Study of the effects of radioactivity on superconducting quantum bits

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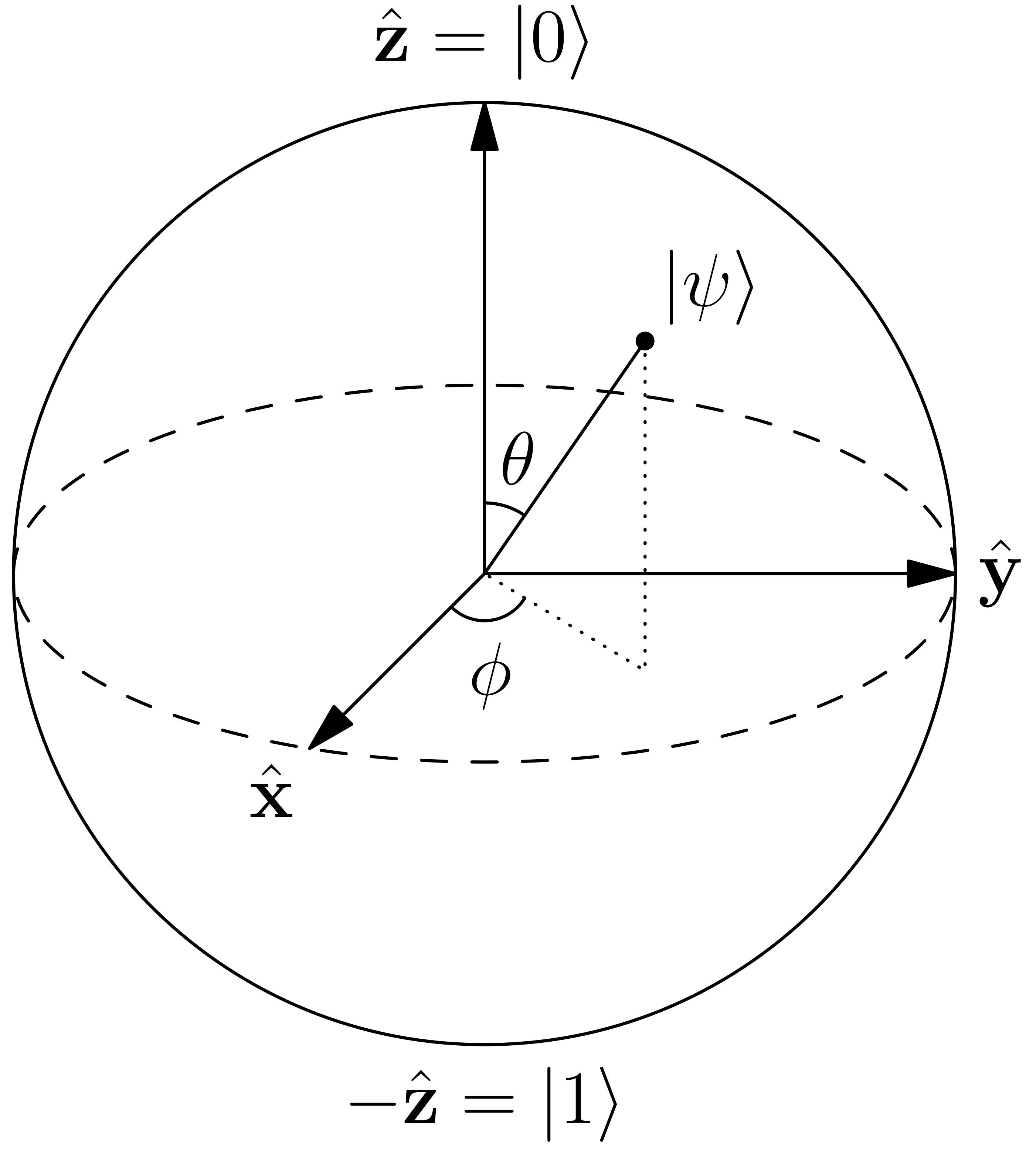
Superconducting qubits

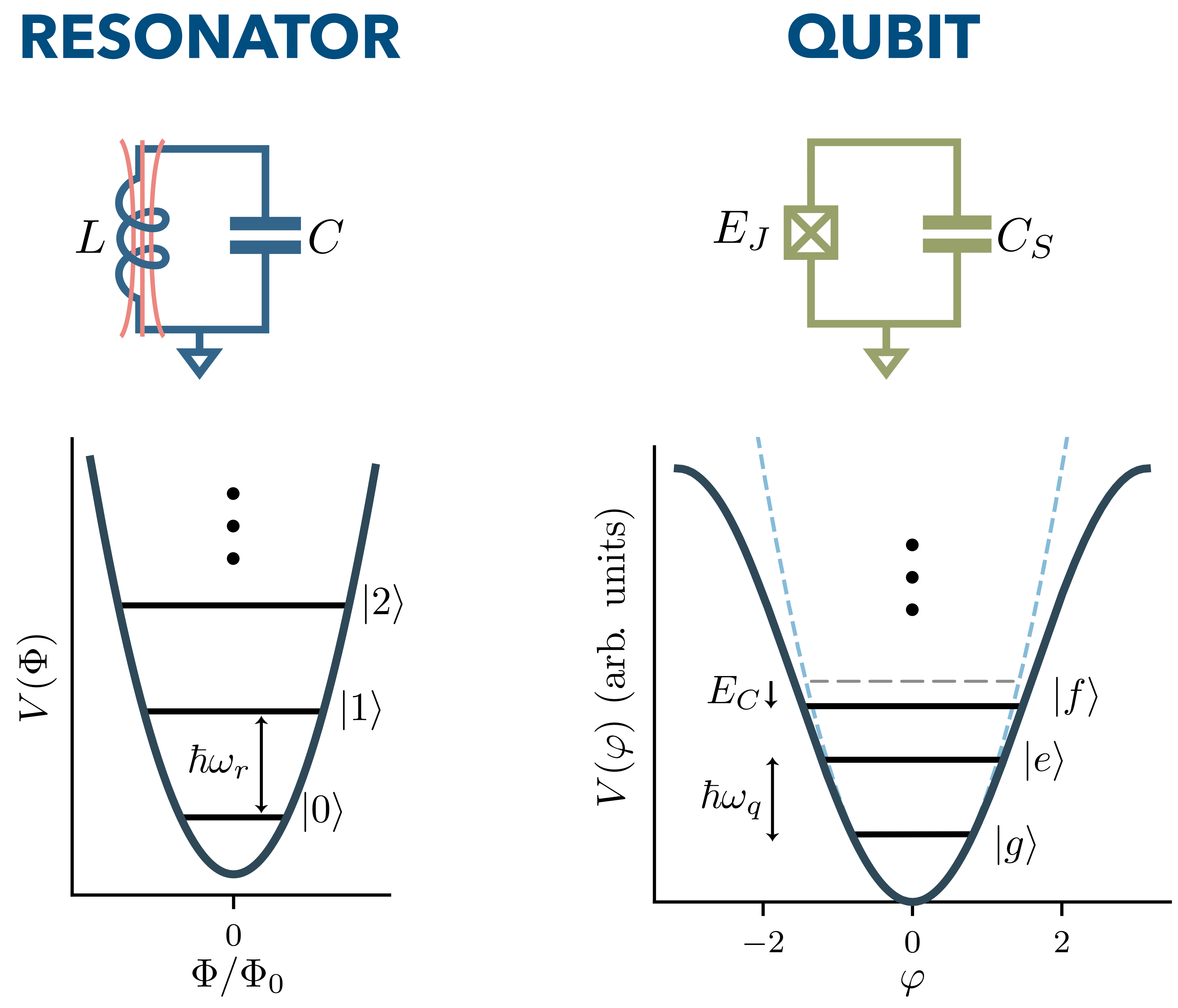
- Quantum counterpart of classical bit;
- Possibility to have superposition states $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$;
- Any two-level quantum system can be operated as a qubit;



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

Superconducting qubits

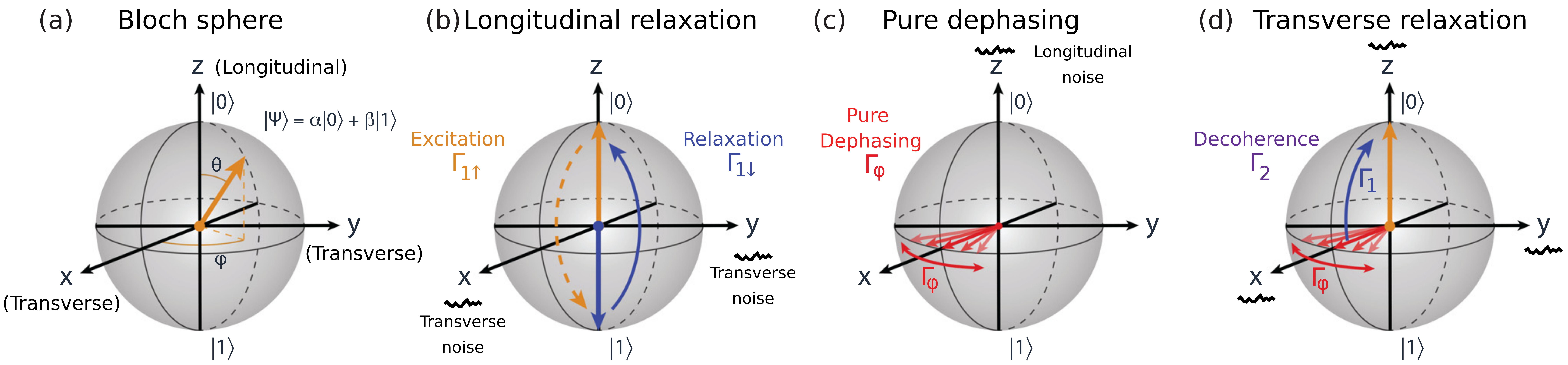
- Superconducting circuit with a Josephson Junction;
- The Josephson Junction acts as a non-linear inductor that produces an anharmonic energy spectrum;
- The anharmonic energy spectrum allows us to populate only the first two energy levels, operating the circuit as an effective qubit.



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

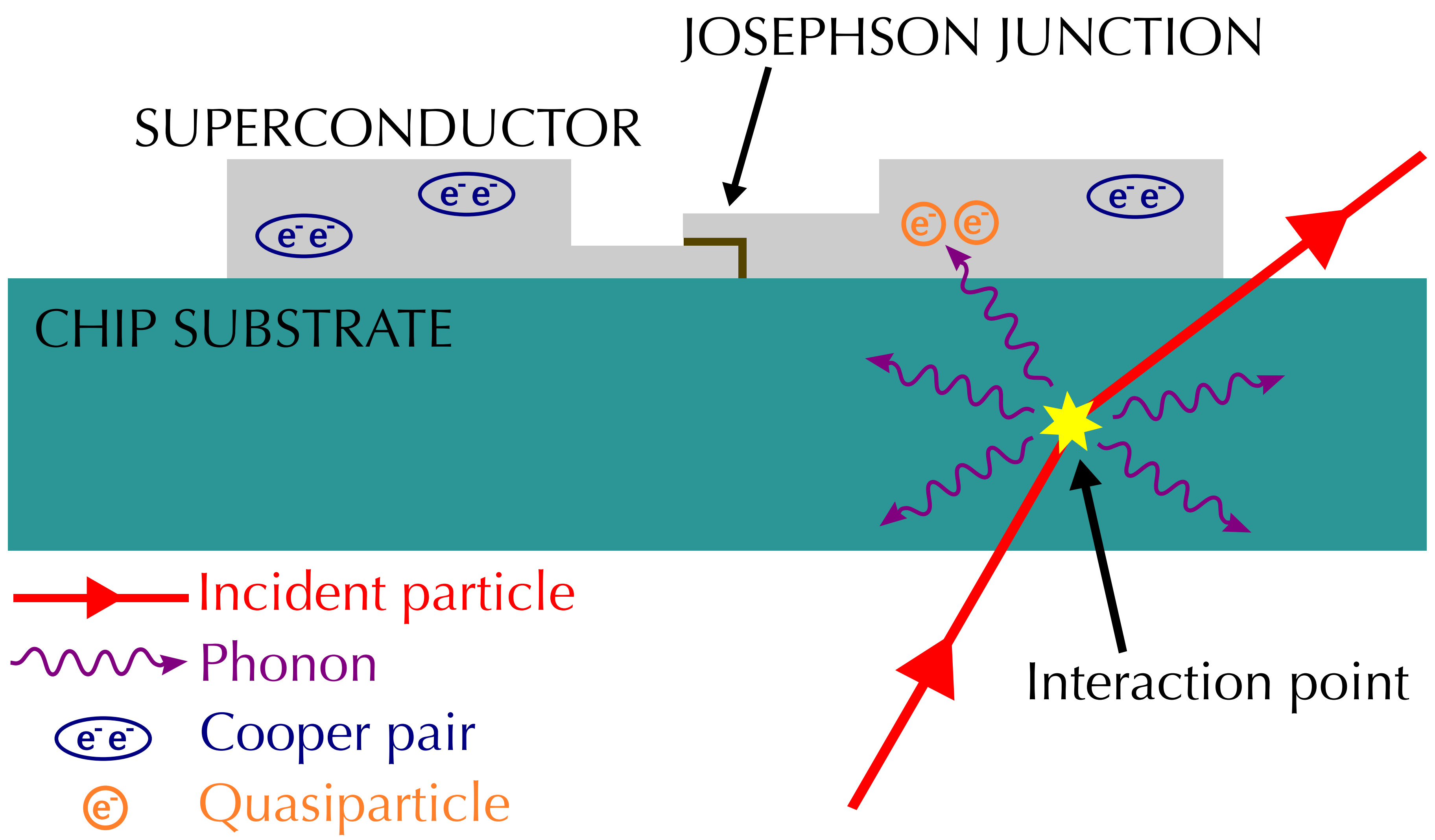
Qubit coherence

- 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**;



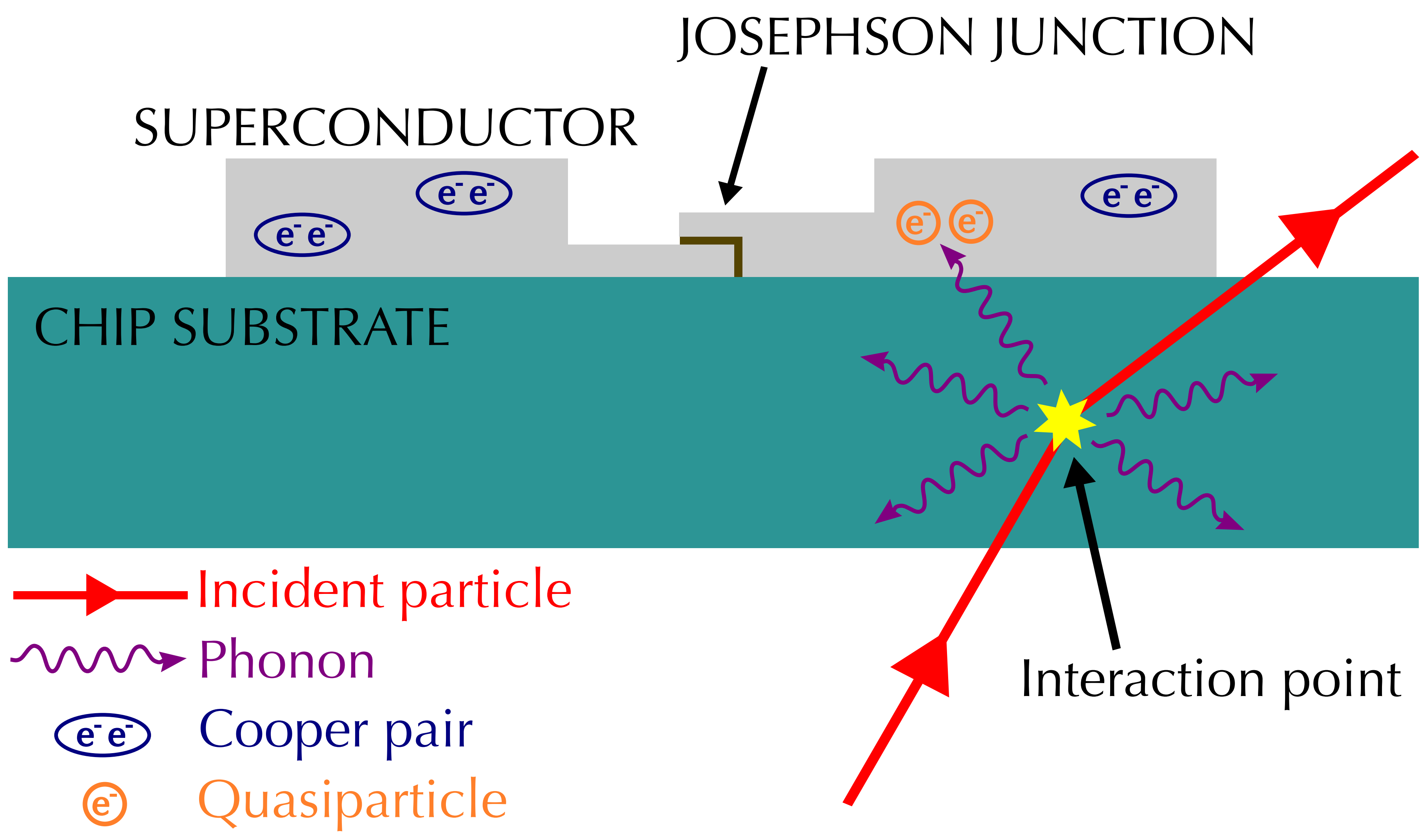
Krantz et al., *Appl. Phys. Rev.* **6**, 021318 (2019)

Qubits and radioactivity



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

Recent results



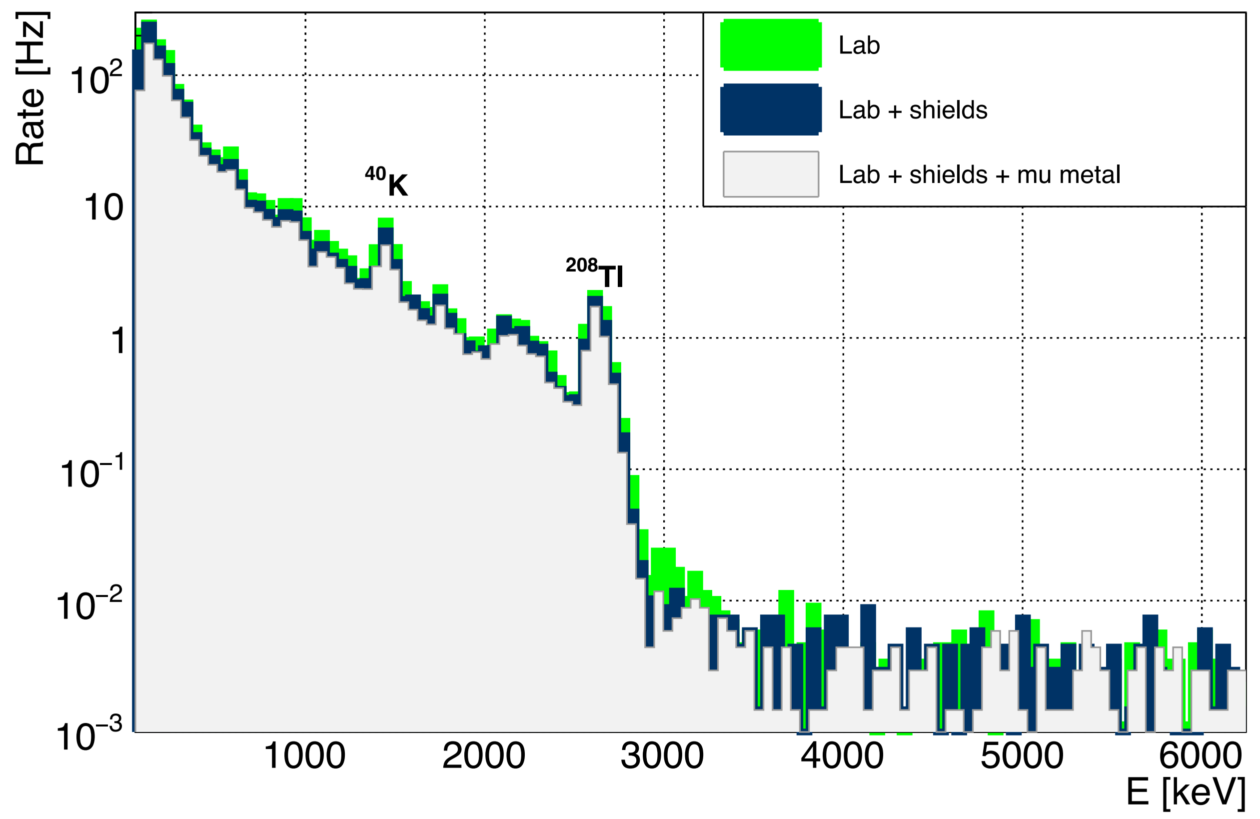
- Radioactivity affects the performances of superconducting quantum circuits [Cardani et al., *Nature Communications* (2021)];
- Radioactivity will limit the coherence time of next-generation qubits [Vepsäiläinen et al., *Nature* (2020)];
- Radioactivity is a source of correlated errors in multi-qubit chips [Wilen et al., *Nature* (2021), McEwen et al., *Nature Physics* (2022)].

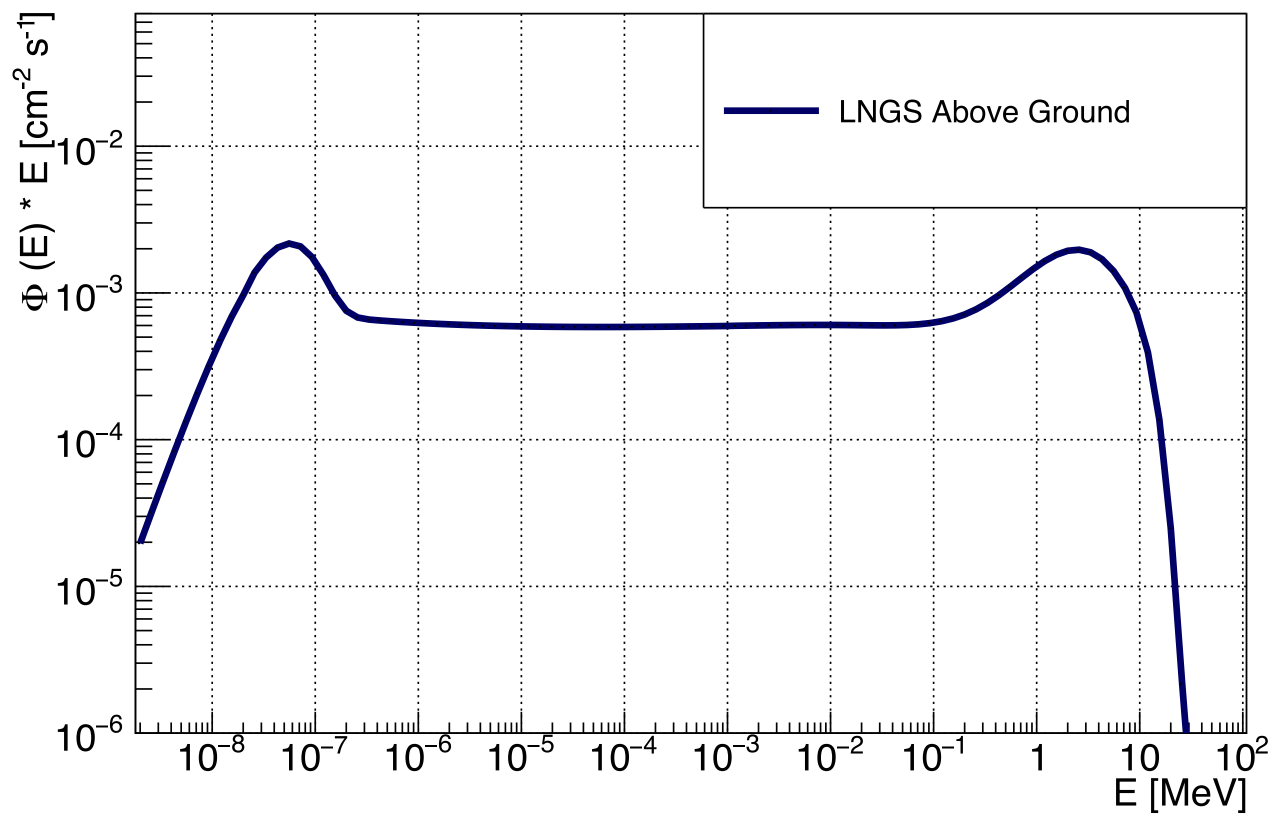
Aim of my research

- Prove that radioactivity is not the main limit to the performance of state-of-the-art qubits;
- Characterization of correlated errors induced by particle impacts in qubit chip substrates;
- Applications of superconducting qubits in particle physics experiments.

Radioactive sources

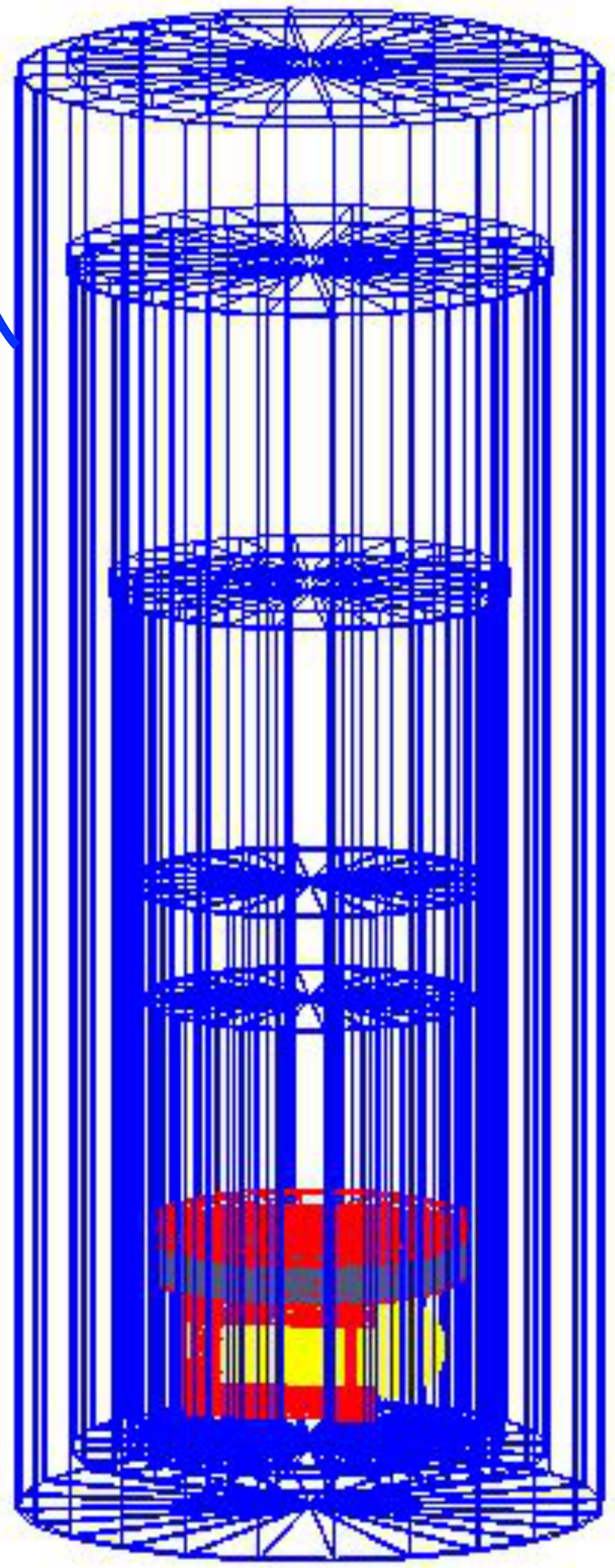
- Two categories of radioactive sources:
  - **Far sources**
    - Environmental gammas (measured);
    - Cosmic muons (literature);
    - Neutrons (measured);
  - **Close sources**
    - Contaminations (measured).





Cardani et al., *Eur. Phys. J. C* **83**, 94 (2023)

Simulations



- Experimental setup reconstructed in a Geant4 simulation;
- Greatest contributions in a "standard" laboratory from *far* sources;
- Contributions from *close* sources due mostly to the Printed Circuit Boards (PCBs) used in some setups;

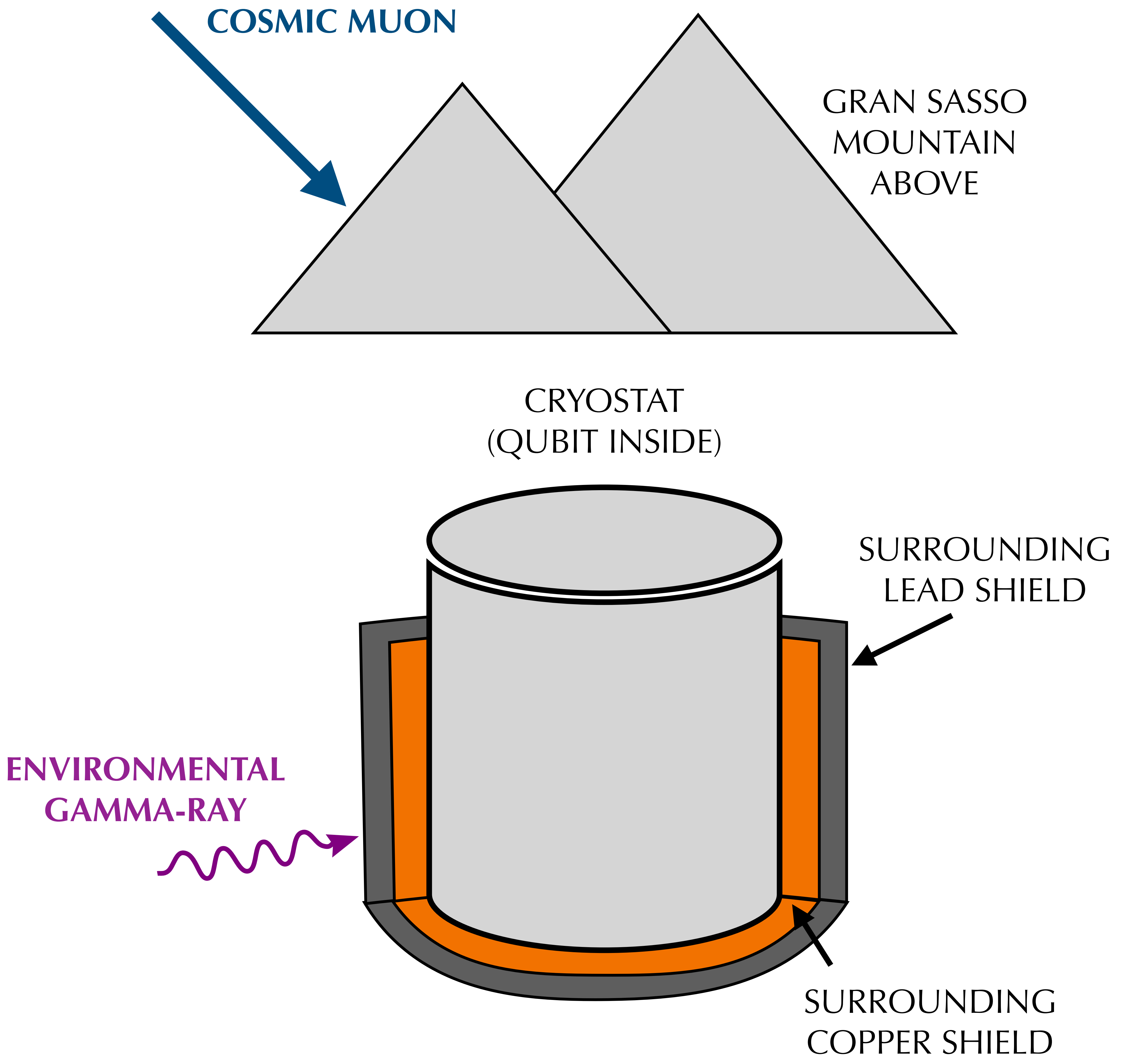
Source	Contribution (mHz)
Lab γ-rays	(18 ± 4)
Muons	(10 ± 0.6)
Neutrons	(0.15 ± 0.05)
Close sources	≤ 5

Cardani et al., *Eur. Phys. J. C* **83**, 94 (2023)

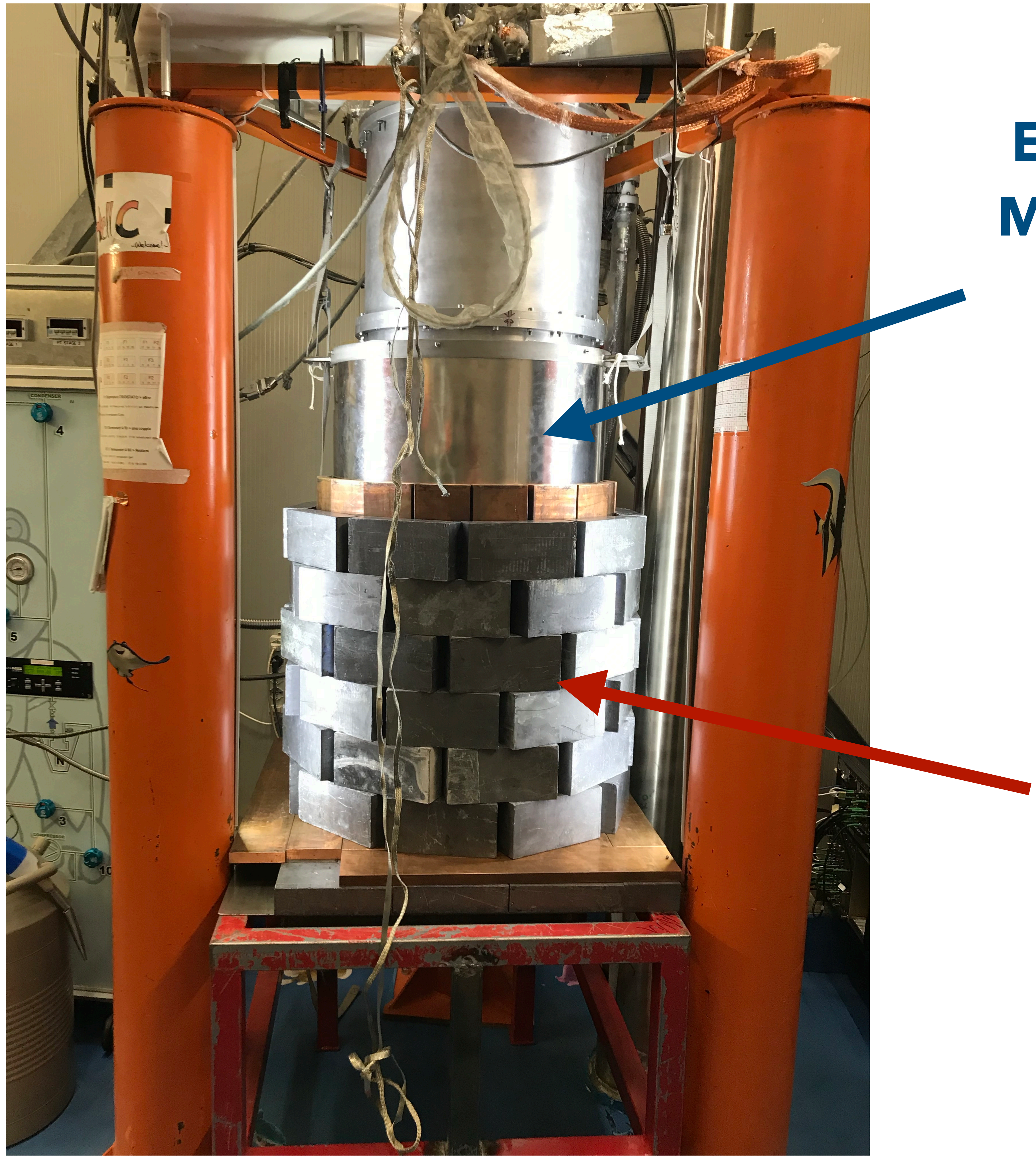
Going underground

- In the LNGS underground laboratories the muon flux is attenuated by a factor 10^6 and also the gamma background is lower compared to other above ground laboratories;

- Measurements with a NaI crystal showed that, by shielding the cryostat with a lead and copper shield, the gamma interaction rate is attenuated further by at least a factor 8.



Shielding


External
Magnetic
Shield
External
Pb+Cu
Shield


Inner Lead Shield (second shield at 4K)
Magnetic Shield (Qubit Inside)

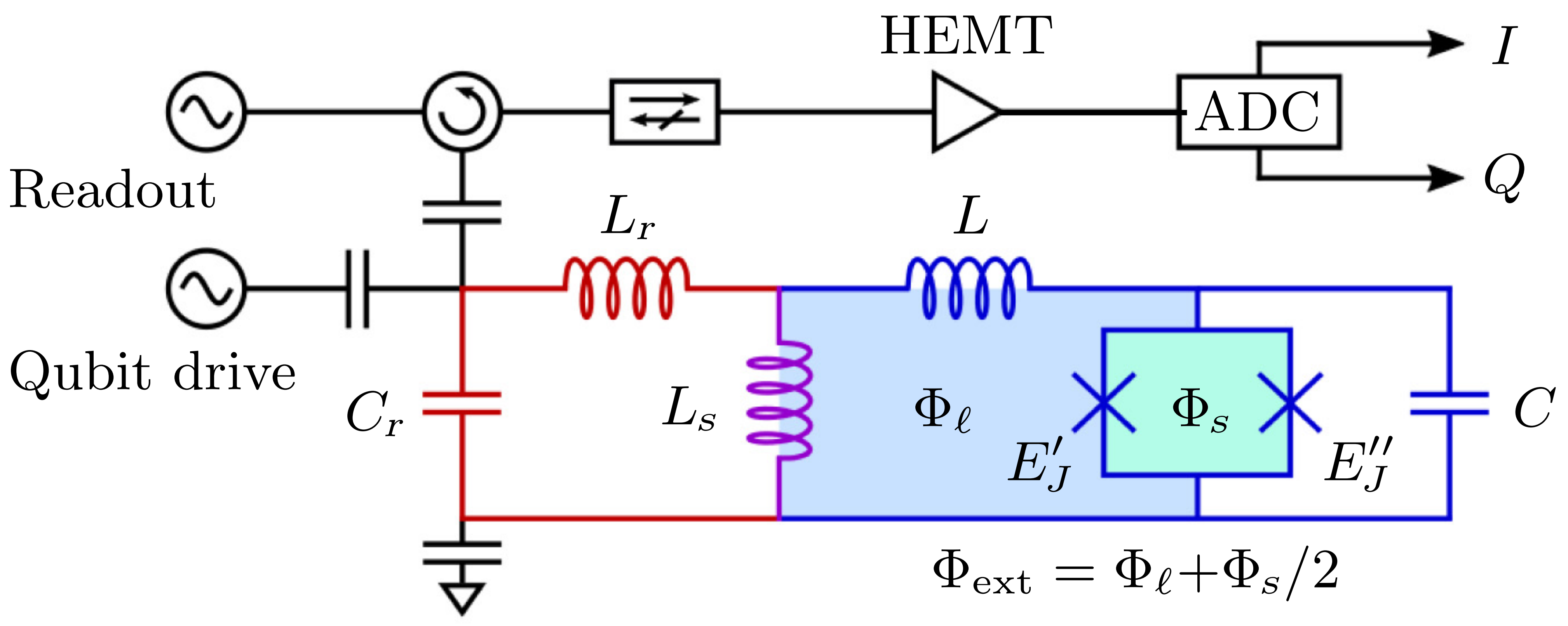
Expected contributions

- In our setup the rate of interactions from *far* sources is expected to drop from tens of mHz to less than 1 mHz;
- Better attenuations are achievable by improving the shielding.

Source	Contributions Above Ground (mHz)	Contributions at LNGS (mHz)
Lab γ-rays	(18 ± 4)	< 1
Muons	(10 ± 0.6)	$< 10^{-5}$
Neutrons	(0.15 ± 0.05)	$< 10^{-4}$
Contaminations	≤ 5	≤ 5

The fluxonium qubit

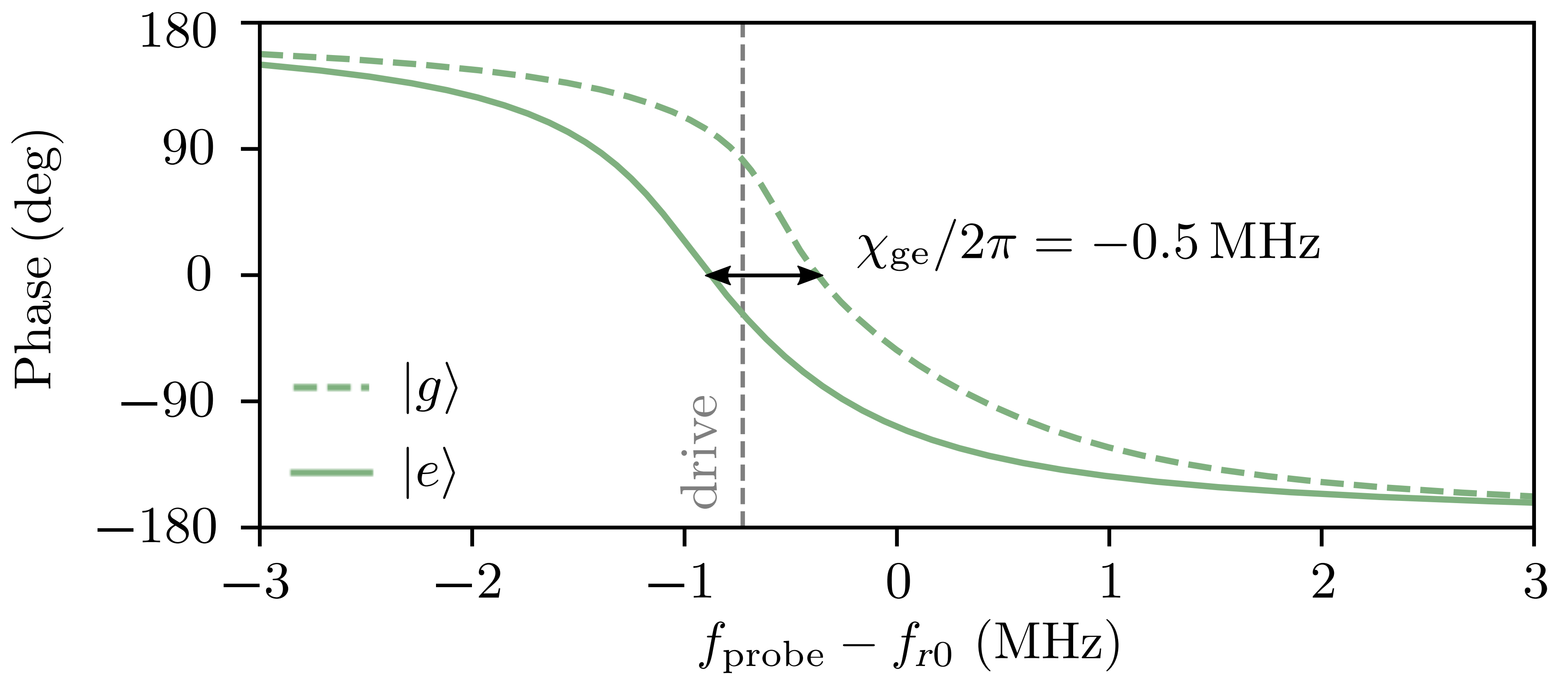
- Measurements in collaboration with the Karlsruhe Institute of Technology, that produced the qubit studied;
- *Fluxonium qubit*: superconducting ring interrupted by Josephson Junctions and shunted by a large inductance;
- Total contribution from radioactivity in LNGS < 1 mHz.

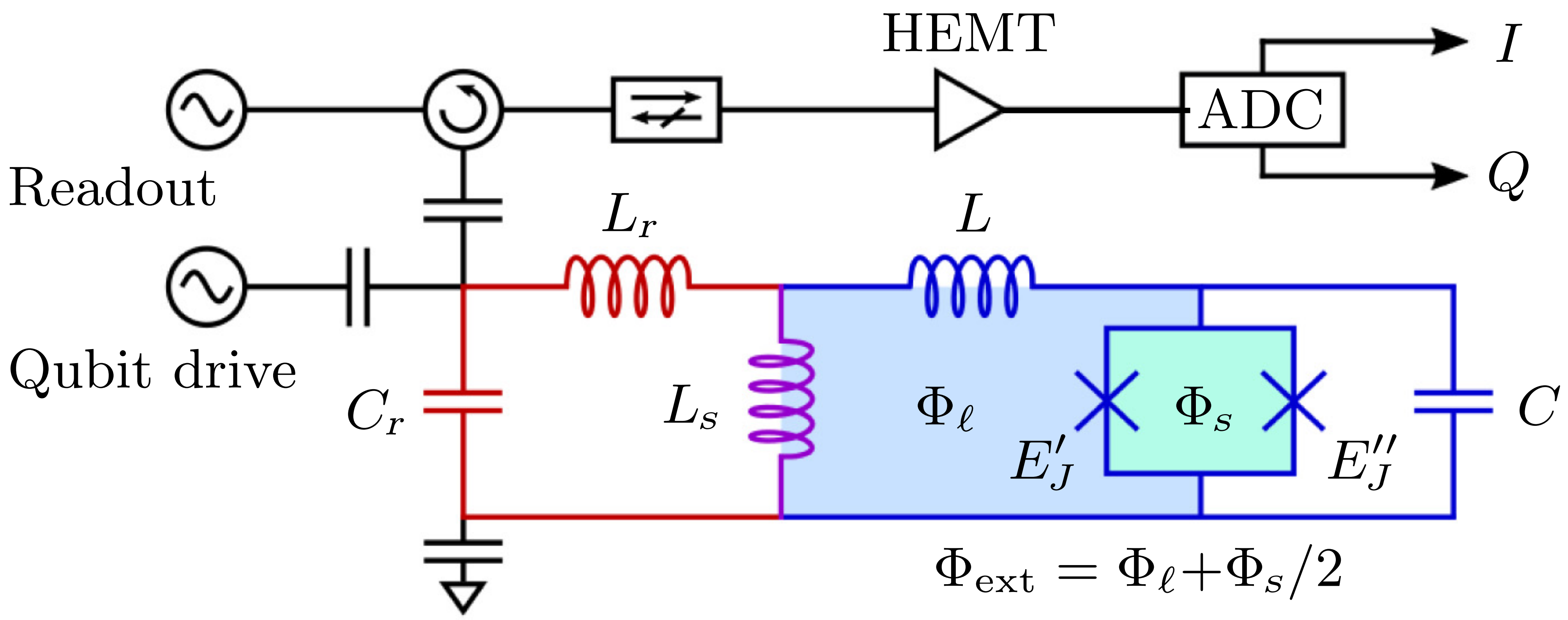


Gusenkova et at., *Phys. Rev. Applied* **15**, 064030 (2021)

State measurement

- The qubit is coupled to a resonator for state readout;
- The resonance frequency of the resonator depends on the qubit state;
- The qubit state is then measured by sending a pulse at the resonance frequency of the resonator and by measuring the output signal.

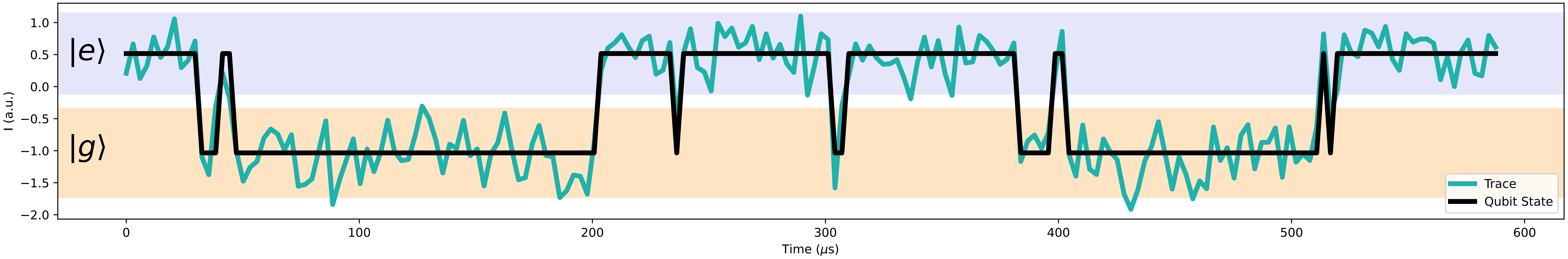




Gusenkova et at., *Phys. Rev. Applied* **15**, 064030 (2021)

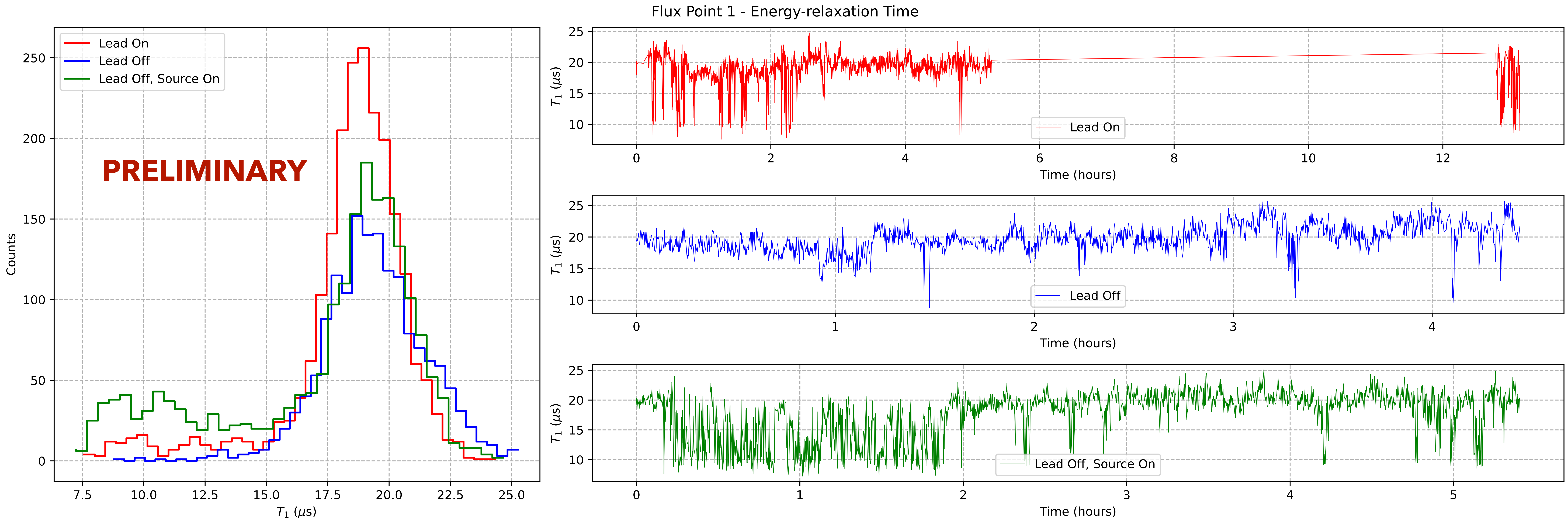
Measurement Strategy

- In our measurements we focused on the estimation of the *energy-relaxation time* of the qubit (time for the qubit to relax from the first excited state to the ground state);
- To infer possible effects of radioactivity on qubit behavior a Thorium source was also used;
- In the experiment readout signals were sent with high frequency to measure the qubit state;
- From the traces quantum jumps frequencies were calculated and used to estimate the energy-relaxation time;



Results

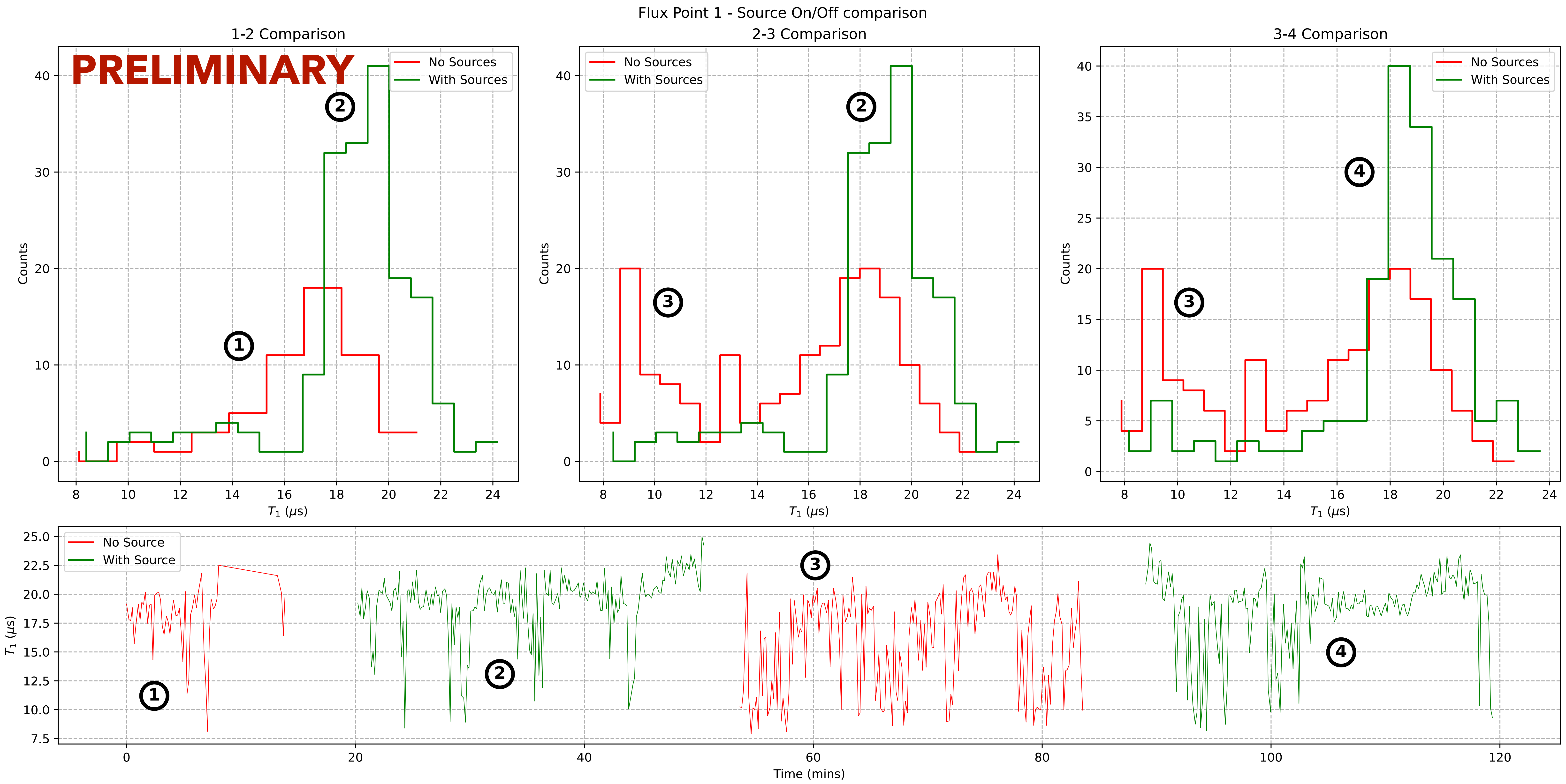
- Three long measurements (~ few hours) on the qubit: with the full shielding, without the lead and copper shielding and with a thorium source next to the cryostat;
- No evidence of direct effects of radioactivity on the energy-relaxation time.



Results

- Short measurements (~ 30 minutes) adding and removing a Thorium source;

- Fluctuations in the energy-relaxation time values are uncorrelated with the presence of the source;



Results

- Measurements on the fluxonium qubit done in a low-radioactivity environment showed no improvement in its energy-relaxation time, proving that radioactivity is not the main limit to its performance;

- This can be explained by the small rate of interactions from radioactivity compared to the average decay rate of the qubit;

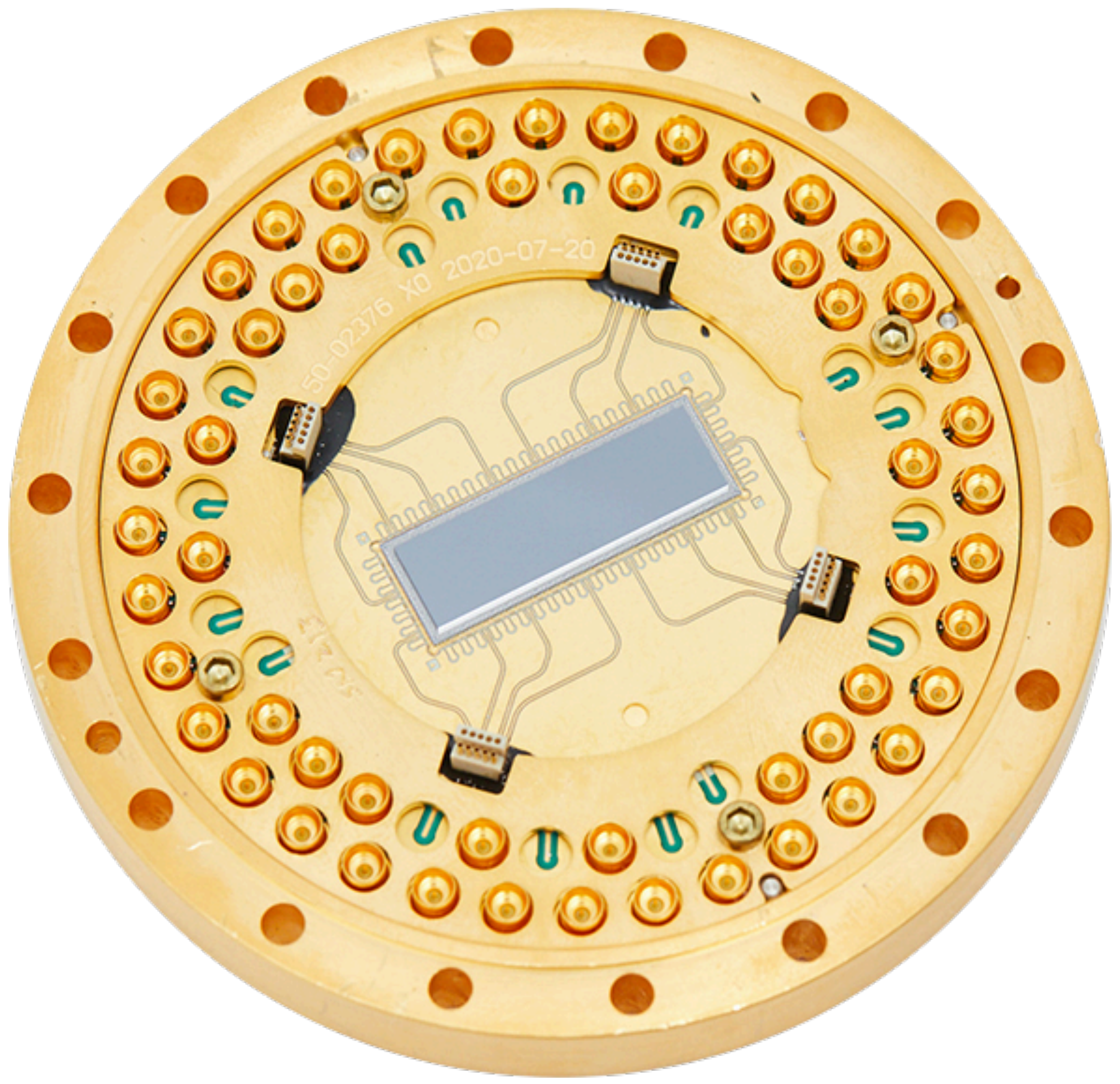
- Radioactivity is expected to play a more significant role in next-generation devices, due both to higher energy-relaxation times and larger chip dimensions.

Aim of my research

- Prove that radioactivity is not the main limit to the performance of state-of-the-art qubits; ✓
- Characterization of correlated errors induced by particle impacts in qubit chip substrates;
- Applications of superconducting qubits in particle physics experiments.

The RoundRobin project

- Project developed within the SQMS collaboration;
- Characterize the same prototypes in different laboratories;
- Focus on transmon qubits;



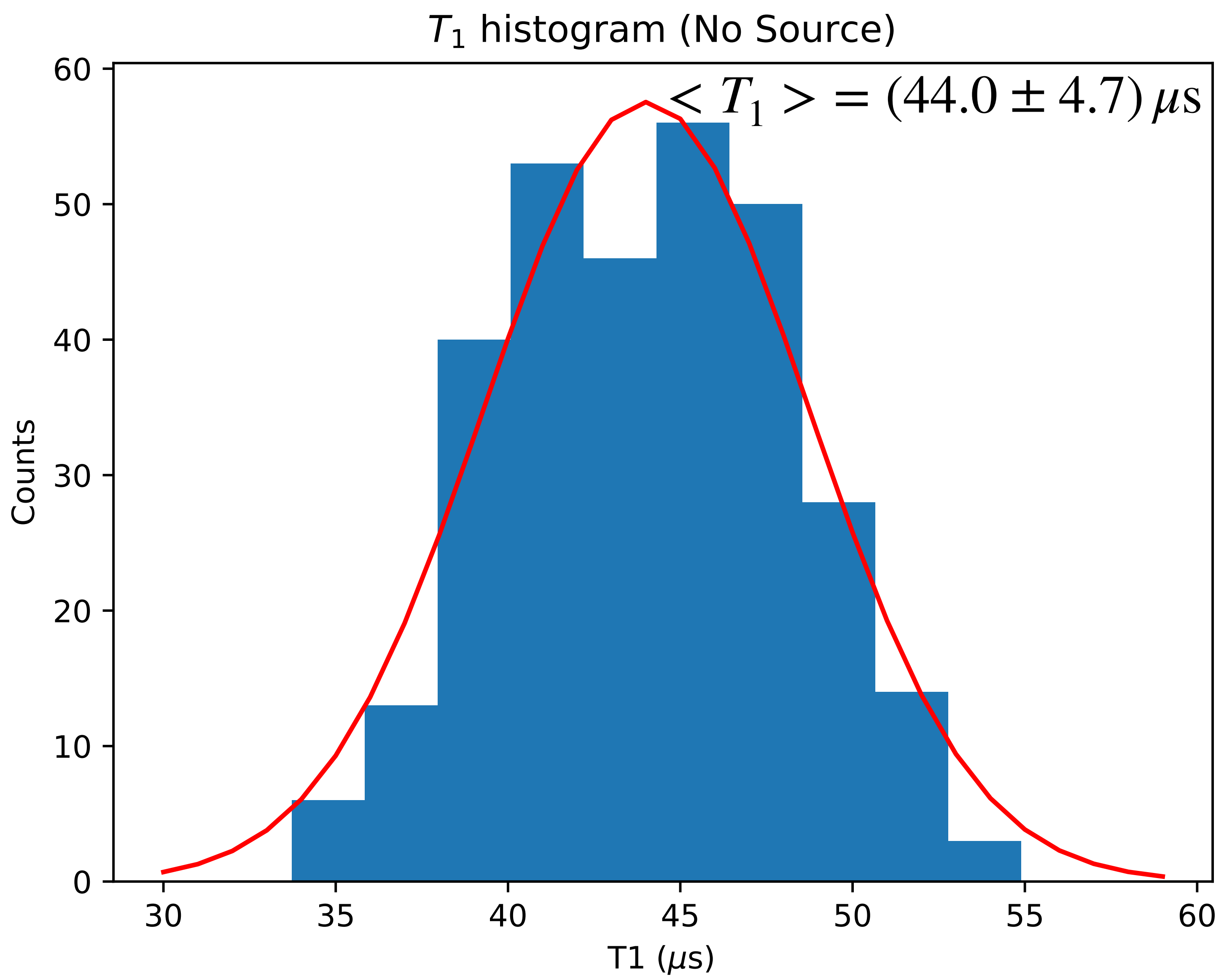
SQMS
SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

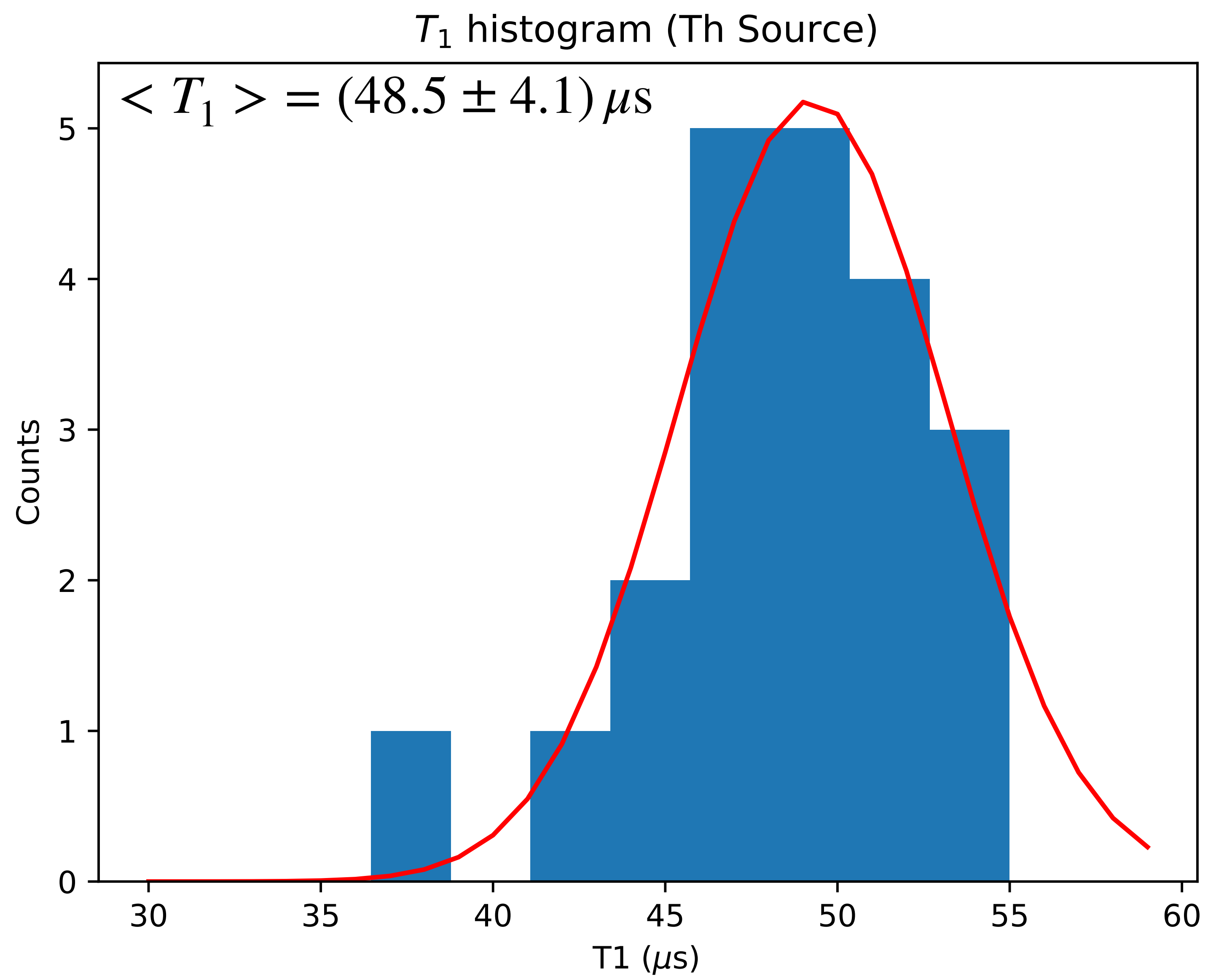
- Get a full picture of the decay mechanisms;
- Measurements at LNGS to investigate effects of radioactivity.

The RoundRobin project

SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

- First prototype tested in June to prove that the facility is ready for measurements;
- Energy-relaxation time of approx. 45 μs, so we expected no direct effects of radioactivity on it;
- Measurements confirmed our hypothesis:

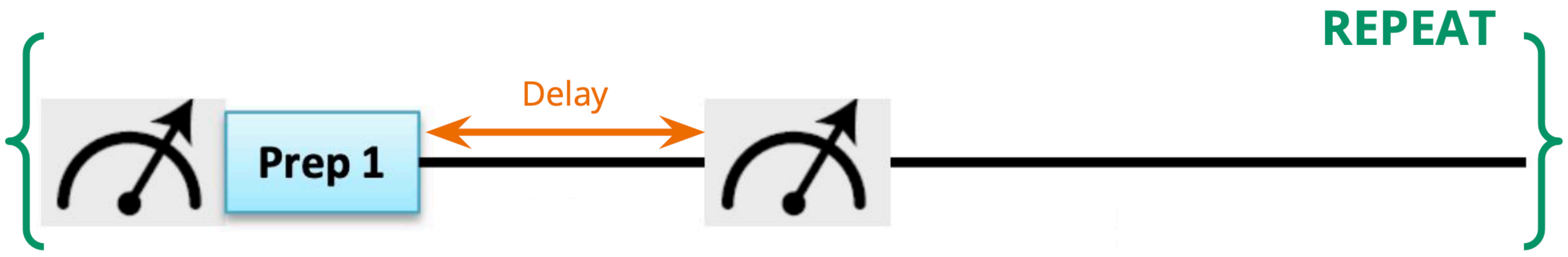


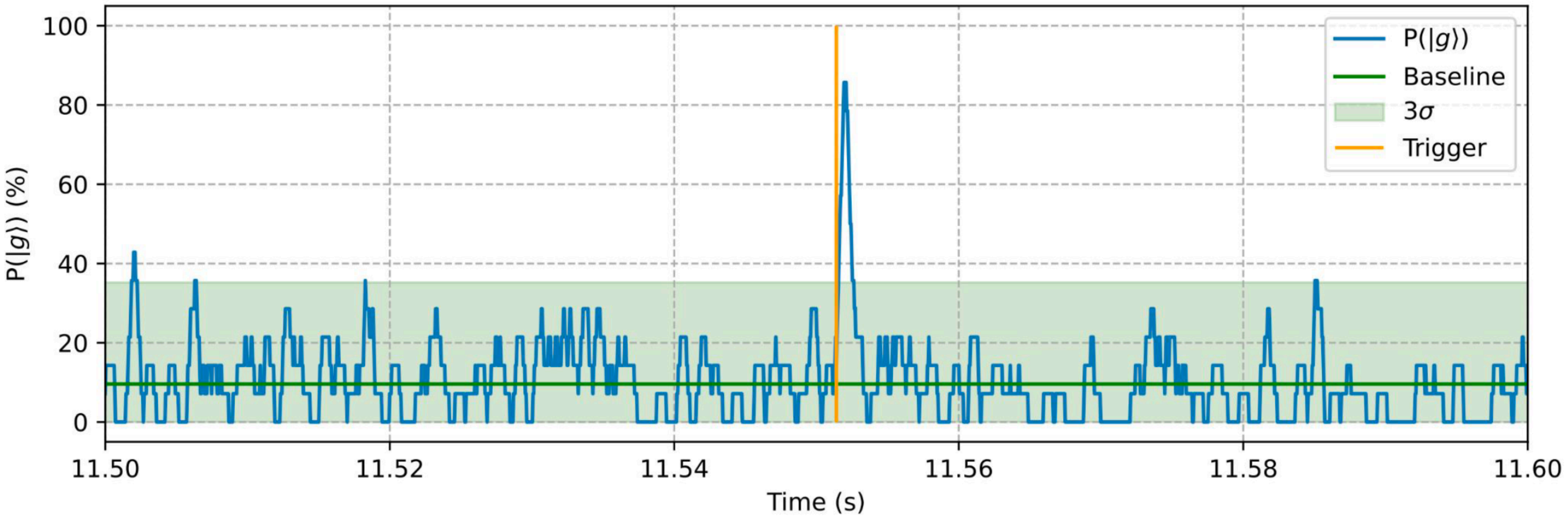


Current work

SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

- Now ongoing the characterization of a new transmon qubit with improved energy-relaxation time, reaching hundreds of μs [Bal et al., arXiv:2304.13257 (2023)];
- New measurements strategies proposed;
- Measurement and analysis of correlated errors, where stronger effect of radioactivity is expected.



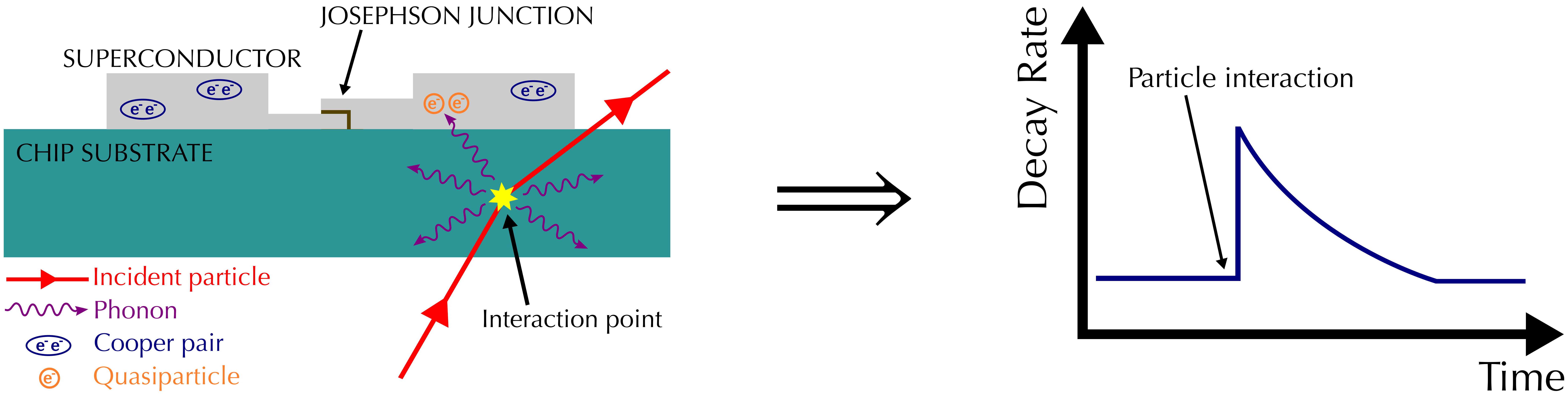


Aim of my research

- Prove that radioactivity is not the main limit to the performance of state-of-the-art qubits; ✓
- Characterization of correlated errors induced by particle impacts in qubit chip substrates; **[*Ongoing*]**
- Applications of superconducting qubits in particle physics experiments.

Prospects

- In the next months study of the possibility to use superconducting qubits as particle detectors;
- First step will be the measure of the qubit response to monochromatic sources (in preparation now).



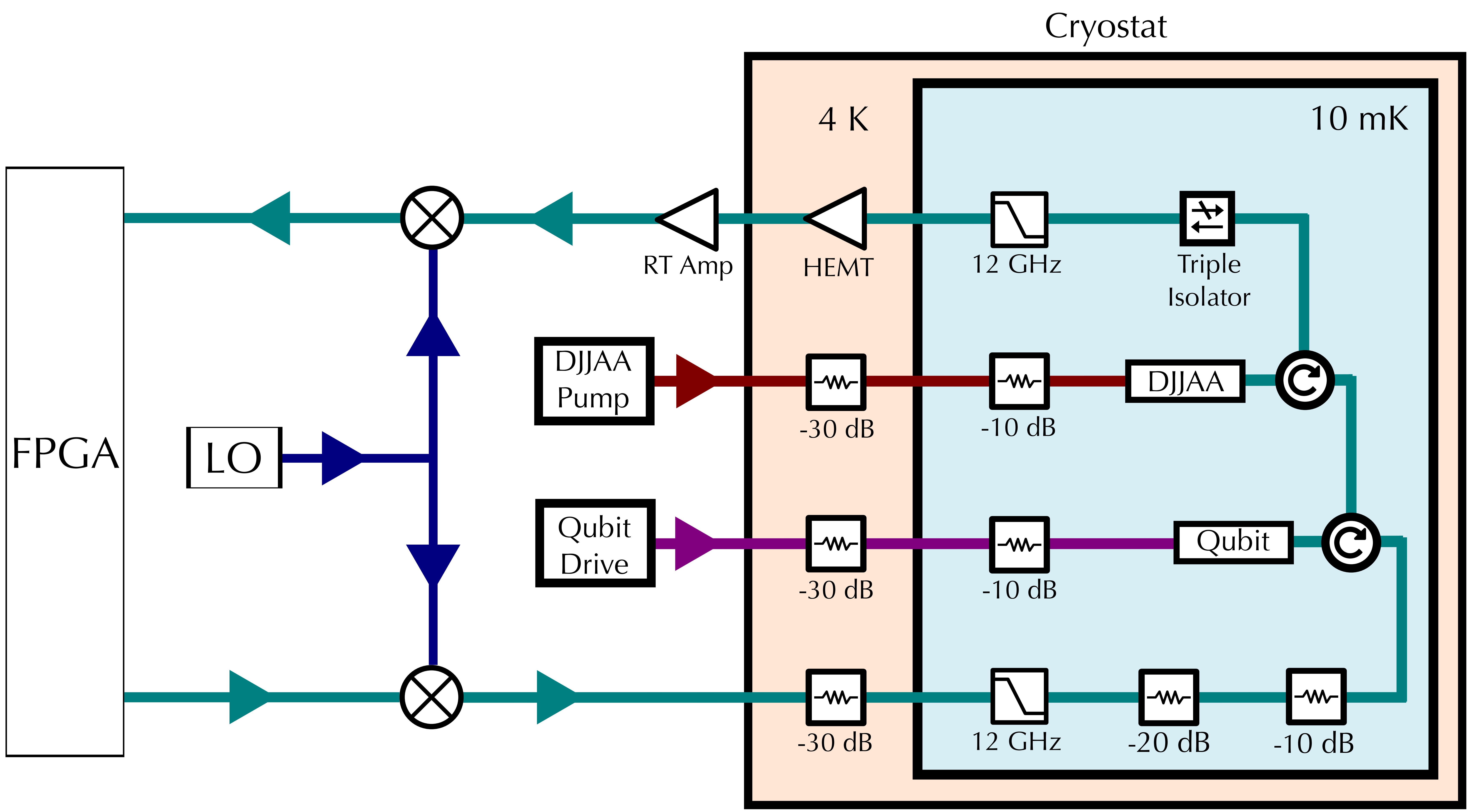
Aim of my research

- Prove that radioactivity is not the main limit to the performance of state-of-the-art qubits; ✓
- Characterization of correlated errors induced by particle impacts in qubit chip substrates; **[*Ongoing*]**
- Applications of superconducting qubits in particle physics experiments. **[*Long Term*]**

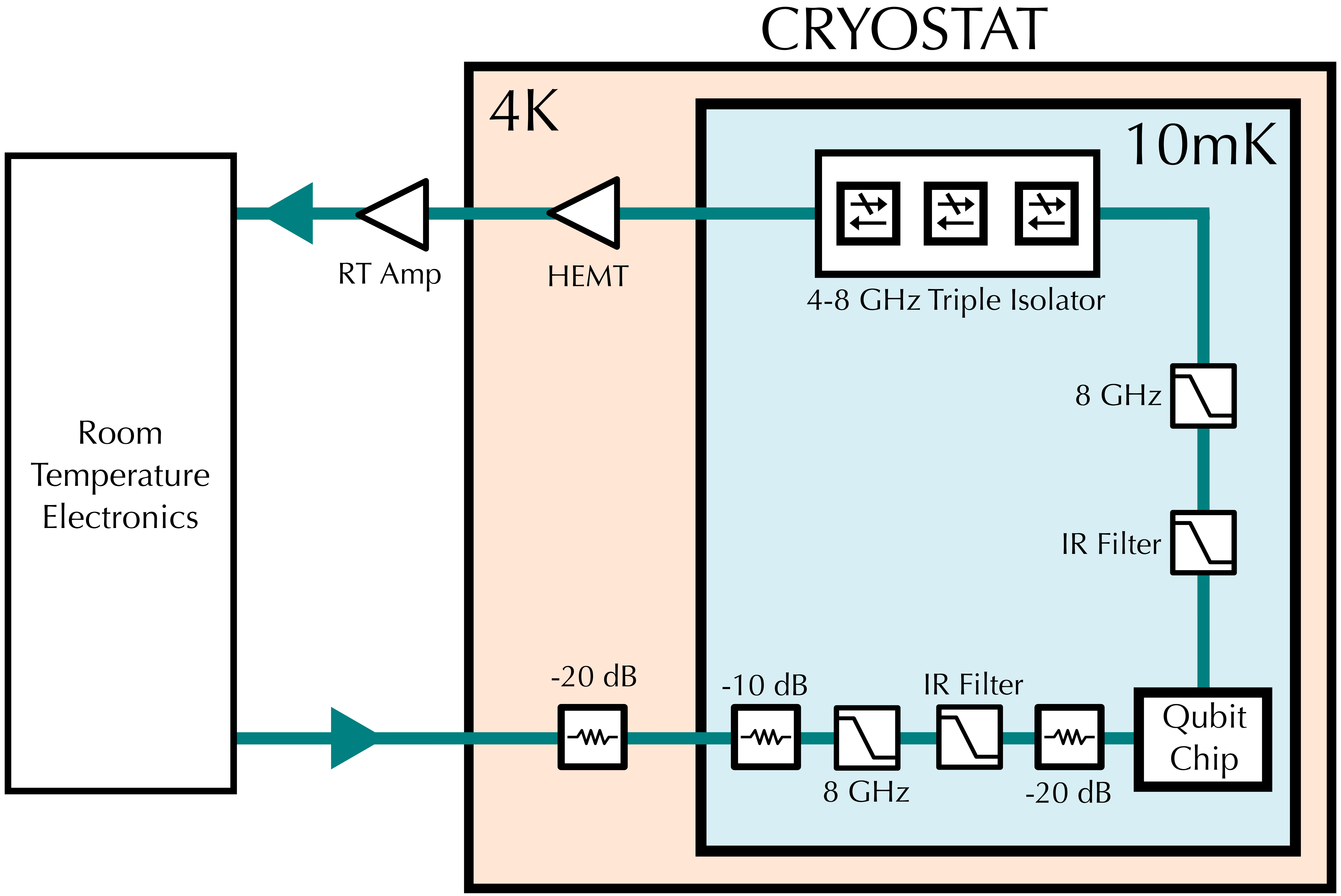
Conclusions

- I developed a Monte Carlo simulation to understand which sources of radioactivity are most concerning for superconducting qubits;
- I was involved in the commissioning of a fully operational underground facility for superconducting qubit experiments in a low radioactivity environment;
- Measurements done during this year proved that radioactivity does not have a direct influence on qubits with energy-relaxation time of tens of μs;
- New experiments with better performing devices and new measurement strategies going on now!

Backup: the Fluxonium setup

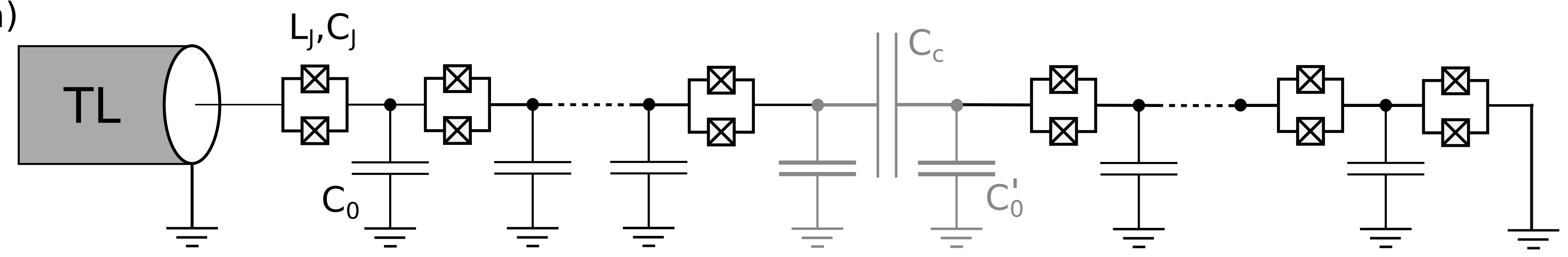


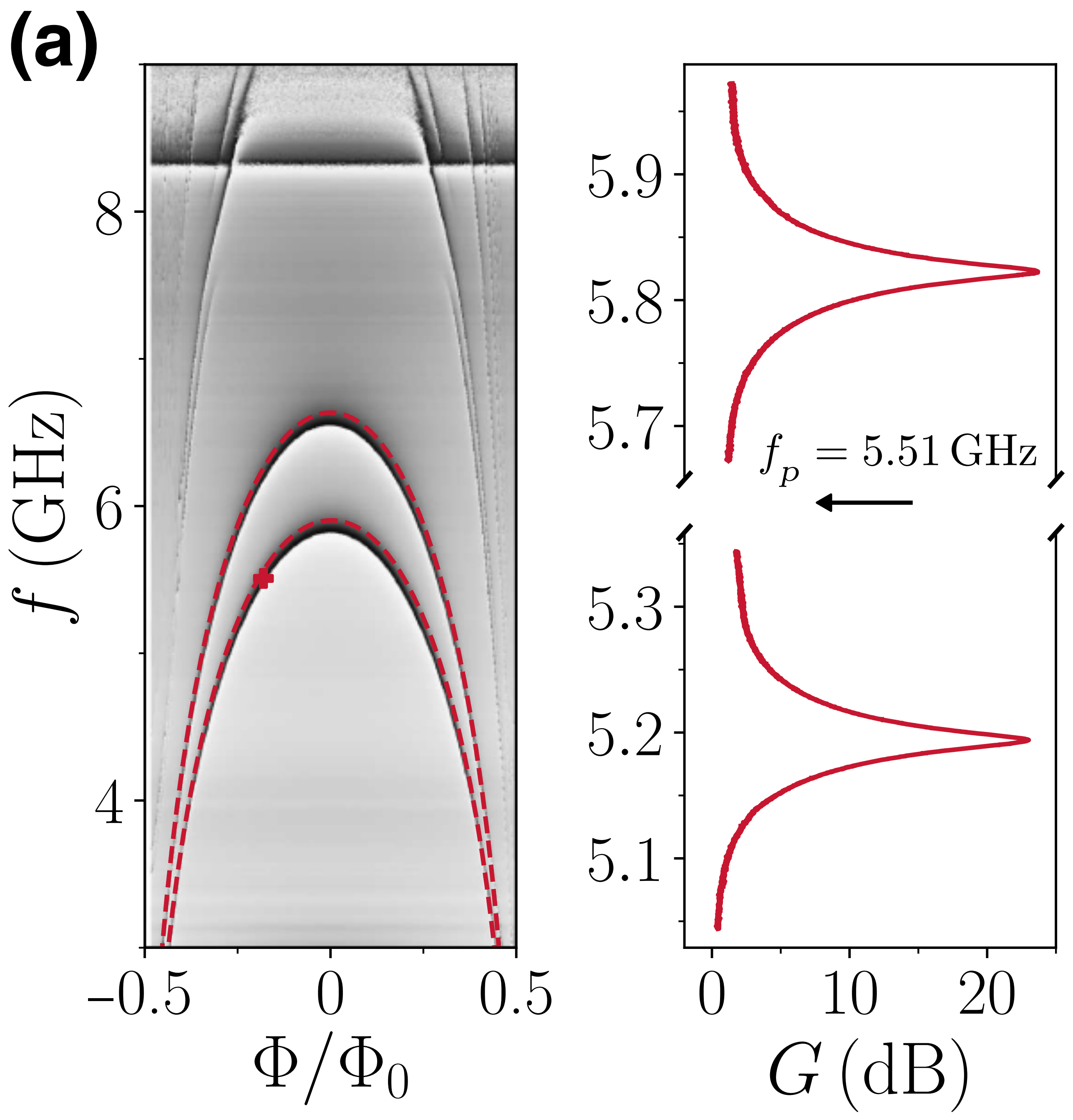
Backup: the Transmon setup



Backup: The DJJAA

(a)

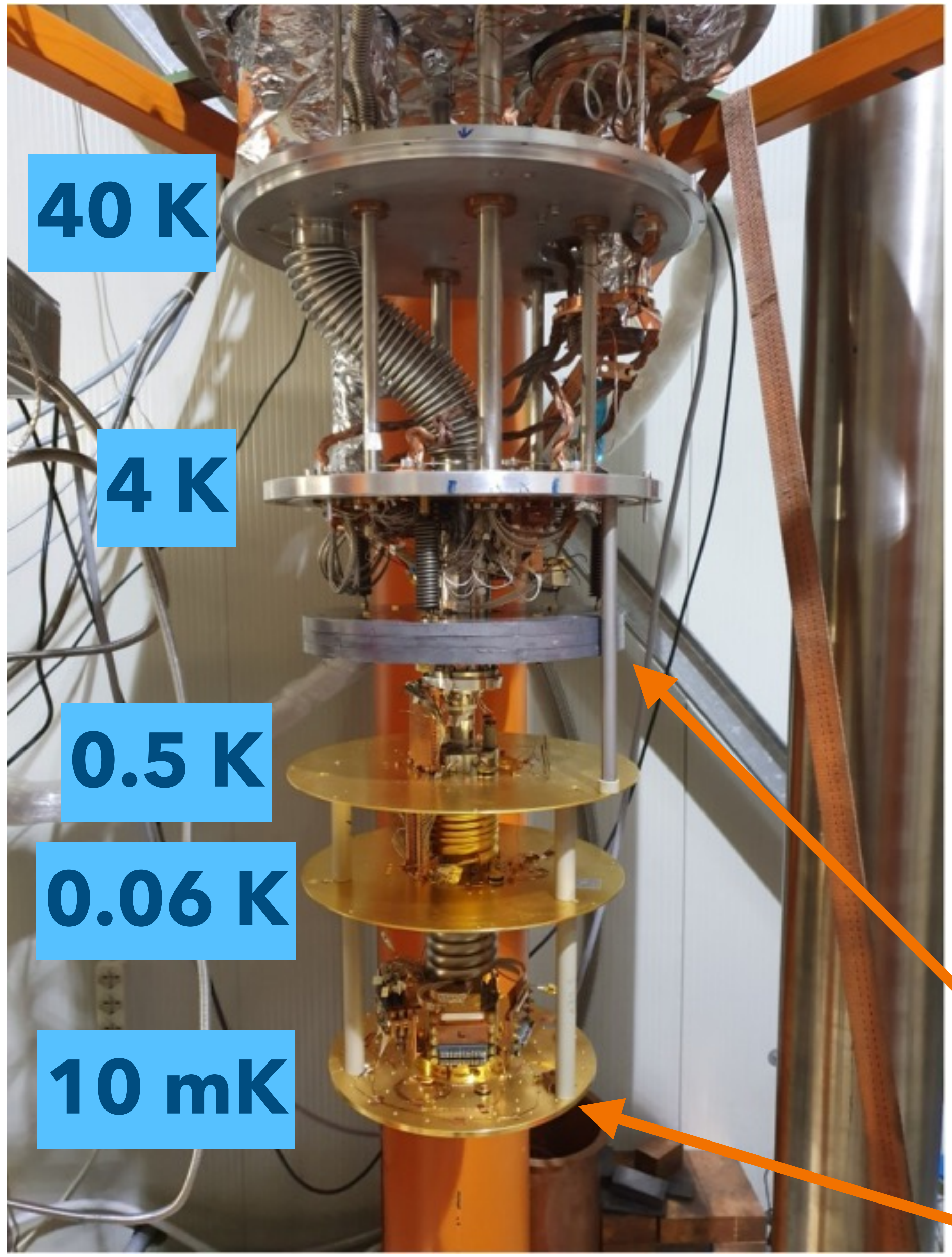




Winkel et al., *Phys. Rev. Applied* **13**, 024015 (2020)

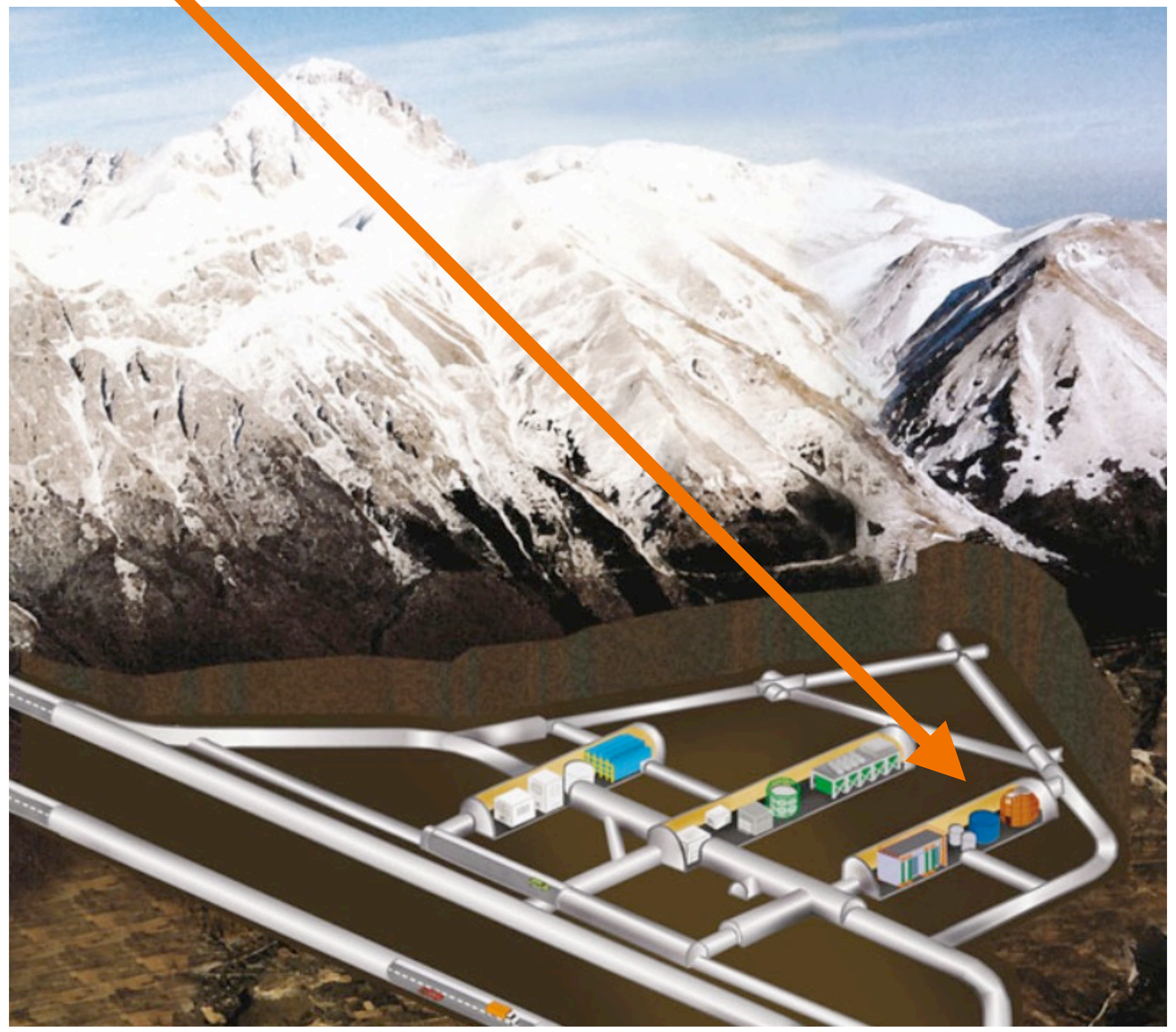
- Parametric amplifier developed at the Karlsruhe Institute of Technology;
- Made by hundreds of Josephson Junctions;
- Flux-tunable resonance frequency;
- Amplifier allows to send less photons to the resonator to read the qubit state, resulting in:
    - Shorter readout time;
    - Lower power of the readout signal.

Backup: the IETI Underground Facility



- Hall C of LNGS Underground Laboratories;
- Pulse Tube based $^3He/^4He$ dilution refrigerator;
- Pulse Tube decoupling plus custom made 3 stage mechanical decoupling system between cold plates and detectors;
- 3 cm internal lead at 4K + additional 3 cm lead at 10 mK;

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



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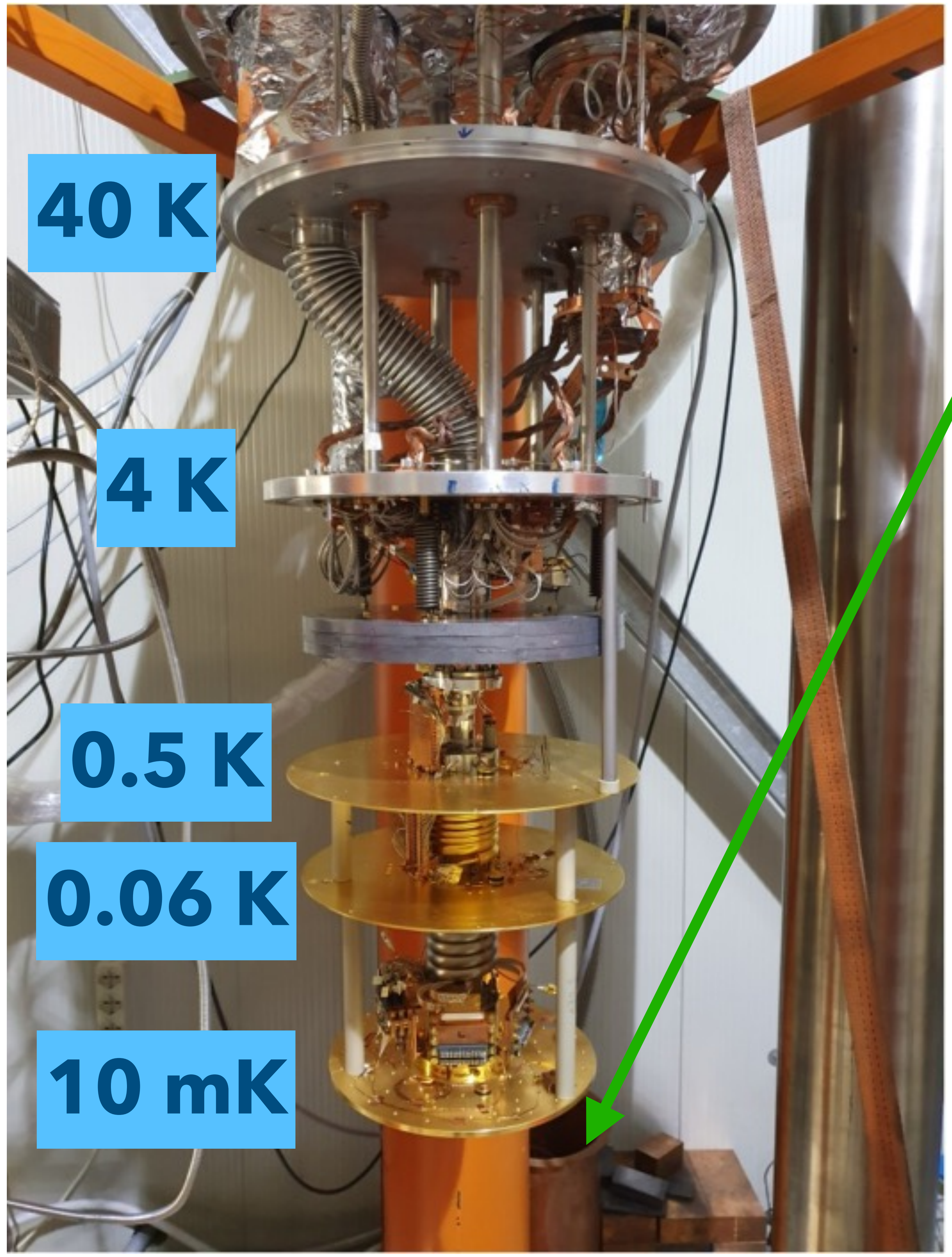

https://ieti.sites.lngs.infn.it/index.html

- 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.