Effects of Radioactivity on Superconducting Qubits

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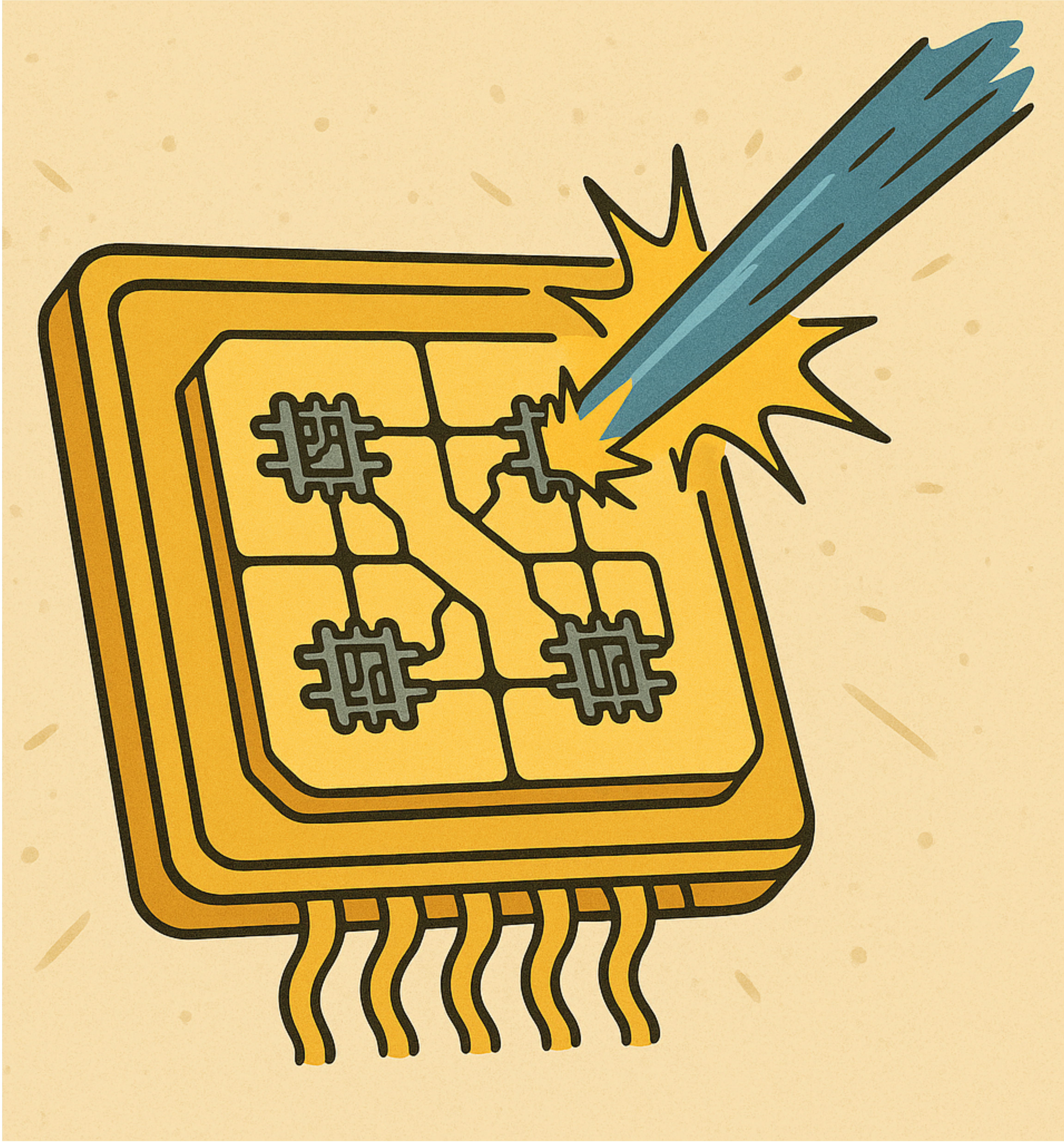
Università di Padova, July 17-18 2025

Outline

- What is Radioactivity?
- Why do we care for qubits?
- Model of the Impact of Radioactivity: Physics
- Validation of this model: measurements



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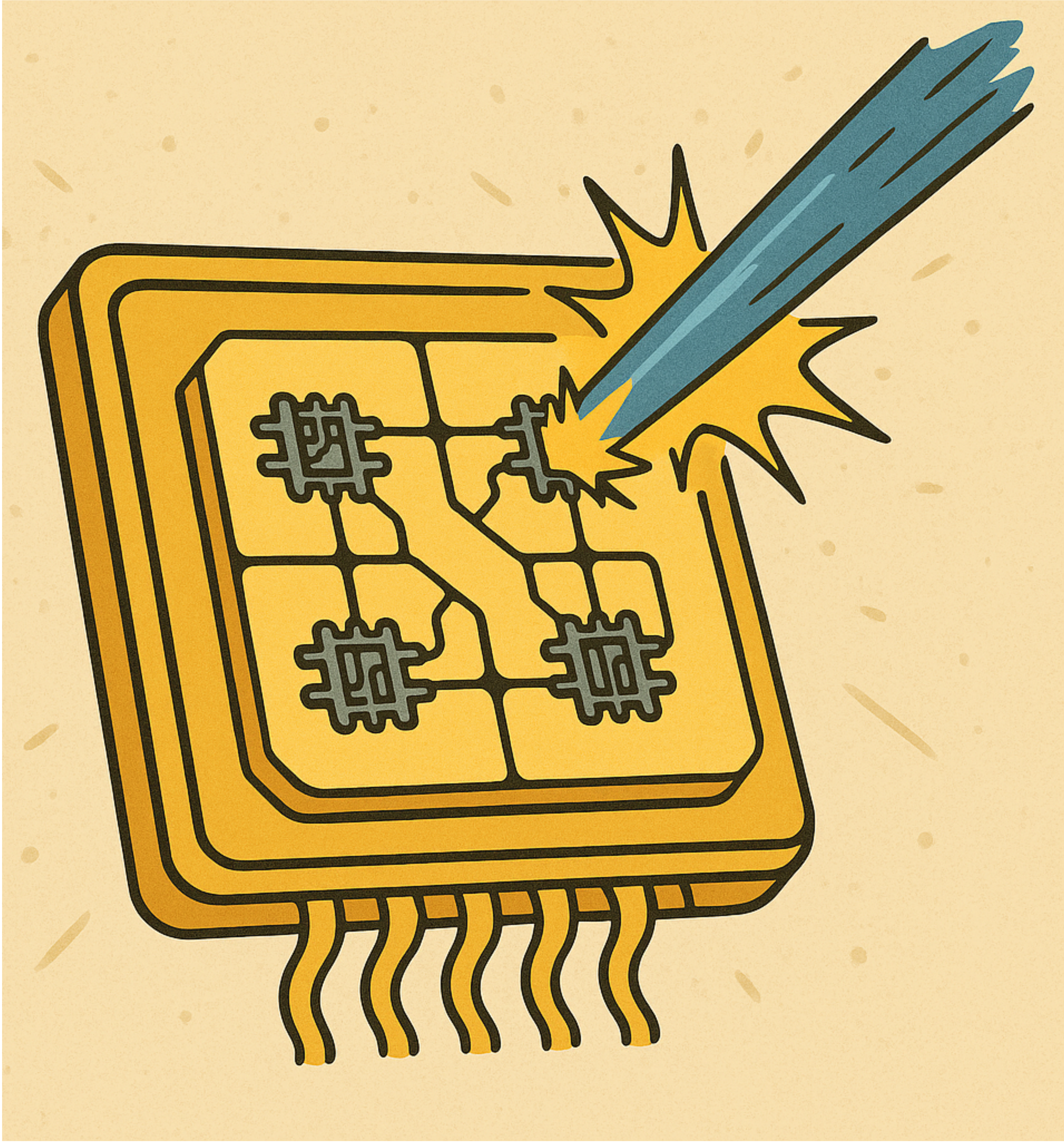
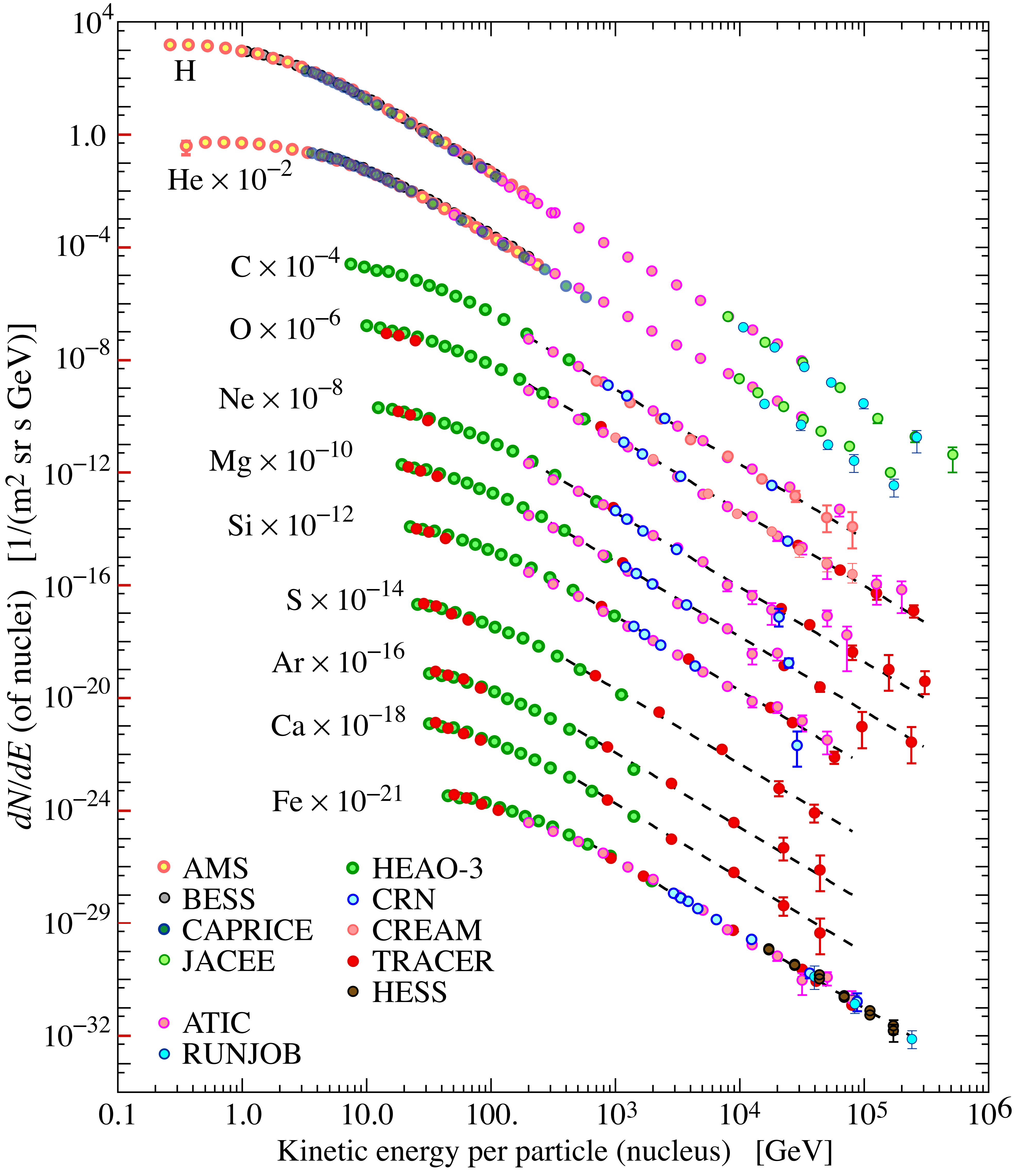


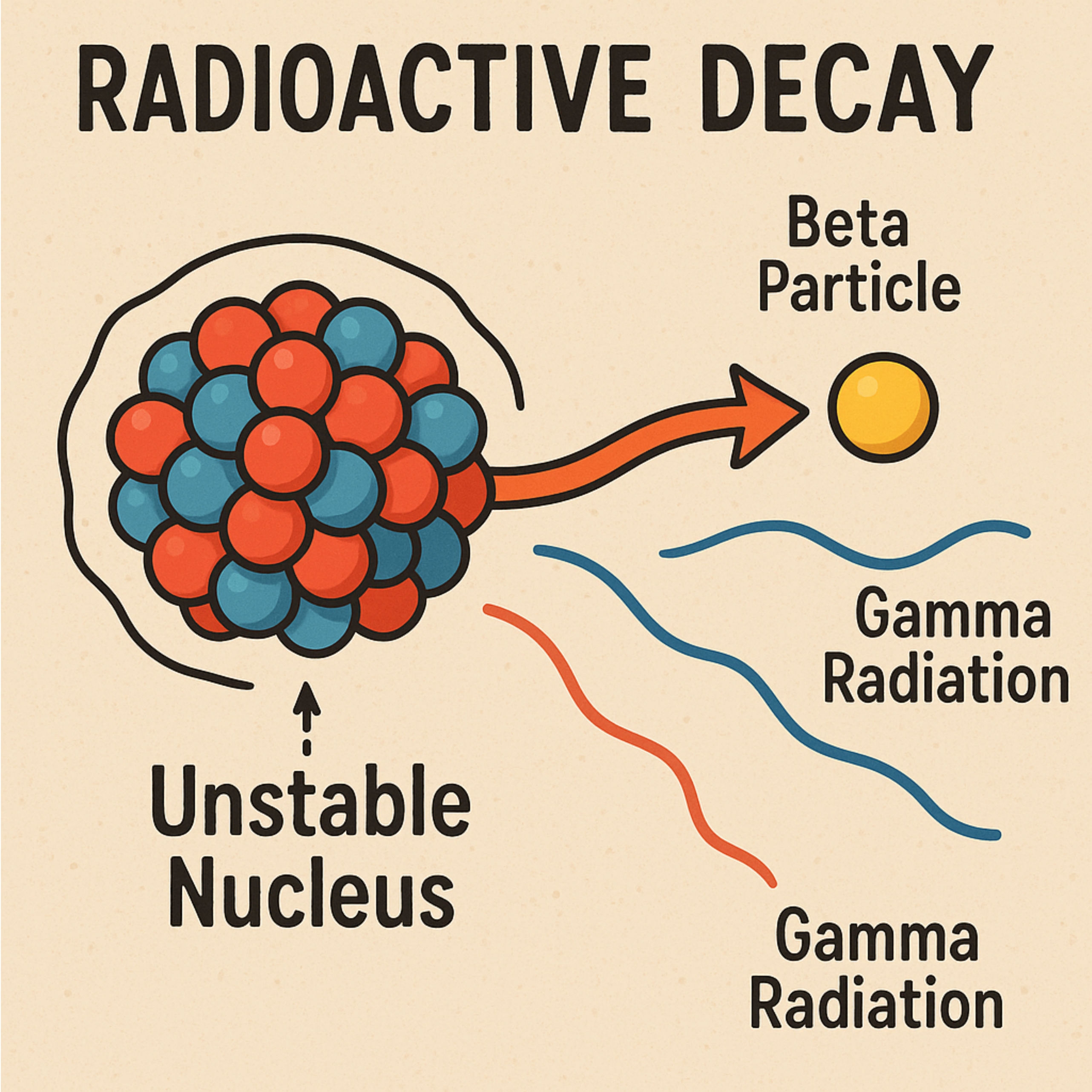
Radioactivity at sea-level: Cosmic Rays



- Primary cosmic rays (mostly from outside the solar system) interact in the atmosphere and reach our surface
- At sea level: dominated by muons
  - Mean Energy: 4 GeV
  - Rate depends on the energy and angular distribution but, on average, ~ 1 μ/cm²/min for horizontal detectors

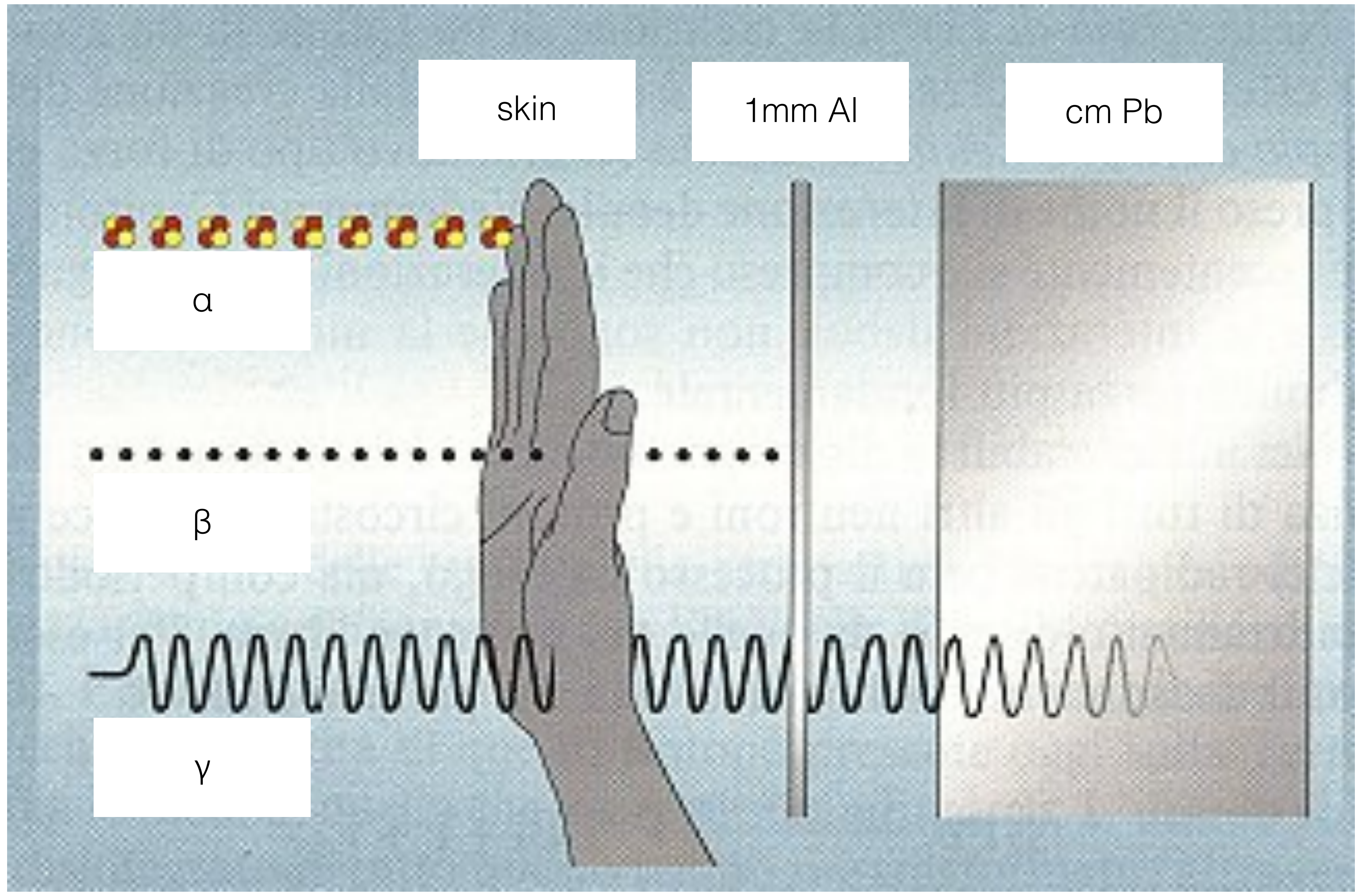
(Natural) Radioactivity

- Radioactivity = spontaneous disintegration of a nucleus
  - Production of particles (alpha, electrons, neutrons) and electromagnetic radiation (gamma rays, X rays)
  - These particles interact with matter via ionisation



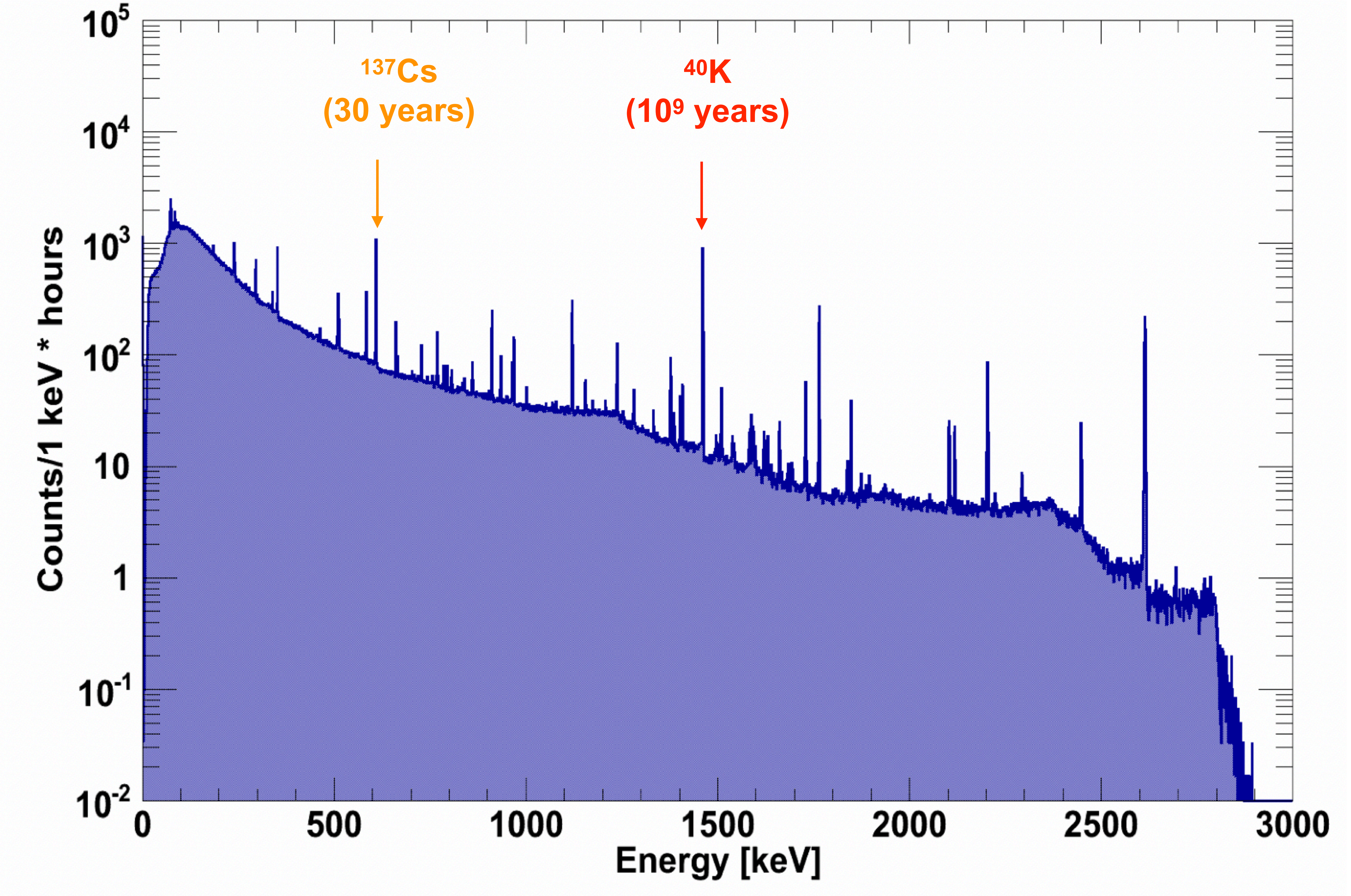
Radioactivity at sea-level: Isotopes

- Naturally radioactive isotopes decay emitting:
  - alpha particles [few MeV] —> microns
  - electrons (β) [tens of keV - few MeV] —> mm
  - gamma rays (γ) [hundreds of keV - MeV] —> cm
  - X-rays [keV - tens of keV] —> tens of microns



Radioactivity at sea-level: Isotopes

- Potassium (^{40}K)
- Nuclear explosions (Cs)
- Thorium and daughters
- Uranium and daughters



In a typical laboratory, 2-3 gammas/cm²/sec.

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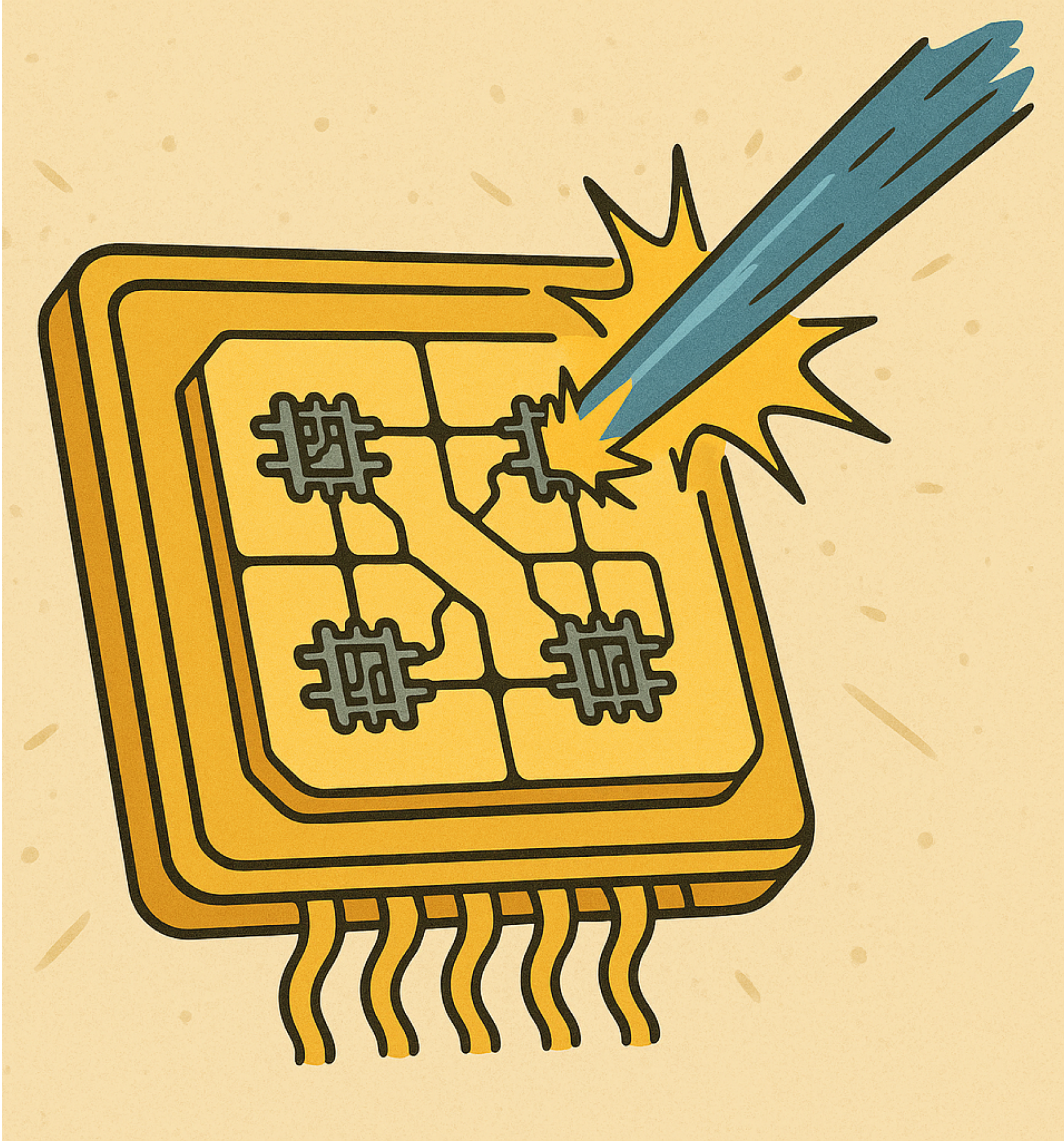
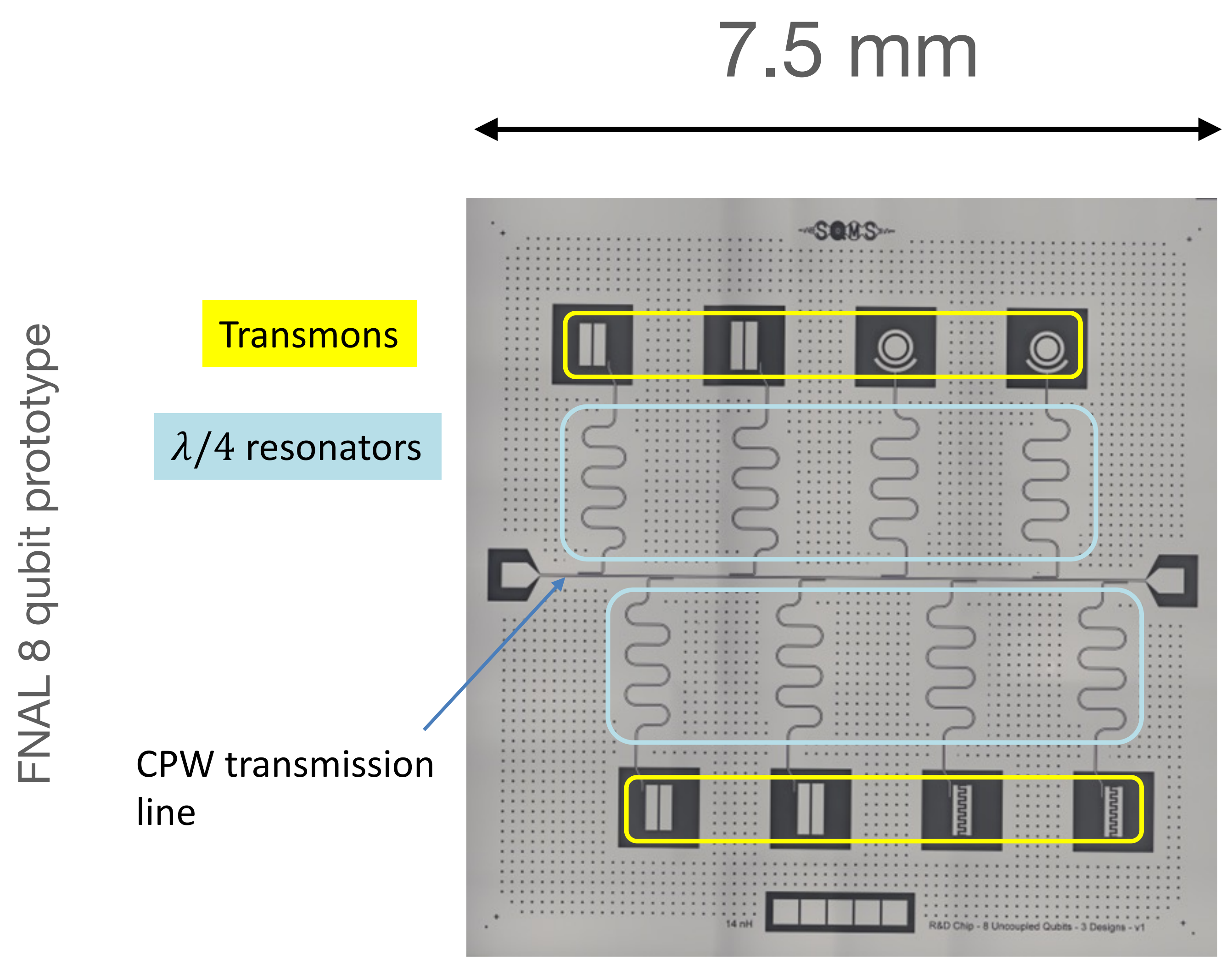


Radioactivity and qubits

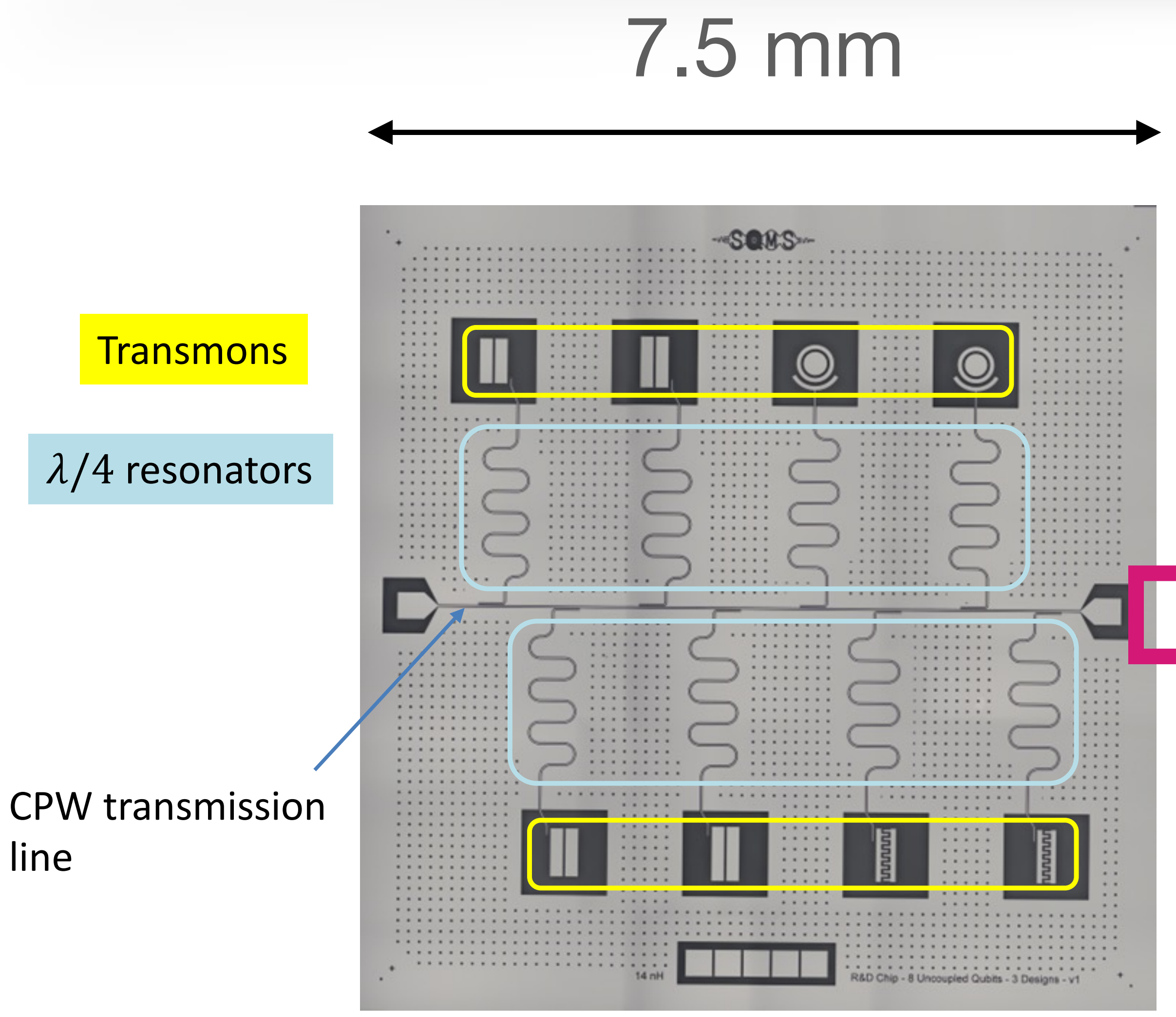
How do superconducting qubits look like?

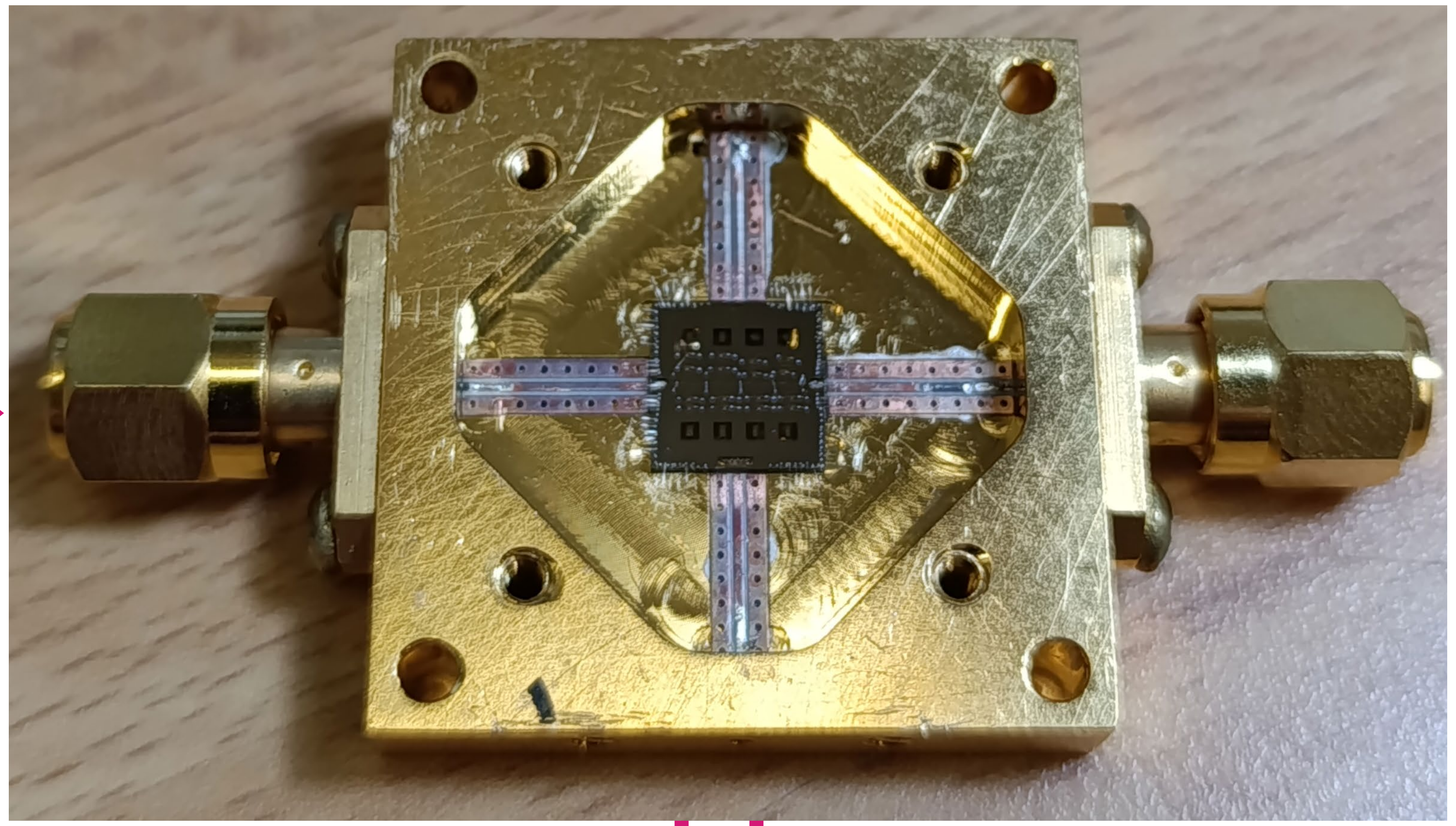
Silicon/sapphire chip of few mm^2, thickness ~ 400 µm

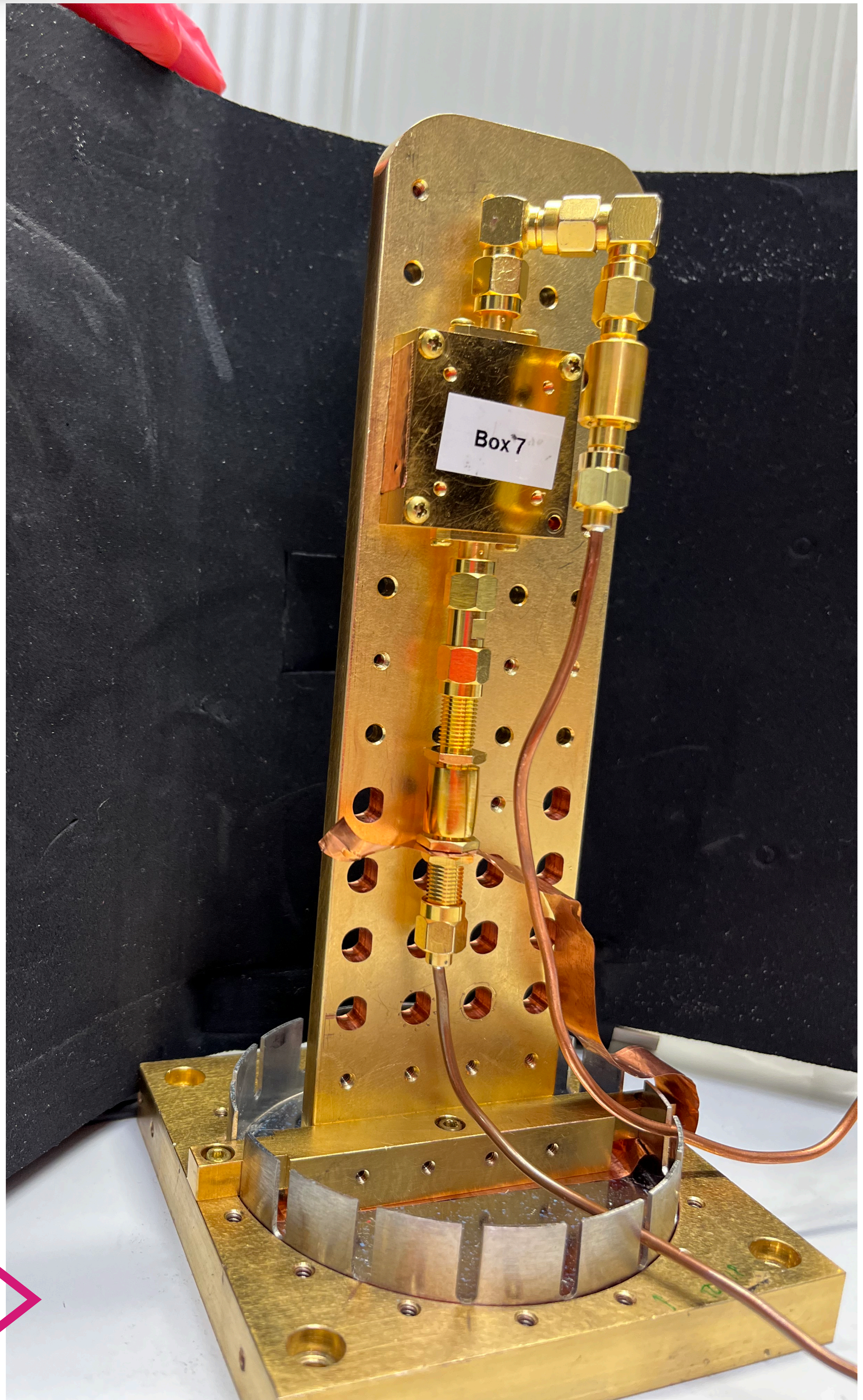
Superconducting circuit fabricated on top of the chip
(each qubit ~ 0.1 mm^2 - hundreds of nm thick)



Radioactivity and qubits (2)

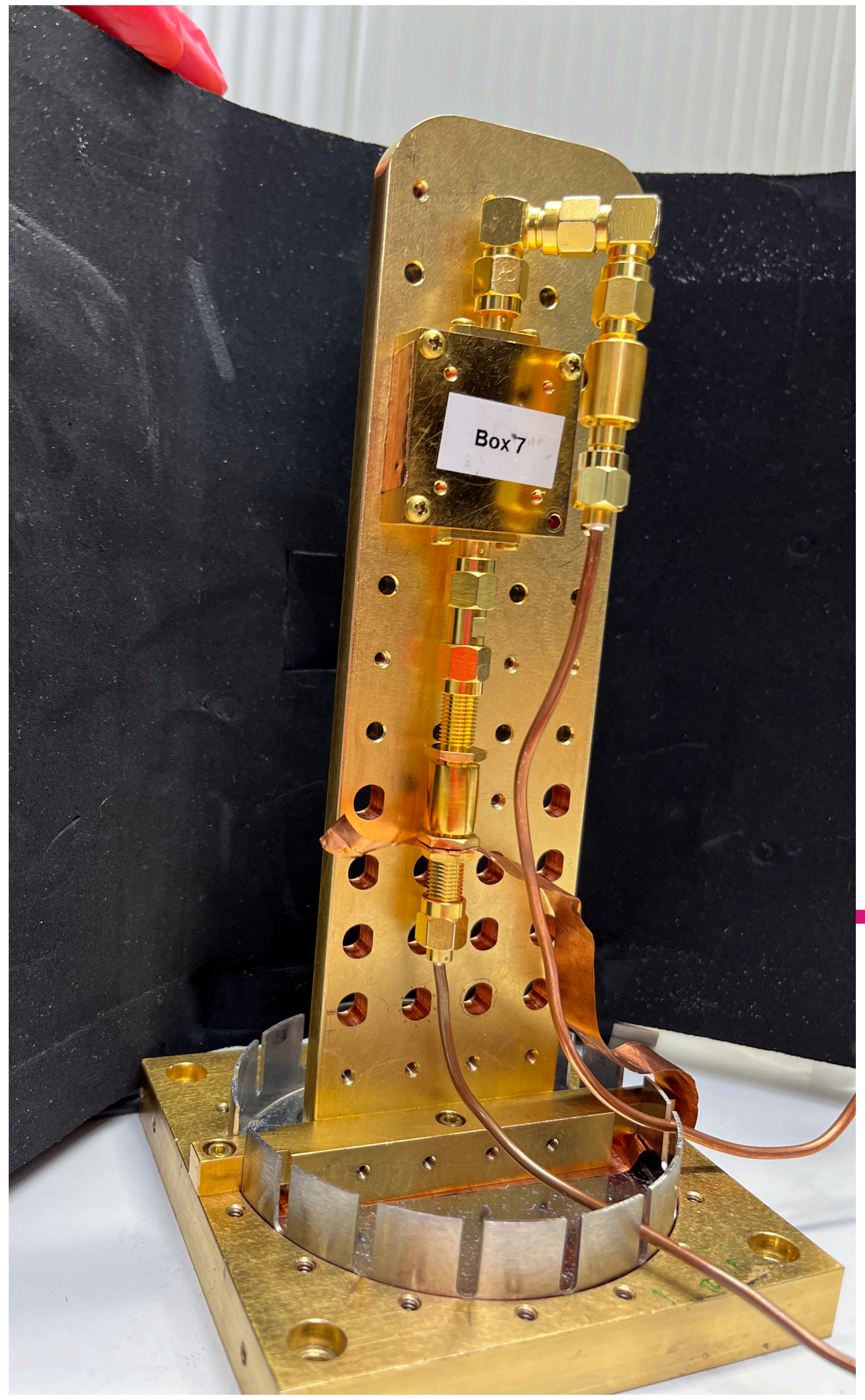






Radioactivity and qubits (3)

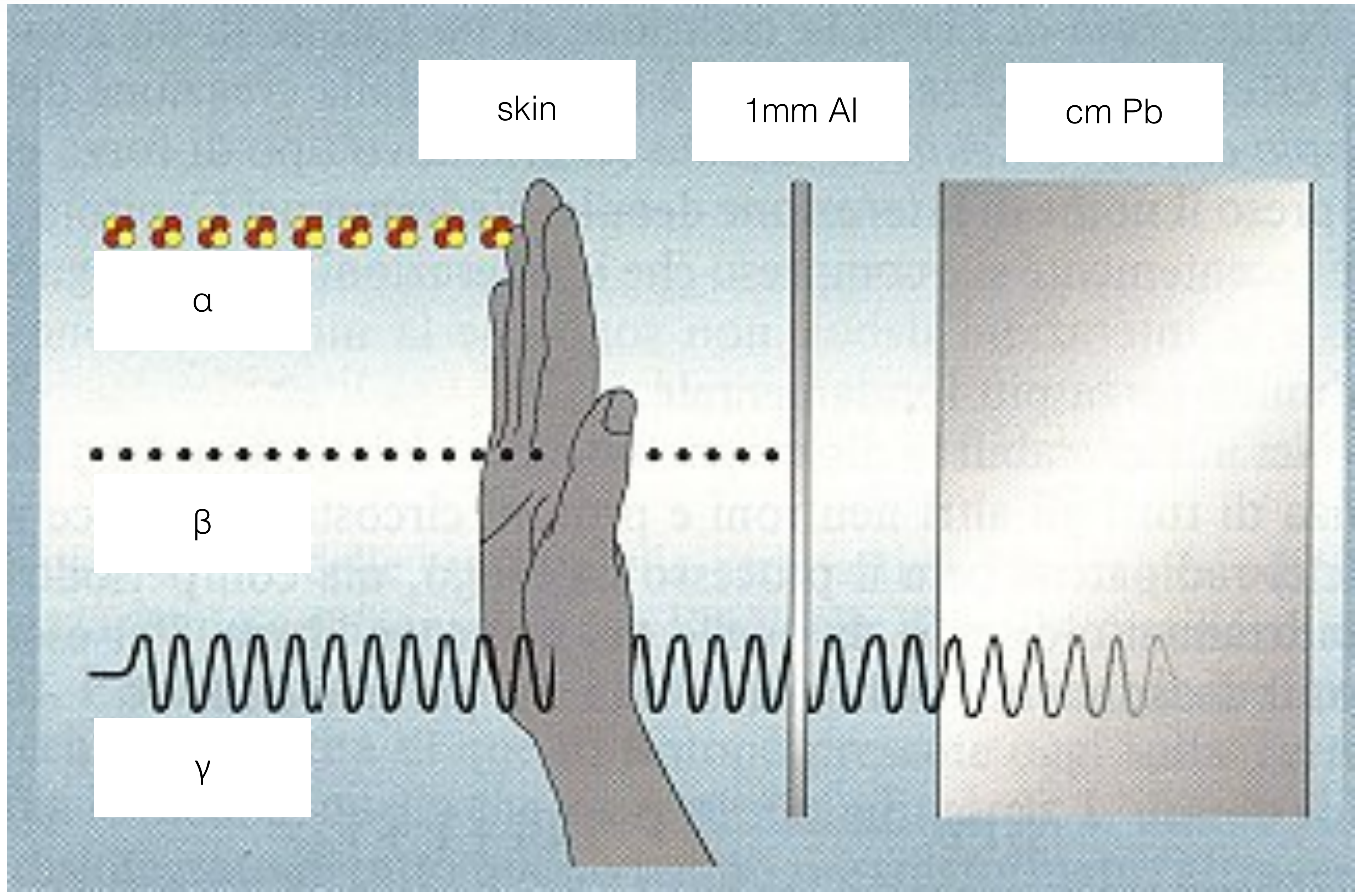
Inserted in a magnetic shield and mounted in the coldest part of a dilution refrigerator (<100 mK)

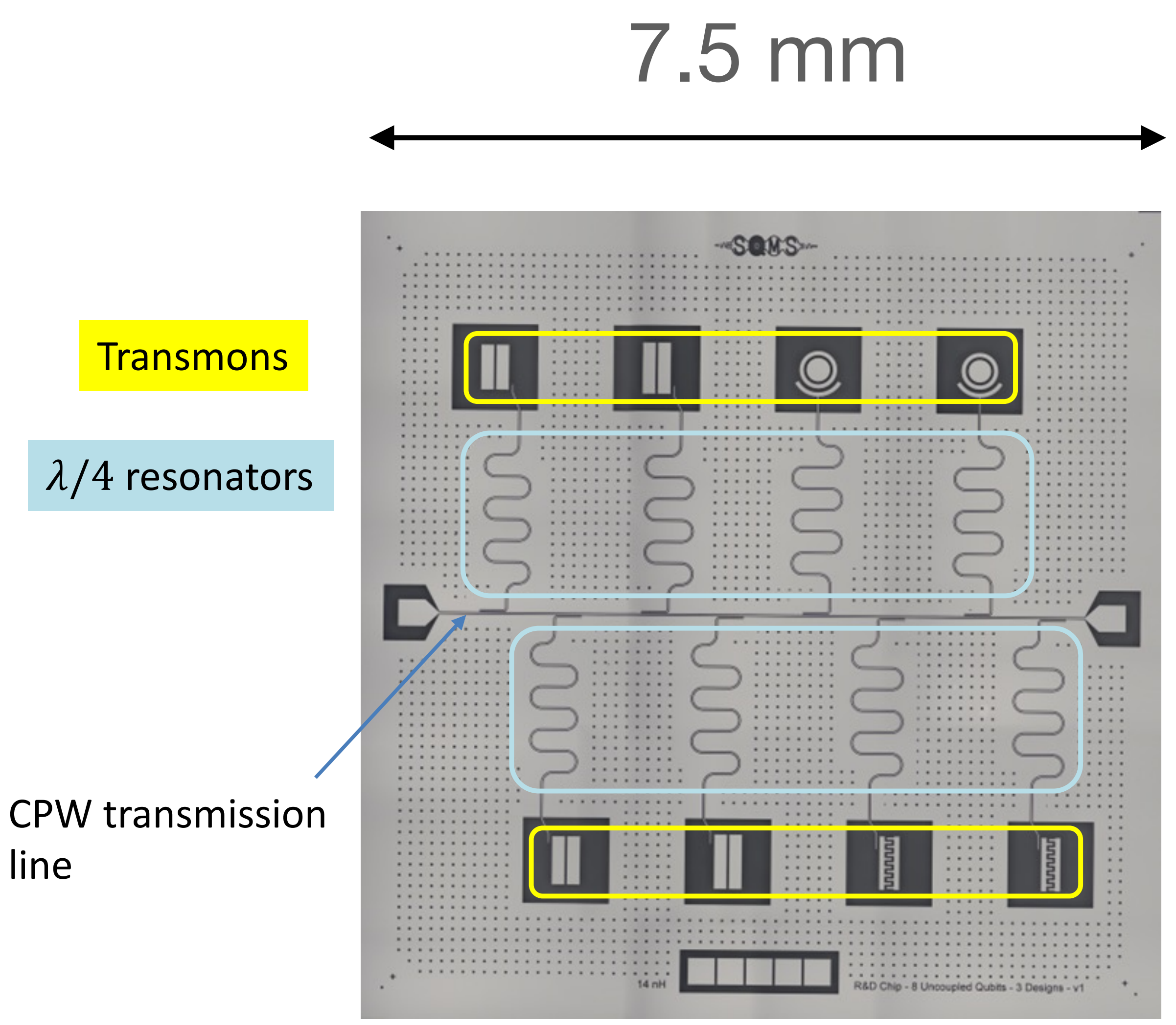


Radioactivity and qubits: 3 questions

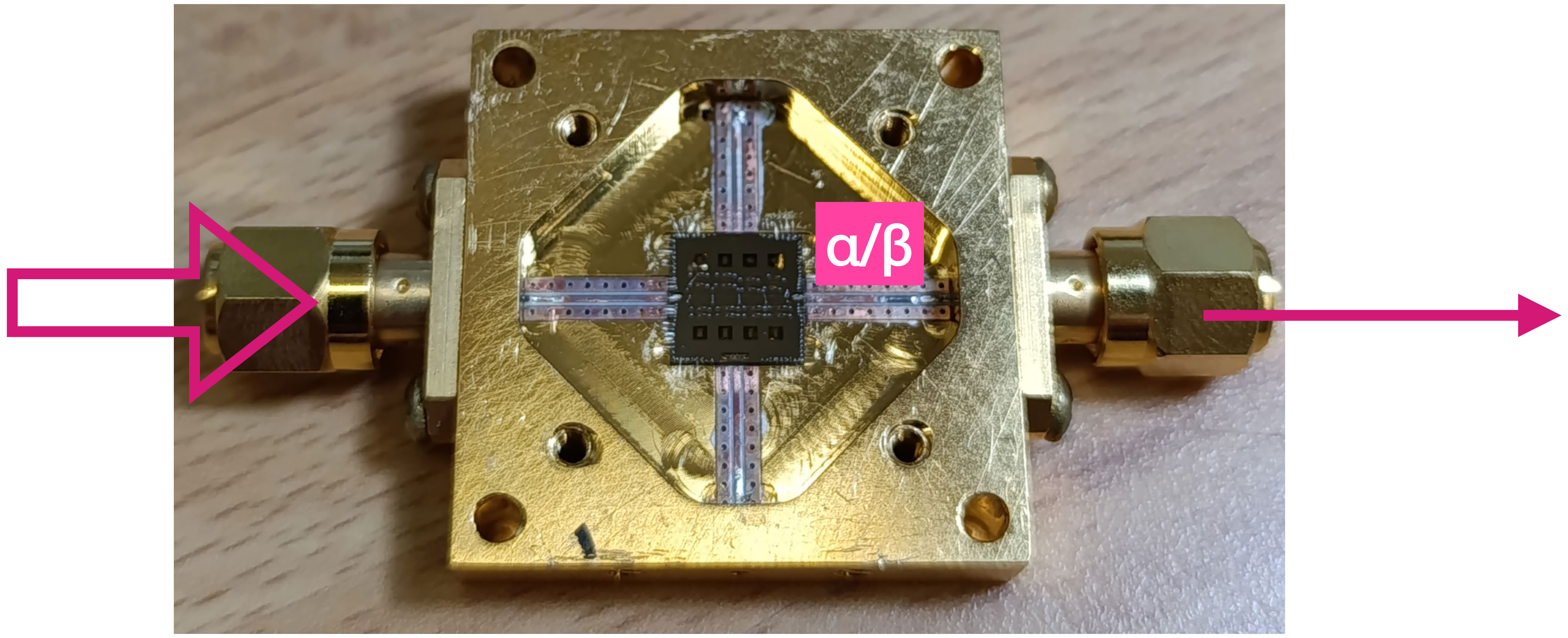
menti.com

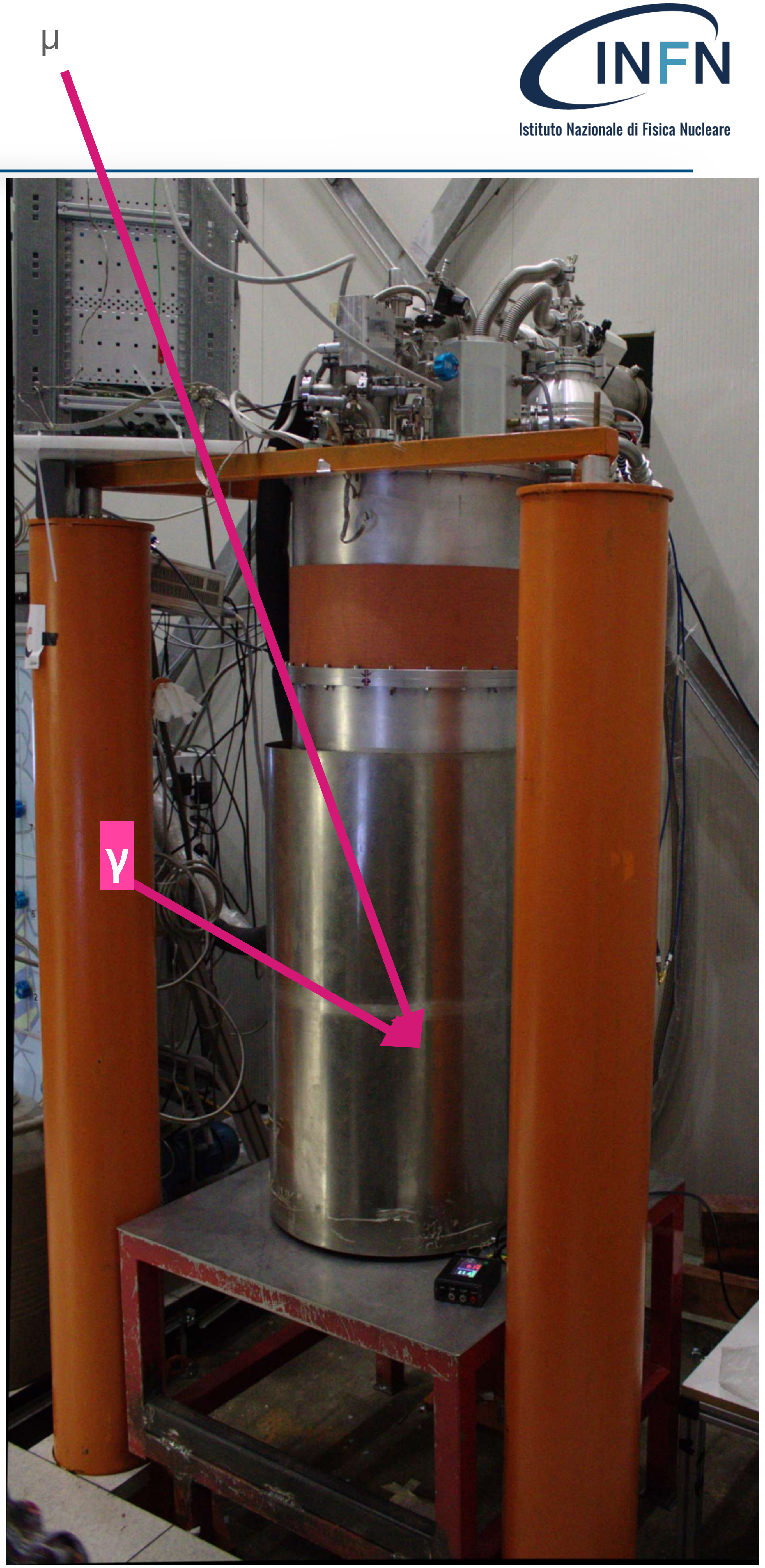
Radioactivity and qubits: questions





FNAL 8 qubit prototype





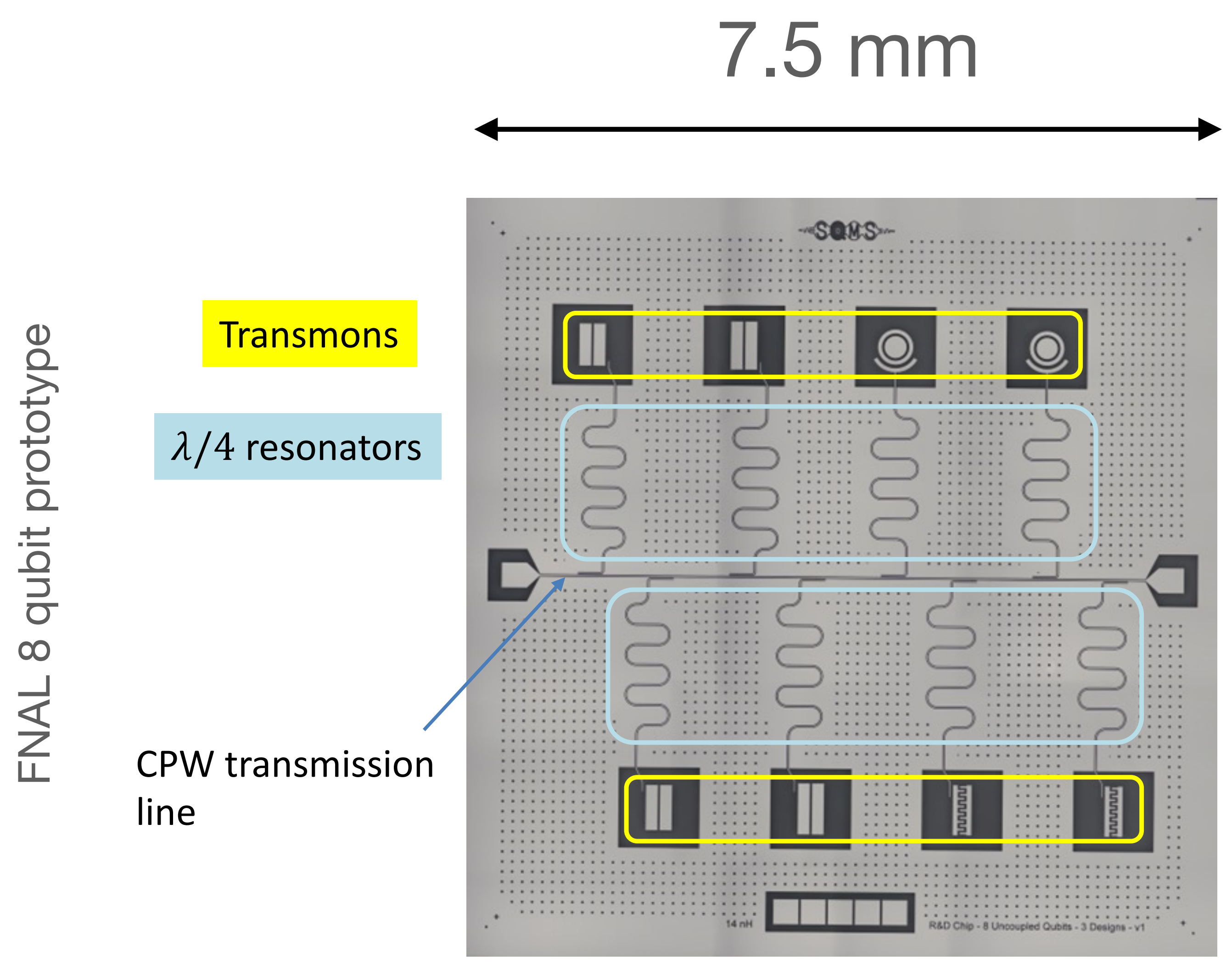
Radioactivity and qubits: “size” of the effect

How do superconducting qubits look like?

Silicon/sapphire chip of few mm², thickness ~ 400 μm

menti.com

Superconducting circuit fabricated on top of the chip
(each qubit ~ 0.1 mm² - hundreds of nm thick)



Let us assume that qubits have lifetime of 1 millisecond.

What is the probability to have an interaction of a gamma in a qubit within the qubit lifetime?

Radioactivity and qubits: “size” of the effect

We would conclude that, typical qubits, do not suffer and will not suffer from radioactivity

But things are not so simple

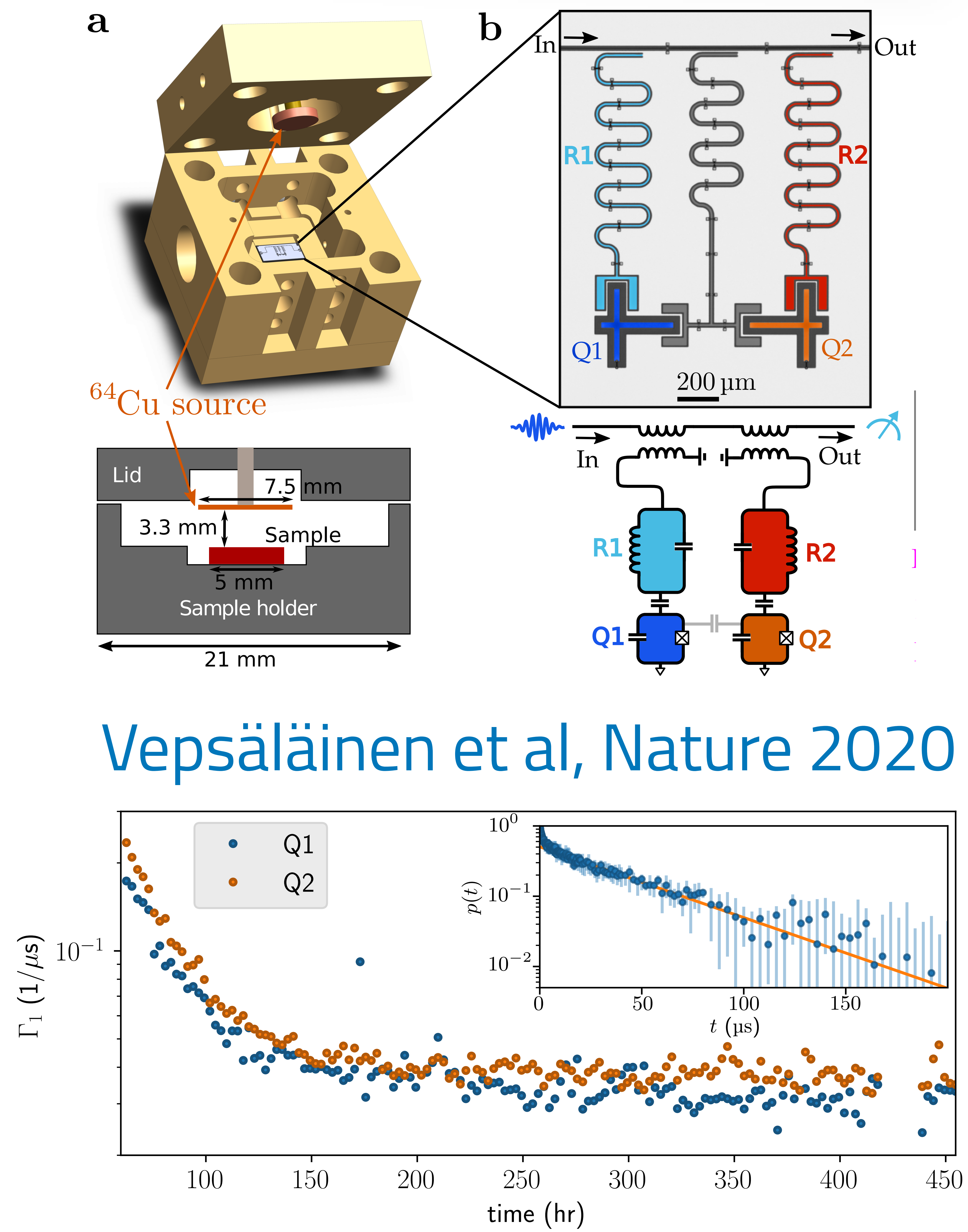
Historical background: MIT/PNLL measurement

- Faced a qubit to a fast-decaying source
- Observed that the coherence of qubit was increasing while the source was decaying

CONCLUSION

- The quasiparticle background induced by radioactivity is $x_{QP} \sim 7\times10^{-9}$
- Radioactivity will limit the performance of qubits with lifetime > 1 millisec

WHY?

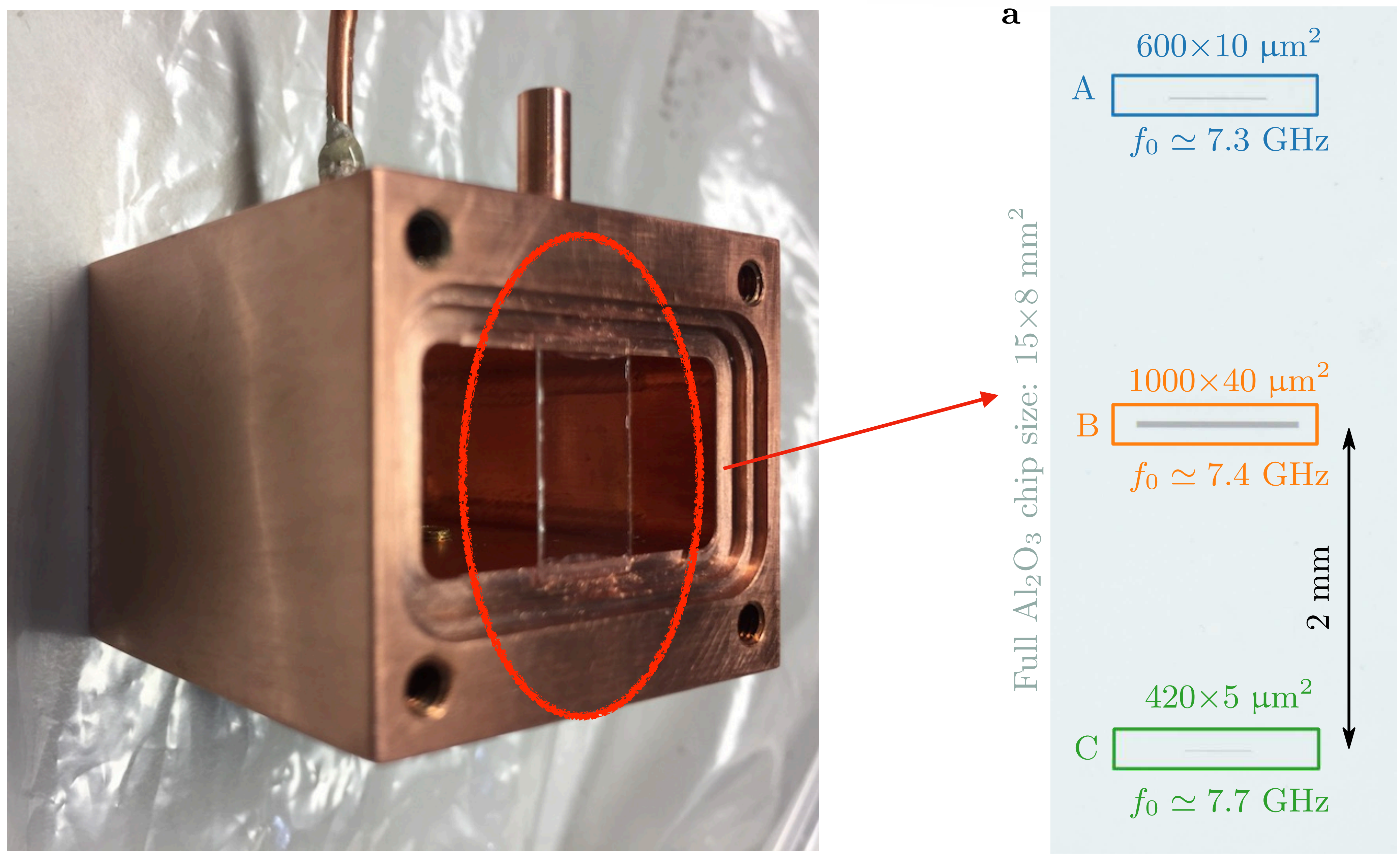


Vepsäläinen et al, Nature 2020

Historical background: INFN/KIT measurements

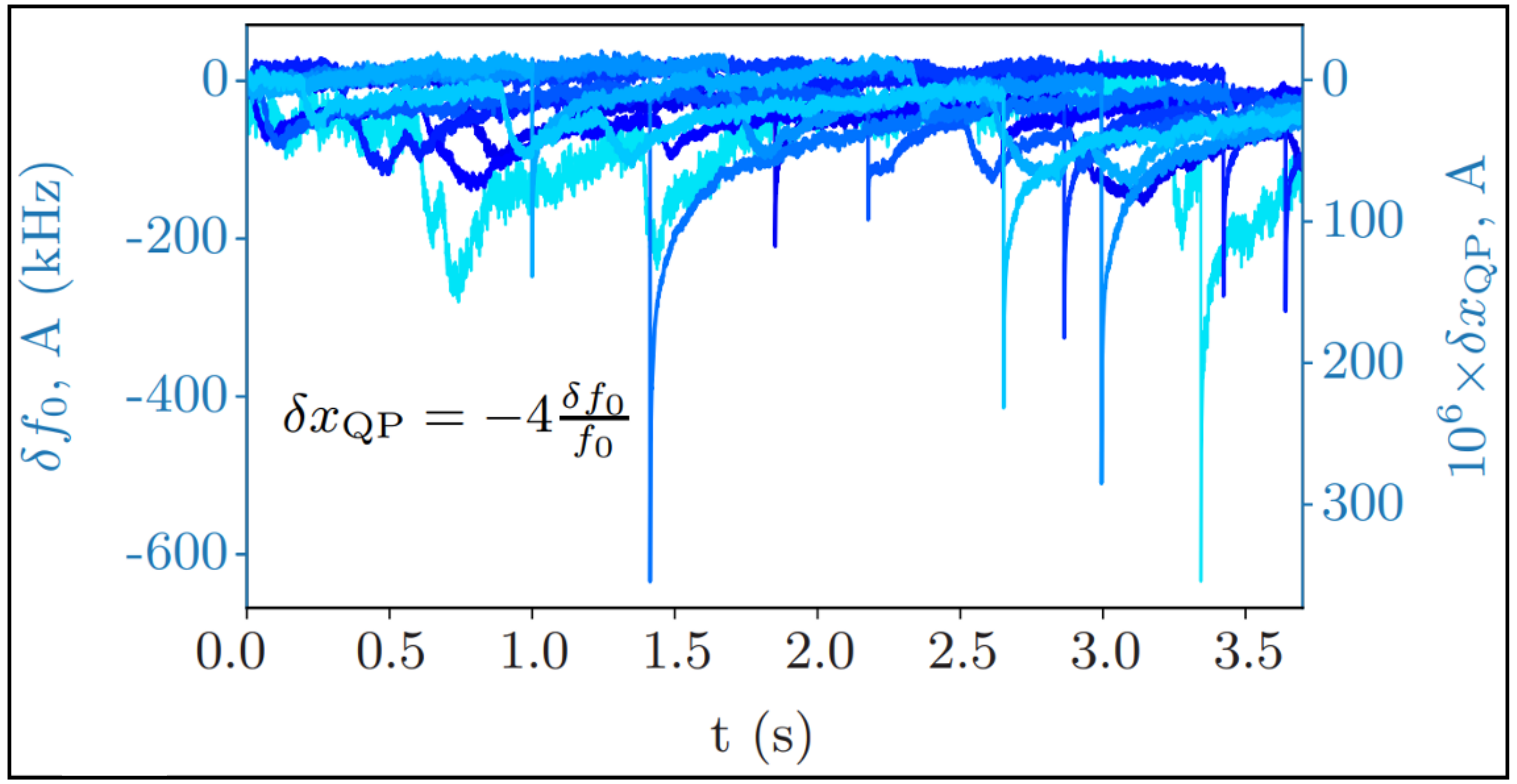
- DEMETRA project:
  - Chip with 3 superconducting circuits
  - Counted “QP bursts”
  - In contrast to “T1” measurements, enables *real-time* detection of the effects

Cardani et al, Nat. Comm. 2021



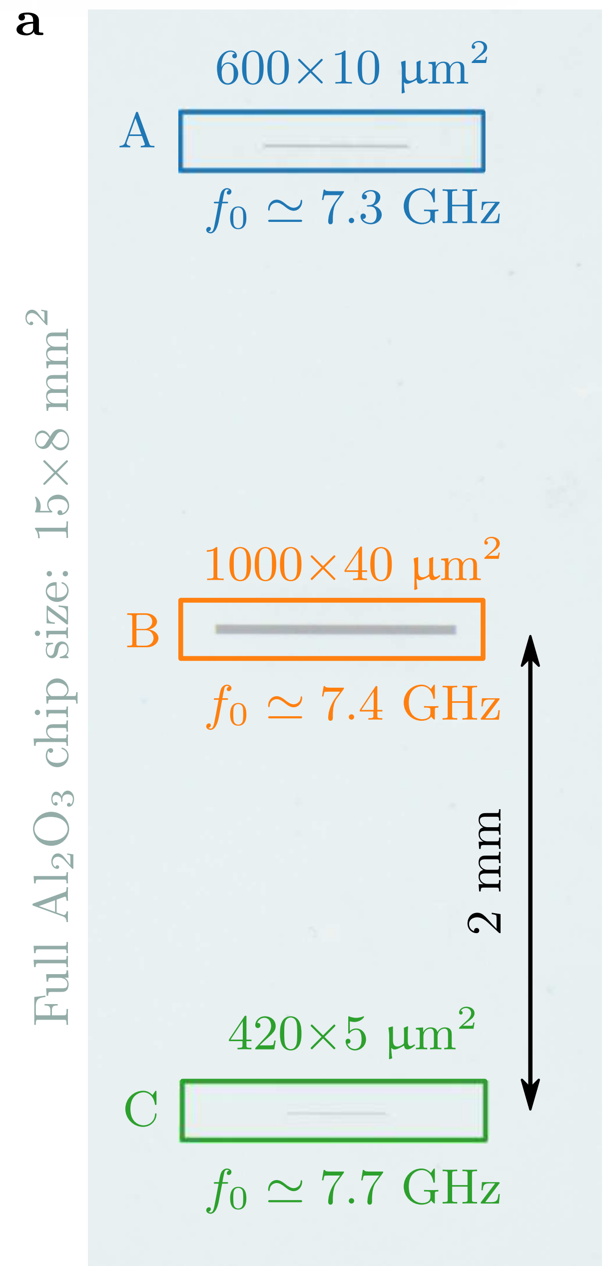
First observation: MIT/PNLL predicted a background from QP bursts of $x_{QP} \sim 7\times10^{-9}$

We measured bursts up to $x_{QP} \sim 3\times10^{-4}$

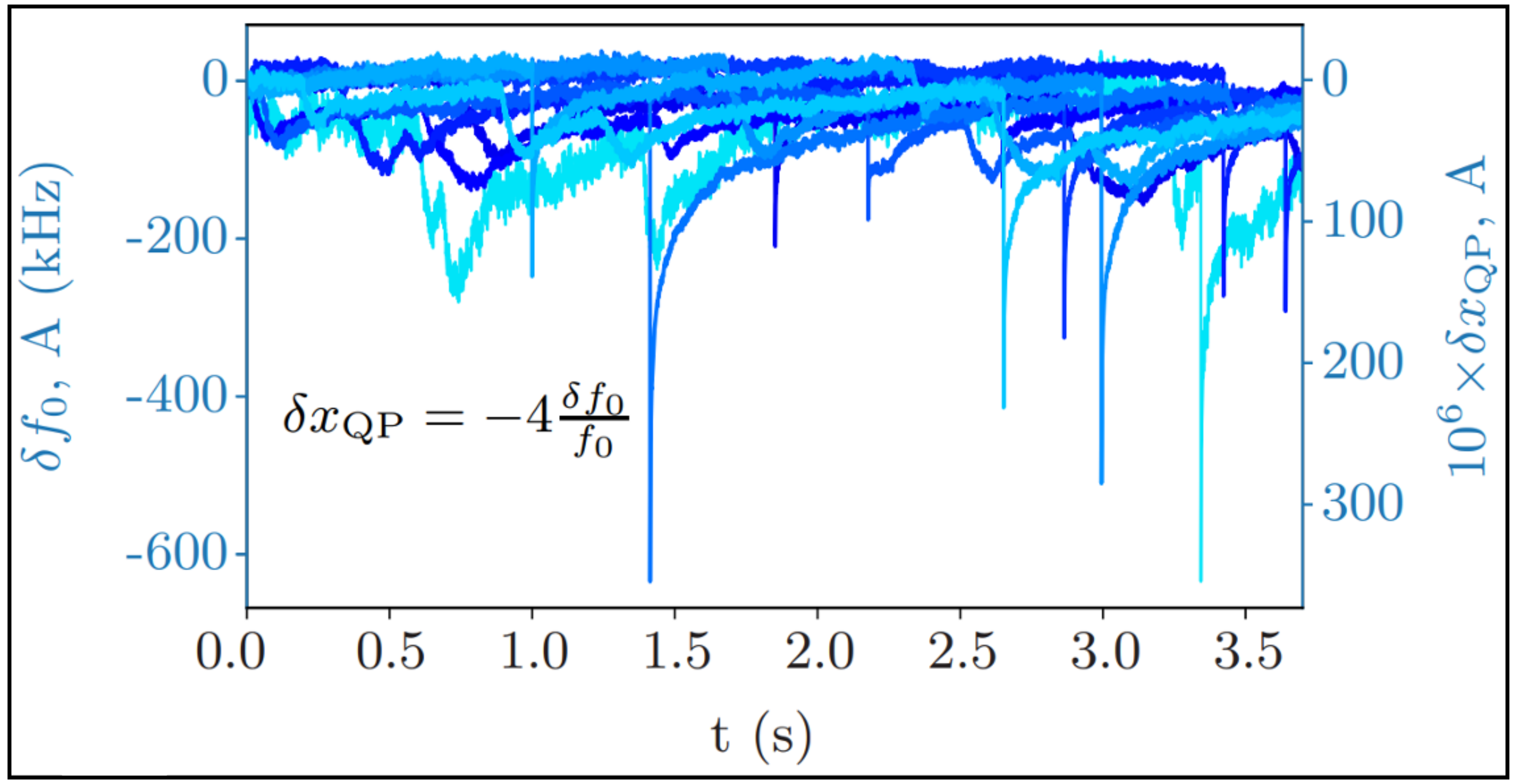


Expectations for radioactivity in sensors

- What is the predicted rate? Let us make a simple estimation:
  - 3 gamma/cm²/sec in a typical lab
  - Multiply by sensor surface
  - From few $6x10^{-5}$ to $1x10^{-3}$ events/second



Circuit	Surface [cm²]	Rate (optimistic*)
A	$6x10^{-5}$	~ $2x10^{-4}$
B	$4x10^{-4}$	~ $1x10^{-3}$
C	$2x10^{-5}$	~ $6x10^{-5}$



* assuming ALL gamma's interact and ALL interactions are detected, which is not!

Expectations for radioactivity in sensors

- What is the predicted rate? Let us make a simple estimation:
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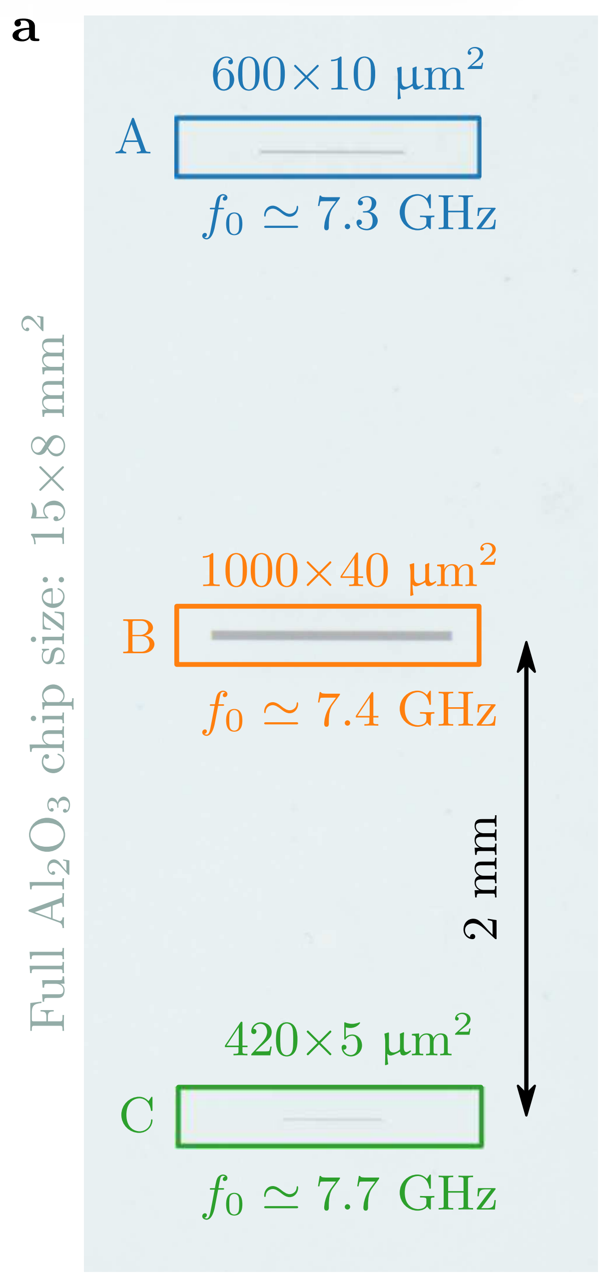
  - Multiply by sensor surface
  - From few 6×10^{-5} to 1×10^{-3} events/second

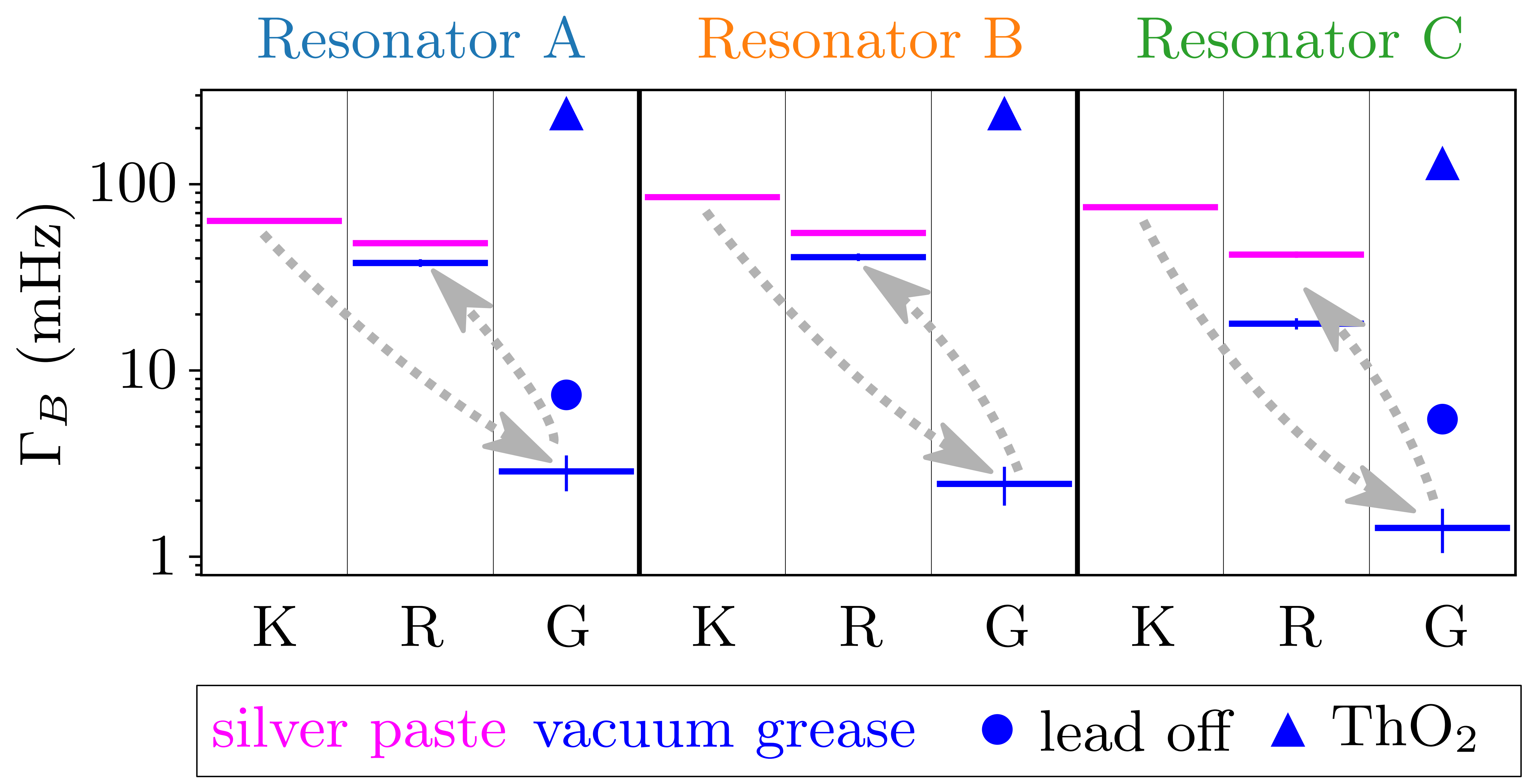


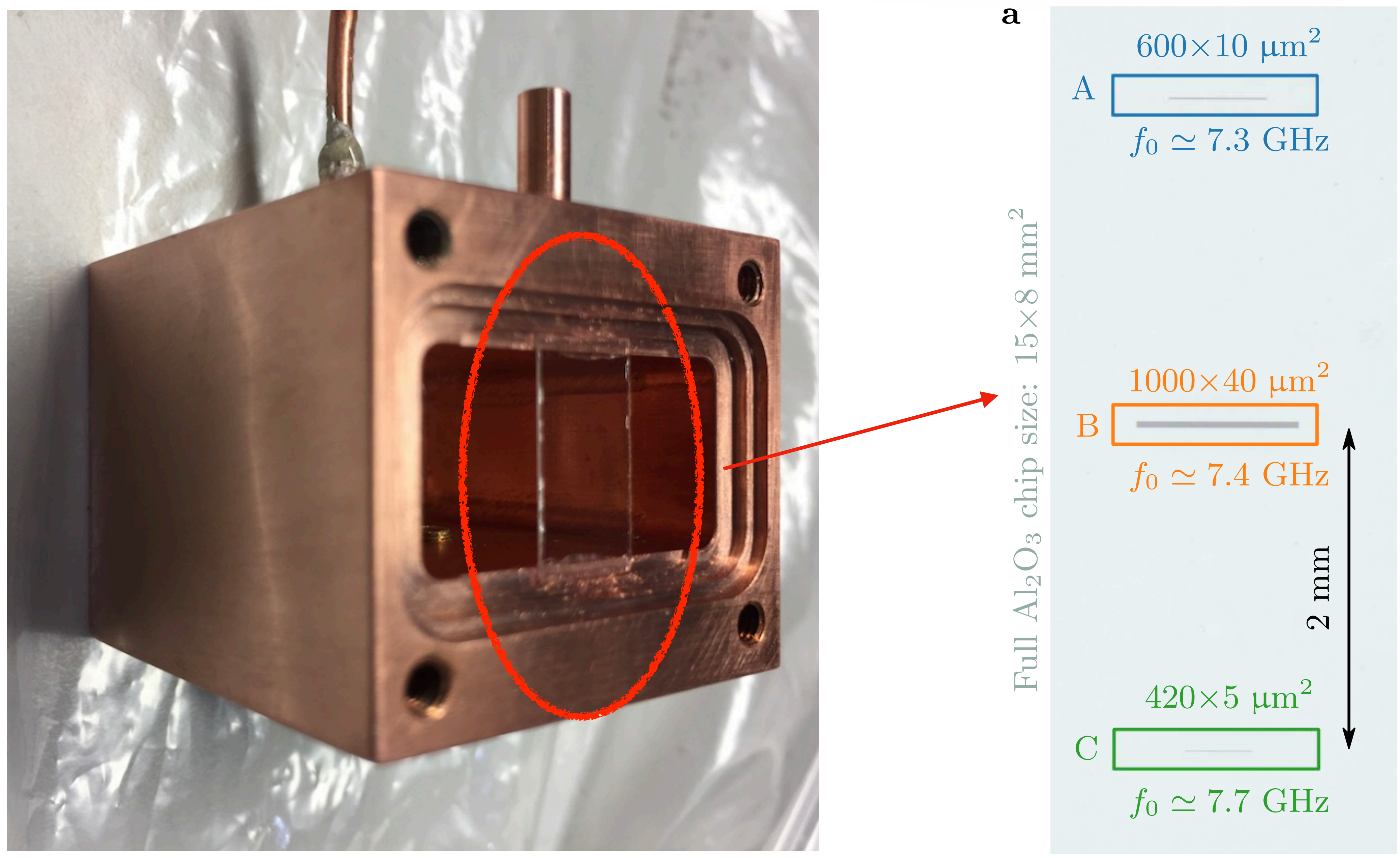
Circuit	Surface [cm²]	Rate (optimistic*)
A	6×10^{-5}	~ 2×10^{-4}
B	4×10^{-4}	~ 1×10^{-3}
C	2×10^{-5}	~ 6×10^{-5}

- Actual rate much smaller
- Big difference among sensors

* assuming ALL gamma's interact and ALL interactions are detected, which is not!

Measurements disagree



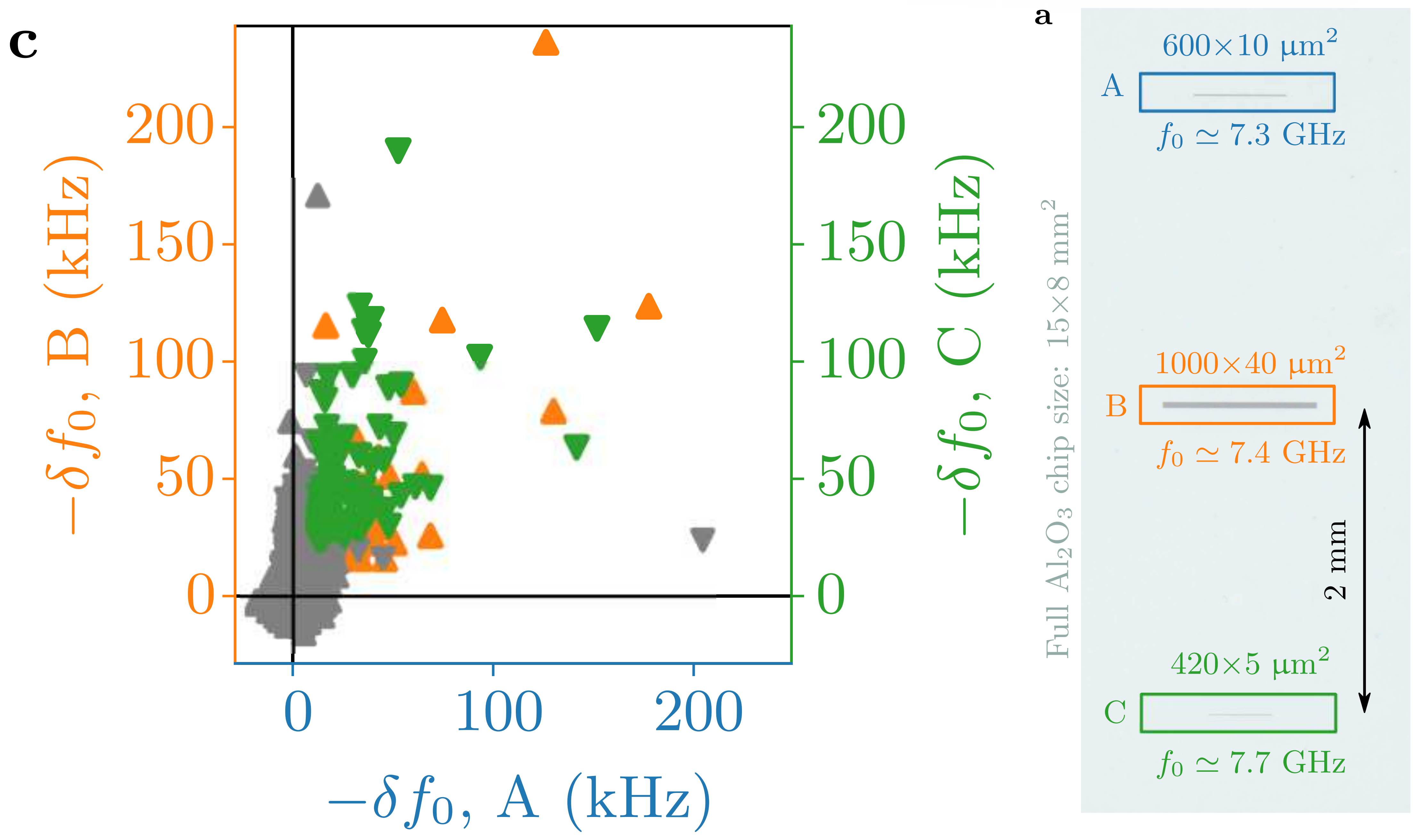


- Expected $6x10^{-5}$ to $1x10^{-3}$ events/second, measured $(7\text{-}9)x10^{-2}$ events/second
- Expected x20 difference between sensors, measured 30% difference

WHY?

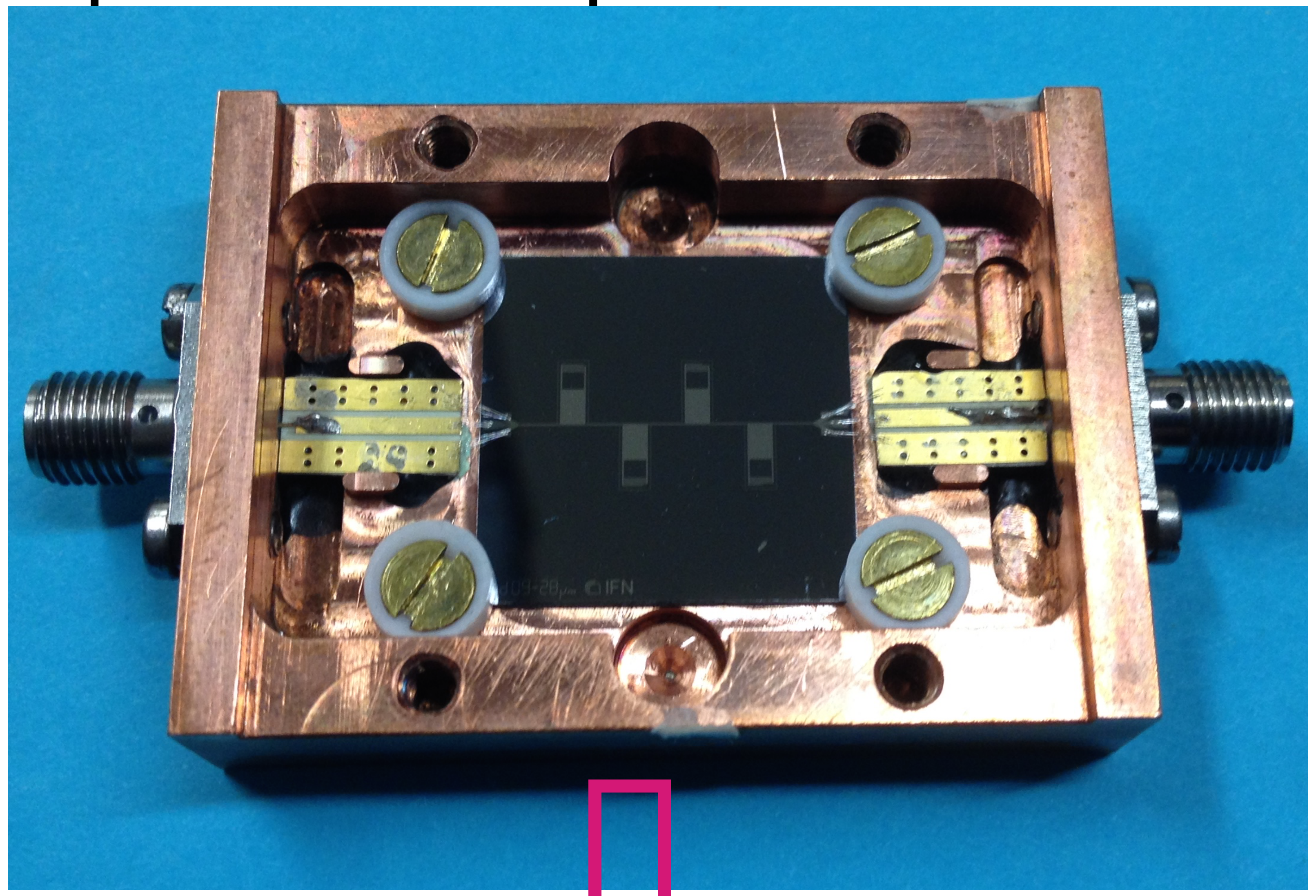
Another hint

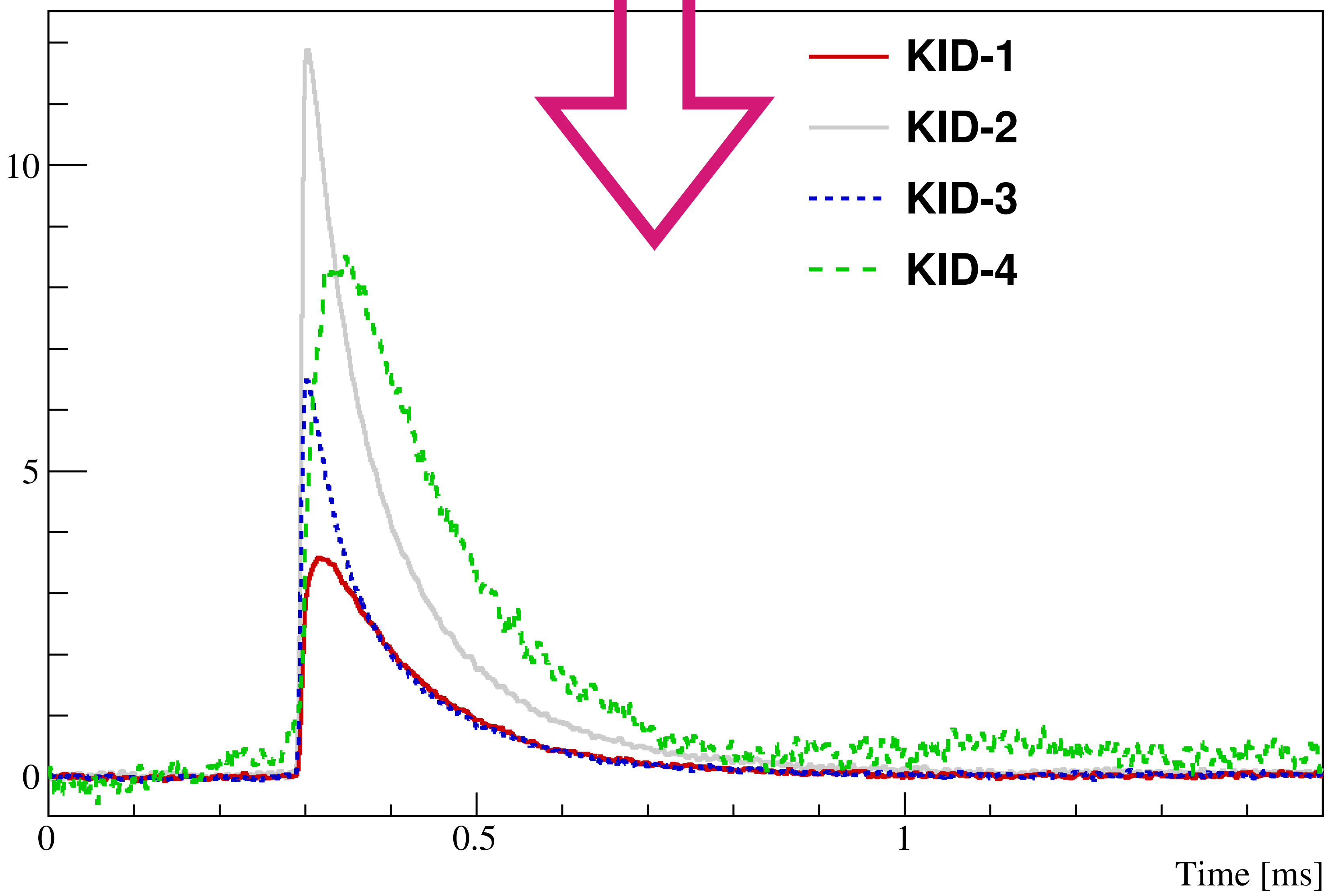
- We acquired simultaneously two sensors
- The QP bursts were in time-coincidence
- Their amplitude was correlated!

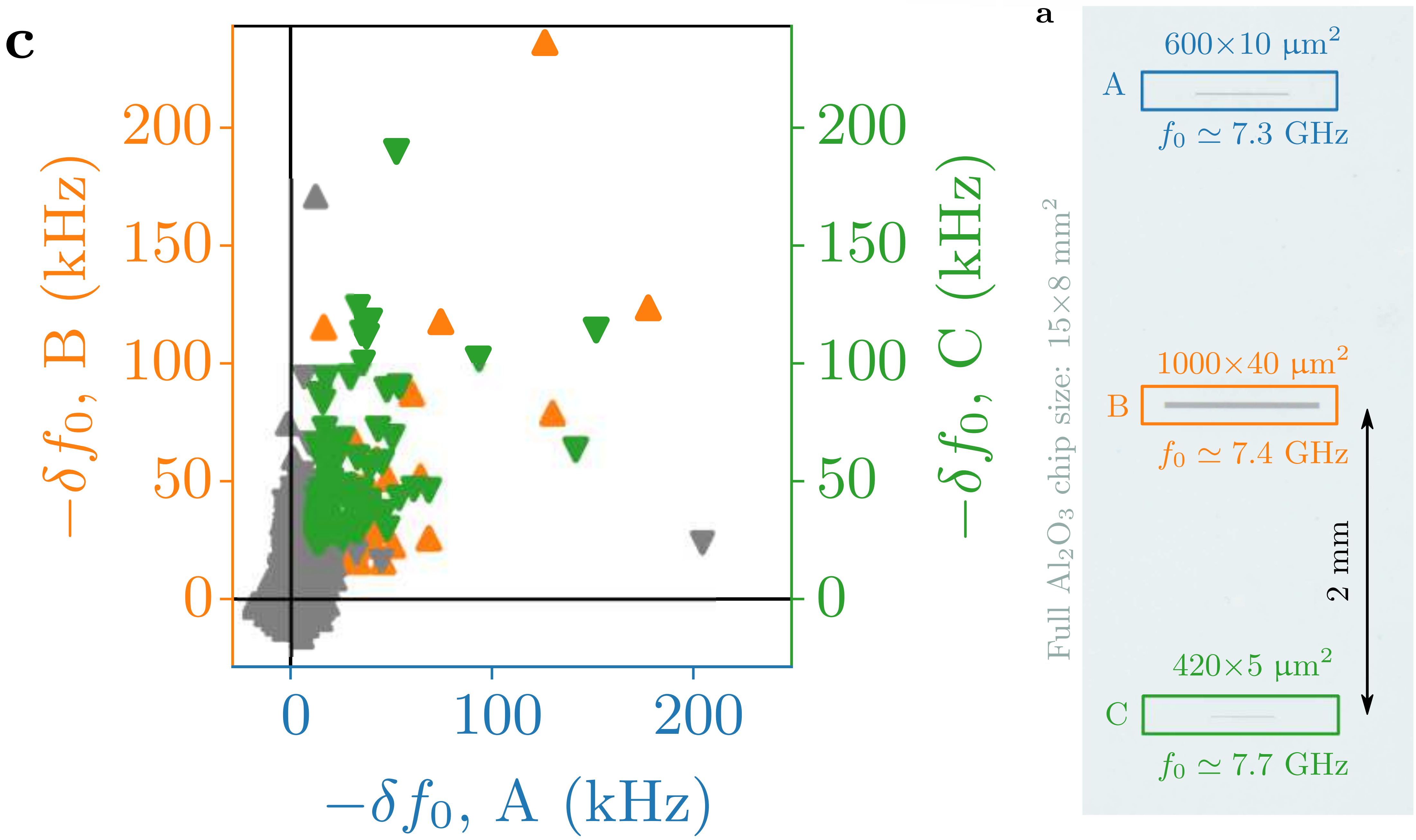


Why does radioactivity impact so much?

- Our experience in particle detectors:







the substrate!

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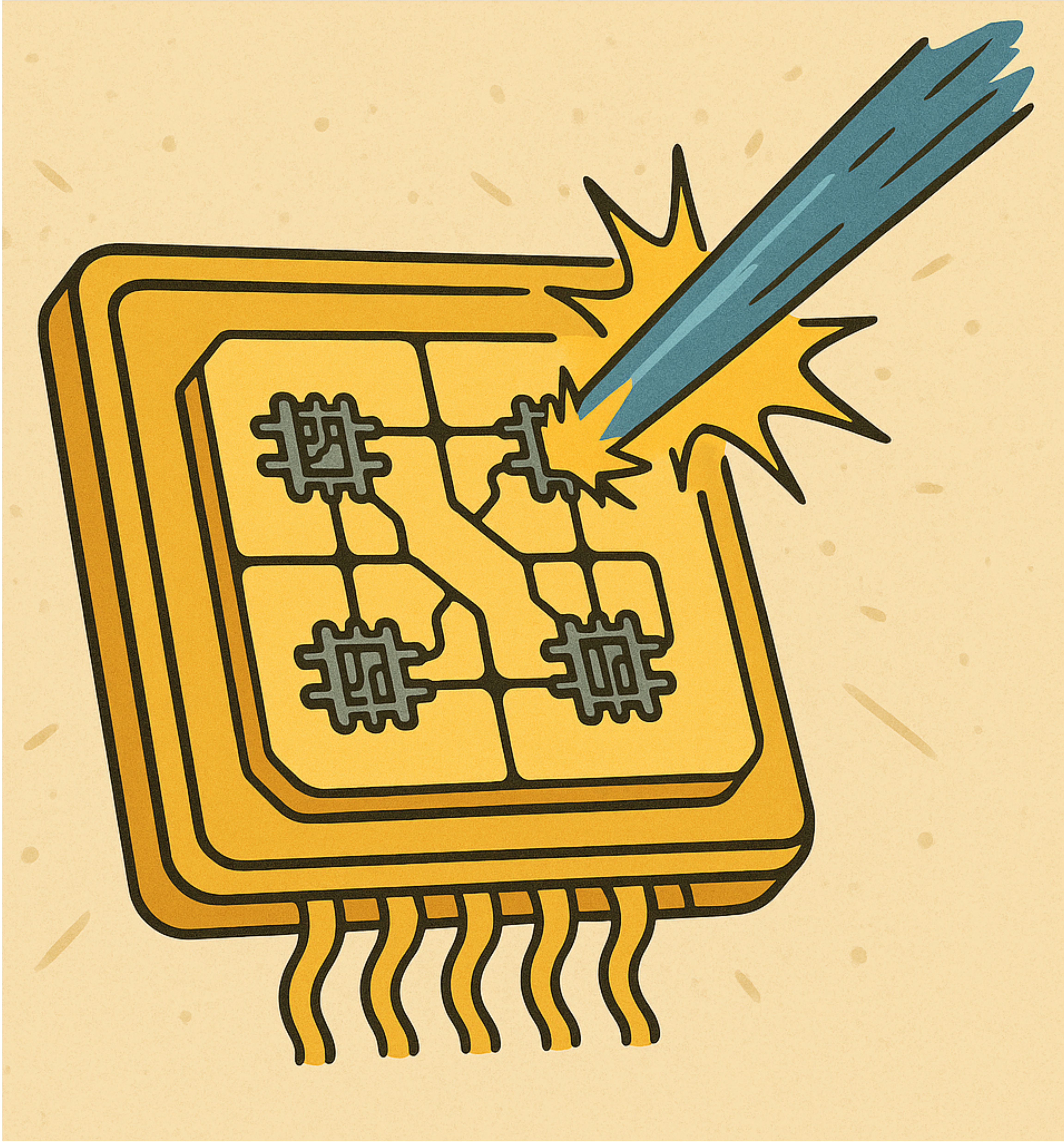
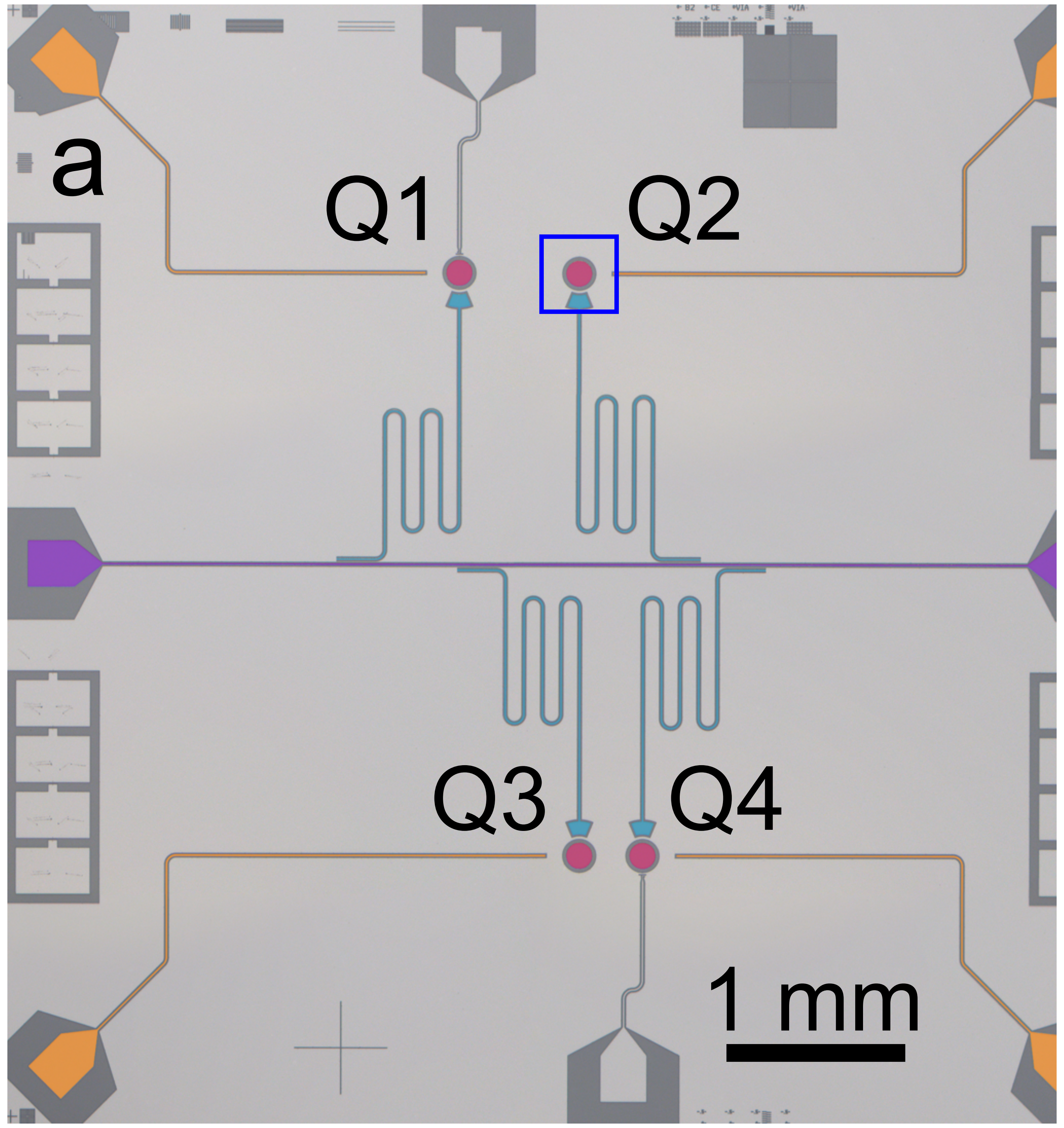
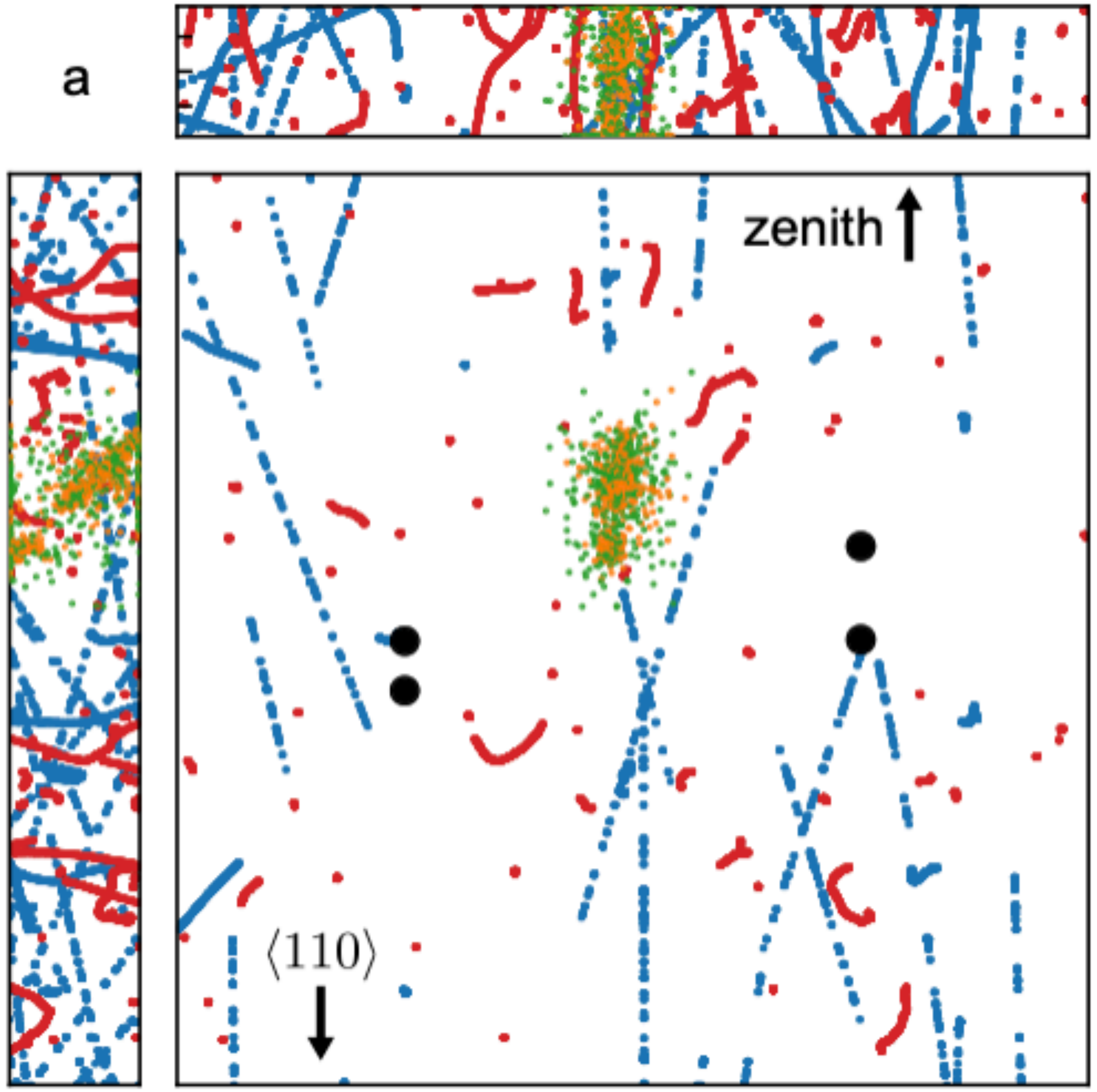


From the substrate to the qubit

Chip with four qubits and its implementation in a Monte Carlo simulation (GEANT-4)

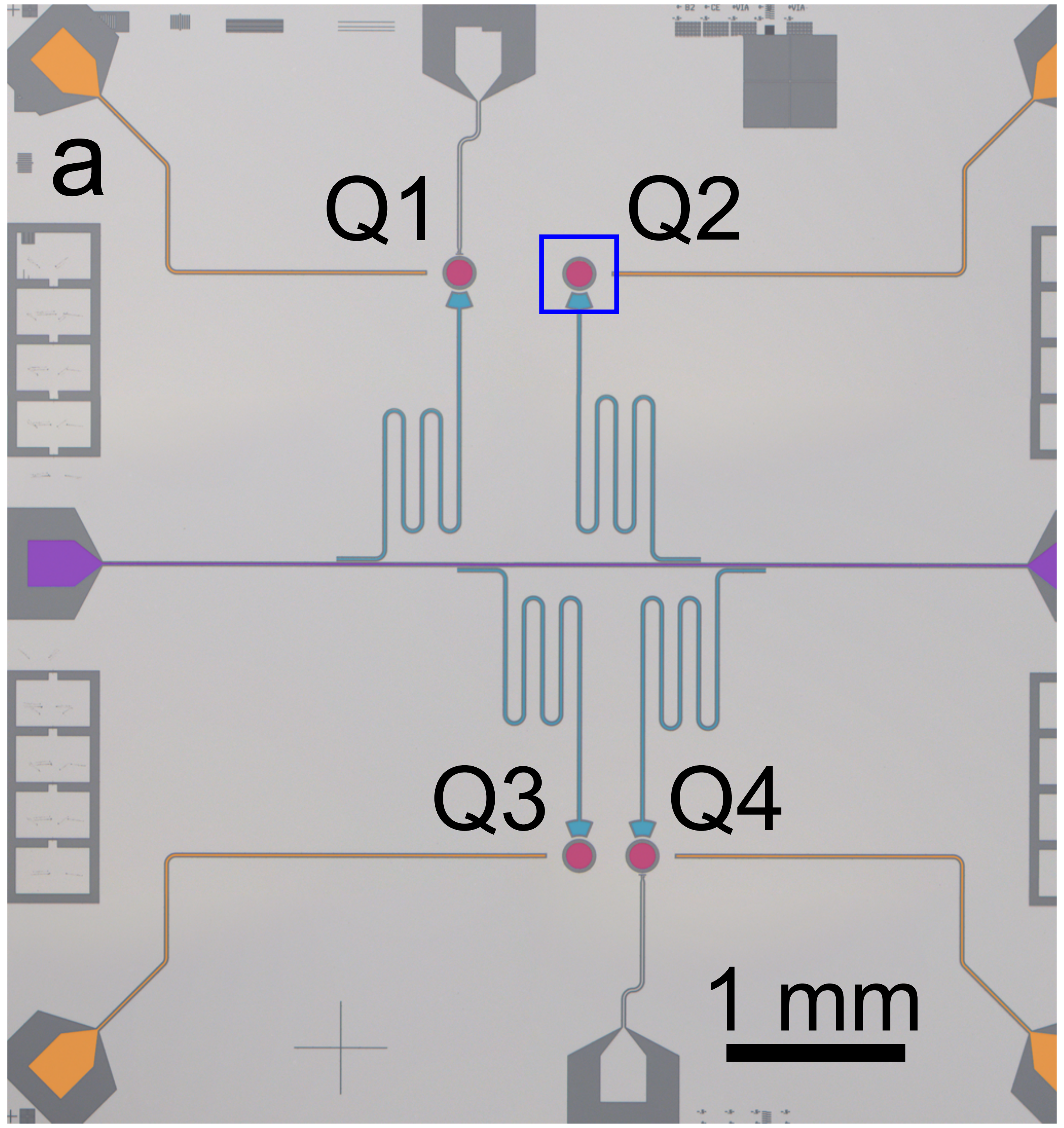
Wilen et al, Nature 2021

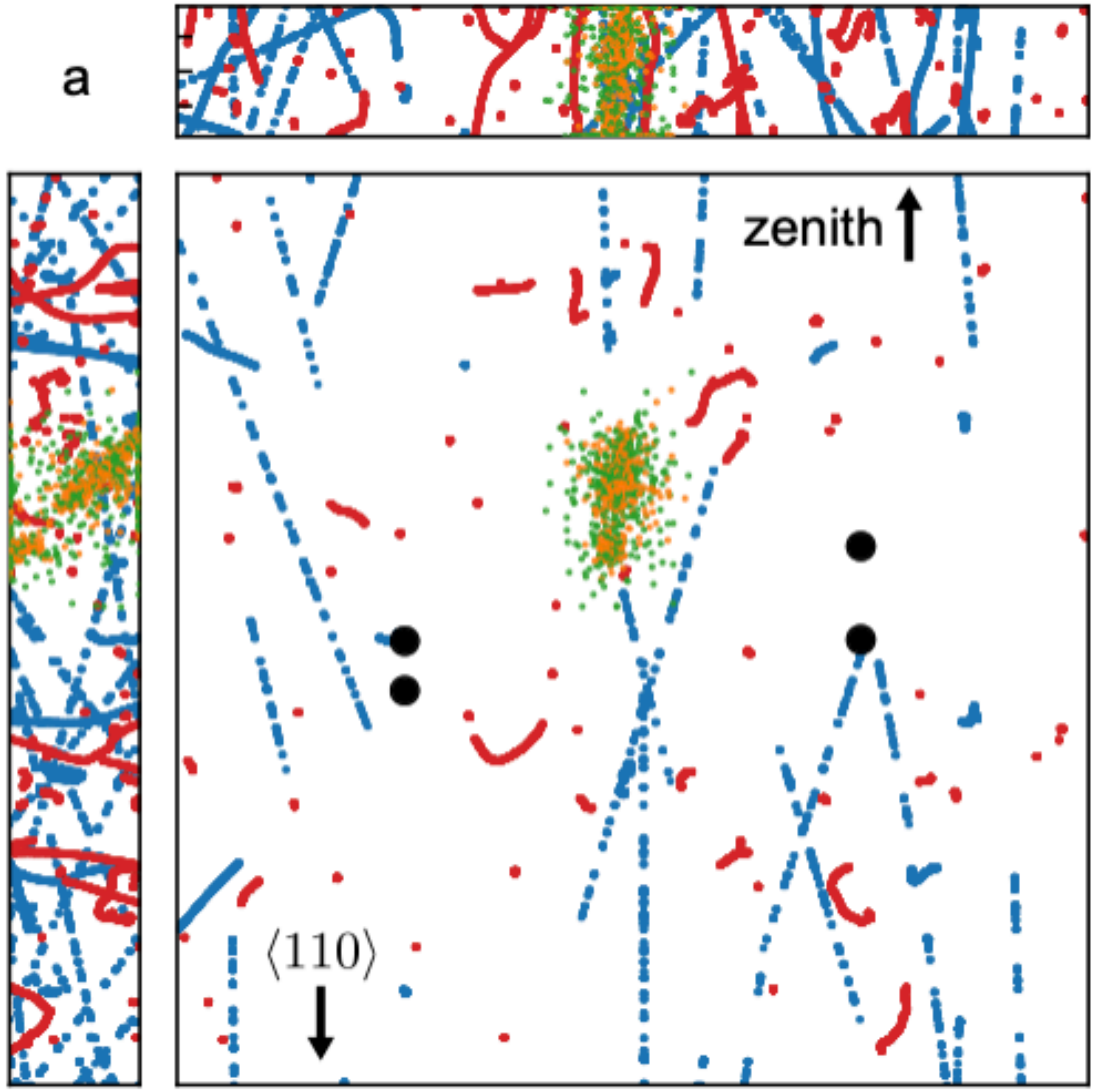




From the substrate to the qubit: interaction

Chip with four qubits and its implementation in a Monte Carlo simulation (GEANT-4)





Blue: muon tracks

Red: gamma rays produce electrons

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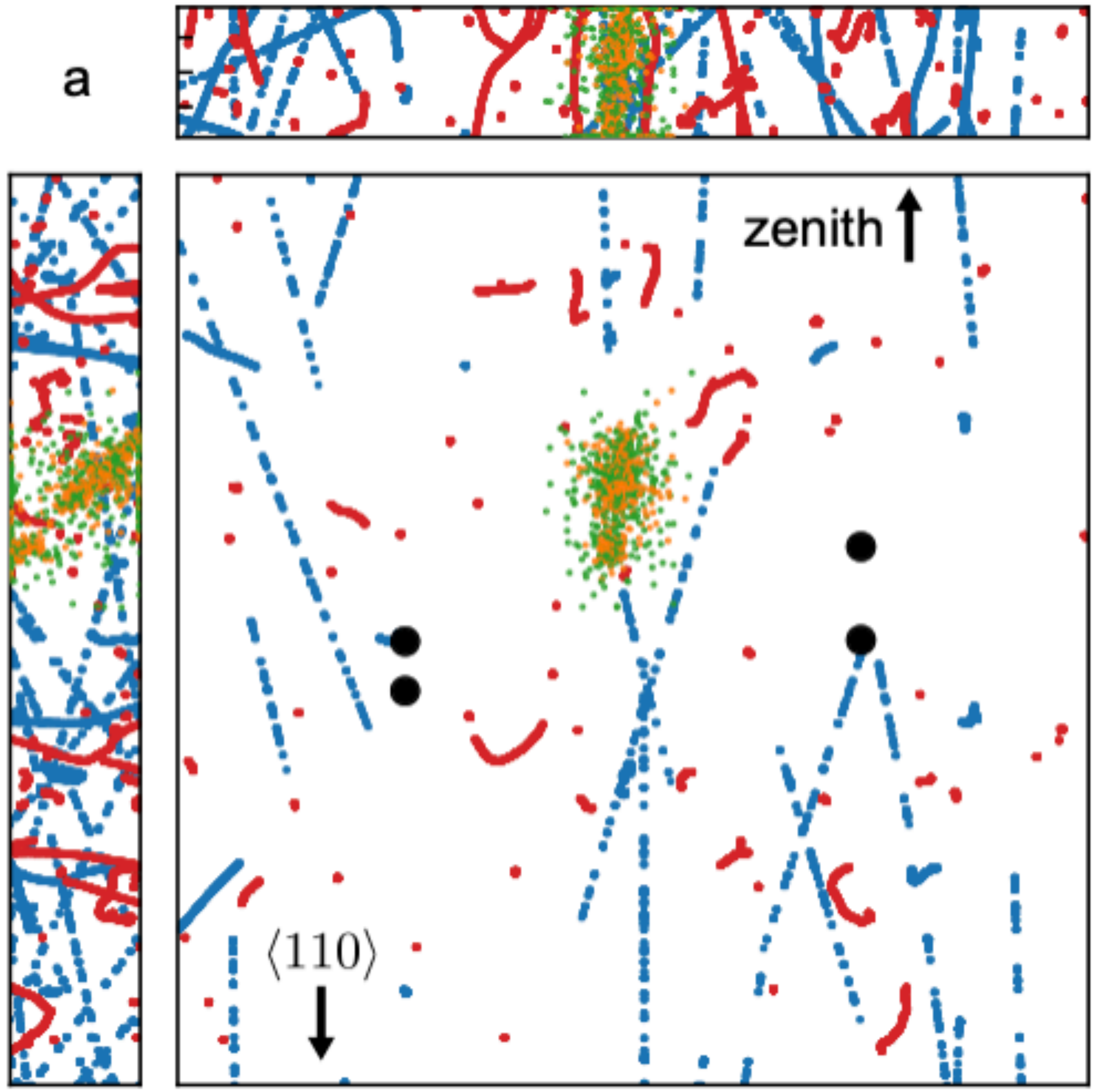
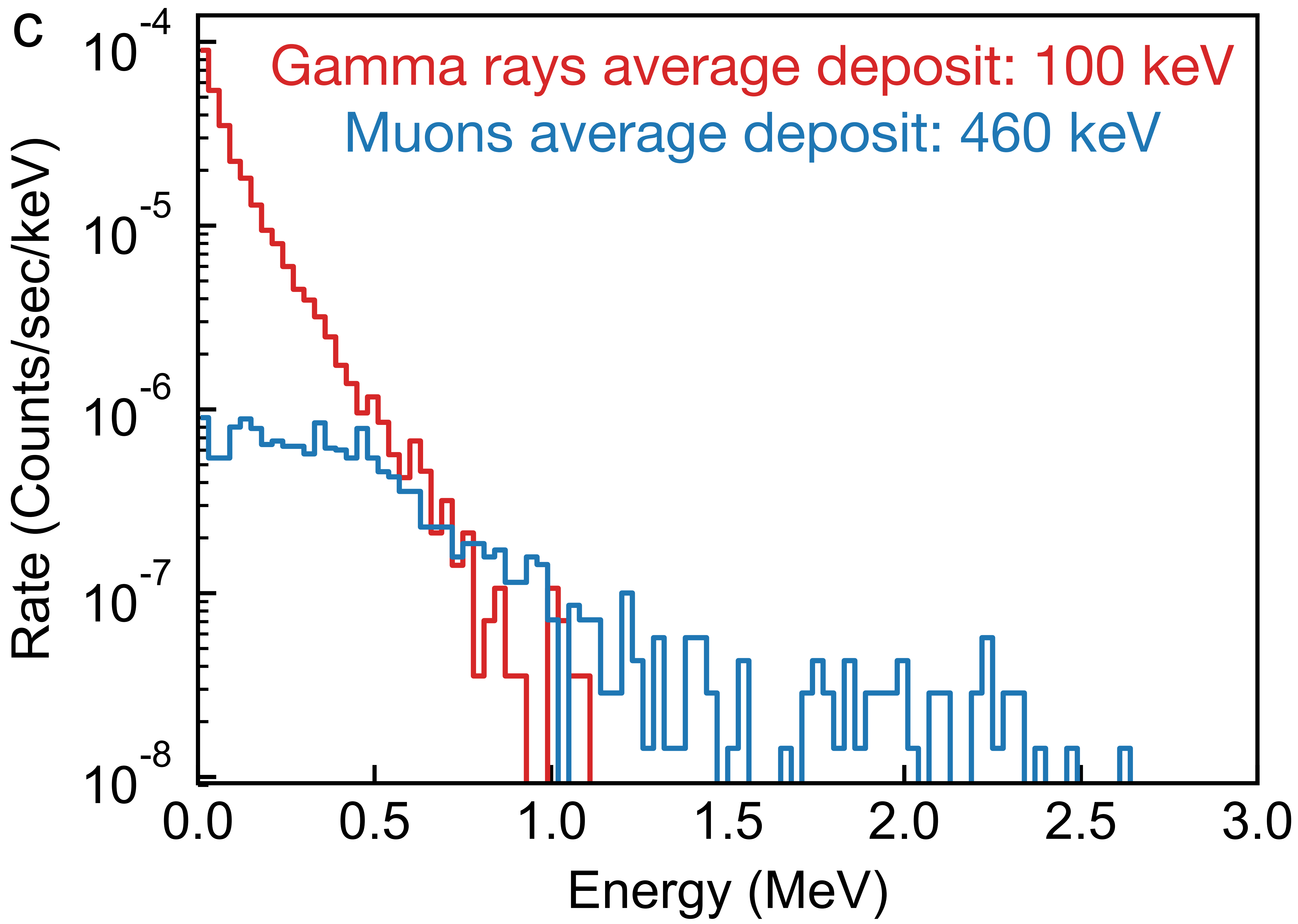
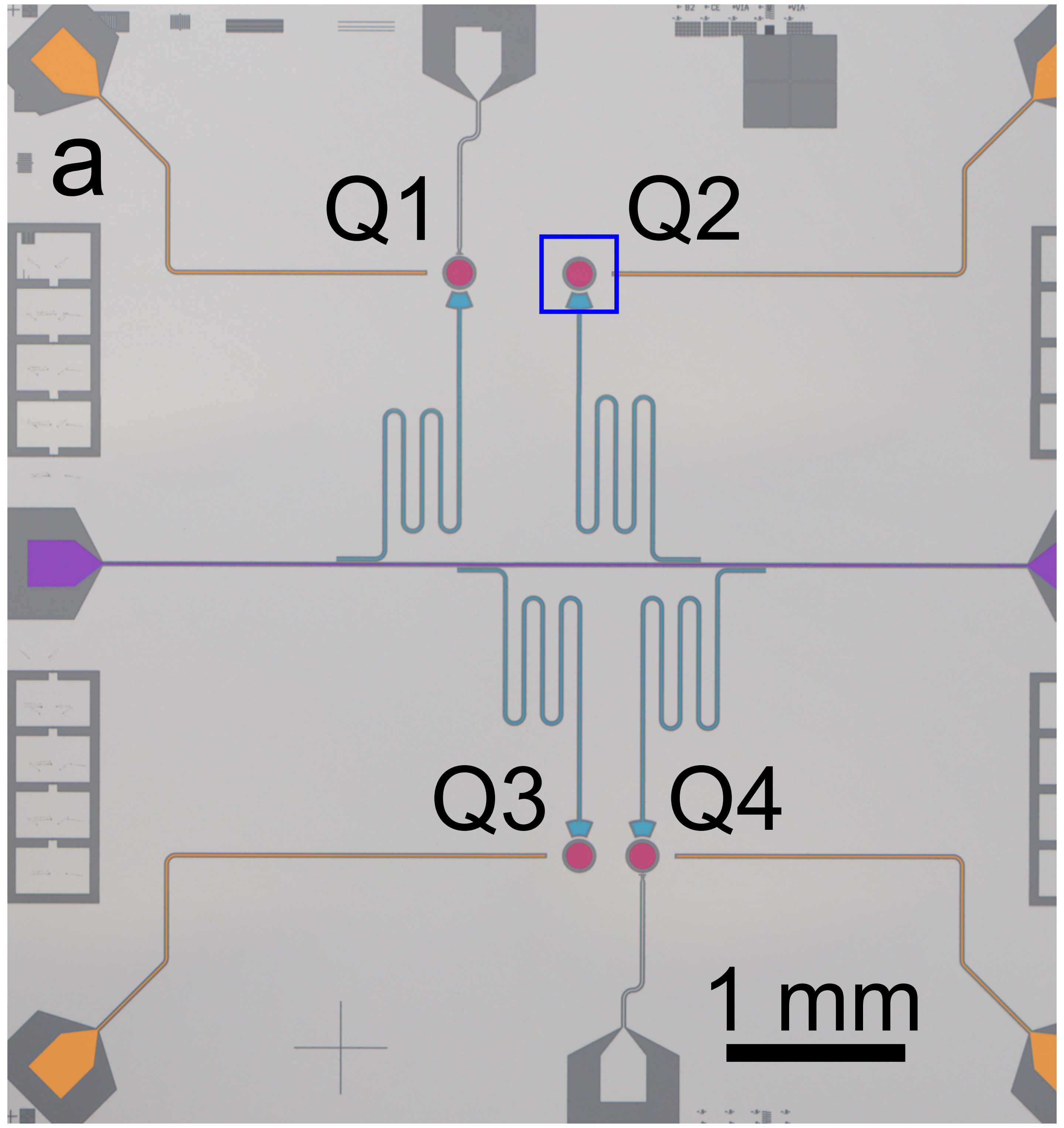
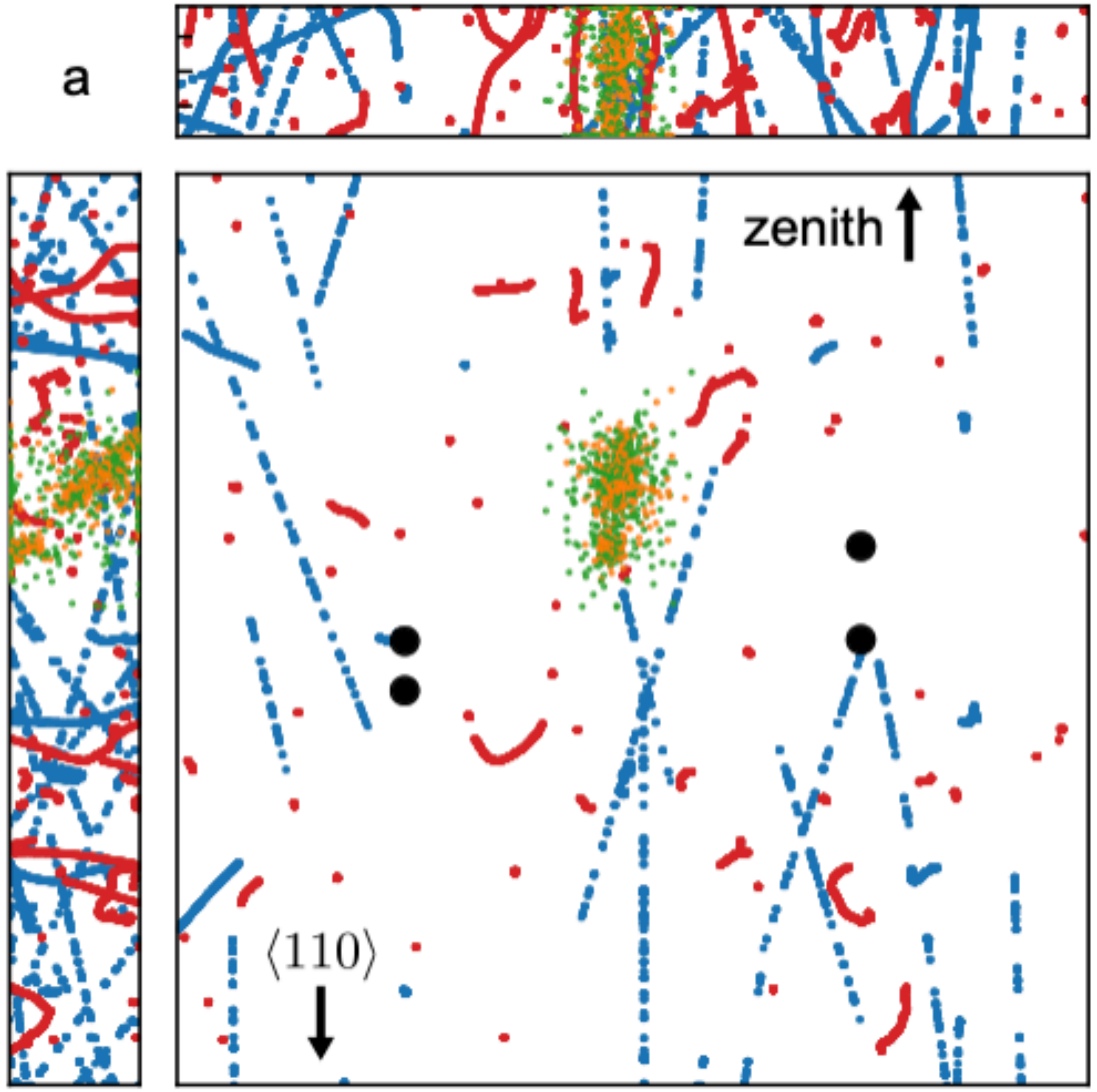




From the substrate to the qubit: evolution

Chip with four qubits and its implementation in a Monte Carlo simulation (GEANT-4)

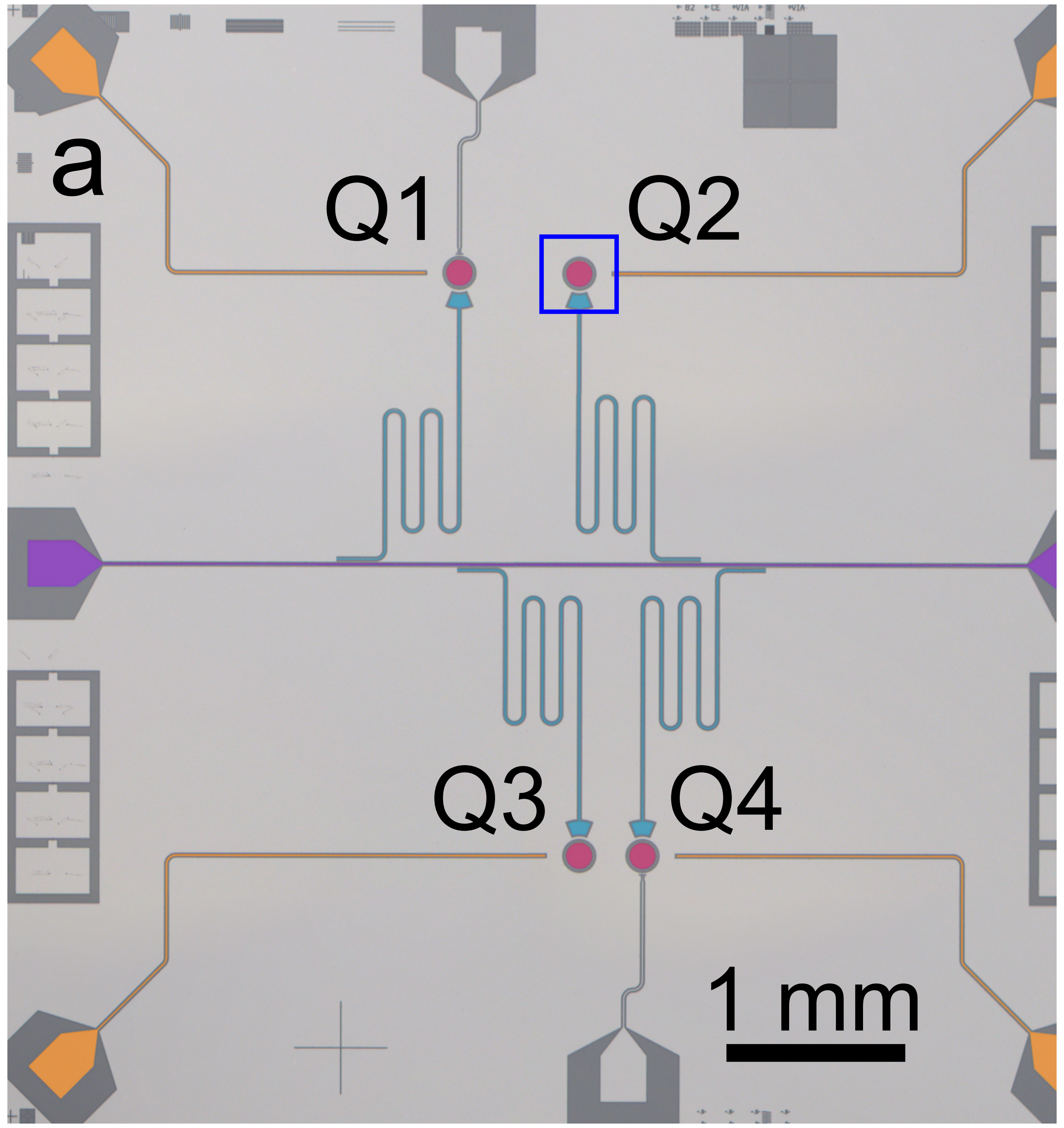


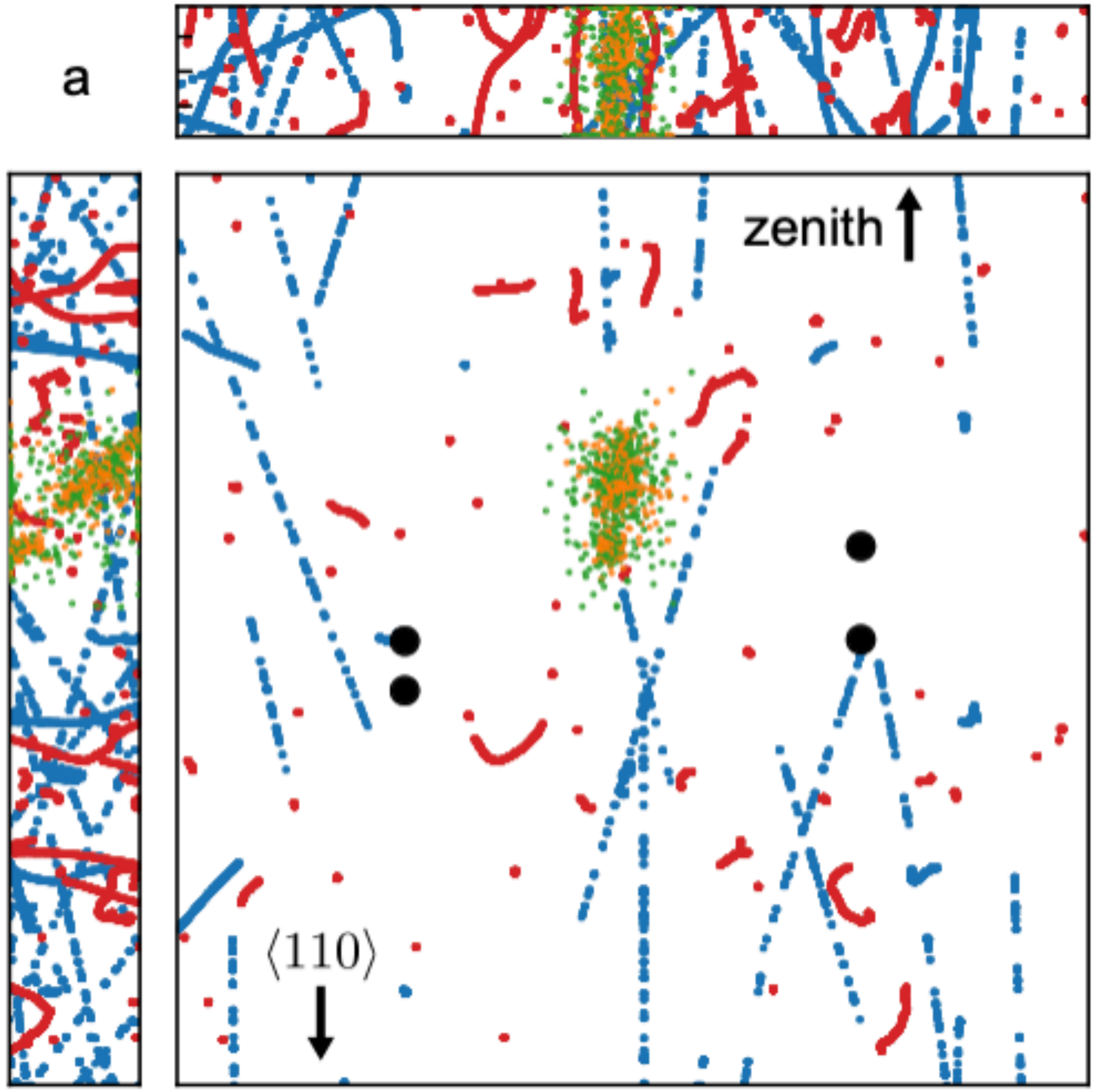


What happens to the energy deposited in the substrate?

From the substrate to the qubit: evolution

Chip with four qubits and its implementation in a Monte Carlo simulation (GEANT-4)





What happens to the energy deposited in the substrate?

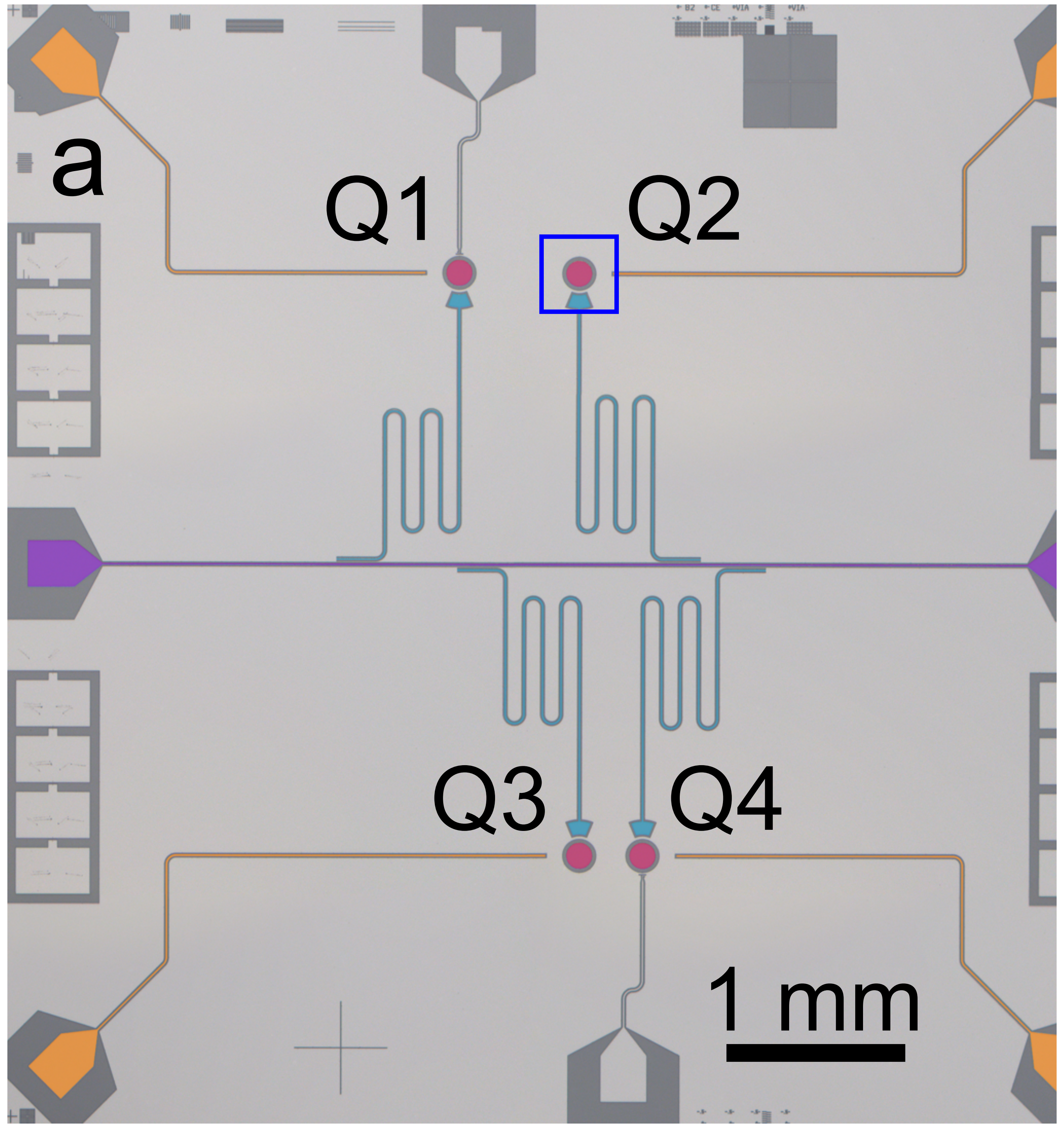
3.6 eV energy in e/h

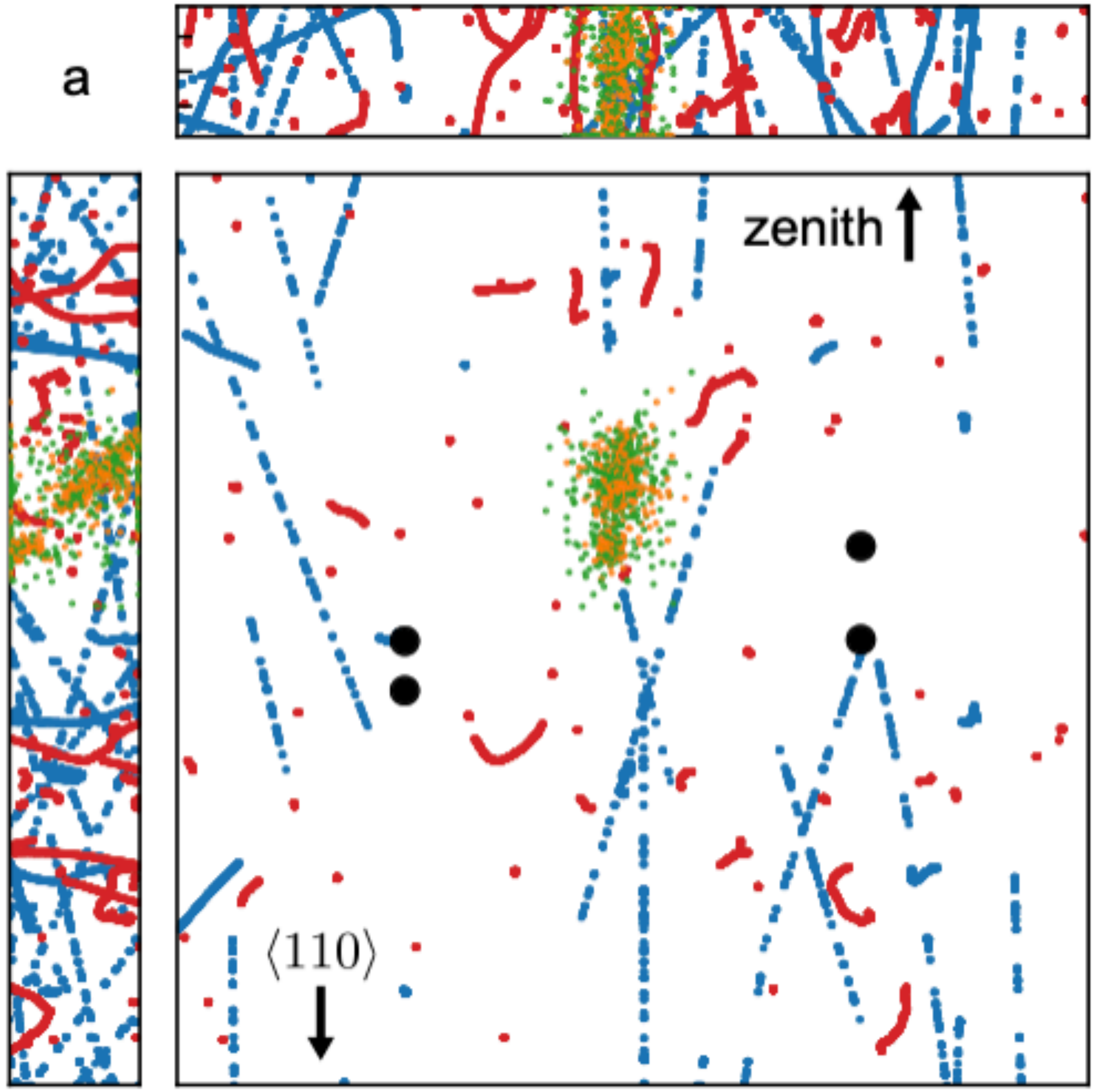
Typical energy deposit of tens of keV

—> 10^4 electron/holes

From the substrate to the qubit: evolution

Chip with four qubits and its implementation in a Monte Carlo simulation (GEANT-4)





Electron/holes do not drift (we are not applying fields)

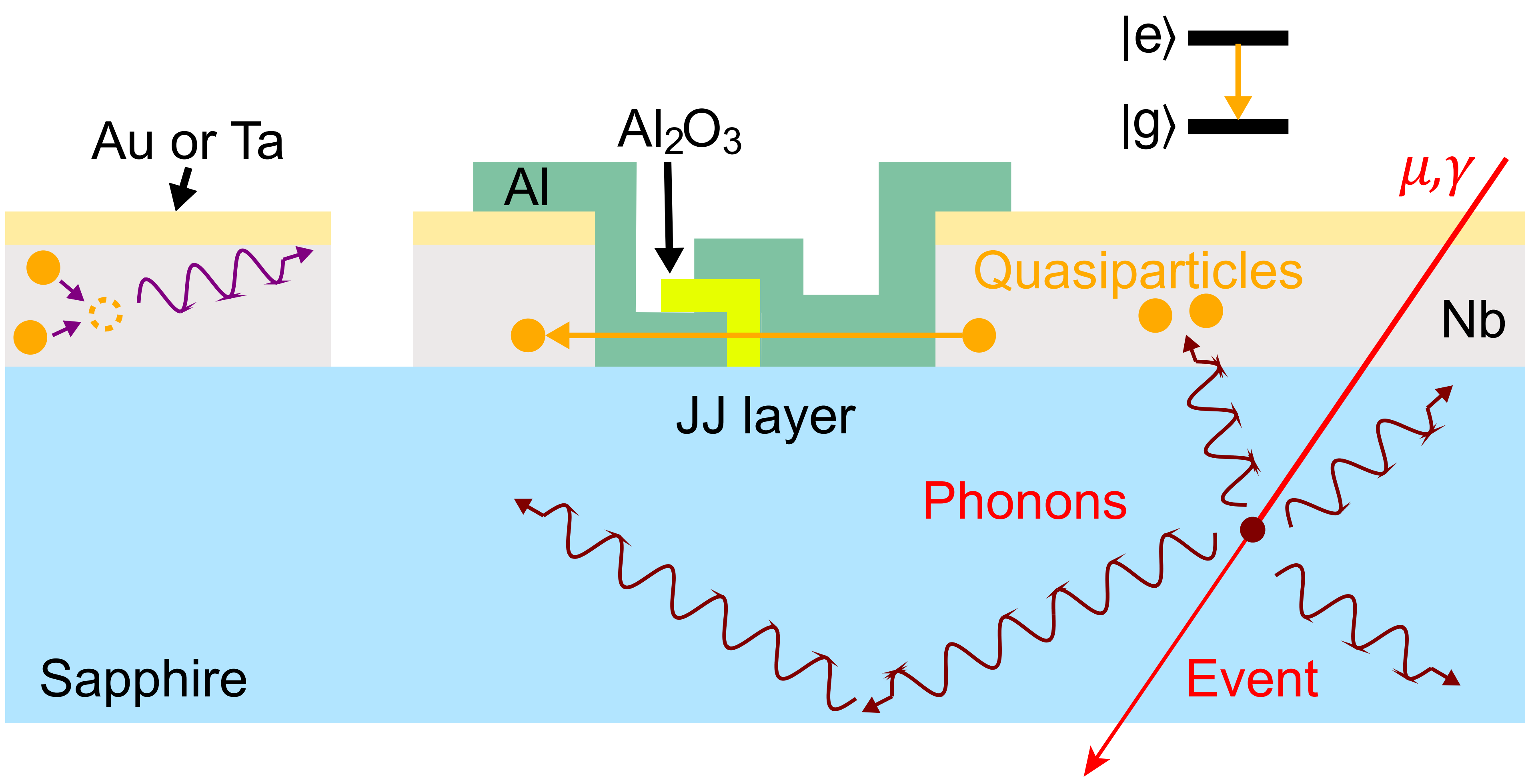
They recombine

The energy goes into *phonons* (collective vibration of the crystal lattice)

Phonons diffuse in the whole substrate

From the substrate to the qubit: evolution

Chip with four qubits and its implementation in a Monte Carlo simulation (GEANT-4)



- Athermal phonons created based on the E;
- High-E phonons down-convert into a large number of lower E phonons, that travel ballistically (nanosec);
- In Silicon, phonos are ballistic at E <= 6 meV;
- For Aluminum, 2Δ ~ 0.4 meV;
- Efficiency to break Cooper pairs ~ 60 %
- QPs diffuse, recombine and are trapped (timescale?)

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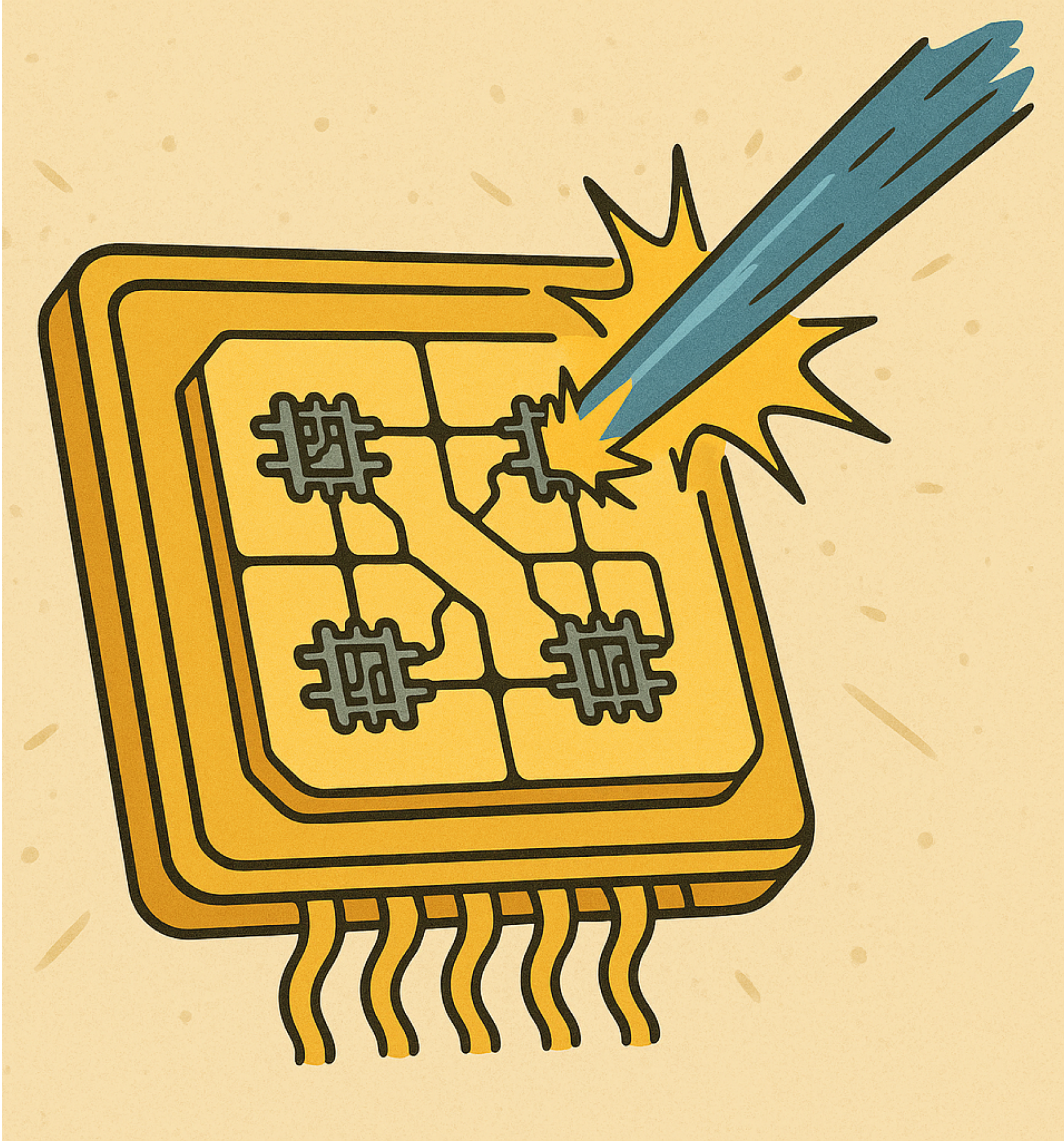
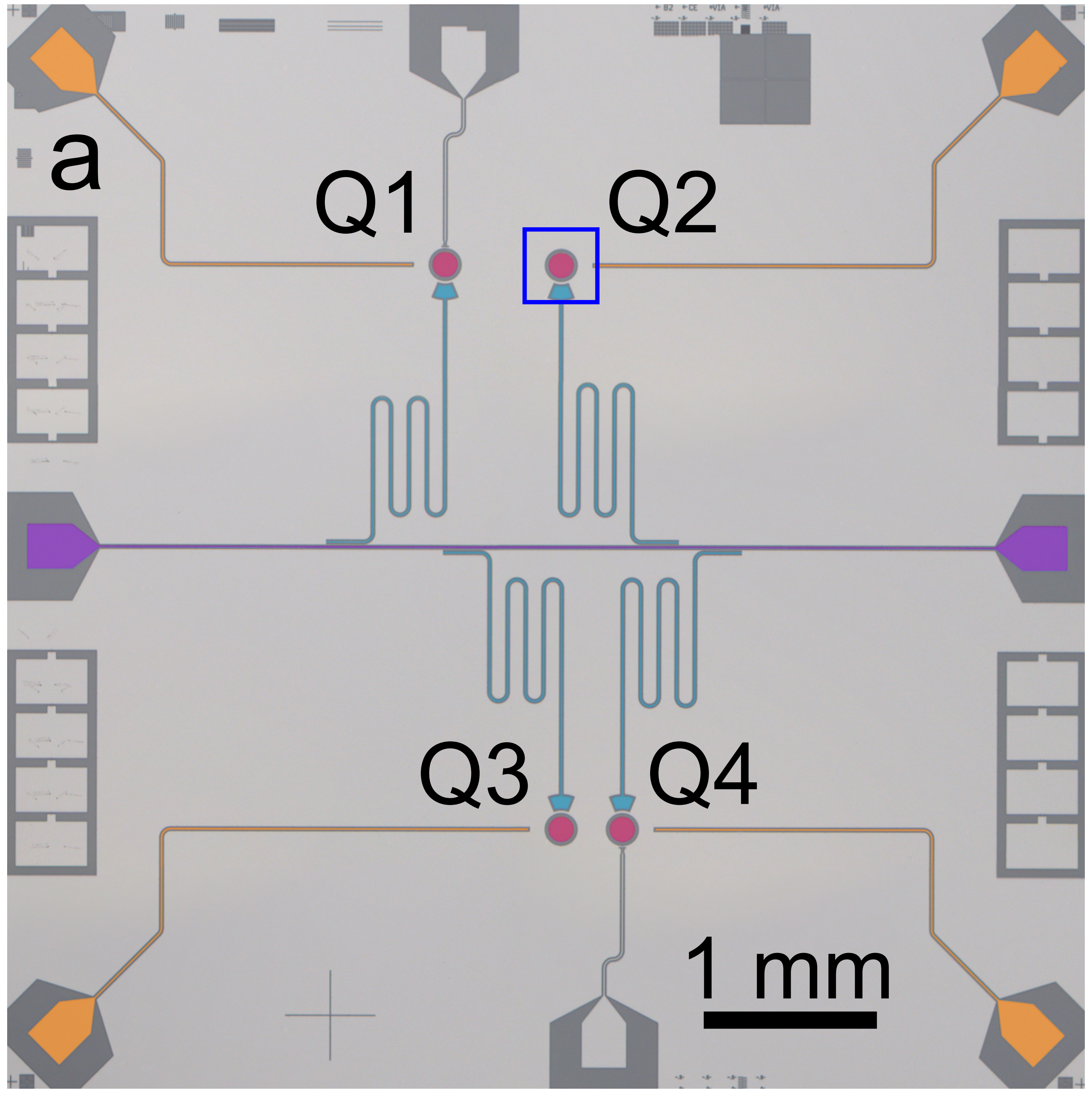
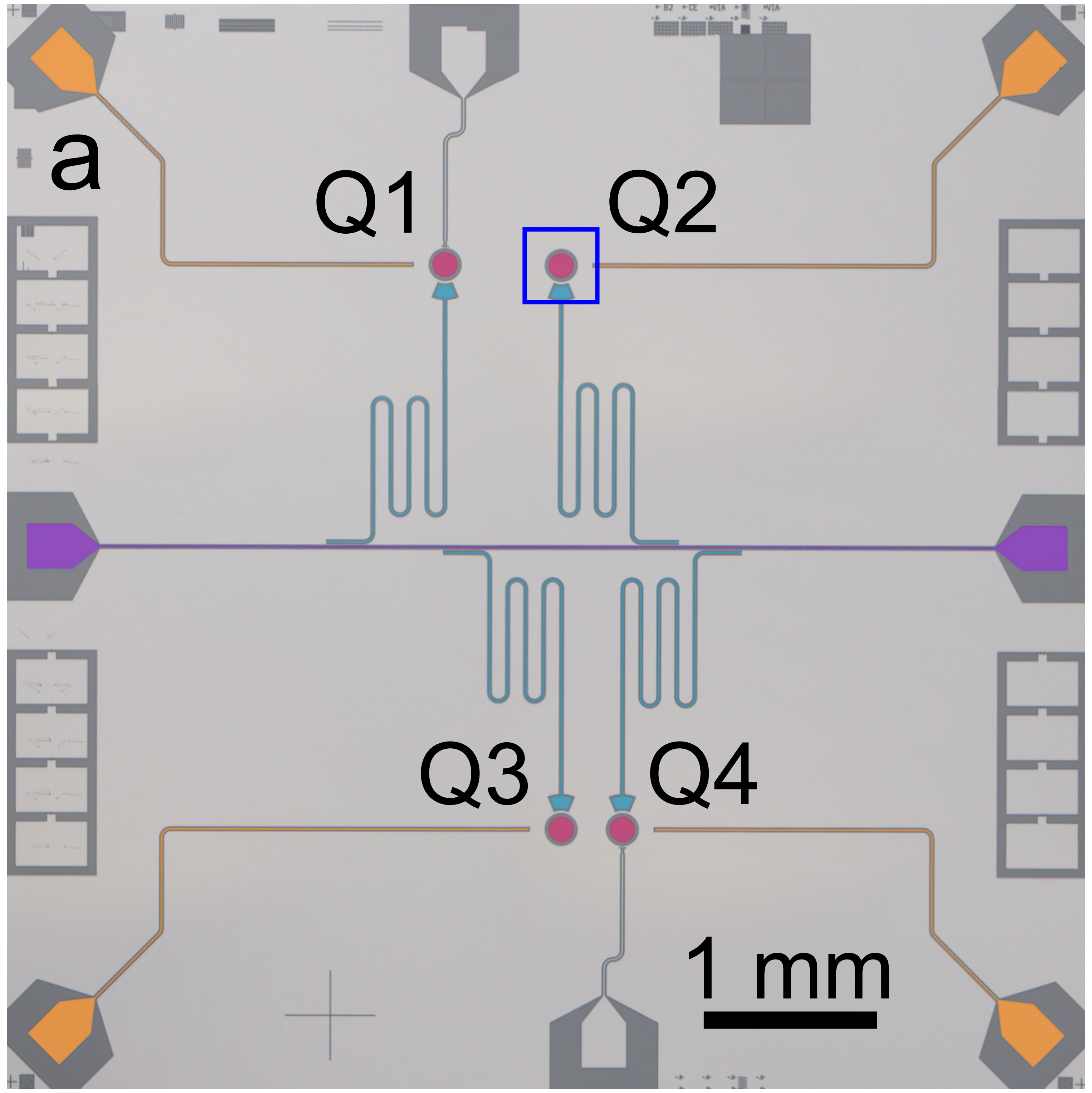


Validation: How?



Validation: How?



If I am producing a cloud of charges

—> my transmons will see an offset charge

If phonons are spreading in the whole chip

—> the T1 of each transmon will suffer

Validation: Offset Charge

INFN
Istituto Nazionale di Fisica Nucleare

Ramsey tomography to measure offset charge

We want to see if this offset charge n_g varies because of radioactivity

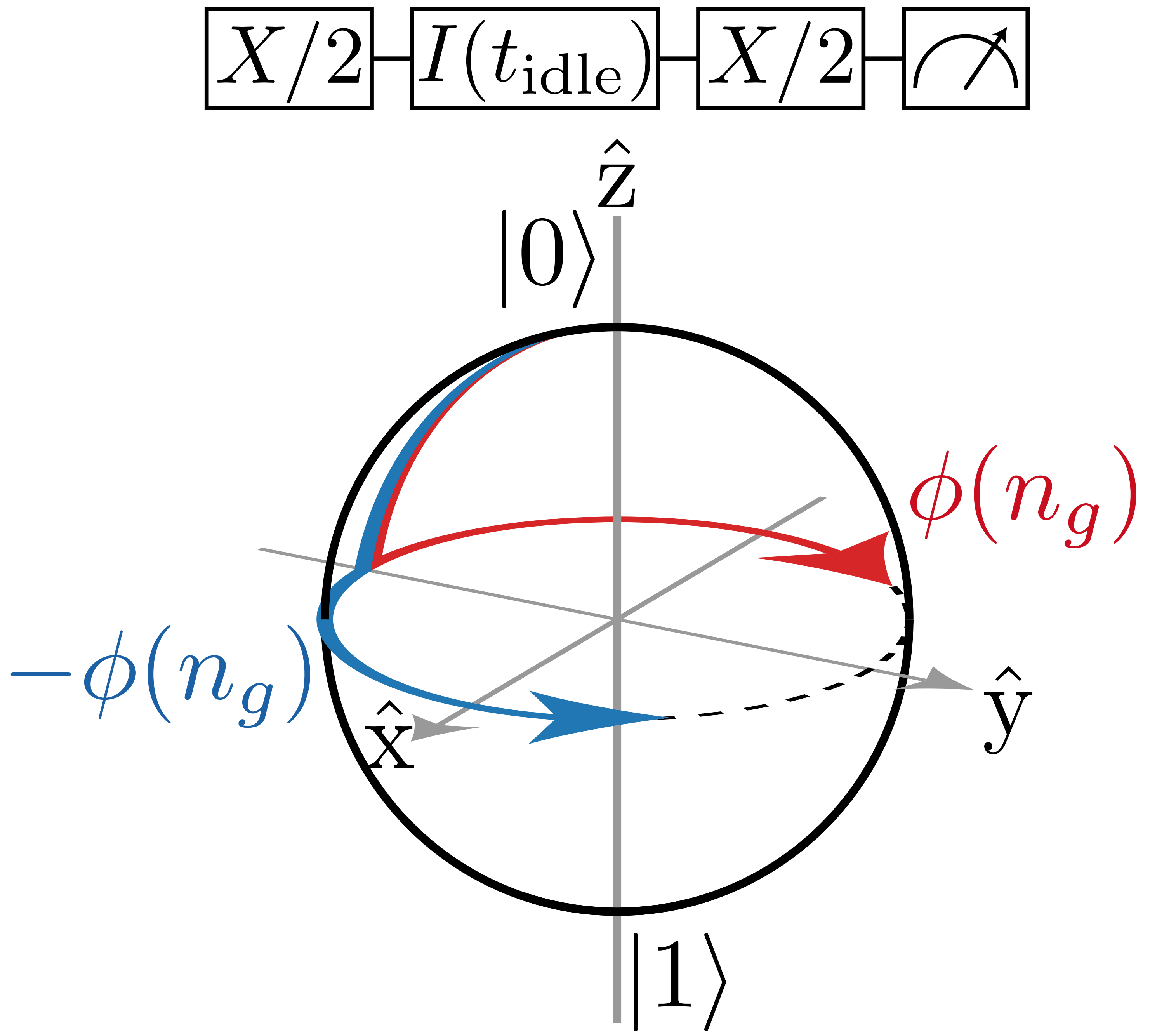
How do we measure n_g?

The qubit frequency *f* depends on n_g

$$f(n_g) = f_{\text{avg}} - A\cos(2\pi n_g)$$

Validation: Offset Charge

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

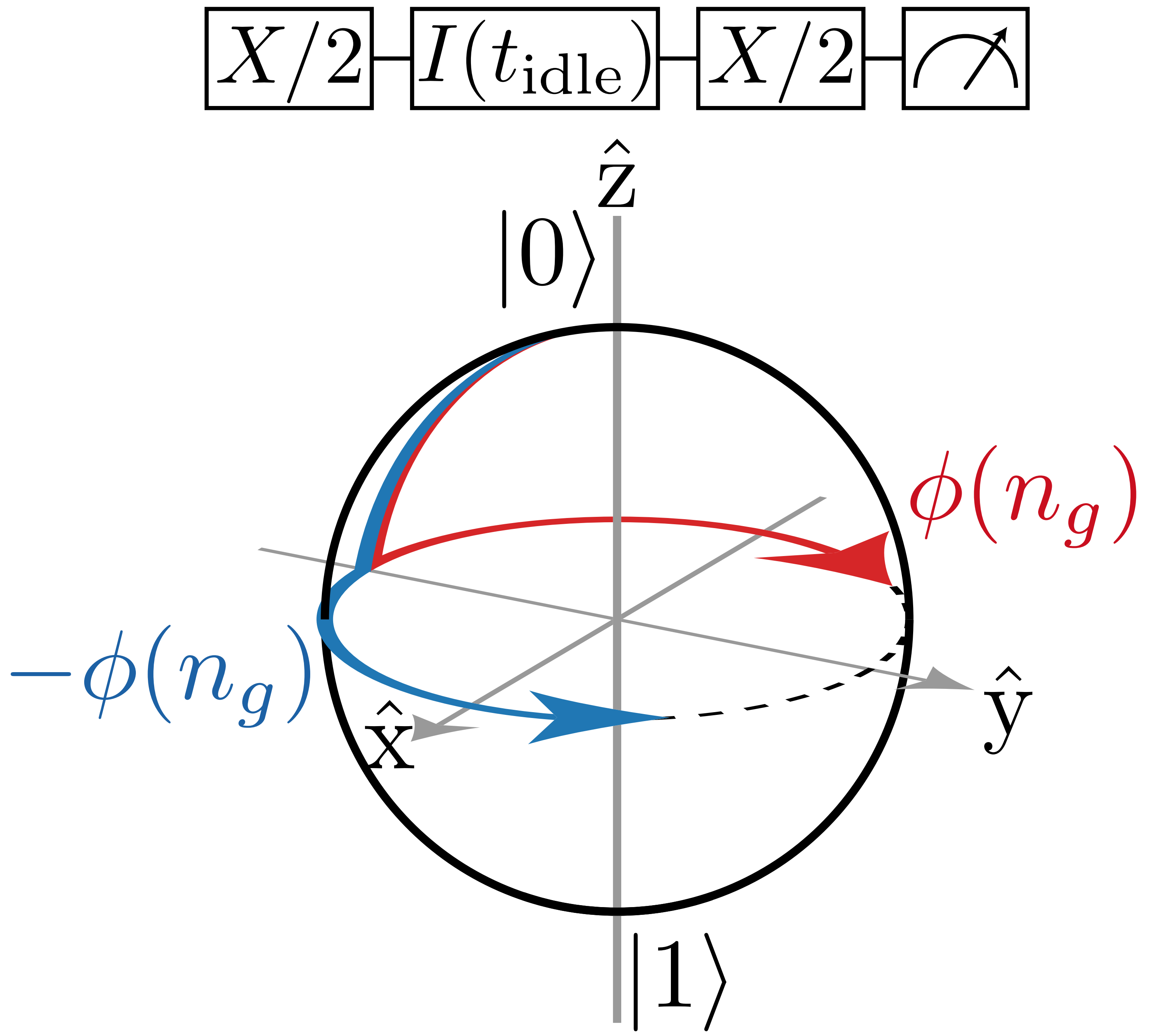
$$P_1(t_{\text{idle}}) = \frac{1}{2}\left(1 - \cos(\Delta\omega \cdot t_{\text{idle}})\right) \cdot e^{-t_{\text{idle}}/T_2^*}$$

Δω: detuning frequency of qubit- frequency drive

T_2^* coherence -including slow noise, ...

Validation: Offset Charge

Ramsey tomography to to measure the qubit frequency



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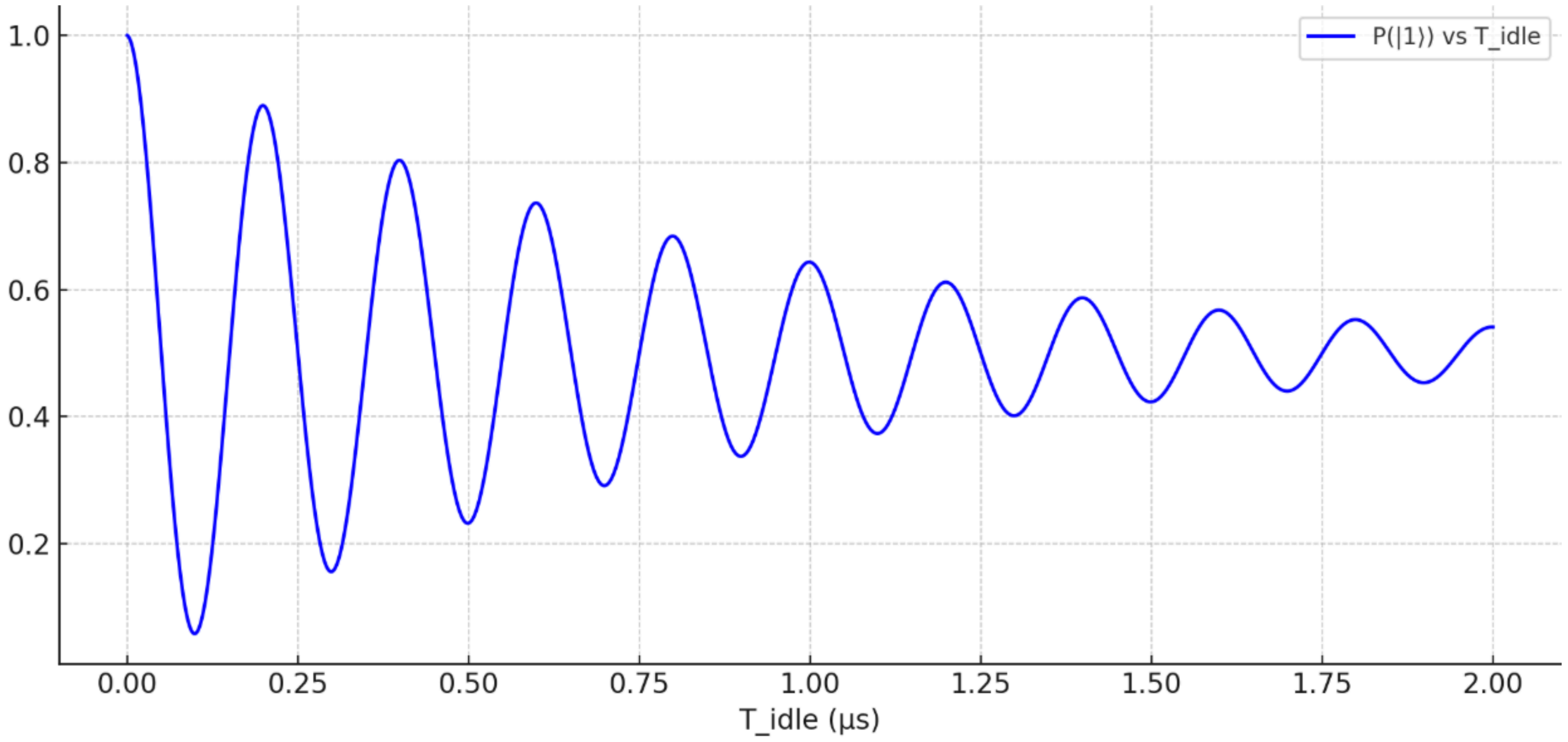
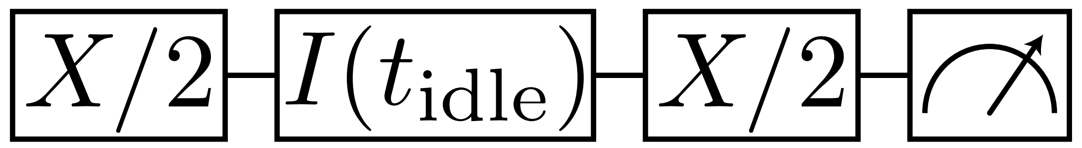


Note on time scales

Ramsey tomography to to measure the qubit frequency



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

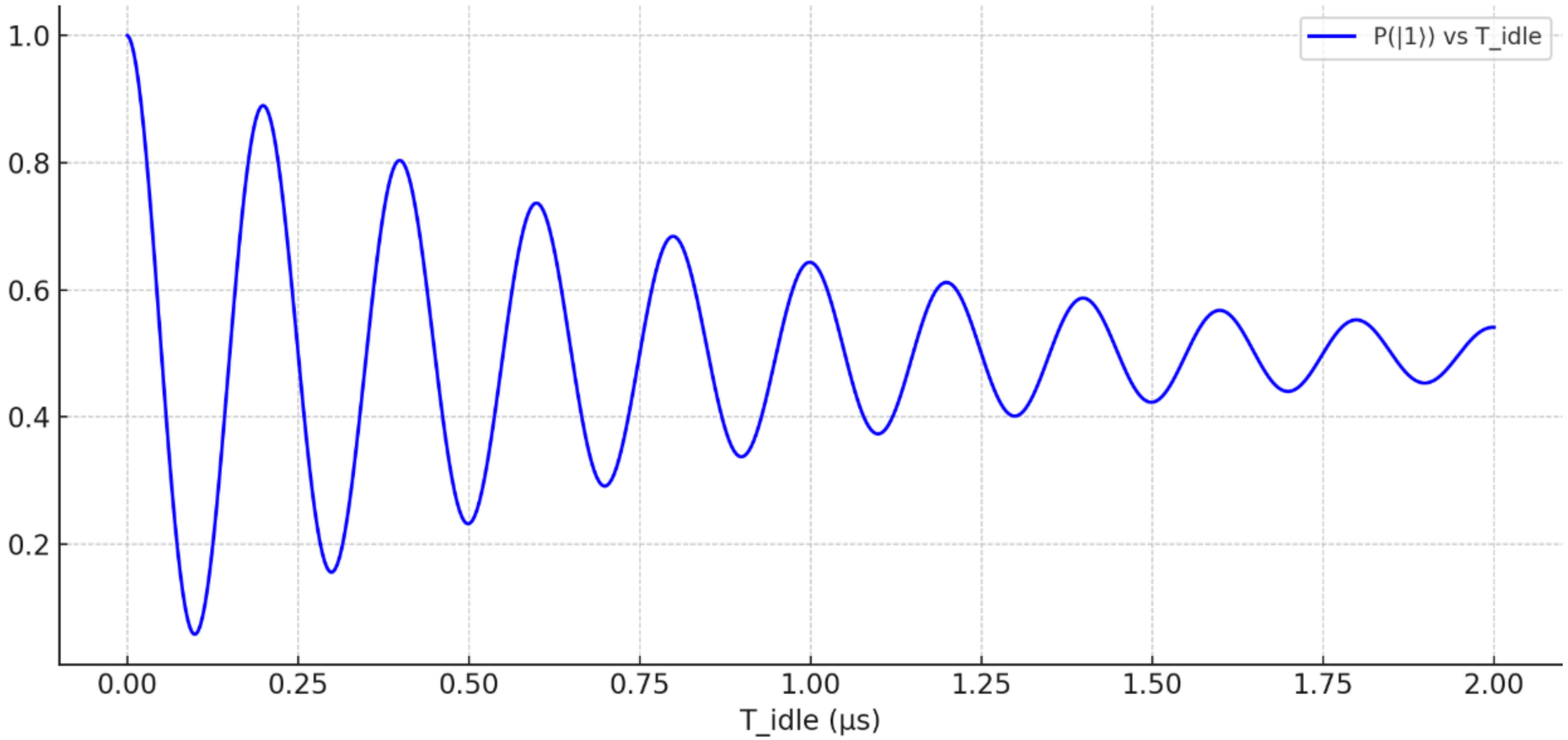
Scan ~100 t_{idle}

Each point x 100/1000 times

Length of a cycle ~ 40 µs

~ 20 seconds

per each charge point!

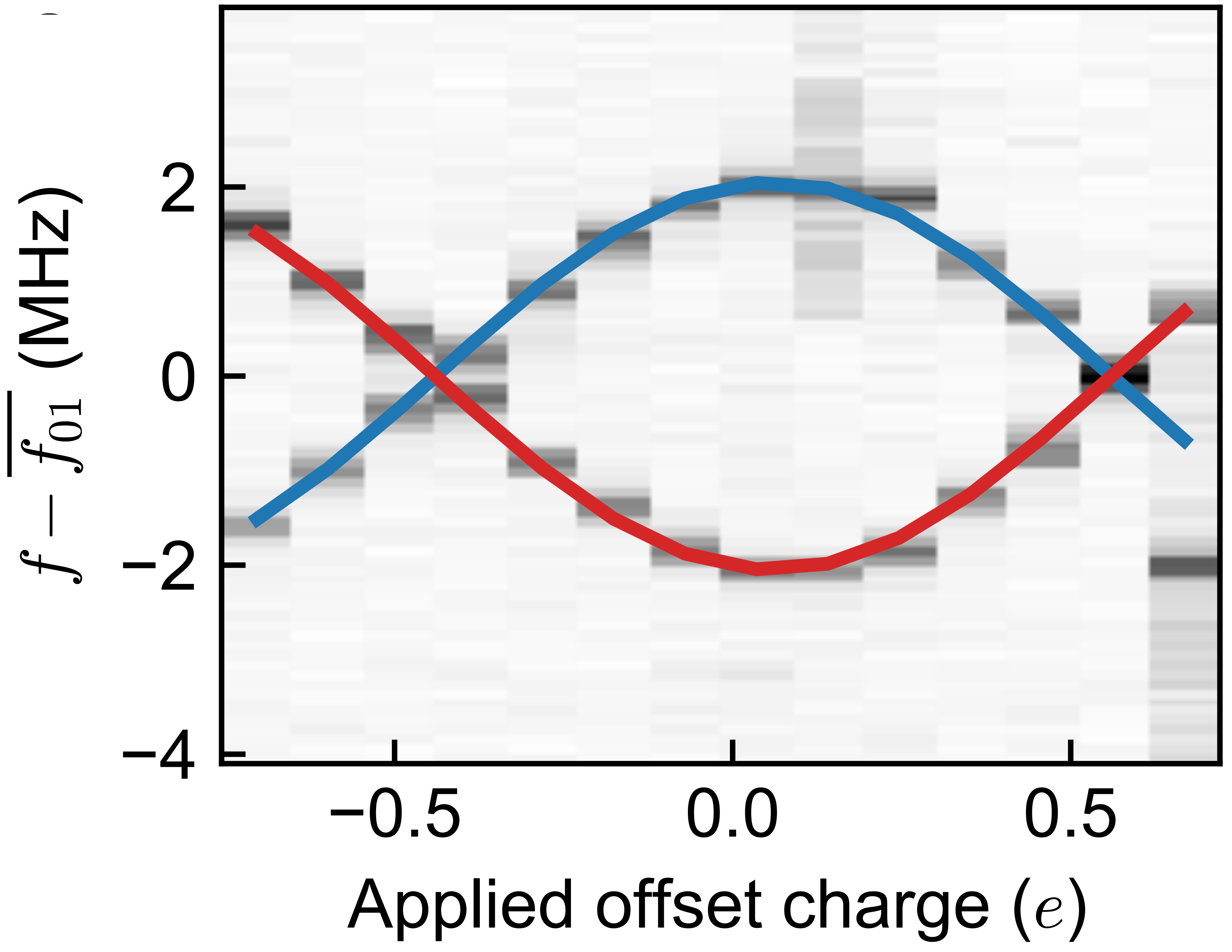


Calibration

Now we are able to compute the qubit frequency *f*

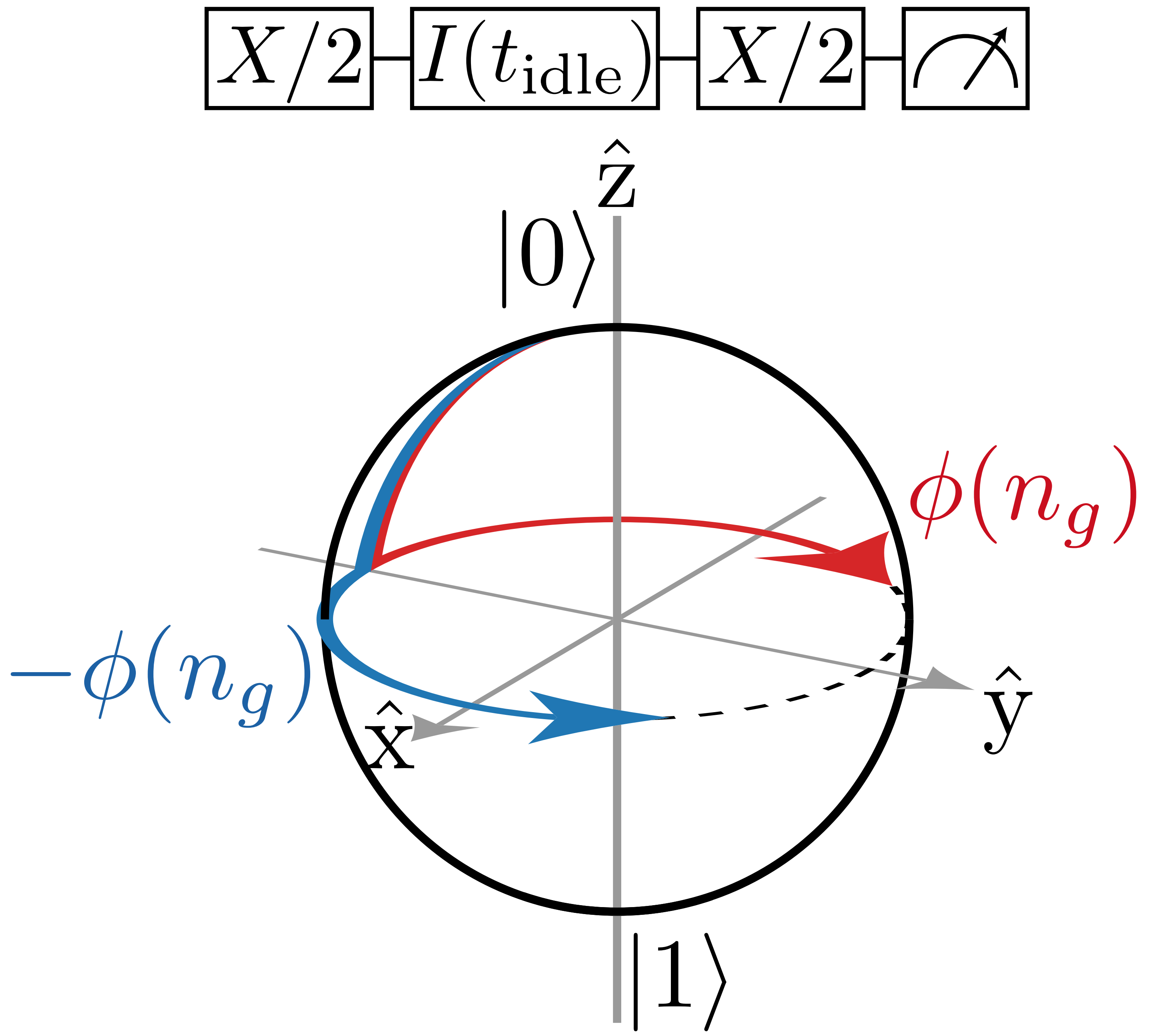
We "calibrate" its relationship with n_g

$$f(n_g) = f_{\text{avg}} - A\cos(2\pi n_g)$$



We inject an offset charge, measure *f*,
then inject another offset charge and measure *f*,
then inject another offset charge, …

An now...

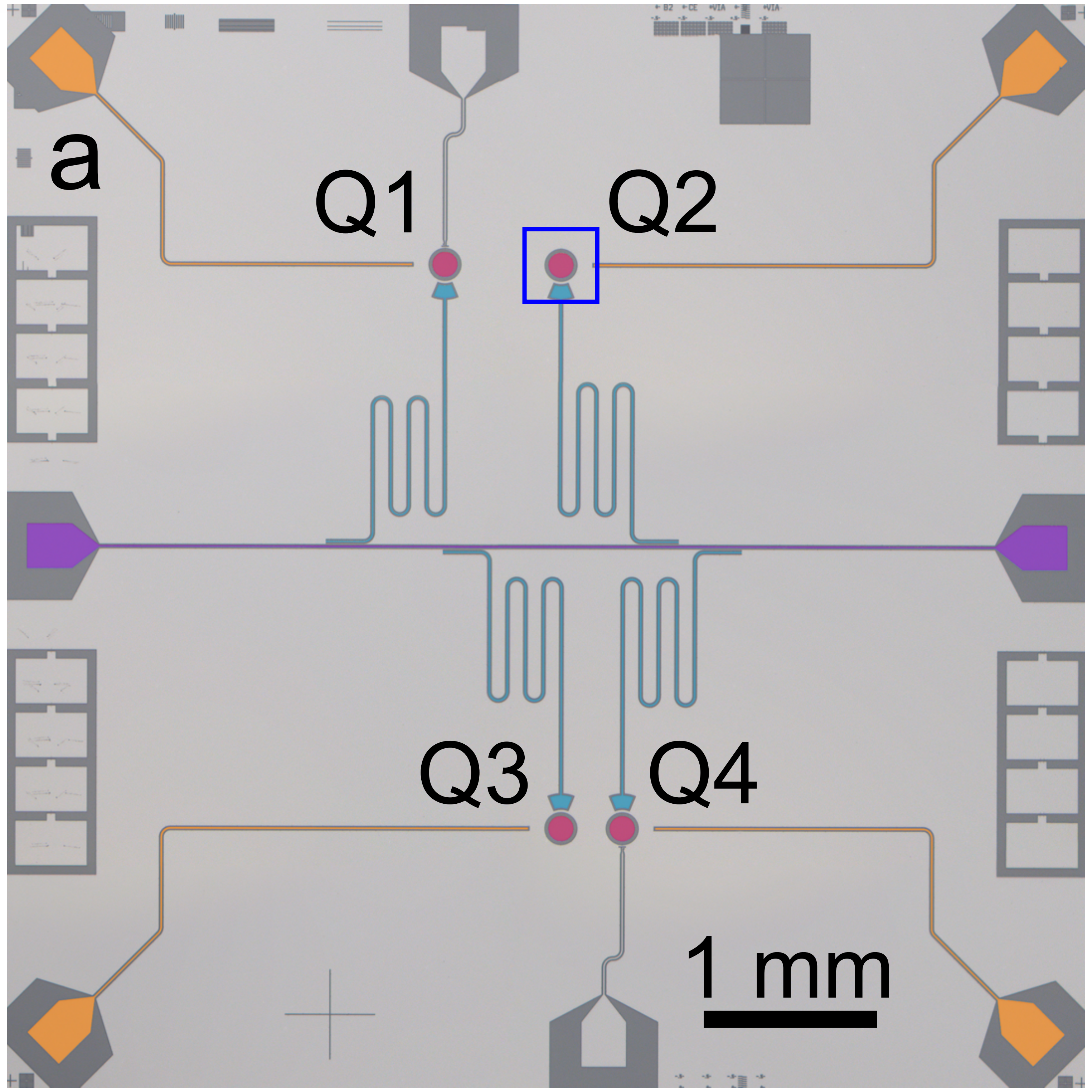


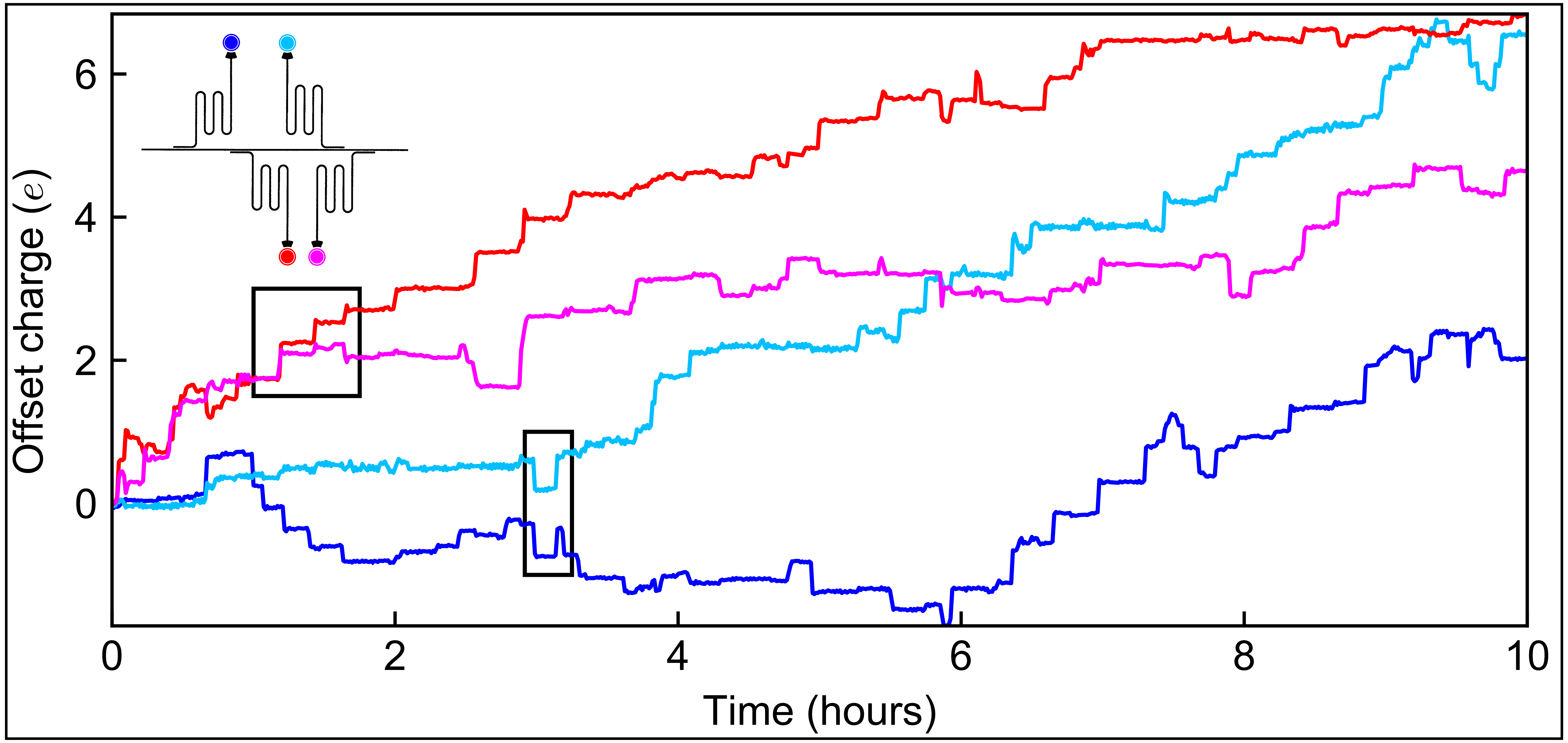
Our measurements begin!

- Ramsey cycle —> infer qubit *f*
- From qubit *f* —> derive offset charge n_g
- Save n_g as a function of time
- Ramsey cycle, ...

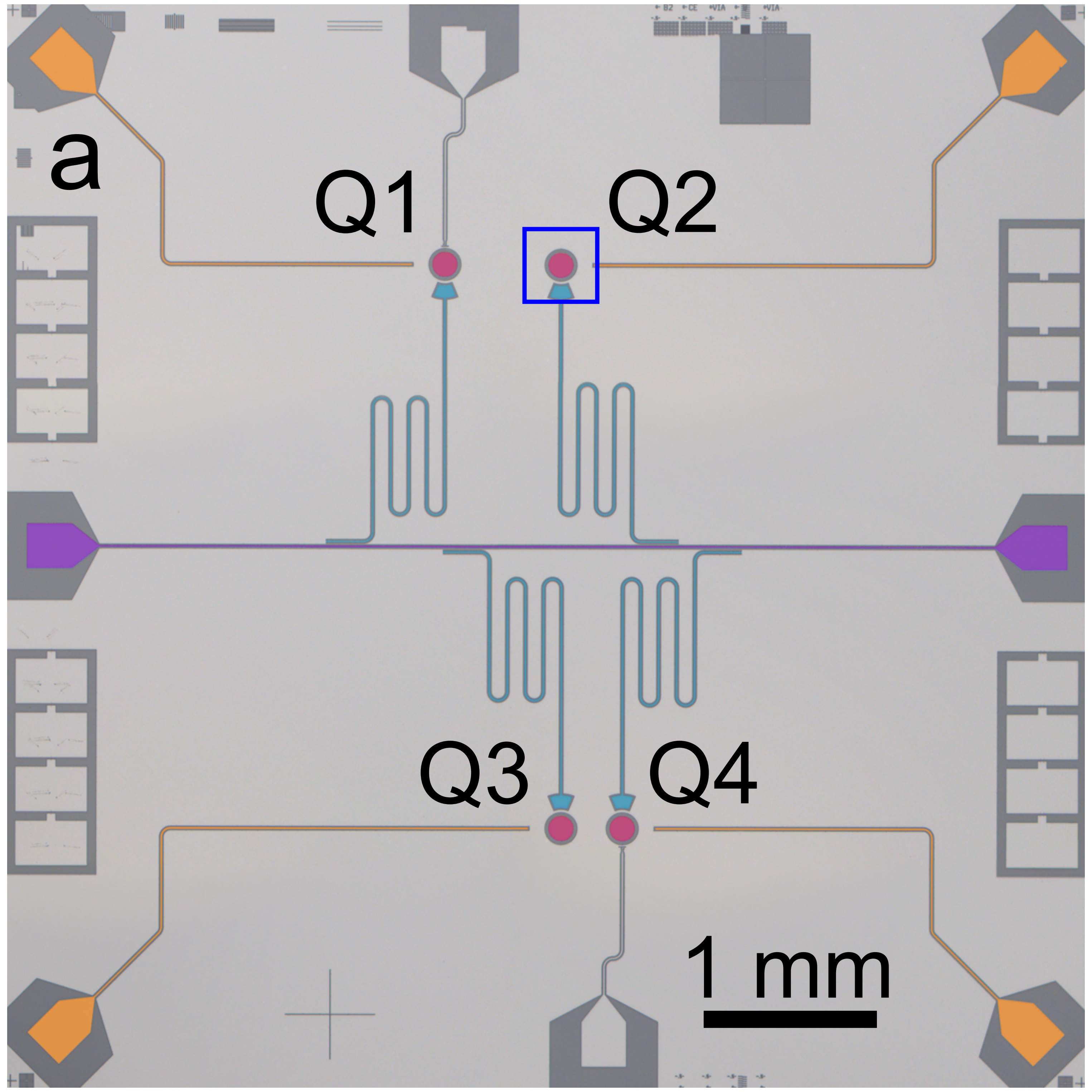
We can now monitor variations in n_g: 1/f noise, telegraph noise, jumps due to clouds of charges?

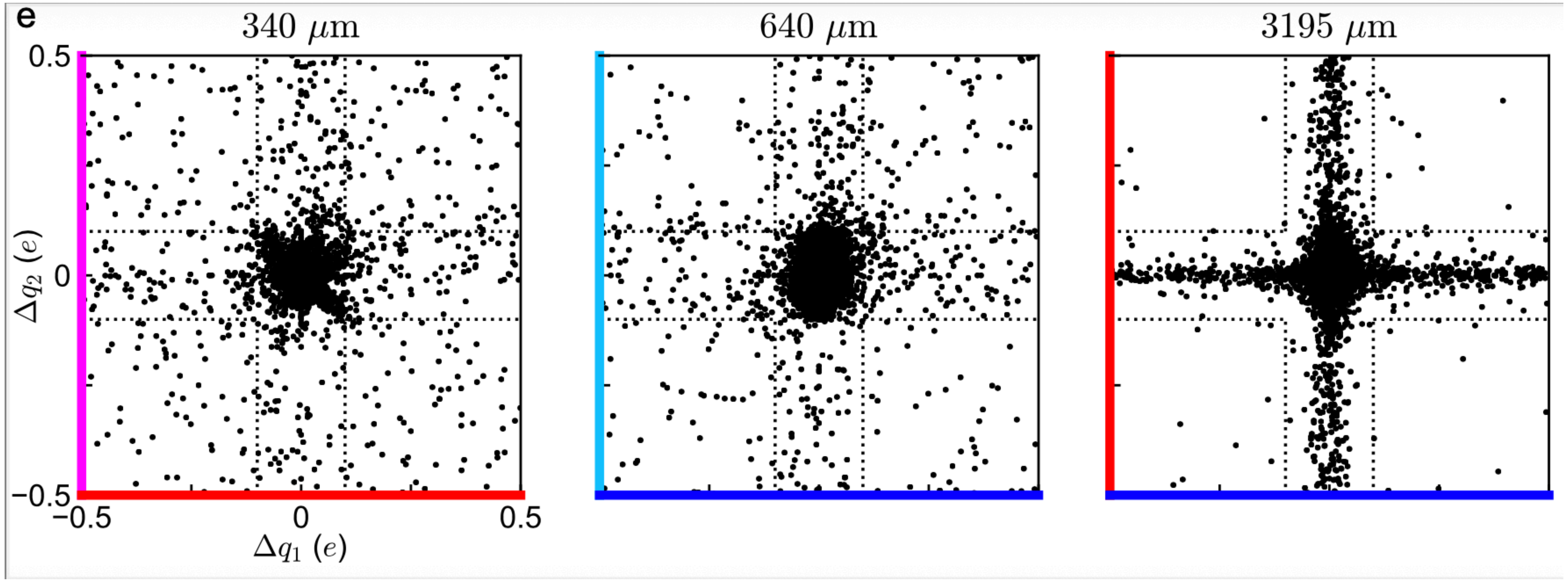
Results





Results

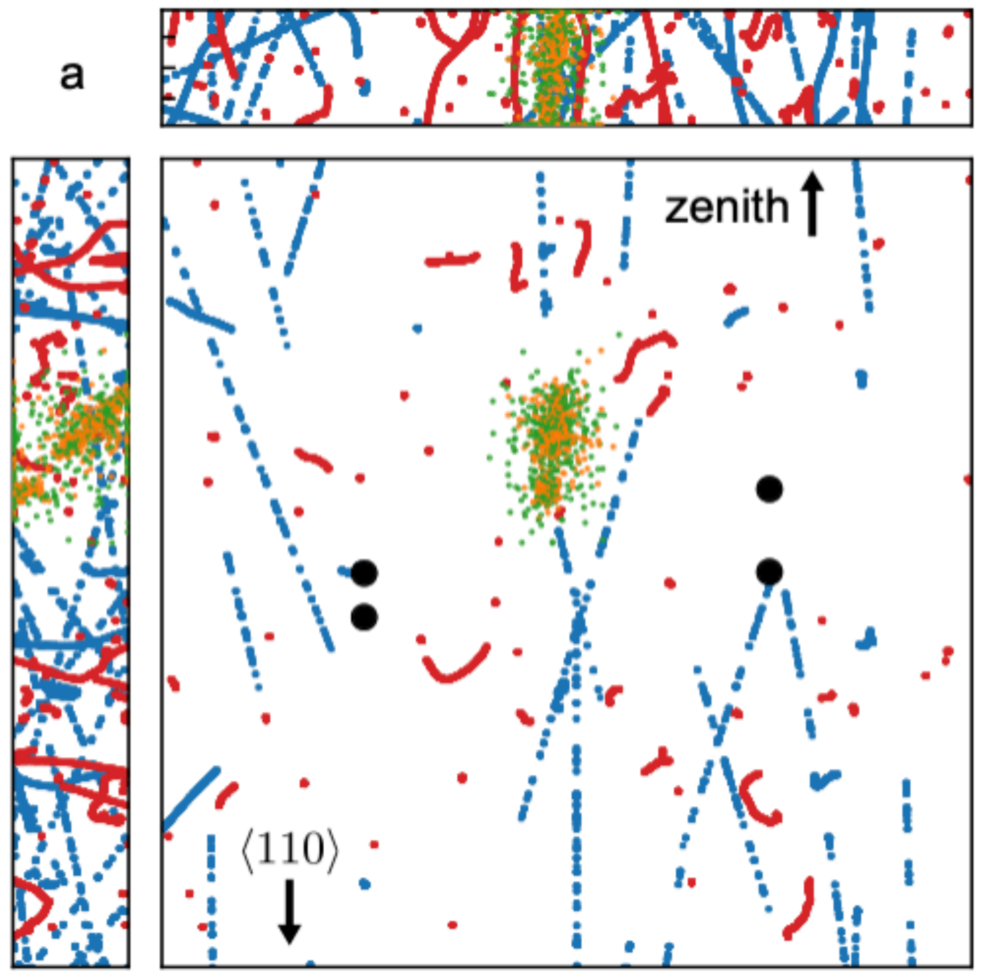




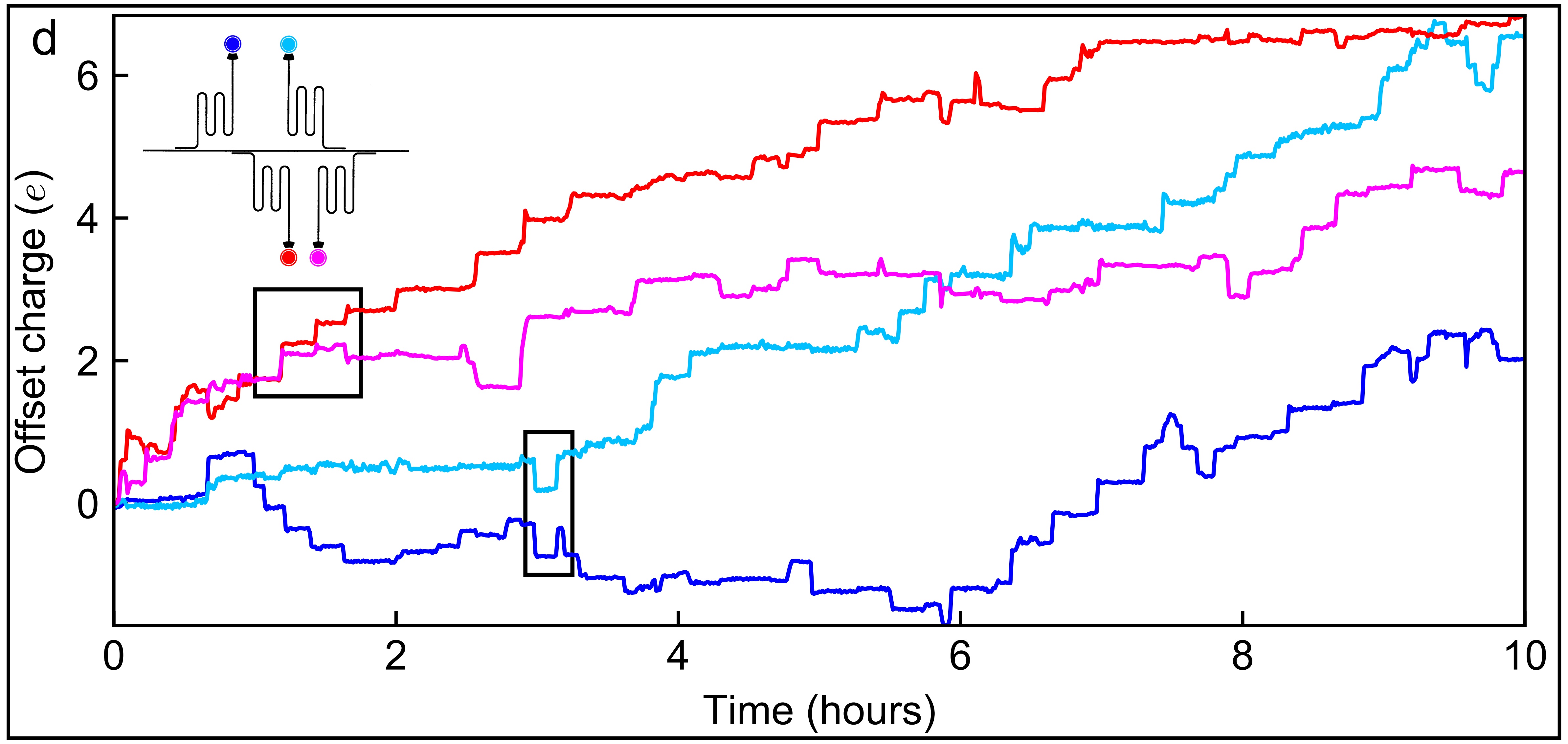
Does Radioactivity Explain this Result? (1)

Chip with four qubits and its implementation in a Monte Carlo simulation (GEANT-4)

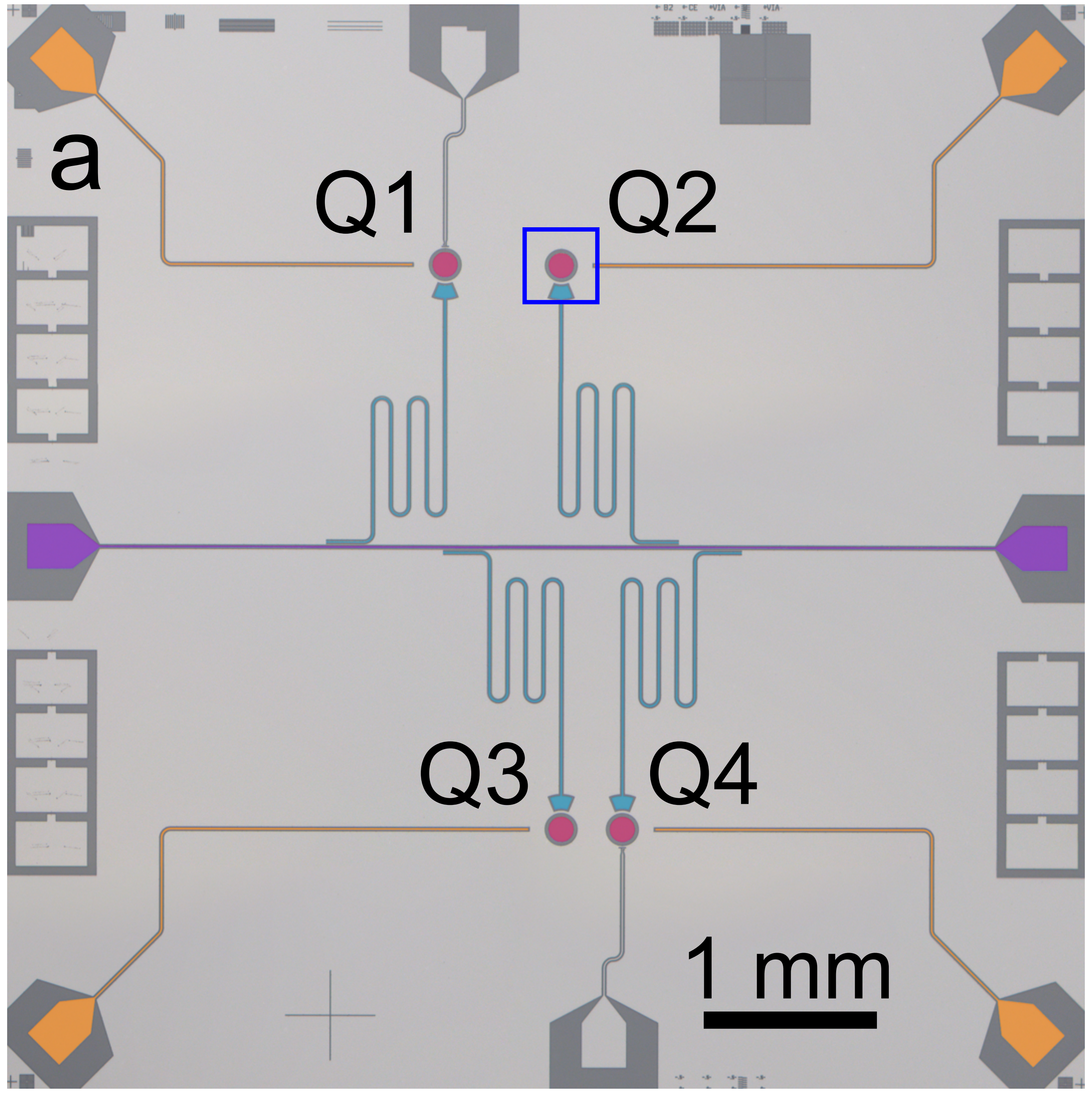
Time traces of the four qubits



- Rate of charge jumps for single qubit: 1 / (75 sec)
- Many simultaneous jumps in 2-qubits:
  - 54% correlation prob. for ΔL = 340 μm
  - 46% correlation prob. for ΔL = 640 μm
  - For ΔL = 3 mm random coincidences
- Consistent with rate of μ's and γ's



Validation: How?



If I am producing a cloud of charges

—> my transmons will see an offset charge

If phonons are spreading in the whole chip

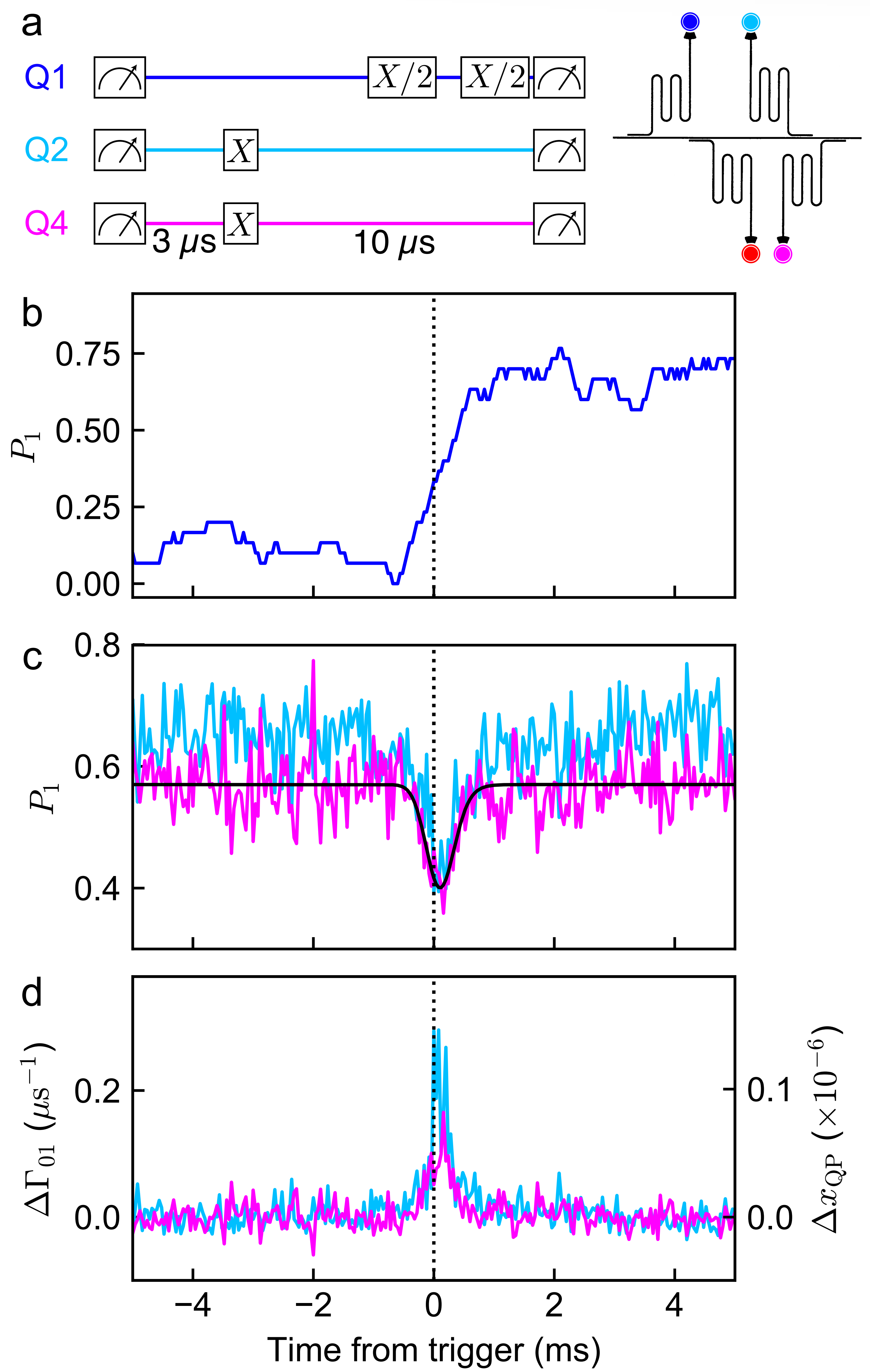
—> the T1 of each transmon will suffer

T1 measurements

Charge Ramsey sequence on Q1

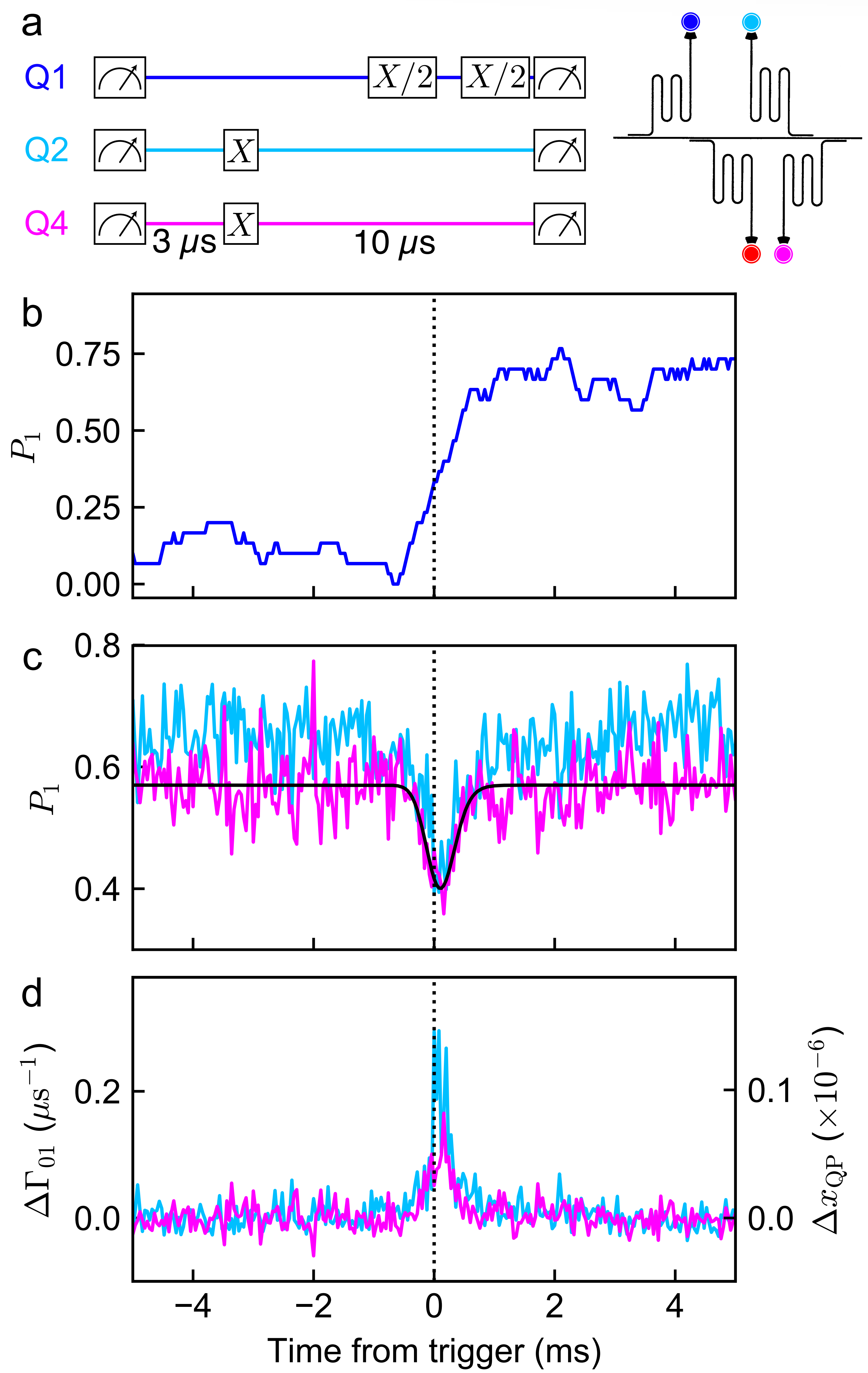
Inversion recovery experiment on Q2/Q4:

- Measurement (check qubit status)
- Rotation to set the qubit in (1)
- Idle time (let it evolve)
- Measurement

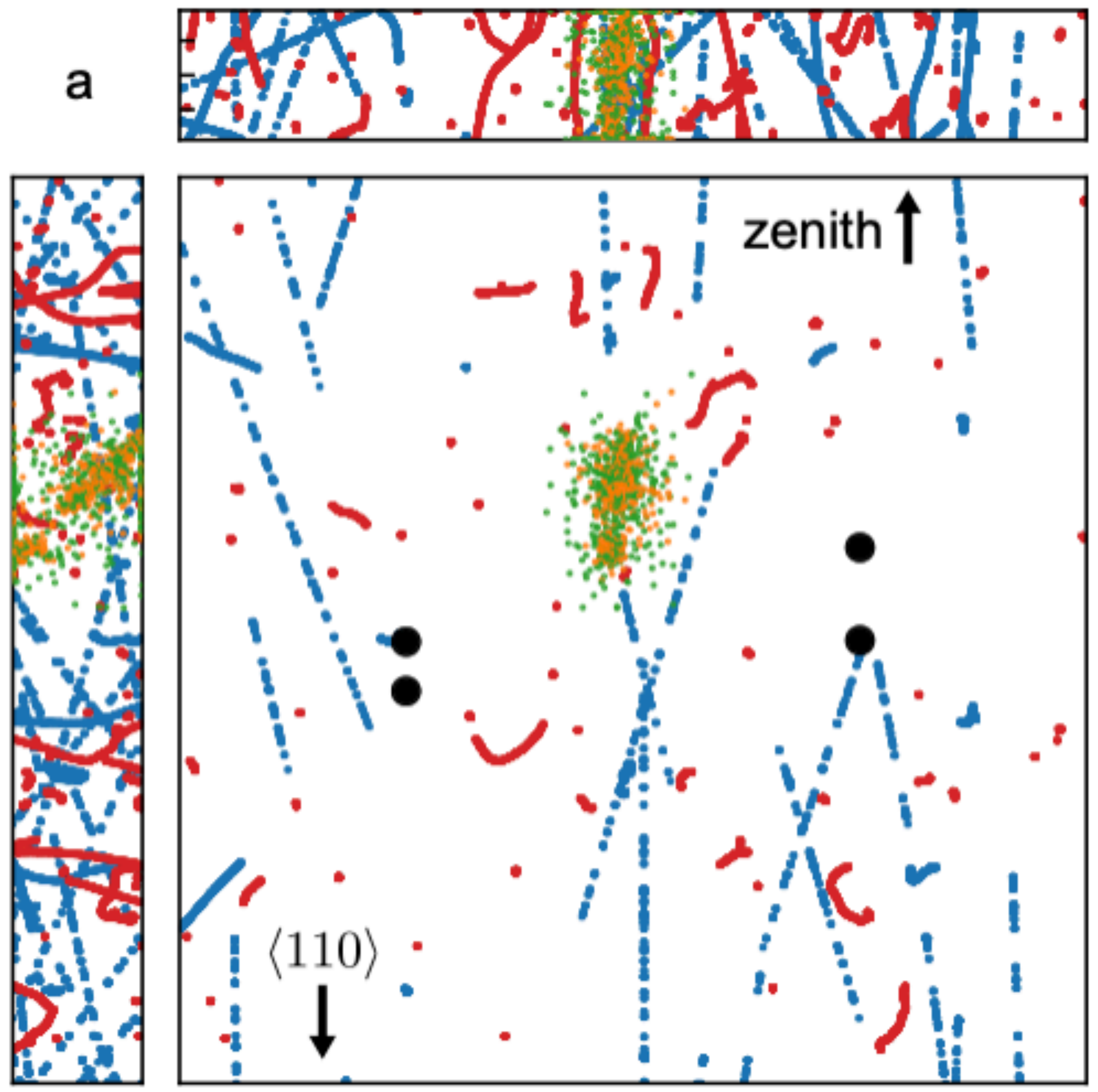


Does Radioactivity Explain this Result? (2)

- Definition of "Burst events"
  - large discrete change in the running average of the Ramsey amplitude measured on Q1
- Absence of burst events
  - the inversion recovery sequence yields average occupations of the qubit |1〉 state consistent with T1
- Presence of busts events
  - clear suppression in the |1〉occupation of Q2 and Q4.
- How long does this last? About 130 μs
  - Typical dwell time of phonons in silicon



Wrap up



- Radioactivity releases energy
- Energy produces charges (electron/holes)

  —> charge jumps, **localised**
- Charges recombine in phonons

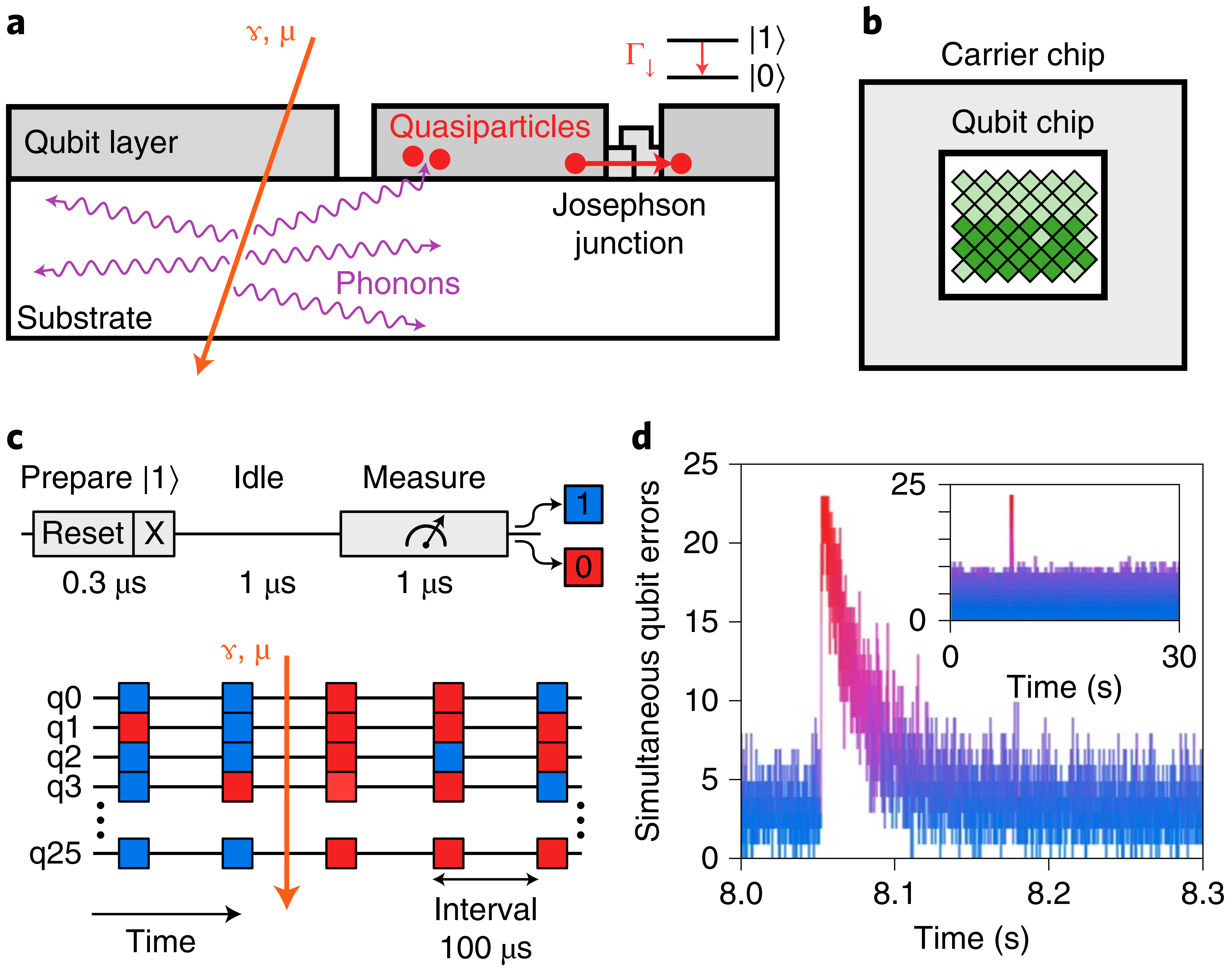
  —> T1 suppression, **chip-wide**

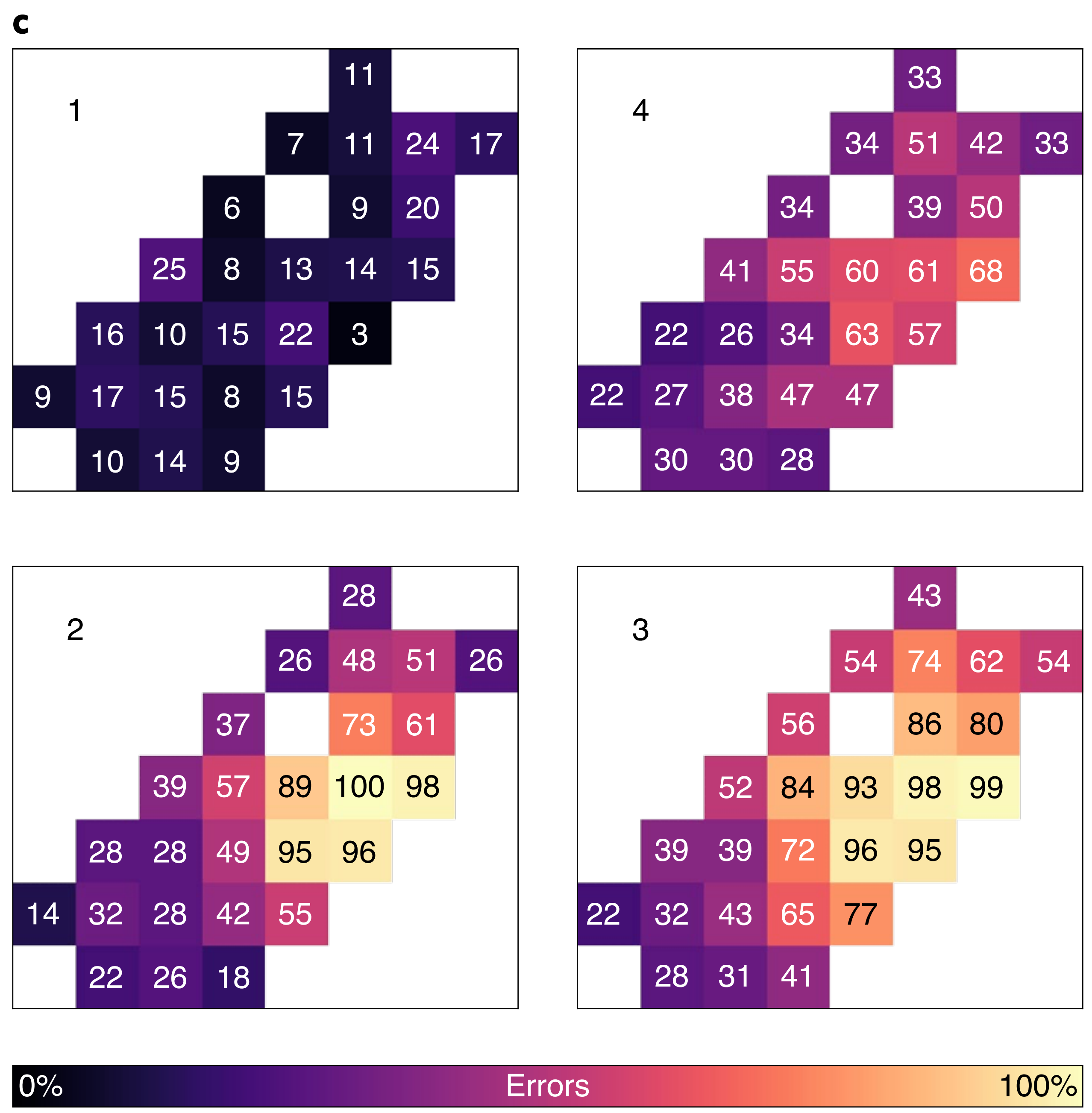
How does this apply to a “real” processor?

Google Sycamore

Google group performed a similar measurement on a “real” quantum processor (sycamore)

Developed a protocol for qubits operation that allowed to monitor errors “online”





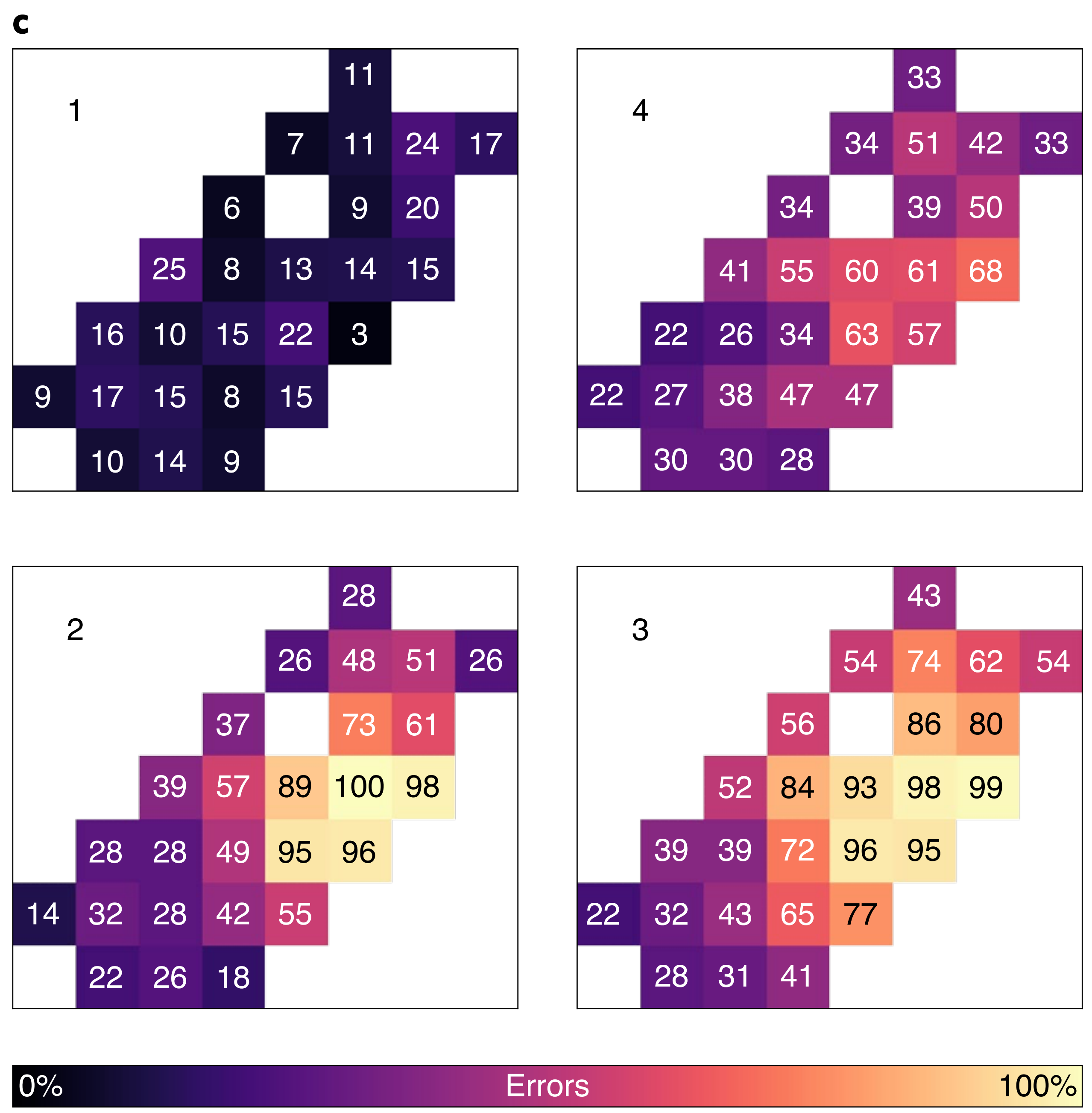
Mc Ewen et al, Nature Physics 18 107-111 (2022)

Google Sycamore: conclusion

Google group performed a similar measurement on a “real” quantum processor (sycamore)

Developed a protocol for qubits operation that allowed to monitor errors “online”

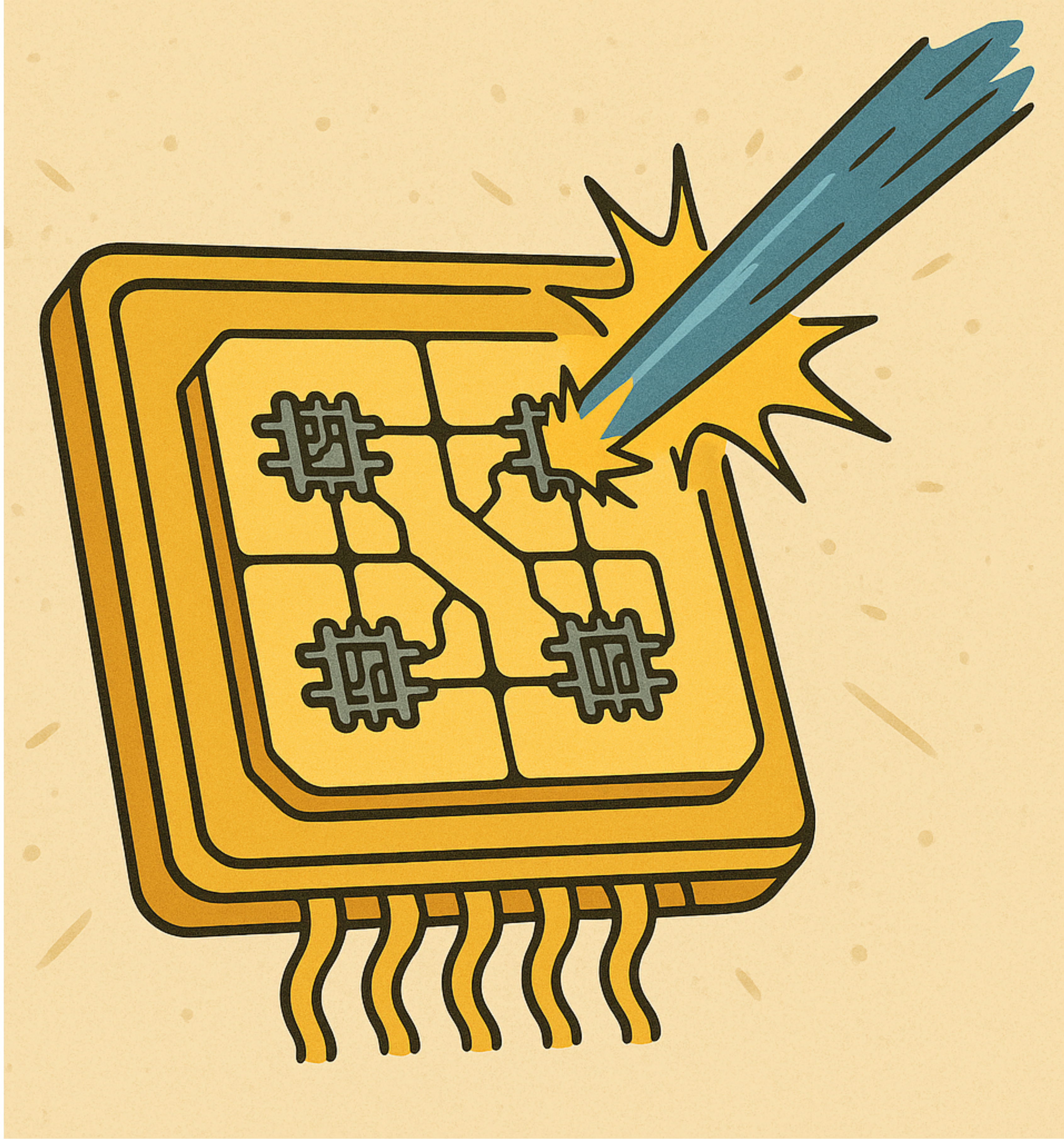
produced by high-energy rays. We track the events from their initial localized impact as they spread, simultaneously and severely limiting the energy coherence of all qubits and causing chip-wide failure. Our results provide direct insights into the impact of these damaging error bursts and highlight the necessity of mitigation to enable quantum computing to scale.



Mc Ewen et al, Nature Physics 18 107-111 (2022)

Summary

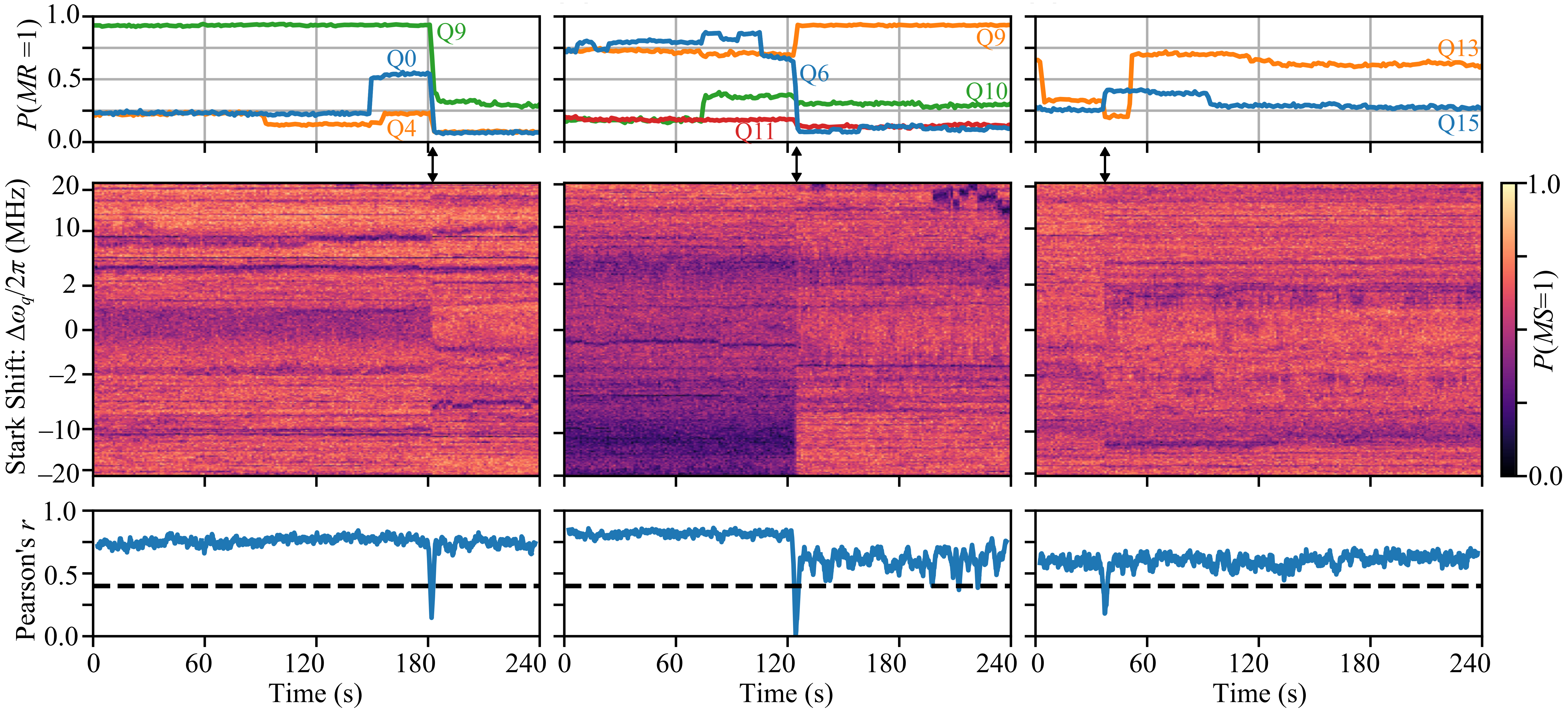
- Until ~ 2018, radioactivity was considered negligible for qubits
- We then discovered that the qubit substrate is a target for radioactivity
  - The larger the substrate, the bigger the effect!
- Today we know that:
  - Radioactivity diminishes the T_1 of a single qubit
  - This effect last as long as phonons are in the substrate
  - Radioactivity creates correlated errors
    —> chip-wide failure



Bonus Slide: IBM studies

Two Level System: dominant loss mechanism in qubits

Destabilises qubits on a ~hour time-scale



Radioactivity causes *scrambling* (radiation causes multiple TLSs jumps in frequency and couple or decouple to qubits, increasing/ decreasing its lifetime)

[Thorback et al, 2023]