Geant4-based simulations for muon imaging of volcanoes

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How it started …

A cross-disciplinary collaboration and a new research direction at the University of Oulu:

- Oulu Mining School
- Sodankylä Geophysical Observatory and Space Physics and Astronomy Research Unit
- Muon Solutions Ltd

Motivation:

No previous experience in muography research and curiosity

Why start with simulations?

Challenges

- No dedicated muography detector available
- Need to understand methodology
- Need a platform for future studies

Research ideas:

- Build a realistic Geant4-based model of the target object
- Compare synthetic muography data with real observations
- Determine optimal observation times for density anomaly detection
- Evaluate multi-detector configurations

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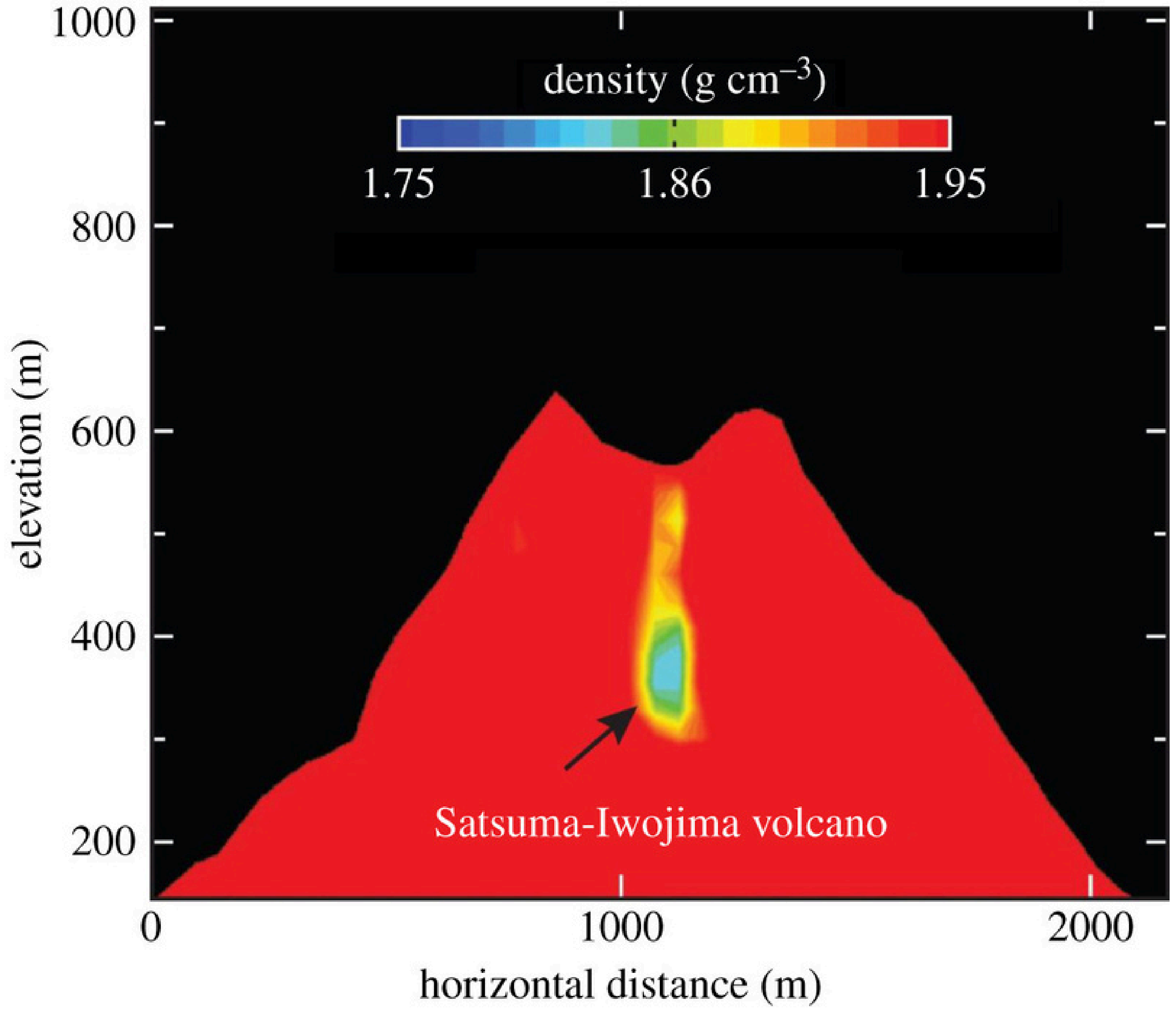
Iwodake volcano

- Specifically tailored to a real volcano **Iwodake**, at the Satsuma-Iojima island, Japan.
- Active rhyolitic volcano with a persistent magma convection.

- Site of pioneering muography studies held by Prof. Tanaka (*Tanaka, H.K.M., Uchida, T., Tanaka, M., Shinohara, H., Taira, H., 2009. Cosmic-ray muon imaging of magma in a conduit: degassing process of Satsuma-Iwojima Volcano, Japan. Geophys. Res. Lett. 36, L01304, http://dx.doi.org/10.1029/2008GL036451.*)

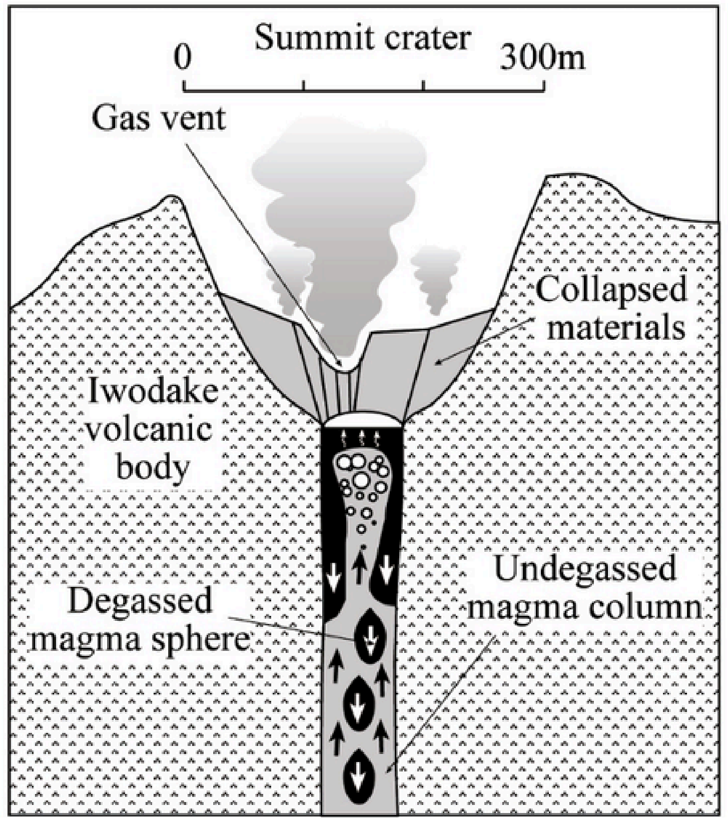
Aerial image of Satsuma-Iojima island (Japan Coast Guard).



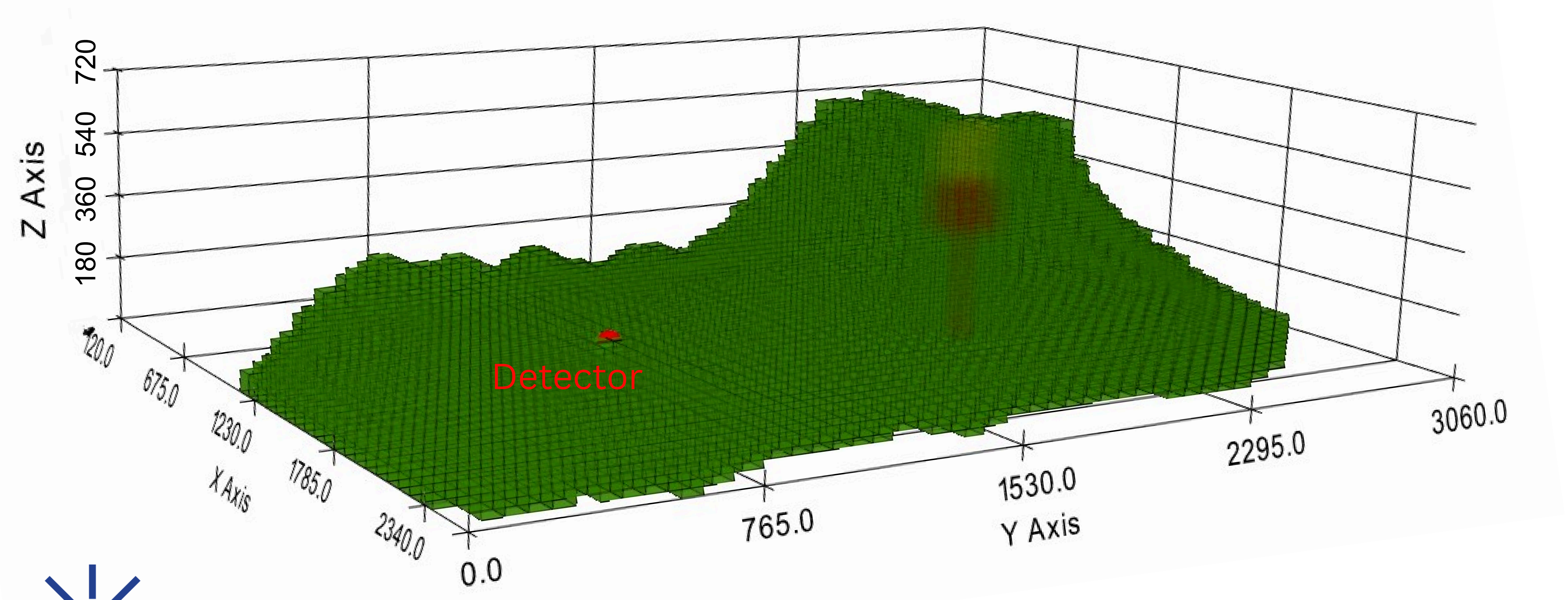
The average density distribution as a projection on the cross-sectional plane (H. K. M. Tanaka et al., 2009)

Volcano model construction

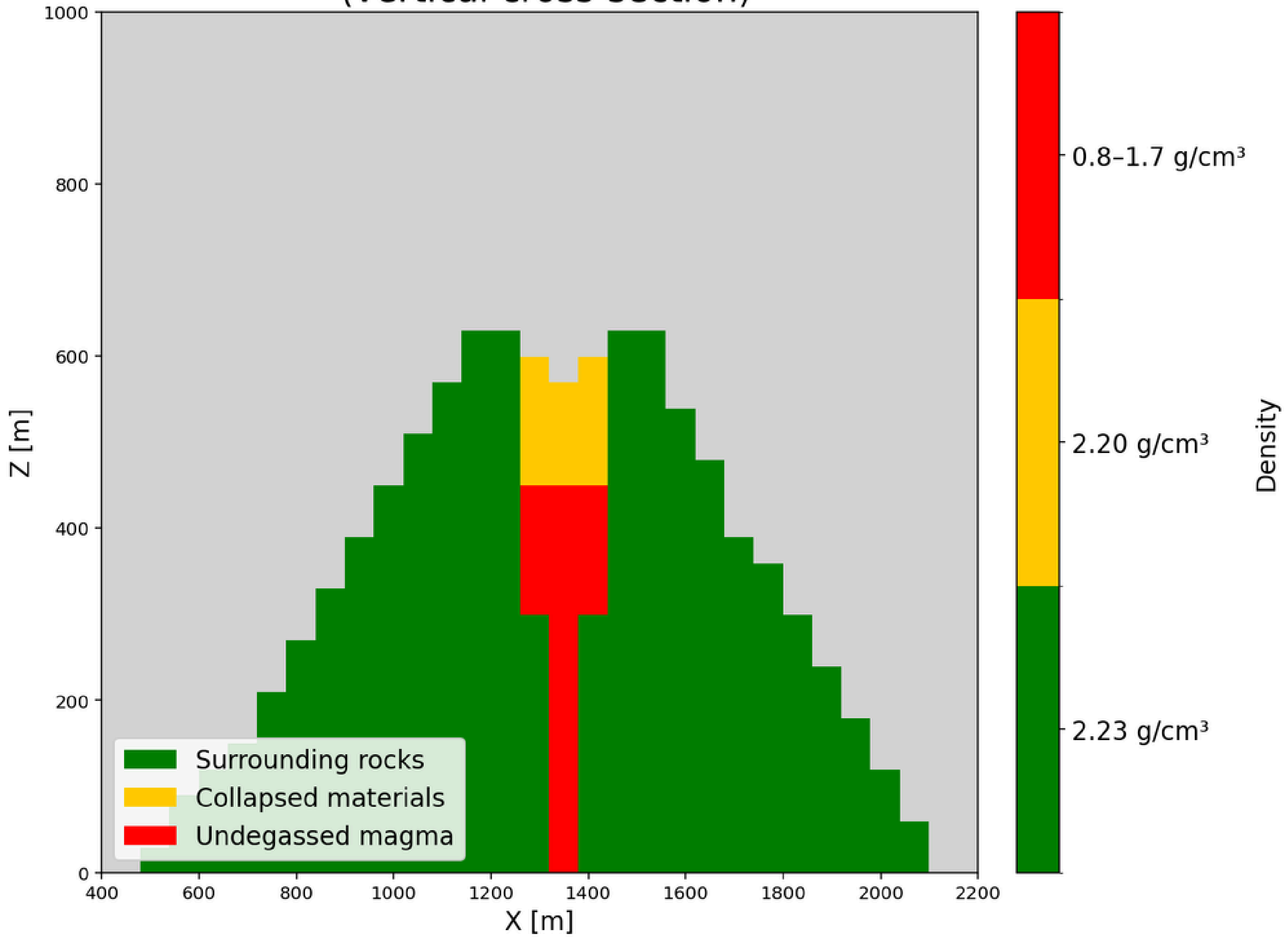
Conduit magma convection model of Satsuma-Iwojima volcano, adapted from Kazahaya et al. (2002) on the degassing process and Shinohara et al. (2002) on Iwodake degassing vent formation.



- Surface topography from NASA SRTM data (30 m resolution).
- Volcano modeled as stacked voxels following topography.
- Density model - simplified representation, focused on density contrasts host rock and conduit.



Volcano density model used for muon simulation (vertical cross-section)



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Volcano model construction

Average bulk density of the volcanic edifice - 2.23 g/cm³

Chemical composition of the magma identical to that of the surrounding solid rock

Chemical formula	%
SiO_2	66.99
Al_2O_3	13.90
FeO	5.36
MgO	1.06
CaO	4.45
Na_2O	3.49
K_2O	1.82
TiO_2	0.31
P_2O_5	0.31
MnO	0.09

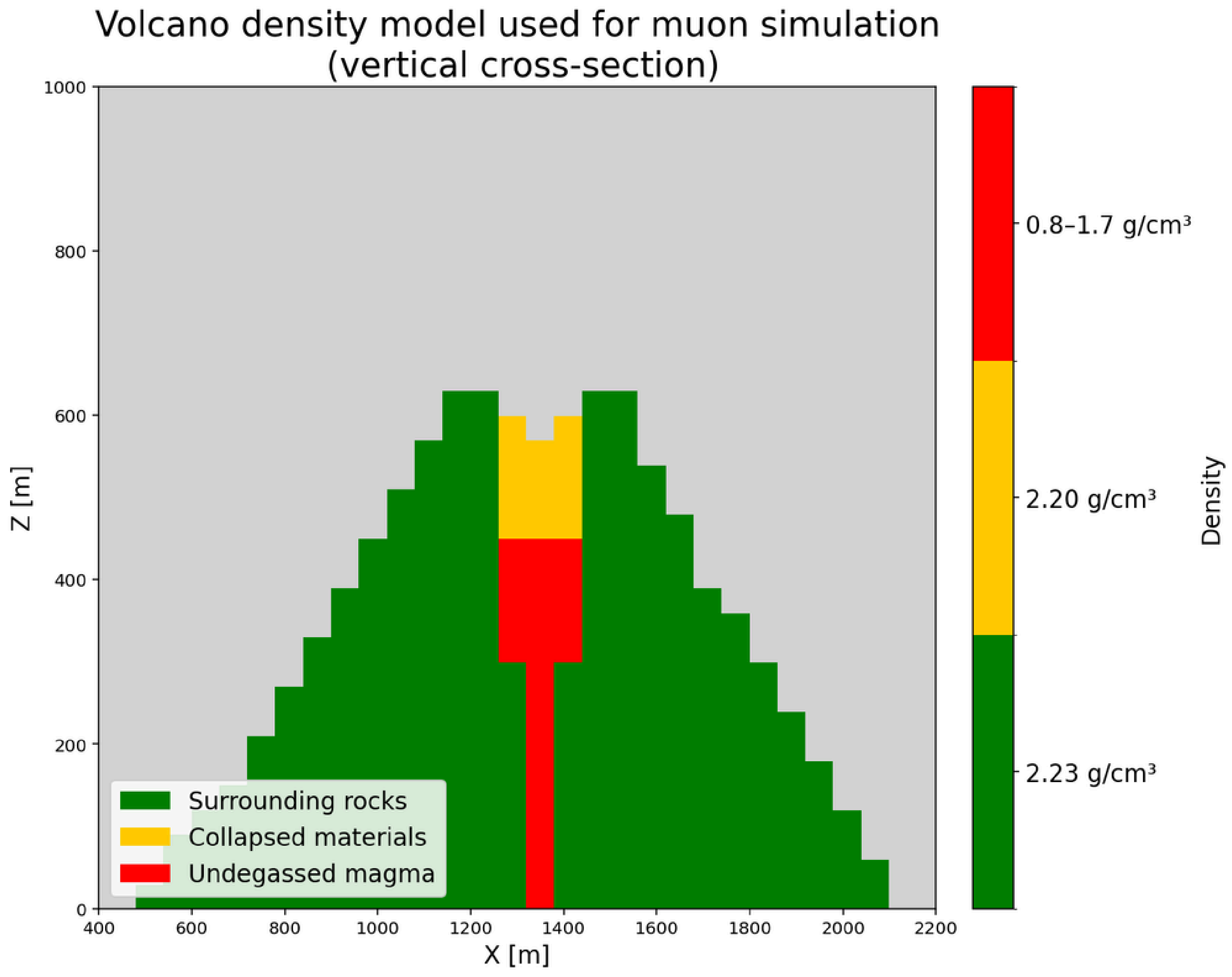
Chemical composition of lava samples from Iwodake. Average of three analyses H. Kuno, 1962

Investigated scenarios:

Conduit densities:

- 0.8 g/cm³
- 1.1 g/cm³
- 1.4 g/cm³
- 1.7 g/cm³

- Open sky
- Uniform-density volcano



Muon source and detector

Atmospheric muon generation:

- Parametrized atmospheric muon flux - **modified parameterization of the Gaisser** formula for sea-level cosmic-ray muons (*Mengyun Guan et al. “A parametrization of the cosmic-ray muon flux at sea-level”. (Sept. 2015). arXiv: 1509.06176*)
- Hemispherical source geometry
- Realistic angular and energy distributions - a cumulative distribution function (CDF) covering a range of energies and zenith angles

Detector:

- **The detector is simplified** to a sensitive detection plane - “ideal detector”
- 1 × 1 m^2 sensitive area
- Same location as in the real experiment

In addition, several strategies are employed **to reduce the computational time** of the simulation.

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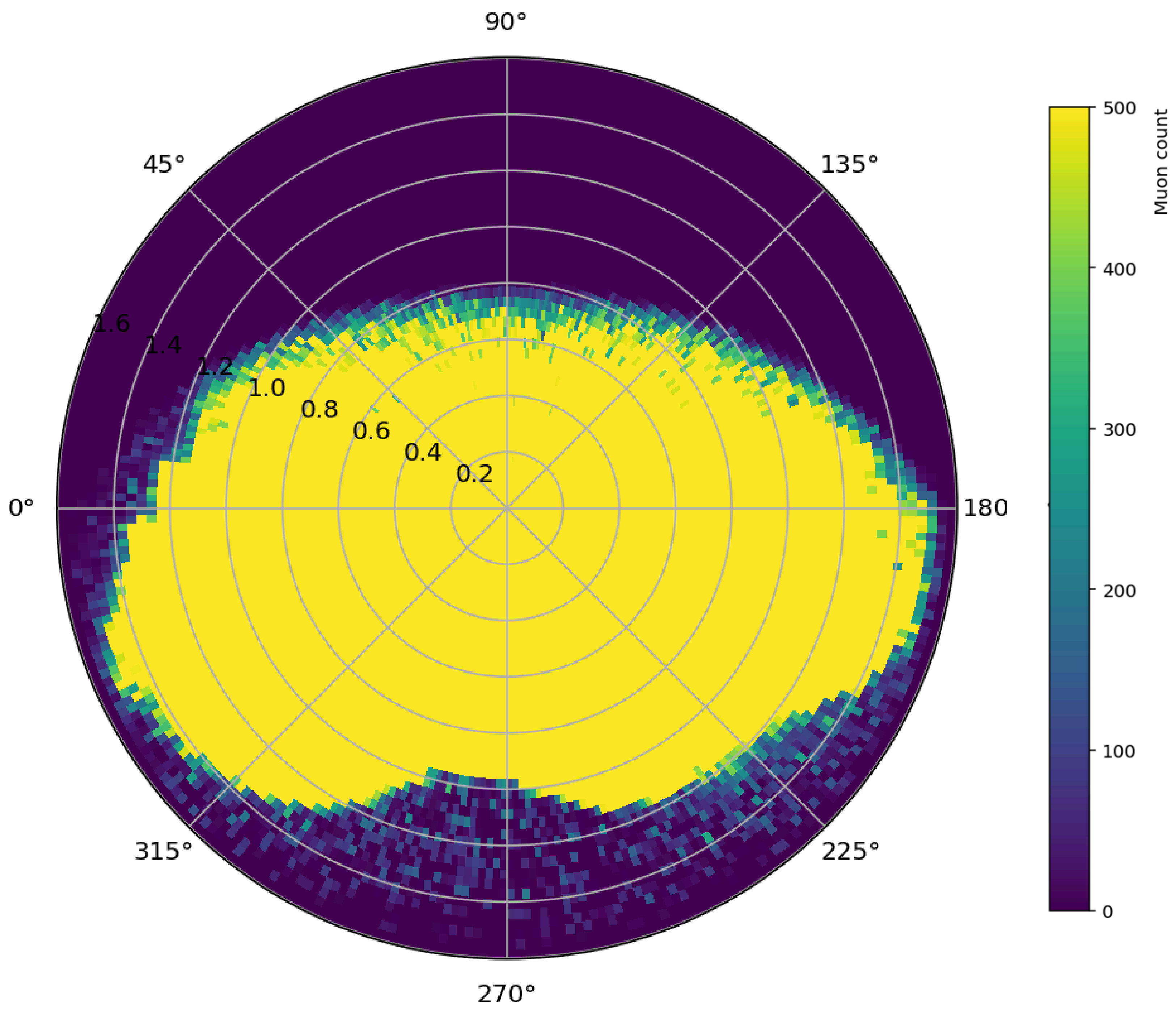
Computational optimization

- Back-tracing implemented - detector-relevant trajectories only
- Energy range: 100 GeV–10 TeV
- Non-muon secondary particles produced during interactions - terminated

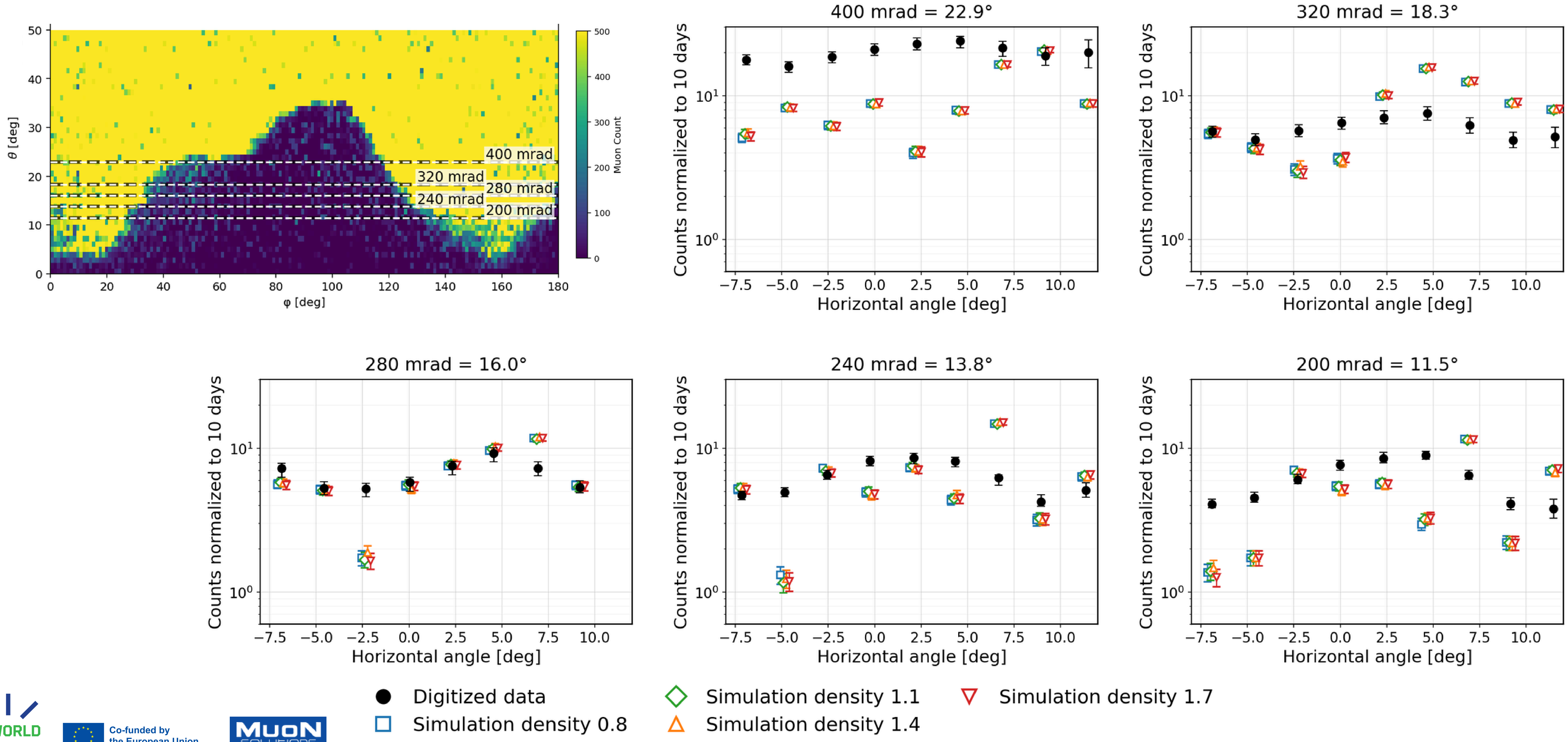
One year of observation - 4 days of simulation

First results

Angular distribution of simulated muons recorded by the detector, shown in polar coordinates. Color indicates muon counts per angular bin.

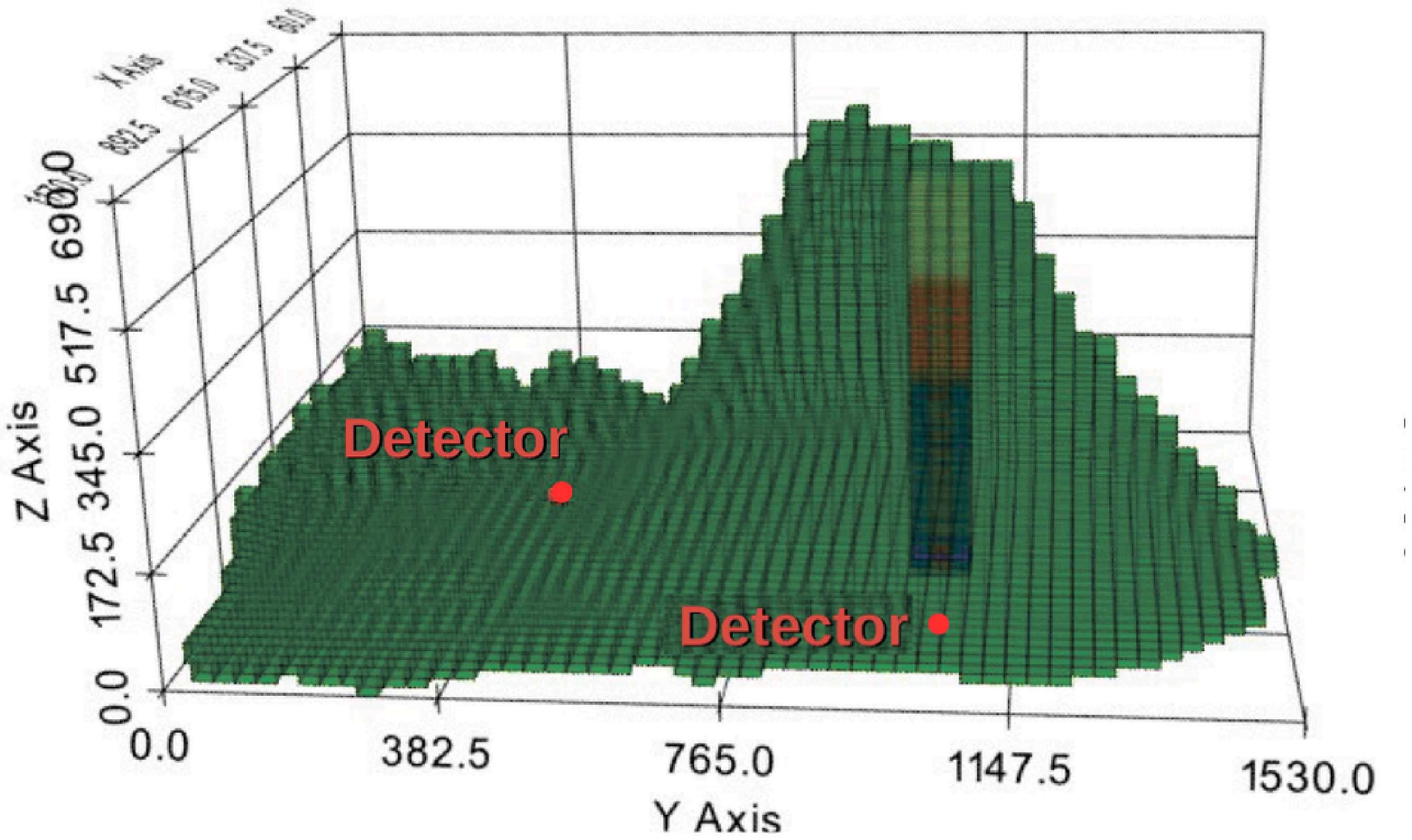


Validation against experimental data



When things didn't go as planned

A topography-scaling error made the model half-size in X–Y. Recalculation is now ongoing.

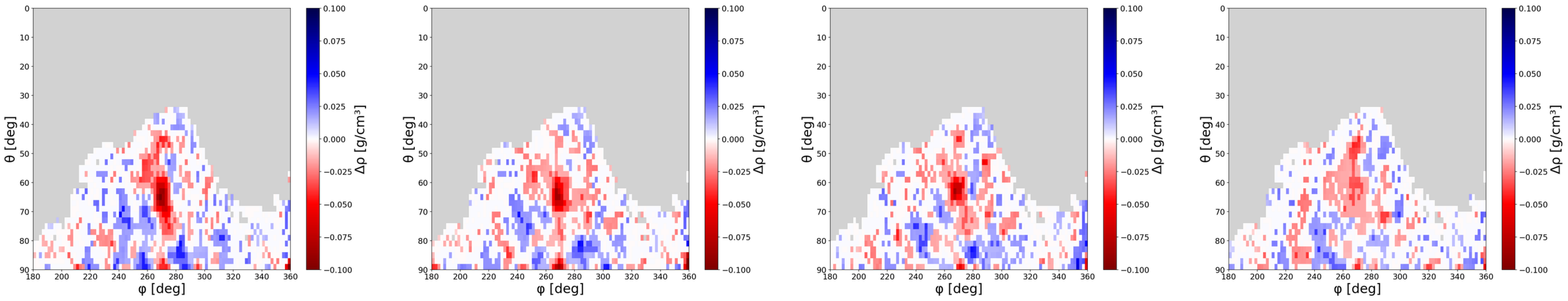


Take-home message: measure twice, simulate once.

Density reconstruction

Reconstructed density difference (Δρ) maps for different conduit densities (0.8, 1.1, 1.4 and 1.7 g/cm³).

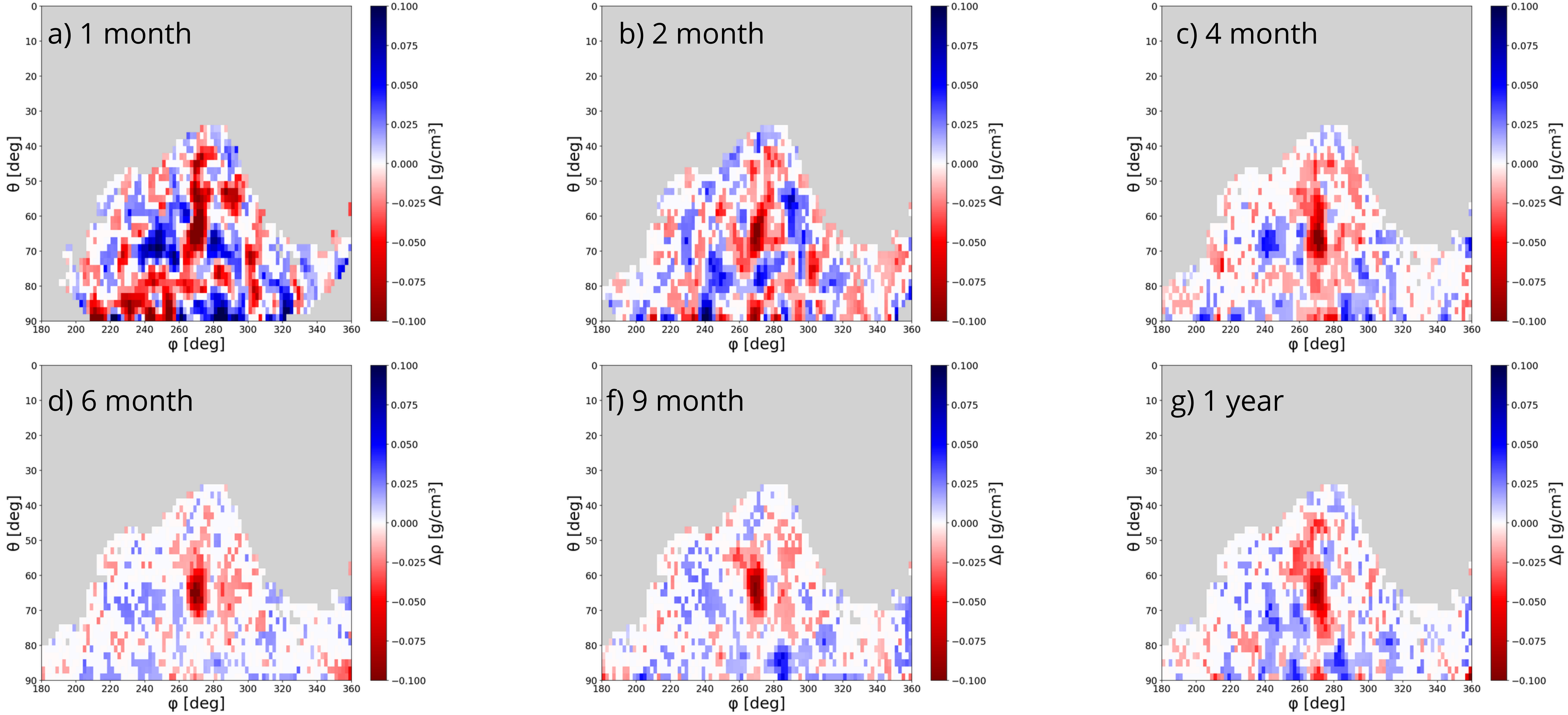
Observation time: 1 year.



a) conduit density ρ = 0.8 g/cm³ b) conduit density ρ = 1.1 g/cm³ c) conduit density ρ = 1.4 g/cm³ d) conduit density ρ = 1.7 g/cm³

Observation time analysis

Reconstructed density difference (Δρ) maps for the conduit density 0.8 g/cm³ for different observation periods



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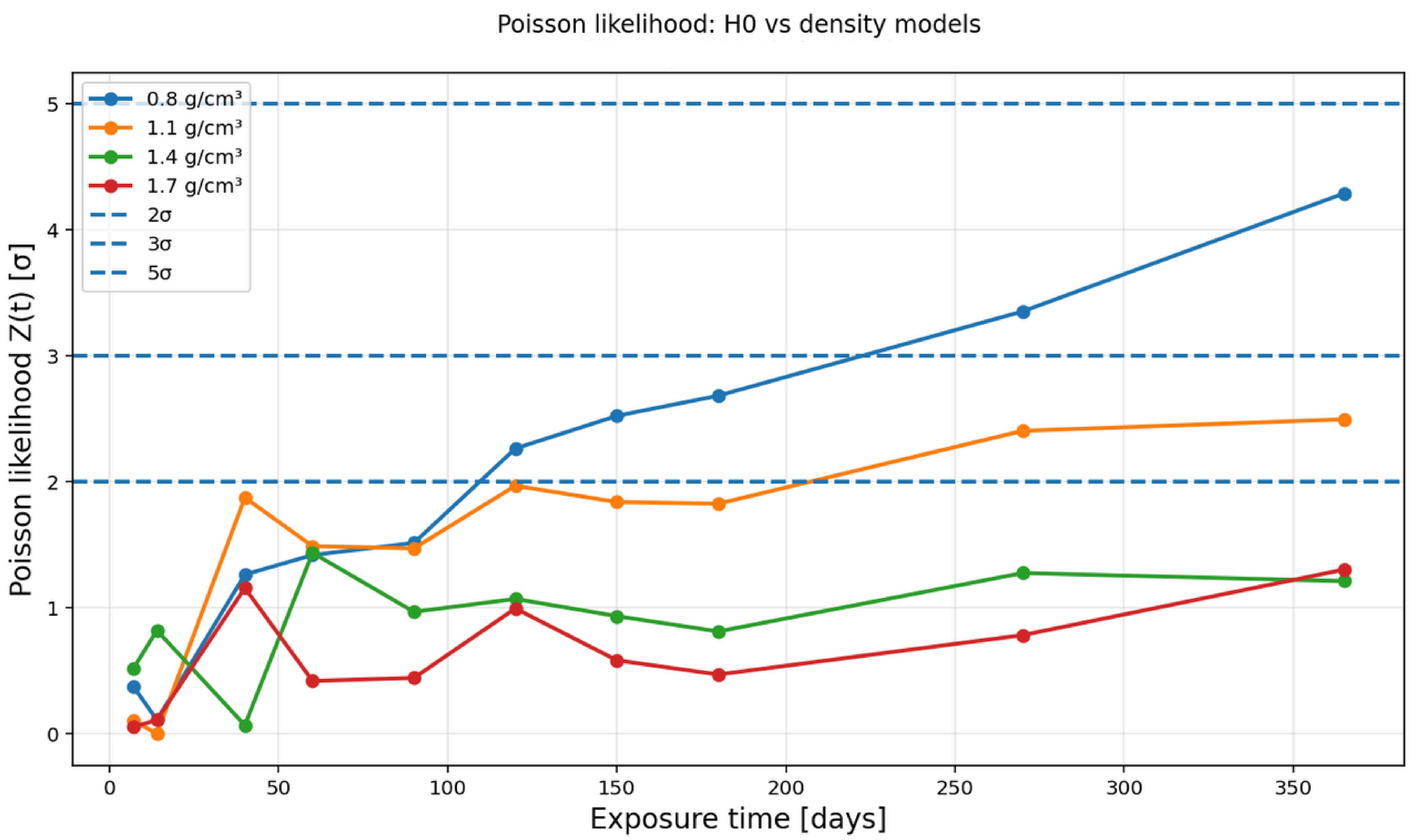
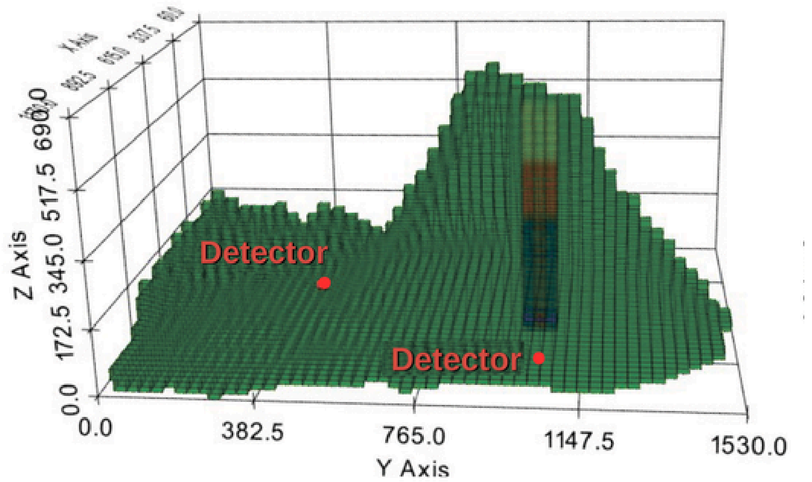
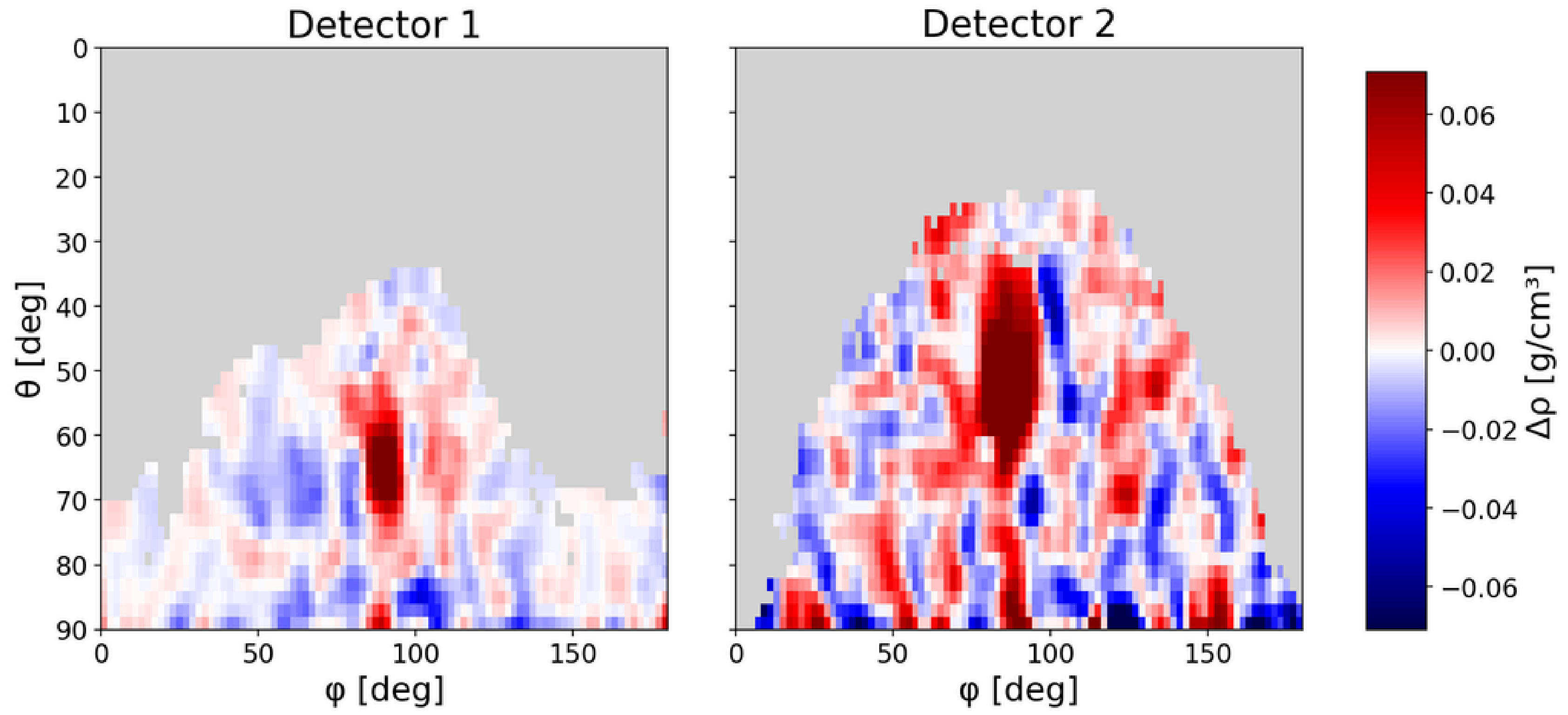
Observation time analysis

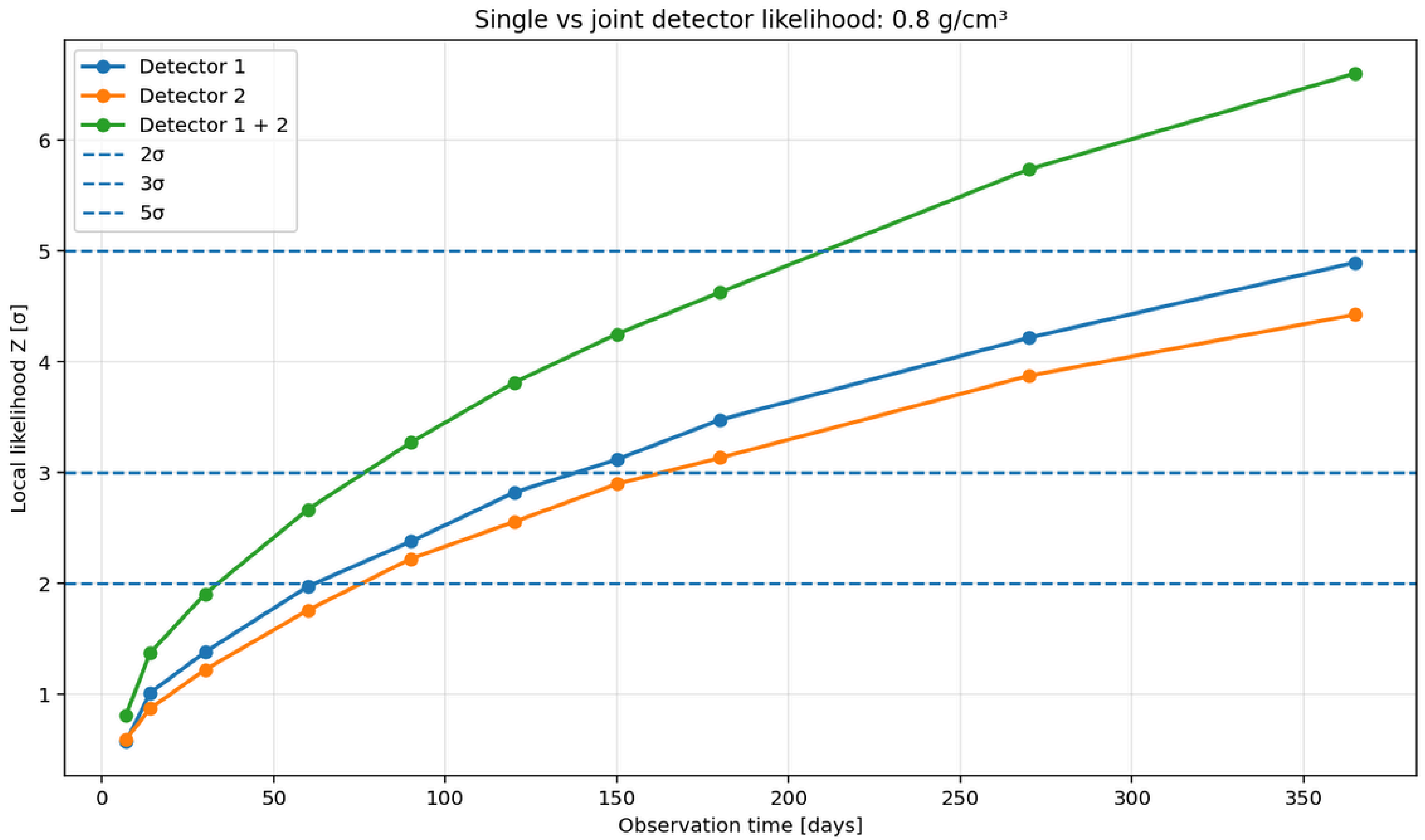


Separation significance Z(t) as a function of exposure time for different density contrasts.

Dual detector configuration







Evolution of the local likelihood significance Z as a function of observation time for Detector 1, Detector 2

Next steps

Volcano case:

- Realistic detector response
- Time-dependent volcanic processes
- Inversion problem

Application beyond volcanoes:

- Mining and tunneling infrastructure in Finland
- Validation using real observed data from industry partner

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Thank you!

This work has received funding from the European Union's Horizon Europe research and innovation program under the Marie Skłodowska-Curie grant agreement no. 101081280.