Muon tomography applied to the Apollonia Tumulus (Preliminary results)

Radiographie par particules cosmiques du tumulus d'Apollonia

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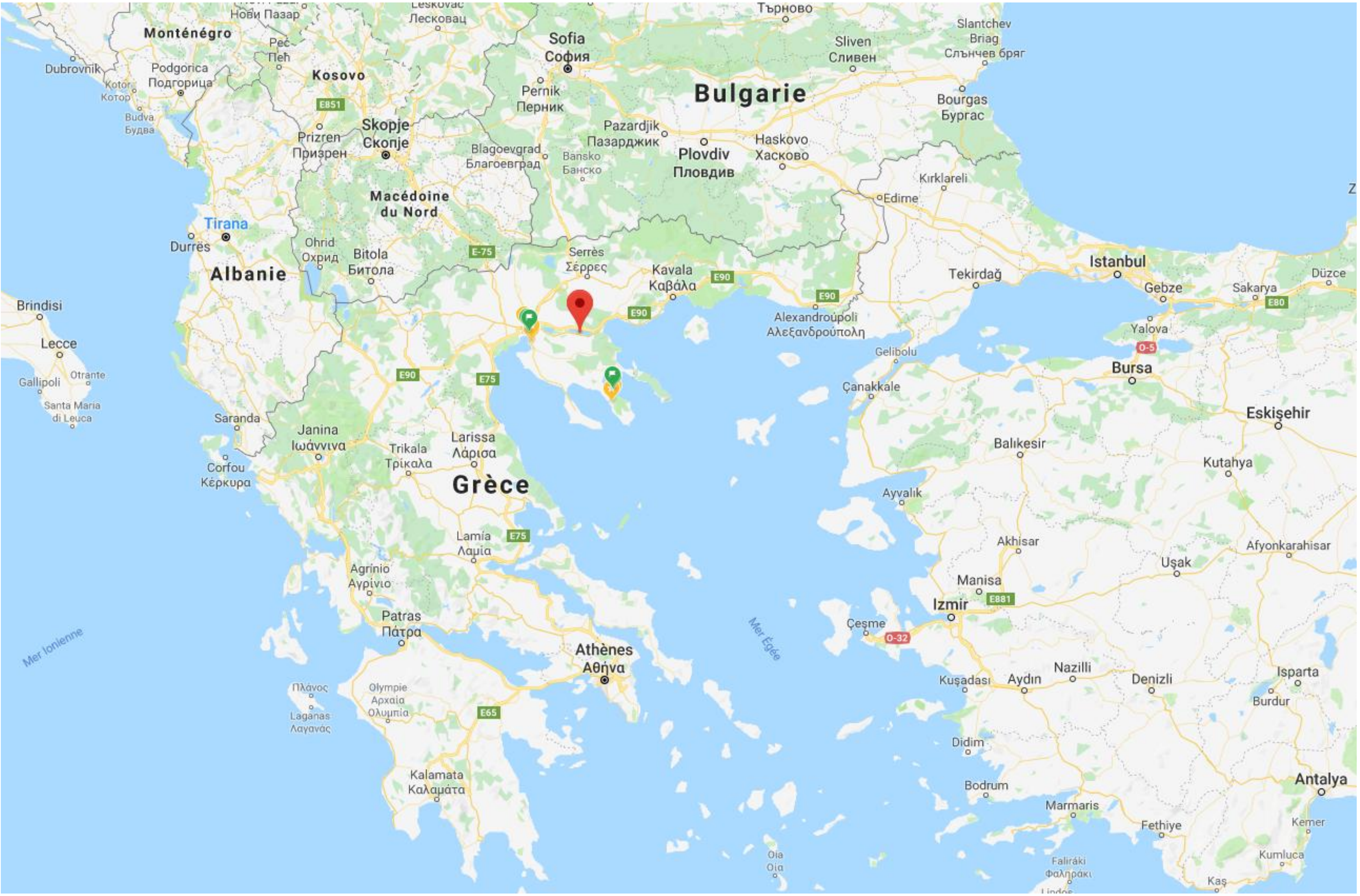
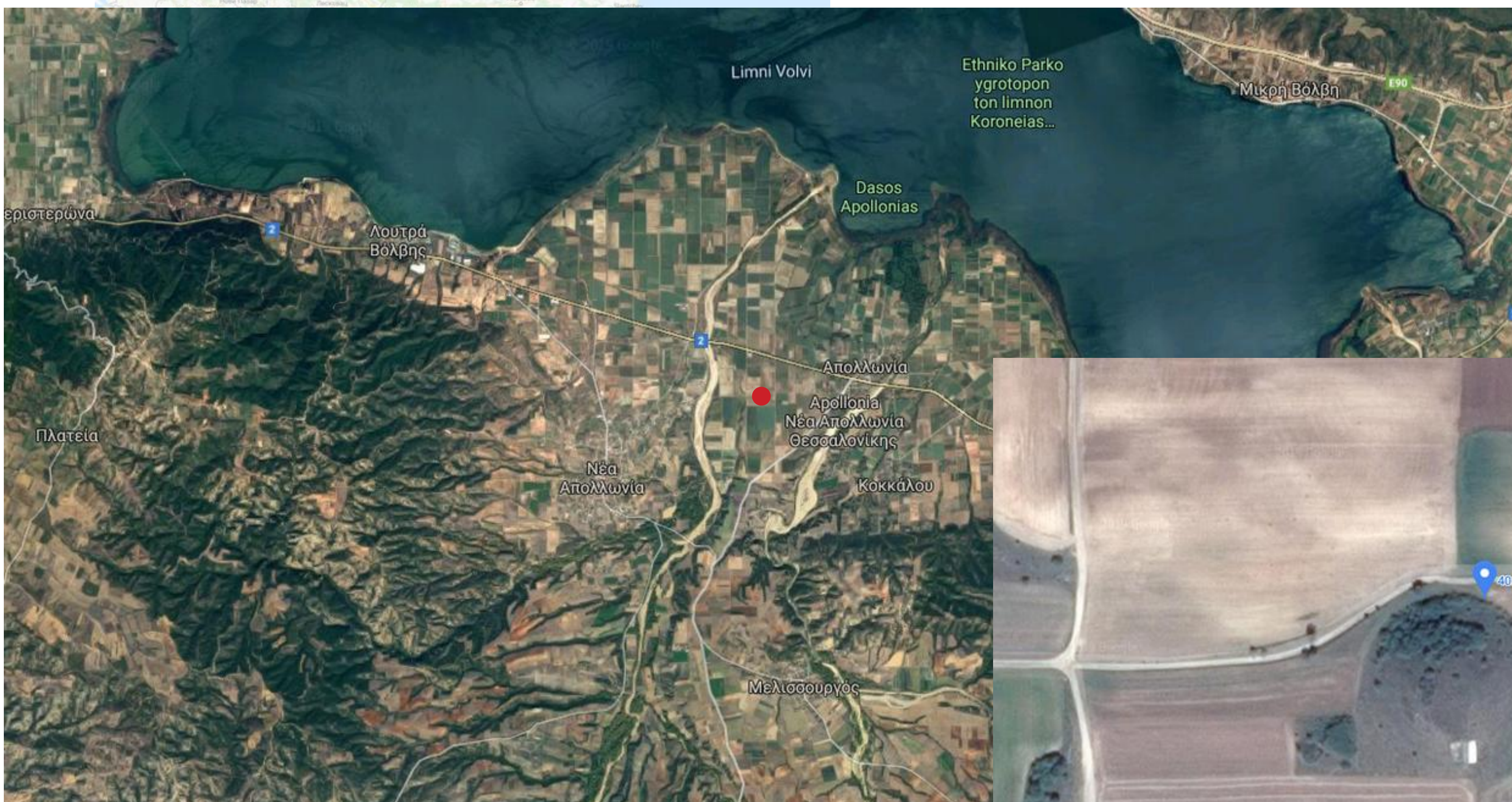
Context of study

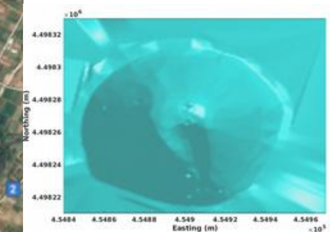
Geography
Historical context
Measurements

South Macedonia / North from Chalkidiki peninsula



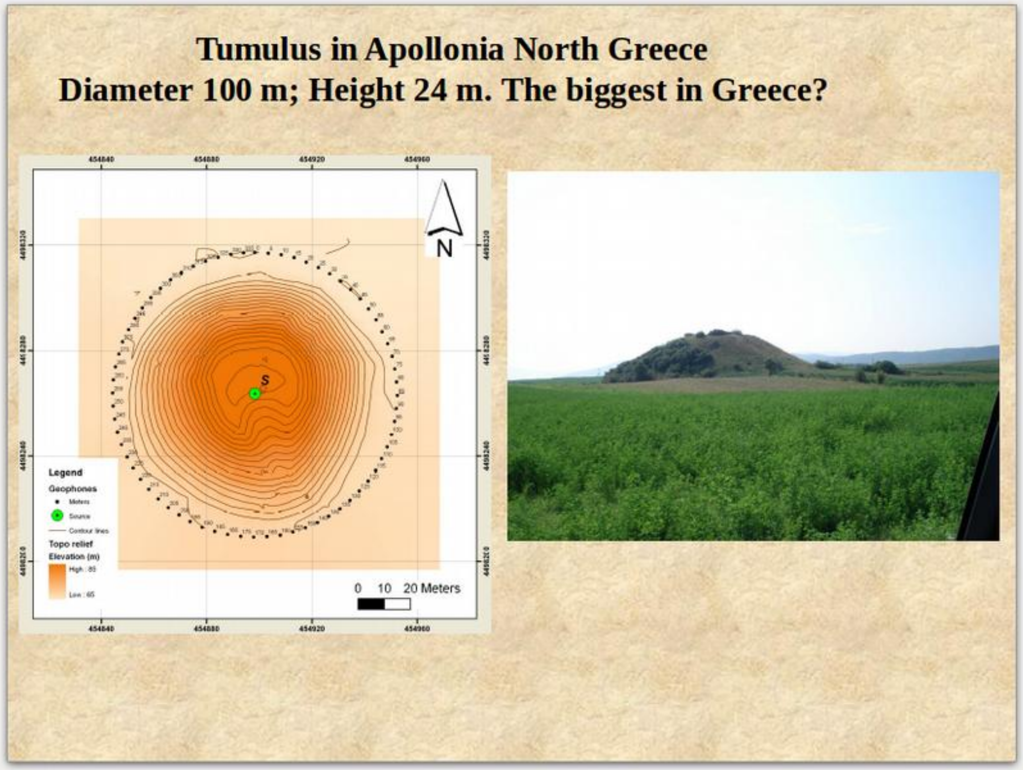
Between Apollonia & Nea Apollonia

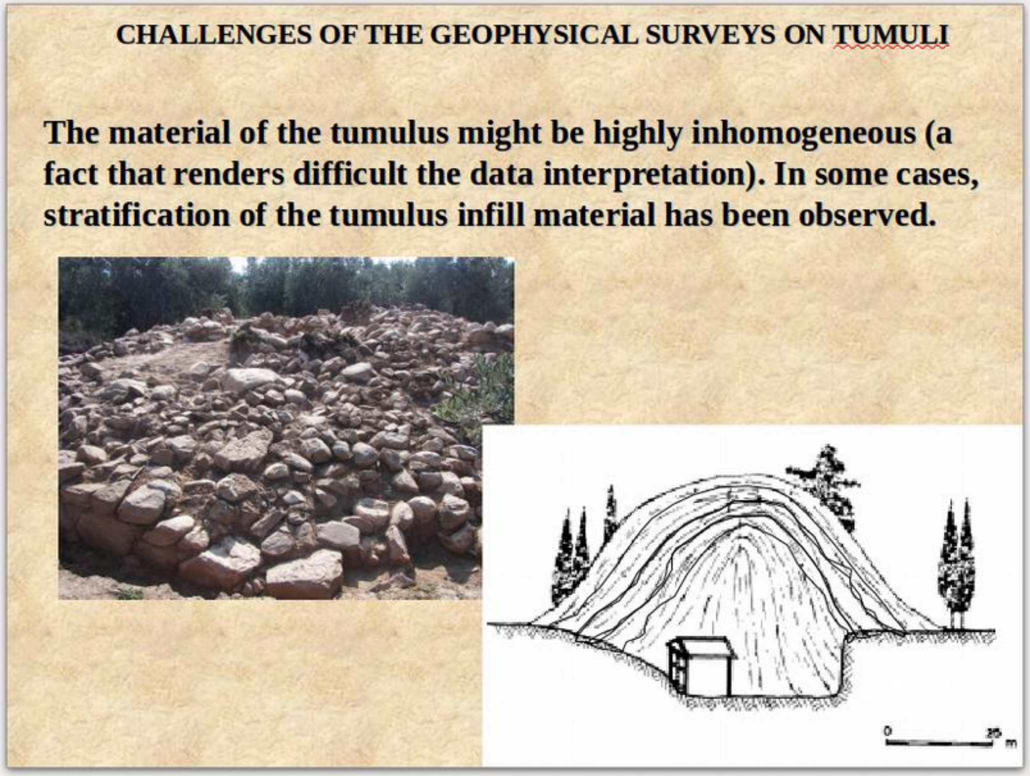




Tumulus & muon-mobile

A massive “Macedonian-type” tumulus





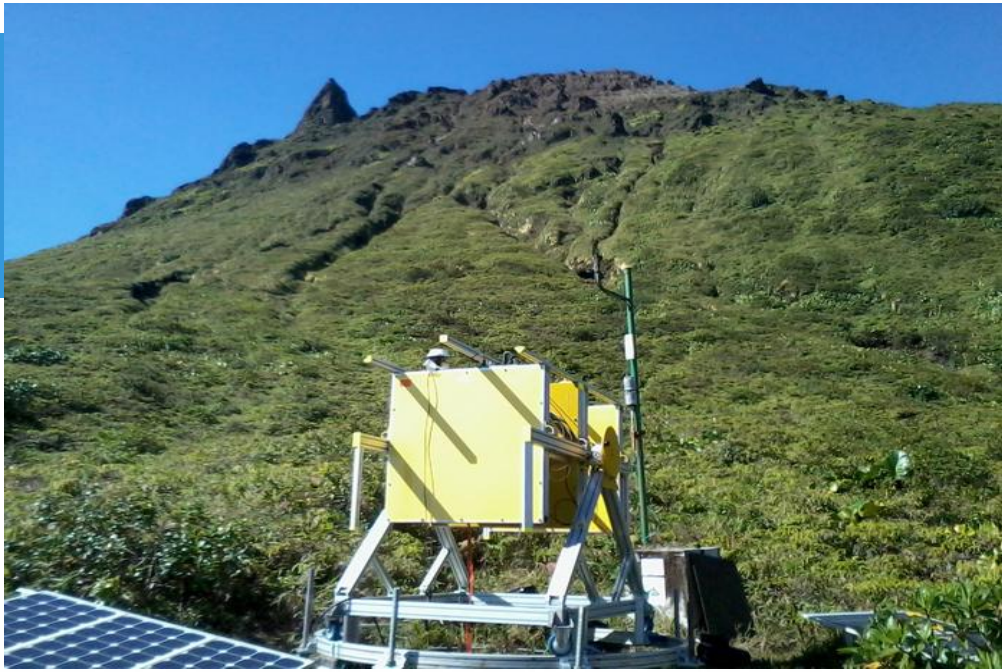
G. Tsokas et al. (2015)

- **What kind of information can the Muon tomography provide to non-destructive tumulus survey ?**

Muon Tomography applied to tumulus targets

Muons: a secondary product of cosmic particles
Muon Telescope, physical principles, zenithal dependency
Limits of Muon tomography applied to archaeological survey (tumulus example)

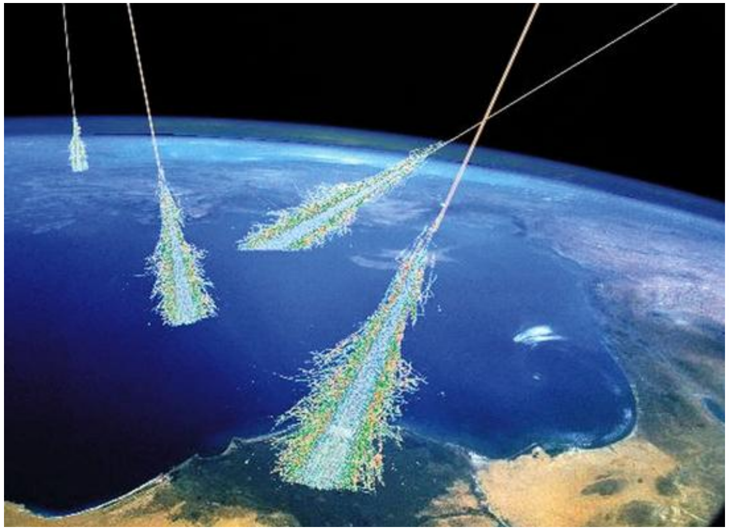
Muography imaging

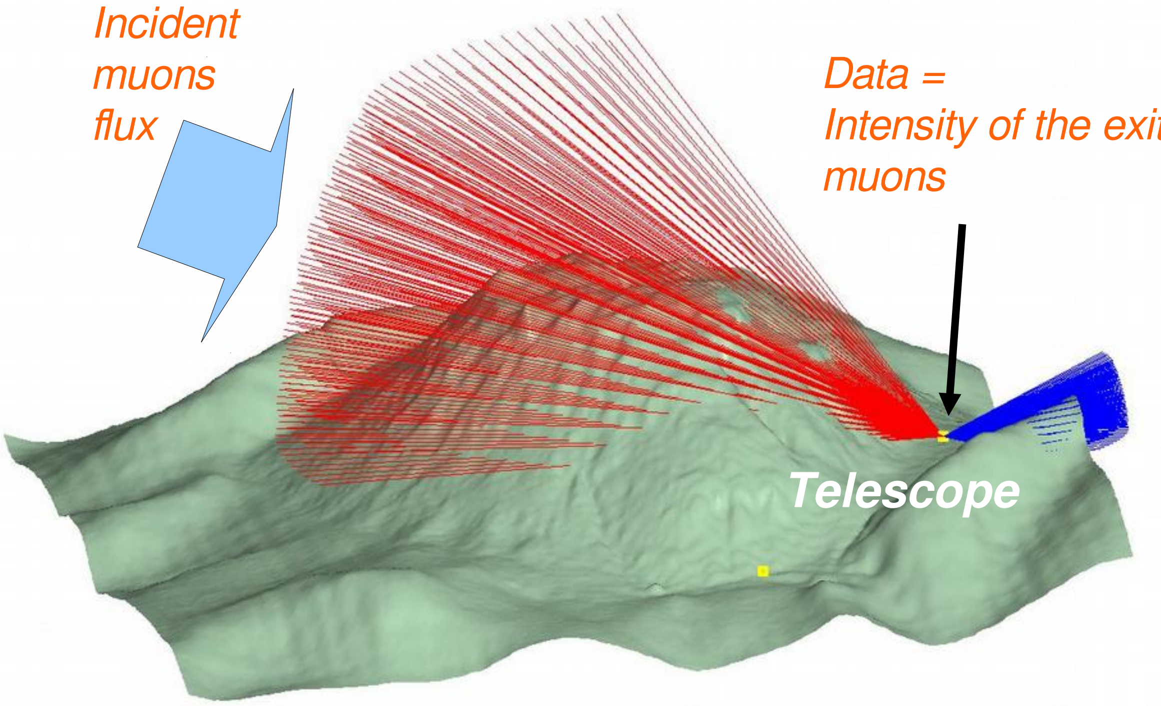


Basic principles

The particles energy loss along their trajectories is controlled by the amount of material encountered

⇒ " clinical radiography " by density contrast



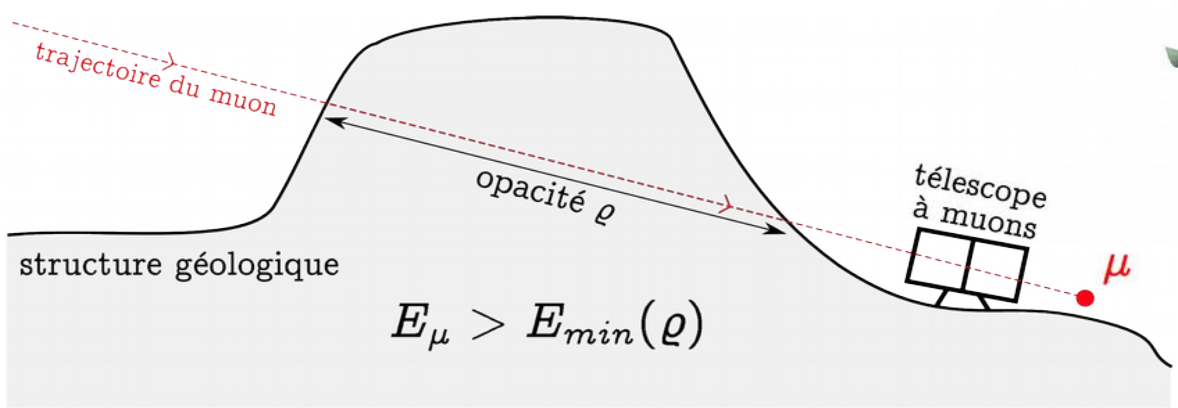


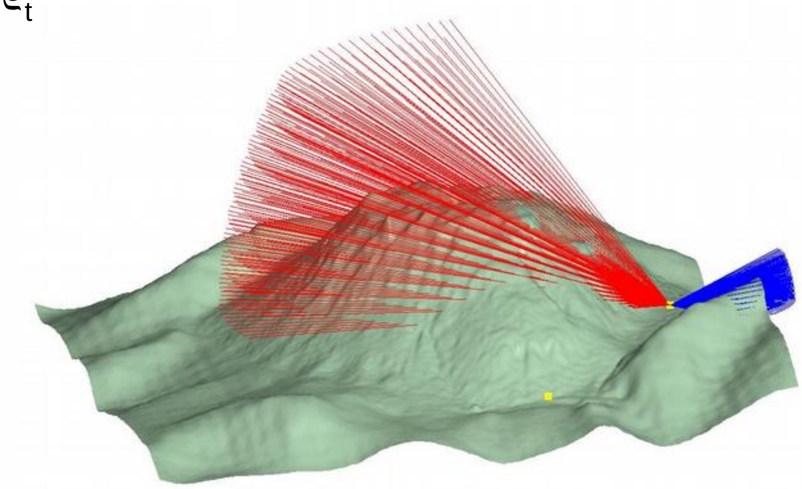
Muons are the particles of geophysical interest because they can cross several kilometers of rocks

Physical principles

In practice, 2D muography is sensible to the **opacity** ϱ_t

$$\varrho_\mathbf{t} = \int_\mathbf{t} \rho(\xi) \times \mathrm{d}\xi = L \times \bar{\rho}$$

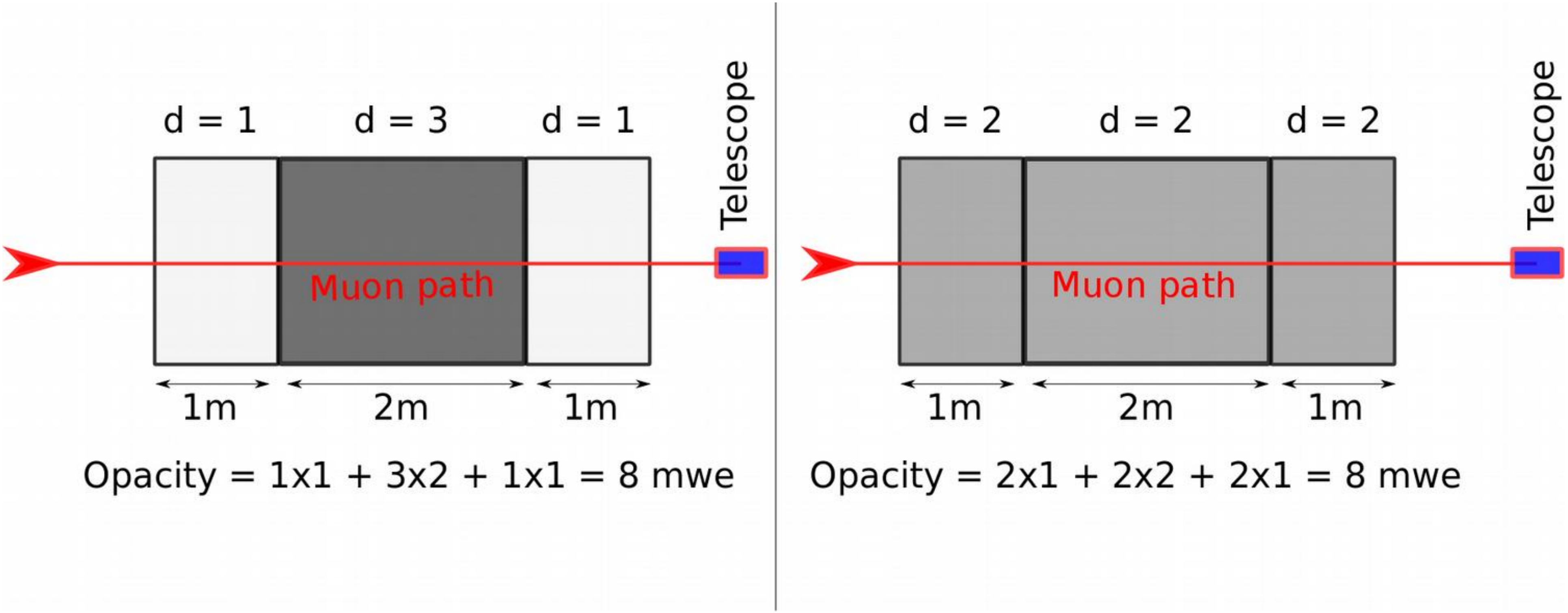




George (1955), Alvarez et al. (1970), Nagamine et al. (1995)

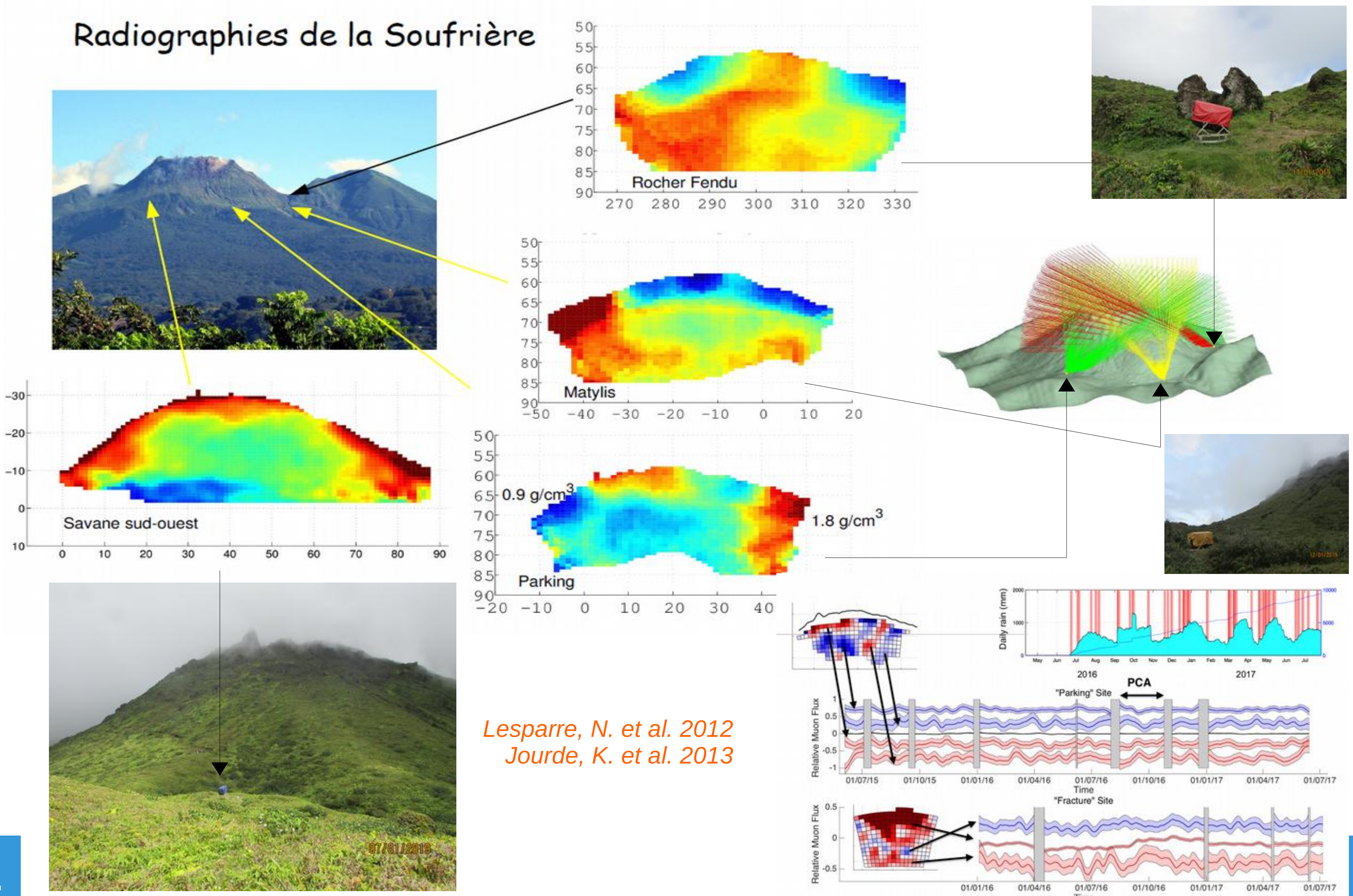
=> strong **equivalences** exist in 2-D muography

Equivalences example (1st order)



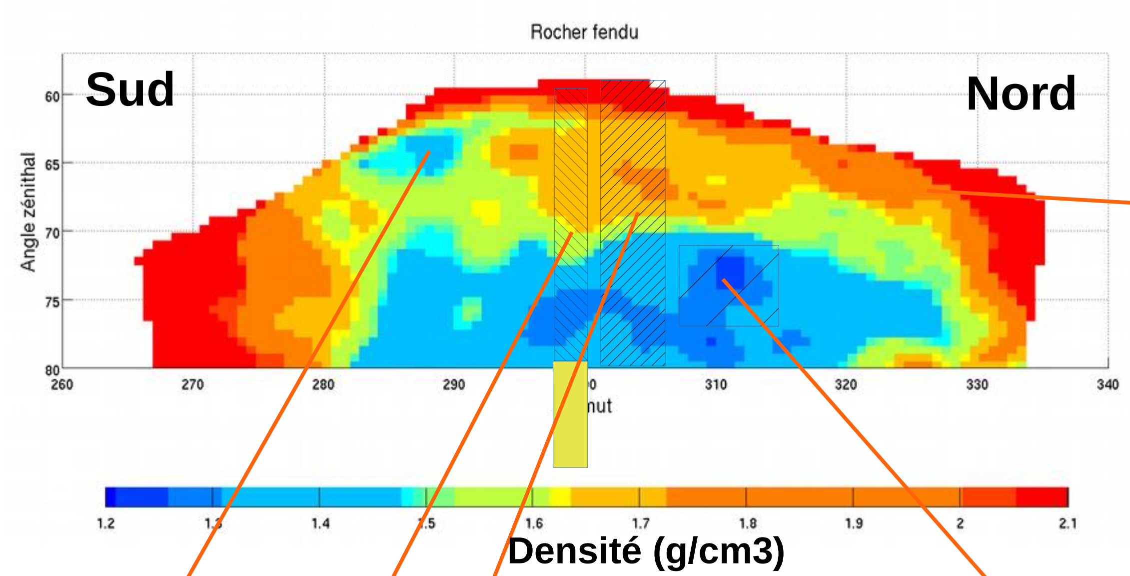
Equivalent !

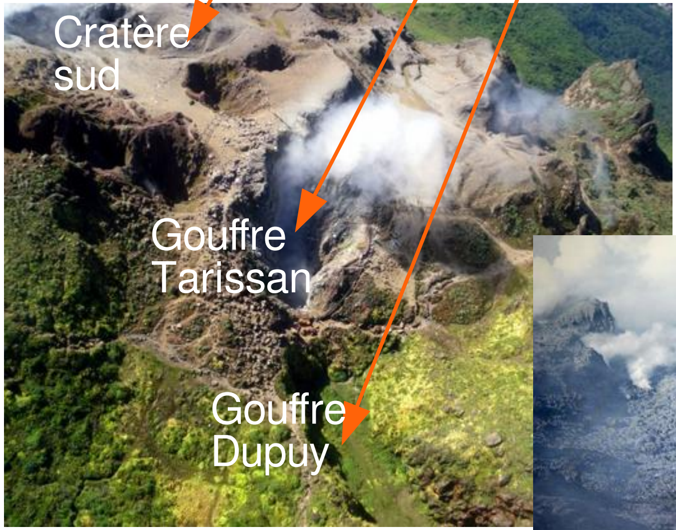
Results: structural & temporal imagery

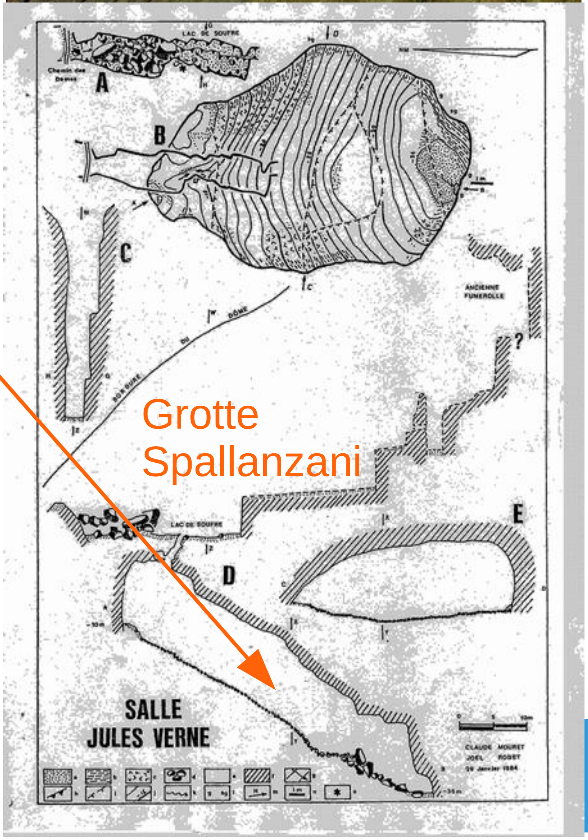


Lesparre, N. et al. 2012
Jourde, K. et al. 2013

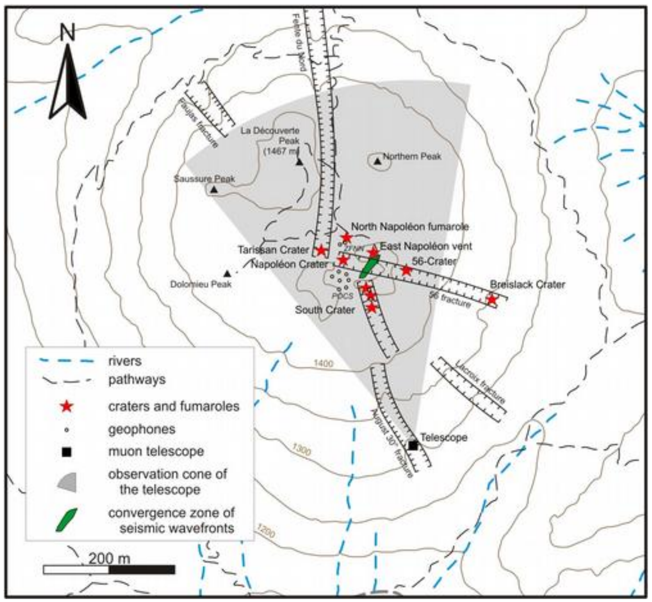
Results: validation with observations

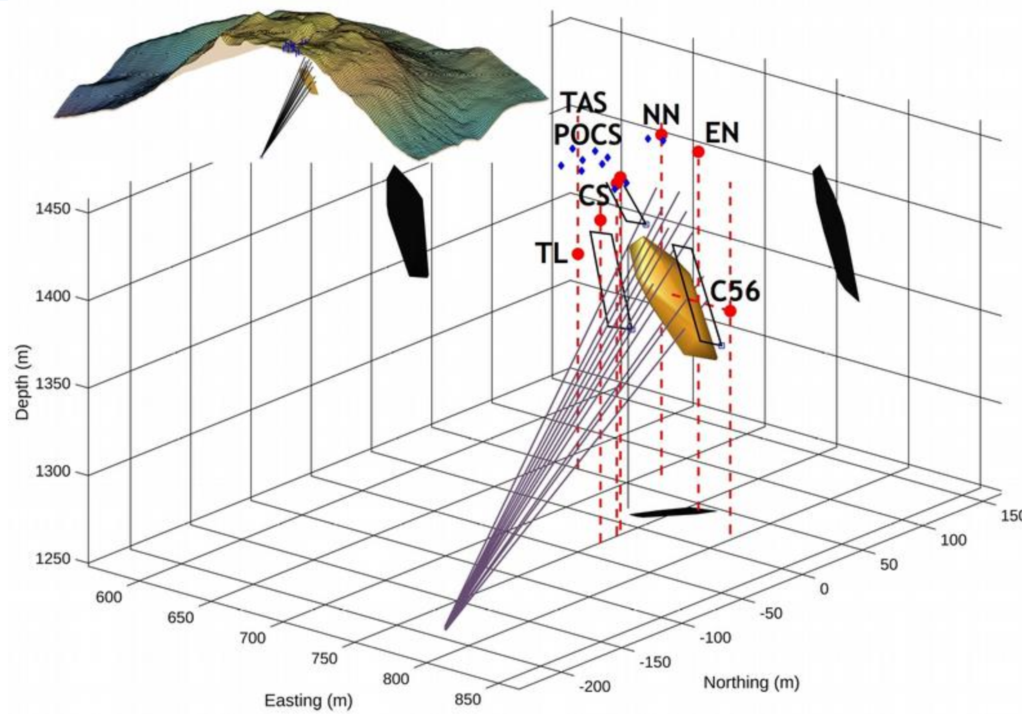




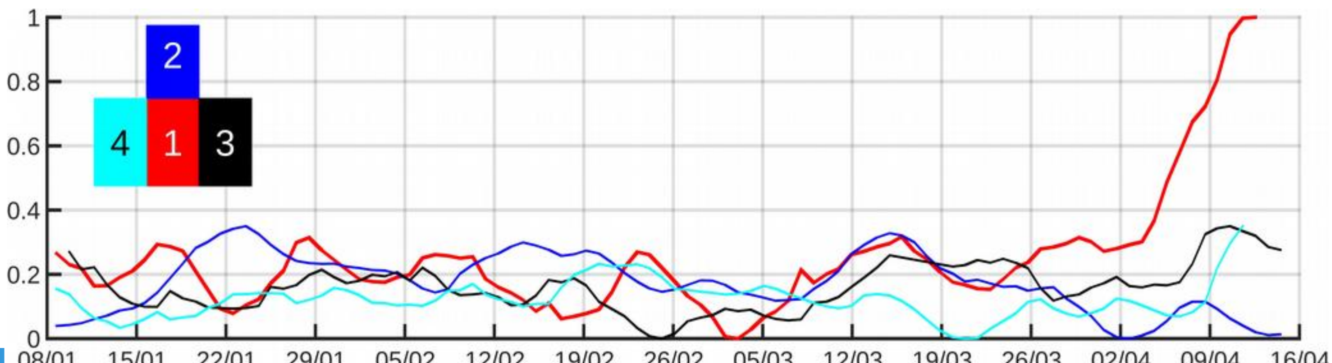


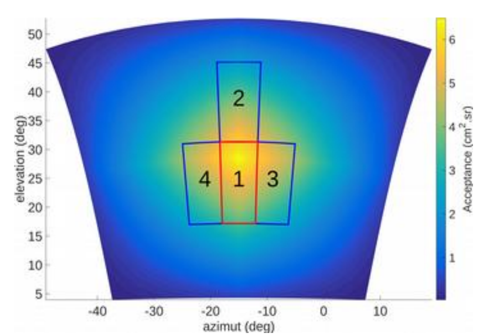
Joint monitoring: seismic / muons





Global analysis of muon and seismic monitoring

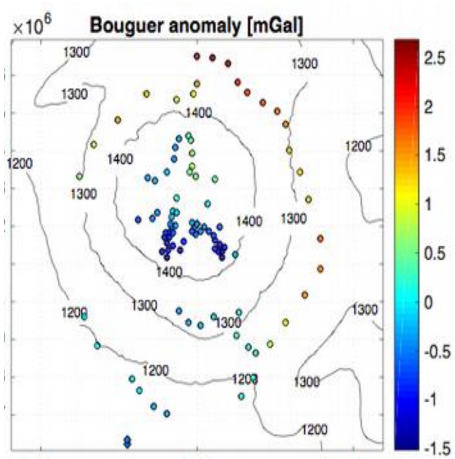




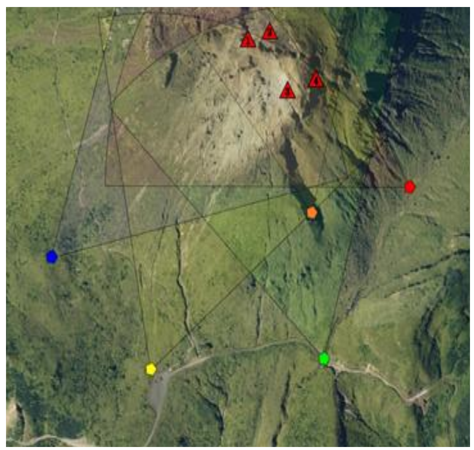
Abrupt changes of hydrothermal activity in a lava dome detected by combined seismic and muon monitoring
Le Gonidec, J.-Y. et al. Scientific Reports 2019

Joint monitoring: gravimetry / muons

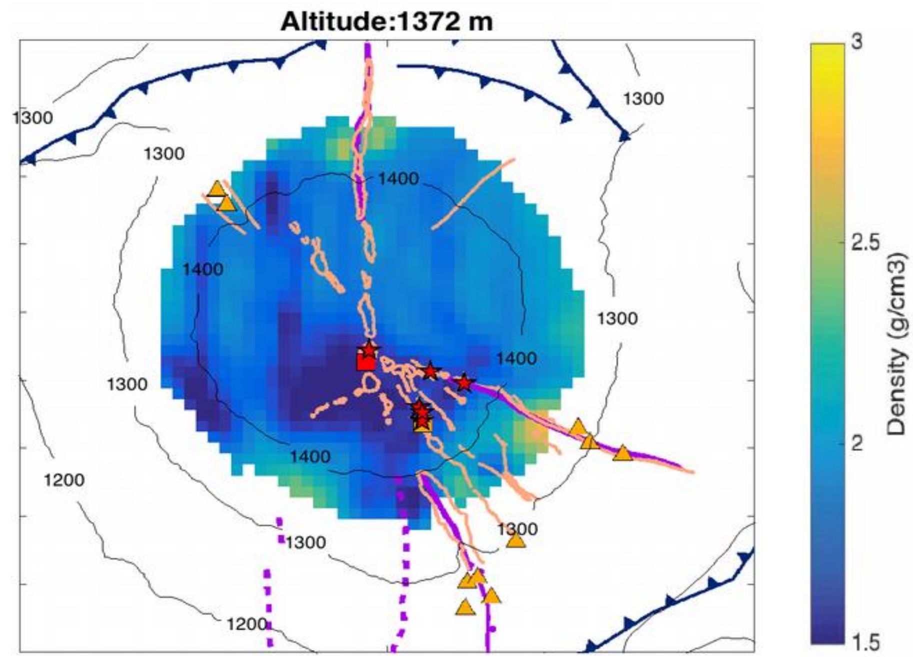
Gravimetry



Muons telescopes



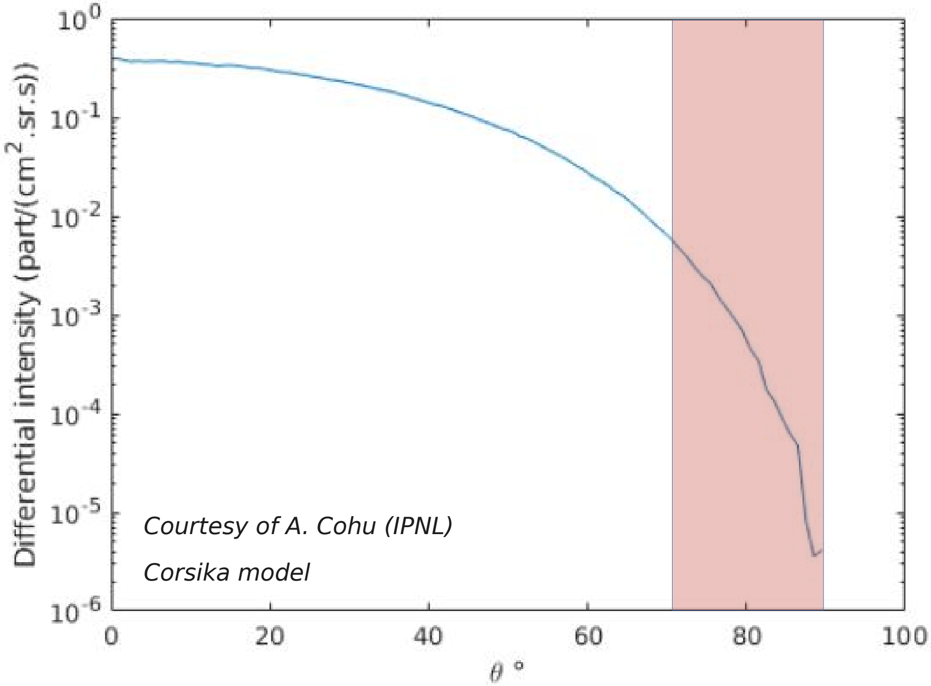
Joint inversion

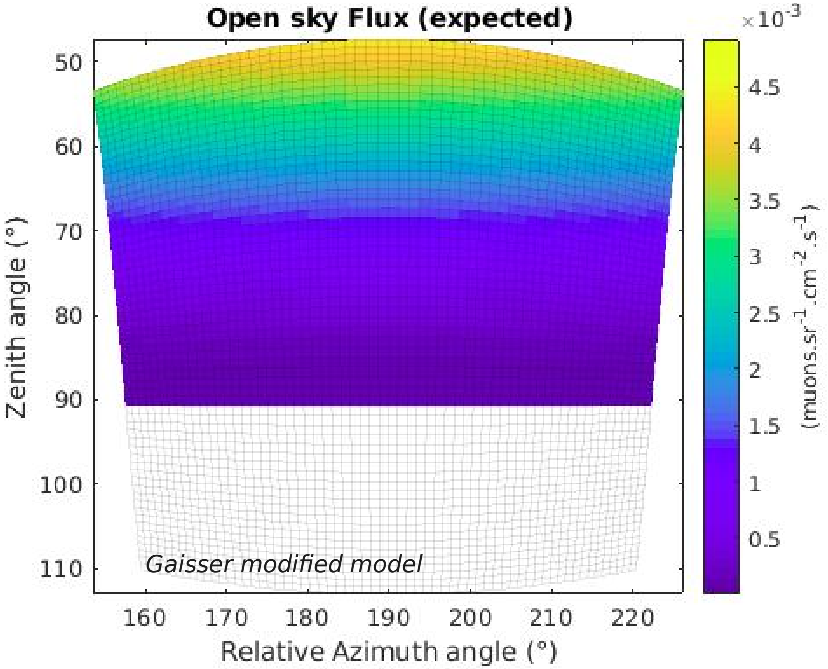


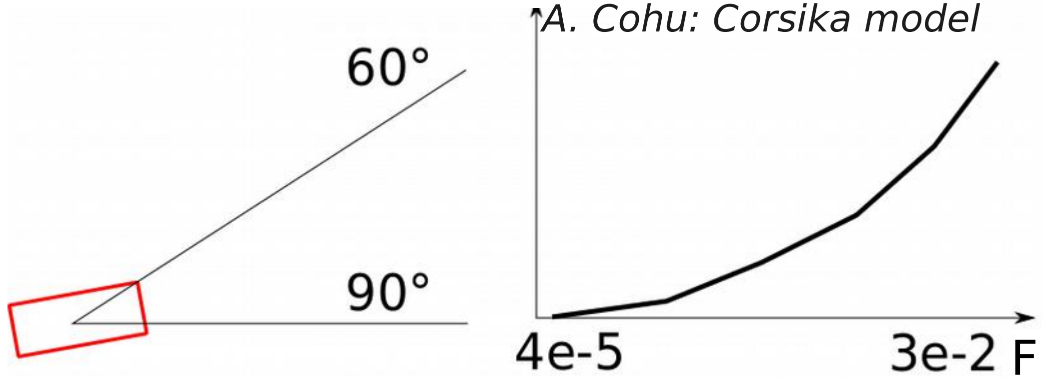
$$\mathrm{G}\begin{bmatrix}\boldsymbol{\rho}_\mu \\ \Delta\rho\end{bmatrix} = \begin{bmatrix}\mathrm{G_g} \\ \mathrm{G}_\mu\end{bmatrix}\begin{bmatrix}\boldsymbol{\rho}_\mu \\ \Delta\rho\end{bmatrix} = \begin{bmatrix}\mathbf{d}_\mathrm{g} \\ \mathbf{d}_\mu\end{bmatrix} = \mathbf{d}$$

Sensible to the same parameters (density/mass)

Zenithal dependency (limitation)

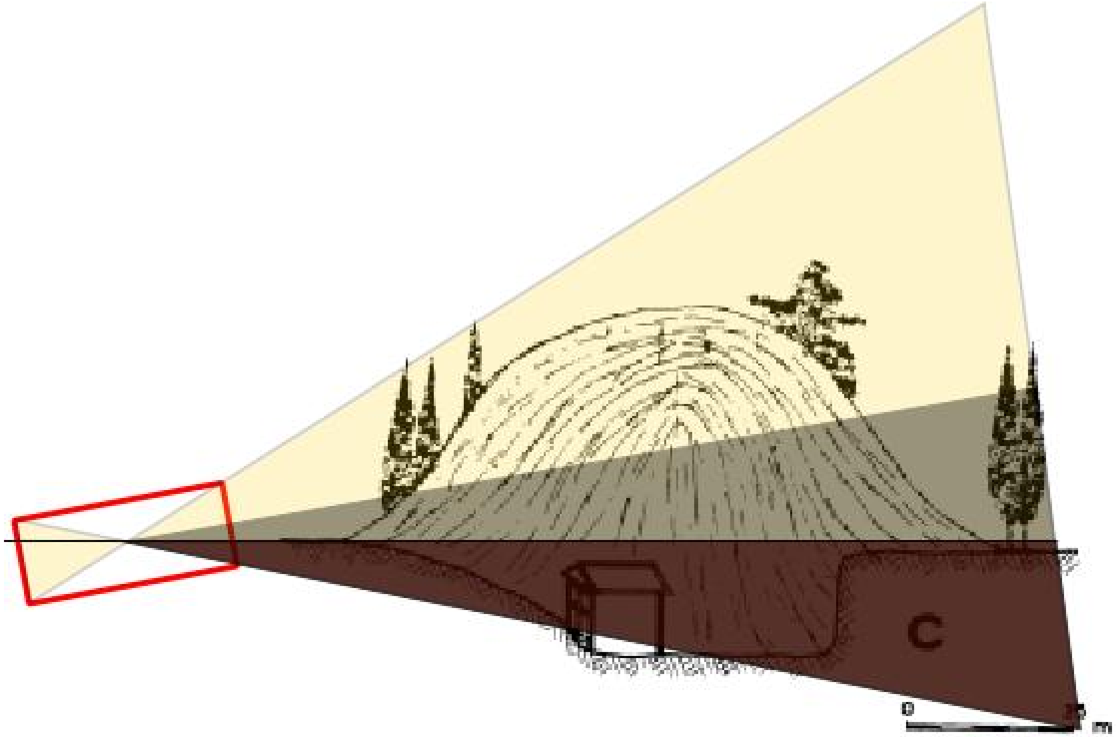






The closest to 90° the target
The more challenging it is.
Lower Flux (less muons)
Lower Flux estimate precision

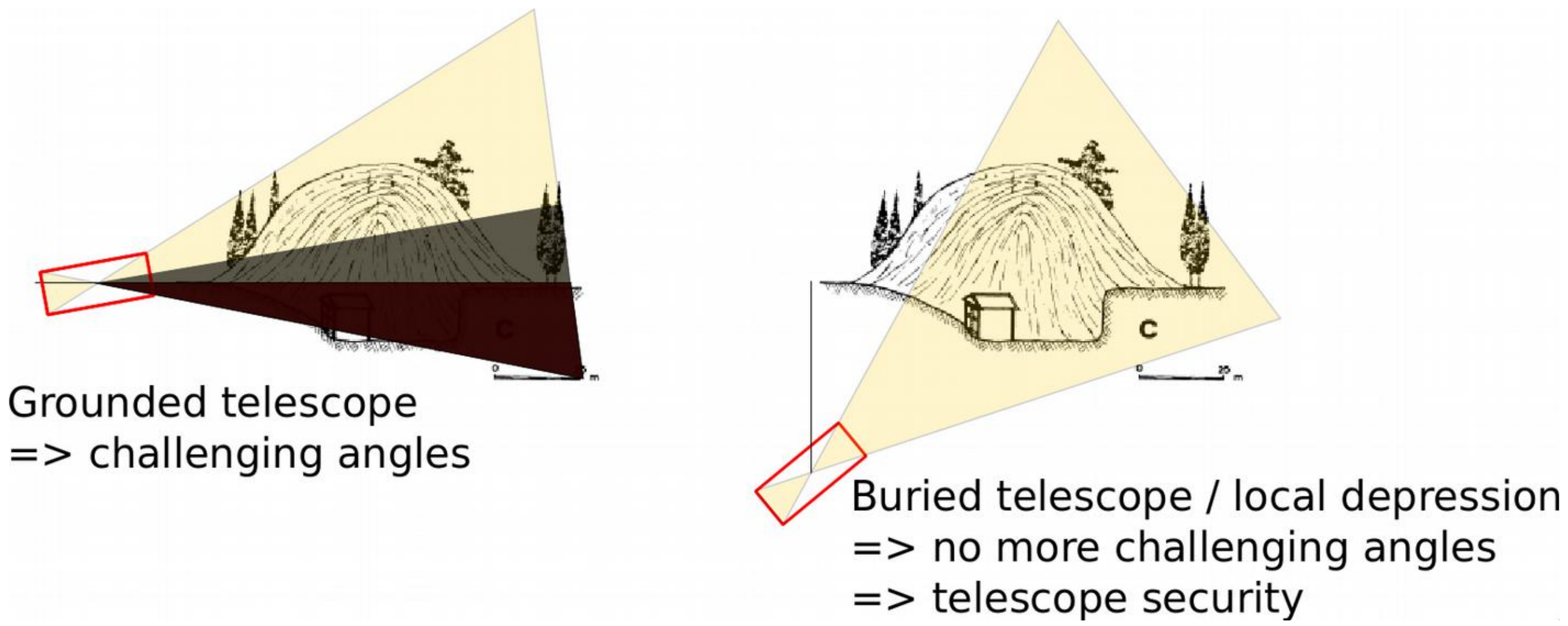
Limits of Muon tomography applied to archaeological survey (e.g. tumulus)



Modified after G. Tsokas et al. (Geophysics, 1995.)

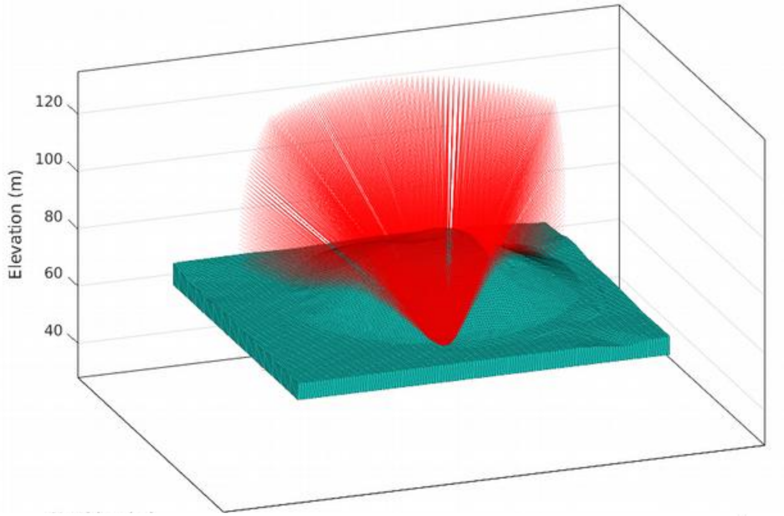
- **Efficiency zone (0-70°)**
- **Challenging zone (70-90°)**
  => Weak muon flux (time)
  => Theoretical flux estimate ~
  => Other targets (Mountains…)
  => Scattering (low energy)
- **Dead angle (Zenith = 90° & bellow)**

Limits of Muon tomography applied to archeological survey (tumulus example)

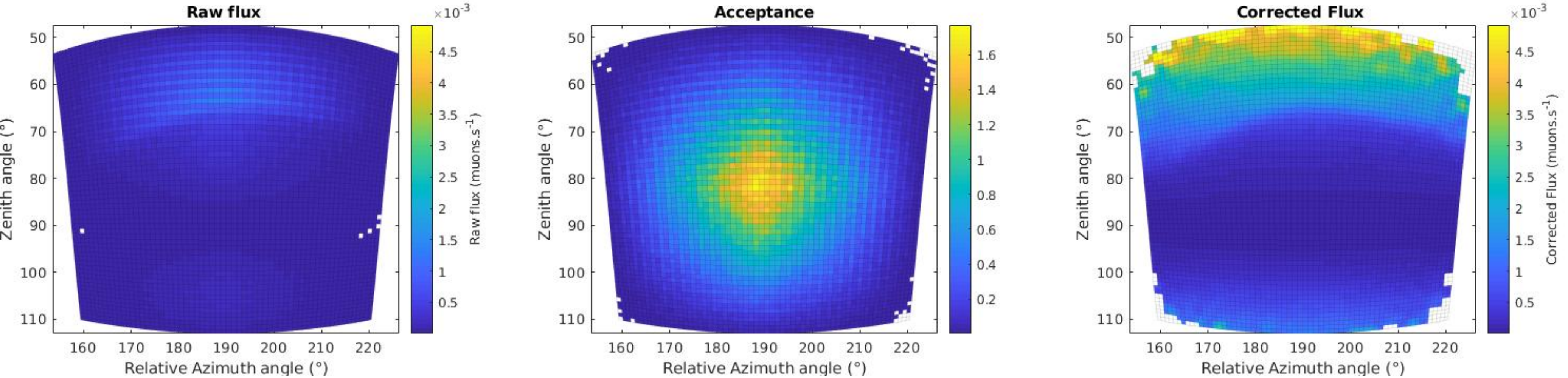


Results of muon tomography in Apollonia

Data processing 1/3: Raw flux to flux

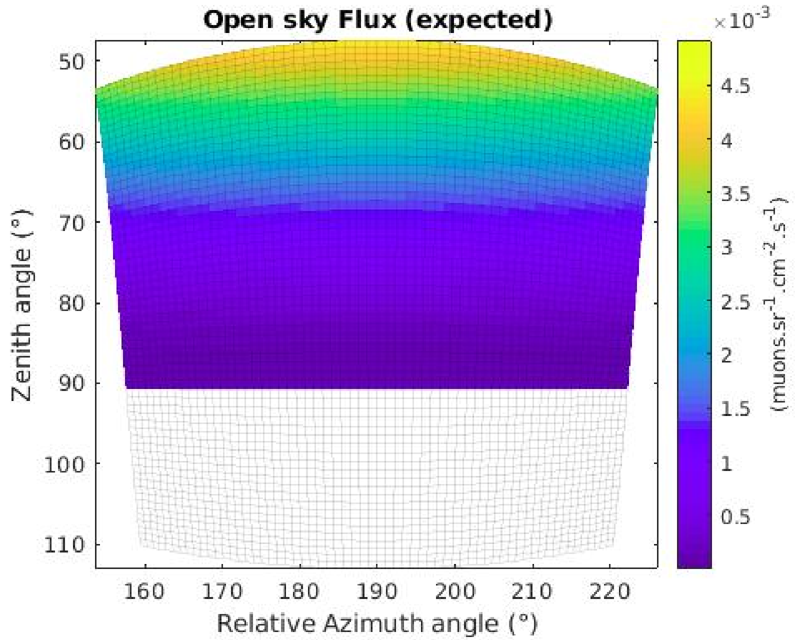


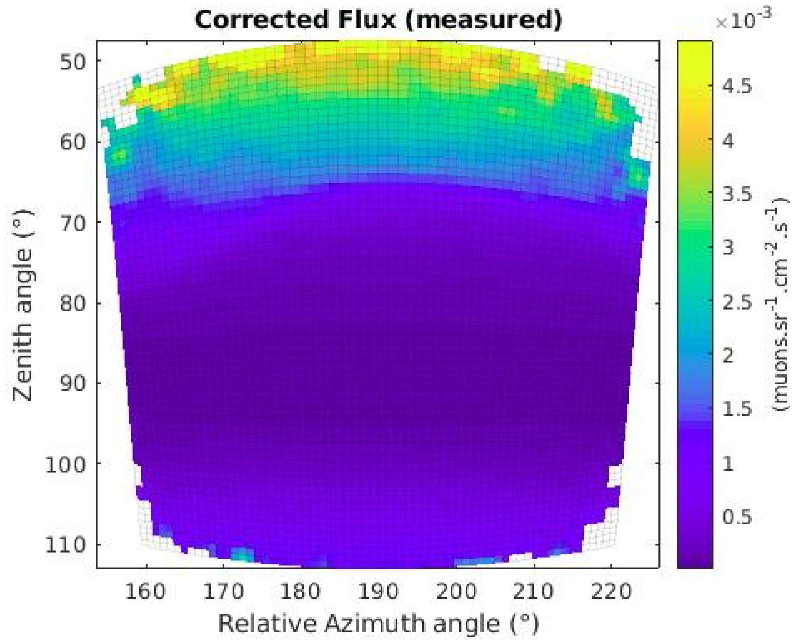
- **3 months data**

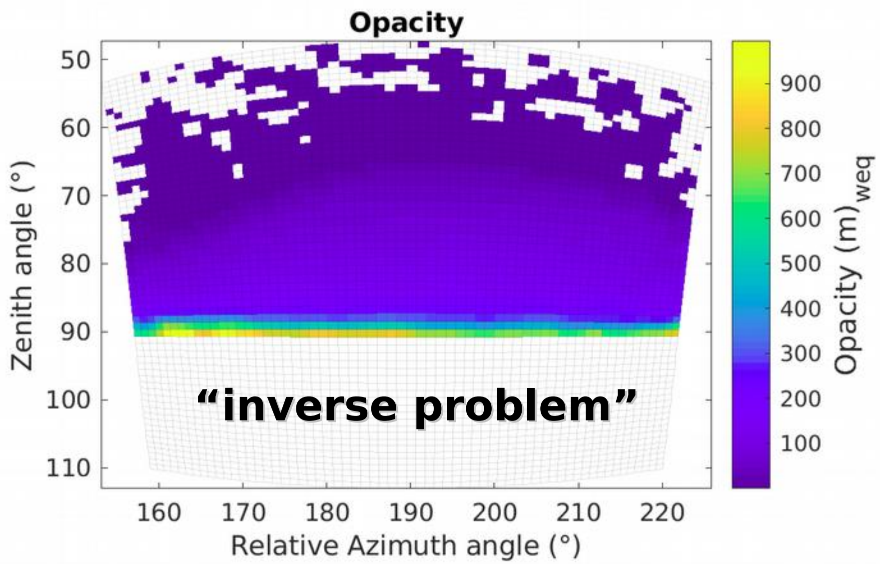


Raw flux **+ Telescope performance bias** **=** **Corrected Flux**

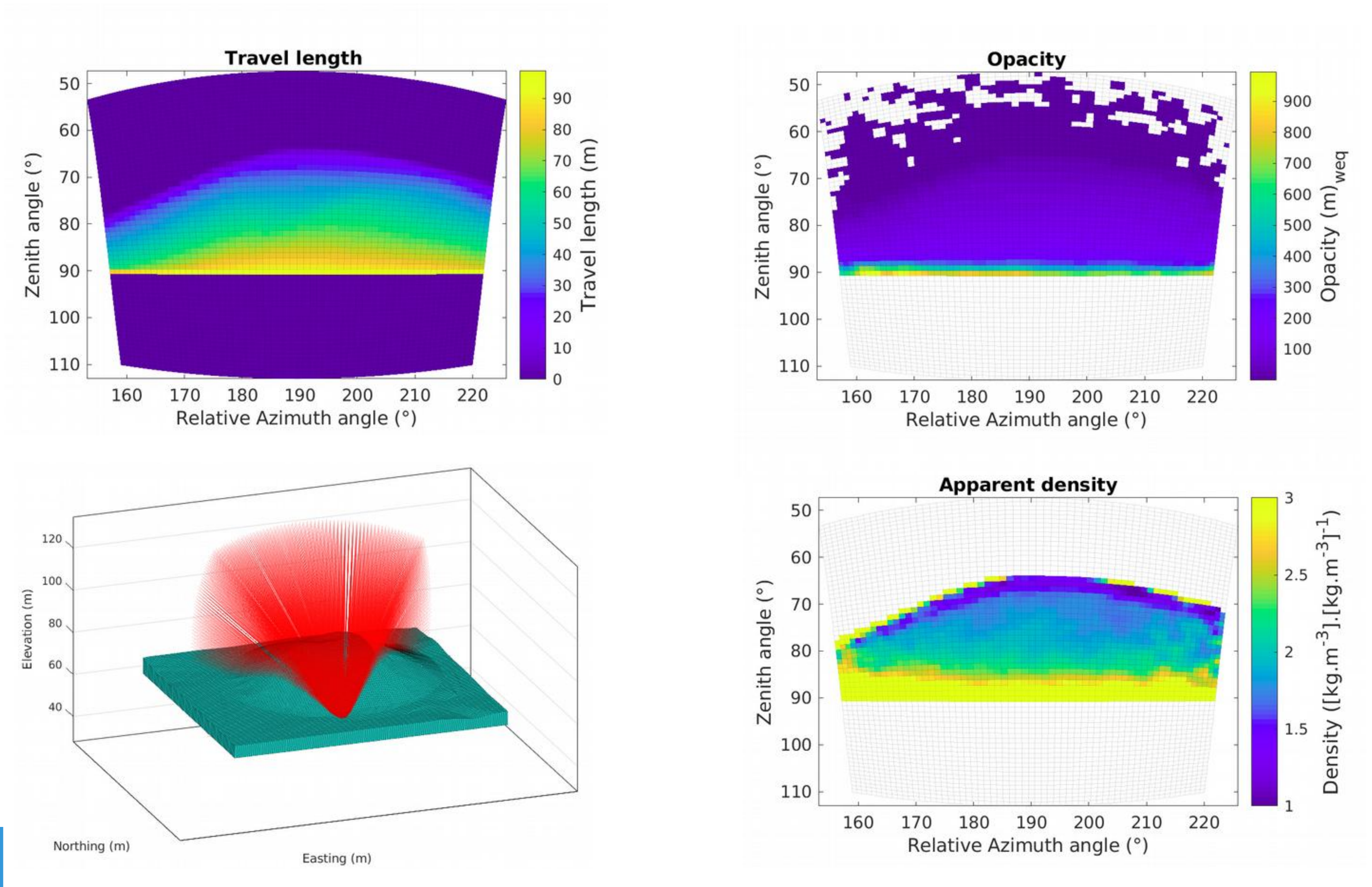
Data processing 2/3: flux to opacity





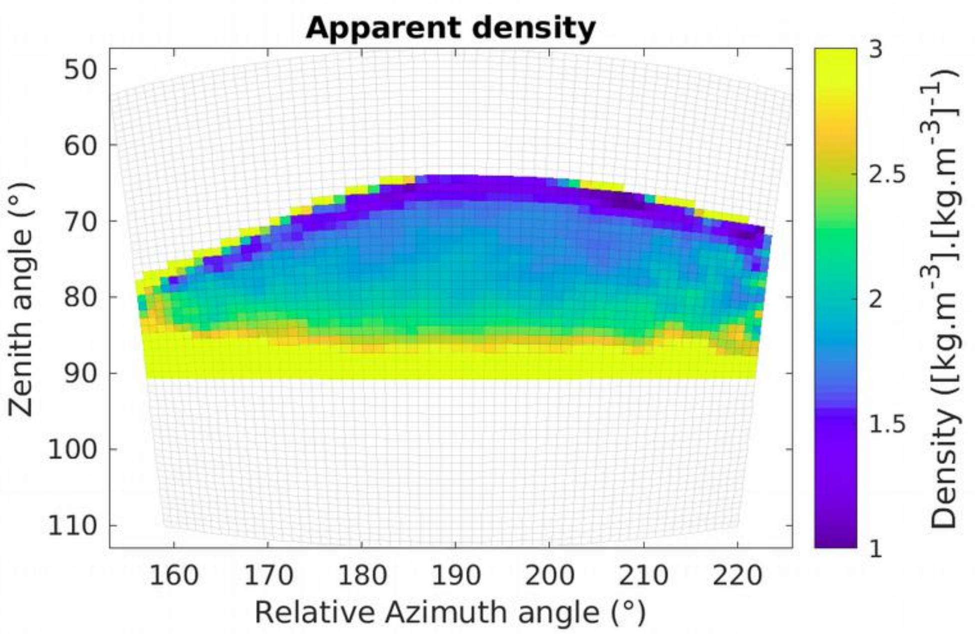


Data processing 3/3: Opacity to density



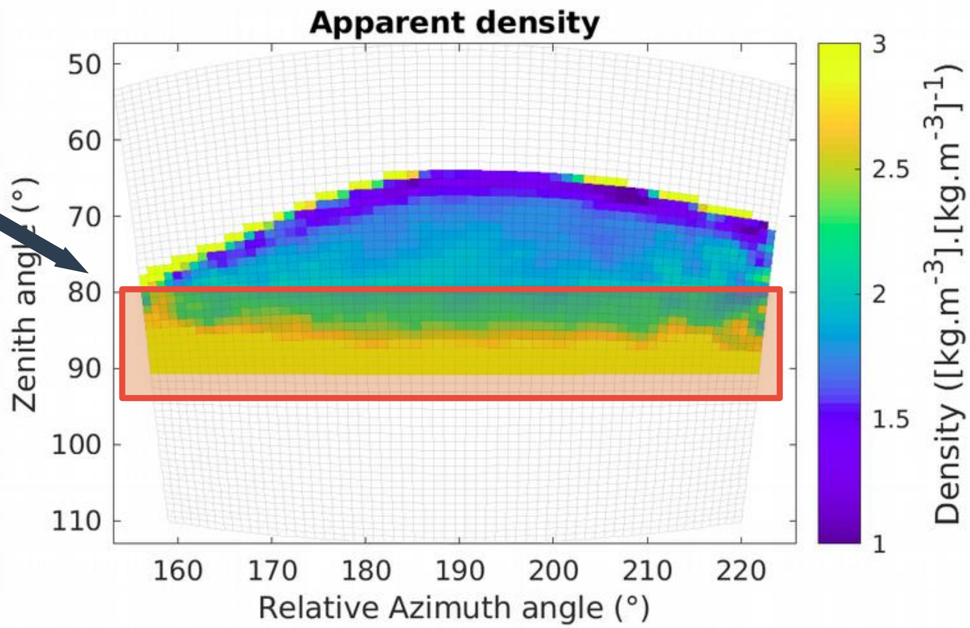
Understanding the Apparent density

- **The density is “apparent”**
- **The structure is 3D, yet the measurement is 2D**
- **The “apparent” conveys the information that it is a density “averaged” over the path of a muon in a structure**



Issues & pre-analysis

- **Bottom ? (over-estimate)**
=> Open-sky flux estimate



- Radial edges (under + over-estimate)
=> Open-sly flux estimate
=> TL slightly off (unlikely)

- Inner-lateral contrasts
=> unless TL slightly off (unlikely)
=> not related to open-sky flux
=> confident

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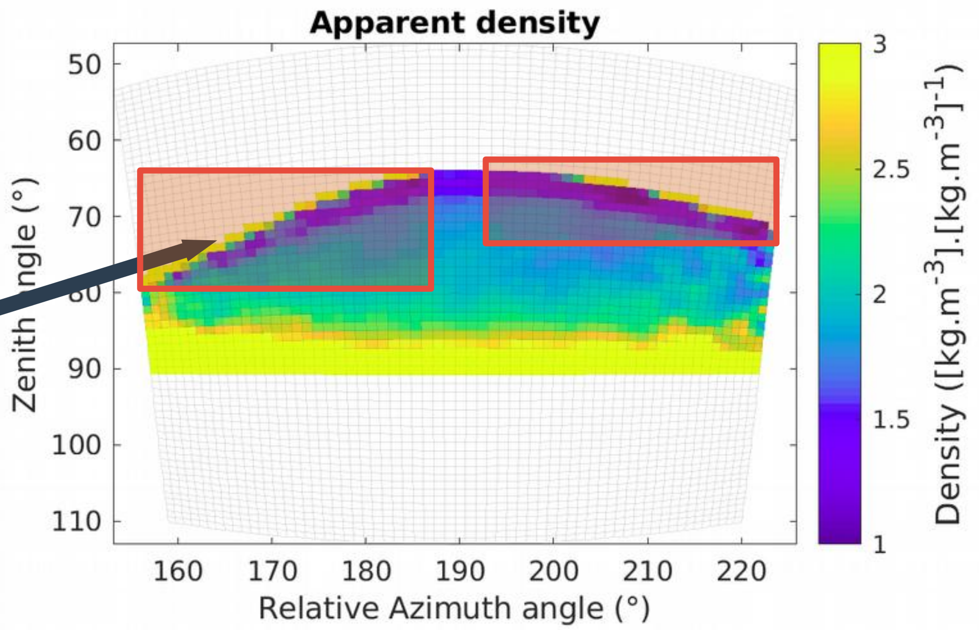

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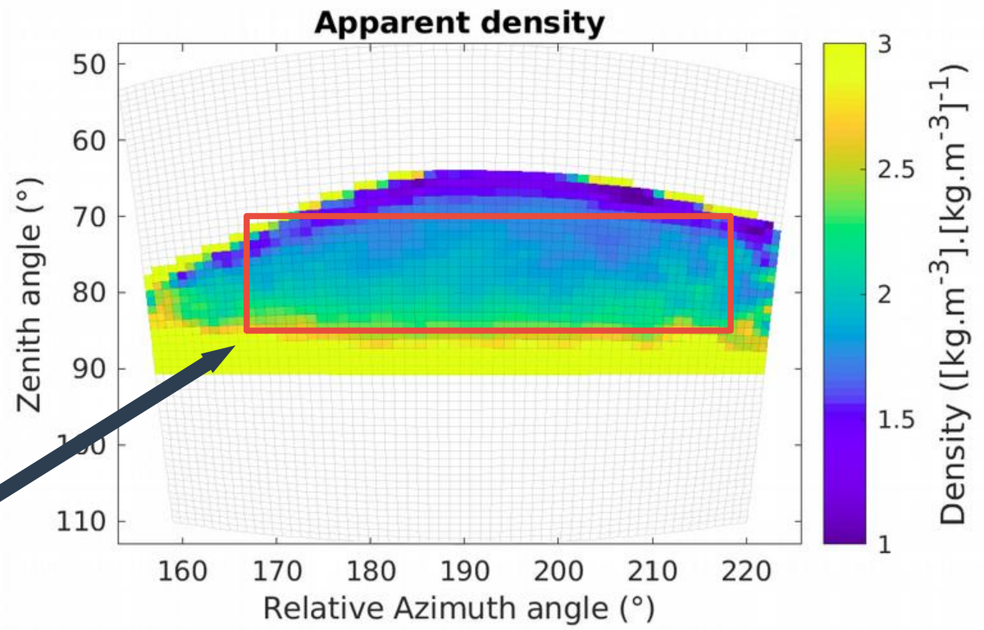
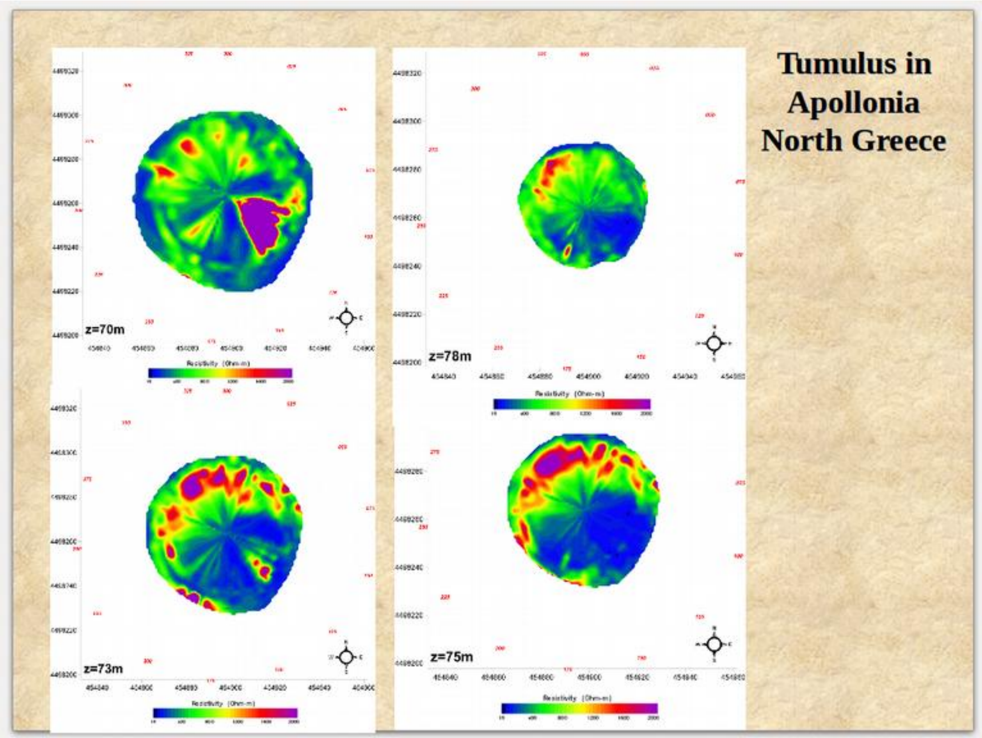
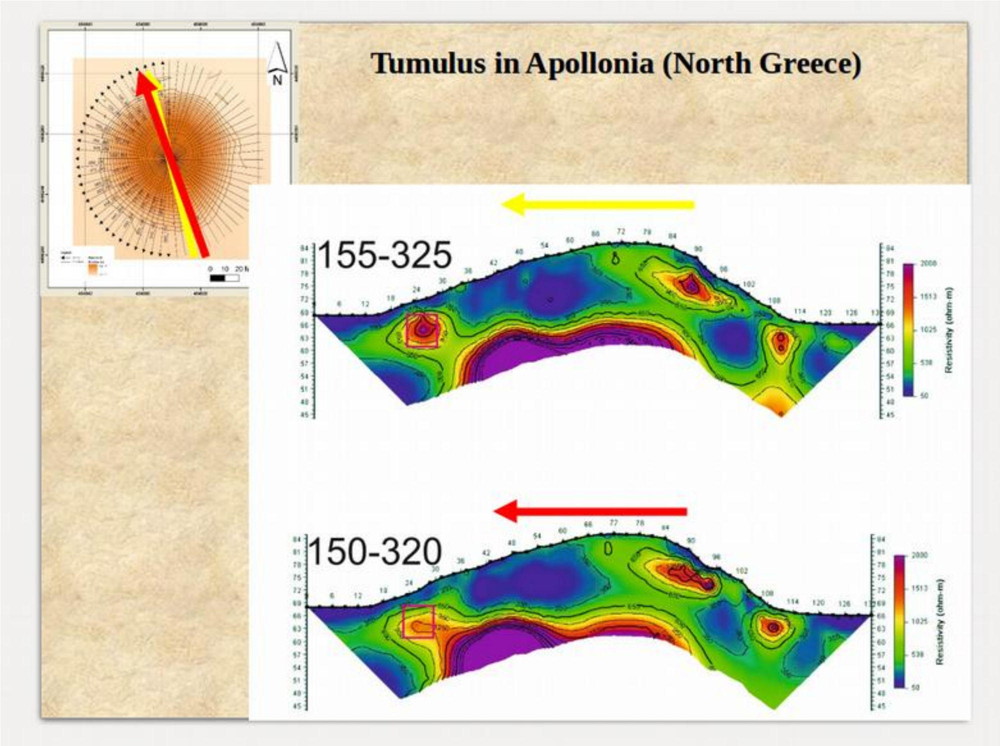


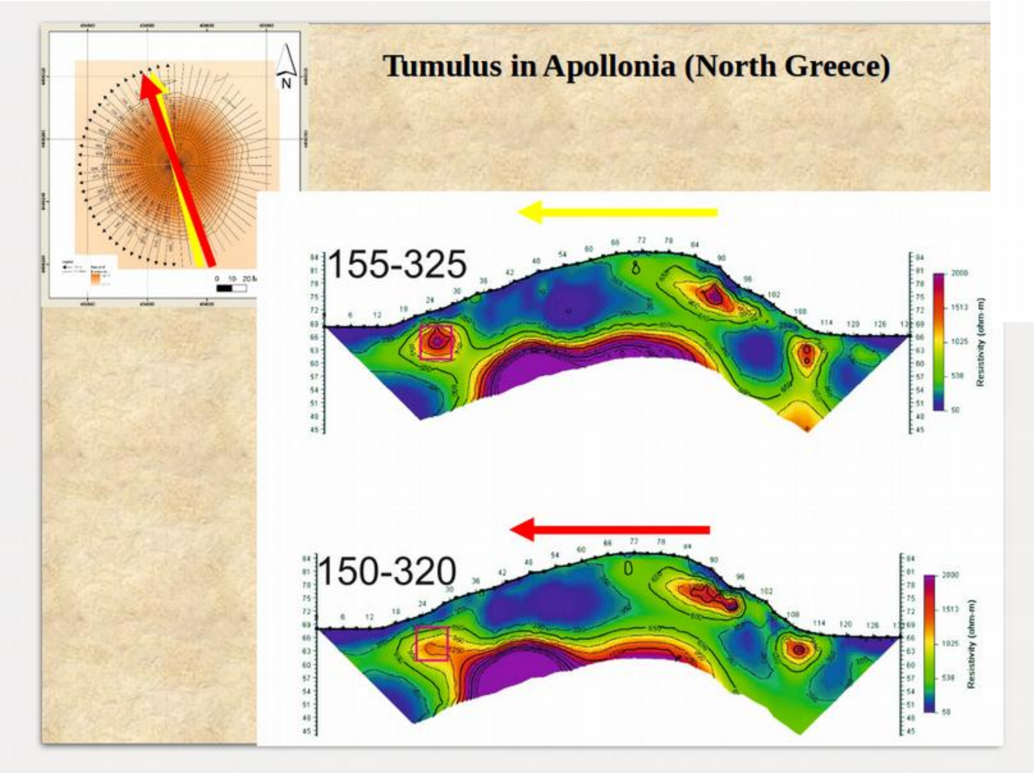
Electric tomography

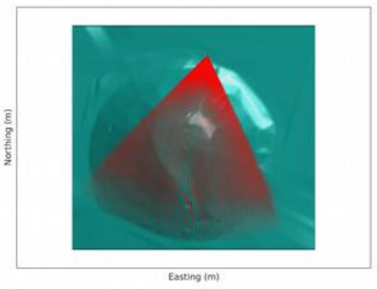


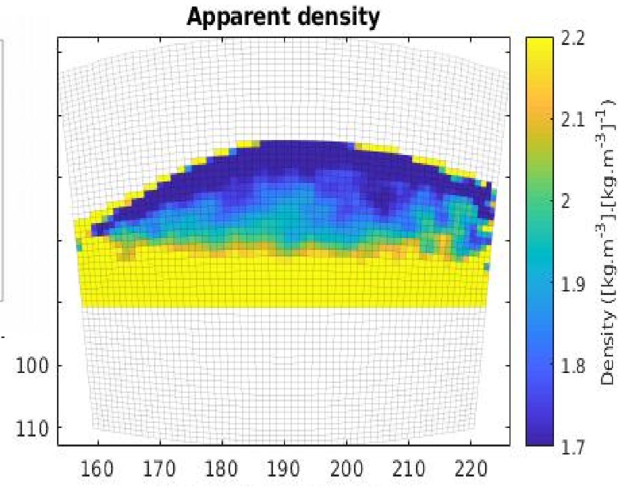


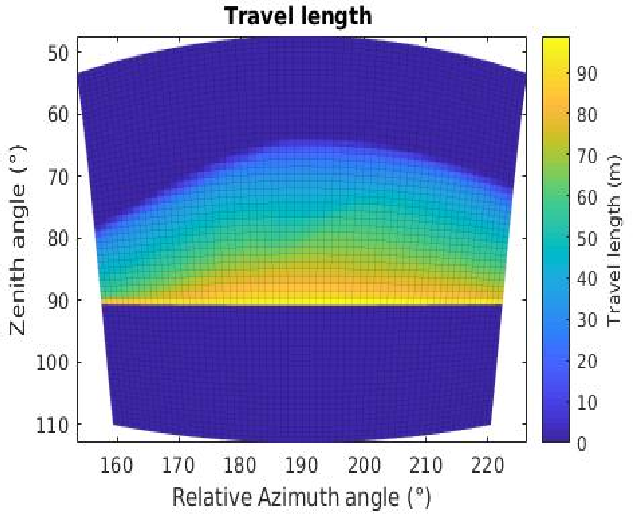
G. Tsokas et al. (2015)

Electrical & Apparent density









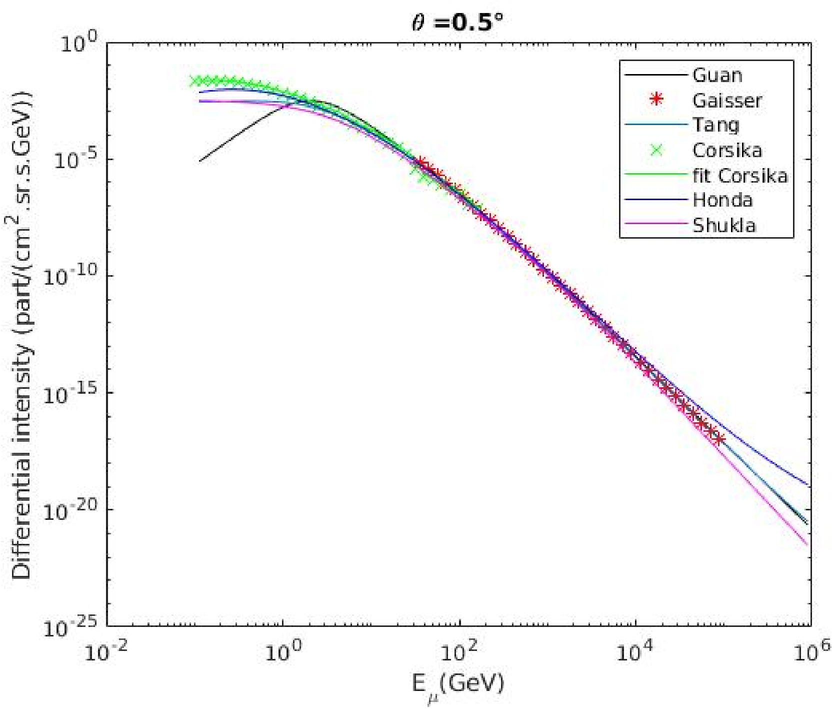
- **Topography variations seem correlated to density variation => Suspicious (for now)**

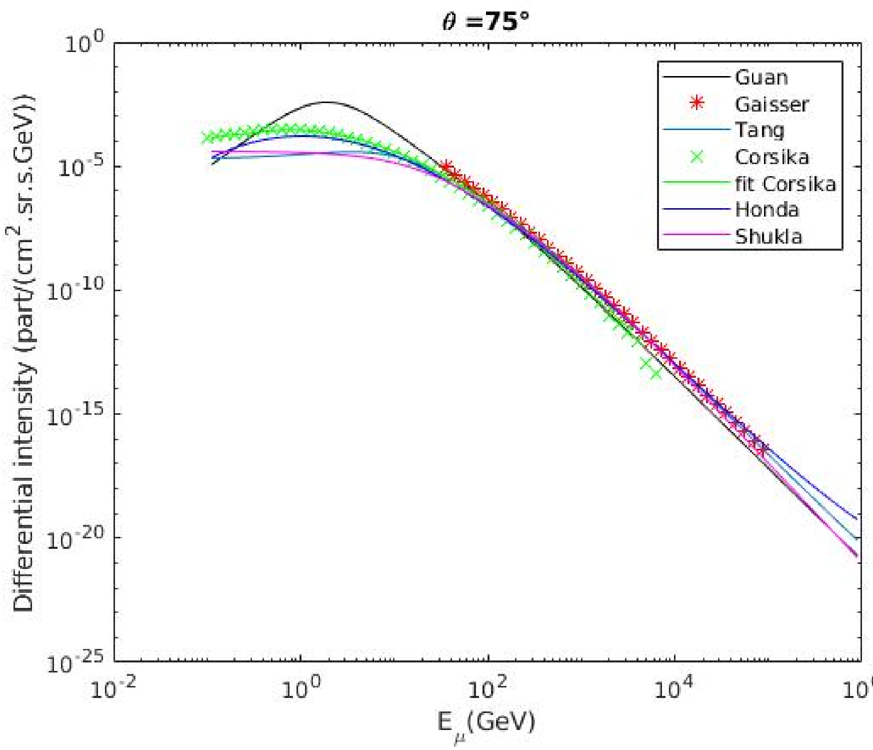
Extending the actual limitations

Dealing with the low-angle flux issue

2D limits

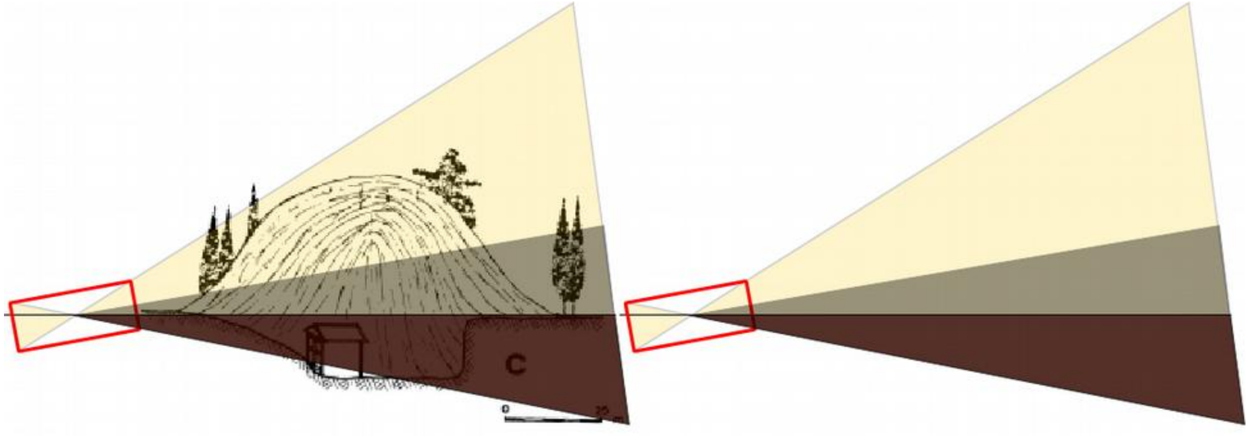
For this project: improving the flux estimate





- **Less muons at low angle than actually expected**

In the future: dealing with the flux issue



Survey telescope

Telescope dedicated to raw flux measurements

- => Deals with :
- Meteorogical variations
- Far away structures
- Theoretical flux

- Require a common open-sky calibration
- => joined 3 panels telescope

Acceptance

Survey

Conclusions

On going project ...

Thank you for your attention...