Mapping Environmental γ-Ray Flux at LNGS: Toward a Systematic Framework for Underground Laboratories

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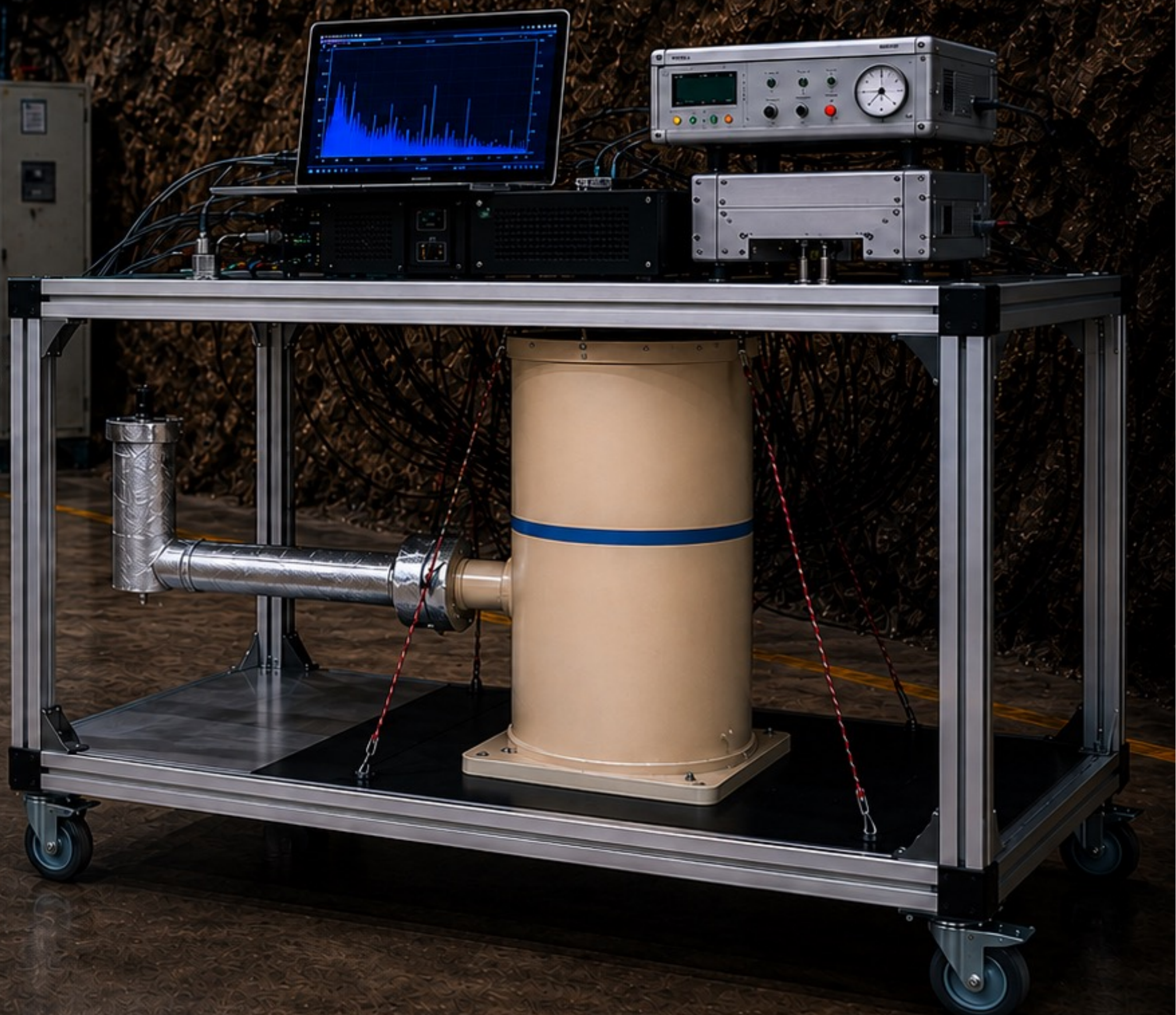

On behalf of

- Paolo Agnes (*GSSI*)
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- Chiara Ghiano (*LNGS*)
- Matthias Laubenstein (*LNGS*)
- Tomasz Mróz (*Jagiellonian University*)
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- Grzegorz Zuzel (*Jagiellonian University*)

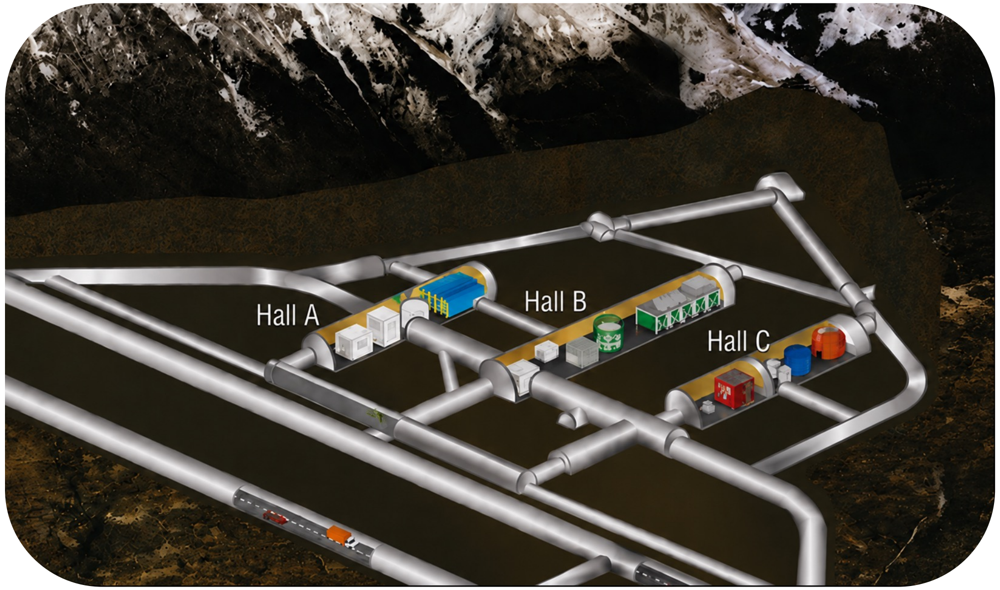
Environmental Radiation Mapping in Underground Laboratories

- Next-generation dark matter experiments in underground laboratories require a detailed characterization of the radiological environment
- Ongoing collaboration between CIEMAT, LNGS, GSSI and Jagiellonian University aimed at:
  - systematic environmental characterization of underground laboratories
  - spatial mapping of radiation backgrounds
  - development of a common calibrated methodology

- First measurement campaign focused on Hall C at LNGS

  L. Luzzi et al., arXiv:2605.09835 (2026)

- Simultaneous environmental monitoring including:
  - γ-rays
  - radon activity
  - neutron measurements (*parallel effort*)



Measuring Station of γ-Rays and Radon

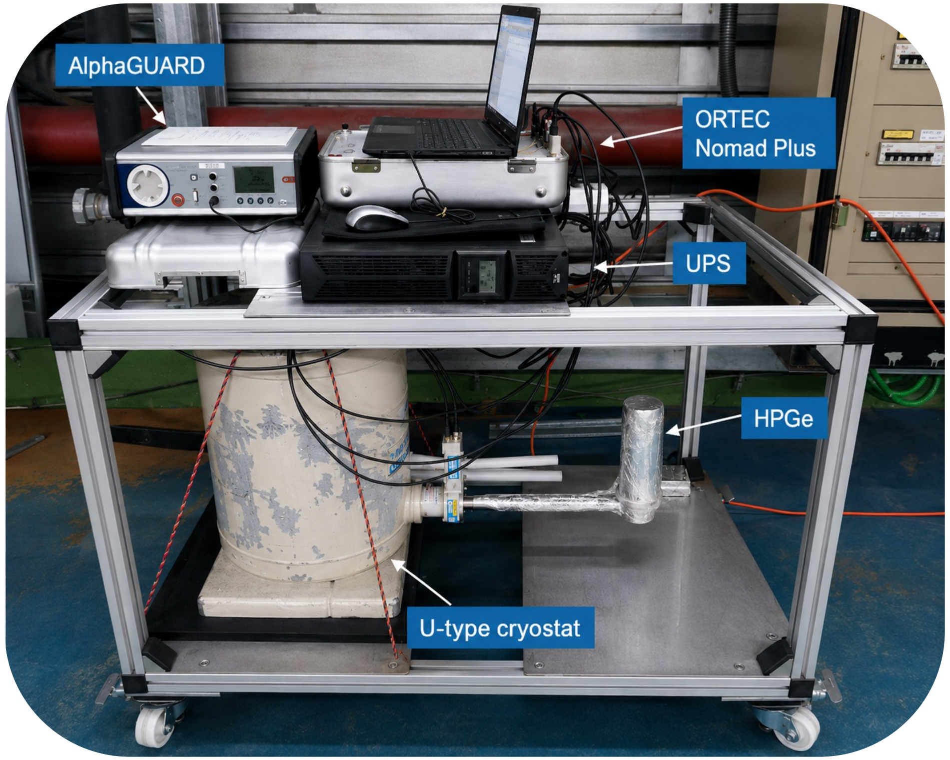
- γ-rays measured with a p-type semi-coaxial high purity germanium (HPGe) detector

- LN_2 dewar with U-type cryostat geometry

- Movable cart for measurements at multiple locations within the laboratory under identical conditions

- Automated hourly spectrum acquisition and data storage

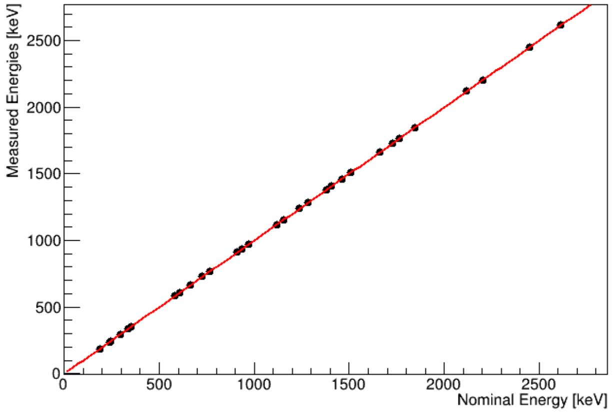
- Energy threshold at 26 keV

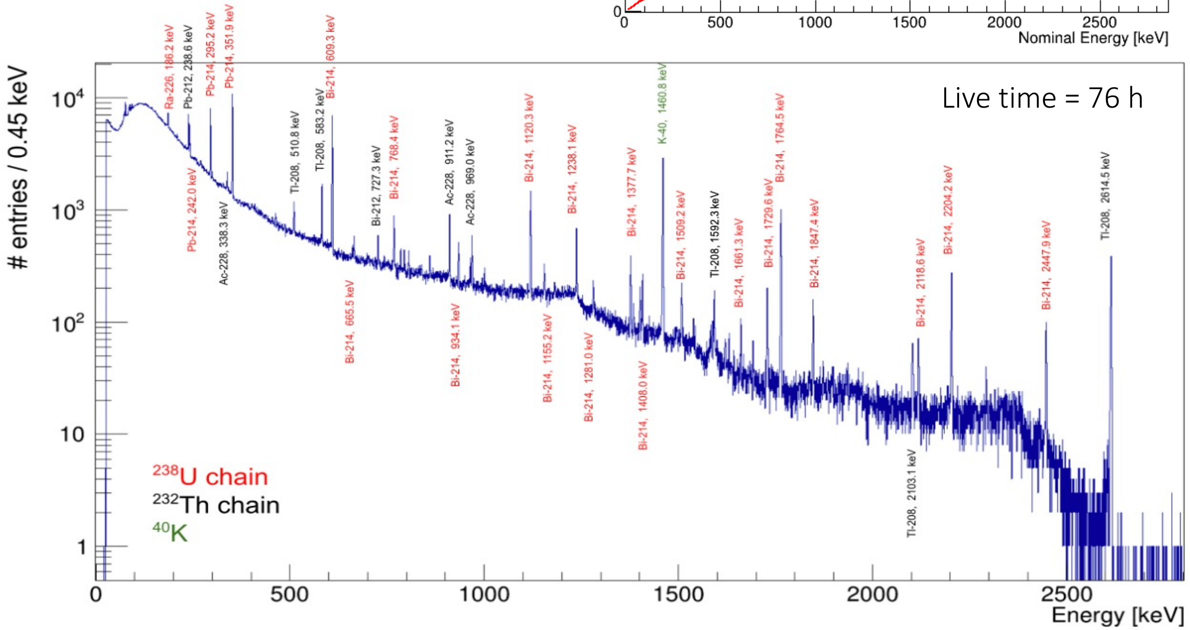


- AlphaGUARD D2000 monitor for ambient radon measurements
    - Correlation studies between environmental γ-ray flux and Rn activity

HPGe Detector Characterization

- Energy calibration using environmental γ-ray lines
- Linear detector response over 57-2800 keV

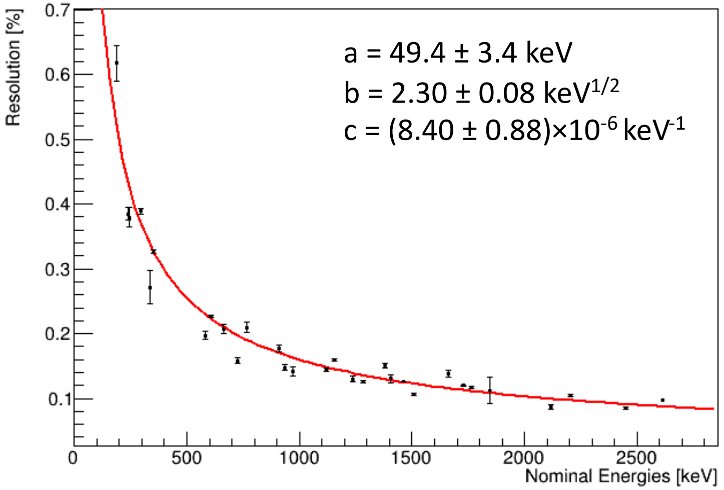


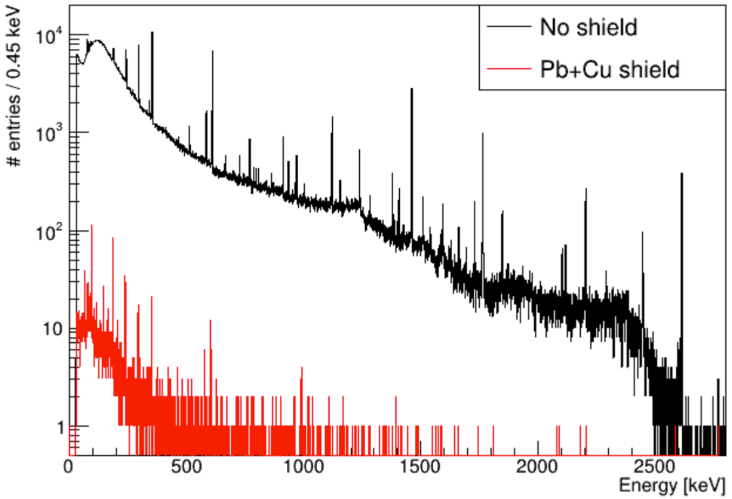


Average environmental γ-ray rate (57-2800 keV):

$(15.00 \pm 0.11)_{\text{stat}}\ s^{-1}$

- Energy resolution from FWHM measurements
- Resolution improves from 0.6% at 100 keV to below 0.1% above 2 MeV





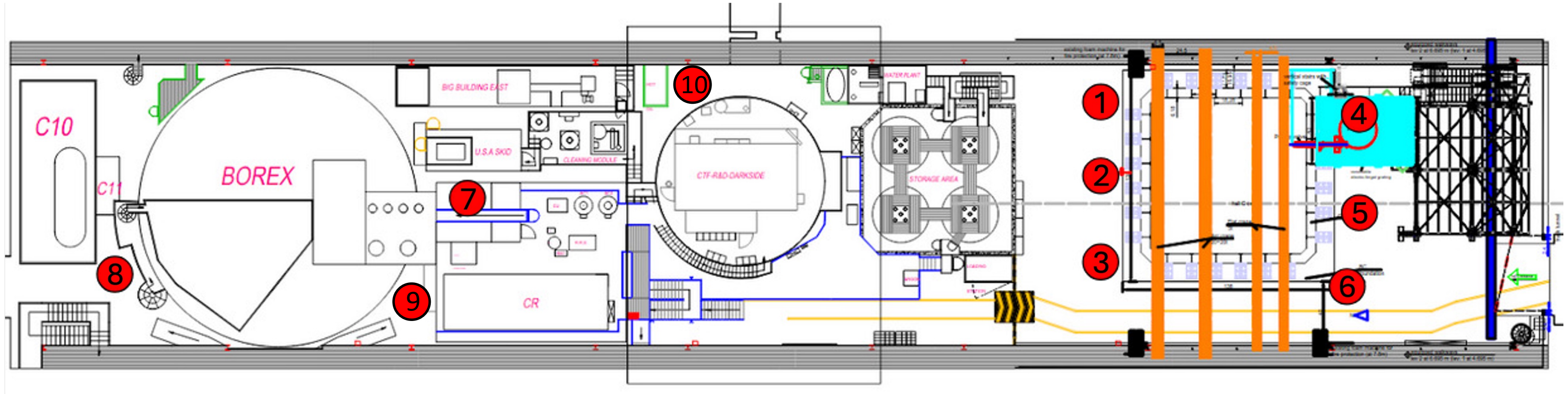
- Intrinsic detector background measured with Pb + Cu shield
- Intrinsic background rate:

$(0.08 \pm 0.004)_{\text{stat}}\ s^{-1}$

<1% of the external rate

Spatial Variation of the Environmental γ-Ray Rate in Hall C

- HPGe was deployed at 10 positions in Hall C to map the environmental γ-ray field
- Positions 7 and 8 show rates ~22% higher than the average of the other positions
- Massive structures inside the hall affect the local γ-ray flux
- The overall average rate in the ROI is **$(16.03 \pm 1.55)\ s^{-1}$**
  - The statistical uncertainty corresponds to the RMS spread across positions



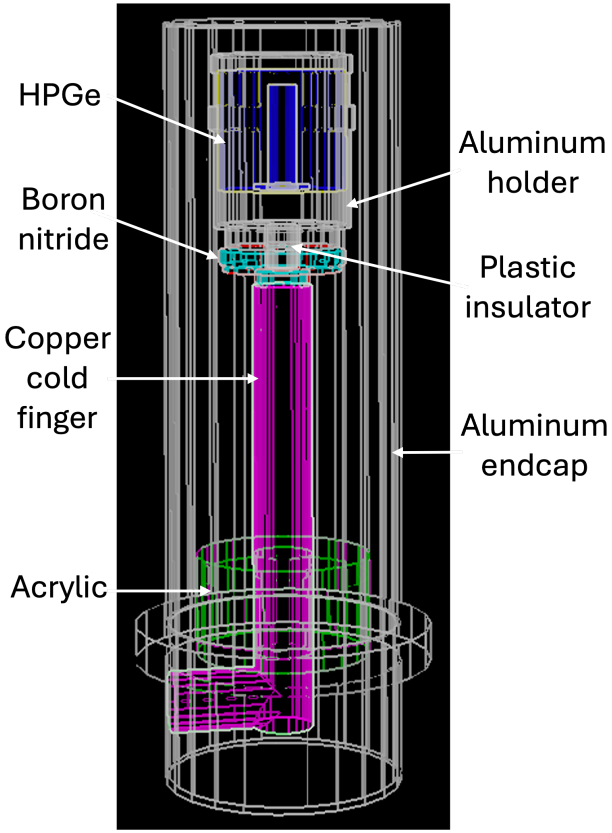
Position	Live Time (h)	Rate (s^{-1})
1	19	14.59 ± 0.09
2	16	14.80 ± 0.76
3	16	15.71 ± 0.53
4	6	15.11 ± 0.20
5	16	15.74 ± 0.11
6	7	14.66 ± 0.11
7	16	19.27 ± 0.13
8	16	18.33 ± 0.10
9	19	16.44 ± 0.13
10	19	15.38 ± 0.08

Monte Carlo Modeling of the Detector Response

- The γ-ray flux is derived from the measured count rate by correcting for detector efficiency the geometrical acceptance:

$$\Phi(E) = \frac{R(E)}{\varepsilon(E)\, S}$$

Goal: calculation of the detector efficiency over a broad energy range



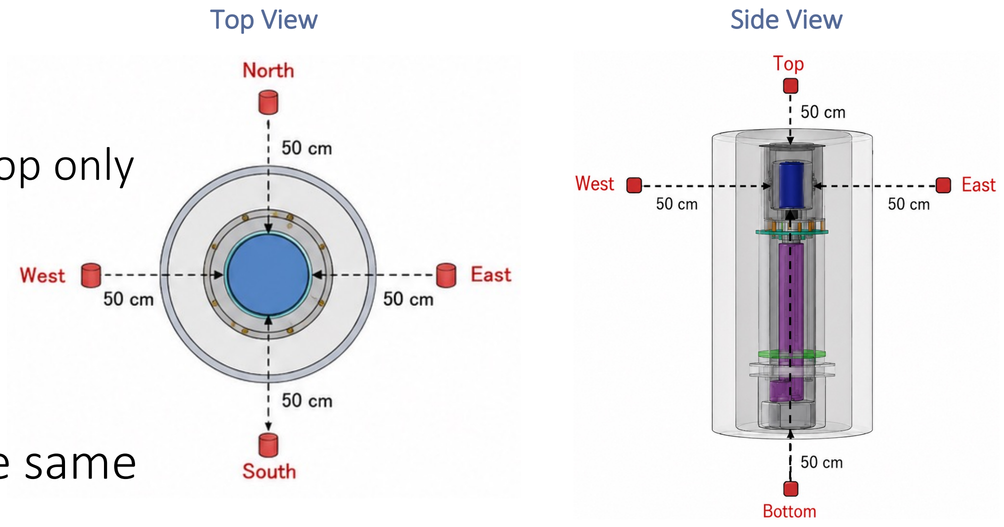
- Detailed HPGe geometry implemented in Geant4, including passive materials and detector dead layers

- The Monte Carlo approach consists of two steps:
  1. Validation of the detector geometry using measurements with calibrated γ-ray sources placed around the detector
  2. Simulation of the response to external γ-rays

The validated MC model provides the energy-dependent detection efficiency used for the environmental γ-ray flux calculation

Monte Carlo Validation with Calibrated Sources

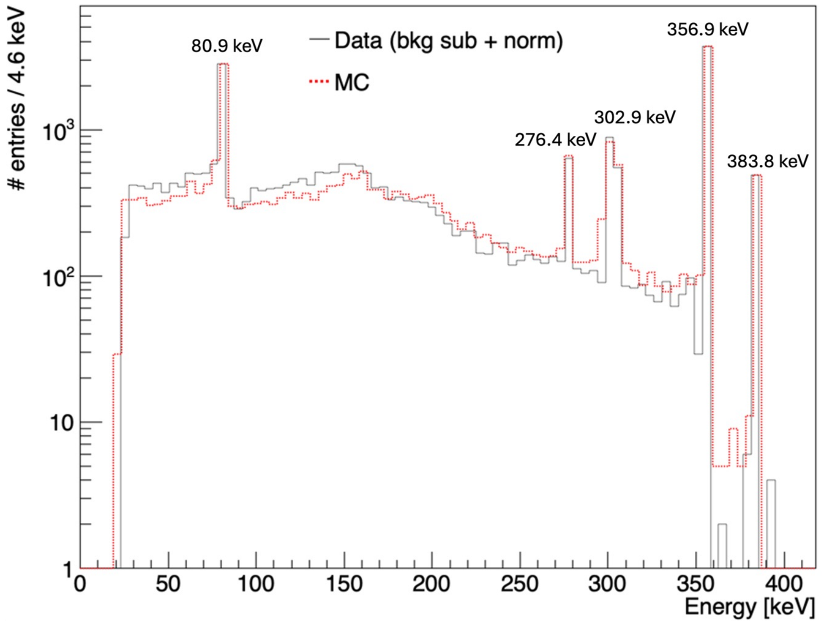
- Calibration data using three γ-ray sources:
  - ^{133}Ba (80.9 keV, 276.4 keV, 302.9 keV, 356.9 keV, 383.8 keV) ▶ top only
  - ^{137}Cs (661.6 keV) ▶ **all six positions**
  - ^{60}Co (1173.2 keV, 1332.0 keV) ▶ top only



- MC simulation performed with point-like sources placed at the same locations around the detector

Goal: ensure agreement between the measured and simulated full-energy-peak efficiencies (FEPEs) for all γ-ray lines and configurations

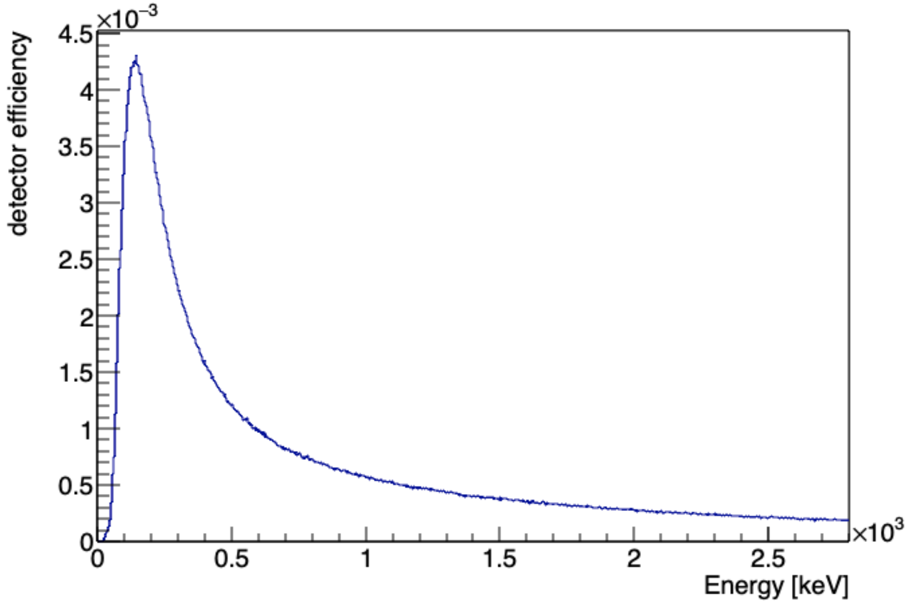
$$\varepsilon^{data}(E_\gamma) = \frac{N_{FEP}^{data}(E_\gamma)}{A\, t\, BR(E_\gamma)} \qquad \varepsilon^{MC}(E_\gamma) = \frac{N_{FEP}^{MC}(E_\gamma)}{N_{sim}\, BR(E_\gamma)}$$

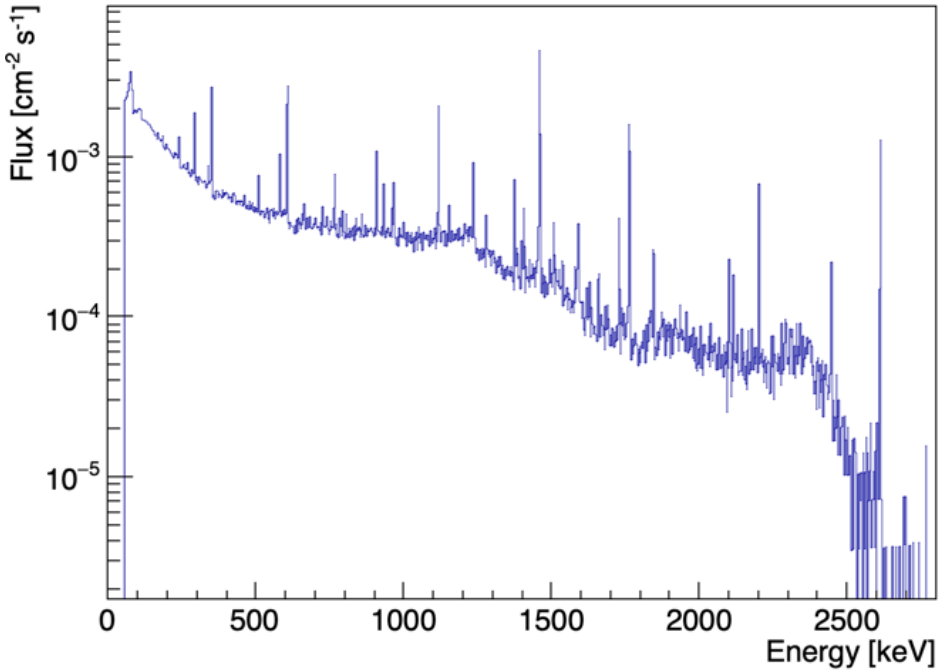


▶ Data/MC FEPE ratios are consistent within ~10% for all source configurations

Detector Efficiency and γ-Ray Flux Calculation

- Environmental γ-rays generated from a spherical surface source surrounding the detector
- Detector efficiency calculated from the ratio between the full-energy deposition events and the generated γ-rays
- Maximum efficiency: 0.43% at 135-145 keV





- The γ-ray flux is obtained by converting the measured energy spectrum into a flux spectrum
- Measured counts converted into γ-ray flux using the MC-derived detector efficiency

$$\Phi_i = \frac{C_i}{\varepsilon_i\, S\, t}$$

Spatial Variation of the Environmental γ-Ray Flux in Hall C

- γ-ray fluxes across Hall C are broadly consistent, with moderate position-dependent variations
- Consistent with previous LNGS measurements using different detectors and techniques
- Statistical uncertainty includes:
  - Poisson fluctuations in the measured spectrum
  - MC statistical uncertainty on the efficiency
- Systematic uncertainty derived from the data/MC efficiency agreement for the ^{137}Cs source

Position	Flux (cm^{-2} s^{-1})	Rn Activity (Bq m^{-3})
1	0.41 ± 0.01 ± 0.03	82.8 ± 12.7
2	0.43 ± 0.05 ± 0.03	87.3 ± 7.8
3	0.44 ± 0.04 ± 0.03	82.6 ± 8.8
4	0.41 ± 0.01 ± 0.03	87.7 ± 7.4
5	0.43 ± 0.01 ± 0.03	91.7 ± 10.2
6	0.41 ± 0.01 ± 0.03	92.0 ± 10.2
7	0.55 ± 0.01 ± 0.03	127.3 ± 10.1
8	0.56 ± 0.01 ± 0.03	116.8 ± 13.0
9	0.47 ± 0.01 ± 0.03	99.7 ± 11.3
10	0.43 ± 0.01 ± 0.03	98.5 ± 9.8

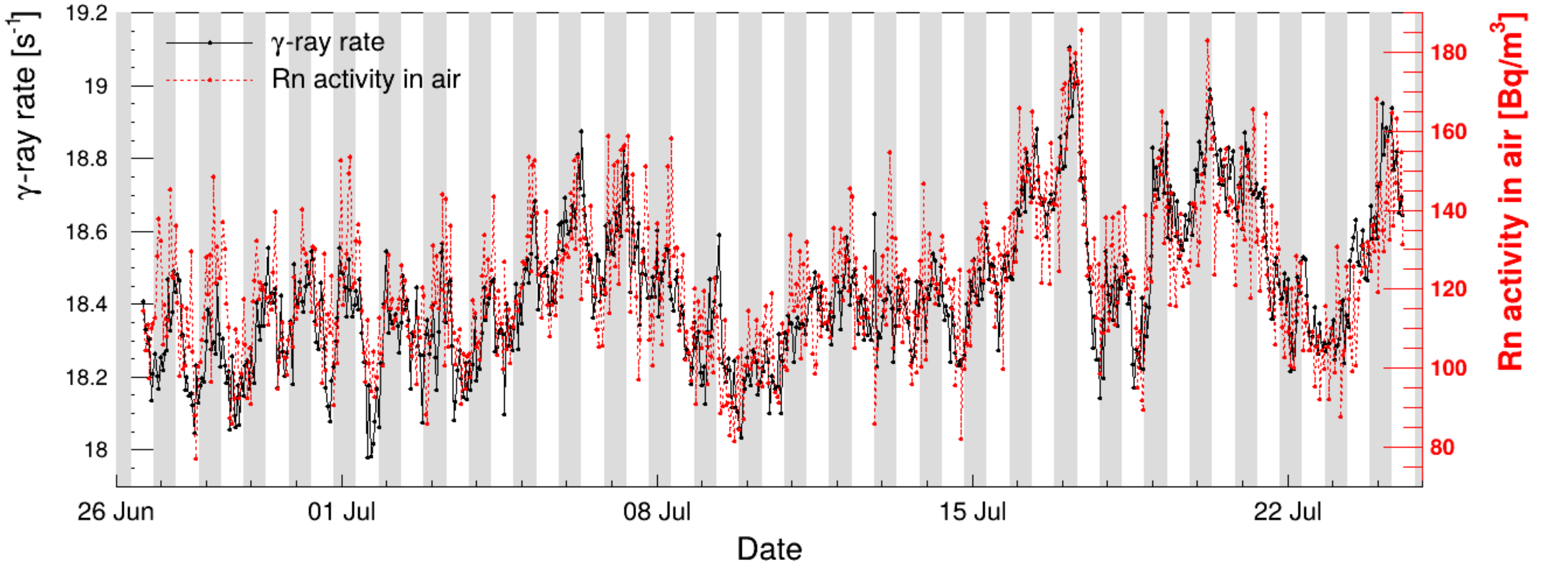
- Positions 7 and 8 show fluxes ~29% higher than the average of the other positions
- Acquisition times < 1 day make the flux sensitive to temporal environmental variations, especially radon activity
- Average γ-ray flux in Hall C:

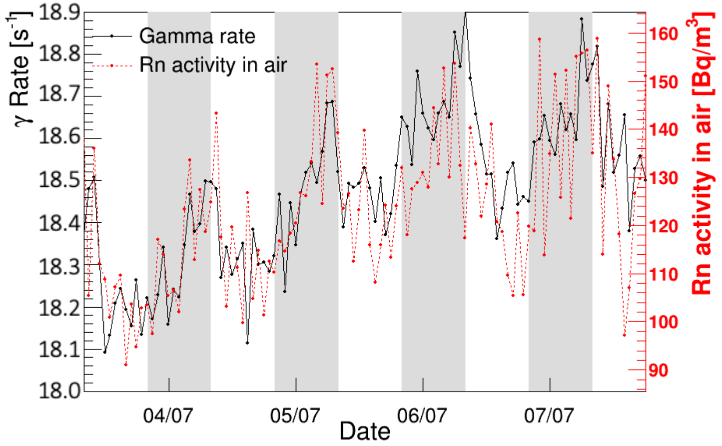
$$(0.46 \pm \underset{\text{stat}}{0.06} \pm \underset{\text{syst}}{0.03})\ \text{cm}^{-2}\ \text{s}^{-1}$$

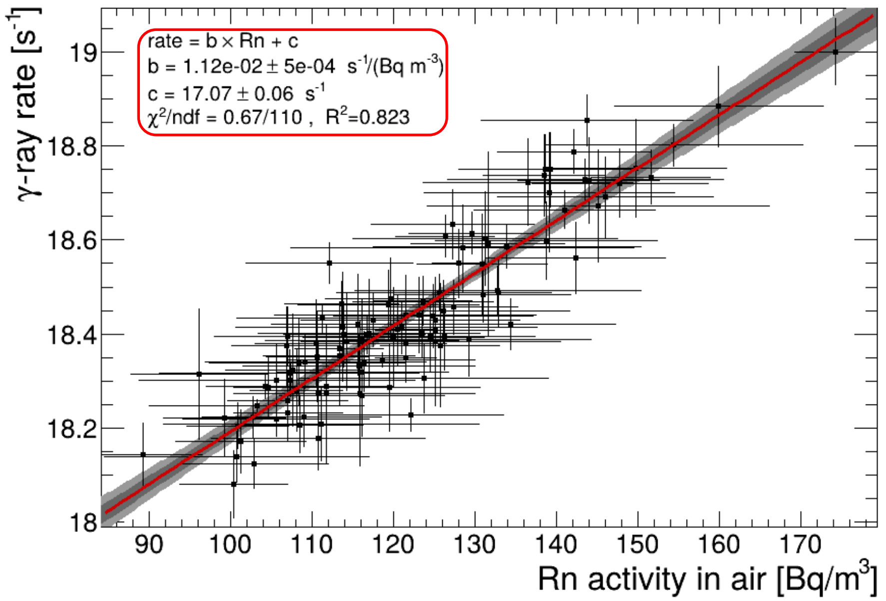
First precision measurement of the environmental γ-ray flux in Hall C

Correlation Between Environmental γ-Ray and Rn Activity

- ^{222}Rn released from the surrounding rock contributes to the environmental γ-ray field through its short-lived daughters (^{214}Pb and ^{214}Bi)
- Long-term measurement performed at position 8 to study the correlation between γ-ray rate and radon activity
- The γ-ray rate follows the day-to-day variations of the Rn activity







the environmental γ-ray field is not stationary, but varies with time

Conclusions and Next Steps

- First systematic spatial mapping of the environmental γ-ray flux in Hall C at LNGS, using a movable HPGe station. A MC-validated detector response enabled the determination of the γ -ray flux in the 57–2800 keV energy range
- Average environmental γ-ray flux in Hall C:

$$(0.46 \pm \underset{\text{stat}}{0.06} \pm \underset{\text{syst}}{0.03})\ \mathrm{cm^{-2}\ s^{-1}}$$

with position-dependent variations across the hall

- Clear correlation observed between environmental γ-ray rate and radon activity
  - the environmental γ-ray field is both spatially and temporally variable

Next Steps:

- Long-term γ-ray and radon measurements in Hall A to reduce the impact of temporal fluctuations
  - First Hall A position already assessed in a 26-d run

Rate (s^{-1})	Flux ($cm^{-2}\ s^{-1}$)	Rn Activity (Bq m^{-3})
11.63 ± 0.14	0.33 ± 0.01 ± 0.02	13.7 ± 5.8

- Extension of the mapping campaign to the full LNGS laboratory and to other underground laboratories using the same calibrated mobile HPGe station
- Direct determination of the radon-independent environmental γ-ray baseline

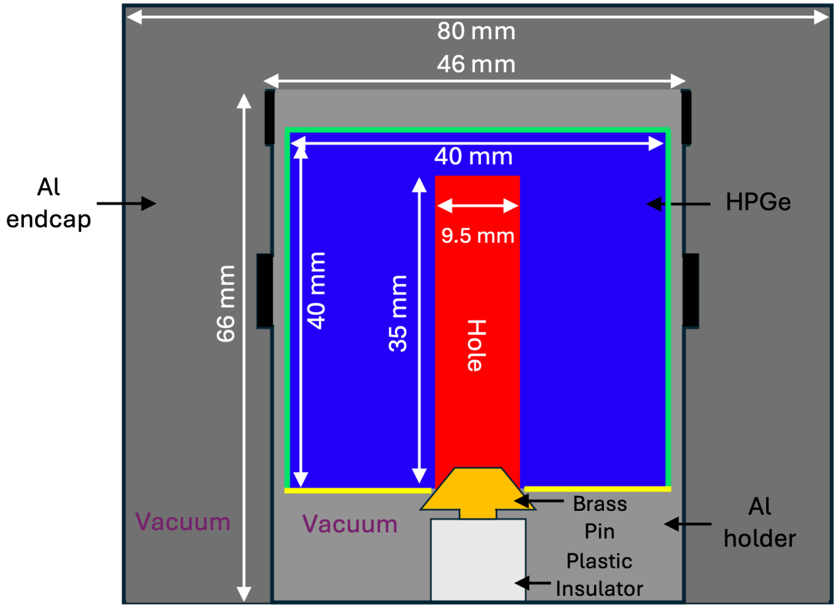
Thank you

BACKUP

Dead Layer Calculation

- Dead layer = inactive Ge region with incomplete charge collection
- Origin: Li diffusion on the outer detector contact
- Strong impact at low γ-ray energies (strong efficiency suppression)
- Two effective dead layers considered:
  - $t_{top/side}$ (green)
  - t_{bottom} (yellow)

  Treated separately due to different fabrication processes



- Geant4 HPGe model validated with ^{133}Ba, ^{137}Cs and ^{60}Co sources
- Iterative optimization algorithm scanning $t_{top/side}$ and t_{bottom} in 0-3.5 mm with 0.1 mm steps
- Minimization of discrepancy between ε^{data} and ε^{MC}

$$(t_{top/side}\,, t_{bottom}) = (1.7\,, 1.7)\ mm$$

Reference	Location	Detector	Flux ($cm^{-2}\ s^{-1}$)
Haffke et al. (2011)	Hall A	NaI(Tl)	0.28 ± 0.02
	Hall B	HPGe	0.33 ± 0.02
Malczewski et al. (2013)	Hall A	HPGe	0.23
	Hall B	HPGe	0.23
Bucci et al. (2009)	Hall A	HPGe	0.73
Arpesella (1992)	Hall C	HPGe	~1