SUPERCONDUCTING QUBITS AS PARTICLE DETECTORS

FRANCESCO DE DOMINICIS, R. Y. Mehmood Khan, D. L. Helis, A. Mariani, L. Tirabasso, A. Ressa, M. Bal, F. Bellini, C. Bonomo, N. Casali, I. Colantoni, F. Crisa, A. Cruciani, S. Garattoni, A. Melchiorre, L. Pagnanini, V. Pettinacci, S. Pirro, A. Puiu, T. Roy, S. Zhu, A. Grassellino and L. Cardani

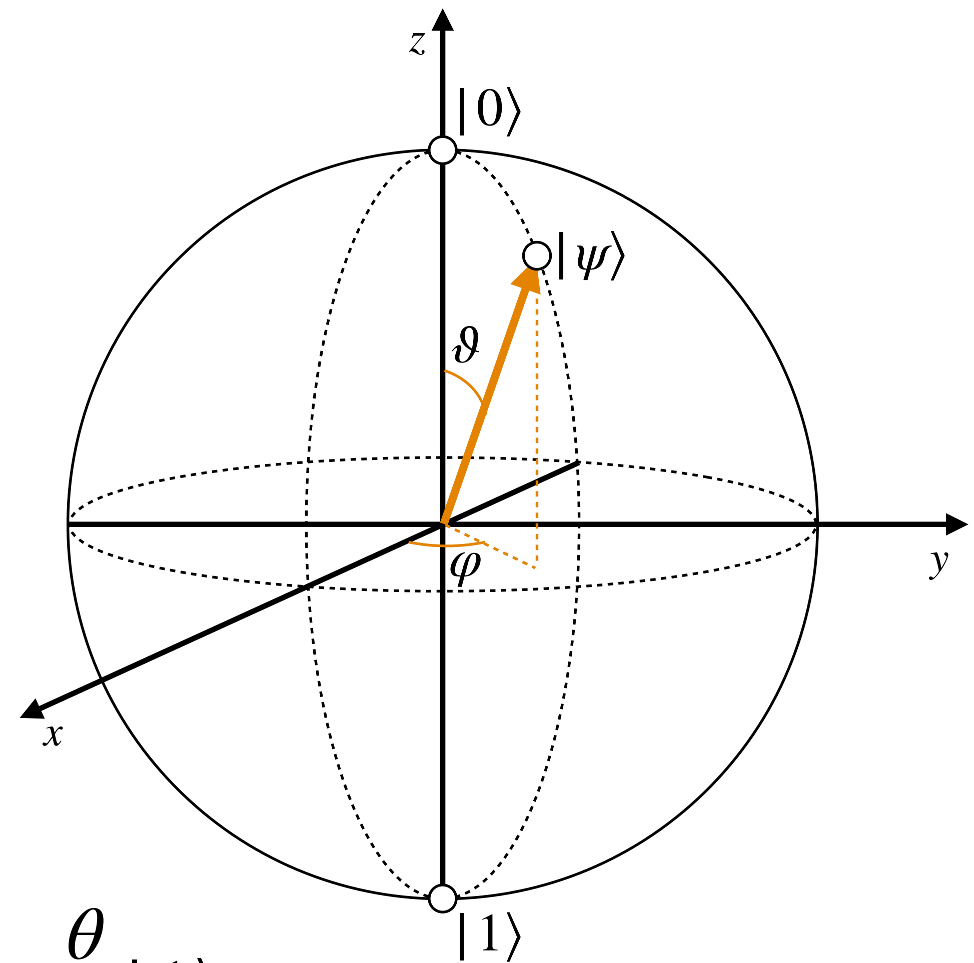
LOW RADIOACTIVITY TECHNIQUES 2026, YORK (UK)

INFN

QUANTUM BITS

- Quantum counterpart of classical bits:

	STATE
CLASSICAL BIT	0
	1



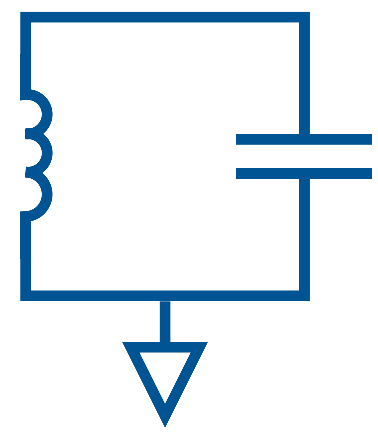
QUANTUM BIT $$|\psi\rangle = \cos\frac{\theta}{2}\,|0\rangle + e^{i\phi}\sin\frac{\theta}{2}\,|1\rangle$$

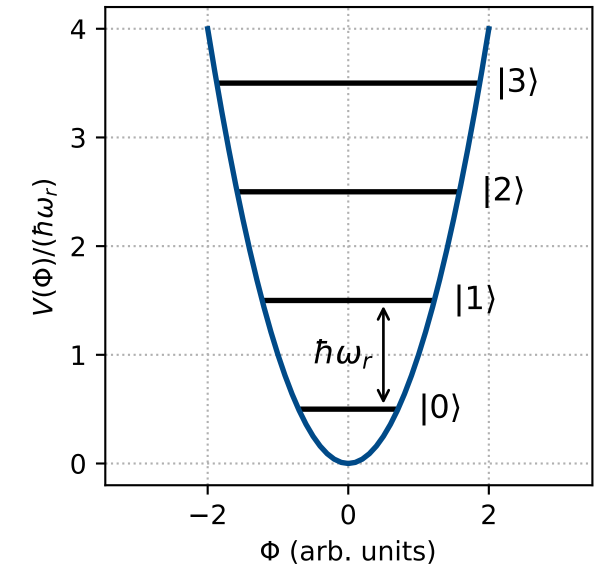
- Enabling quantum behavior such as *superposition* and *entanglement*.

SUPERCONDUCTING QUBITS

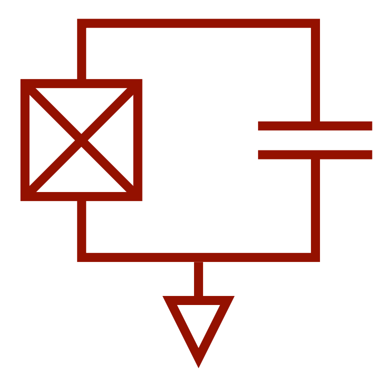
- Superconducting circuits featuring a Josephson Junction;
- The Josephson Junction acts as a non-linear inductor, producing an anharmonic energy spectrum;
- In this way it is possible to populate only the first two states and operate the circuit as a qubit.

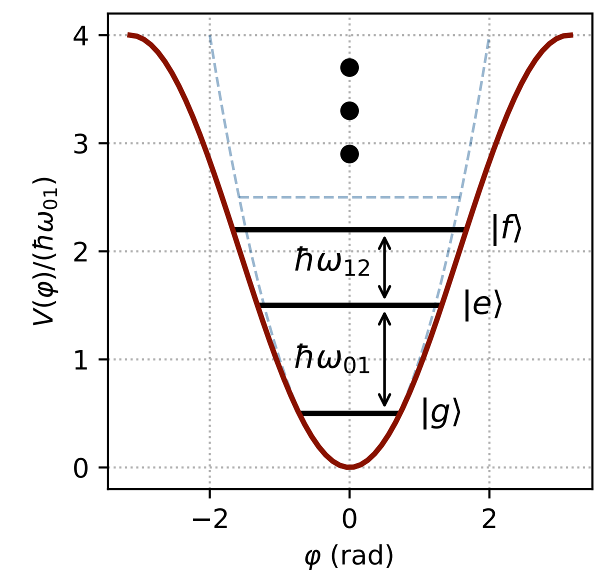
RESONATOR





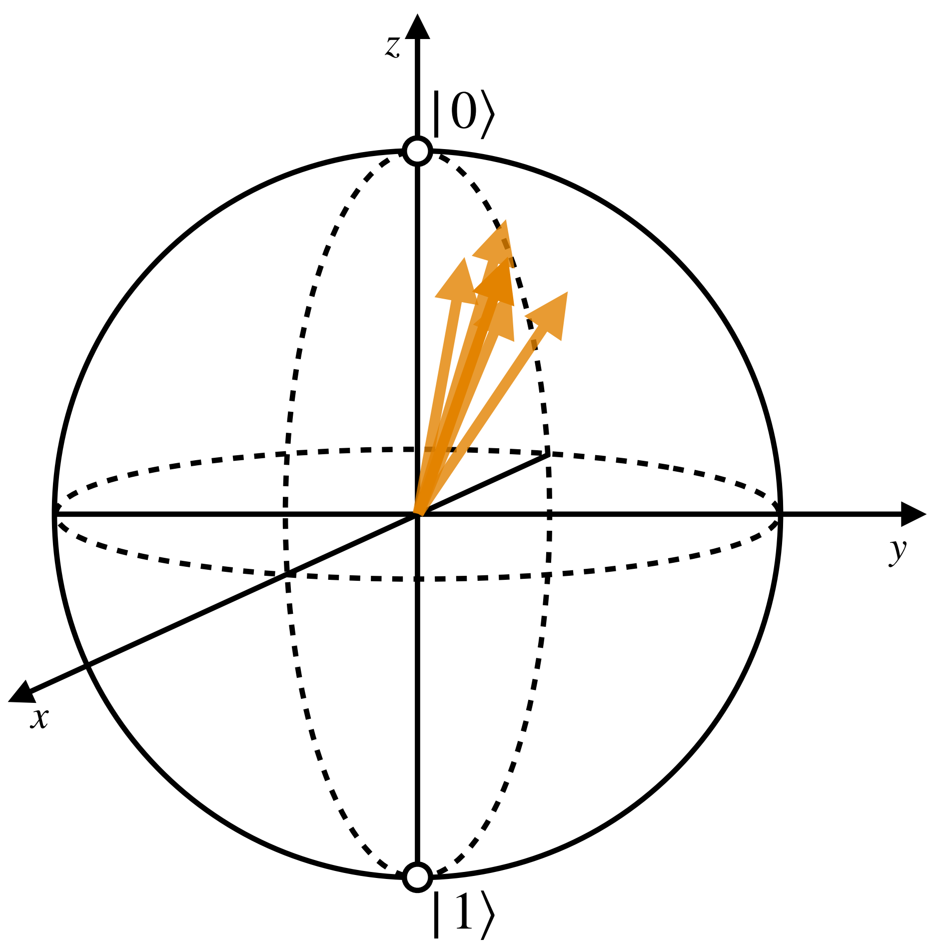
QUBIT





DECOHERENCE

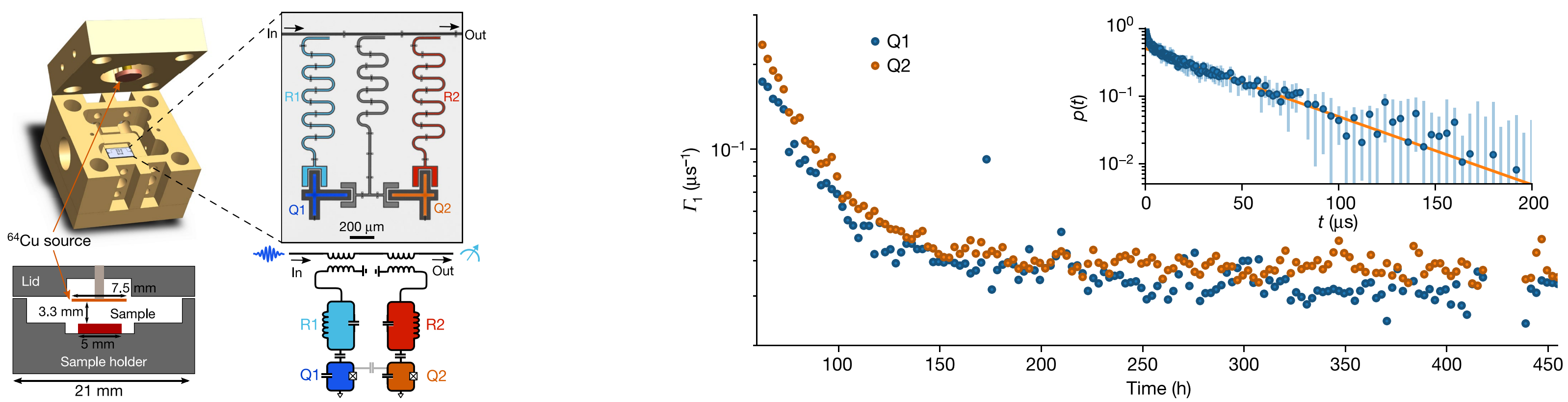
- One feature of superconducting qubits is of particular interest for particle detection: *decoherence*



1. The qubit has unwanted interactions with the surrounding environment;
2. Its state changes unpredictably;
3. The information it was storing is lost.

QUBITS AND RADIOACTIVITY

- Low energy gap (< 1 meV) of superconductors makes them very sensitive to ionizing radiation:



Vepsäläinen *et al.*, *Nature* **584**, 551-556 (2020)

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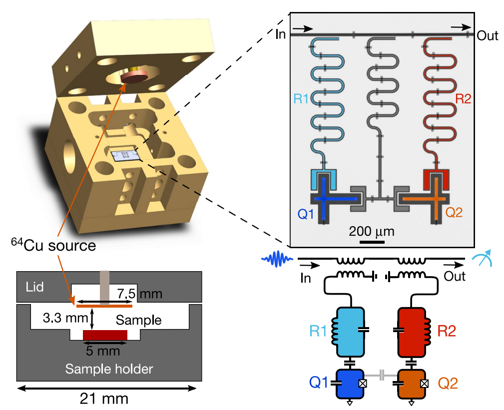

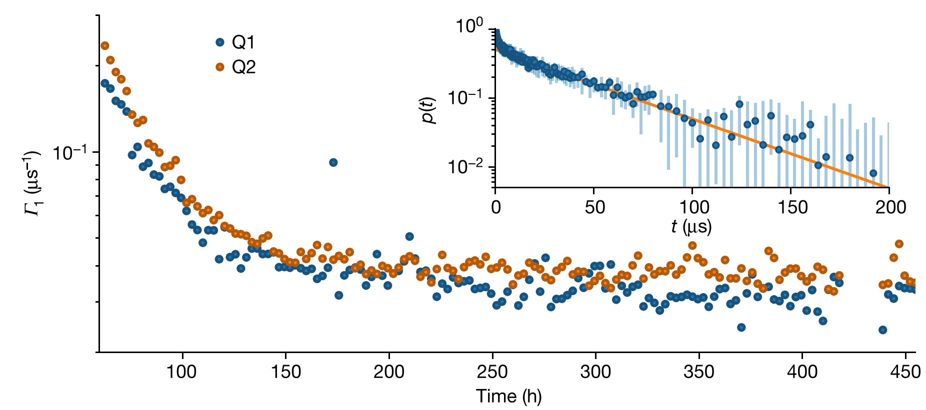

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- But particles can interact also in the chip substrate, affecting multiple qubits simultaneously:

Qubits and Radioactivity

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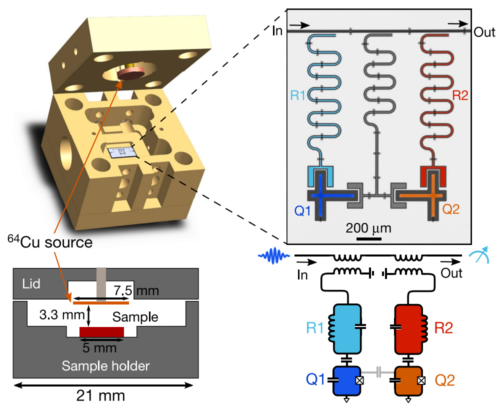

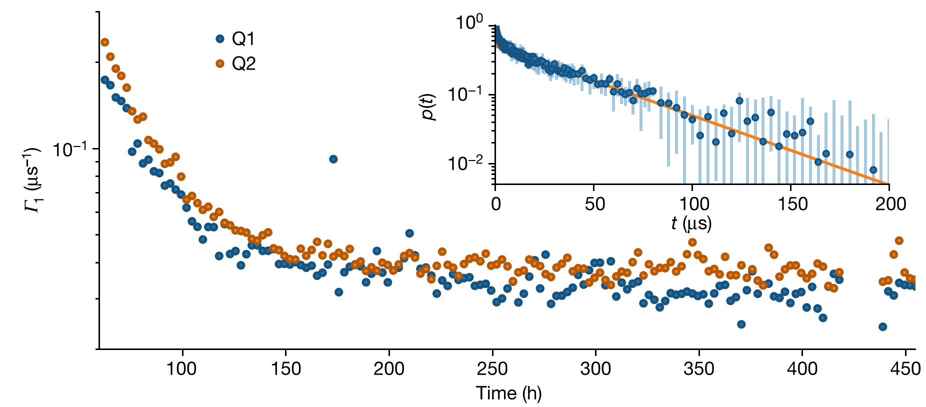

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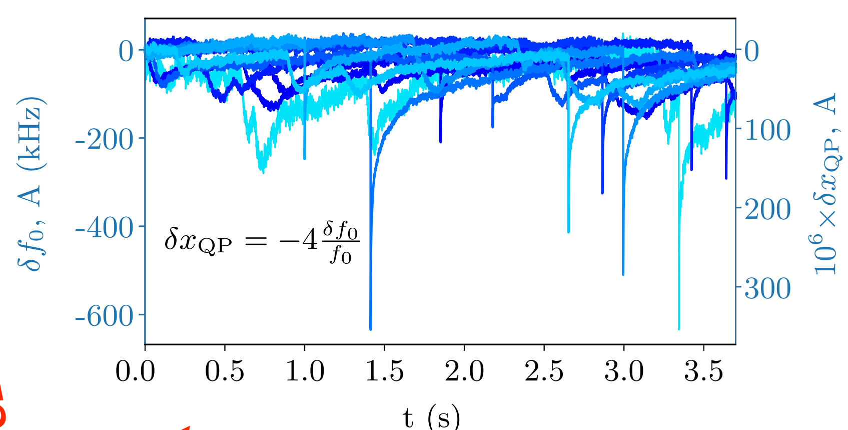

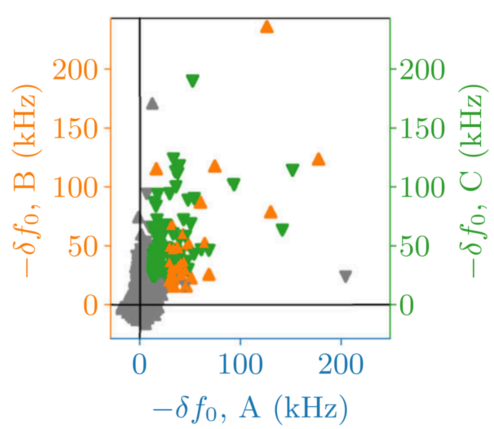

PRESENTED AT LRT2019

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

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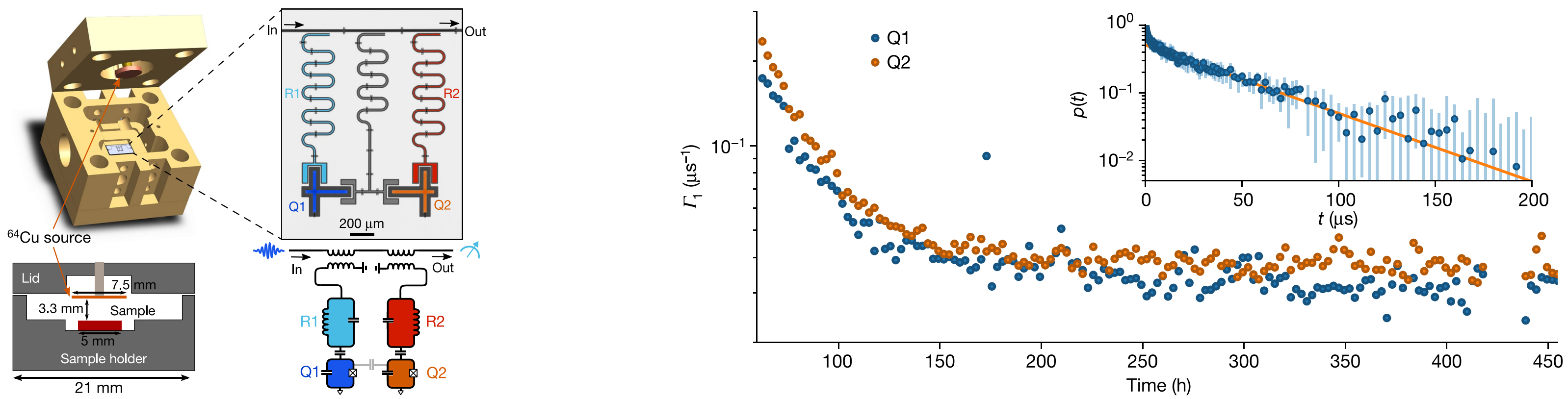

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PRESENTED AT LRT2022

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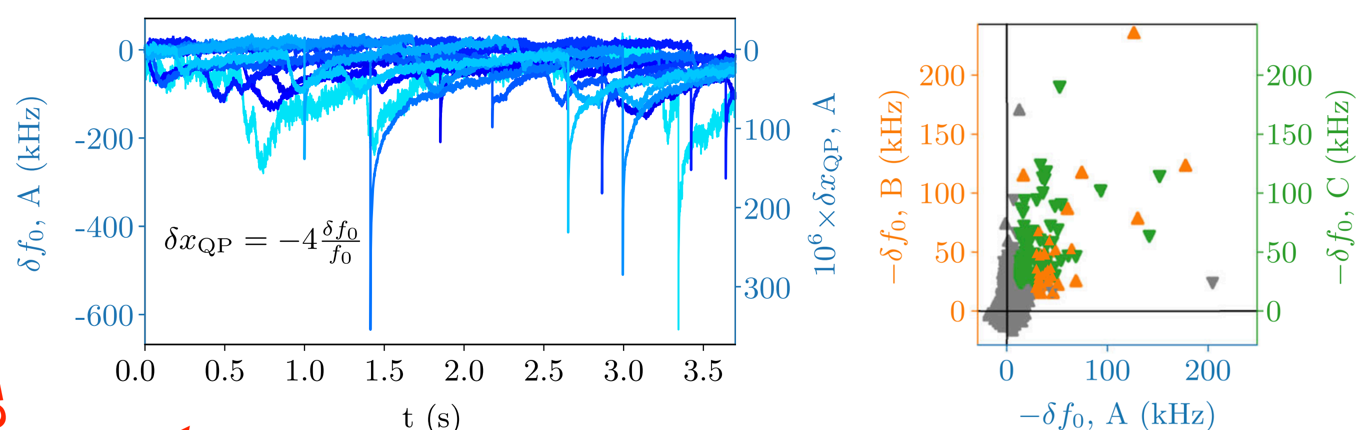
PRESENTED AT LRT2019



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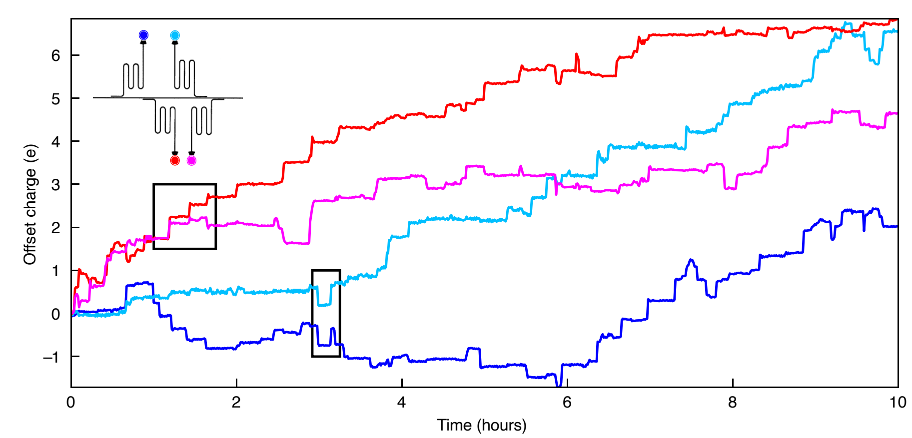


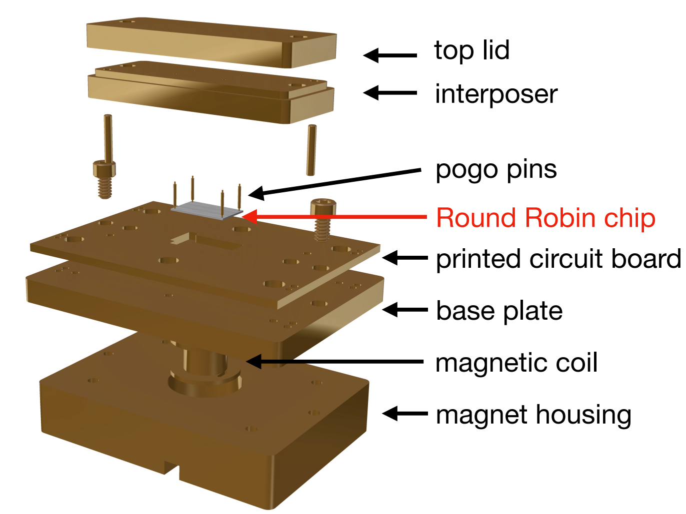
Wilen *et al.*, *Nature* **594**, 369-373 (2021)

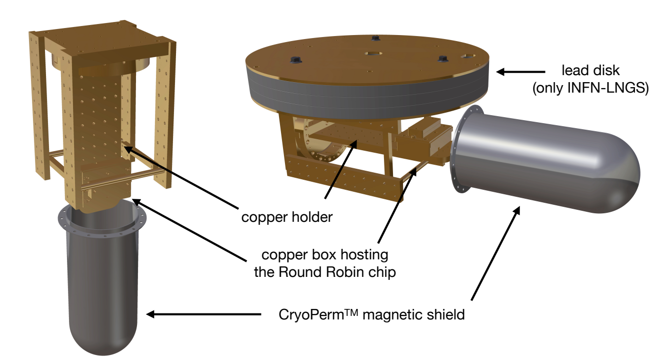
QUBITS AND RADIOACTIVITY

- A concern for quantum computing experiments:

PRESENTED AT LRT2022

COMPONENT	^{232}Th (mBq/kg)	^{238}U (mBq/kg)	^{235}U (mBq/kg)	^{40}K (mBq/kg)	^{137}Cs (mBq/kg)
Printed Circuit Board	(18000 ± 1000)	(11500 ± 400)	(710 ± 110)	(12000 ± 1000)	< 30
Printed Circuit Board (v2)	(5410 ± 330)	(4200 ± 200)	(230 ± 50)	(4200 ± 500)	< 40
Gold-plated Cu box	< 1.5	< 1.2	< 4	< 9	< 0.6
CryoPerm magnetic shield	< 8.4	< 8.3	< 8.4	< 35	< 2.7
SMA adapters	(46 ± 13)	(42 ± 10)	(70 ± 30)	(240 ± 90)	< 10
Cu coaxial cables	(54 ± 12)	(44 ± 11)	(34 ± 17)	(740 ± 130)	< 12
Cryogenic switch	(1880 ± 100)	(1340 ± 60)	(130 ± 30)	(2200 ± 300)	< 11.2
Low-pass filters	(23 ± 4)	< 9.1	(60 ± 10)	< 100	< 1.9
Circulator	< 310	< 330	< 410	< 2000	< 60
Dual-junction circulator	< 250	< 380	< 380	< 2600	< 60
Triple-junction isolator	< 190	< 240	< 220	< 2000	< 50
Attenuators	< 52	(200 ± 20)	<47	< 140	< 13
NbTi coaxial cables	< 750	< 1000	< 380	< 7000	< 230





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

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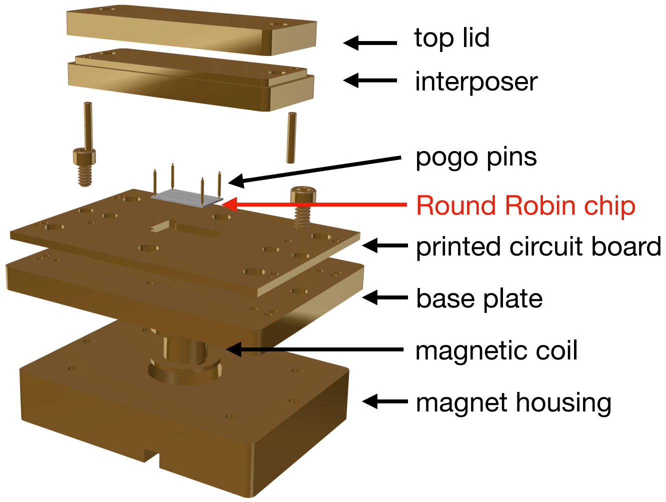
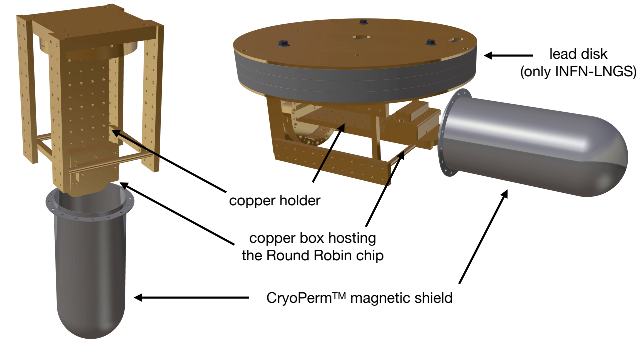




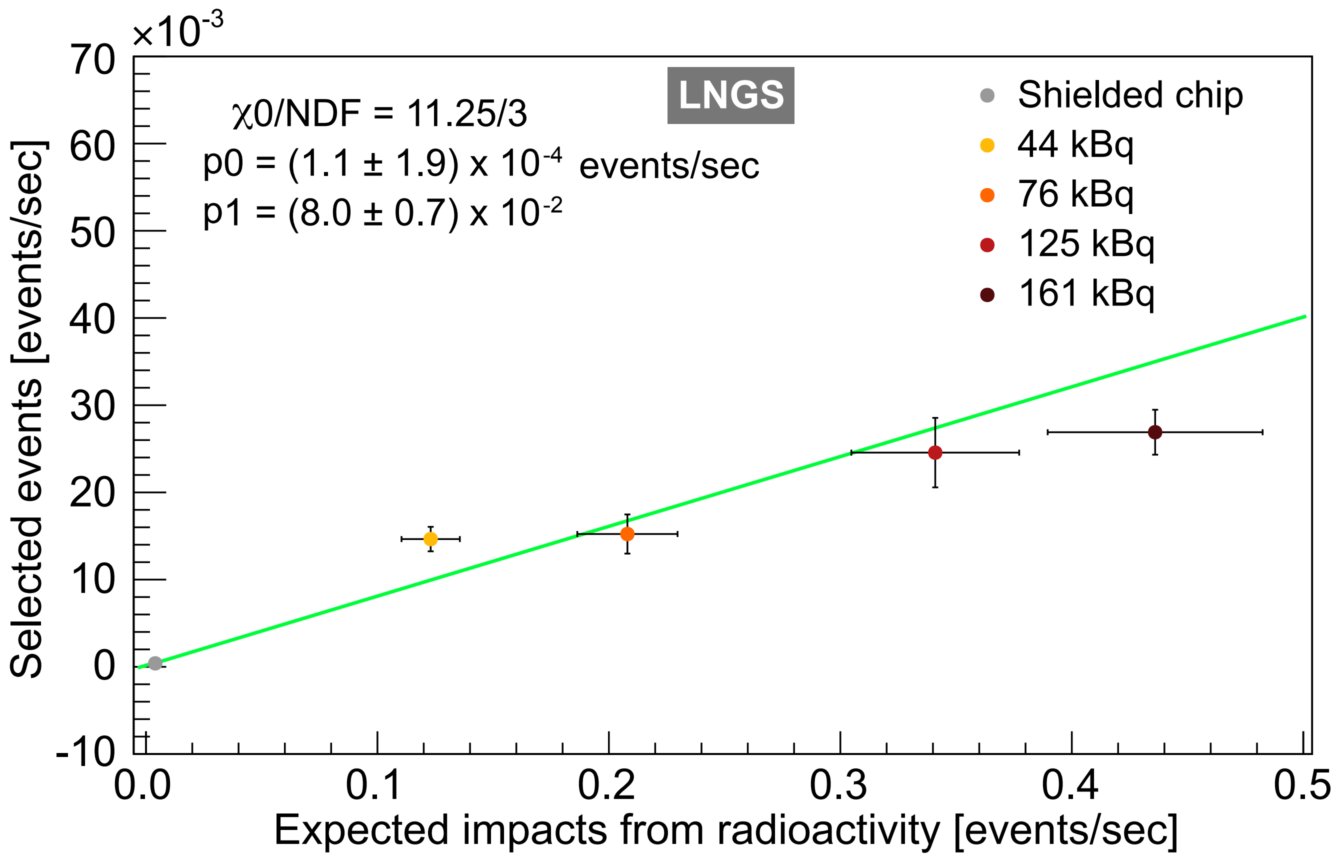
Cardani *et al.*, *Eur. Phys. J. C* **83**, 94 (2023)

Can it work as a particle detector?

A First Result

- Transmon qubit exposed to gamma sources with increasing activity;

A First Result

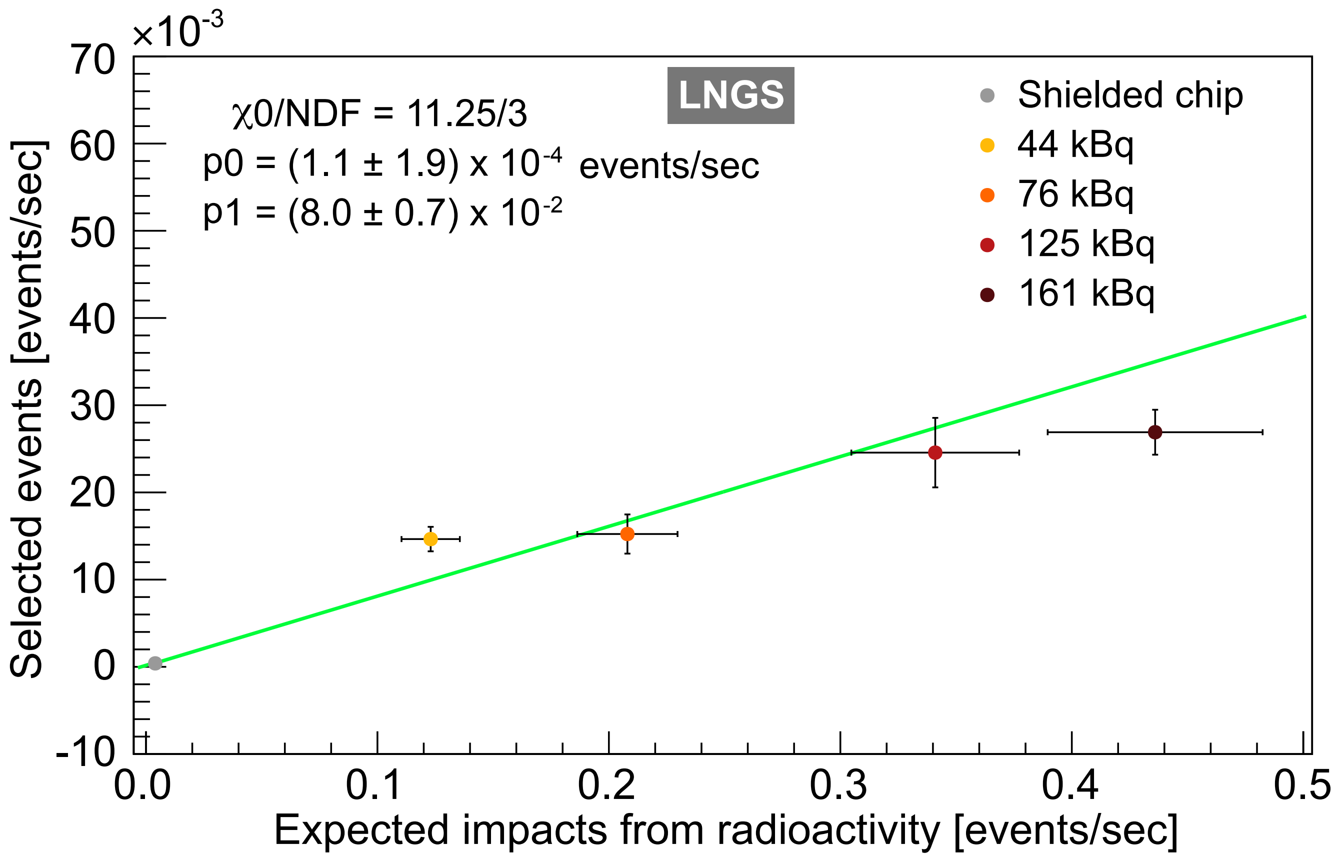


De Dominicis *et al.*, *EPJ Quantum Technol.* **13**, 47 (2026)

PRESENTED AT LRT2024

- Transmon qubit exposed to gamma sources with increasing activity;
- Rate of errors increasing with the activity of the sources!

A First Result



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Presented at LRT2024

- Transmon qubit exposed to gamma sources with increasing activity;
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- However, estimated detection efficiency < 10%

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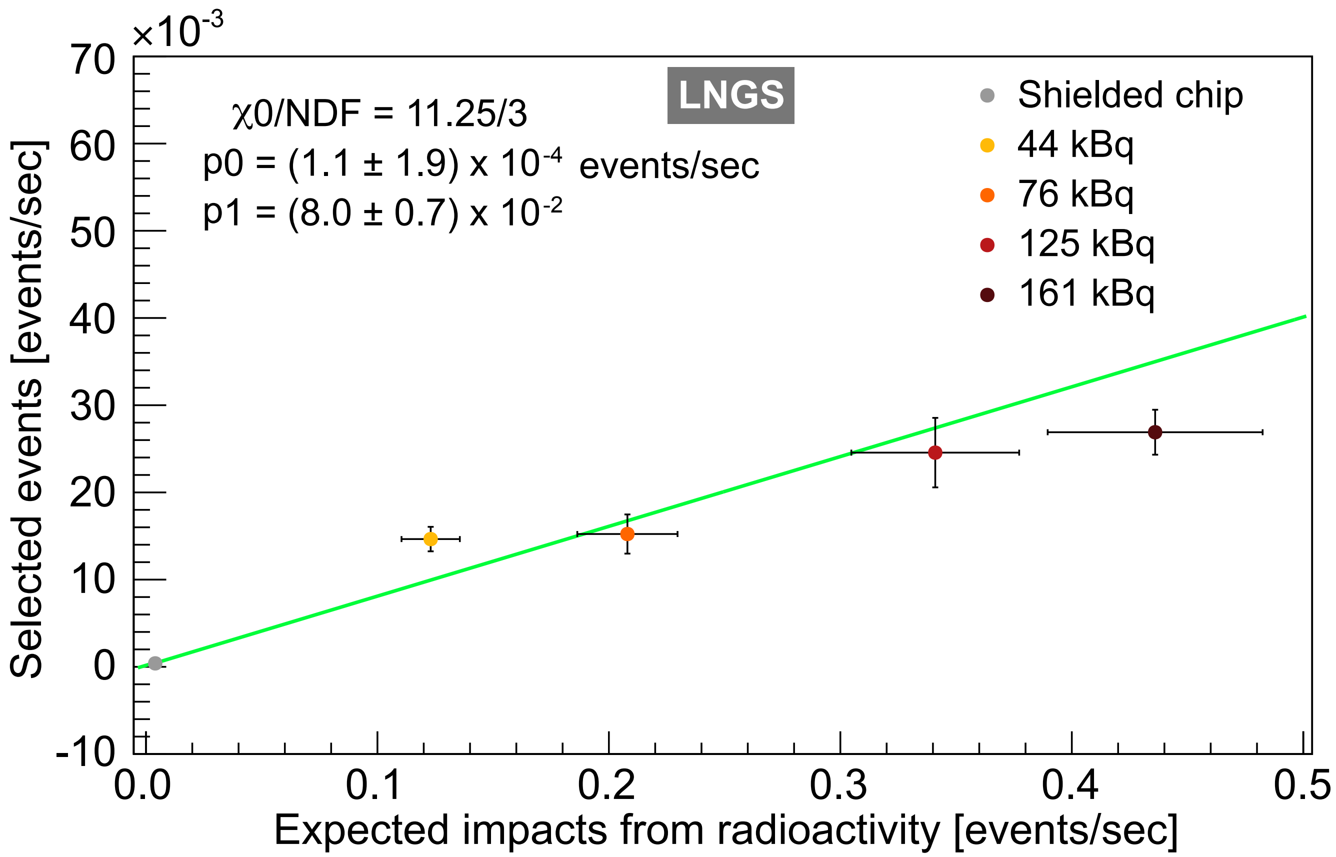
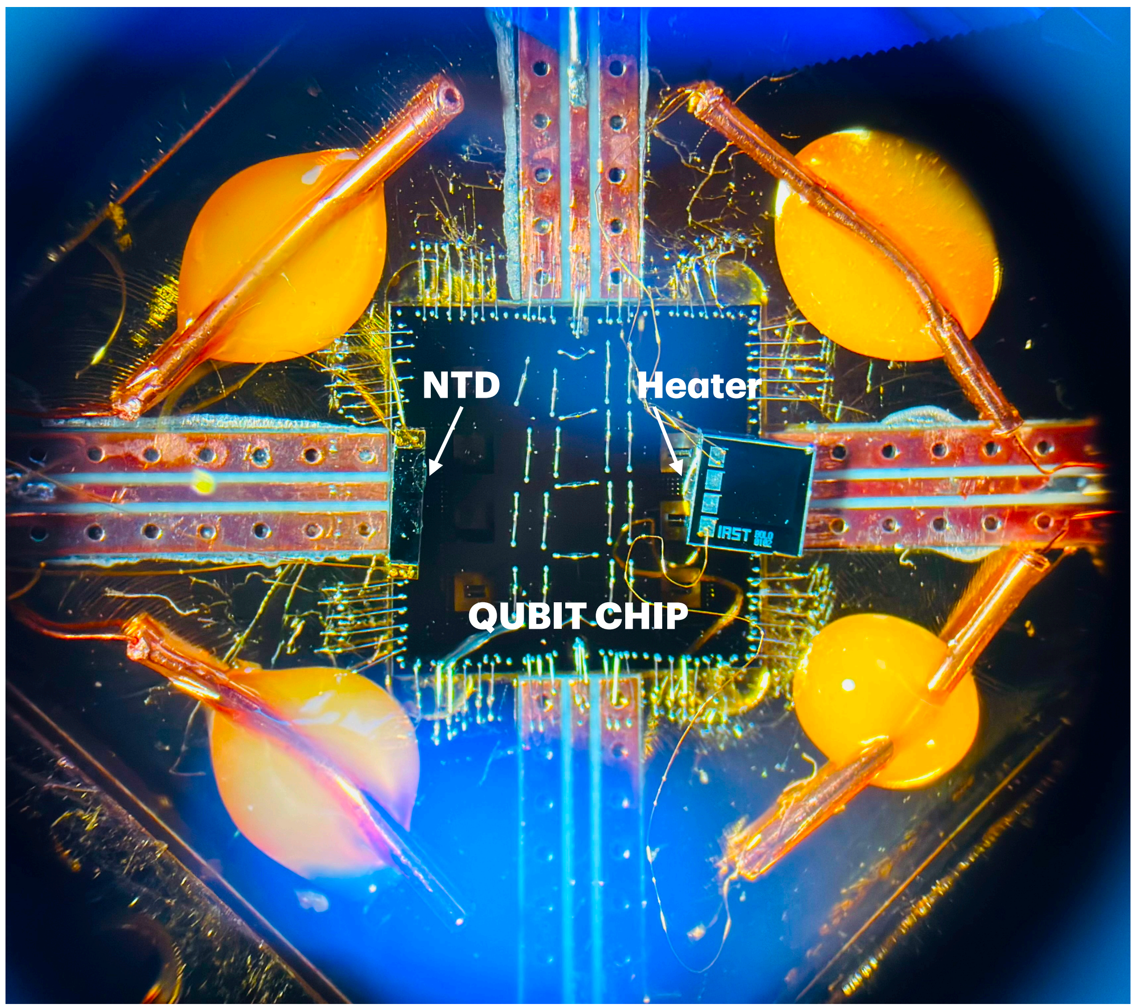


De Dominicis *et al.*, *EPJ Quantum Technol.* **13**, 47 (2026)

Presented at LRT2024

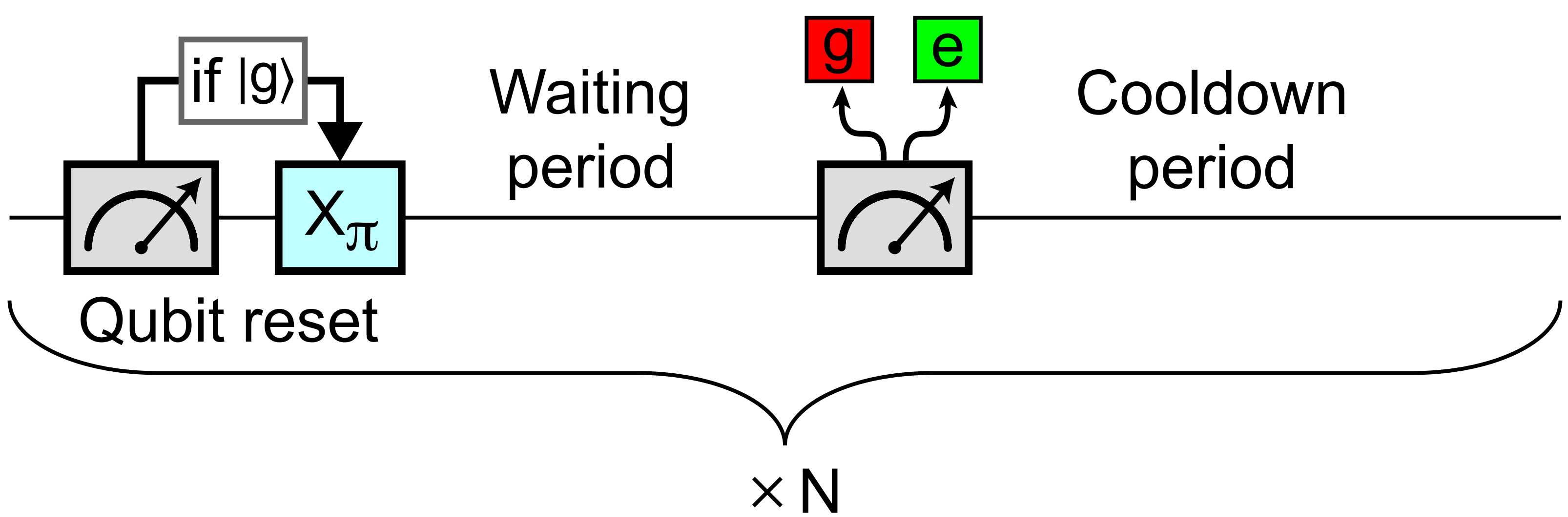
- Transmon qubit exposed to gamma sources with increasing activity;
- Rate of errors increasing with the activity of the sources!
- However, estimated detection efficiency < 10%
- Room for improvement!

The New Setup

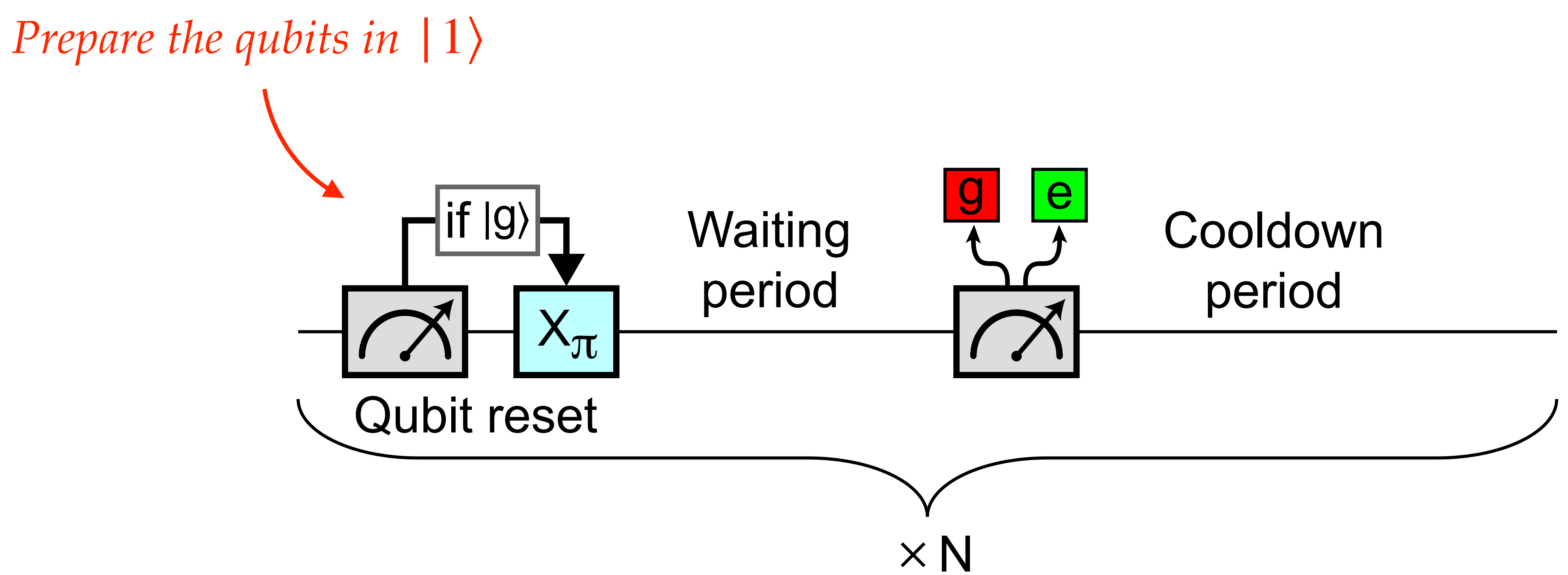


- Chip with 8 transmon qubits developed by the SQMS Center;
- NTD thermistor for interaction rate measurement and direct measurement of qubit detection efficiency;
- Heater for controlled thermal phonons injection.

Event Detection



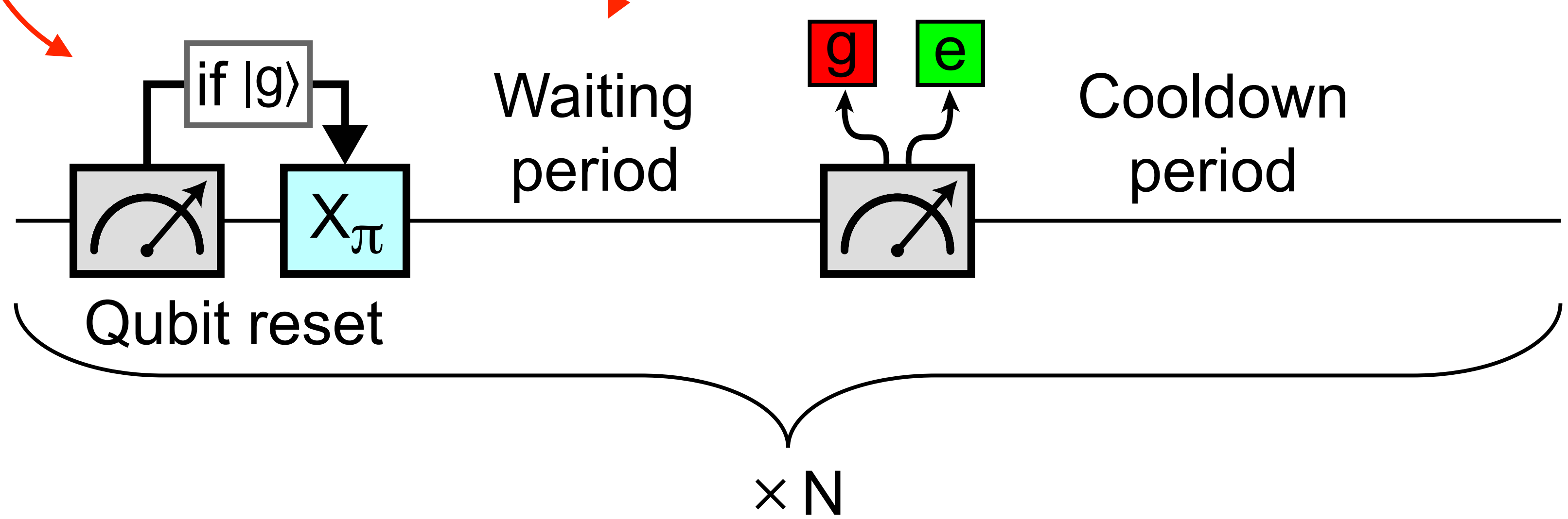
Event Detection



Event Detection

Wait a few μs ($\ll T_1$)

Prepare the qubits in $|1\rangle$



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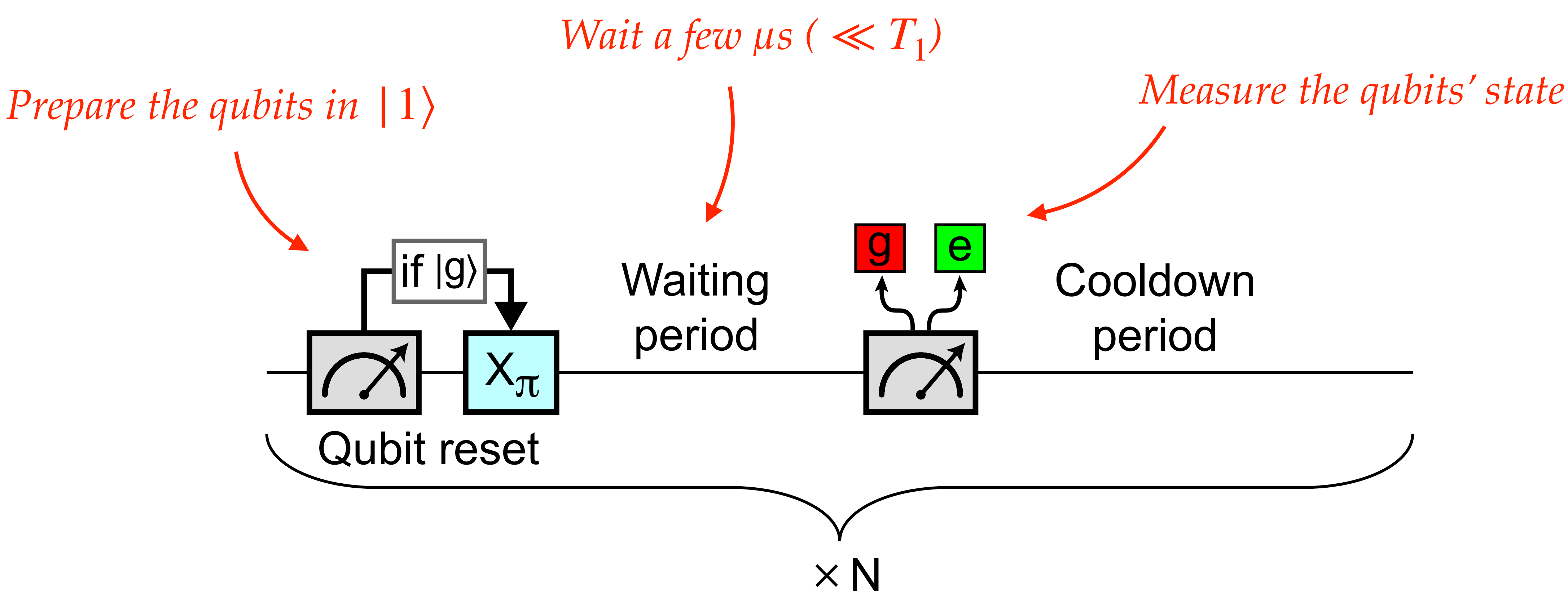

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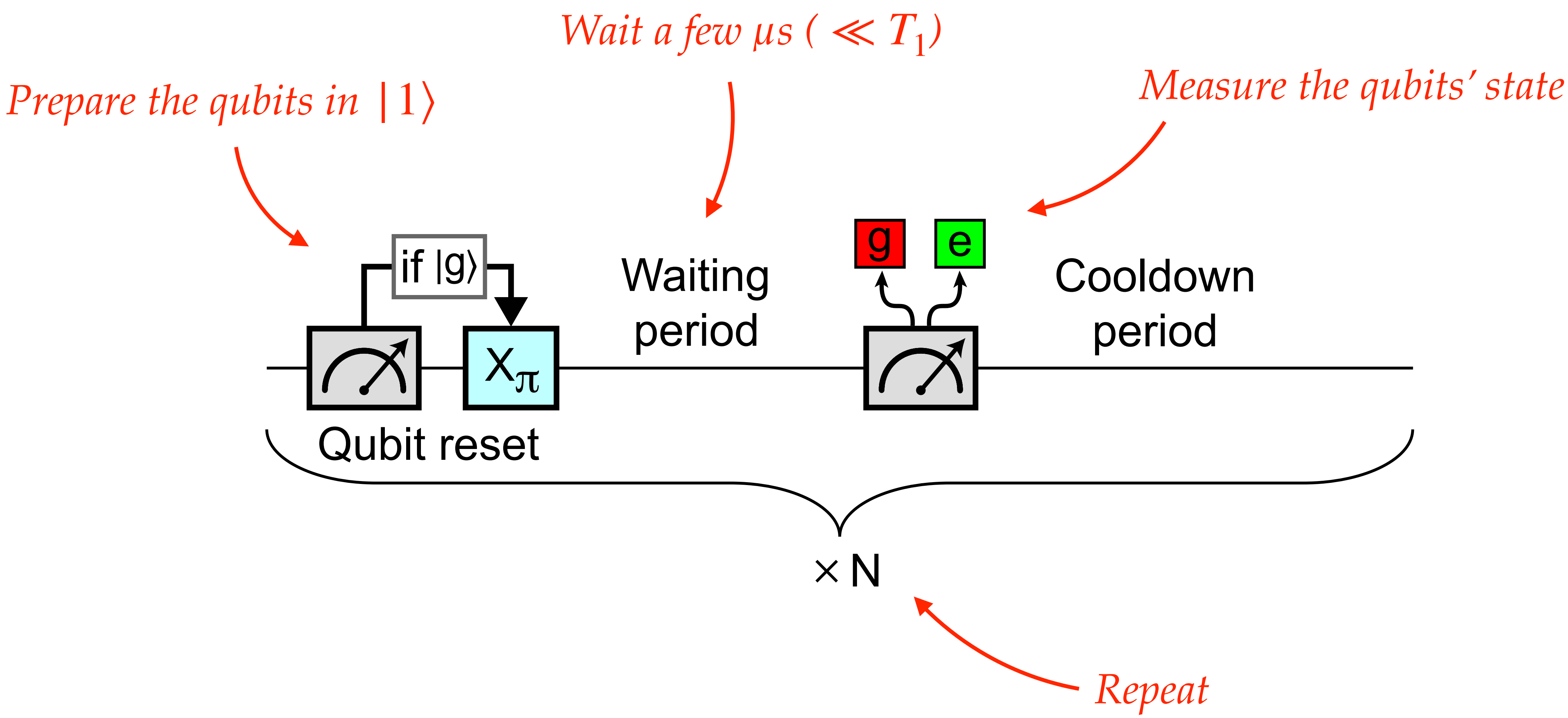
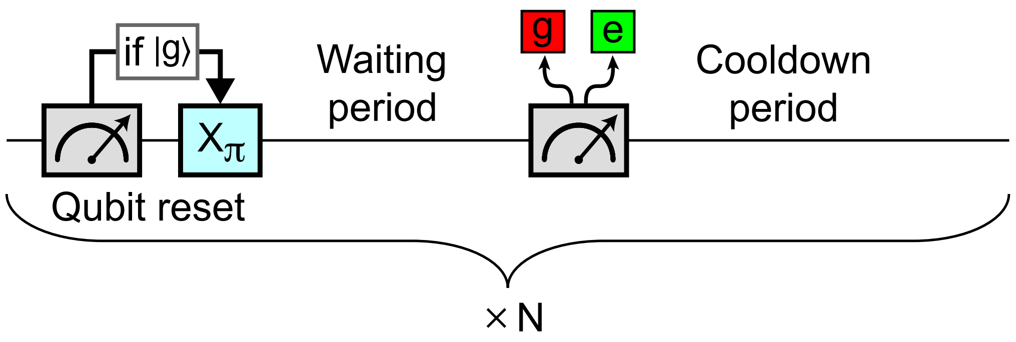
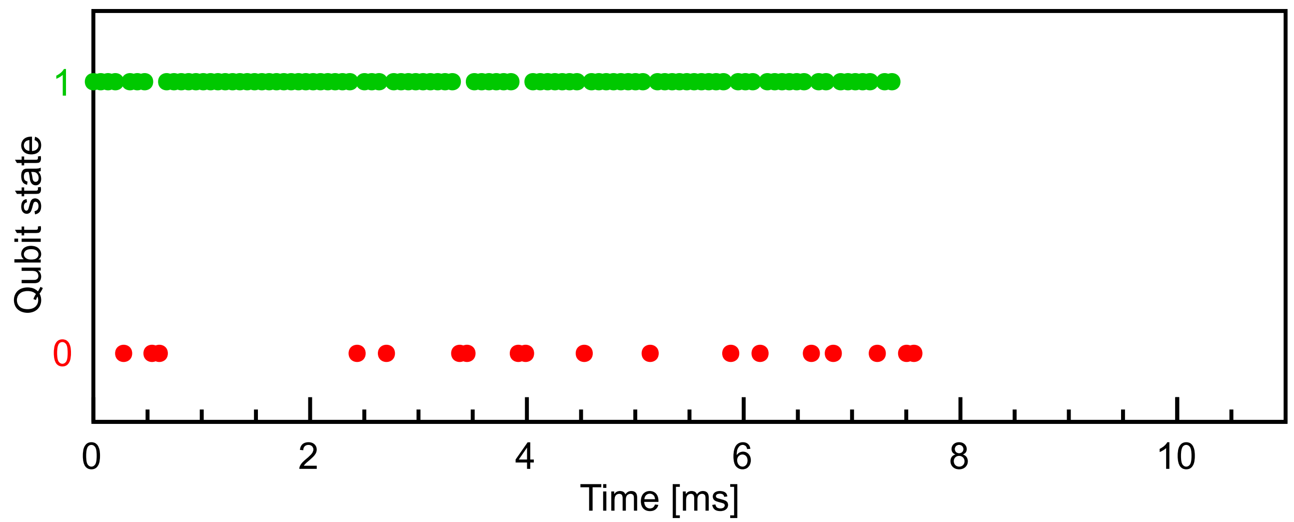


EVENT DETECTION

- Waiting time $\ll T_1$, so qubits in $|0\rangle$ most of the time:





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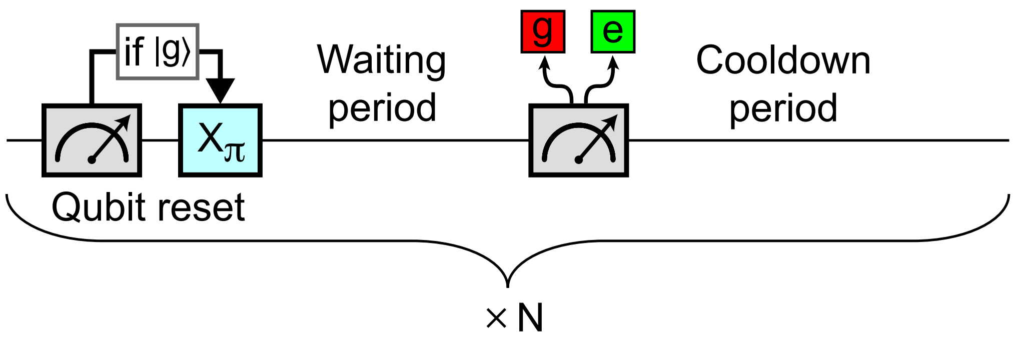
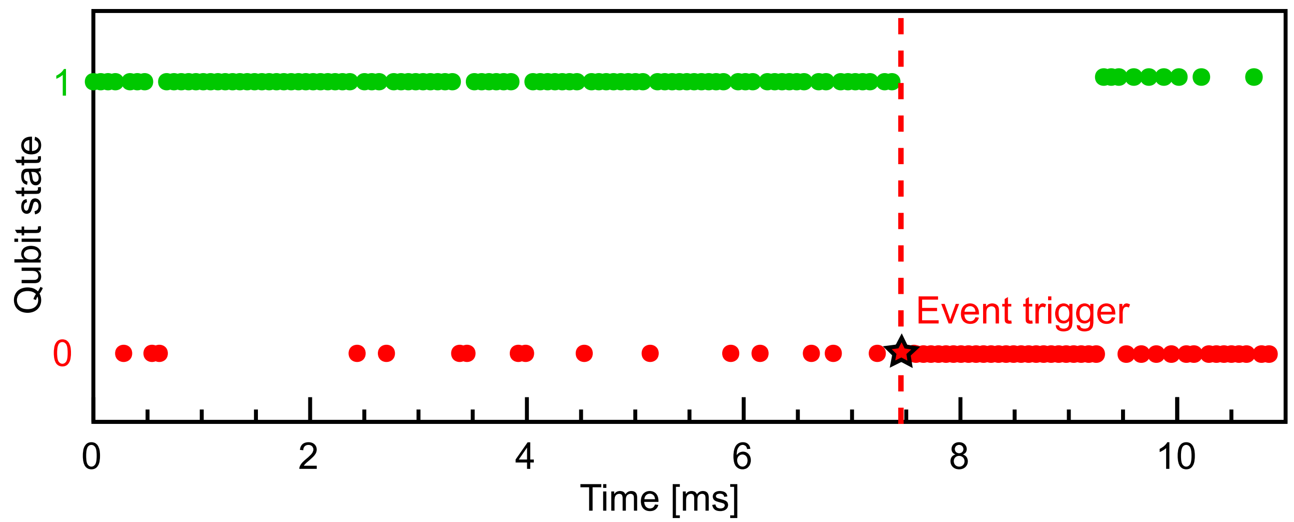


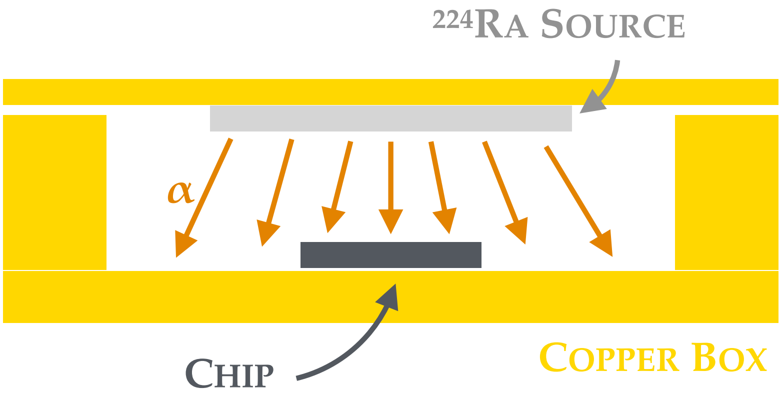


- When the qubits suffer from quasiparticle poisoning, though, decay time drops and we observe a stream of $|0\rangle$'s!

RESULTS

- We focused on the two best performing qubits and exposed the chip to a ^{224}Ra source;

- Started by analyzing the two qubits independently;



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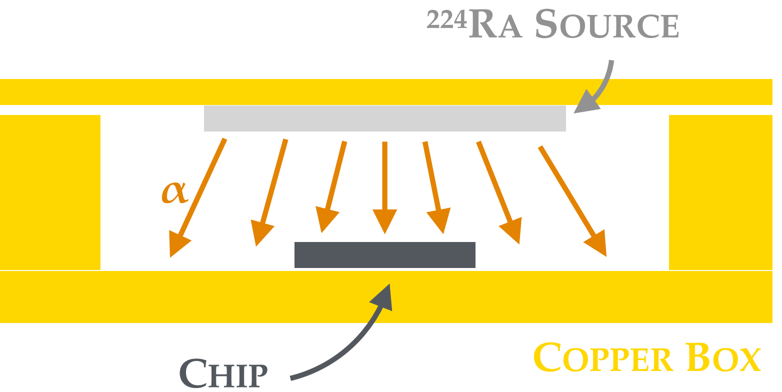
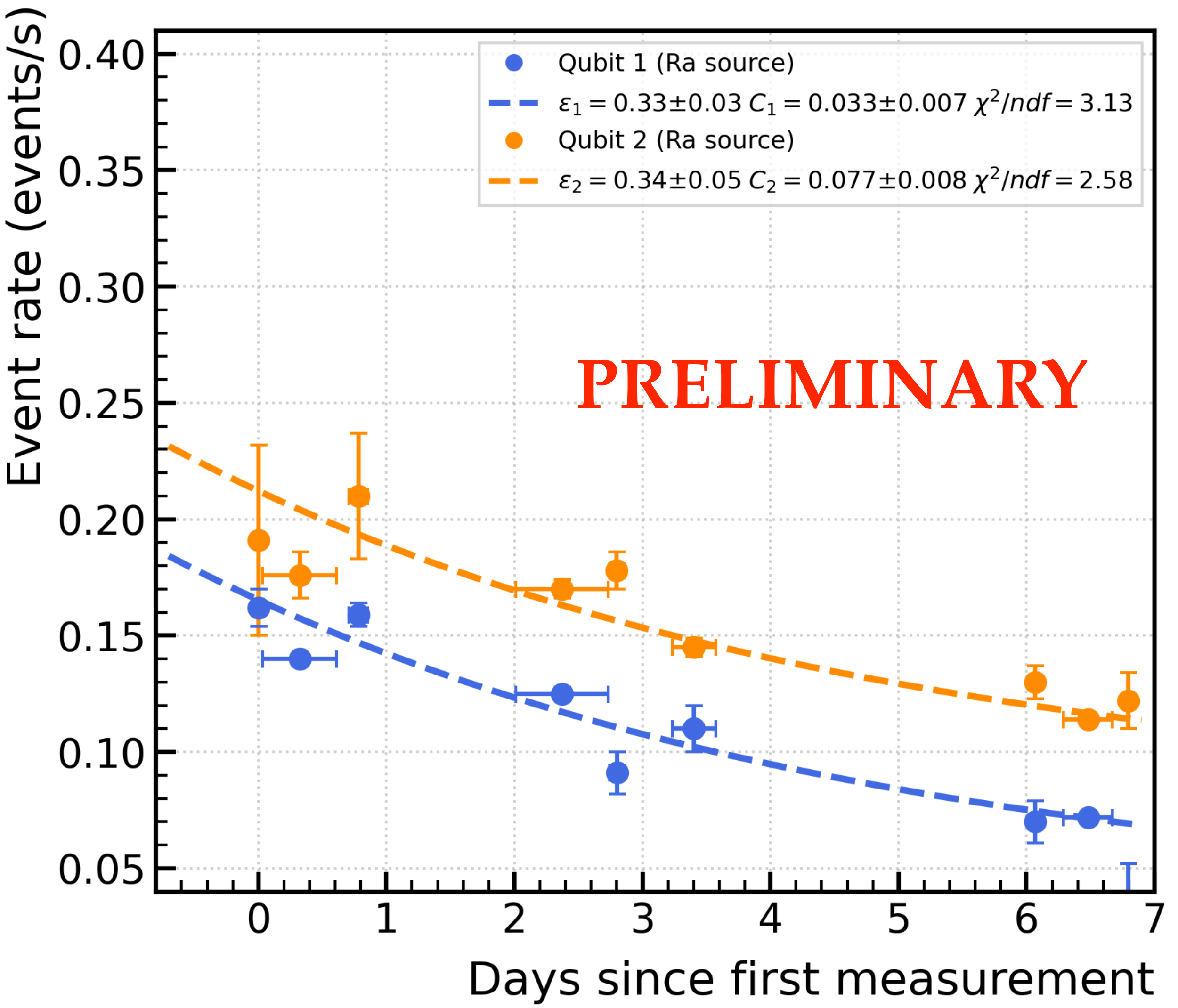
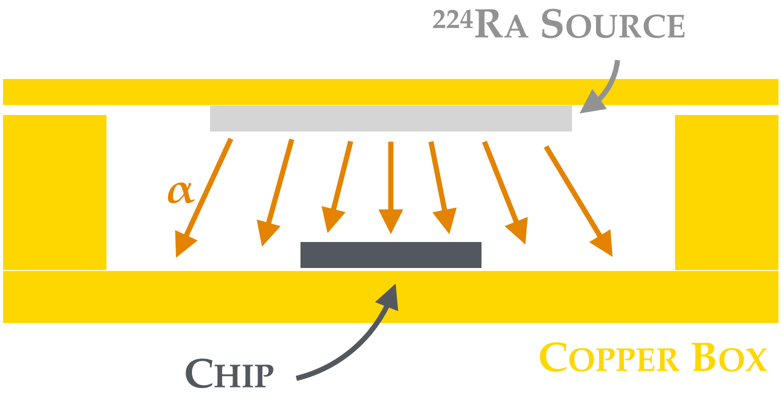
- For both the rate of events followed the exponential decay of the source!

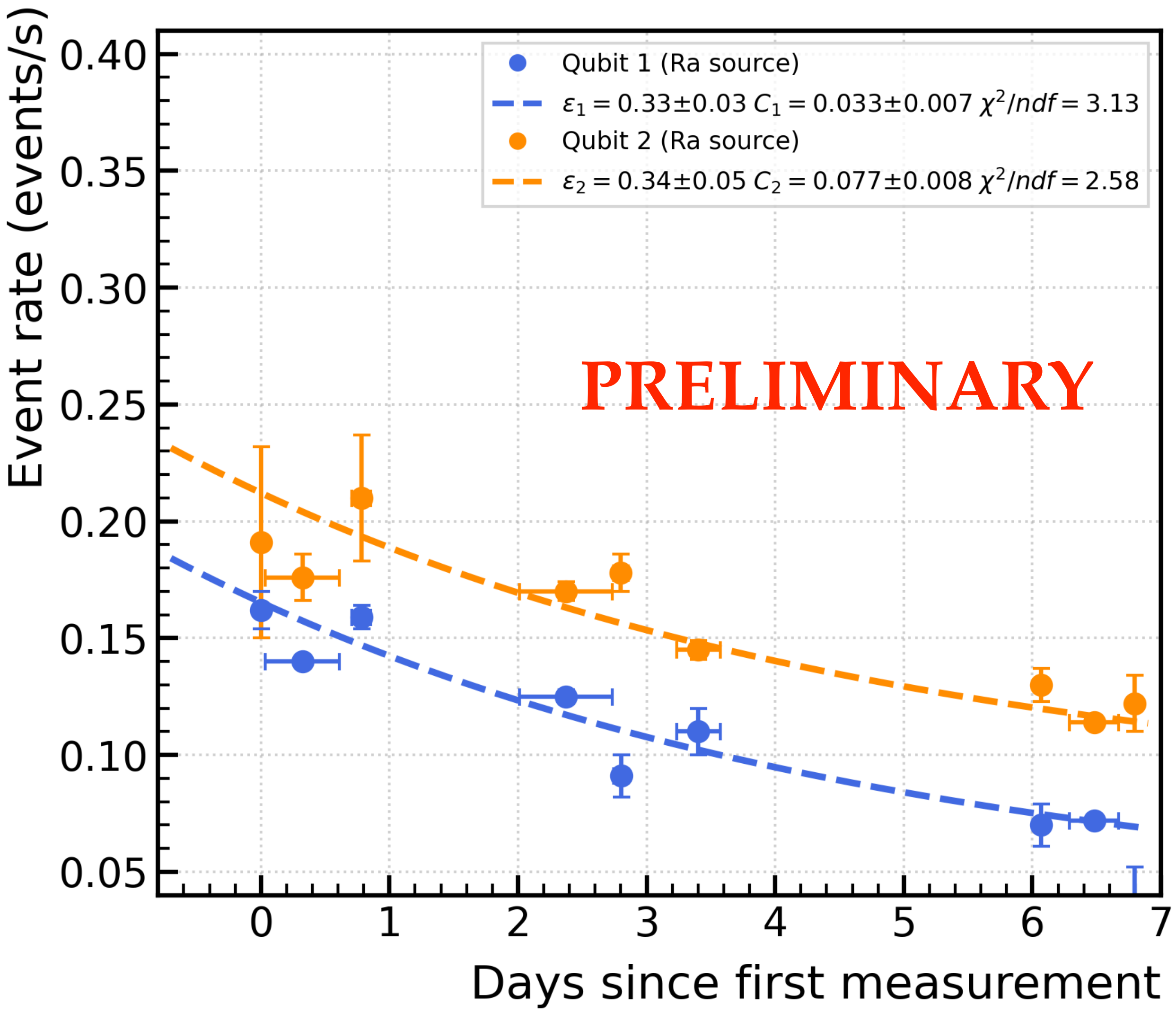




RESULTS

- NTD + Monte Carlo simulations to determine detection efficiency;
- Found ≈33-34% for both qubits;
- Great improvement from previous work (<10%), mostly due to better analysis technique;





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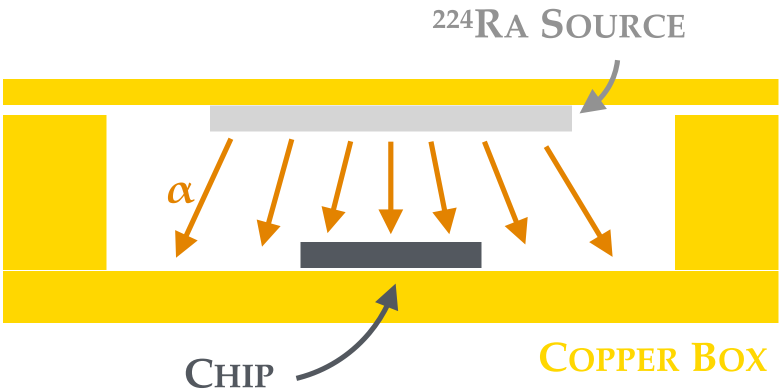

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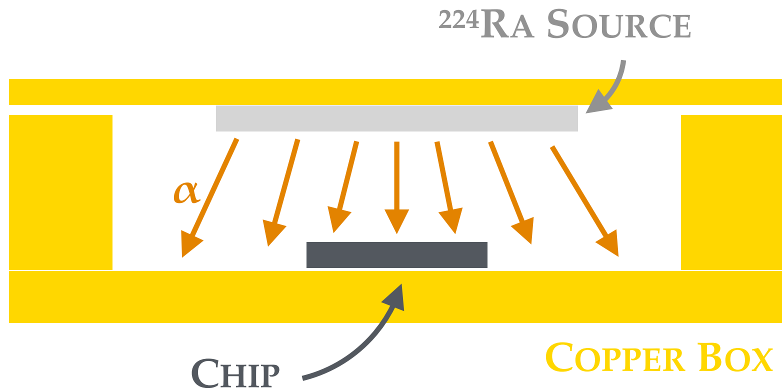
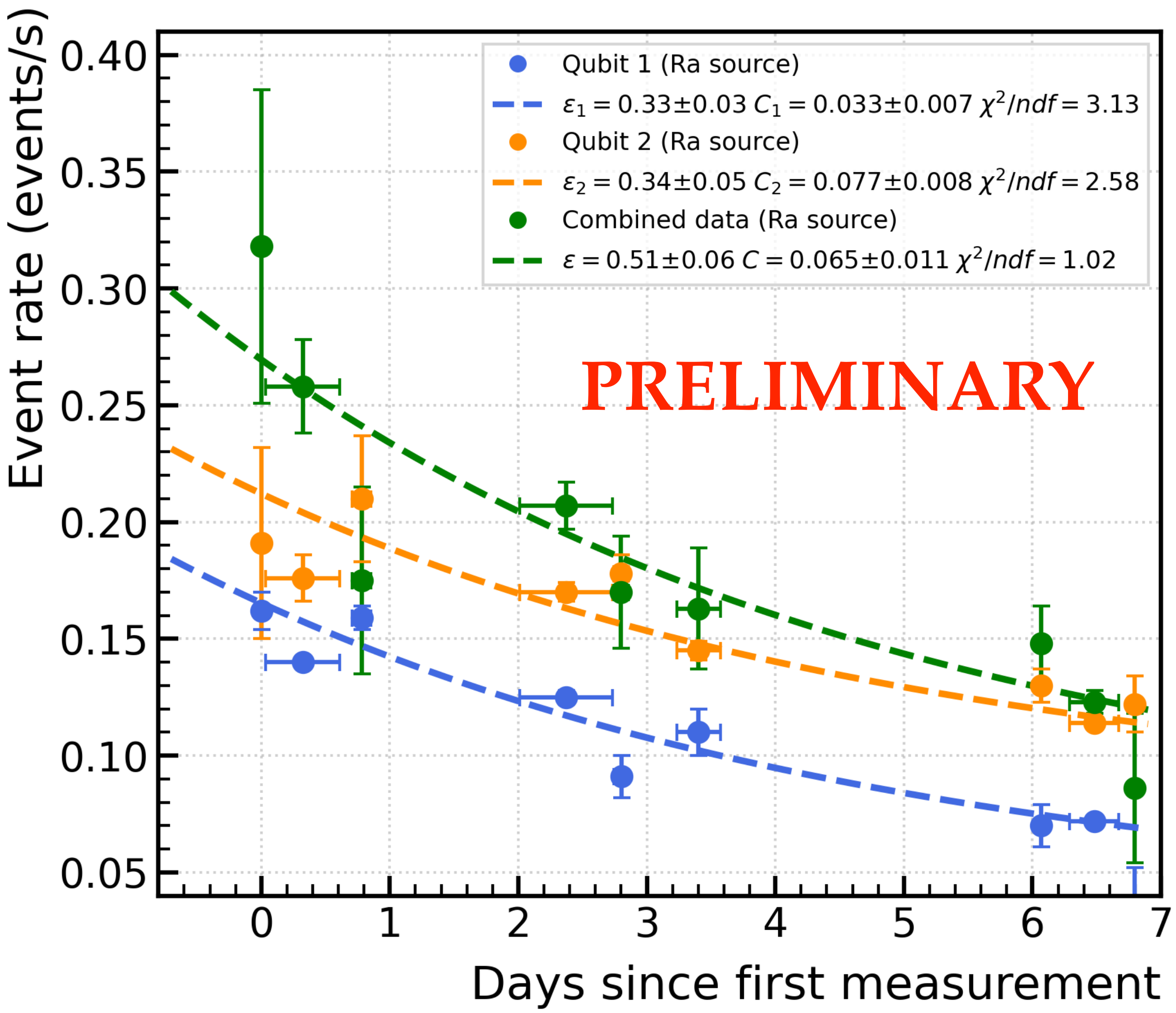
- The detection efficiency increased up to ≈50%!





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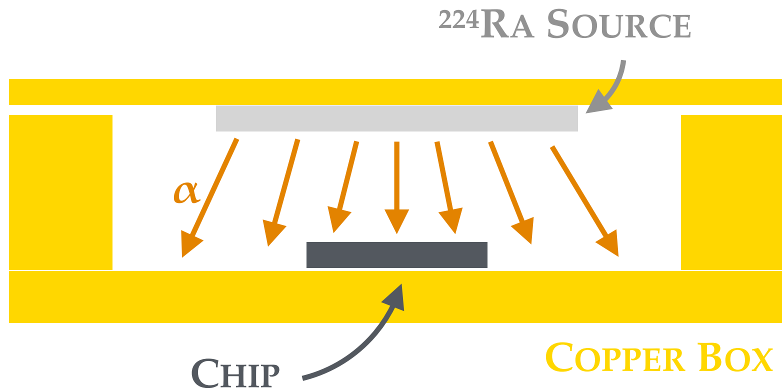
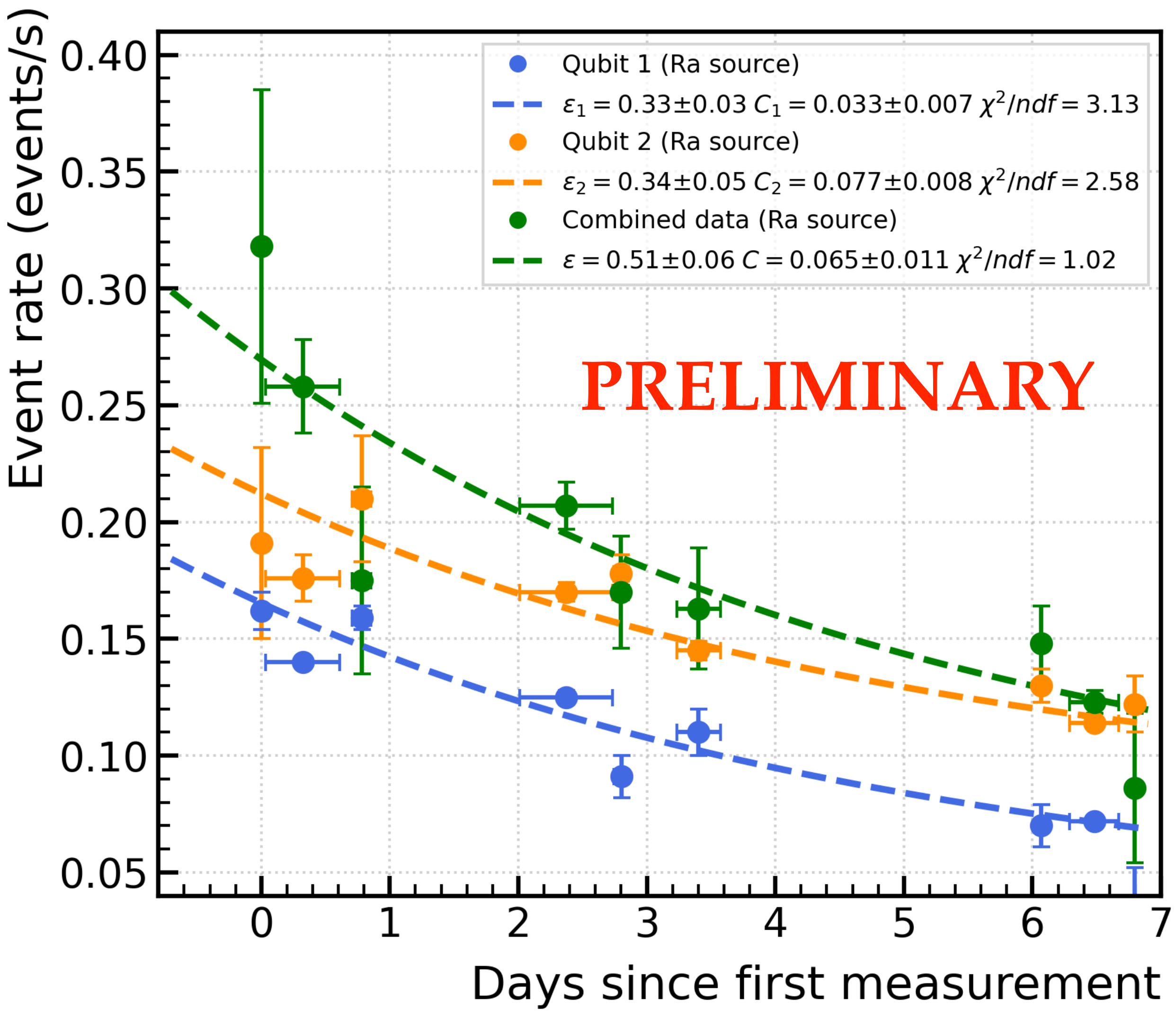
- However, such efficiency is still far from what expected from particle detectors;





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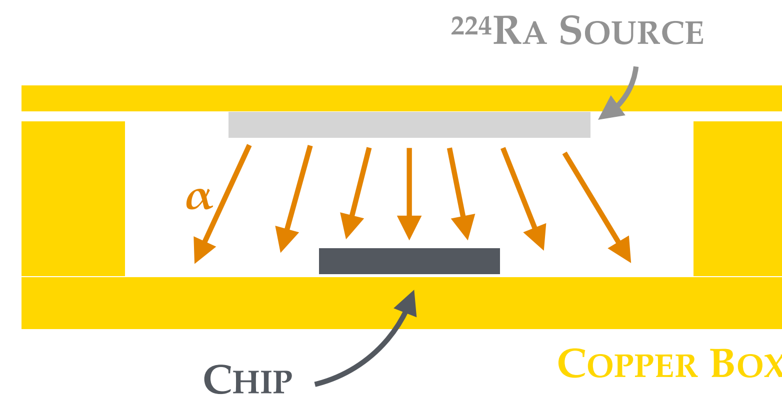
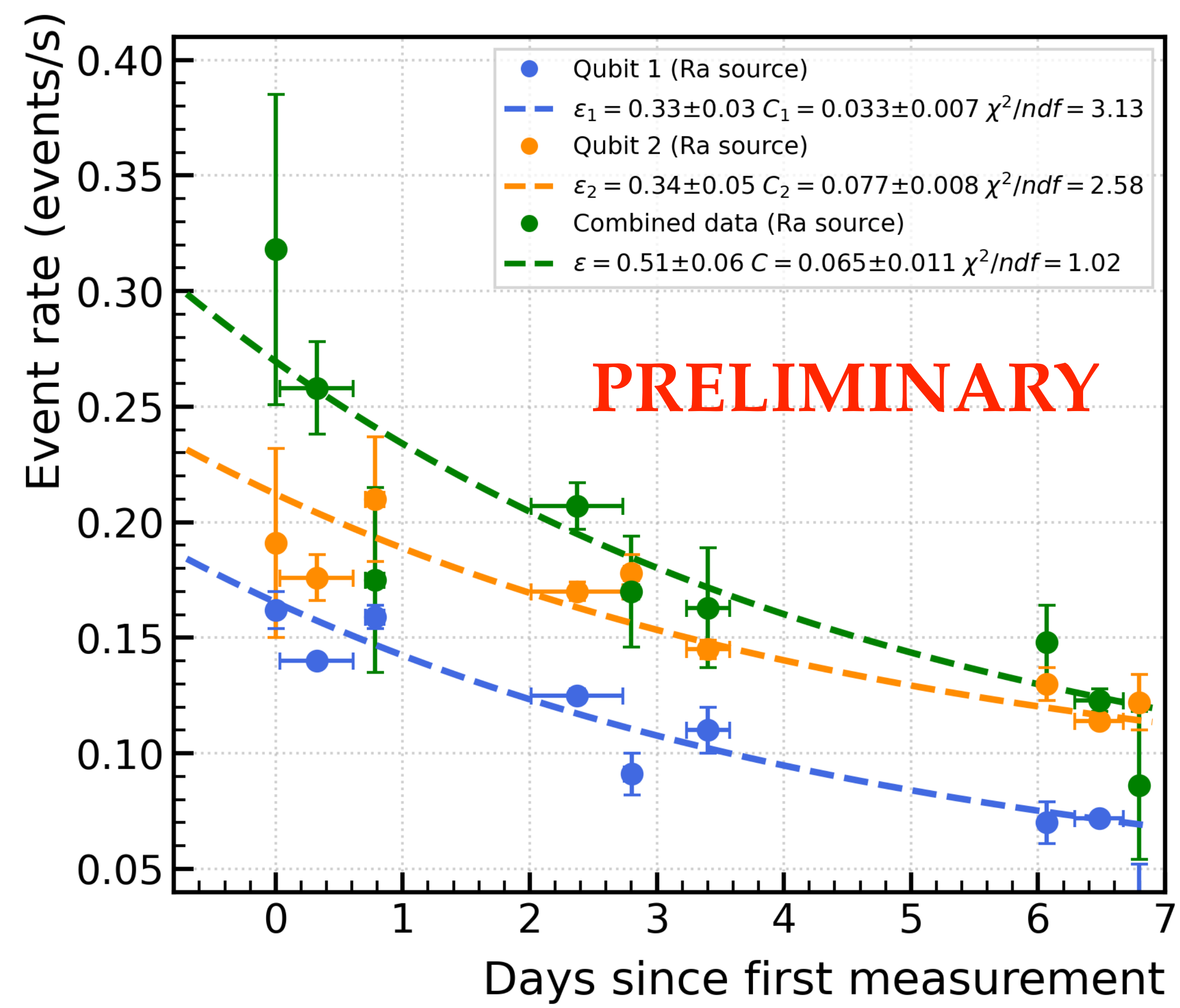
- However, such efficiency is still far from what expected from particle detectors;
- What is limiting it?





RESULTS

- We started by investigating ENERGY THRESHOLD;
- Exposed the qubits to a γ radiation source close to the cryostat (one of them severely affected by electronic noise and discarded though);
- Monte Carlo simulation to reconstruct the rate of interactions in the chip coming from the source;

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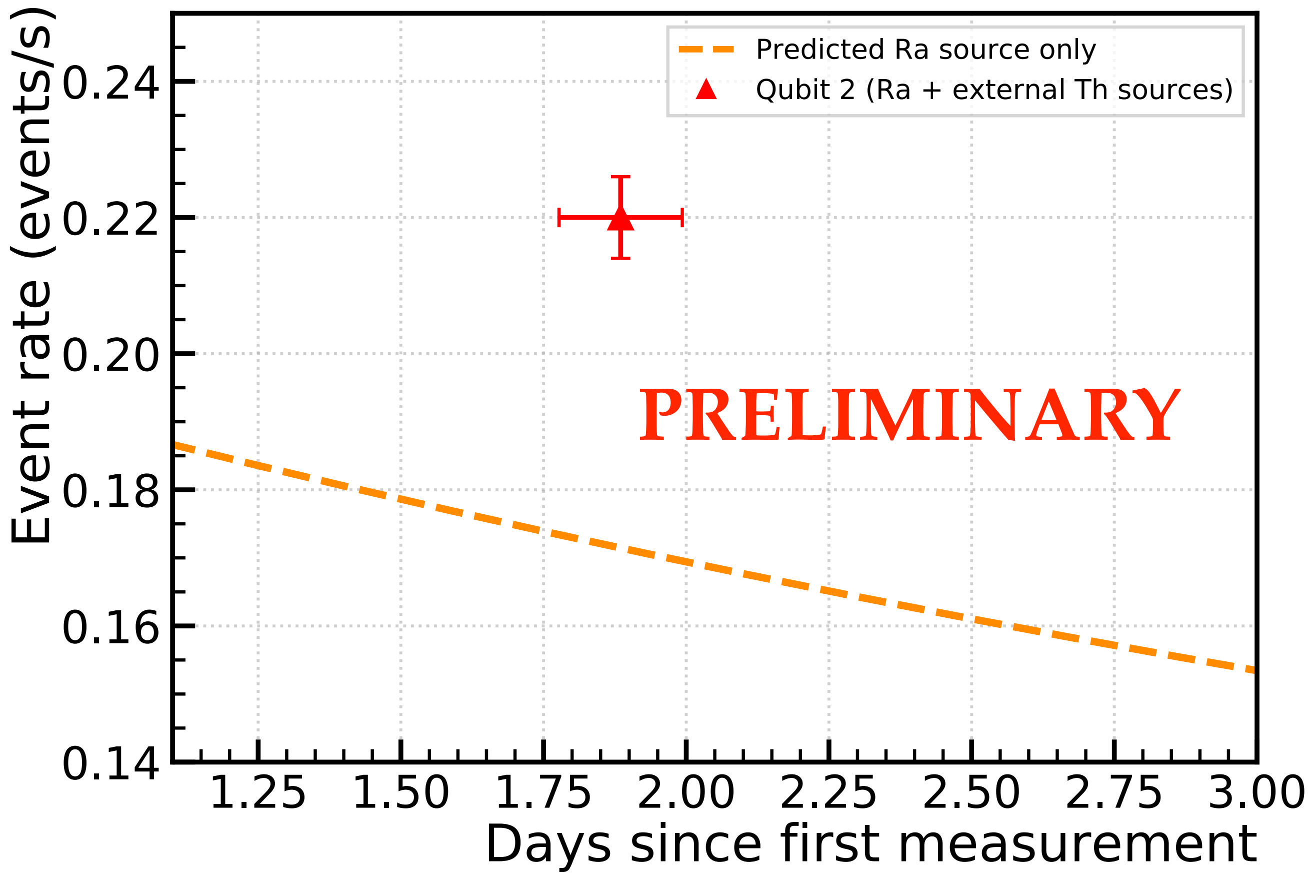
- Exposed the qubits to a γ radiation source close to the cryostat (one of them severely affected by electronic noise and discarded though);
- Monte Carlo simulation to reconstruct the rate of interactions in the chip coming from the source;
- Detection efficiency dropped to 23%, confirming a threshold effect!



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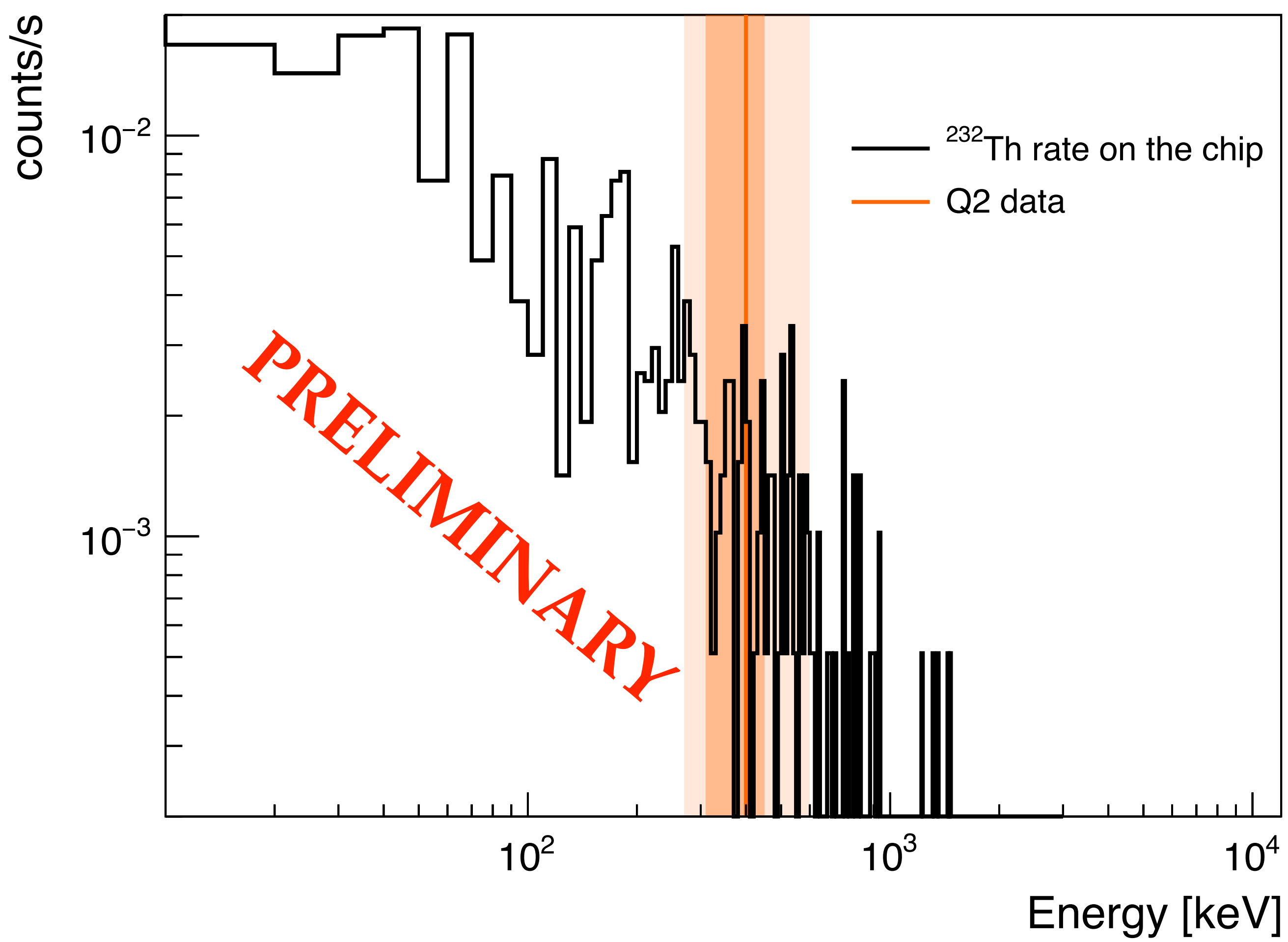
- Integrated the simulated spectrum of the energy deposited by γ radiation from the Th source to estimate energy threshold:



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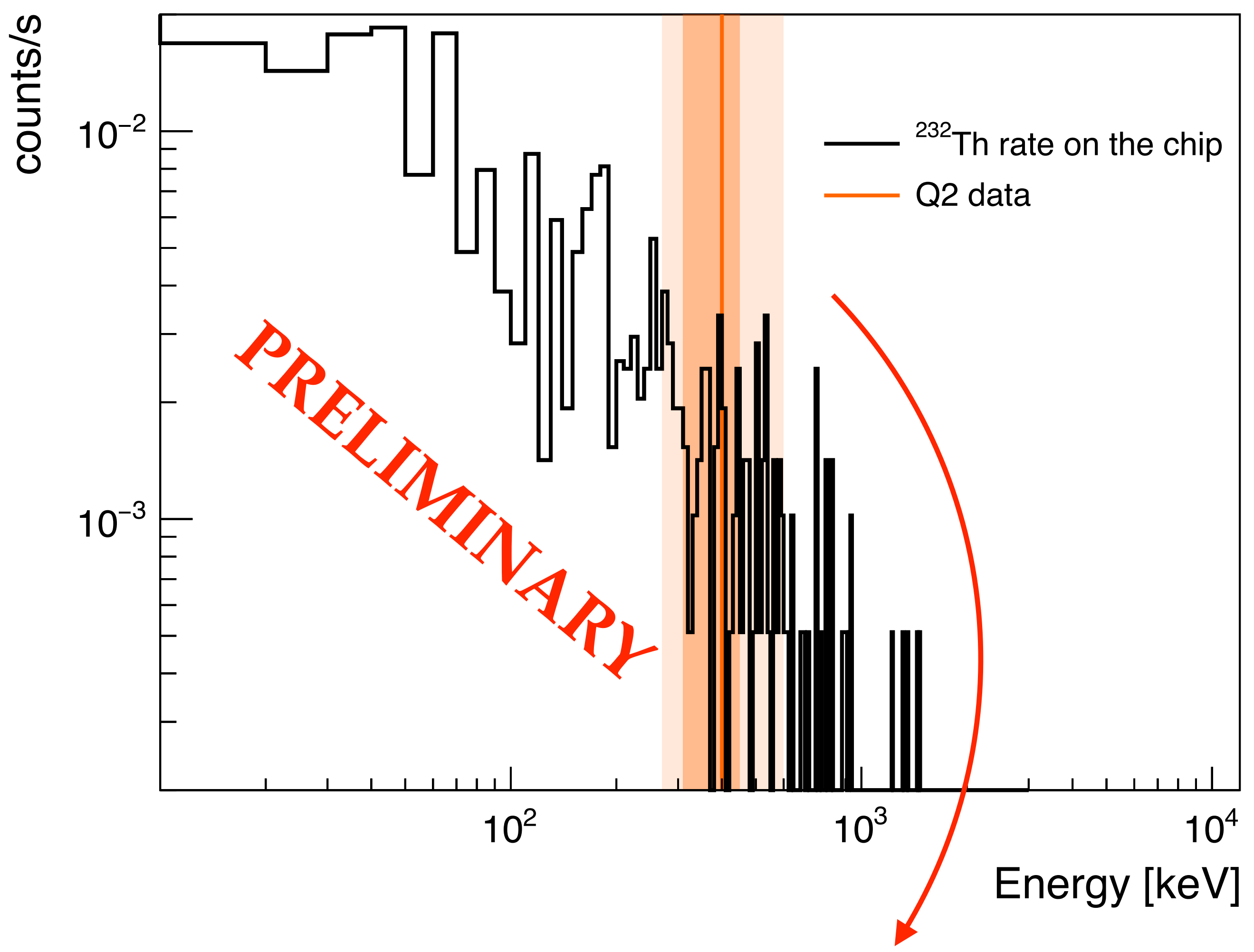
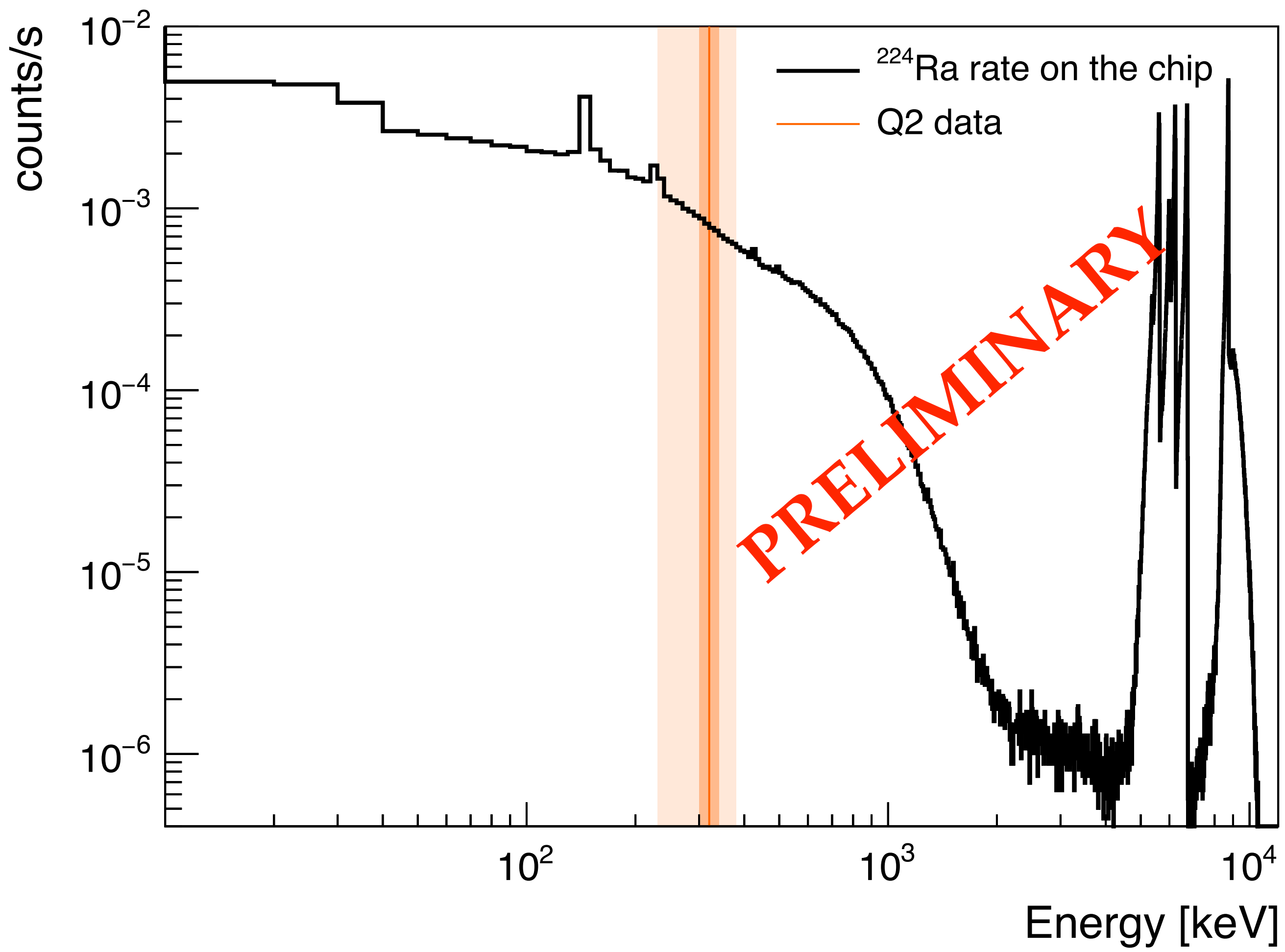


$$E_{thresh}^{Q2} = 400^{+200}_{-130}\,(\mathrm{stat})^{+50}_{-90}\,(\mathrm{syst})\,\mathrm{keV}$$

RESULTS

- Same calculation was repeated for consistency using the ^{224}Ra data, this time integrated the energy spectrum measured with the NTD:



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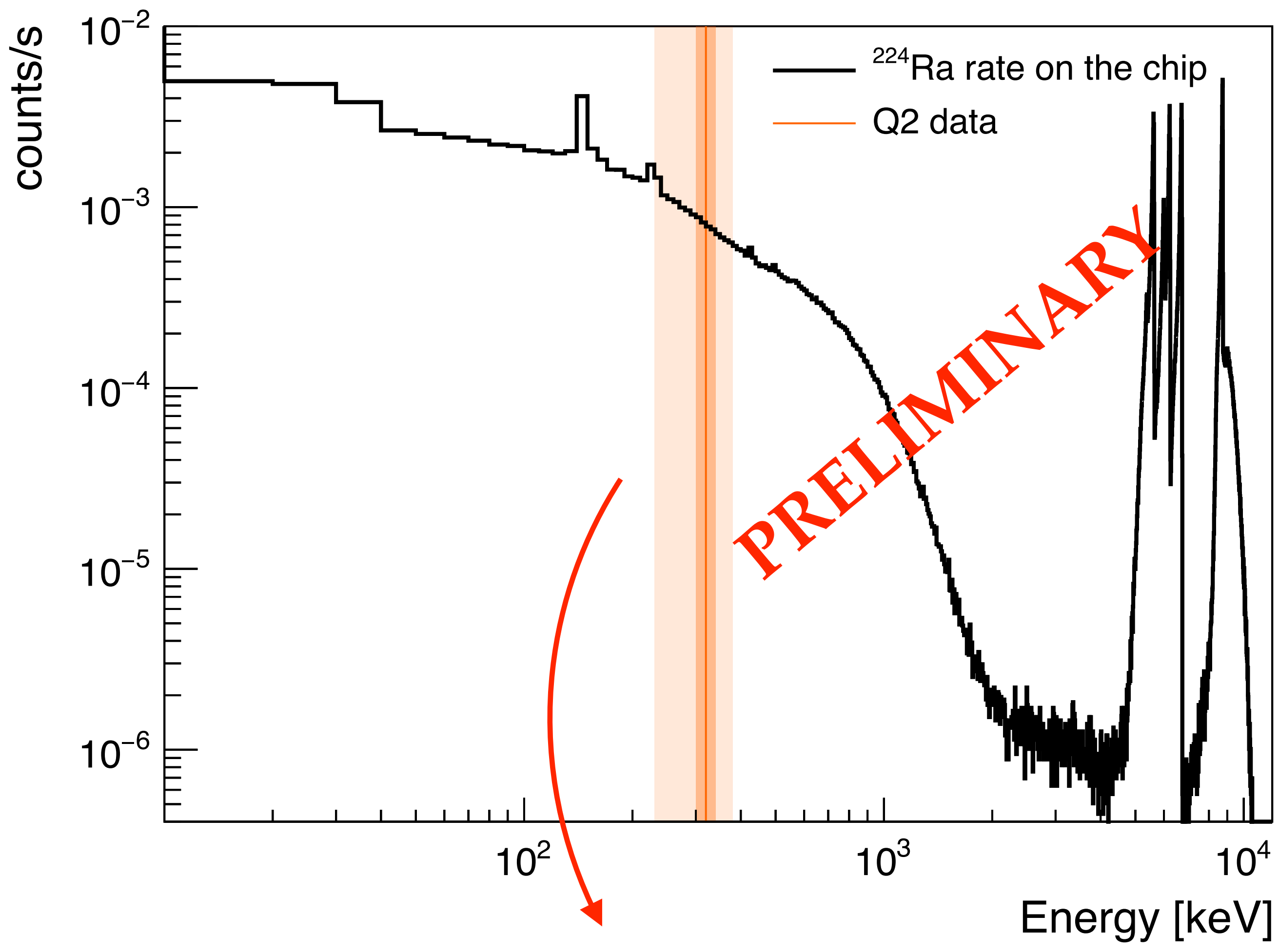
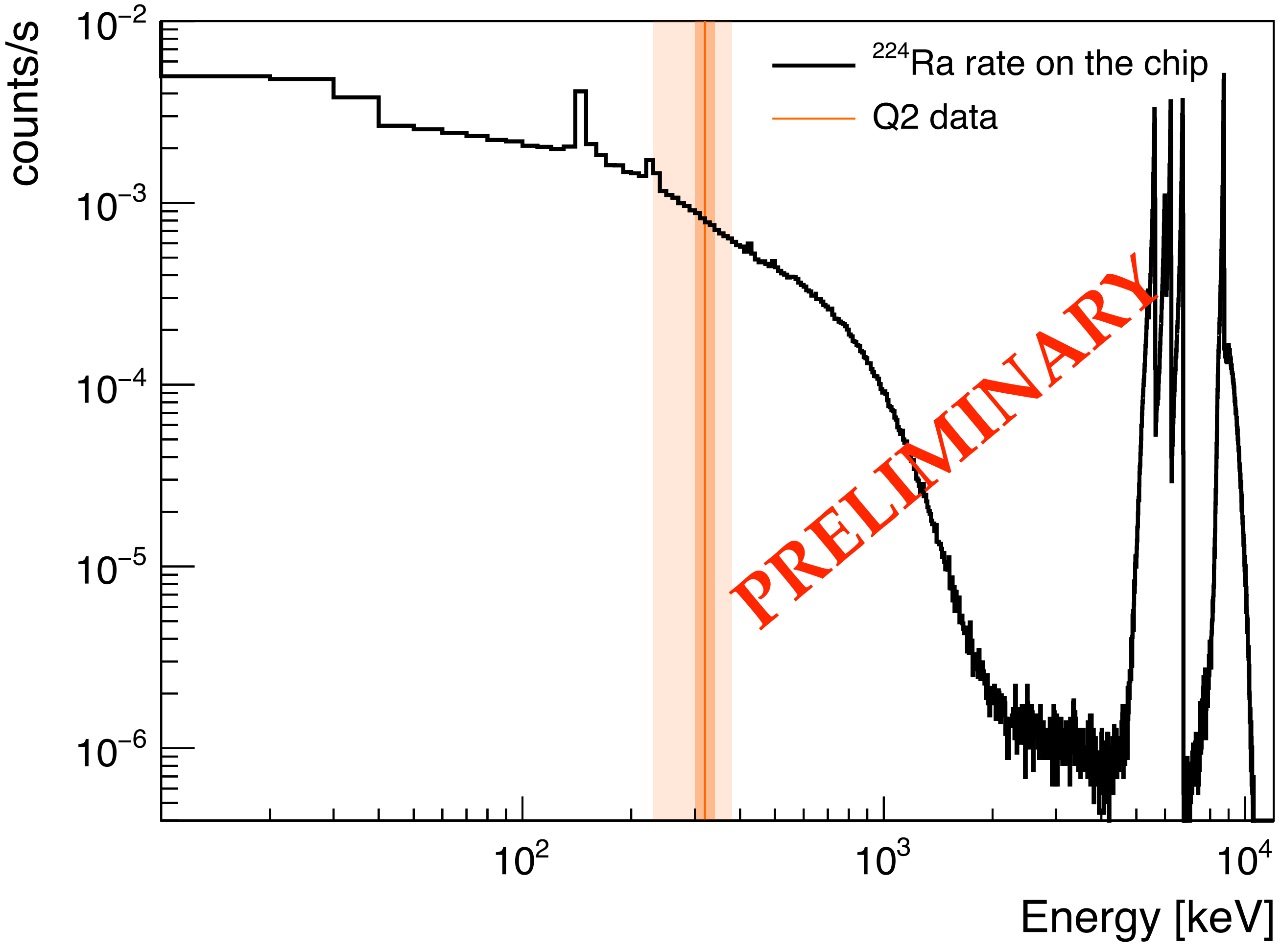


$$E_{thresh}^{Q2} = 320 \pm 20\,(\text{stat})^{+60}_{-90}\,(\text{syst})\,\text{keV}$$

RESULTS

- However, we saw that when combining data from both qubits the detection efficiency increases up to ≈50%;
- This would correspond to an energy threshold:



Results

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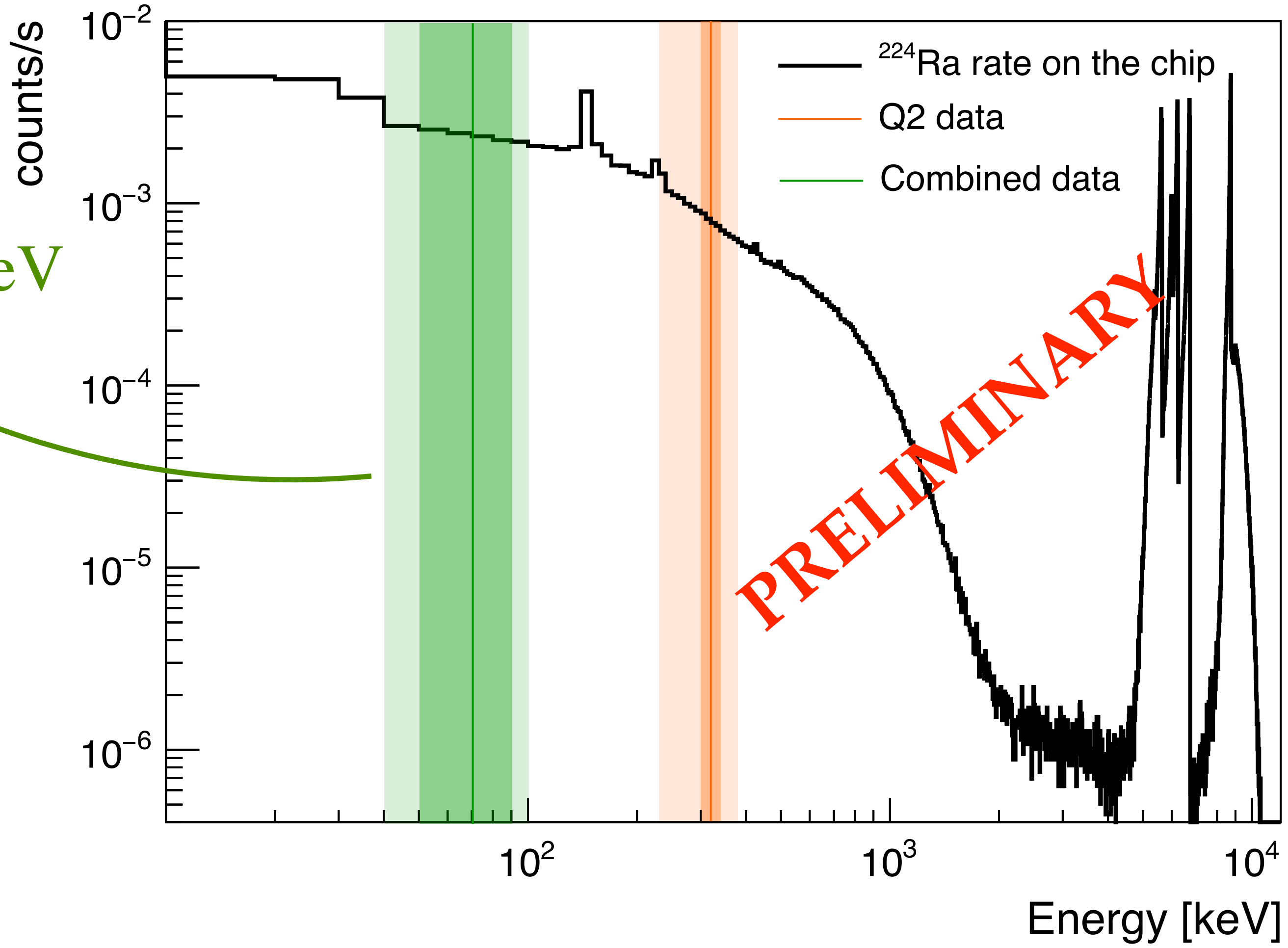
$$E_{thresh}^{Q1+Q2} = 70 \pm 20\,(\text{stat}) \pm 30\,(\text{syst})\,\text{keV}$$



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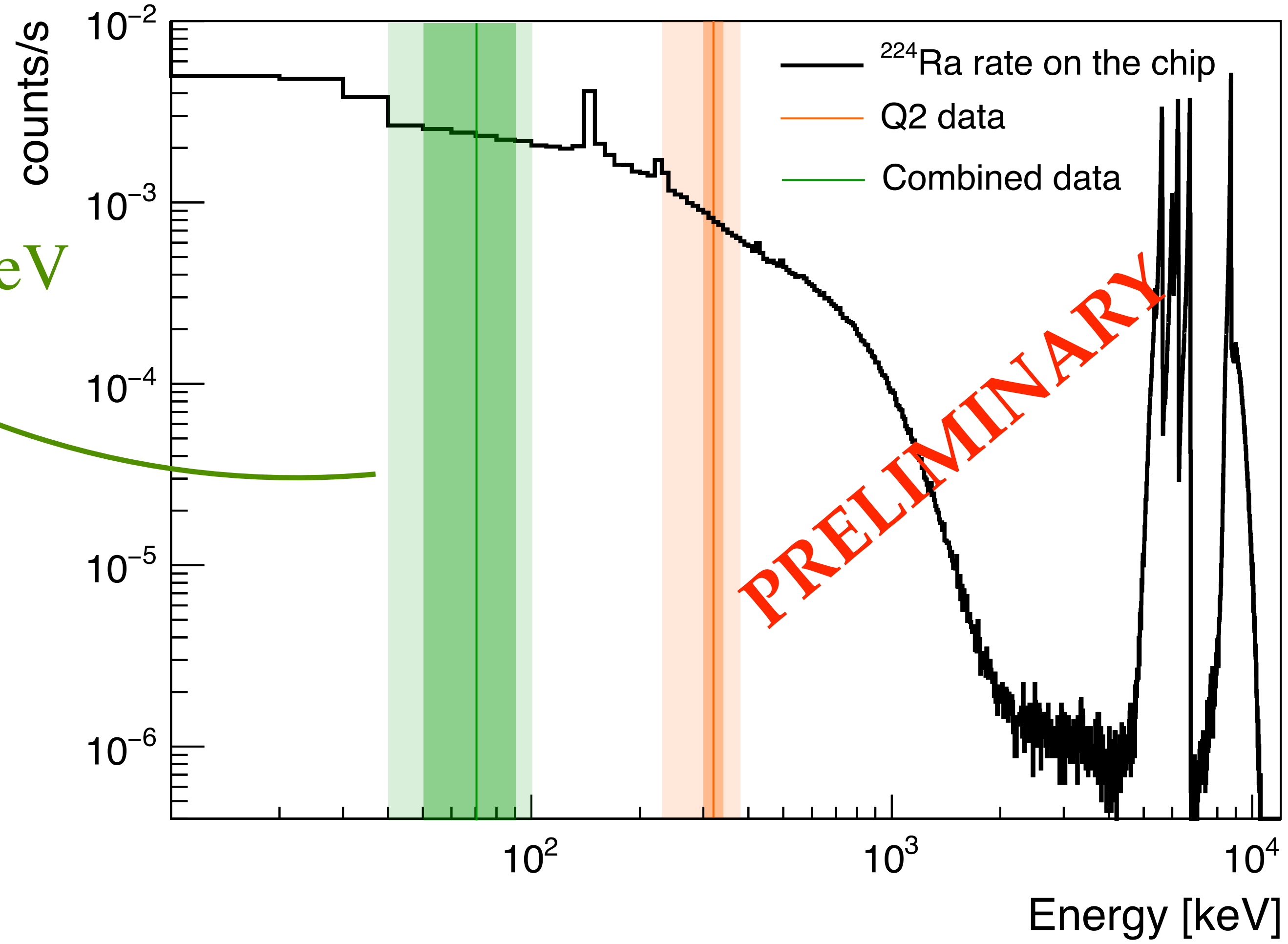

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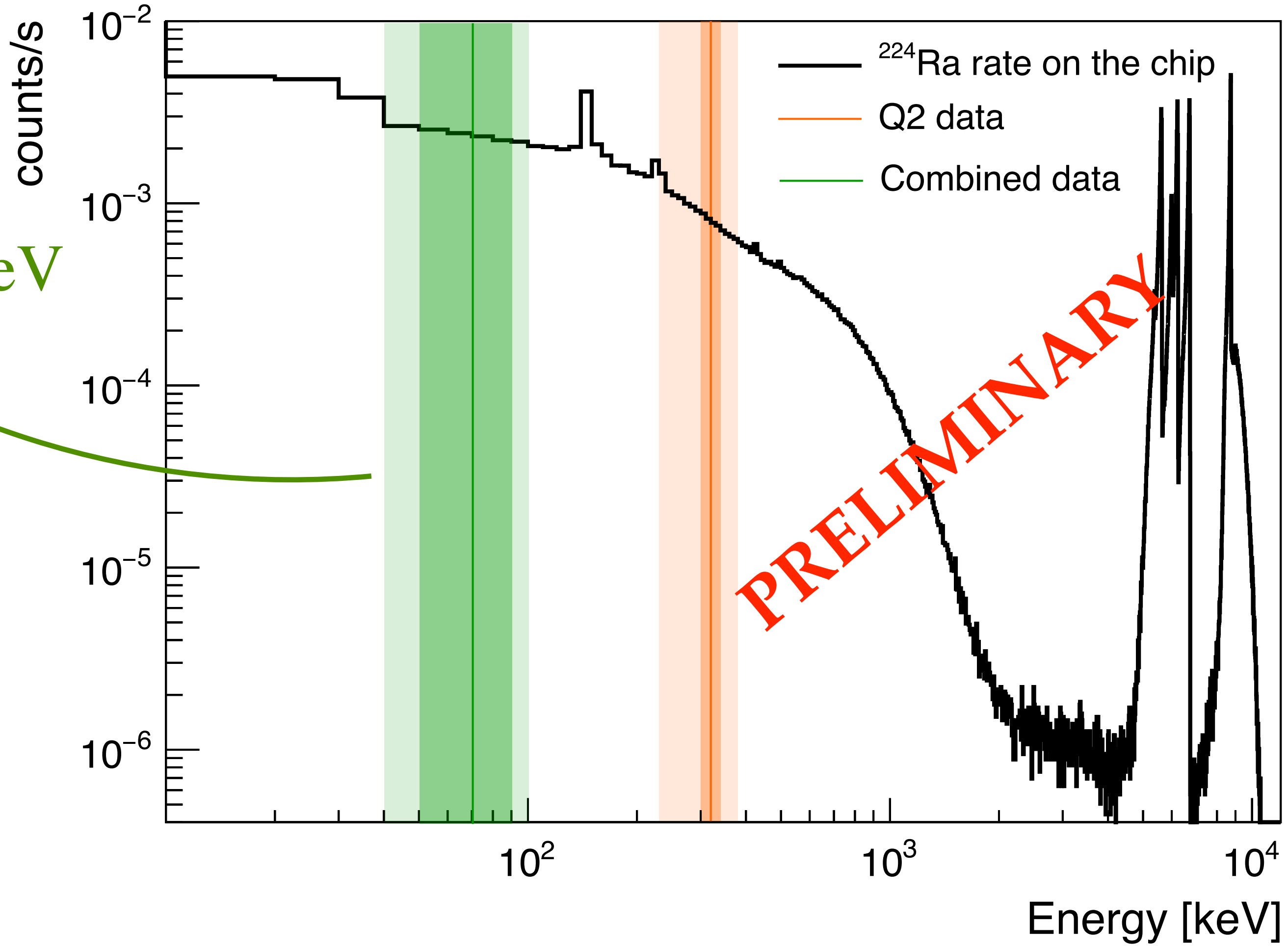

- It is likely that also the distance between the interaction point the qubits is playing a role in undermining the efficiency!

- Thresholds computed should then be considered as upper limits!

WHAT NEXT?

- A lot of questions are still open and are being addressed:
  - Is there a better detection strategy?
  - How can we reconstruct the energy deposited in the chip?
  - Can we discriminate the particle interacting?
  - How can we design qubits in order to improve phonon collection and reduce the threshold?
- And so on…

Conclusion

- New experiment operating transmon qubits as particle detectors achieved a detection efficiency up to ≈50%!
- Result achieved despite qubits being designed to be insensitive to charge noise, confirming the potential of this technology;
- Analysis showed that both the energy deposited in the chip and the position of the interaction affect detection efficiency, requiring more in-depth study;
- Article with these results currently in preparation!

THANK YOU FOR YOUR ATTENTION!

ACKNOWLEDGEMENTS

INFN

SQMS
SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

MUR
Ministero dell'Università e della Ricerca
PRIN 2022
Chasing Light Dark Matter with Quantum Technologies

Ministero degli Affari Esteri e della Cooperazione Internazionale

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CONTACTS

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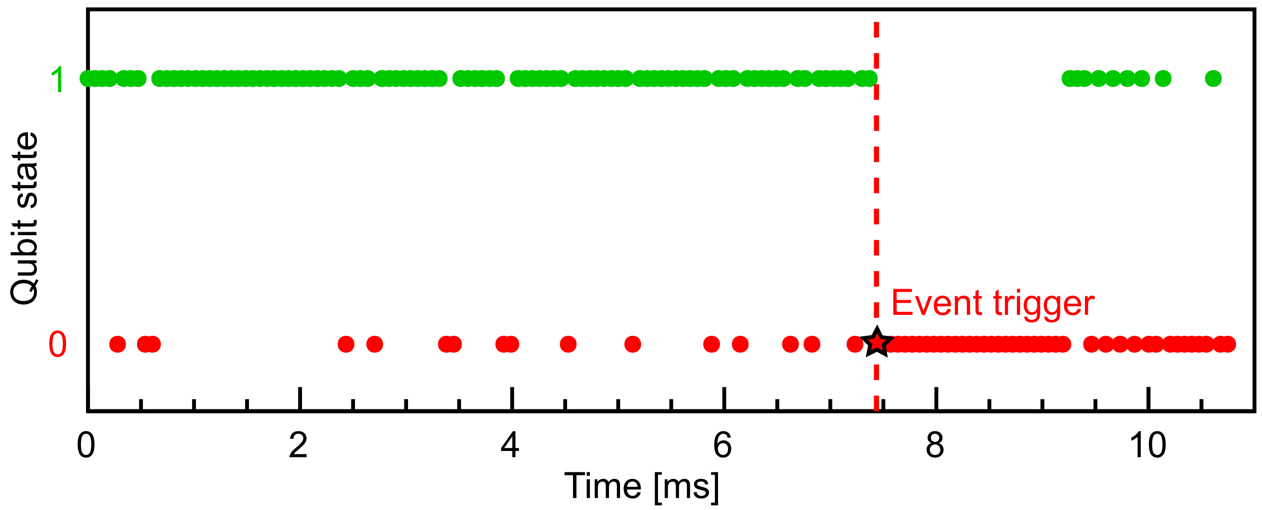
Laura Cardani (head of the group): laura.cardani@roma1.infn.it

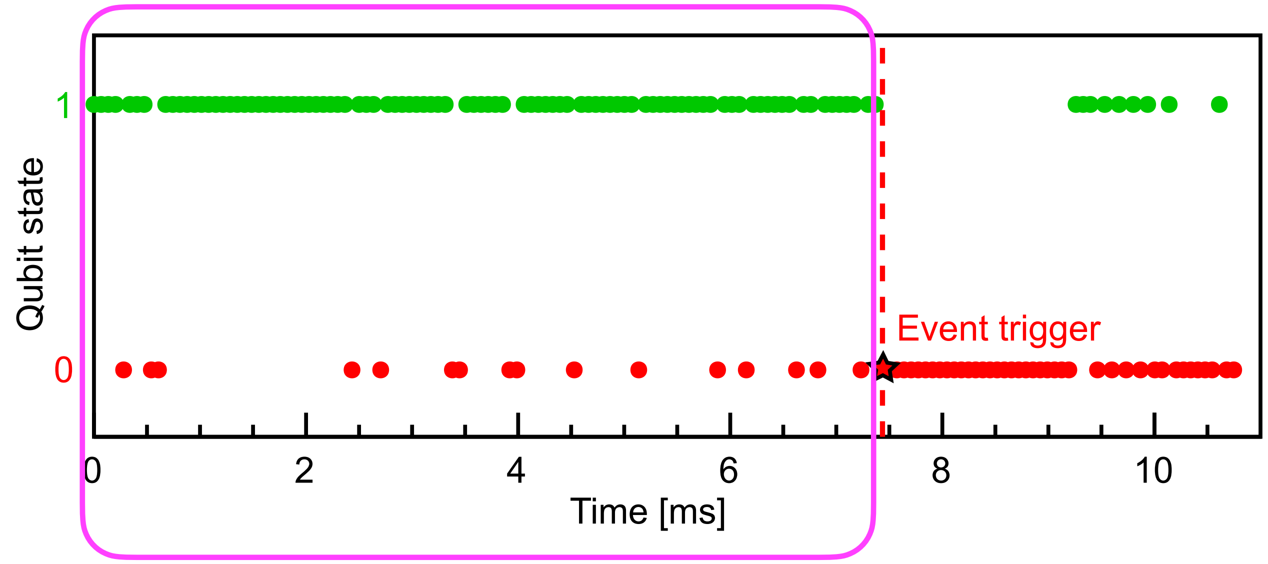
BACKUP SLIDES

Event Selection

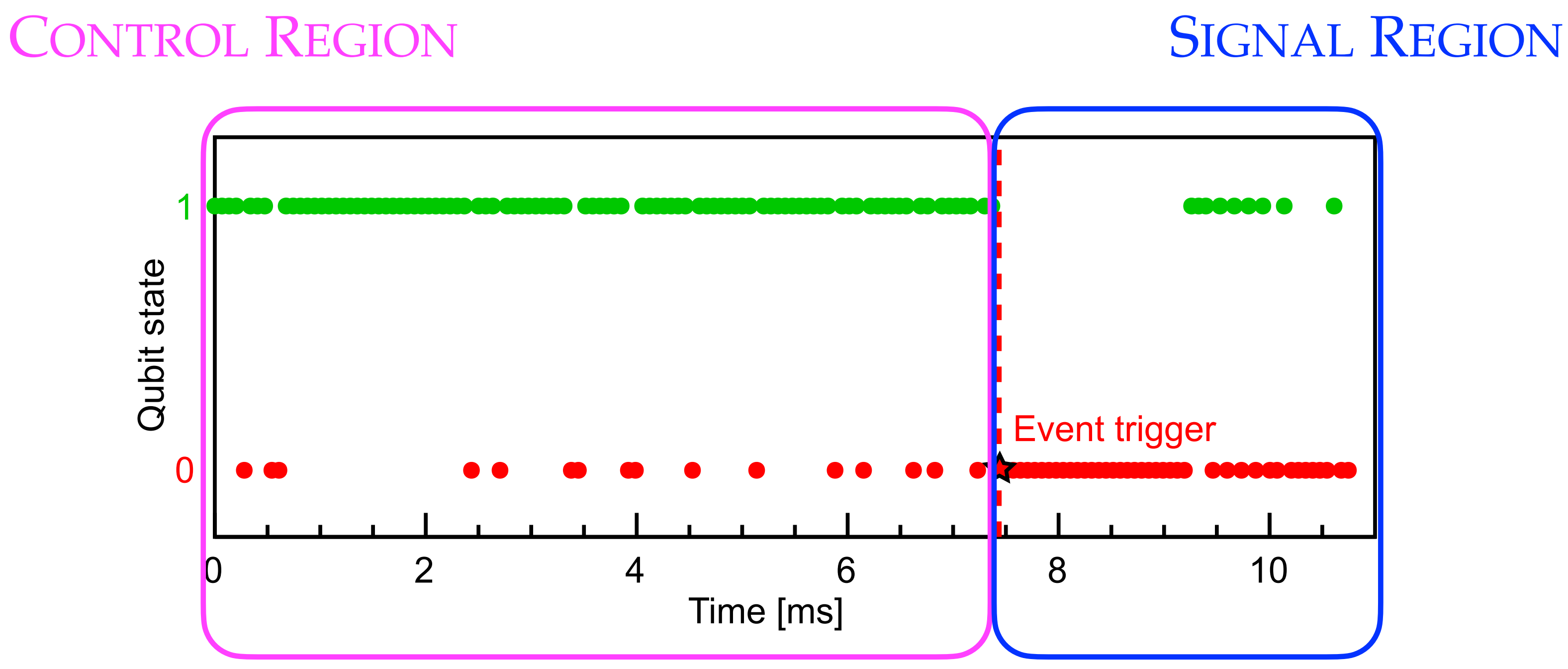


Event Selection

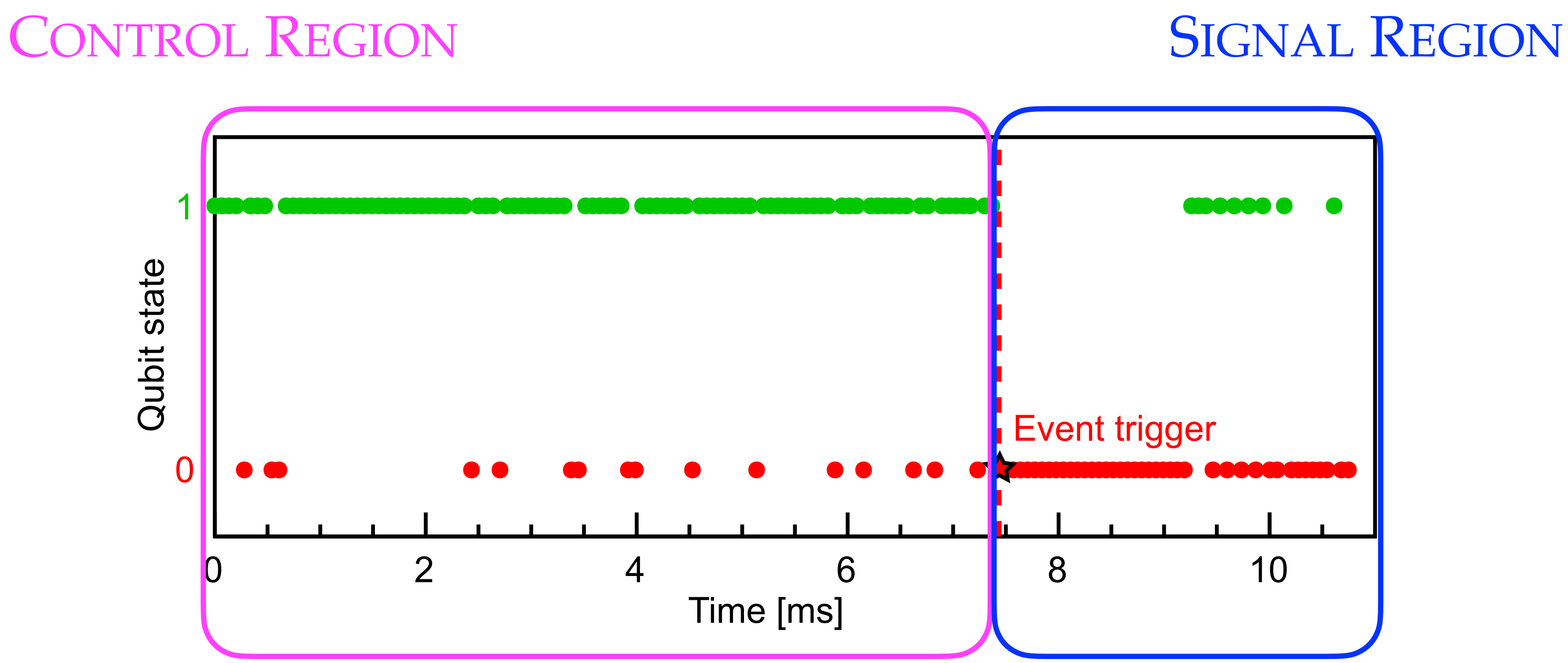
Control Region



Event Selection

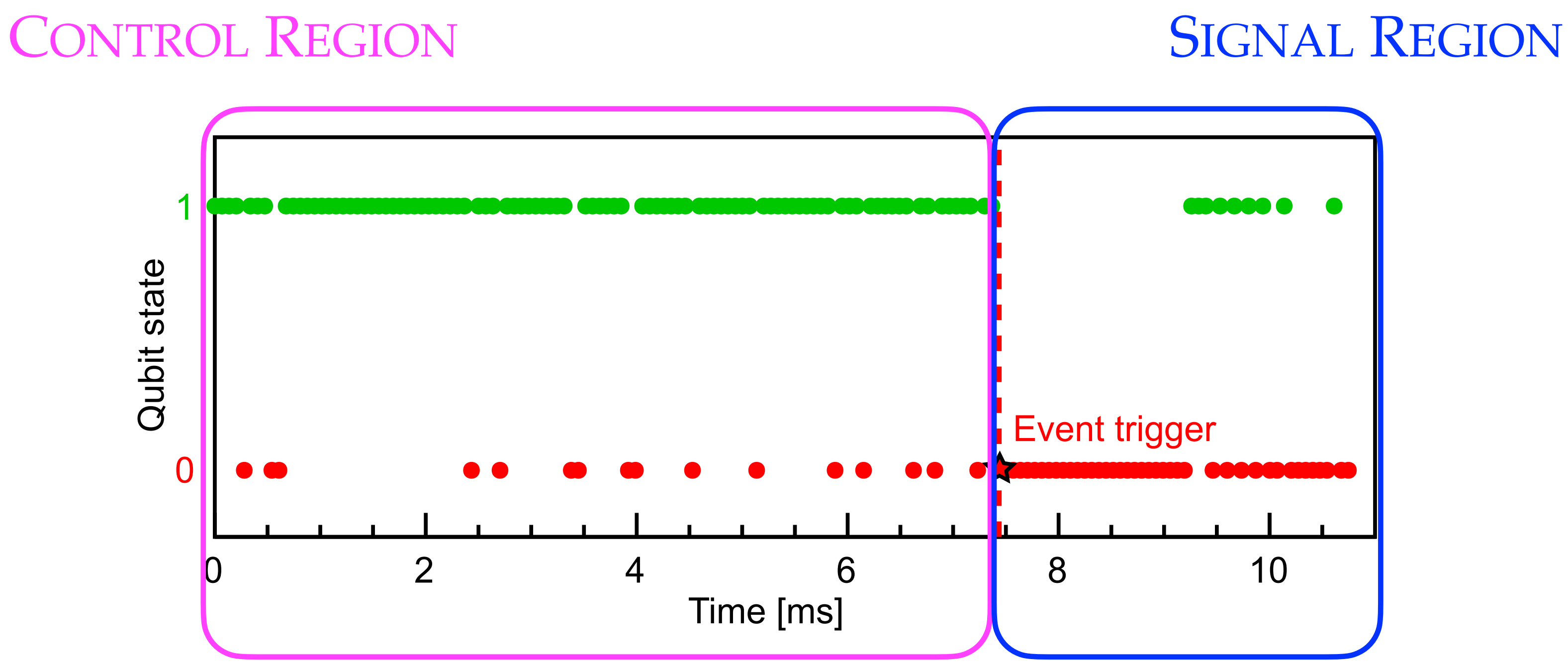


Event Selection



$$P_S(k_{signal}|N_{signal}, k_{control}, N_{control}) = 1 - \sum_{k=k_{signal}}^{N_{signal}} \int_0^1 P(k|N_{signal}, p) P(p|k_{control}, N_{control}) dp$$

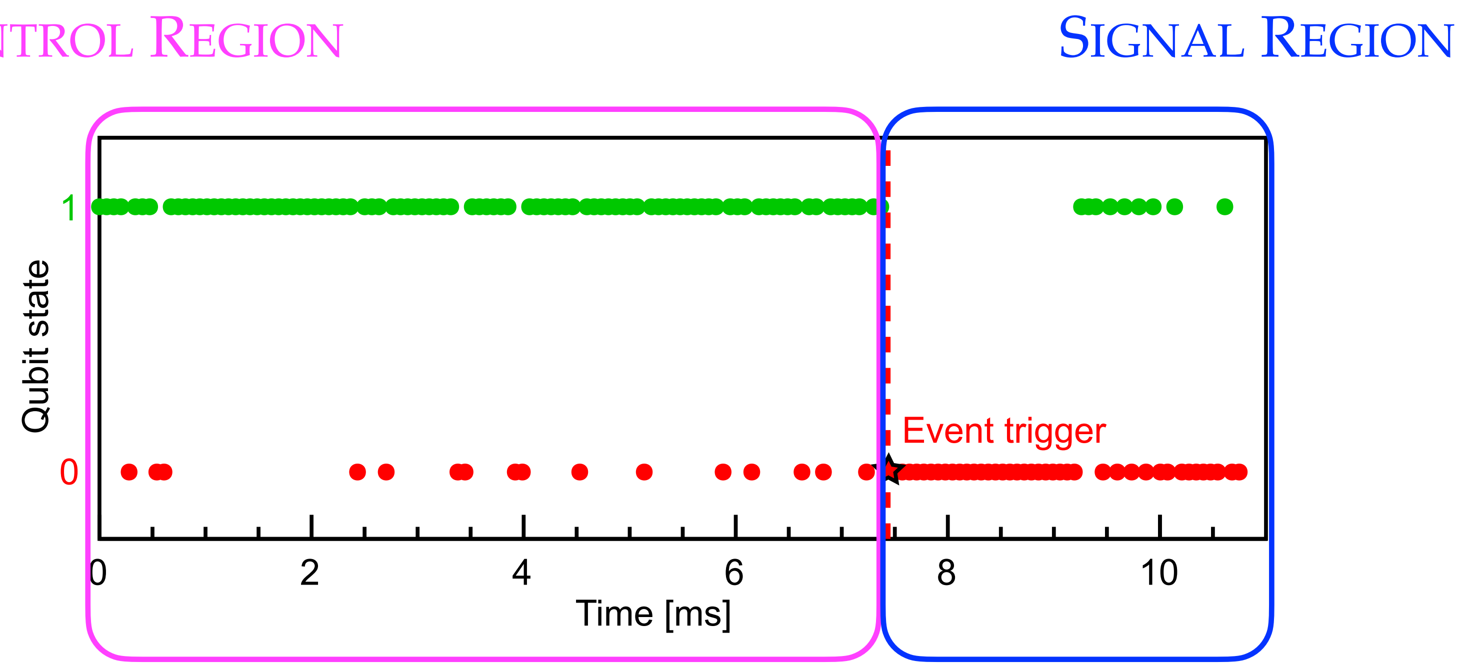
Event Selection



Probability that k_{signal} 0's in the signal region are not due to qubit normal behavior

$$P_S(k_{signal} | N_{signal}, k_{control}, N_{control}) = 1 - \sum_{k=k_{signal}}^{N_{signal}} \int_0^1 P(k | N_{signal}, p) P(p | k_{control}, N_{control}) dp$$

Event Selection

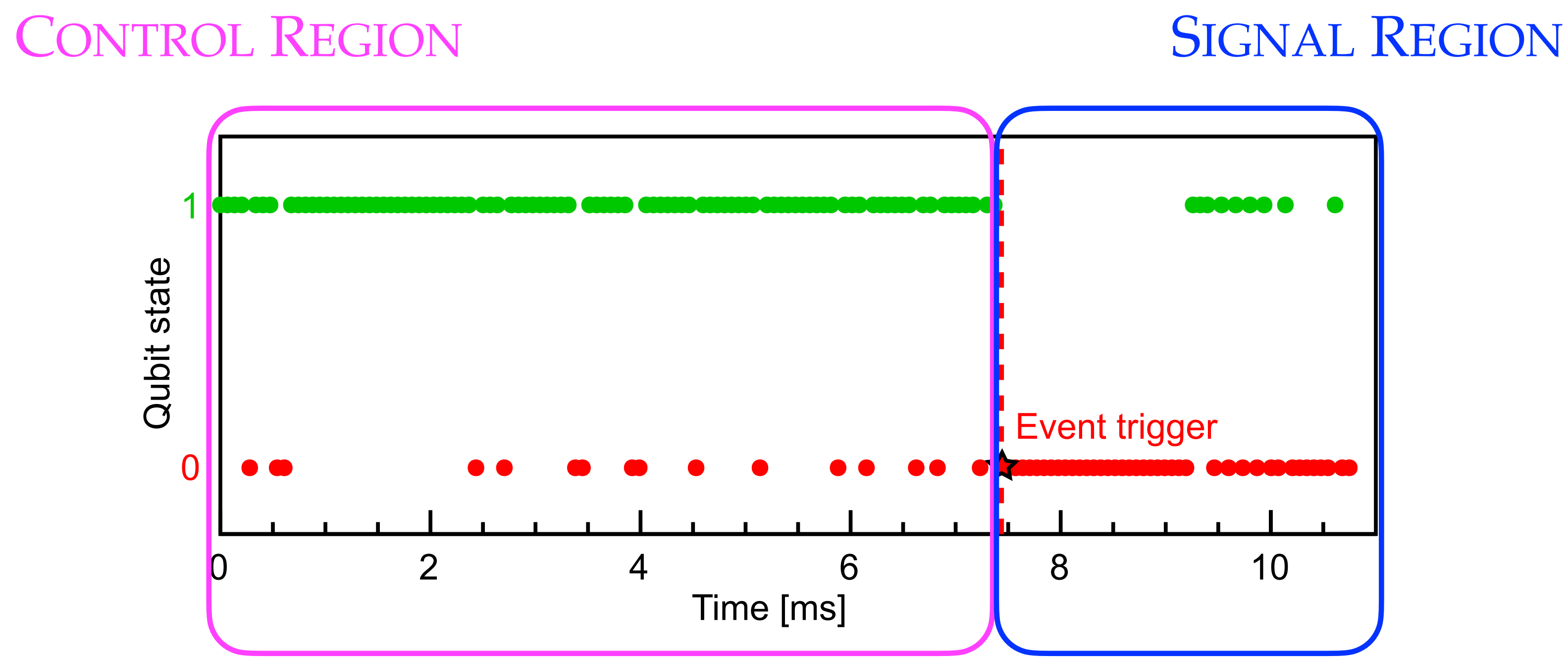


Probability that k_{signal} 0's in the signal region are not due to qubit normal behavior

$$P_S(k_{signal} \mid N_{signal}, k_{control}, N_{control}) = 1 - \sum_{k=k_{signal}}^{N_{signal}} \int_0^1 P(k \mid N_{signal}, p) P(p \mid k_{control}, N_{control}) dp$$

Size of the signal region

Event Selection



Probability that k_{signal} 0's in the signal region are not due to qubit normal behavior

0's in the control region

$$P_S(k_{signal} \,|\, N_{signal}, k_{control}, N_{control}) = 1 - \sum_{k=k_{signal}}^{N_{signal}} \int_0^1 P(k \,|\, N_{signal}, p) P(p \,|\, k_{control}, N_{control}) dp$$

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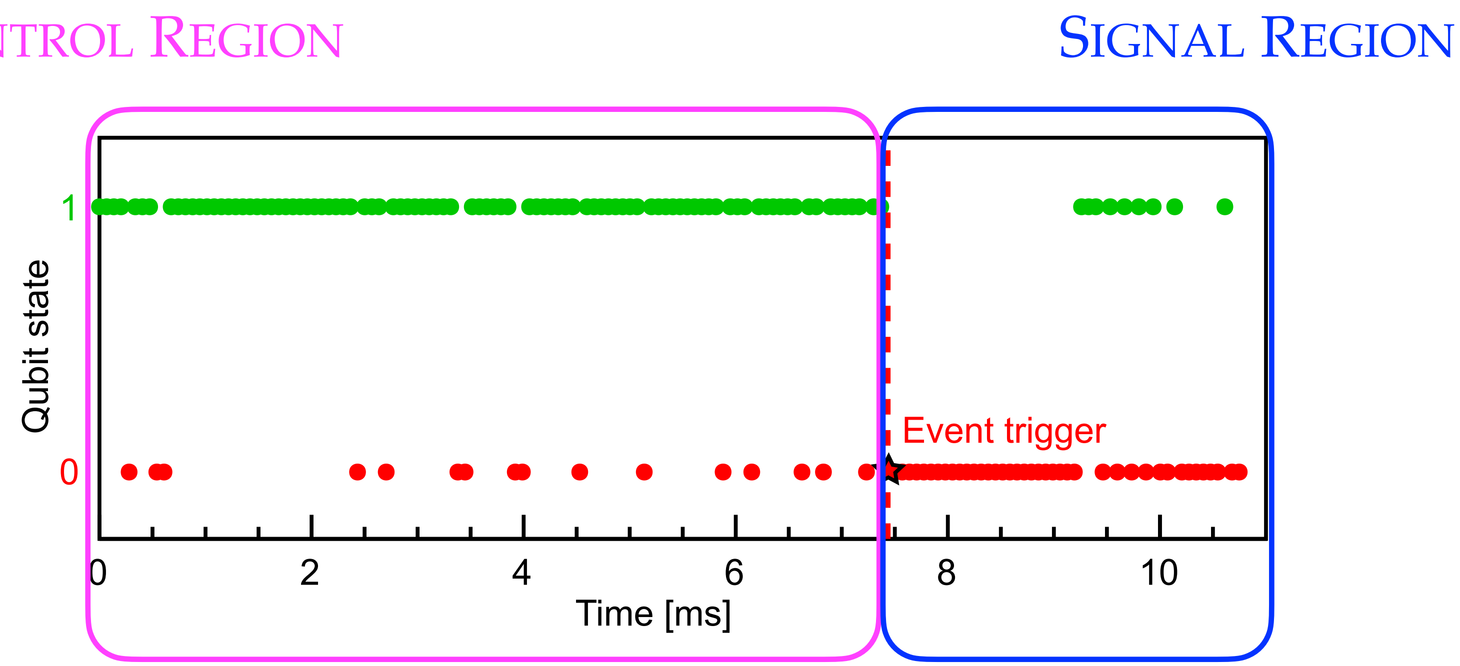

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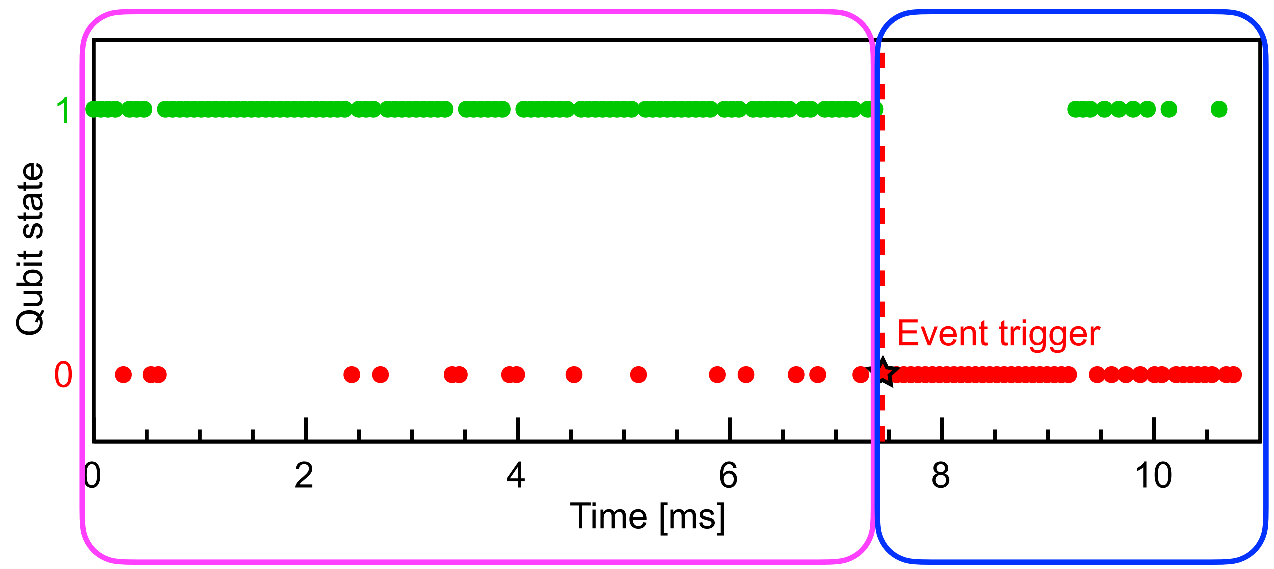
Size of the signal region

Size of the control region

Event Selection

Control Region | Signal Region



Probability that k_{signal} 0's in the signal region are not due to qubit normal behavior

0's in the control region

Binomial probability to measure 0

$$P_S\left(k_{signal} \mid N_{signal}, k_{control}, N_{control}\right) = 1 - \sum_{k=k_{signal}}^{N_{signal}} \int_0^1 P\left(k \mid N_{signal}, p\right) P\left(p \mid k_{control}, N_{control}\right) dp$$

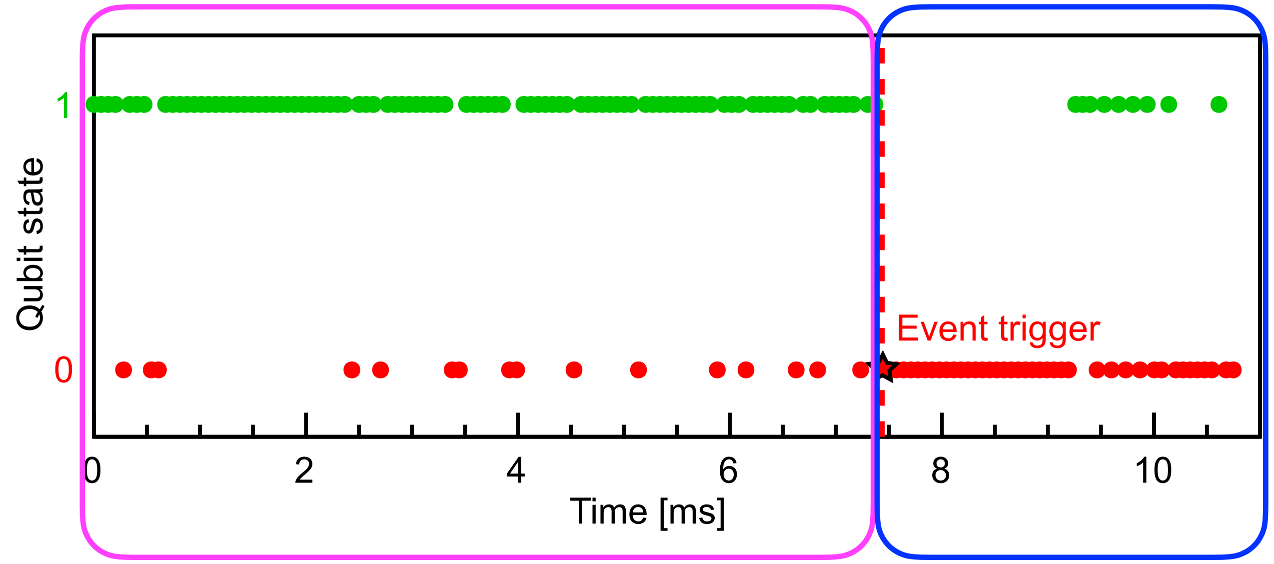
Size of the signal region

Size of the control region

Event Selection

Control Region

Signal Region



Probability that k_{signal} 0's in the signal region are not due to qubit normal behavior

Probability to have k 0's in the signal region given p

Binomial probability to measure 0

0's in the control region

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Size of the signal region

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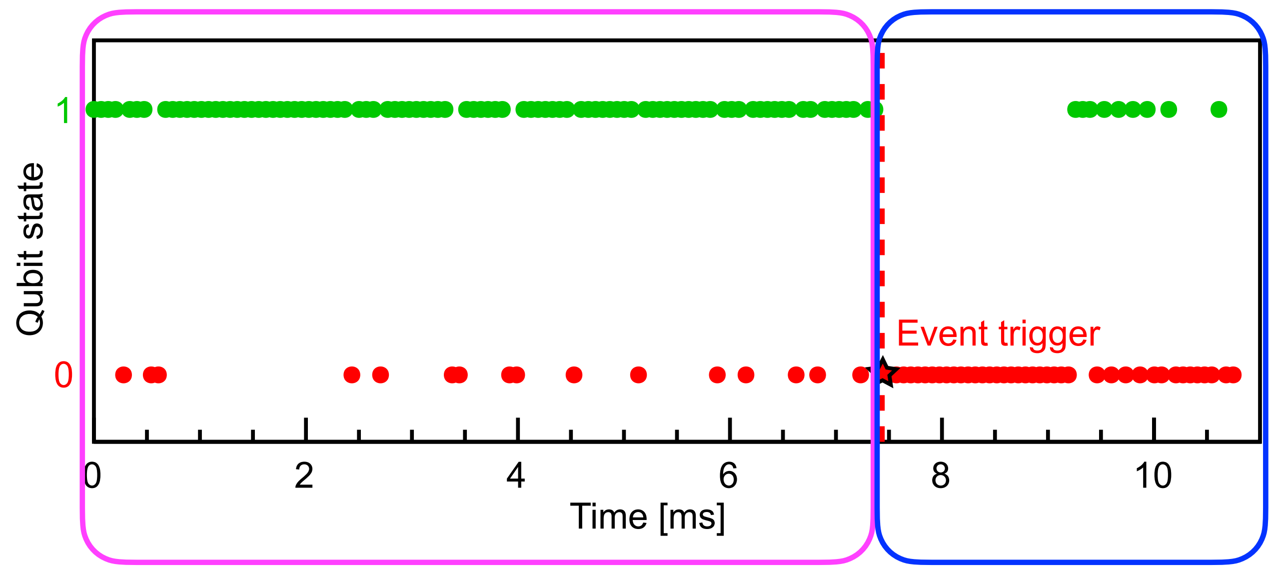
EVENT SELECTION

CONTROL REGION SIGNAL REGION



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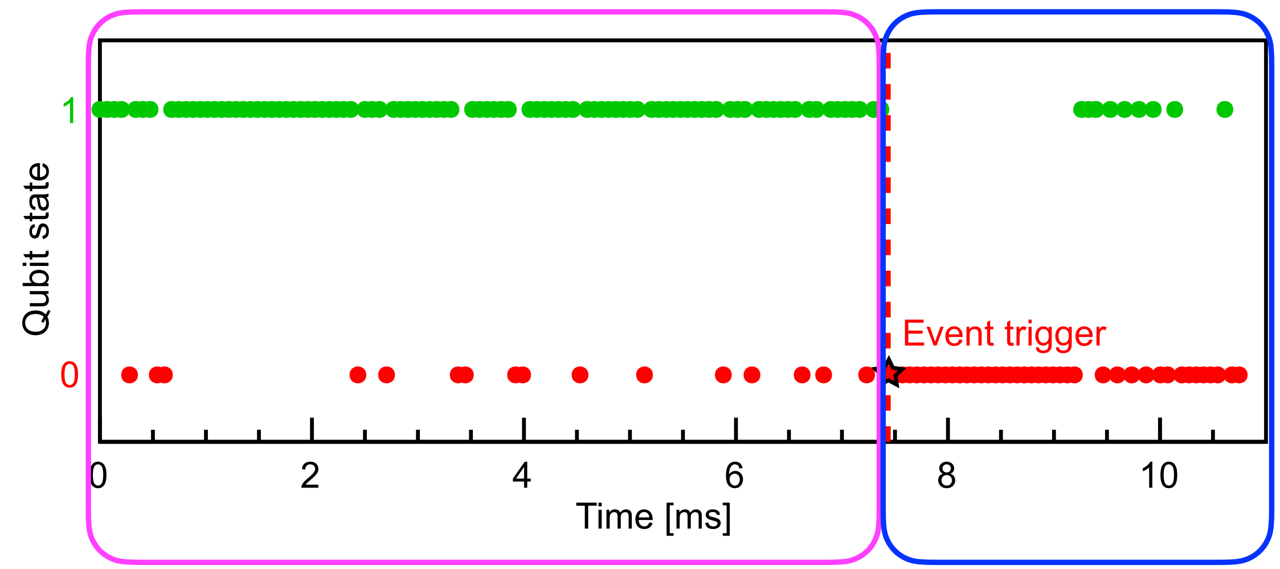
Size of the signal region

Size of the control region

Posterior probability for p given the control region

Event Selection

Control Region | Signal Region



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Probability to have k 0's in the signal region given p

Binomial probability to measure 0

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Size of the signal region

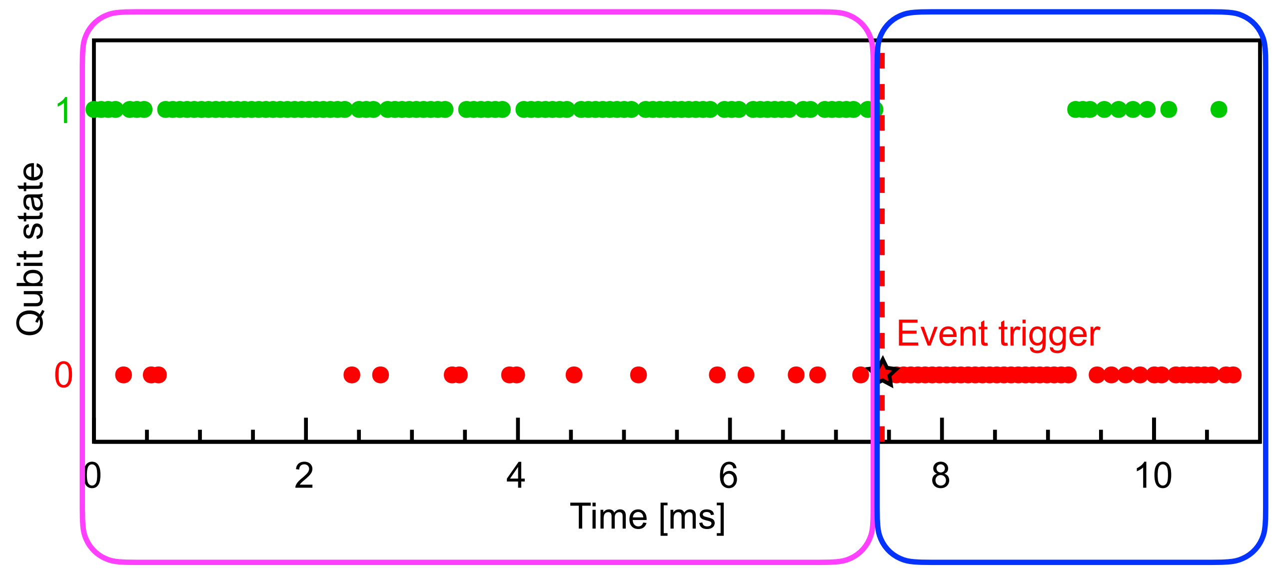
Size of the control region

Posterior probability for p given the control region

Probability to have k 0's in the signal region given the control region

EVENT SELECTION

CONTROL REGION SIGNAL REGION



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Size of the signal region

Size of the control region

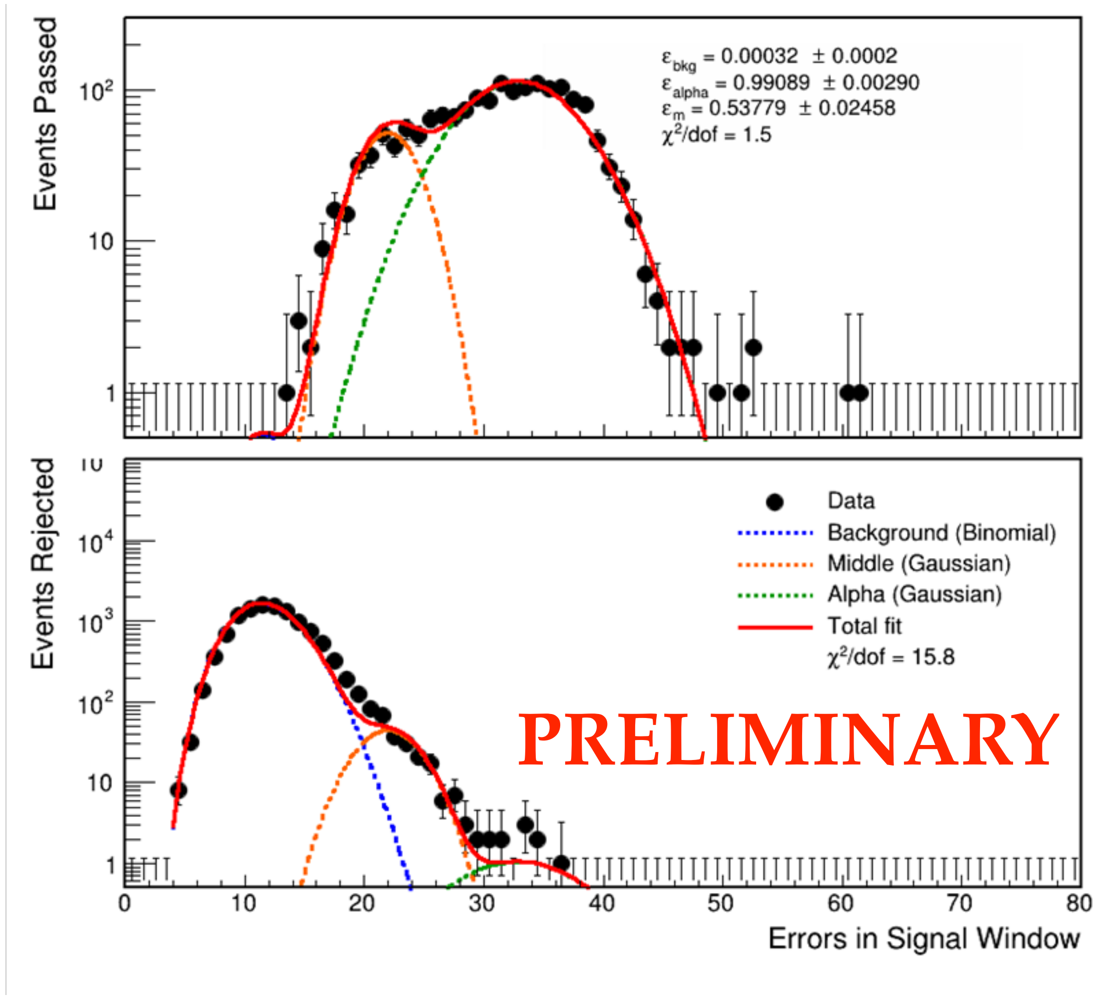
Posterior probability for p given the control region

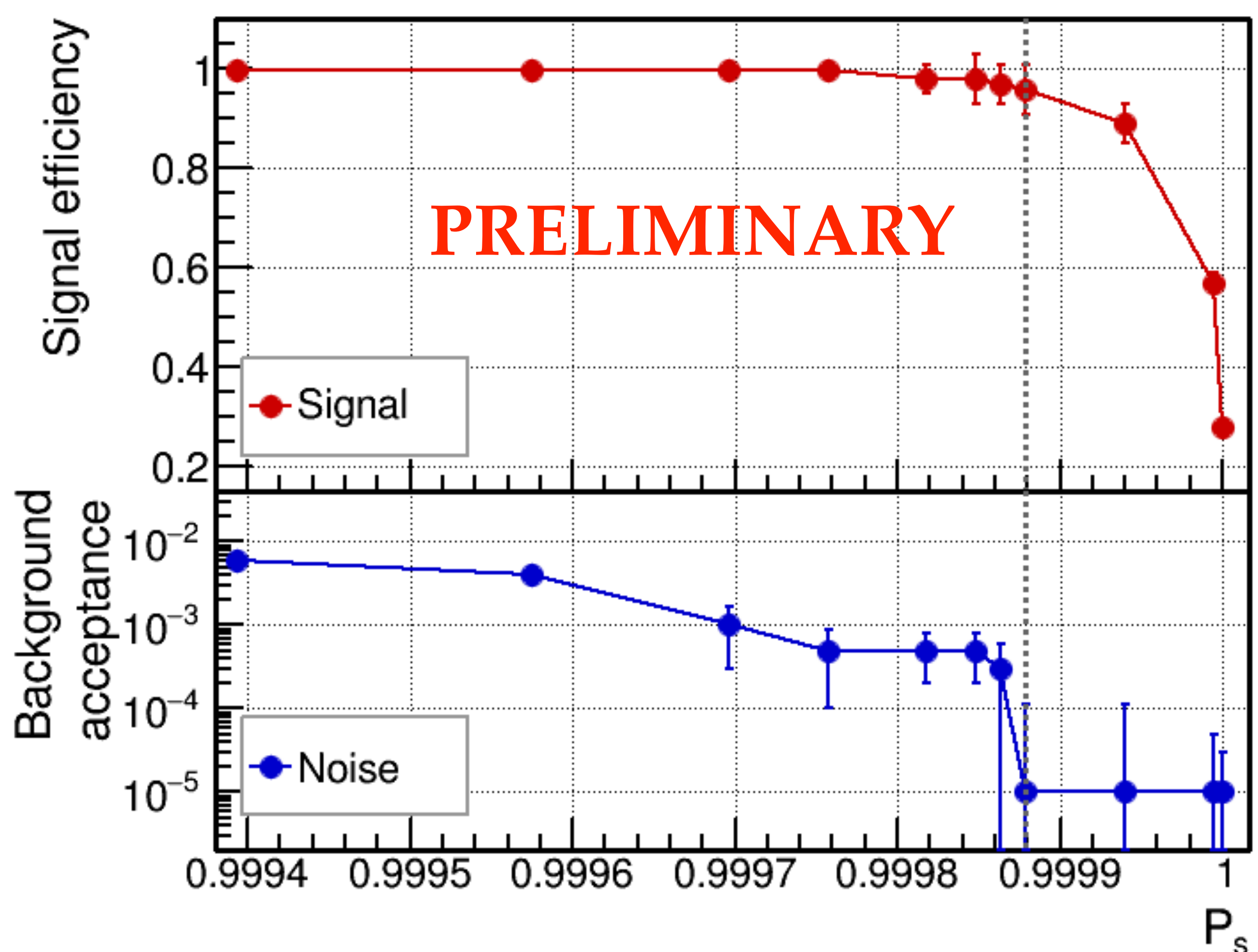
Probability that in normal condition we observe at least k_{signal} 0's in the signal region

Probability to have k 0's in the signal region given the control region

EVENT SELECTION

- Trigger with 4 consecutive zeros and cut on P_S to select the events;
- Simultaneous fit of histograms of accepted and rejected events to determine the best P_S cut.

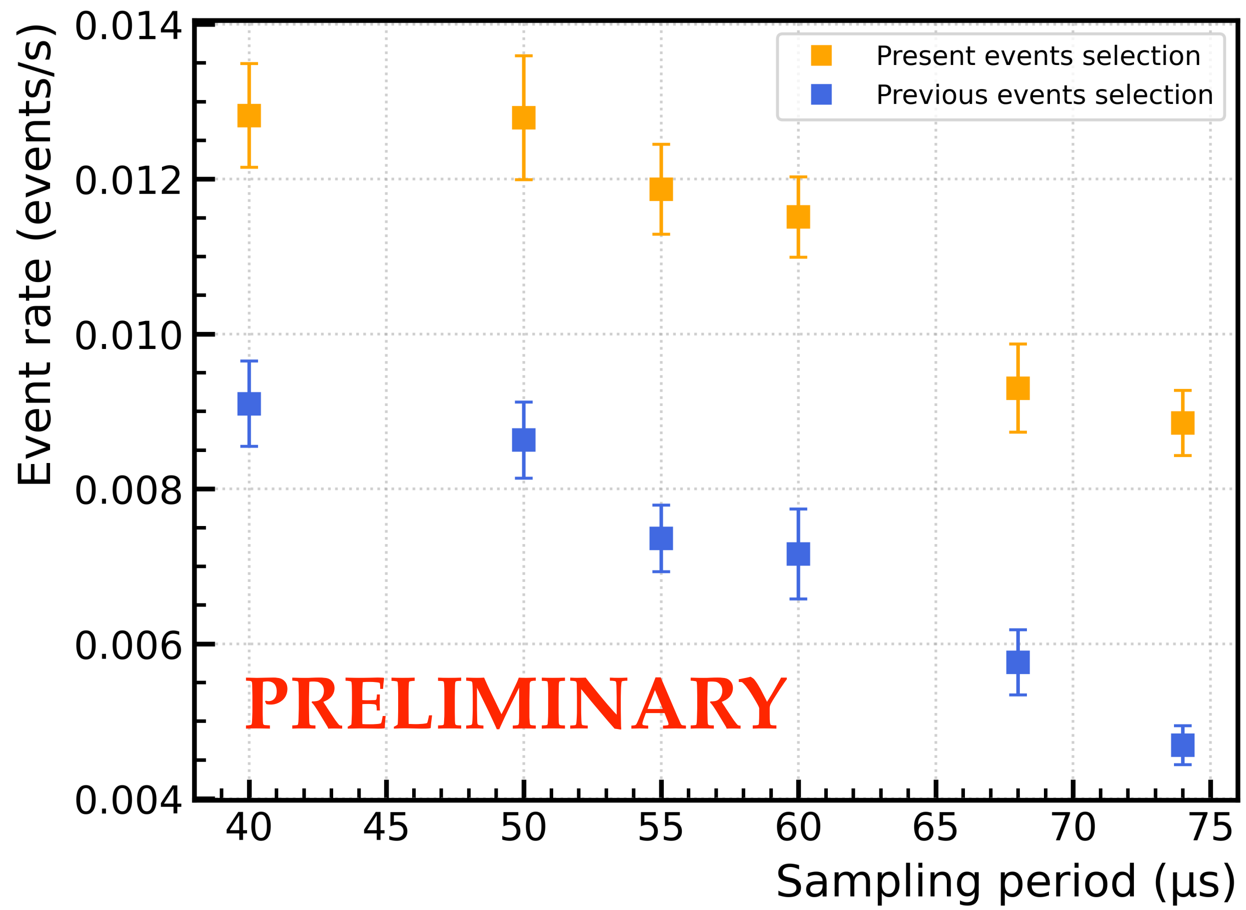




Validation With Old Data

- New analysis strategy was validated with old data from De Dominicis *et al.*, *EPJ Quantum Technol.* **13**, 47 (2026);

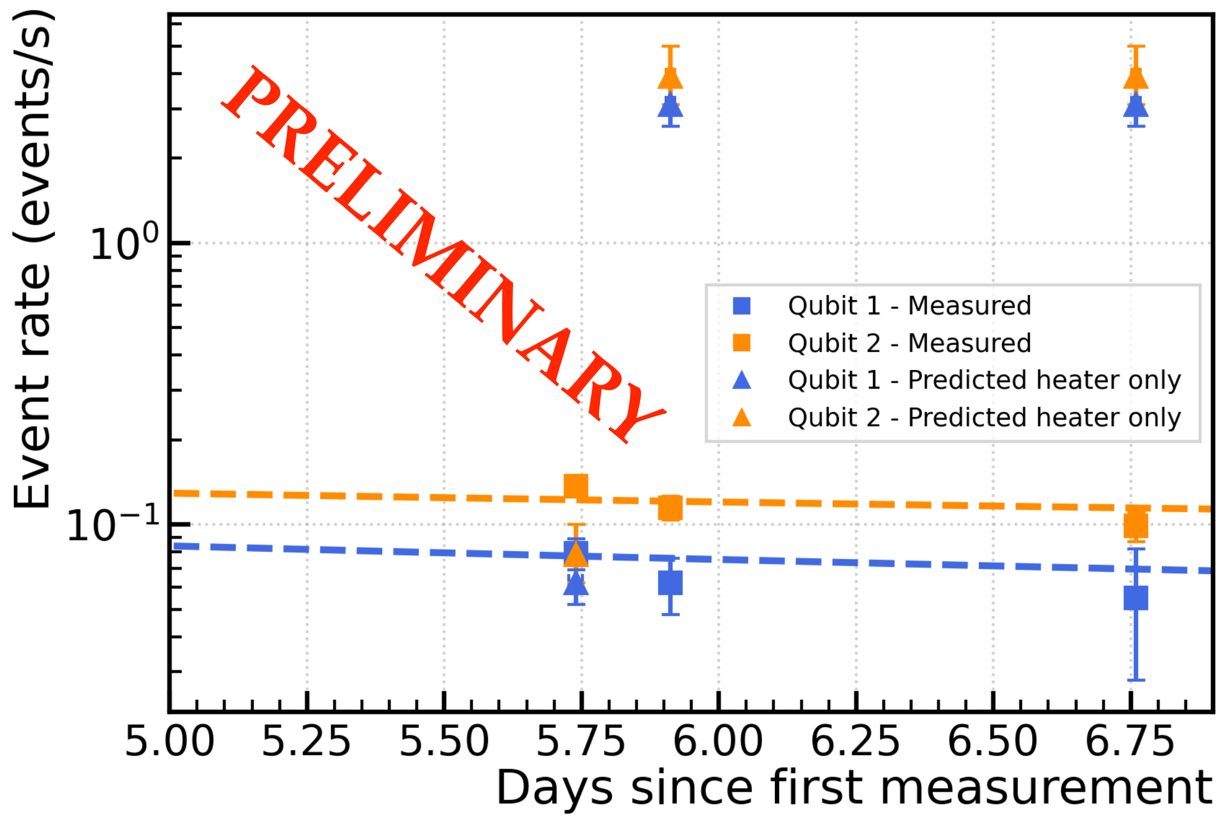
- Detection efficiency systematically improved in all datasets with respect to the old analysis:



The Heater

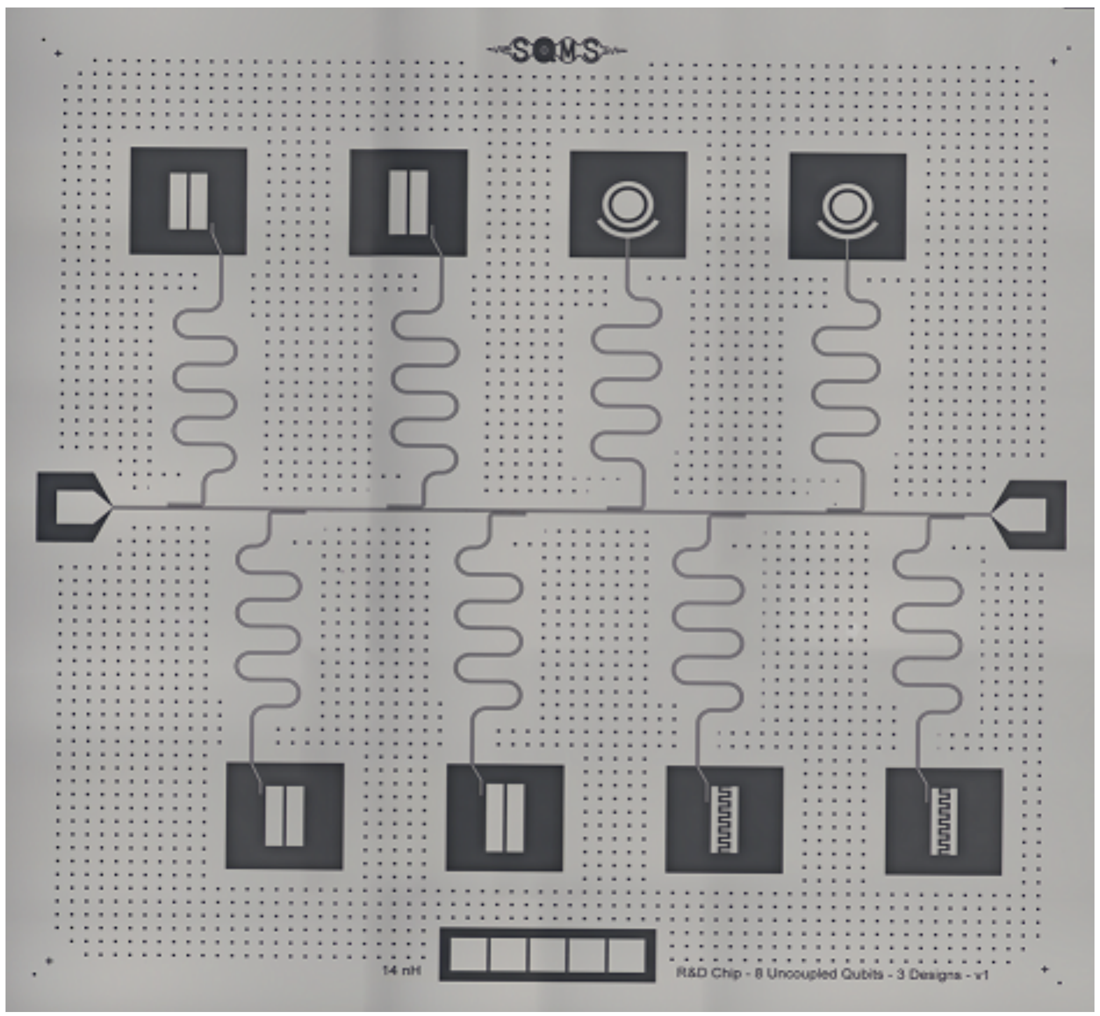
- Periodically injected thermal pulses with energies ranging from ≈0.9 MeV up to ≈11 MeV;

- Looked for increases in the population of the excited states, no significant variation was observed;



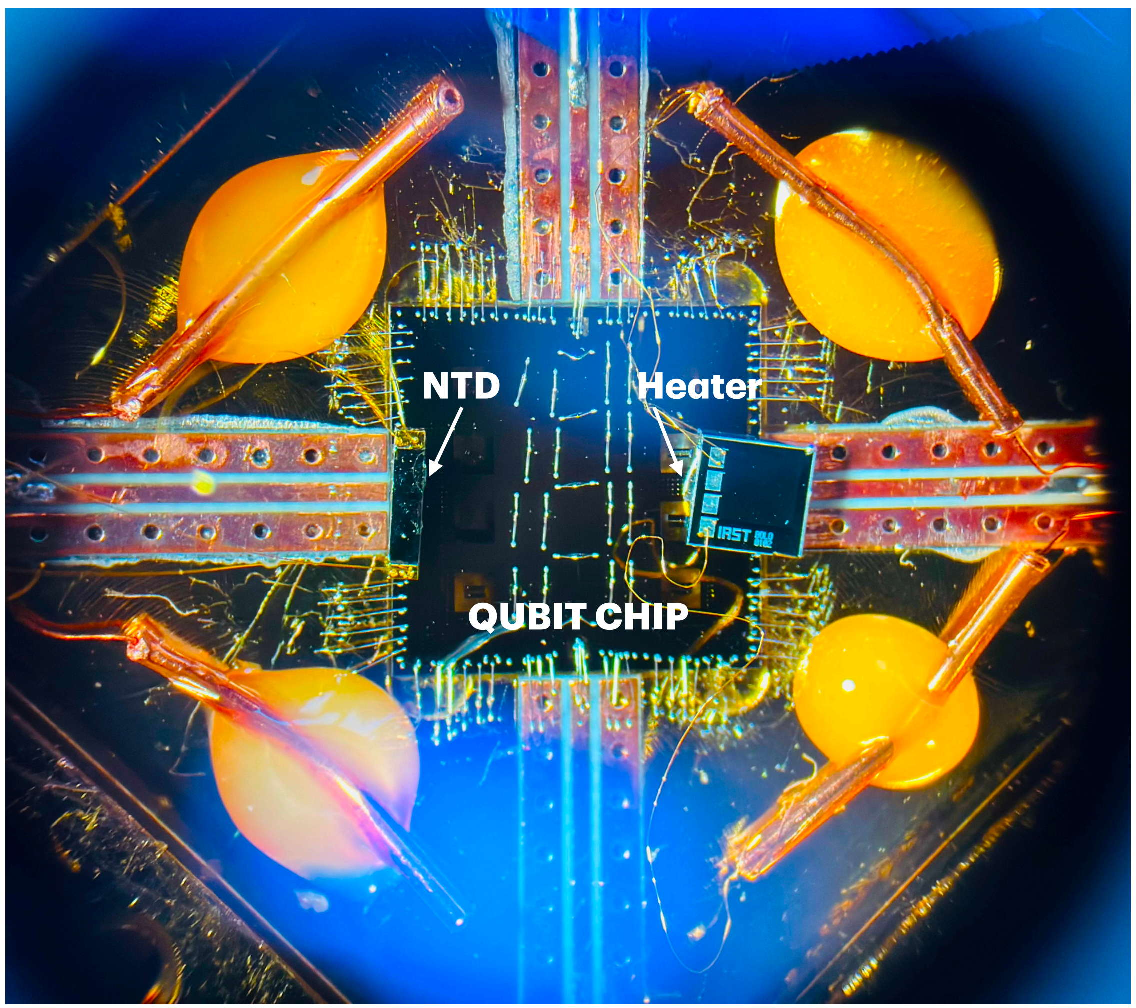
- Also when using the event-selection algorithm used for radiation-induced events no significant excess of events was observed.

The Chip



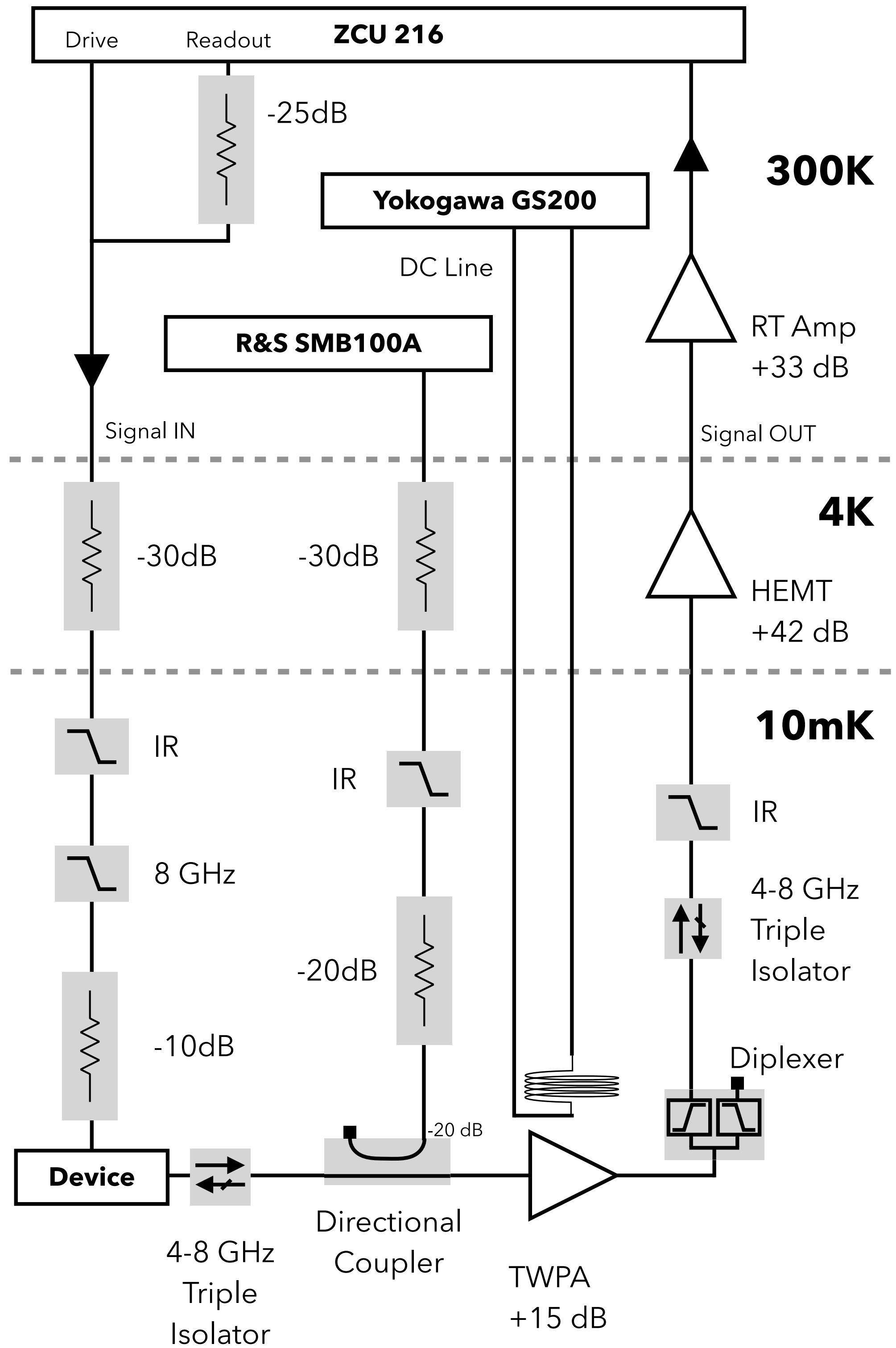
- Chip fabricated by the SQMS Center;
- Eight Nb transmon qubits with Al/AlOx/Al Josephson junctions;
- $7.5 \times 7.5\,\mathrm{mm}^2$, 432 μm-thick sapphire substrate;
- ≈10 nm Ta capping to prevent dielectric losses from Nb_2O_5.

The NTD

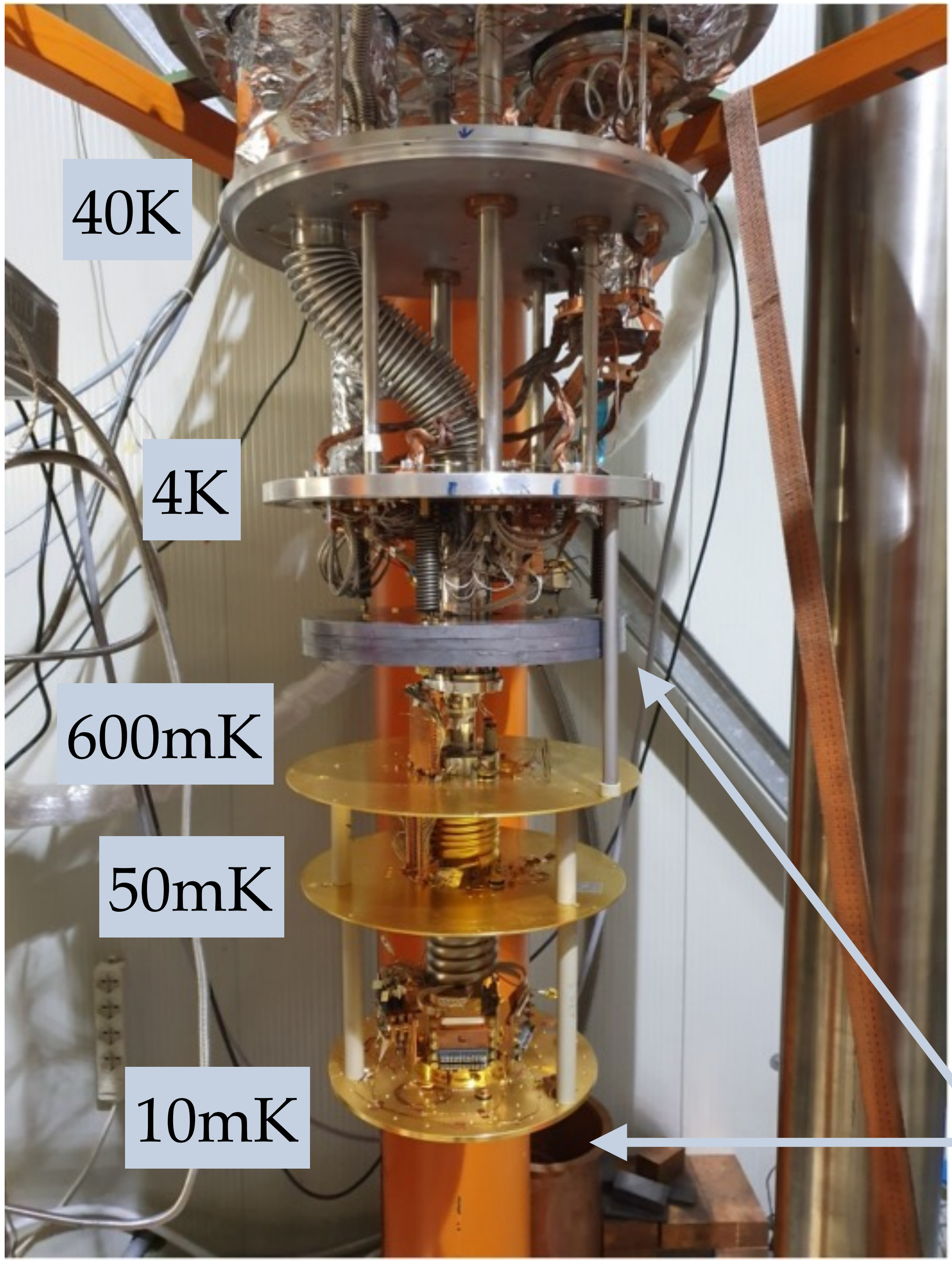


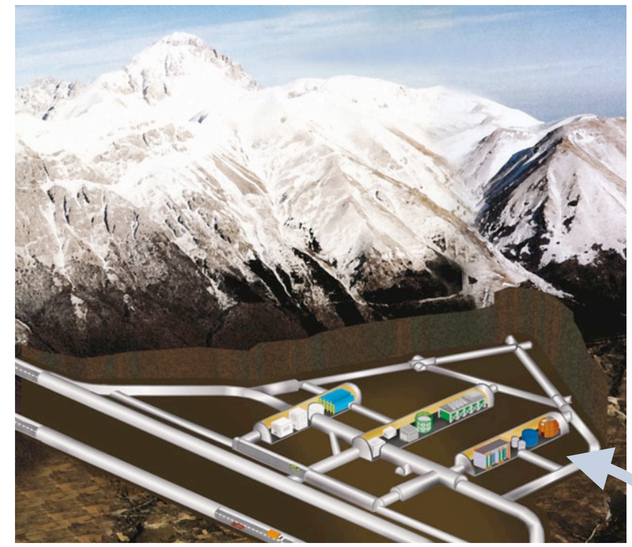
- $3 \times 0.6 \times 0.4\,\mathrm{mm}^3$ Germanium neutron-transmutation-doped thermistor;
- Material resistivity strongly depending on the temperature;
- Phonons produced by particle interactions cause a transient increase in the chip temperature, and a decrease of the NTD resistivity.

THE SETUP


Drive
Readout
ZCU 216
-25dB
Yokogawa GS200
300K
DC Line
R&S SMB100A
RT Amp
+33 dB
Signal IN
Signal OUT
-30dB
-30dB
4K
HEMT
+42 dB
10mK
IR
IR
IR
8 GHz
4-8 GHz
Triple
Isolator
-20dB
-10dB
Diplexer
-20 dB
Device
4-8 GHz
Triple
Isolator
Directional
Coupler
TWPA
+15 dB

The Ieti Underground Facility





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

- Hall C of LNGS Underground Laboratories;
- Pulse tube based 3He/4He dilution refrigerator with mechanical decoupling between cold plate and detector;
- 3 cm internal lead shield at 4K and at 10mK.