Volcanoes and muons

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NOW 2012, Sept. 9-16, 2012

- **Muon Radiography: concept, history, what's for**
- **Pioneering radiographies of volcanoes in Japan**
- **La Soufrière of Guadeloupe: DIAPHANE**
- **Puy de Dôme: TOMUVOL**
- **Stromboli: nuclear emulsion**
- **The challenge (dream) of Mt. Vesuvius: MU-RAY**
- **Final remarks**

Muons: a gift of Nature from the Cosmos

Cosmic ray interactions in the atmosphere generate

high energy muons

from pion decays

penetrating particles

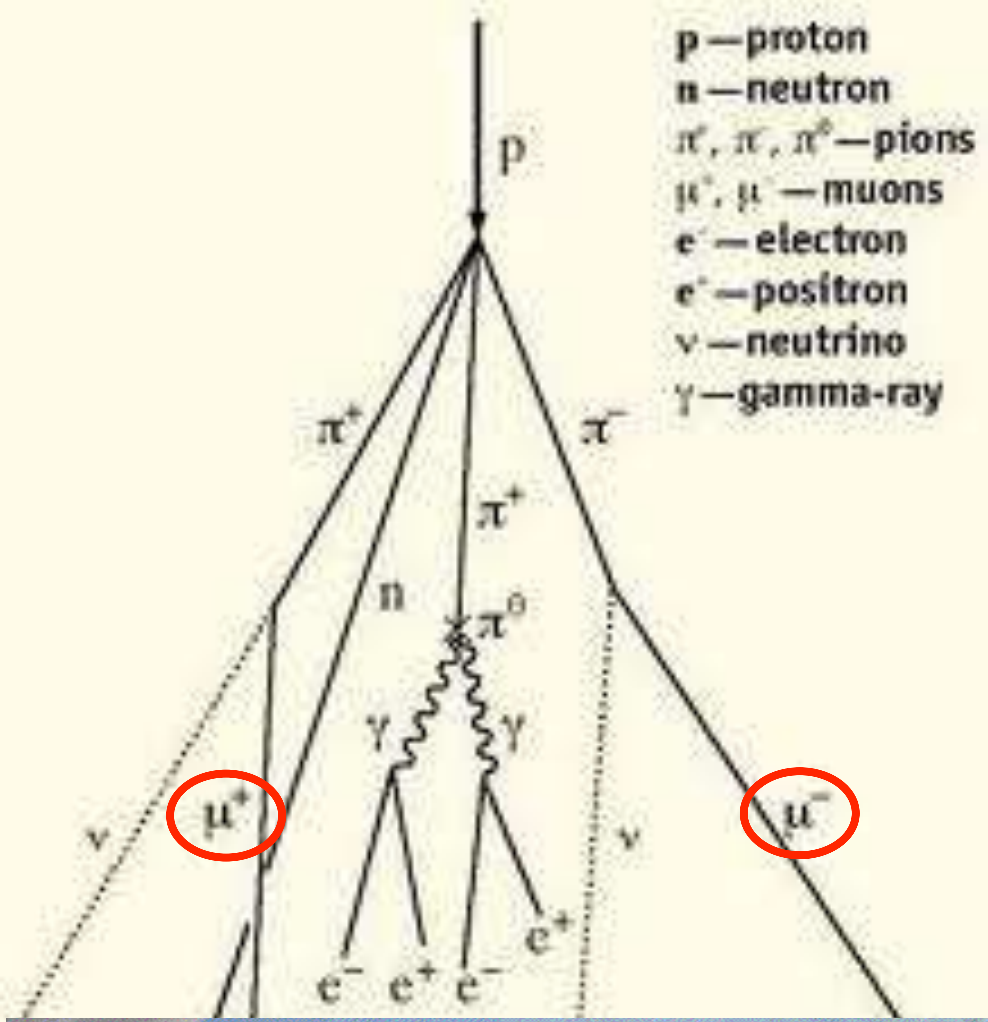
no strong interactions

little brehmstrahlung

(~ 200 x electron mass)

⬇

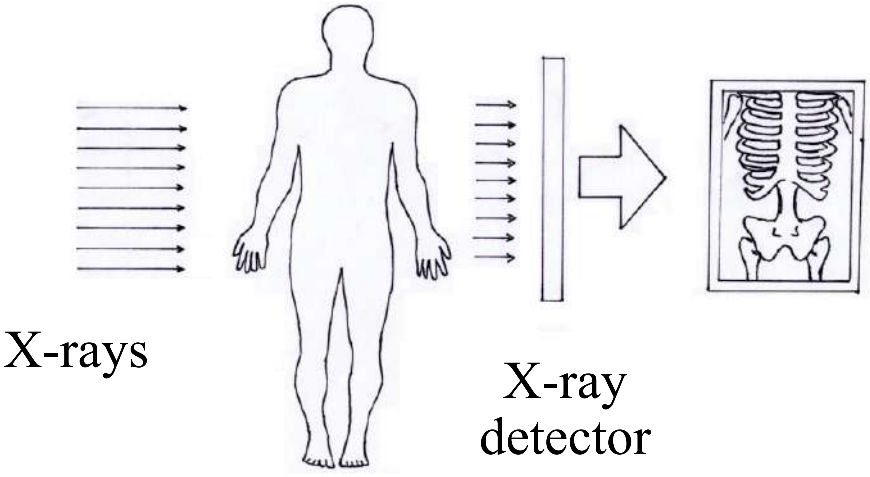
"Muon Radiography"



Muon radiography

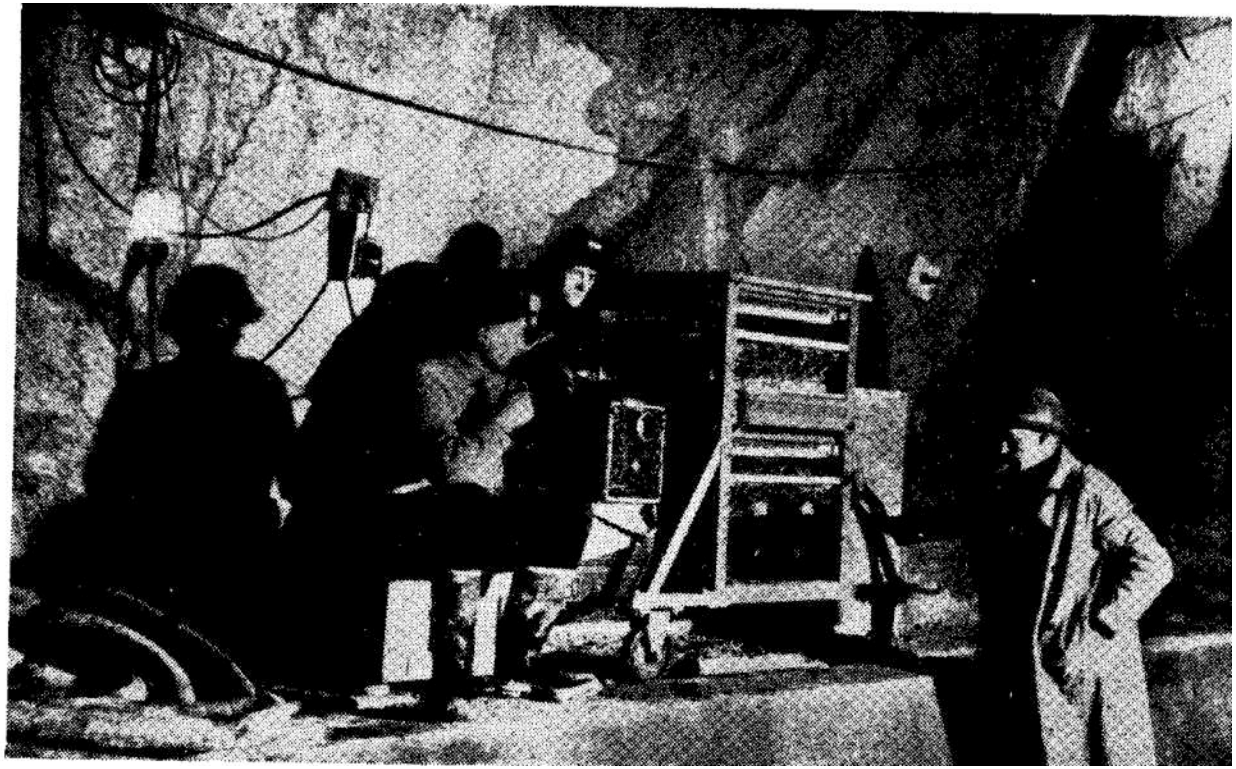
“See the invisible” as a “shadow”
by observing muon absorption (or scattering)
depending on density (or Z) of matter

As with X-rays



The early work

Cosmic Rays Measure Overburden of Tunnel

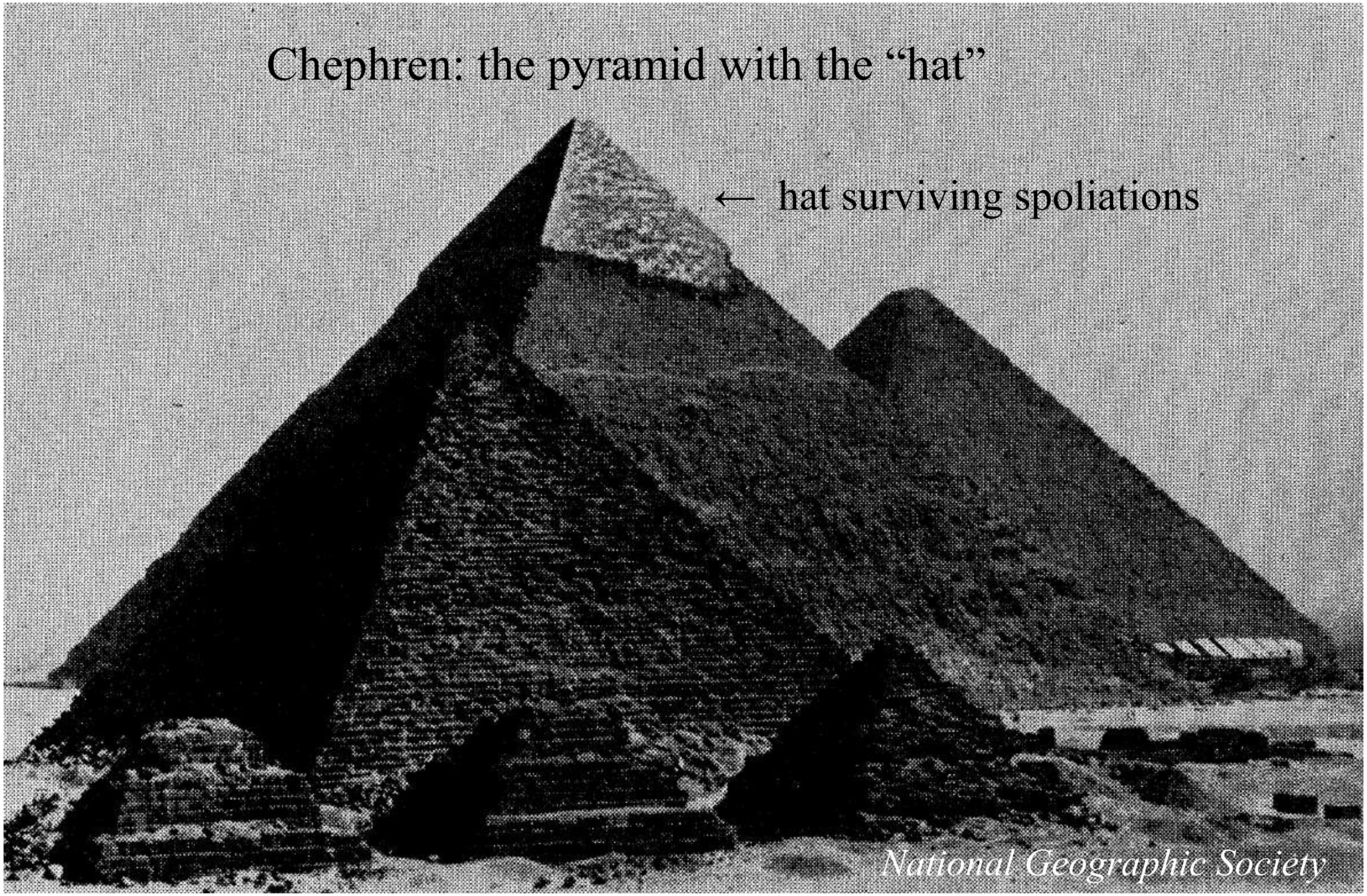


● Fig. 1—Geiger counter "telescope" in operation in the Guthega-Munyang tunnel. From left are Dr. George and his assistants, Mr. Lehane and Mr. O'Neill.

Geiger counter telescope used for mass determination at Guthega project of Snowy Scheme . . . Equipment described

E. P. George, Commonwealth Engineer (1955) 455

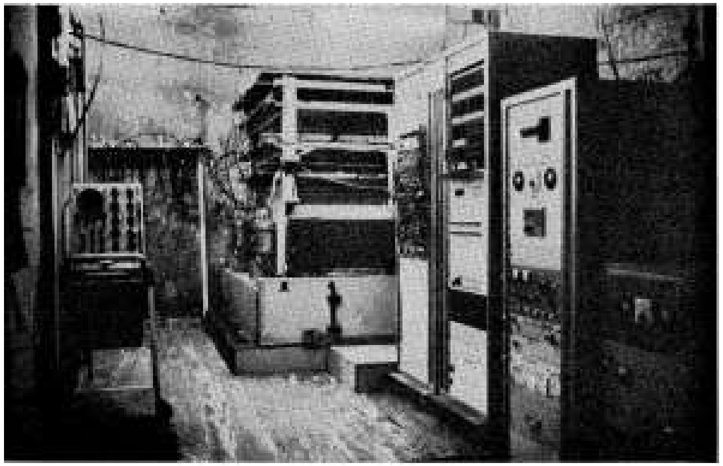
The first "radiography"



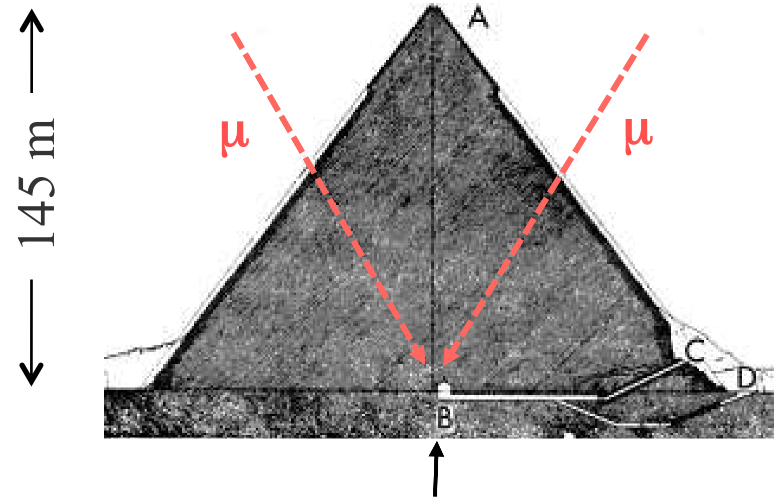
Search for hidden chambers in the Chephren's Pyramid

L.W. Alvarez et al. Science 167 (1970) 832

No hidden chamber

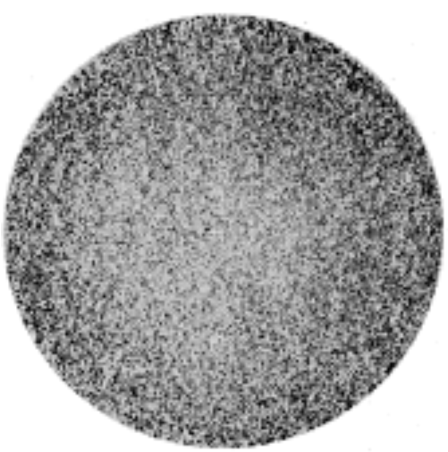


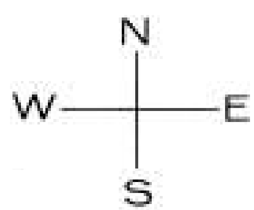
Spark chamber “muon telescope”



Telescope in Belzoni chamber

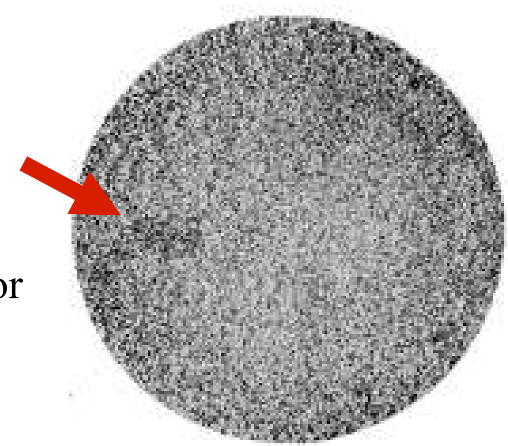
Data





Data and simulation corrected for pyramid structure and telescope acceptance

Simulation with chamber

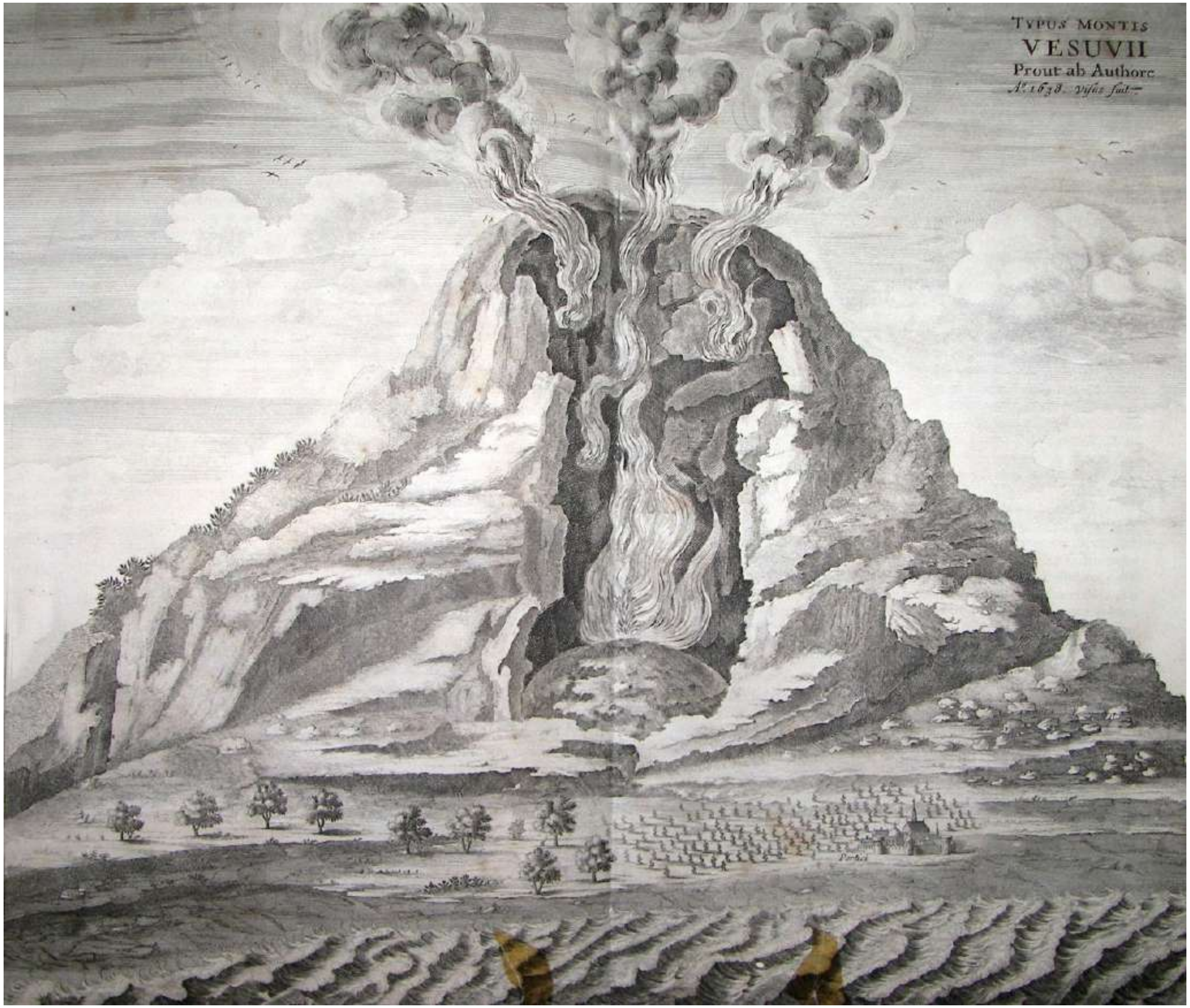


Possible applications in various fields

Archaeology, Civil Engineering, Security,
Geological structures .... Volcanoes

Breakthrough of Muon Radiography with volcanoes

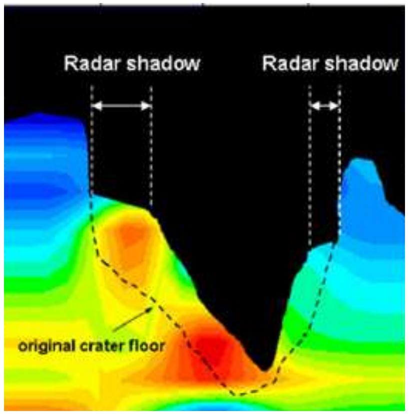
The interior of volcanoes: a fascinating question

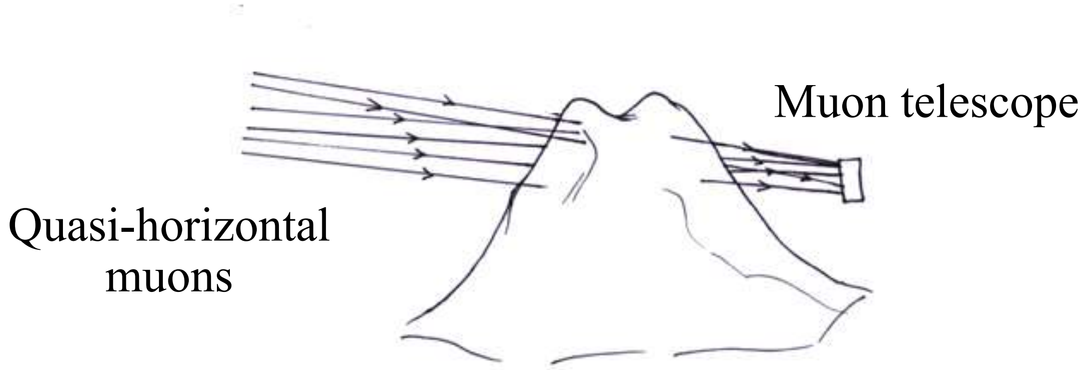


Athanasius Kircher, Mt. Vesuvius (1638)

Hypothesis that volcanoes are connected to the interior of the Earth

Muon radiography of volcanoes





- *<u>Detect</u> quasi-horizontal muons having traversed the volcano*
- *Determine the muon <u>absorption</u> as a function of direction*
- *Construct an "<u>image</u>" (in projective geometry) of the <u>average rock density</u>*

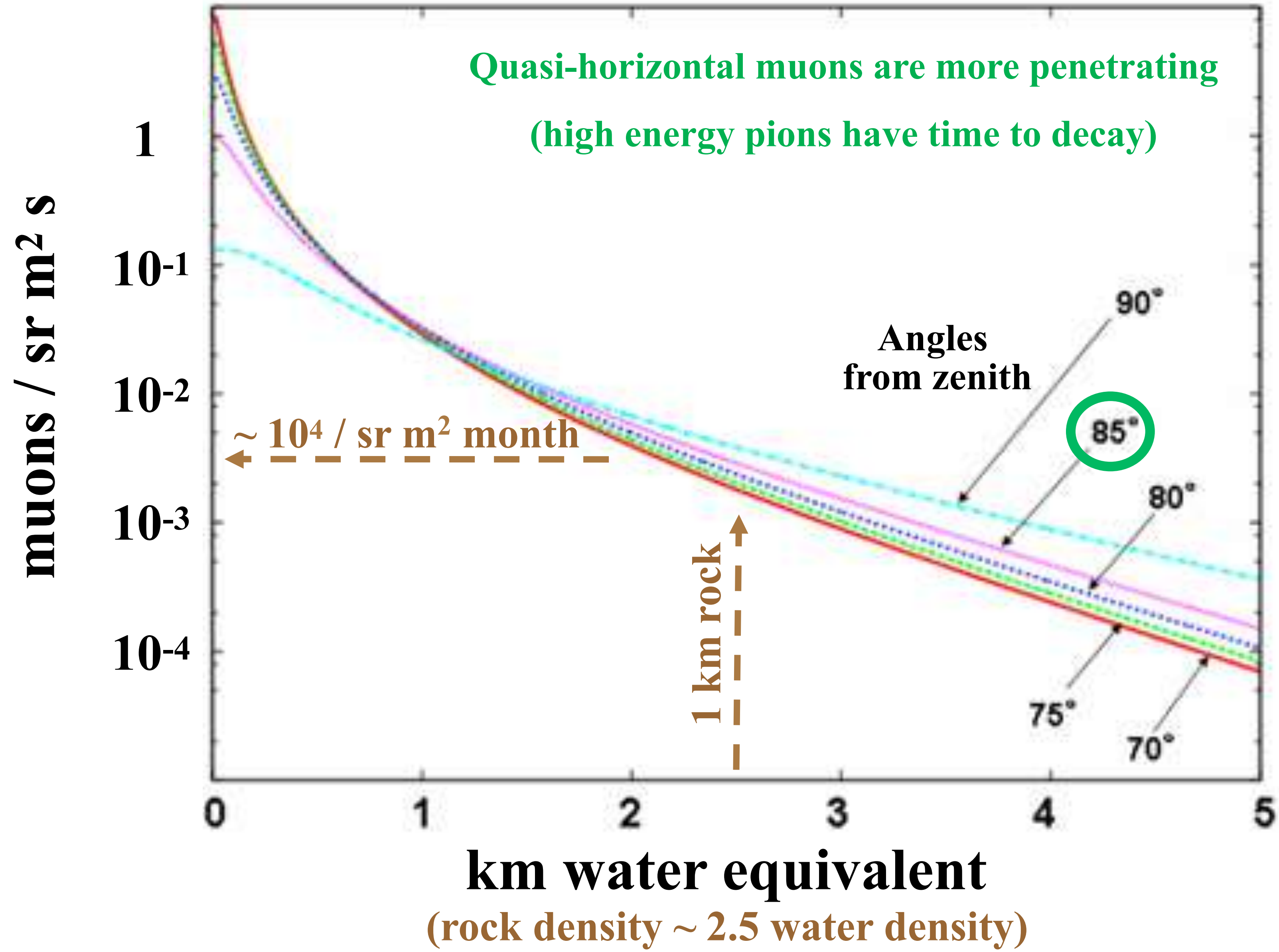
The seminal paper

K. Nagamine

Geo-tomographic observation of inner-structure of volcano with cosmic-ray muons

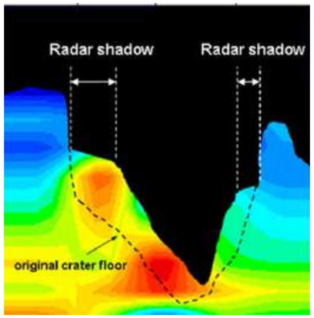
J. Geography, 104 (1995) 998

How large and penetrating is the muon flux?



Plot from HKM Tanaka et al., EPS 62 (2010) 119

What's for



Imaging technique

Intrinsic resolution : tens of m

Higher than with conventional indirect techniques (seismic, gravimetric, …)

Practical limitation from statistics

Can detect evolution with time, depending on muon rate

Potentially 3D, synergy with conventional techniques

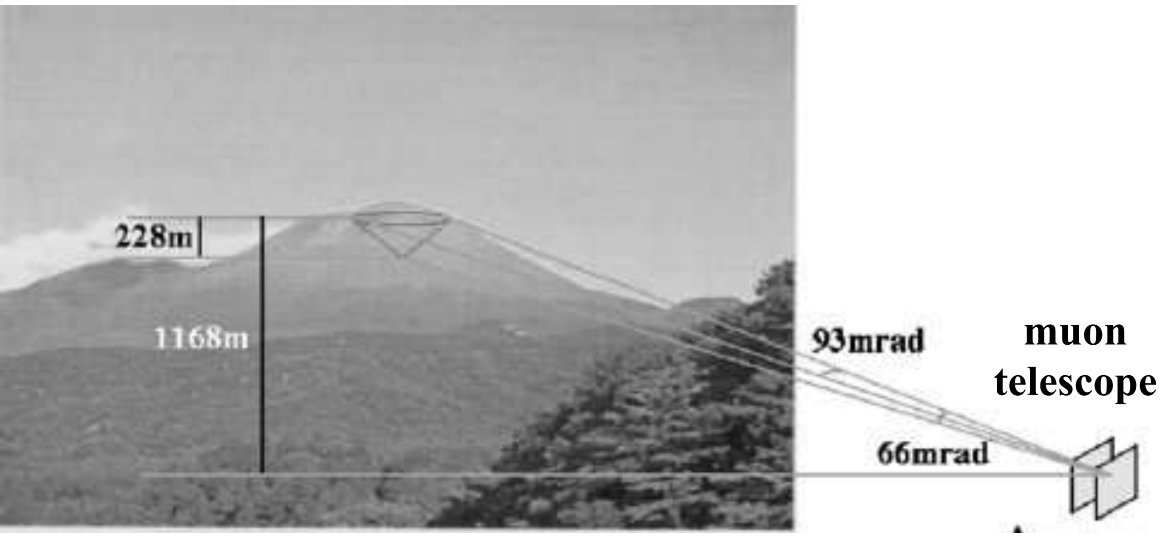
Limited to the volcano's edifice

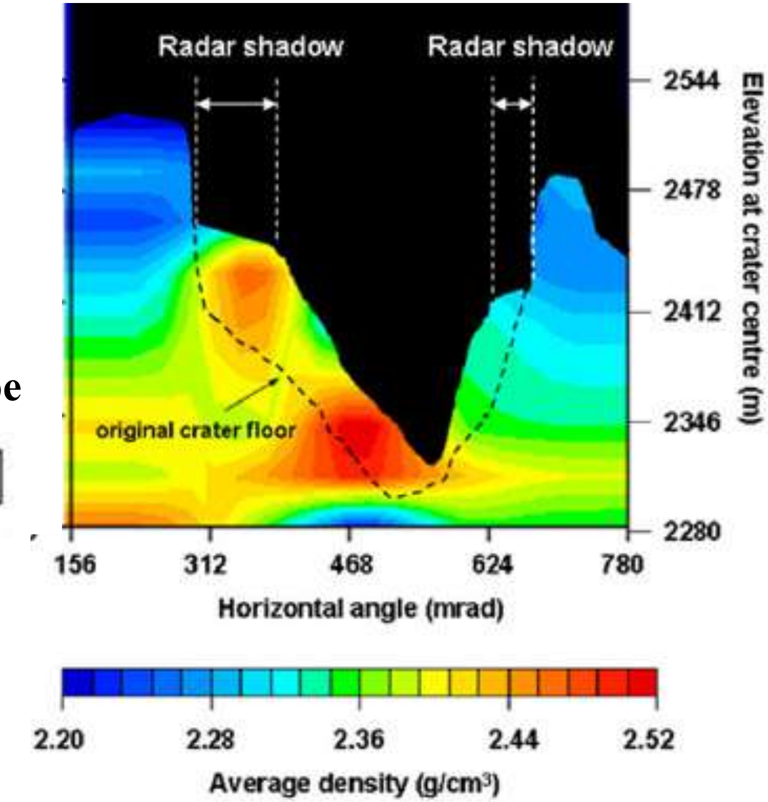
(very strong muon absorption beyond 1 km thickness)

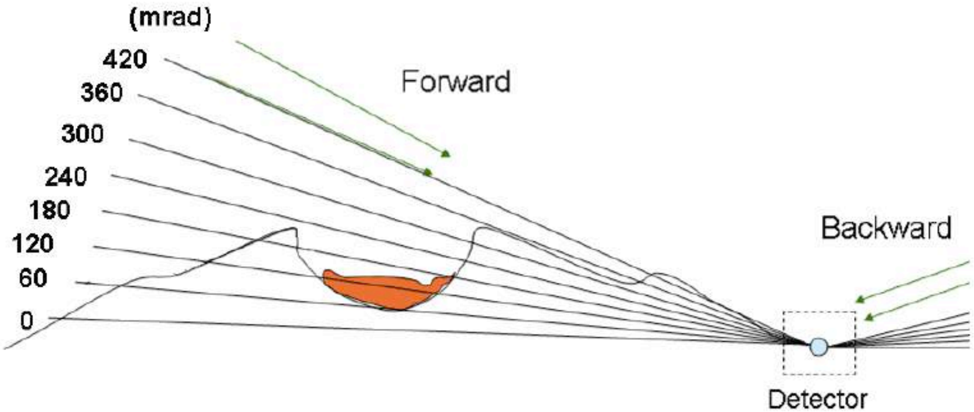
Input to simulations to predict "how" an eruption could develop

No information on "when" it may happen

Pioneering radiography: Asama volcano







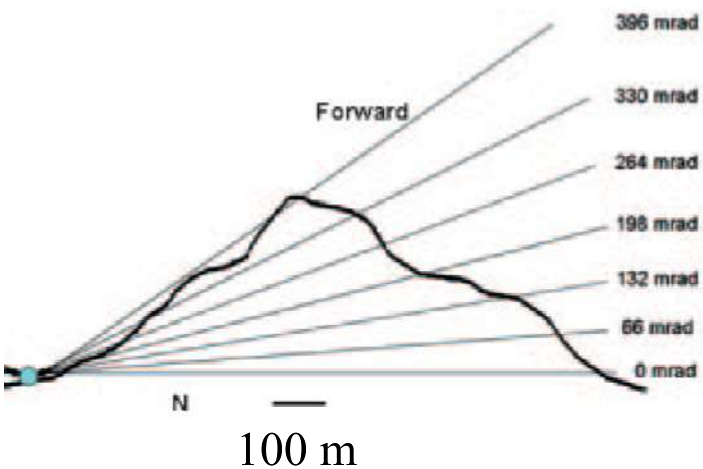
Nuclear emulsion
(same as in OPERA experiment)
for the muon telescope

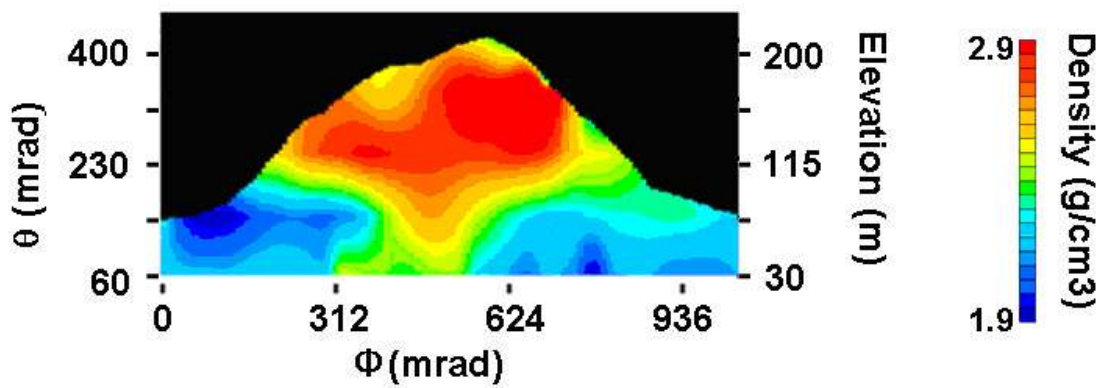
A (red) region with higher density visible in the caldera

Below the caldera, a (blue) region with lower density

H.K.M. Tanaka and coll.
EPS Lett. 263 (2007) 104

How light and muons see the Usu lava dome





Nuclear emulsion for the muon telescope

H.K.M. Tanaka and I. Yokoyama, Proc. Jpn. Acad. B84 (2008) 107

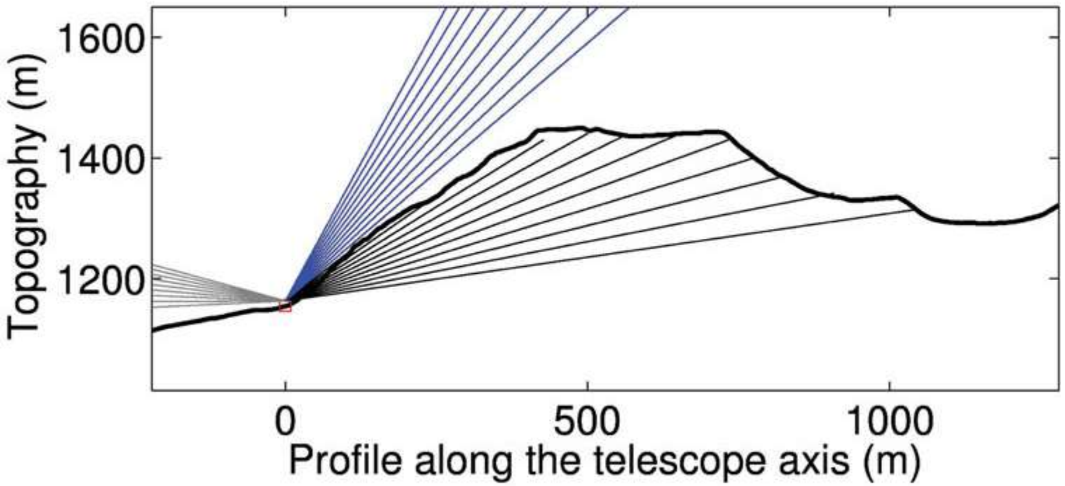
La Soufrière of Guadeloupe

In the last 12,000 years:

a succession of lava dome eruptions with explosive phases intercalated with prolonged periods of ash-producing phreatic explosive activity

One of the most hazardous in the Lesser Antilles

Mountain profile and DIAPHANE detector



Reference rock density for analysis
1.3 g/cm^3 (rather low)

Max 1 km

Plastic scintillator strips

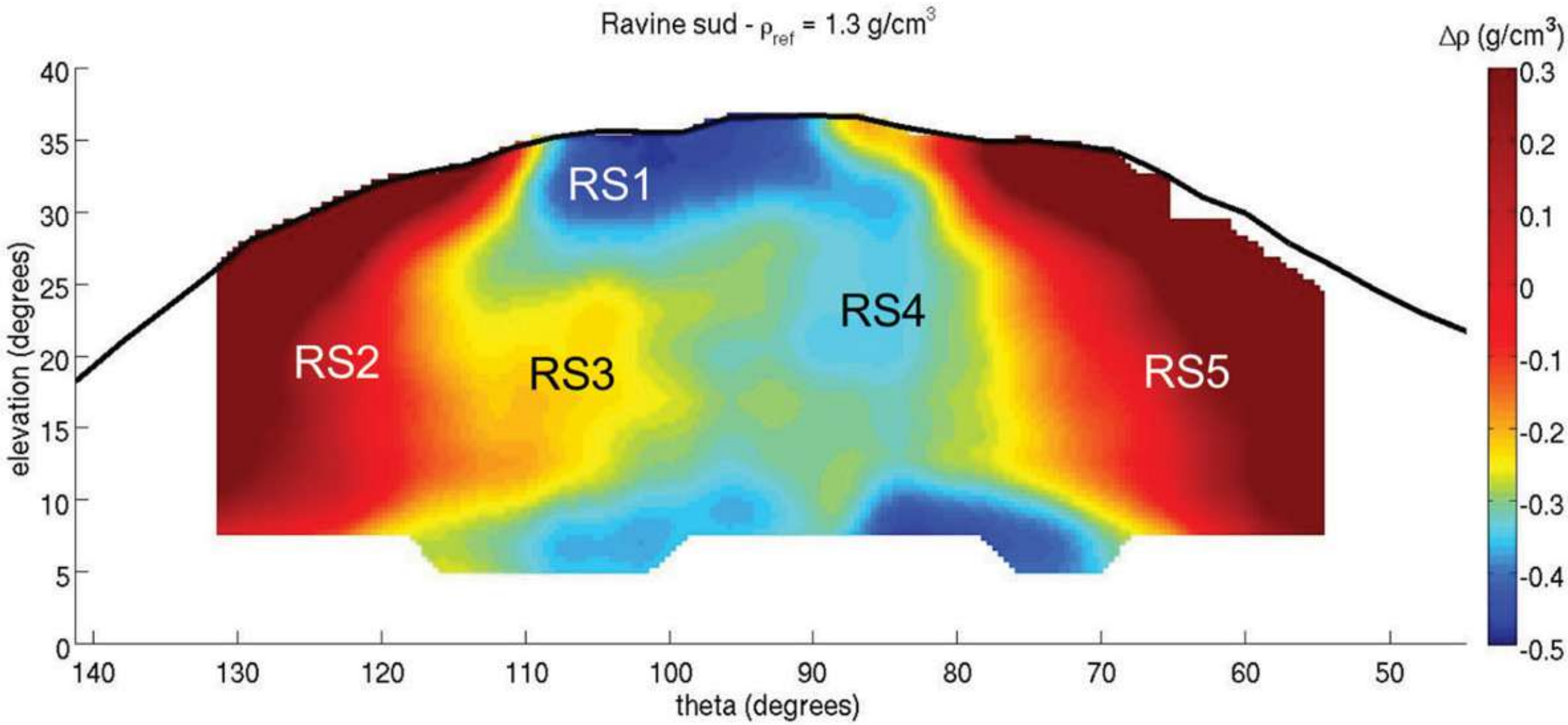
(as in OPERA experiment)

5 cm strip width
3 x-y planes
1 m telescope length
1 m^2 area
~ 3 month exposures

(investigations started at Etna using a similar detector)

Muon Radiography by DIAPHANE

N. Lesparre et al., Geophys. J. Int. (2012) 1



Average density deviation $\Delta\rho$ with respect to reference density 1.3 g/cm^3

Strong density structure (about ±30%)
Two observation points (→ 3D in the future)
Correlation with electrical resistivity and gravity measurements
In the future inversion of combined data

Le Puy de Dôme in the Massif Central (France)

A 400 m high trachytic dome
(height gives scale of rock thickness)

The morphology suggests the presence of two units

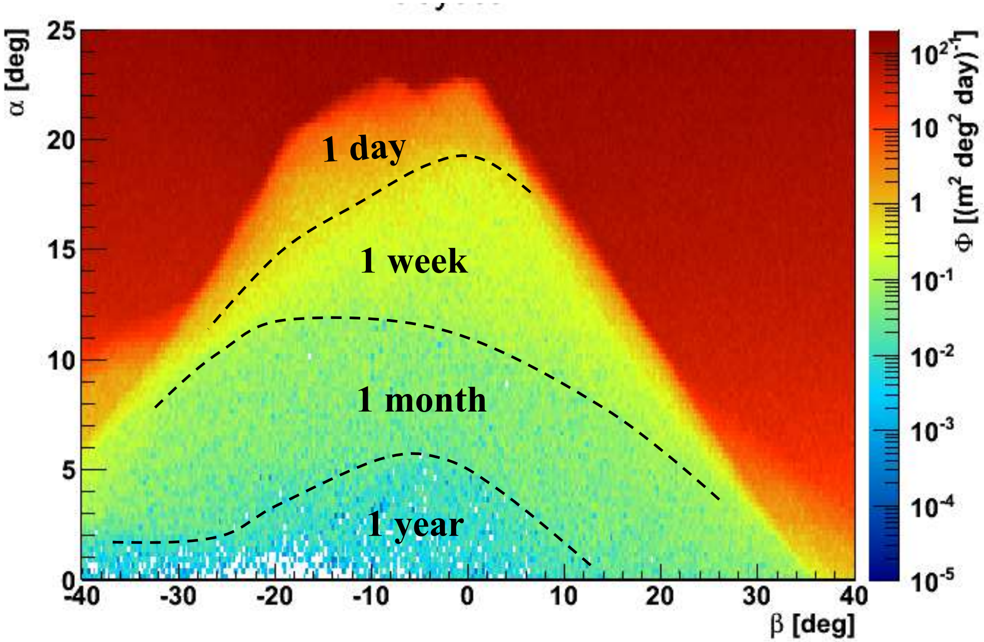
~11,000 years old
Last eruption ~8,000 years ago

~10 km from Clermont Ferrand

A "laboratory"
for collaborative work:
standard infrastructure,
understand methodology and backgrounds

TOMUVOL detector and expected visible zone

<u>Glass RPCs</u>
(possible because in a building)
3 planes
1 m telescope length
1 m^2 area
~ 2 month exposure in 2012
~10^7 candidate tracks

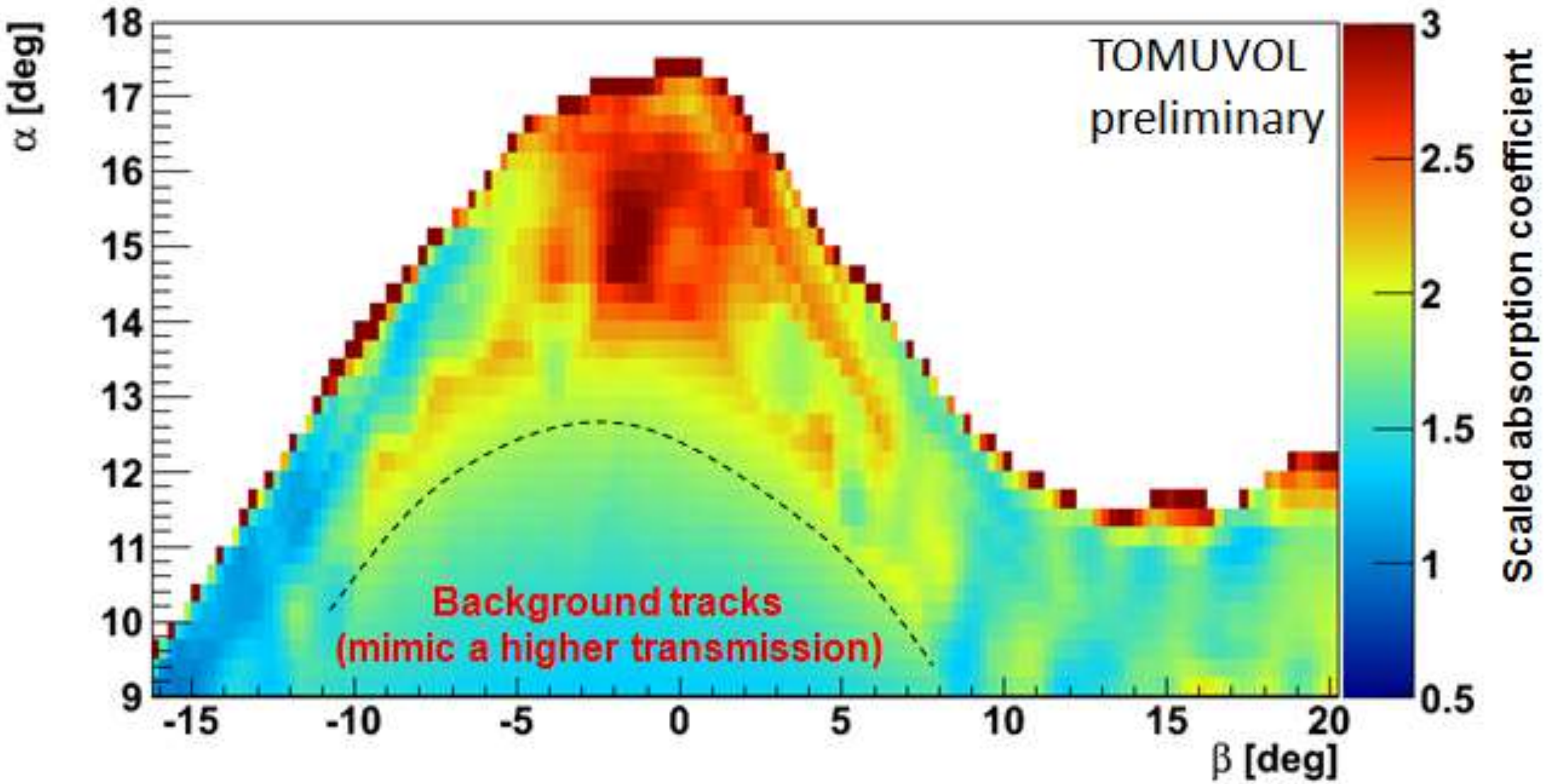


Assumptions:
Rock density 1.66 g/cm^3
<u>No background</u>

Background problem expected
at the base

Preliminary result by TOMUVOL

V. Niess, MNR 2012, Clermont Ferrand



Absorption coefficient scaled with rock thickness

Hints of a structure in the summit region
At the base, background tracks mimic a higher transmission

Stromboli

- **"Strombolian" activity**
  - essentially open conduit
  - intermittent eruptions due to build up of gas pressure
  - rare effusive activity
- **Summit at 926 m a.s.l.**
- **Crater at ~ 750 m a.s.l.**

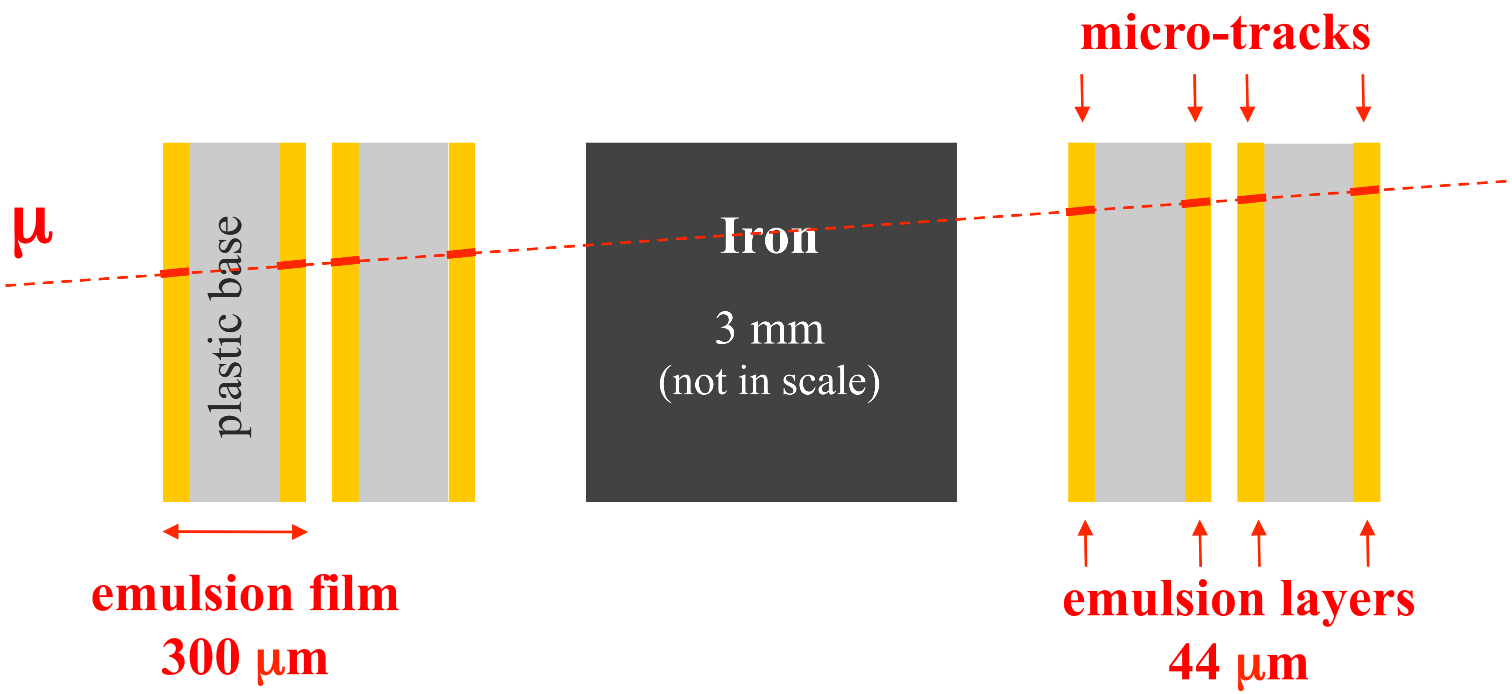
Muon Radiography of Stromboli

- **Scientifically very interesting**
  - Open conduit
  - Studied at best using conventional techniques
  - Synergy by combining information

- **Large rock thickness**
  - similar problems as for Mt. Vesuvius (see later on)
  - harsher environment

- **Top part of the conduit (crater region)**
  being investigated using OPERA nuclear emulsion

Emulsion telescope: very compact



4 emulsion films / 8 emulsion layers / 8 micro-tracks

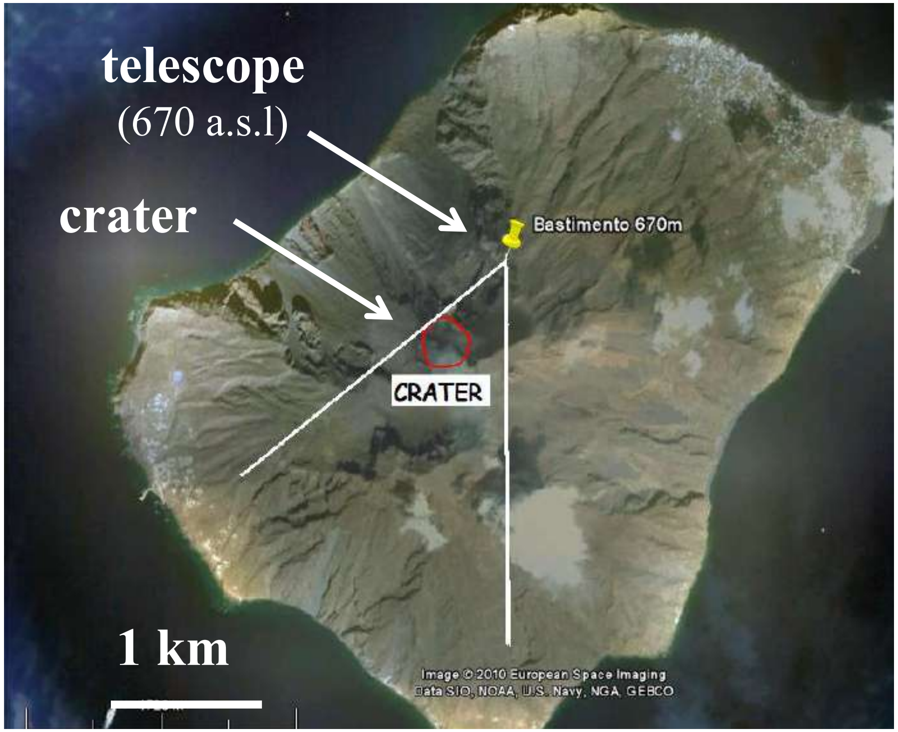
Redundant and precise (μm resolution**) tracking**

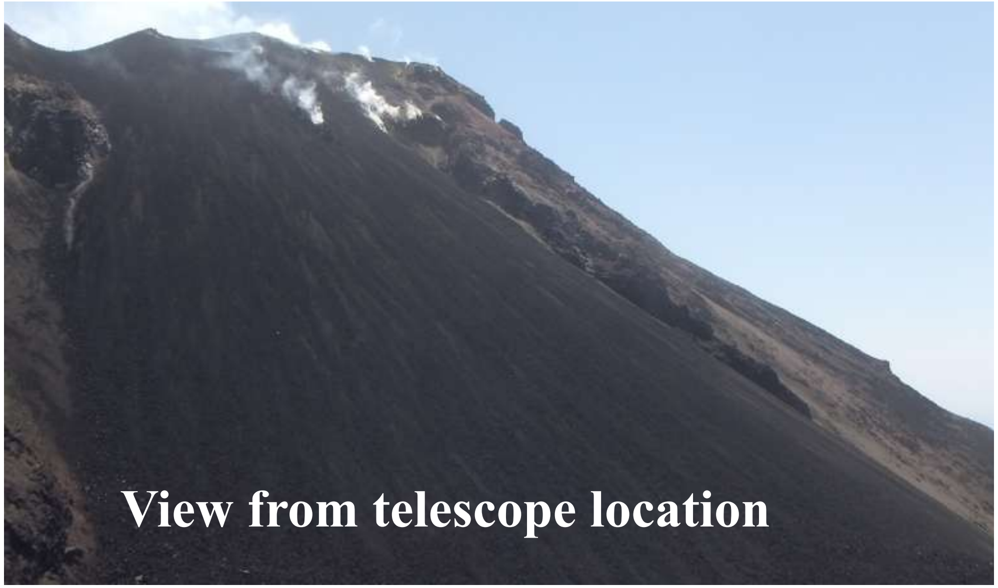
Angular resolution ~10 mrad

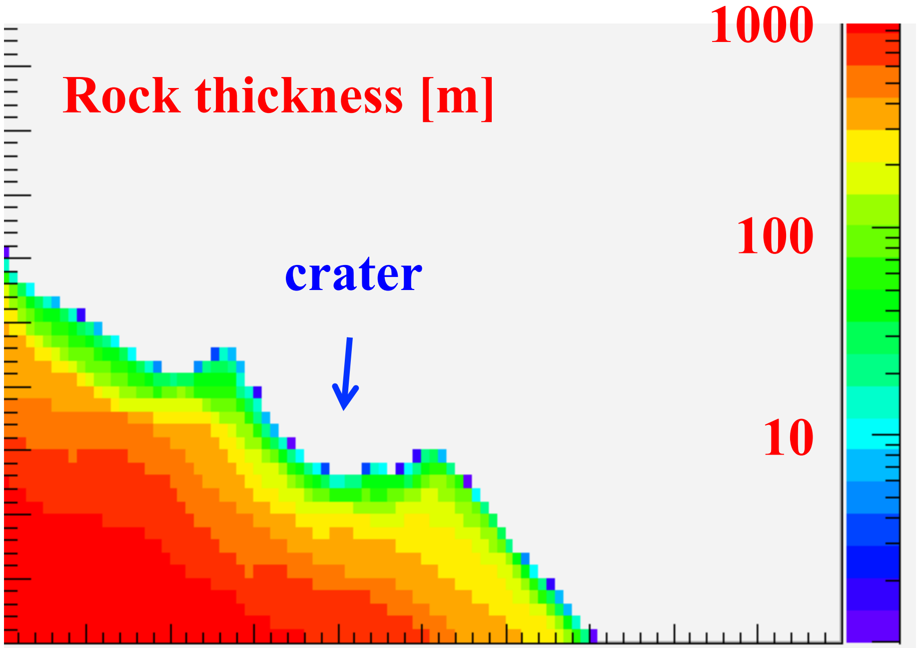
Iron to absorb soft electrons, identify low en. μ (scattering)

Transportable, no infrastructure

Muon Radiography of the crater region





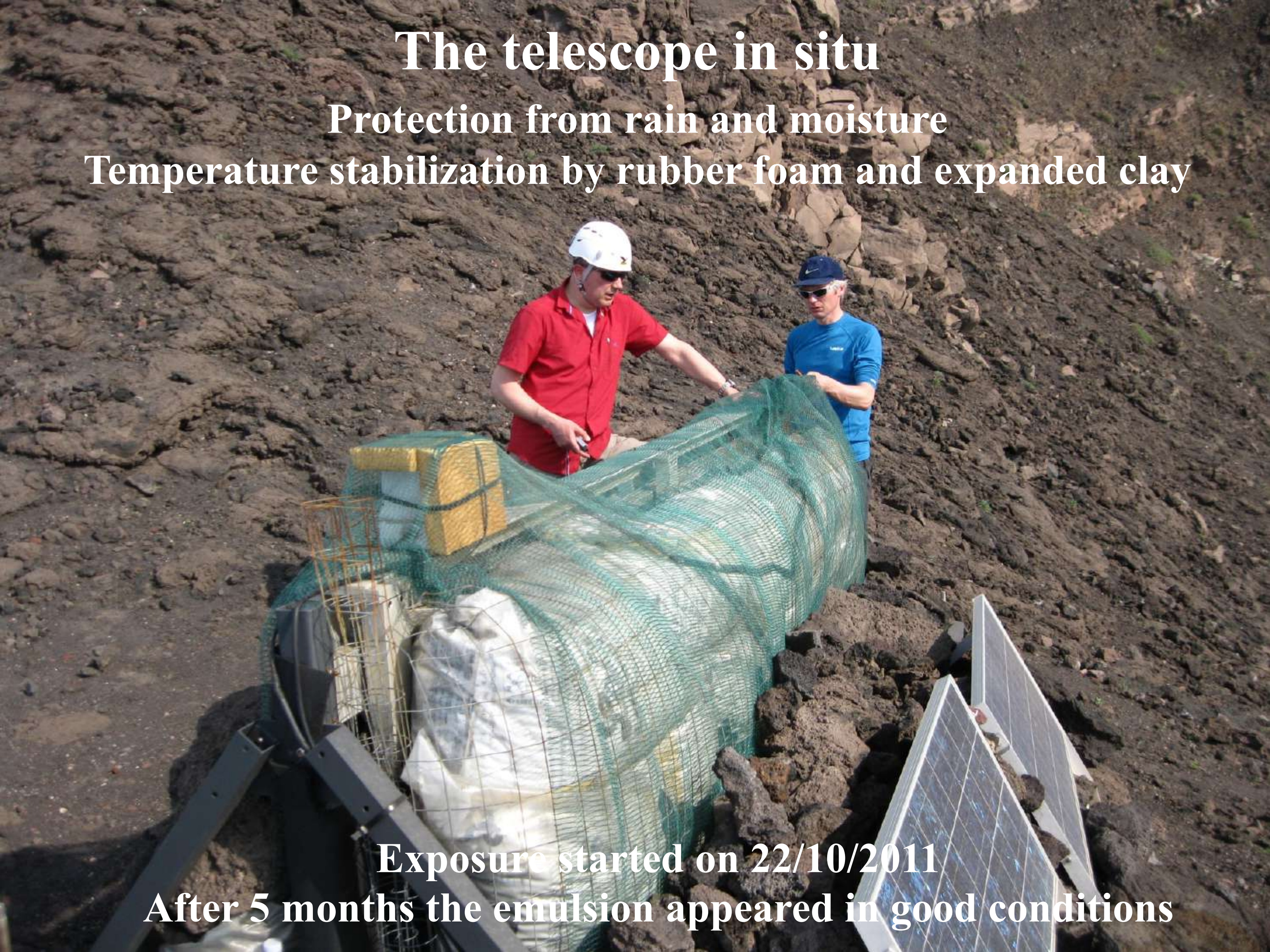


A 1 m^2 nuclear emulsion telescope has taken data last winter (5 months)

The telescope in situ

Protection from rain and moisture

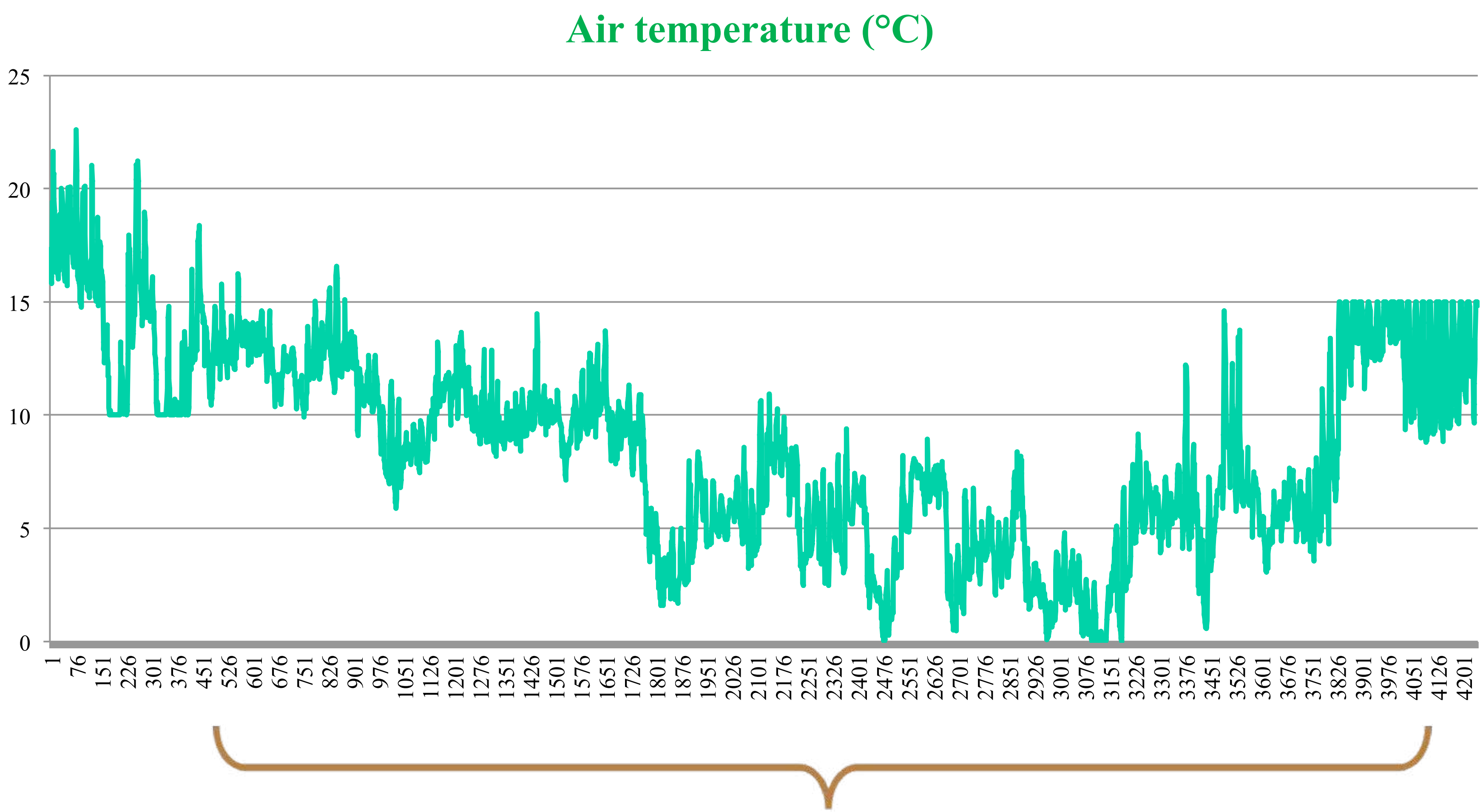
Temperature stabilization by rubber foam and expanded clay



Exposure started on 22/10/2011

After 5 months the emulsion appeared in good conditions

Nuclear emulsion suffer high temperature



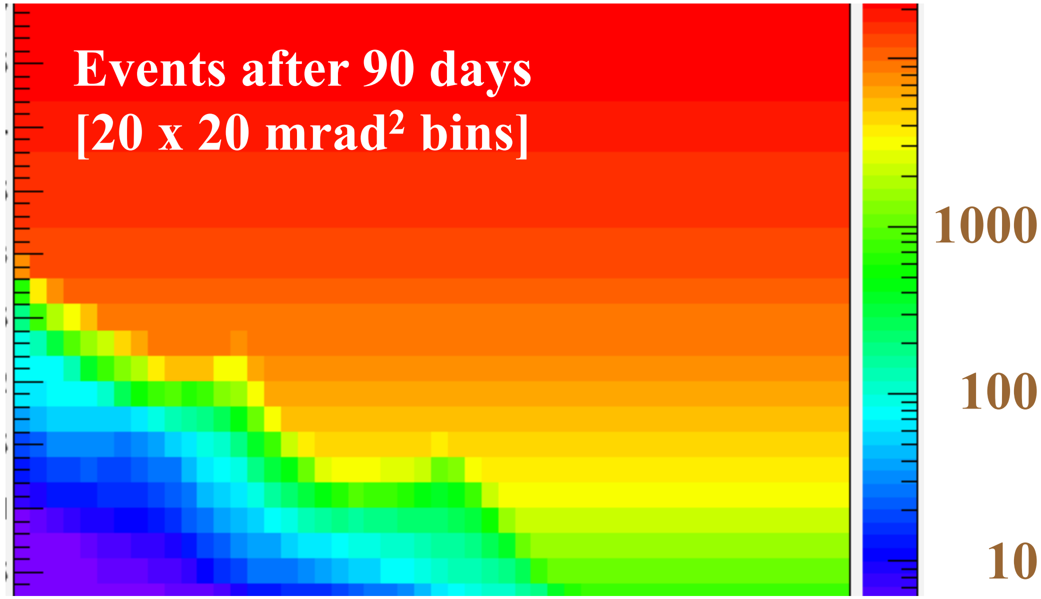
Exposure 22/10/2011 – 24/3/2012

Acceptable temperature

The harsh environment

(here the mechanical structure left in place after the exposure)

Expected events
(in absence of background)



To see deeper inside the volcano:
a challenge as for Mt. Vesuvius

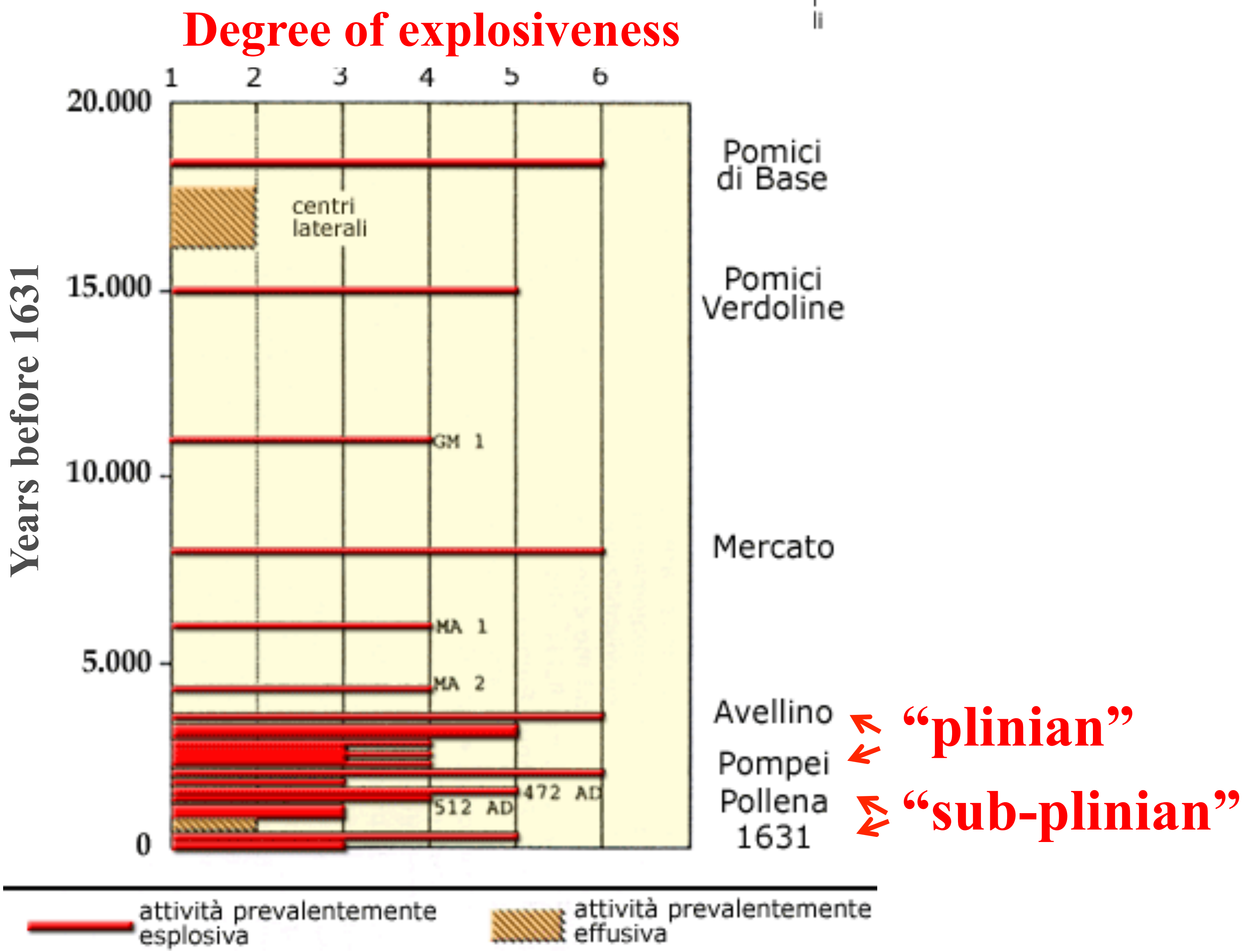
The challenge of Mt. Vesuvius

Mt. Somma and its caldera

"Gran Cono" with a 300 m deep caldera: large rock thickness to see below it

The most violent explosive eruptions → 1631

(www.ov.ingv.it)



Before the A.D. 79 eruption: seen as a "mountain" by Pompeii people?

This is Vesuvius, green yesterday with viny shades; here had the noble grape loaded the dripping vats; these ridges Bacchus loved ….

Martial, *Epigrams (IV.44)*

Dionysus (Bacchus) **and** (presumably) **Mt. Somma**

Fresco from Casa del Centenario, Pompeii
Now at Naples Archaeological Museum

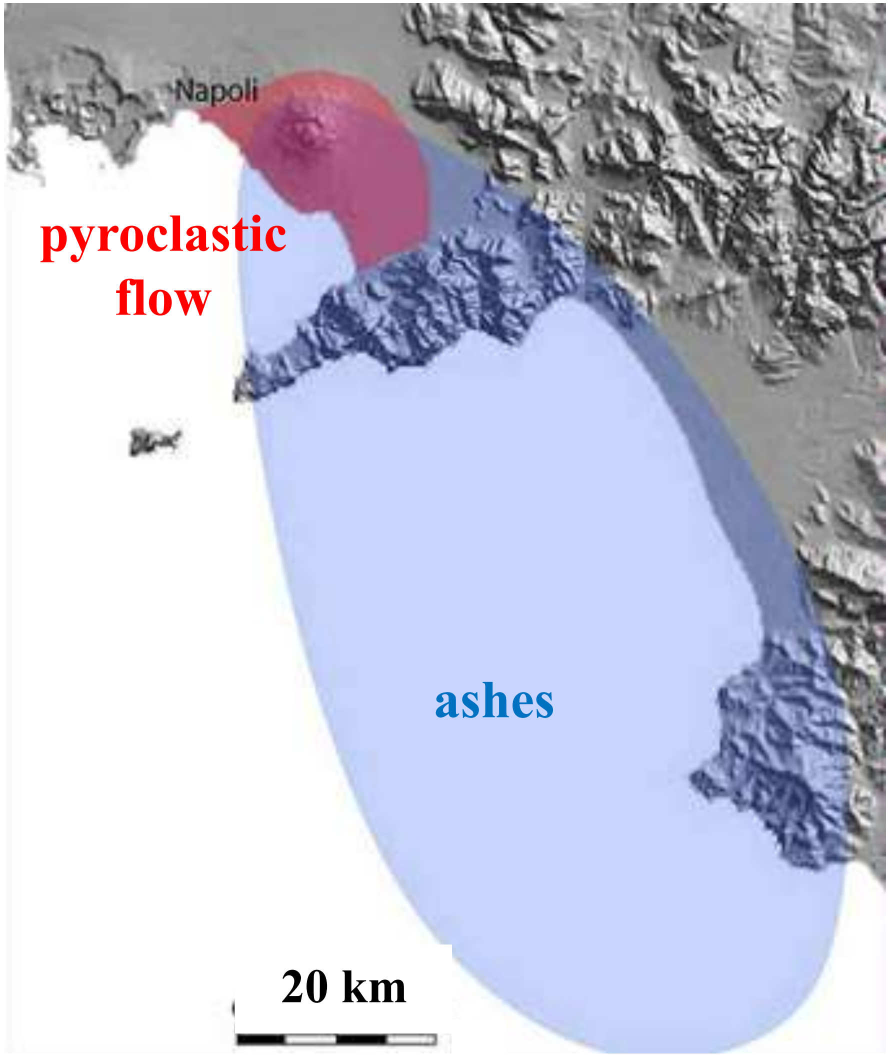
The A.D. 79 plinian eruption

A vast area covered by pyroclastic flow

Destruction of the towns Pompeii, Herculaneum and Stabiae

Read

C. Plinius Caecilius Secundus (Pliny the Younger)
Letters to C. Tacitus VI.16 and VI.20

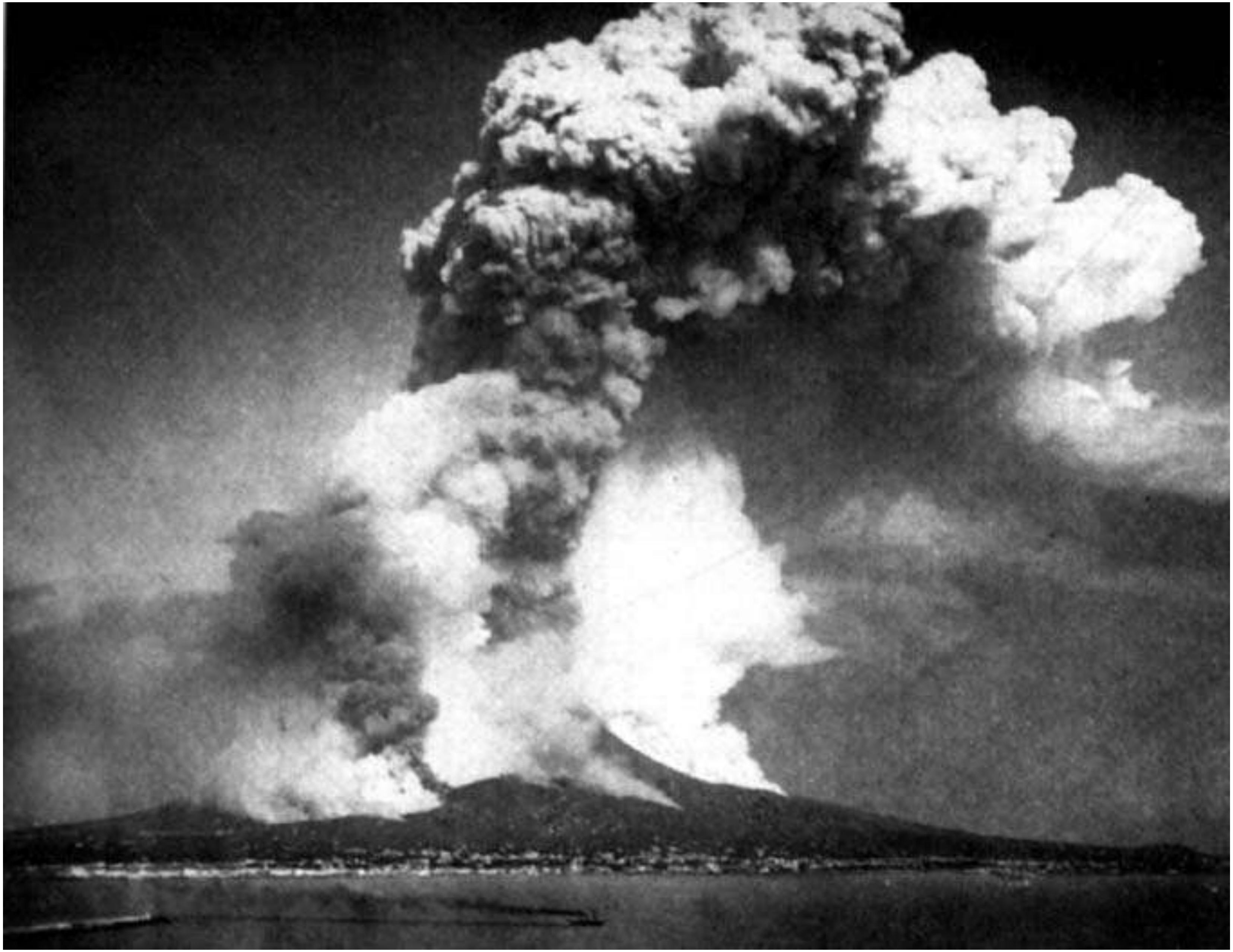


from www.ov.ingv.it

The last sub-plinian eruption (1631)

Micco Spadaro (1610-1675): San Gennaro stops the eruption

The 1872 eruption



The 1906 eruption


TERZA EDIZIONE

IL GIORNO

politico letterario illustrato del mattino

SPAVENTOSA ESPLOSIONE DEL VESUVIO - 150 MILA PERSONE FUGGITE

La lava invade Torre Annunziata—Un nuovo cratere nel centro di Boscotrecase—L'arrivo del Re—Napoli non ha nulla da temere

Una preghiera

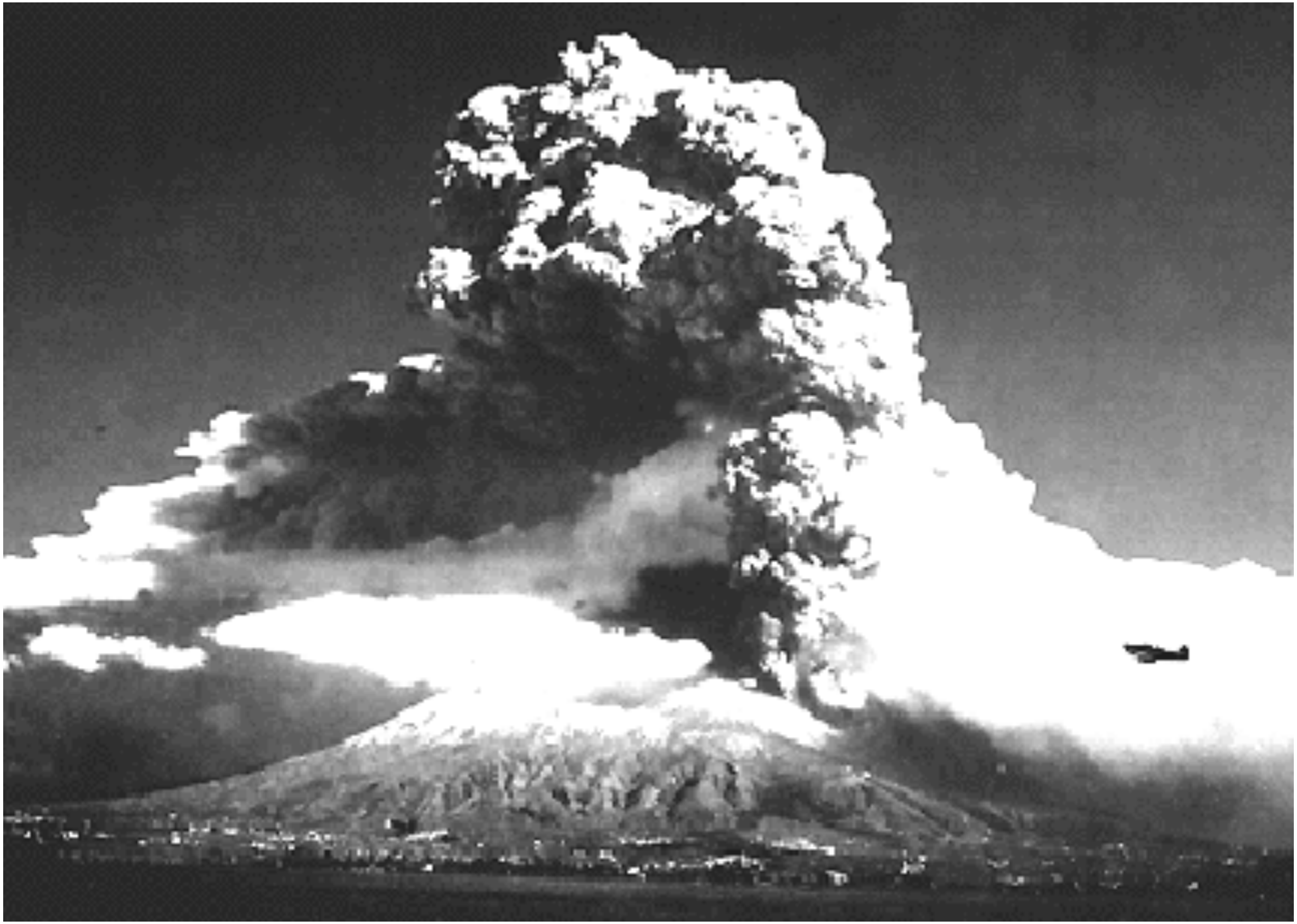
Le notizie da Resina

Emeroteca-Biblioteca Tucci

“Frightening explosion of Mt. Vesuvius 150,000 people fled away”

(in times when the population around and on the slopes of Mt. Vesuvius was by far less dense than it is now)

The last eruption (1944)



Documented by reporters of the Allied Army at the end of the 2° World War

Periodicity in the years 1631 - 1944

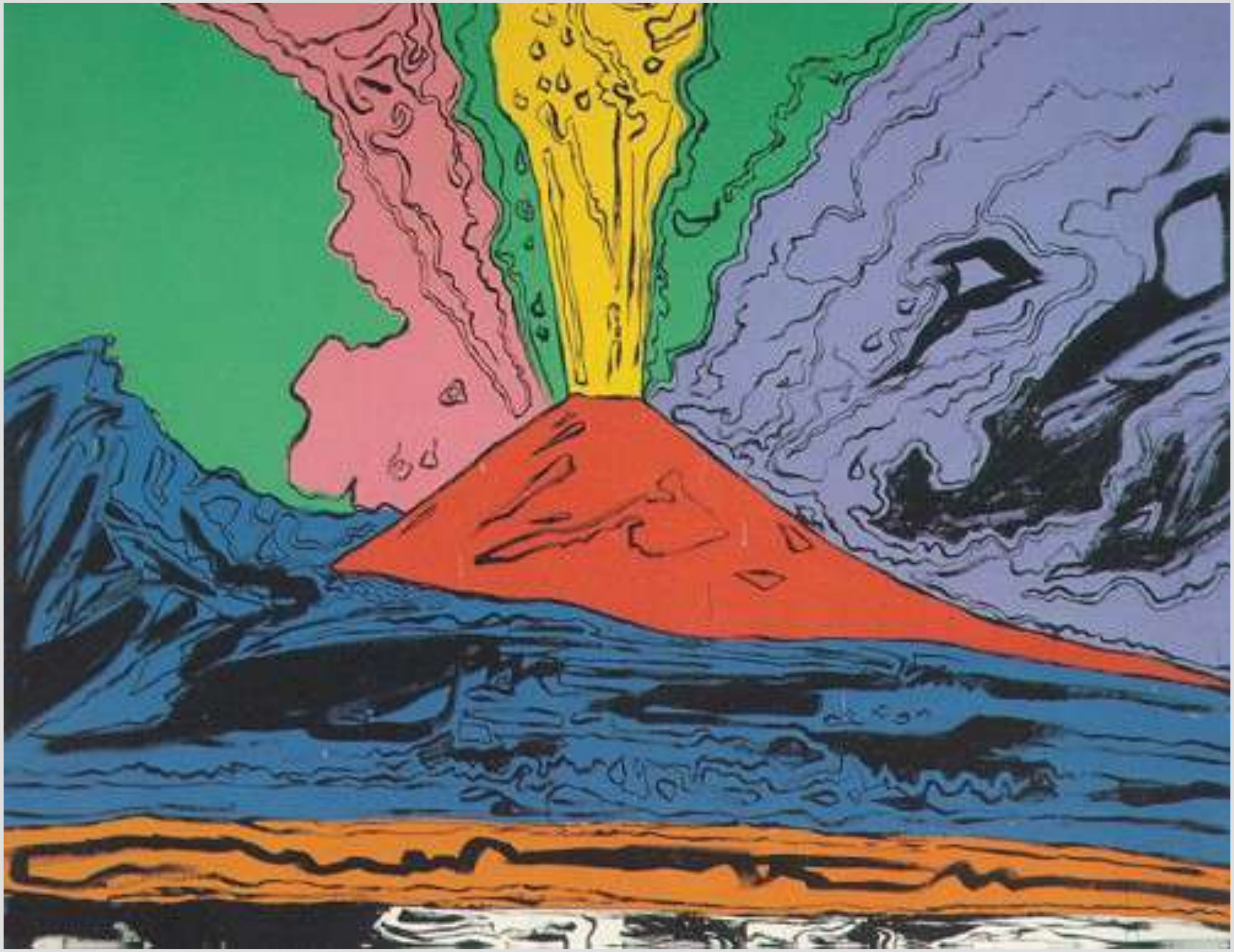
- 18 “Strombolian” periods: <u>conduit essentially open</u>
- Each period closed by
  a violent “final” eruption (<u>explosive</u> and effusive)
- Within each period mainly effusive eruptions
- Quiescence <u>never longer than 7 years</u>

After the “terminal” 1944 eruption

- Transition to a state with closed conduit
- Quiescence since ~70 years (>> 7 years) !

Today’s Vesuvius looks “unusual” compared to its history

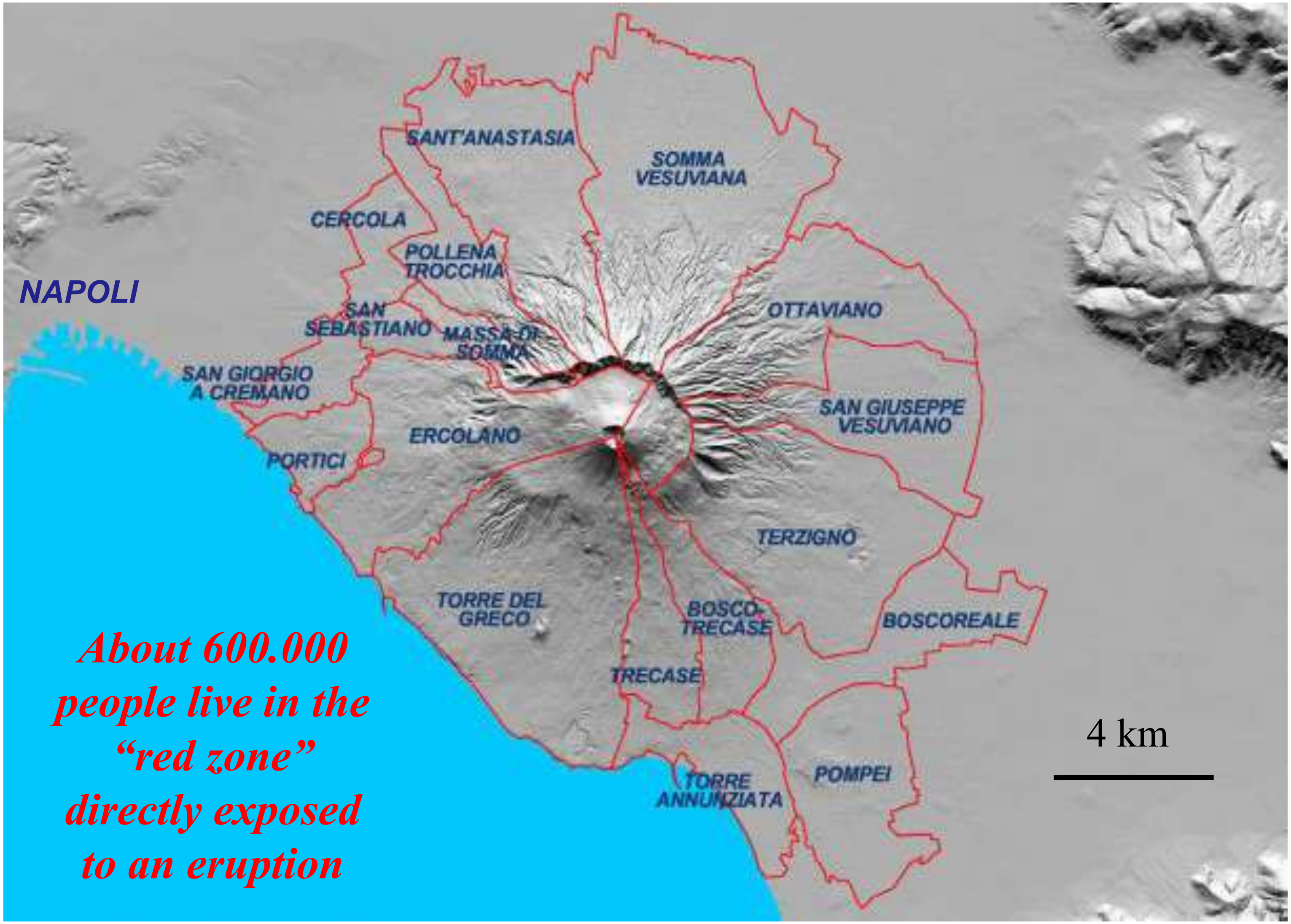
A huge stored energy?



A. Warhol (1928-1987): Vesuvius (1985)

Capodimonte Museum, Naples

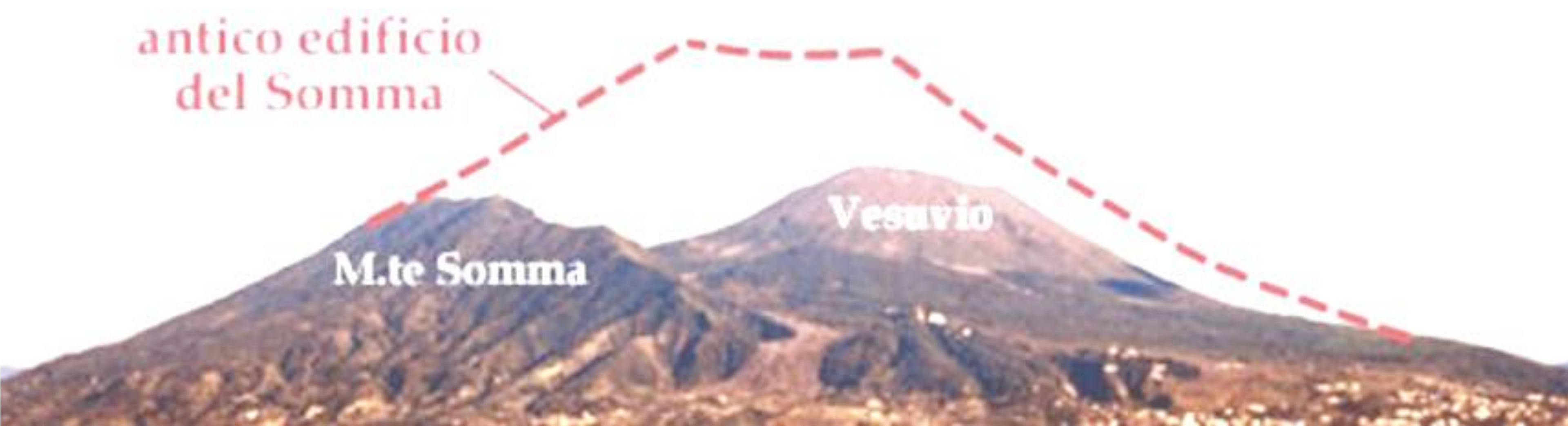
The highest volcanic risk in Europe



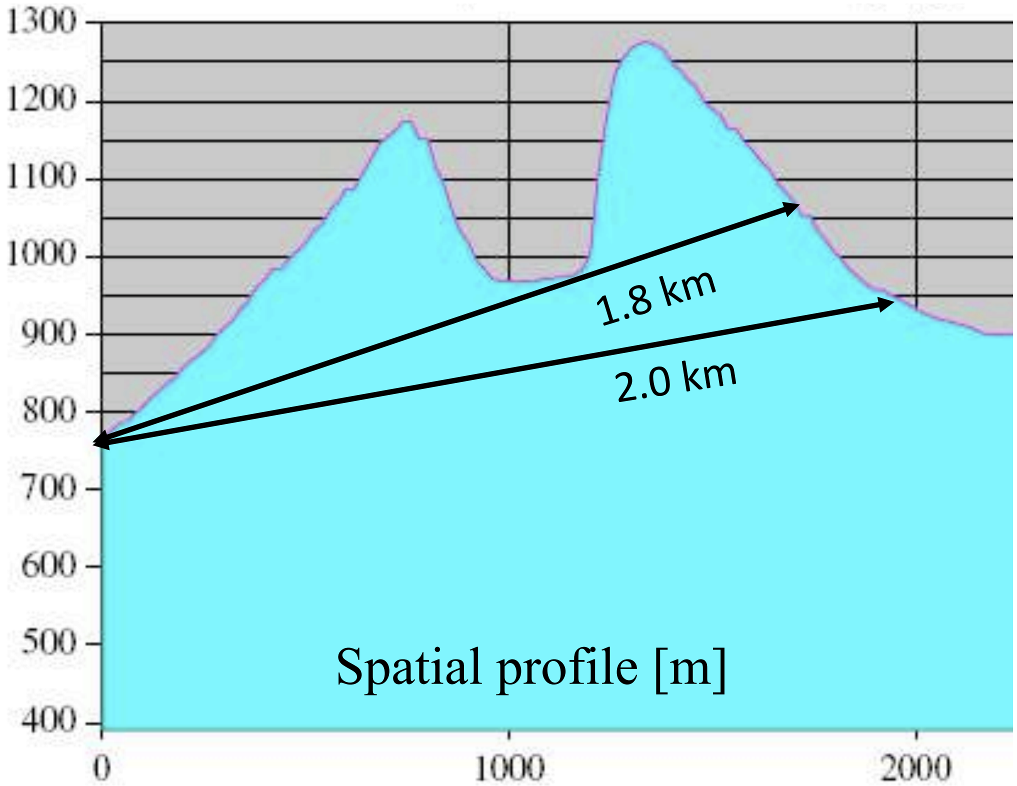
Strongly motivates the challenge of a muon radiography

Present morphology

- Gran Cono (Mt. Vesuvius)
  - summit at 1280 m a.s.l. ,
  - a deep caldera inside (bottom at 950 m a.s.l.)
- Grown in the caldera of an older, higher volcano (Mt. Somma)
- A secondary cone (Colle Umberto) “born” in 1898



Rock thickness at Mt. Vesuvius



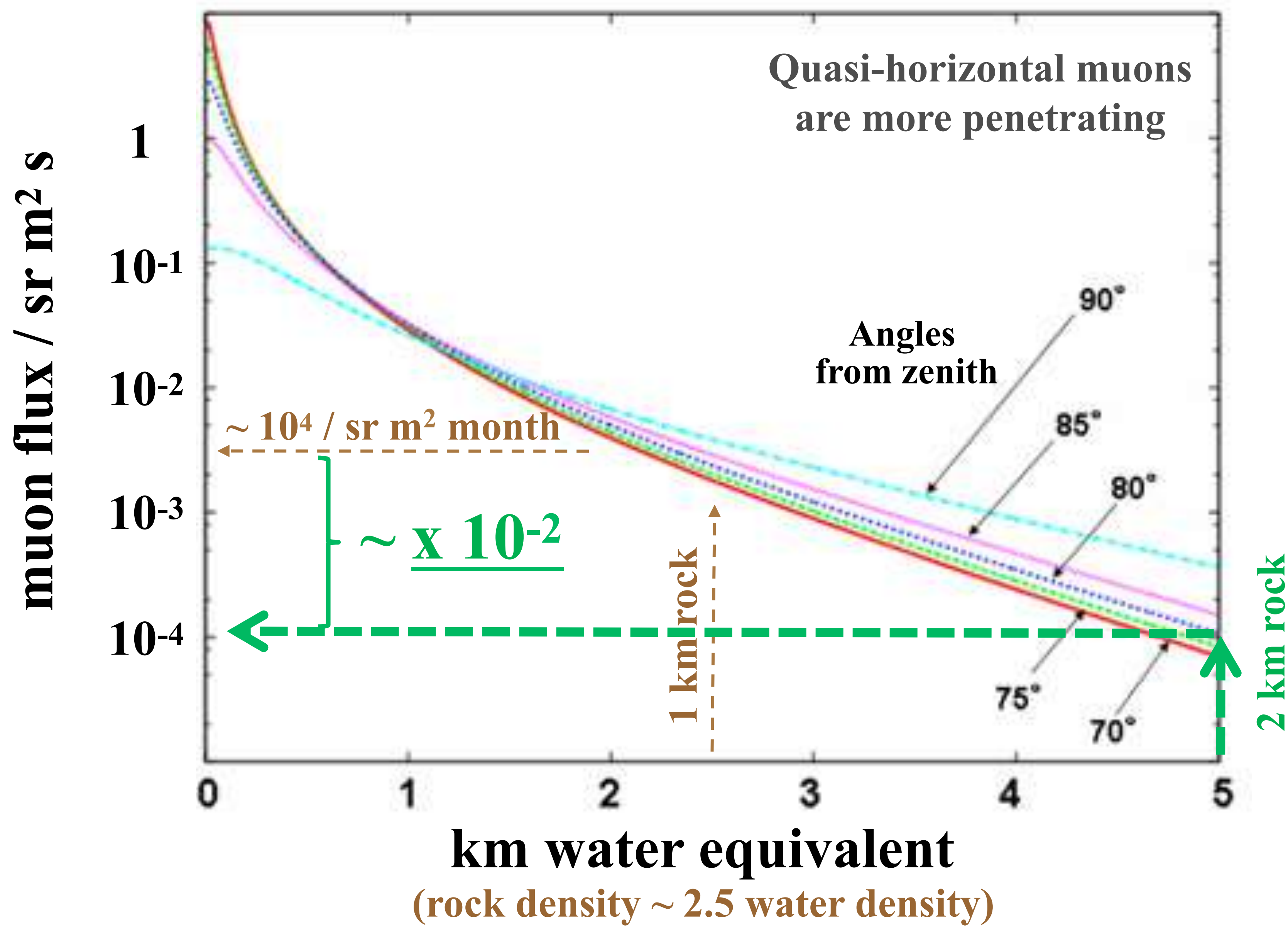
2 km rock thickness from a telescope at 750 m a.s.l.

↓

<u>Substantially improve the sensitivity (x 10^2)</u>

with respect to previous radiographies (< 1 km rock)

Muon flux reduction for 1→ 2 km rock thickness



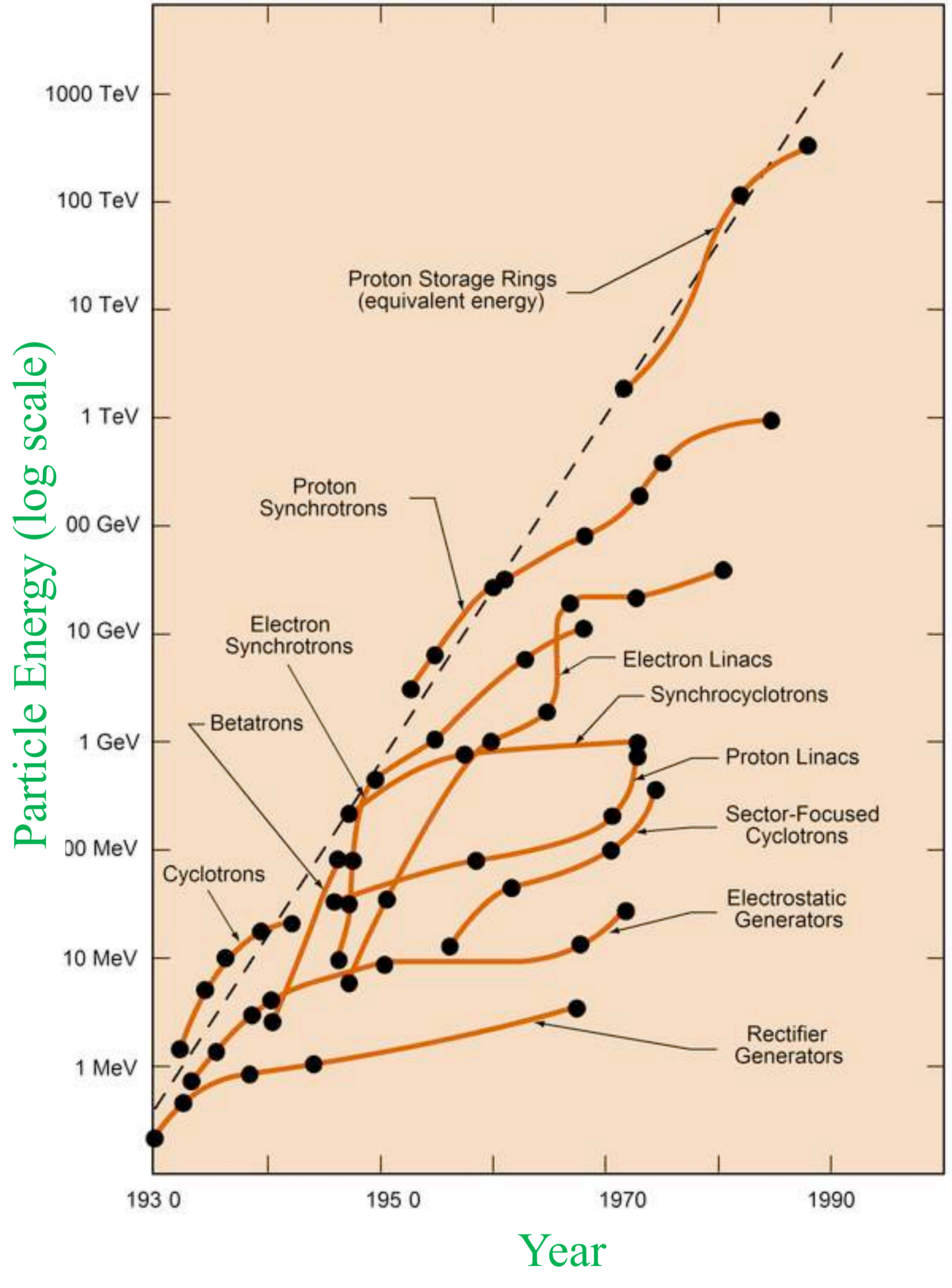
Plot from HTM Tanaka et al., EPS 62 (2010) 119

To improve the sensitivity x 10^2

- **Area: 1 → 10 m^2 or more** (array of telescopes)
- **Large number of channels: reduce power/channel**
- **Data taking: months → years**
- **<u>Background rejection is crucial: new tools</u>**

The detector must be suitable to work in volcanic environments without electricity supply

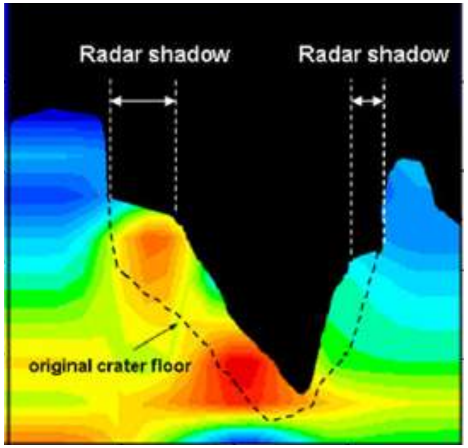
In any field, the progress comes from new technologies



The "Livingston plot"

Saturation in energy for any accelerator technology

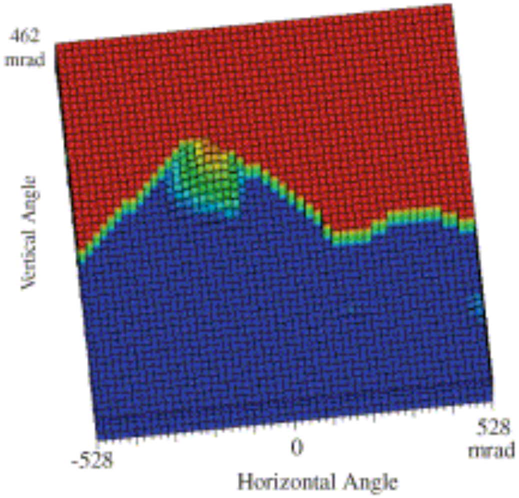
Experimental techniques



Mt. Asama
Tanaka and coll.
<u>Telescope area ~1 m^2</u>

EPS Lett. 263 (2007) 104

Resolution ~ 70 mrad
NIM A507 (2003) 657



NUCLEAR EMULSION

Precise muon tracking
Resolution ~10 mrad (as scattering)
Minimal infrastructure
No electric power
Usable in difficult locations
Unusable in warm season
<u>Area limited</u> by scanning power

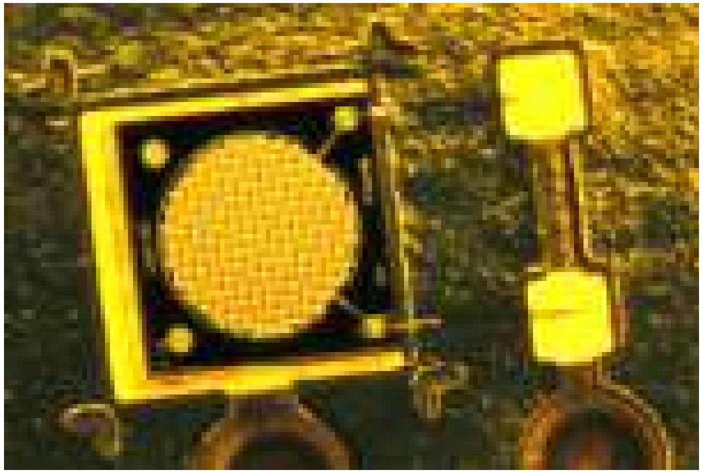
PLASTIC SCINTILLATOR STRIPS

Analysis in real-time
Increase n. of channels: improve resolution
Time of flight possible: b.g. reduction
<u>Larger area possible</u>
<u>Long exposures possible</u>
New technologies to reduce el. power

Plastic scintillators to see through > 1 km

A new technology: *Silicon Photo-Multipliers (SiPM)*

- **Matrix of diodes operated in Geiger mode** (inverse polarization)
- **Analog sum of the signals**
  → **amplification** ~ 10^6 (depending on temperature)
  → **proportionality**
- **Solid state device** (as transistor replacing thermionic tubes)
  → **dark noise problem** (depending on temperature): apply sharp threshold
  → **no HV and very low power consumption** (tens of μW)



Φ = 1.4 mm, ~ 300 diodes

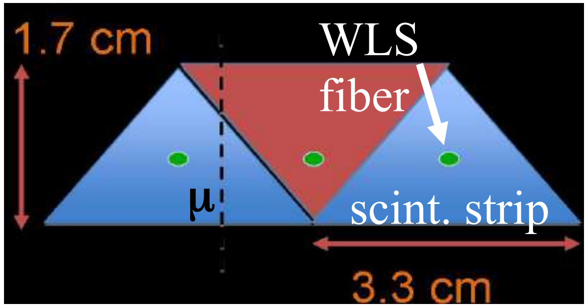
A "naked" SiPM
by FBK-IRST (Trento, Italy)
developed in a joint venture with INFN

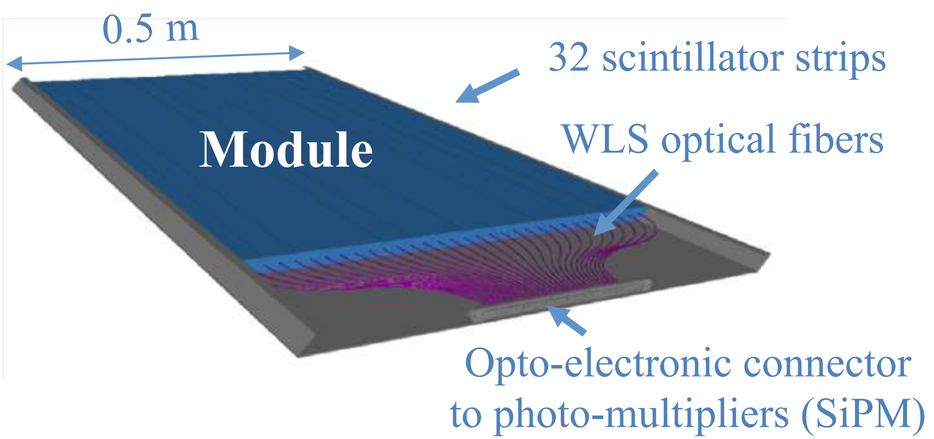
Best producer: Hamamatsu, but ….

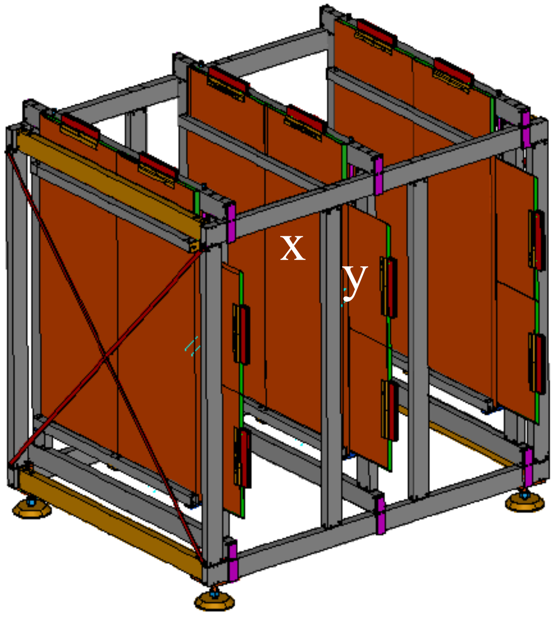
Need investment in time and efforts

The MU-RAY muon telescope

- **Plastic scintillators strips**
  of triangular section with 3.3 cm base
- WLS fibres and SiPMs
- Front-end ASIC chip Spiroc
- **Precise and redundant tracking**
  3 x-y measuring stations or more
  ~ 5 mm space resolution possible
  ~ 10 mrad **angular resolution**
- **Time of Flight** for b.g. reduction
- **Event-by-event information**:
  p.h., …. for b.g. reduction
- **1 m² prototype telescope tested**
- **Soon at Mt. Vesuvius**
  … plans for Puy de Dôme lab

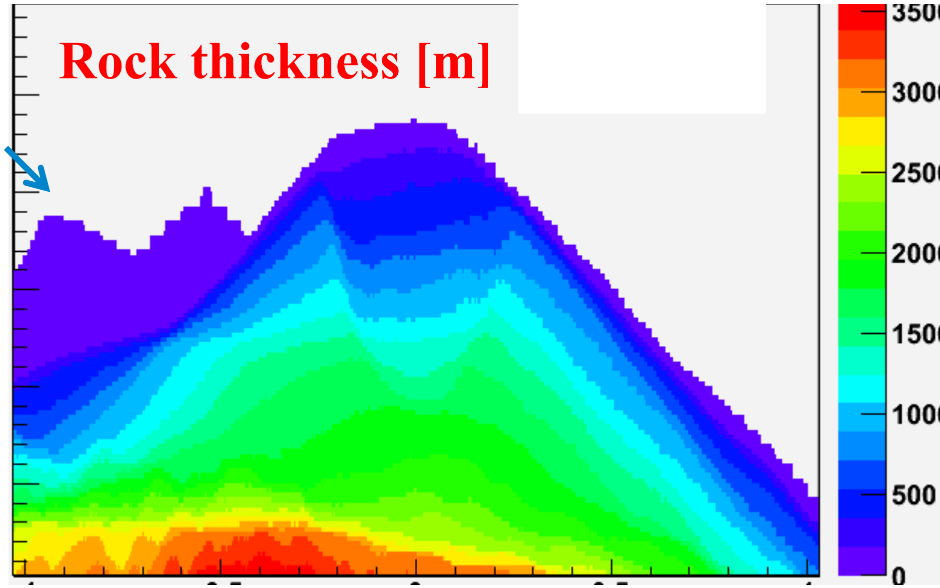


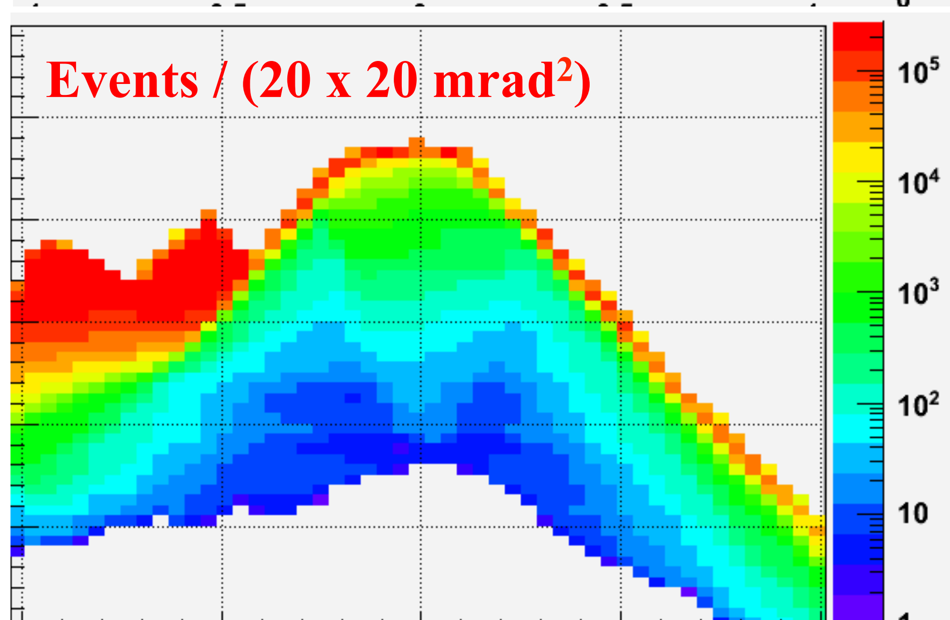




Expected from the 1 m^2 prototype telescope
(one year run, no background)

Mt. Somma





A first step in the "Mt. Vesuvius challenge"

Final remarks

- "See" inside volcanoes: an historical dream
- Conventional methods (seismic, …): indirect information
- Muon Radiography: "imaging", high intrinsic resolution
- Pioneering radiographies in Japan
- La Soufrière Guadeloupe: first results
- Puy de Dôme: preliminary results, a "laboratory"
- Stromboli: exposure of nuclear emulsion
- Mt. Vesuvius: large rock thickness, a challenge (dream)

Muon Radiography of volcanoes still at its beginnings

Particle Physics techniques for Society