

PCA-Based Multivariate Analysis of Muography Time Series at the Sos Enattos Mine

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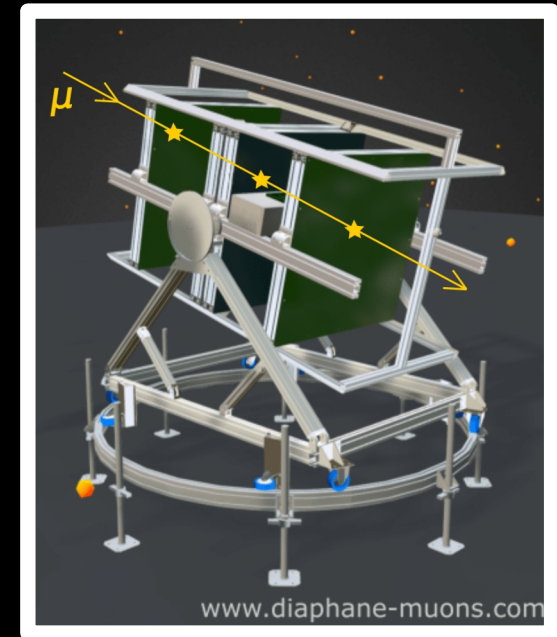
Muographers 2026 - Budapest, Hungary - 3 June 2026



Introduction

- **Muon detector**

- Detector composed of **three plastic scintillator panels**.
- The reconstructed muon trajectories define the **detector lines of sight (LoS)**.
- **Muon rate time series** can be computed **independently** for each LoS or groups of LoS.



Schematic view of the
muon detector

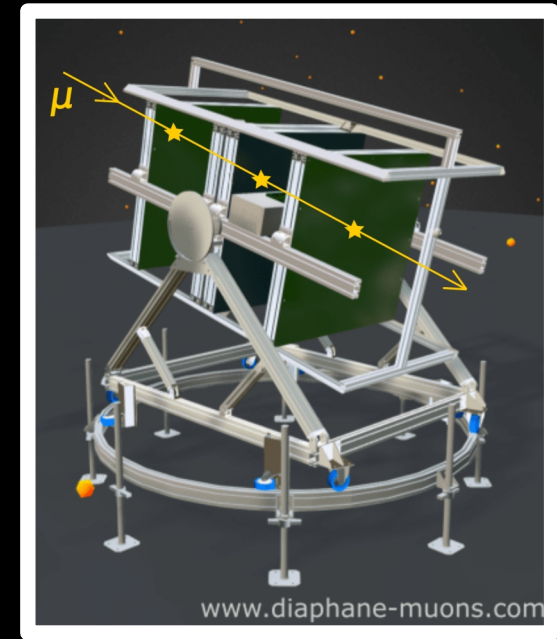
Introduction

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- The reconstructed muon trajectories define the **detector lines of sight (LoS)**.
- **Muon rate time series** can be computed **independently** for each LoS or groups of LoS.

- **Motivation**

- **Muon rate time series** are typically obtained by **grouping LoS**.
- This grouping may combine regions with **different temporal behaviors**.
- Regions with **high muon rate** tend to **dominate the signal** and may **mask weaker ones**.
- **Objective:** identify **coherent spatio-temporal signals** while **reducing grouping bias**.



Schematic view of the muon detector

Sos Enattos Mine (Sardinia, Italy)

- **Candidate site** for the future **Einstein Telescope** gravitational-wave observatory.
- **Motivation:** support geological characterization of the overburden.
- **A muon detector** deployed at two **underground** locations in 2024.
- **Depth:** ~200 m.



Sos Enattos Mine



Muon detector

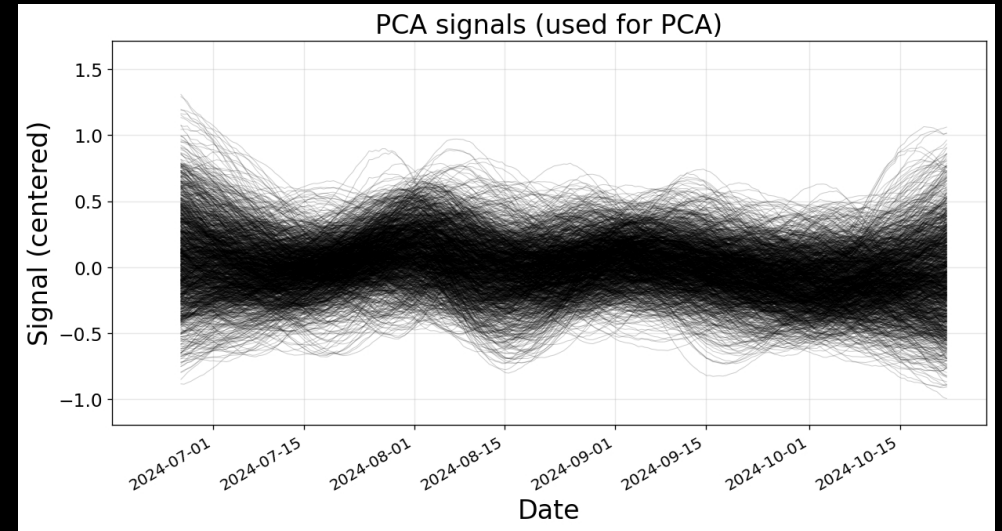


The two sites where the detector was installed

Methodology

- **Objective:** To identify coherent spatial variations in the muon rate
 - Group neighboring lines of sight (LoS) into overlapping spatial blocks
 - Compute muon rate time series per block
 - **Principal Component Analysis (PCA)** to extract **coherent temporal patterns**
 - Identification of regions with correlated variations

1 group of neighboring LoS → 1 block → 1 signal



Signals in sliding blocks (RUN 1)

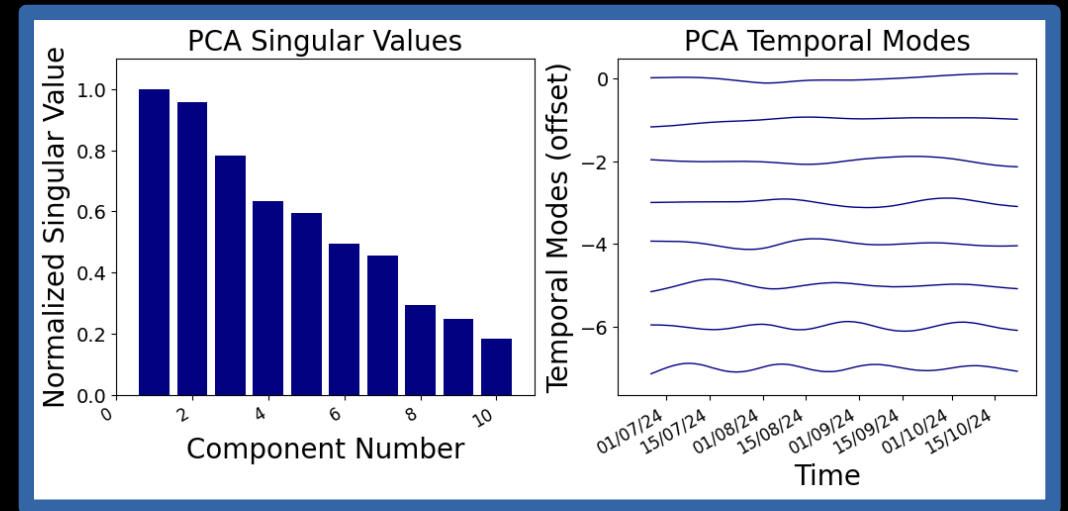
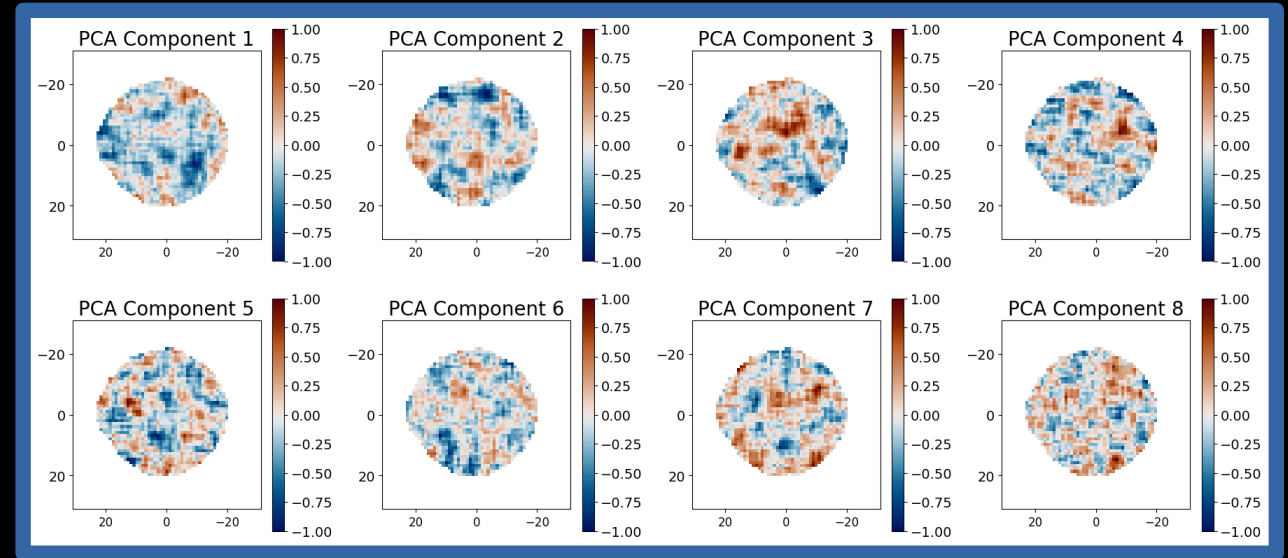
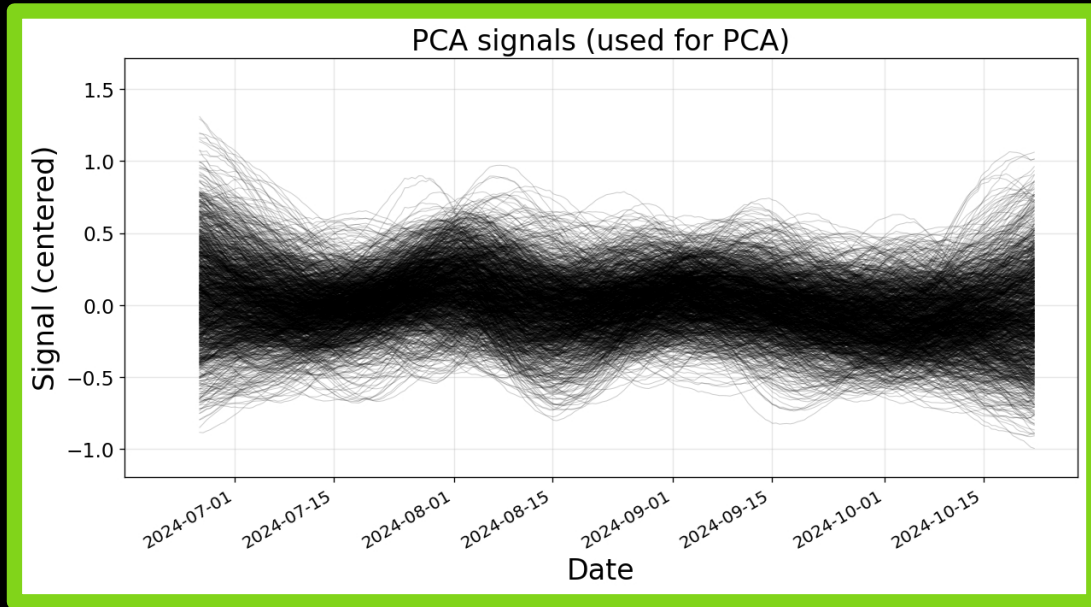
$$X_c = U\Sigma V^T$$

- $X_c(\vec{r}, t)$: Centered signals
- $U(\vec{r})$: Spatial modes
- $V(t)$: Temporal modes
- Σ : Singular values (weights)

PCA formulation

Implementation

- RUN 1
 - ~115 days of data



$$x(\vec{r}, t) \simeq \sum_k u_k(\vec{r}) \times \sigma_k \times v_k(t)$$

PCA formulation

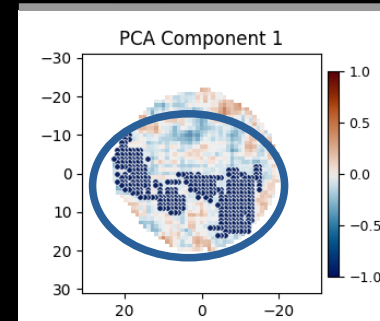
Spatial modes

Singular values

Temporal modes

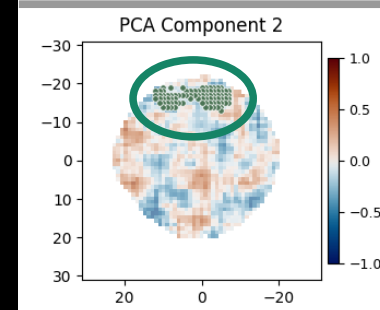
Results: RUN 1

- Selection of regions based on **PCA spatial modes**



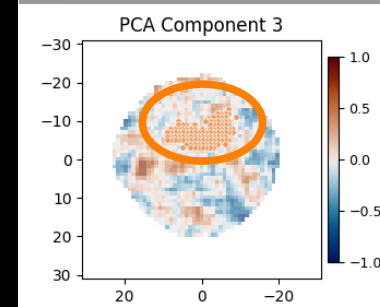
Region 1

- low values of spatial mode 1 (u_1)



Region 2

- low values of spatial mode 2 (u_2)

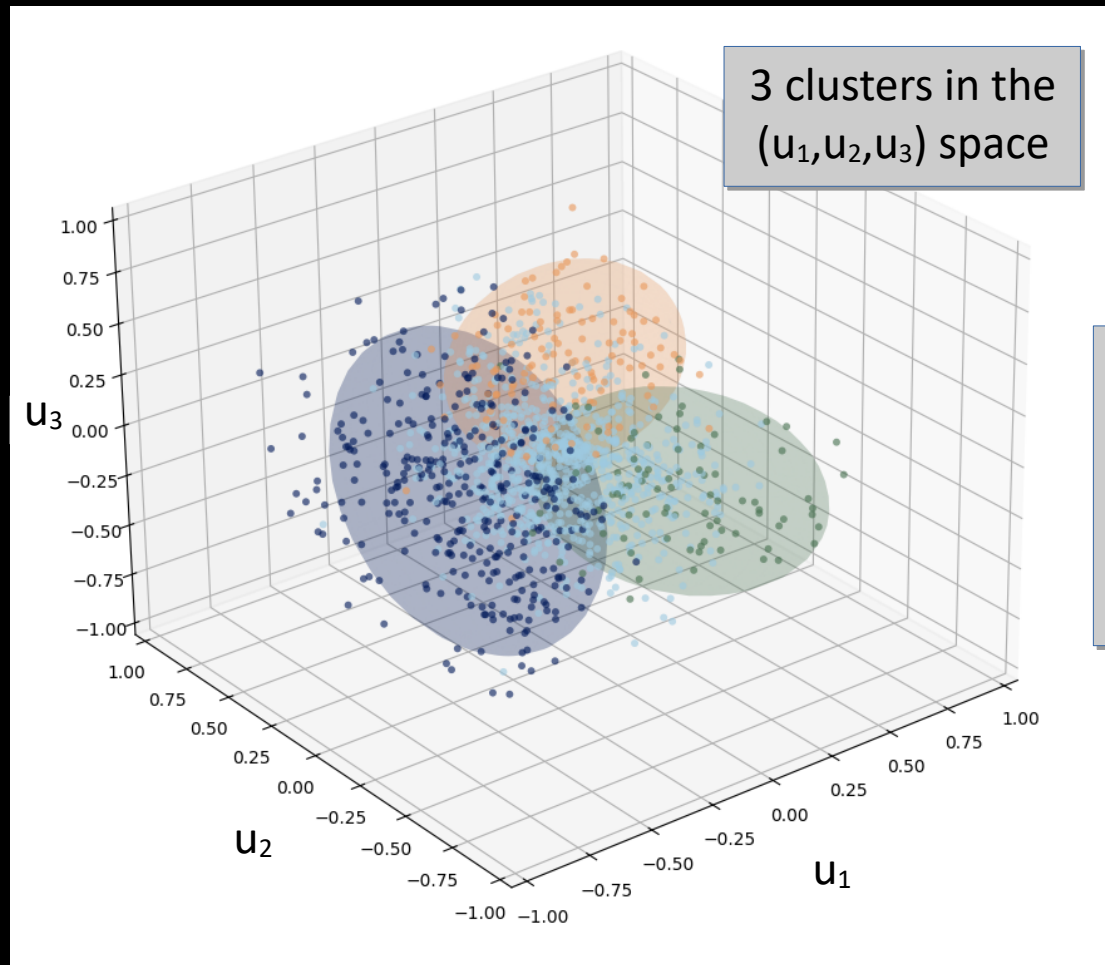


Region 3

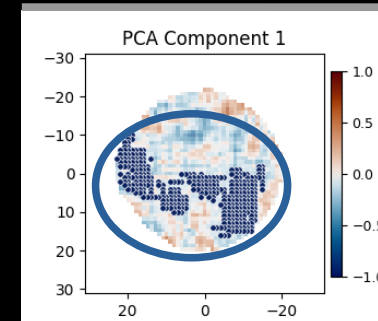
- high values of spatial mode 3 (u_3)

Results: RUN 1

- Selection of regions based on **PCA spatial modes**

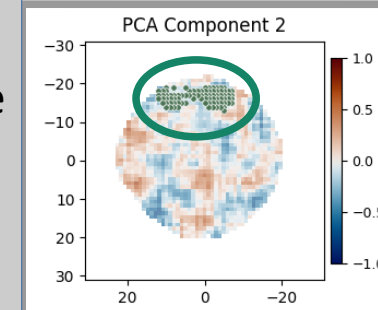


one pixel
spatial mode
↓
one point
 (u_1, u_2, u_3)



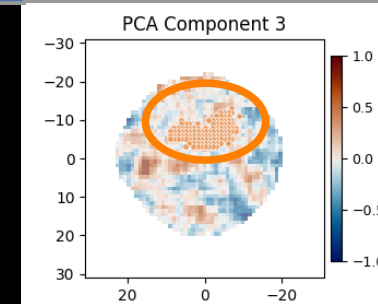
Region 1

- low values of spatial mode 1 (u_1)



Region 2

- low values of spatial mode 2 (u_2)

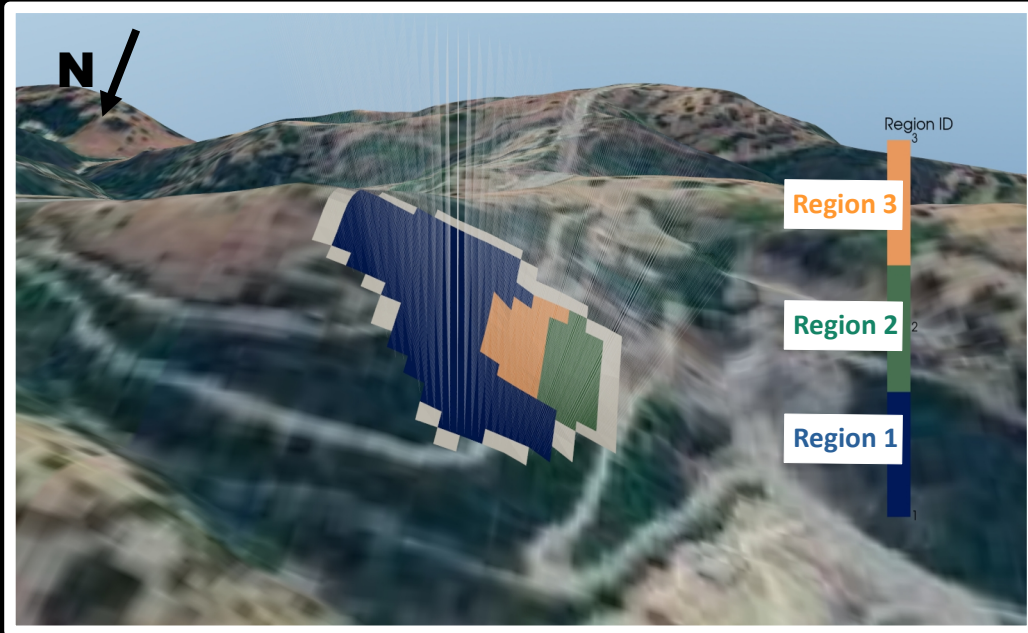


Region 3

- high values of spatial mode 3 (u_3)

Results: RUN 1

- Selection of regions based on **PCA spatial modes**

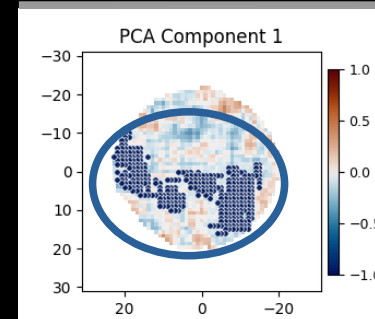


Regions mapped at the surface. Lines of sight in gray lines.

Mean rock thickness

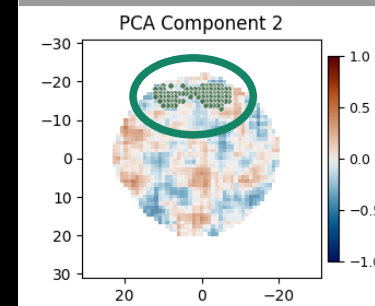
- Region 1: (180 ± 15) m
- Region 2: (155 ± 5) m
- Region 3: (160 ± 4) m

Spatial modes to lines of sight mapping



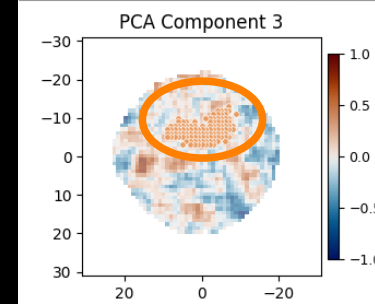
Region 1

- low values of spatial mode 1 (u_1)



Region 2

- low values of spatial mode 2 (u_2)

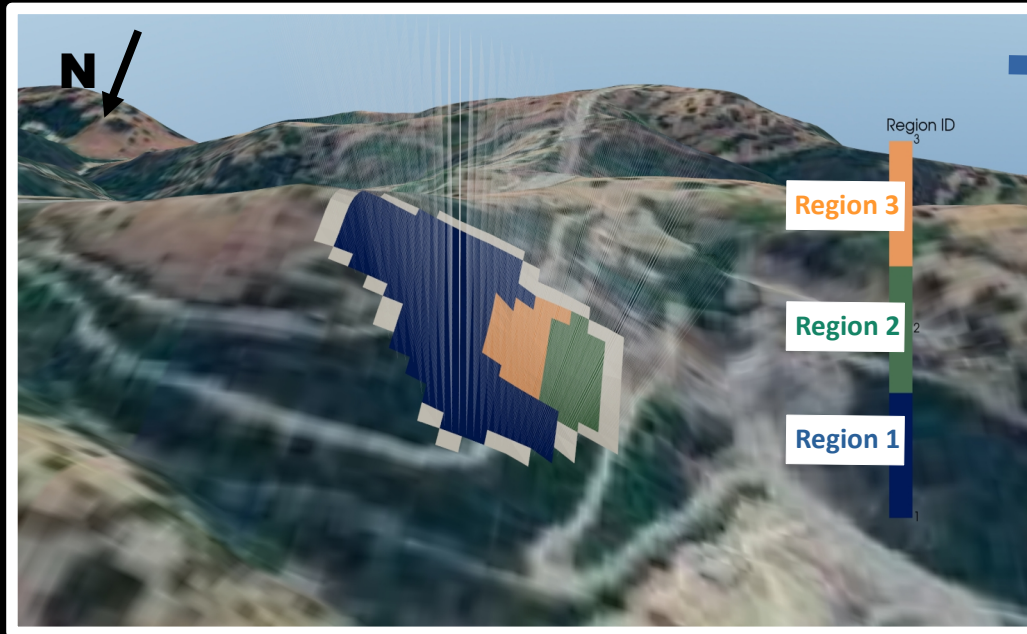


Region 3

- high values of spatial mode 3 (u_3)

Results: RUN 1

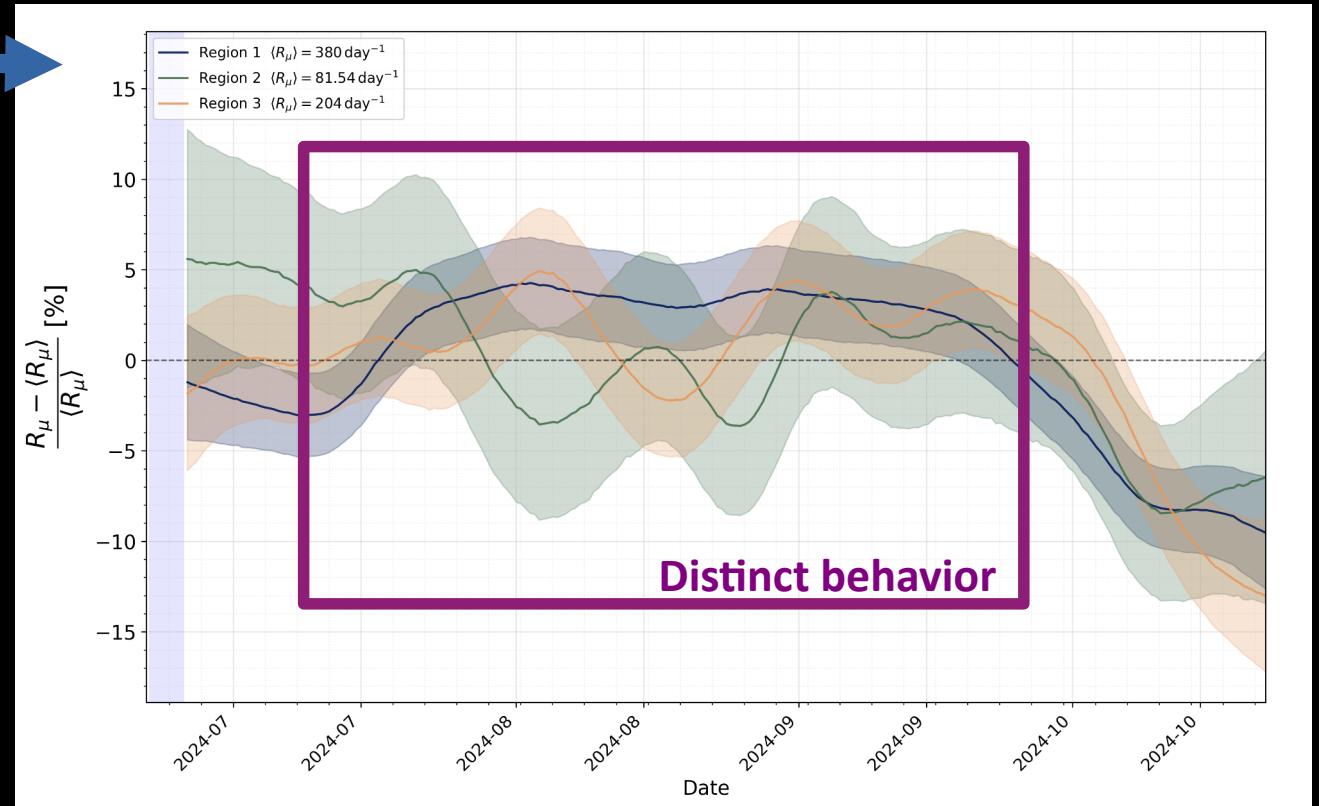
- Muon rate computation for each region.



Regions mapped at the surface. Lines of sight in gray lines.

Mean rock thickness

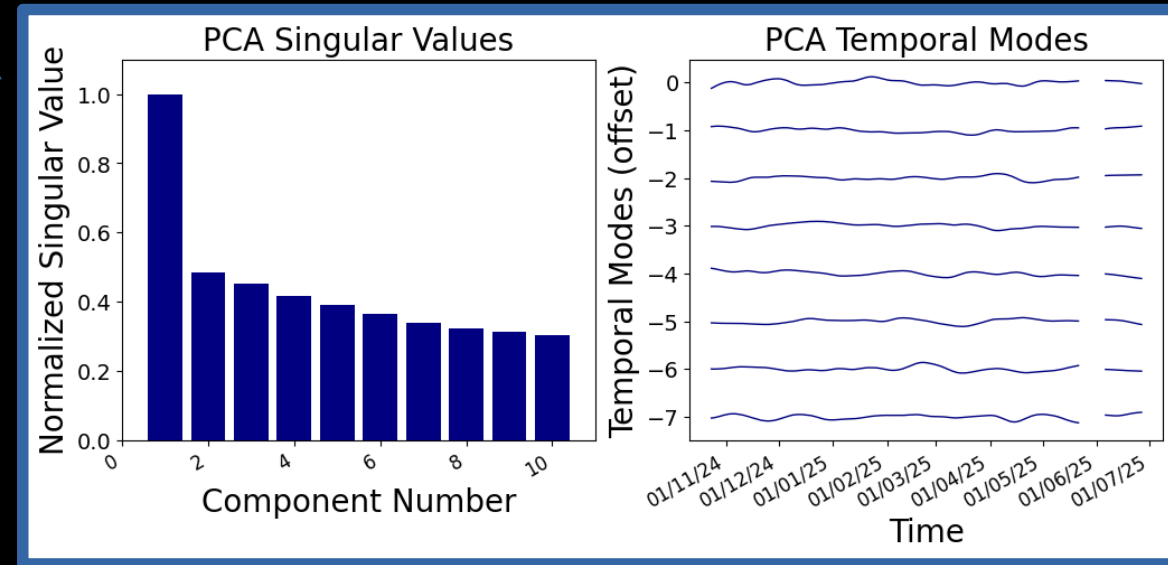
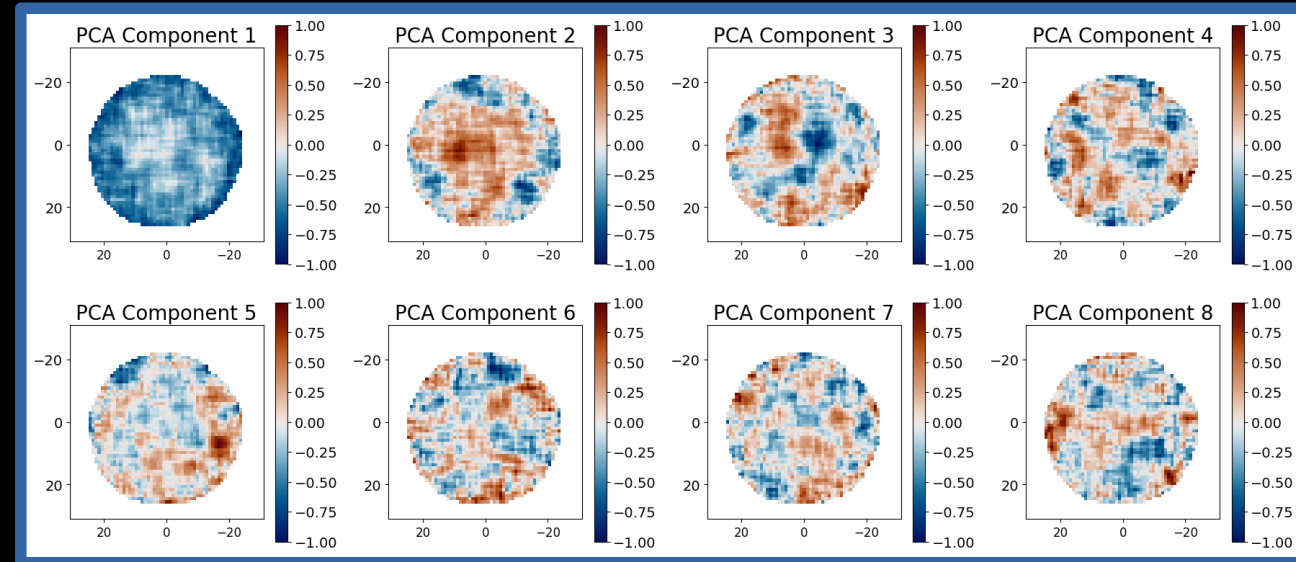
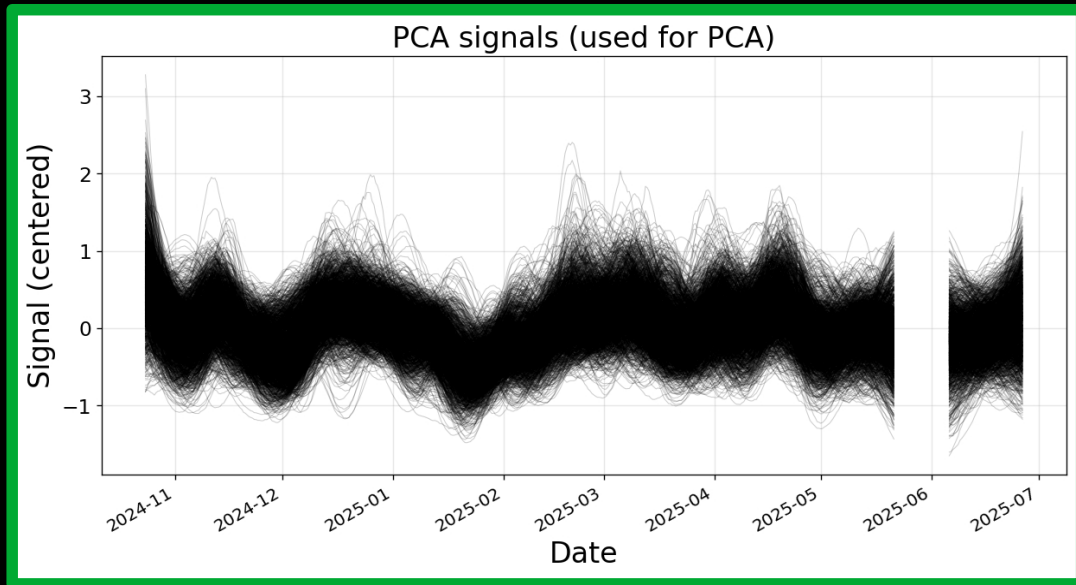
- Region 1: (180 ± 15) m
- Region 2: (155 ± 5) m
- Region 3: (160 ± 4) m



Muon rate in each region represented as the deviation from the mean.

Results: RUN 2

- RUN 2
 - ~225 days of data



$$x(\vec{r}, t) \simeq \sum_k u_k(\vec{r}) \times \sigma_k \times v_k(t)$$

PCA formulation

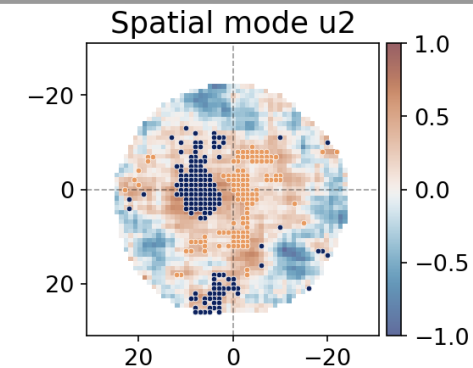
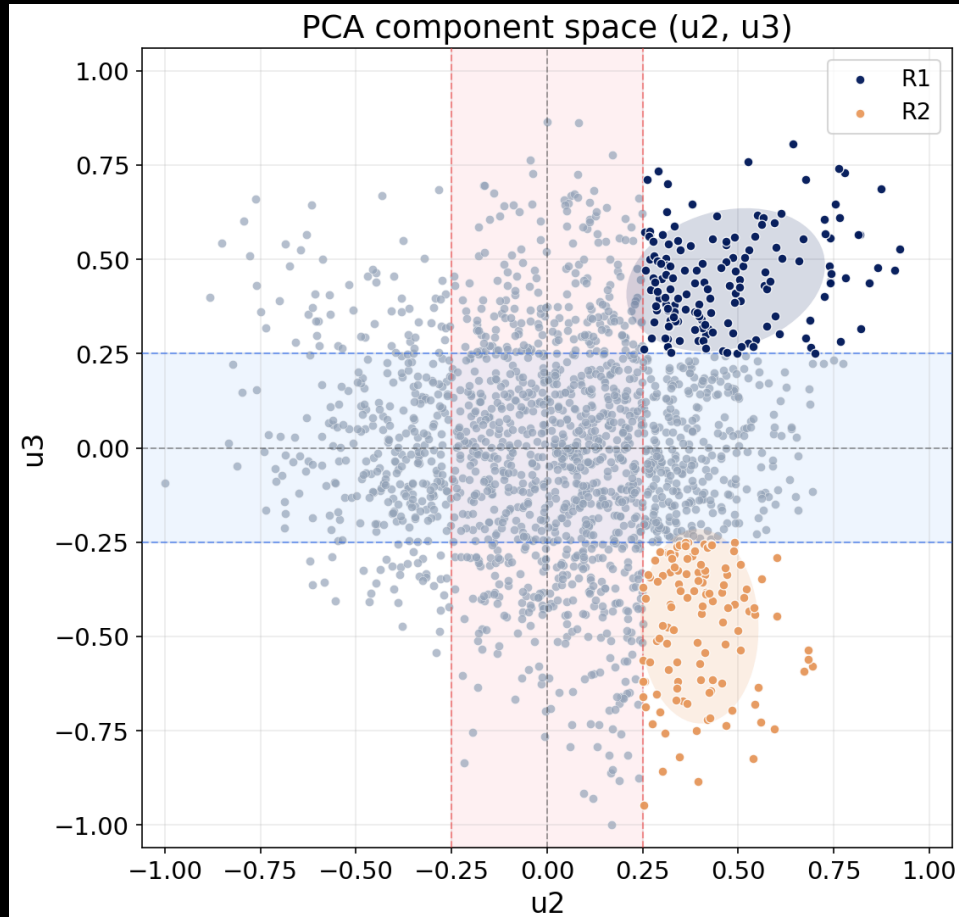
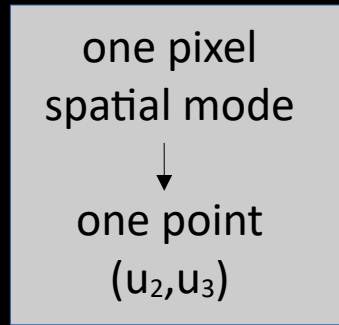
Spatial modes

Singular values

Temporal modes

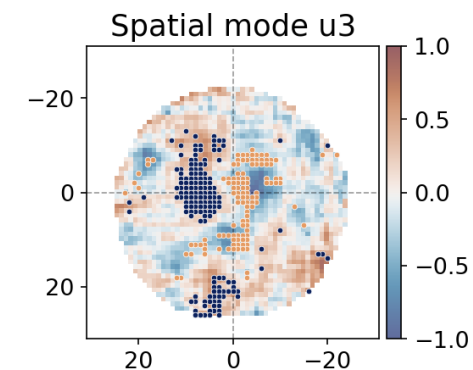
Results: RUN 2

- Selection of regions based on **PCA spatial modes**



Region 1

- $u_2 > 0.25$
AND
• $u_3 > 0.25$

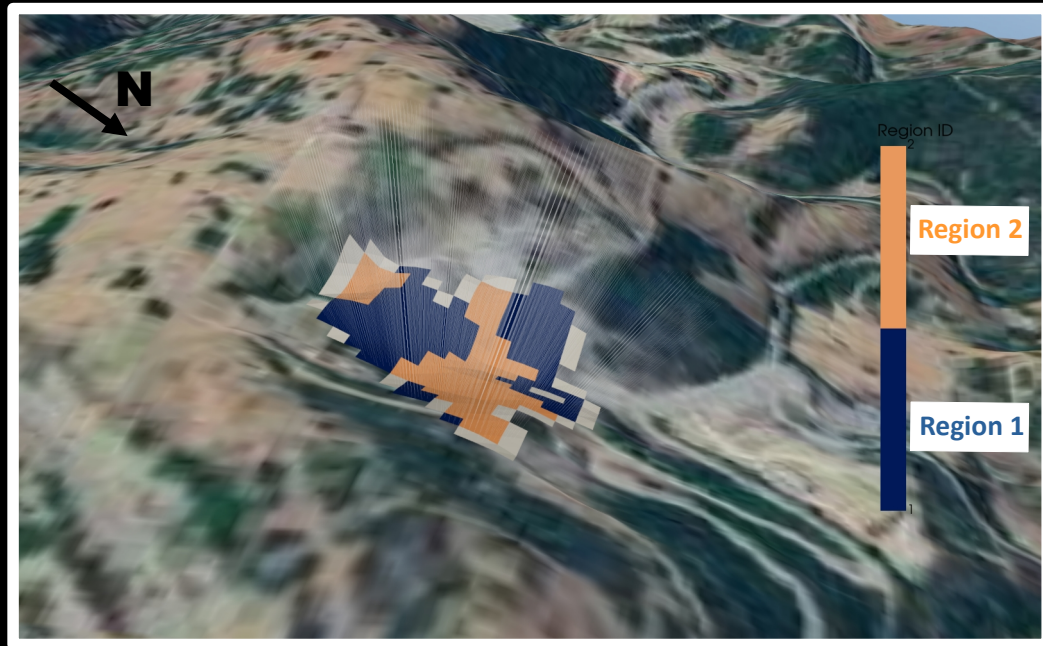


Region 2

- $u_2 > 0.25$
AND
• $u_3 < -0.25$

Results: RUN 2

- Selection of regions based on **PCA spatial modes**

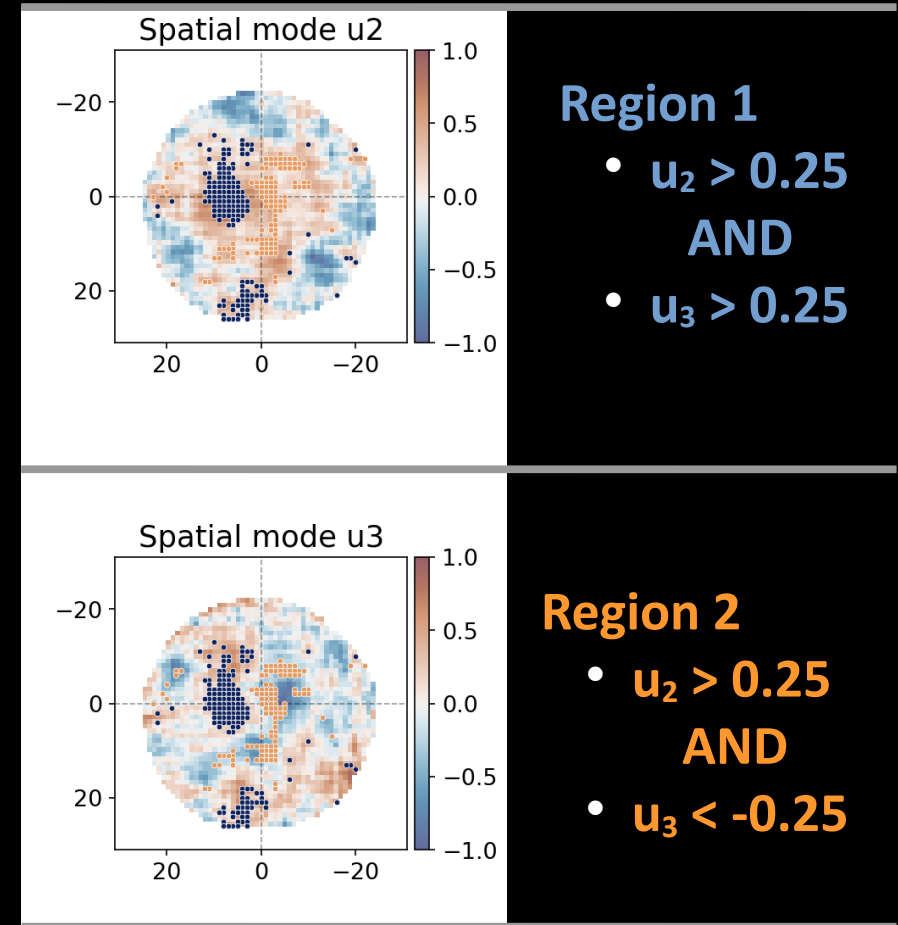


Regions mapped at the surface. Lines of sight in gray lines.

Mean rock thickness

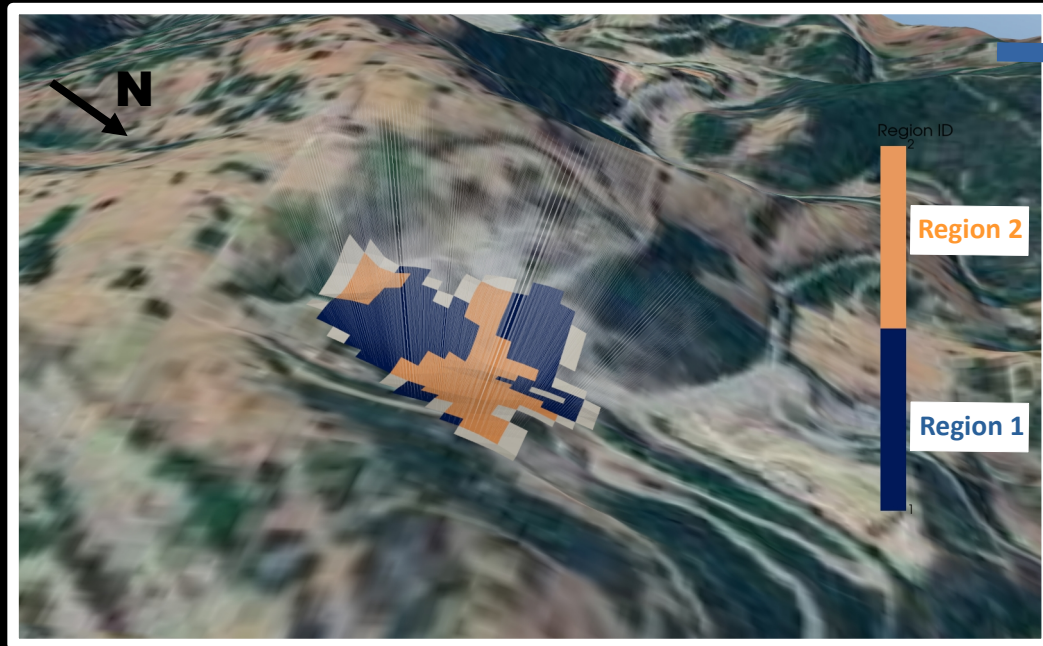
- Region 1: (165 ± 10) m
- Region 2: (160 ± 15) m

Spatial modes to lines of sight mapping



Results: RUN 2

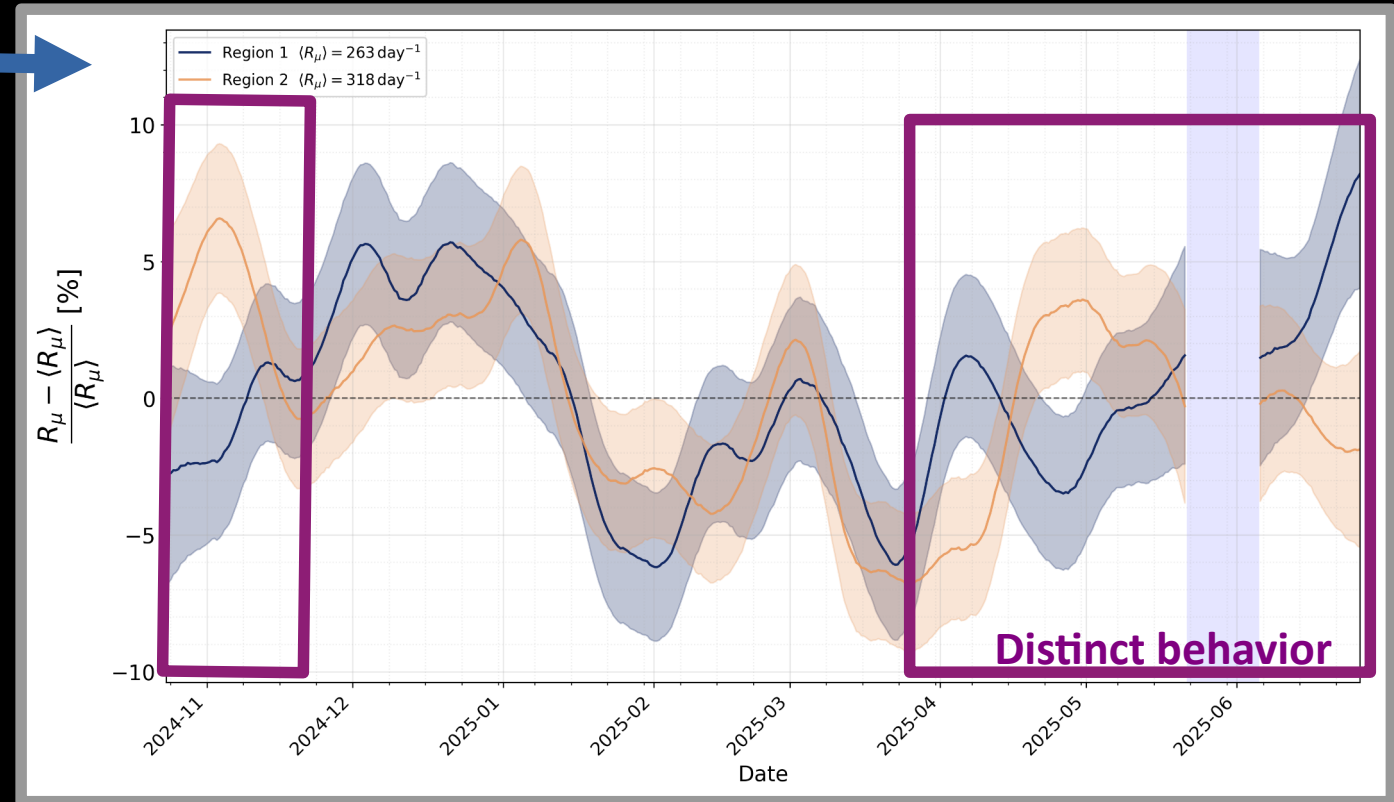
- Muon rate computation for each region



Regions mapped at the surface. Lines of sight in gray lines.

Mean rock thickness

- Region 1: (165 ± 10) m
- Region 2: (160 ± 15) m



Muon rate in each region represented as the deviation from the mean.

Conclusions and perspectives

- **Conclusions**

- PCA helps identify coherent spatio-temporal variations in muon data.
- PCA reduces bias introduced by line-of-sight grouping.

- **Next steps**

- Further grouping criteria based on PCA results.
- Comparison with external datasets (e.g., atmosphere, groundwater).

- **Perspectives**

- Data-driven definition of coherent regions.
- Applications to underground monitoring and site characterization.

Thank you for your attention!

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