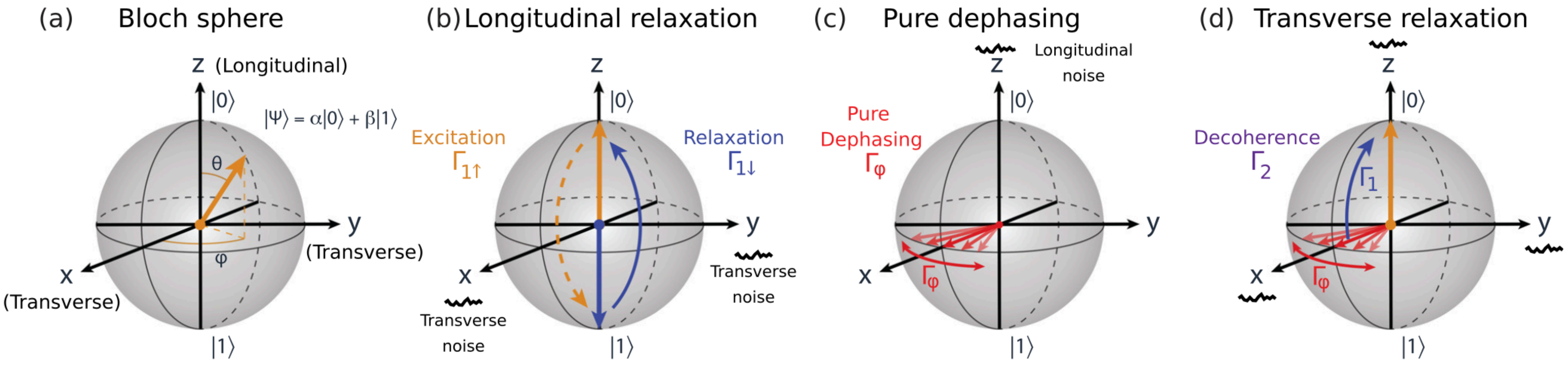
# Qubits as Particle Detectors

## Analysis of Runs at LNGS and FNAL

Ambra Mariani for the INFN team, 24 July 2024 - Roma

# How Does a Qubit Work

A **quantum state** can be geometrically represented on the **Bloch Sphere.**

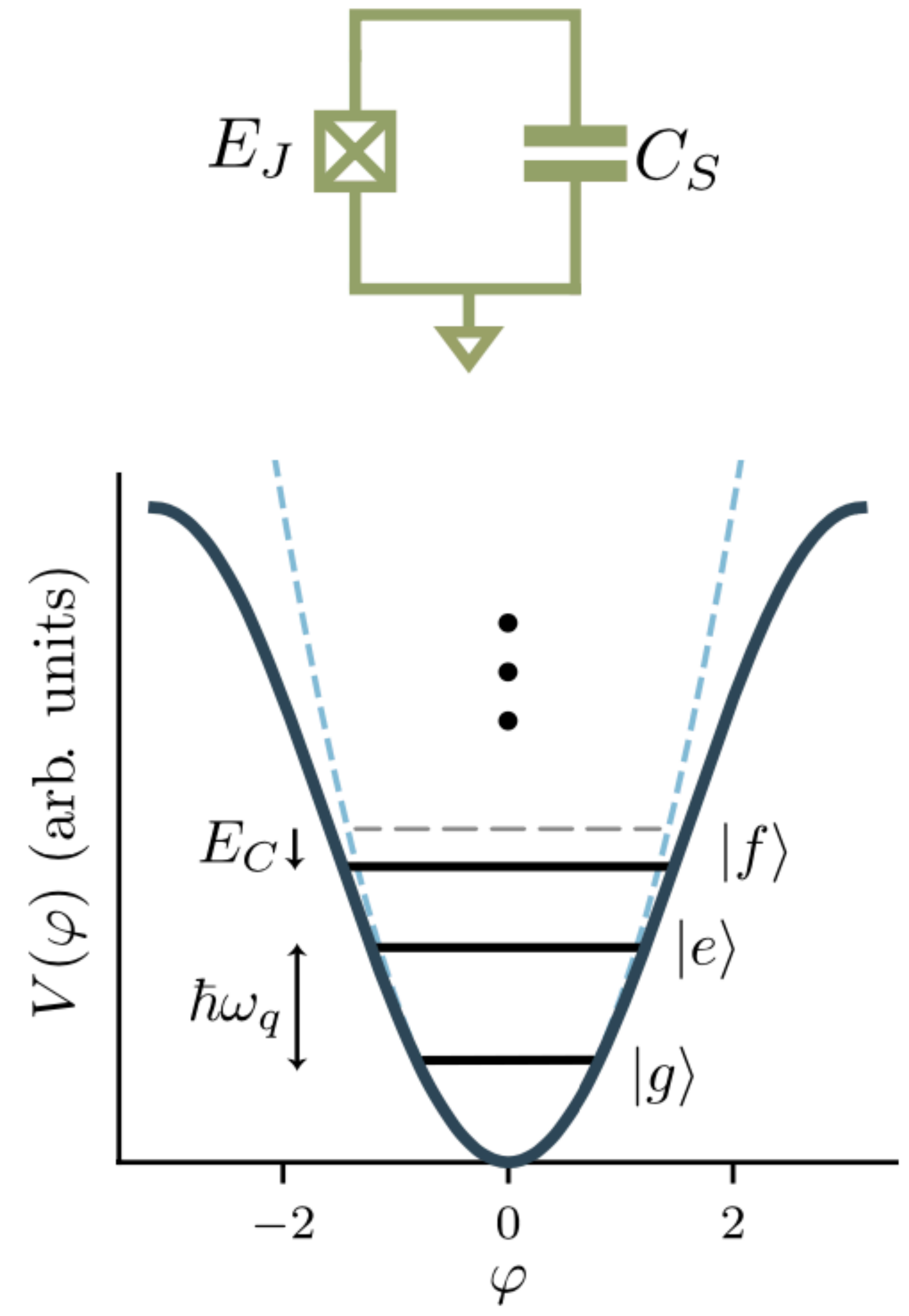



[ Krantz et al., Appl. Phys. Rev. **6**, 021318 (2019) ]

- Interactions with the environment can lead to unpredictable changes in the qubit state;
- When they occur the information stored by the qubit is lost (**decoherence**).

# Transmon Qubit

(Charge-insensitive) **superconducting circuit** with a **Josephson Junction (JJ).**

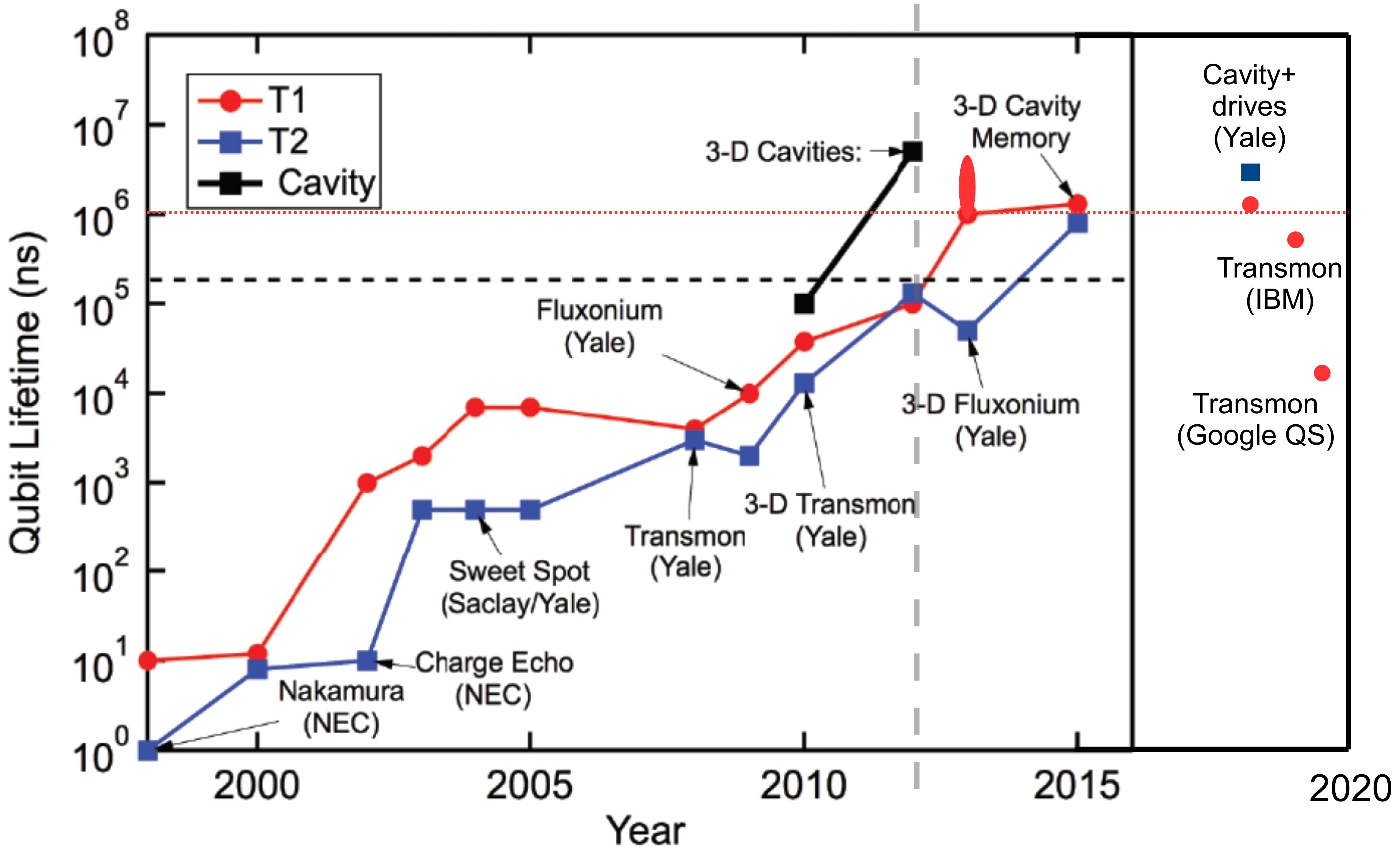



**Anharmonic energy spectrum**
**—> Two-level system**

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

Typical **relaxation times T1:**

From **tens** up to **hundreds** of **μs**

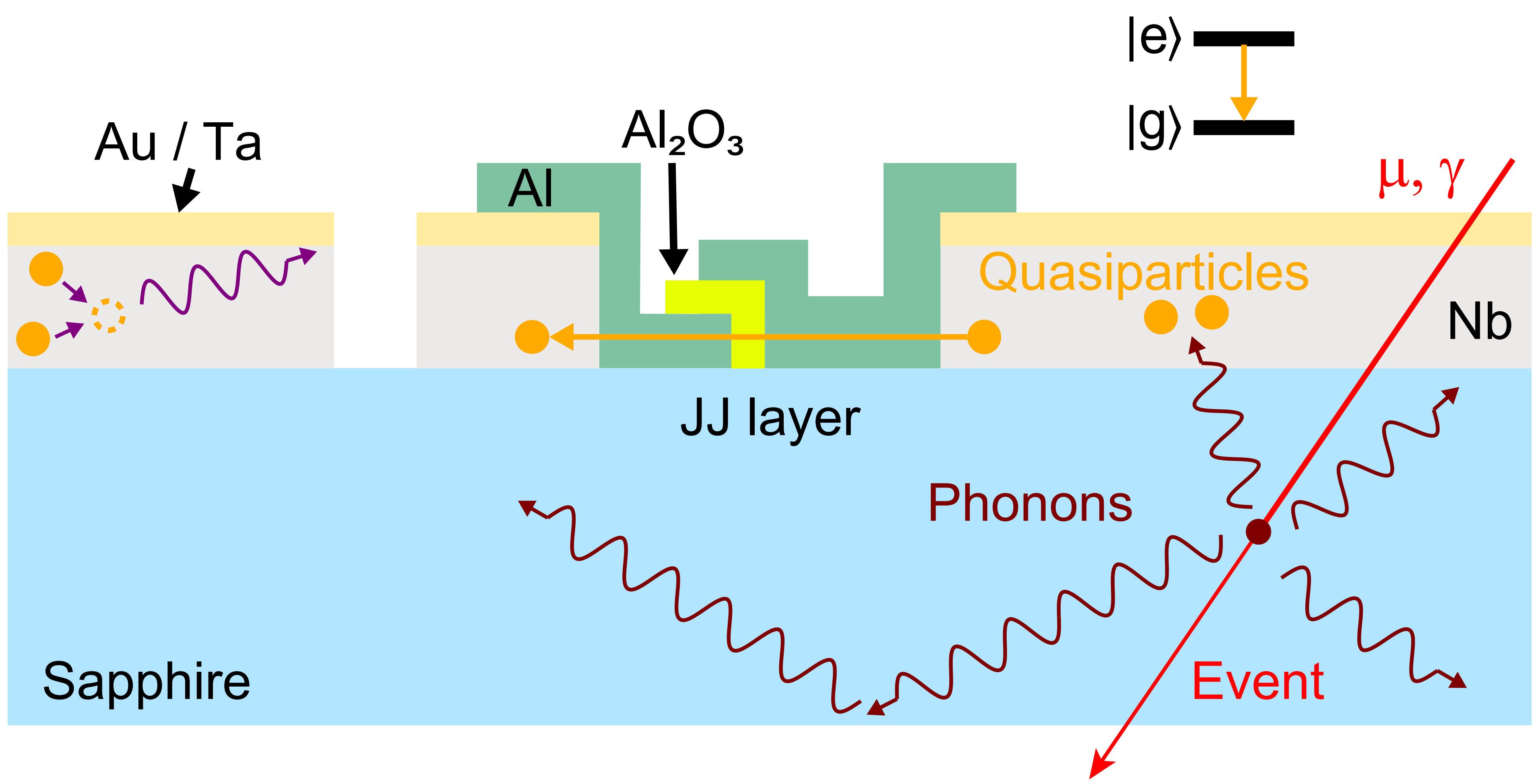



Original plot (up to 2012): [ M.H. Devoret & R.J. Schoelkopf, *Science* **339**, 1169 (2013) ]

Extension (up to 2015): [ M. Reagor, PhD thesis (Yale) ]

# What about Ionizing Radiation?

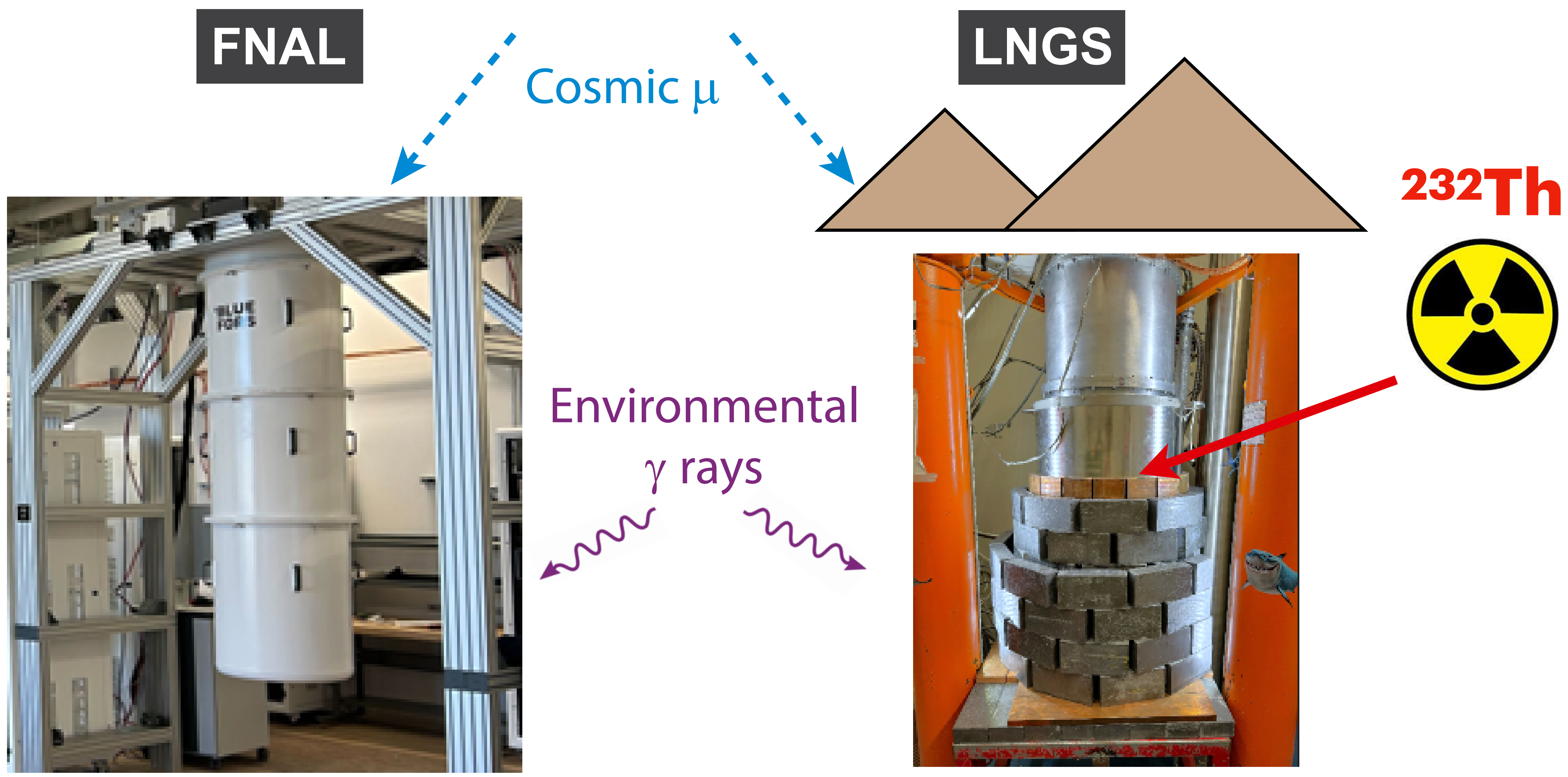
**Superconducting qubits** can be **sensitive** to **particle interactions** within the **substrate**.




1. **Energy deposits** produce thousands of **charges**;
2. Many charges recombine creating **phonons** that diffuse throughout the chip;
3. In the superconductor, these phonons can break Cooper pairs into **quasiparticles**;
4. If **quasiparticles tunnel through** the **JJ**, the **qubit** loses its energy and quickly **decays** to its **ground state**.

**Quasiparticles take some time to dissipate and tunneling events can continue to occur —> T1 drops!**

# Our Experimental Conditions




We acquired data in **three different conditions:**

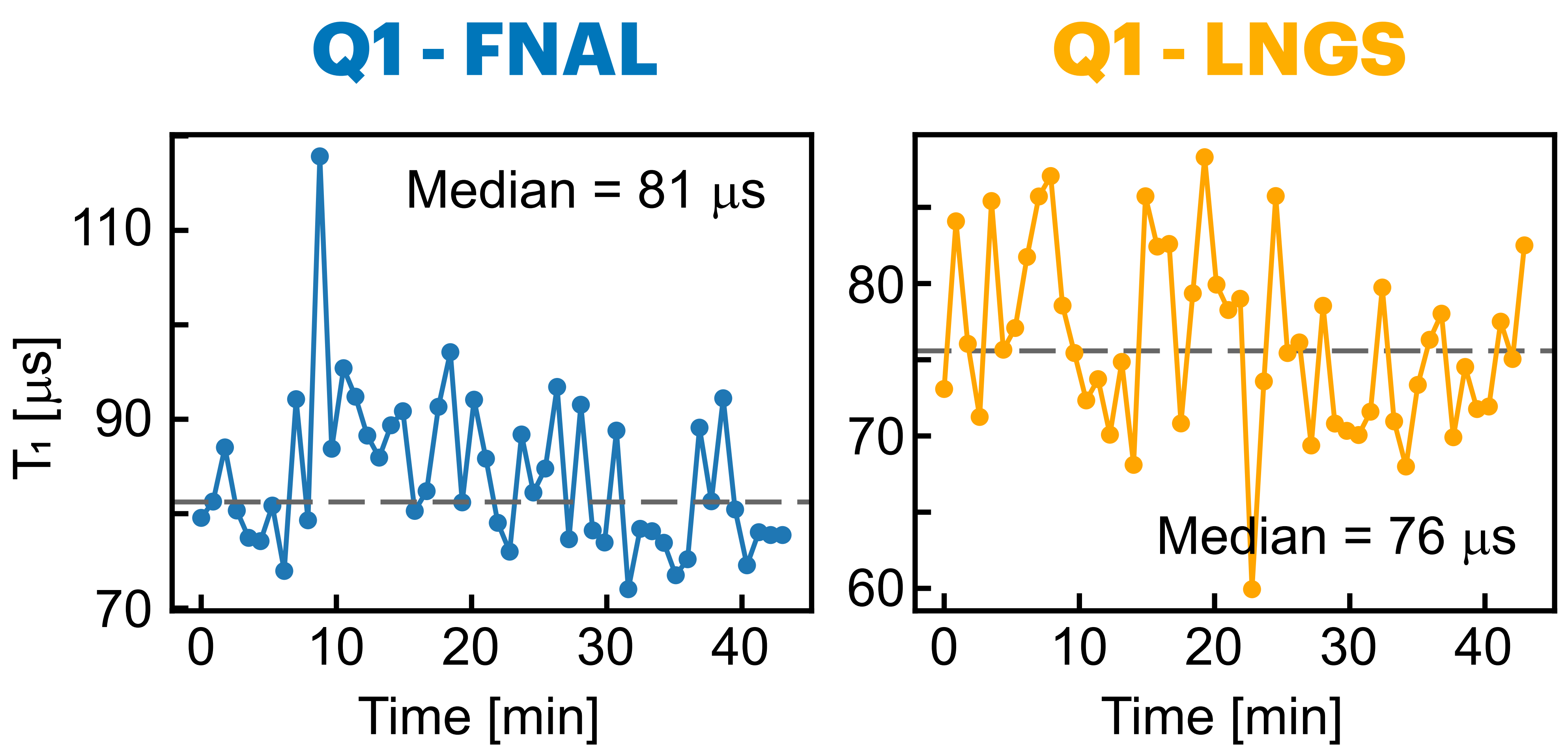
1. **Chip exposed** to **cosmic rays** and **environmental gammas (FNAL)**
   - Predicted rate ~0.057 events/sec.
2. **Chip shielded** from external radiation **(LNGS)**
   - Predicted rate ~ 0.004 events/sec.
3. **Chip exposed to Thorium radioactive sources** with increasing activity levels **(LNGS)**
   - Expected rates ranges from 0.12 to 0.43 events/sec.

# Standard T1 experiment

- The qubit is prepared in |1> and its state is measured after different time intervals ($\tau$):

$$P(t=\tau) = P_{t=0}\ e^{-\tau/T_1}$$

- We **monitored** the **energy relaxation time** for close to an hour at both FNAL and LNGS.
- **No sudden T1 drops** were observed (typical fluctuations only).

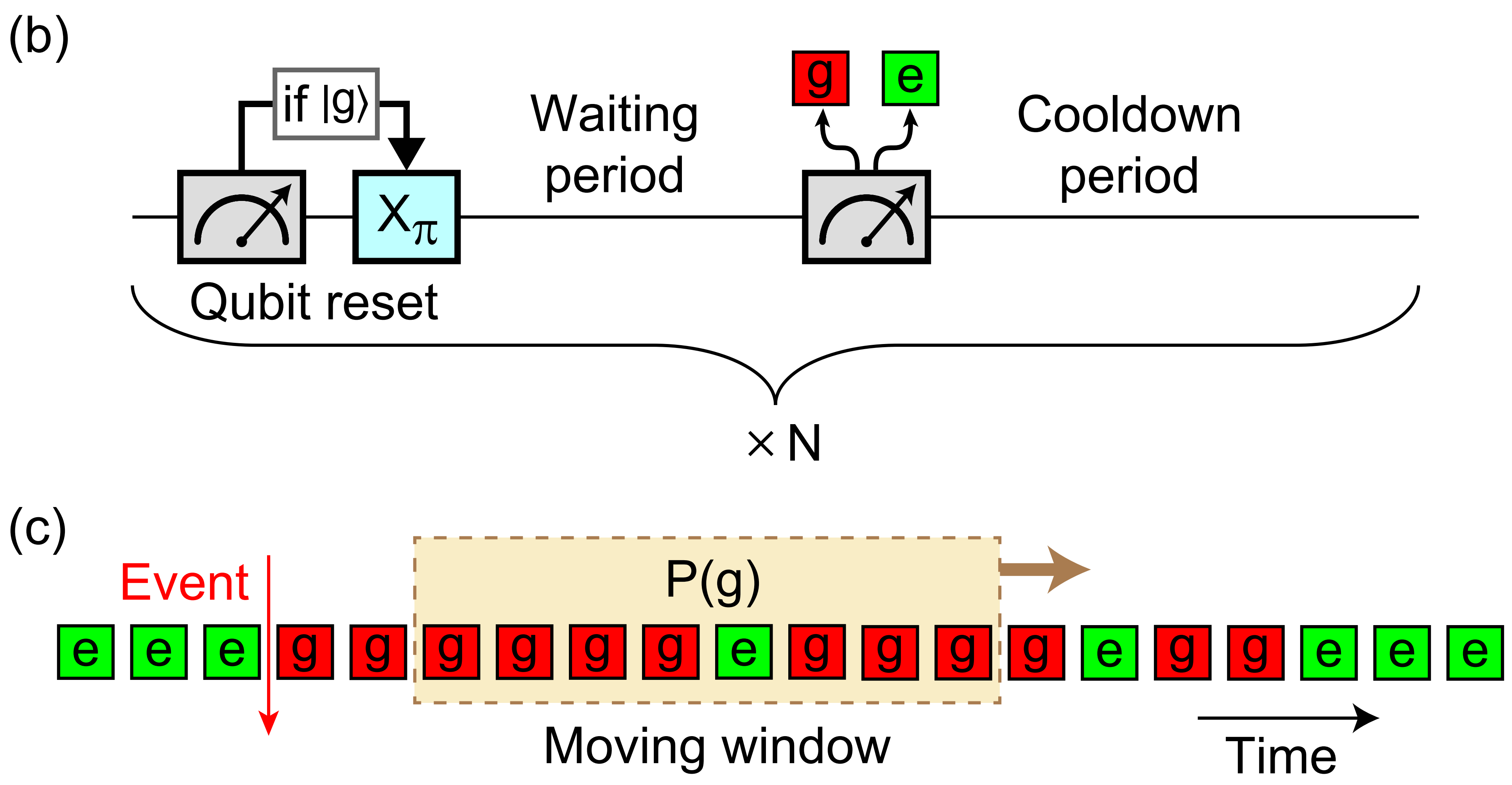



**Standard T1 measurements are slow —> not sensitive to energy deposits in the chip**

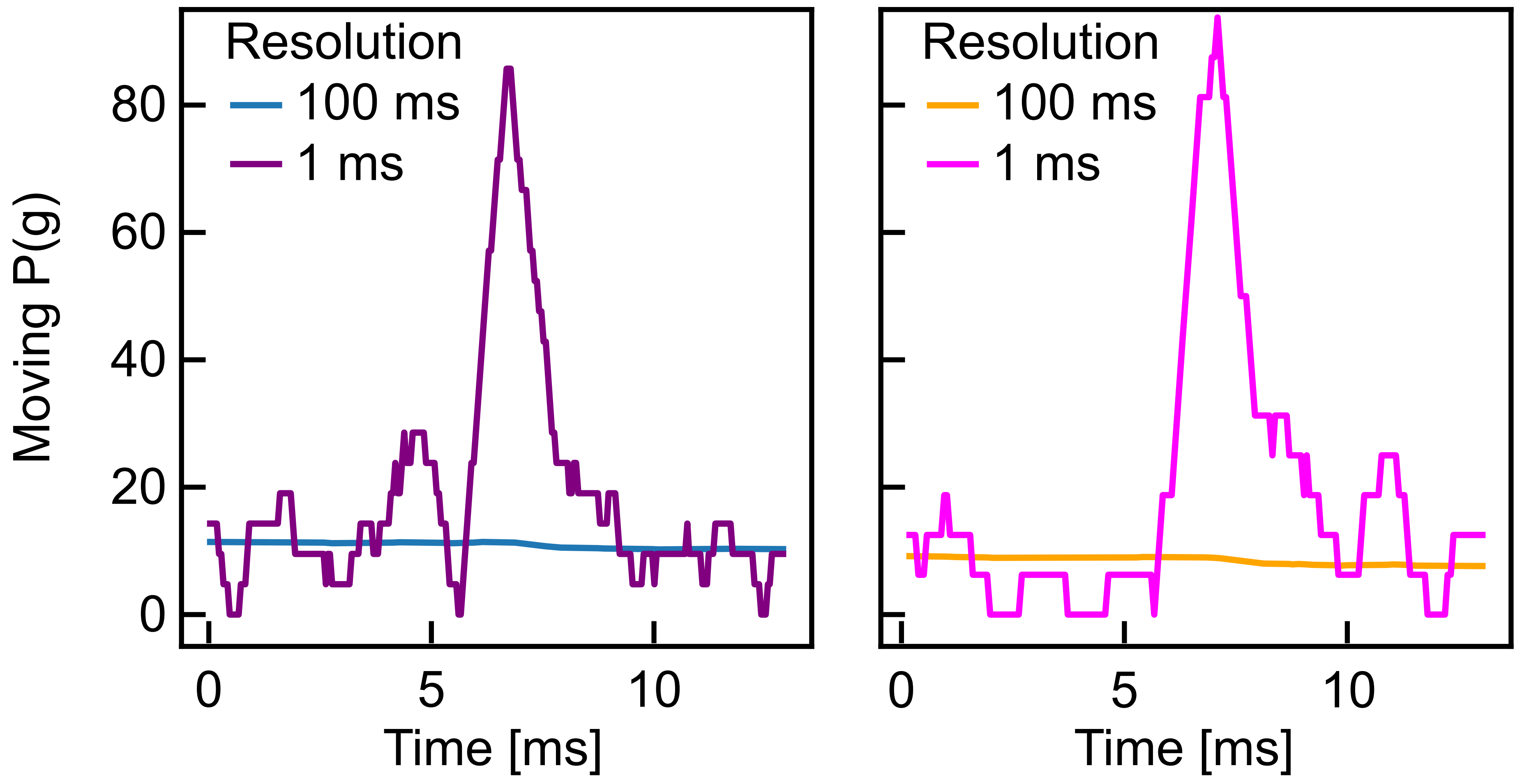
**Dedicated protocols are needed.**

# Fast Decay Detection Protocol

1. **Set qubit in |1>** by applying a conditional π-pulse if qubit is found in |0>;
2. **Wait** few μs;
3. **Measure** its status.

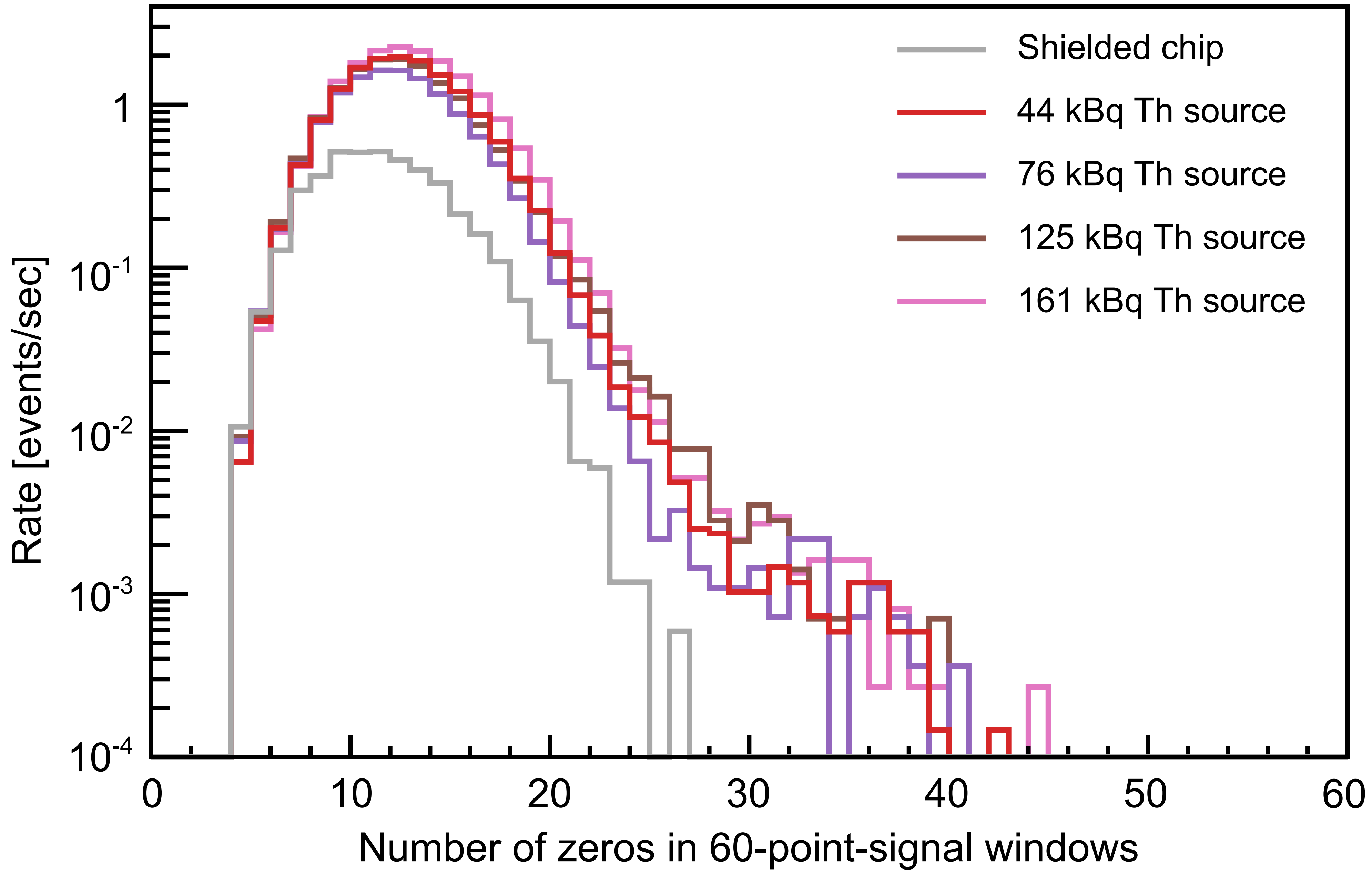



- The qubit T1 is tens of μs, so the majority of times it should still be in |1>.
- Ionizing radiation breaks Cooper pairs in the qubit, with an effect lasting ~milliseconds.
  - The qubit will decay in |0>.
  - If I reset it quickly in |1>, I will find it again and again in |0>.



# A Basic Approach

- Every time we find **4 consecutive zeros** we save an analysis window.
  - High signal efficiency while reducing false triggers from qubit spontaneous decay —> we expect ~12-35 zeros for radiation-induced events lasting 1 millisecond, depending on the run.
- We compute the number of zeros in this window.



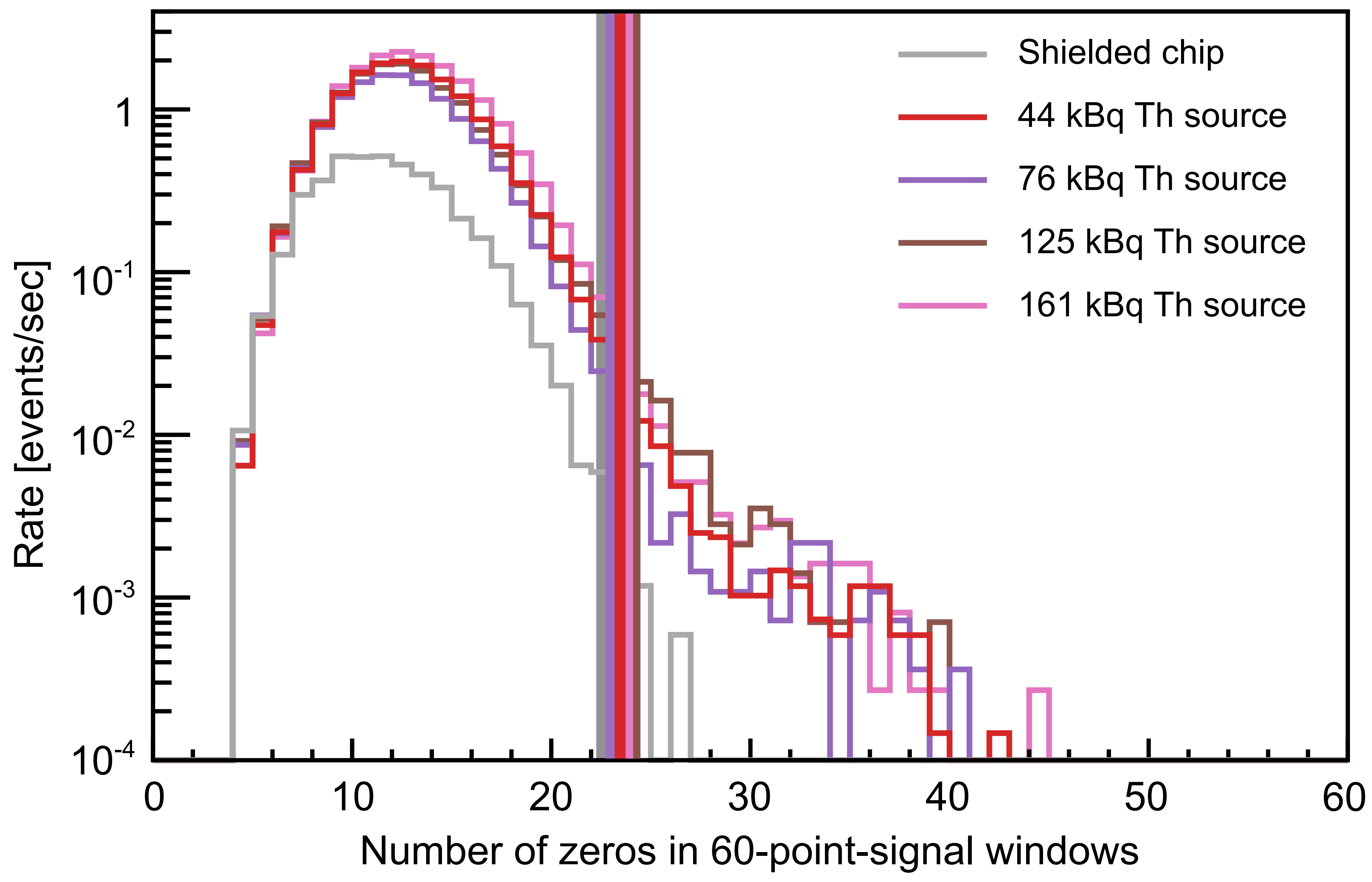

The **number of zeros** follows a **Binomial distribution** according to the T1 of the qubit, with some **deviations at 30-40 zeros —> radiation-induced events?**

**Overall rate still dominated by qubit spontaneous decay.**

# Data Selection

We asked ourselves: **what is the minimum number of zeros that ensure a negligible rate from spontaneous decay?**

This **depends on the qubit T1** that, unfortunately, varies on a short timescale.



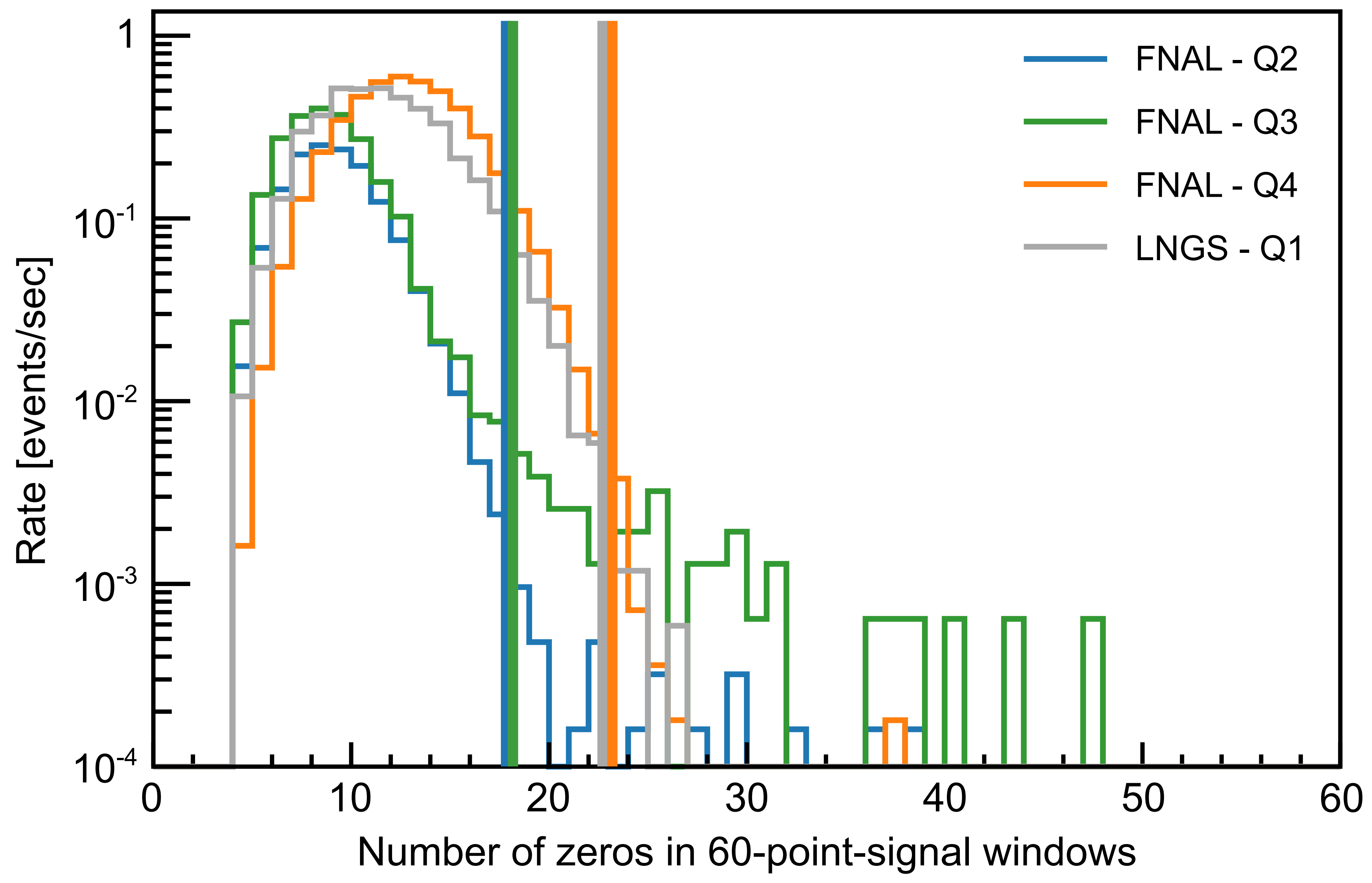

For **each run:**

- We calculated an average T1;
- Based on that value, we **set a minimum number of zeros** (18-24) to minimize false triggers from qubit spontaneous decay;
- We **counted the events above this threshold.**

# Results - (1)

In qubits with similar designs, we observed a **rate** that **depends mostly** on the **qubit** and on its **noise level.**

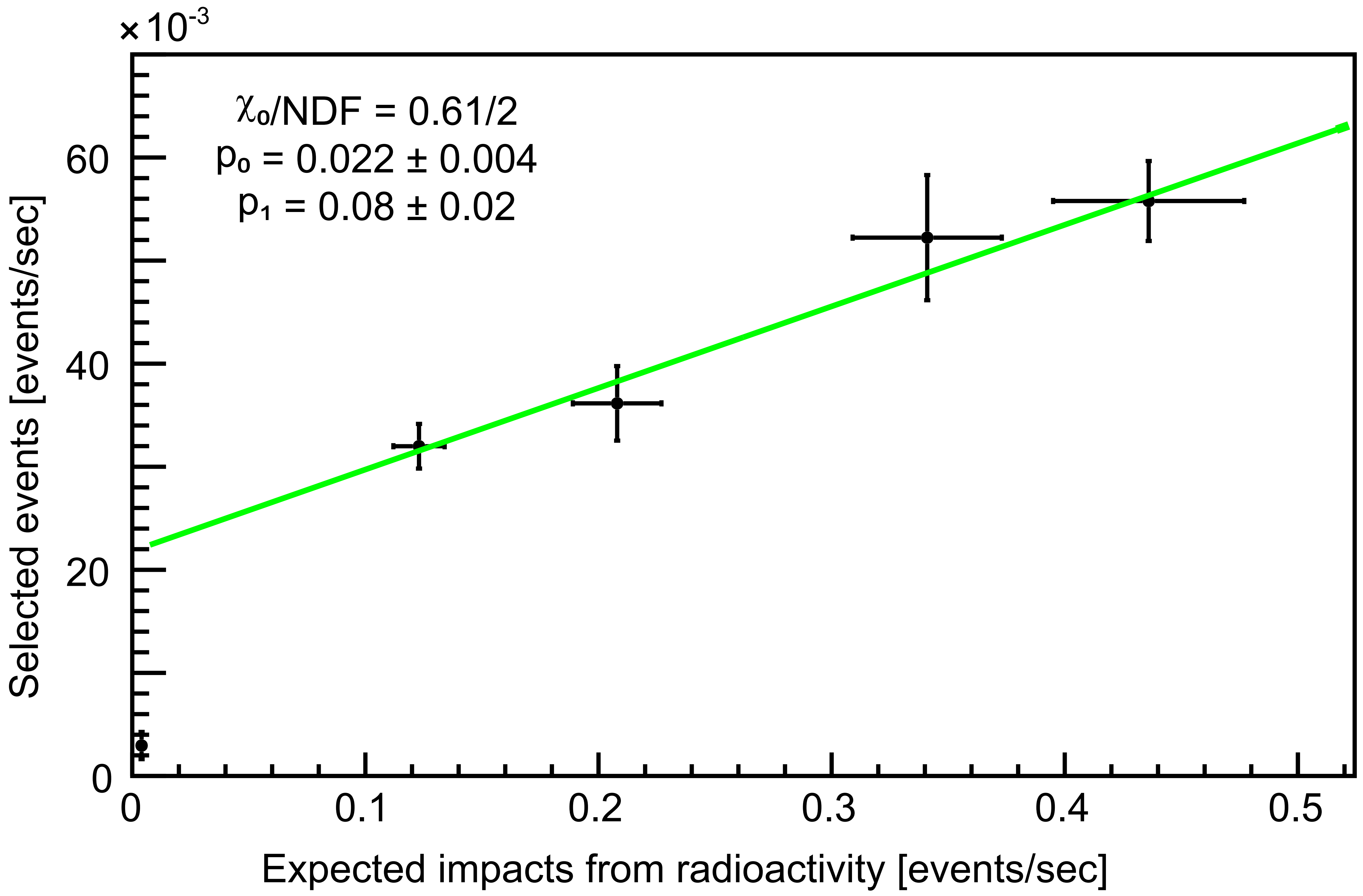
**Even a protocol designed to disentangle radioactivity is not very effective.**




| Datasets | Measured Rate [events/sec] | Radioactivity Contribution [events/sec] |
|---|---|---|
| Shielded chip | $(2.9 \pm 1.3)\times10^{-3}$ | $(4.0 \pm 0.6)\times10^{-3}$ |
| FNAL Q2 | $(3.2 \pm 0.7)\times10^{-3}$ | |
| FNAL Q3 | $(4.7 \pm 0.9)\times10^{-3}$ | $(57 \pm 3)\times10^{-3}$ |
| FNAL Q4 | $(25 \pm 4)\times10^{-3}$ | |

# Results - (2)

However, by deploying **sources with increasing activity** we were able to see a **linear correlation.**




**Comparing with expected rate, we found an efficiency of 8%.**

# What Next: Tomorrow

We are **improving** the **analysis protocol:**

- For each defined window, we compute the Binomial probability to obtain that distribution of zeros;
- Such a probability depends on T1, that can be computed right before the interaction for an on-line correction;
- However, runs with significantly different T1 must be somehow scaled for an effective comparison.

# What Next: The Day After Tomorrow

**Signal efficiency limited by the cut on the number of zeros.** With signals developing in ~1 millisecond (~12-35 zeros) using a cut at 18-24 zeros is bad.

**We need to limit the qubit spontaneous decay:**

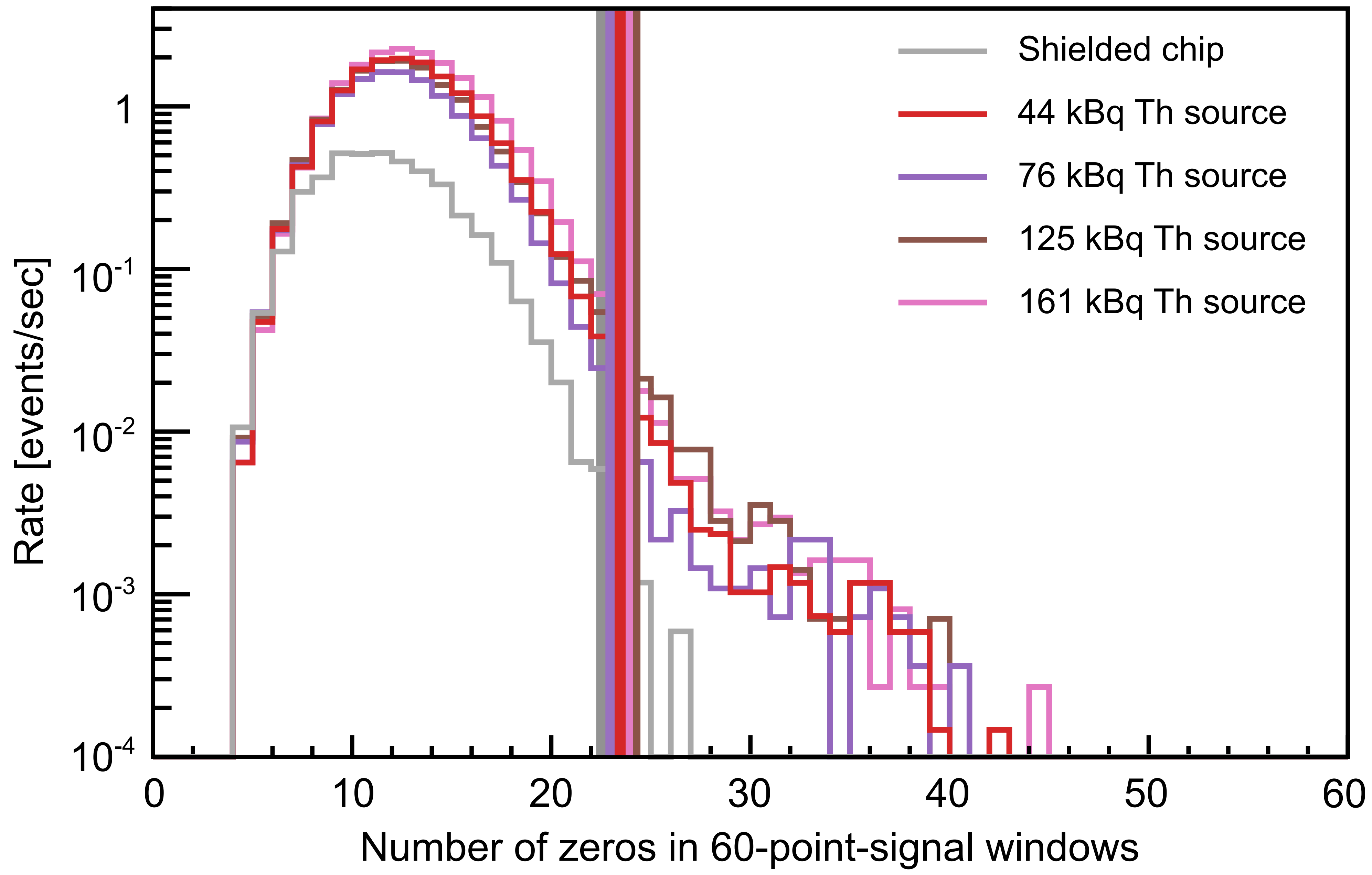
—> longer T1 (chip already available);

—> faster protocol (tests ongoing);

—> coincidence between qubits (to be implemented);

**We need higher fidelity** (now ~ 80%):

—> JPA or other amplifiers with good performance.



# What Next: INTREPID

- **Modification** to the **chip/qubit design** to ensure **high phonon collection:**
  - SQMS available for fabrication, G. Catelani available for theoretical guidance, simulation of phonons needed unless we want to open the collaboration to Q2A.
- Implementation of **coincidences among qubits:**
  - SQMS detains key expertise, Francesco De Dominicis is deeply involved.
- **Robust software environment:**
  - Present analysis scheme needs to be validated (other approaches might be better?);
  - Data and metadata must be stored and accessed without hard-coded values.

# Thank you!