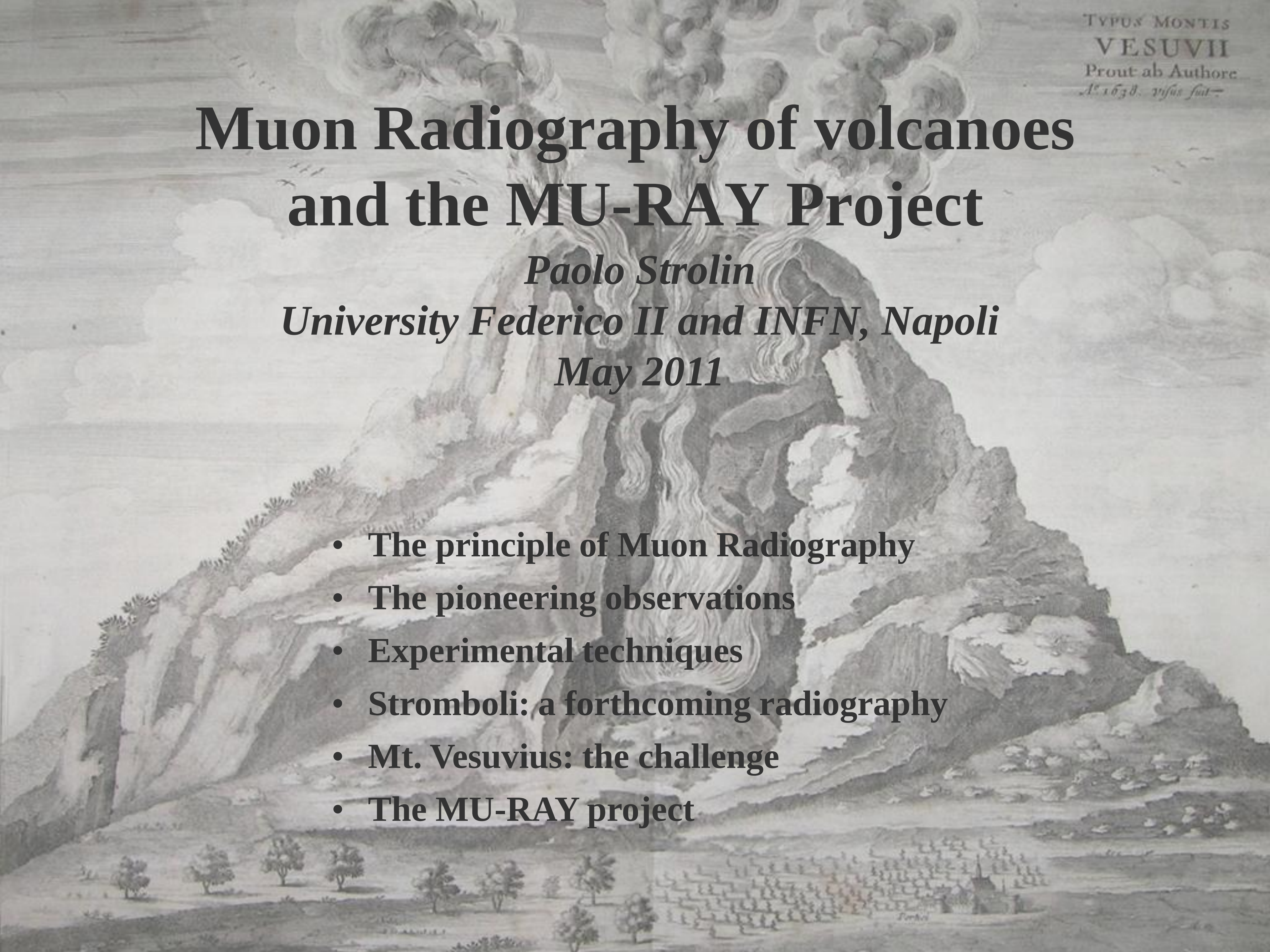


Muon Radiography of volcanoes and the MU-RAY Project

Paolo Strolin
University Federico II and INFN, Napoli
May 2011

- **The principle of Muon Radiography**
- **The pioneering observations**
- **Experimental techniques**
- **Stromboli: a forthcoming radiography**
- **Mt. Vesuvius: the challenge**
- **The MU-RAY project**

A multi-disciplinary research and team

(particle physicists and volcanologists)

MU-RAY project

Universities and INFN Firenze, Napoli and Perugia
Vesuvian Observatory – INGV
Earthquake Research Institute (ERI) - Tokyo
Fermilab, IN2P3-CNRS Orsay

Stromboli and Unzen lava dome

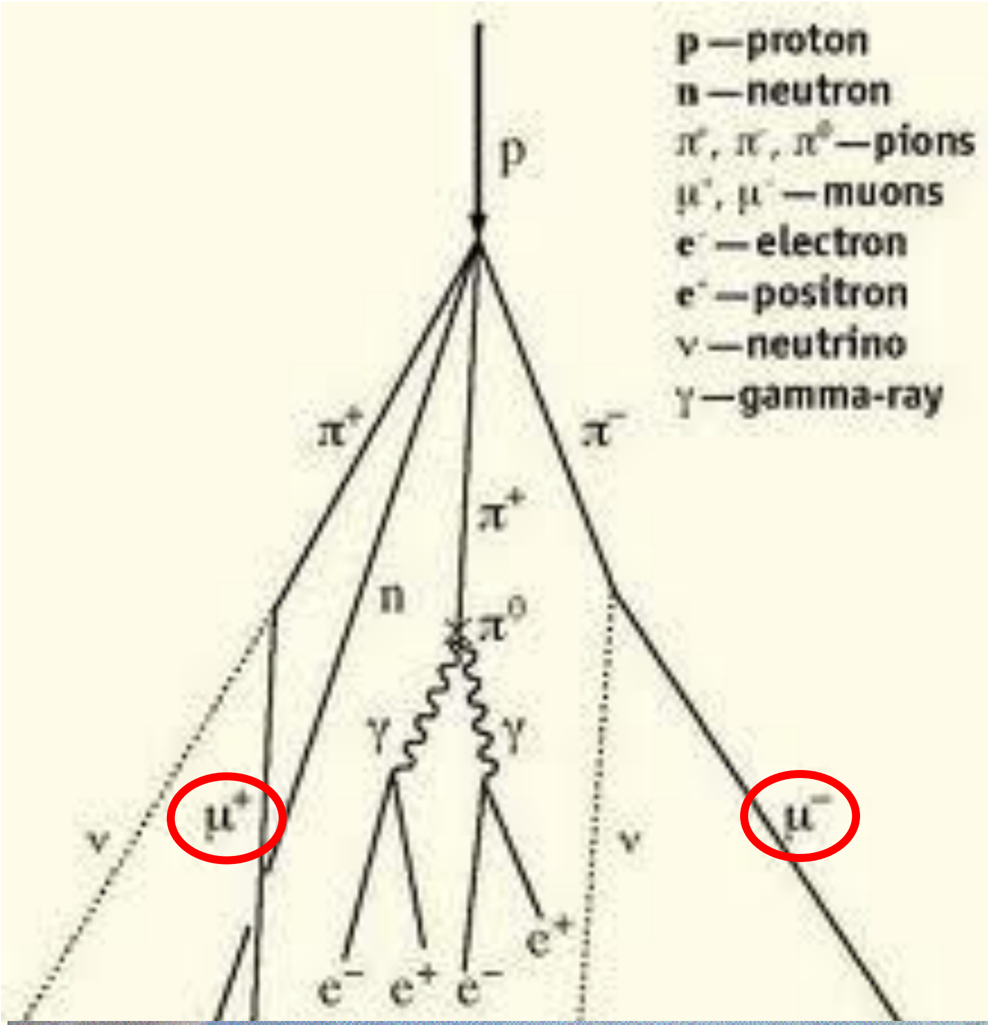
Universities and INFN Napoli and Salerno
Gran Sasso Laboratory - INFN
Vesuvian Observatory - INGV
ERI - Tokyo

Muons: a gift from the Cosmos

Cosmic ray interactions in the atmosphere provide a flux of <u>very high energy muons</u> from pion decays

Muons are <u>penetrating particles</u>:
no strong interactions
mass ~ 200 x electron mass

“<u>Muon Radiography</u>”

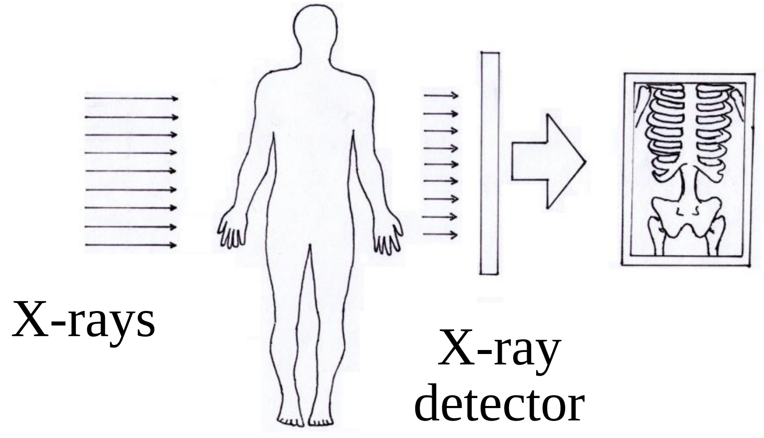



G.B. Lusieri (1755-1821)

Muon radiography

"See the invisible"
by observing the muon absorption in matter
depending on its density

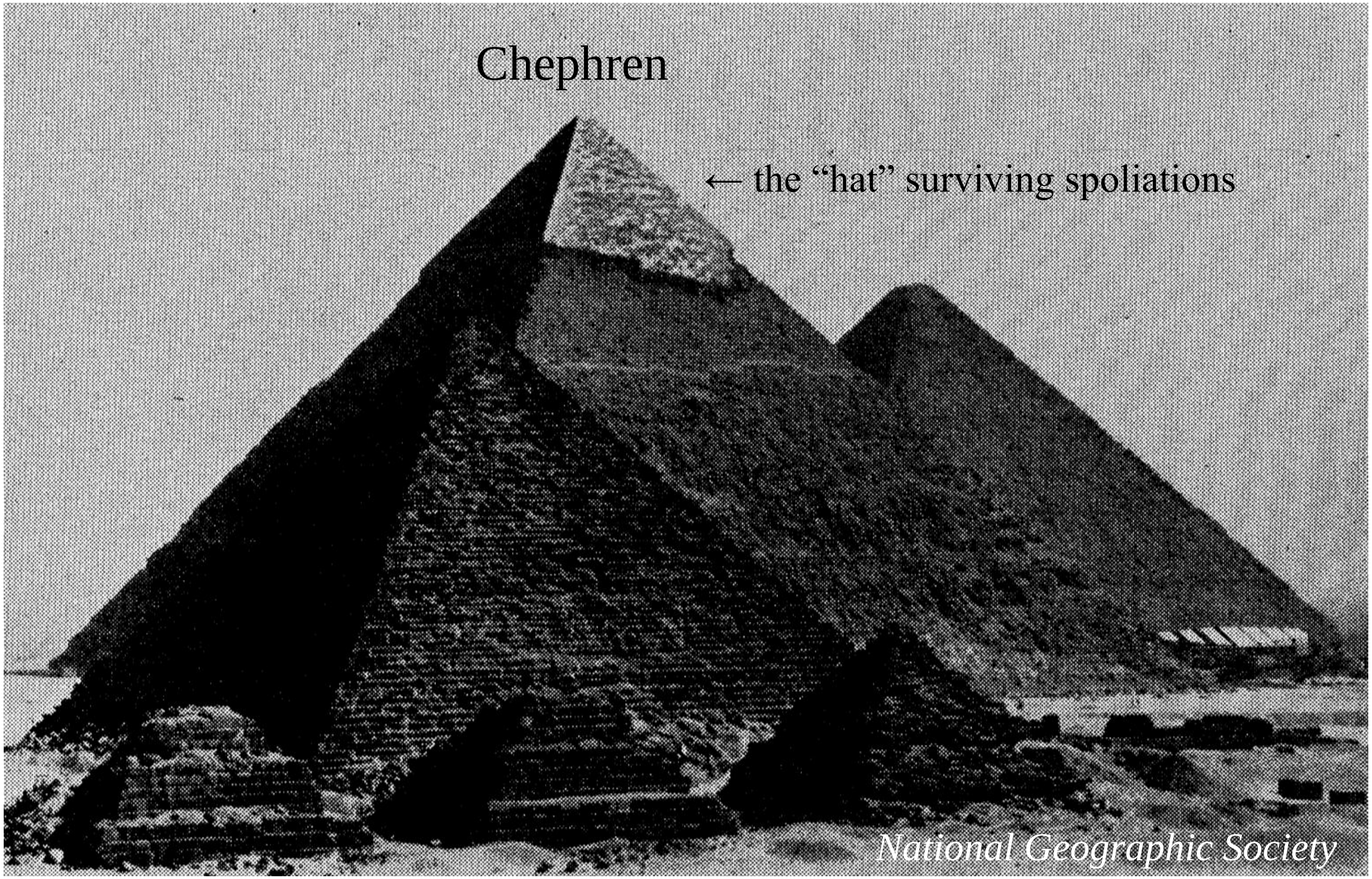
As we do with X-rays
but at much larger depths in matter



First proposed to determine the thickness of snow layers on a mountain
E. P. Georg, Commonw. Eng., July 1955

Possible applications in various fields

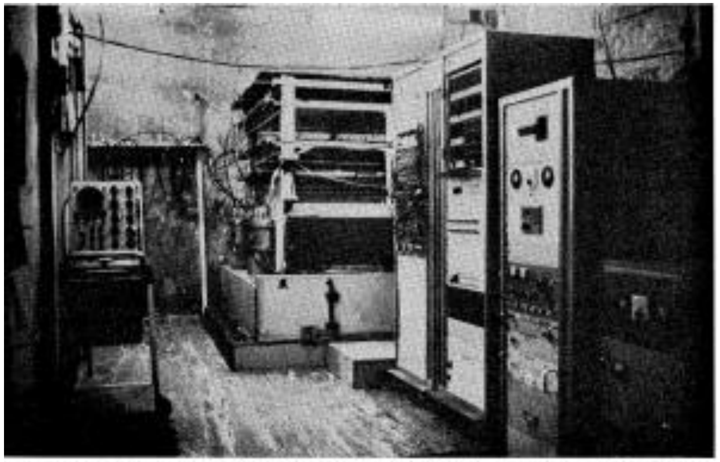
The first application of Muon Radiography



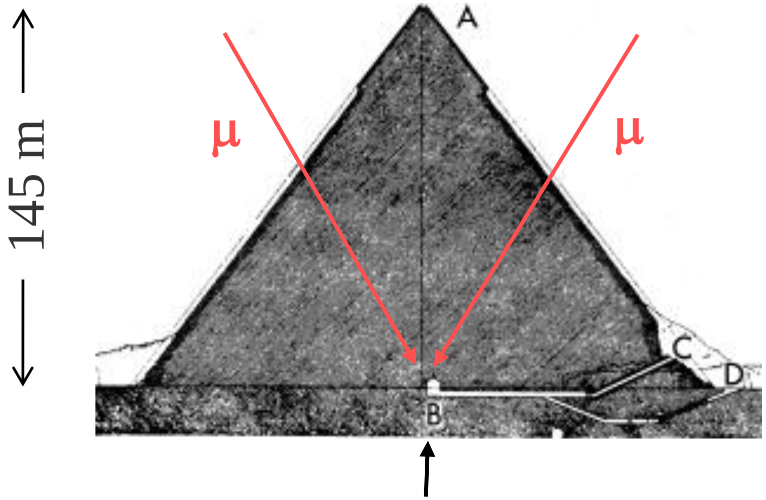
Search for hidden chambers in the Chephren's Pyramid

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

No hidden chamber in the pyramid

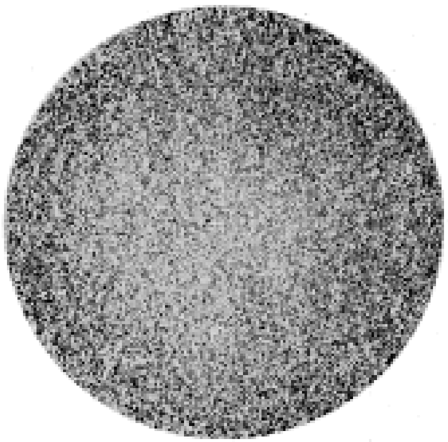


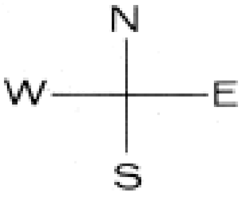
Spark chamber "muon telescope"



Telescope in Belzoni chamber

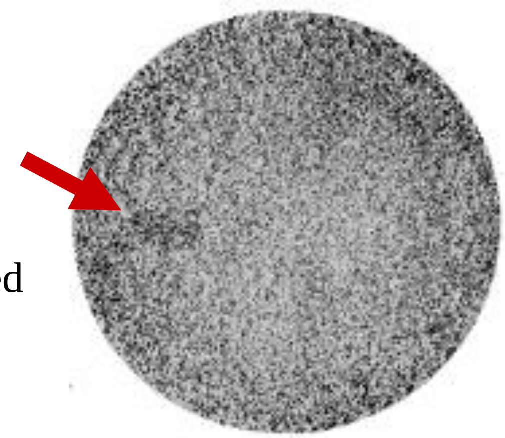
Data



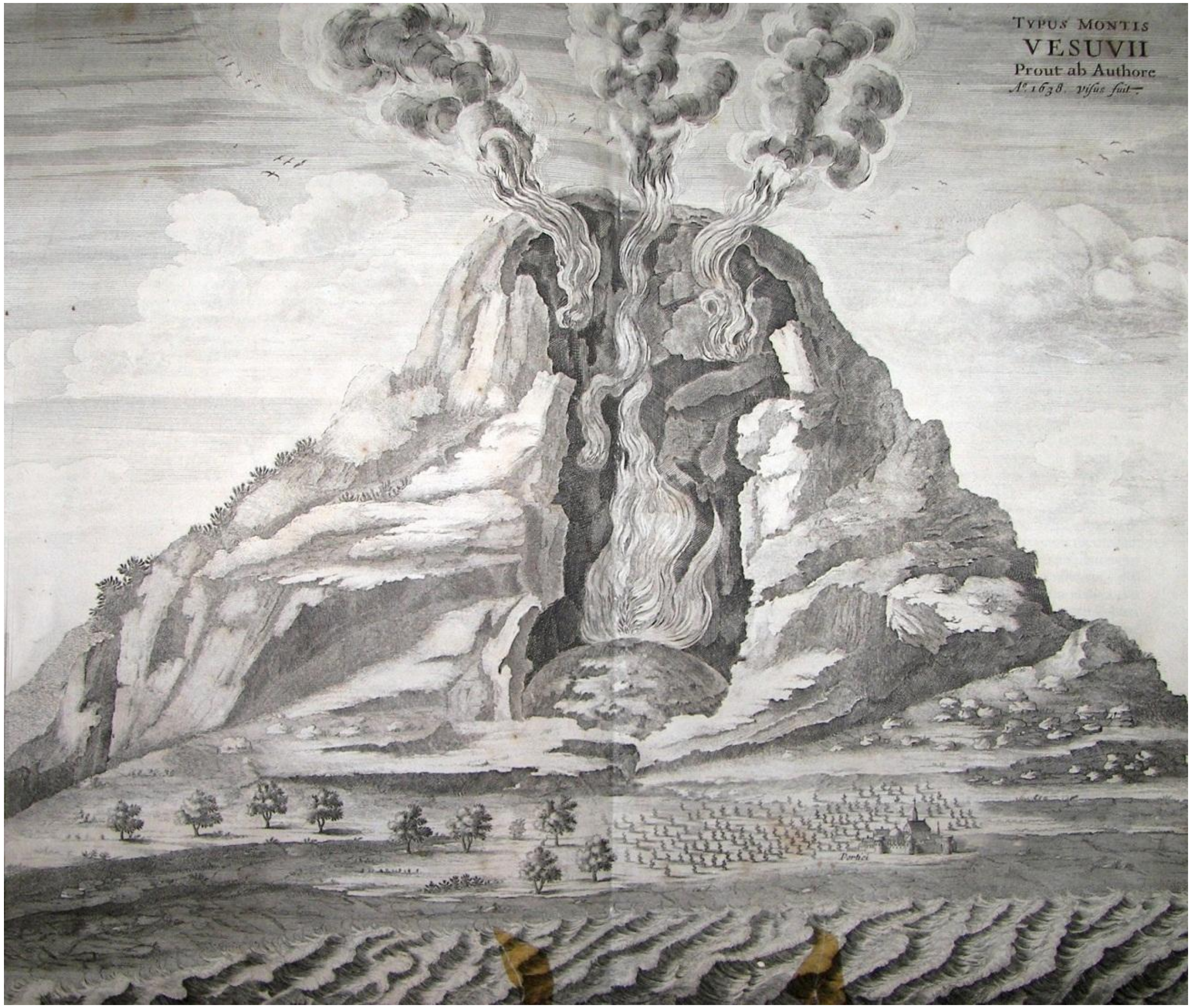


Data and simulation are corrected for pyramid structure and telescope acceptance

Simulation with hidden chamber



An old question: what inside volcanoes?



Athanasius Kircher, Mt. Vesuvius (1638)

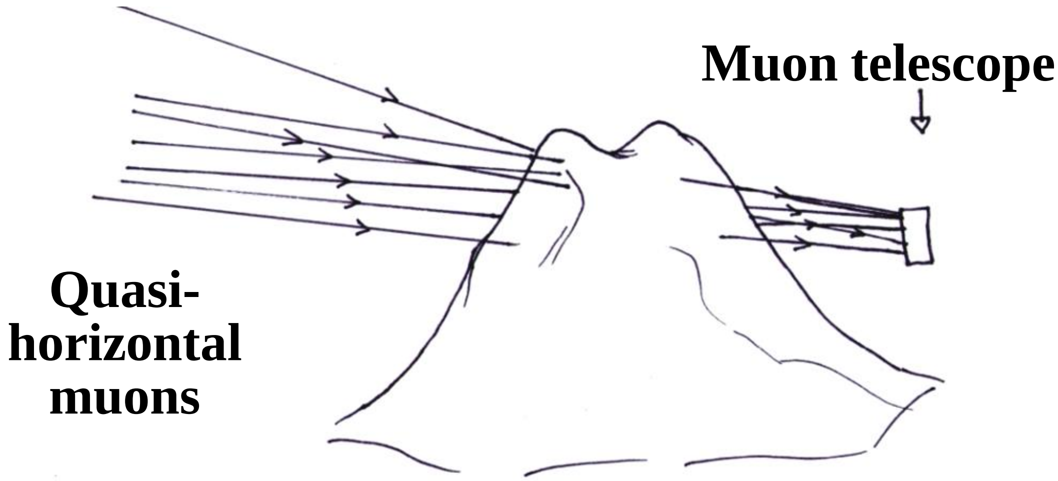
Hypothesis that volcanoes are connected to the center of the Earth

An old question: what inside volcanoes?

Athanasius Kircher, Mt. Vesuvius (1638)

Hypothesis that volcanoes are connected to the center of the Earth

Muon radiography of volcanoes



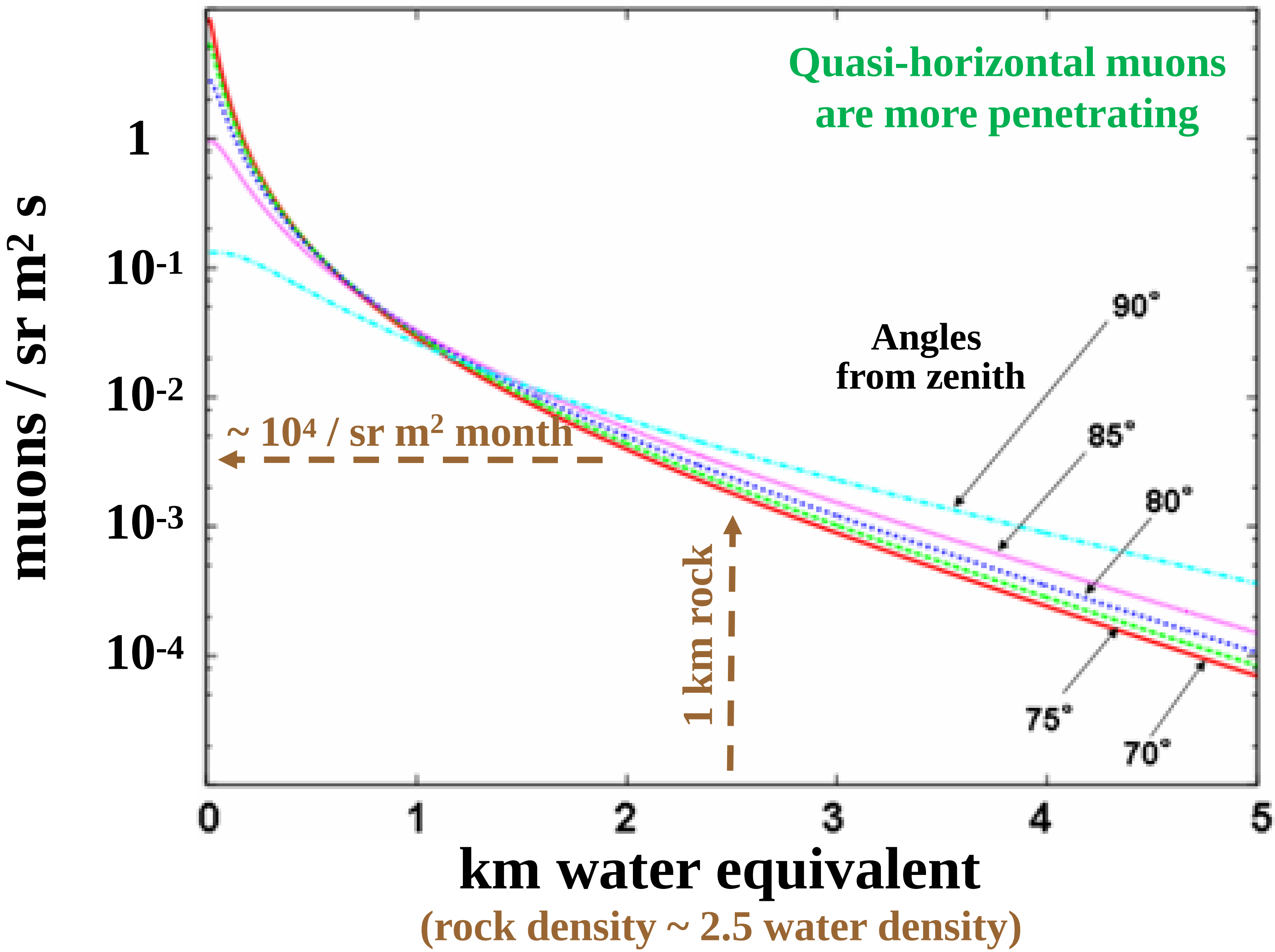
- *Reconstruct <u>muon trajectories</u> by a "muon telescope"*
- *Measure the muon flux <u>absorption</u> as a function of the muon direction*
- *……*
- *Draw a map (in projective geometry) of the <u>average rock density</u>*

Limited to the <u>upper part</u> of the volcano

Can help computer models in predicting "<u>how</u>" an eruption could develop

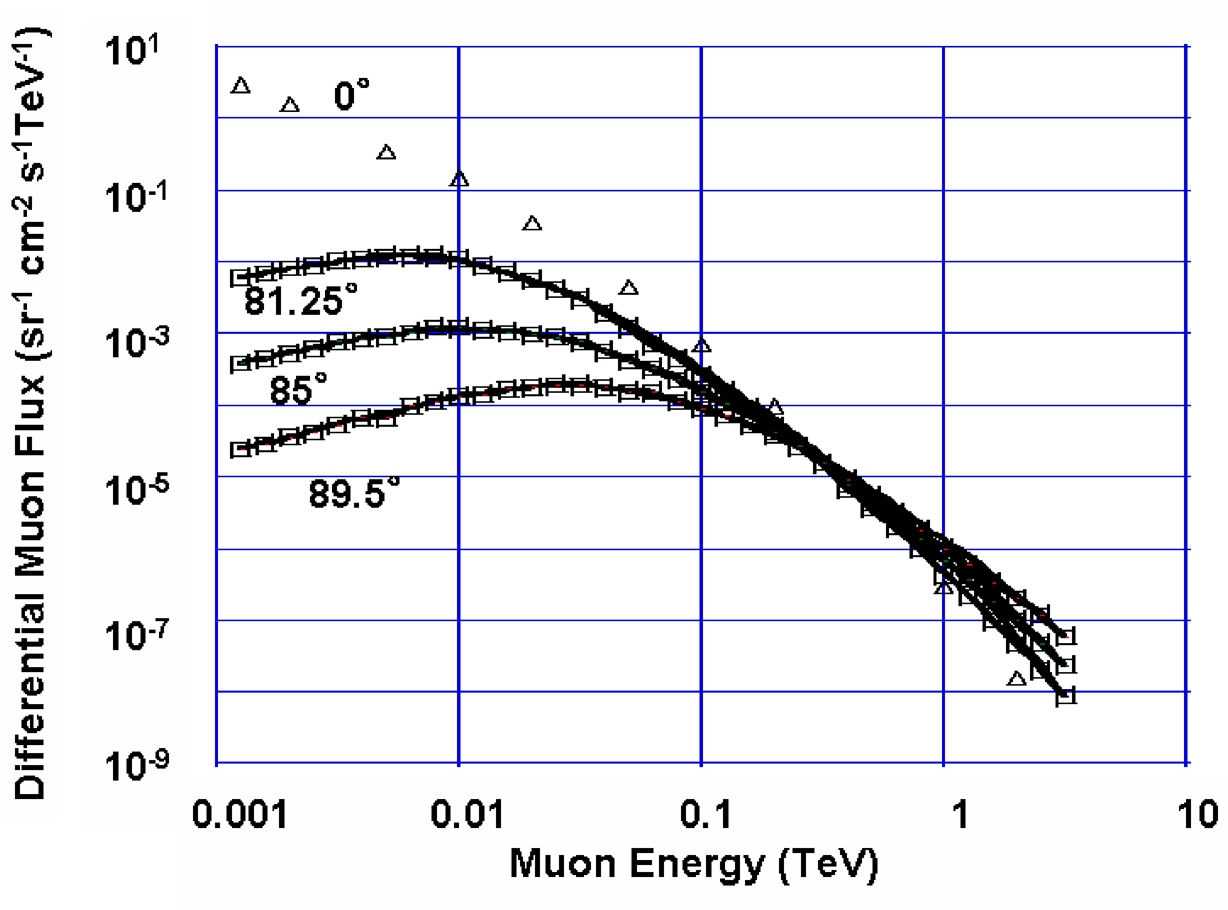
Nothing on "<u>when</u>" it may happen

How large and penetrating is the muon flux?



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

Harder spectrum for quasi-horizontal muons

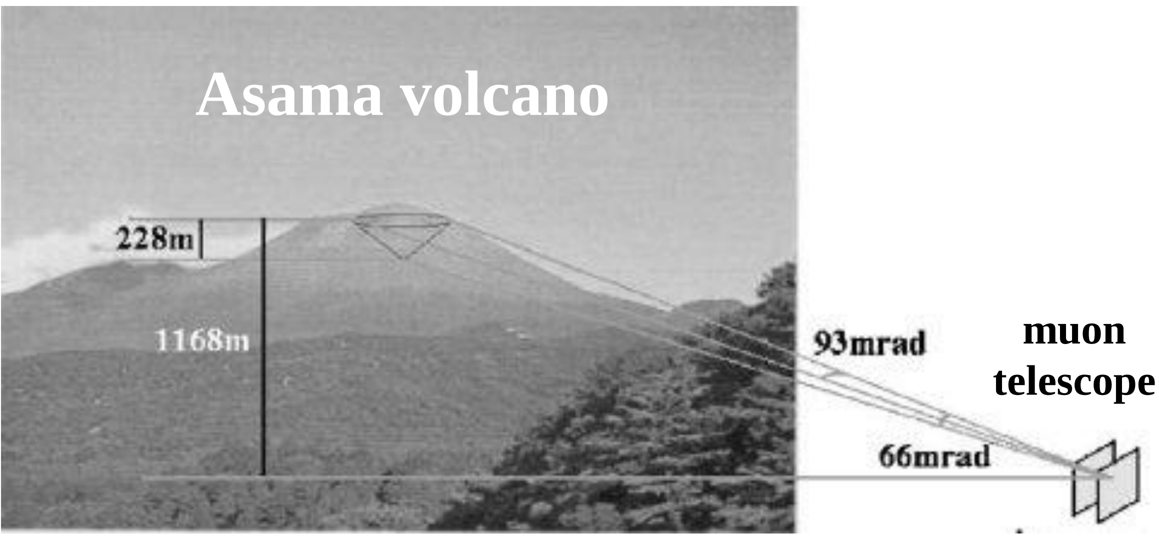


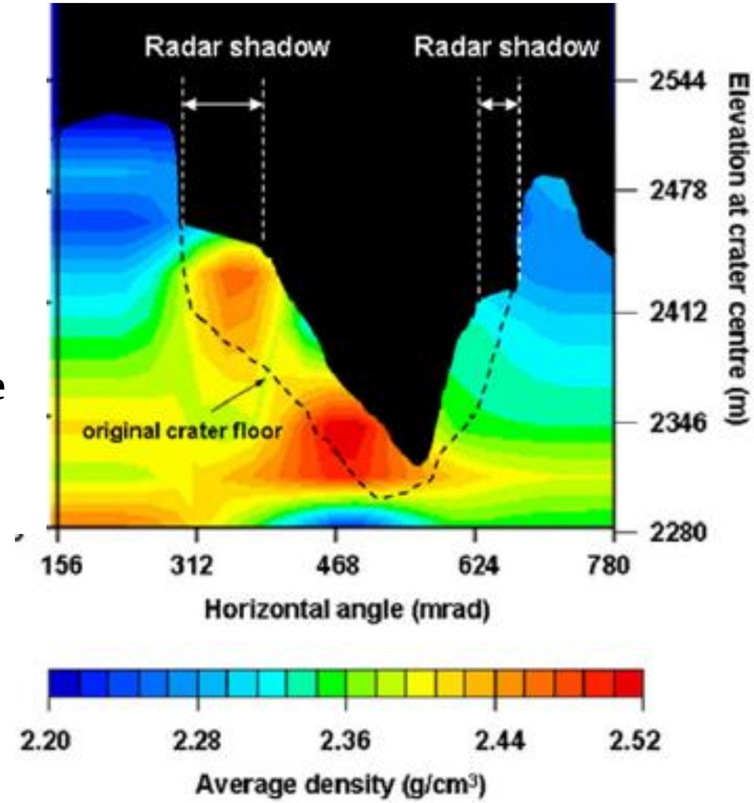
Quasi-horizontal high energy pions have time to decay

(always thanks to Lorentz time-dilation)

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

Pioneering radiographies in Japan since 2003





An "imaging" technique

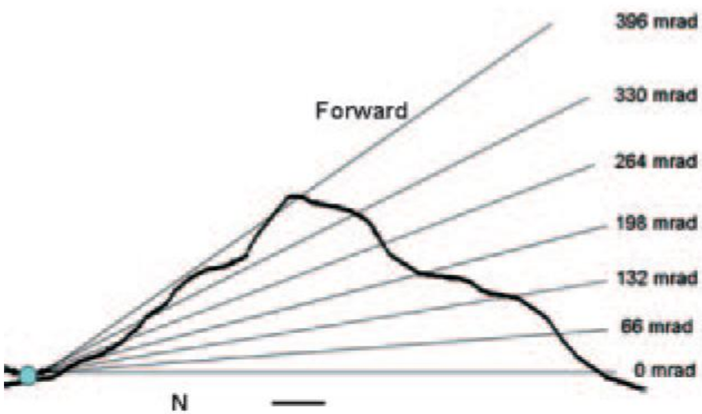
Resolution (tens of meters) unattainable with conventional "indirect" techniques
(gravimetric, seismic, …)

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

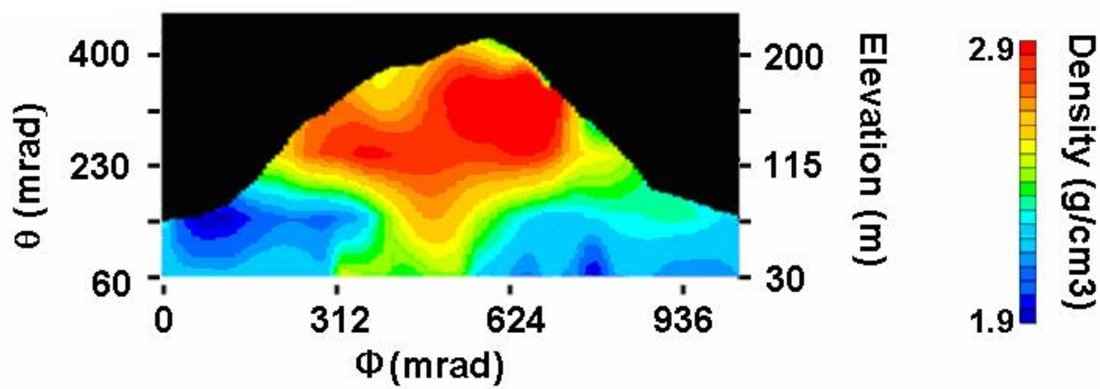
Below it, one sees (blue) a region with lower density

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

How light and muons see the Usu lava dome

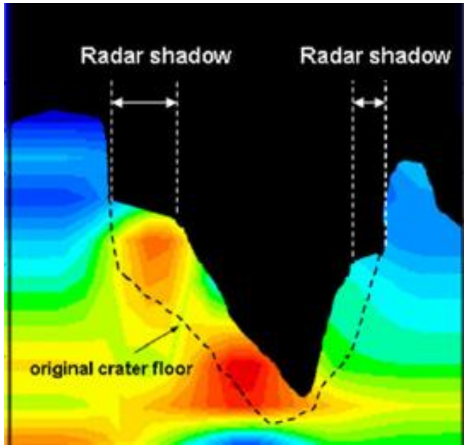


100 m



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

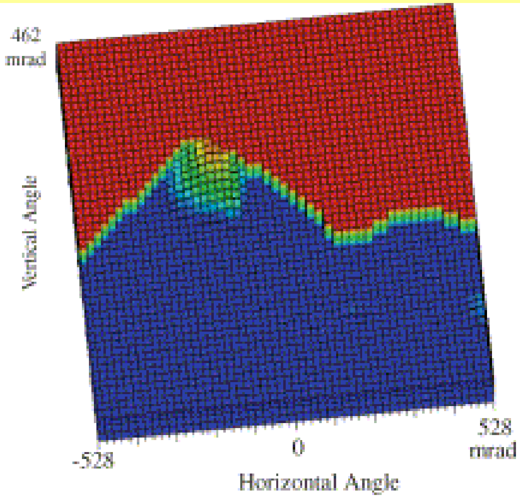
Experimental techniques



Mt. Asama
H.T.M. Tanaka and coll.
Telescope area ~1 m^2

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
Area limited by scanning power

↓

Stromboli, Unzen lava dome

PLASTIC SCINTILLATORS

Analysis in real-time
Long exposures possible

Nuclear emulsion muon telescopes

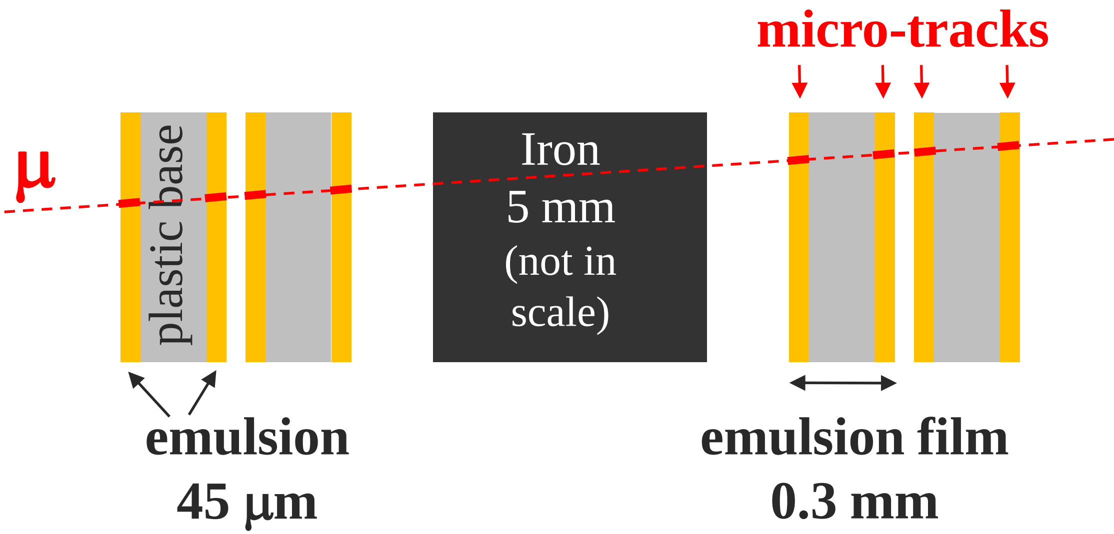
Longitudinal structure

4 emulsion films

1 iron plate

Very compact

Precise and redundant tracking (1 micro-track / em. film)

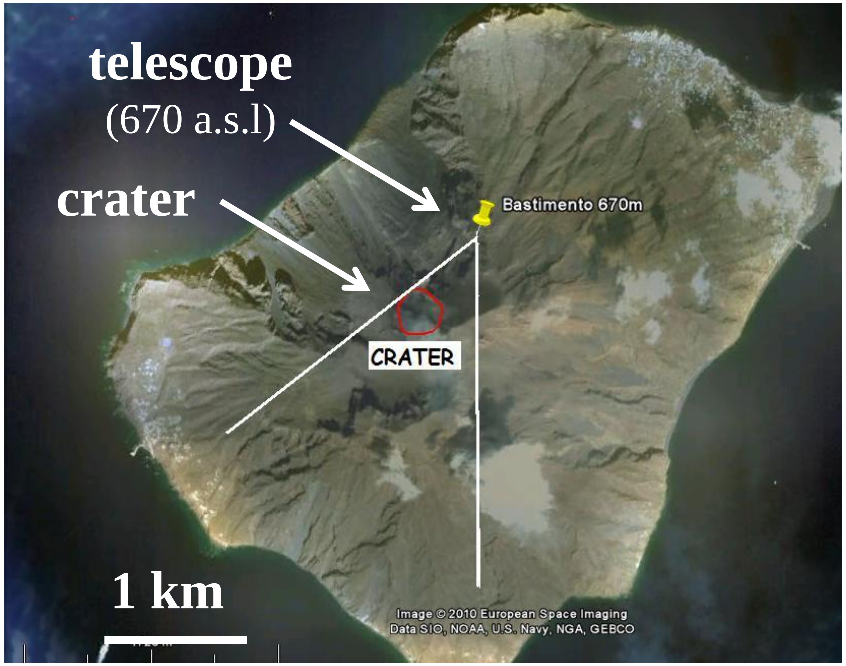


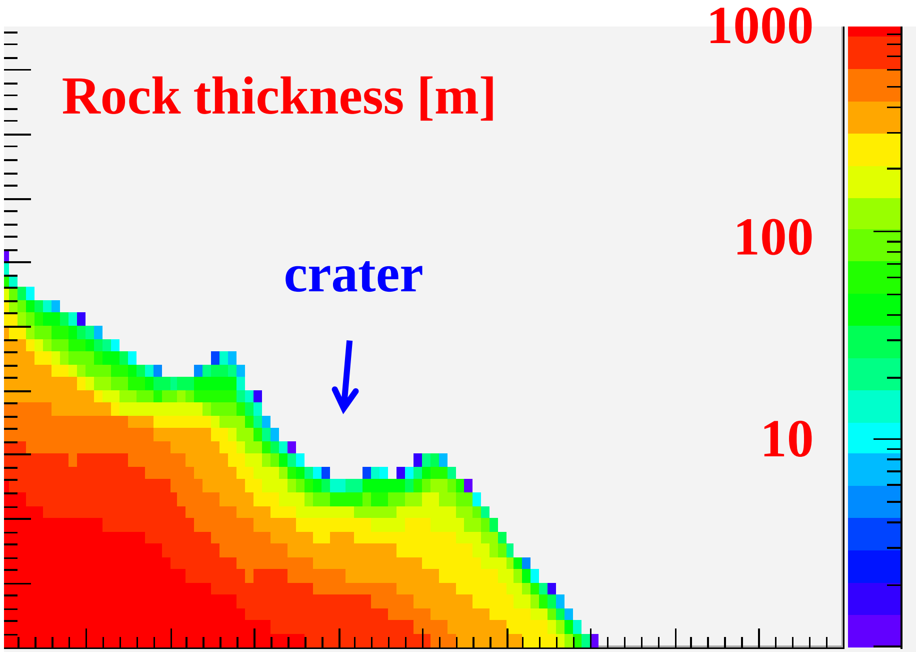
- **A 1 m² telescope taking data at Unzen lava dome**
- **A 1 m² telescope at Stromboli next winter**

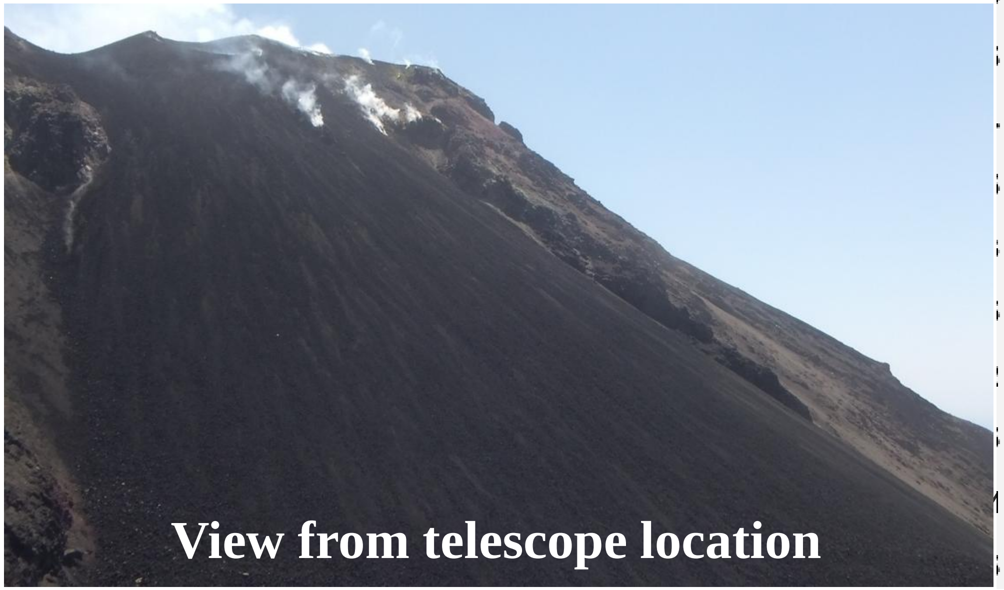
Stromboli

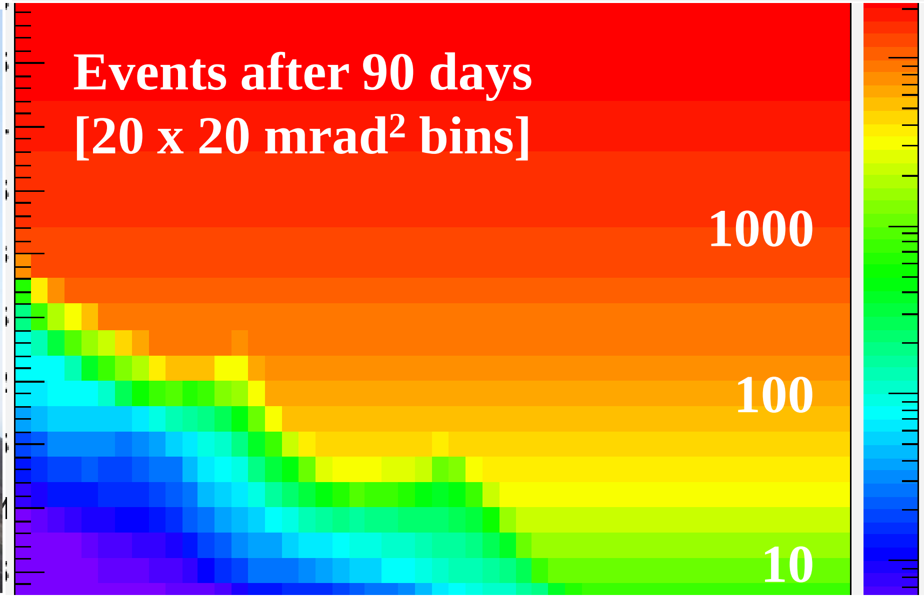
- **"Strombolian" activity**
  - essentially open conduit
  - intermittent eruptions due to increase in gas pressure
  - rare effusive activity
- **Summit at 926 m a.s.l.**
- **Crater at ~ 750 m a.s.l.**
- **Large scientific interest**

Expected at Stromboli





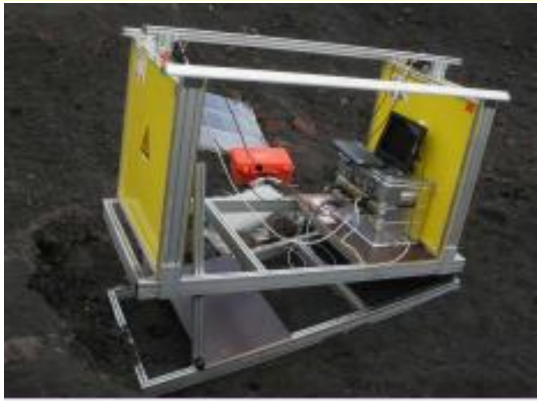




An expanding field

DIAPHANE project for volcanoes in the Lesser Antilles

- 5 cm wide plastic scintillator strips
- Multi-anode Photo-Multiplier Tubes
- 0.64 m^2 area
- Rock thickness < **<u>0.5 km</u>**
- 3 telescopes at La Soufrière (Guadeloupe) for 3D tomography

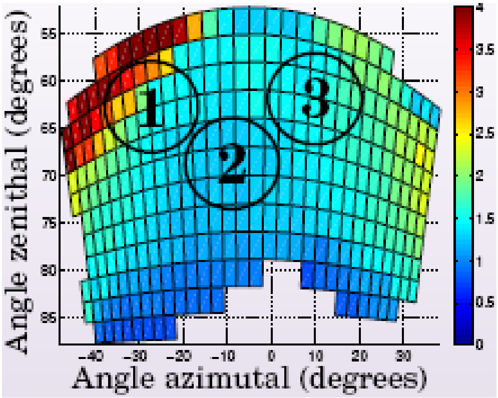


Studies of geological structures from underground locations

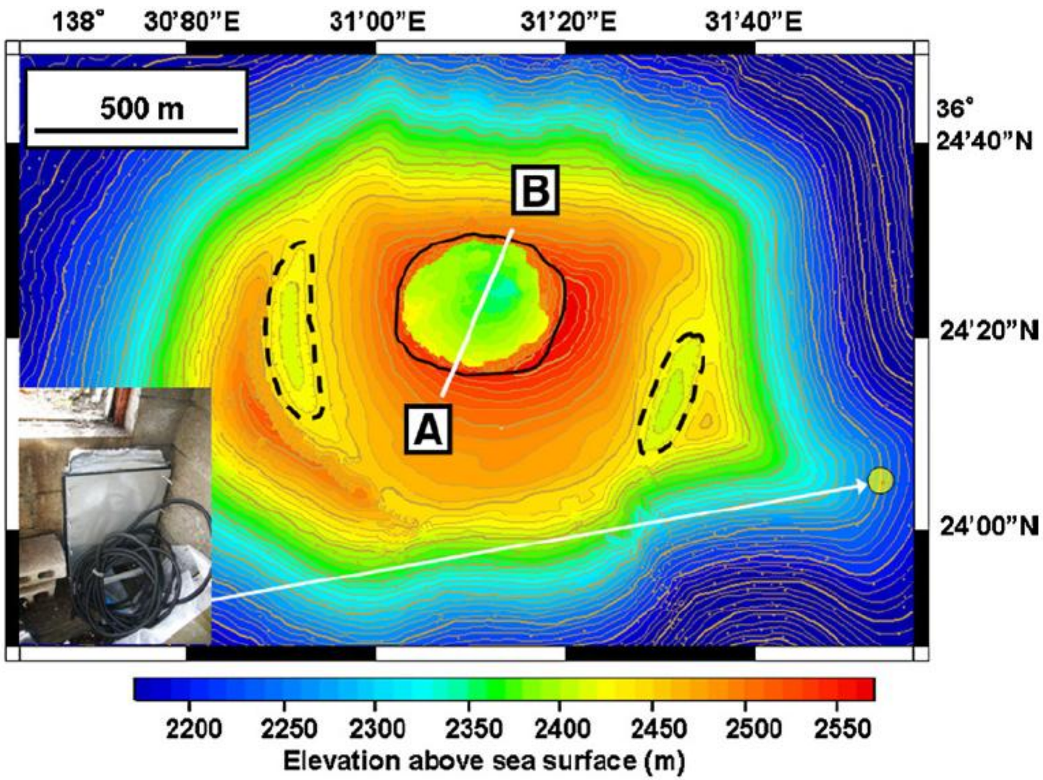
Archeology

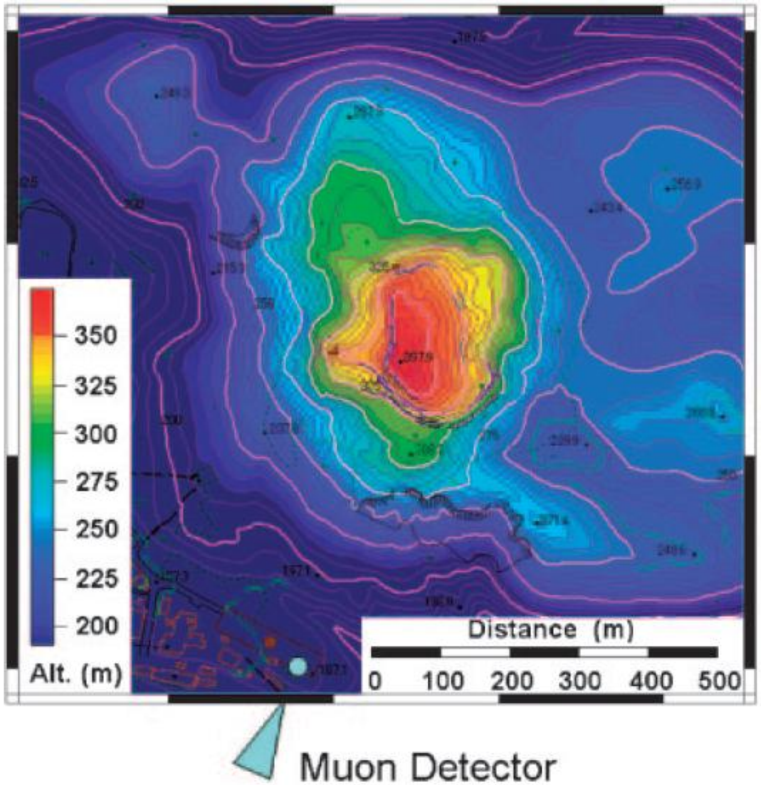
…..

Rock density [g/cm³]



Rock thickness





Mt. Asama

Usu lava dome

<u>So far < 1 km</u>

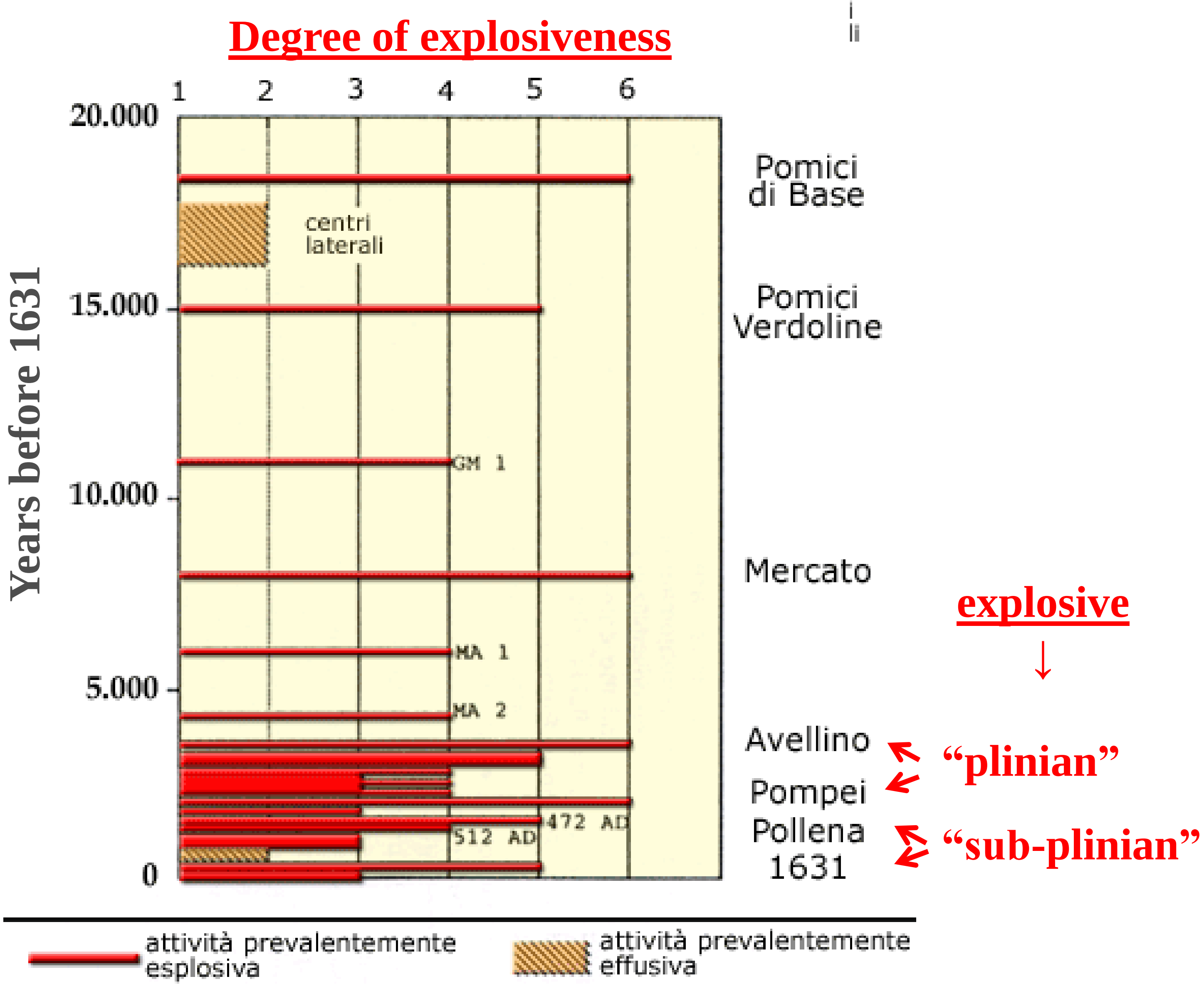
<u>**Improve sensitivity for larger rock thickness**</u>

(telescope area, data taking time <u>and</u> background rejection)


Mt. Vesuvius

The most violent eruptions

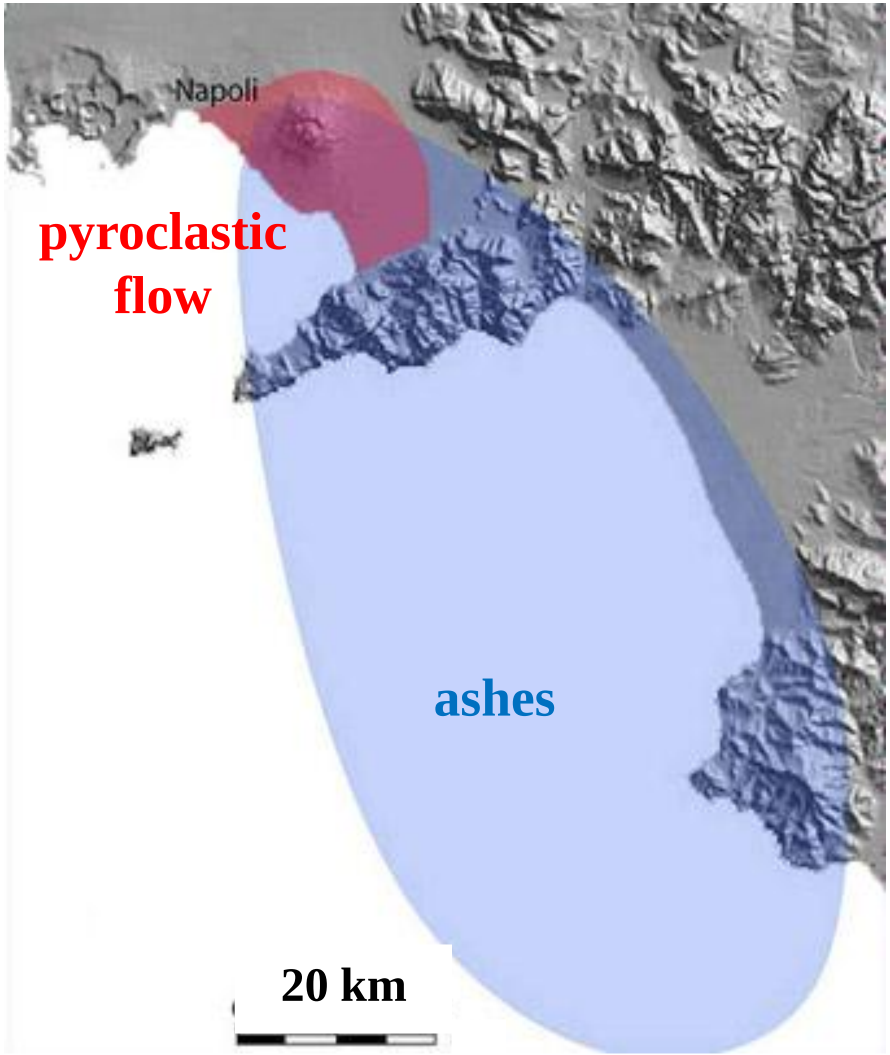
(from website of the Vesuvian Observatory: www.ov.ingv.it)



The A.D. 79 plinian eruption

A vast area covered by pyroclastic flow

Destruction of the towns Pompeii, Herculaneum and Stabiae



from www.ov.ingv.it

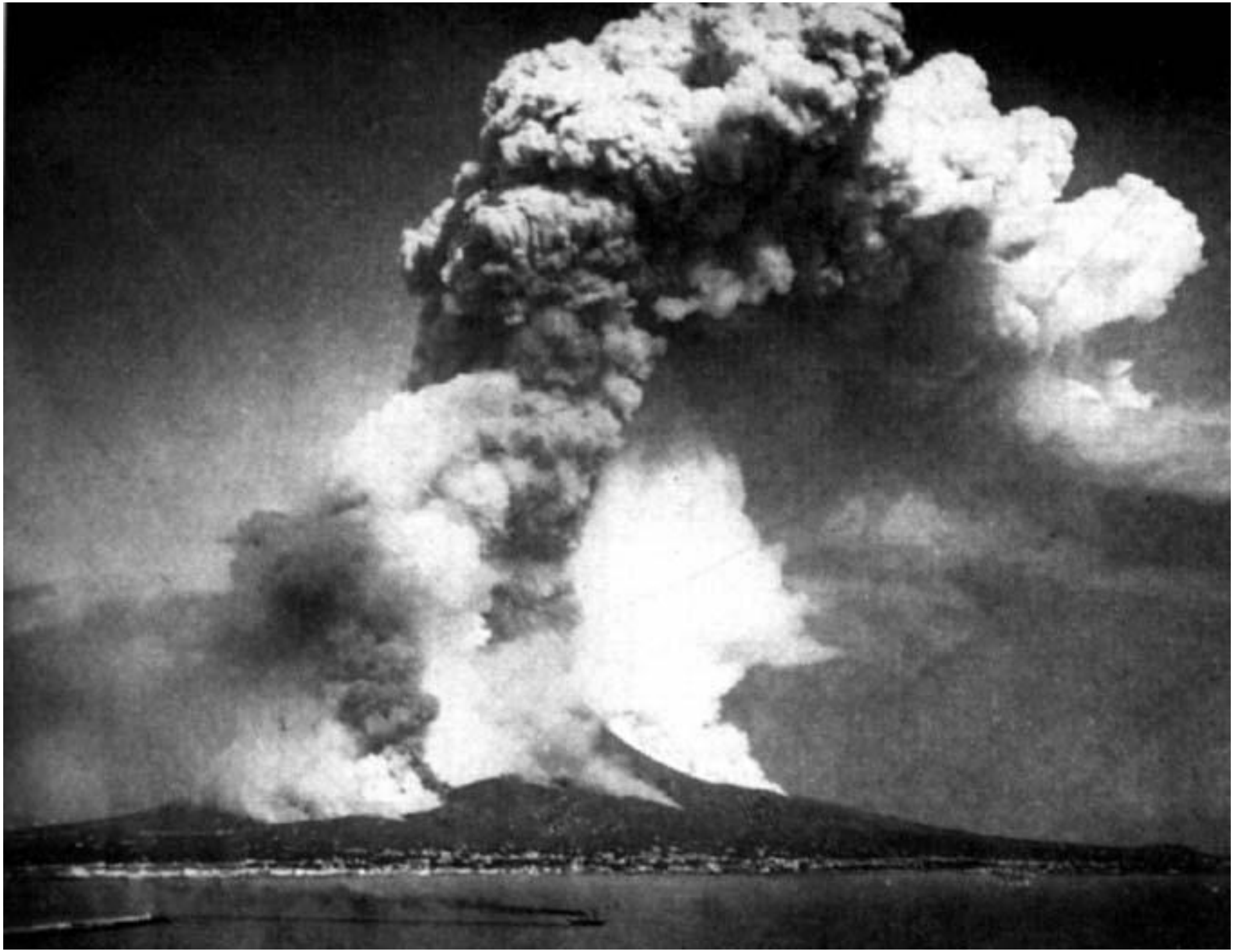
Read!

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

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

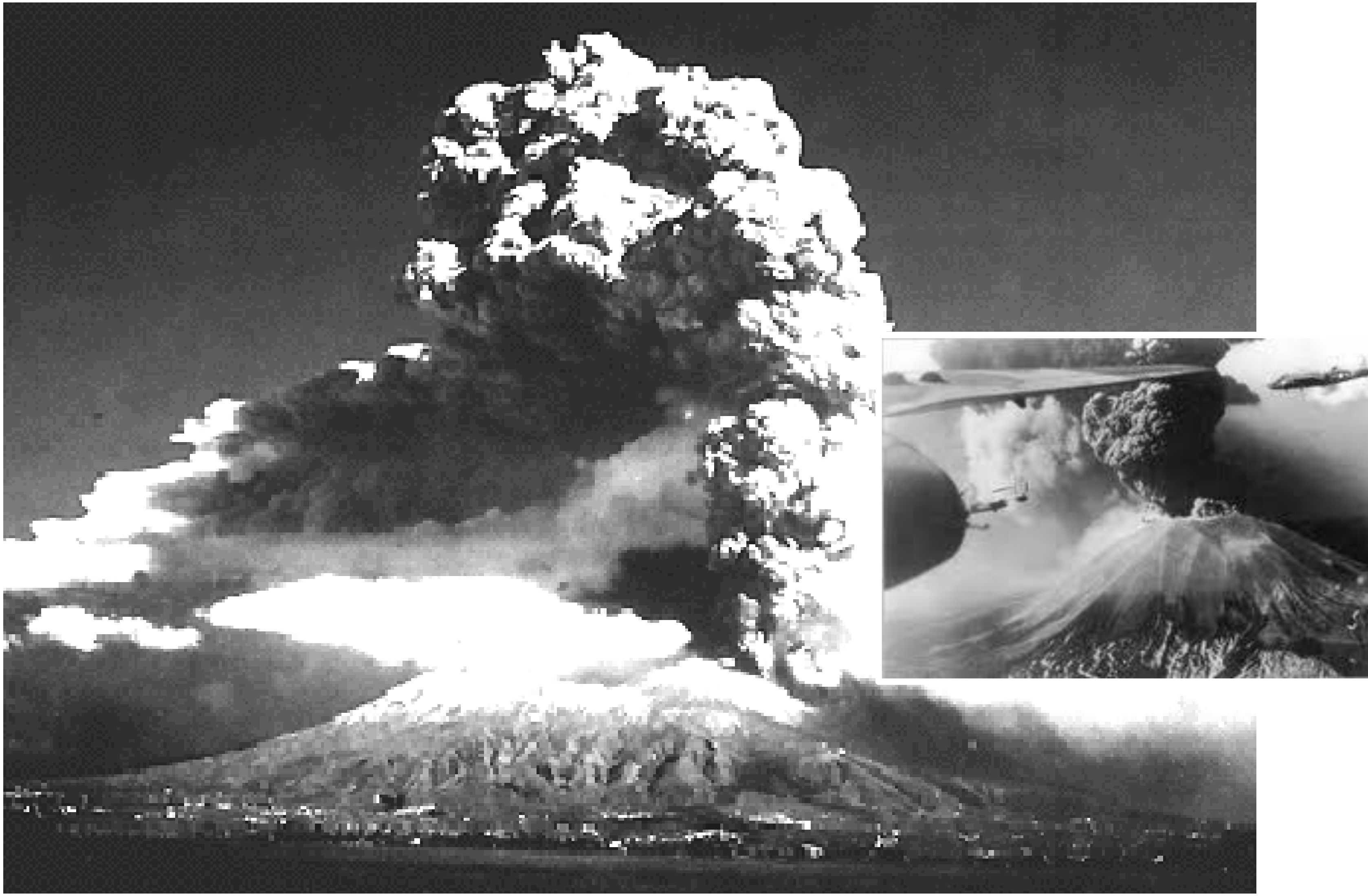
Una preghiera

Emeroteca-Biblioteca Tucci

“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 in 1944



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

Stored energy?

1631-1944

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

After the “terminal” 1944 eruption

- Transition to a state with closed conduit
- A quiescence period lasting since 67 years

Today’s Vesuvius looks “unusual”

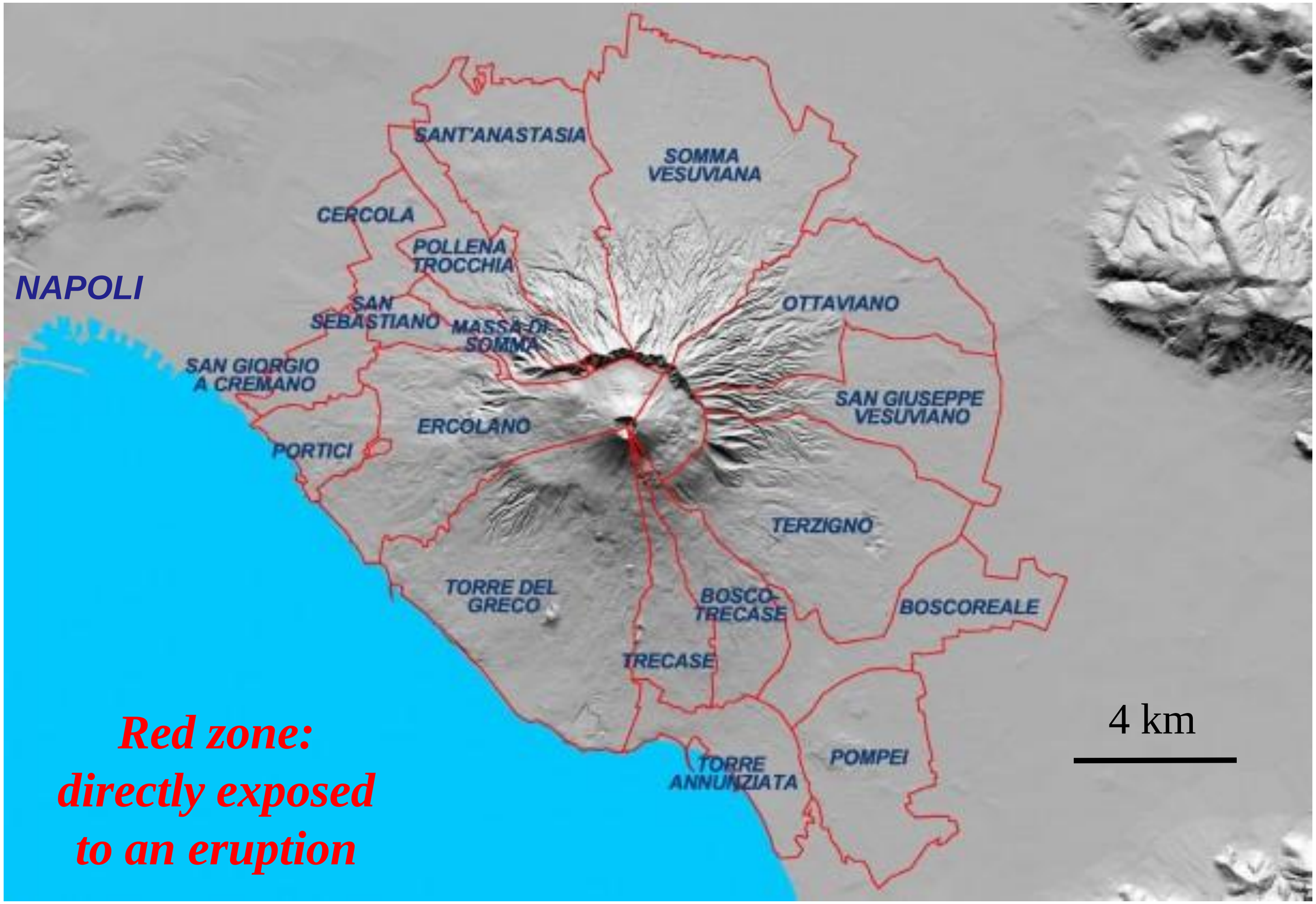
?

A (now quiescent) explosive volcano !

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

A dense population

The highest volcanic risk in Europe



About 600,000 people live in the "red zone"

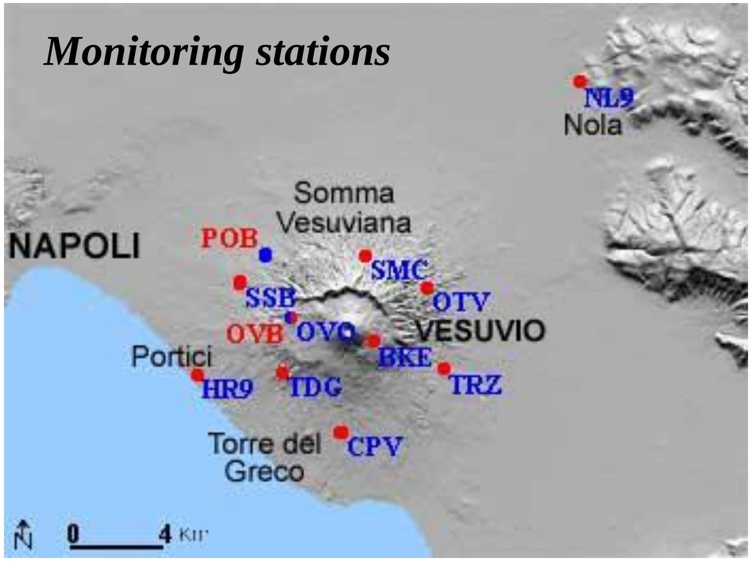
Monitoring Mt. Vesuvius

Continuous monitoring

- Monitoring stations:
  - seismicity
  - soil deformation
  - emission of gas from soil
  - fumaroles
- Data radio-transmitted to Vesuvian Obs.
- Online data analysis
  (under supervision by experts)

Periodic measurements

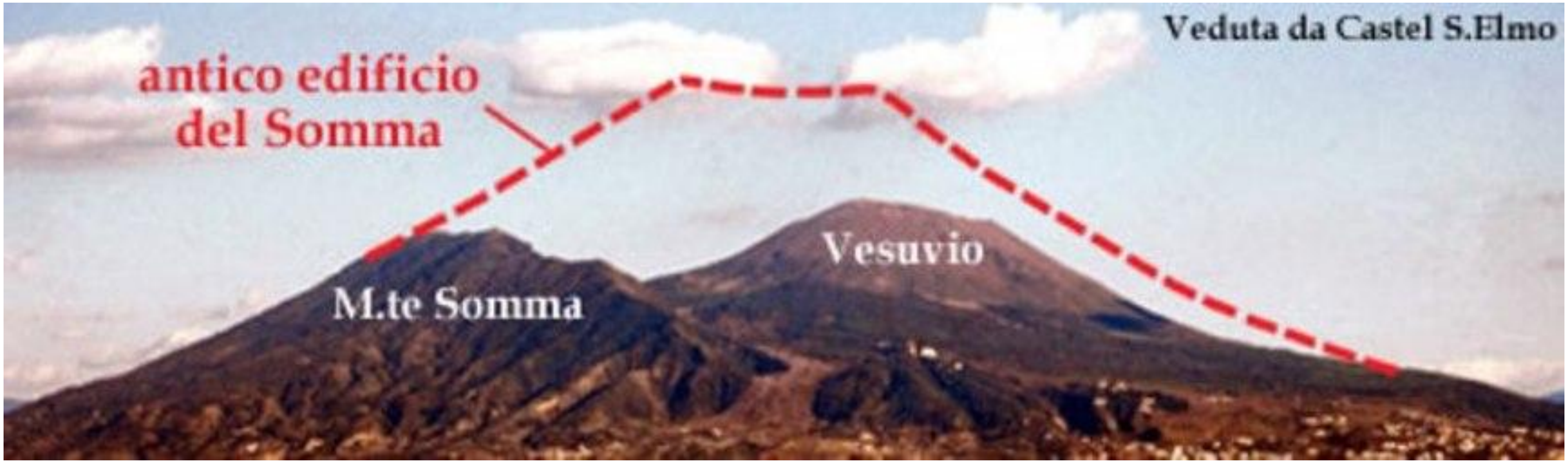
of geophysical and geochemical parameters



Monitoring room at Vesuvian Observatory

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 (now Mt. Somma)
- A secondary cone (Colle Umberto) “born” in 1898



Mt. Vesuvius today

Before Pompeii's eruption: "a mountain" ?

Dionysus and Mt. Somma (presumably) before the AD 79 eruption

Fresco from Casa del Centenario, Pompeii

Now at Naples Archaeological Museum

Morphological evolution 1630-1944

(website Vesuvian Observatory www.ov.ingv.it)

Morphology and muon radiography

Severe difficulties

- **Large rock thickness (to see below the 330 m deep caldera)**
- **Shadow of Mt. Somma and of Colle Umberto**

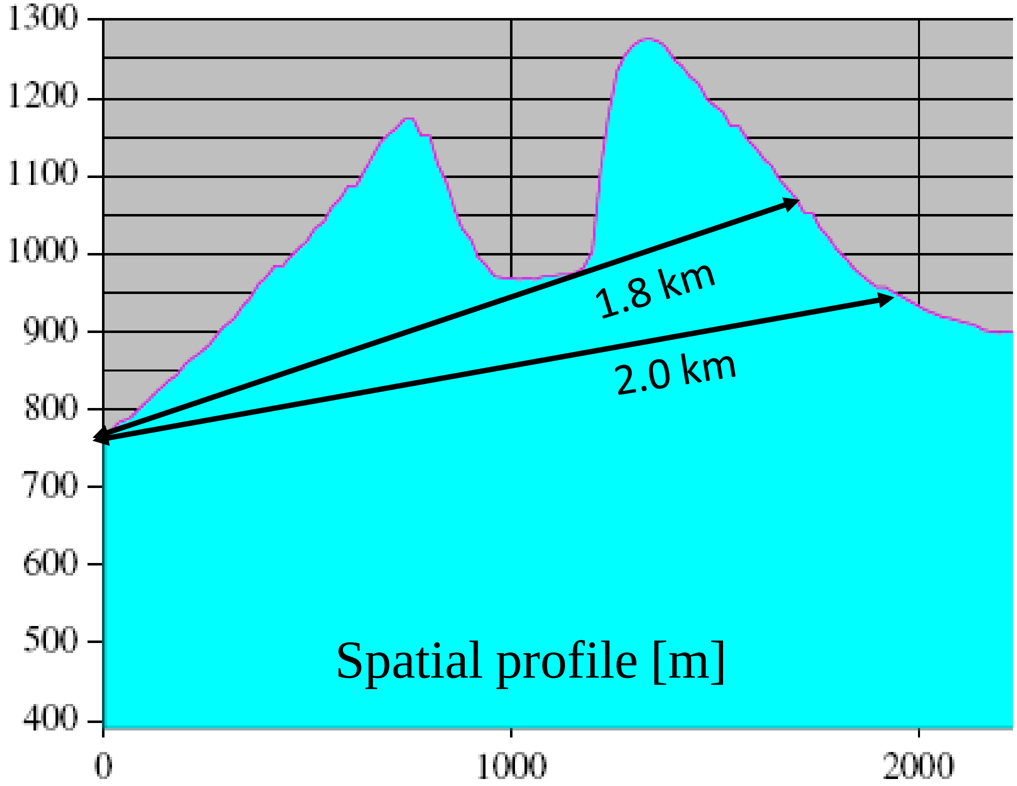
⬇

Muon radiography of Mt. Vesuvius is a "challenge"

Strong motivation

A measurement of the average rock density would already be useful

Rock thickness at Mt. Vesuvius



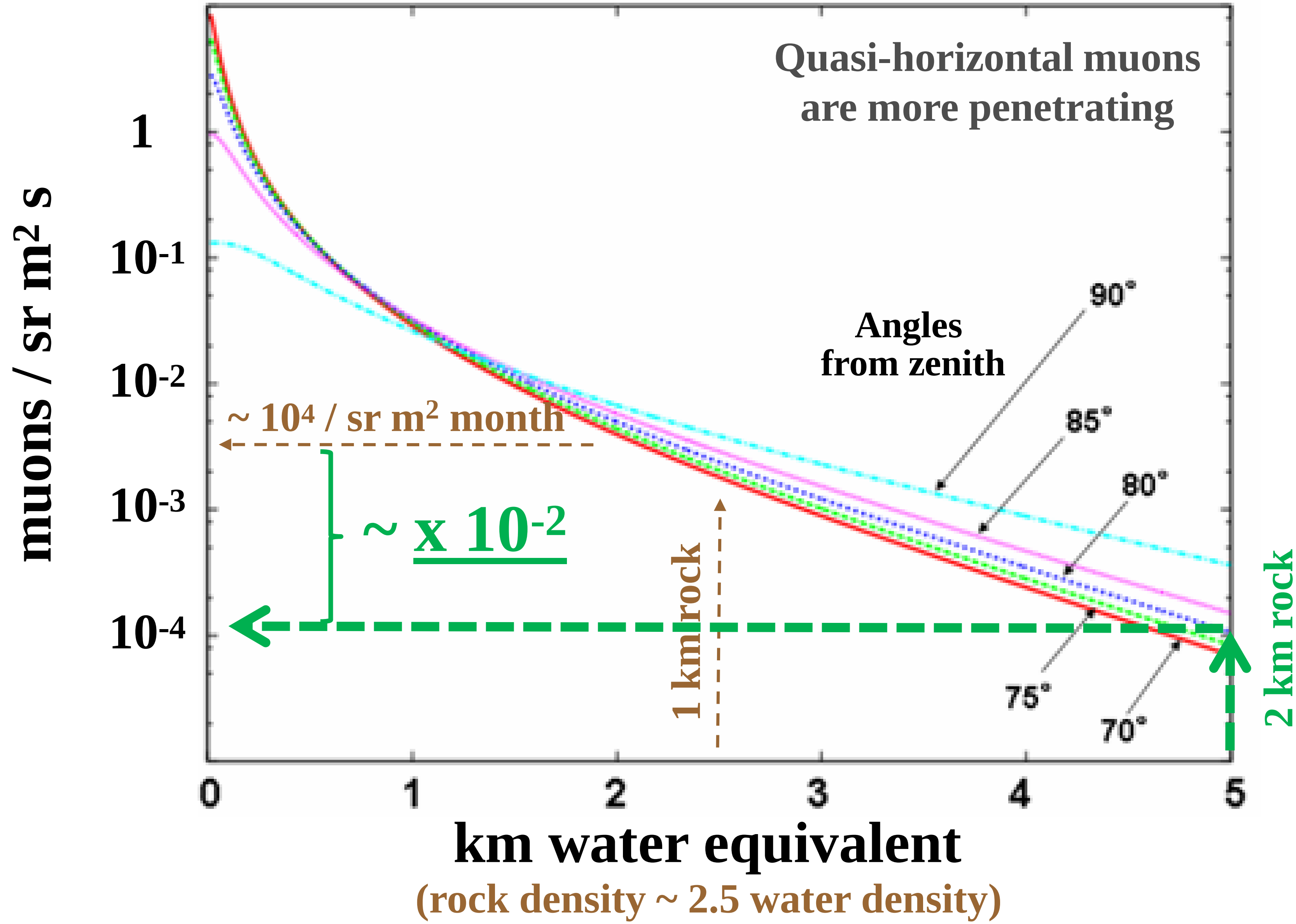
~ 2 km rock from a telescope at 750 m a.s.l.

↓

<u>Improve sensitivity</u>

with respect to previous radiographies (< 1 km rock)

Improve the sensitivity: by how much?

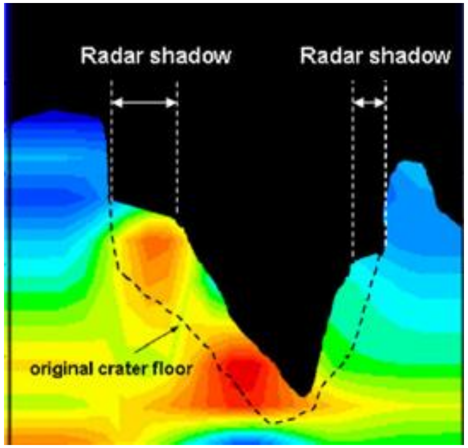


Plot from HTM Tanaka et al., EPS 62 (2010) 119

How to improve the sensitivity x 10^{-2}

- **Area: 1 → 10 m² or more** (modular structure)
- **Data taking: a few months → a few years**
- **Improve background rejection**

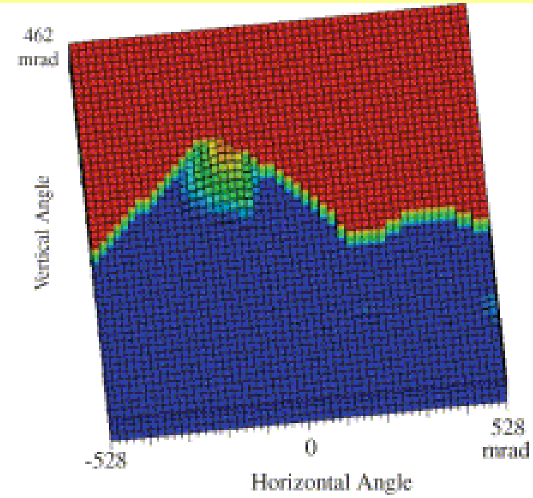
Experimental techniques



Mt. Asama
H.T.M. Tanaka and coll.
Telescope area ~1 m^2

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
Area limited by scanning power

↓

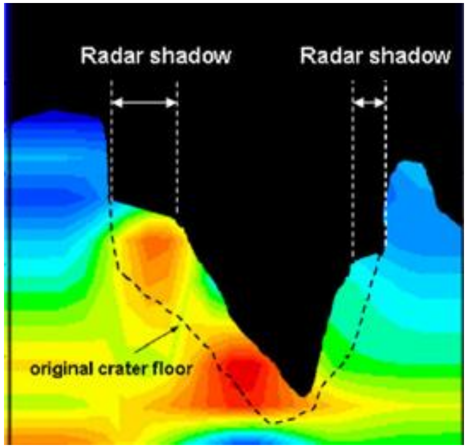
Stromboli, Unzen lava dome

PLASTIC SCINTILLATORS

Analysis in real-time
Long exposures possible

↓

Experimental techniques
(complementary)



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Stromboli, Unzen lava dome

PLASTIC SCINTILLATORS

Analysis in real-time
Long exposures possible

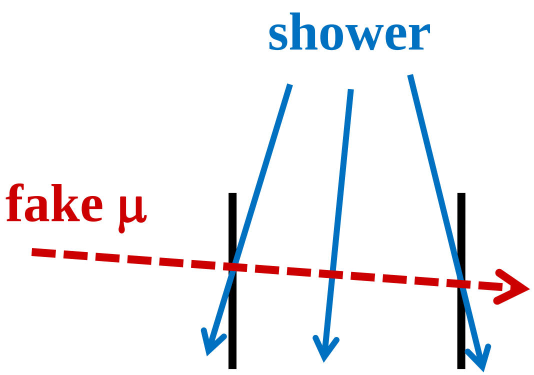
↓

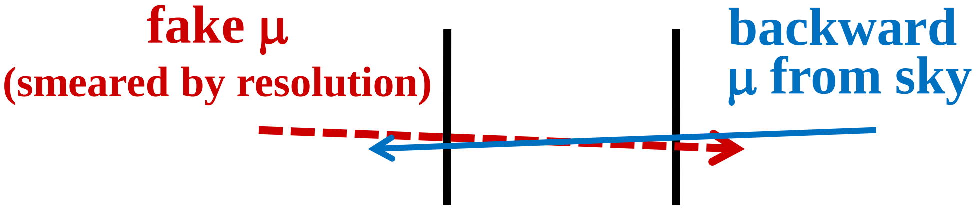
MU-RAY Project
Large areas (~10 m^2)
Improved background rejection
Resolution ~ 10 mrad

↓

Mt. Vesuvius (Stromboli)

Backgrounds





….. ?

MU-RAY tools for background direction

- **Precise and redundant tracking**
  (also improves the resolution)

- **Muon direction discrimination (forward-backward) : time of flight**

- **Event-by-event detailed analysis:**
  hit multiplicities, pulse heights, …

A telescope previously used in Japan

is taking data at Mt. Vesuvius (at 750 m a.s.l.) since 2009

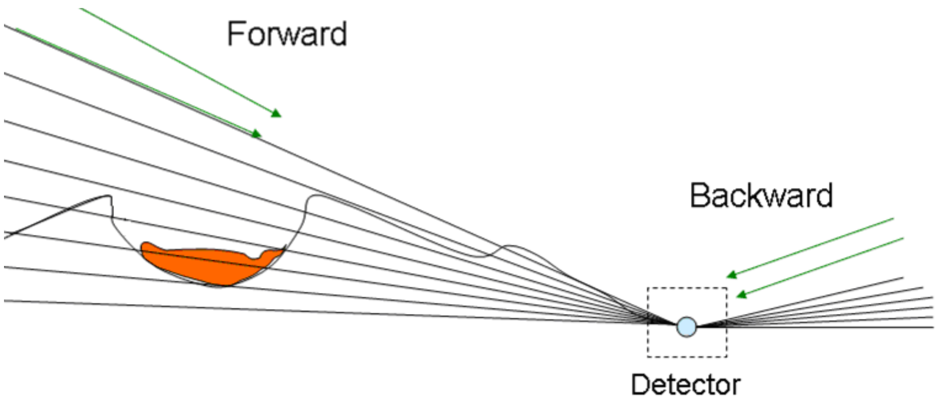
- Two x-y measuring stations
- 1 m^2 area
- 8 cm wide plastic scintillator strips
- Hardware filling of a counter coincidence matrix (no info on single events)
- Hardware multiplicity cut (1 hit/plane) to reject fake muons from showers
- No forward-backward discrimination

- **Practice with experimental methods (e.g. muon flux normalization)**
- **Support to MU-RAY choices:**
  - → **tools for background rejection**
  - → **better resolution**
- **Infrastructure ready for prototype MU-RAY telescope**

Methods for muon flux normalization

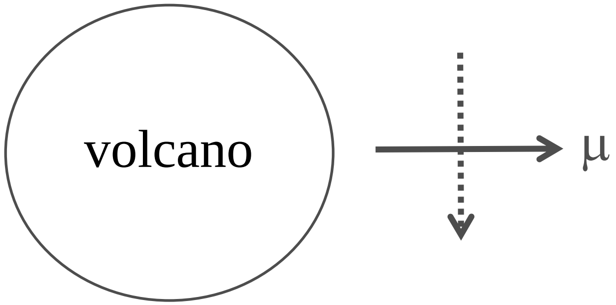
“Backward” method

- Muons from sky on opposite side
- In parallel with data taking
- Used in previous radiographies



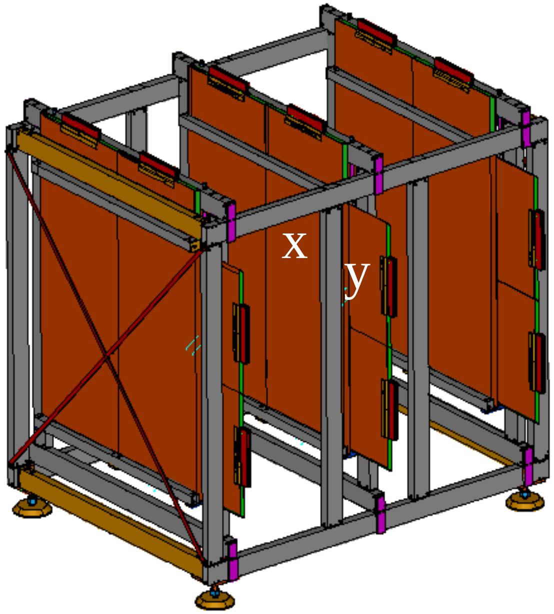
“90°” method

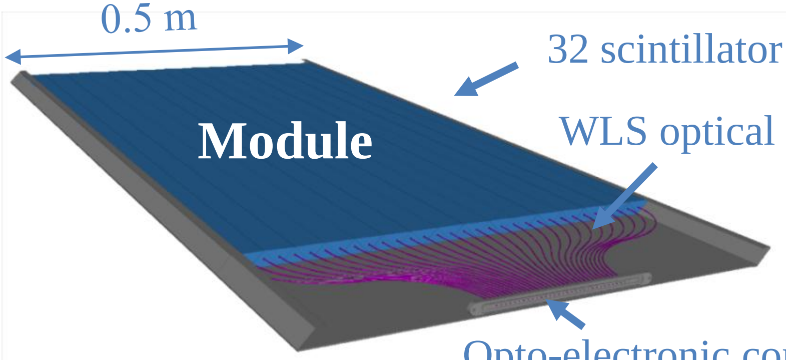
- Muons from sky at 90°
- Special (short) runs with rotated telescope
- Same angles, same counter coincidences
- <u>Successfully tried at Mt. Vesuvius</u>



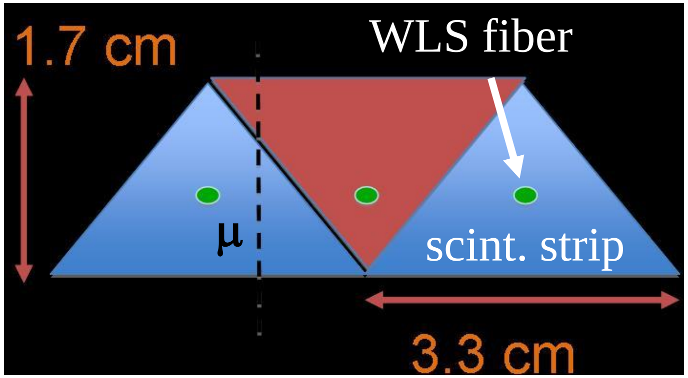
The MU-RAY muon telescope

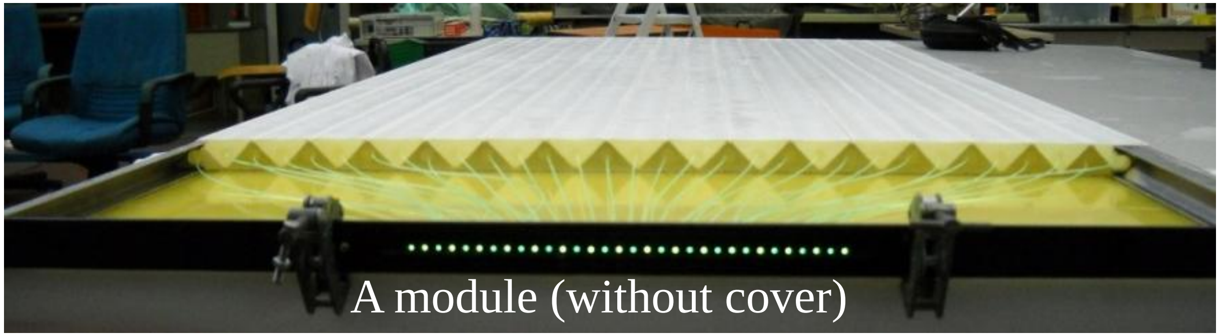
- Basic technique: strips of plastic scintillators
- **Precise and redundant tracking**
  3 x-y measuring stations
  ~ 5 mm space resolution
  ~ 10 mrad **angular resolution**
- 1-4 m^2 area for one telescope (1 m^2 for prototype)
- Modular construction
- **Event-by-event information** for offline analysis
  → time of flight
  for muon direction discrimination
  → pulse height
  from each scintillator strip
  → hit multiplicities



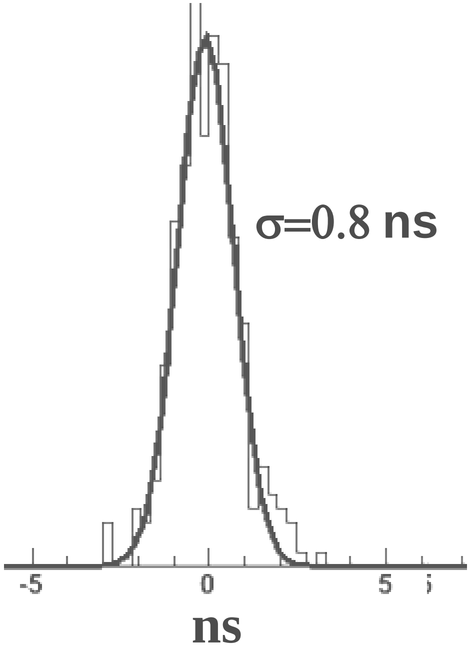


Scintillator strips and WLS fibers



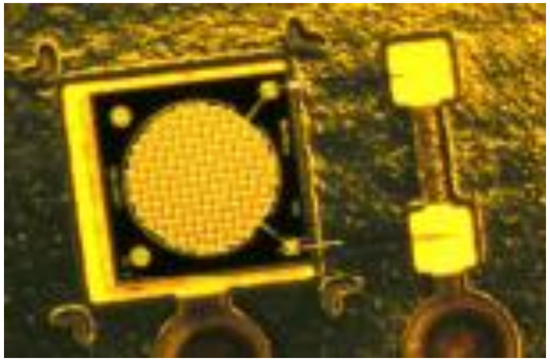


- Strips with triangular section (NICADD-Fermilab)
- ~ 5 mm **space resolution**
  by interpolating signals in adjacent strips
- Co-extruded hole for Wave Length Shifting (WLS) optical fibers
- **Fast re-emitting fibers** (Bicron BCF 92)
  for time of flight measurement within ~ 1 ns
- Fibers convey light to an opto-electronic connector
- 32 strips glued together to form a "module"



Time resolution

Silicon Photo-Multipliers (SiPM)



A naked SiPM wire bonded
(Φ = 1.4 mm, ~ 300 diodes)

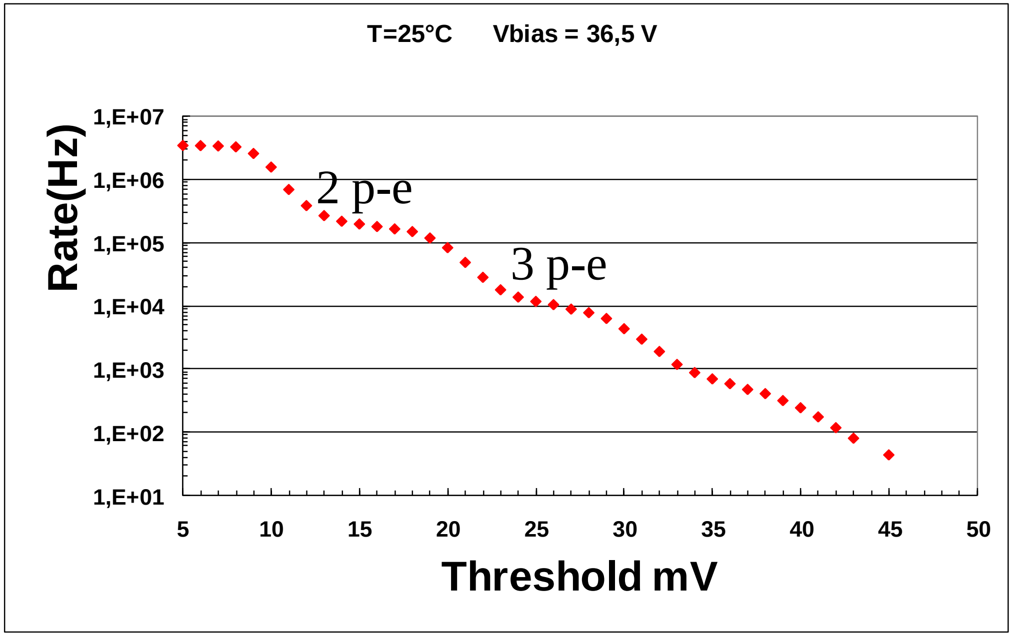
NEW TECHNOLOGY

MU-RAY:
"naked" SiPMs

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

- **Matrix of diodes in Geiger mode** (inverse polarization)
  Analog sum of the signals
  → **amplification ~ 10^6** (depending on V_{bias} and temperature)
  → **proportionality**
  → **photo-electron counting** (useful for gain monitoring and control)
- Photo-detection efficiency = quantum x geometric x Geiger ~ 50%
- Solid state device: **no HV and very low power consumption** (tens of µW)
  → applications where electricity supply is not available
  (muon radiography of volcanoes, physics in space, …)

Dark noise of SiPMs



Dark noise rate (FBK-IRST)

- **increasing with temperature (solid state device)**
- **decreasing with number of photo-electrons: ~10^{-1}/p-e**

→ Maintain temperature under control (<25°)

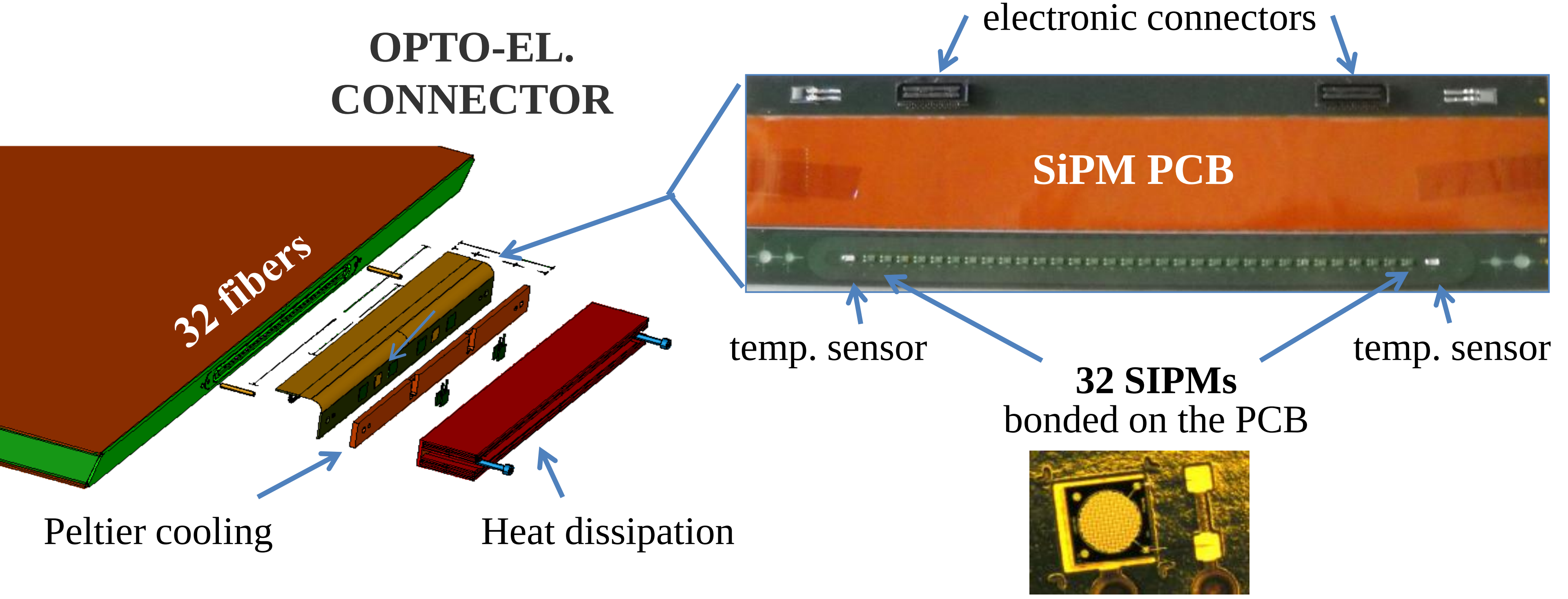
→ Set threshold on number of photo-electrons

(and multiple coincidences, anyhow)

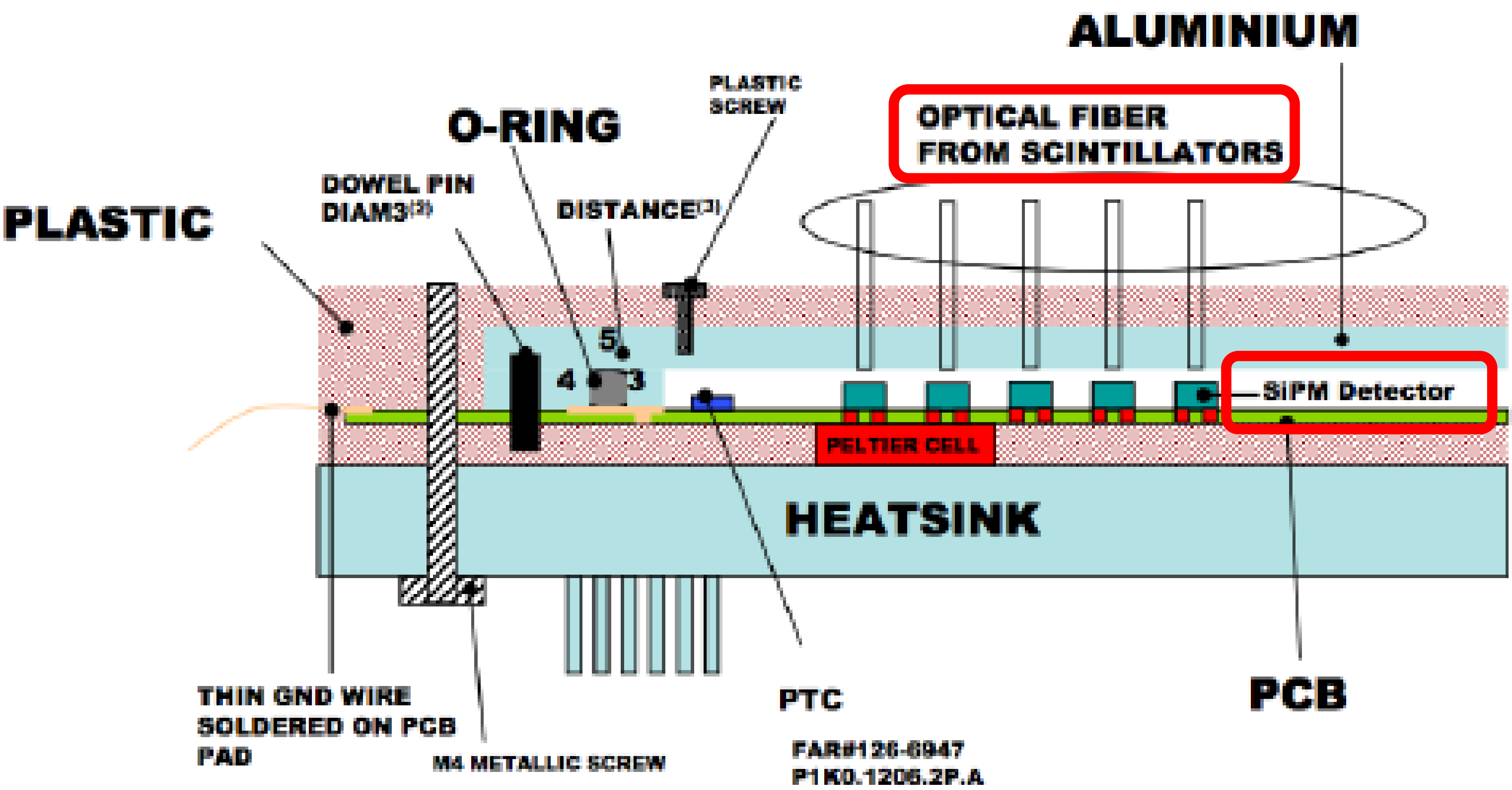
SiPM PCB and opto-electronic connector

- Naked SiPMs wire bonded on a custom designed **<u>Printed Circuit Board</u> (PCB)** thermally isolated from the environment : cool only the SiPMs (Peltier)

- PCB mounted on the **<u>opto-electronic connector</u>** **:** fibers and corresponding SiPMs are relatively positioned within <100 µm



Detail of the opto-electronic connector



The front-end electronics

Based on the
Application-Specific Integrated Circuit (ASIC)

SPIROC

(developed by the Omega group at LAL-Orsay)

SPIROC1 (designed for collider experiments) at present

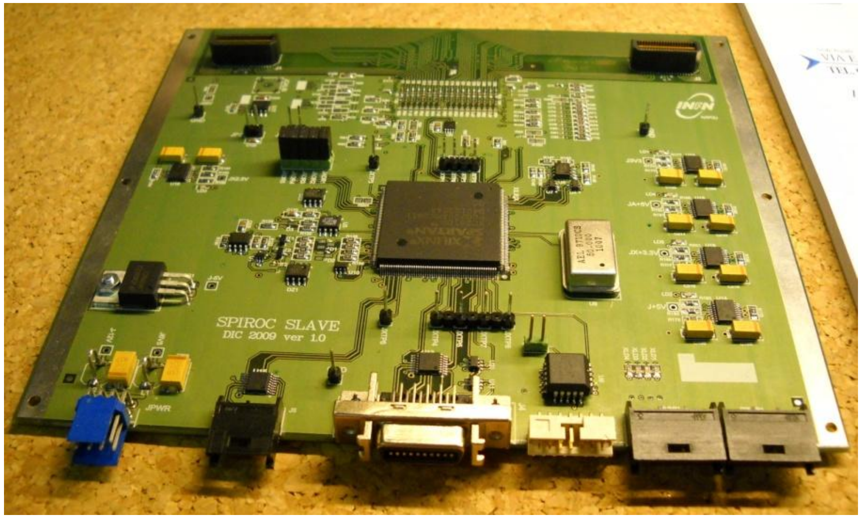
- Up to 36 channels (SiPMs) management
- Independent V_{bias} fine setting for gain control of each SiPM
- Independent threshold setting fro each channel
- Variable gain for signal amplification
- Fast amplifier for time measurement
- Power consumption 20 μW/channel
- Multiplexed analog output
- External trigger

SPIROC-light (designed for experiments in space) in the future

The read-out and DAQ electronics

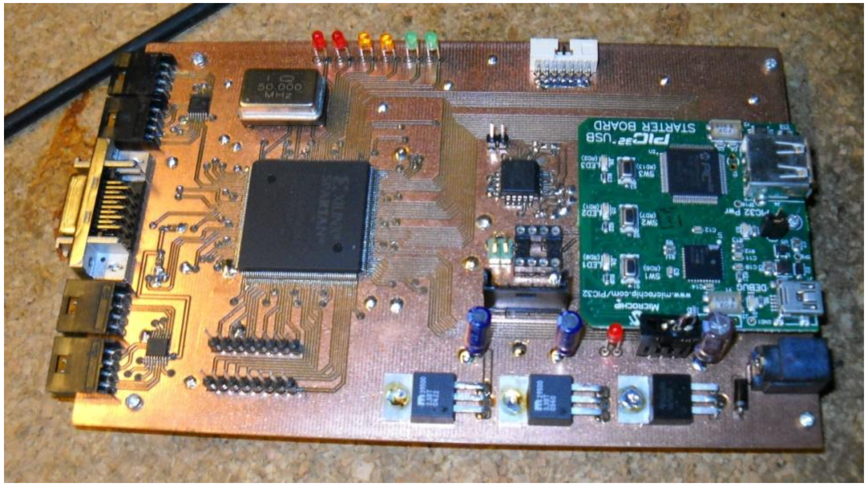
Slave Board (one/module)

- control of the SPIROC
- digitization of charge and time



Master Board (one/telescope)

- control of the Slave Boards
- communications with the SPIROCs
- trigger logic
- data readout from Slave Boards
- data transfer to the external world



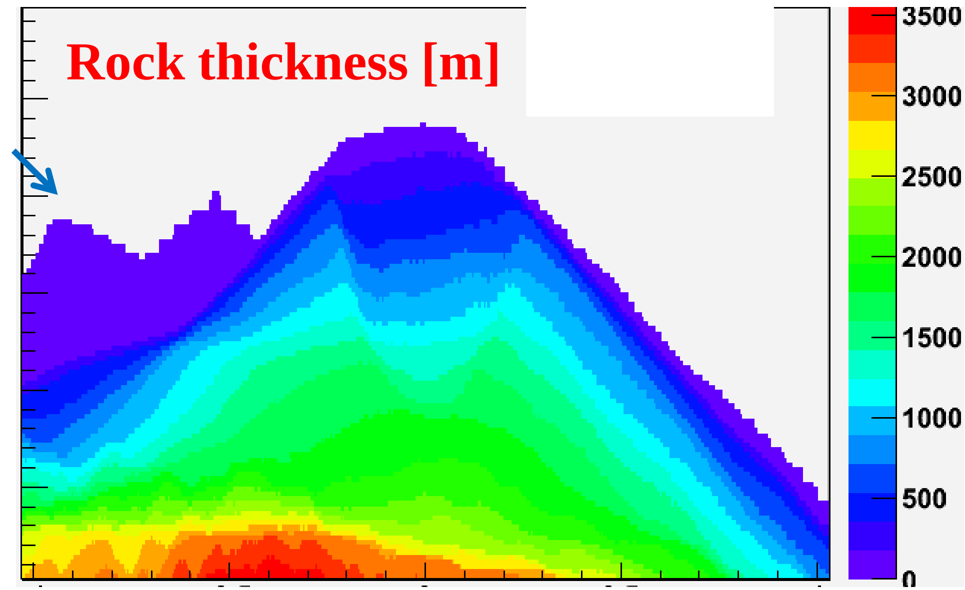
Master and Slave Boards designed by MU-RAY

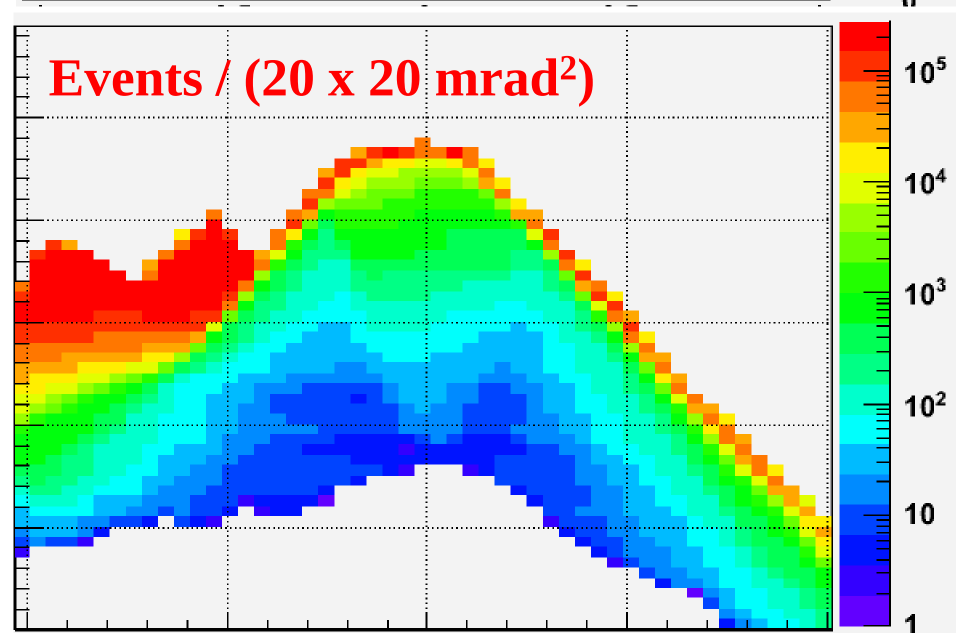
Status of the 1 m^2 prototype telescope

- ✓ Modules constructed
- ✓ SiPMs PCB and opto-electronic connectors ready
- ✓ SiPMs cooling in progress
- ✓ Electronics ready
- ✓ Telescope going to be assembled for tests in the lab
- ✓ ………..
- ✓ Infrastructure at Mt. Vesuvius ready
- ✓ Installation in a few months

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

Mt. Somma





Forthcoming first step in the "Mt. Vesuvius challenge"

Conclusions

- Beautiful results for rock thickness up to 1 km
- Mt. Vesuvius (and Stromboli) require a sensitivity x 10^{-2}: the MU-RAY challenge
- New technology: Silicon Photo-Multipliers
- A MU-RAY muon telescope prototype soon at Mt. Vesuvius
- A collaboration of physicists and volcanologists
- Know-how in particle physics for a research of public interest

Reserve slides

Where we are now

- ✓ Modules completely assembled
- ✓ SiPM PCBs ready
- ✓ Slave boards ready and tested
- ✓ Master prototype board ready and under test
- ✓ Temp. control prototype ready and under test
- ✓ Measurement set-up for modules characterization ready
- ✓ Mechanical support completed