Muography activities at INAF

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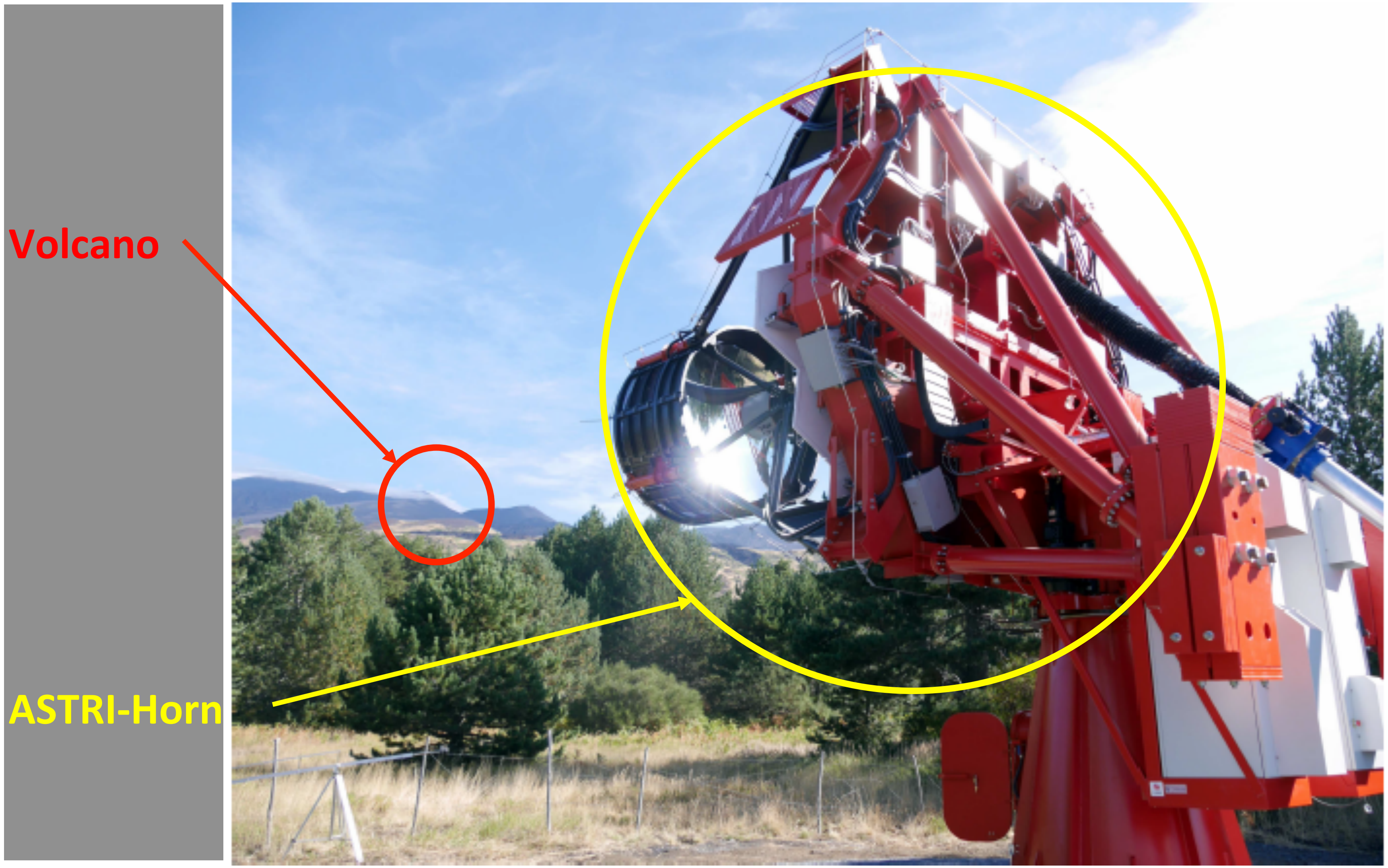
on behalf of the INAF ASTRI-MUOGRAPHY Collaboration

ASTRI Astrofisica con Specchi a Tecnologia Replicante Italiana

THE ACTORS



ASTRI (Astrofisica con Specchi a Tecnologia Replicante Italiana) is a project of the Italian Ministry of Education, University and Research (MIUR), led by the Italian National Institute of Astrophysics (INAF).

AIM: consolidating the technologies for future Imaging Atmospheric Cherenkov Telescopes (IACT), with particular reference to the CTAO (Cherenkov Telescope Array Observatory).

ASTRI-Horn prototype: IACT located in Sicily on the slope of the Etna volcano at the Serra La Nave astronomical site operated by INAF Catania

THE PROTOTYPE ASTRI-Horn

Imaging Atmospheric Cherenkov Telescope (IACT)

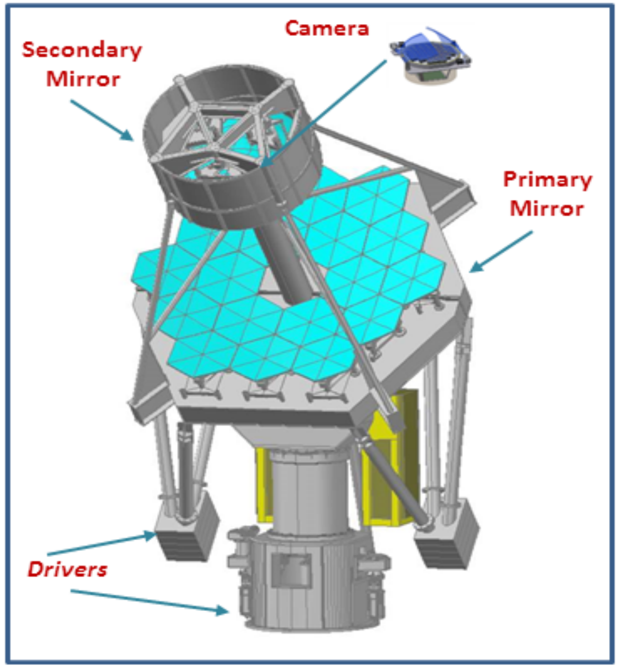
A telescope equipped with an optical system composed of high reflectivity mirror that focuses the Cherenkov light onto a multi-pixel focal camera.

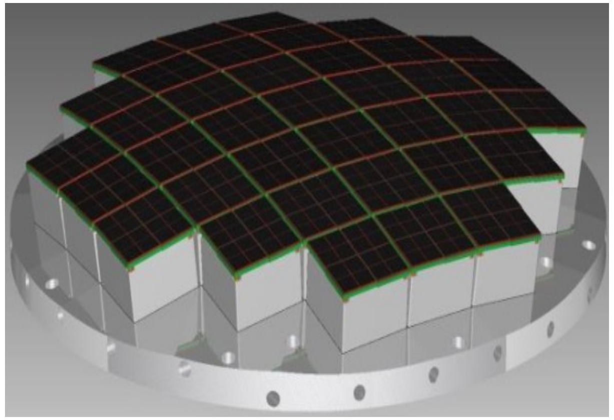
ASTRI-Horn Optics characteristics

- dual mirror optical design (Schwarzschild-Couder configuration)
- Segmented primary mirror: 4.3m
- Monolithic secondary mirror: 1.8m
- Equiv. Focal Length = 2.15m
- Field of View ~ 9.6°

ASTRI-Horn Focal Plane characteristics

- radius of curvature: ~ 1m
- ~2000 pixels (7x7mm^2)
- pixel FoV = 0.19°
- 37 Photon Detection Modules of 8x8 SiPM pixels

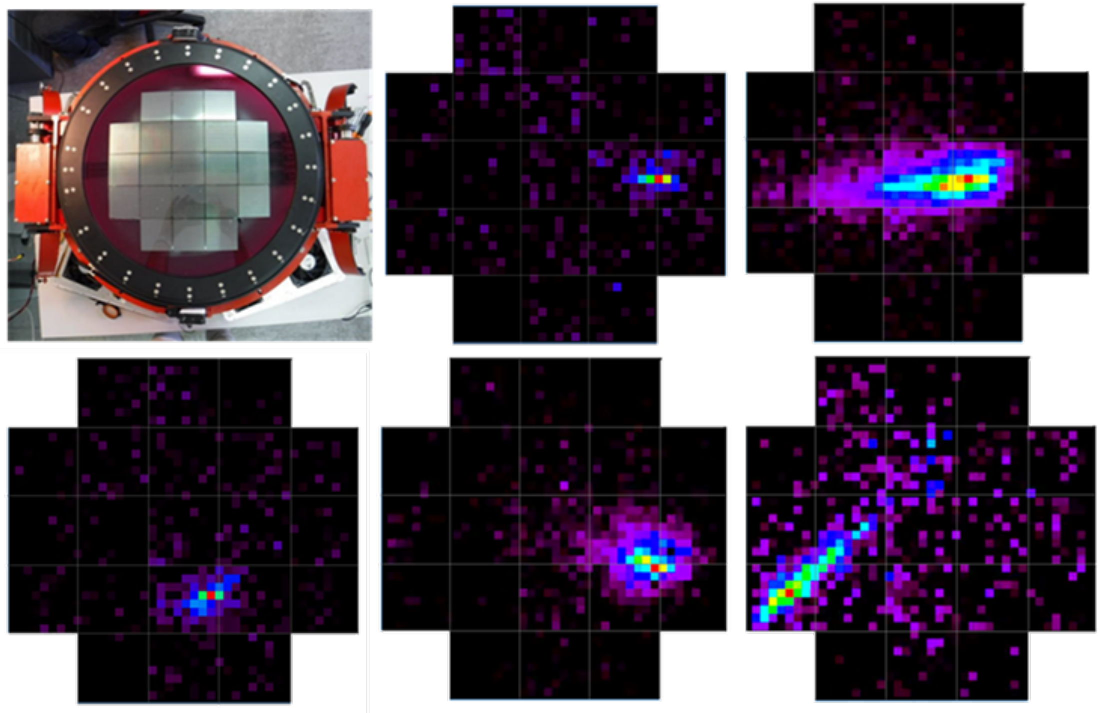




ASTRI-Horn FIRST LIGHT

- The ASTRI-Horn camera has been completely integrated on 2017 May.
- Although the runs were mainly engineering and only few PDMs were active,

on May 26th the first Cherenkov events were observed, allowing us to achieve the "first light".



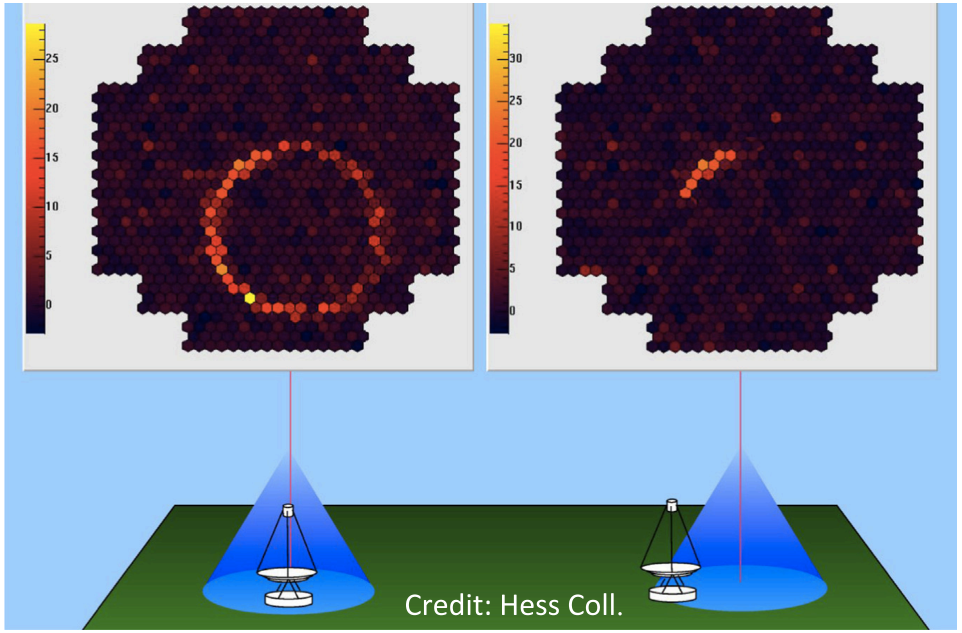
Muon imaging with an Imaging Atmospheric Cherenkov Telescope

<u>Cherenkov light (blu and UV) is</u> emitted when charged particles travel through a dielectric medium at velocity higher than the speed of light in that medium.

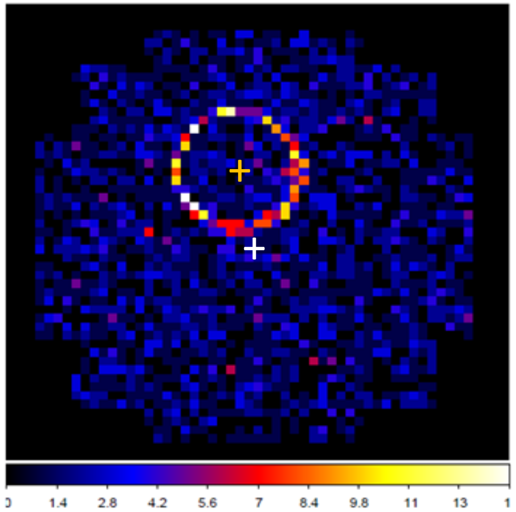
Cherenkov photons induced by a muon (≥ 5 GeV at sea level) are imaged on an IACT camera as a characteristic ring (or arc) shape.

A relatively simple geometrical analysis of the ring allows us to reconstruct the muon physical parameters, in particular the arrival direction.

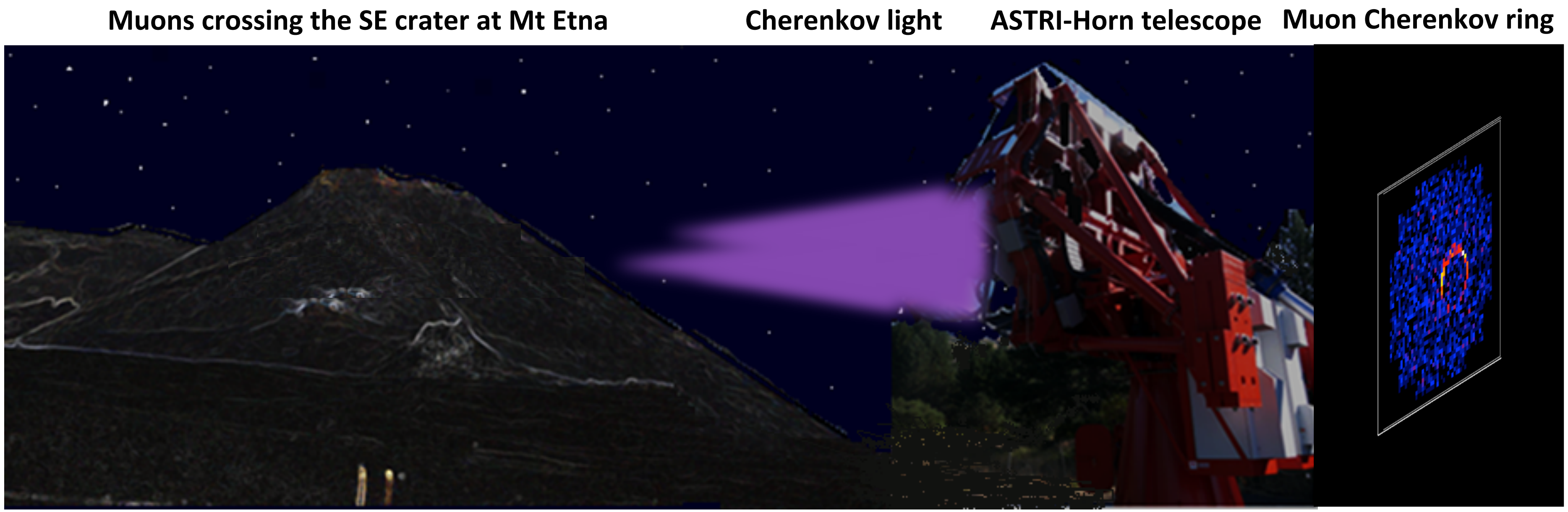
The position of the center gives the direction of the detected muon with respect to the telescope optics axis.



Credit: Hess Coll.



THE IDEA: MUOGRAPHY WITH AN IACT

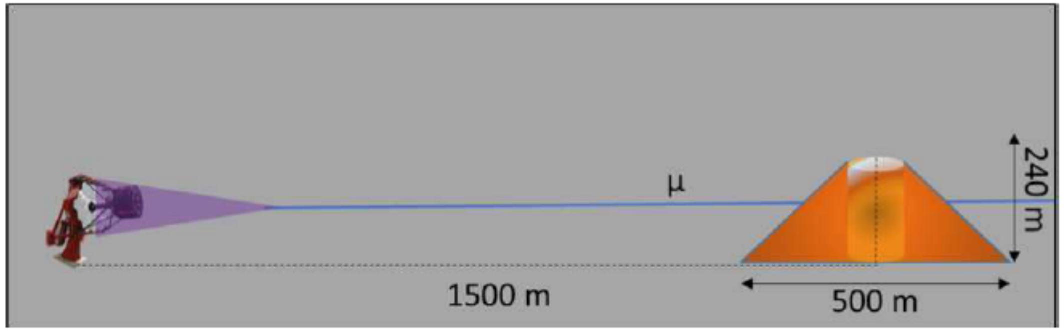


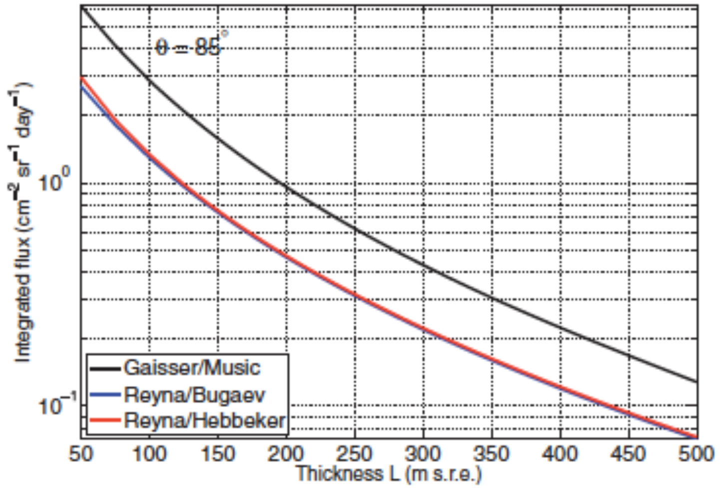
- ASTRI-Horn at 5 km from the South East crater
- Muon detection capability (observations carried out at night only)

- due to the imaging capabilities, an IACT dedicated to the muon radiography is not affected by accidental coincidences
- because of the Cherenkov threshold at ≈5 GeV, neither by low energy muons (affected by significant scattering)

We only expect a negligible background due to the back-scattered muons from the ground
(about $3x10^{-3}$ ”fake” events per night, see Catalano et al., 2016, NIMPA, 807, 5).

Toy-model simulations





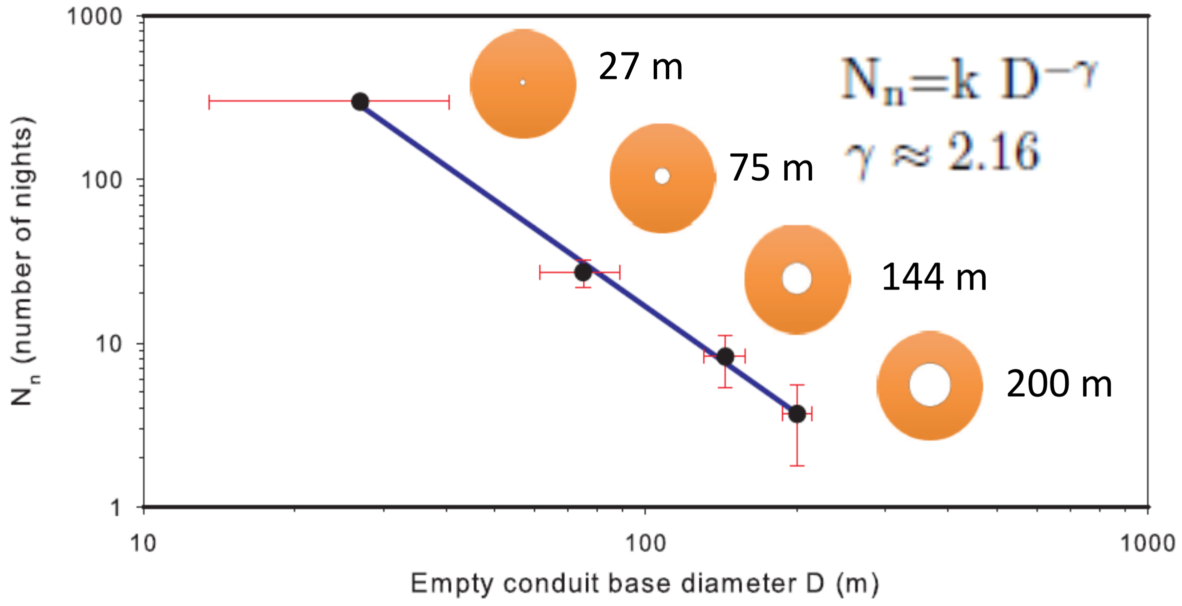
Lesparre+10

- ASTRI-Horn at 1500 m from the South-East crater of the Etna volcano.
- The crater was assumed as a cone.
- Different size hollow cylinders to simulate the volcano conduits.
- Integrated muon flux computed (Lesparre+10) for standard rock (ρ =2.65 g cm^{-3}) and for θ =85°.

Toy-model simulations: results

Feasibility condition of the muon imaging to investigate the density distribution inside a target structure (Lesparre+10)

$$\Delta T \times \Gamma \times \frac{\Delta I^2(X_0, \delta X)}{I(X_0)} > 1$$



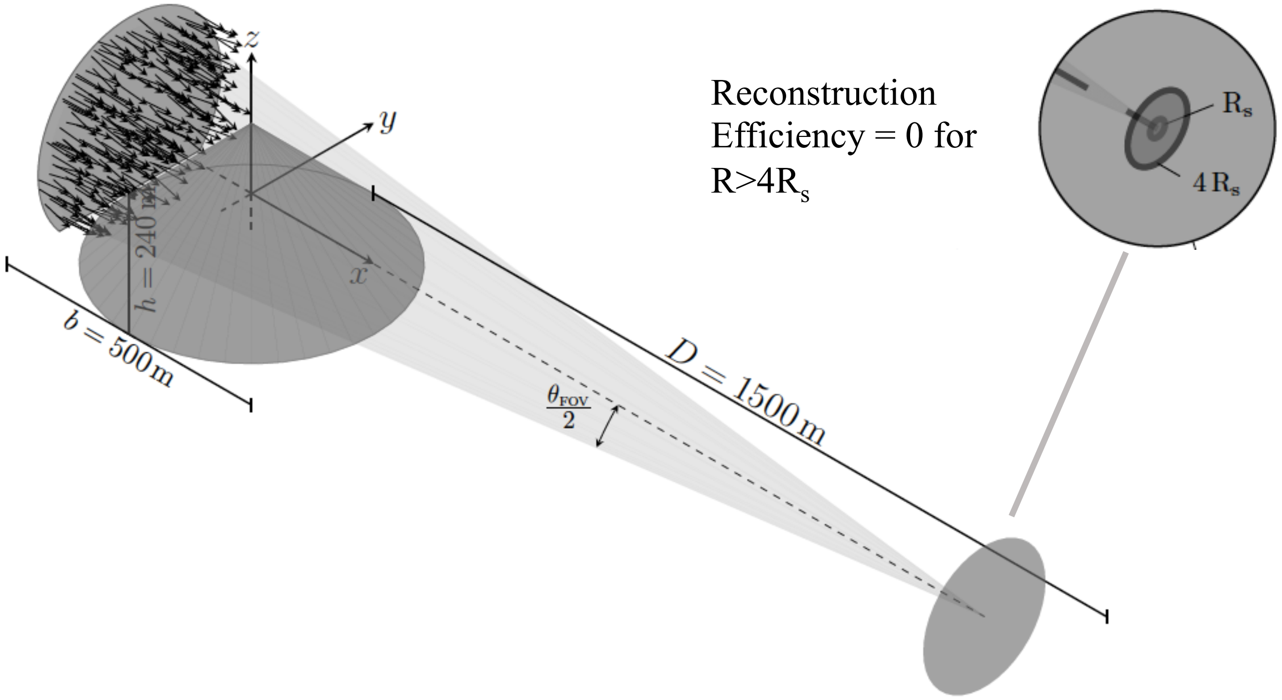
- Acceptance
- Integrated flux difference
- Fixed total opacity of the medium
- Required resolution level
- Acquisition time

We roughly estimated a sensitivity improvement of a factor of ten compared with the experiment performed by Tanaka with a better spatial resolution (~15 m) than that achieved by the current experiments (Catalano+16).

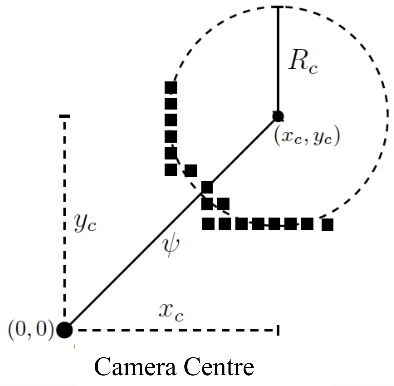
Current Activities: Geant4 Simulations

A Geant4 simulator *(D. Mollica)*

- The input muon spectrum is the Reina-Bugaev spectrum computed at 85°.
- It computes muon propagation within a standard density rock ($\rho = 2.65$ g cm^{-3}), its energy loss and scattering.
- Cherenkov photons induced by muons travelling the atmosphere between the mountain and the telescope.



- The telescope response is obtained by the ray-tracing stand-alone simulator developed for ASTRI-Horn, which includes the mirror transmission, the detector efficiency, electronics and the diffuse environmental background.
  - Muon rings with pixels ≥7 are reconstructed with the Taubin method.

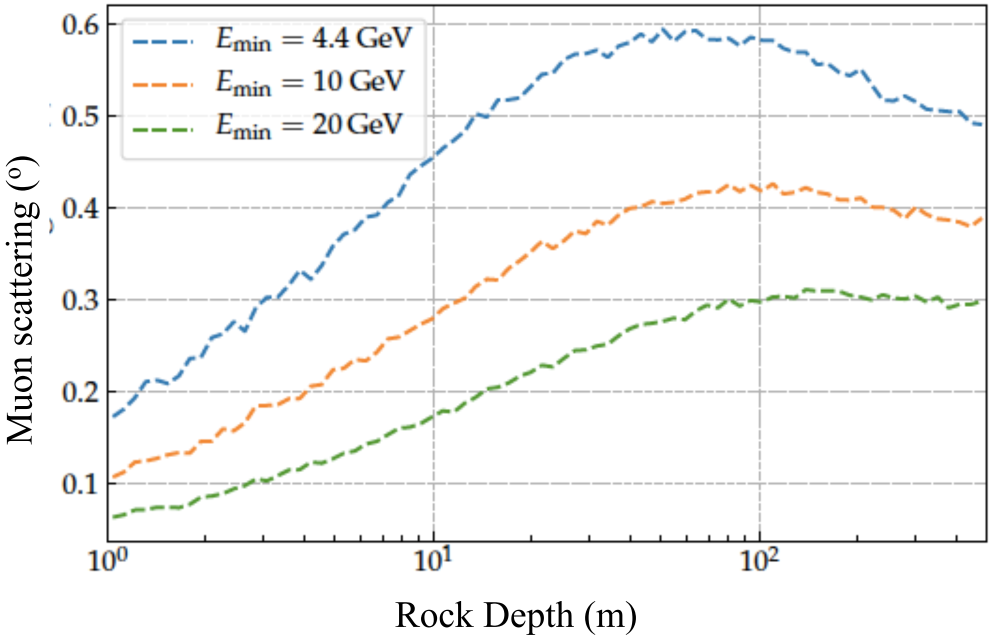


$$\xi = \frac{\sum[(X-X_c)^2+(Y-Y_c)^2-R^2]^2}{\sum[(X-X_c)^2+(Y-Y_c)^2]}$$

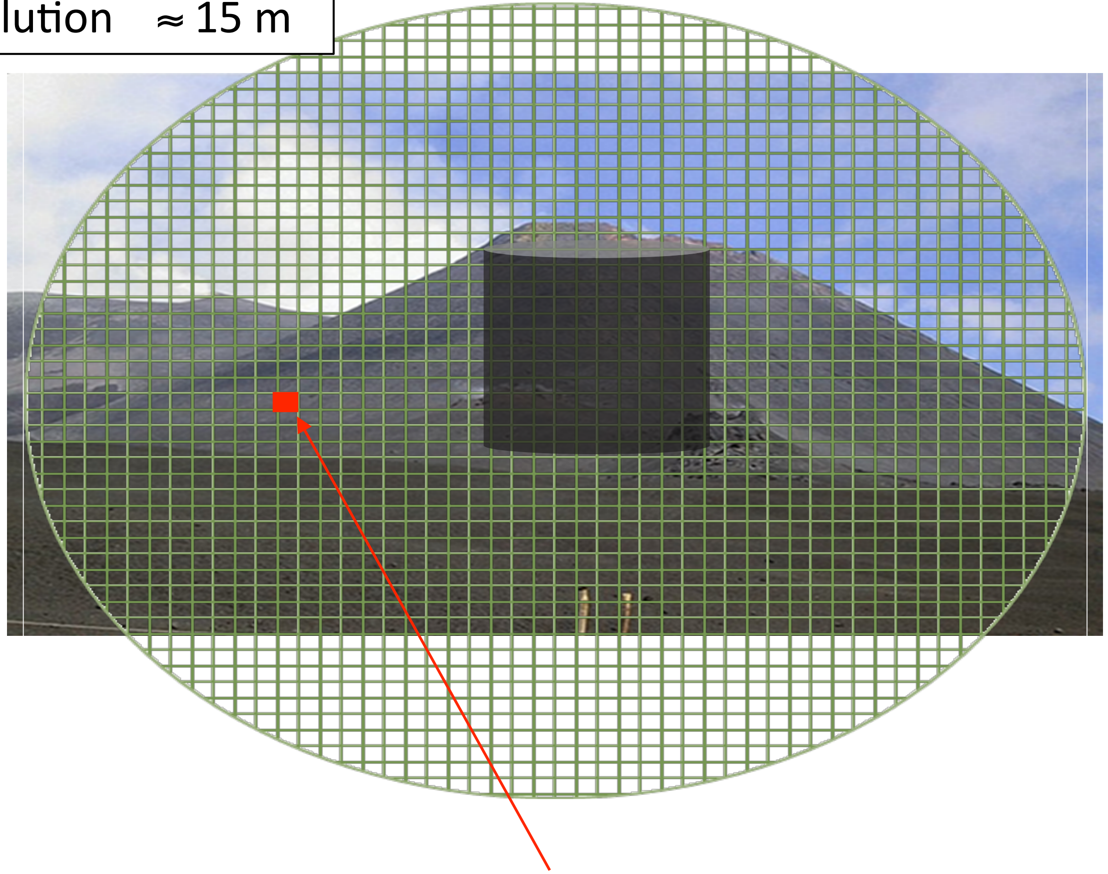
Spatial resolution

Pixel angular Resolution ≈ 0.19° → Projected spatial resolution ≈ 5 m

3x3 pixels angular Resolution ≈ 0.57° → Projected spatial resolution ≈ 15 m



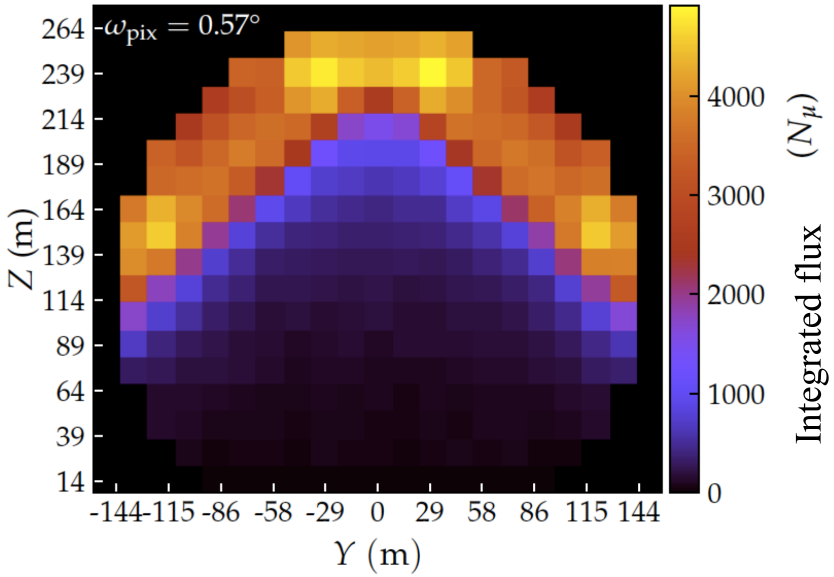
The latter is comparable to the muon angular deviation

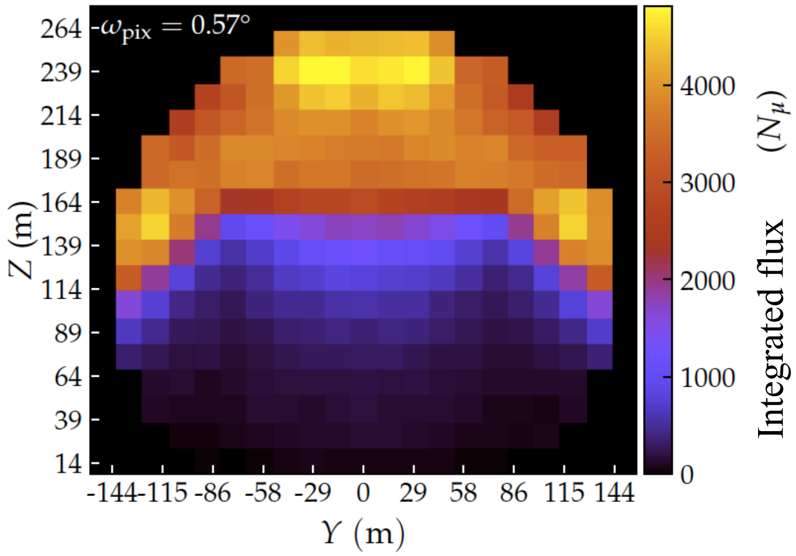


Projected Spatial Resolution

SIMULATIONS

- Three different size conduits inside the volcano (140 m, 70m and 35m diameter)
- 30 nights of observations.
- Different spatial resolution
- Two methods to compute the number of nights necessary to resolve the inner structure at 1σ, 3σ and 5σ.





Comparison with the simulated integrated flux after crossing the full cone

$$I(\theta)_{d_c} = \Delta t_N \Omega_{\text{pix}} A_{\text{eff}}(\theta) \int_{E_\mu^{\min}}^{\infty} P_{E_{\text{th}}}(x_{d_c}(\theta), E_\mu)\, \Phi_{R\text{-}B}(E_\mu, 85^\circ)\; \mathrm{d}E_\mu$$

Comparison with the expected integrated flux after crossing the full cone

15 m RESOLUTION RESULTS

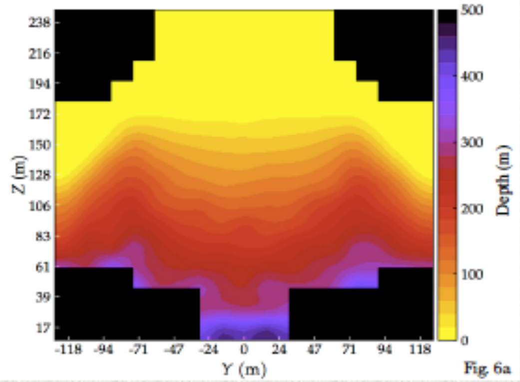


Fig 6a

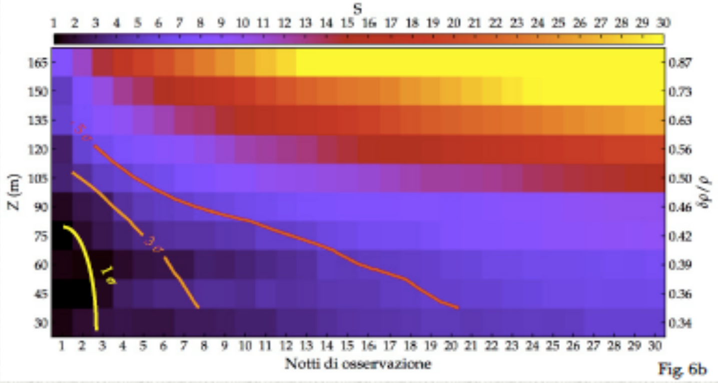


Fig 6b

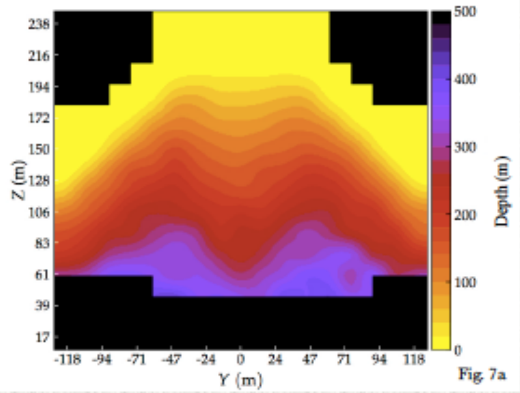


Fig 7a

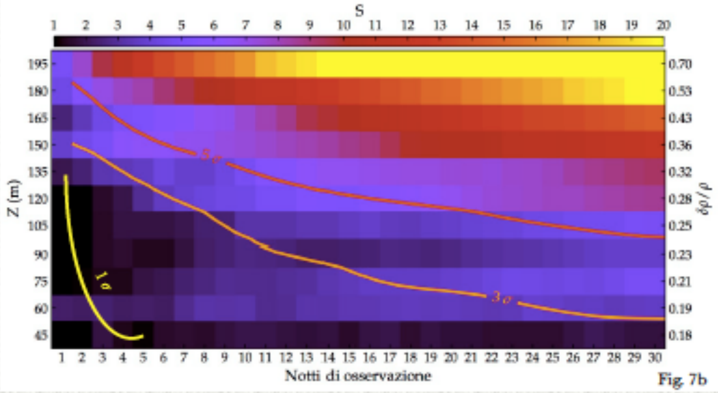


Fig 7b

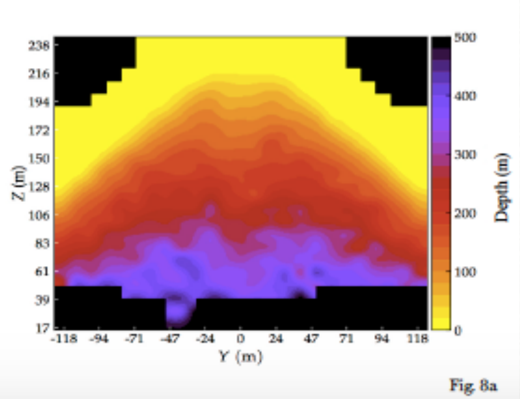


Fig 8a

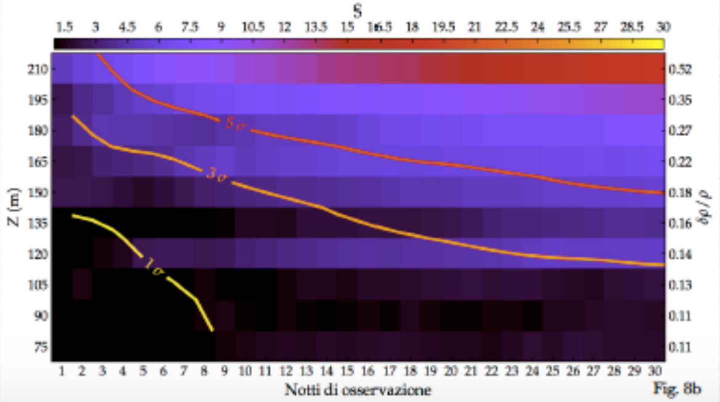
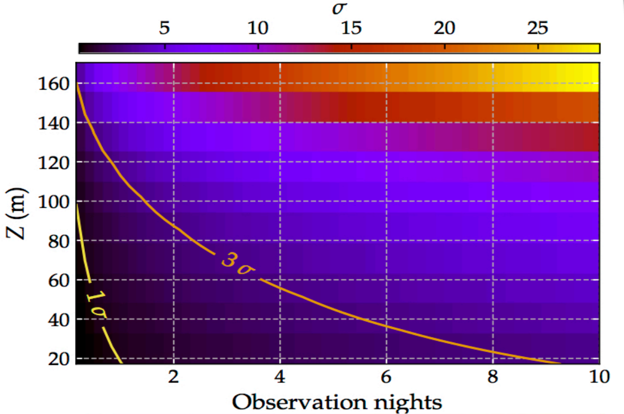
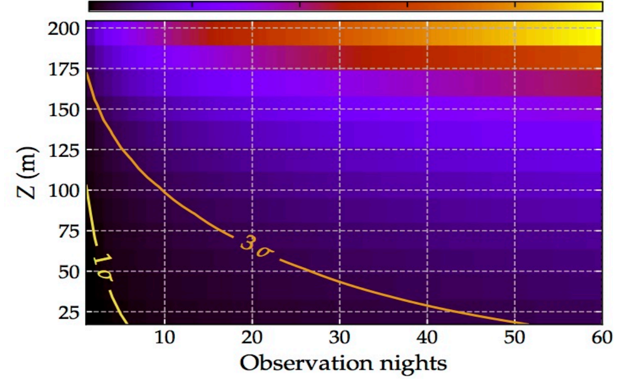


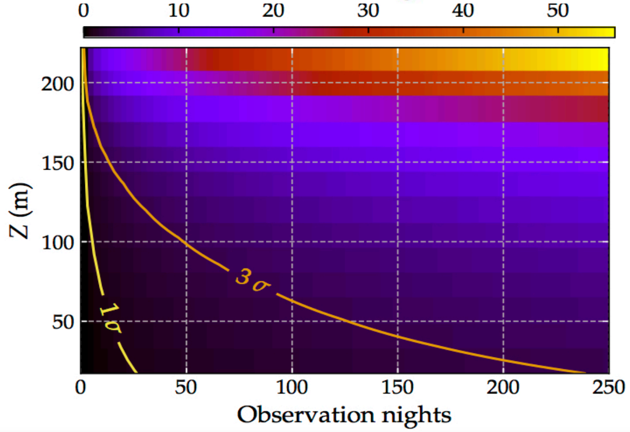
Fig 8b



the 140 m diameter conduit in 3 nights and 9 nights at 1σ and 3σ levels, respectively



The 70 m diameter conduit above a height from the base of 40 m, in 5 nights at 1σ and in 29 nights at 3σ levels. About 10 and 50 nights for the whole conduit (at 1σ and 3σ levels, respectively).



The 35 m diameter conduit above a height from the base of 75 m in 9 nights at 1σ level. About 30 and 250 nights for the whole conduit (at 1σ and 3σ levels, respectively).

Satellite Meeting of the Muography Community: Washington, 2018 December 10th

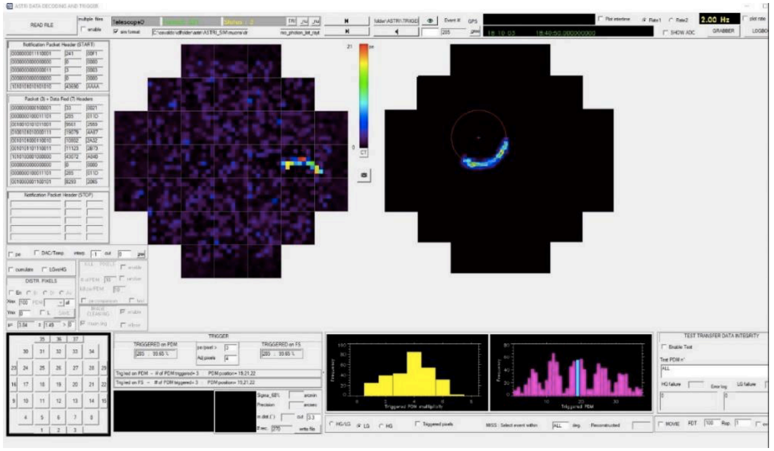
Current Activities: Ad-hoc ELECTRONICS

A fast read-out electronics with low noise is required for signals that last less than 1 ns

Preliminary set of simulations to compare Charge integration system versus single photon counting

(A. Miccichè Master Thesis)

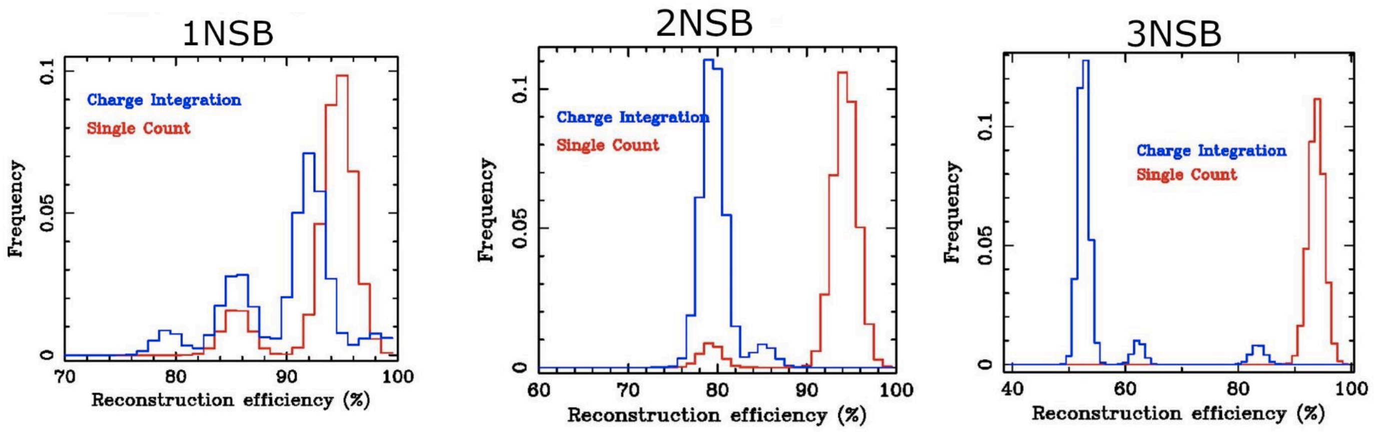
1NSB = 0.67 ph/m^2/ns/degrees^2
2NSB = 1.34 ph/m^2/ns/degrees^2
3NSB = 2.01 ph/m^2/ns/degrees^2



Muon rings reconstruction with the Taubin method

Tabella 5.1: Media anelli ricostruiti.

NSB	Single Photon C.	Charge Integration
1	93.4%	89.8%
2	93.3%	79.8%
3	93.8%	55.3%



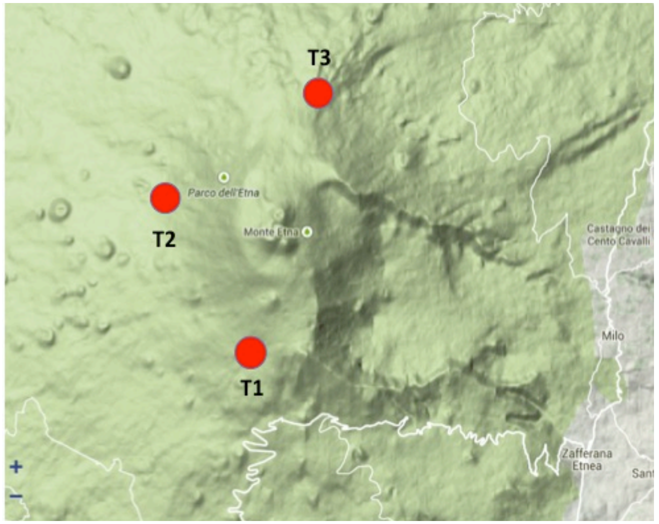
A read-out based on the single photon counting allows for a higher detection efficiency compared to the charge integration mode.

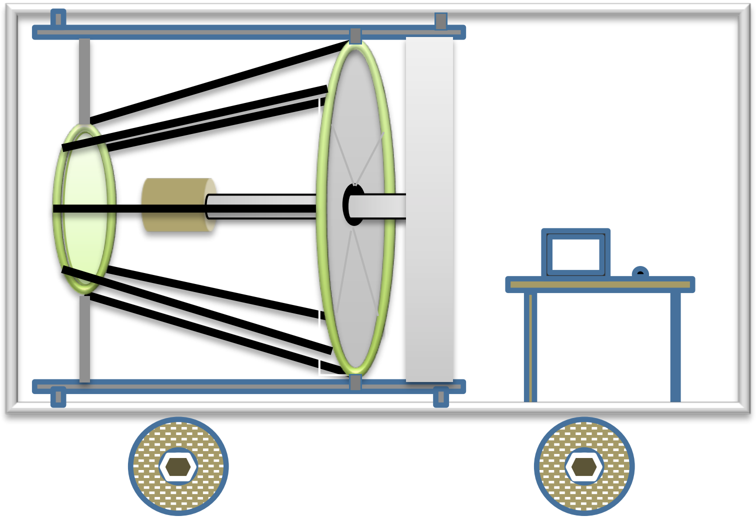
REQUESTED FUNDING

- Progetti di Rilevante Interesse Nazionale (*PRIN*) - (outcome by March 2019)
  Feasibility study for a prototype telescope dedicated to the muon radiography
- ATTRACT European Union's Horizon 2020 - (outcome by March 2019)
  Multimodal ASIC design and characterization of a Cherenkov device for muon radiography

TOMOGRAPHY

Our idea is to install the instrumentation on mobile vehicles, with low environmental impact technologies, to reach different observation sites for the same target, allowing 3D radiography (Del Santo et al. 2017, NIMPA, 876, 111).





With more than one movable Cherenkov telescope we can perform the tomography of the target and/or improve the sensitivity of a factor of $N^{1/2}$, where *N* is the number of telescopes.

CONCLUSIONS

1. Preliminary results from a Geant4 simulator for the muon radiography by Cherenkov telescopes are very encouraging: will be able to perform muon radiography of volcanoes with good spatial resolution.
2. **ASTRI-Horn telescope will be used to test the new proposed method.**
3. Future improvements of the Geant4 simulator, laboratory measurements on SiPM detectors and read-out electronics, are propaedeutic to develop a final design for an ad-hoc Cherenkov telescope for muography.

THANKS FOR YOUR ATTENTION