SUPERCONDUCTING QUBITS AS PARTICLE DETECTORS

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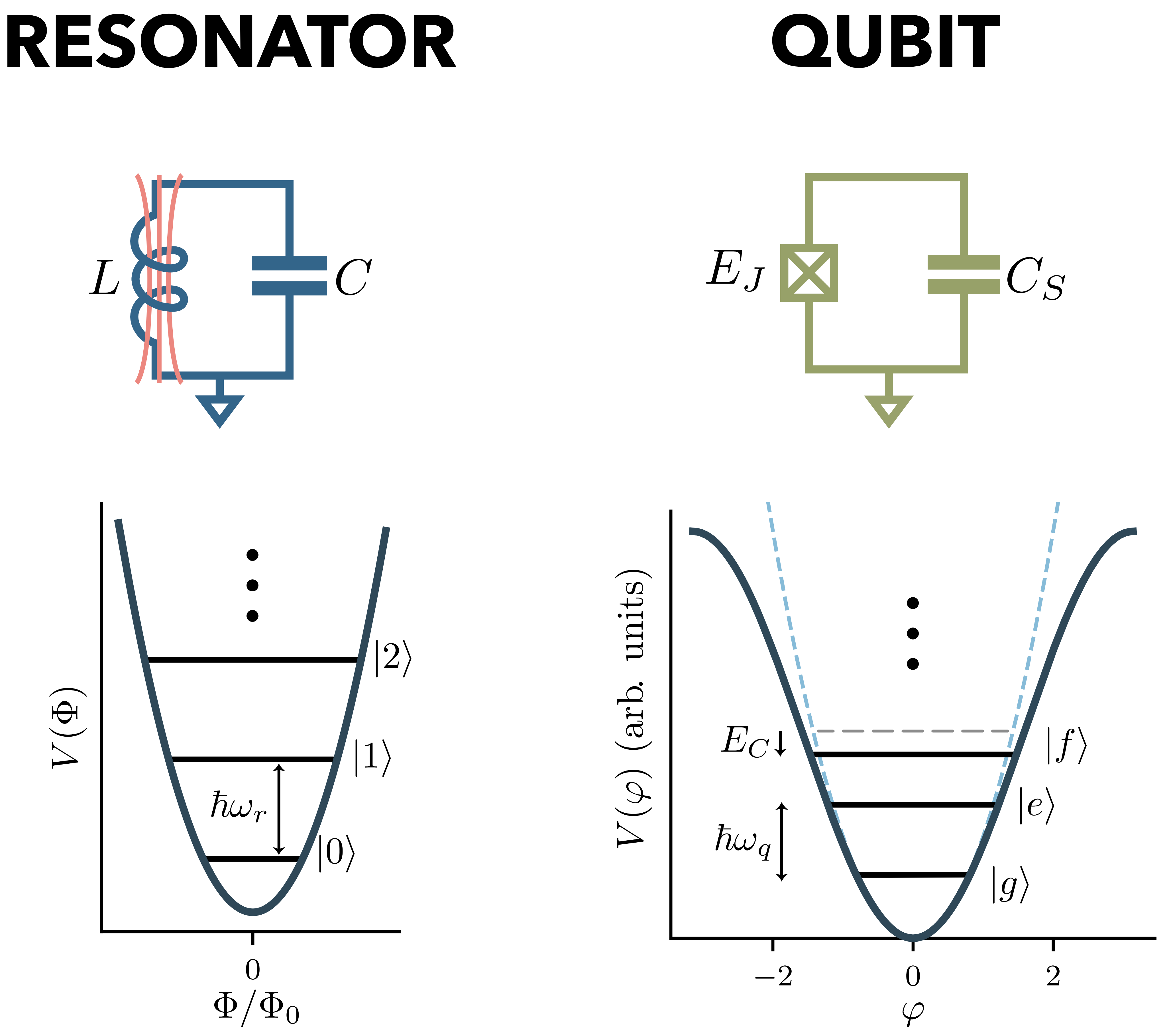
Superconducting Qubits

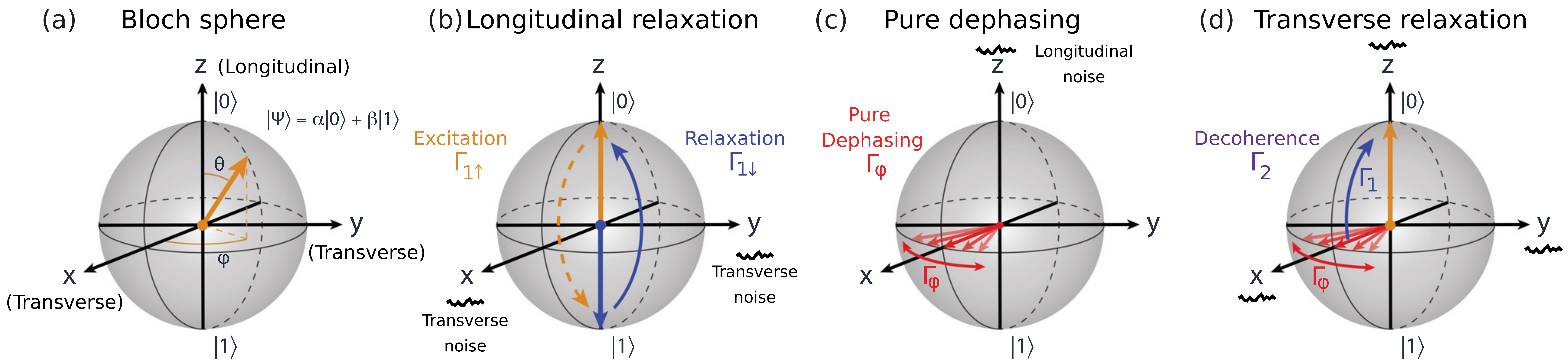
- Superconducting circuits with a Josephson Junction;
- The Josphson Junction acts as a non-linear inductor that produces an anharmonic energy spectrum;
- In this way it is possible to populate only the first two states and operate the circuit as a qubit.



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

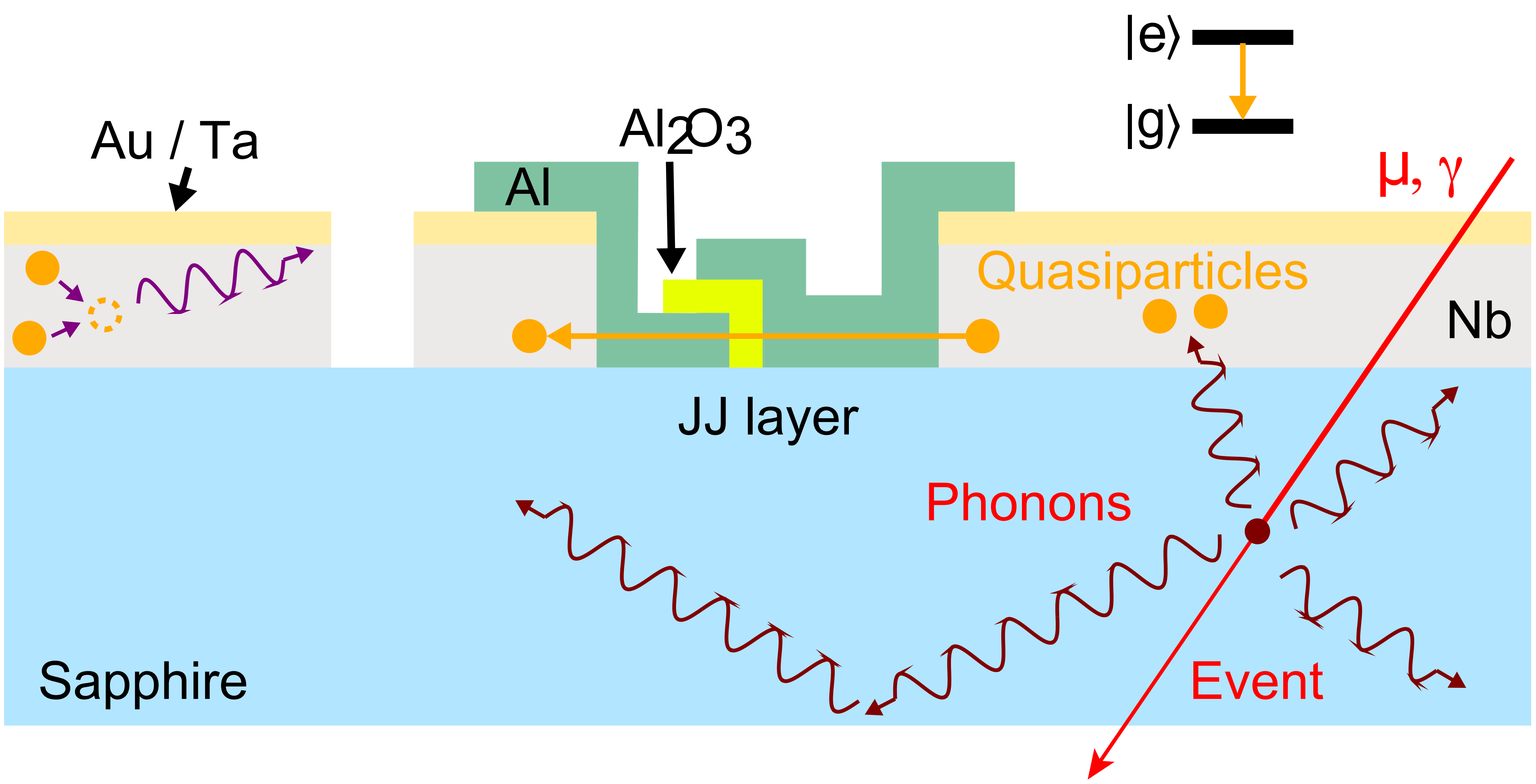
Decoherence

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



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

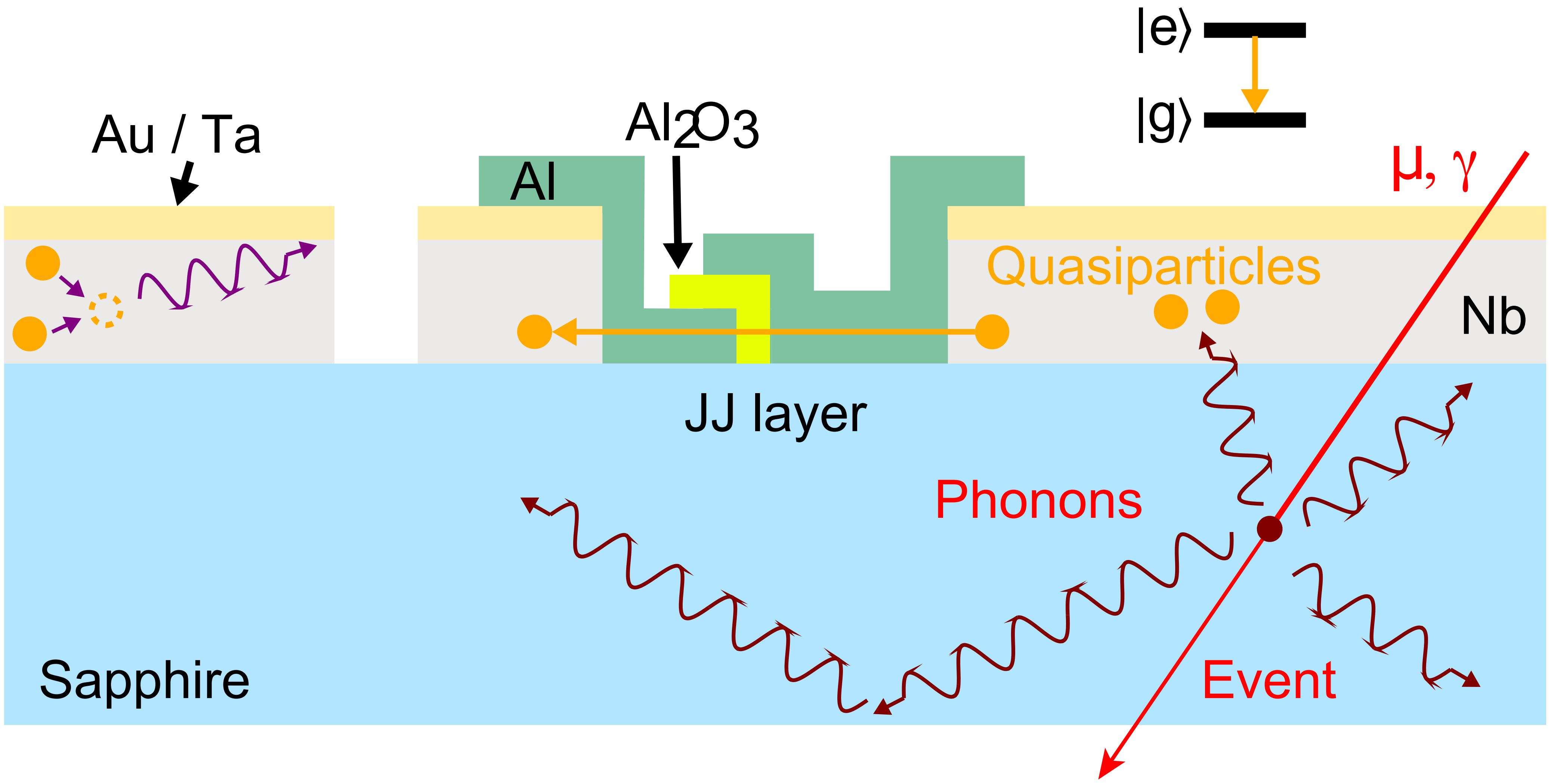
Qubits and Radioactivity



De Dominics et al., arXiv:2405.18355

- Radioactivity was first proposed as a limit for superconducting qubits coherence in 2018 (DEMETRA project, INFN);
- Incident particles deposit energy in the chip substrate, producing phonons;
- Phonons break Cooper pairs and produce quasiparticles;
- Quasiparticles can be responsible for the loss of coherence.

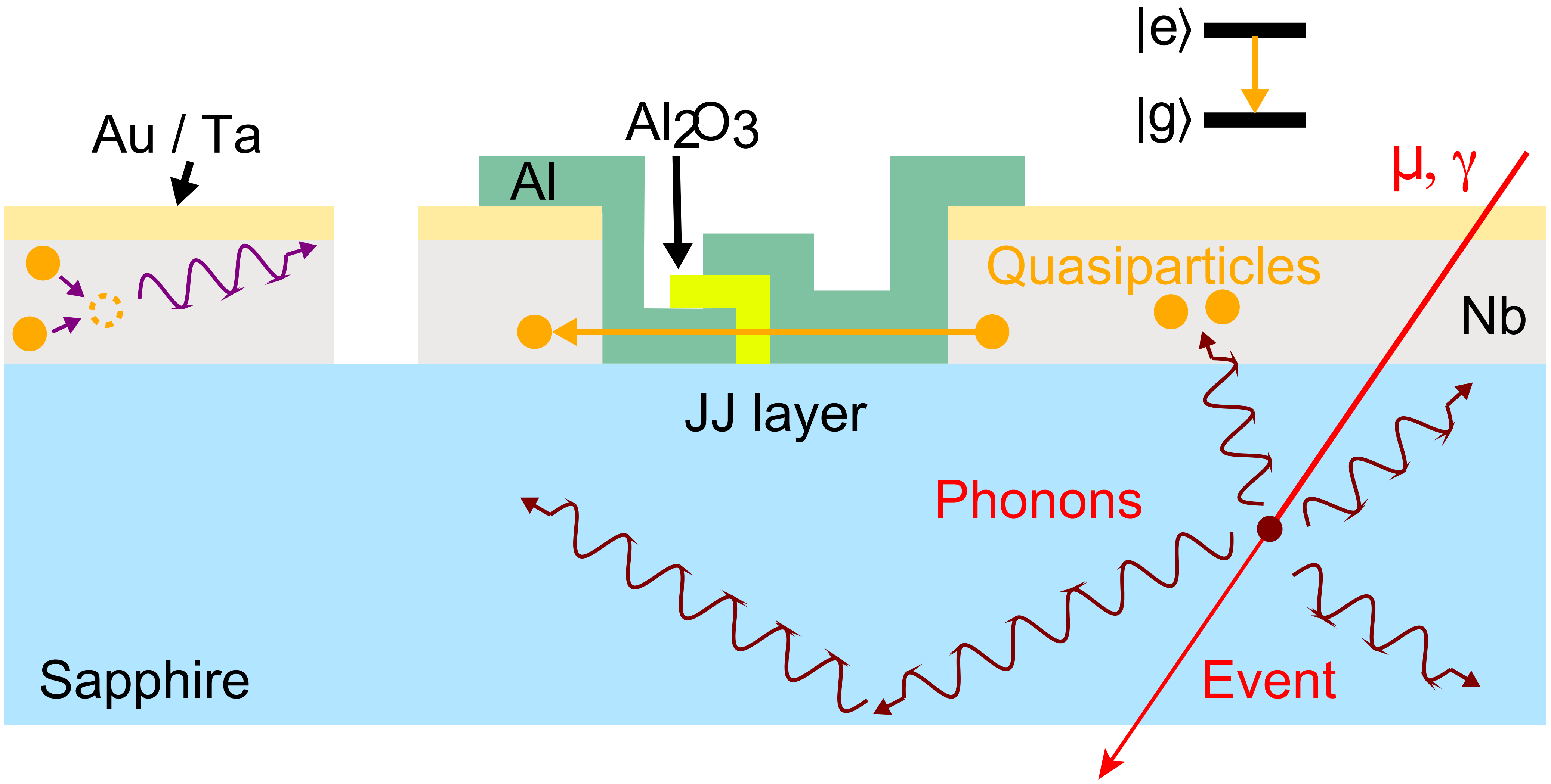
Qubits and Radioactivity



De Dominics et al., arXiv:2405.18355

- Previous researches showed that:
  - Radioactivity affects the performances of superconducting quantum circuits [Cardani et al., *Nature Communications* (2021)];
  - Radioactivity will limit the lifetime of next generation qubits [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)]

Qubits and Radioactivity

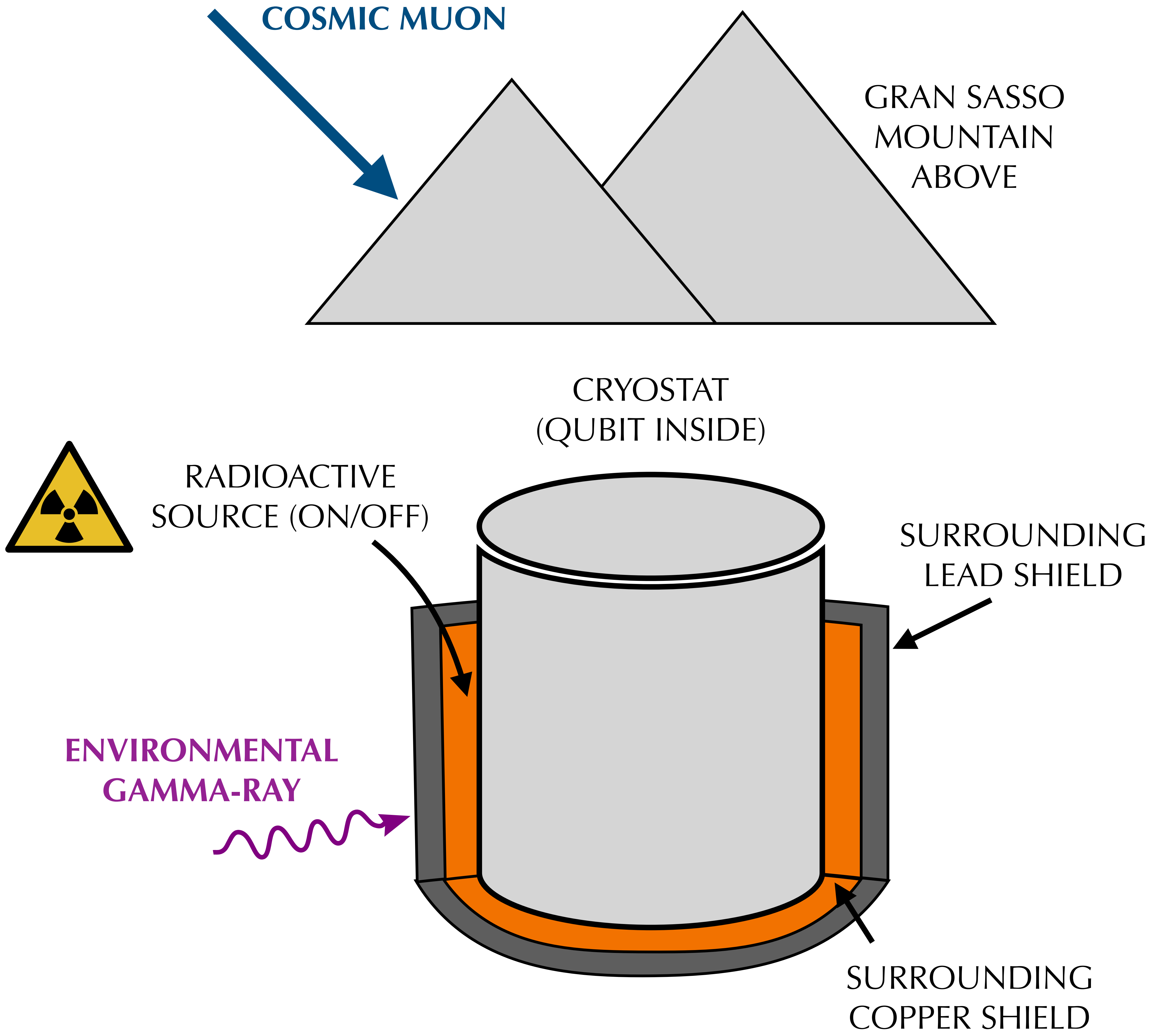


De Dominics et al., arXiv:2405.18355

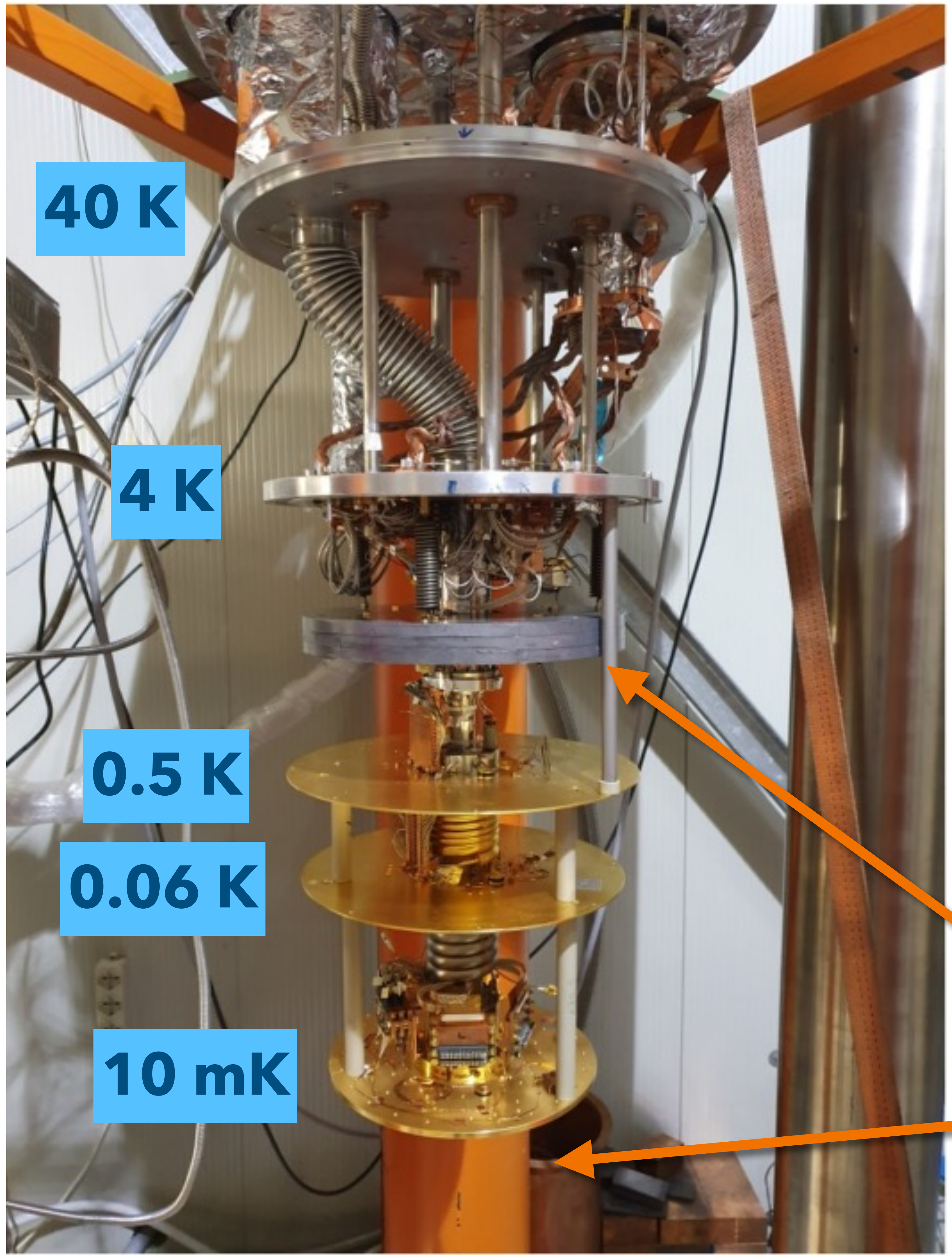
- Superconducting qubits are indeed sensitive to ionizing radiation;
- Can their sensitivity be useful for particle physics experiment?
- Can we use qubits for particle detection?

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 a radioactive source and repeat the measurement;
    - Compare the results.



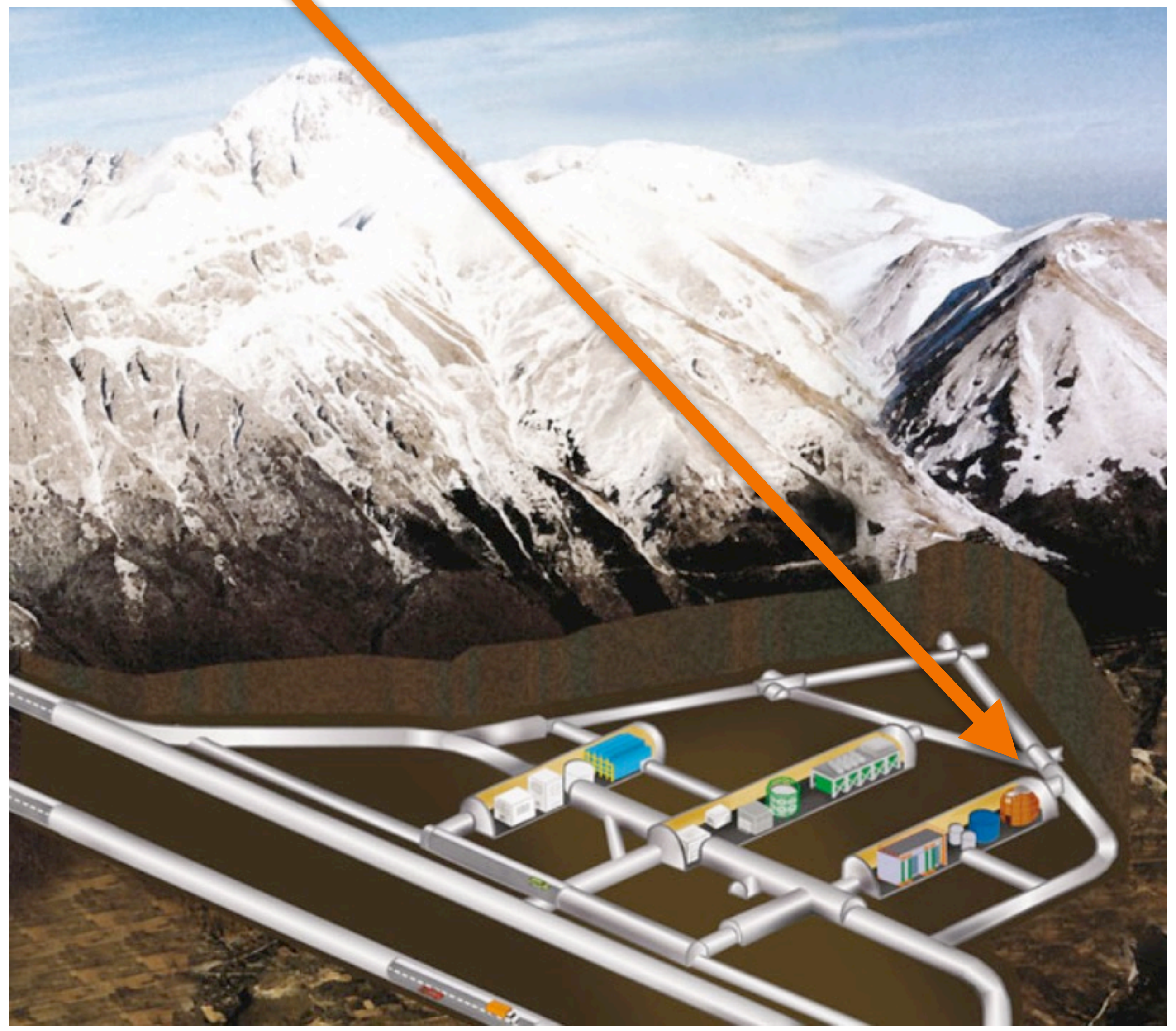
The IETI Underground Facility



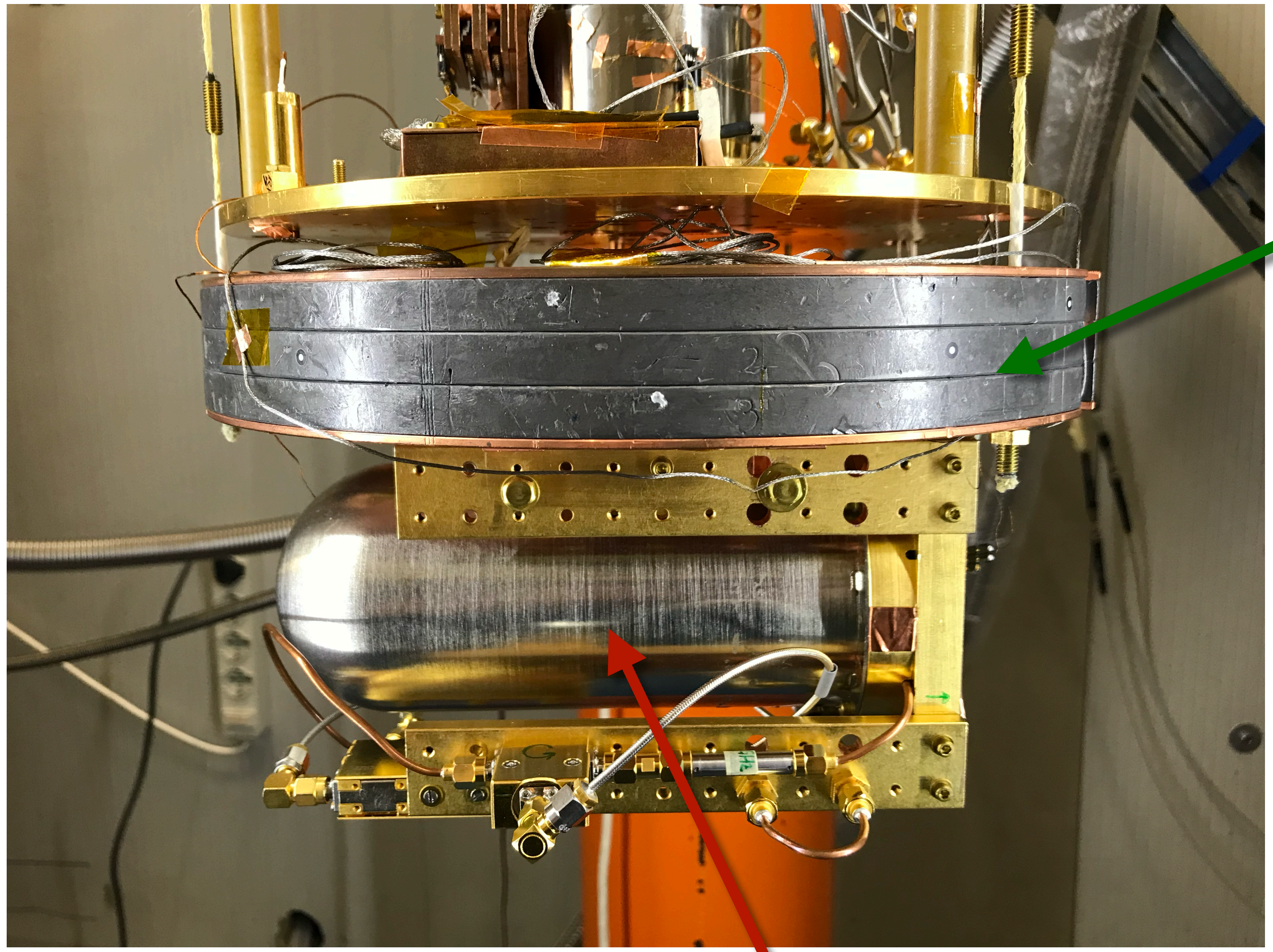
- Hall C of LNGS Underground Laboratories;
- Pulse tube based $^{3}He/^{4}He$ dilution refrigerator;
- Pulse tube decoupling plus custom-made 3 stages mechanical decoupling system between cold plates and detector;
- 3 cm internal lead at 4K plus additional 3 cm lead at 10 mK.

IETI

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



Shielding



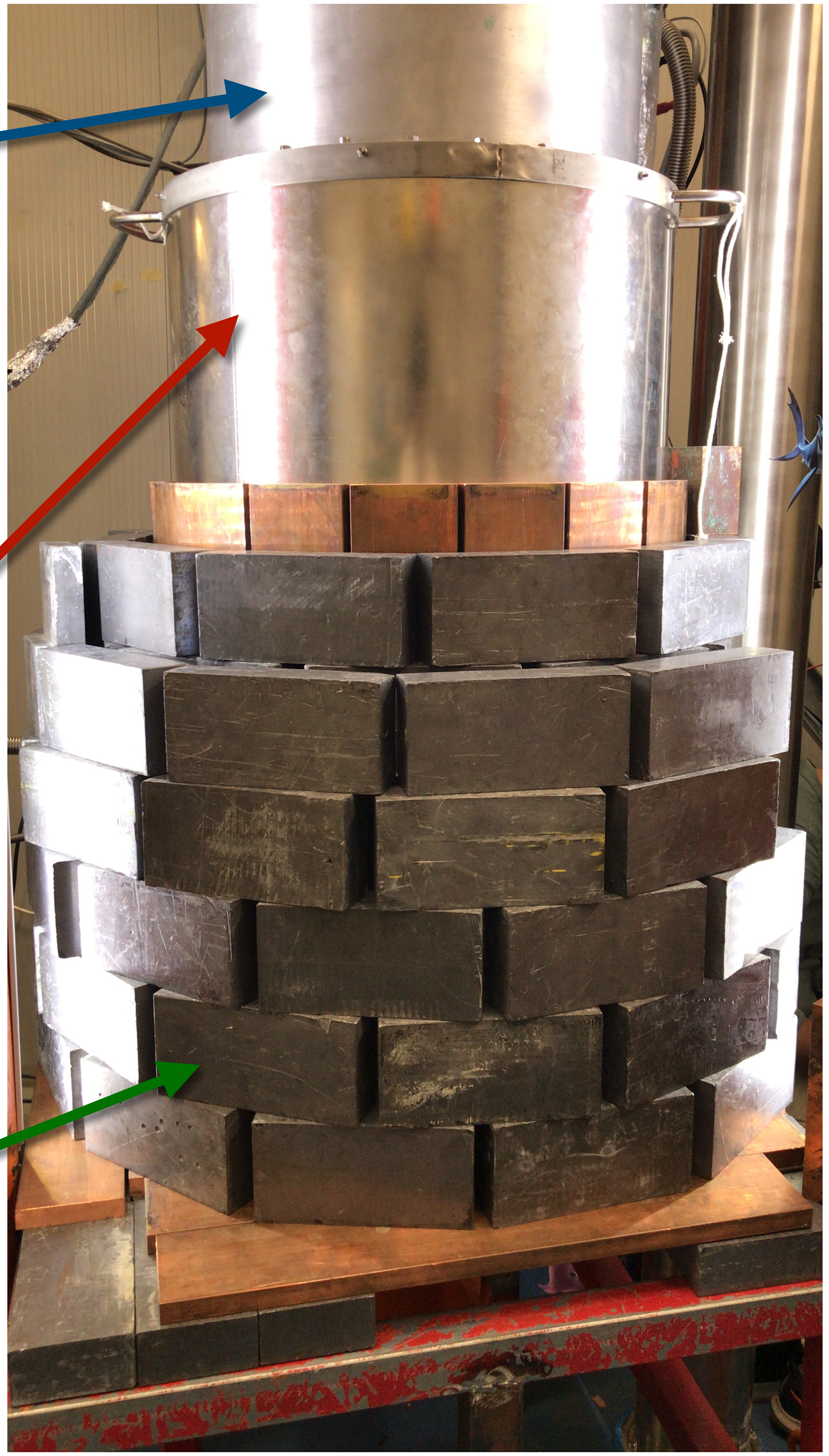
INNER MAGNETIC SHIELD
(QUBIT INSIDE)

CRYOSTAT

INNER LEAD SHIELD

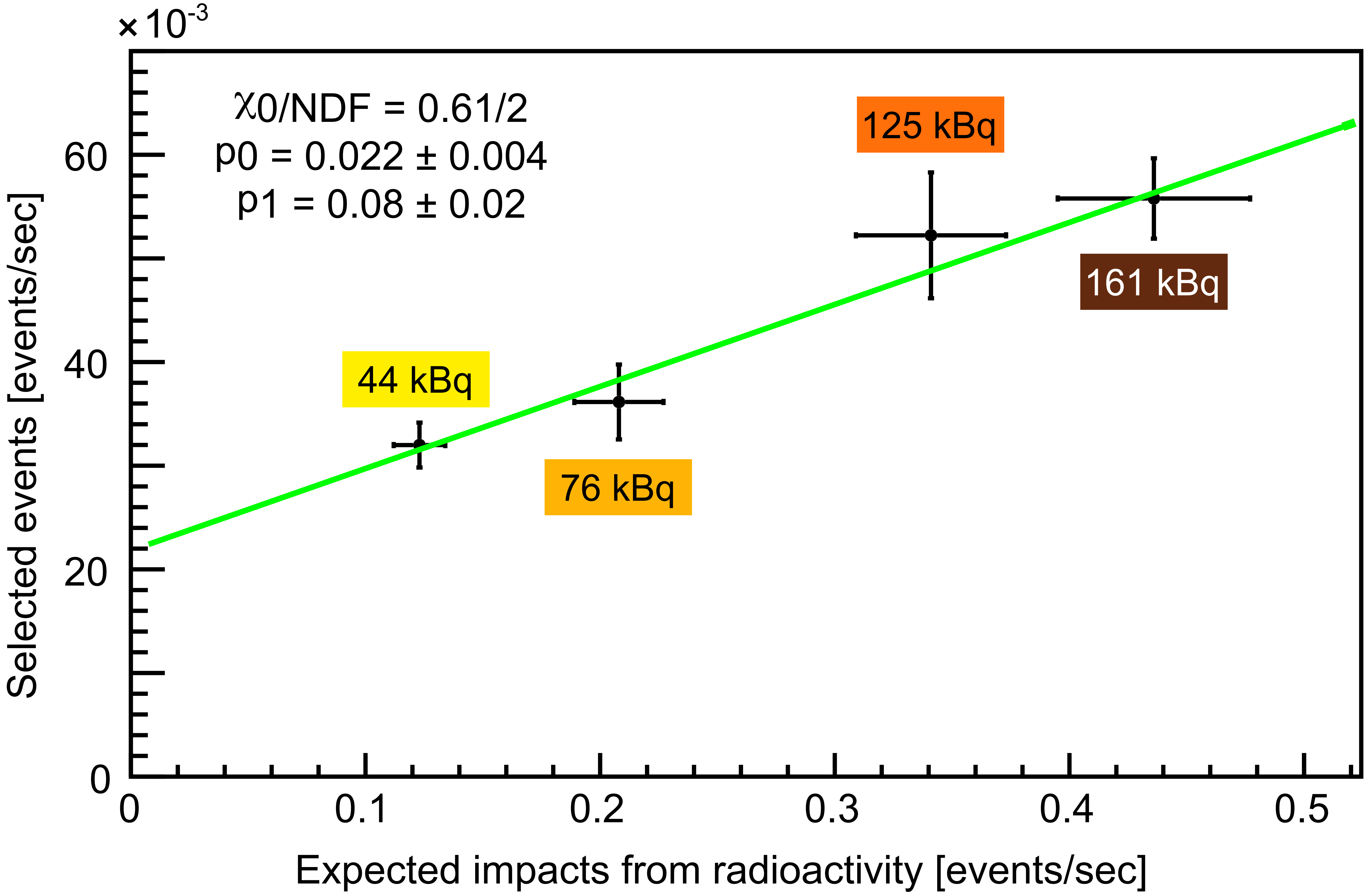
EXTERNAL MAGNETIC SHIELD

EXTERNAL Pb+Cu SHIELD



Can we use qubits as particle detectors?

- We exposed a transmon qubit to gamma radiation sources with different activities;
- We saw qubit decay events correlated with the presence of the source;
- The rate of these events increase linearly with the activity of the source;
- First time that a superconducting qubit is used for MeV-scale gamma detection!



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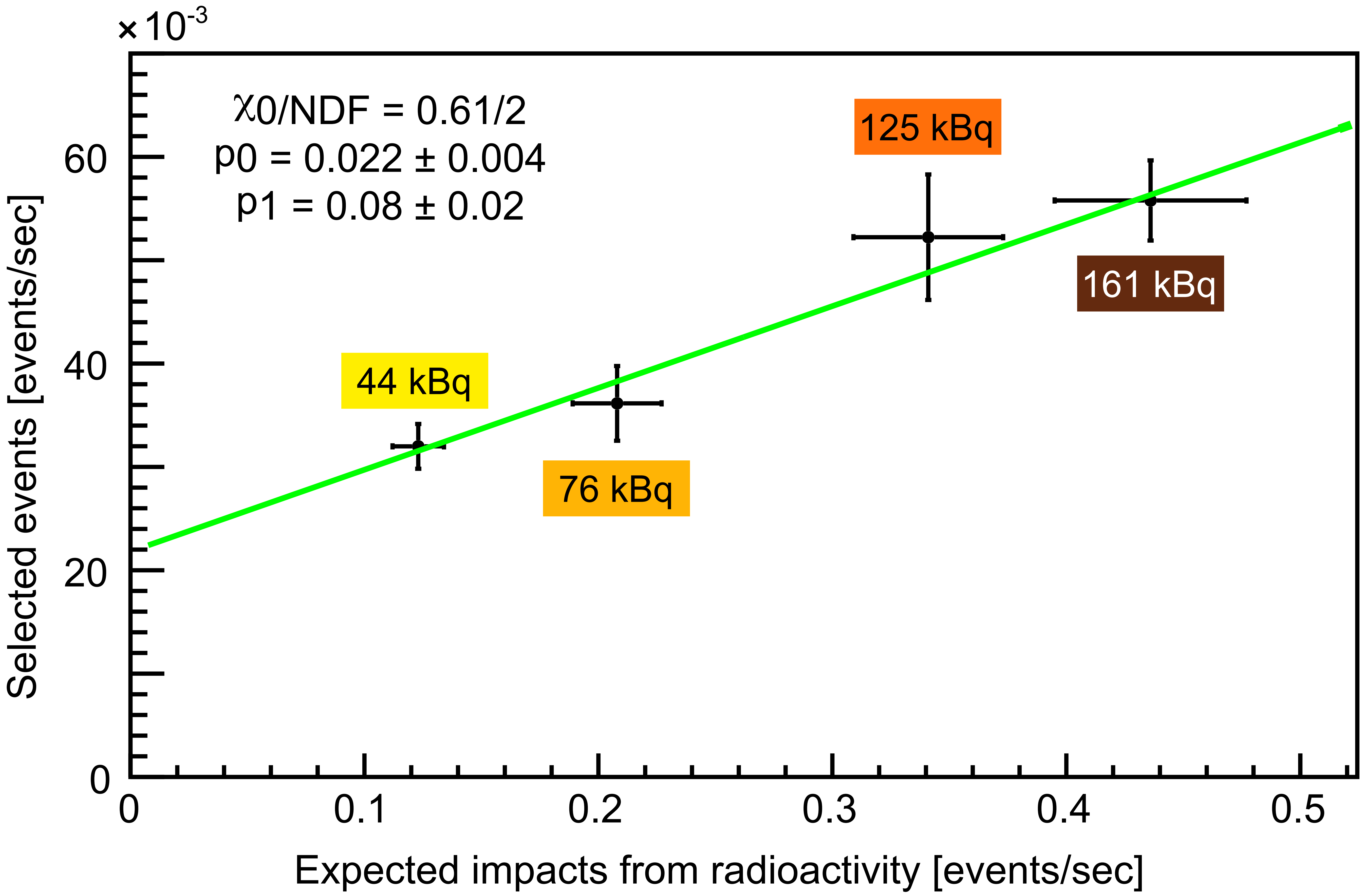
Can we use qubits as particle detectors?

- Two main limits at the moment:
    - The detection efficiency is currently very low (approx. 8%);
    - We are observing a lot of noise events (approx. 0.02 events/s).



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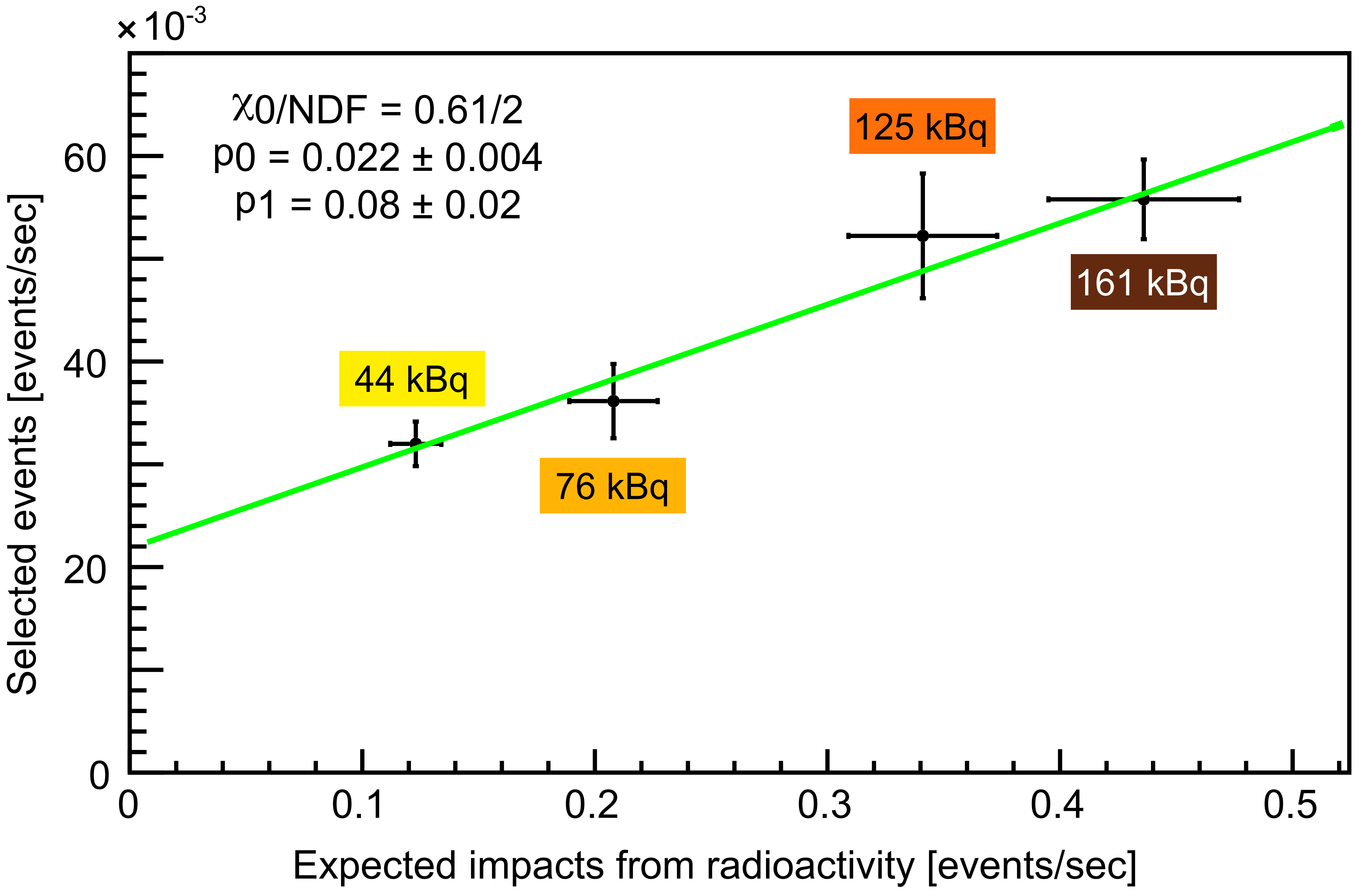
Can we use qubits as particle detectors?

- The qubit that we used was designed for maximally decoupling it from the environment;
- Also, the measurement strategy was similar to what usually done in quantum computing experiments;
- Is there a "smarter" way to operate the qubit for particle detection?
- How can we engineer the qubit in order to increase its sensitivity to phonons?



De Dominics et al., arXiv:2405.18355

Open questions

- In future measurements we also want to address a lot of questions that are still open:
  - What is the energy threshold for detection?
  - How does the position of the impact affect affect the detection?
  - How can we estimate the energy deposited in the chip?
  - And so on…

Conclusions

- We successfully operated a superconducting qubit as a gamma detector!
- The detection efficiency is only 8%, but we expect to obtain a much higher value by improving the detection strategy and by properly engineering the qubit;
- We also observe "noise" events which we are currently investigating;
- **Results have been uploaded on arXiv:2405.18355**

ACKNOWLEDGMENTS

INFN

SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

MUR PRIN 2020 https://cold.unimib.it/home-page

Ministero degli Affari Esteri e della Cooperazione Internazionale

This work was supported in part by the Italian Ministry of Foreign Affairs and International Cooperation, grant number US23GR09

CONTACTS

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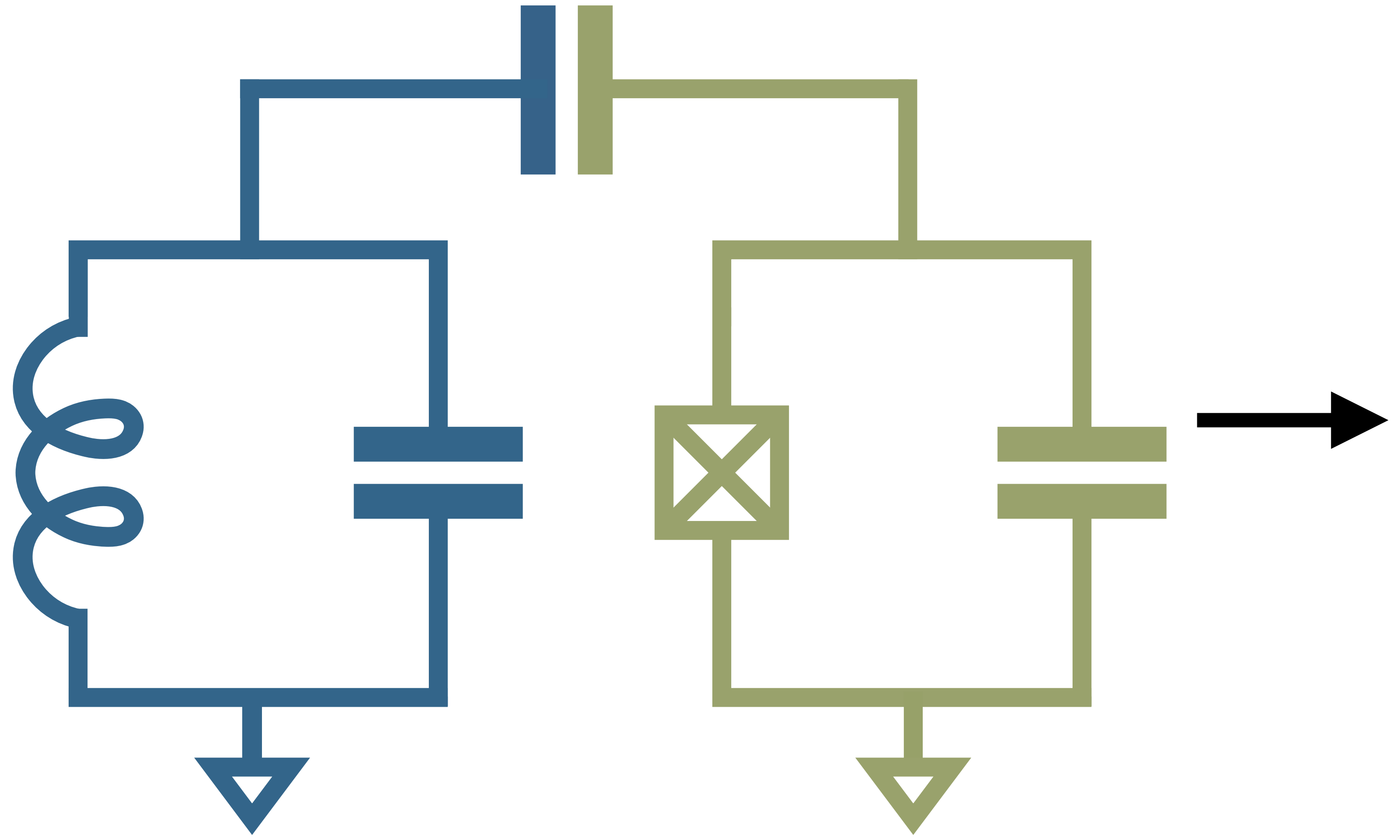
Backup: Dispersive Shift Readout

- Qubits are coupled to a LC resonator for state readout;
- The coupling affect the resonance frequency of the resonator, which value depend on the qubit state;
- The qubit state is then determined by measuring that resonance frequency.



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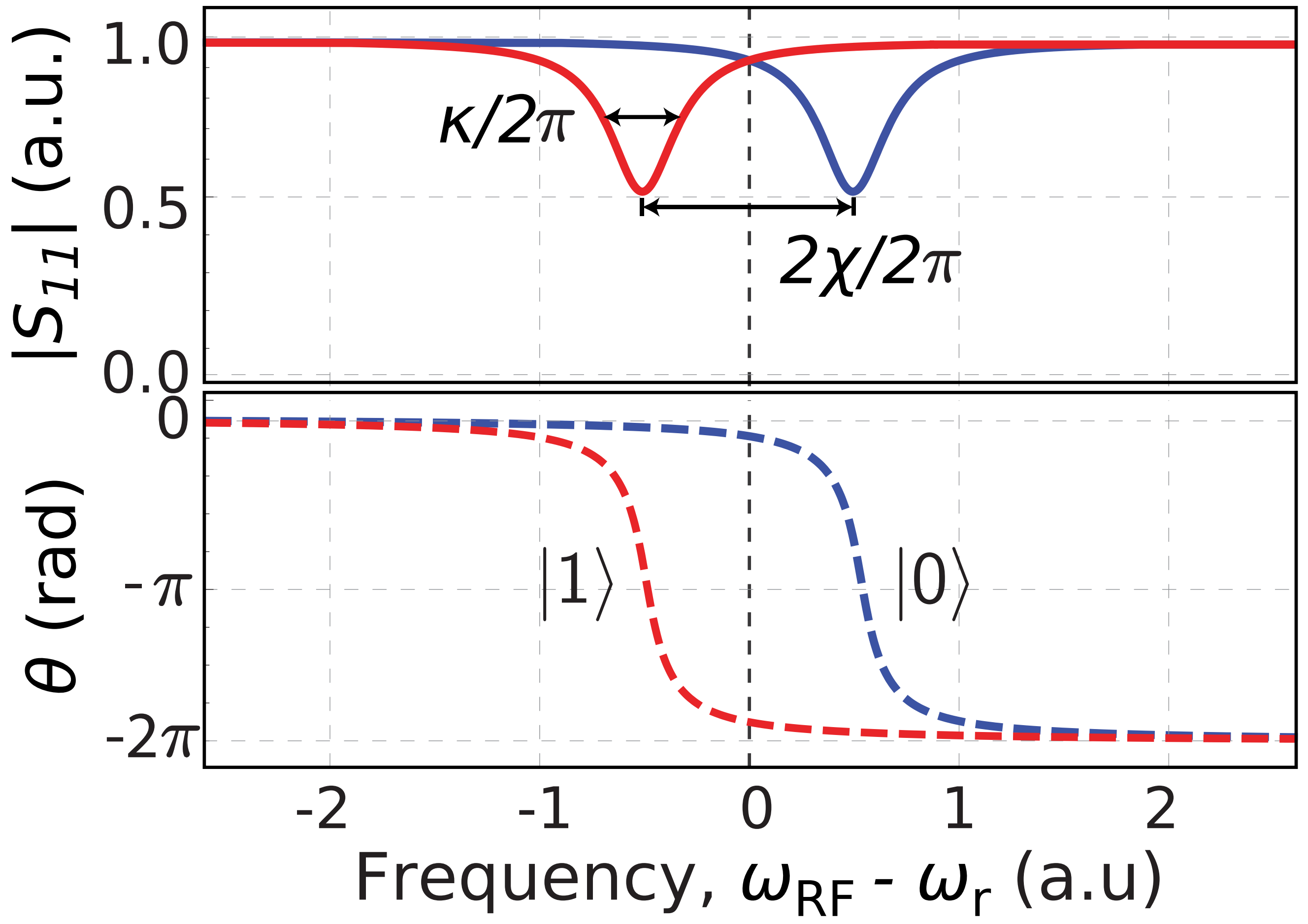

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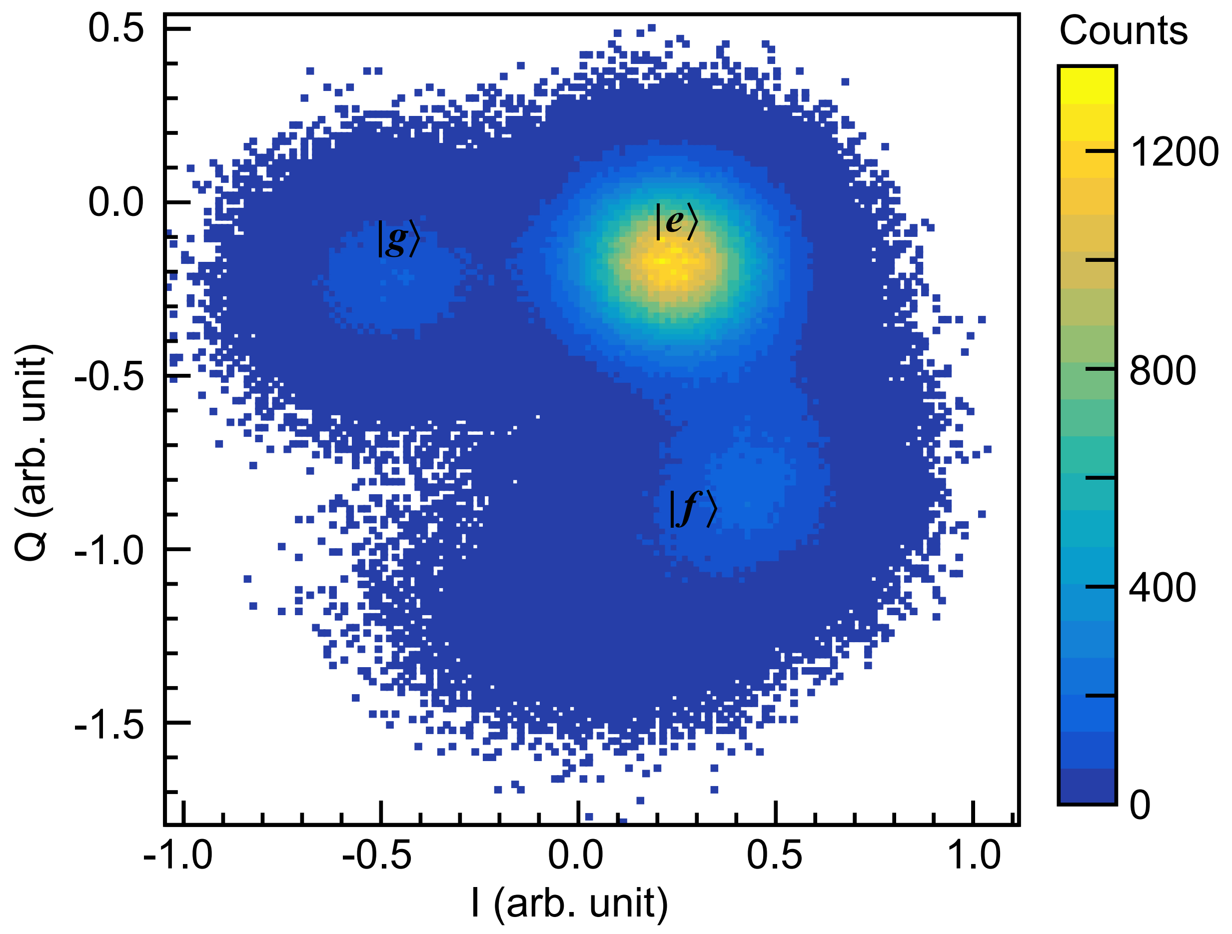

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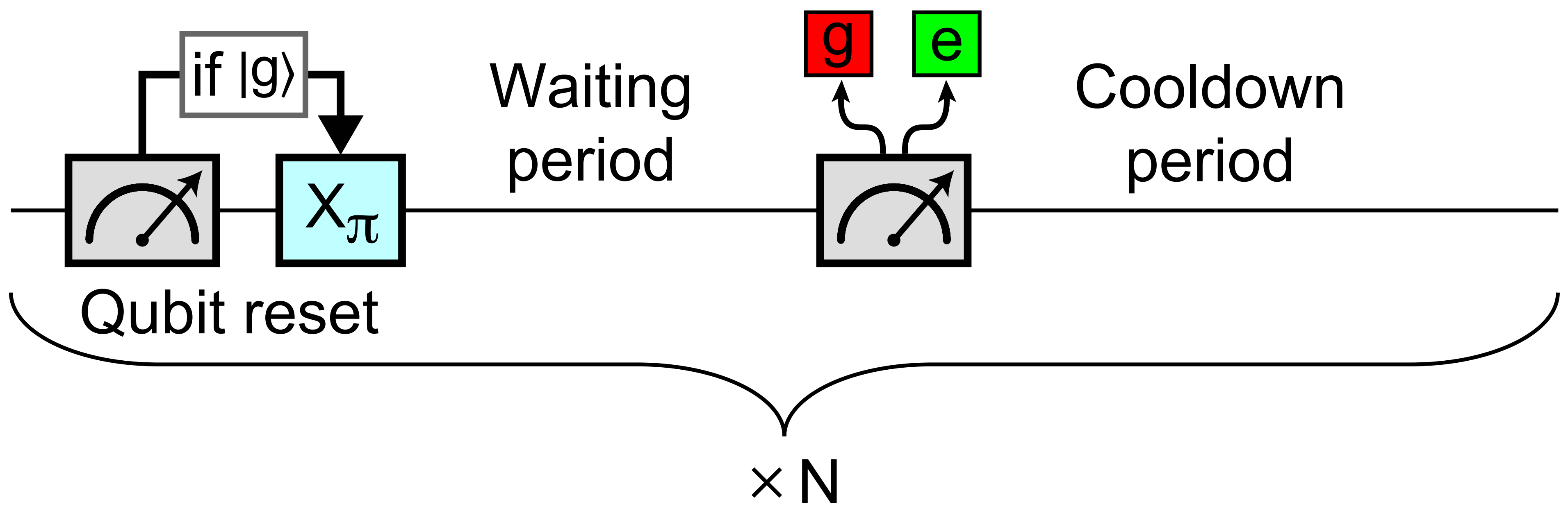
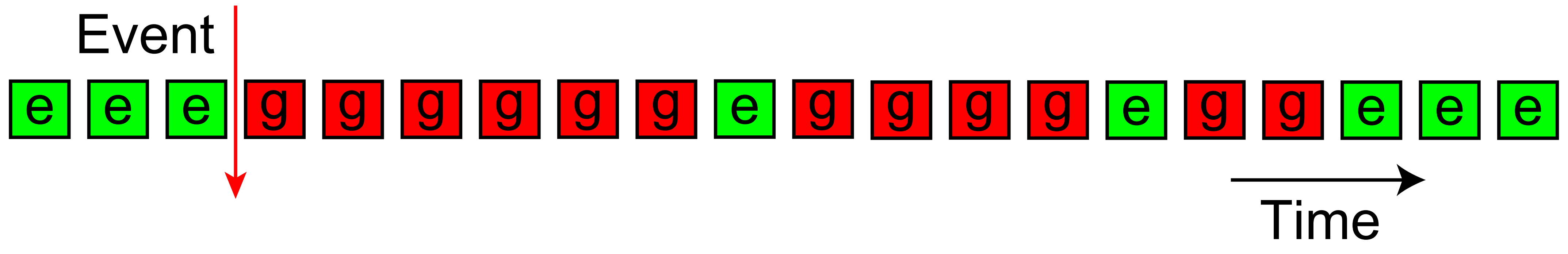
Backup: The fast detection protocol

- **Measurement protocol:**
    - Prepare the qubit in $|e\rangle$;
    - Wait 5 μs;
    - Measure the qubit state.
- Qubit decay time ≫ 5 μs, so we expect to observe the qubit in $|e\rangle$ most of the times;
- When the qubit is disturbed by a particle interaction, though, the decay time drops and we observe a stream of $|g\rangle$'s in the data.





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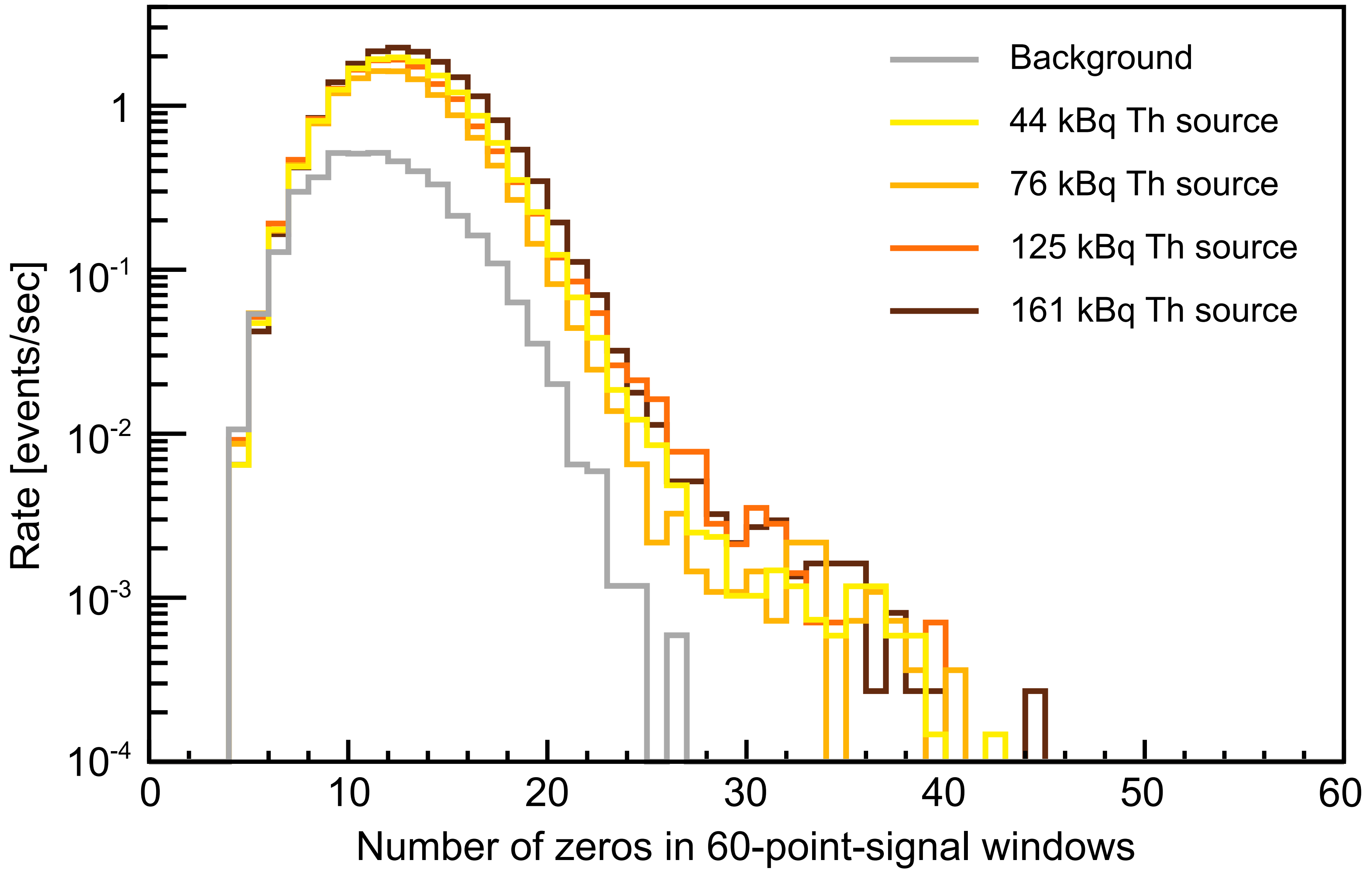
Backup: Results

- When exposing the qubit to the gamma source we observe streams of $|g\rangle$'s lasting up to almost 50 points;
- These type of events are not observed in the background dataset, and their rate increases linearly with the activity of the source.



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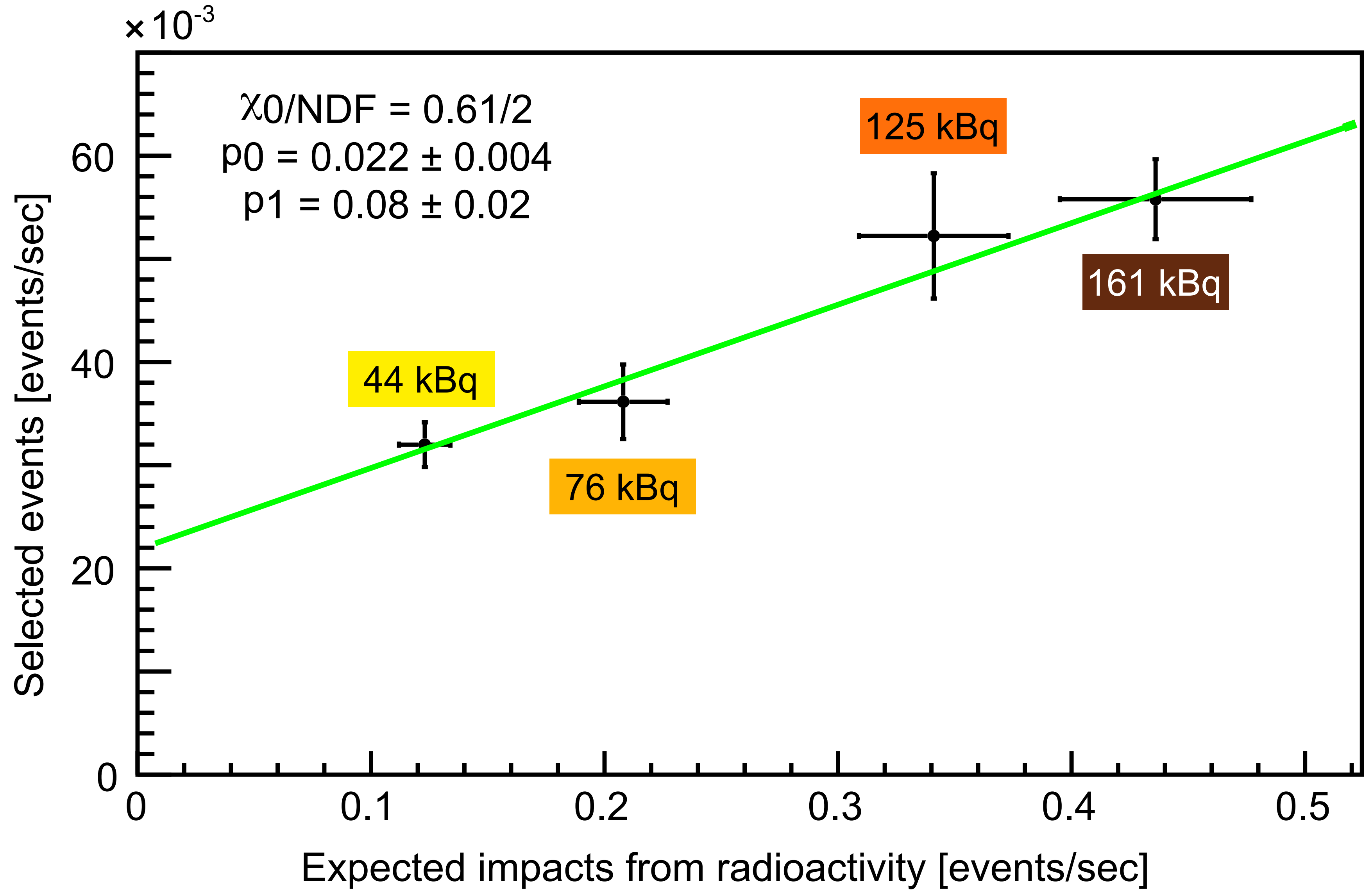

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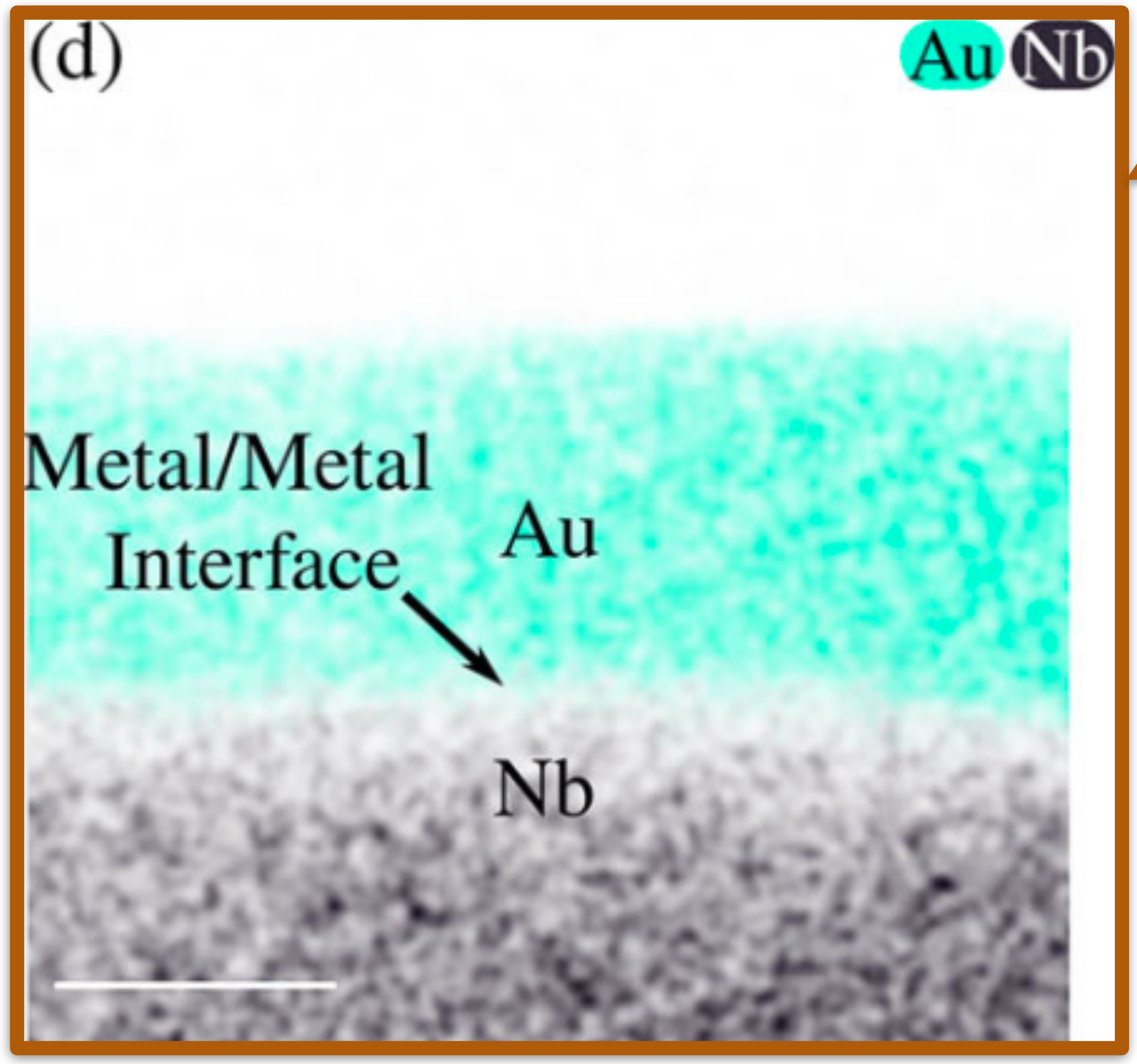
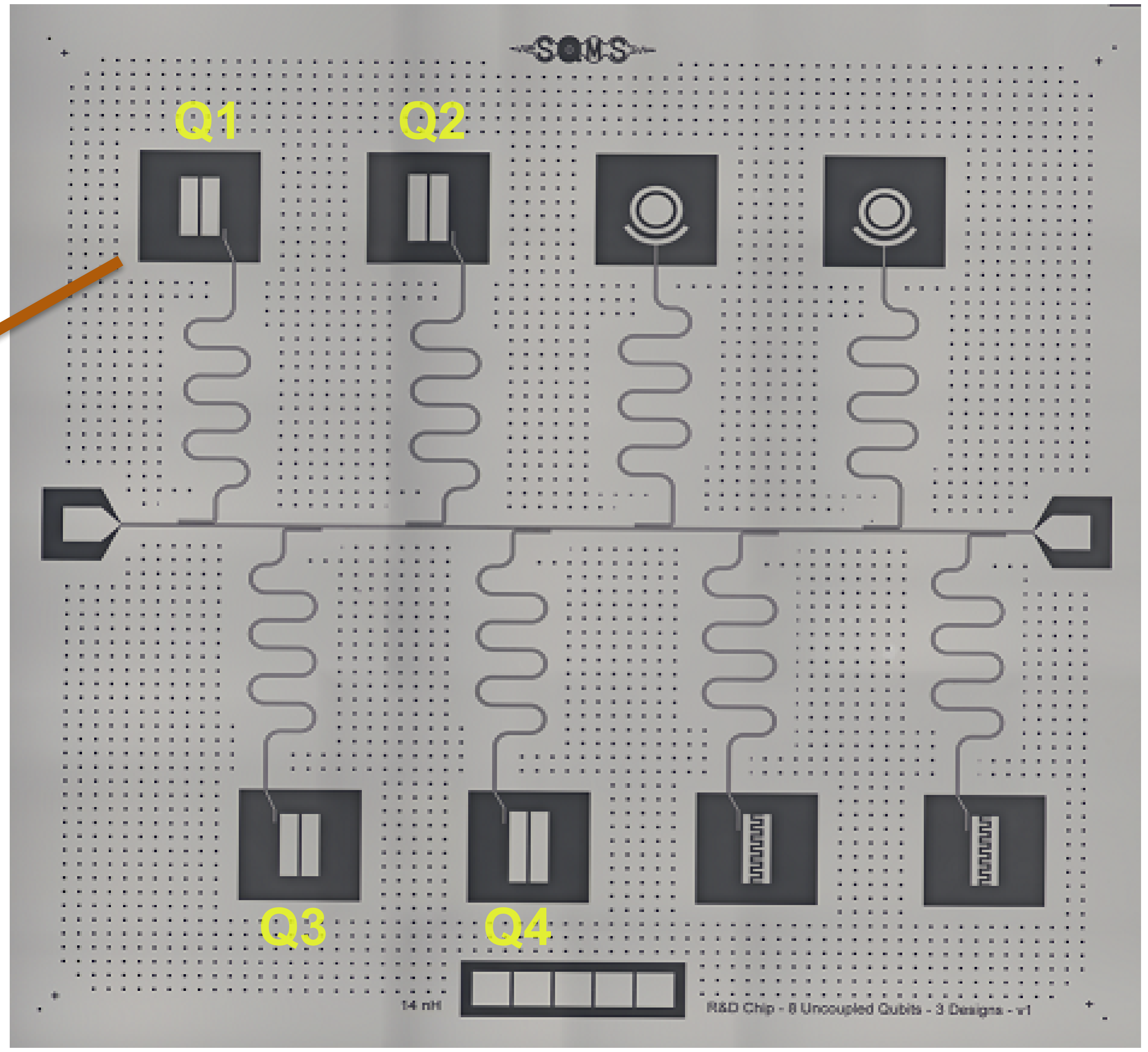
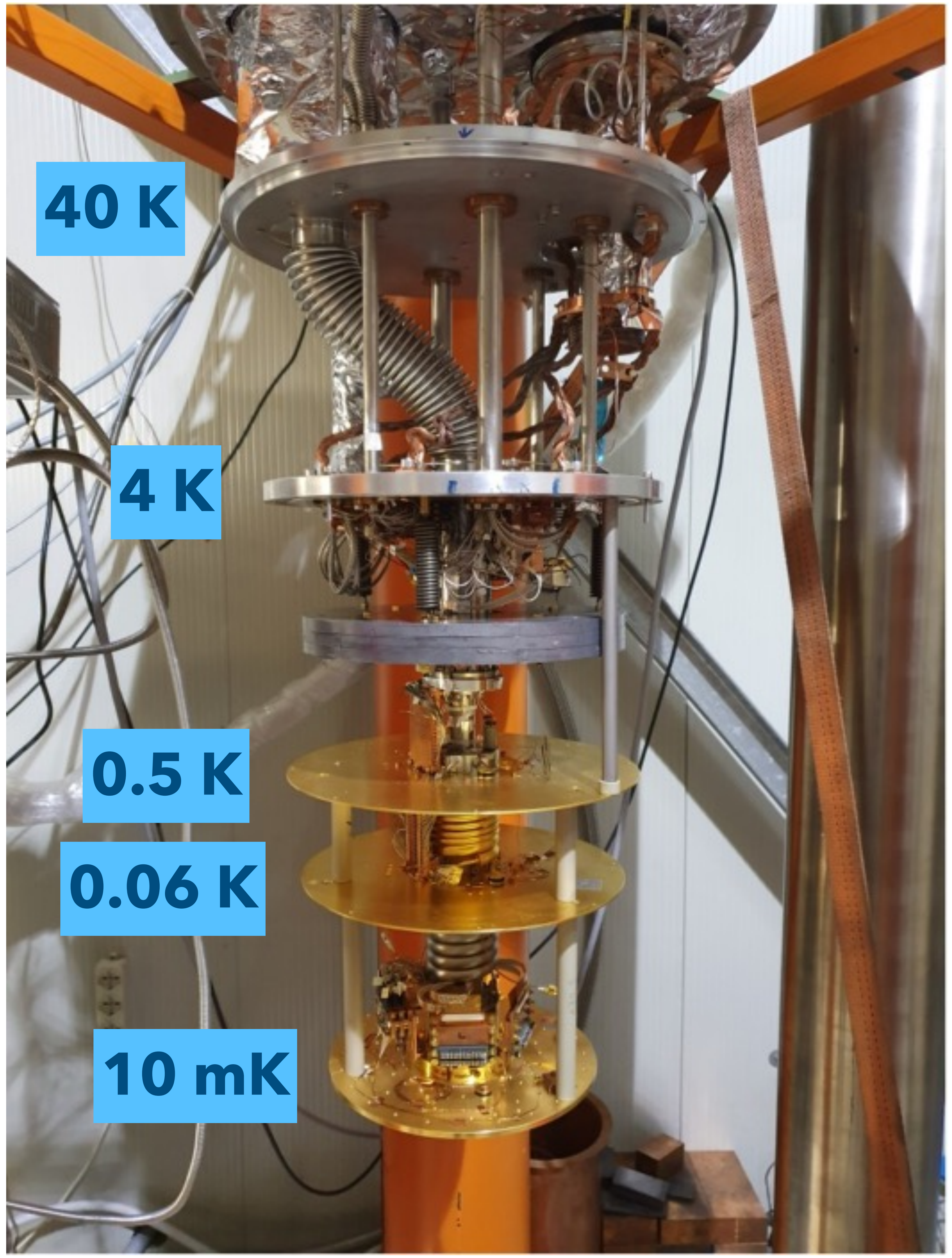
Backup: The Chip

- Niobium Transmon qubit on Sapphire substrate;
- Approx. 10 nm Gold capping to prevent losses from the formation of Nb_2O_5;
- Median T_1 = 76 μs





Backup: the IETI Underground Facility



- Experimental volume: 25 cm diameter, 13 cm height;
- 12 electronics channels with low noise voltage amplifiers (2 nV/√Hz) (R&D CUPID);
- 3 Magnicon SQUIDs (R&D COSINUS);
- 8 low-attenuation SMA coax cables from room temperature to 4K plus 8 NbTi coax cables from 4K to MC (R&D DEMETRA / SQMS);
- 48 twisted superconducting wires from room temperature to MC;
- A ^{60}Co crystal for absolute thermometry calibration.

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

Backup: Scheme of the RF lines