The Abdus Salam
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United Nations
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IAEA
International Atomic Energy Agency

2047-15

Workshop Towards Neutrino Technologies

13 - 17 July 2009

A roadmap for geoneutrino studies

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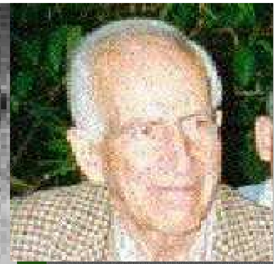
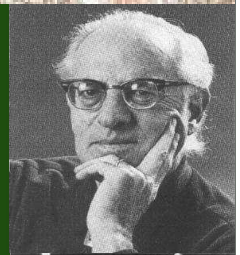
Via Saragat, 1

Una breve storia del neutrino

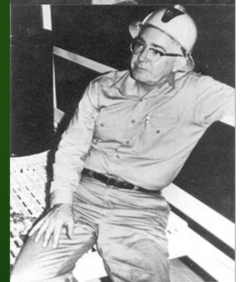




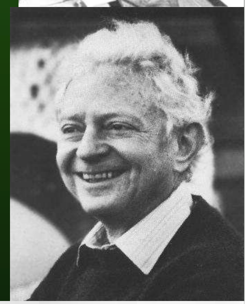
1898 Discovery of the radioactivity
1926 Problem with beta radioactivity
1930 Pauli invents the neutrino particle
1932 Fermi baptizes the neutrino and builds the theory of weak interaction



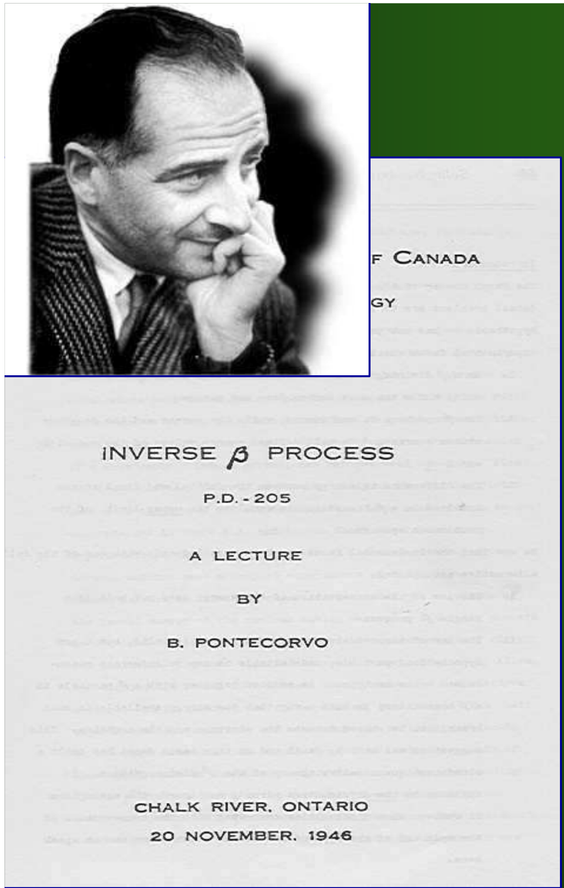
1946 Pontecorvo program of neutrino detection
1956 First observation of the neutrino by an experiment



1957 Pontecorvo: neutrino oscillations
1962 Discovery of an other type of neutrino: ν_μ
1970 Davis experiment opens the solar neutrino puzzle
1974 Discovery of neutral currents thanks to the neutrinos



1987 Neutrinos from SN 1987A
1991 LEP experiments show that there are only three light neutrinos
1992 Missing solar neutrinos confirmed by Gallium expts.
2000 ν_τ observed
2001 SNO closes the solar neutrino puzzles, by directly proving the transformation of solar neutrinos
2002 Kamland observes transmutation of man made (reactor) neutrinos
2005 Kamland observes geo-neutrinos…

F CANADA

GY

INVERSE β PROCESS

P.D. - 205

A LECTURE

BY

B. PONTECORVO

CHALK RIVER, ONTARIO

20 NOVEMBER, 1946

A lesson from Bruno Pontecorvo: from neutrons to neutrinos

Neutron Well Logging - A New Geological Method Based on Nuclear Physics, Oil and Gas Journal, 1941, vol.40, p.32-33.1942.

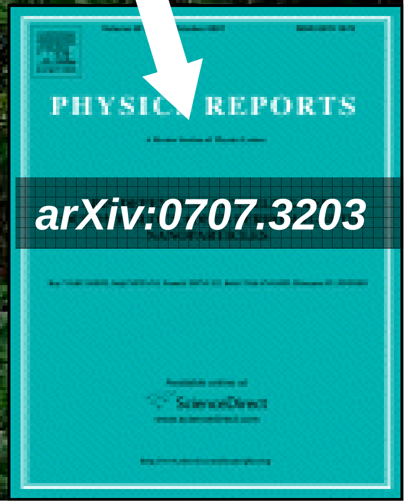
- An application of Rome celebrated study on slow neutrons, the neutron log is an instrument sensitive to Hydrogen containing substances (=water and hydrocarbons), used for oil and water prospection.

- Now that we know the fate of neutrinos, we can learn a lot from neutrinos.
- The determination of the radiogenic contribution to Earth energetics is an important scientific question, possibily the first fruit we can get from neutrinos.

Gianni Fiorentini
Ferrara University & INFN

A roadmap for geo-neutrinos: theory and experiment

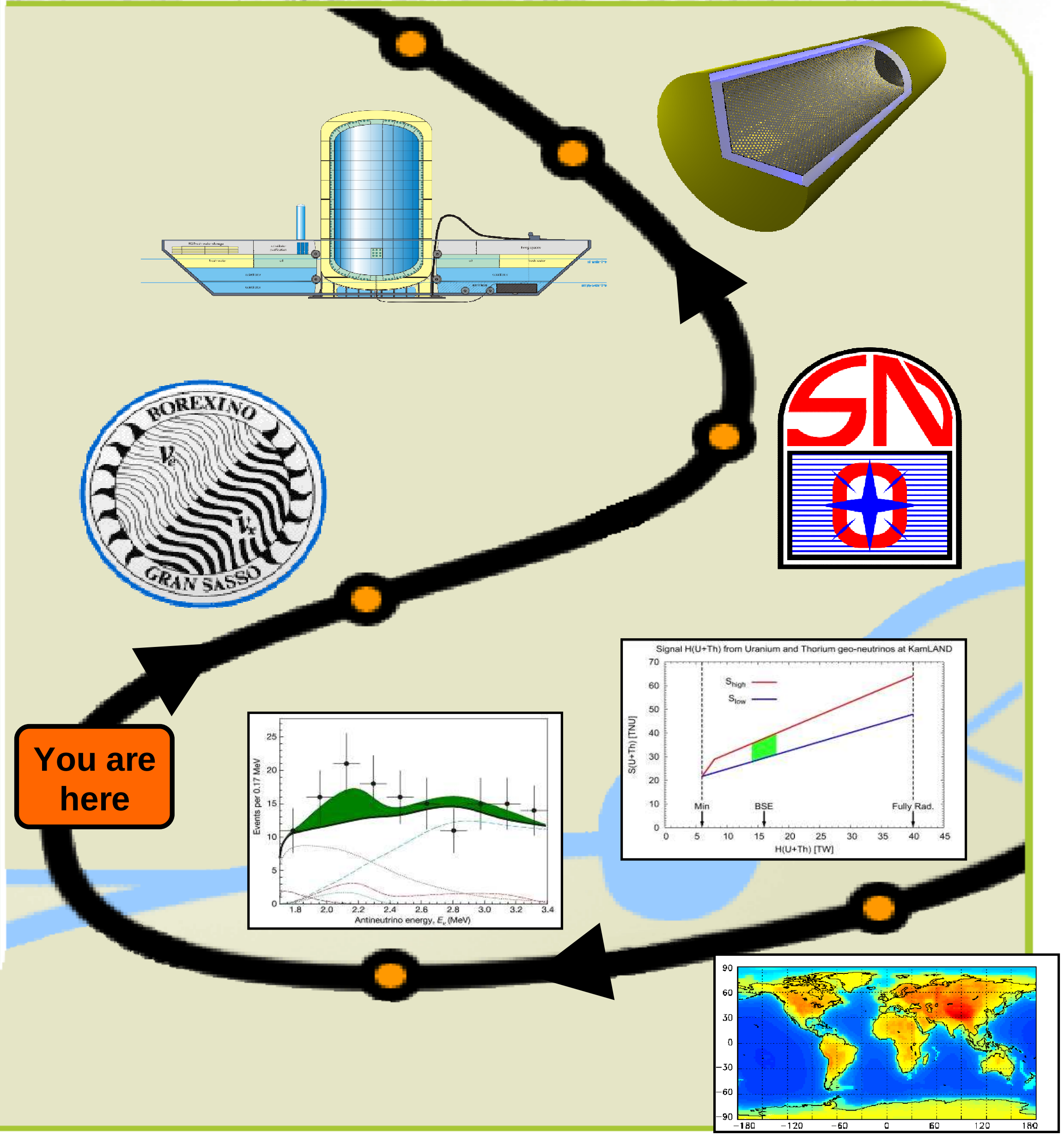
A primer,
both for Earth and nuclear scientists



arXiv:0707.3203

Summary

- Geo-neutrinos: a new probe of Earth's interior
- Open questions about radioactivity in the Earth
- The impact of KamLAND
- The potential of future experiments
- A possible shortcut in the roadmap
- (Optional?) excursions



Geo-neutrinos: anti-neutrinos from the Earth

U, Th and ^{40}K in the Earth release heat together with anti-neutrinos, in a well fixed ratio:

Decay	$T_{1/2}$ $[10^9$ yr$]$	E_{max} [MeV]	Q [MeV]	$\varepsilon_{\bar{\nu}}$ $[\mathrm{kg}^{-1}\mathrm{s}^{-1}]$	ε_H [W/kg]
$^{238}\mathrm{U} \to {}^{206}\mathrm{Pb} + 8\,{}^4\mathrm{He} + 6e + 6\bar{\nu}$	4.47	3.26	51.7	7.46×10^7	0.95×10^{-4}
$^{232}\mathrm{Th} \to {}^{208}\mathrm{Pb} + 6\,{}^4\mathrm{He} + 4e + 4\bar{\nu}$	14.0	2.25	42.7	1.62×10^7	0.27×10^{-4}
$^{40}\mathrm{K} \to {}^{40}\mathrm{Ca} + e + \bar{\nu}$ (89%)	1.28	1.311	1.311	2.32×10^8	0.22×10^{-4}

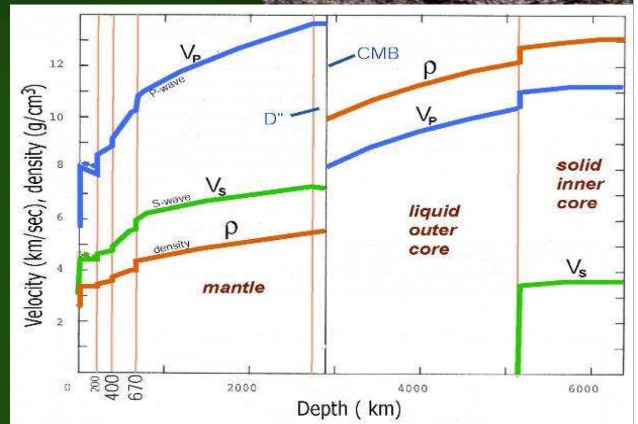
- Earth emits (mainly) antineutrinos $\Phi_{\bar{\nu}} \sim 10^6\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ ereas Sun shines in neutrinos.

- A fraction of geo-neutrinos from U and Th (not from ^{40}K) are above threshold for inverse β on protons: $\bar{\nu} + p \to e^+ + n - 1.8\ \mathrm{MeV}$

- Different components can be distinguished due to different energy spectra: e. g. anti-ν with highest energy are from Uranium.

Probes of the Earth’s interior

- Deepest hole is about 12 km
- Samples from the crust (and the upper portion of mantle) are available for geochemical analysis.
- Seismology reconstructs density profile (not composition) throughout all Earth.



Geo-neutrinos: a new probe of Earth's interior

✓ They escape freely and instantaneously from Earth’s interior.

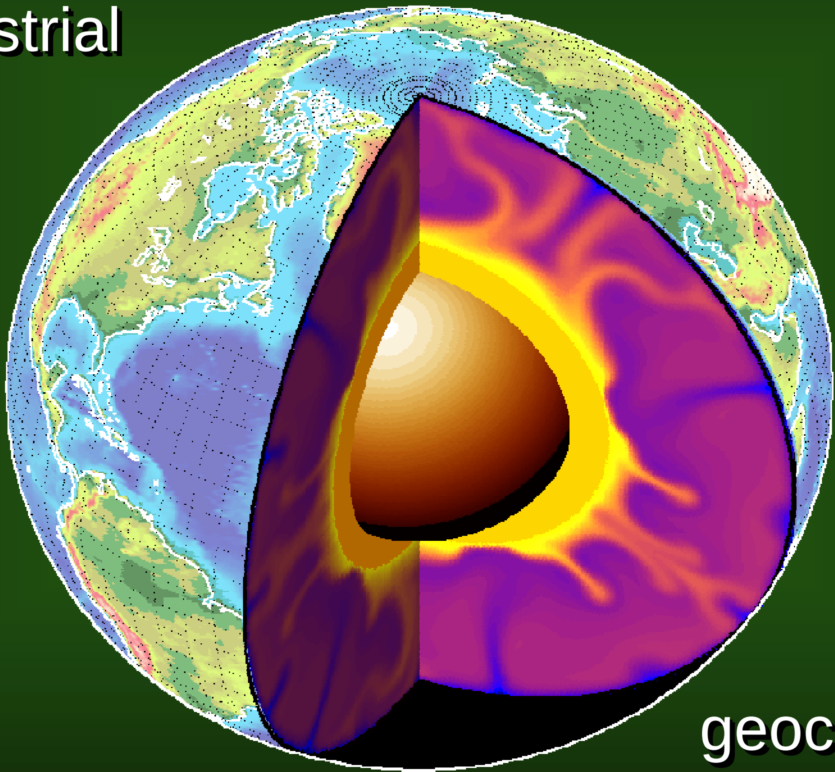
✓ They bring to Earth’s surface information about the chemical composition of the whole planet.

Open questions about natural radioactivity in the Earth

1 - What is the radiogenic contribution to terrestrial heat production?

2 - How much U and Th in the crust?

3 - How much U and Th in the mantle?



4 - What is hidden in the Earth's core? (geo-reactor, ^{40}K, …)

5 - Is the standard geochemical model (BSE) consistent with geo-neutrino data?

“Energetics of the Earth and the missing heat source mistery” *

- Heat flow from the Earth is the equivalent of some 10000 nuclear power plants

$$H_{Earth} = (30 - 44)TW$$

- The BSE canonical model, based on **cosmochemical** arguments, predicts a radiogenic heat production ~ 19 TW:

~ 9 TW **estimated** from radioactivity in the (continental) crust

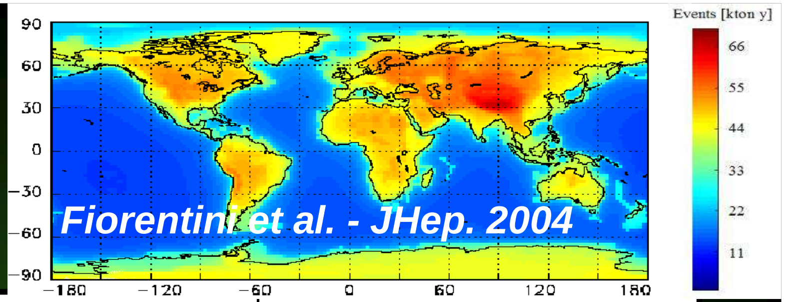
~ 10 TW **supposed** from radioactivity in the mantle

~ 0 TW **assumed** from the core

- Unorthodox or even heretical models have been advanced…

** D. L. Anderson (2005),Technical Report, www.MantlePlume.org*

Geo-ν: predictions of the BSE Reference Model



Signal from U+Th [TNU]	Mantovani et al. (2004)	Fogli et al. (2005)	Enomoto et al. (2005)
Pyhasalmi	51.5	49.9	52.4
Homestake	51.3		
Baksan	50.8	50.7	55.0
Sudbury	50.8	47.9	50.4
Gran Sasso	40.7	40.5	43.1
Kamioka	34.5	31.6	36.5
Curacao	32.5		
Hawaii	12.5	13.4	13.4

- 1 TNU = one event per 10^{32} free protons per year
- All calculations in agreement to the 10% level
- Different locations exhibit different contributions of radioactivity from crust and from mantle

Geo-neutrino signal and radiogenic heat from the Earth

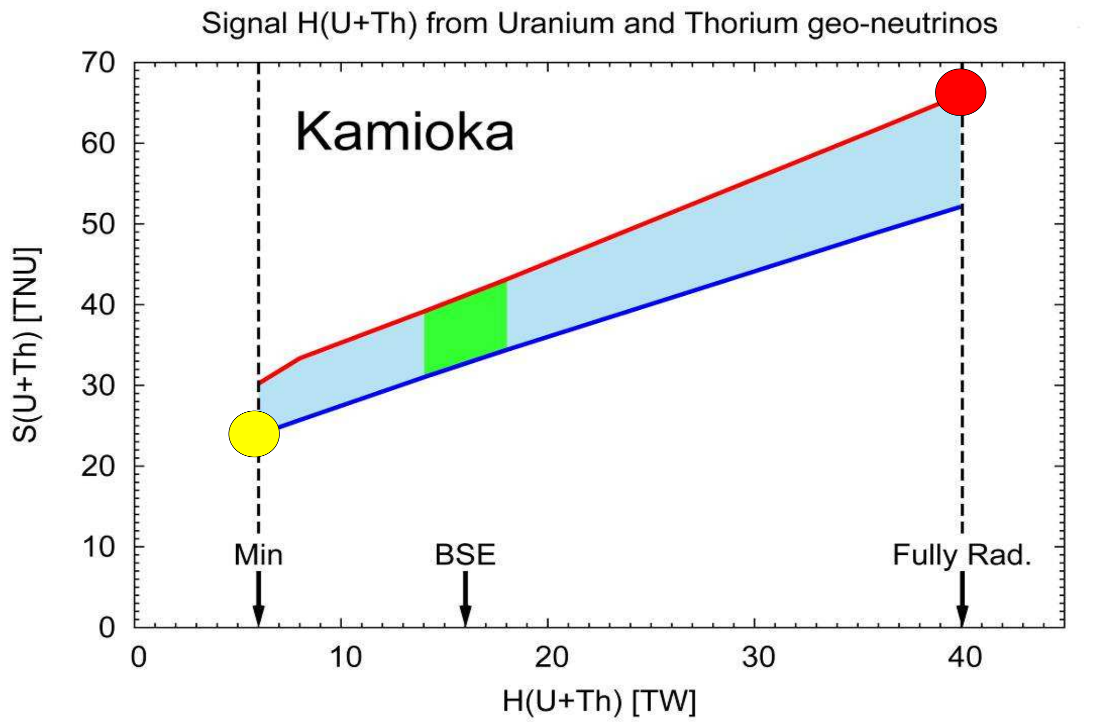
region allowed by BSE: signal between 31 and 43 TNU

region containing all models consistent with geochemical and geophysical data

U and Th measured in the crust implies a signal at least of 24 TNU

Earth energetics implies the signal does not exceed 62 TNU

Fiorentini et al. (2005)



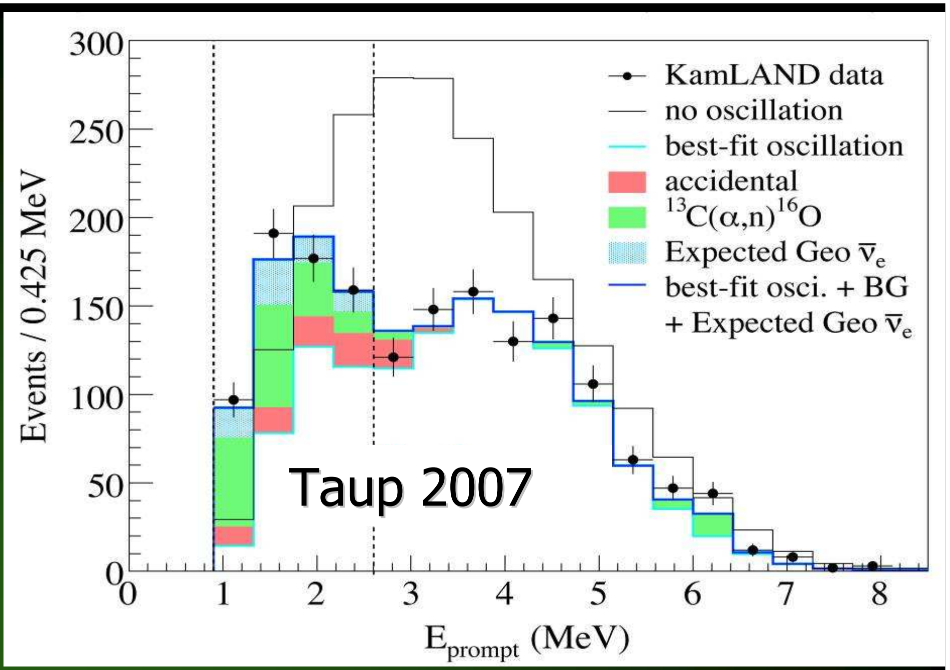
The graph is site dependent:

✓ the "slope" is universal

✓ the intercept depends on the site (crust effect)

✓ the width depends on the site (crust effect)

KamLAND 2002-2007 results on geo-neutrino



- **In five years data ~ 630 counts in the geo-ν energy range:**

~ 340 reactors antineutrinos

~ 160 fake geo-ν, from $^{13}C(\alpha,n)$

~ 60 random coincidences

- ~ 70 **Geo-neutrino events are obtained from subtraction.**
- **Adding the "Chondiritic hypoythesis" for U/Th:**

N (U+Th)=75±27

- **This pioneering experiment has shown that the technique for identifying geo-neutrinos is now available!!!**

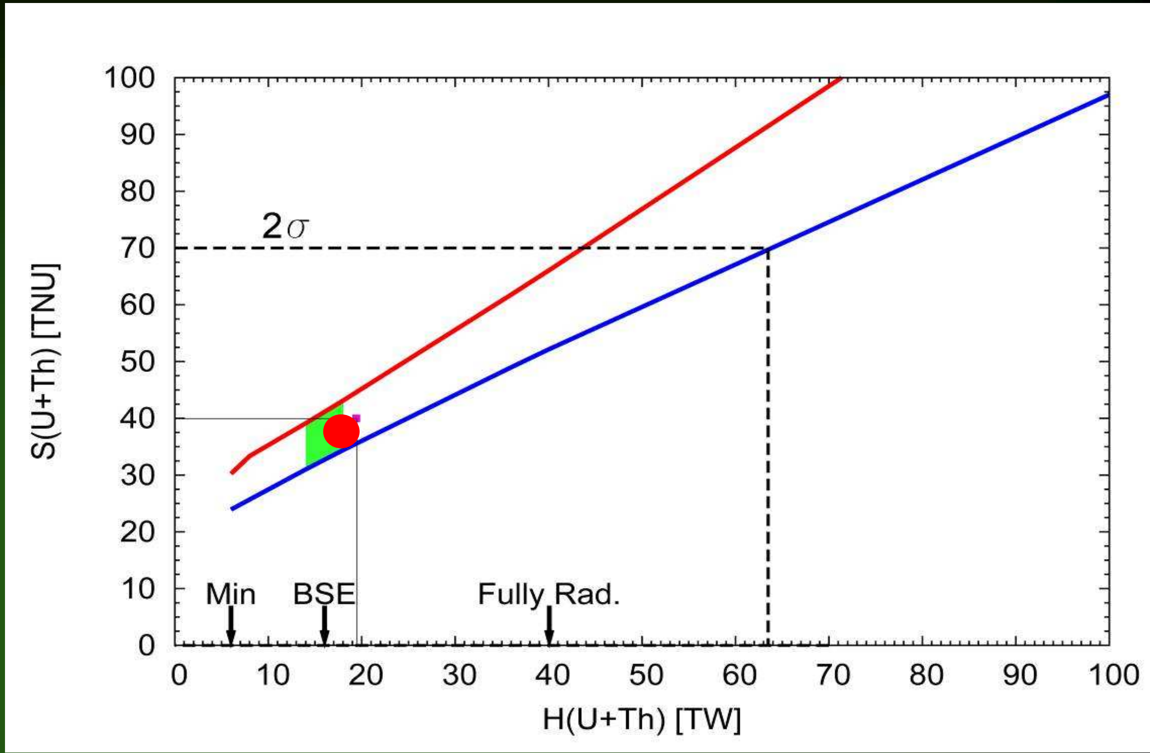
Implications of KamLAND result

- The KamLAND signal **39±15 TNU** is in perfect agreement with BSE prediction.

- It is consistent within 1σ with:

-Minimal model

-Fully radiogenic model



- Concerning radiogenic heat, the 95% CL upper bound on geo-signal translates into* H(U+Th)<65 TW

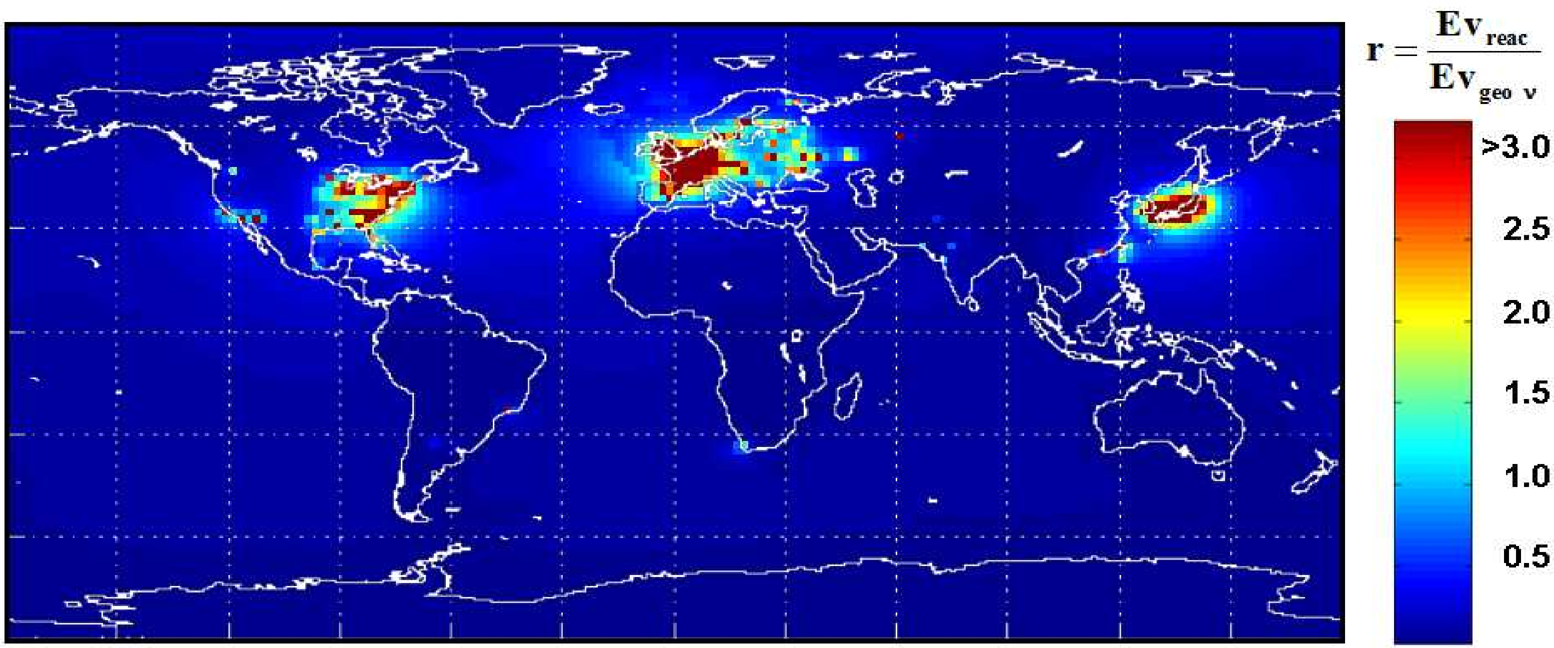
** G. Fiorentini et al. - Phys.Lett. B 629 – 2005 - hep-ph/0508048*

Nuclear reactors: the enemy of geo-neutrinos

$$r = \frac{\mathrm{Events}_{\mathrm{reactors}}}{\mathrm{Events}_{\mathrm{geo}\ \nu}}$$

In the geo-neutrino energy window

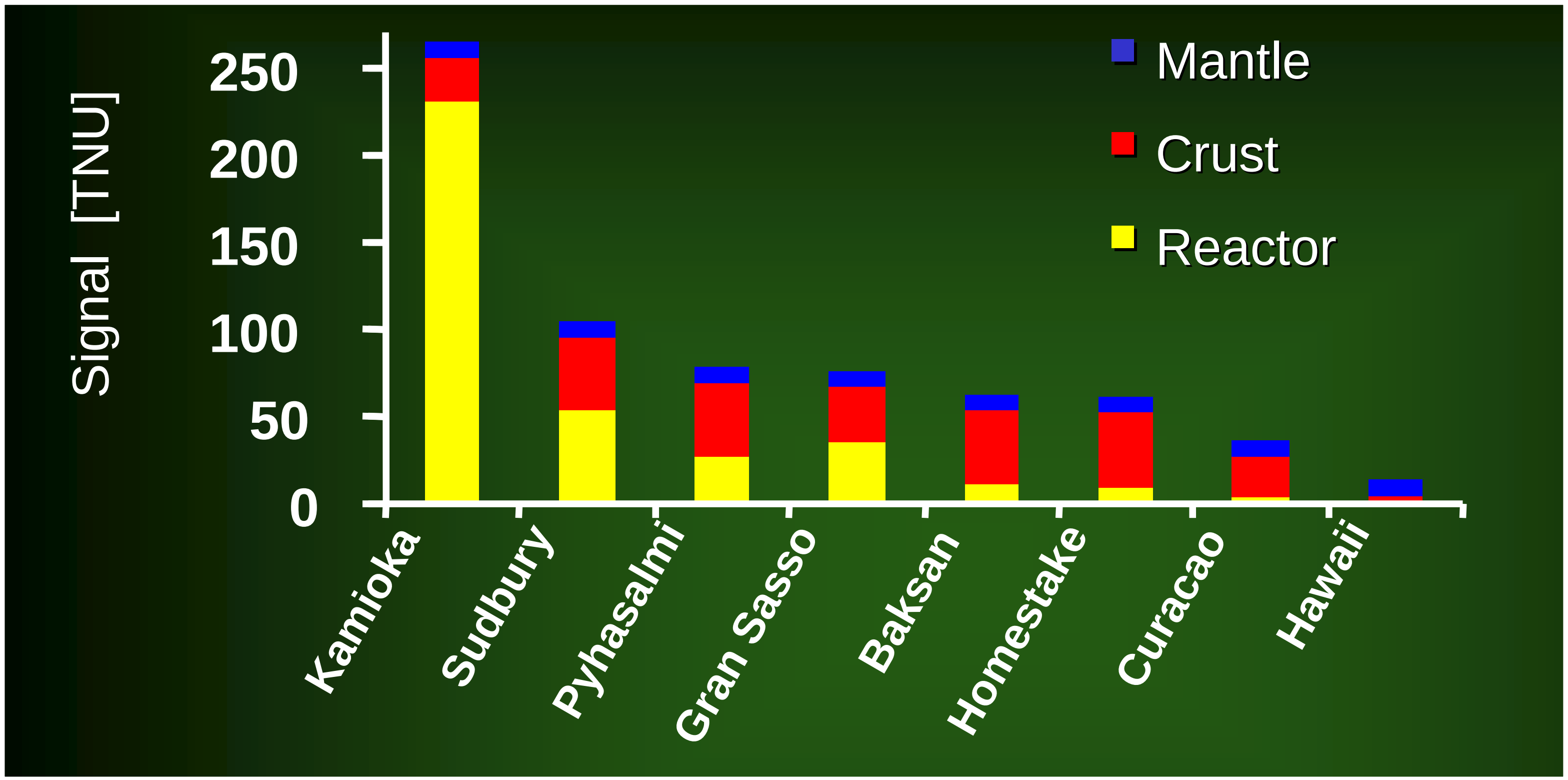
	r
Kamioka	6.7
Sudbury	1.1
Gran Sasso	0.9
Pyhasalmi	0.5
Baksan	0.2
Homestake	0.2
Hawaii	0.1
Curacao	0.1

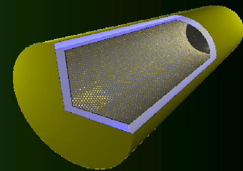


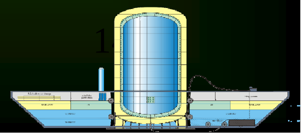
- Based on IAEA Database (2000)
- All reactors at full power

Fiorentini et al - Earth Moon Planets - 2006

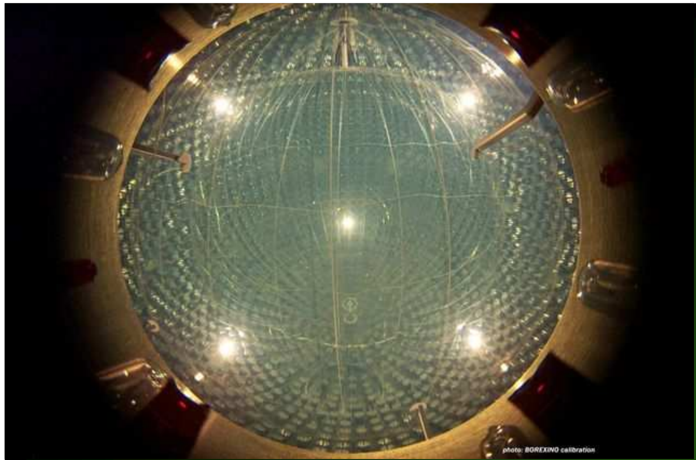
Running and planned experiments





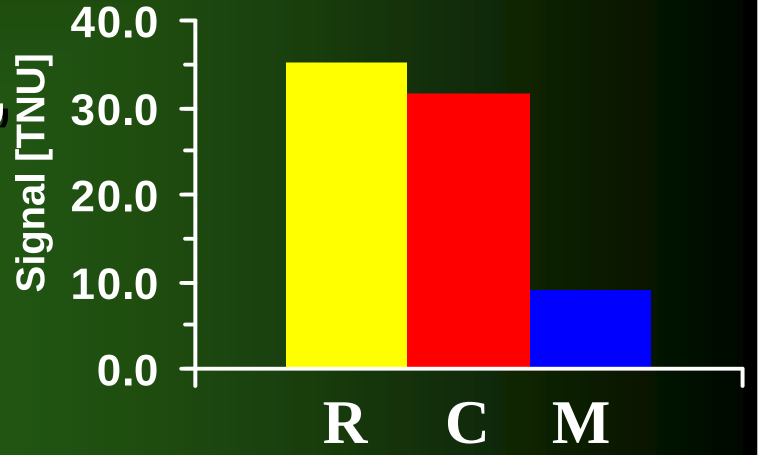


- **Several experiments, either running or under construction or planned, have geo-ν among their goals.**
- **Figure shows the sensitivity to geo-neutrinos from crust and mantle together with reactor background.**

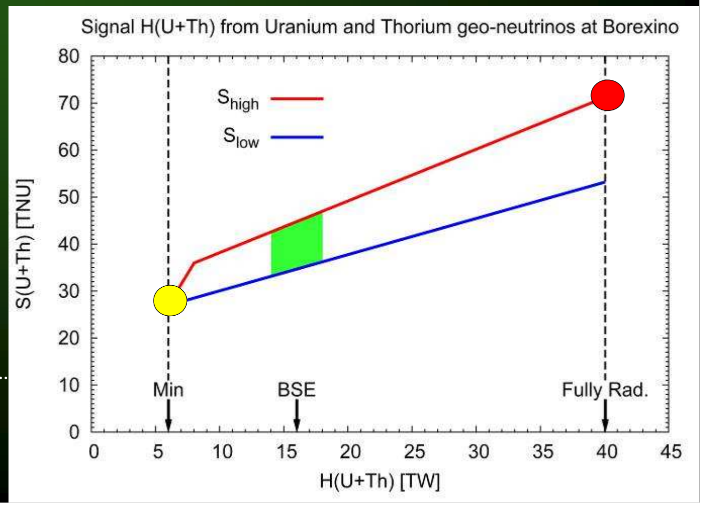


Borexino at Gran Sasso

- A 300-ton liquid scintillator underground detector, **running** since may 2007.



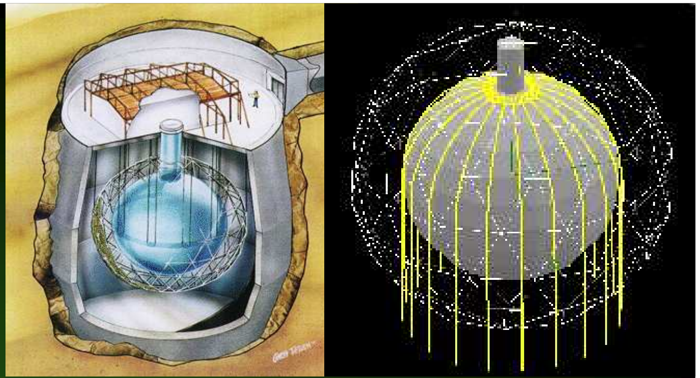
- Signal, mainly generated from the crust, is comparable to reactor background.
- From BSE expect 5 – 7 events/year*
- In about two years should get 3σ evidence of geo-neutrinos.



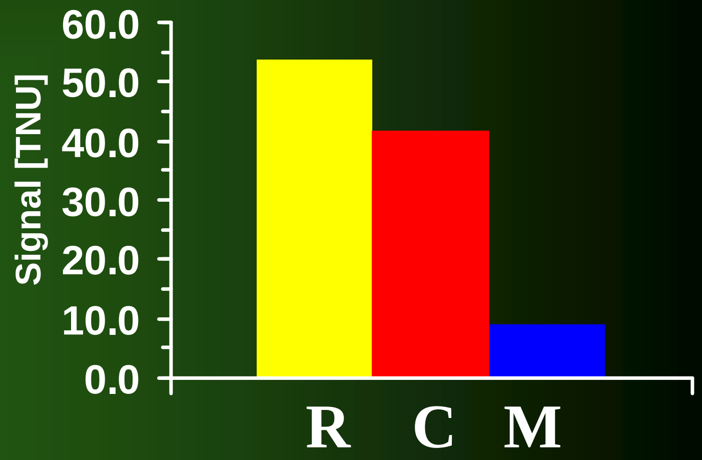
* For 80% eff. and 300 tons C_9H_{12} fiducial mass

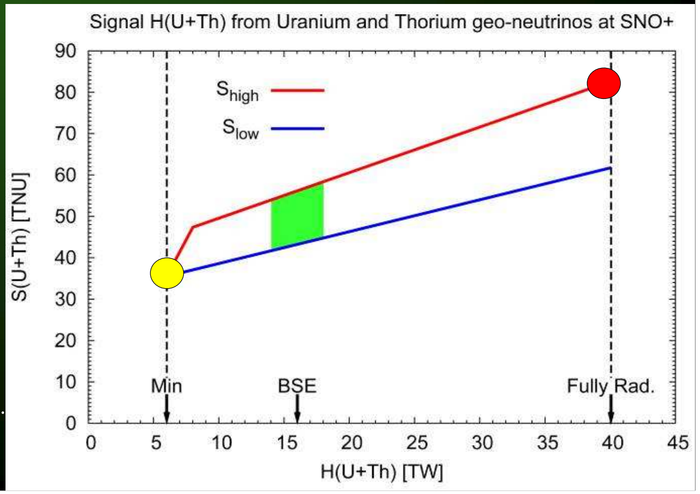
Borexino collaboration - European Physical Journal C 47 21 (2006) - arXiv:hep-ex/0602027

SNO+ at Sudbury



- A 1000-ton liquid scintillator underground detector, obtained by replacing D_2O in SNO.
- The SNO collaboration has planned to fill the detector with LS in 2009
- 80% of the signal comes from the continental crust.
- From BSE expect 28 – 38 events/year*
- It should be capable of measuring U+Th content of the crust.





* assuming 80% eff. and 1 kTon CH_2 fiducial mass

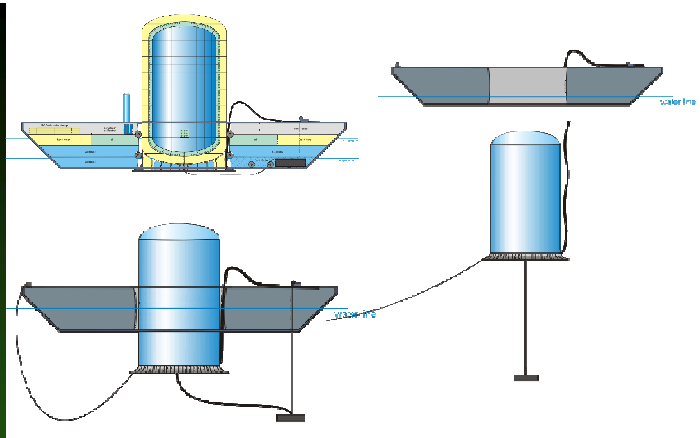
Chen, M. C., 2006, Earth Moon Planets 99, 221.

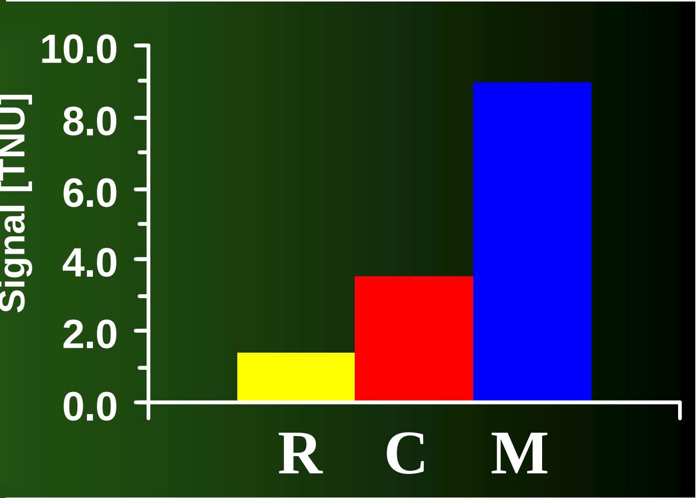
Hanohano at Hawaii

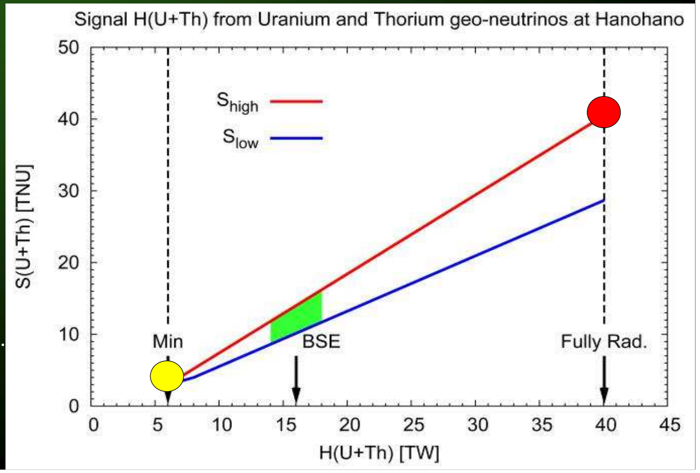
- Project of a 10 kiloton movable deep-ocean LS detector
- ~ 70% of the signal comes from the mantle
- From BSE expect 60 – 100 events/year*
- It should be capable of measuring U+Th content of the mantle

* assuming 80% eff. and 10 kTon CH_2 fiducial mass

J. G. Learned et al. – ``XII-th International Workshop on Neutrino Telescope", Venice, 2007

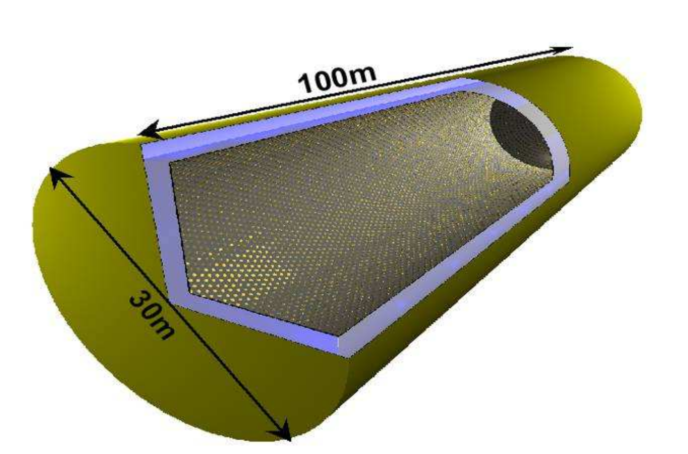


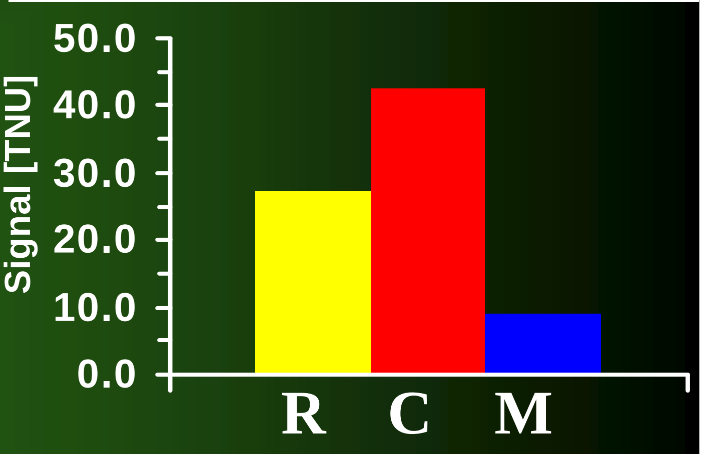


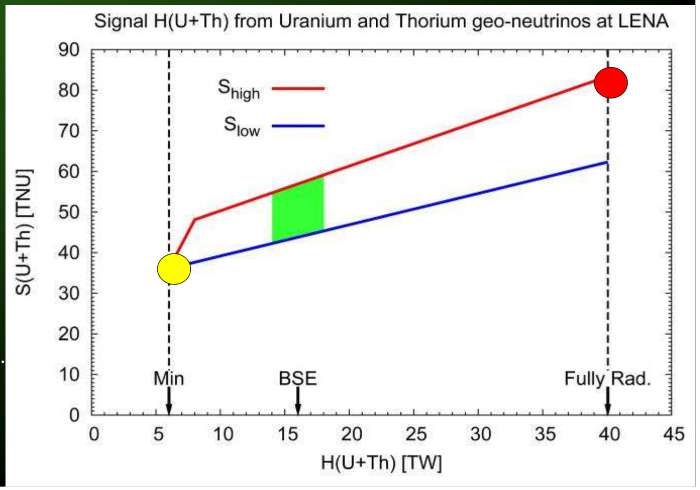


LENA at Pyhasalmi

- Project of a **50** kiloton underground liquid scintillator detector in Finland
- 80% of the signal comes from the crust
- From BSE expect **800 – 1200** events/year*
- LS is loaded with 0.1% Gd which provides:
  - better neutron identification
  - moderate **directional** information







* For 2.5 10^{33} free protons and assuming 80% eff.

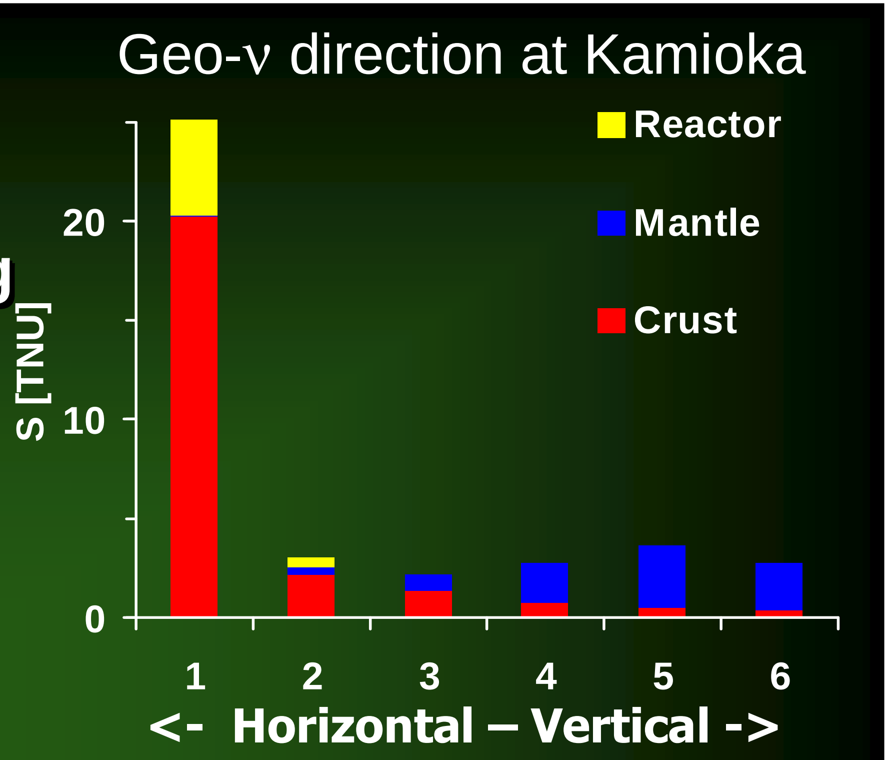
K. A. Hochmuth et al. - Astropart.Phys. 27 (2007) - arXiv:hep-ph/0509136 ; Teresa Marrodan @ Taup 2007

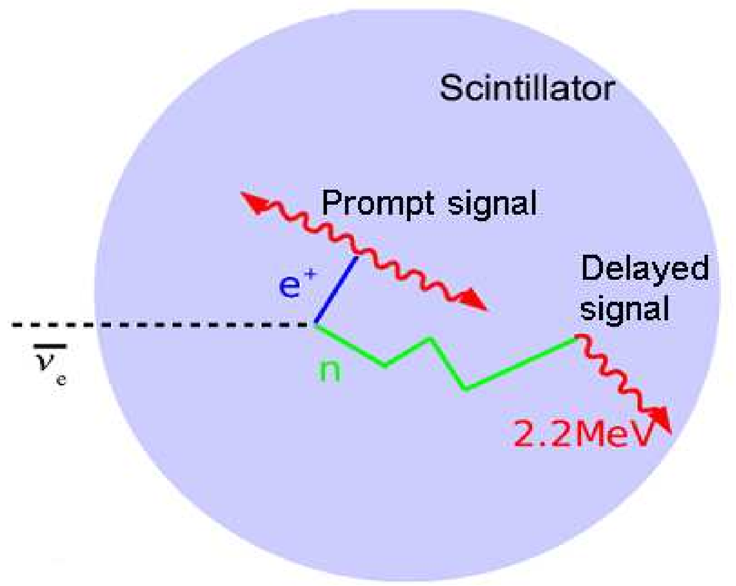
Move the mountain or the prophet?

- Geo-ν direction knows if it is coming from reactors, crust, mantle…
- Even a moderate directional information would be sufficient for source discrimination.
- $\vec{P}$ conservation implies the neutron starts moving "forwards"

  angle (geo-ν, n) < 26^0

- Directional information however is degraded during neutron slowing down and thermal collisions, but is not completely lost…

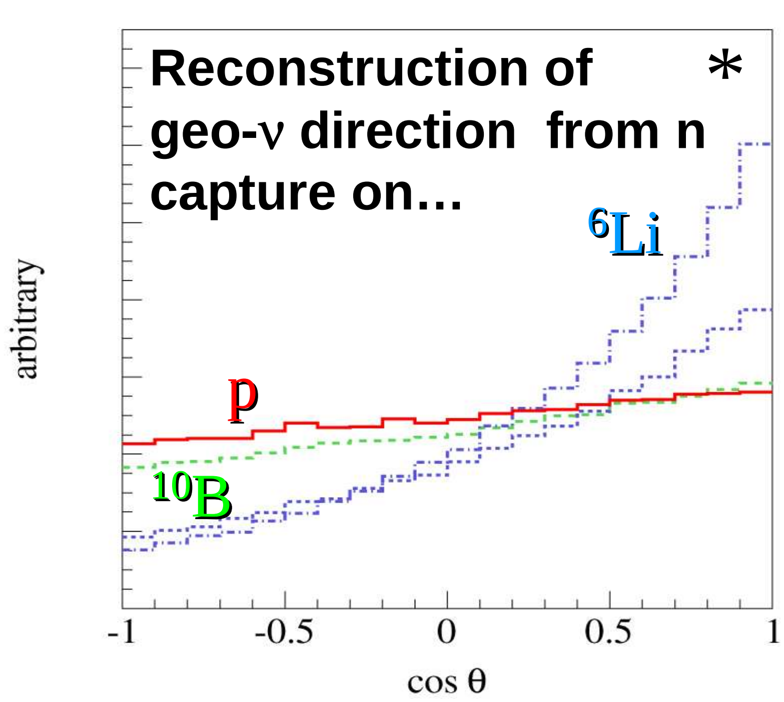


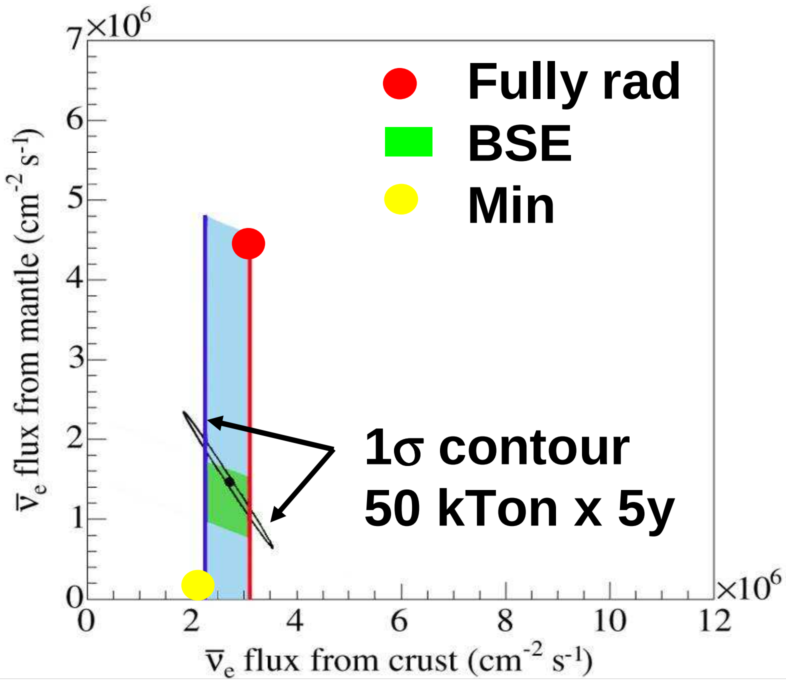


A shortcut in the roadmap?

- Reconstruction of geo-ν direction with Gd, Li and B loaded LS is being investigated by several groups. (See Shimizu*, Domogatsky et al., Hochmuth et al., nice_lady.nice_job@this.conf)
- A 50 kTon 1.5% ^{6}Li loaded LS in 5 years could discriminate crust and mantle contribution at the level of BSE prediction.

A. Suzuki: "…direction measurement is the most urgent task in future geo-neutrino experiments"

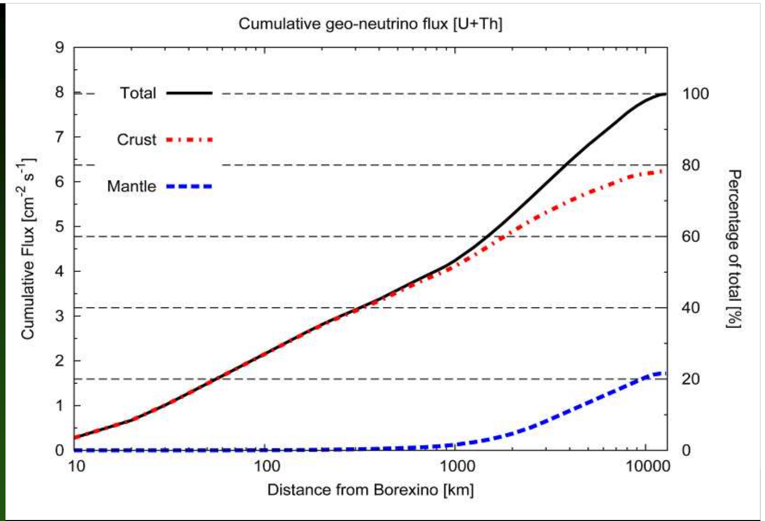




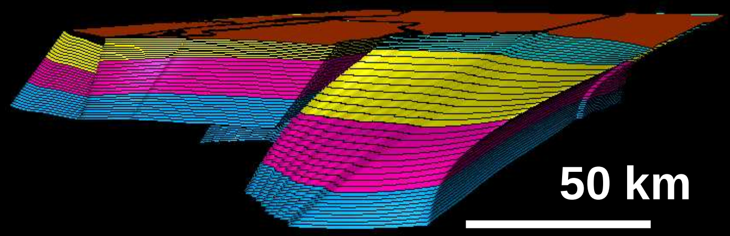
What is needed for interpreting experimental data?

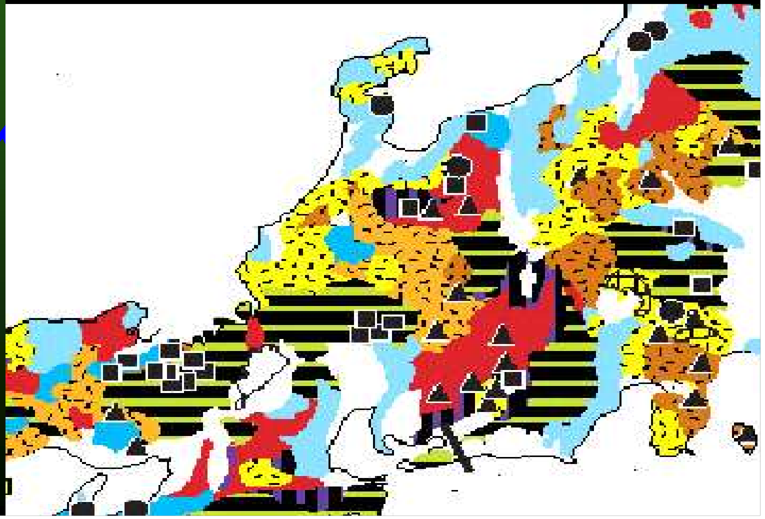
➡ Regional geology

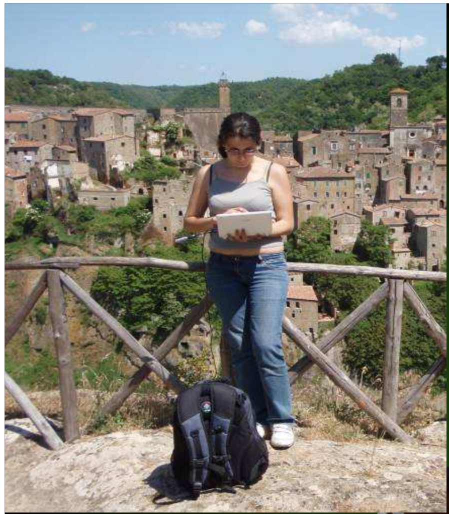
- A geochemical and geophysical study of the region (~ 200 km) around the detector is necessary for extracting the global information from the geo-neutrino signal.
- This study has been performed for Kamioka (Fiorentini et al., Enomoto et al.), it is in progress (on geological times scale) for Gran Sasso and is necessary for the other sites.



Crustal 3D model of Central Italy

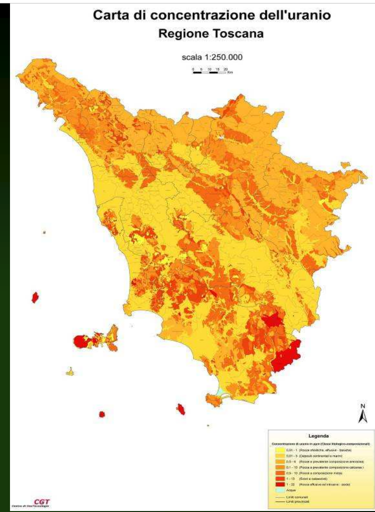






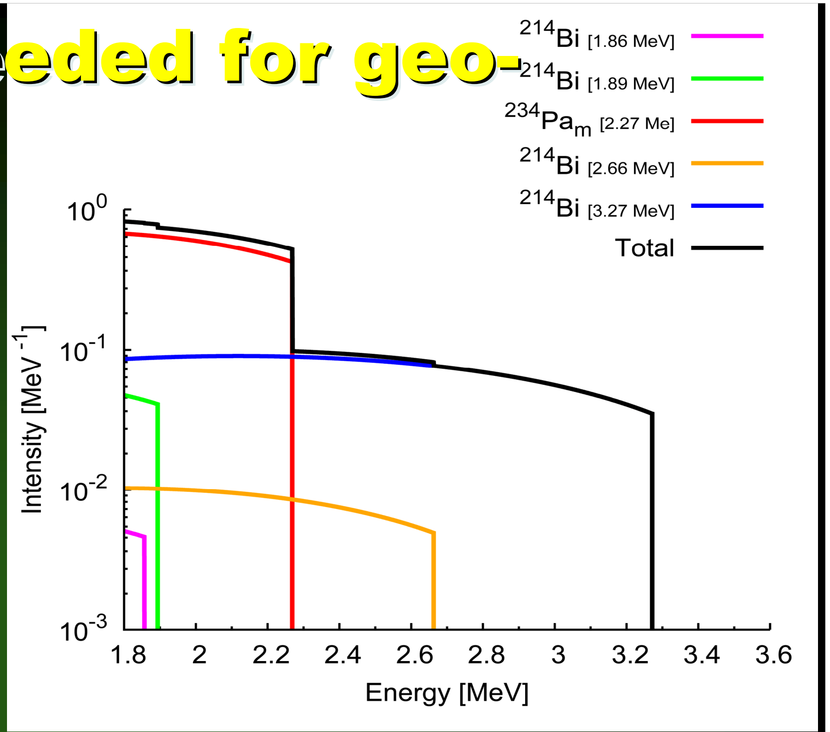
Practical application (I)

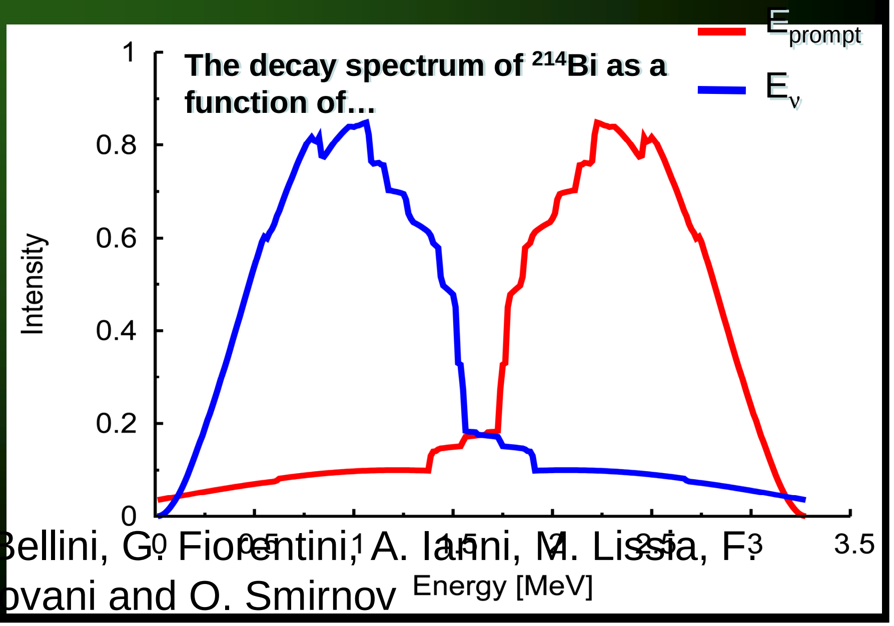
Map of natural radioactivity of Tuscany soil



Nuclear physics inputs needed for geo-neutrino studies*

- Neutrino spectra are necessary for calculating the geo-neutrino signal. So far, they are derived from theoretical calculations. We propose to measure them directly.
- For each nuclear decay, the neutrino energy E_ν and the "prompt energy" $E_{prompt} = T_e + E_\gamma$ are fixed by energy conservation: $Q = E_\nu + E_{prompt}$
- Measure E_{prompt} and will get E_ν
- With CTF @ LNGS a method for experimental determination of geo-neutrino spectra has been developed measuring the "prompt energy" of ^{214}Bi decay





* G. Bellini, G. Fiorentini, A. Ianni, M. Lissia, F. Mantovani and O. Smirnov

Study of ^{214}Bi decay with CTF @ LNGS

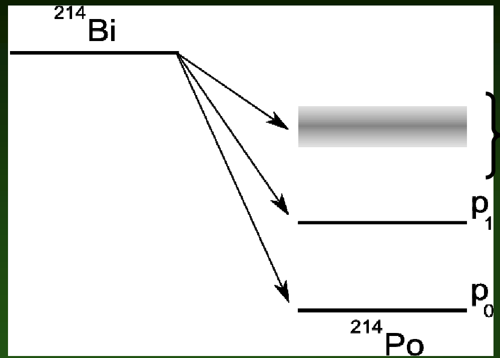
✓ Geo-neutrinos are produced through β and β-γ transitions:

$$X \rightarrow X' + e + \bar{\nu}_e \qquad X \rightarrow X'^{*} + e + \bar{\nu}_e$$
$$\hookrightarrow X' + n\gamma$$

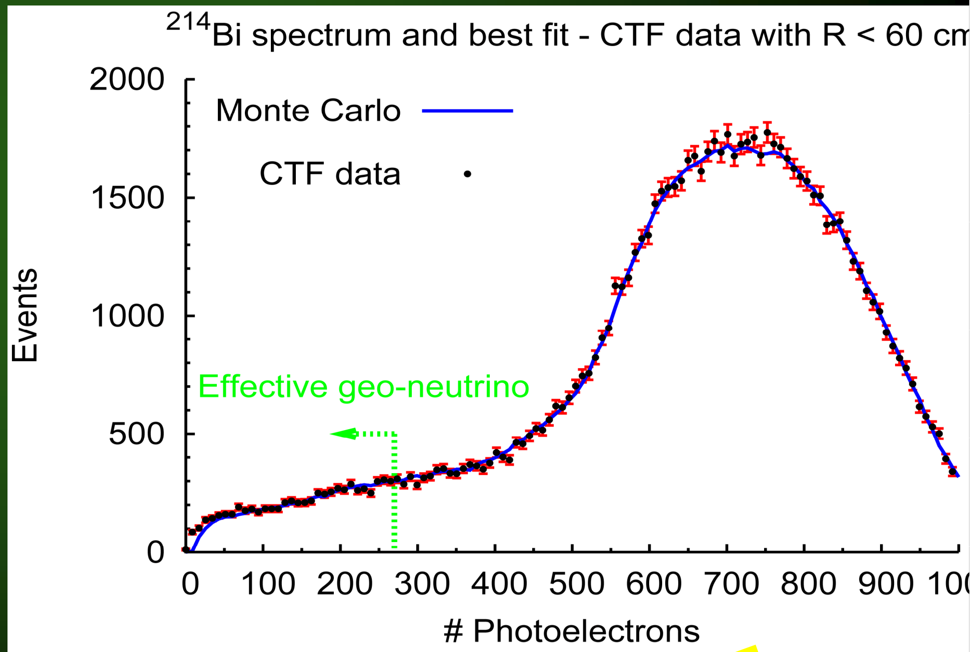
✓ **For geo-neutrino studies only the ground and first excited state are relevant.**

✓ **By using data from a ^{222}Rn contamination of CTF, we measured the feeding probabilities p_0 and p_1 of these states.**

✓ **The result is consistent and of comparable accuracy with that found in Table of Isotopes (derived from indirect measurements of γ line intensities and theoretical assumptions)**



E_γ(max) [keV]	S_{U+Th}(%)
… 1894	0
2663	1.6
3272	46



	CTF	[illegible]I
p_0	0.174 [illegible]	0.182 ± 0.006
p_1	0.021 [illegible].005	0.017 ± 0.006

preliminary

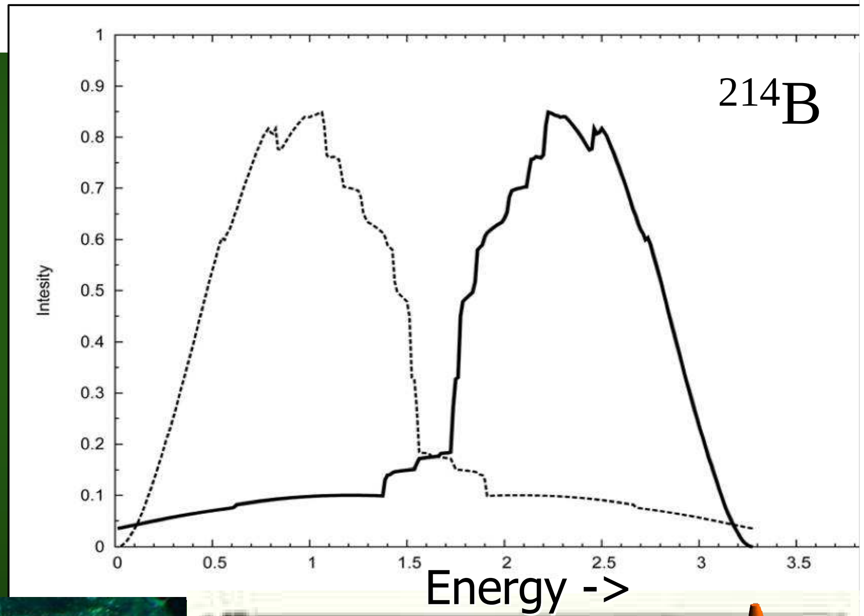
Nuclear physics inputs needed for geo-neutrino studies *

G Bellini[1,2], G Fiorentini[3,4], A Ianni[5], M Lissia[6], F Mantovani[4,7,9] and O Smirnov[8]

Abstract. Geo-neutrino studies are based on theoretical estimates of geo-neutrino spectra. We propose a method for a direct measurement of the energy distribution of antineutrinos from decays of long lived radioactive isotopes.

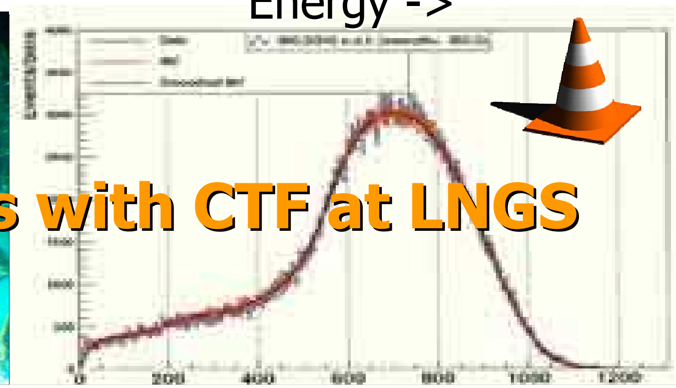
- Geo-ν are produced in β and βγ transitions

$$\boxed{\begin{aligned} X \quad \rightarrow \quad & X'^{*} + e + \overline{\nu}_{e} \\ & \hookrightarrow X' + n\,\gamma \end{aligned}}$$



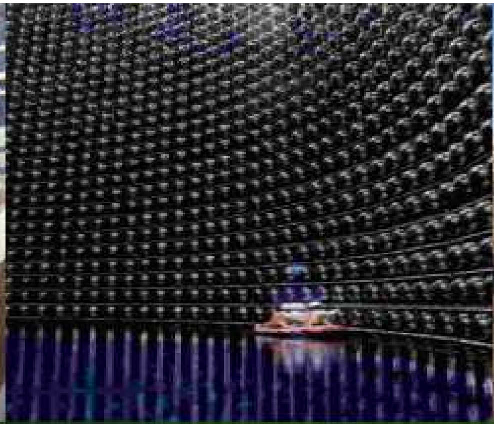
- With LS can measure the sum of energy deposited by e and γ.
- Anti-ν spectrum can thus be deduced from energy conservation

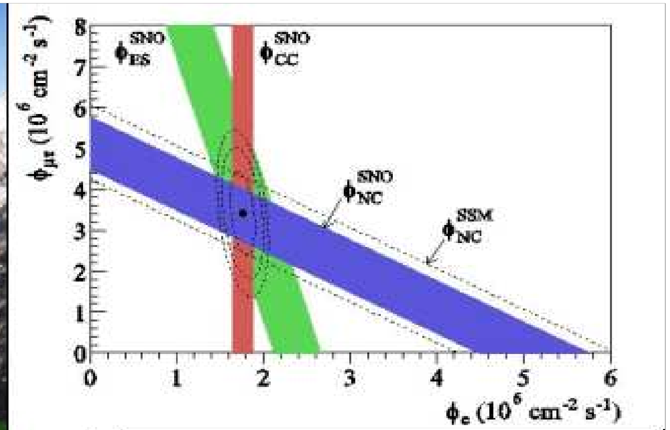
$$\boxed{Q = E_{\nu} + T_{e} + E_{\gamma}}$$



Work in progress with CTF at LNGS

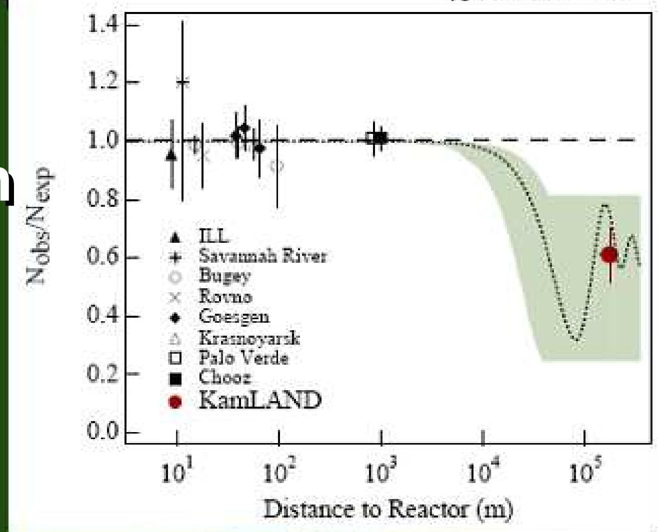
*arXiv:0712.0298v1 [hep-ph]



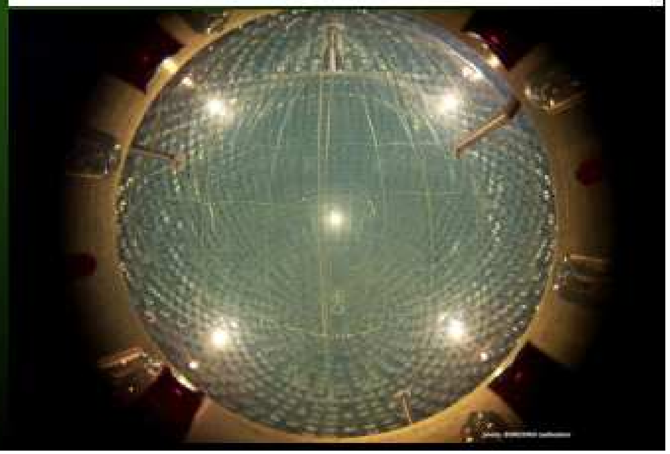
The lesson of solar neutrinos

✓ Solar neutrinos started as an investigation of the solar interior for understanding **sun energetics**.



✓ A long and fruitful detour lead to the discovery of oscillations.

✓ Through several steps, we achieved a direct proof of the solar energy source, experimental solar neutrino spectroscopy, neutrino telescopes.



The study of Earth's energetics with geo-neutrinos will also require several steps and hopefully provide surprises…