An example of combined inversion: muon tomography

Marina Rosas-Carbajal

In collaboration with: R. Bajou, M. Tramontini, J. Marteau

cnrs

IPGP | Université Paris Cité

iP2i LES 2 INFINIS LYON

International Workshop on Multi-messenger Tomography of the Earth, July 2023

Motivation

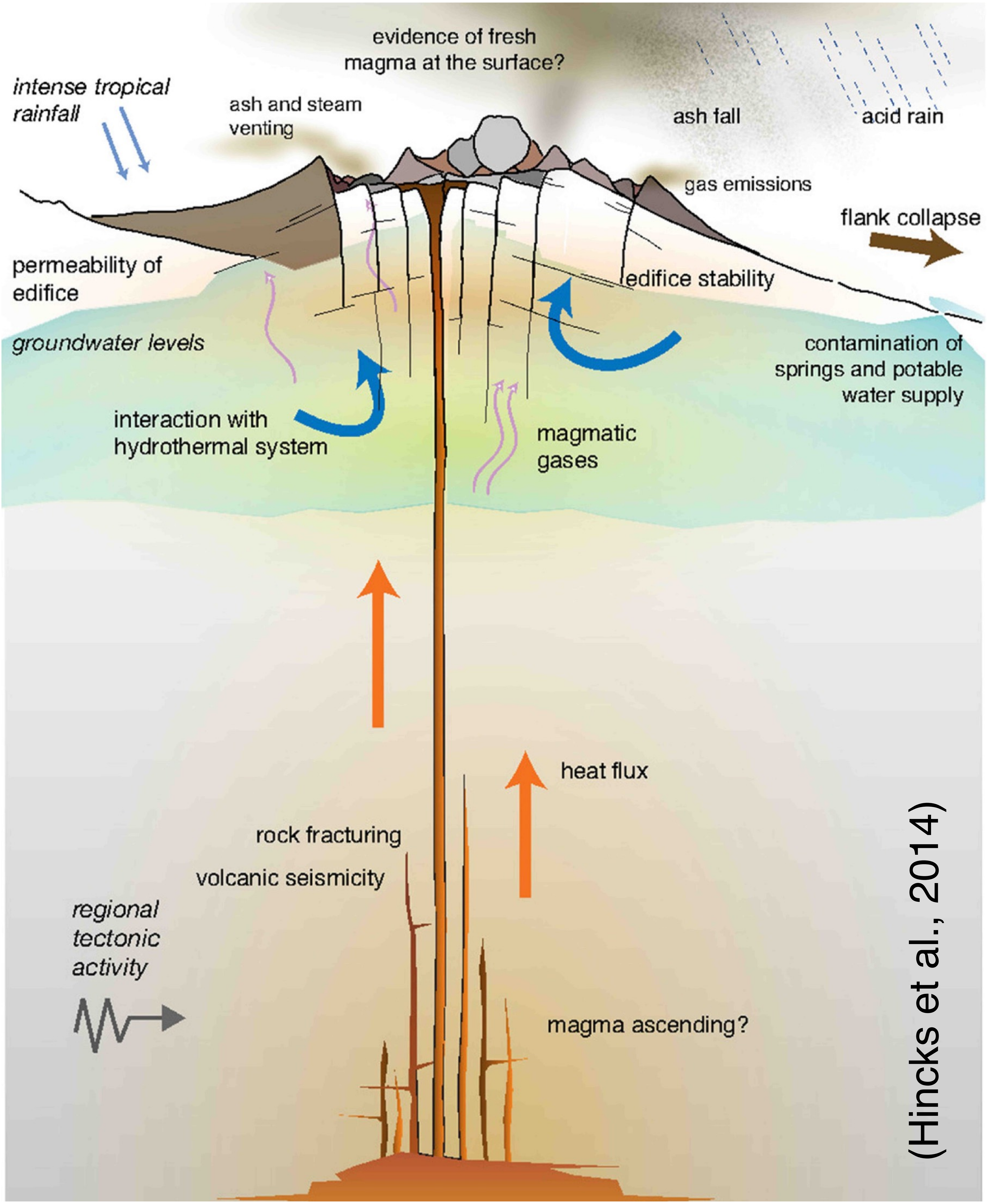
Volcanic eruptions

Magmatic (e.g. St Helens)

Non-magmatic (e.g. Ontake)

Volcano hydrothermal systems

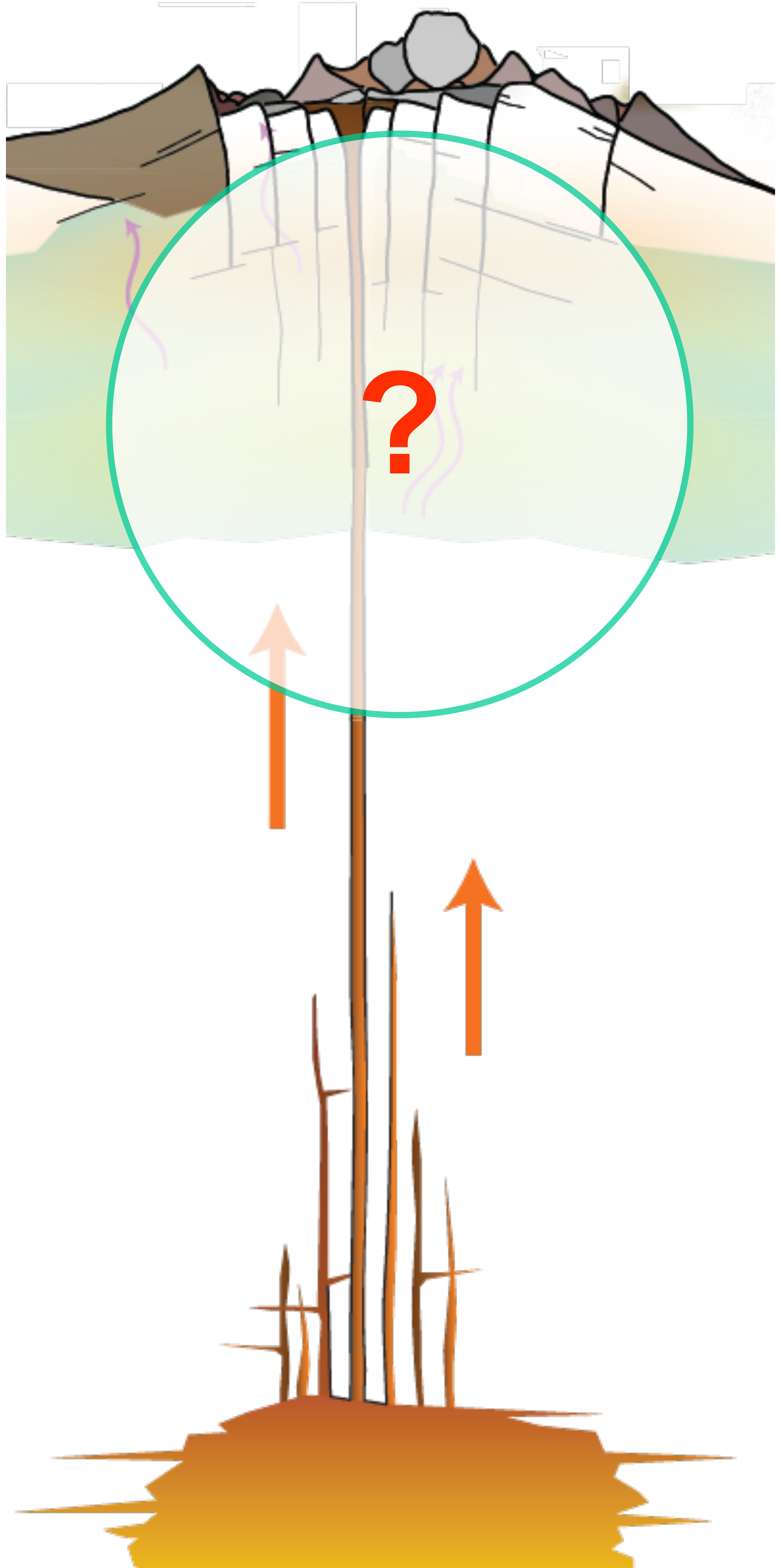
- Volcano hydrothermal systems (VHS) are at the core of unpredictable volcanic hazards
- Complex interplay between internal and external forcing
- Information on 3-D distribution of rock properties and fluid saturation are key to understand their dynamics
- Classical geophysics provide limited information on spatio-temporal dynamics



(Hincks et al., 2014)

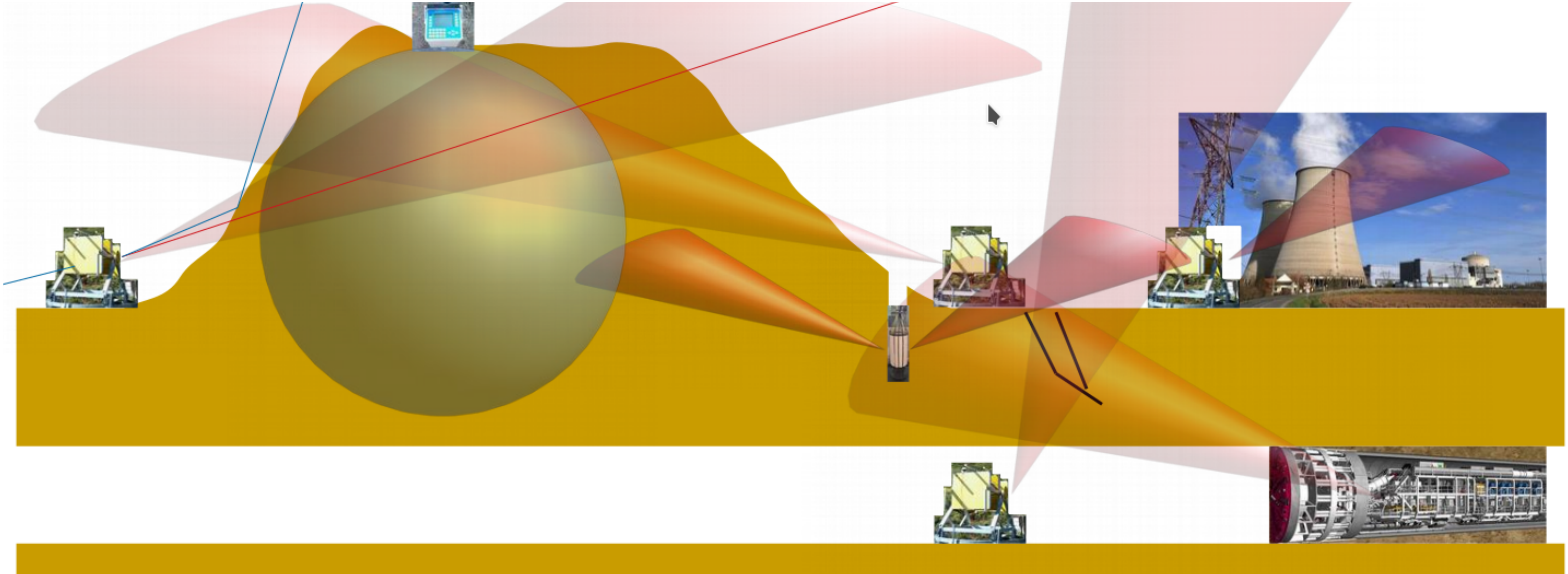
Outline

- Muon radiography. Ideal setups and limitations
- Examples in Volcanology
- Combining Muon and Gravity data.
- Conclusions and future opportunities



Why muon radiography

- Single installation for full radiography (less cost, less hazards)
- Stand alone system
- Only contribution to the signal is the actual rock being scanned
- 3-D tomographies possible

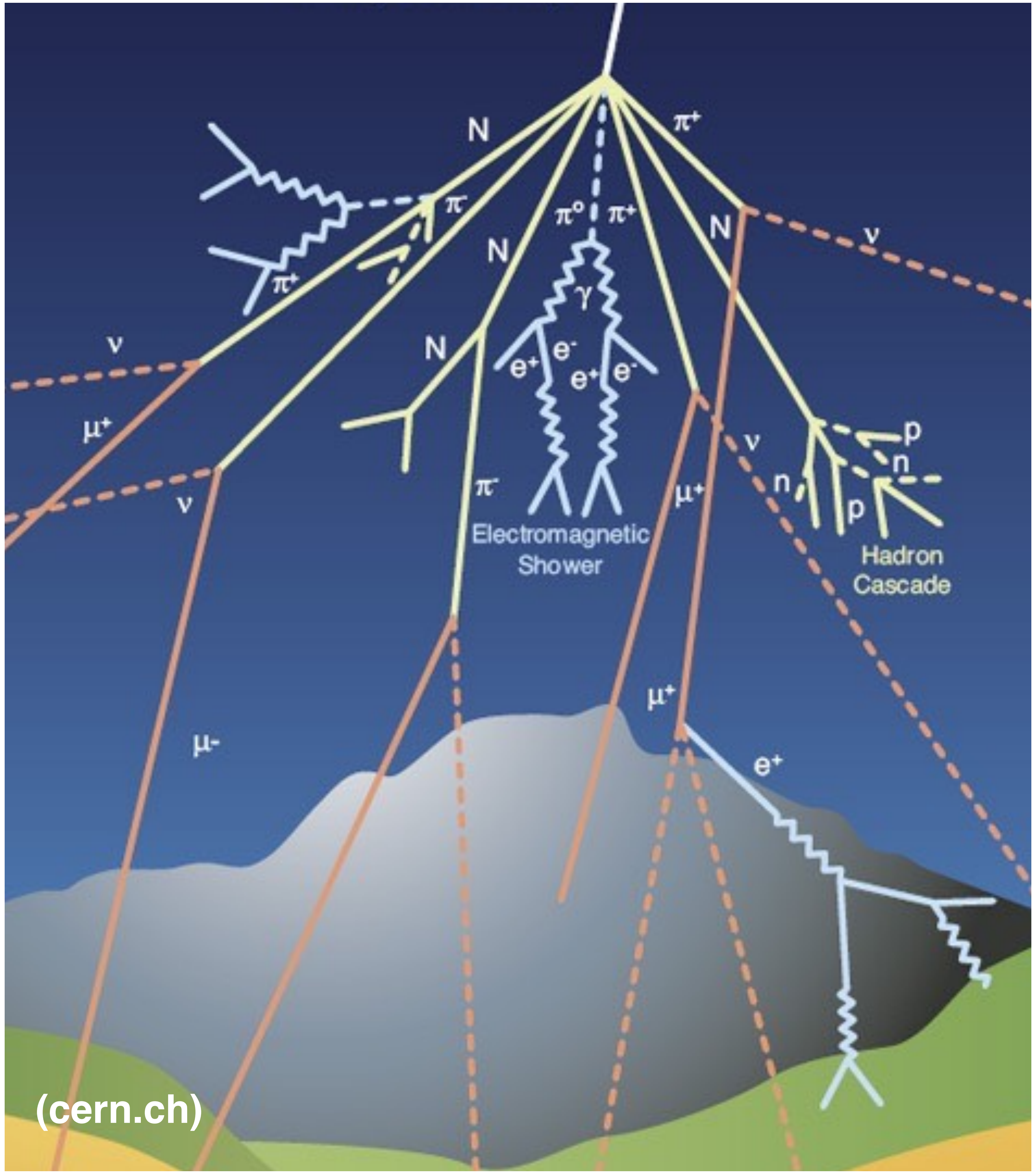


Muon radiography

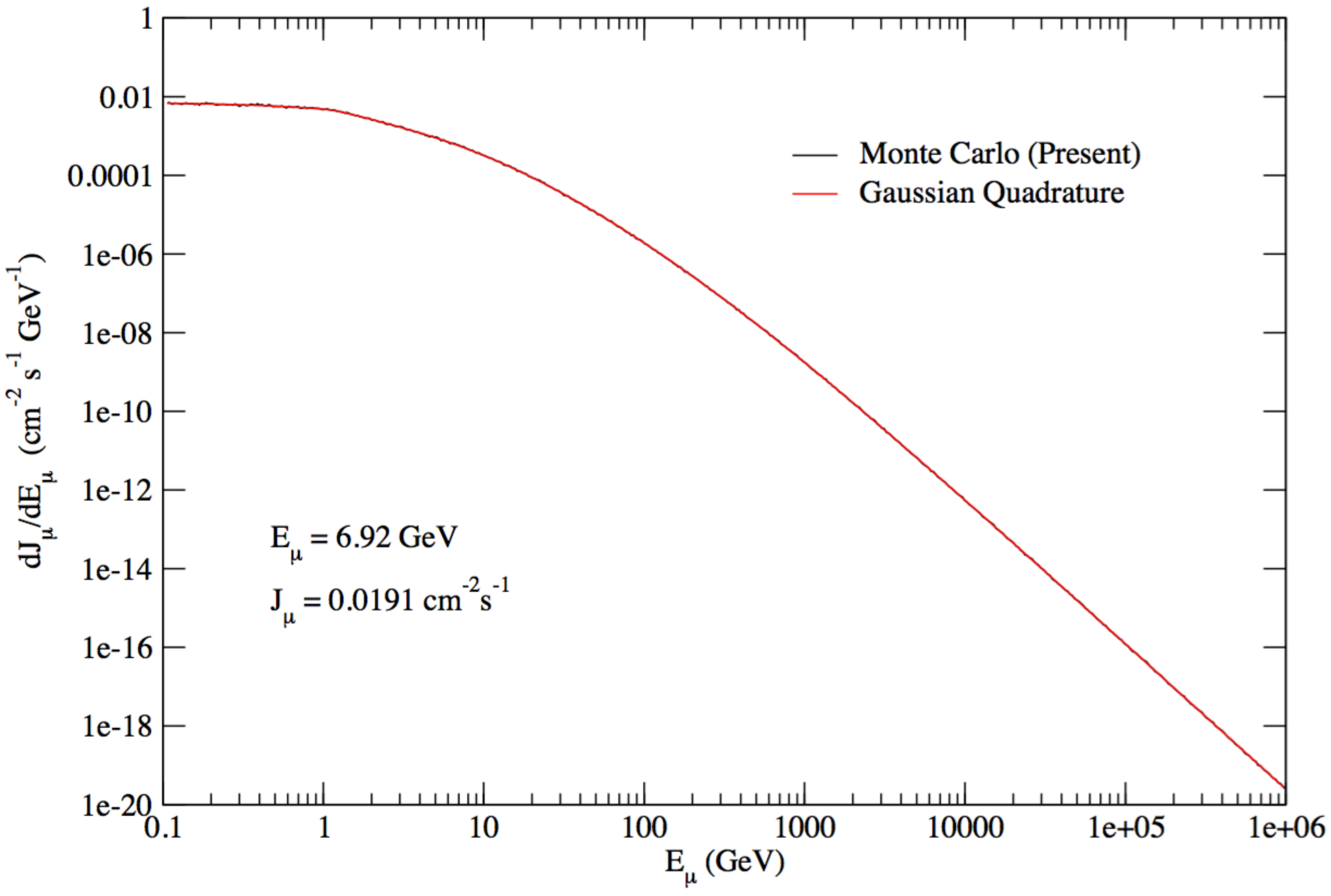
Method to **infer the average bulk density** of a large body by measuring the amount of muons that are able to traverse it

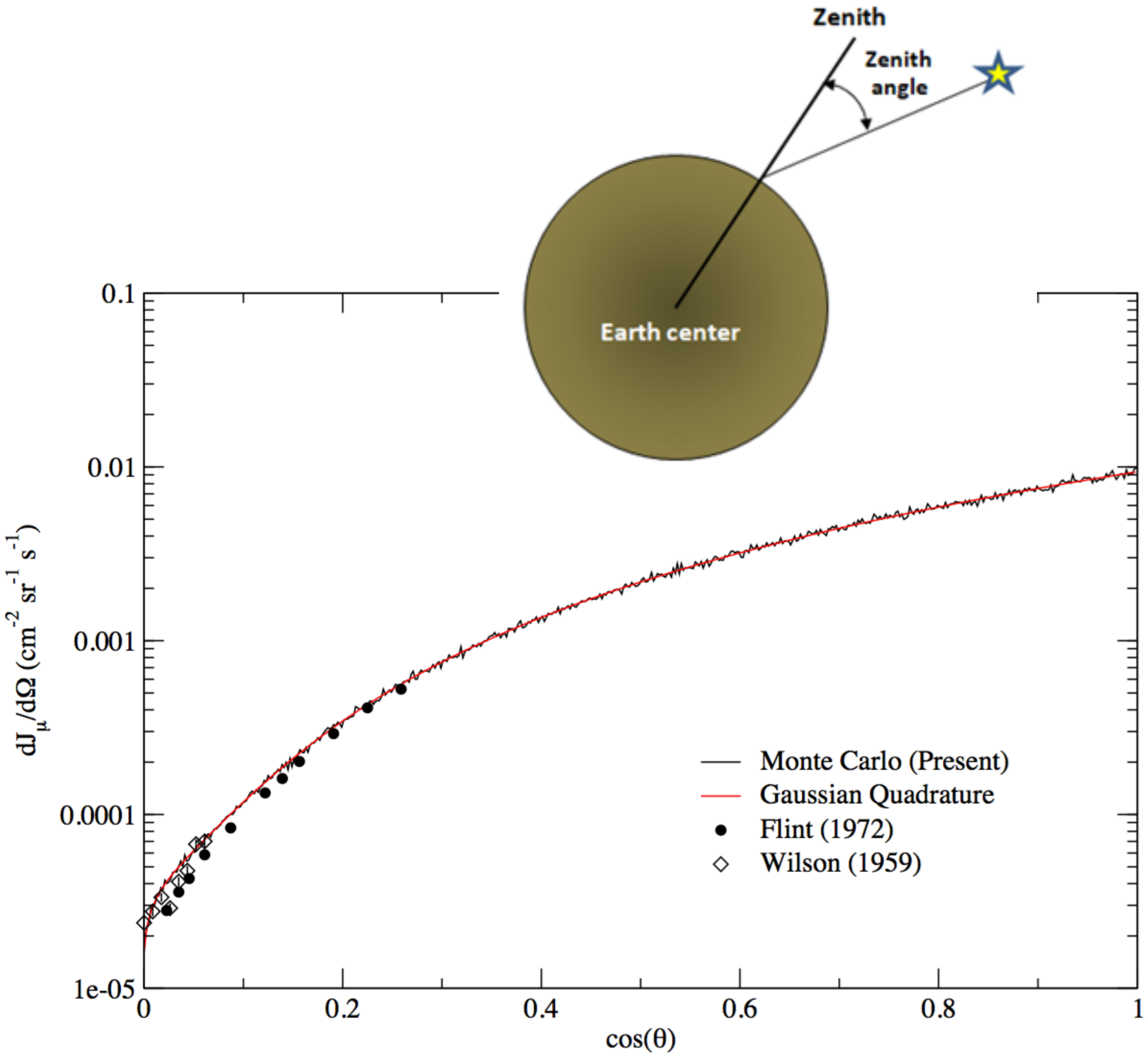
Muons are **naturally produced** by the interaction of cosmic particles with the atmosphere

Muons are charged particles with large mass, and they loose energy when traversing matter



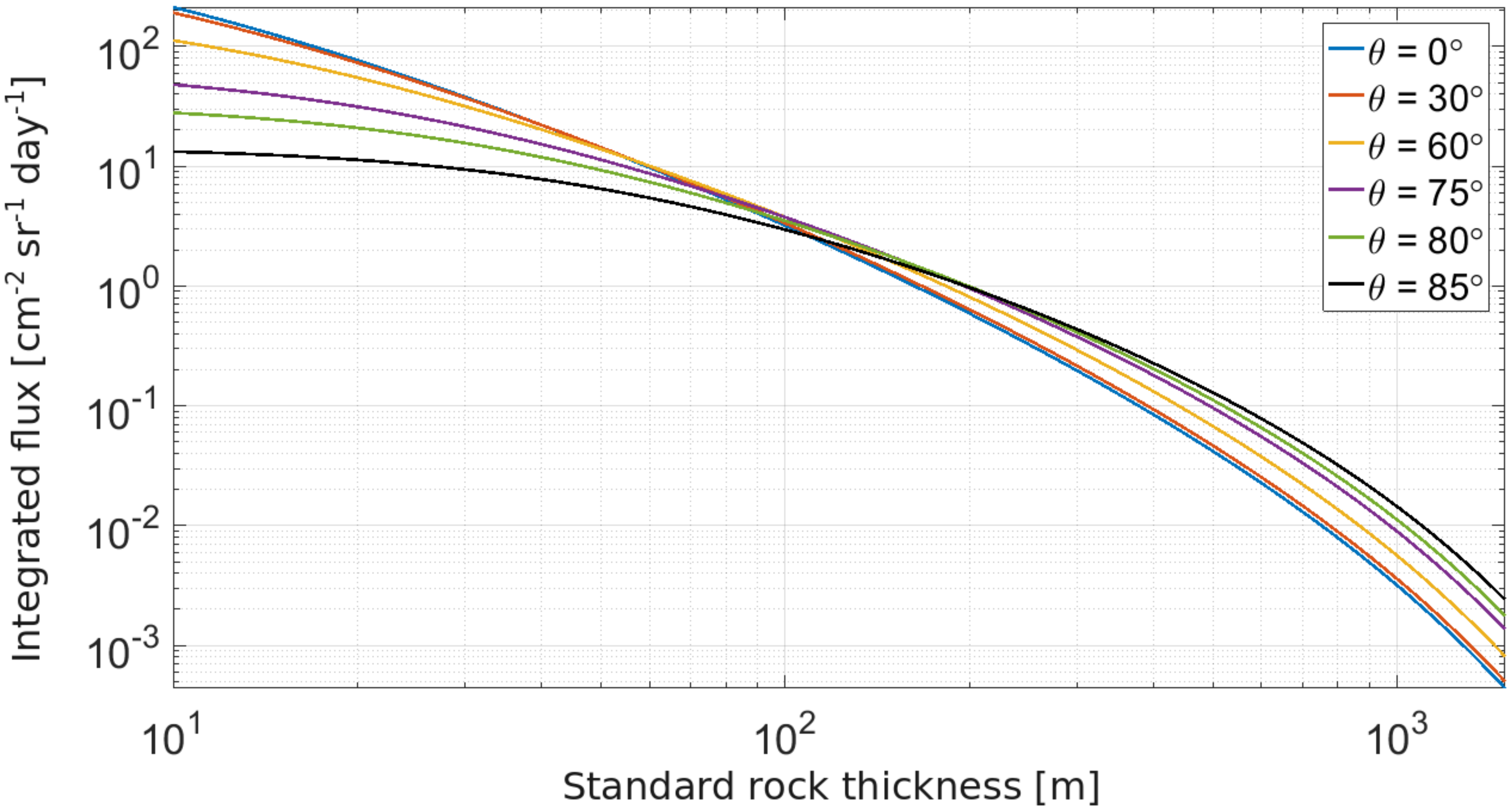
We know the natural muon flux

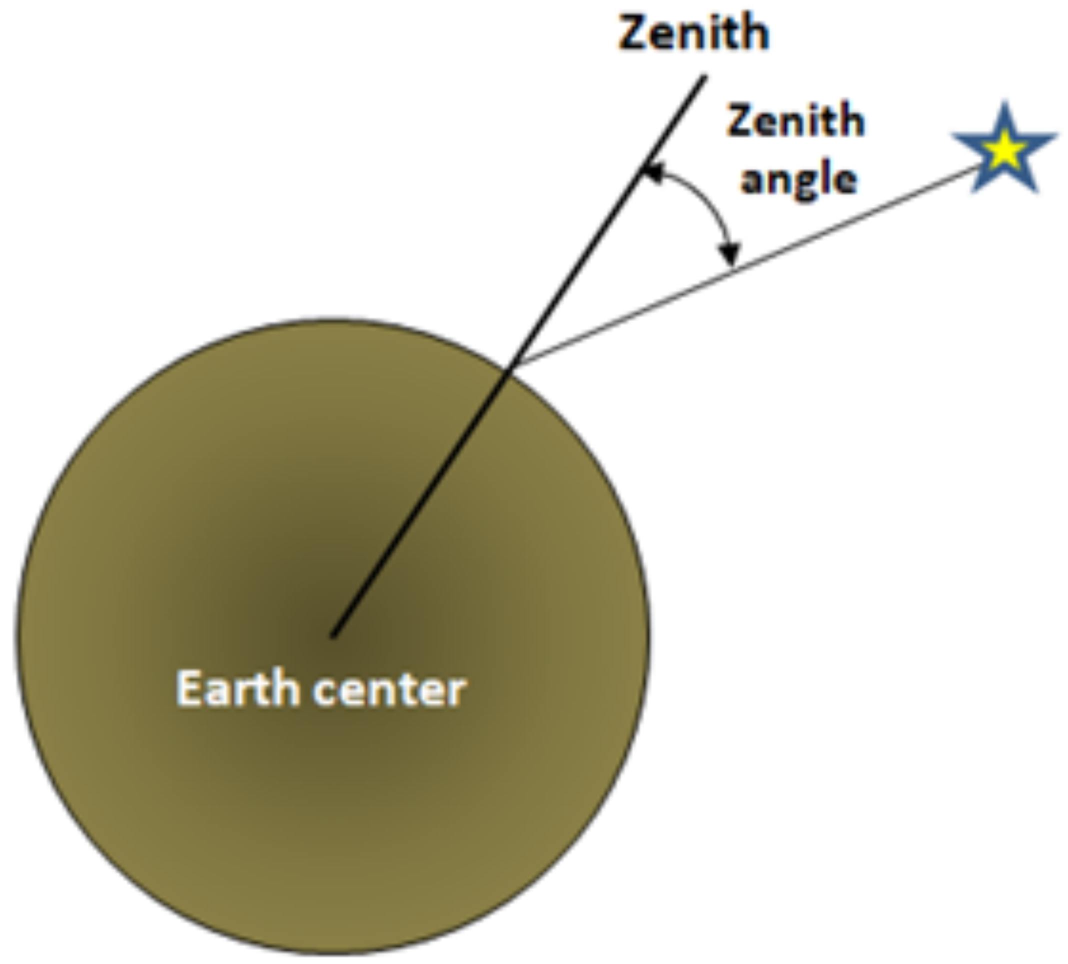




(Tang et al., 2008)

We know how muons loose energy when they pass through matter





(Tramontini MS thesis, 2018)

Muon Radiography in practice

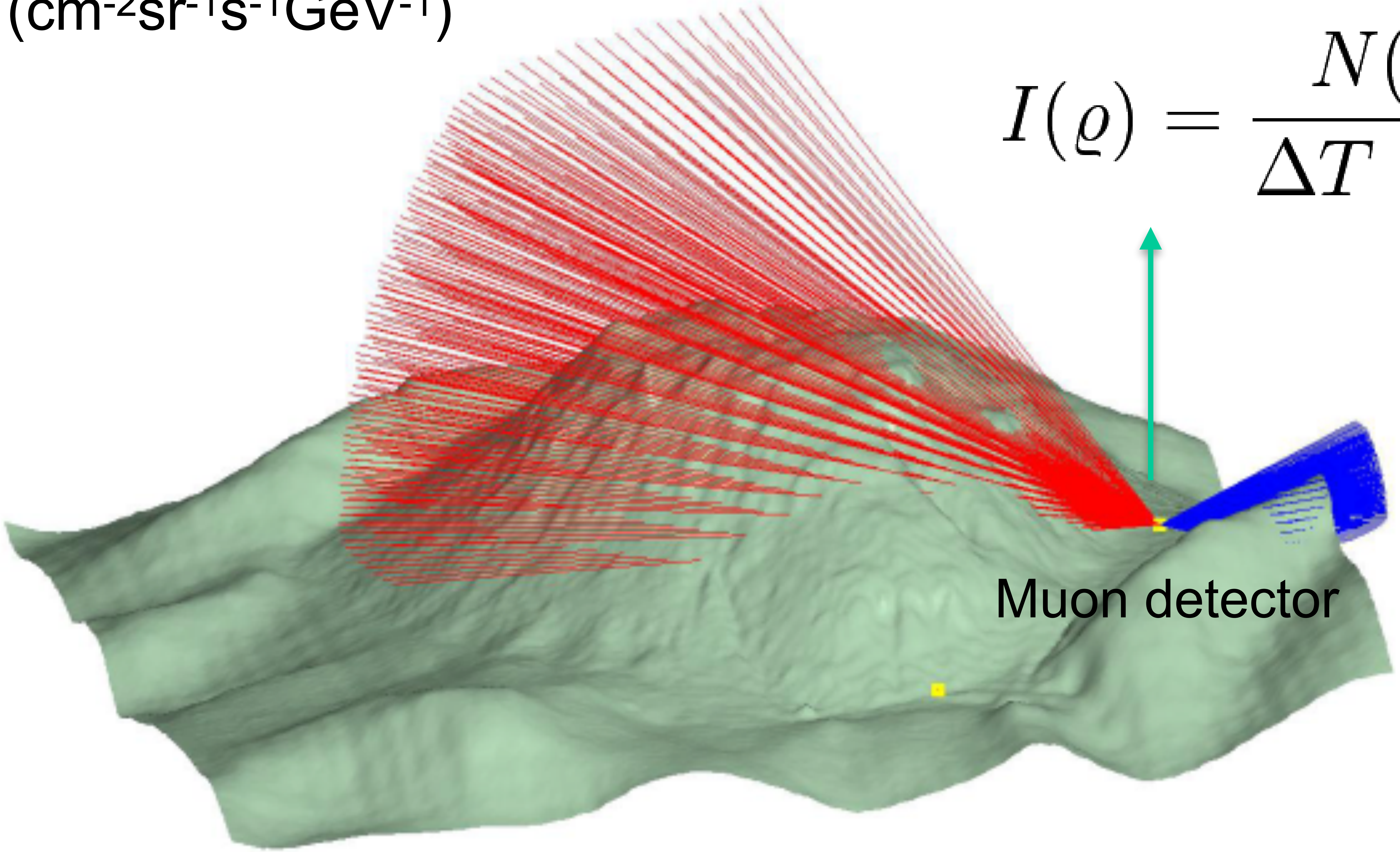
Incoming flux
($cm^{-2}sr^{-1}s^{-1}GeV^{-1}$)

Outgoing flux

$$I(\varrho) = \frac{N(\varrho)}{\Delta T \times \mathcal{T}}$$

→ Data

→ Acceptance



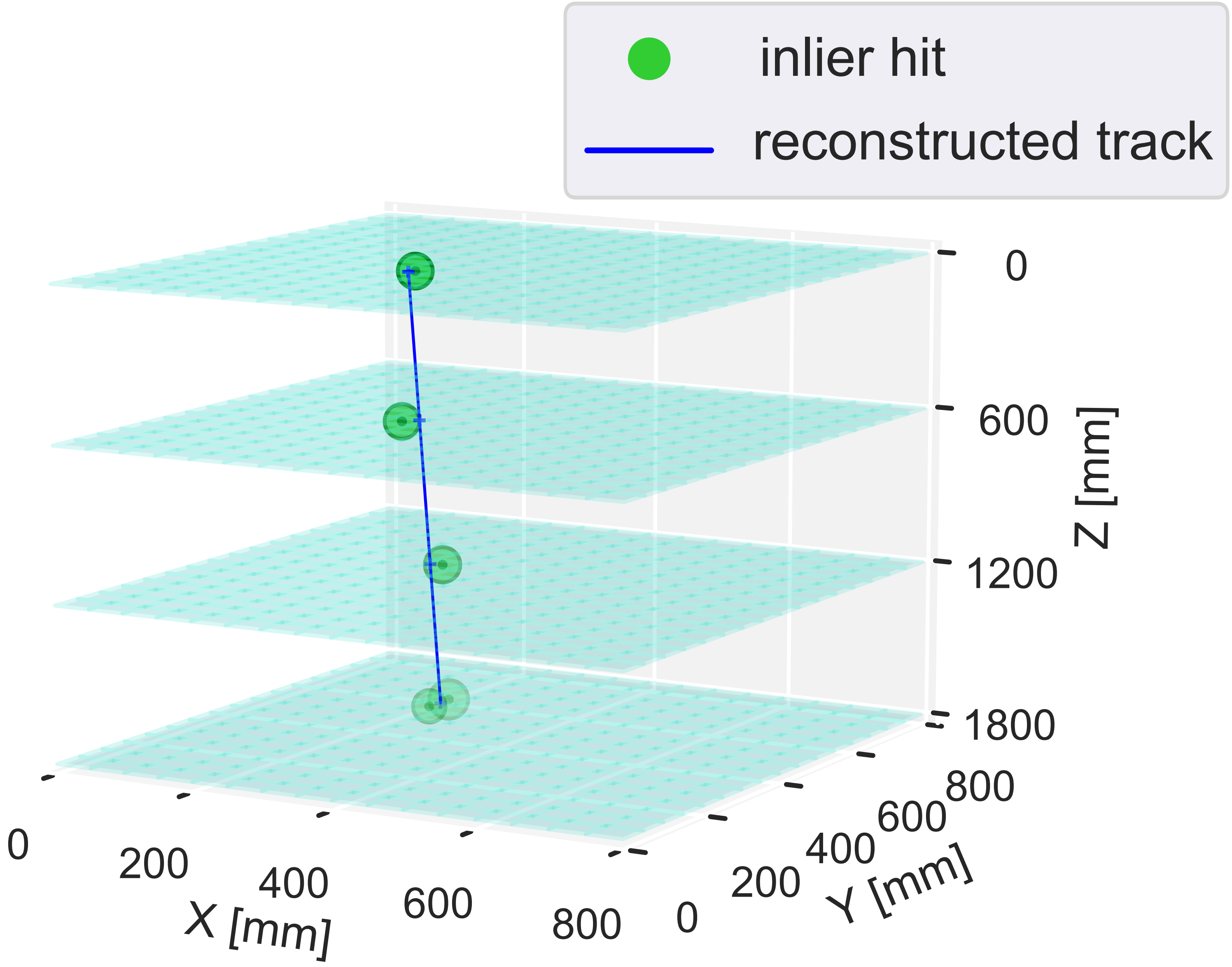
Opacity (g/cm^2):

$$\varrho(L) \equiv \int_L \rho(\xi)\mathrm{d}\xi,$$

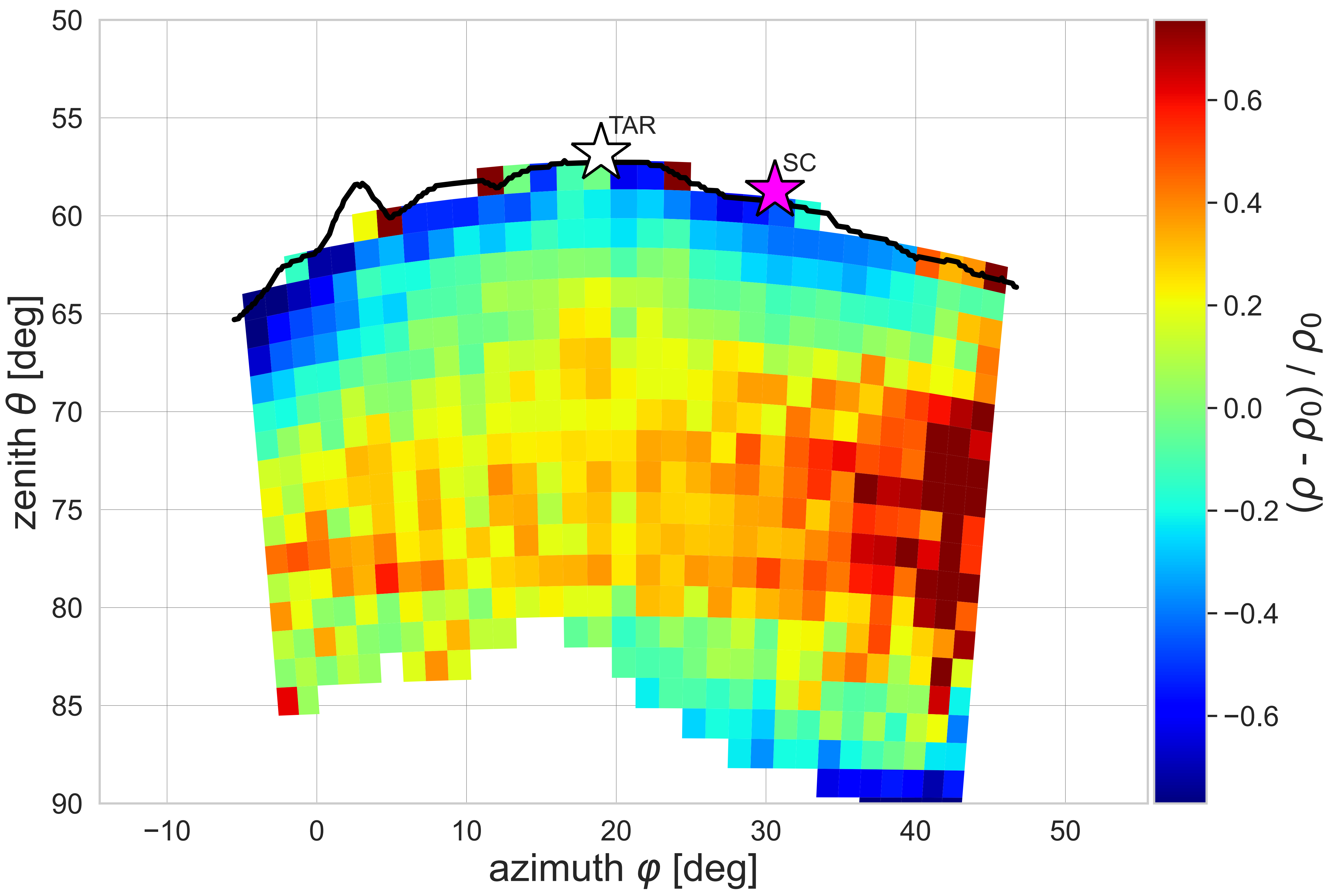
(ray length)

Average density: $\overline{\rho} = \frac{\varrho}{L}$

Muon Radiography in practice



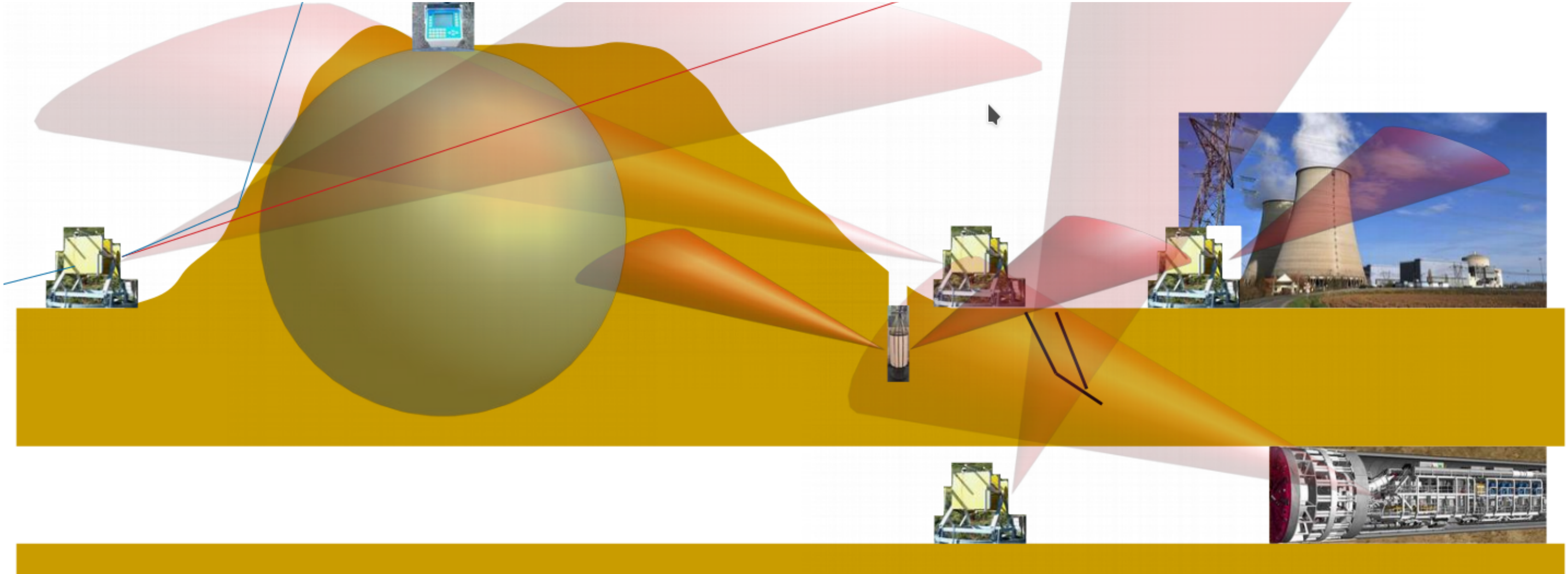
Example of a scintillator-based muon detector



(Bajou et al., accepted)

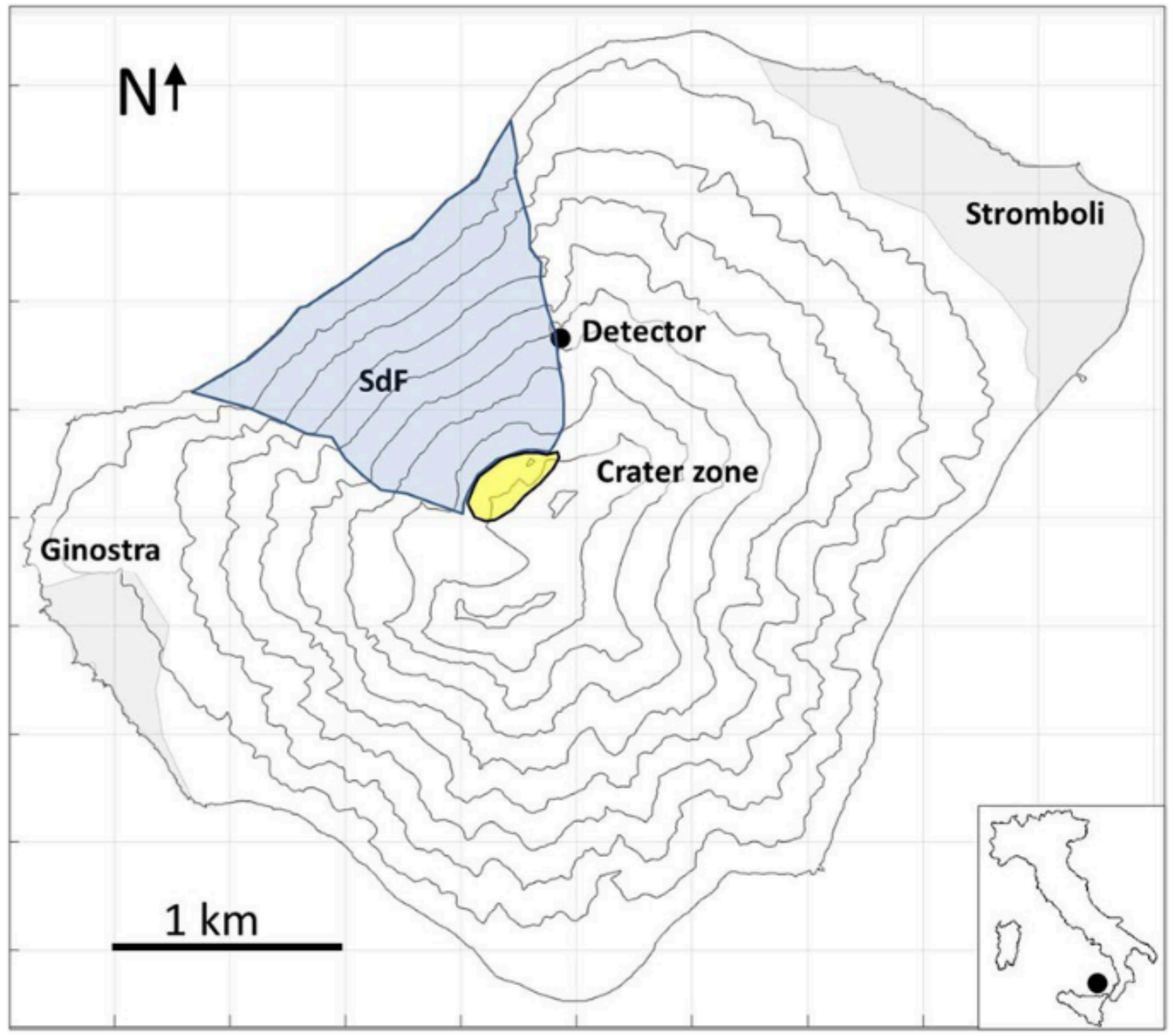
Limitations

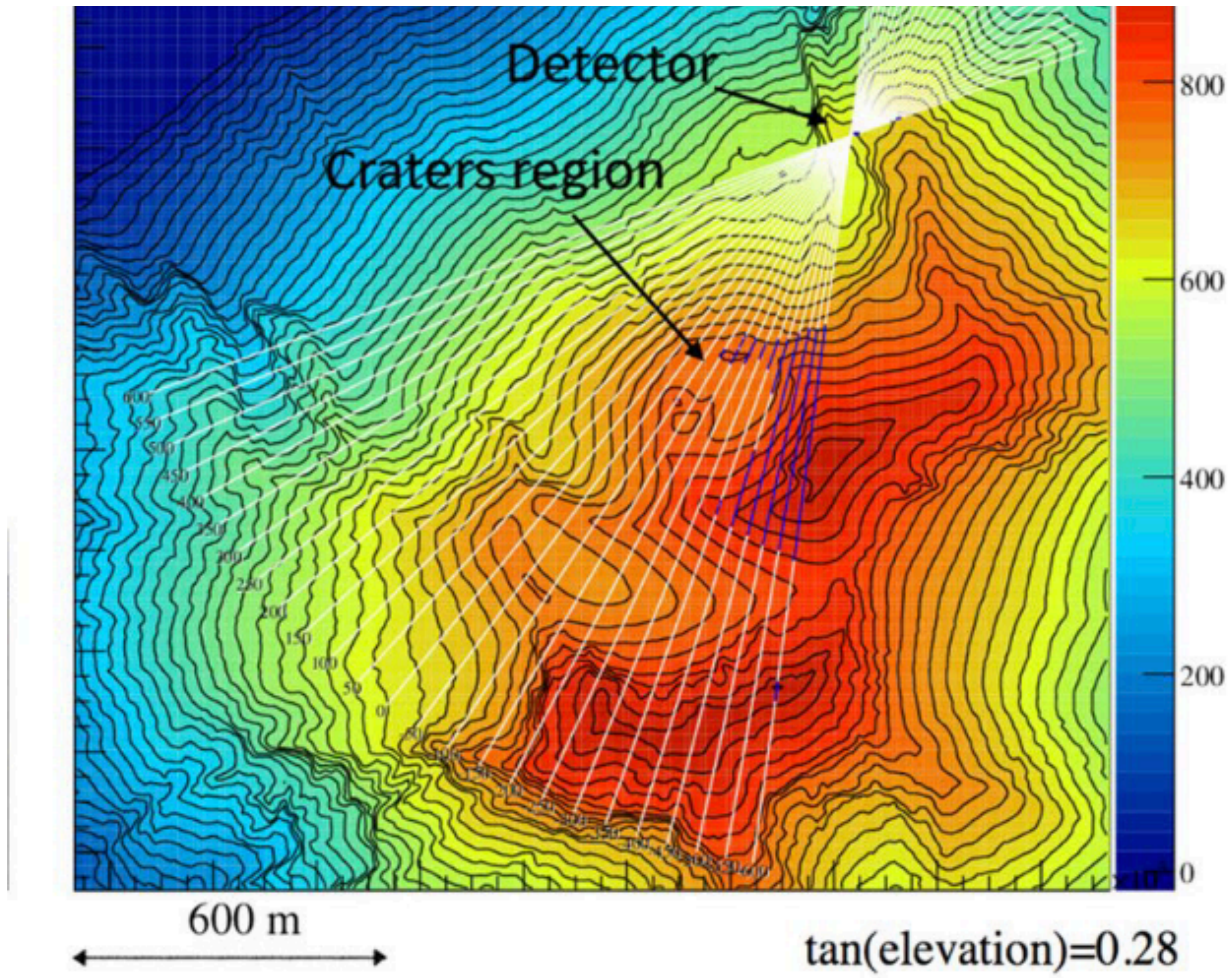
- Intrinsic limit on opacity of bodies to scan
- Have to look to the scanned body from below (pointing towards the sky)
- Noise sources
- No commercial equipment

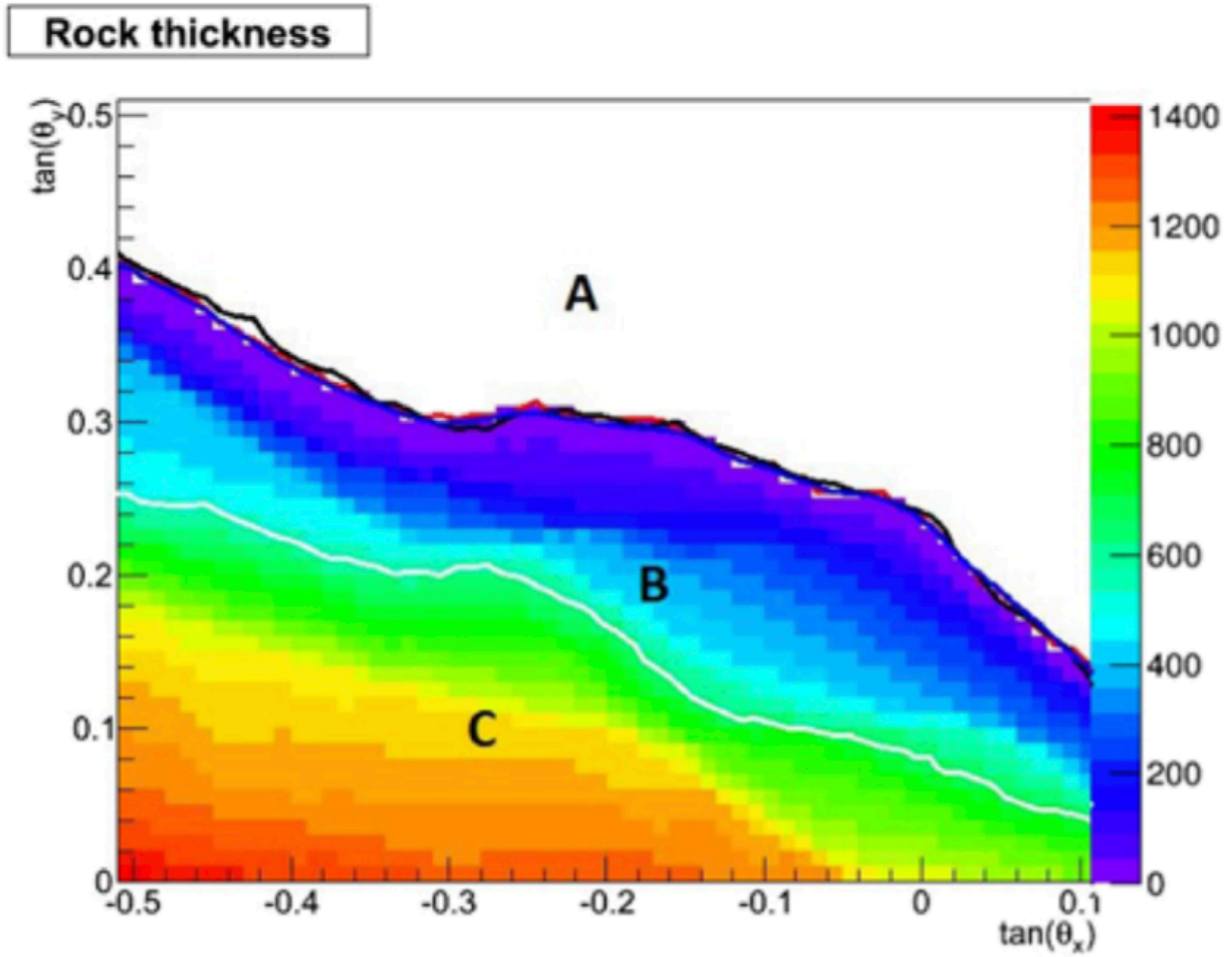


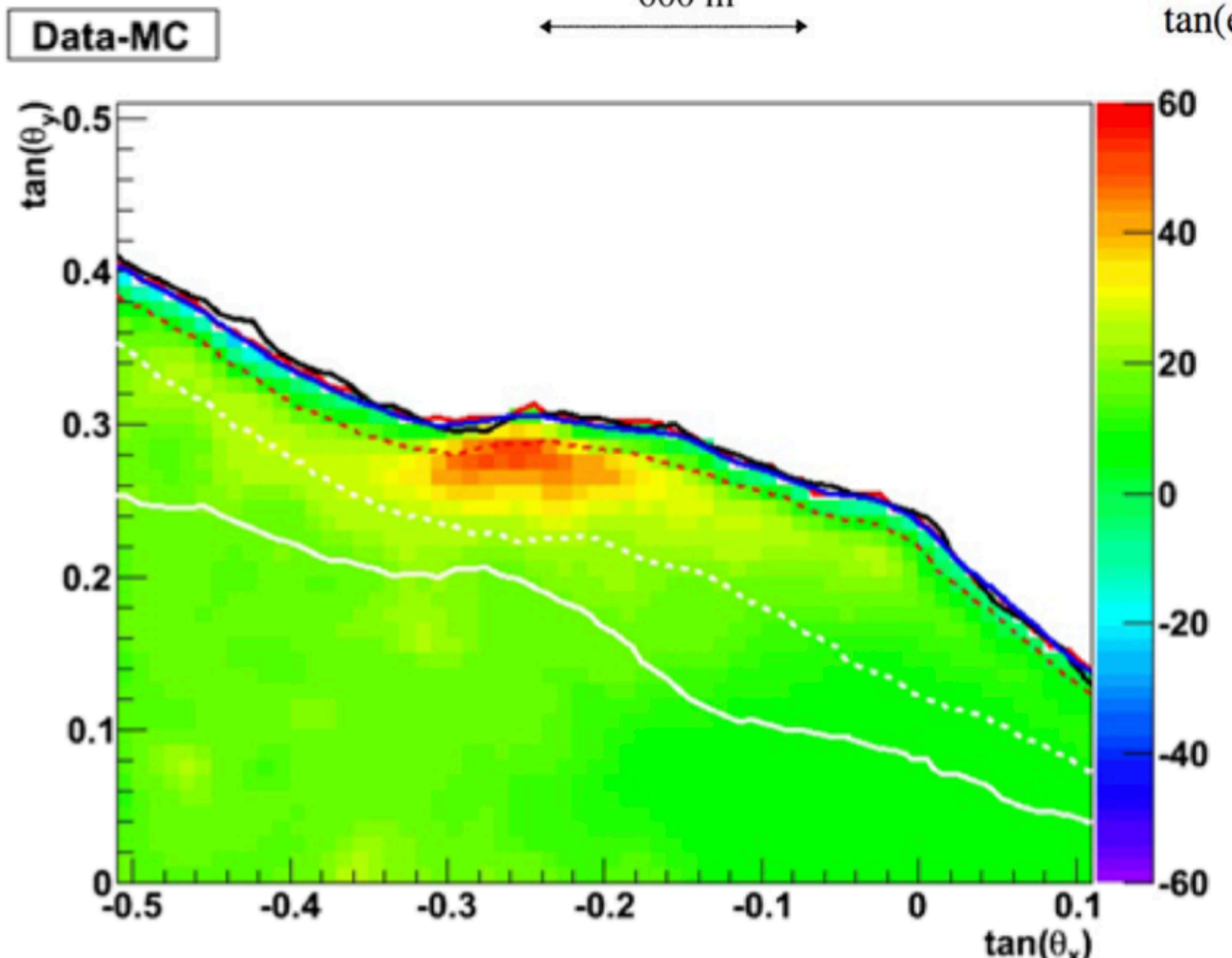
Stromboli volcano

(Tioukov et al., 2019)



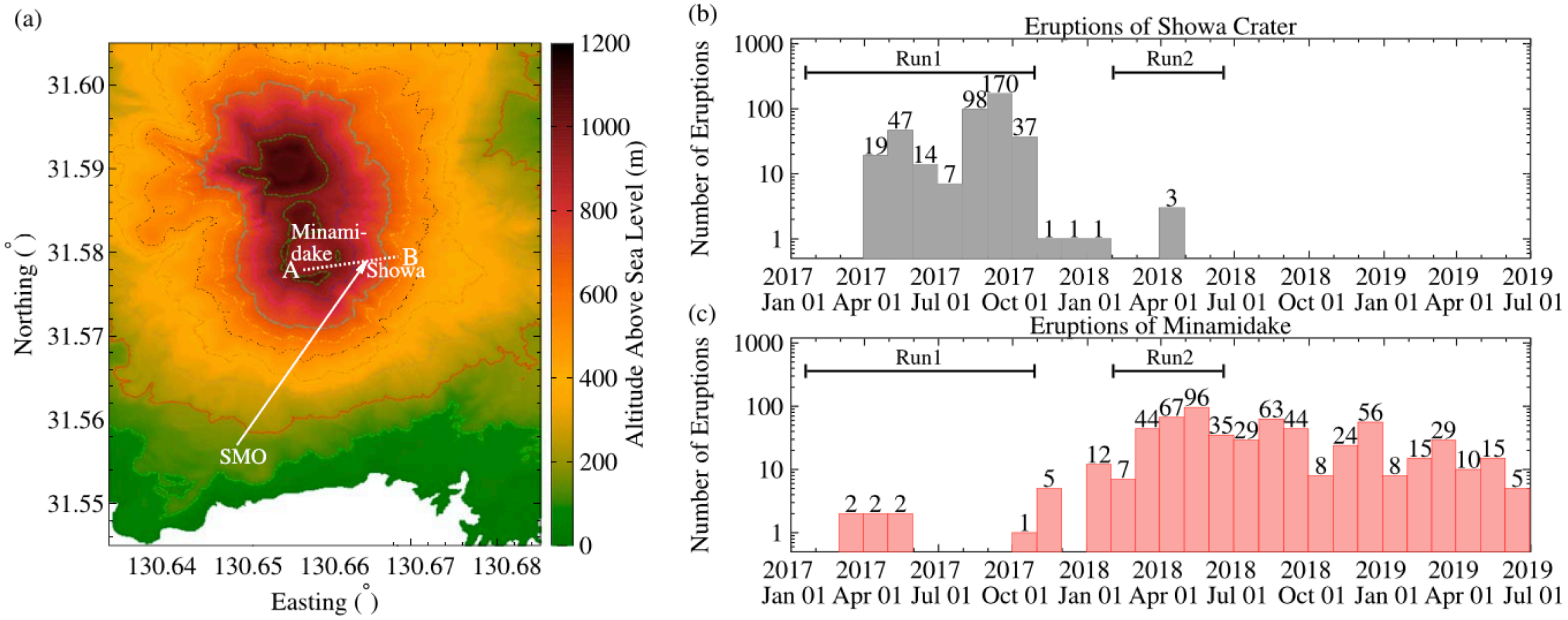


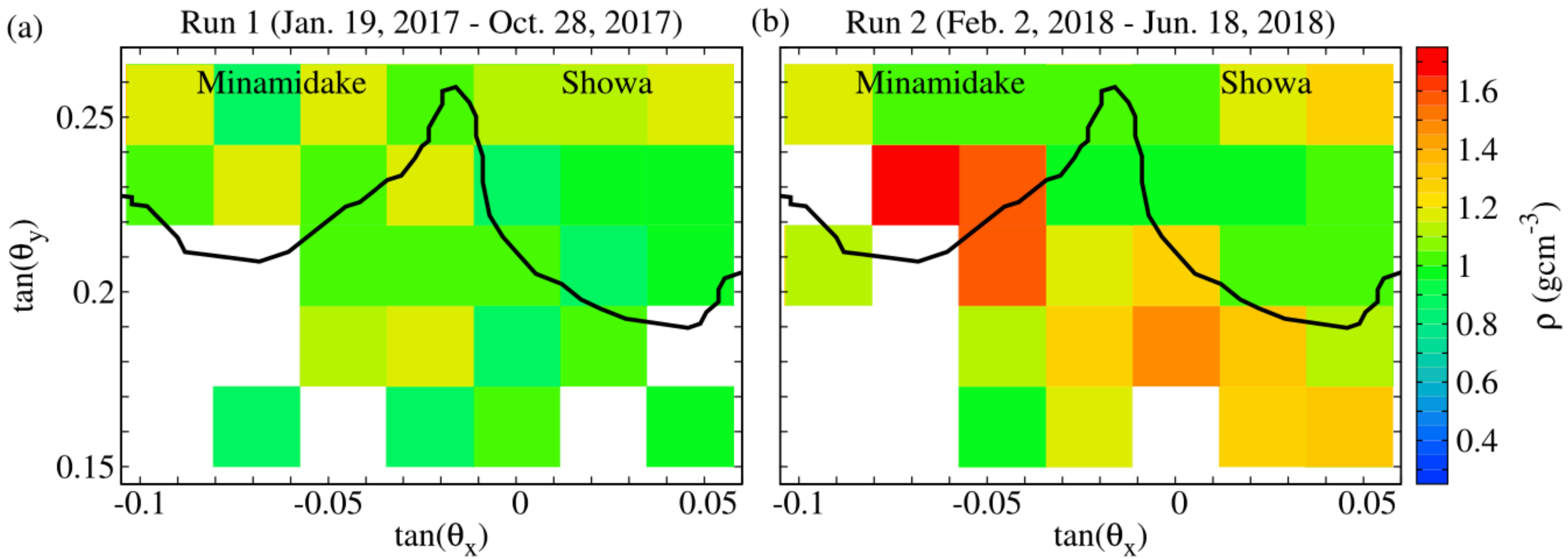




Sakurajima volcano

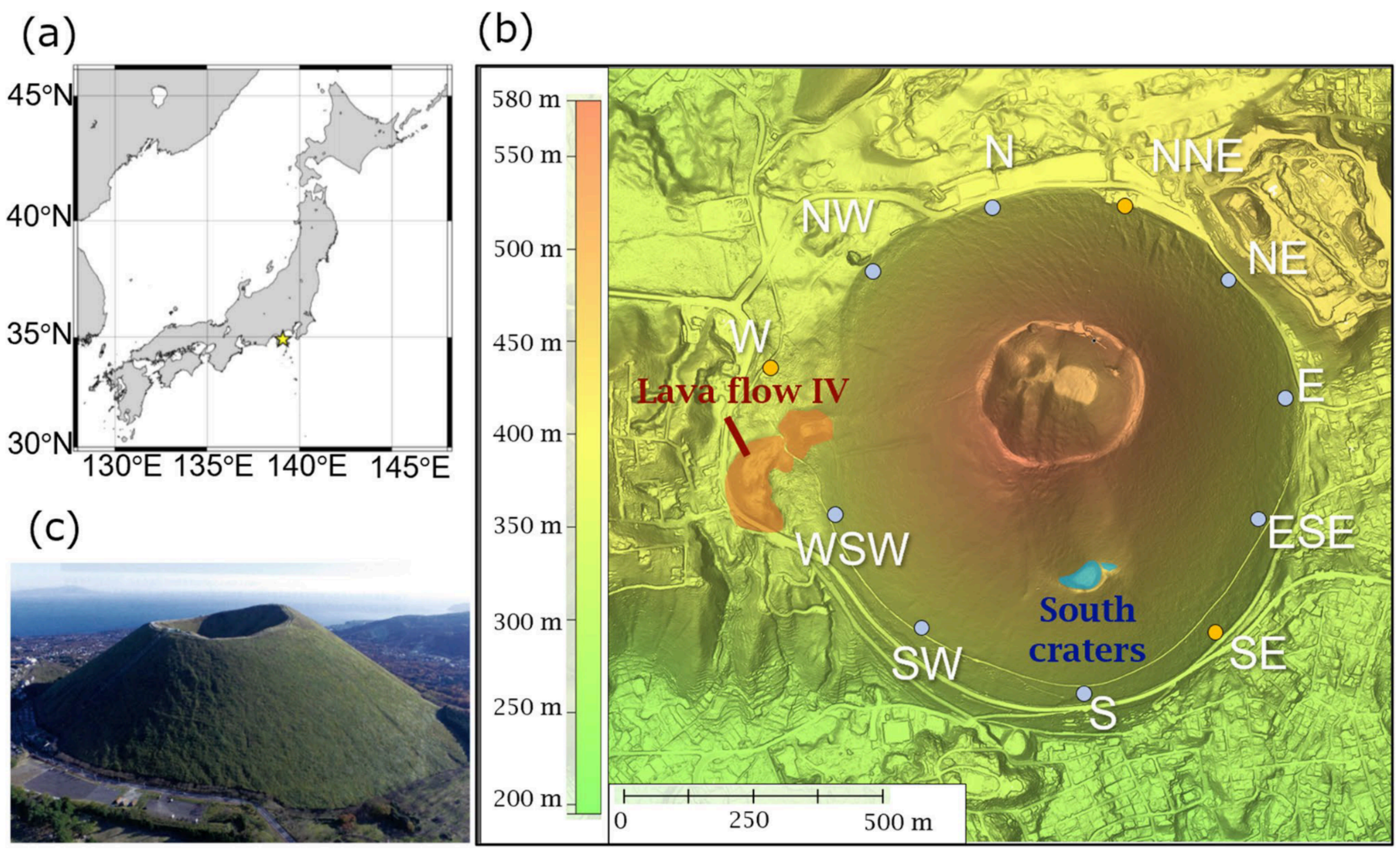
(Olah et al., 2019)

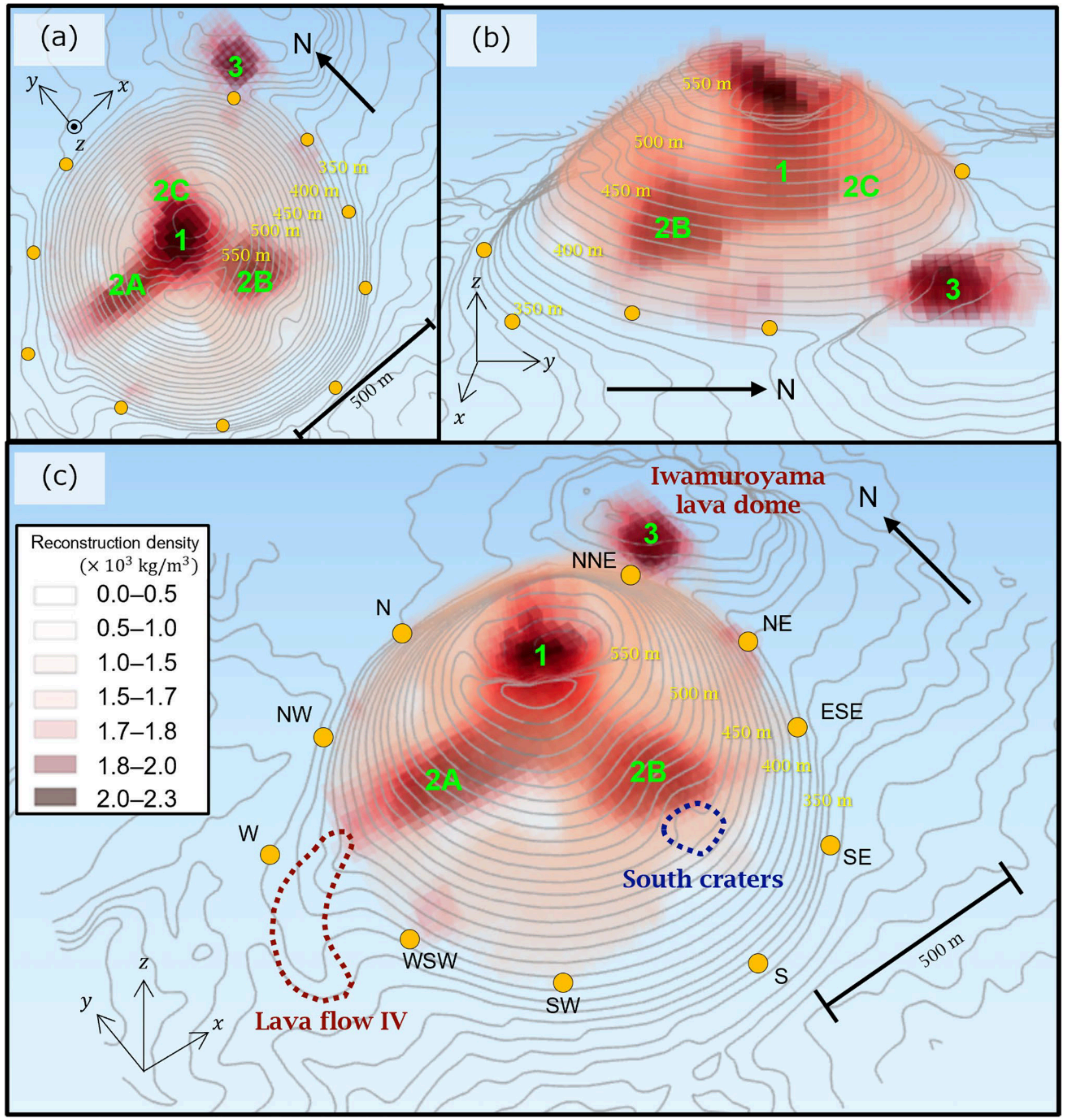




Higashi–Izu volcano

(Nagahara et al., 2022)





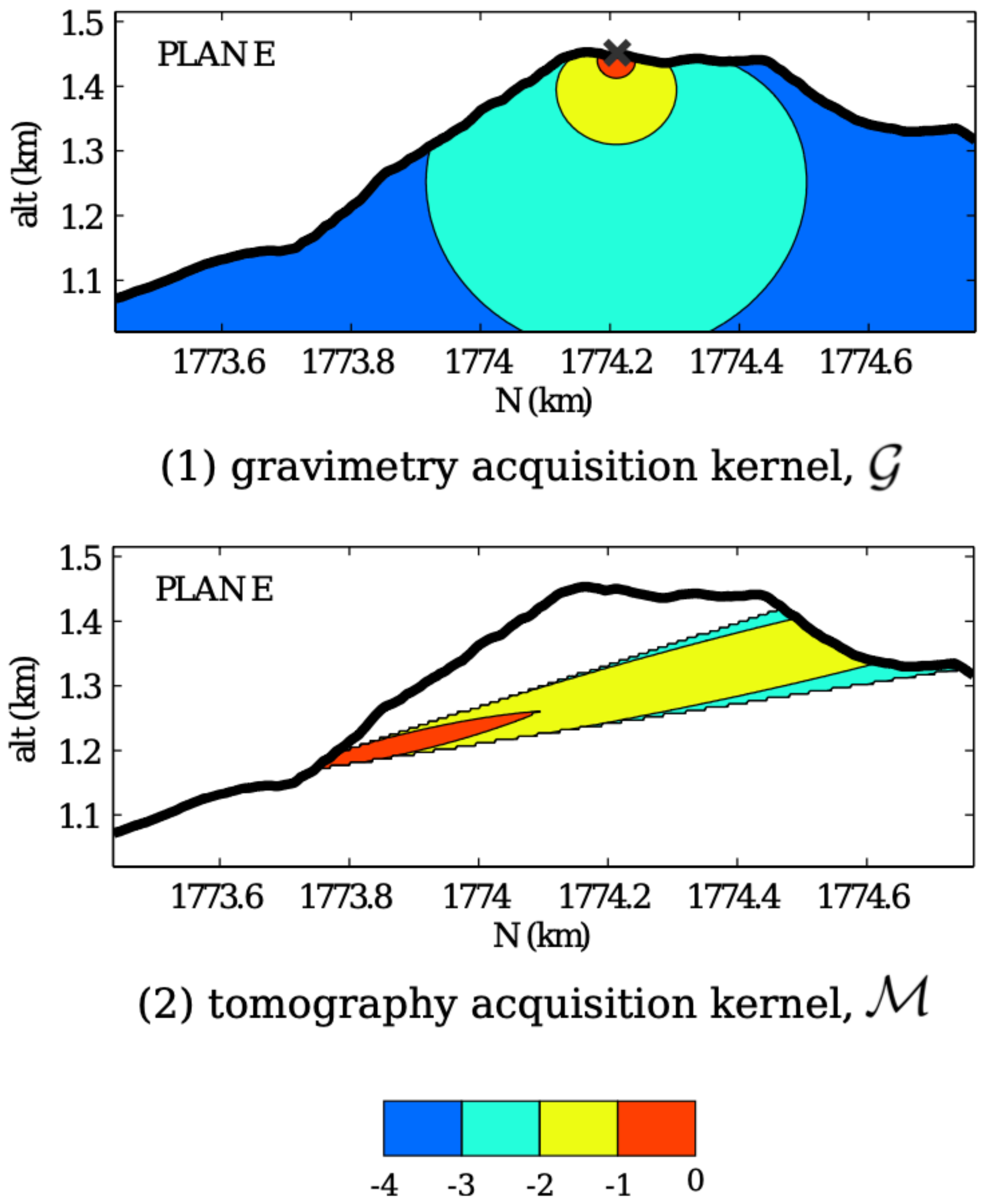
3-D joint inversion of muon and gravity data

• Gravity anomalies are also sensitive to density distribution but in a different way than muon data

• Gravity problem is linear and muon problem can be safely linearized

• Relative gravity measurements are sensitive to absolute density distributions in presence of topography.

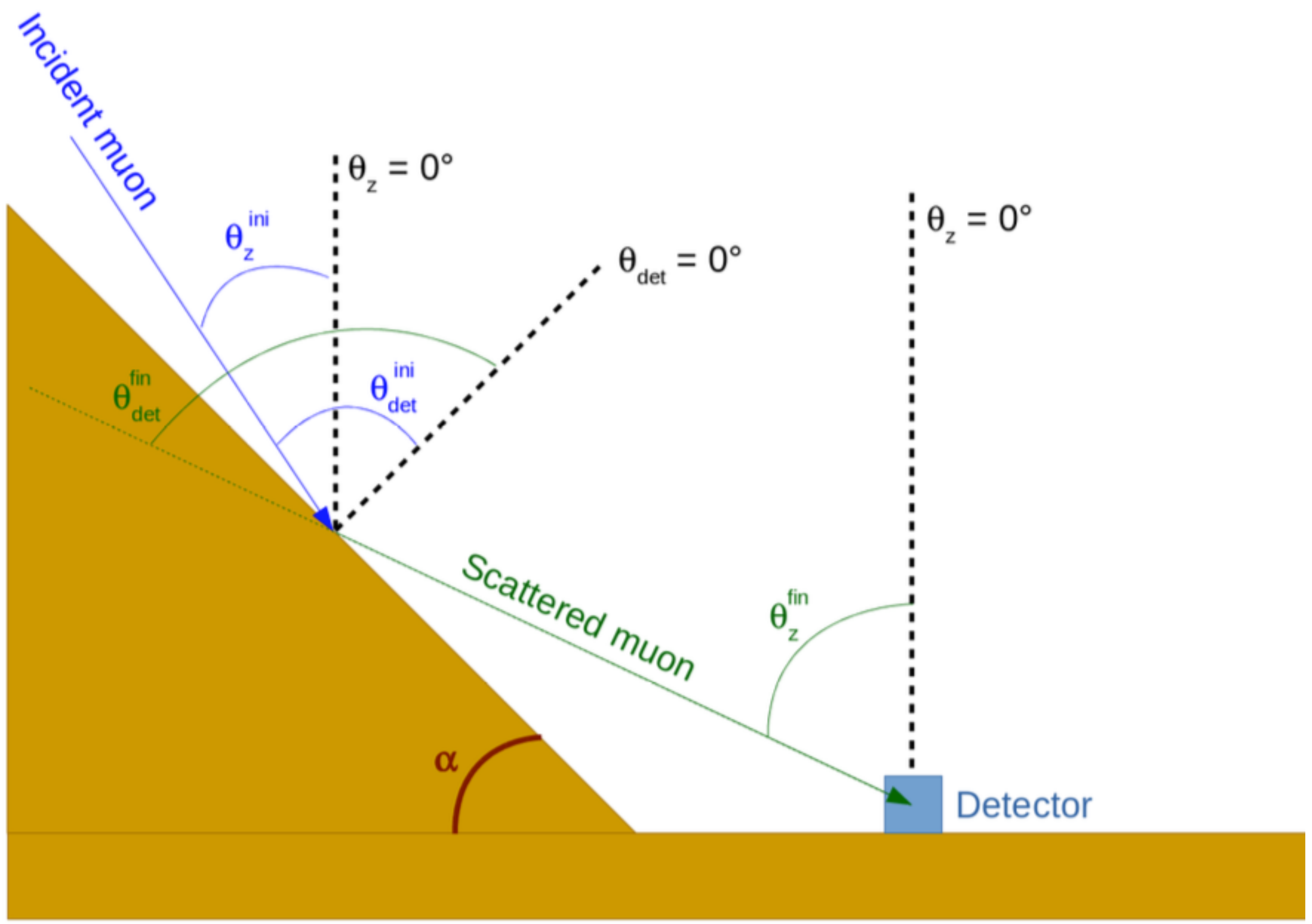
• This should be the case also for muons but…



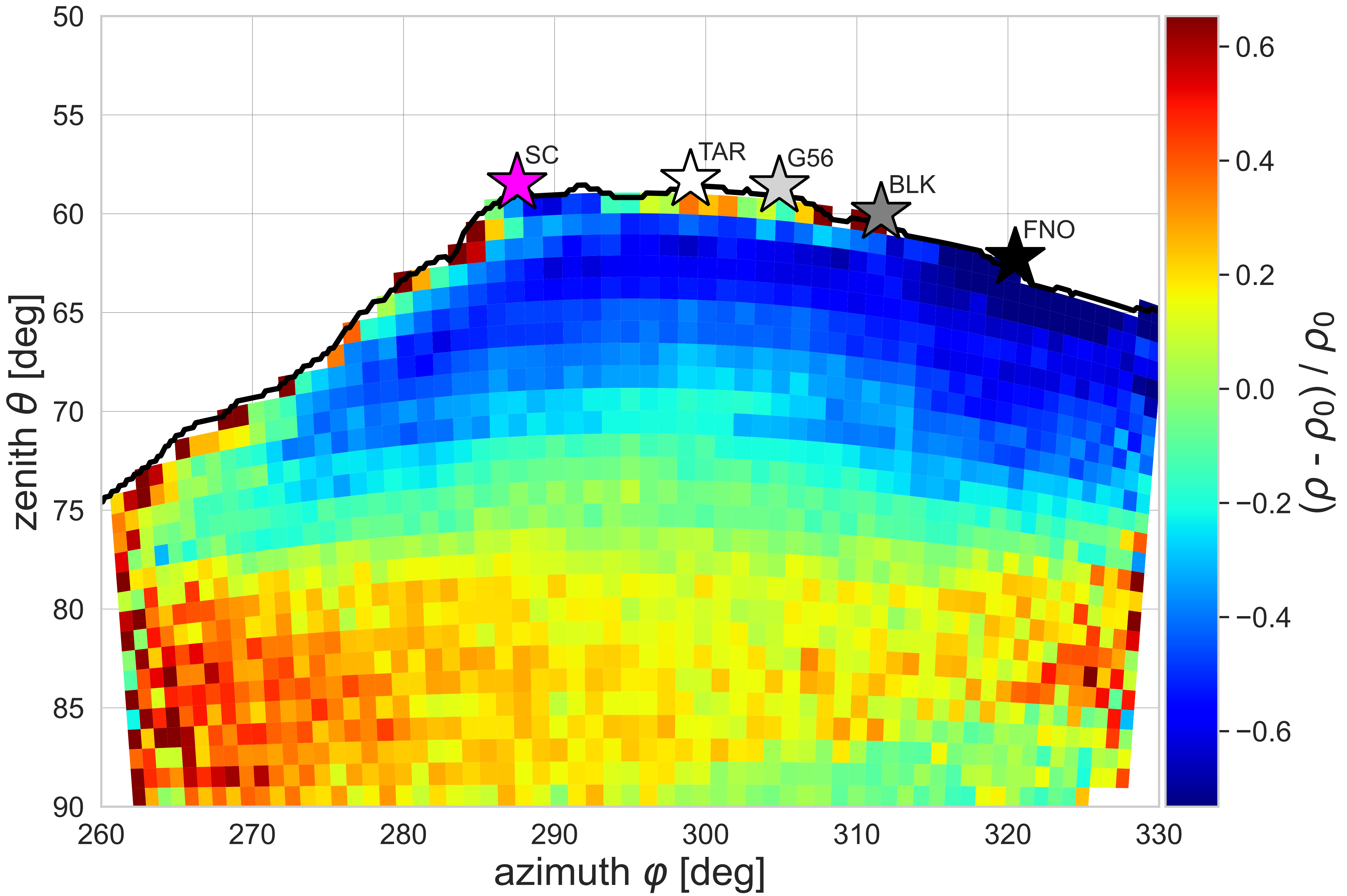
(Jourde et al., 2015)

Forward scattering of muons

Forward-scattered muons make the absolute density values estimated with muon radiography lower than the real ones



(Gomez et al., 2017)



(Bajou et al., accepted)

3-D joint inversion of muon and gravity data

- Accounting for a density offset due to the forward scattering of muons

$$\boldsymbol{\rho}_g = \boldsymbol{\rho}_\mu + \Delta\rho.$$

$$G \begin{bmatrix} \boldsymbol{\rho}_\mu \\ \Delta\rho \end{bmatrix} = \begin{bmatrix} G_g \\ G_\mu \end{bmatrix} \begin{bmatrix} \boldsymbol{\rho}_\mu \\ \Delta\rho \end{bmatrix} = \begin{bmatrix} \mathbf{d}_g \\ \mathbf{d}_\mu \end{bmatrix} = \mathbf{d},$$

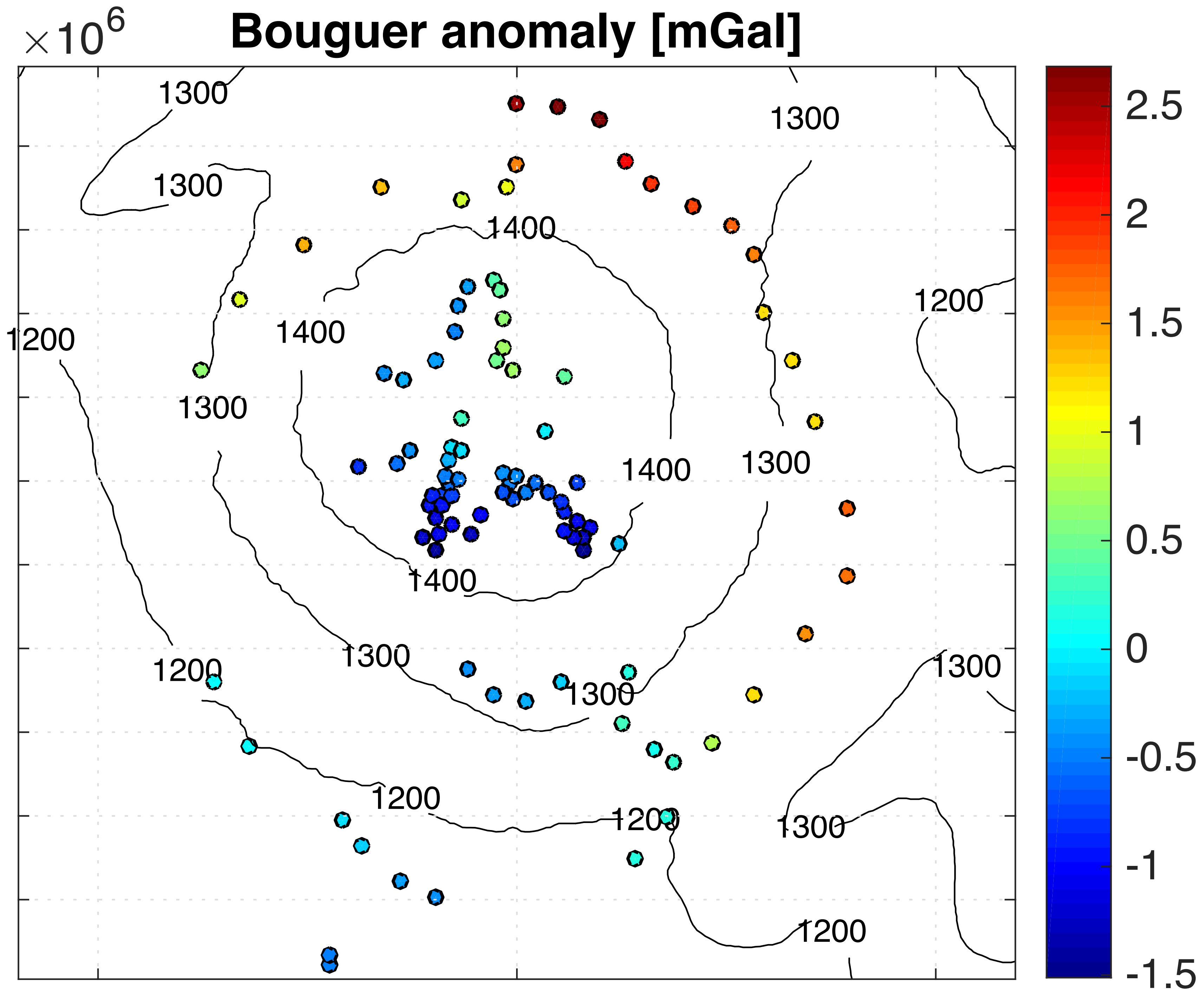
Gravity data

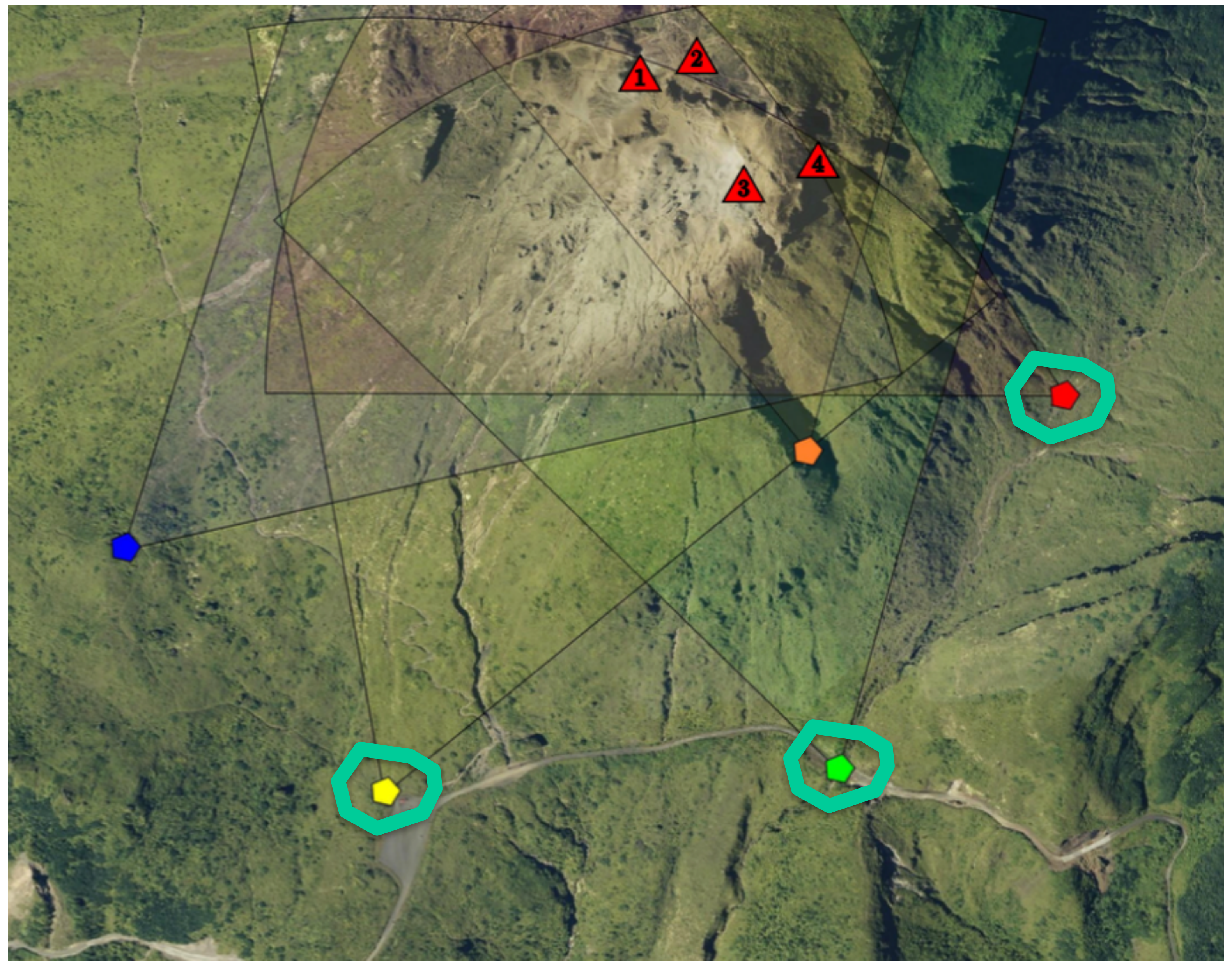
Muon data
(each telescope)

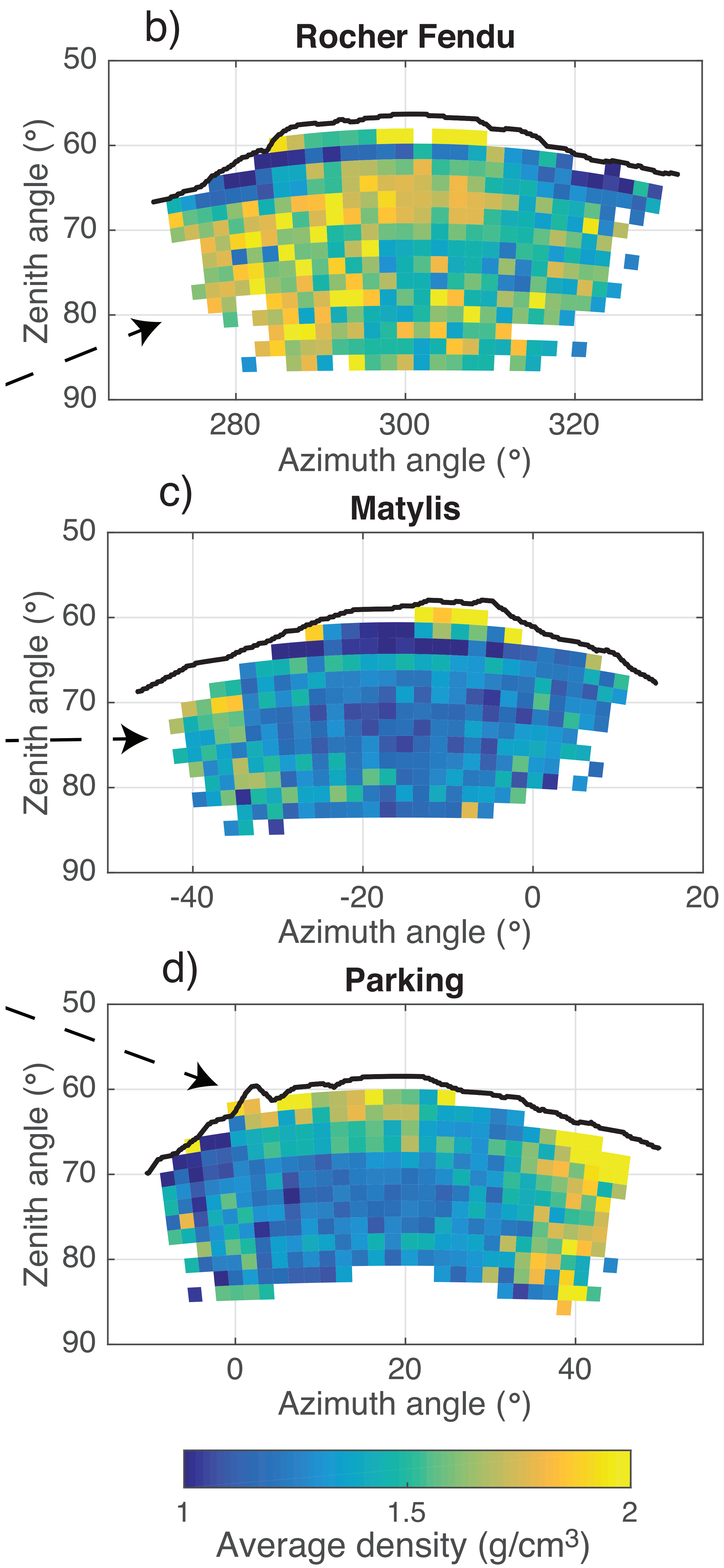
$$\mathbf{m} = [\boldsymbol{\rho}_\mu, \Delta\rho],$$

(Rosas-Carbajal et al., 2017)

3-D joint inversion of muon and gravity data







3 muon detectors scanning La Soufrière de Guadeloupe + ~100 gravity data points

(Rosas-Carbajal et al., 2017)

3-D joint inversion of muon and gravity data

- Linear, deterministic inversion with model regularization

$$\phi(\mathbf{m}) = (\mathbf{d} - \mathrm{G}\mathbf{m})^{\mathrm{T}} \mathrm{C}_{\mathrm{d}}^{-\mathbf{1}} (\mathbf{d} - \mathrm{G}\mathbf{m}) + \\ + \epsilon^2 (\mathbf{m} - \mathbf{m}_{\mathrm{prior}})^{\mathrm{T}} \mathrm{C}_{\rho}^{-\mathbf{1}} (\mathbf{m} - \mathbf{m}_{\mathrm{prior}}),$$

Smoothing

Damping

Matrix scaling

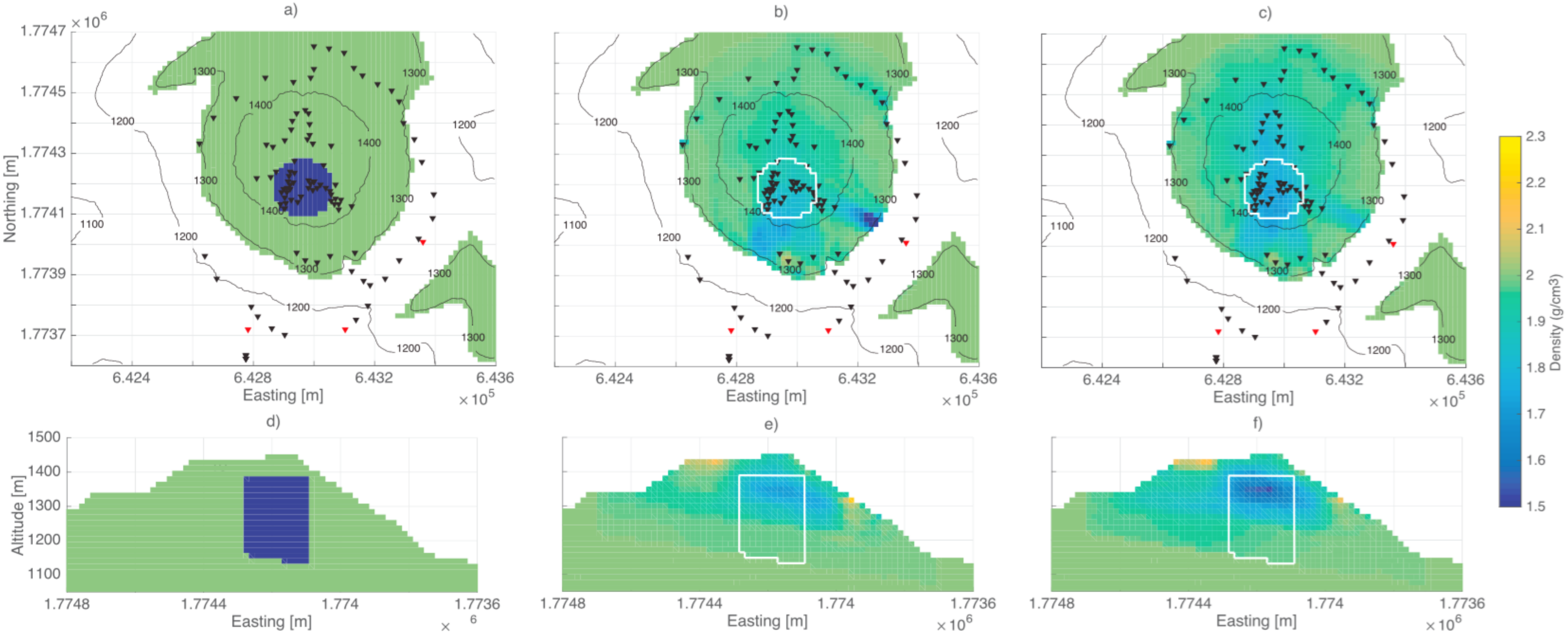
- Matrix scaling (depth weighting in the regularization matrix to counteract the natural decay of the kernels)

$$\mathrm{W}_i = \frac{1}{\min\left\{(z_{\mathrm{min},i} + z_0)^2, r_{\mathrm{min},i}^{1.5}\right\}}$$

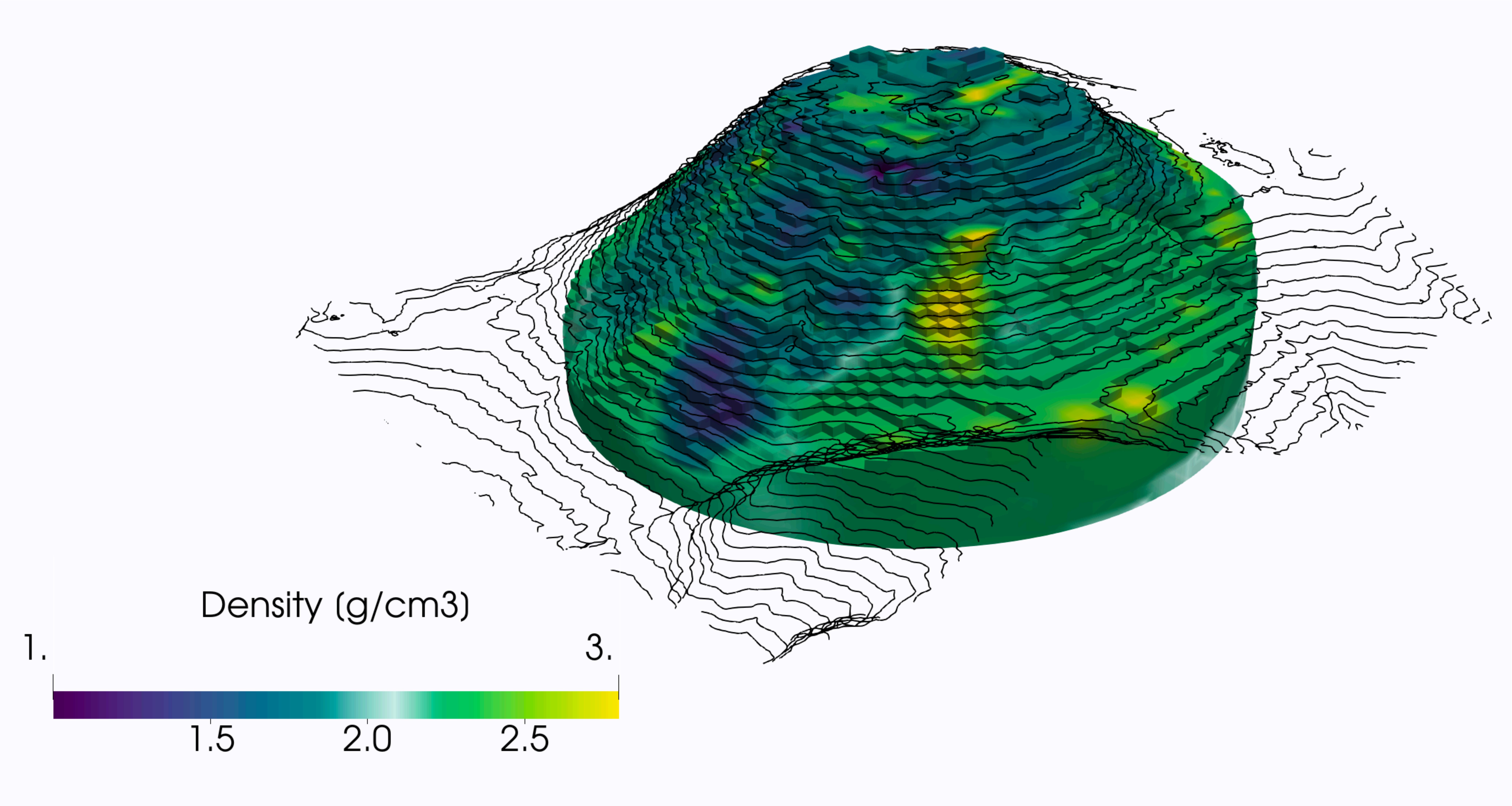
- Parameterization based on cubes of 8x8x8 m^3

(Rosas-Carbajal et al., 2017)

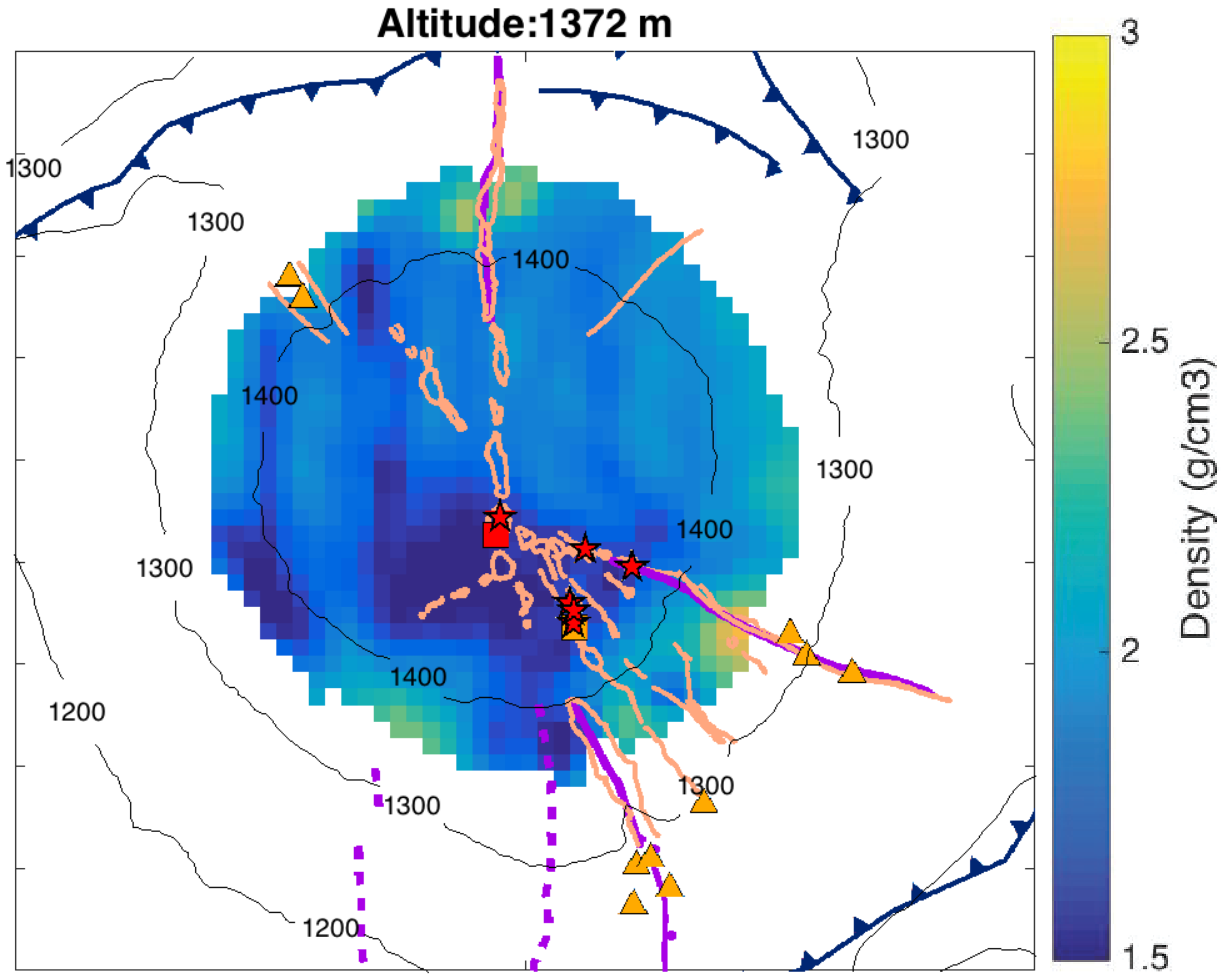
Importance of scaling the regularization matrix

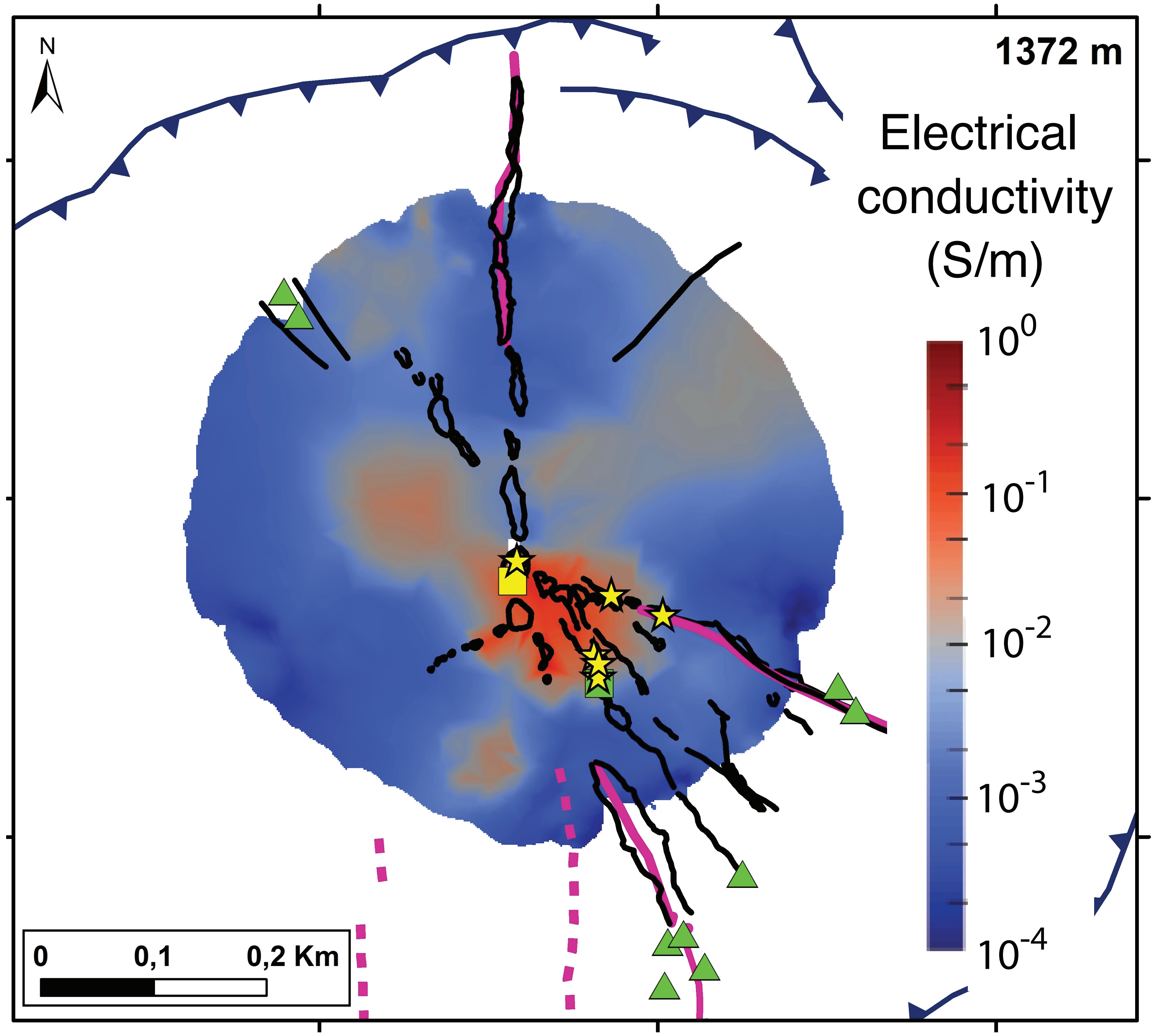


3-D density model of La Soufrière lava dome



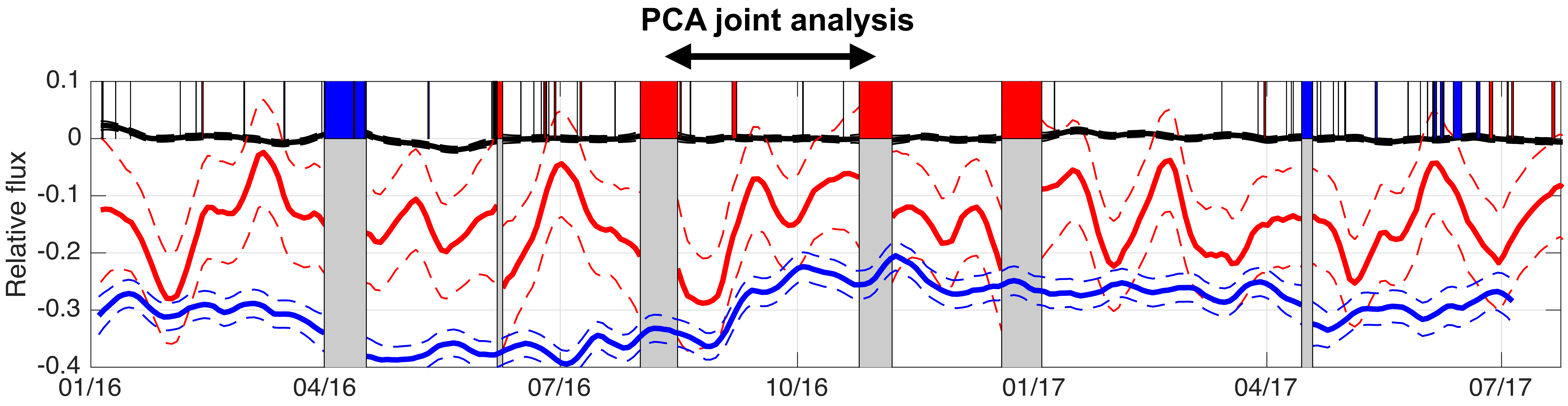
Horizontal slices of density and electrical conductivity models



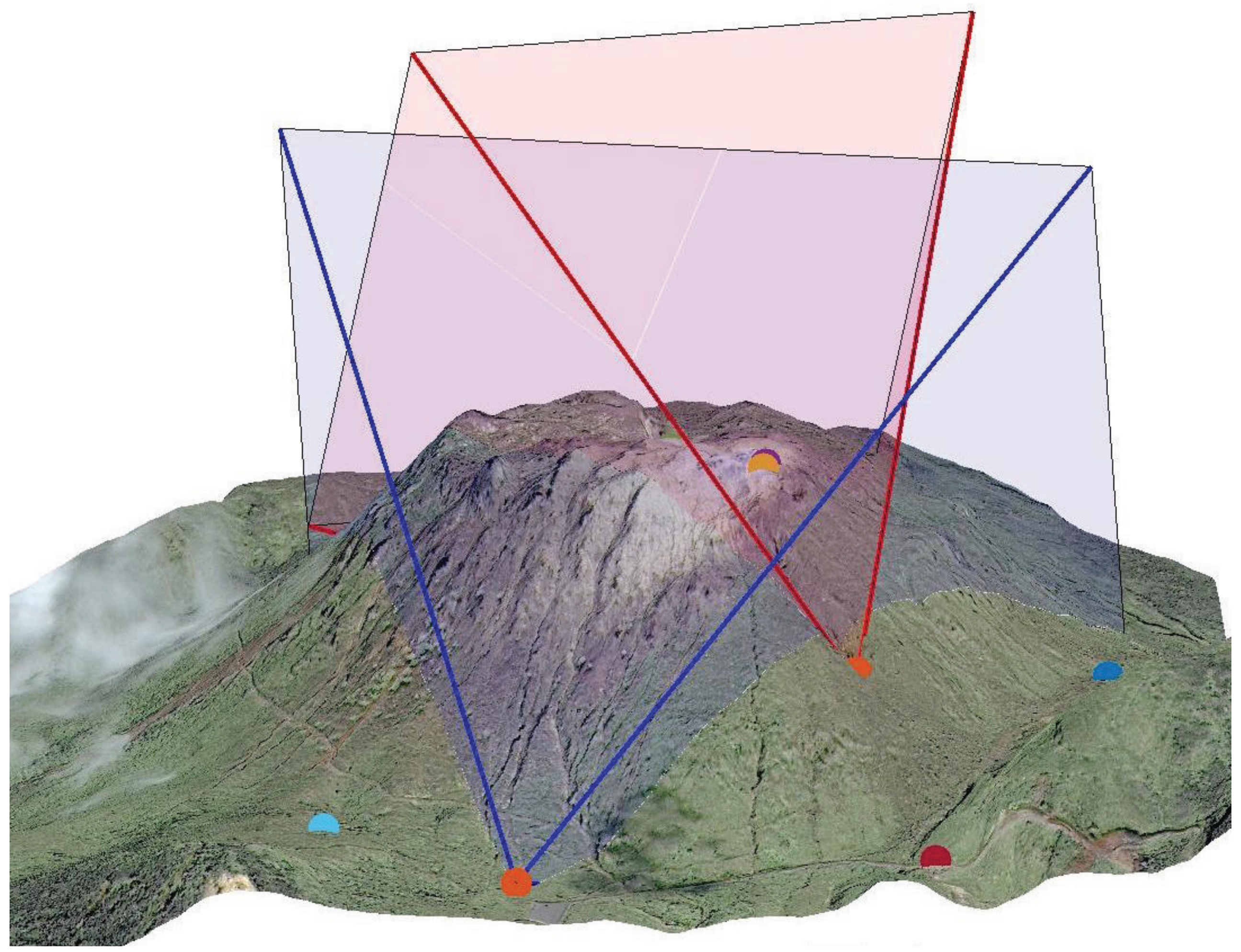


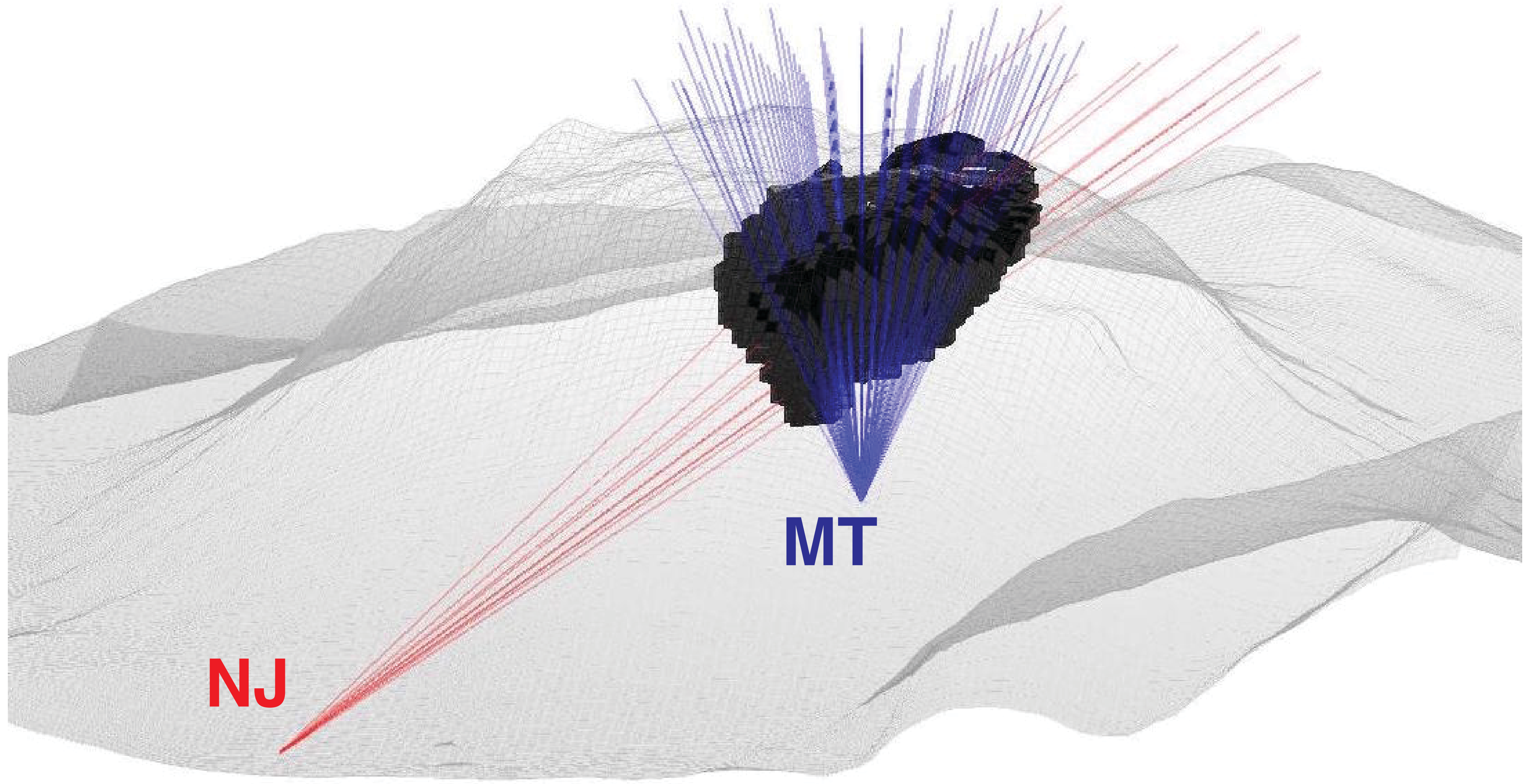
(Rosas-Carbajal et al., 2016, 2017)

Flux variations measured by each detector in selected zone



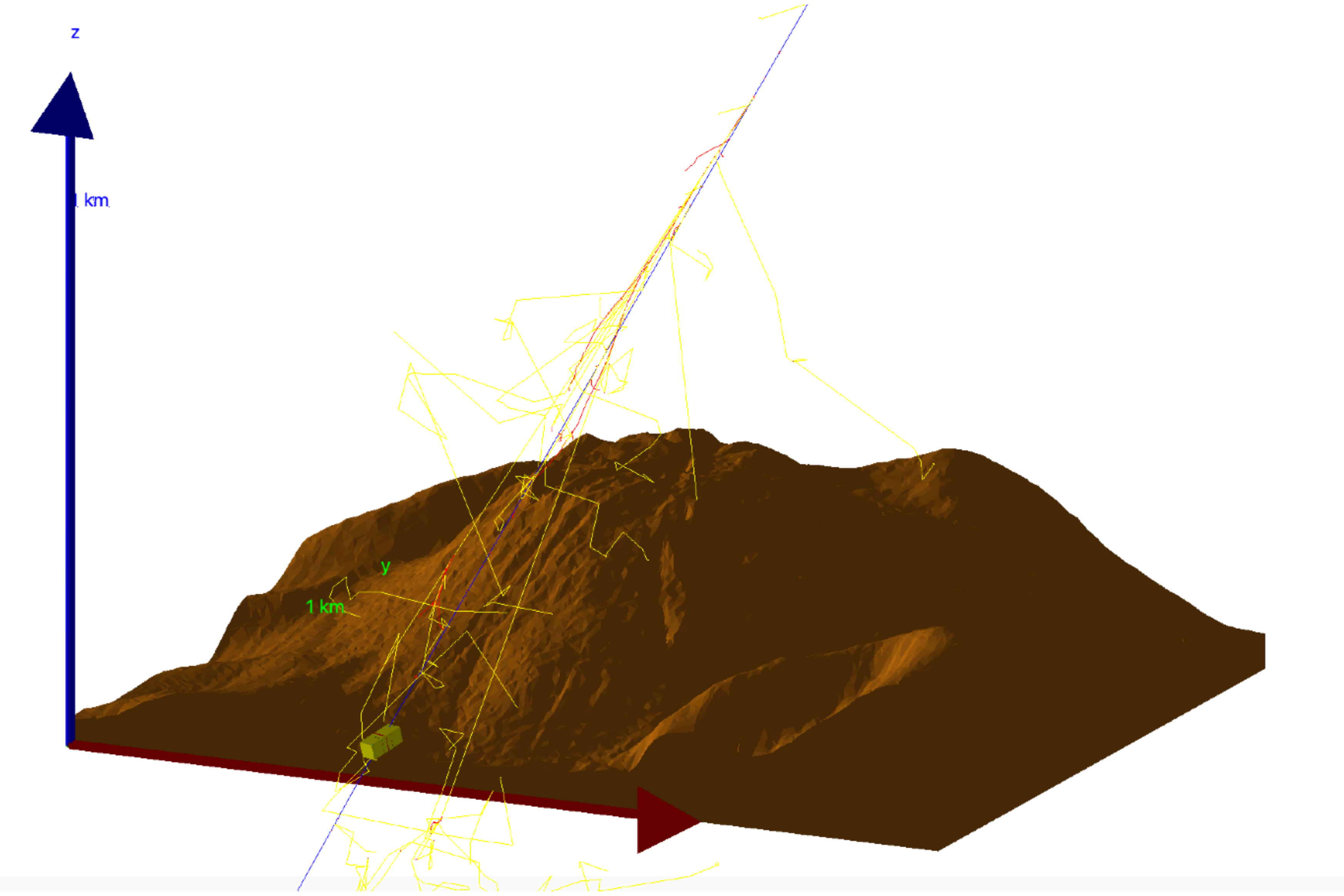
Coherent increase in the muon flux with a 4 % decrease in average density.





Conclusions

- Muon tomography is increasingly used to image volcanoes
- Joint inversion of muon and gravity data helps to better constrain the density model
- Muon tomography can be used to track density changes without repeating insight fieldwork



Where should methodological research focus

- Numerical simulations of noise source contributions
- Effort to build standard equipment and raw data formats
- More involvement of the geological / geophysical community
- Propose muon studies combined with other methods for the particle-physics community

Thank you !

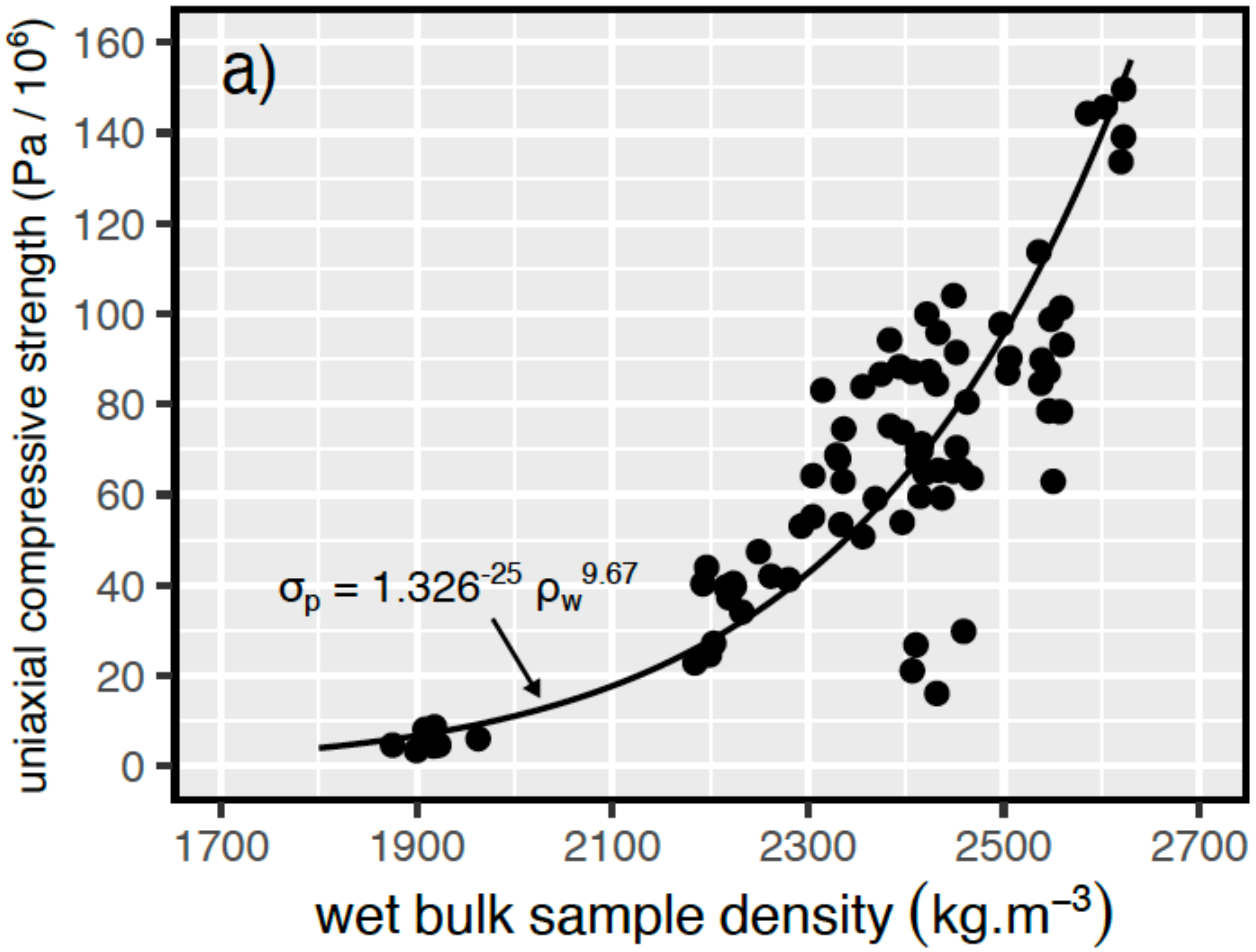
Marina Rosas-Carbajal (rosas@ipgp.fr)
In collaboration with: R. Bajou, M. Tramontini, J. Marteau

cnrs

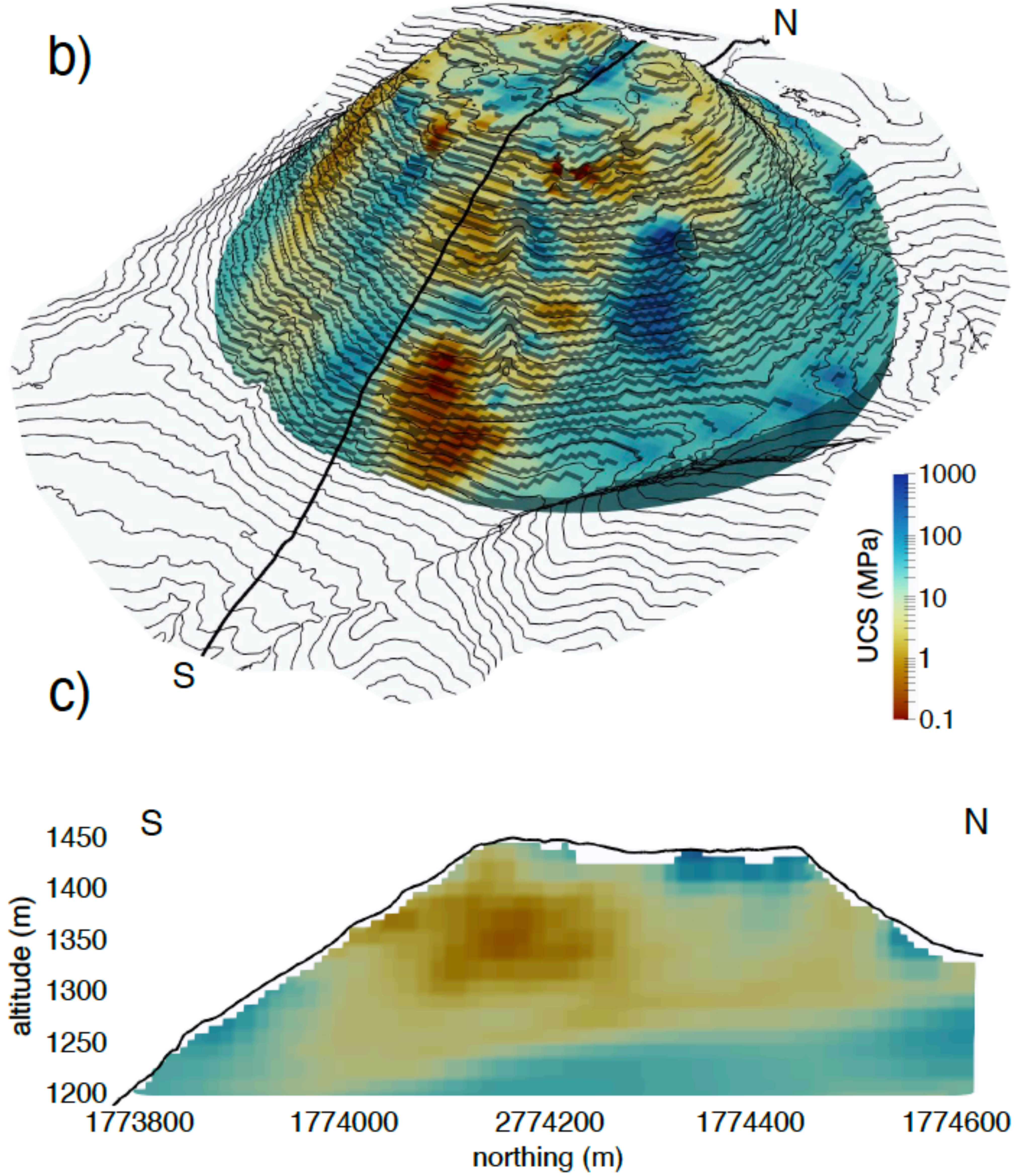
IPGP | Université Paris Cité

iP2i LES 2 INFINIS LYON

Upsaling rock strength values

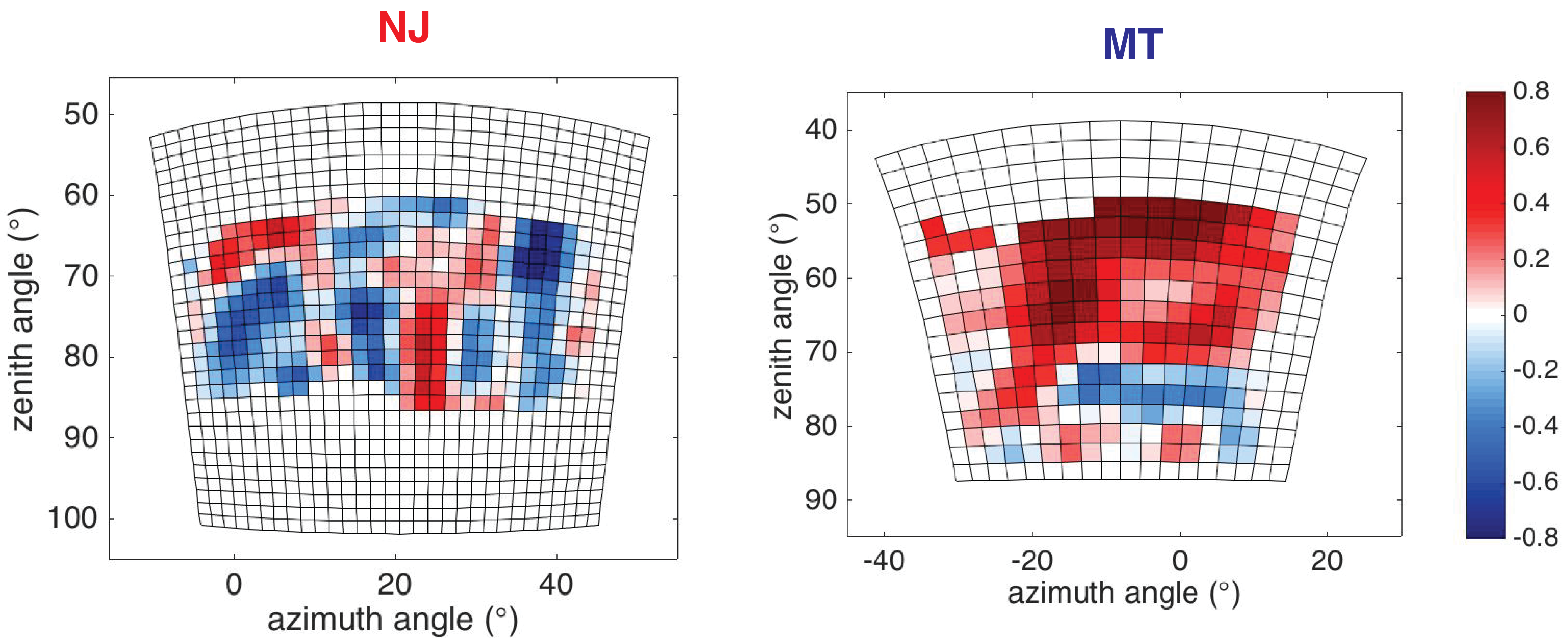


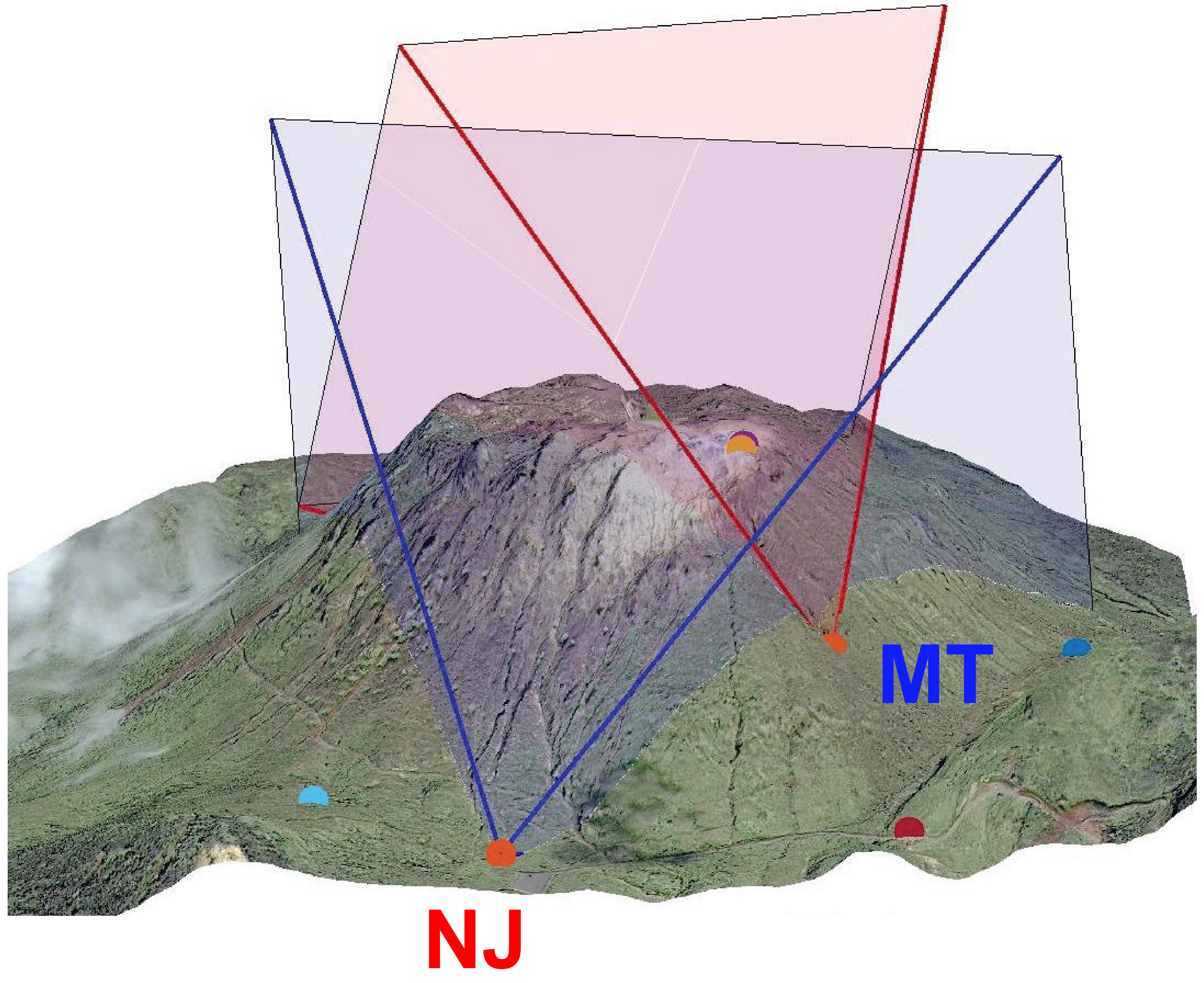
(Heap et al., 2021)



Density variations from continuous muon measurements

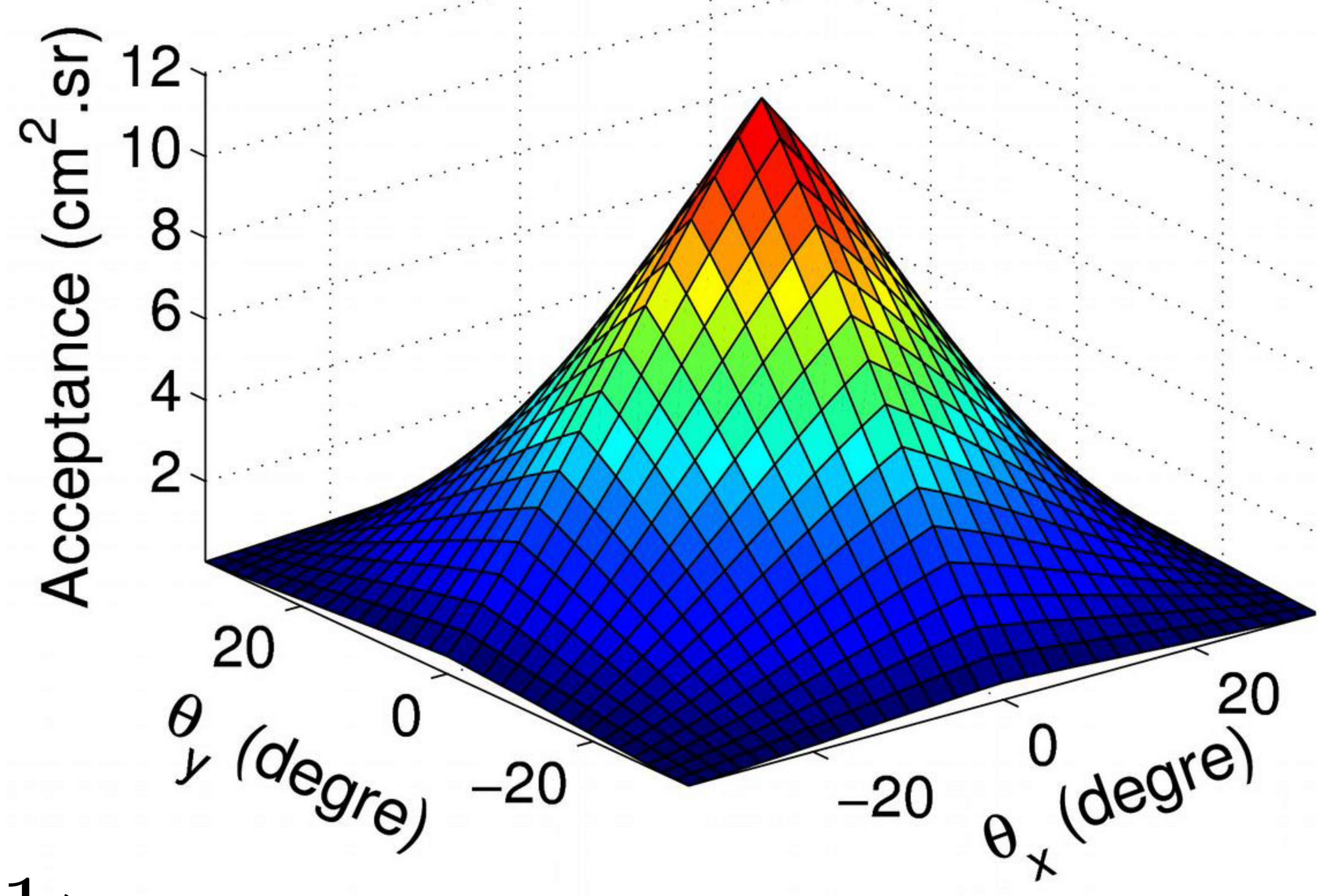
- Continuous muon measurements with 2 muon detectors
- Common regions scanned include fumarolic zone
- Coherent variations found with PCA analysis





Muon tomography

Outgoing flux $I(\varrho) = \dfrac{N(\varrho)}{\Delta T \times \mathcal{T}}$ → Data, → Acceptance

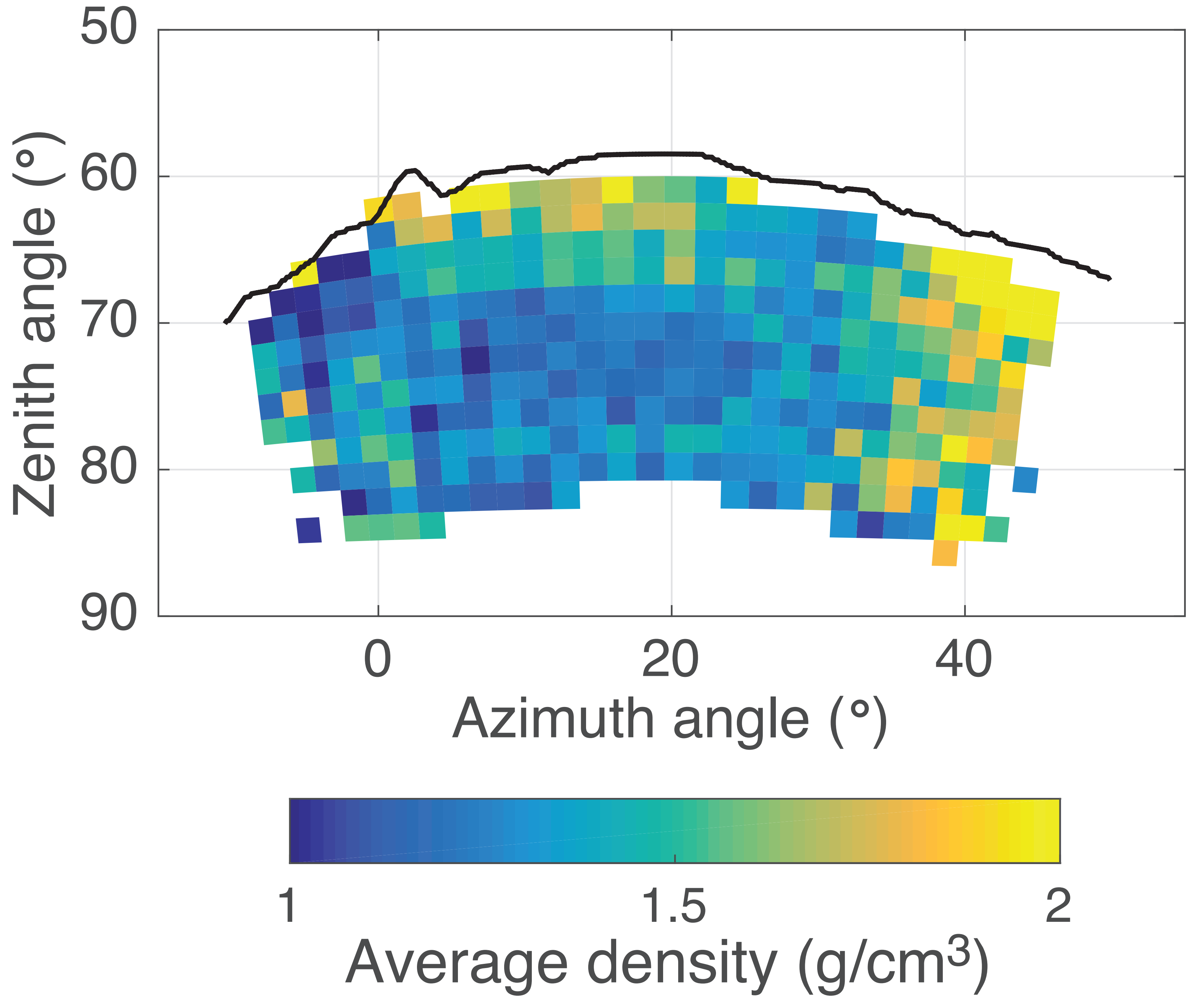


$$I = \int_0^\infty W(E, \varrho) \times \Phi(\theta, E) \times dE (\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1})$$

Survival probability of a particle (non-linear function of opacity)

Incoming flux (open sky)

Average density $\overline{\rho} = \dfrac{\varrho}{L}$



(Rosas-Carbajal et al., 2017)