Lava dome rock strength estimation with 3-D muography at La Soufrière de Guadeloupe

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OUTLINE

I. La Soufrière de Guadeloupe : Motivations and challenges

II. Muons data reconstruction and analysis

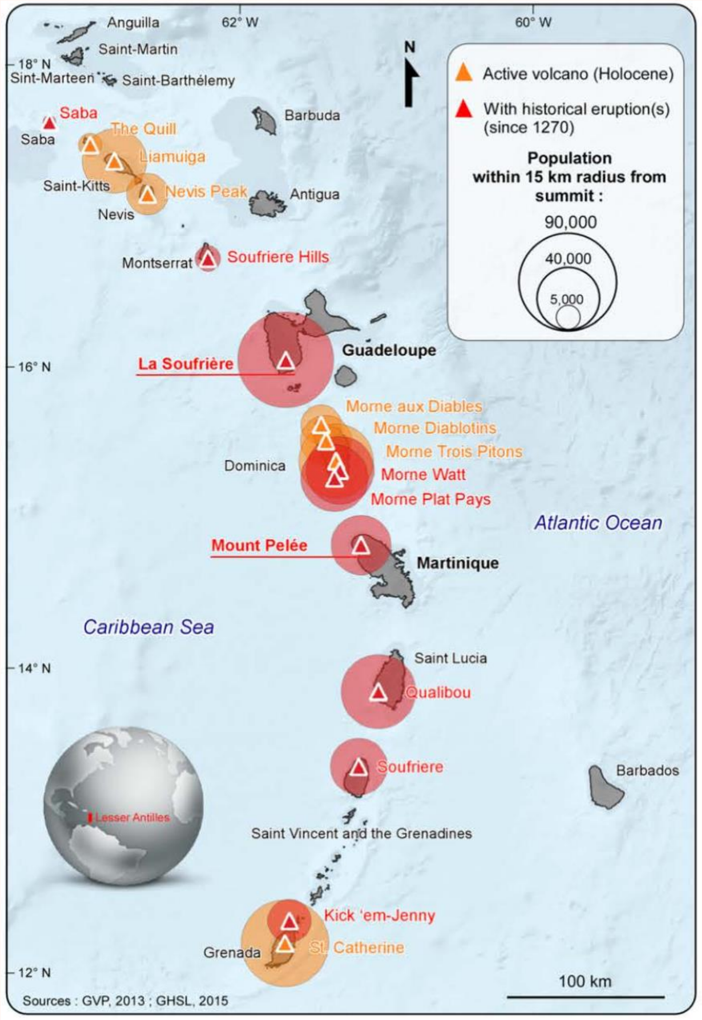
III. 3-D modeling and inversion

IV. Perspectives and conclusion

La Soufrière de Guadeloupe, May 2022

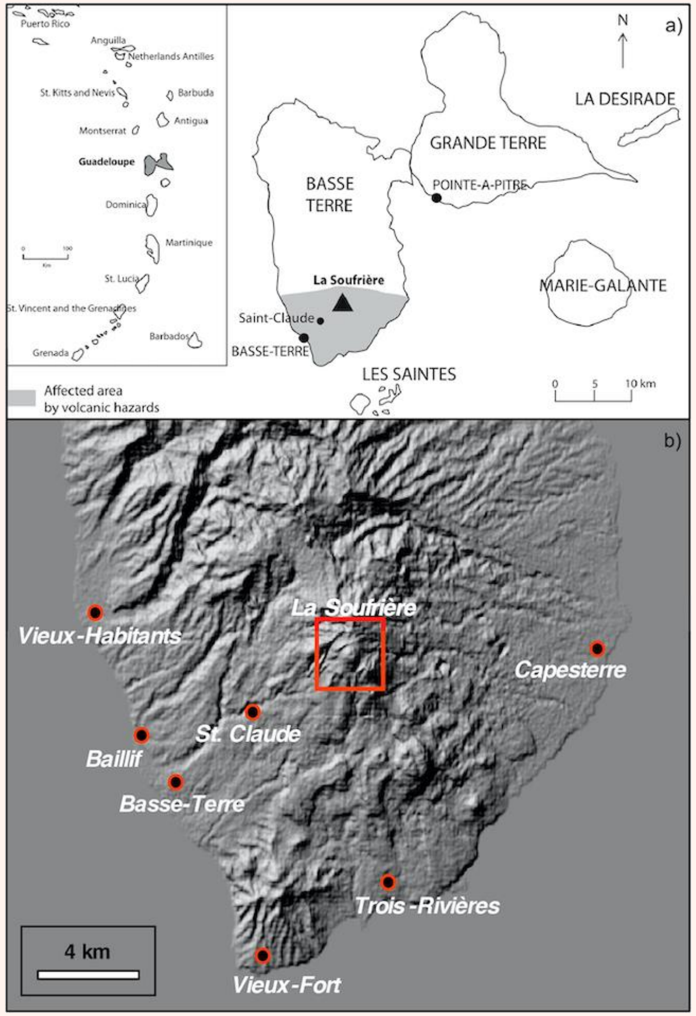
La Soufrière de Guadeloupe

Lesser Antilles Volcanic arc



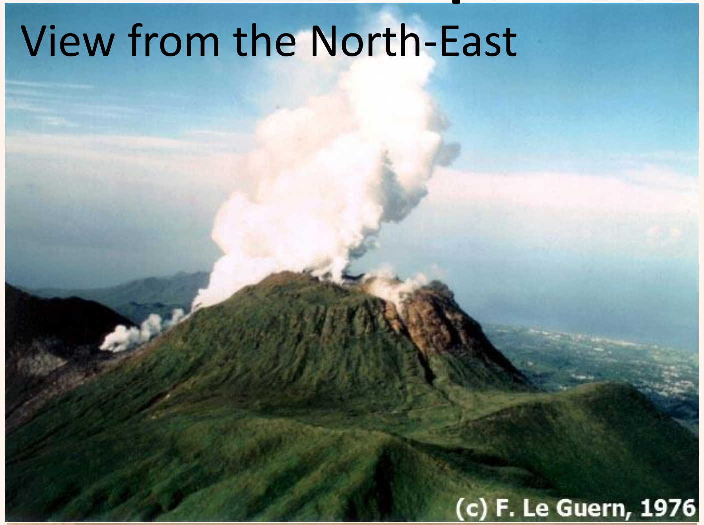
Leone et al., 2019

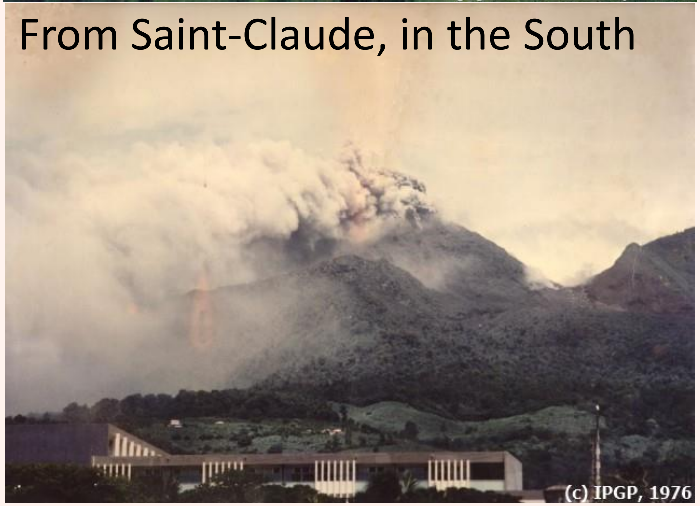
Guadeloupe



Massaro et al., 2022

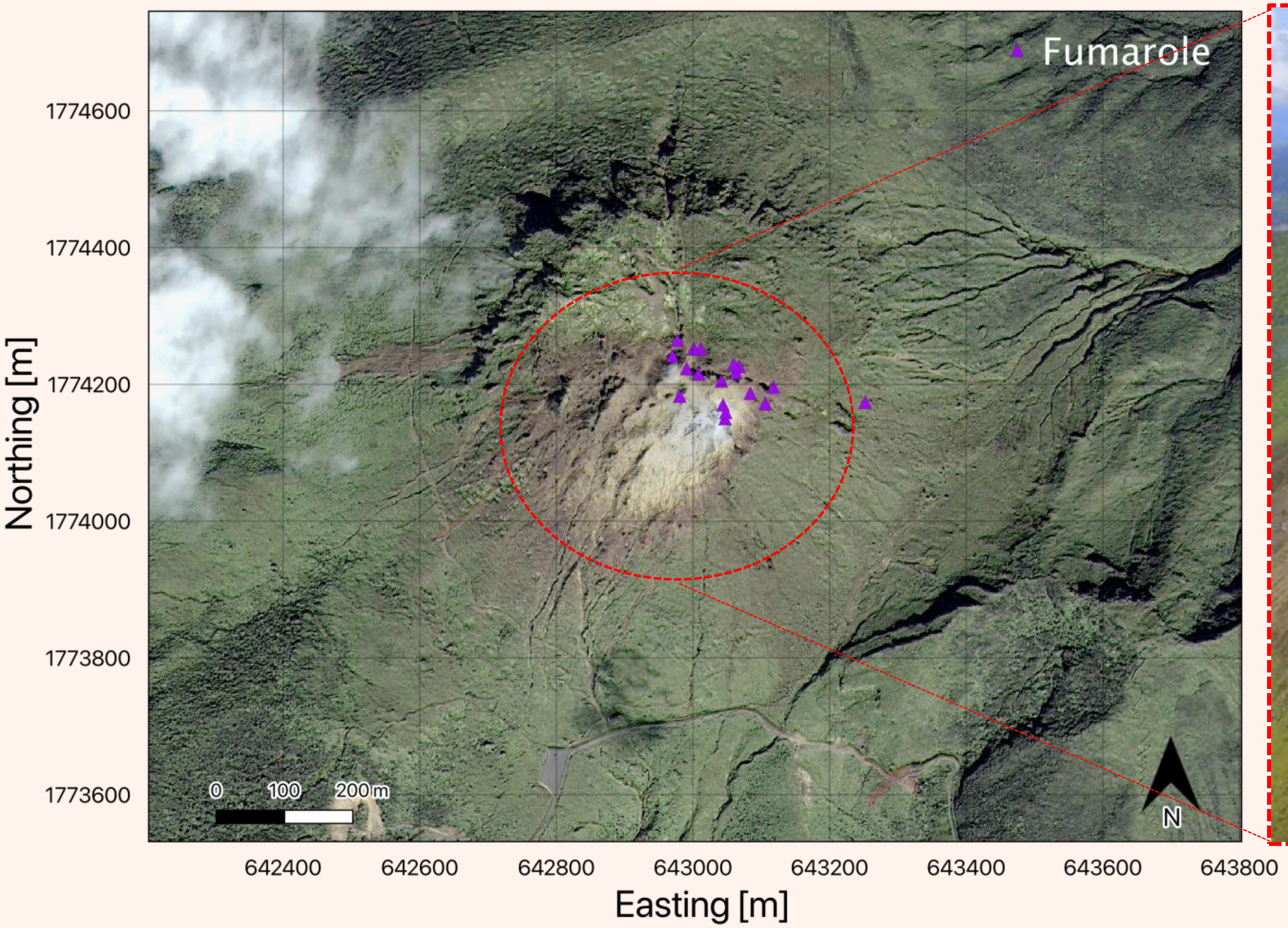
1976-1977 eruption





Credit: IPGP

Present : intense Fumarolic Activity at the dome summit



Natural Hazard at La Soufrière

- **Hydrothermal activity** favours physicochemical process (e.g. **rock alteration**) worsening the dome mechanical stability

  ☛ Potential **partial flank collapse**

- **Structural characterization** with various observables (seismic p-wave velocity, gravimetry, electrical tomography)

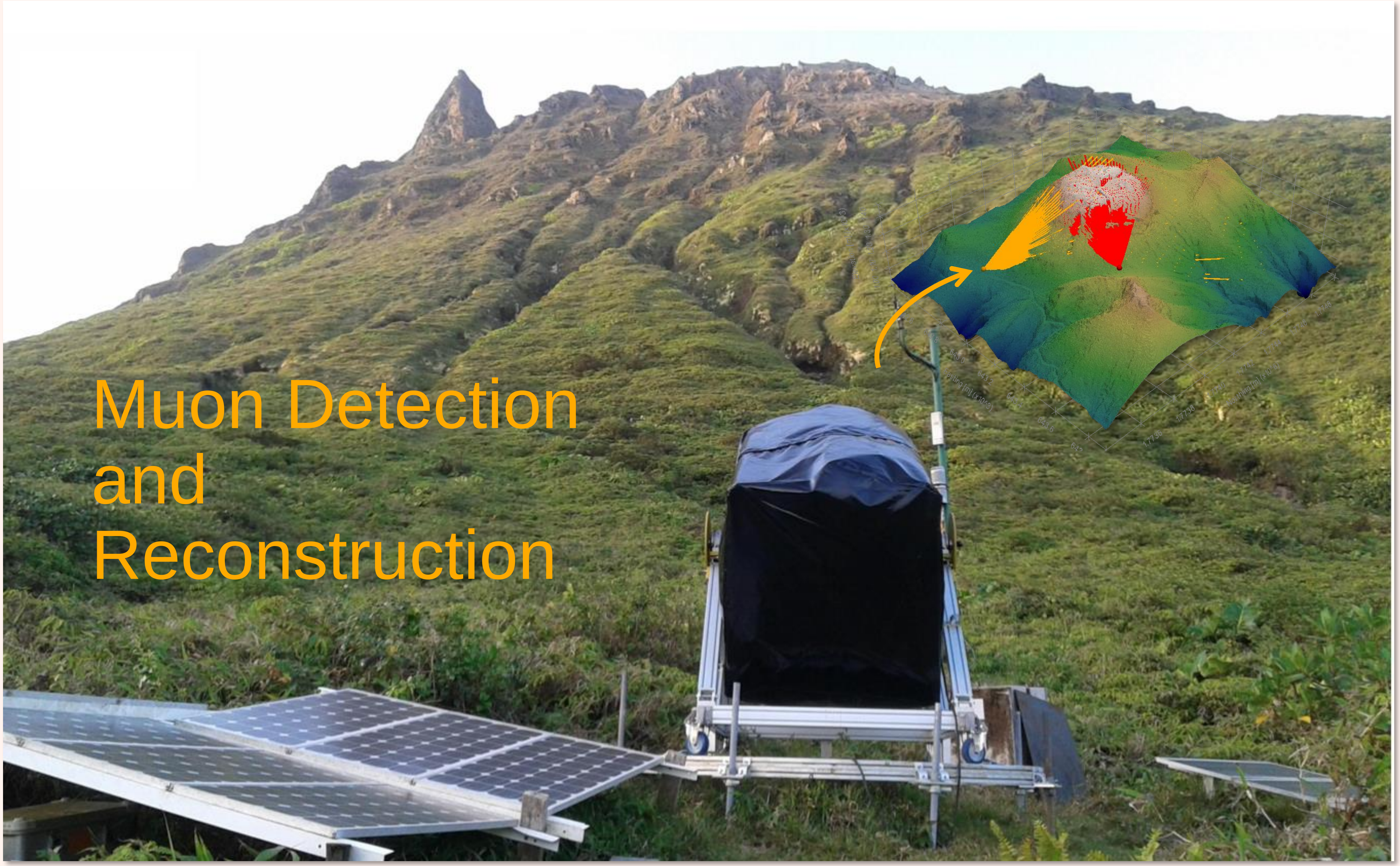
  ☛ Input to numerical modeling of the edifice stability

but each has limits (e.g. spatial coverage, depth, resolution)…

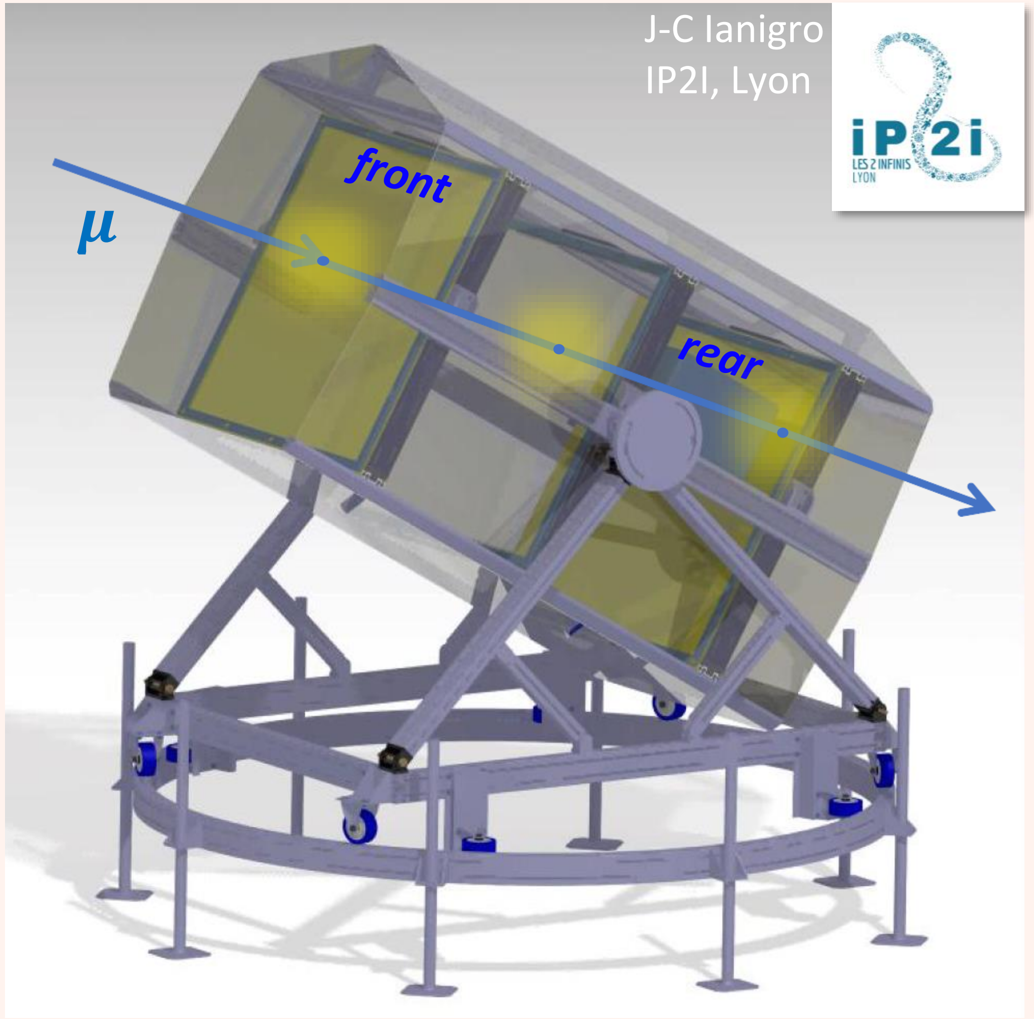
Need for refined characterization of the lava dome density structure …

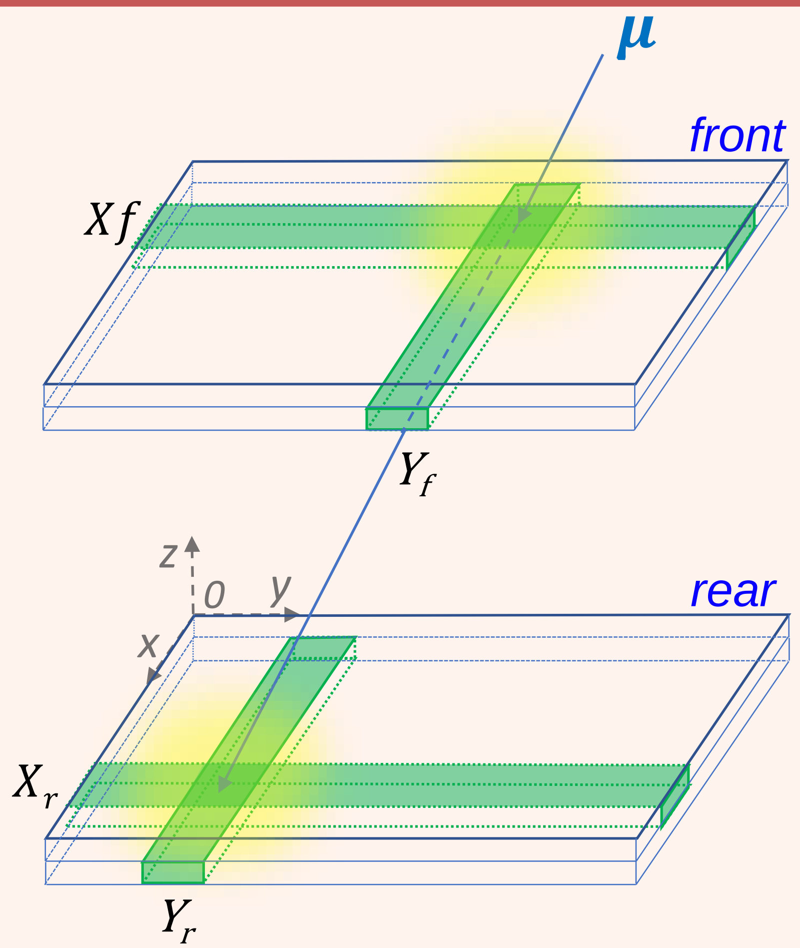
$\Rightarrow$ **Muography**

Muon Detection and Reconstruction



Muon telescope





More info on the readout system: Lesparre et al. 2012, Marteau et al. 2013

2 detector layouts :
- 3 matrices 32x32 scint. (80x2.5x1 cm^3) + 7-cm lead/steel shielding panel (SB, BR, OM detectors)
- 4 matrices 16x16 scint. (80x5x1 cm^3) + shielding panel (SNJ)

Data Reconstruction

Optimization of a **Random Sampling Consensus** (RANSAC) algorithm.

Comparison to other algorithms:
- **The Hough transform** (Dalitz et al., 2017)
- **Straightness check** (former analysis, Lesparre et al., 2012)

The tracking performances were studied with **GEANT4.**

RANSAC

Outline:

1) Randomly select a minimal subset of hits

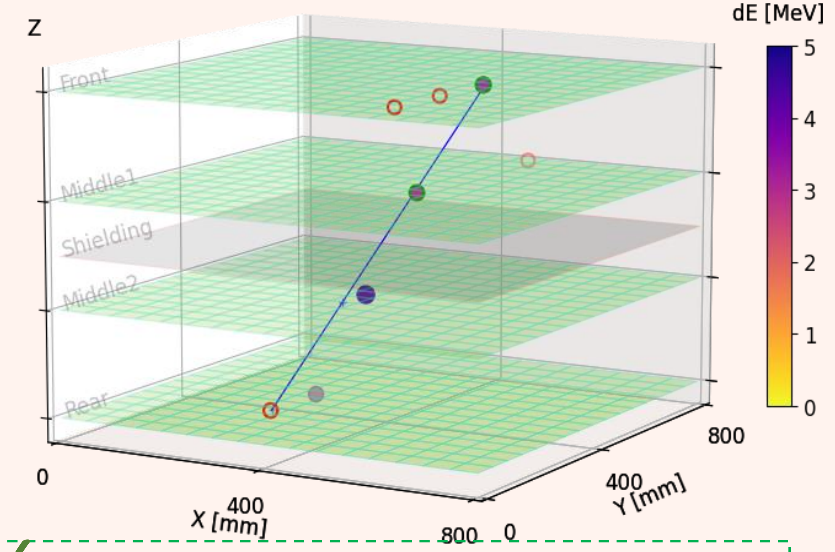
2) Fit a hypothesized model to that subset

3) Tag hits that are below a distance ***threshold*** to the model as « ***inliers*** » and tag the rest as « ***outliers*** »

4) Iterates N times over the three previous steps and selects the best model that maximizes the number of ***inliers.***

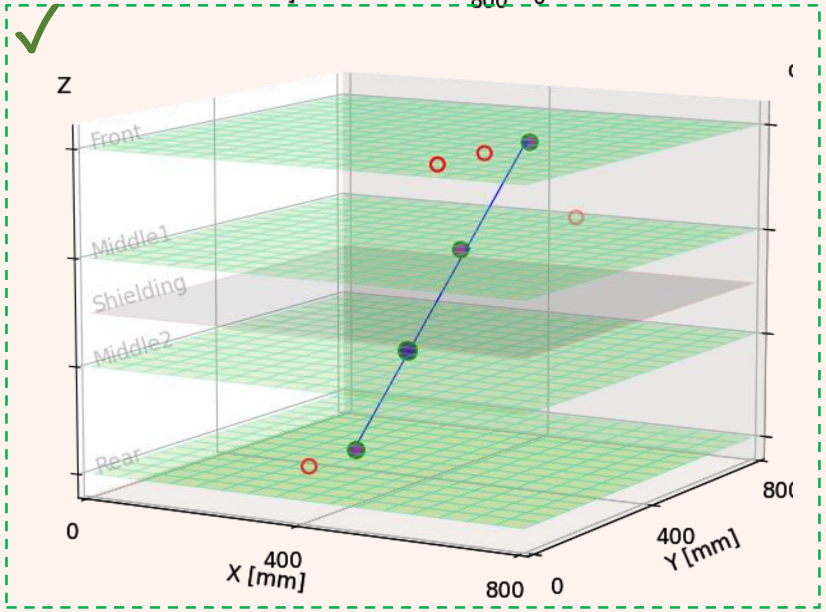
Reconstruction of a 10 GeV muon + noise

TRIALS
N=2

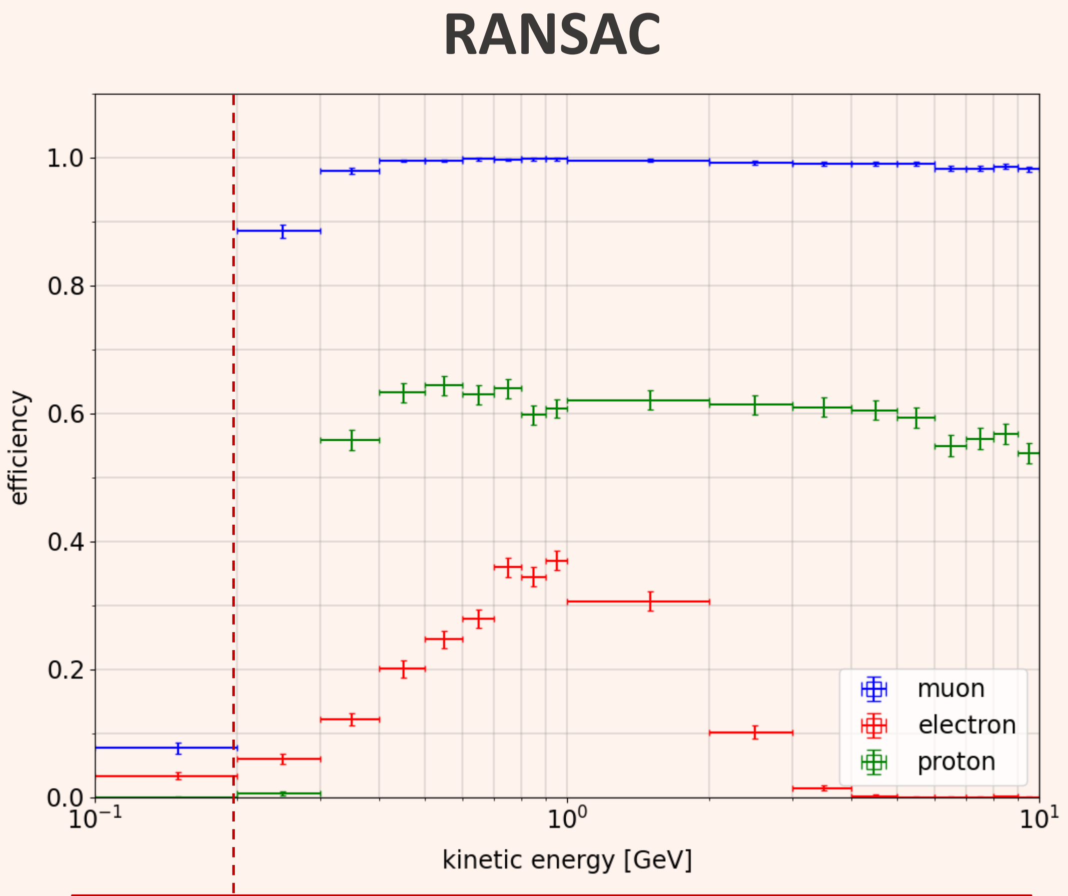


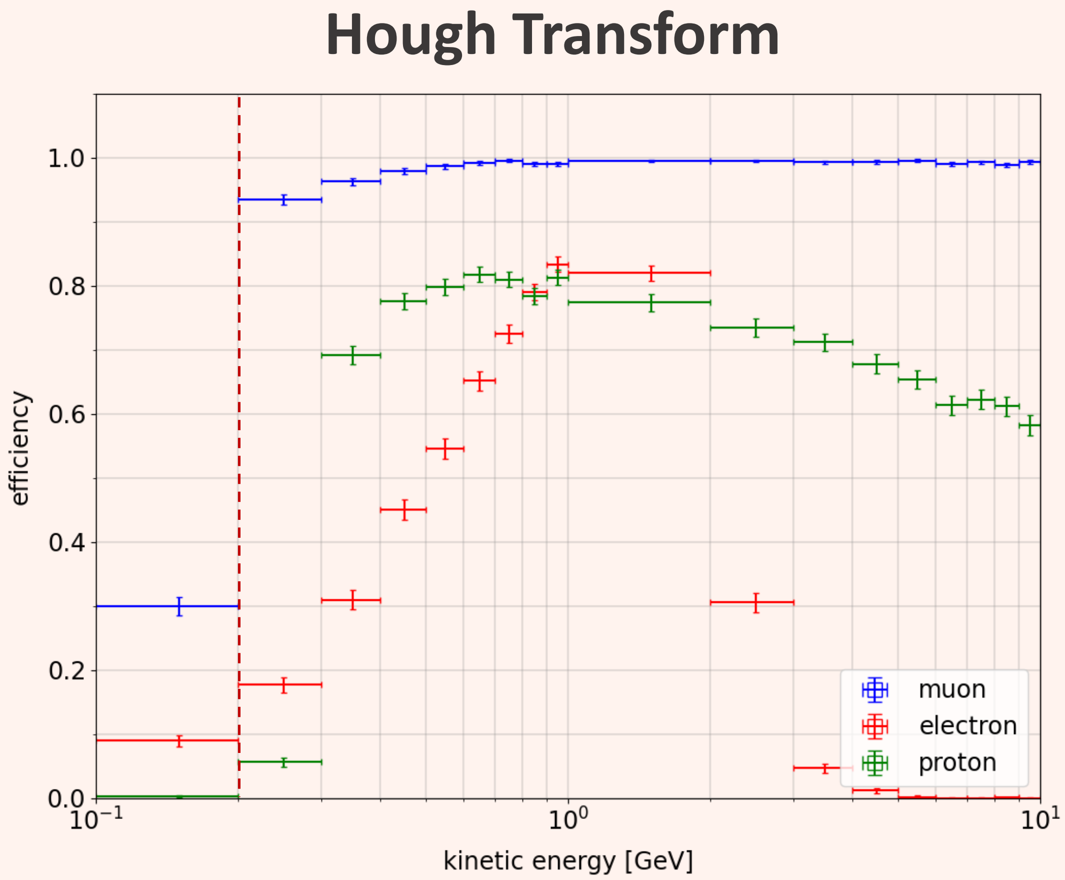
⋮

N=20



Reconstruction efficiency





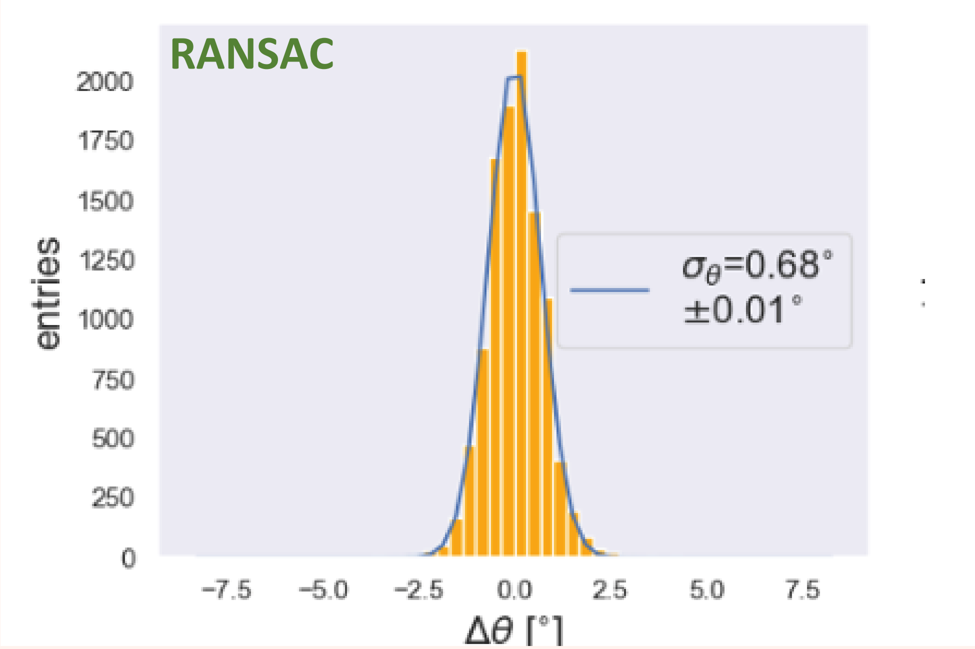
Shielding cut-off ≈ 200 MeV
☛ too low to reject ”soft” muons background

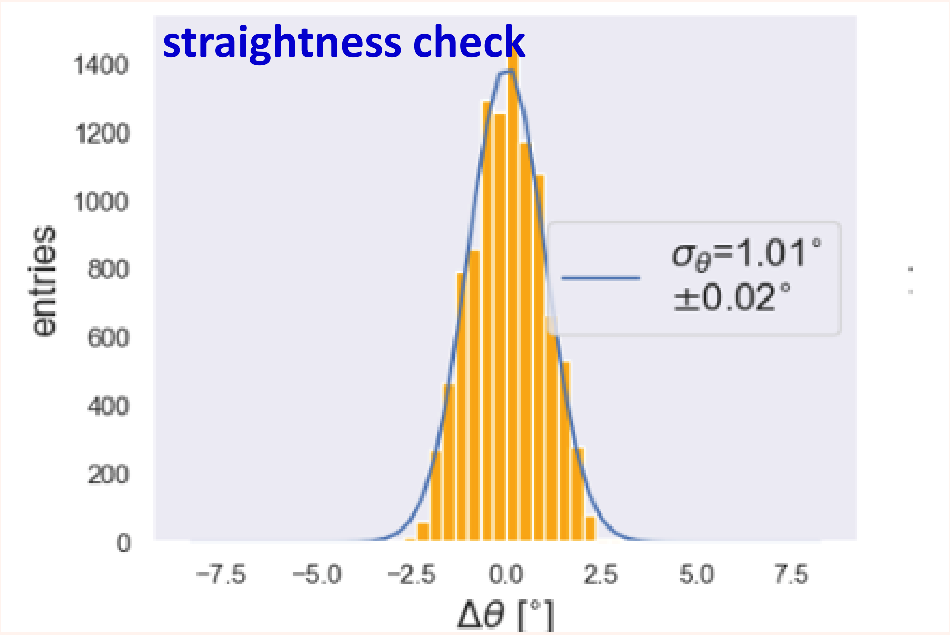
Summary performances

☛ **RANSAC** exceeds both the **Hough transform** and the **former reconstruction (straightness check)** performances in: angular resolution, electrons and protons rejection and random outlier hits mitigation.

Angular residuals

Bajou et al., 2021

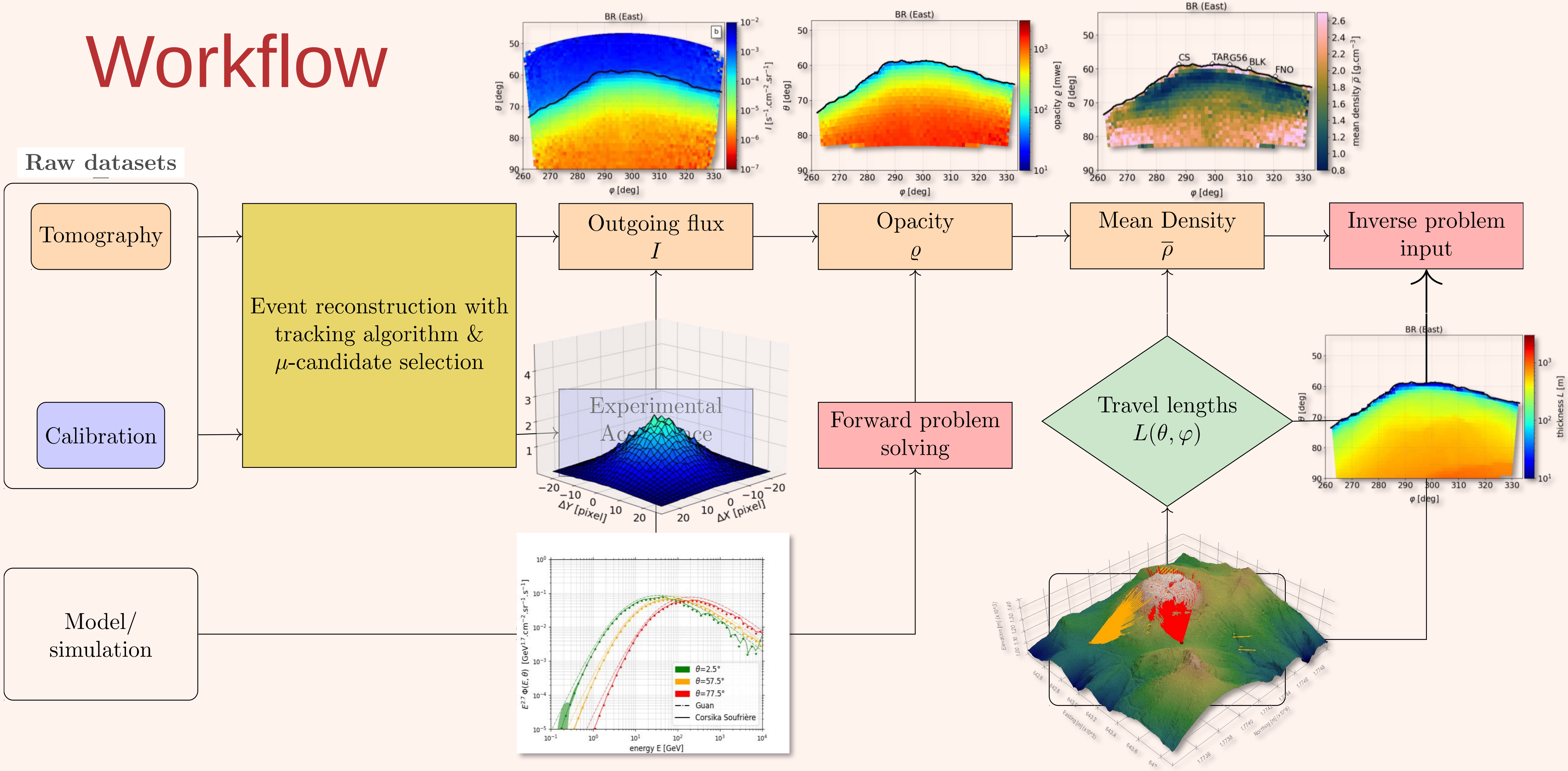




Muography of a VHS: application to La Soufrière

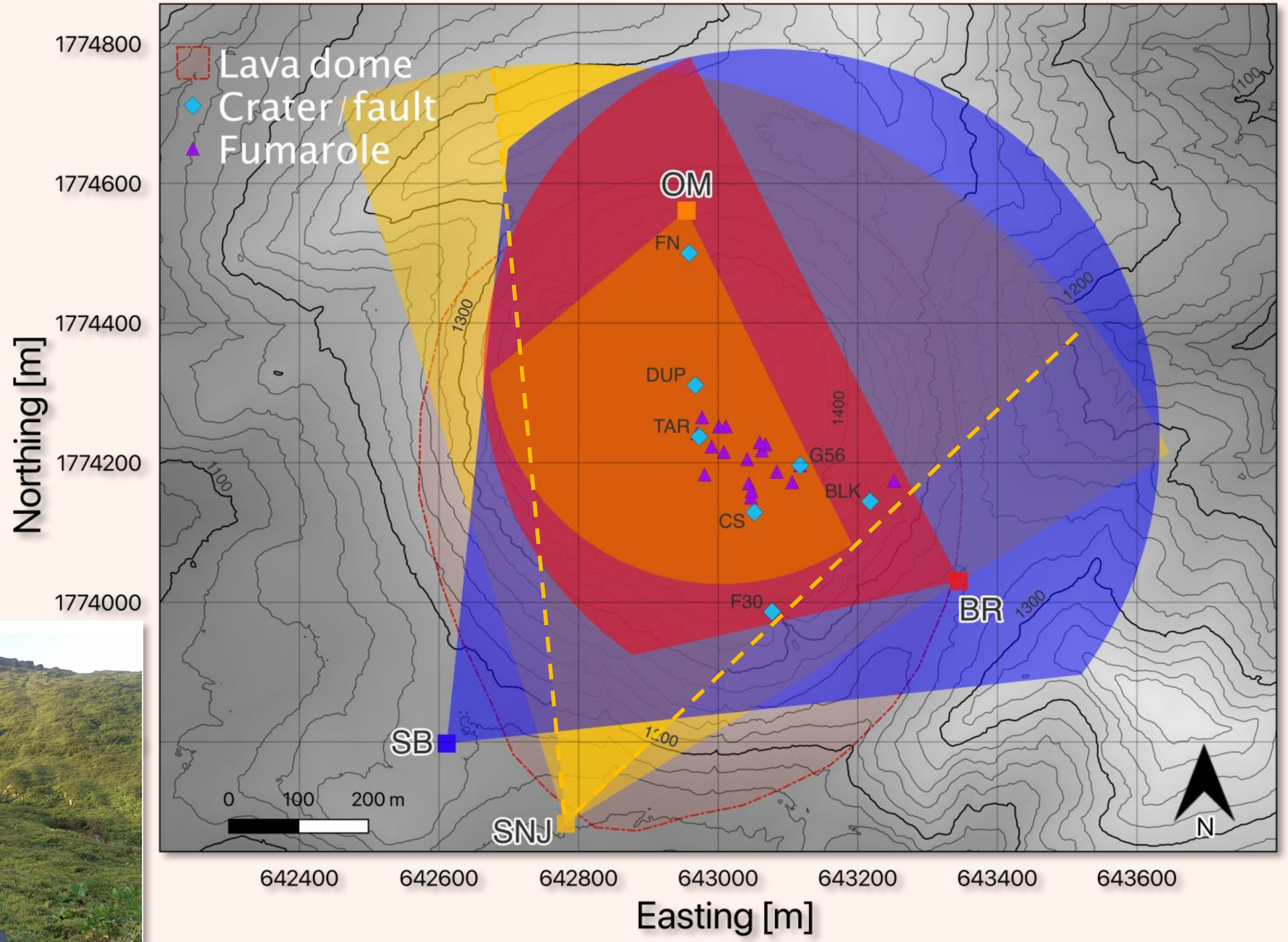
From muon counts to dome density estimates

Workflow



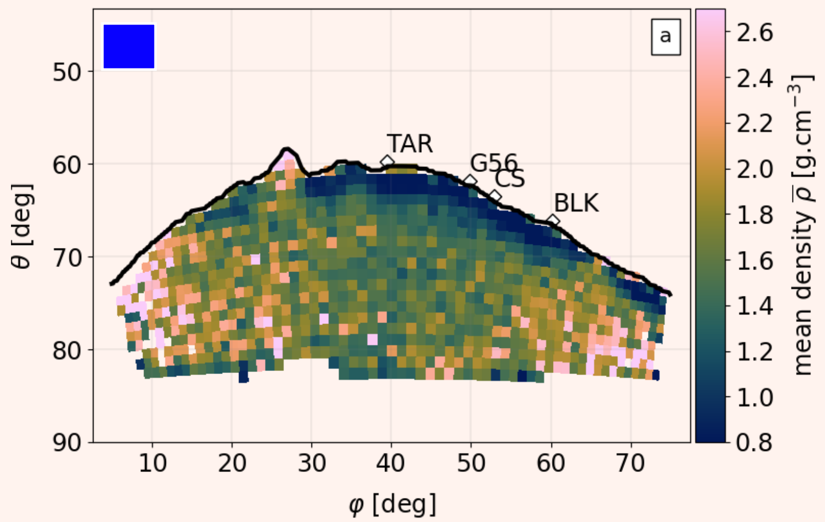
Estimated with CORSIKA

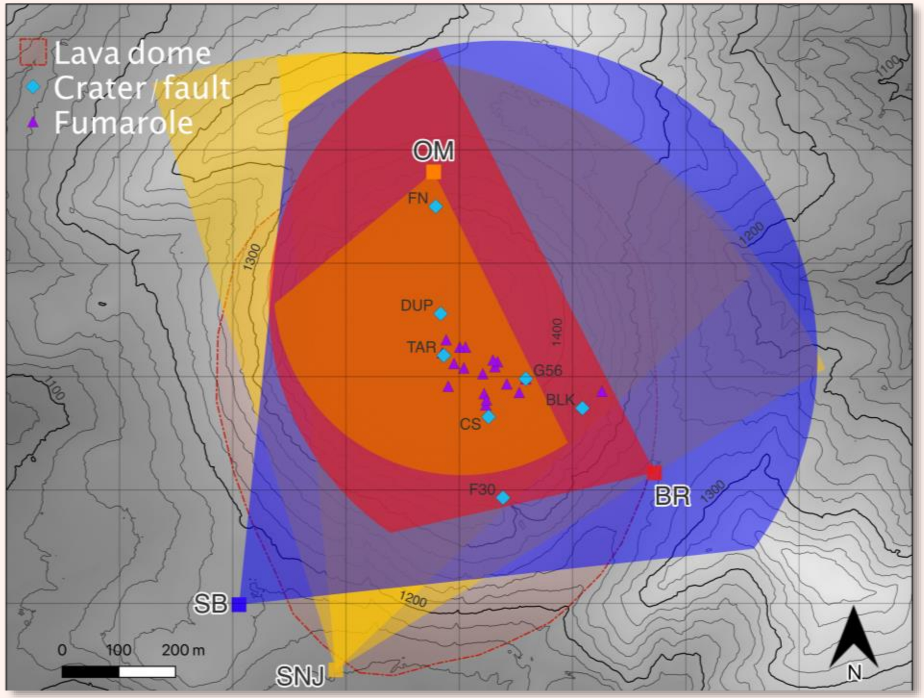
La Soufrière muon survey

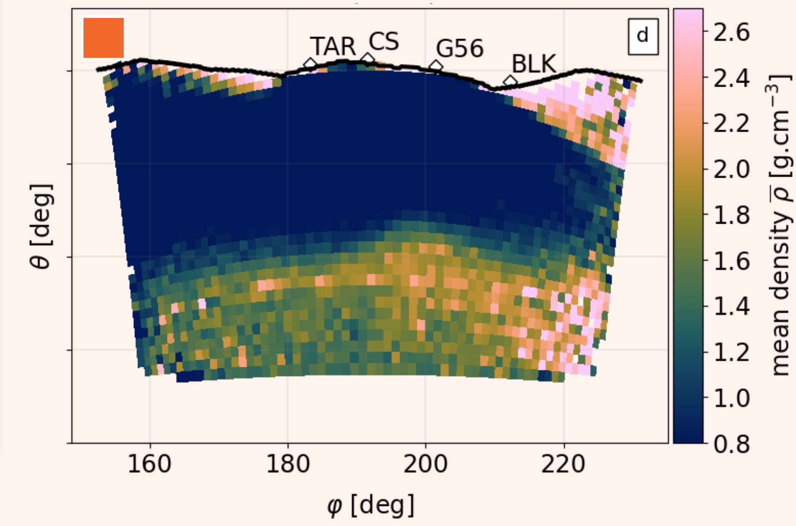


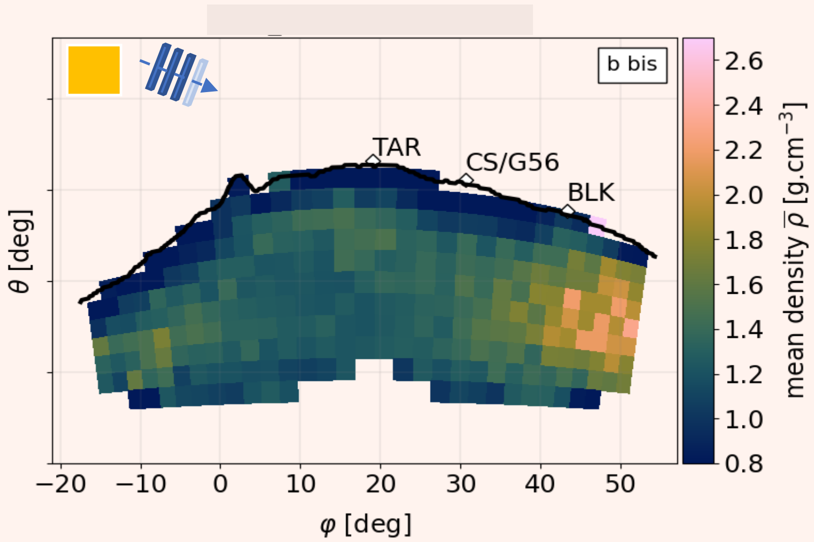
Mean density maps

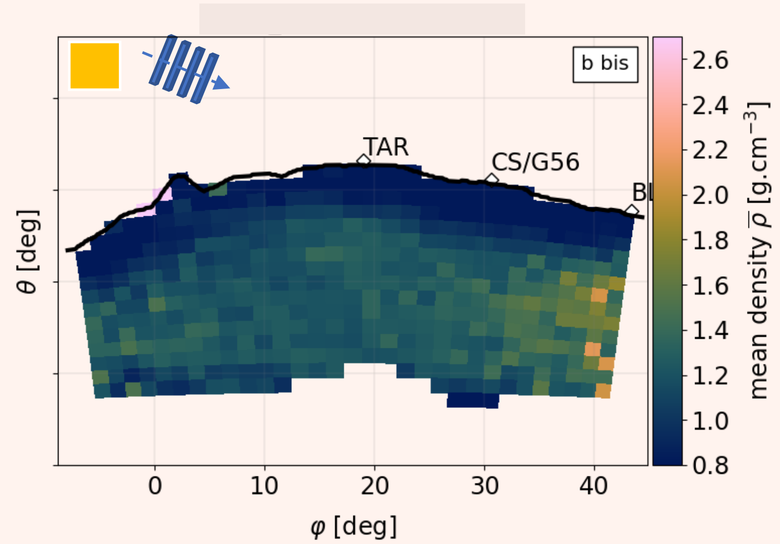
Bajou et al., *in rev.*

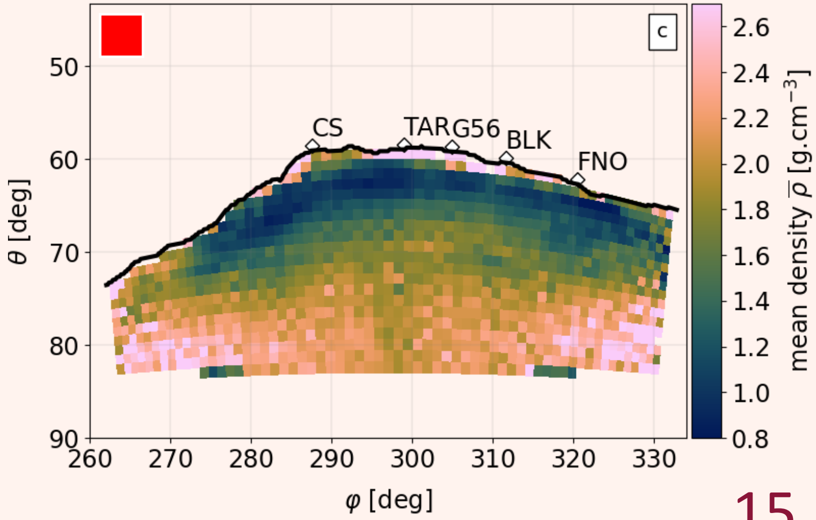




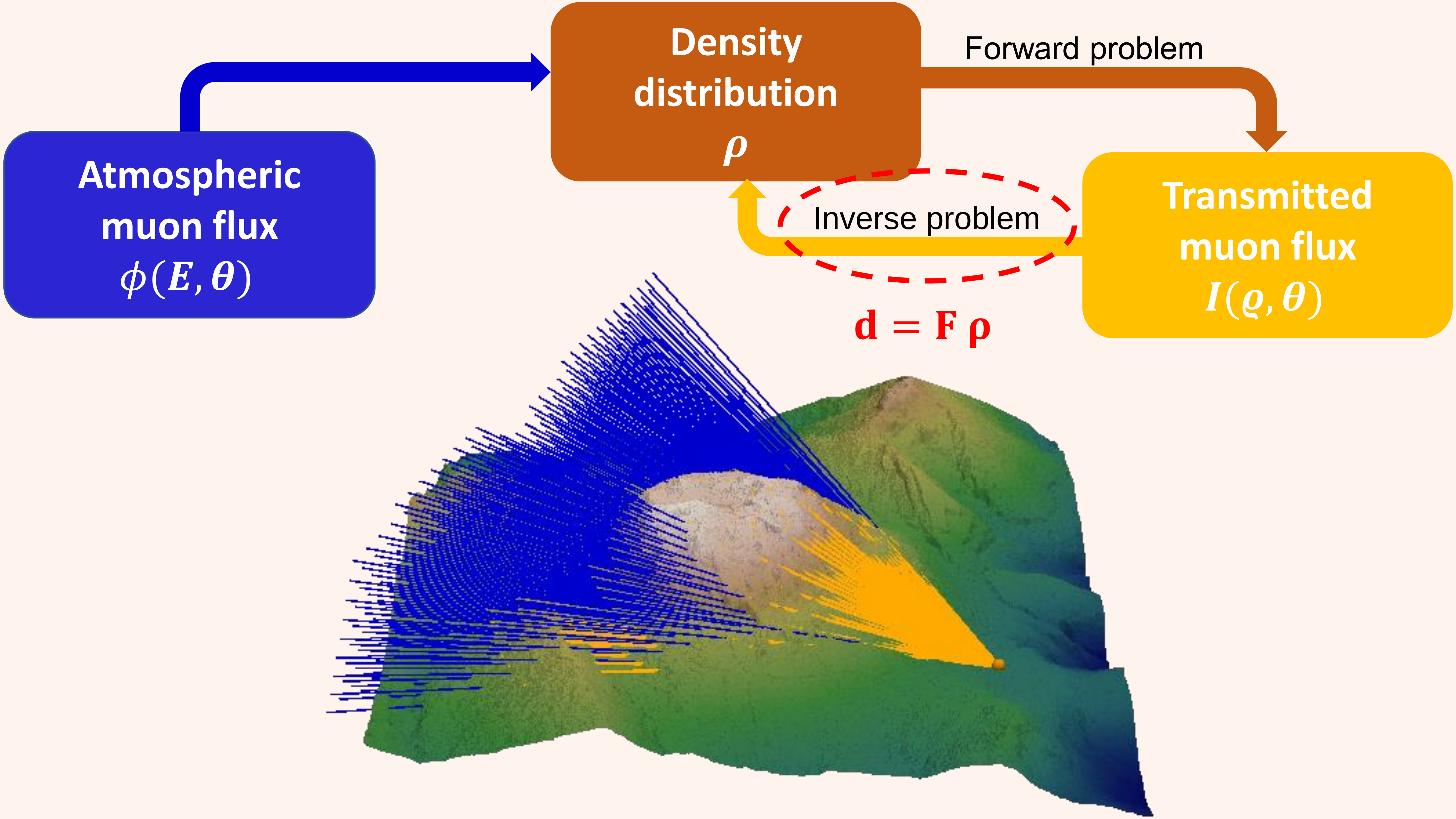






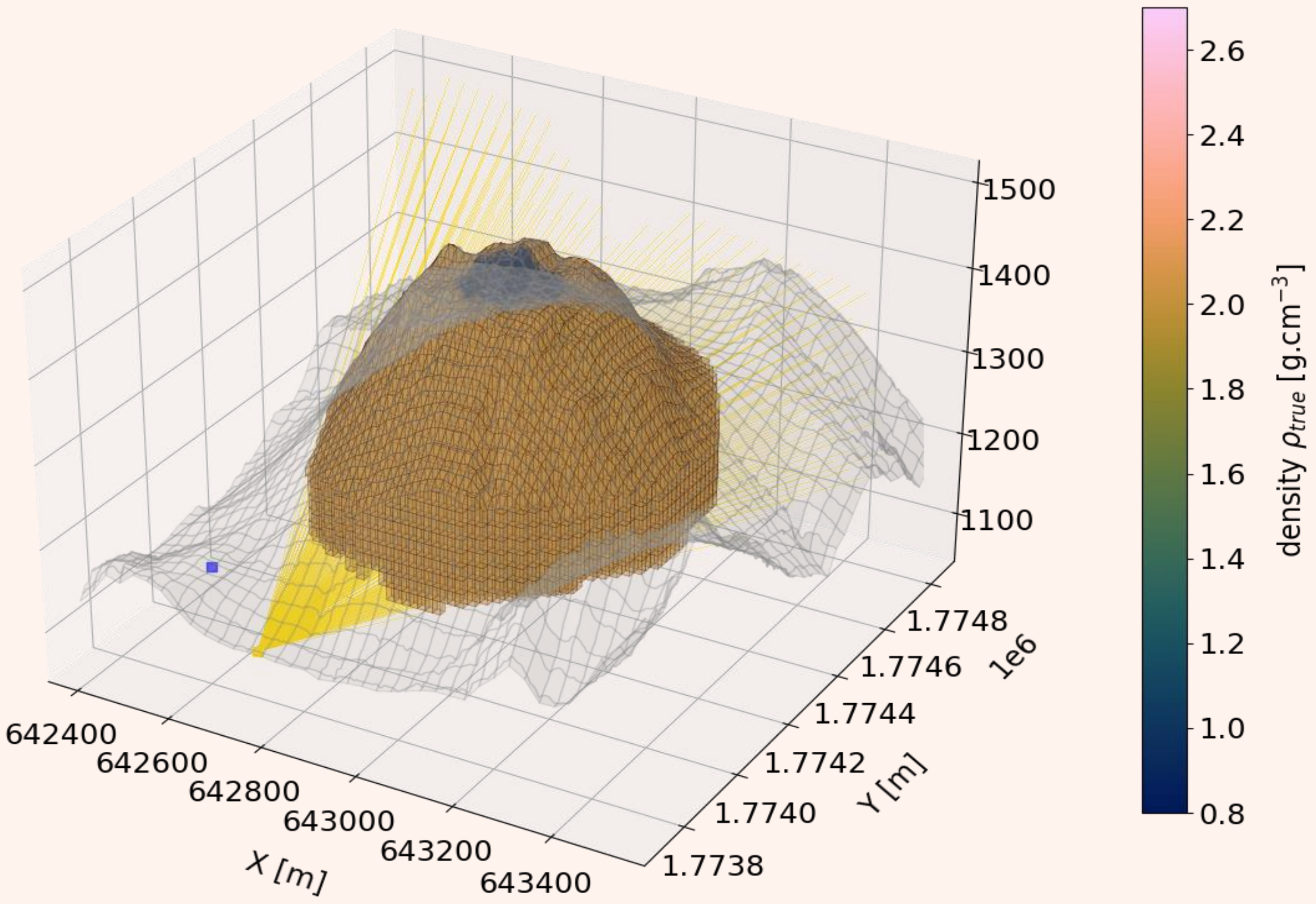


3-D Density Modeling



Lava Dome volume

- La Soufrière digital elevation model (DEM)*, 1 m resolution
- Discretized into **16032 voxels** of **16 m³**
- Total volume covered by the 4 telescopes: **1.5x10⁷ m** (~30% of the total dome volume)



* Obtained from the SHOM campaign: Litto3D (LiDAR)

Bayesian inversion (Tarantola & Valette)

Minimization cost function :

Kernel matrix — Model parameters

$$\phi = (\mathrm{d} - \mathrm{F}\rho)^T C_d^{-1} (\mathrm{d} - \mathrm{F}\rho) + (\rho - \rho_0)^T C_\rho^{-1} (\rho - \rho_0)$$

Data — Data covariance — Prior density — Model regularization covariance

Posterior density estimates

$$\tilde{\rho} = \rho_0 + (\mathrm{F}^T C_d^{-1} \mathrm{F} + C_\rho^{-1})^{-1} \mathrm{F}^T C_d^{-1} (\mathrm{d} - \mathrm{F}\rho_0)$$

Model regularization: $C_\rho(i,j) = \sigma_\rho{}^2 \, e^{-\frac{r(i,j)}{l_c}}$:

where $r(i,j)$: distance inter-voxels, $\boldsymbol{\sigma_\rho}$: prior error, $\boldsymbol{l_c}$: correlation length

☛ Tuning reg. parameters with synthetic data inversion:

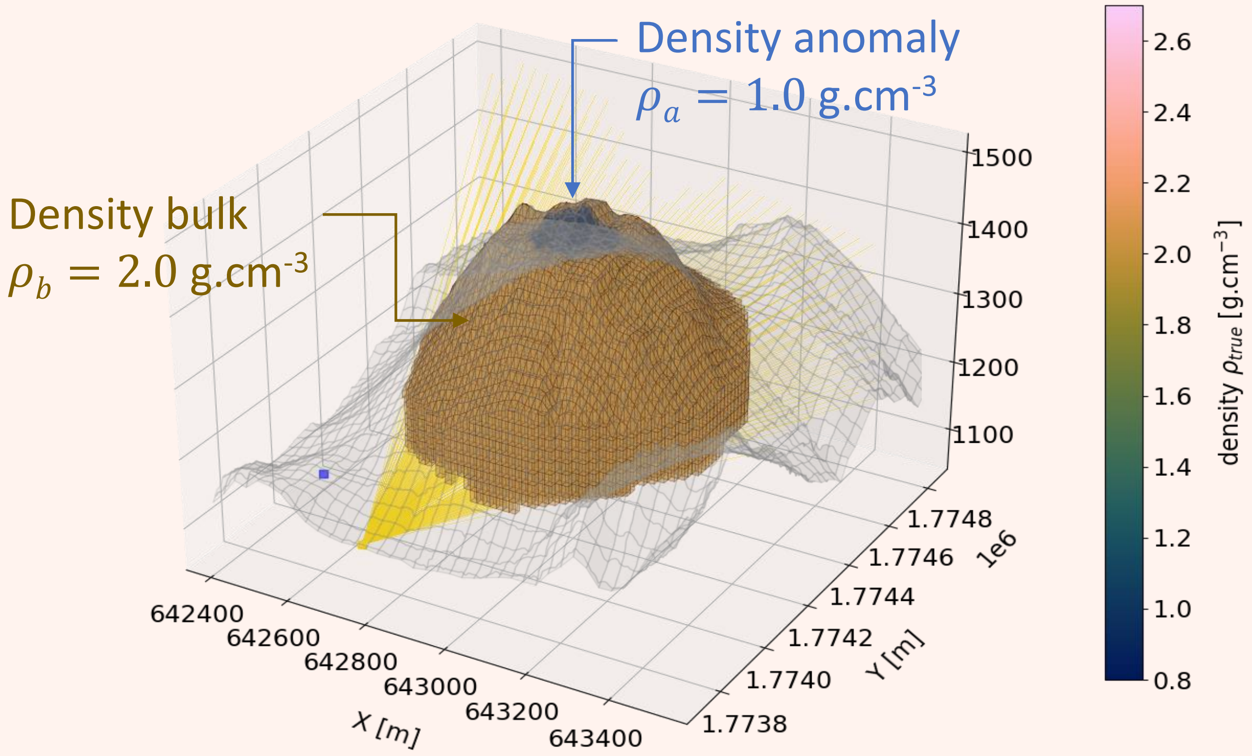
$(\boldsymbol{\sigma_\rho}, \boldsymbol{l_c})$ = (0.3 g.cm^{-3} , 200 m)

Synthetic tests

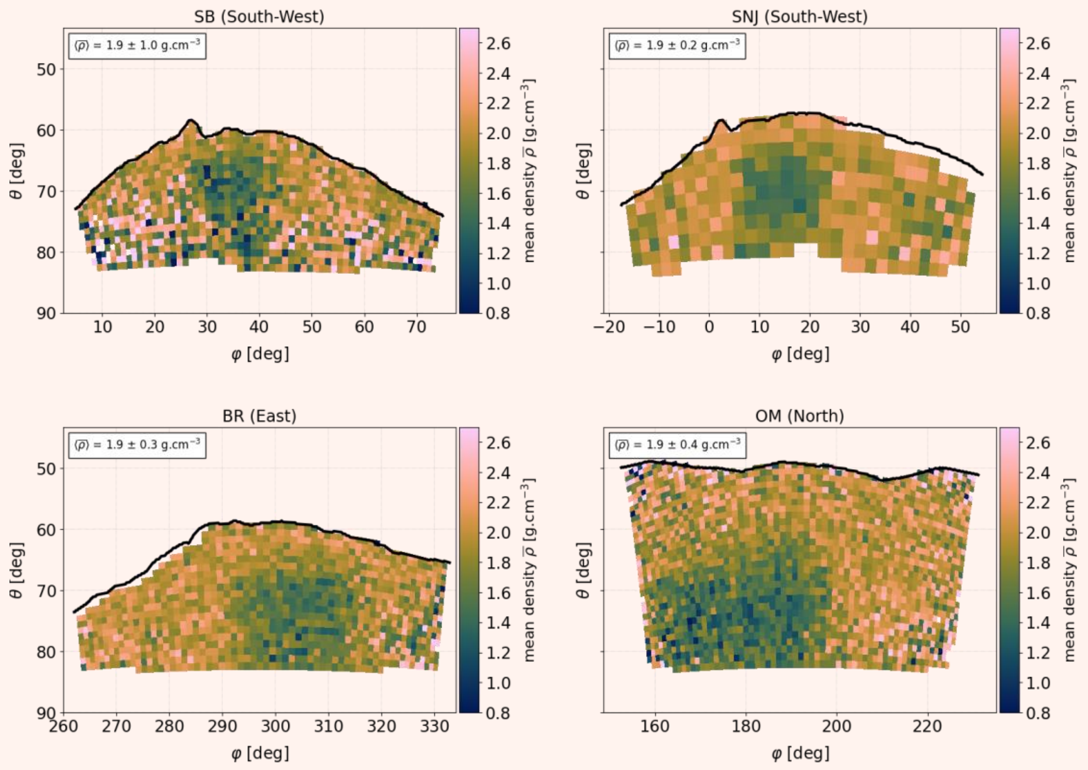
$\bar{\rho}_{\mathrm{syn}} = \rho_{\mathrm{true}} + \mathcal{N}(0, \Delta_{\mathrm{real}}\,\rho_{\mathrm{true}})$: synthetic data set

where $\mathcal{N}(0, \Delta_{\mathrm{real}}\,\rho_{\mathrm{true}})$: Gaussian noise
with Δ_{real} : total relative uncertainty on real data estimates $\bar{\rho}$

$\boldsymbol{\rho_{true}}$



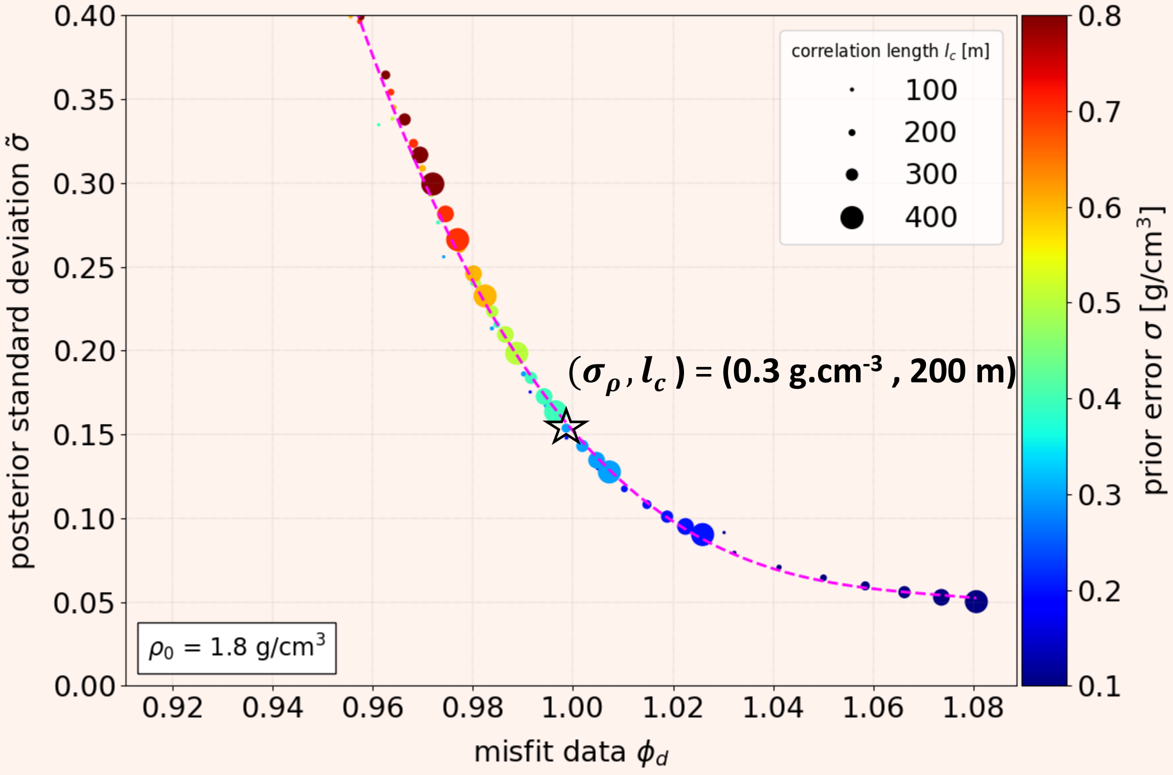
$\boldsymbol{\bar{\rho}_{syn}}$

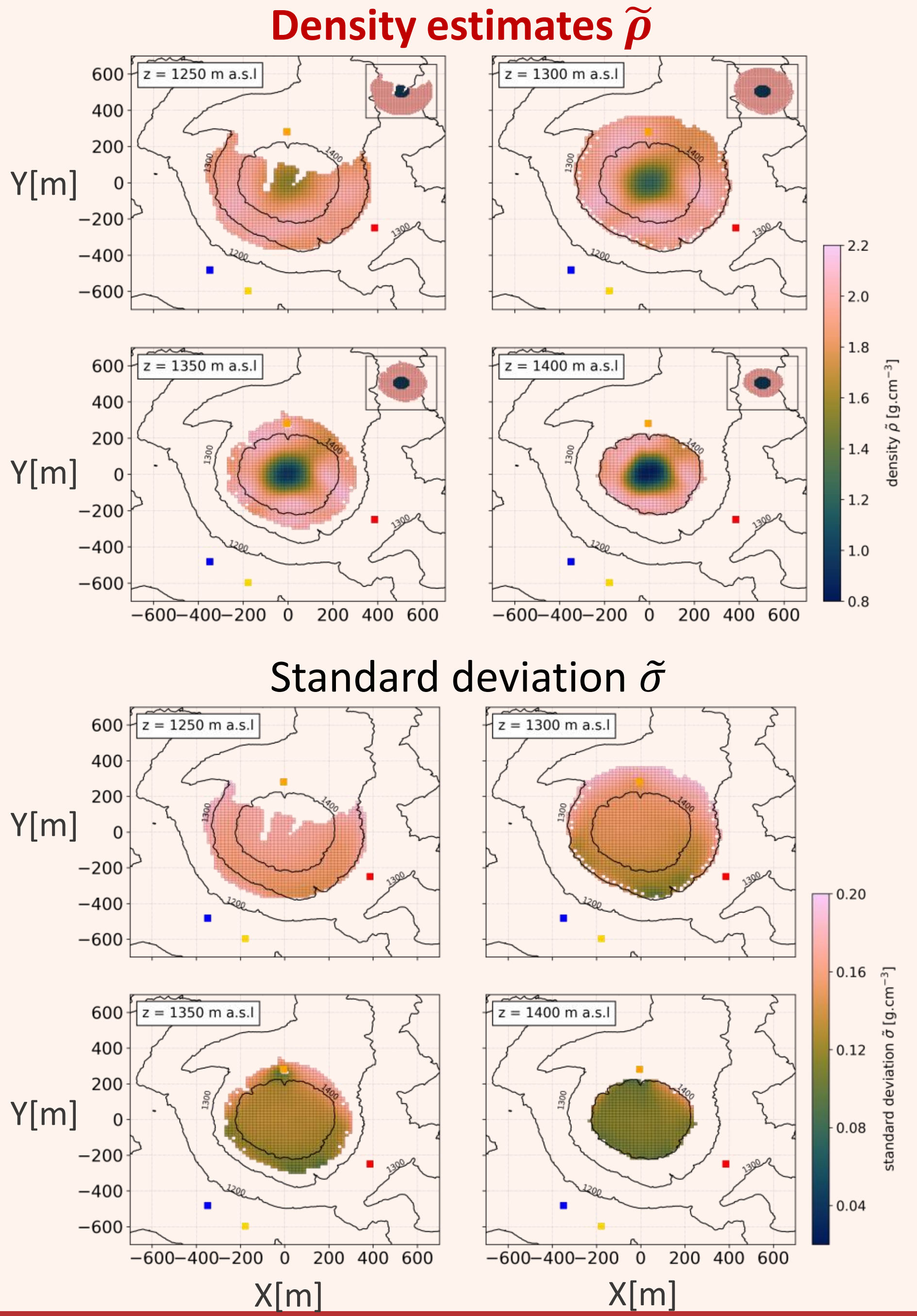


Synthetic tests

Tuning regularization parameters

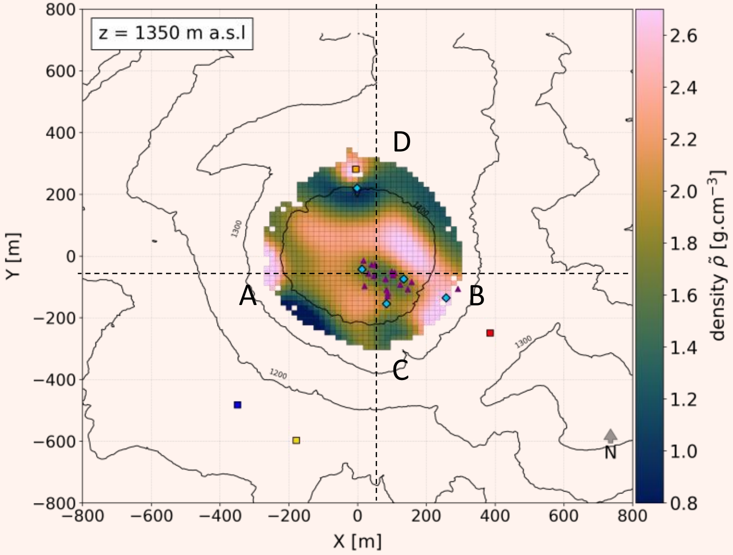
(Harris et al., 1987; Barnoud et al., 2019)



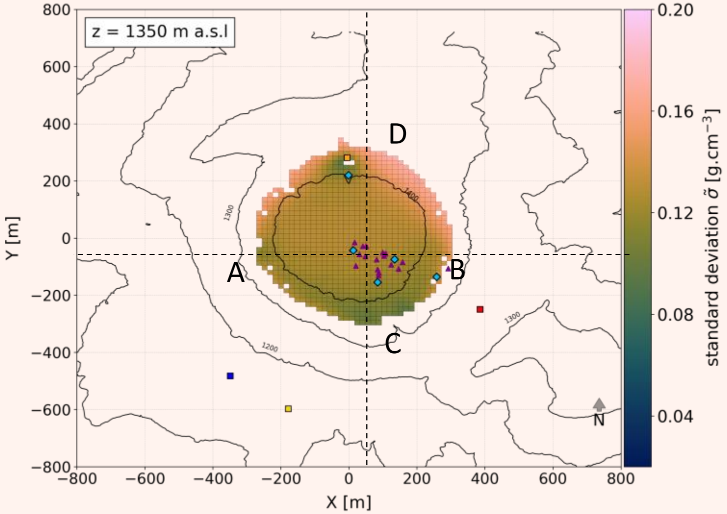


3-D Density estimates (real data)

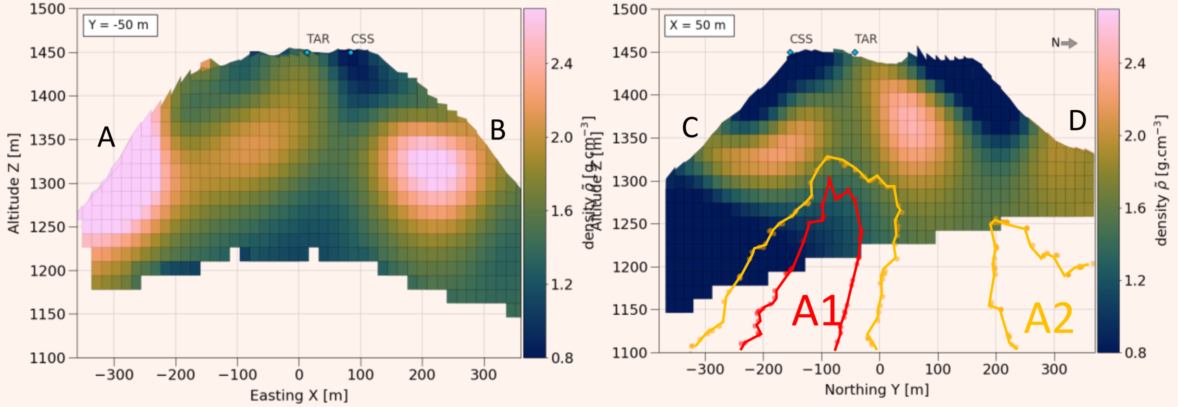
Posterior density $\tilde{\rho}$

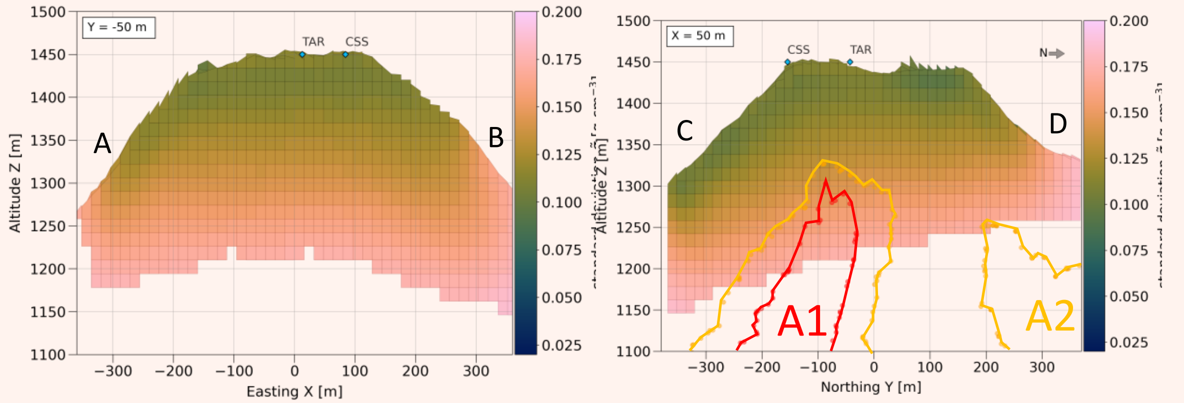


Posterior standard deviation $\tilde{\sigma}_\rho$



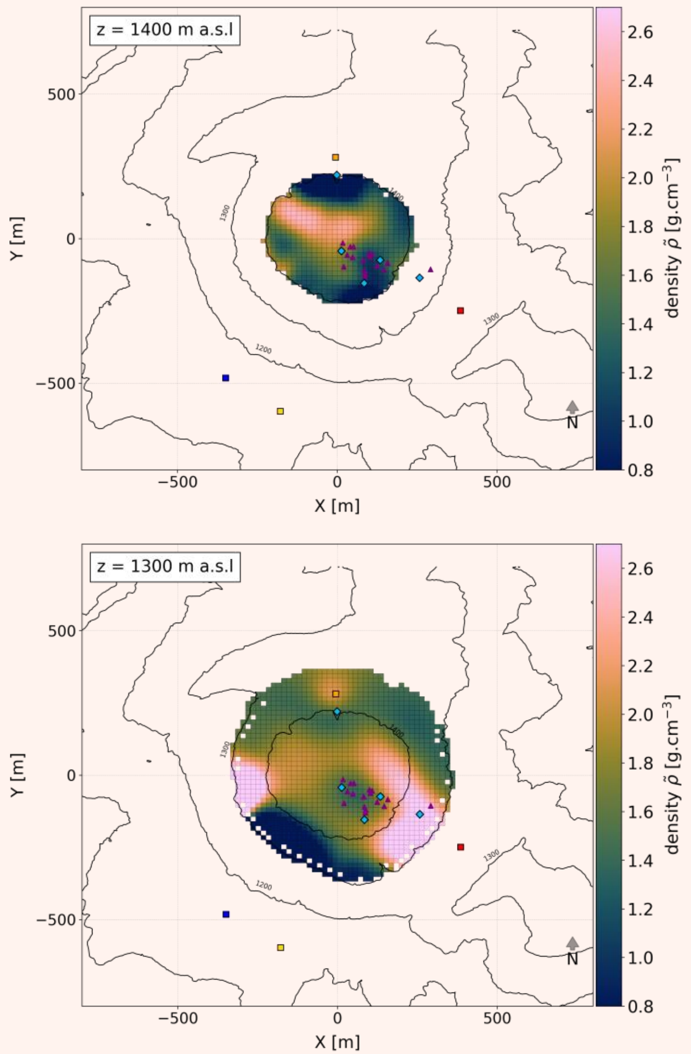
- Highest-density located on the East and West flanks
- Low-density anomaly coincides with high-conductivity conduit



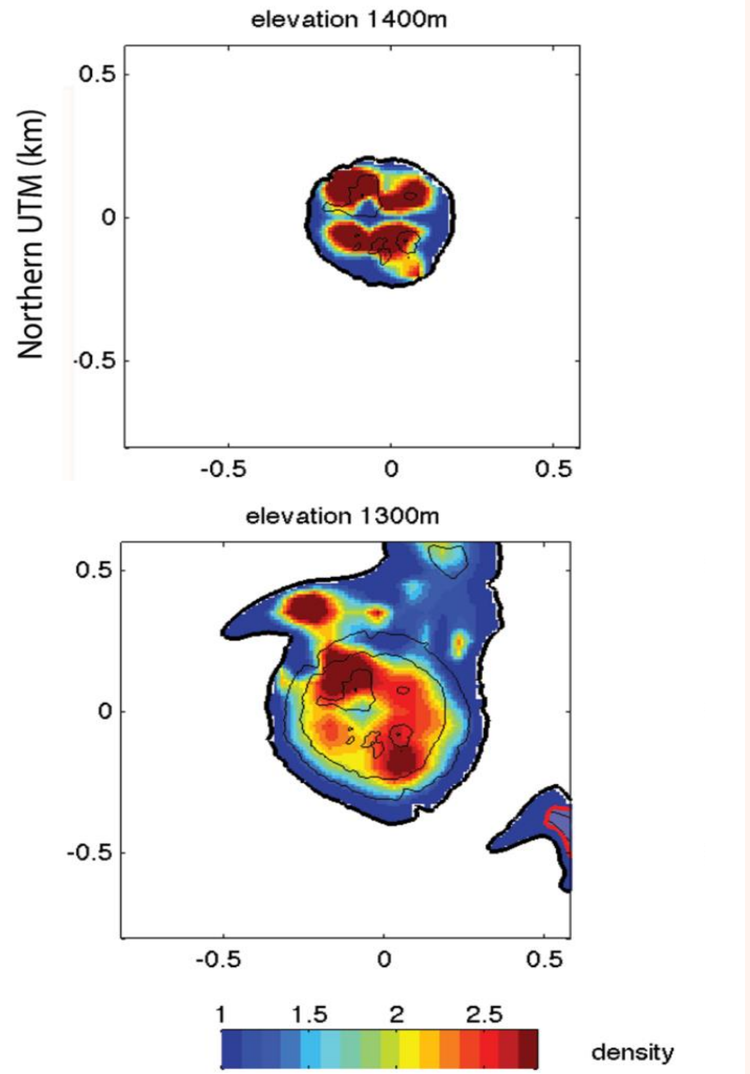


*A1, A2 : conductivity anomalies from Rosas-Carbajal et al., 2016

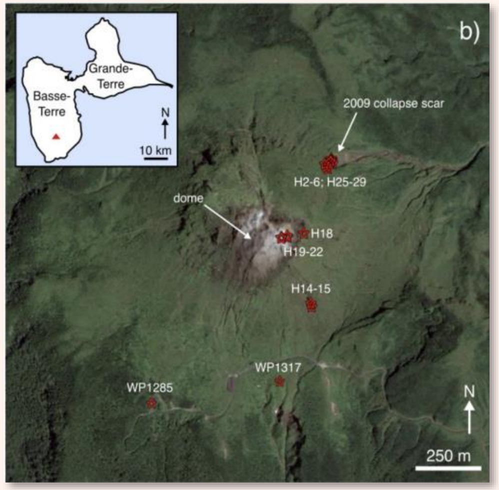
New model
4 muon telescopes data

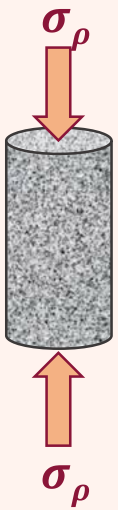


Joint P-wave velocity - gravity data
(Coutant et al., 2012)



Rock strength

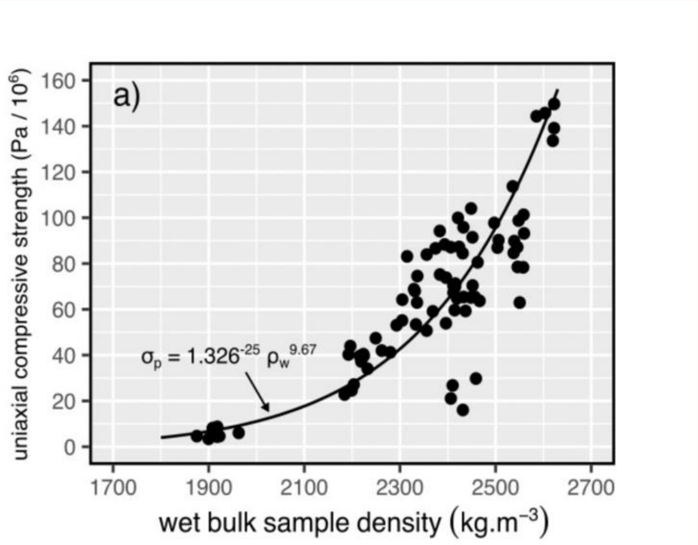




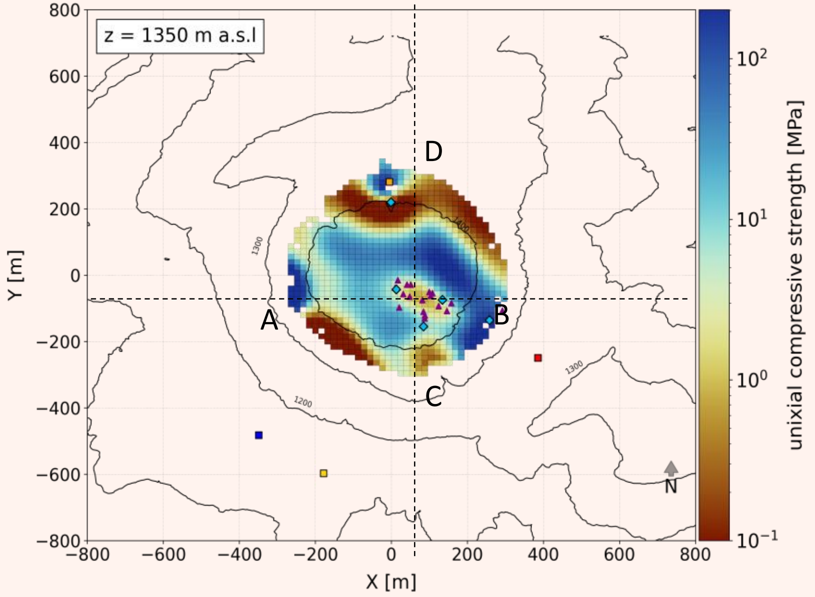
From lab measurements of uniaxial compressive strength (Heap et al. 2021) :

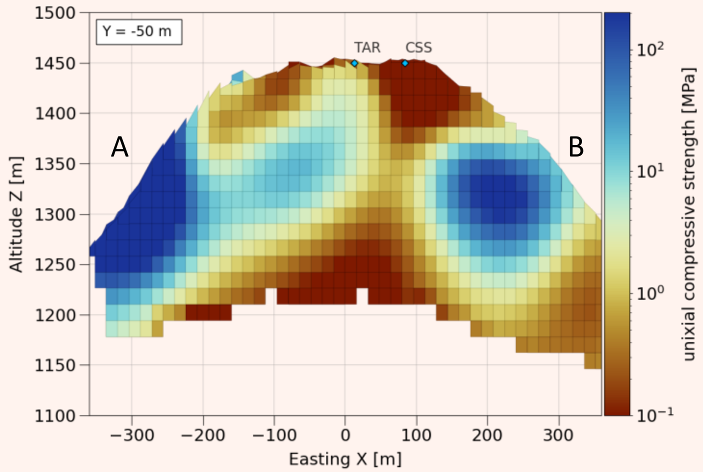
$$\sigma_\rho = C\,\rho_w^{\,9.67}$$

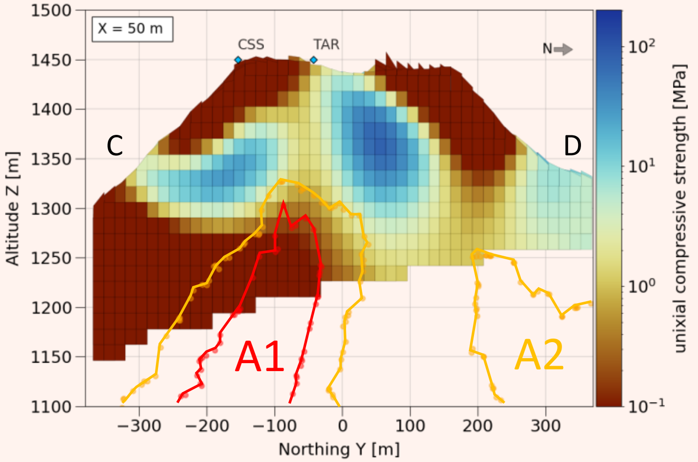
where $C = 1.326.10^{-25}$ MPa.(kg.m^3)$^{-9.67}$



From Heap et al. 2021

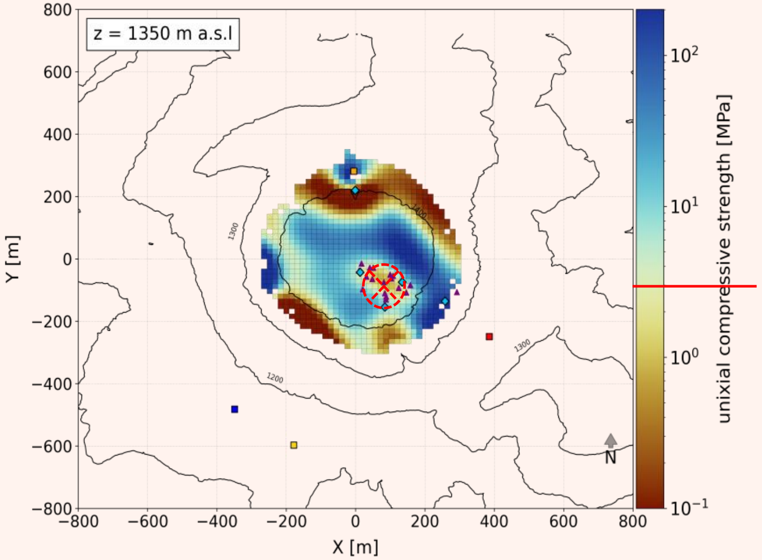




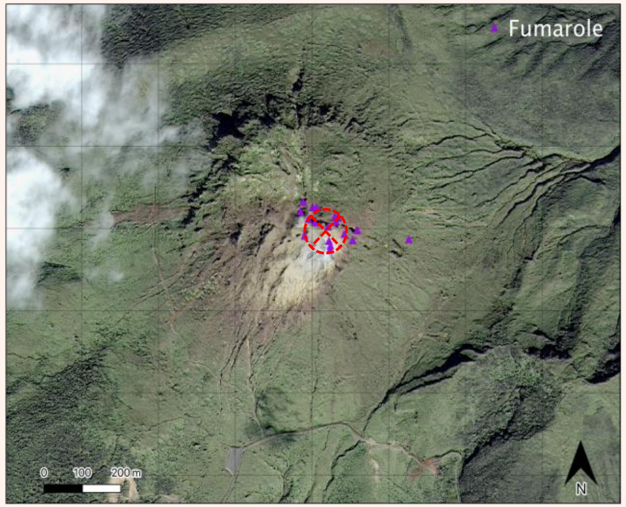


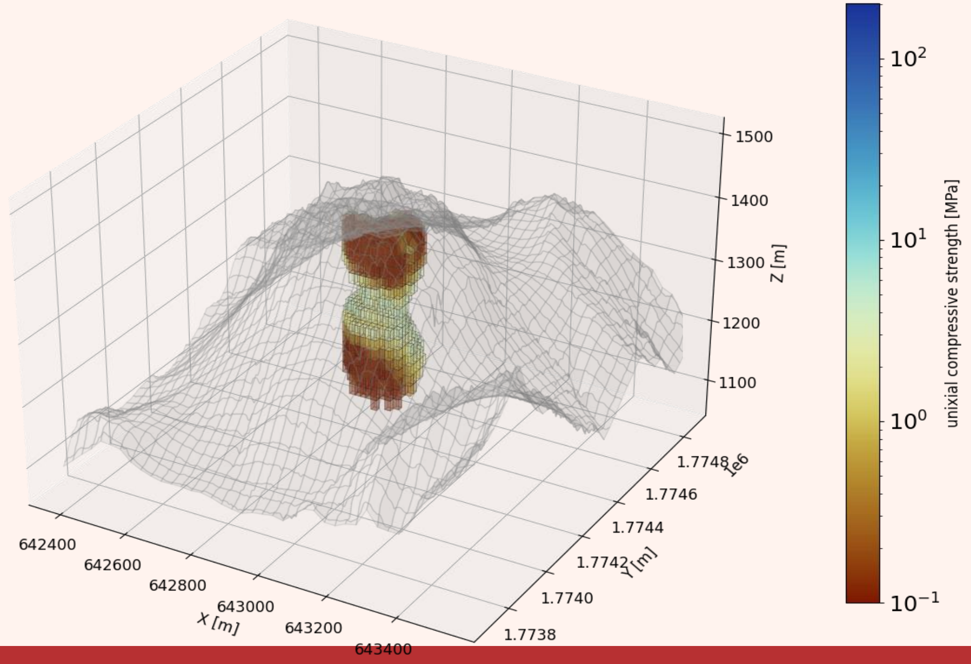
*A1, A2 : conductivity anomalies

Cratère Sud anomaly volume



3MPa (*)





Detection of Southern low-strength anomaly (< 3MPa, Heap et al. 2021) covering **8.1-12.8%** of the dome's total volume

(=5.10^{7}m^3, Boudon et al. 2008)

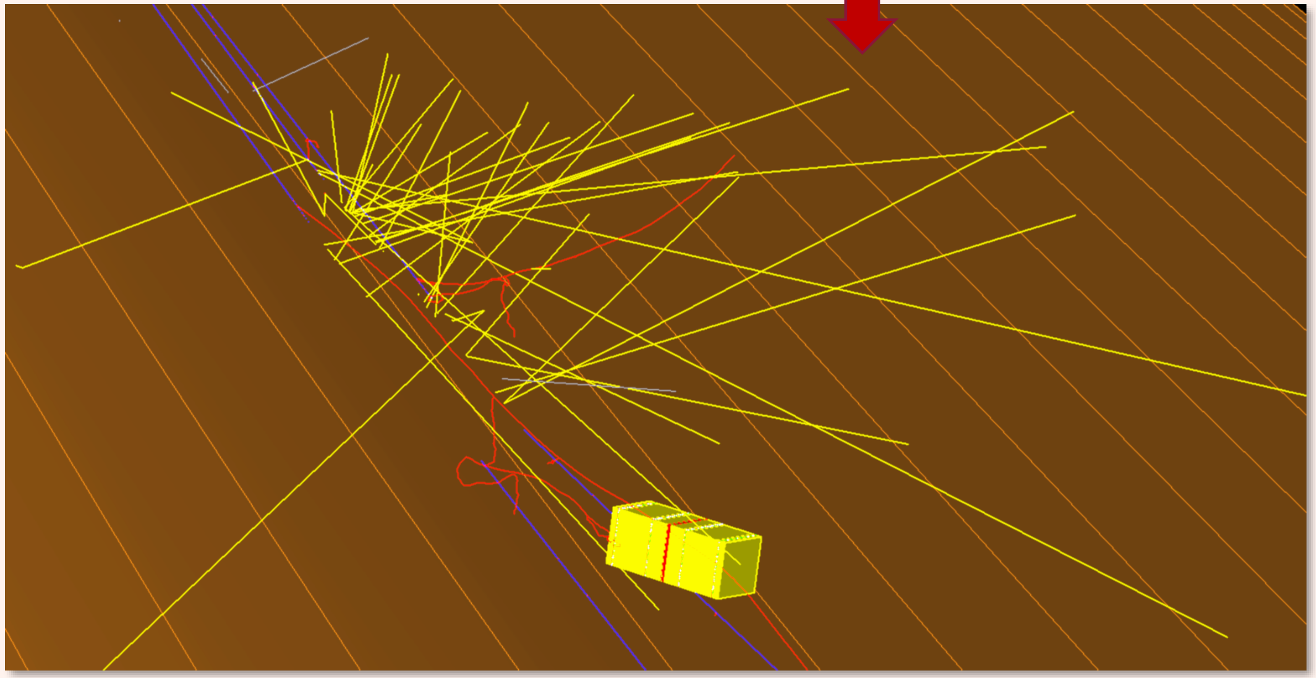
(*) Heap et al. 2021

Perspectives

Improve absolute density estimation

Background characterization improvement :

☛ Correction from low-energy particle scattering estimation



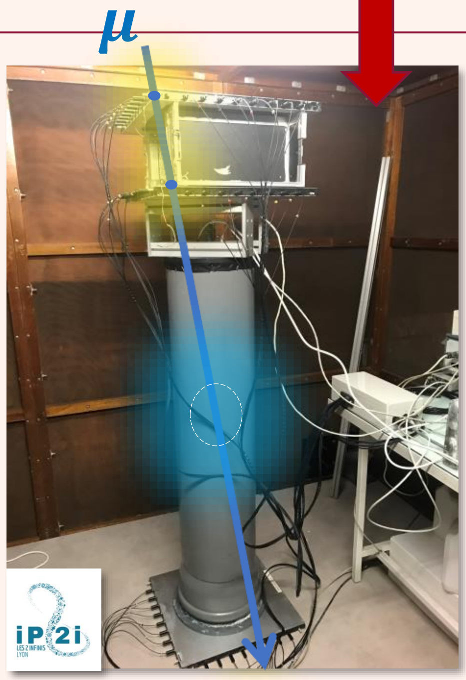
200 MeV muon scattering on standard rock

Future developments

Development of a **water-Cherenkov tank** to replace the passive lead shielding

GOAL: improve the rejection of GeV electron

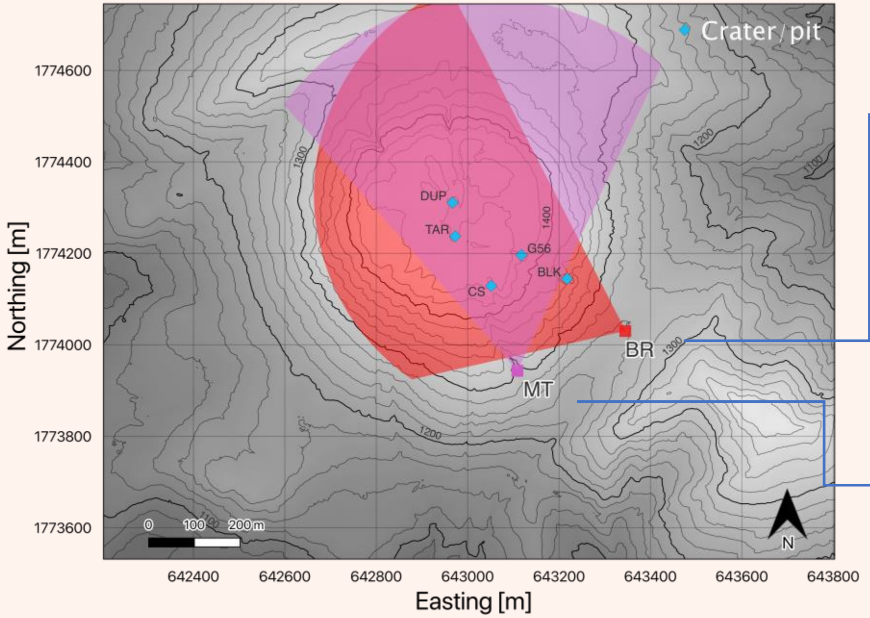
(cf. T. Avgitas' presentation)

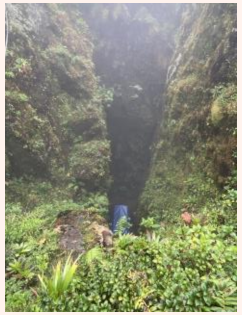


Perspectives

- Towards monitoring: temporal flux variations (Jourde et al., 2016)
- Combination with other geophysical data (e.g. gravimetry surveys)

- Current data taking:





Summary and Outlook

- La Soufrière = ideal natural laboratory to apply and develop muography
- Improved and versatile data processing (tracking) and Monte-Carlo simulation pipelines to assess detector performances
- The first inversion of muon data with a wide 4-telescope coverage
- Low-density anomaly in the Cratère Sud region corresponding to the most active and mechanically weak zone on La Soufrière dome summit (8-12% of the dome total volume)

Future developments

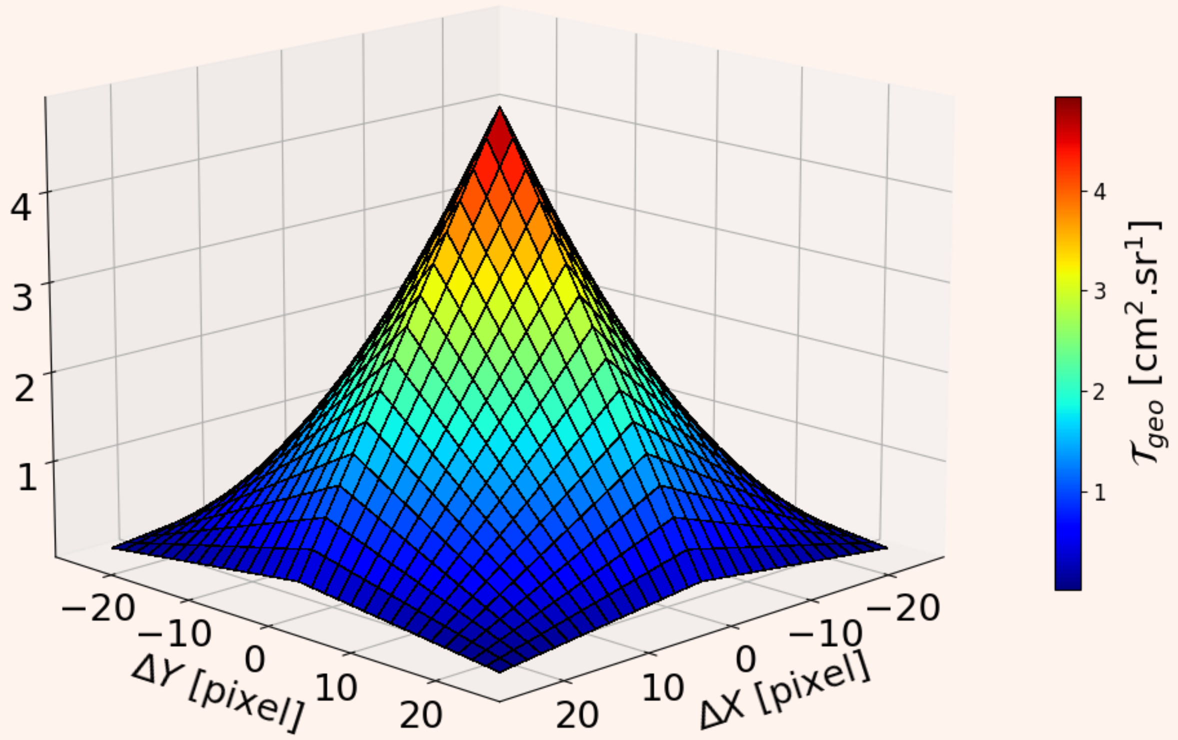
- Instrumental upgrades and better rejection of the low-energy physical background
- Temporal monitoring
- Joint-inversion with gravimetry data

Backup slides

Experimental acceptance

To correct for the telescope detection efficiency in the transmitted flux estimation, we assess an **experimental acceptance $\mathcal{T}_{exp}$** from the ratio between the open-sky event rate and a reference open-sky flux.

Geometrical acceptance $\mathcal{T}_{\text{geo}}$

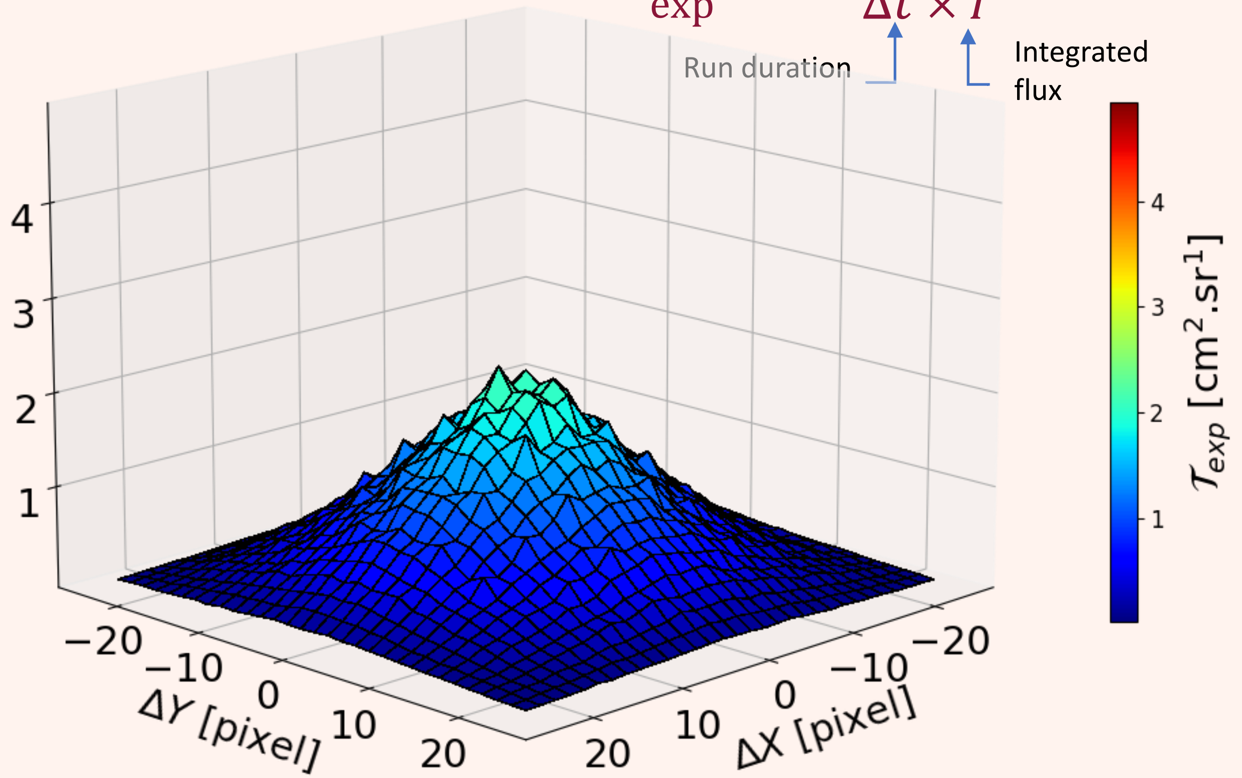


Experimental acceptance $\mathcal{T}_{\text{exp}} = \frac{N^{OS}}{\Delta t \times I^{OS}}$

Number of detected particles

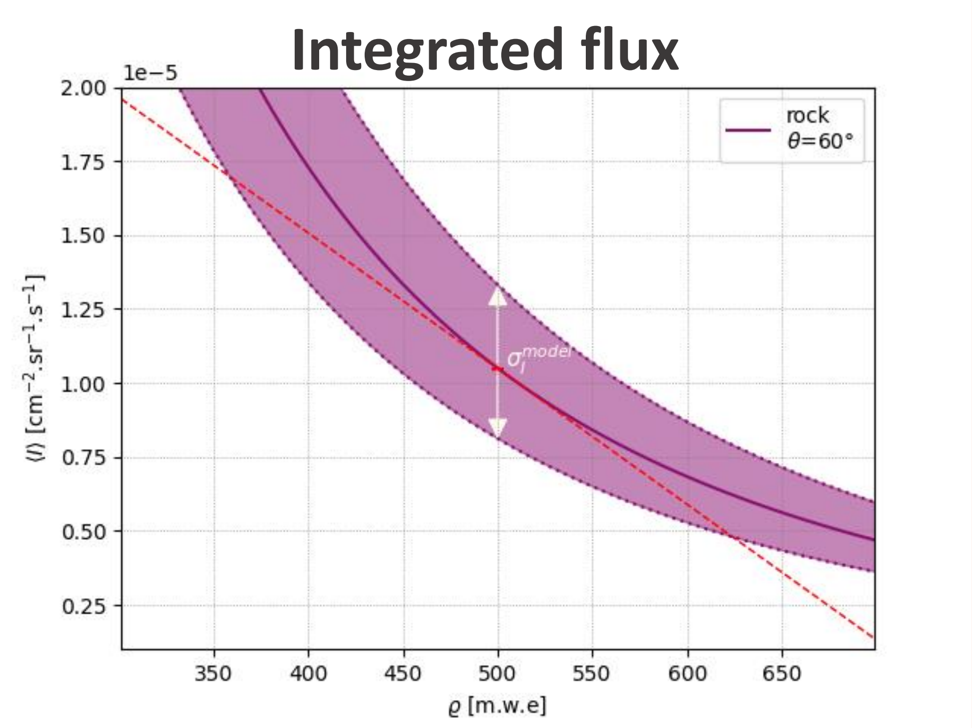
Run duration

Integrated flux



Here for a 4-panel telescope

Systematic effects



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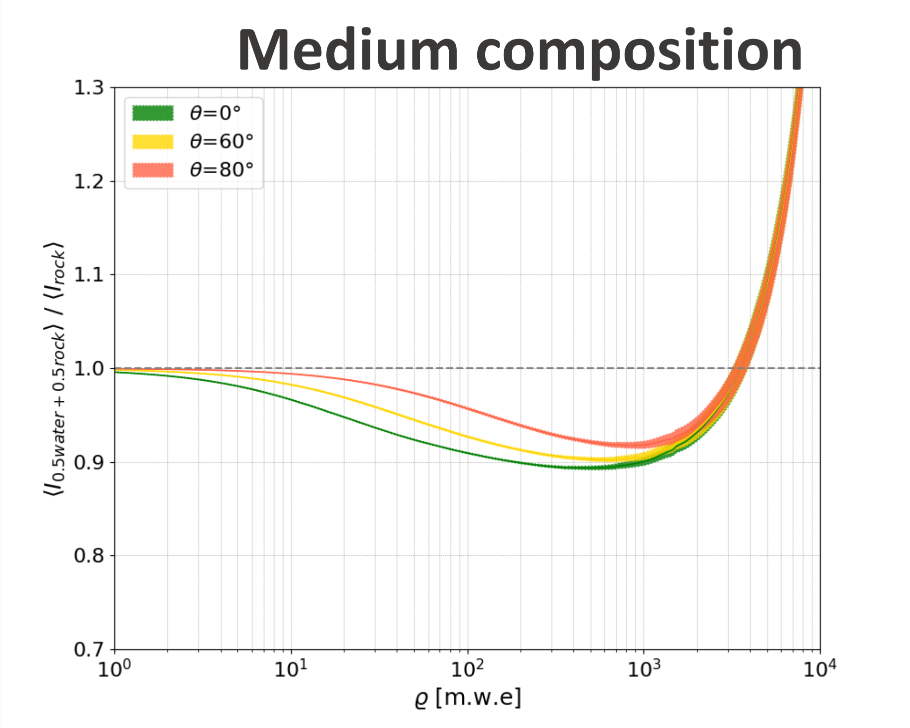
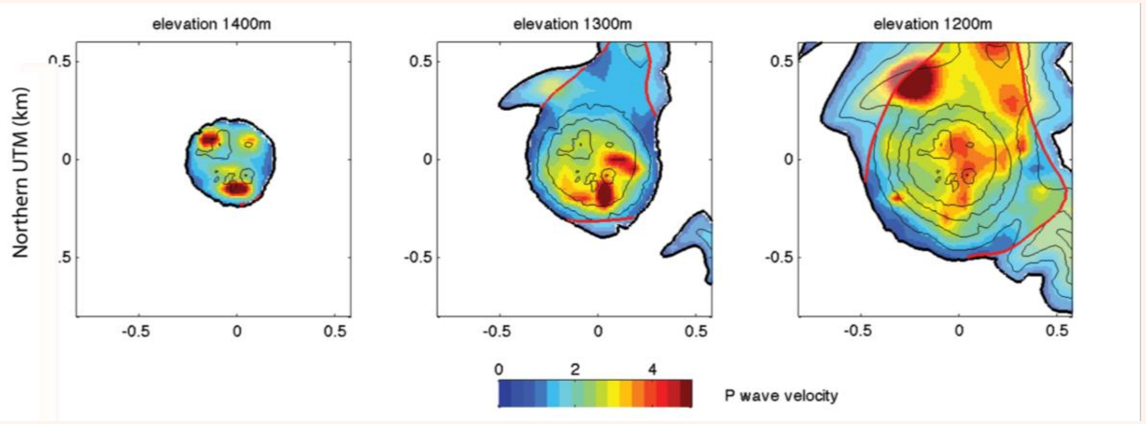


+ Telescope orientation

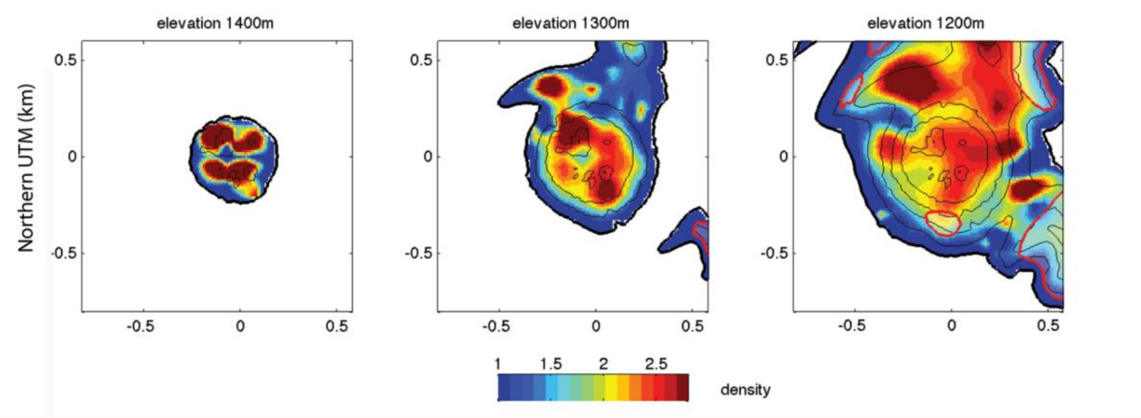
+ Detection efficiency ☛ acceptance $\mathcal{T}_{\text{exp}}$

Structural characterization with tomography

Seismic P-waves velocity model

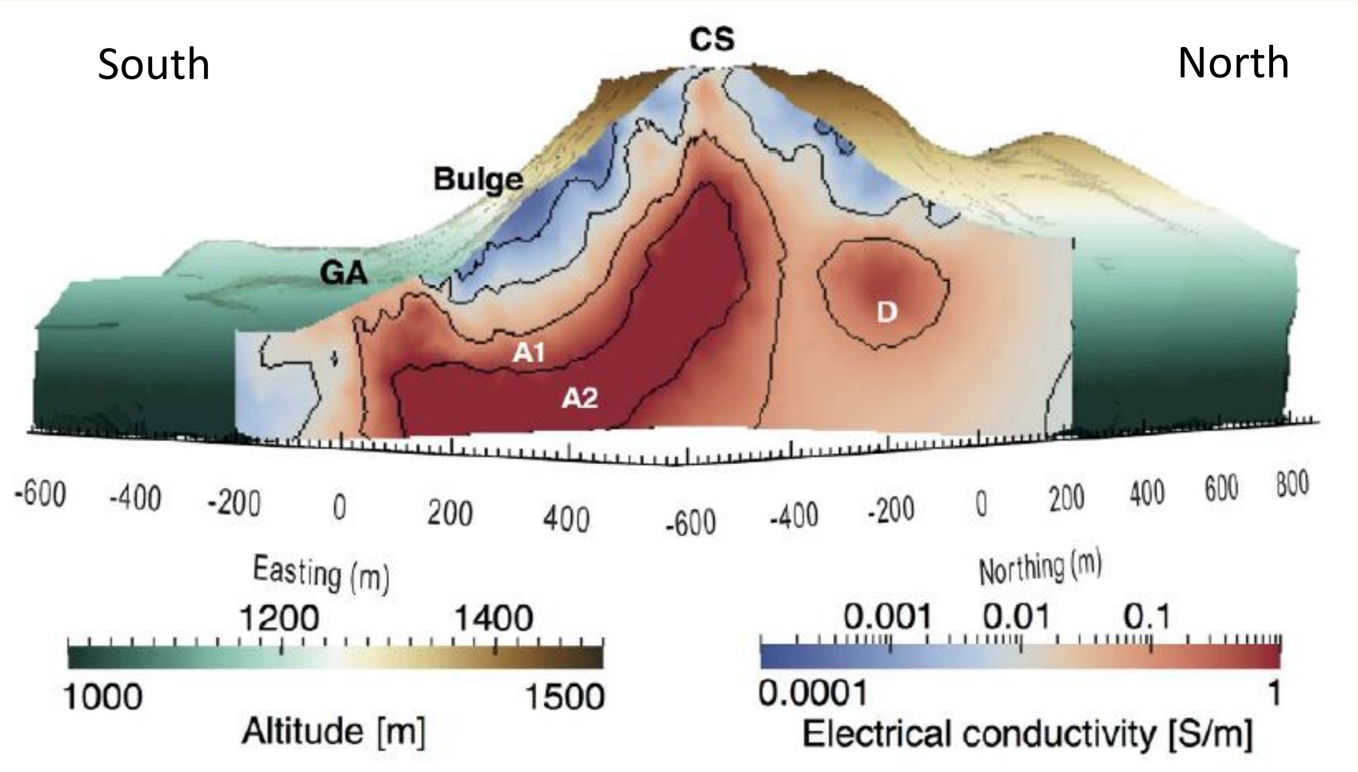


Density model (velocity + gravimetry data)



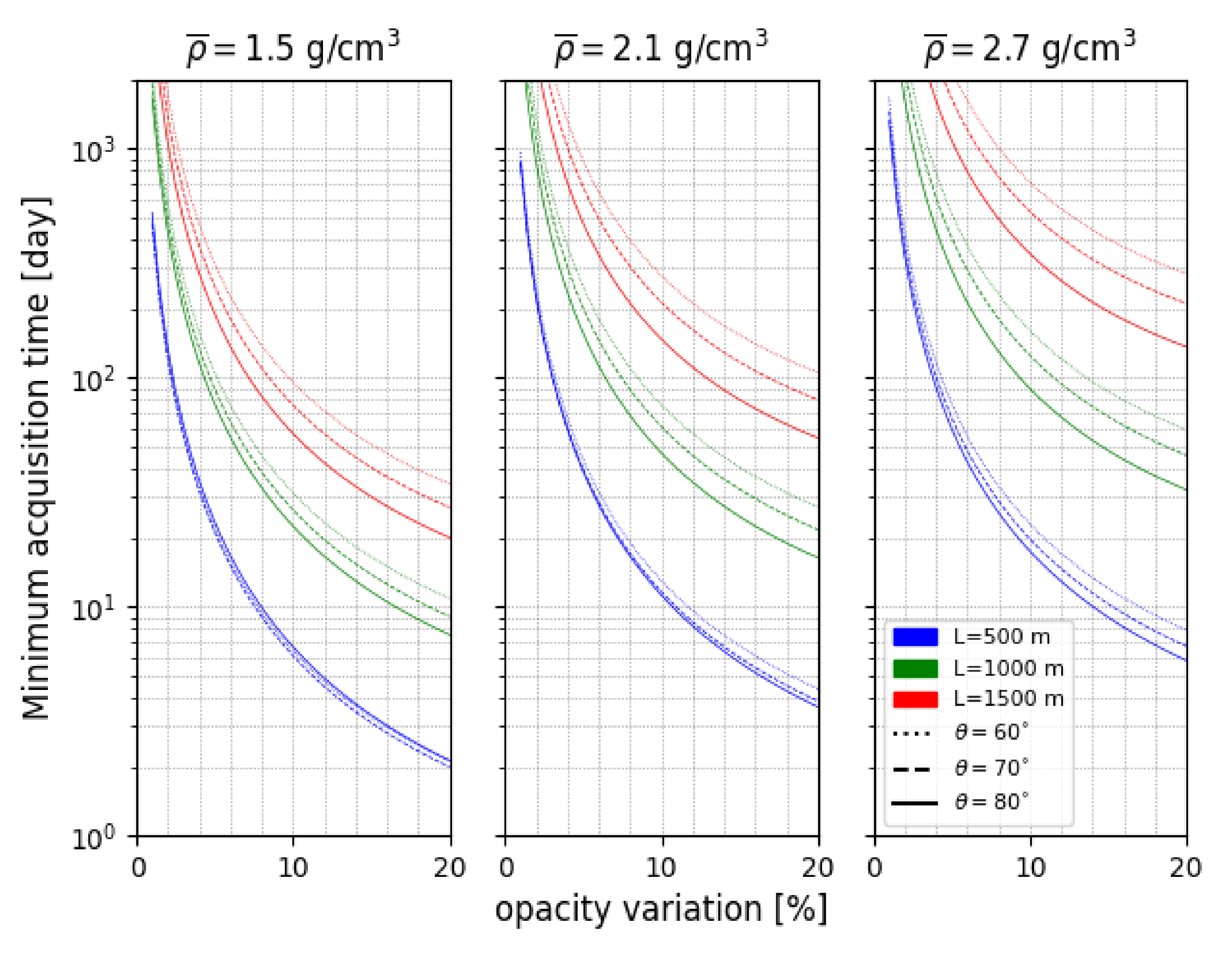
Coutant et al. 2012

Electrical conductivity model



Rosas-Carbajal et al. 2016

Minimal acquisition time



$$\Delta T > \frac{\gamma^2}{\mathcal{T}_{geo}} \frac{I(\varrho)}{\Delta I(\varrho,\Delta\varrho)^2}$$

(Lesparre et al.2010)

where

γ : number of Gaussian standard deviations,

$\mathcal{T}_{geo}$: the geometrical acceptance,

$I(\varrho)$: integrated muon flux over $[E_{min}(\varrho), +\infty[$,

and $\Delta I(\varrho, \Delta\varrho) = I(\varrho + \Delta\varrho) - I(\varrho)$ i.e is the variation of flux linked to a

$\Delta\varrho$ shift in opacity.

Comparison tracking algorithms

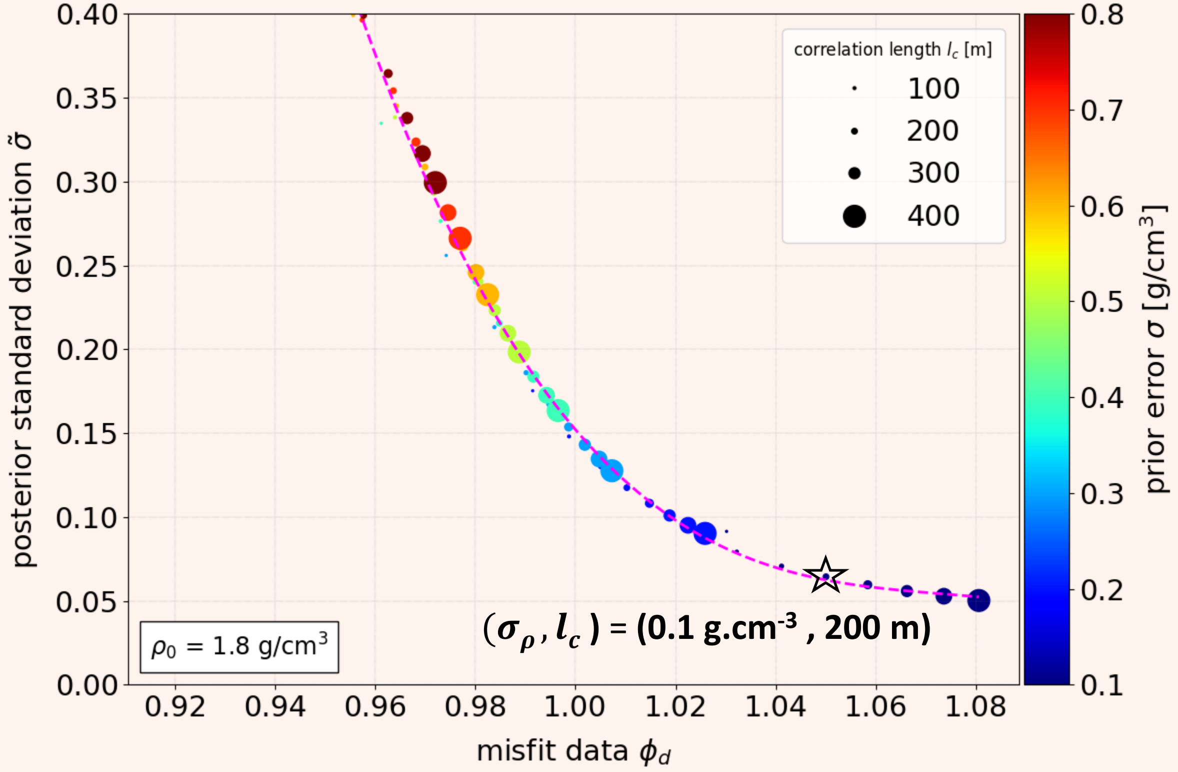
10^6 muons μ E∈[0.1, 10^5] GeV without noise (all θ)	RANSAC	HOUGH
Reco. Efficiency $\langle \varepsilon \rangle$	0.94 +/- 0.02	0.66 +/- 0.03
Angular resolution (RMSE)	12.47 +/- 0.04	31.09 +/- 0.24
Processing time Δt [s]	2122	7042

Reco. Efficiency (vertical $\theta = 0$)		RANSAC	HOUGH
<0.2 GeV	μ	0.08 +/- 0.01	0.30 +/- 0.01
	e	0.03 +/- 0.01	0.09 +/- 0.01
	p	0.0 +/- 0.0	0.0 +/- 0.0
0.2 – 1 GeV	μ	0.92 +/- 0.01	0.98 +/- 0.02
	e	0.25 +/- 0.11	0.56 +/- 0.23
	p	0.54 +/- 0.22	0.69 +/- 0.26
10-100 GeV	μ	0.97 +/- 0.01	0.98 +/- 0.01
	e	0.0 +/- 0.0	0.0 +/- 0.0
	p	0.54 +/- 0.02	0.56 +/- 0.02

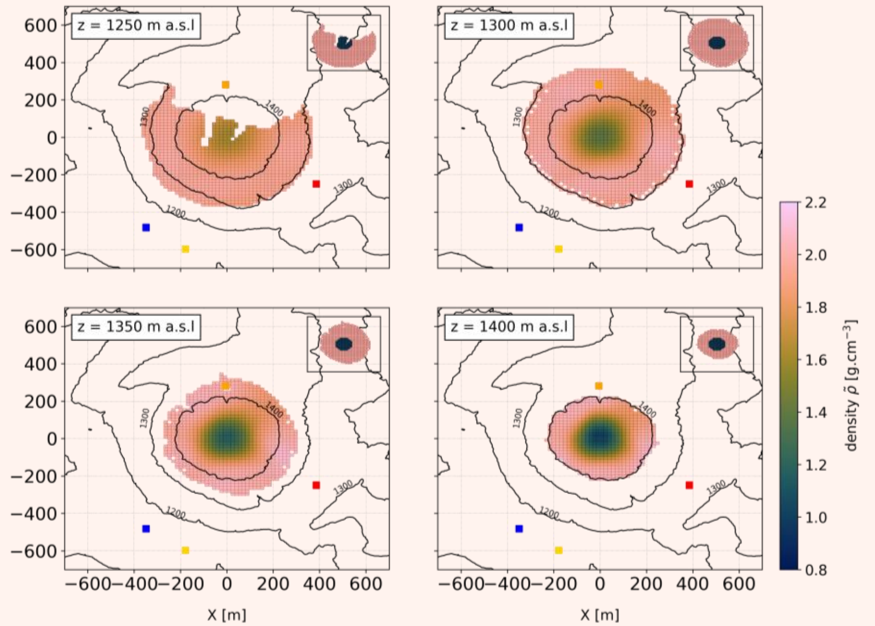
La Soufrière muon datasets

characteristics		telescopes			
		Sacre bleu (SB)	Super Nain Jaune (SNJ)	Baron Rouge (BR)	Orange Mécanique (OM)
configuration	number of panels length L [cm] scint. bars X × Y (front and rear matrices)	3 120 32 × 32	4 180 16 × 16	3 120 32 × 32	3 120 32 × 32
position & orientation	site X (UTM zone 20) Y (UTM zone 20) Z (WSG84) elevation [°] azimuth [°]	Savane South-West 642611 1773798 1185 10.0 44.9	Parking lot 642782 1773683 1145 15.1 20.0	Roche Fendue 643346 1774030 1268 19.5 295.0	Fente du Nord 642955 1774561 1345 13.9 192.0
run	start stop total duration [days] number of events (raw)	24/08/2016 01/04/2017 202.9 $1.38.10^7$	24/02/2019 11/08/2019 145.0 $2.23.10^7$	09/03/2017 19/08/2019 640.3 $1.1.10^8$	11/03/2017 01/05/2018 191.2 $2.81.10^6$
geometrical acceptance	max [cm^2.sr]	2.78	11.11 (3p) / 6.25 (4p)	2.78	2.78
rock thickness	min [m] center [m] max [m]	6 748 1272	14 (3p) / 5 (4p) 797 (3p) / 797 (4p) 1301 (3p) / 1301 (4p)	1 607 1164	1 394 1209
scanned volume ($V_{tot}^{dome} \sim 5.10^7$ m^3)	estimate [m^3]	$1.33.10^7$	$1.41.10^7$	$9.89.10^6$	$3.83.10^6$

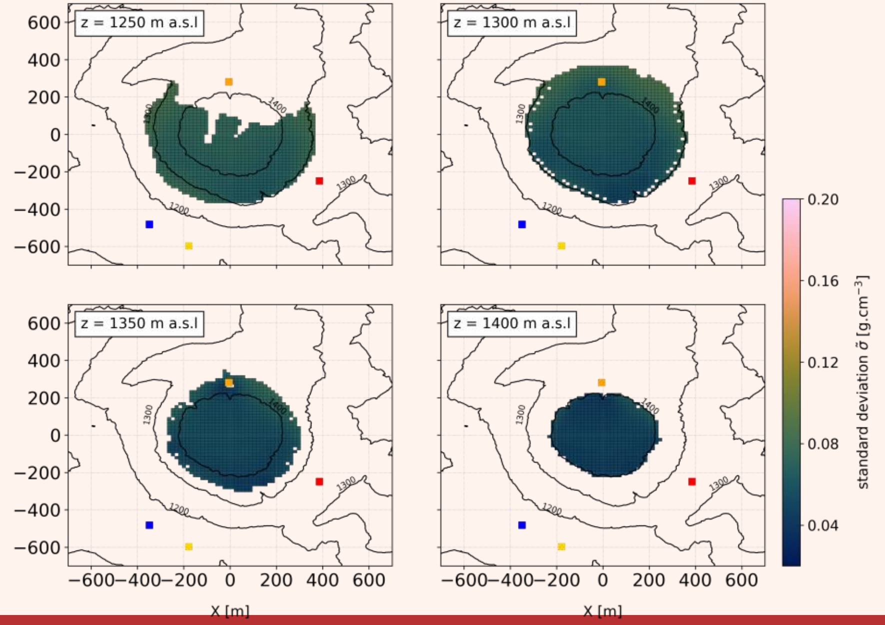
Synthetic test



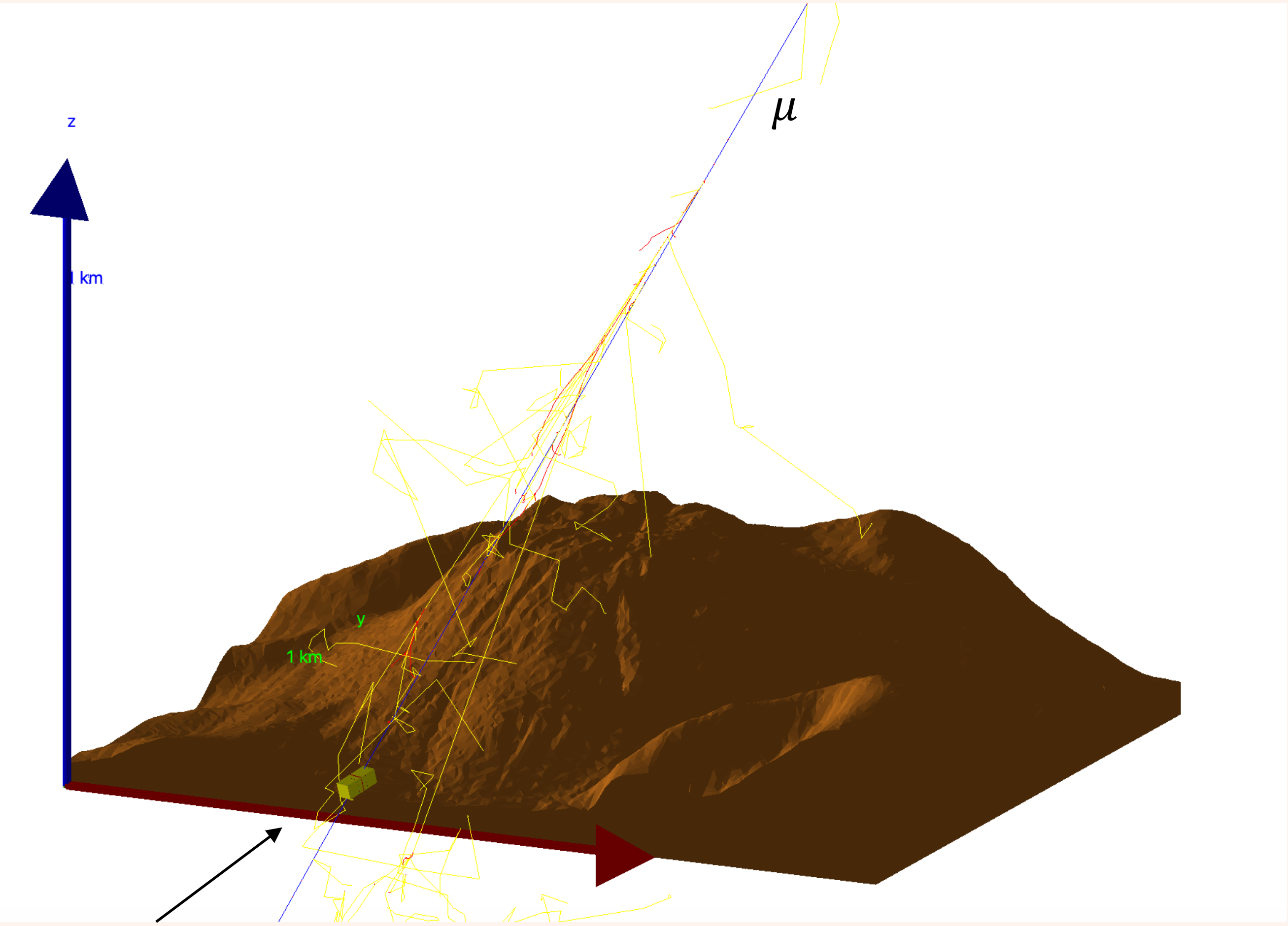
Density estimates $\tilde{\rho}$



Standard deviation $\tilde{\sigma}$

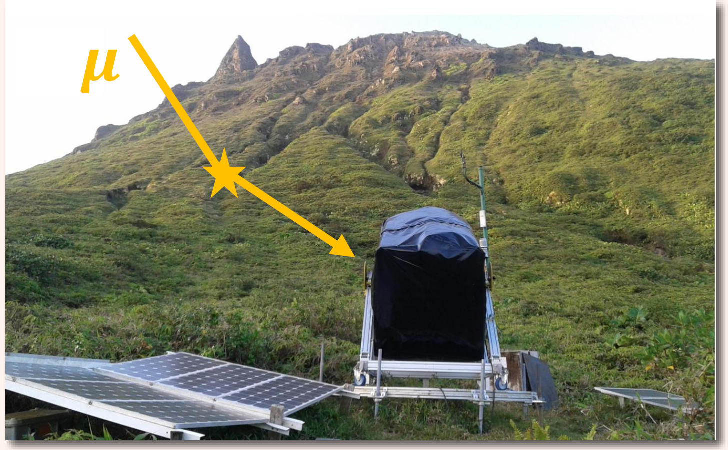


La Soufrière Dome in Geant4

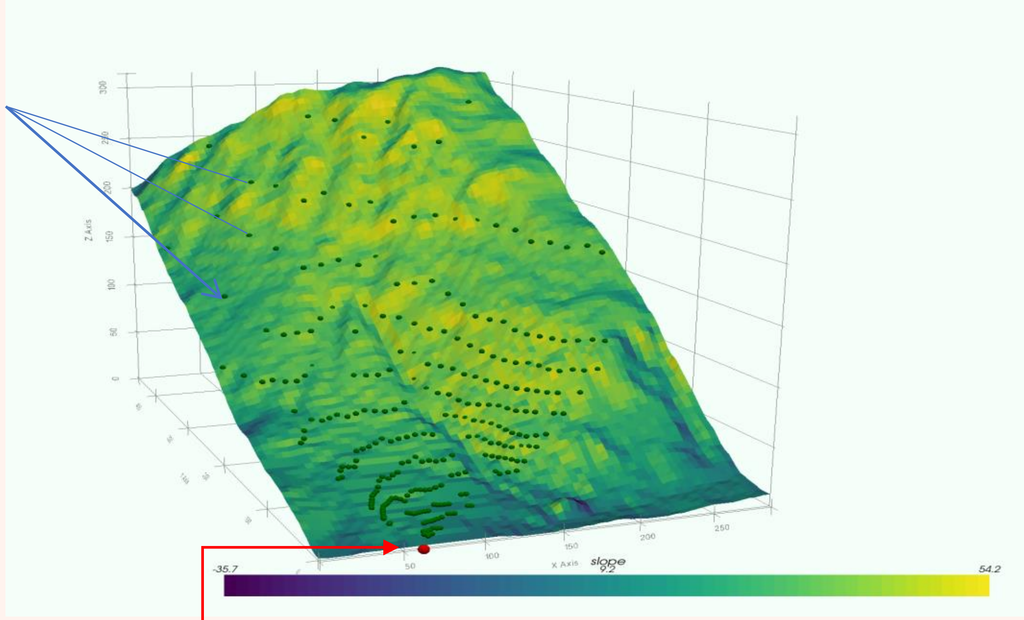


Detector (size x 30)

Scattering simulation setup

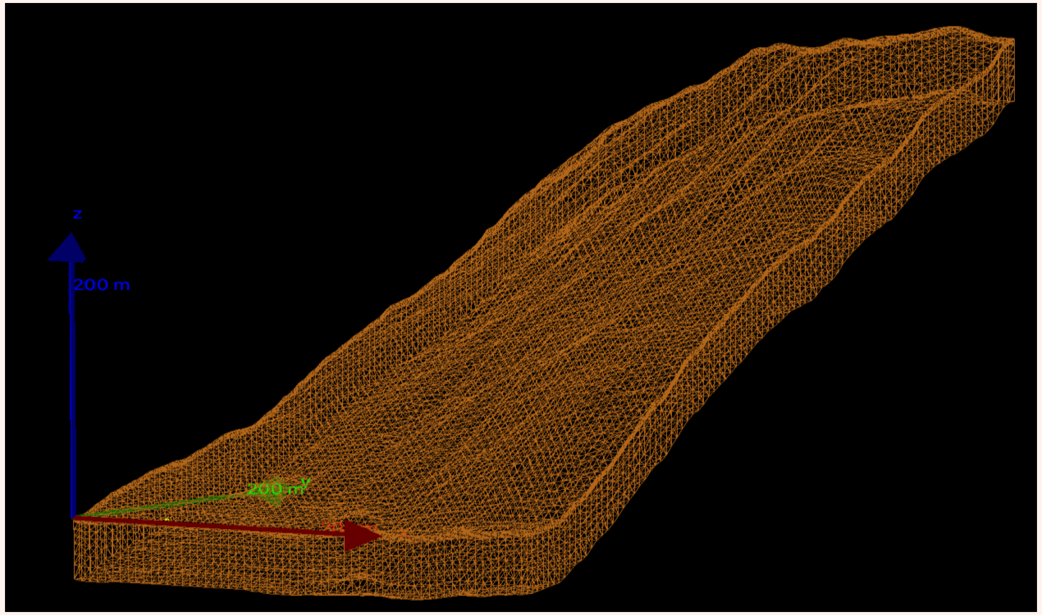


Exit points line-of-sights



Telescope position

Southern flank dome
with slope ∈ [-35; 54]°



Same mesh in GEANT4