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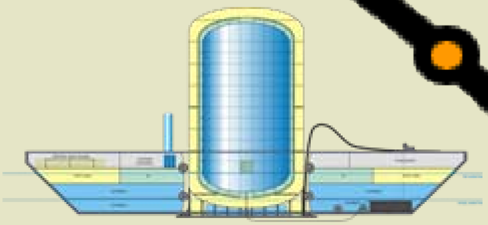
# A roadmap for geo-neutrinos: theory and experiment

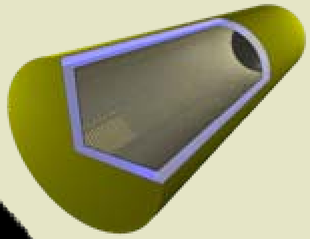
A primer,
both for Earth and nuclear scientists


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





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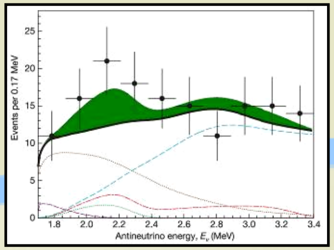
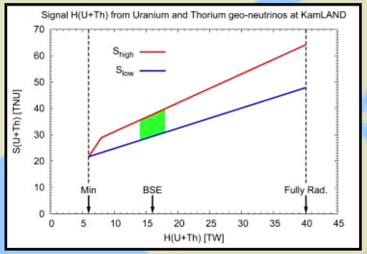
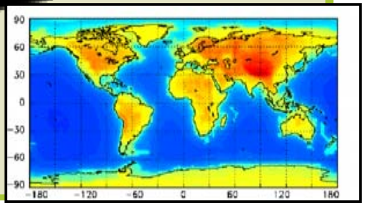


# Geo-neutrinos: anti-neutrinos from the Earth

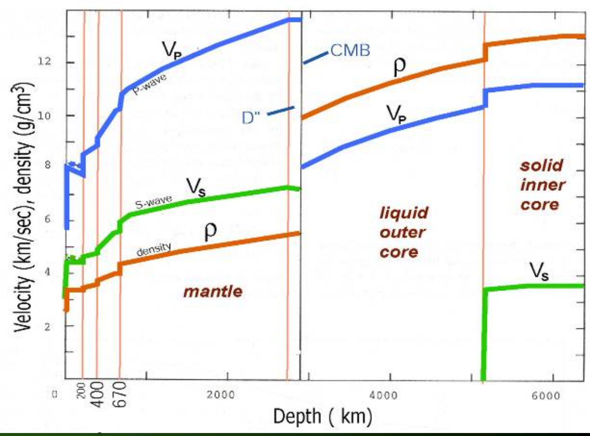
**U, Th and $^{40}$K in the Earth release heat together with anti-neutrinos, in a well fixed ratio:**

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

- Earth emits (mainly) antineutrinos $\Phi_{\bar{\nu}} \sim 10^6\,\mathrm{cm^{-2}s^{-1}}$ whereas 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

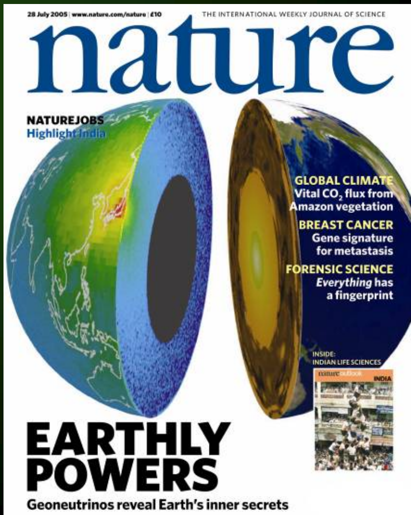
- Deepest hole is about 12 km
- Samples from the crust (and the upper portion of mantle) are available for geochemical analysis.
- Seismology reconstructs density profile (not composition) throughout all Earth.




# 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.

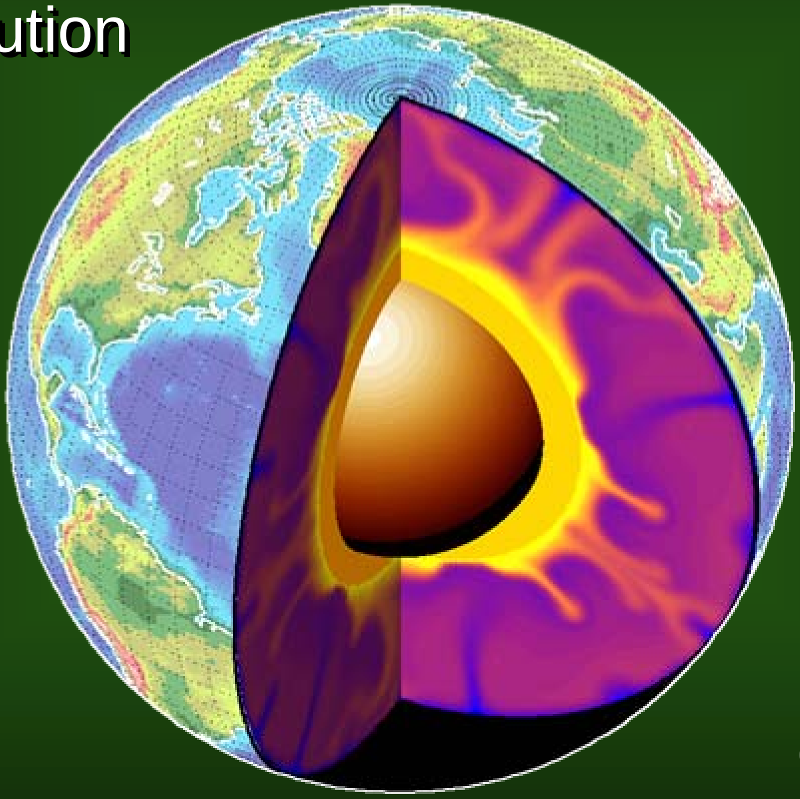


# Open questions about natural radioactivity in the Earth

**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

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

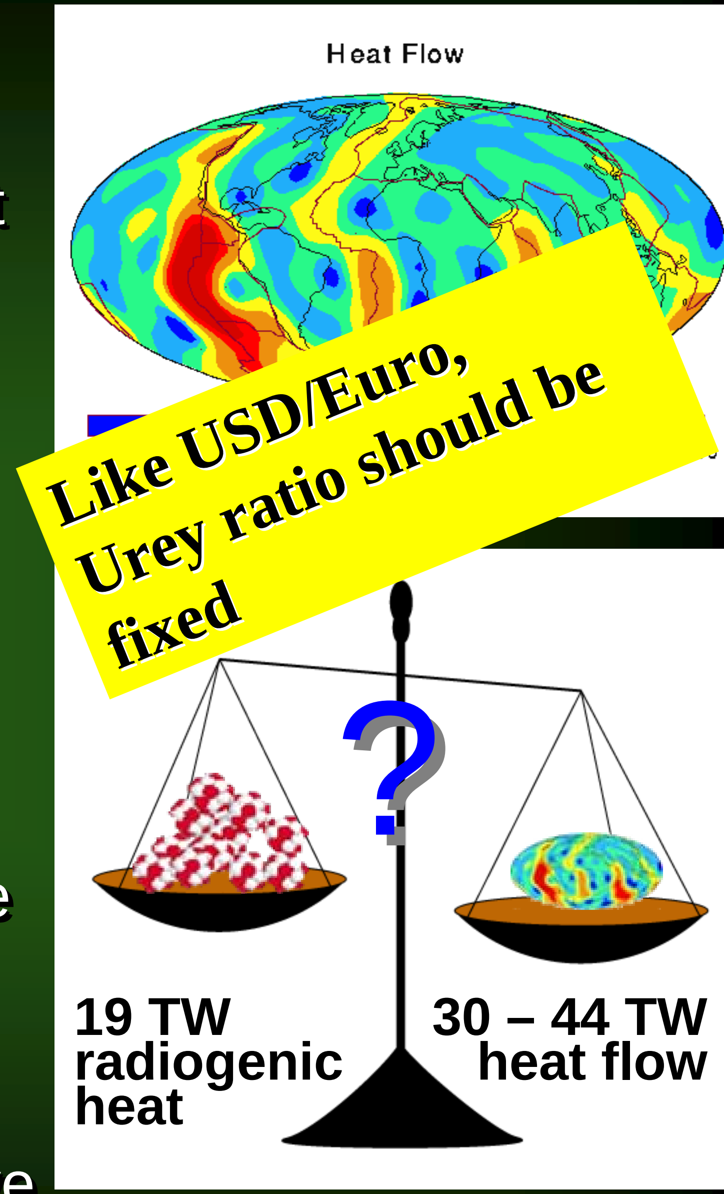
- The BSE canonical model, based on **cosmochemical** arguments, predicts a radiogenic heat production ~ 19 TW:

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

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

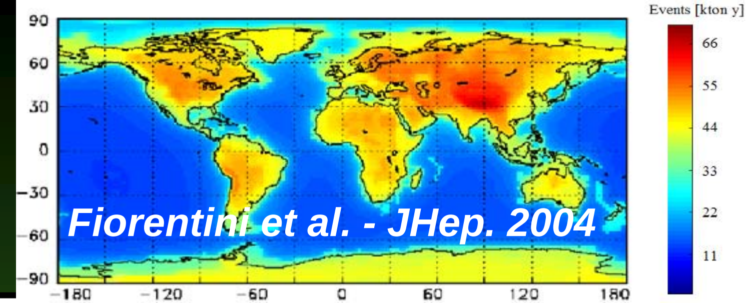
~ 0 TW **assumed** from the core

- 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

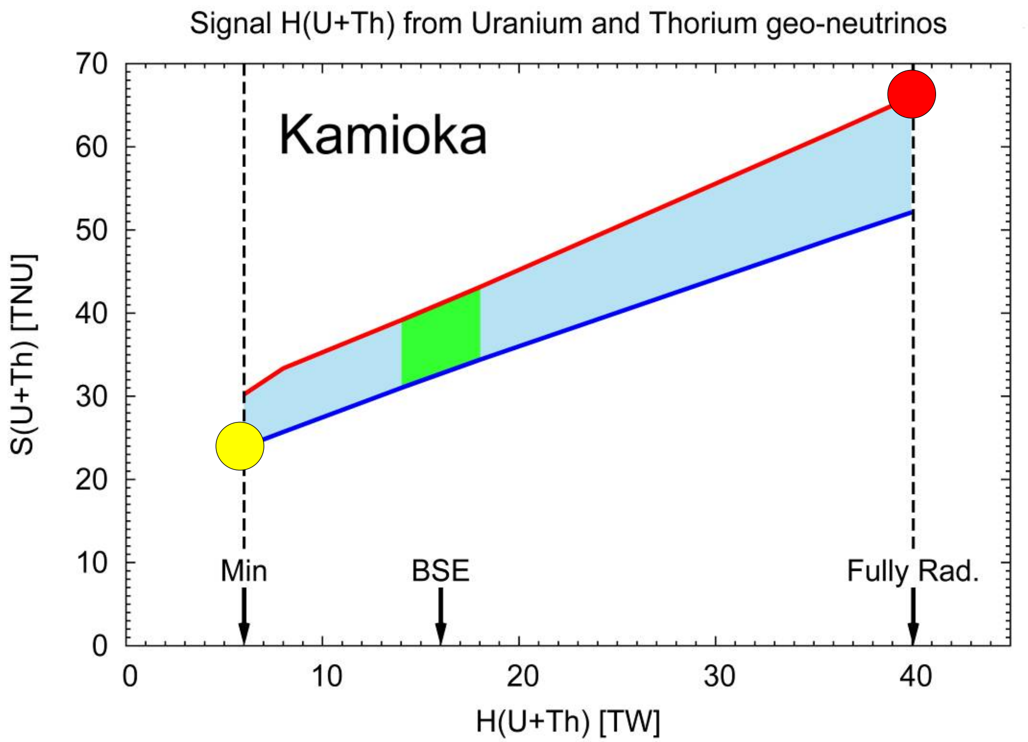
region allowed by BSE: signal between 31 and 43 TNU

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)

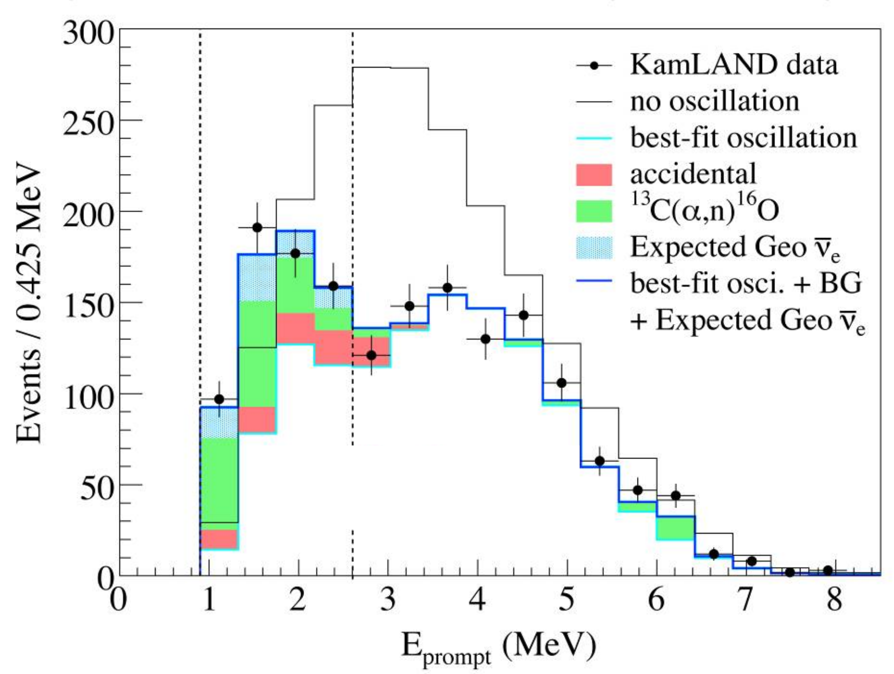
# KamLAND 2002-2007 results on geo-neutrino

- **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!!!**

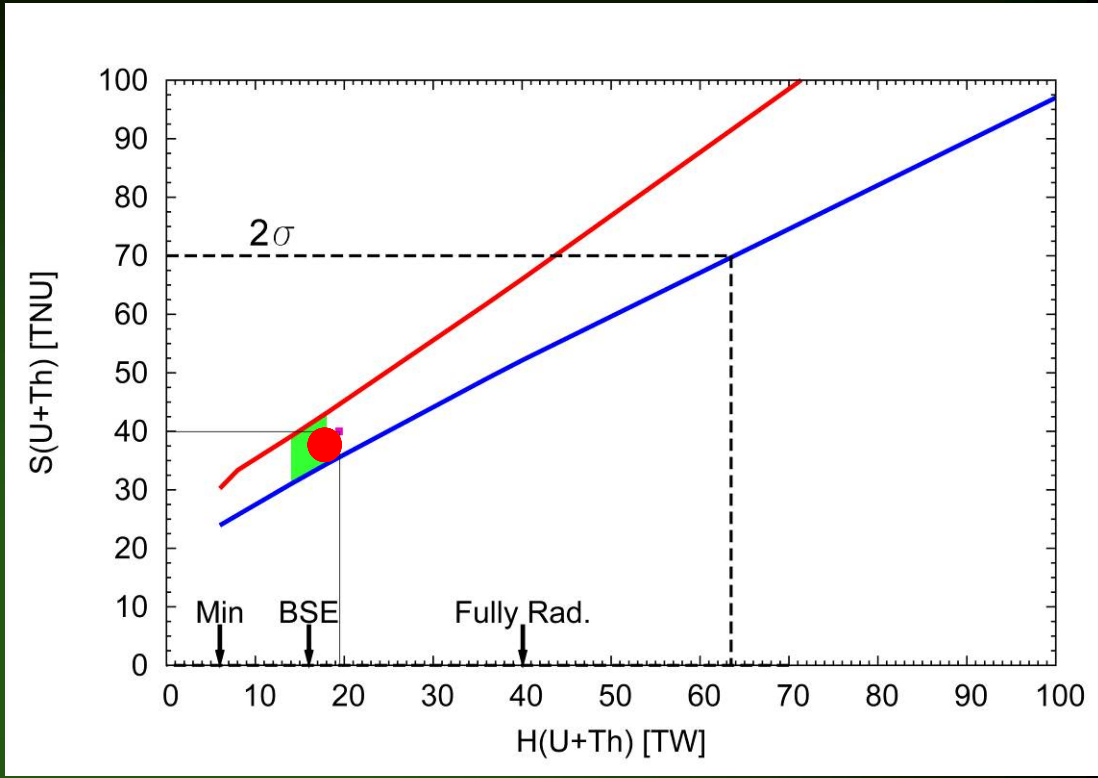
# Implications of KamLAND result

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

- **It is consistent within 1$\sigma$ with:**

**-Minimal model**

**-Fully radiogenic model**




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



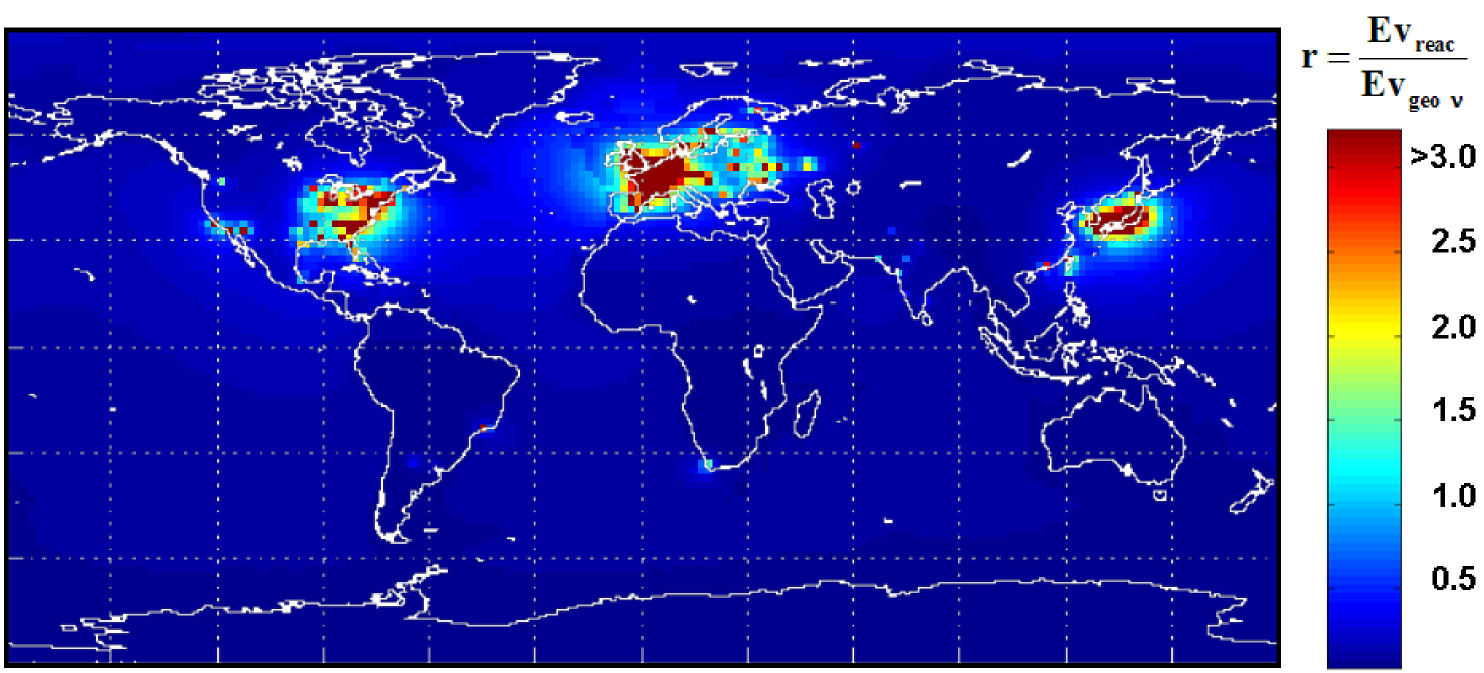
** G. Fiorentini et al. - Phys.Lett. B 629 – 2005 - hep-ph/0508048*

# Nuclear reactors: the enemy of geo-neutrinos

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

In the geo-neutrino energy window

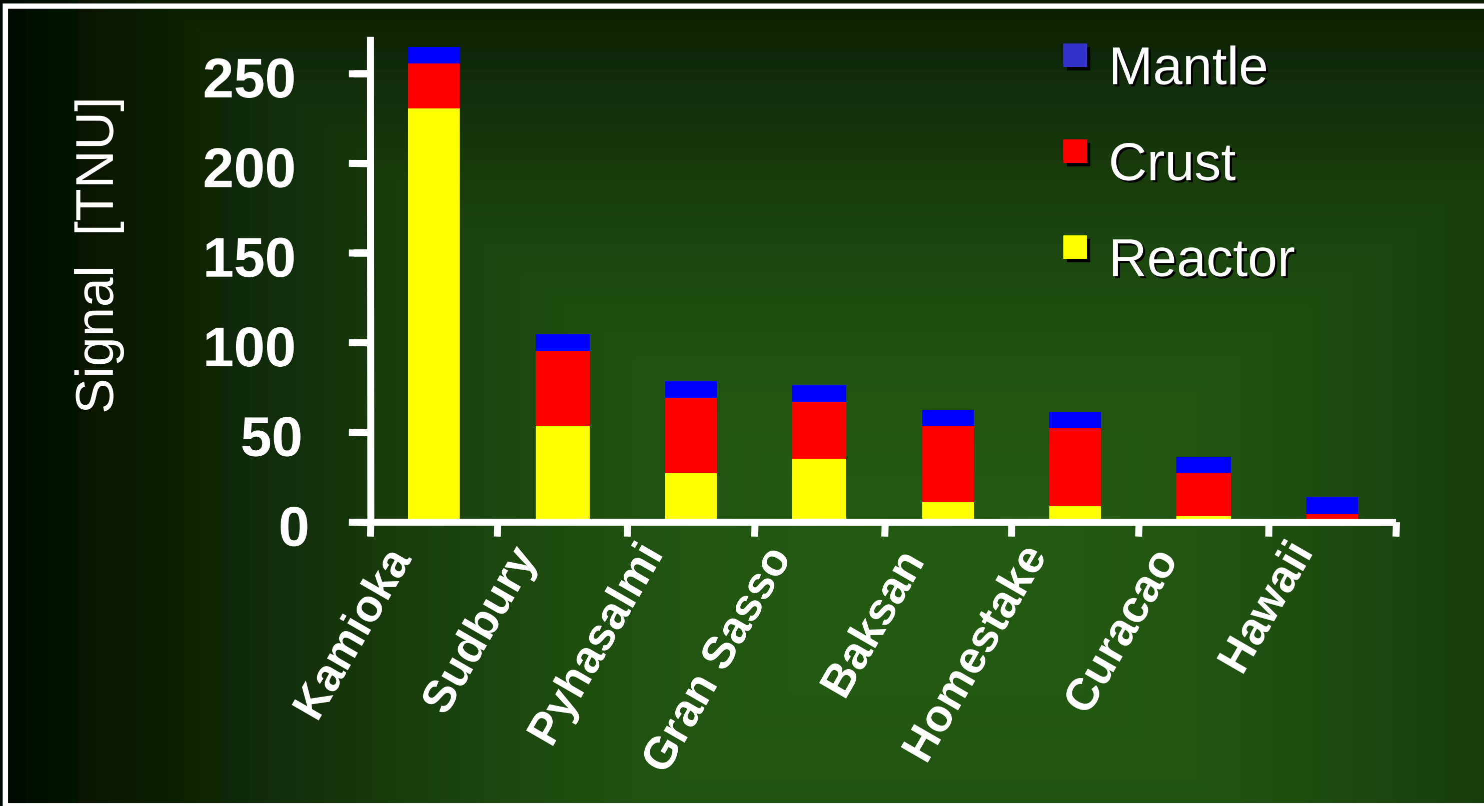
| | r |
|---|---|
| Kamioka | 6.7 |
| Sudbury | 1.1 |
| Gran Sasso | 0.9 |
| Pyhasalmi | 0.5 |
| Baksan | 0.2 |
| Homestake | 0.2 |
| Hawaii | 0.1 |
| Curacao | 0.1 |

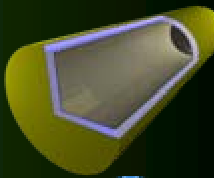



*Fiorentini et al - Earth Moon Planets - 2006*

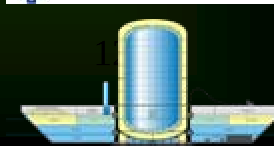
- Based on IAEA Database (2000)
- All reactors at full power

# Running and planned experiments



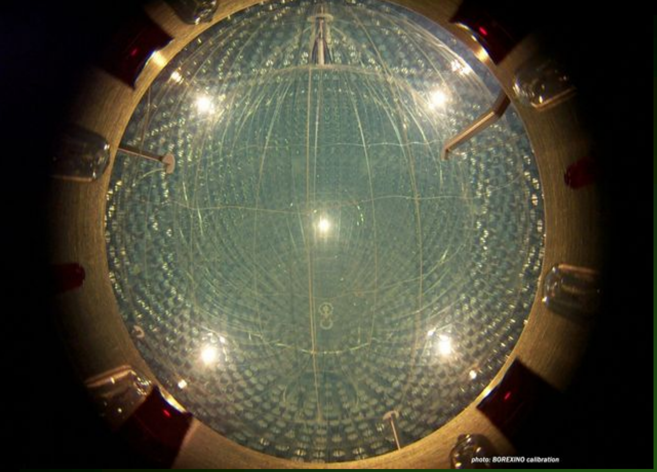




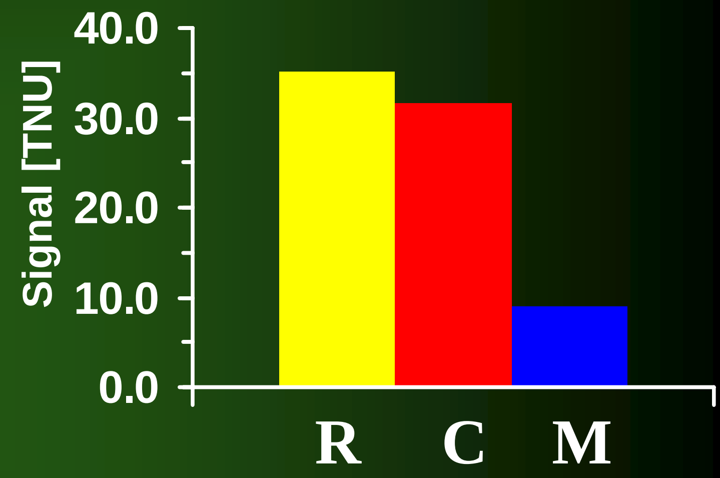
- **Several experiments, either running or under construction or planned, have geo-ν among their goals.**

- **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.

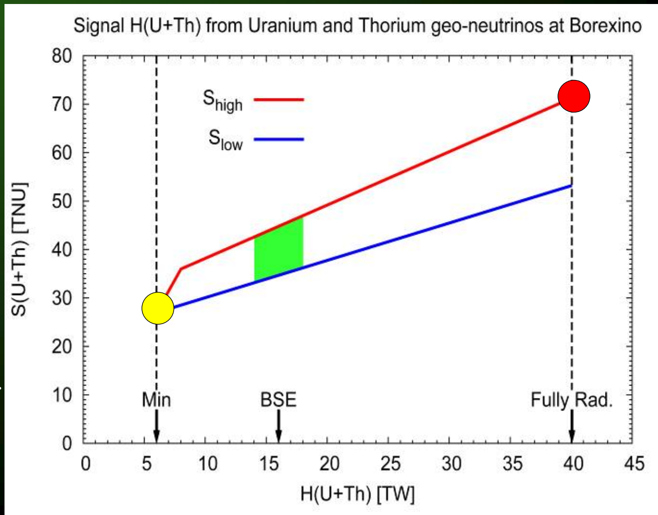



- Signal, mainly generated from the crust, is comparable to reactor background.

- From BSE expect 5 – 7 events/year*

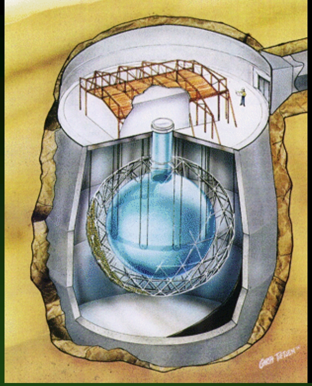
- In about two years should get 3$\sigma$ evidence of geo-neutrinos.

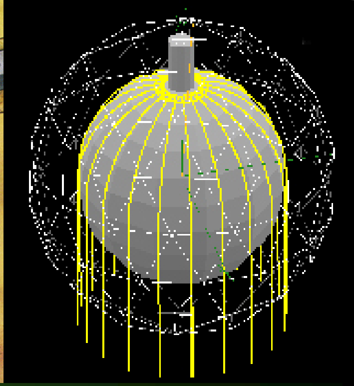
* For 80% eff. and 300 tons $C_9H_{12}$ fiducial mass



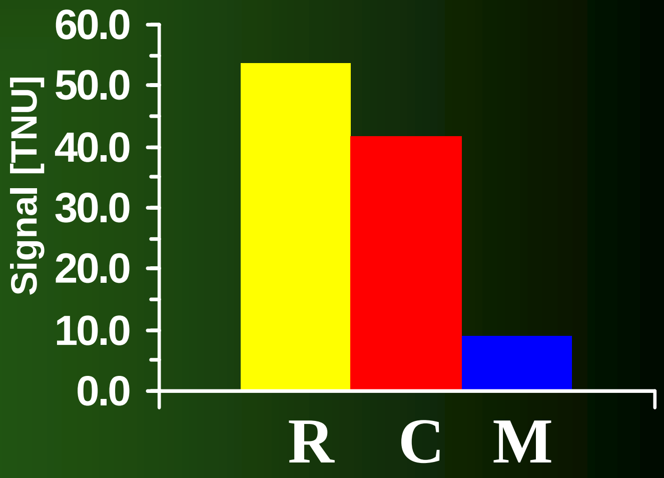

*Borexino collaboration - European Physical Journal C 47 21 (2006) - arXiv:hep-ex/0602027*

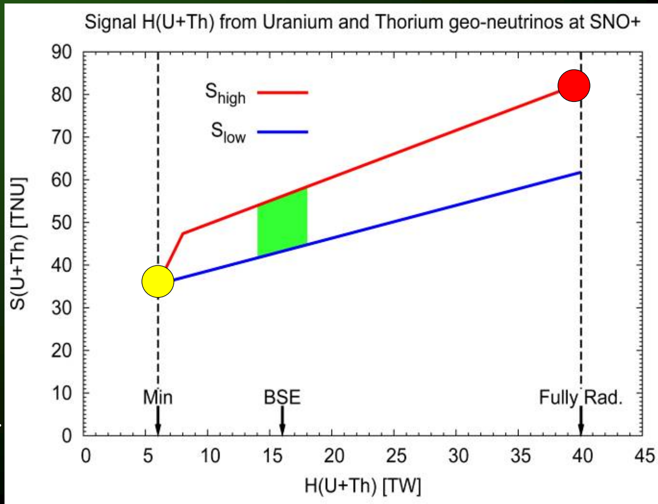
# SNO+ at Sudbury





- 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.



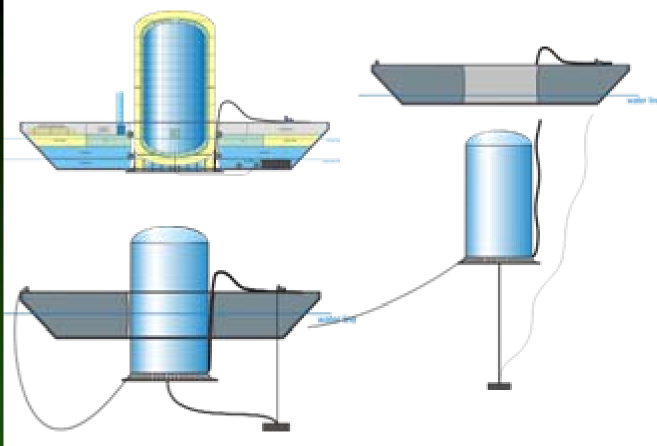



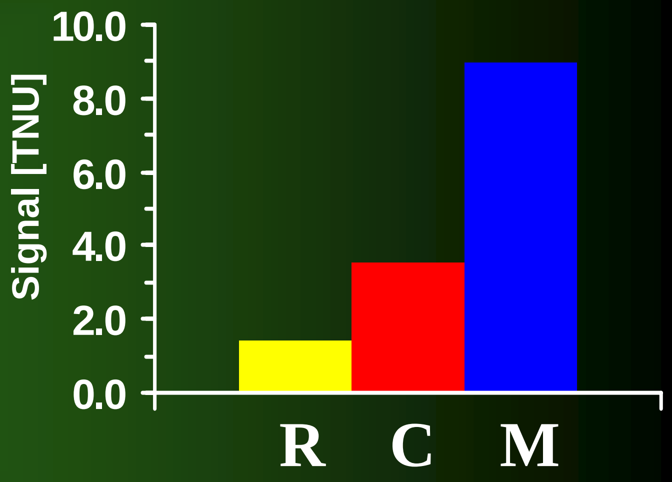

* assuming 80% eff. and 1 kTon $CH_2$ fiducial mass

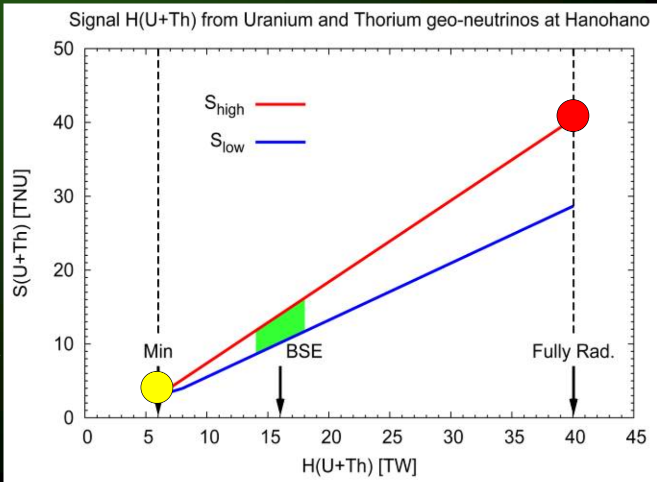
*Chen, M. C., 2006, Earth Moon Planets 99, 221.*

# 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





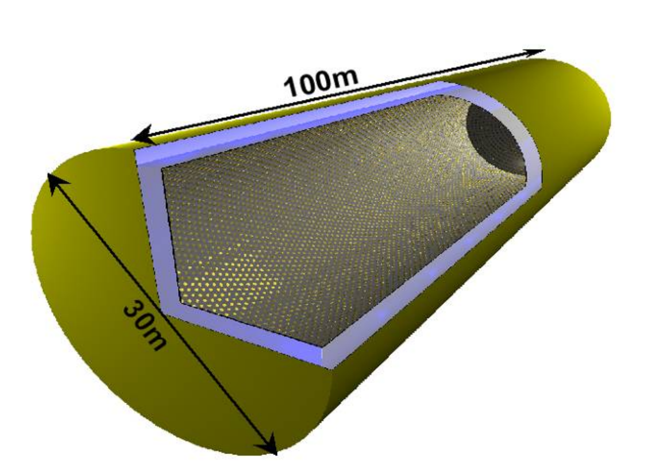



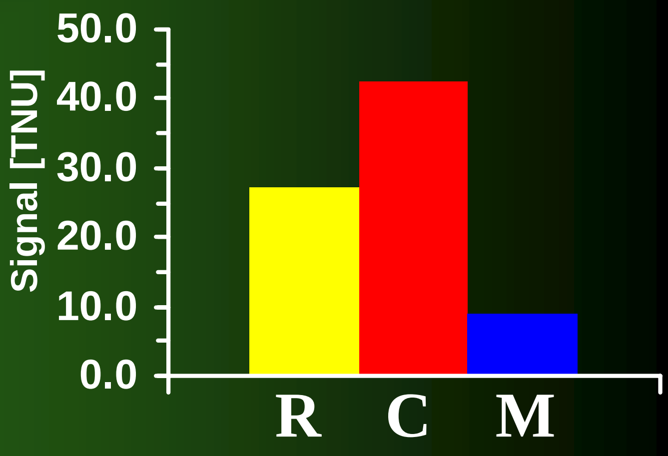

* assuming 80% eff. and 10 kTon $CH_2$ fiducial mass

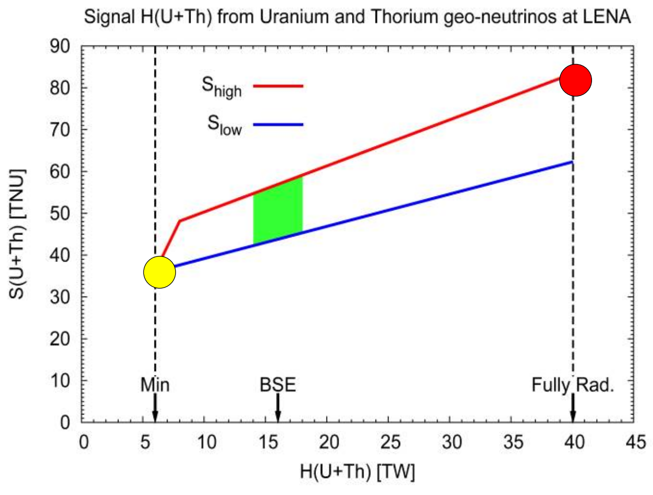
*J. G. Learned et al. – ``XII-th International Workshop on Neutrino Telescope", Venice, 2007*

# 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



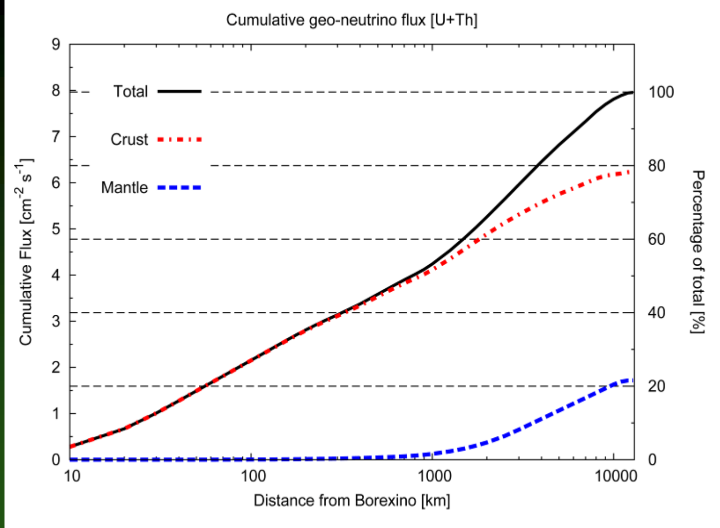

* For 2.5 $10^{33}$ free protons and assuming 80% eff.

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

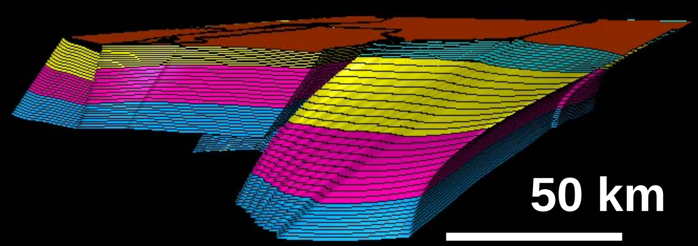
# What is needed for interpreting experimental data?

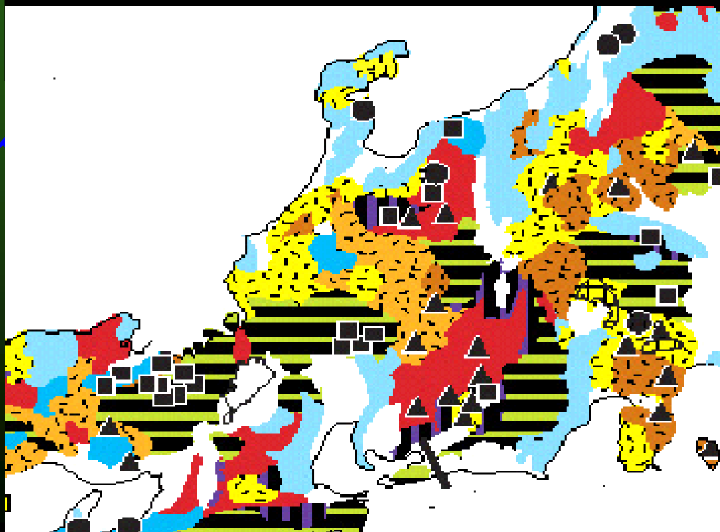
## Regional geology

- 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 just completed  for Gran Sasso and is necessary for the other sites.




Crustal 3D model of Central Italy



# A Refined Reference Model for the Geo-neutrino Signal in Borexino

R. Boraso1, M. Coltorti1, G. Di Carlo2, G. Fiorentini3,4, F. Mantovani3,4, S Mariani4,5, M. Morsilli1, S. Nisi2, A. Riva1, G. Rusciadelli6, R. Tassinari1, C. Tomei2

## Abstract

The regional contribution to the geo-neutrino signal at the Gran Sasso National Laboratory (LNGS) has been determined on the grounds of a detailed geological, geochemical and geophysical study of the region. A 3D model has been developed on an area of 2° x 2°, centred on the LNGS and identifying lower crust, upper crust and four main sediment reservoirs. For the rest of the regional area (6° x 6°) a simpler 3D model has been built, distinguishing three reservoirs only: lower crust, upper crust and sediments. Several samples from the sedimentary cover around Gran Sasso and from various crust outcrops in northern Italy were collected and their U and Th abundances have been analyzed by using ICP-MS and scintillation (NaI) methods. The results have been used to obtain estimates of U and Th abundances in the different layers of the studied area, so as to calculate the regional contribution to the geo-neutrino signal. When summed with the calculations for the rest of the world based on [Mantovani et al., 2004], we obtain our Refined Reference Model prediction for the geo-neutrino signal in the Borexino detector at LNGS: S(U)= (28.8± 3.7) TNU and S(Th)= (7.7 ± 1.0) TNU.

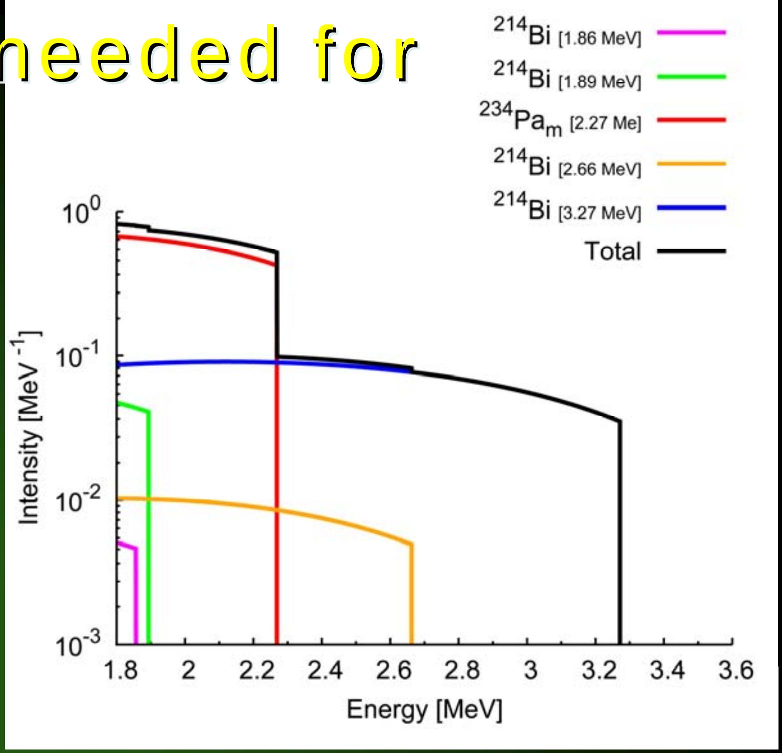
# Nuclear physics inputs needed for geo-neutrino studies*

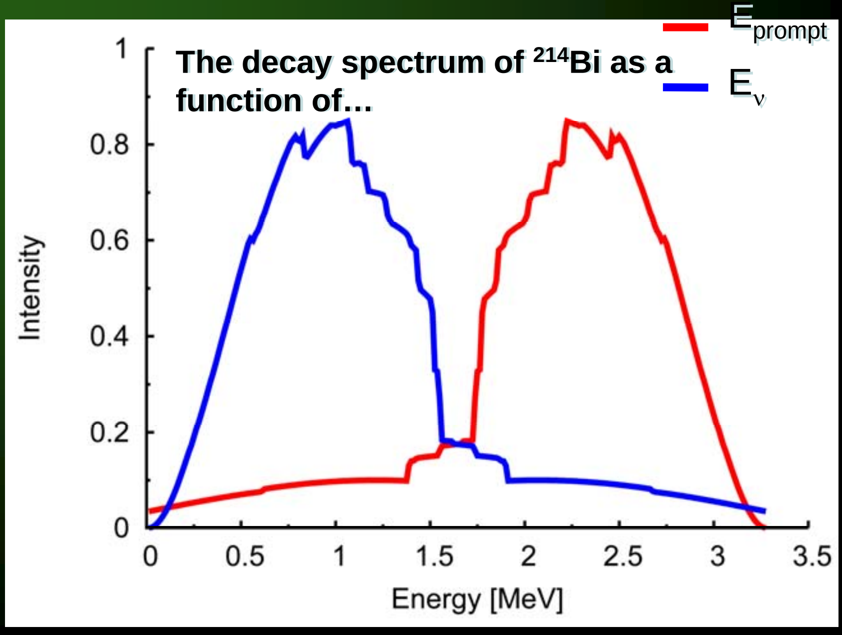
- ✓ Neutrino spectra are necessary for calculating the geo-neutrino signal. So far, they are derived from theoretical calculations. We propose to measure them directly.

- ✓ For each nuclear decay, the neutrino energy $E_\nu$ 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 $E_\nu$

- ✓ With CTF @ LNGS a method for experimental determination of geo-neutrino spectra has been developed measuring the "prompt energy" of $^{214}$Bi decay



# Nuclear physics for geo-neutrino studies*

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[10]*Joint Institute for Nuclear Research, 141980, Dubna, Russia*

(Dated: August 24th, 2009)

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. We present preliminary results for the geo-neutrinos from $^{214}$Bi decay, a process which accounts for about one half of the total geo-neutrino signal. The feeding probability of the lowest state of $^{214}$Bi — the most important for geo-neutrino signal — is found to be $p_0 = 0.177 \pm 0.004$ (stat) $^{+0.003}_{-0.001}$ (sys), under the hypothesis of Universal Neutrino Spectrum Shape (UNSS). This value is consistent with the (indirect) estimate of the Table of Isotopes (ToI). We show that achievable larger statistics and reduction of systematics should allow to test possible distortions of the neutrino spectrum from that predicted using the UNSS hypothesis. Implications on the geo-neutrino signal are discussed.

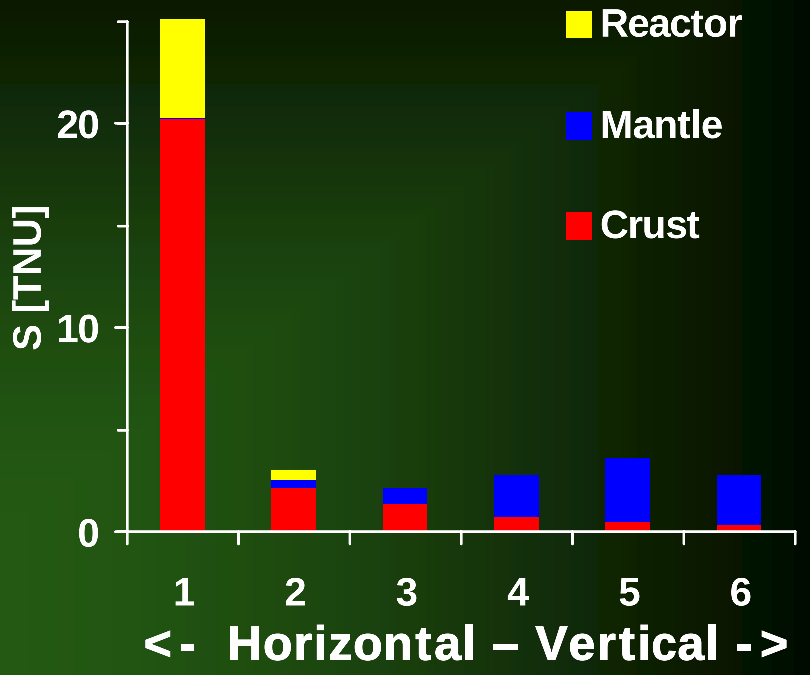
# Move the mountain or the prophet?

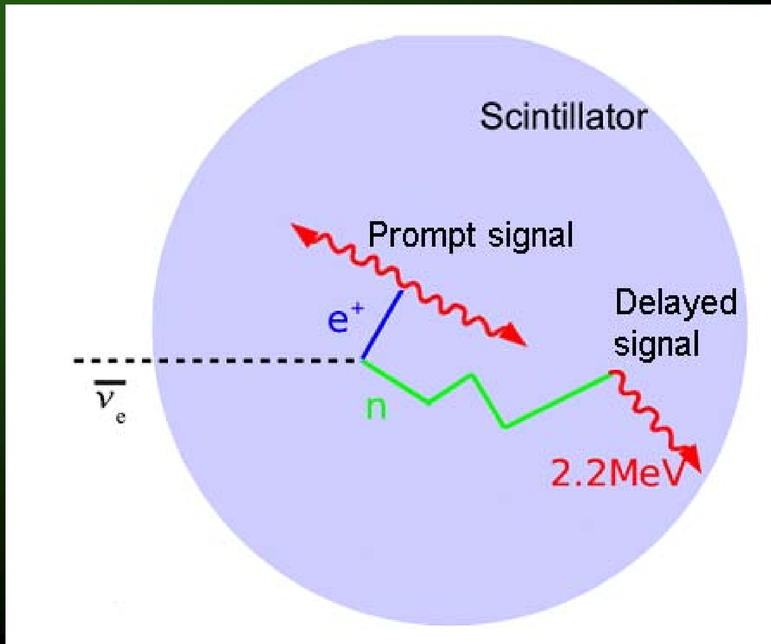
- Geo-ν direction knows if it is coming from reactors, crust, mantle…
- Even a moderate directional information would be sufficient for source discrimination.
- $\vec{P}$ conservation implies the neutron starts moving "forwards"

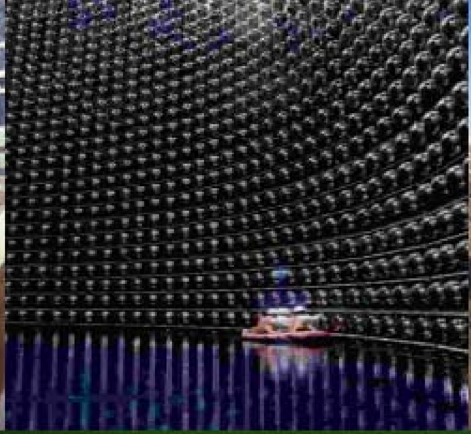
  angle (geo-ν, n) < $26^0$

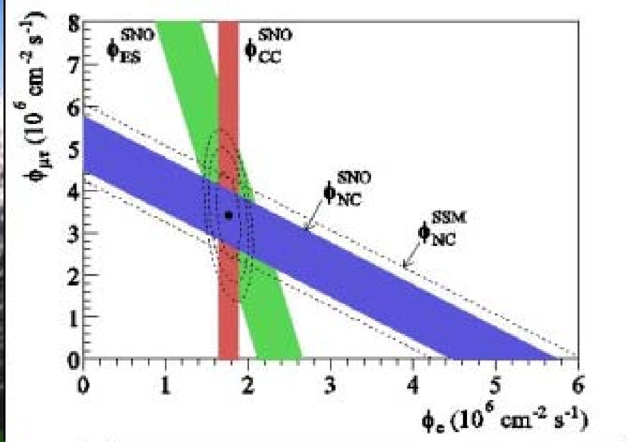
- Directional information however is degraded during neutron slowing down and thermal collisions, but is not completely lost…

Geo-ν direction at Kamioka





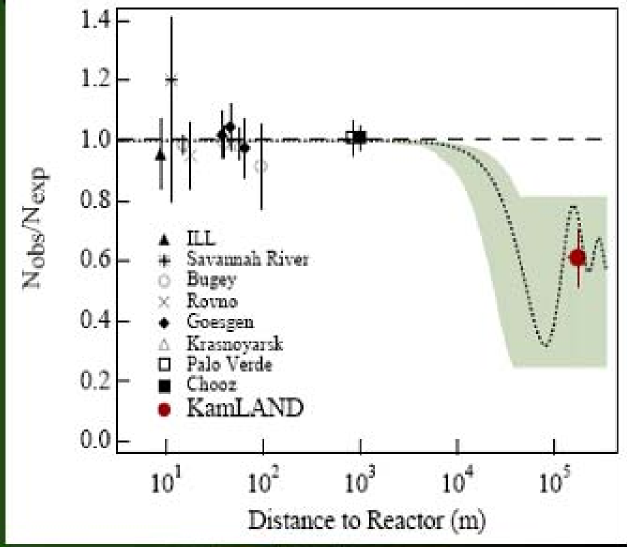


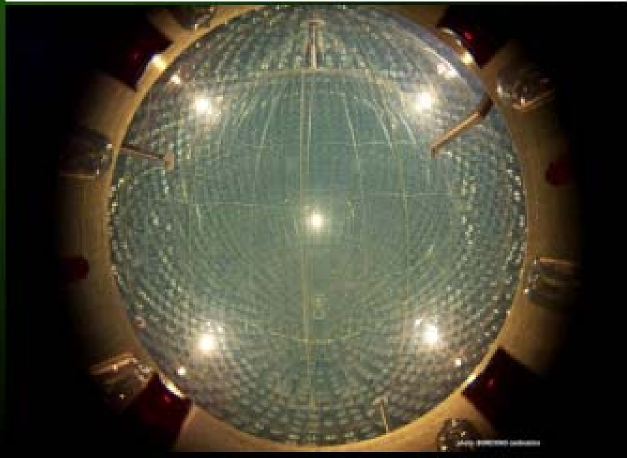

# The lesson of solar neutrinos

✓ 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…


KAMLAND 2005

1st evidence of geo-ν

GAMOW 1953

geo-ν were born here