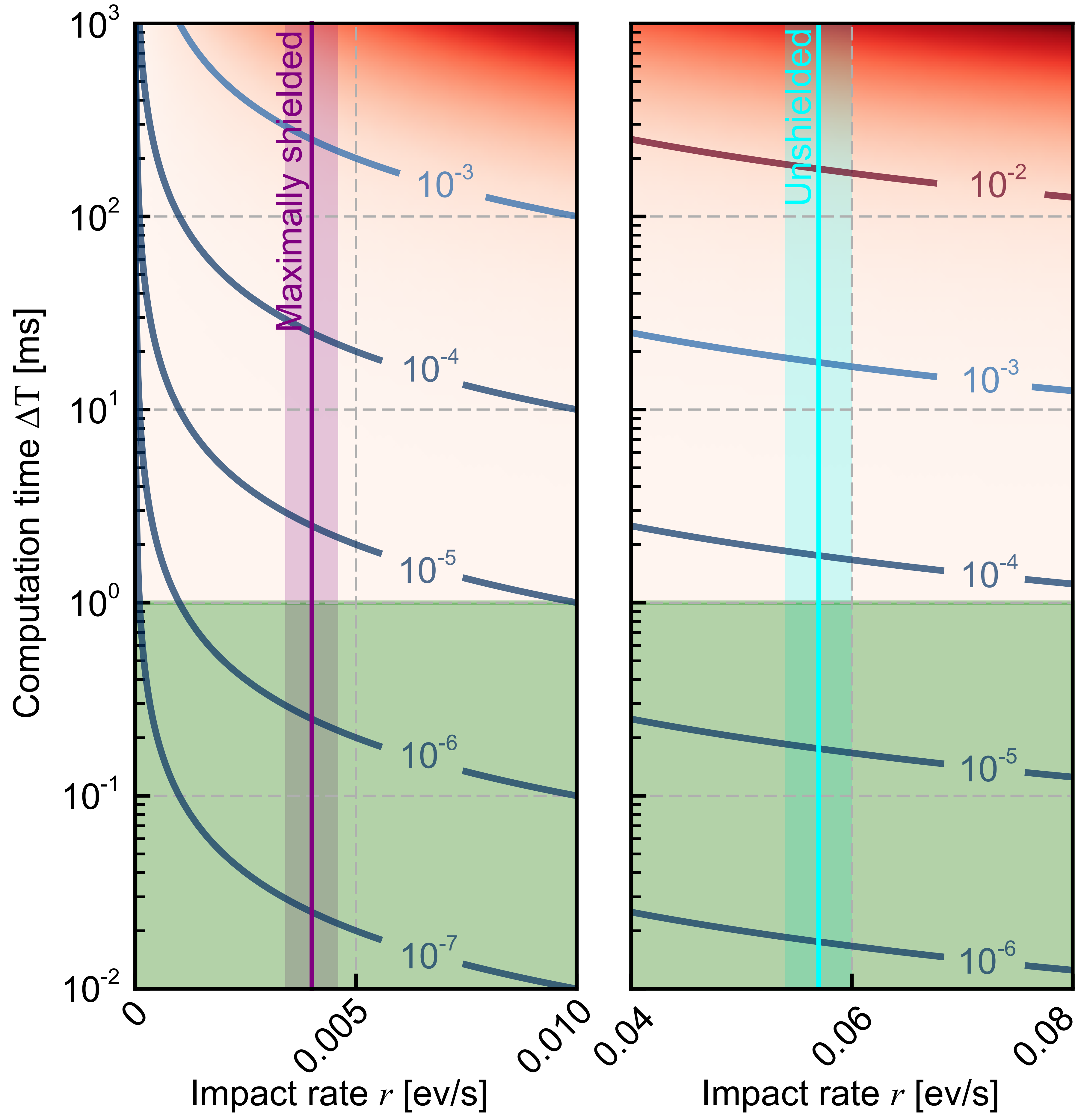
Source	Above Ground (events/s)	LNGS (events/s)
Lab γ-rays	$(46 \pm 2)\times 10^{-3}$	$(1.3 \pm 0.1)\times 10^{-3}$
Muons	$(8.0 \pm 0.5)\times 10^{-3}$	$< 10^{-5}$
Contaminations	$(2.7 \pm 0.5)\times 10^{-3}$	$(2.7 \pm 0.5)\times 10^{-3}$
Total	$\mathbf{(57 \pm 3)\times 10^{-3}}$	$\mathbf{(4.0 \pm 0.6)\times 10^{-3}}$



De Dominicis et al., arXiv:2405.18355

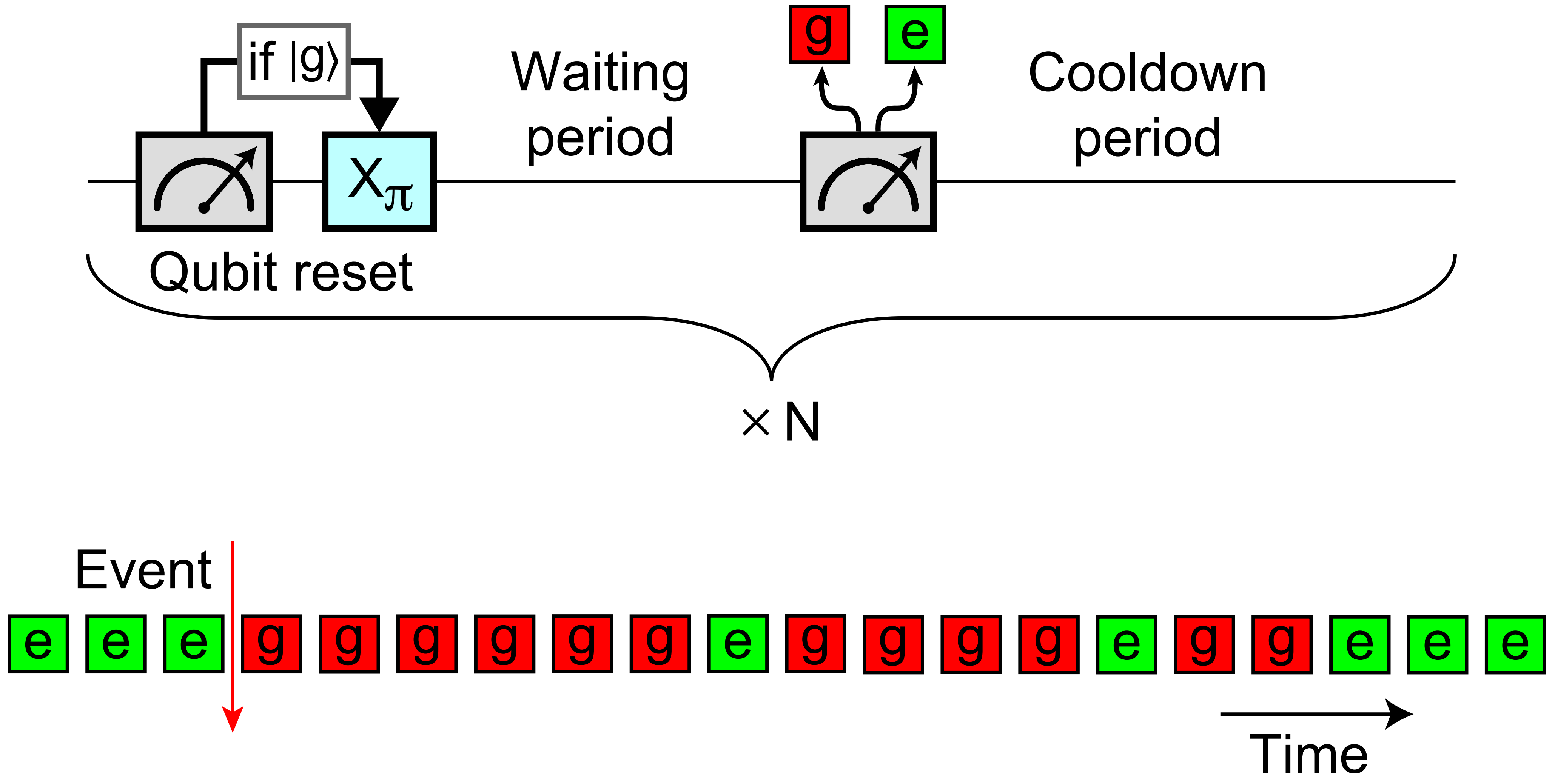
Is radioactivity a limit for qubits?

- Even when the qubit is exposed to the source, particle impacts are rare, one every few seconds, while other decay mechanisms are orders of magnitude more frequent;
- As a consequence, radioactivity is not the main limit for the lifetime of present-day qubits;
- Results suggest that radioactivity will be a limiting factor when the lifetime of qubits will reach O(1 s) or greater.



New measurement strategy

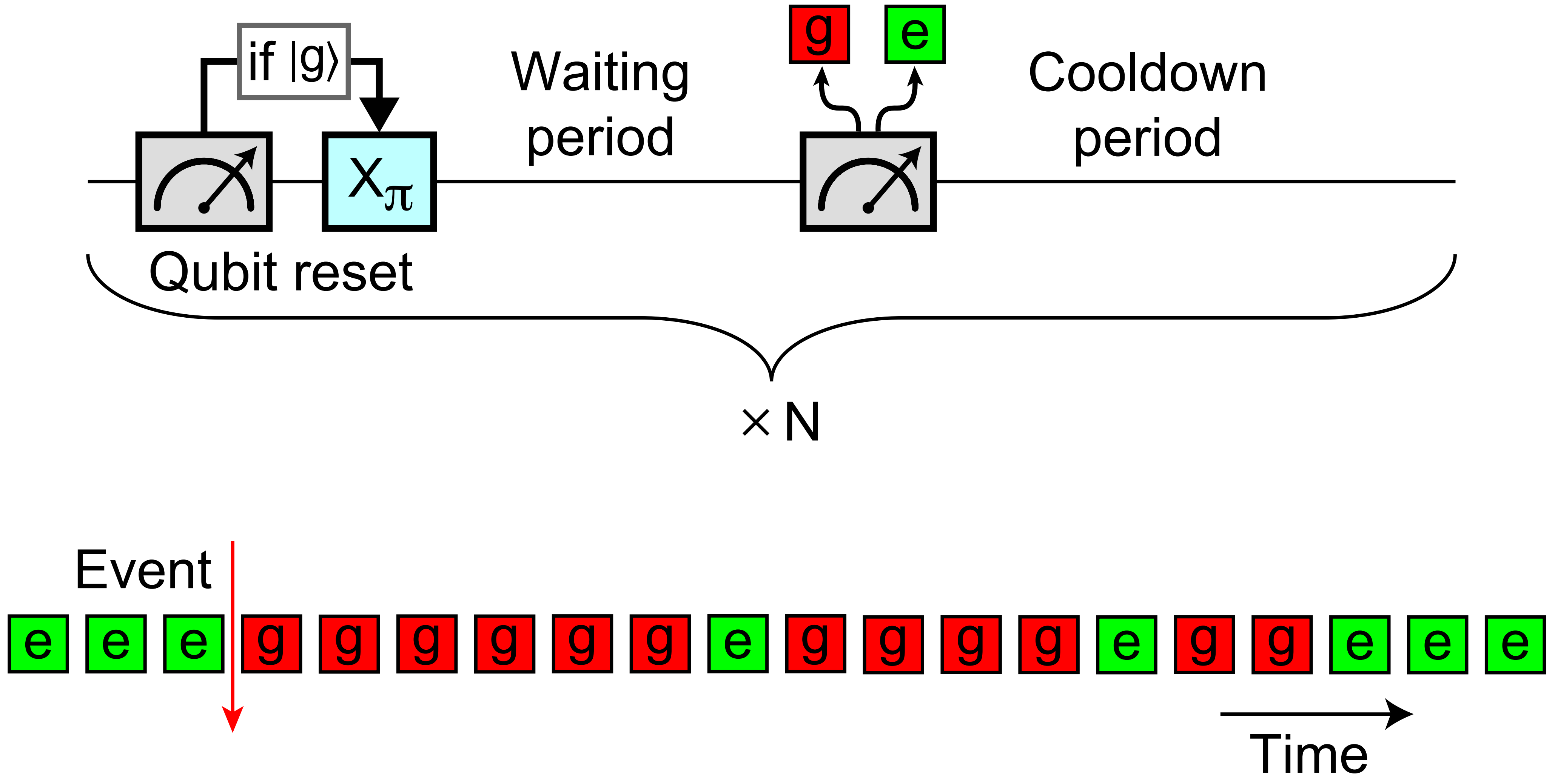
- We prepare the qubit in $|e\rangle$;
- We wait 5 μs;
- We measure the qubit state;
- We repeat;
- The entire cycle lasts tens of μs.



De Dominicis et al., arXiv:2405.18355

New measurement strategy

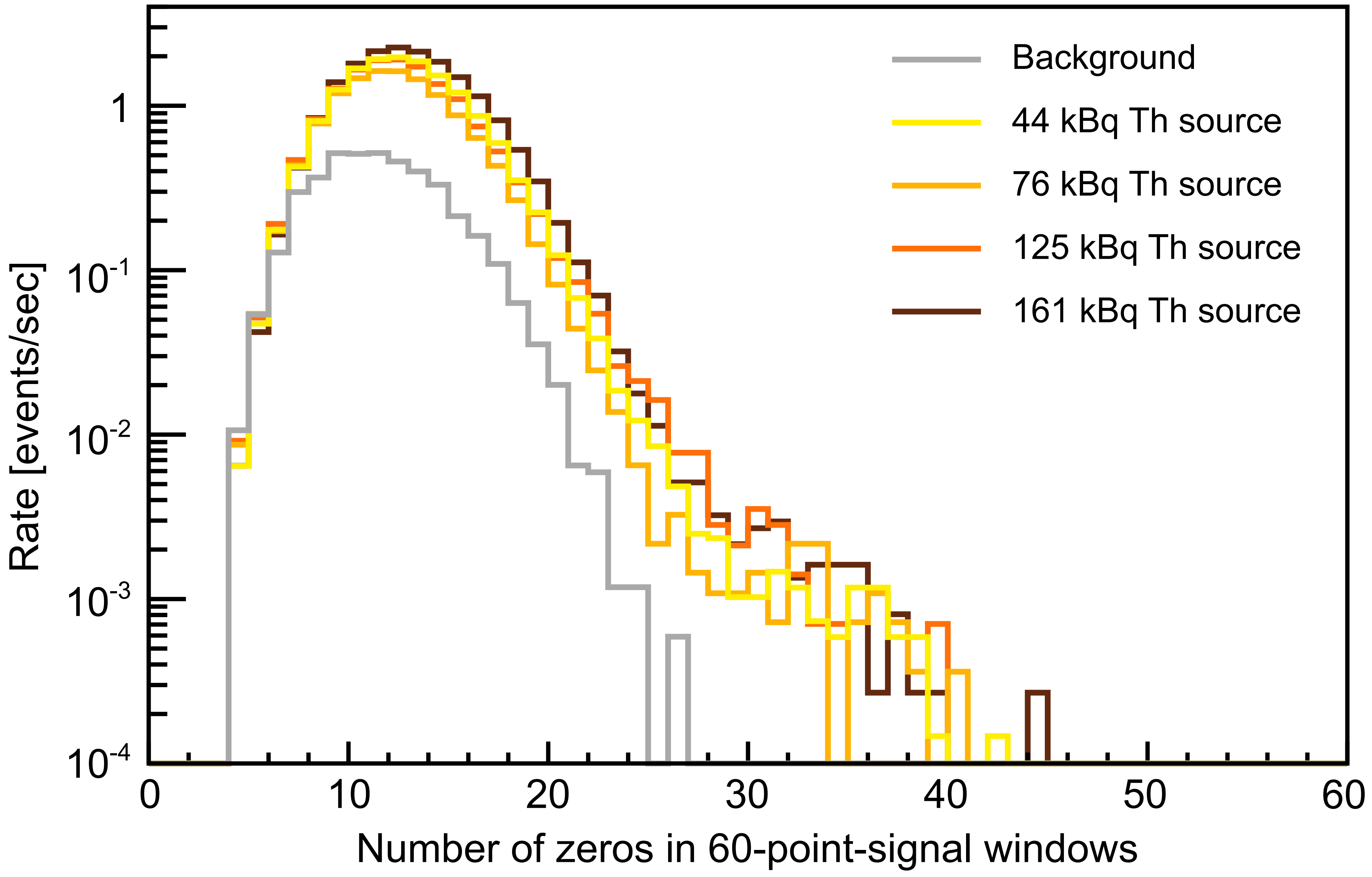
- $T_1 \gg 5\,\mu s$, so we expect that after 5 μs we measure most of the times the qubit in $|e\rangle$;
- If we have a particle interaction, though, T_1 drops and we observe a stream of measurements of the qubit in $|g\rangle$.

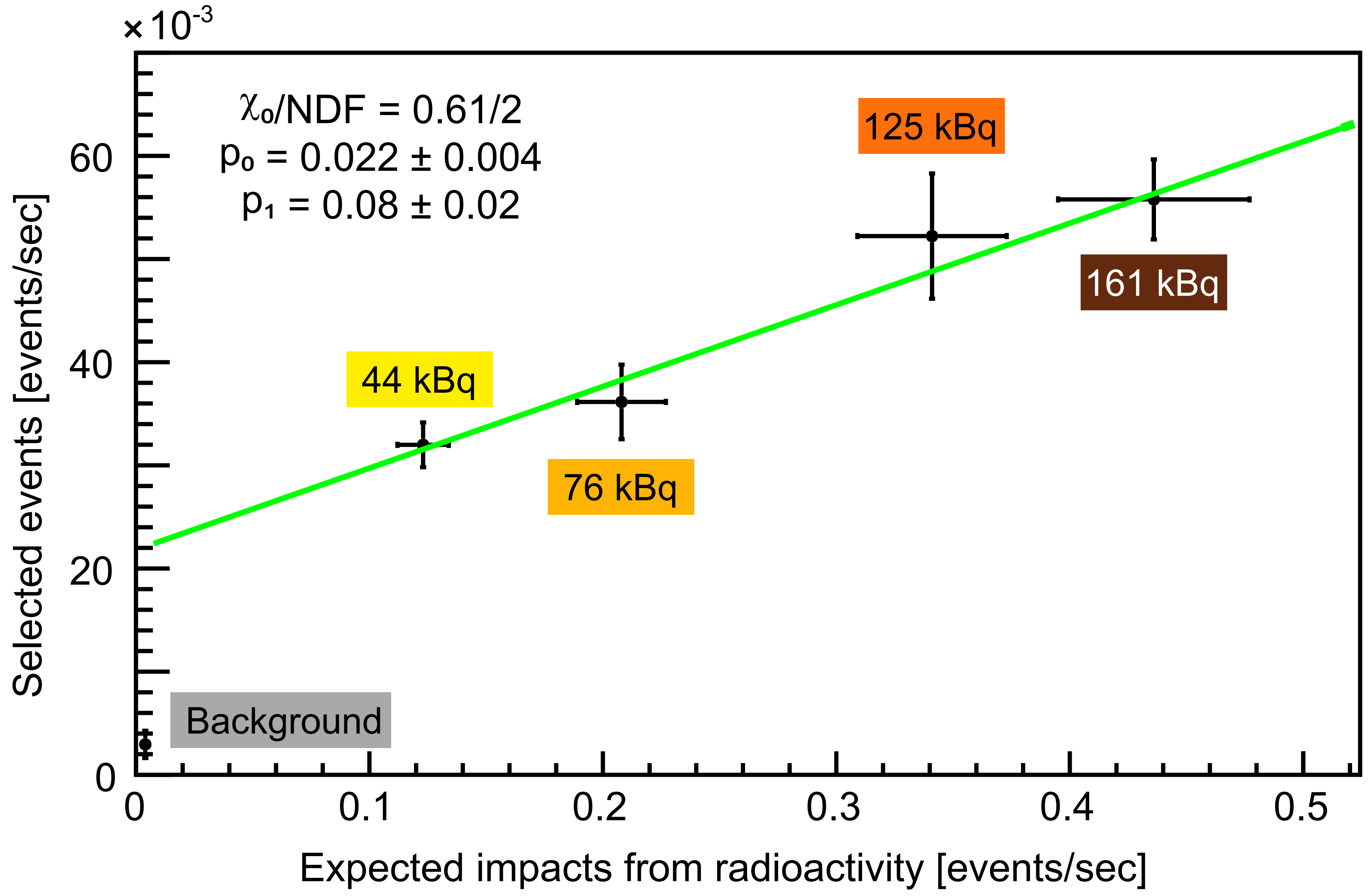


De Dominicis et al., arXiv:2405.18355

Results

- When exposing a transmon qubit to gamma radiation sources we observed an excess of events with high occurrence of $|g\rangle$!
- The rate of these events increases linearly with the activity of the source:

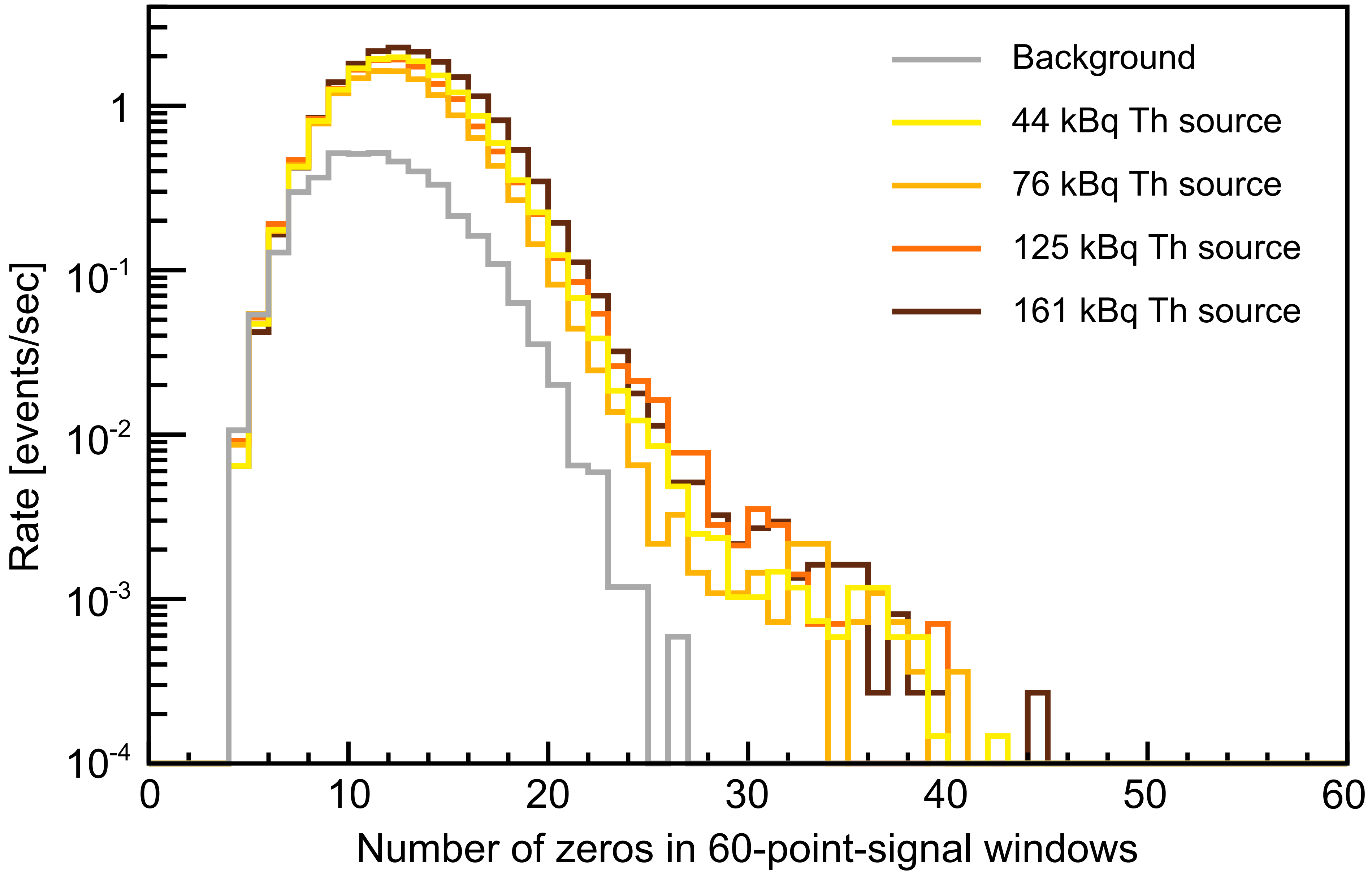


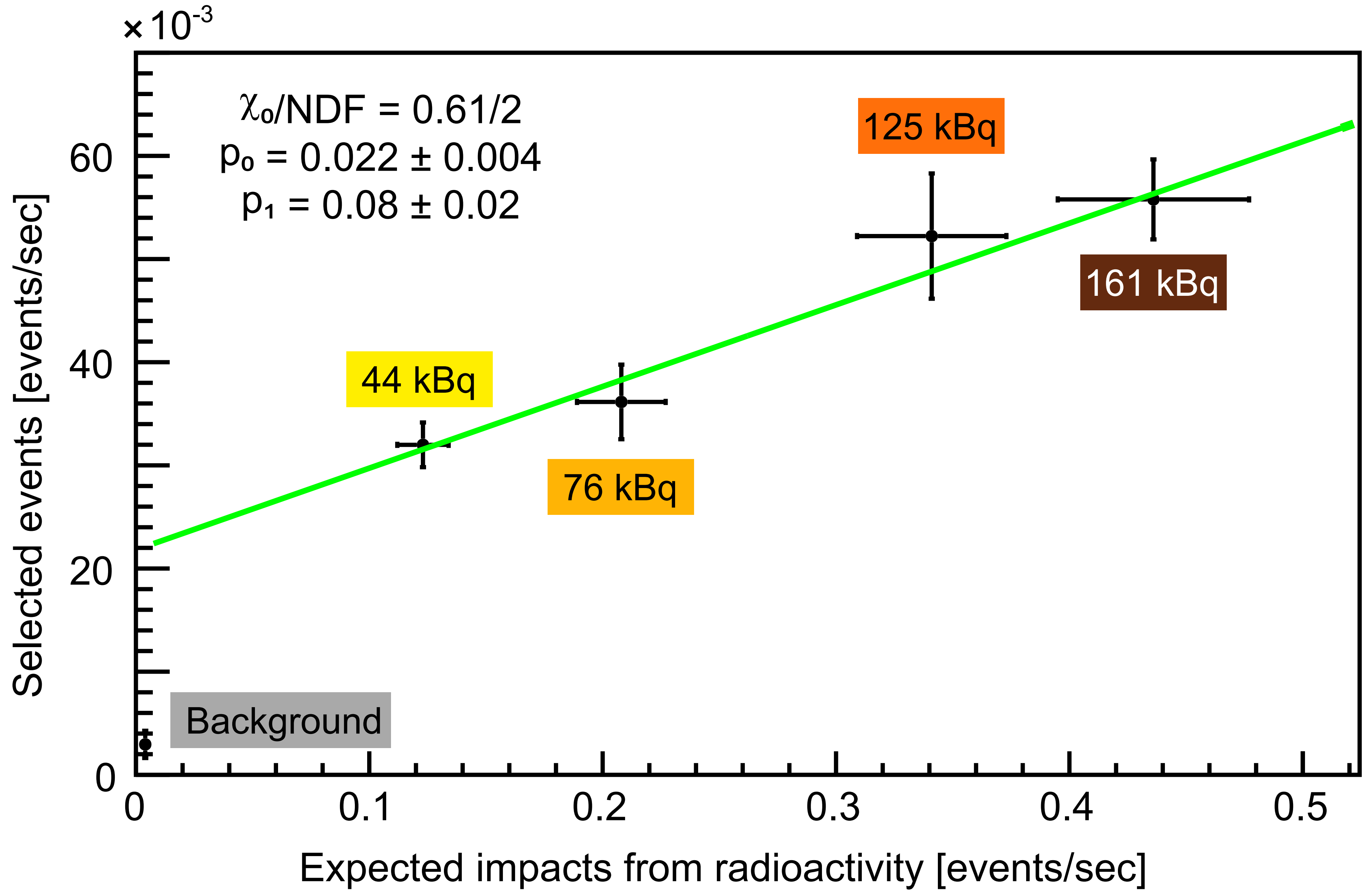


De Dominicis et al., arXiv:2405.18355

Results

- By looking at the slope of the linear fit we estimate a detection efficiency of approx. 8%;
- The low efficiency is most likely a consequence of the very aggressive cuts used to reduce the rate of noise events.

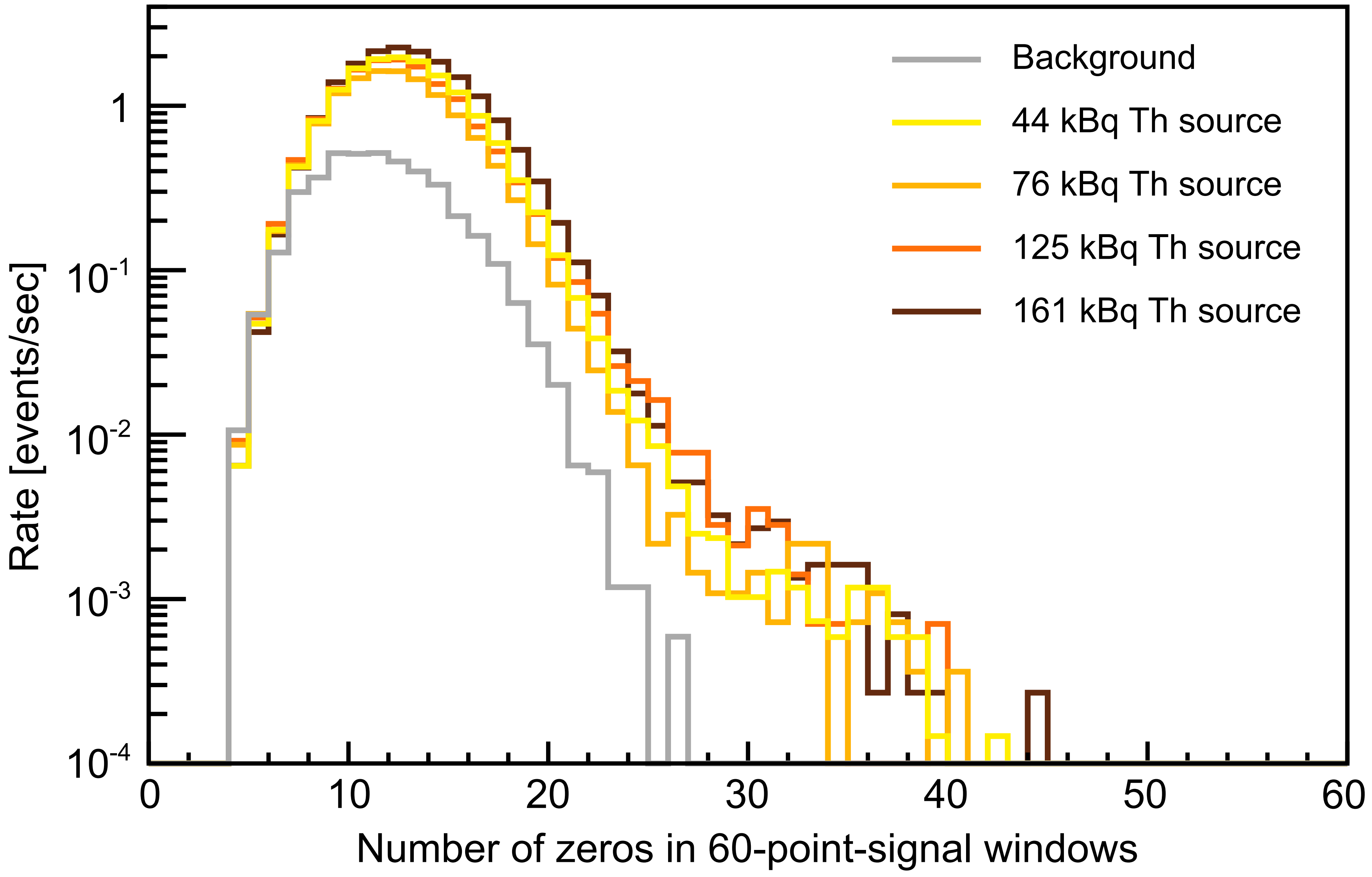


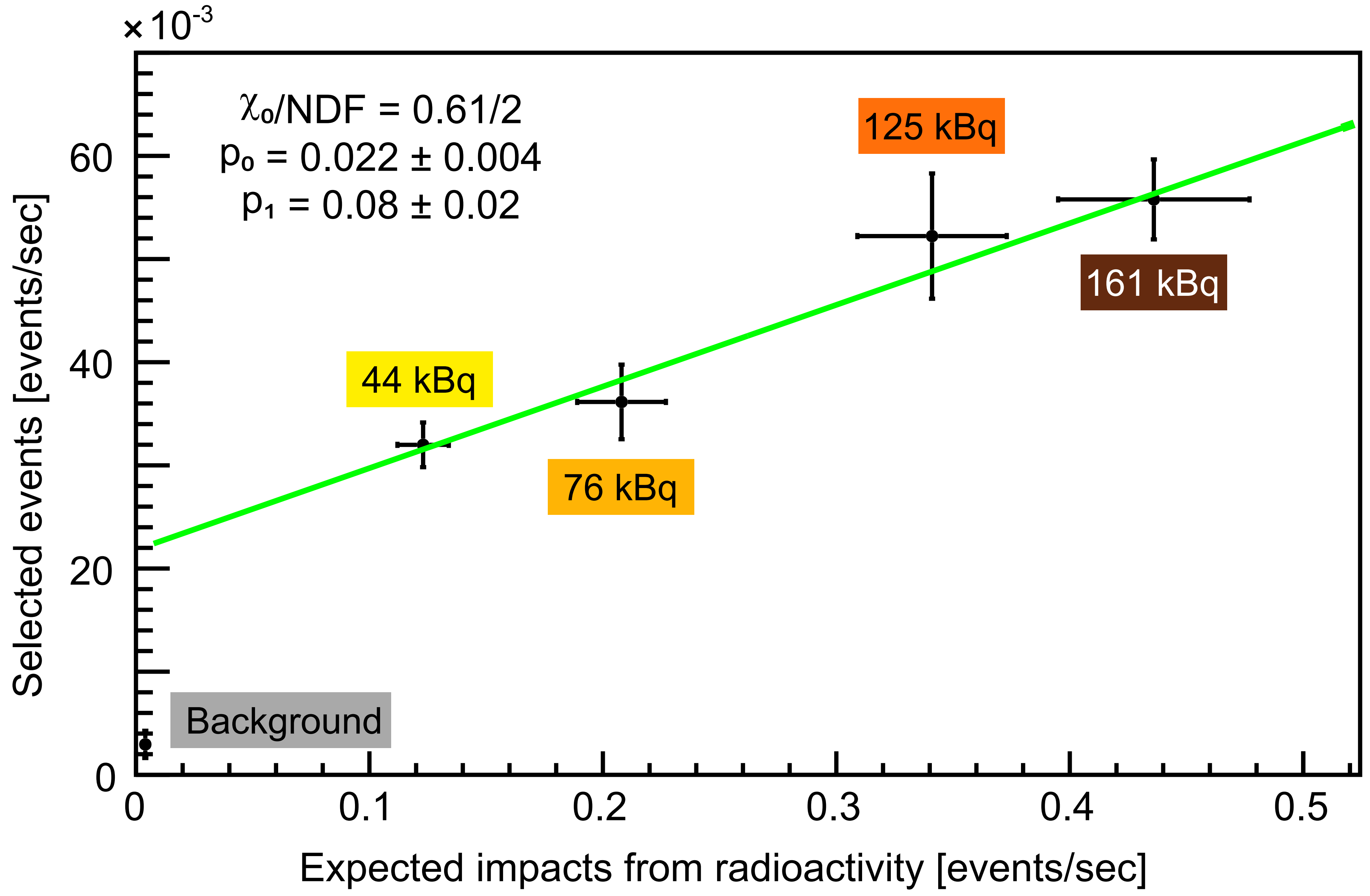


De Dominicis et al., arXiv:2405.18355

Results

- First application of superconducting qubits for gamma detection!
- A lot of work still to do: energy threshold, calibration, reduction of noise events…





De Dominicis et al., arXiv:2405.18355

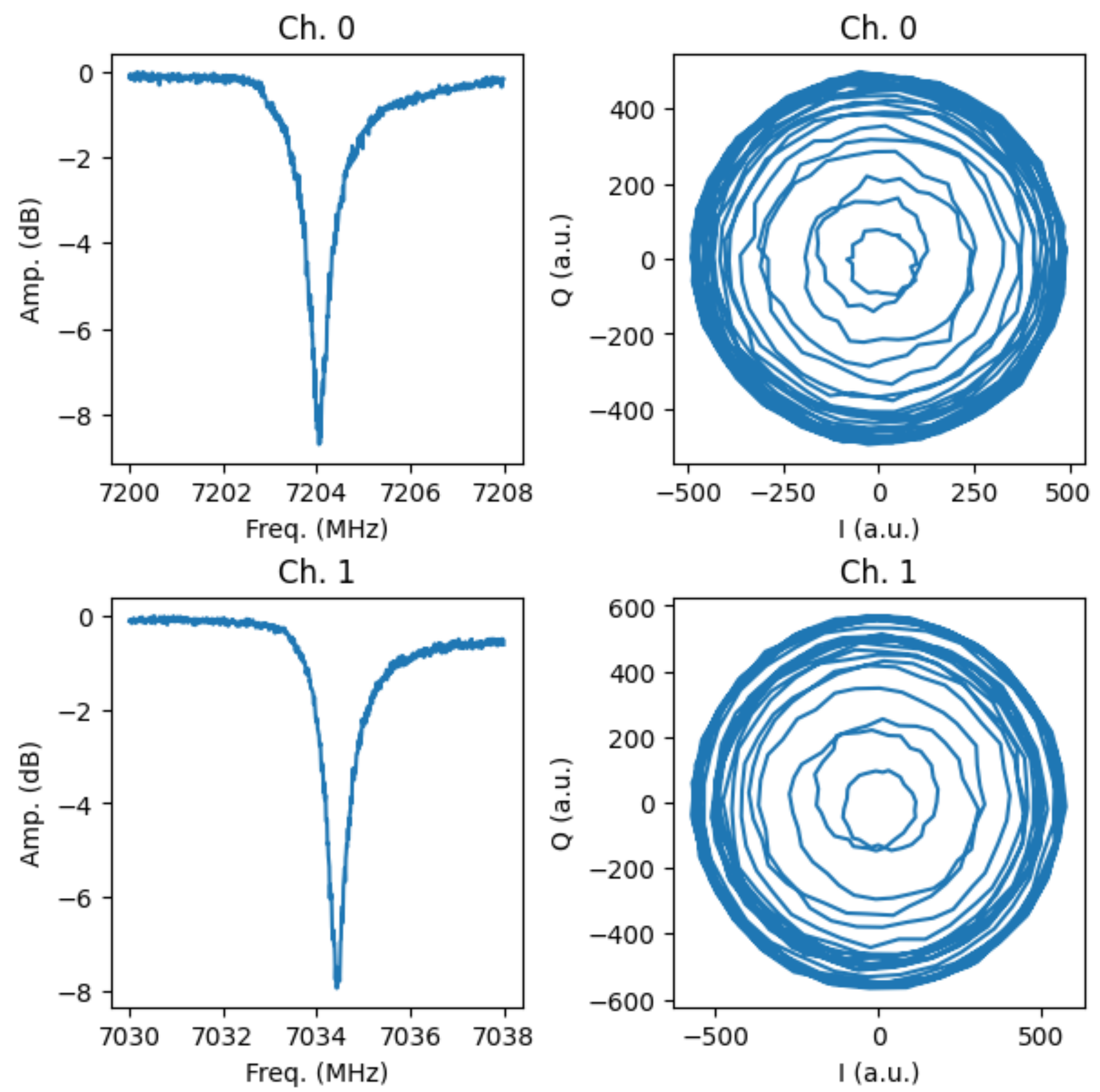
Development of multiplexed readout

- Single-qubit measurements are affected by a high occurrence of noise events that makes the detection of particle impacts difficult;
- A possible solution to overcome this issue is to look for coincident events in multiple qubits;
- “ARQ - Abatement of Radioactivity for Qubits” project, funded by the NGI Enrichers program;

NGI ENRICHERS TRANSATLANTIC

Development of multiplexed readout

- 3-months fellowship in Fermilab to develop a new firmware for the FPGA-based board used in the measurements;
- New firmware is able to produce multi-tone pulses to simultaneously probe multiple qubits;
- First test on qubits at the end of September 2024 at LNGS, successful;
- Measurements in the coming months :)



NGI ENRICHERS TRANSATLANTIC

Conclusions

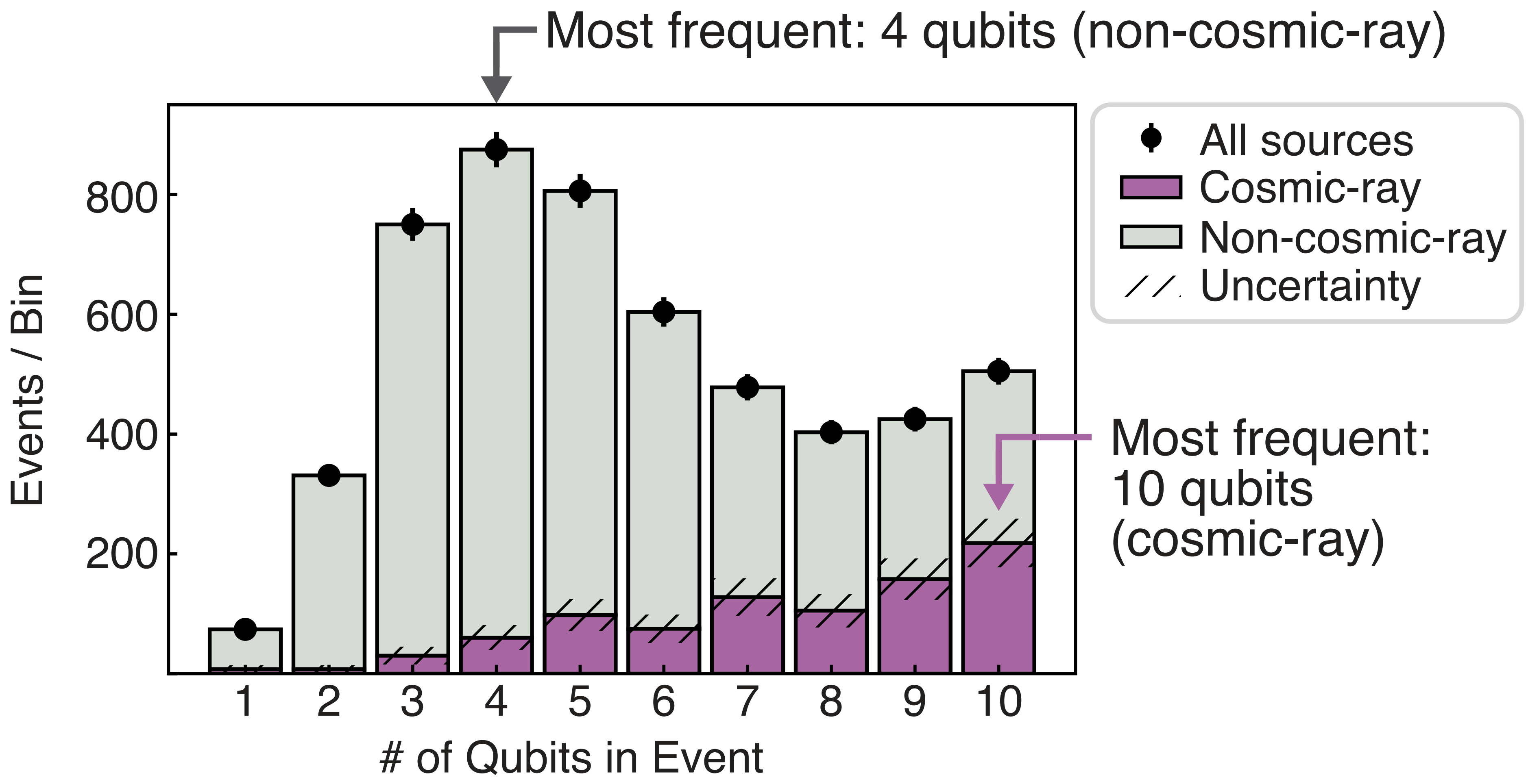
- Research activity carried during my first three years of PhD proved that:
  - Radioactivity is not the main limiting factor for the performance of superconducting qubits;
  - Superconducting qubits can be operated as particle detector, with possible applications in future particle physics experiments;
- In the coming months new measurements with simultaneous measurement of multiple qubits!

Prospects

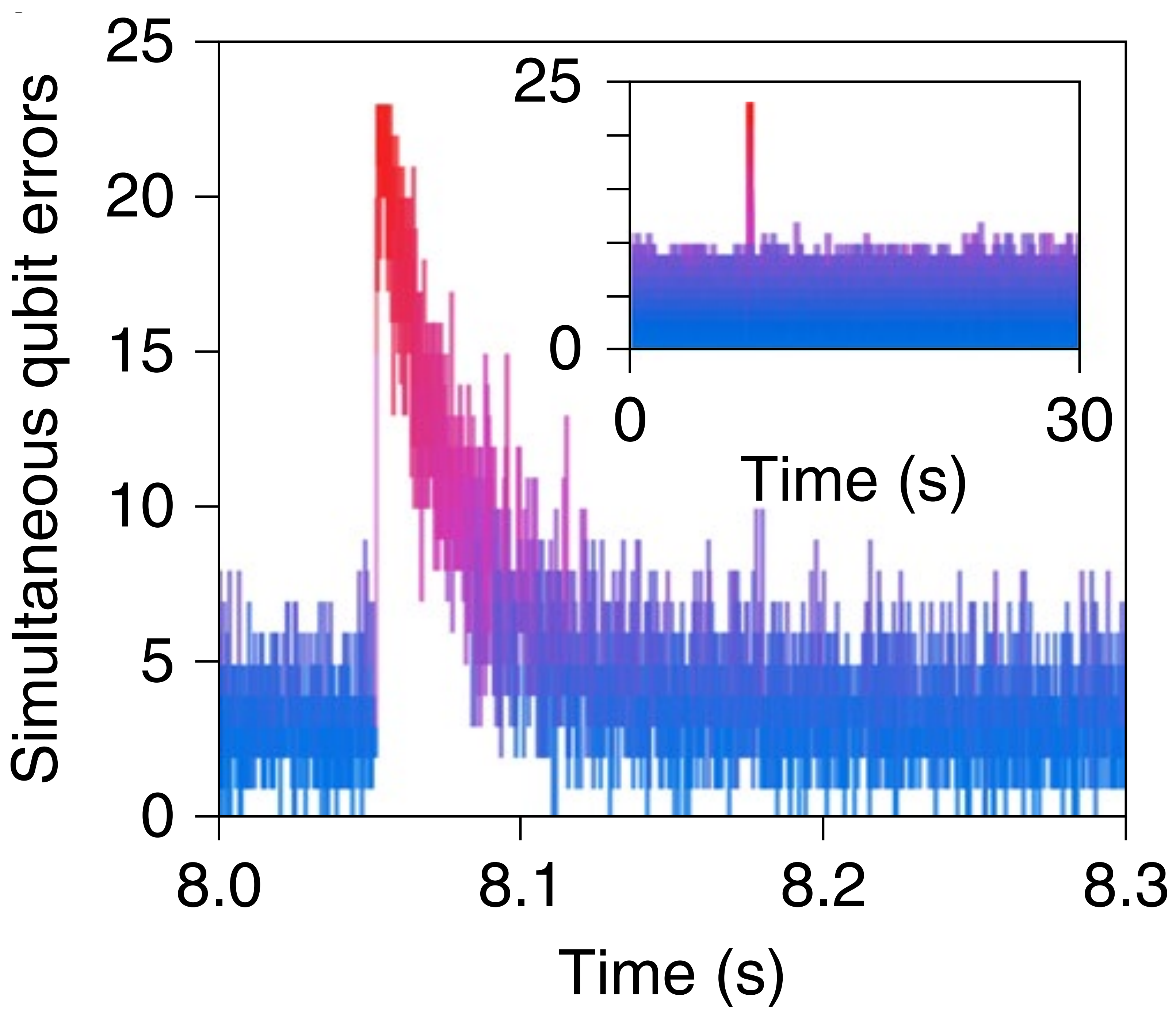
- Software improvements:
  - In this research qubits has been operated as in quantum computation experiments, but it could not be the most efficient way for particle detection;
  - The implementation of multiplexing could reduce drastically the noise rate;
  - New analysis techniques;
- Hardware improvements (how to make the qubit more sensitive):
  - Improved lifetime;
  - Better phonon collection;
  - And so on…

Backup: Correlated Errors

- Simultaneous decay of multiple qubits;
- Approx. 20% of them induced by cosmic rays;
- No estimation of contribution from gamma radioactivity yet.

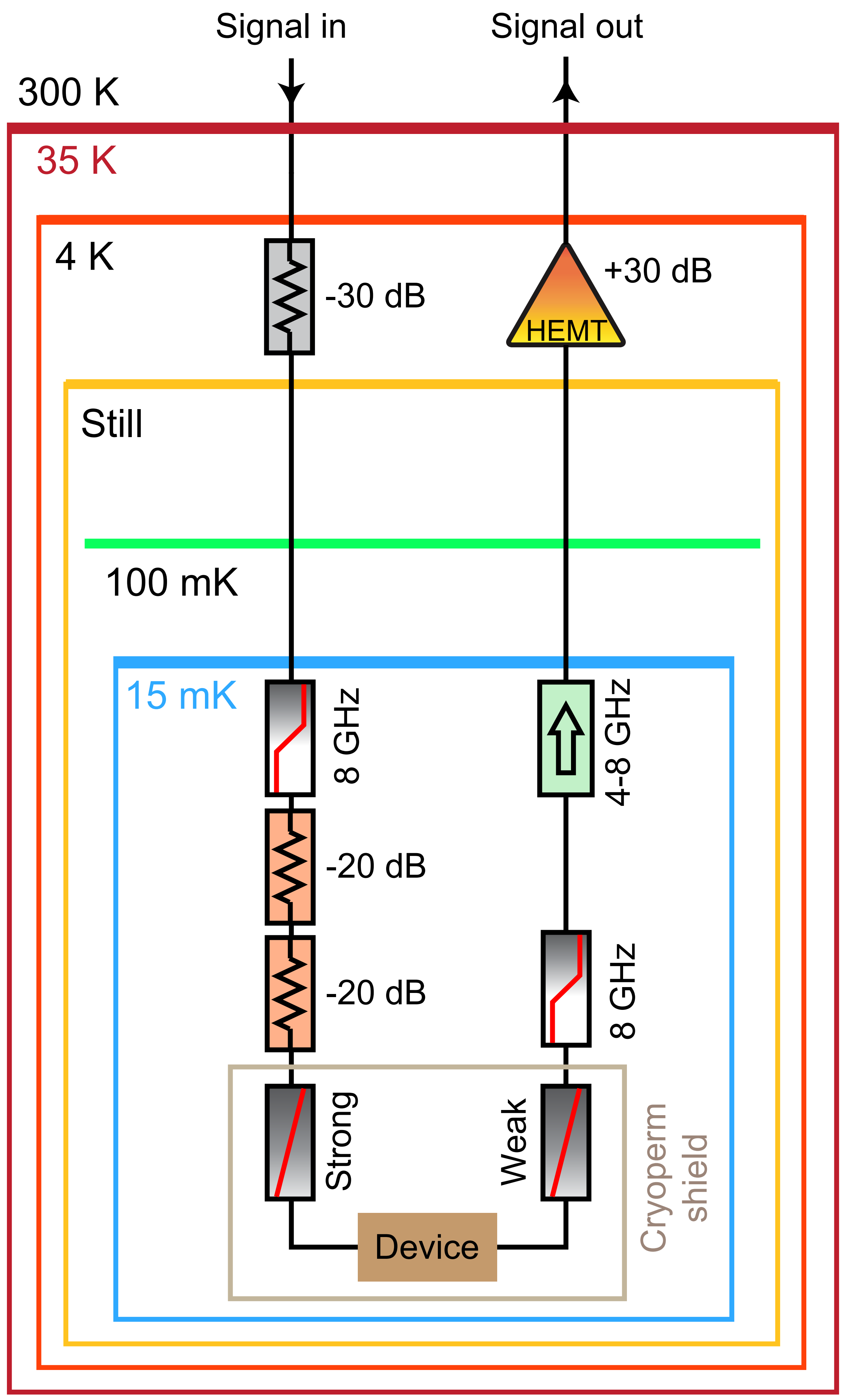


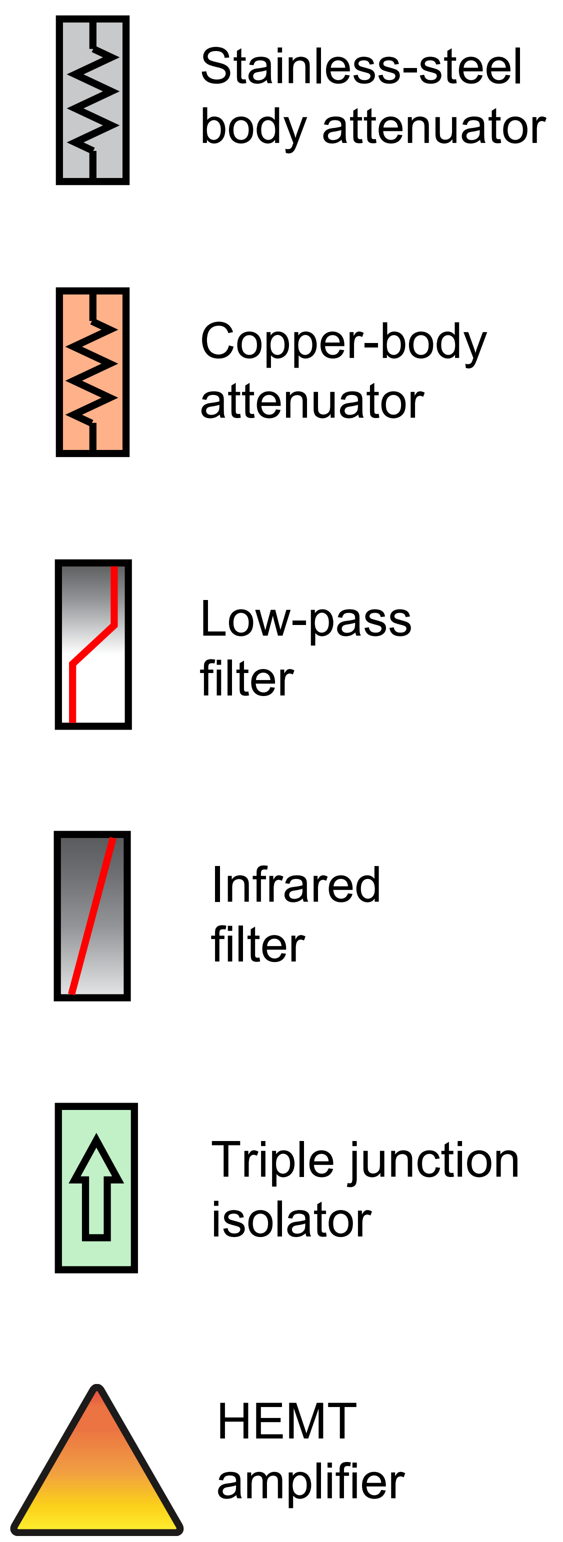
Harrington et al., arXiv:2402.03208



McEwen et al., *Nature Physics* **18**, 107-111 (2021)

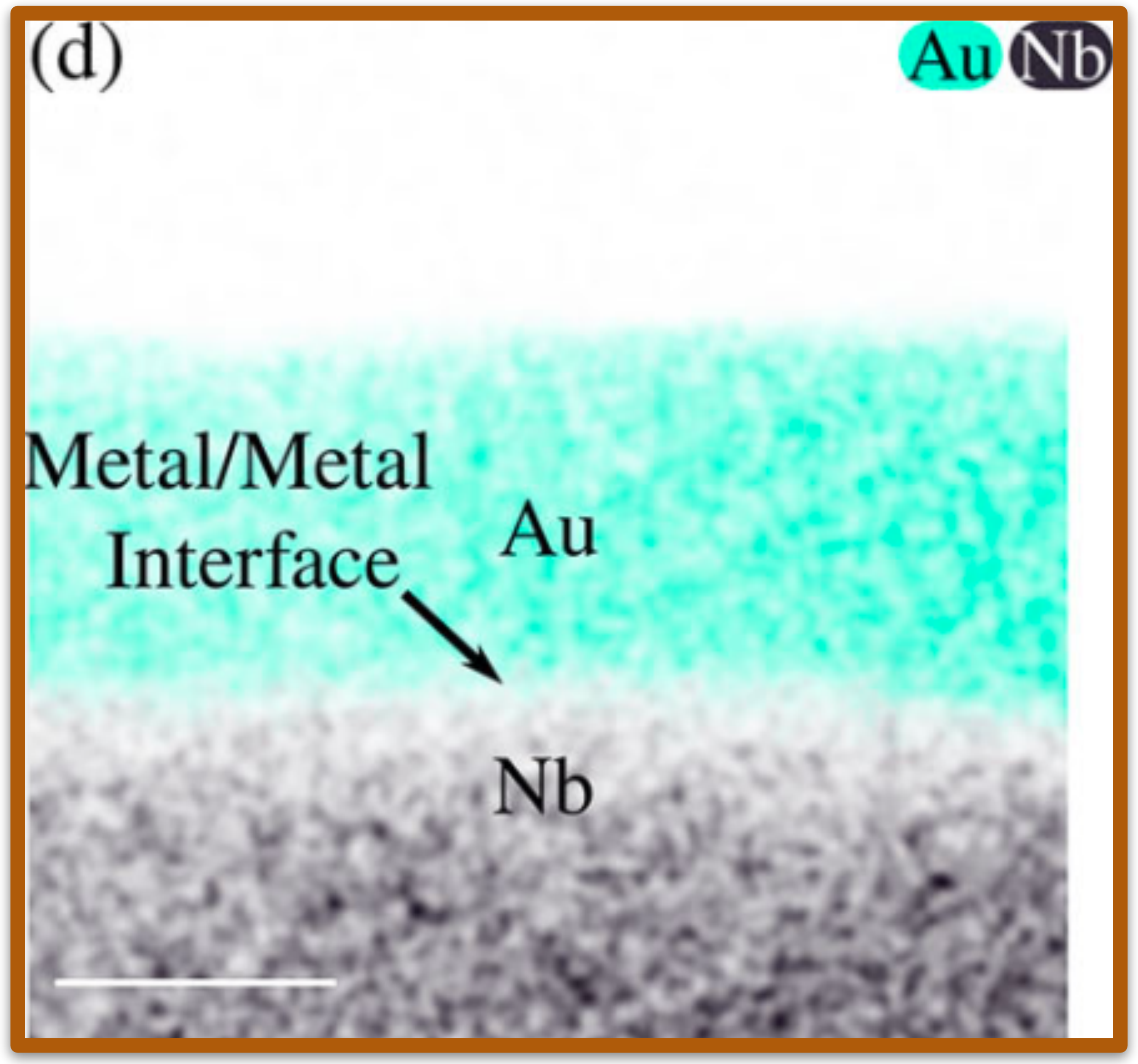
Backup: scheme of the RF Lines

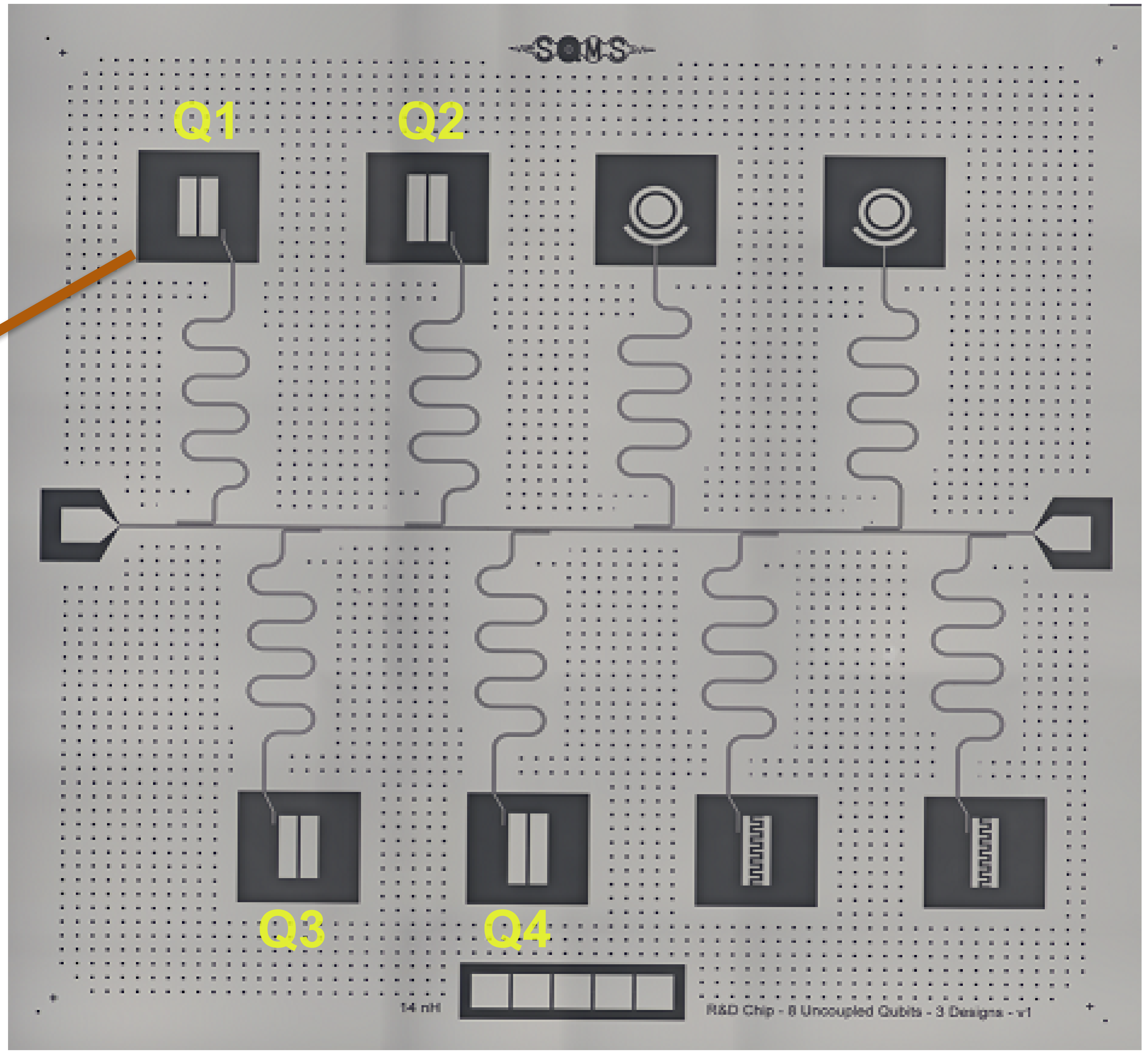




Backup: The chip

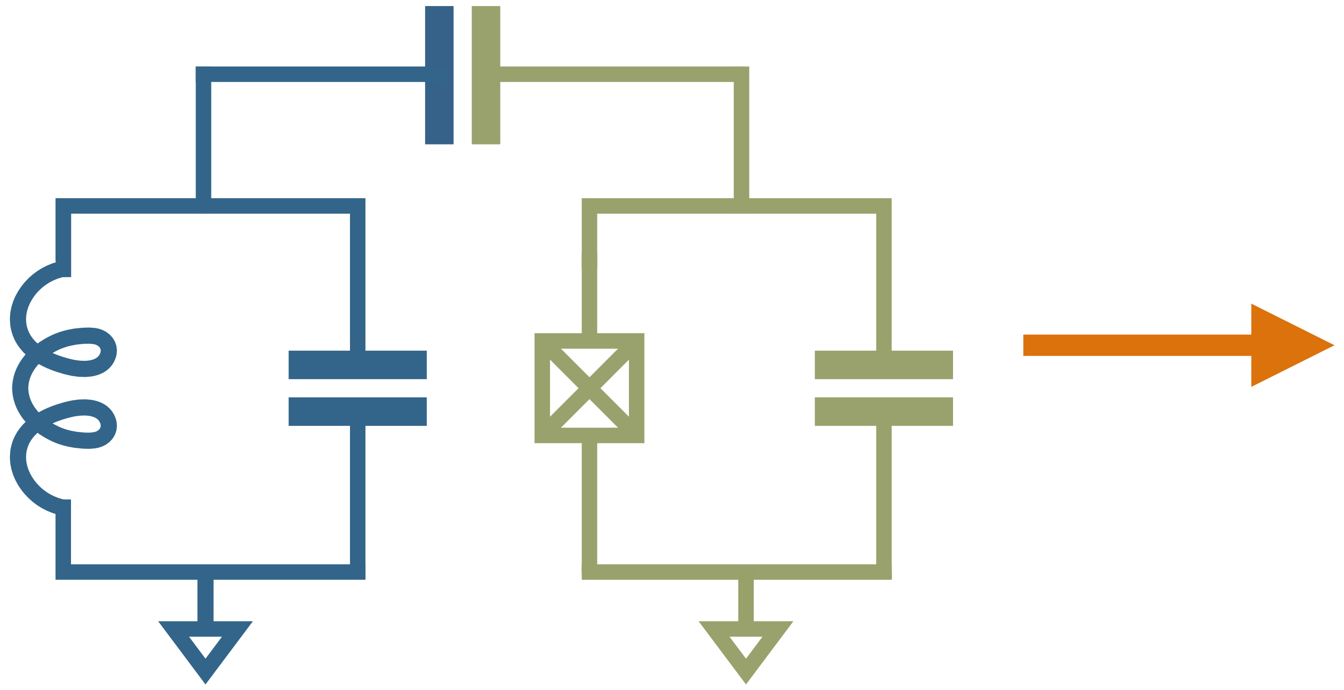
- Niobium transmon qubit on Sapphire substrate;
- Approx. 10 nm gold capping to prevent losses from the formation of Nb_2O_5;
- Median T1 = 76 μs.

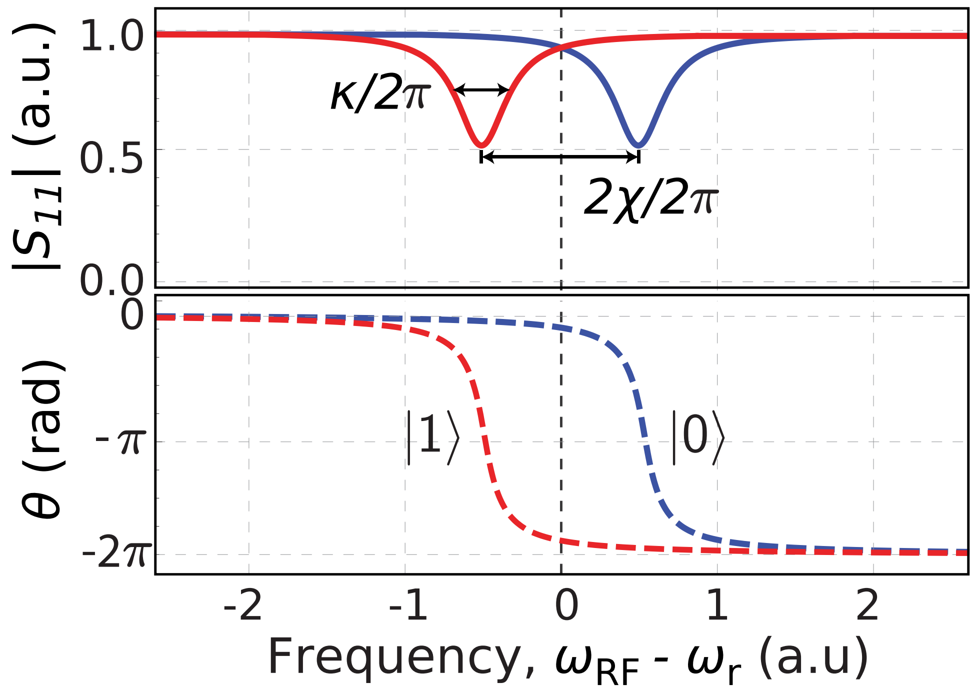


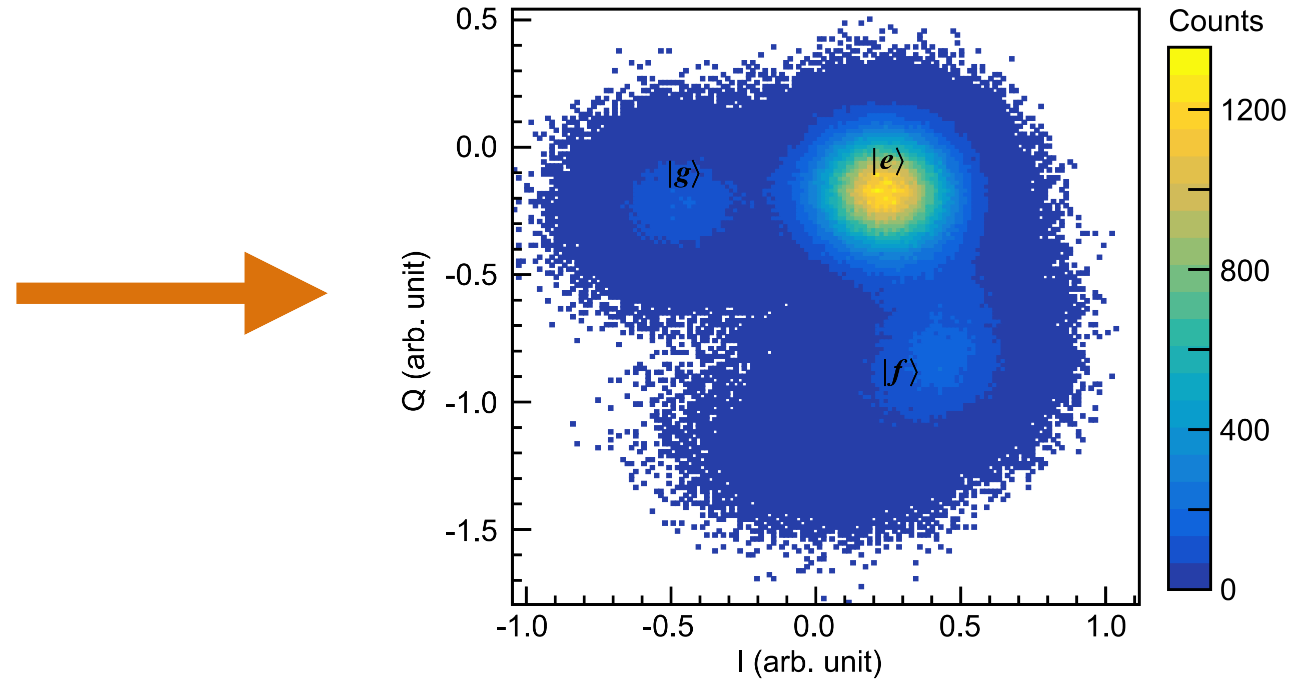


Backup: Dispersive shift readout

- Qubits are coupled to LC resonators for state readout;
- The coupling affect the resonance frequency of the resonator, producing a shift that depends on the qubit state;
- The qubit state is then measured by sending a pulse at the resonance frequency of the resonator and measuring the output.



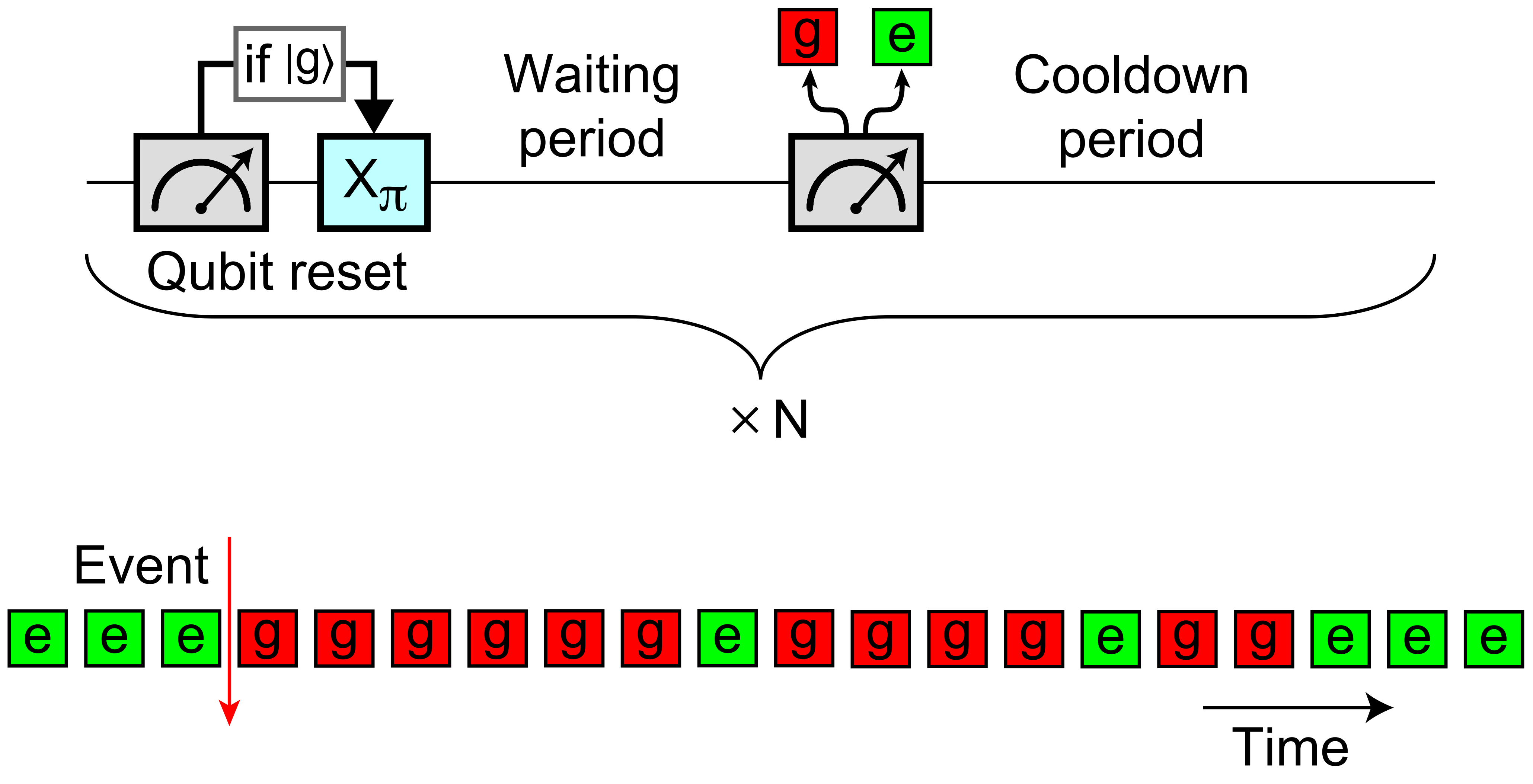




Blais et al., *Rev. Mod. Phys* **93**, 025005 (2021) Krantz et al., *Appl. Phys. Rev.* **6**, 021318 (2019) De Dominicis et al., arXiv:2405.18355

Backup: Data Analysis

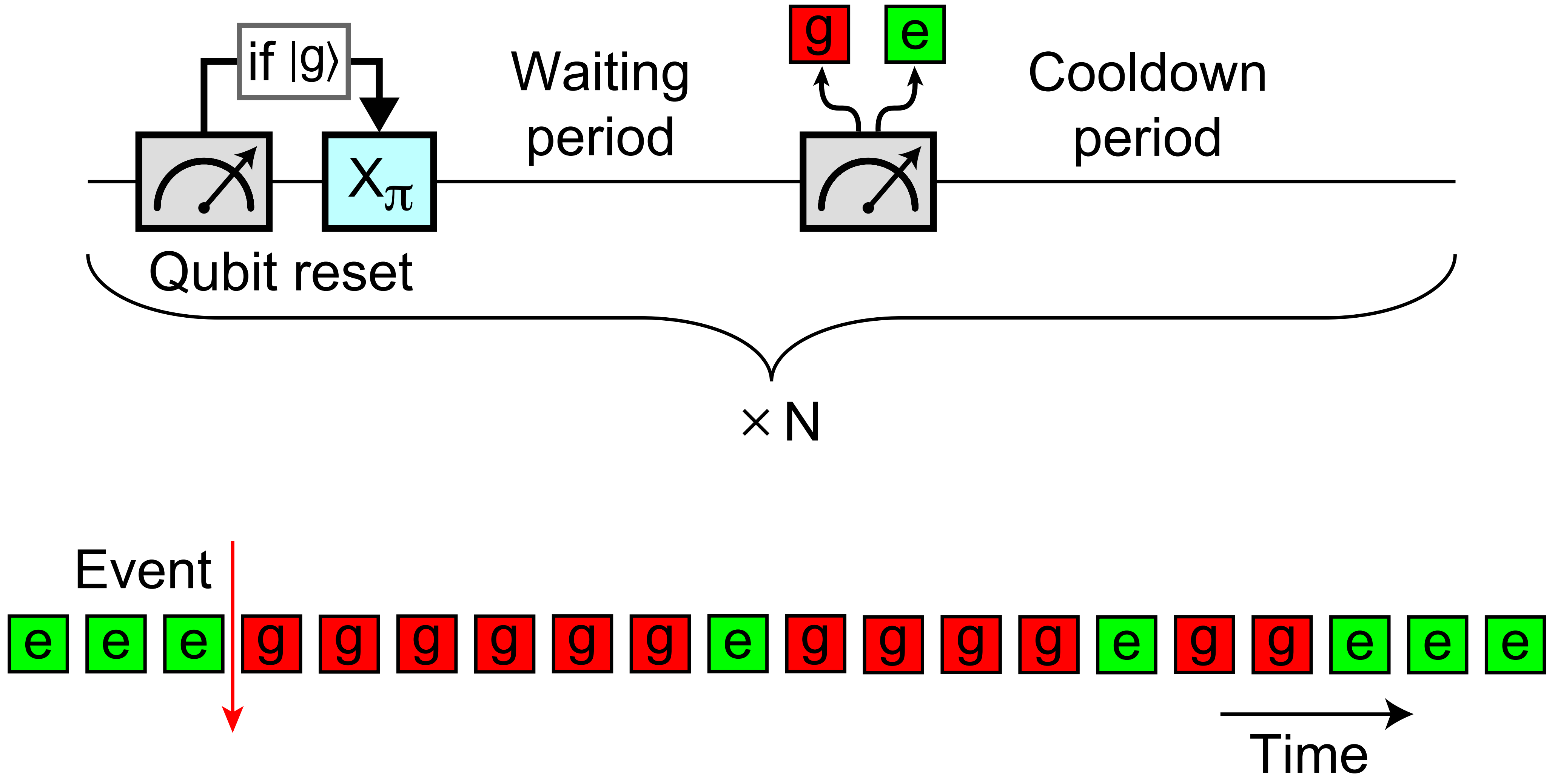
- The entire stream of data is saved and analyzed offline;
- A signal is registered if the number of measurements of the qubit in $|g\rangle$ in a 60-point long window exceeds a threshold value;
- The trigger condition for acquiring the window is the presence of three consecutive measurements of the qubit in $|g\rangle$.



De Dominicis et al., arXiv:2405.18355

Backup: Data Analysis

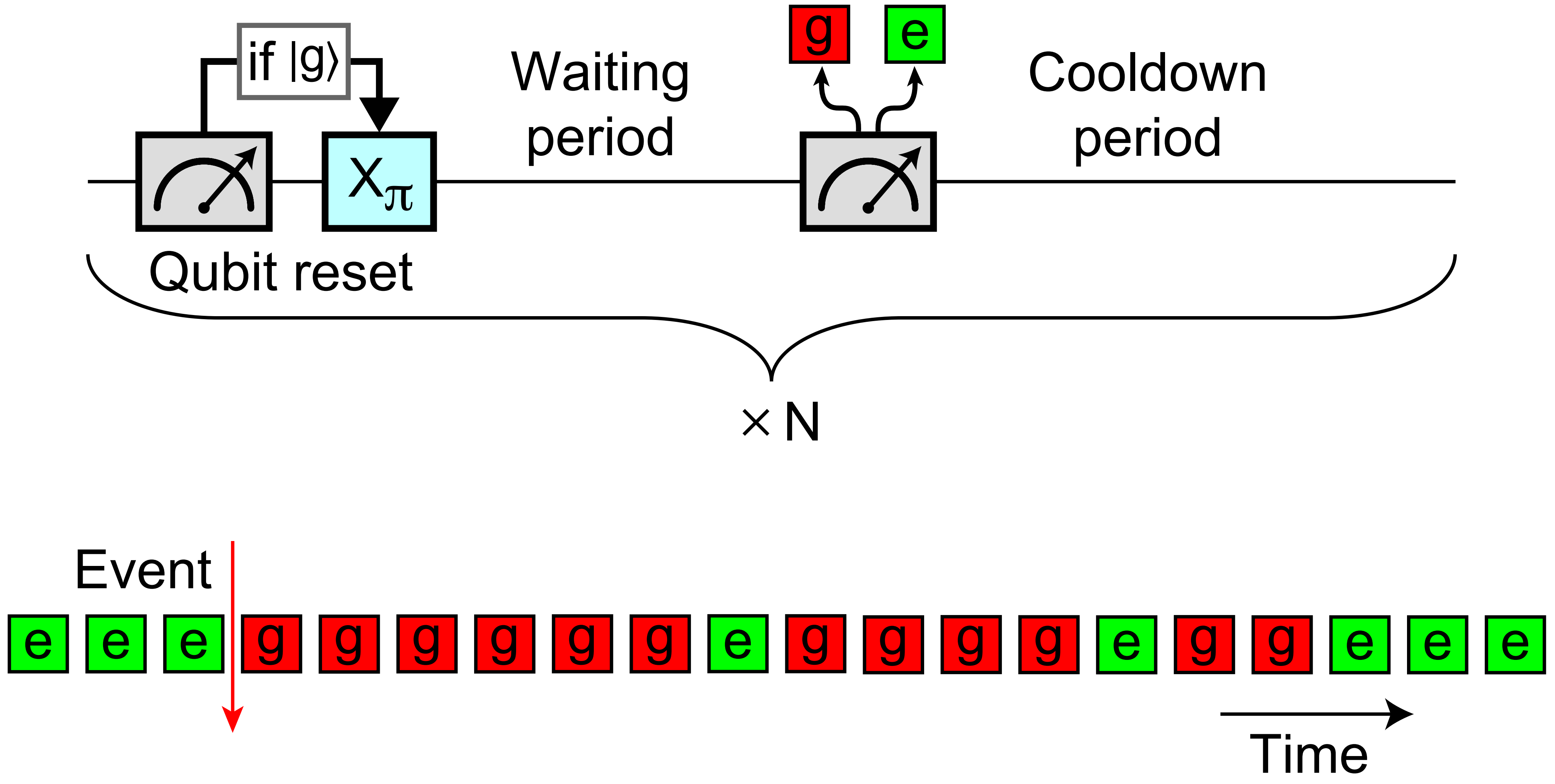
- The threshold value is such that the rate of noise events that would be detected is one order of magnitude lower than the rate of particle interactions in the qubit chip;
- To estimate the rate noise events we compute the probability to have a number of $|g\rangle$ measurements above threshold given the standard decay time of the qubit;
- That probability is then multiplied by the rate of measurements of that specific run.



De Dominicis et al., arXiv:2405.18355

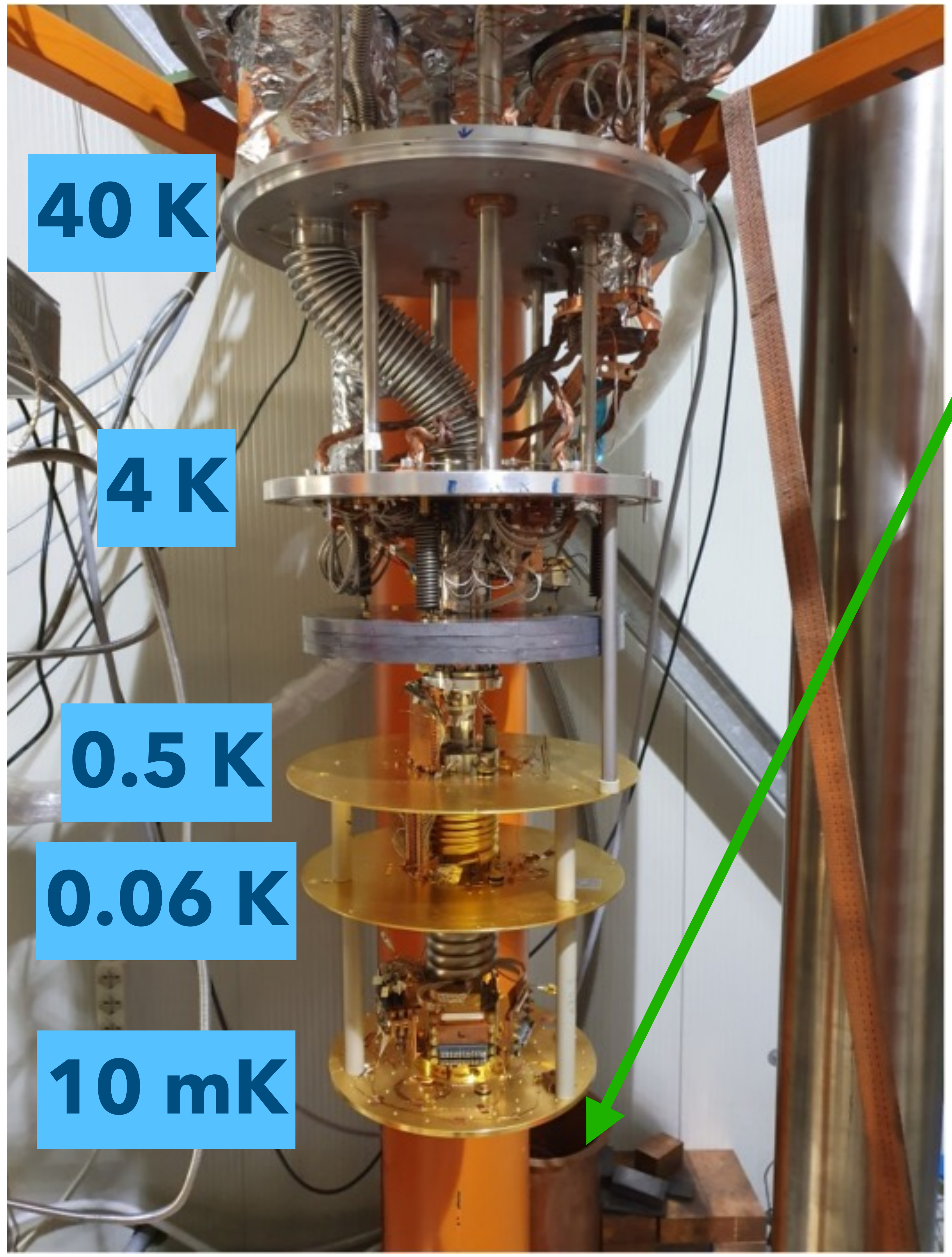
Backup: Data Analysis

- A 60-point long pre-trigger region is also acquired to estimate the average number of $|g\rangle$ measurements before the trigger;
- In this way it is possible to identify and discard periods in which the qubit is noisy.



De Dominicis et al., arXiv:2405.18355

Backup: the IETI Underground Facility



https://ieti.sites.lngs.infn.it/index.html

- Experimental volume: 25 cm of diameter, 16 cm height;
- 12 electronic channels with low noise voltage preamplifiers (2 nV/√Hz) (R&D CUPID);
- 3 Magnicon SQUIDS (R&D COSINUS);
- **8 low attenuation SMA coax cables from room temperature to 3 K plus 8 NbTi Superconductive coax cables from 3 K to MC (R&D DEMETRA/SQMS);**
- 48 twisted superconductive wires from room temperature to MC;
- A ^{60}Co crystal for absolute thermometry calibration.