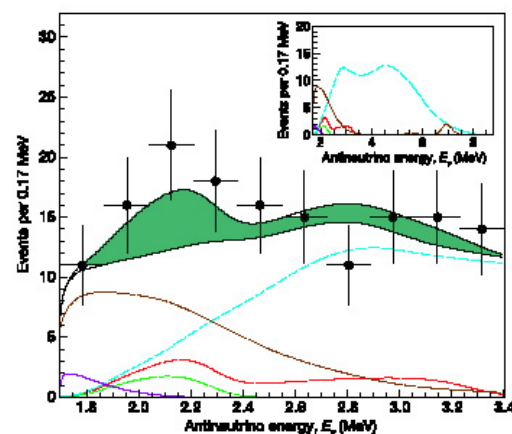
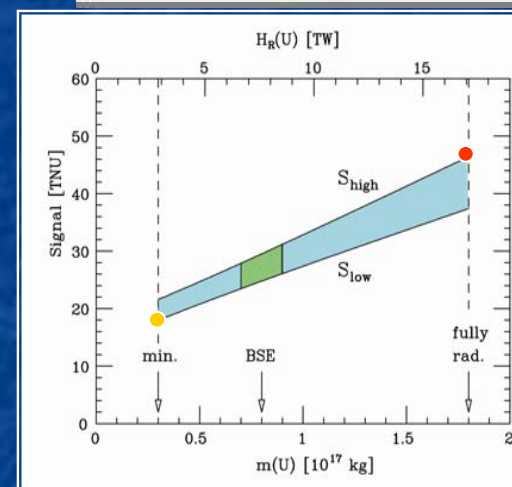
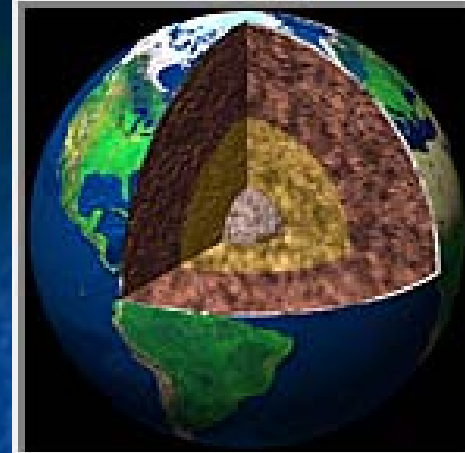


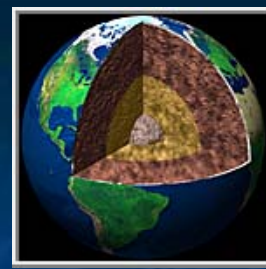
Geo-Neutrinos : a new probe of Earth's interior

- What is the amount of U, Th and ^{40}K in the Earth?
- Test a fundamental geochemical paradigm: the Bulk Silicate Earth
- Determine the radiogenic contribution to terrestrial heat flow
- The KamLAND results and future prospects



**based on work with Carmignani, Coltorti, Lasserre, Lissia Mantovani Ricci Schoenert R. Vannucci*

Geo-neutrinos: anti-neutrinos from the Earth



- Uranium, Thorium and Potassium in the Earth release heat together with anti-neutrinos, in a well fixed ratio:

| Decay | Q [MeV] | $\tau_{1/2}$ [10^9 yr] | E_{max} [MeV] | ϵ_H [W/kg] | $\epsilon_{\bar{\nu}}$ [$\text{kg}^{-1}\text{s}^{-1}$] |
|--|--------------|------------------------------|--------------------|------------------------|---|
| $^{238}\text{U} \rightarrow ^{206}\text{Pb} + 8^4\text{He} + 6e + 6\bar{\nu}$ | 51.7 | 4.47 | 3.26 | $0.95 \cdot 10^{-4}$ | $7.41 \cdot 10^7$ |
| $^{232}\text{Th} \rightarrow ^{208}\text{Pb} + 6^4\text{He} + 4e + 4\bar{\nu}$ | 42.8 | 14.0 | 2.25 | $0.27 \cdot 10^{-4}$ | $1.63 \cdot 10^7$ |
| $^{40}\text{K} \rightarrow ^{40}\text{Ca} + e + \bar{\nu}$ | 1.32 | 1.28 | 1.31 | $0.36 \cdot 10^{-8}$ | $2.69 \cdot 10^4$ |

- Earth emits (mainly) antineutrinos, Sun shines in neutrinos.
- Geo-neutrinos from U and Th (**not** from K) are above threshold for inverse β on protons: $\bar{\nu} + p \rightarrow e^+ + n - 1.8\text{MeV}$
- Different components can be distinguished due to different energy spectra: anti- ν with highest energy are from Uranium



A few references*



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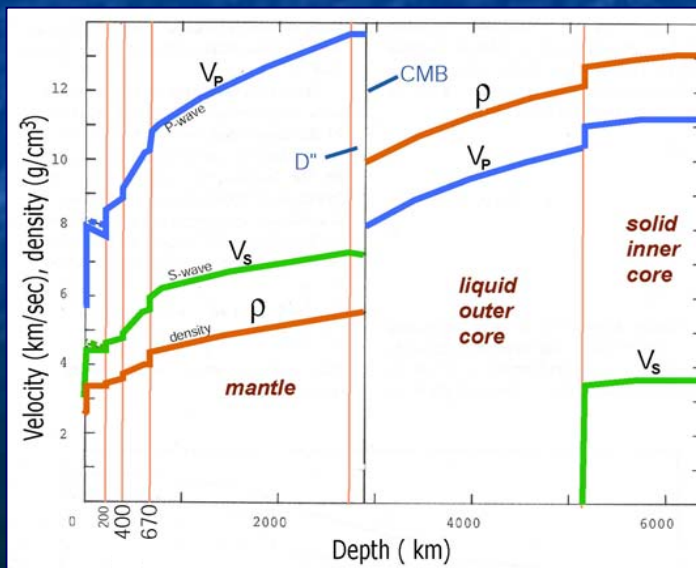
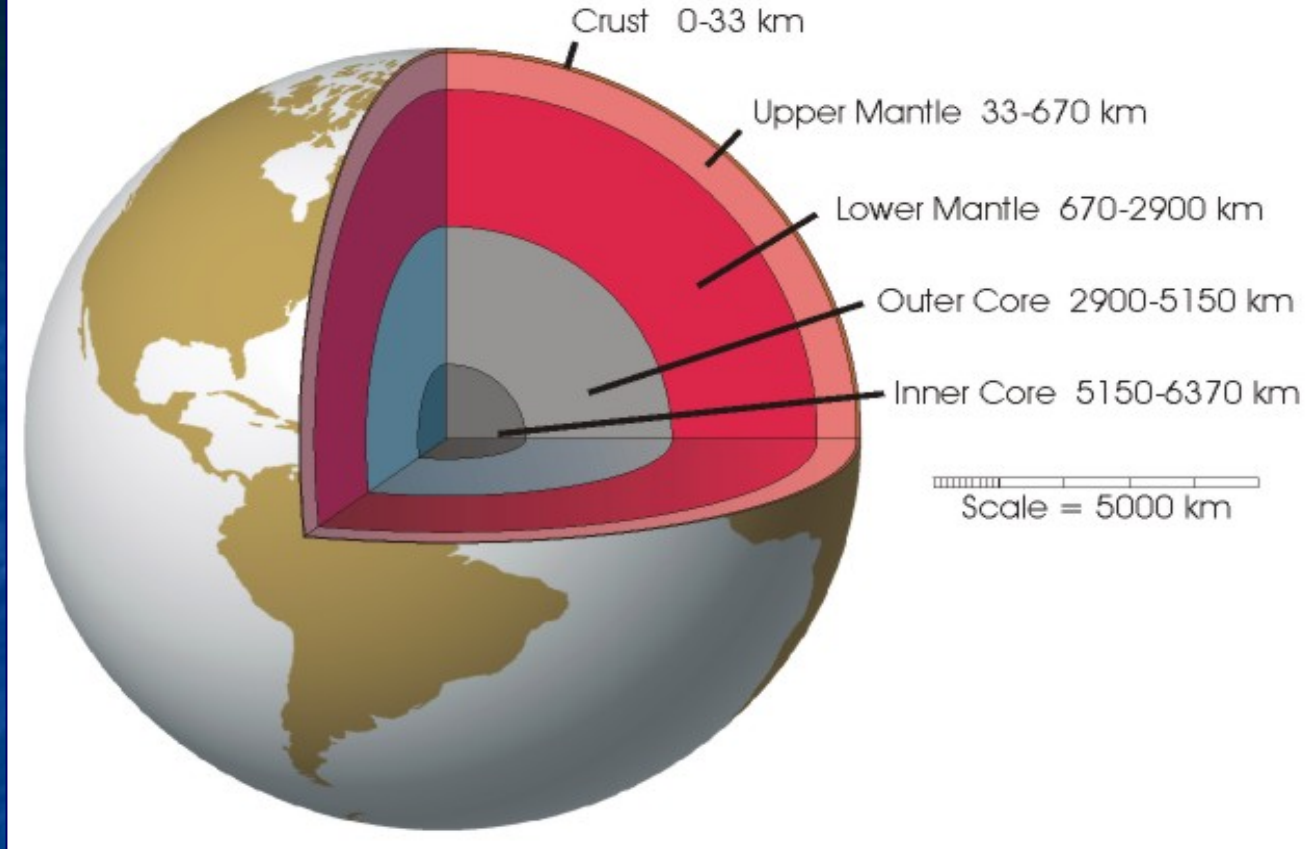
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*Apologize for missing references

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Probes of the Earth's interior

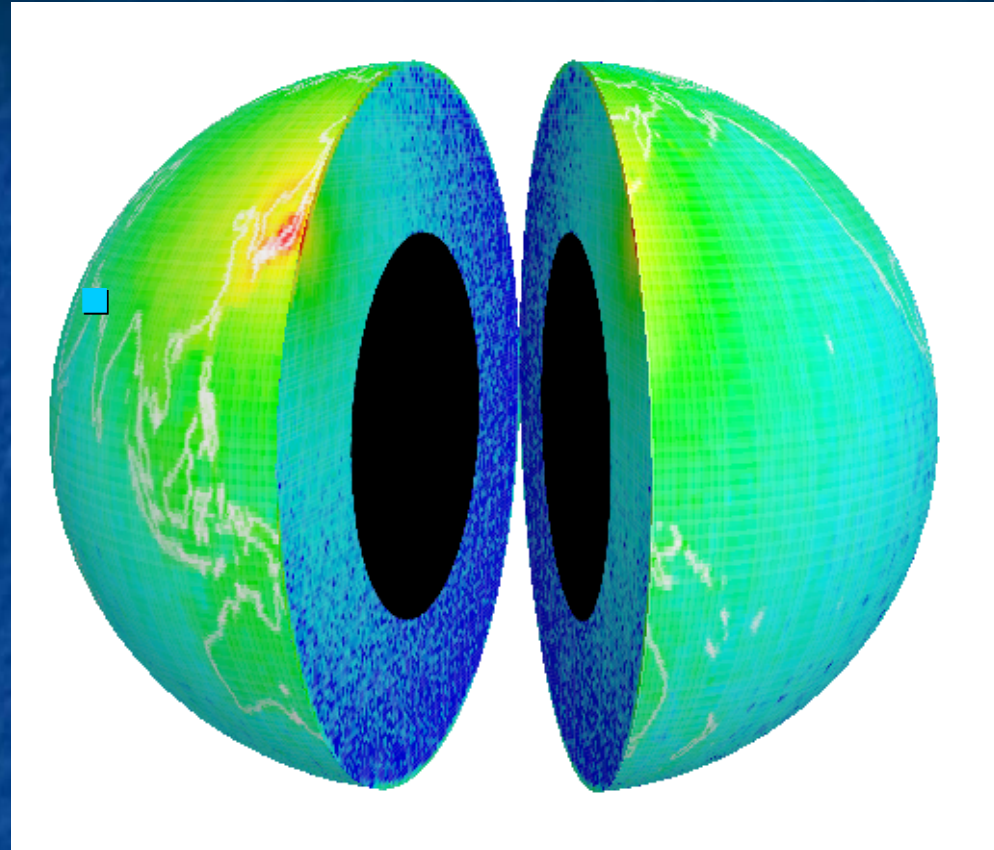
- Deepest hole is about 12 km.
- The crust (and the upper mantle only) are directly accessible to geochemical analysis.



■ Seismology reconstructs density profile (not composition) throughout all Earth.

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

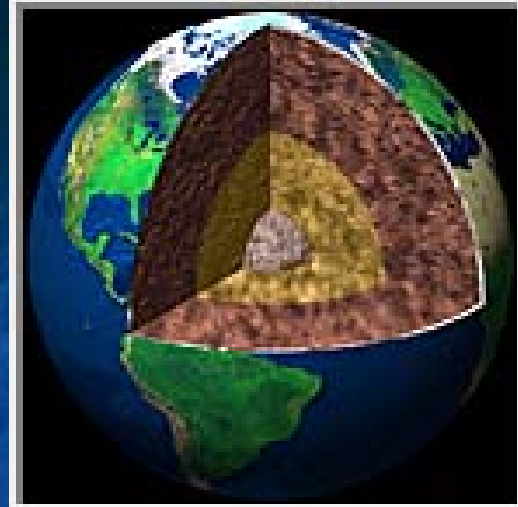
- Half of the signal in KamLAND is generated within 200 km from the detector
- The remaining is from the rest of the world.



- Geo-neutrinos bring to Earth's surface information about the chemical composition (U,Th and possibly K*) of the whole planet.

*Remind that only anti- ν from U and Th are above threshold for inverse β on free p. 5

What we (think we) know about U, Th and ^{40}K in the Earth?



The canonical paradigm:

- Their ratio is well fixed from observations:

$$m(\text{U}):m(\text{Th}):m(^{40}\text{K})=1:4:1$$

(Once you know one you know all)

- All of them are lithophile (incompatible) elements:
- They accumulate in the continental crust.
- They are absent from the (unexplored) core.

Un-orthodox or even heretical views:

- Additional potassium might be present in the core (in most chondrites $^{40}\text{K}/\text{U}=7$, good for sustaining the geodynamo)
- Some argue (see e.g. Hofmeister and Criss) that U and Th might also be in the core,
- This might provide the source of a geo-reactor according to Herndon.

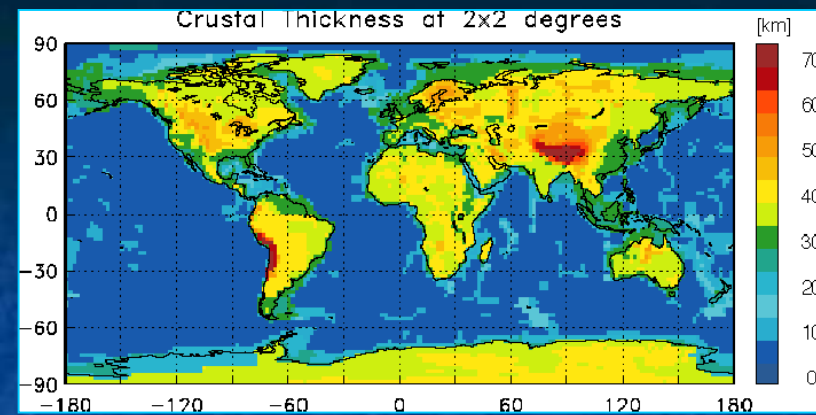
How much Uranium is in the Earth ? (cosmo-chemical arguments)



- The material form which Earth formed is generally believed to have the same composition as CI-chondrites.
- By taking into account losses and fractionation in the initial Earth one builds the “Bulk Silicate Earth” (**BSE**), the standard geochemical paradigm which predicts $m(\text{U})=(0.7-0.9) 10^{17}\text{kg}$
- **Remark:** The BSE is grounded on solid geochemical + cosmochemical arguments, it provides a composition of the Earth in agreement with most observational data, however it lacks a direct observational test, which can be provided by geo-neutrinos.

How much Uranium do we see in the Earth ?

- Observational data on the crust



■ By combining data on Uranium abundances from selected samples with geological maps of Earth's crust one concludes:

$$m_C(\text{U}) = (0.3-0.4)10^{17}\text{kg}$$

- No reliable observational data for the (lower) mantle.
- The best assumption for a reference model is to deduce from BSE the amount of U in the mantle:

$$m_m(\text{U}) = m_{\text{BSE}}(\text{U}) - m_C(\text{U}) = (0.4-0.5)10^{17}\text{kg}$$

- Otherwise, when building models, you can leave it as a free parameter...

Heat released from the Earth

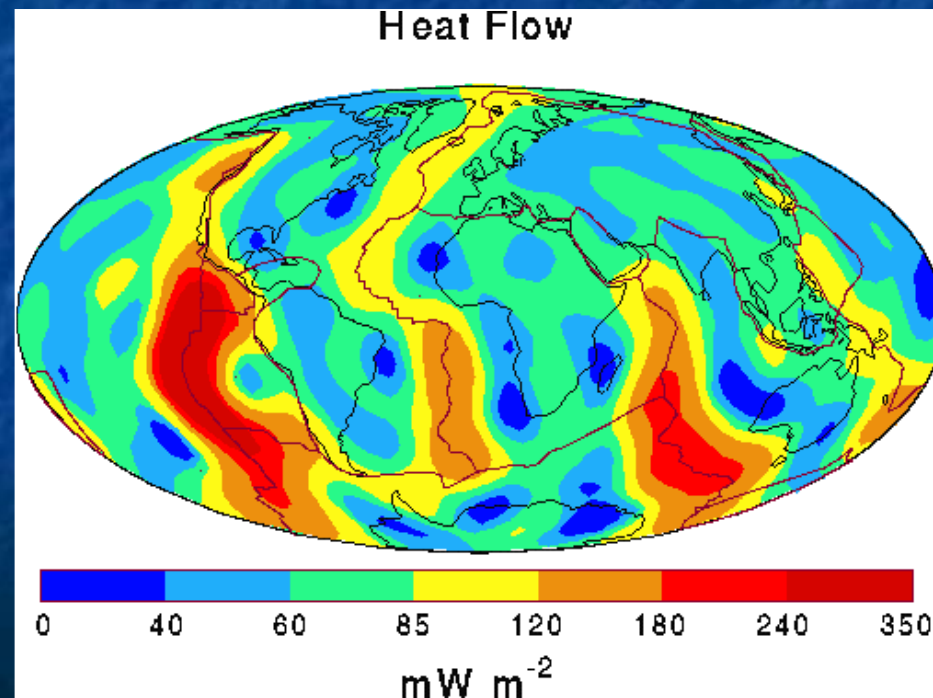
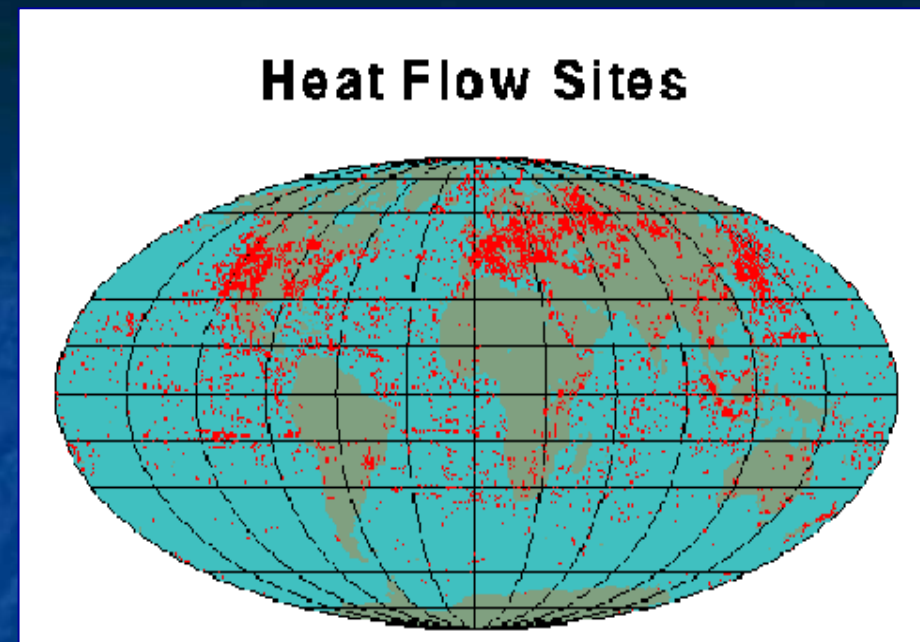
- The tiny flux of heat coming from the Earth ($\Phi \approx 60 \text{ mW/m}^2$) when integrated over the Earth surface gives a total flow:

$$H_E = (30-45) \text{ TW}$$

- It is equivalent to 10^4 nuclear power plants.

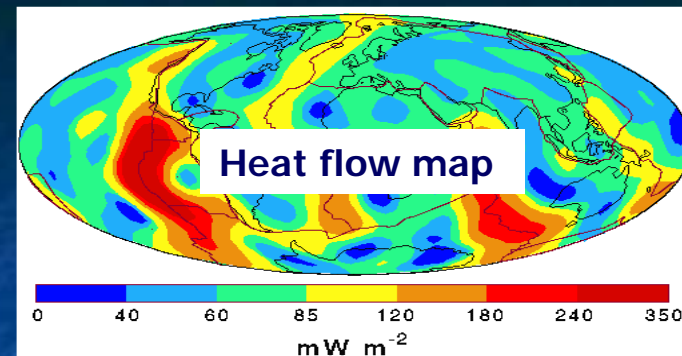
- Warning: the classical $44 \pm 1 \text{ TW}$ (Pollack 93) recently revised to the “old” $31 \pm 1 \text{ TW}$ (Hofmeister & Criss 04)

- What is its origin?



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

■ The BSE model predicts a present radiogenic heat production :



$$H(U+Th+K) = 19 \text{ TW} **$$

■ Just a fraction of the estimated present heat flow from the Earth:

$$H_{\text{Earth}} = 30-44 \text{ TW} **$$

■ We need to determine the total mass of U, Th and ⁴⁰K in the Earth by means of geo-neutrinos, in order to fix the radiogenic contribution.

■ Values of m(U) twice those of BSE are allowed by Earth's energetics.

*The title of a review by Anderson 2004 ** 8TW each from U and Th, 3 TW from K)

***) The frequently quoted 43 ± 1 TW estimate by Pollack has been recently criticized by Hofmeister & Criss, back to the old value.

How much Uranium can be tolerated by Earth energetics?

- For each elements there is a well fixed relationship between heat presently produced and its mass:

$$H_R = 9.5 m(U) + 2.7 m(\text{Th}) + 3.6 m(^{40}\text{K})$$

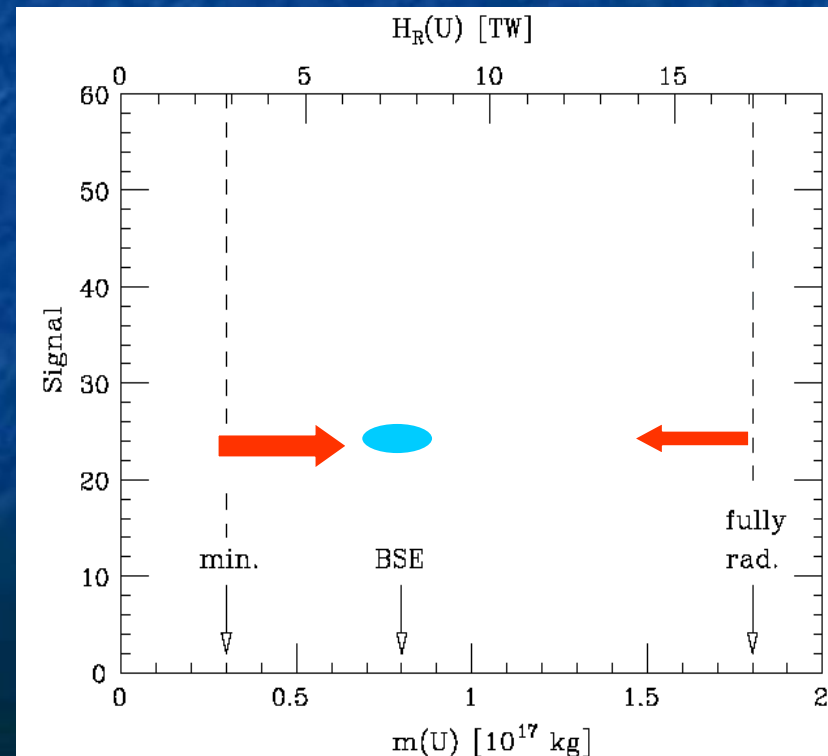
where units are TW and 10^{17}kg .

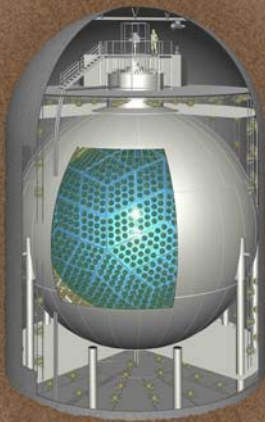
- Since $m(\text{Th}) : m(\text{U}) : m(^{40}\text{K}) = 4 : 1 : 1$ one has:

$$H_R = 24 M(\text{U})$$

- Present radiogenic heat production cannot exceed heat released from Earth:

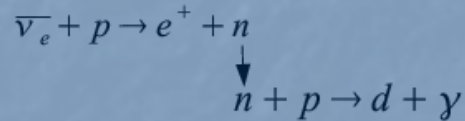
$$m(\text{U}) < 1.8 \cdot 10^{17} \text{kg}$$





From the amount of Uranium to anti-neutrino detection

Reaction Process: inverse β -decay



Scintillator is target and detector

• Distinct two-step signature:

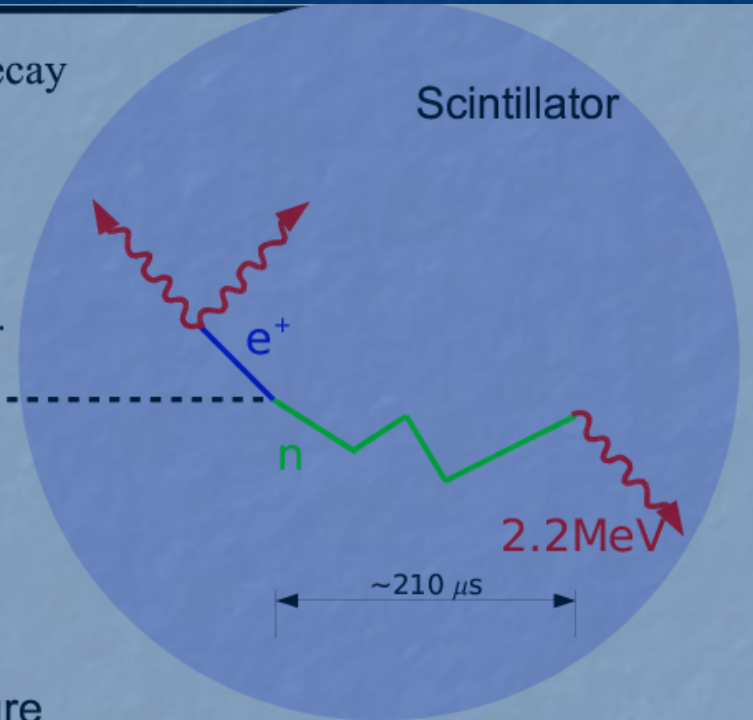
• prompt event: positron

$$E_\nu \approx E_{e^+} + 0.8 \text{ MeV}$$

• delayed event: neutron capture after $\sim 210 \mu\text{s}$

- 2.2 MeV gamma

Delayed coincidence: good background rejection



Order of magnitude estimate for the signal

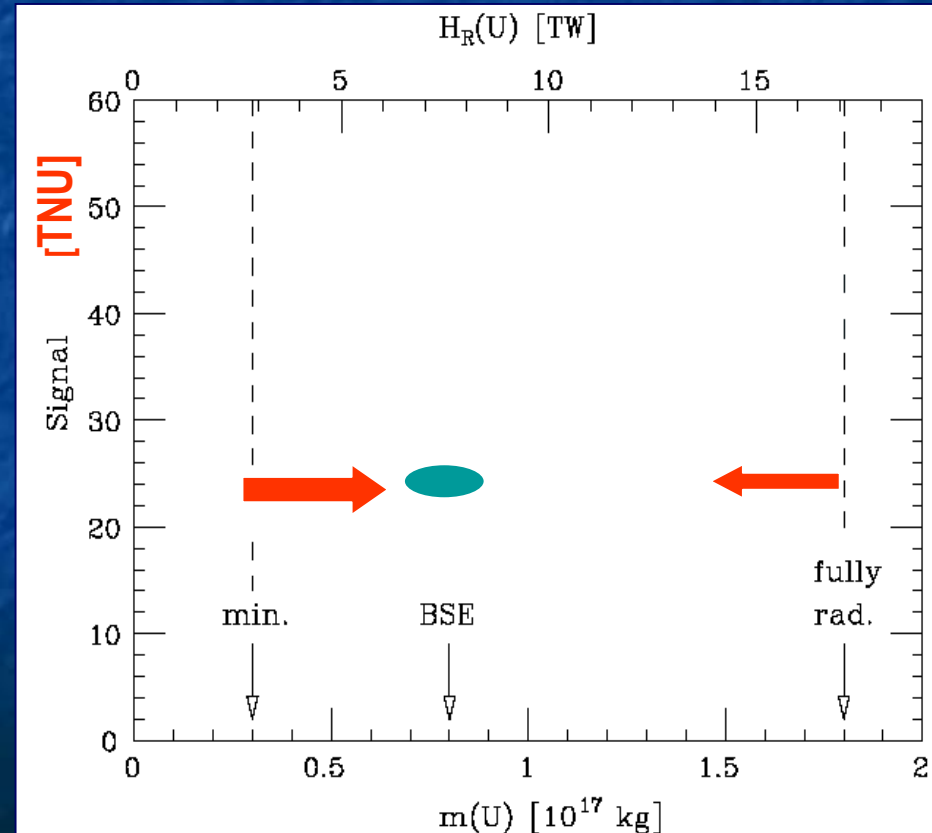
- From $m(U)$ one immediately derives the geo-neutrino luminosity L , and an estimate for the flux $\Phi \approx L/4\pi R_{\text{Earth}}^2$
- Fluxes are of order $10^6 \nu \text{ cm}^{-2} \text{ s}^{-1}$, same as ^8B .
- From spectrum and cross section one gets the signal:

$$S = 13.2 \left(\frac{\Phi_{ar}}{10^6 \text{ cm}^{-2} \text{ s}^{-1}} \right) \left(\frac{N_p}{10^{32}} \right) \text{ yr}^{-1}$$

- Signal is expressed in Terrestrial Neutrino Units:

$$1 \text{ TNU} = 1 \text{ event} / (10^{32} \text{ prot} \cdot \text{yr})$$

(1kton LS contains $0.8 \cdot 10^{32}$ prot)



The geo-neutrino signal and the Uranium mass: the strategy

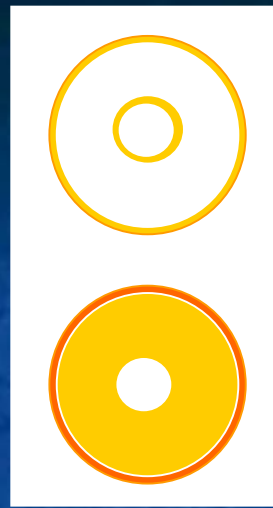
- Goal is in determining $m(\text{U})$ from geo- neutrino measurements.
- Signal will also depend on where detector is located:
- For $m(\text{U})=m_{\text{BSE}}$ we expect at Kamioka:

- $\frac{1}{2}$ of the signal from within 200 km
- This requires a detailed geochemical & geophysical study of the area.
- It is insensitive to $m(\text{U})$

- The remaining $\frac{1}{2}$ from the rest of the world.
- this is the part that brings information on $m(\text{U})$

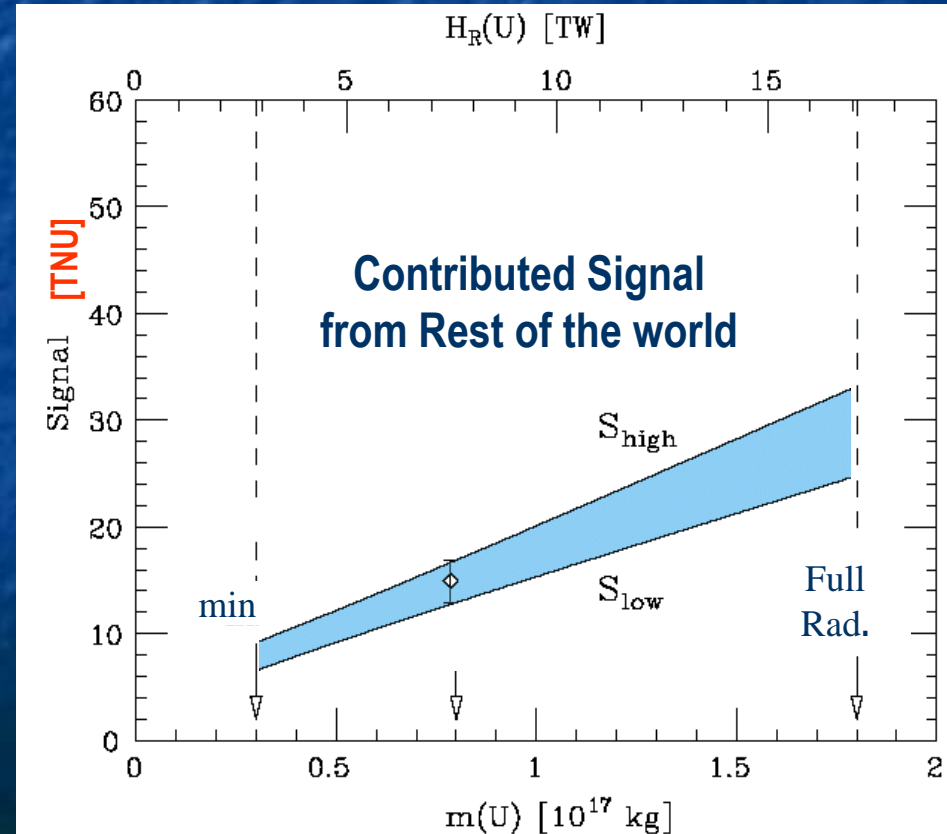
The rest of the world.

- Signal depends on the value of Uranium mass and on its distribution inside Earth.
- For a fixed $m(U)$, the signal is maximal (minimal) when Uranium is as close (far) as possible to the detector:



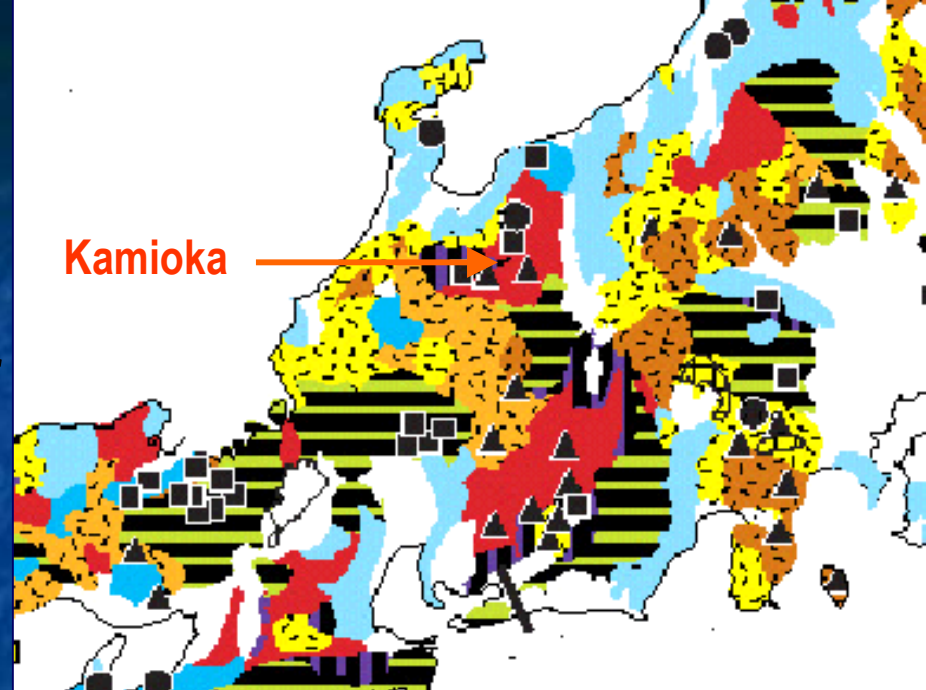
| Signal | U in the Crust | U in the Mantle |
|--------|----------------|-----------------|
| Low | Poor | Retreated |
| High | Rich | Homog. |

• Given $m(U)$, the signal from the rest of the world is fixed within $\pm 10\%$



The region near Kamioka

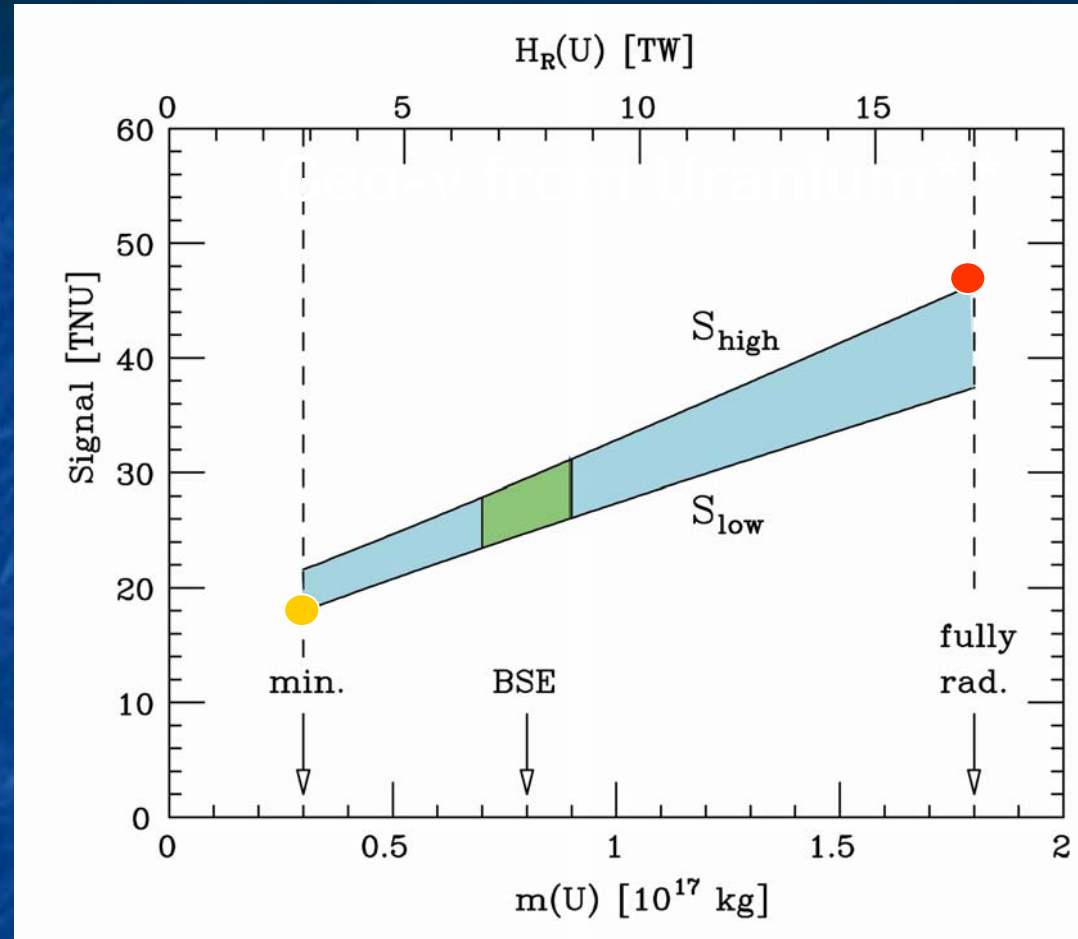
- Use a geochemical study of the Japan upper crust (scale $\frac{1}{4}^0 \times \frac{1}{4}^0$) and detailed measurements of crust depth.
- Use selected values for LC
- Take into account:
 - (3σ) errors on sample activity measurements
 - Finite resolution of geochemical study
 - Uncertainty from the Japan sea crust characterization
 - Uncertainty from subducting plates below Japan
 - Uncertainty of seismic measurements



- In this way the accuracy on the local contribution can be matched with the uncertainty of the global estimate.

Geo-neutrino signal at Kamioka and Uranium mass in the Earth⁺

- 1) Uranium measured in the crust implies a signal of at least **18 TNU****
- 2) Earth energetics implies the signal does not exceed **46 TNU**
- 3) **BSE** predicts a signal between **23 and 31 TNU**



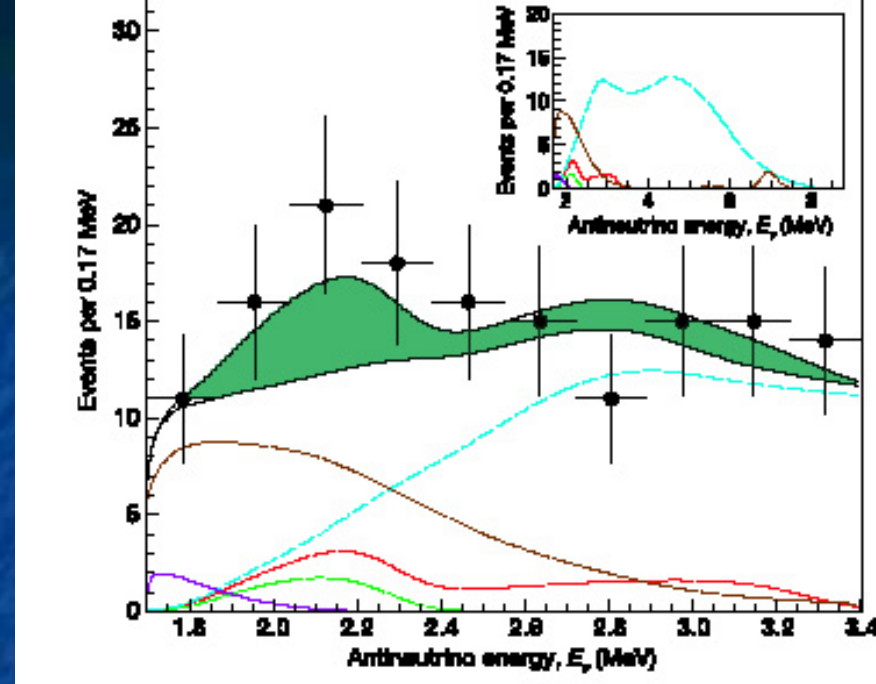
* Terrestrial Neutrino Unit:
 $1\text{TNU} = 1 \nu \text{ capture } / (10^{32} \text{ p x year})$

** $S(U+Th) = 5/4 S(U)$

⁺from g.f. et al PRD 2005

KamLAND result*

- In two years 152 counts in the geo-neutrino energy range:
- Background is dominated by:
 - reactor events (80.4 ± 7.2)
 - fake geo-neutrinos from $^{13}\text{C}(\alpha, n)$ (42 ± 11)
- The result** is $N(\text{U+Th}) = 28_{-15}^{+16}$ geo-neutrino events from U+Th in the Earth (one event / month !)
- A pioneering experiment, showing that the technique for identifying geo-neutrinos is now available.

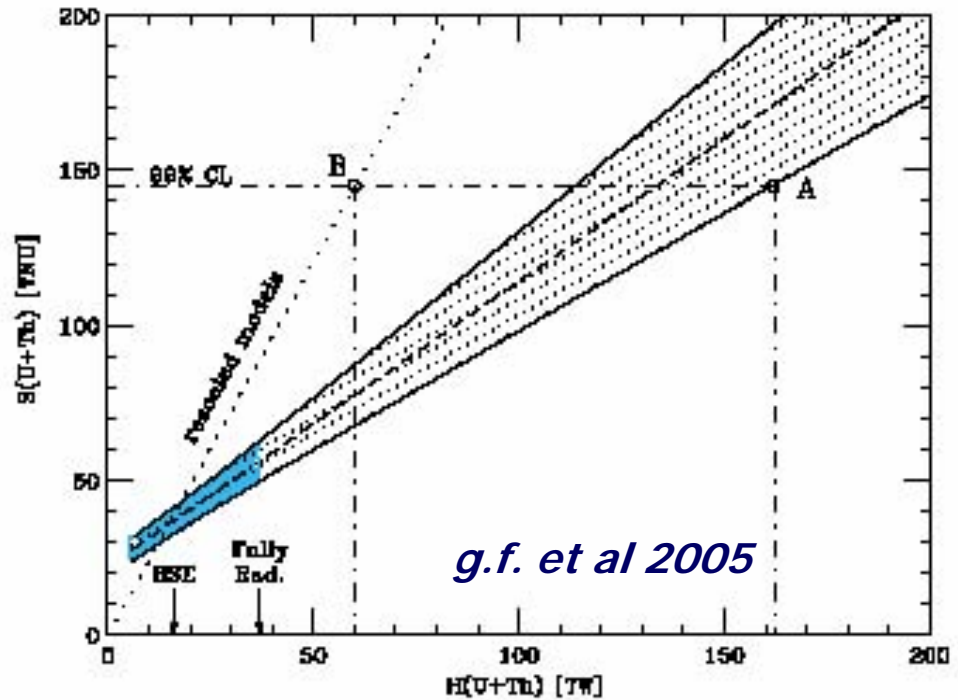


*Nature 28 July 2005

**After subtraction of other minor background (4.6 ± 0.2) and some info from spectral shape

What do we learn from KamLAND ?

- The KamLAND signal is $S(U+Th) = 57_{-31}^{+33}$ TNU
- From the geo-neutrino signal to power relationship we get:
 $H(U+Th) = 38_{-32}^{+35}$ TW
- Consistent within 1σ with:
 - A) no radiogenic power
 - B) BSE
 - C) fully radiogenic model



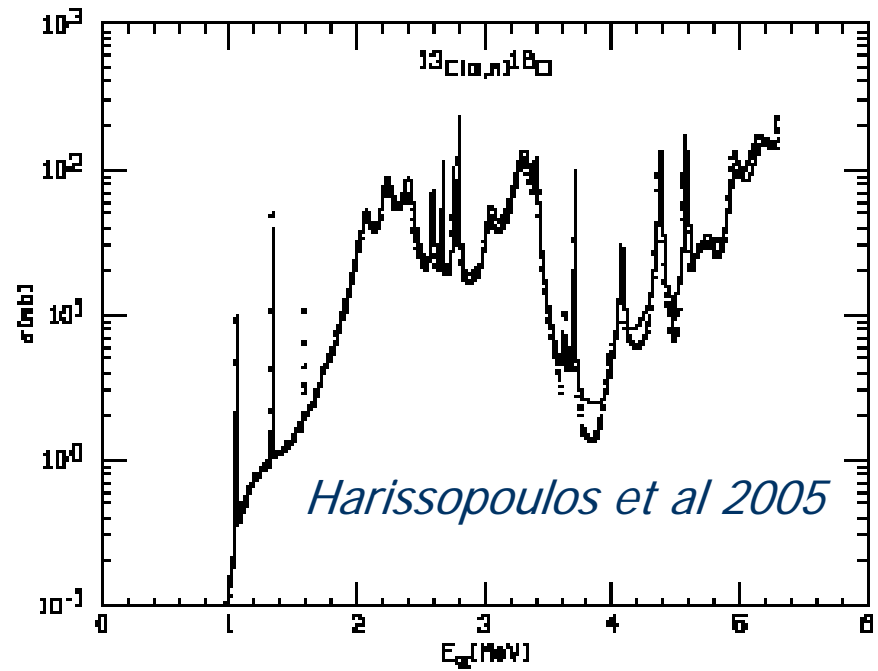
- The 99% CL upper bound on geo-signal translates into

$$H(U+Th) < 160 \text{ TW.}$$

Beating the fake

geo-neutrinos

- A major uncertainty arises from the $^{13}\text{C}(\alpha,n)$ cross section.
- KamLAND adopts values from old and partially consistent measurements (individual accuracy about 20%).
- A recent measurement by Rolfs group provides (smaller) cross sections with an accuracy of 4%



- This corroborates (bringing to 2.5σ from 0) geo-neutrino evidence*:

$$N(\text{U+Th}) = 31_{-13}^{+14}$$

*according to GF et al 2005; an analysis by the KamLAND group most welcome

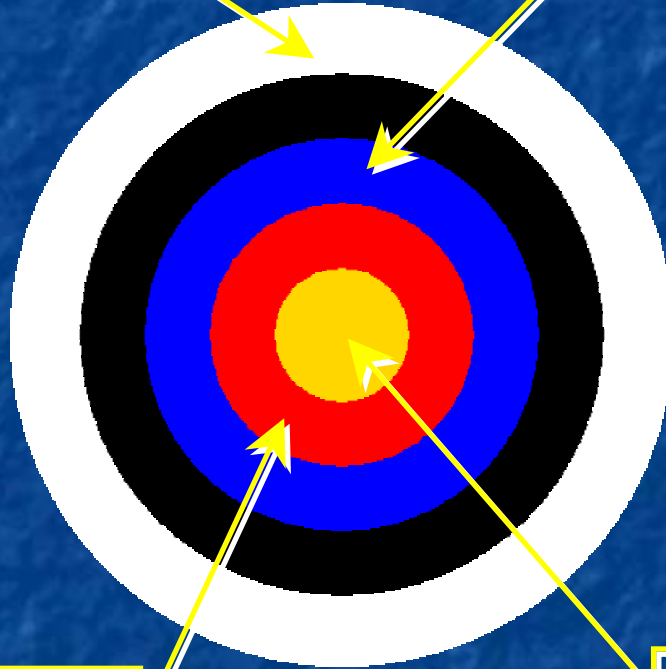
The goals of future experiments

1) Definite evidence of geoneutrinos (3 σ at least)

2) How much Uranium and Thorium in the crust?

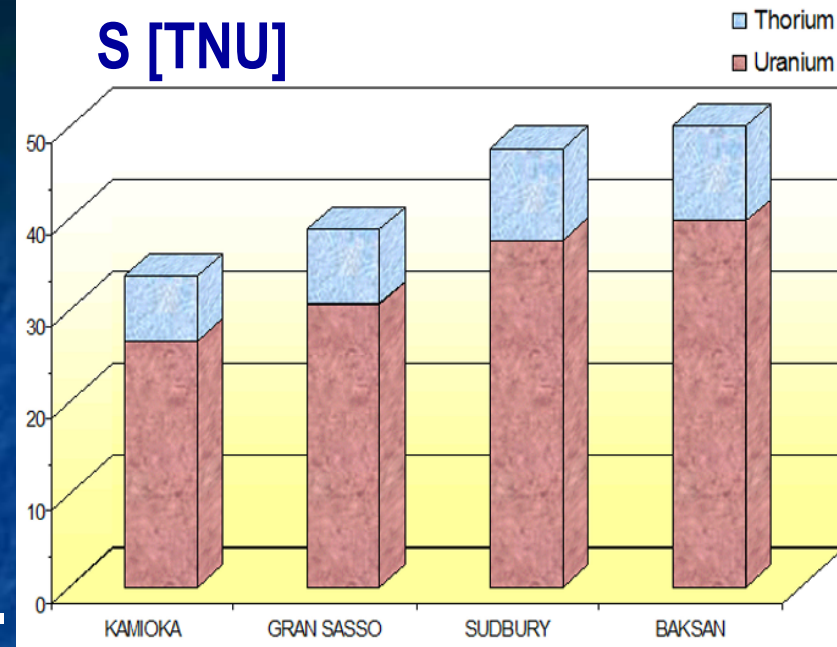
3) How much Uranium and Thorium in the mantle?

4) What about the core?



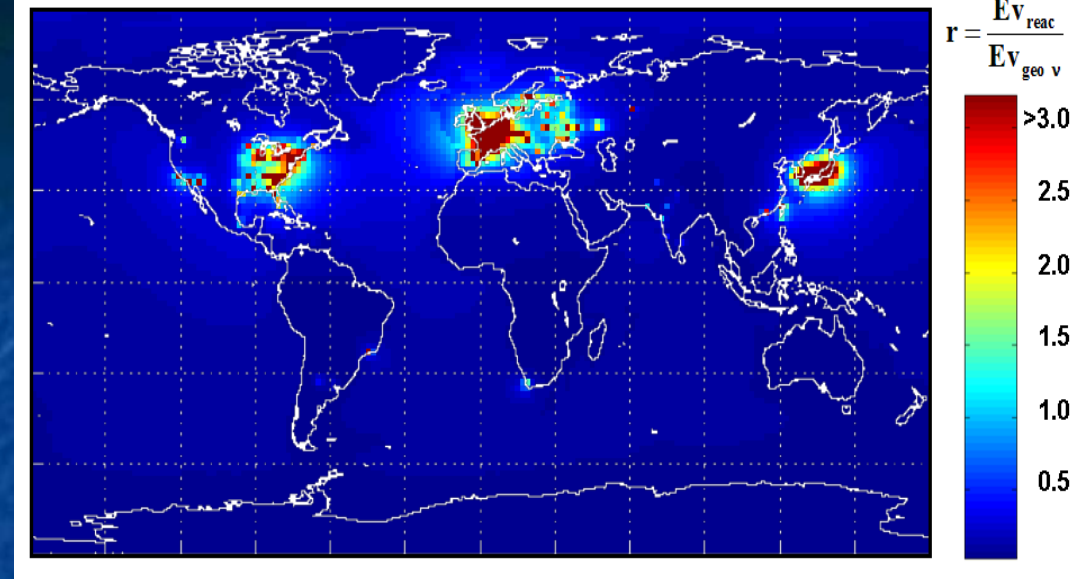
Looking forward to see new data

- KamLAND has provided a proof of the method.
- Borexino at Gran Sasso will have smaller mass but better geo/reactor.
- SNO with liquid scintillator will have excellent opportunities to determine the Uranium abundance in the crust.
- A detector at Hawaii, very far from nuclear reactors and from the continental crust, would be most sensitive to the Mantle composition.



- At Baksan a 1Kton detector is being considered, again rather from nuclear reactors.
- LENA in Finland envisages a 30Kton LS detector.

Nuclear reactors: the enemy of geo-neutrinos



- For geo- ν at Kamioka a severe “background” is provided from reactors.

- An important parameter is the ratio r of reactor to geo-neutrino events in the geo-neutrino energy window.

- For the study of geo-neutrinos, better to move from Kamioka.

| | $r = N_{\text{rea}} / N_{\text{geo}}^*$ |
|------------|---|
| Kamioka | 8 |
| Sudbury | 1/1 |
| Gran Sasso | 1/1 |
| Hawaii | 1/8 <small>23</small> |

The contributions of crust and mantle within the reference model*

S(U+Th) [TNU]

| | Sudbury | G.S. | Kamioka | Hawaii |
|--------|---------|------|---------|--------|
| crust | 41 | 31 | 26 | 4 |
| mantle | 9 | 9 | 9 | 9 |
| total | 50 | 40 | 35 | 13 |

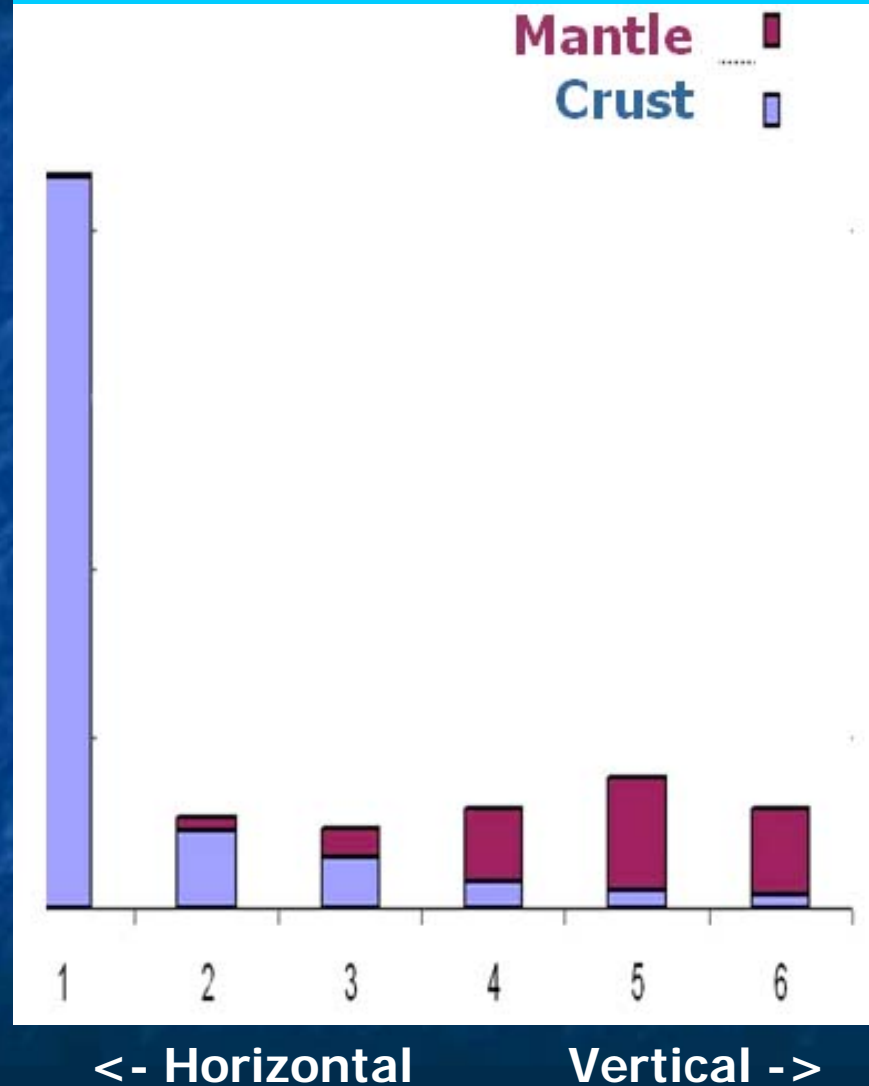
- At Sudbury 80% of the signal is expected from the crust.
- At Hawaii 70% of the signal is expected from the mantle.

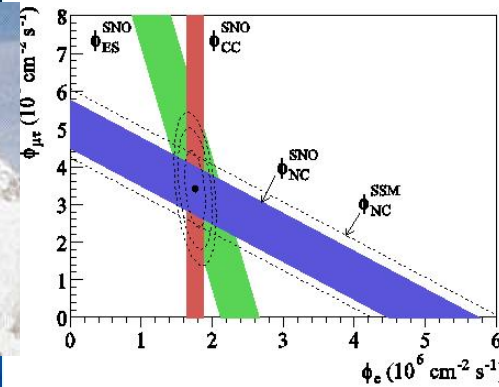
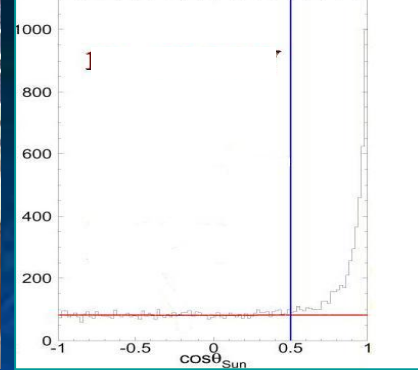
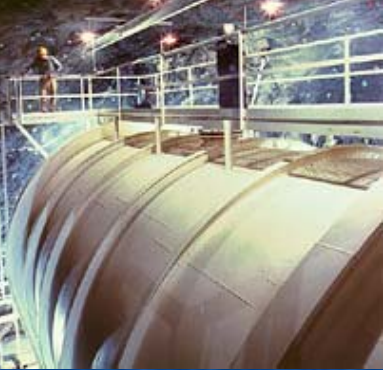
Directionality ?

- So far, only the total (=angle integrated) yield can be determined.
- Even a moderate directional information would be important for discriminating the contributions from different layers in the Earth*.
- The neutron knows where the geo-neutrino was coming from.
- Directional information is lost in the thermalization process...

*and also from reactors...

The zenithal distribution of geo-neutrinos at Kamioka





The lesson from solar neutrinos

- The study of solar neutrinos started as an investigation of the solar interior.
- A long and fruitful detour lead to the discovery of oscillations.
- Through several steps, we have now a direct proof of the solar energy source, we are making solar neutrino spectroscopy, we have neutrino telescopes.
- Understanding the Earth's energetics with terrestrial neutrinos will also require several steps.
- Expect surprises, concerning Earth and/or neutrinos...