Muon Survey Tomography Based On Micromegas Detectors For Unreachable Sites Technology (MUST²). Principles, experimental results and overlook.

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1. T2DM2 COLLABORATION

- ✓ Originally conceived to characterize **local density variations** due to the water motion across unsaturated zones.
- ✓ Develop a new tool based on the **cosmic muon** flux directional measurement for in-situ **imaging and monitoring** the **density** of large volumes of matter.
- ✓ Complementary collaboration between academic and industrial partners towards the creation of a sturdy, reliable, **portable** and ergonomic detector for **ground and underground operation**.

MUST² camera

The MUST² camera is a gaseous detector consisting of a thin time projection chamber read by a resistive Micromegas[1].

I. The muon ionizes the gas blend in several points along its trajectory inside the detector's drift chamber.

II. The electrons so generated drift towards the electric field, and arrive sequentially.

III. This triggers an electronic cascade in the amplification zone and the charge, collected by the resistive layer, induces a signal in the readout planes.
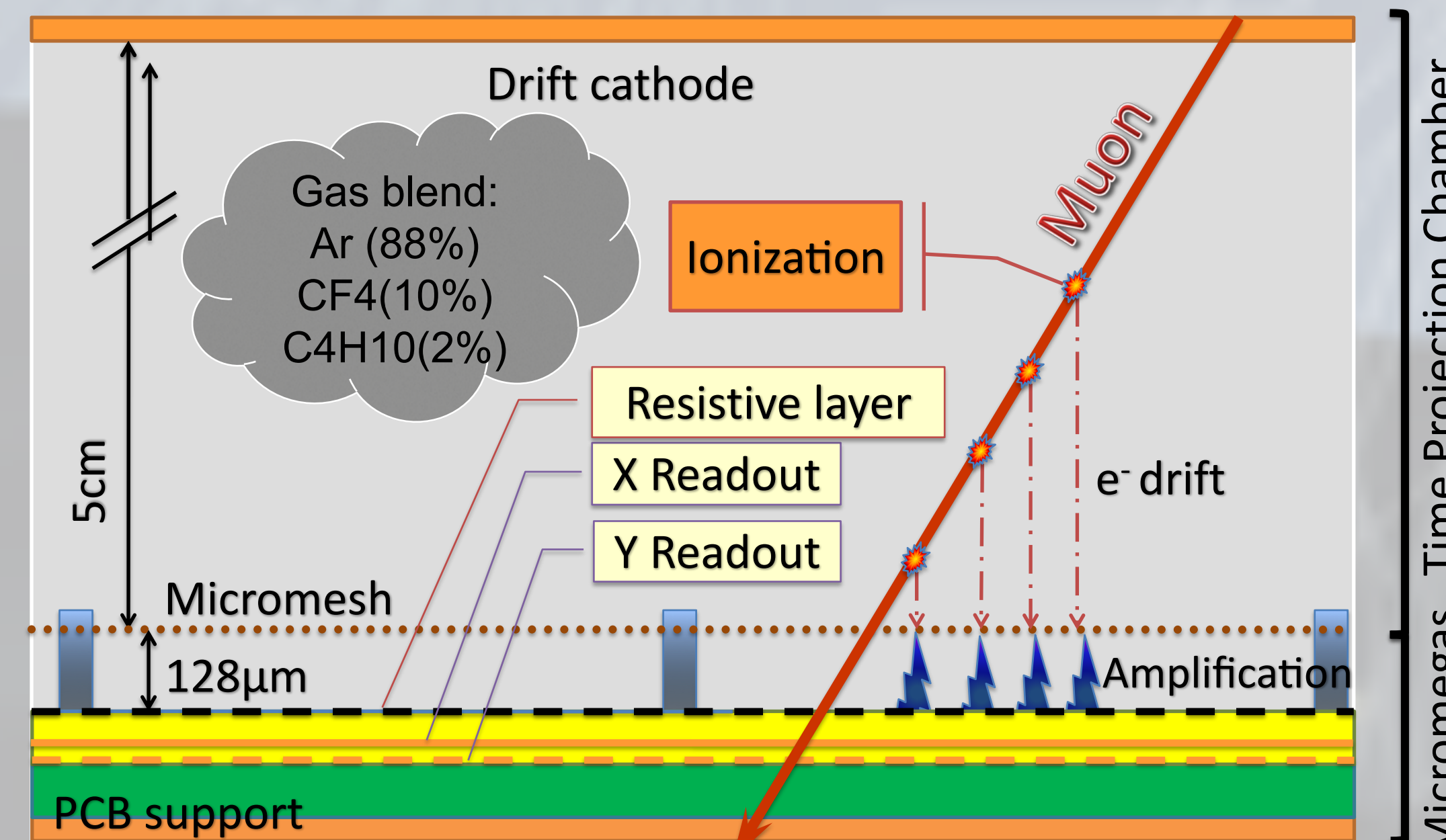
Figure 2.1. Schematic cross-section of the MUST² to illustrate its functioning principle.

The MUST² camera allows retrieving the following information:

- Muon passage time (few ns resolution).
- 2D Position (0.4mm resolution).
- Muon incidental trajectory, characterized by the zenith and azimuth angles.

2. HOW DOES IT WORK?

Muography

- Cosmic muons are a natural, permanent, passive source, capable to penetrate up to several hundreds of meters underground.
- The muon flux scatters and decreases progressively, with an absorption correlated with the medium density and length
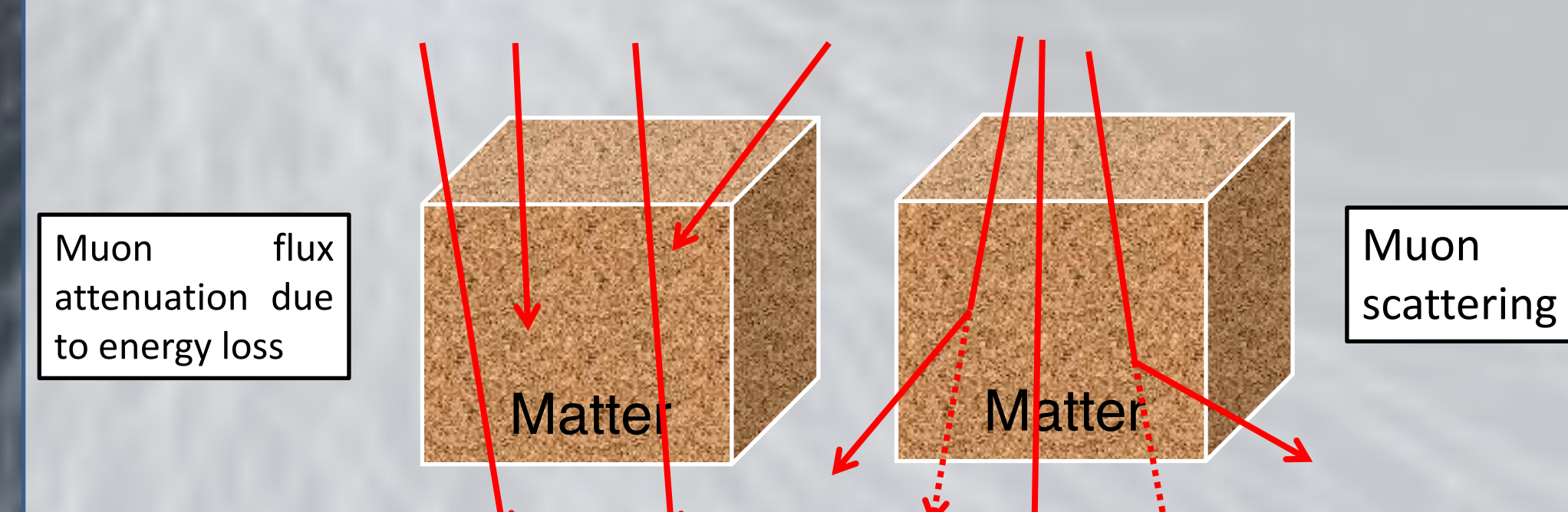
Figure 2.2. (Left) Principle of transmission tomography. (Right) Principle of scattering tomography due to the deviation of the muon.

- The muon flux characterization at ground level and underground is fundamental. The Tang empirical model[2] allows to estimate surficial flux as a starting point for the tomography.
- Figure 2.3.C provides the efficiency distribution of the muon trajectory reconstruction, and is used to correct the measurements.
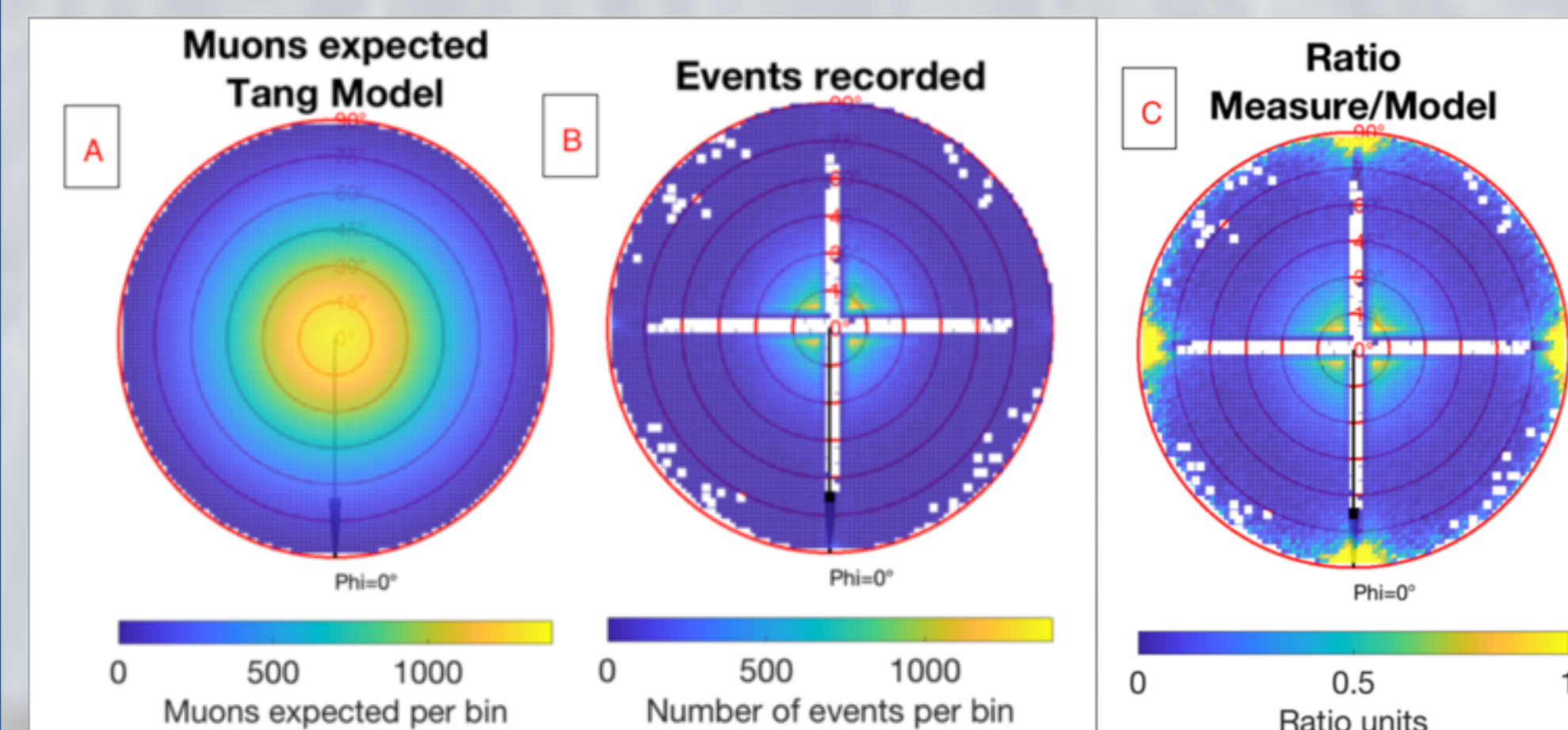
Figure 2.3. Polar chart of the muon arrival distribution according to the Tang model (A), experimental open sky measurement (B) and ratio between them (C).

- The **underground muon flux** can be estimated by multiplying the survival probabilities with the surficial flux.
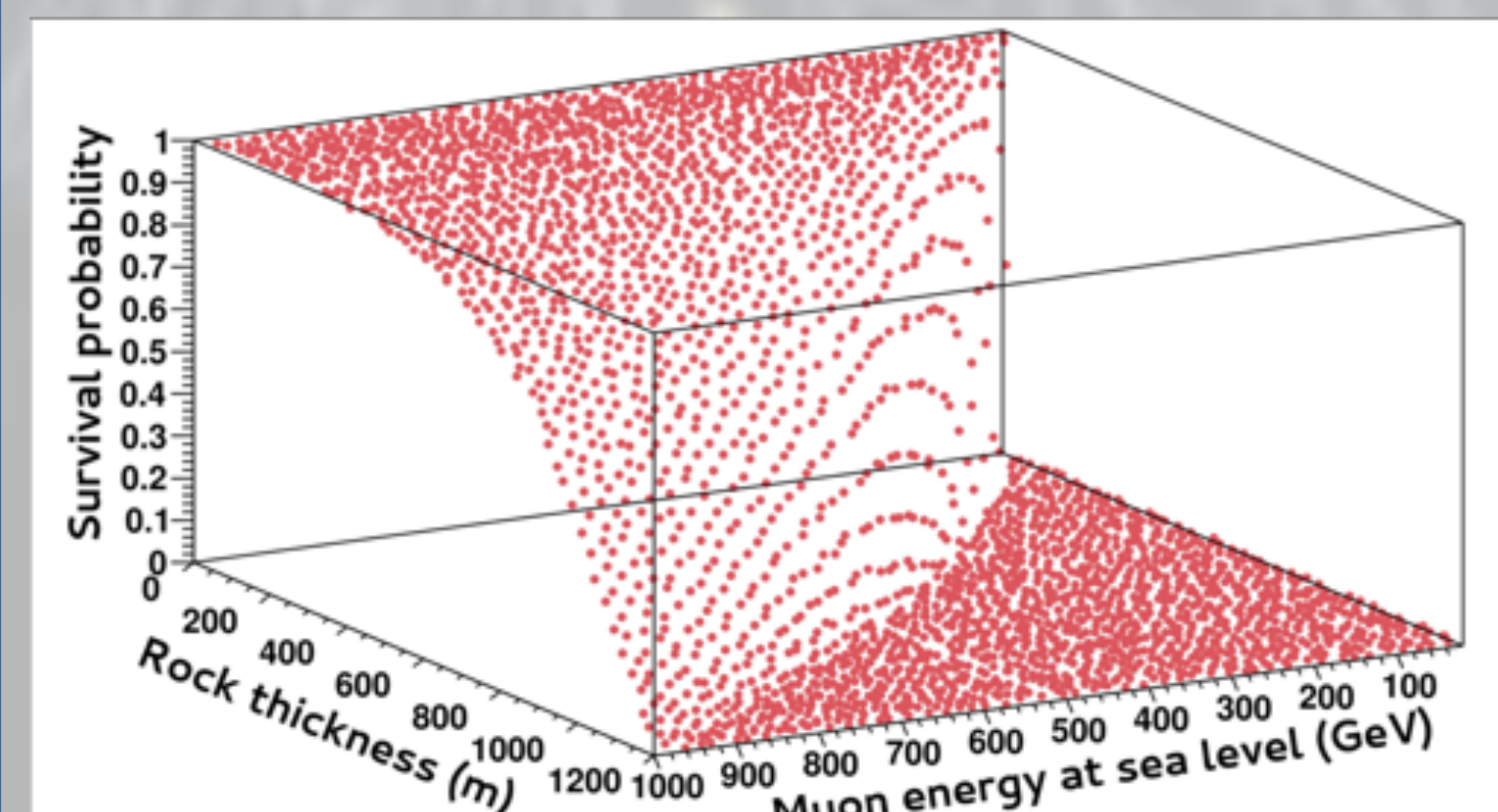
Figure 2.4. Muon survival probabilities as a function of the muon's energy for a standard rock density (2.65 g/cm³), from Hivert[3].

3. STUDY CASE: DAM

Digital model (A) › Opacity simulation (B) › Experimental measurement (C) › Temporal monitoring (D)

- Two superimposed models considering the medium heterogeneity:
  - Water $\rho = 1.000\ kg/m^3$.
  - Geology and dam* $\rho = 2.400\ kg/m^3$.
- Customizable water level.

- The digital model of 3.A allows to simulate the opacity of the targeted volume.
- The opacity is defined as the density integrated over the path's length and measured in meters of water equivalent.
- Provides an estimation of target's muon flux attenuation power.

- Integration time ~90h.
- It is possible to recognize the following elements:
  - Frontier between open sky and dam structure (green dot-dashed line).
  - Rock body of the water reservoir (red dotted line).

- Small density contrast (<1%) due to the water level variation during the measurements.
- Two superimposed behaviors:
  - Influence of the inverse of temperature in the muon trajectory reconstruction performance and the water level measurement (sinusoidal oscillations).
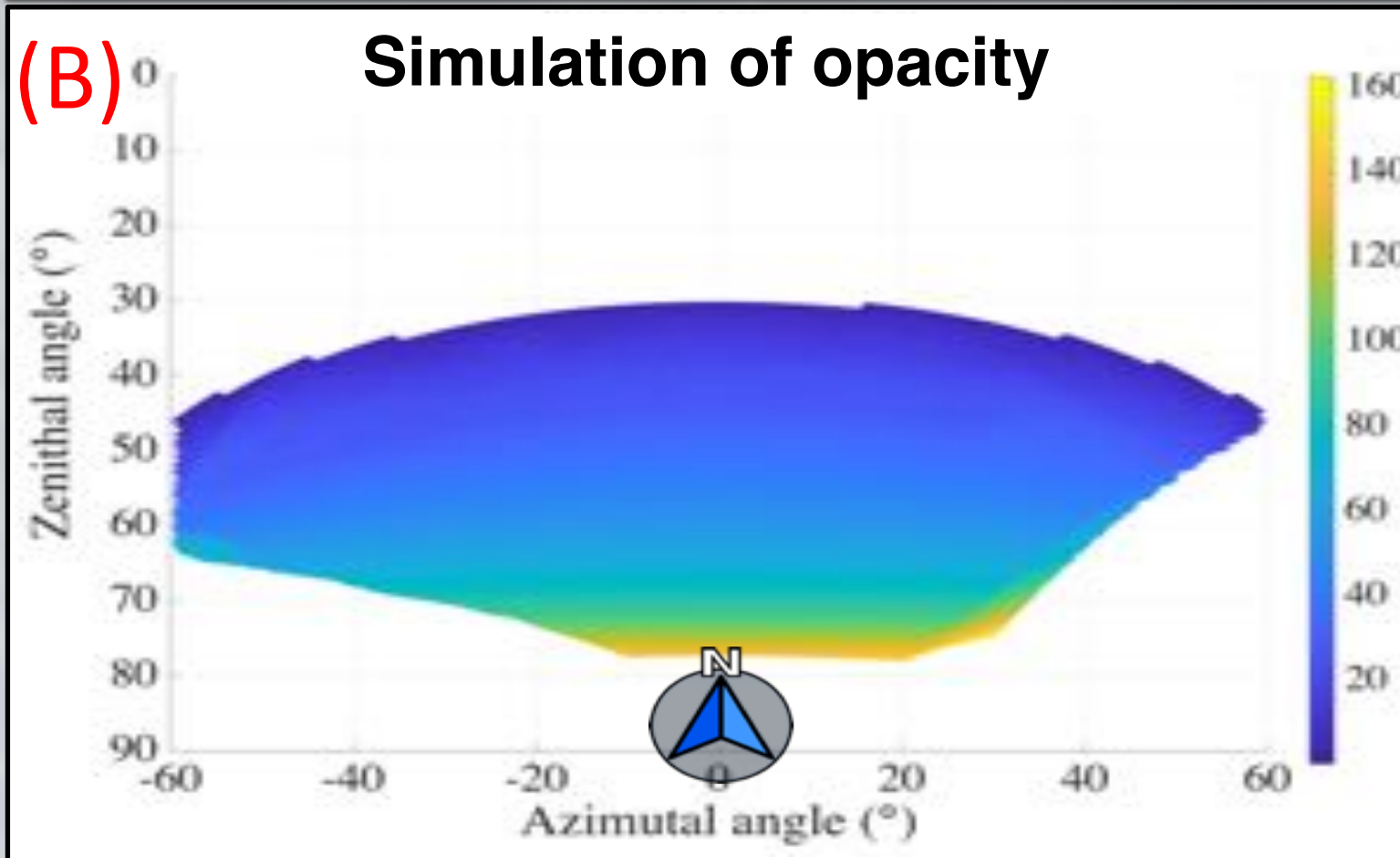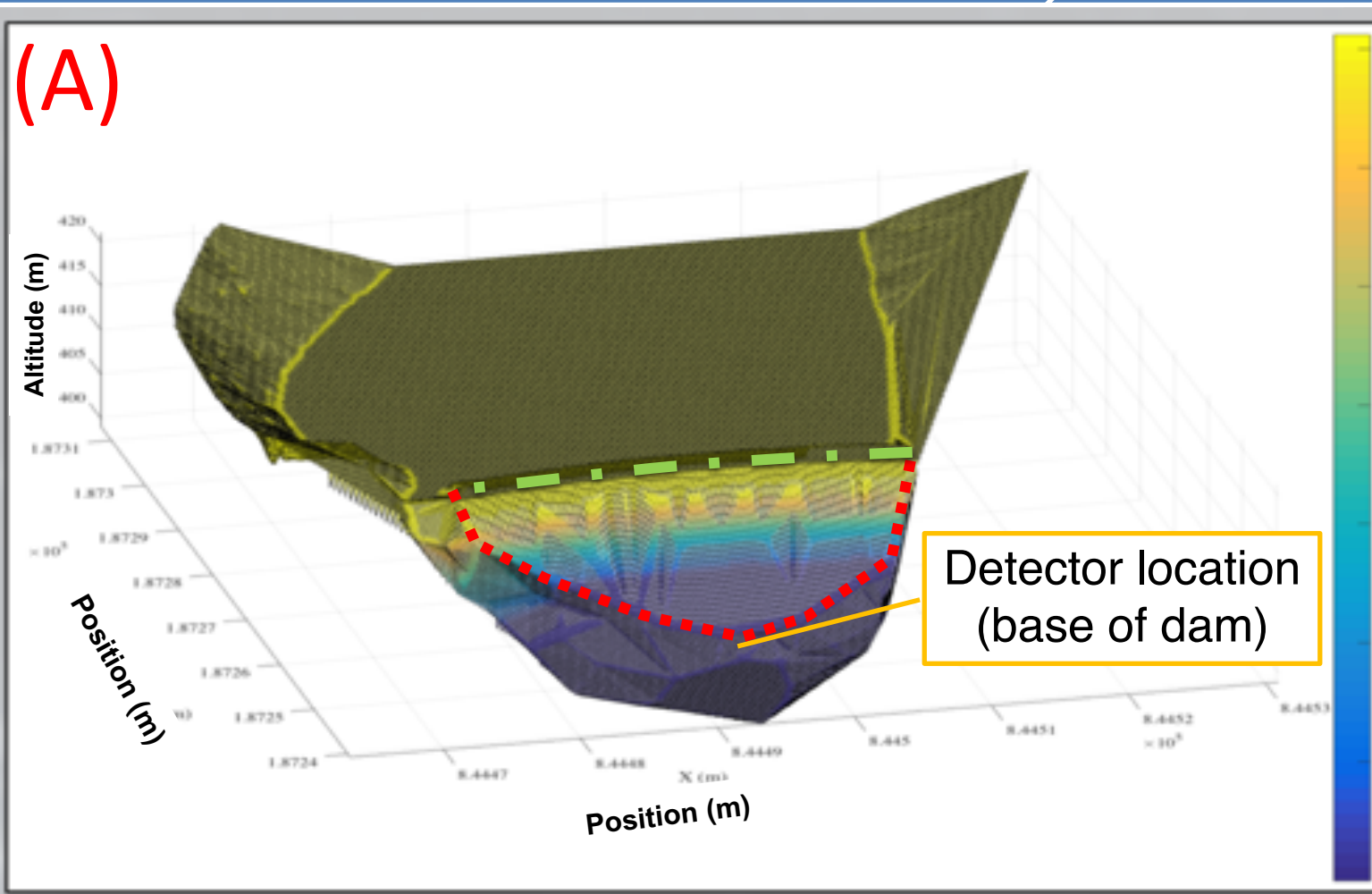 - The emptying trend of the dam (33 mm in four days) leads to a rise of the reconstructed muon flux as expected.

Figure 3.A. Digital model of Saint-Saturnin-lès-Apt (Fr) dam and water reservoir
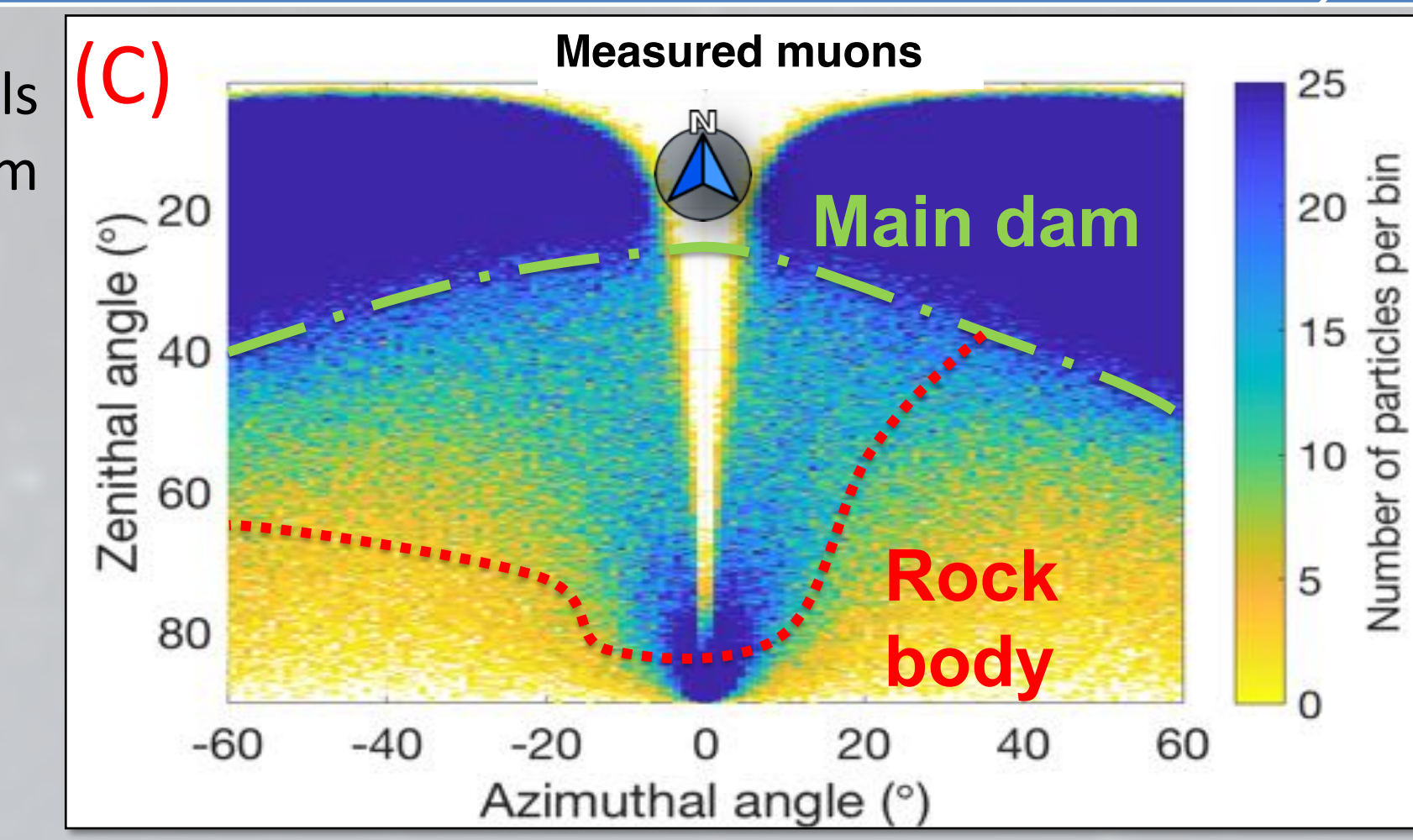Figure 3.B. Simulated opacity of the dam from the point of view of the MUST² camera
Figure 3.C. Muons measured coming from the direction of the dam
Figure 3.D. Temporal evolution of (blue) water level of the dam and (orange) recorded muon flux.

4. WHAT'S NEXT ?

- ✓ Minimize performance variability of MUST² due to temperature fluctuations: adaptive gain.
- ✓ Test the new muon trajectory reconstruction algorithm, completely new approach.
- ✓ Construction and deployment at the LSBB of a network of 20 autonomous cameras integrating all the improvements (funded by FEDER LSBB2020). Versatile setup configurations:
  - ➢ Monitoring: network of stand-alone cameras.
  - ➢ Deep measurements: clustered cameras to increase detection surface.
  - ➢ Scatter measurements: trackers upstream/downstream object (different scales).
  - ➢ Multilayer operation: stacked detectors to improve angular resolution.

Figure 4.1. Visualization of the Low Background Noise Laboratory (LSBB) galleries underneath the mountain and scheme with the detector's location.

5. CONCLUSIONS

- ✓ MUST² is a useful tool for the direction-sensitive measurement of the muon flux towards muographic applications.
- ✓ More data required to fully validate temporal monitoring capability due to small density contrast and gain fluctuations during outdoor experiment.
- ✓ Field transportability and reliability validated during outdoor measurements.
- ✓ The network of cameras, soon deployed at the LSBB, will allow versatile configurations to enhance the cosmic muon absorption/scattering measurements.
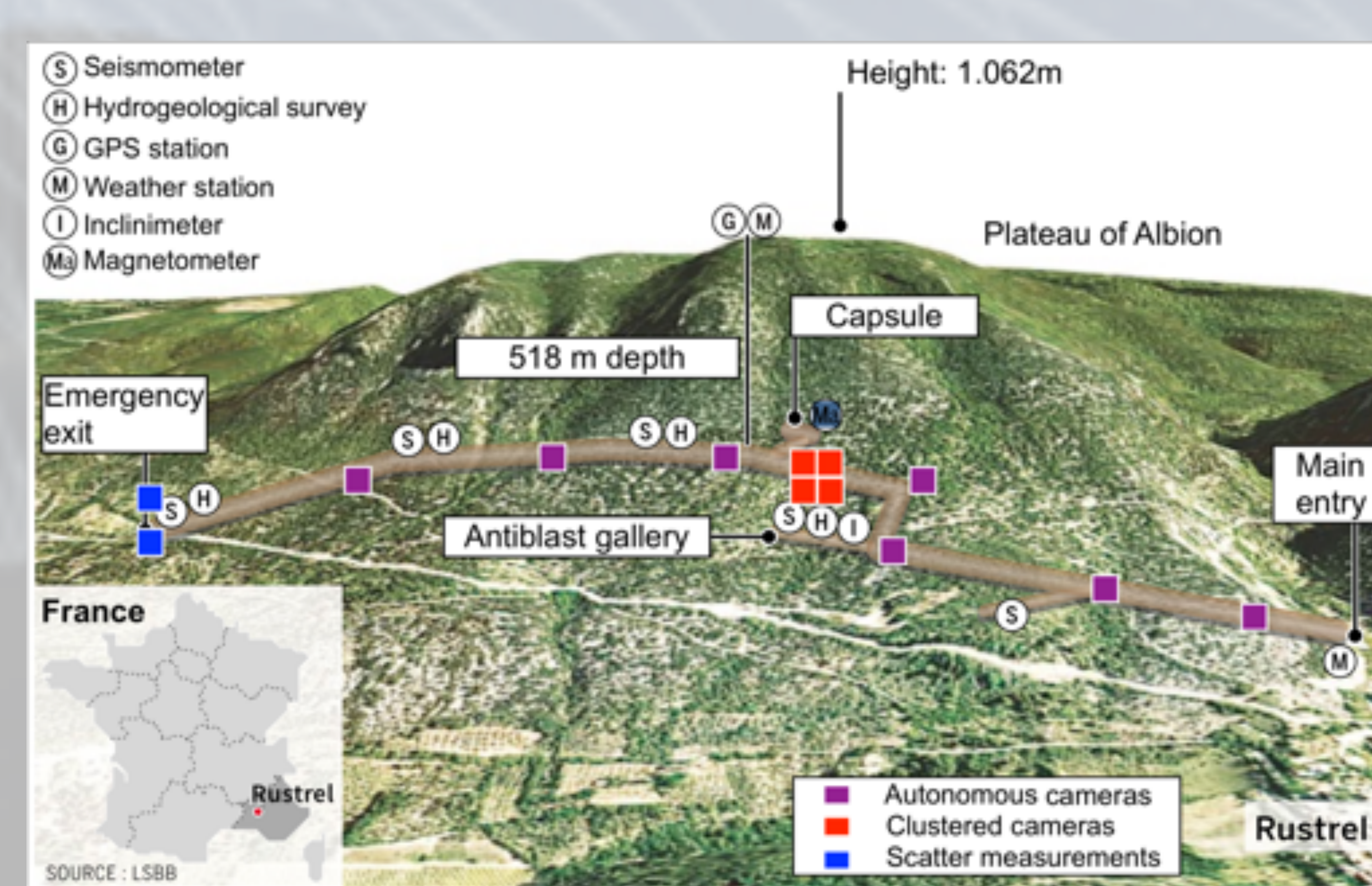
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References
[1] Ignacio Lázaro Roche. Design, construction and in situ testing of a muon camera for Earth science and civil engineering applications. Thesis on instrumentation and detectors. Université Côte d'Azur, 2018 (Fr). English. (DOI:10.13140/RG.2.2.25719.68008)
[2] Tang, A., Horton-Smith, G., Kudryavtsev, V. A. & Tonazzo, A. (2006). Muon simulations for super-kamiokande, kamland, and chooz. Phys. Rev. D74, 053007 (DOI:10.1103/PhysRevD.74.053007)
[3] Hivert, F. (2015). Caractérisation de la densité des roches et de ses variations spatiales et temporelles à partir des muons : application au LSBB. Doctoral dissertation.

Collaborators

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