Effects of Radioactivity on Superconducting Qubits

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Università di Padova, July 17-18 2025

Longer answer to a question of yesterday

Istituto Nazionale di Fisica Nucleare

Energy absorption in superconductor

INFN
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How do we know the amount of energy absorbed by a superconductor from Δf?

The absorption of E creates a δN_{qp}

$$E = \Delta_0 \, \delta N_{qp} = \Delta_0 \left(\frac{1}{p_0} \frac{f - f_0}{f_0} \right)$$

$$p_0 = \alpha S_2(f, T) / 4 N_0 V \Delta_0$$

- α: fraction of kinetic inductance
- S2: slow function of T and f, relates the phase variation of the complex conductivity to Cooper pairs breaking (2.3 - 2.6)
- N0: depends on material
- V: active volume of the resonator

L. Cardani et al, 2017

Energy absorption in superconductor

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$$p_0 = \alpha S_2(f, T) / 4 N_0 V \Delta_0$$

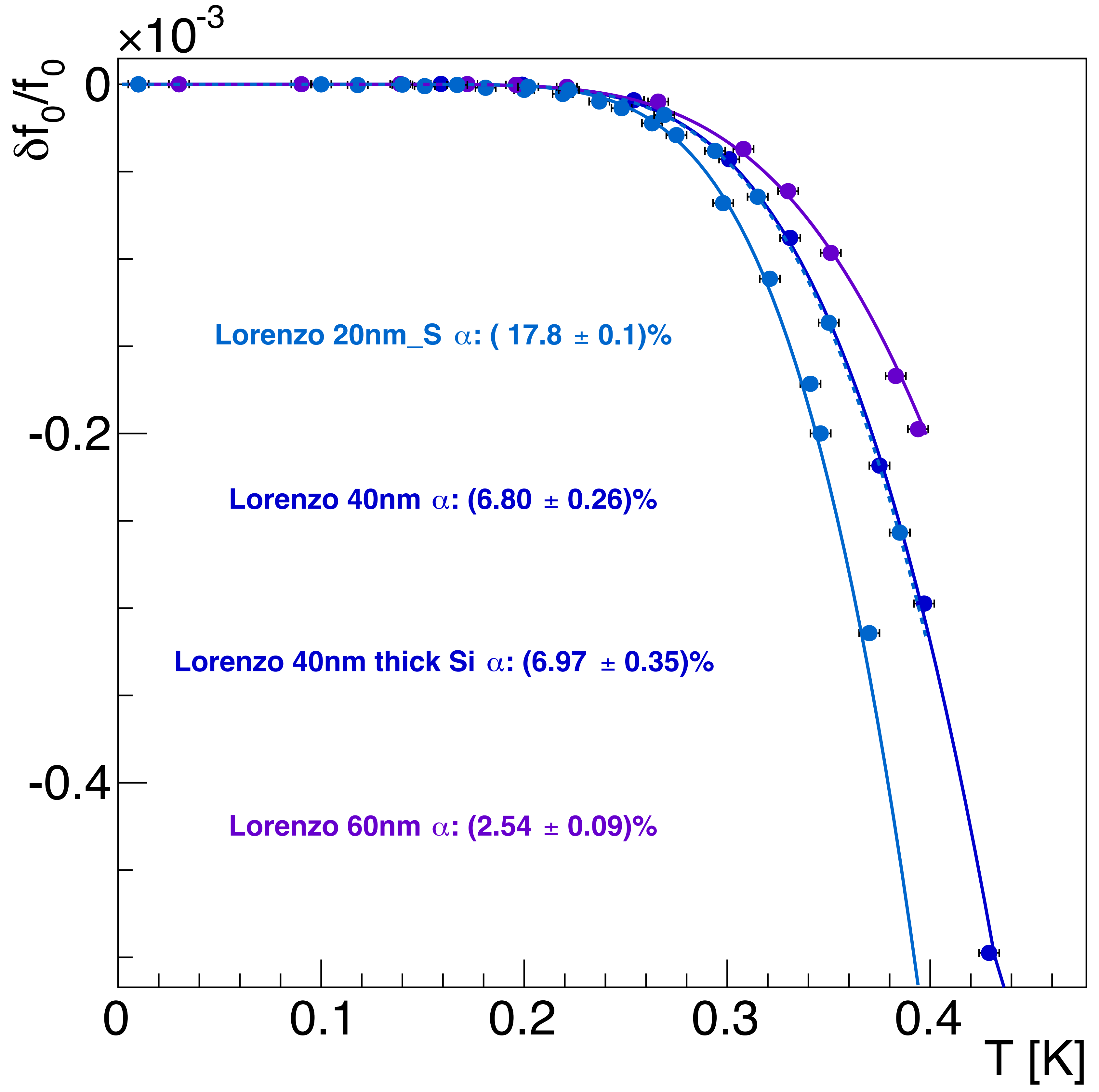
$$\frac{\delta f_r(T)}{f_r} = \frac{f_r(T) - f_r(0)}{f_r(0)} = -\frac{\alpha}{2} \frac{\sigma_2(T) - \sigma_2(0)}{\sigma_2(0)}$$

$$\frac{\sigma_2}{\sigma_n} = \frac{\pi \Delta(T)}{\hbar \omega} \left[1 - 2 e^{-\Delta(0)/k_B T} e^{-\hbar\omega/2k_B T} I_0(\hbar\omega / 2k_B T) \right]$$

Approximate form of mattis-bardeen

Gao's thesis, Doyle's thesis, many other works on superconducting resonators…

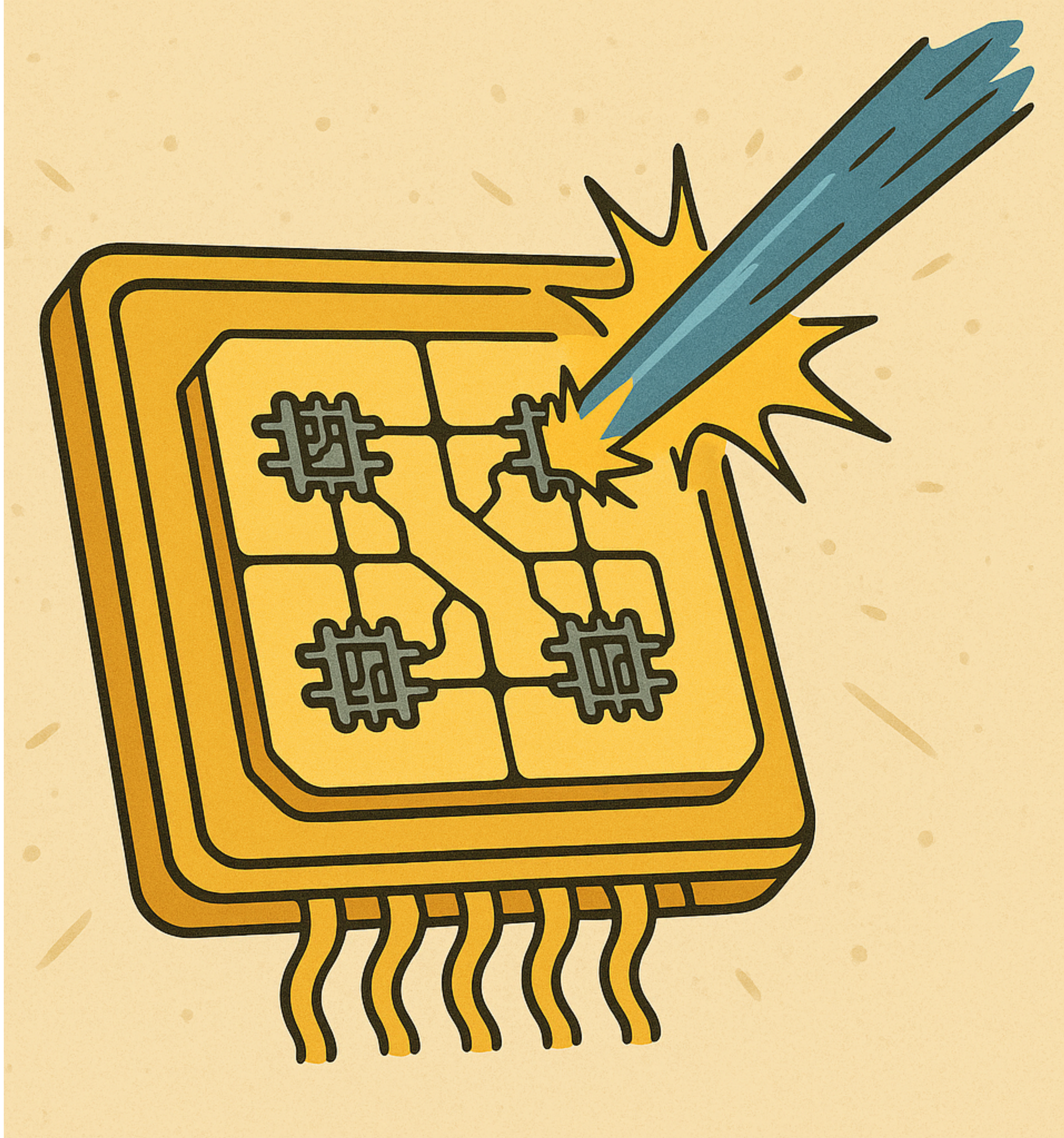
L. Cardani et al, 2017



Summary (of yesterday)

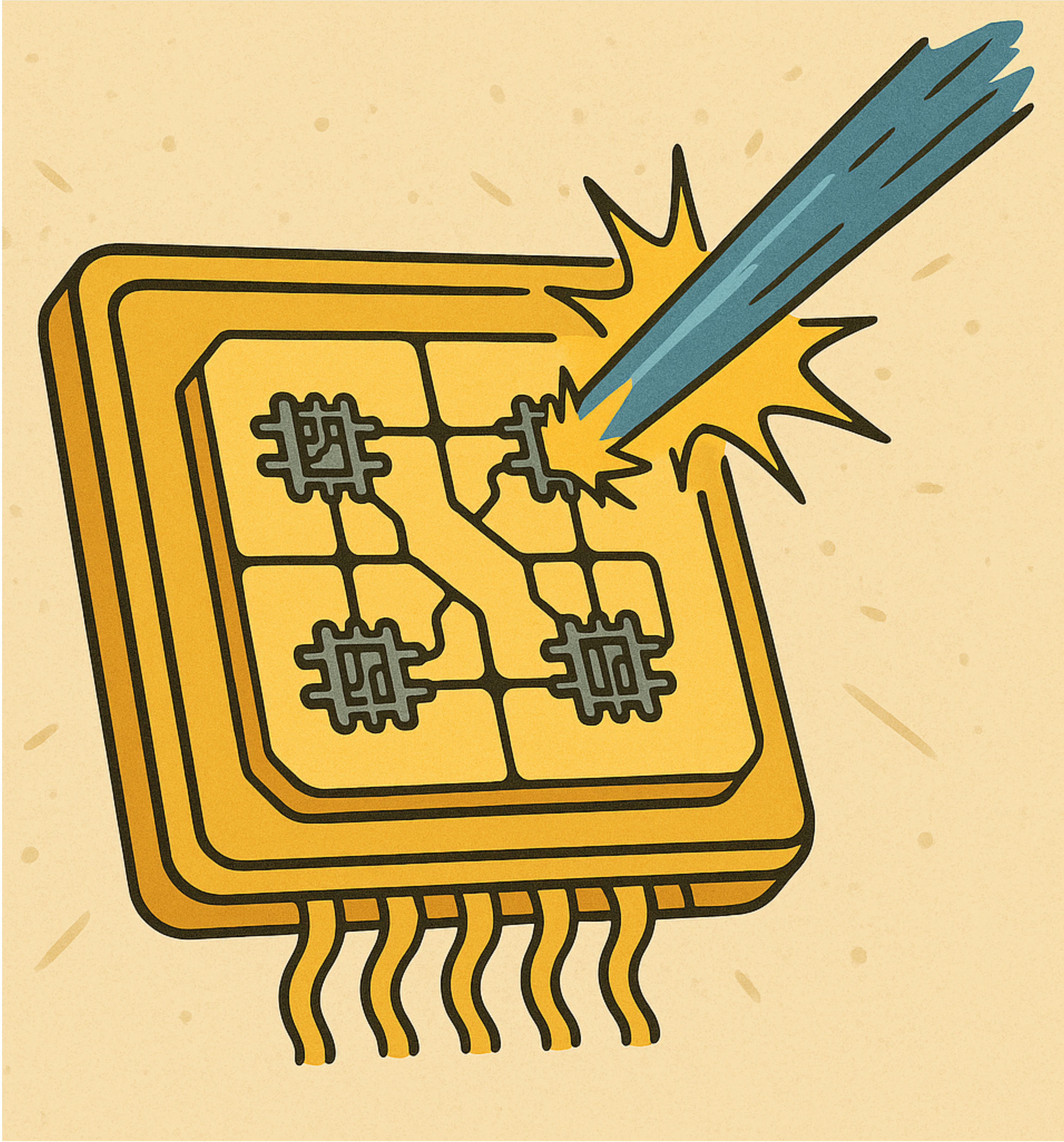
The qubit substrate is a target for radioactivity

- Production of e/h charges —> localised effect
- Phonon aftermath —> chip-wide effect
- Phonon absorption in superconductor
  - Puzzling timescale (ms? Tens of ms?)
  - Yet faster than typical T_1/T_2 readout protocols
- Phonon evacuation, QP recombination —>equilibrium



Outlook

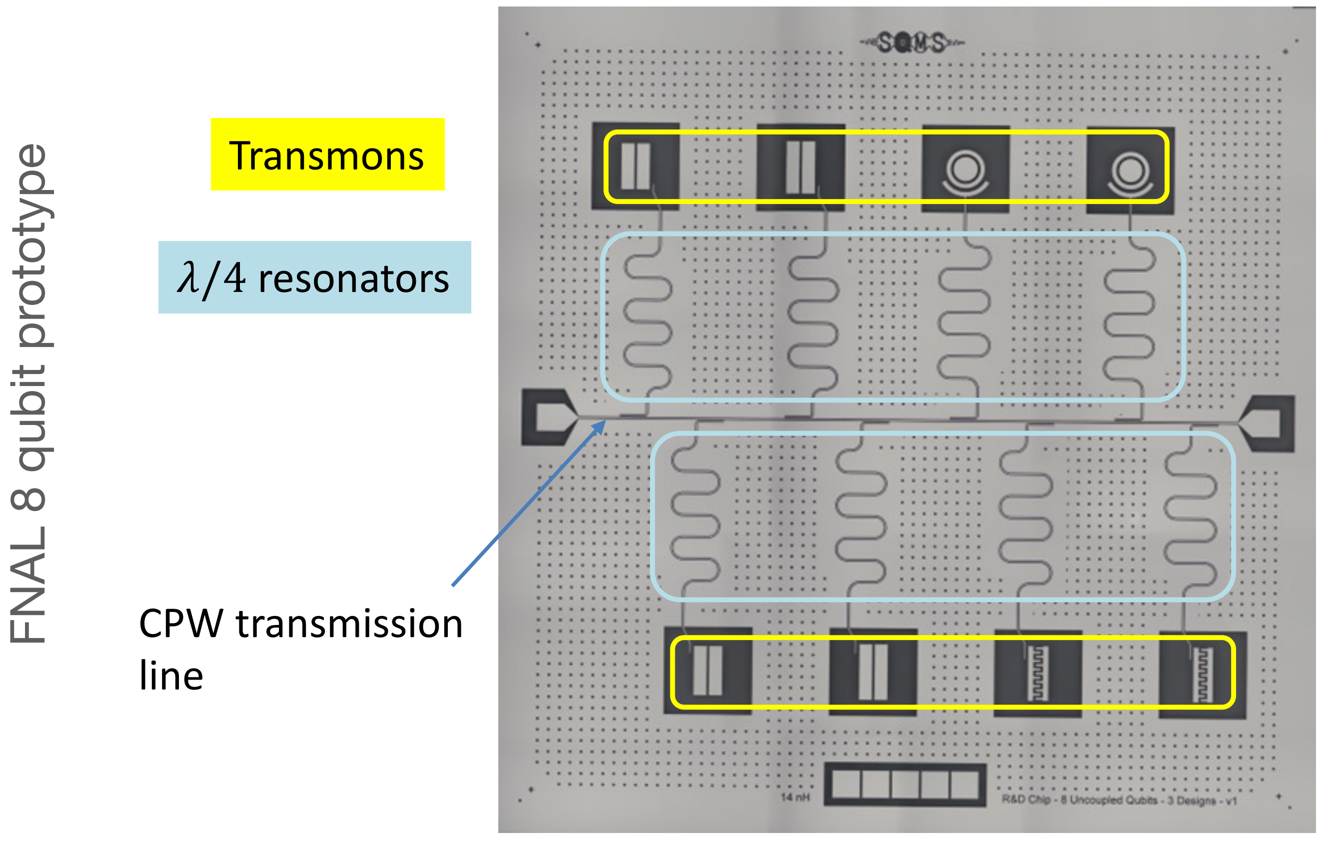
- Mitigation of Radioactivity
  - Where does it come from
  - Shielding
  - Results: microwave resonators
  - Results: fluxonium qubits
- Disentangling Radioactivity
- Perspectives for particle detection

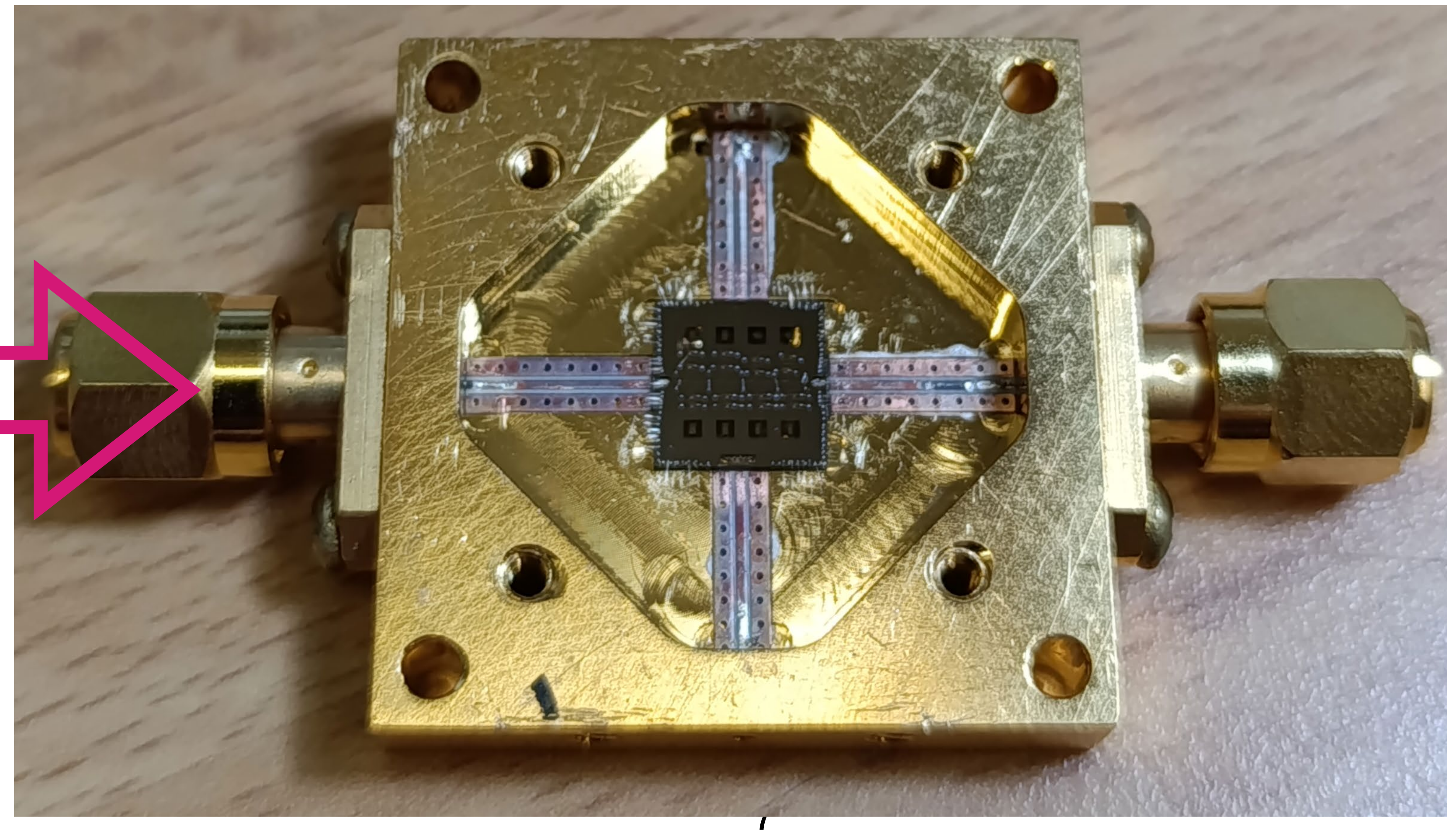


Where does Radioactivity Come From?

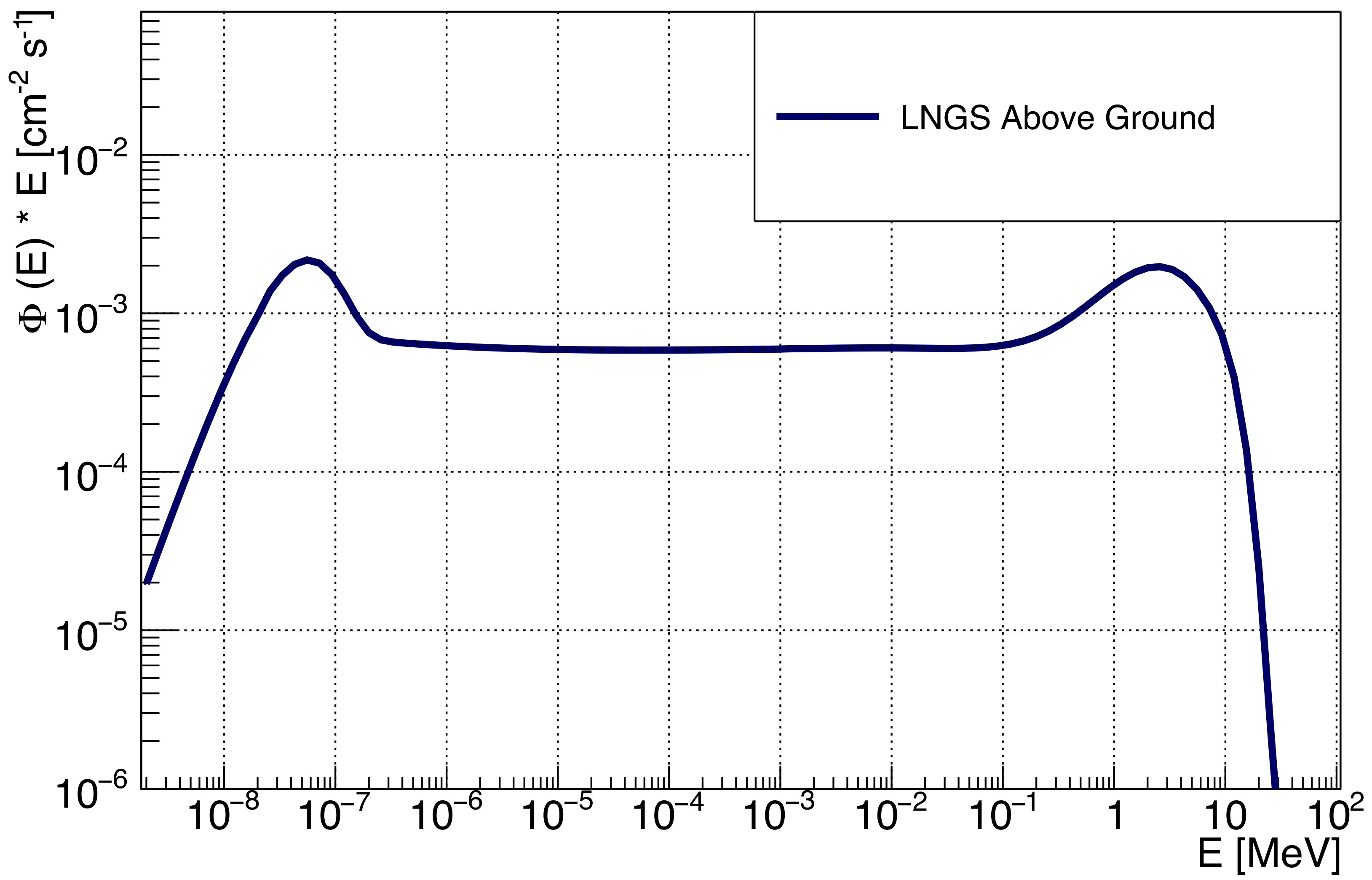
- Measurement of all possible sources of radioactivity, from environment to components

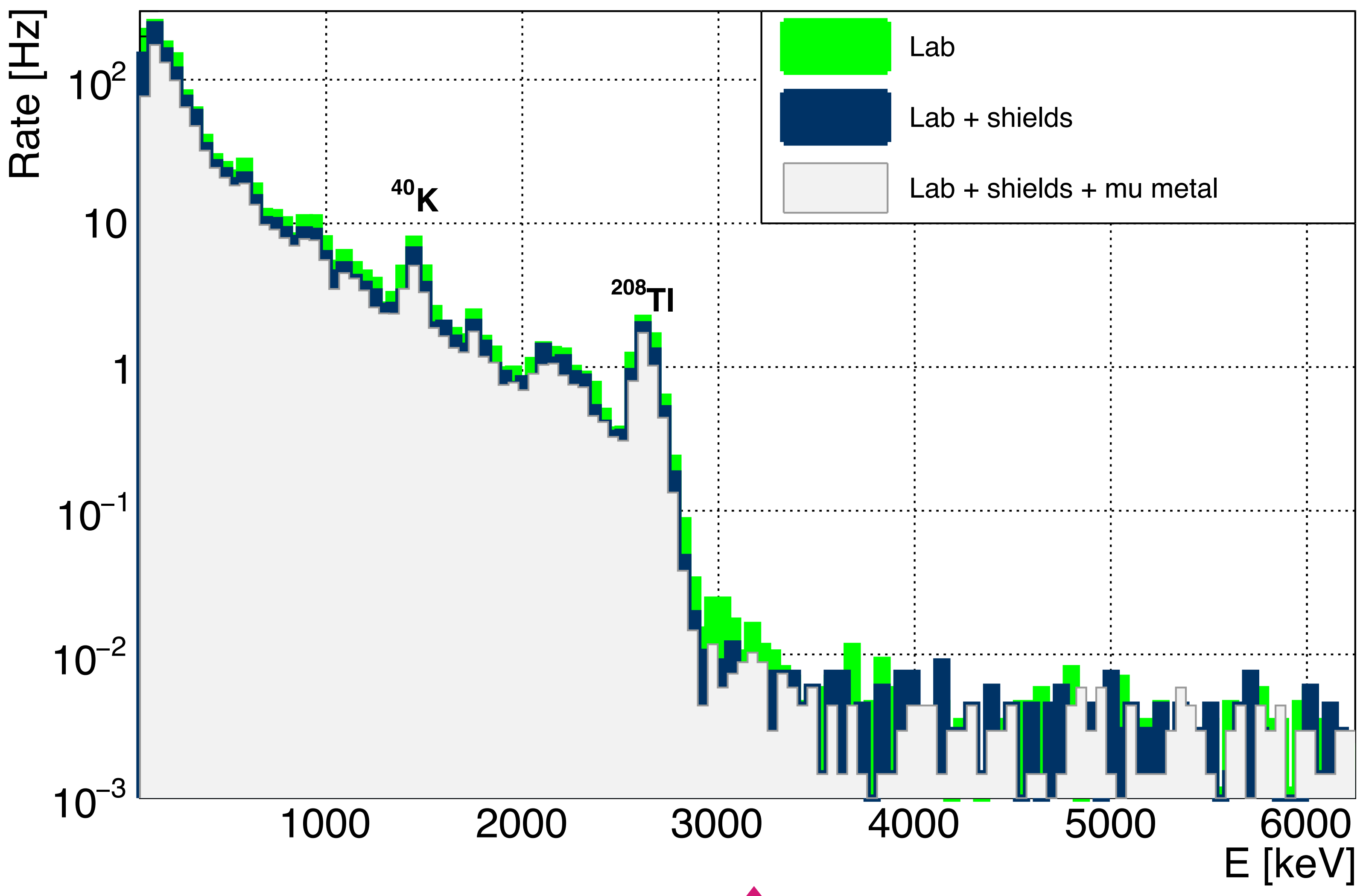
- Monte Carlo simulation of their interaction rate *in the substrate*

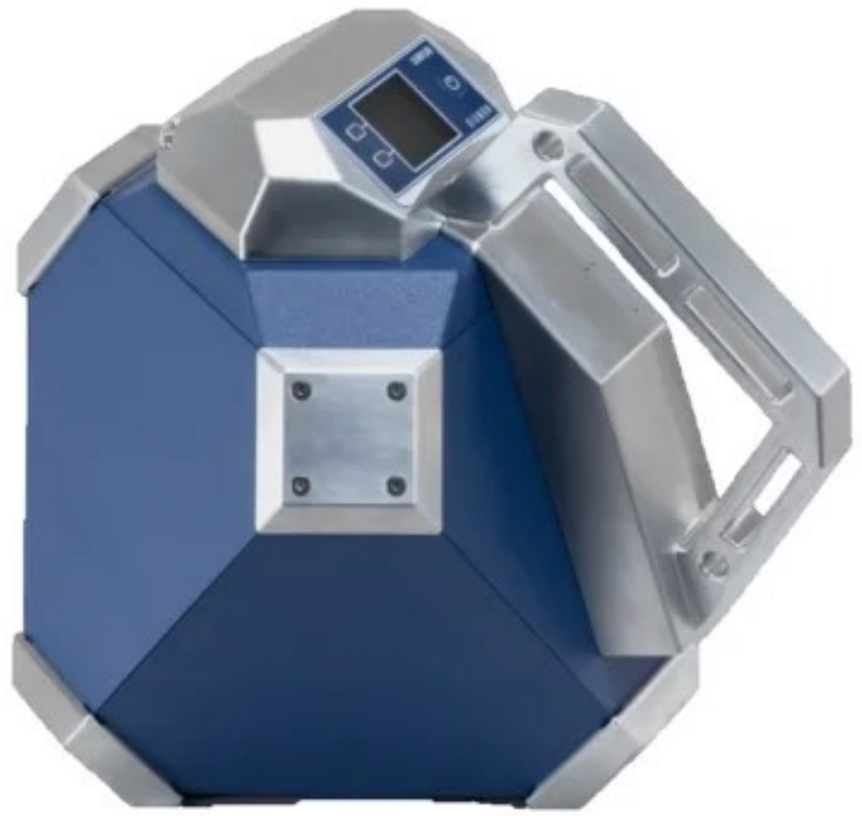




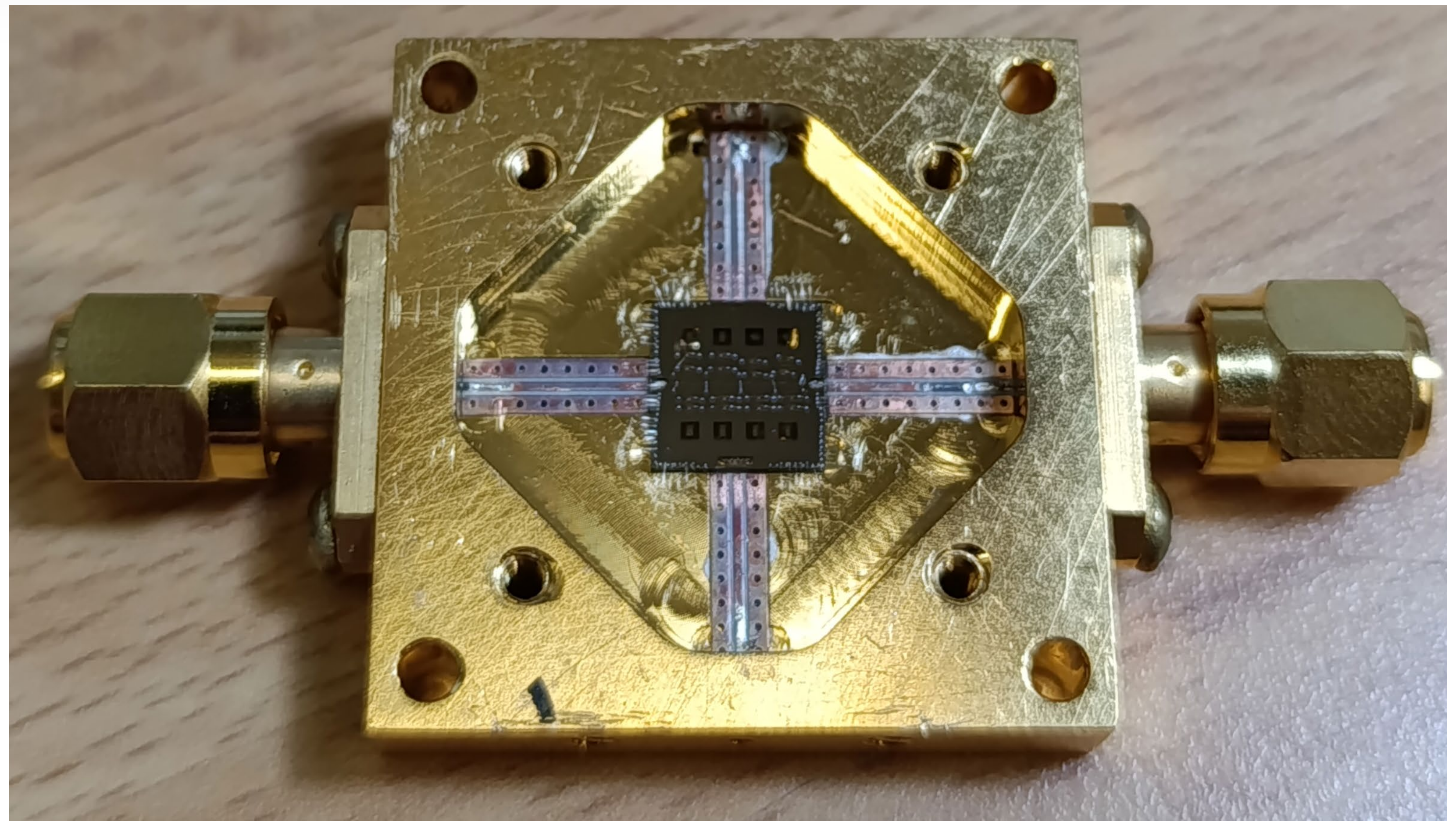
Environment

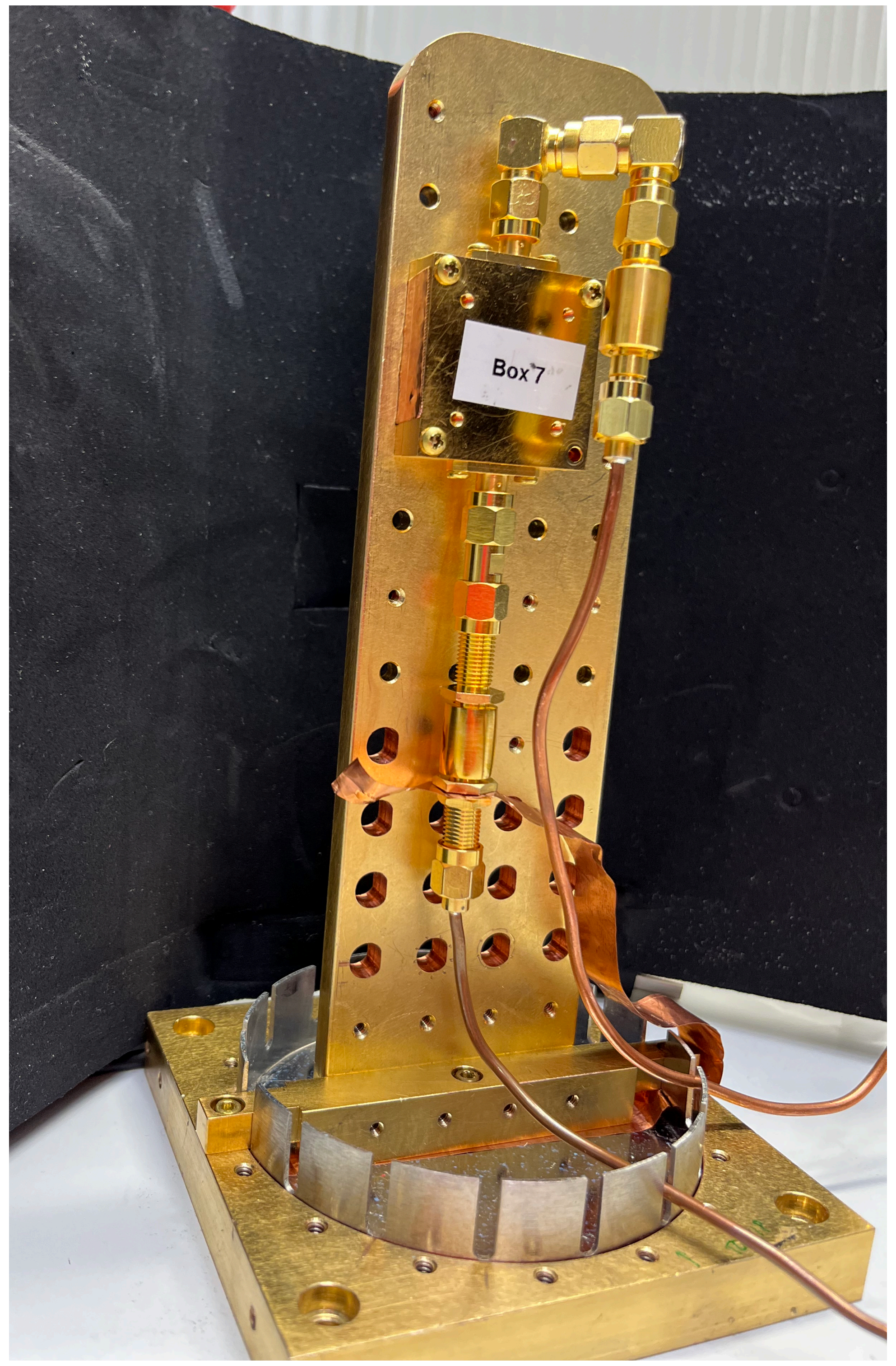


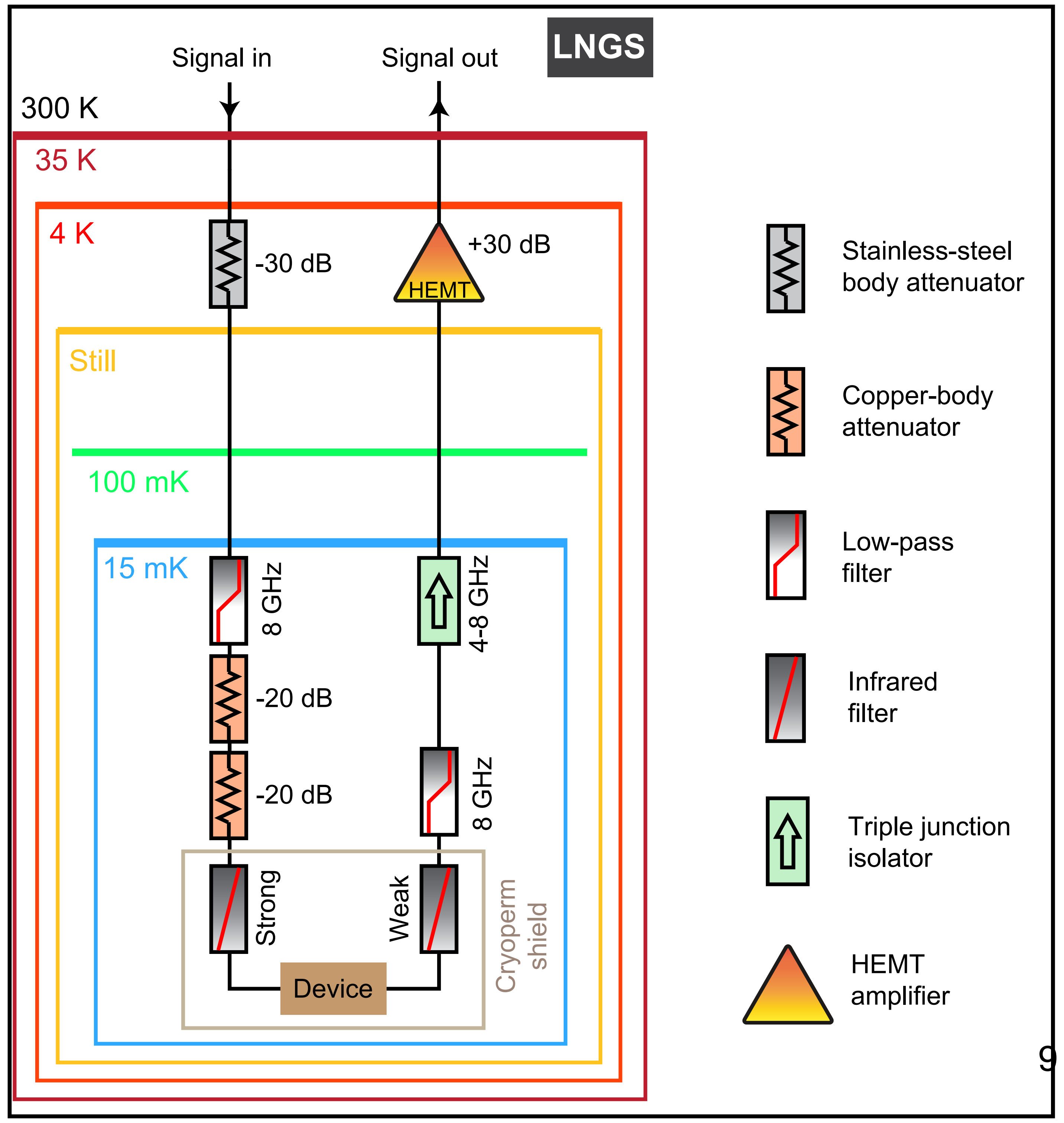




Close components







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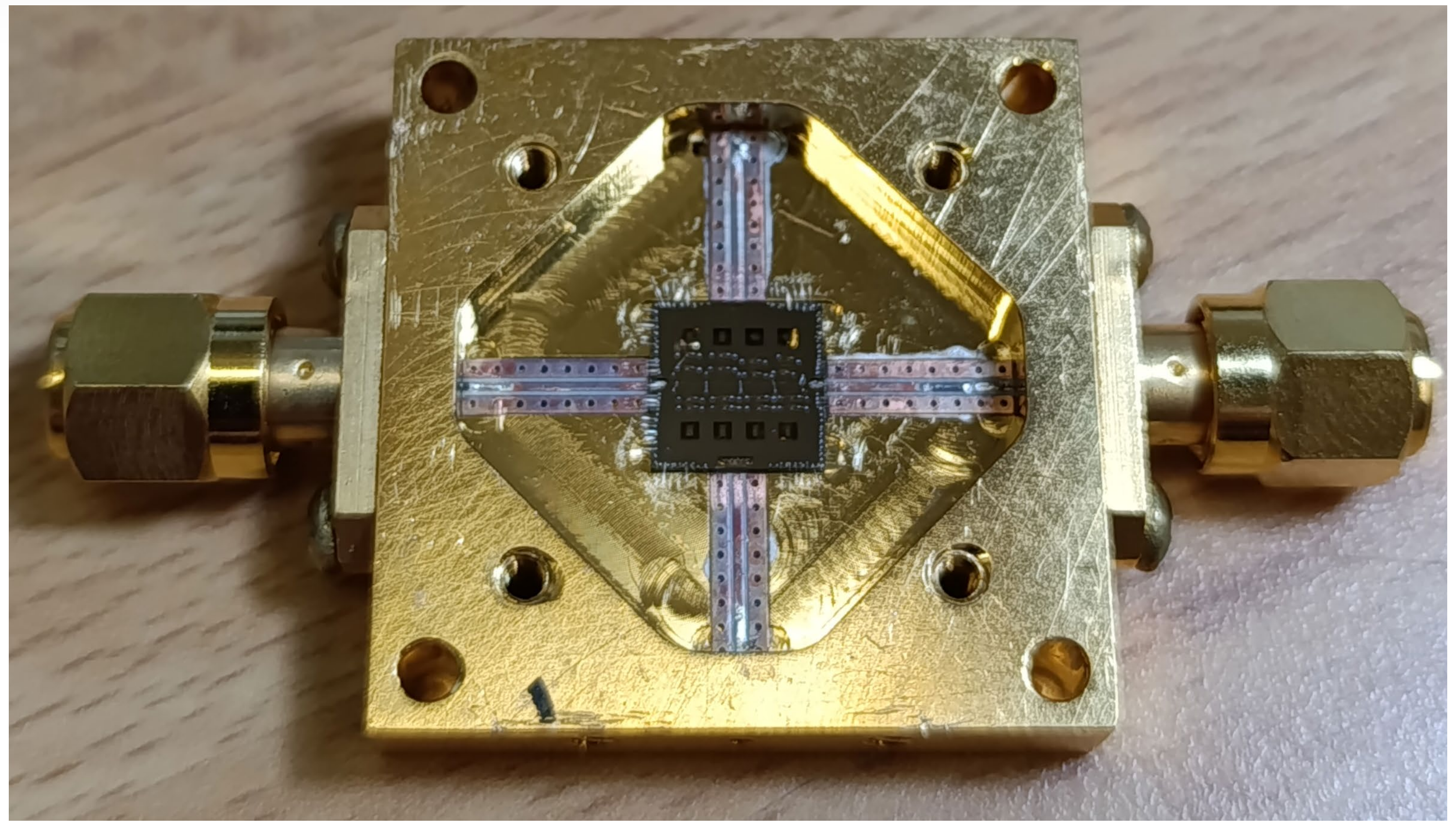
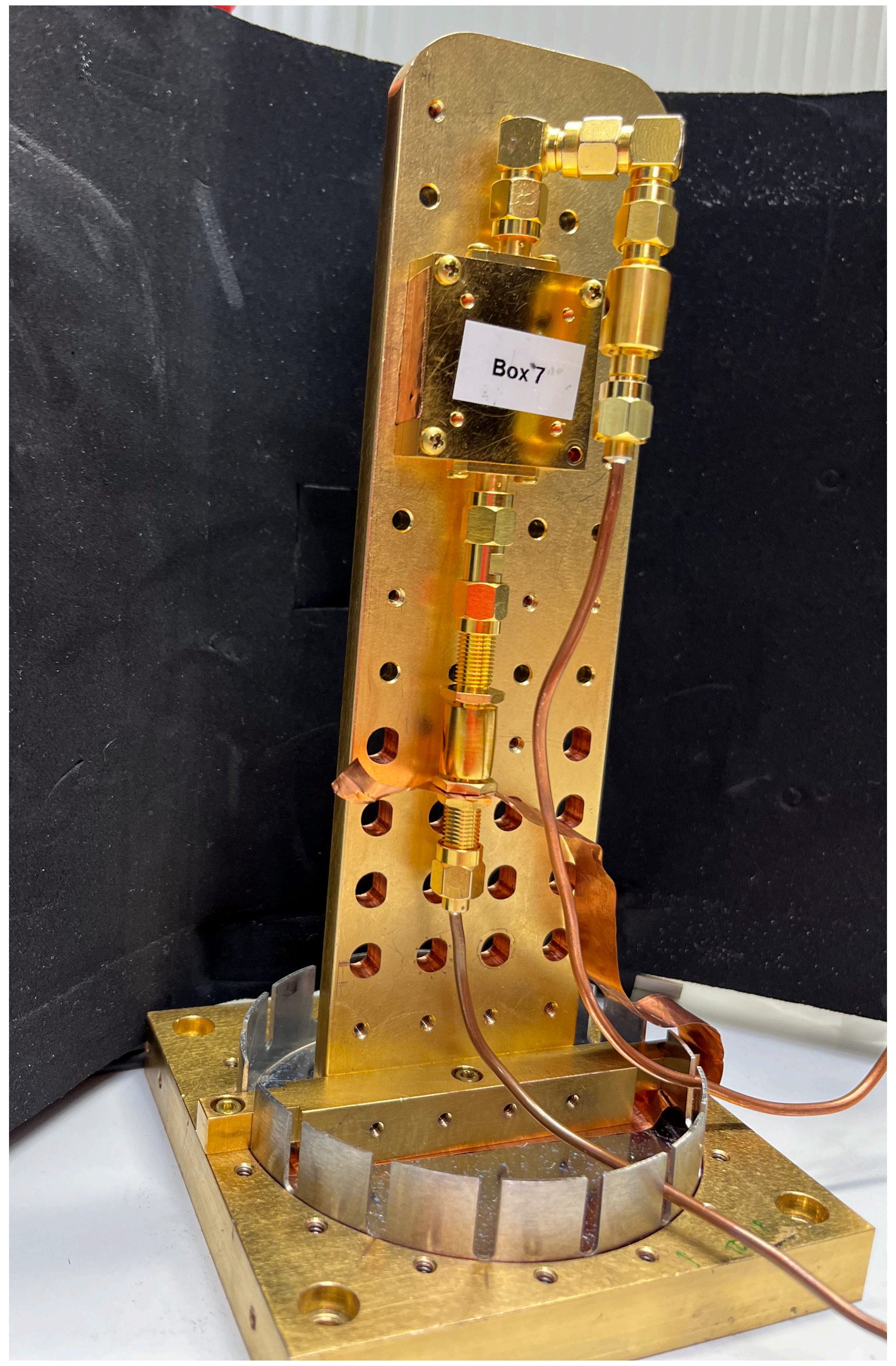
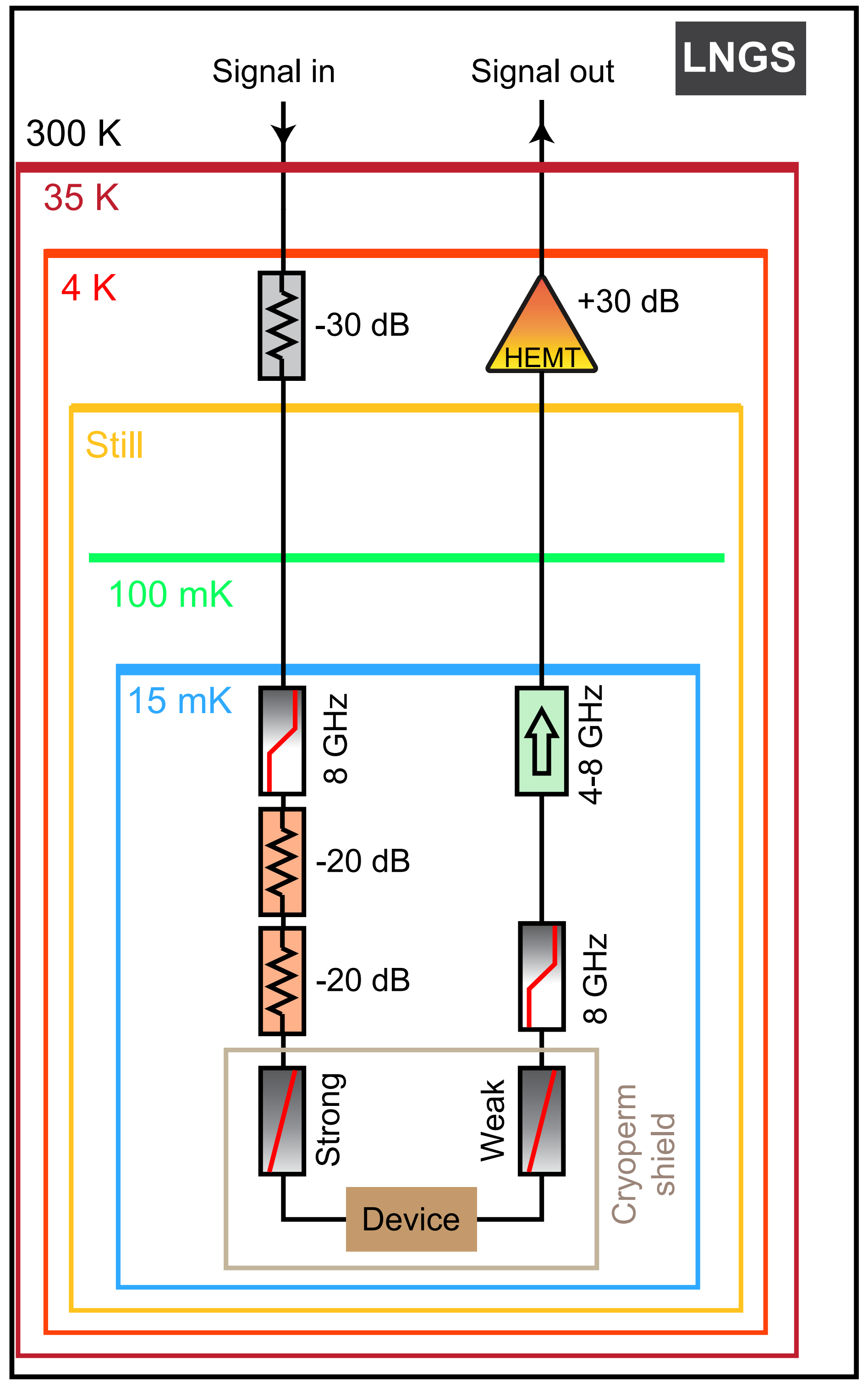


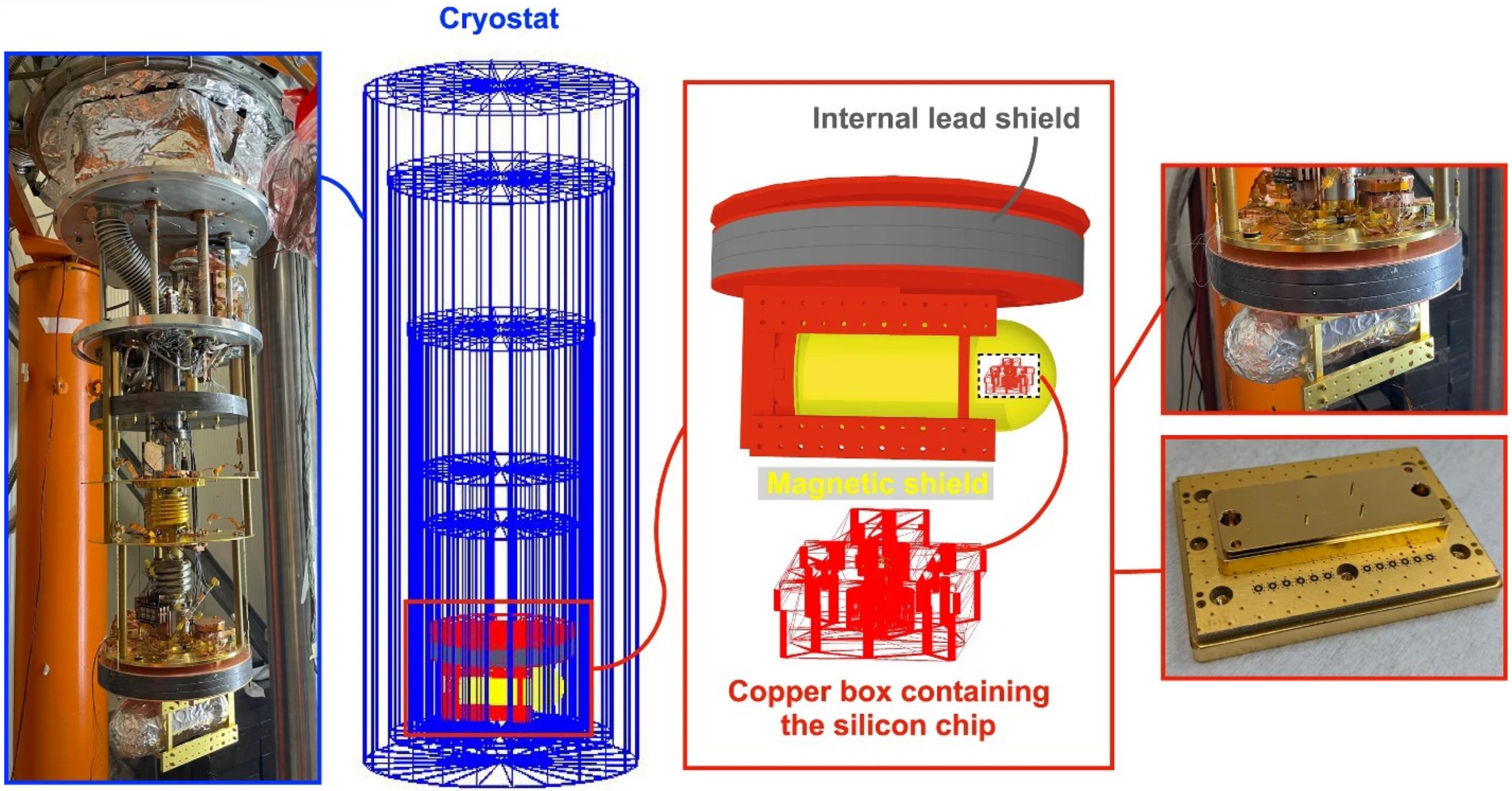




Component	^{232}Th [mBq/kg]	^{238}U [mBq/kg]	^{235}U [mBq/kg]	^{40}K [mBq/kg]	^{137}Cs [mBq/kg]
PCB	(18000 ± 1000)	(11500 ± 400)	(710 ± 110)	(12000 ± 1000)	< 30
PCB (2)	(5410 ± 330)	(4200 ± 200)	(230 ± 50)	(4200 ± 500)	< 40
Holder	< 1.5	< 1.2	< 4	< 9	< 0.6
Magnetic Shield	< 8.4	< 8.3	< 8.4	< 35	< 2.7
SMA	(46 ± 13)	(42 ± 10)	(70 ± 30)	(240 ± 90)	< 10
Cu coax cables	(54 ± 12)	(44 ± 11)	(34 ± 17)	(740 ± 130)	< 12
Cryogenic switch	(1880 ± 100)	(1340 ± 60)	(130 ± 30)	(2200 ± 300)	< 11.2
Circulator	< 310	< 330	< 410	< 2000	< 60
Dual-junct. circulator	< 250	< 380	< 380	< 2600	< 60
Triple-junct. isolator	< 190	< 240	< 220	< 2000	< 50
Attenuators	< 52	(200 ± 20)	< 47	< 140	< 13
Low Pass Filters	(23 ± 4)	< 9.1	(60 ± 10)	< 100	< 1.9
NbTi cables	< 750	< 1000	< 380	< 7000	< 230
Cryogenic amplifier	< 890	< 1000	< 850	< 10000	< 210
Cu-Be cables	(240 ± 40)	< 78	(350 ± 90)	< 500	< 20
Stycast glue	(53 ± 4)	(9400 ± 900)	(350 ± 30)	(290 ± 40)	< 2.2
Cryogenic Grease	< 10	< 11	< 4.5	< 87	< 5

High Purity Germanium Spectroscopy

Where does Radioactivity Come From?



L. Cardani et al,
Eur. Phys. Journ C 83, n.o 94 (2023)

Where does Radioactivity Come From?

INFN
Istituto Nazionale di Fisica Nucleare

Source	Interactions in chip
Lab γ rays	1 event / 32 seconds ~ 2 events / minute
Muons	1 / 125 seconds ~ 1 event / 2 minutes
Materials	1 / 370 seconds ~1 event / 6 minutes
Neutrons	1 / (2 hours)
Total	1 event / 24 seconds

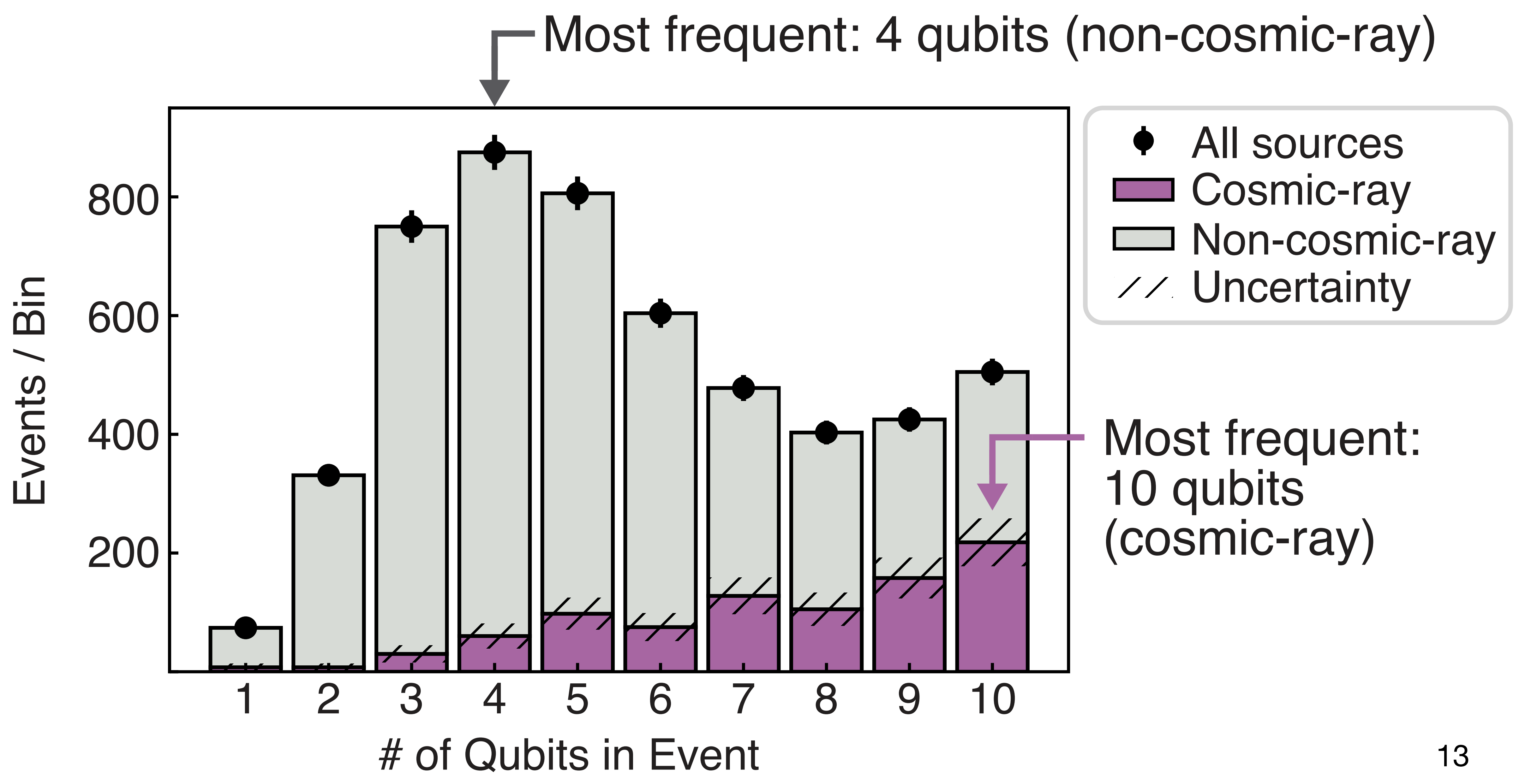
← 19% of the total number of events (Muons)

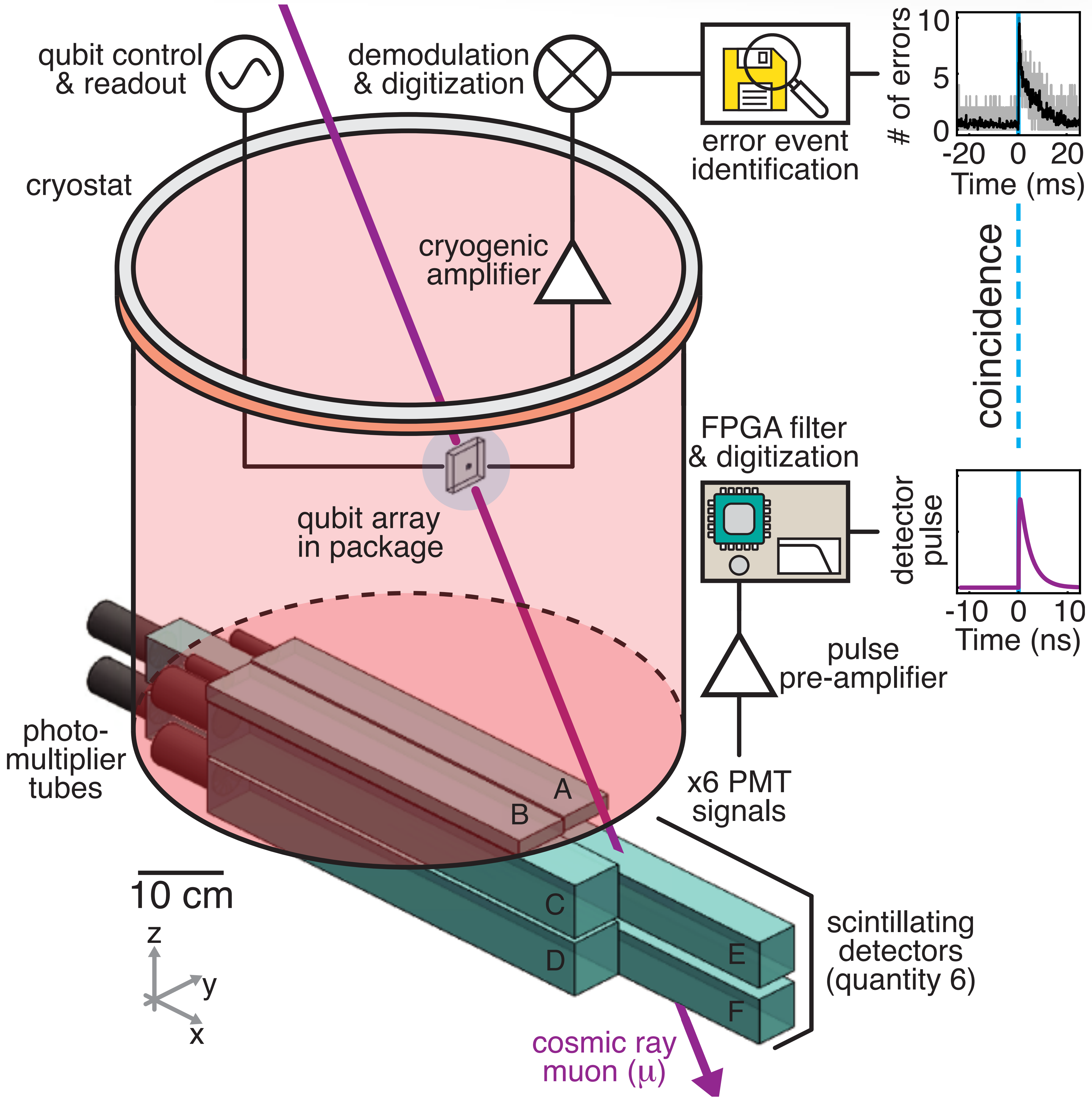
← Almost entirely dominated by the PCB (Materials)

Fowler 2024 repeated these simulations on their device and made a validation against data with a resonator

Recent result: validation (US group)

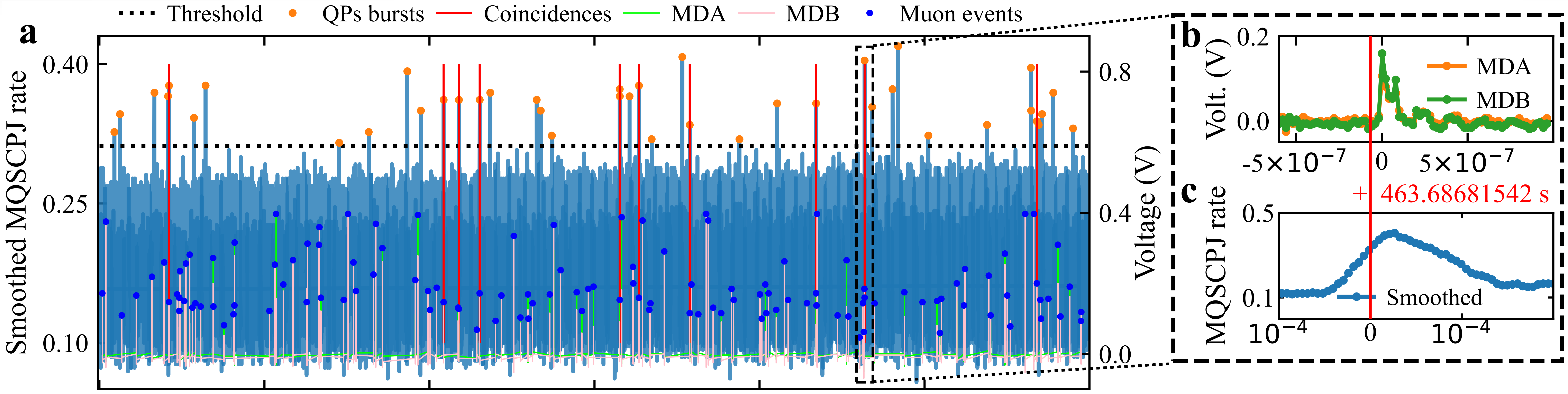
- Correlated errors: 1 / (100 sec)
- Only 17% of correlated errors come from cosmic rays
- Cosmic rays affect a large number of qubits





P. M. Harrington et al. 2024

Recent result: validation (China group)



* I changed unit compared to the original paper for consistency in the presentation

- Correlated errors: 1 /(12.3 sec)
- With minimal lead shield: 1/ (16.7 sec)
- Cosmic rays account for (only) 19% of the events
- *Evacuation time of 20-40 µs*, 2 orders of magnitude faster w.r.t. Google.
  - Hypothesis: tantalum as ground plane is effective.

Xue-Gang Li et al. 2024

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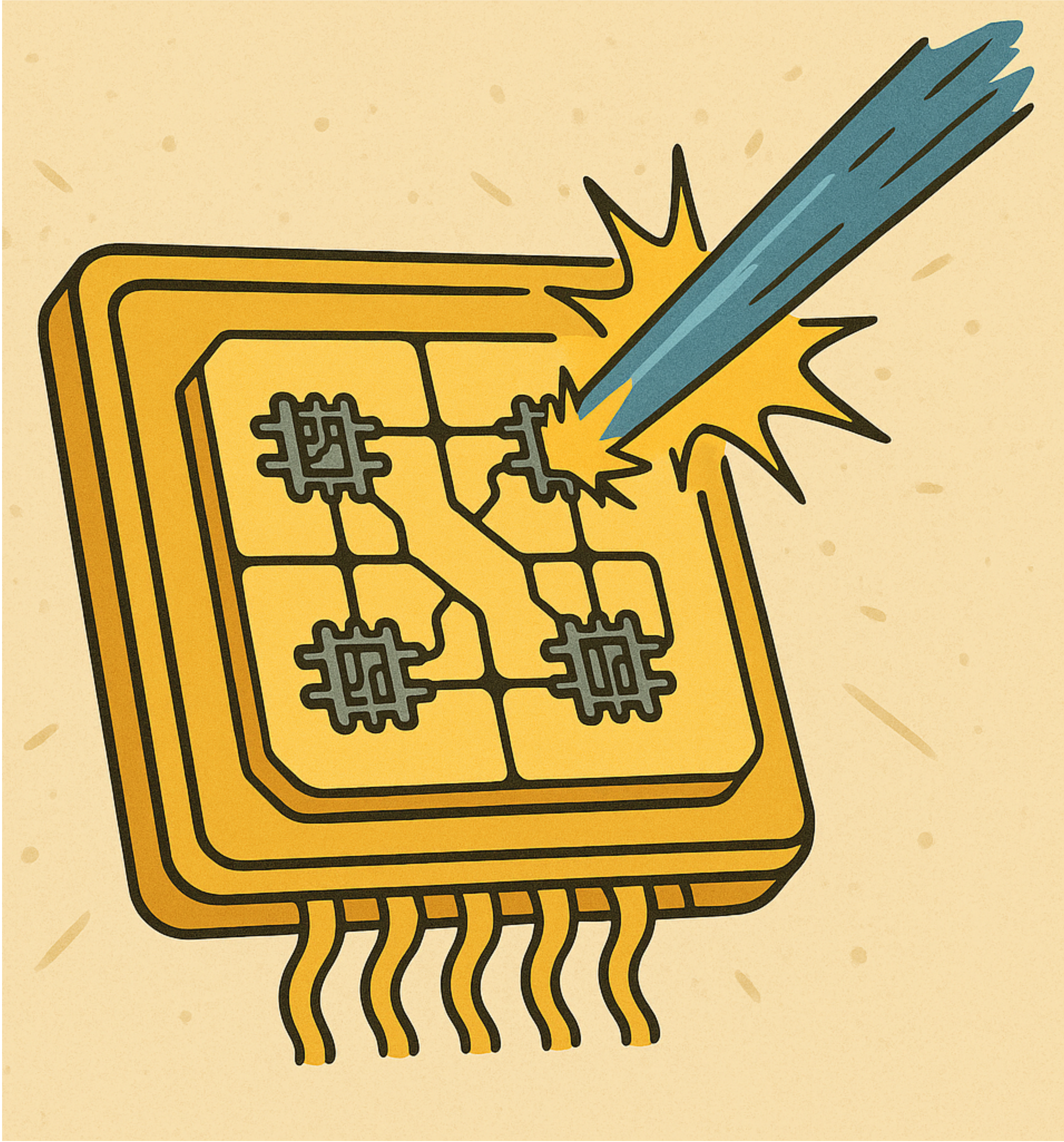

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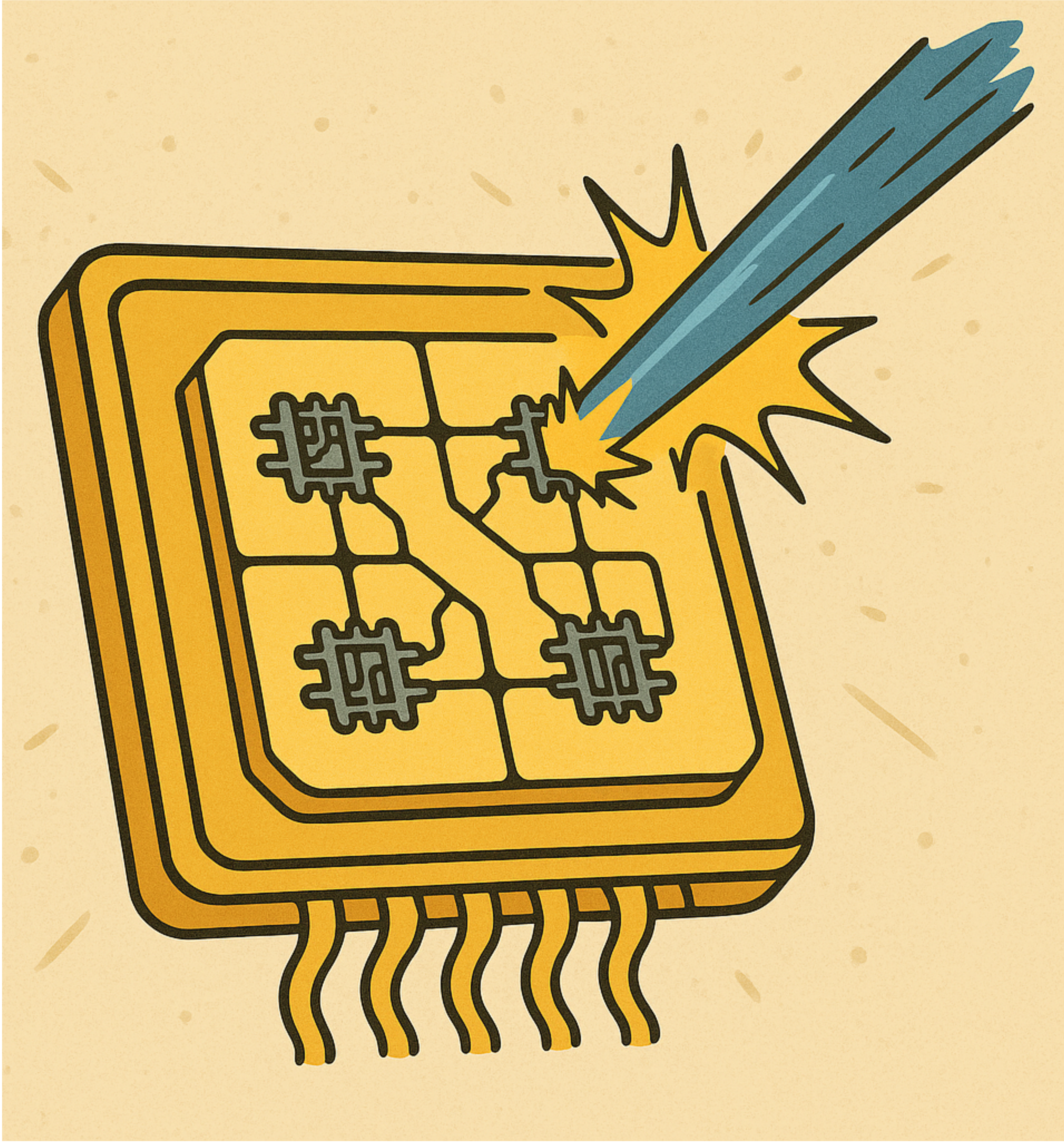

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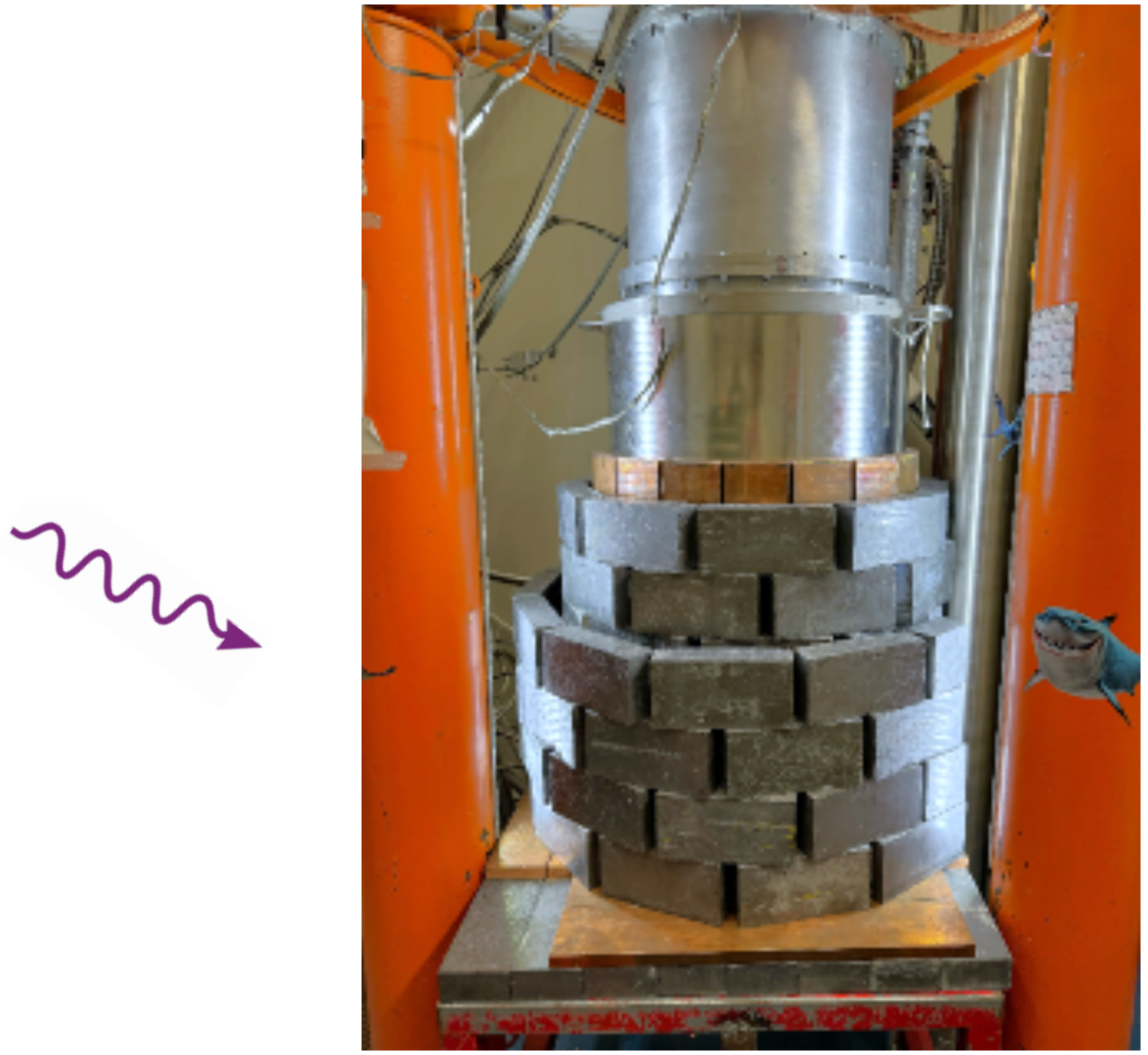

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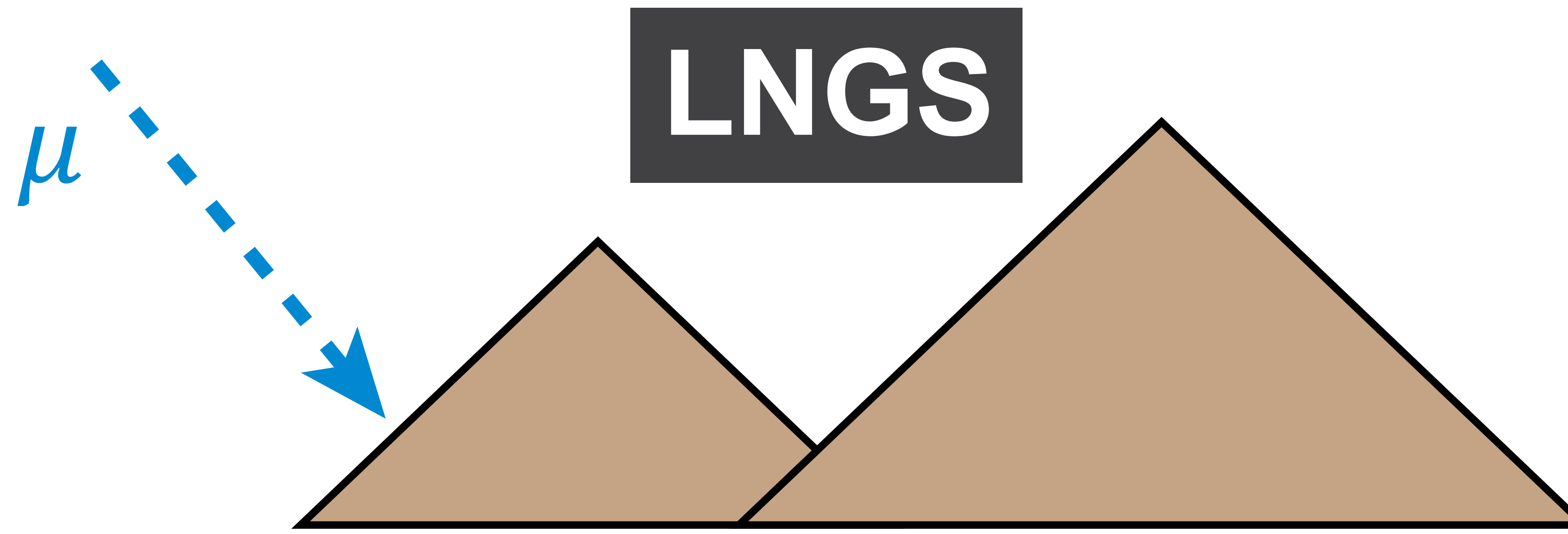

Gran Sasso: rock overburden 1.4 km

Where does Radioactivity Come From?

Istituto Nazionale di Fisica Nucleare

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Neutrons	1 / (2 hours)

Alternatives to PCBs can come from field of particle detectors

Summary: underground shielded lab

Source	Interactions in chip	In Gran Sasso
Lab γ rays	1 event / 32 seconds	1 event / 700 seconds
Muons	1 / 125 seconds	~~1 / 12[illegible] seconds~~
Materials	1 / 370 seconds	1 / 370 seconds
Neutrons	1 / (2 hours)	~~1 / [illegible] hours)~~
Total	1 event / 24 seconds	1 event / 250 seconds

Factor 10 improvement!

See also study done in another facility by B. Loer et al (2024)

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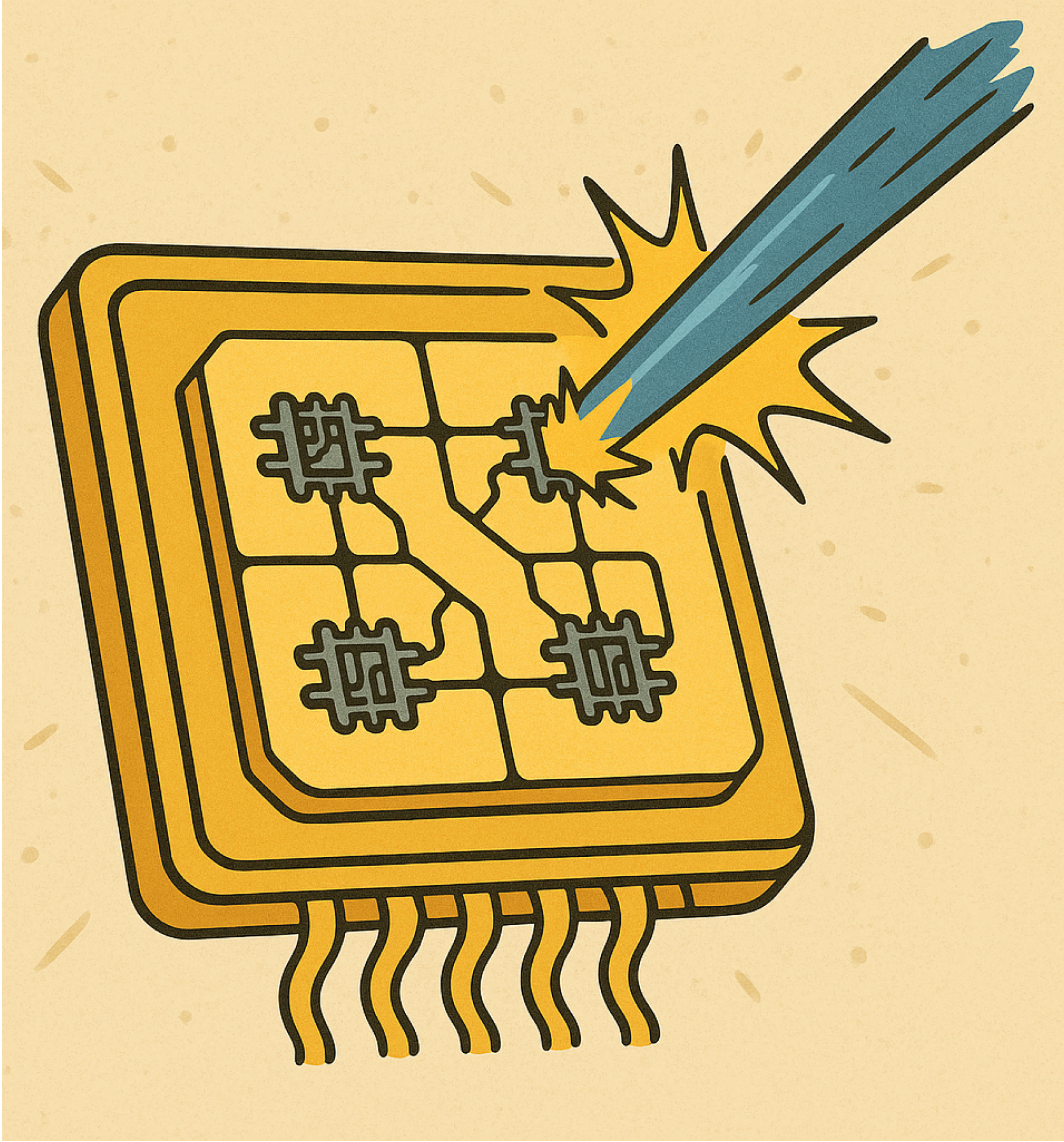
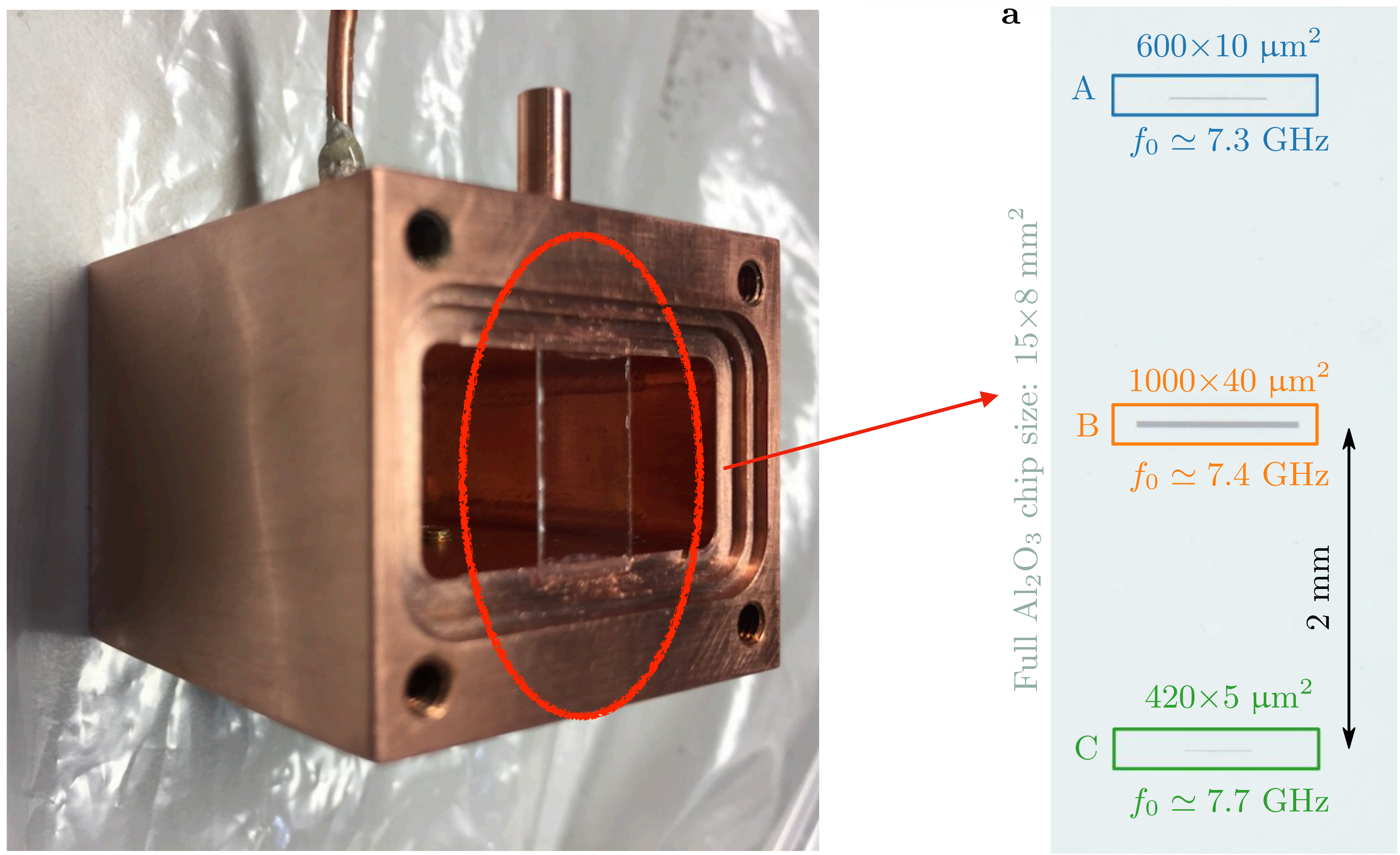


Historical background: INFN/KIT measurements

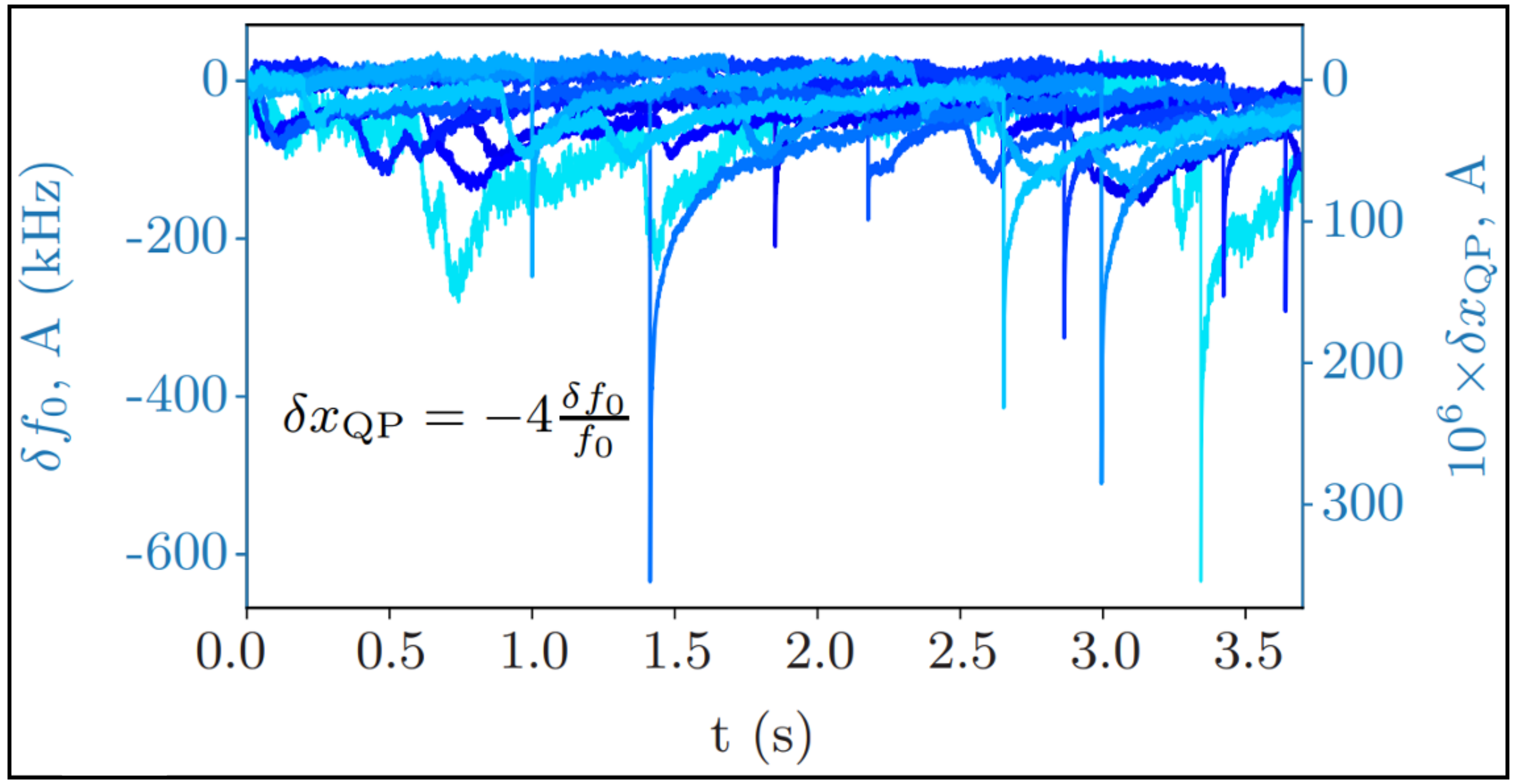
- DEMETRA project:
  - Chip with 3 superconducting circuits
  - Counted "QP bursts"
  - In contrast to "T1" measurements, enables *real-time* detection of the effects

Cardani et al, Nat. Comm. 2021

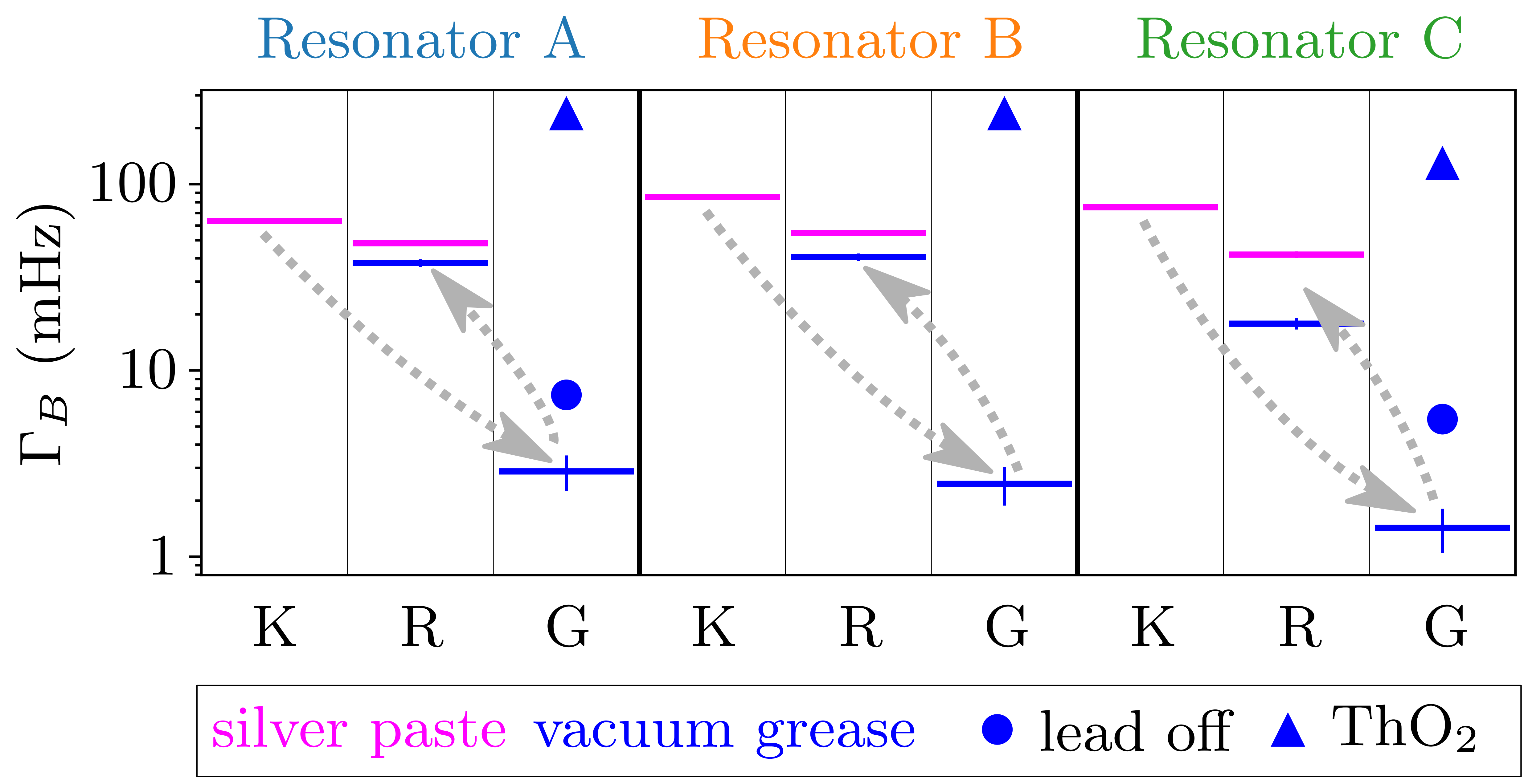


First observation: MIT/PNLL predicted a background from QP bursts of $x_{QP} \sim 7 \times 10^{-9}$

We measured bursts up to $x_{QP} \sim 3 \times 10^{-4}$



Results: radioactivity



The rate of QP bursts (radioactive impacts) changes according to the predictions

Removal of lead shield further confirmed the predictions

Deployment of source to increase the rate to values higher than environmental radioactivity

L. Cardani et al, Nature Comm. 2021

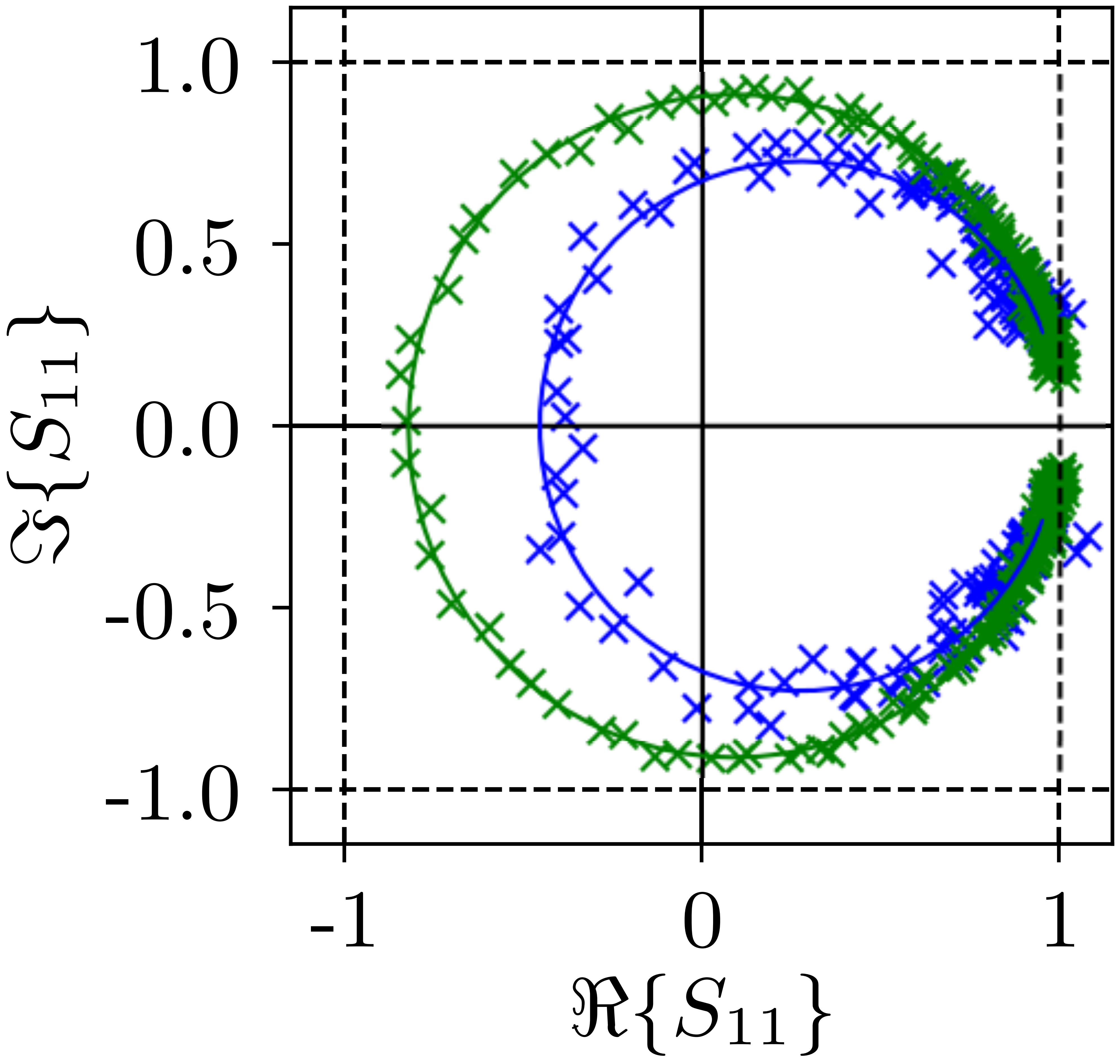
Results: global performance?

What is the effect on the device?

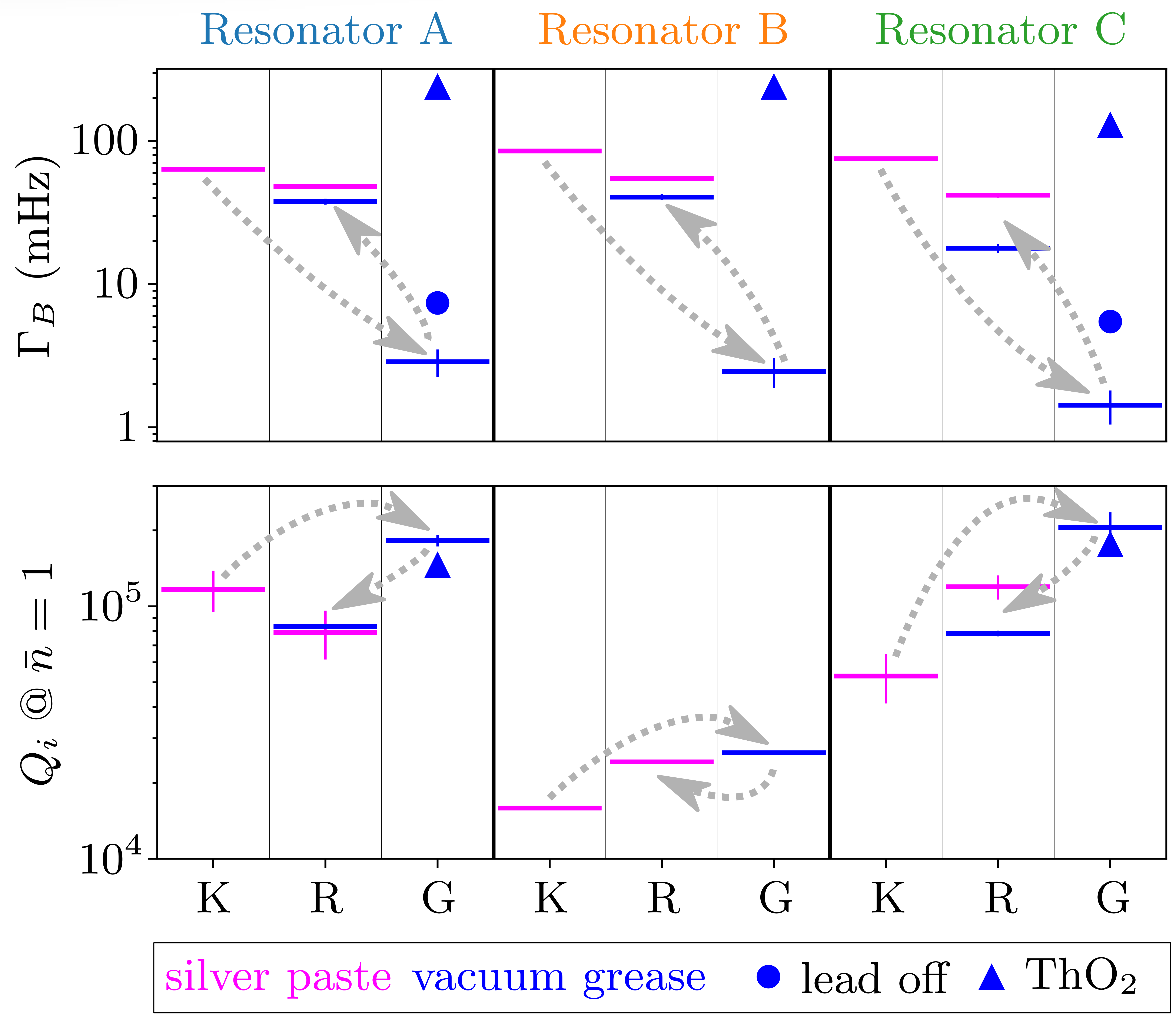
In this case, we are operating them as resonators

—> no T1, T2, ...

We did monitor the internal quality factor: the higher the quality factor, the longer the coherence



Results: global performance?



Radioactivity diminished by ~ 30/50

Quality factor improved for all the three resonators!

BUT

It improved by 2-3 compared to KIT

Same environment: we deployed the source, it diminished by only 20%

Why?

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- When radioactivity changed by x100 with all other experimental conditions fixed, quality factor worsen **but** only by ~20%

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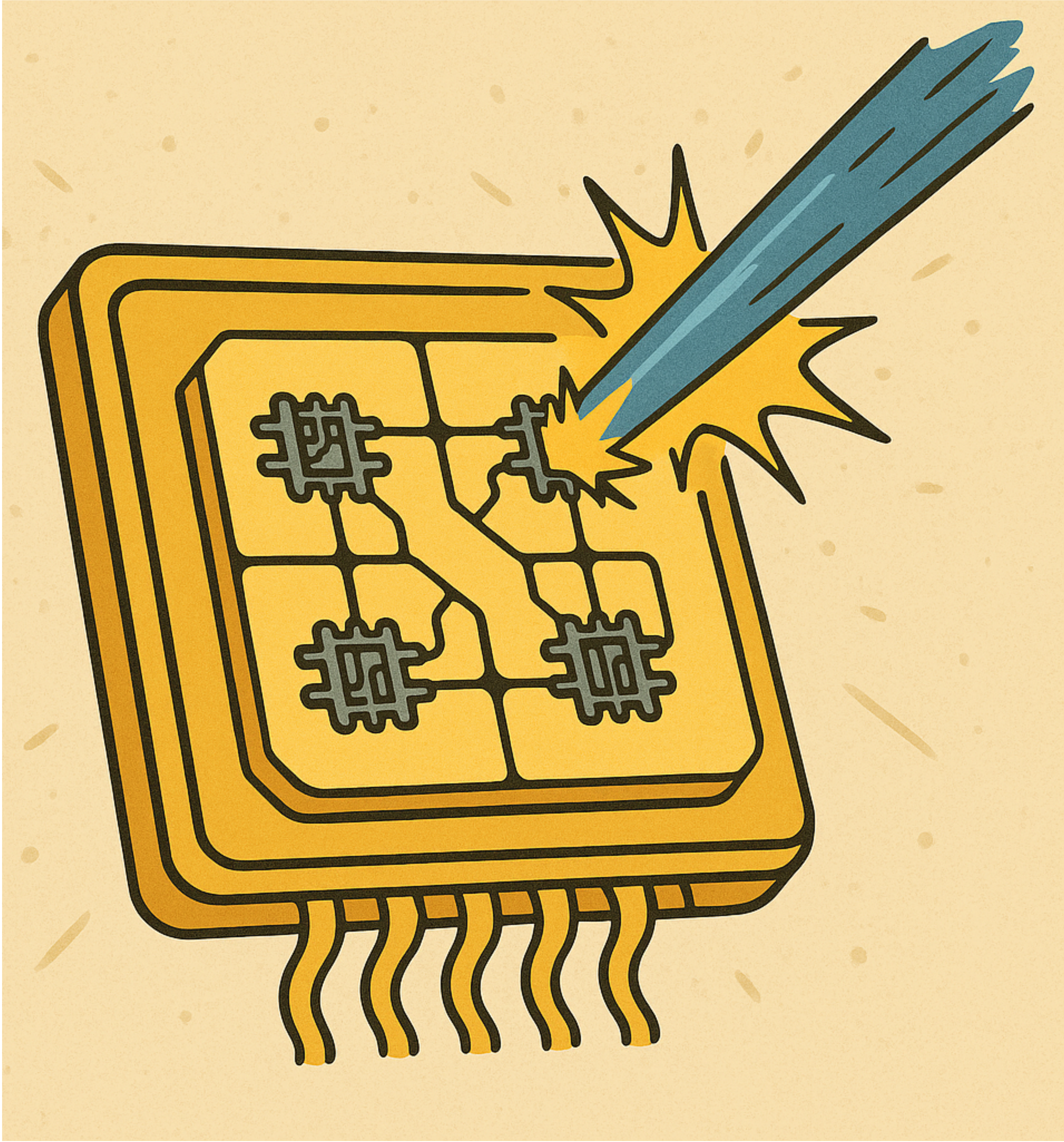


Fluxonium qubit

What changes from TRANSMON

Two conjugate variables:

- *Φ*: The phase difference across the two sides of JJ
- *n*: The number of Cooper pairs transferred across JJ

$$H = 4E_C(\hat{n} - n_g)^2 - E_J \cos(\hat{\phi})$$

$$E_C = \frac{e^2}{2C} \qquad E_J = \frac{\hbar I_c}{2e}$$

$E_J >> E_C$

- The phase difference is well defined
- Small fluctuations in the charge are irrelevant

Fluxonium qubit

FLUXONIUM

Evolution of transmon (+ large inductance)

We add another energy scale: the inductive energy E_L

($E_J > E_C$) —> the phase is still well defined but:

($E_J >> E_L$) —> the phase can explore more potential minima

How do I create these potential structures?

I apply a B_{ext} —> induce a ϕ_{ext} —> change the potential levels

$$H = 4E_C\hat{n}^2 + \frac{1}{2}E_L(\hat{\phi} - \phi_{\text{ext}})^2 - E_J\cos(\hat{\phi})$$

$$E_C = \frac{e^2}{2C}$$

$$E_J = \frac{\hbar I_c}{2e}$$

$$E_L = \frac{(\Phi_0/2\pi)^2}{2L}$$

$$\Phi_0 = \frac{h}{2e}$$

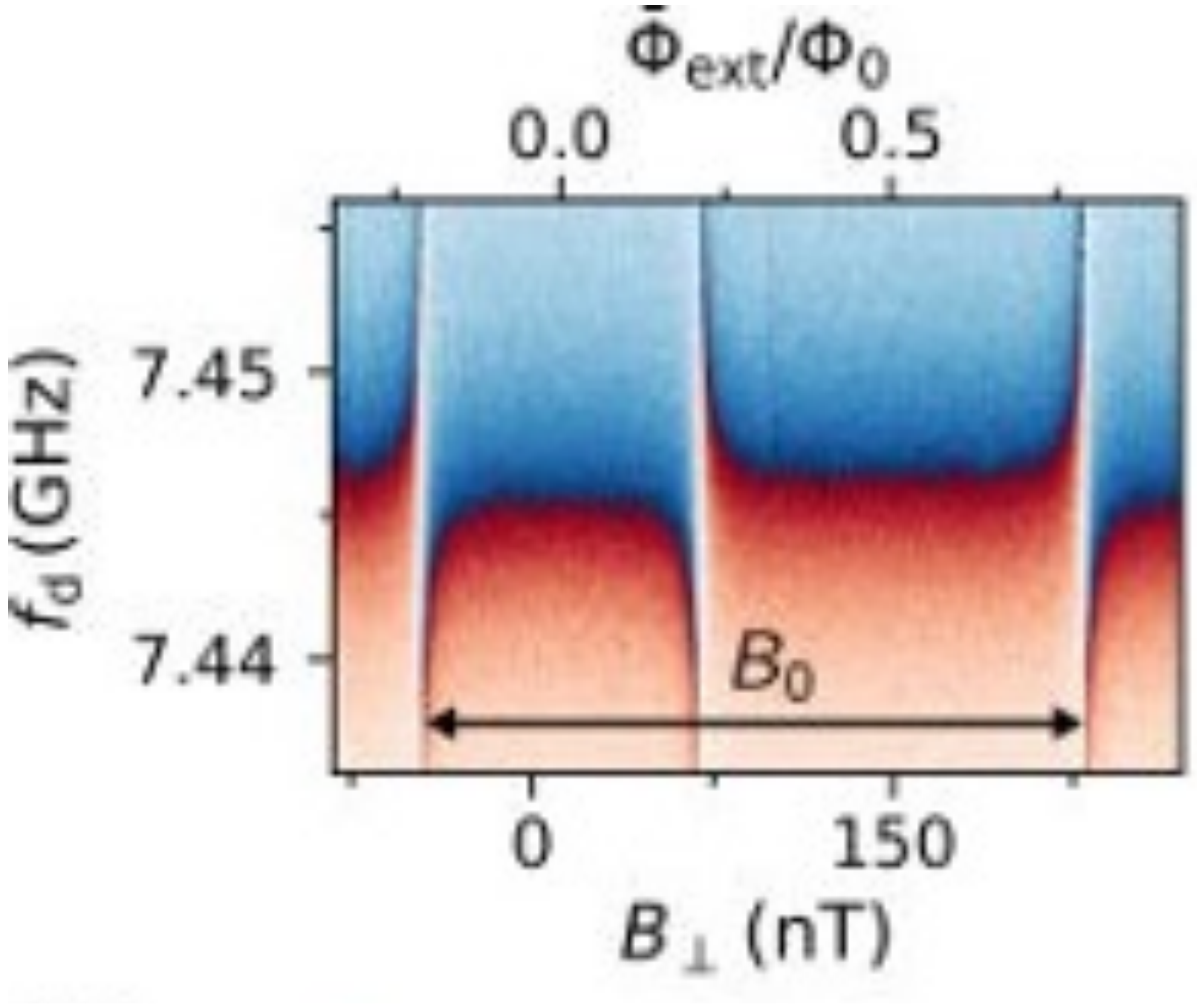
Fluxonium qubit: advantages

- In transmon, states |0> and |1> are in the same potential well
  - wavefunction highly localised
  - Couples strongly to any nearby defect (TLS)
  - fluxonium: delocalise quantum states in multiple wells and this spread wavefunction
- Higher non-linearity: less leakage from (too) excited states
- For a particular choice of ϕ_{ext}, the system has a symmetry that suppresses flux noise (even though still present)

Measurements Initialisation

Optimisation of the magnetic field (coil)

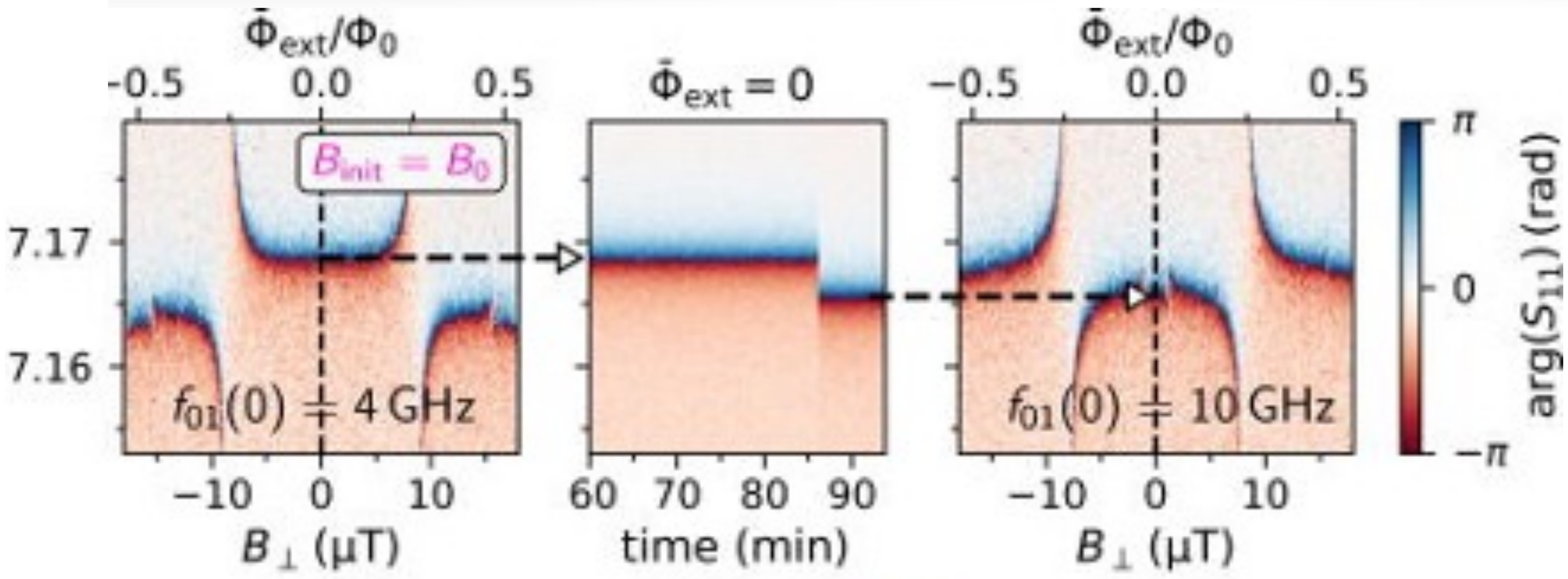
- Start scanning the resonator coupled to the qubit
- Apply current to the coil —> B —> Φ_{ext} —> f_{01} changes
- Increase current in the coil —> increase B; ...



f_{01} of the fluxonium *crosses* the resonator *f* multiple times

Fast energy exchange with resonator —> qubit not isolated anymore

Radioactivity Effect (1)



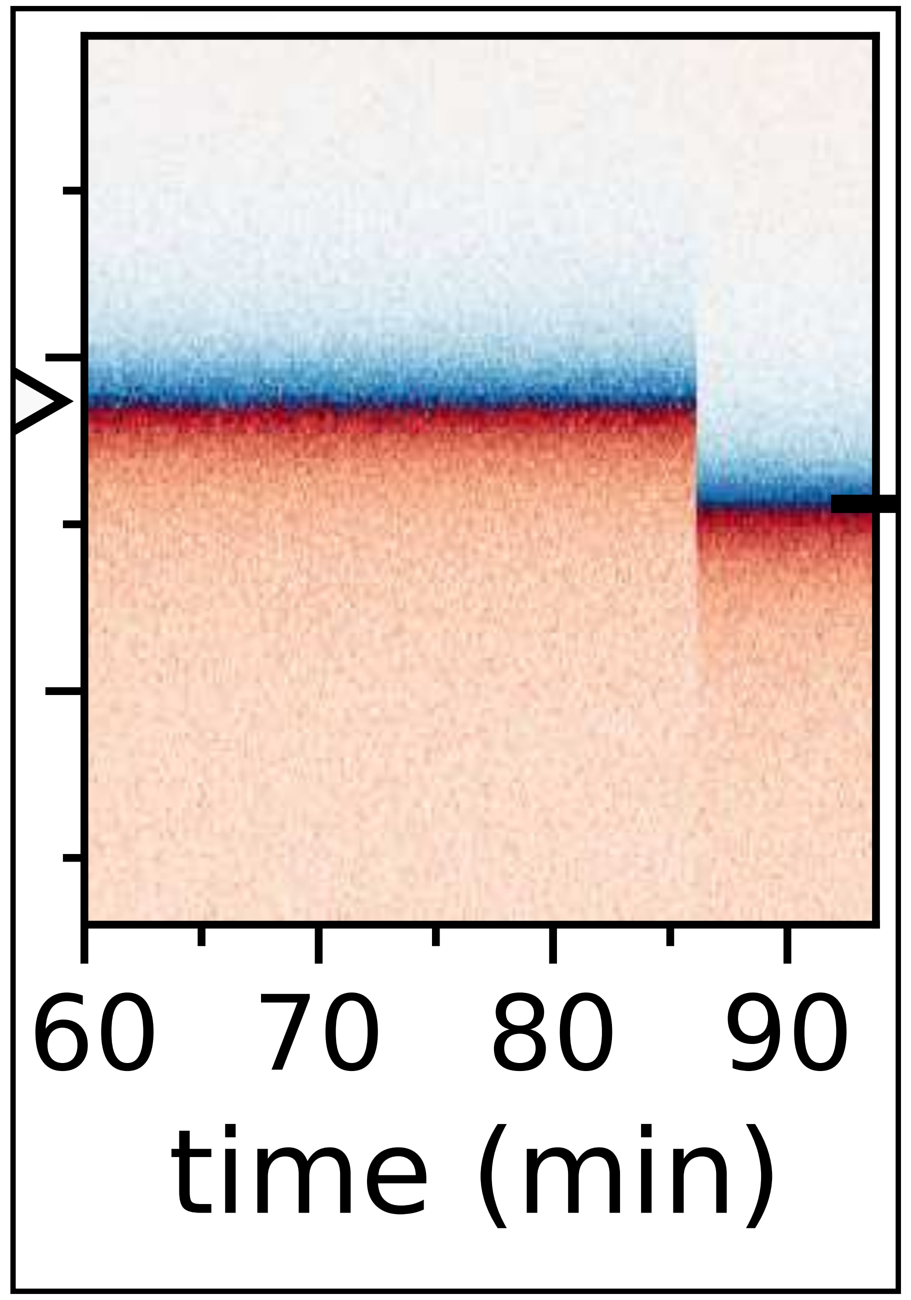
We selected our "sweet spot", where the qubit has long coherence, less noise, ...

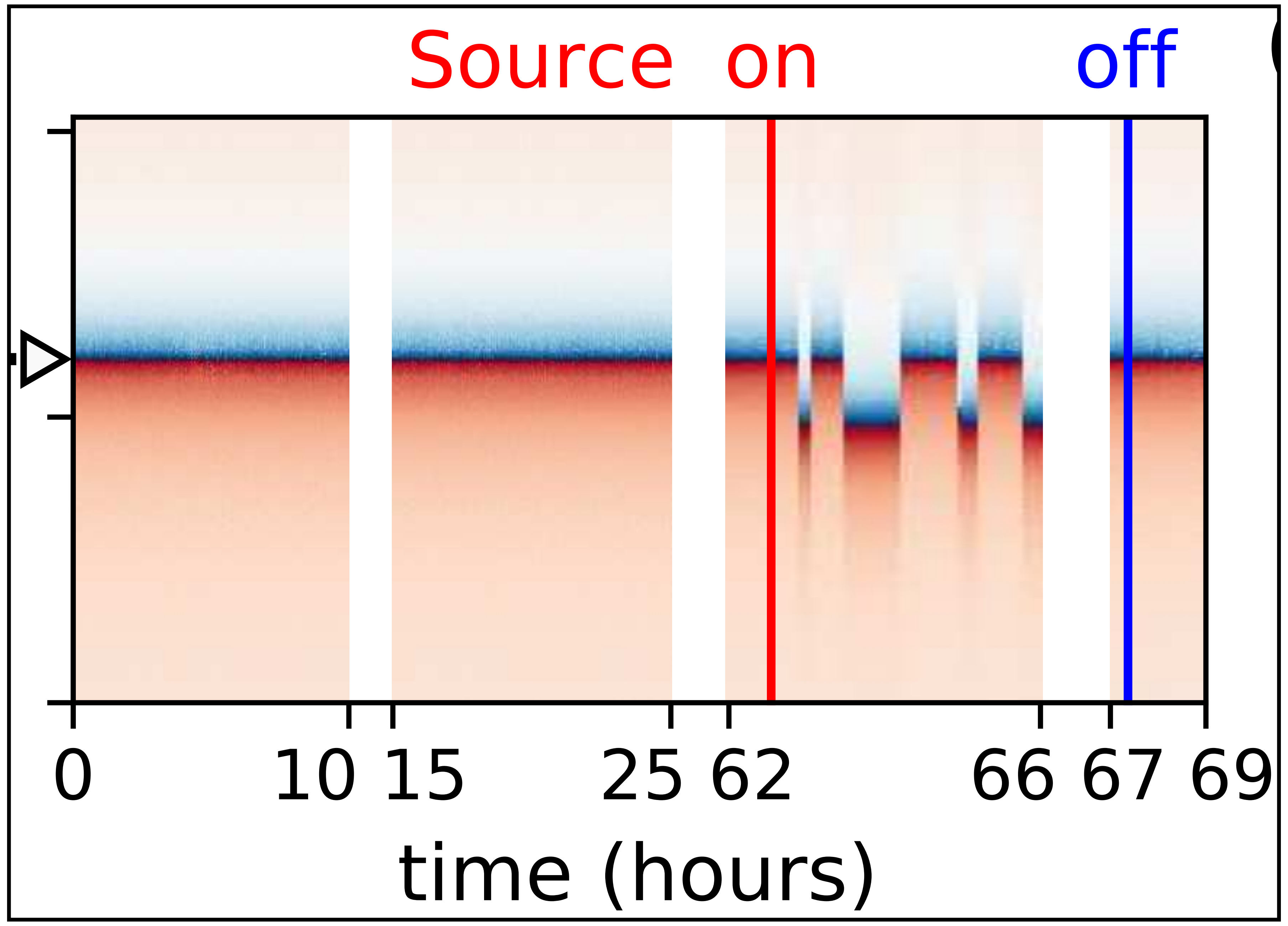
We monitor the resonator frequency: what happens?

Frequency jump = trapped flux escaped

We have to start all over again :(

Radioactivity Effect (2)





Operating the same device in a radio pure environment improves the time locking from tens of minutes to days!

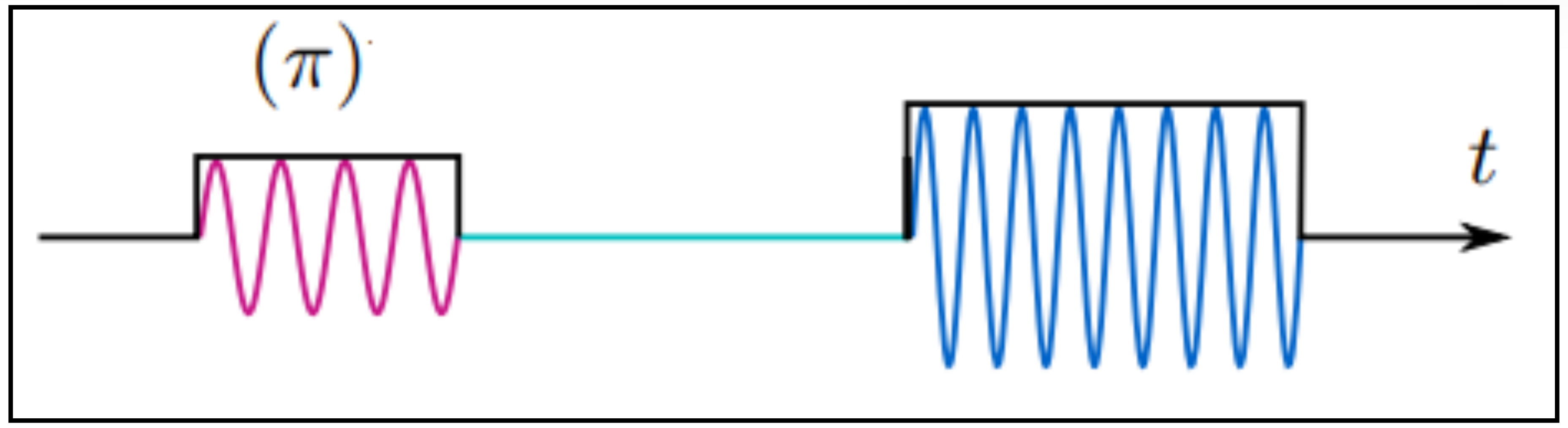
And what happen if we start manipulating the qubit?

D. Gusenkova et al,
Appl. Phys. Lett 120 054001 (2022)

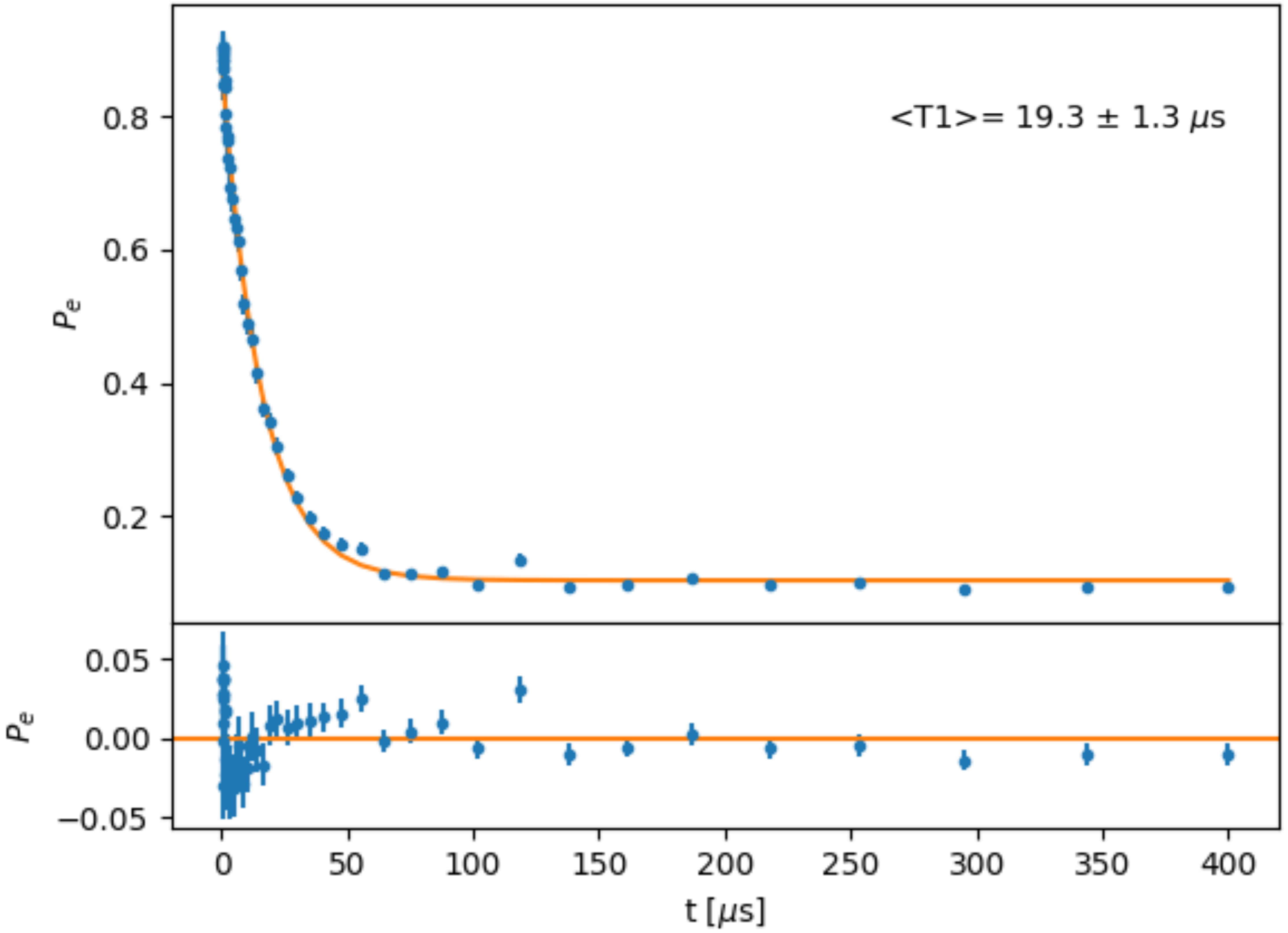
T1 measurement

Measurement scheme:

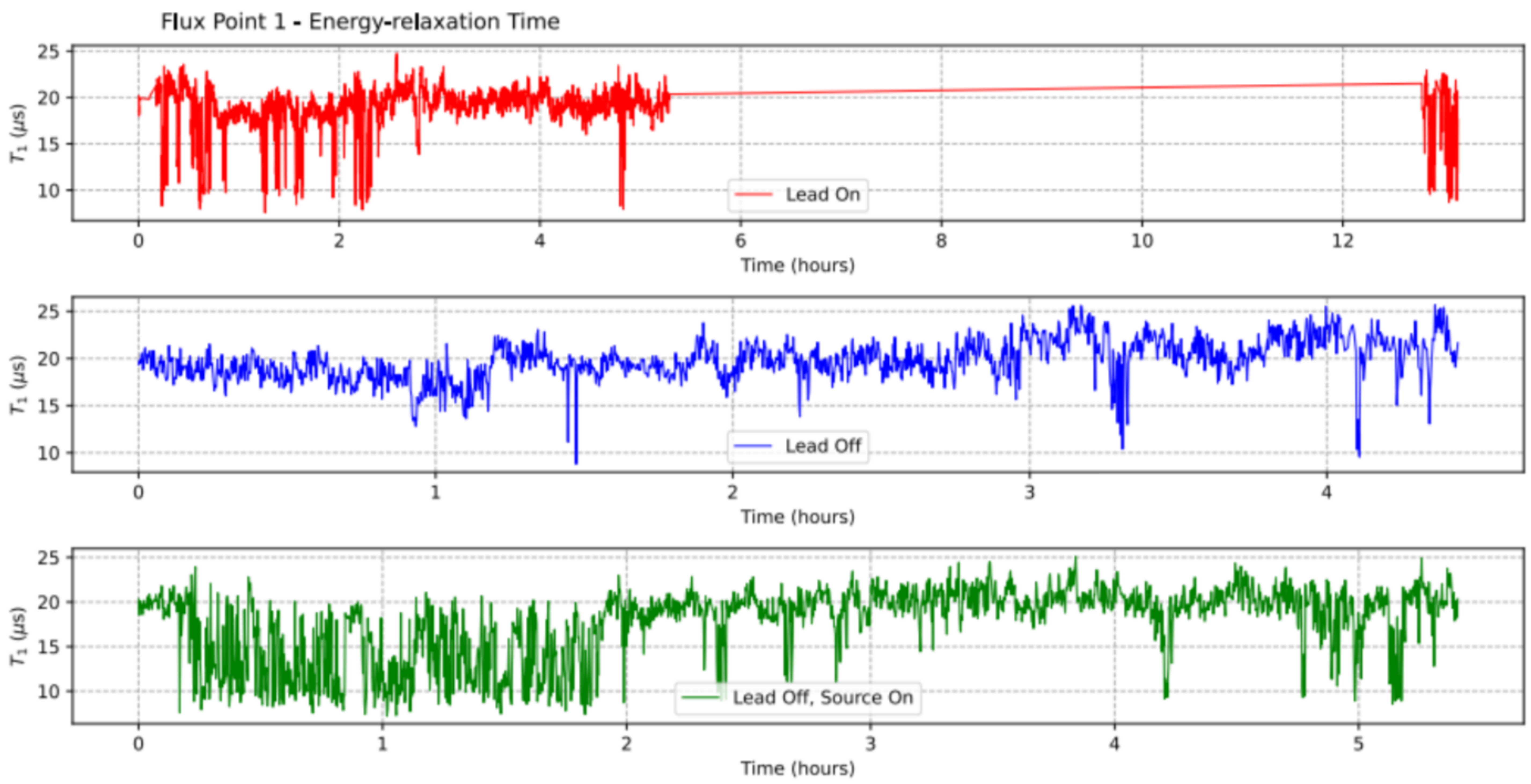
- Prepare the qubit in status (1)
- Wait t: measure the qubit status
- Wait t+ΔT: measure the qubit status
- Wait t+2ΔT: measure the qubit status
- Repeat each point *O*(10000) times
- Fit to derive qubit T1



(1) —> (0)



T1 measurements: radioactivity



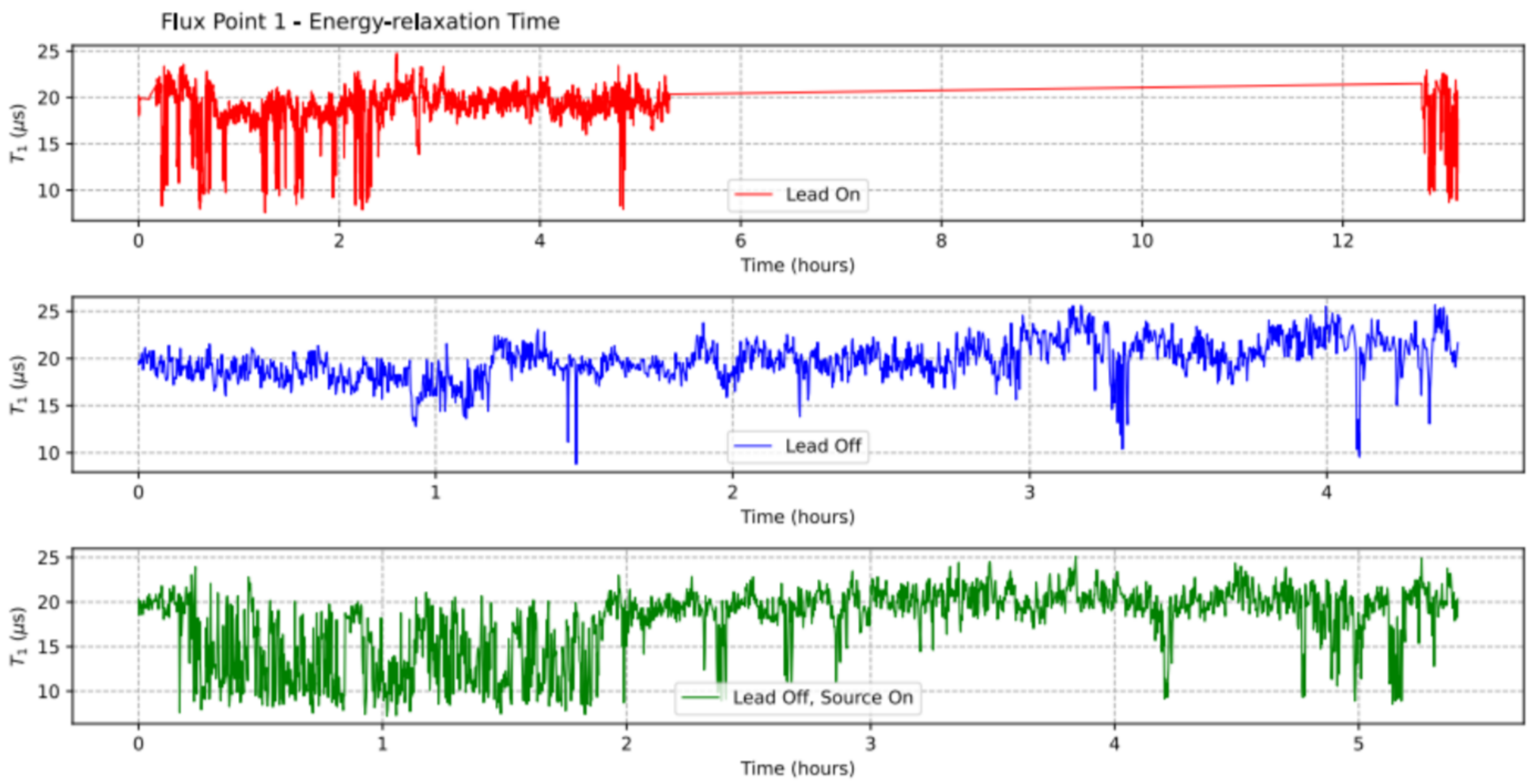
lead on: $\langle T_1 \rangle = 19.3 \pm 1.3\ \mu s$

lead off: $\langle T_1 \rangle = 19.2 \pm 2.1\ \mu s$

lead off + sources $\langle T_1 \rangle = 18.5 \pm 1.5\ \mu s$

NO SIZEABLE EFFECTS FROM RADIOACTIVITY!

T1 measurements: radioactivity (2)



IS THIS REASONABLE?

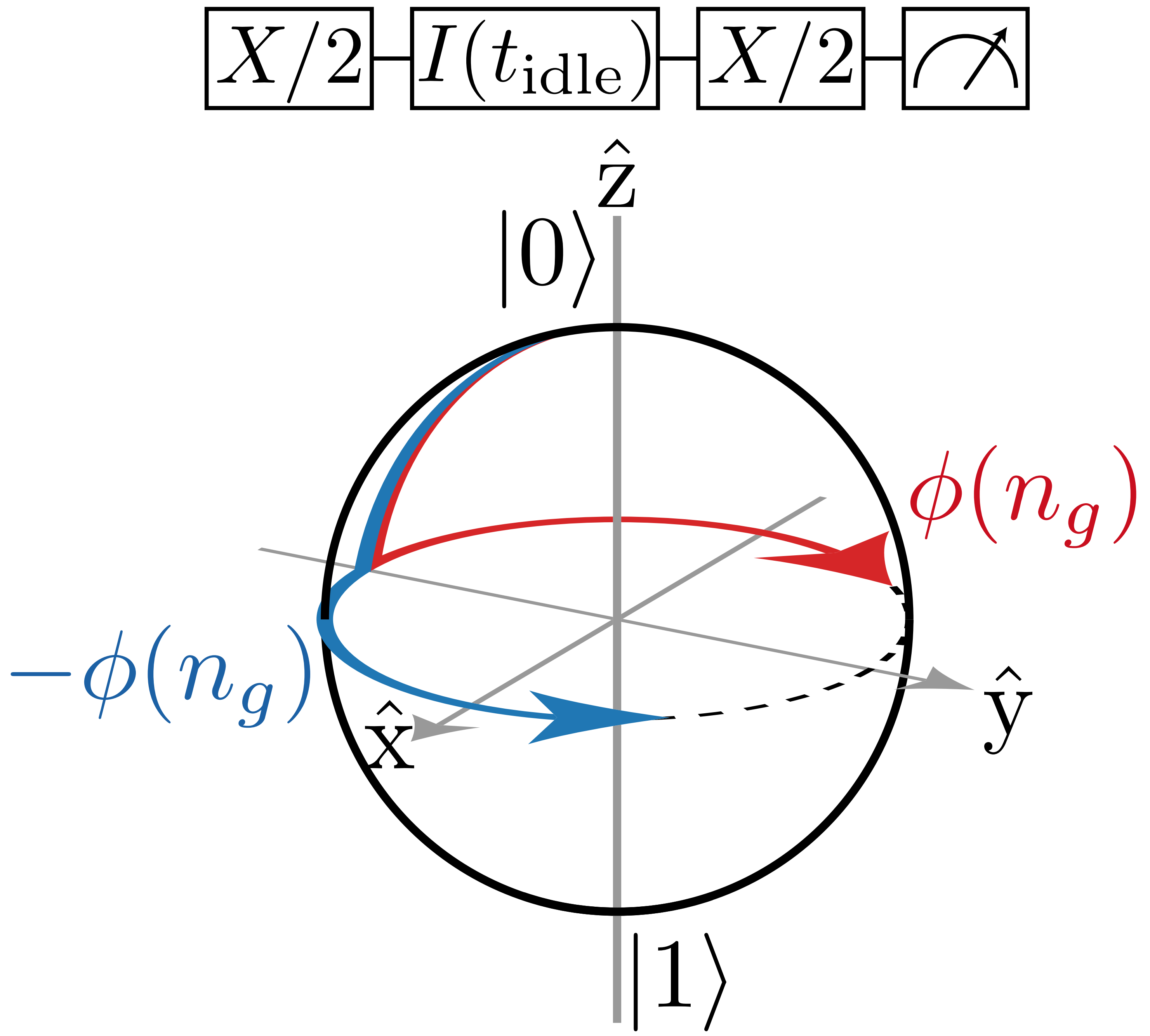
T2 measurement

Same protocol as yesterday…

Validation: Offset Charge

Slide from yesterday's lesson :)

Ramsey tomography to to measure the qubit frequency



A cycle allows to derive the accumulated phase

To do it, we map the qubit (after evolution) into 0 or 1

$$P_1(t_{\text{idle}}) = \frac{1}{2}\left(1 - \cos(\Delta\omega \cdot t_{\text{idle}})\right) \cdot e^{-t_{\text{idle}}/T_2^*}$$

Δω: detuning frequency of qubit- frequency drive

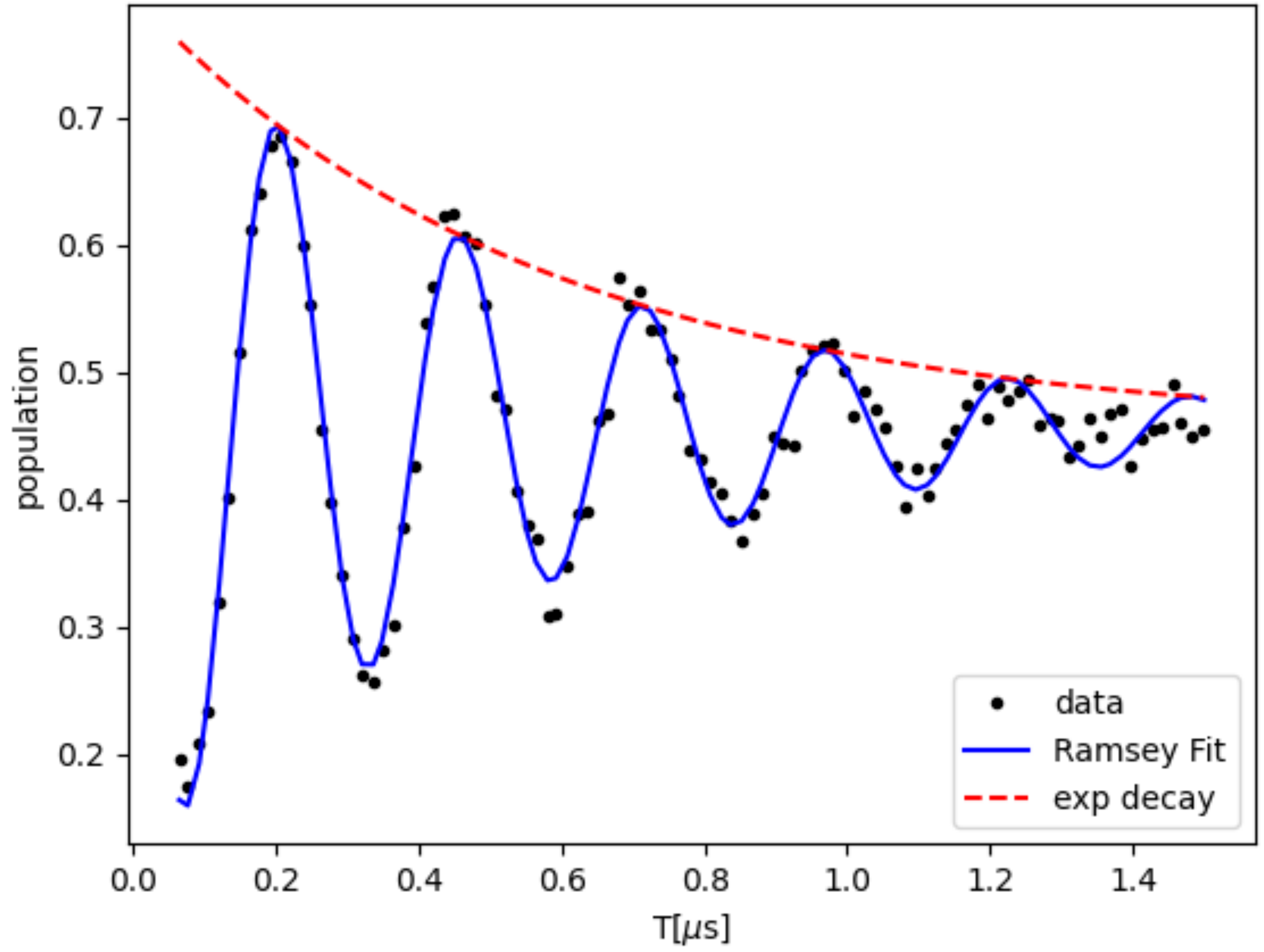
T_2* coherence -including slow noise, ...

T2 measurement

T2 of 0.56 +- 0.02 µs

(This qubit is phase-limited so we expected $T_2 << T_1$)

No effects from radioactivity of course :)



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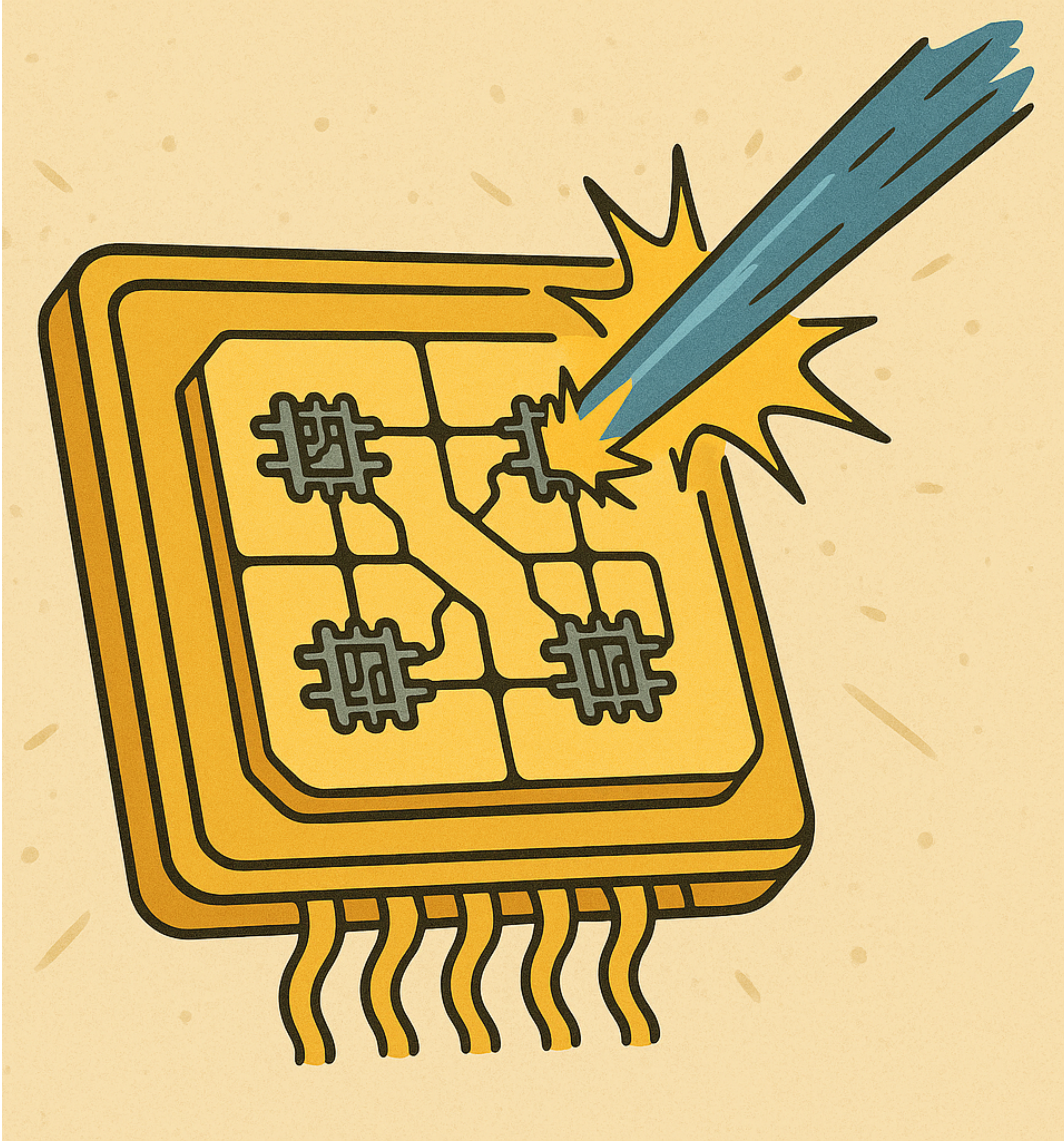

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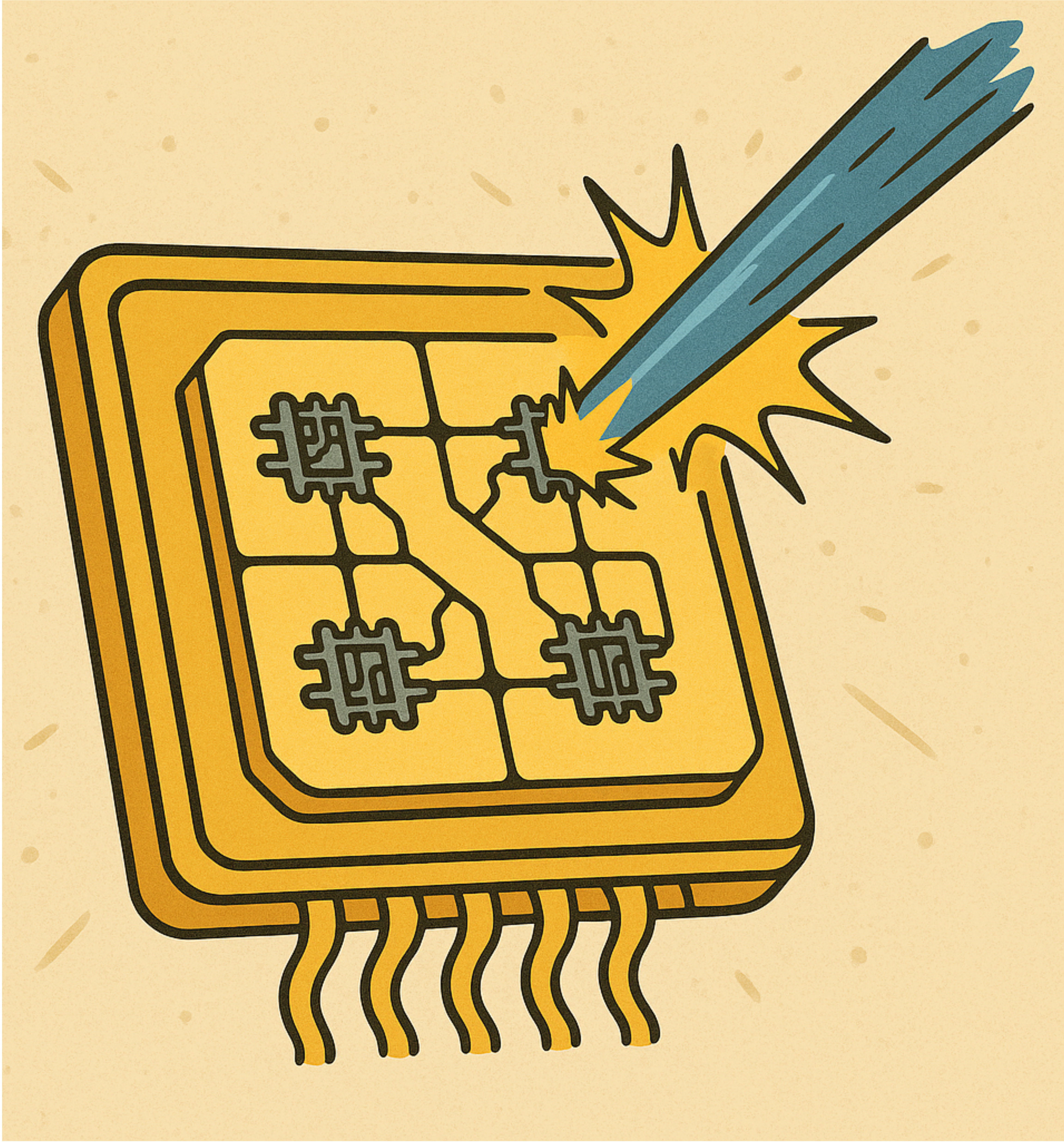
- Mitigation of Radioactivity
  - Where does it come from
  - Shielding
  - Results: microwave resonators
  - Results fluxonium qubits
- Disentangling Radioactivity
- Perspectives for particle detection

- When radioactivity changed by x100 with all other experimental conditions fixed, quality factor worsen **but** only by ~20%
- Locking at the sweet spot improved from ~1 hour to days suppressing radioactivity
- **But** no effects on T_1, T_2

Recap

- Mitigation of Radioactivity
  - Where does it come from
  - Shielding
  - Results: microwave resonators
  - Results fluxonium qubits
- Disentangling Radioactivity
- Perspectives for particle detection



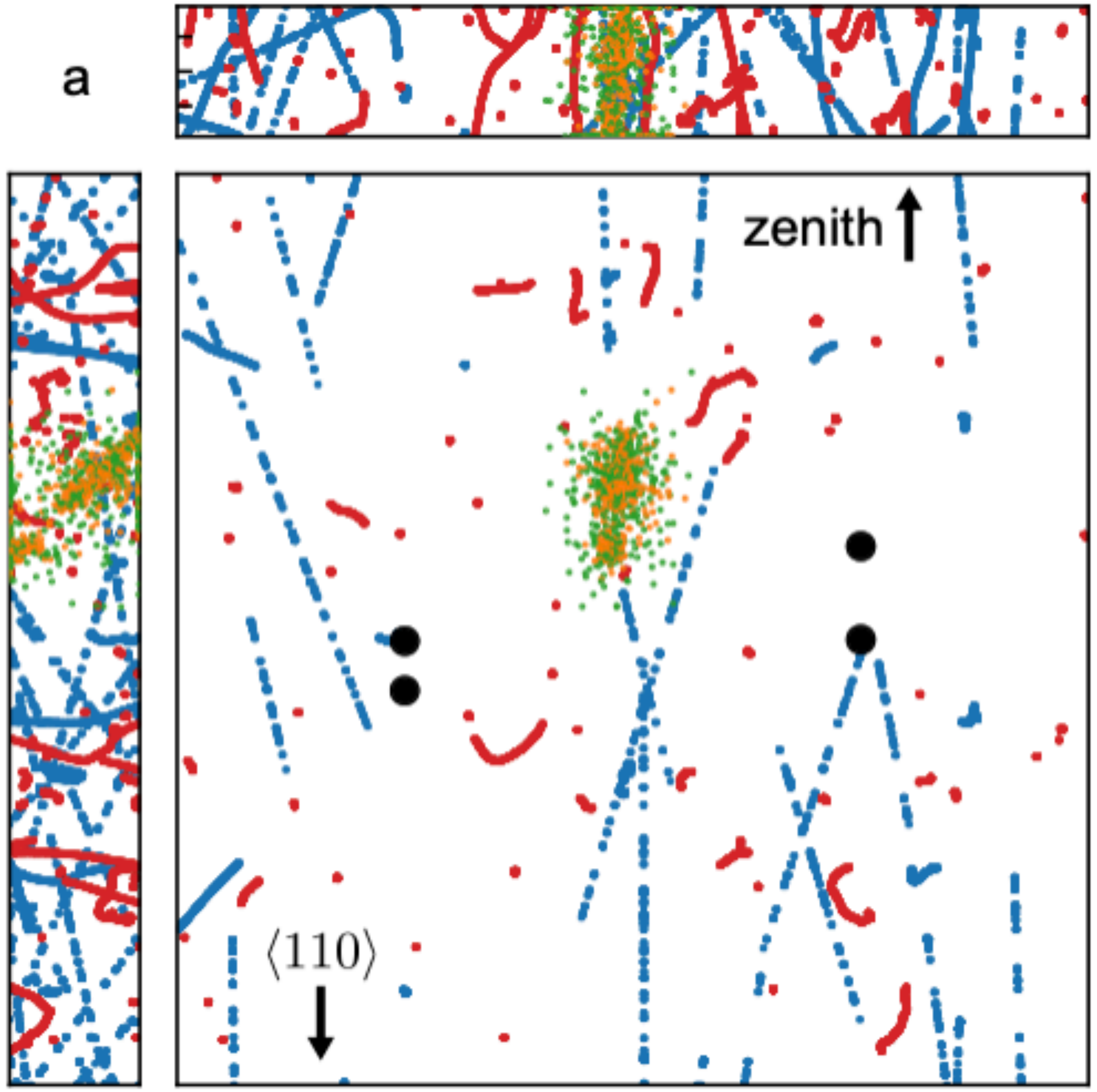
How

- Plenty of evidence that, typical qubit measurements of T_1 and T_2, are not capable of resolving fast effects of radioactivity

- How can we operate a *real** transmon or fluxonium in order to understand how sensitive it is to particles?

(*) We don't want to design a bad transmon specifically sensitive to noise due to radioactivity :)

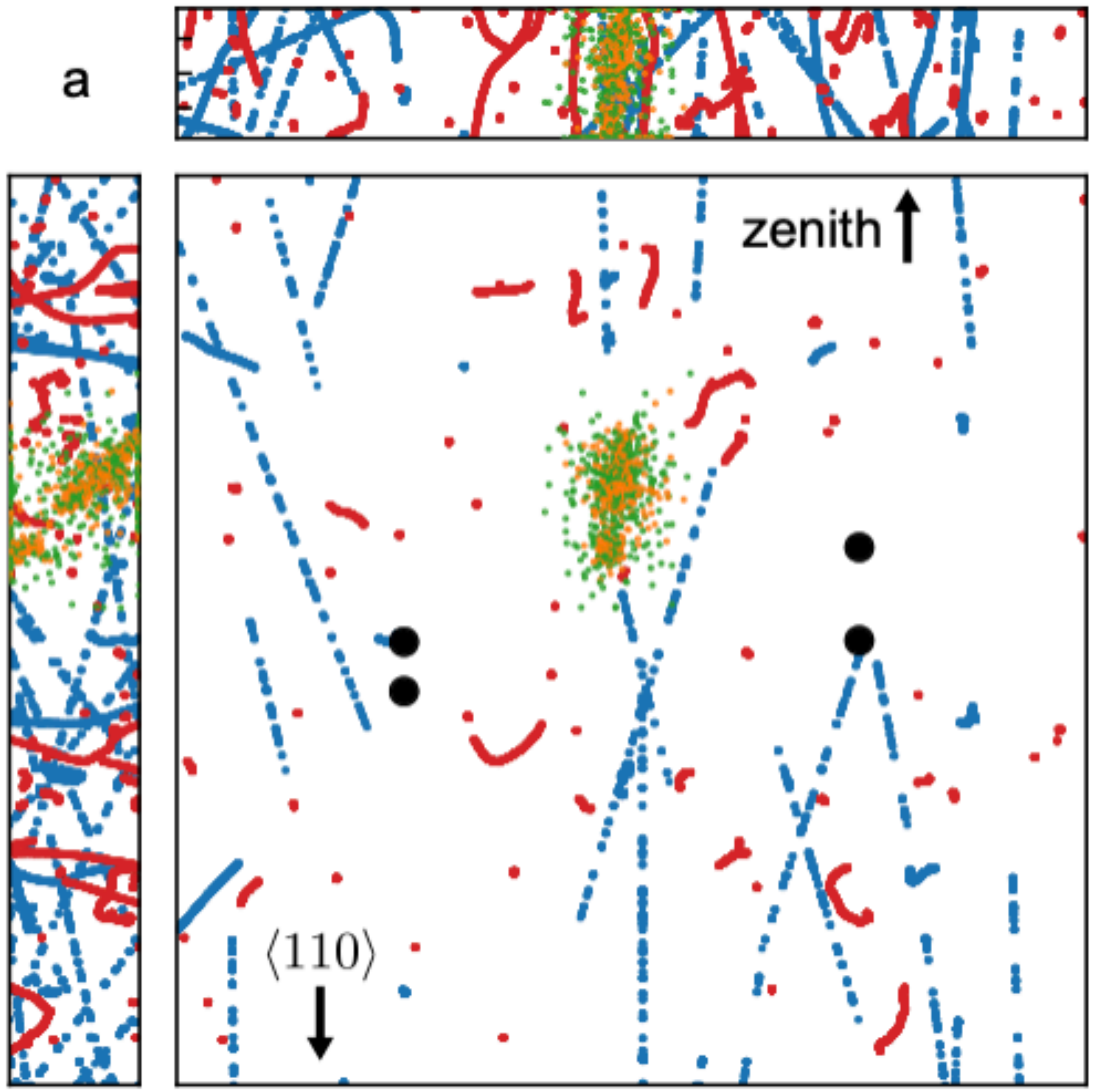
Let us go back to physics



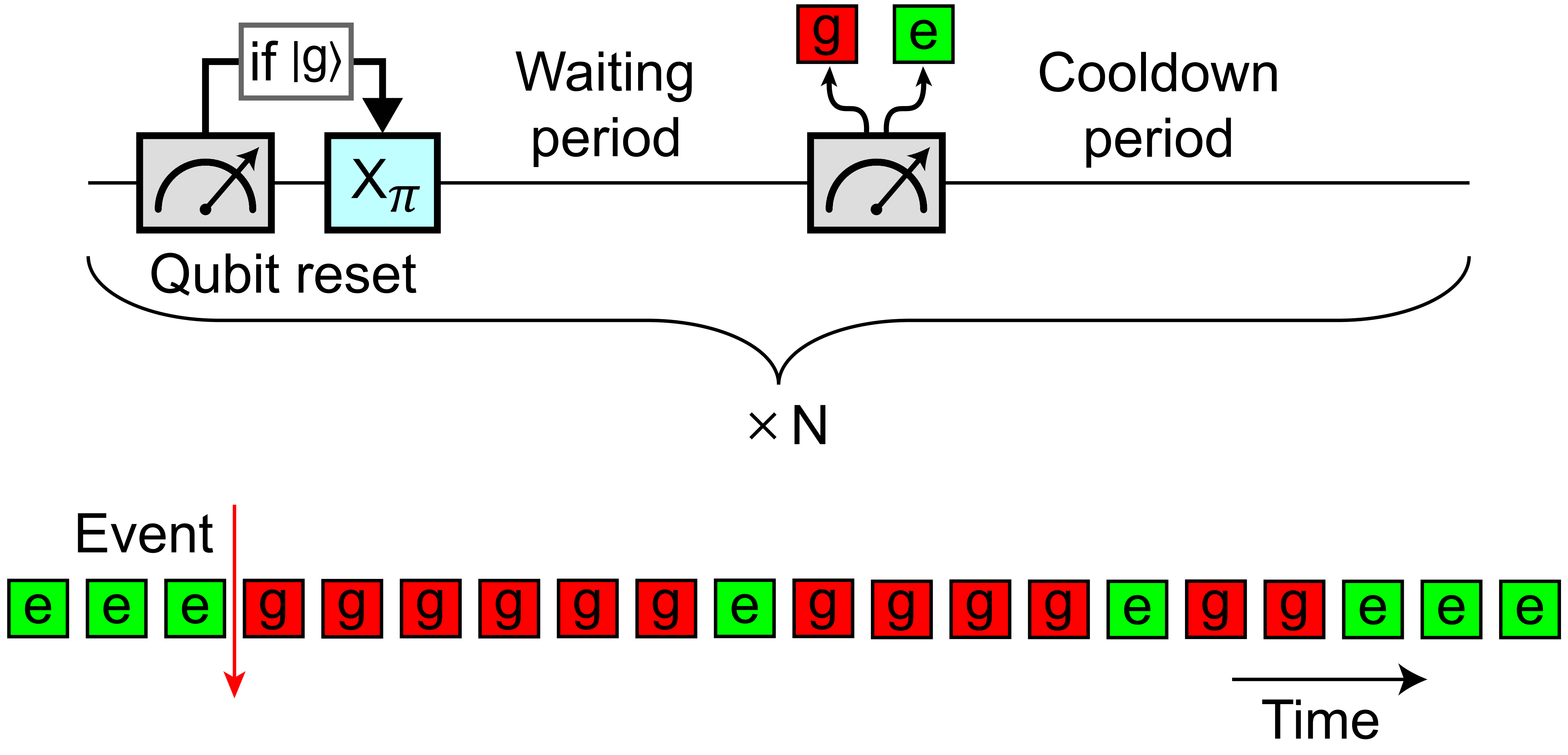
- Radioactivity releases energy
- Energy produces charges (electron/holes)
- Charges recombine into phonons
- Phonons scatter all over the substrate
- Phonons can be absorbed by the superconductor, where they break Cooper pairs: they take up to milliseconds to recombine

Our protocol must be faster than milliseconds

A new protocol



As long as phonons are in the qubit, I can keep putting the qubit in (1) but it will keep falling into (0)

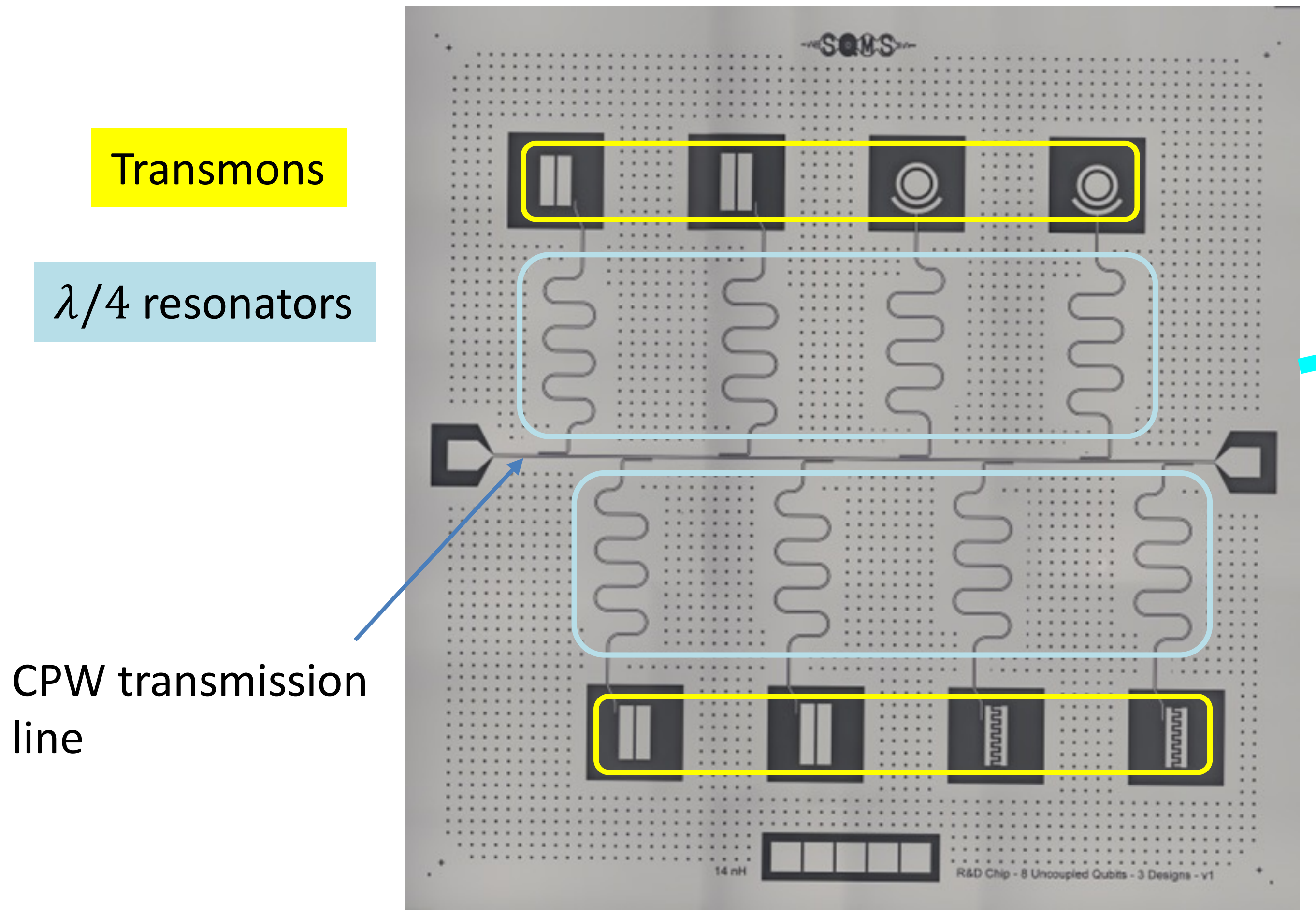


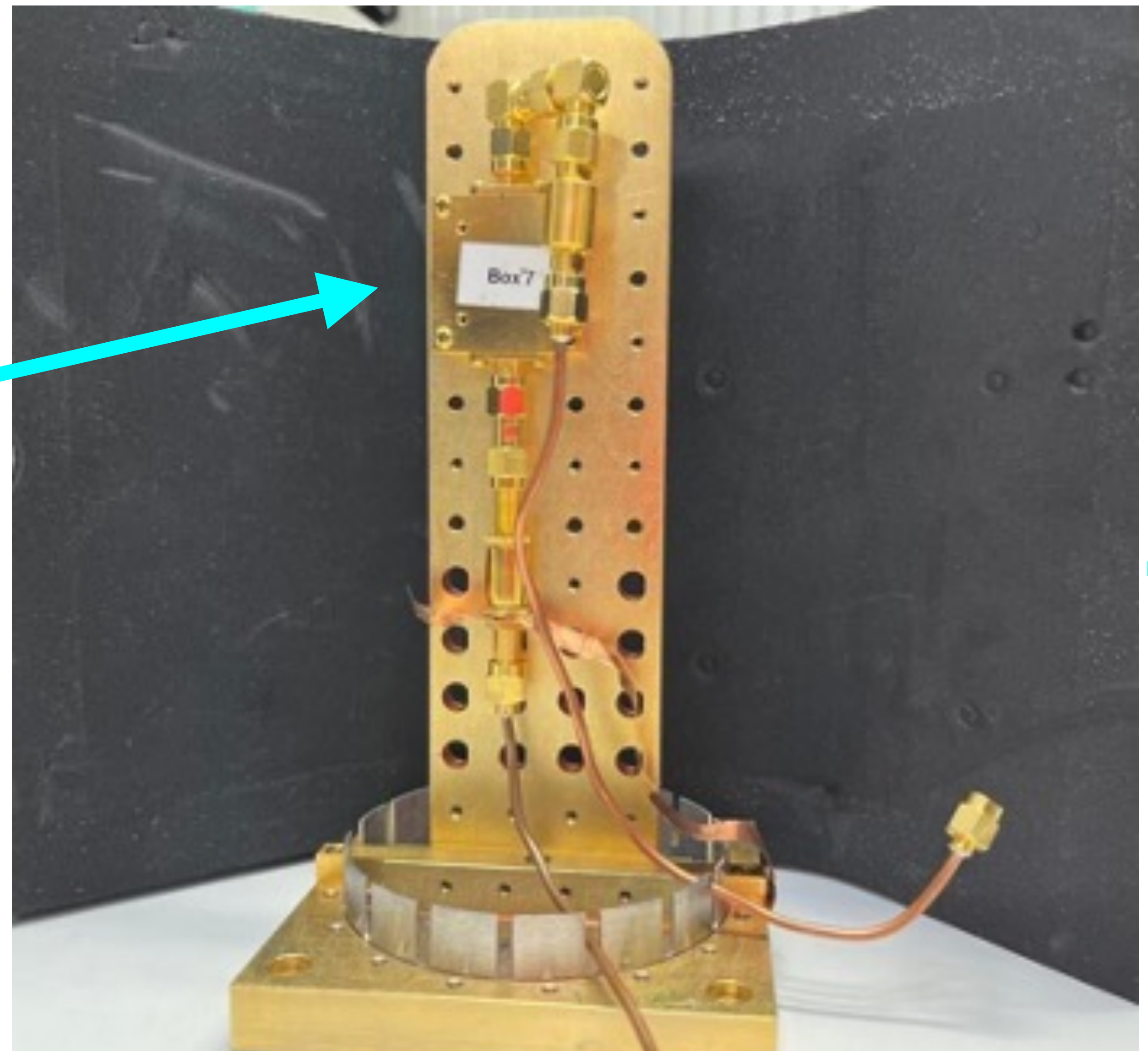
Measurements

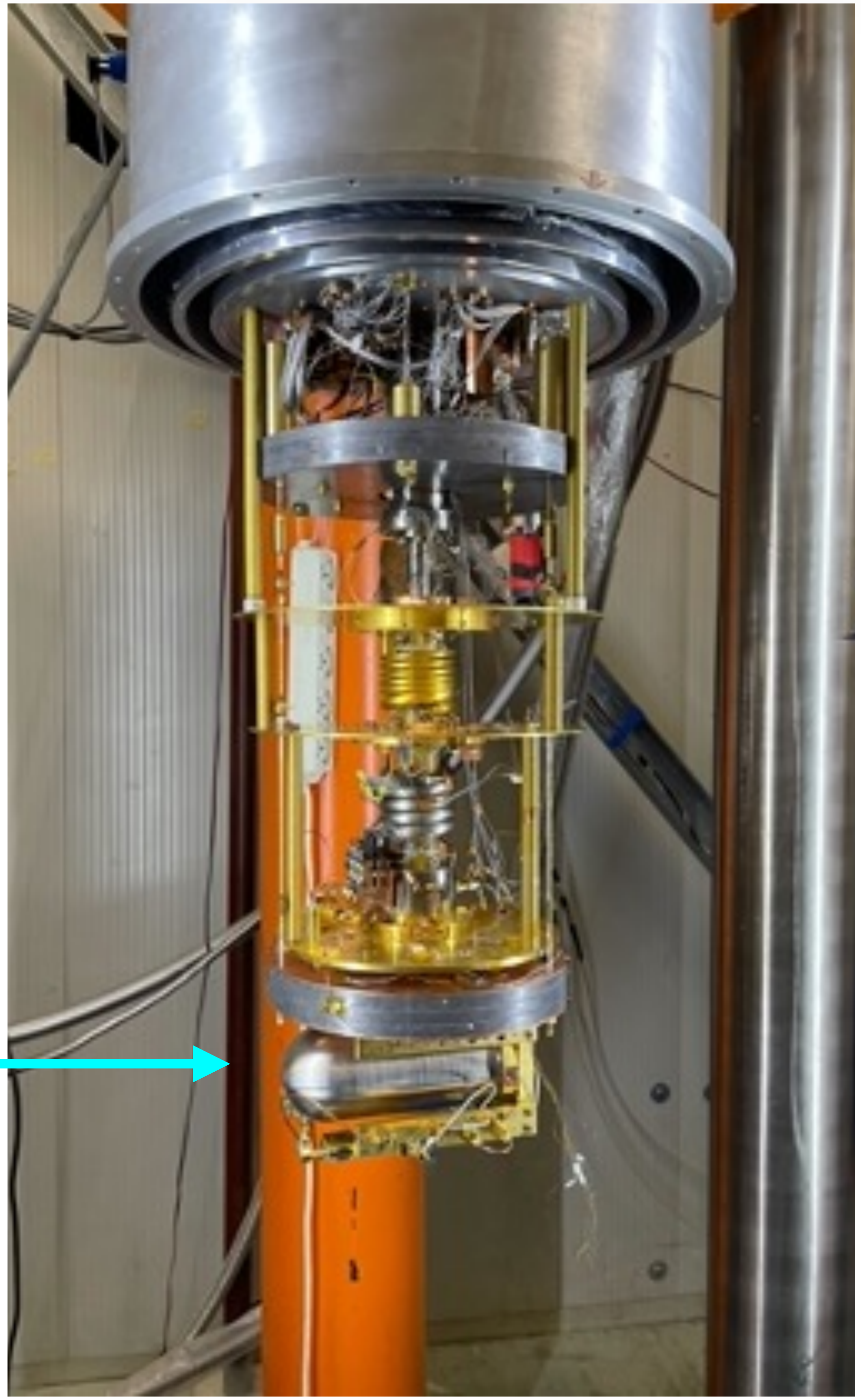
8-transmon chip produced by SQMS center

First prototype with decent T1 (0.1 millisecond)

DeDominicis 2025







Measurements

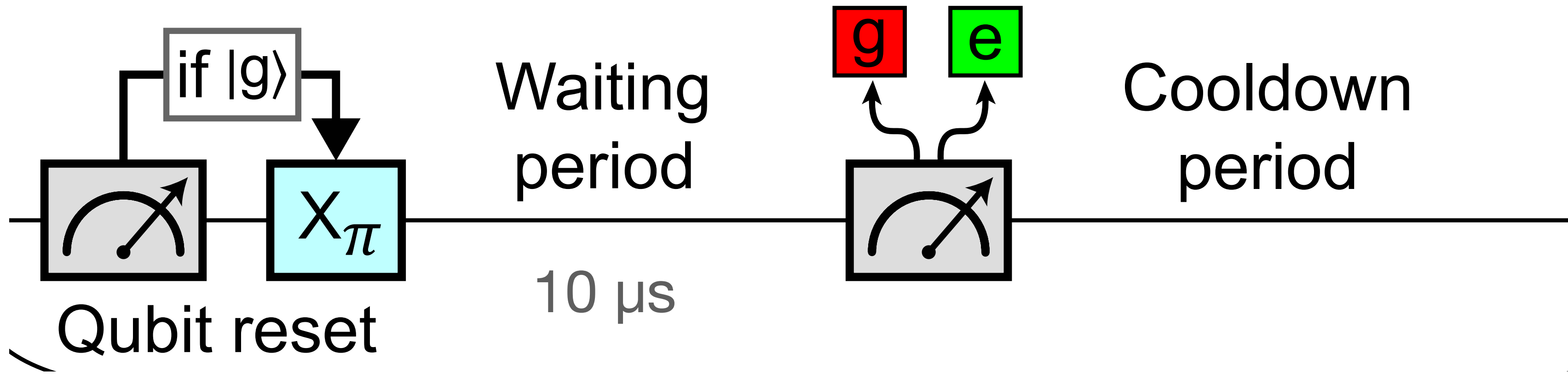
Measurements were done in two sites

Underground Gran Sasso laboratories (+ sources)

Quantum Garage at Fermilab (US)

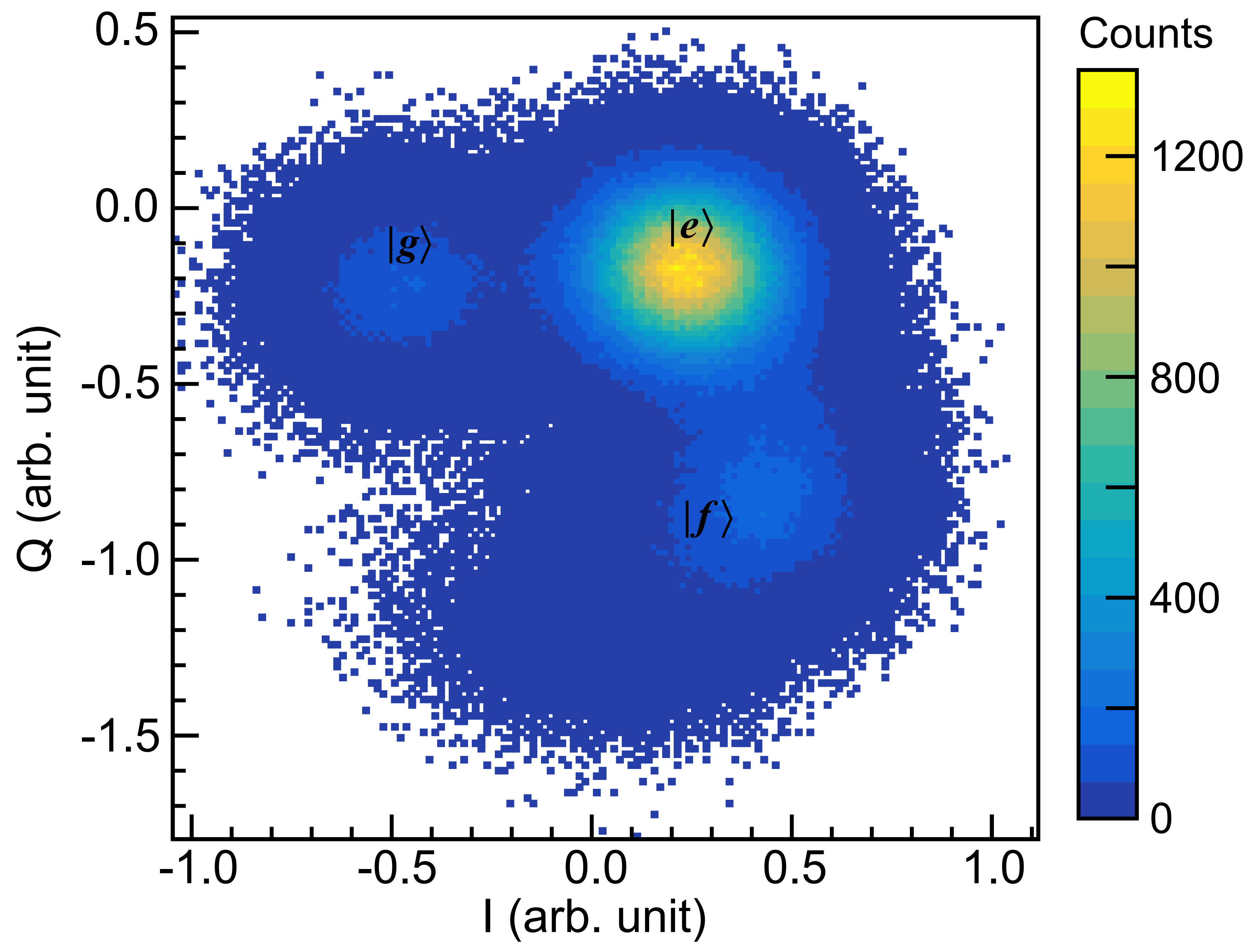
Measurements: Who Is 0 and who is 1?

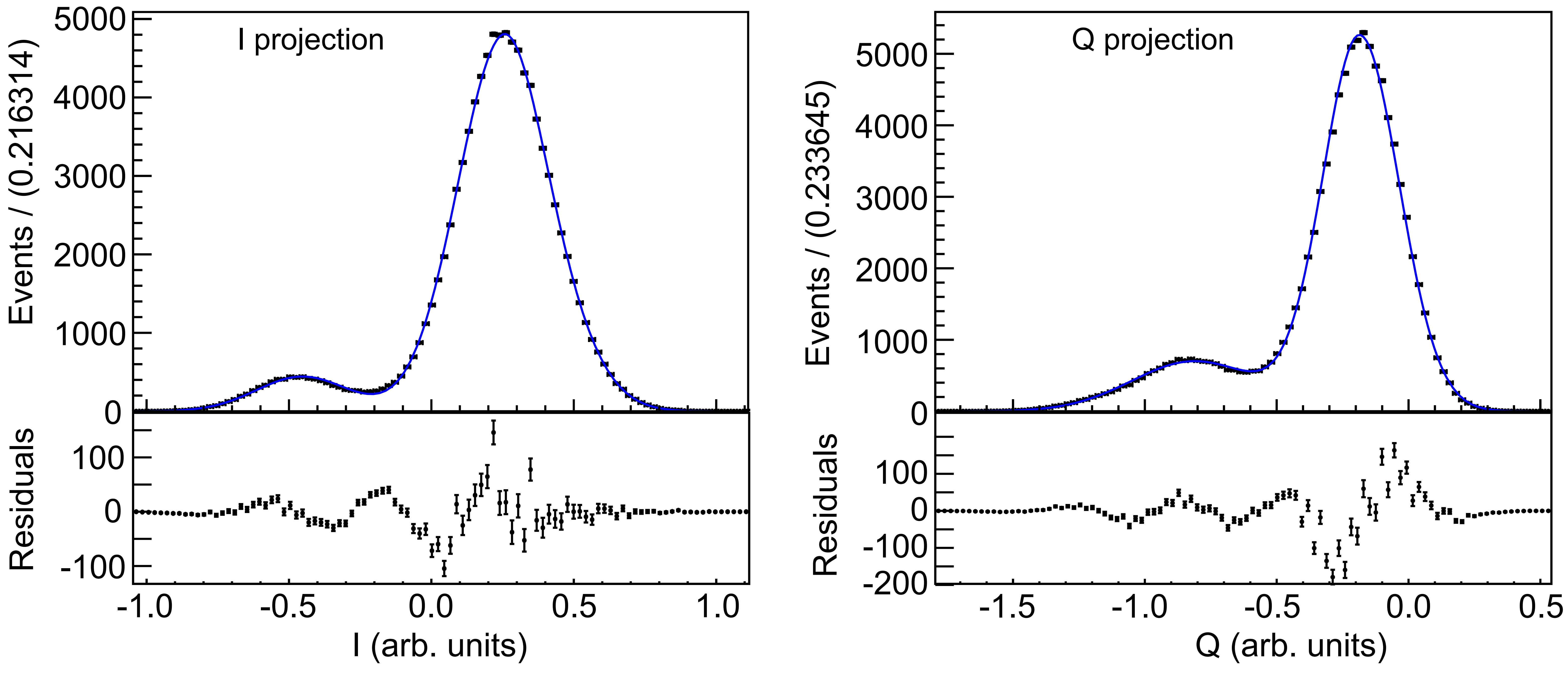
We set the qubit in (1), wait 10 μs, measure



Again and again

We obtain:

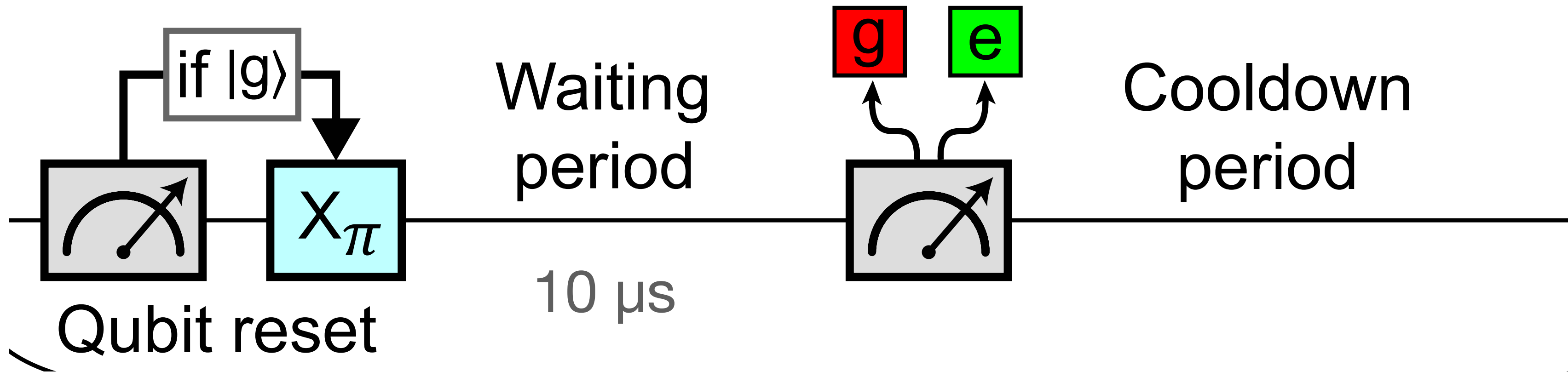




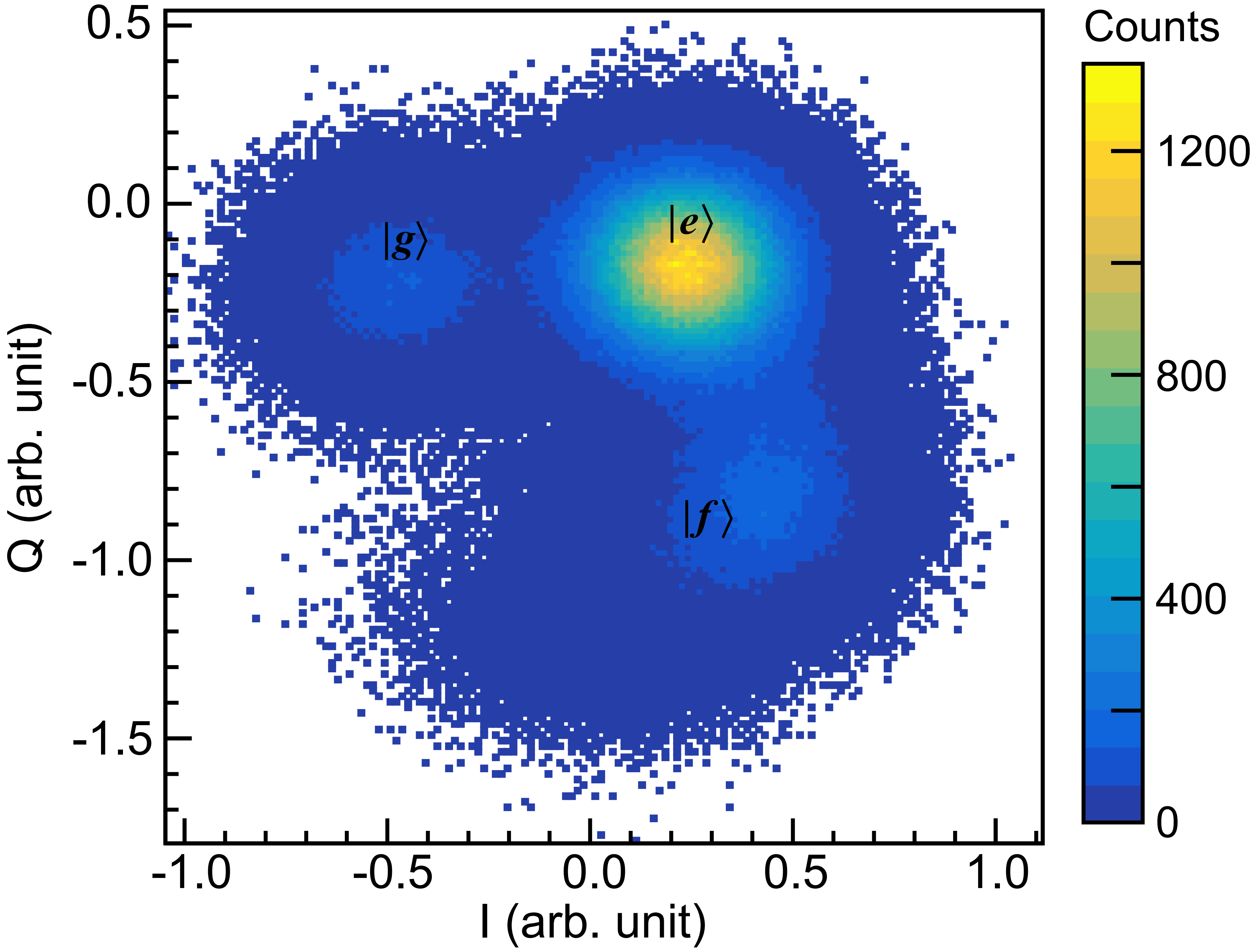
Measurements: Outcome

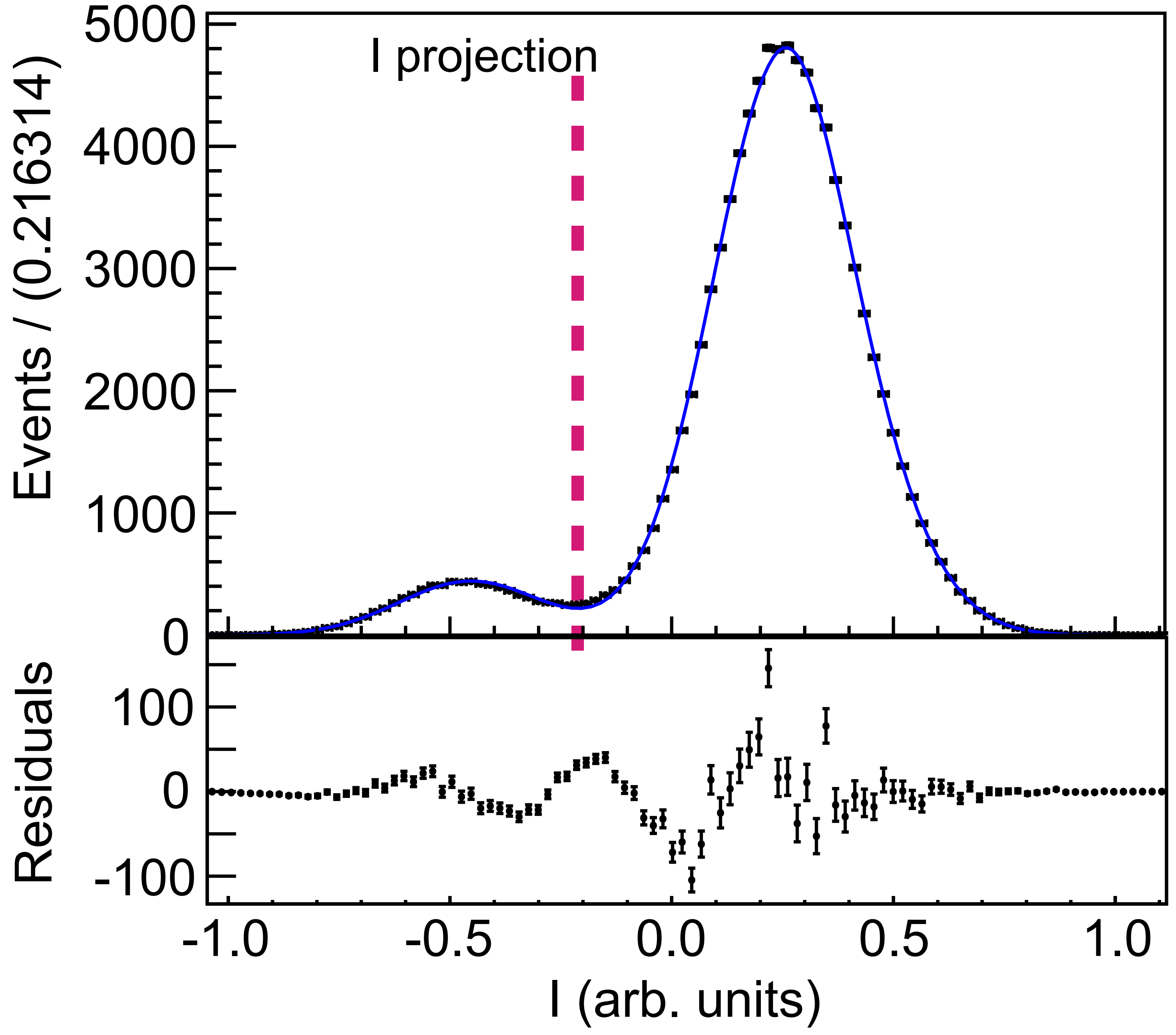
We are able to create a stream of 0/1

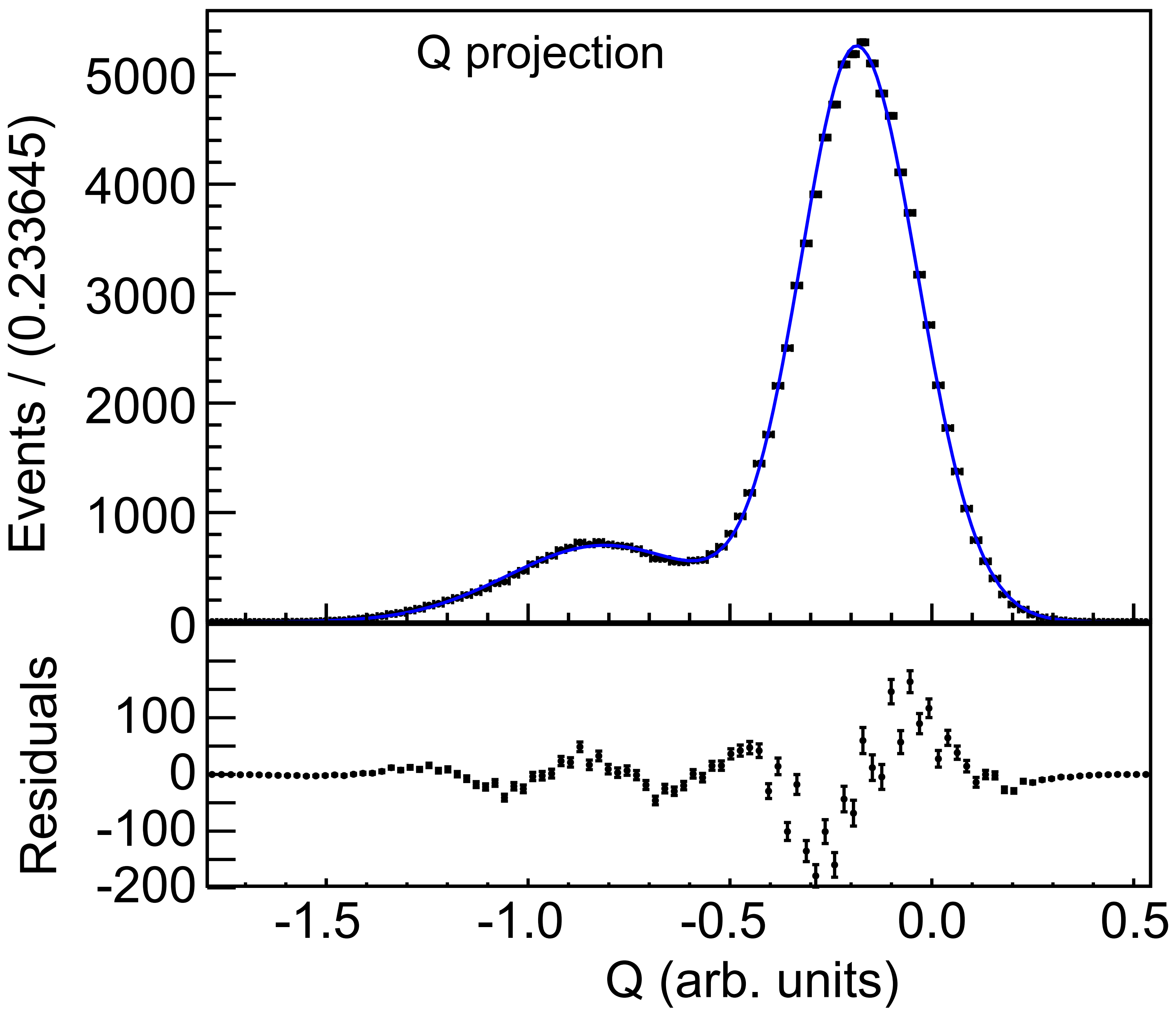
1 1 1 1 0 1 1 1 1 1 1 0 1 1 ....



Why do we measure also zeros?



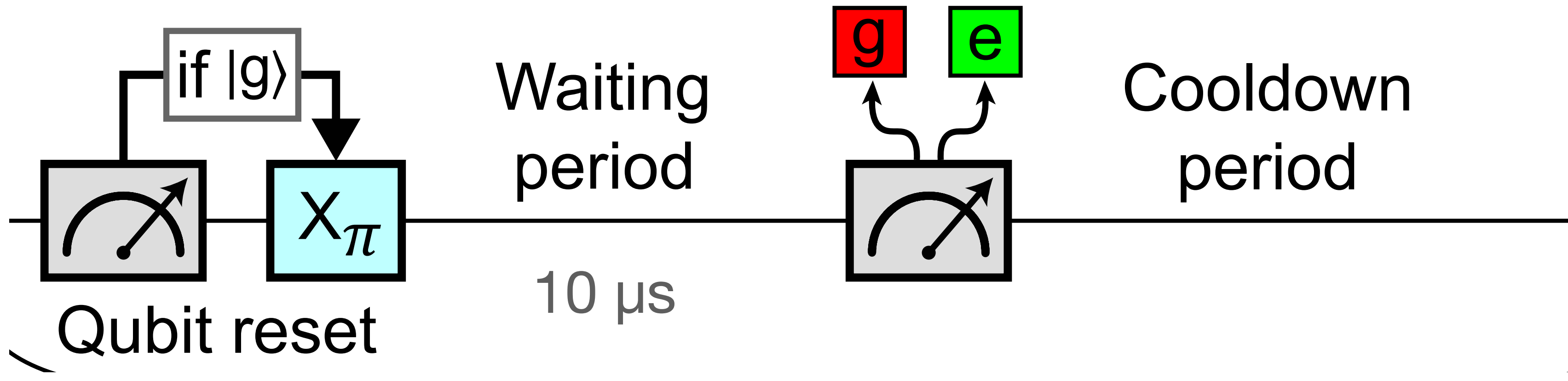




Measurements: Noise

We are able to create a stream of 0/1

1 1 1 1 0 1 1 1 1 1 1 0 1 1 ....

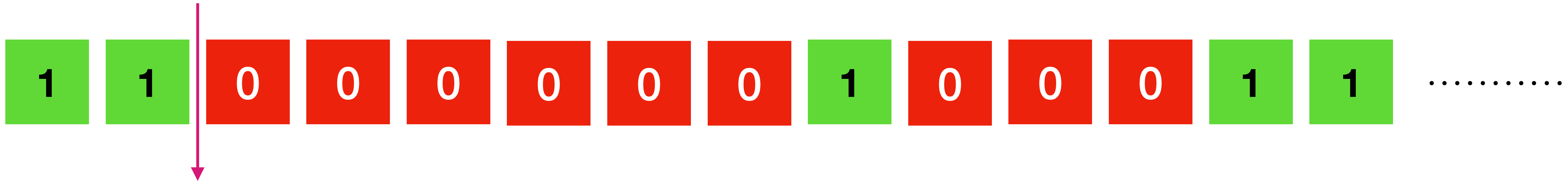


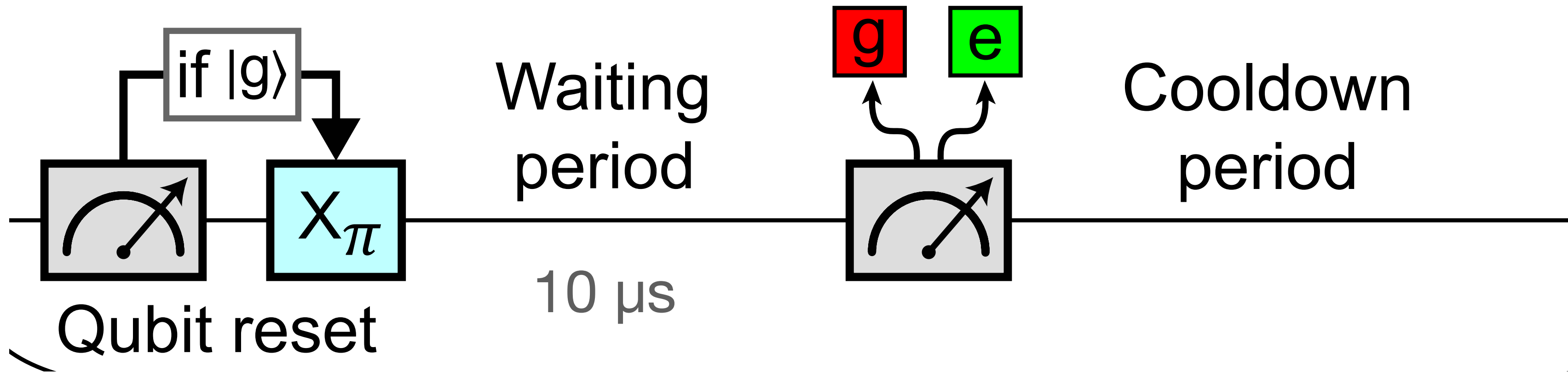
Why do we measure also zeros?

- Fidelity: clouds are not points
- Qubit decay:
  - we read qubit after T_{Idle}~ 10 μs, its T_1 is ~100 μs
  - About (10 μs)/(100 μs) ~ 10 % of zeros

Measurements: Signal

We are able to create a stream of 0/1



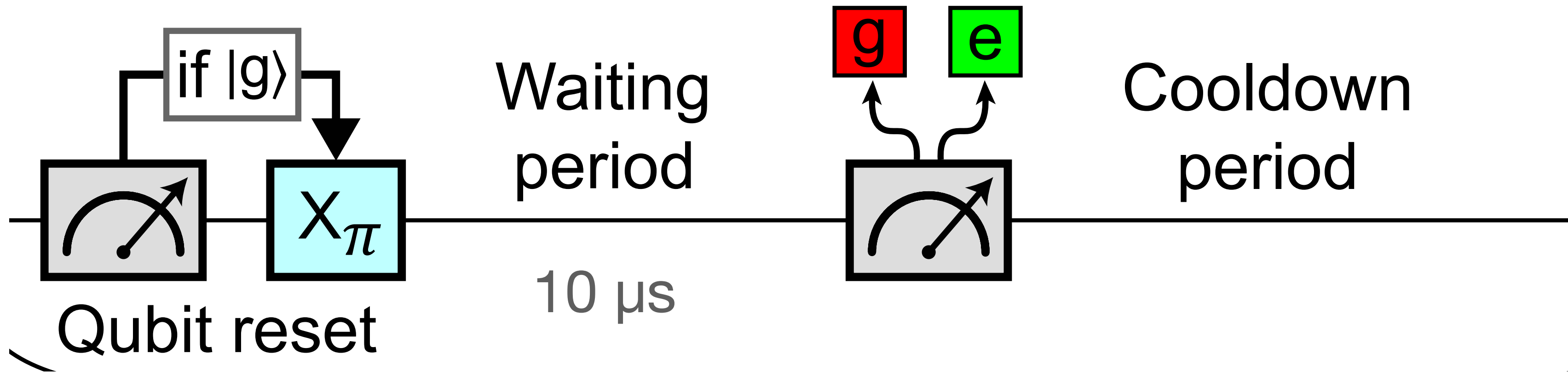


Why do we measure also one?

Measurements: Trigger

We are able to create a stream of 0/1

1 1 1 1 0 1 1 1 1 1 1 0 1 1



We trigger when we detect X consecutive zeros.

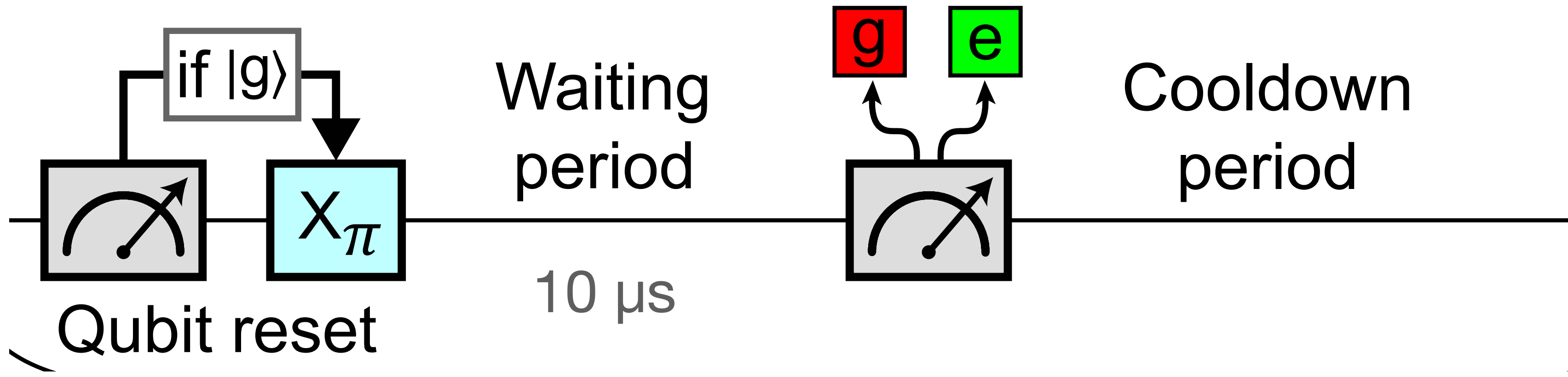
Question:

- P(0) = 0.1
- I trigger on **three** consecutive zeros —> P(three 0) ?
- Each cycle (point) takes 10^{-4} seconds

Measurements: Trigger

We are able to create a stream of 0/1

1 1 1 1 0 1 1 1 1 1 1 0 1 1



We trigger when we detect X consecutive zeros.

Question:

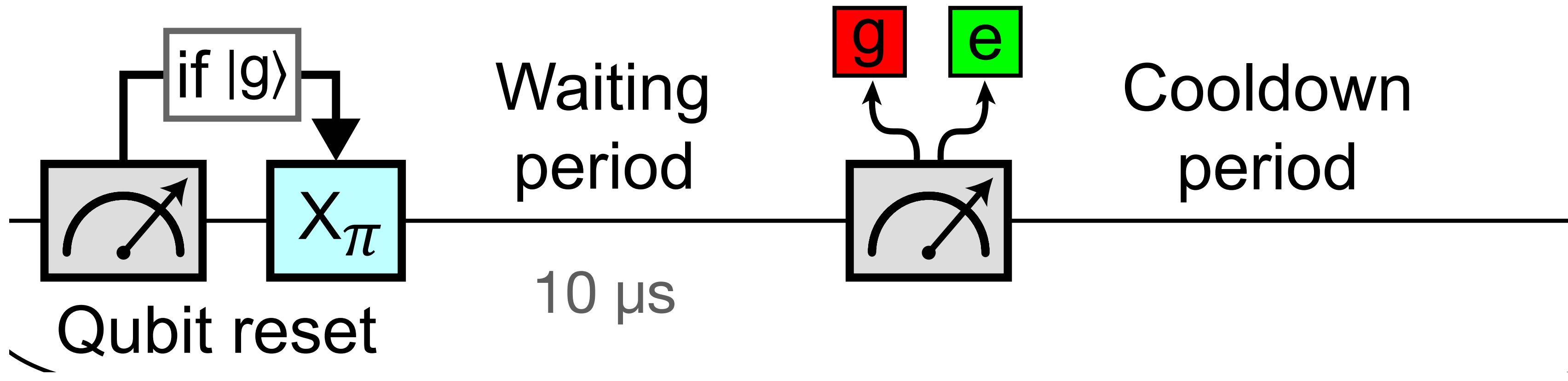
- P(0) = 0.1
- I trigger on **three** consecutive zeros —> 10^{-3}
- Each cycle (point) takes 10^{-4} seconds —> $10^{-3}/(10^{-4}$ sec)

Few events per second! What are we searching for?

Measurements: Trigger

Noise after trigger ~ few events per second

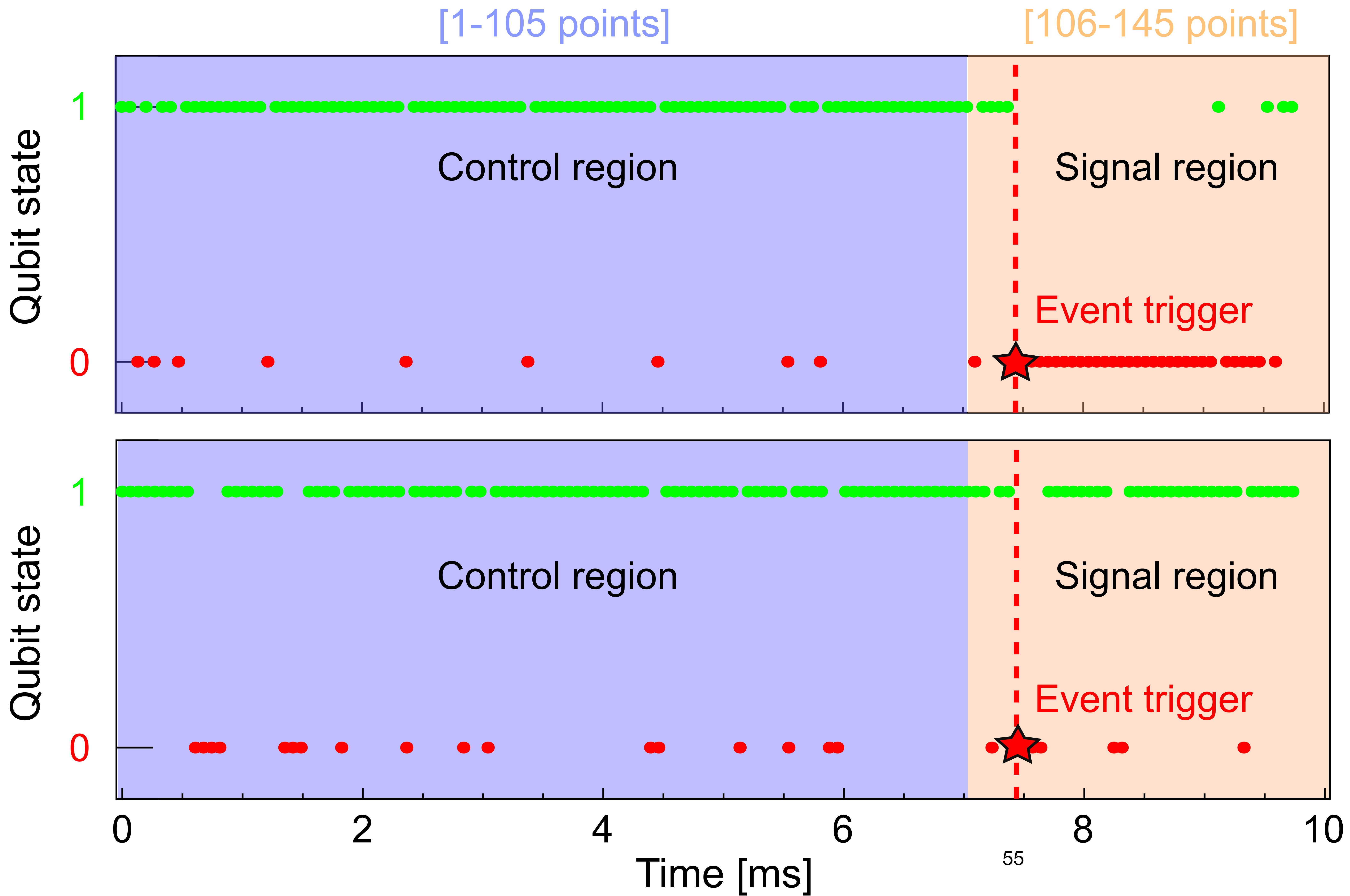
1	1	1	1	0	1	1	1	1	1	1	0	1	1



Source	Interactions in chip	In Gran Sasso
Lab γ rays	1 event / 32 seconds	1 event / 700 seconds
Muons	1 / 125 seconds	1 / 125 seconds
Materials	1 / 370 seconds	1 / 370 seconds
Neutrons	1 / (2 hours)	1 / (2 hours)
Total	1 event / 24 seconds	1 event / 250 seconds

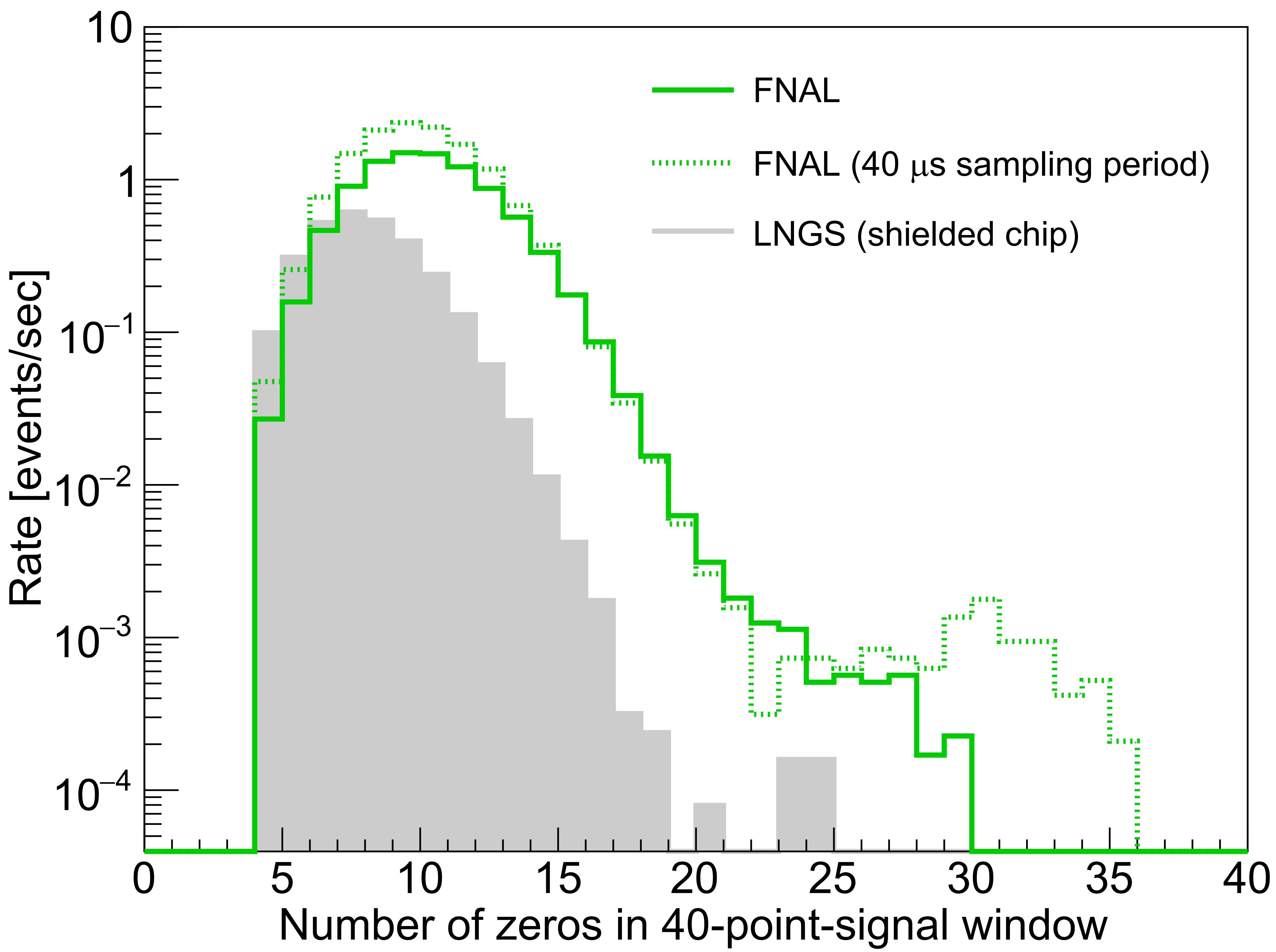
Typical Event

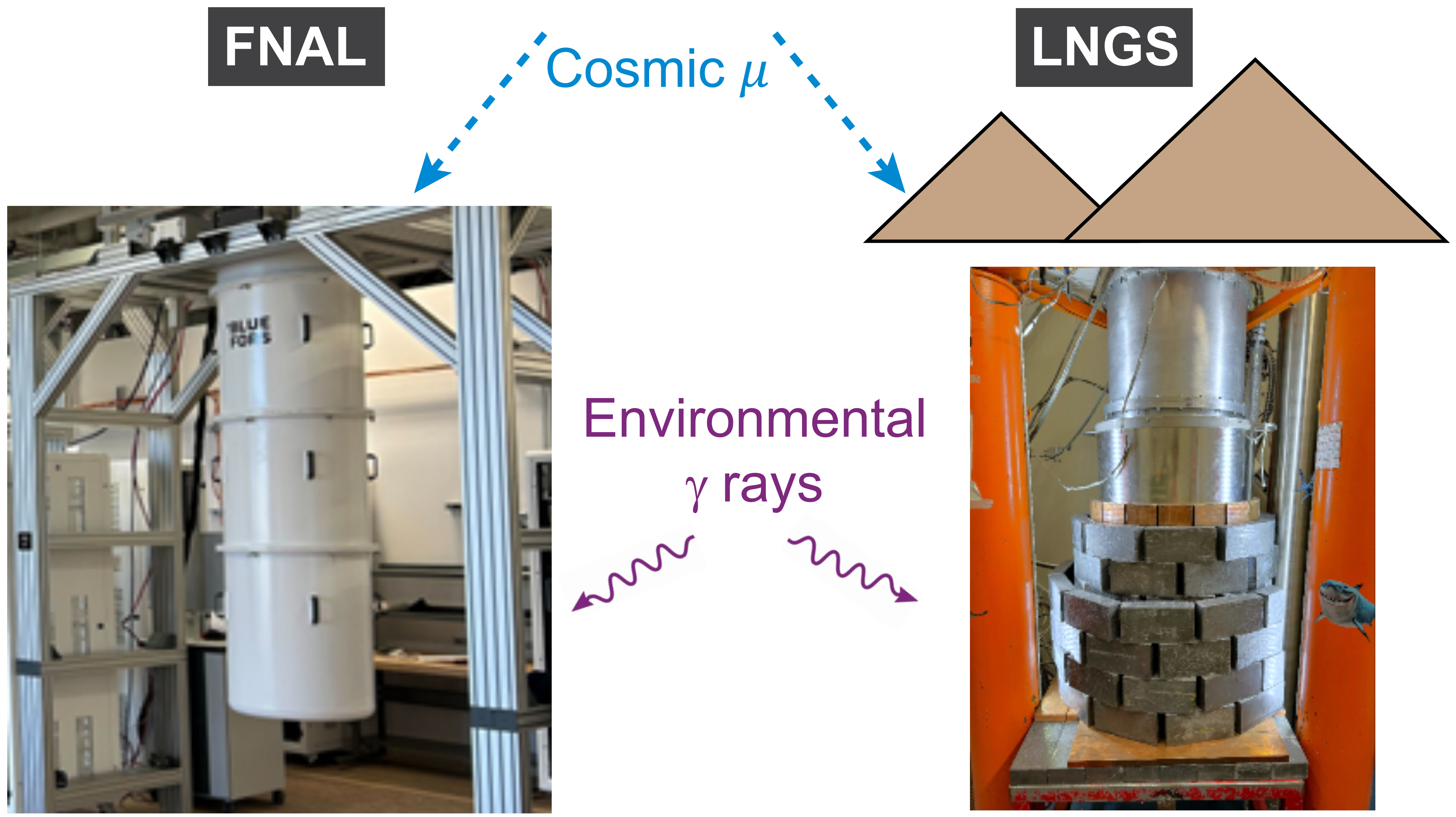
Trigger on **four** consecutive zeros: noise from qubit decay *O*(0.1-1) ev/second



Results

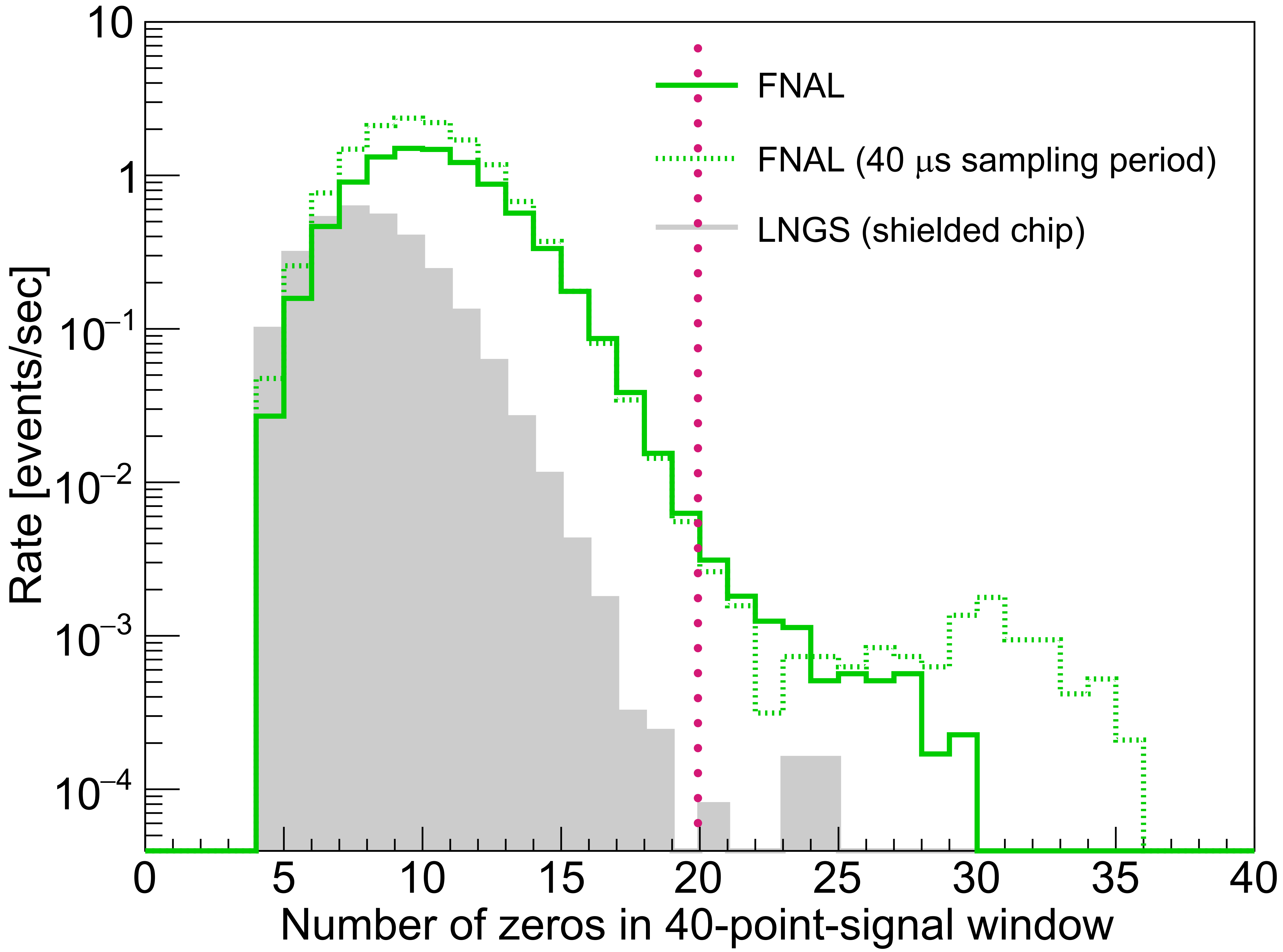
We count the number of zeros in the signal window (of 40 points)



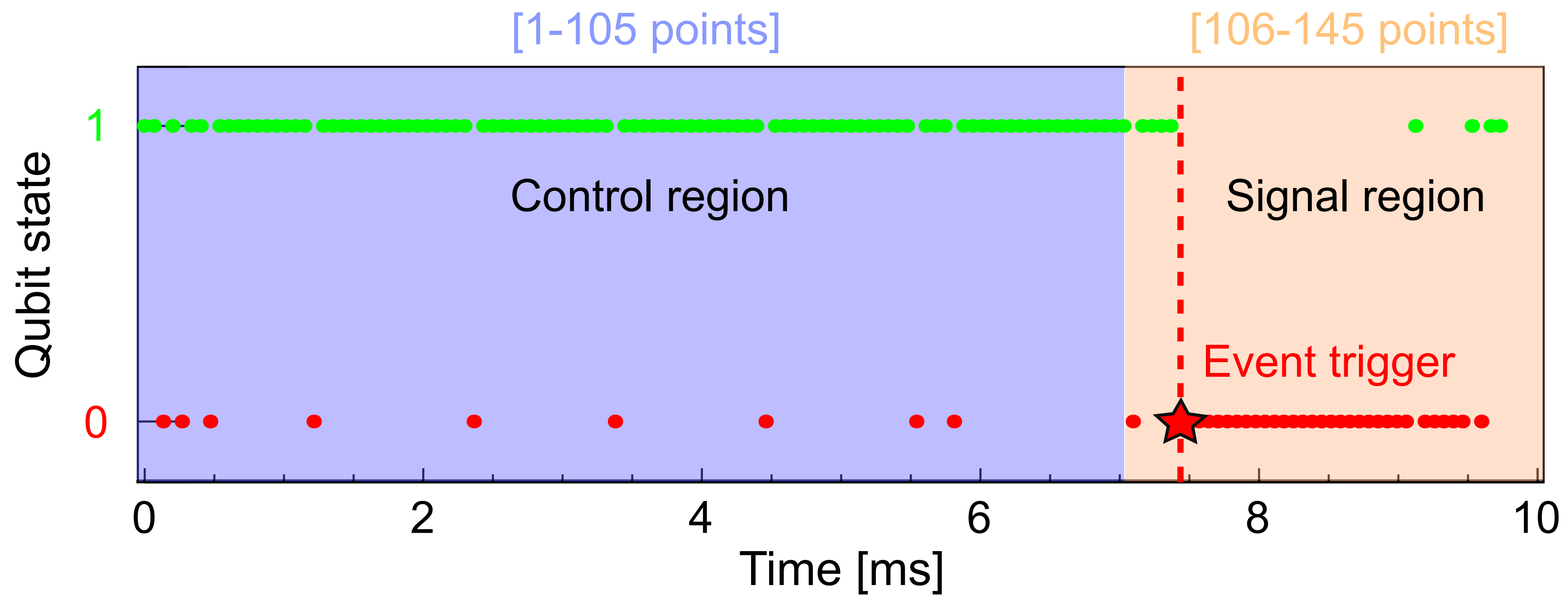


Analysis Selection

We count the number of zeros in the signal window (of 40 points)



We ask the number of zeros in the signal region to be not-compatible with qubit decay

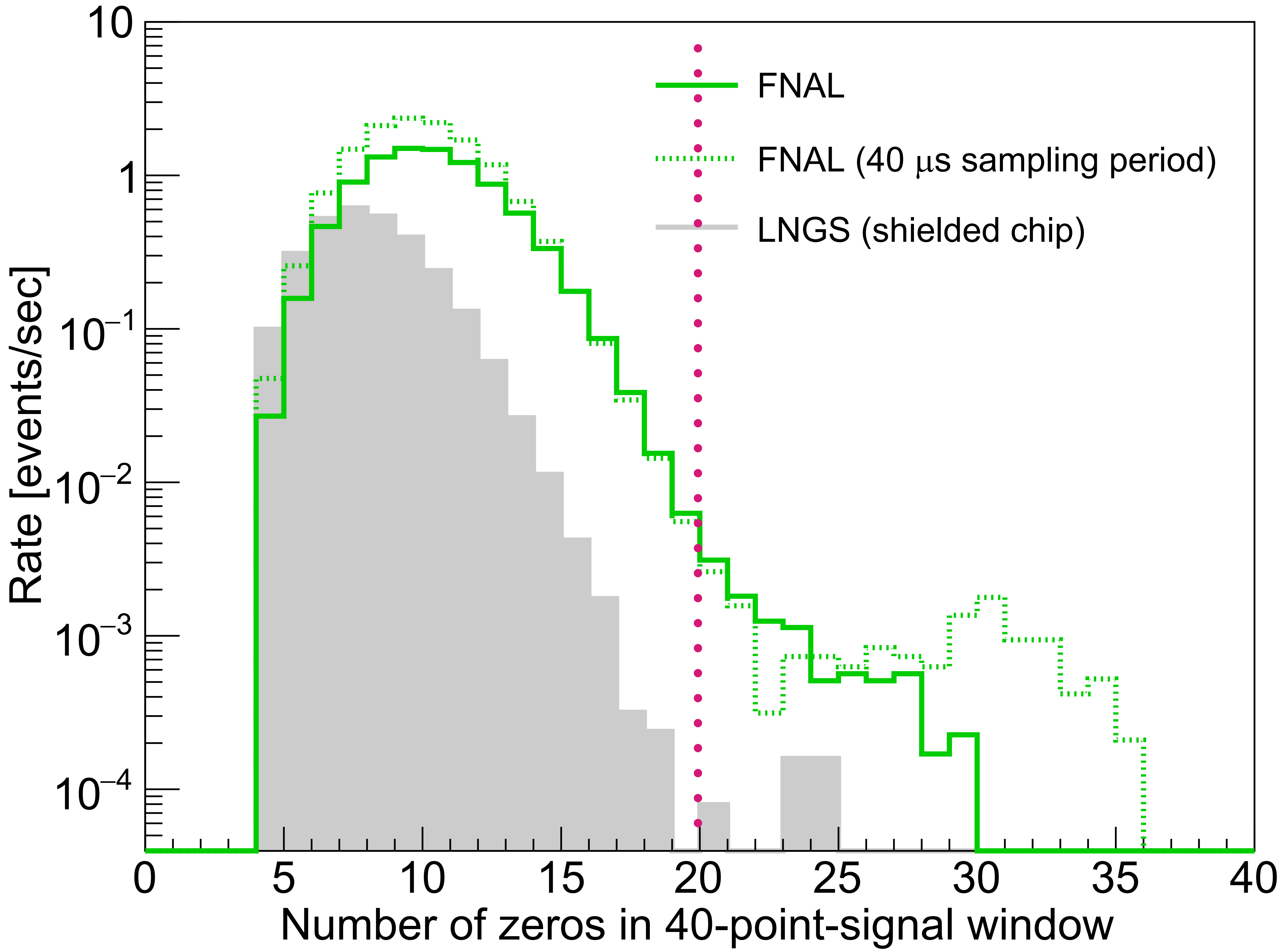


Define *not compatible*?

We use Binomial distribution with P(0) computed before trigger

Results

We count the number of zeros in the signal window (of 40 points)



	FNAL [ev/second] x 10^{-3}	**Gran Sasso [ev/second] x 10^{-3}**
Expected	42 ± 3	4.0 ± 0.6
Measured	4.68 ± 0.26	0.40 ± 0.18

Results

We count the number of zeros in the signal window (of 40 points)

At Gran Sasso, we were expecting x10 less events than at FNAL

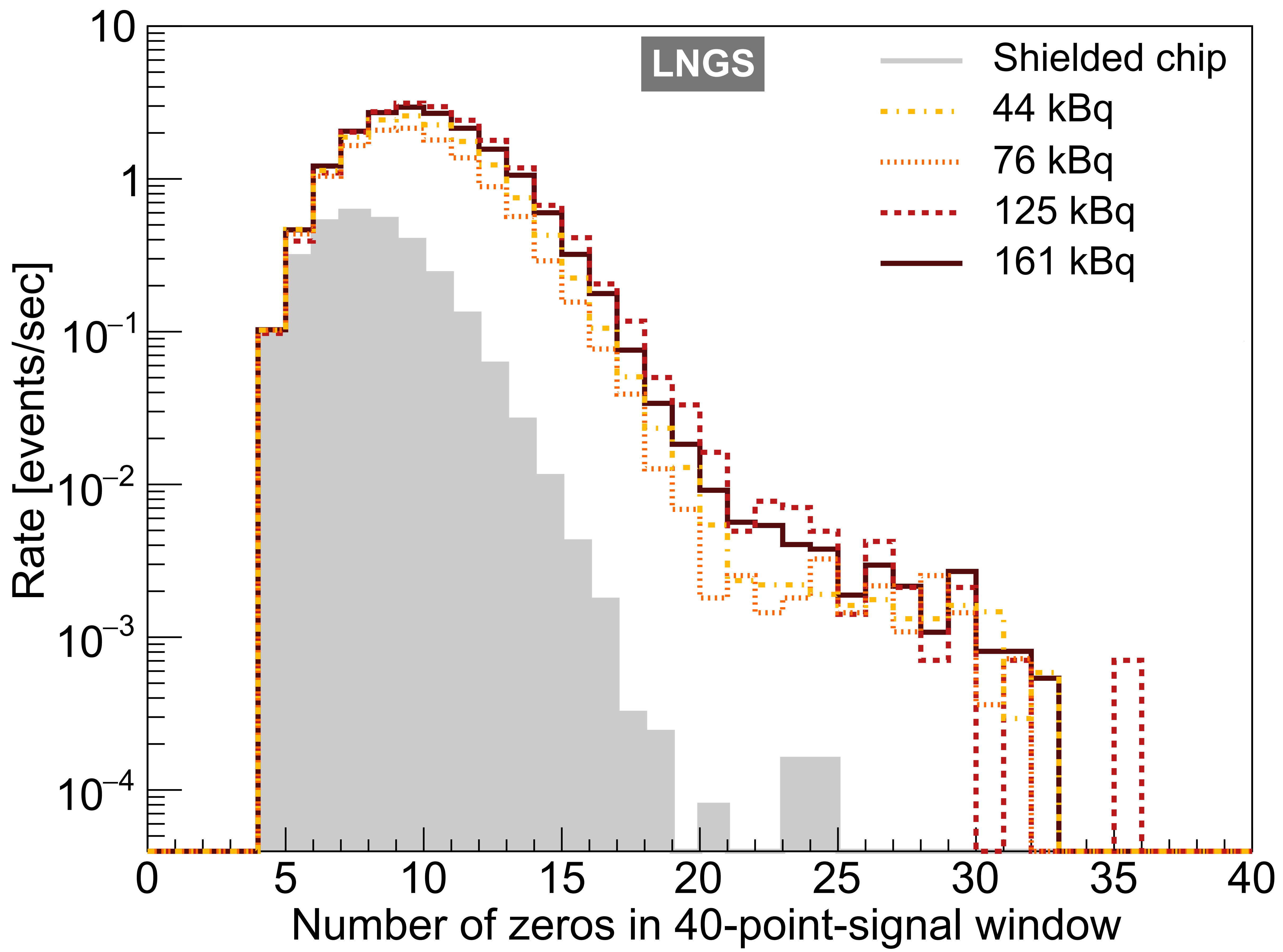
—> true

But in both cases, this scheme allows to detect about 10% of the events

	FNAL [ev/second] x 10^{-3}	Gran Sasso [ev/second] x 10^{-3}
Expected	42 ± 3	4.0 ± 0.6
Measured	4.68 ± 0.26	0.40 ± 0.18

Validation

We exposed the chip operated at Gran Sasso to a controlled radioactive source



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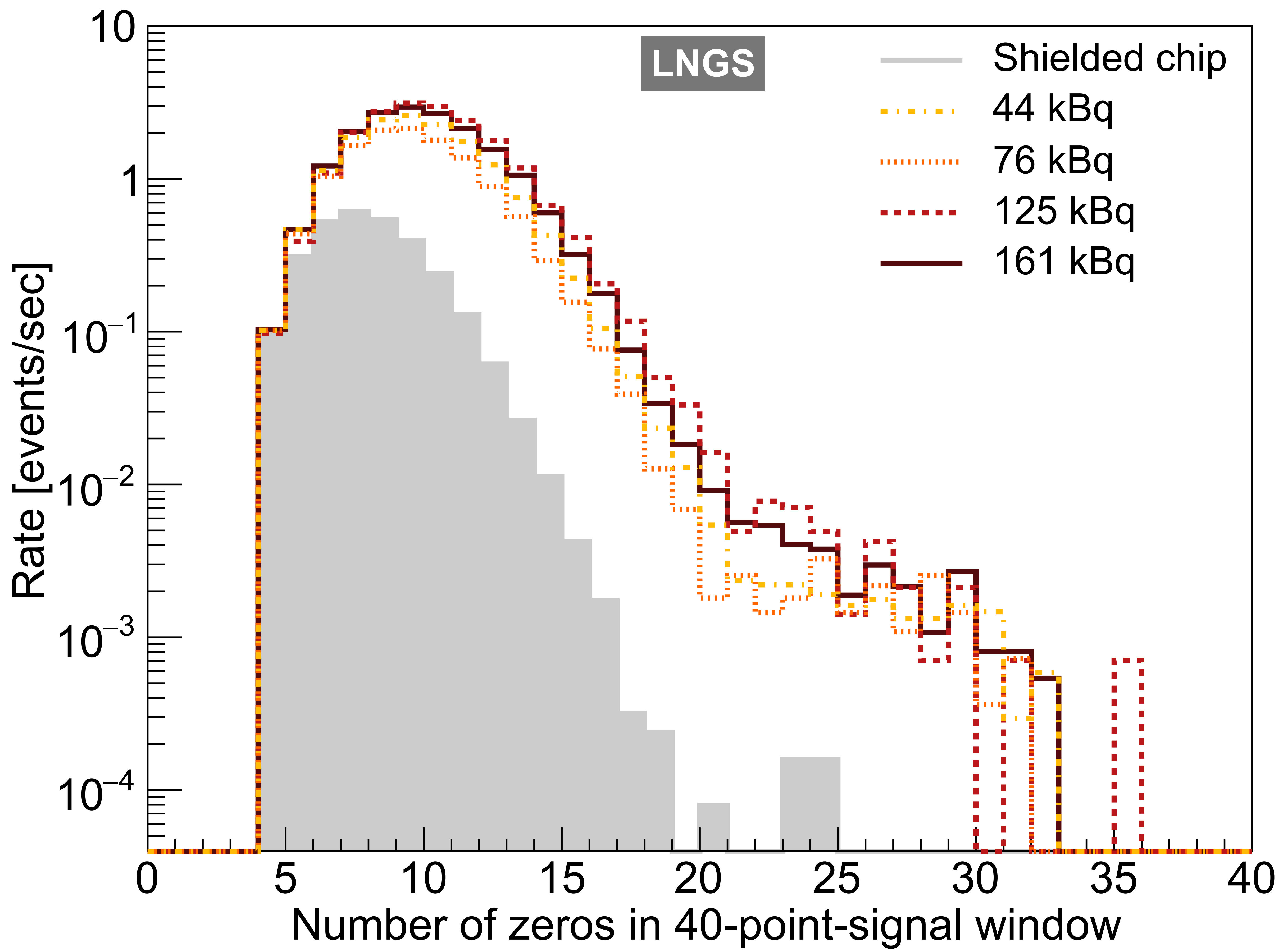
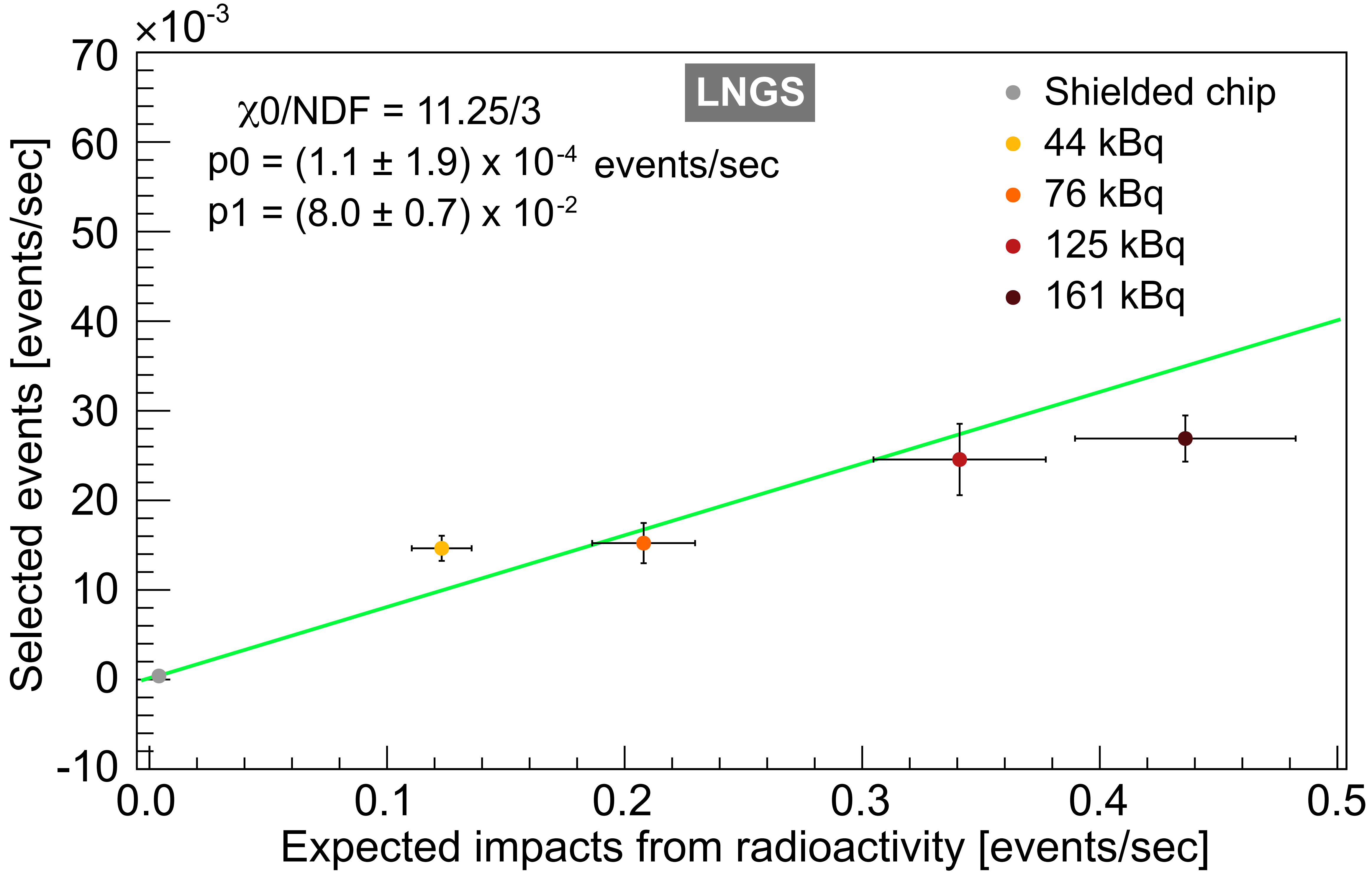


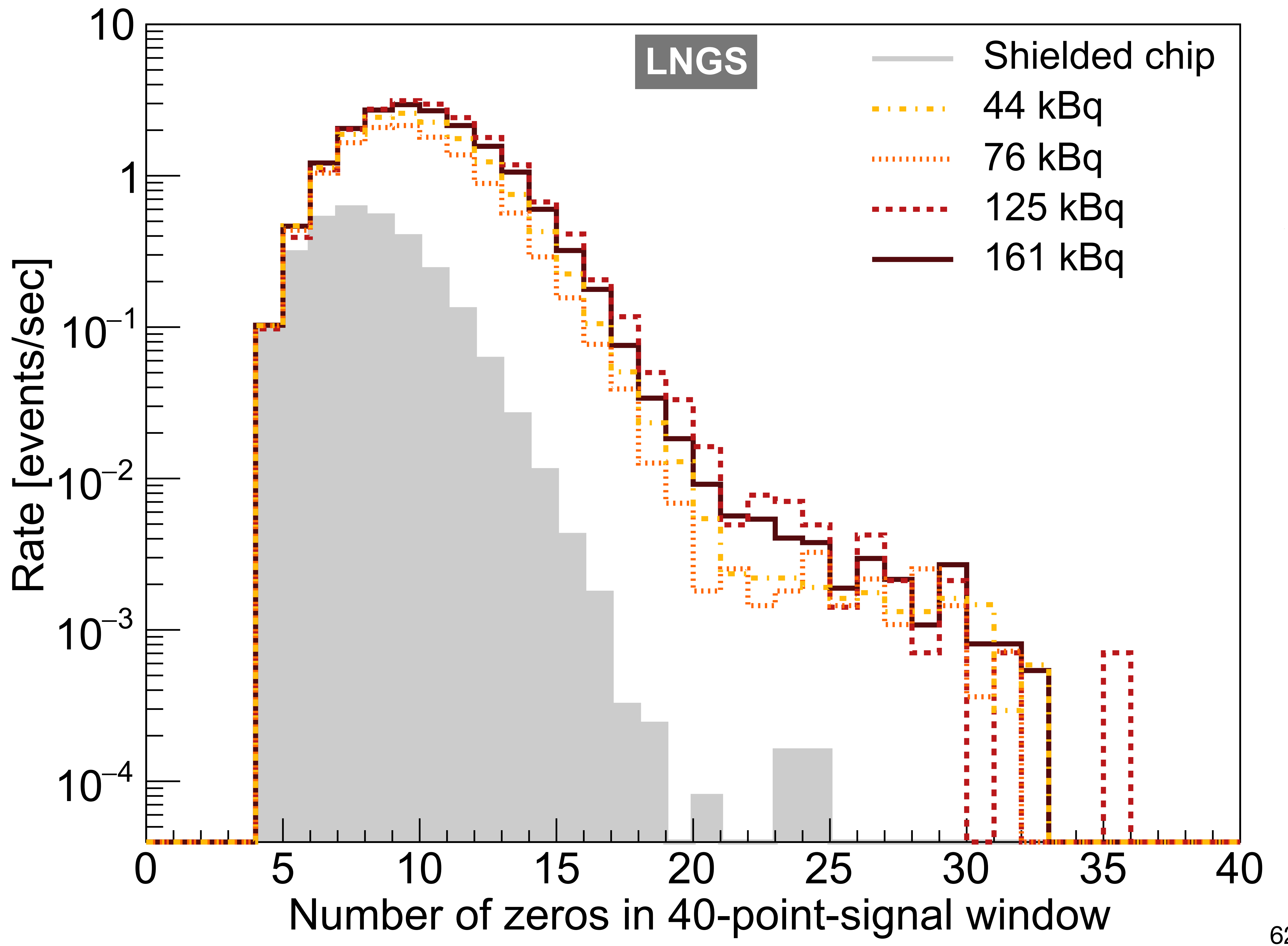


Again, about 8% efficiency

Why?

Are transmon really sensitive to 10% of the radioactive impact in their chips?

Or is our protocol to be improved?



How can we

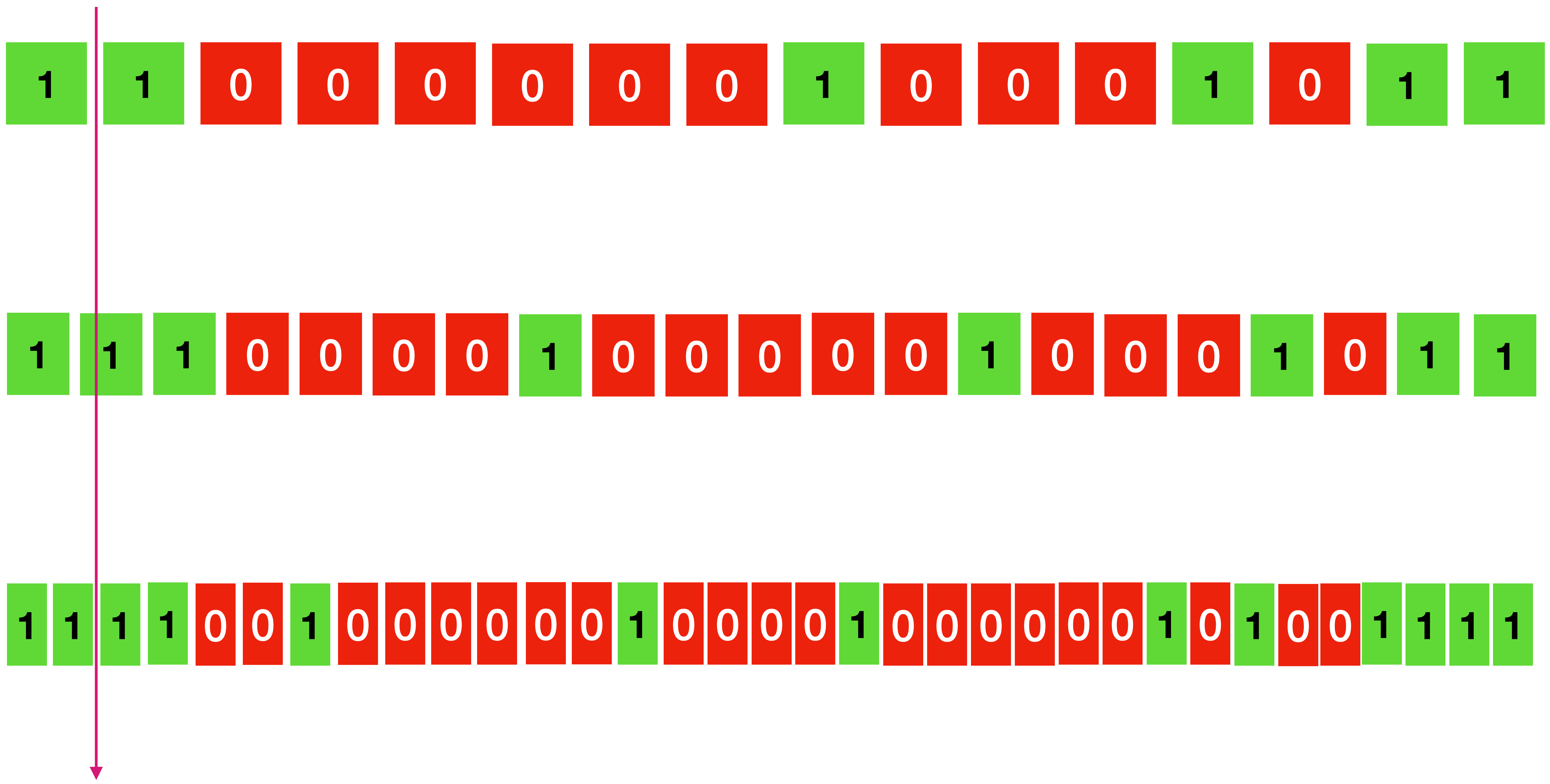
- Increase the signal?
- Diminish the noise?

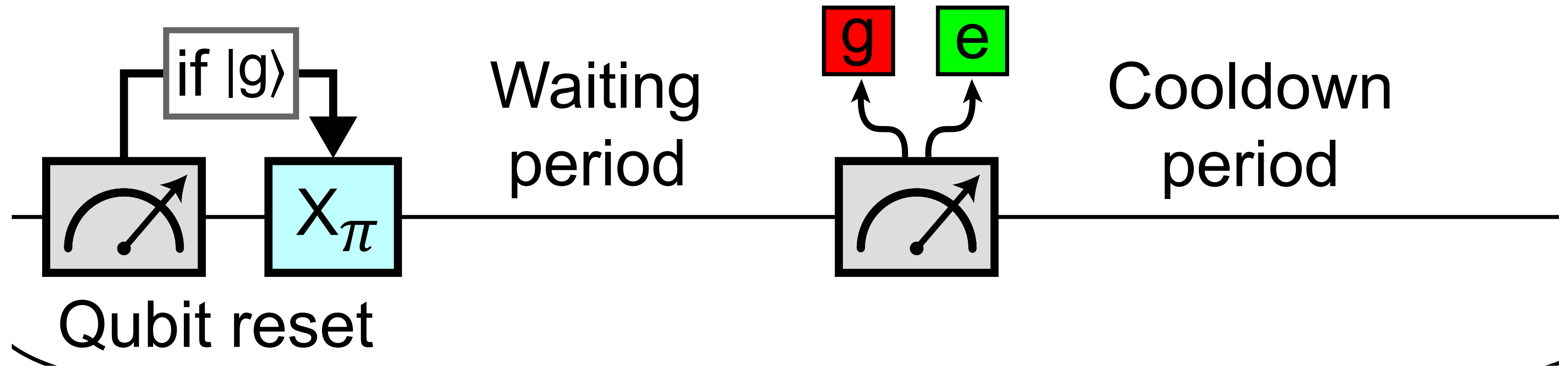
Increasing the Signal

INFN
Istituto Nazionale di Fisica Nucleare

We produce 20-30 zero’s but about 10 of them are due to spontaneous qubit decay

If we run our protocol faster, we should be able to see more zeros from signal





An improvement

We produce 20-30 zero's but about 10 of them are due to spontaneous qubit decay

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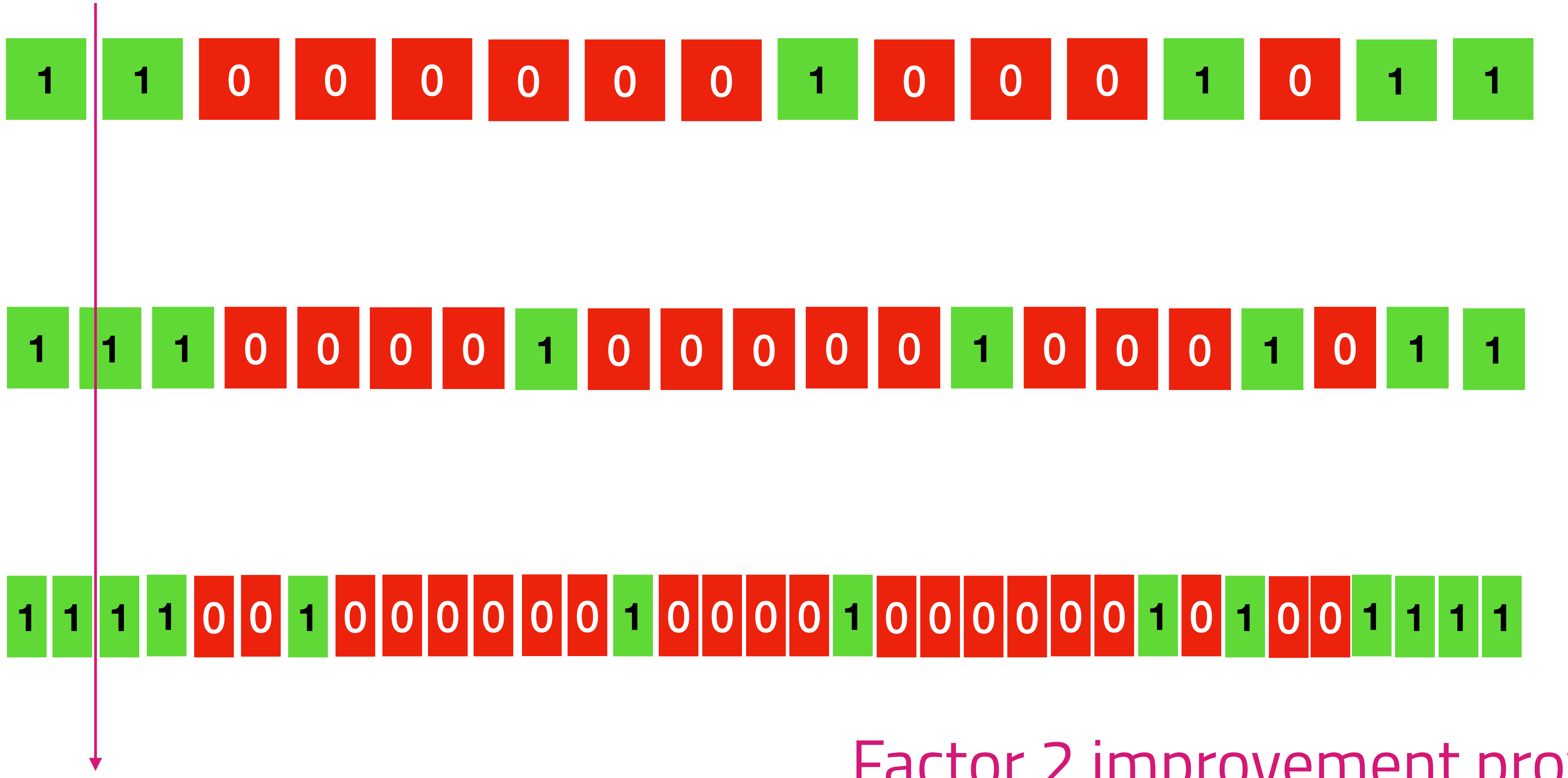
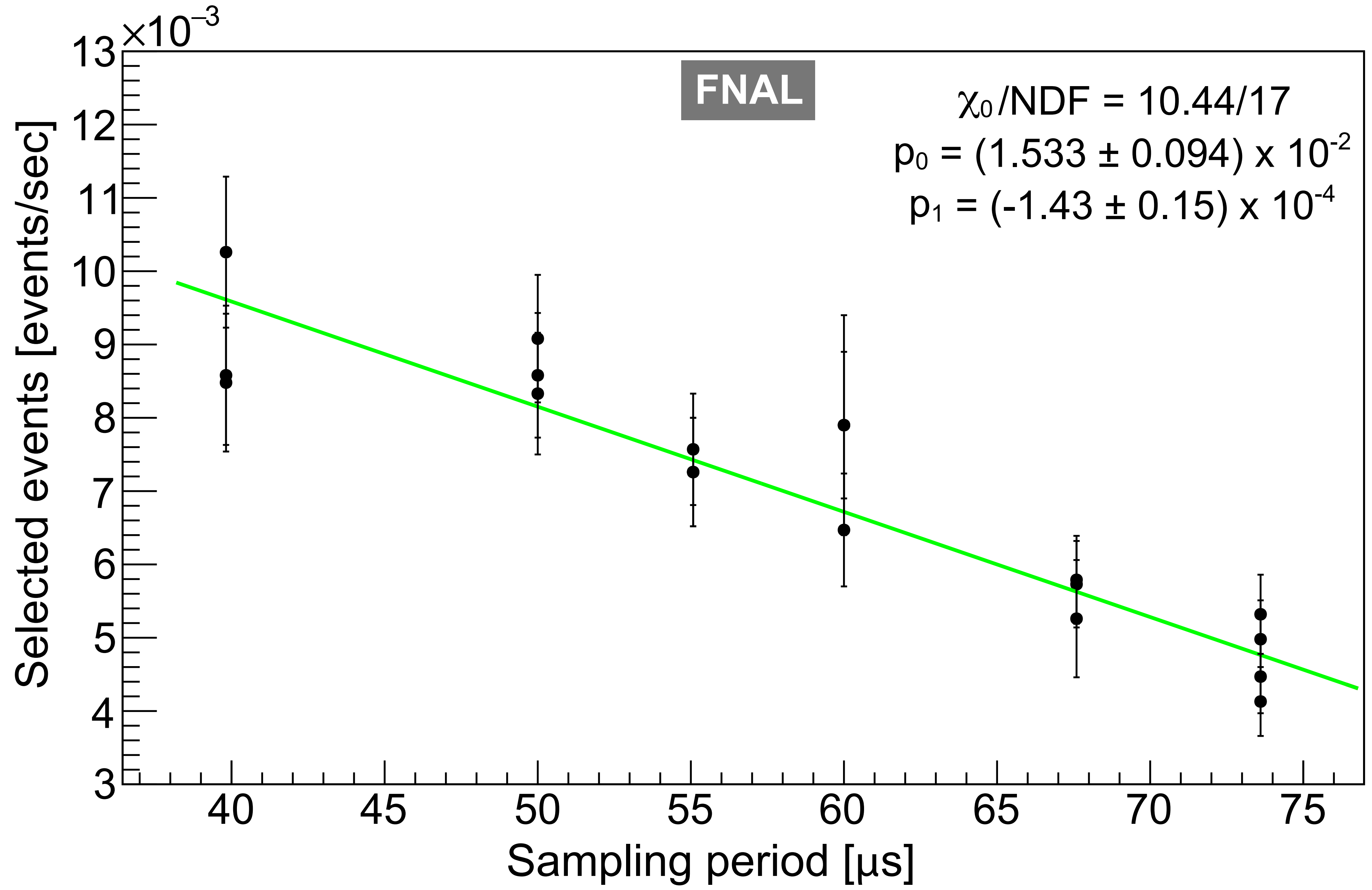
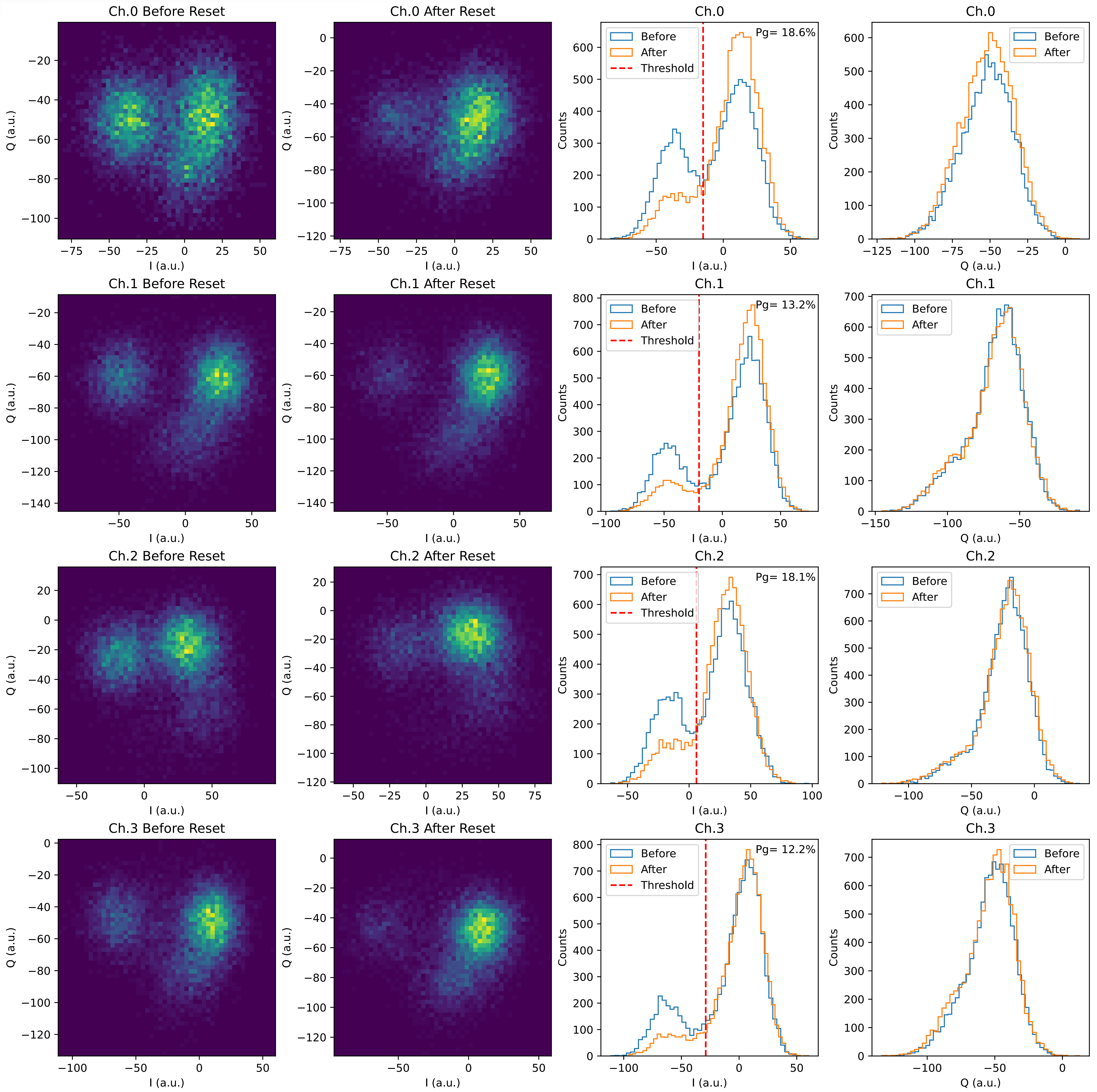




Factor 2 improvement proved

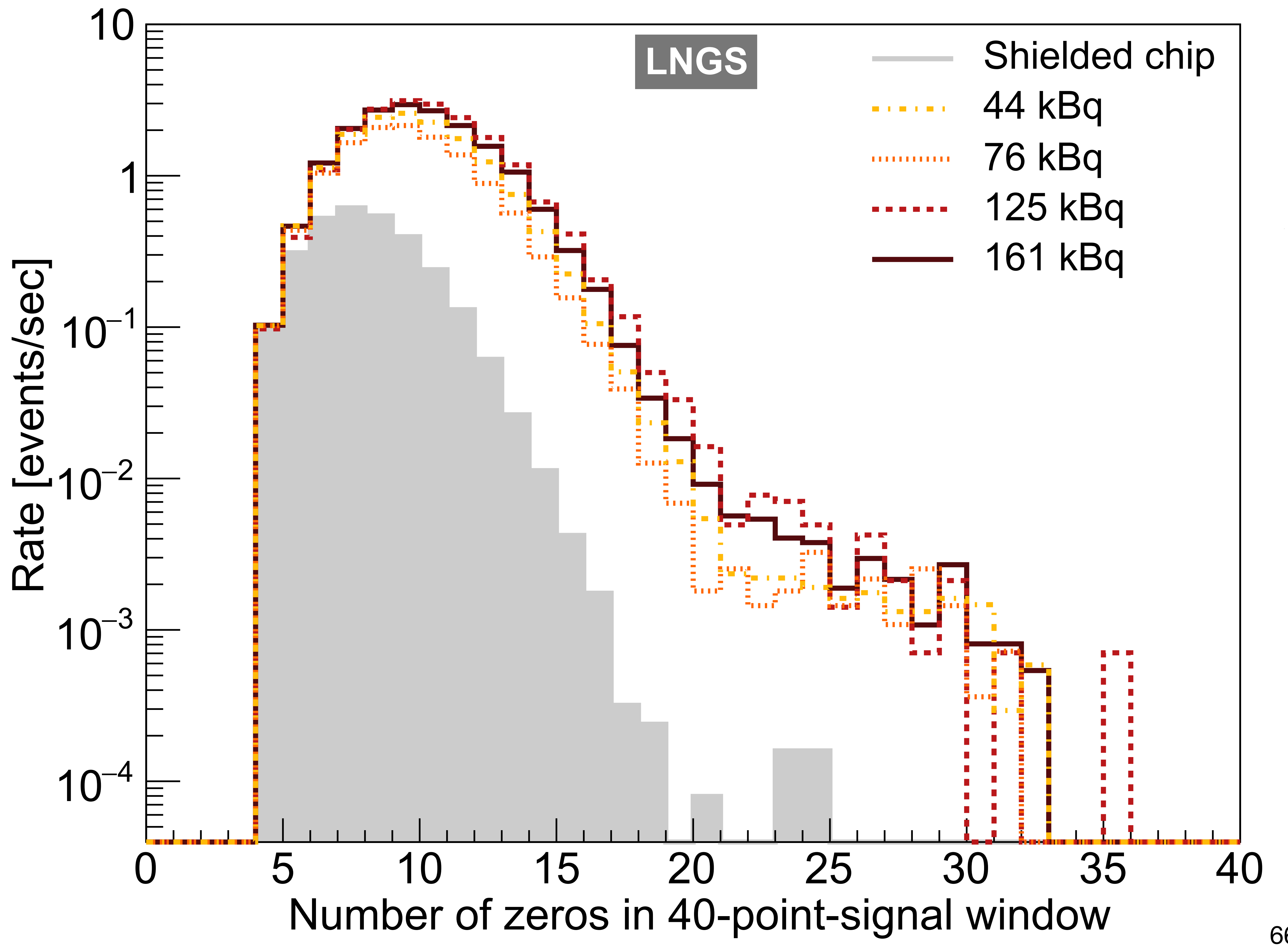
Another strategy: Multiplexing



Suppressing the noise

Are transmon really sensitive to 10% of the radioactive impact in their chips?

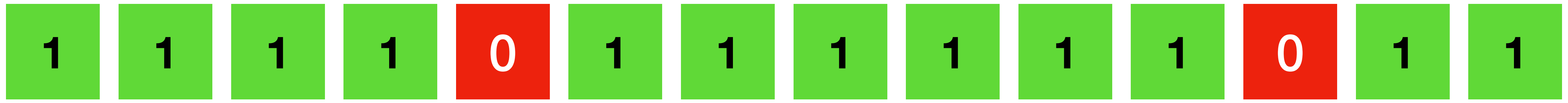
Or is our protocol to be improved?

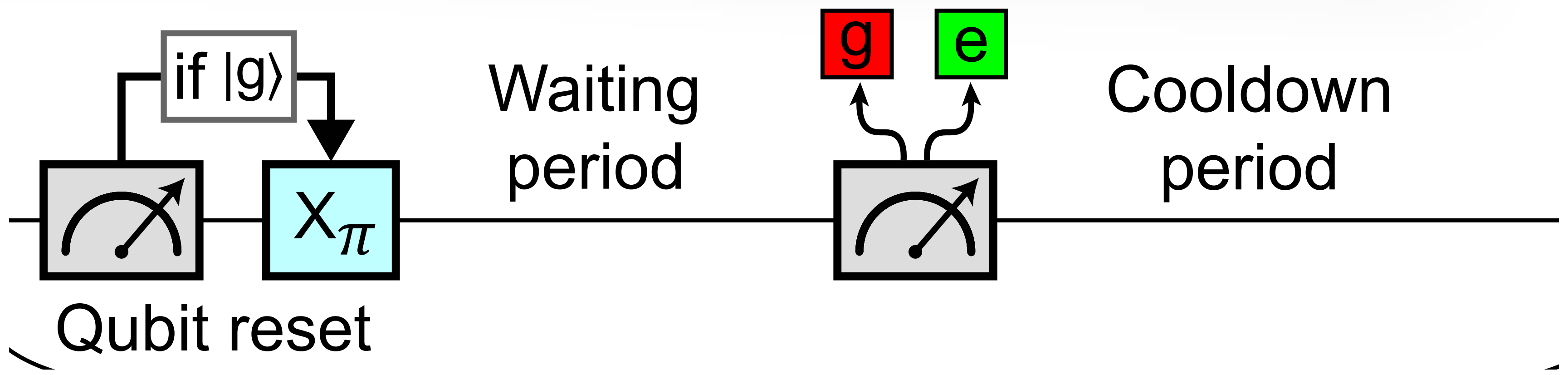


How can we

- Increase the signal?
- Diminish the noise?

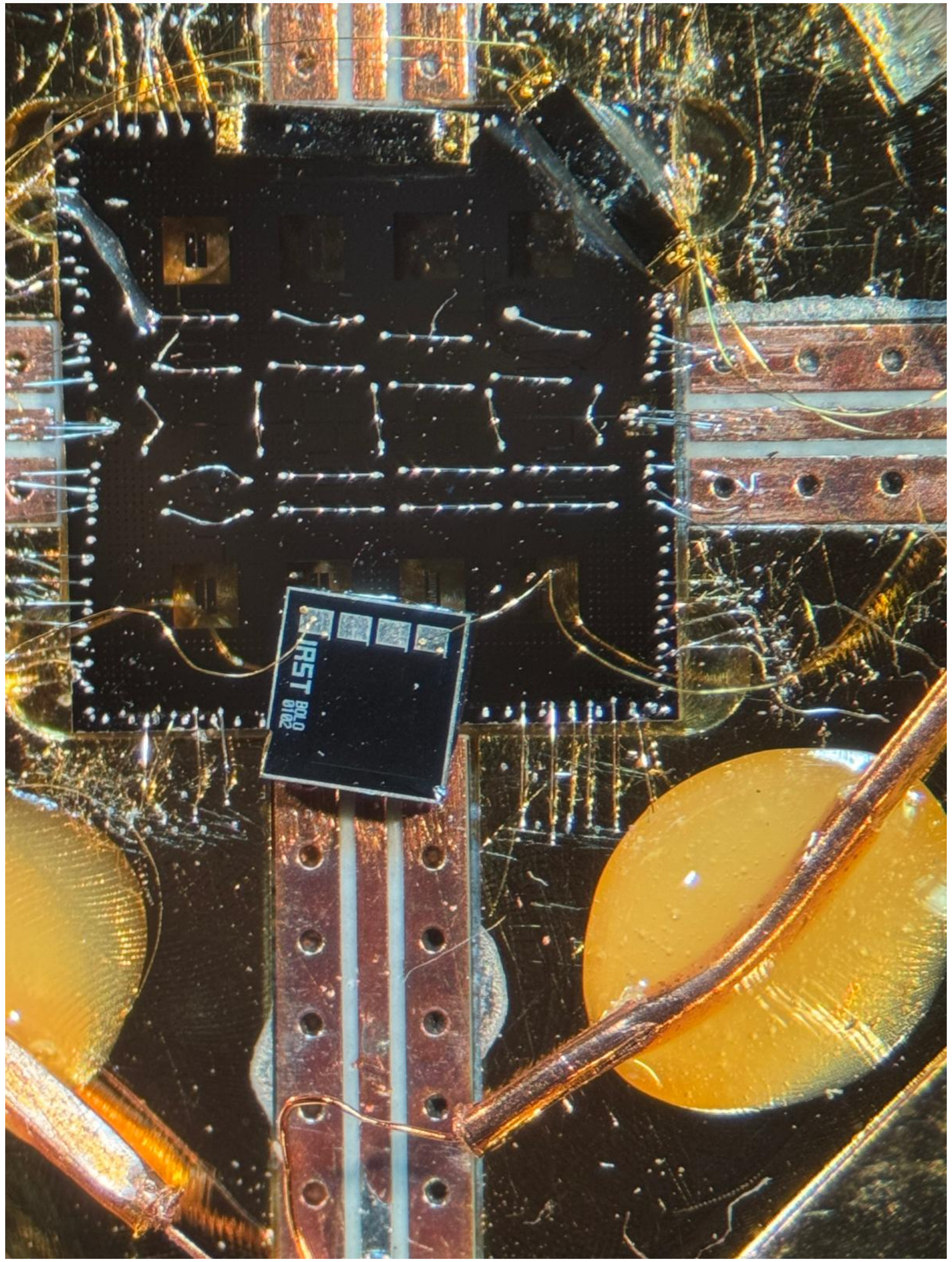
Suppressing the Noise





- Qubit spontaneous decay:
  - $P_0 \sim T_{Idle}/T1$
    - T1 depends on qubit
    - Make T_{Idle} faster
- Fidelity:
  poor separation of I/Q state -> misidentified

What next



Transmons proved to be sensitive to ~20% of impacts

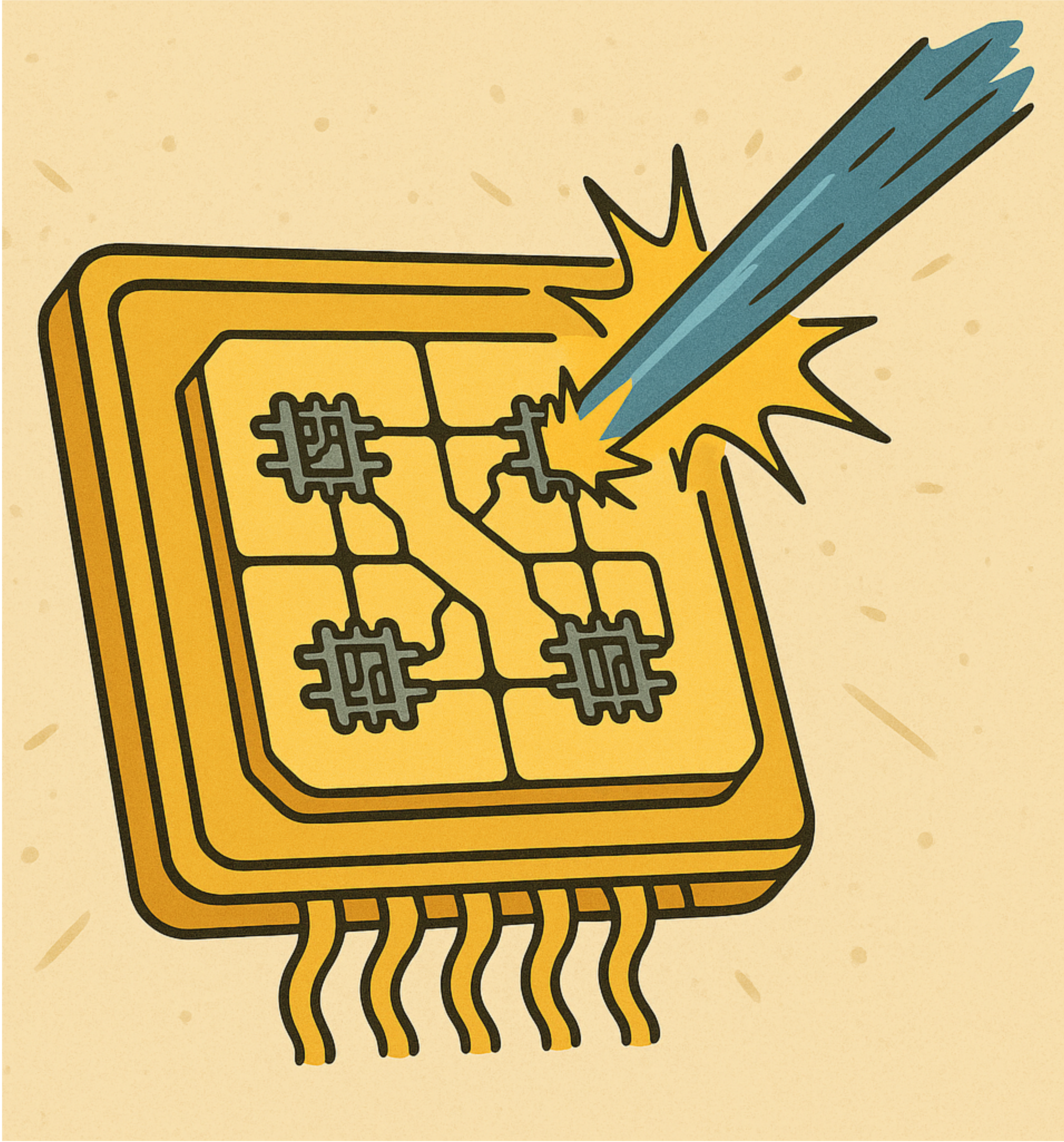
Now we have a chip with slightly longer T_1~300 µs

- Faster protocol (increase signal)
- Multiple qubits to suppress noise
- Increased the fidelity from 70 to >90% using a TWPA

Goal: Demonstrate that transmon are sensitive to much more than 20% or radioactive impacts

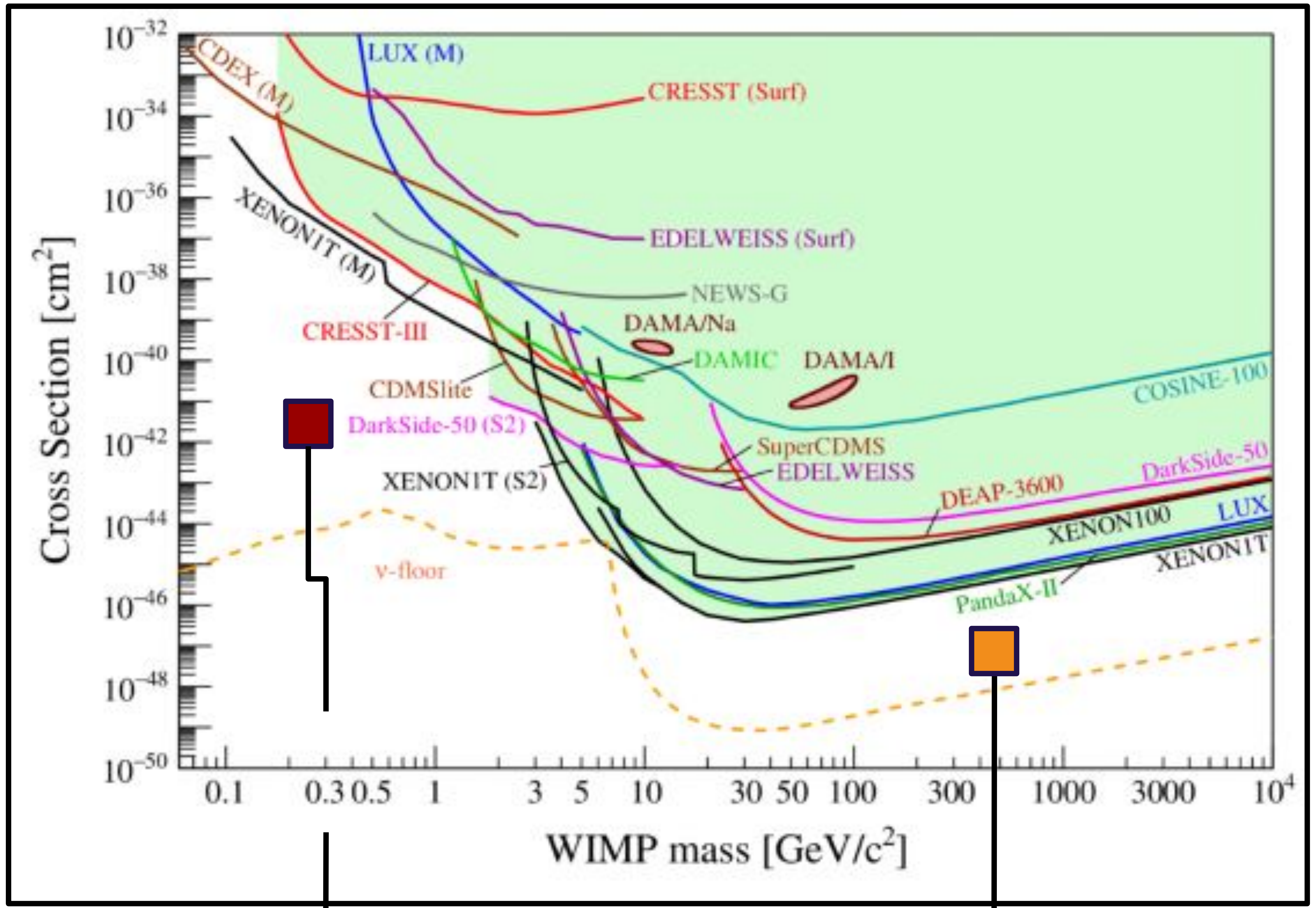
Recap

- Mitigation of Radioactivity
  - Where does it come from
  - Shielding
  - Results: microwave resonators
  - Results fluxonium qubits
- Disentangling Radioactivity
- Perspectives for particle detection



What can we do with qubits?

- Evidence of a massive, cold, non baryonic "dark" matter
- Very abundant yet ... no direct detection
- Experiments searching for particle-like DM are excluding region GeV-TeV
- Now looking at lower masses [50 keV - MeV]



Sub-GeV range still mostly unexplored even if still theoretically valuable

High WIMP masses largely excluded by multi-ton liquid scintillators

1 MeV dark matter particle that scatters on a nucleus would require a threshold as low as 1eV

What can we do with qubits?

- Evidence of a massive, cold, non baryonic "dark" matter
- Very abundant yet ... no direct detection
- Experiments searching for particle-like DM are excluding region GeV-TeV
- Now looking at lower masses [50 keV - MeV]

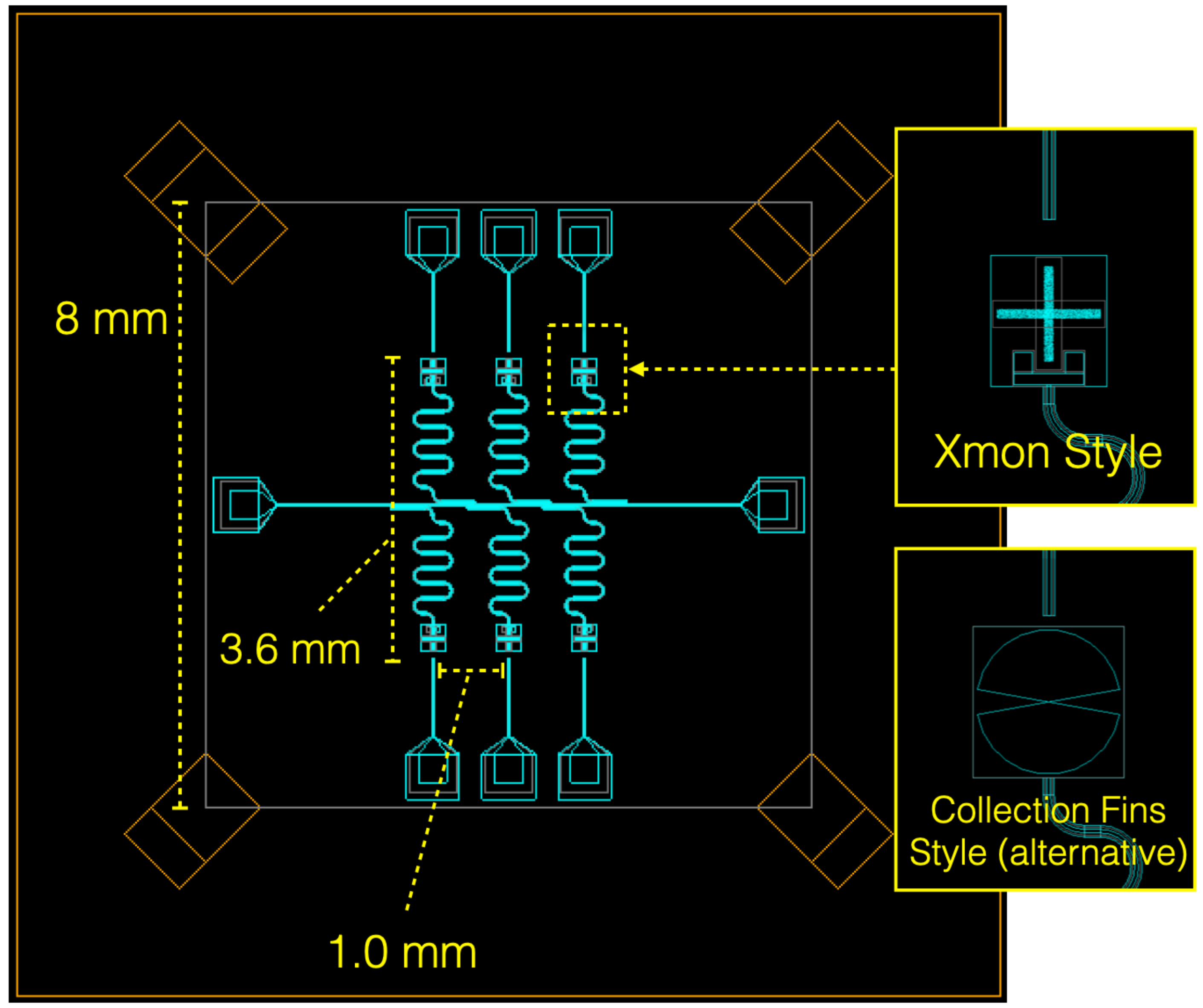
Qubits have very small transition frequencies

- 4.1 GHz = 1×10^{-5} eV
- Tiny energy deposits can affect qubits
- Can we hope to convert them into phonon detectors?

1 MeV dark matter particle that scatters on a nucleus would require a threshold as low as 1eV

Qubits as "phonon detectors"

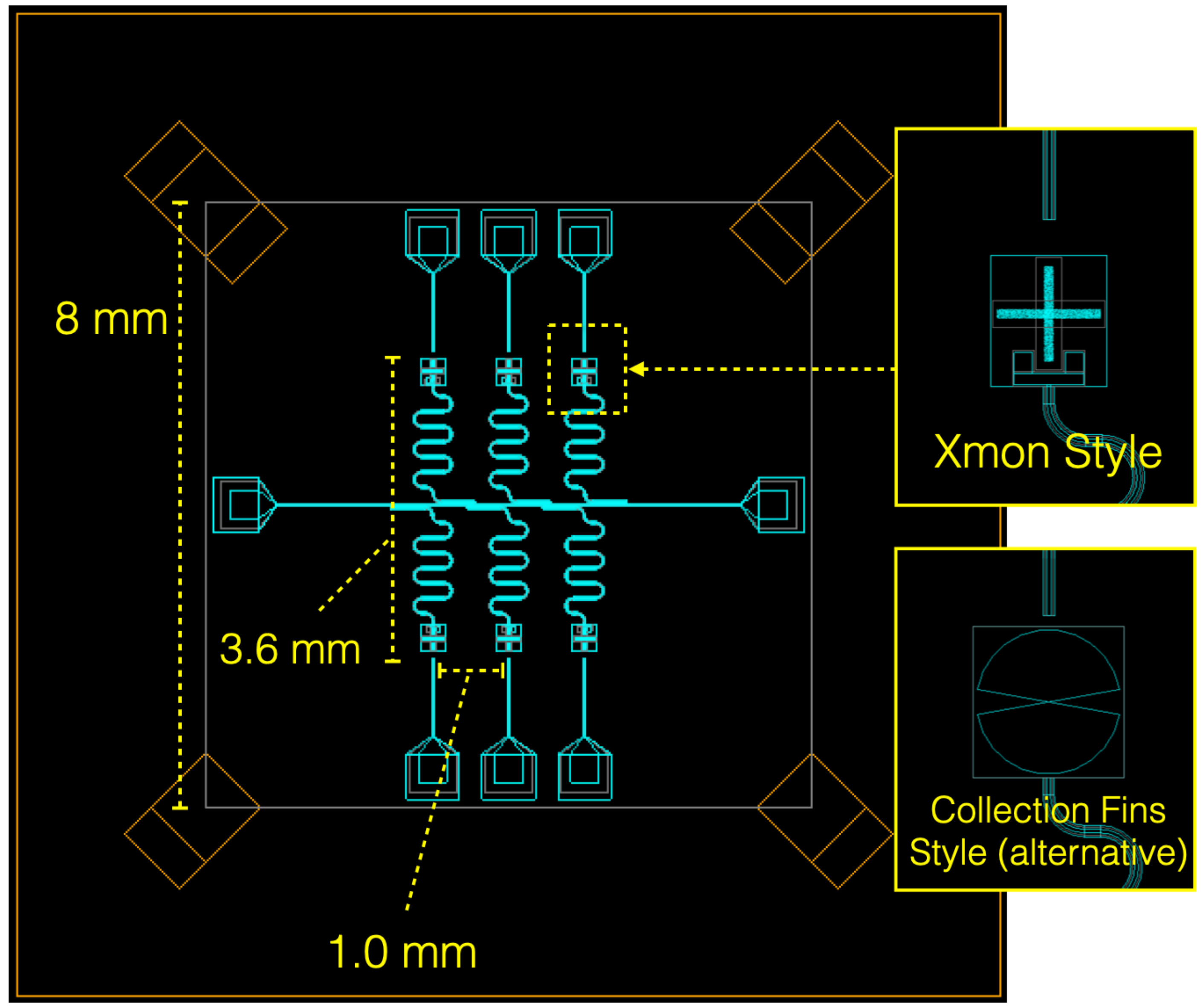
- Simulated potential of transmon qubits for particle detection
- Chip with 6 transmon in three configuration
  - "full" ground plane, which is standard
  - Limited ground plane
  - Change of qubit design adding collection fins



Linehan 2025

Phonons evolution

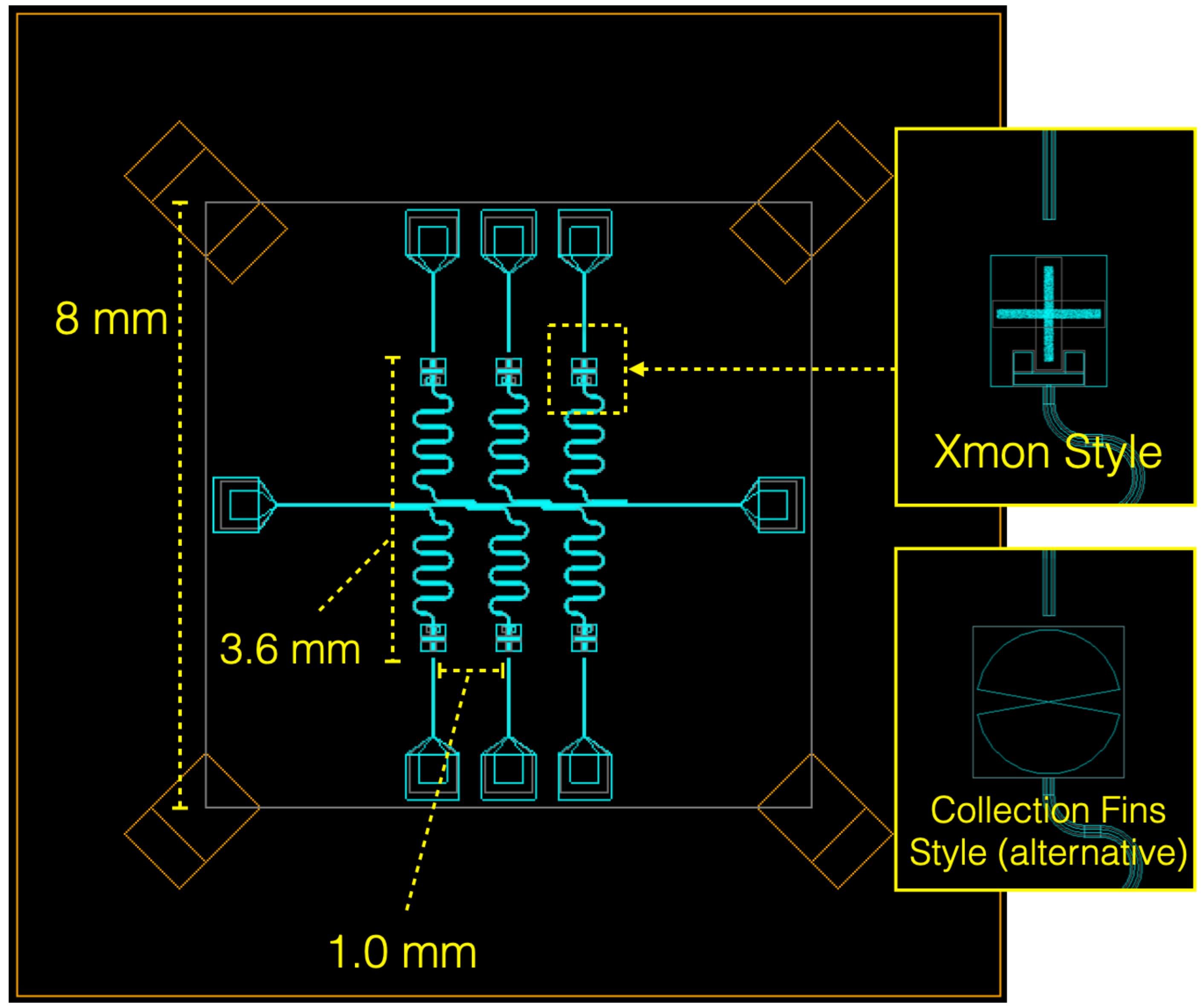
- Phonons down convert to less energetic phonons that travel ballistically in the substrate
- Phonons scatter on isotopic impurities within the lattice
- When the mean free path for both processes are longer than device dimensions, phonons stream unimpeded
- Typical silicon substrates: phonons are ballistic < 6 meV



Linehan 2025

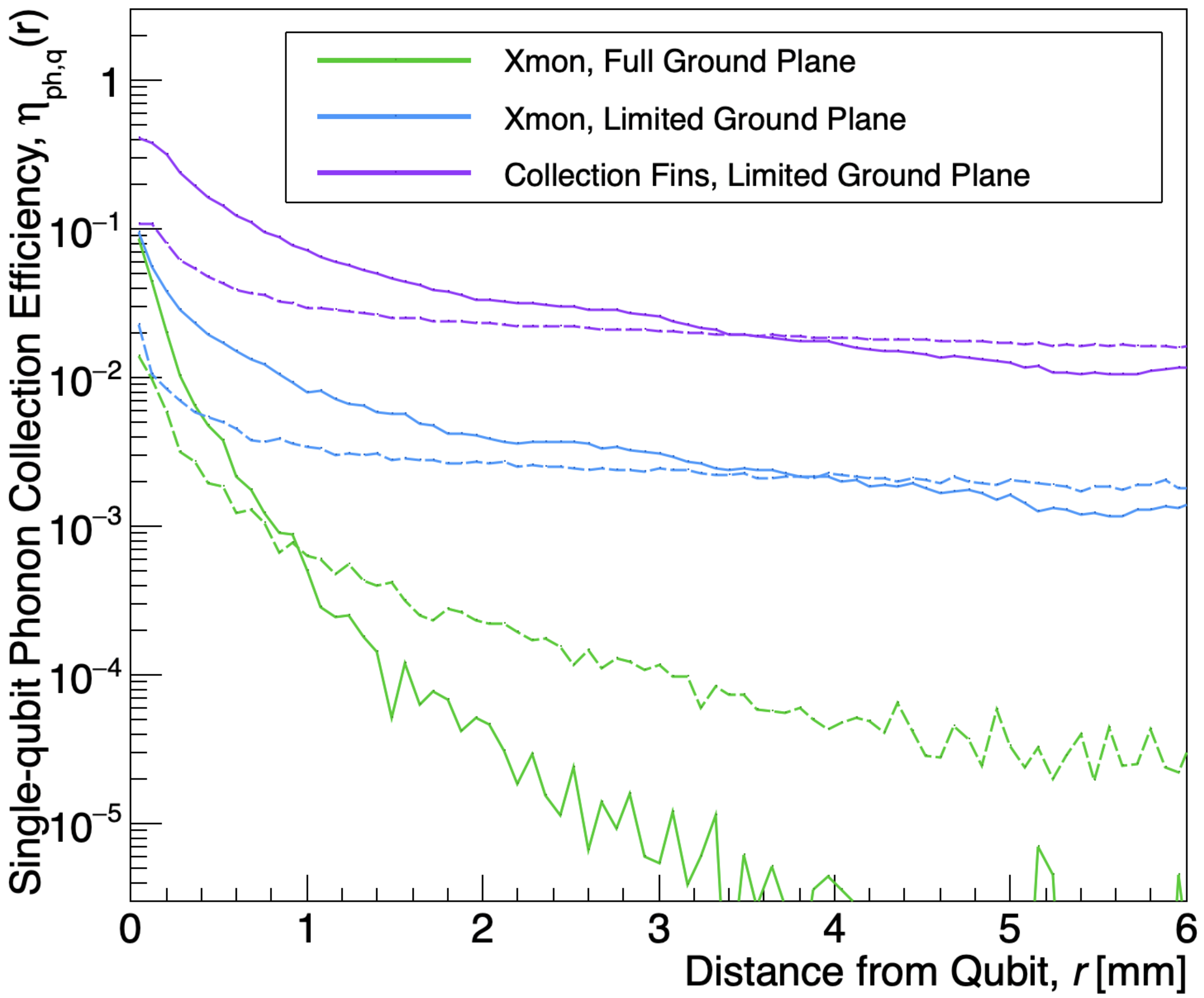
Phonons absorption

- Phonons down convert to less energetic phonons that travel ballistically in the substrate
- Phonons scatter on isotopic impurities within the lattice
- When the mean free path for both processes are longer than device dimensions, phonons stream unimpeded
- Typical silicon substrates: phonons are ballistic < 6 meV
- These phonons travel, can be absorbed by superconductor (qubit OR ground plane)
- The copper thermalisation compete in absorbing phonons



$$p_{a,s} \simeq 1 - \exp\left[-\frac{2l}{\pi v_s \tau_0^{ph}} \left(\frac{E_{ph}}{\Delta} \right) \right]$$

Phonon absorption: simulation



When making the spatial average of the phonon collection efficiency of the 6 qubits, we get:

- 0.1% for transmons with full ground plane
- 1-2 % for transmons with limited ground plane
- 13-17 % for transmons with collection fins

Kind of known from experiments with microwave resonators

Proposed by Fink et al in 2024

Measurements to be done

Expected Sensitivity

A fraction of phonons is absorbed by the qubit

A fraction of them (0.6 for aluminum) will break Cooper pairs into quasiparticles N_{QP}

$E_{absorbed} = \Delta \times N_{QP}$

Expected Sensitivity

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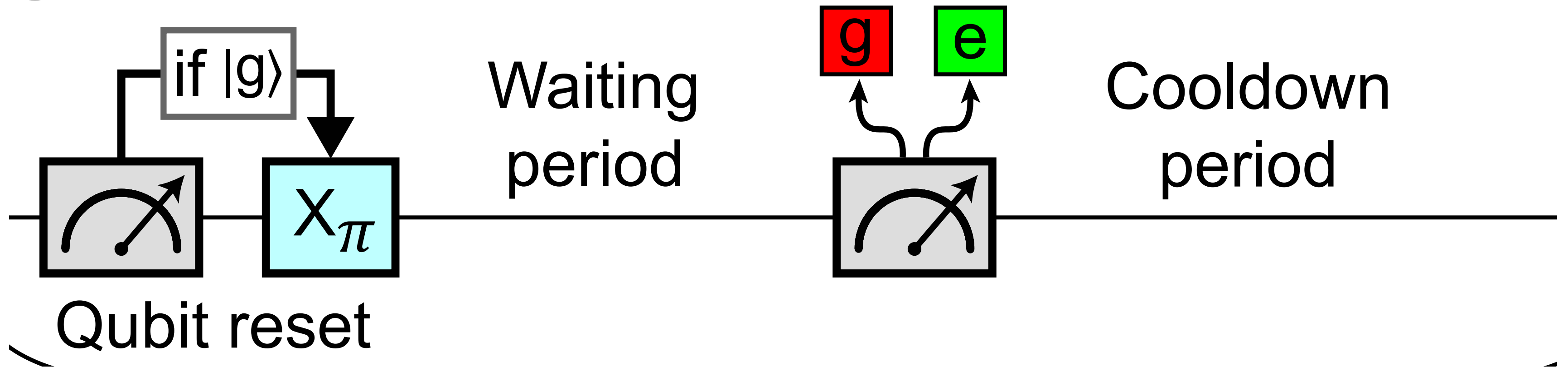
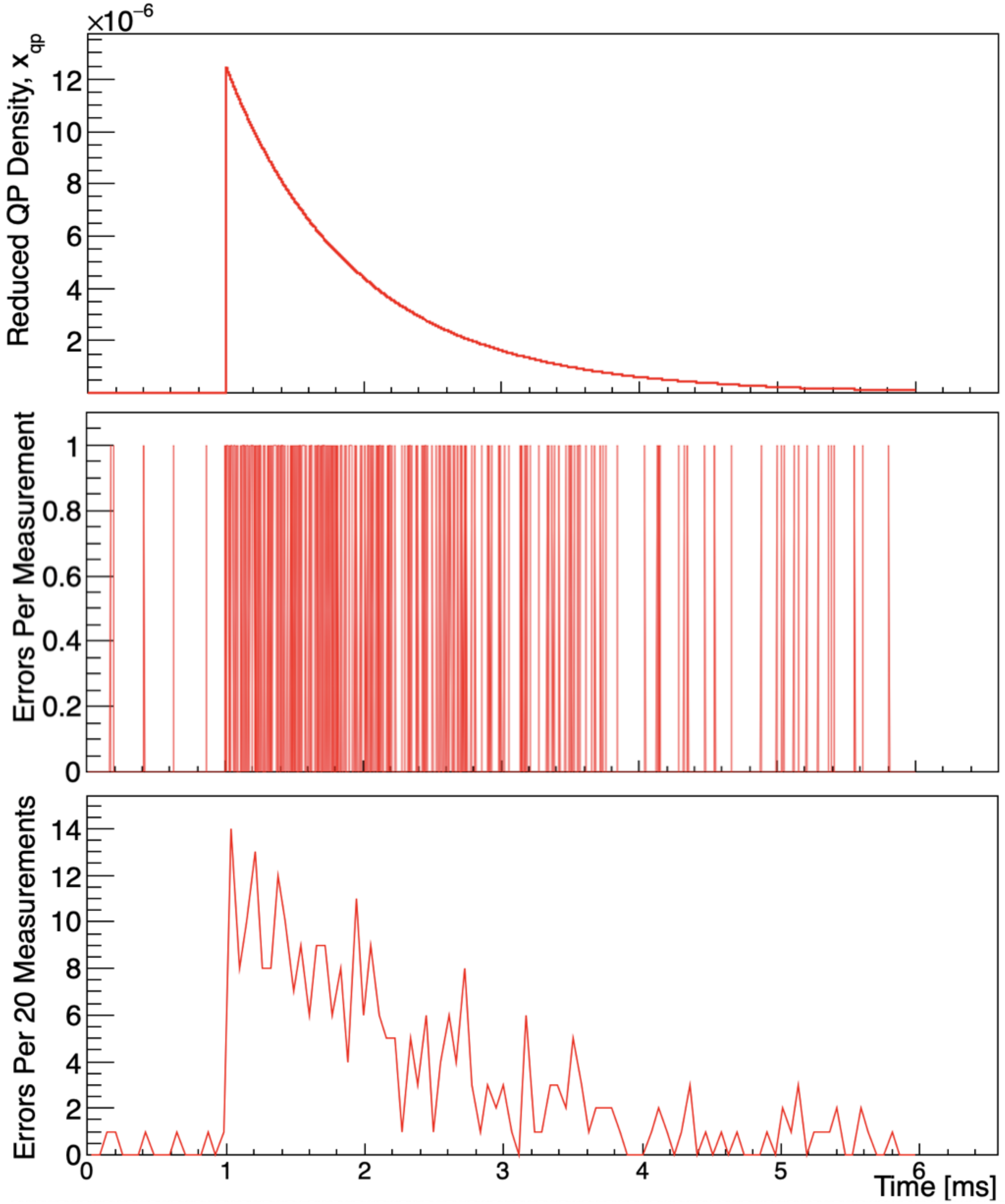
A fraction of them (0.6 for aluminum) will break Cooper pairs into quasiparticles N_{QP}

$E_{absorbed} = \Delta \times N_{QP}$

Make reasonable assumptions for QPs diffusion, recombination, trapping

Run our protocol to extract "events" and simulate their energy





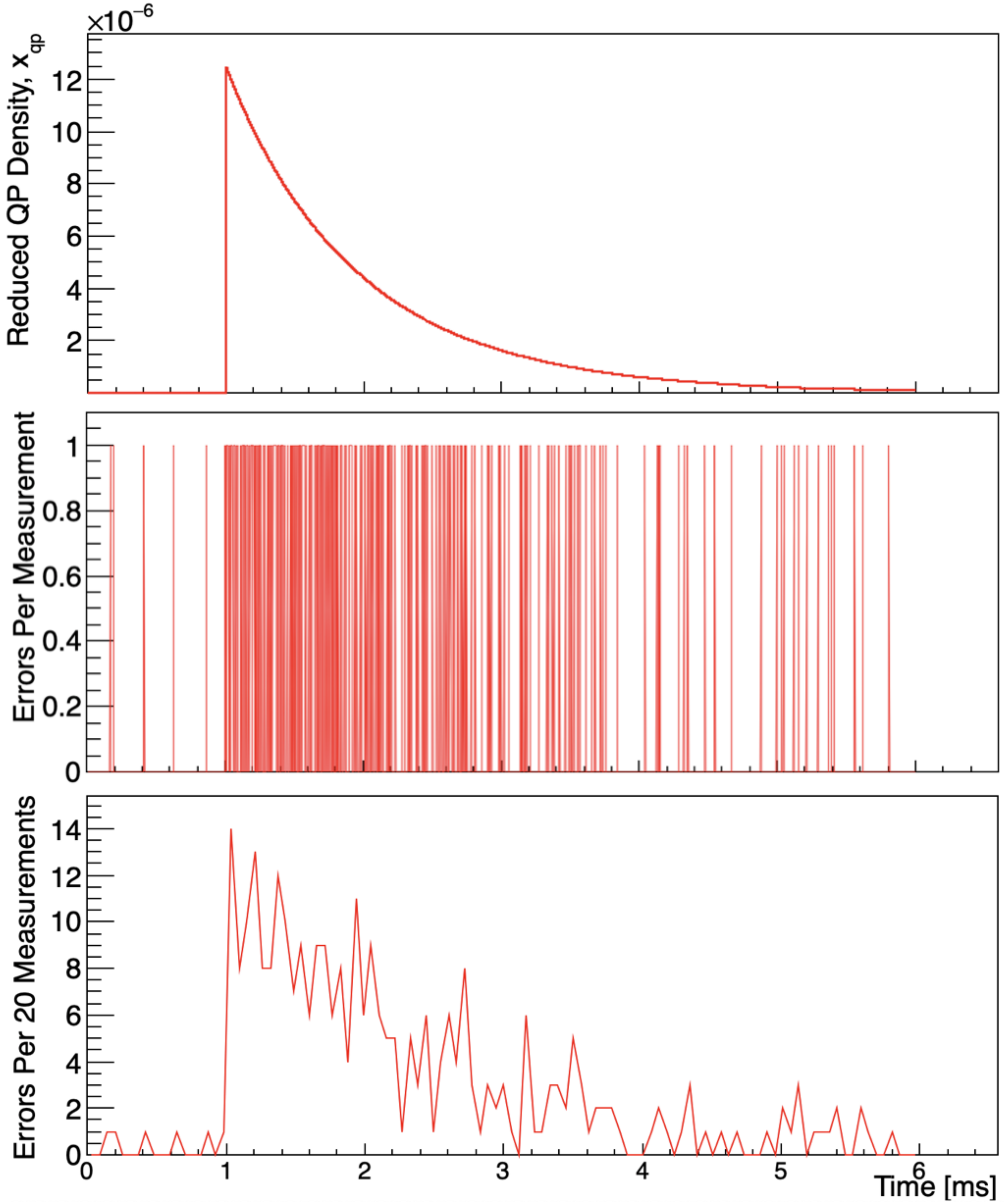
Expected Sensitivity

Qubit Design	Ground Plane	Si-SC phonon absorption prob. $p_{a,s}$	Si-Cu phonon absorption prob. $p_{a,c}$	Spatially-averaged phonon collection eff. $\eta_{ph,sp}$	Chip Threshold $E_{thr,chip}$
Xmon	Full	1.0	0.1	0.14%	737 eV
Xmon	Full	0.1	0.1	0.12%	860 eV
Xmon	Limited	1.0	0.1	2.07%	49 eV
Xmon	Limited	0.1	0.1	1.44%	71 eV
Collection Fins	Limited	1.0	0.1	17.0%	O(0.1) eV
Collection Fins	Limited	0.1	0.1	12.6%	O(0.1) eV

In principle, standard transmon can match the sensitivity of MKIDs resonators (but are far from the one of TES)

However, they have the unique potential to go to much much lower thresholds

—> very exciting field



Caveat

Qubit Design	Ground Plane	Si-SC phonon absorption prob. $p_{a,s}$	Si-Cu phonon absorption prob. $p_{a,c}$	Spatially-averaged phonon collection eff. $\eta_{ph,sp}$	Chip Threshold $E_{thr,chip}$
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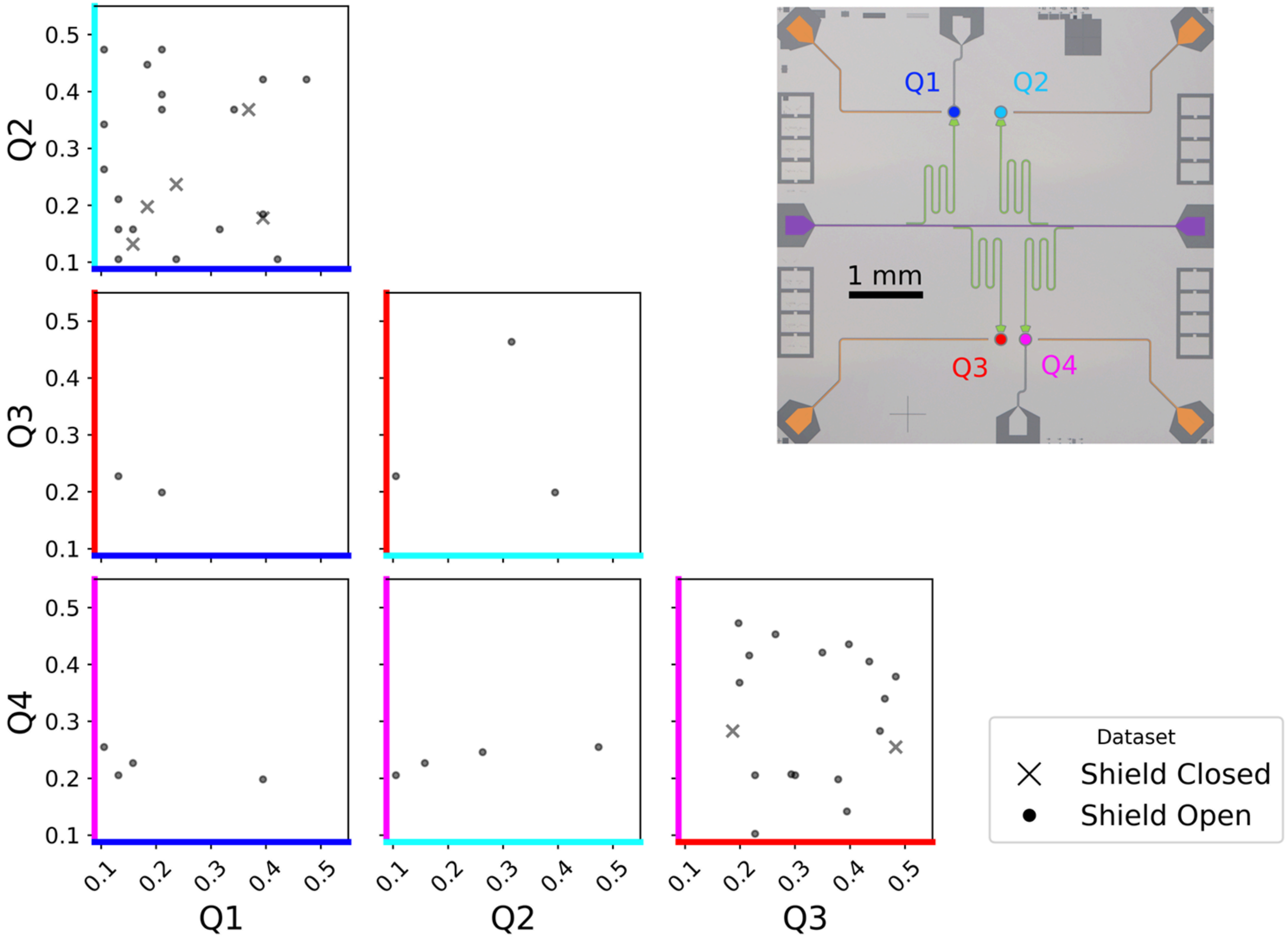
Collection Fins	Limited	1.0	0.1	17.0%	O(0.1) eV
Collection Fins	Limited	0.1	0.1	12.6%	O(0.1) eV

At the moment, the only (far from be optimised) measurement proved a transmon efficiency of ~ 20%, which means a threshold of hundreds of keV

We're far from there yet — but the very possibility of getting there is what drives the community. The path ahead is challenging, but full of promise.

Thanks for the attention

Bonus Slide



The same chip that we already studied in lesson 1 was measured at NEXUS (107 meters below Earth suraface) where muons are suppressed by 99%

Correlated errors diminished by ~ one order of magnitude compared to above ground tests

Bratrud 2025