# A new technique for probing the internal structure of volcanoes using cosmic-ray muons

@Del Santo M.[1], Catalano O.[1], Mineo T.[1], Cusumano G.[1], Maccarone M. C.[1], La Parola V.[1], La Rosa G.[1], Sottile G.[1], Vercellone S.[1], Pareschi G.[2], Carbone D.[3], Zuccarello L.[3]

[1]INAF/Istituto di Astrofisica Spaziale e Fisica Cosmica di Palermo (Italy); [2]INAF/Osservatorio Astronomico di Brera (Italy); [3]INGV, Sezione di Catania –Osservatorio Etneo (Italy)

@ Contact: melania@ifc.inaf.it

## Principle of muon imaging of volcanoes

Thanks to their high penetration capability, cosmic-ray muons can travel through huge structures losing a fraction (up to the total) of energy proportionally to the thickness of the crossed material. In particular, by measuring the differential attenuation of the muon flux crossing a volcano, it can be determined the density distribution of its interior. This is the principle of muon radiography which is a promising technique to study the inner structure of volcanoes (Tanaka et al., 2014, Nature Comm.).

**The quantitative understanding of the inner structure of volcanoes is a key-point to forecast the dangerous stages of activity and mitigate volcanic hazards.**

The minimum initial energy ($E_{min}$) needed by a muon to cross a length of rock of a given density (Fig. 1, Carbone et al. 2013, Geoph. J. Int.), is determined from the energy loss of muons across rock and is used to compute the theoretical integrated muon flux, *I*, after the target has been crossed, starting from the model of the differential incident flux ($\Phi_0$). Lesparre et al. (Geoph. J. Int., 2010) defined a relation linking the muon flux *I*, the acquisition time ΔT, the amount of crossed matter (opacity) and the telescope acceptance, Γ (this latter depends on the telescope geometric area and on the angular resolution).

The following equation represents the feasibility condition:

$$\Delta T \times \Gamma \times \frac{\Delta I^2(\varepsilon_0, \delta\varepsilon)}{I(\varepsilon_0)} > 1$$

The left-hand term of the condition is determined by the fixed total opacity of the medium ($\varepsilon_0$) and by the desired resolution level ($\delta\varepsilon$). This sets the minimum value for Γ x ΔT and the question is to determine whether this value is reachable or not.

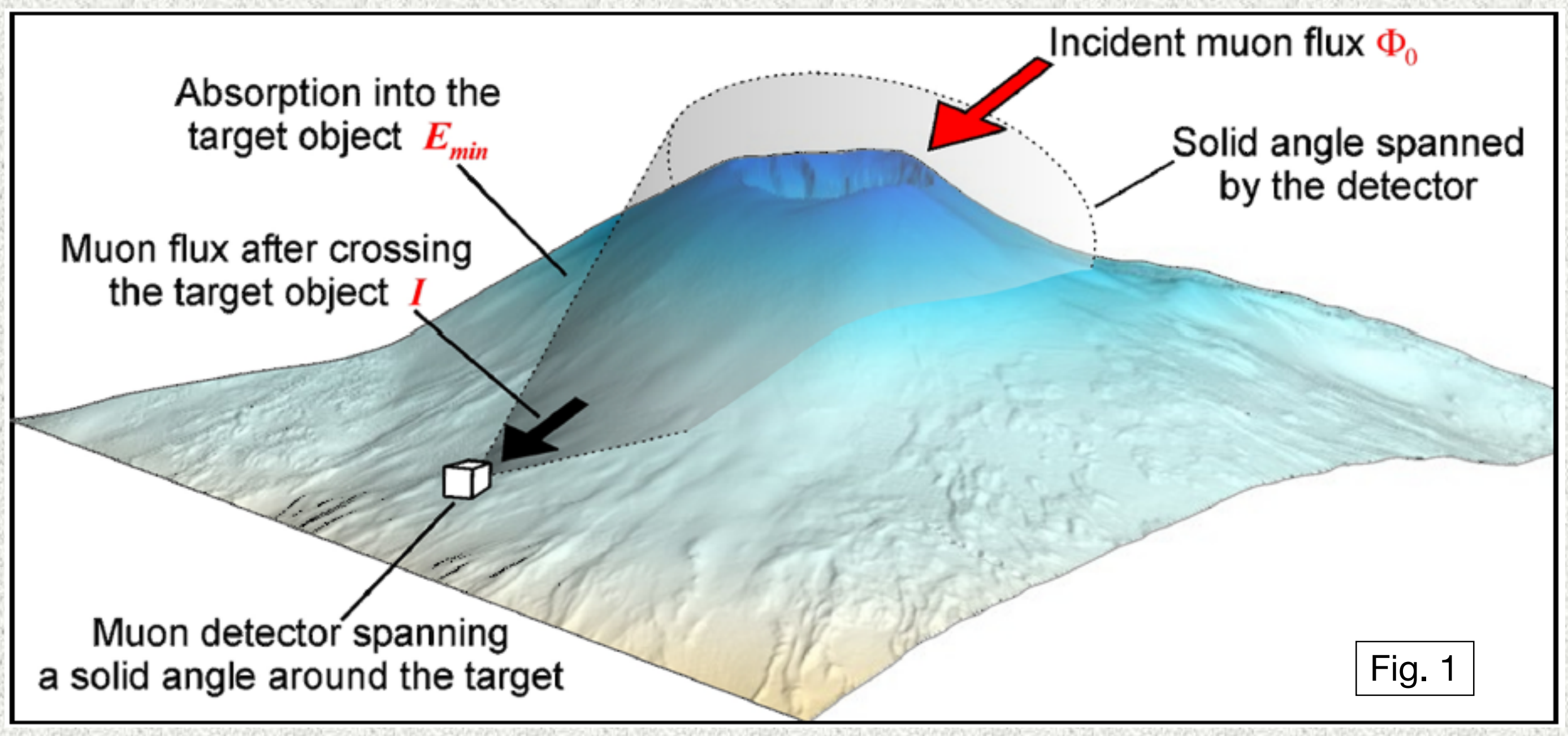

Fig. 1

## Current Experiments

Up to now, measurements of the inner structure of volcanoes using muons have been based on the detection of muon-track crossing hodoscopes made up of scintillators or nuclear emulsion planes. However, this technique requires several detection layers and a sufficiently high timing resolution to reduce the level of fake coincidences due to the unavoidable charged particles background.

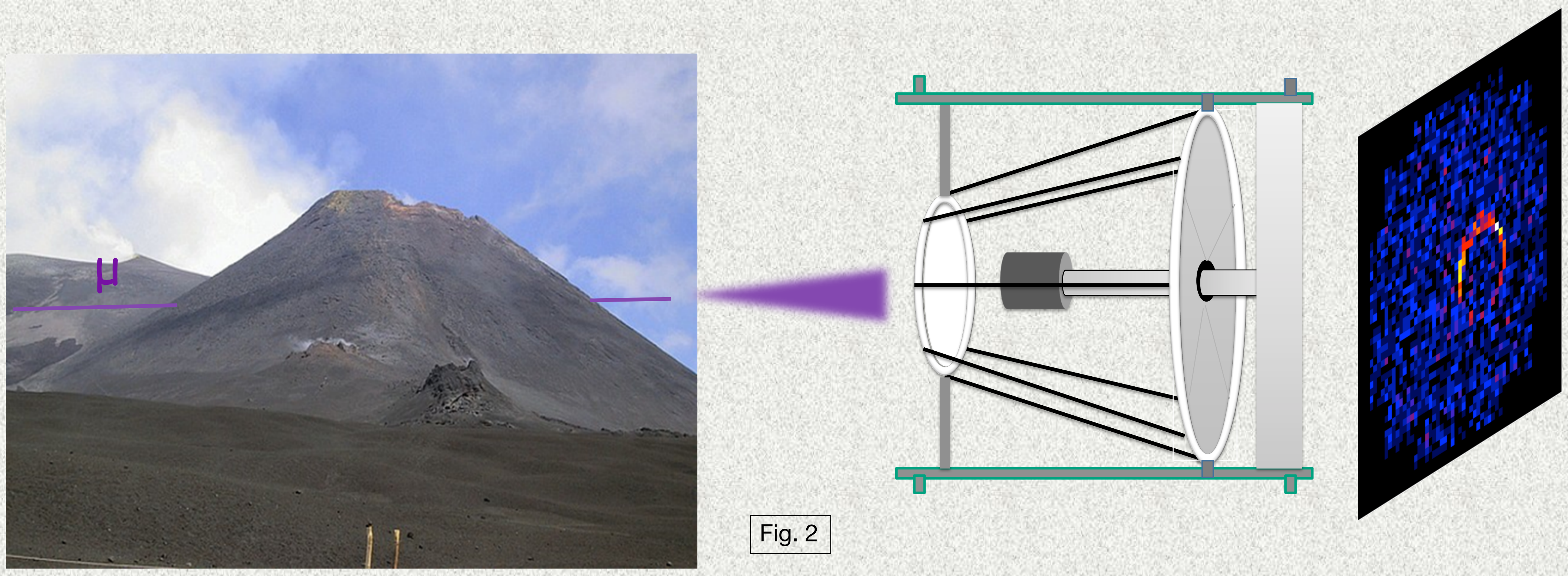

Fig. 2

## Muon radiography of volcanoes with Cherenkov Telescope

**We propose an alternative technique based on the detection of the Cherenkov light produced by muons. Our new approach offers the advantage of a negligible background, an improved spatial resolution and the capability to measure the particles energy (Catalano et al. 2016, NIMA).**

Cherenkov light is emitted in the blue and ultraviolet regions of the spectrum when charged particles travel through a dielectric medium with velocity higher than the speed of light in that medium. Since muons with energy higher than about 5 GeV (at sea level) induce Cherenkov light in the atmosphere, muon radiography of volcanoes can be achieved with a Cherenkov telescope. We propose an instrument equipped by an optical system composed of high reflectivity mirror that focus the Cherenkov light onto a multi-pixel focal camera with fast read-out electronics. The camera images the Cherenkov photons by a muon with a characteristic ring shape. A simple geometrical analysis of the annular pattern allows us to reconstruct the muon physical parameters, i.e. its energy and arrival direction (see Fig. 2).

## Simulation set-up

We assumed a dual mirror optical system with a focal number, defined as the ratio of the lens's focal length to the diameter of the entrance pupil, *f*=0.5. The camera consists of a matrix of Silicon Photomultiplier (SiPM) sensors covering a 9.6° full field of view (FOV). The volcano geometry is represented by a simple cone of base 500 m and and a height of 240 m (toy-model) which is located 1500 m far from the Cherenkov telescope. The positioning resolution of such an optical system is 13.5m (Fig. 3) which corresponds to an acceptance of 9 cm$^2$ sr. The whole cone is included in the telescope FOV (Fig. 3). Then, we have assumed a hollow cylinder as volcanic conduit and estimated the number of nights necessary to resolve conduits of different diameter (144m and 27m) and height h=135m.

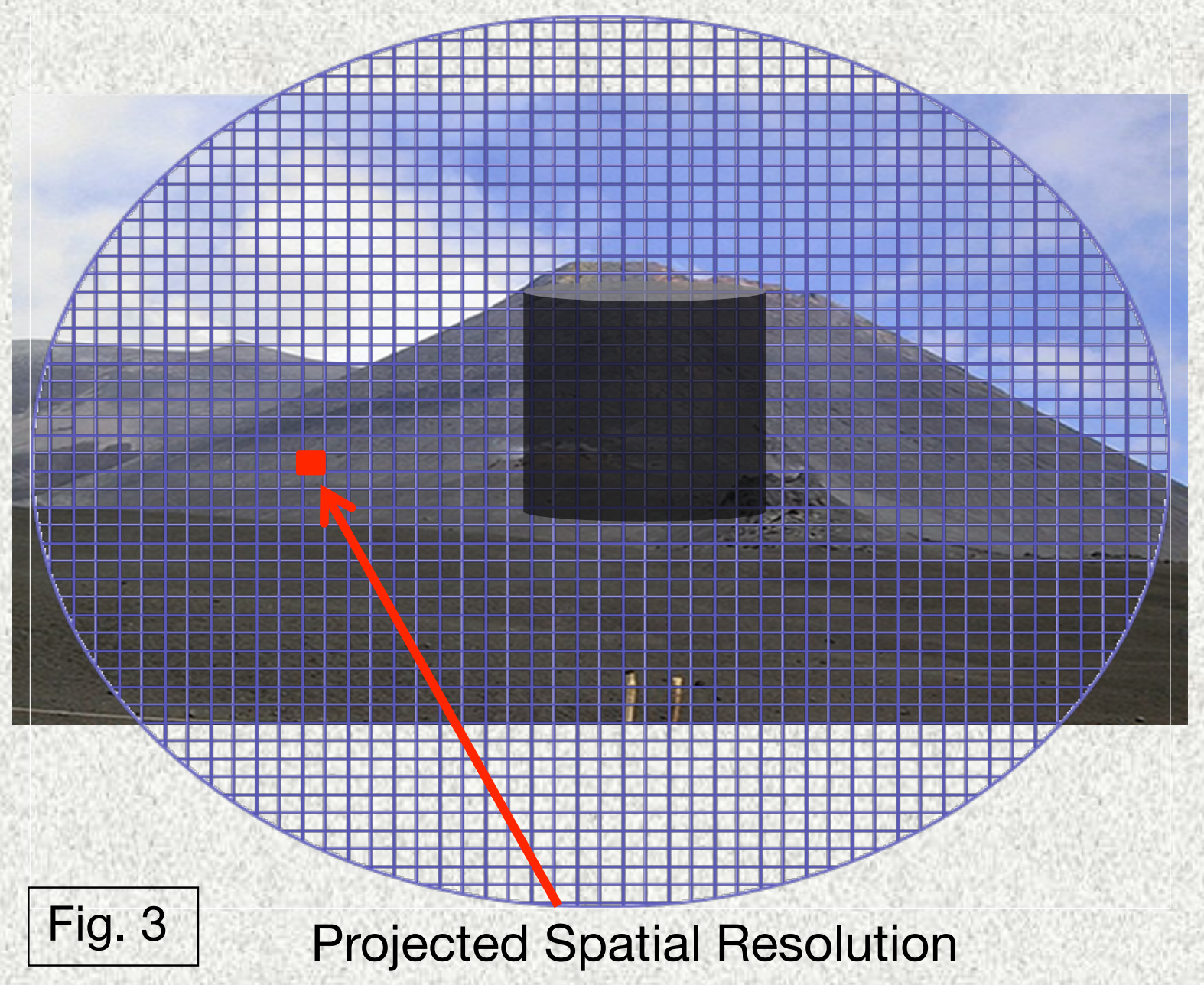

Fig. 3

Projected Spatial Resolution

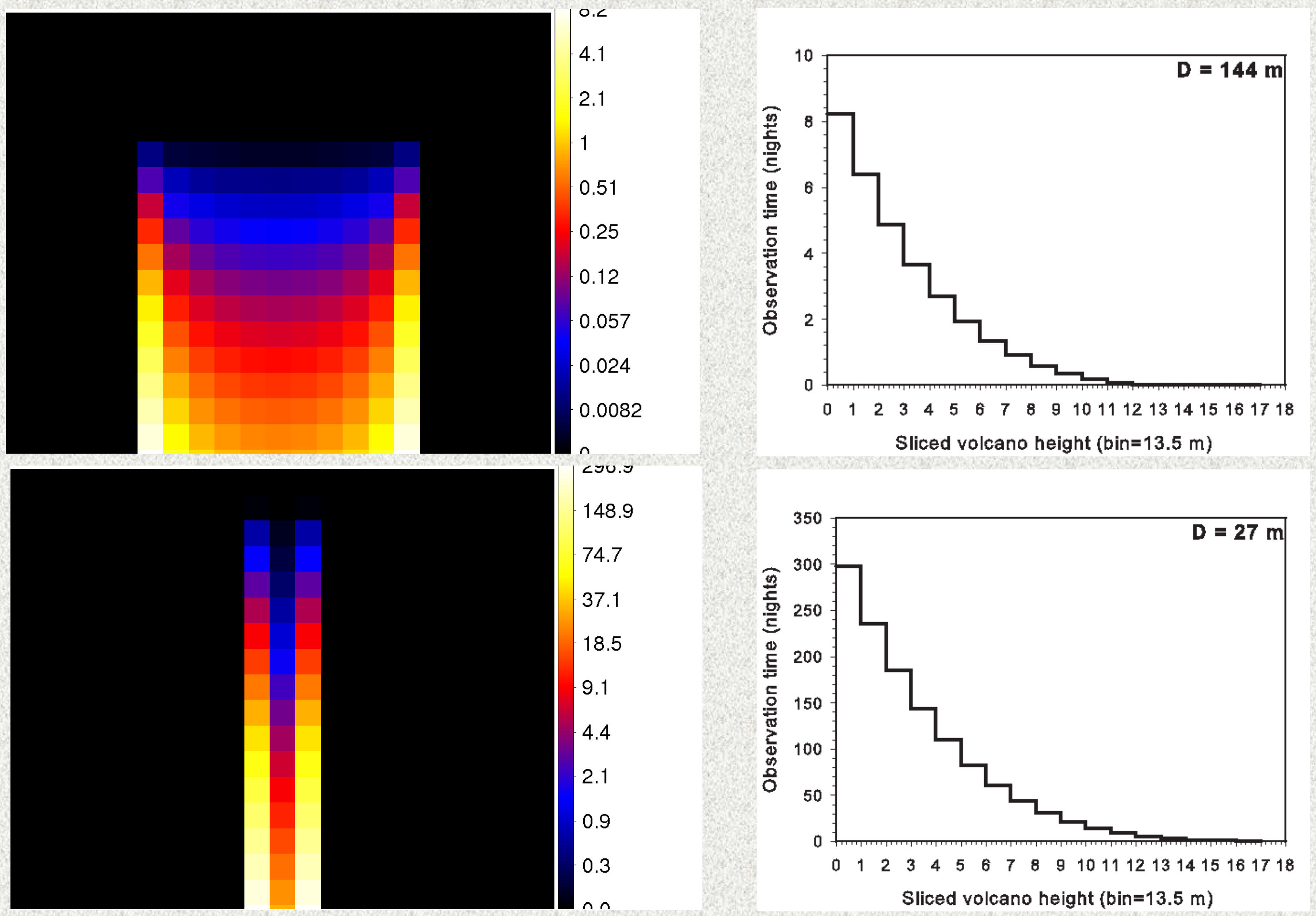

Fig. 4

## Results

Assuming the ground level measurement of upward directed atmospheric muons of $3 \times 10^{-6}$ cm$^{-2}$ sr$^{-1}$ day$^{-1}$ (see Gredier 2001, Cosmic Rays at Earth), a rough estimation of the level of this muon background results in a rate of about $3 \times 10^{-3}$ "fake" events per observation night within the telescope FOV (see Catalano et al. 2016, NIMA).

Assuming 8 hr as a mean duration of 1 night, we show the opacity (at a confidence level of 68%) for cylinders of 144m and 27m diameter (Fig. 4). It results that for a 144m diameter cylinder we need about 9 nights to resolve the entire conduit, while about 300 nights are required to resolve a very thin volcano conduit of 27m diameter.

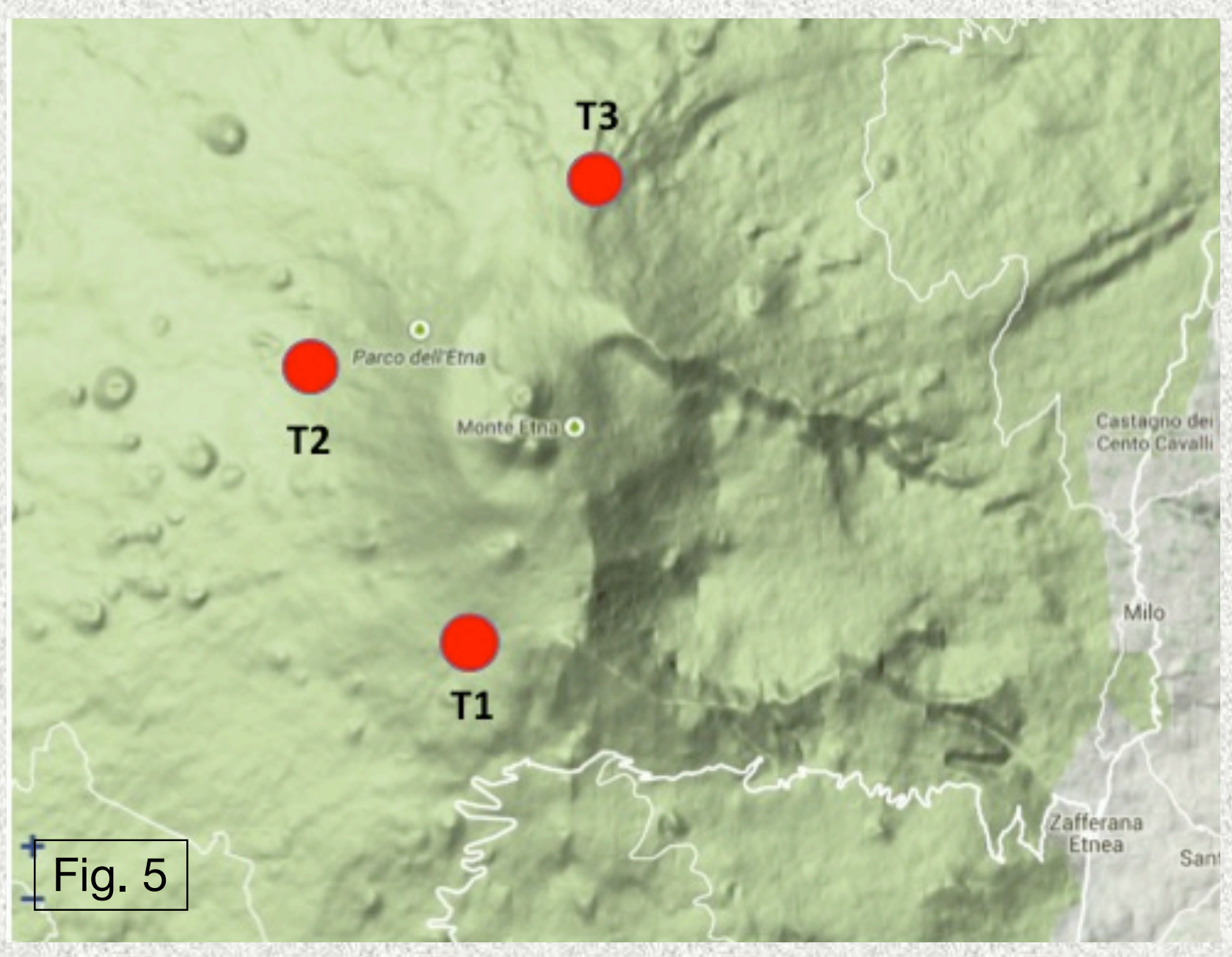

Fig. 5

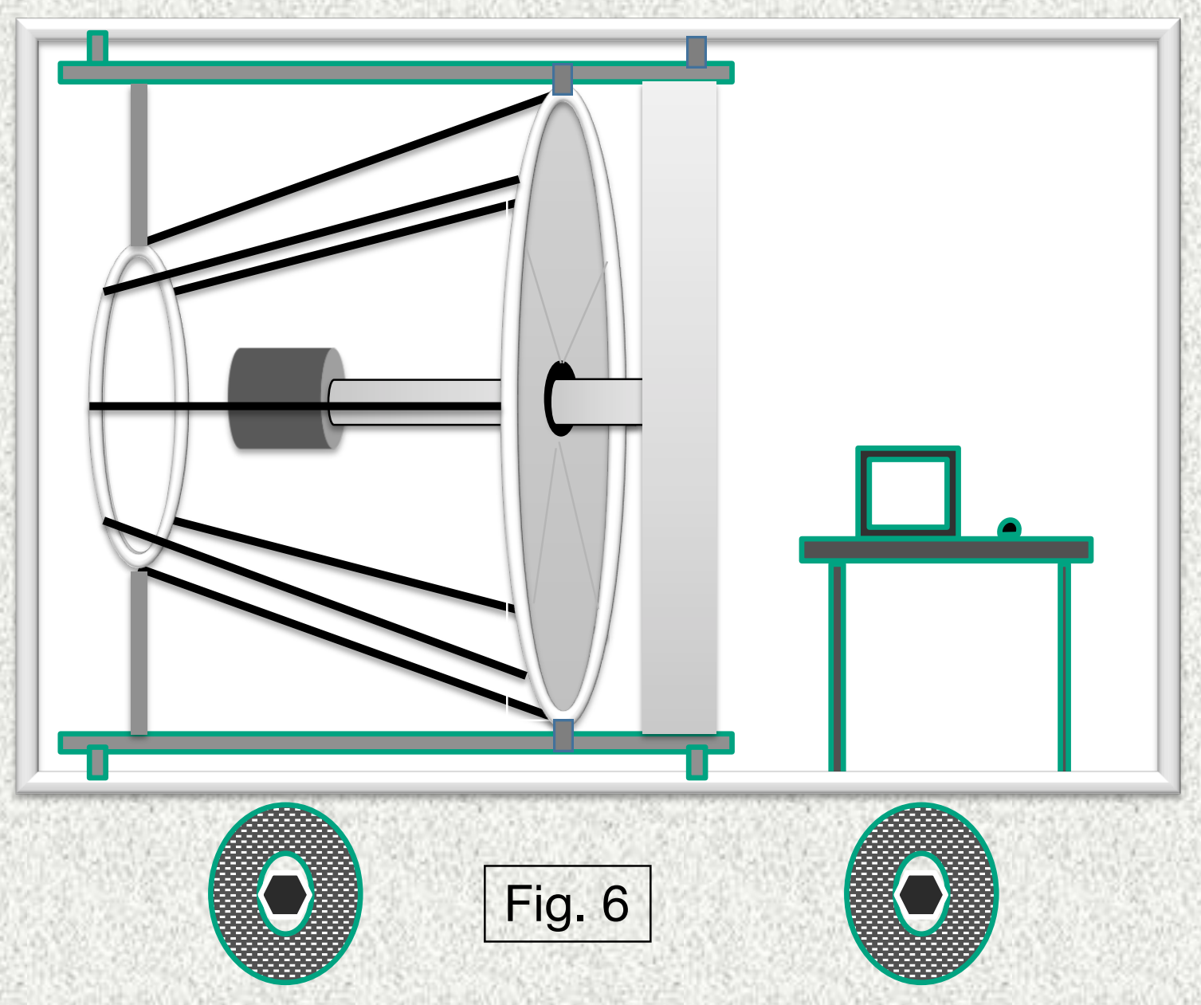

Fig. 6

## From Volcano radiography to tomography

Measuring the muon flux absorption as a function of the muon direction resolves only the average density distribution along individual muon paths. Obviously, several telescopes at different positions around the volcano would be required for the multidirectional radiography (tomography). This can resolve the exact position of a region with anomalous density, its shape and its alignment by superimposing images obtained by each telescope and producing three dimensional images of the region of interest. In Fig. 5 we show a possible configuration of Cherenkov telescopes dedicated to the Mt. Etna tomography. For this purpose the design of a telescope prototype is in progress and an application for a patent has been filed. Our idea is to install the instrumentation on mobile vehicles (Fig. 6), possibly solar powered, in order to realize ecologic instrumentations which can be positioned in the desired and variable configuration and can be easily removed.