

# Alliance to Penetrate Mysteries of the Deep Earth

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*Hiroyuki Tanaka (Univ. of Tokyo)*

International Workshop Muographers 2014, Tokyo



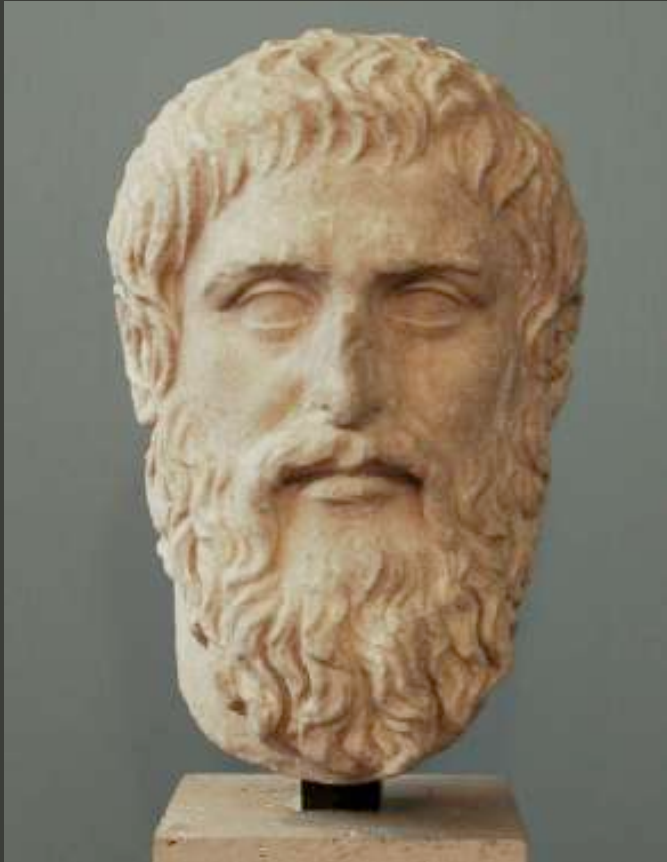
*A successful growth*

*Ginkgo Biloba "Kitakanegasawa no-ichou"*

[[http://www.monumentaltrees.com/en/jpn/tohoku/aomori/3146\\_kitakanegasawa/](http://www.monumentaltrees.com/en/jpn/tohoku/aomori/3146_kitakanegasawa/)]

***Fundamental issues  
have deep roots***

# Mythology of ancient Greece: “Pyriphlegethon”, a “fire-flaming” river in deep Earth



Plato, portrait by Silanion (ca. 370 BC)

Roman copy, Musei Capitolini, Rome

[<http://ancientrome.ru/art/artwork/img.htm?id=4204>]

Plato (ca. 425-348 BC)

“A stream of fire, which coils round the Earth and flows into the depths of Tartarus” (*Phaedo*, 112b)

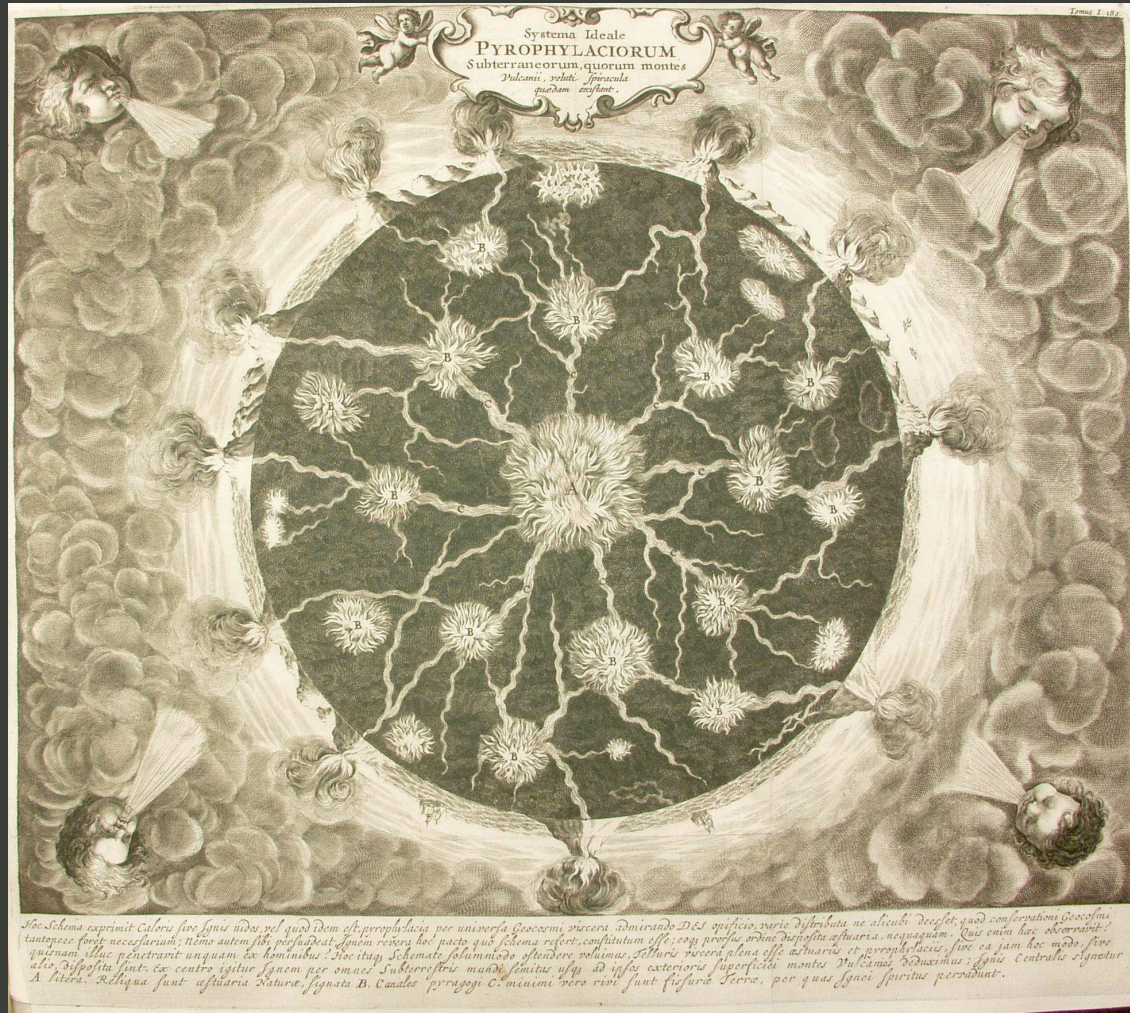
*Hades*: the underworld of the dead

Five rivers in the *Hades*: *Pyriphlegeton*, *Styx*, *Lethe*, *Cocytus* and *Acheron*

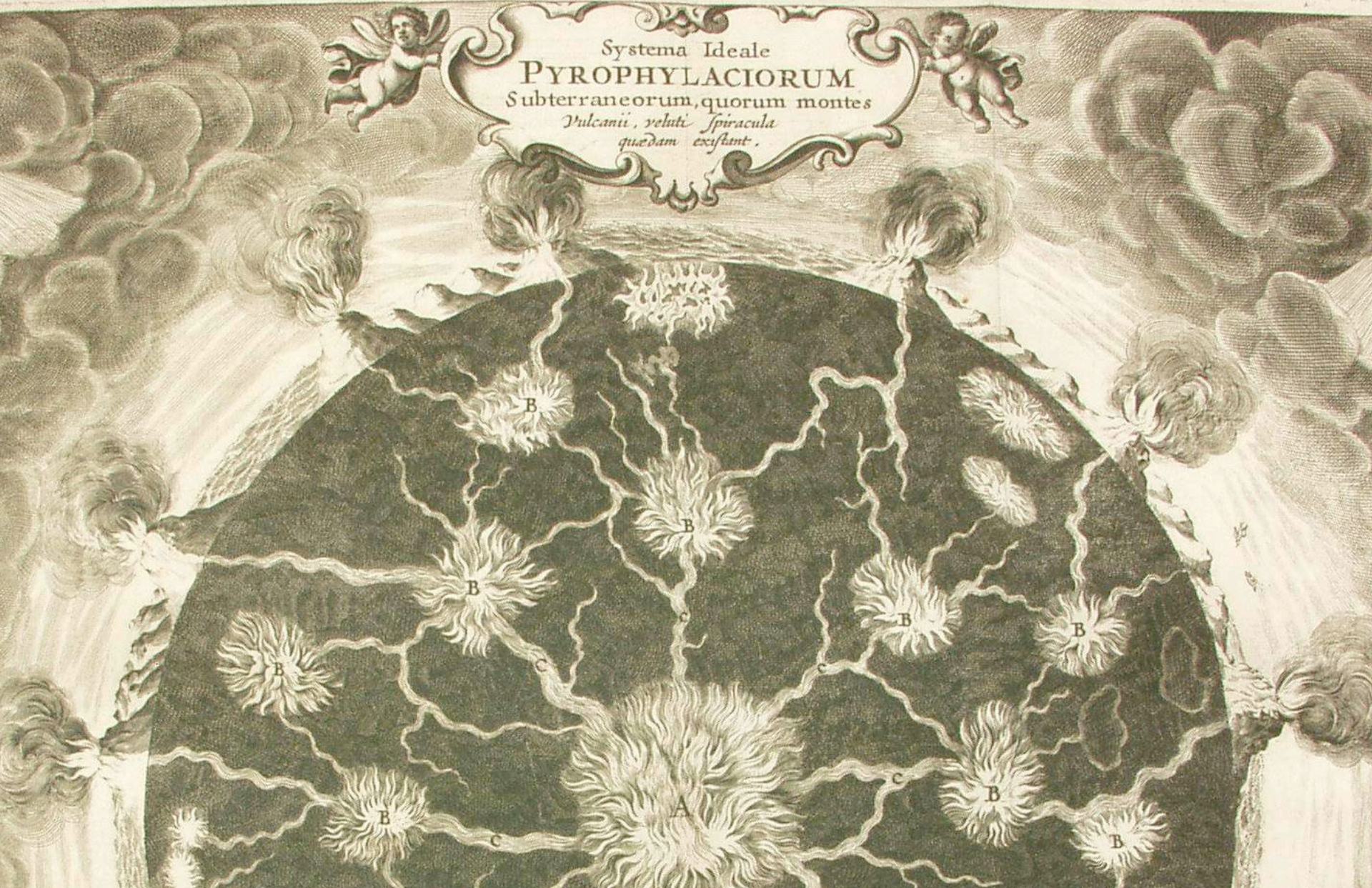
*Tartarus*: the underworld of dead banished by Deity Zeus (became the Christian *Hell*)

Homer (ca. 700 BC): *Tartarus* is “as far beneath Hades as Heaven is high above the Earth” (*Iliad*)

# Proto-theory: volcanos as “vents” of Earth’s “internal fire”



Athanasius Kircher, *Mundus subterraneus* (Underground World), 1664  
(Galileo: 1564-1642)



***“The volcano mountains, such as vents of internal fire of the Earth”***



# Athanasius Kircher (1602-80)

## Medicine and Biology

*Observation of microbes through a microscope  
Prevention of infections by microorganisms  
Hybridization of species: a “proto-evolutionist”?*

**Theology:** *Biblical studies*

**Sinology:** *History studies, Encyclopedia of China*

## Geology and Paleontology

*Observations on Mt. Vesuvius  
Volcanism (and tides) originate from an “Underground World”  
Study on fossils as remnants of ancient animals*

## Egyptology

*Links between Copts and ancient Egyptians, hieroglyphs’ interpretation*

## Mathematics, Physics and Technology

*Combinatorial calculus  
“Ars magna lucis and umbrae”: Art of light and shadow  
Magnetic clock, automaton, the first megaphone*

Athanasius Kircher was a  
***“scientist”***

The categorization of his work  
in terms of today’s

***“scientific disciplines”***

is an exercise done  
*“a posteriori”*

# *The expansion and deepening of “Science” implied focusing of interests to “disciplines”*

*... sometimes with excessive  
sacrifice of unitary vision*

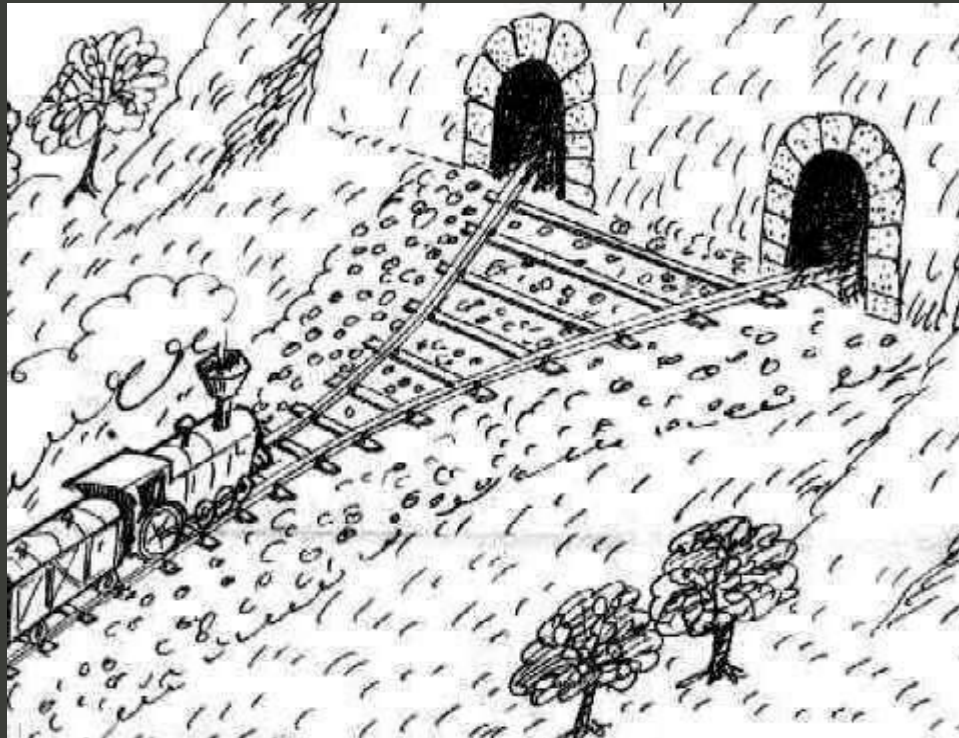


Image Mysearch [<http://www.mysearch.org.uk/website1/html/522.Duality.html>]



# *“Disciplines”*: young compared to “Science”

Foundation of “discipline oriented” Societies  
(for example Physics)

German Physical Society	1845
French Physical Society	1873
Physical Society of London → IoP	1874
Japan Physical Society	1877
Italian Physical Society	1897
American Physical Society	1899

*And very successful*

# CONSEIL DE PHYSIQUE SOLVAY

BRUXELLES 1911



Photo Couprin, Bruxelles

GOLDSCHMIDT  
NERNST

PLANCK  
BILLOUIN

KUBENS  
SOLVAY

L'INDENMANH  
SOMMERFELD  
DE BROGLIE  
LORENZE

HAENDL  
HOEULET  
KNUDSEN  
WARBURG  
PERRIN

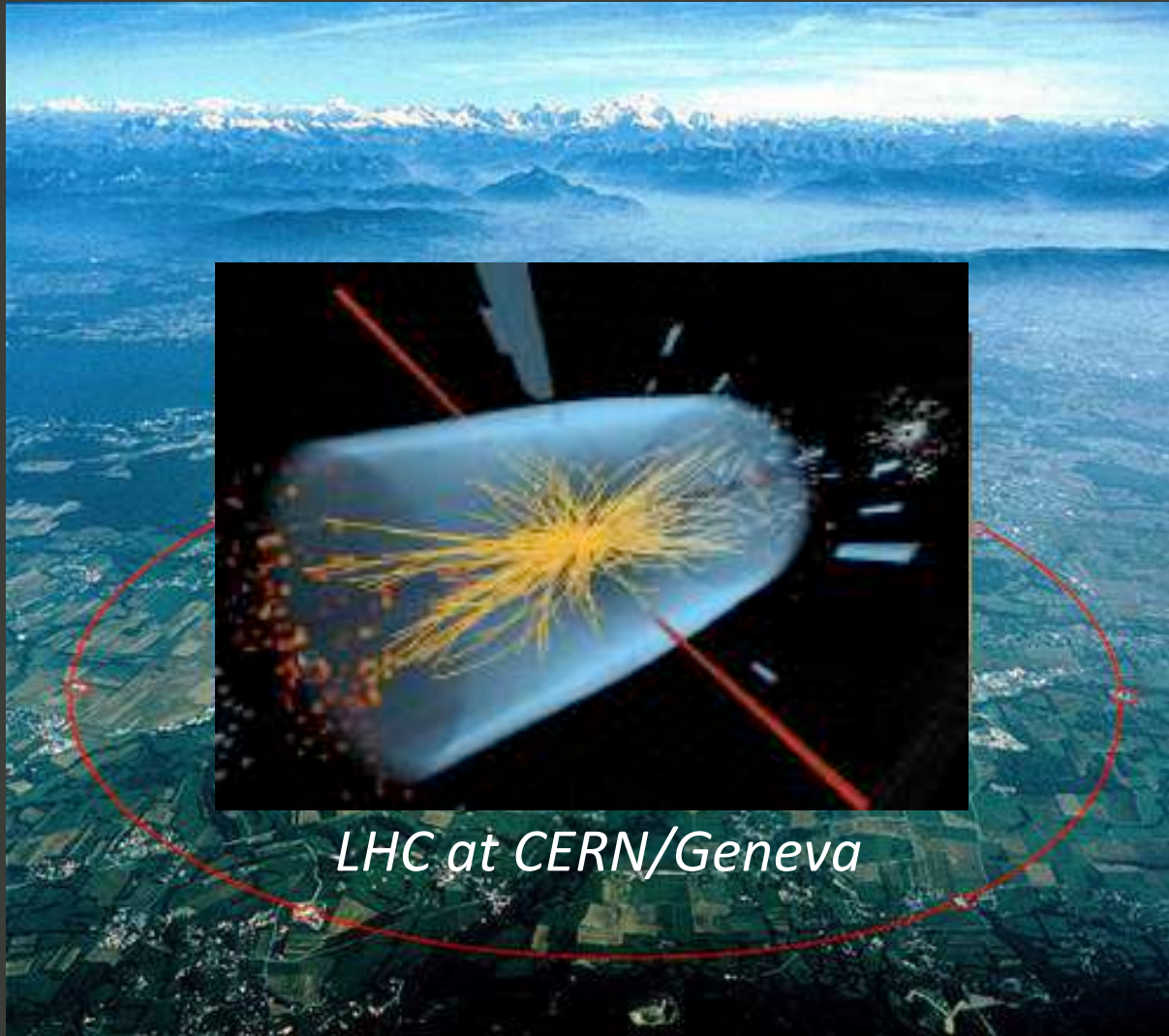
HERZEN  
WIEN  
MADAME CURIE

JEANS  
RUTHERFORD  
POINCARÉ

LANGMUIR  
LANGEVIN  
LAWRENCE  
IRVING

ERSTEN  
LANGVEIN

# Disciplines: a necessity for researches requiring extreme specialization



*LHC at CERN/Geneva*

**A unitary vision of Science became difficult**

**Cross-fertilization among “disciplines”**

occurred in the form of:

Technological transfer “other” disciplines

Researches requiring expertise from “several” disciplines  
(current multi-disciplinary researches)

**What about “Earth Science”?**



*Earth Science has traditionally offered a  
field of research open  
to multi-disciplinary contributions*

**However ...**

# New challenges require new synergies



*Earth rise on the Moon (NASA Apollo 11 mission, 1969)*

# *New challenges in Earth Science connected to Particle Physics*

$\mu$



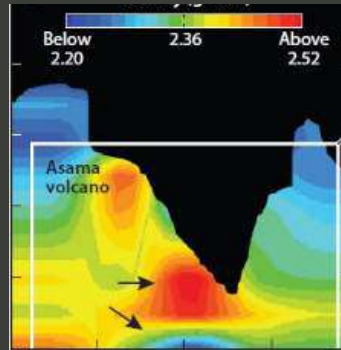
$\nu$

# New challenges in Earth Science

## *Muography*

### Volcanoes

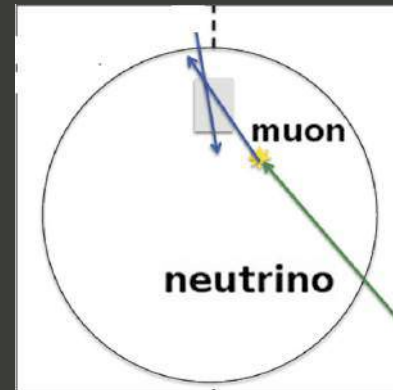
Nagamine, Tanaka et al. + ...



## *Neutrinoigraphy*

### Earth Core

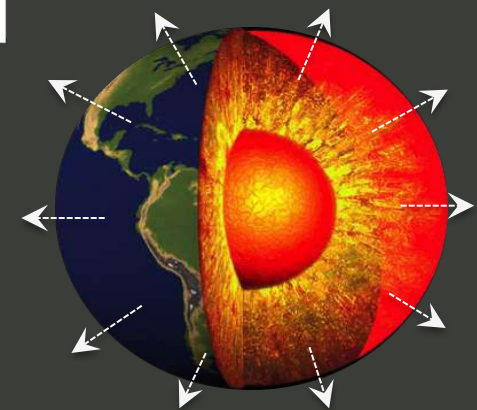
... IceCube, ... Km3Net



## *Geoneutrinos*

### Earth Mantle

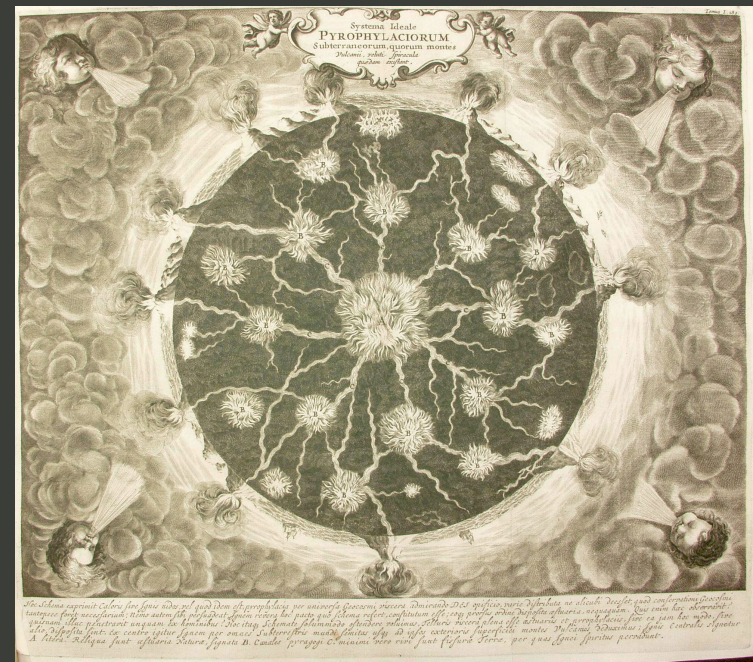
KamLAND, Borexino, ...





# That's simply "Science"

*as at the times of  
Athanasius Kircher*



*Kitakanegasawa no-ichou*

**"Alliance"  
among disciplines  
and Earth Science  
to face  
new challenges**

“Kitakanegasawa no-ichou” grew higher by an  
“alliance of trunks”



# *Kitakanegasawa no-ichou in autumn splendor*

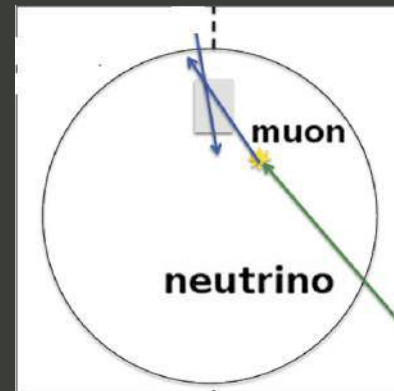
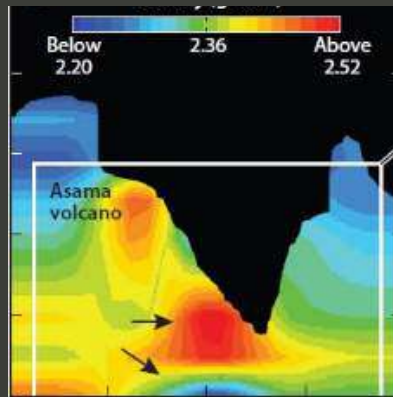


[[http://huben.jp/desc/02\\_09.html](http://huben.jp/desc/02_09.html)]

***New challenges***

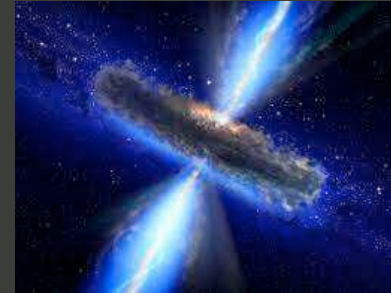
# *Muography*

# *Neutrino-graphy*

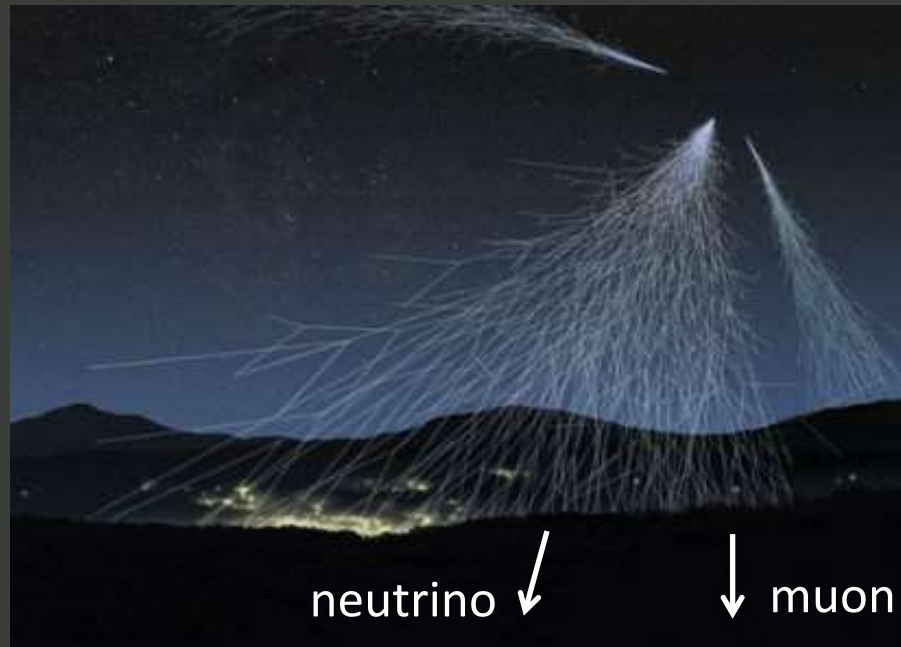


# Nature provides muons and neutrinos

*Very high energy particles from cosmic accelerators: “cosmic rays”*



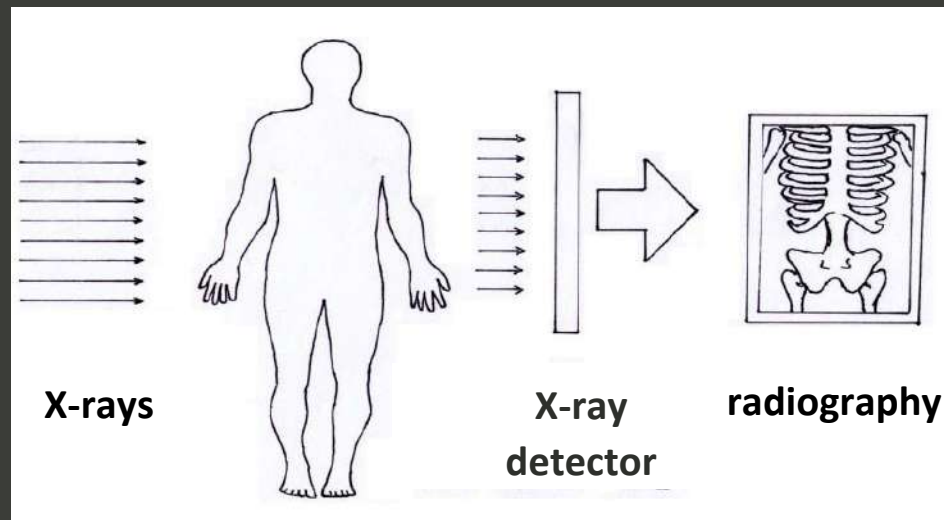
*“Shower” of particles produced by cosmic rays hitting the atmosphere*



*Particles absorbed at the Earth’s surface*

***muons and neutrinos penetrate inside the Earth***

# Principle of internal imaging techniques



*Source of penetrating particles*

*Absorption by higher densities*

*A detector sees internal structures as “shadows”*

	<b>Particle</b>	<b>Penetration</b>	<b>Source</b>
Radiography	X –rays (radiations)	human body	artificial
Muography	Muons	(small) mountains	cosmic rays
Neutrinoigraphy	Neutrinos	the Earth	cosmic rays

# *Muography*

*“See the hidden”  
inside volcano edifices*



Antonio Corradini, *The Veiled Truth* (1752)  
Sansevero Chapel, Napoli

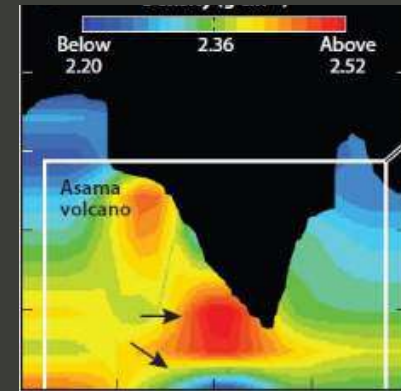
[<http://www.italianways.com/la-pudicizia-scultura-e-segreti/>]



# Volcano muography



cosmic ray  
interactions  
In atmosphere



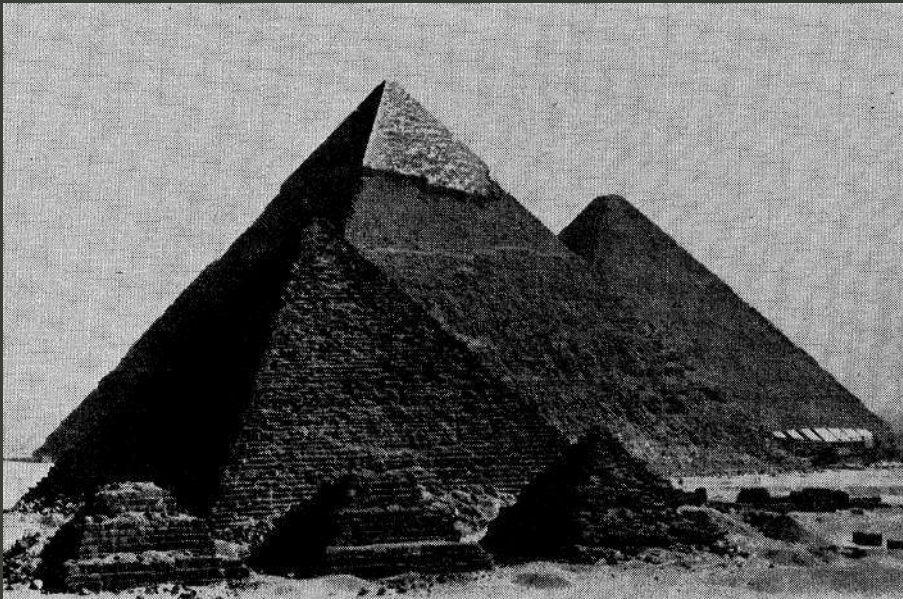
density map

**Muon absorption creates a shadow and projects a “density map”**

Combined analysis with resistivity and gravity data

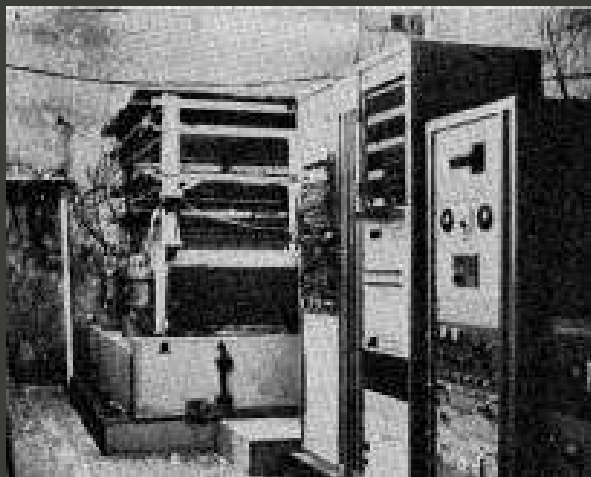
Muography applicable also to geological structures, Mining,  
Archaeology, Civil Engineering, Security, ...

# The first muography: Archaeology

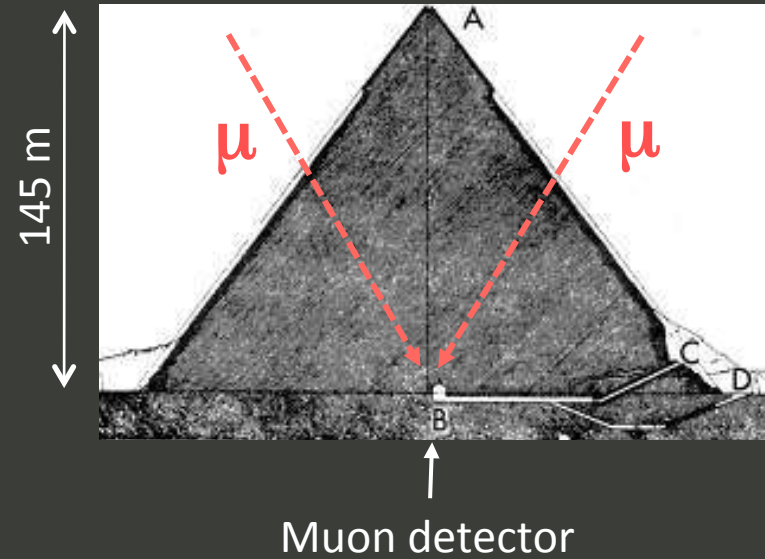


Search for a hidden chamber in the Chephren's Pyramid

(L.W. Alvarez et al., 1970)



Spark chamber muon detector

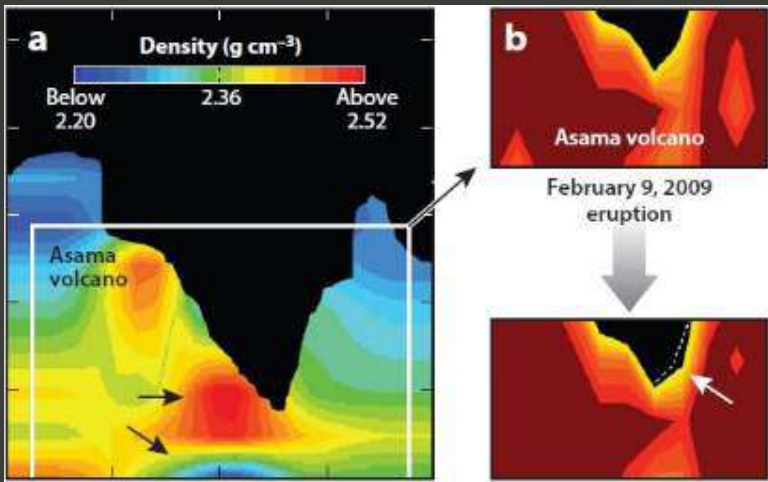


# Volcano muography

## Breakthrough

Summit of Mt. Asama  
Rock density in colour scale  
(Tanaka et al. 2007)

Muon detector  
technique developed for  
**OPERA neutrino experiment**



## Until now

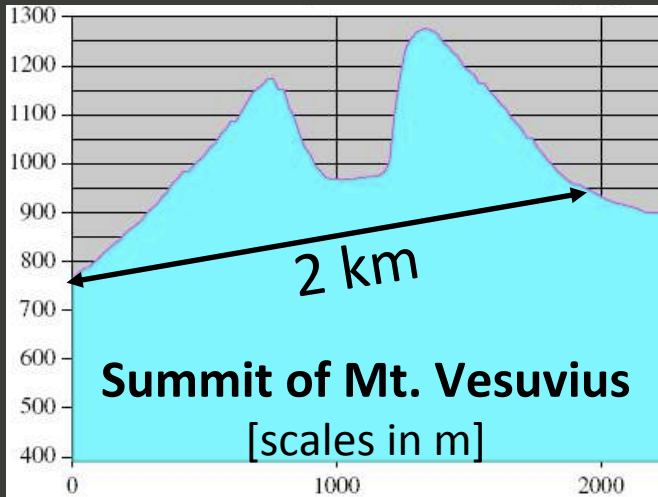
Observations and know-how in Japan, France and Italy  
Impressive results, also combined with other techniques  
Observation of time evolution

# Towards a current “tool”

## Rock thickness



“Rule of thumb”  
2 km for 0.5-1 km height



## The challenge

**Sensitivity x 100**

(Detector area x time) x 100

Very substantial background reduction

Angle resolution 10 mrad



**Larger + better detectors, R&D**

**Strong and effective  
collaborations**

# Also Science can do something for people



*Saint Gennaro  
listened to people*



*... and stopped  
the eruption*

*Napoli people invoke Saint Gennaro during  
the last sub-plinian eruption of Mt. Vesuvius (1631)*

*Micco Spadaro (1610-1675)*

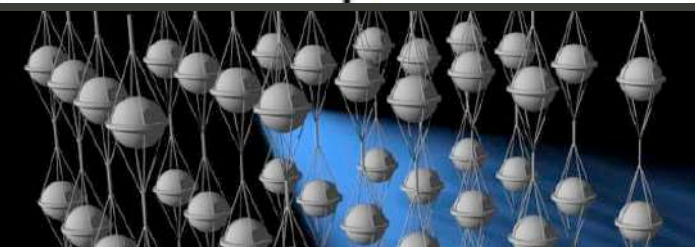
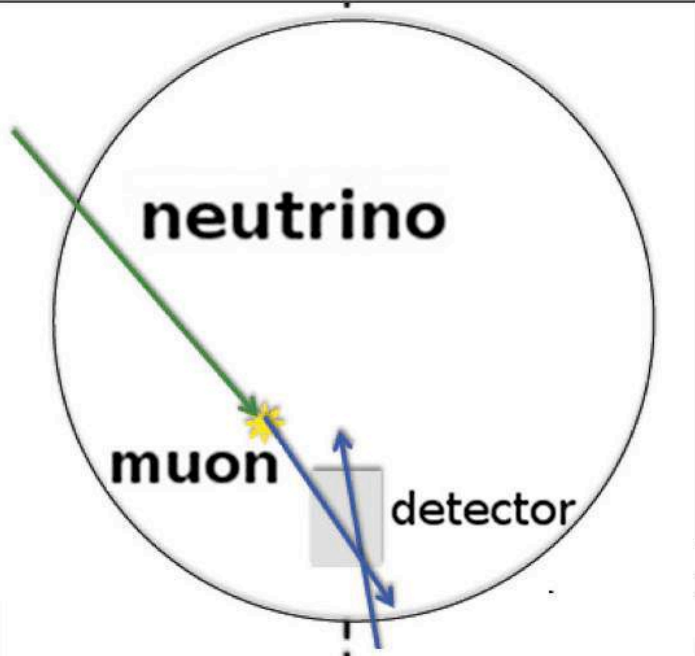
# *Neutrino-graphy*

*Penetrating into  
the Core of the Earth*



# Concept of Earth's neutrinography

(density map given by neutrino absorption through Earth)



## Neutrinos $\nu$

Cosmic rays interacting in the atmosphere generate neutrinos



## Earth: $\nu$ absorber and $\nu$ - $\mu$ converter

neutrinos interacting close to the detector generate observable muons  $\mu$

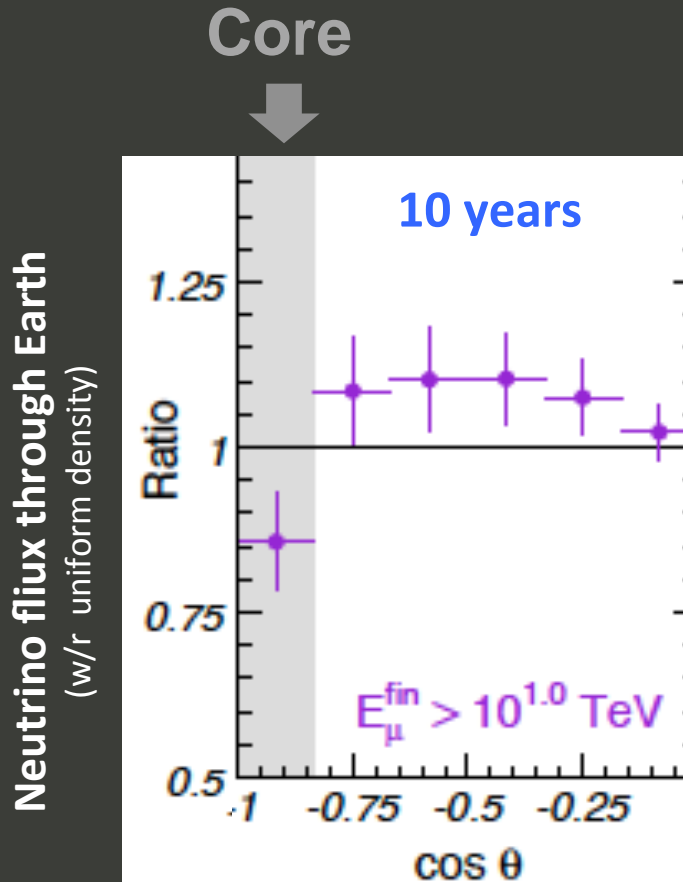


## Muon detector

IceCube experiment under Antarctic ice sees Čerenkov light produced by muons  
(as future Km3Net exp. in deep sea)

# Computer simulation of an estimate of the Earth's Core density

(IceCube x 10 years)



Azimuthal angle



Neutrinos from antipodes

Current Earth's density model (PREM)

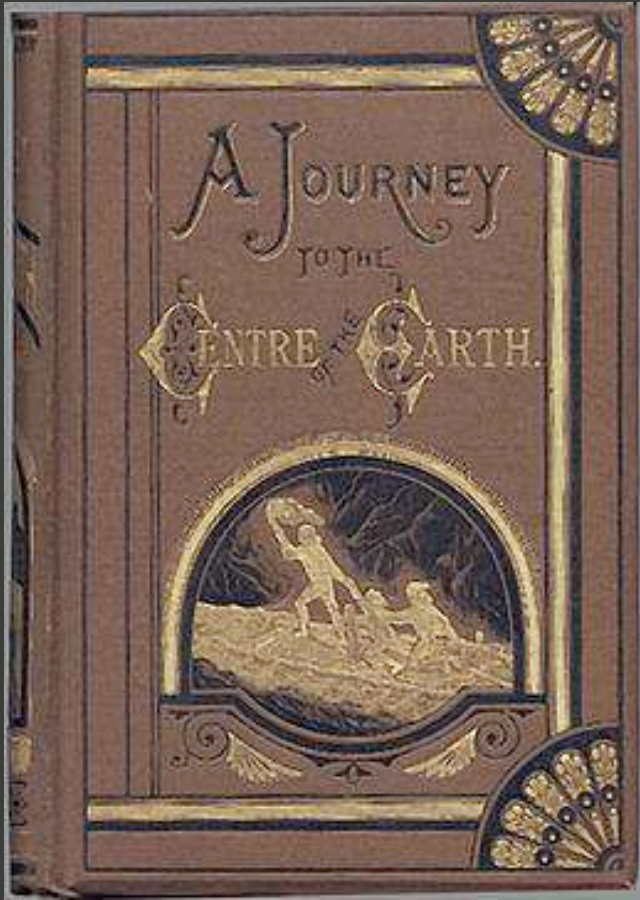
Select very high energy neutrinos  
(higher interaction probability)

The lower neutrino flux through the Earth's Core indicates a higher absorption and gives an estimate of its density

*Radiography of the Earth's core and mantle with atmospheric neutrinos*  
(Gonzalez-Garcia et al., 2008)



# Neutrinos penetrate much deeper than imagined by Jules Verne, the precursor of Science Fiction

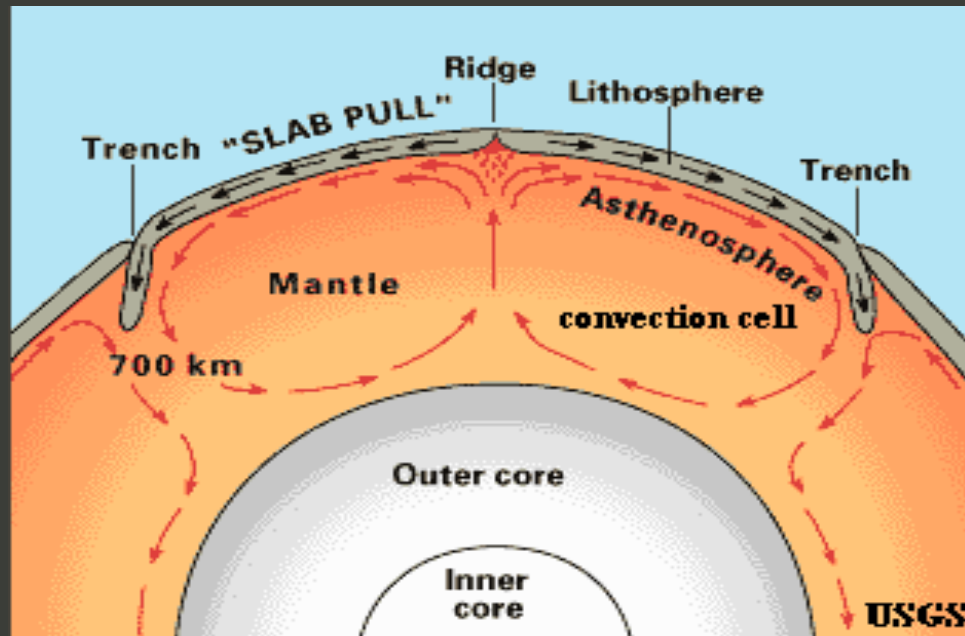


*A Journey to the Centre of the Earth (1864)*

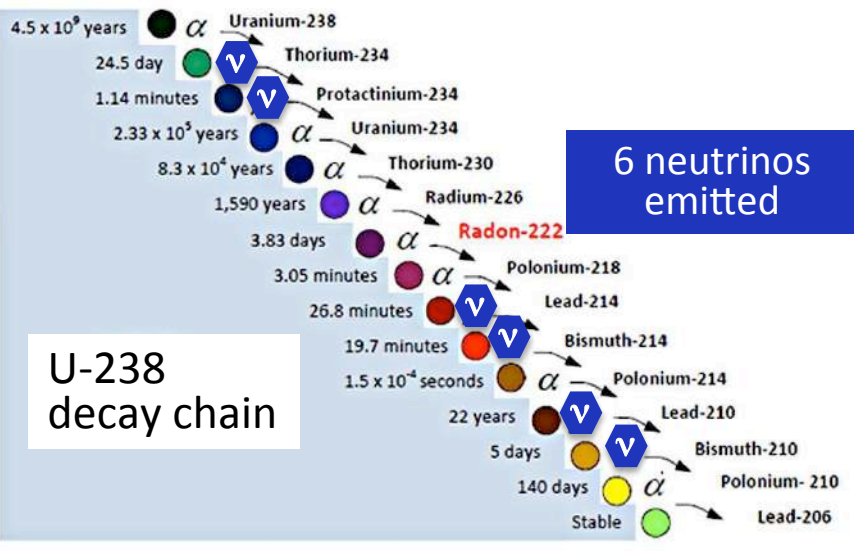
Jules Verne (1828-1905), Illustrations by Edouard Riou

# *Geo-neutrinos*

## *Messengers from deep Earth*



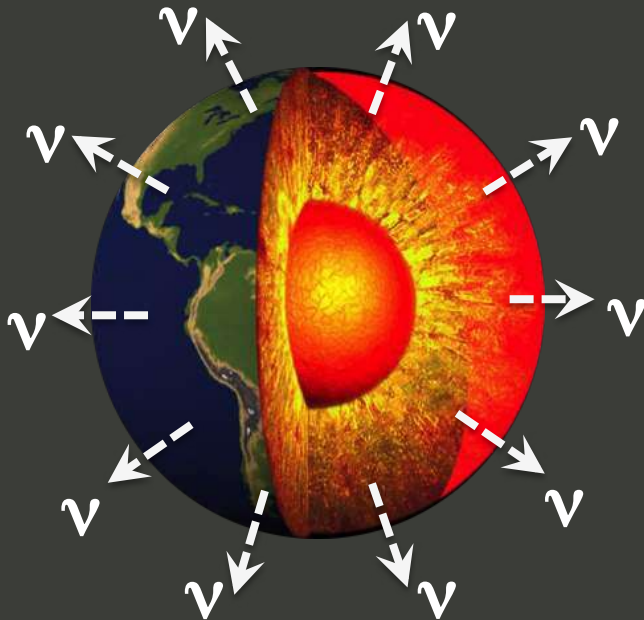
# “Geoneutrinos”



Radioactive decay chains  
of Uranium-238, Thorium-232  
and Potassium-40



Emission of (anti-)neutrinos  $\bar{\nu}$   
+ Heat from energy  
made available



Measure geoneutrino flux



estimate “radiogenic” heat

# Our lives stand on the Earth's Mantle: geoneutrinos tell us about it's dynamics



*Pop Art Murales in the Milwaukee's Metro*

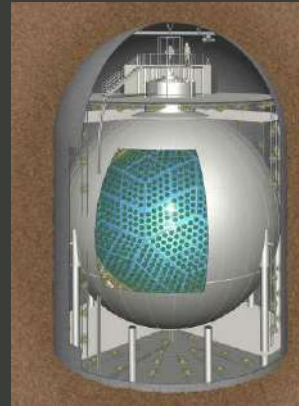
Keith Haring (1958-1990)

[<http://www.escopri.it/316512/keith-haring-il-murales-milwaukee-mostra-alla-reggia-caserta.html>]

# “Geoneutrino” discovery by “neutrino” detectors in underground Physics/Astrophysics Laboratories

2005 **KamLAND**: first detection

2010 **Borexino**: detection with low  
background from nuclear reactors



**KamLAND (> 2002)**  
Liquid scintillator  
1 kt, 1900 PMTs



**Borexino (> 2007)**  
Liquid scintillator  
0.3 kt, 2200 PMTs

2011 **Radiogenic contribution to Earth’s heat** (+ primordial source?)  
Uranium and Thorium abundances

2013 **Radiogenic heat from Earth’s Mantle** from combined analysis

**The first estimates**

# Coming soon: SNO+

## KamLAND

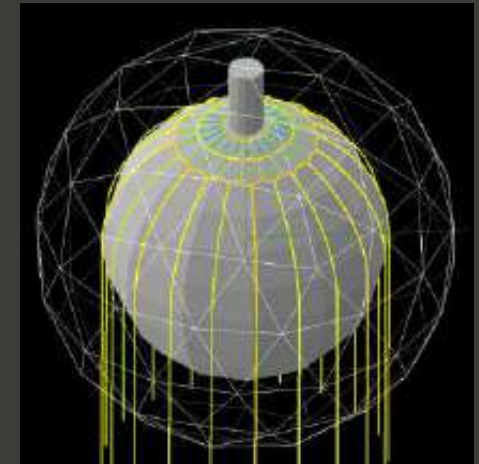
Liquid Scintillator  
1 kt, 1900 PMTs  
> 2002

## Borexino

Liquid Scintillator  
0.3 kt, 2200 PMTs  
> 2007

## SNO+

Liquid Scintillator  
0.8 kt, 9000 PMTs  
> 2014



## Borexino .vs. both others

Lowest Liquid Scintillator mass  
Lowest background

## SNO+ .vs. KamLAND

Similar Liquid Scintillator mass  
Background from nuclear reactors x 1/4

# What can radiogenic heat from Earth's Mantle tell us?

Source of Earth's internal heat

Power supply for Mantle convection, plate tectonics, ...

A key to mysteries of deep-Earth phenomena affecting our lives



# Future “geoneutrino detectors”



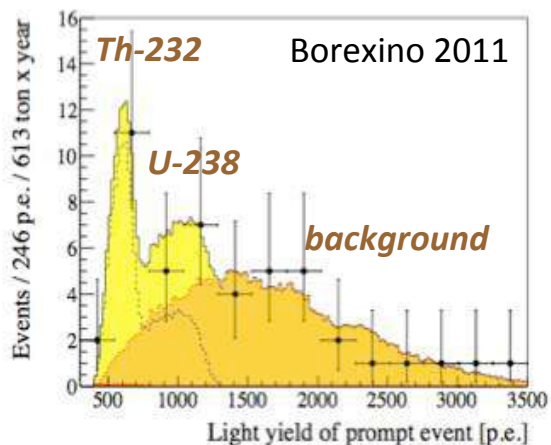
The “electronic eyes” inside Borexino

## Breakthrough detectors *[see figures]*

Limited mass (< 1kt) and low statistics

Location for physics and astrophysics

“Blind counting” and looking for “peaks” in energy distribution



Thorium and Uranium peaks over background in the positron energy distribution (46 events)

## New features

Mass x 10, hence larger statistics

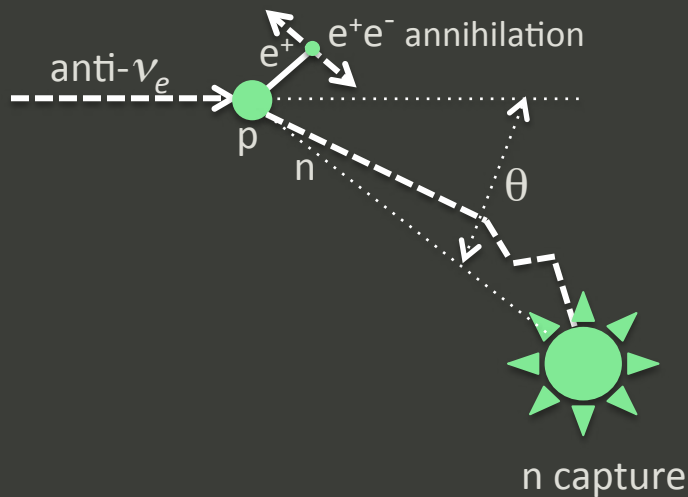
Location for geoneutrinos:

Mantle and Crust signals, background from reactors

Tracing back geoneutrinos for source imaging



# Tracing back geoneutrinos for source imaging




Liquid Scintillator: mostly Hydrogen ( $H$ )

The neutrino ( $\bar{\nu}_e$ ) interacts on  $H$  nuclei ( $p$ ) producing a positron  $e^+$  and a neutron  $n$

Interaction point seen through the prompt  $e^+$  annihilation on  $e^-$

**The neutron recoil “remembers” the geoneutrino direction**

Neutron diffusion at low energies before capture by a nucleus and measurement error on capture location: **memory lost**

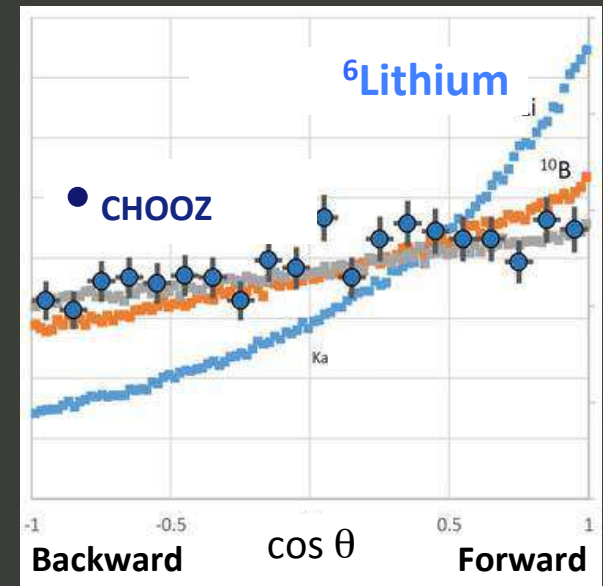
peak in correct neutrino direction 

## With $^6\text{Lithium}$ -loaded Liquid Scintillator

Neutron soon captured, hence little diffusion  
(also with Gadolinium loading)

Better location of the neutron capture  
(not with Gadolinium loading)

**The neutron maintains memory of the neutrino direction**



Apollonio et al. Phys. Rev D61 (2000): CHOOZ, with Gadolinium loading

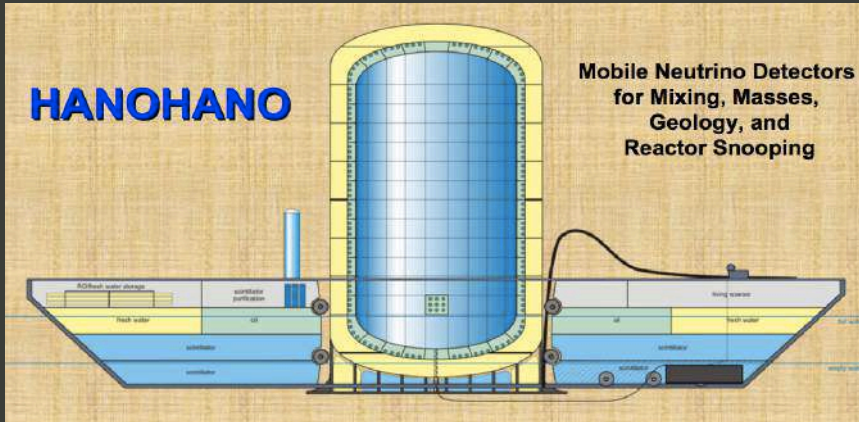
Shimizu, Nucl. Phys. B 168 (2007)

Tanaka and Watanabe, Nature Scientific Reports 4 (2014)

Angle  
w/r neutrino direction

# Close to the source of Mantle geoneutrinos

J. Learned, S. Dye and S. Pakvasa  
Neutrino Telescopes, 2007



Mobile detector (10 kt)  
to be deployed and retrieved from a barge

On Continents:

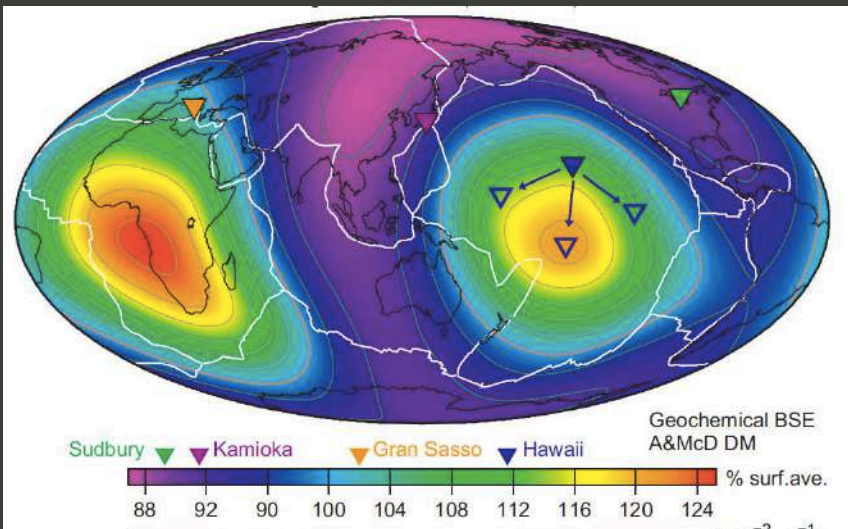
Crust geoneutrinos overwhelming  
Location bound to caverns

In deep Ocean:

Clean Mantle signal

**Mobile submarine detectors: Hanohano**

Sramek et al.  
Ea. Pl. Sci. Lett. 361, 2013



*The technique is suitable for monitoring the  
existence of nuclear power reactors:  
can this attract a special support by  
governments?*

Mantle geoneutrino flux (%/average)  
Proposed Hanohano sites in Pacific Ocean

For all the above  
new challenges

*Alliance to penetrate  
mysteries of the deep Earth*

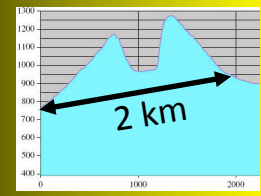
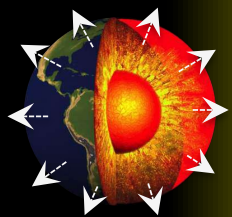


*Listening to people*

***A vision  
on the road  
towards the future***

1970      2005      2010      2015      2030      2050      2100

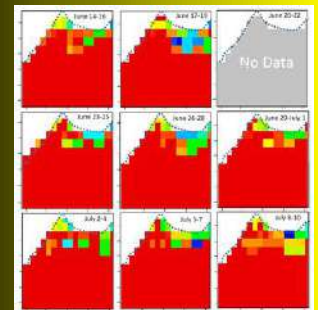
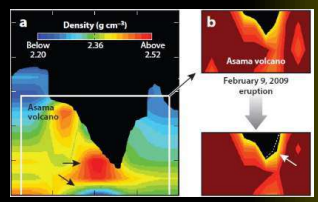
# Earth Science



❌ Impossibile visualizzare l'immagine. La memoria del computer potrebbe essere insufficiente per aprire l'immagine oppure l'immagine potrebbe essere danneggiata. Riavviare il computer e aprire di nuovo il file. Se viene visualizzata di nuovo la x rossa, potrebbe essere necessario eliminare l'immagine e inserirla di nuovo.

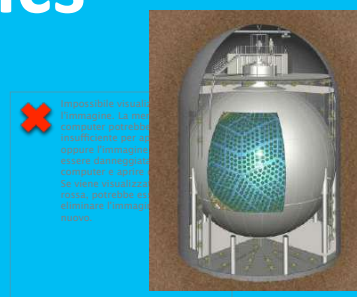
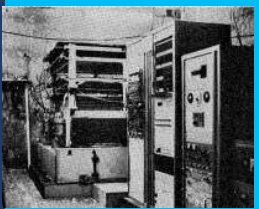
## New challenges in Earth Science

❌ Impossibile visualizzare l'immagine. La memoria del computer potrebbe essere insufficiente per aprire l'immagine oppure l'immagine potrebbe essere danneggiata. Riavviare il computer e aprire di nuovo il file. Se viene visualizzata di nuovo la x rossa, potrebbe essere necessario eliminare l'immagine e inserirla di nuovo.



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# Particle Physics



❌ Impossibile visualizzare l'immagine. La memoria del computer potrebbe essere insufficiente per aprire l'immagine oppure l'immagine potrebbe essere danneggiata. Riavviare il computer e aprire di nuovo il file. Se viene visualizzata di nuovo la x rossa, potrebbe essere necessario eliminare l'immagine e inserirla di nuovo.

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***Alliance ERI-INFN-INGV:  
engine for a boost forward***

... by a solid synergy of expertise

A photograph of a megalithic dolmen in Ballykeel, Ireland. The dolmen consists of three large, grey, rectangular stone blocks. Two vertical blocks support a horizontal block on top. The stones are weathered and have some moss on them. In the background, there are rolling hills and a house with a chimney. The sky is blue with some light clouds. The text is overlaid on the image in white, bold, sans-serif font.

**NEW CHALLENGES  
IN EARTH SCIENCE**

**ERI  
Earth  
Science**

**INGV  
Earth  
Science**

**INFN  
muons  
neutrinos**

*A megalithic dolmen, Ballykeel, Ireland (4000-2500 BC)*

# In a tradition of collaboration between Italy-Japan

*K. Hokusai  
(1760-1849)*

***Great Wave***



*P. Fabris  
(1740-92)*

***Mt. Vesuvius***

*From "Science and School" [<http://scienzaescuola.fisica.unina.it>]*

**Similar concerns in Earth Science:  
Earthquakes and volcanoes**

**Different cultures create synergic waves**