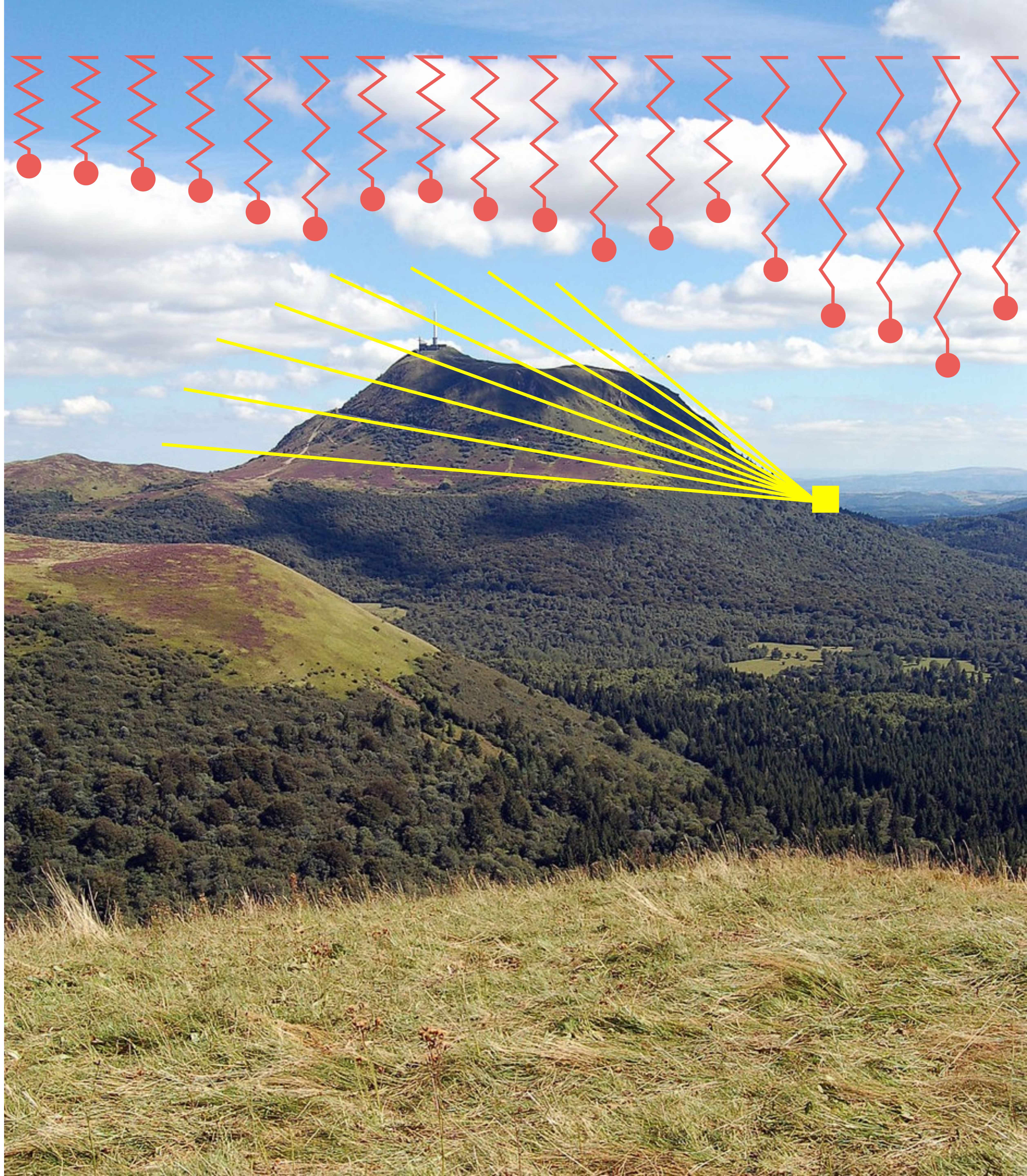
Imaging of the puy de Dôme volcano from gravimetric and muographic data

Anne Barnoud

LPC - Clermont-Ferrand - 09/06/17



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Outline

- Introduction on geophysical imaging

- Puy de Dôme

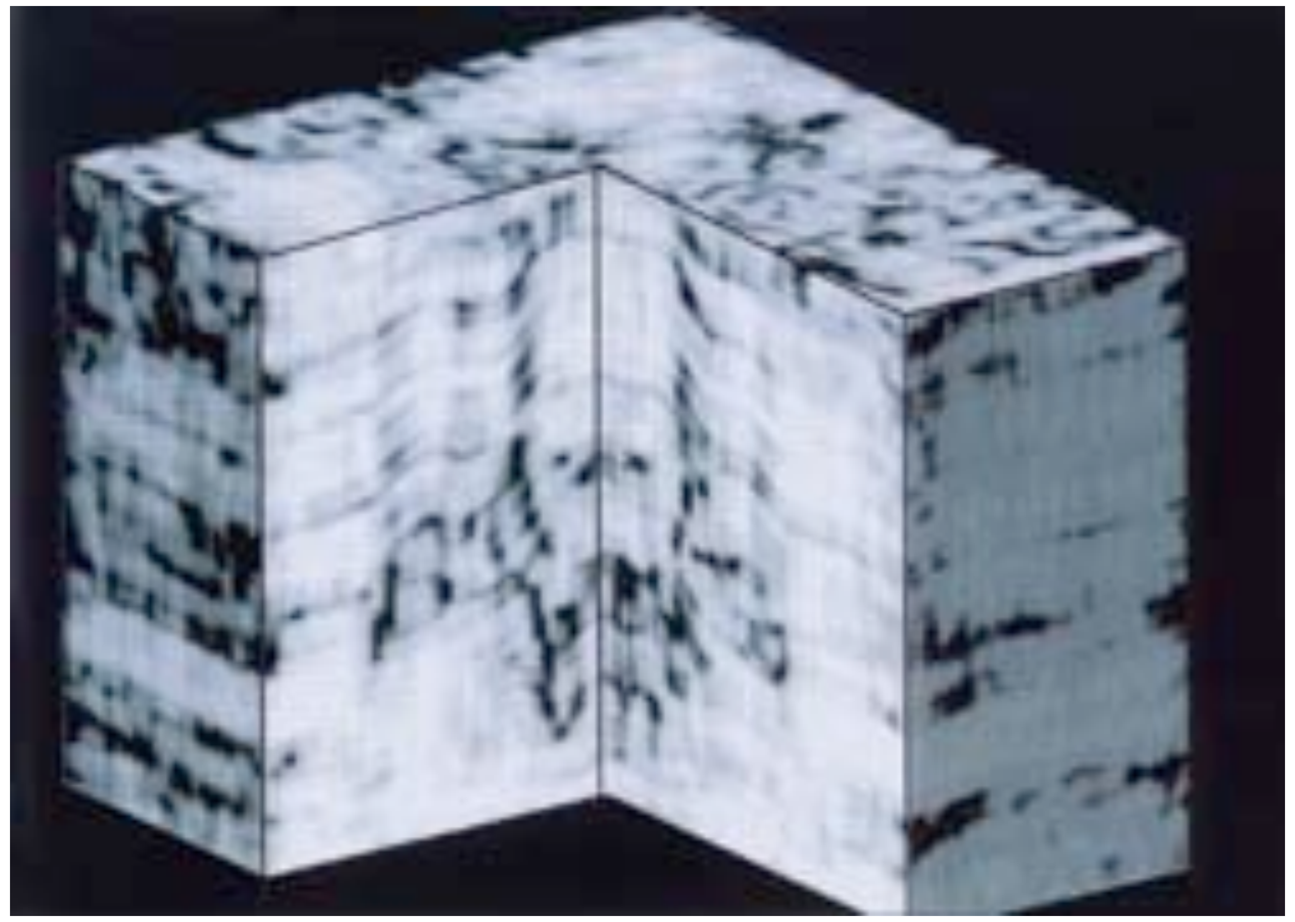
- Gravimetry
  - Principle of the method
  - Inversion approach
  - Inversion of the puy de Dôme data

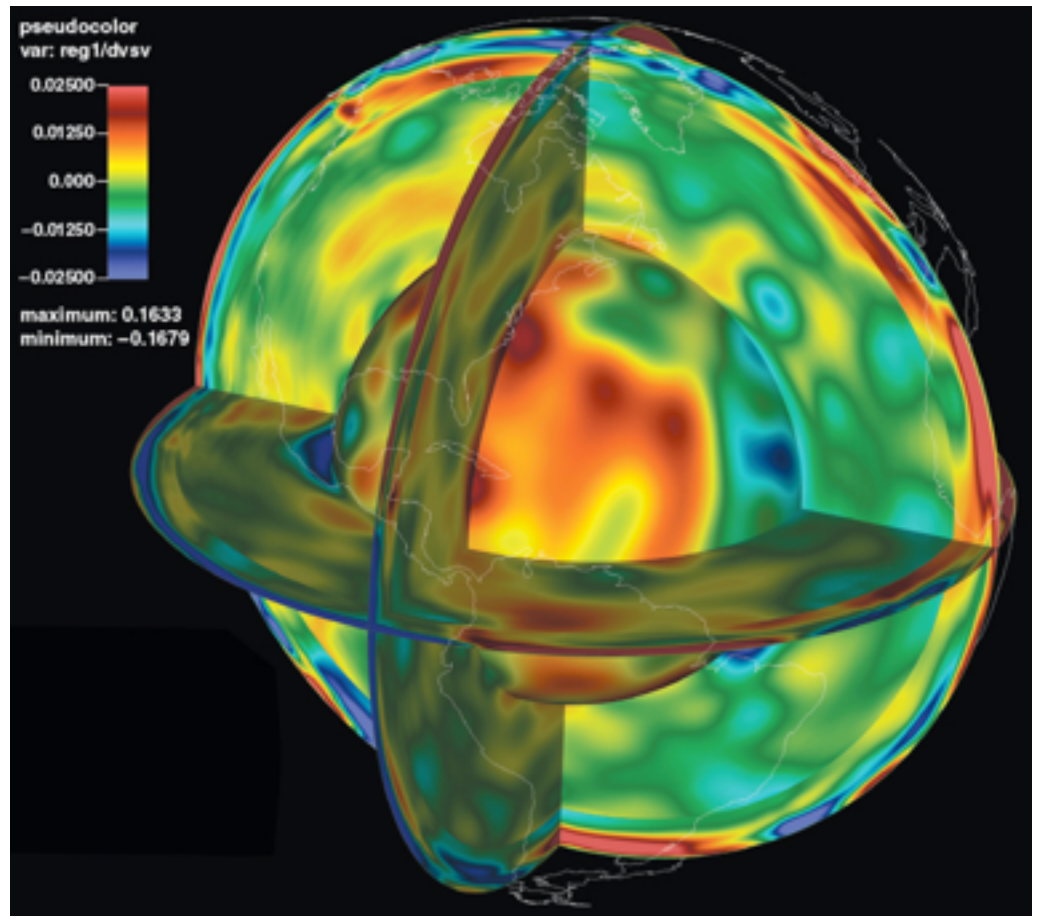
- Muography
  - Principle of the method
  - Muography of the puy de Dôme

- Joint inversion

Medical imaging to see inside the **human body**

Geophysical imaging to see inside the **Earth**

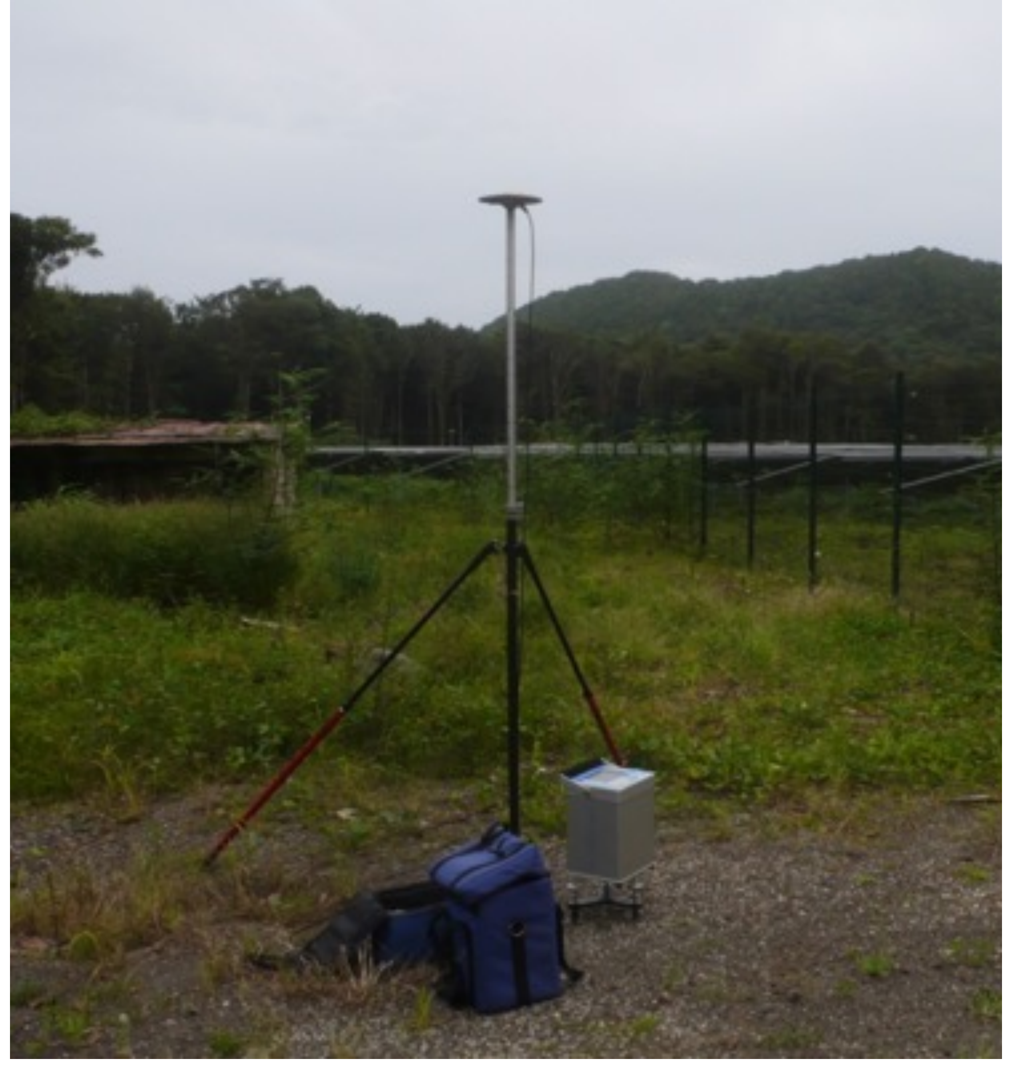




Non destructive sounding of the Earth's subsurface, from local to global scale

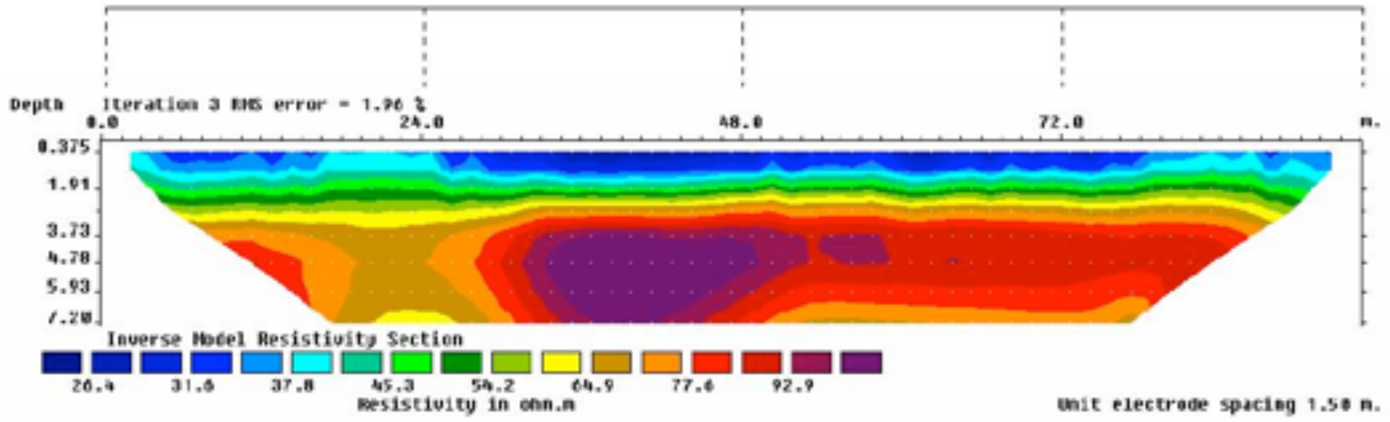
Some geophysical methods

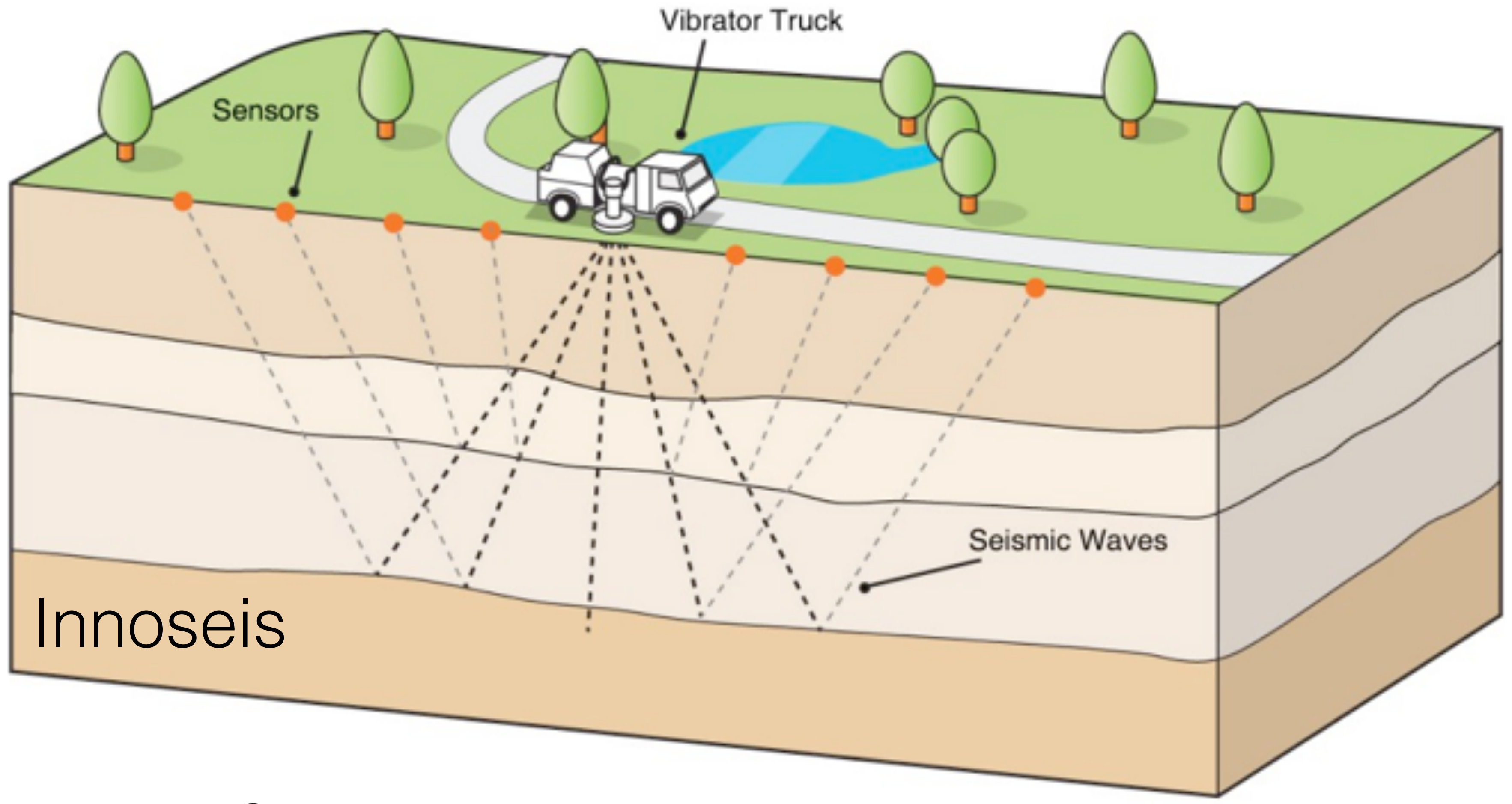
Gravimetry



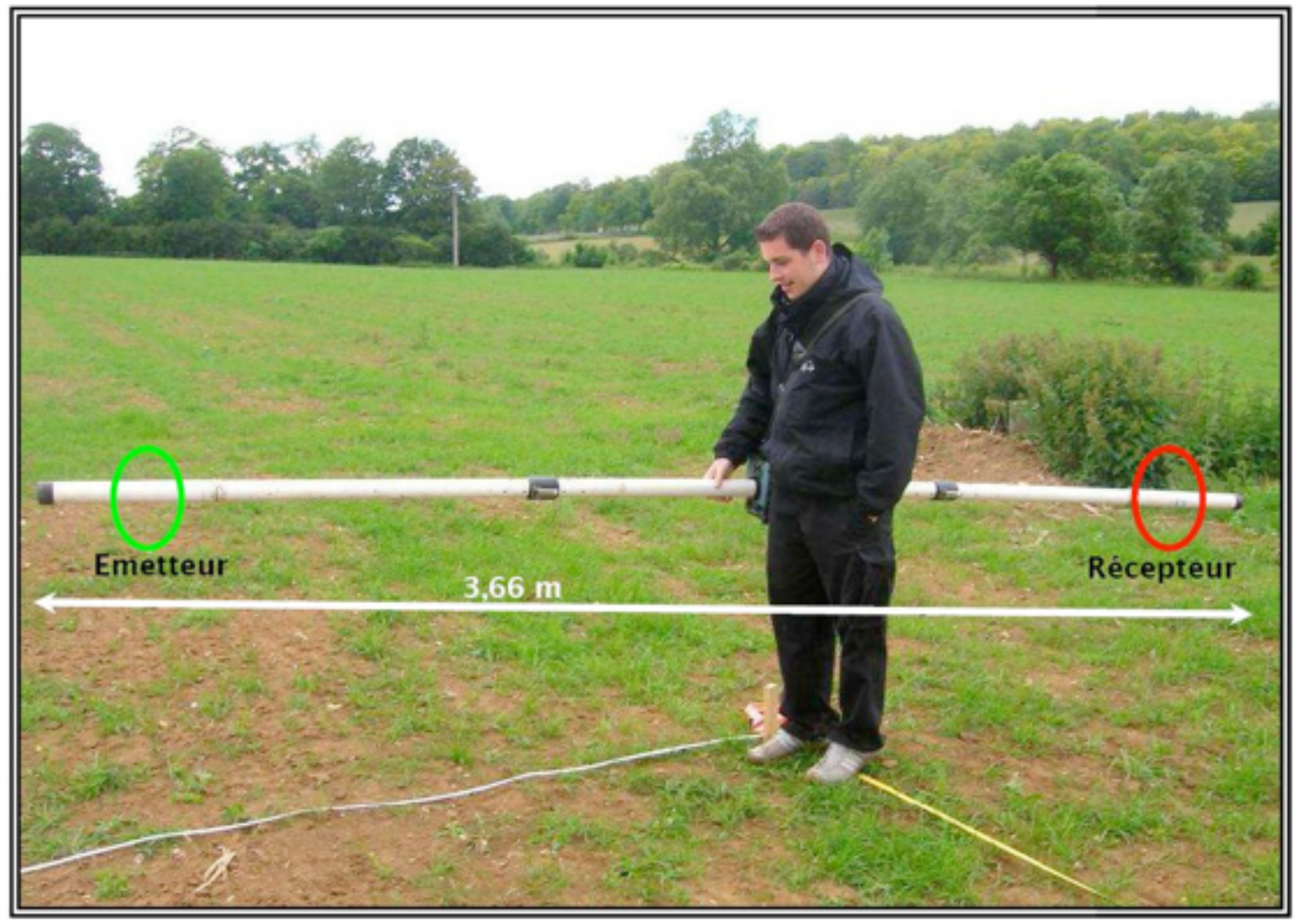
Heliborne magnetic and electromagnetic

Electrical resistivity

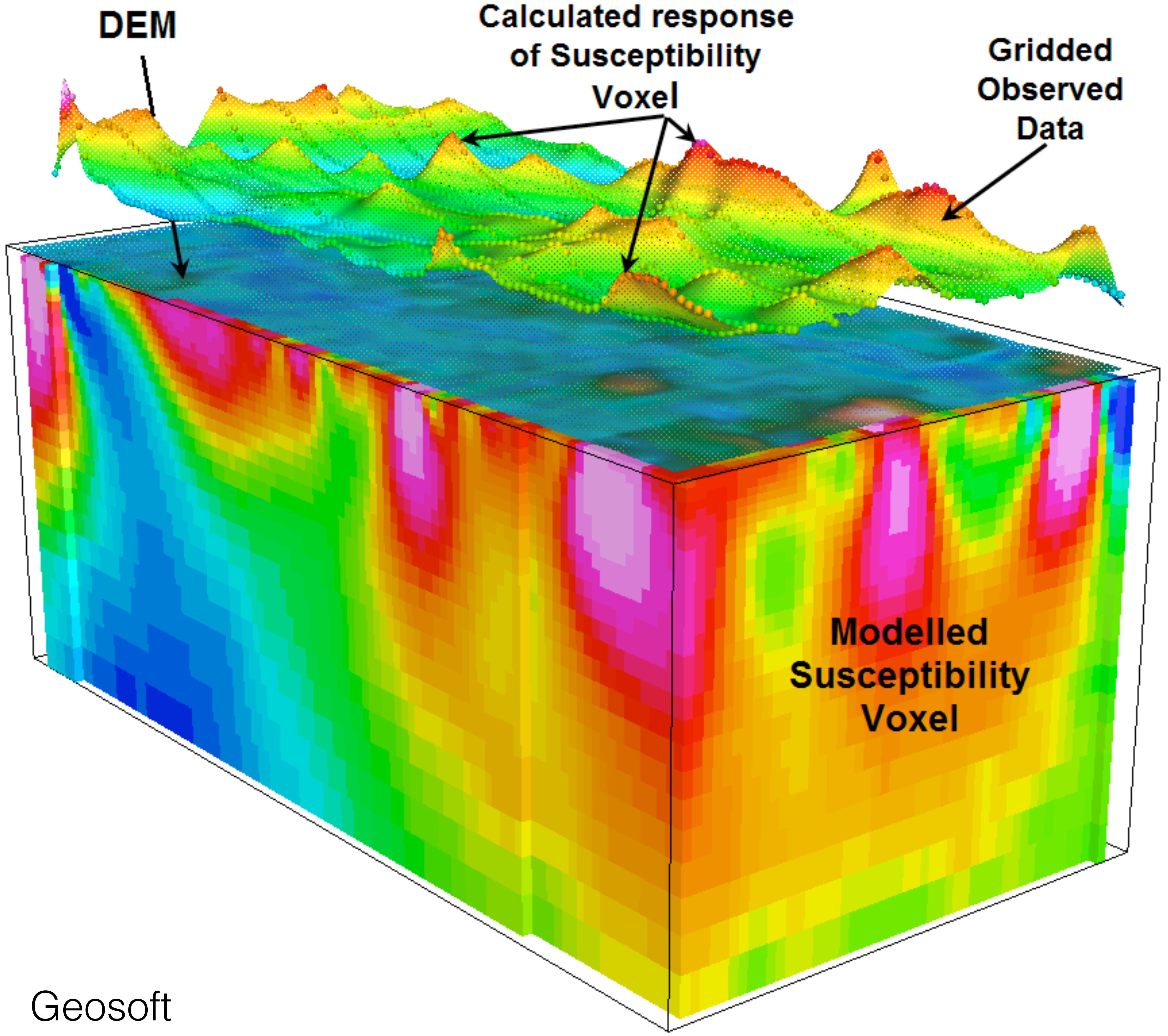




Seismic methods



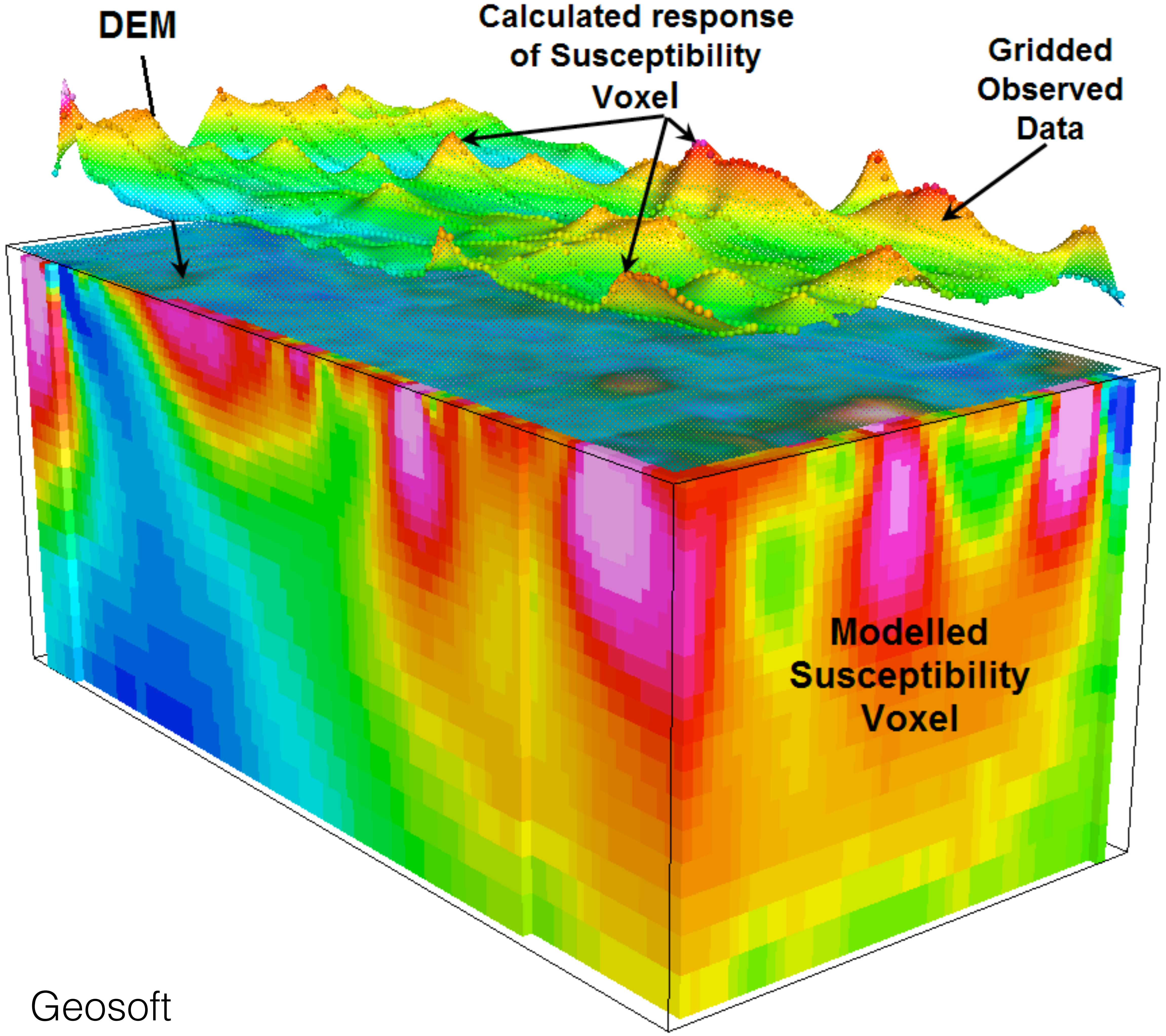
Electromagnetism



Geosoft

Data, eg.:
- seismic wave travel times
- gravitational field of the Earth

Model, eg.:
- seismic velocity and density
- density



Geosoft

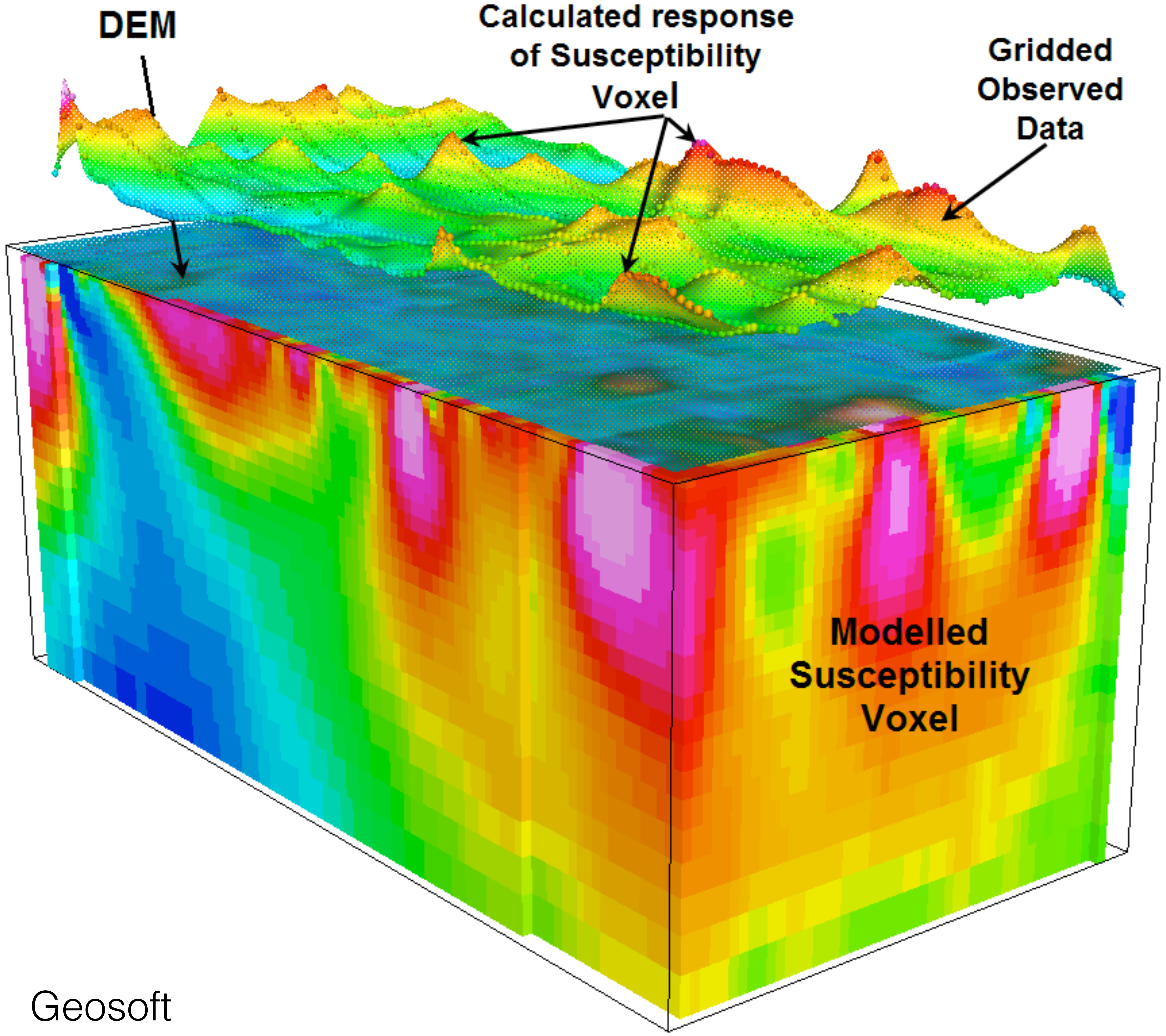
$$g(\boldsymbol{m}) = \boldsymbol{d}$$

Data, eg.:
- seismic wave travel times
- gravitational field of the Earth

Modelling — Physics

Model, eg.:
- seismic velocity and density
- density

Inversion in geophysics



Geosoft

$$g(\boldsymbol{m}) = \boldsymbol{d}$$

Data, eg.:
- seismic wave travel times
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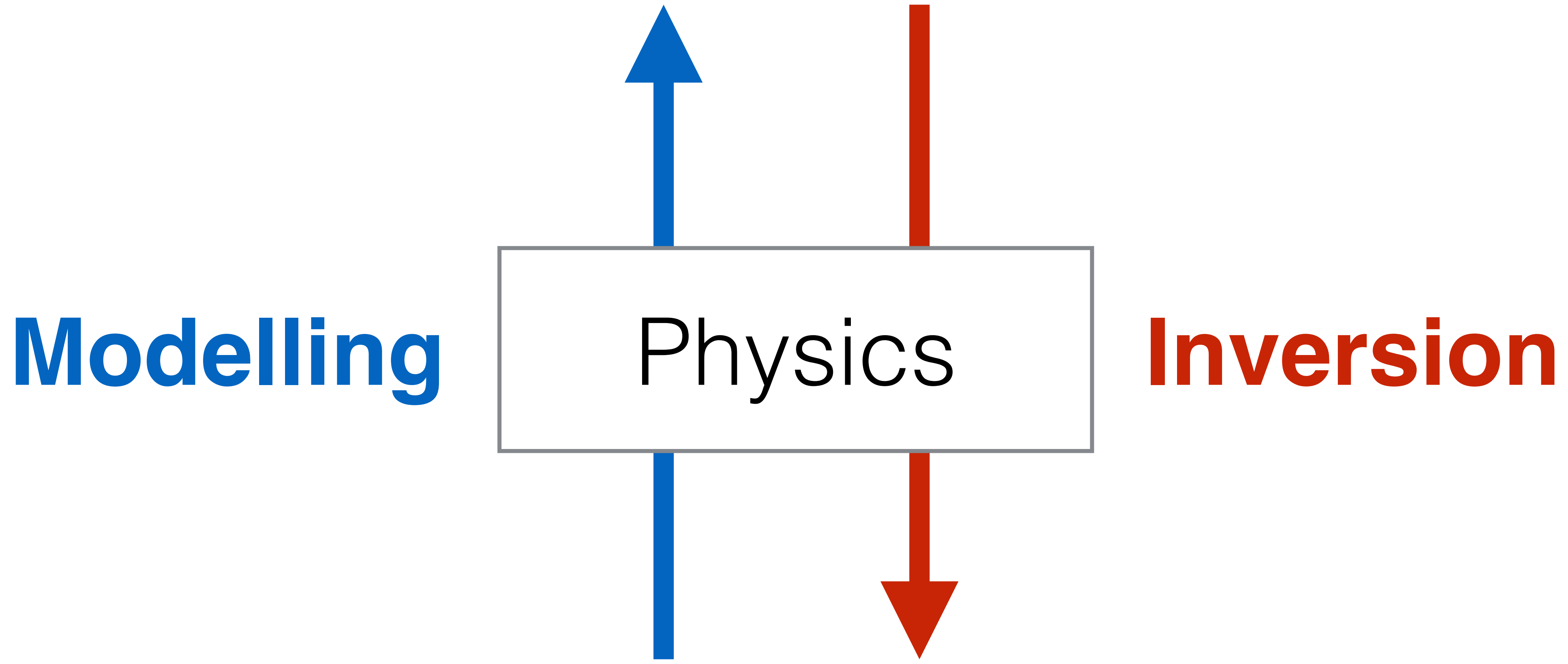


Model, eg.:
- seismic velocity and density
- density

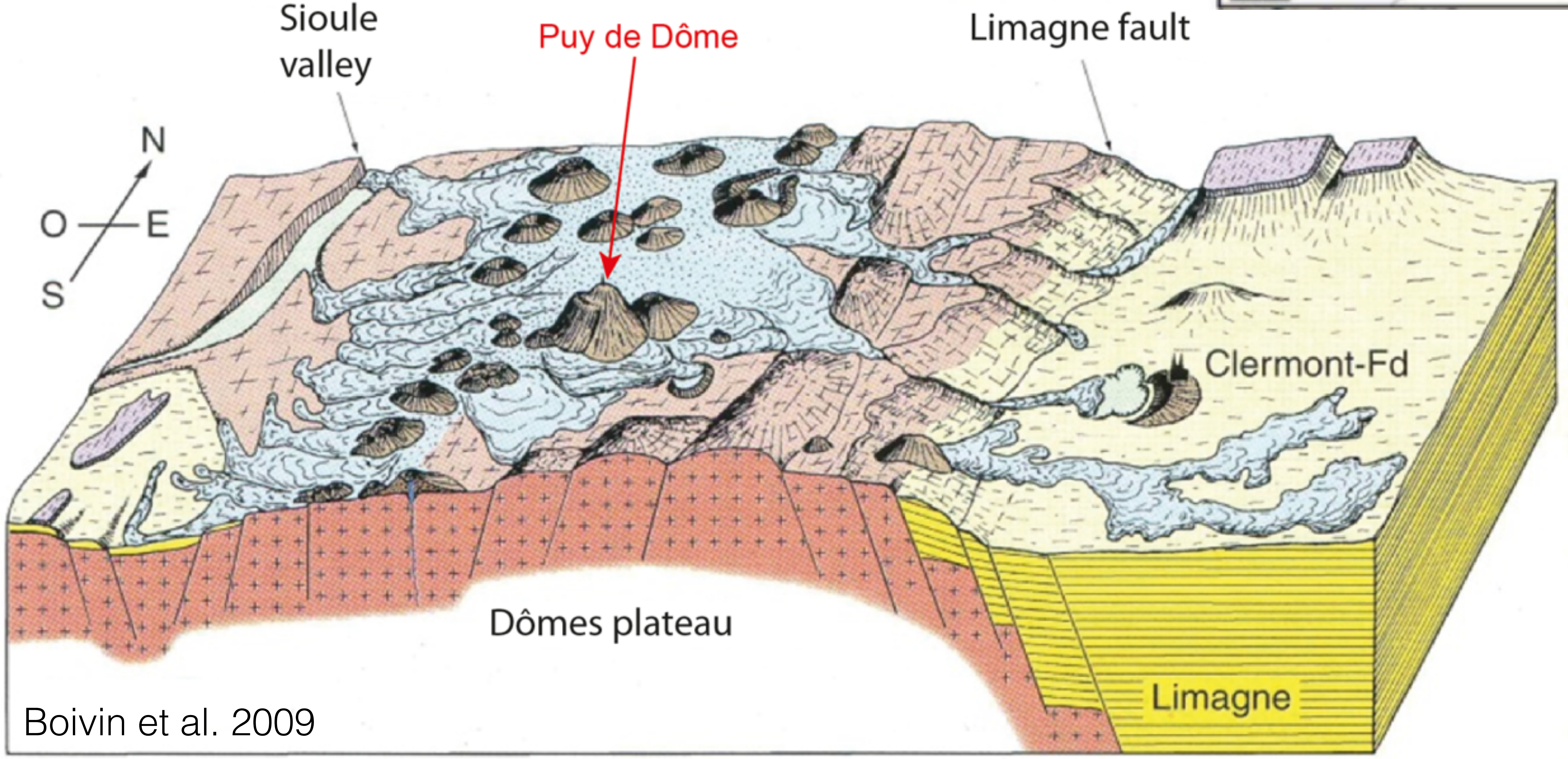
Puy de Dôme volcano

- located in the French Massif Central ancient volcanic zone

- lies on a hercynian basement
- about 11000 year old

- dome **400 m high** and **1.8 km wide**
- formed by two distinct extrusions
- hydrothermal alteration

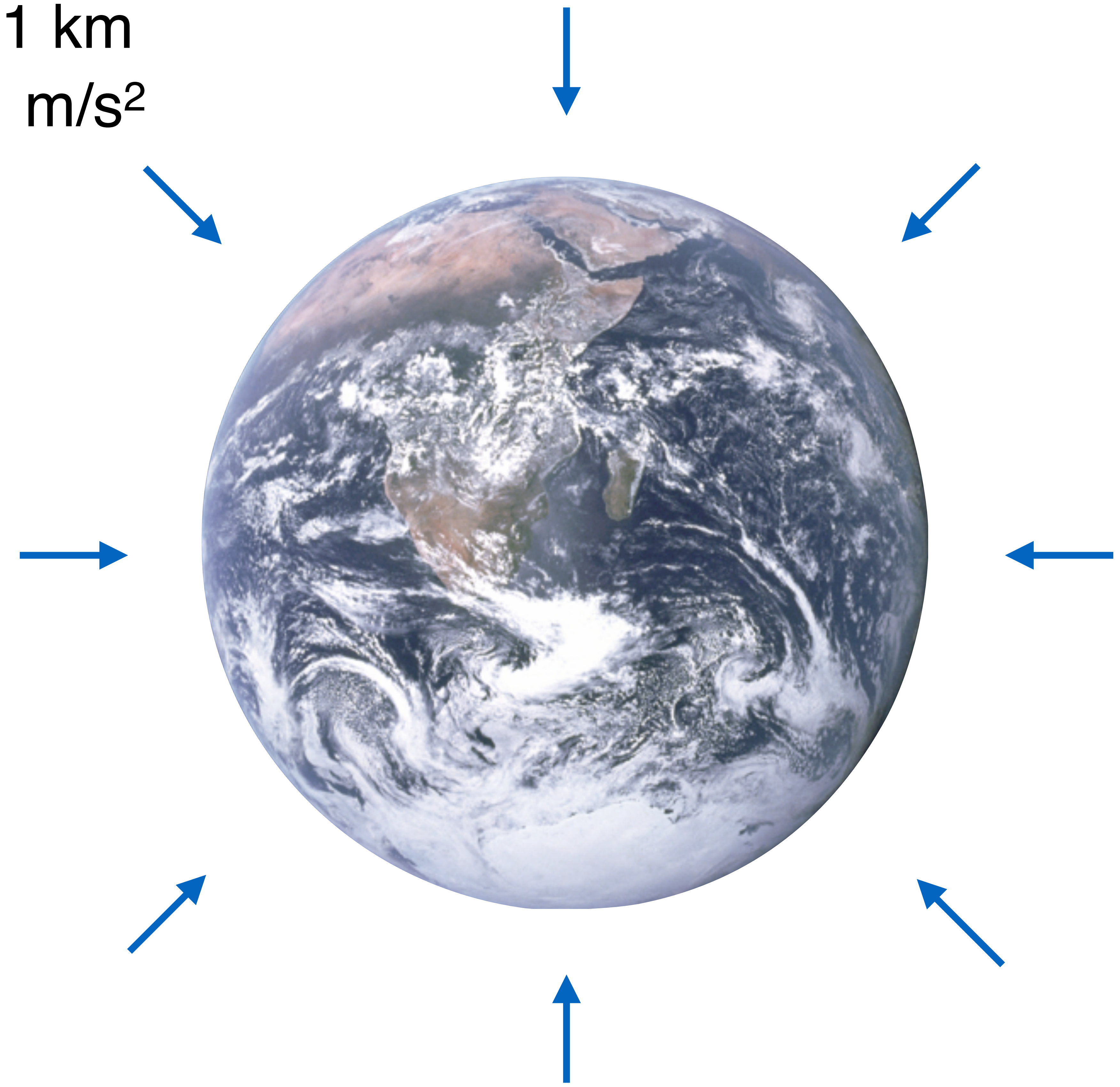
- **isolated** from neighbor edifices



Boivin et al. 2009

Spherical Earth

R = 6371 km
g = 9,81 m/s²



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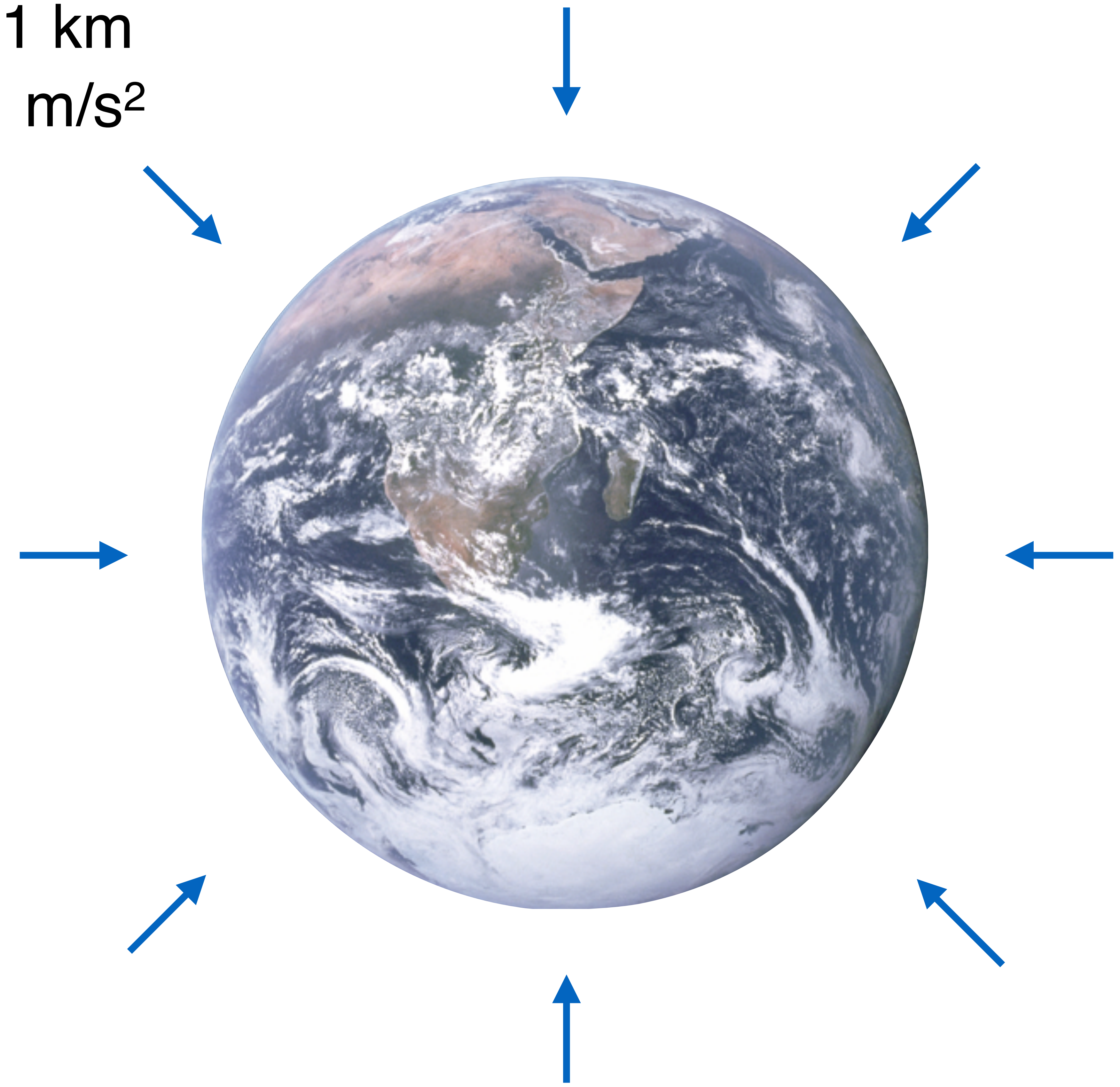
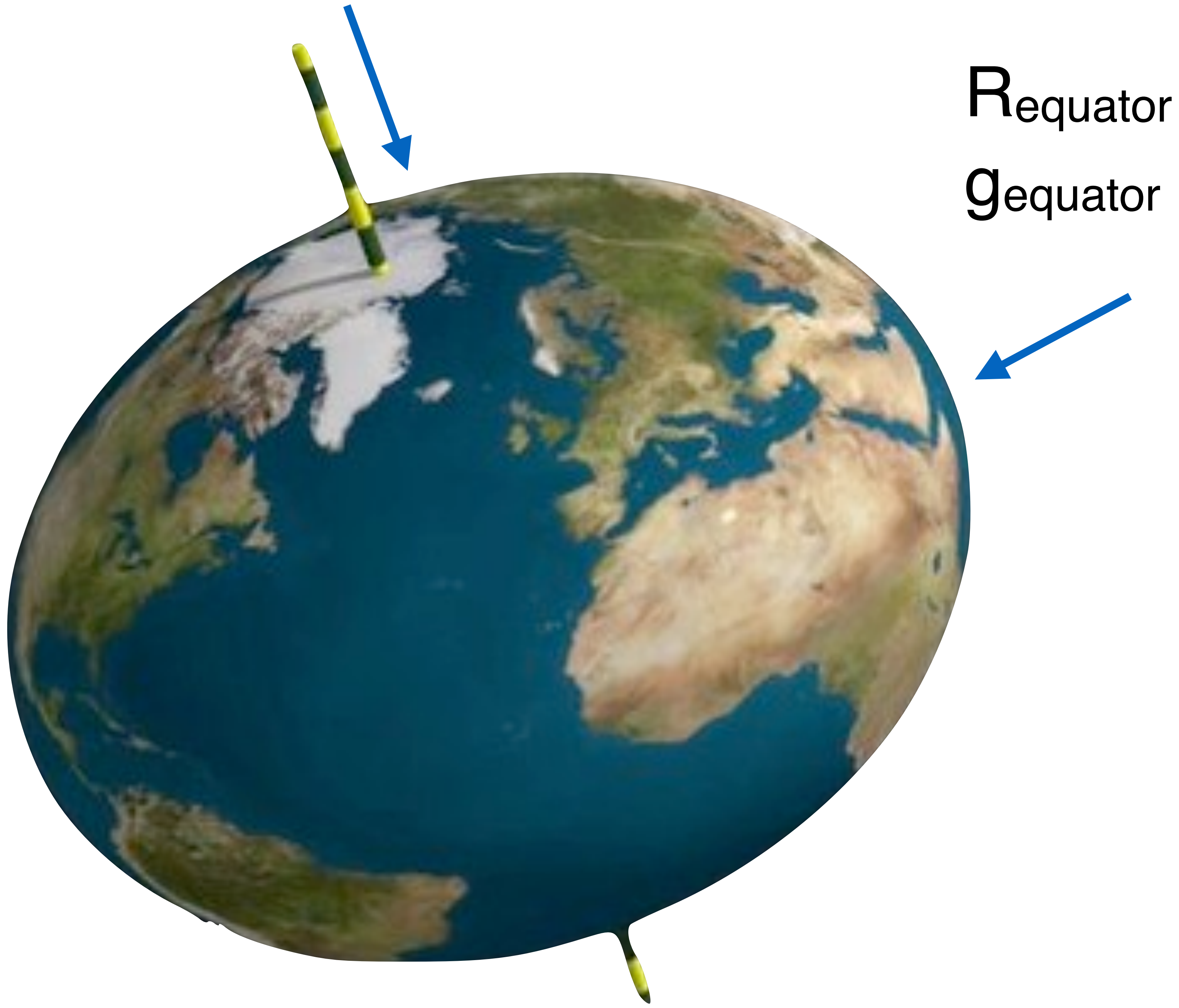


Ellipsoidal Earth

$R_{poles} = 6357$ km
$g_{poles} = 9{,}832$ m/s^2

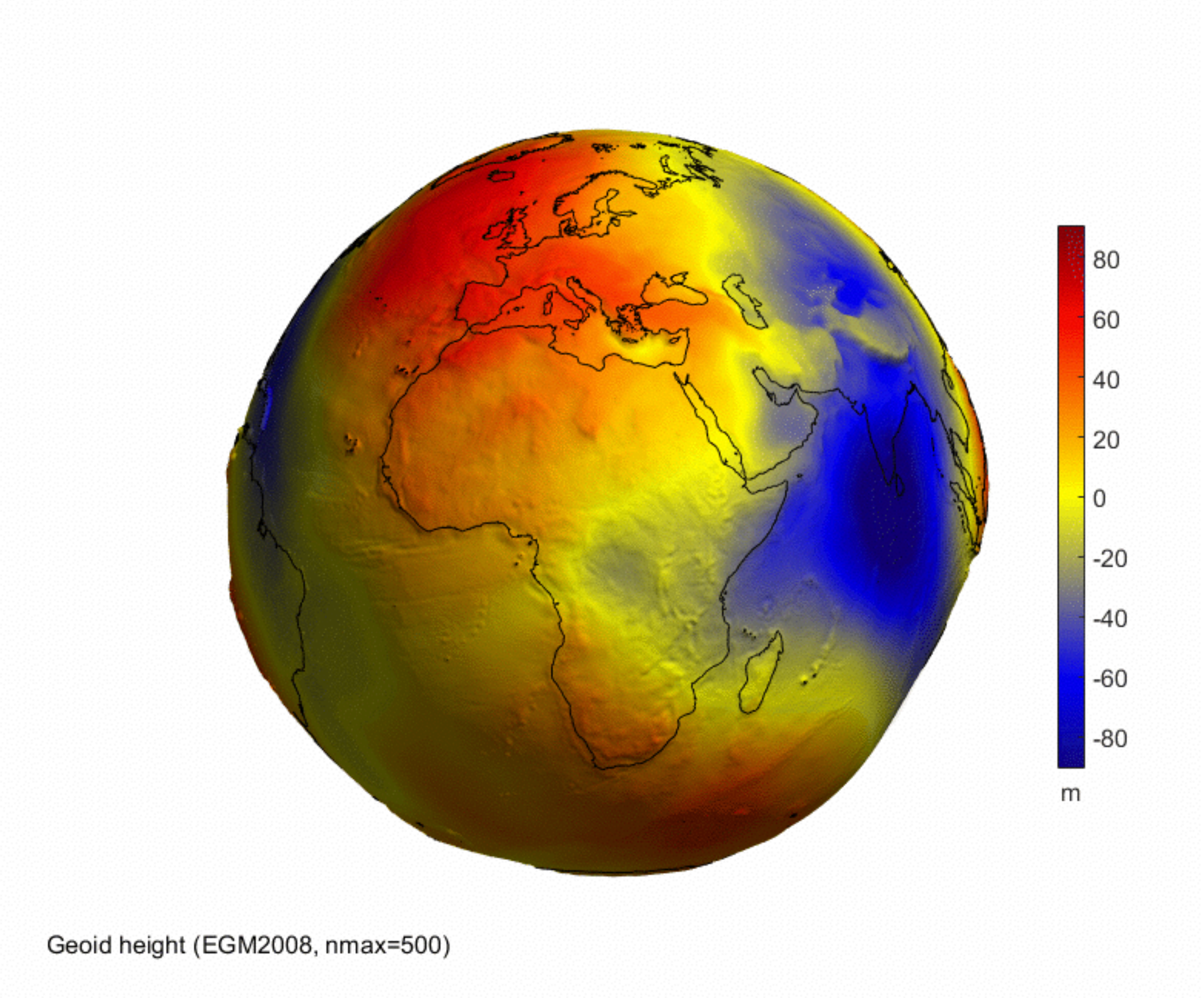
$R_{equator} = 6378$ km
$g_{equator} = 9{,}780$ m/s^2



$dg = 0{,}05$ m/s^2

Earth shape and gravity field

Geoid (equipotential surface following the averaged sea level)



Bezdek and Sebera 2013

Earth shape and gravity field

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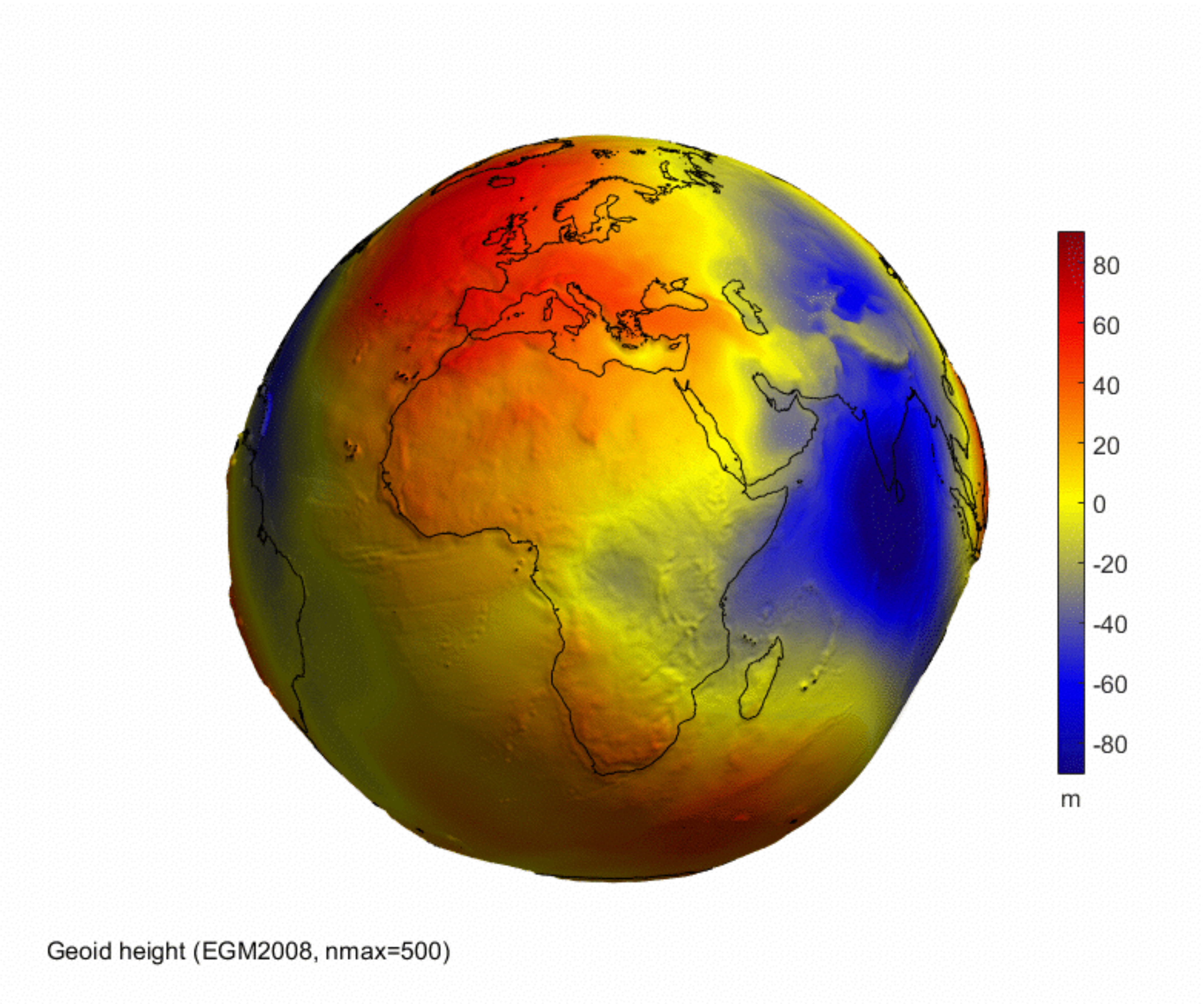
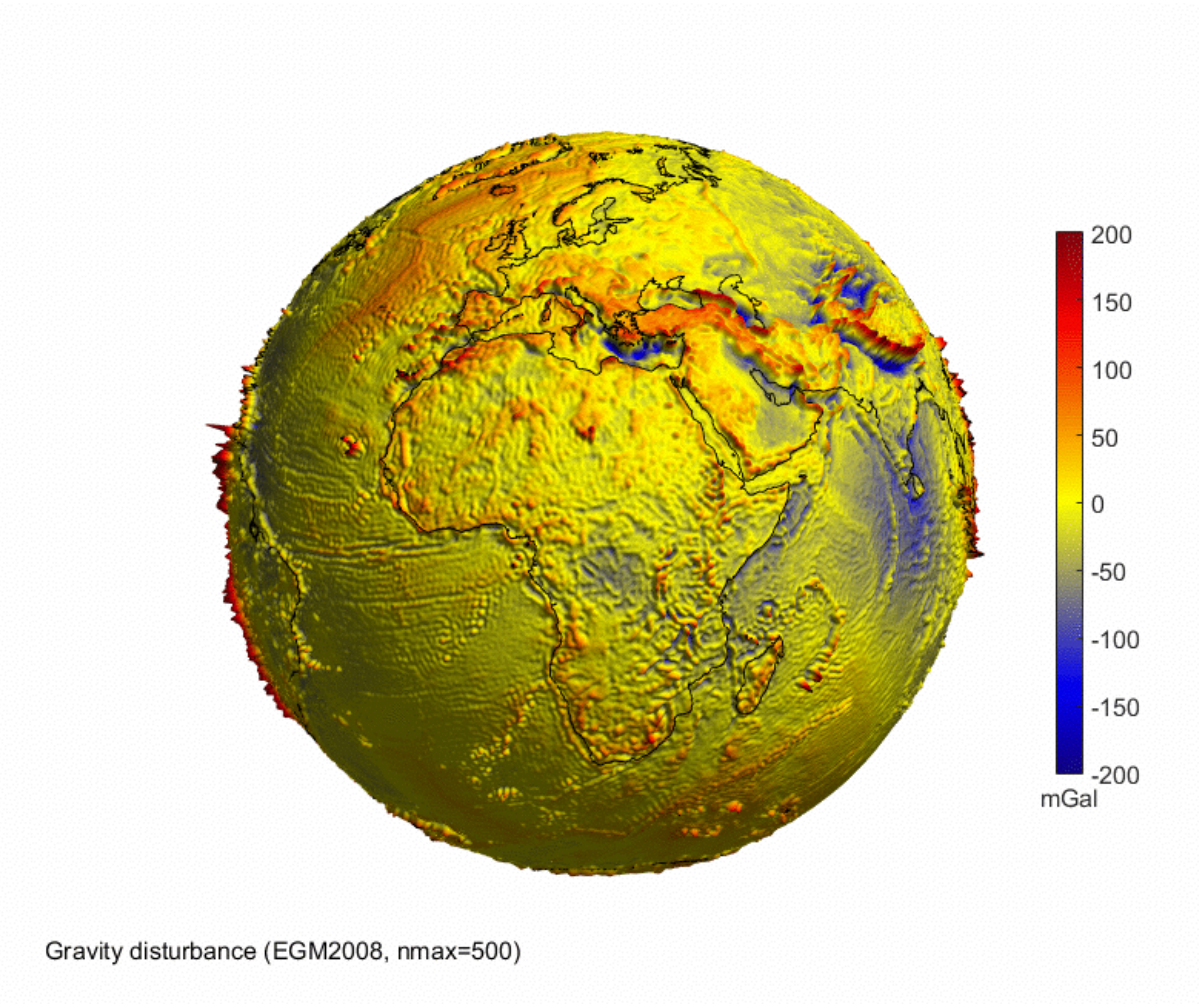


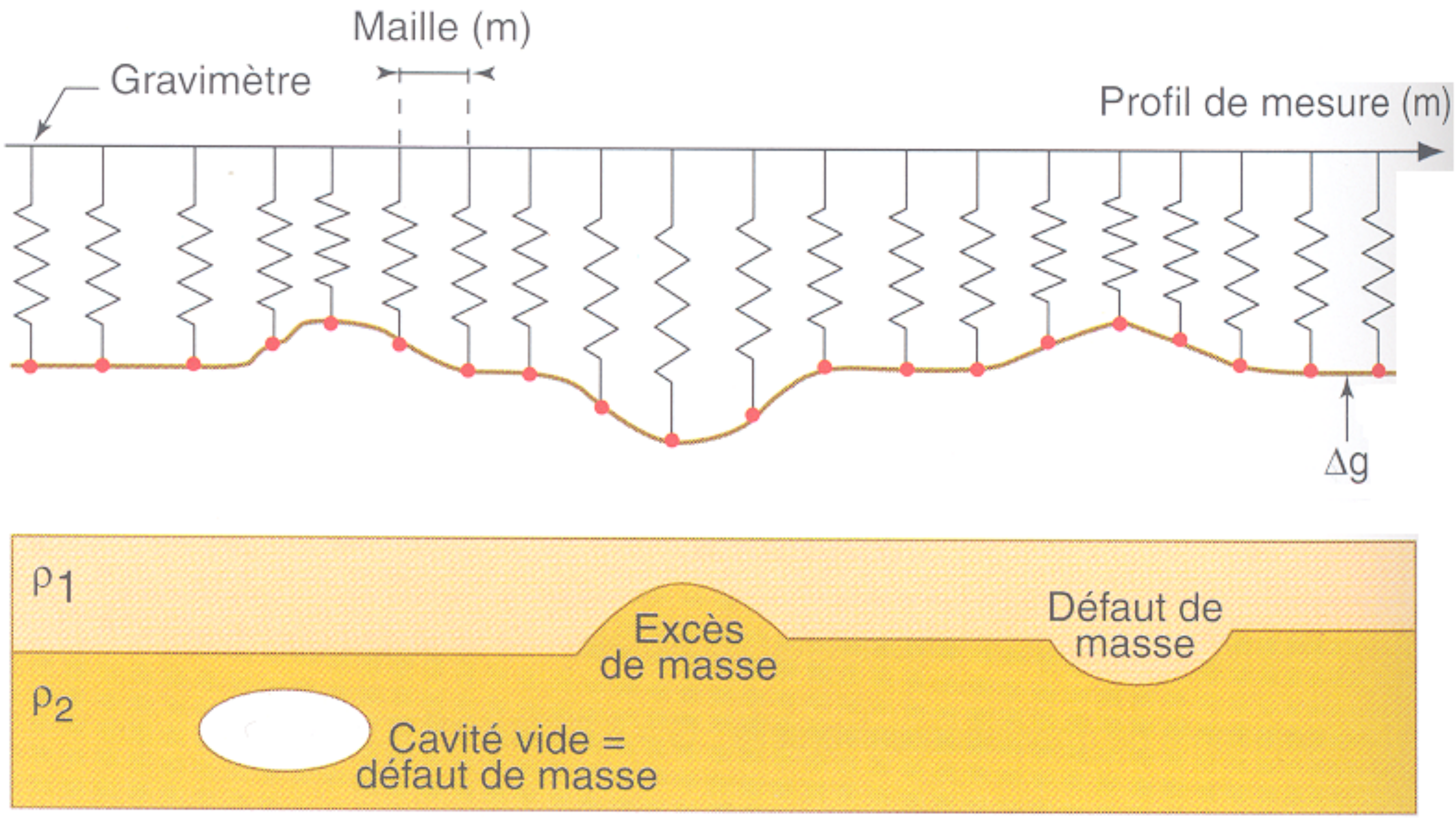
Gravity field variations due to density variations



Bezdek and Sebera 2013

dg = 0,004 m/s^2 = 400 mGal

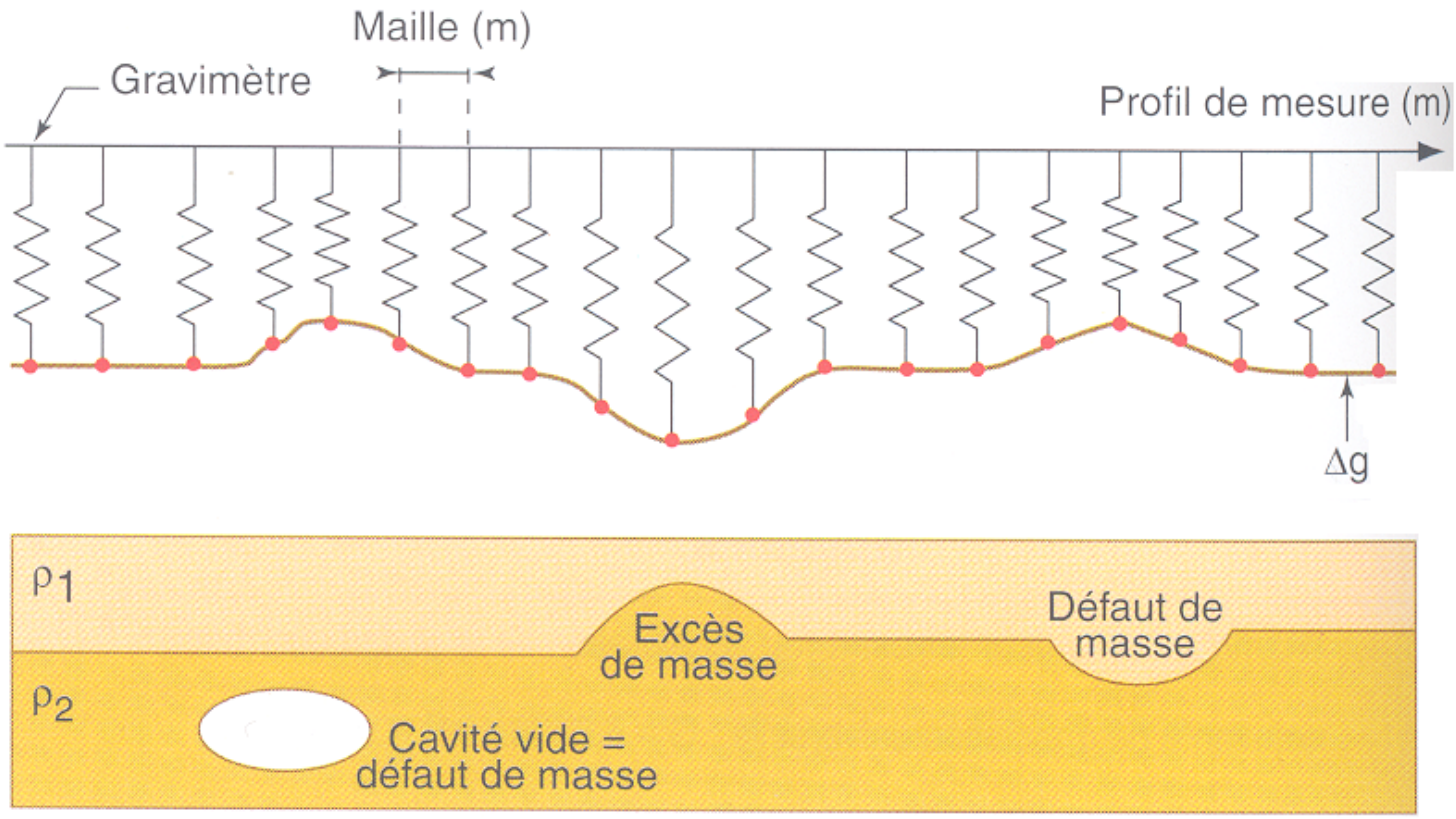
Local gravimetric variations



LCPC 2004

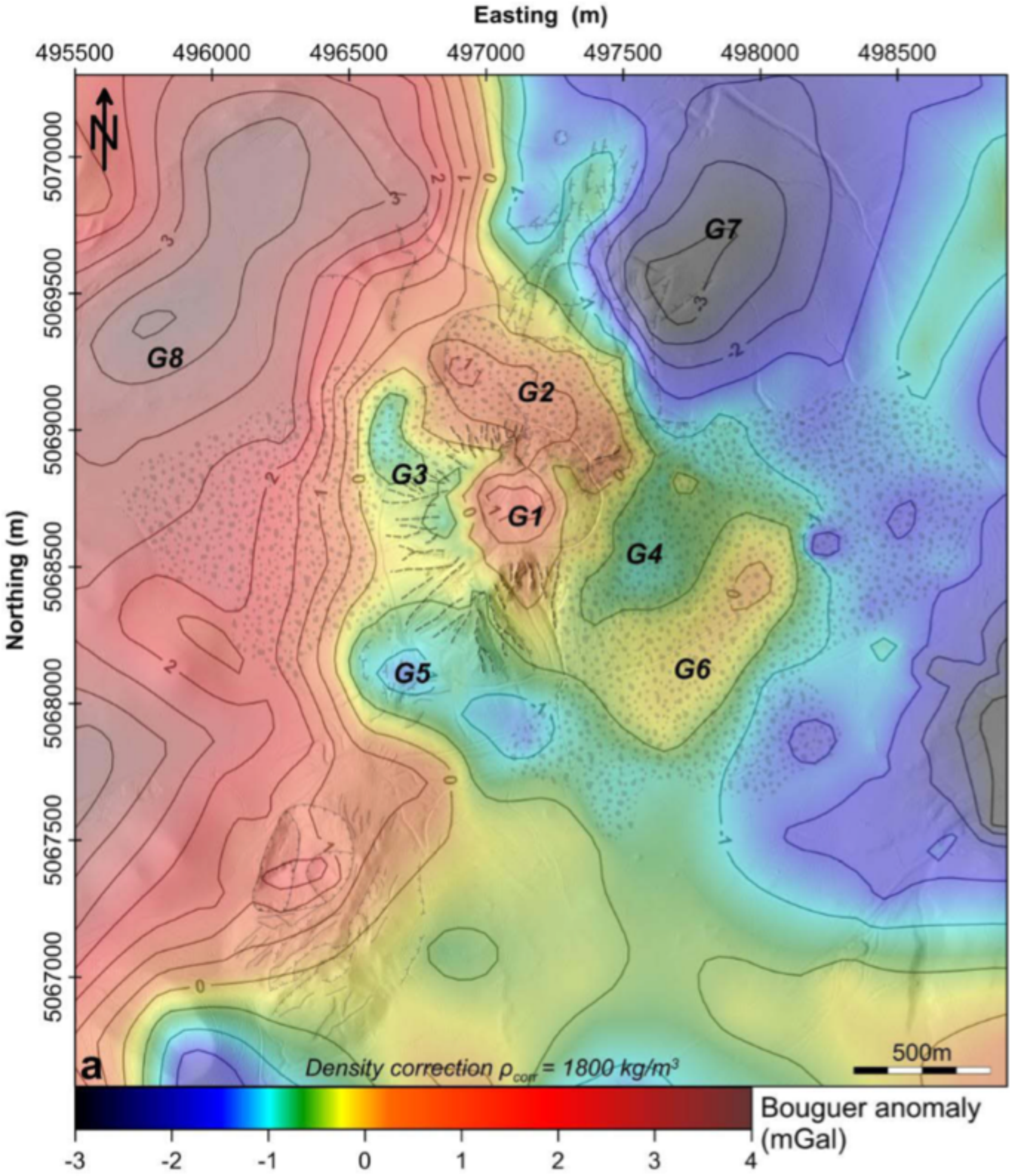
Portal 2015

Local gravimetric variations



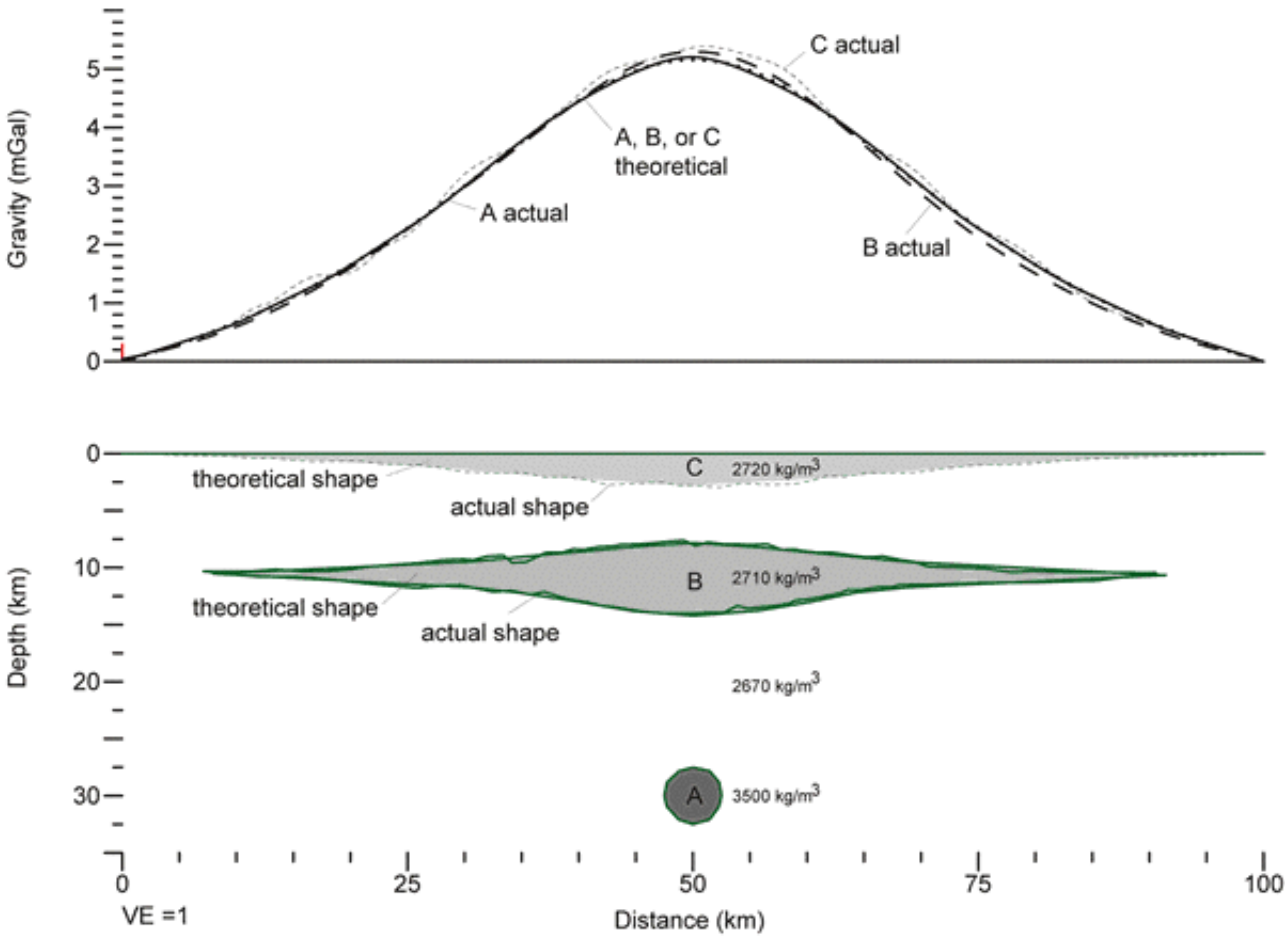
LCPC 2004

Portal *et al.* 2016



dg ~ 0,00001 m/s² = 1 mGal

Non-unicity of the gravimetric method



Saltus & Blakely 2011

Linear gravimetric inverse problem

- Modelling
  - Nodes of density
  - Topography taken into account

- Linear problem

sensitivity matrix (derivatives)

densities

gravimetric data

$$\mathbf{G}\boldsymbol{\rho} = \boldsymbol{d}$$

- Ill-posed

Inversion method

- Function to minimize: Bayesian regularization (Tarantola & Valette 1982)

$$\mathbf{G}\boldsymbol{\rho} = \boldsymbol{d}$$

$$\phi(\tilde{\boldsymbol{\rho}}) = (\boldsymbol{d} - \mathbf{G}\tilde{\boldsymbol{\rho}})^t \mathbf{C}_\mathrm{D}^{-1} (\boldsymbol{d} - \mathbf{G}\tilde{\boldsymbol{\rho}}) + (\tilde{\boldsymbol{\rho}} - \boldsymbol{\rho}_{prior})^t \mathbf{C}_\mathrm{P}^{-1} (\tilde{\boldsymbol{\rho}} - \boldsymbol{\rho}_{prior})$$

$$\mathbf{C}_{\mathrm{D},ii} = \boldsymbol{\sigma}_{d,i}$$

$$\mathbf{C}_{P,ij} = \sigma^2_{\rho,ij} \exp^{-\frac{D^2_{ij}}{\lambda^2}}$$

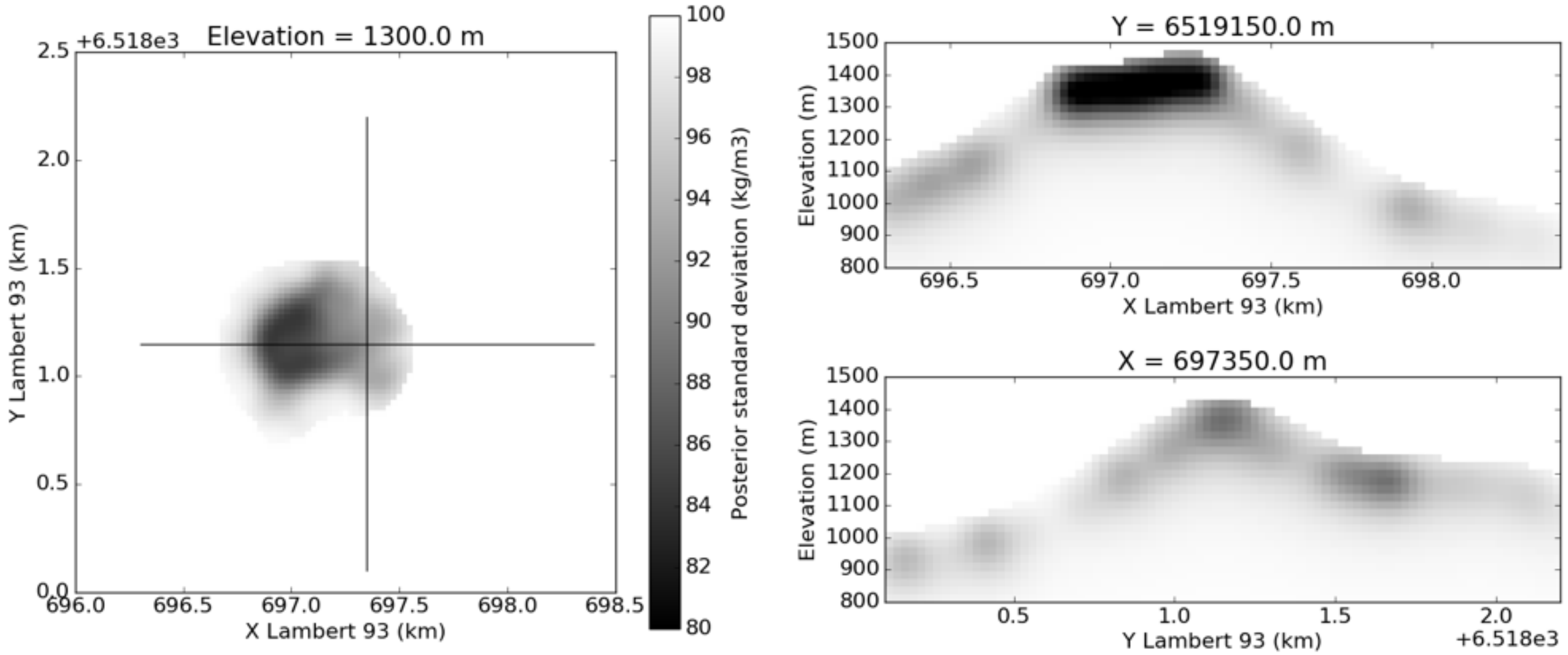
$$\begin{bmatrix} 1/\sigma_{\boldsymbol{d}}^2 & & 0 \\ & \ddots & \\ 0 & & 1/\sigma_{\boldsymbol{d}}^2 \end{bmatrix}$$

$$\begin{bmatrix} 1/\sigma_{\boldsymbol{\rho}}^2 & \cdots & \cdots \\ \cdots & \ddots & \cdots \\ \cdots & \cdots & 1/\sigma_{\boldsymbol{\rho}}^2 \end{bmatrix}$$

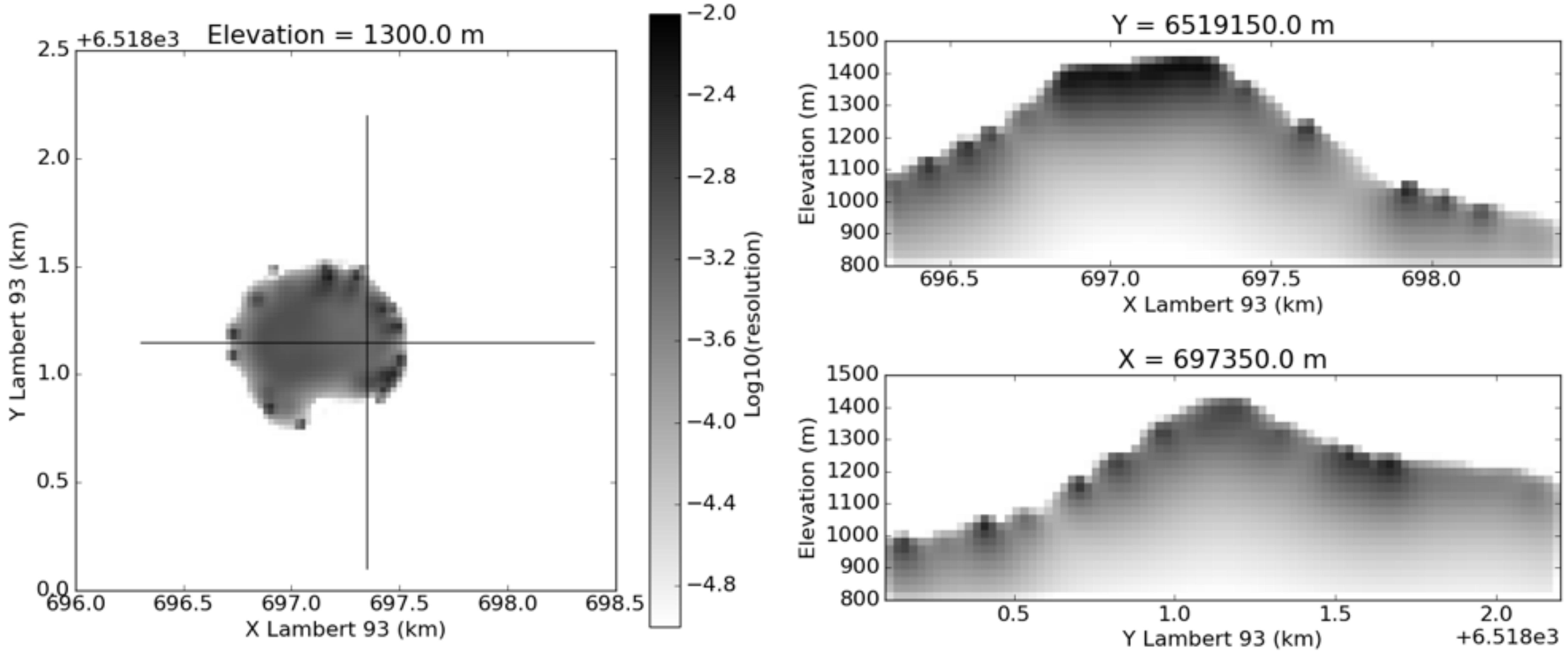
- data error

- a priori density standard deviation
- spatial correlation length

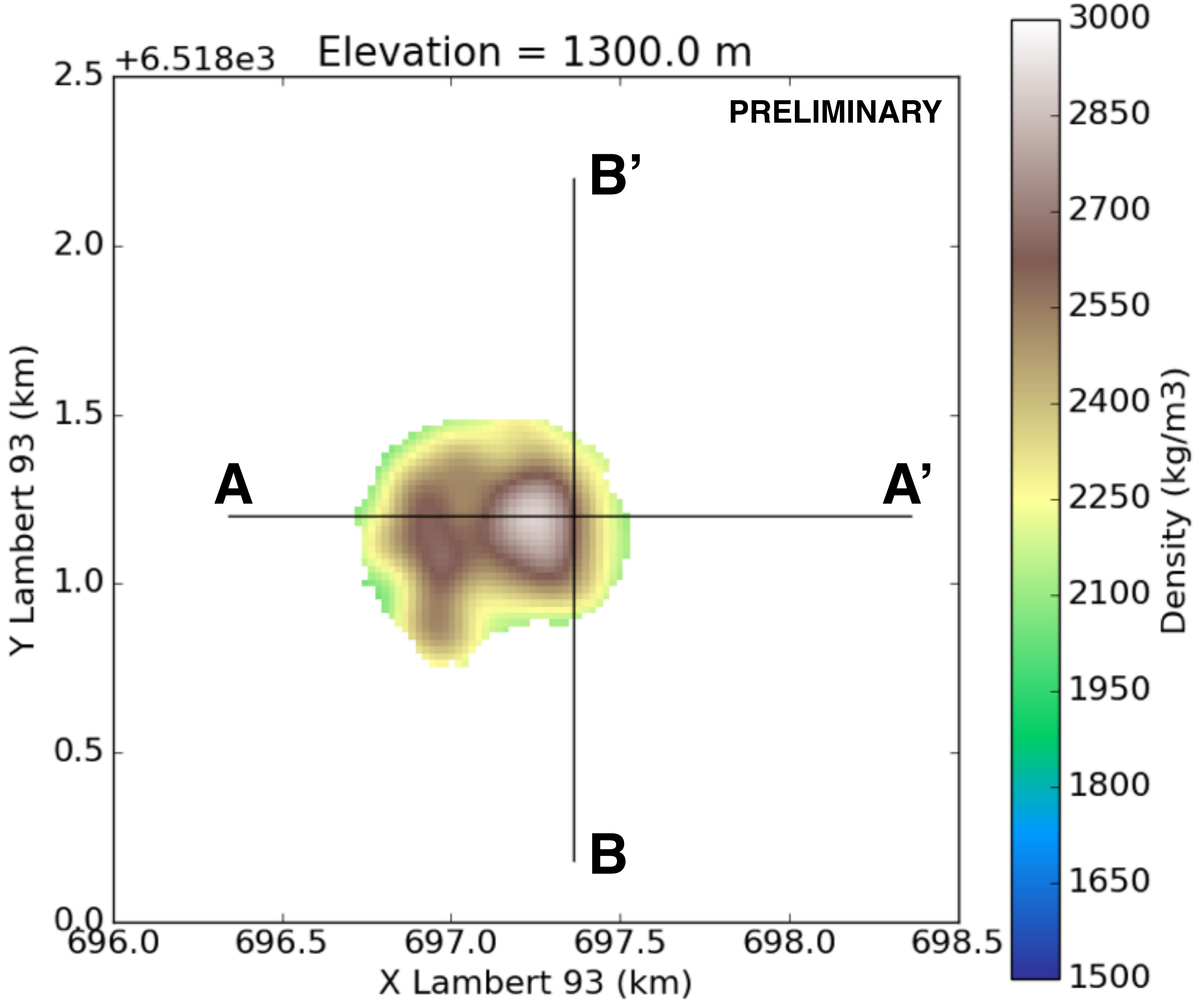
Resolving power of the gravimetric inversion: Cas of the puy de Dôme

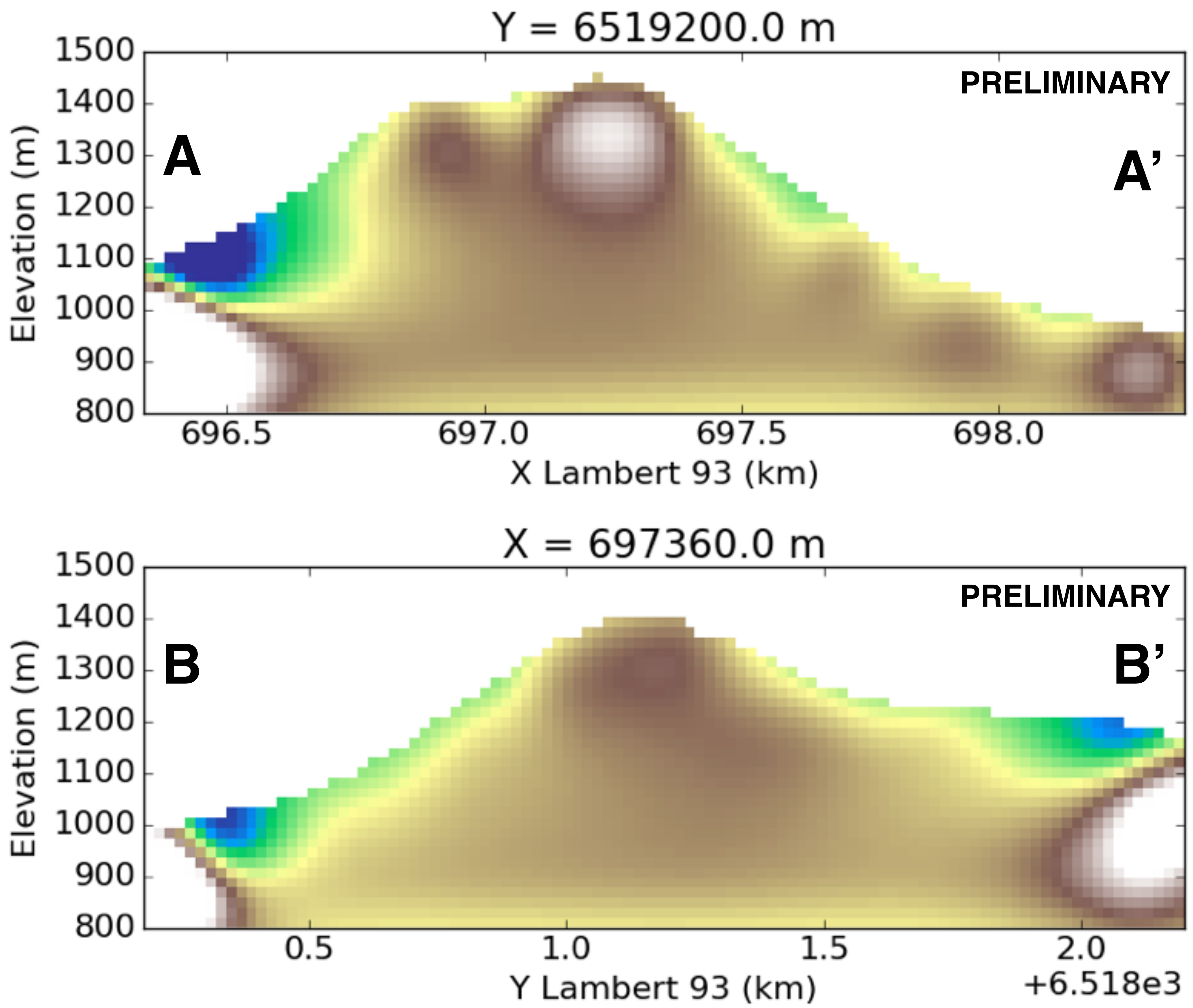


- weak vertical resolution
- good lateral resolution at shallow depth
- lateral resolution length increasing with depth



Result of the inversion of the puy de Dôme gravimetric data





Gravimetric data RMS = 0.70 mGal

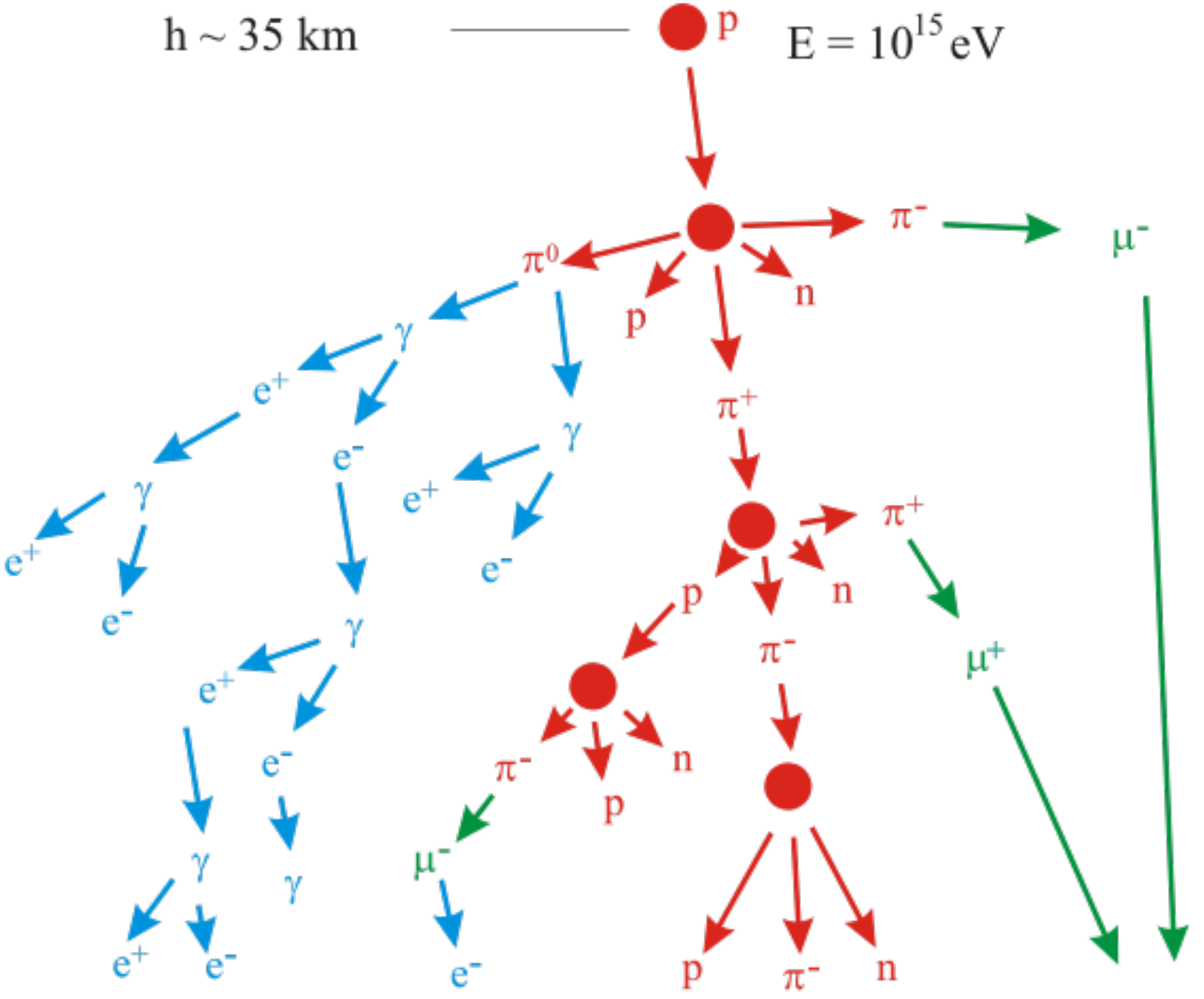
Source: CERN

What is muography?

Idea: radiography with muons
-> 2D images of averaged density

Muons

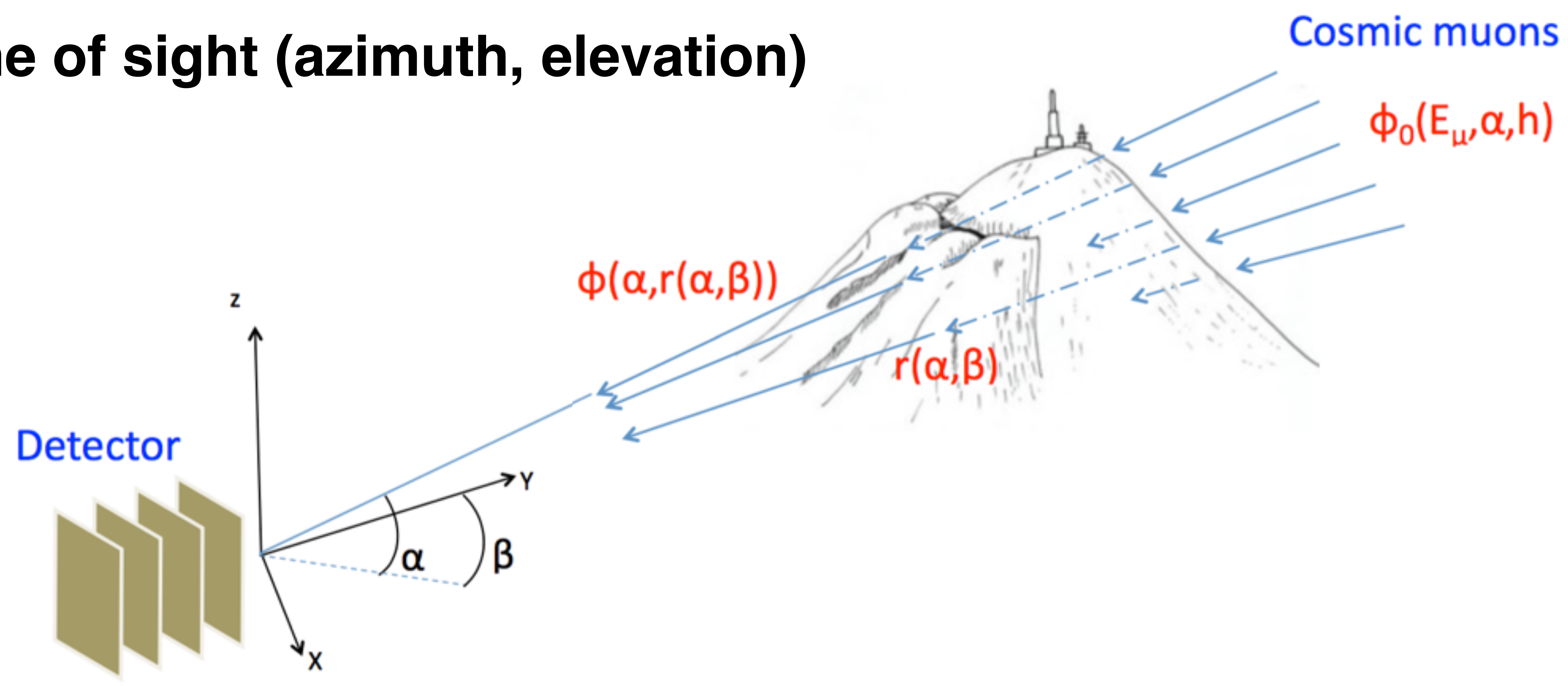
- come from the interaction of **cosmic rays** with the atmosphere (free!)
- similar to electron, 200 times heavier
- large energy spectrum 100 MeV -> PeV
- **interact with matter in a stochastic way** (depending on their energies and medium density)
- at high energy **cross several kms of matter** before decaying



At sea level: ~1 muon/cm²/min
i.e. ~1 muon/s crosses one's hand

Principle of transmission muography

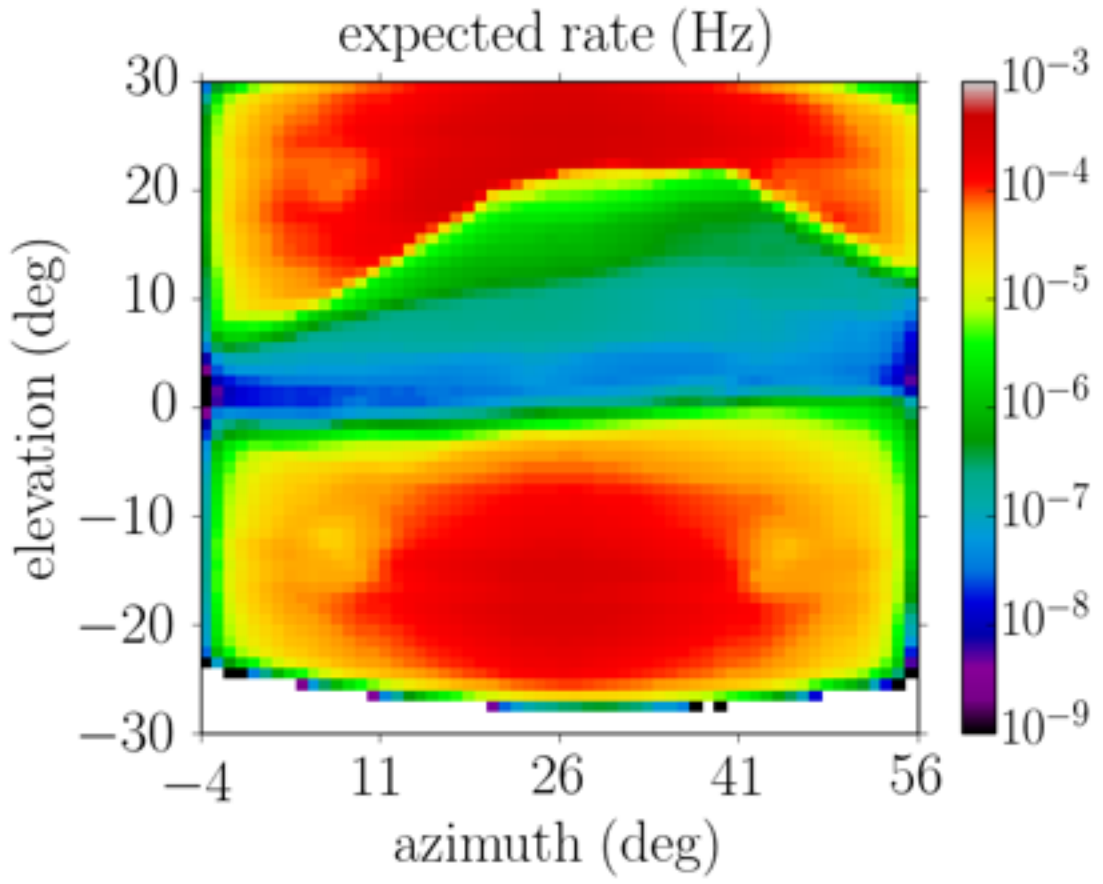
Muon telescope: counts the number of muons along **line of sight (azimuth, elevation)**



- A uniform density is assumed along the line of sight to compute the transmitted flux.

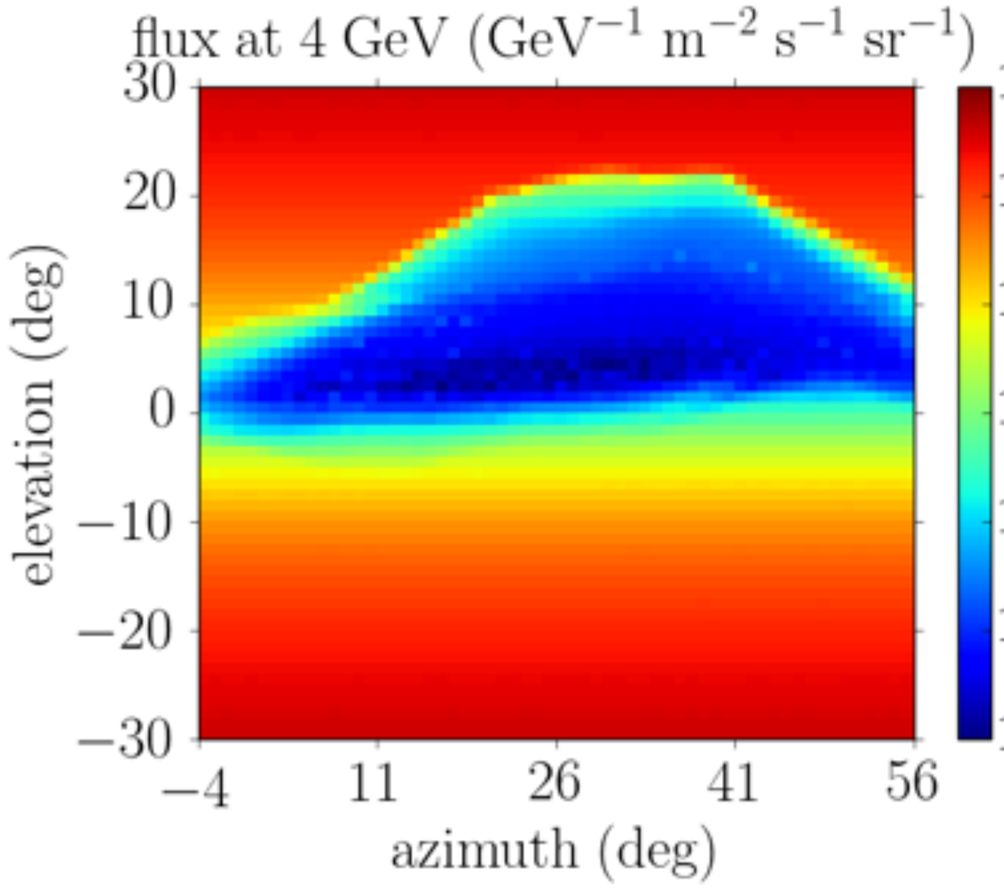
- For each line of sight, the observed rate is matched to the best density hypothesis.

observed rate of muons



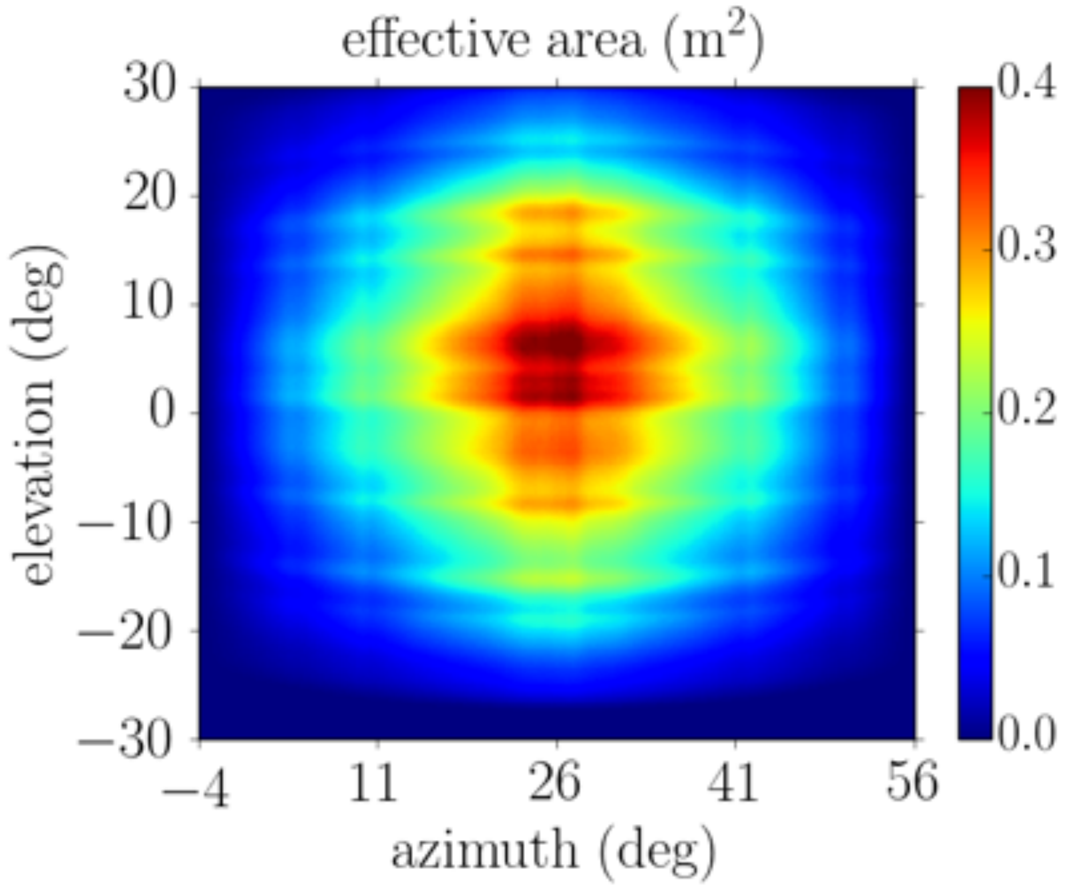
$$= \int$$

transmitted flux



$$\times$$

effective area of the detector



$$\mathrm{d}E$$

What can be imaged with muography?

- **Exposure**: number of days to reach a precision on density of 5% in a 1°x1° solid angle and with a detector of 1 m^2

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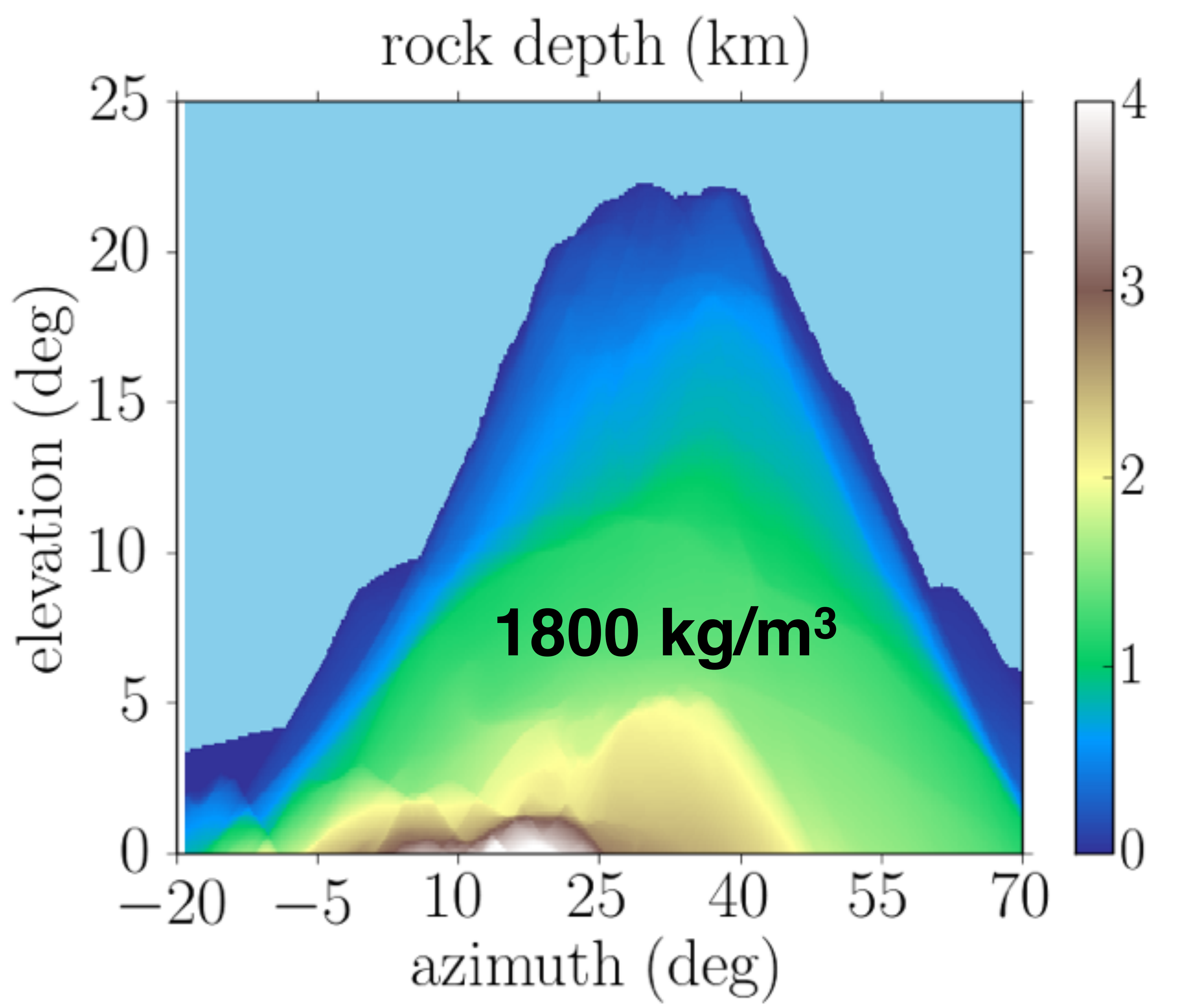
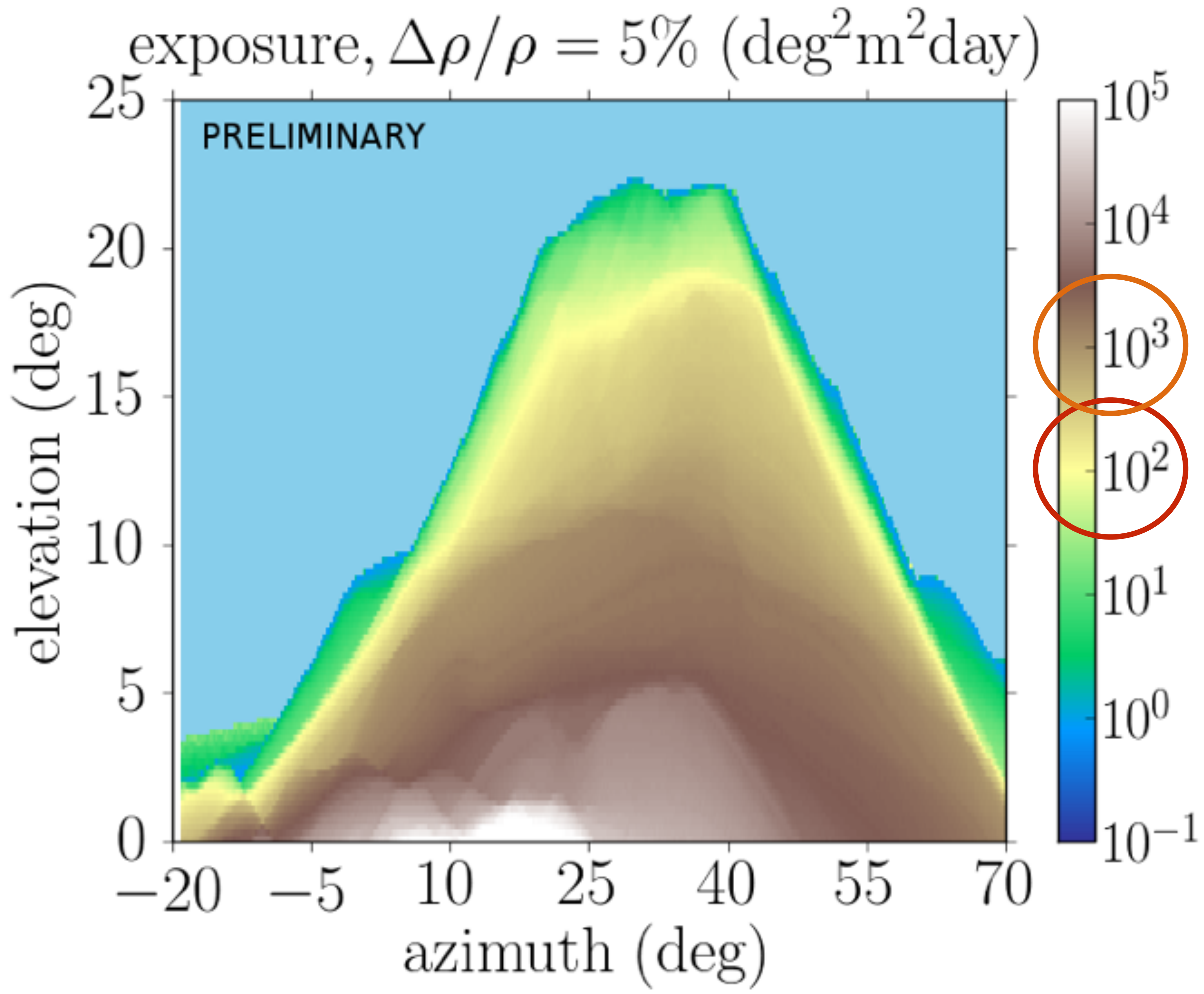


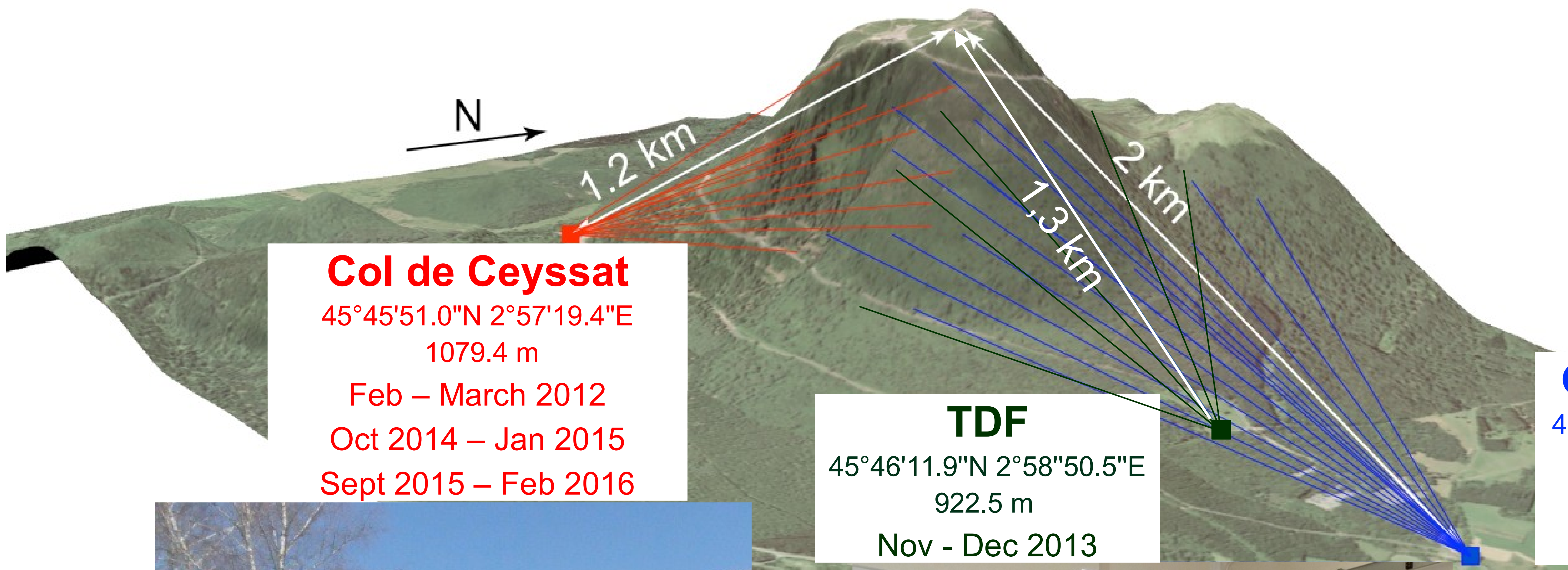


100 days for (5 %, 3°x3°, 1 m²)
100 days for (5 %, 1°x1°, 1 m²)
10 days for (5 %, 1°x1°, 10 m²)

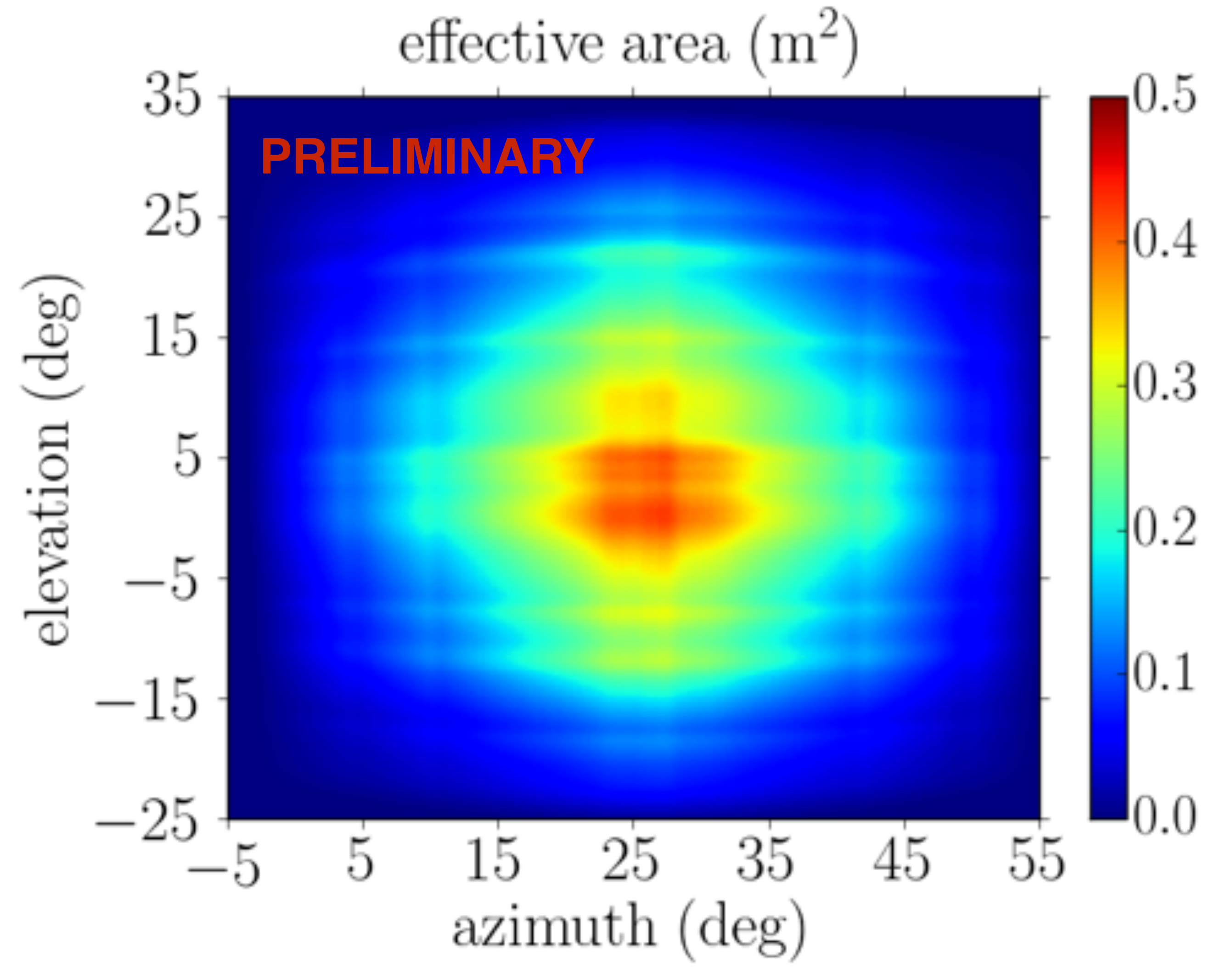
Muography of puy de Dôme volcano - Acquisition and track reconstruction

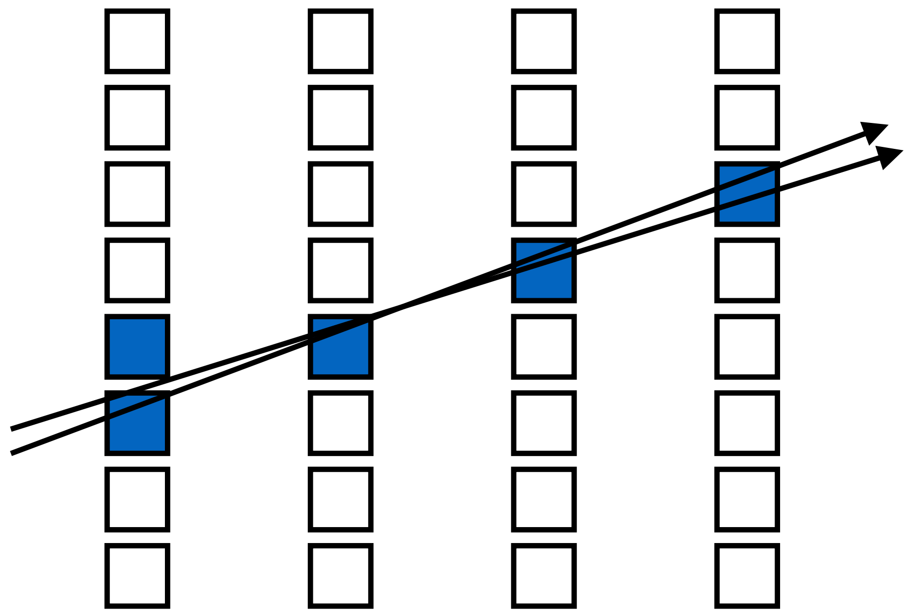
- Col de Ceyssat campaign 2015-2016: equivalent to **100 days of data**

$$S_{eff}=S_{det}\varepsilon_{det}A_{geom}\varepsilon_{illum}$$

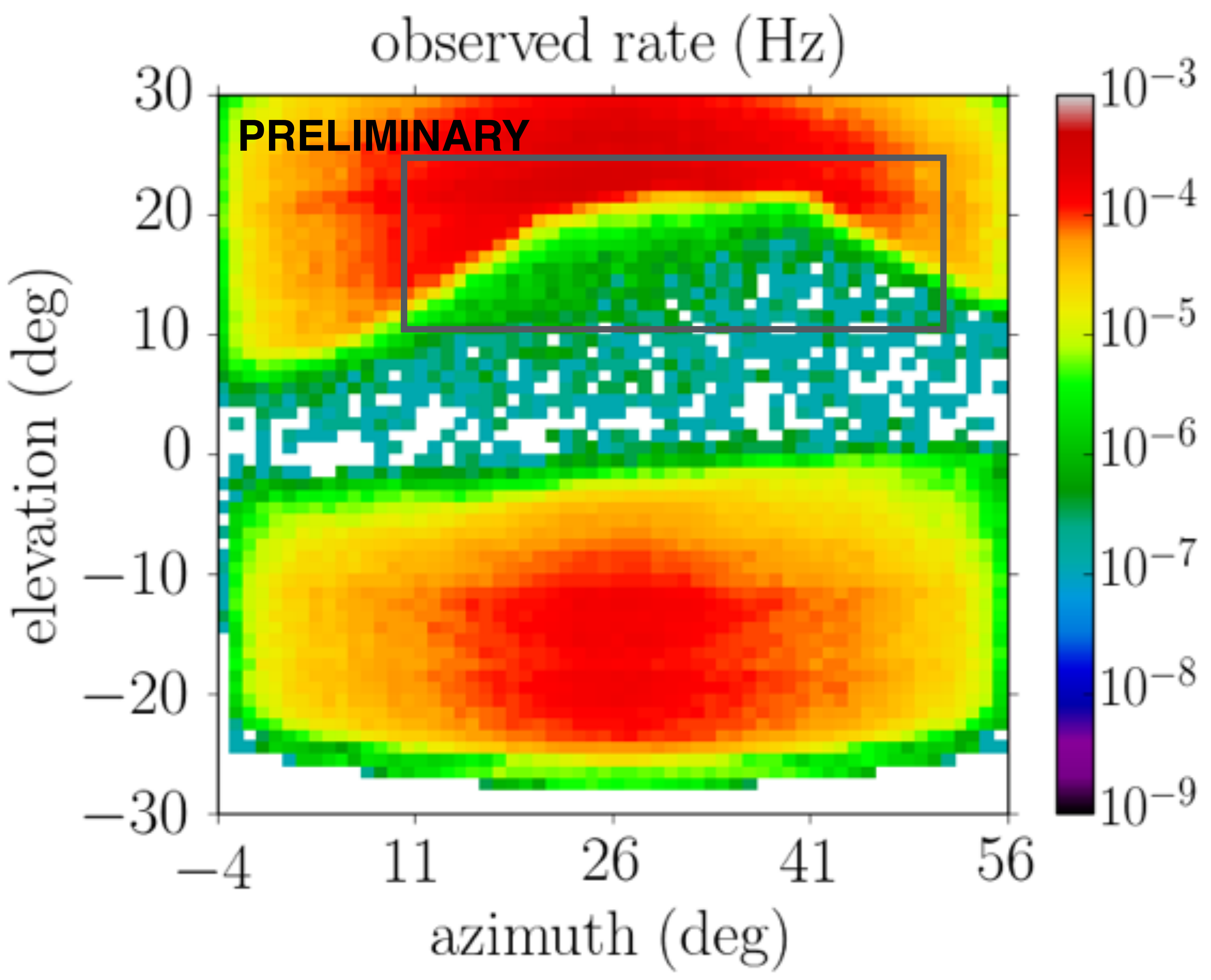


4 layers of gas resistive plate chambers (GRPCs)

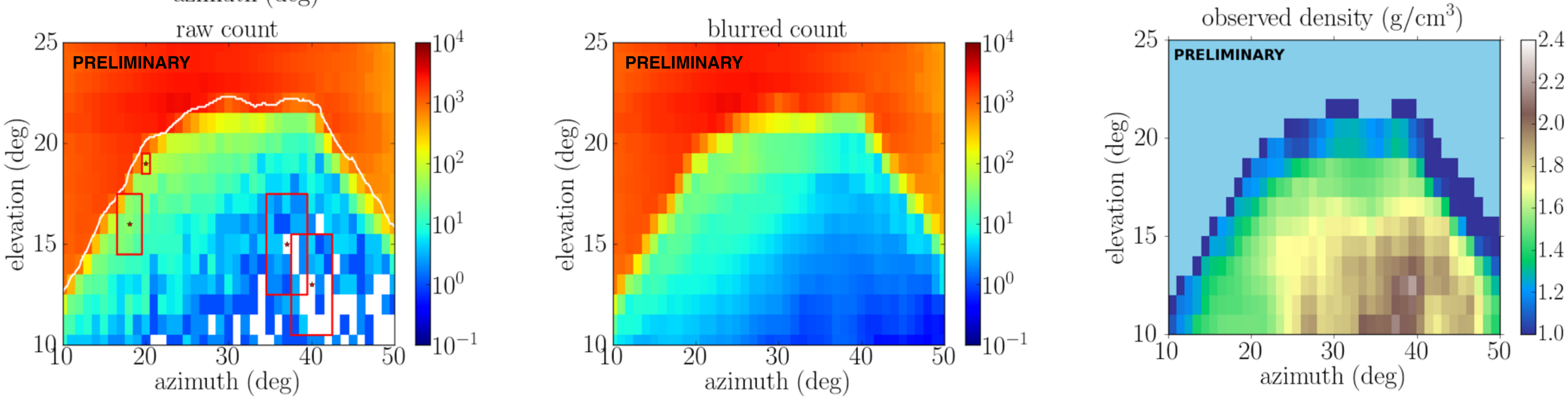




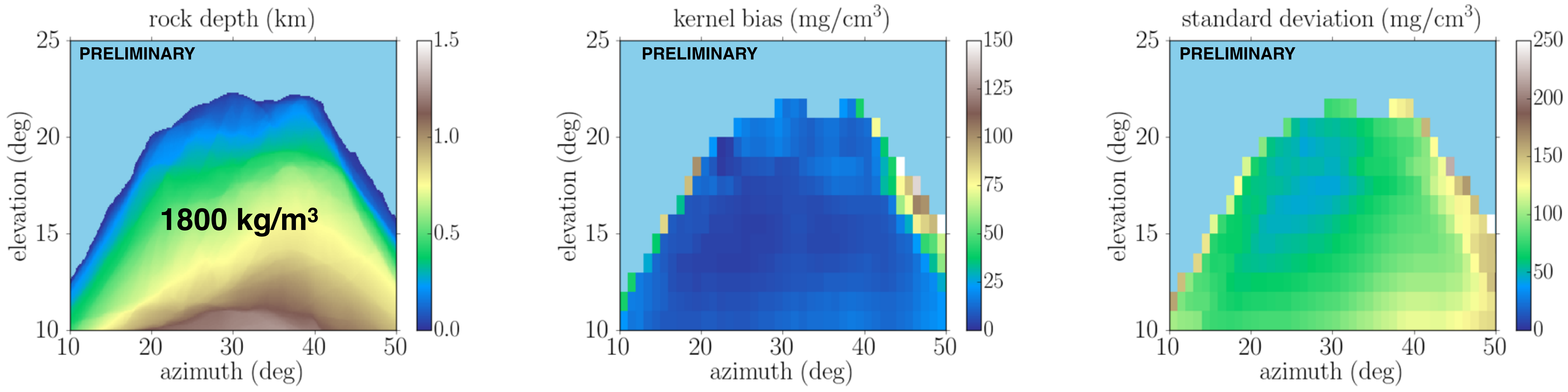
Track reconstruction with measurement uncertainties



- In practice, the rate of transmitted muons is low.
- A **kernel method** (blurring) is used to equalize statistical uncertainties. The angular resolution is degraded at large rock depths where rates are low.
- A bootstrap procedure allows to estimate the resulting **statistical uncertainty** and the **bias**, assuming a uniform density distribution.



Crosscheck for a uniform density model of 1800 kg/m³



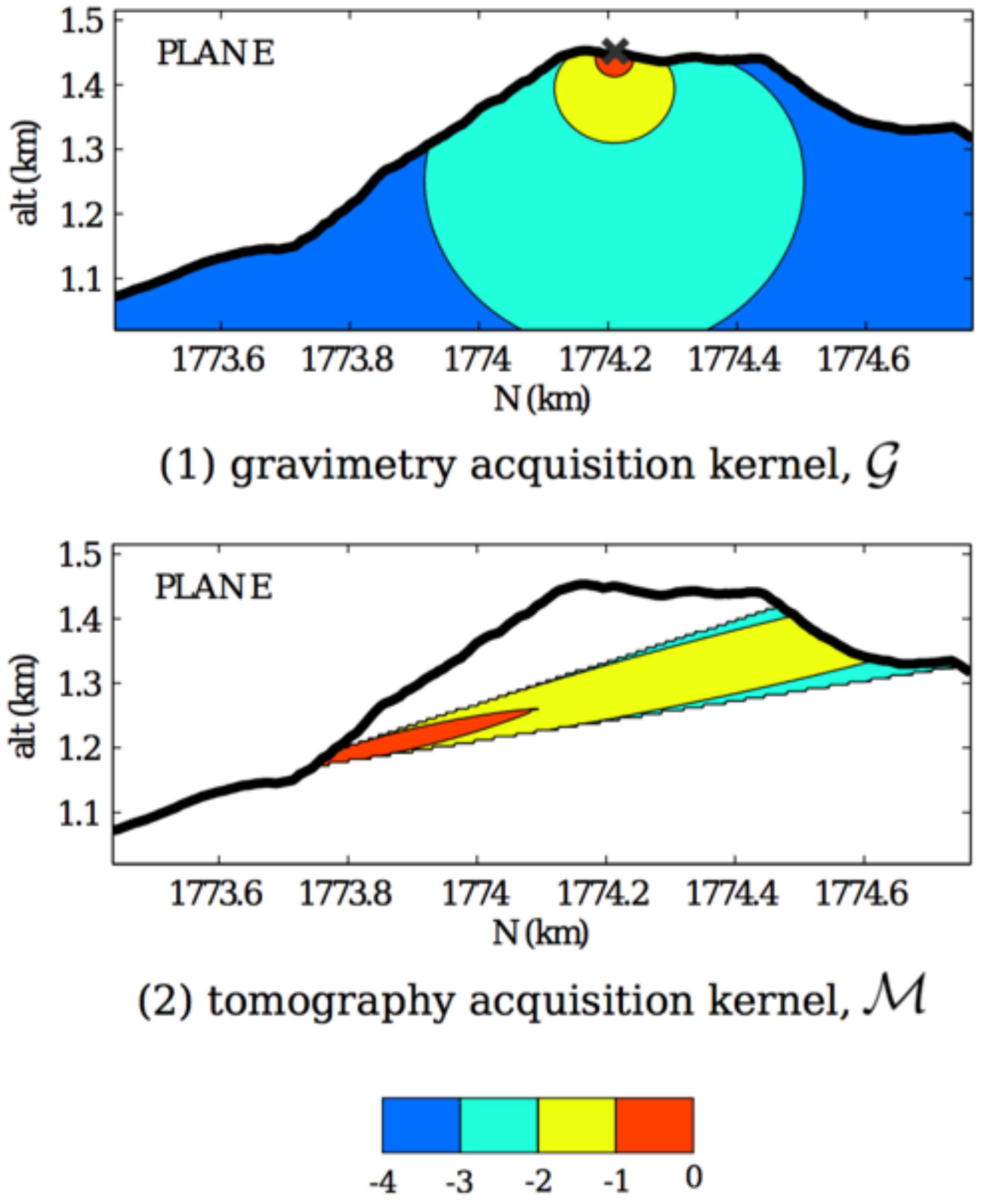
- Few degrees from the border:
  - bias negligible (~10-20 kg/m³)
  - statistical uncertainties below ~100 kg/m³

- Close to the rock border: mixing of transmitted and free sky flux increases bias and uncertainties
- Small rock depths: muon flux weakly sensitive to density

Motivation for the joint inversion of gravimetric and muographic data

- Both methods are sensitive to **density**.
- Muography provides 2D images of density averaged along given directions.
- Gravimetry allows for 3D reconstruction of density variations through inversion.

Jourde *et al.* 2015



Gravimetry

- Advantages: good resolution of shallow structures and lateral variations
- Limitations: rapid decrease of resolution with depth, non unicity of the method

Muography

- Advantages: localized measurement of density along lines of sight, high resolution in space and density
- Limitations: less sensitive close to the surface: smaller attenuation due to smaller rock depths, muon scattering…
- Resolution depending on aperture and time of exposure

Examples: Nishiyama *et al.* 2014, Jourde *et al.* 2015

$$\mathbf{A} \quad \boldsymbol{\rho} = \boldsymbol{d}$$

$$\begin{bmatrix} \mathbf{G} \\ \mathbf{M} \end{bmatrix} \begin{bmatrix} \boldsymbol{\rho} \end{bmatrix} = \begin{bmatrix} \boldsymbol{g} \\ \boldsymbol{\varrho} \end{bmatrix}$$

← gravimetric data

← densities averaged along lines of sight

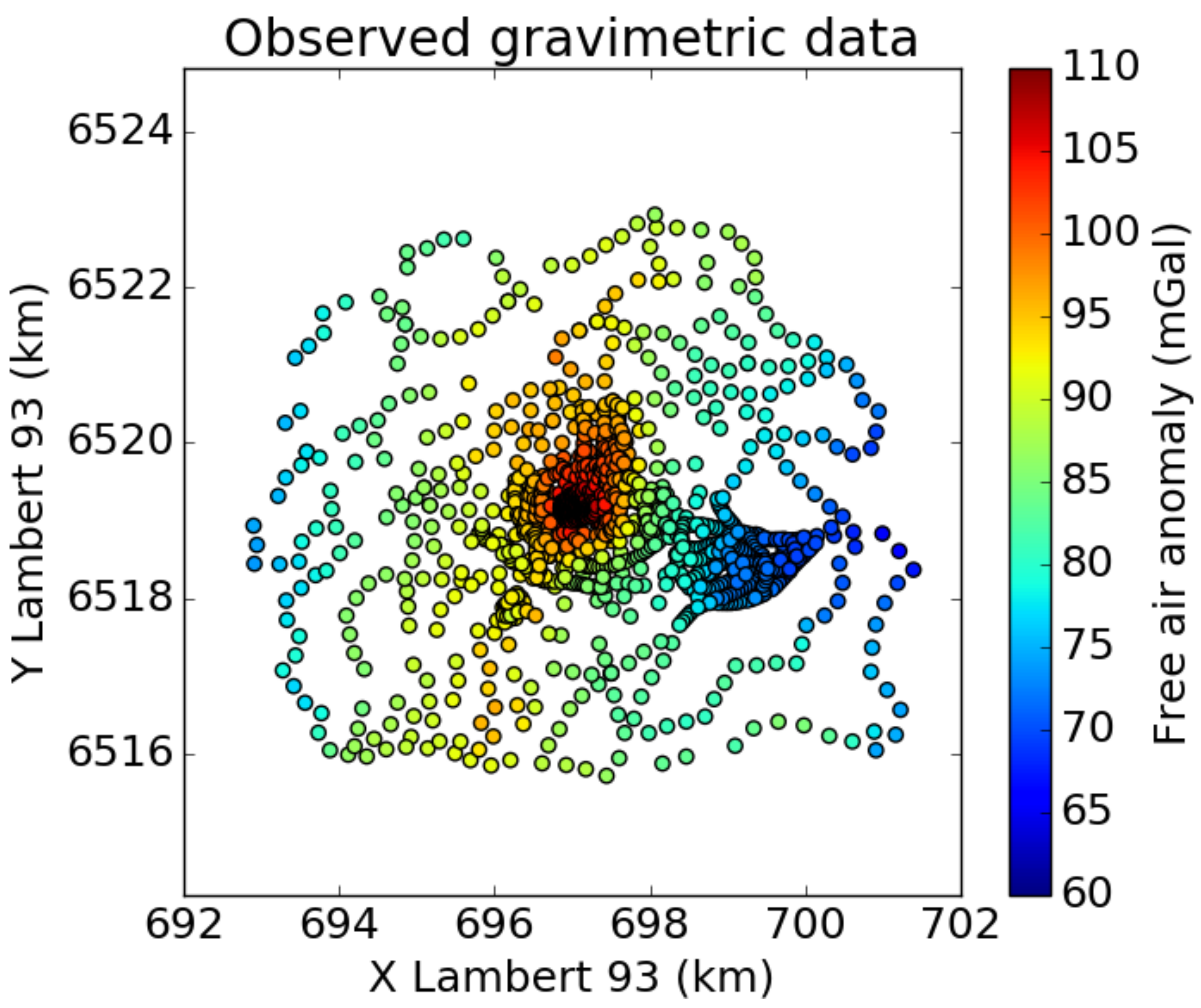
↑ densities at the nodes of the investigated volume

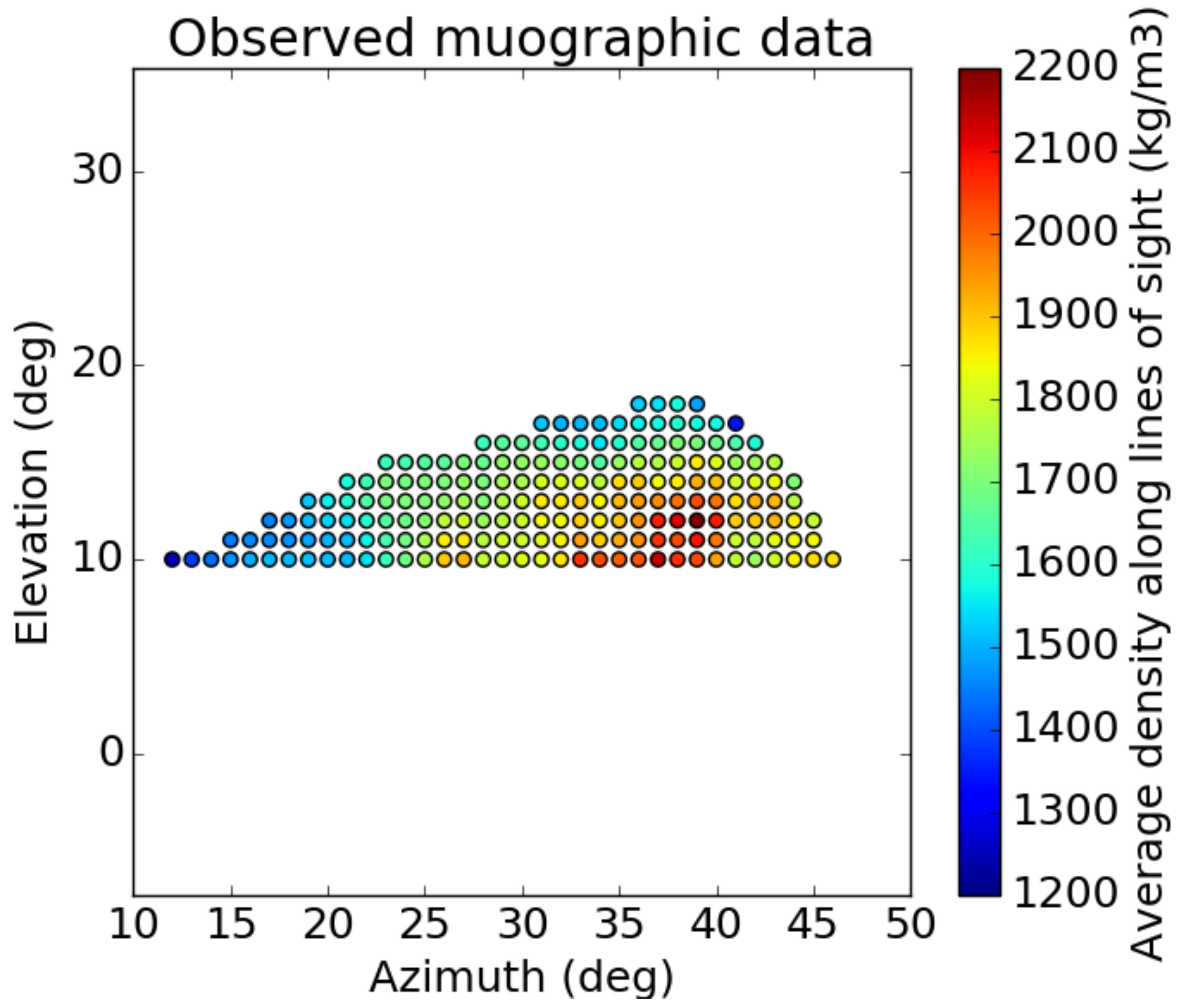
We minimize:

$$\begin{aligned} \phi(\boldsymbol{\rho}) &= ||\boldsymbol{d} - \mathbf{A}\boldsymbol{\rho}||^2_{\mathrm{D}} + ||\boldsymbol{\rho} - \boldsymbol{\rho}_{prior}||^2_{\mathrm{P}} \\ &= (\boldsymbol{d} - \mathbf{A}\boldsymbol{\rho})^t \mathbf{C}_{\mathrm{D}}^{-1} (\boldsymbol{d} - \mathbf{A}\boldsymbol{\rho}) + (\boldsymbol{\rho} - \boldsymbol{\rho}_{prior})^t \mathbf{C}_{\mathrm{P}}^{-1} (\boldsymbol{\rho} - \boldsymbol{\rho}_{prior}) \end{aligned}$$

Joint inversion: Data from the puy de Dôme volcano

- Data for the inversion





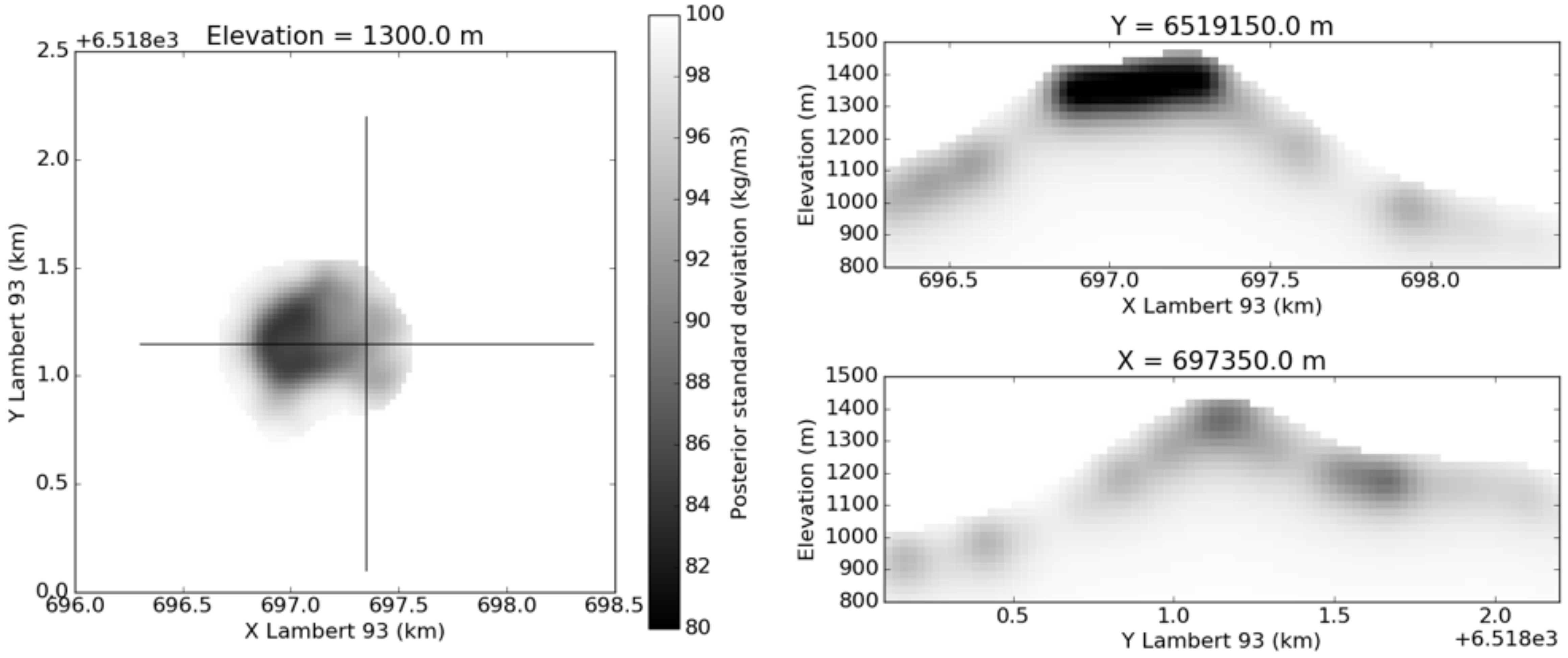
Data from Portal *et al.* 2016

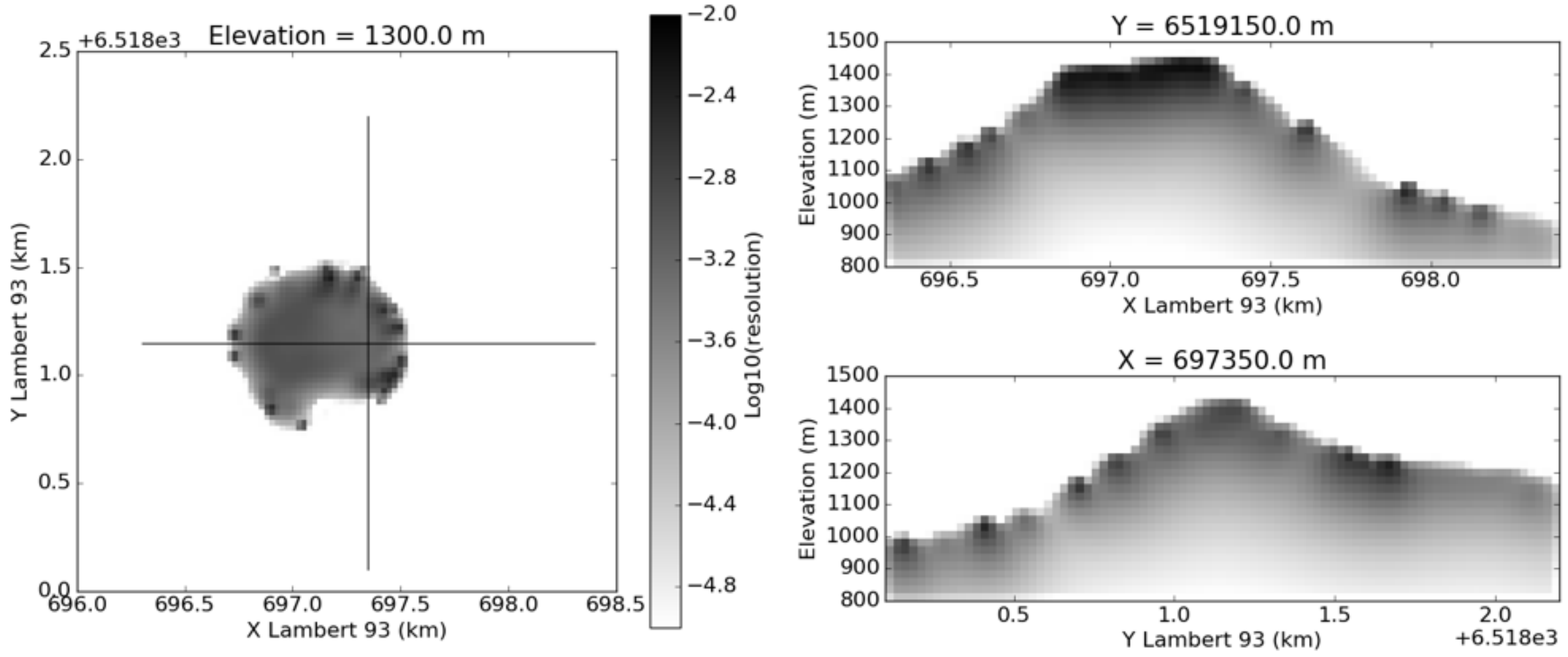
Resolution

Posterior density standard deviation (kg/m³)

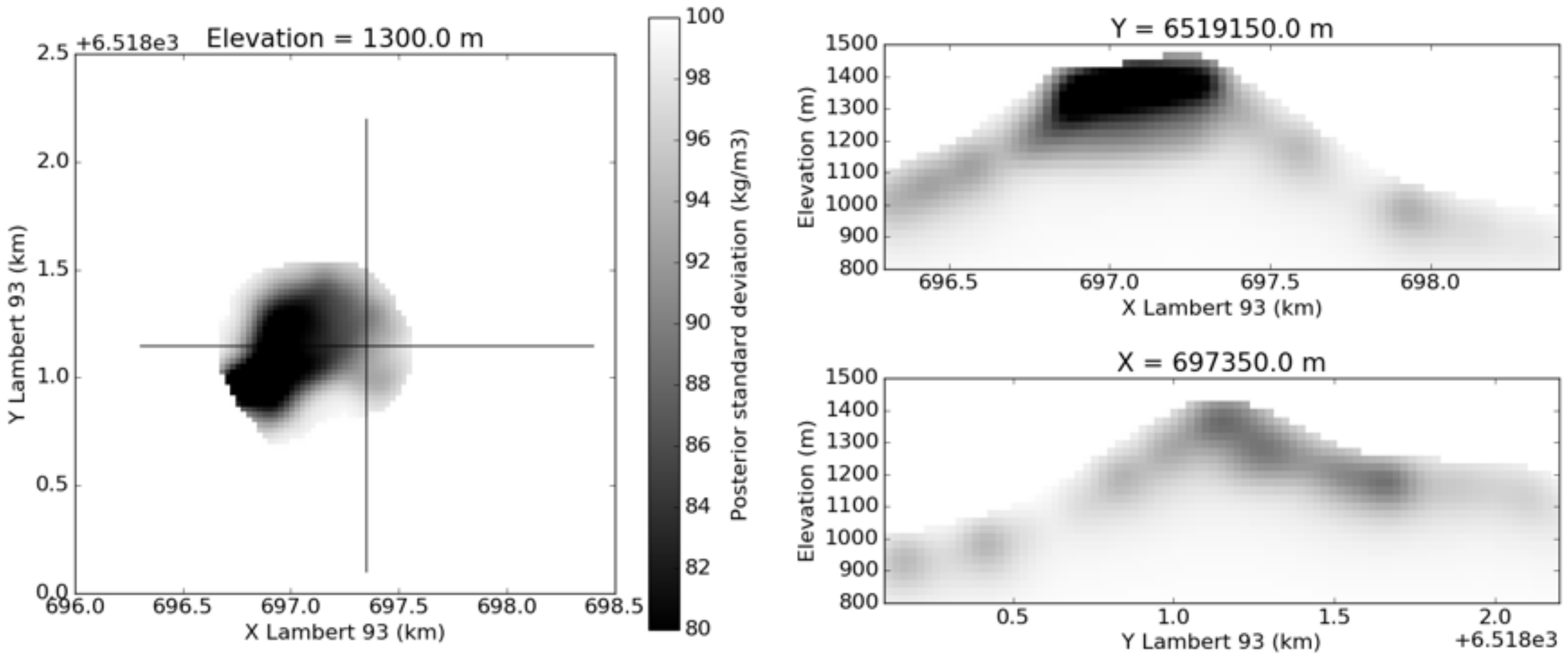
Log Resolution

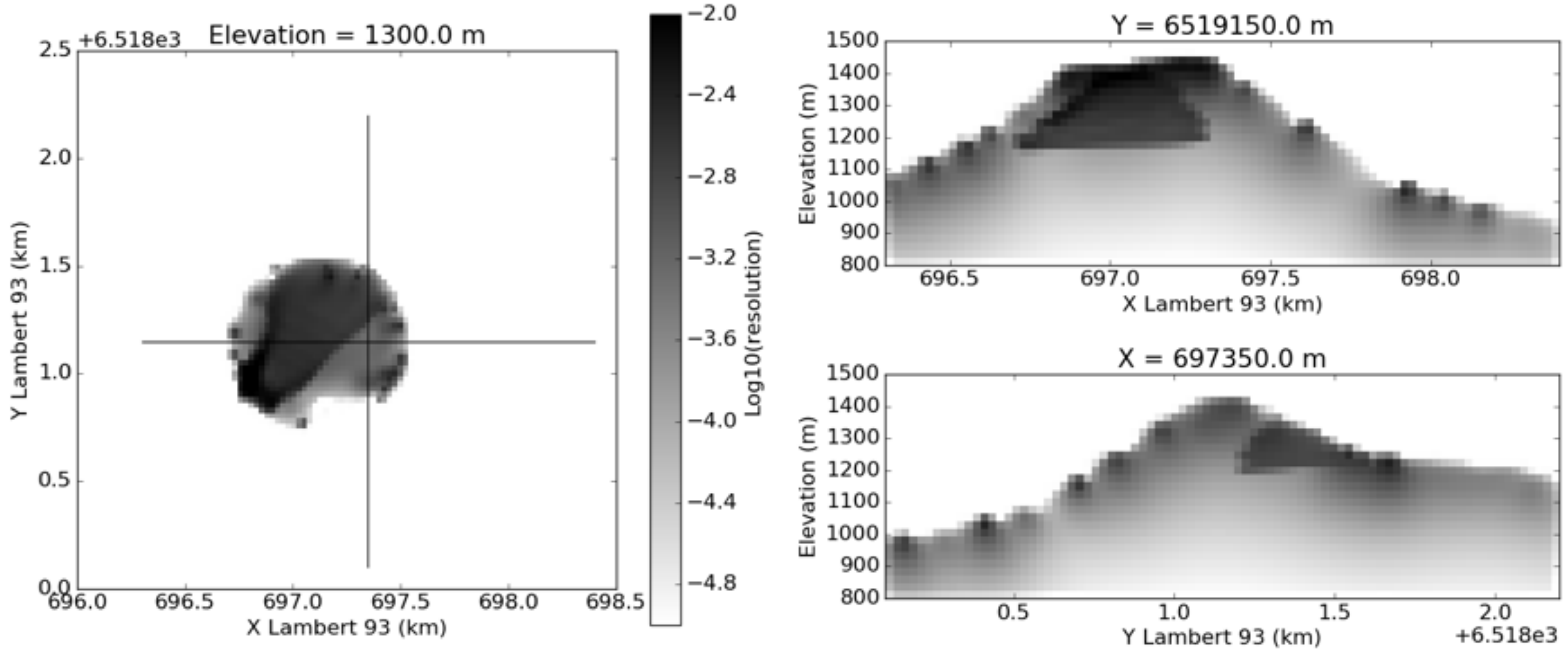
Gravimetry only



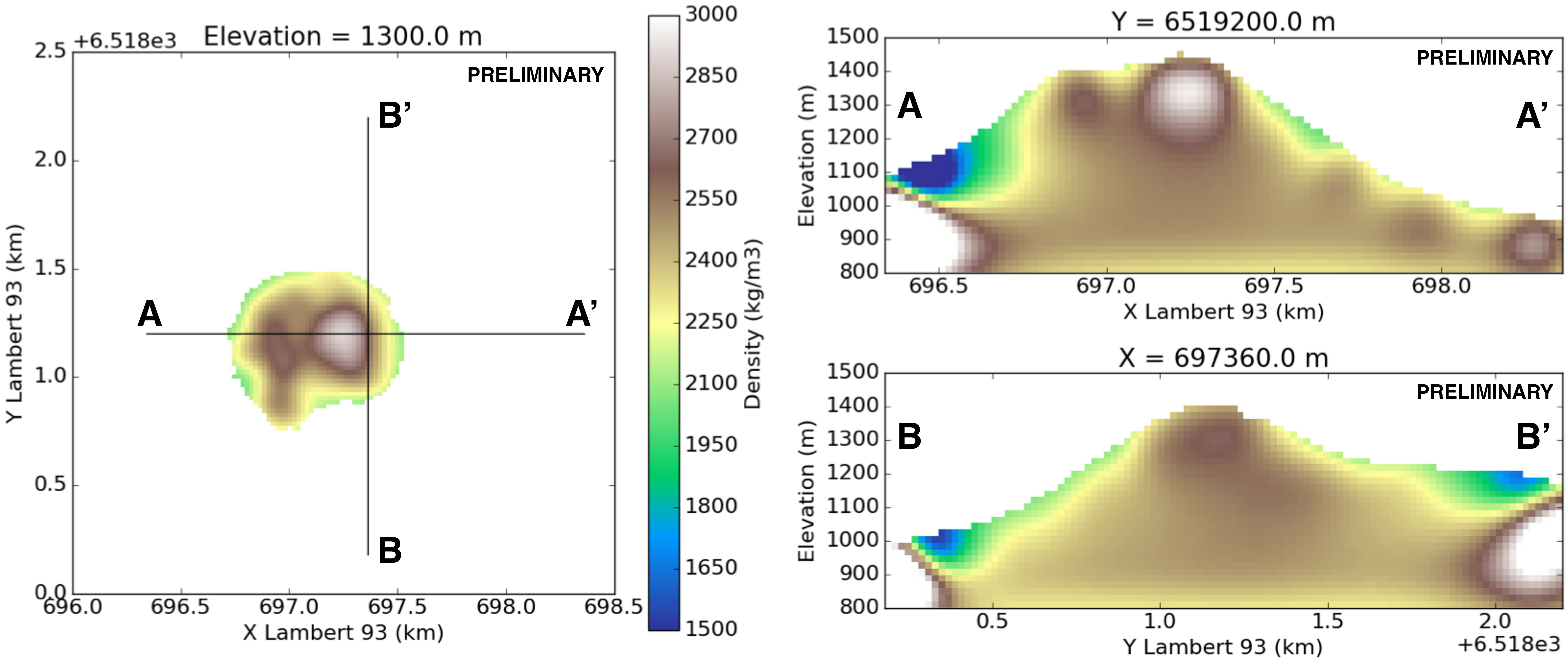


Gravimetry and muography



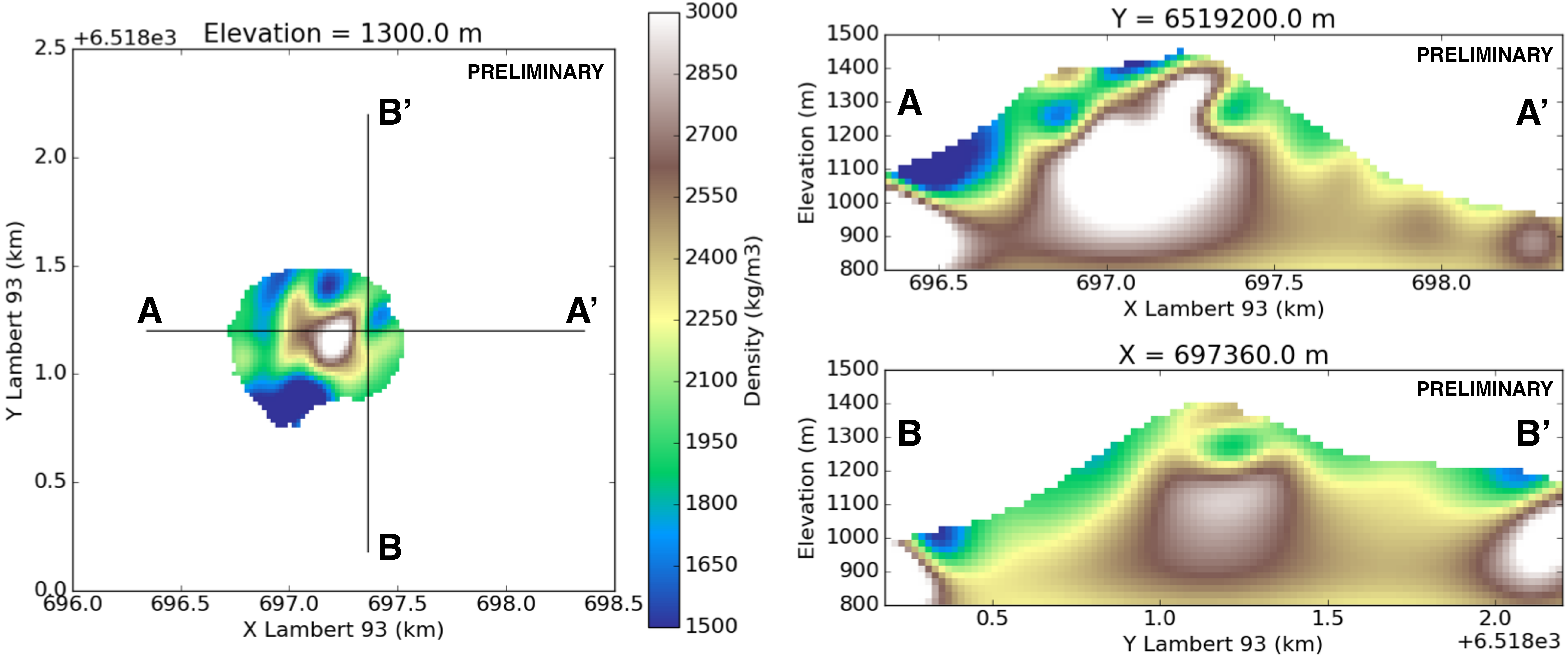


Result of the inversion of gravimetric data only



Gravimetric data RMS = 0.70 mGal

Result of the joint inversion of gravimetric and muographic data



Gravimetric data RMS = 0.70 mGal - Muographic data RMS = 40 kg/m3

Conclusion

- promising preliminary results for the muography and the combined inversion
- joint inversion improves resolution compared to gravimetric only inversion, equally fitting the data

- ongoing improvements
  - muography: muon scattering taken into account, refined description of instrumental response, background…
  - inversion: synthetic tests, systematic estimation of regularization parameters
  - muon tomography with several view points

- density imaging of active volcanoes (Vesuvius and Stromboli)

Thank you for your attention!
Questions?