Impact of radioactivity on qubits

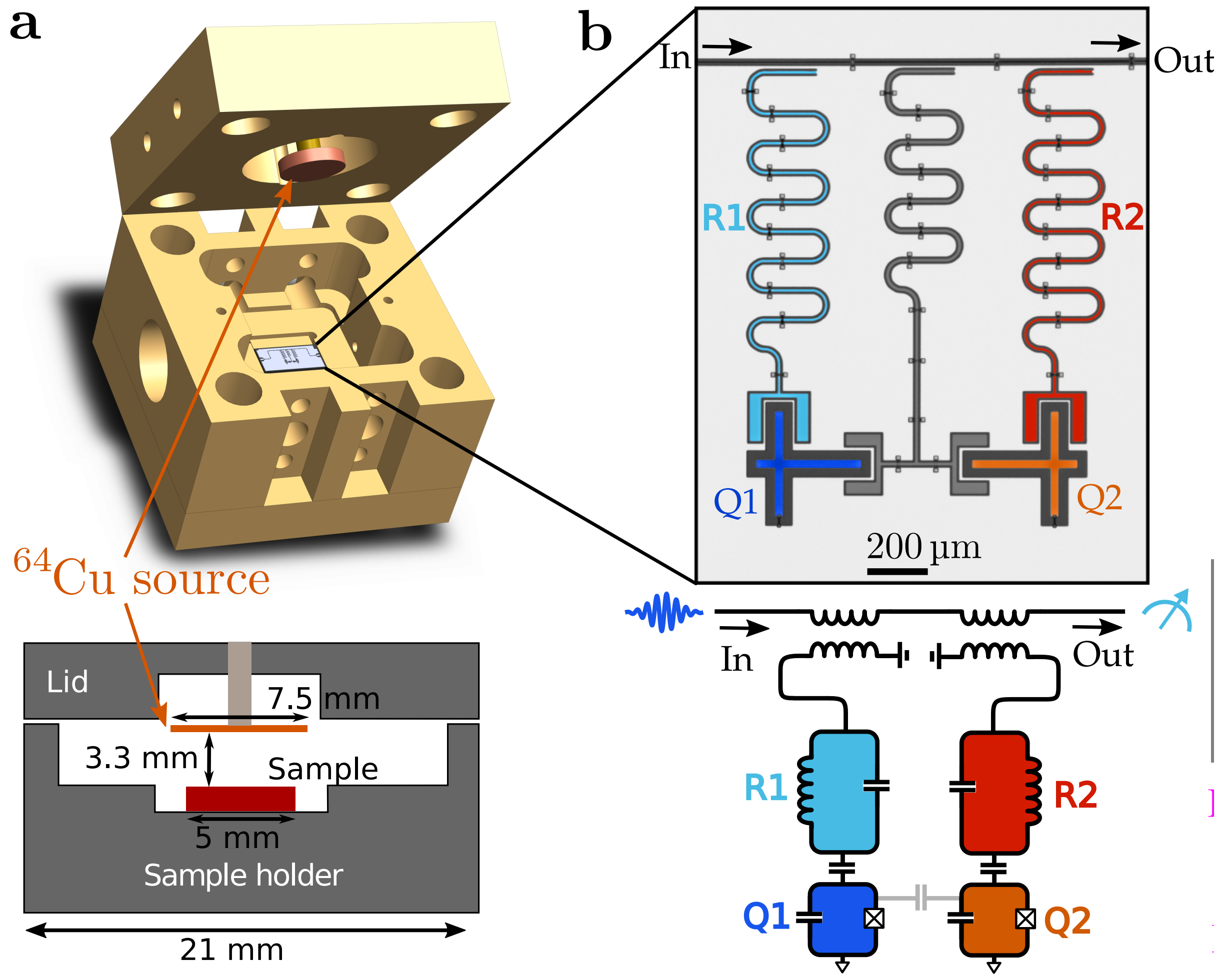
Laura, 15/12/2022

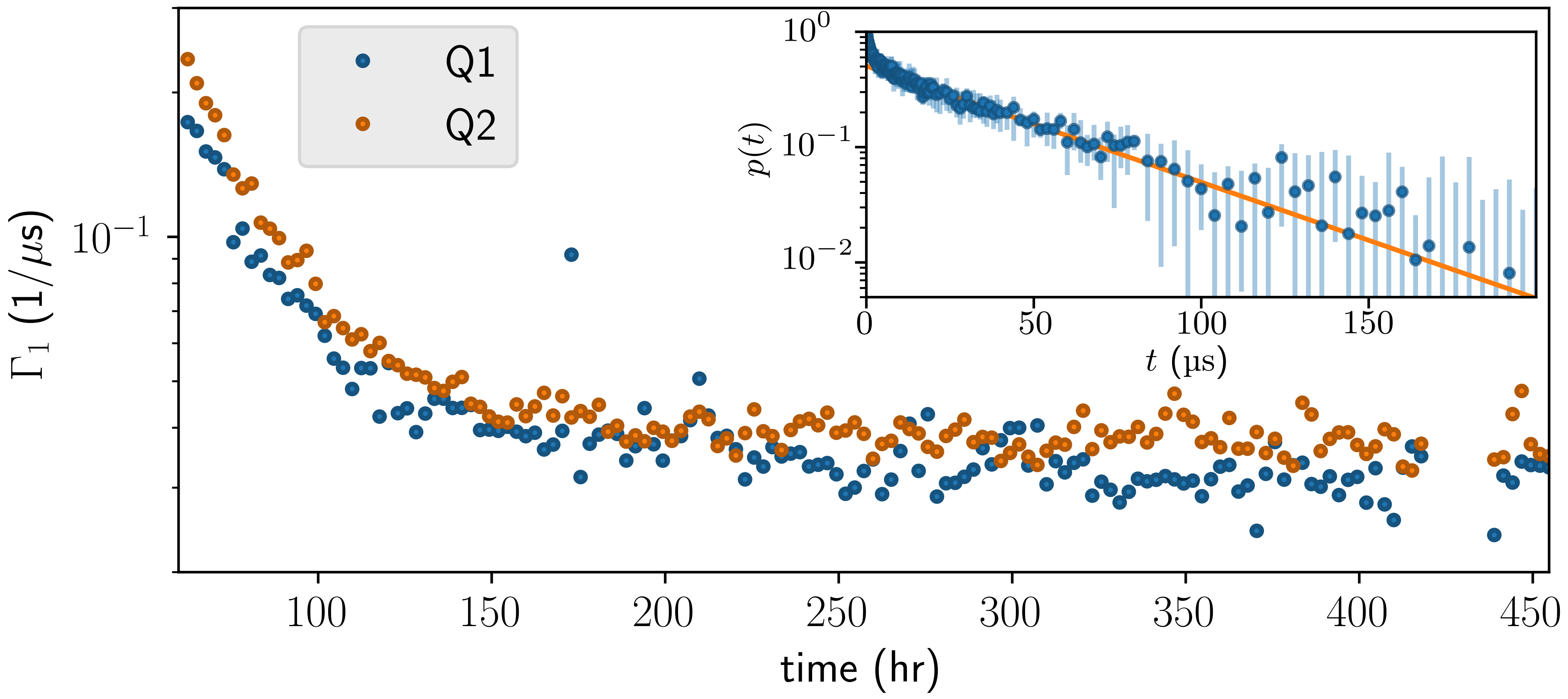
Motivation

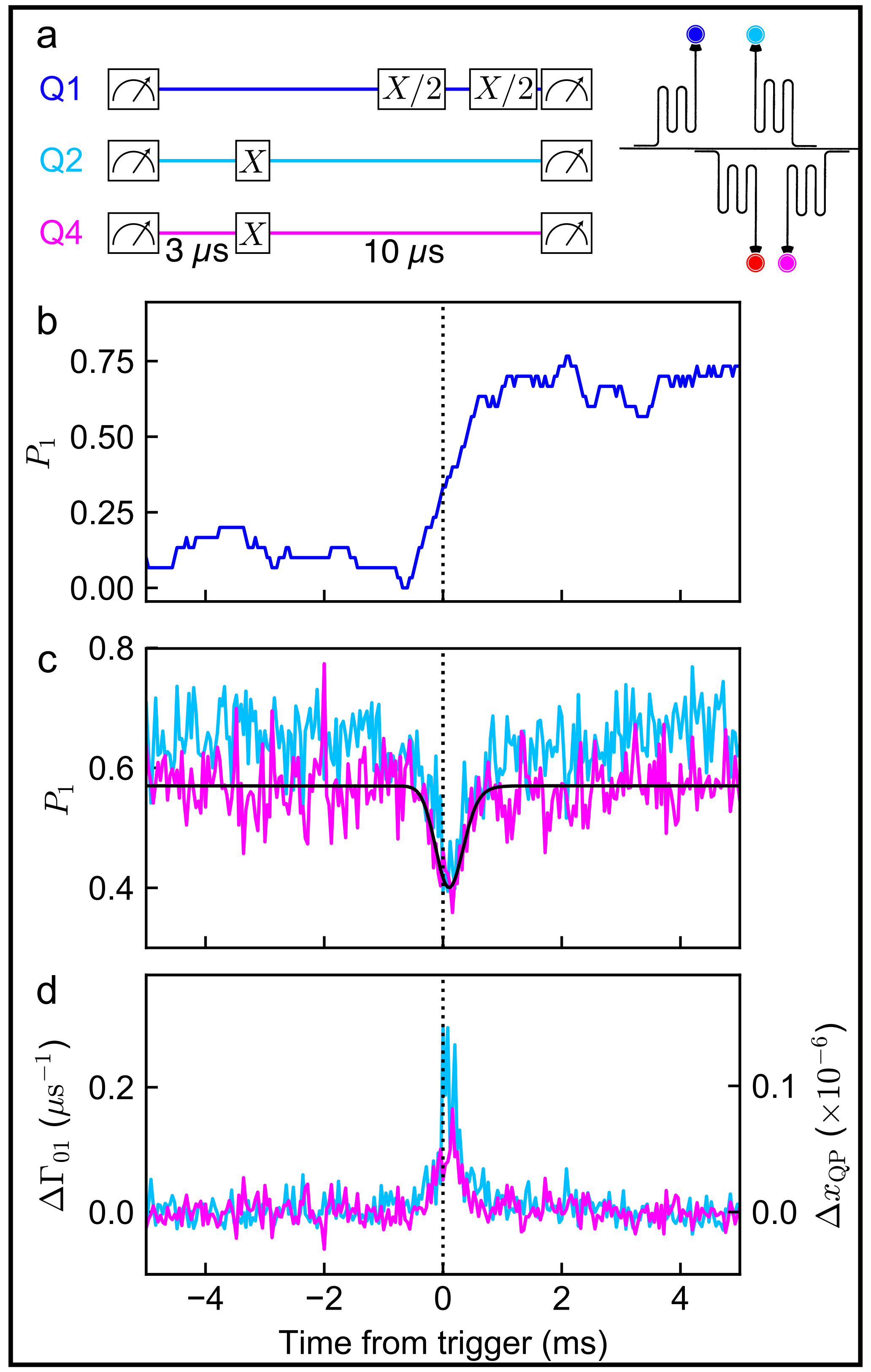
2018: DEMETRA project with INFN starting grant. Today we know that radioactivity:

- Can limit the coherence of qubits

[Vepsäläinen et al, Nature 2020], [Wilen et al, Nature 2021]







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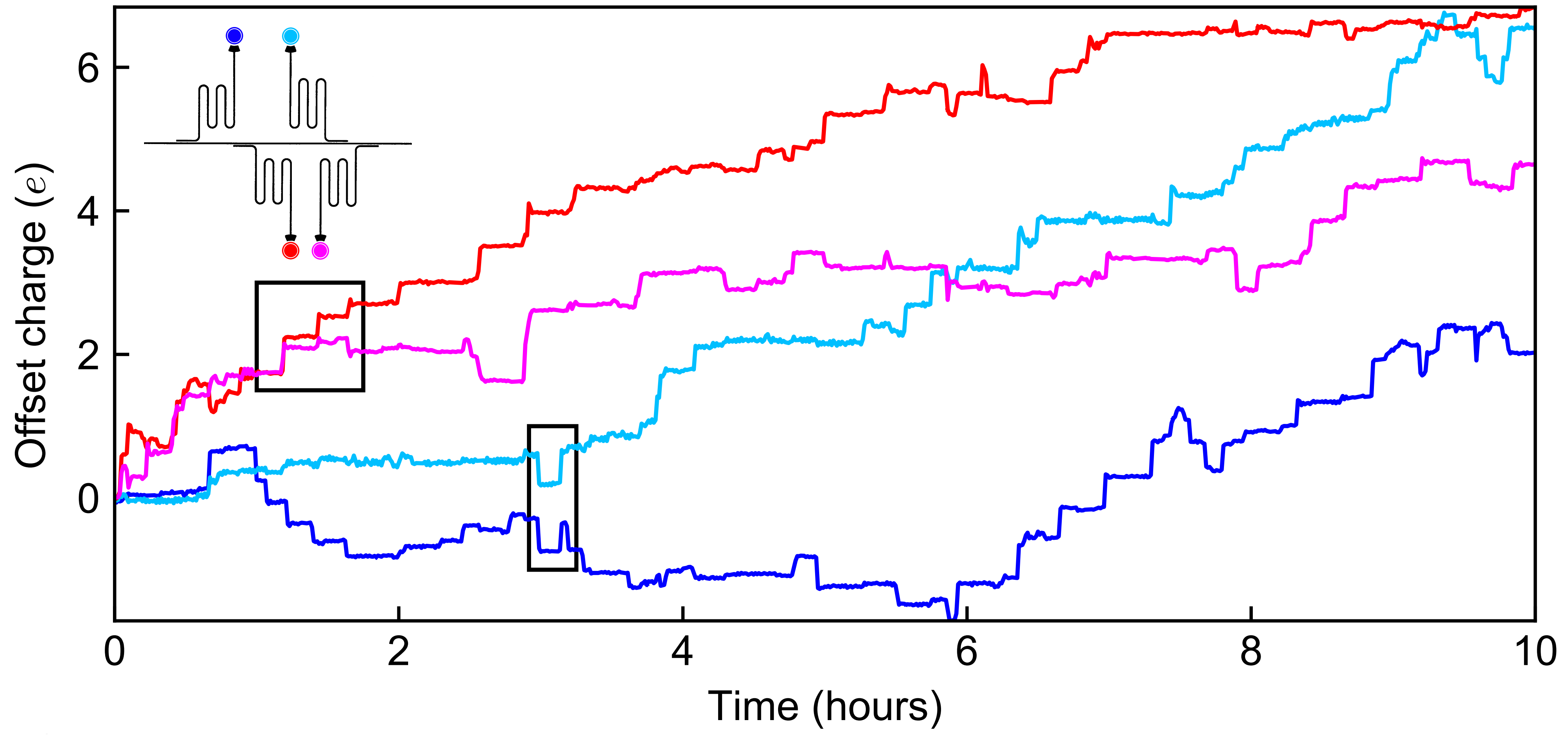
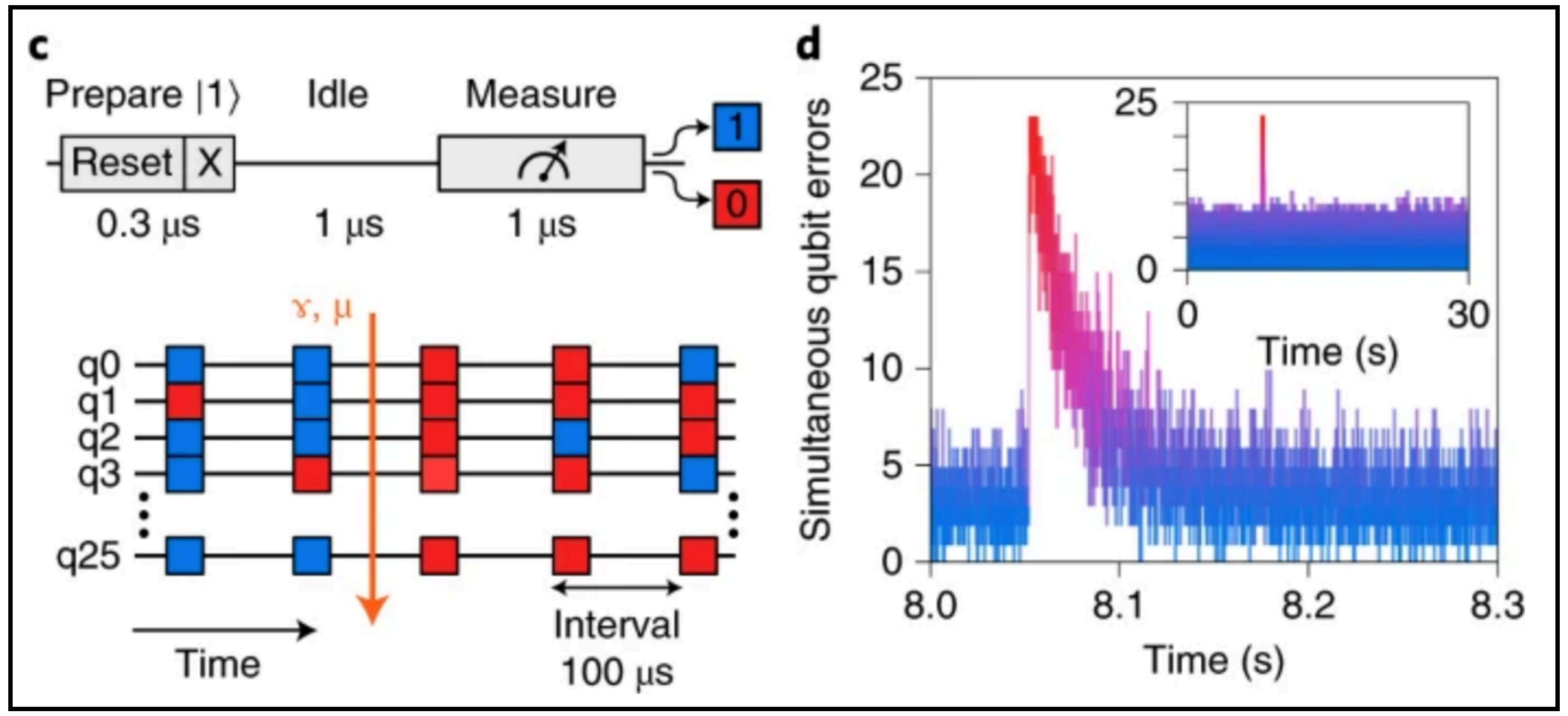
- Limits quantum error correction in a matrix of qubits

[Wilen et al, Nature 2021], [McEwen et al., Nature Physics 2022]





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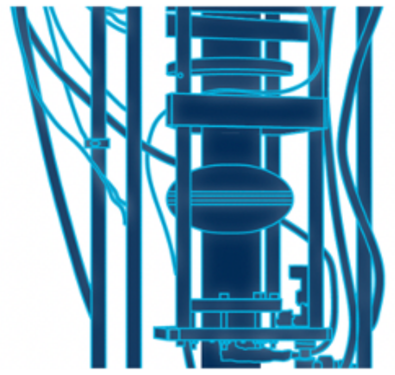
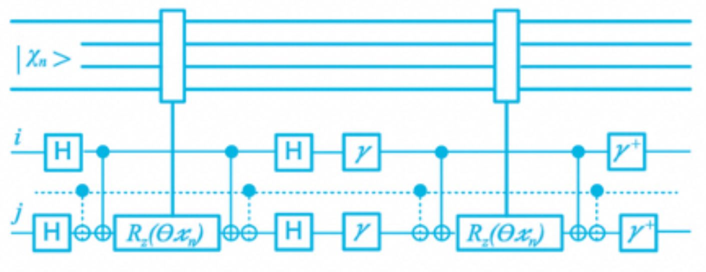
[Wilen et al, Nature 2021], [McEwen et al., Nature Physics 2022].

- Causes f jumps in multiple TLSs, limiting the stability of the device and inducing fluctuations in the qubit lifetime

[Thorbeck 2022, arXiv:2210.04780]





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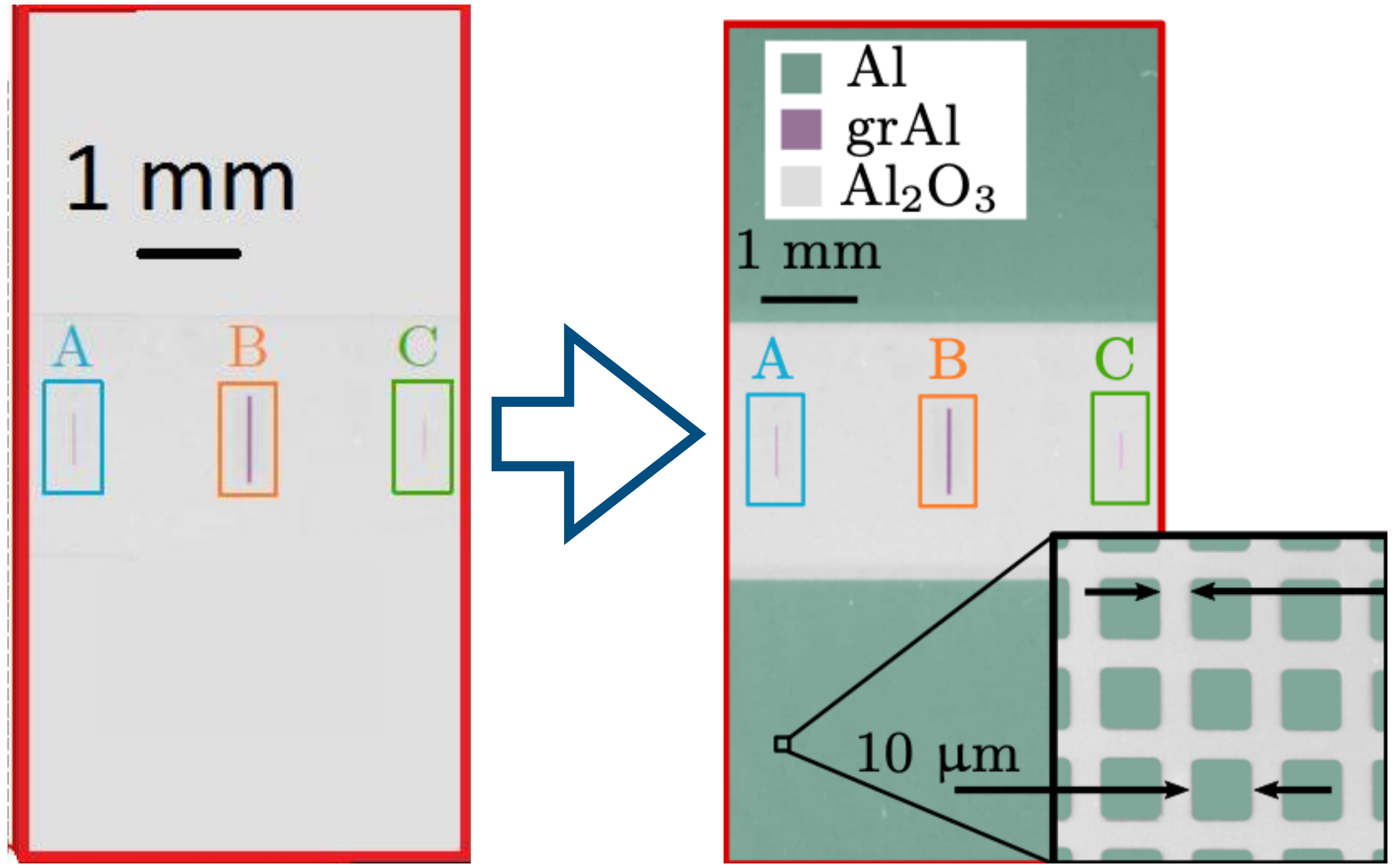
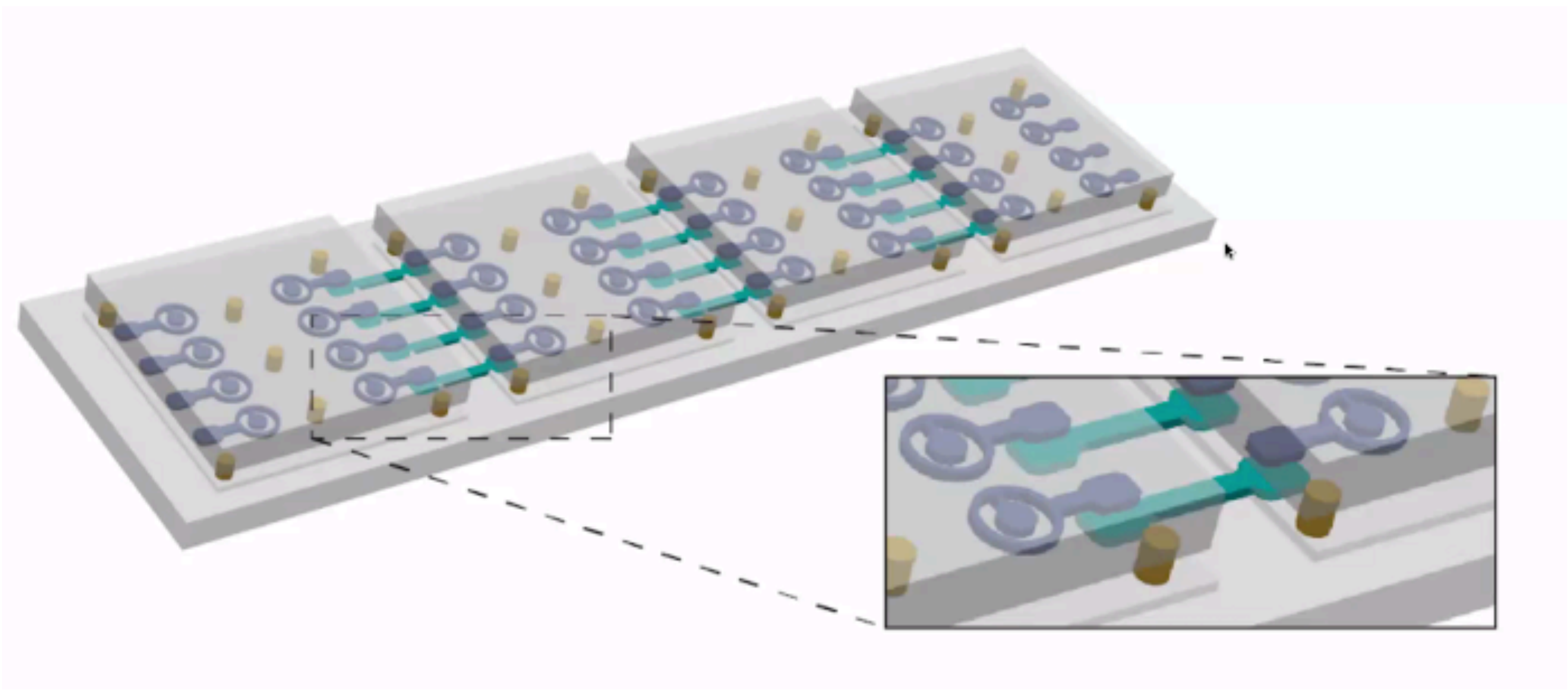
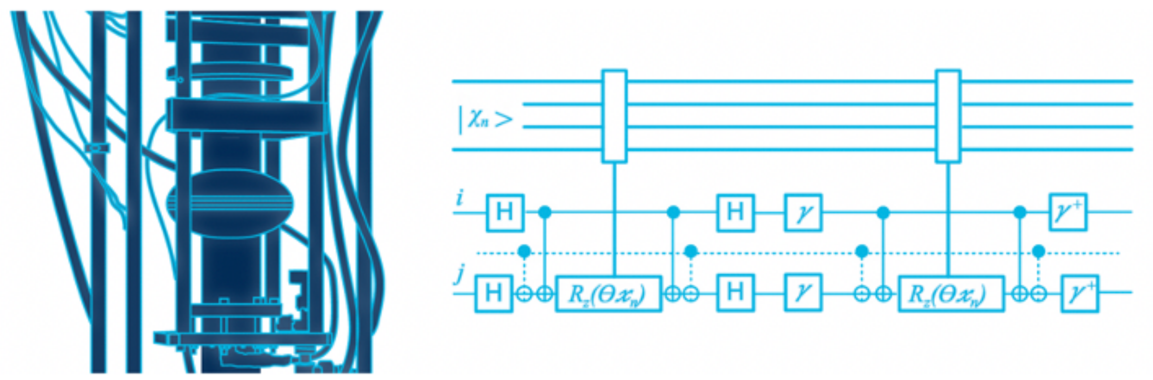
Solutions

Increasing number of proposals

- Suppressing the sources of radioactivity
- Traps on the substrate to protect the qubit
- Spread qubits on decoupled processors
- Sensor-assisted qubits
- ....







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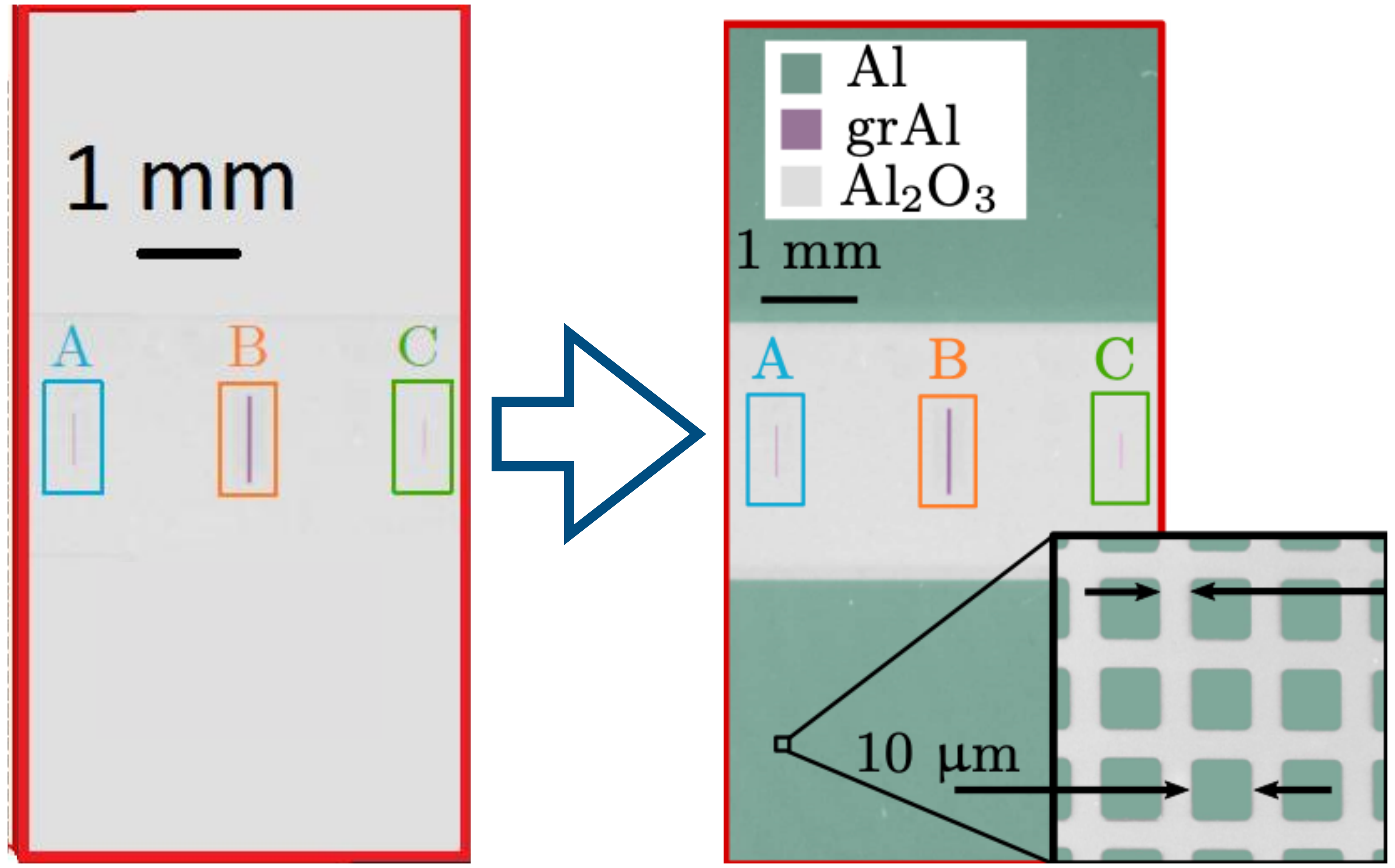
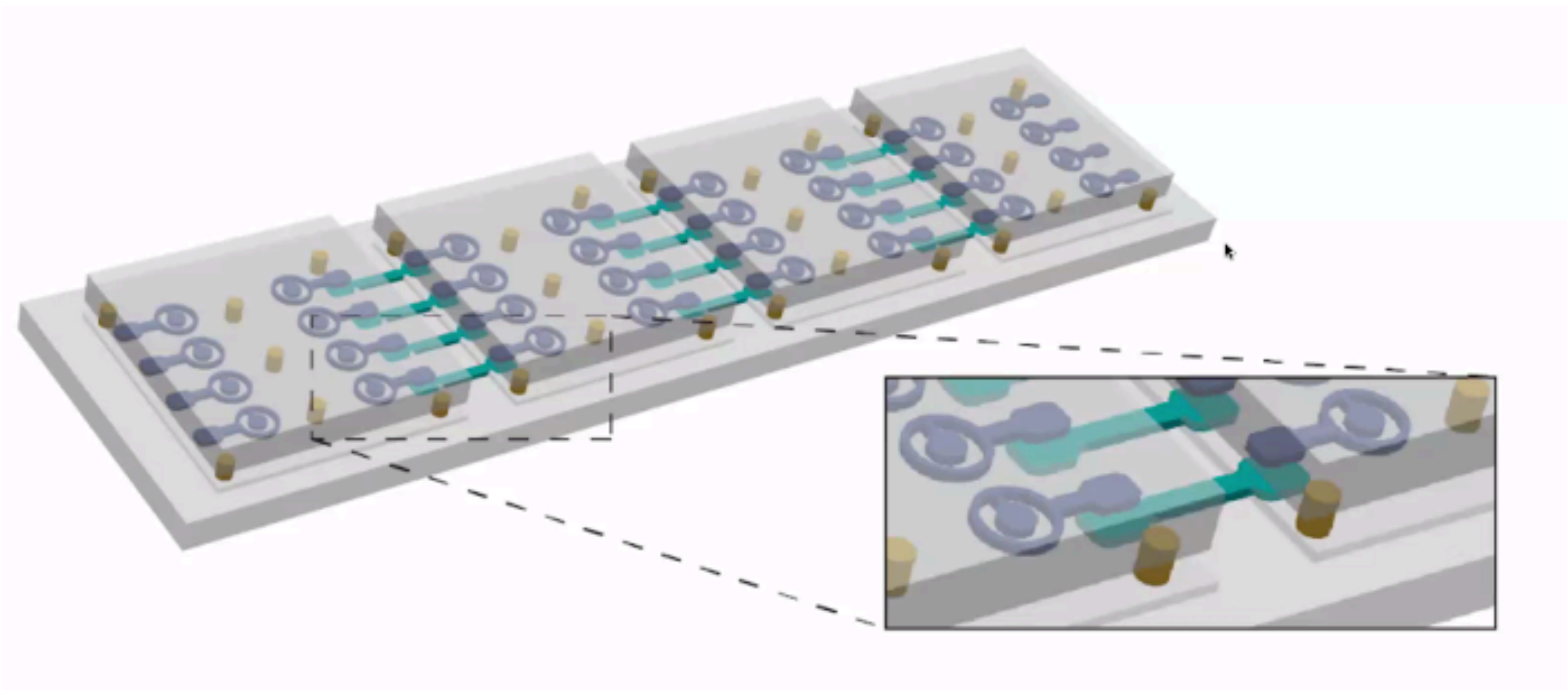
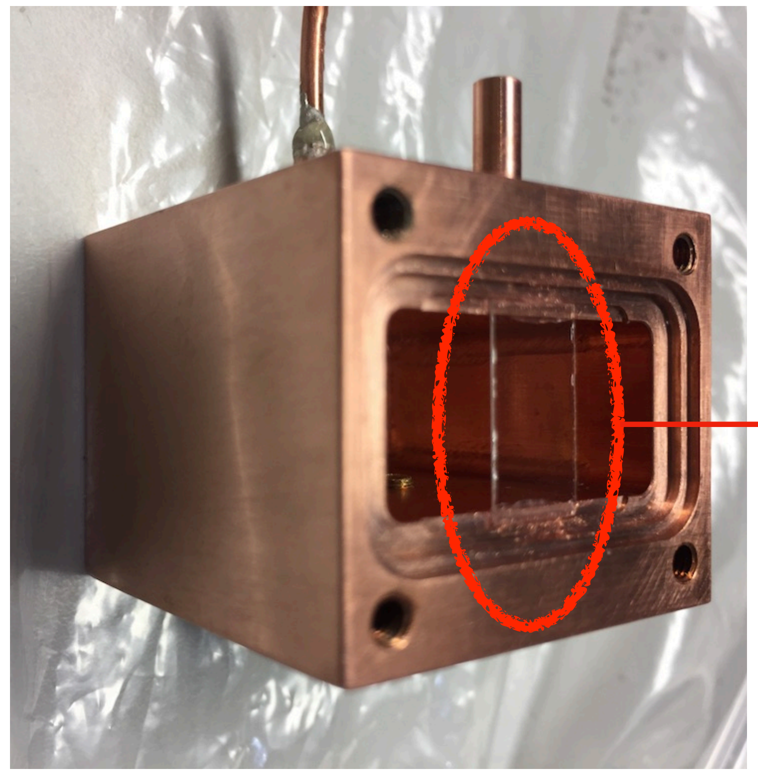
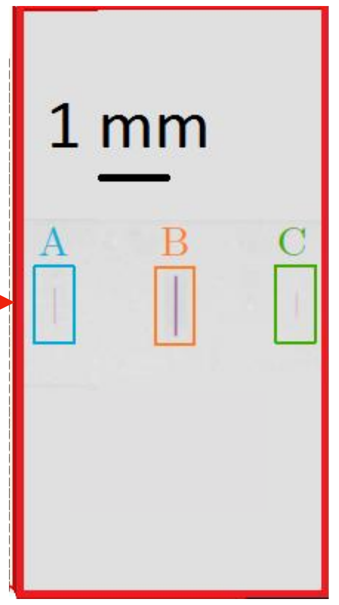


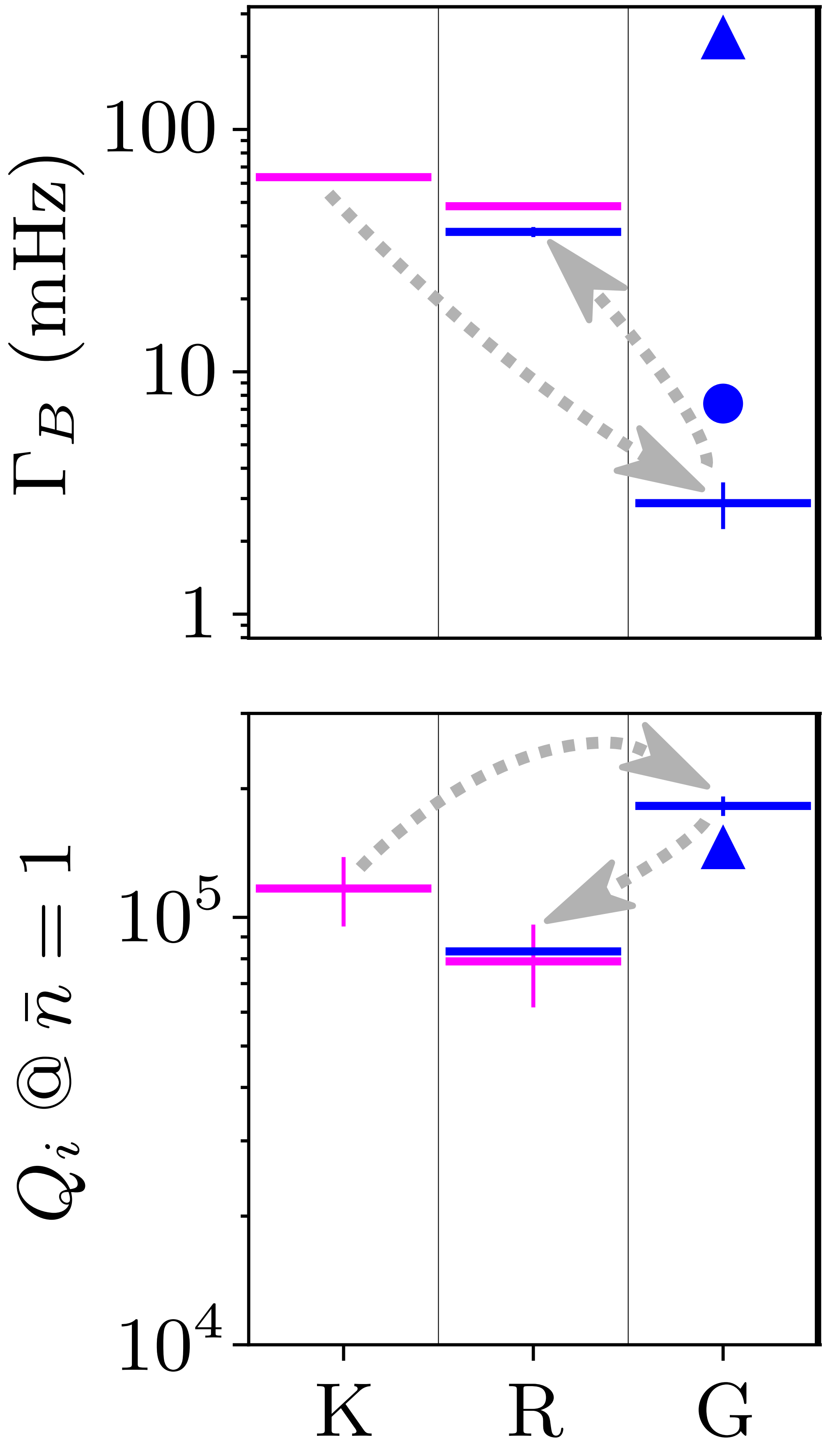


Two successful cases

(1) Operation of superconducting resonator in low radioactivity







Rate of events suppressed from tens of mHz to ~1 mHz

Internal Q improved by a factor 2-3

Cardani et al, Nature Communications 2021

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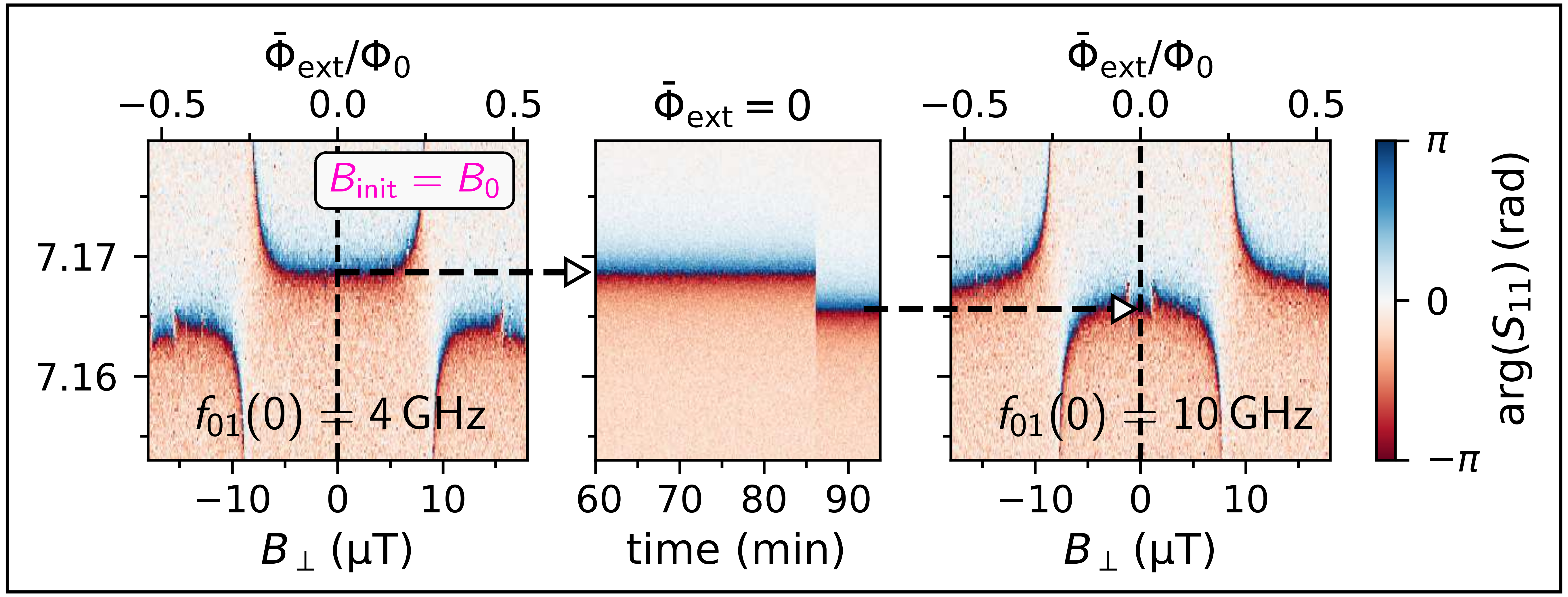
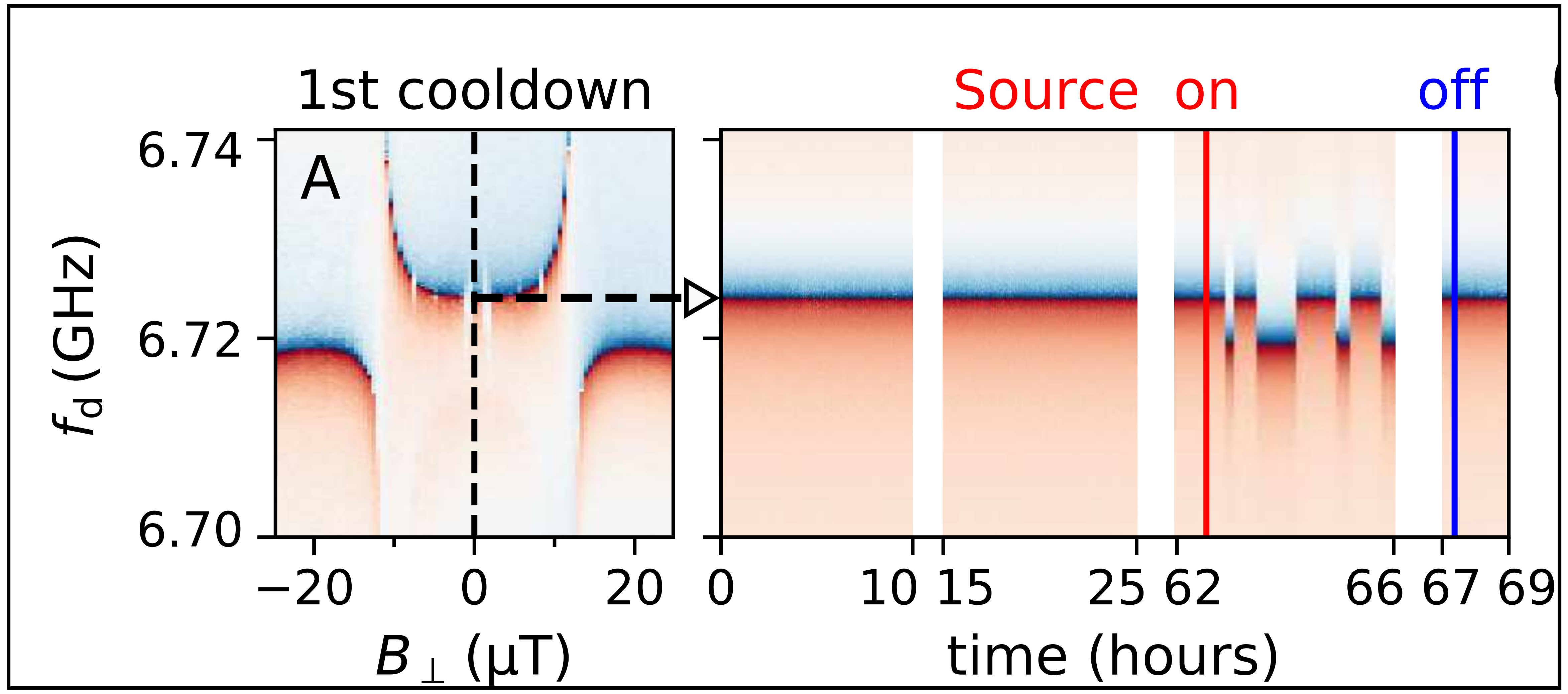
Two successful cases

(2) Operation of gradiometric qubit in low radioactivity





Impressive improvement of frequency stability, from tens of minutes to days

Gusenkova et al, APL 2022.

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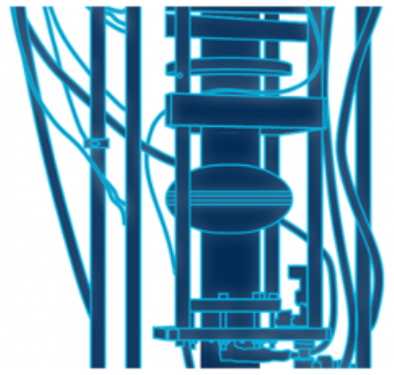
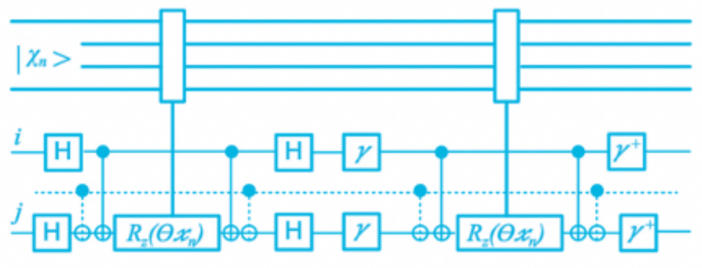
Coming to SQMS

Focus Area	Major Activity	Deliverables and Benchmarks	Center Year				
			1	2	3	4	5
Materials for 2D and 3D Quantum Devices	(1) Infrastructure & Testbeds *Impacts: (2), (3), (4), (5),*	Infrastructure upgrades to enable low (T~1.5K) and ultralow (T<=100mK) temperature characterization stations at partner institutions **Risk mitigation: risk reduction via creation of additional testing bandwidth to evaluate new ideas*					
		SRF cavity-based testbed available for characterizing dielectrics in quantum regime at Fermilab					
		SRF cavity-based testbed available for characterizing dielectrics in the quantum regime at Northwestern and NIST/UColorado					
	(2) Advanced Materials Studies *Impacts: (4), (5)* *Drives: (1)*	Initial exploration of dominant quasiparticle sources including underground measurements (INFN) of the 2D Rigetti transmon **Risk mitigation: by testing the same devices in different testbeds by different experimenters, environments and techniques that maximize performance can be identified*					





SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

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3D Quantum Devices	(1) Infrastructure & Testbeds *Impacts:* *(2), (3),(4),(5),*	Infrastructure upgrades to enable low (T~1.5K) and ultralow (T<=100mK) temperature characterization stations at partner institutions **Risk mitigation: risk reduction via creation of additional testing bandwidth to evaluate new ideas*					
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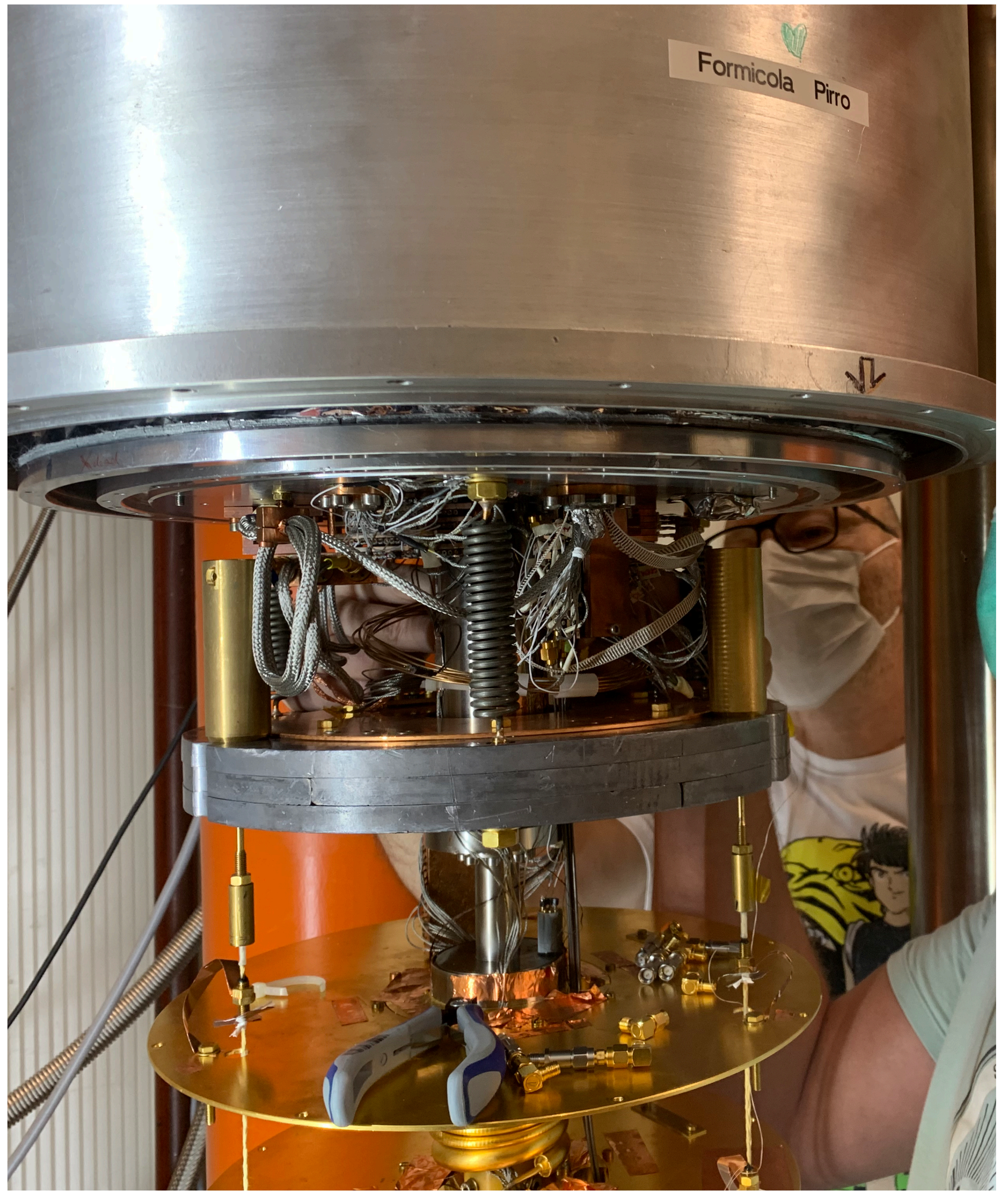

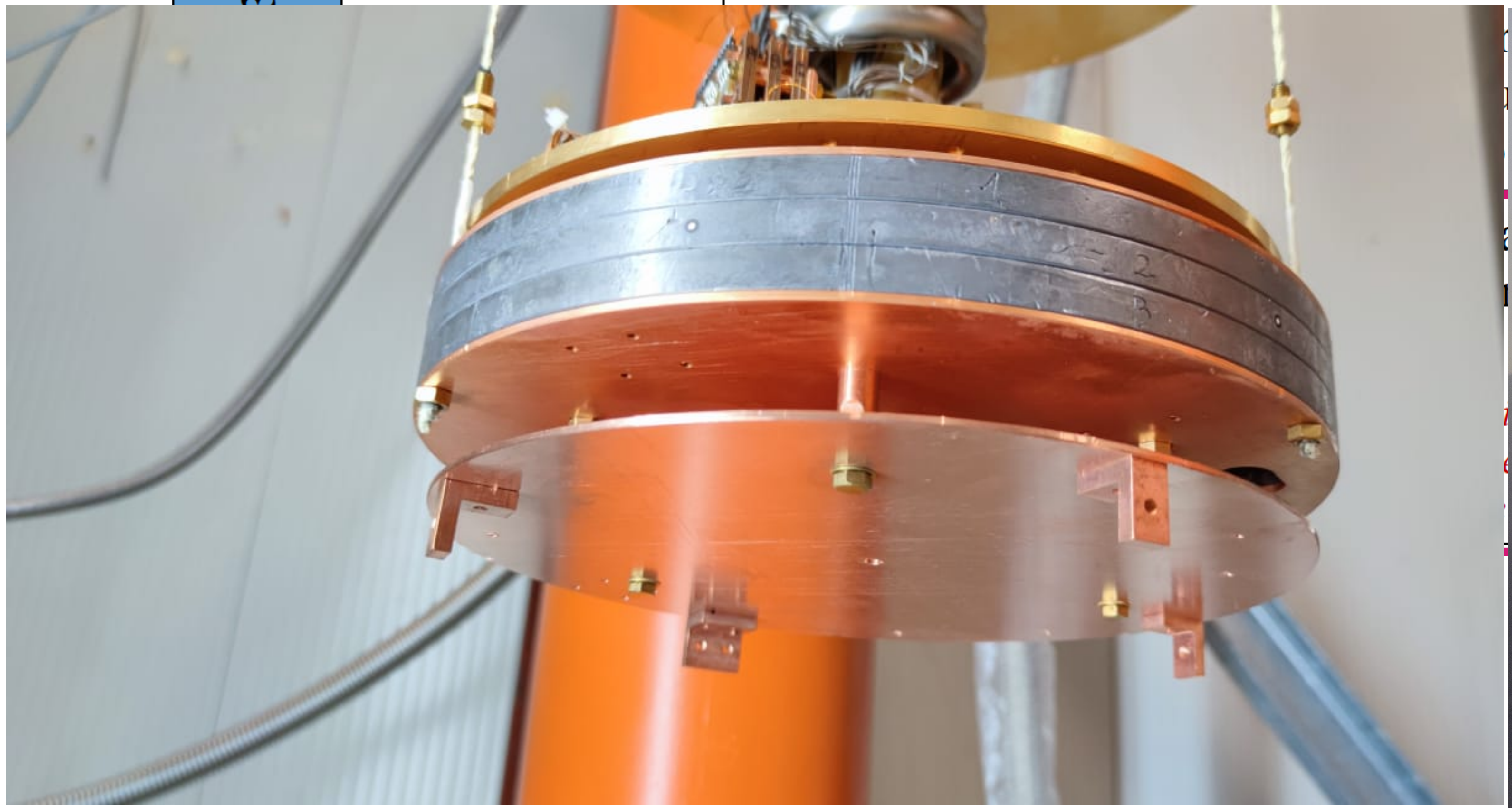

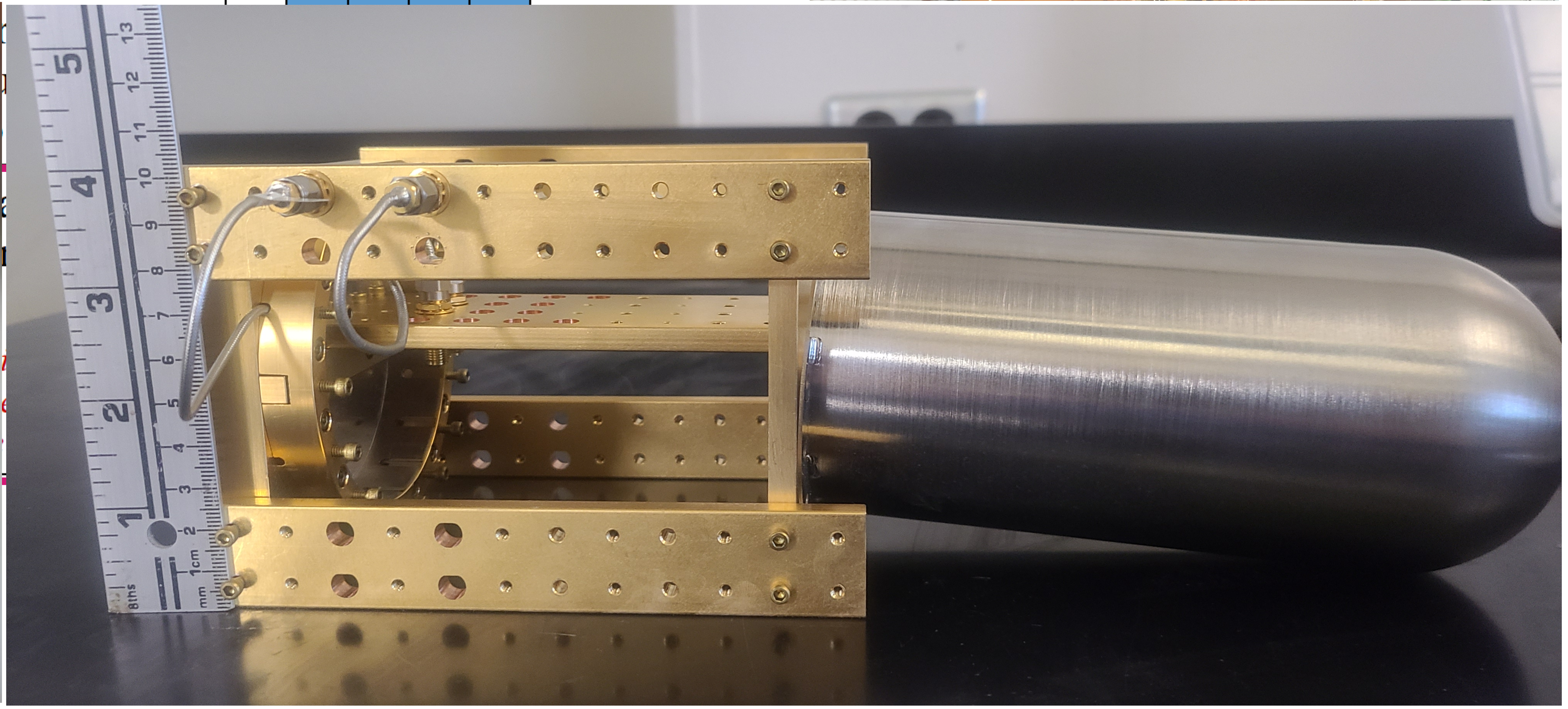

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Room-T Electronics to be procured

- FNAL reluctant to deliver the Keysight prepared for INFN
- PNNR funds to procure ad independent electronics (S. Pirro), probably Zurich Instruments

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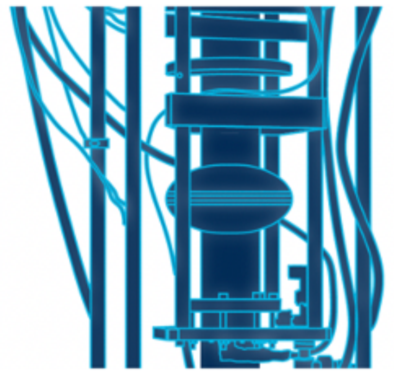
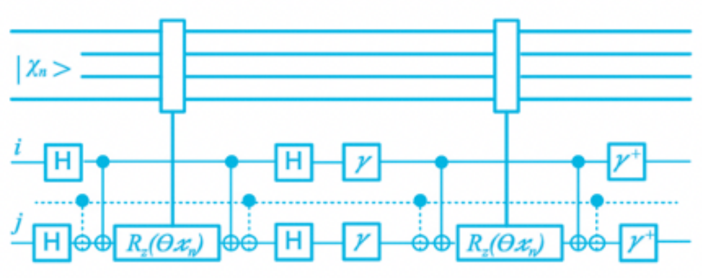
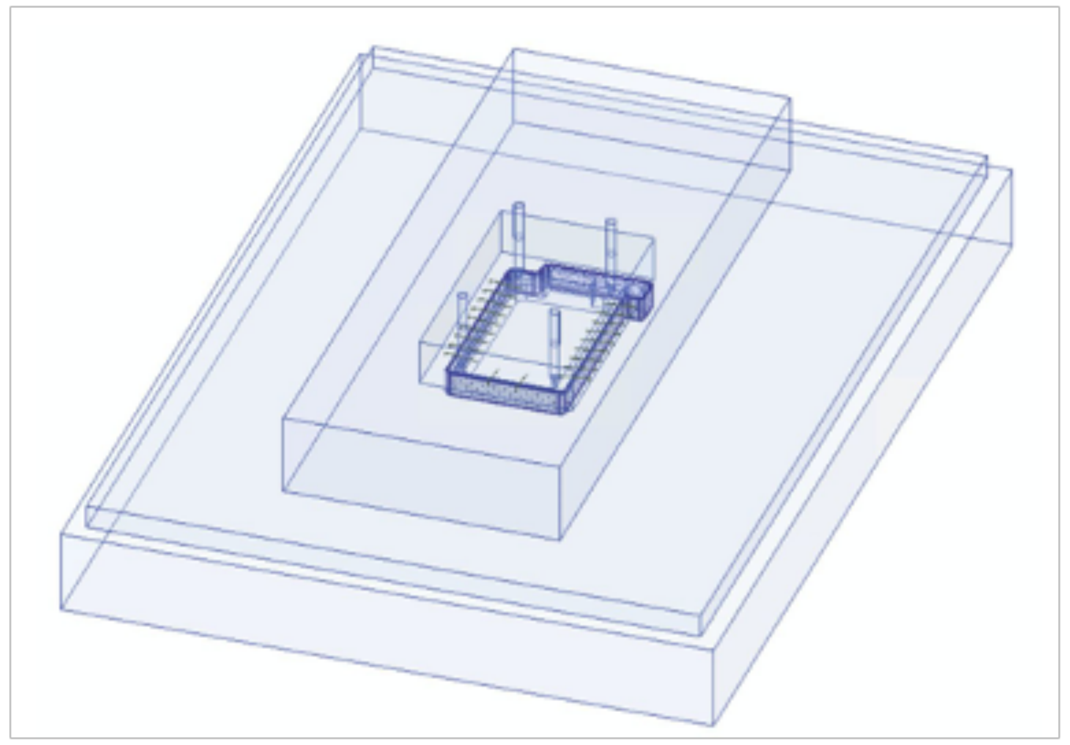
(Long Term) plan with SQMS

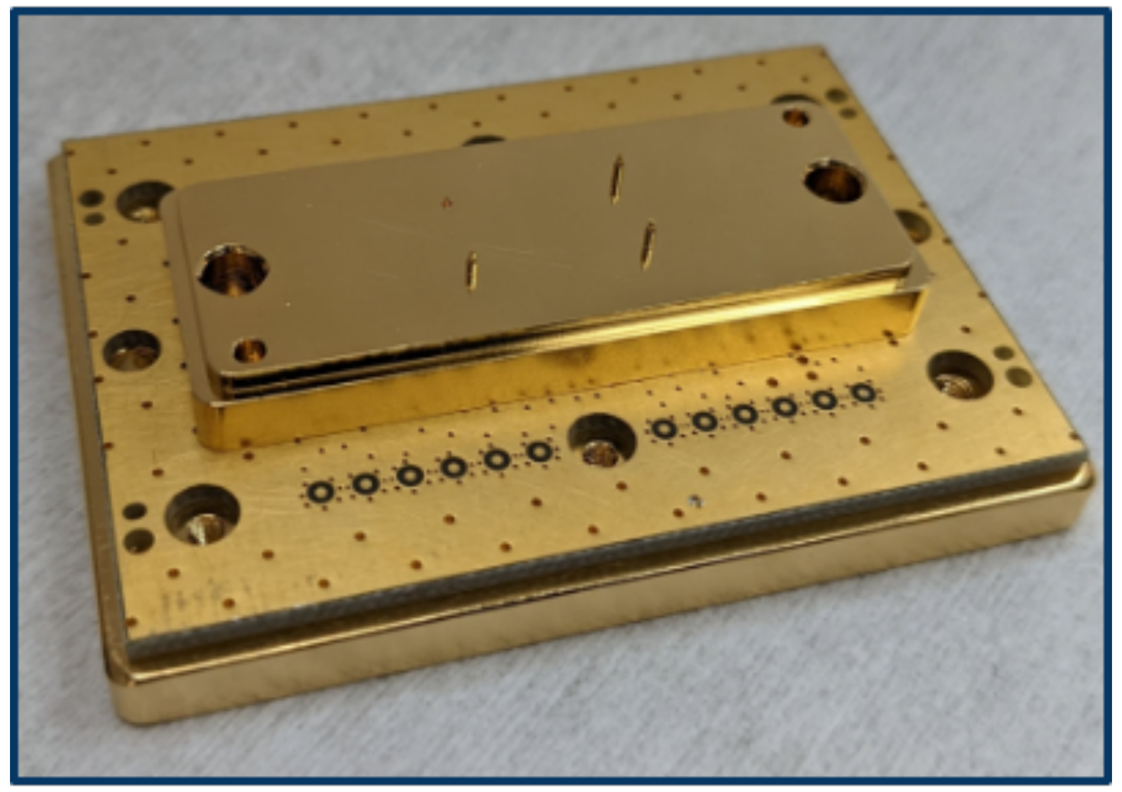
Laboratory	Sample
Characterise laboratory radioactivity	Characterise contaminations of materials
Develop a simulation describing the effects of such radioactivity on the SQMS prototype	Develop a simulation describing the effects of such contaminations on the SQMS prototype
Design a shield to suppress such effects	Develop selection/cleaning protocols



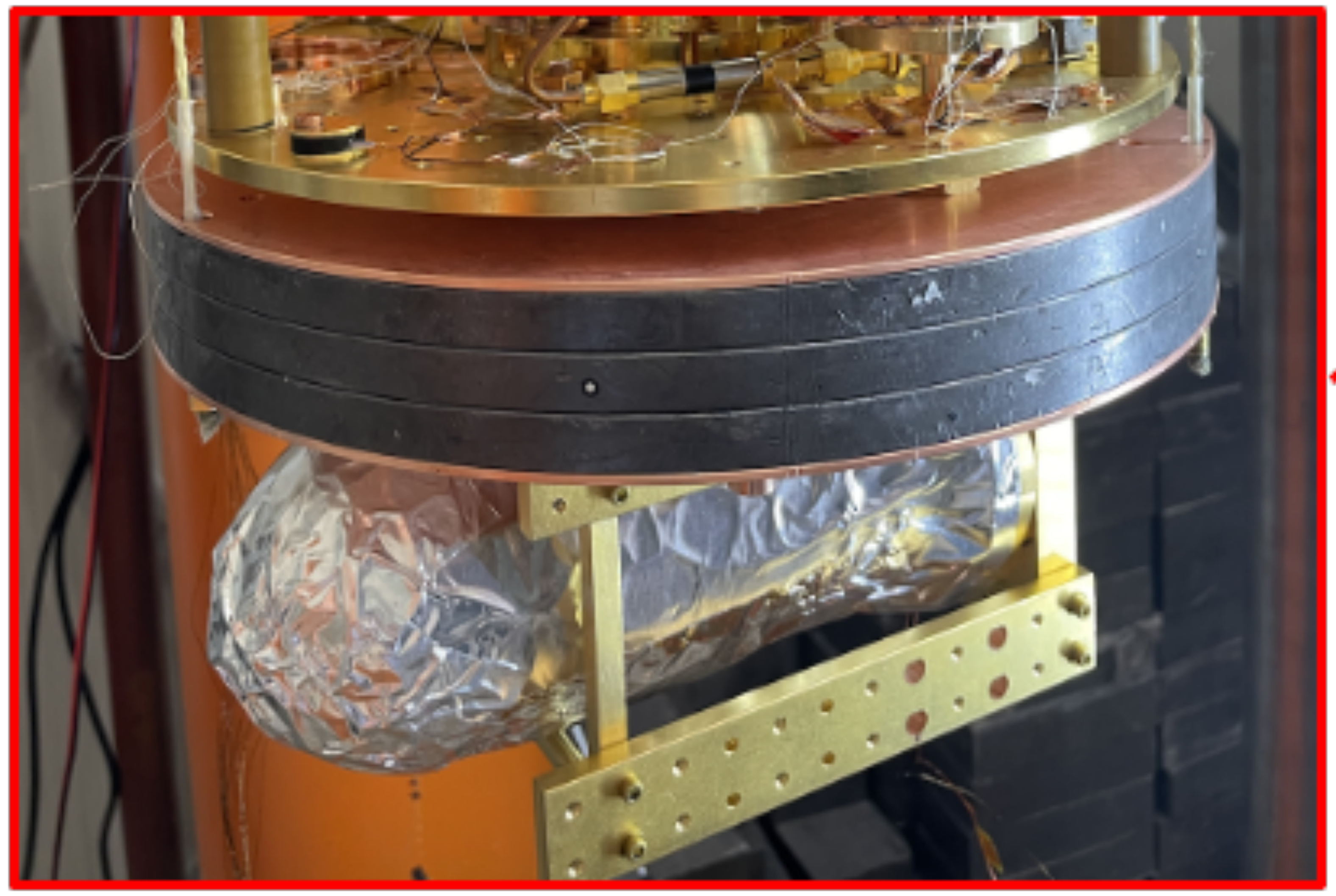


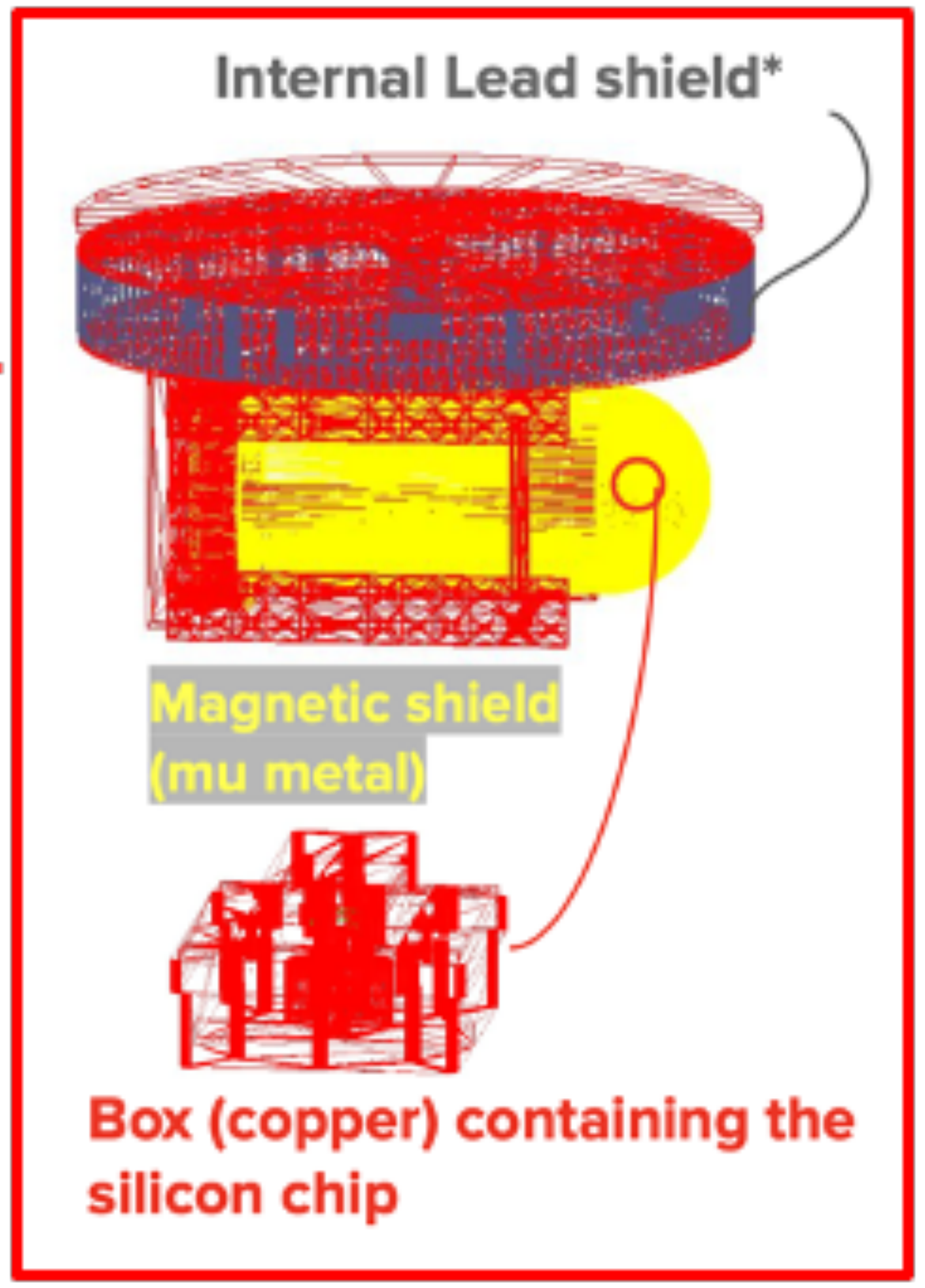
Round Robin chip

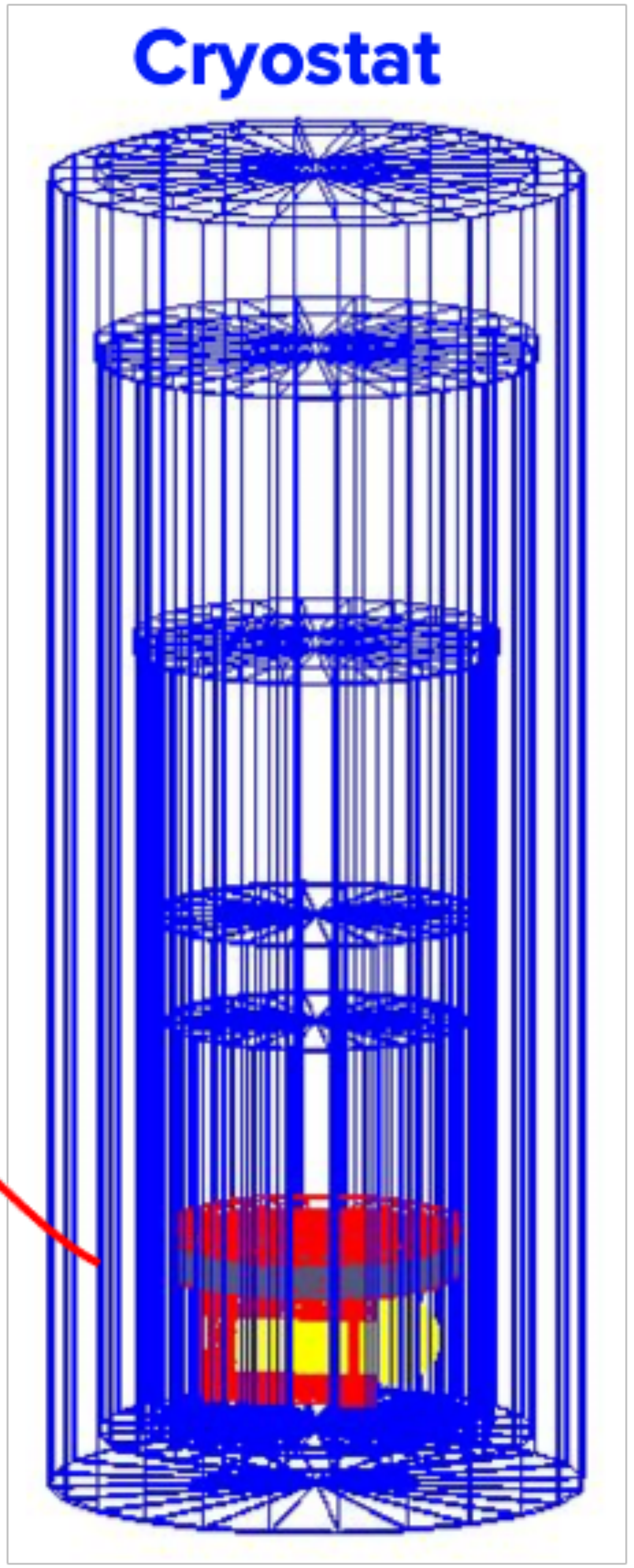




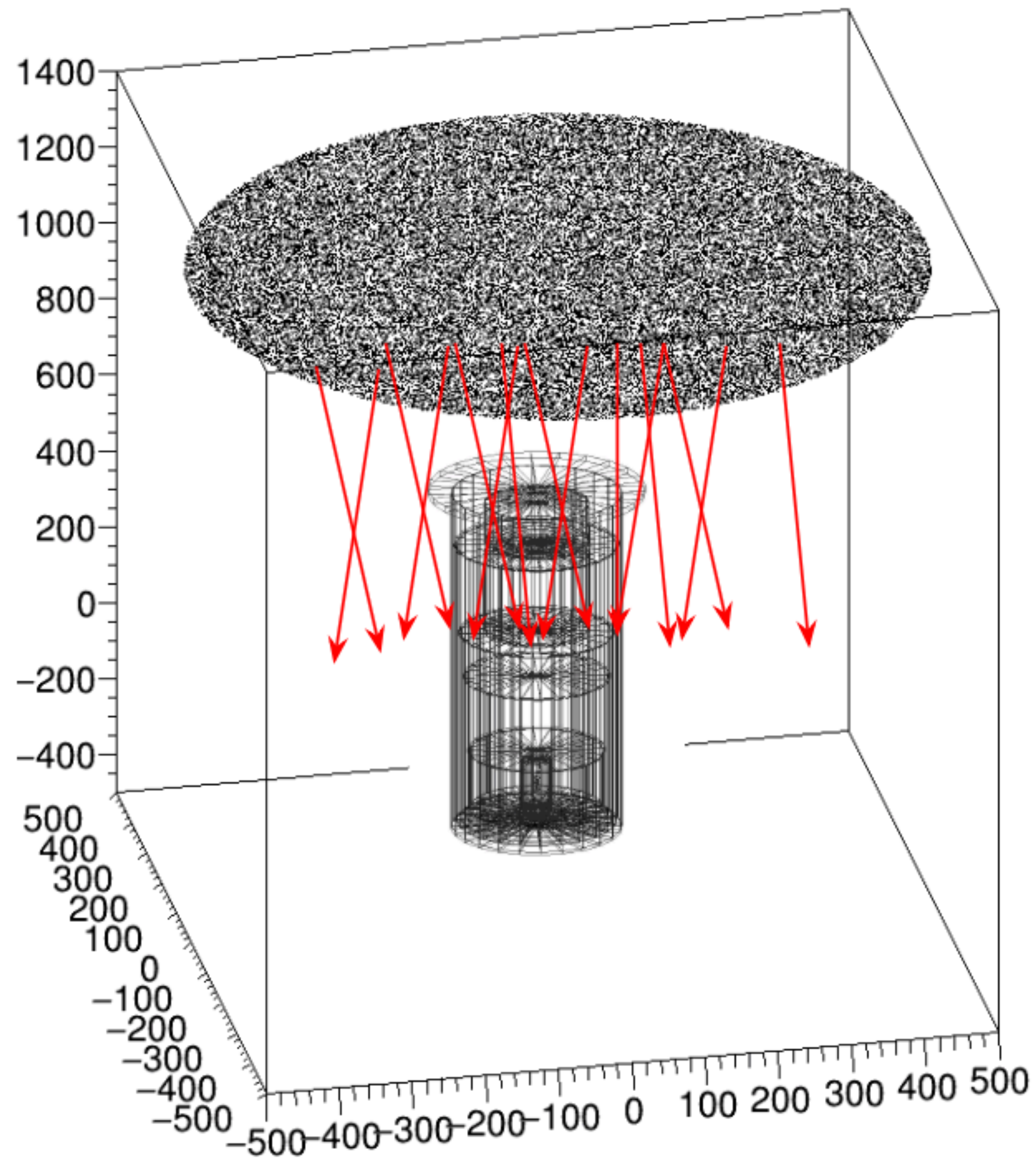
In measurement at FNAL





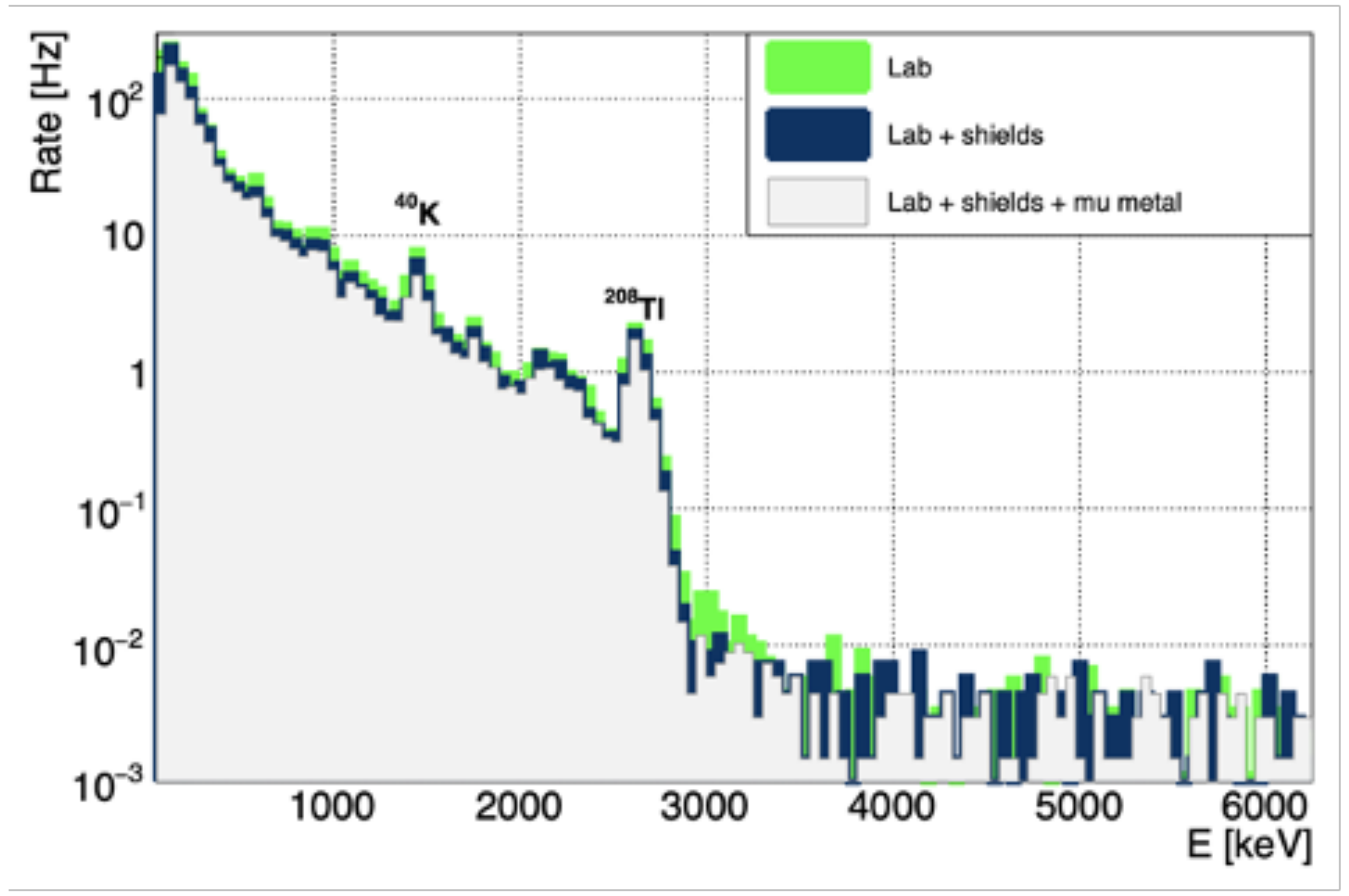


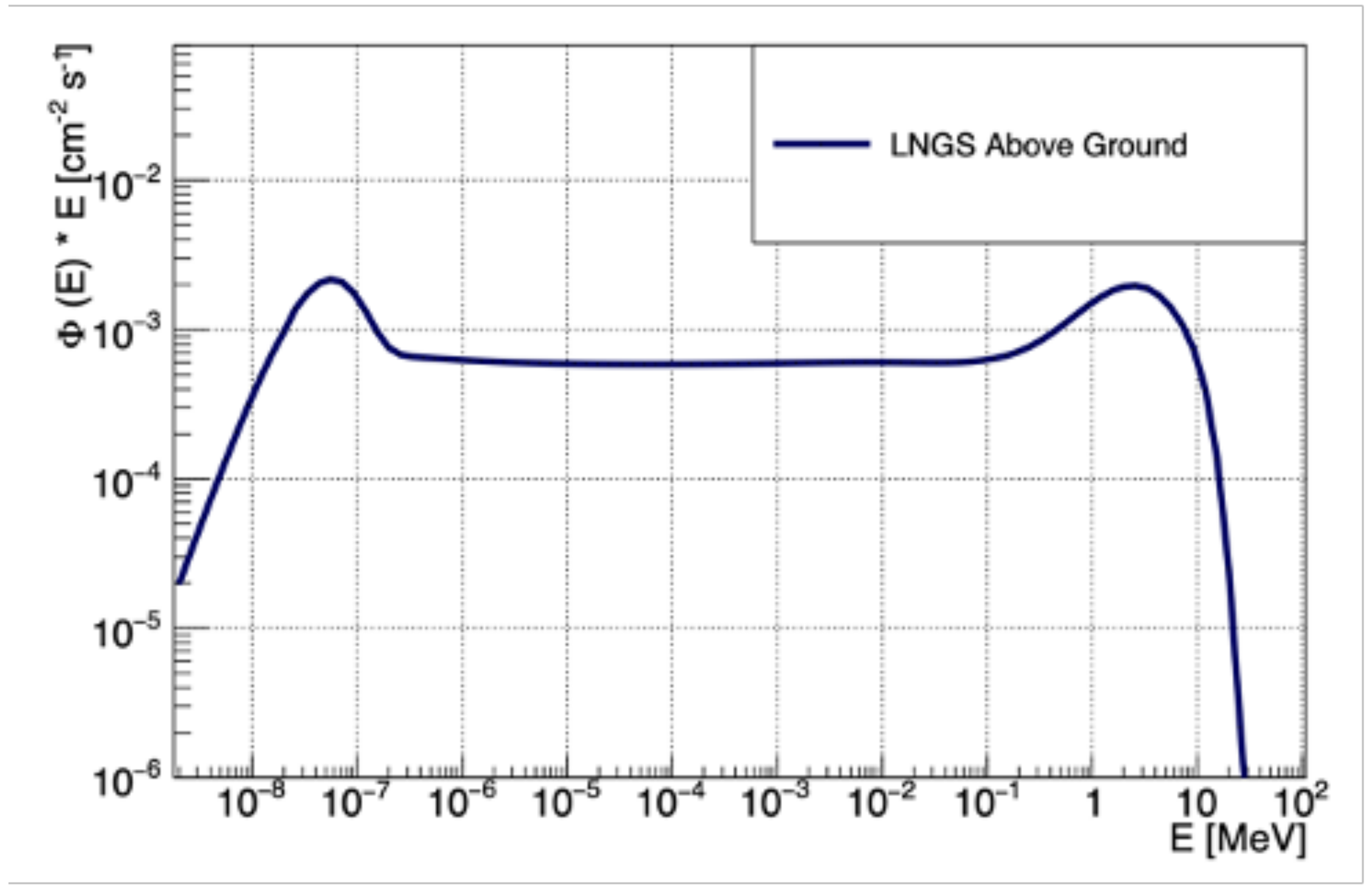
External Sources



We simulated:

- Muons (from known rate)
- Laboratory gamma's (measurements done in LNGS, while reasonable assumption for other sites)
- Neutrons (measurements done in LNGS)

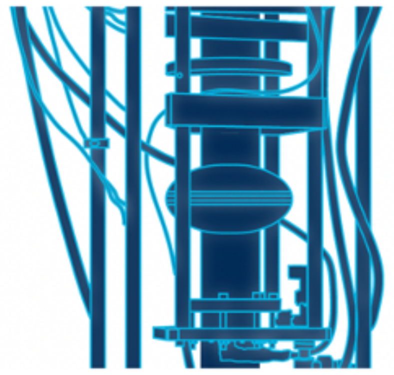


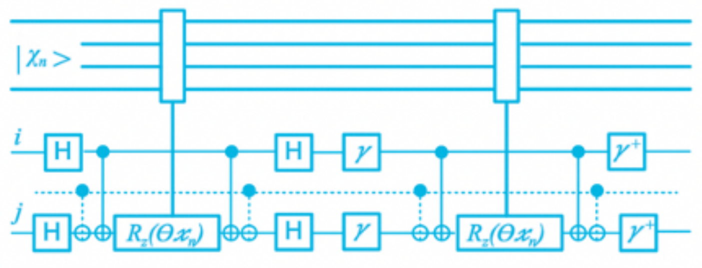


Close Sources

HPGe measurements in LNGS (Laubenstein and Pagnanini) and MiB (Nastasi)

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
COPPER BOX + COPPER FINGER	< 1.5	< 25	< 4	< 9	< 0.6
MAGNETIC SHIELD	< 8.4	< 8.3	< 8.4	< 35	< 2.7
SMA ADAPTERS	< 48	(1800 ± 600)	(70 ± 30)	(240 ± 90)	< 10
COPPER COAX CABLES	(54 ± 12)	(1500 ± 400)	(34 ± 17)	(740 ± 130)	< 12
RADIALL SWITCH	(1880 ± 100)	(1340 ± 060)	(130 ± 30)	(2200 ± 300)	< 11.2
SINGLE-JUNCT CIRCULATOR	< 190	< 330	< 410	< 2000	< 60
DUAL-JUNCT CIRCULATOR	< 240	< 380	< 380	< 2600	< 60
TRIPLE-JUNCT ISOLATOR	< 0.19	< 0.24	< 0.22	< 2000	< 50
XMA ATTENUATORS	< 52	< 2100	< 47	< 140	< 13
K&L LOW PASS FILTERS	< 1.0	< 1.0	< 1.0	< 1.0	< 0.0
NiTi COAX CABLES	< 750	< 1000	< 380	< 7000	< 230
CRYO AMPLIFIER	< 890	< 12000	< 850	< 10000	< 210
CuBe COAX CABLES	(240 ± 40)	(8000 ± 3000)	(350 ± 90)	< 500	< 20
EPOXY GLUE	< 40	< 50	< 50	< 25	< 10
CRYOGENIC GREASE	(40 ± 5)	(500 ± 60)	(60 ± 20)	(360 ± 40)	< 2





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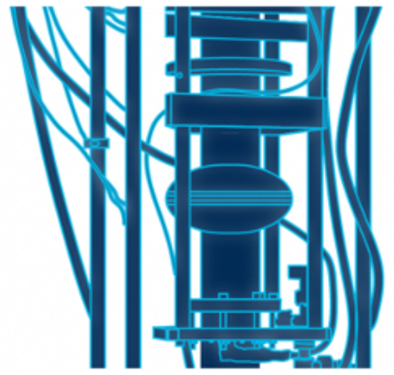
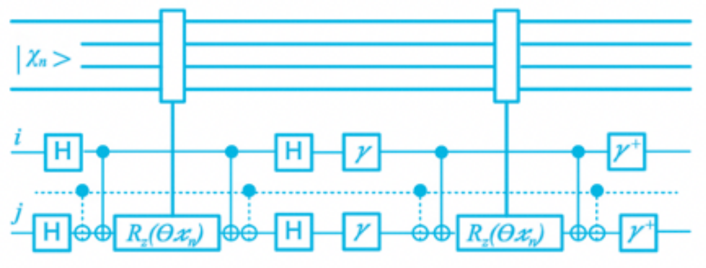
Close Sources

… and simulation of their impact

Component	Description	Rate [mHz]
A	PCB	4.52 ± 0.04
B	Box	$[1-6]\times10^{-3}$
$B*$	Holder	$[2-4]\times10^{-4}$
C	Magnetic Shield	$[2-9]\times10^{-4}$
D	**SMA**	$(2\pm0.4)\times10^{-5}$
E	**Cu coax cables**	$(3\pm0.6)\times10^{-5}$
F	Cryogenic switch	$(1.0\pm0.2)\times10^{-2}$
G	Circulator	$<8\times10^{-4}$
$H*$	Dual-junct. circulator	$<2\times10^{-3}$
$I*$	Triple-junct. isolator	$<2\times10^{-3}$
J	**Attenuators**	$[0.5-1]\times10^{-5}$
K	**Low Pass Filters**	$(1\pm0.2)\times10^{-5}$
L	**NbTi cables**	$<4\times10^{-4}$
M	Cryogenic amplifier	$<2\times10^{-5}$
N	**Cu-Be cables**	1×10^{-6}

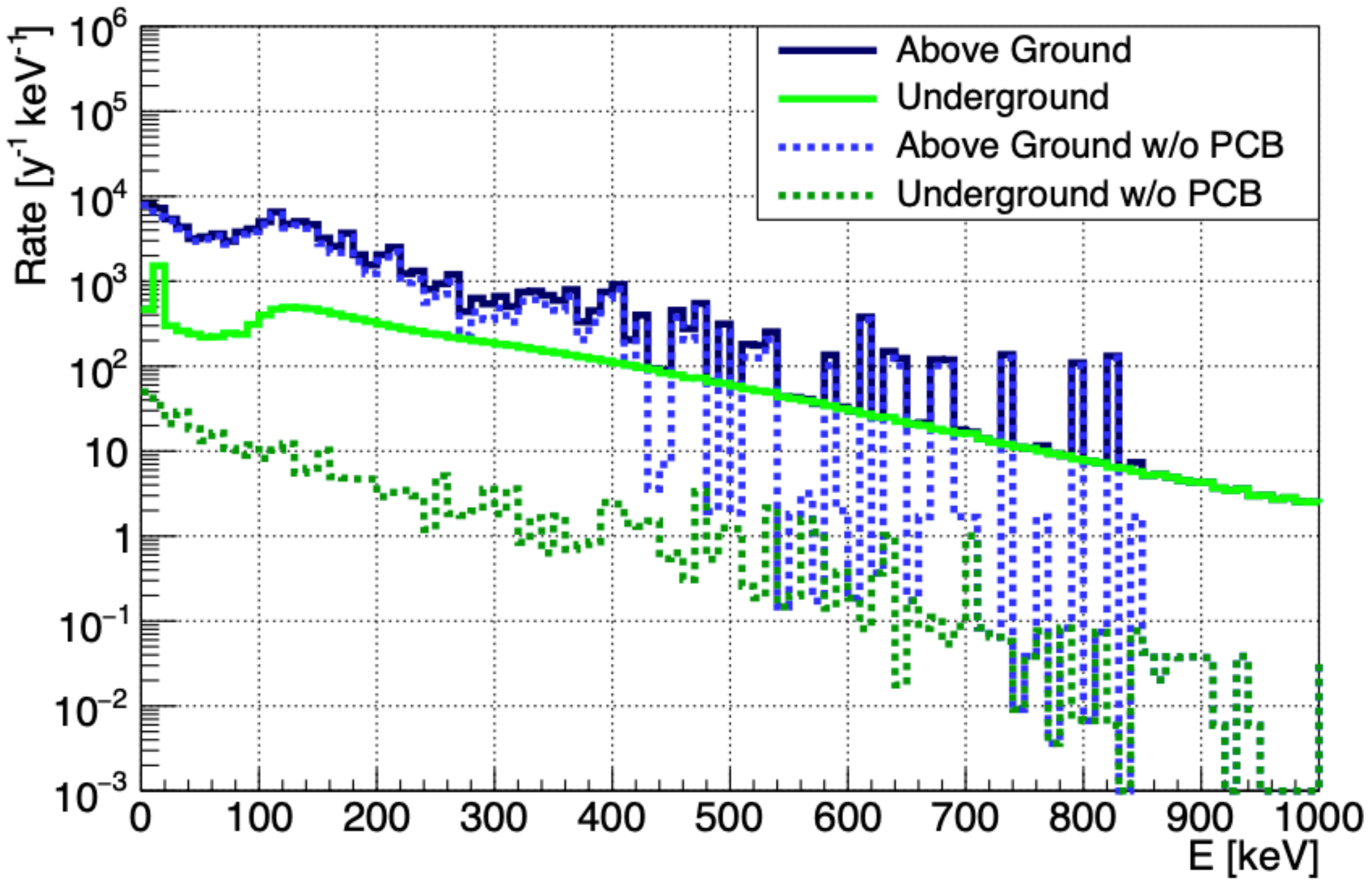
Only the PCB has a sizeable impact





Results

	FNAL [mHz]	LNGS [mHz]
Lab gamma's	18	7 <<1 with lead shield
Muons	10	$<10^{-5}$
Materials	5 (PCB dominated)	5 (PCB dominated)
Neutrons	0.1	$<10^{-4}$



LNGS allows to suppress from ~35 to ~5 mHz -> meet RR requirements

Mariani, De Dominicis, "Disentangling the sources of ionizing radiation in superconducting qubits", https://arxiv.org/abs/2211.13597

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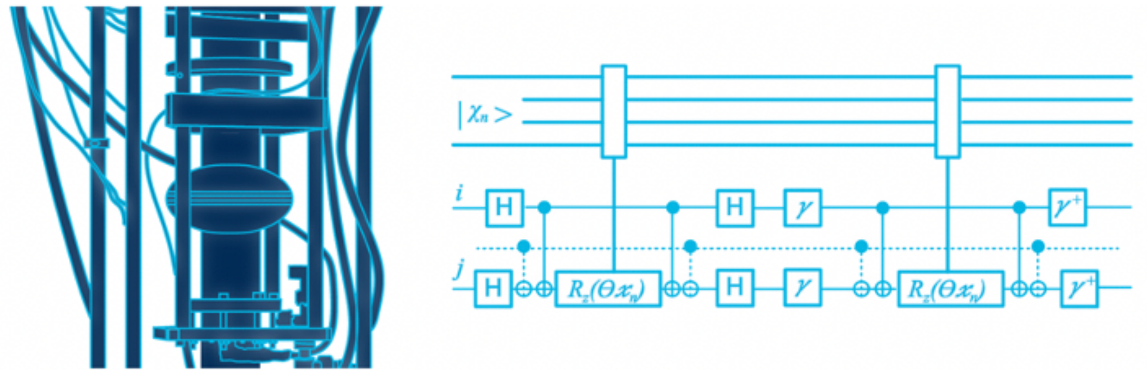
Suppressing the radioactivity above ground not simple (muons…)

In LNGS we would need new PCBs

Already identified PCBs x3 better, R&D can be done



….Y3

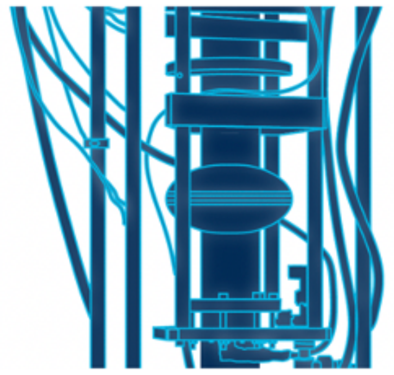
Commissioning of the Keysight electronics

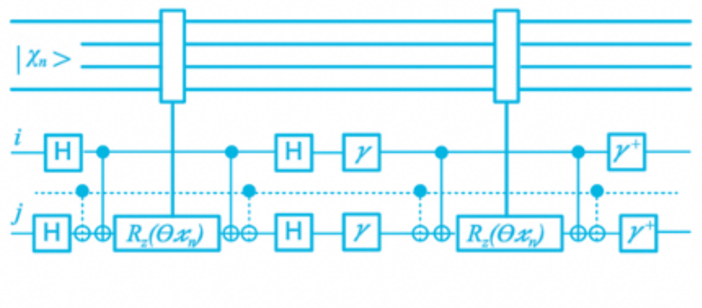
Measurement of the RR chip in the low-radioactivity LNGS facility

Spin-off (with Rigetti): measurement of transmission past indium bonding

Spin-off (with Anna and David): study of a muon-veto for above ground operations

Spin-off (with LNL, PRIN project COLD): development of phonon traps





Thanks for the attention

L. Cardani

N. Casali

I. Colantoni (CNR)

A. Cruciani

F. De Dominicis (GSSI)

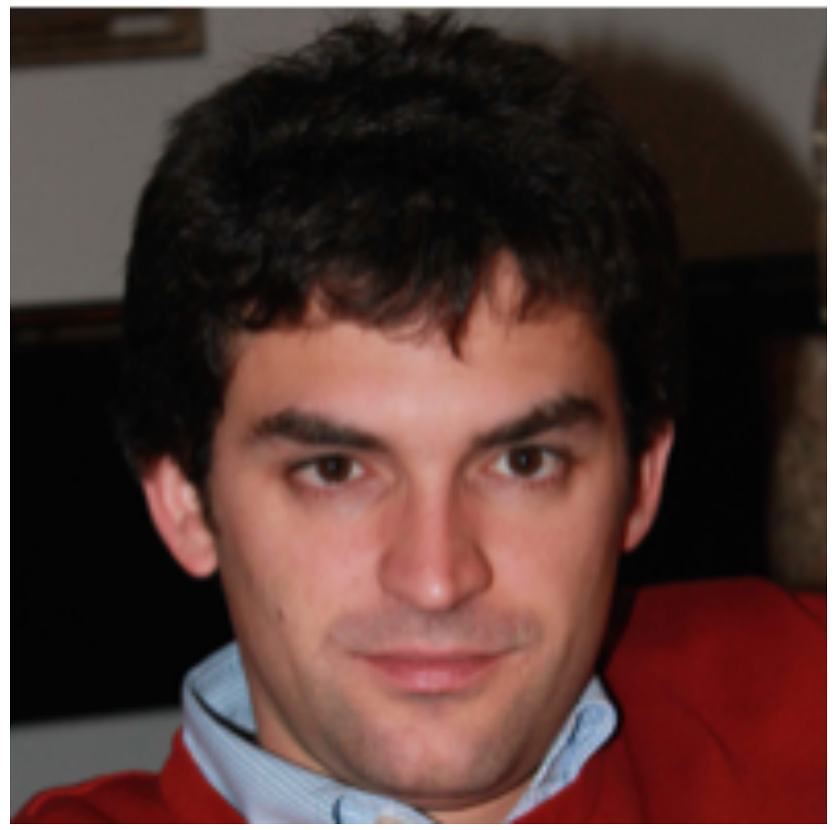
G. D'Imperio

A. Mariani

C. Tomei

V. Pettinacci

S. Pirro (LNGS)



M. Vignati (Sapienza)