Istituto Nazionale di Geofisica e Vulcanologia

Looking inside volcanoes with the Imaging Atmospheric Cherenkov Telescopes

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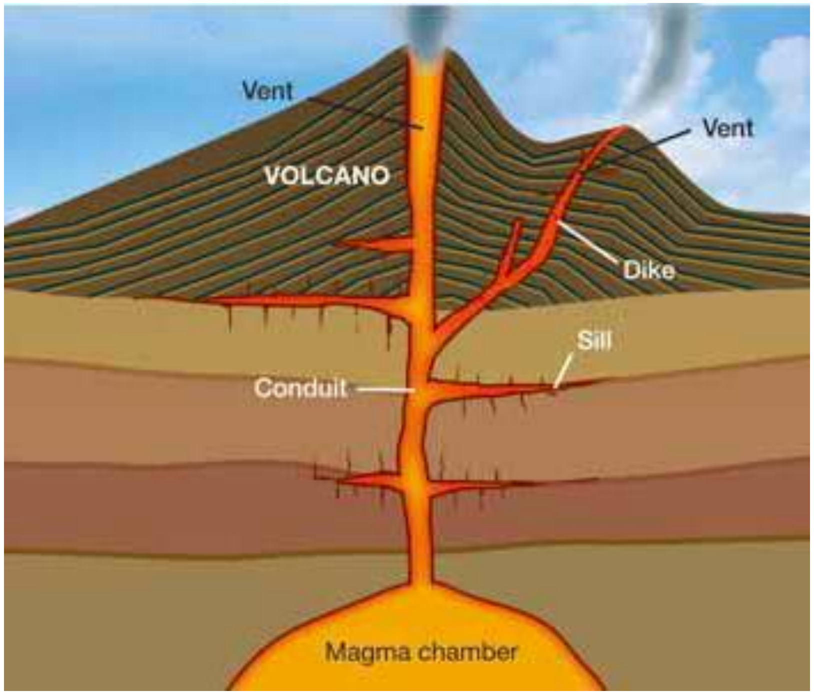
ASTRI Astrofisica con Specchi a Tecnologia Replicante Italiana

VOLCANO MUON RADIOGRAPHY: BASICS

The quantitative understanding of the inner structure of a volcano is a key-point to monitor the stages of the volcano activity, to forecast the eruptive style and mitigate volcanic hazards.

Conduit geometry
Estimation of the magma level
Obstructed conduits
Secondary conduits



MUON RADIOGRAPHY
Measuring differential attenuation of the cosmic-ray muon flux as a function of the amount of rock crossed along different directions, it is possible to determine the density distribution of the interior of a volcano.

MUON RADIOGRAPHY: BASICS

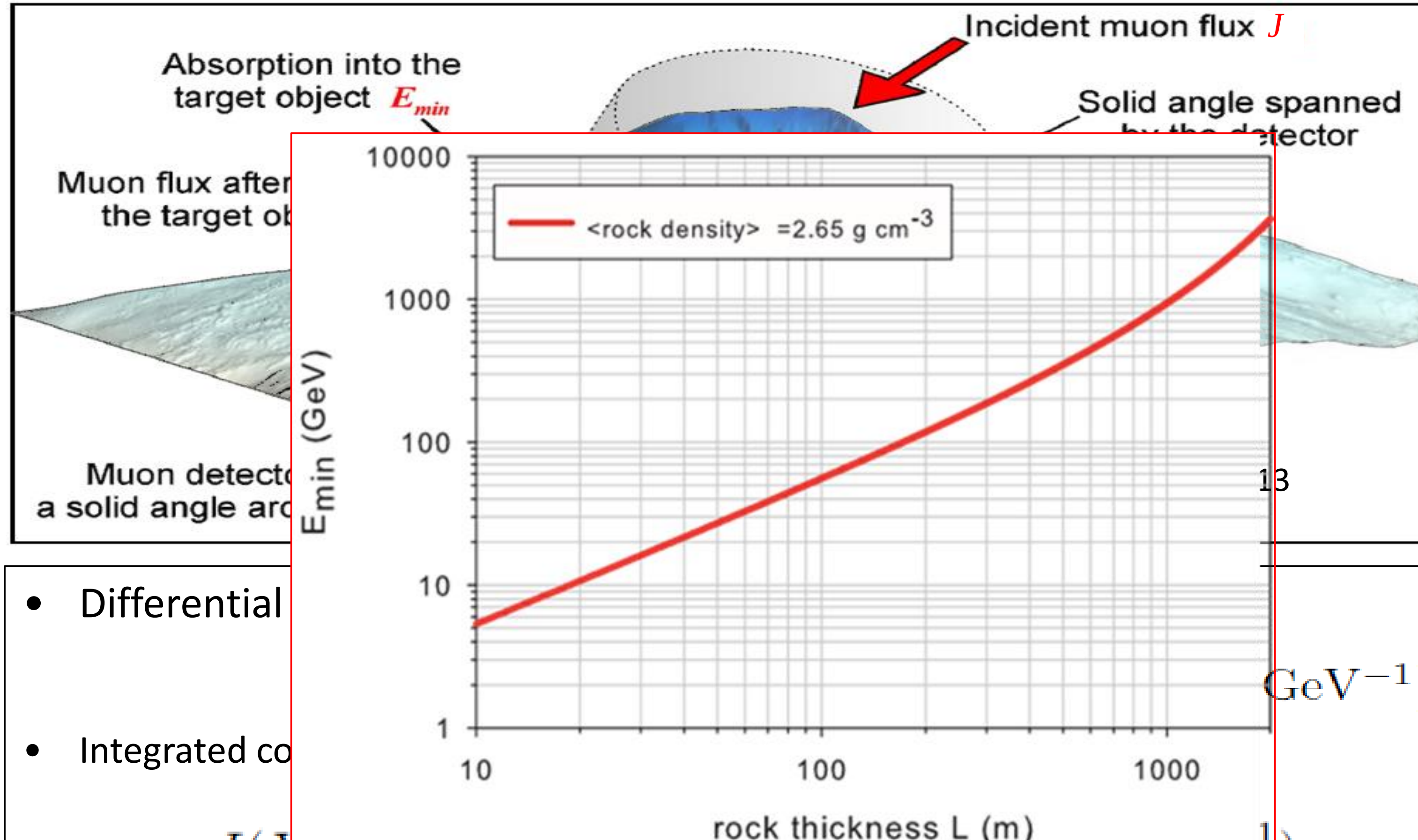
The basic idea can be explained through the following steps:

- High penetration capability: cosmic-ray muons can travel through huge structures losing a fraction, ***up to the total***, of their energy.
- a unique relationship exists between the opacity X and the intensity of the penetrating cosmic-ray muons
- The cosmic-ray muon energy spectrum depends on vertical angle.

Volcano imaging through cosmic-ray muons is a promising technique (Tanaka et al.)

First radiographic observation of the ascent and descent of magma along a conduit utilizing muography with dynamic radiographic imaging.
(Tanaka+14, Nature)

MUON RADIOGRAPHY: BASIC FORMULAS



- Differential … $\mathrm{GeV}^{-1})$
- Integrated co…

$$I(X,\theta) = \int_{E_{\min}} J(E,\theta)\, \mathrm{d}E \;(\mathrm{cm^{-2}\,sr^{-1}\,day^{-1}})$$

- E_{min}: minimum muon energy required to cross a depth with opacity X

$$X(L) \equiv \int_L \rho(\xi)\, \mathrm{d}\xi \;(\mathrm{g\ cm^{-2}})$$

MUON RADIOGRAPHY: FEASIBILITY EQUATION

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 $\Gamma = A \times 2\pi(1 - \cos(\alpha/2))$
- Integrated flux difference $\Delta I(X_0, \delta X) = I(X_0 + \delta X) - I(X_0)$
- Fixed total opacity of the medium X_0
- Required resolution level δX
- Acquisition time ΔT

This equation establishes a useful condition to evaluate the ***acquisition time*** *ΔT necessary to collect a statistically significant* ***number of muons*** *to resolve the target with a resolution level* ***δX****.*

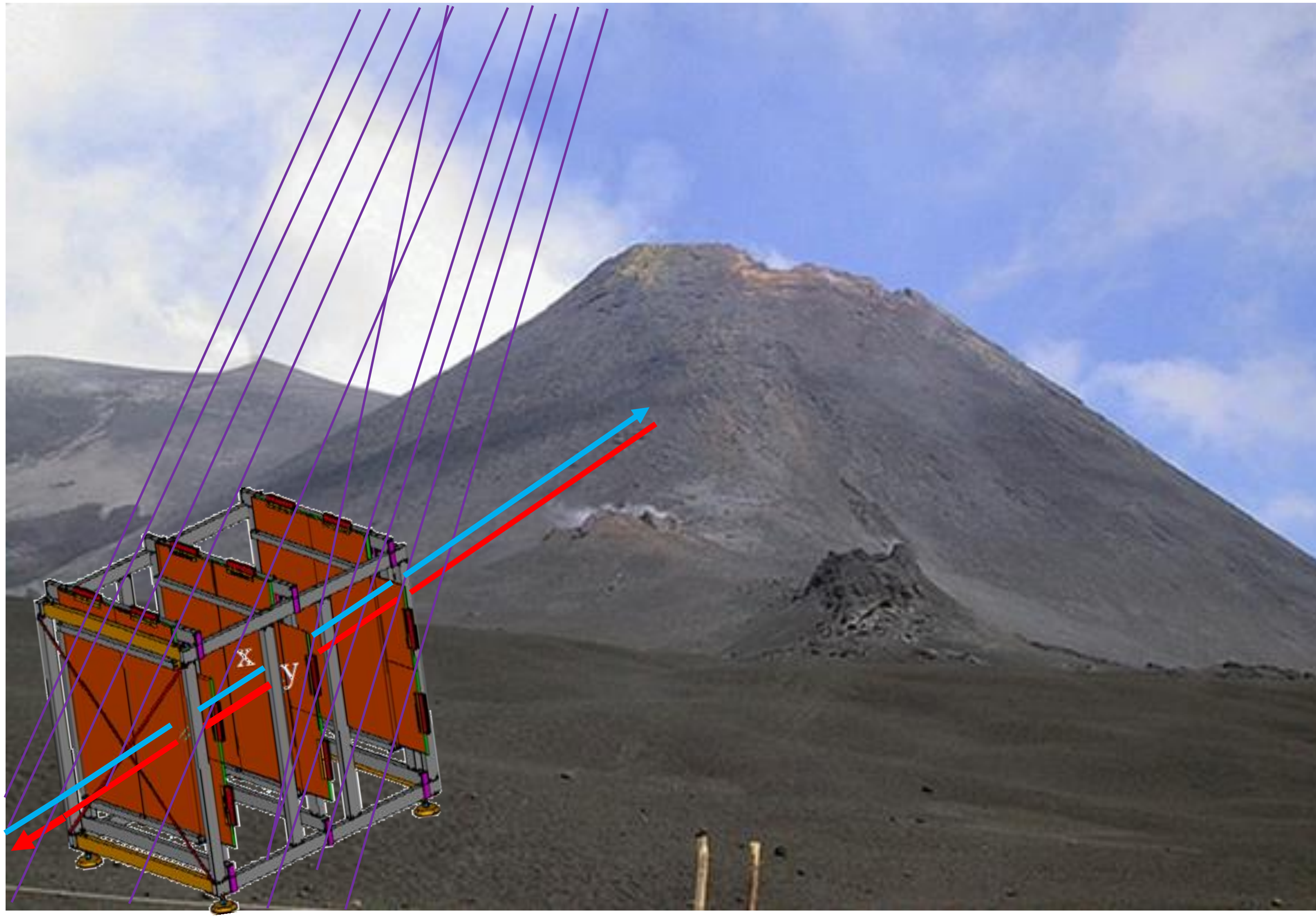
CURRENT PROJECTS

- DIAPHANE project (Gilbert+10)
- MURAY project (Ambrosi+11)
- Etna radiography (Carbone+13)

Detection of muon-tracks crossing hodoscopes made up of scintillators or nuclear emulsion planes.

HIGH BACKGROUND

(FALSE POSITIVE)

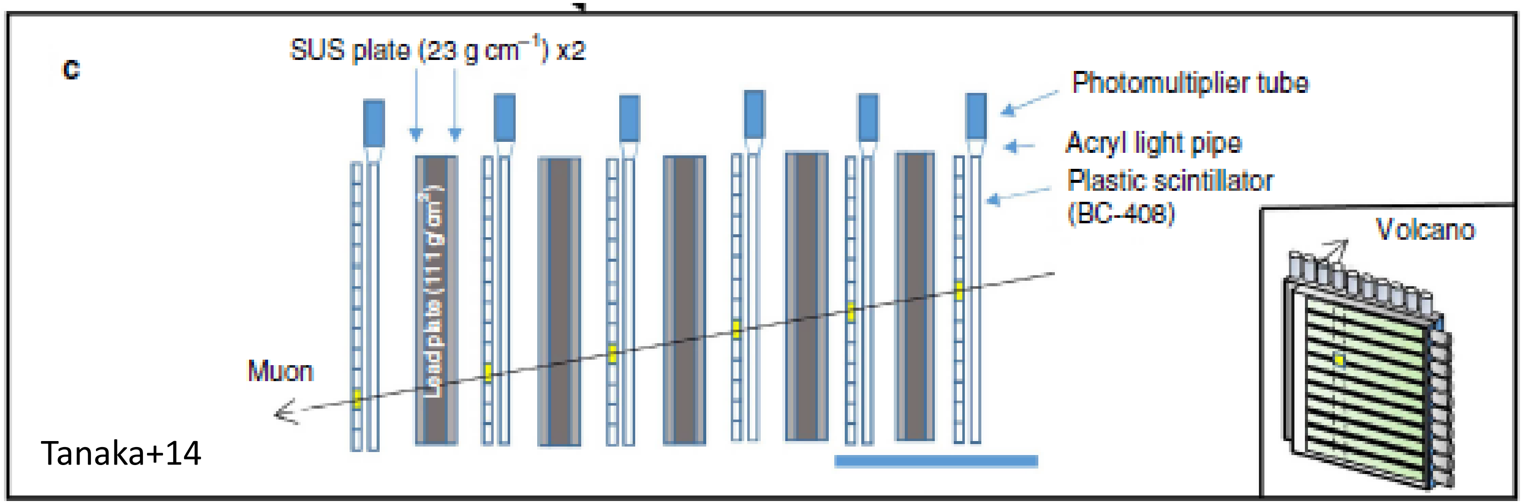


The major source of the fake muon tracks (in position sensitive systems) is the accidental coincidence of vertical EM shower particles.

In order to discard such accidental events, redundant counters are often added to the system.

CURRENT PROJECTS: three or more planes is mandatory

The background noise or the fake tracks triggered by horizontal high energy electrons and low energy muons can be reduced by inserting a thick steel or lead shields in between the planes.



Five lead plates supported by stainless steel plates and six layers of scintillators.

HEAVY – EXPENSIVE – UNMOVABLE

A NEW TECHNIQUE FOR MUON RADIOGRAPHY

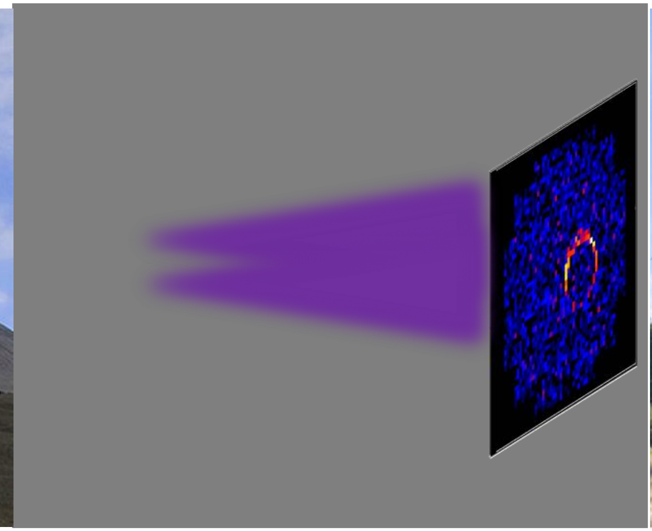
IS VOLCANO MUON RADIOGRAPHY FEASIBLE WITH CHERENKOV TELESCOPES?

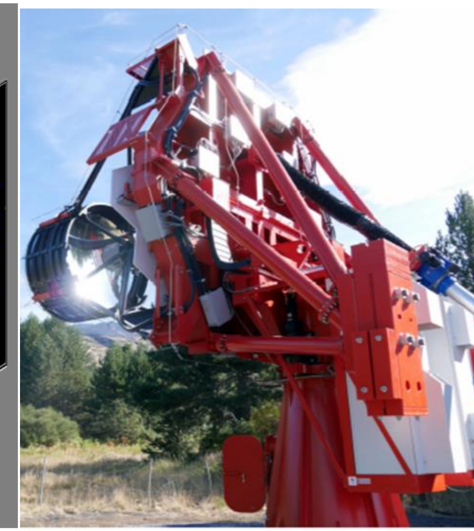
Are they able to determine width, structure and shape of volcano conduit?

THE IDEA

Muons crossing the SE crater at Mt Etna

Muon Cherenkov ring





- Etna volcano
- ASTRI SST-2M at 5 km from the SE crater
- Muon detection capability

ALL THE INGREDIENTS ARE HERE

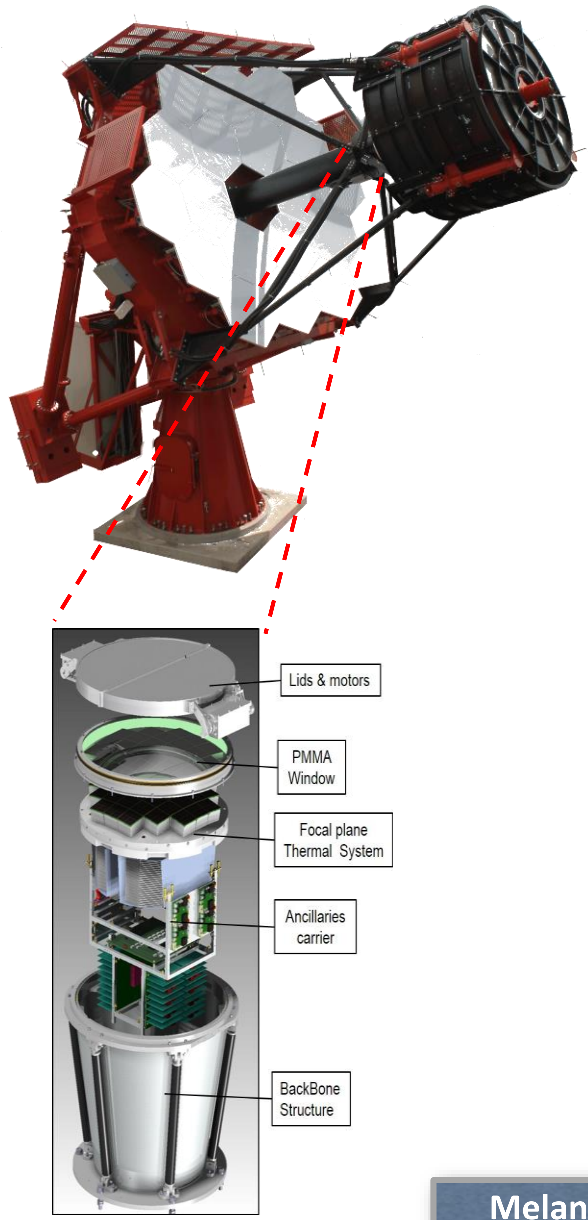
THE ASTRI PROJECT

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

ASTRI SST-2M is and Imaging Atmospheric Cherenkov Telescope located on the Etna volcano at the Serra La Nave Astrophysical Observatory (Catania).

The first aim is to develop an end-to-end prototype proposed for the **small-sized telescopes of the CTA** dedicated to very high-energy gamma-ray Astrophysics.
After the commissioning phase, ASTRI SST-2M will perform scientific observations of the Crab Nebula, Mrk 421, and Mrk 501 with the maximum sensitivity range above 2 TeV.

ASTRI SST-2M



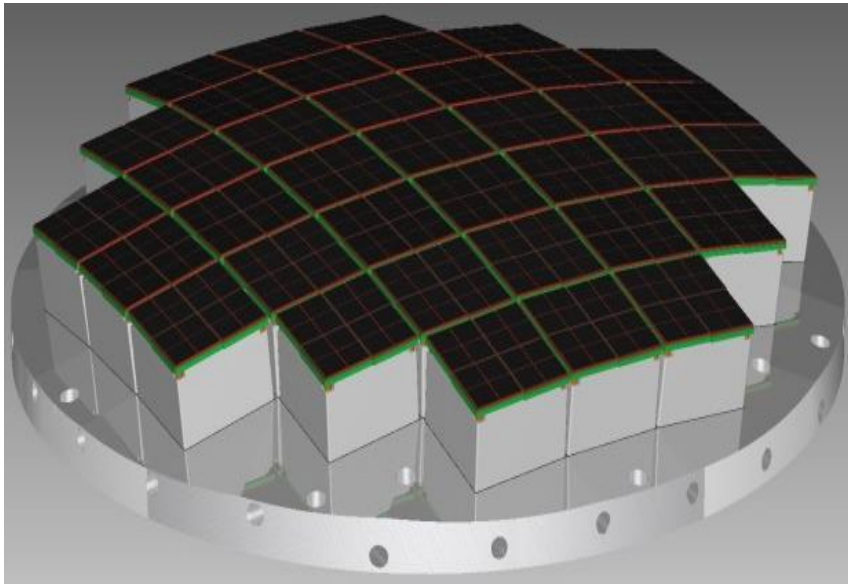
Optics characteristics

- dual mirror optical design (Schwarzschild-Couder config.)
  ➡ *small size camera (50x50x50 cm^3 – ~50 kg)*
- Segmented primary mirror: 4.3m
- Monolithic secondary mirror: 1.8m
- Equiv. Focal Length = 2.15m
- Field of View ~ 9.6°

Focal Plane characteristics

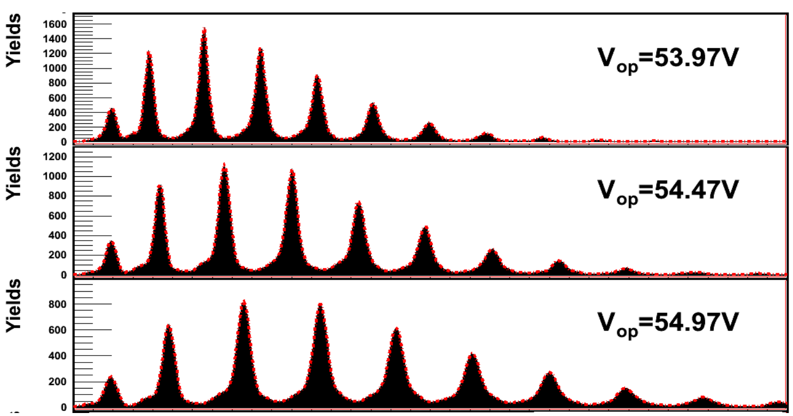
- radius of curvature: ~ 1m
- ~2000 pixels (6.9x6.9mm^2)
- pixel FoV = 0.19°
- Modular (37 Photon Detection Modules of 8x8 SiPM pixels)

THE ASTRI FOCAL PLANE



SiPM performance

- Excellent single photo-electron resolution
- high PDE (~40% @400nm)
- safe ambient light exposure
- insensitive to magnetic field



Pulse height distribution of one pixel

ADVANTAGES OF THE CHERENKOV TECHNIQUE

The background is due to muons hitting the primary mirror with an incidence angle within the FOV and not coming from the mountain:

mainly back-scattered from the ground.

- ground level measurement of upward directed atmospheric muons: $3\text{x}10^{-6}$ cm^{-2} sr^{-1} day^{-1}

≈$3\text{x}10^{-3}$ "fake" events per observation night (8 hours) within the field of view of ASTRI SST-2M

compared

5000 muons/night are expected to hit the telescope mirror

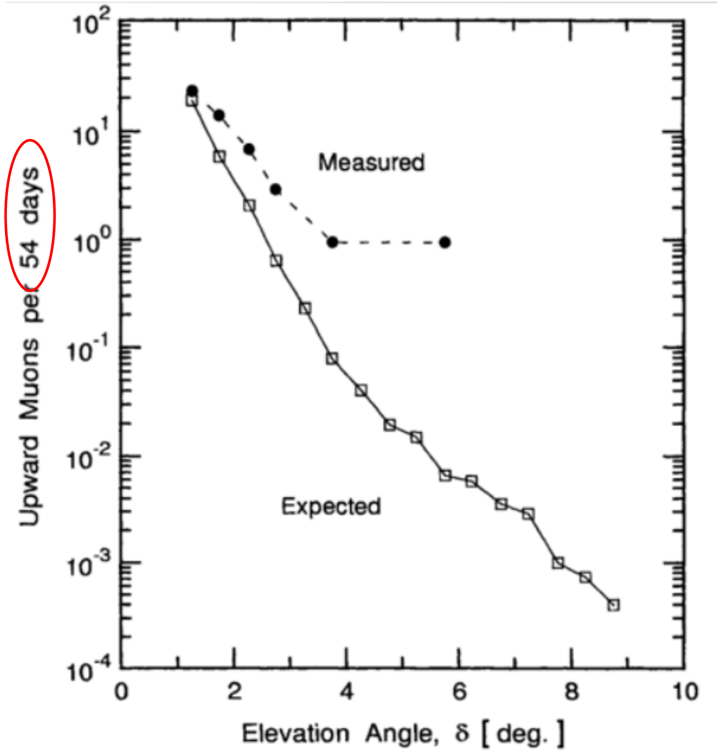
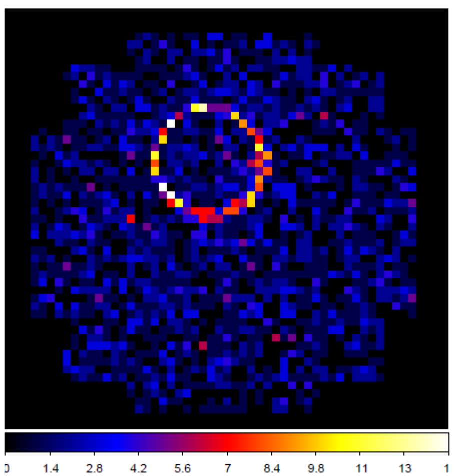


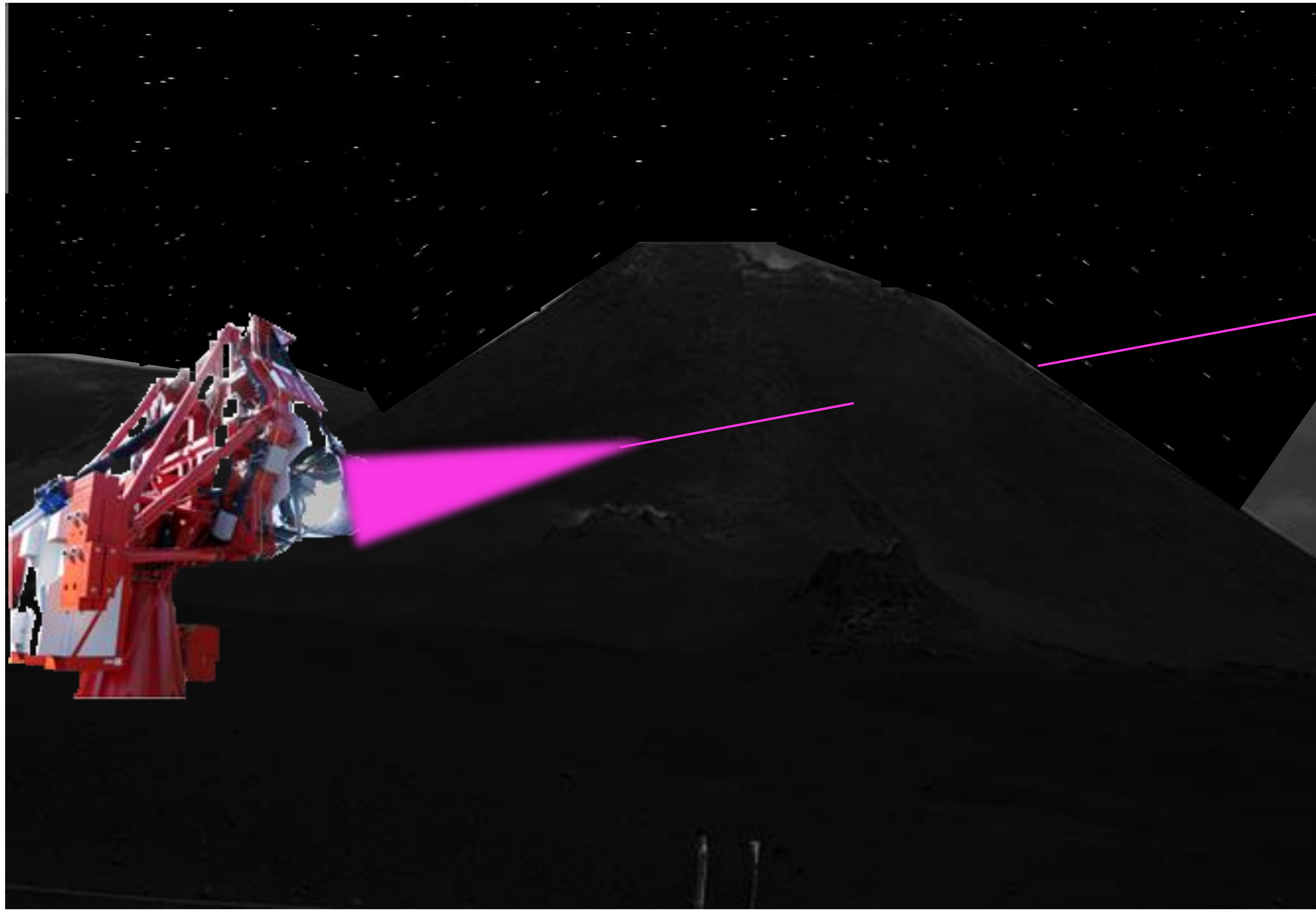
Figure 3.79: Ground level measurement of upward directed atmospheric muons of energy ≥4 GeV resulting from backscattering in the ground compared with a prediction. The horizontal telescope had an area of 2 m² and a horizontal depth of 11.07 m. (Abbrescia et al. (1993).

NO BACKGROUND

MUONS WITH CHERENKOV TELESCOPES

Muons create typical annular patterns in the multi-pixels camera placed at the focus of the converging optics of the telescope.

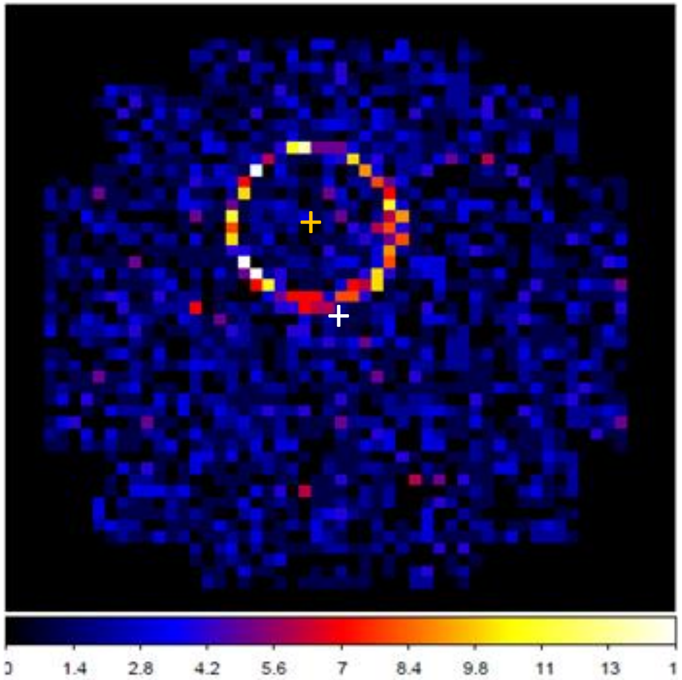




PHYSICAL PARAMETERS DETERMINATION

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

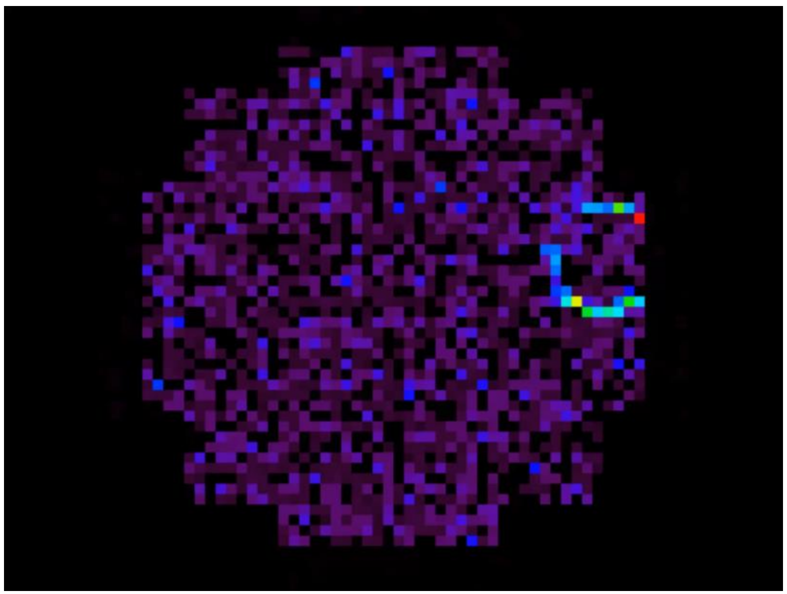
The position of the center gives the direction of the detected muon with respect to the telescope optics axis.



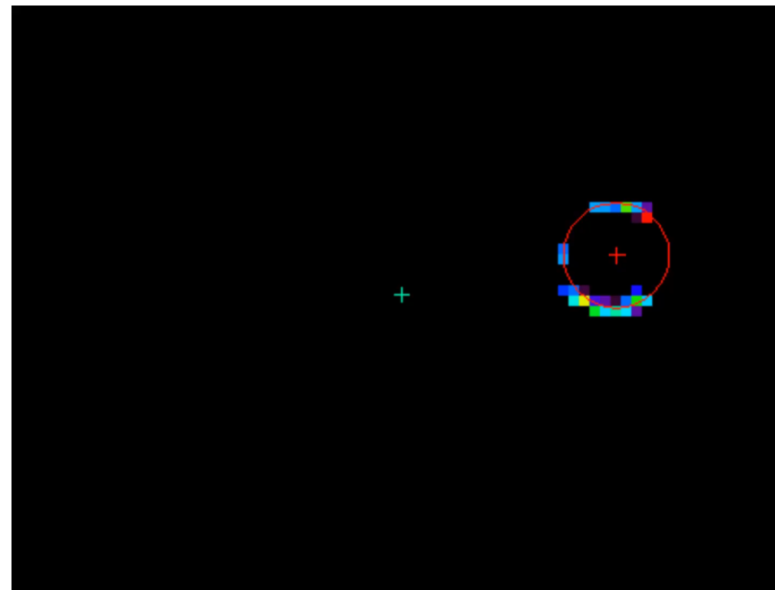
The capability to reconstruct muon rings depends on the impact point on the telescope mirror, on the telescope entrance pupil area and on the camera efficiency.

MUONS RECONSTRUCTION

ASTRI SST-2M is able to reconstruct muons with energy higher than 20 GeV with a precision on the direction reconstruction of about 0.14° (Strazzeri+13).

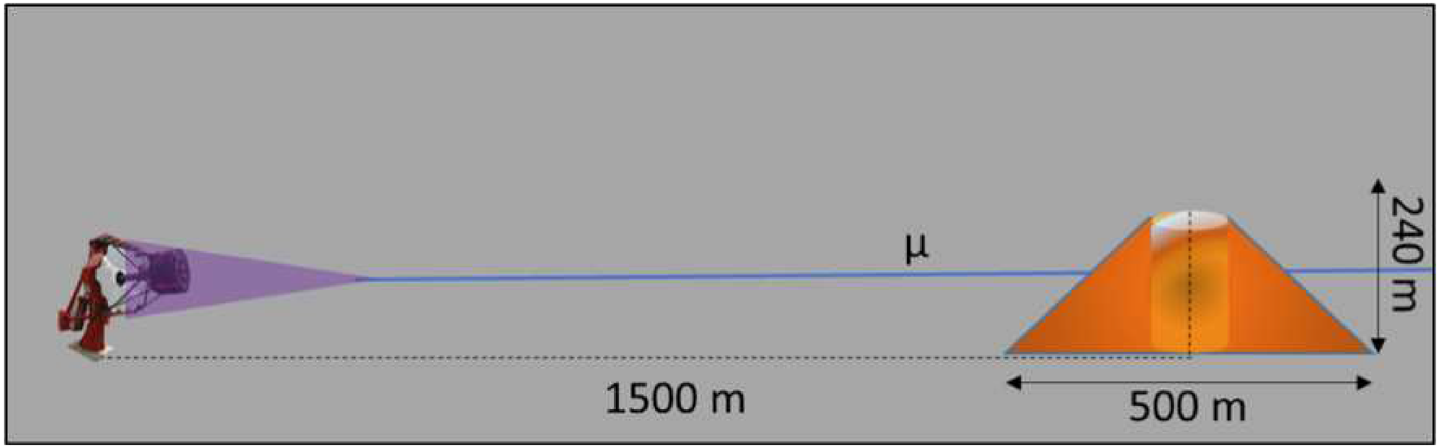


RAW DATA



RECONSTRUCTED (96%)

SIMULATIONS SET-UP



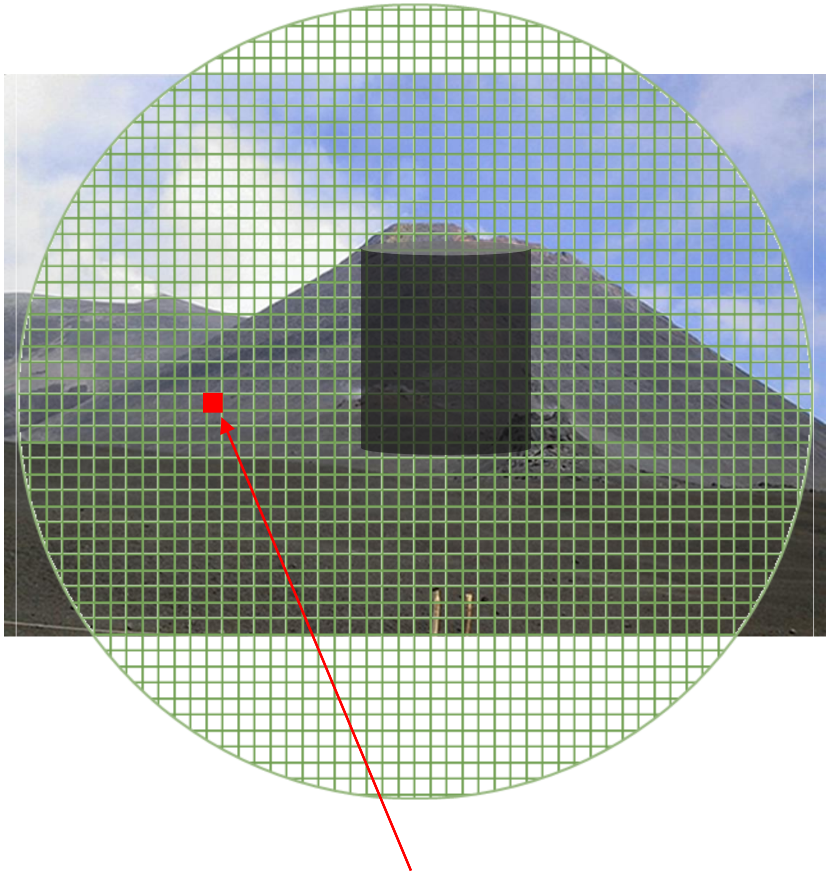
- The volcano geometry: a simple cone of base 500 m and and a height of 240 m (dimensions of the South-Est mouth of Mt Etna)
- Conduits of various dimensions are simulated as hollow cylinders
- Distance between crater and Cherenkov telescope is 1500 m
- ASTRI SST-2M like telescope
- Integrated muon flux computed (Lesparre+10) for standard rock (ρ =2.65 g cm^{-3}) and for θ =85°
- Observations during the night: 8 hours

SIMULATIONS

Angular Resolution ≈ 0.5°
Projected Spatial Resolution ≈ 13.5 m

Bin detector acceptance ≈ 9 cm^2 sr

This pixel size is comparable to the muon angular deviation expected from multiple scattering in crossing the mountain (Nagamine03)

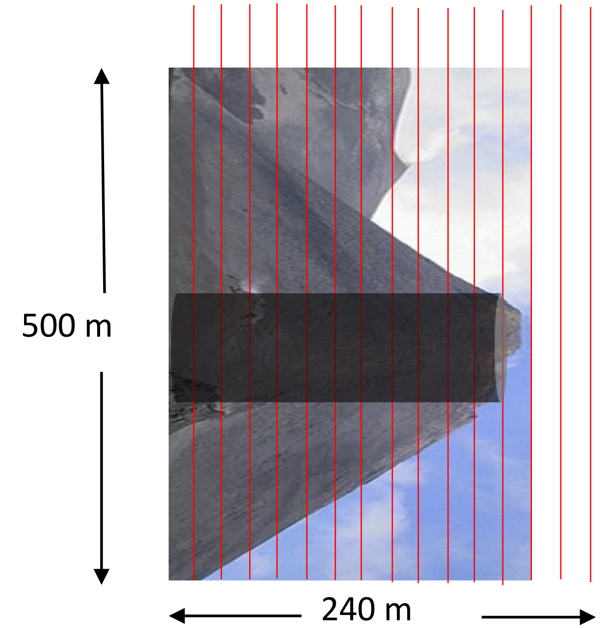


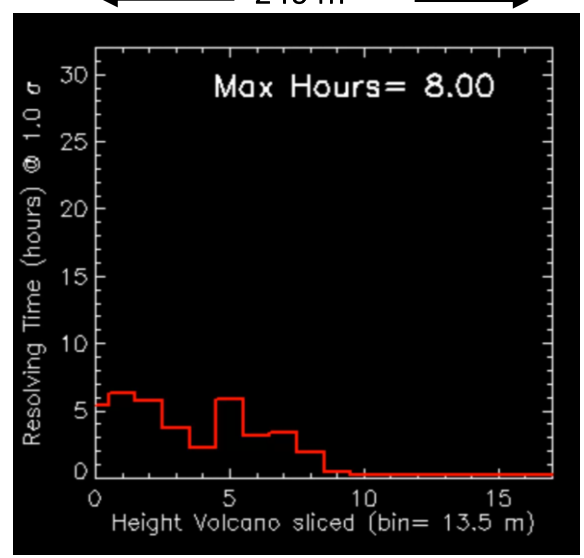
Projected Spatial Resolution

SIMULATIONS

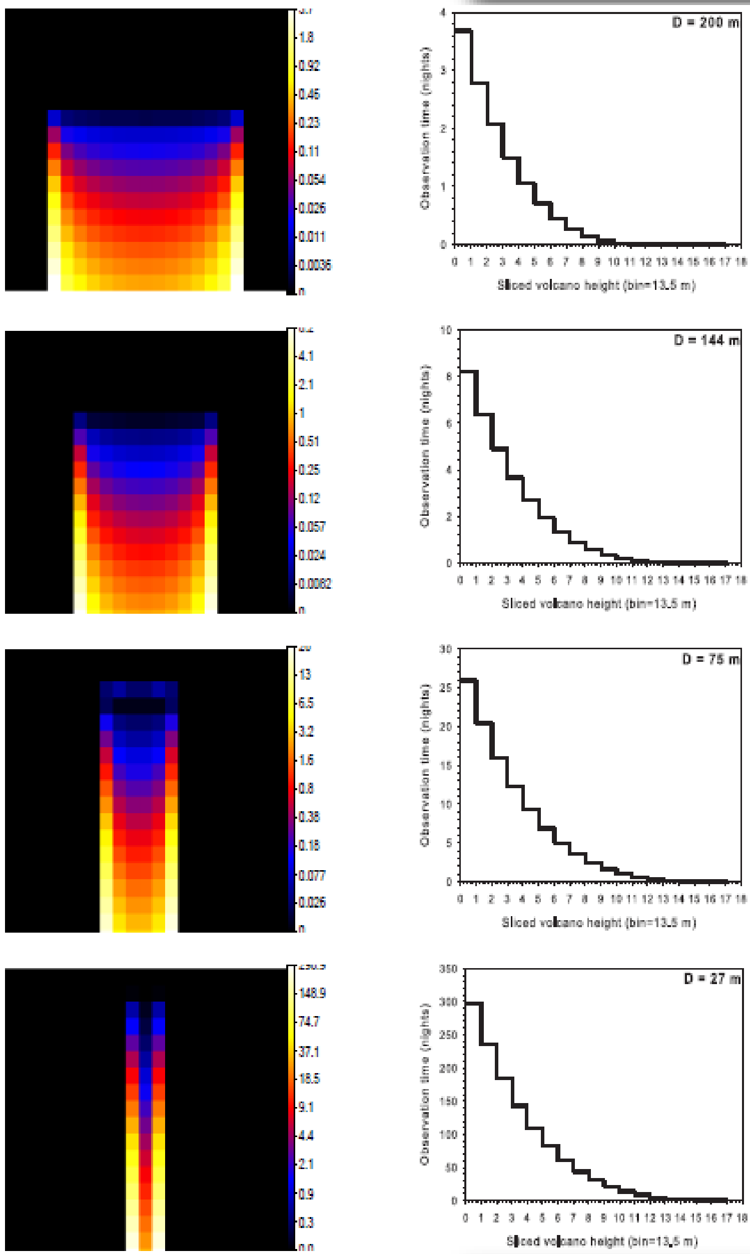
No Conduit: Muon Flux per bin

200 m Conduit: Muon Flux per bin



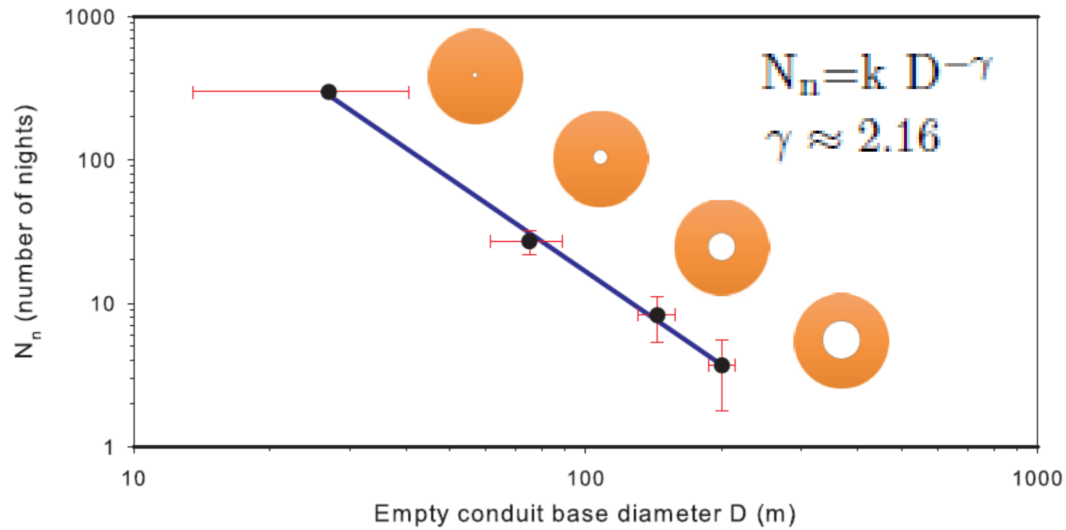


SIMULATIONS



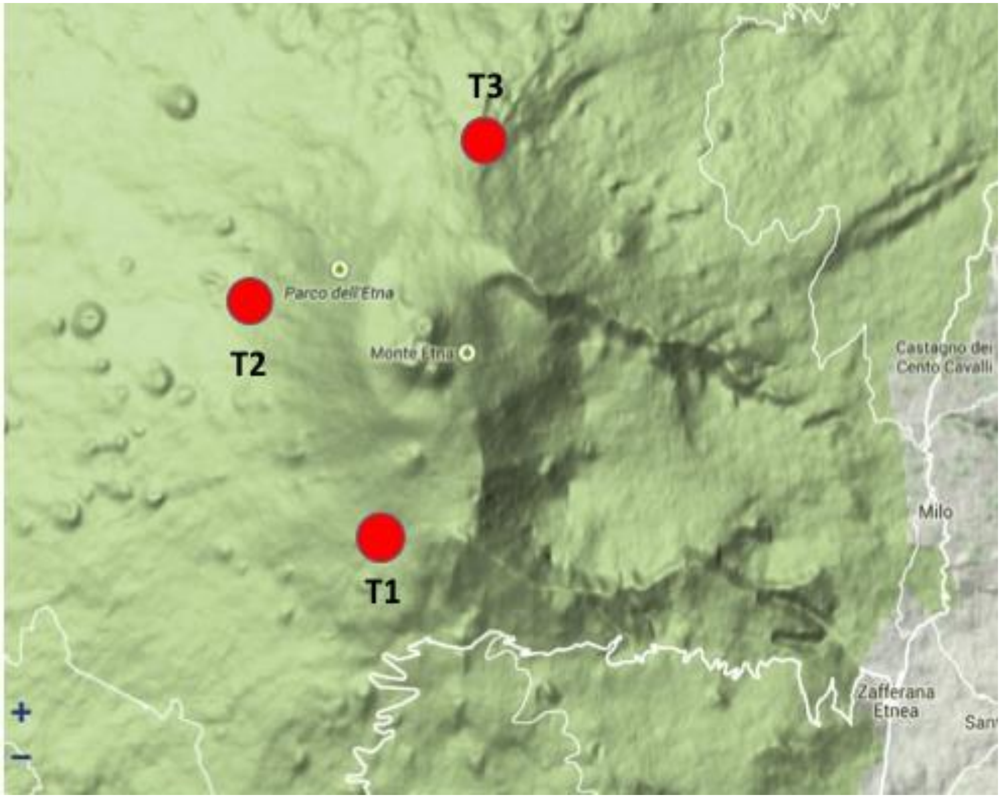
We have estimated the number of nights necessary to resolve conduits of different diameter: 200m, 144m, 75m, 27m.

Catalano et al. 2016, NIMPA, 807, 5



Minimum number of observation nights as a function of the conduit diameters. The diameter of each disc represents the cone base, while the hollow part of each disc are the dimension of the simulated conduit.

TOMOGRAPHY



Multidirectional radiography (tomography) can resolve the exact position of the density anomaly its shape and its alignment by superimposing images obtained by each telescope and producing three dimensional images of the region of interest.

A POSSIBLE CONFIGURATION

The new IACT will be ASTRI-like, i.e. with a double mirrors optics and multi-pixel focal plane made-up of SiPM

However:

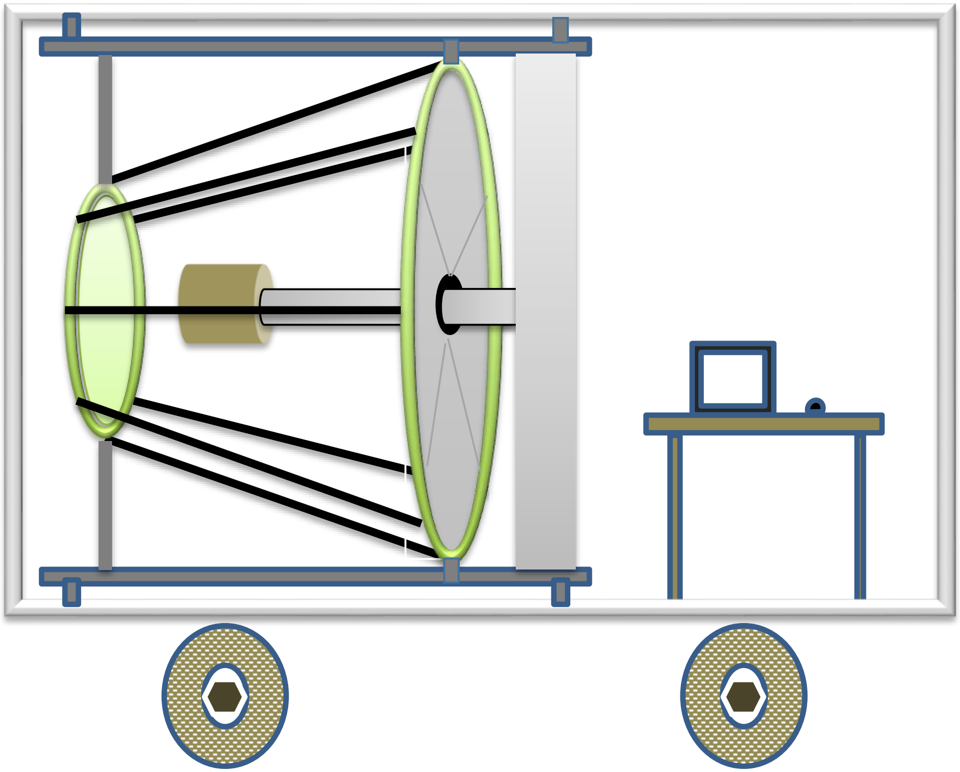
it will be smaller, lighter (200 kg) and low-cost (150 keuro).

In particular:

1) focal plane: 16 Photon Detection Modules of 8x8 SiPM pixels (each module of 57mm x 57mm x 30mm)
2) primary mirror with 8 hexagonal facets (aperture 2.1 m), monolithic 0.8 m secondary mirror)
3) FOV: 12^{o}
4) lighter structure
5) no pointing system

(Patent n. 102015000075497 registered at Ministero dello Sviluppo Economico, Italy).

A POSSIBLE CONFIGURATION



Our idea is to install the instrumentation on **mobile vehicles**, possibly **solar powered**, in order to realize ecologic instrumentations which can be positioned in the desired and variable configuration and can be easily removed.

CONCLUSIONS

1. From our simulations it results that imaging Cherenkov telescopes are able to perform muon radiography of volcanoes with a good spatial resolution.
2. IACTs do not suffer of the high background affecting most of the current experiment.
3. ASTRI SST-2M will be used to test the new method proposed.
4. Comparing our technique with a previous Mt Etna experiment (based on scintillator strips), we gain a factor of 10 in sensitivity.
5. The new proposed Cherenkov telescope is low cost, easily removable and ecologic.
6. The volcano tomography can be performed by using 2 or more telescopes that can be positioned in different configuration around the volcano.

THANKS FOR YOUR ATTENTION