SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

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# Detection of single particle event in a superconducting qubit

## 16th Pisa meeting on advanced detectors

### La Biodola, Isola d'Elba, May 28-June 1, 2024

**Dounia L Helis** on behalf of Mustafa Bal, Laura Cardani, Nicola Casali, Ivan Colantoni, Francesco Crisa, Angelo Cruciani, Francesco De Dominicis, Anna Grassellino, Ambra Mariani, Roman M Pilipenko, Valerio Pettinacci, Lorenzo Pagnanini, Stefano Pirro, Andrei Puiu, Alexander Romanenko, Tanay Roy, David v Zanten, Shaojiang Zhu, **May 30th, 2024**
Contact: laura.cardani@roma1.infn.it

De Dominicis et al, arXiv:2405.18355

# Outline

- What are the superconducting qubits?
- Qubits are sensitive to radioactivity
- Can we use a superconducting qubits as a particle detector ?
- Measurement of a superconducting qubits in a underground facility
- Conclusions and prospects

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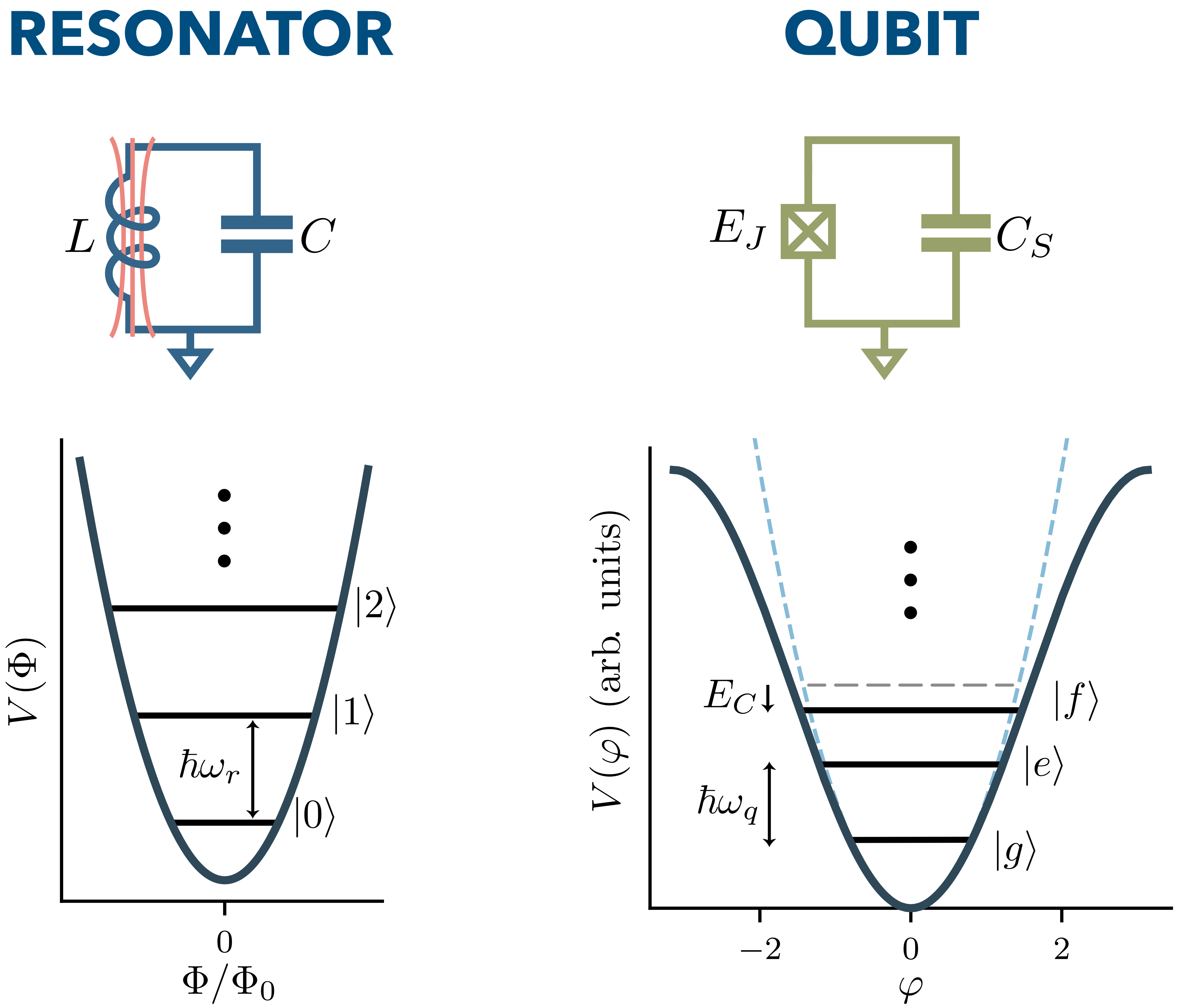
# Superconducting qubits

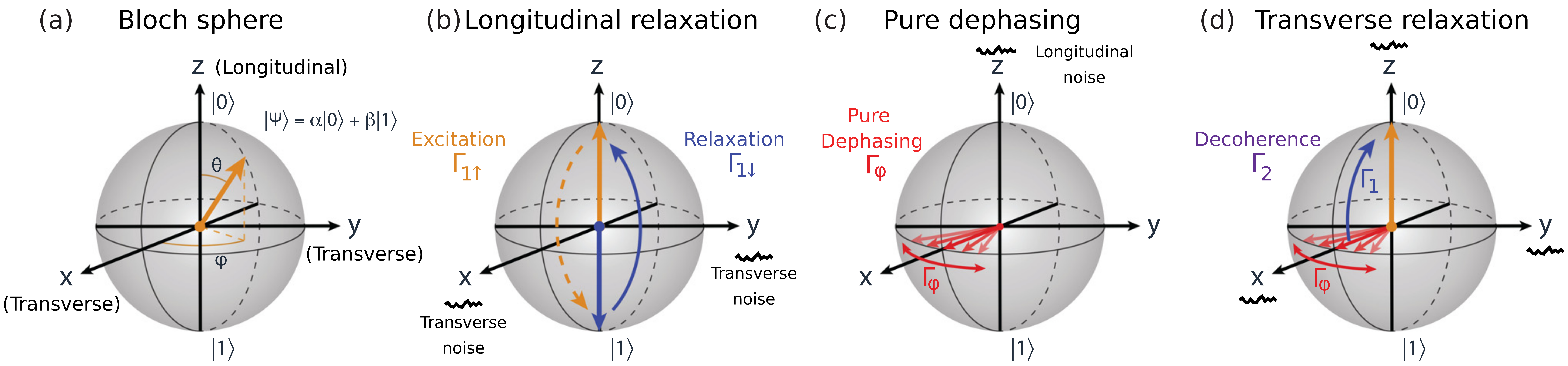
## Or anharmonic oscillator

- Possibility to have superposition states $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$
- Any two-level quantum system can be operated as a qubit
- Superconducting circuit with a Josephson Junction that acts as a non linear inductor
- Anharmonic energy spectrum => populate only the first two levels, We have our QUBIT!



# Qubits coherence

- Qubits interaction with the environment changes its state
- The infos stored in the qubit are lost when the qubit changes state
- This is called the decoherence
- Transmon qubits can reach a coherence of few hundreds of us

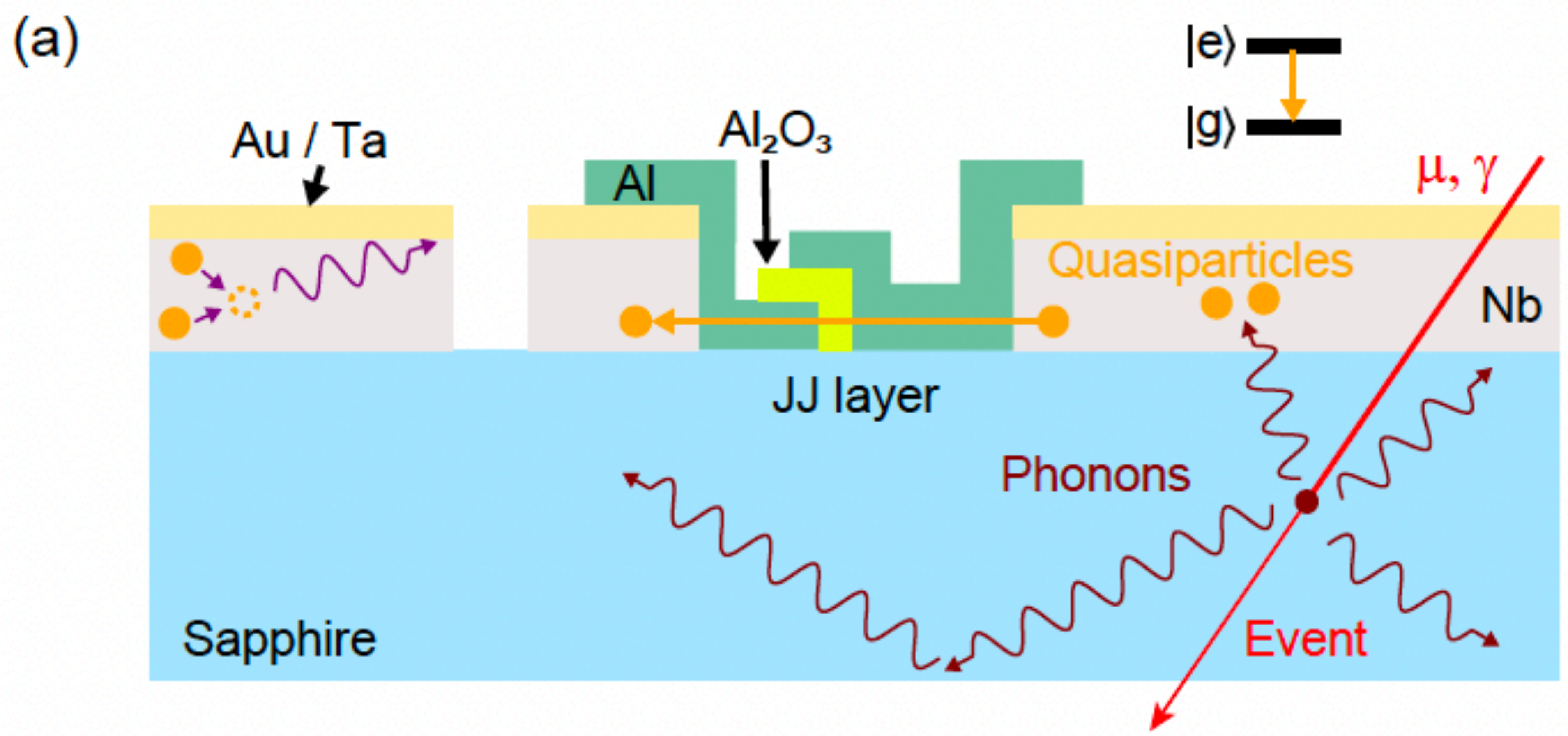



Krantz et al., *Appl. Phys. Rev.* **6**, 021318 (2019)
Bal et al, npj Quantum Inf 10, 43 (2024)

# Are qubits really sensitive to radioactivity ?

## State of Art

- Radioactivity was studied as a limit for qubit coherence
- Particles can deposit energy on the qubit and produce charges and phonons
- Phonons production breaks the Cooper pairs creating quasiparticles
- Quasiparticles can be responsible for the loss of coherence



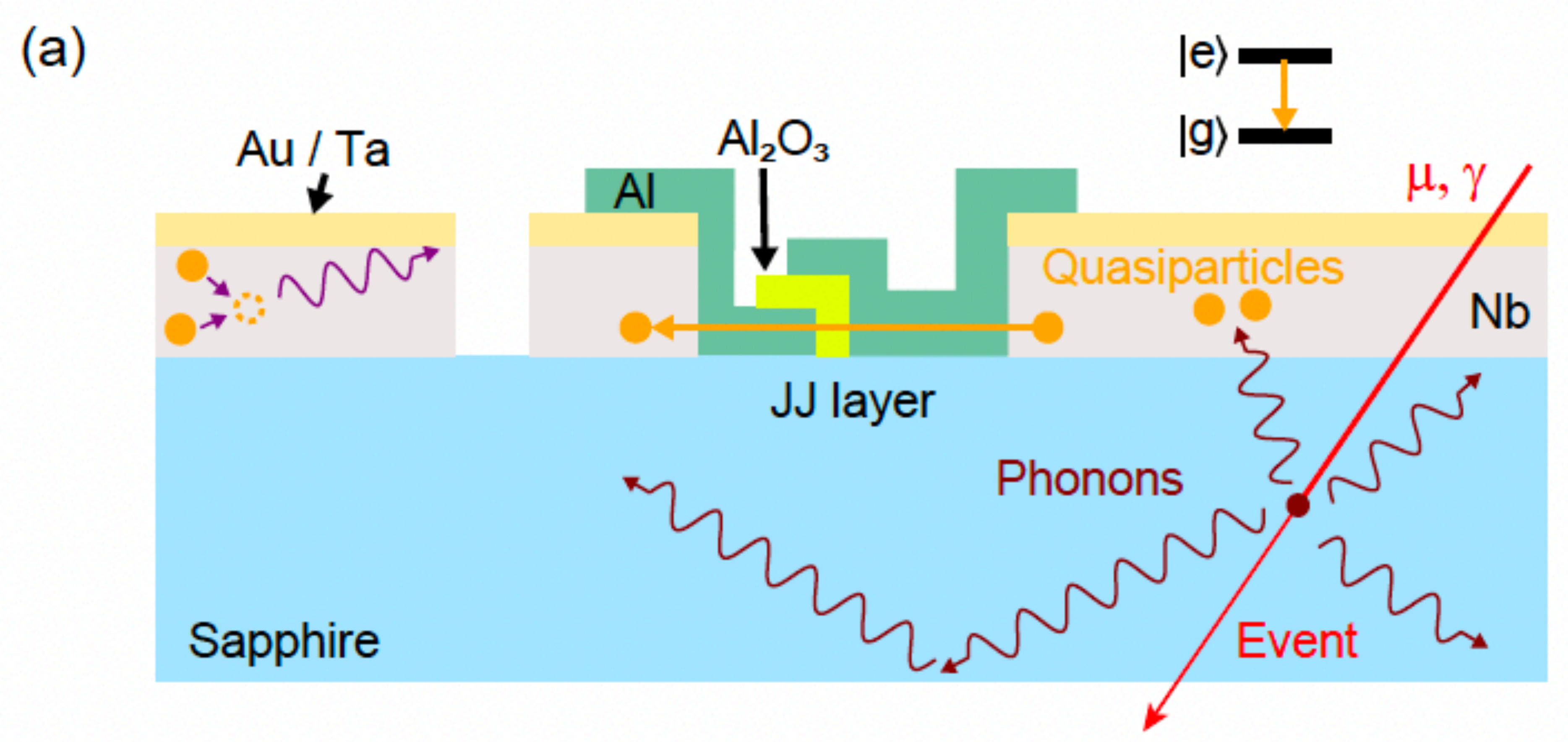

Cardani et al., *Nature Communications* (2021)
Vepsäläinen et al., *Nature* (2020)
Wilen et al., *Nature* (2021)
McEwen et al., *Nature Physics* (2022)

# Are qubits really sensitive to radioactivity ?

## State of Art

- It will be a limit for the next generation qubits
- It is a source of correlated error in multi-qubit chips
- What can we do with this infos ?

Test a transmon qubit as a particle detector !

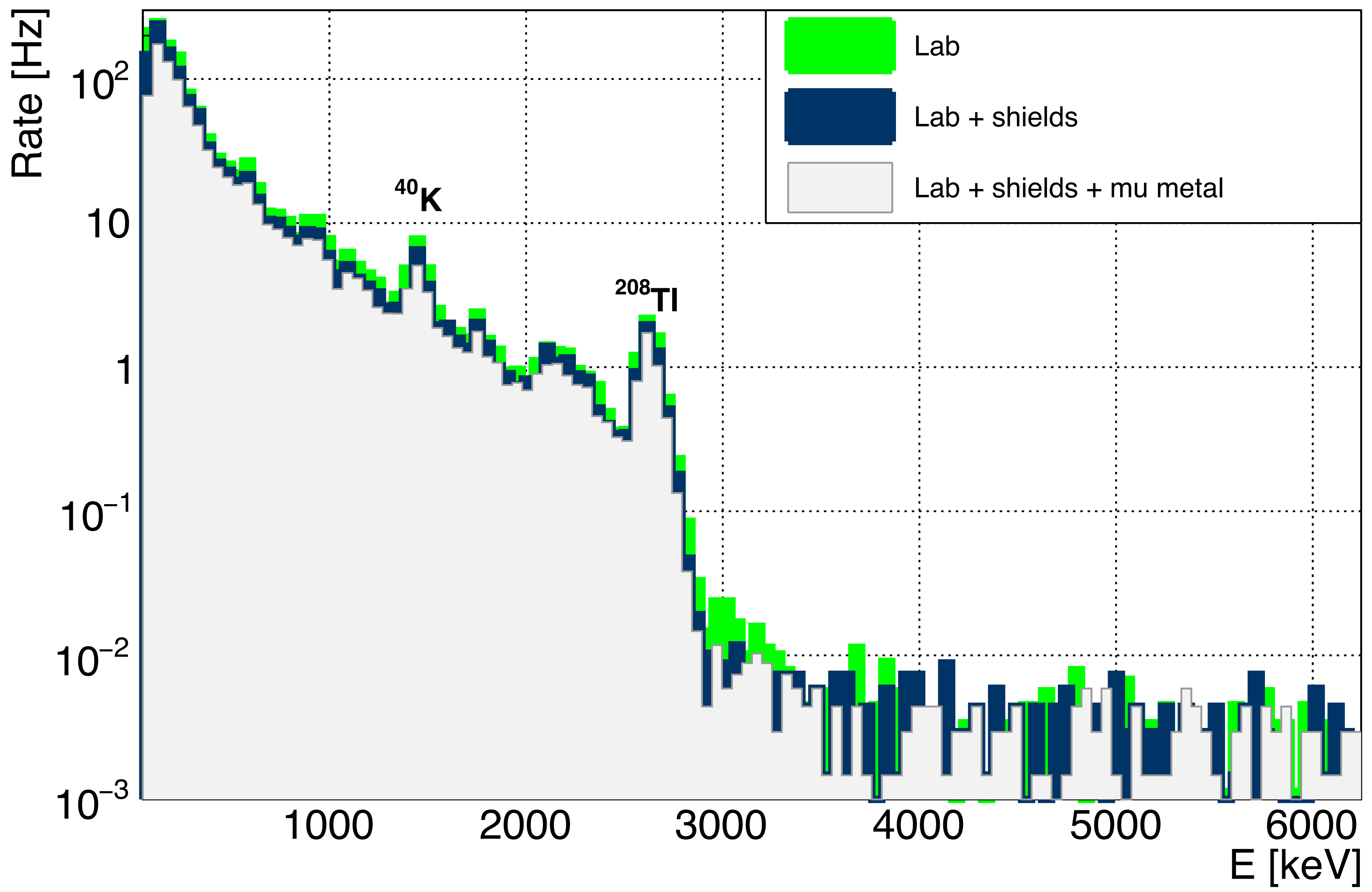


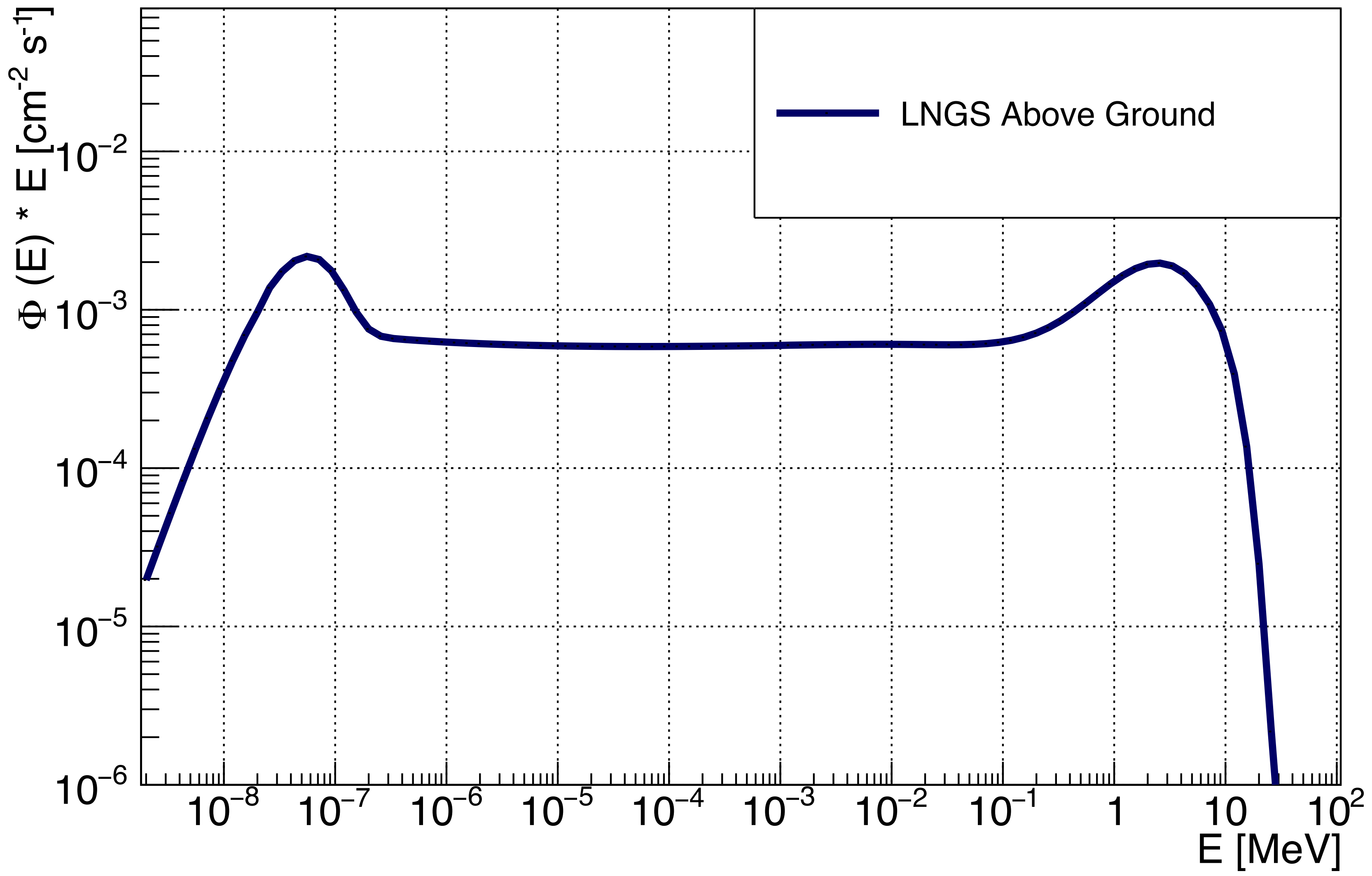

**Development of HW & SW tools to operate a transmon qubit as a $\gamma$ detector**

# Particle impact?

## Yes but from what ?

- Radioactivity comes from different sources
  - Far sources: gamma particles, atmospheric muons, neutrons
  - Close sources: radioactive contamination around
  - The predicted rate on the qubit is extracted from Monte Carlo simulations




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

# Particle impact?

**What does the simulations predict ? Aboveground and Underground?**

- Above and underground experimental setup simulated to predict the radioactive rate
- Going underground reduces the rate to less then 1 mHz
- The main contribution underground is from the PCB
- Can we study the particle impact on the qubit ?

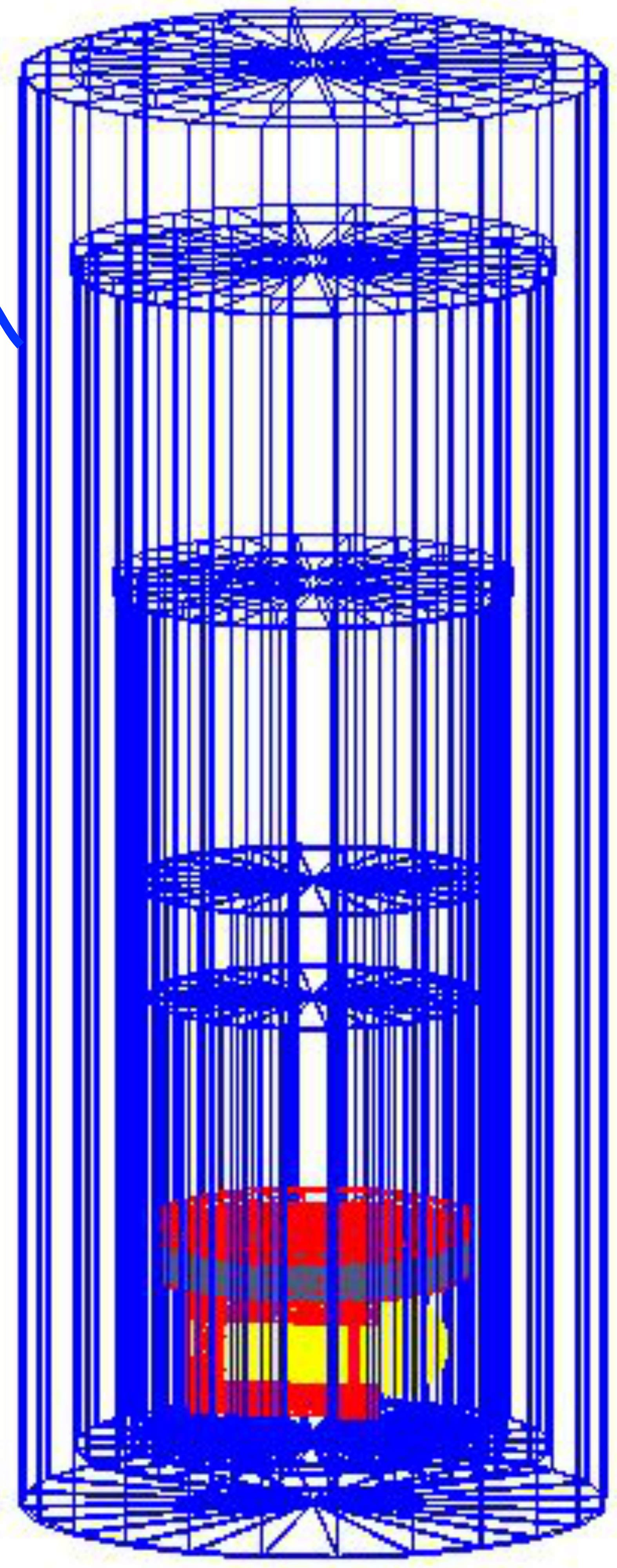
| Source | FNAL [events/sec] | INFN-LNGS [events/sec] |
|---|---|---|
| Lab $\gamma$-rays | $(46 \pm 2) \times 10^{-3}$ | $(1.3 \pm 0.1) \times 10^{-3}$ |
| Muons | $(8 \pm 0.5) \times 10^{-3}$ | $< 10^{-5}$ |
| Setup | $(2.7 \pm 0.5) \times 10^{-3}$ | $(2.7 \pm 0.5) \times 10^{-3}$ |
| Total | $(57 \pm 3) \times 10^{-3}$ | $(4.0 \pm 0.6) \times 10^{-3}$ |

De Dominicis et al, arXiv:2405.18355

# Let's go deep underground

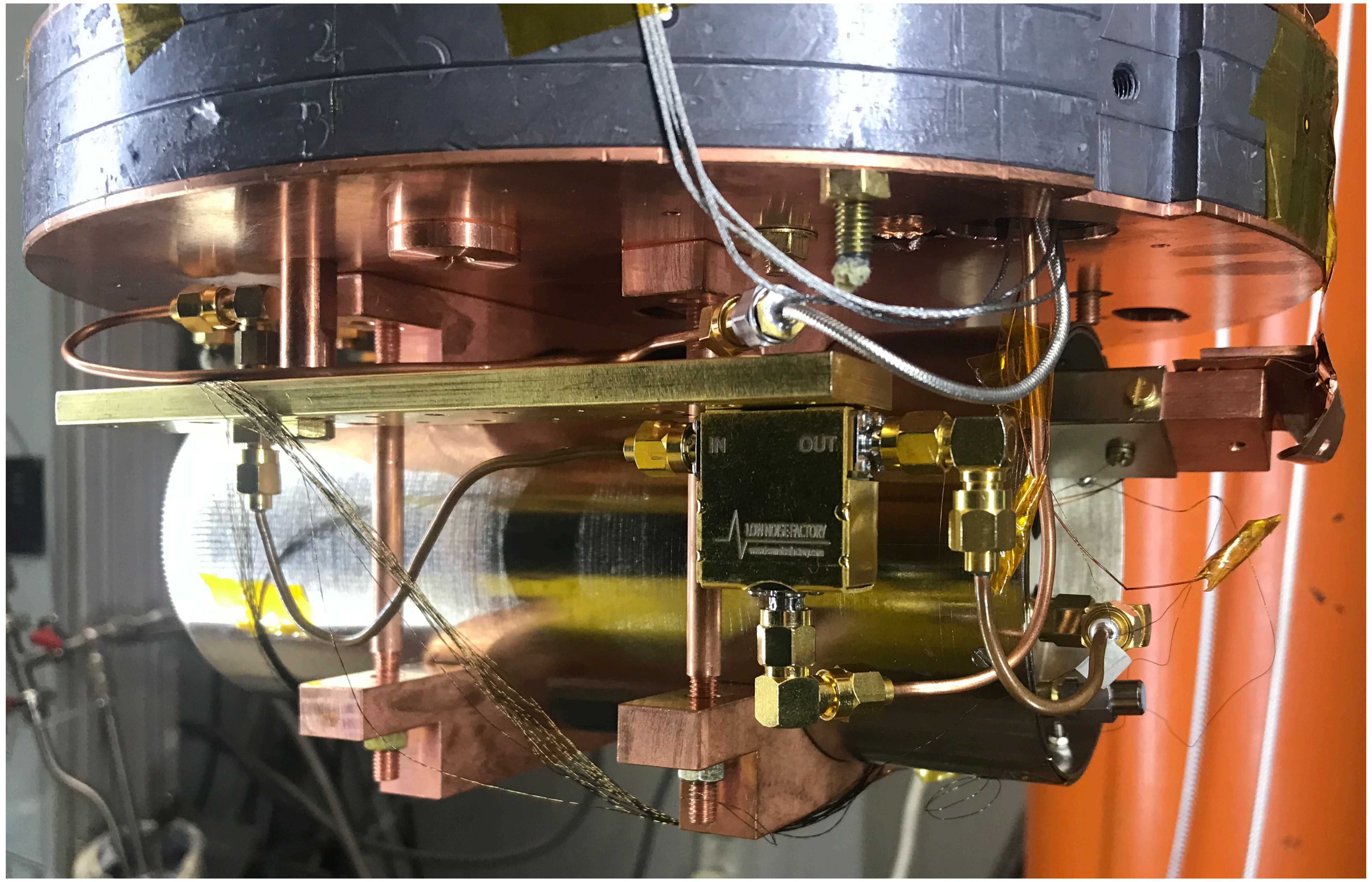
## Underground facility at LNGS!

- Located in Hall C at LNGS
- Dry dilution refrigerator
- The muon flux is attenuated by a factor $10^6$ at LNGS
- Low radioactivity facility (shielding!)
- Shield the cryostat for qubits in a similar way to particle detectors



# Let's go deep underground

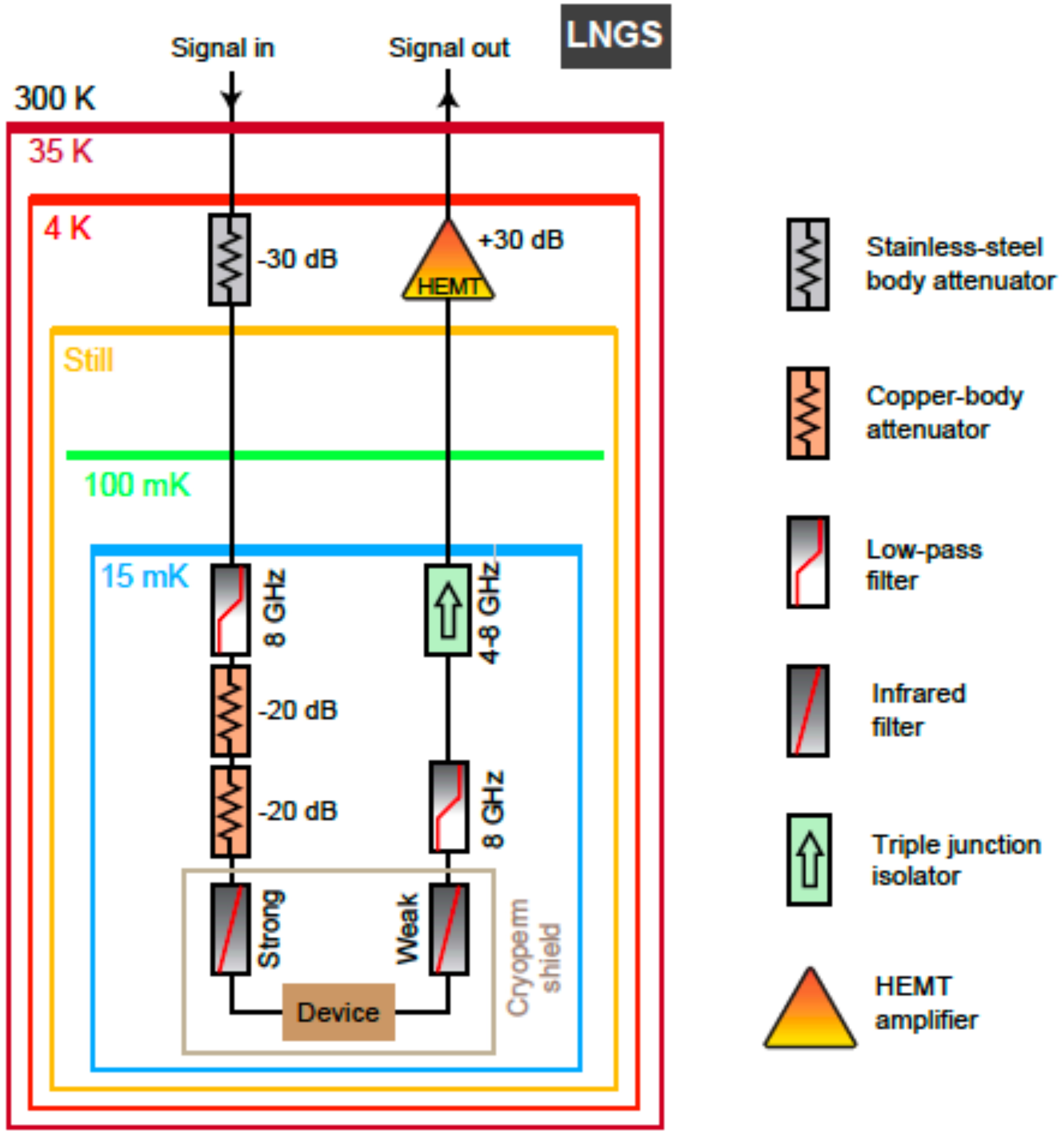
## And put shielding!




# How to use a qubit as a particle detector ?

## Experimental setup and protocol

- Use of the $^{232}Th$ sources with different activities (44 kBq, 76 kBq, 125 kBq and 161 kBq)
- Study the qubit behaviour when exposed to high radioactive source via particle interaction
- Qubit looses energy and quickly decrease to $|0\rangle$

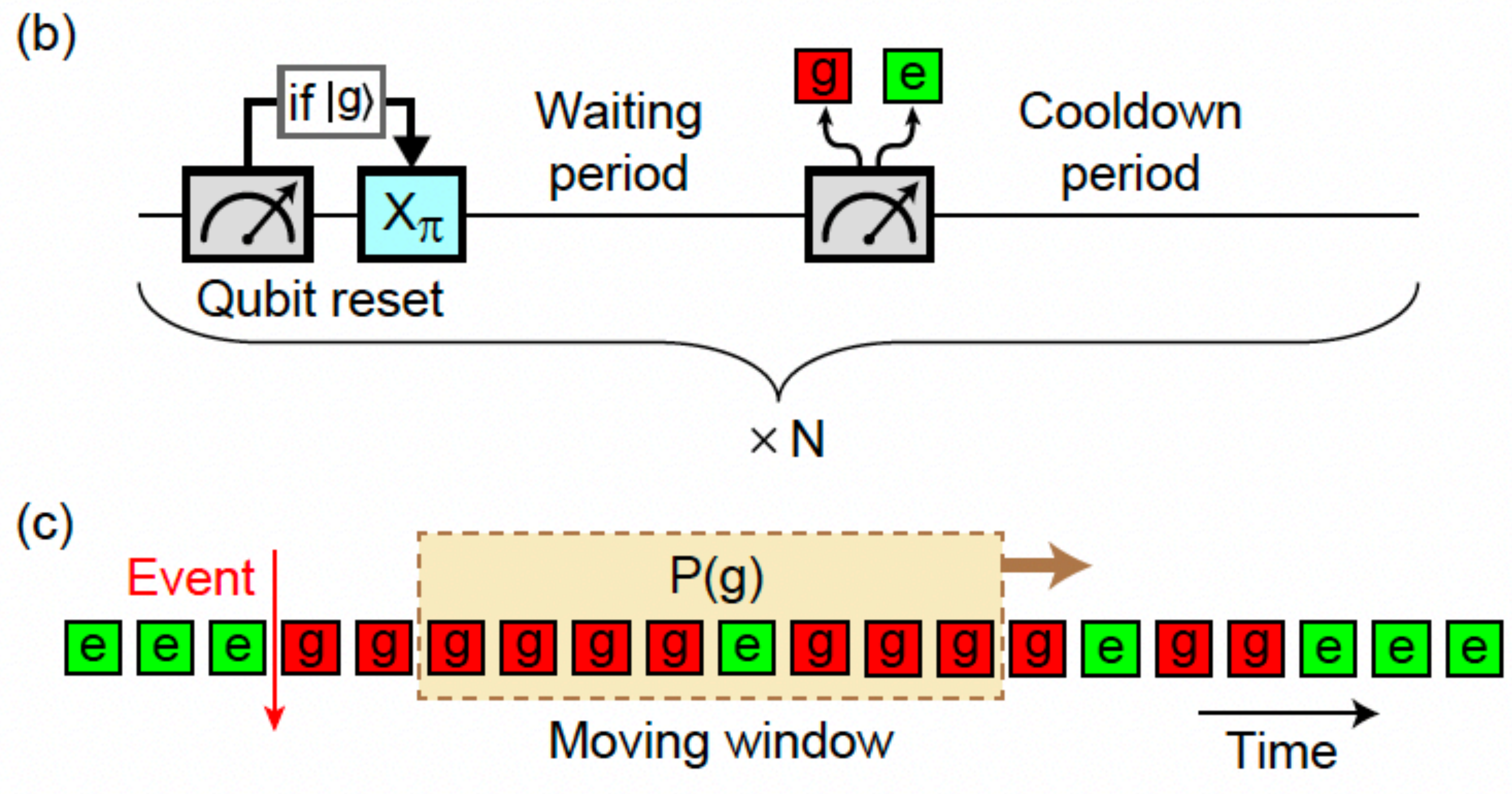



De Dominicis et al, arXiv:2405.18355

# How to use a qubit as a particle detector ?

## Experimental setup and protocol

1. Reset the qubit to $|1\rangle$ if found in $|0\rangle$
2. Measure its state every $\Delta T$ ~ us
3. If T1 is long enough, the probability to find the qubit in $|1\rangle$ is higher
4. If particle interaction T1 is shorter, the probability to find the qubit in the $|0\rangle$ becomes higher
5. Repeat the measurement

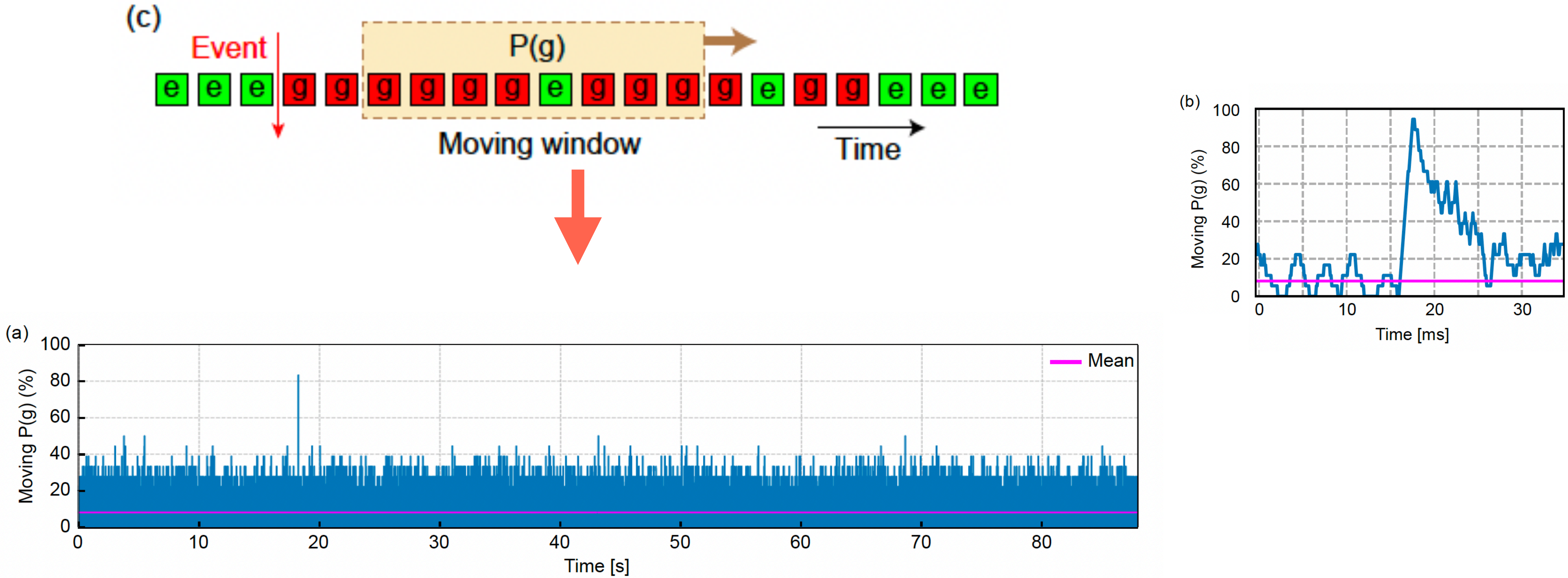



Particle interaction

De Dominicis et al, arXiv:2405.18355

# How to use a qubit as a particle detector ?

## Event detection, first look at the data with P(g)

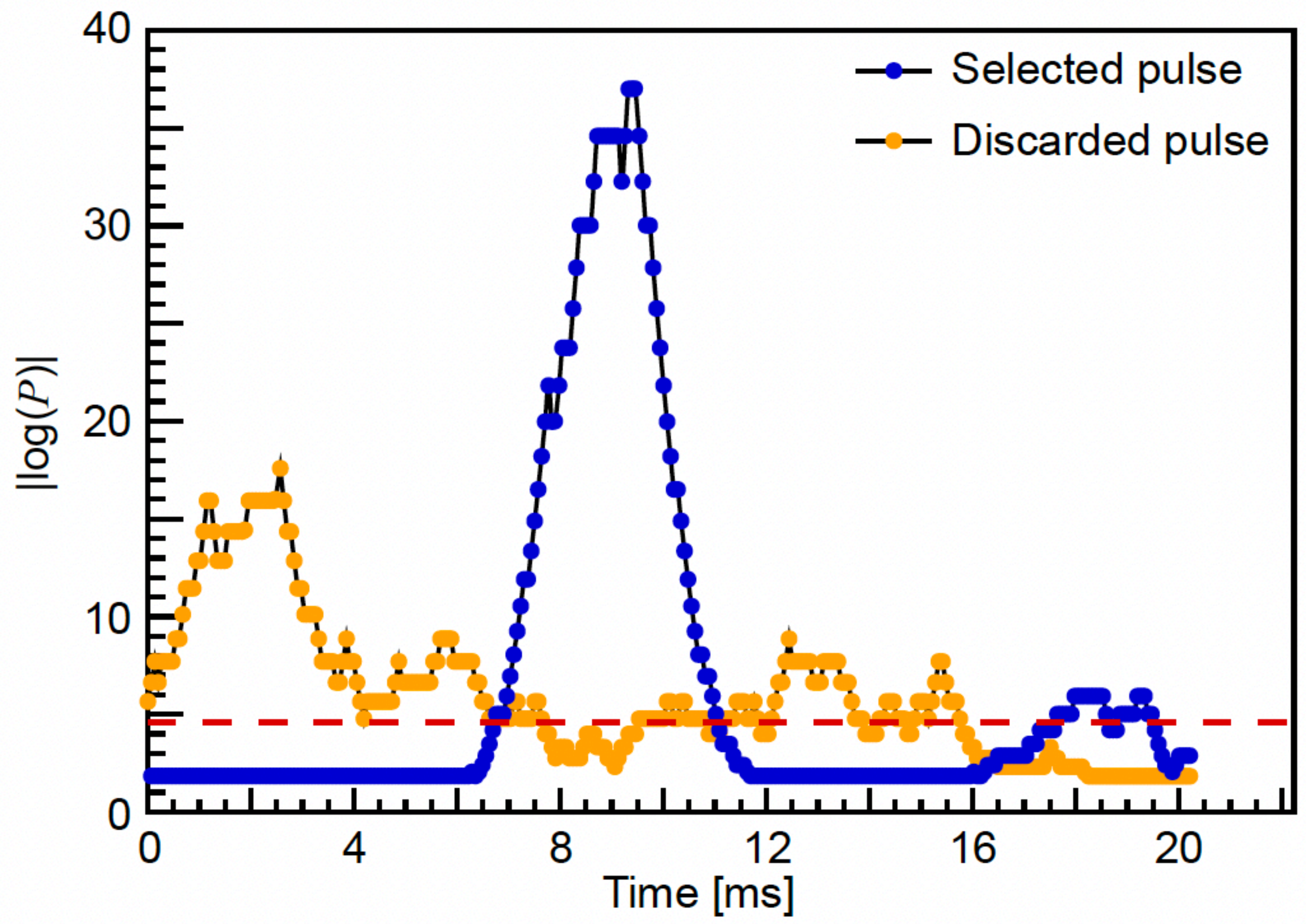



De Dominicis et al, [arXiv:2405.18355]()

# How to use a qubit as a particle detector ?

## Pulse reconstruction and triggering

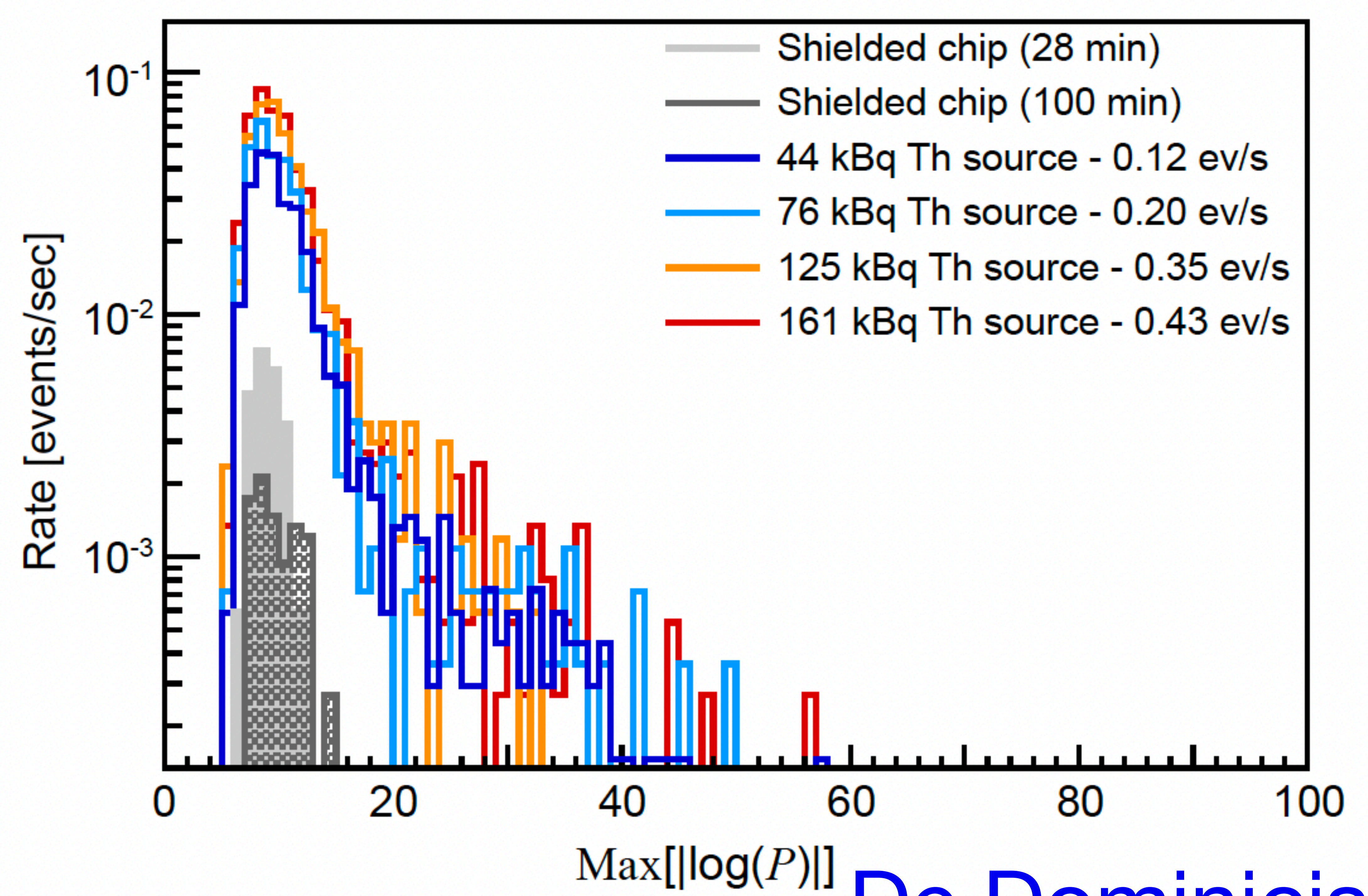
- Compute the probability P for observing 0 or 1 using the Binomial distribution
- The probability for the qubit to be in the $|1\rangle$ is 85% => the probability to observe many 0 is very small
- If this probability is smaller then 1%, the trigger fires

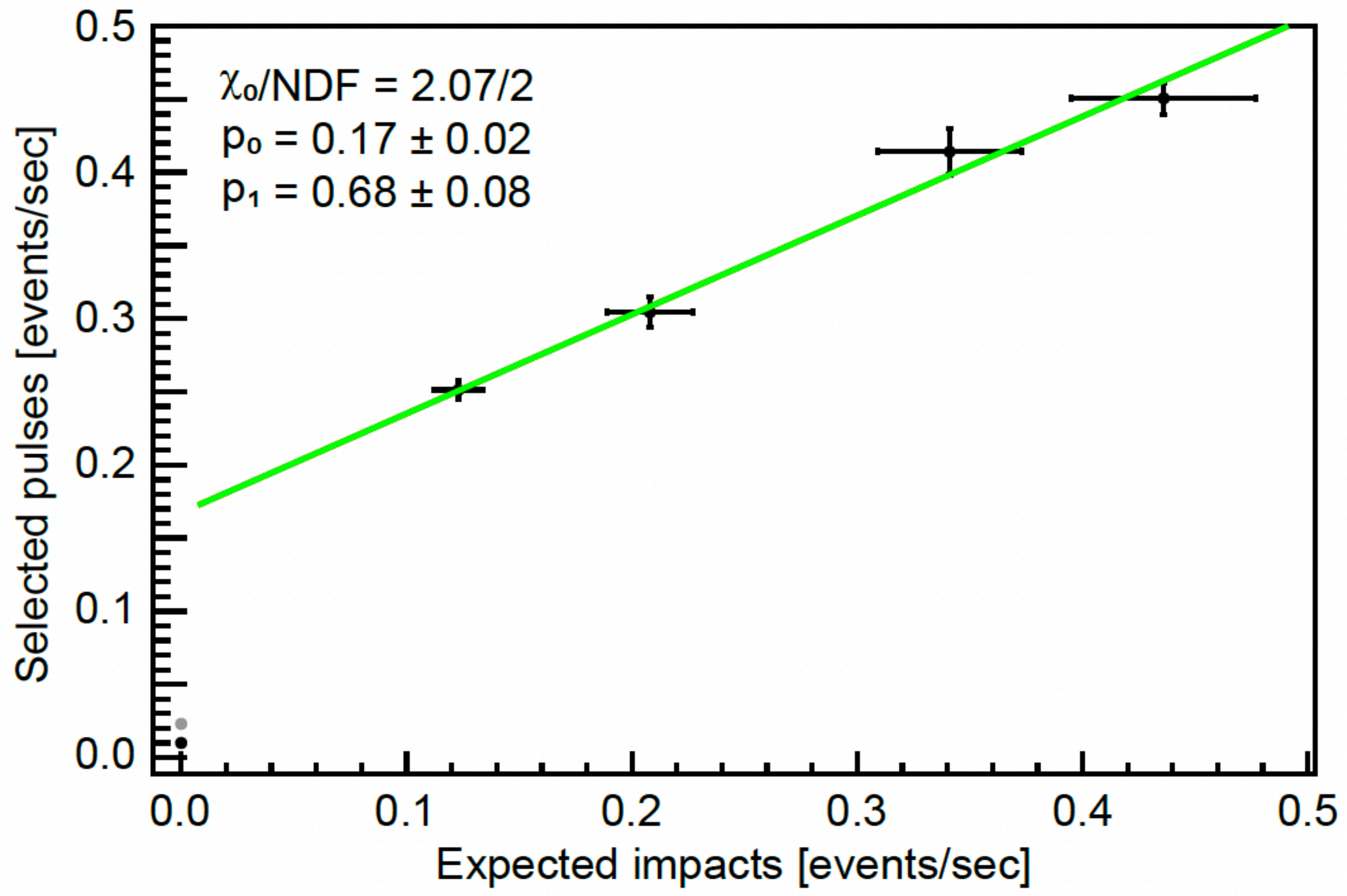



De Dominicis et al, [arXiv:2405.18355](arXiv:2405.18355)

# How to use a qubit as a particle detector ?

## Results !!

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**Qubits are sensitive to particle interactions! To gammas!**

**Qubits can be used as particle detectors**

# Conclusions and perspectives

- We successfully operated a superconducting qubit in an underground facility at LNGS
- The chip was exposed to radioactive sources with different activities
- A qubit can be operated as a particle detector
- Qubits are efficient in detecting particle impact

**Evaluating radiation impact on transmon qubits in above and underground facilities**

Francesco De Dominicis,[1,2,*] Tanay Roy *,[3,†] Ambra Mariani,[4,‡] Mustafa Bal,[3] Nicola Casali,[4]
Ivan Colantoni,[4] Francesco Crisa,[5] Angelo Cruciani,[4] Fernando Ferroni,[1,4] Dounia L Helis,[2]
Lorenzo Pagnanini,[1,2] Valerio Pettinacci,[4] Roman M Pilipenko,[3] Stefano Pirro,[2] Andrei Puiu,[2]
Alexander Romanenko,[3] David v Zanten,[3] Shaojiang Zhu,[3] Anna Grassellino,[3] and Laura Cardani[4]

[1] *Gran Sasso Science Institute*
[2] *INFN, Laboratori Nazionali del Gran Sasso*
[3] *Superconducting Quantum Materials and Systems Division, Fermi National Accelerator Laboratory (FNAL), Batavia, IL 60510, USA*
[4] *INFN, Sezione di Roma*
[5] *Illinois Institute of Technology*

(Dated: May 29, 2024)

Superconducting qubits can be sensitive to abrupt energy deposits caused by cosmic rays and ambient radioactivity. Previous studies have focused on understanding possible correlated effects over time and distance due to cosmic rays. In this study, for the first time, we directly compare the response of a transmon qubit measured initially at the Fermilab SQMS above-ground facilities and then at the deep underground Gran Sasso Laboratory (INFN-LNGS, Italy). We observe same average qubit lifetime $T_1$ of roughly 80 microseconds at above and underground facilities. We then apply a fast decay detection protocol and investigate the time structure, sensitivity and relative rates of triggered events due to radiation versus intrinsic noise, comparing above and underground performance of several high-coherence qubits. Using gamma sources of variable activity we calibrate the response of the qubit to different levels of radiation in an environment with minimal background radiation. Results indicate that qubits respond to a strong gamma source and it is possible to detect particle impacts. However, when comparing above and underground results, we do not observe a difference in radiation induced-like events for these sapphire and niobium-based transmon qubits. We conclude that the majority of these events are not radiation related and to be attributed to other noise sources which by far dominate single qubit errors in modern transmon qubits.

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