Istituto Nazionale di Fisica Nucleare

Superconducting Qubits as Particle Detectors

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On behalf of:
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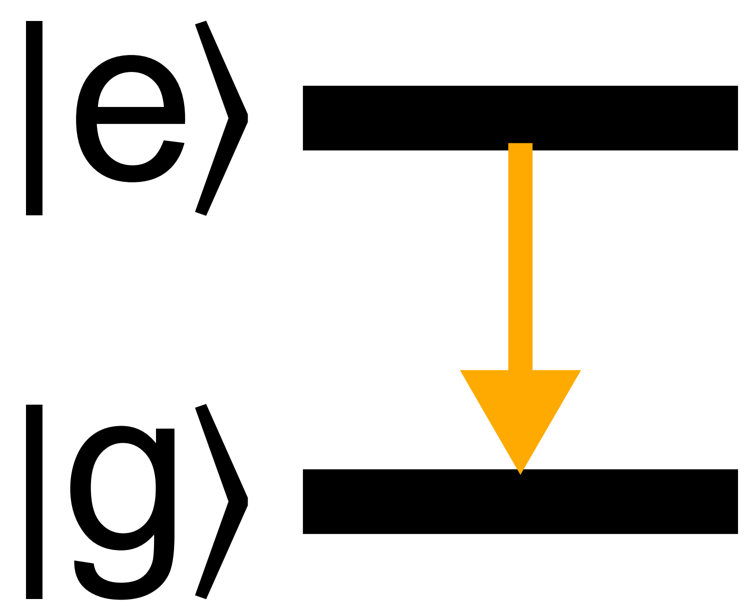
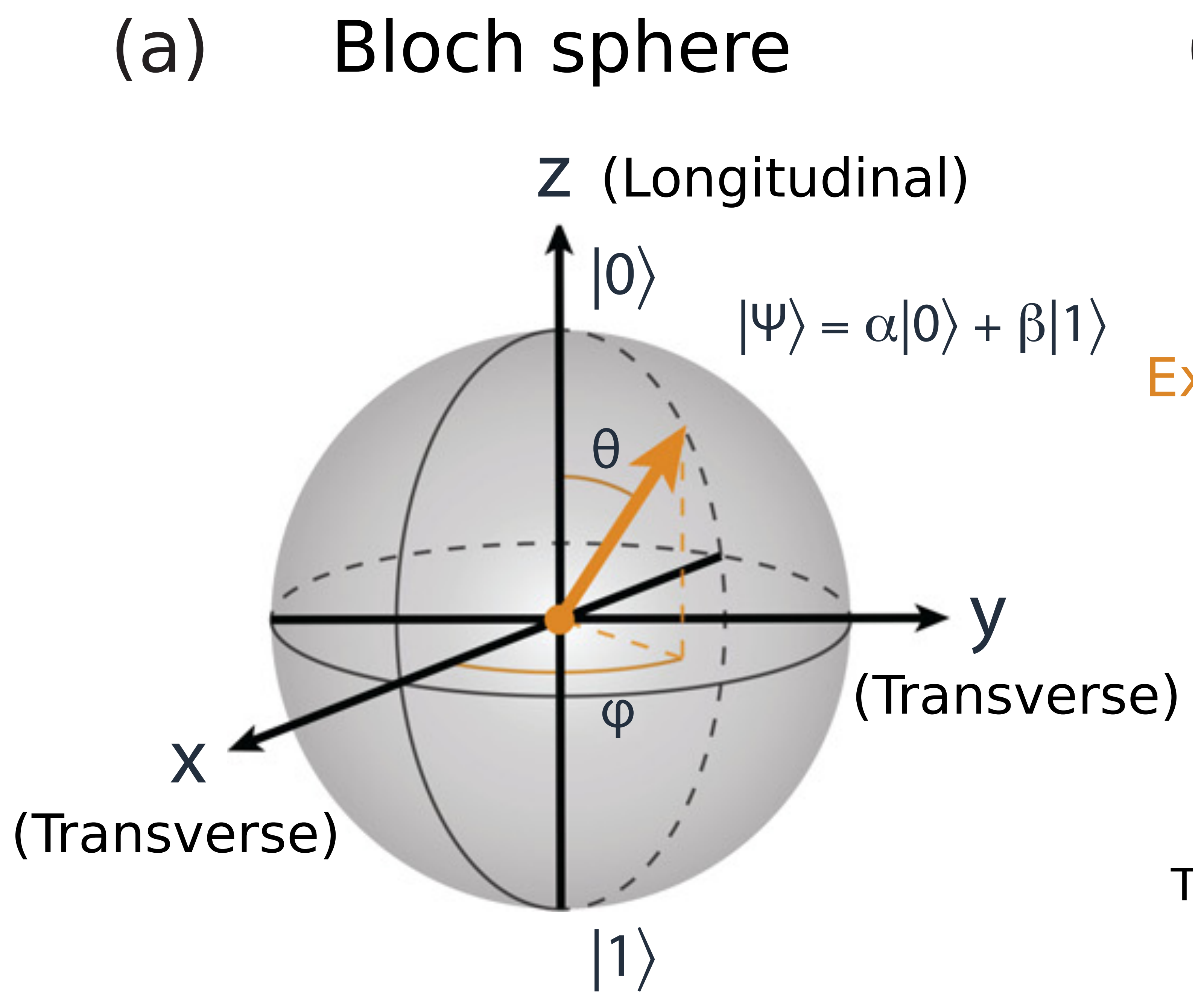
TAUP XICHANG

Quantum Bits

- What are they?
  - Quantum counterpart of a classical bit
  - Possibility to have superposition states:
  - Need of a two level quantum system



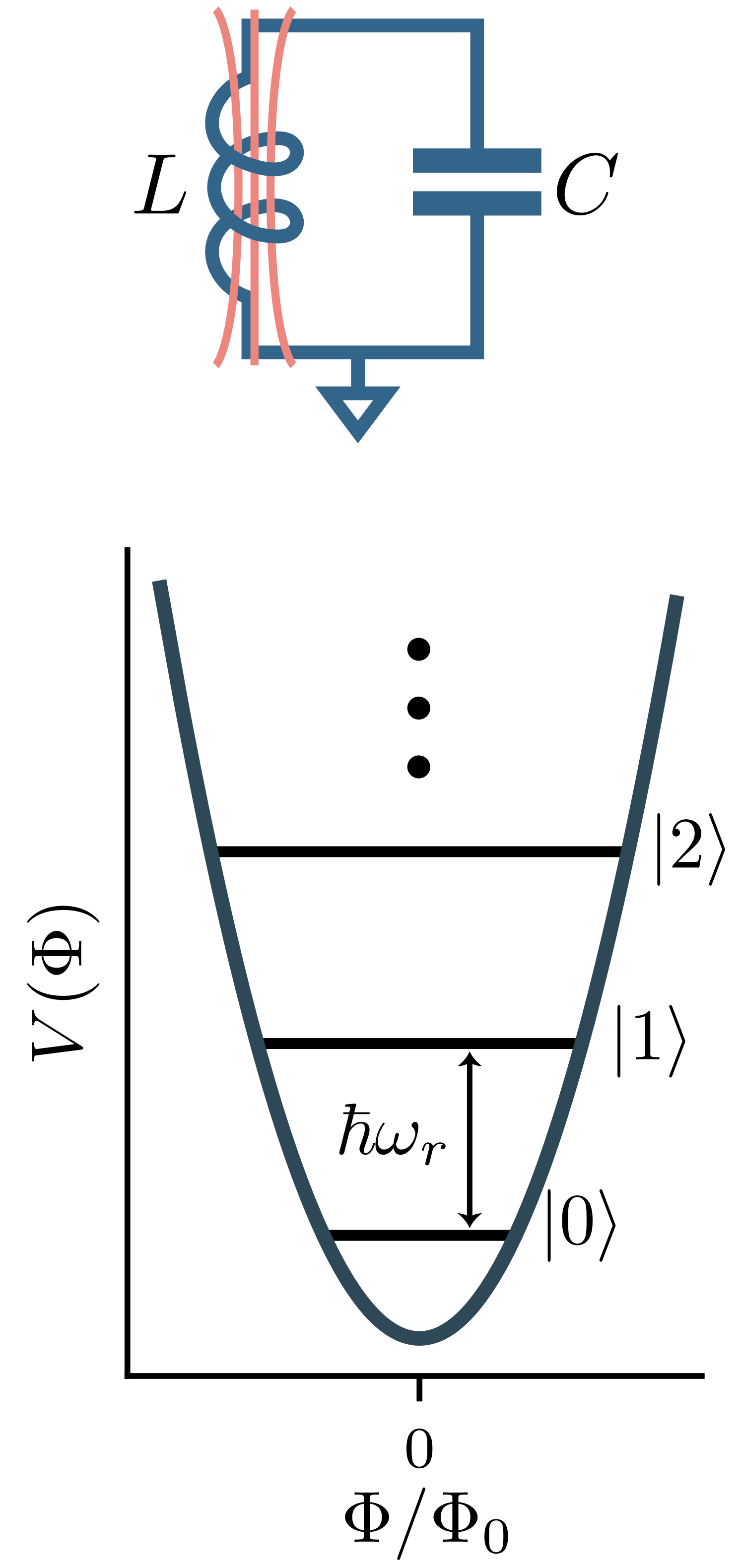
$$|\psi\rangle = \alpha|g\rangle + \beta|e\rangle$$



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

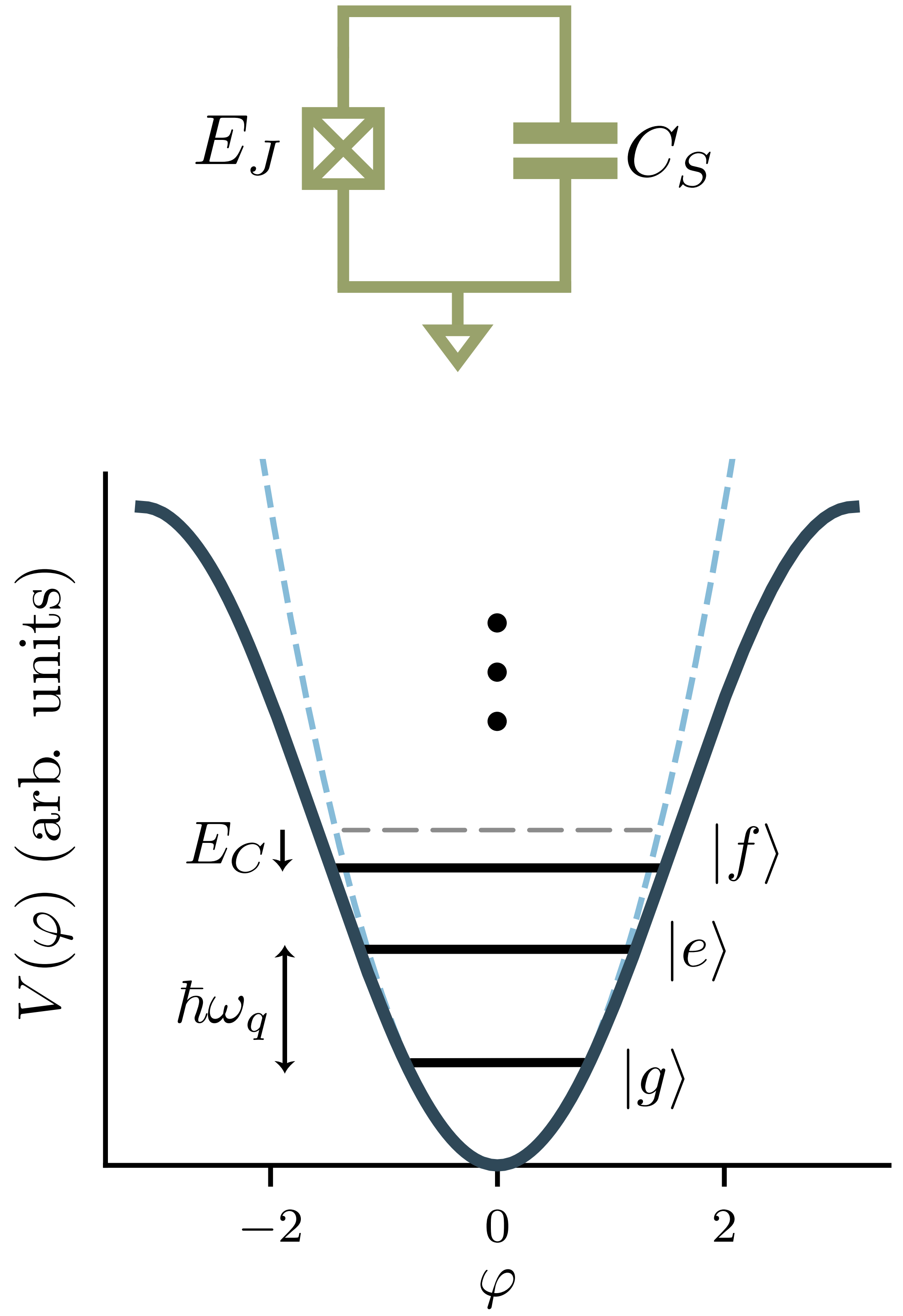
Quantum Bits

RESONATOR



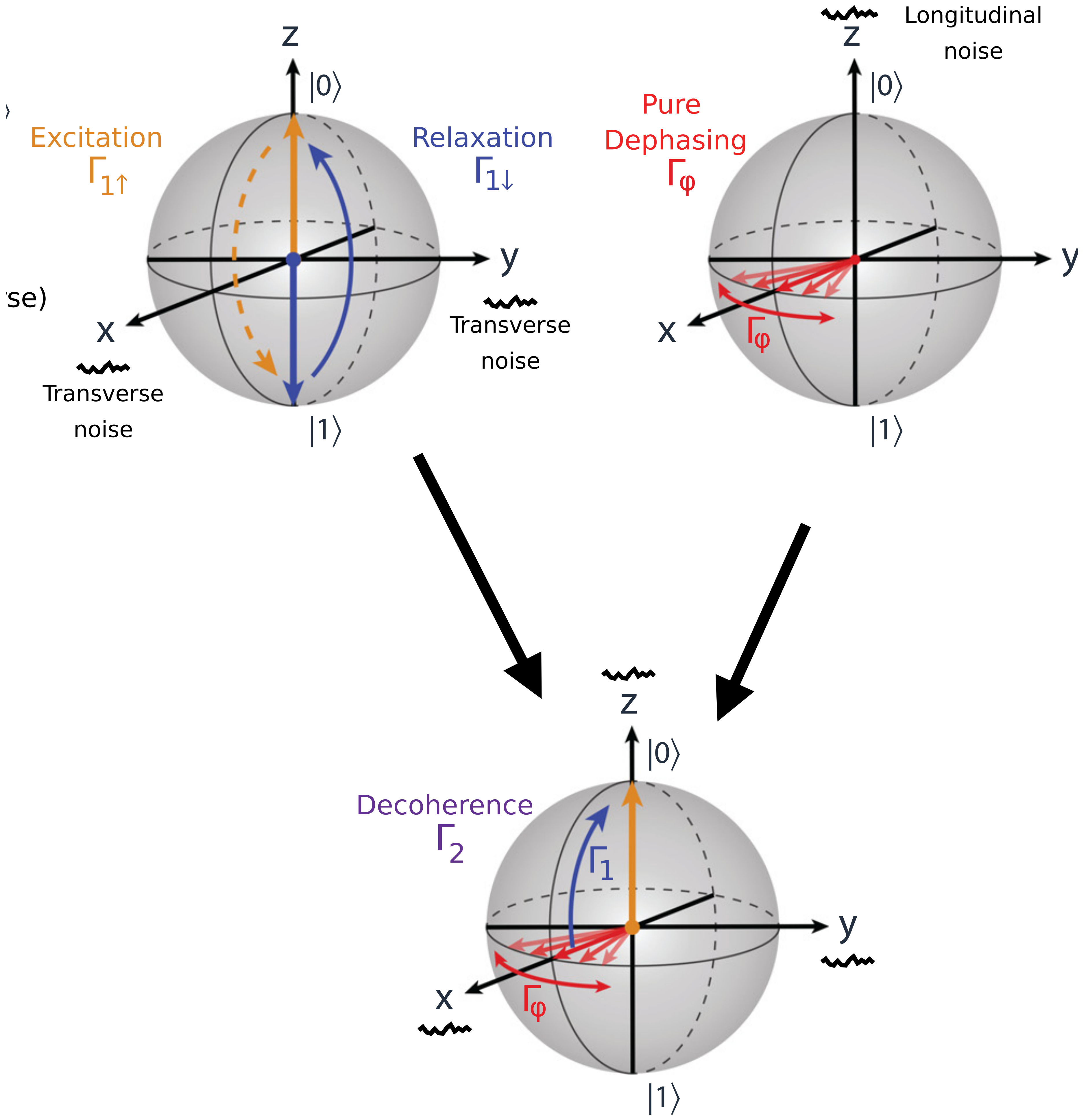
- What are they made of?
  - Superconducting circuit with a Josephson Junction
  - Non-linear inductor → Non-linear quantum levels (Anharmonic oscillator)
  - Populating only the first two levels we have a qubit

QUBIT



Quantum Bits

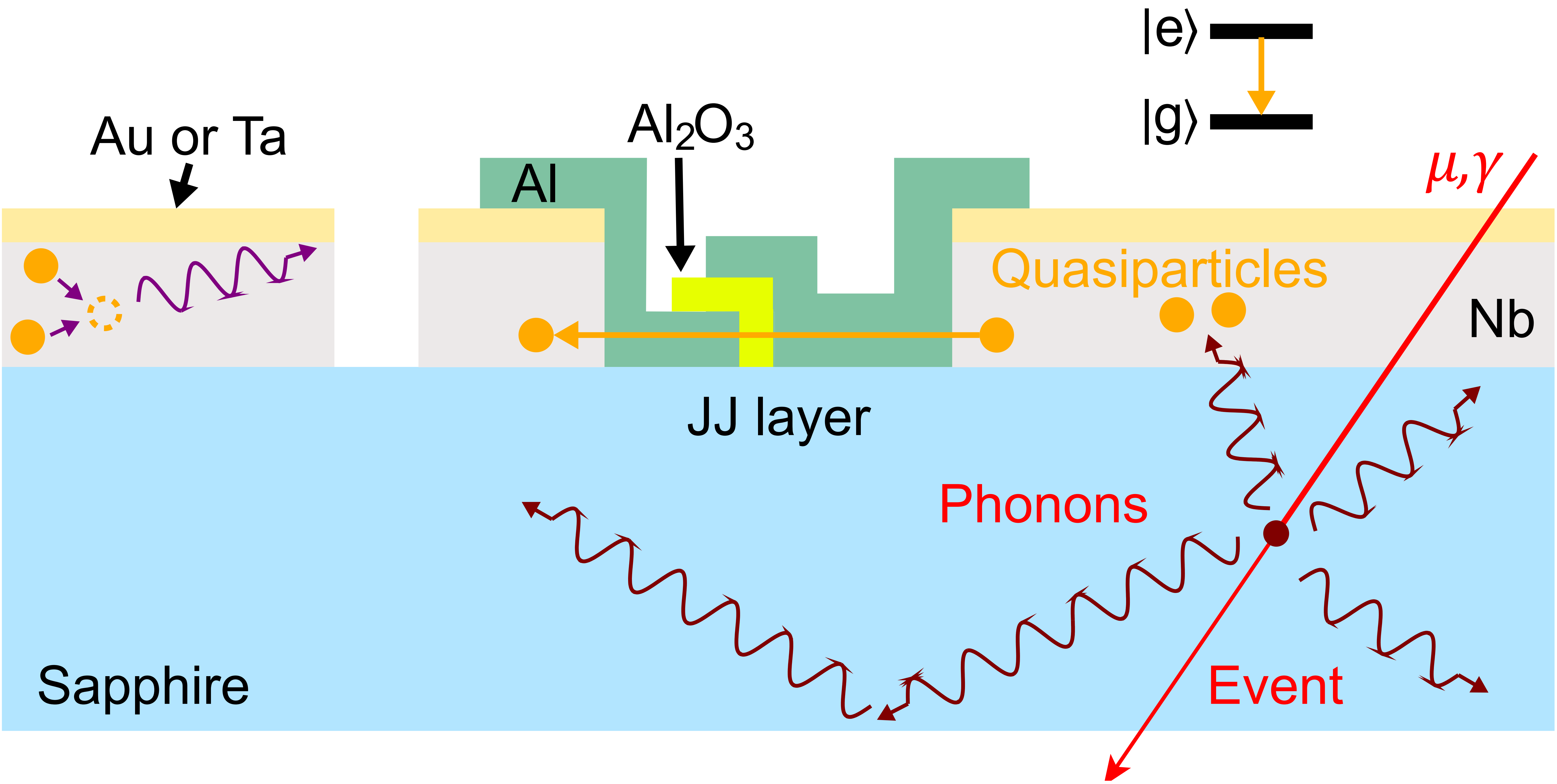
- Coherence:
  - Average amount of time these devices can store information
  - Or: average time before they change state
  - Change of state can be induced by interaction with environment, which spoils the coherence
  - Qubits today reach $\sim 100\ \mu s$



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

Radiation Effect

- Environment also means radioactivity:
  - Far sources: atmospheric muons, neutrons, gamma rays
  - Close sources: radioactive contaminants of setup components



- Direct ionisation on qubit: rare (smaller dimensions)
- Phonons production in the substrate
  - Break Cooper pairs of quits superconducting material
  - Loose Coherence!

Radiation Effect

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

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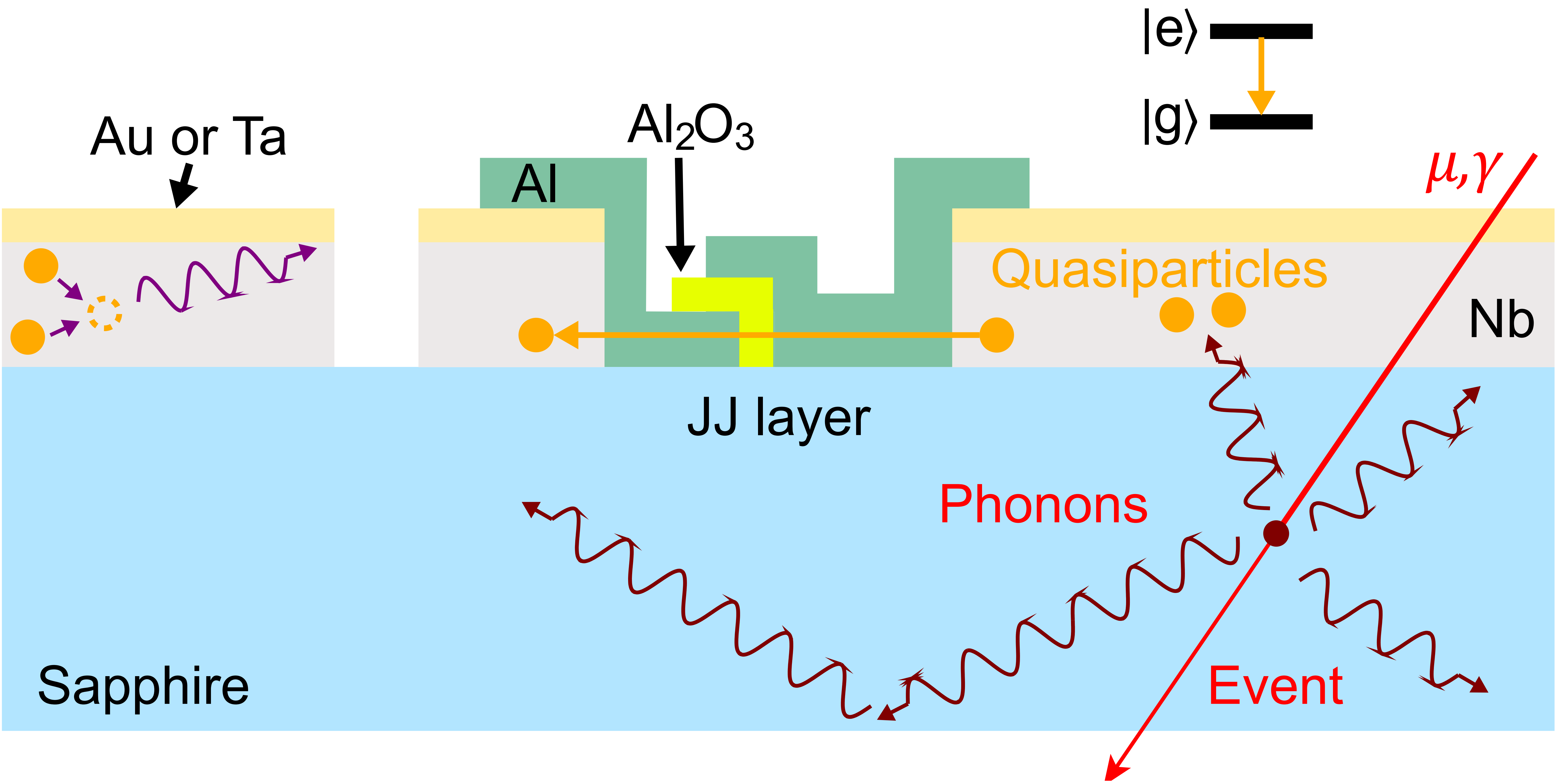


- As of today subdominant with respect to other effects that reduces coherence time
- But will be relevant for future devices
  - Coherence capability increases fast along years!

Qubits are sensitive to radiation

Loss of Coherence

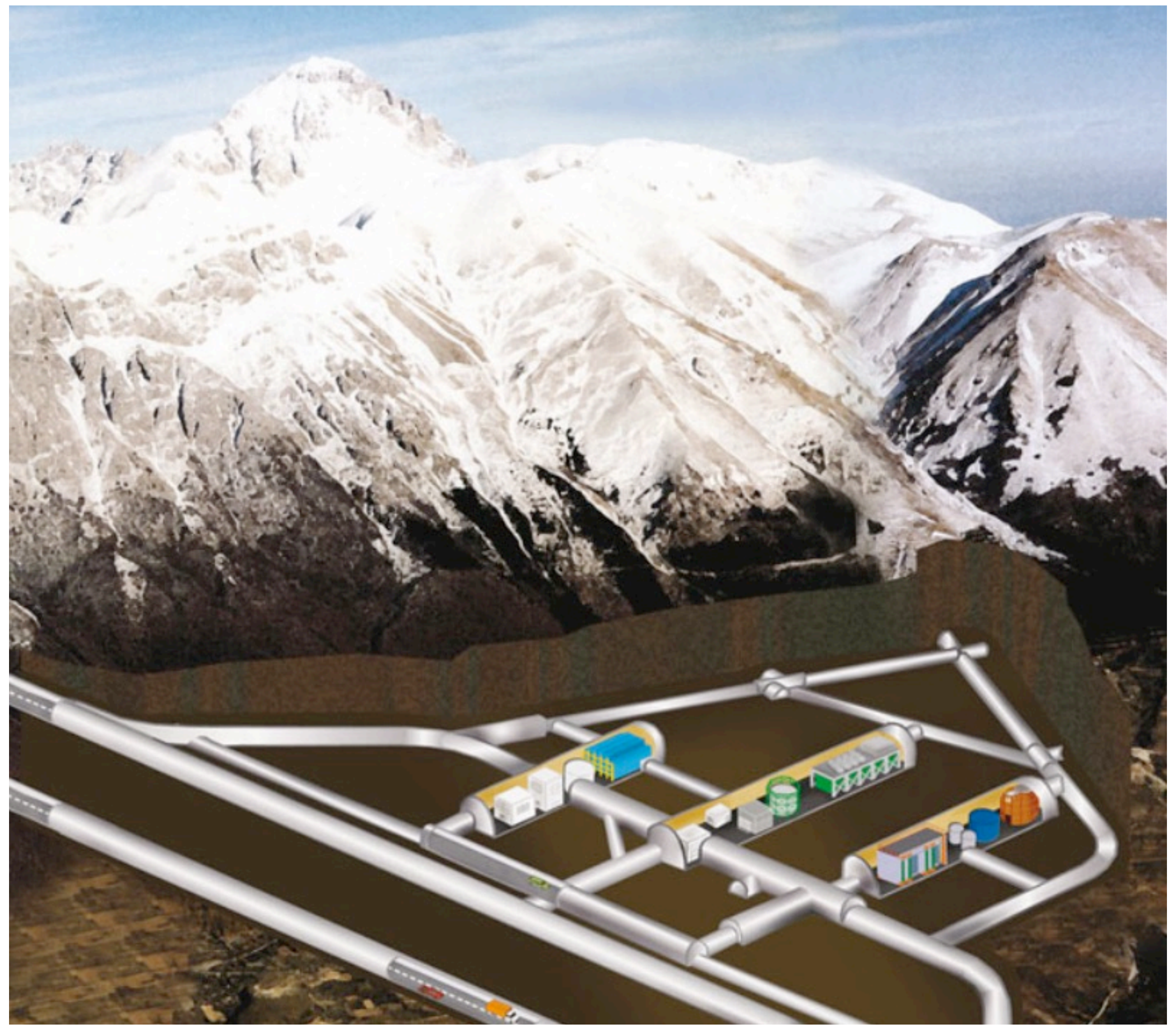
Particle Detectors

Identify and disentangle radiactivity

Improve Coherence

Radiation Effect

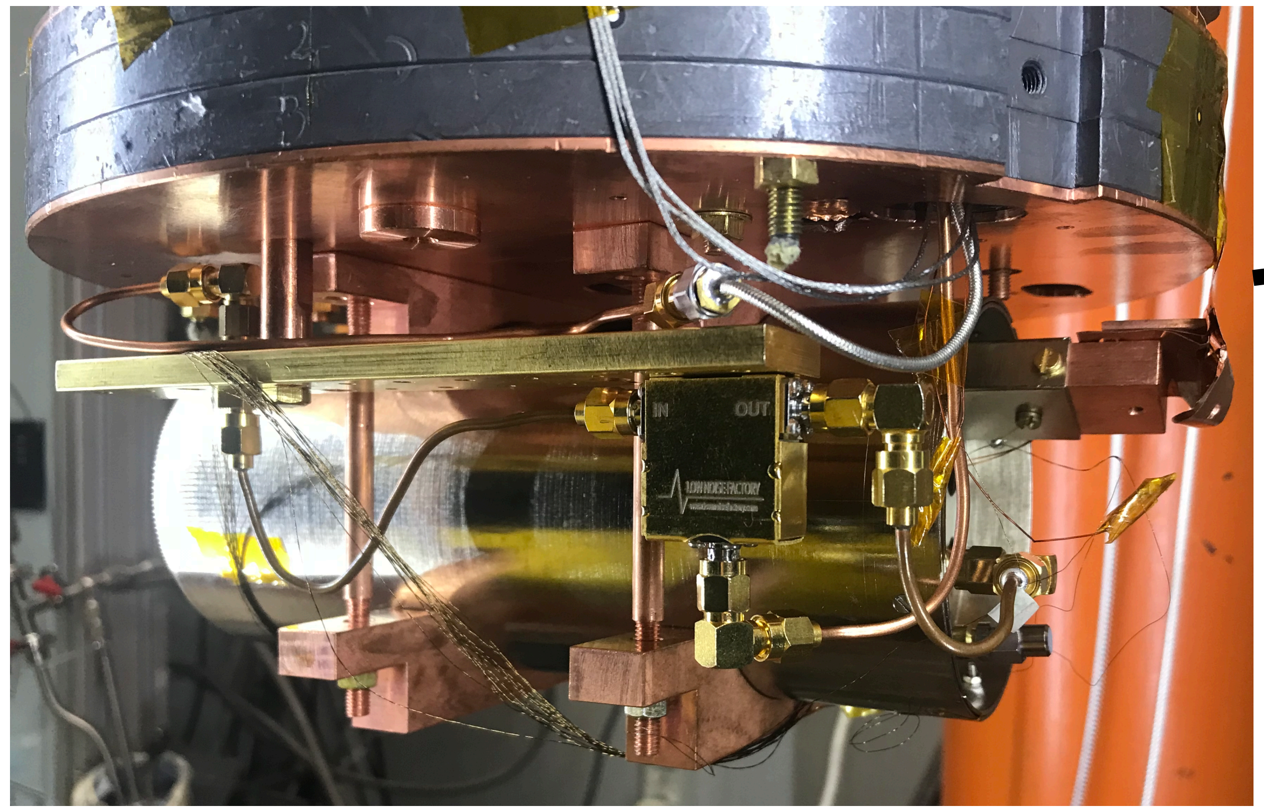
- Laboratori Nazionali del Gran Sasso - Hall C - IETI facility
- Dry dilution refrigerator (7 mK base temperature)
  - Same facility operated for several particle detectors!

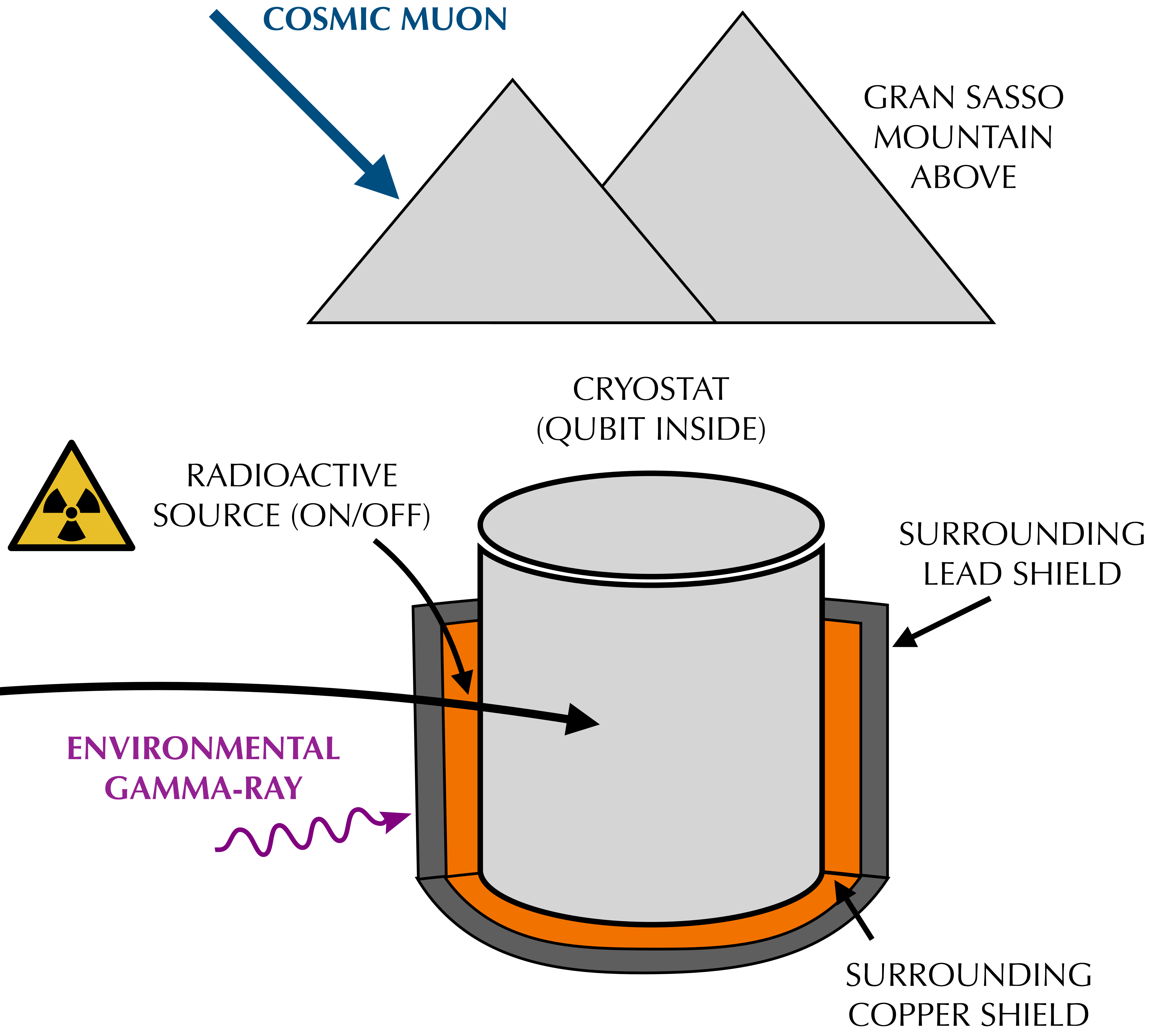


- 3600 m.w.e. reduce cosmic rays flux of a factor 10^6
- Internal + External Pb shield against radioactivity
- Internal + External magnetic shield

Experimental Setup

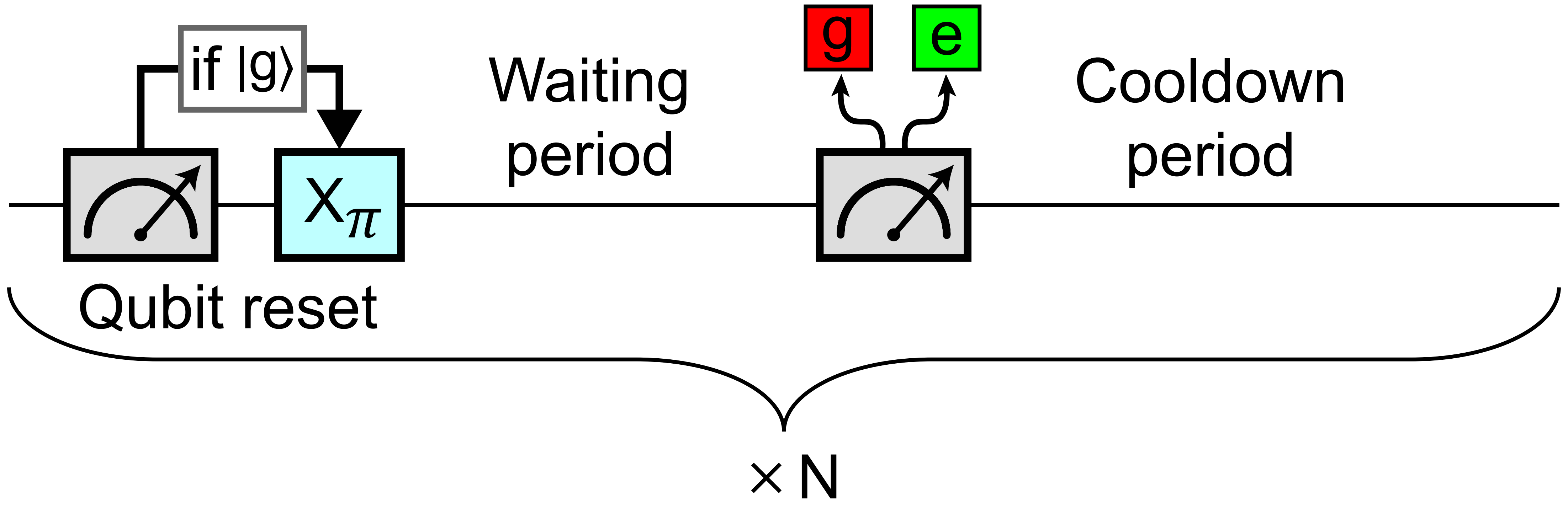
1. Cooldown the qubit to $\sim$ 35 mK
2. Characterize it in a low-radioactivity environment
3. Expose it to ^{232}Th sources placed outside of the cryostat
   - Activities: 44 kBq, 76 kBq, 125. kBq, 161 kBq



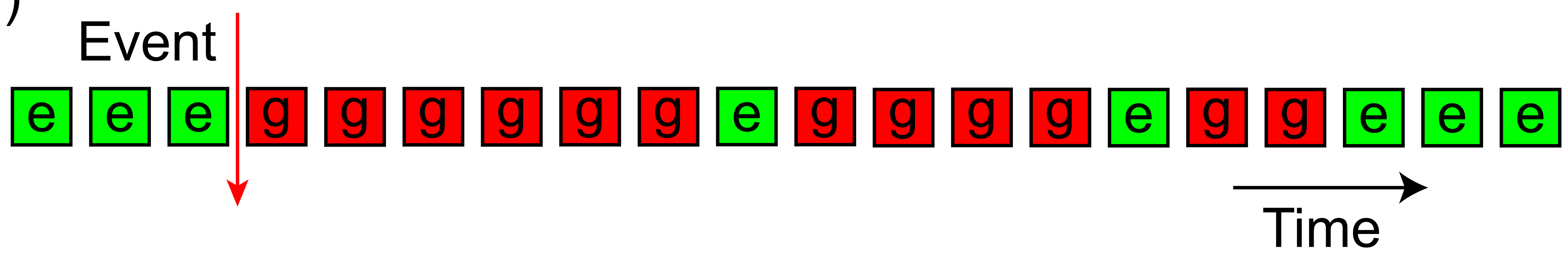


Detection Strategy

1. If $|g\rangle$
   - Reset to $|e\rangle$
   - Via π-pulse
2. Wait a few μs (<<dechoerence time)
3. Measure the qubit state: expect $|e\rangle$ if no interaction with environment

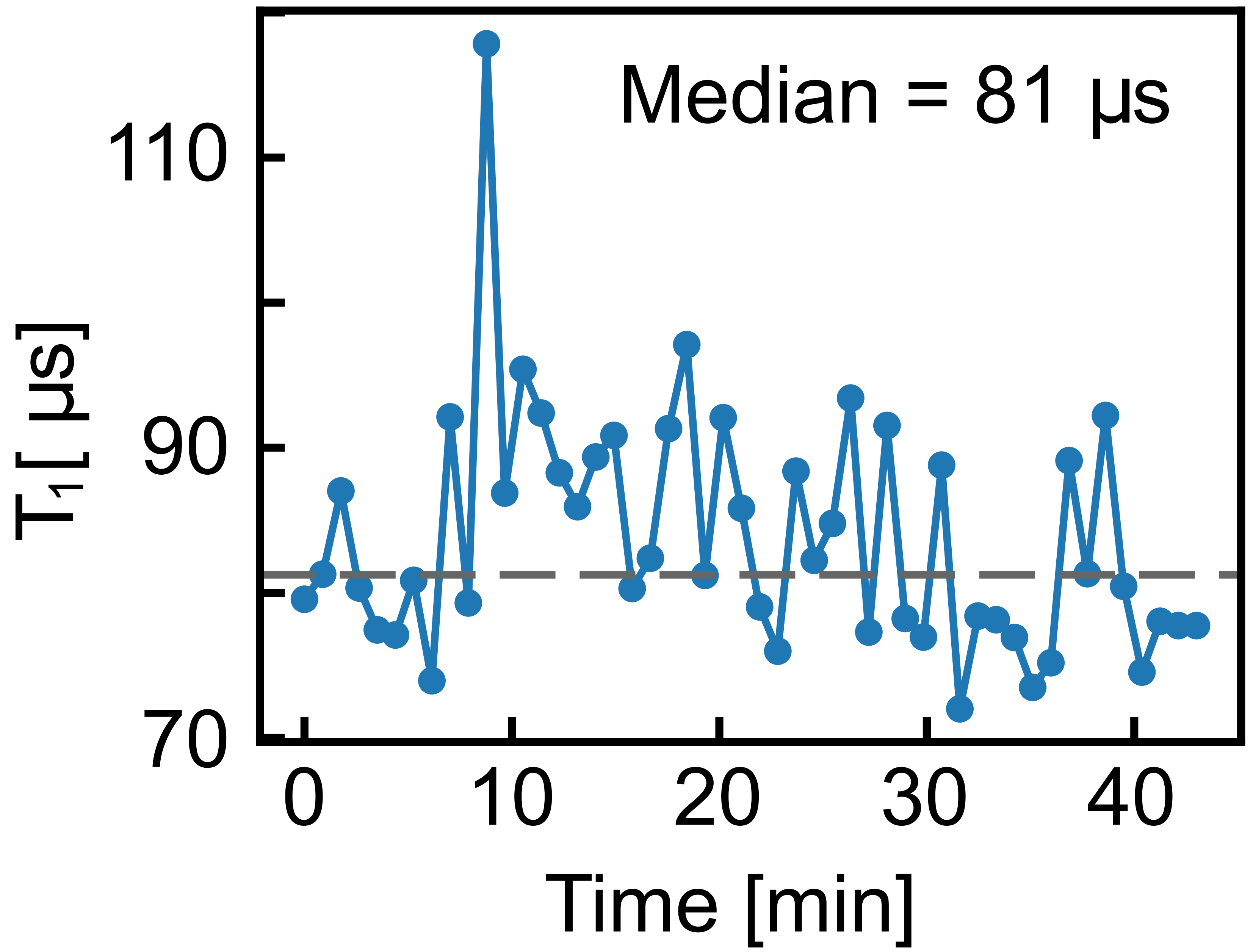


4. Wait a "cool down" period before next measurement
5. Repeat N times



T_s = waiting time + cooldown

Analysis Strategy



Occurrence of $|g\rangle$ with probability:

$$P(g) = 1 - e^{-\frac{\Delta t}{T_1}} \simeq \frac{\Delta t}{T_1}$$

The energy relaxation time (T_1) is estimated with long samples of measurement ($\sim 50\ s$) and then averaged

The waiting time (Δt) is fixed to $5 \mu s$

An interaction of the qubit with the environment breaks
this behaviour, causing an excess of ground measurements

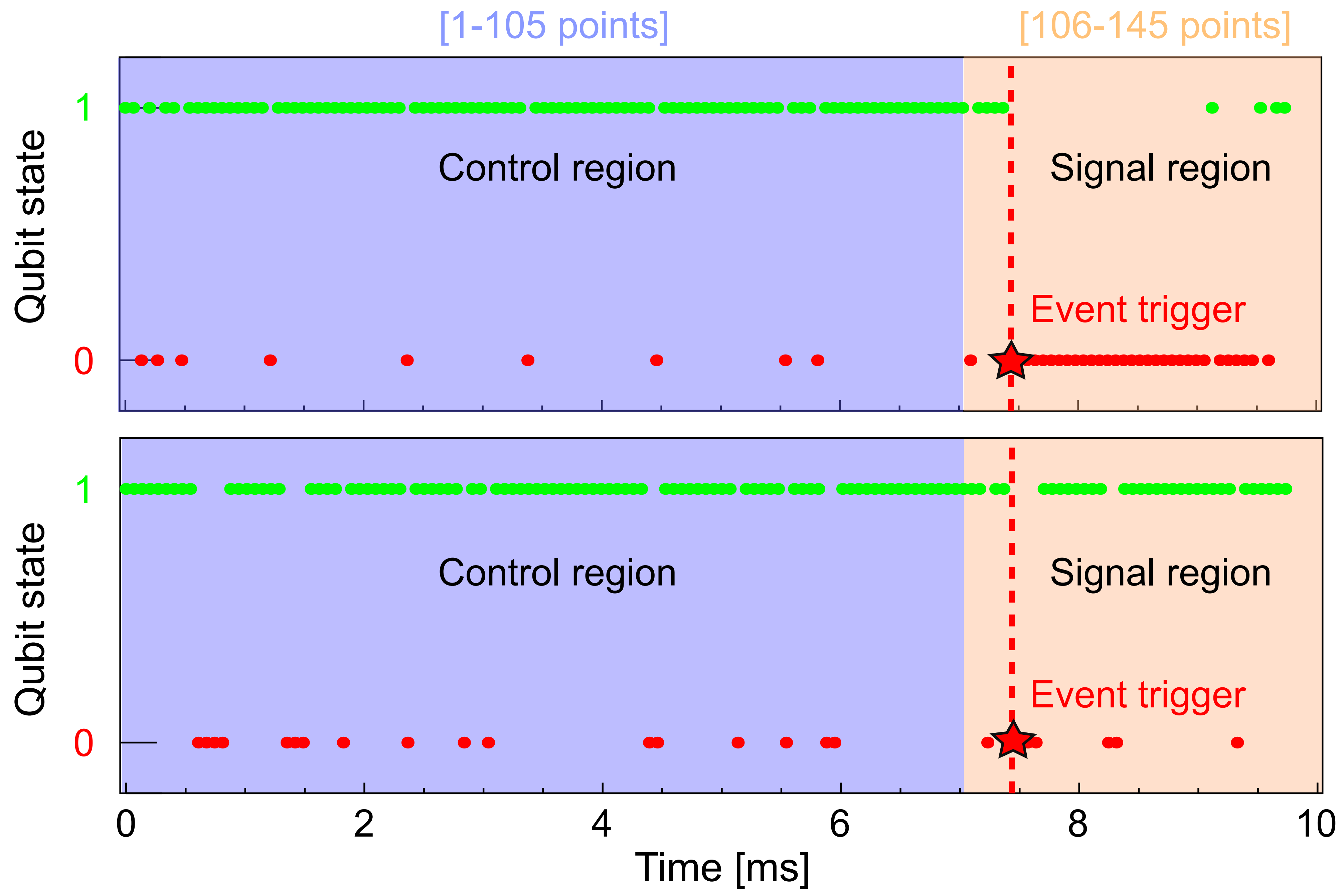
Analysis Strategy

- Trigger if 4 consecutive zeros (or $|g\rangle$)
- Signal Region + Control Region (to compute $P(g)$ locally)

"Spontaneous decohoerence" rate of:

$$\frac{P(g)^4}{T_S}$$

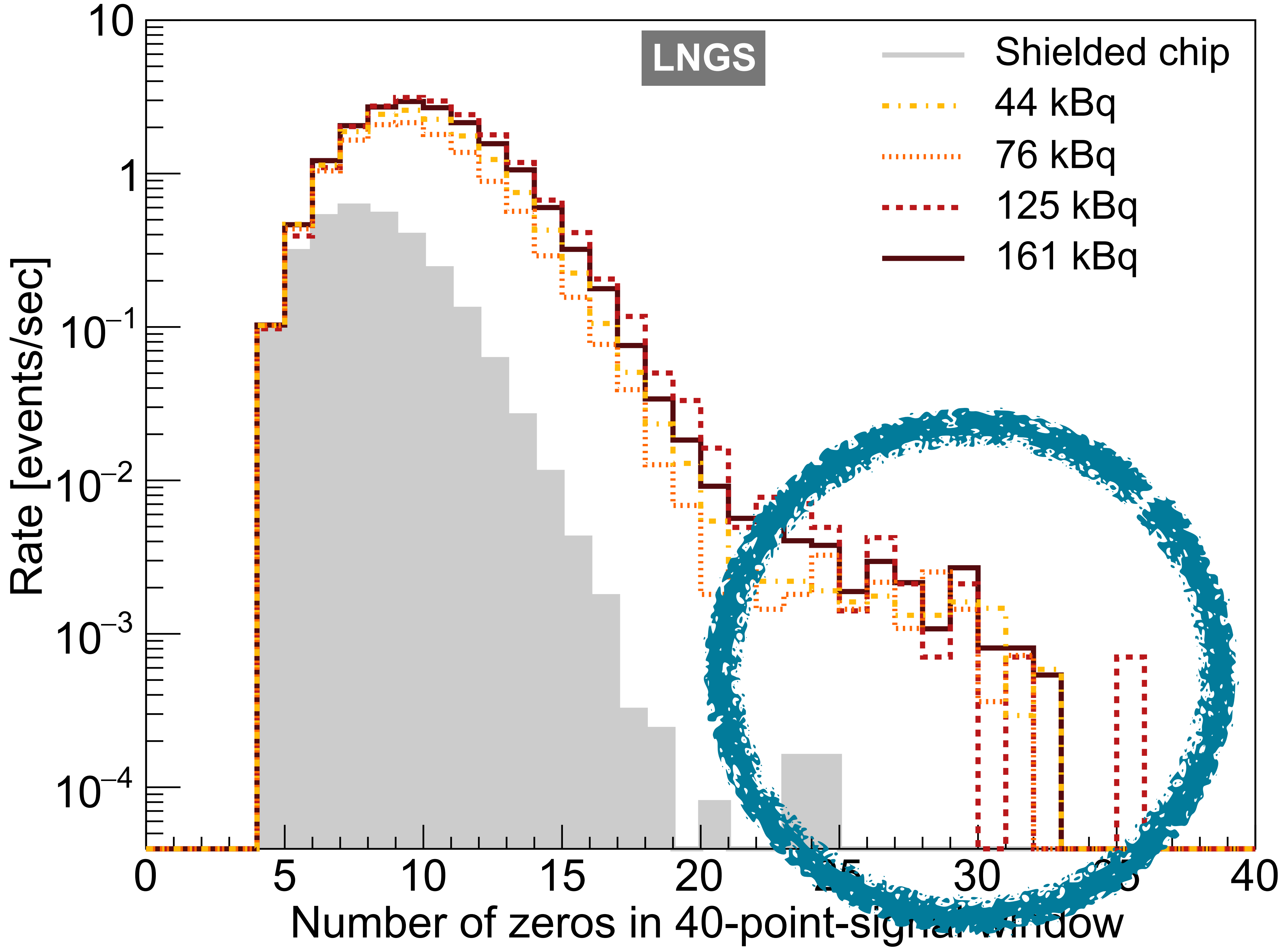
4 $|g\rangle$ compromise noise rate minimisation over signal efficiency



Signal Event

Spurious Trigger

Results



- Binomial bulk + right-end tail
- A spectrum for each radioactivity source at increasing level
- Tail more pronounced in case of sources
  - Radioactivity events!

De Dominicis et al, arXiv:2405.18355

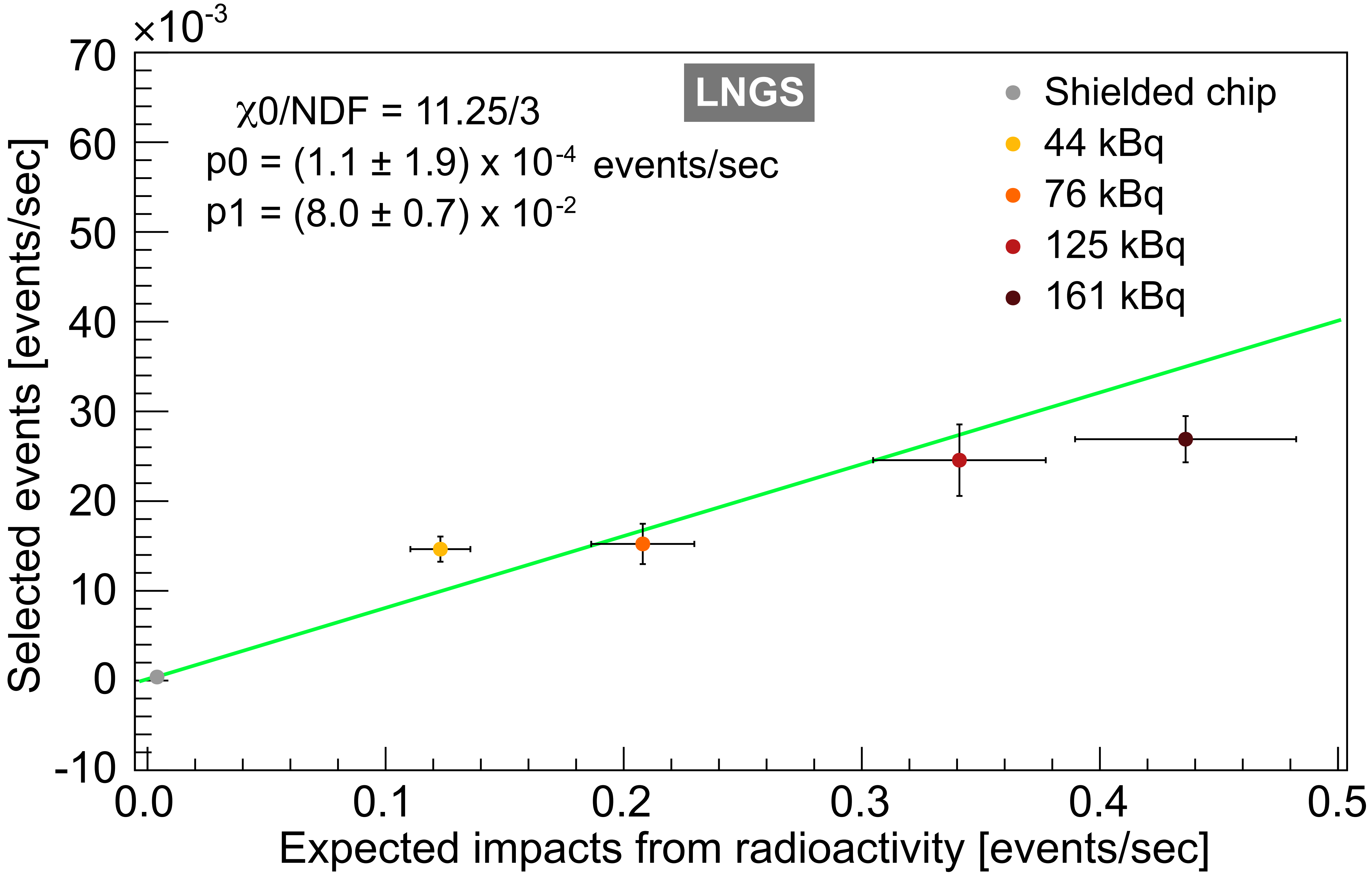
Results

Quality cuts:

1. High number of zeros by requiring:

   Spontaneous decoherence rate < Radioactivity impact from MC

2. Reject events with anomalous number of zeros in the control region

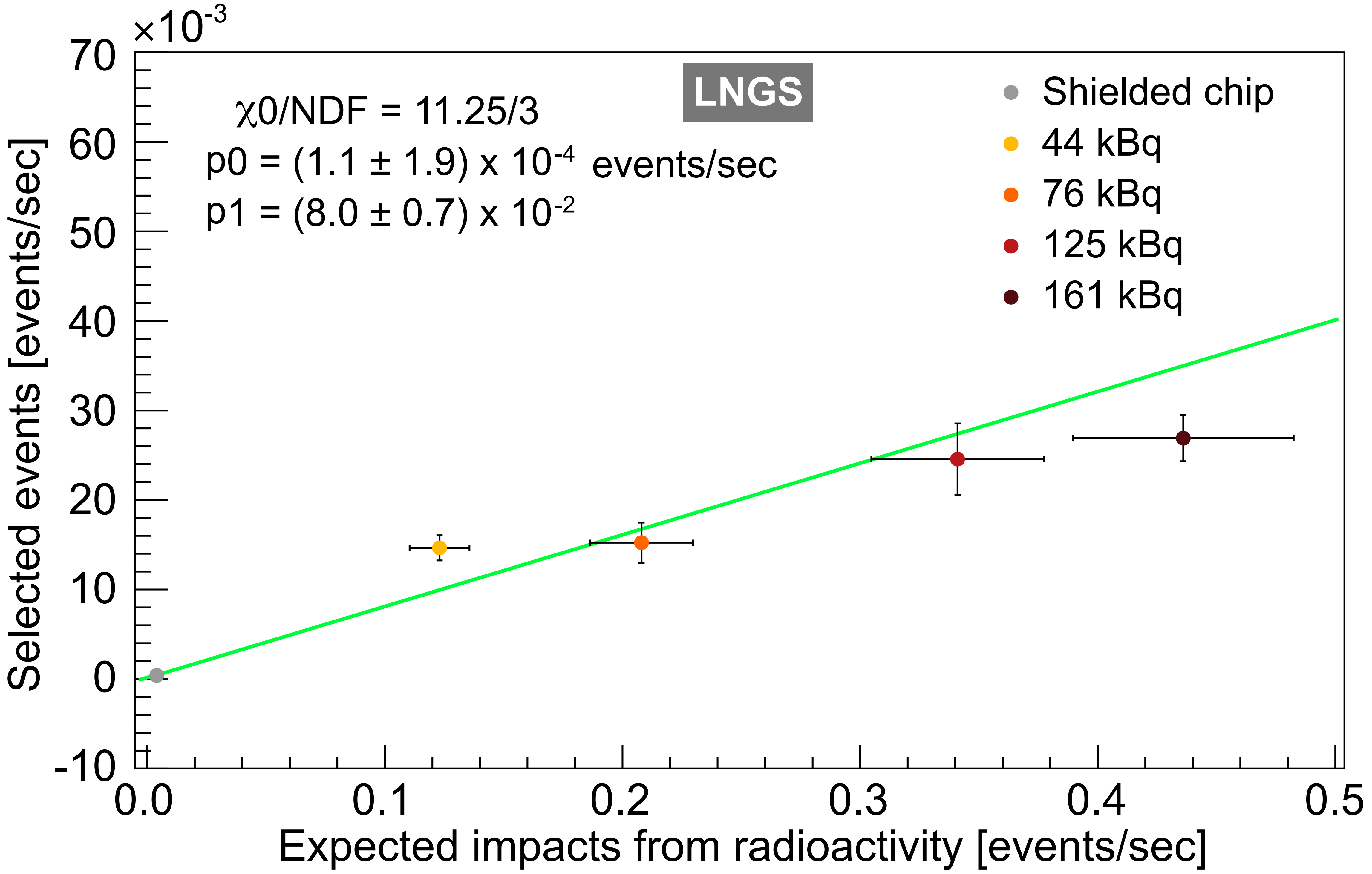


Resulting rate compared with MC simulation

https://doi.org/10.1140/epjc/s10052-023-11199-2

Results

- Linear behaviour demonstrate sensitivity to the increasing exposure to sources
- Signal efficiency < 8%
  - There is room to refine quality cuts
  - Ongoing development for new measurement to asses the efficiency independently



Results

- Same measurement repeated at FNAL above ground

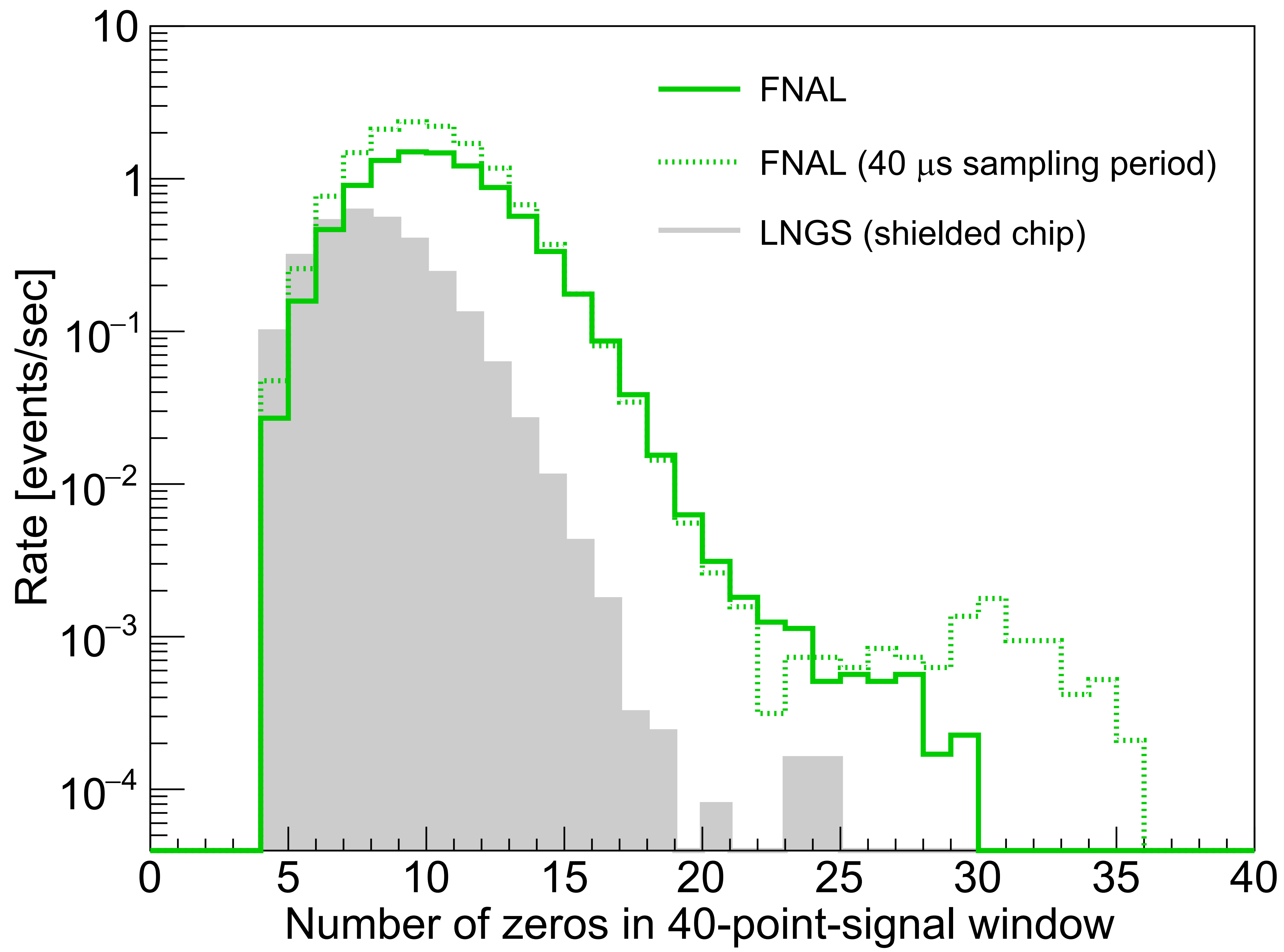
  - No sources

  + Muons

- The measured rate agrees with the simulation predictions:

  ~10 times more than underground

- We can measure cosmic rays with a qubit!



Conclusions

- We successfully operated a superconducting qubit to observe radioactivity in underground and above ground facilities
- We set the basis to understand and analyse qubits events
- Many more questions to come:
  - Which are their features as particle detectors? Efficiency, Energy Threshold...
  - Are qubits sensitive to different interactions or different position of energy deposit?
  - Can we disentangle the radioactivity to improve coherence time?
- Many more measurements coming soon!

Thanks for your attention!

Backup

Sampling Period

- Effect from sampling period
  - More measurements implies more zero
- Higher sensitivity to particle events
  - Better capability of disentangling spurious and signal events