Effects of Background Radiation on Qubits

EXCESS2022 Workshop

Istituto Nazionale di Fisica Nucleare

Laura Cardani, 17/02/2022

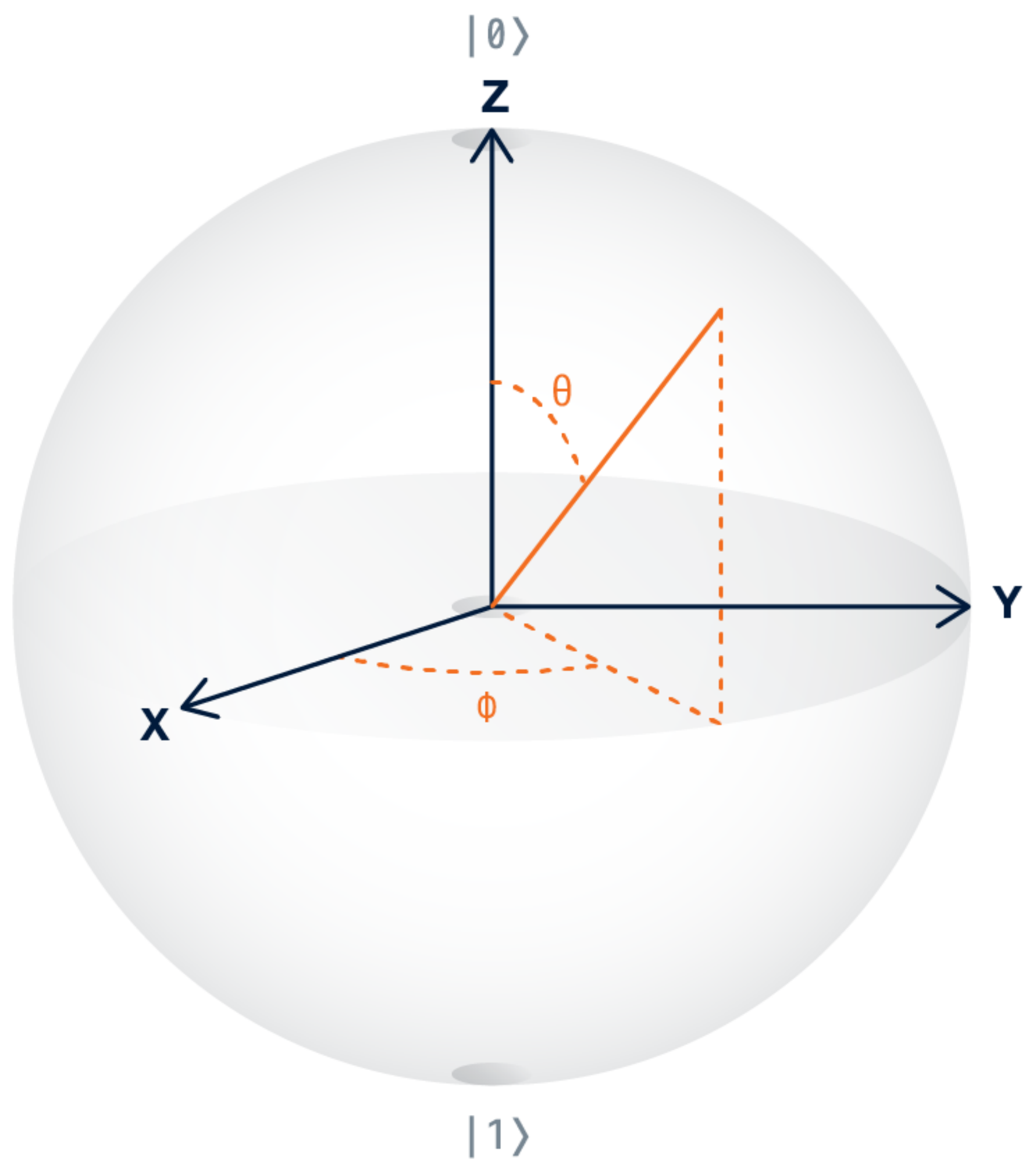
Quantum Bits

Ideal Features

1. Strongly coupled to other qubits [entanglement]

   n classical bits = string with *n* [0,1] — *n* entangled qbits = 2^n -1 complex nums

2. Decoupled from the world [quantum coherence]



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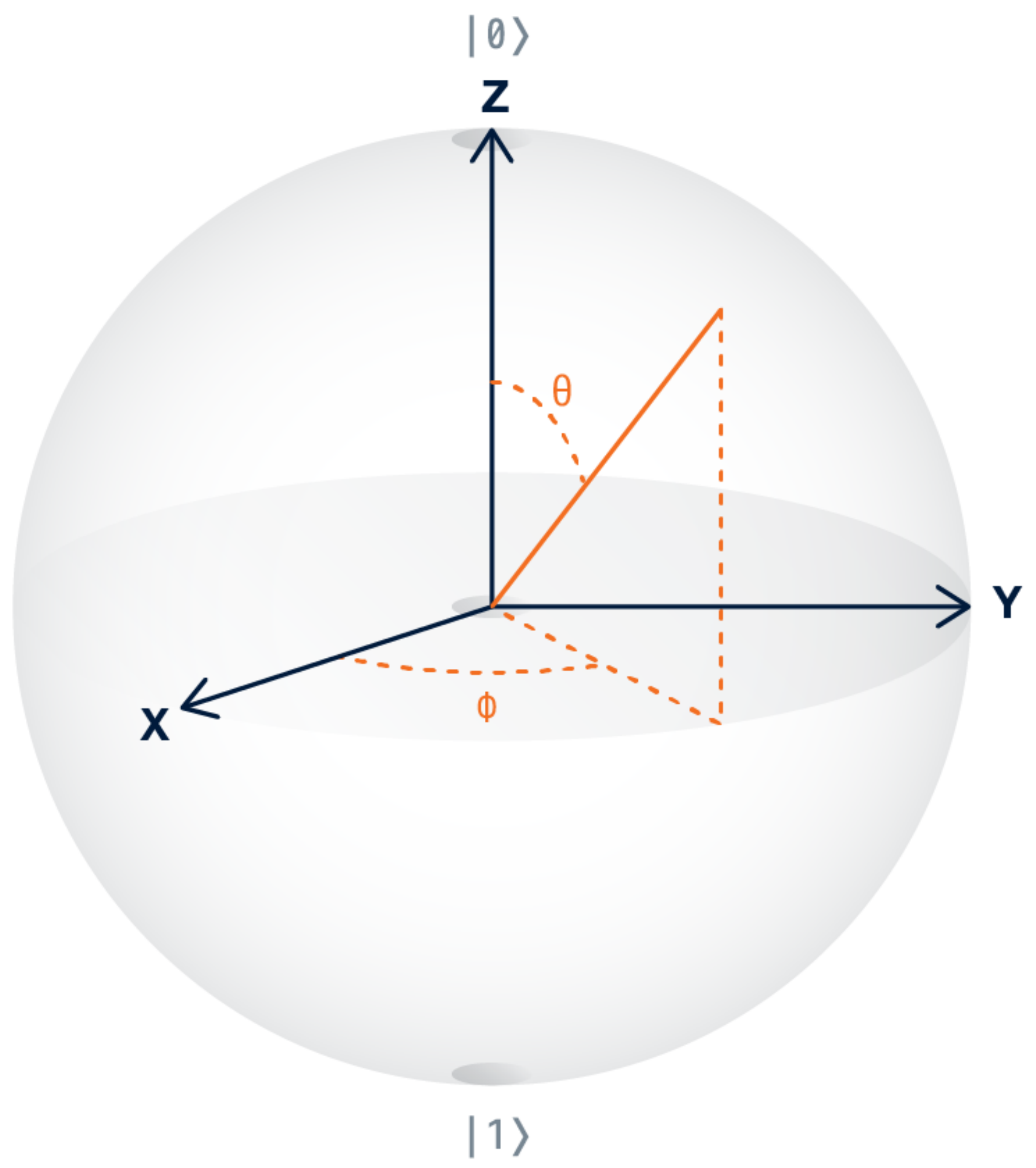
2. Decoupled from the world [quantum coherence]

   - Trapped Ions
   - Photons (lasers)
   - …
   - Superconducting circuits



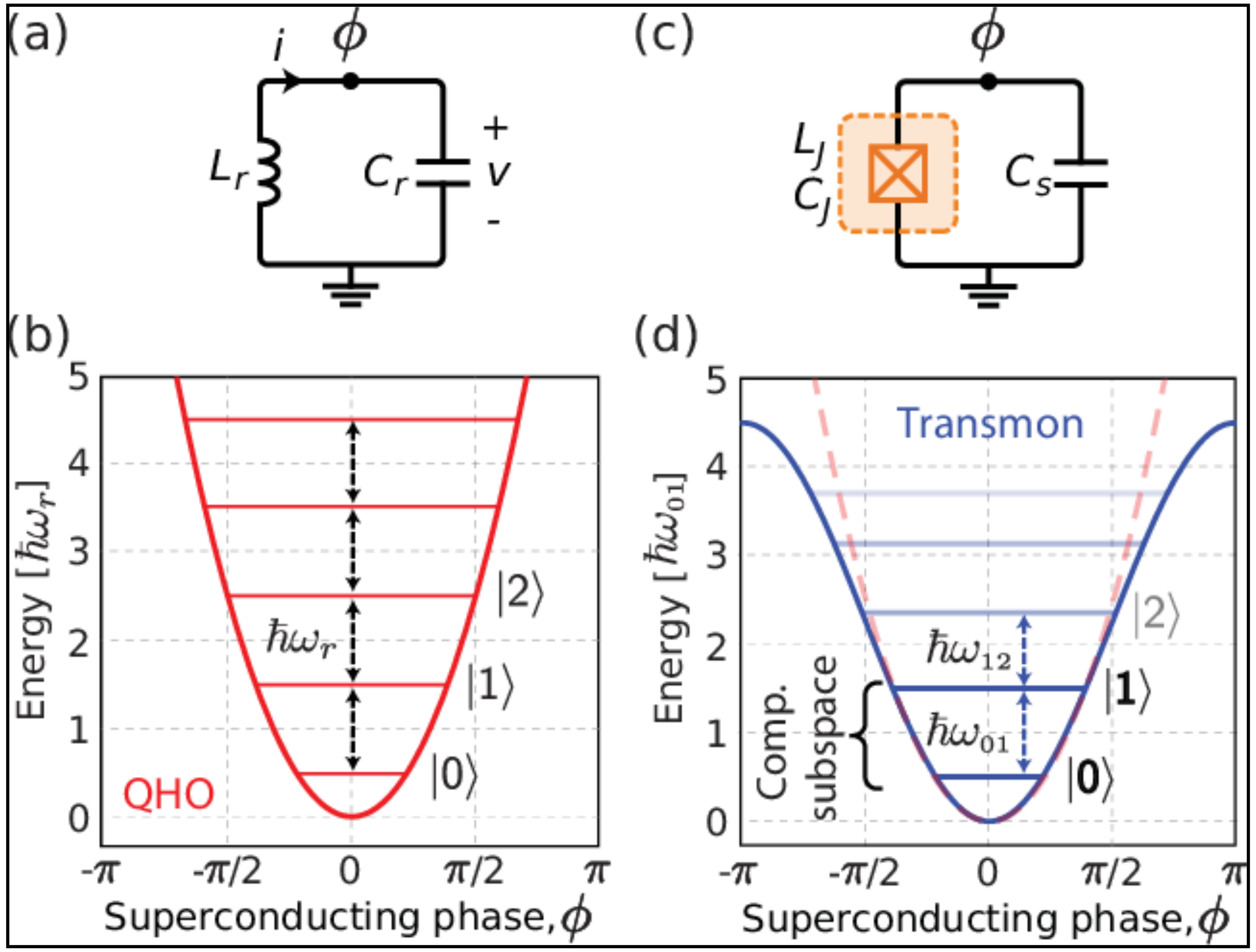
Superconducting Circuits

In a nutshell

Macroscopic circuits consisting of:

- capacitor
- inductor
- wires
- Josephson Junction

Simple elements to make a non-linear two-level system

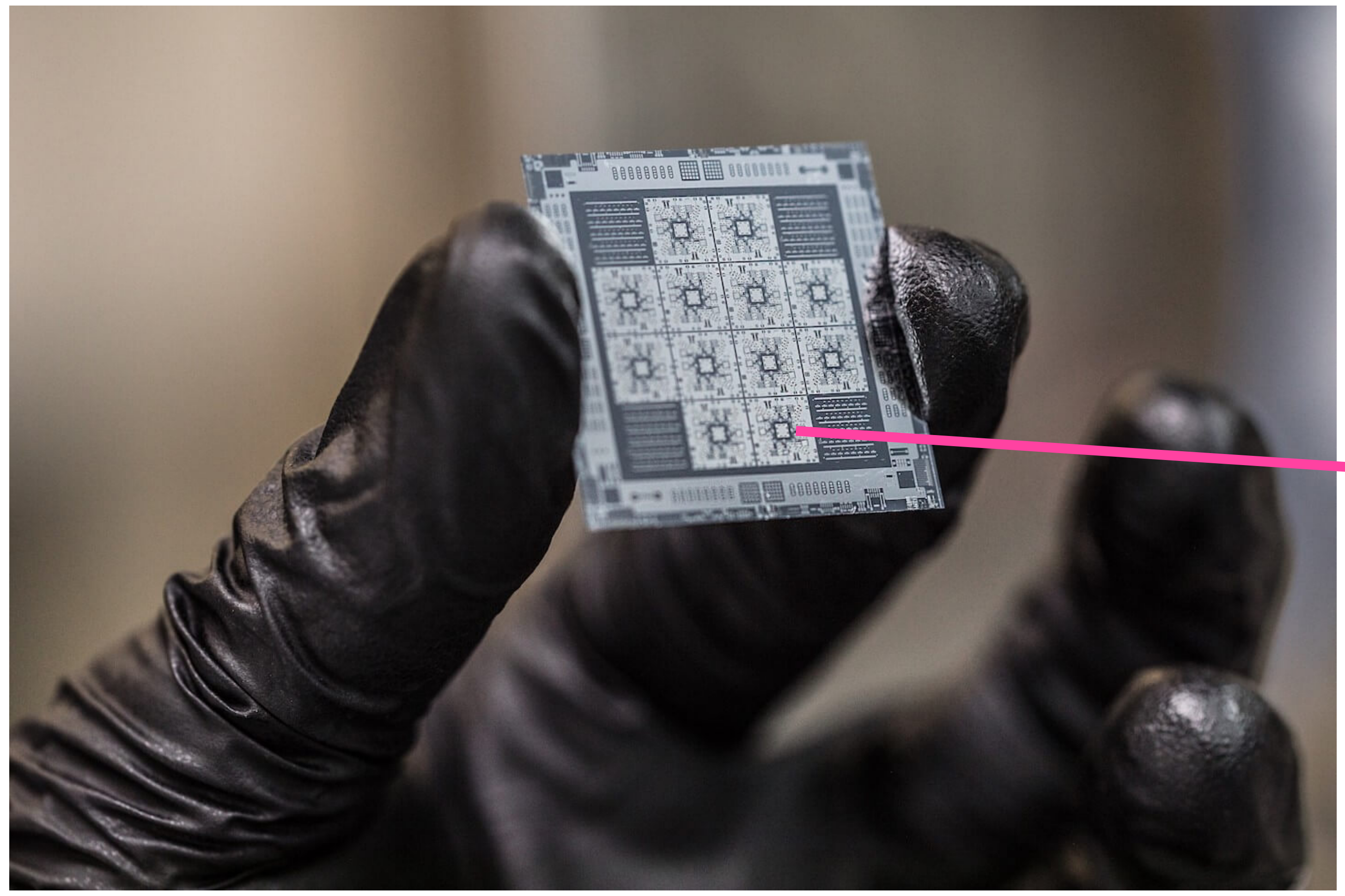


https://arxiv.org/pdf/1904.06560.pdf

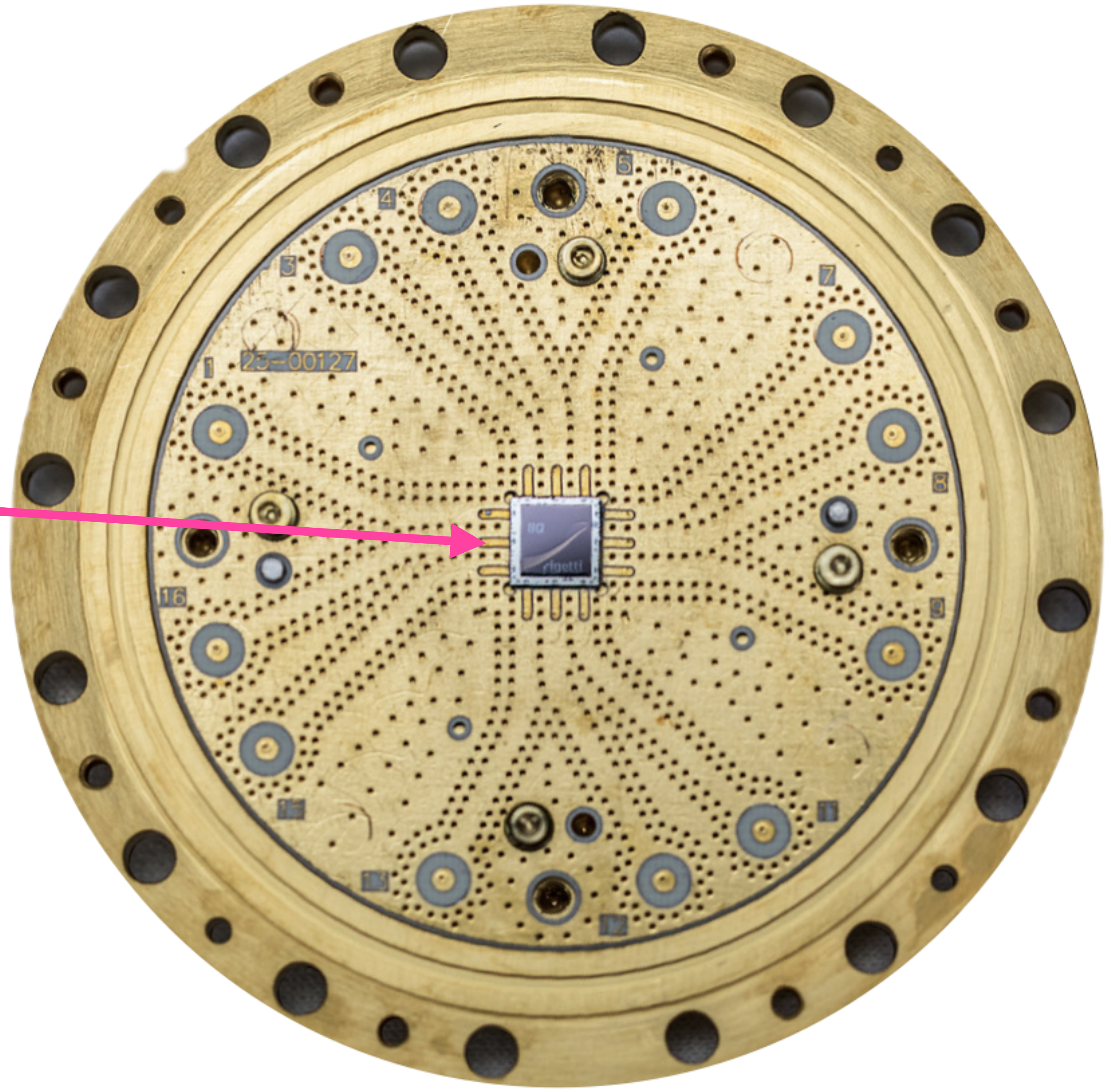
Superconducting Circuits

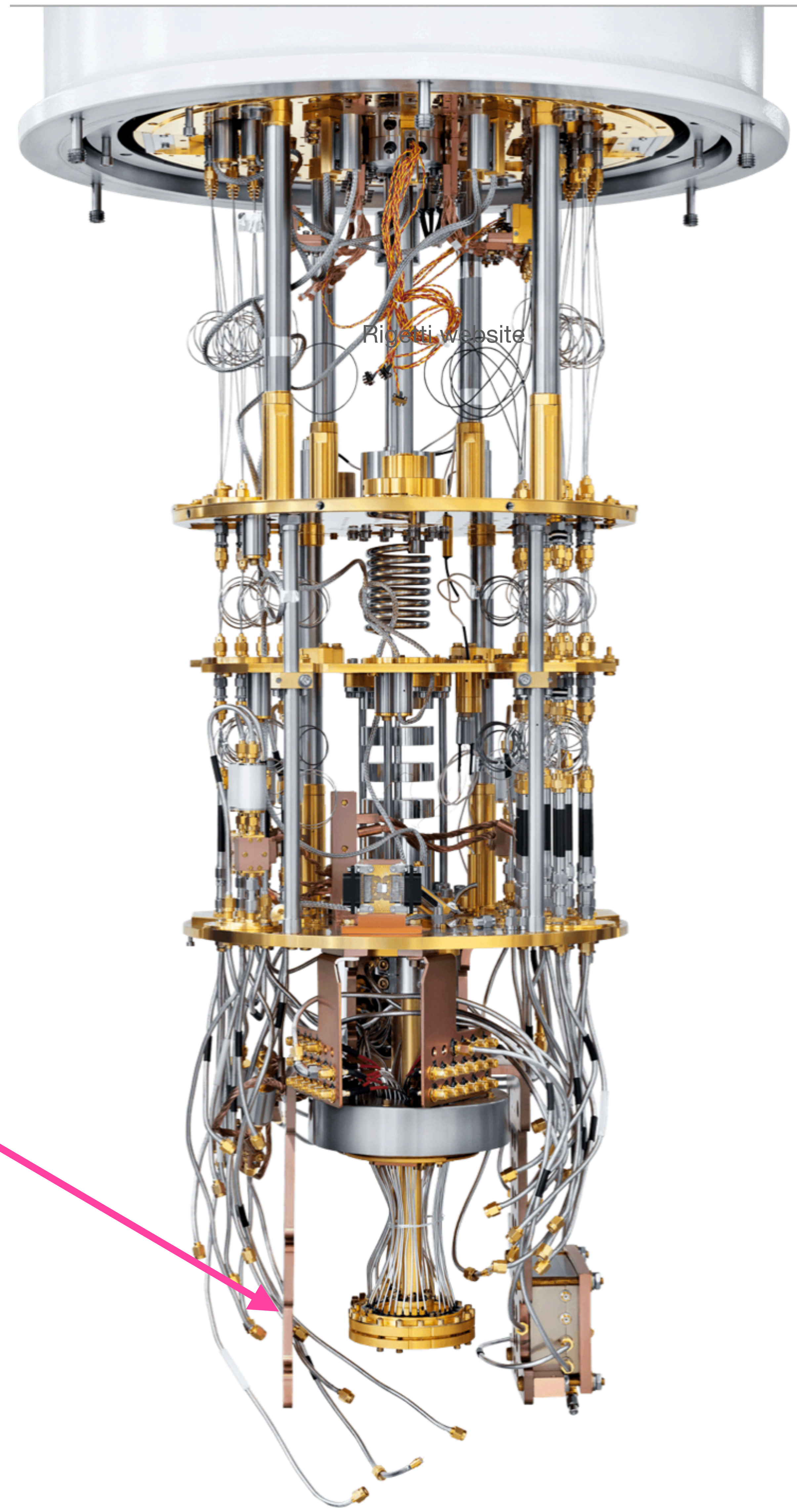
In a nutshell

Superconductor (hundreds of nm of aluminum or niobium) deposited over ~cm^2 substrate (silicon or sapphire)



Rigetti 8-qubit





Superconducting Circuits

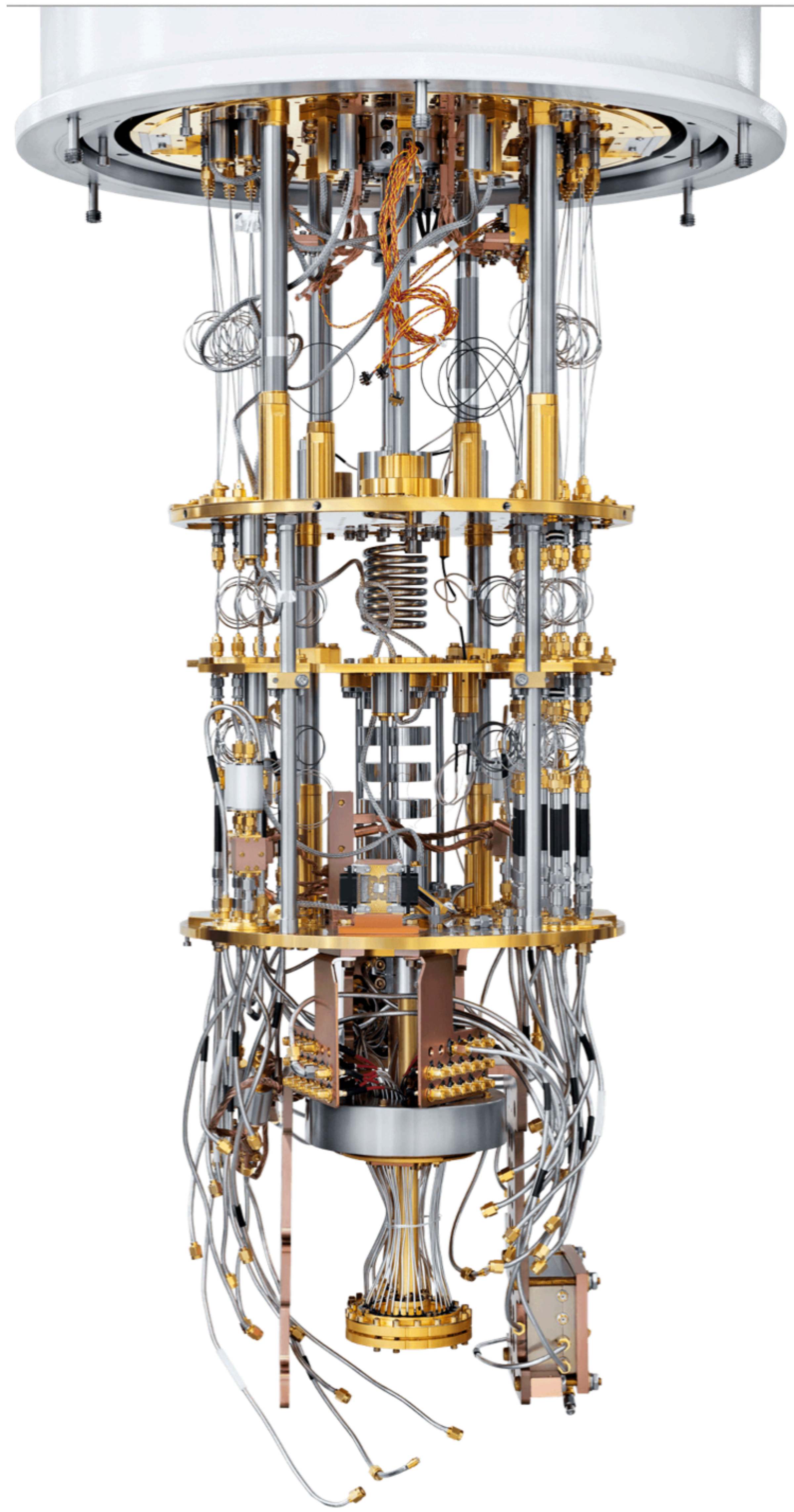
Pros/Cons

- Ideal qubit:
  - strongly coupled to other qubits [entanglement]

    Feasible (Sycamore, Aspen-9, Zu Chongzhi…, recently IBM presented a processor with > 100 qubits)

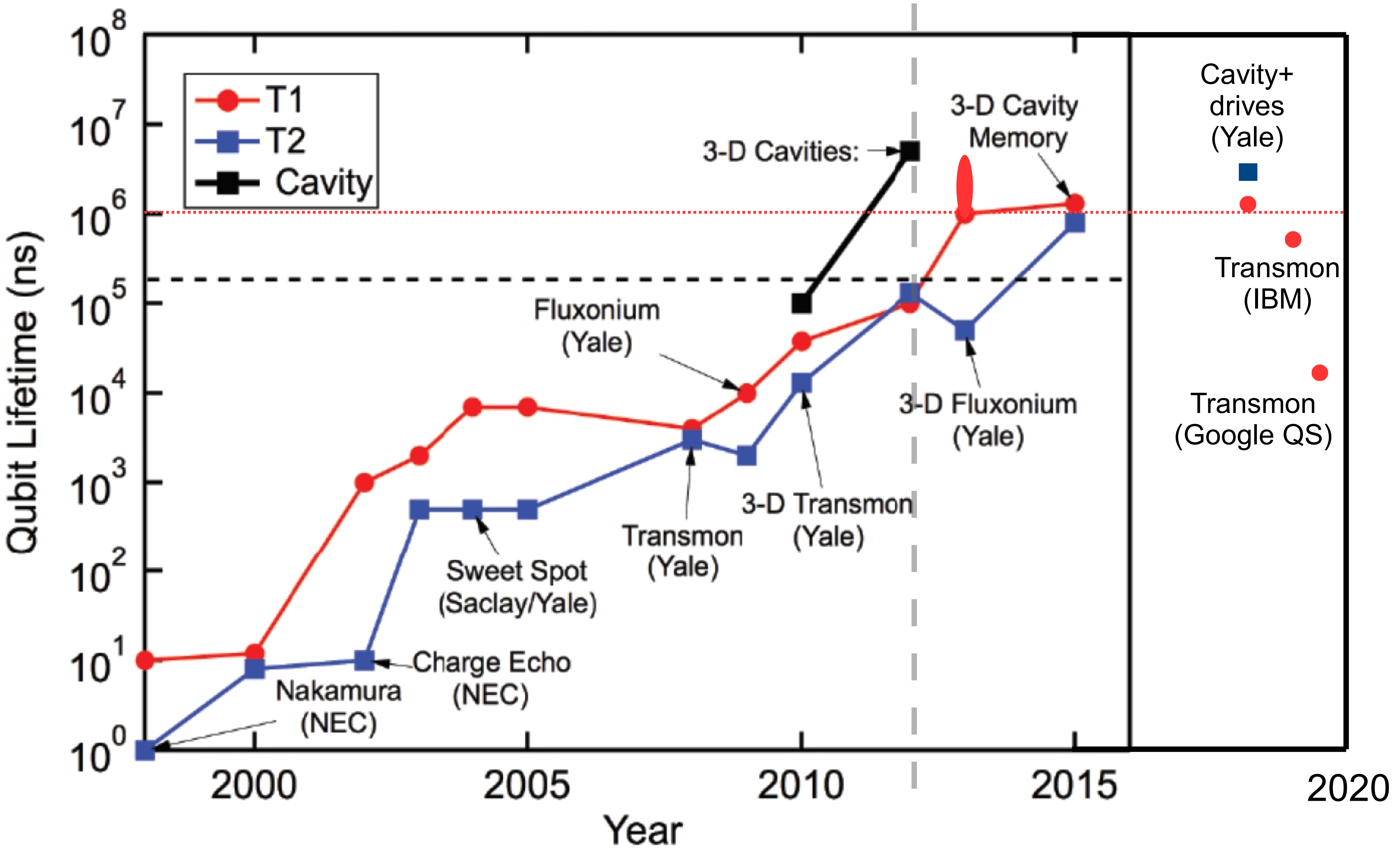
  - decoupled from the world [quantum coherence]

    Main limit of this technology



Coherence

- The longer, the better
- Must be much longer (>10^2 - 10^4) than gate operation time
- Goal: millisecond scale or beyond

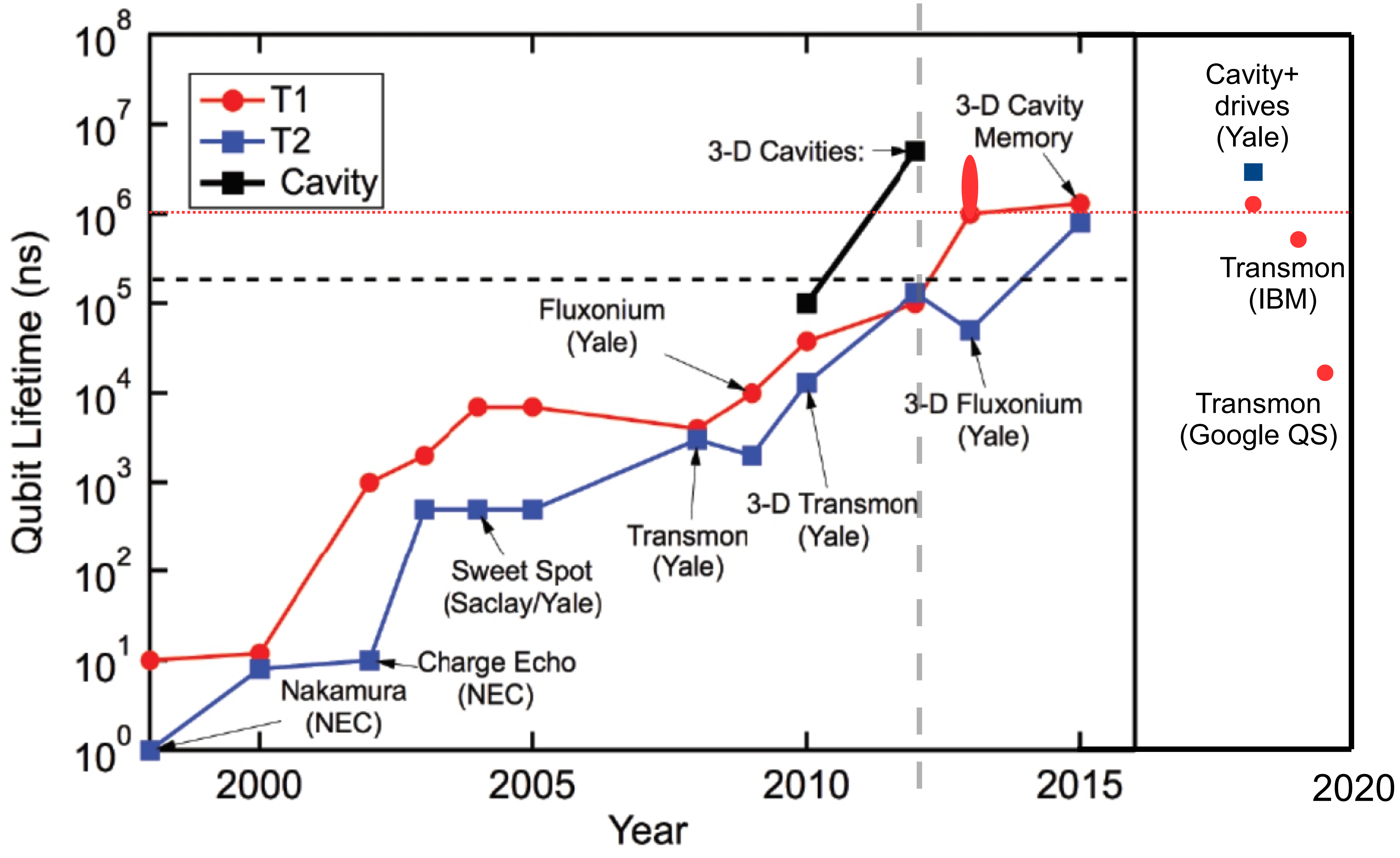


original plot (up to 2012): M.H. Devoret & R.J. Schoelkopf, Science **339**, 1169 (2013)
extension (up to 2015): M. Reagor, PhD thesis (Yale)

Coherence

Many sources under investigation.
Among the most important:

- Two Level System noise
  - Unclear microscopic origin
  - Related to materials
  - Huge international effort
- Quasiparticles



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Quasiparticles

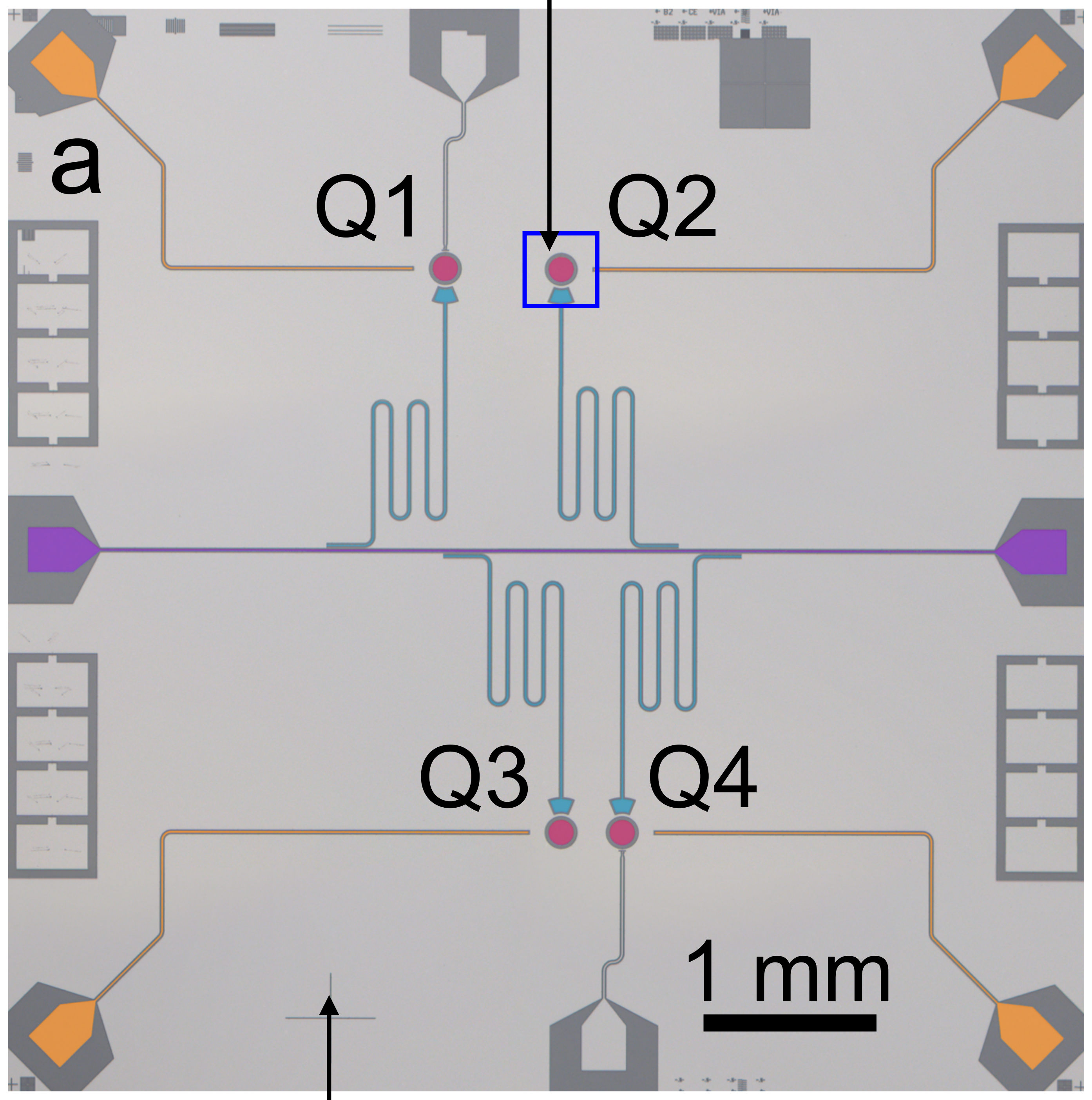
- Superconductors: electrons bound into Cooper pairs (no dissipation)
- Many mechanisms can break Cooper pairs into quasiparticles (Δ_0 ~ 0.1 meV)
- Quasiparticles are dissipative (in contrast to Cooper pairs)
- Sources: any energy dissipation
  - Infrared radiation
  - Thermal stress
  - …
  - Cosmic rays and environmental radioactivity [DEMETRA project]

Radioactivity vs Qubit

Mechanism

- Direct interaction in qubit: unlikely
- Indirect interaction in the substrate
  - Different scenario: cm^2 of Si or Al_2O_3
  - Radioactivity deposits energy
  - Energy produces charges and phonons that can hit the qubit

Interaction in the qubit



Indirect interaction in the substrate

A bit of Context

When we proposed the DEMETRA project (2018, INFN starting grant), this was just a hypothesis. Today we know that:

1. Radioactivity will be (or already is) the ultimate limit the coherence of qubits
2. Radioactivity limits quantum error correction in a matrix of qubits
3. Suppressing radioactivity improves the performance of quantum circuits

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   Vepsäläinen et al, Nature 2020.

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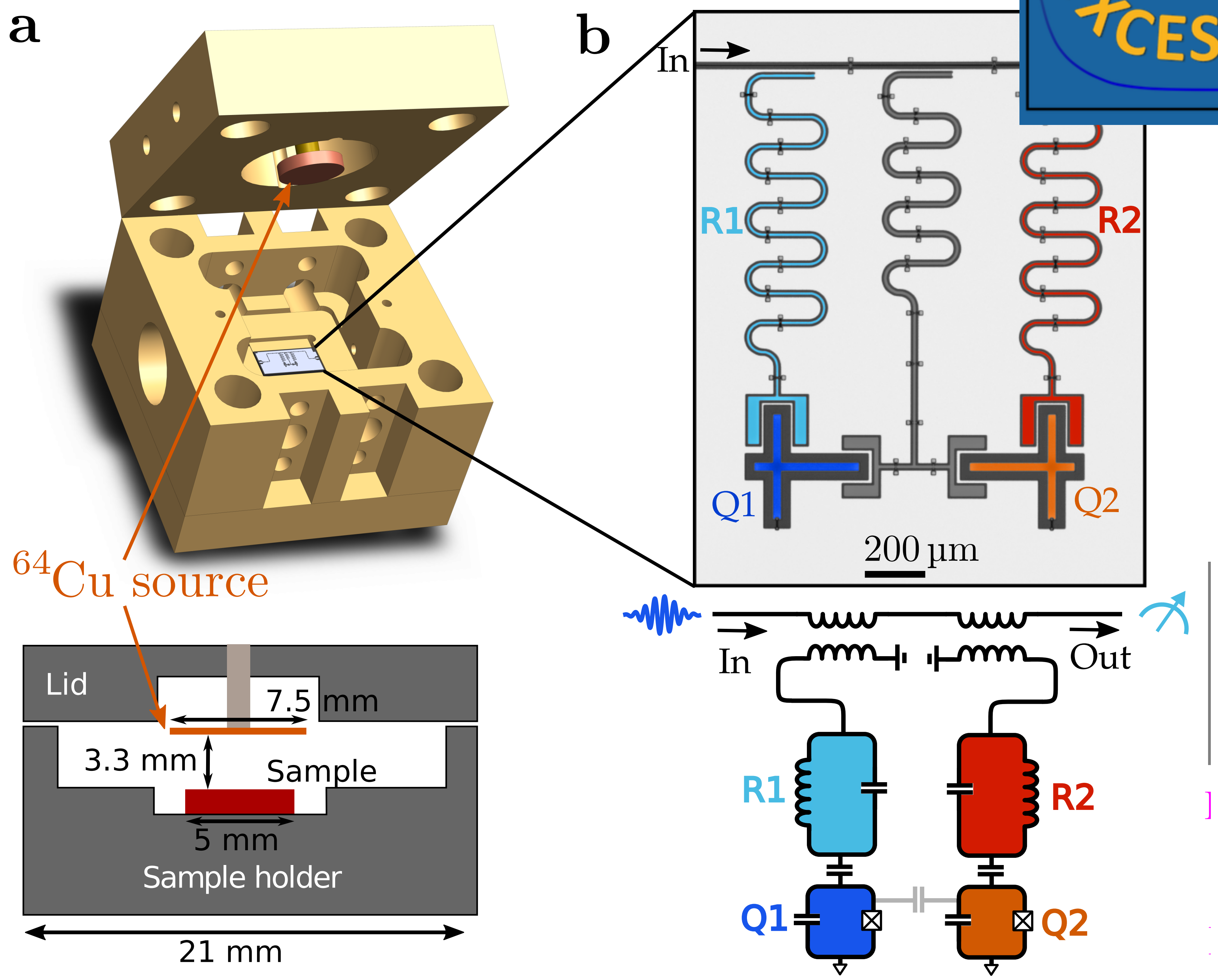
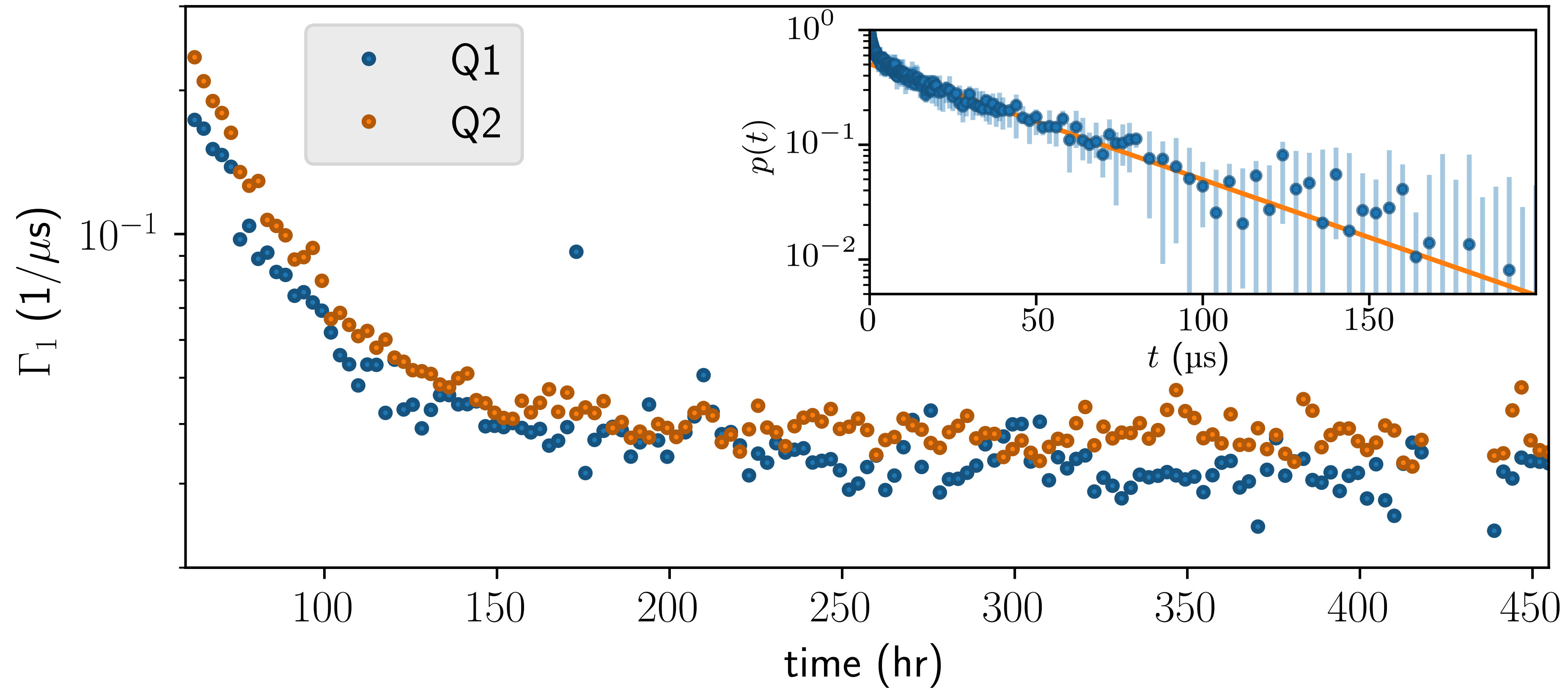
Radioactivity vs Coherence

[Vepsäläinen et al, Nature 2020]

- Faced a qubit to a fast-decaying source
- Observed that the coherence of qubit was increasing while the source was decaying
- Concluded: "*The effect of ionizing radiation [..] would ultimately limit the coherence times of superconducting qubits of the type measured here to milliseconds. Albeit a small effect for today's qubits, reducing or mitigating the impact of ionizing radiation will be critical for realizing fault-tolerant superconducting quantum computers.*"





A bit of Context

When we proposed the DEMETRA project (2018, starting grant of INFN), this was just a hypothesis. Today we have 3 papers stating that:

1. Radioactivity will be (or already is) the ultimate limit the coherence of qubits

Vepsäläinen et al, Nature 2020.

2. Radioactivity limits quantum error correction in a matrix of qubits

Wilen et al, Nature 2021.

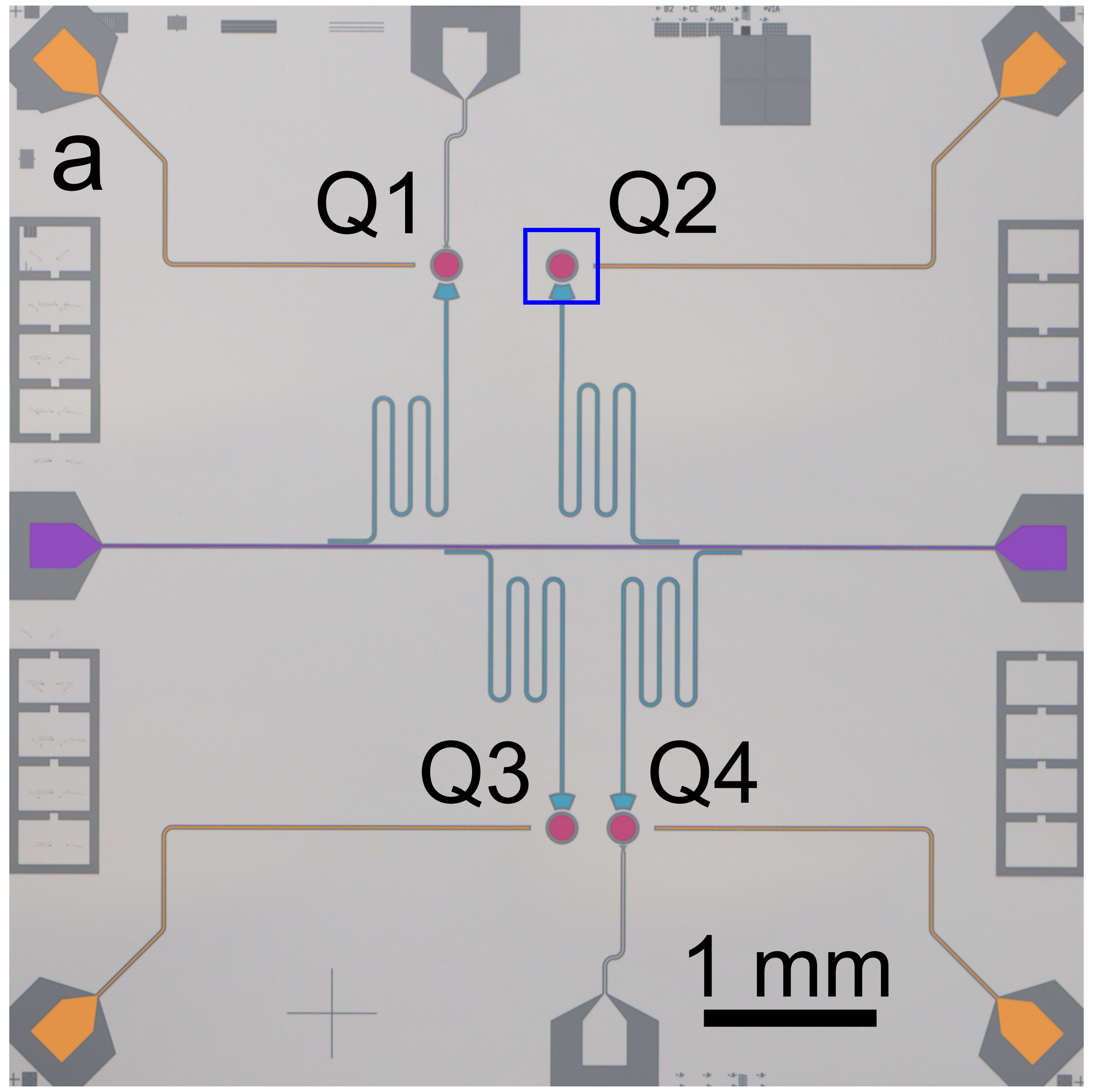
McEwen et al., Nature Physics 2022.

Suppressing radioactivity improves the performance of quantum circuits

Quantum Error Correction

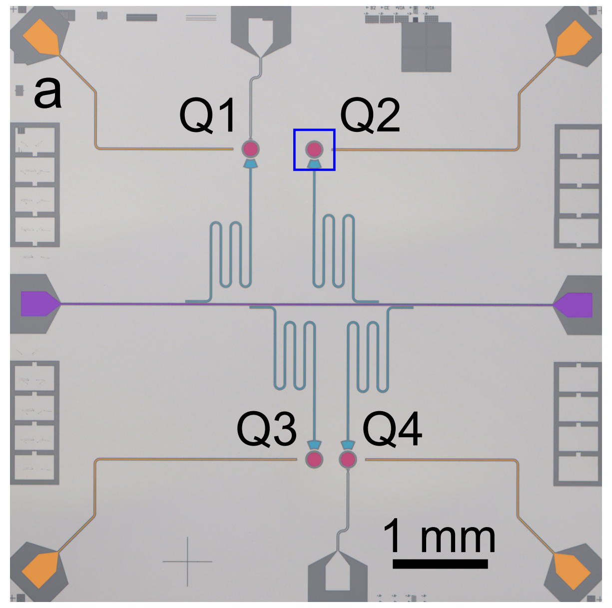
The issue

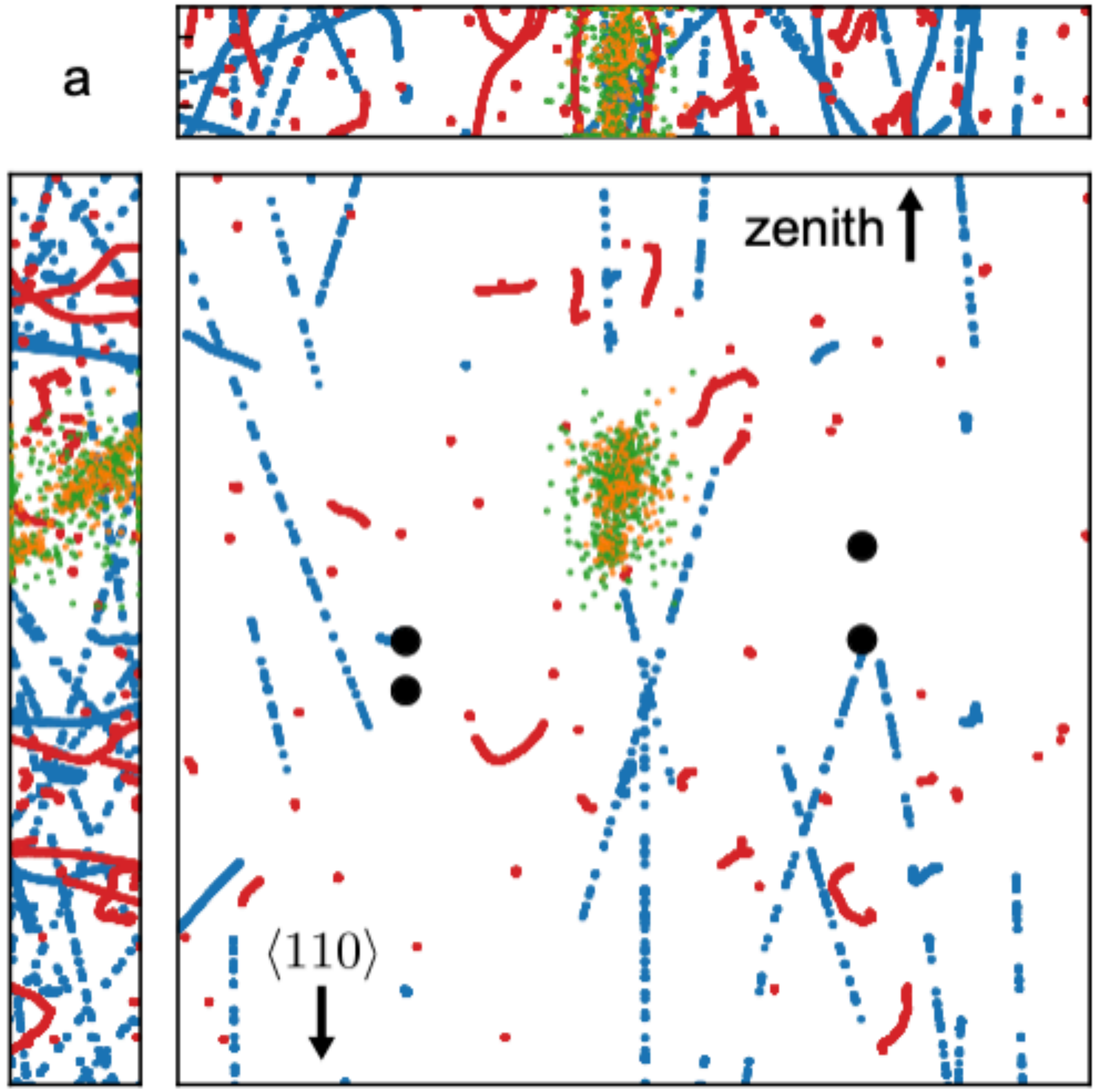
- Most popular idea for quantum error correction: encode quantum information in a matrix of qubits
- Key assumption: errors across the qubits belonging to this matrix are uncorrelated in space and time
- Events in the substrate can simultaneously affect more qubits



Quantum Error Correction

Predicted Effect





1) Energy deposit

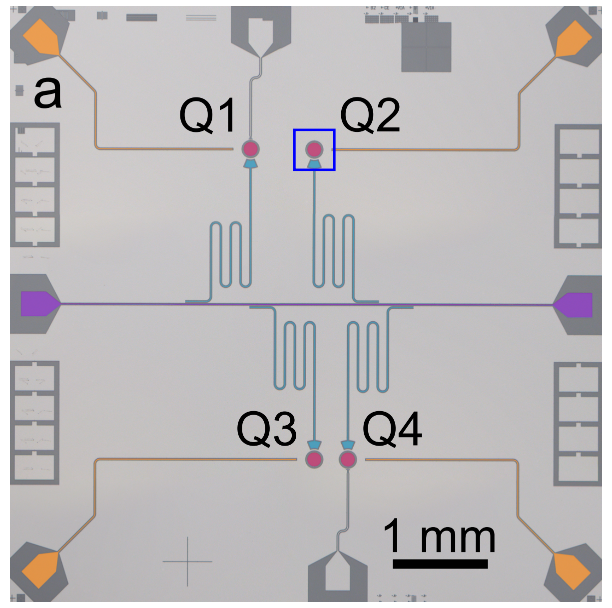
- Muons: 0.5 mHz, ~500 keV *in substrate*
- Laboratory: 8 mHz, ~100 keV *in substrate*

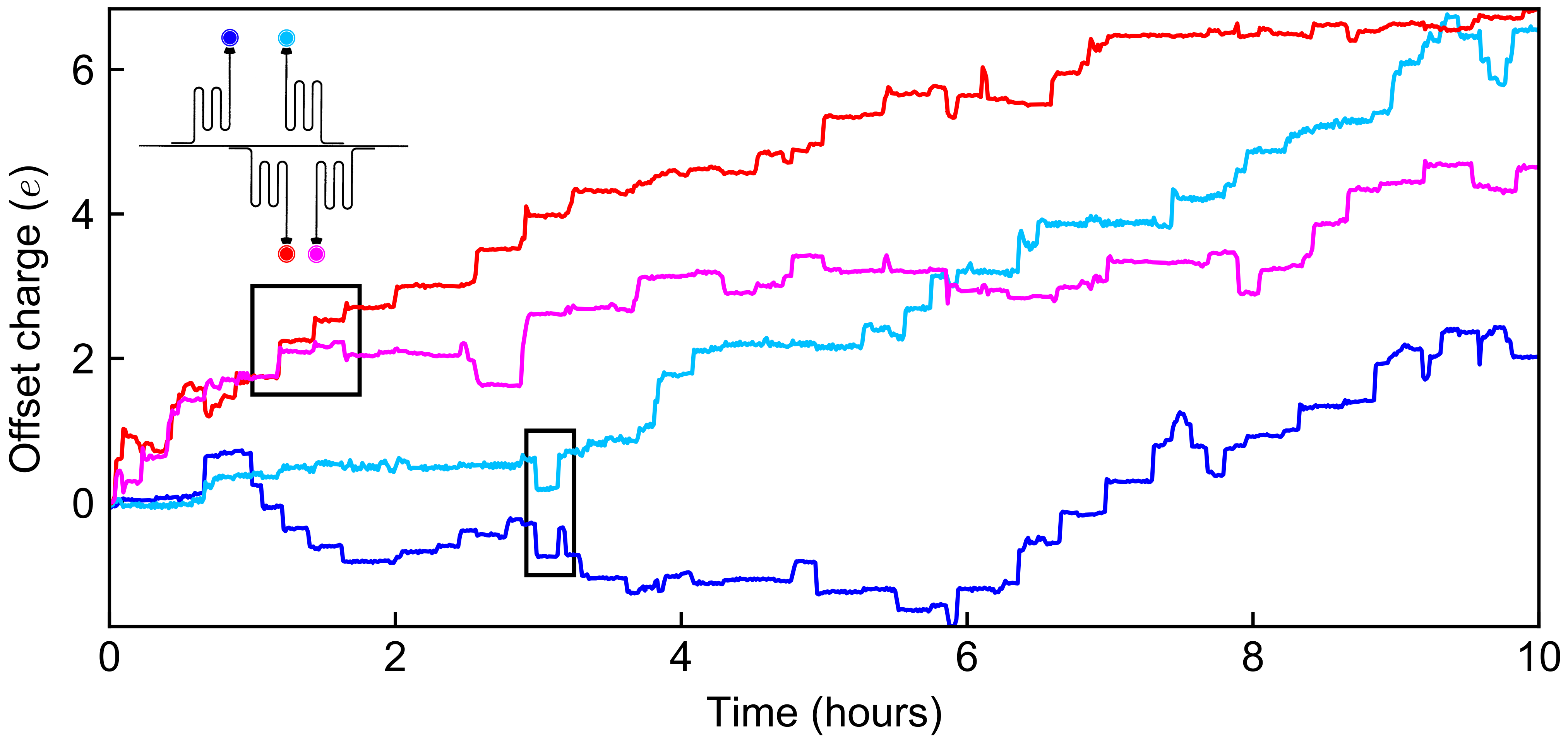
2) Creation of e/h pairs (3.8 eV each -> 10^4)

3) Charges diffuse creating phonons until they trap or encounter a surface

Quantum Error Correction

Measurements (1)

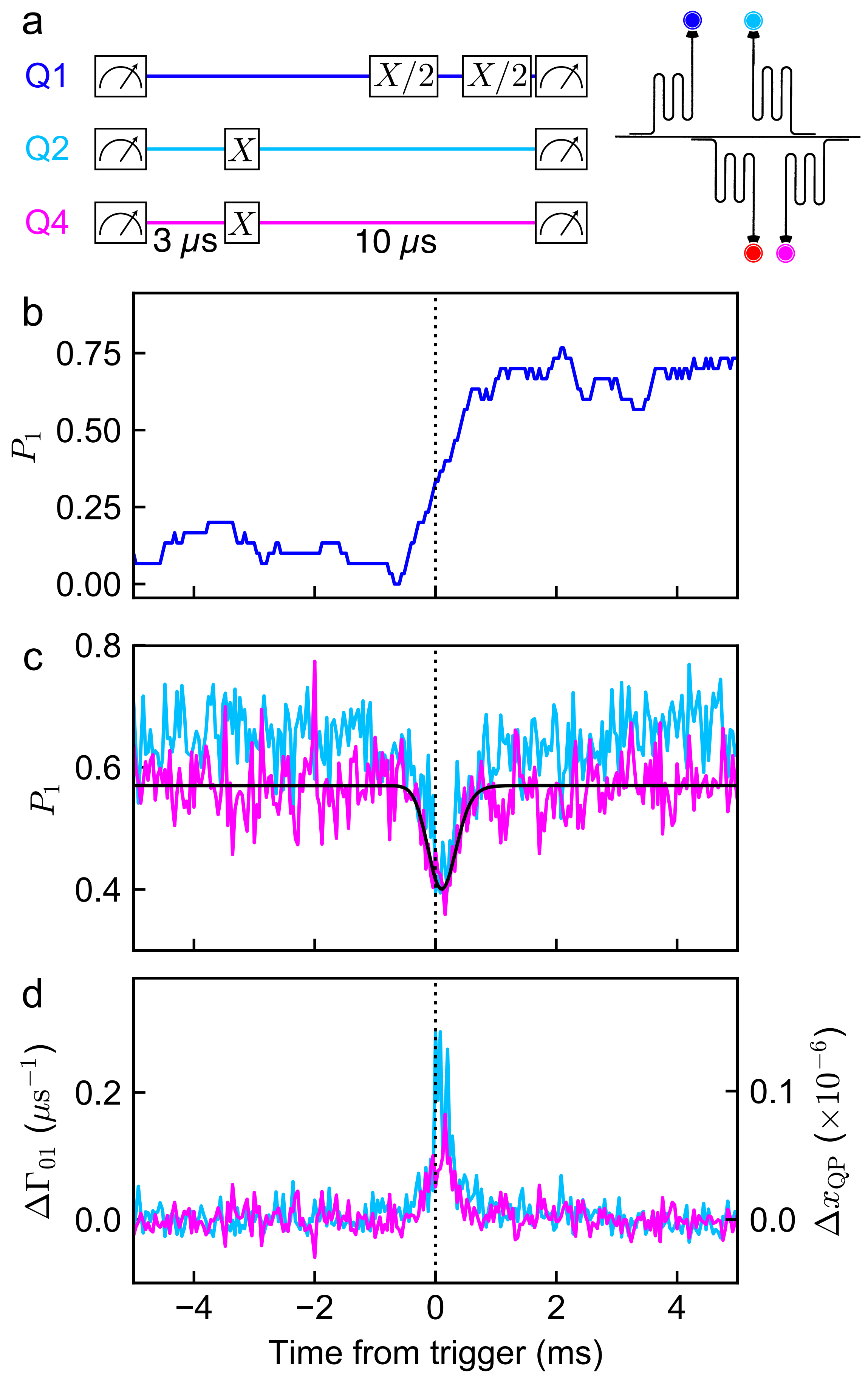


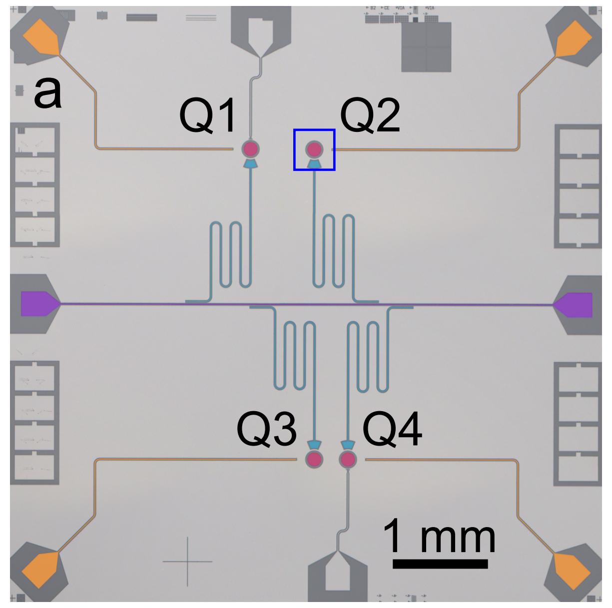


- Ramsey tomography on 4 qubits to generate time series of fluctuating offset charge
- Rate of charge jumps for single qubit: 1.35 mHz
- Many simultaneous jumps in 2-qubits:
  - 54% correlation prob. for ΔL = 340 μm
  - 46% correlation prob. for ΔL = 640 μm
  - For ΔL = 3 mm random coincidences

Coherence - again

Measurements (2)

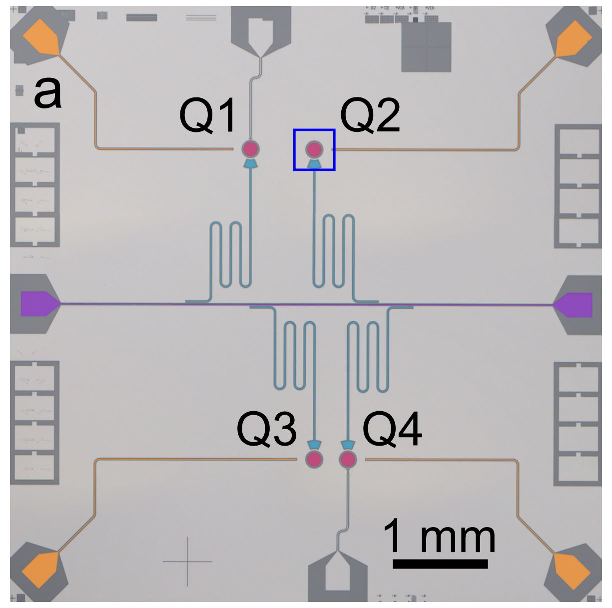




- Charges have a small footprint, but phonons can travel across the entire substrate
- Q1 used as "trigger" for a charge event
- Q2 and Q4 to monitor the relaxation time
- Recovery timescale: 130 μs
- In agreement with dwell time of athermal phonons
- Phonon suppress coherence of all qubits on the chip

Results

Two important consequences



1) Energy deposit

- Muons: 0.5 mHz, ~500 keV *in substrate*
- Laboratory: 8 mHz, ~100 keV *in substrate*

2) Creation of e/h pairs —> **errors correlated in space and time**!

3) Charges diffuse creating phonons —> **coherence worsening**!

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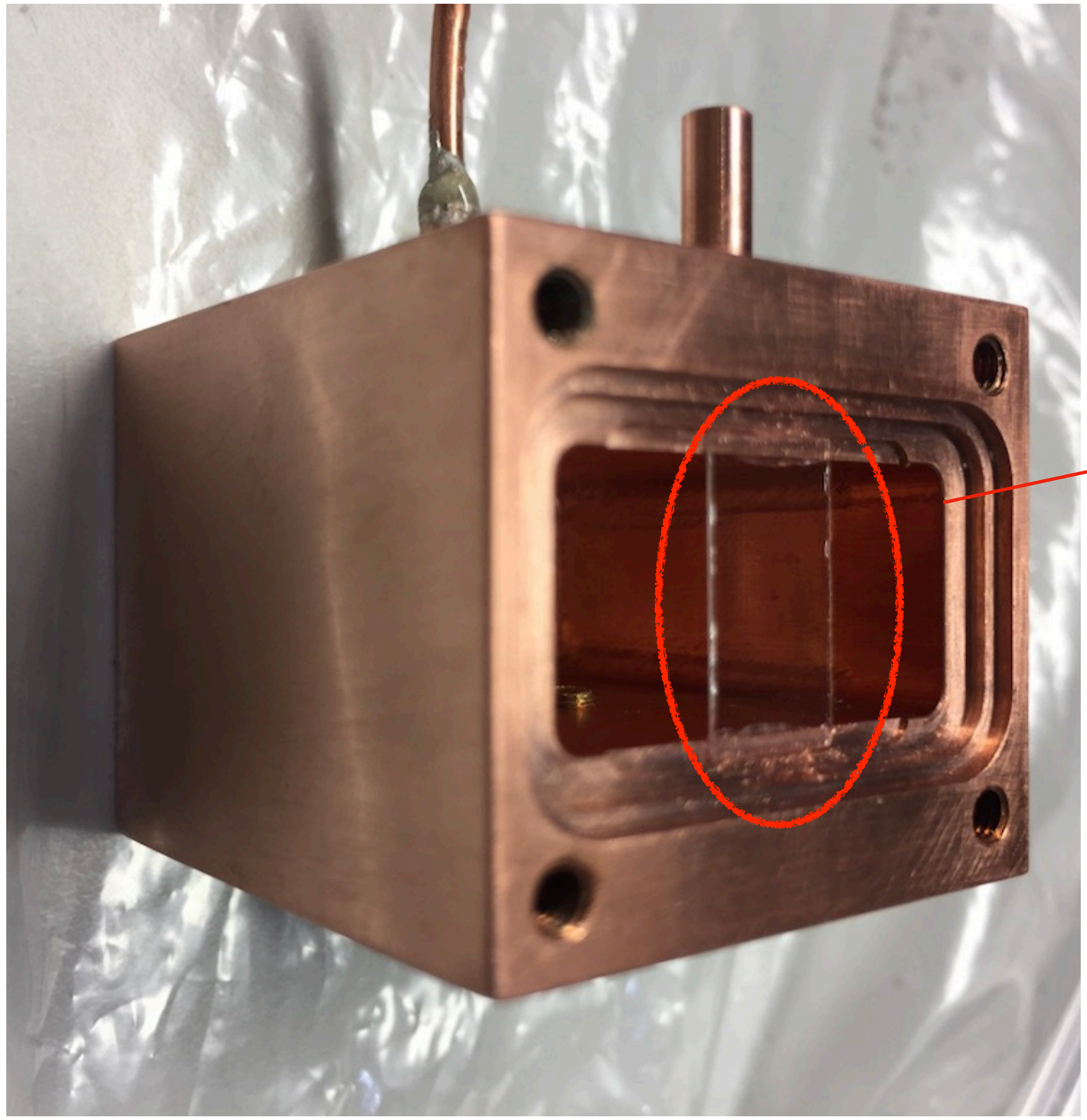
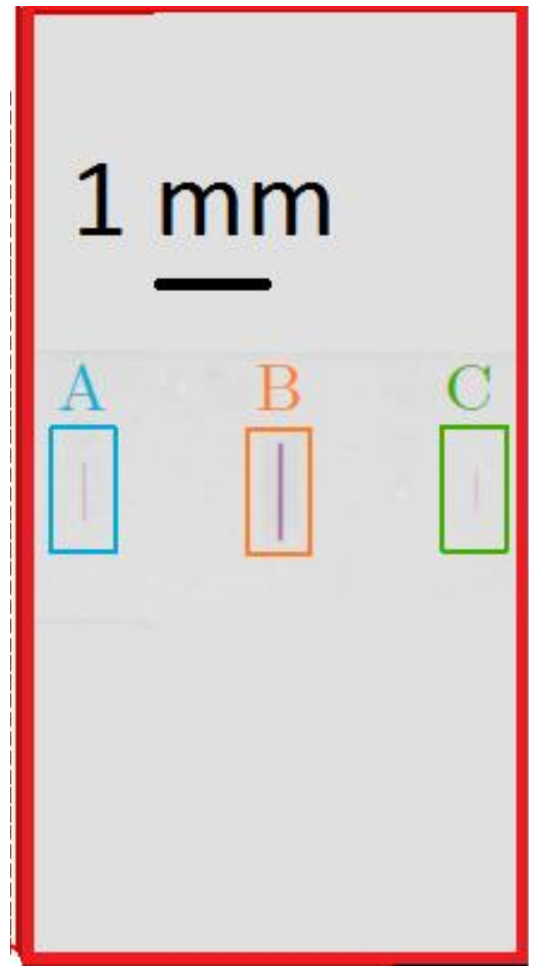
Cardani et al., Nature Communications 2021.

Gusenkova et al., Appl. Phys. Lett. 2022.

DEMETRA

Prototype

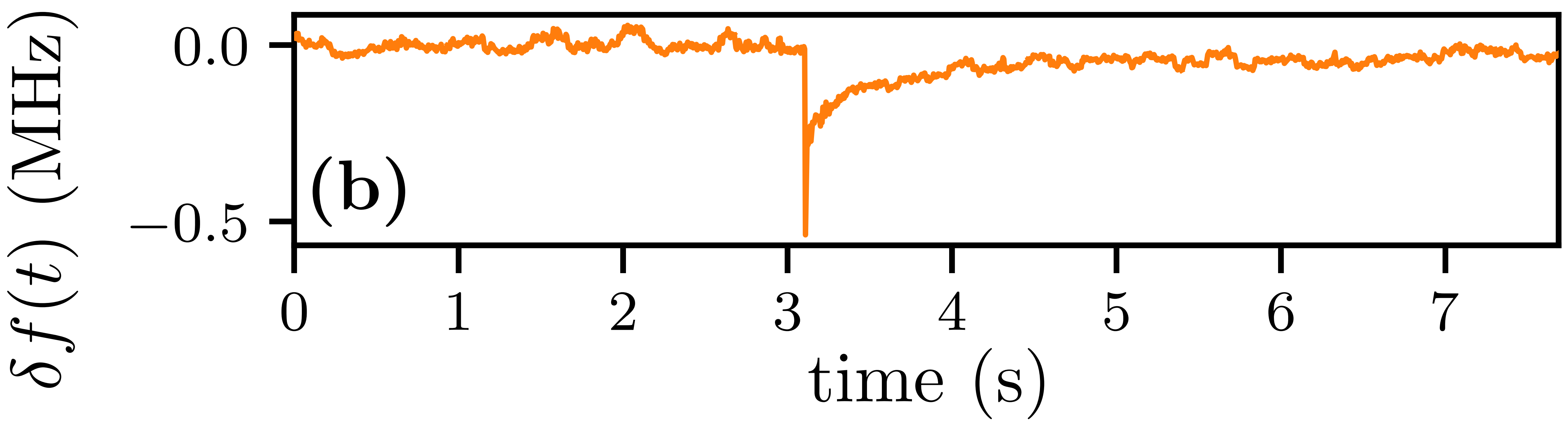


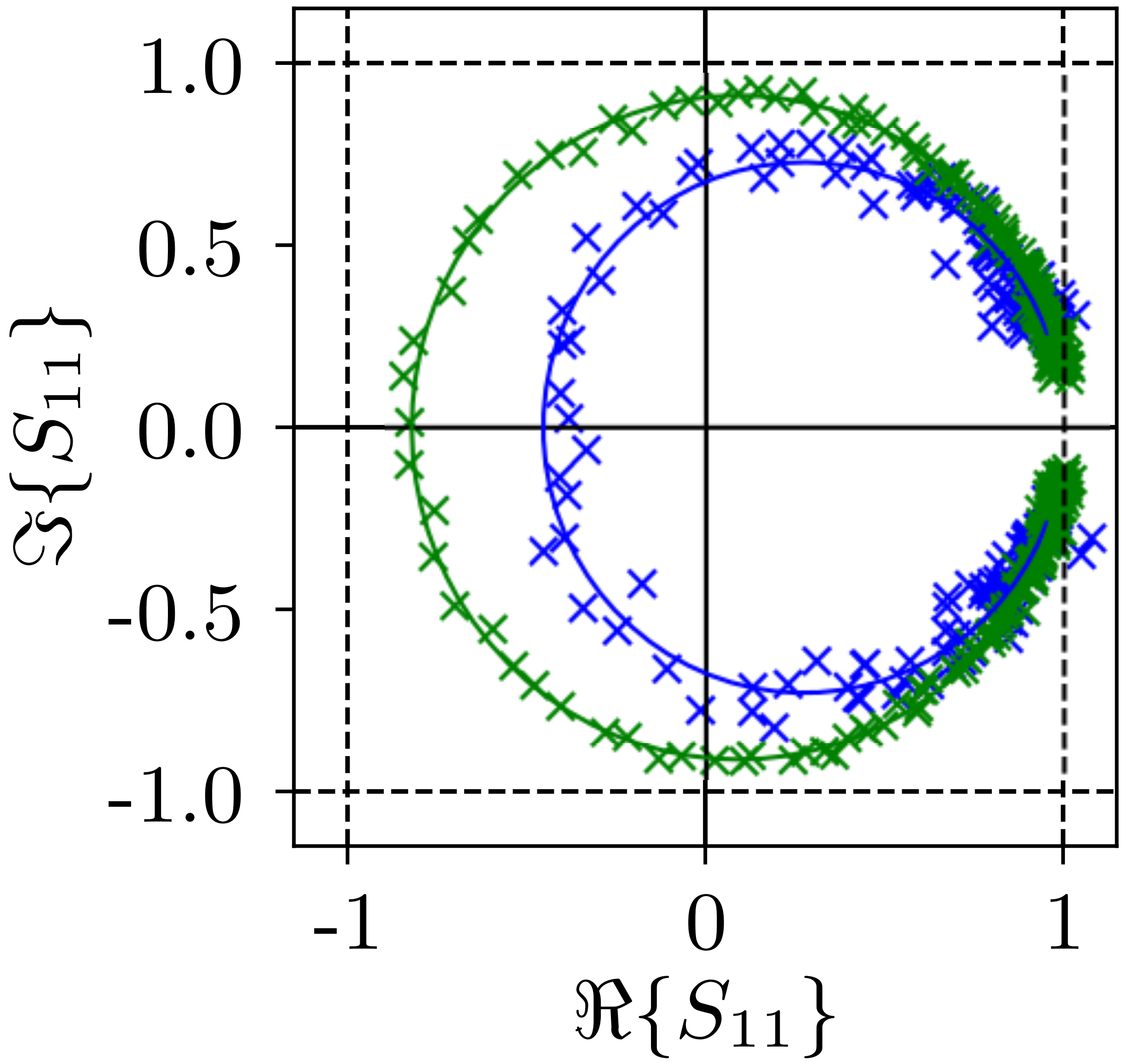


- Sapphire substrate ~1cm^2 x 300μm
- Three (20 nm thick) GrAl films with different active surfaces

Why a resonator

- Rate of QP bursts: tells us how many impacts in the chip
- Quality factor: tell us the intrinsic performance of the superconducting circuit



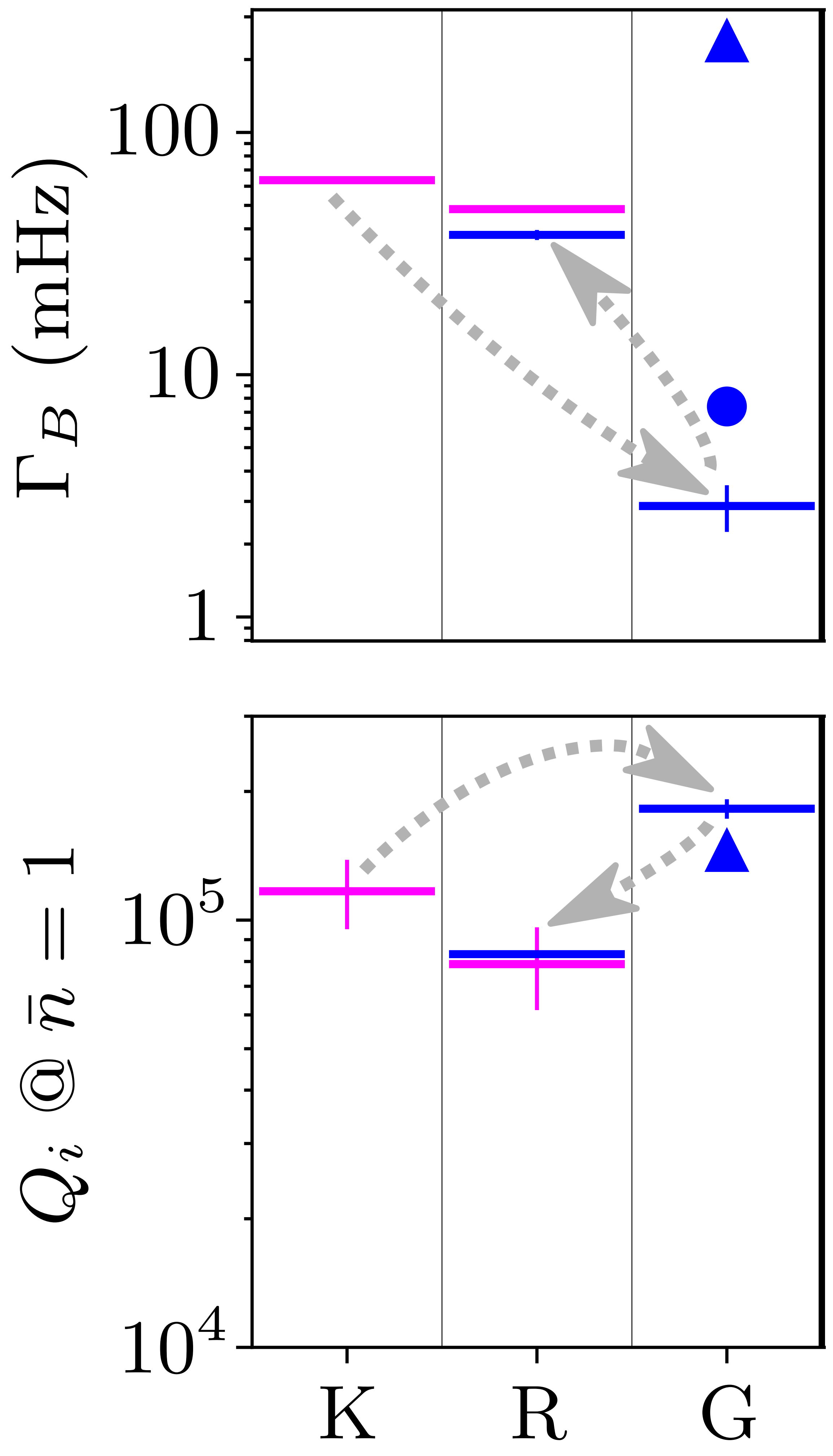


Radioactivity Suppression

Measurements

Tests in 3 environments:

- KIT (K): "standard" for qubits
- Underground LNGS (G): low radioactivity, "basic" readout line
- Roma (R) for crosscheck: "standard" radioactivity, same "basic" readout line as LNGS



Radioactivity Suppression

Results

QP bursts (rate of interactions):

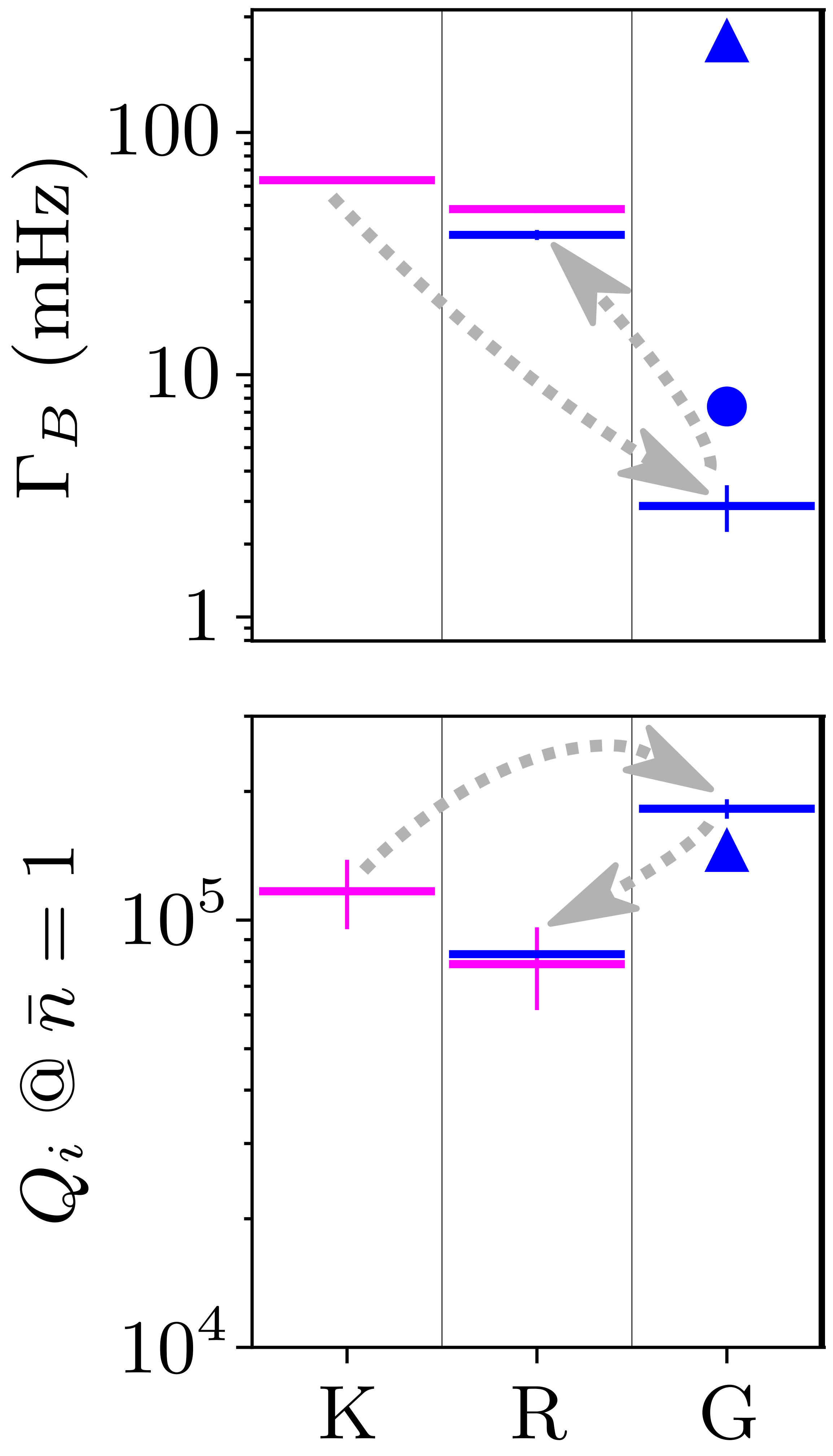
70 mHz (30 mHz from laboratory alone) in KIT/Rome

To 2.5 mHz (1.5 mHz from laboratory alone)

To >100 mHz in LNGS using a radioactive source

Improve Q_{int} by a factor 2-3

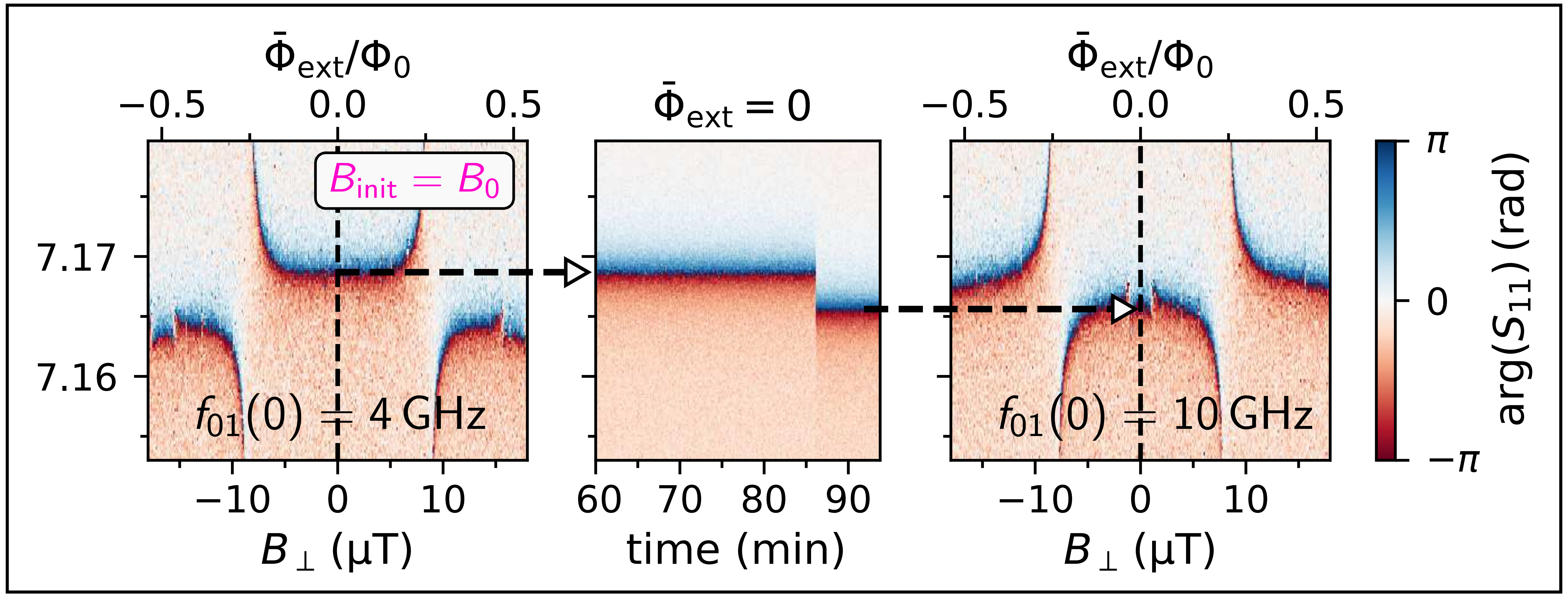
Other improvements possible with a better readout

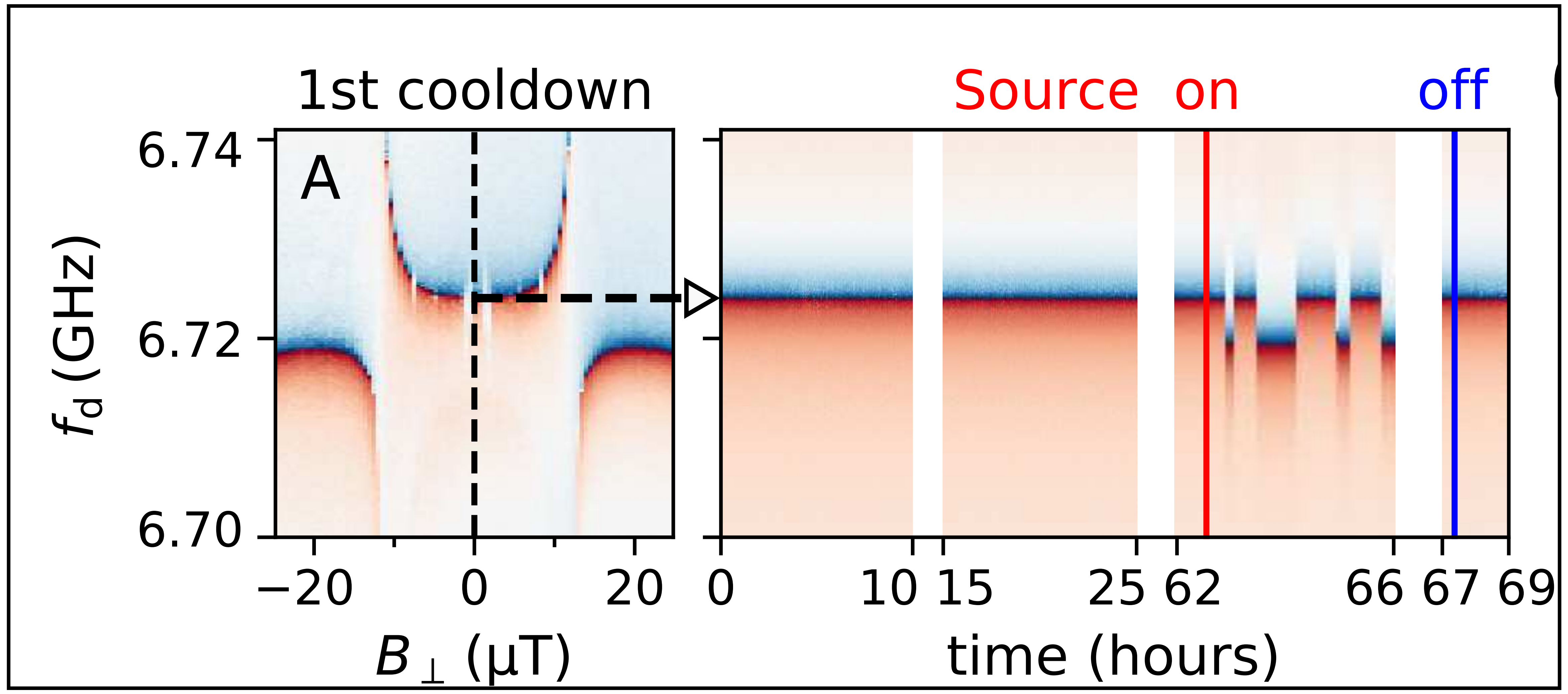


A (novel prototype) qubit

- Readout line at LNGS upgraded

- Measure a (gradiometric fluxonium) test qubit instead of resonators





- Large improvement of frequency stability

- Soon measurements with more performing fluxonium and transmon qubits

Summary

- Enhancing coherence: one of the main challenges for qubits
- Evidences that radioactivity:
  - Will be the ultimate limit for coherence for some types of qubits
  - Is likely the ultimate limit for coherence for other types of qubits
  - Severly affects quantum error correction
- Evidences that suppressing radioactivity improves quantum bits
- How far can we go?

Perspectives

"Low radioactivity" side

- Work on a new environment for qubit:
  - Radio-pure materials for the qubits/holders
  - Shields for the "cold" electronics and cryogenic environment
  - Shields from laboratory environment
  - Deep underground operation
  - ….
- Provide a "friendly" environment that does not require modifications/R&D on the qubit itself

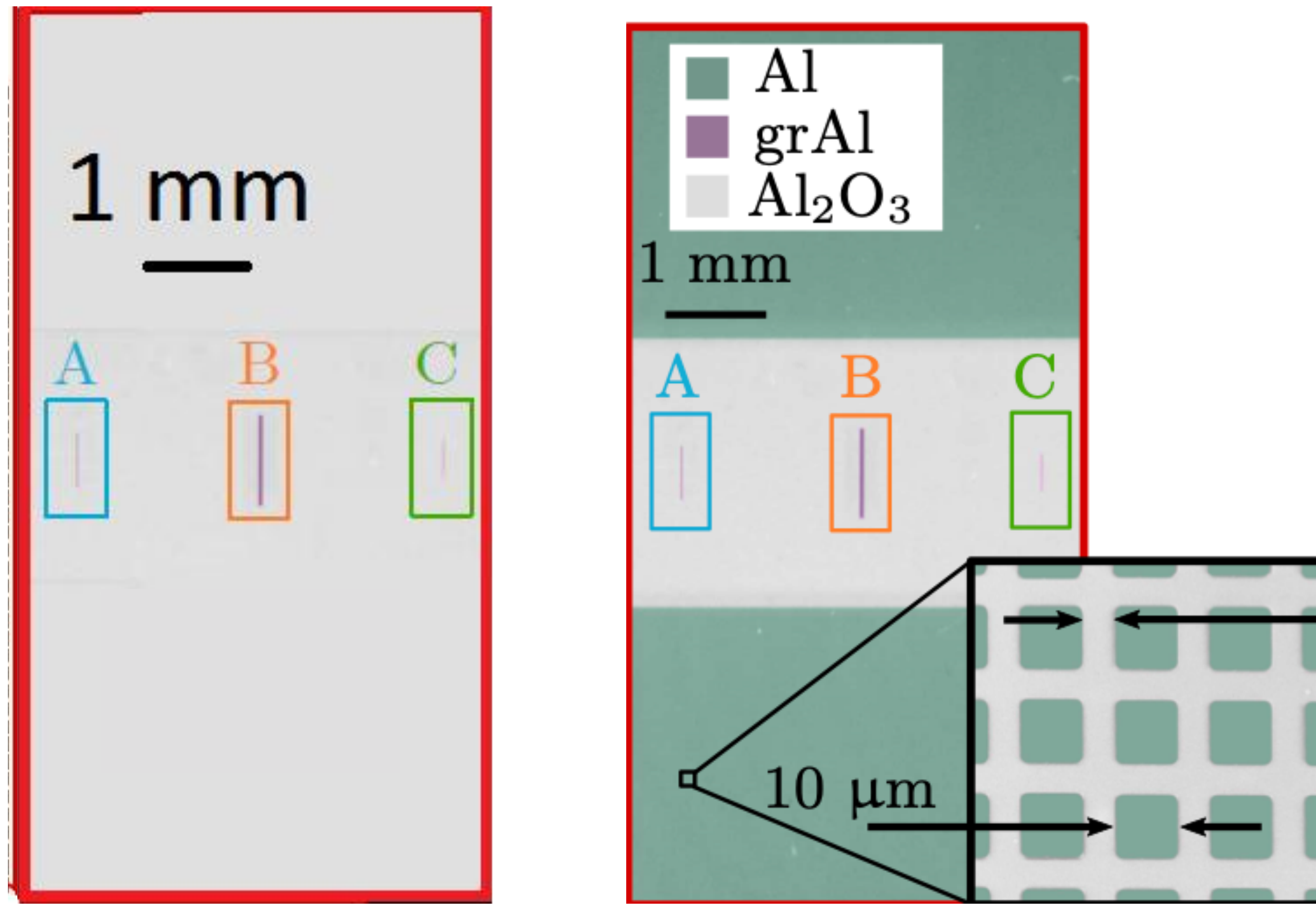
Perspectives (2)

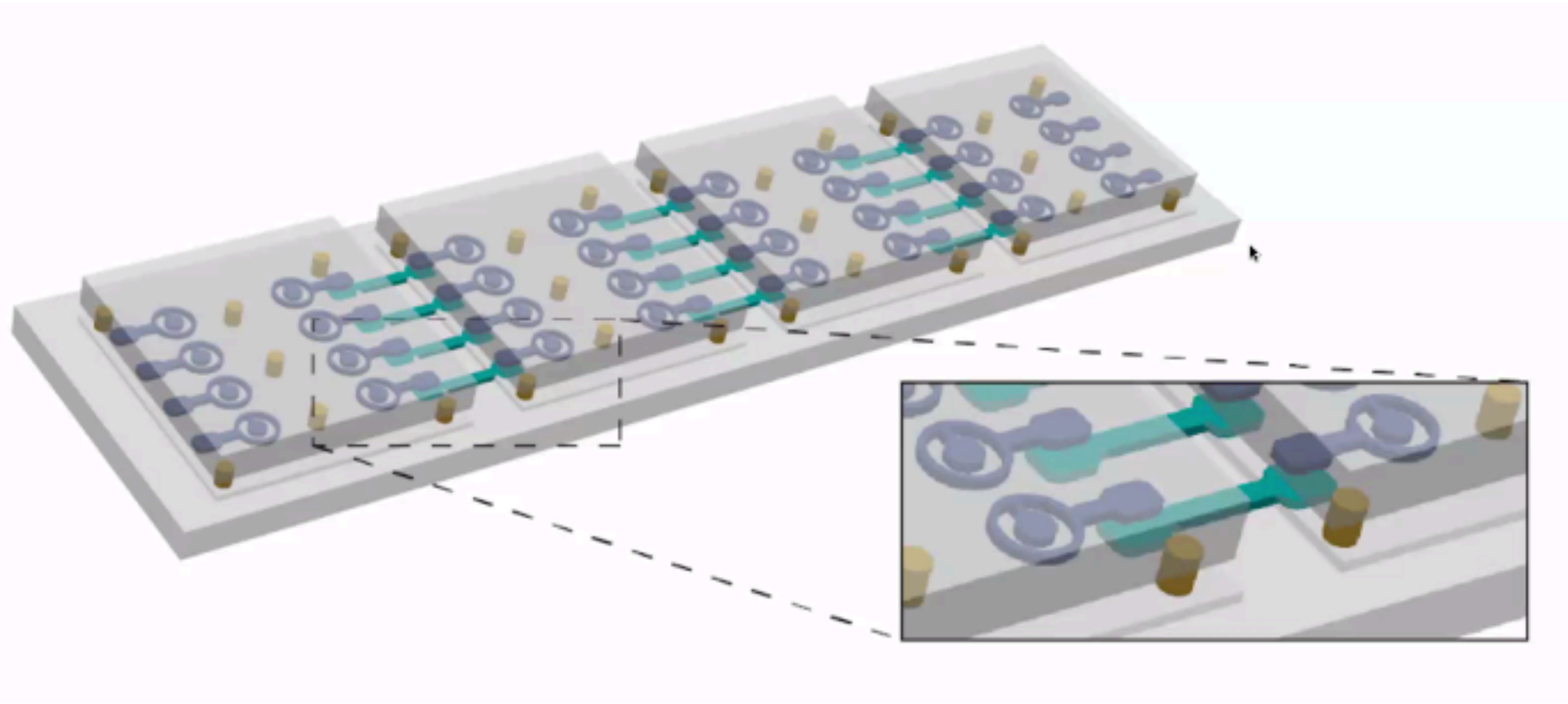
Novel chip design

- Equip the substrate with "traps" to prevent phonons to reach the detector [F. Henriques et al. Appl. Phys. Lett. 2019, J. Martinis npj Quantum Information 2021, …]

- Decouple chips from each others as much as possible [A. Gold et al., npj Quantum Information 2021, …]

- "Sensor" assisted qubits [J. Orrell and B. Loer, Phys. Rev. Appl. 2021, activities of P. For Diaz at Canfranc, …]





My personal view

- Since 2018: a lot of progress, new bridges between communities
- The community of astro-particle physics has knowledge - expertise that would significantly advance the comprehension and performance of these devices
- Particle physicists are getting excited: quantum sensing to search for dark photons, axions, ALPs, but also technological breakthroughs for other applications (paramp, …)

Thank you for the attention!