

P R N

PROGETTI DI RICERCA DI
RILEVANTE INTERESSE
NAZIONALE



Istituto Nazionale di Fisica Nucleare

Response of qubits to particles and thermal phonons

Alberto Ressa

RIS*
2026

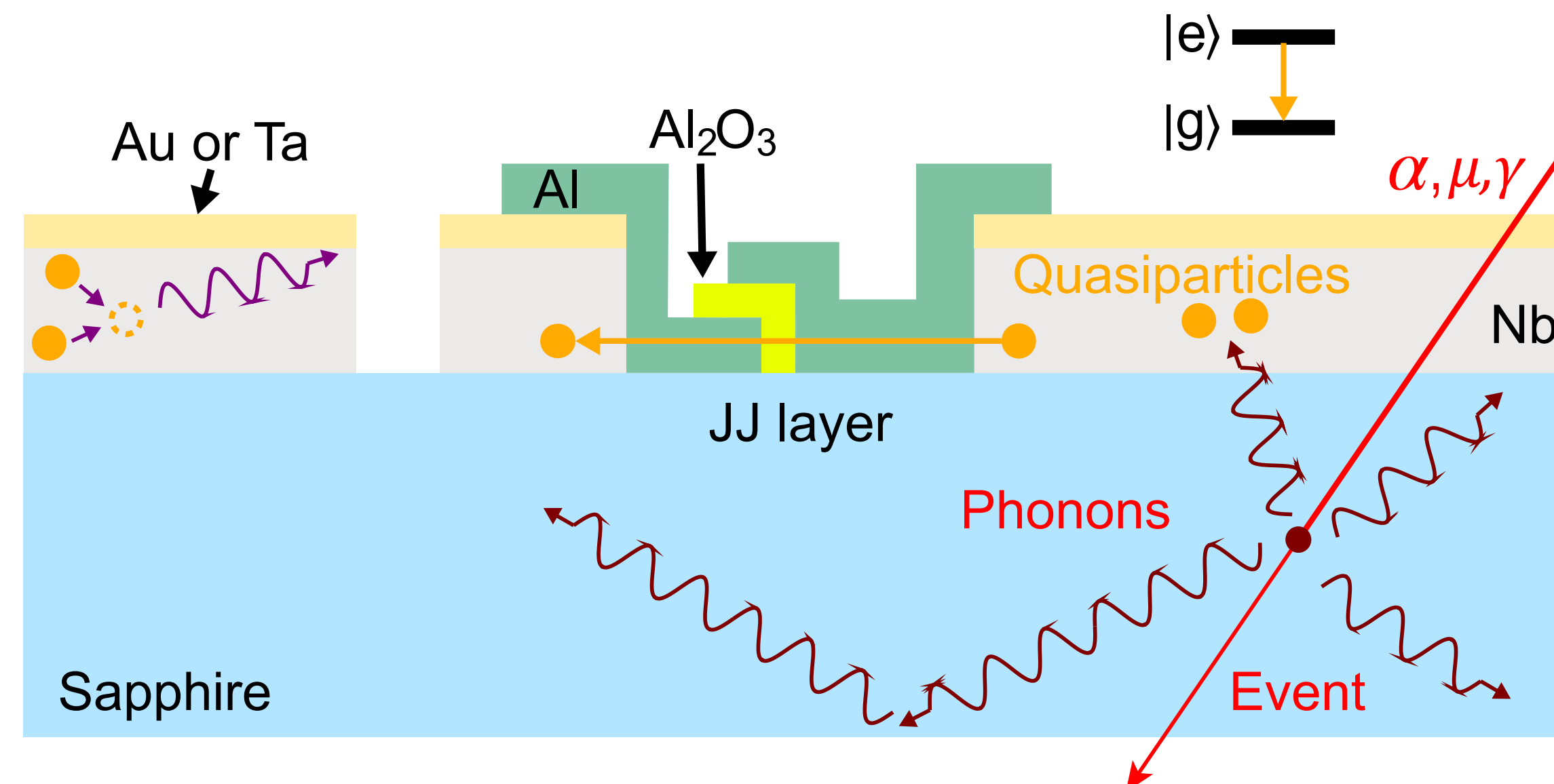
*On behalf of:

M. Bal, F. Bellini, C. Bonomo, N. Casali, I. Colantoni, F. Crisa, A. Cruciani, F. Ferroni, F. De Dominicis, A. Grassellino, D. L. Helis, Mehmood Khan Yasir Raja, A. Mariani, L. Pagnanini, R. Pilipenko, S. Pirro, A. Puiu, A. Ressa, A. Romanenko, T. Roy, L. Tirabasso, D. van Zanten, S. Zhu, and L. Cardani

Motivation and Outline

We know qubits are sensitive to cosmic muons and environmental γ -sources, but several questions are still open:

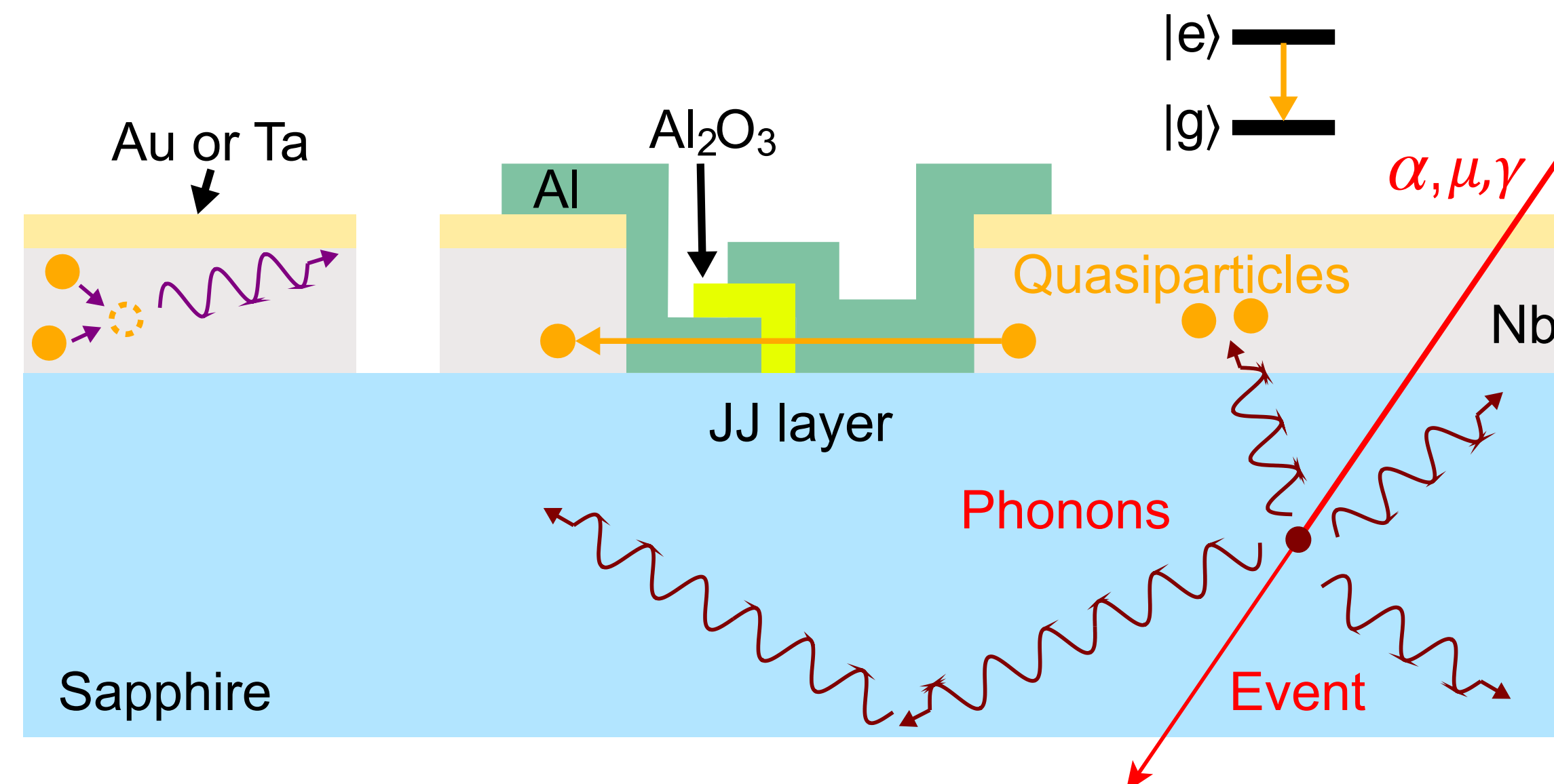
- What is their response to close sources? Very common contamination in any assembly
- Are they sensitive to any kind of particle?
- What is their detection efficiency and energy threshold?



Motivation and Outline

With this work we aim at:

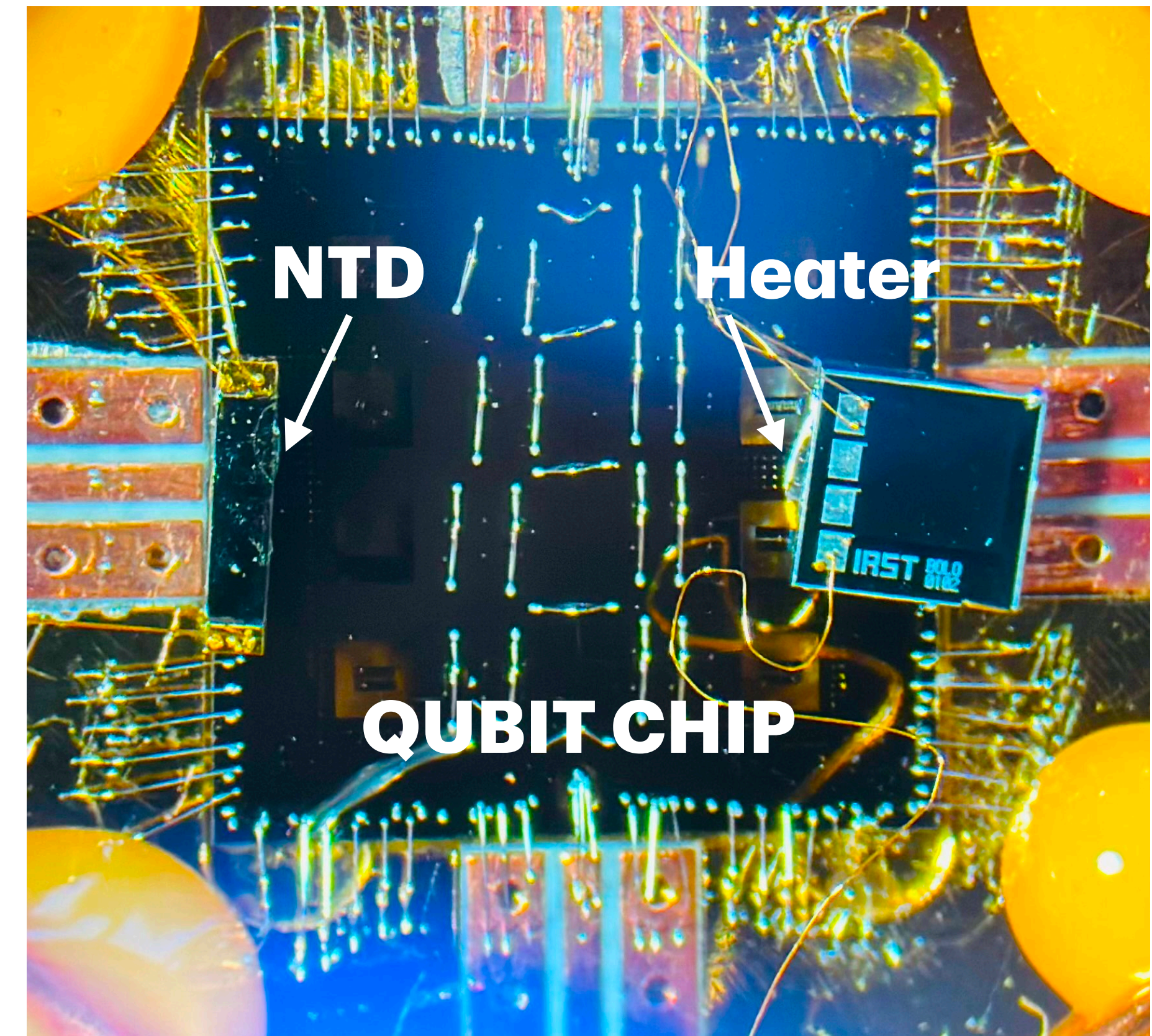
- Cross-validate the sensing with an independent sensor
- Define a robust analysis strategy
- Estimate basic properties as particle detectors



Experimental Setup

- 432 μm -thick sapphire substrate ($7.5 \times 7.5 \text{ mm}^2$), fully coated with niobium*
- Four fixed-frequency niobium transmons with varying geometries (standard Al/AlO_x/Al Josephson junctions)
- Capped with a $\sim 10 \text{ nm}$ Tantalum layer (reduce losses associated with the formation of Nb_2O_5)

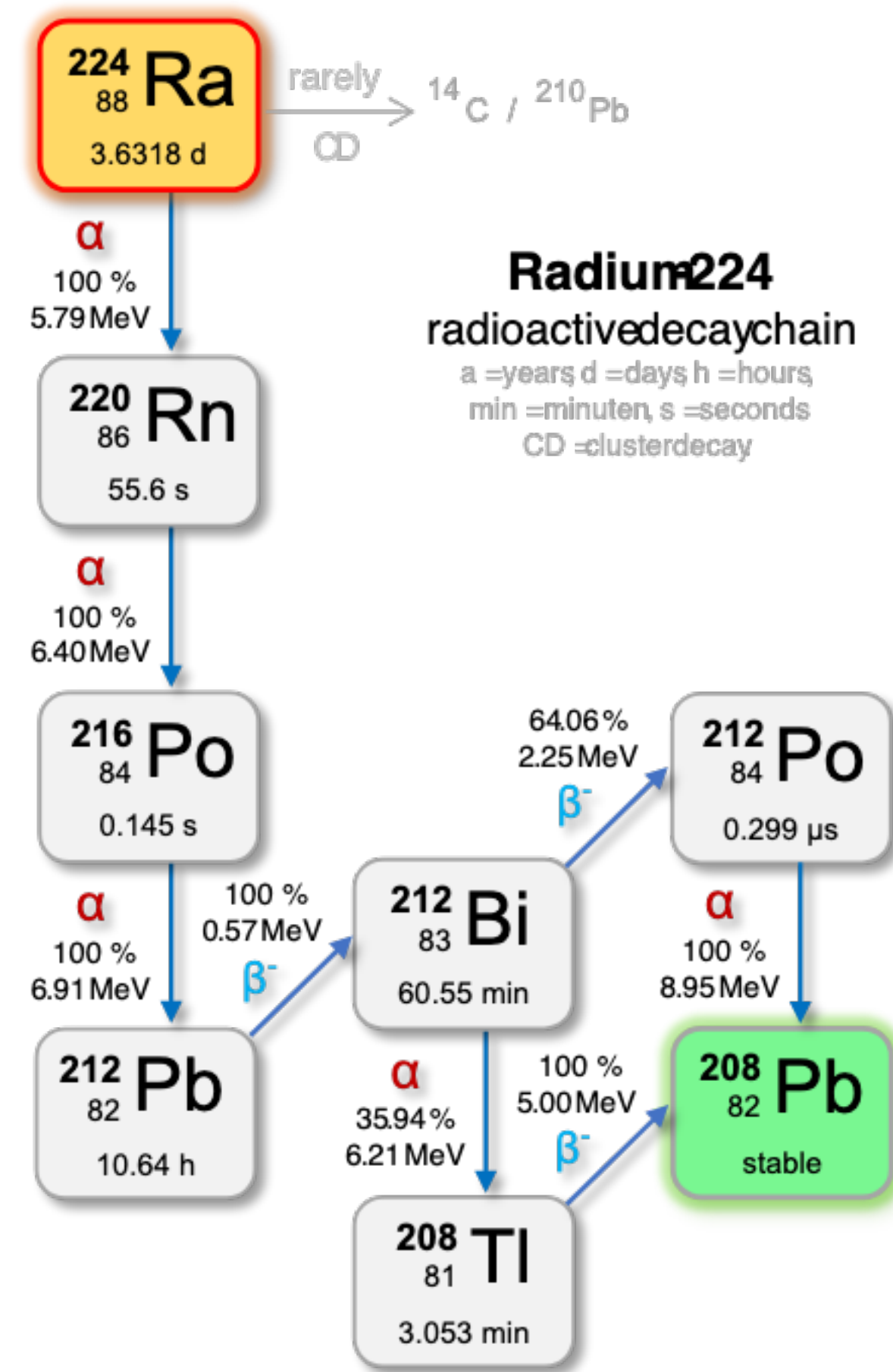
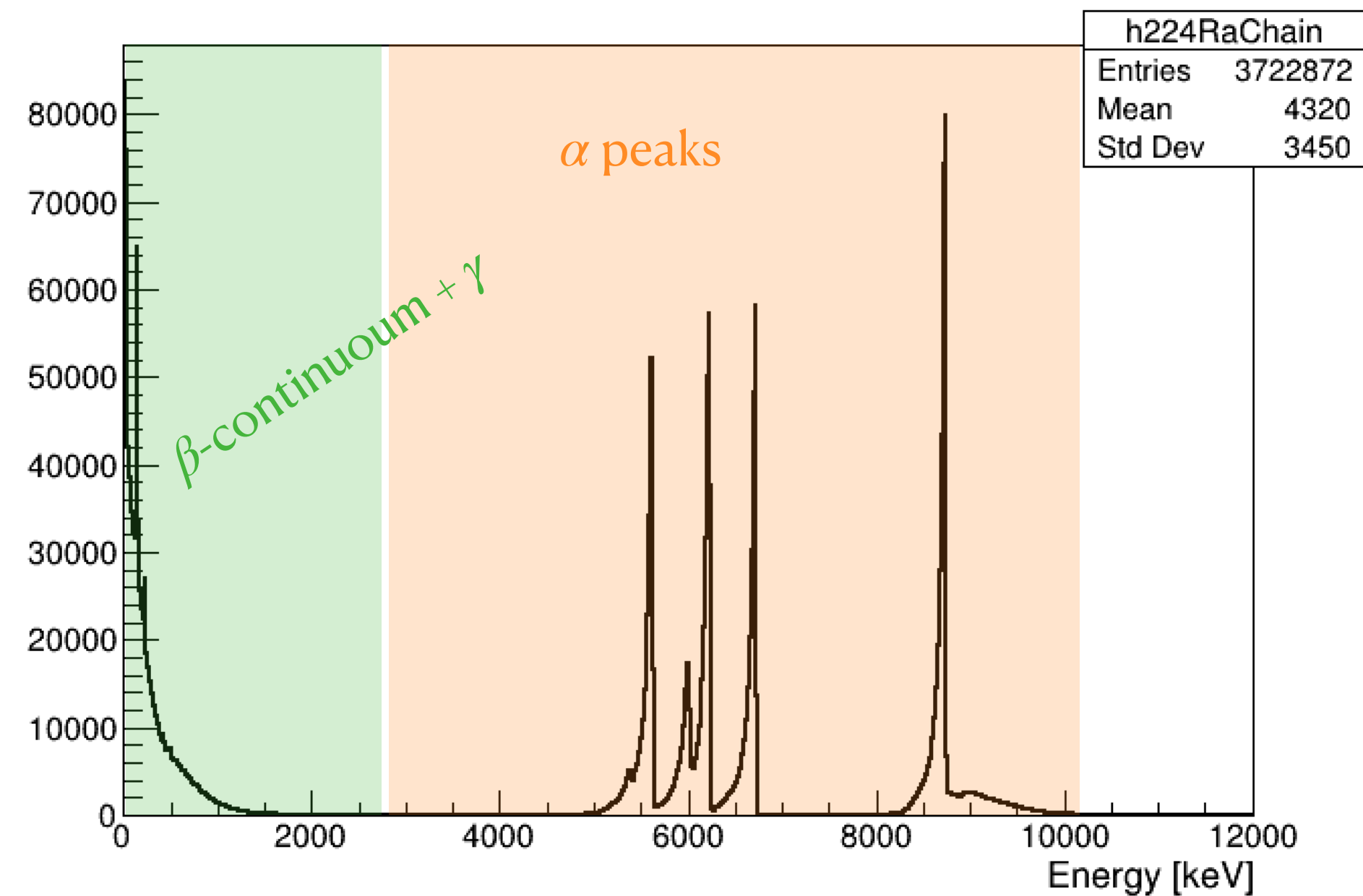
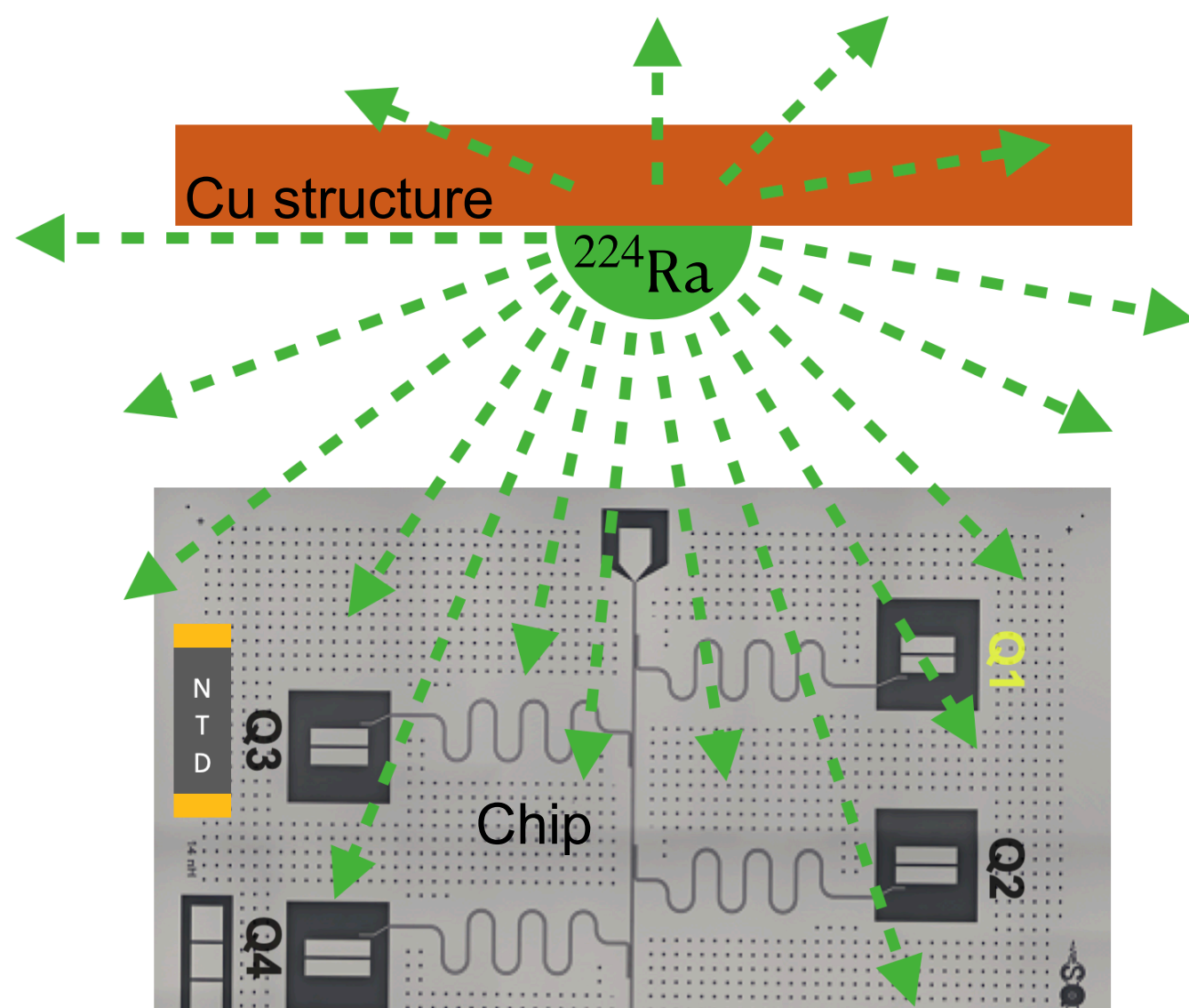
- Thermal sensor: $3 \times 0.4 \times 0.6 \text{ mm}^3$ Neutron Transmutation Doped germanium thermistor
- Silicon heater to inject controlled thermal phonons
 - Glued on substrate with epoxy Araldite Rapid (standard for cryogenic detectors)



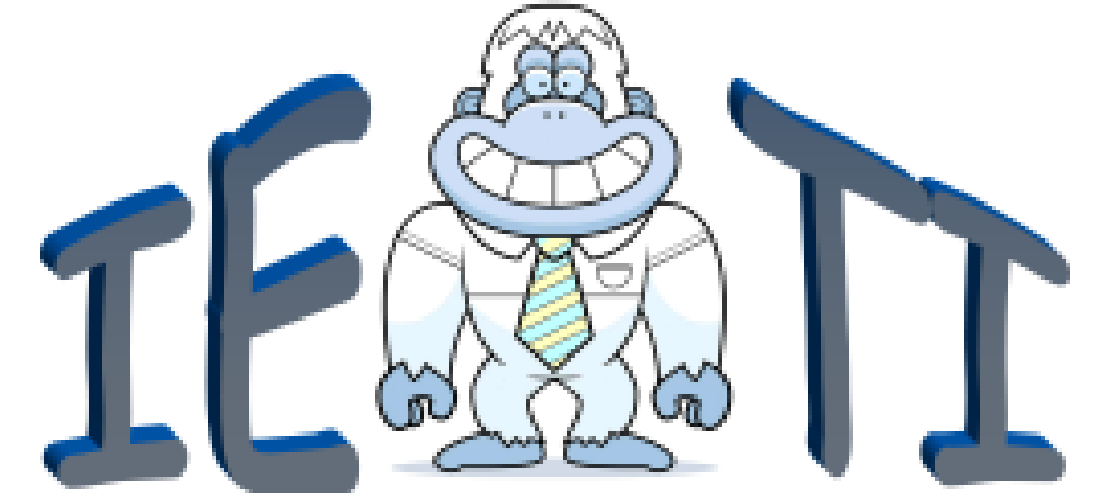
*Bal, M., Murthy, A.A., Zhu, S. et al., npj Quantum Inf 10, 43 (2024)

Experimental Setup

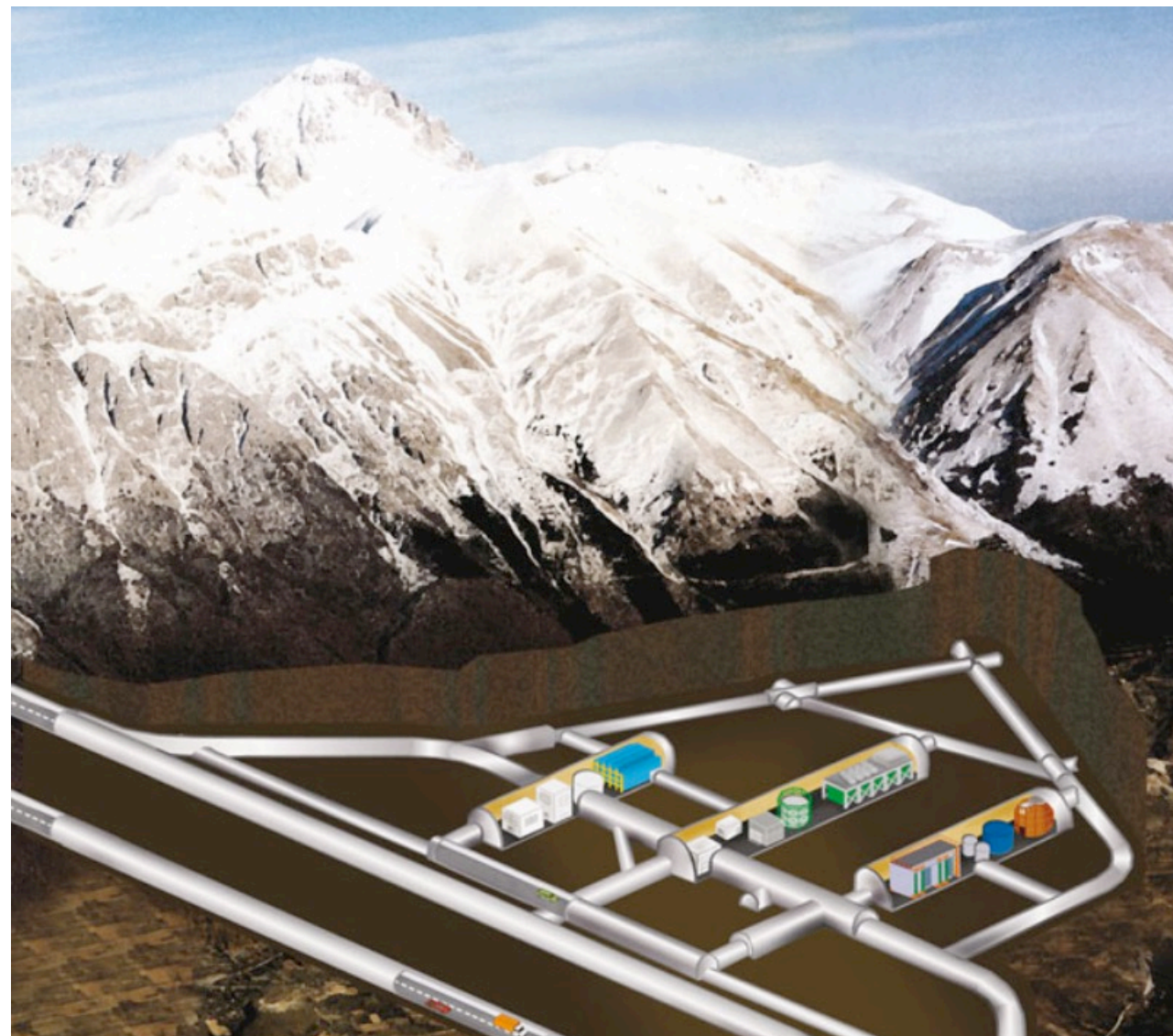
- ^{224}Ra source placed by the setup
- Nominal half-life of ~ 3.6 days
- It provides a continuous spectrum spanning up to ~ 9 MeV
- β/γ up to ~ 3 MeV, mainly α above this value



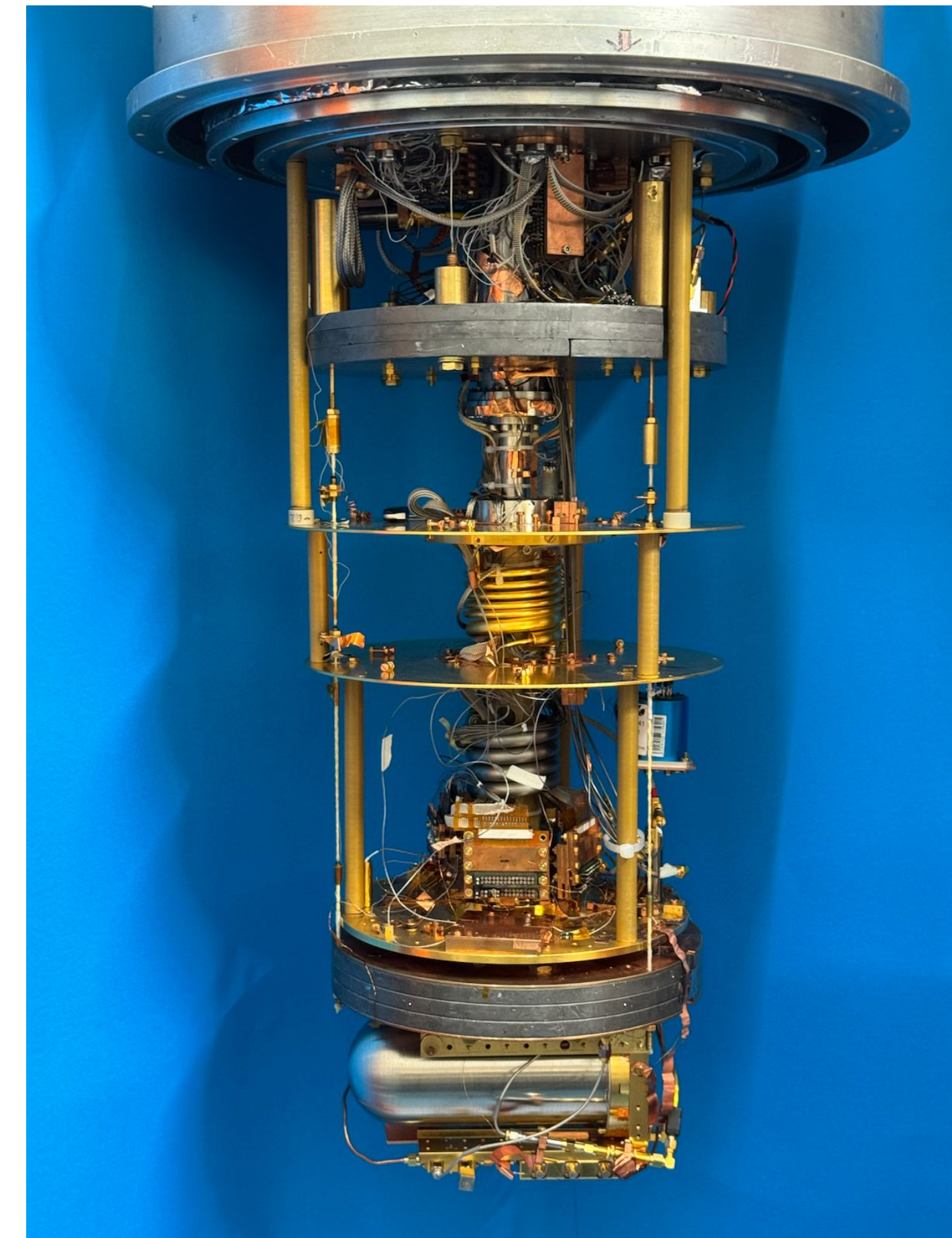
Experimental Setup



- 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 Pb shield against radioactivity
- Internal magnetic shield

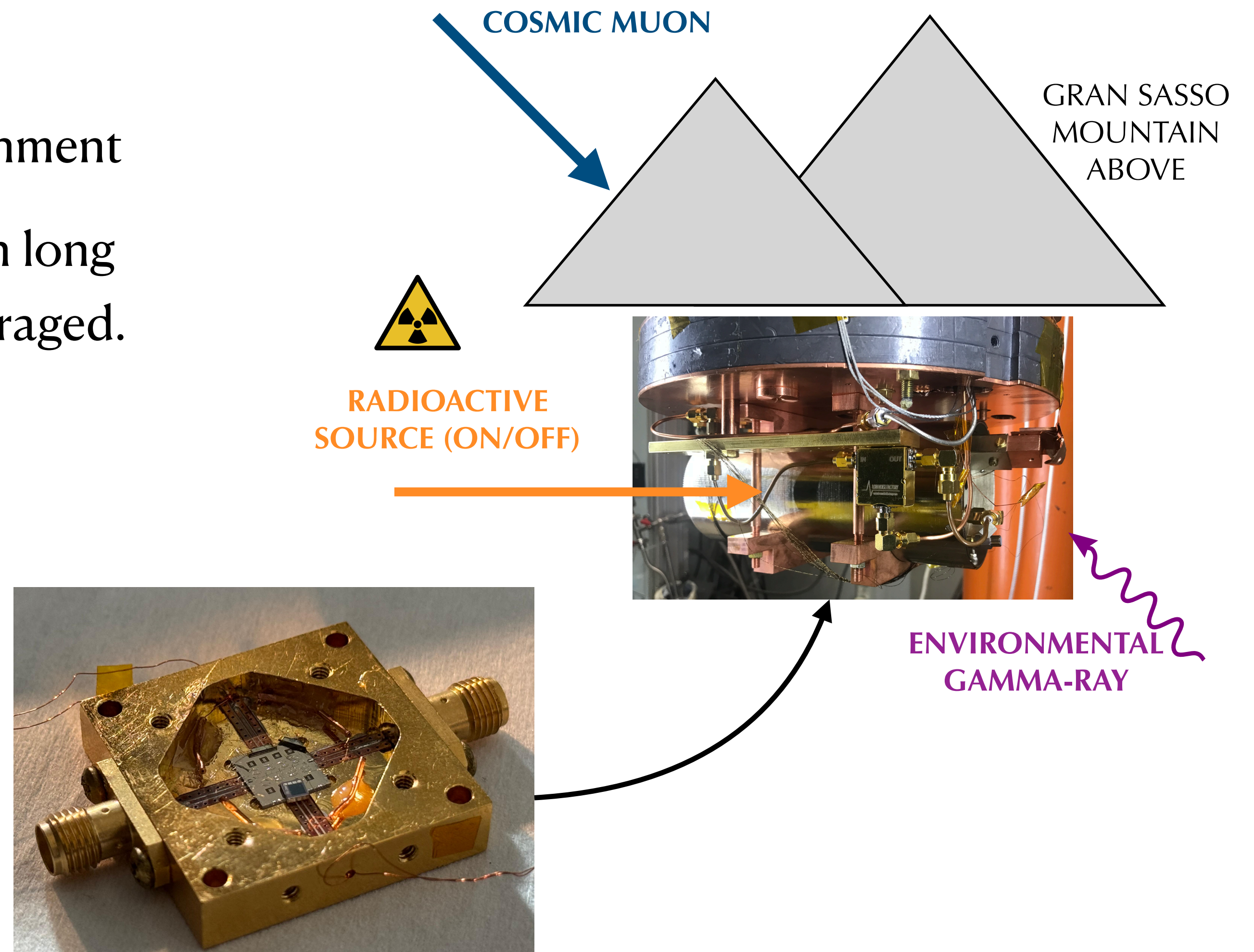


Experimental Setup

- Cooldown the chip to ~ 35 mK
- Characterization in a low-radioactivity environment

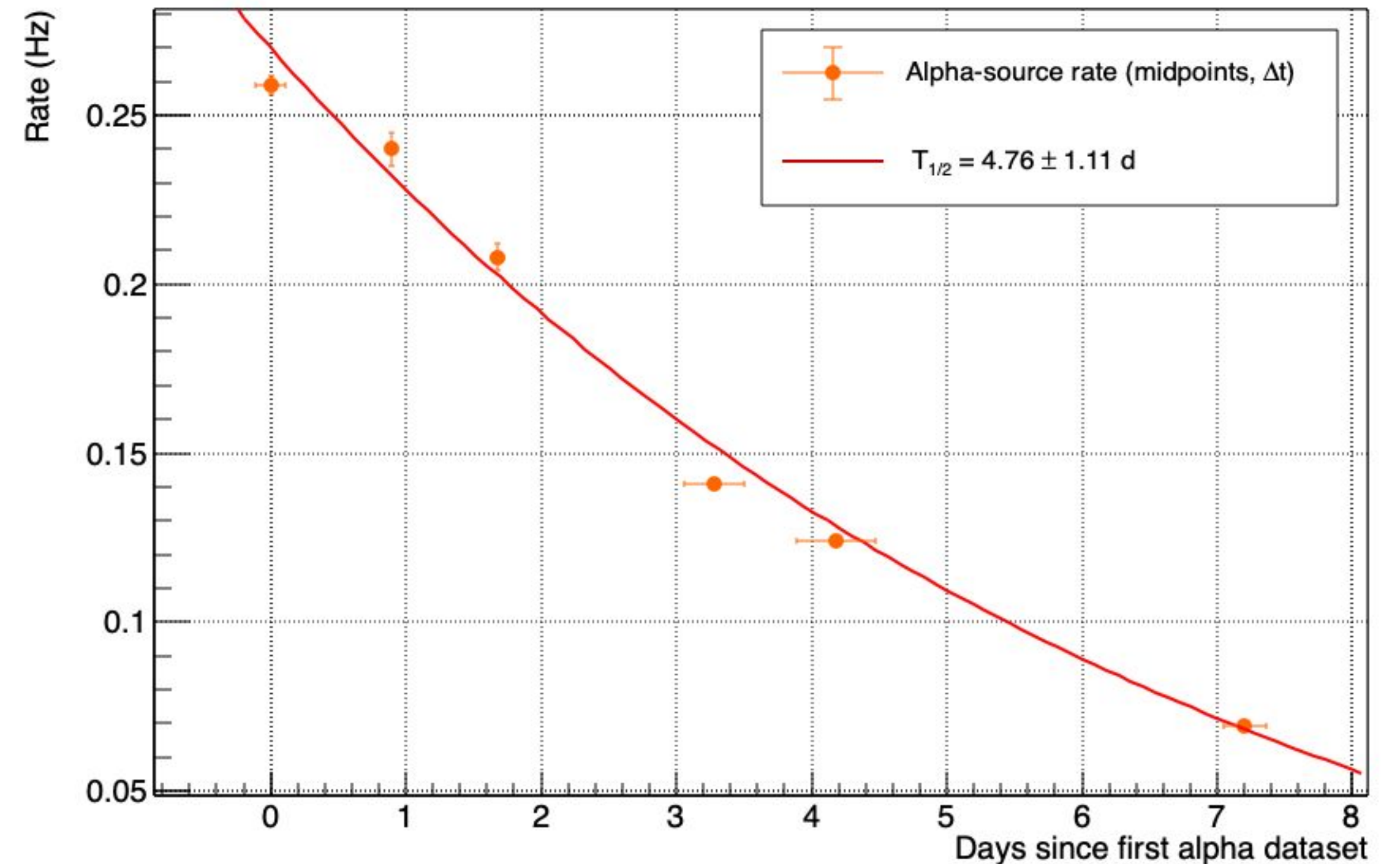
The energy relaxation time (T_1) is estimated with long samples of measurement (~ 50 s) and then averaged.

$T_1 \sim 100$ (nominal) – $50 \mu\text{s}$ (effective)



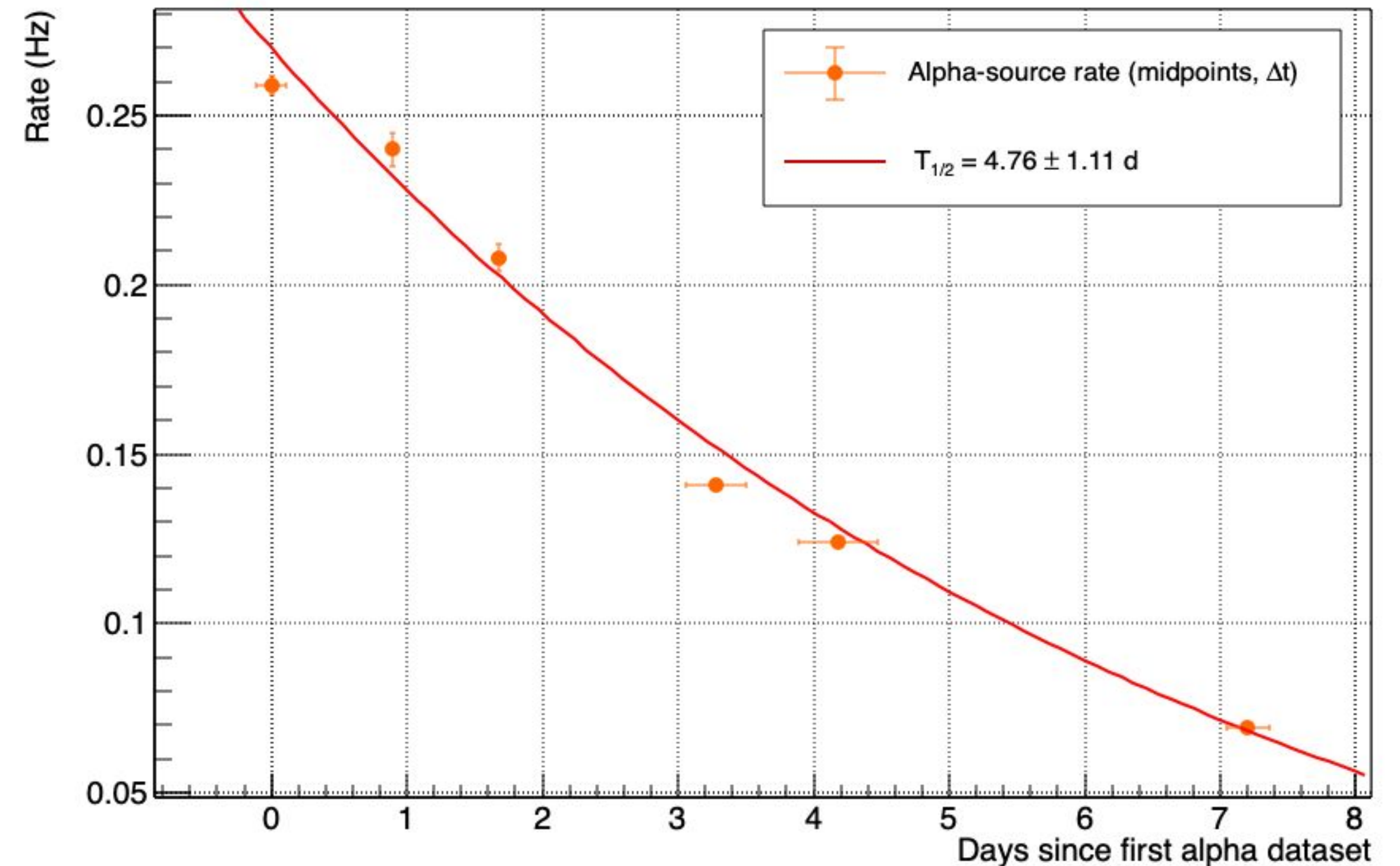
Source Activity Reconstruction

- We used a standard NTD thermistor for a cross-reconstruction
 - $R(T) \sim R_0 e^{(T_0/T)^{1/2}}$
 - Excellent for wide energy range operation (keV-MeV)
 - Able to work at different temperatures (10-30 mK) with similar performances



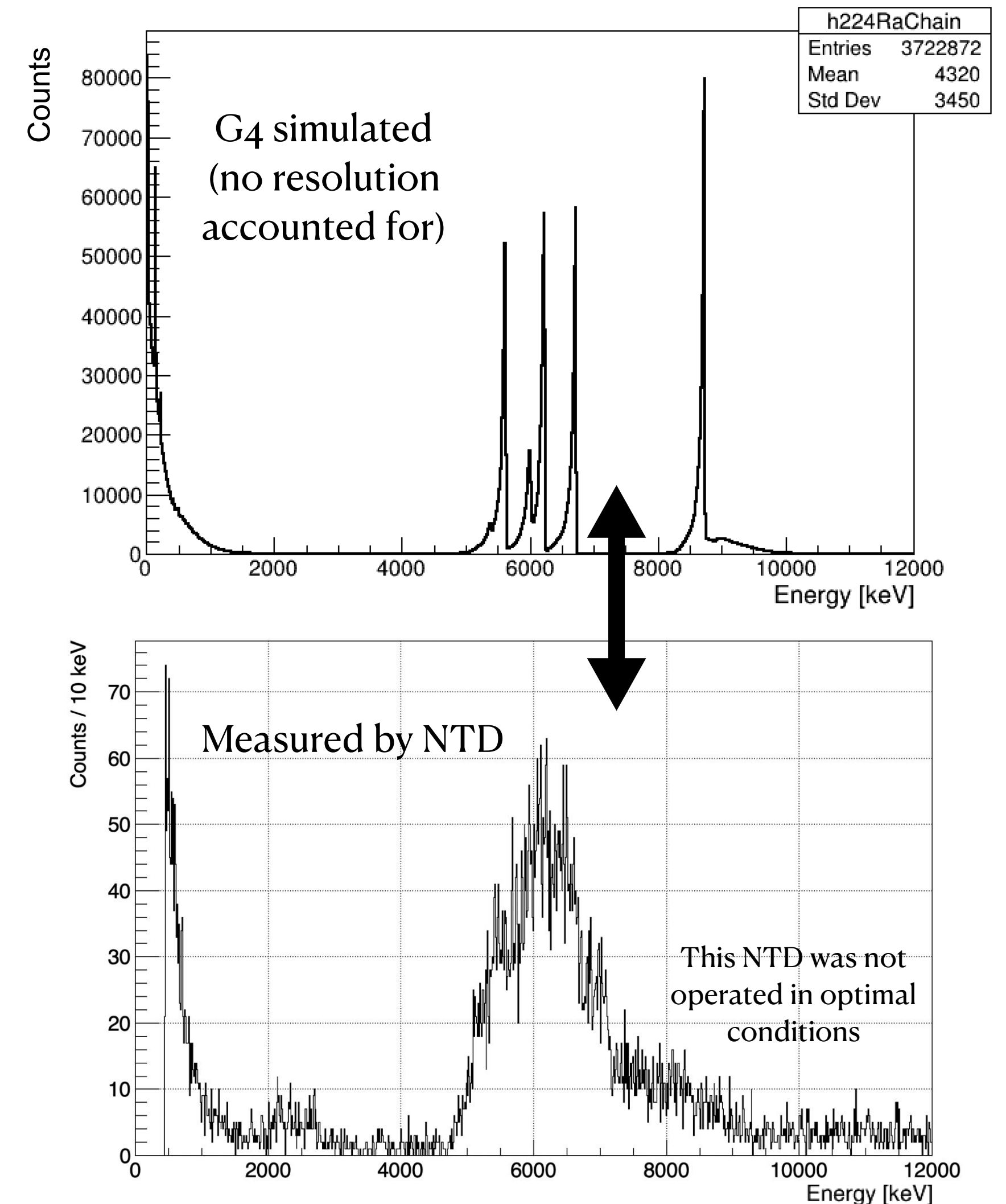
Source Activity Reconstruction

- We used a standard NTD for a cross-reconstruction
- Detection efficiency estimated with the heater:
 - inject reference thermal pulses at different energies
- Apply standard quality cuts and estimate the rate in the α energy region (> 3 MeV, 100% efficiency)



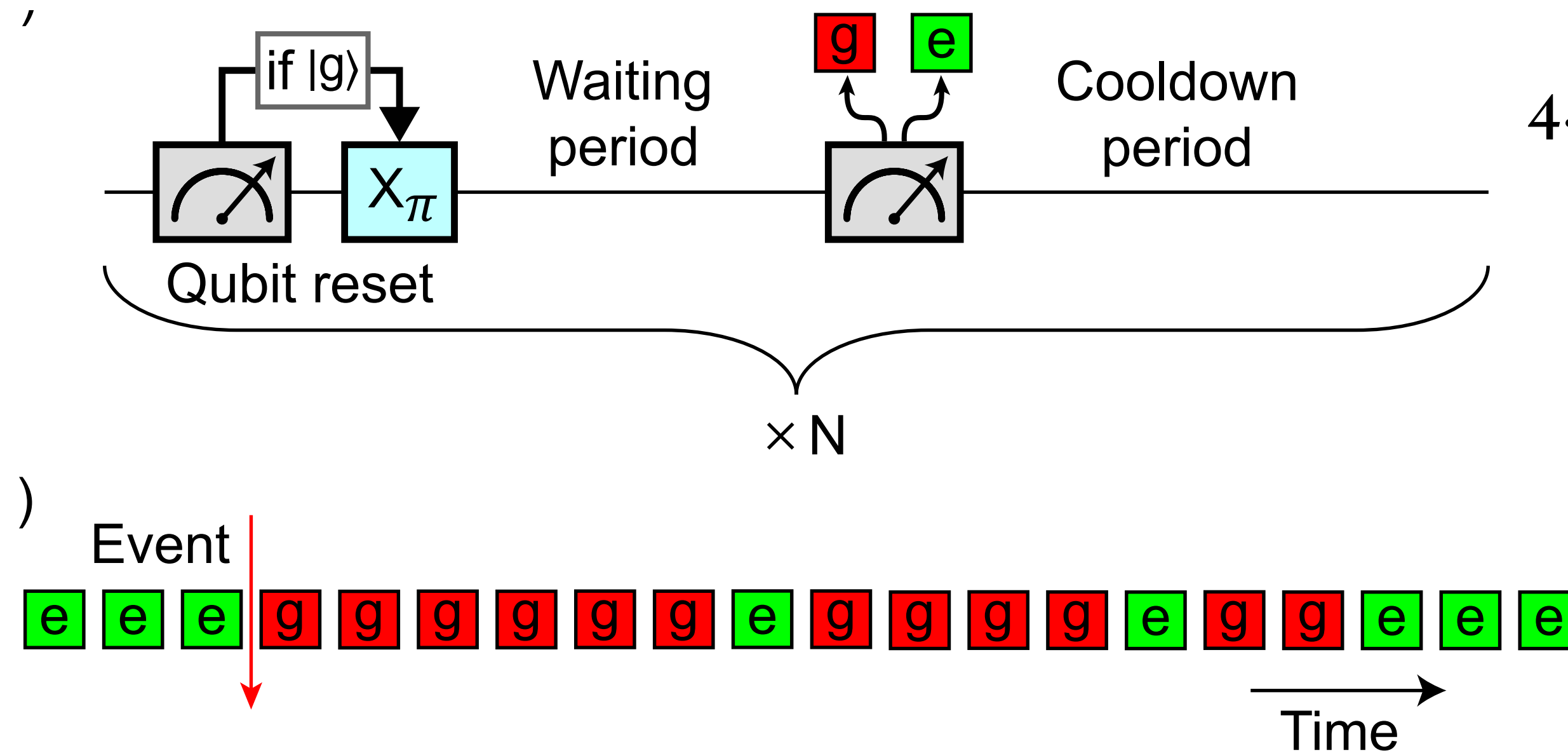
Source Activity Reconstruction

- We simulated (Geant4 based) the ^{224}Ra implementing the chip geometry and materials
 - We estimated a scale coefficient
 - From the counts of the NTD in the α energy region
 - We scaled the whole simulation to estimate the initial source activity (accounting for environmental radioactivity)
- ➔ **In this way we know the exact rate hitting on the chip at every time along the data taking**



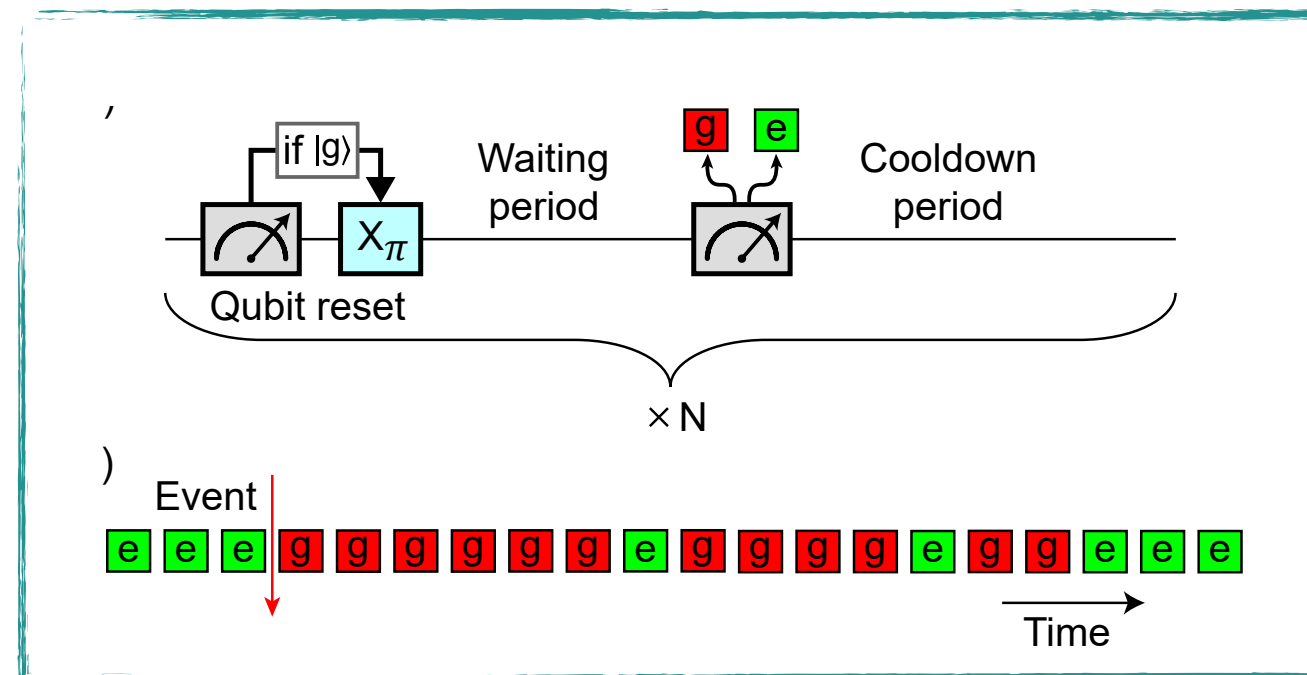
Detection Strategy

1. If $|g\rangle$
 - Reset to $|e\rangle$
 - Via π -pulse
2. Wait a $2\ \mu s$ (\ll 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

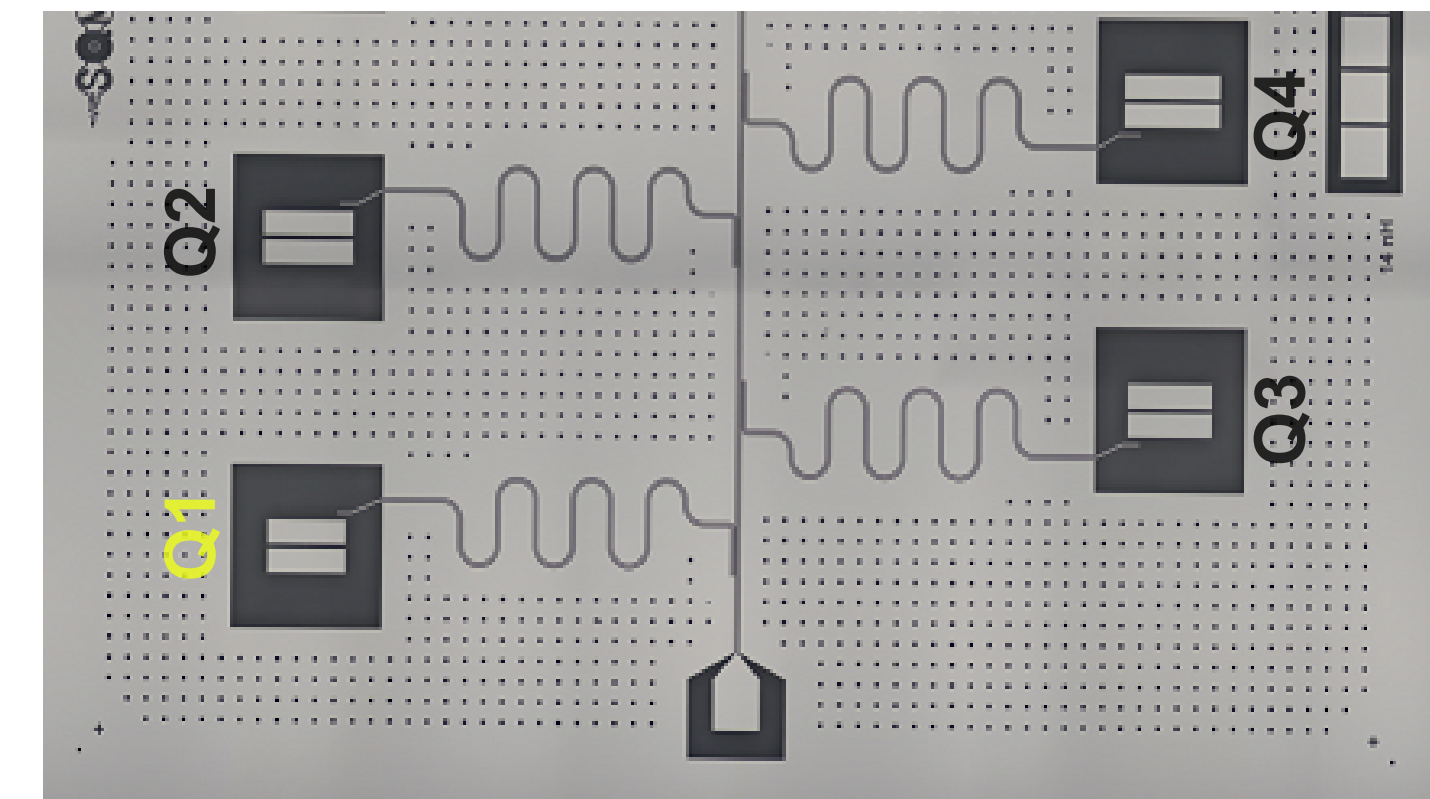


$$T_s = \text{waiting time} + \text{cooldown} (= 60.7\ \mu s)$$

Detection Strategy

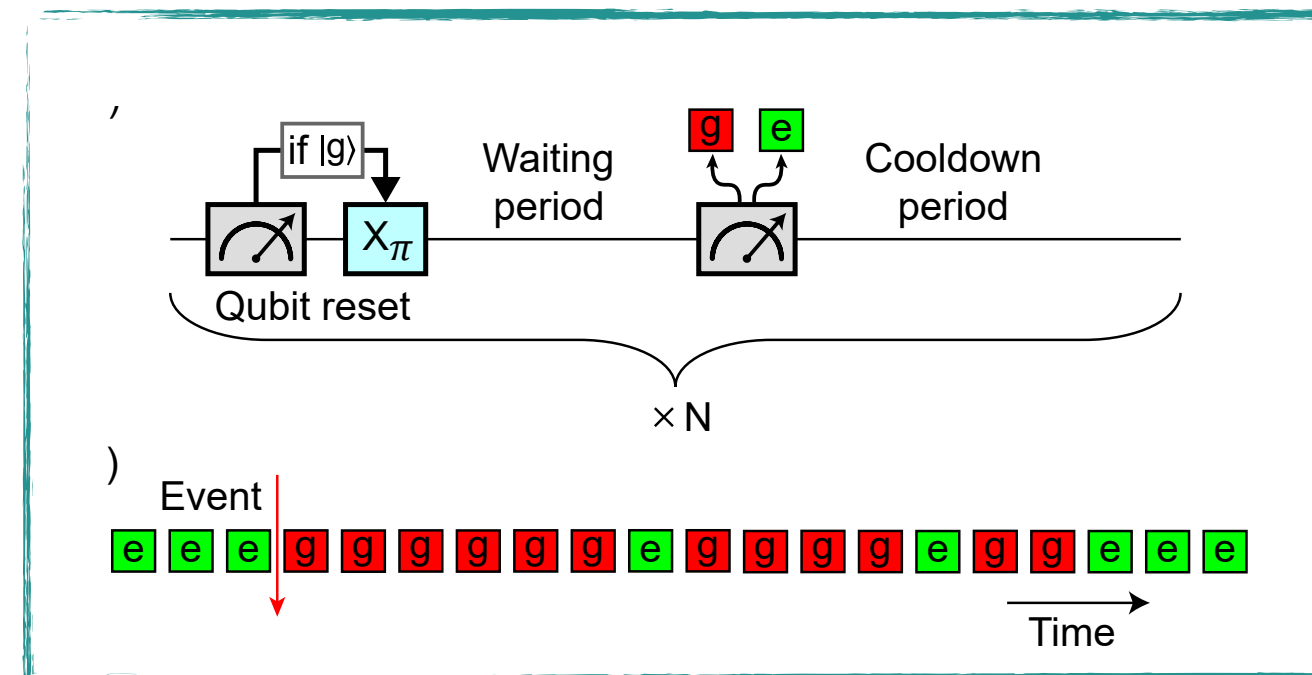


\times number of qubits on the chip (we made it to 4)



- Multiplexed Qubit Reset
 - π -pulse is conditional, depends on single qubit state
 - Modified to include only the frequency tones corresponding to qubits found in $|g\rangle$

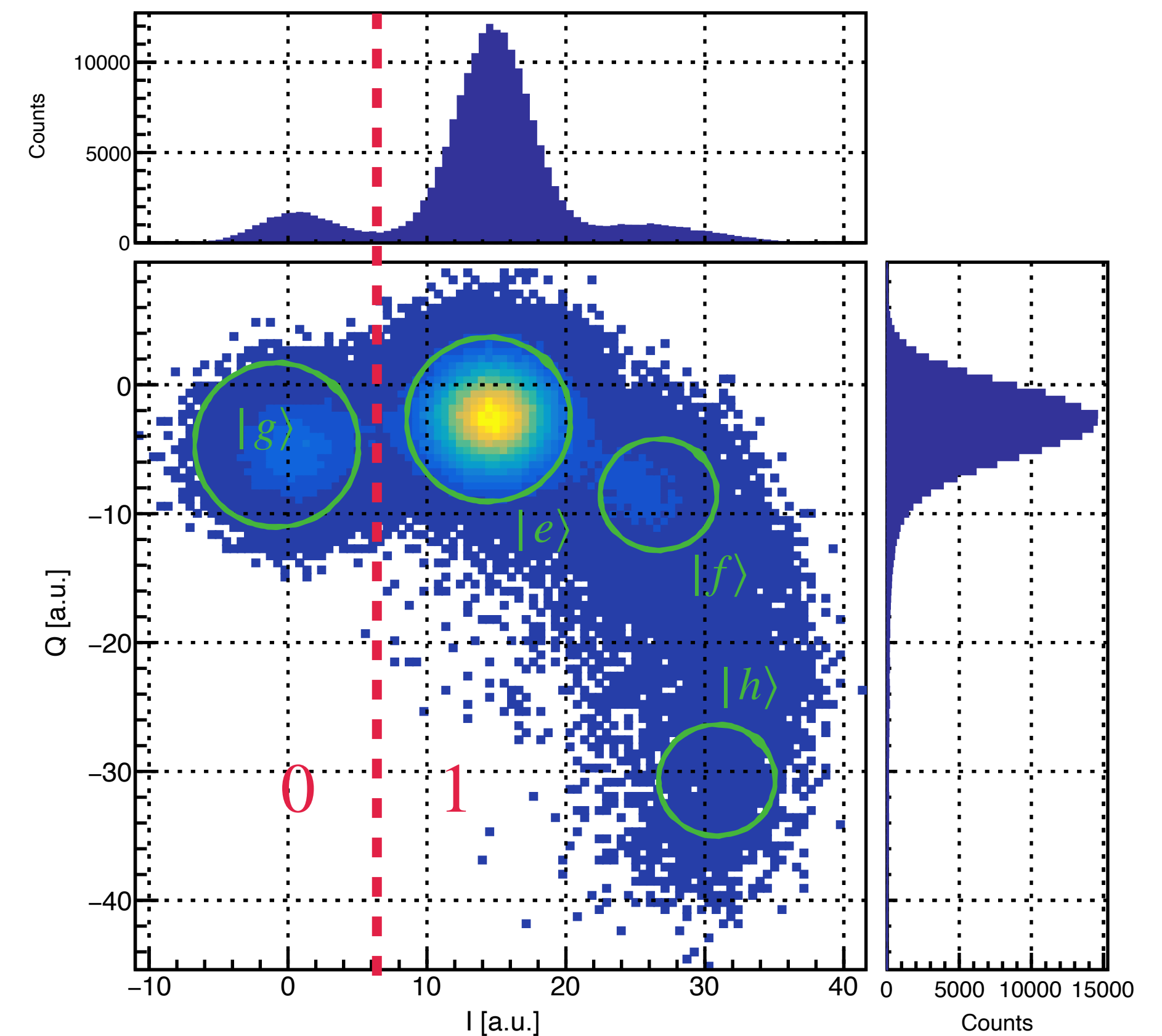
Detection Strategy



× number of qubits on the chip (we made it to 4)

How to identify the state?

- Group N measurements ($N = 10^5 \rightarrow \sim 6.1 \text{ s}$)
- Perform multi-gaussian 2D fit to identify states populations
- Optimize Fidelity on the I variable
- Assign 0-1 to every sample



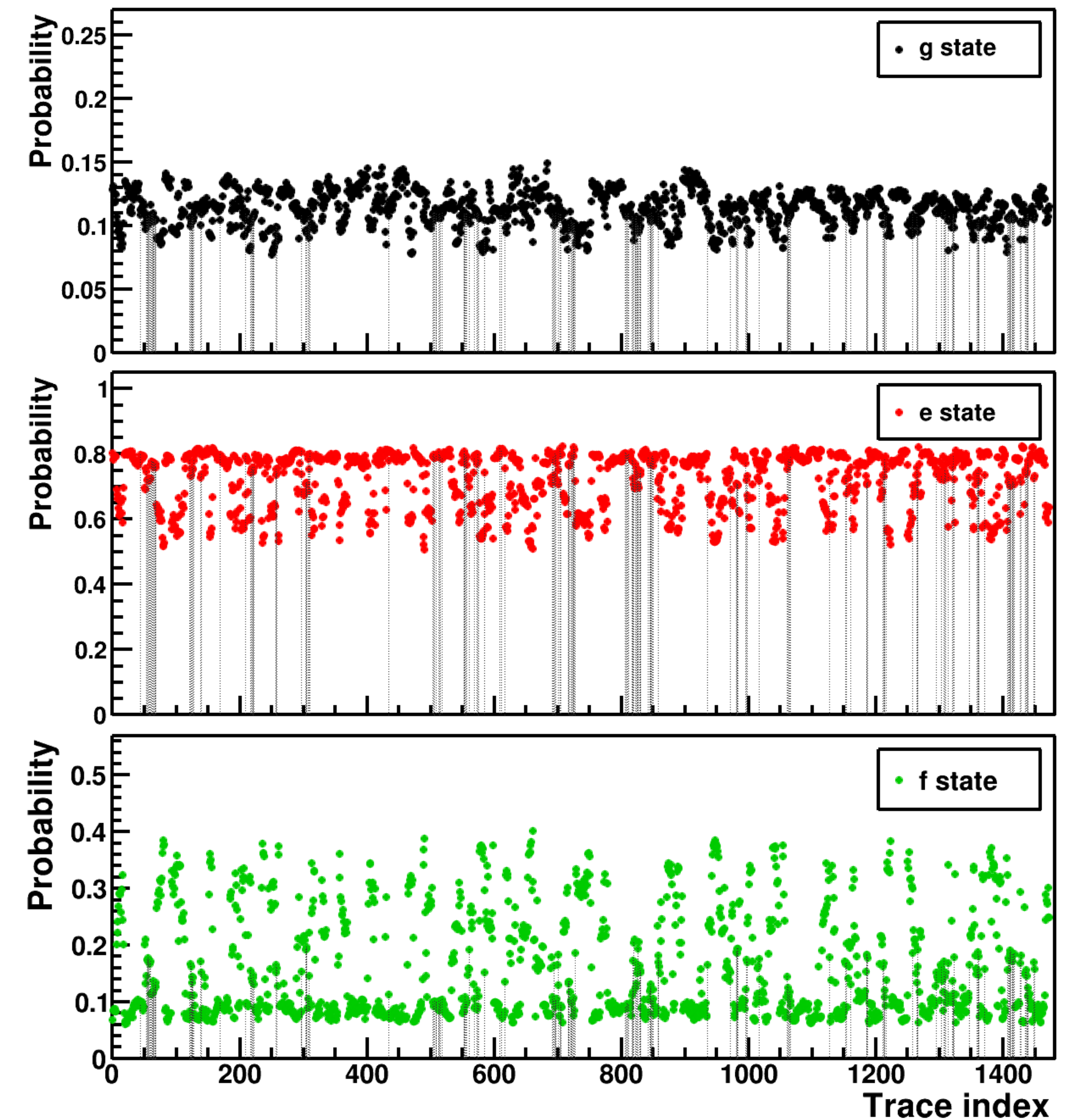
Preliminary Data-Quality Selection

To overcome higher-states leakage we performed a time-interval selection

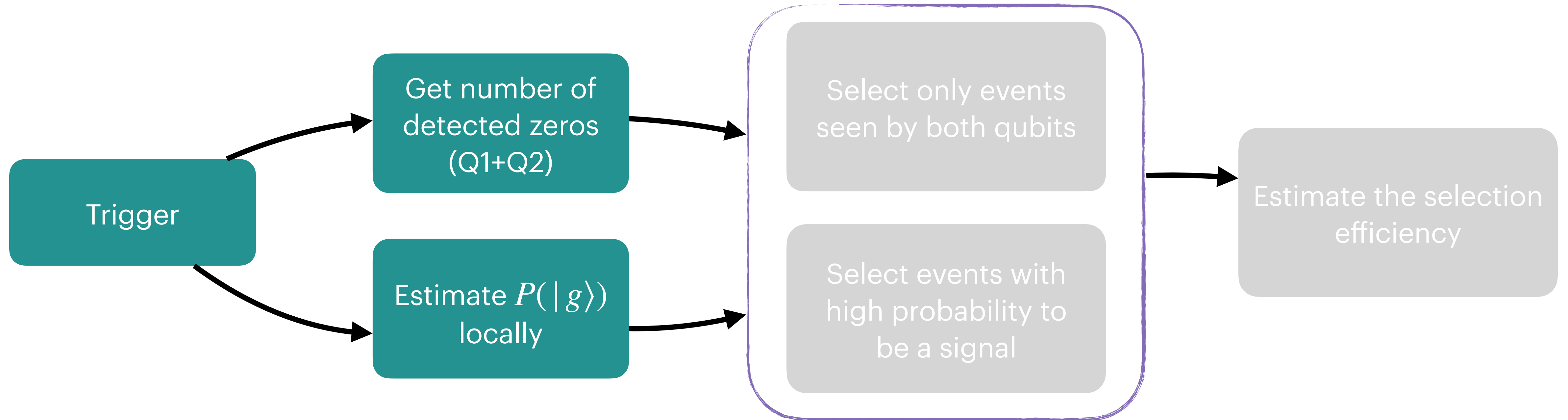
- $P(|g\rangle) < 11\%$
- $P(|e\rangle) > 70\%$

Compromise to minimize spontaneous decoherence and higher-states leakage and statistics maximisation

We performed systematic studies by varying this selection (see later in the slides)

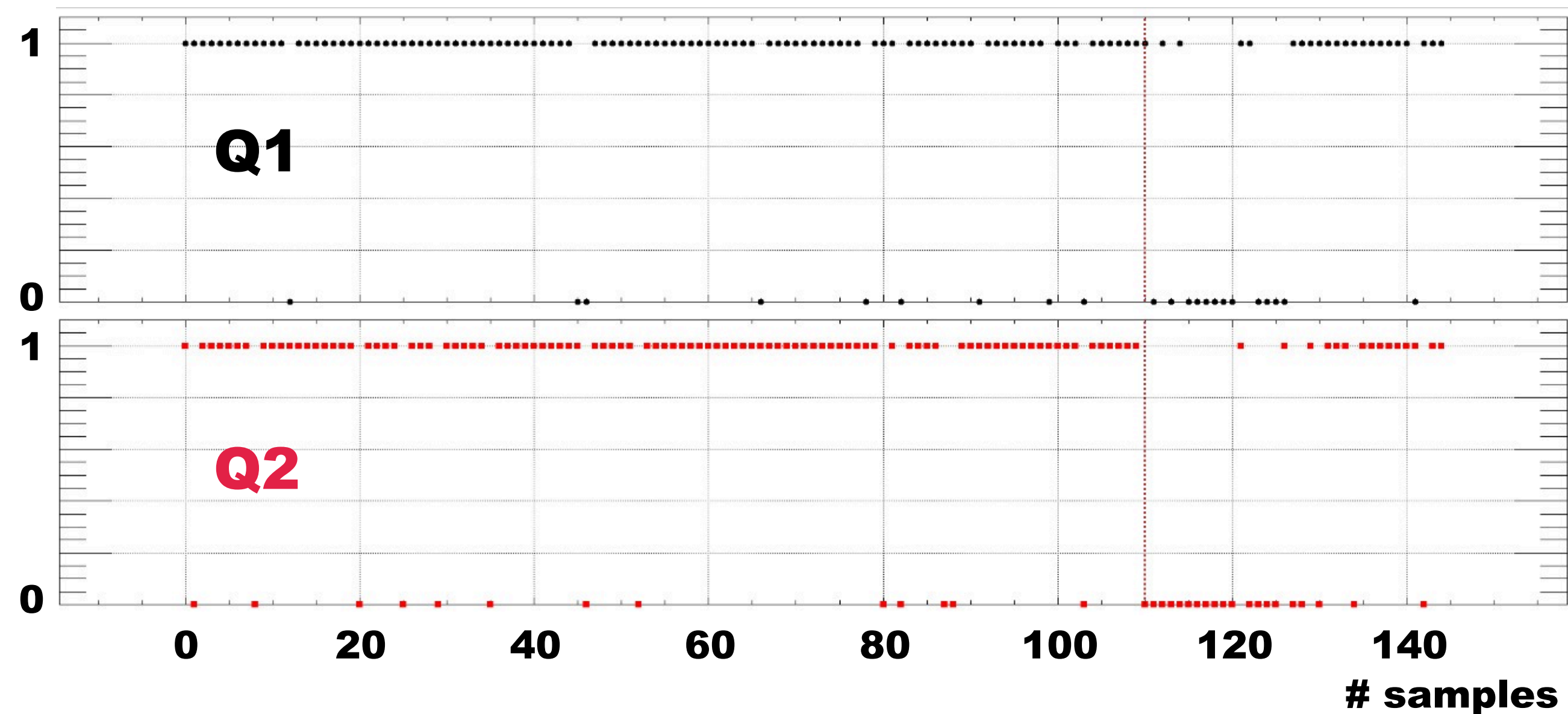


Analysis Strategy



Trigger Strategy

- Trigger if 4 consecutive zeros (or $|g\rangle$)
- Simultaneously acquire all the qubits: we focused on the two best performing



Trigger Strategy

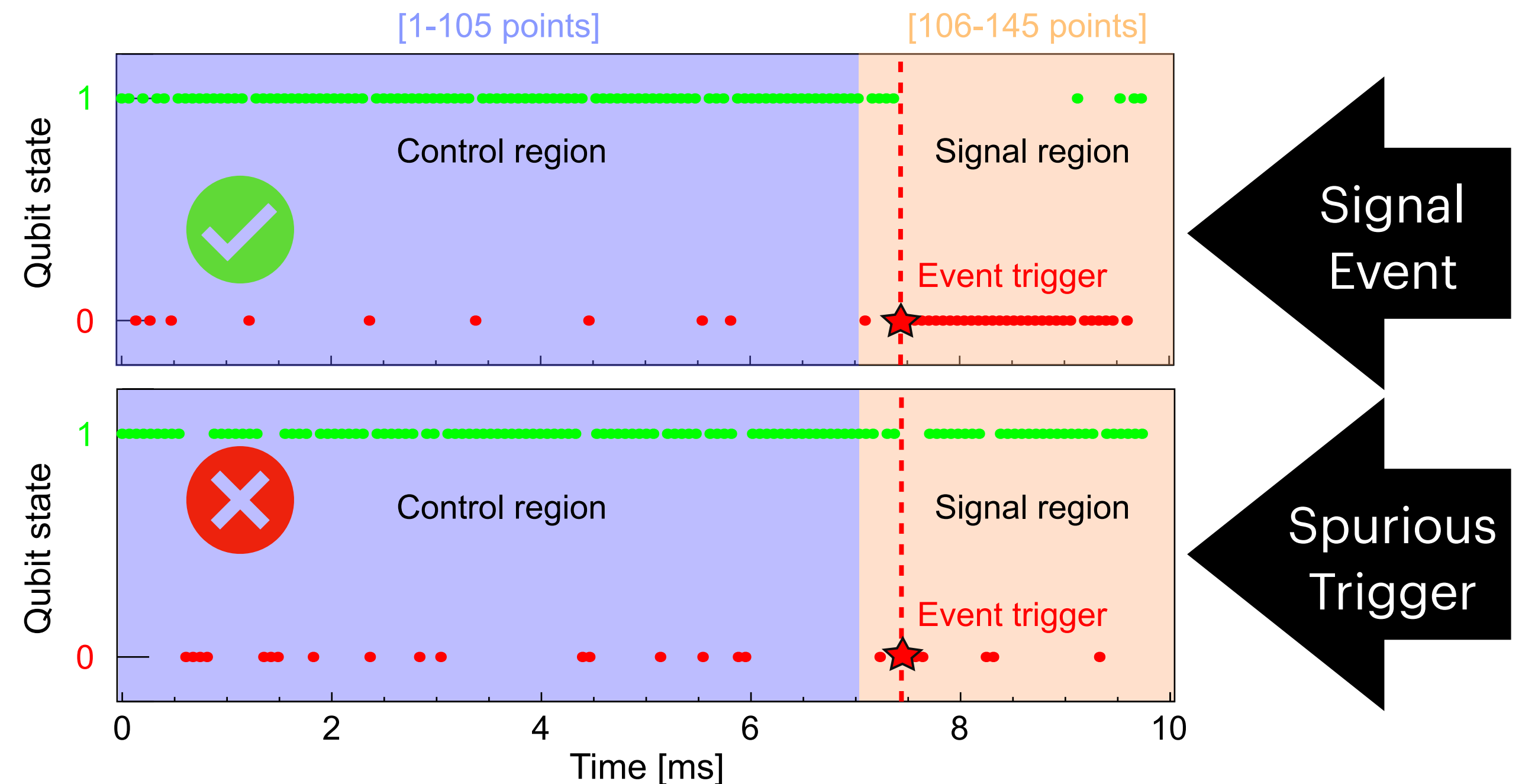
- Trigger if 4 consecutive zeros (or $|g\rangle$)
- Simultaneously acquire all the qubits: we focused on the two best performing

- Signal Region + Control Region (local $P(|g\rangle)$)

- “Spontaneous decoherence” rate of:

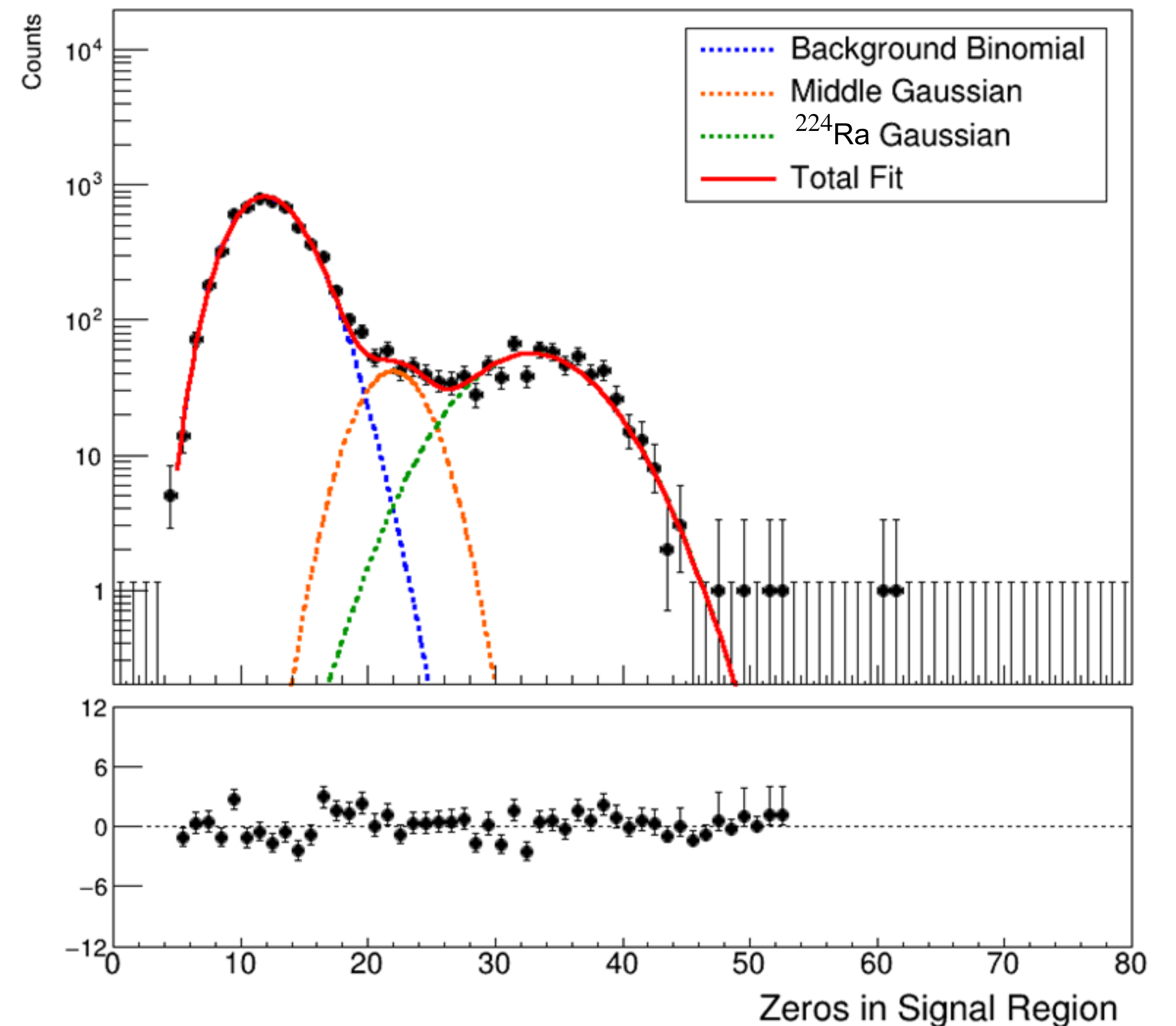
$$\frac{P(g)^4}{T_S}$$

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

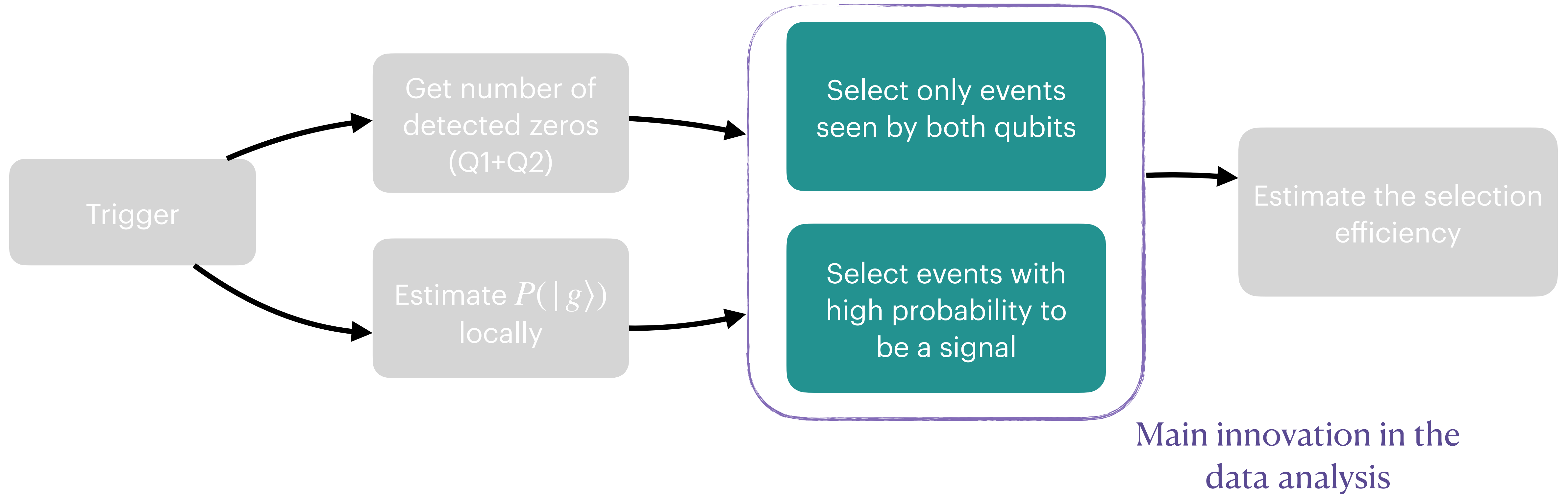


Event Distribution

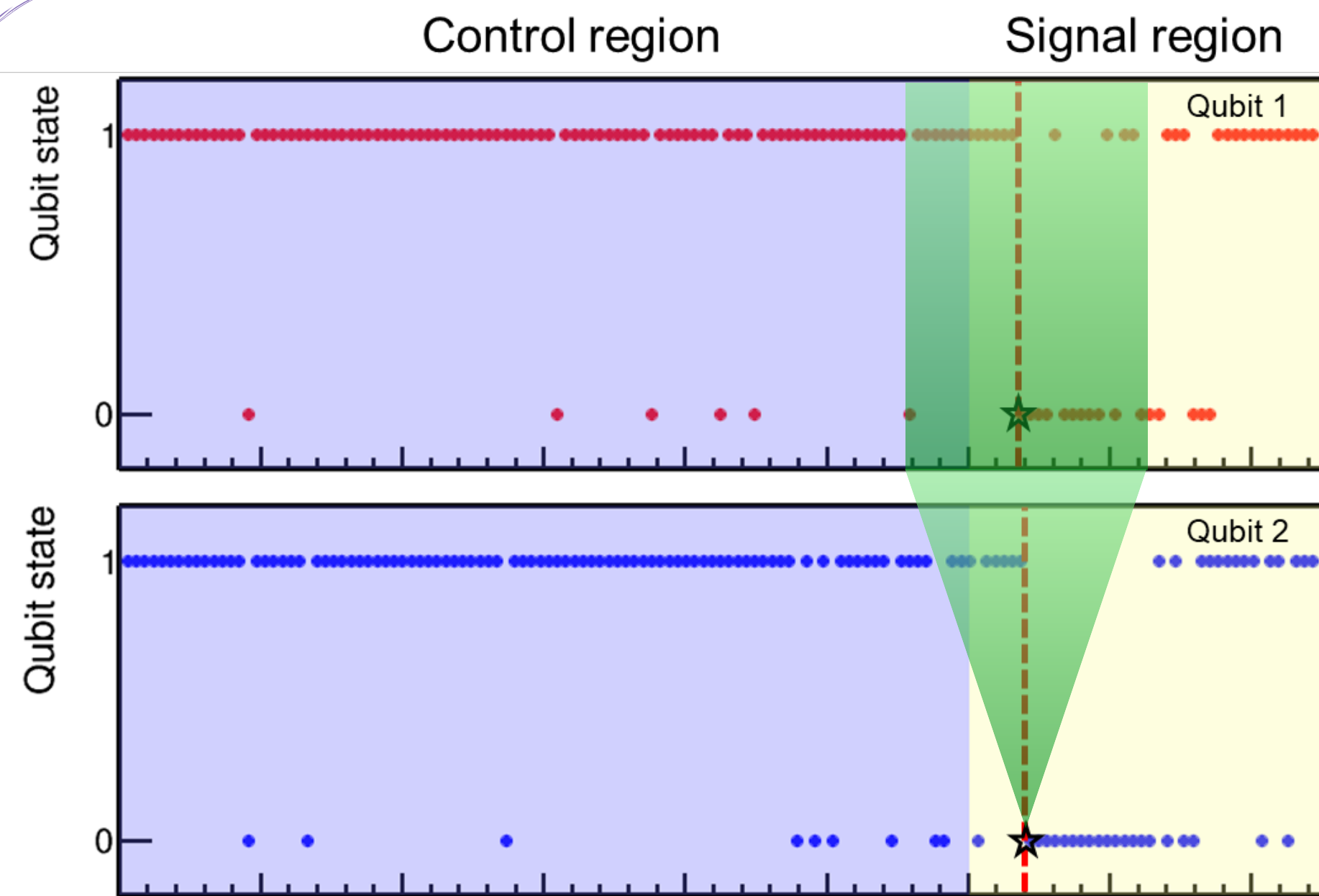
- Sum the number of zeros of the 2 qubits
 - Trigger set on the best performing qubit (in terms of T1)
- Fit the distribution
 - Binomial distribution (given at least 4 zeros):
 $P(|g\rangle)$
 - Signal Gaussian: μ_s, σ_s
 - “Middle” Gaussian: we interpret this as signals seen by only one of the two qubits. Needed to fully describe the distribution: μ_m, σ_m



Analysis Strategy



Data Selection



Select only events
seen by both qubits

- Select events triggered by both qubits to enhance the sensing

Data Selection

How likely the number of detected $|g\rangle$ is NOT due to a Bernoulli process?

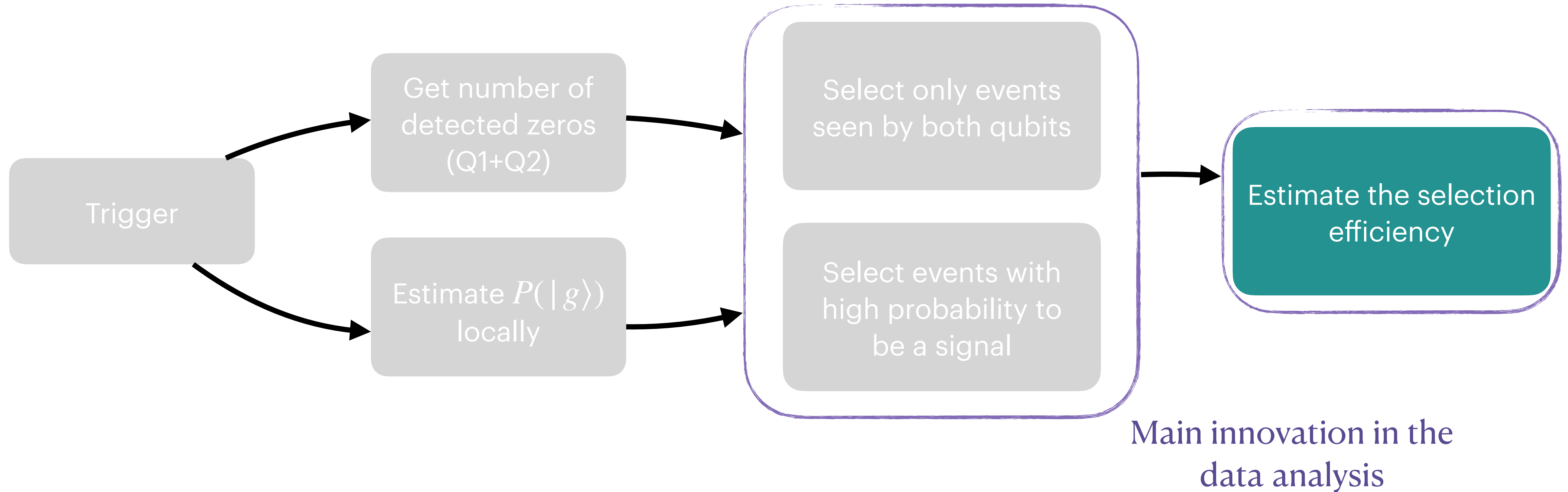
$$P_S = 1 - \sum_{k_s}^{N_s} \int_0^1 \mathcal{B}(k_s | N_s, p) P(p | N_c, k_c) dp$$

- $k = \#$ of $|g\rangle$
- $N = \#$ of samples
- $S =$ signal region, $C =$ control region

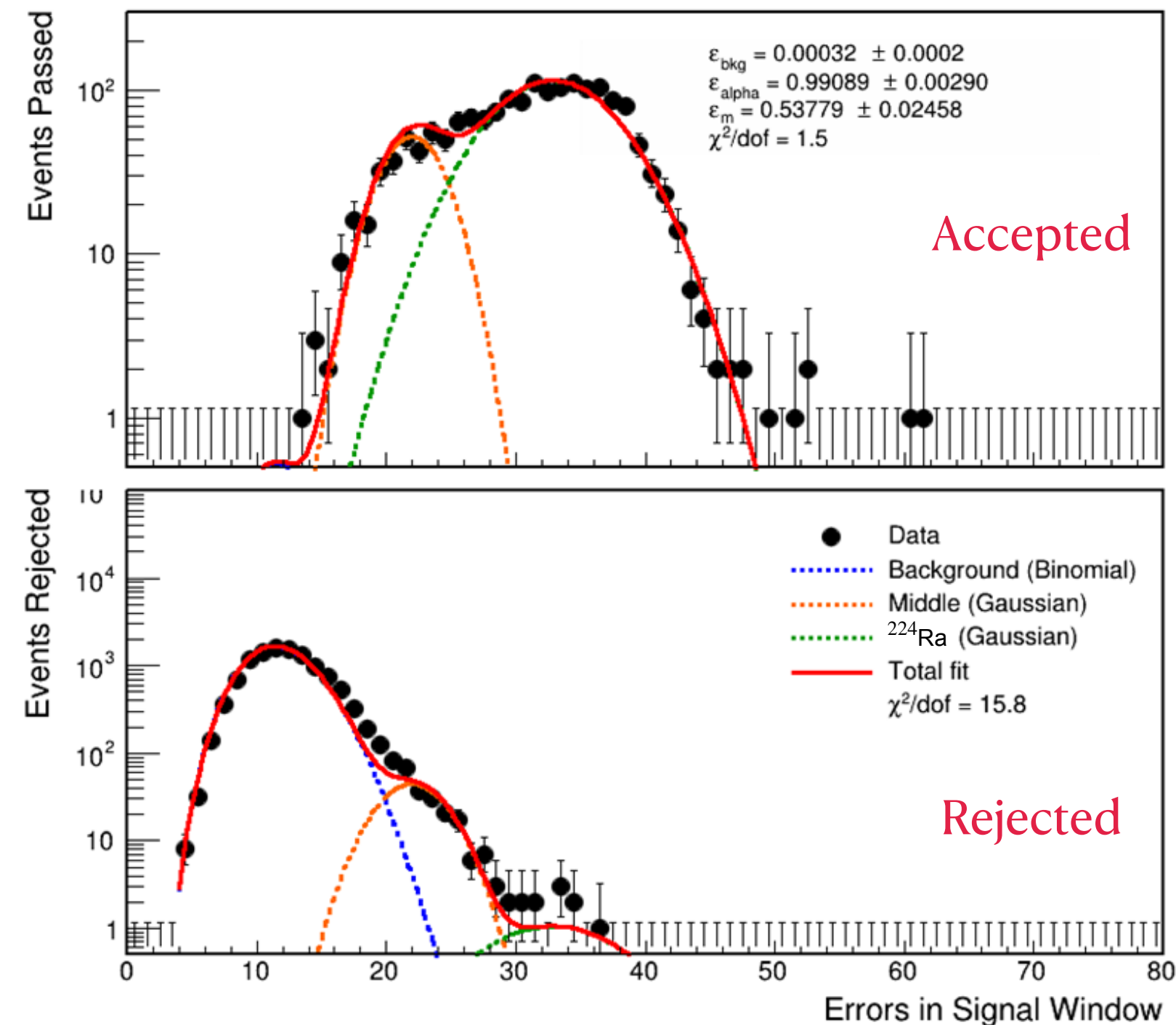
Incorporates local $P(|g\rangle)$ in binomial probability of spontaneous decoherence

Select events with high probability to be a signal

Analysis Strategy



Data Selection

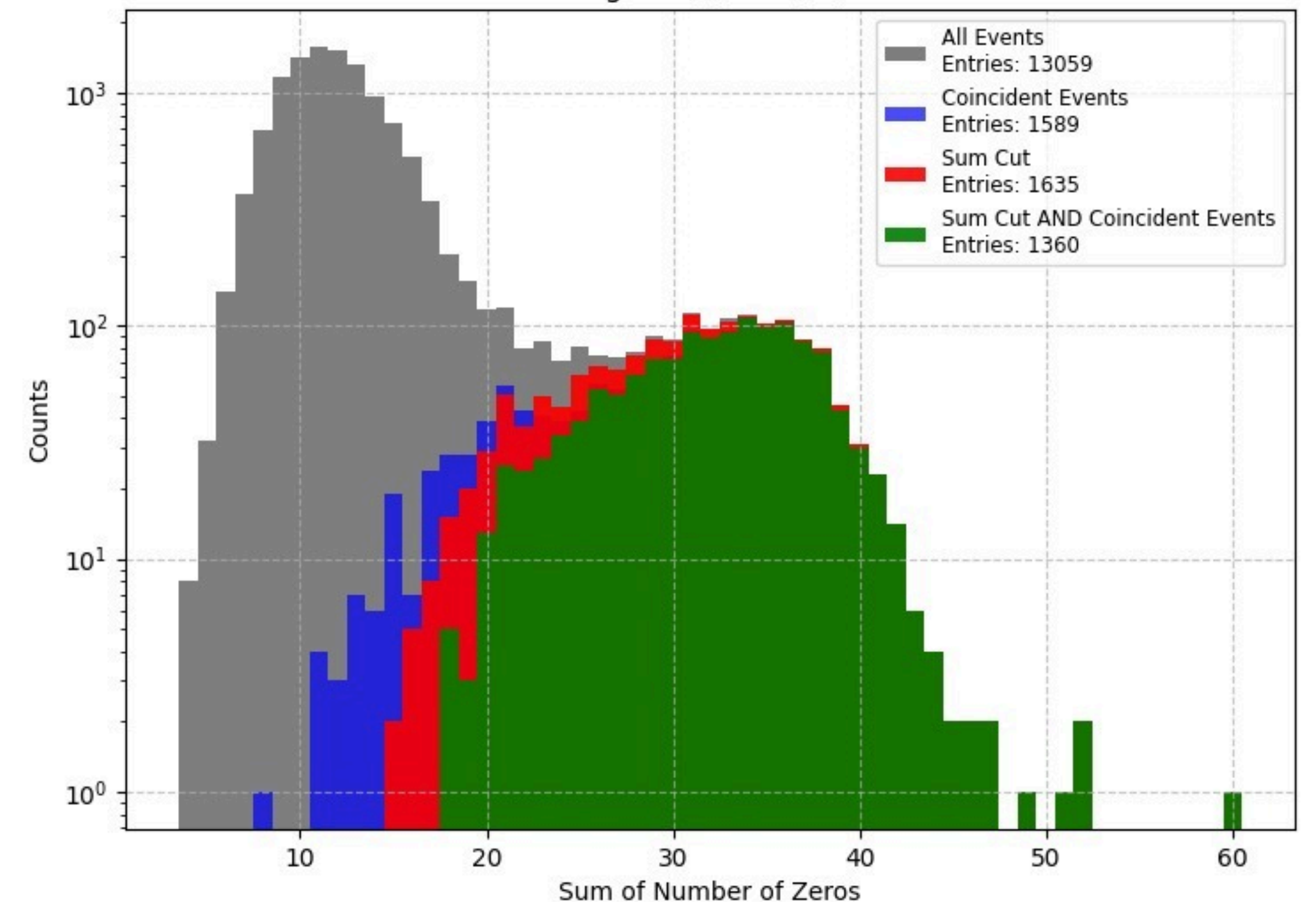


- Simultaneous fit to accepted and rejected events, with common efficiencies
- Template from the overall distribution
- Independent datasets used to define cuts and estimate efficiency

Estimate the selection efficiency

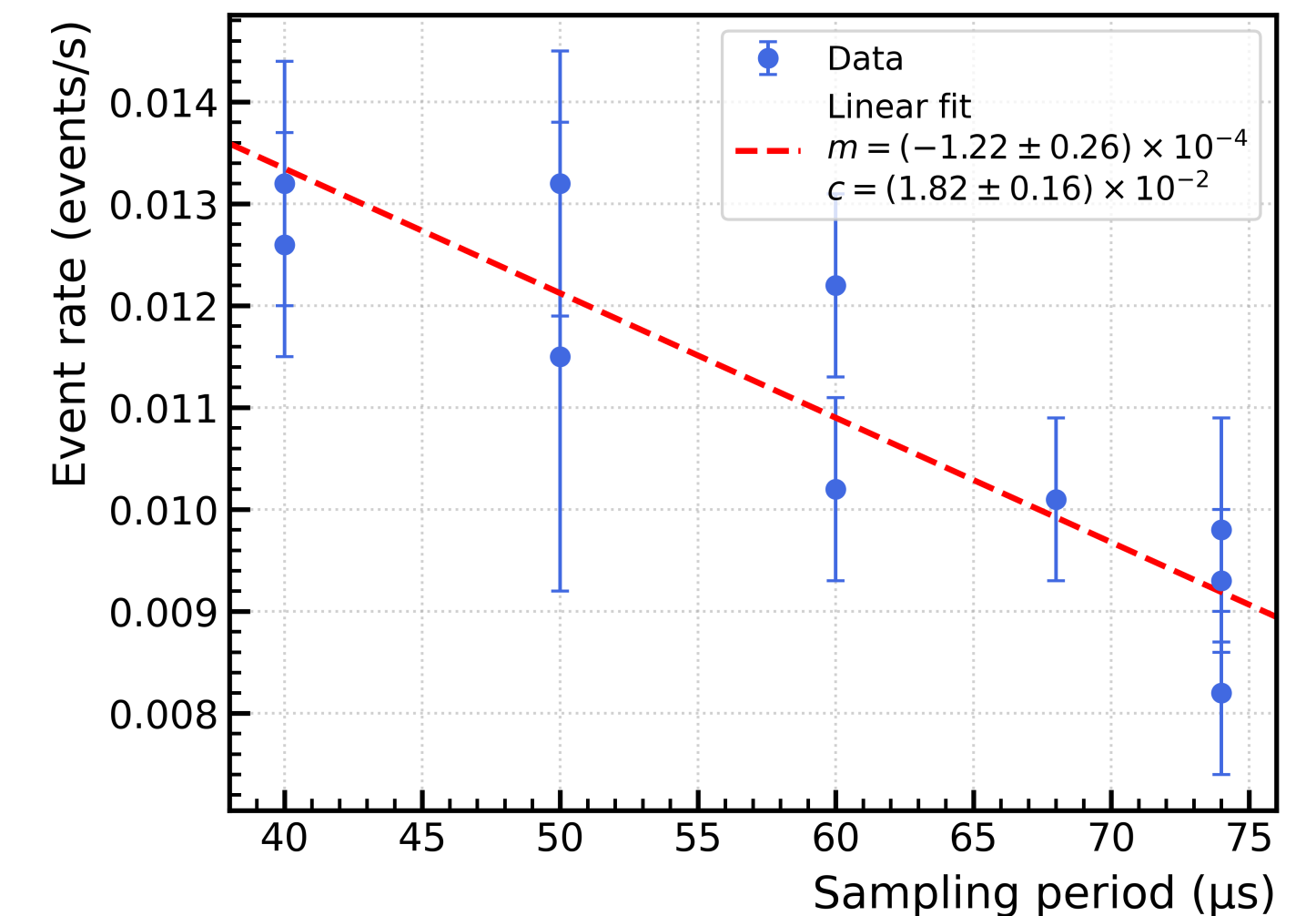
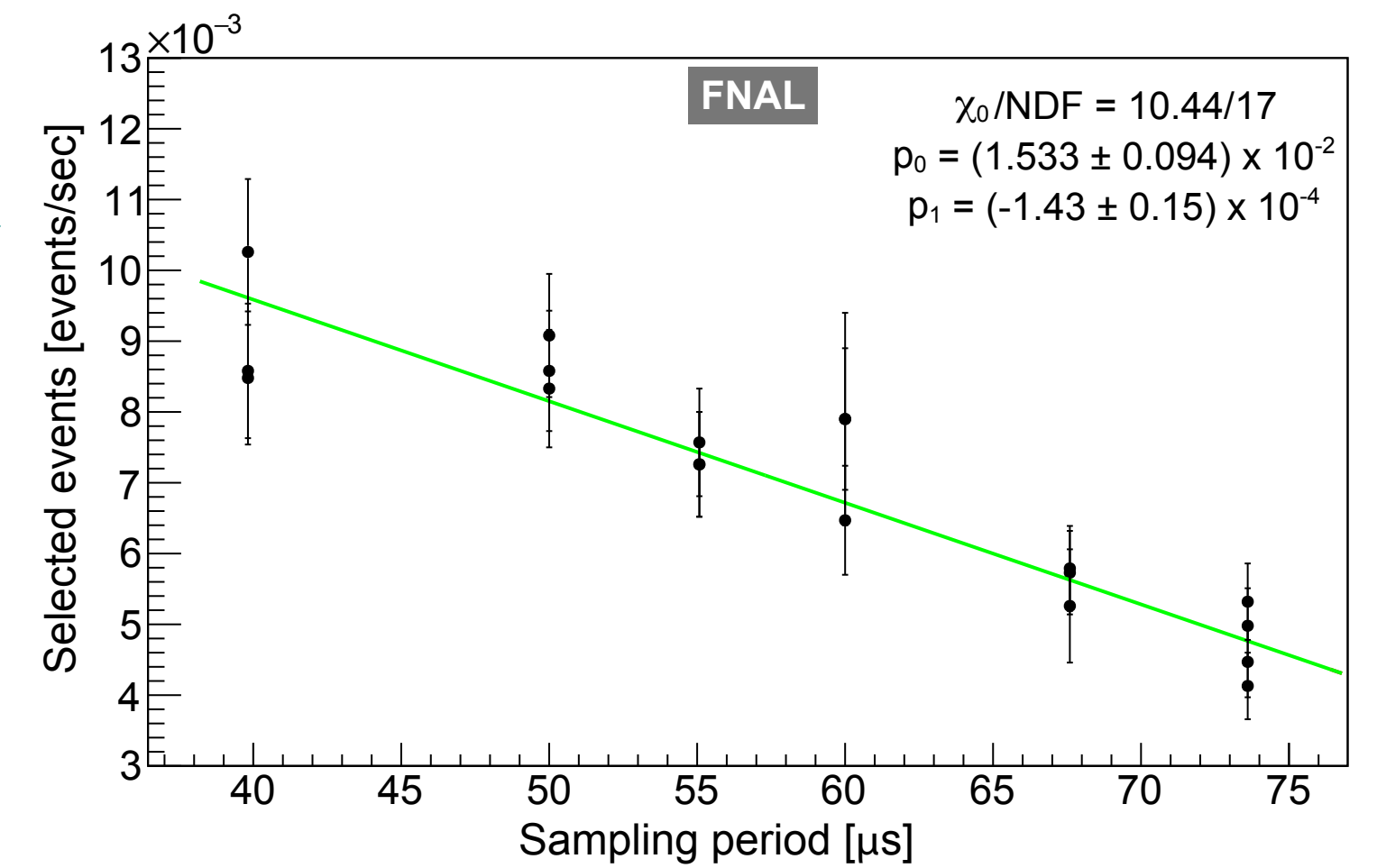
Analysis Summary

1. Trigger on best qubit
2. Sum zeros of “all” qubits
3. Reject fake coincidences
4. Reject low signal probability events
5. Estimate overall efficiency of the selection
6. **Estimate the rate and correct by the selection efficiency**



Results

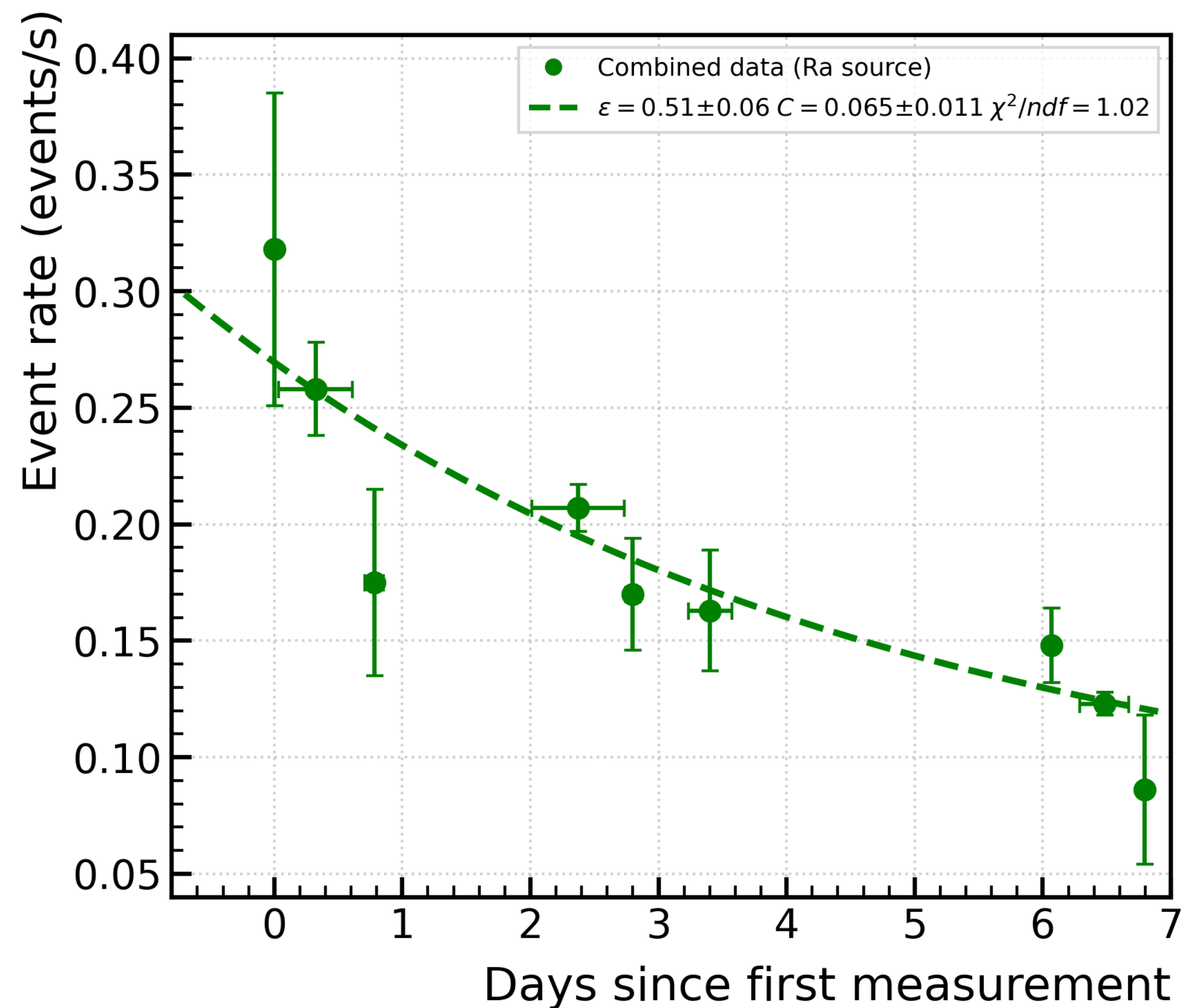
- Main innovations with respect to our previous work (De Dominicis, F., Roy, T., Mariani, A. et al., EPJ Quantum Technol. (2026)):
 - Systematic selection of time-intervals based on states populations
 - Signal probability selection with local $P(|g\rangle)$ estimate
- ➔ $\sim 30\%$ efficiency improvement



[De Dominicis, F., Roy, T., Mariani, A. et al., EPJ Quantum Technol. \(2026\)](#)

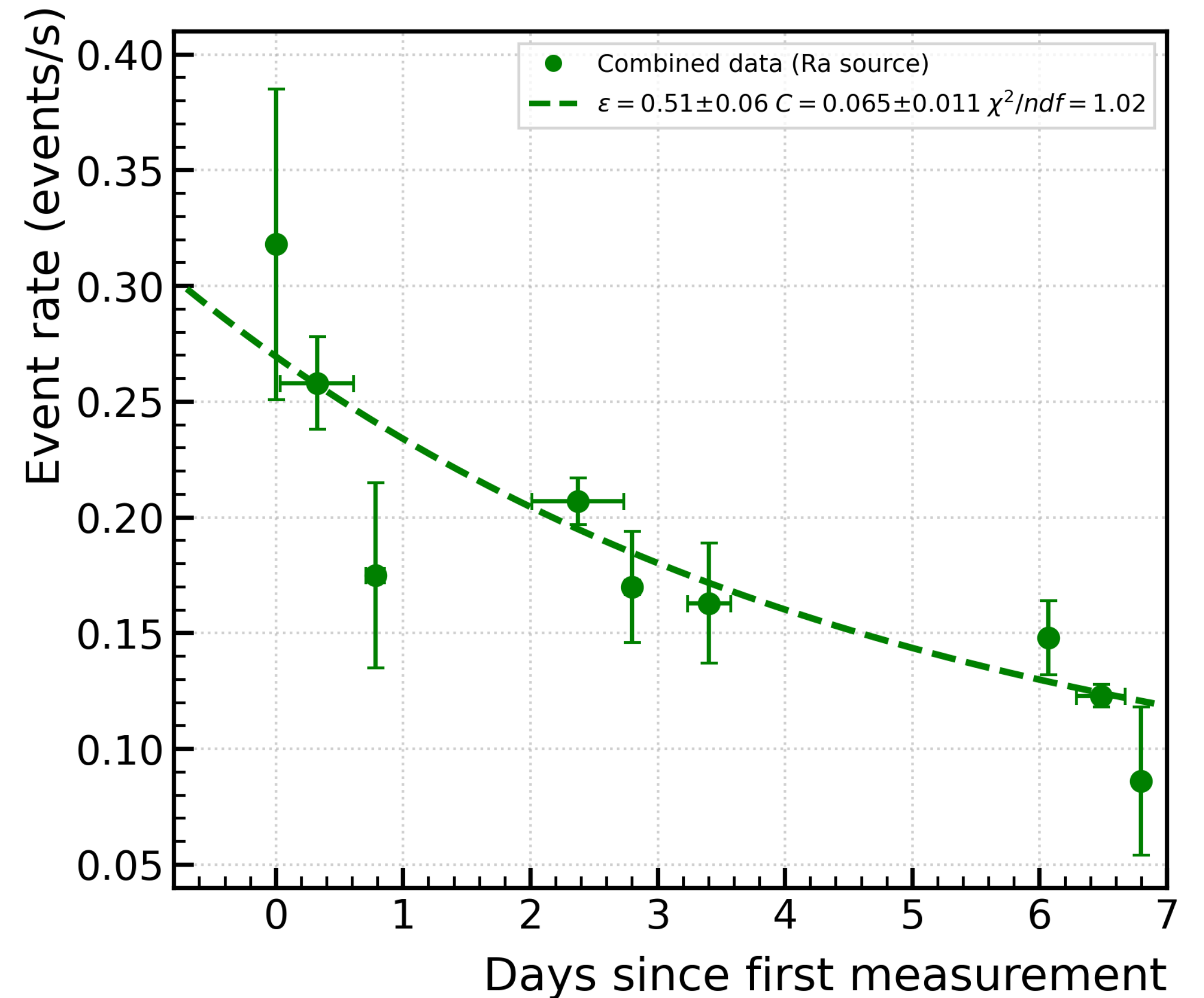
Results

- We repeat the selection with data acquired at different time
- We observe the rate decaying, as expected by the ^{224}Ra source
- We fit with $\varepsilon R_{true} e^{-t/\tau} + C$
 - R_{true} fixed to the one found by the simulation + NTD
 - τ fixed to its nominal value
 - ε is the qubits detection efficiency



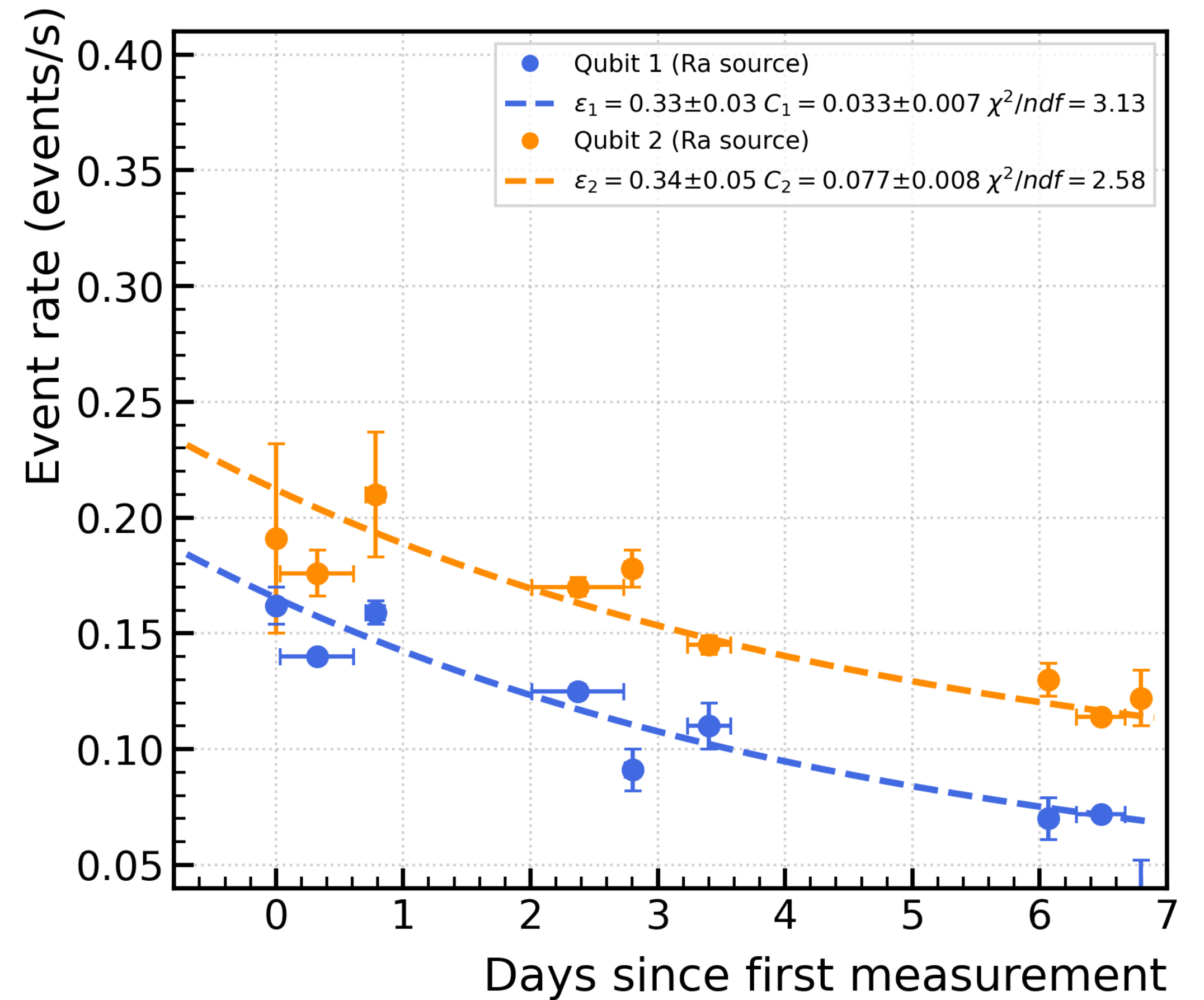
Results

- Uncertainty accounts for systematics on:
 - Population cuts: $\pm 1\%$ on $P(|g\rangle)$, $\pm 5\%$ on $P(|e\rangle)$
 - Signal + Control regions length (± 5 samples)
 - Trigger: ± 1 consecutive $|g\rangle$



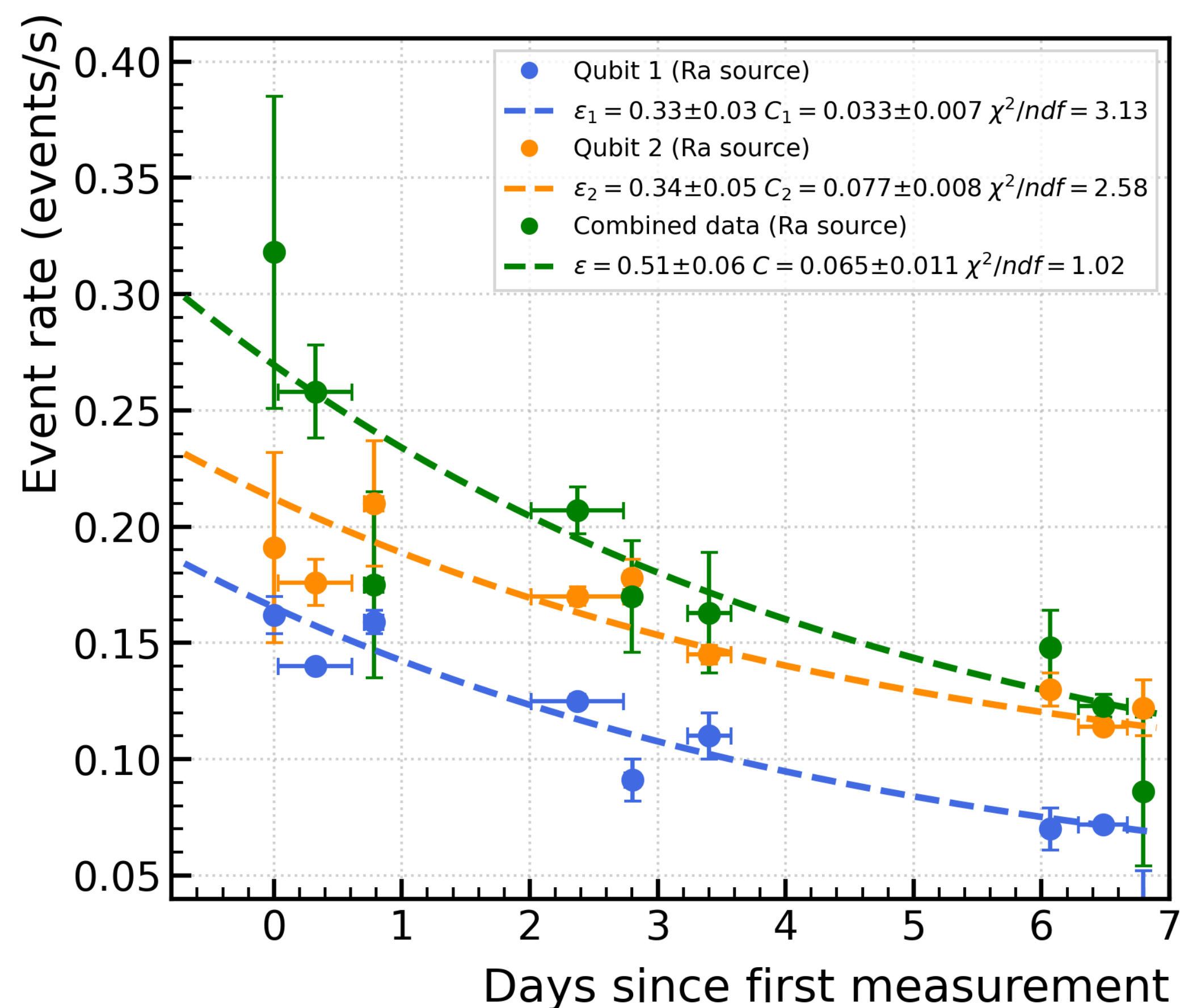
Results

- We repeat the study using single qubits
- We applied the selection based on probability and estimated efficiency (as for the 2 qubits case)



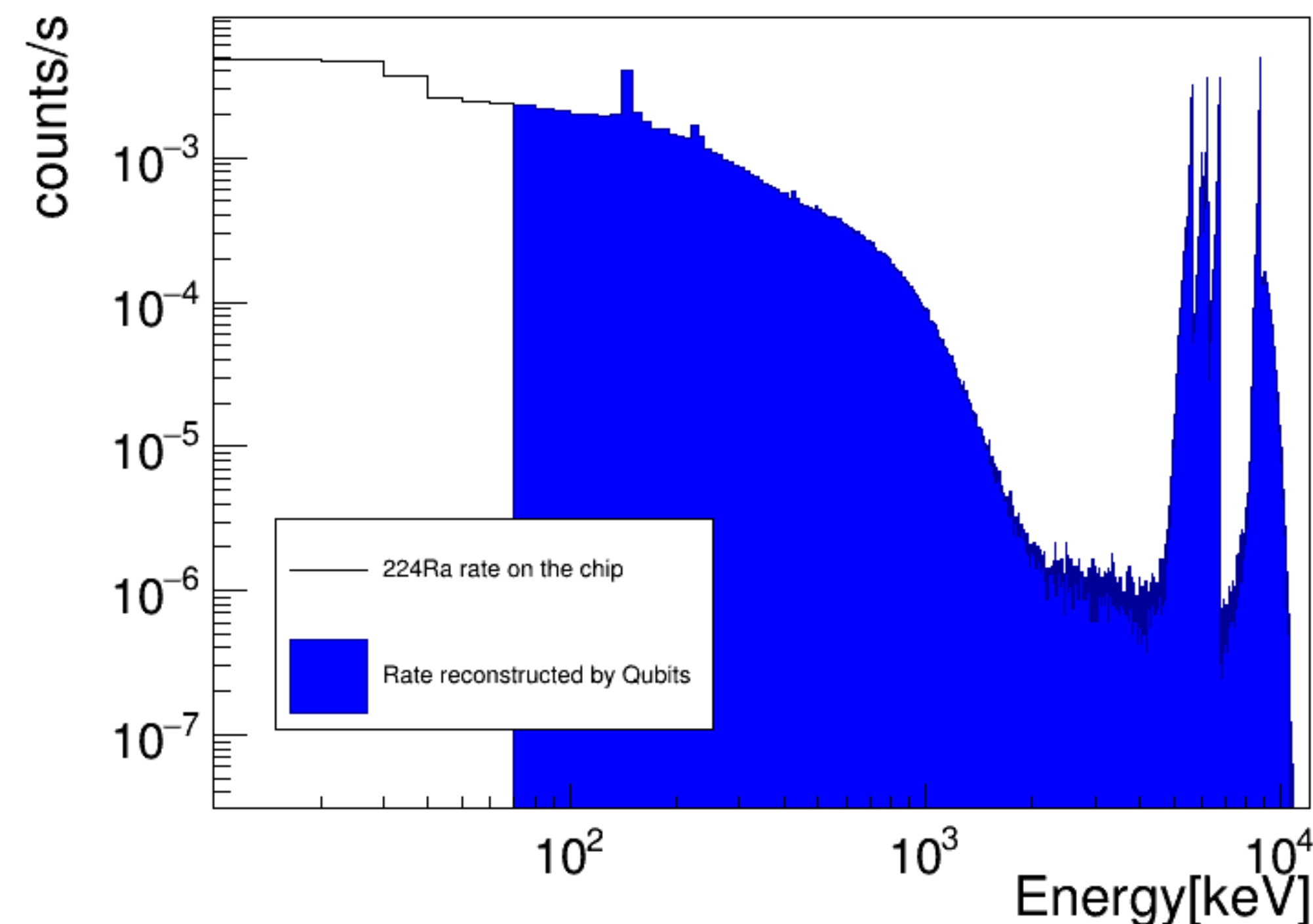
Results

- We repeat the study using single qubits
- We applied the selection based on probability and estimated efficiency (as for the 2 qubits case)
- By summing the 2 qubits we improve the detection efficiency up to $\sim 50\%$



Results

- Energy Threshold estimate
 - Scale the ^{224}Ra simulation spectrum to have the same events recorded by the NTD in the α region ($E > 3 \text{ MeV}$ with 100% detection efficiency)
 - Lower energy environmental background taken into account
 - Scale coefficient is applied to the whole simulation

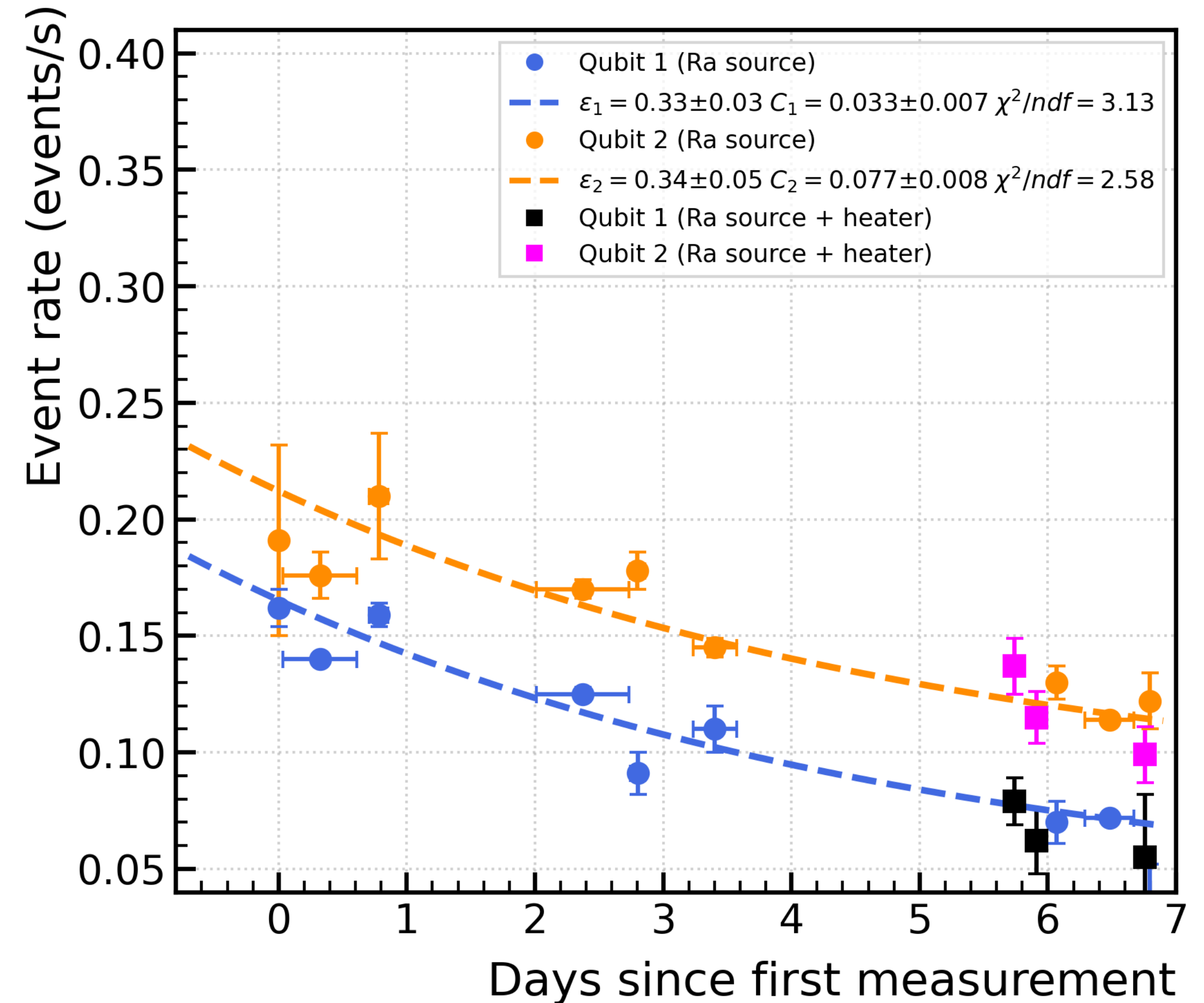


- $\int_{thr}^{inf} S(E)dE = R_Q \rightarrow$ integrate spectrum to get same rate detected by the qubits

$$thr = 70 \pm 20(\text{stat})_{-30}^{+30}(\text{syst}) \text{ keV}$$

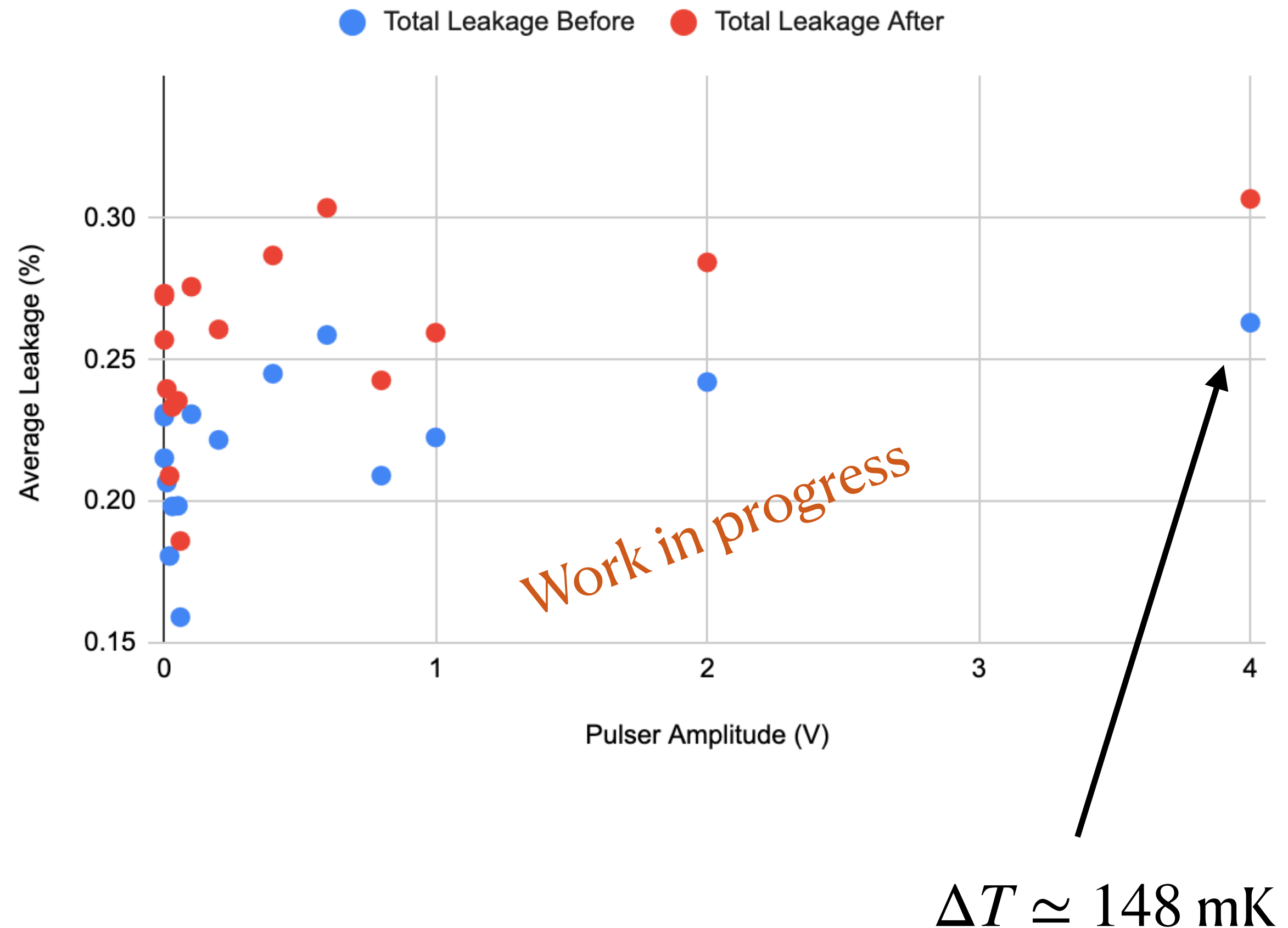
Thermal Phonons

- Heater injecting thermal phonons with 8-ms-long pulses firing at 10Hz
- Measurements done with different pulse amplitudes, maximum energy injected estimated with the NTD to be $\simeq 3$ MeV ($\rightarrow \Delta T \simeq 148$ mK)
- Rate of quasiparticle-induced events consistent with what expected from environmental radioactivity and α source.
 - ➔ Thermal phonons produced by the heated did not induce quasiparticle poisoning in the qubit due to their low energy



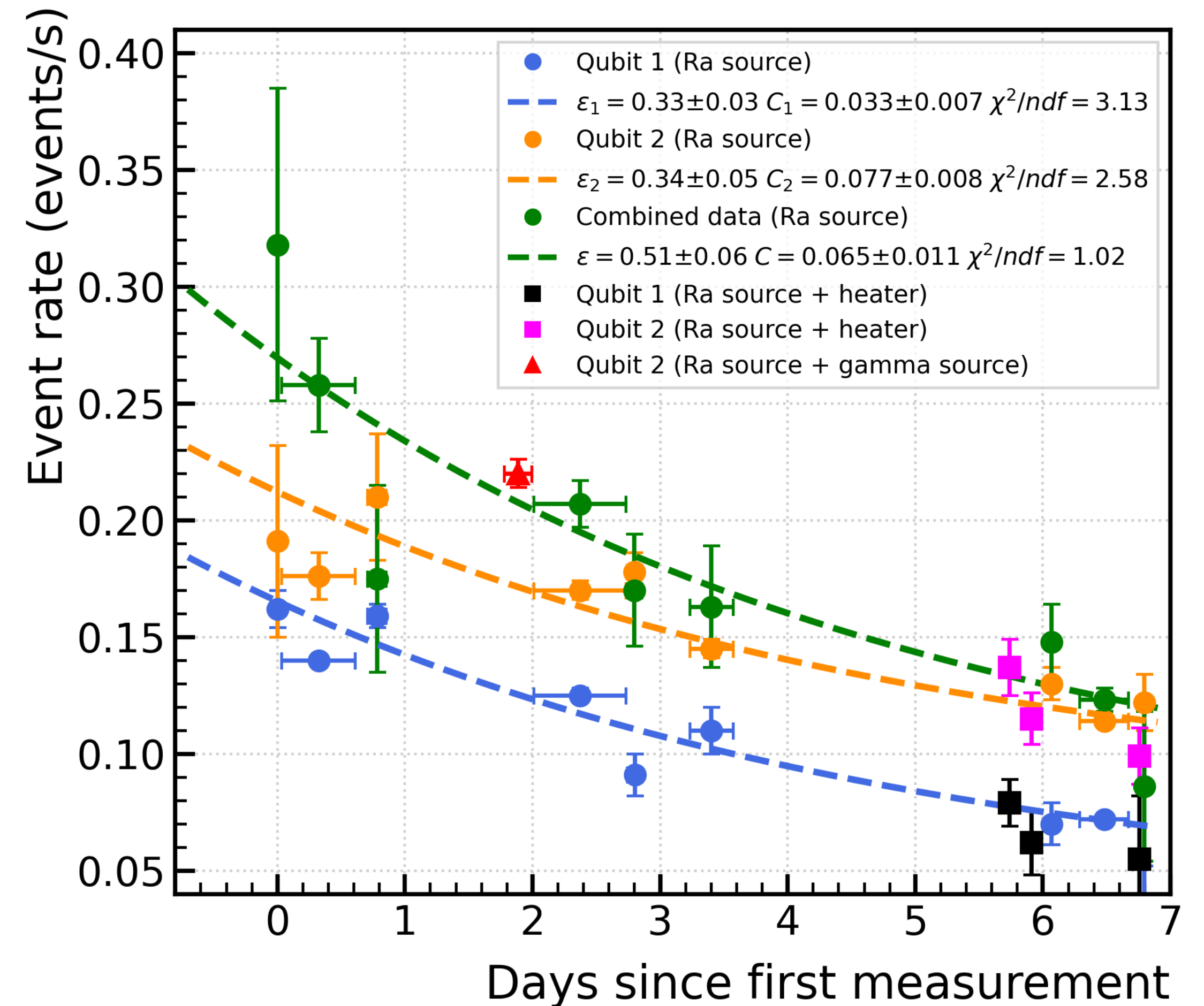
Thermal Phonons

- However, O(100 mK) temperature fluctuations could induce leakage to the higher energy states.
- The analysis of their effect on higher state populations showed a correlation in one qubit only
- However, no periodical leakage fluctuations were observed



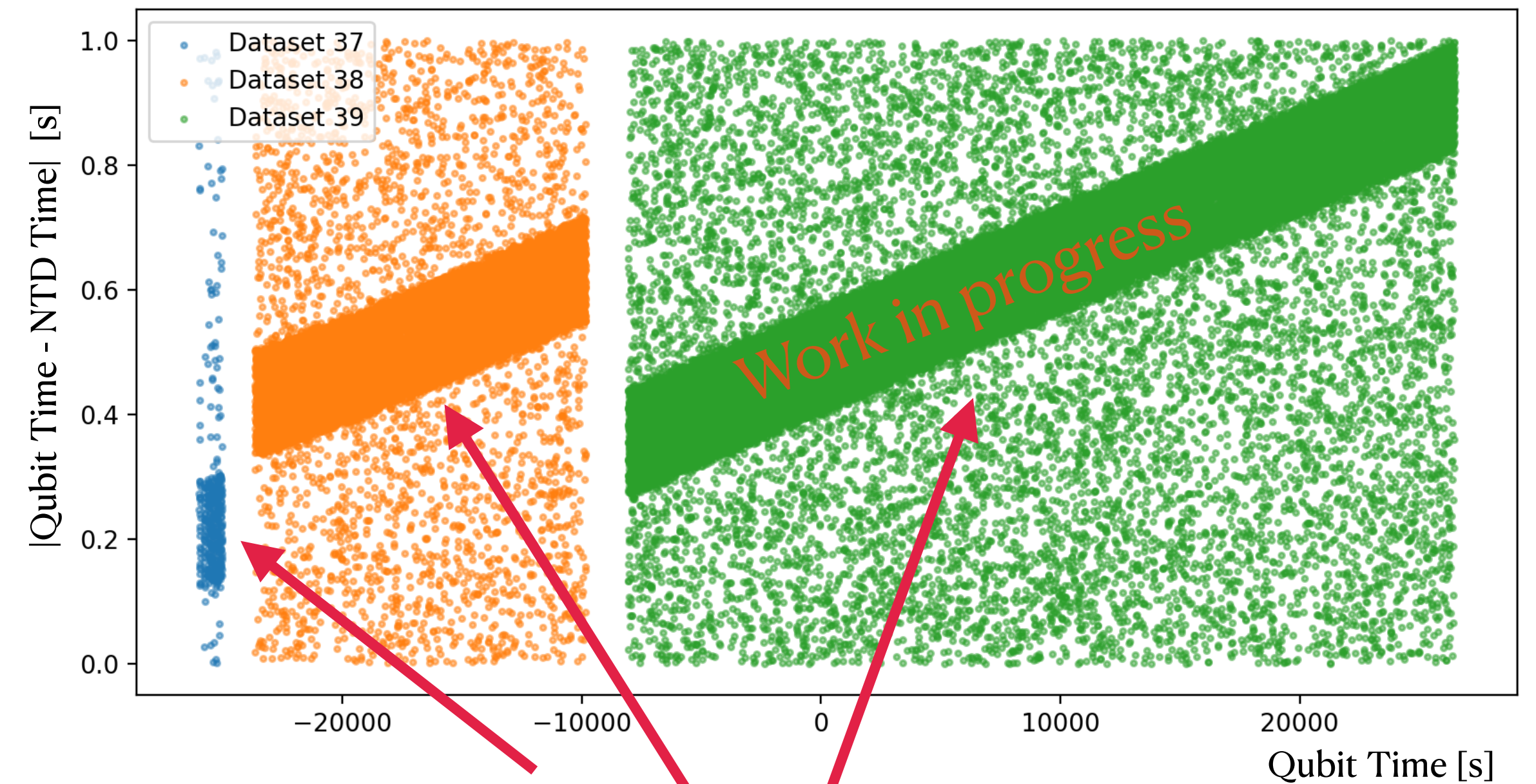
Conclusion

- We outline detection and analysis for radiation induced events on qubits
 - Diagnosis tool againsts quasi-particle poisoning
 - Potentiality for a particle detector: we face limitations due to low T_1 and fidelity
- We performed a week-long radioactivity measurement on a close-source with qubits
- We improve the detection efficiency found in our previous work up to $\sim 50\%$
- Paper in preparation



What's Next?

- We aim to synchronize Qubits vs NTD through LED pulses
 - Clearly seen by qubit (very large number of $|g\rangle$ events)
 - We have technical issues related to a moving jitter



LED populations in different runs

- Biggest potentiality of double-sensor readout:
 - ➡ assign qubit events an energy with a few % uncertainty
 - ➡ Aim to validate this analysis and improve our understanding for the next data-taking

P R N

PROGETTI DI RICERCA DI
RILEVANTE INTERESSE
NAZIONALE

S Q M S



Istituto Nazionale di Fisica Nucleare

Thank You!

RIS* 2026

*On behalf of:

M. Bal, F. Bellini, C. Bonomo, N. Casali, I. Colantoni, F. Crisa, A. Cruciani, F. Ferroni, F. De Dominicis, A. Grassellino, D. L. Helis, Mehmood Khan Yasir Raja, A. Mariani, L. Pagnanini, R. Pilipenko, S. Pirro, A. Puiu, A. Ressa, A. Romanenko, T. Roy, L. Tirabasso, D. van Zanten, S. Zhu, and L. Cardani

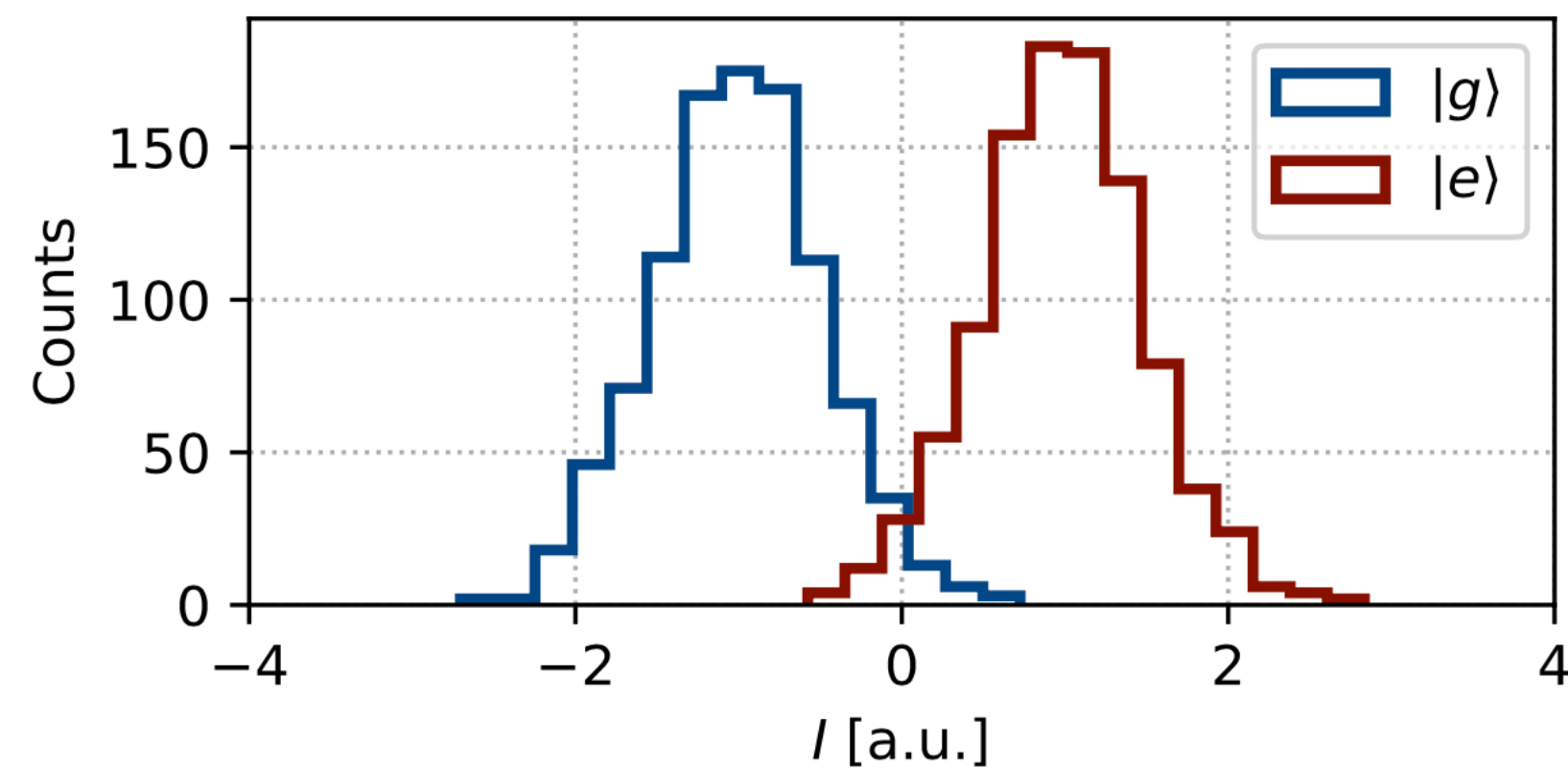
Backup



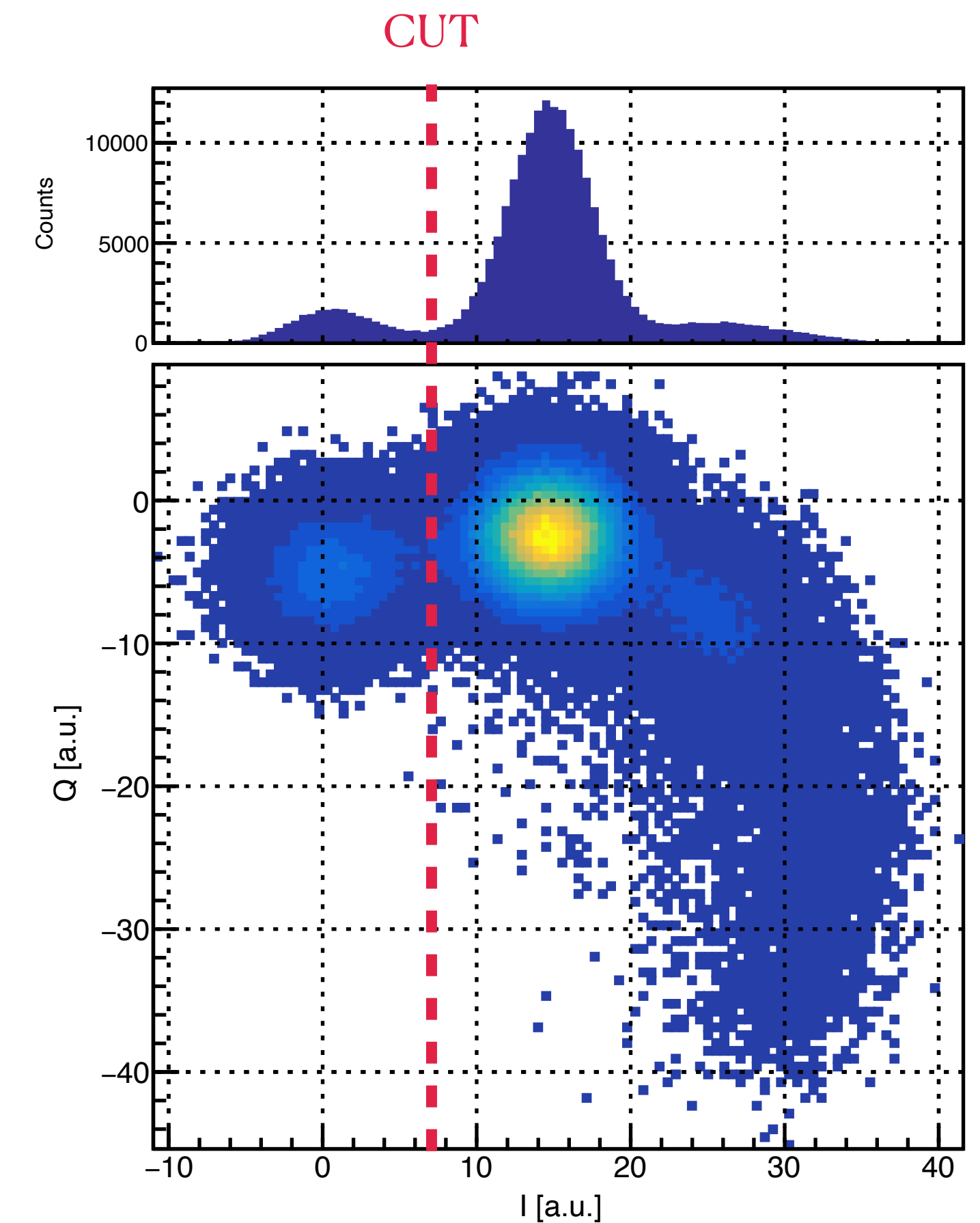
Fidelity Optimisation

- Fit the I distribution with two-gaussians

- $P(1 | 0) = \int_{-\infty}^{CUT} \mathcal{G}_1$ “left-tail of $|e\rangle$ ”
- $P(0 | 1) = \int_{CUT}^{\infty} \mathcal{G}_0$ “right-tail of $|g\rangle$ ”

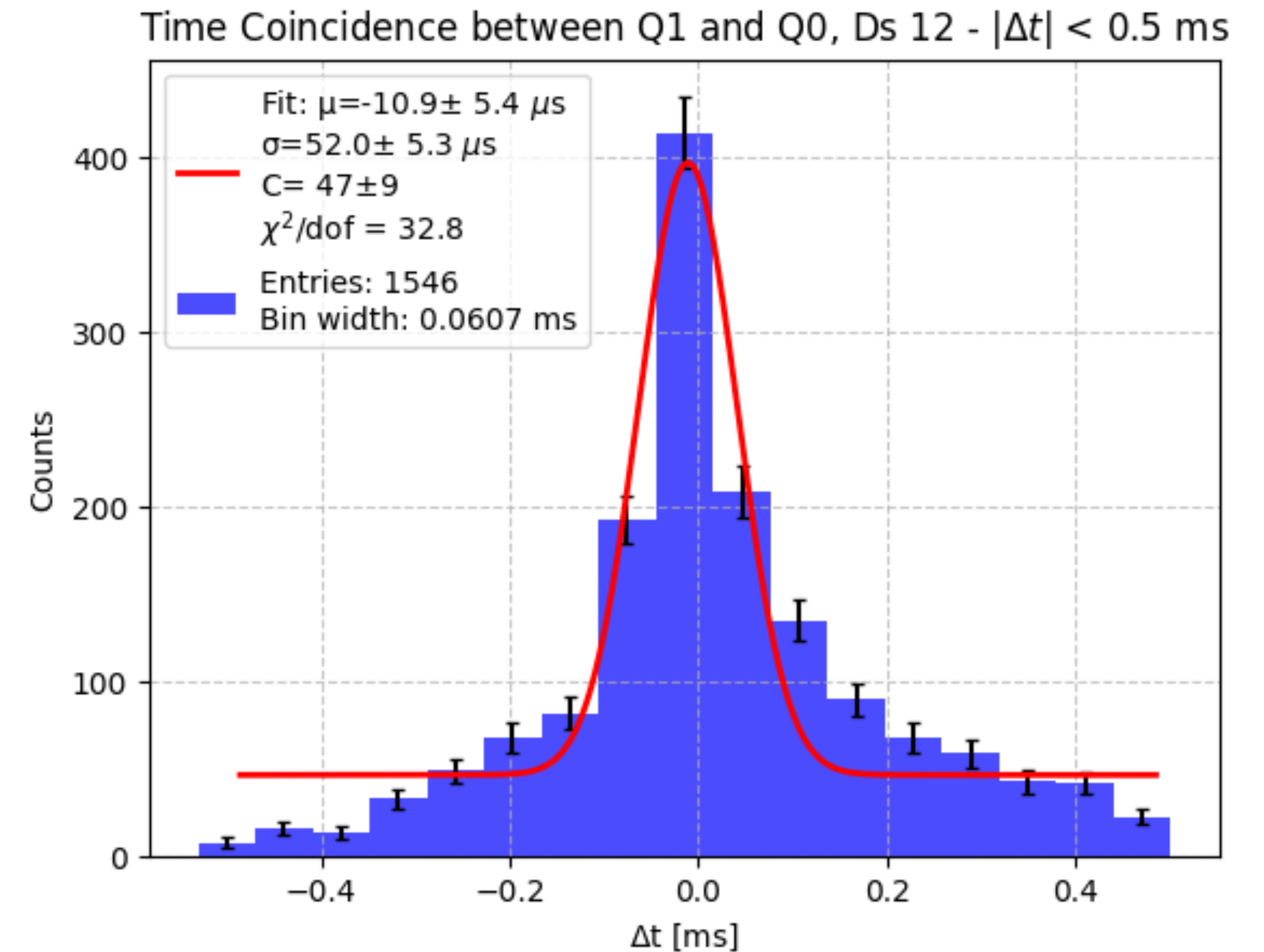


$$\mathcal{F} = 1 - \frac{1}{2}[P(|e\rangle||g\rangle) + P(|g\rangle||e\rangle)]$$



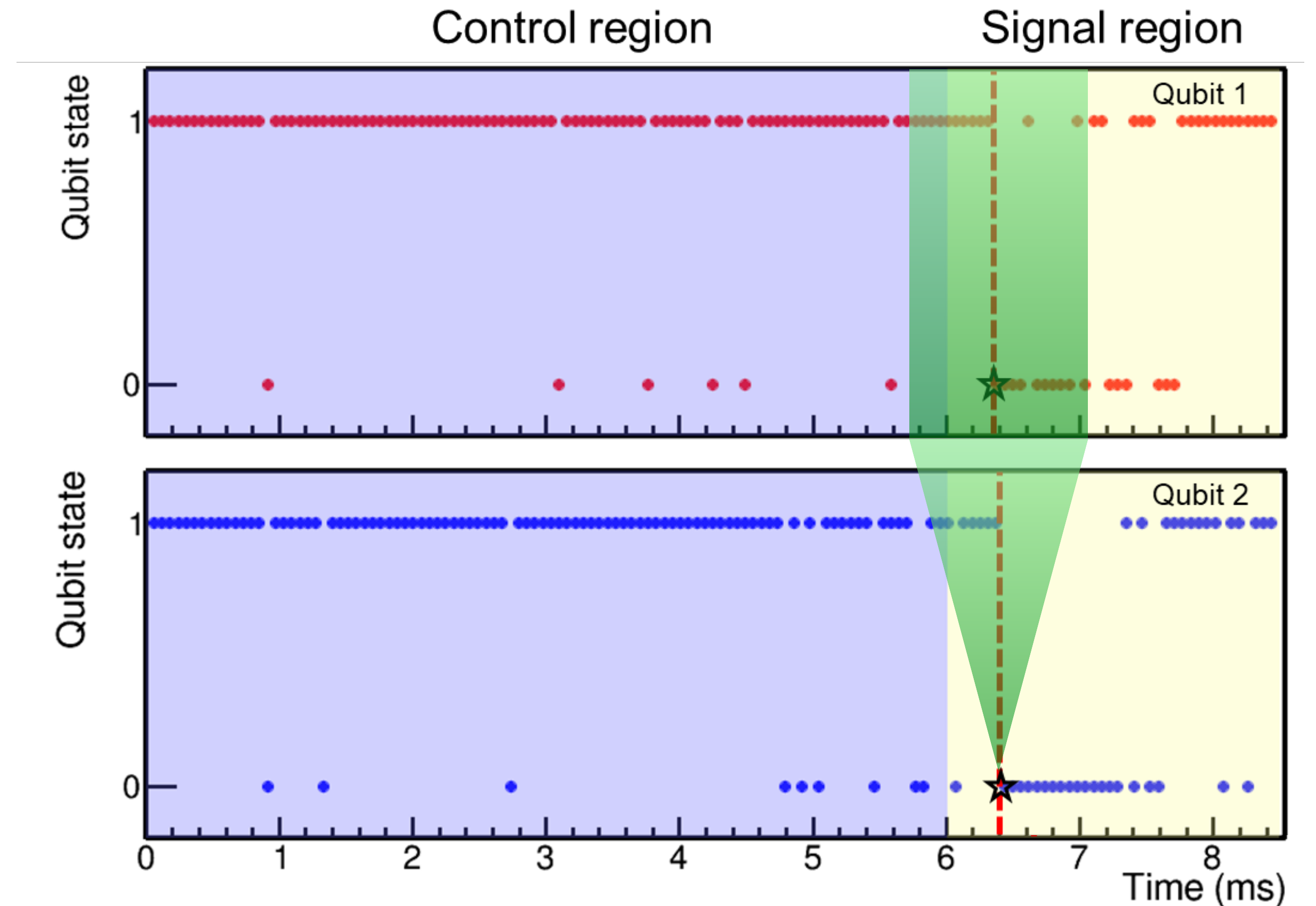
Simultaneous Qubits Operation

- To deal with 2 qubits we made sure they are coincident
 - Trigger difference distribution
 - 5σ of the gaussian is contained within ± 25 ms (over a signal window of 2.4ms)
 - Tail events are part of the background (spontaneous decoherence): see next slides



Simultaneous Qubits Operation

- To deal with 2 qubits we made sure they are coincident
 - Set the trigger on the best performing qubit
 - Look at ± 10 samples of the other qubits
 - Select the whole event if it finds other 4 $|g\rangle$



Data Selection

- Quality Selection based on Probability:
 - If no particles interaction we expect a Bernoulli process
 - Ruled by $P(|g\rangle)$ locally estimated for each event
 - What is the probability that an event is NOT described by the Bernoulli process?
 - i.e. that it is a signal

Reject events below a certain probability

Signal Probability

$$P(k_1 | N_1, k_0, N_0) = \int_0^1 P(k_1 | N_1, p) P(p | N_0, k_0) dp$$

$\mathcal{B}(k_1 | N_1, p)$ ← ← $P(p | N_0, k_0) = \frac{\mathcal{B}(k_0 | N_0, p) P_0(p)}{\int_0^1 P(k_0 | p) P_0(p) dp} \simeq 1$

$$P(k_1 | N_1, k_0, N_0) = \int_0^1 P(k_1 | N_1, p) P(p | N_0, k_0) dp$$

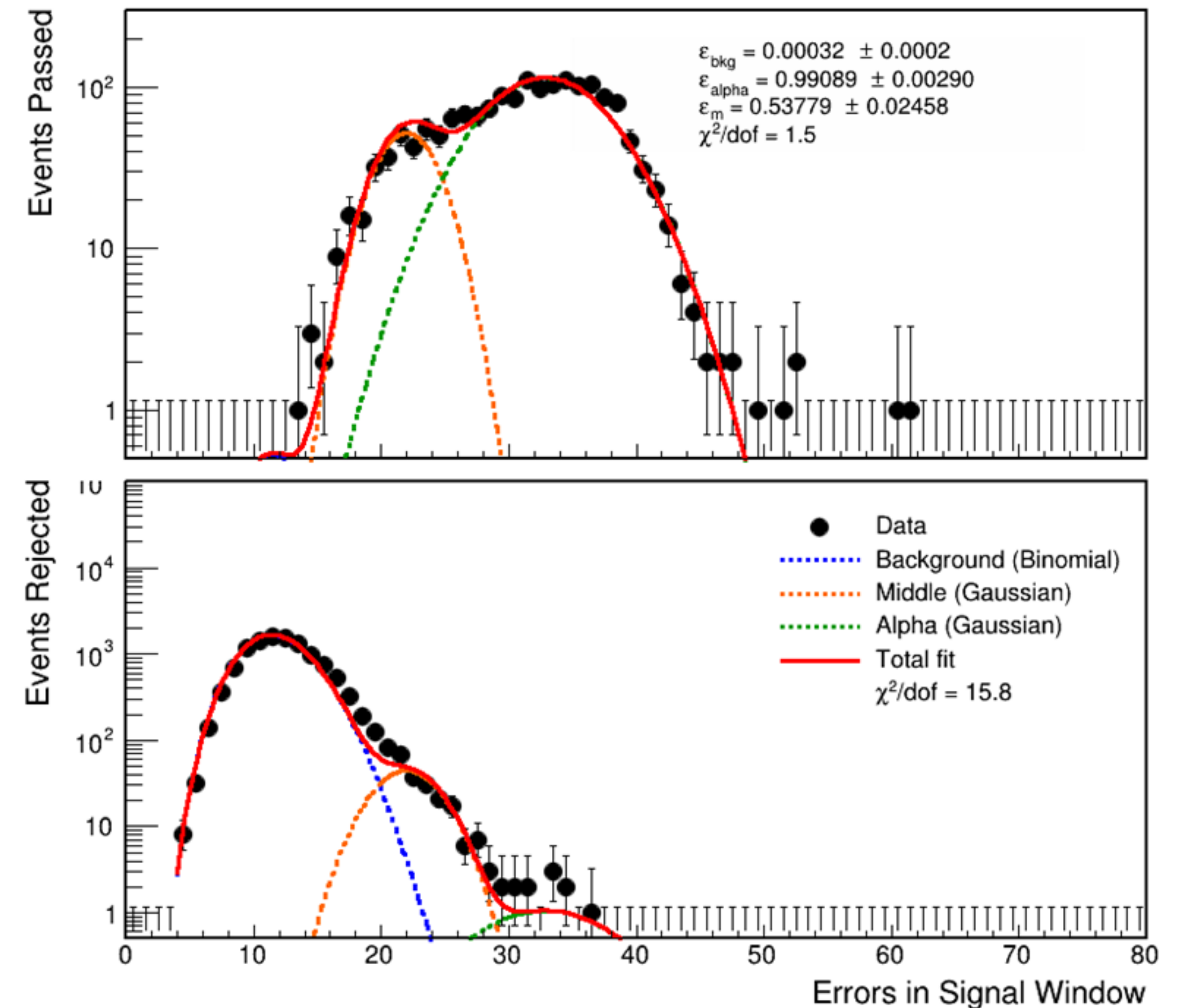
$$\equiv \binom{N_1}{k_1} \frac{B(k_1 + k_0 + 1, N_1 - k_1 + N_0 - k_0 + 1)}{B(k_0 + 1, N_0 - k_0 + 1)}$$

with $B(\alpha, \beta) = \int_0^1 \mathcal{B}(k = \alpha - 1, N = \beta + k - 1, p) dp$

- k_1 : #0s in signal window
- N_1 : signal window length
- k_0 : #0s in pre-trigger
- N_0 : pre-trigger window
- \mathcal{B} : Binomial Distribution

Data Selection

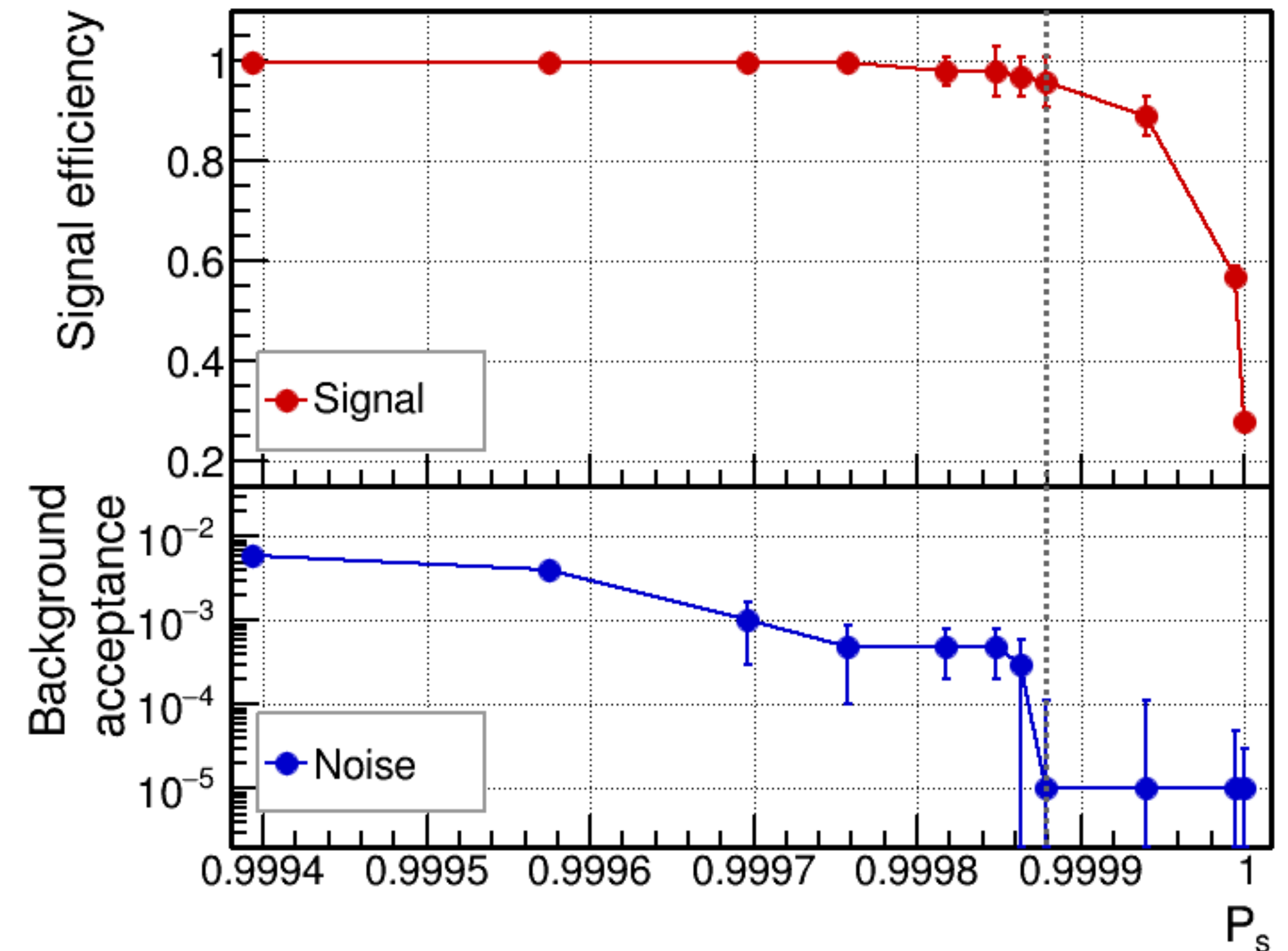
- How to find the best cut?
 - Scan over many probability cuts
 - Build two zeros distributions: accepted and rejected events
 - Simultaneous fit of the two with common efficiencies
 - Signal efficiency: ε_S (accepted) and $1 - \varepsilon_S$ (rejected)
 - Background Acceptance: ε_B (accepted) and $1 - \varepsilon_B$ (rejected)



Data Selection

- How to find the best cut?
 - Select optimal cut that:
 1. Saturates signal efficiency
 2. Keeps background compatible with 0

Optimization found “sacrificing” part of the data, and applied to all the others

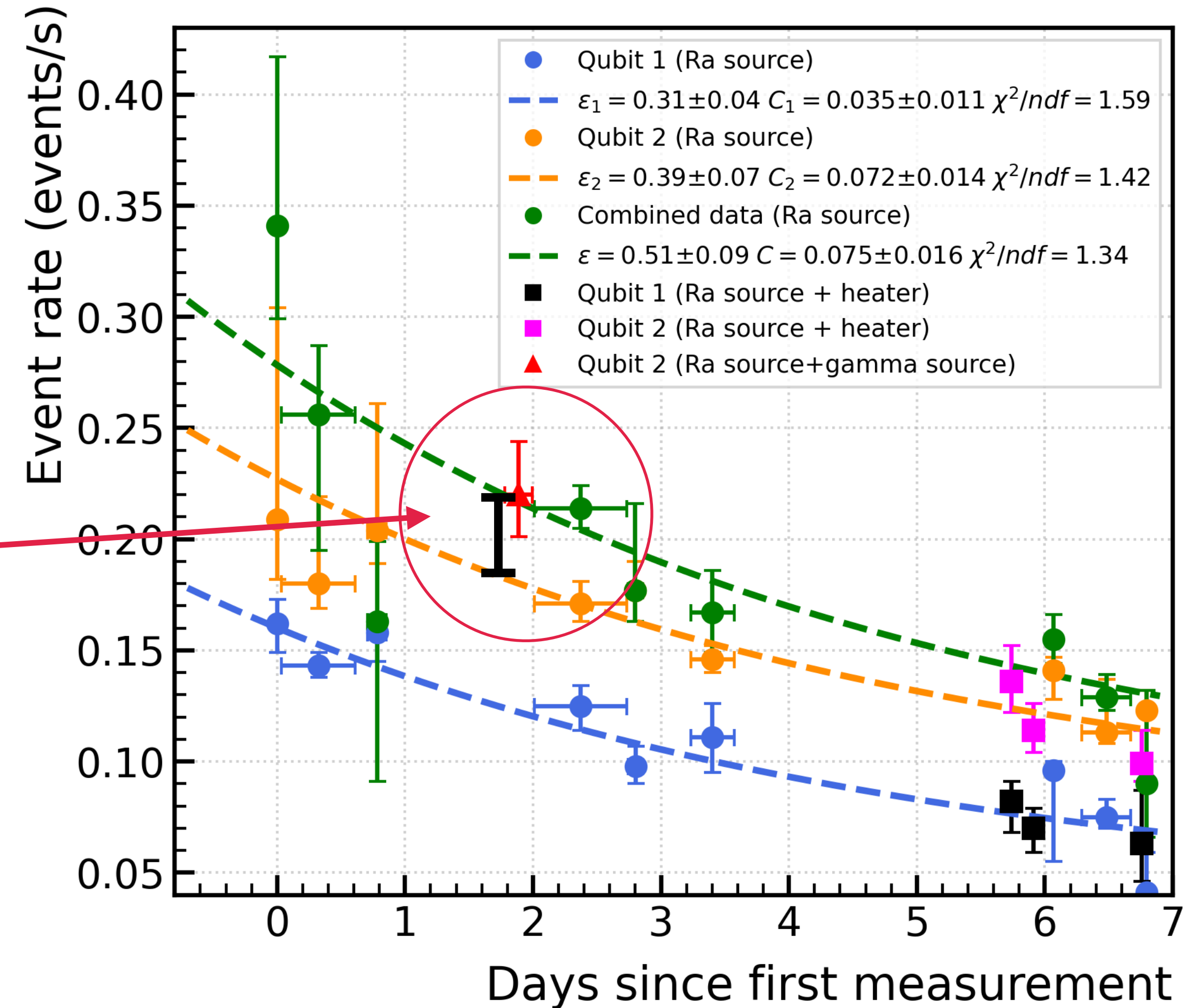


Threshold Calculation

1. $R_{NTD}(> 3MeV) =$ rate from NTD above 3MeV
2. $N_{MC} =$ number of simulated events
3. $CF(>3MeV) = \frac{N_{MC}}{N_{MC}(> 3MeV)}$ correction factor to scale ^{224}Ra activity above 3MeV to the overall one
4. R_{bkg} simulated rate from environment + PCS (negligible $>3\text{MeV}$)
5. Scale simulated ^{224}Ra spectrum by $\frac{R_{NTD}(> 3MeV) \cdot CF(> 3MeV) + R_{bkg}}{N_{MC}}$
6. $\int_{thr}^{inf} S(E)dE = R_Q$, $S(E) =$ scaled ^{224}Ra spectrum, $R_Q =$ qubits rate

Threshold Cross-Check

- Method cross validated in presence of external gamma sources:
 - Use the predicted rate by placing a 161kBq ^{232}Th source outside the cryostat
 - Scale the simulation
 - Estimate the rate induced ONLY by the gamma source by subtracting the one from ^{224}Ra extrapolated at the same time



Threshold Cross-Check

- “Sanity Check” on the method to compute the threshold
- Perform same estimate on NTD sensor
 - We know its threshold from heater pulses scan: 450 keV → independent estimate!
- Get the overall rate reconstructed by the NTD above 450 keV
- Compare it with the simulated spectrum to have the same integral, and account for environmental radioactivity
 - Threshold found to be ~ 250 keV
 - Uncertainty are of the order of 50 keV on both sides estimation