Superconducting Quantum Bits at Underground Facilities

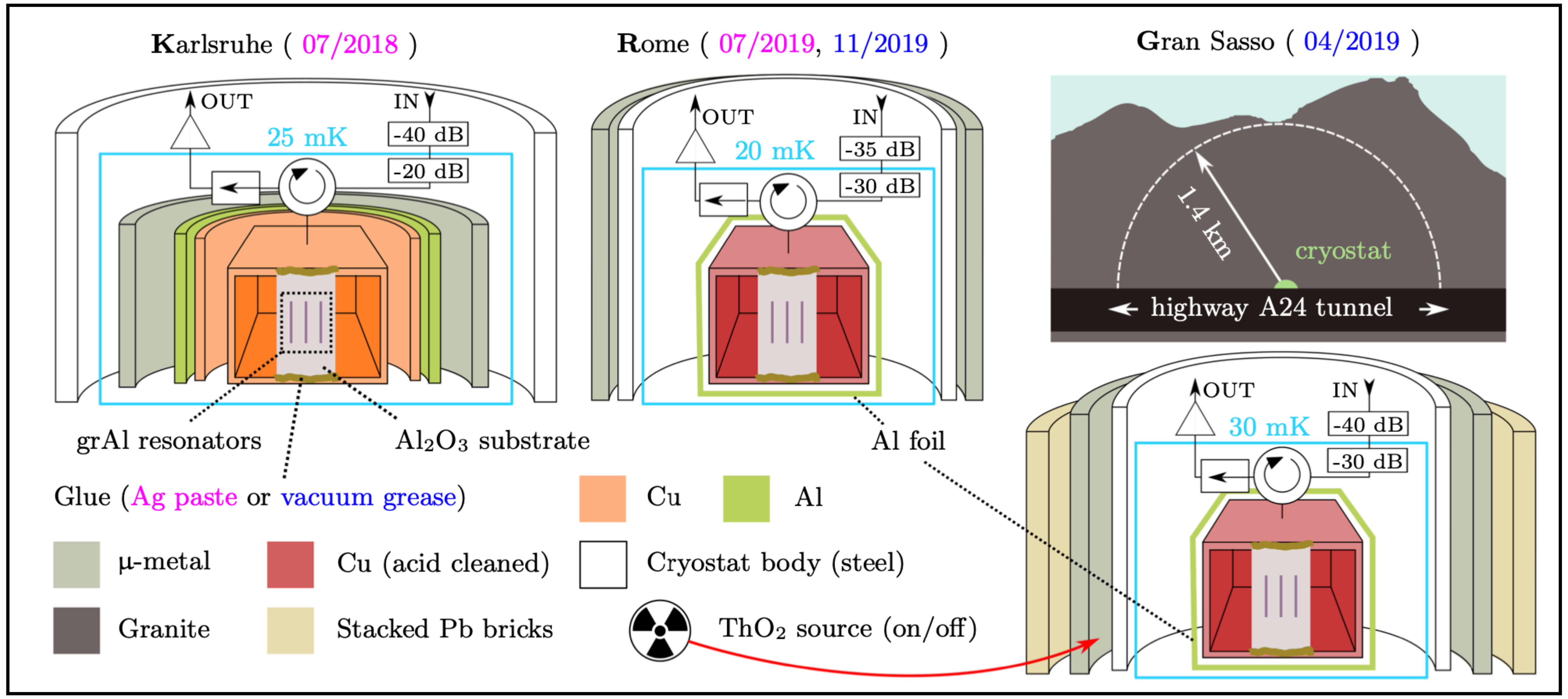
Future Projects Workshop - SNOLAB

Istituto Nazionale di Fisica Nucleare

Laura Cardani, 11/05/2021

Outline

1. Qubits underground: why?
2. Requirements
3. Underground laboratories already involved: how?



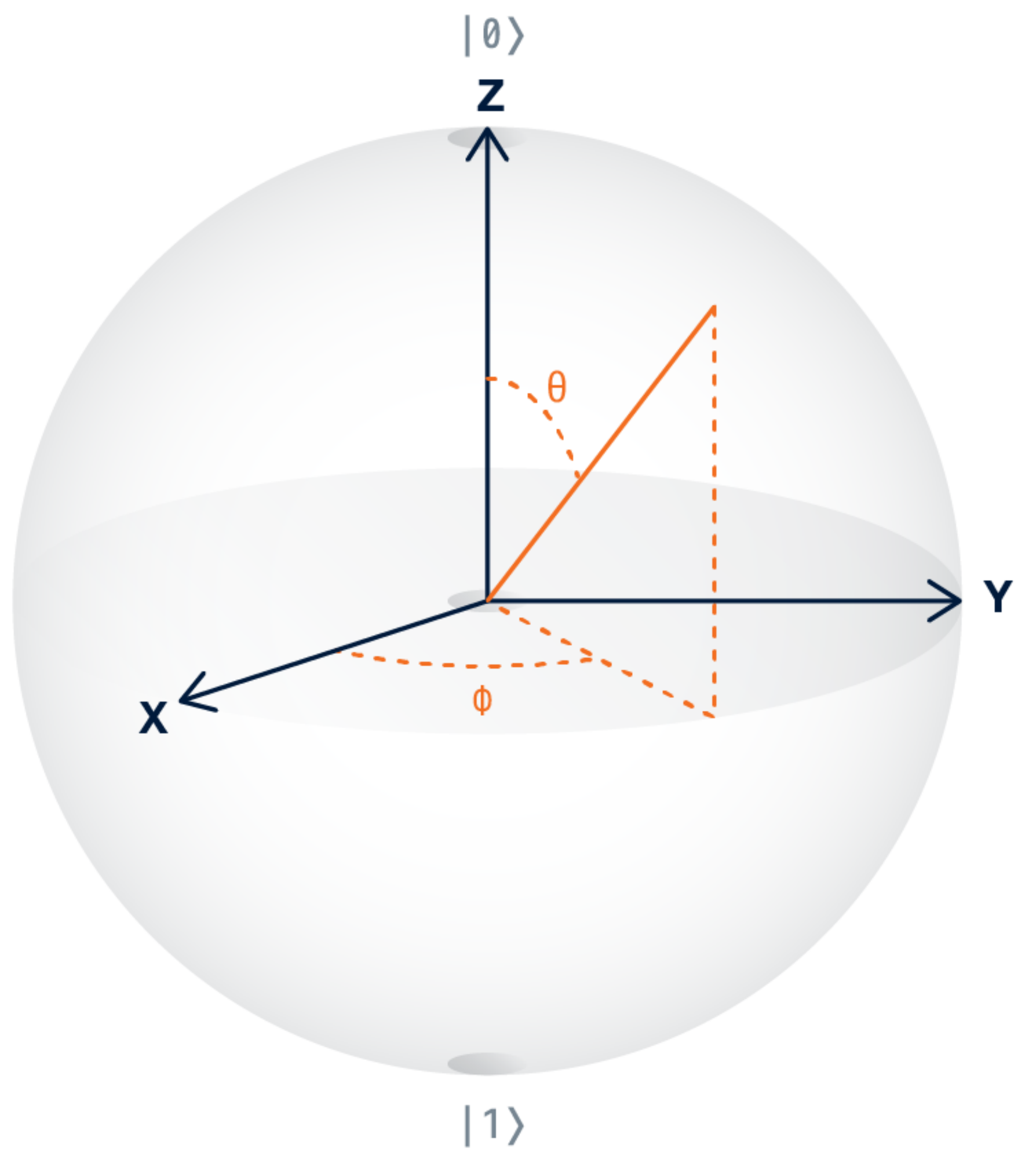
Quantum Bits

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]



Superconducting Circuits

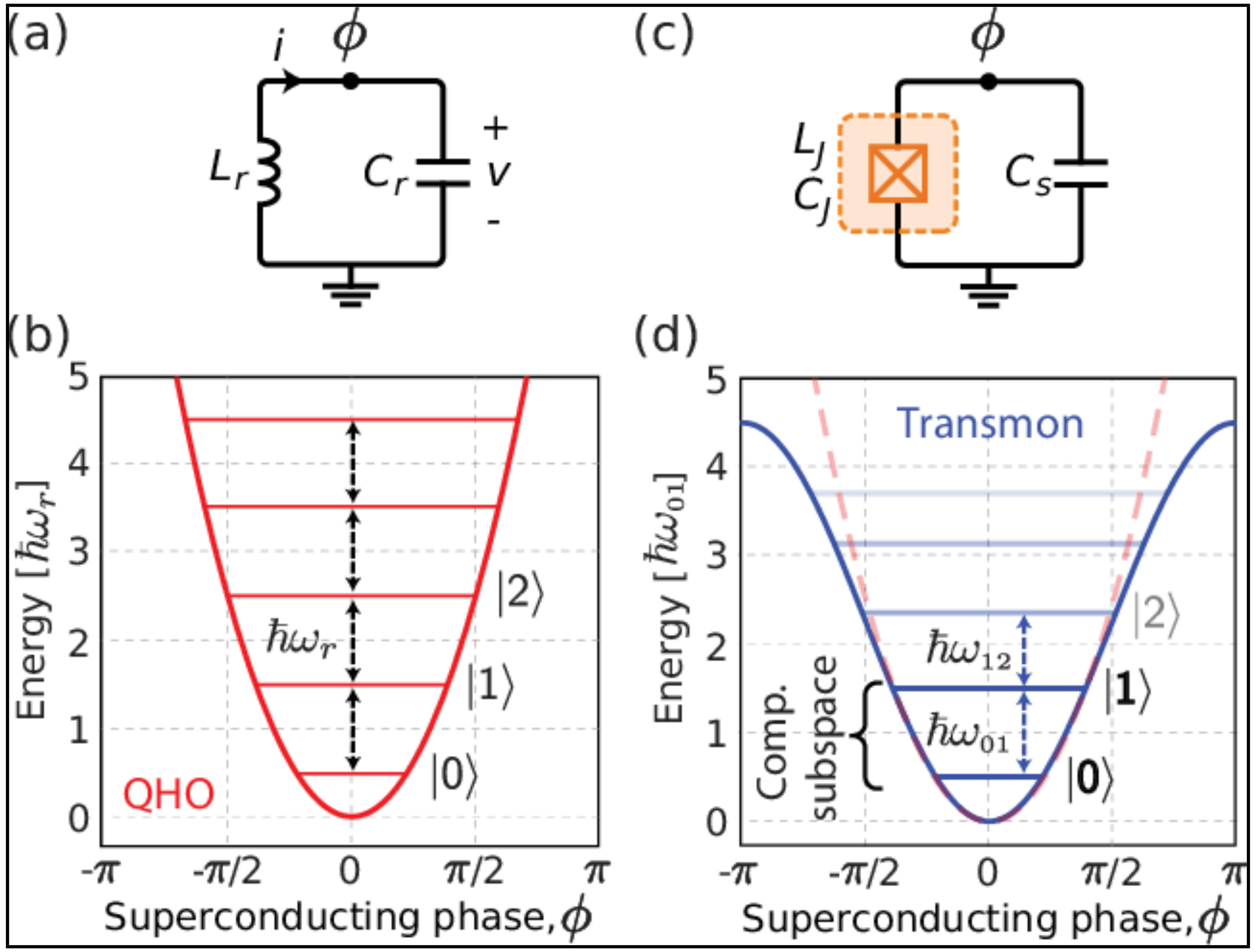
In a nutshell

Macroscopic circuits consisting of:

- capacitor
- inductor
- Josephson Junction

Build a non-linear two-level system

Superconductor: no dissipation



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

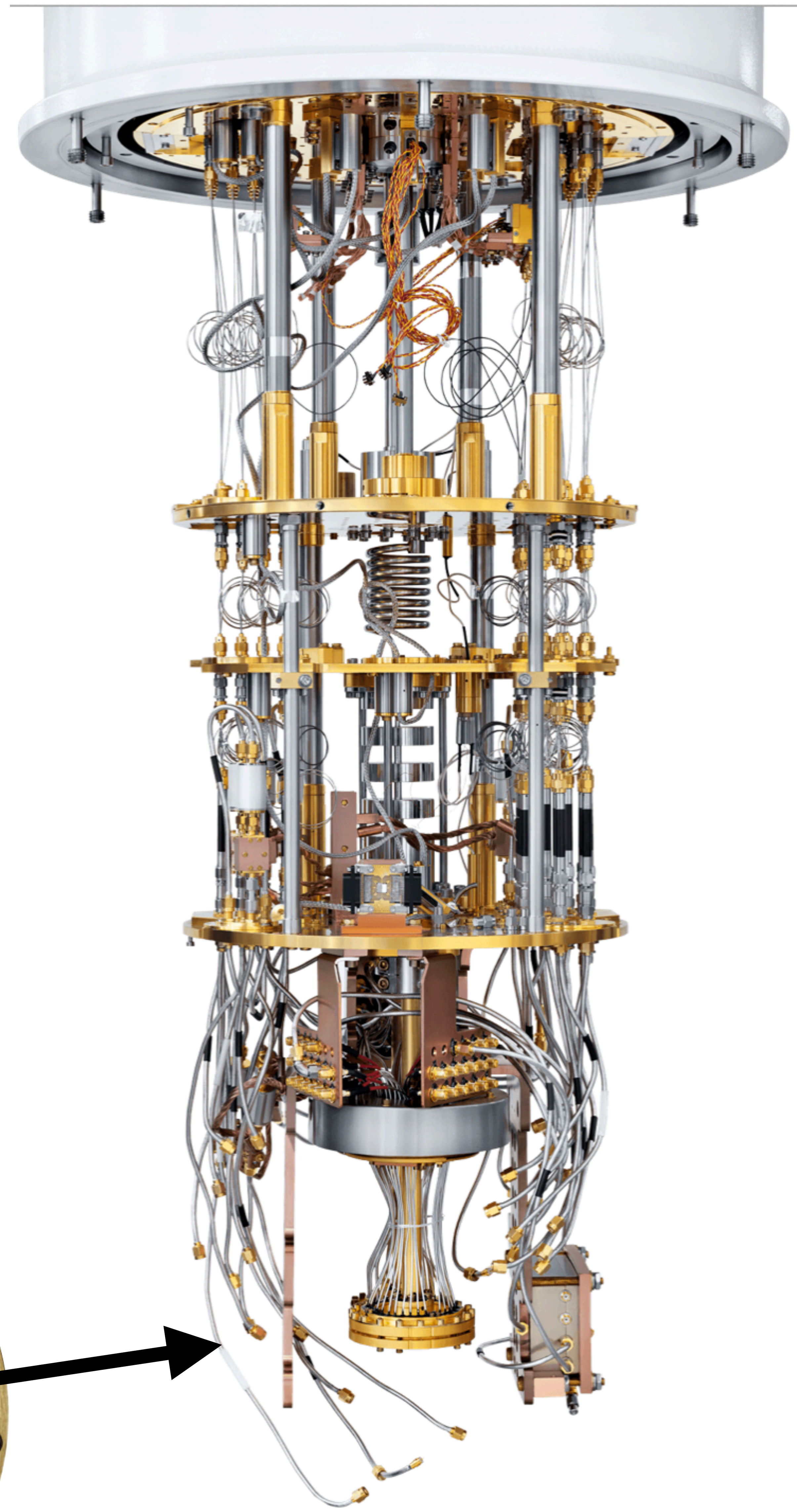
Superconducting Circuits

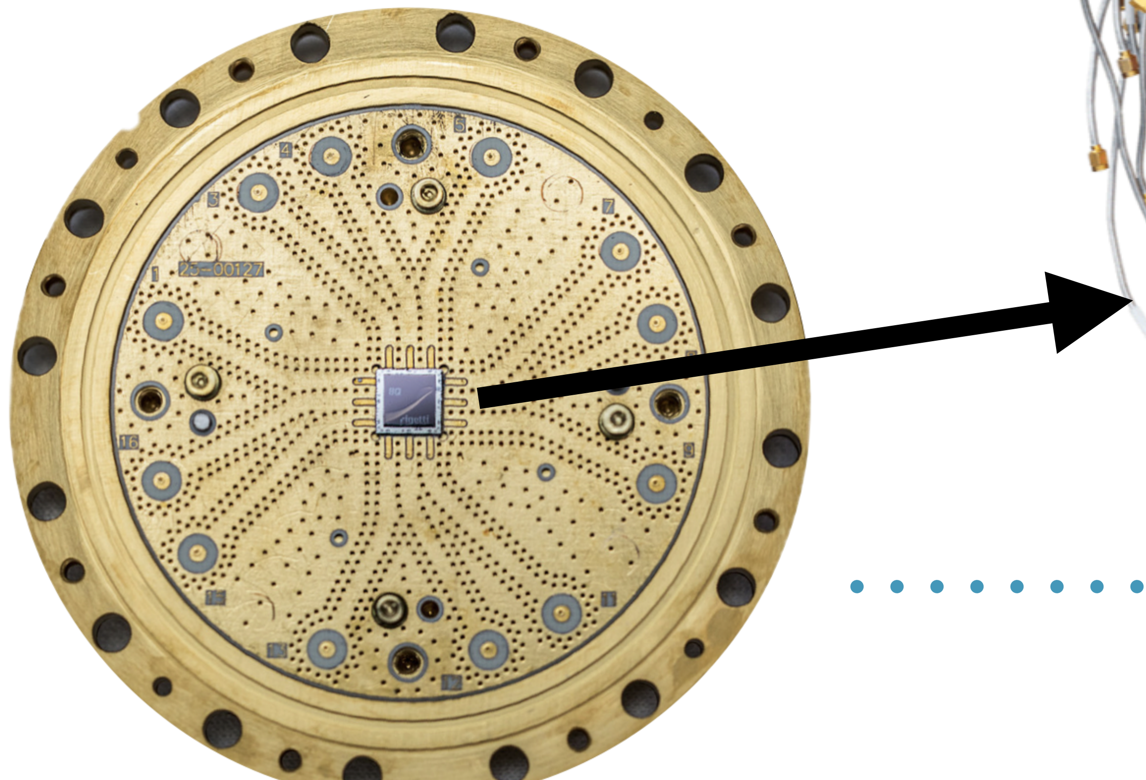
Compared to “ideal” qubits

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

    Feasible and demonstrated with tens of qubits
  - decoupled from the world [quantum coherence]

    Main **limit** of this technology





Superconducting Circuits

Compared to “ideal” qubits

- Ideal qubit:
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  Feasible and

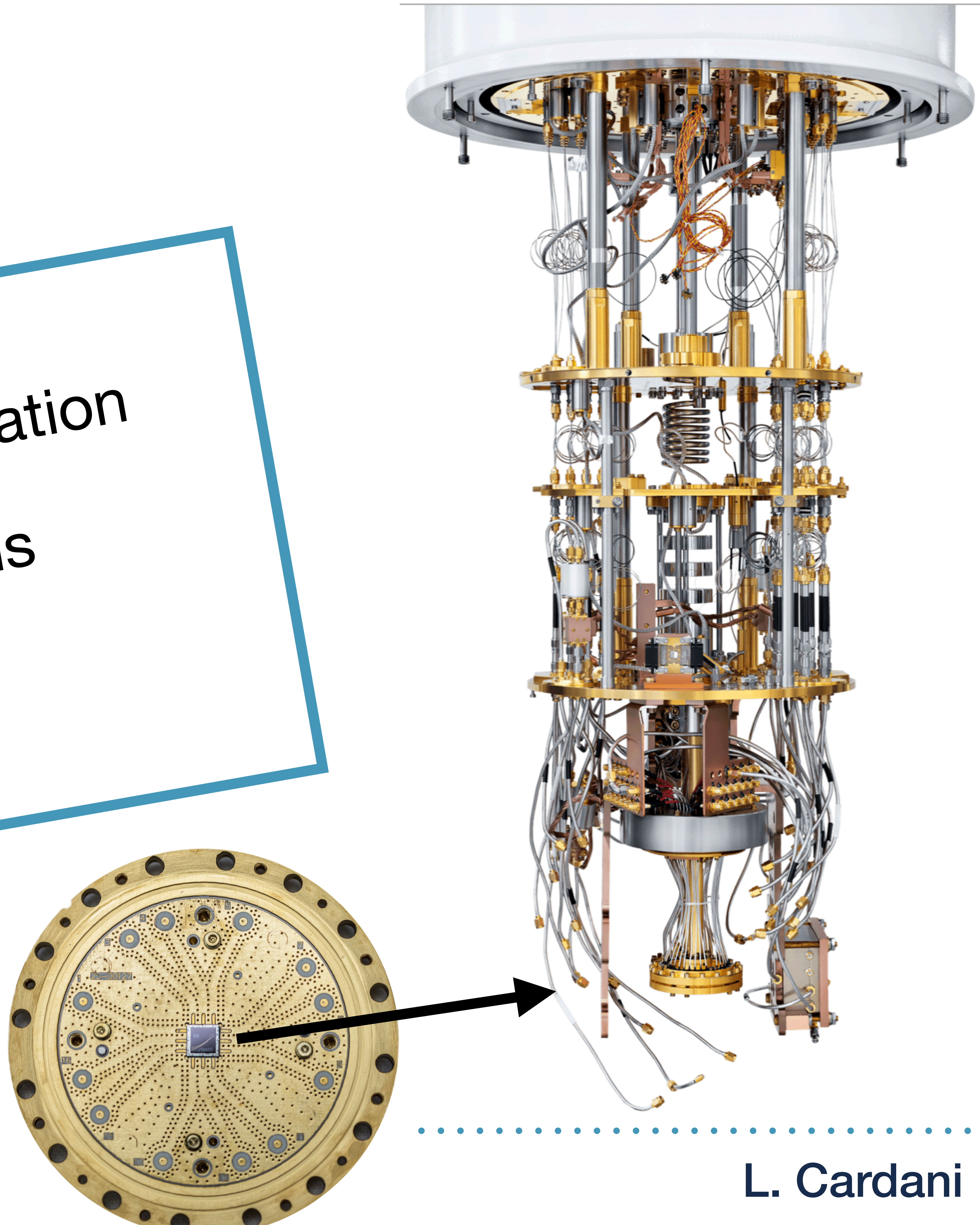
  - decoupled fr…

  Main **limit** of t…

Depends on qubit implementation

For transmons: tens of μs

Goal: millisecond



Radioactivity as Source of Decoherence

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

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

   [Vepsäläinen, Nature 2020]

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

   [Wilen, Nature 2021] and [McEwen, arXiv:2104.05219]

3. Suppressing radioactivity improves the performance of quantum circuits

   [Cardani, Nat. Comm. 2021]

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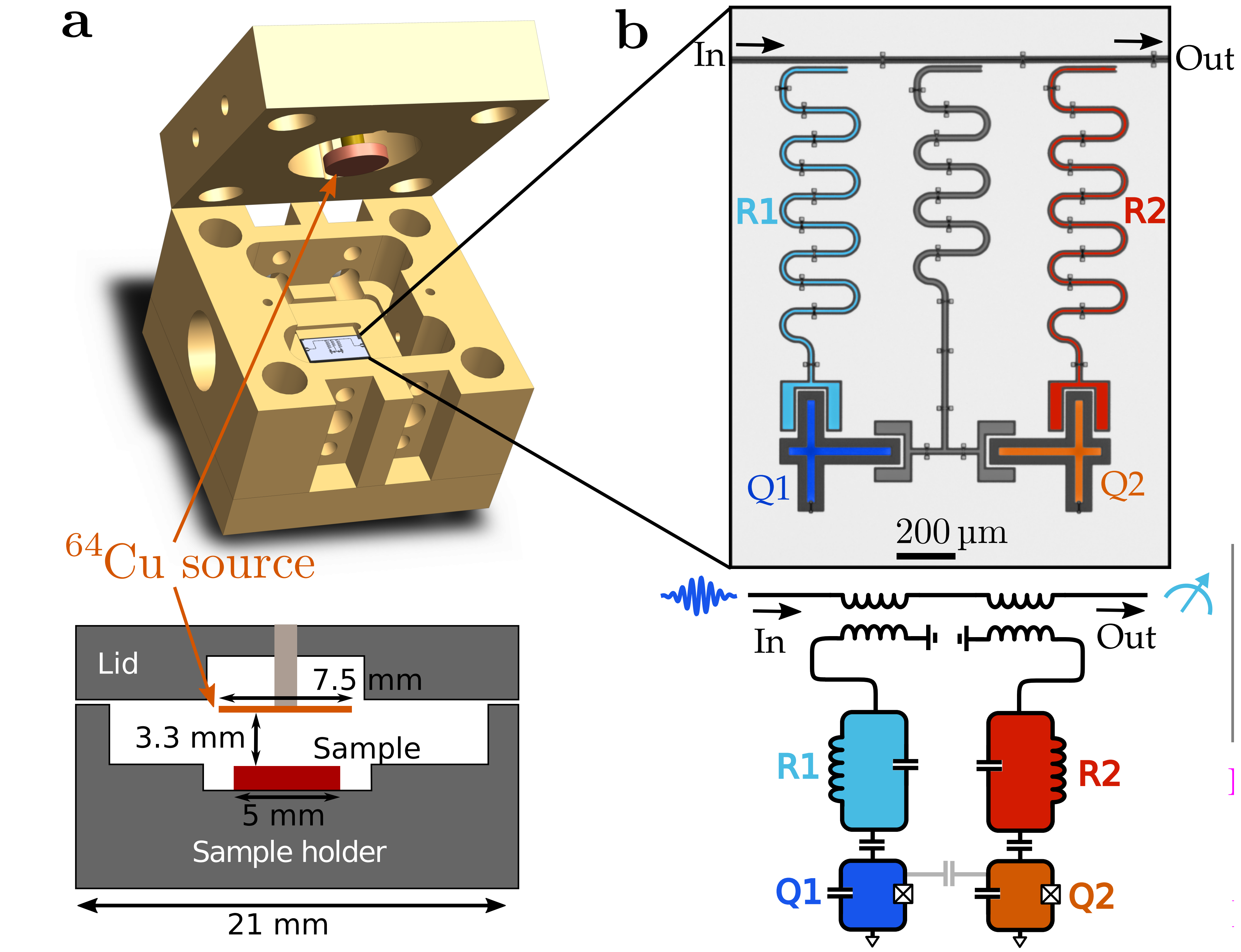
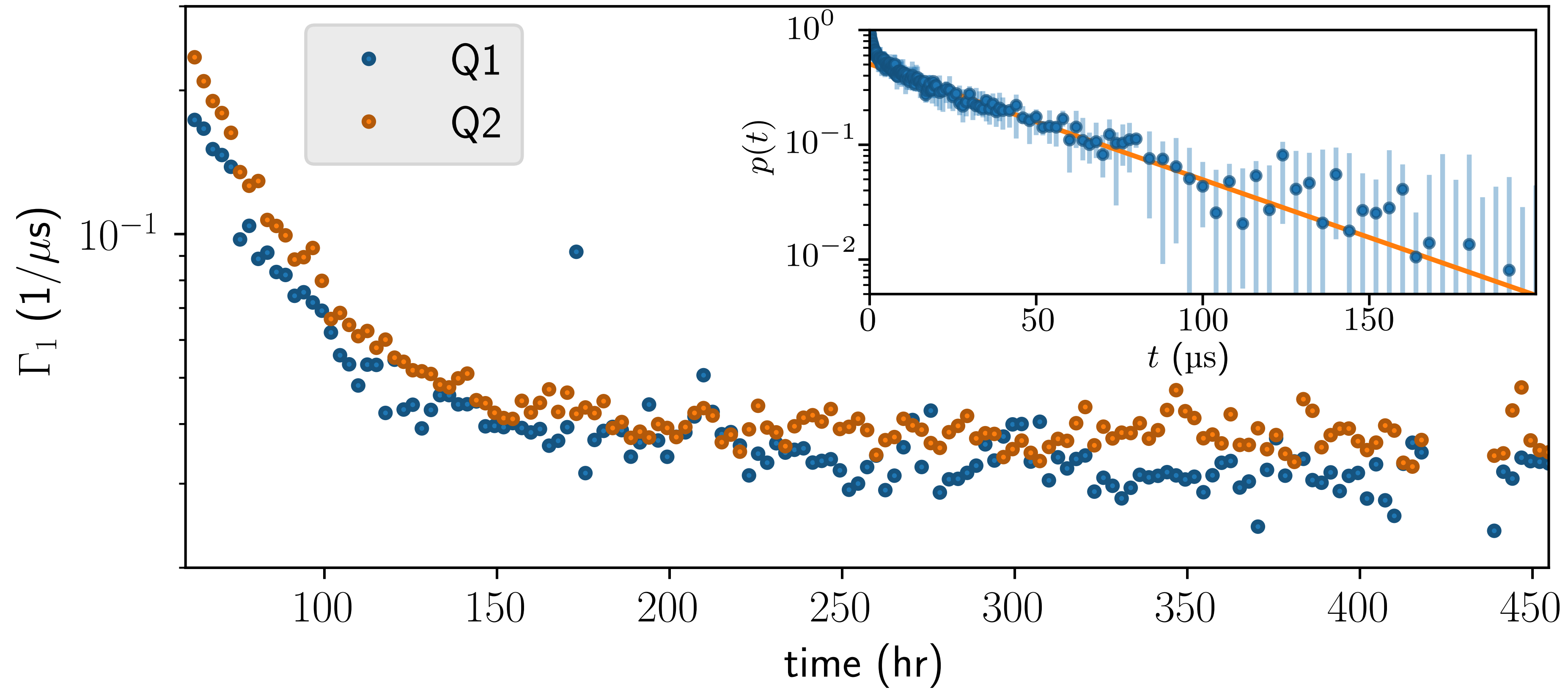
Radioactivity vs Coherence

[Vepsäläinen et al, Nature 2020]

- First evidence that qubit “see" radioactivity
- Concluded: “*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.*”





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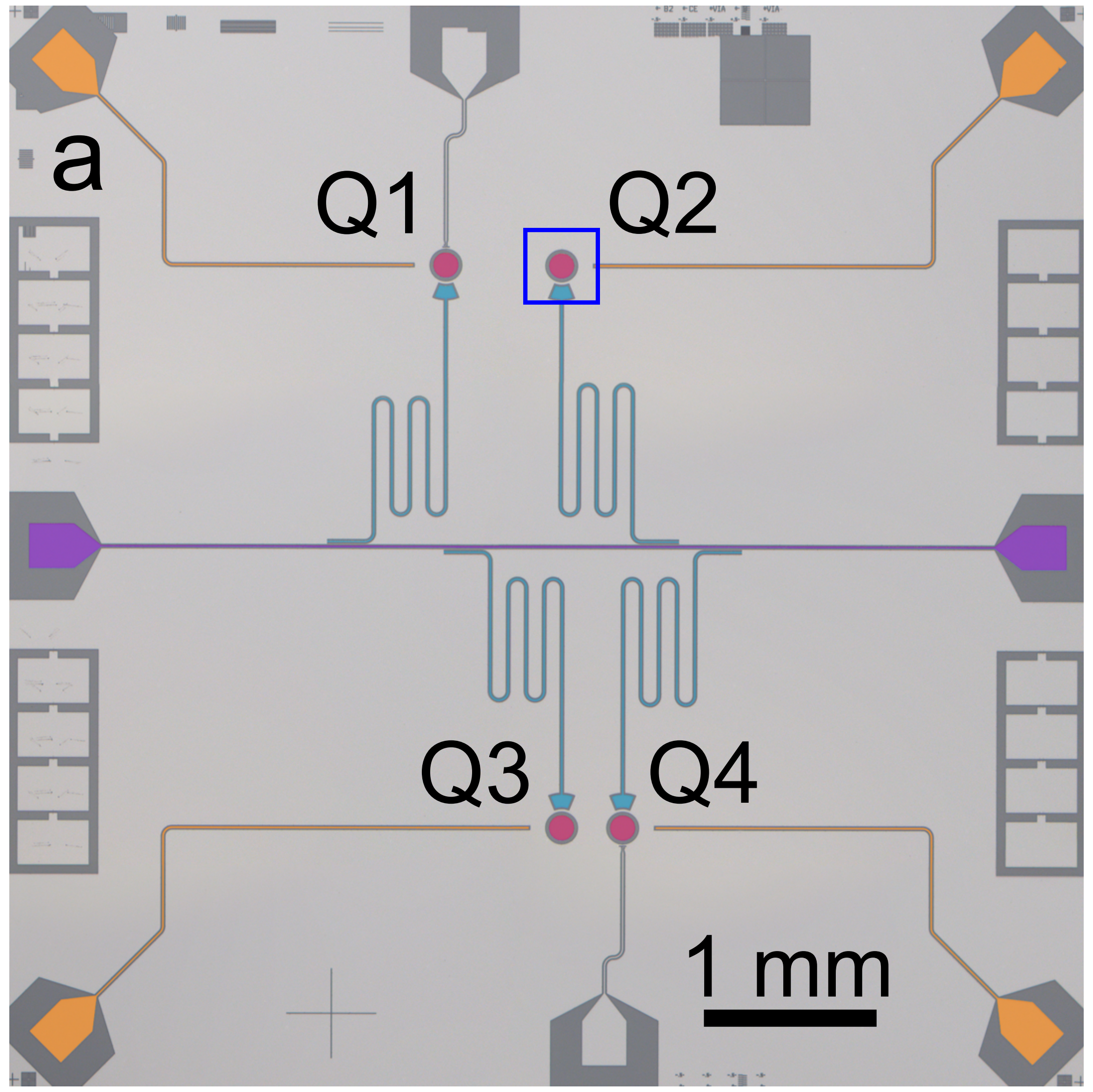
Quantum Error Correction

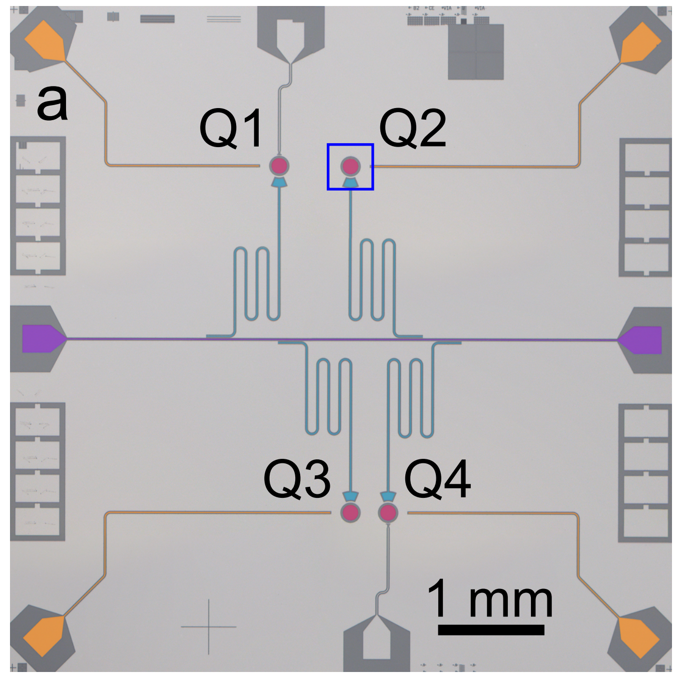
The issue

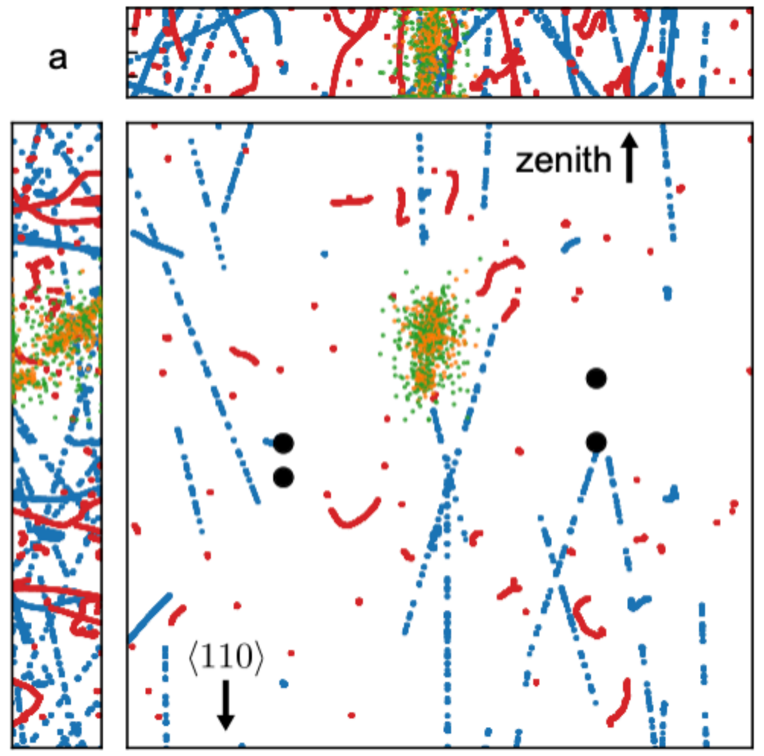
- Most popular idea for quantum error correction: encode quantum information in a matrix of qubits
- Key assumption: errors across the qubits belonging to this matrix are uncorrelated in space and time
- Events in the substrate can simultaneously affect more qubits

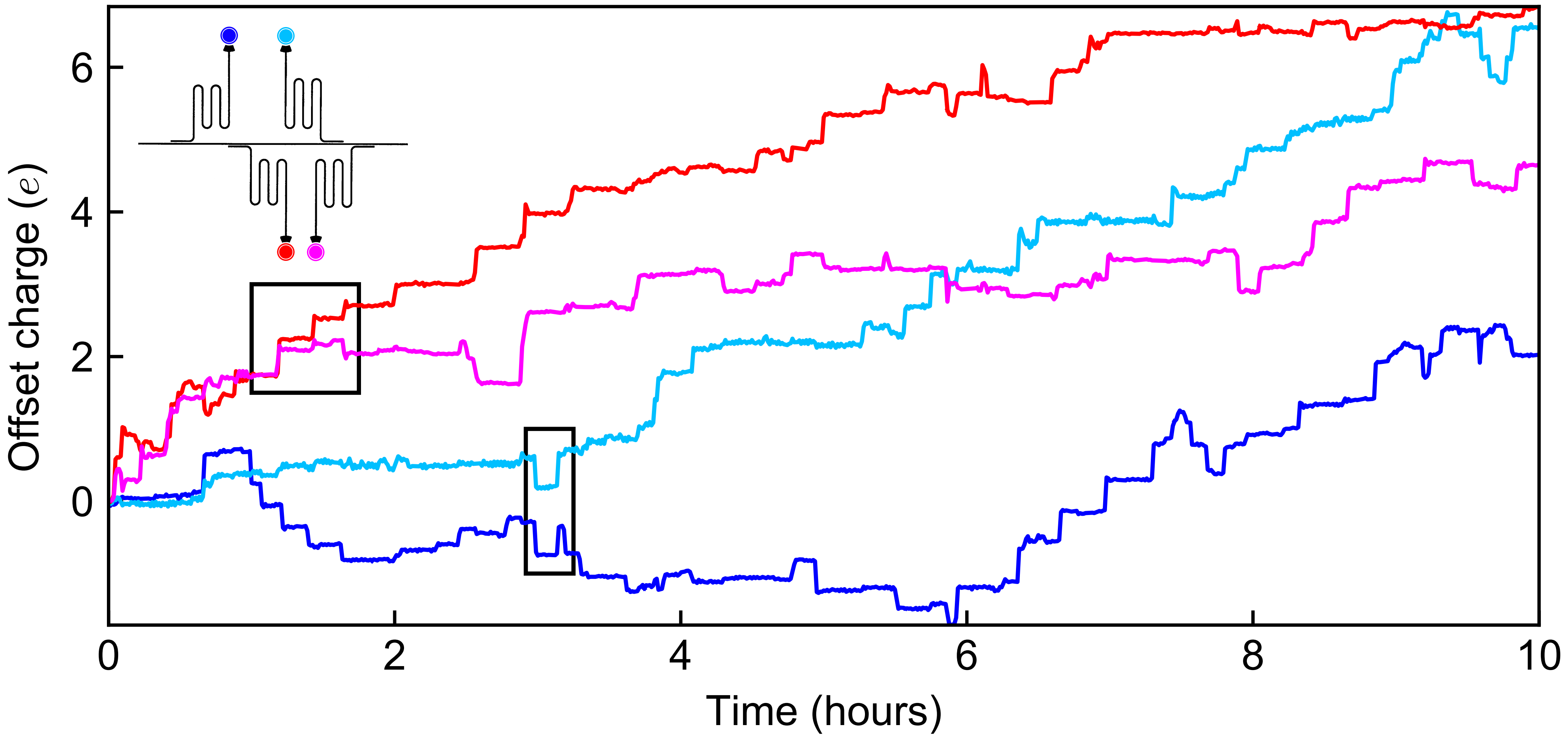


Quantum Error Correction

[Wilen et al, arXiv:2012.06029]



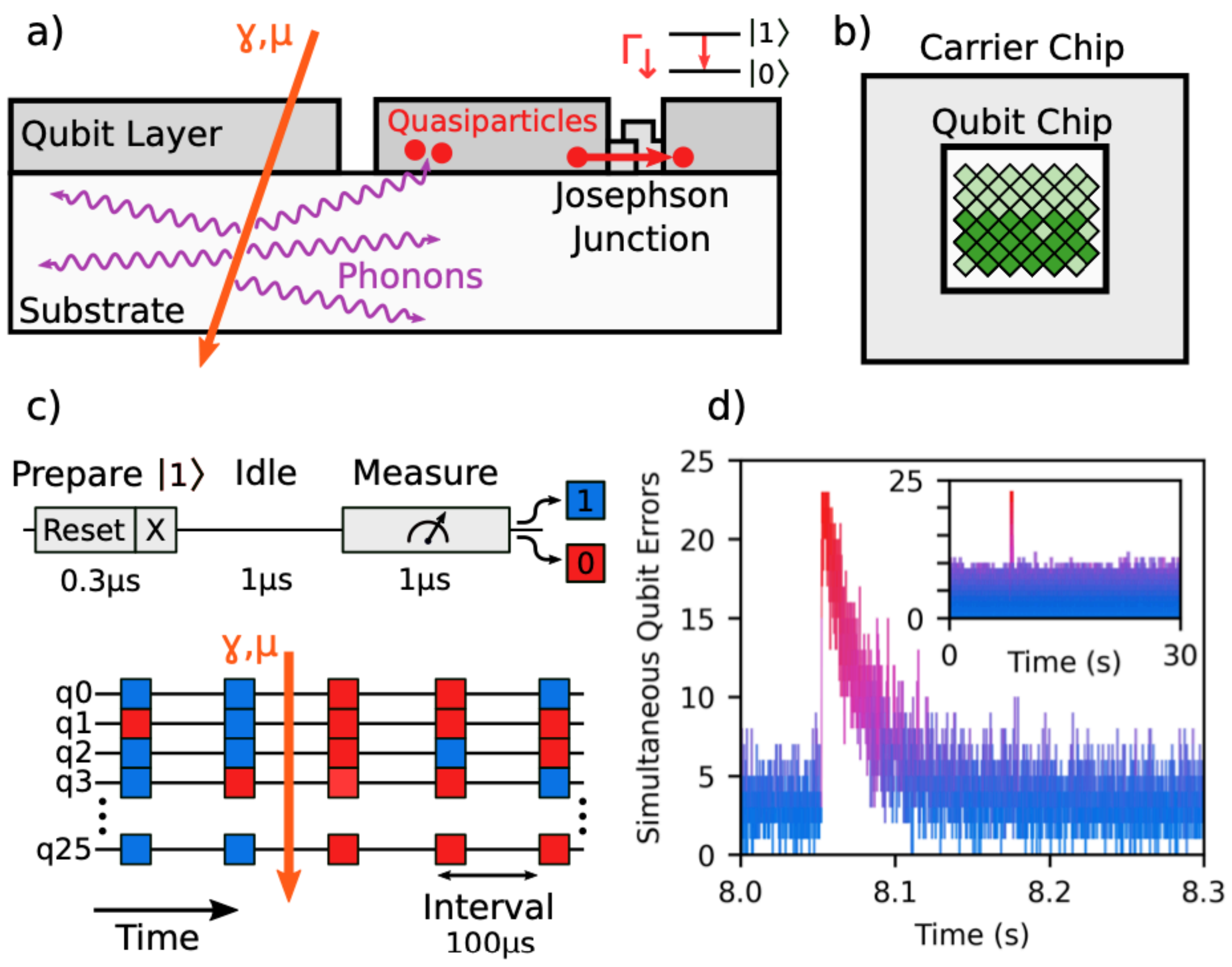




- Charge jumps of qubits compatible with radioactive deposits
- Many **simultaneous** jumps in 2-qubits:
  - 54% correlation prob. for ΔL = 340 μm
  - 46% correlation prob. for ΔL = 640 μm
  - For ΔL = 3 mm random coincidences
- Effects on the **coherence** of single qubits

Quantum Error Correction

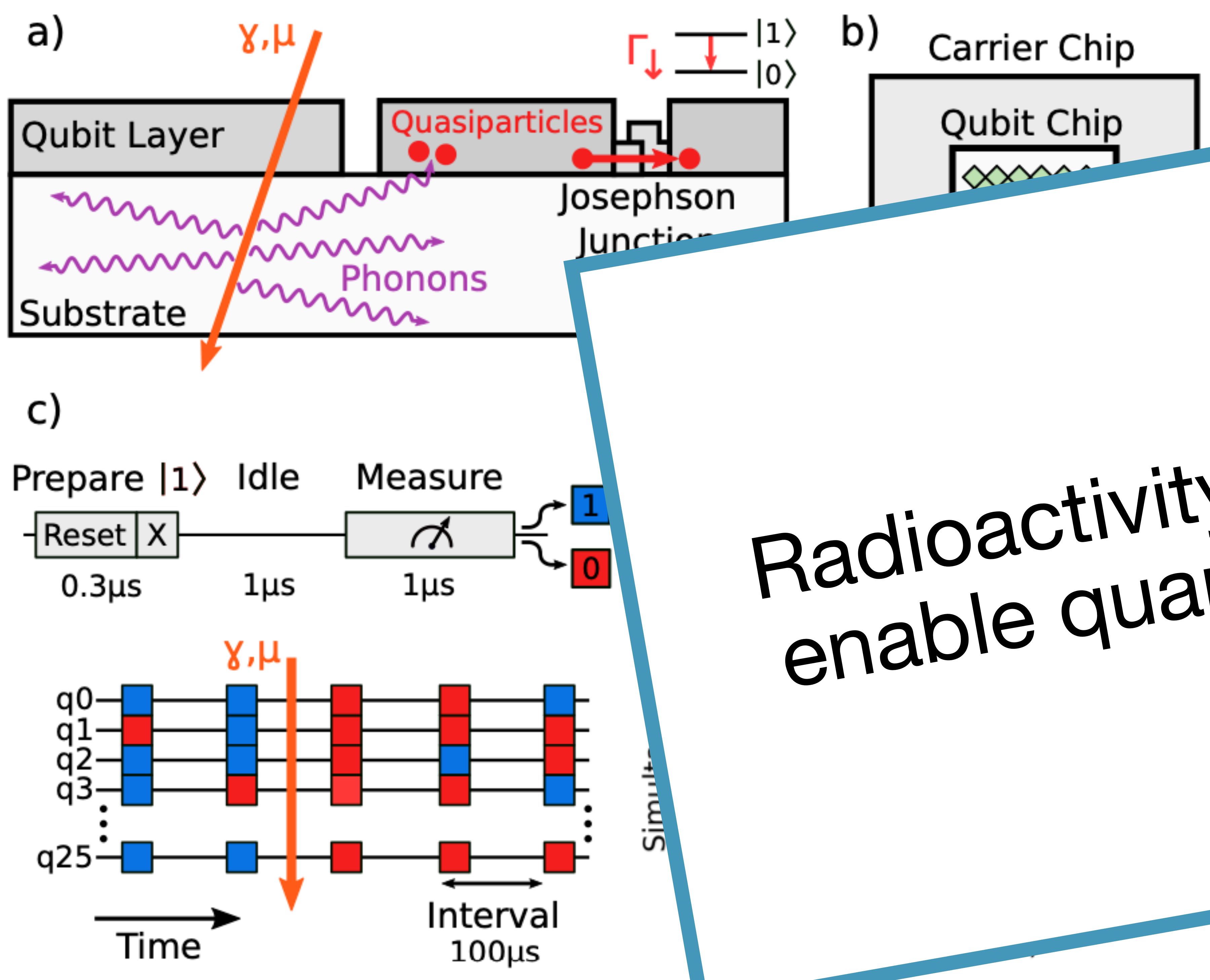
[McEwen et al, arXiv:2104.05219]



- Refined our study with Google Sycamore processor
- *High energy events produce discrete bursts of errors that affect an entire qubit patch of the processor, effectively lasting for thousands of errors correction cycles*
- *Monitor the coherence time during an event and find it to be severely suppressed across all chip*

Quantum Error Correction

[McEwen et al, arXiv:2104.05219]



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Radioactivity mitigation necessary to enable quantum computing to scale

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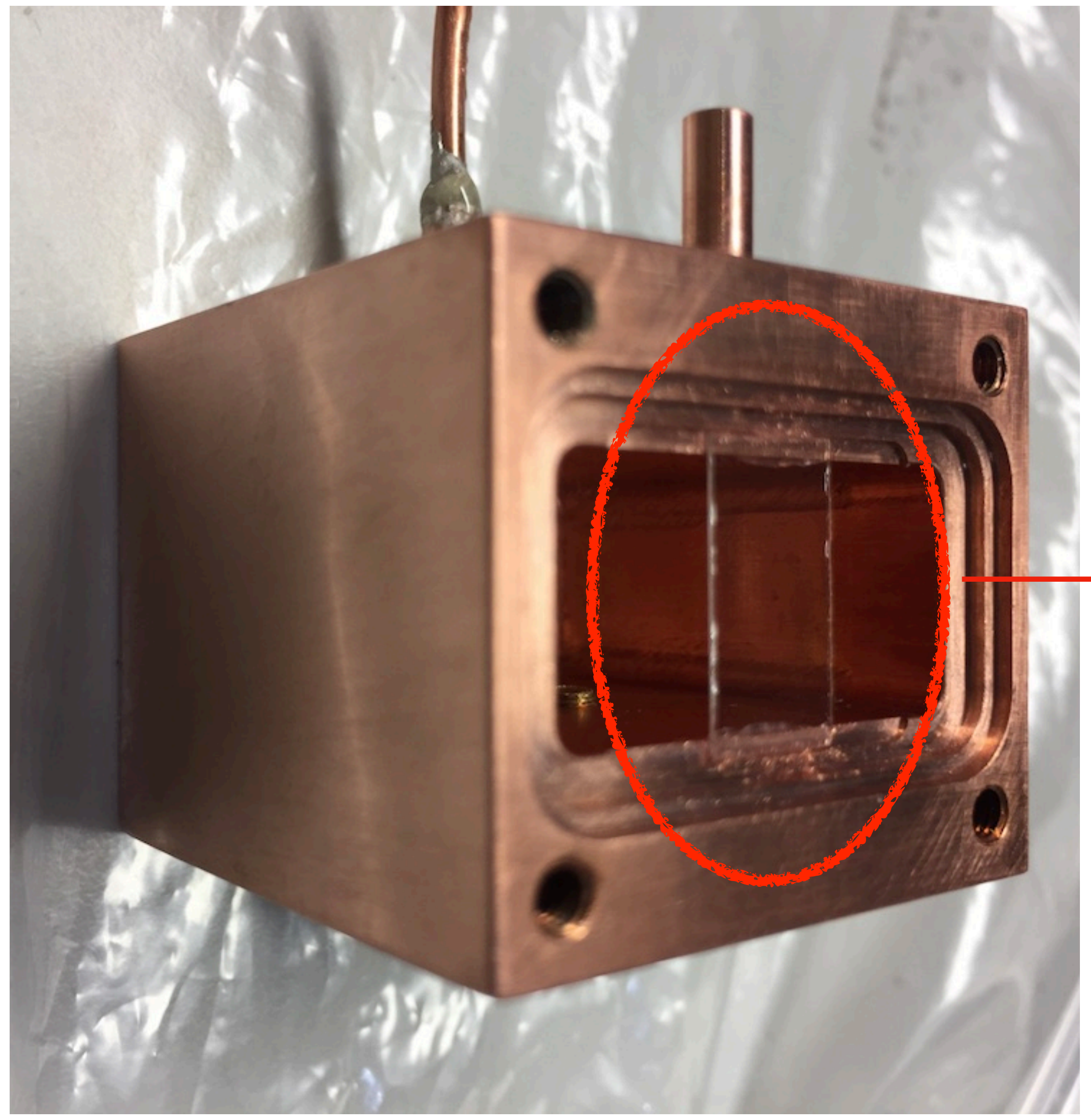
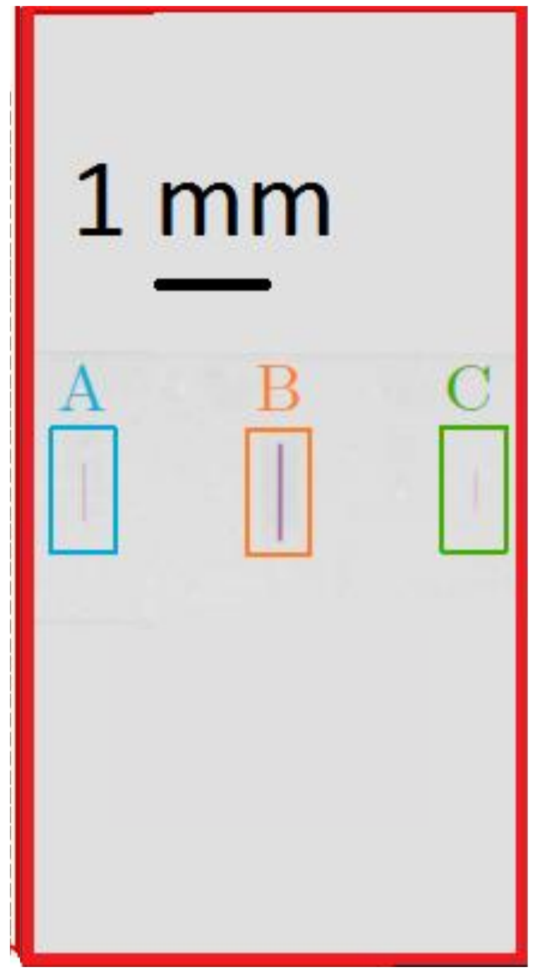
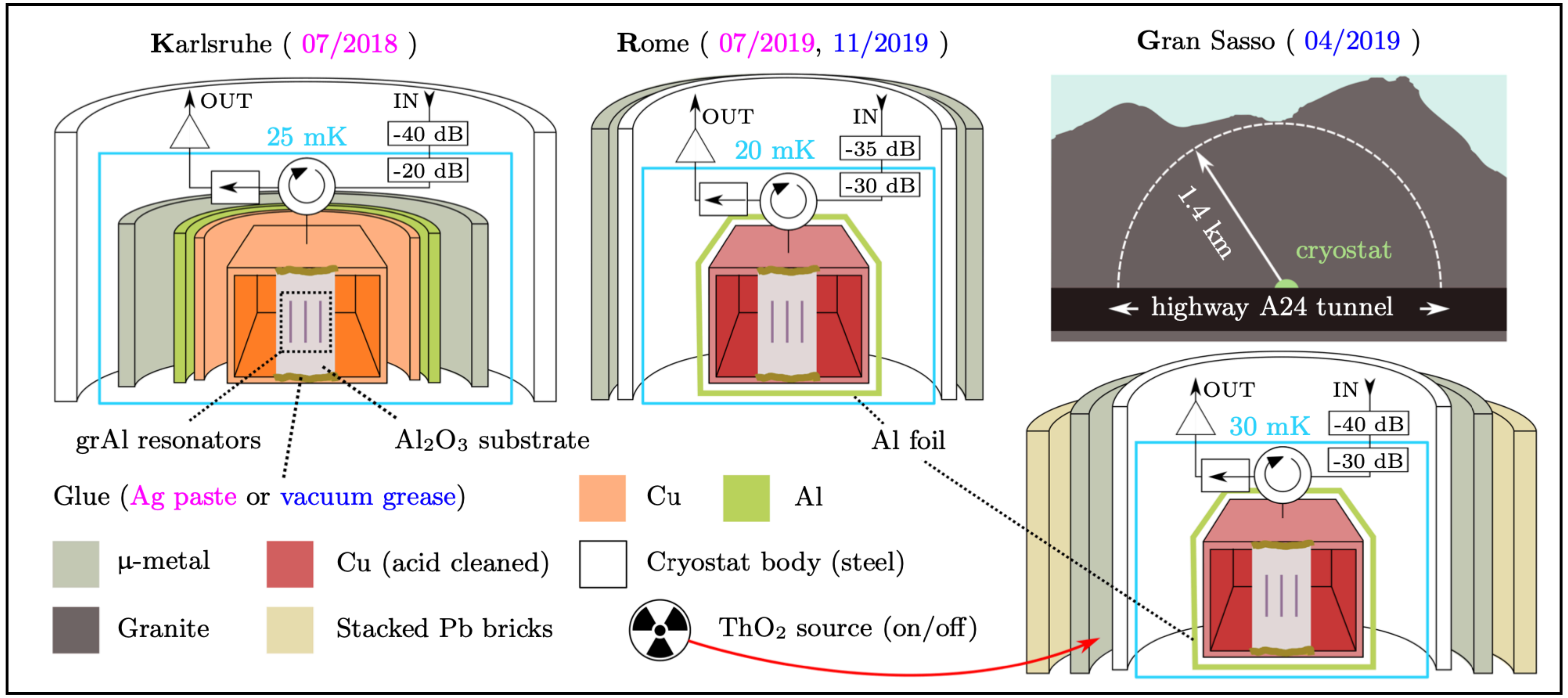
A solution

[Cardani et al, Nat. Comm. 2021]







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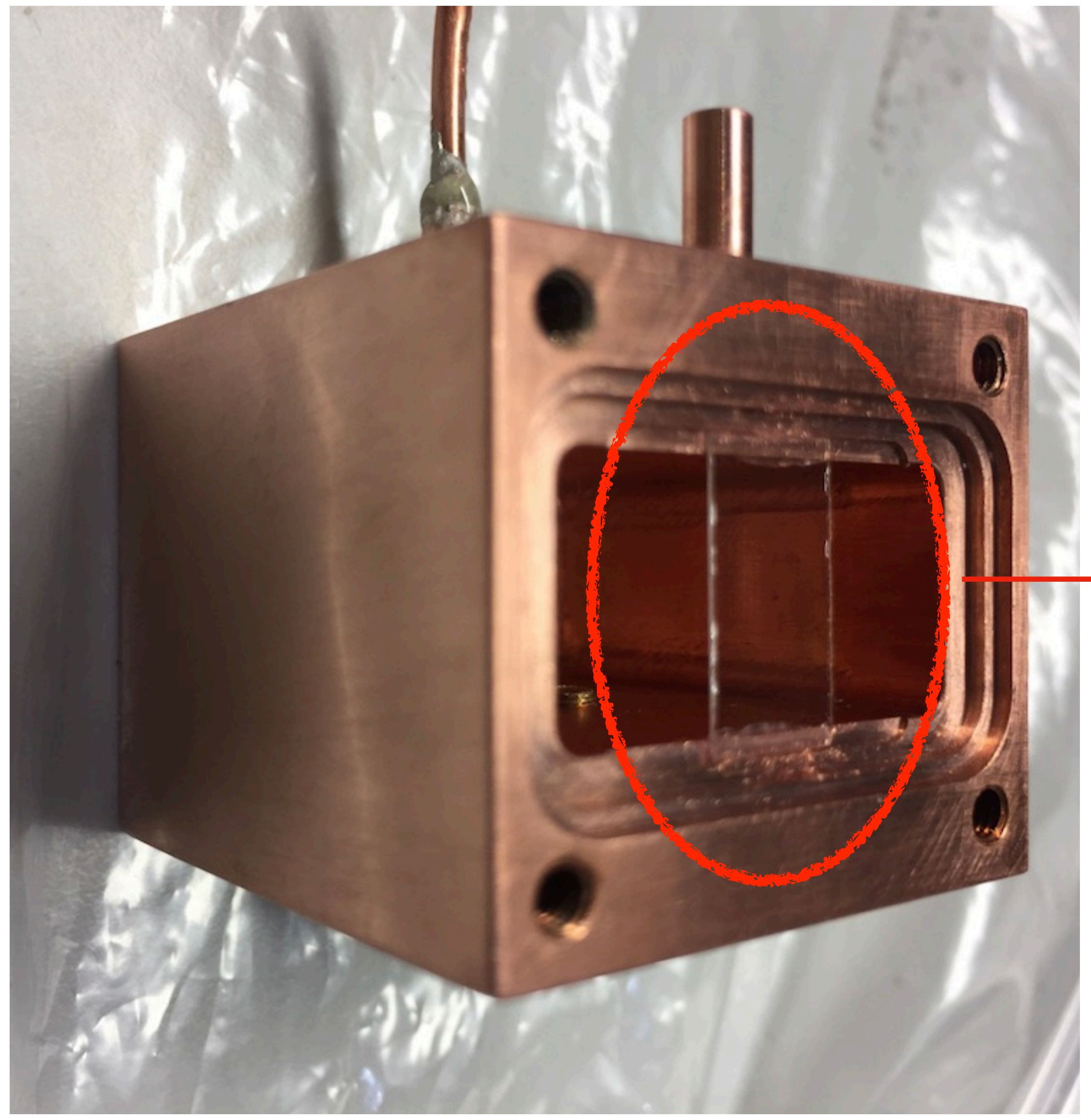

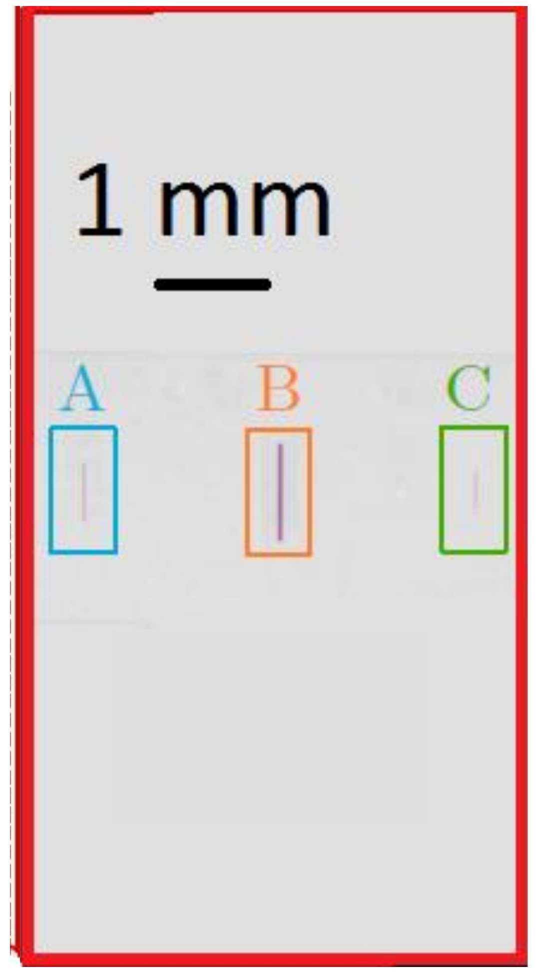

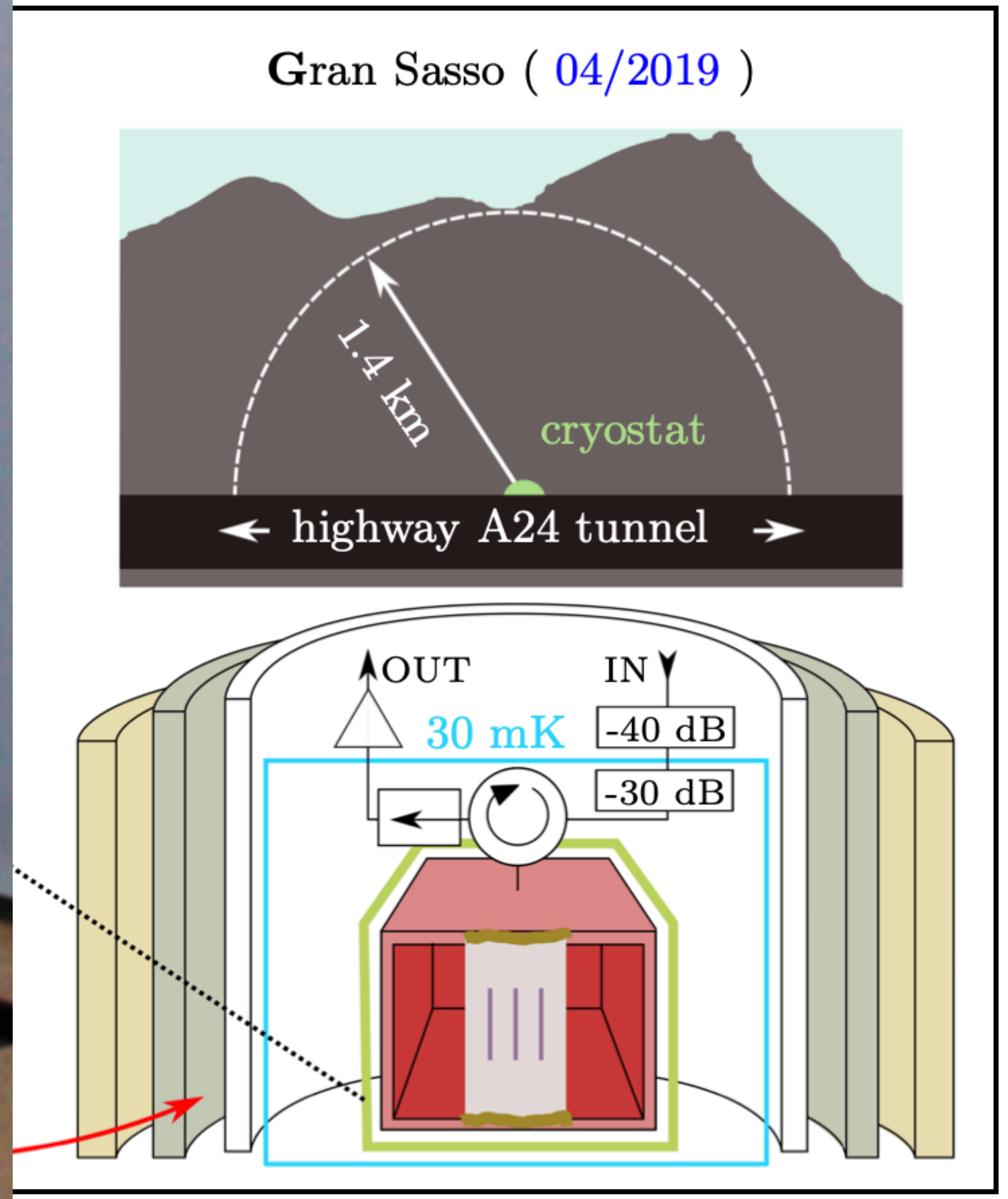

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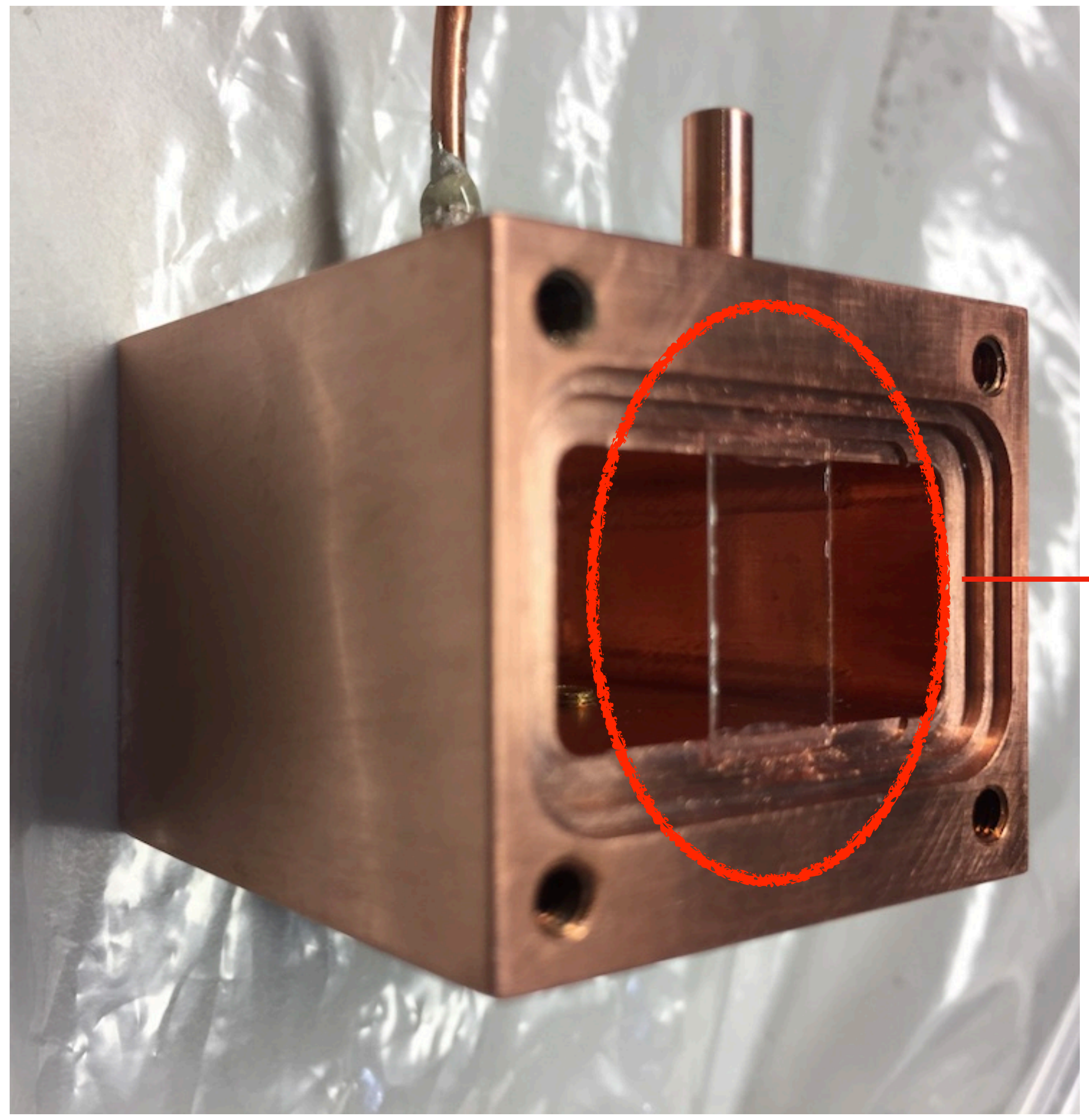
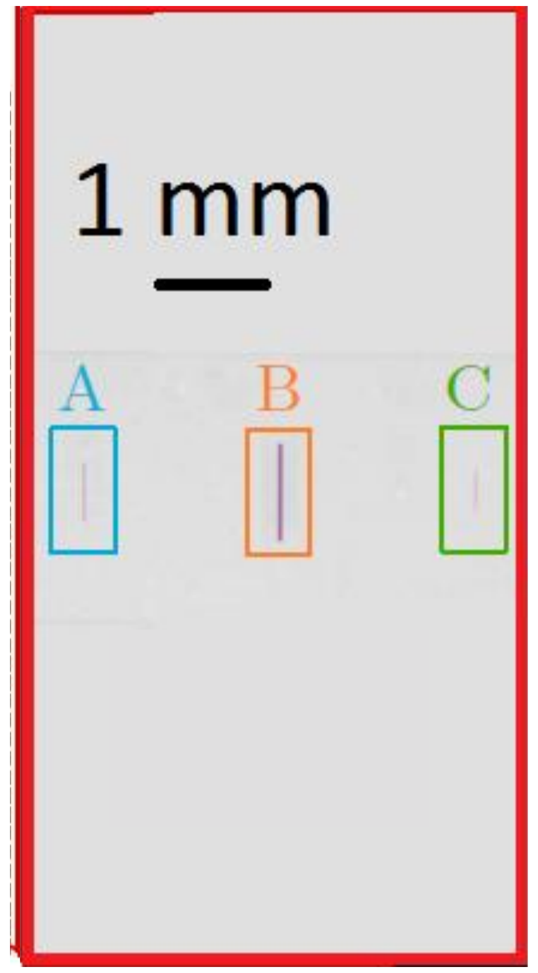
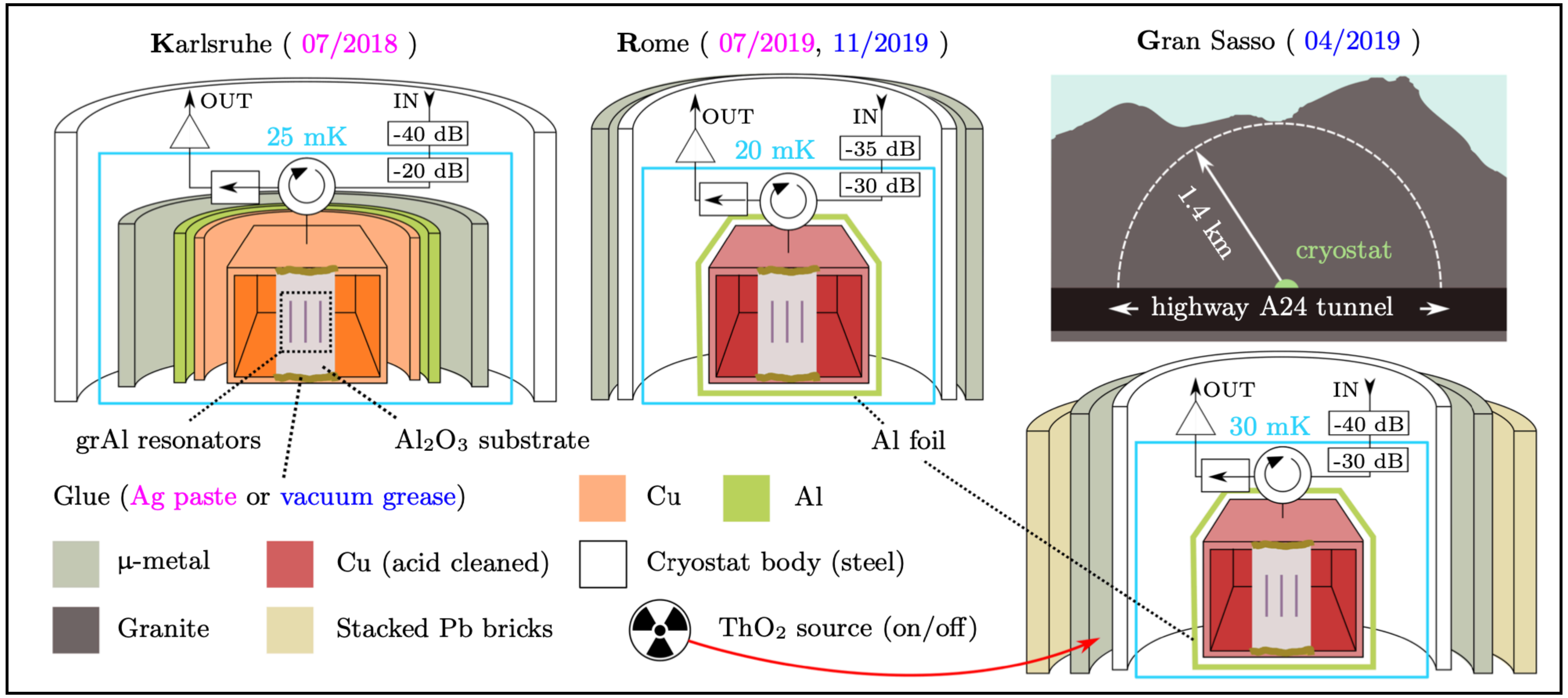






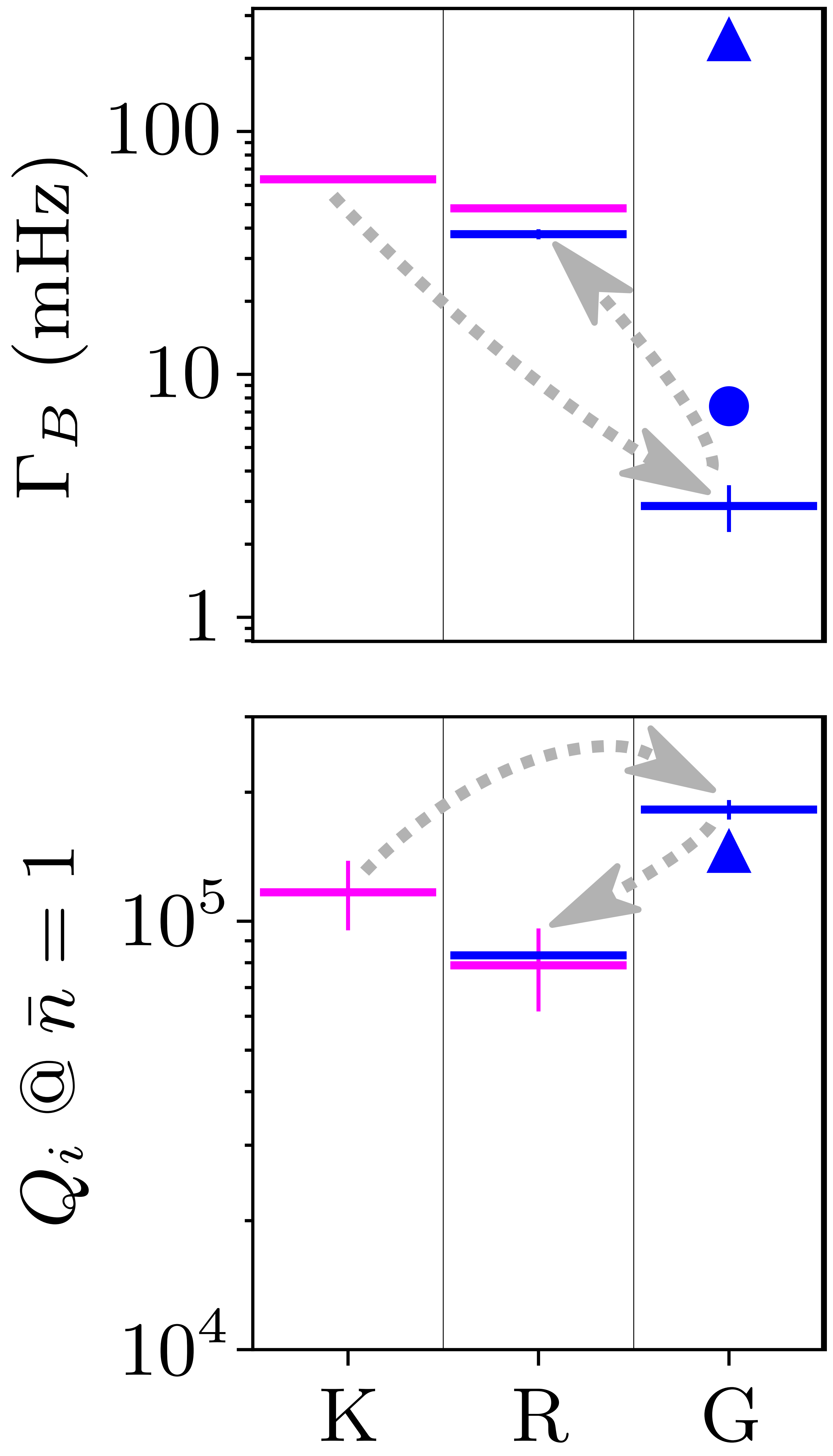
A solution

[Cardani et al, Nat. Comm. 2021]

Rate of impacts [= “errors”] reduced by ~30

Coherence can be improved by 2-4*

* if the loss is dominated by phonons, this is not the case for all superconducting qubits



Perspectives

Improving qubit performances relies on two complementary strategies:

- Decrease radioactivity
- Mitigate its effect through “phonon traps” or novel chip design [Gold2020, Martinis2020, Karatsu2019, Henriques2019, Nsanzineza2014, Wang2014]

Coupling Experiment and Simulation to Model
Non-Equilibrium Quasiparticle Dynamics in Superconductors

A. Agrawal[9], D. Bowring[*1], R. Bunker[2], L. Cardani[3], G. Carosi[4], C.L. Chang[15], M. Cecchin[1], A. Chou[1], G. D’Imperio[3], A. Dixit[9], J.L DuBois[4], L. Faoro[16,7], S. Golwala[6], J. Hall[13,14], S. Hertel[12], Y. Hochberg[11], L. Ioffe[5], R. Khatiwada[1], E. Kramer[11], N. Kurinsky[1], B. Lehmann[10], B. Loer[2], V. Lordi[4], R. McDermott[7], J.L. Orrell[2], M. Pyle[17], K. G. Ray[4], Y. J. Rosen[4], A. Sonnenschein[1], A. Suzuki[8], C. Tomei[3], C. Wilen[7], and N. Woollett[4]

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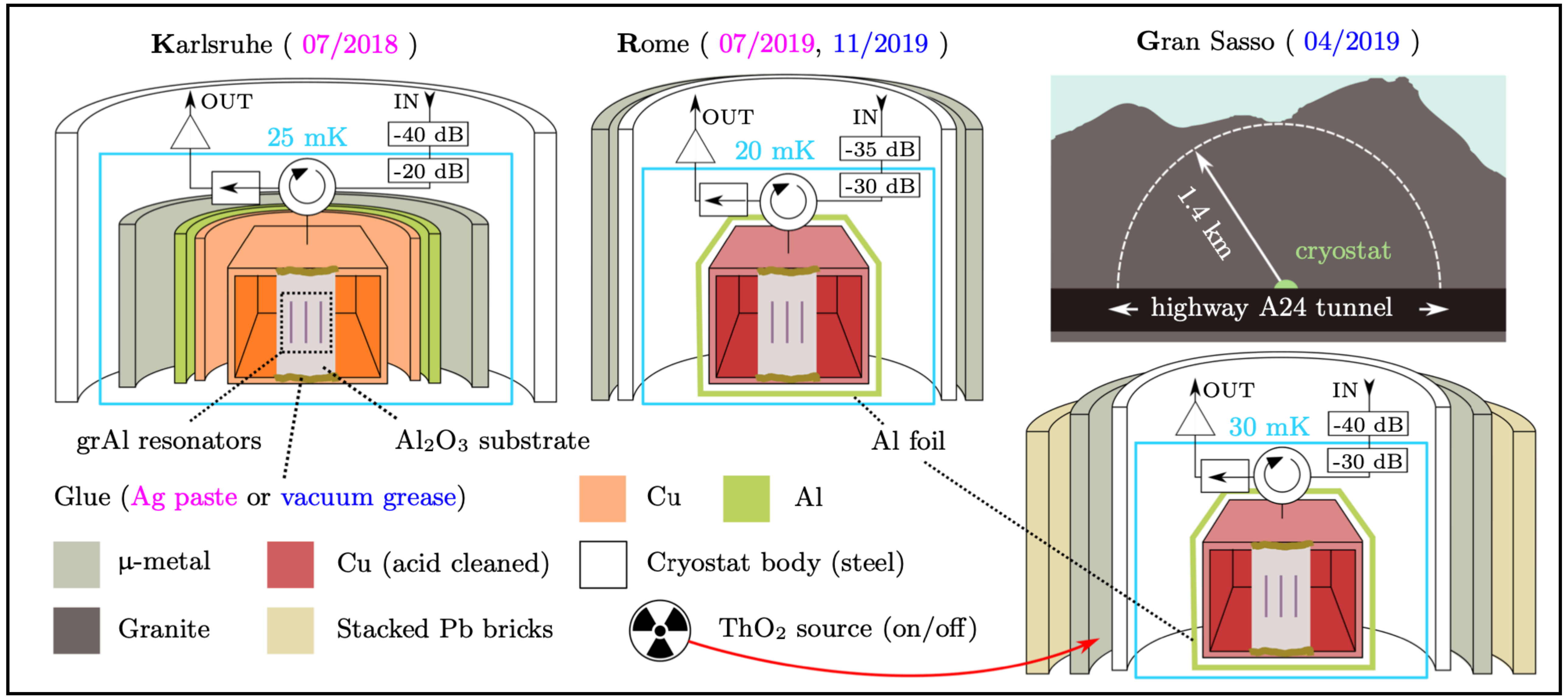
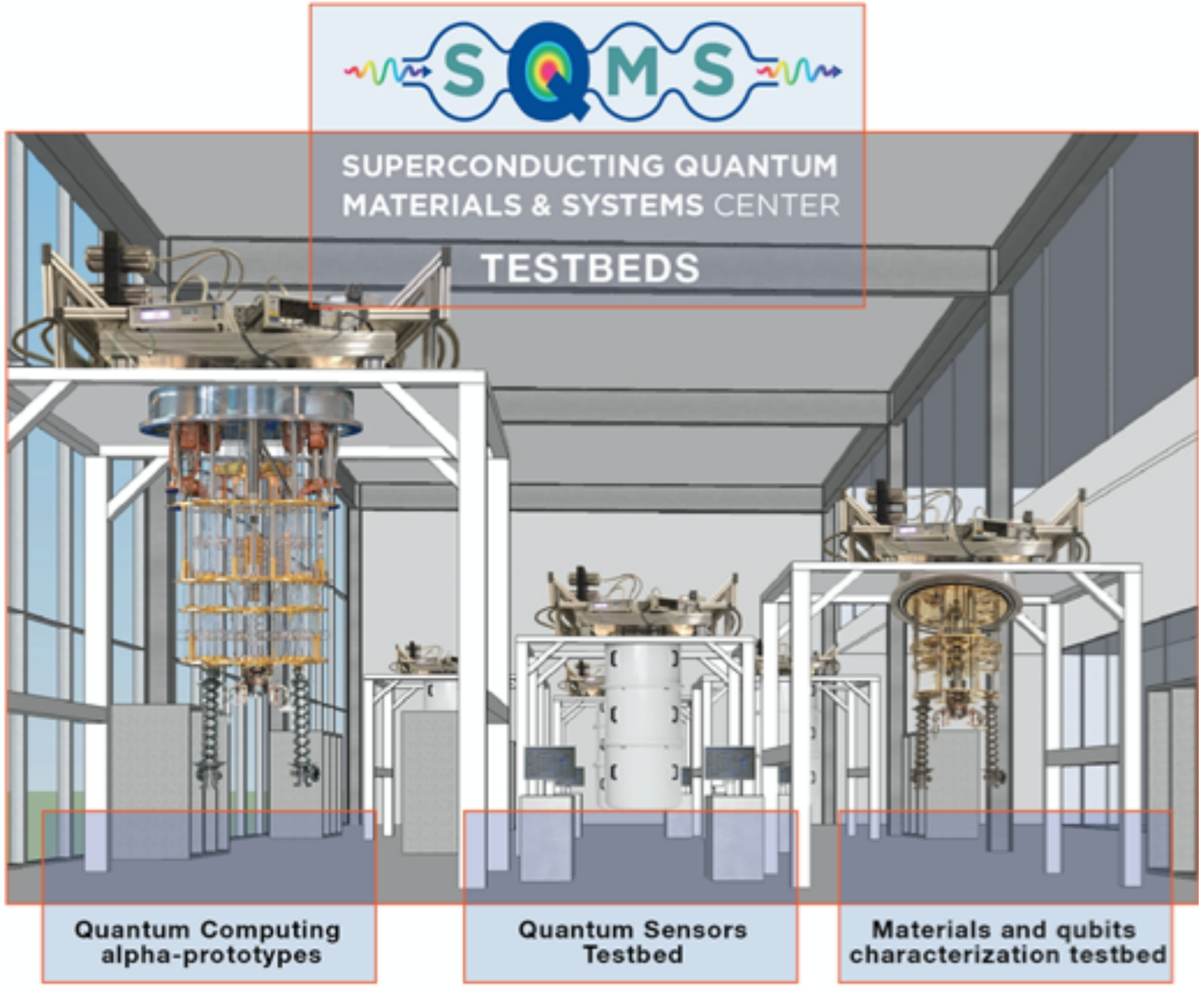
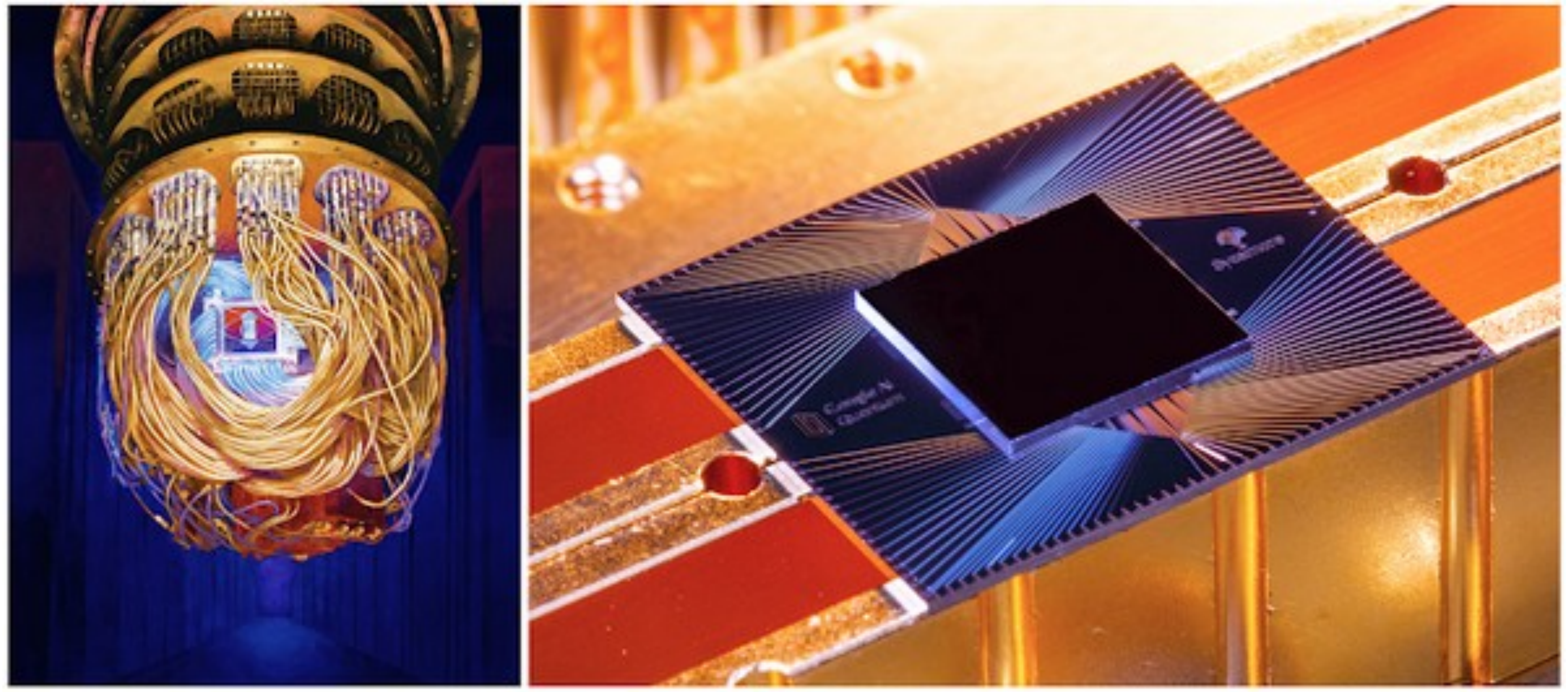


Requirements to “enter the game”

- Underground fridge with 10 mK
- High live-time in stable conditions (~weeks)
- Radiopurity (clean materials, lead shield, …)
- Then, depends on application:
    - For large project, super-custom facilities

Two examples of “large” scale projects





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  - For small projects:
  - few RF channels
  - reasonable RF equipment (~60 keuro: circulators, insulators, attenuators, HEMT, …)
  - room-temperature electronics (~50-100 keuro)

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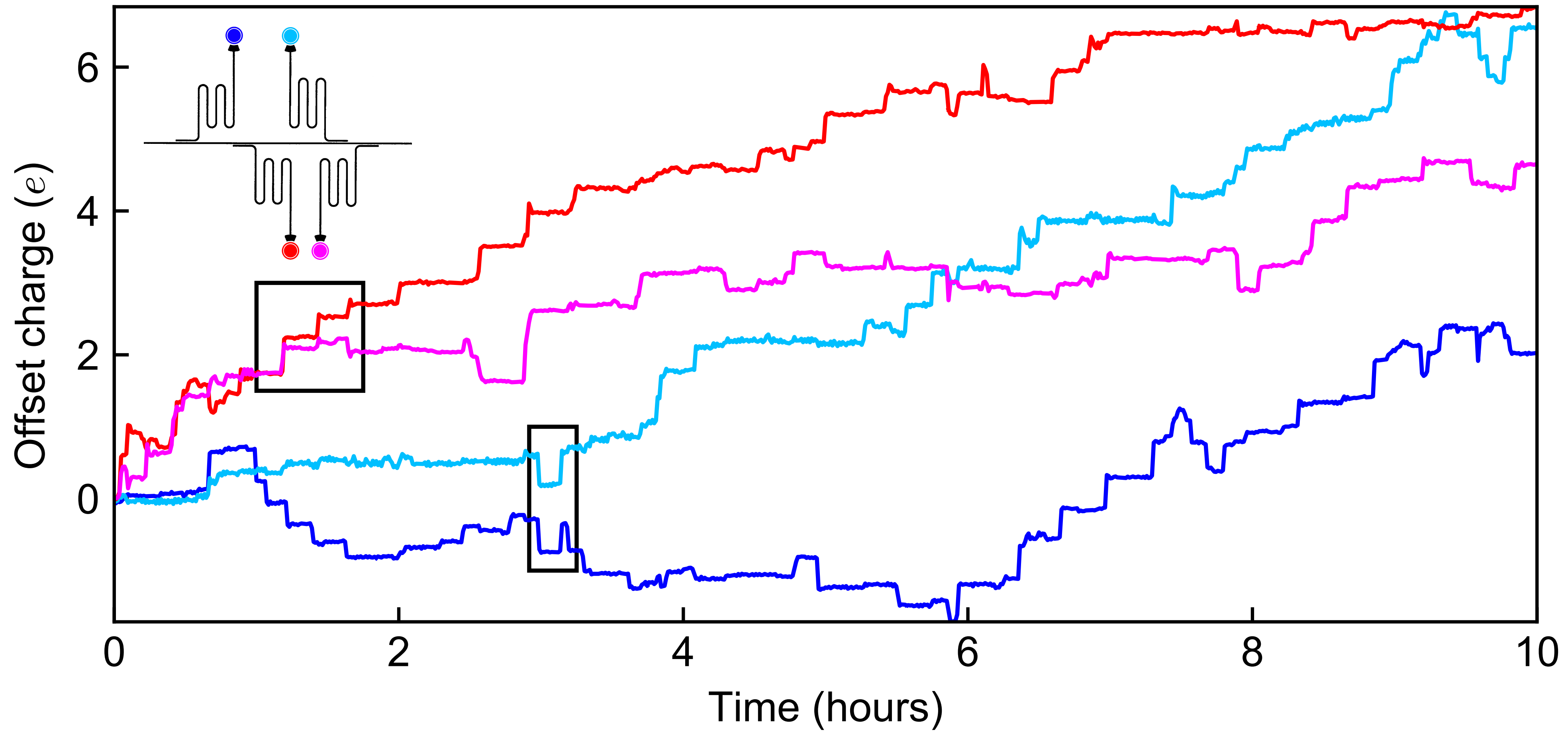

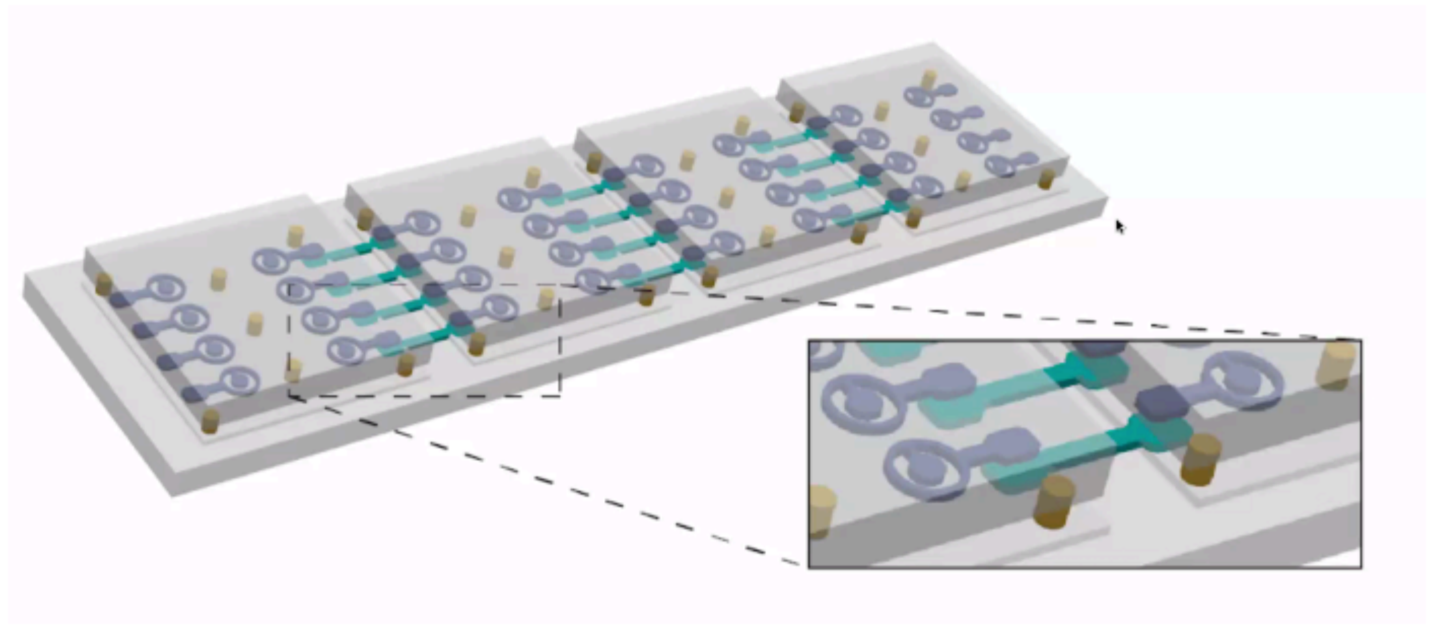

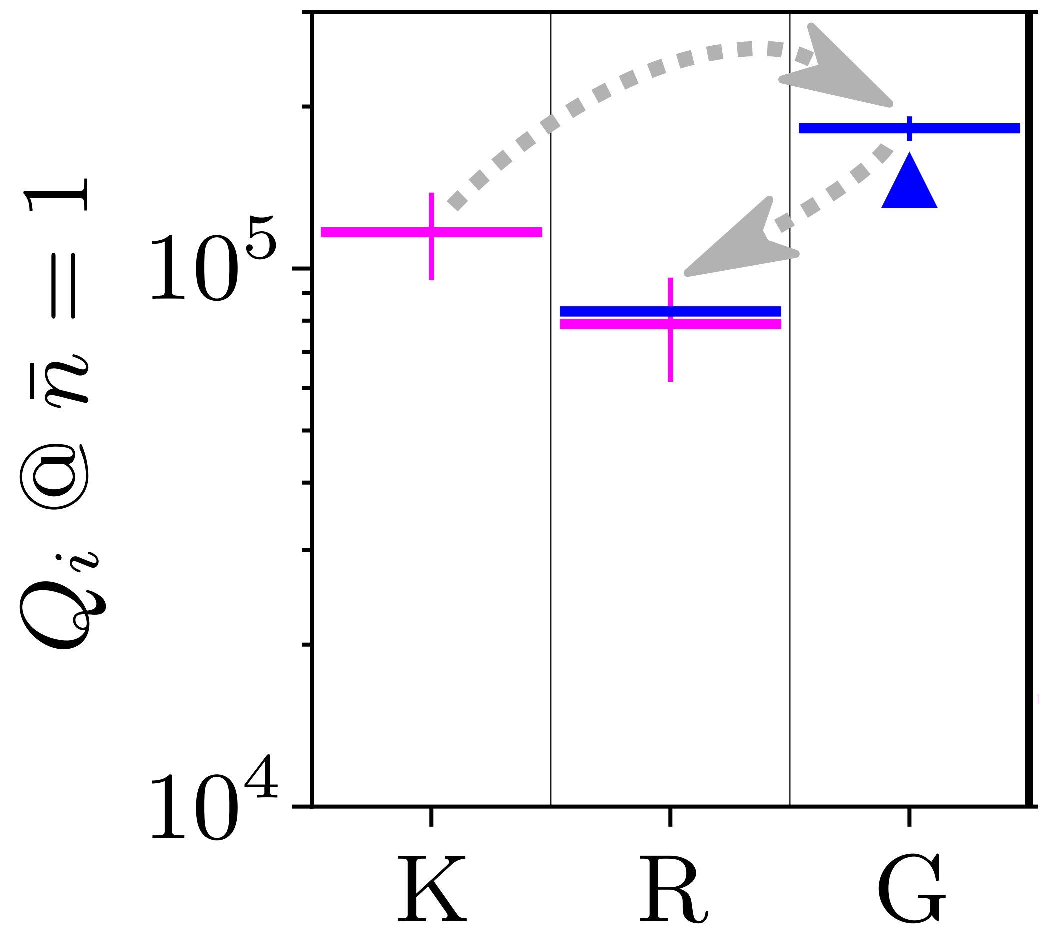

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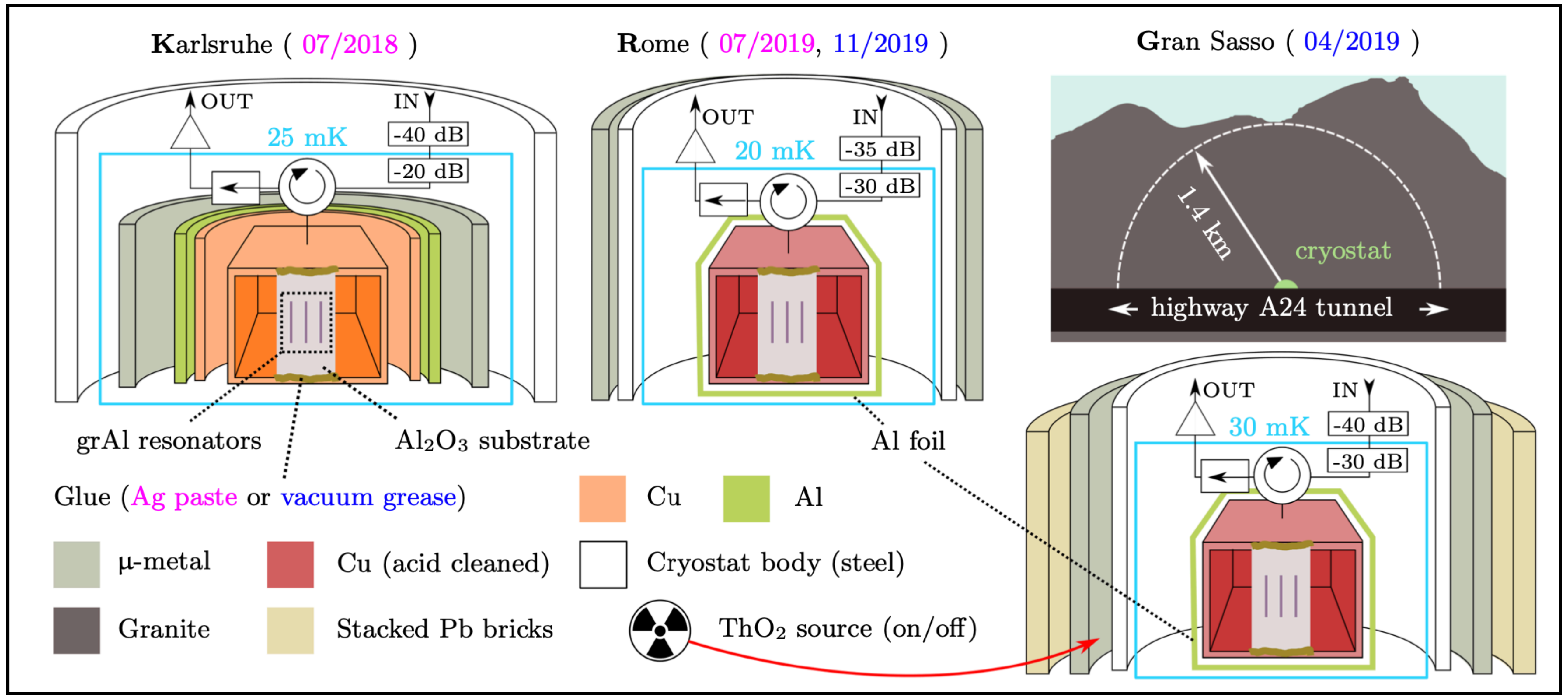
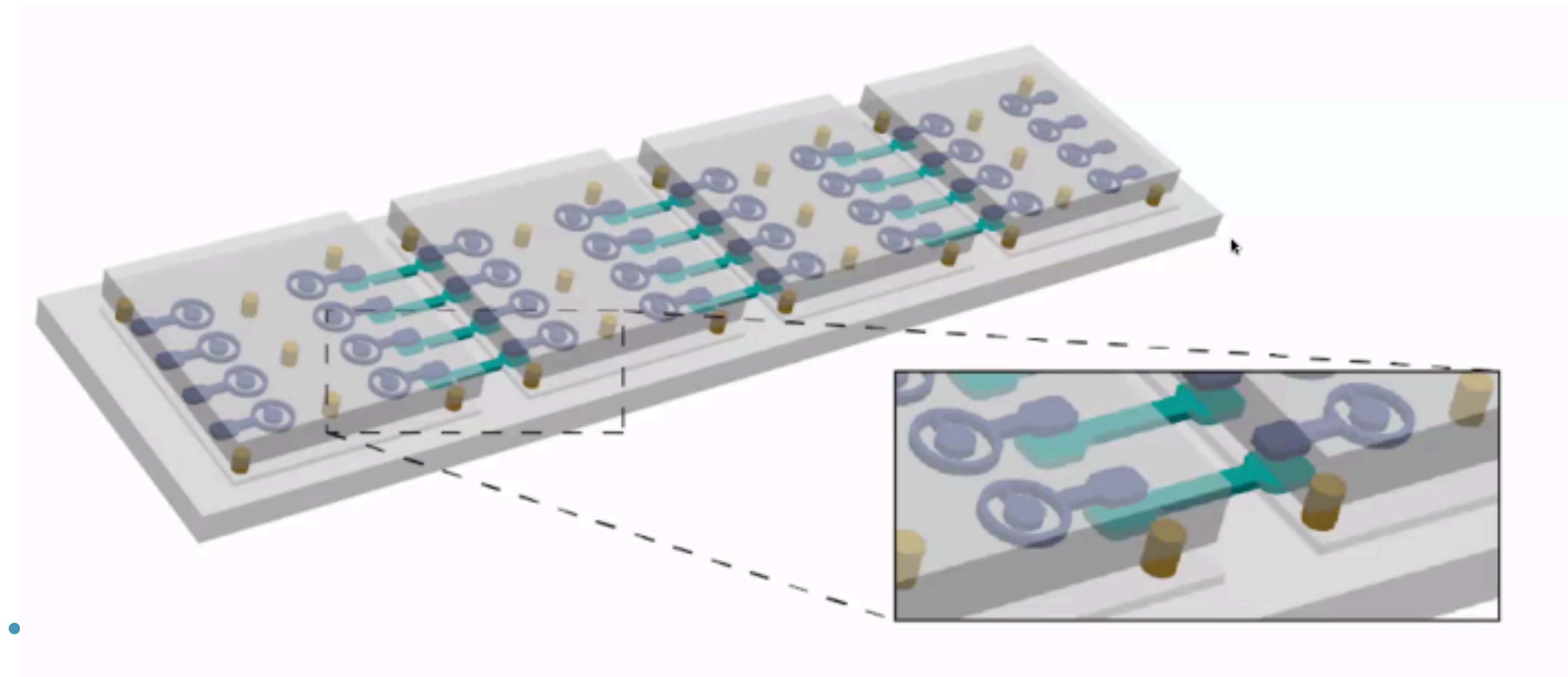


Europe

[LNGS - Italy]

- Pioneered this field. Now: upgrade of the readout of the test cryostat [S. Pirro, M. Junker scientific and technical coordinators]
- Test of flux qubit scheduled in Sep 2021
- Tests of Rigetti prototype planned for late 2021 - early 2022 within the SQMS center

SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER



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[LNGS - Italy]

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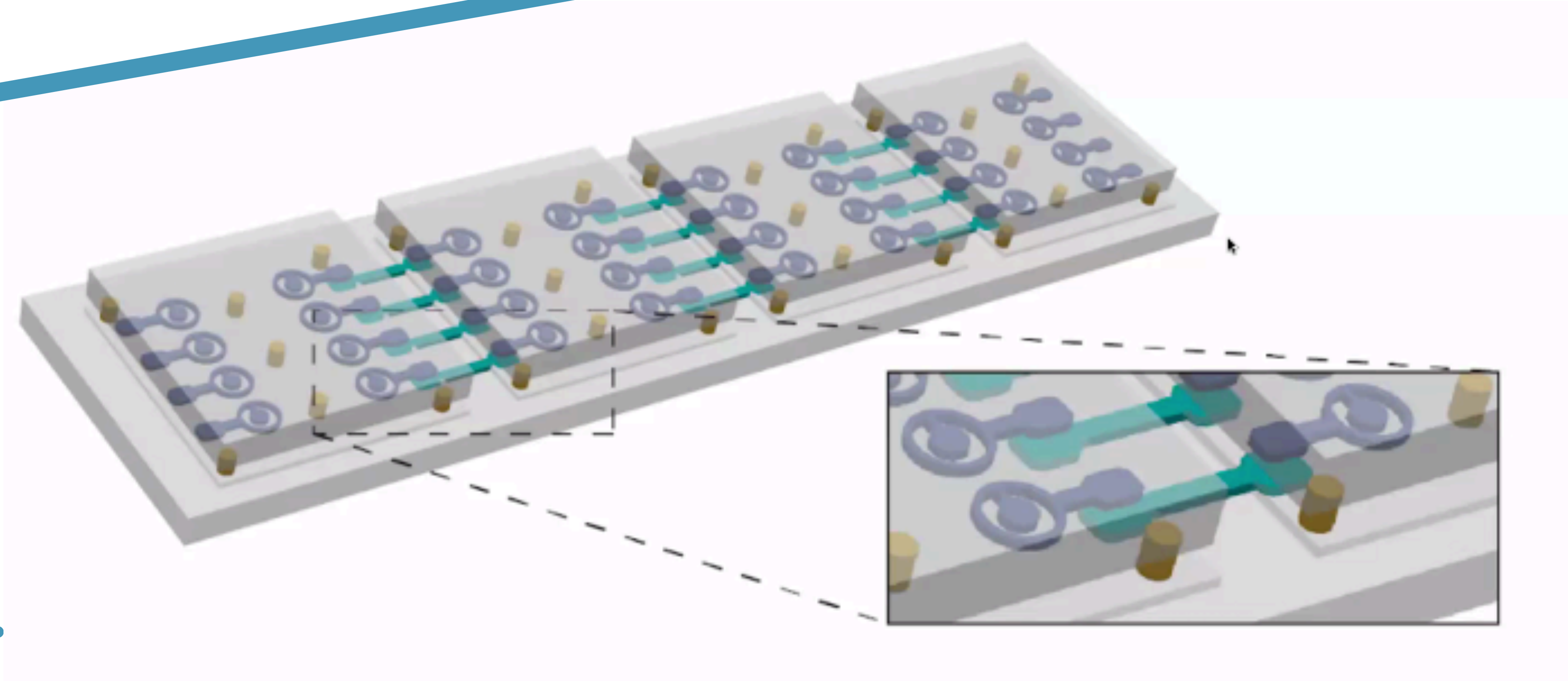
- 20… Pirro,
- T…
- Te… early 20…

Collaboration with the **SQMS quantum center**

Procurement of a larger fridge ongoing to test SQMS final prototypes in radio-pure environment

SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER



Europe

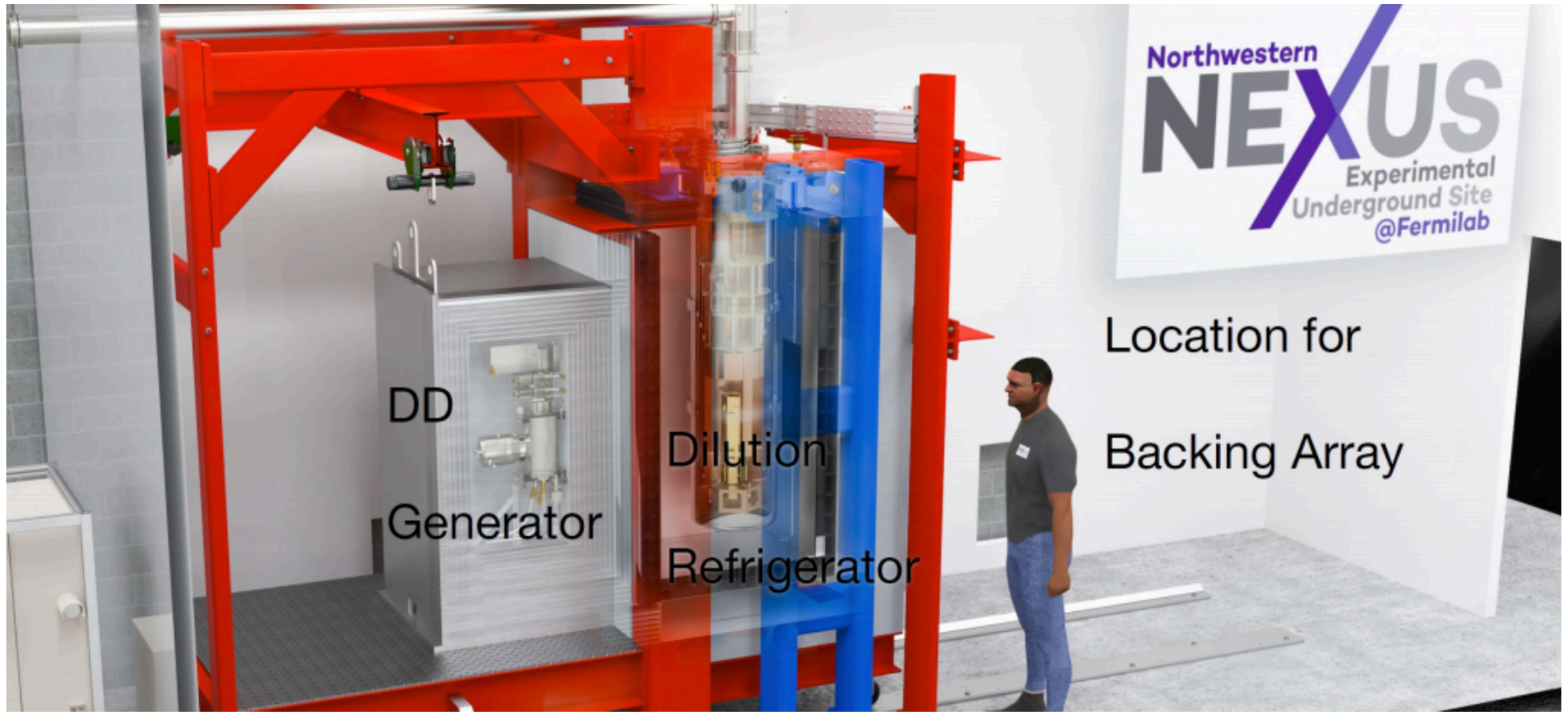
[LSC - Spain]

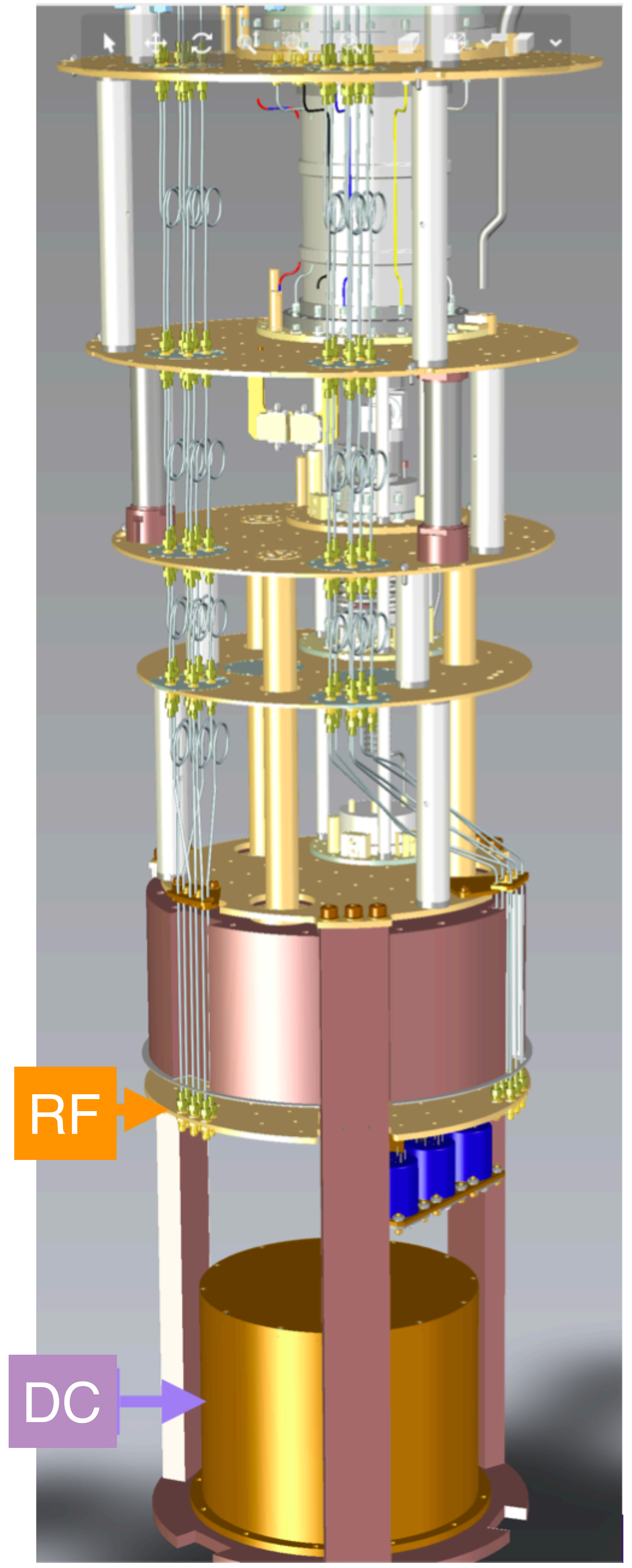
- Plan to install a qubit-compatible cryogenic measurement station at Canfranc
- Asked for: 3x3 m2 station to install a fridge with 10 mK base temperature, with Radon-free system, underground clean room
- Other advantages of LSC: radiopurity service (material screening) and electroforming service
- Proposal submitted to Spanish “Plan National” (fall 2020) and will be submitted to QuantERA calls (may 2021)

US

[NEXUS - Fermilab]

- Underground (300 mwe), class 10,000 clean-room, lead shield
- 10 RF + 8 DC SQUIDs + many 4-wire ch + RF filtered fibers
- Plan to scale up number of channels





US

[ORLN quantum science center]

- ORLN quantum science center will install a second cryostat (QUIET) to test quantum sensors and qubits that might be useful for low-mass dark matter searches

- Test of how qubits improve underground (with focus on background for dark matter searches)

Searching for Dark Matter with a Superconducting Qubit

Akash V. Dixit, Srivatsan Chakram, Kevin He, Ankur Agrawal, Ravi K. Naik, David I. Schuster, and Aaron Chou
Phys. Rev. Lett. **126**, 141302 – Published 8 April 2021

Conclusions

- Radioactivity was recently discovered as a major problems for superconducting qubits
- Underground laboratories would not be the “ideal” choice for qubits companies
- Until other mitigation strategies are envisioned (traps, novel circuits designs) they might be the most comfortable site
- Underground labs are moving in this direction (in Europe + NEXUS)
- Unique opportunity to cross-pollinate our fields of particle detector and qubits

Thanks for the attention

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WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

Fermilab

Google

Lawrence Livermore National Laboratory

JÜLICH
FORSCHUNGSZENTRUM

Stanford University

Thanks to many people for plots and discussion