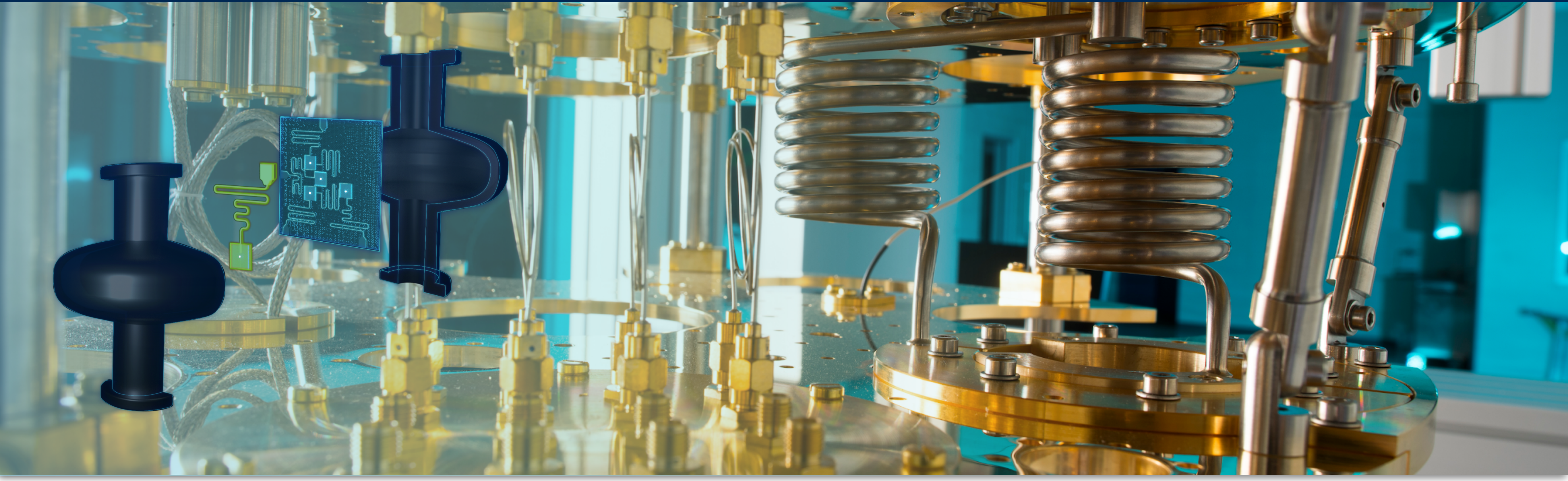

Geant4 Lab Modeling Techniques

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G4CMP Workshop 2024

May 29, 2024, Fermilab, Batavia, IL 60510

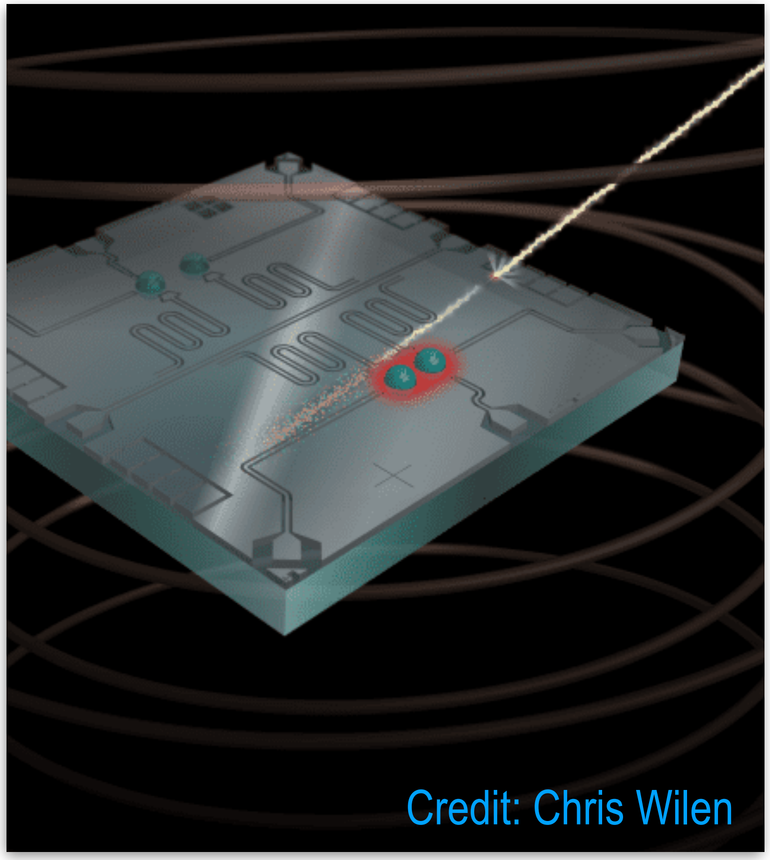
Ministry of Foreign Affairs
and International Cooperation

Istituto Nazionale di Fisica Nucleare

OUTLINE

- GEANT4-BASED MONTE CARLO SIMULATIONS
- OUR SIMULATION FRAMEWORK - DEMETRA
- SIMULATION INPUTS
- METHODOLOGY
- RESULTS
- COMPARISON WITH MEASUREMENTS

Focus on superconducting qubits and simulation of ionizing radiation impacts in these devices



Credit: Chris Wilen

GEANT4-BASED MC SIMULATIONS

MC simulations are an important tool to:

- **Predict the effect** of radiation impacts in a given detector/sensor;
- **Identify** the **major sources of ionizing radiation**;
- **Optimize** the experimental setup;
- **Study** the performance of our **detector**.

GEANT4
A SIMULATION TOOLKIT

Toolkit for the **MC simulation** of the interaction of **particles** with **matter.**

- **Event-based**, MC-driven simulation engine;
- Enables **modeling** of **complex geometries** composed of volumes with defined properties;
- Includes the ability to simulate **different radiation sources**;
- **Tracks particle interactions** within the modeled geometry.

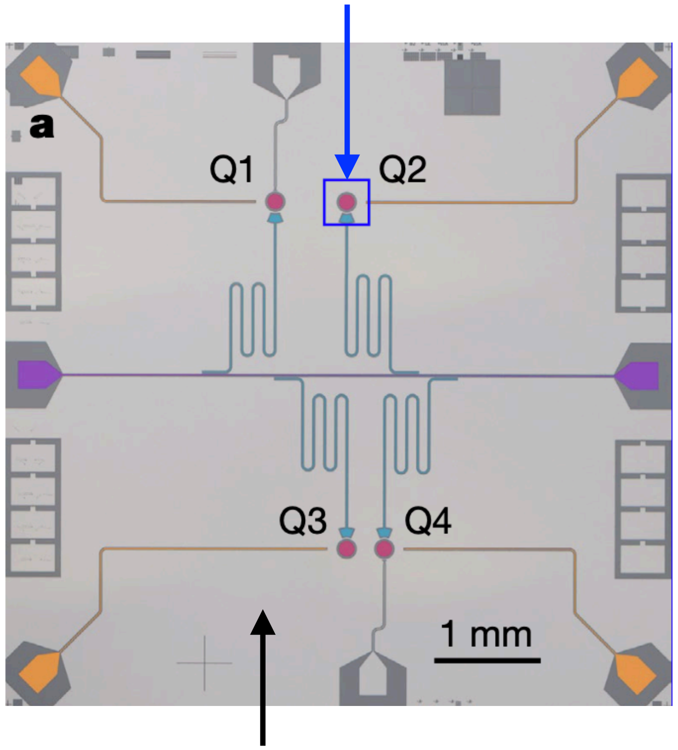
OUR SIMULATION FRAMEWORK - DEMETRA

AIM: Predict ionizing radiation impacts rate and **energy deposited** on **superconducting qubit chips**

Geant-4 based simulation (v10.5.1), with the following inputs:

- **Geometry** of the **experimental setup** (chip, box, holder, shields, cryostat…);
- **Flux of μ, γ, n** (measurements + literature);
- **Radioactivity** of the **setup materials** (measurements).

Direct interaction in the qubit:
unlikely (qubit dimension < 100 μm)



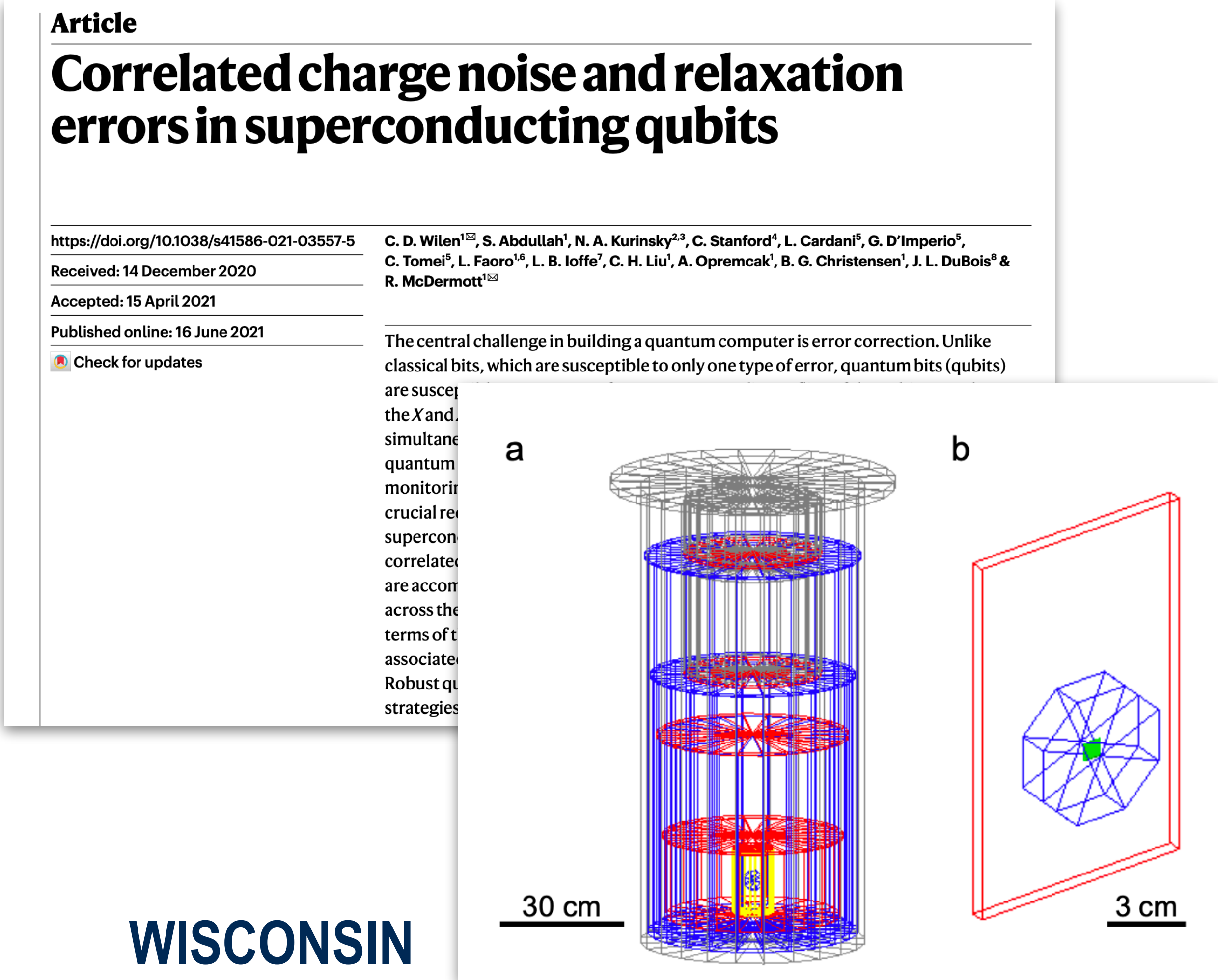
Indirect interaction in the substrate (~1 cm^2)

[C.D. Wilen et al., *Nature* **594**, 369–373 (2021)]

Substrate only active volume
(single qubits NOT modeled in our simulation).

OUR SIMULATION FRAMEWORK - DEMETRA

Designed to implement and adapt to **various cryostats** (Wisconsin, Rome, Gran Sasso Lab) and **chips** (Wisconsin, Rigetti, Fermilab).



Article

Correlated charge noise and relaxation errors in superconducting qubits

https://doi.org/10.1038/s41586-021-03557-5

Received: 14 December 2020

Accepted: 15 April 2021

Published online: 16 June 2021

Check for updates

C. D. Wilen[1✉], S. Abdullah[1], N. A. Kurinsky[2,3], C. Stanford[4], L. Cardani[5], G. D'Imperio[5], C. Tomei[5], L. Faoro[1,6], L. B. Ioffe[7], C. H. Liu[1], A. Opremcak[1], B. G. Christensen[1], J. L. DuBois[8] & R. McDermott[1✉]

The central challenge in building a quantum computer is error correction. Unlike classical bits, which are susceptible to only one type of error, quantum bits (qubits)
are suscep
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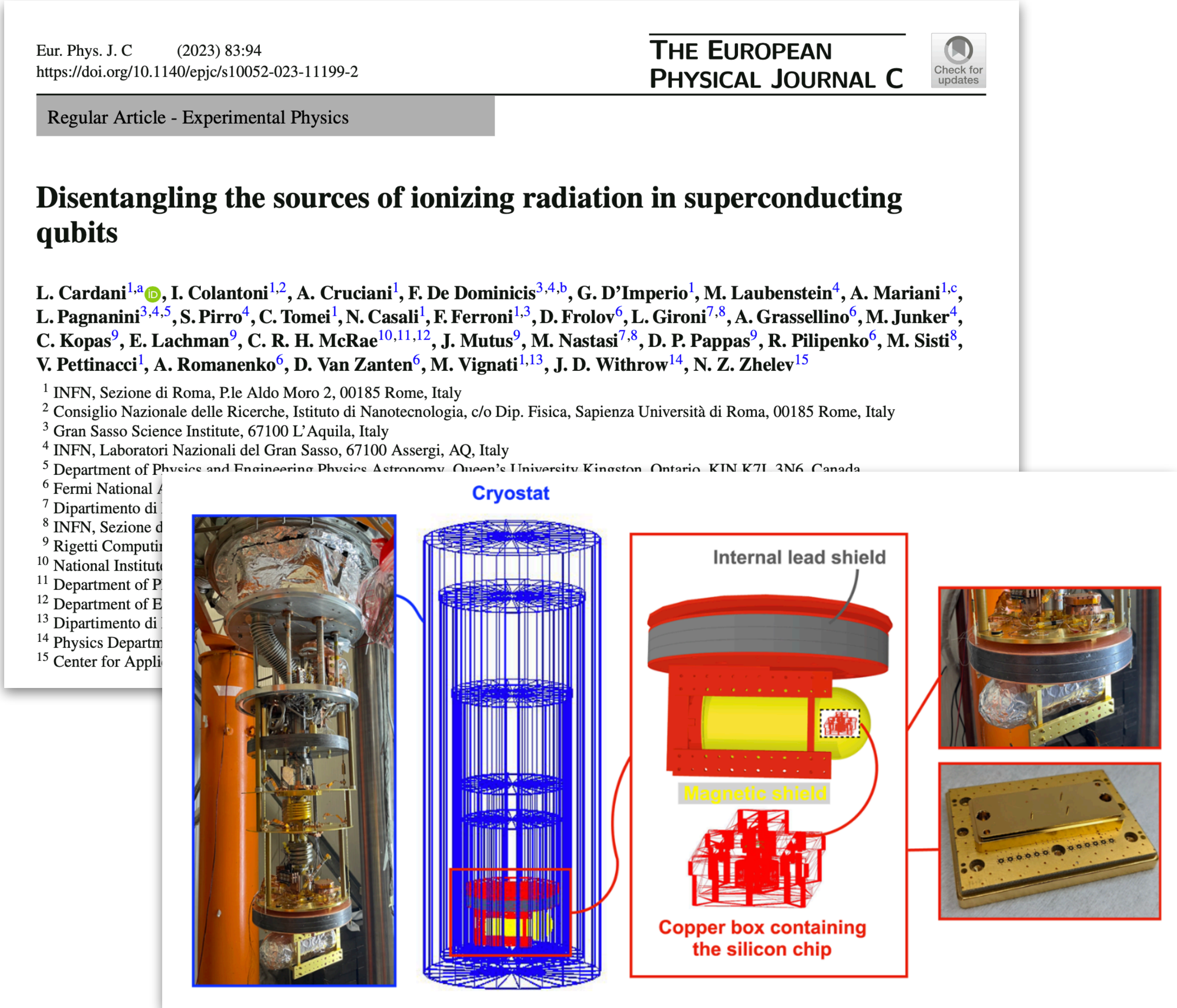

Eur. Phys. J. C (2023) 83:94
https://doi.org/10.1140/epjc/s10052-023-11199-2

THE EUROPEAN PHYSICAL JOURNAL C

Check for updates

Regular Article - Experimental Physics

Disentangling the sources of ionizing radiation in superconducting qubits

L. Cardani[1,a], I. Colantoni[1,2], A. Cruciani[1], F. De Dominicis[3,4,b], G. D'Imperio[1], M. Laubenstein[4], A. Mariani[1,c], L. Pagnanini[3,4,5], S. Pirro[4], C. Tomei[1], N. Casali[1], F. Ferroni[1,3], D. Frolov[6], L. Gironi[7,8], A. Grassellino[6], M. Junker[4], C. Kopas[9], E. Lachman[9], C. R. H. McRae[10,11,12], J. Mutus[9], M. Nastasi[7,8], D. P. Pappas[9], R. Pilipenko[6], M. Sisti[8], V. Pettinacci[1], A. Romanenko[6], D. Van Zanten[6], M. Vignati[1,13], J. D. Withrow[14], N. Z. Zhelev[15]

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[6] Fermi National
[7] Dipartimento di
[8] INFN, Sezione d
[9] Rigetti Computi
[10] National Institut
[11] Department of P
[12] Department of E
[13] Dipartimento di
[14] Physics Departm
[15] Center for Appli

GRAN SASSO LAB (LNGS)

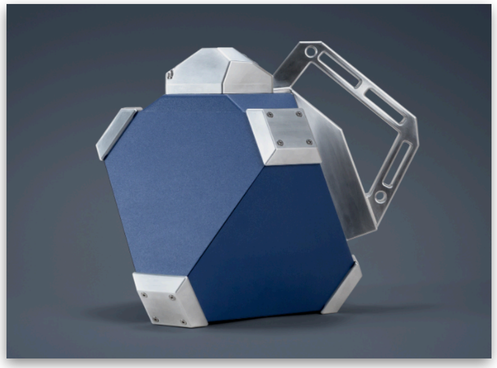
Can accommodate other configurations upon request

SIMULATION INPUTS - MEASUREMENTS OF IONIZING RADIATION SOURCES

Dedicated tools and **facilities** to **measure fluxes** from **"far" sources** and **internal contaminations of materials ("close" sources)**

"Far" sources

NaI(Tl) scintillation detector for **gammas**



DIAMON spectrometer for **neutrons**

"Close" sources

- **STELLA (SubTerranean Low-Level Assay)** facility @LNGS;
- **HPGe** detectors.

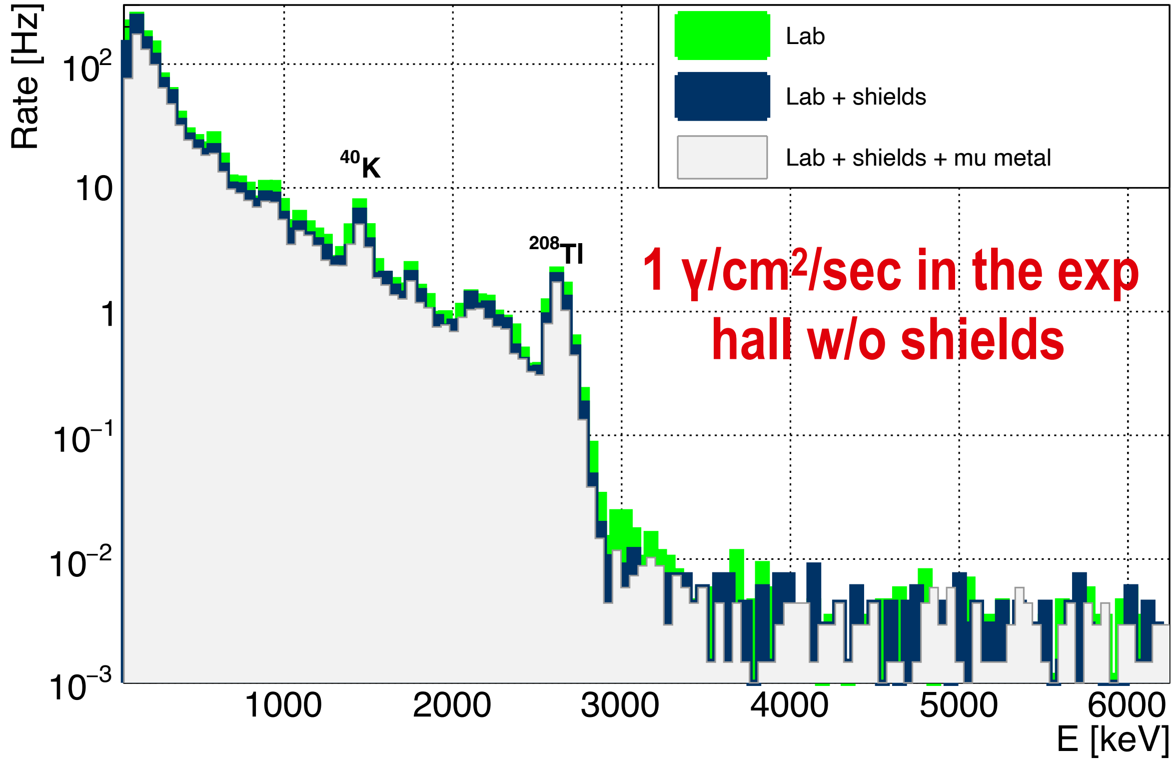
- **Chemistry Lab** @LNGS;
- **ICP-MS**.

Provide accurate and reliable data for our simulation

SIMULATION INPUTS - “FAR” SOURCES

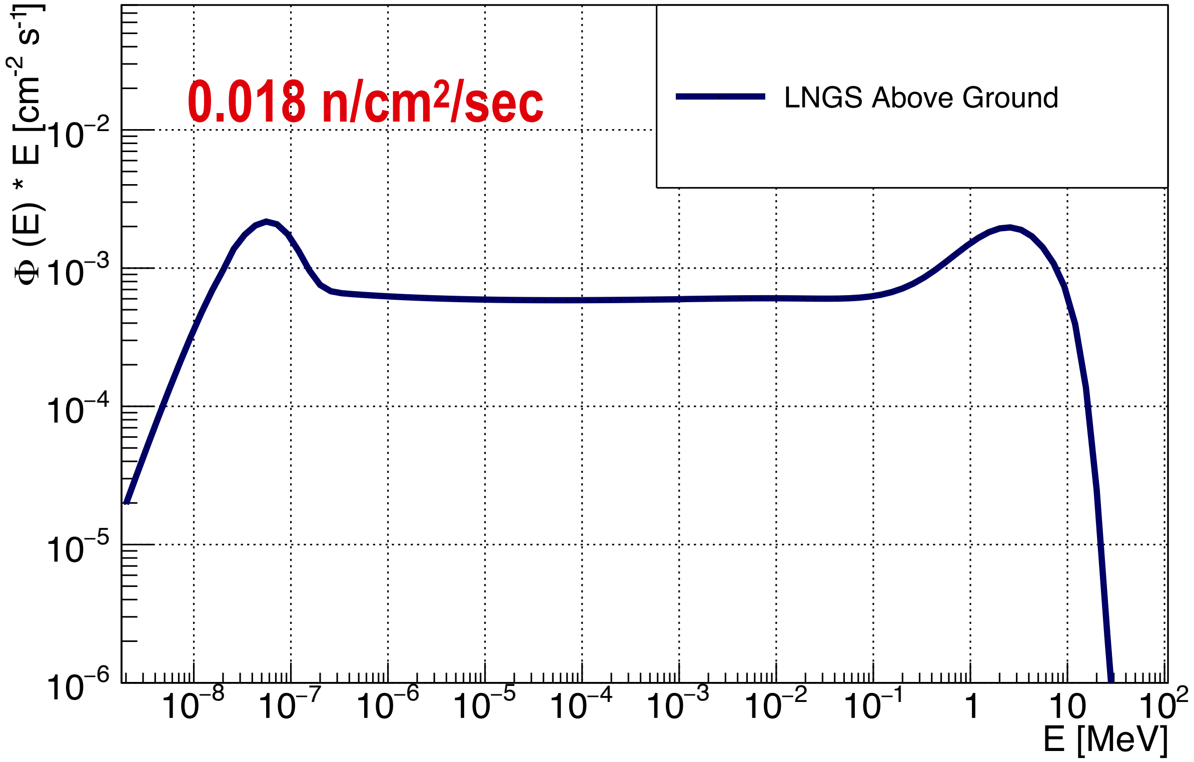
- **Muons** → literature [IJMP A. Vol. 33, No.30, (2018)] (**sub-dominant underground**);
- **Gammas** → measurements @ underground cryogenic facility of LNGS and in other above-ground labs;
- **Neutrons** → measurements @ different locations above-ground (**sub-dominant underground**).

Energy spectrum of environmental γs measured underground @LNGS with different shielding conditions



1 γ/cm²/sec in the exp hall w/o shields

Energy spectrum of neutrons measured above-ground @LNGS



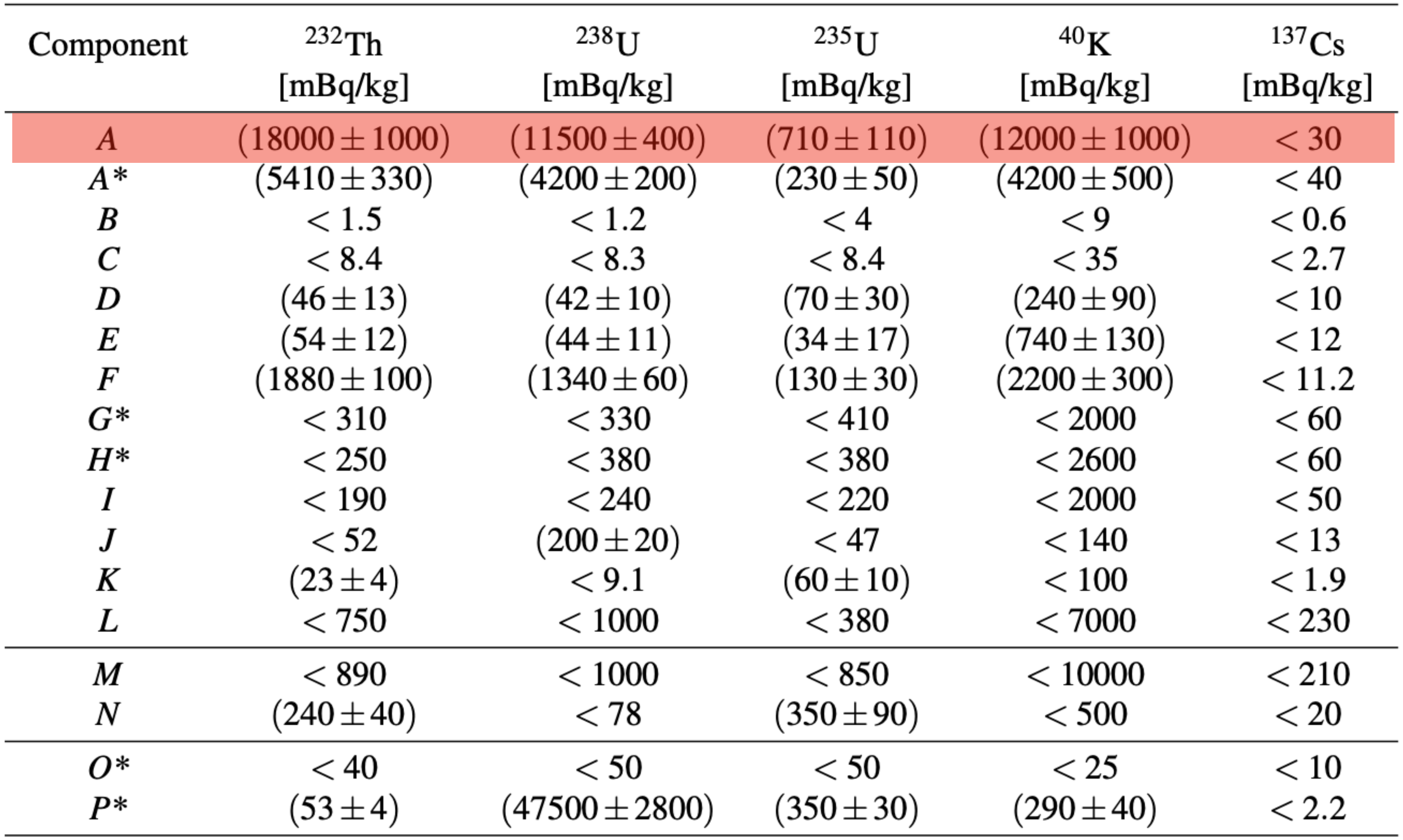
0.018 n/cm²/sec

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

Similar spectral shapes but different fluxes expected in other laboratories

SIMULATION INPUTS - “CLOSE” SOURCES

Measurements of **radioactive isotopes activities** in all the setup components with High-Purity Germanium (HPGe) detectors @INFN-LNGS STELLA underground facility.

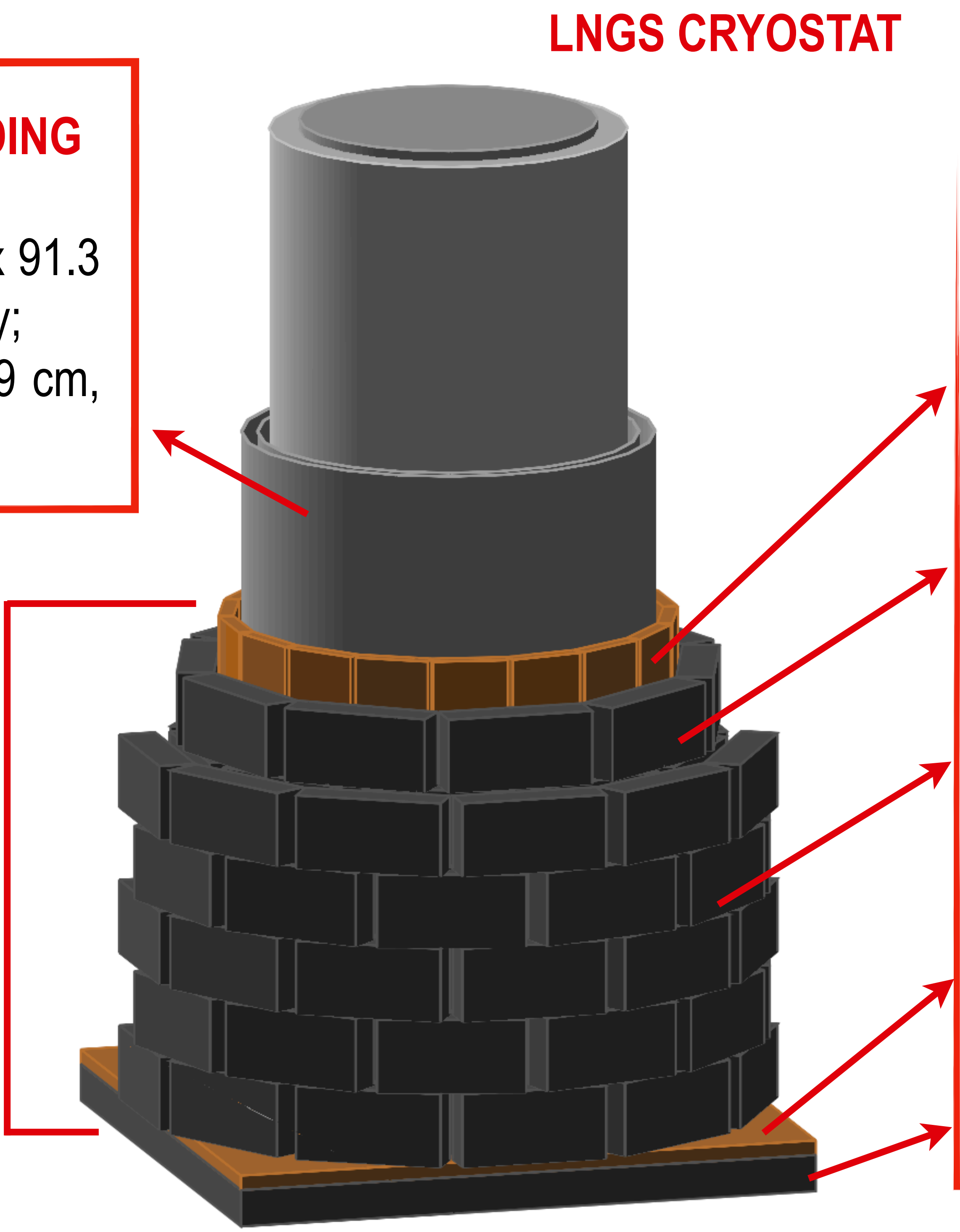


	Component	^{232}Th [mBq/kg]	^{238}U [mBq/kg]	^{235}U [mBq/kg]	^{40}K [mBq/kg]	^{137}Cs [mBq/kg]
PCB	*A*	(18000 ± 1000)	(11500 ± 400)	(710 ± 110)	(12000 ± 1000)	< 30
A-MAGNETIC PCB	*A**	(5410 ± 330)	(4200 ± 200)	(230 ± 50)	(4200 ± 500)	< 40
COPPER BOX + COPPER FINGER	*B*	< 1.5	< 1.2	< 4	< 9	< 0.6
MAGNETIC SHIELD	*C*	< 8.4	< 8.3	< 8.4	< 35	< 2.7
SMA ADAPTERS	*D*	(46 ± 13)	(42 ± 10)	(70 ± 30)	(240 ± 90)	< 10
COPPER COAX CABLES	*E*	(54 ± 12)	(44 ± 11)	(34 ± 17)	(740 ± 130)	< 12
RADIALL SWITCH	*F*	(1880 ± 100)	(1340 ± 60)	(130 ± 30)	(2200 ± 300)	< 11.2
SINGLE-JUNCT CIRCULATOR	*G**	< 310	< 330	< 410	< 2000	< 60
DUAL-JUNCT CIRCULATOR	*H**	< 250	< 380	< 380	< 2600	< 60
TRIPLE-JUNCT ISOLATOR	*I*	< 190	< 240	< 220	< 2000	< 50
XMA ATTENUATORS	*J*	< 52	(200 ± 20)	< 47	< 140	< 13
K&L LOW PASS FILTERS	*K*	(23 ± 4)	< 9.1	(60 ± 10)	< 100	< 1.9
NiTi COAX CABLES	*L*	< 750	< 1000	< 380	< 7000	< 230
CRYO AMPLIFIER	*M*	< 890	< 1000	< 850	< 10000	< 210
CuBe COAX CABLES	*N*	(240 ± 40)	< 78	(350 ± 90)	< 500	< 20
EPOXY GLUE	*O**	< 40	< 50	< 50	< 25	< 10
CRYOGENIC GREASE	*P**	(53 ± 4)	(47500 ± 2800)	(350 ± 30)	(290 ± 40)	< 2.2

Most radioactive component

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

SIMULATION GEOMETRY - A SPECIFIC CASE



2 LAYERS MAGNETIC SHIELDING

- **Outer layer:** 55.6 cm (OD) x 91.3 cm, 1.5 mm-thick Permimphy;
- **Inner layer:** 51 cm (ID) x 89 cm, 1.5 mm-thick Permimphy.

RADIATION SHIELDING

1 round of 10 x 66.5 cm^2, 2 cm-thick Cu bars

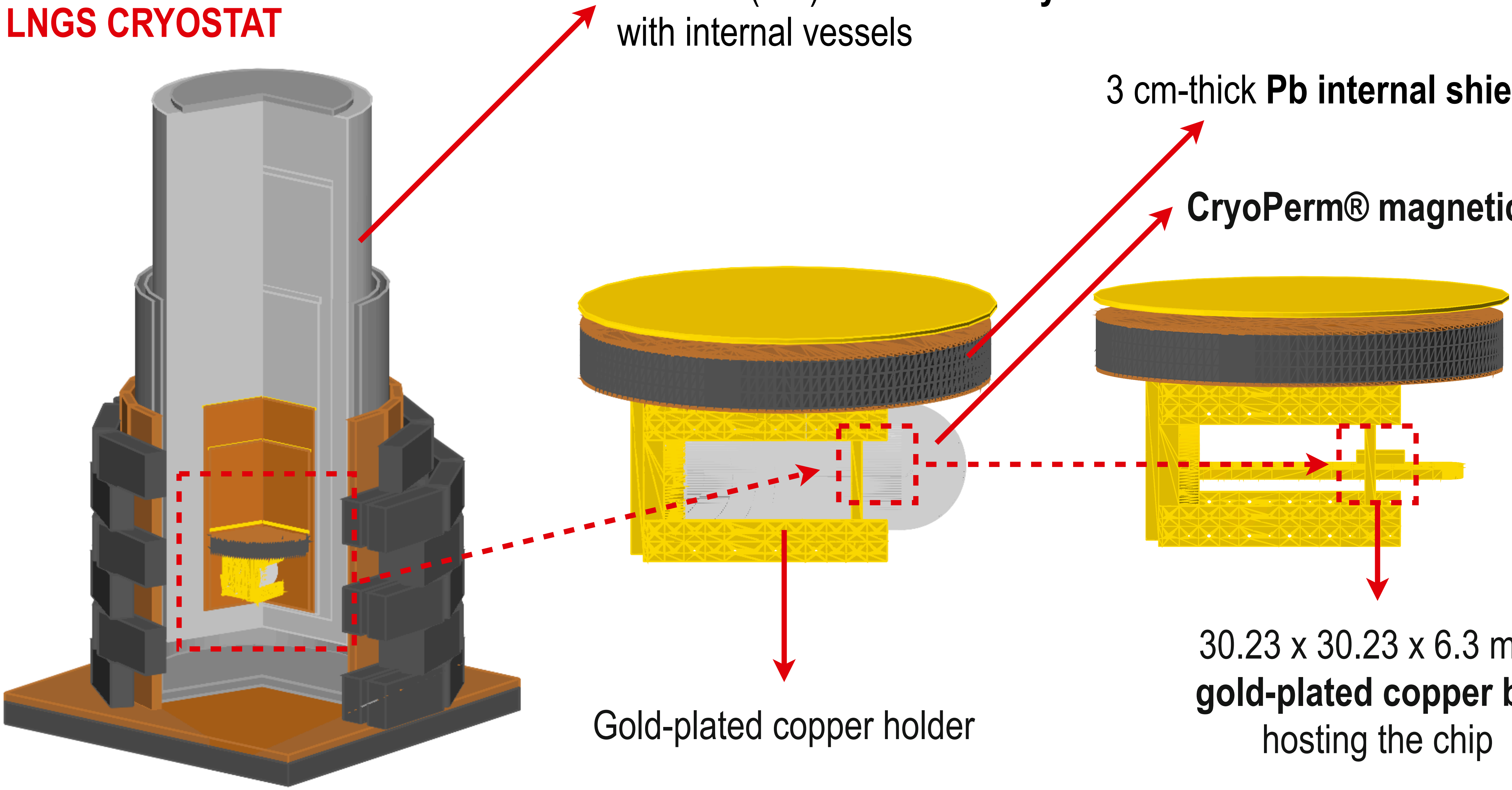
1 round of 10 x 20 cm^2, 5 cm-thick Pb bricks

½ round of 10 x 20 cm^2, 5 cm-thick Pb bricks

80 x 80 cm^2, 2 cm-thick Cu

80 x 80 cm^2, 5 cm-thick Pb

SIMULATION GEOMETRY - A SPECIFIC CASE



LNGS CRYOSTAT

48.1 cm (OD) x 119.5 cm **cryostat** with internal vessels

3 cm-thick **Pb internal shield**

CryoPerm® magnetic shield

Gold-plated copper holder

30.23 x 30.23 x 6.3 mm^3
gold-plated copper box
hosting the chip

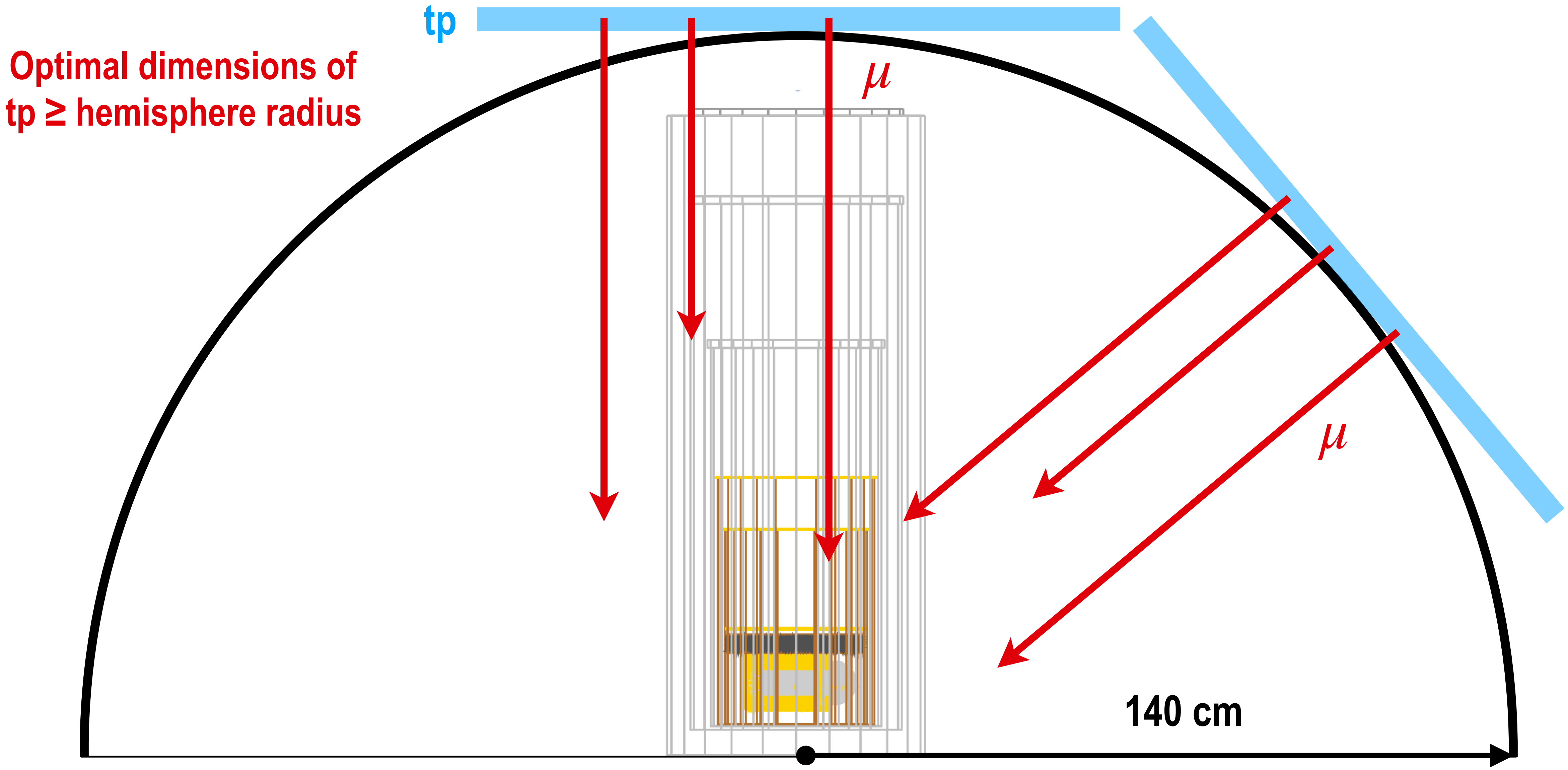
SUPERCONDUCTING CHIP

- 7.5 x 7.5 mm^2, 432 µm-thick **HEMEX Sapphire substrate**;
- **Nb** 160 nm-thick **(bottom) layer;**
- **Au** 10 nm-thick **(top) layer.**

METHODOLOGY

SIMULATION STRATEGY - ATMOSPHERIC MUONS

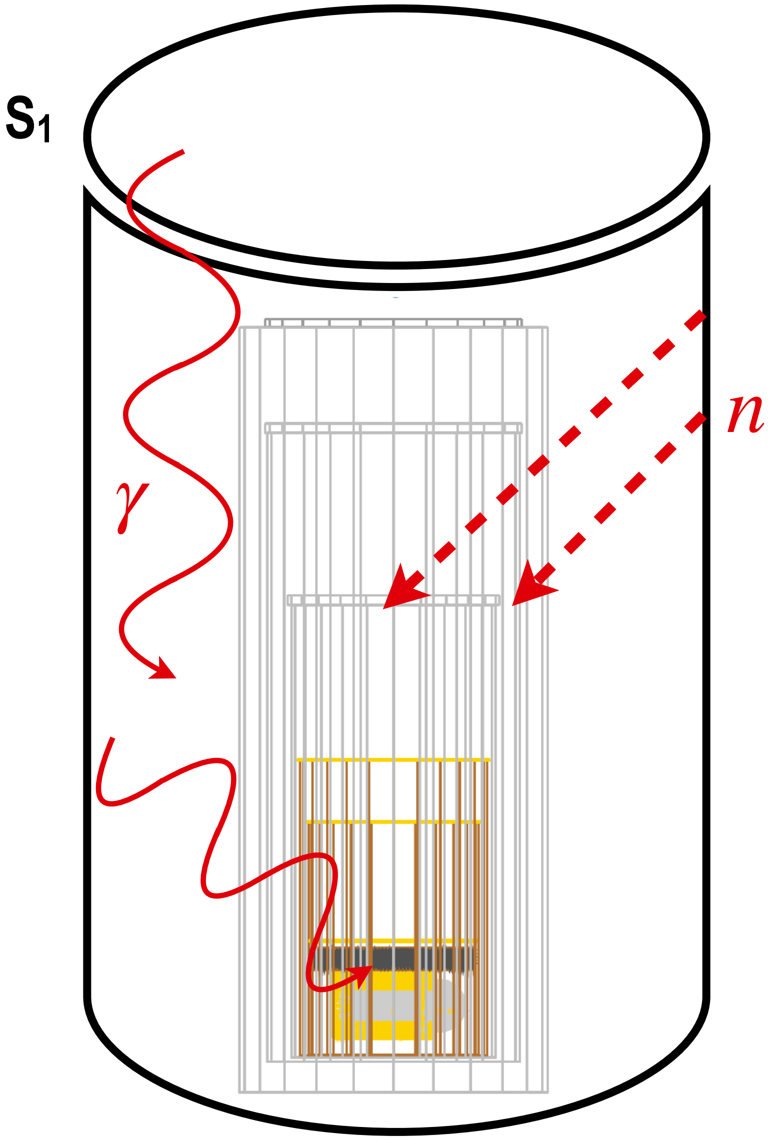
- **Positions** randomly generated on a hemisphere surrounding the cryostat, according to a **$\cos^2$ distribution**;
- For every sampled position, **muons** perpendicularly generated from a **(140x140) cm^2 tangent-plane (tp)** to the hemisphere.



Optimal dimensions of tp ≥ hemisphere radius

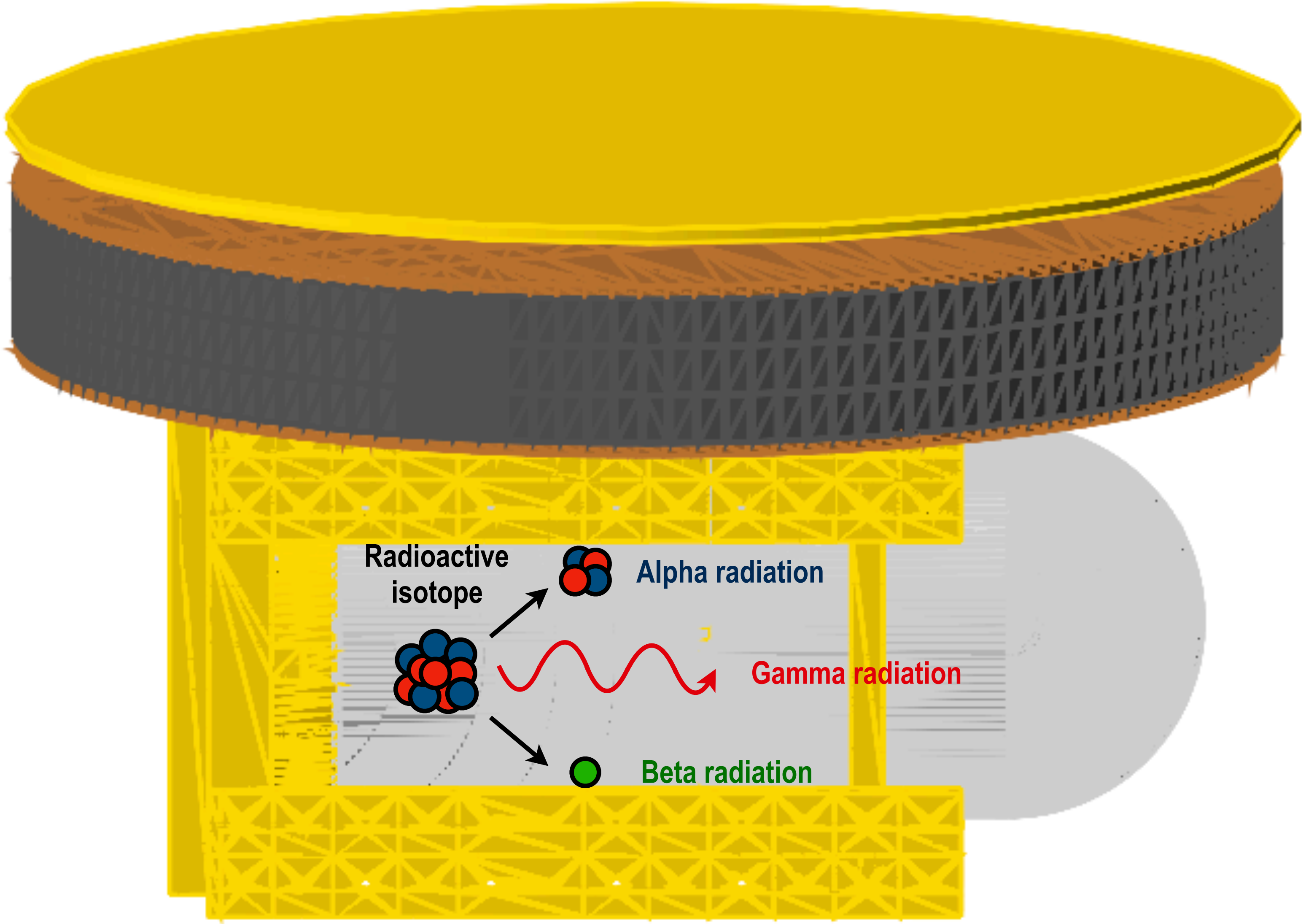
SIMULATION STRATEGY - ENVIRONMENTAL GAMMAS AND NEUTRONS

- **Gammas** and **neutrons** randomly (and uniformly) generated from a **cylindrical surface (S_1)** based on measured spectra with isotropic momentum distribution;
- Interaction rate in the substrate estimated by scaling the number of recorded events to flux measurements.

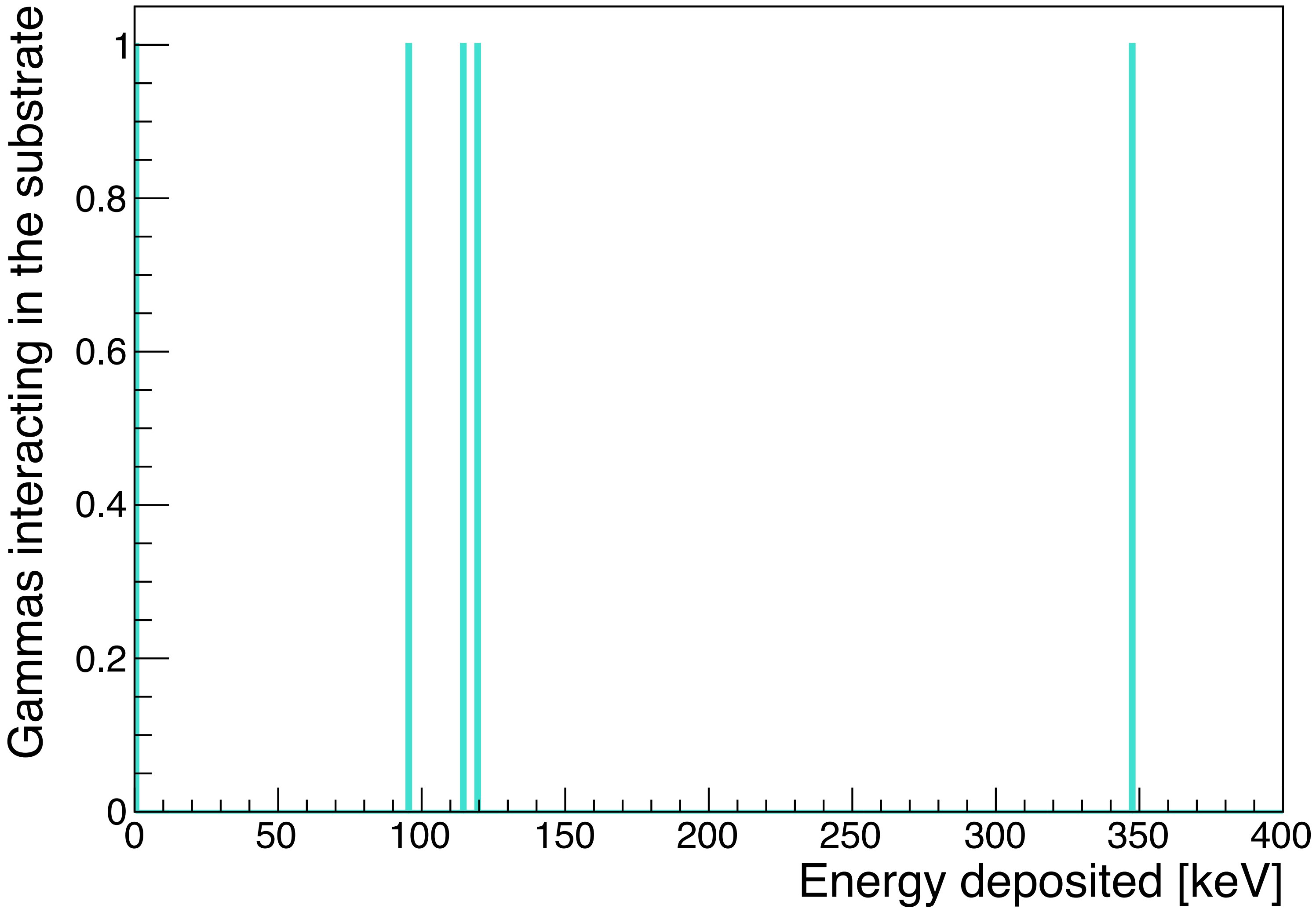


SIMULATION STRATEGY - CLOSE SOURCES OF RADIOACTIVITY

- **Radioactive decays** of relevant isotopes (^{40}K, ^{232}Th and ^{238}U chains) uniformly distributed within the **volumes of the setup components**;
- Interaction rate in the substrate estimated by scaling the number of recorded events to measured isotope activities.



ENVIRONMENTAL GAMMAS - SIMULATION CHALLENGE



- **Number of generated events:**

$1e^8$

- **Gammas interacting in the substrate (no shield):**

5

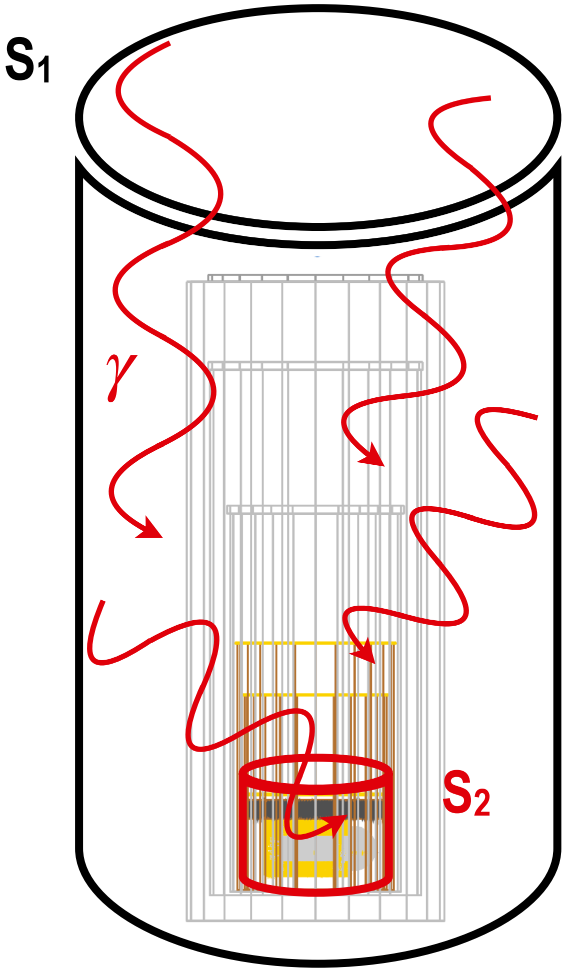
Statistics is too low!!

5 gammas interacting in the substrate every 100 million

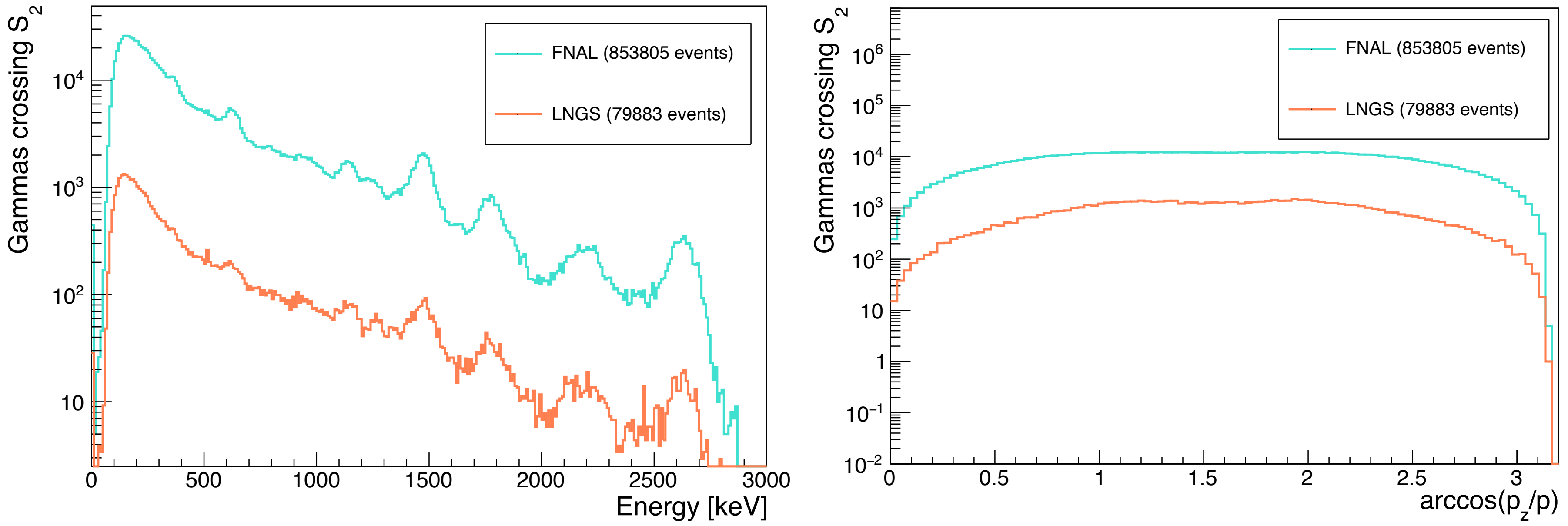
ENVIRONMENTAL GAMMAS - SIMULATION SOLUTION

Environmental gammas can be simulated in TWO STEPS:

- **Gammas** randomly (and uniformly) generated with isotropic momentum distribution from a **cylindrical surface (S_1)** based on measured spectrum with isotropic momentum distribution;
- **Energy** and **momentum** of γs crossing a smaller **cylindrical surface (S_2)** recorded to start a **2nd generation**, according to measured energy and angular distributions in S_2;
- Interaction rate in the substrate estimated by scaling recorded event counts to flux recorded in S_2 (requires geometry correction factor).



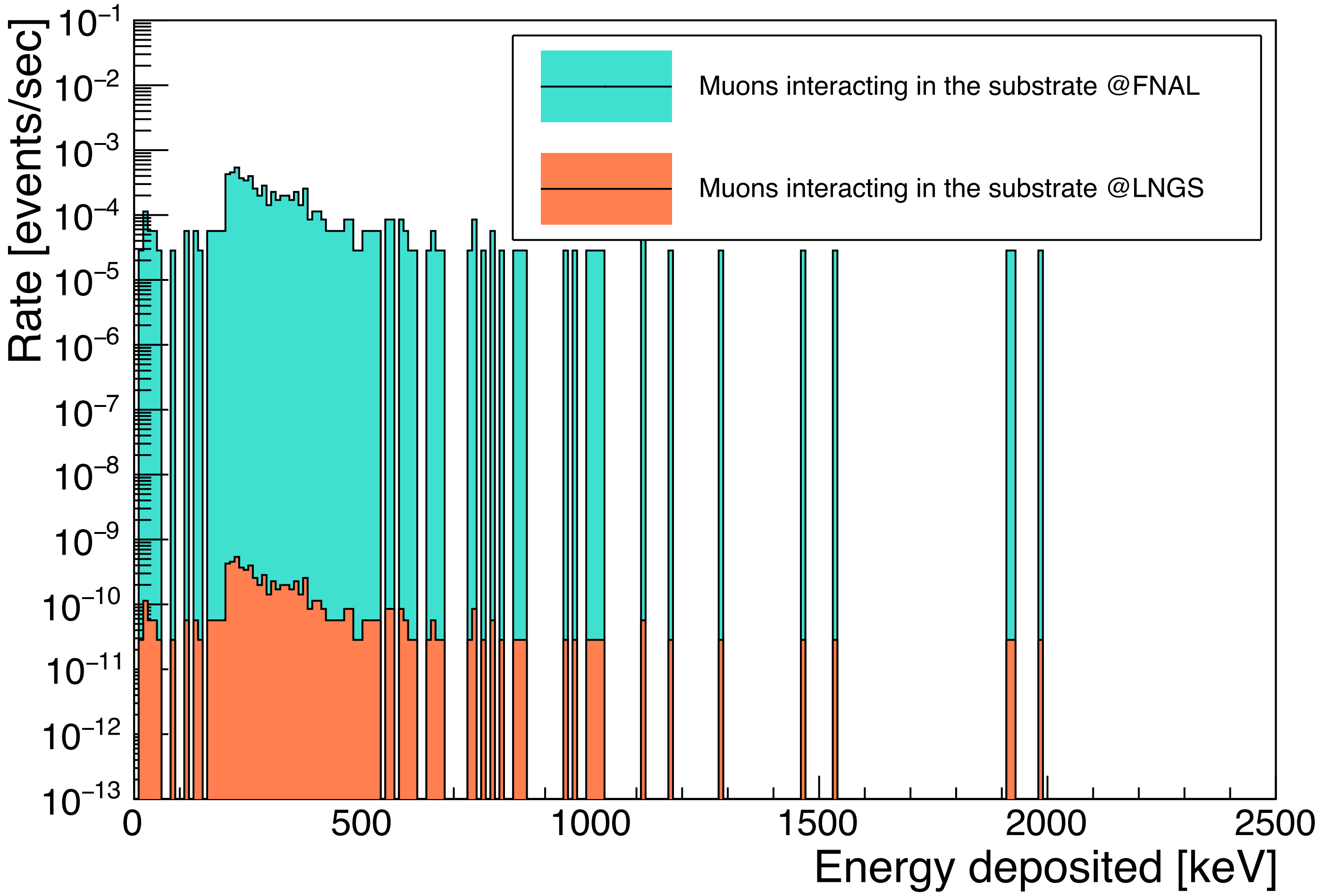
Energy and angular distributions of γs crossing S_2



SIMULATION RESULTS

SIMULATION RESULTS - ATMOSPHERIC MUONS

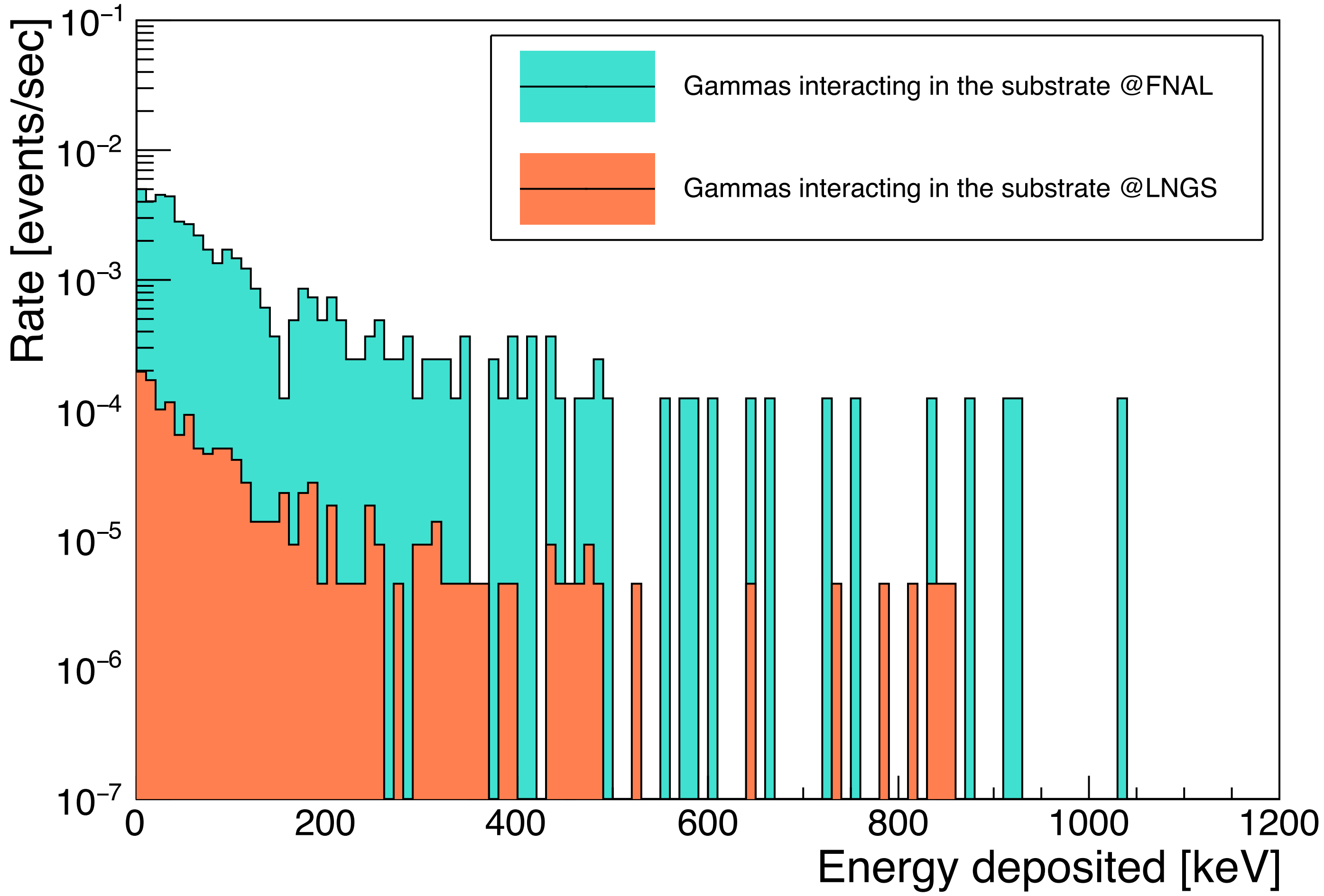
	FNAL **(no shield)**	**LNGS** **(Cu + Pb shield)**
Flux in exp hall [μ/cm^2/min]	1 (literature)	$1e^{-6}$ (literature)
Number of generated events	$11.5e^{6}$	$11.5e^{6}$
Simulation equivalent time [sec]	$352e^{2}$	$352e^{8}$
μs interacting in the substrate [events/sec]	(8.0 ± 0.5) x 10^{-3}	(8.0 ± 0.5) x10^{-9}



- **~1 μ / 125 sec @FNAL;**
- **~1 μ / 4 years @LNGS.**

SIMULATION RESULTS - ENVIRONMENTAL GAMMAS

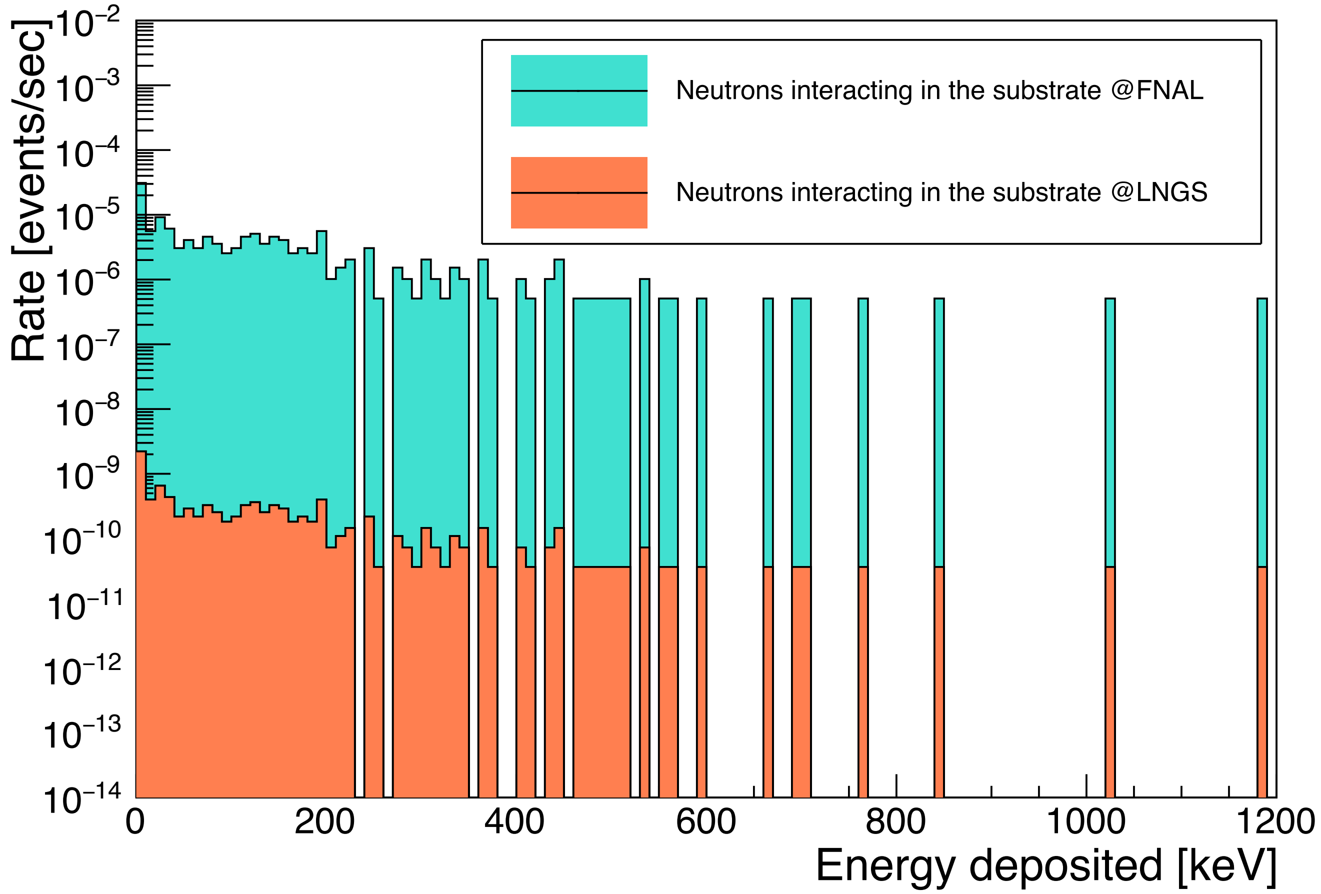
	FNAL (No shield)	**LNGS (Cu + Pb shield)**
Flux of γs crossing S_2 [γ/cm²/s]	~1.5	$5.6e^{-2}$
Number of generated events	$1e^8$	$1e^8$
Simulation equivalent time [sec]	$163e^2$	$438e^3$
γs interacting in the substrate [events/sec]	$(46 \pm 2) \times 10^{-3}$	$(1.3 \pm 0.1) \times 10^{-3}$



- **~1 γ / 22 sec @FNAL;**
- **~1 γ / 769 sec @LNGS.**

SIMULATION RESULTS - NEUTRONS

	FNAL (No shield)	**LNGS (Cu + Pb shield)**
Flux in exp hall [n/cm^2/sec]	0.014 (averaging measured fluxes in "standard" labs)	1e^{-6} (measured)
Number of generated events	13e^8	13e^8
Simulation equivalent time [sec]	191e^4	267e^8
ns interacting in the substrate [events/sec]	$(1.0 \pm 0.3) \times 10^{-4}$	$(7.0 \pm 0.5) \times 10^{-9}$

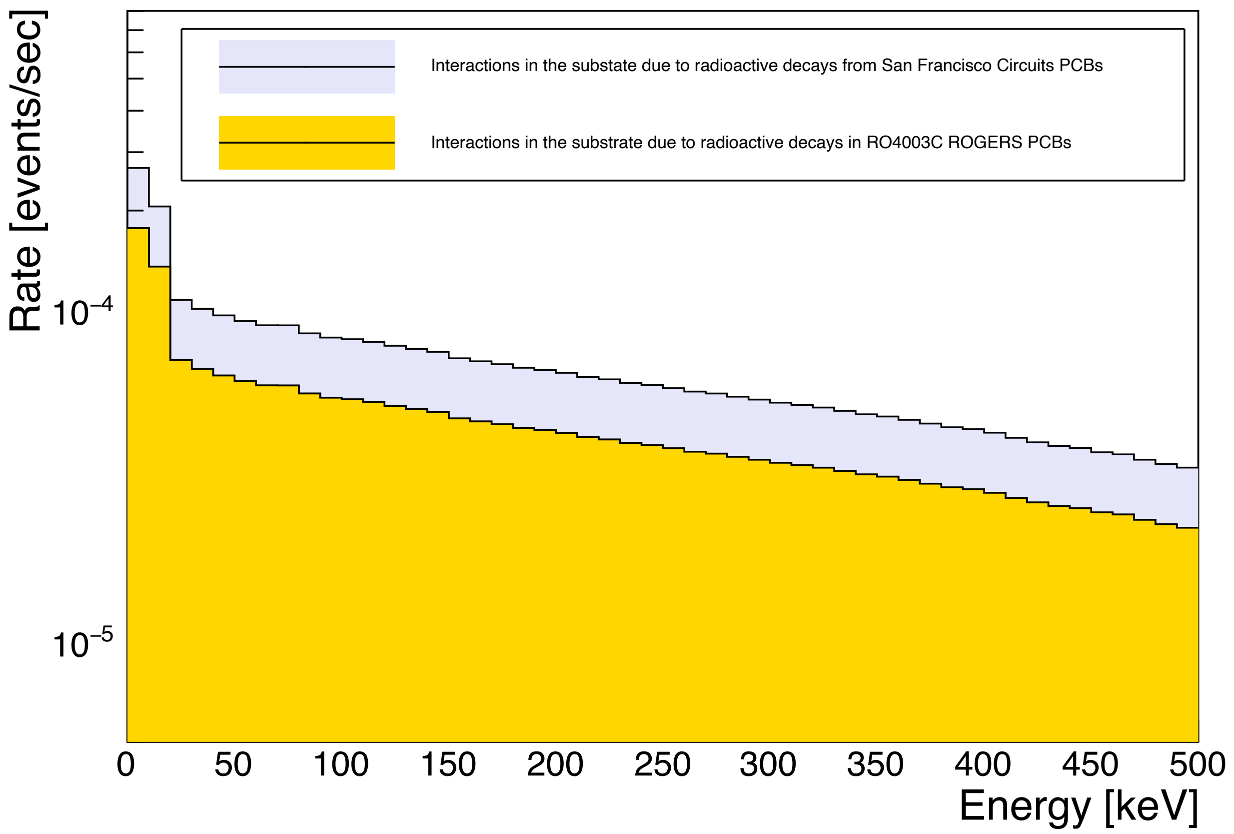


- **~1 n / 3 hours @FNAL;**
- **~1 n / 4.5 years @LNGS.**

SIMULATION RESULTS - CLOSE SOURCES OF RADIOACTIVITY

Component	Description	Rate [events/sec]
A	PCB	[3 - 4.5] x 10^{-3}
B	Box	[1 - 6] x 10^{-6}
B*	Holder	[2 - 4] x 10^{-7}
C	Magnetic Shield	[2 - 9] x 10^{-7}
D	SMA	(2.0 ± 0.4) x 10^{-8}
E	Cu coax cables	(3.0 ± 0.6) x 10^{-8}
F	Cryogenic switch	(1.0 ± 0.2) x 10^{-5}
G	Circulator	< 8 x 10^{-7}
H*	Dual-junct. circulator	< 2 x 10^{-6}
I*	Triple-junct. isolator	< 2 x 10^{-6}
J	Attenuators	[0.5 - 1] x 10^{-8}
K	Low Pass Filter	(1.0 ± 0.2) x 10^{-8}
L	NbTi cables	< 4 x 10^{-7}
M	Cryogenic amplifiers	< 2 x 10^{-8}
N	Cu-Be cables	< 1 x 10^{-9}

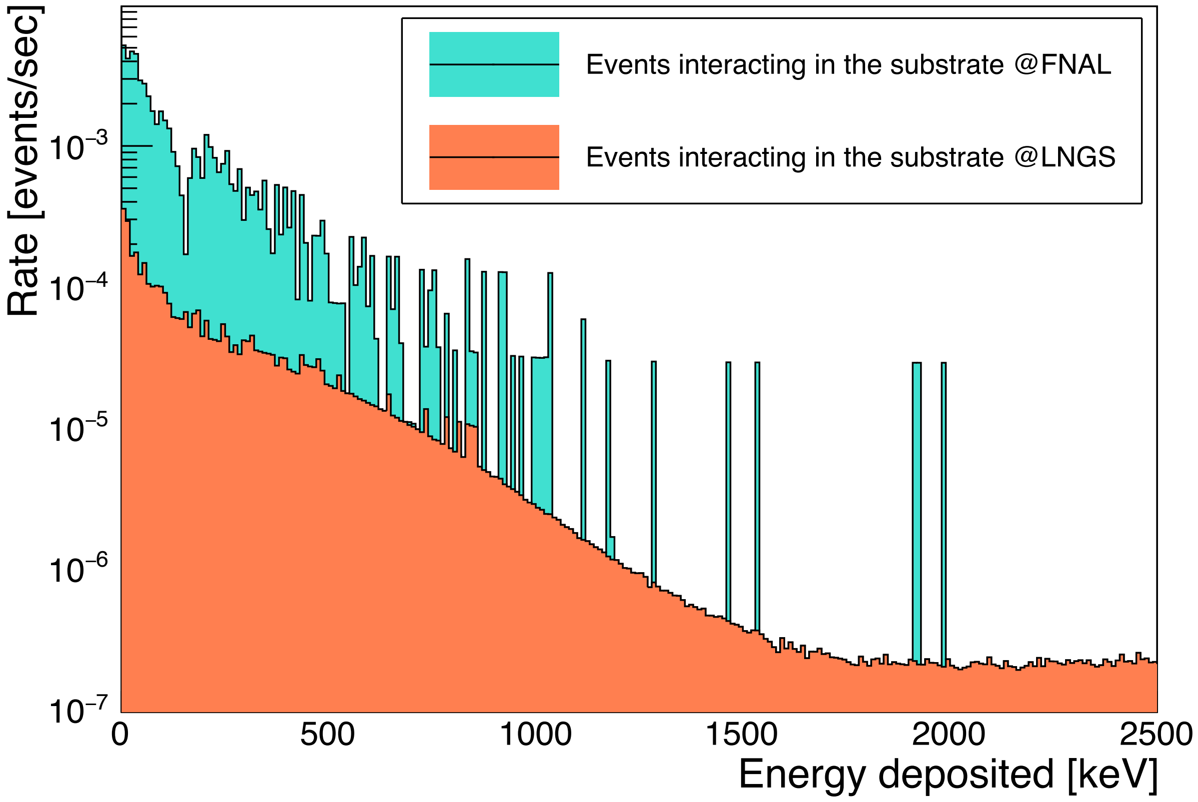
Assumed equal contributions for FNAL and LNGS



Only the PCB has a significant impact:
~ 1 event / 280 sec

SIMULATION RESULTS - SUMMARY

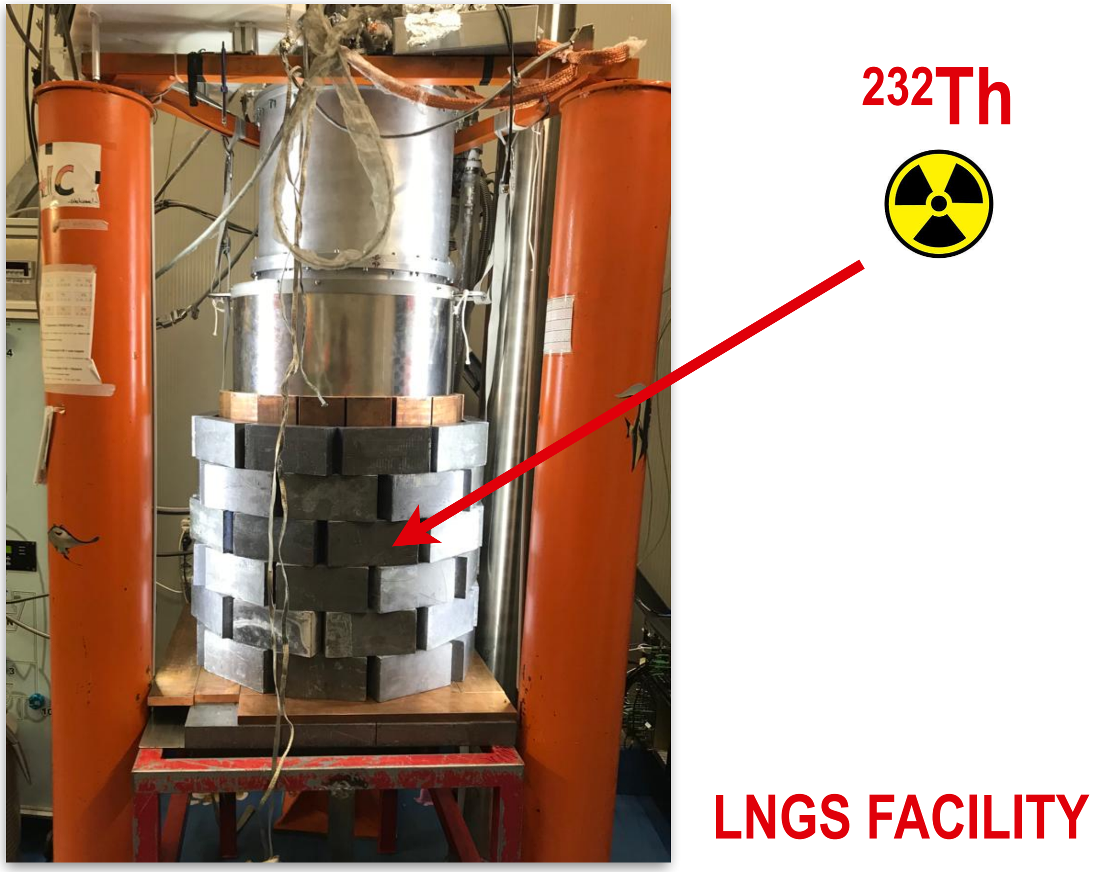
Source	Rate in the substrate [events/sec]	
	FNAL (No shield)	**LNGS (Cu + Pb shield)**
Lab's gammas	$(46 \pm 2) \times 10^{-3}$	$(1.3 \pm 0.1) \times 10^{-3}$
Muons	$(8.0 \pm 0.5) \times 10^{-3}$	$(8.0 \pm 0.5) \times 10^{-9}$
Neutrons	$(1.0 \pm 0.3) \times 10^{-4}$	$(7.0 \pm 0.5) \times 10^{-9}$
Close sources	$(3.0 \pm 0.7) \times 10^{-3}$ (PCB dominated)	$(3.0 \pm 0.7) \times 10^{-3}$ (PCB dominated)
Total	$(57 \pm 3) \times 10^{-3}$	$(4.3 \pm 0.8) \times 10^{-3}$



- **~1 event / 17 sec @FNAL;**
- **~1 event / 233 sec @LNGS.**

COMPARING SIMULATION WITH MEASUREMENTS

MEASUREMENTS WITH RADIOACTIVE SOURCES

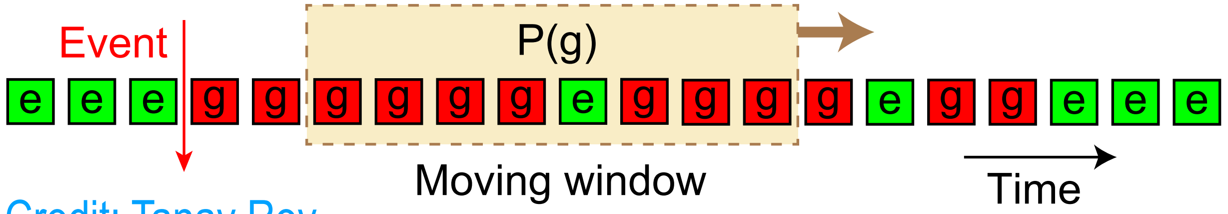


- **Superconducting qubits exposed to Thorium radioactive sources** with increasing activity levels;
- **Sources positioned** between the cryostat and the copper bars, approximately at the **same height as the chip**.

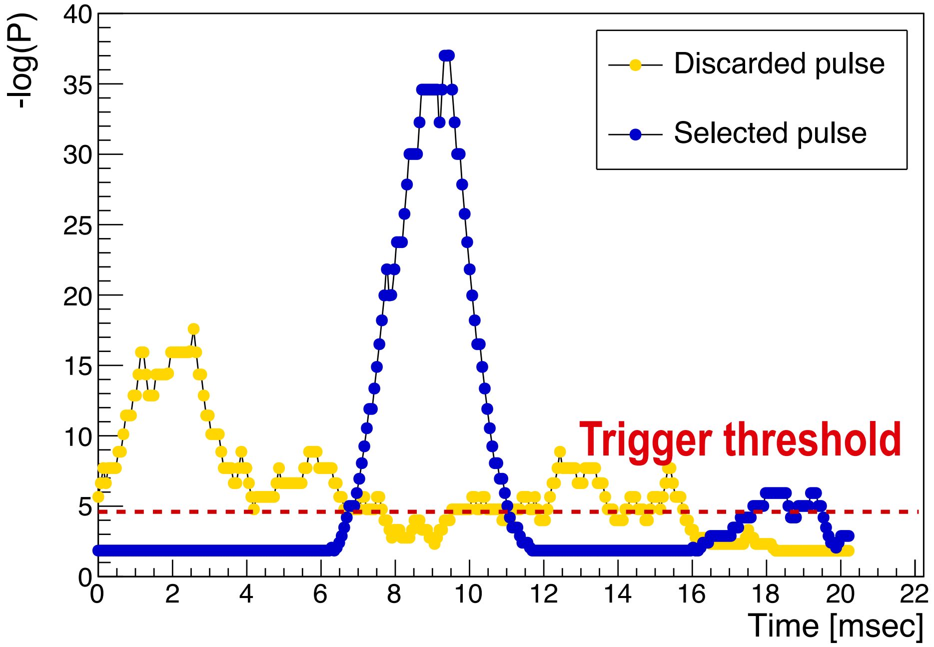
Talk by Tanay Roy at RISQ 2024 on Thursday

[De Dominicis et al., *arXiv:2405.18355* (2024)]

- **Fast decay detection protocol** for **single qubit**;
- Pulses selected based on the probability of observing a certain stream of $|e>$ and $|g>$ states

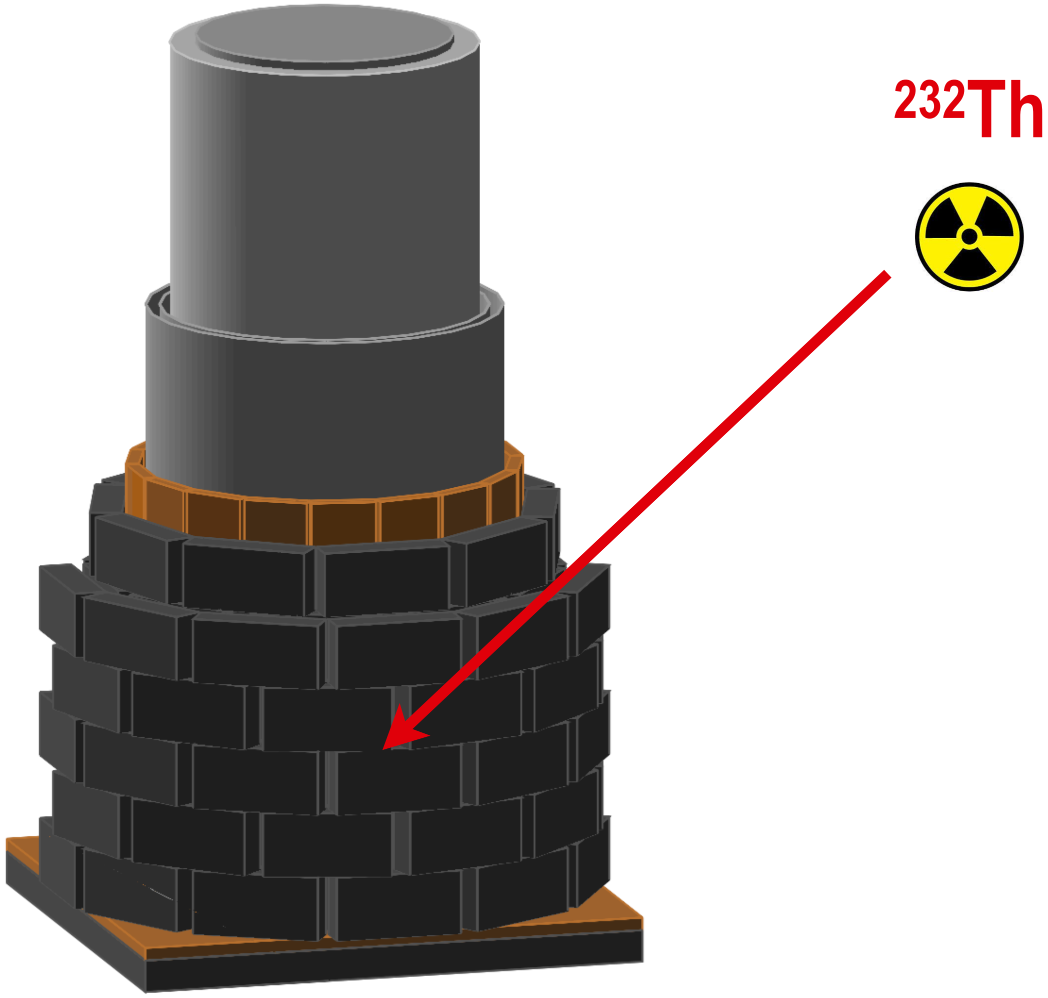


Credit: Tanay Roy

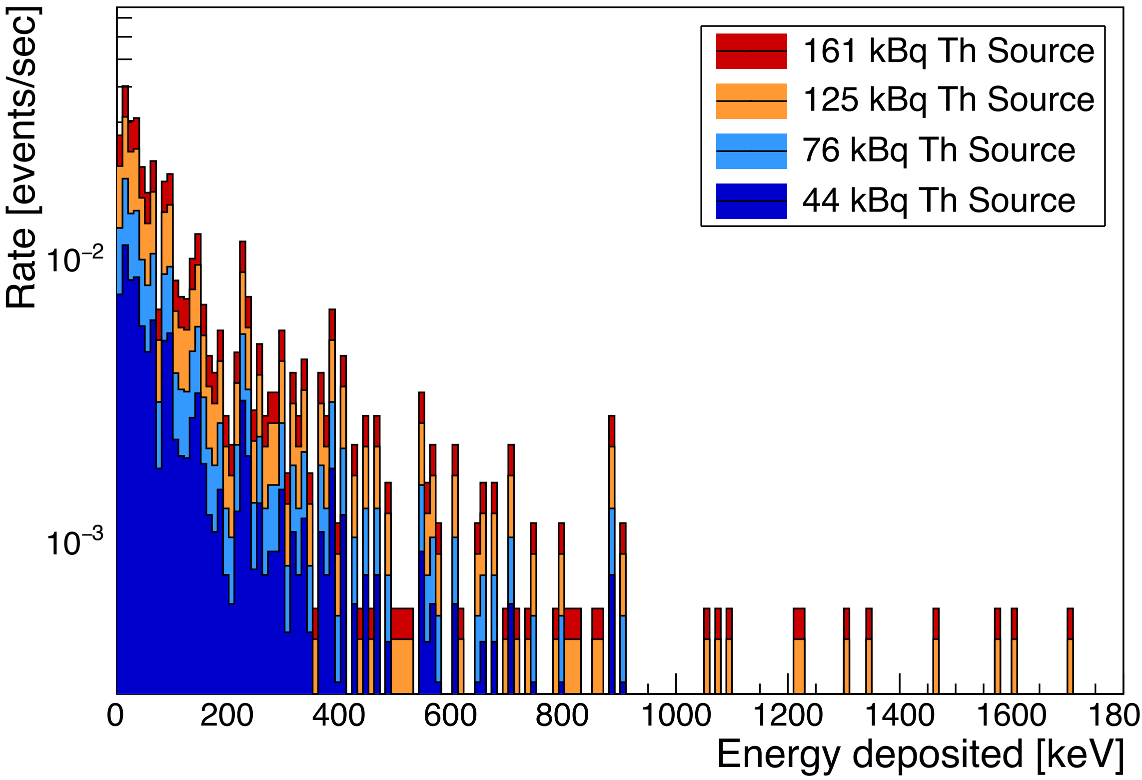


SIMULATION OF RADIOACTIVE SOURCES

- Radioactive decays generated from a **point-like ^{232}Th radioactive source,** considering <u>only gamma emitters</u> in the chain: ^{228}Ra, ^{228}Ac, ^{212}Pb, ^{212}Bi, ^{208}Tl.



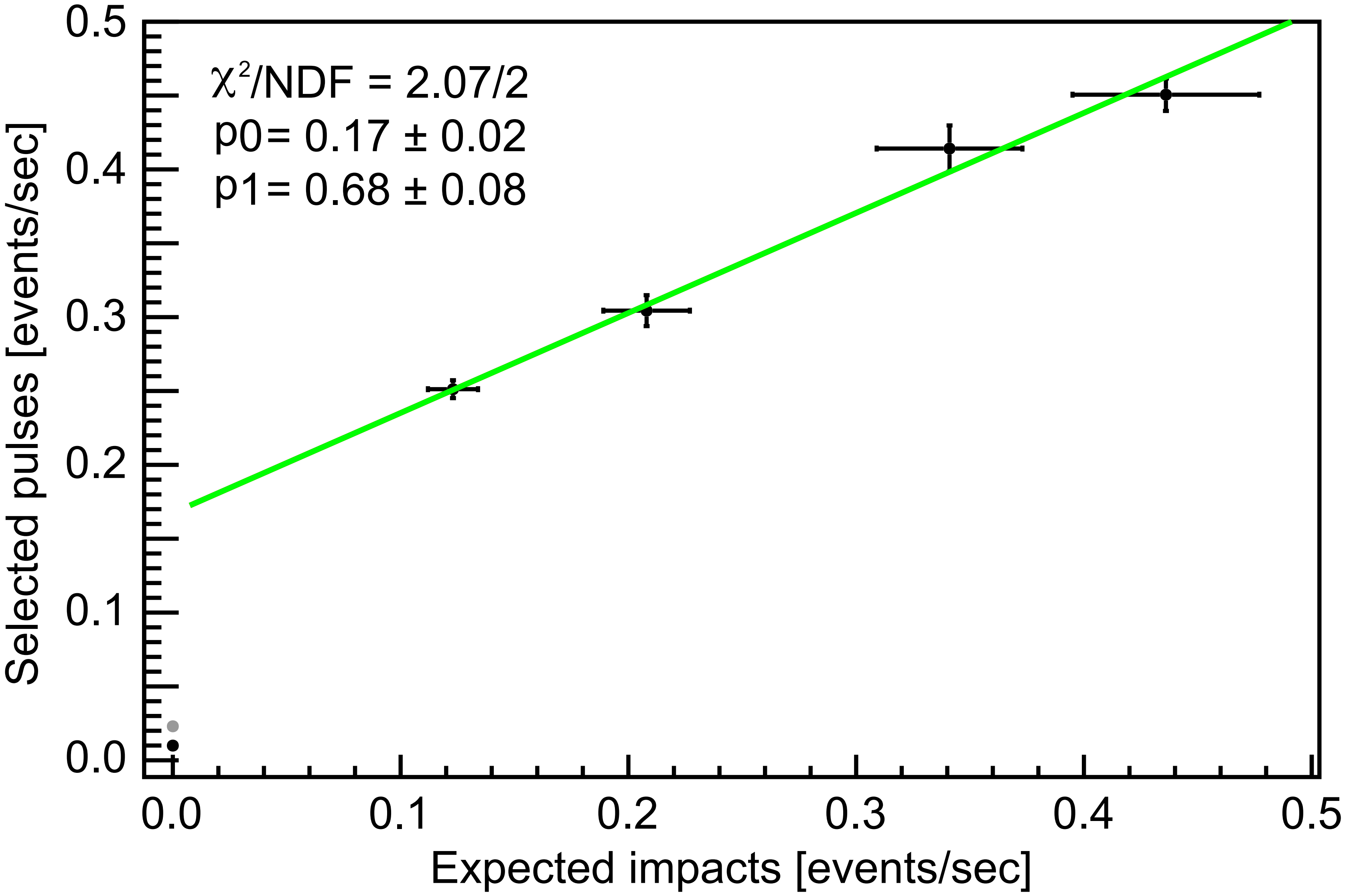
Source Activity [kBq]	Rate in the substrate [events/sec]
44.2	0.12 ± 0.01
75.9	0.20 ± 0.02
125.4	0.34 ± 0.03
161.0	0.43 ± 0.04



From 1 event / 8 sec to 1 event / 2 sec

[De Dominicis et al., *arXiv:2405.18355* (2024)]

SIMULATION VS. MEASUREMENTS



- p_0 = “background” rate
- p_1 = detection efficiency

Expected background rate

(< 0.01 events/sec)

<

Measured “background” rate

(0.17 events/sec)

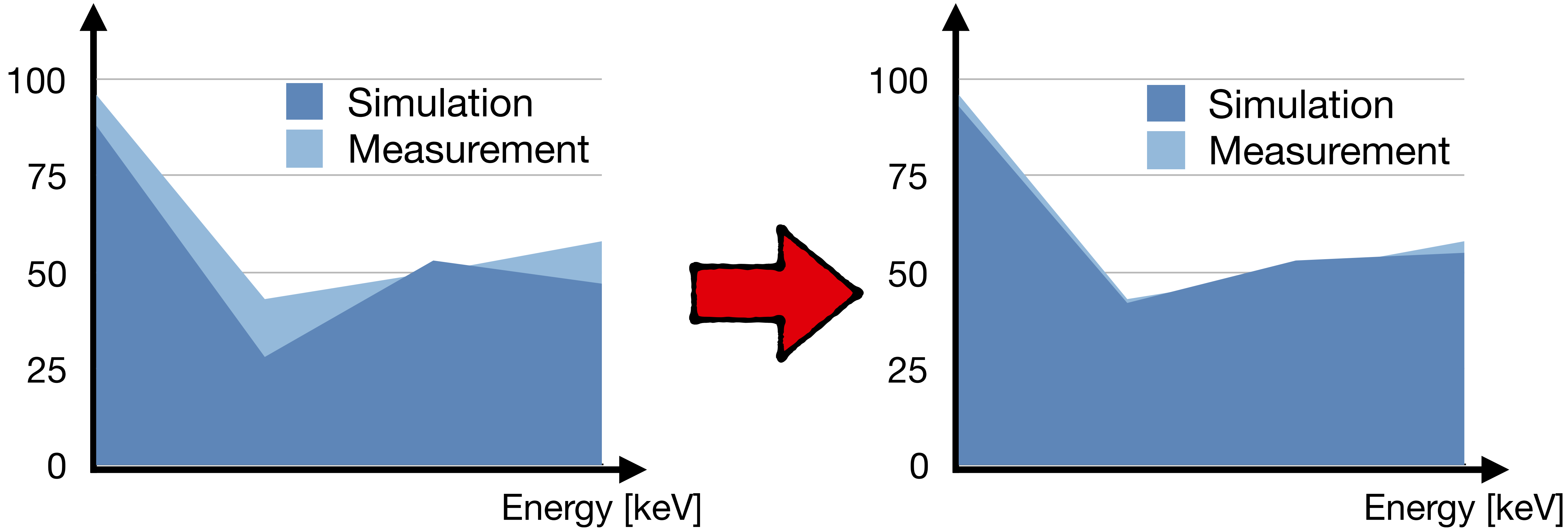
[De Dominicis et al., *arXiv:2405.18355* (2024)]

Excess noise or unpredicted effect??

Charges and phonons modeling would be very helpful, along with additional measurements!

CONCLUSIONS

- **Superconducting quantum devices** are currently a **highly relevant topic** of research;
- Can be used both for **quantum computing** and **sensing** (such as light dark matter detectors);
- Measurements have revealed **unexpected additional counts** compared to **simulated data**;
- **Deepening** our **understanding** is **crucial** for all applications;
- **Urgent need for increasingly accurate MC simulations**;
- Comparative analysis with **G4CMP** results would **significantly contribute** to **advancing** this **understanding**.



THANKS FOR YOUR ATTENTION!

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