

Volcanoes and muons

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TYPUS MONTIS
VESUVII
Prout ab Authore
A^o 1638. visus fuit.

- **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

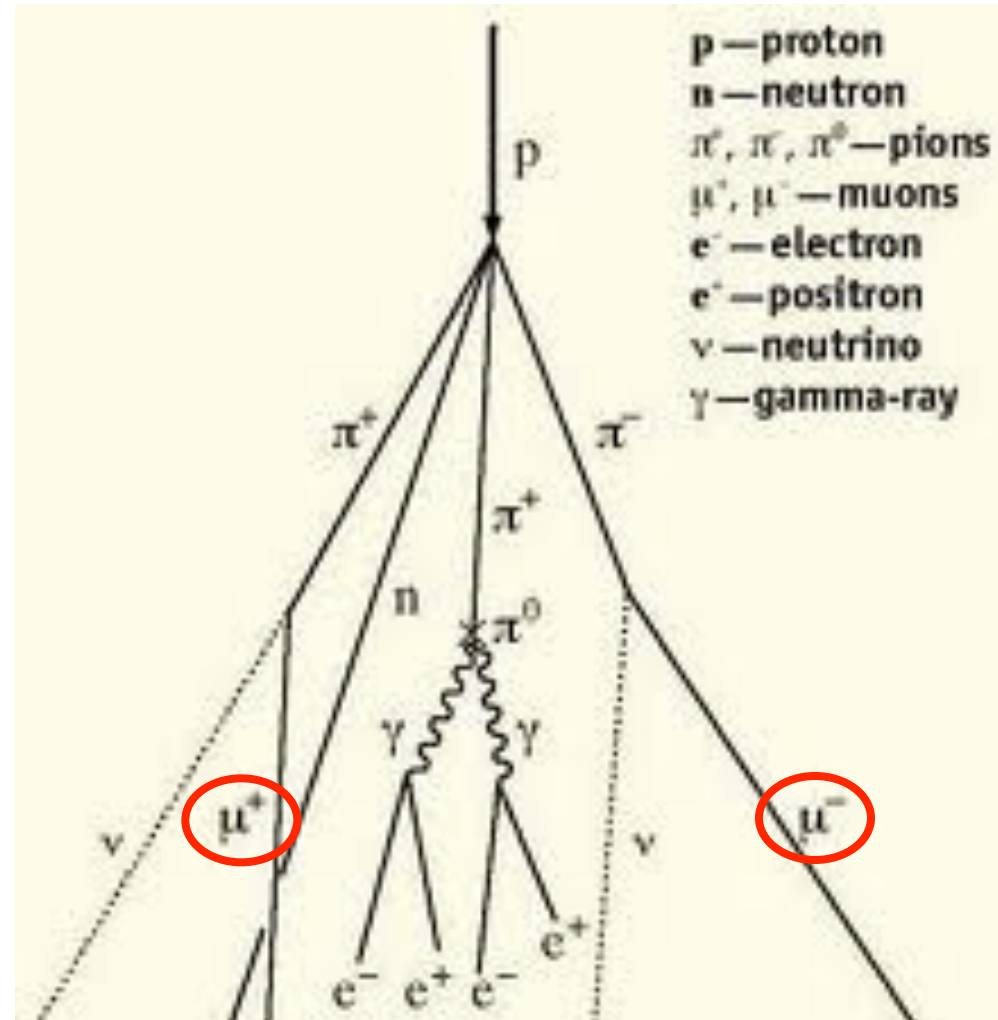
no strong interactions

little brehmstrahlung

($\sim 200 \times$ electron mass)



“Muon Radiography”



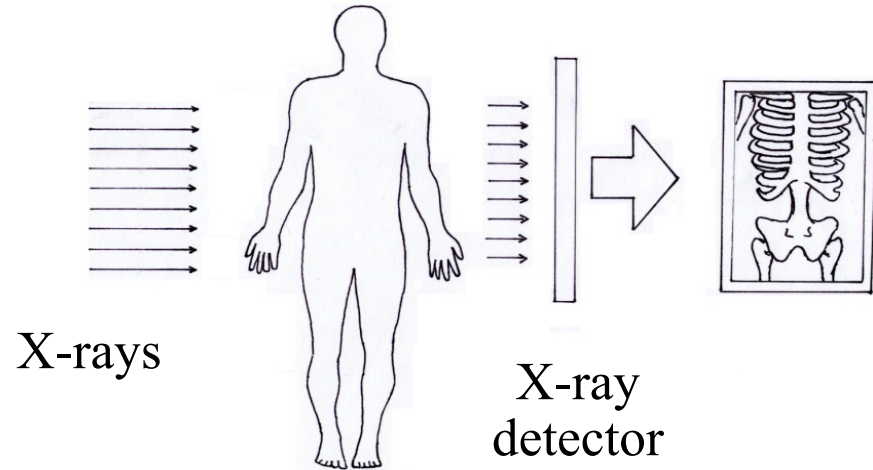
G.B. Lusieri (1755-1821)



Muon radiography

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

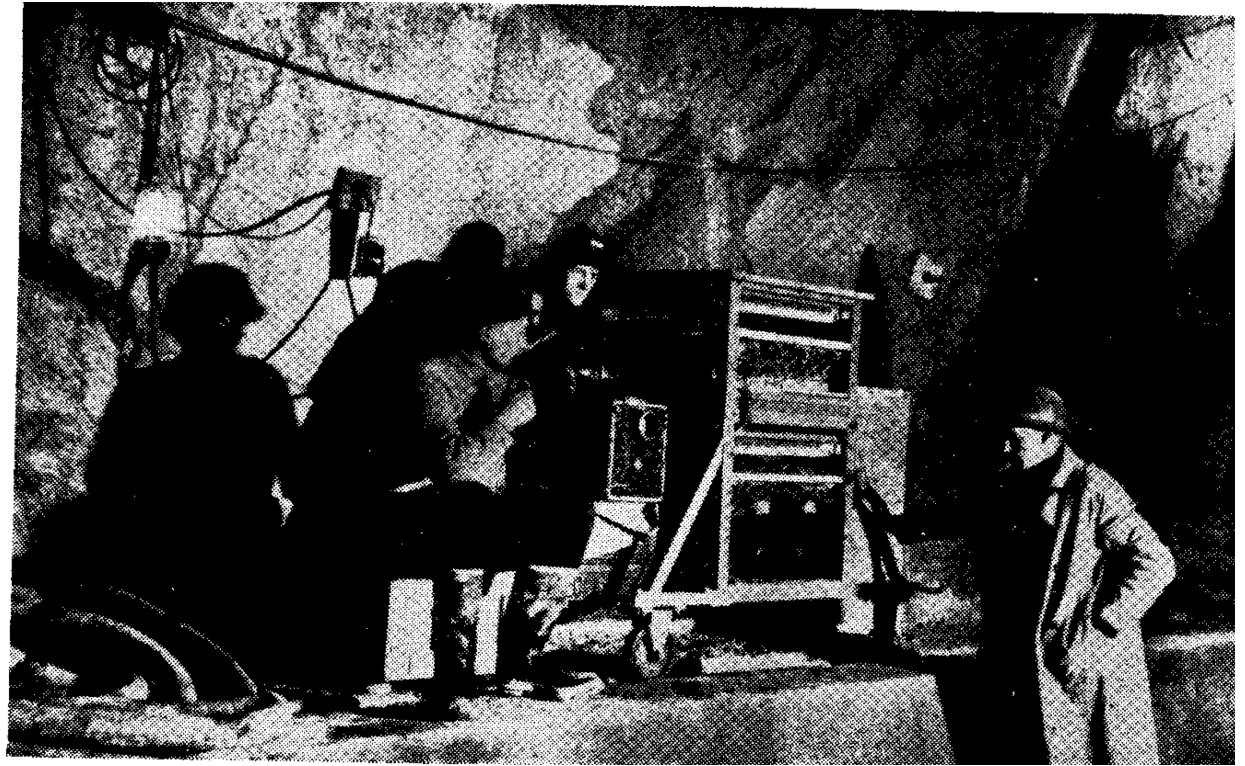
As with X-rays



The early work

Cosmic Rays Measure Overburden of Tunnel

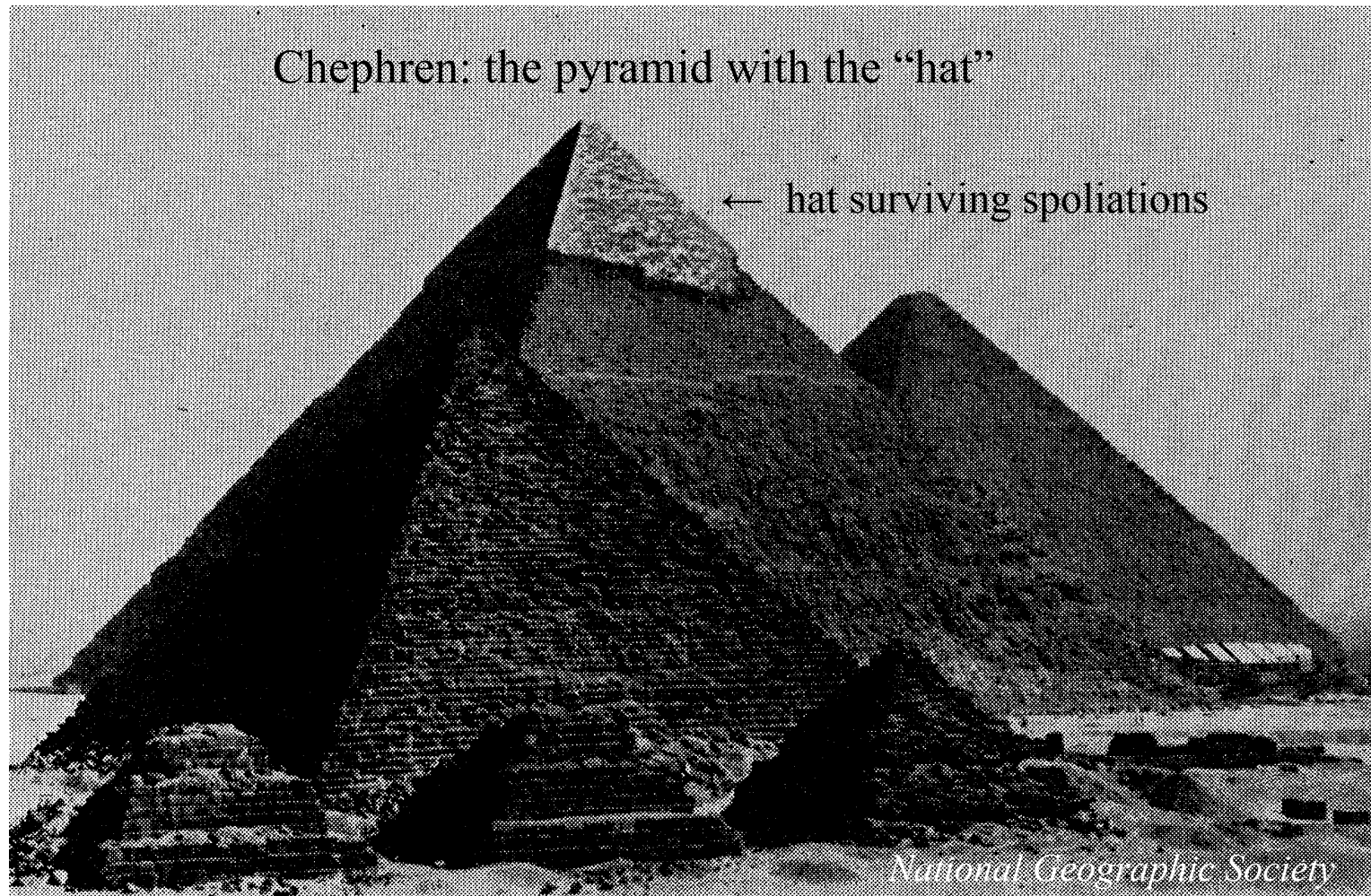
- Fig. 1—Geiger counter “telescope” in operation in the Guthega-Munyang tunnel. From left are Dr. George and his assistants, Mr. Lehane and Mr. O’Neill.



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

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

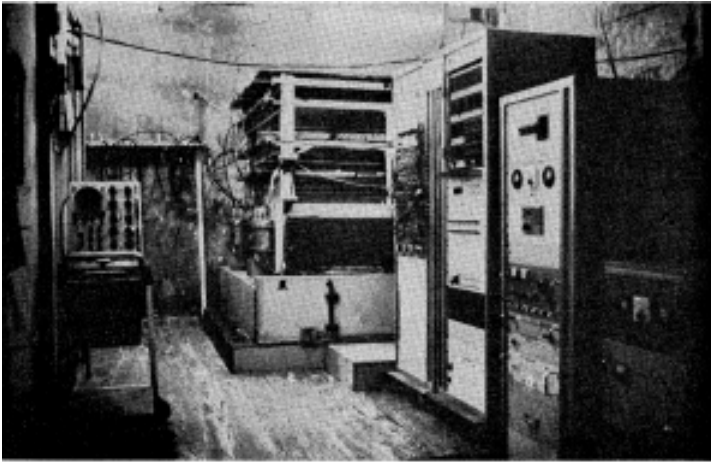
The first “radiography”



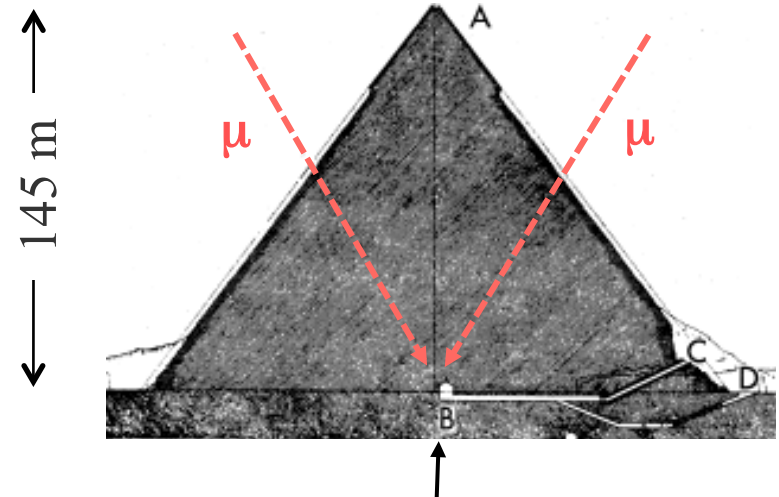
Search for hidden chambers in the Chephren's Pyramid

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

No hidden chamber

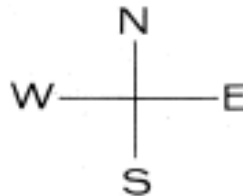
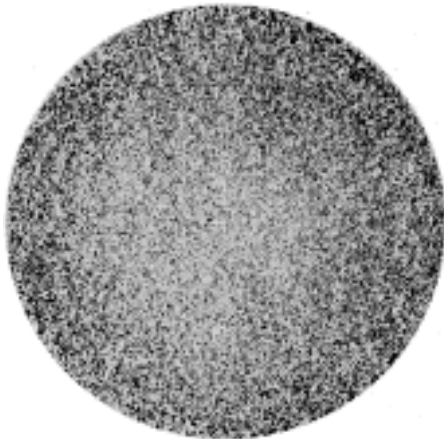


Spark chamber “muon telescope”



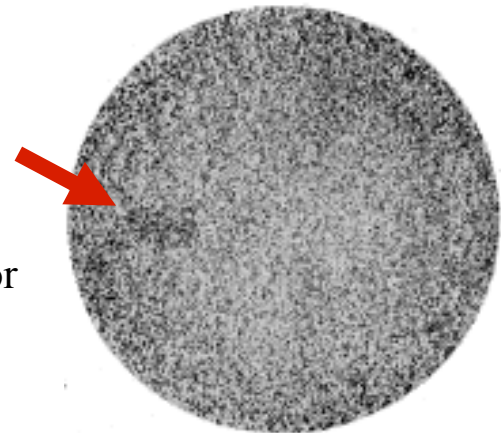
Telescope in Belzoni chamber

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

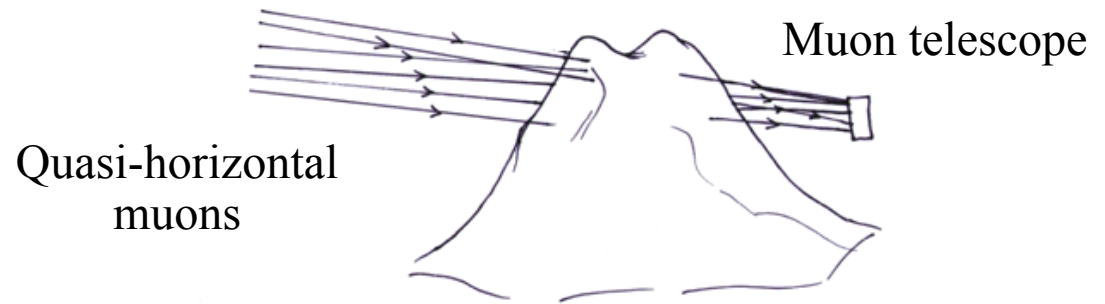
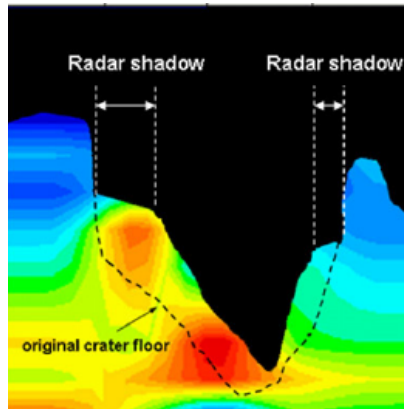
The interior of volcanoes: a fascinating question



Athanasius Kircher, Mt. Vesuvius (1638)

Hypothesis that volcanoes are connected to the center of the Earth

Muon radiography of volcanoes



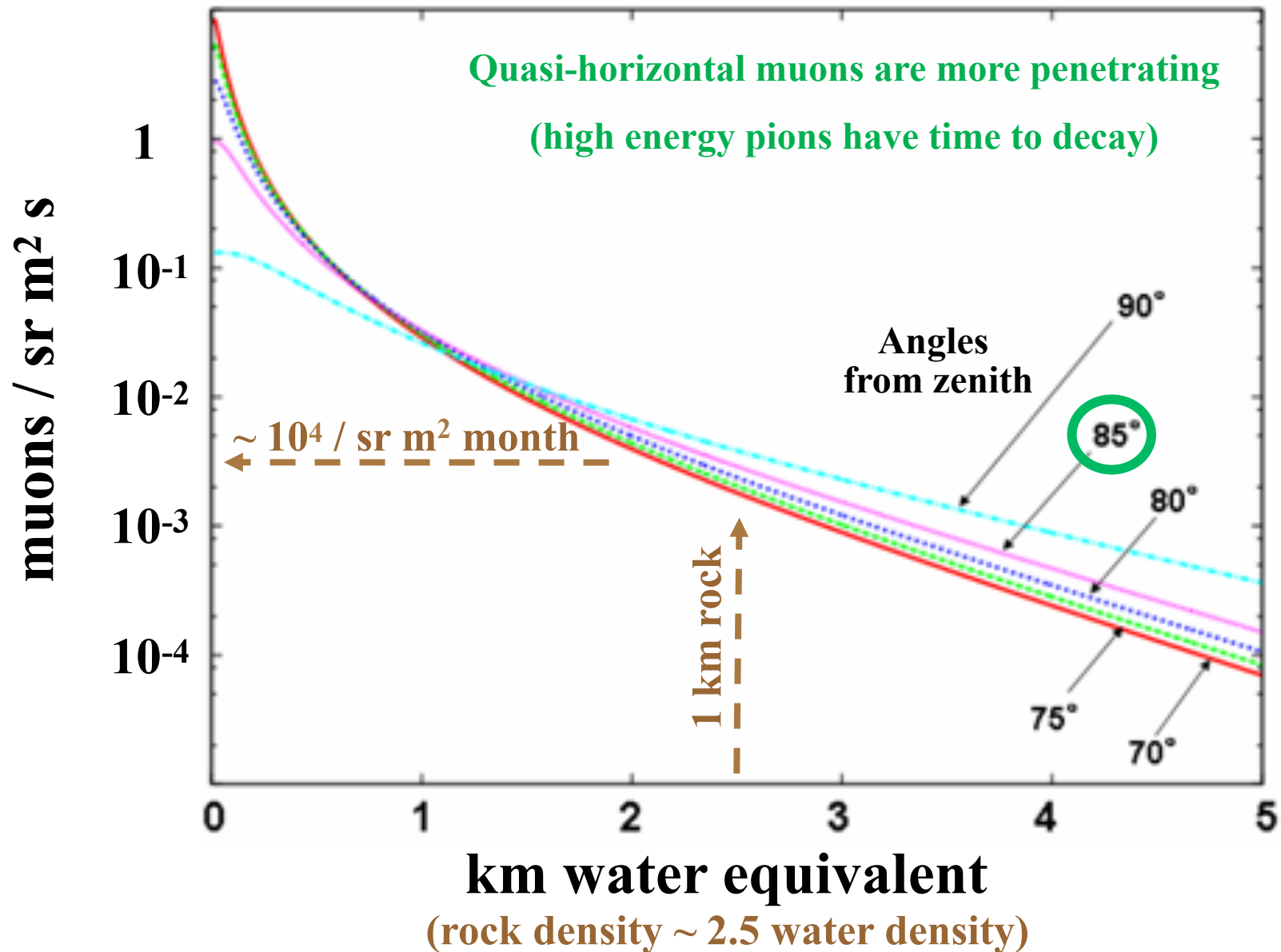
- Detect quasi-horizontal muons having traversed the volcano
- Determine the muon absorption as a function of direction
- Construct an “image” (in projective geometry) of the average rock density

The seminal paper

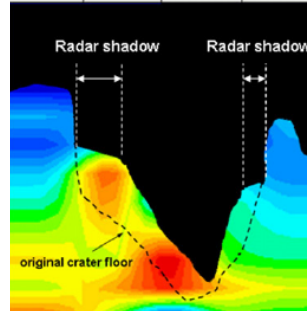
K. Nagamine

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?



What's for



Imaging technique

Intrinsic resolution : tens of m

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

A practical limitation from limited statistics

Improves the knowledge of the interior of volcanoes

(potentially 3D, synergy with conventional techniques)

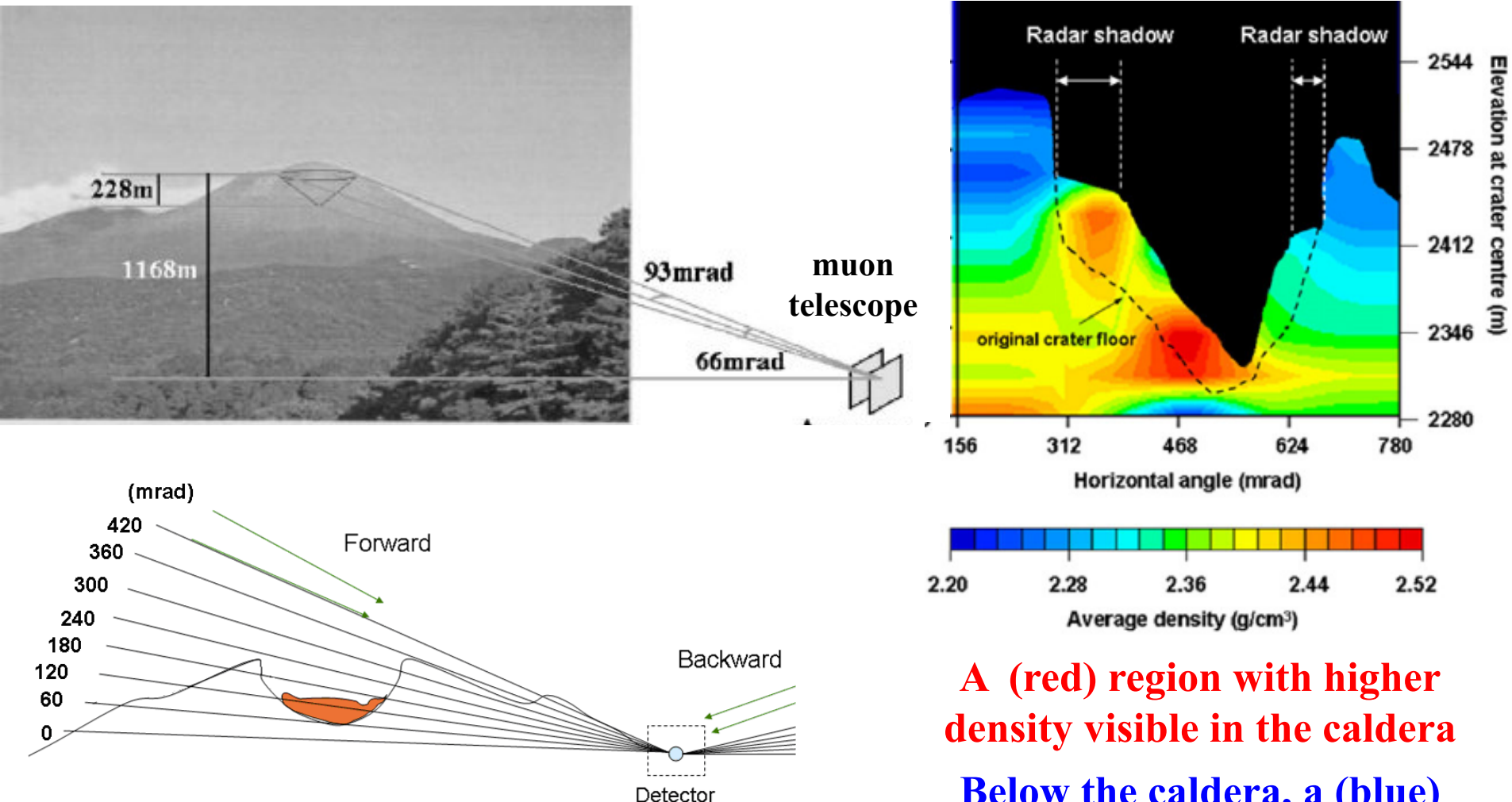
Limited to the upper part of the volcano's edifice

(very strong muon absorption beyond 1 km scale)

Input to simulations to predict “how” an eruption could develop

No information on “when” it may happen

Pioneering radiography: Asama volcano

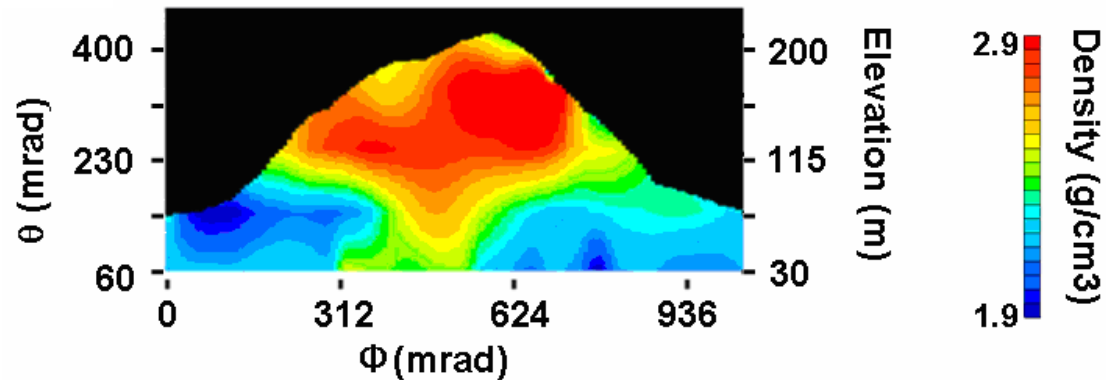
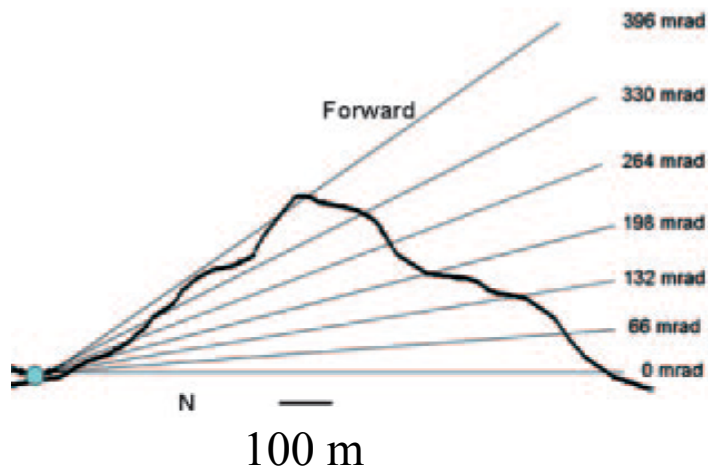


Nuclear emulsion
(same as in OPERA experiment)
for the muon telescope

A (red) region with higher density visible in the caldera
Below the caldera, a (blue) region with lower density

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

How light and muons see the Usu lava dome



Nuclear emulsion for the muon telescope

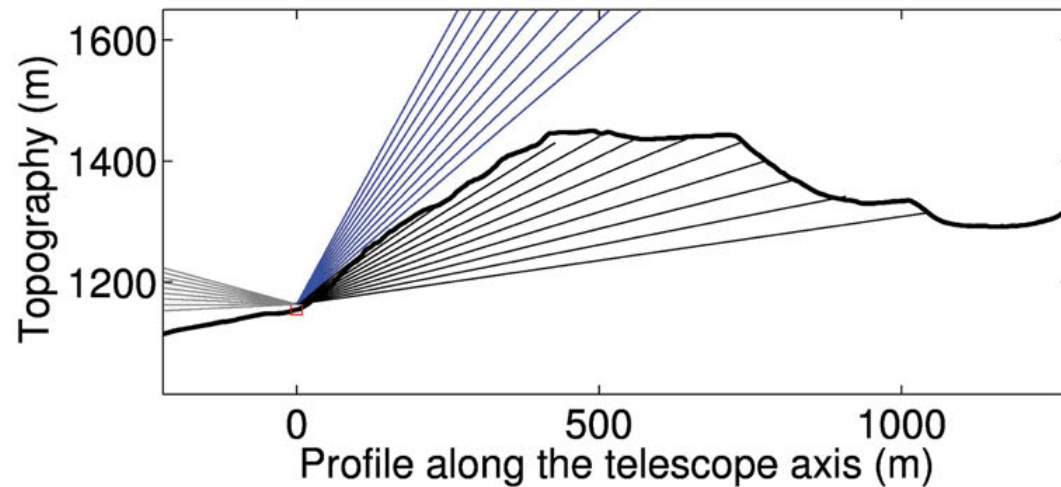
La Soufrière of Guadeloupe



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

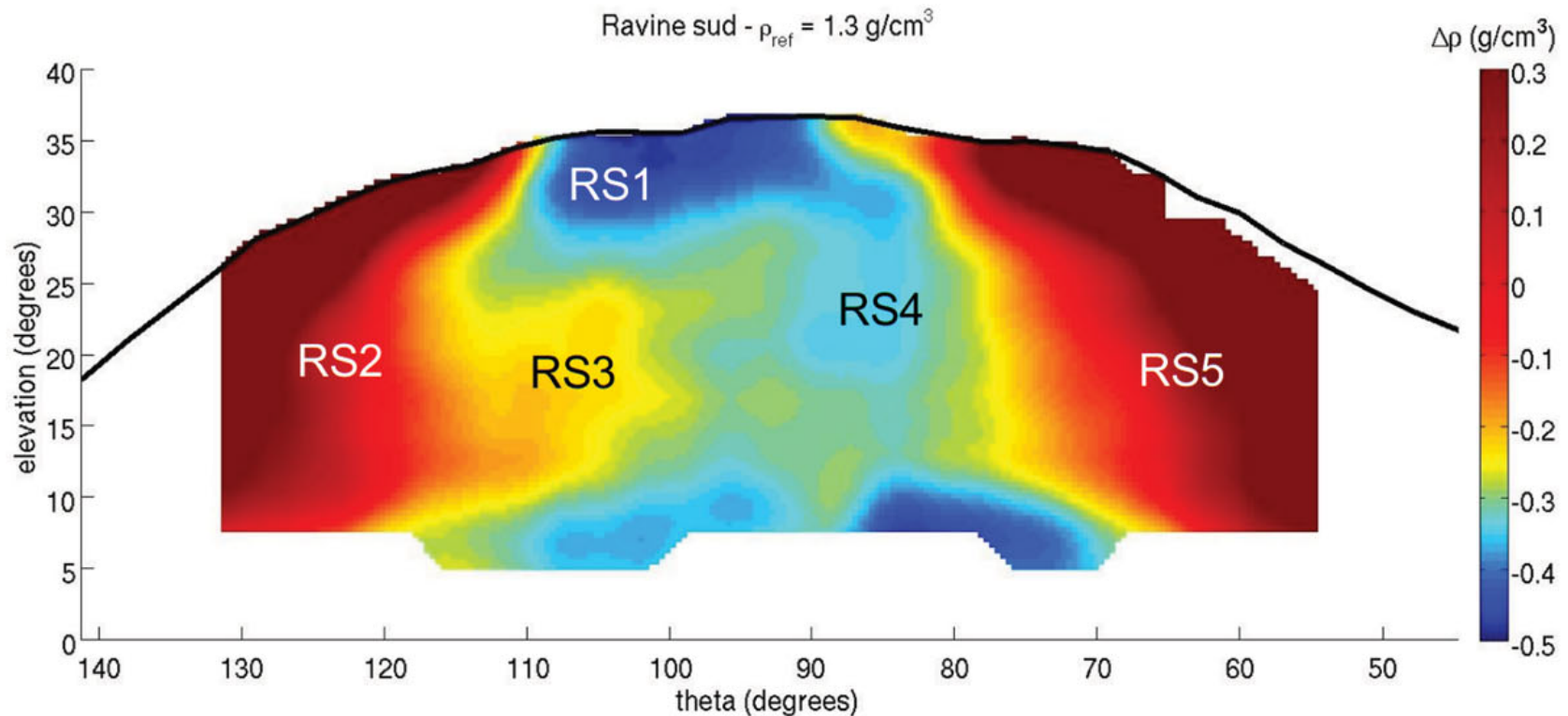
1 m^2 area

~ 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 $\pm 30\%$)

Two observation points ($\rightarrow$ 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



Glass RPCs

(possible because in a building)

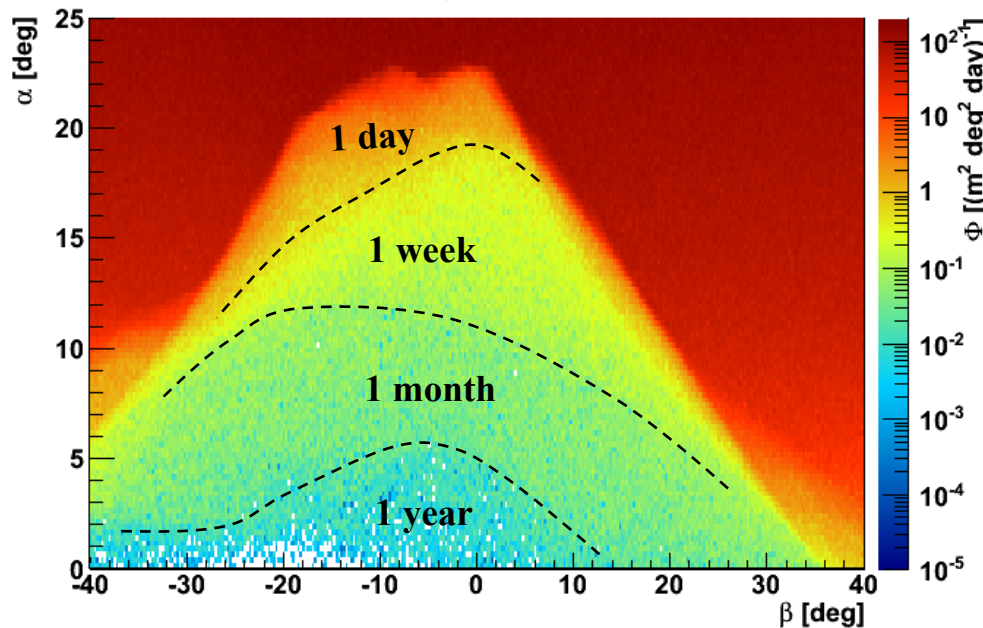
3 planes

1 m telescope length

1 m² area

~ 2 month exposure in 2012

~10⁷ candidate tracks



Assumptions:

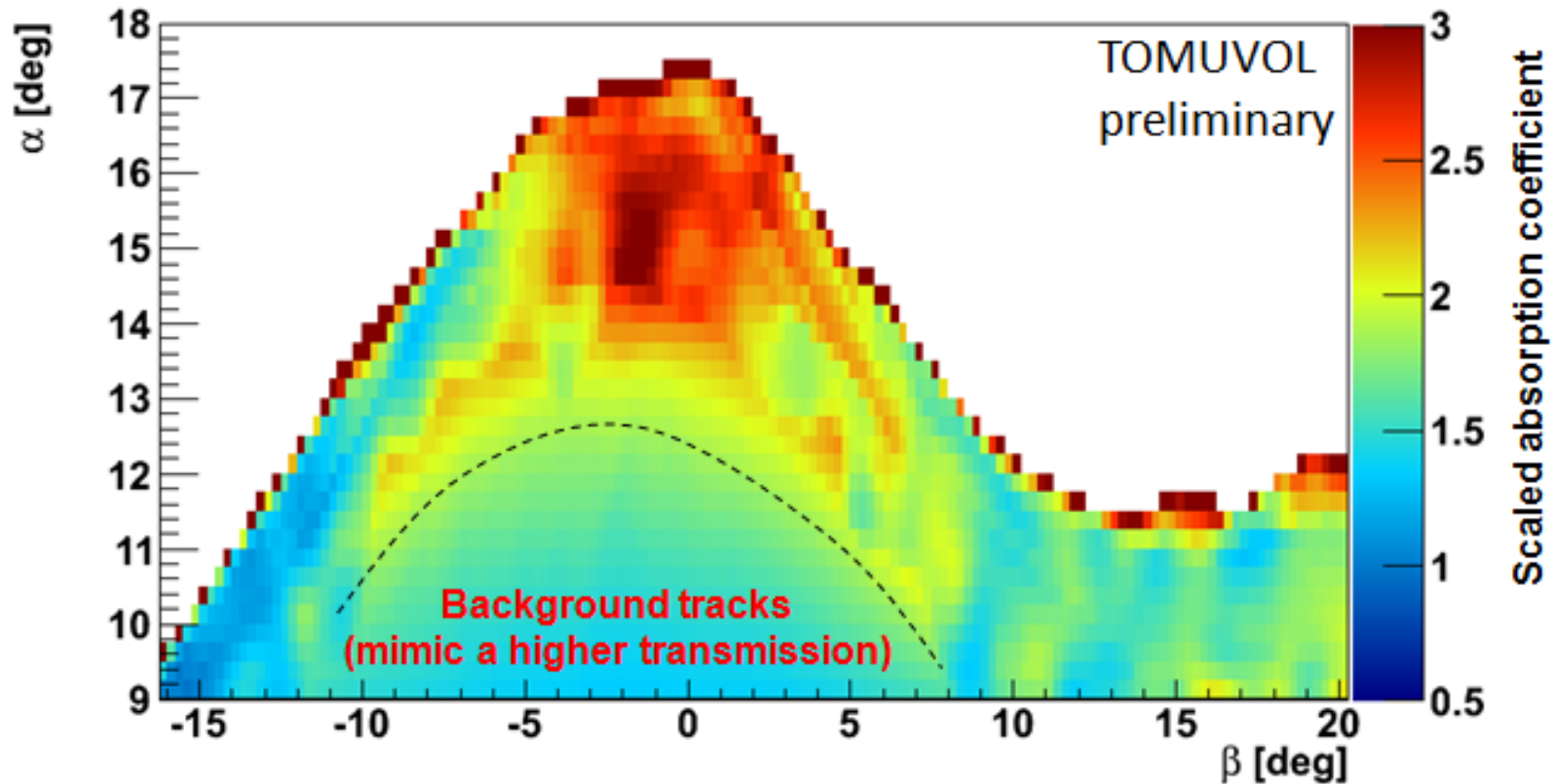
Rock density 1.66 g/cm³

No background

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

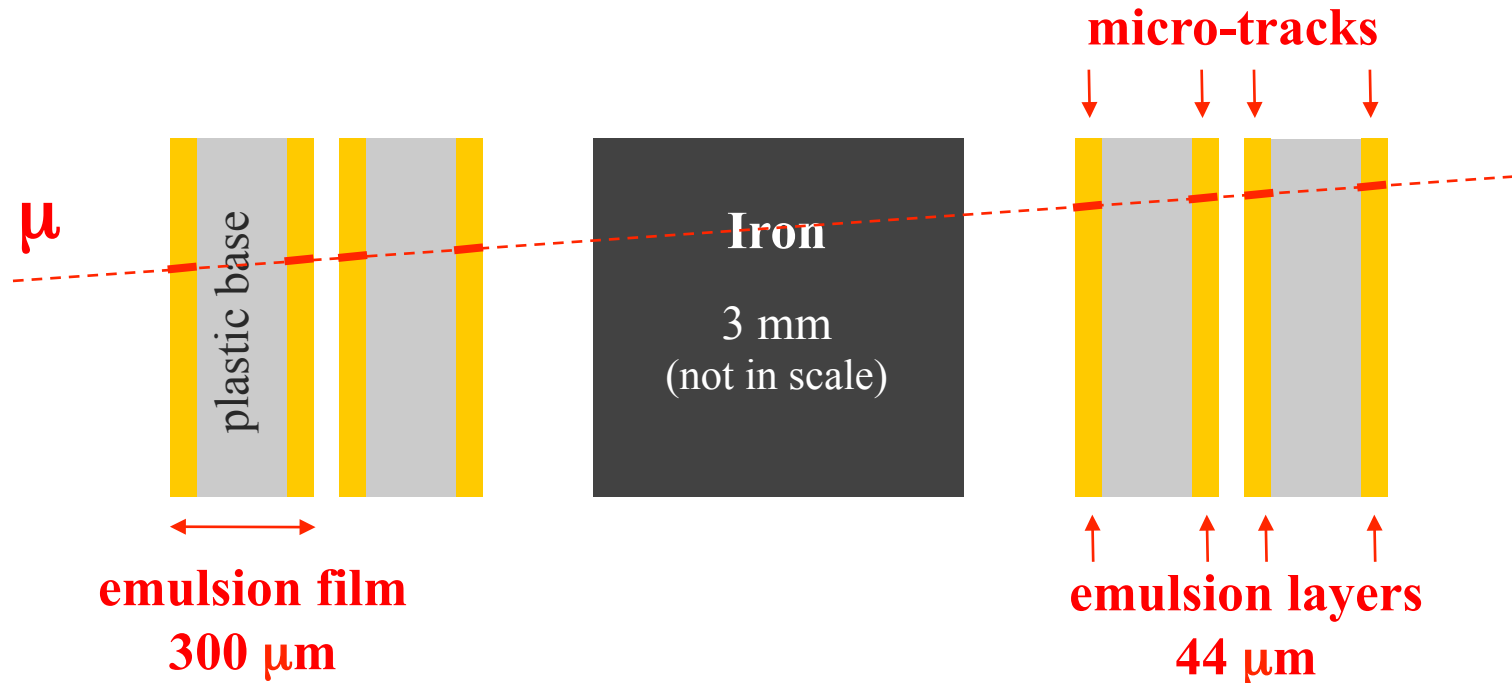
- **“Strombolian” activity**
 - essentially open conduit
 - intermittent eruptions due to build up of gas pressure
 - rare effusive activity
- **Summit at 926 m a.s.l.**
- **Crater at ~ 750 m a.s.l.**



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

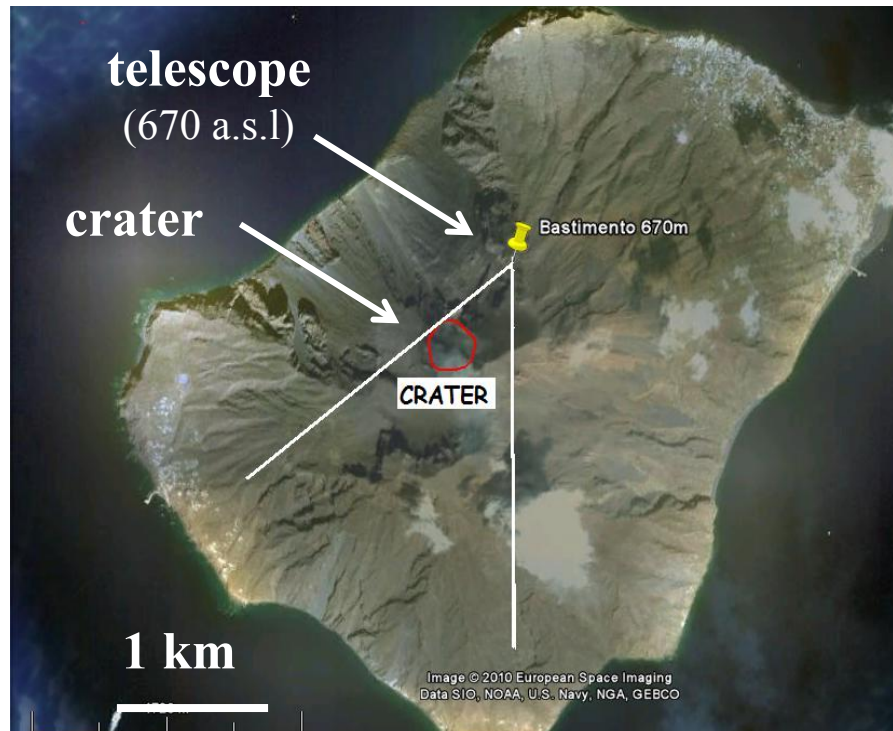
Redundant and precise (μm resolution) tracking

Angular resolution ~ 10 mrad

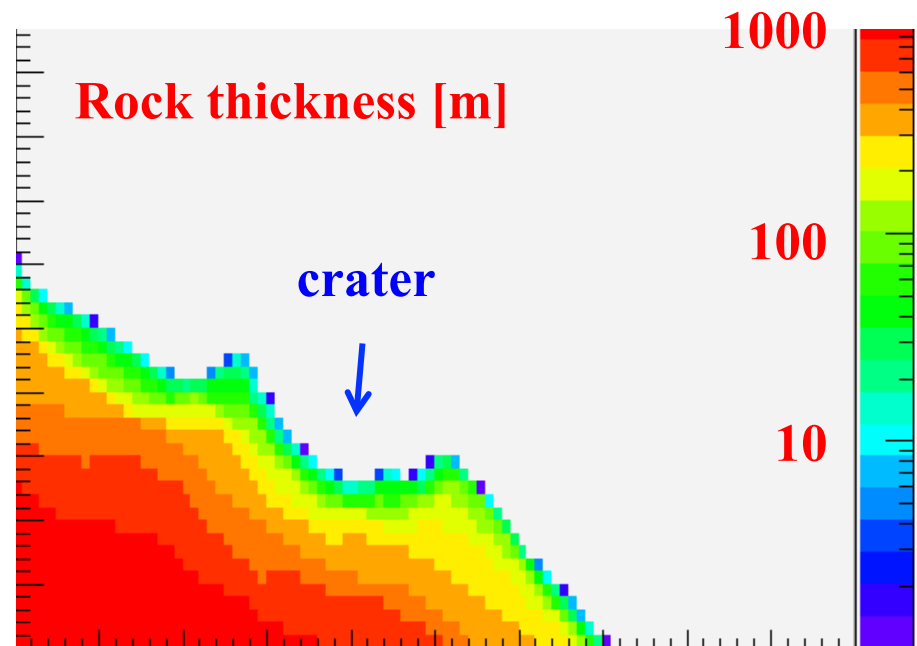
Iron to absorb soft electrons, identify low en. μ (scattering)

Transportable, no infrastructure

Muon Radiography of the crater region



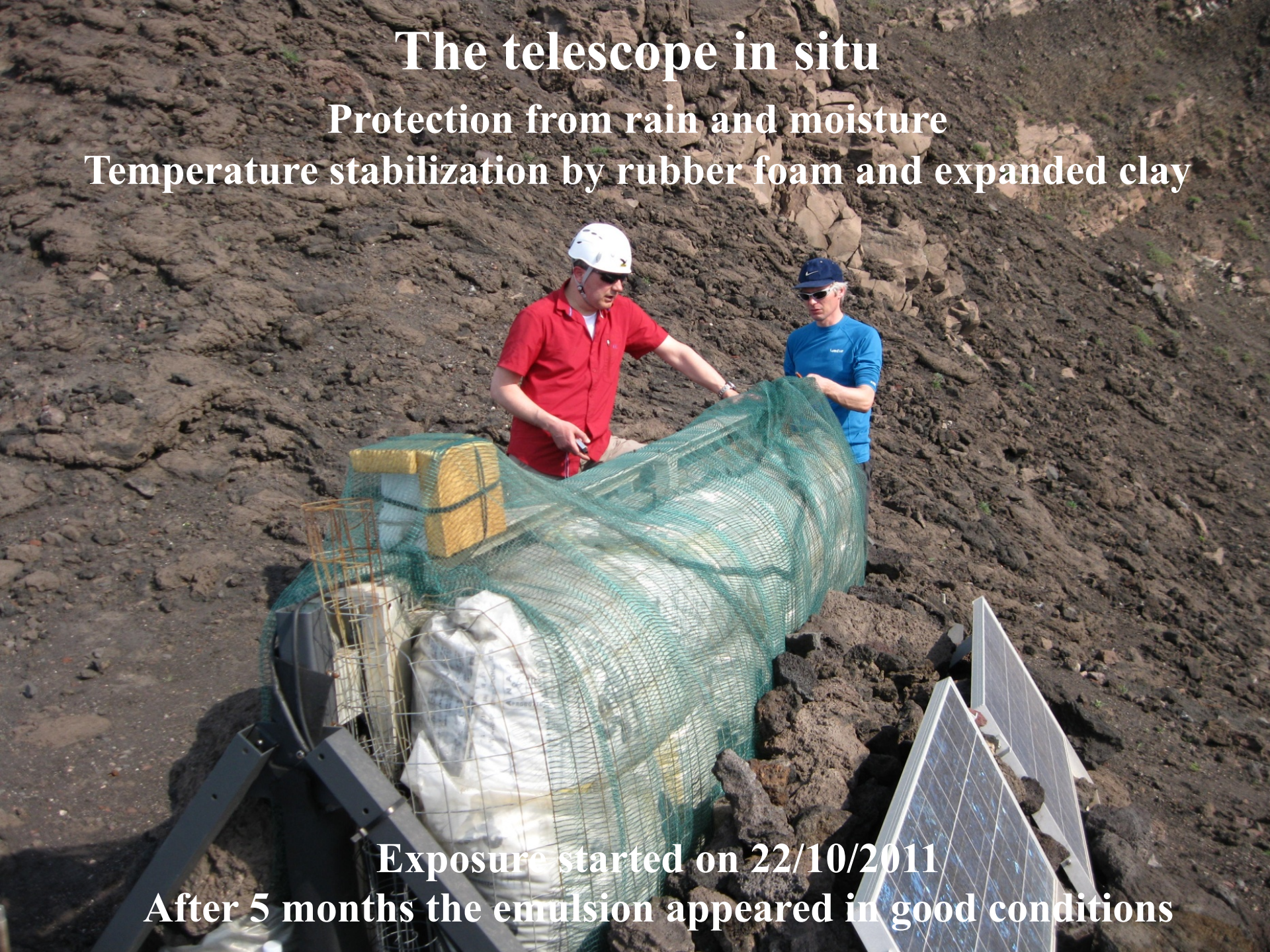
A 1 m² nuclear emulsion
telescope has taken data
last winter (5 months)



The telescope in situ

Protection from rain and moisture

Temperature stabilization by rubber foam and expanded clay

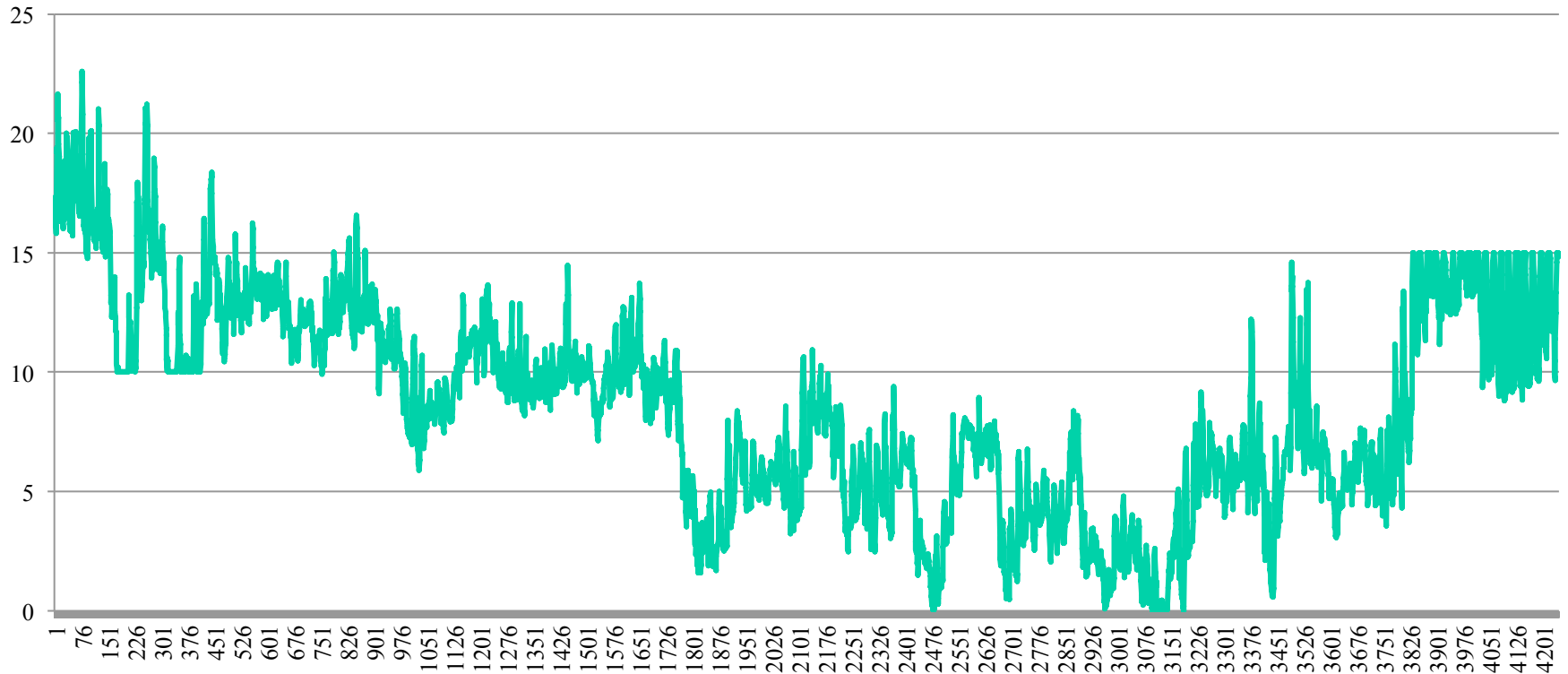


Exposure started on 22/10/2011

After 5 months the emulsion appeared in good conditions

Nuclear emulsion suffer high temperature

Air temperature (°C)



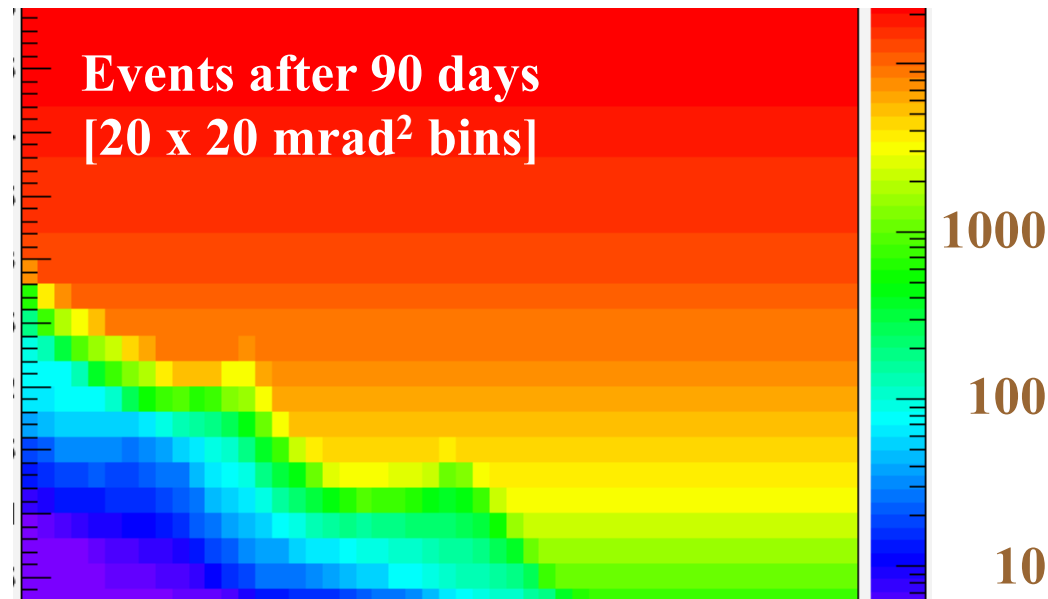
Exposure 22/10/2011 – 24/3/2012
Acceptable temperature



The harsh environment
(here the mechanical structure left in place after the exposure)

Expected events

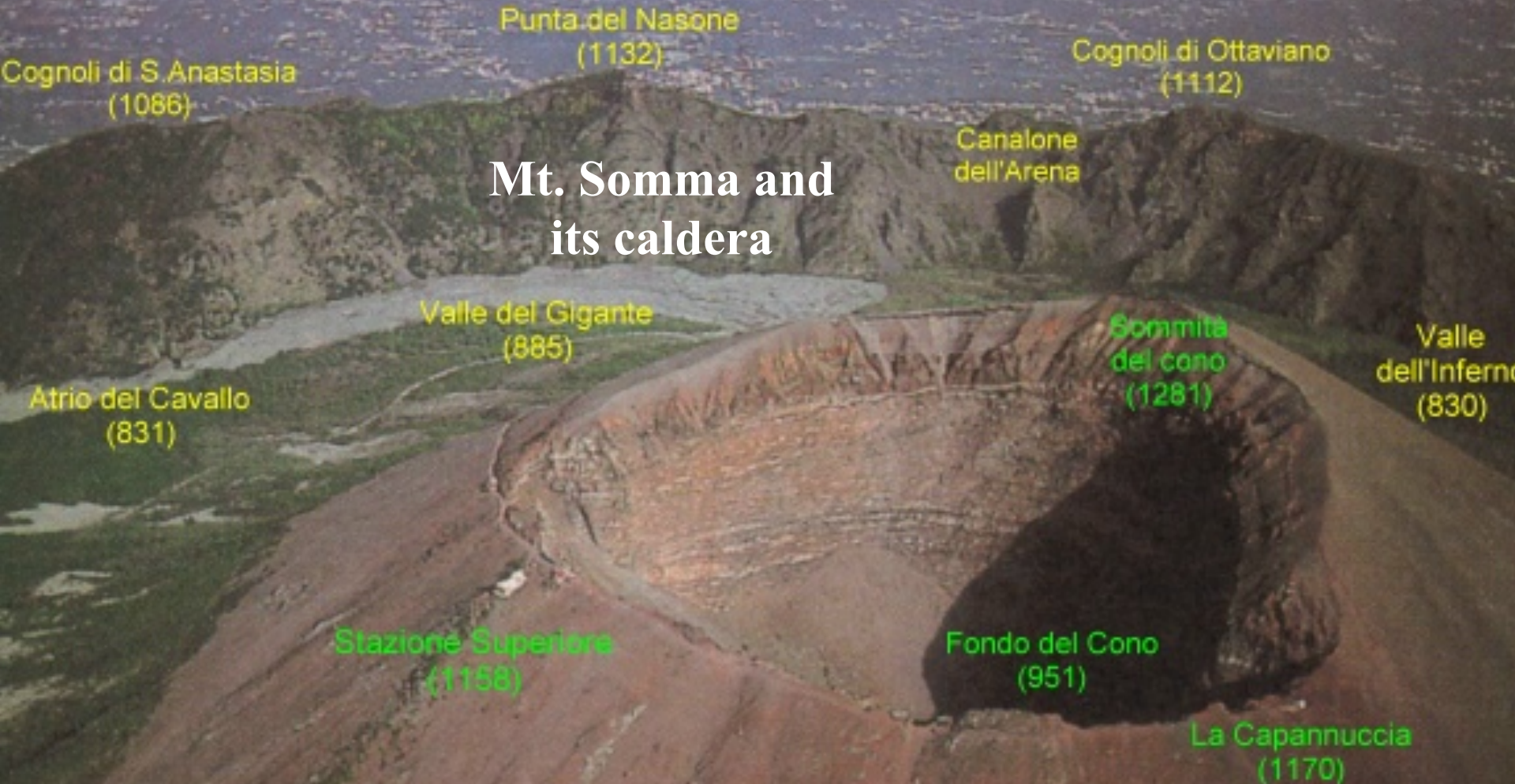
(in absence of background)



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

The challenge of Mt. Vesuvius

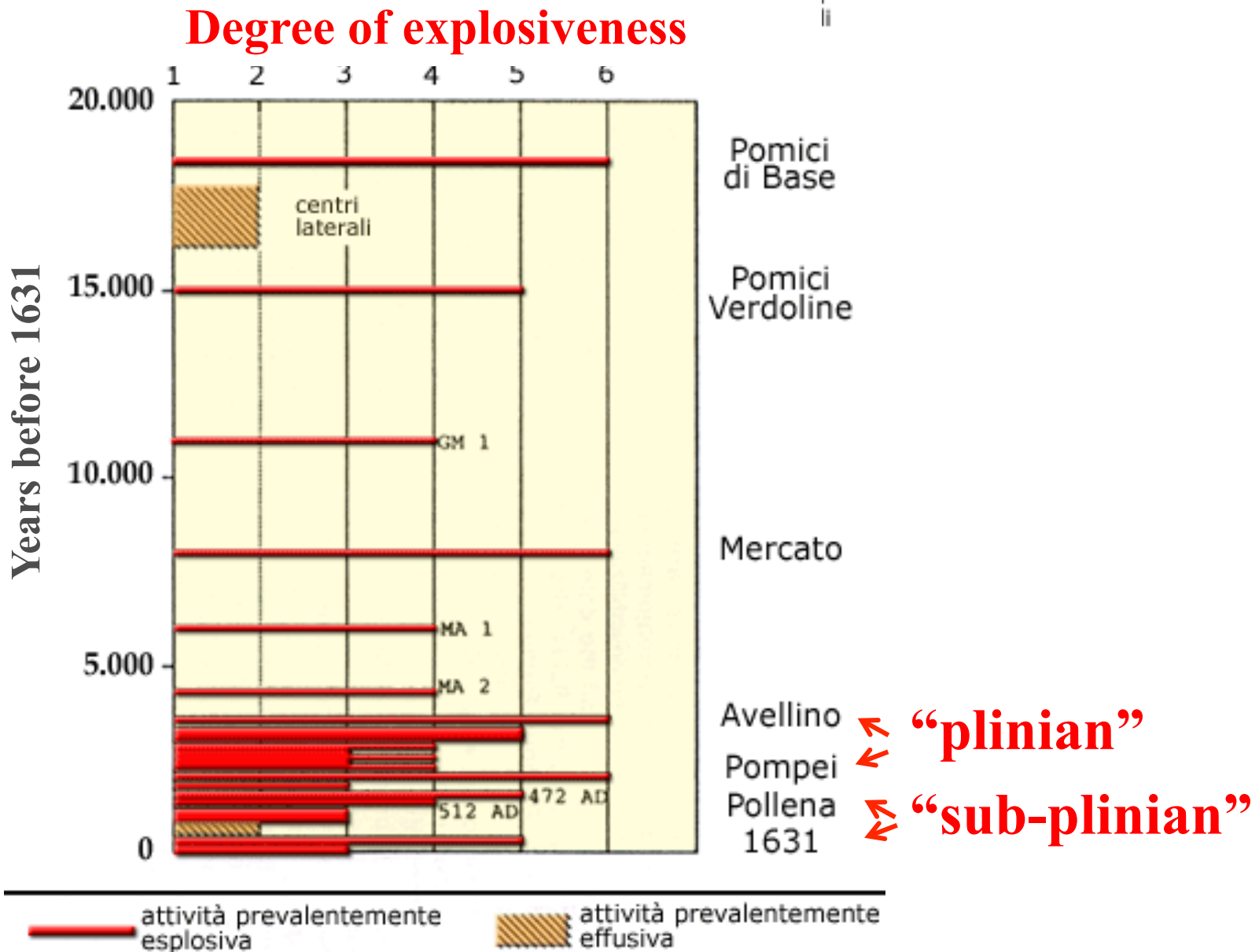
Mt. Somma and its caldera



“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

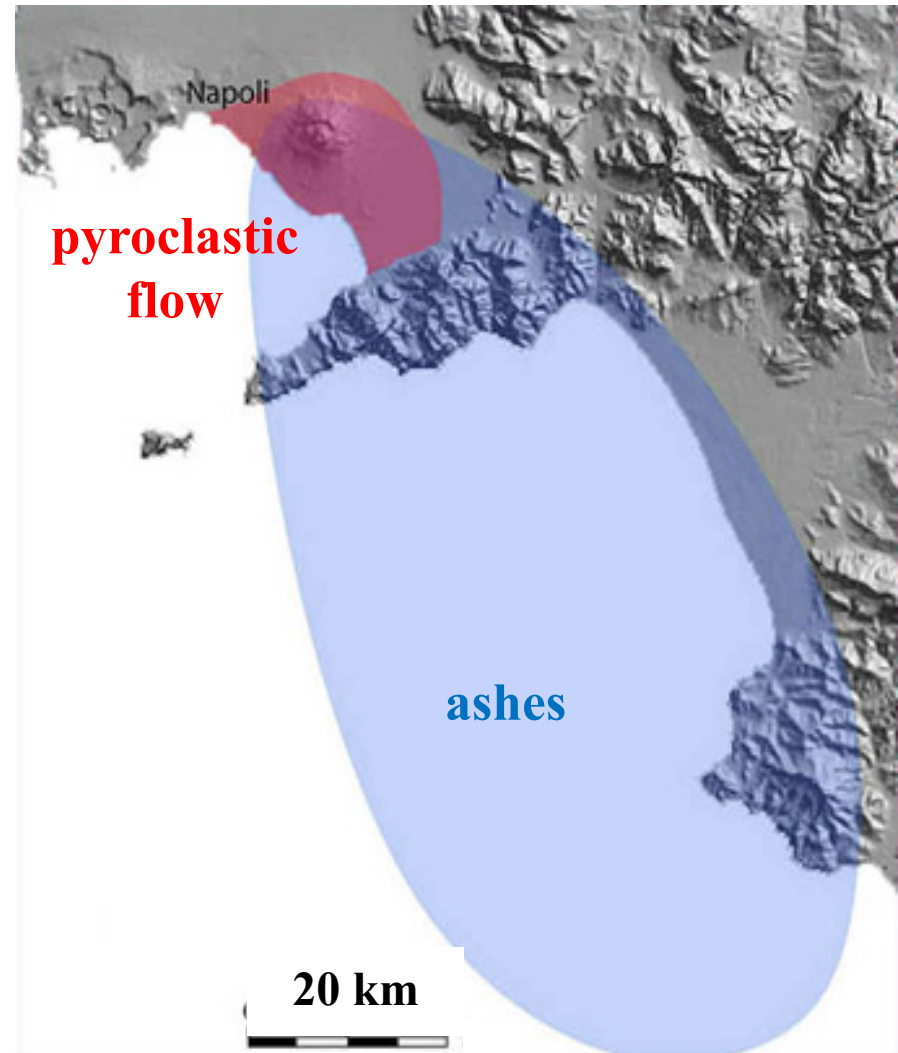
**A vast area covered by
pyroclastic flow**

**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



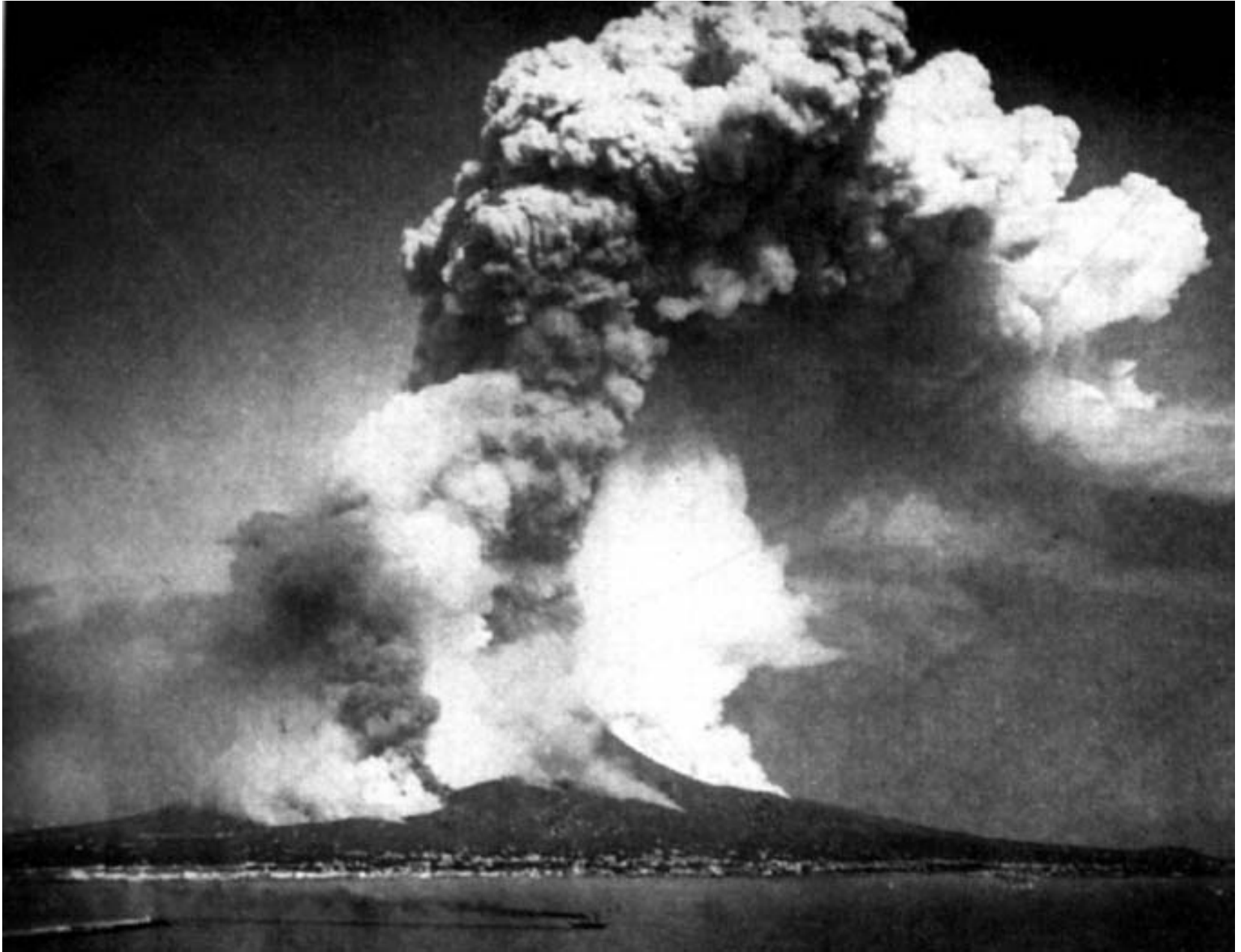
from www.ov.ingv.it

The last sub-plinian eruption (1631)



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

The 1872 eruption



The 1906 eruption

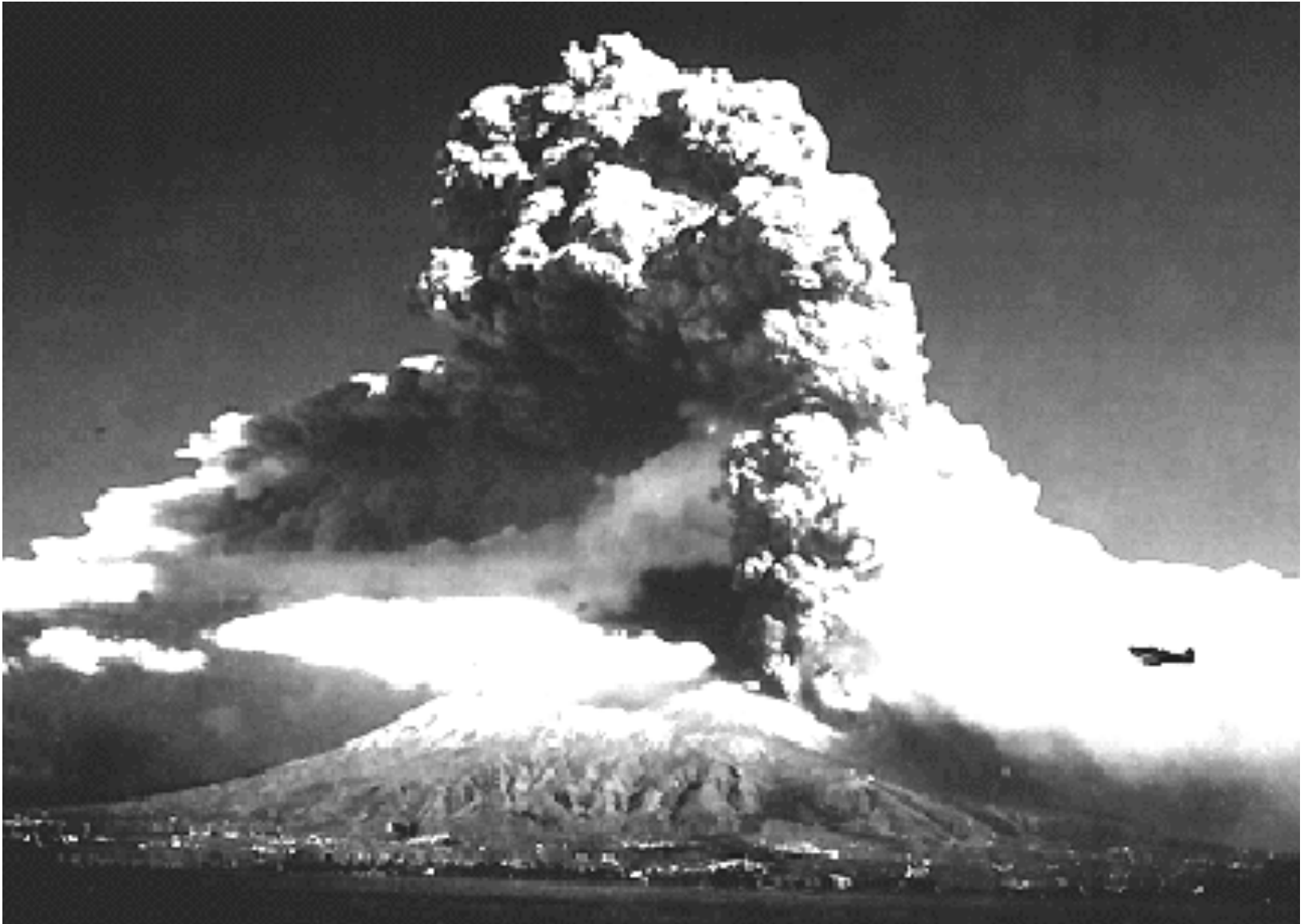


**“Frightening explosion
of Mt. Vesuvius
150,000 people fled away”**

*(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^o World War

Periodicity in the years 1631 - 1944

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

After the “terminal” 1944 eruption

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



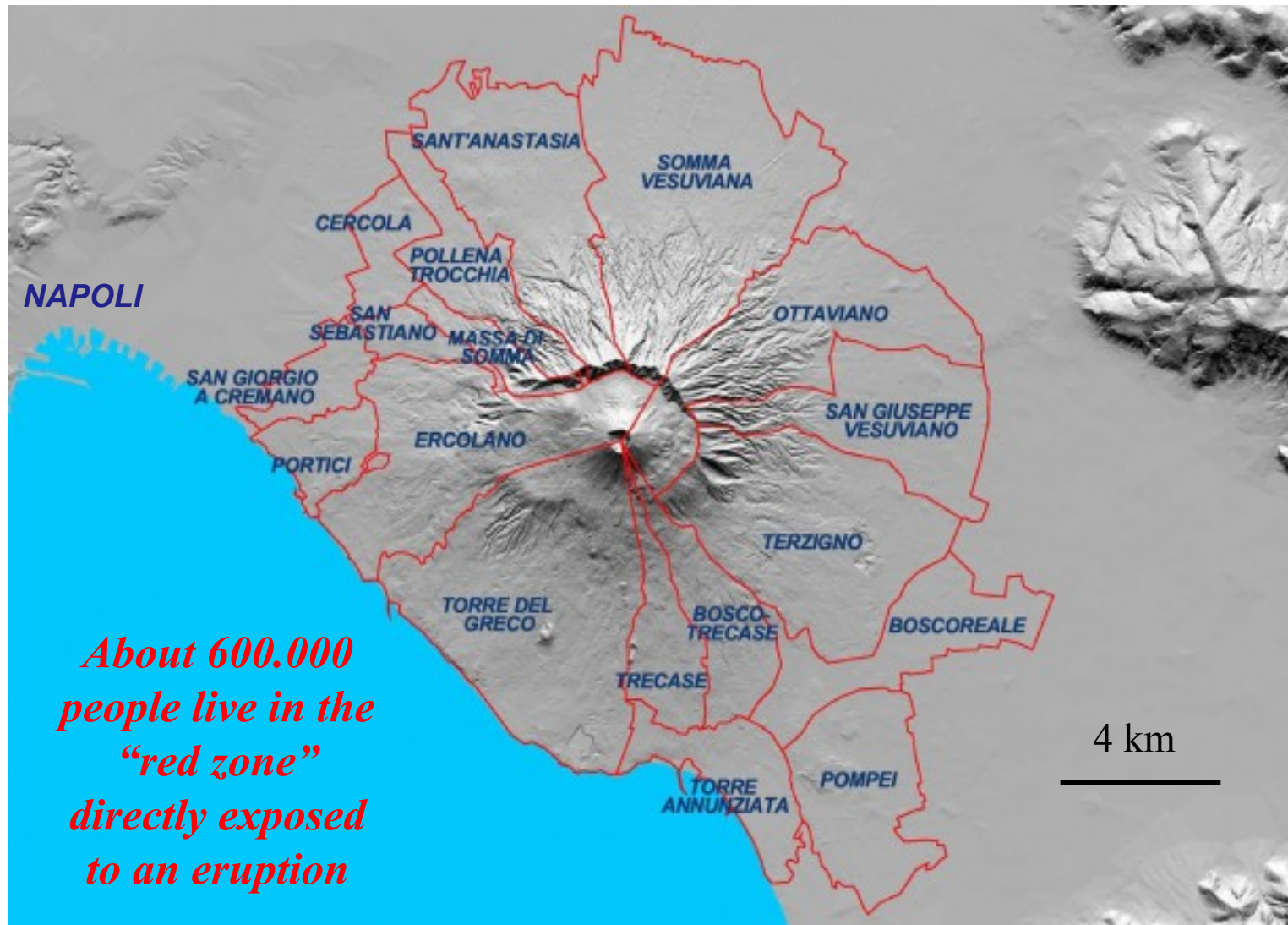
Today's Vesuvius looks “unusual” compared to its history

A huge stored energy?



A. Warhol (1928-1987): Vesuvius (1985)
Capodimonte Museum, Naples

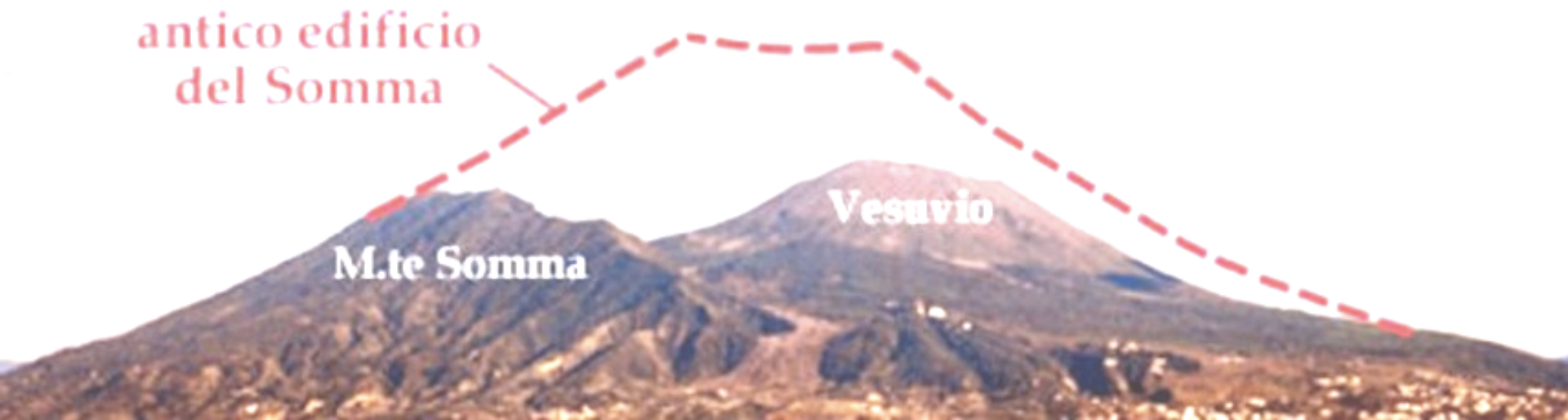
The highest volcanic risk in Europe



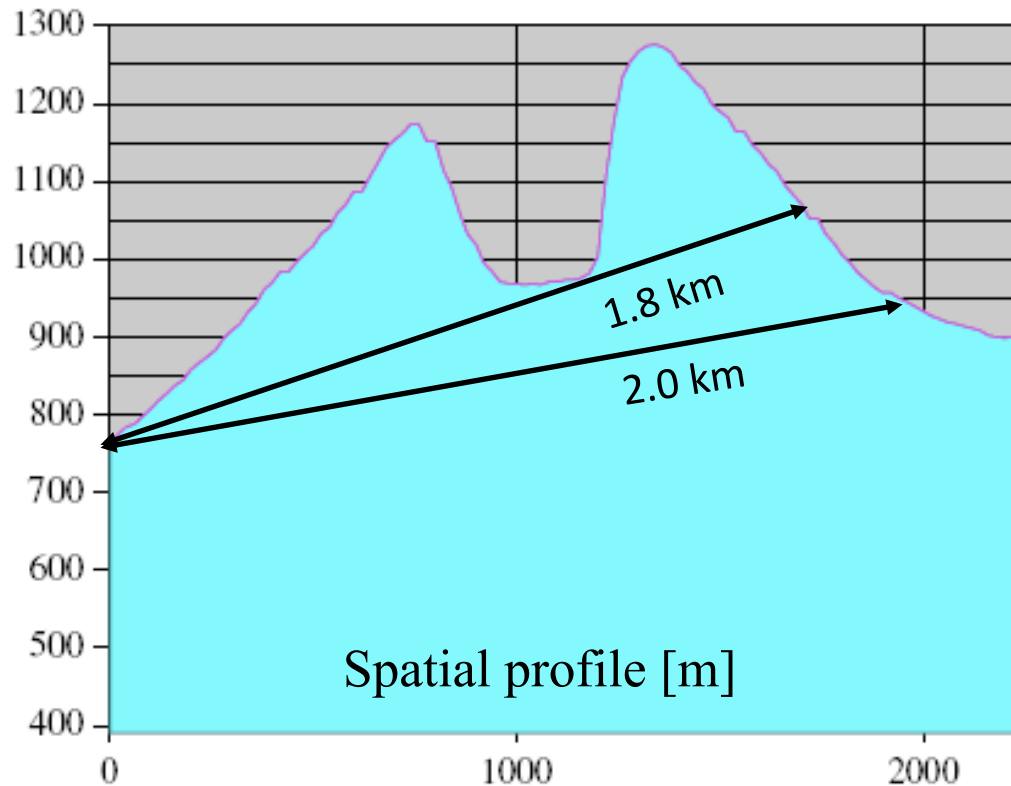
Strongly motivates the challenge of a muon radiography

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

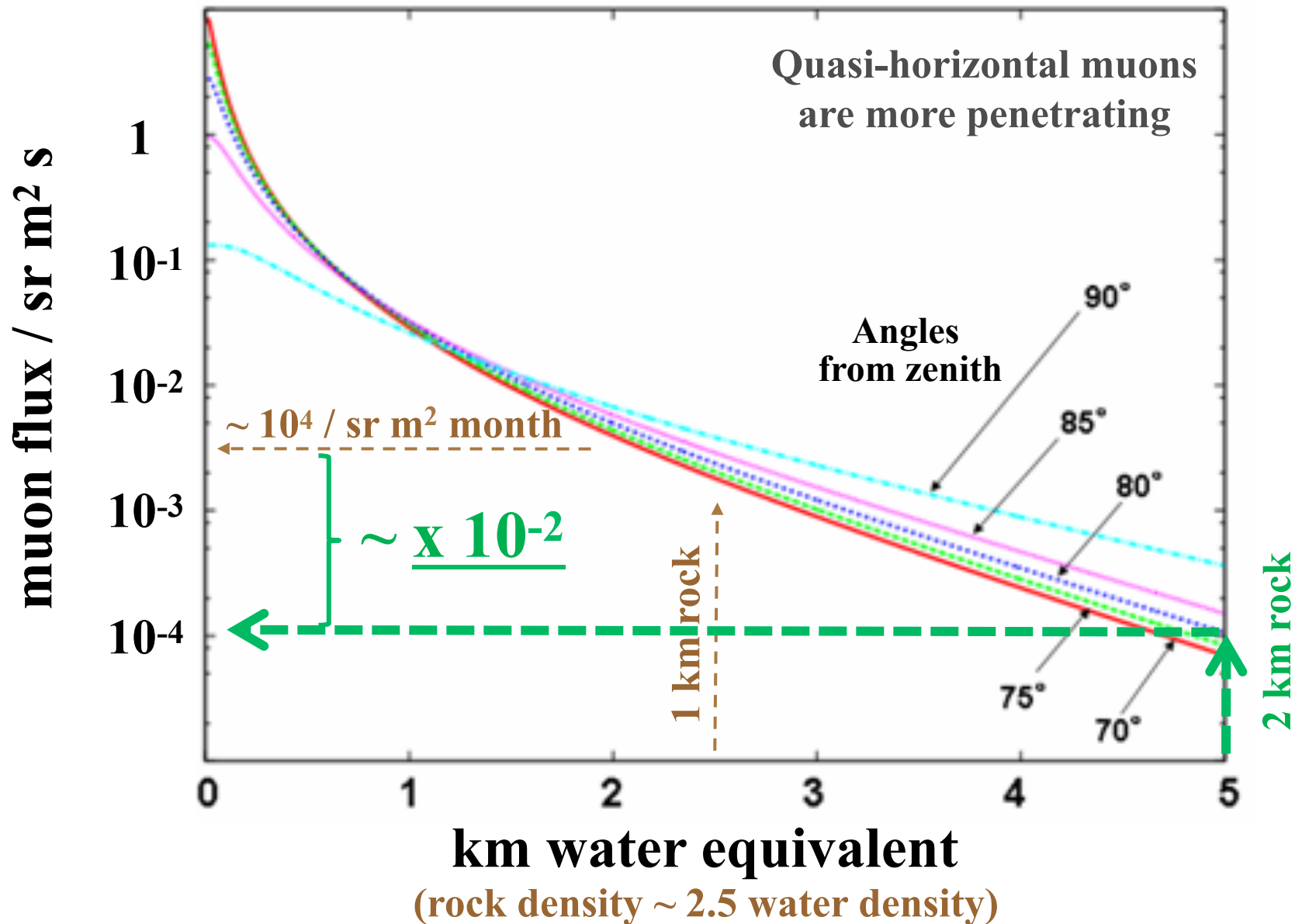


2 km rock thickness from a telescope at 750 m a.s.l.



Substantially improve the sensitivity ($\times 10^2$)
with respect to previous radiographies (< 1 km rock)

Muon flux reduction for 1→2 km rock thickness



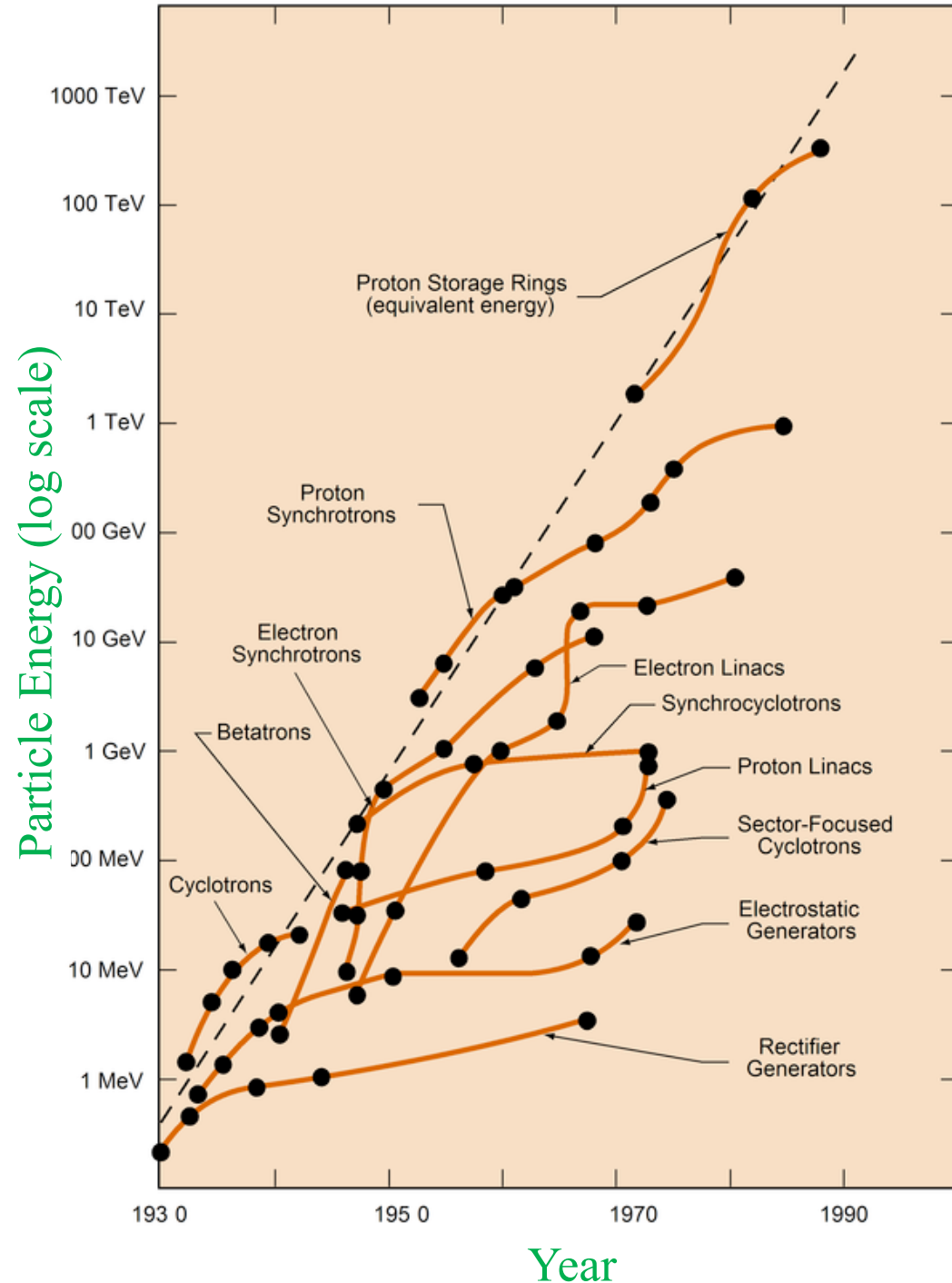
To improve the sensitivity $\times 10^2$

- **Area: $1 \rightarrow 10 \text{ m}^2$ or more** (array of telescopes)
- **Large number of channels: reduce power/channel**
- **Data taking: months $\rightarrow$ years**
- **Background rejection is crucial: new tools**

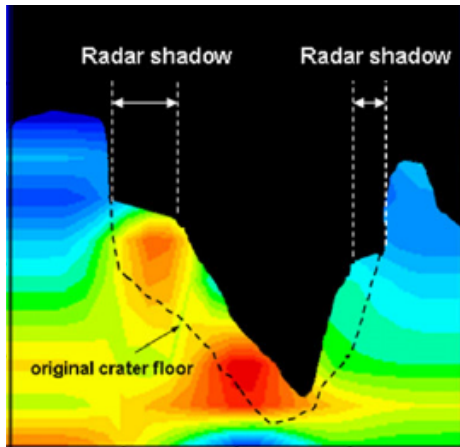
The detector must be suitable to work in volcanic environments without electricity supply

In any field, the progress comes from new technologies

The “Livingston plot”
Saturation in energy for any
accelerator technology



Experimental techniques



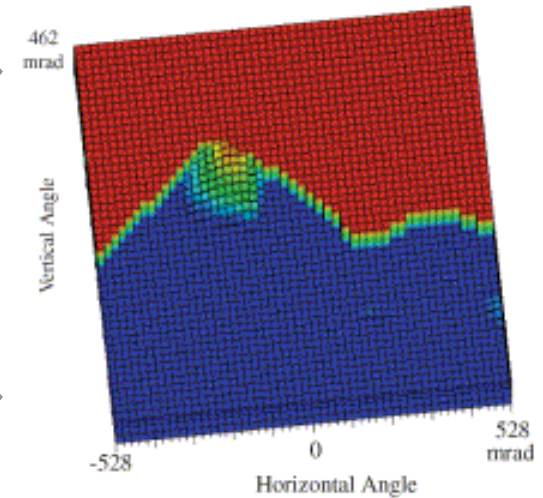
Mt. Asama

Tanaka and coll.

Telescope area $\sim 1 \text{ m}^2$

EPS Lett. 263 (2007) 104

Resolution $\sim 70 \text{ mrad}$
NIM A507 (2003) 657



NUCLEAR EMULSION

Precise muon tracking

Resolution $\sim 10 \text{ mrad}$ (as scattering)

Minimal infrastructure

No electric power

Usable in difficult locations

Unusable in warm season

Area limited by scanning power

PLASTIC SCINTILLATOR STRIPS

Analysis in real-time

Increase n. of channels: improve resolution

Time of flight possible: b.g. reduction

Larger area possible

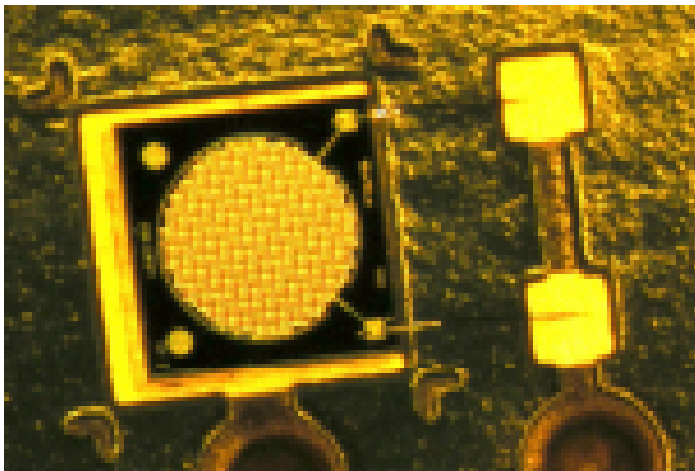
Long exposures possible

New technologies to reduce el. power

Plastic scintillators to see through $> 1 \text{ km}$

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

- **Matrix of diodes operated in Geiger mode** (inverse polarization)
- **Analog sum of the signals**
 - amplification $\sim 10^6$ (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)



$\Phi = 1.4 \text{ mm}$, ~ 300 diodes

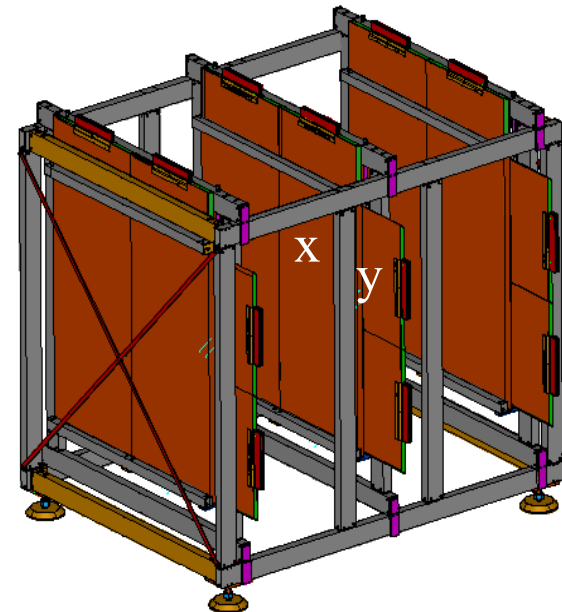
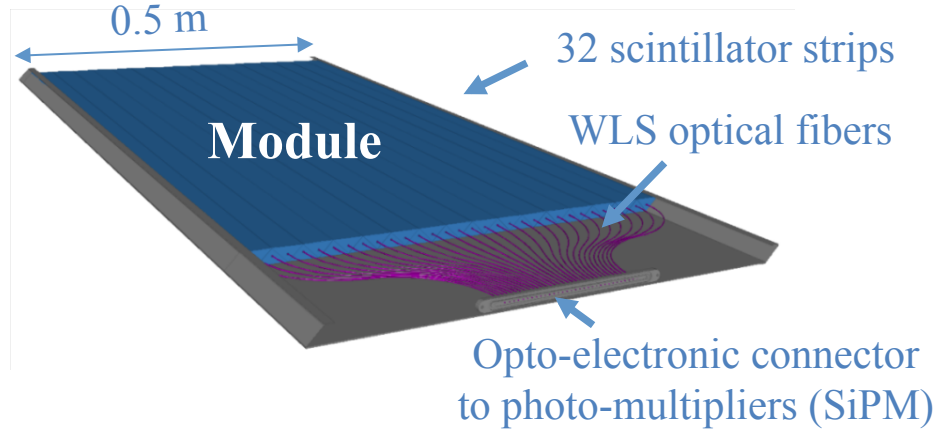
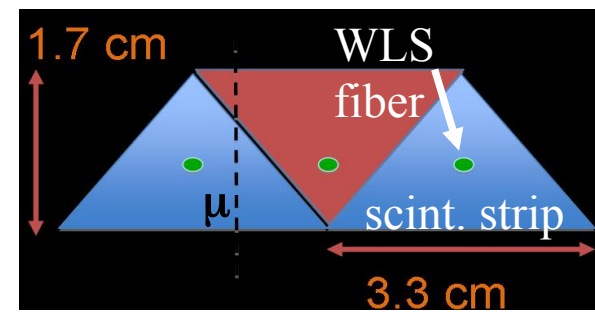
A “naked” SiPM
by FBK-IRST (Trento, Italy)
developed in a joint venture with INFN

Best producer: Hamamatsu, but

Need investment in time and efforts

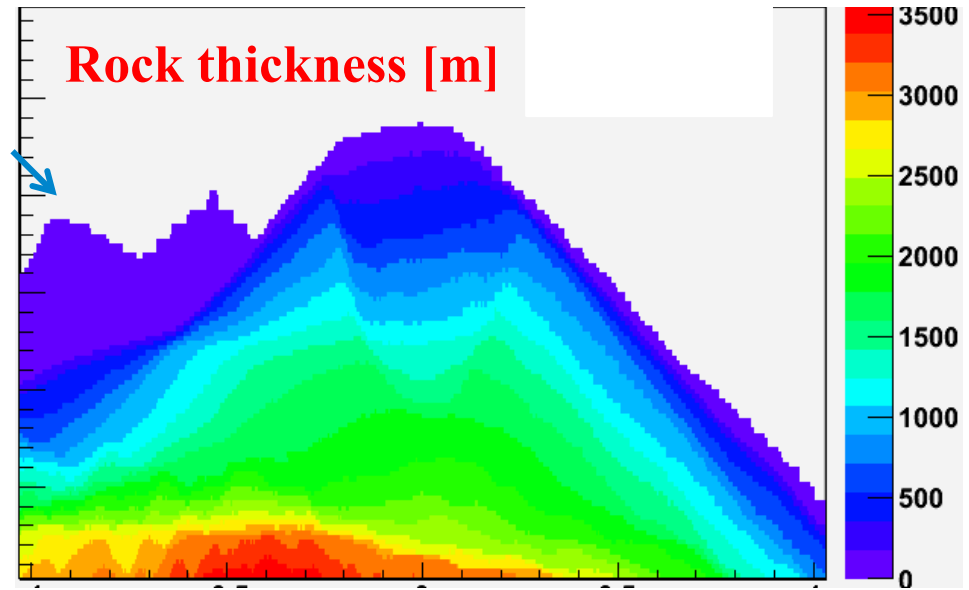
The MU-RAY muon telescope

- **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

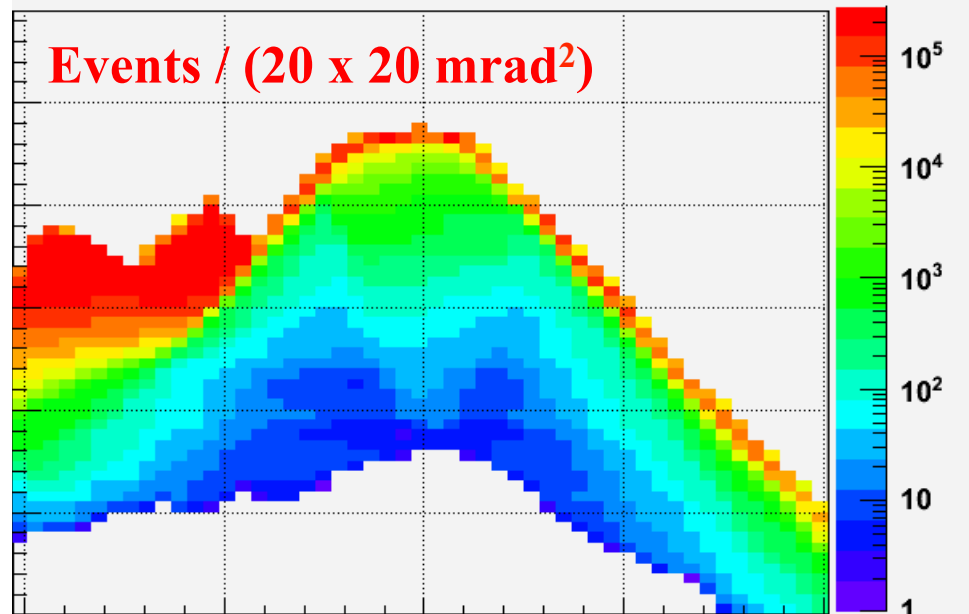


Expected from the 1 m² prototype telescope (one year run, no background)

Mt. Somma



A first step in the
“Mt. Vesuvius challenge”



Final remarks

TYPUS MONTIS
VESUVII
Prout ab Authore
A^o 1638. visus fuit.

- “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