

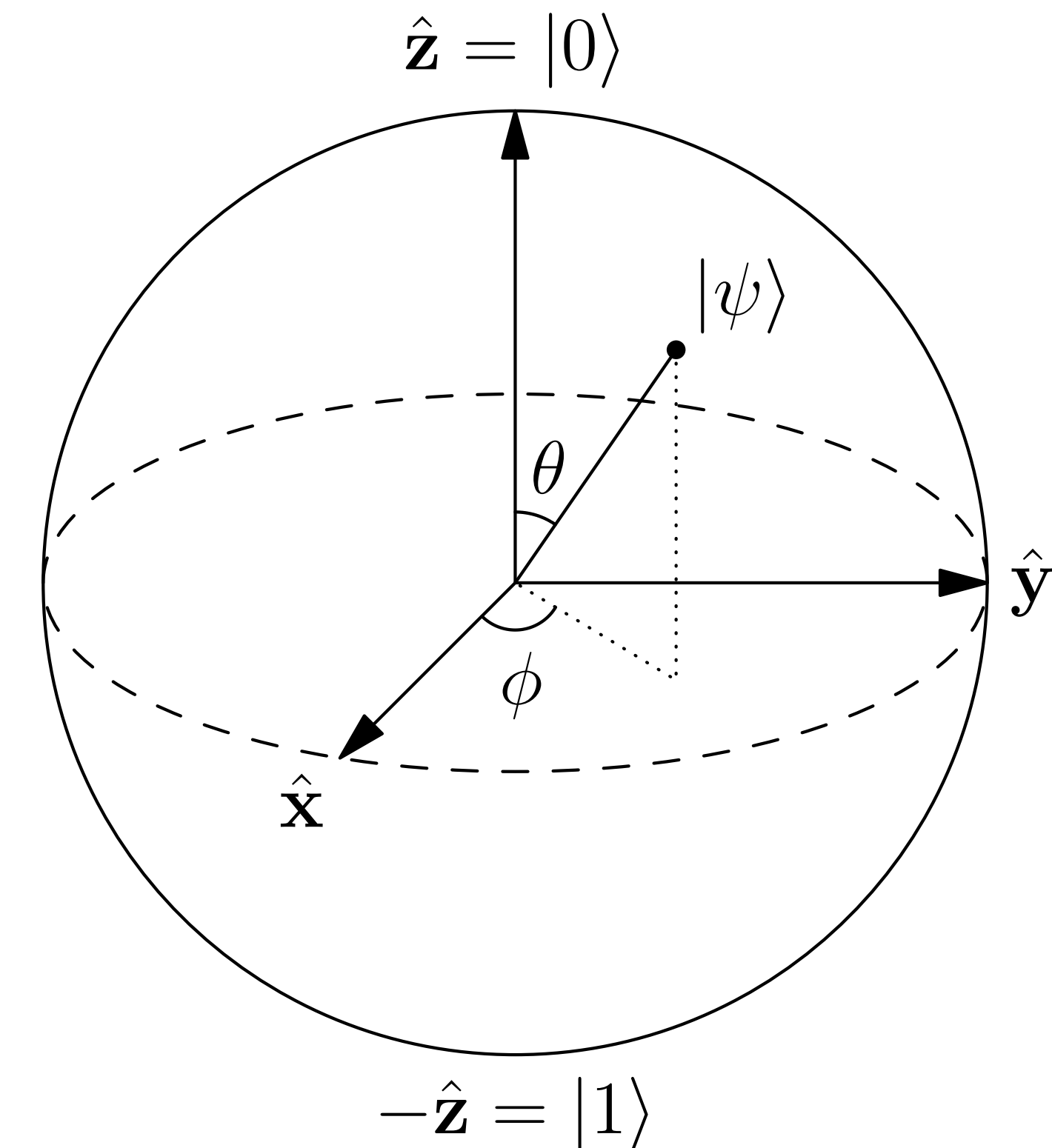
Measurement of a superconducting qubit in a deep underground laboratory

Francesco De Dominicis, Laura Cardani, Nicola Casali, Ivan Colantoni, Angelo Cruciani, Nicolas Gosling, Ambra Mariani, Stefano Pirro, Ioan M. Pop, Martin Spiecker and Nicolas Zapata



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;

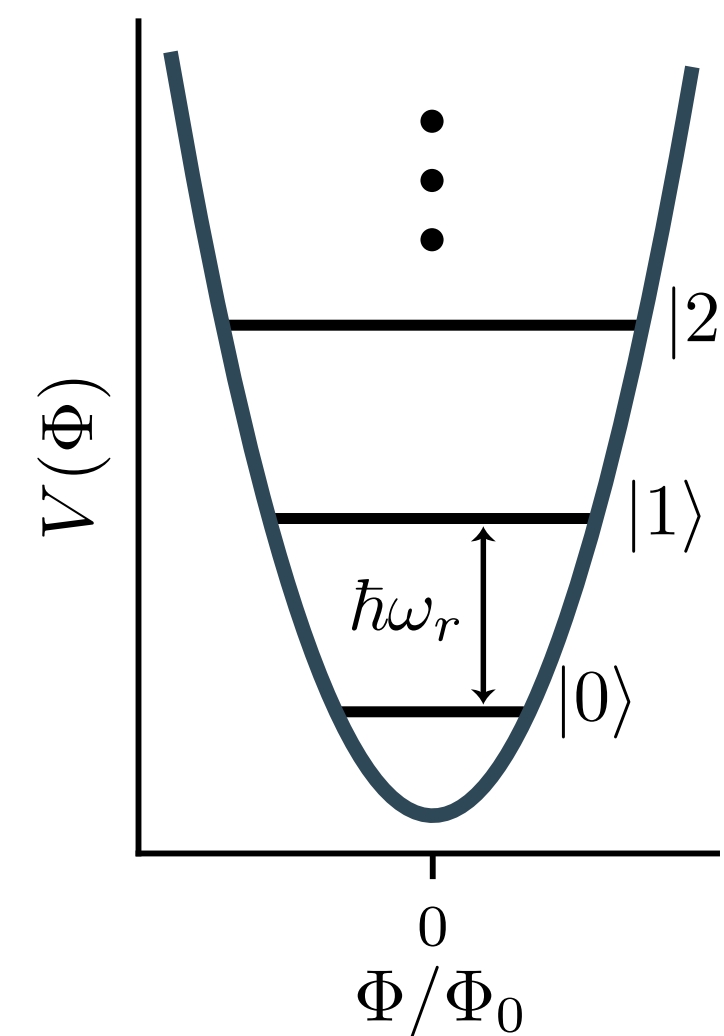
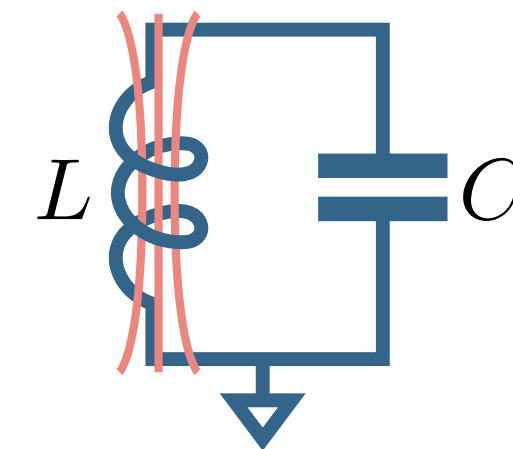


$$|\psi\rangle = \cos \frac{\theta}{2} |0\rangle + e^{i\phi} \sin \frac{\theta}{2} |1\rangle$$

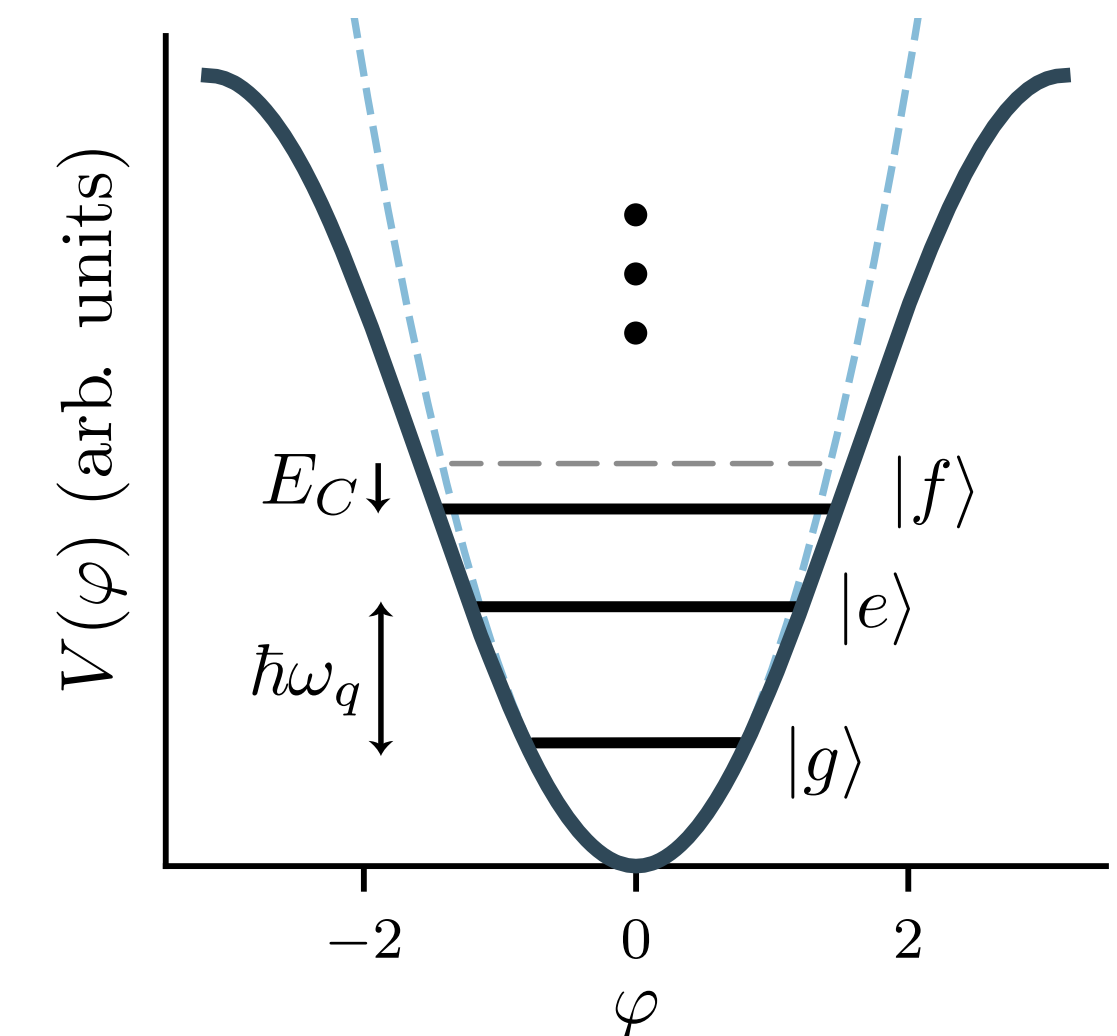
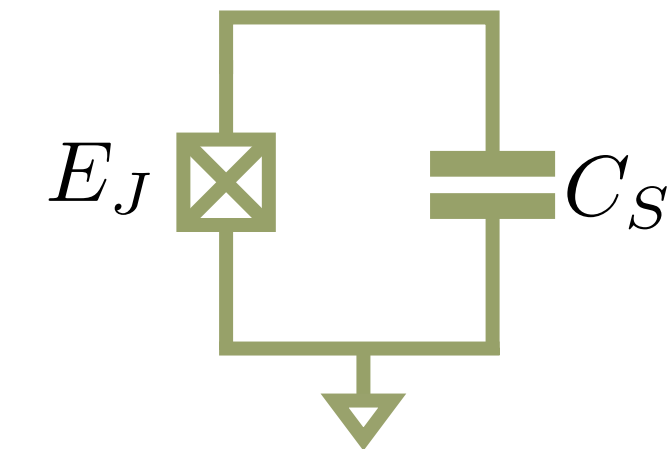
Superconducting qubits

- 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.

RESONATOR



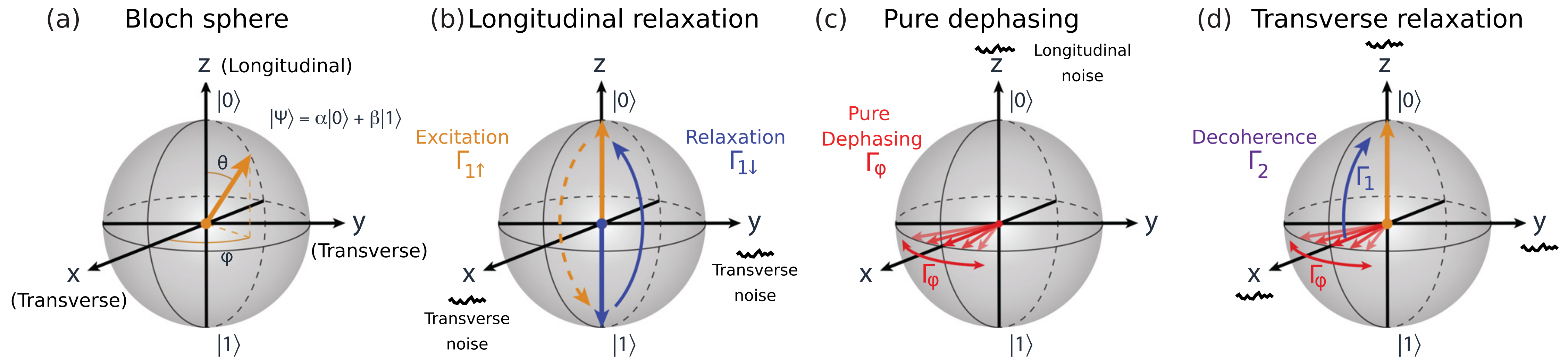
QUBIT



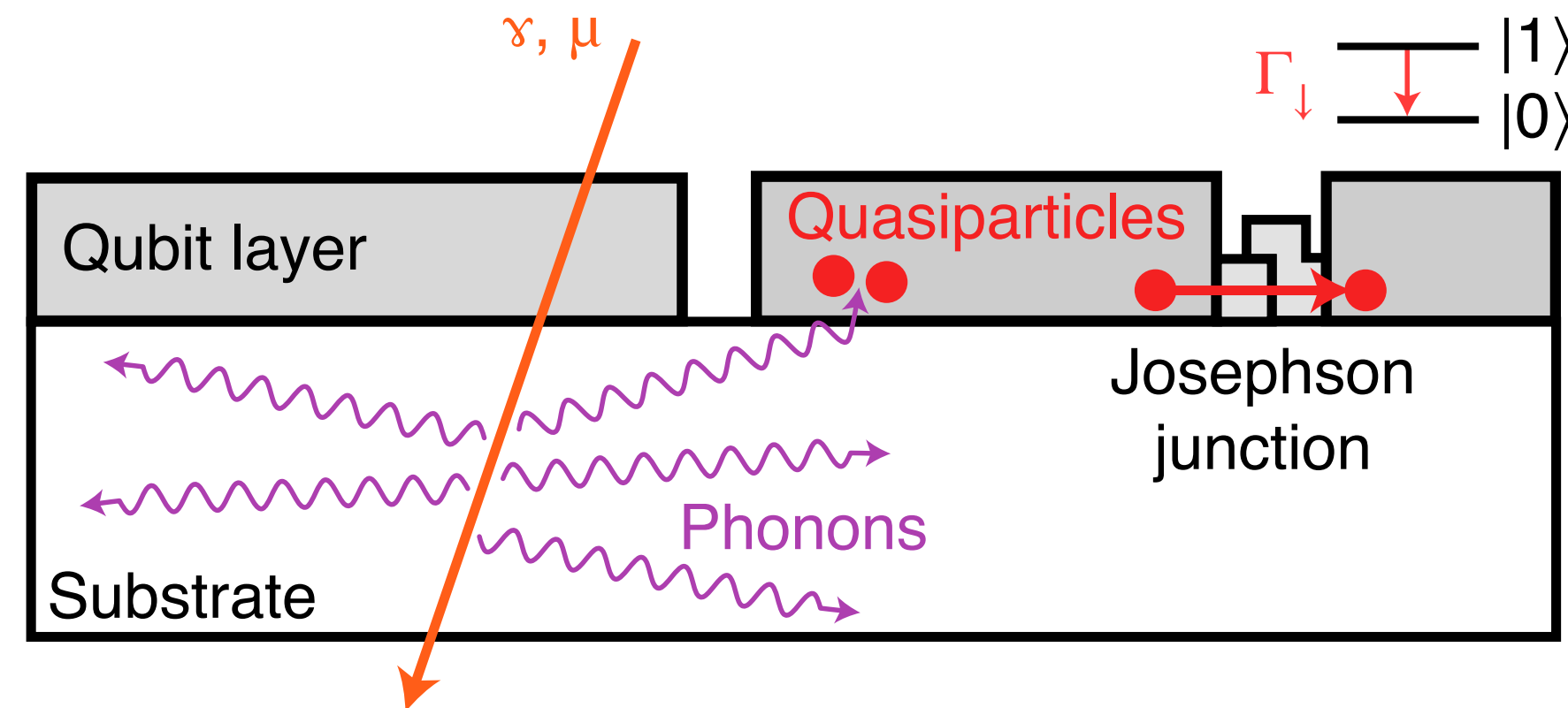
Blais et al., *Rev. Mod. Phys.* **93**, 025005 (2021)

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**;



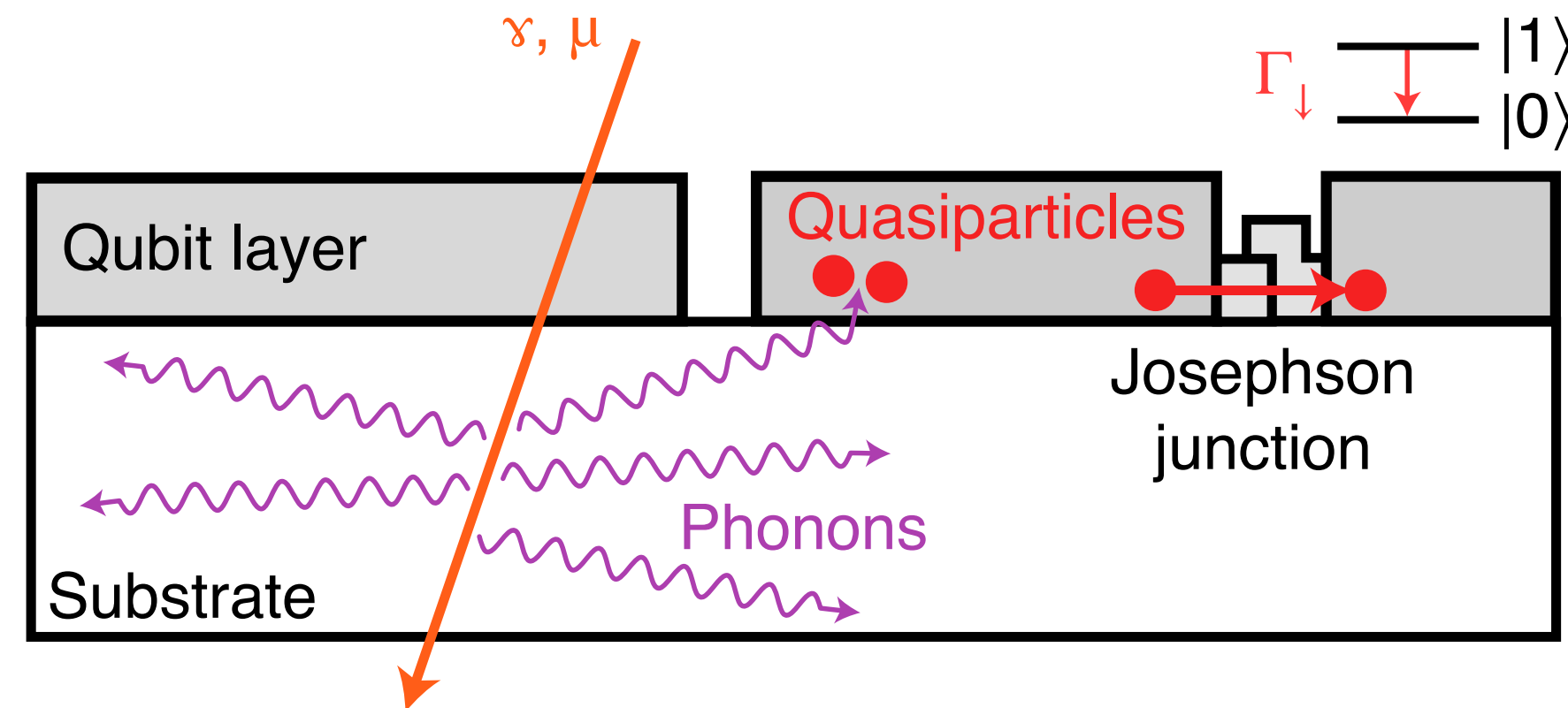
Qubits and radioactivity



McEwen et al., *Nat. Phys.* **18**, 107-111 (2022)

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

Recent results



McEwen et al., *Nat. Phys.* **18**, 107-111 (2022)

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

Radioactive sources

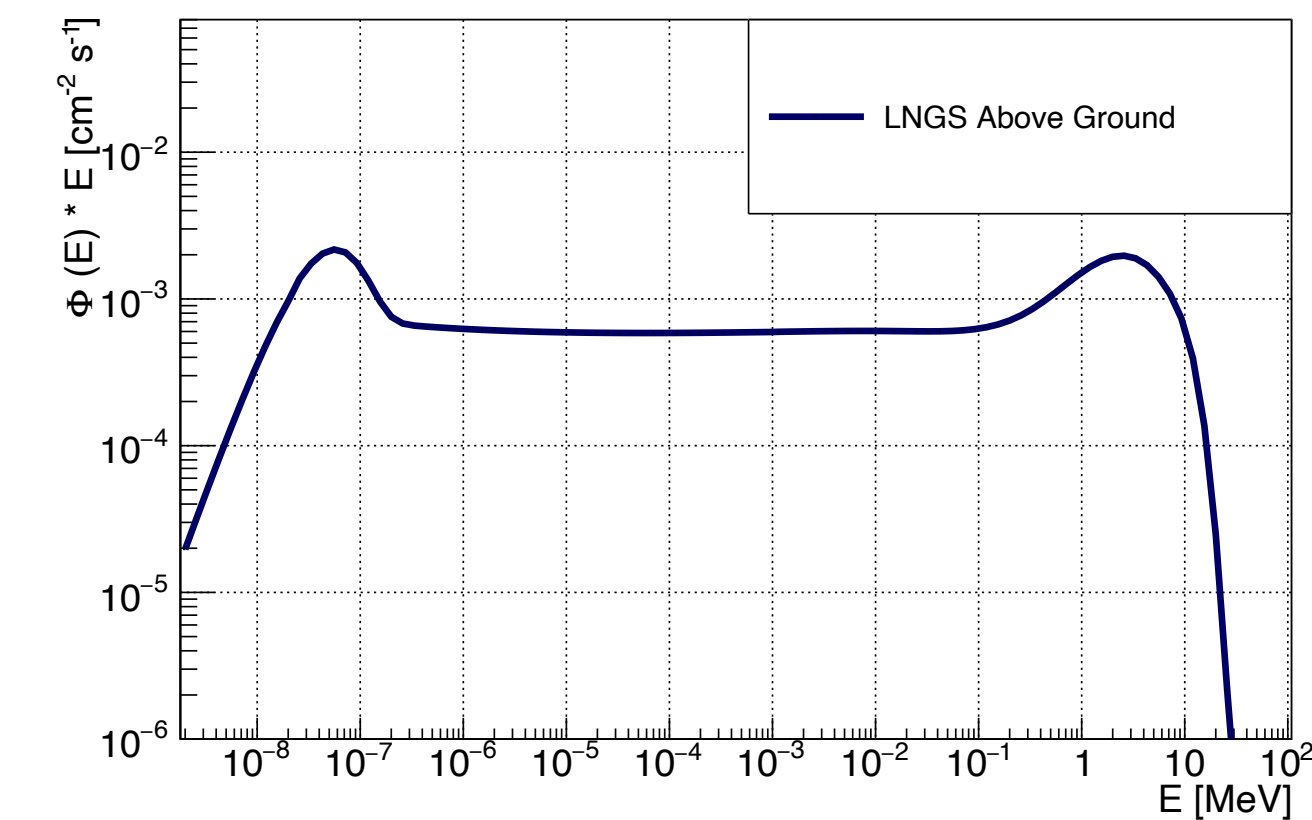
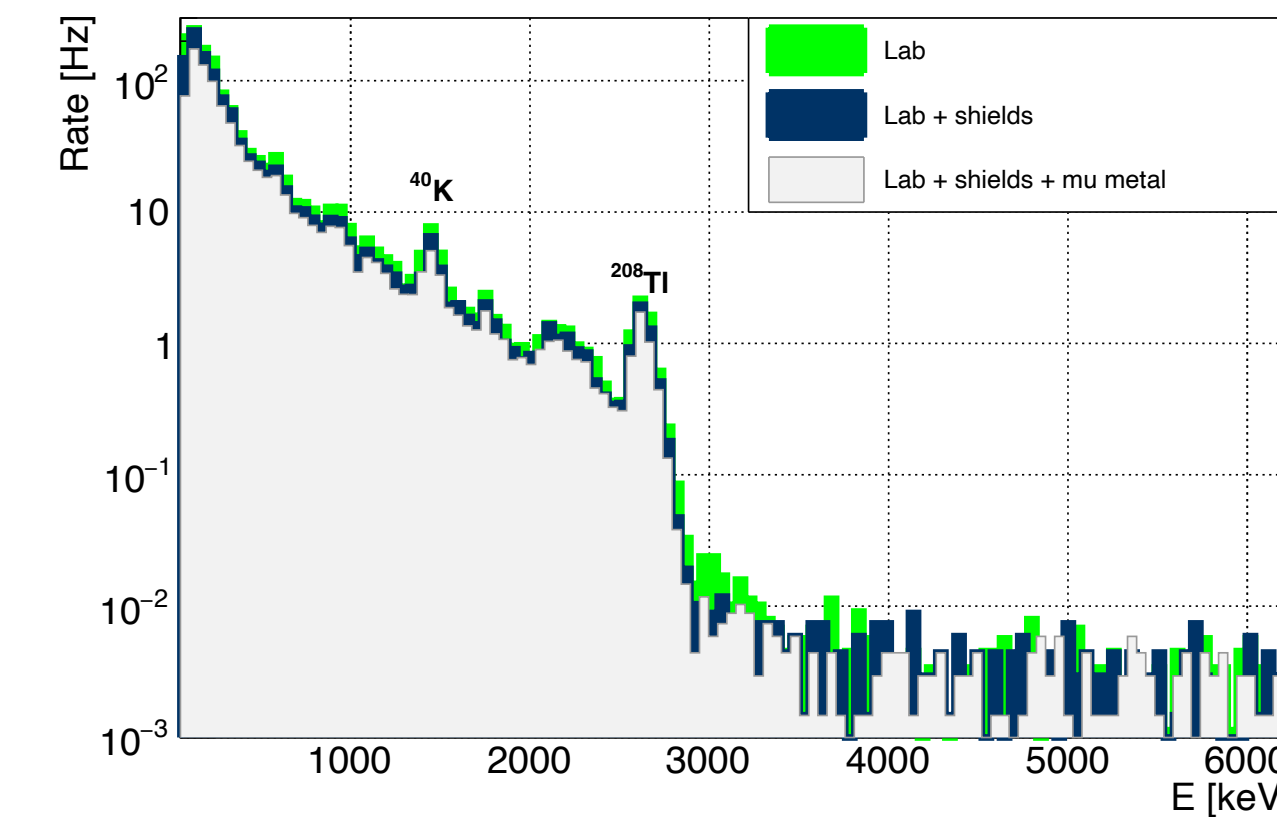
- Two categories of radioactive sources:

- **Far sources**

- Environmental gammas (measured);
- Cosmic muons (literature);
- Neutrons (measured);

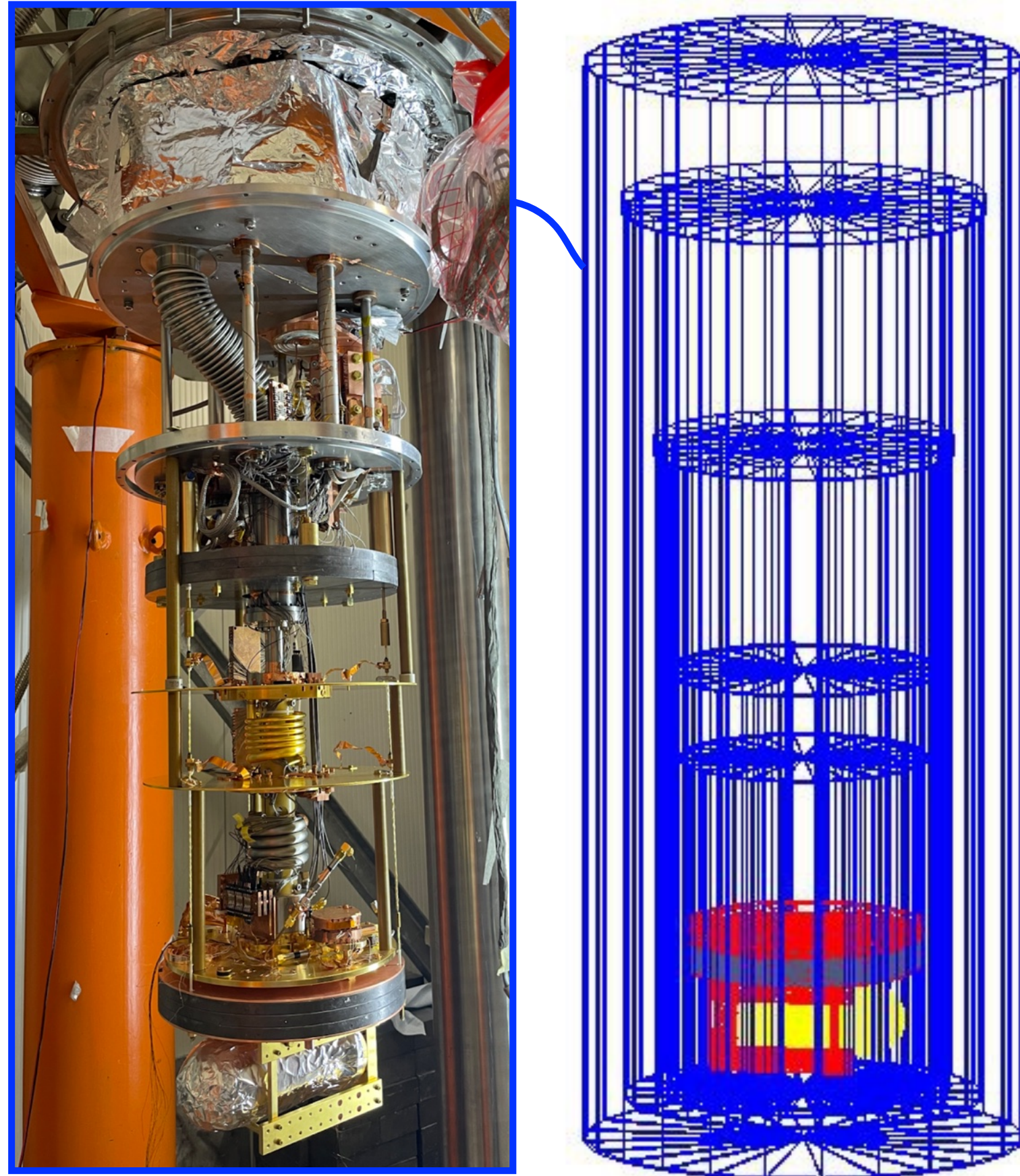
- **Close sources**

- Contaminations (measured).



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

Simulations



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

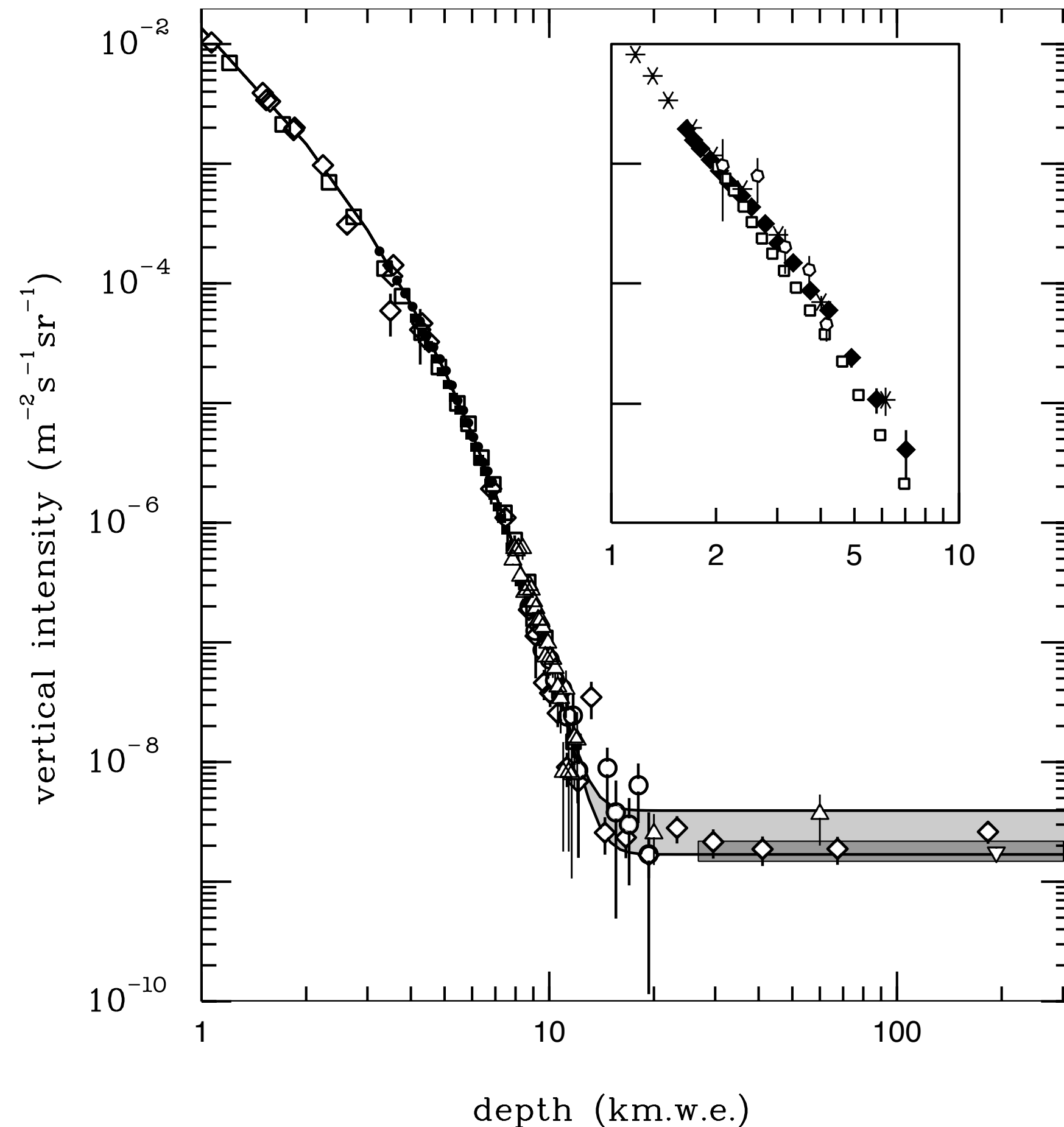
- Experimental setup reconstructed in a Geant4 simulation;
- For the far sources we generated particles around the cryostat with the given energy and angular distributions;
- For close sources we simulated radioactive decays in the setup components;
- Contributions estimated from the fraction of simulated events with interactions in the chip.

- Greatest contributions in a “standard” laboratory from far sources;
- Contributions from close sources depending on the materials used to make the chip and the other elements of the setup;

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

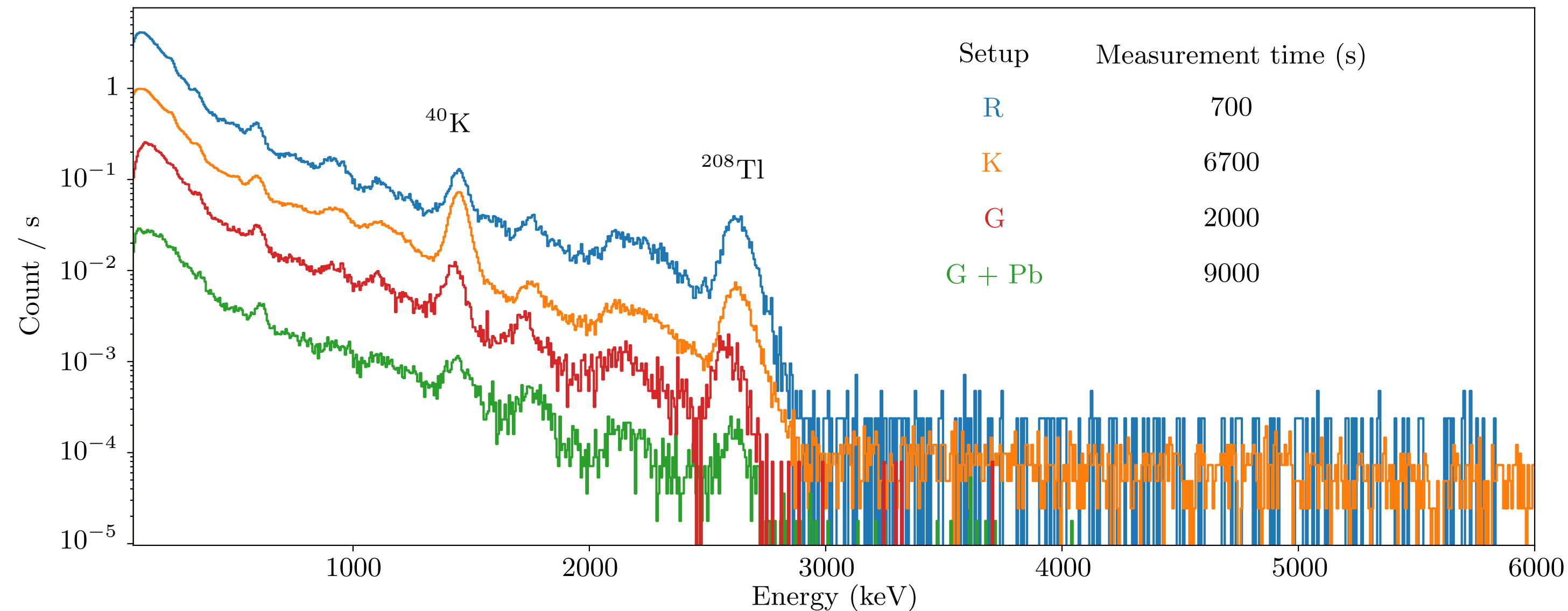


- Mitigation strategies developed for particle physics experiments can also be used in qubit experiments;
- Contribution from cosmic muons can be abated by moving the experiment to an underground laboratory;
- In the LNGS underground laboratories the muon interaction rate is attenuated by a factor 10^6 ;

Workman et al., *Prog. Theor. Exp. Phys.* **2022**, 083C01 (2022)

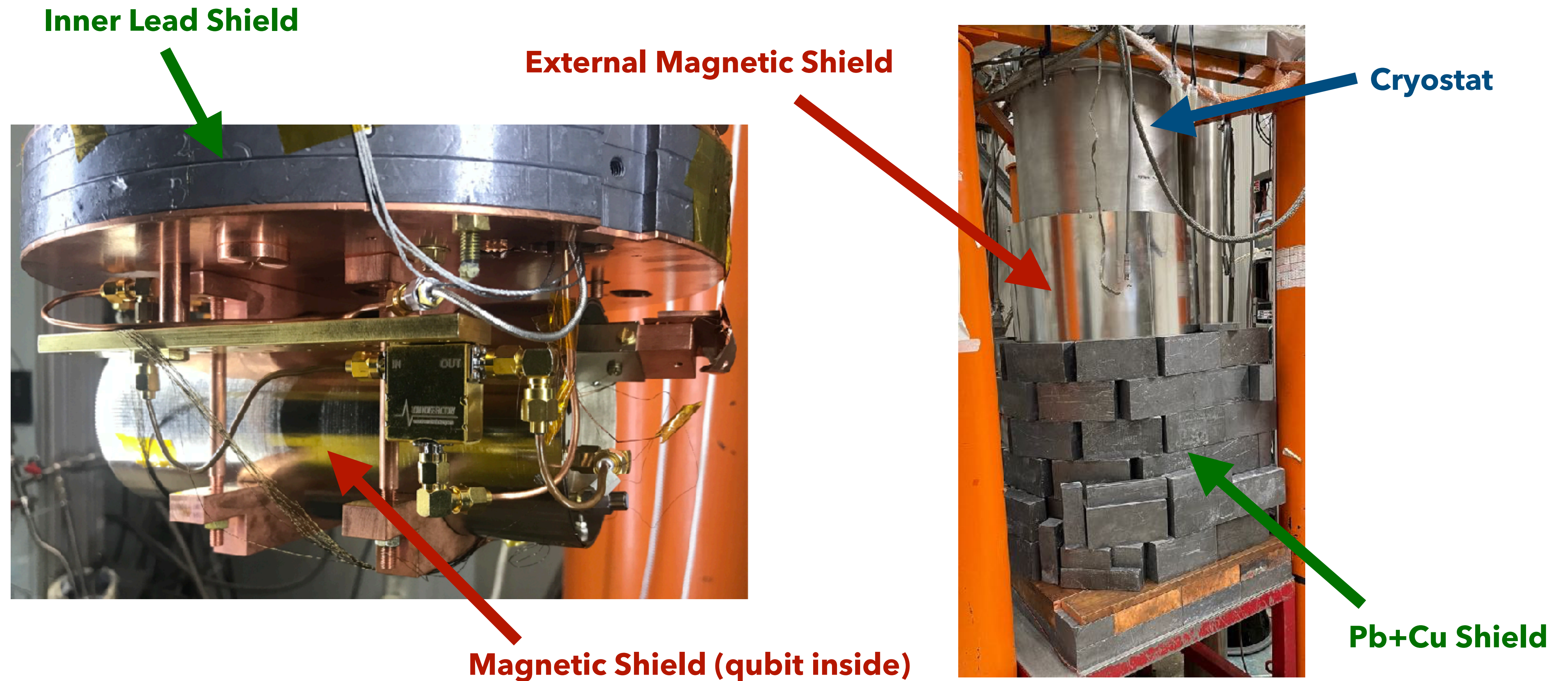
Going underground

- The LNGS underground laboratories also have a lower gamma background compared to other above ground laboratories;
- Measurements with a NaI crystal showed that, by shielding the cryostat with 10 cm of lead, the gamma interaction rate is attenuated further by a factor 8.



Cardani et al., *Nat. Commun.* **12**, 2733 (2021)

Shielding

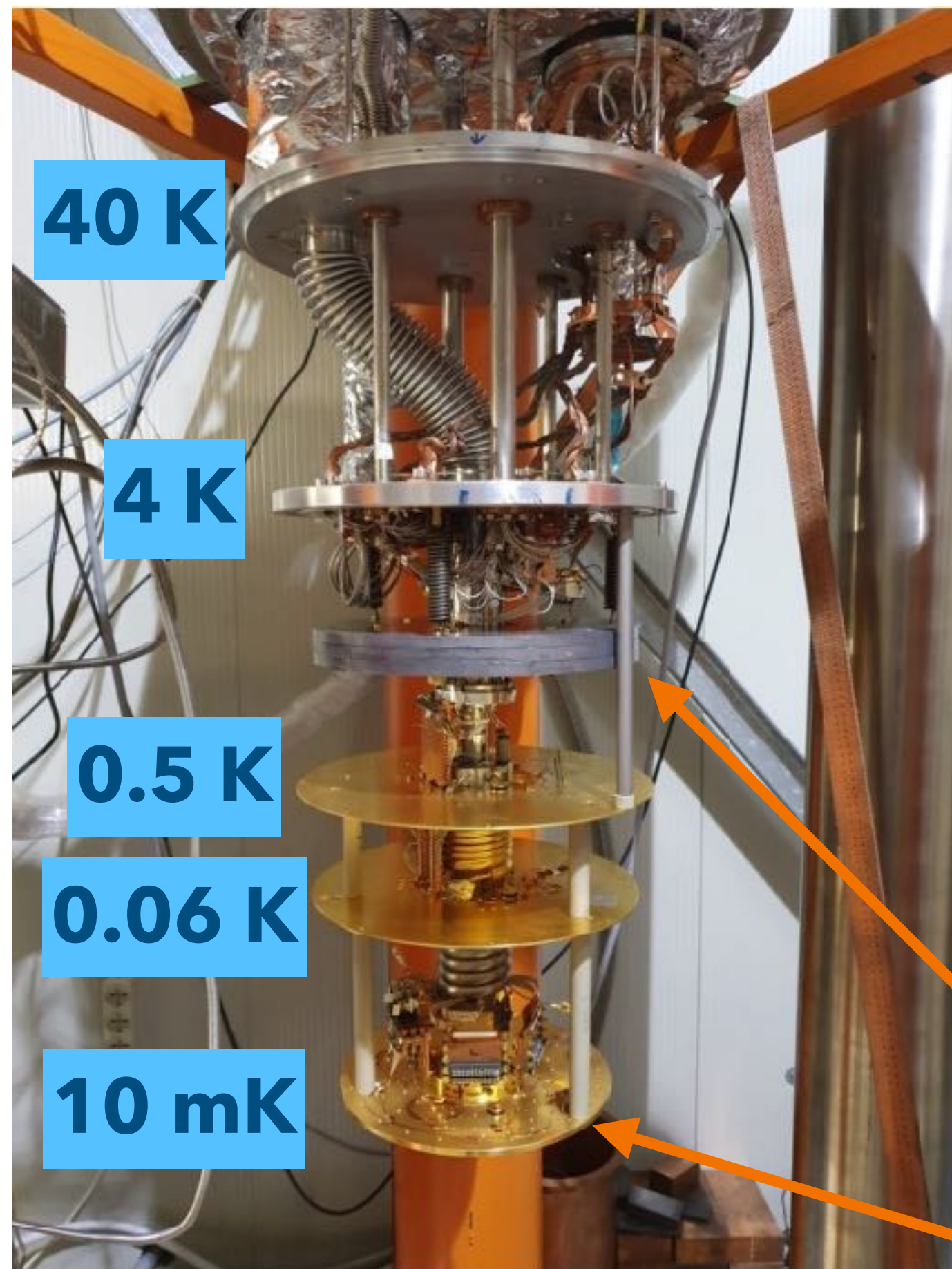


Expected contributions

- In our setup the total rate of interaction 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)	$< 10^{-4}$

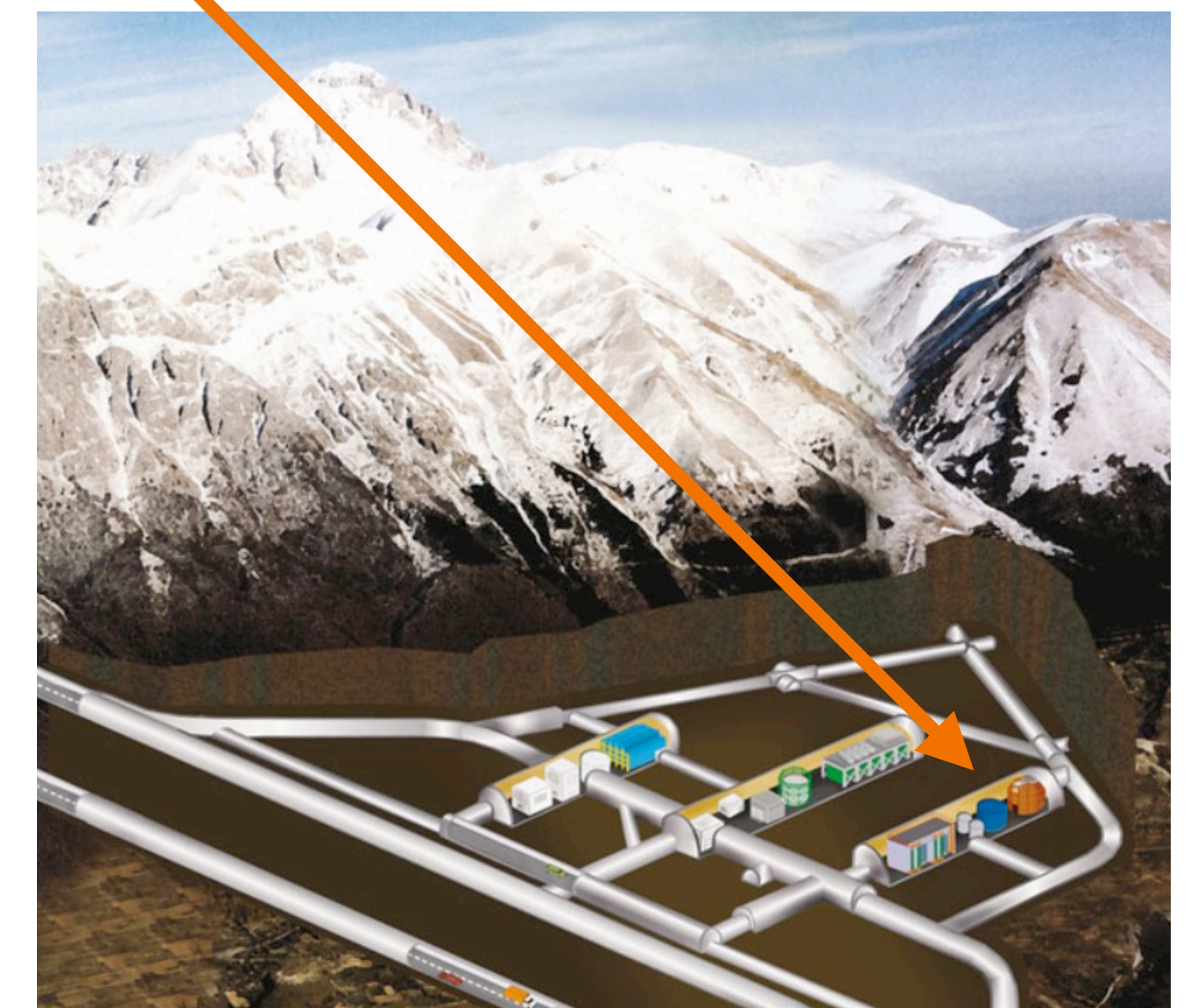
The IETI Underground Facility



- Hall C of LNGS Underground Laboratories;
- Pulse Tube based $^3\text{He}/^4\text{He}$ 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;

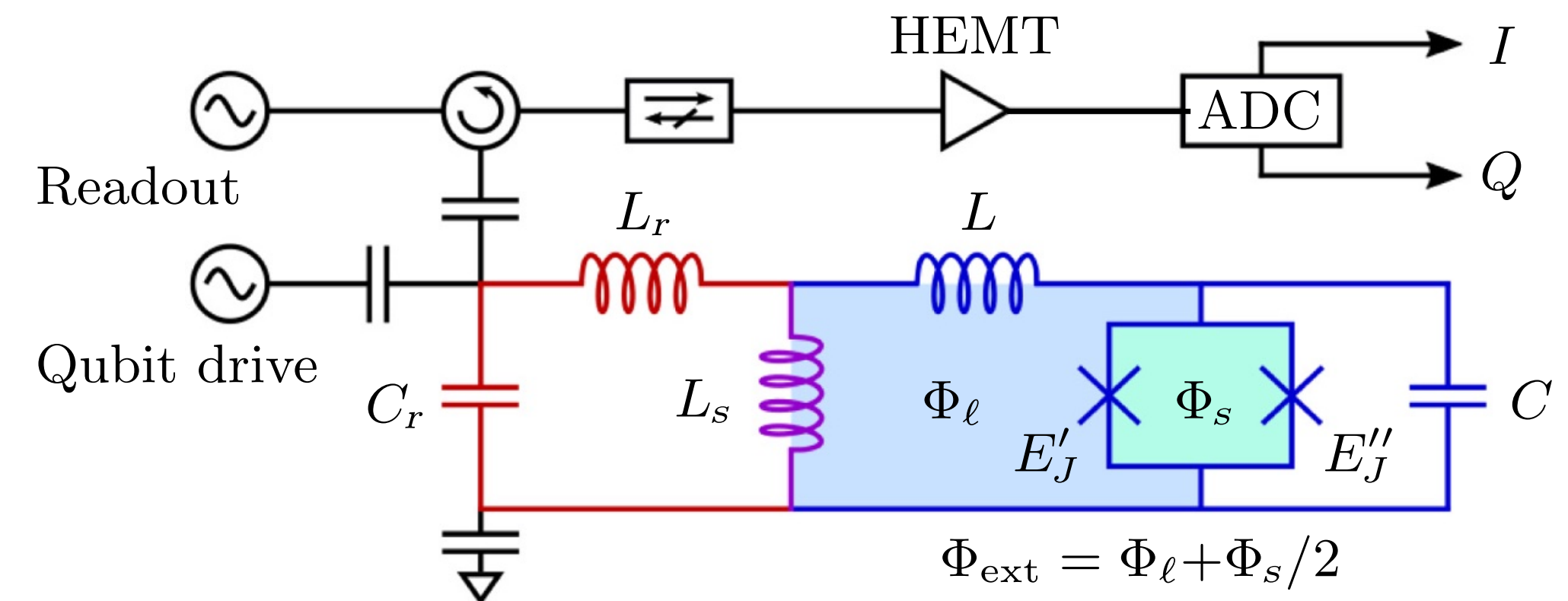


<https://ieti.sites.lngs.infn.it/index.html>



The fluxonium qubit

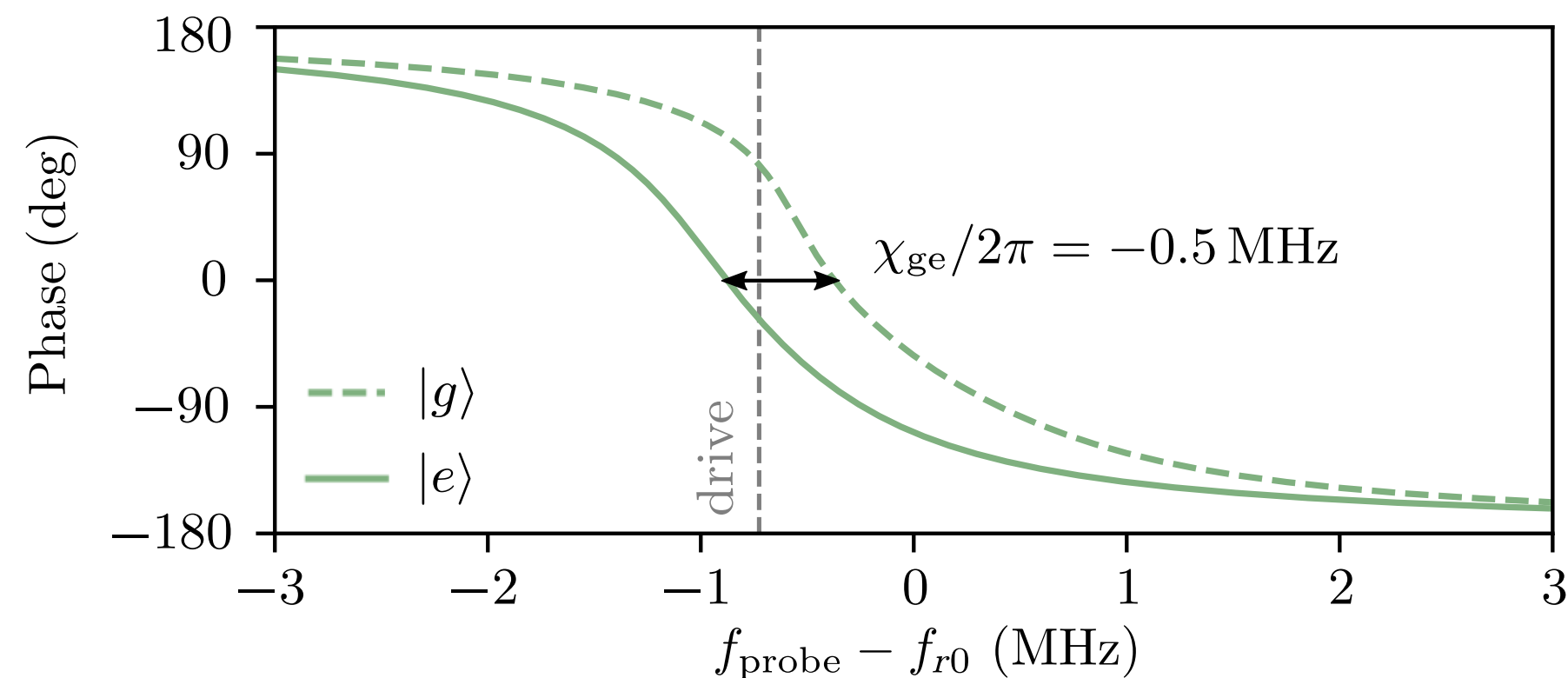
- Measurements in collaboration with the Karlsruhe Institute of Technology, that produced the qubit studied;
- *Fluxonium qubit*: superconducting ring interrupted by a Josephson Junctions and shunted by a large inductance;
- Two Josephson Junctions to make it flux-tunable;
- The qubit is coupled to a resonator for state readout;



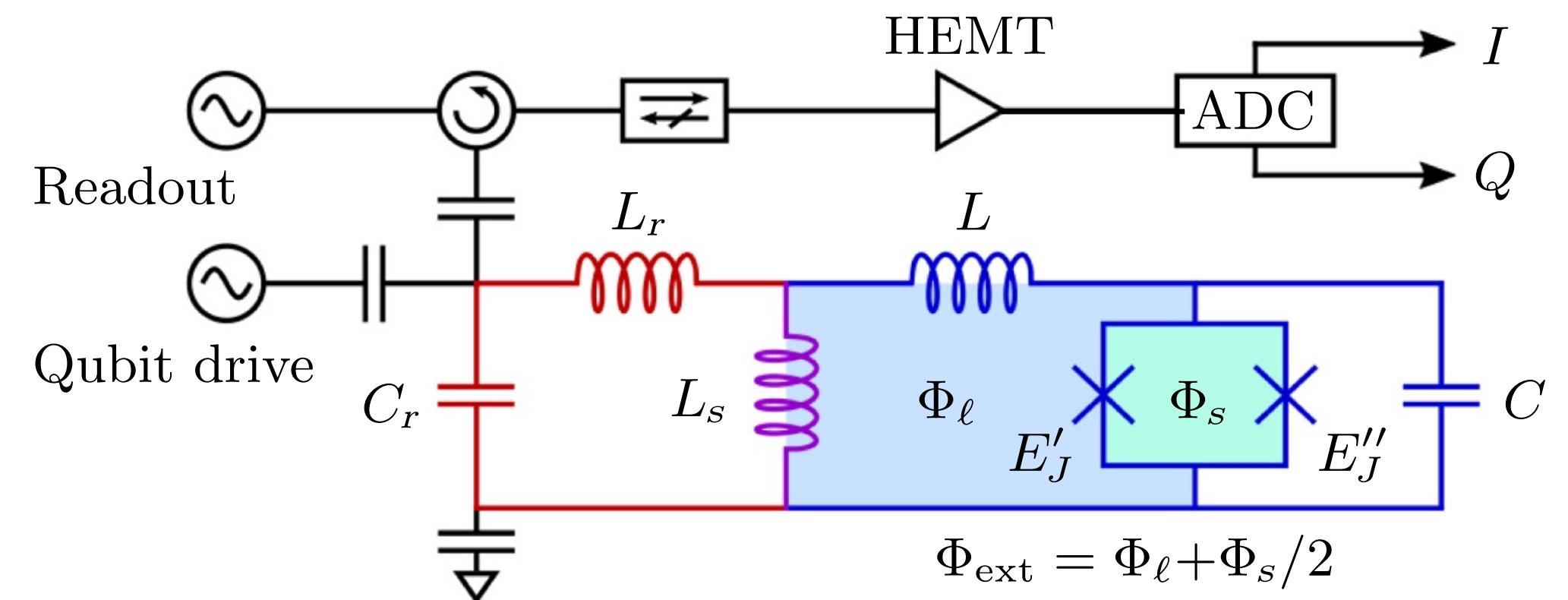
Gusenкова et al., *Phys. Rev. Applied* **15**, 064030 (2021)

State measurement

- 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.



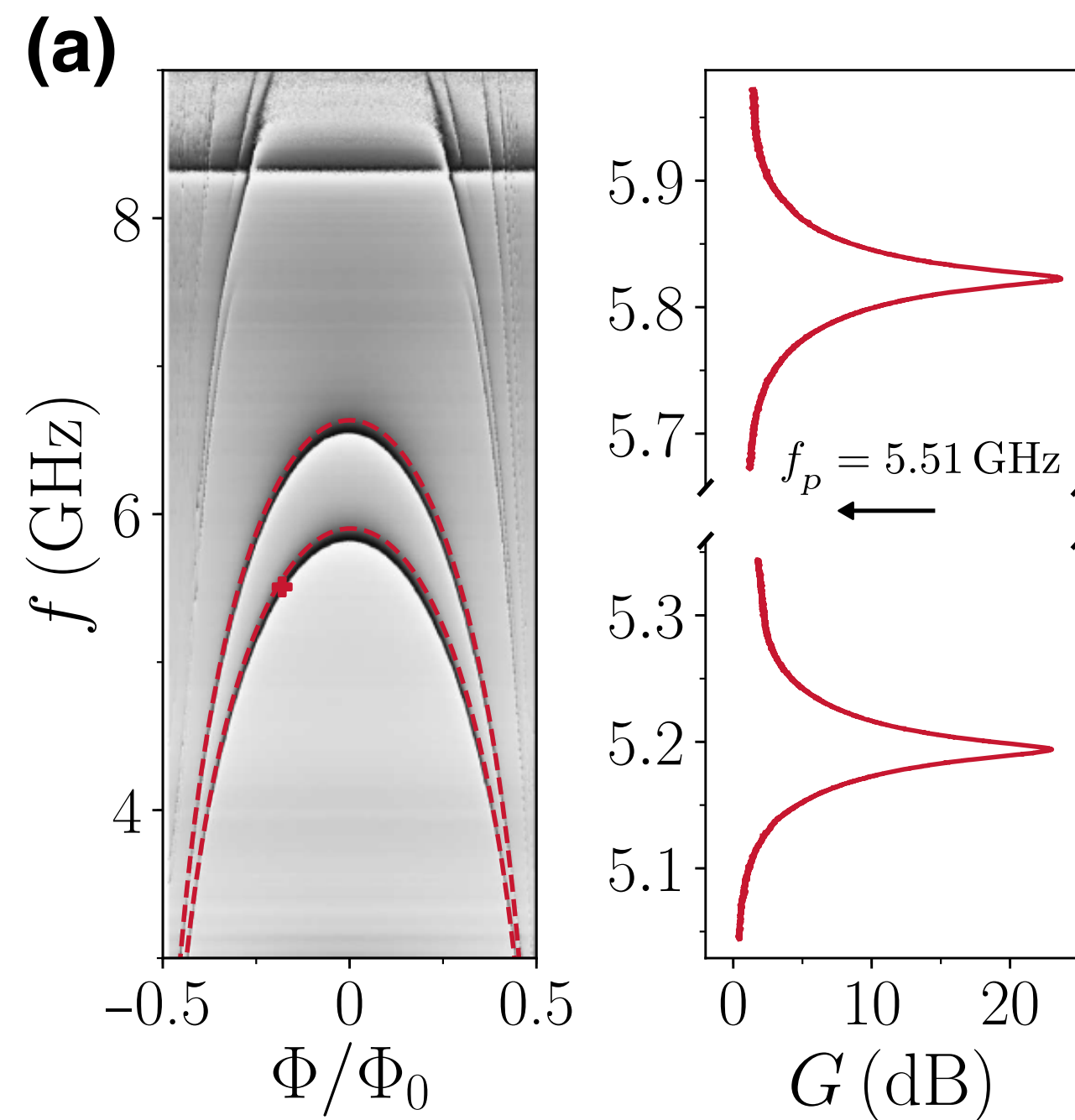
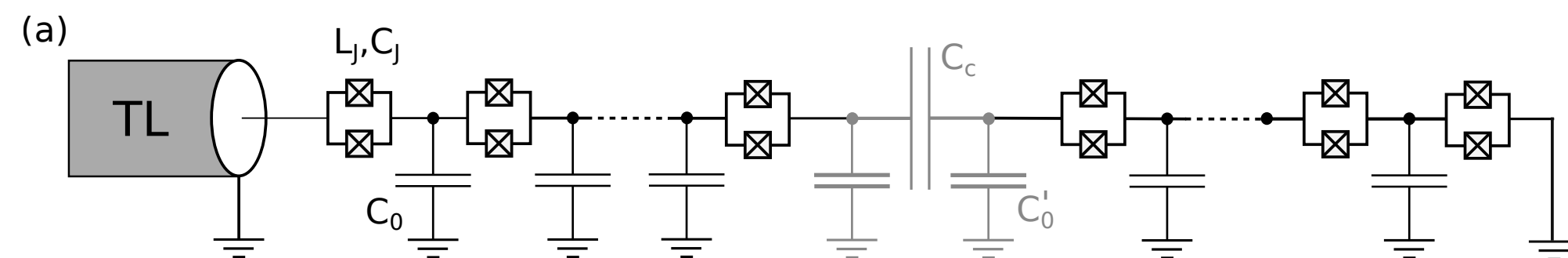
Gusenкова et al., *Phys. Rev. Applied* **15**, 064030 (2021)



Signal amplification

- Readout signals can induce state transitions in the qubit, reducing the measurement fidelity;
- Because of that, weak and short pulses are needed;
- The output signal, though, could be overwhelmed by noise when measured;
- A solution is using amplifiers with near-quantum-limited noise;

The DJJAA

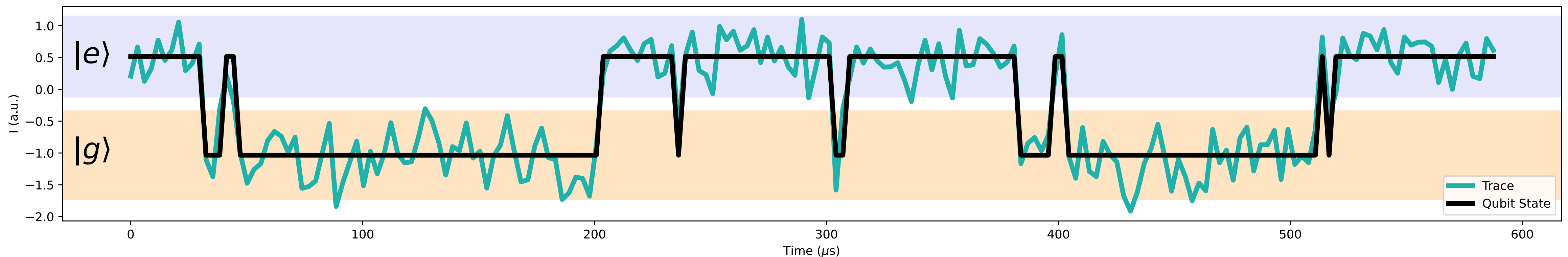


Winkel et al., *Phys. Rev. Applied* **13**, 024015 (2020)

- 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.

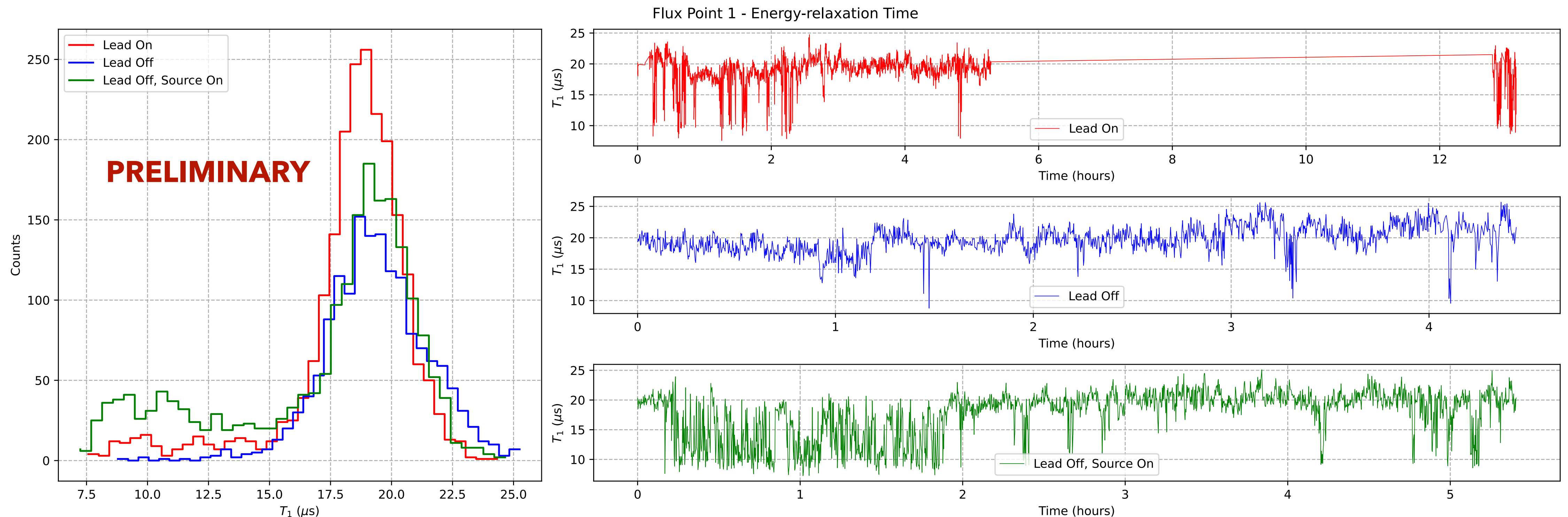
Measurement Strategy

- 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;



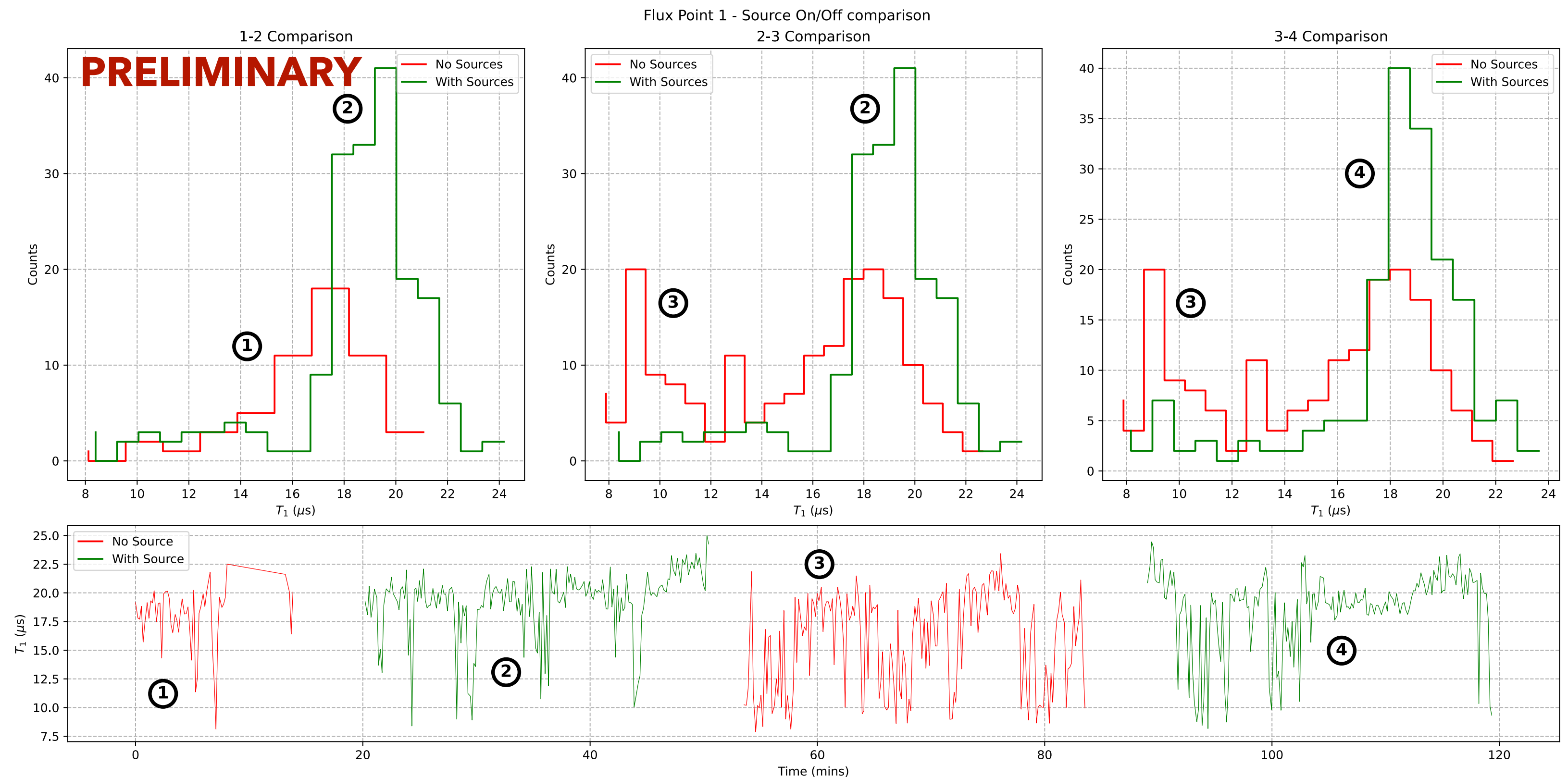
Results

- 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 T_1 .



Results

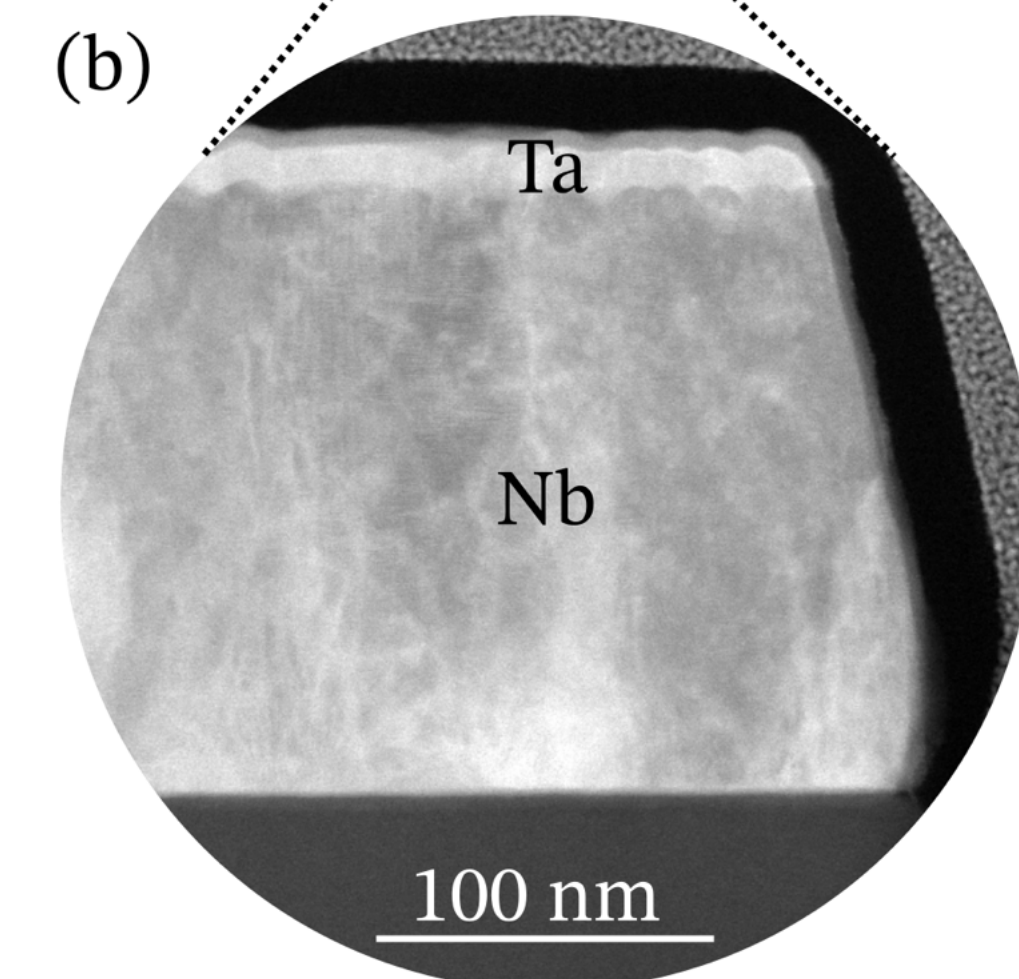
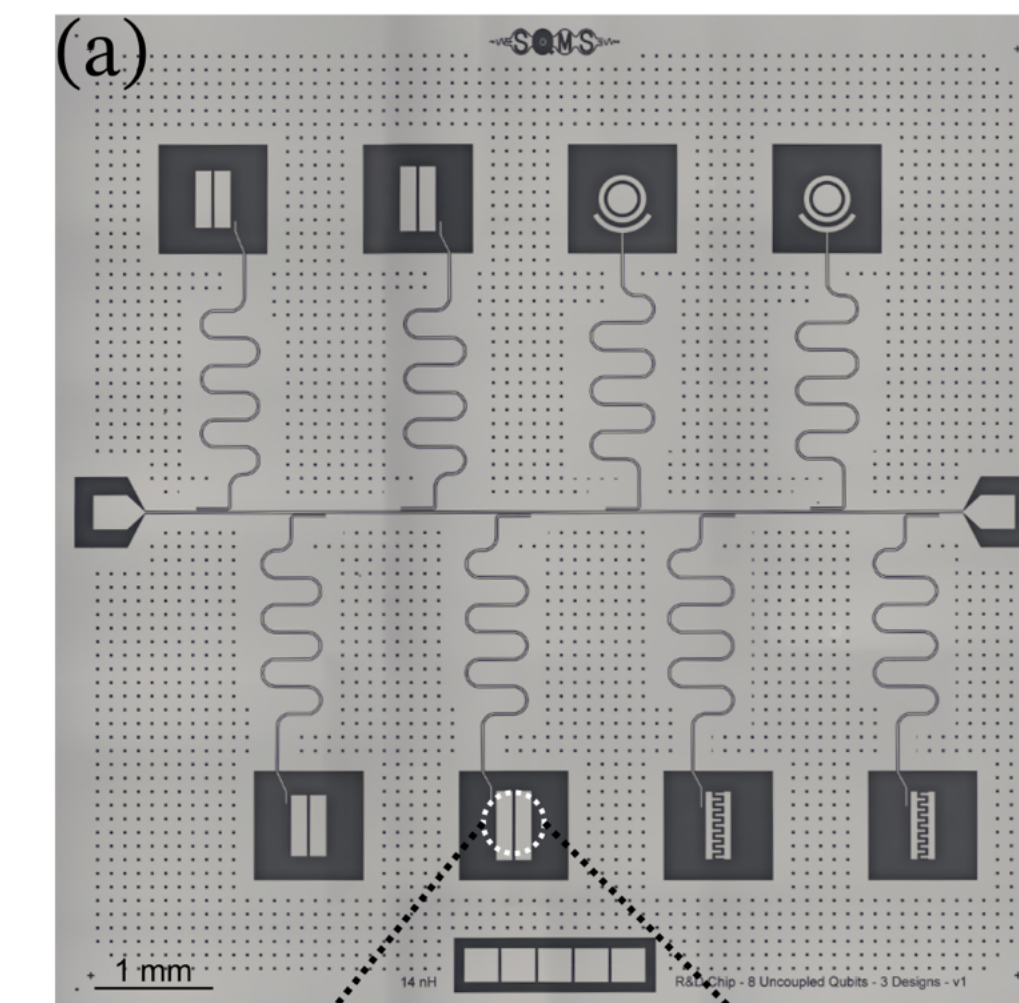
- Short measurements (~ 30 minutes) adding and removing a Thorium source;
- Fluctuations in T_1 values are uncorrelated with the presence of the source;



- Measurements in a low-radioactivity environment confirmed the result obtained by Vepsäläinen et al. that radioactivity is not a major limit for qubit with energy-relaxation times of tens of μs ;
- This can be explained by the small rate of interactions from radioactivity compared to the average decay rate of the qubit;
- Nonetheless, qubit performances are improving fast and chip dimensions are increasing to store more qubits, so bigger effects are expected to be observed in new devices.

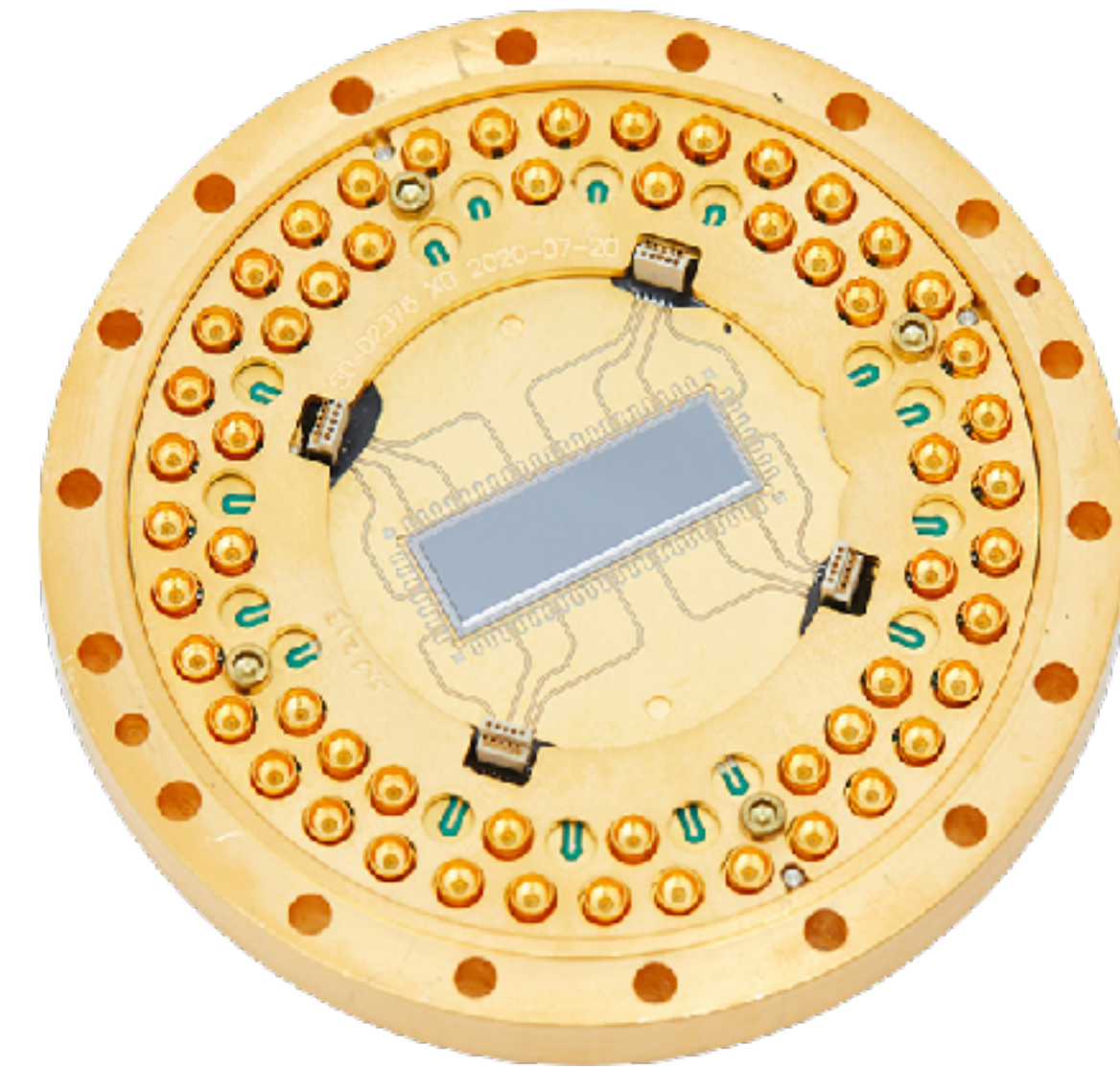
Prospects

- New experiments in preparation within the SQMS collaboration;
- In the near future characterization of a new transmon qubit featuring a Tantalum coating, with energy-relaxation time of hundreds of μs [Bal et al., [arXiv:2304.13257](https://arxiv.org/abs/2304.13257) (2023)];



Prospects

- In the long term test and characterization of the future SQMS prototypes, aiming at energy-relaxation times of milliseconds.



- The facility is also open for new collaborations! :)

Conclusions

- We developed 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 measurements with qubits with energy-relaxation time of hundreds of μs and more coming soon!

CONTACTS

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Conclusions

ACKNOWLEDGEMENTS



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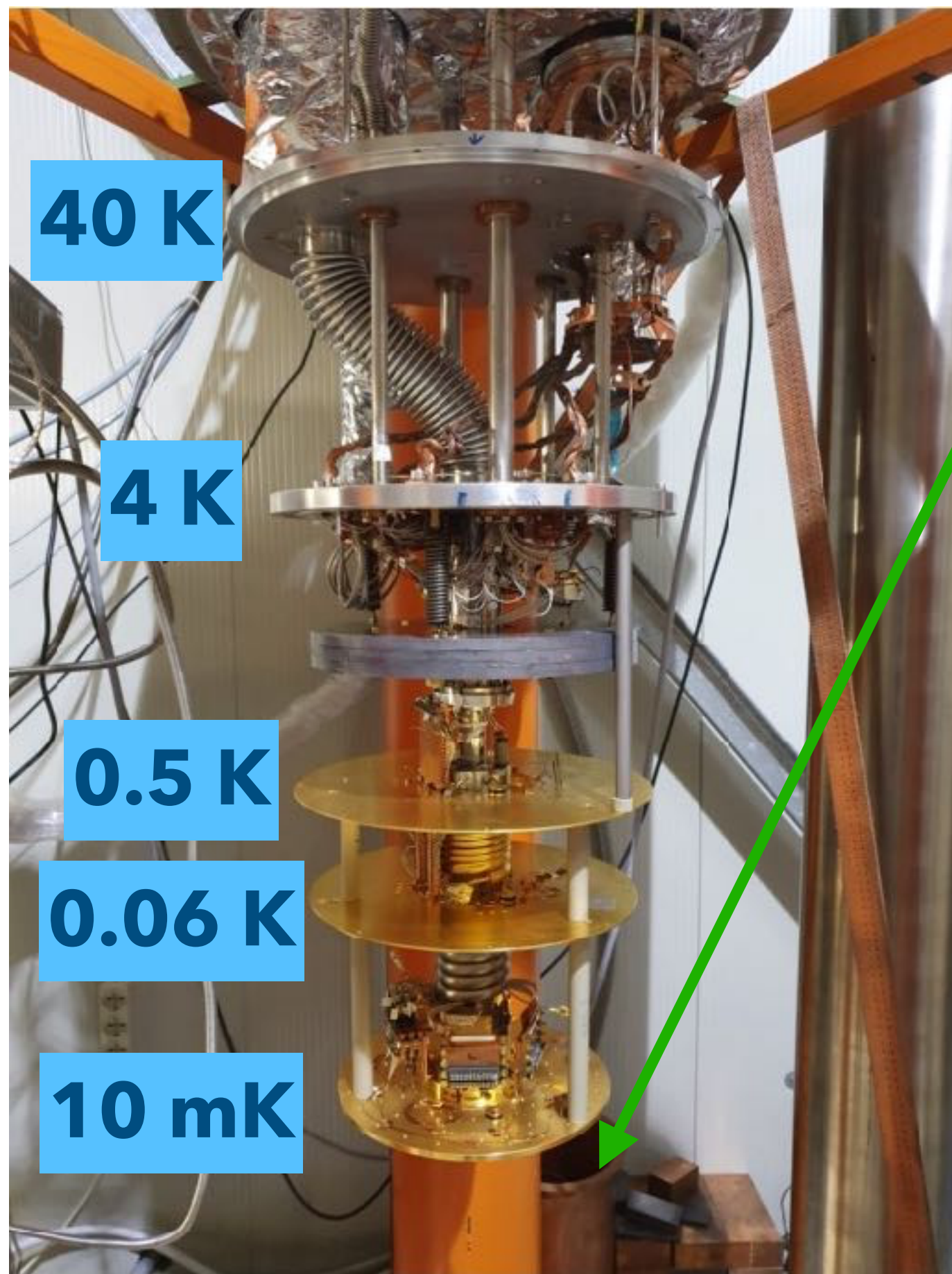
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CONTACTS

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Laura Cardani (head of the group): laura.cardani@roma1.infn.it

Backup: the IETI Cryostat



- Experimental volume: 25 cm of diameter, 16 cm height;
- 12 electronic channels with low noise voltage preamplifiers (2 nV/ $\sqrt{\text{Hz}}$) (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.



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

Backup: RF lines

