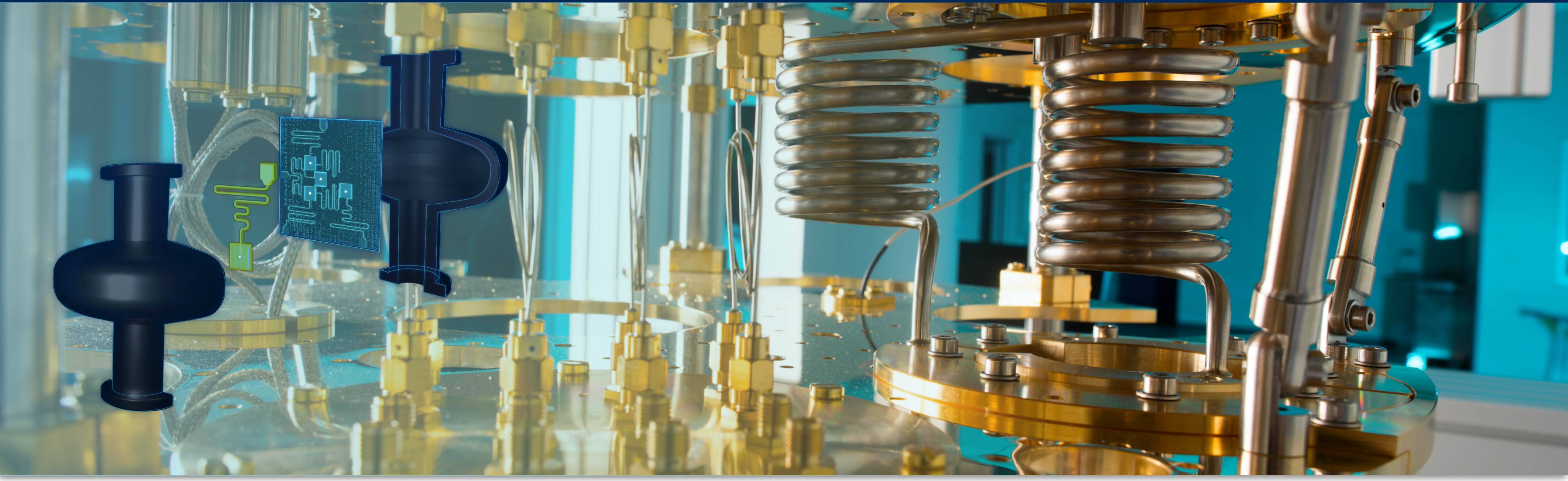


Muon tagging using Kinetic Inductance Detectors

A. Mariani, M. Bal, L. Cardani, N. Casali, I. Colantoni, A. Cruciani, F. De Dominicis, D. L. Helis, A. Grassellino, V. Pettinacci, S. Pirro, T. Roy, D. Van Zanten, M. Vignati

Radiation Impact on Superconducting Qubits - RISQ 2024
May 30–31, 2024, Fermilab, Batavia, IL 60510

Ministry of Foreign Affairs and International Cooperation

Istituto Nazionale di Fisica Nucleare

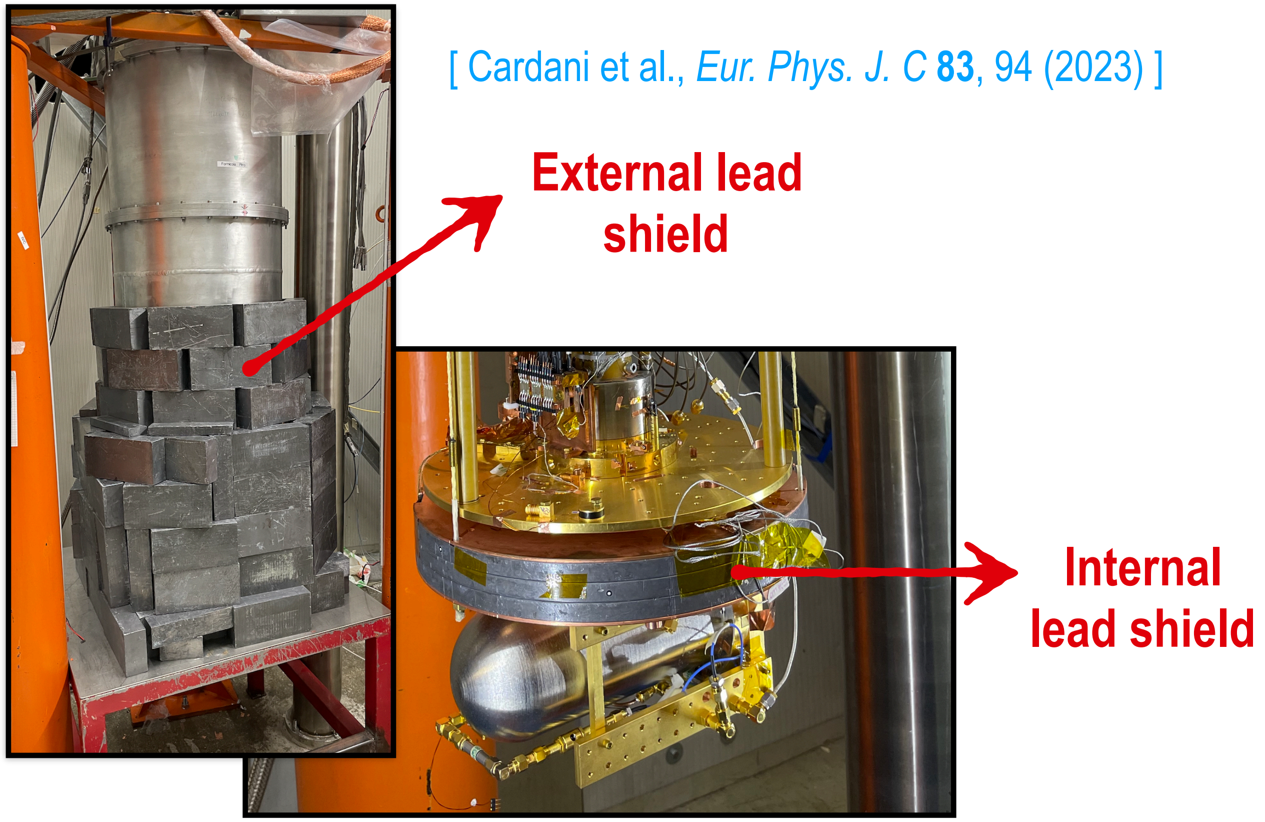
INTRODUCTION

Major sources of ionizing radiation in a typical qubit chip (~1 cm²)

Source	Rate of impacts [mHz]
Environmental gammas	~20-30
Muons	~10

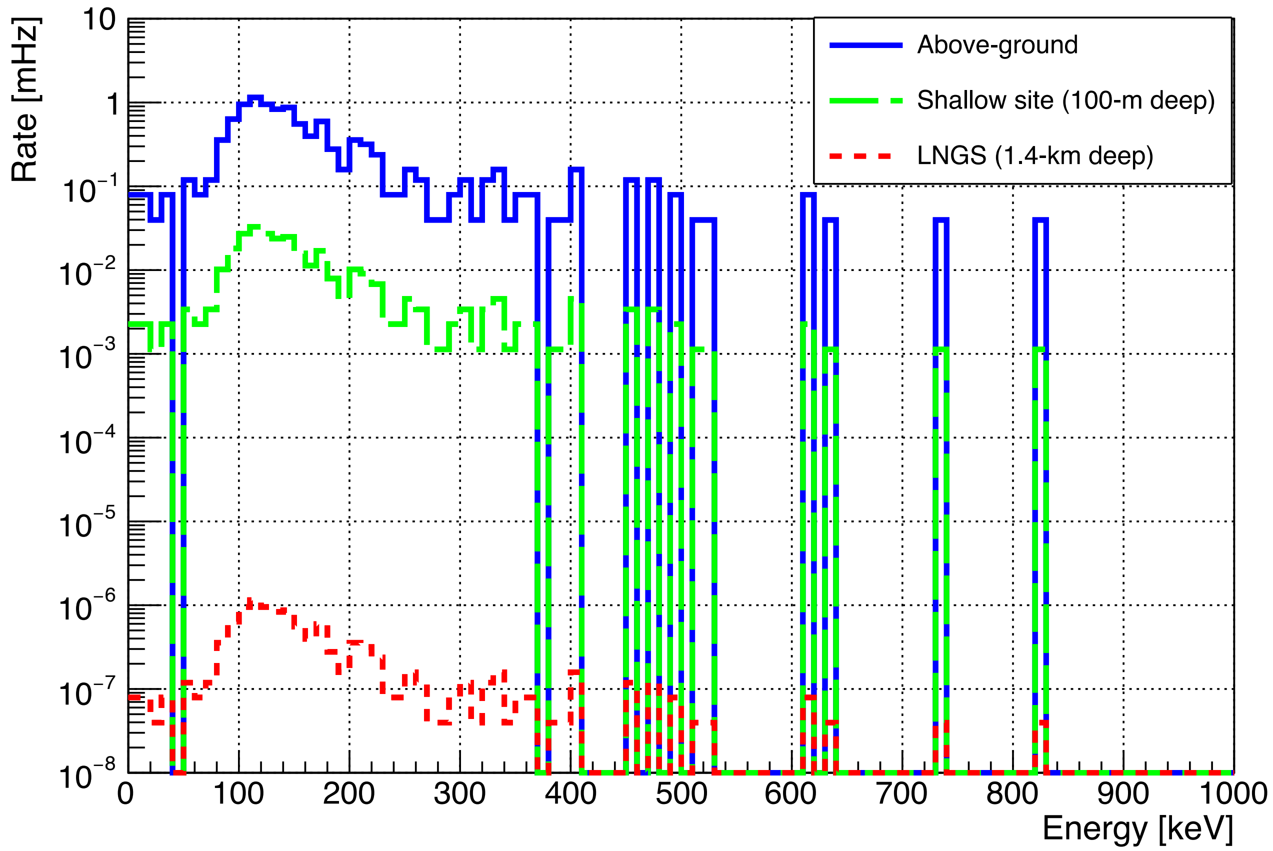
CURRENT MITIGATION STRATEGIES:

- **Copper and/or lead shields** to reduce **environmental gammas;**
- **Deep-underground laboratories** to drastically reduce **muons.**



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

Energy distribution of muons interacting in the chip in different location



[Mariani et al., *2023 IEEE International Conference on Quantum Computing and Engineering* (2023)]

THE IDEA

WHAT:

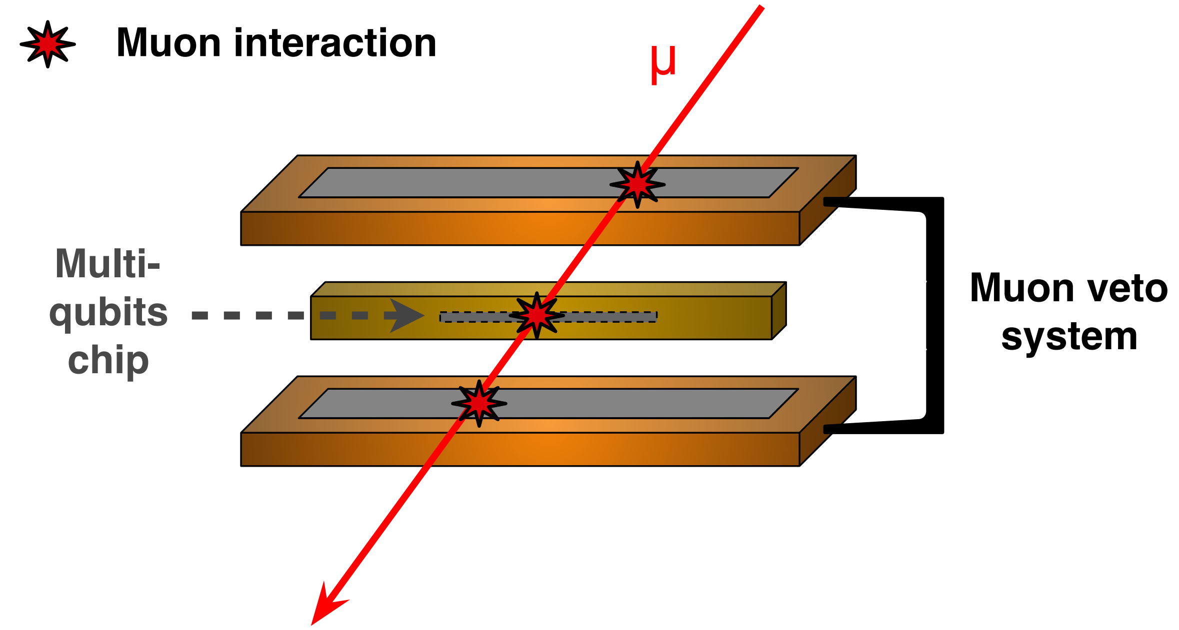
Develop a new class of quantum processors equipped with a **muon veto**.

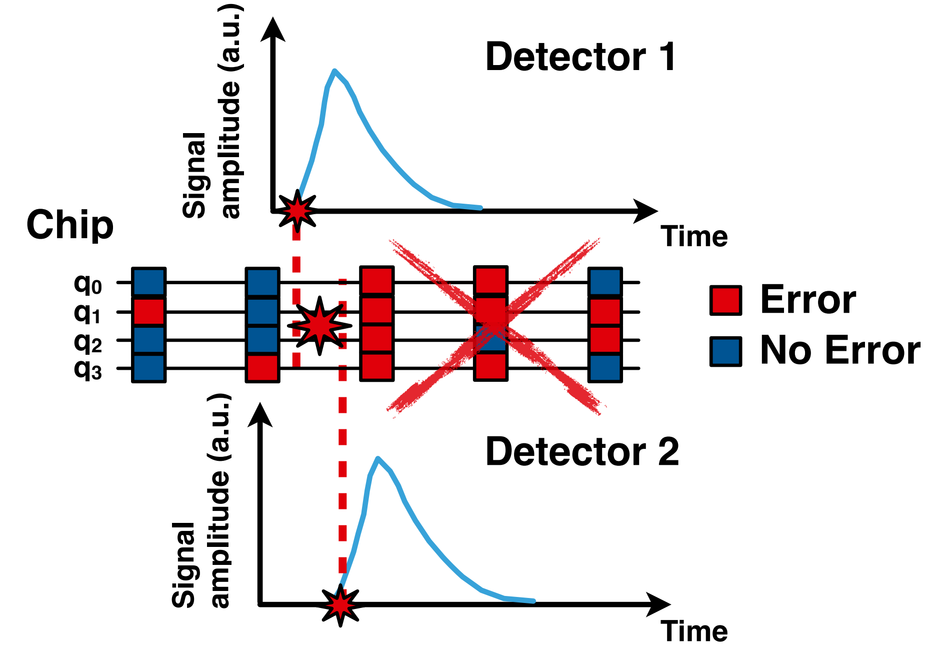
WHY:

Protect superconducting-based quantum computers from the detrimental effects of **atmospheric muons**.

HOW:

Tagging muons to identify and reject (or correct) operations performed following a muon interaction within the chip.





ADVANTAGE:

Enables quantum processors above-ground operation.

THE MUON VETO DETECTOR - REQUIREMENTS

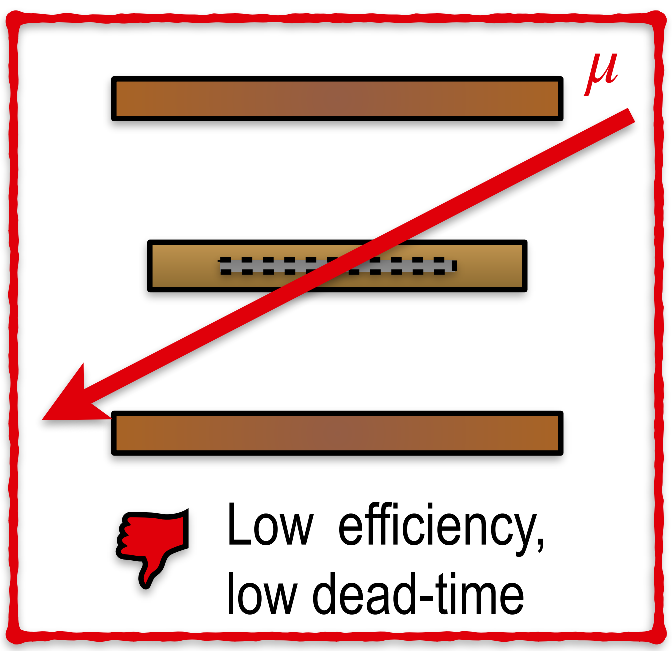
1) High (geometrical) efficiency:

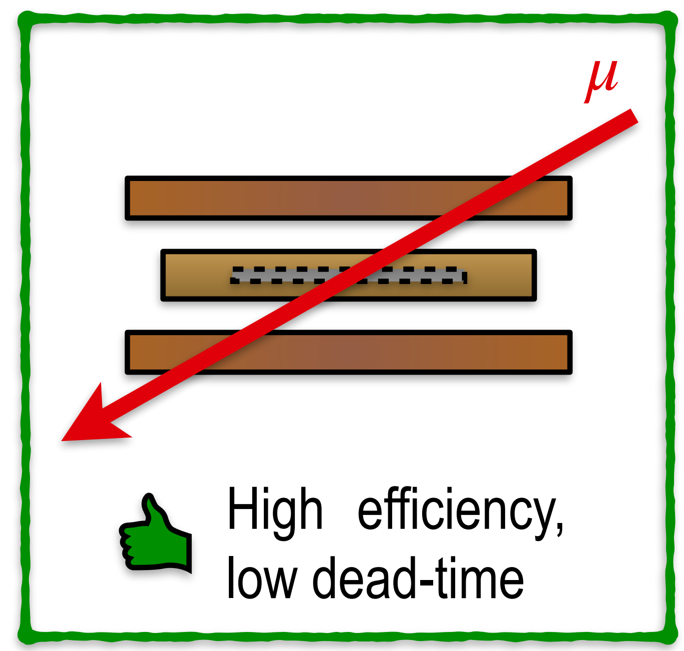
≥ 90%

2) Low dead-time:

< 1%

Sufficiently wide surface area to ensure high geometrical efficiency, but not so wide as to increase the interaction rate considerably (and consequently, dead-time).





The muon veto detector must be as close as possible to the chip.
It must work at the operation temperature of qubits (tens of mK).

OUR PROJECTS

"Saving quantum computers from cosmic rays"

- Bi-lateral collaboration **IT - INFN** and **US - SQMS Center, Fermilab**
- Funded by **MAECI (Ministry of Foreign Affairs and International Cooperation of Italy);**
- Budget: **~250 k€;**
- **Three-year** duration (2023-2025).

Ministry of Foreign Affairs and International Cooperation

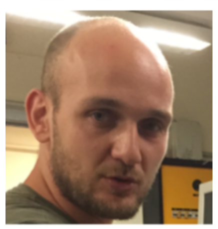
ACE-SuperQ (Abatement of Correlated Errors in Superconducting Qubits)

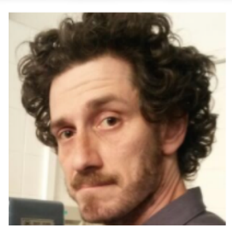
- **INFN - CSN5 Grant for Young Researchers;**
- Budget: **~150 k€;**
- **Two-year** duration (2024-2026).

People involved:


L. Cardani


N. Casali


I. Colantoni (CNR)

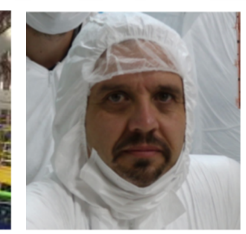

A. Cruciani


F. De Dominicis (GSSI)


D. L. Helis (LNGS)


A. Mariani


V. Pettinacci


S. Pirro (LNGS)


M. Vignati (Sapienza)

INFN Istituto Nazionale di Fisica Nucleare


M. Bal


A. Grassellino


T. Roy


D. Van Zanten

Fermilab

SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

GOALS

1) Demonstrate the feasibility of a cryogenic muon veto for superconducting qubits

➡ Operation of the first prototype.

2) Gain a better understanding of ionizing radiation effects on superconducting qubits

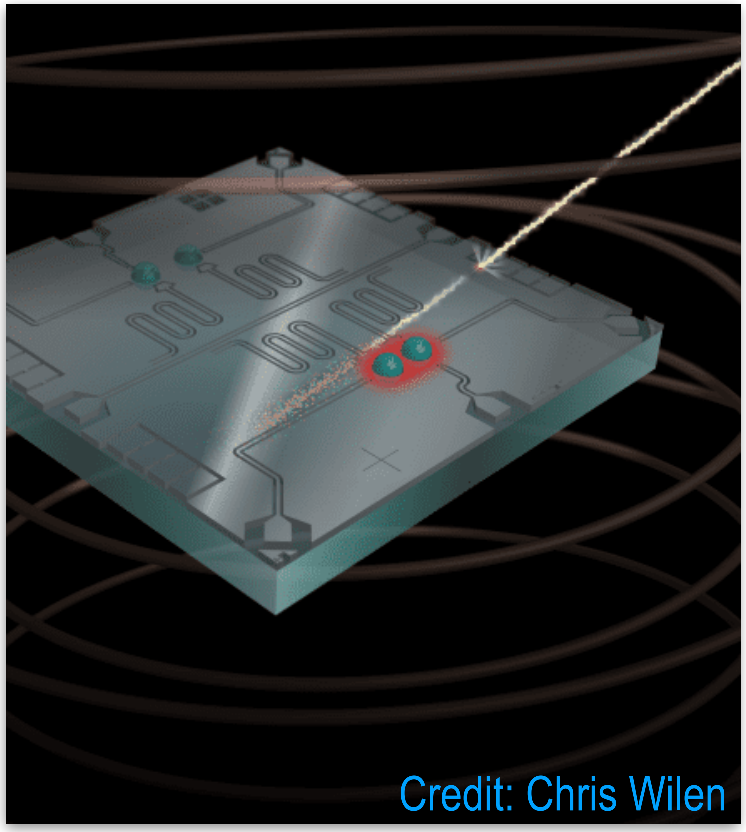
➡ Synergistic operation of muon veto and high performing superconducting multi-qubits chip with energy-relaxation times $T_1 \sim 100$ μs.

3) Improve superconducting quantum chip performances

➡ Correlated error rate reduction;

➡ Longer T_{1};

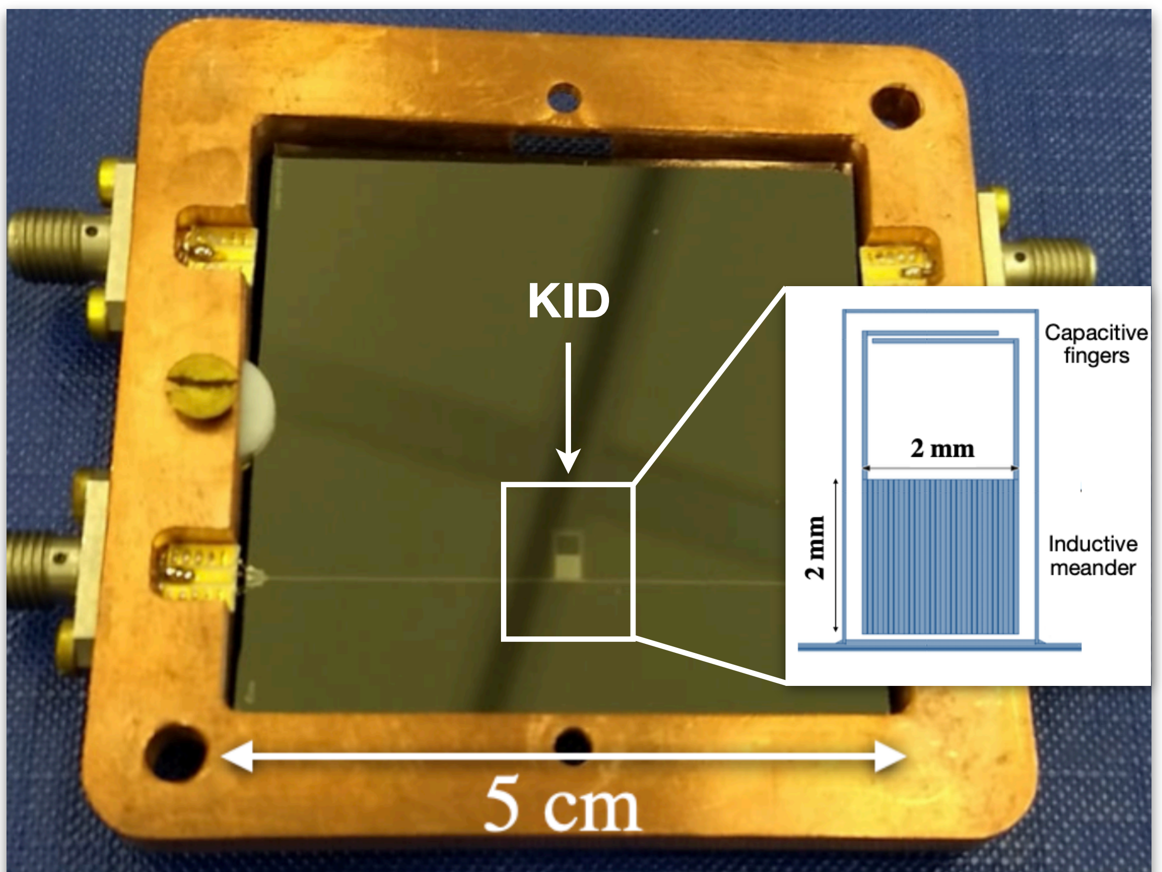
➡ Improved frequency stability.



THE MUON VETO DETECTOR - TECHNOLOGY

Ideal device already developed within the **CALDER** (Cryogenic wide Area Light detectors with Excellent Resolution) project (2014-2020).

CALDER PROTOTYPE



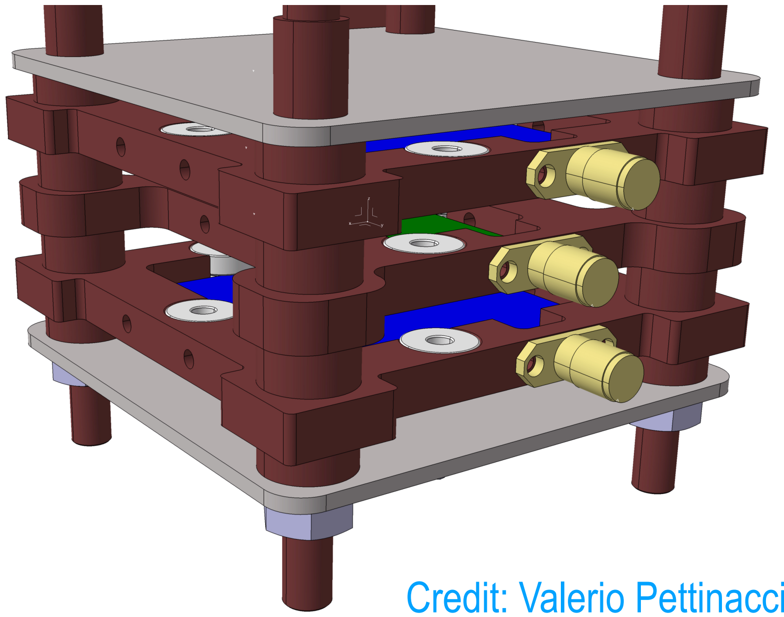
[N. Casali et al., *Eur. Phys. J. C* **81**, 636 (2021)]

- **Kinetic Inductance Detector (KID)** made of a three-layer aluminum-titanium-aluminum deposited on a 5x5 cm^2, 650-μm thick **silicon wafer**;
- **Signal rise-time:** 120 μs;
- **Energy threshold:** ~0.5 keV.

THE MUON VETO DETECTOR - TECHNOLOGY

Two CALDER-like prototypes will be used for the **muon veto system**:

- **Same KID** geometry on a **4.5x4.5 cm² , 650-μm thick silicon substrate**.

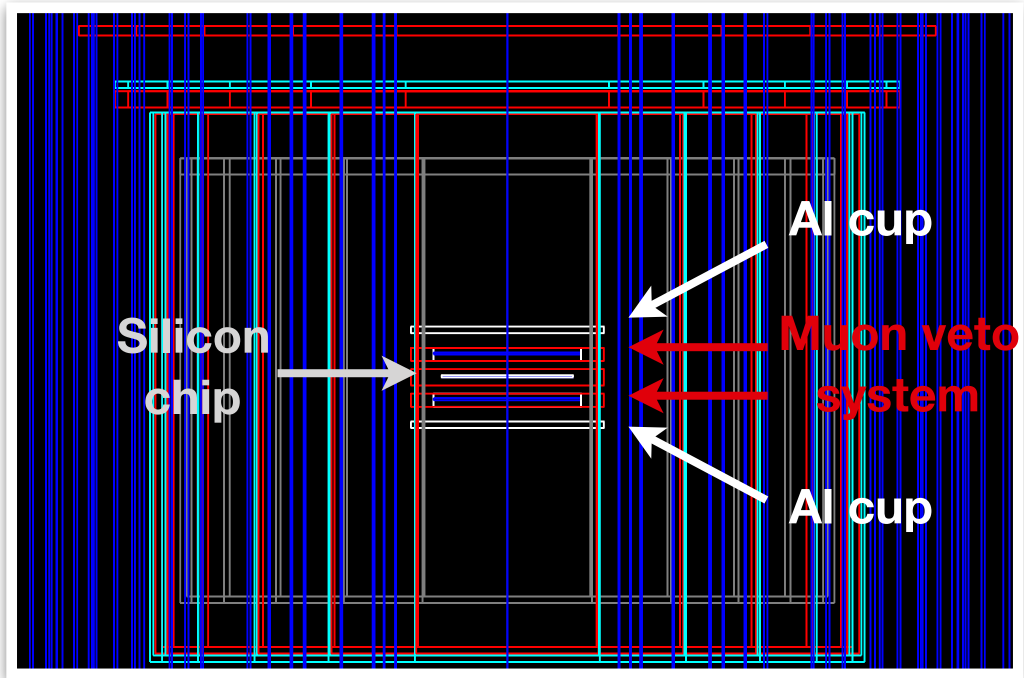


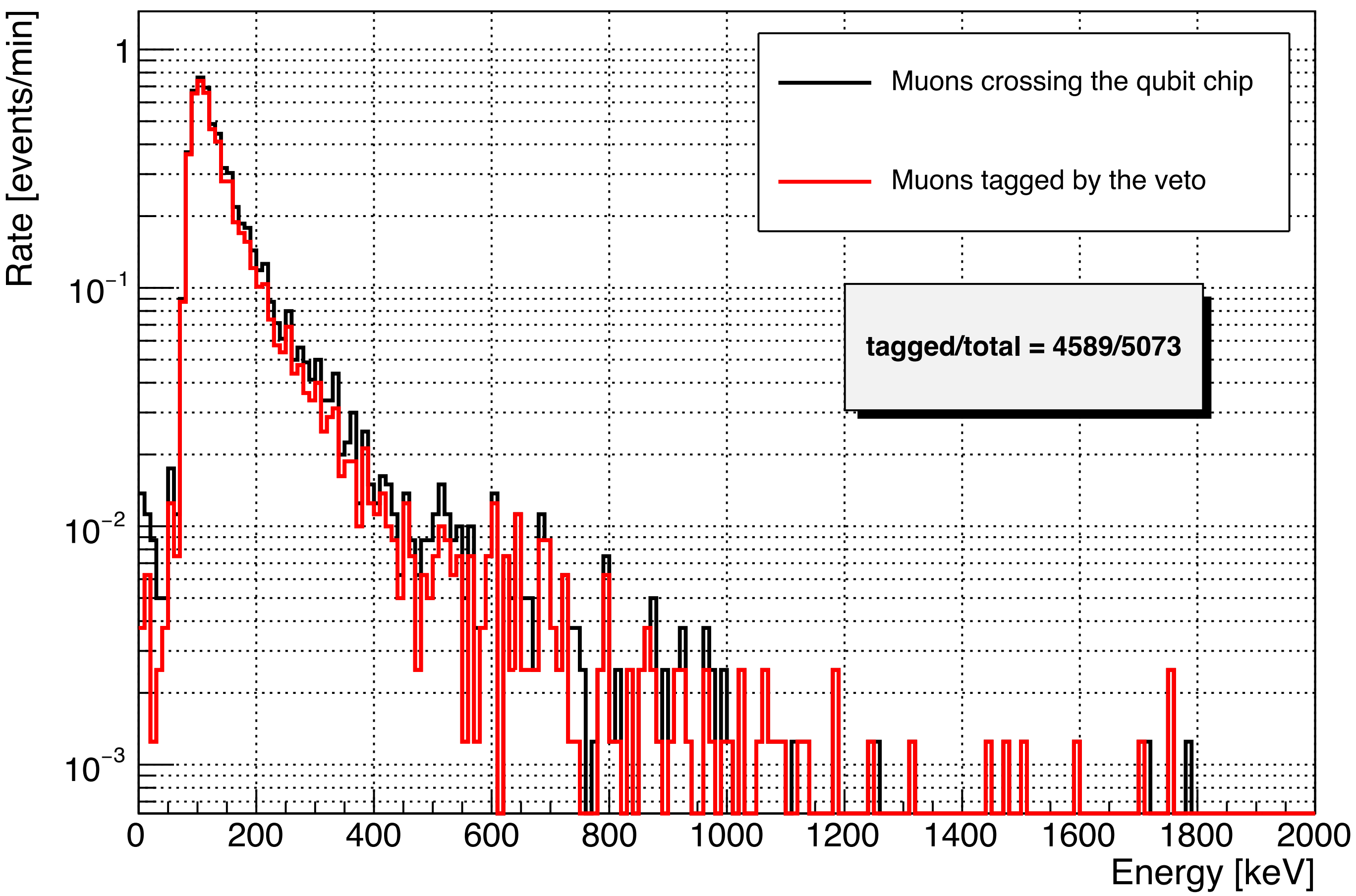
Credit: Valerio Pettinacci

ADVANTAGE	WHY?
Compatible with cryogenic temperatures	Fits close to the chip, reduces size and dead-time
Easy integration (hardware and readout)	KIDs are RF resonators
Large active area (> 20 cm²)	High geometrical efficiency
Fast signal development (< 1 ms, whole pulse)	Negligible dead-time, prompt muon detection
High muon detection efficiency (~100%)	Muons mean energy deposit, O(100 keV), well above detector energy threshold

MONTE CARLO SIMULATION

Geant4-based Monte Carlo (MC) simulation developed to study the muon veto performance and optimize its design.



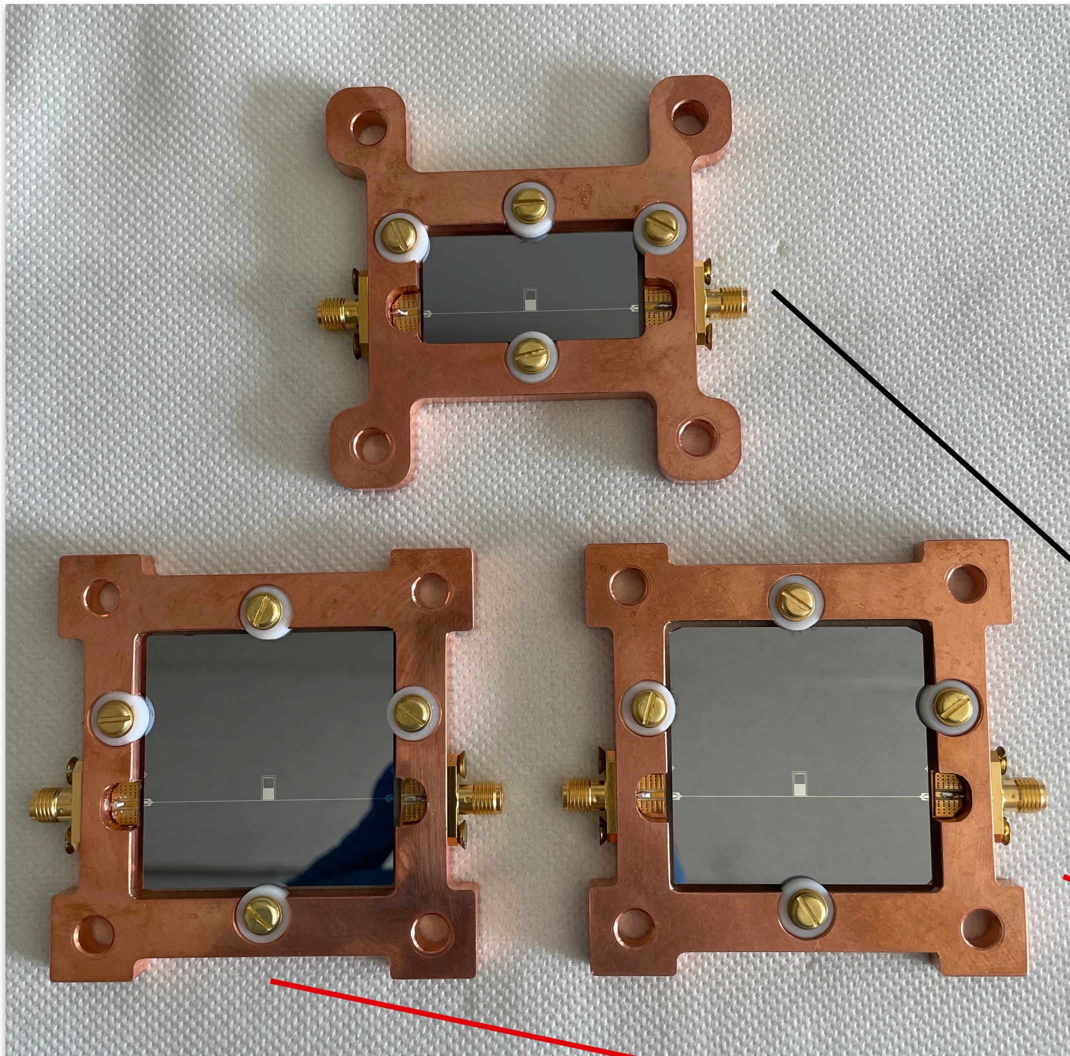


Analog simulation performed for environmental gammas to determine the gamma-induced dead-time.

RESULTS:

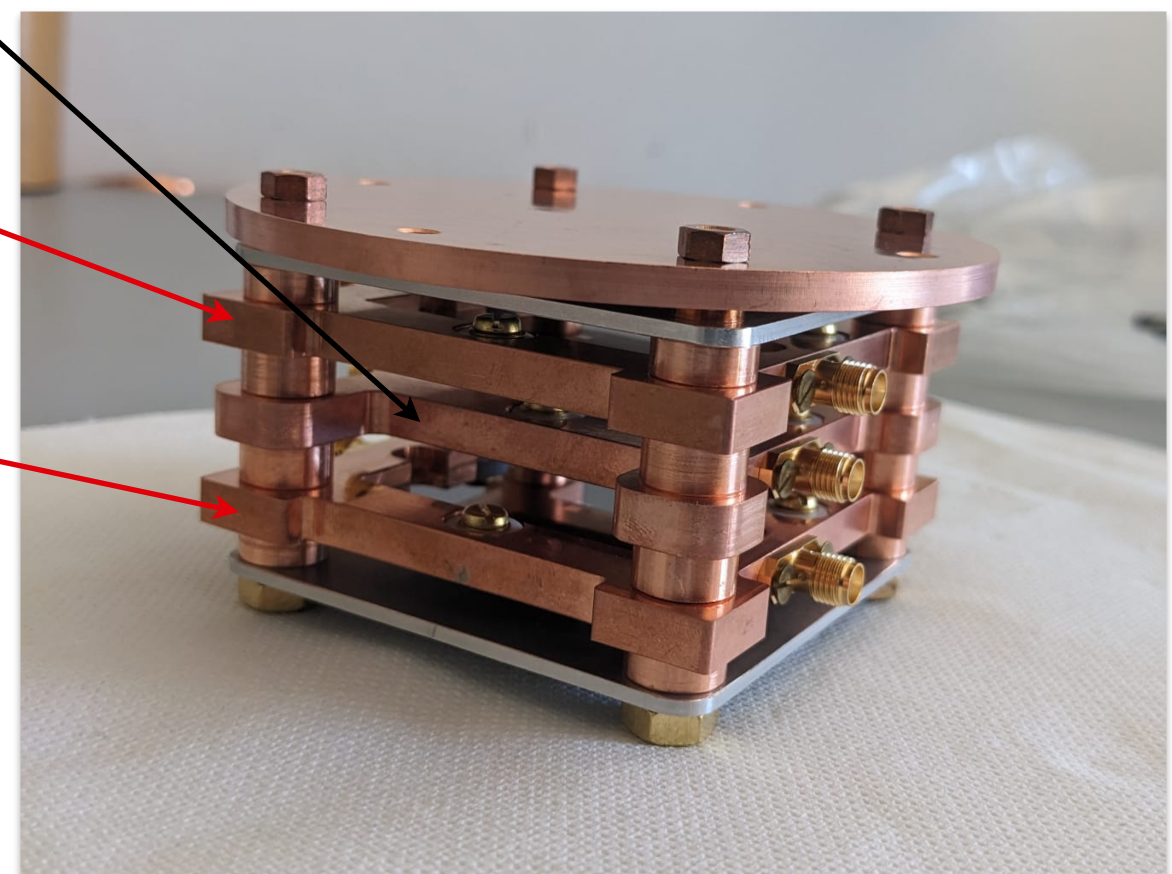
- **Veto efficiency: ~90%;**
- **Gamma-induced dead-time: ~0.02%.**

THE MUON VETO DETECTOR - FIRST PROTOTYPE



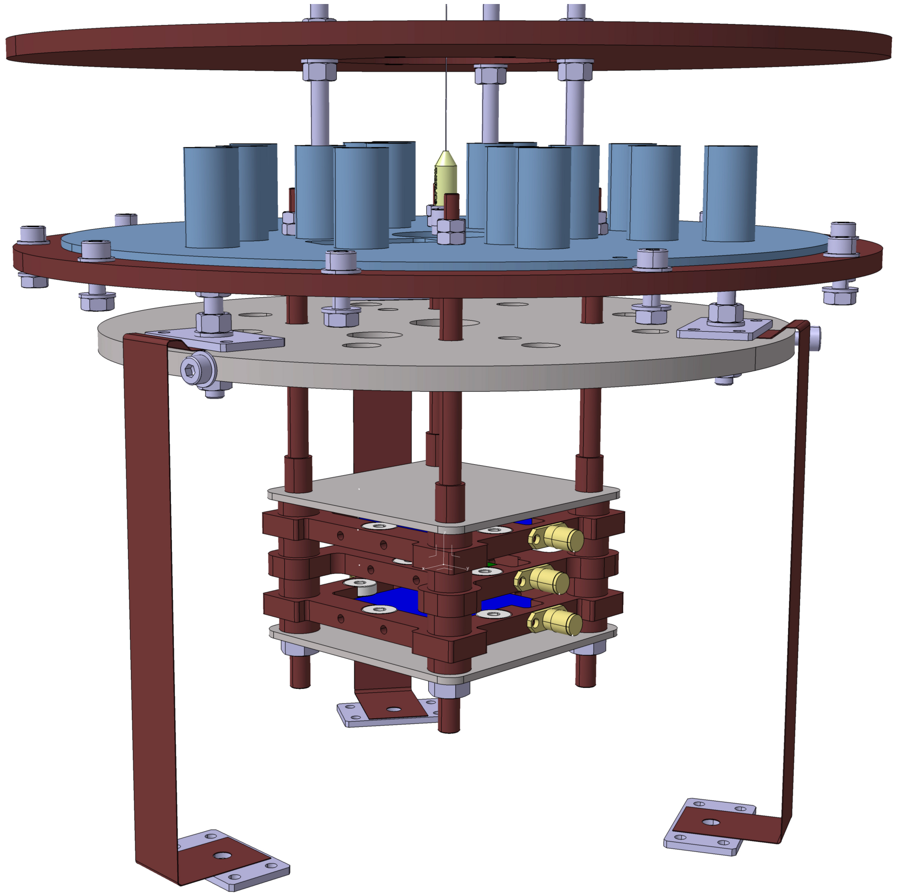
Smaller KID (2x4 cm^2) used as a **central detector** in our first prototype (it will be replaced by a superconducting quantum chip)

KIDs used **for** the **muon veto system**



NEXT STEPS

1) **Characterization** of the **muon veto detector prototypes**;
2) **Optimization** of the **cryogenic muon veto** for superconducting quantum devices;
3) **Commissioning** of a high performing **superconducting multi-qubit chip** (lifetimes T1 ~ 100 μs) **equipped with muon veto**;
4) **Measurement** of the **qubits lifetimes** and **study** of **correlated errors** with and without the use of the muon veto system.



Credit: Valerio Pettinacci

CONCLUSIONS

- **Ionizing radiation**, including cosmic-ray muons, can **degrade the performance of superconducting qubits**;
- **Muon-induced errors can disrupt quantum error correction and qubit coherence**, posing a significant challenge for future quantum processors;
- **Mitigation** currently **requires** deep **underground labs;**
- **Our projects** propose a **cryogenic muon veto for above-ground quantum processors**.
- **First tests** of the **muon veto** system within **this year**.

THANKS FOR YOUR ATTENTION!

"This work was supported in part by the Italian Ministry of Foreign Affairs and International Cooperation", grant number US23GR09

ACKNOWLEDGEMENTS:

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INFN Istituto Nazionale di Fisica Nucleare

Fermilab

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