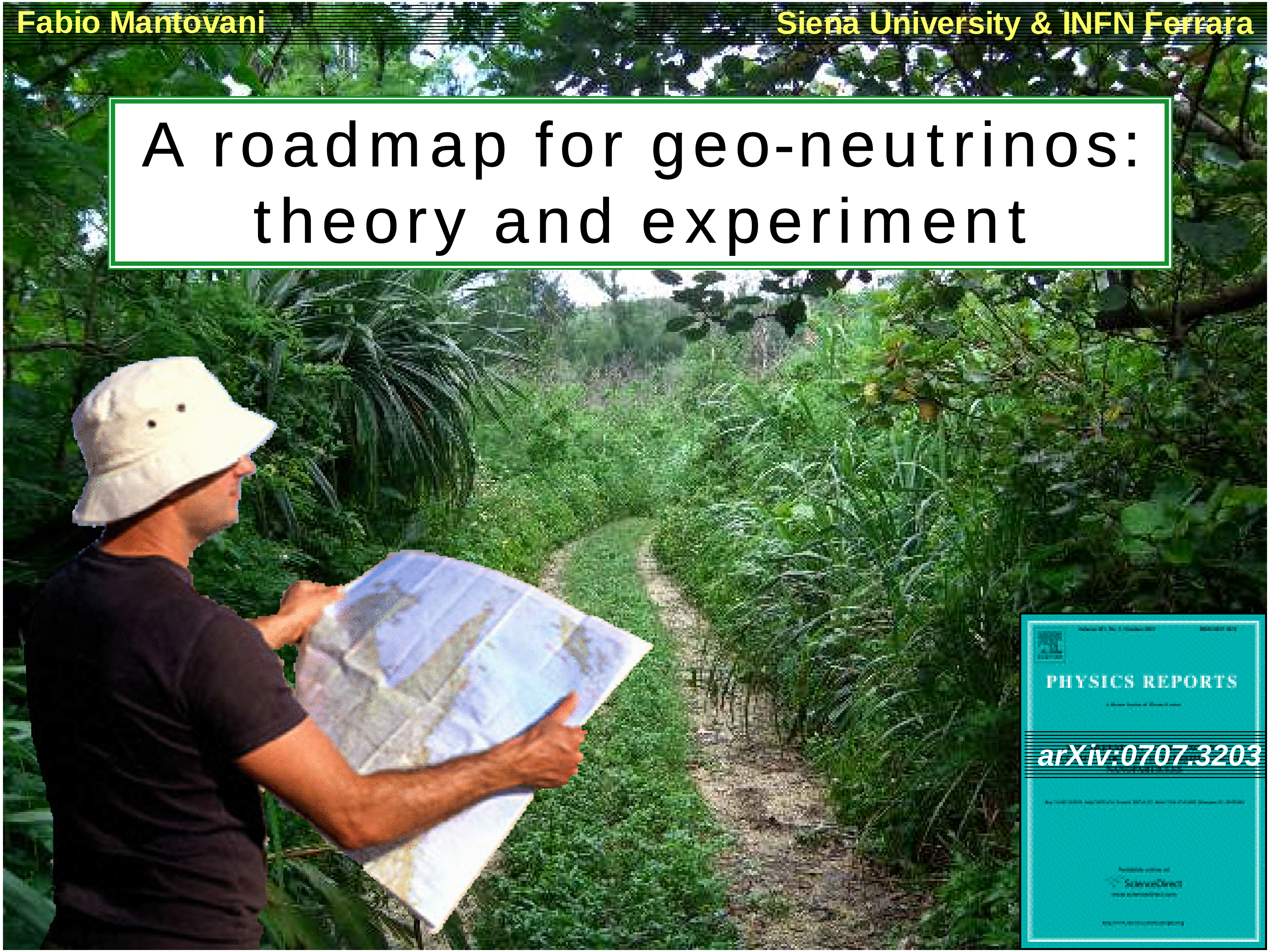
Fabio Mantovani

Siena University & INFN Ferrara

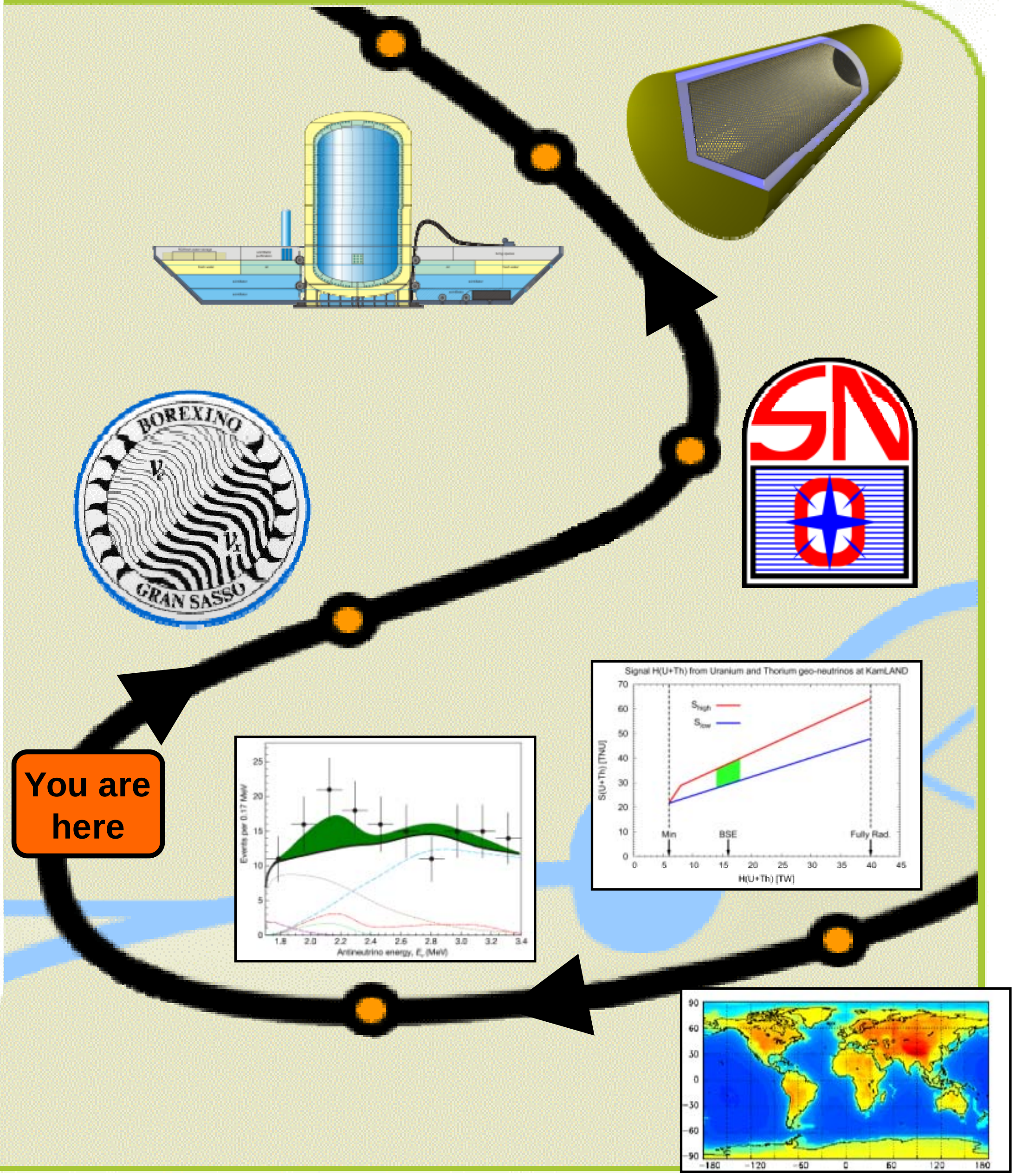
A roadmap for geo-neutrinos: theory and experiment



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



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]	$\varepsilon_{\bar{\nu}}$ [$\mathrm{kg^{-1}s^{-1}}$]	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}

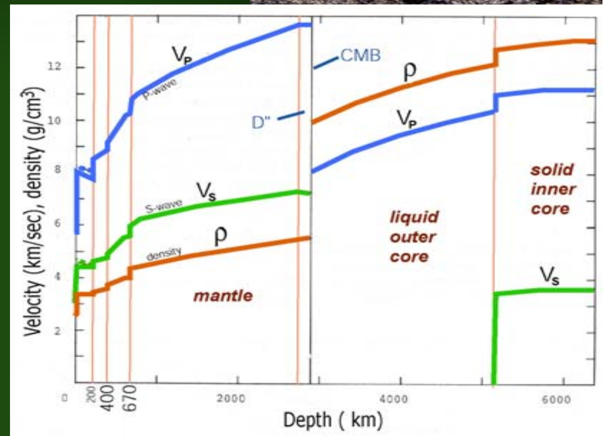
- Earth emits (mainly) antineutrinos $\Phi_{\bar{\nu}} \sim 10^6\,\mathrm{cm^{-2}s^{-1}}$ whereas Sun shines in neutrinos.

- 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.

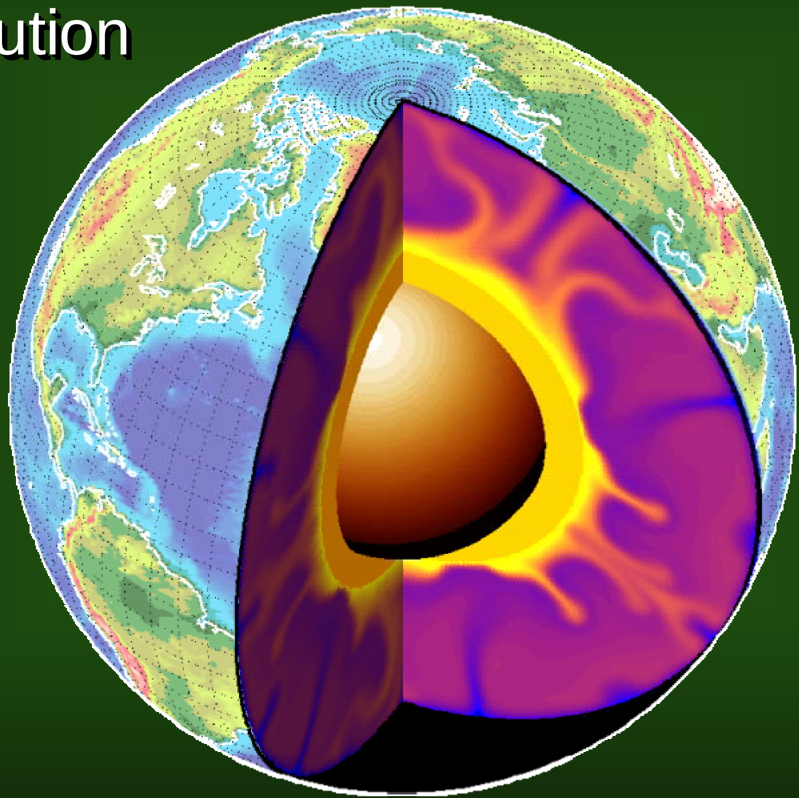
✓ They bring to Earth's surface information about the chemical composition of the whole planet.

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

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

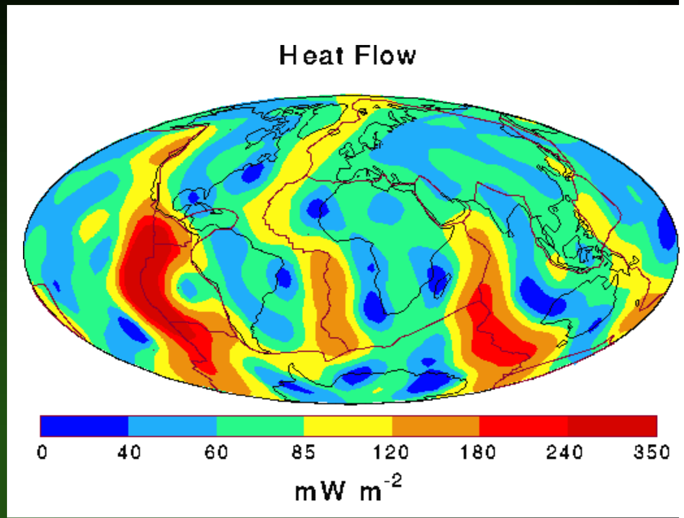
- The BSE canonical model, based on **cosmochemical** arguments, predicts a radiogenic heat production ~ 19 TW:

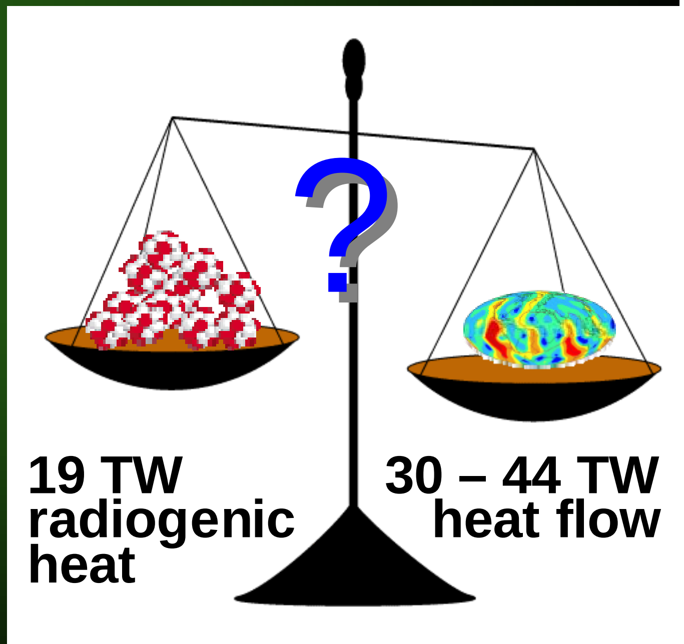
~ 9 TW **estimated** from radioactivity in the (continental) crust

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

~ 0 TW **assumed** from the core

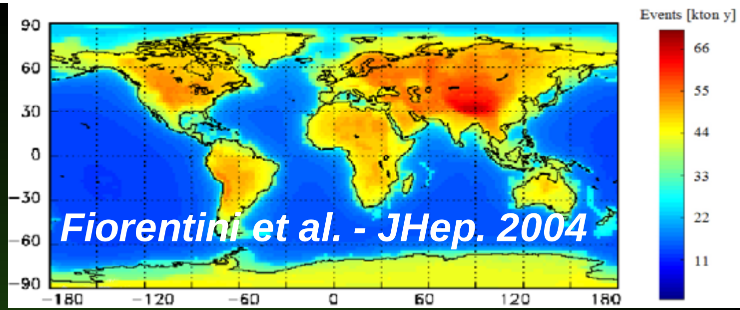
- Unorthodox or even heretical models have been advanced…





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

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

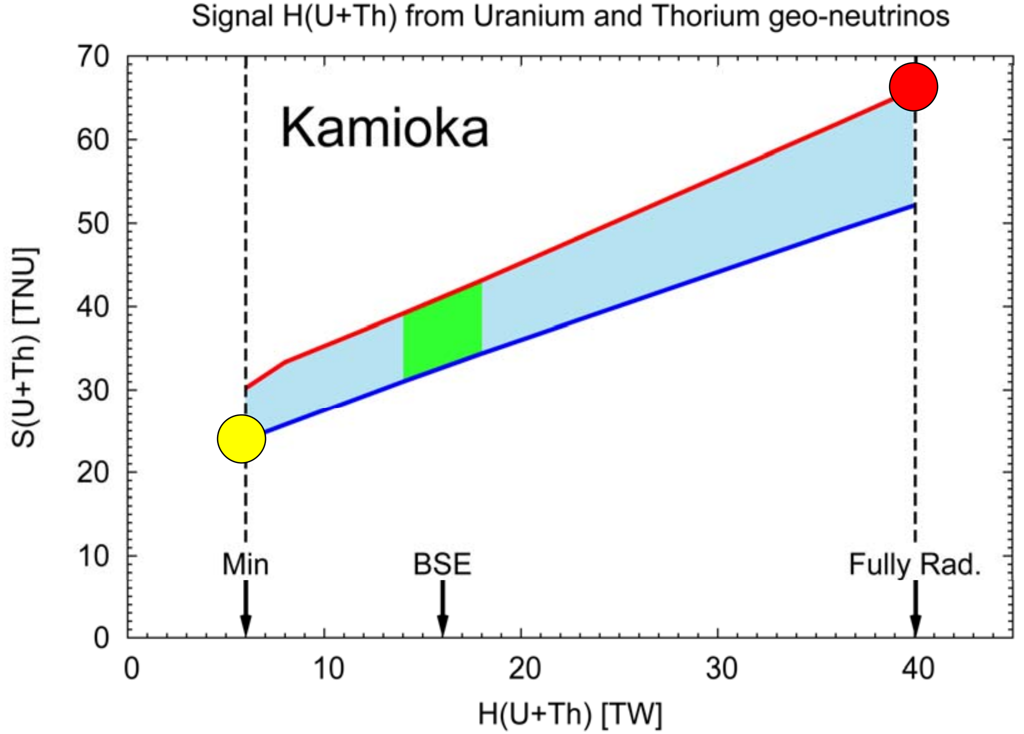
region allowed by BSE: signal between 31 and 43 TNU

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

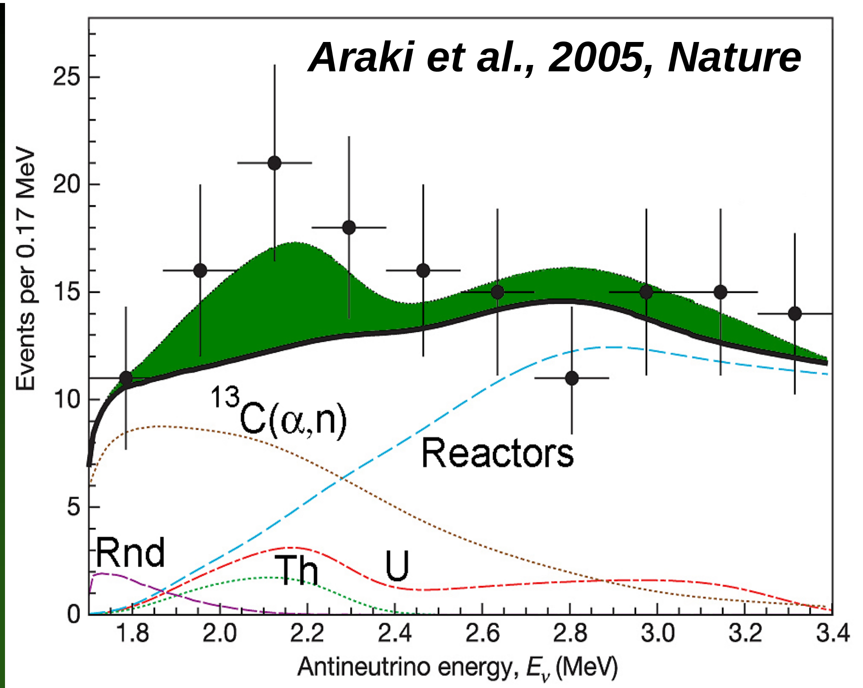
Fiorentini et al. (2005)



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 2005 results on geo-neutrino



- In two years data 152 counts in the geo-neutrino energy range:

~ 82 reactors antineutrinos

~ 42 fake geo-neutrinos, from $^{13}C(\alpha,n)$

~ 3 random coincidences

- Geo-neutrino events are obtained from subtraction:

$$N(U+Th) = 25^{+19}_{-18}$$

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

- Very limited info on radiogenic heat, H(U+Th) < 160 TW*

**BSE prediction is H(U+Th) = 16 TW*

…waiting KamLAND results @ TAUP 2007!!!

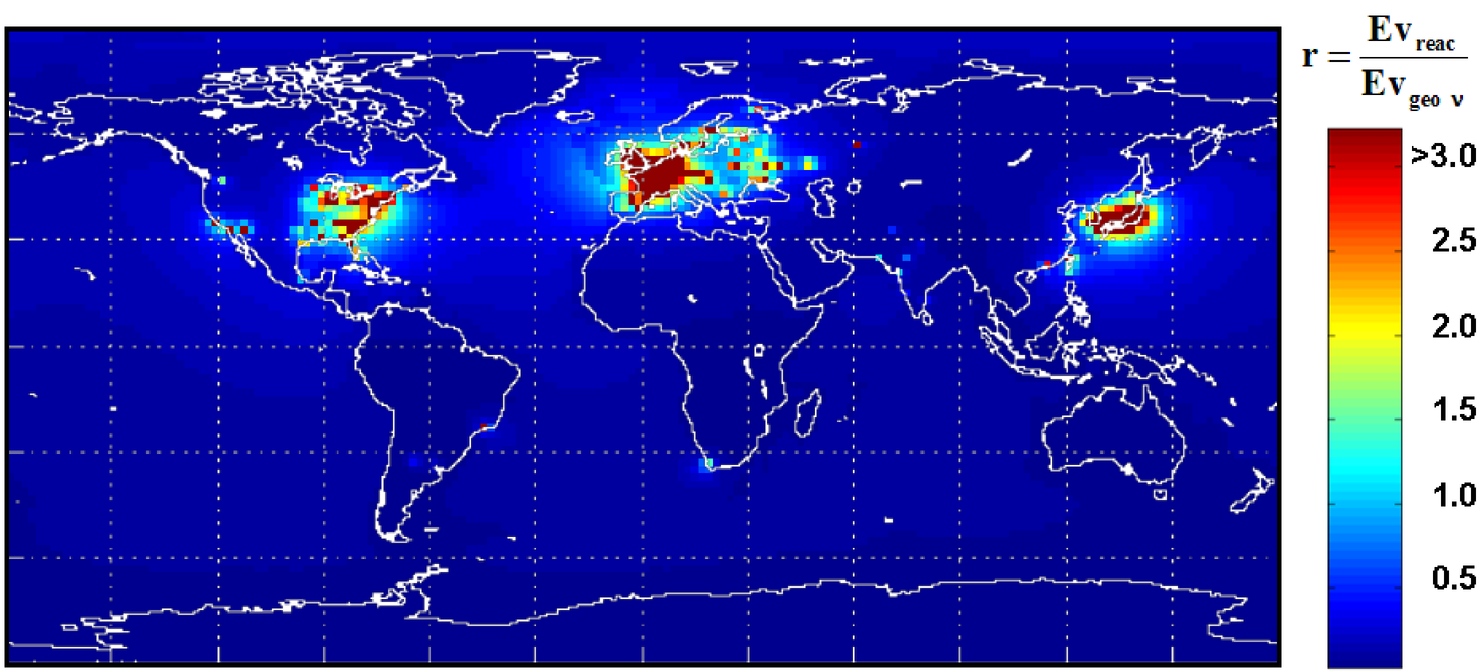
I. Shimizu talk this afternoon

Nuclear reactors: the enemy of geo-neutrinos

$$r = \frac{Events_{reactors}}{Events_{geo\ \nu}}$$

In the geo-neutrino energy window

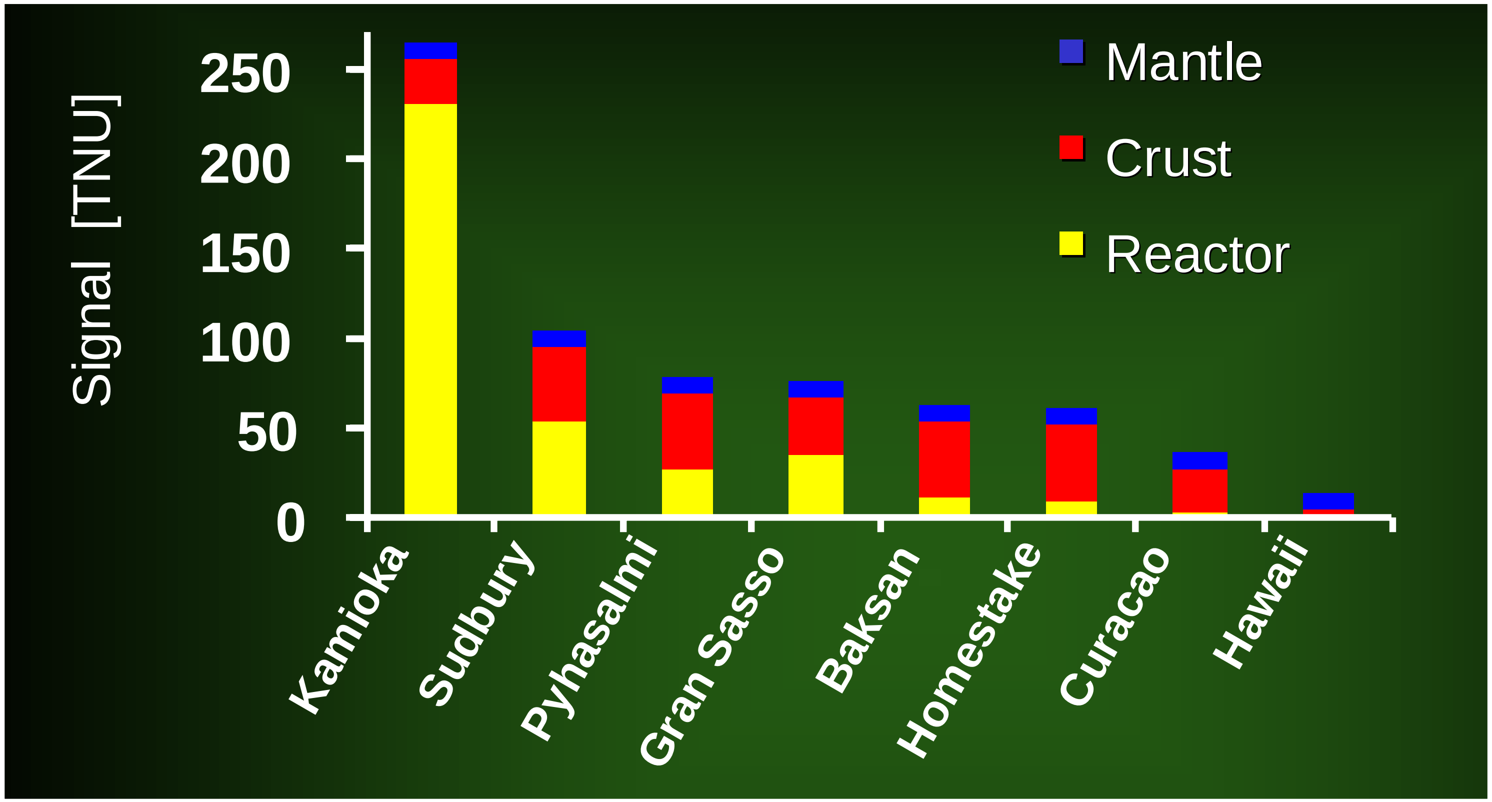
	r
Kamioka	6.7
Sudbury	1.1
Gran Sasso	0.9
Pyhasalmi	0.5
Baksan	0.2
Homestake	0.2
Hawaii	0.1
Curacao	0.1

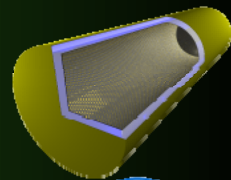


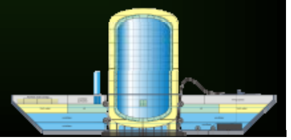
- Based on IAEA Database (2000)
- All reactors at full power

Fiorentini et al - Earth Moon Planets - 2006

Running and planned experiments

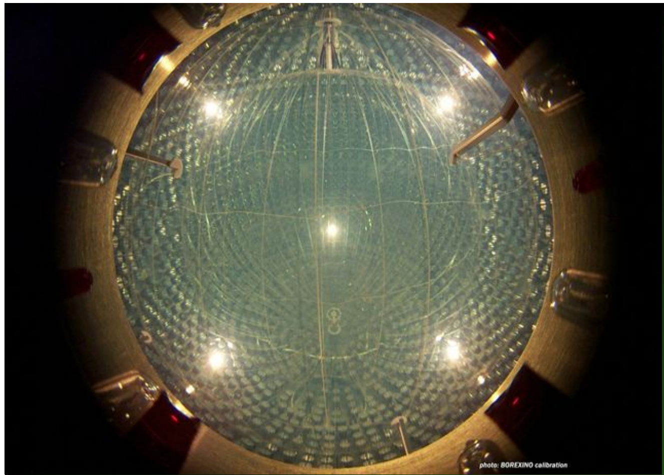




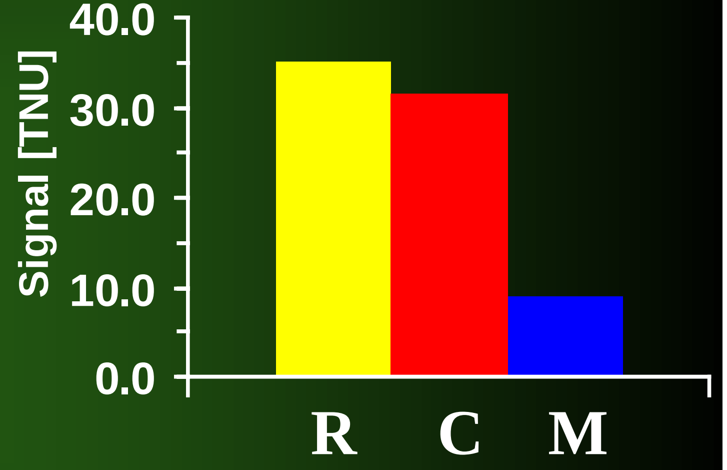


- **Several experiments, either running or under construction or planned, have geo-ν among their goals.**
- **Figure shows the sensitivity to geo-neutrinos from crust and mantle together with reactor background.**

Borexino at Gran Sasso



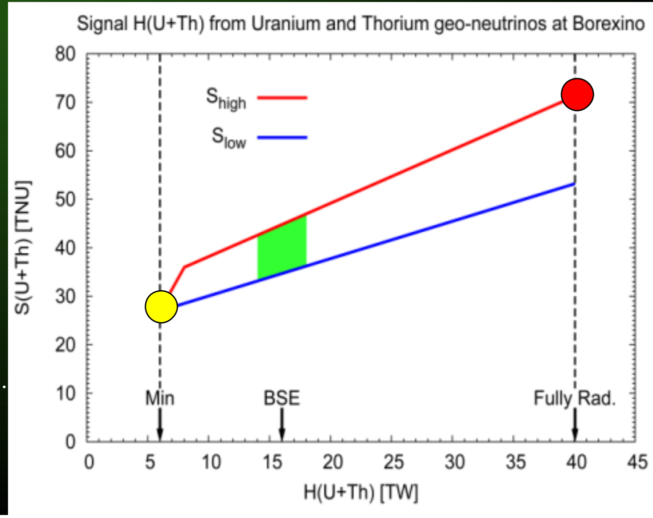
- A 300-ton liquid scintillator underground detector, running since may 2007.



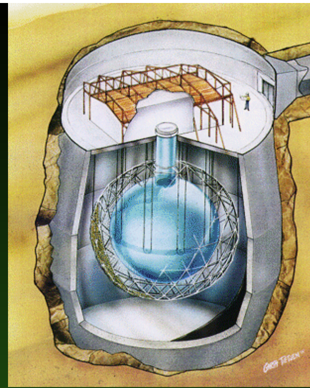
- Signal, mainly generated from the crust, is comparable to reactor background.
- From BSE expect 5 – 7 events/year*
- In about two years should get 3σ evidence of geo-neutrinos.

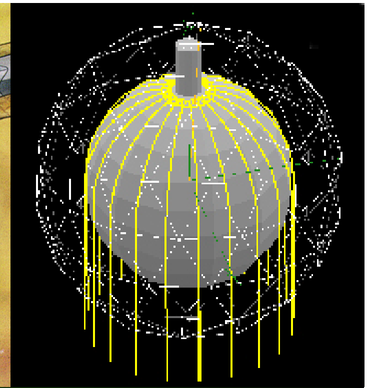
* For 80% eff. and 300 tons C_9H_{12} fiducial mass

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



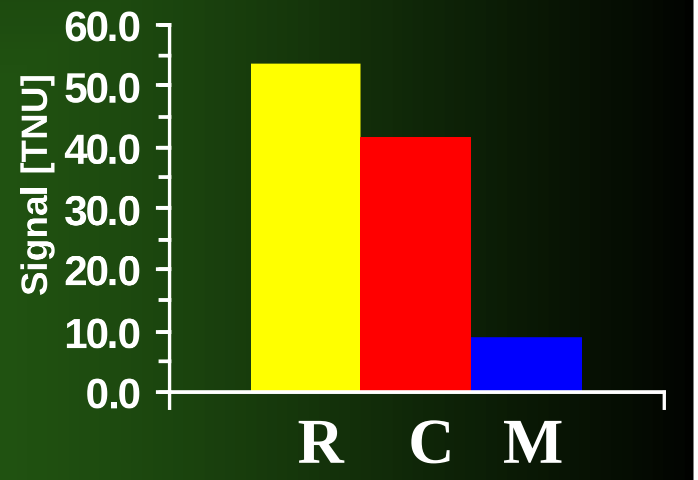
SNO+ at Sudbury

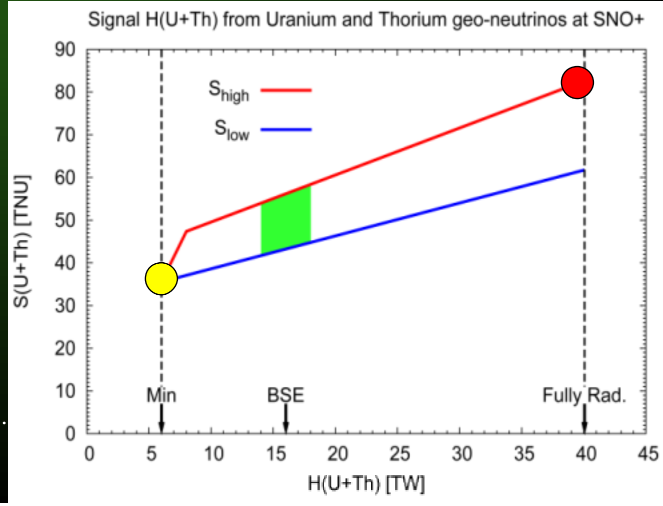




- A 1000-ton liquid scintillator underground detector, obtained by replacing D_2O in SNO.
- The SNO collaboration has planned to fill the detector with LS in 2009
- 80% of the signal comes from the continental crust.
- From BSE expect 28 – 38 events/year*
- It should be capable of measuring U+Th content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

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

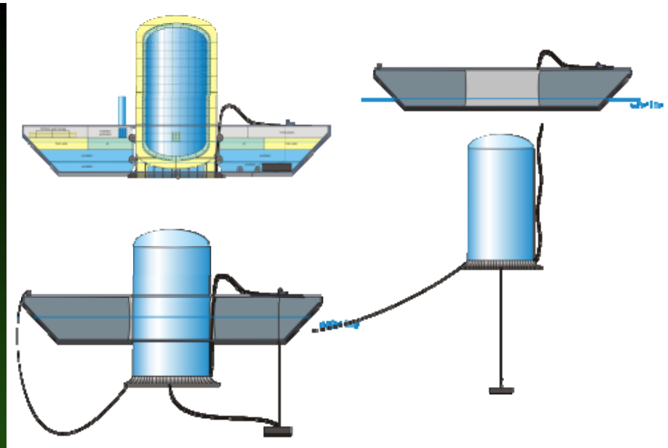


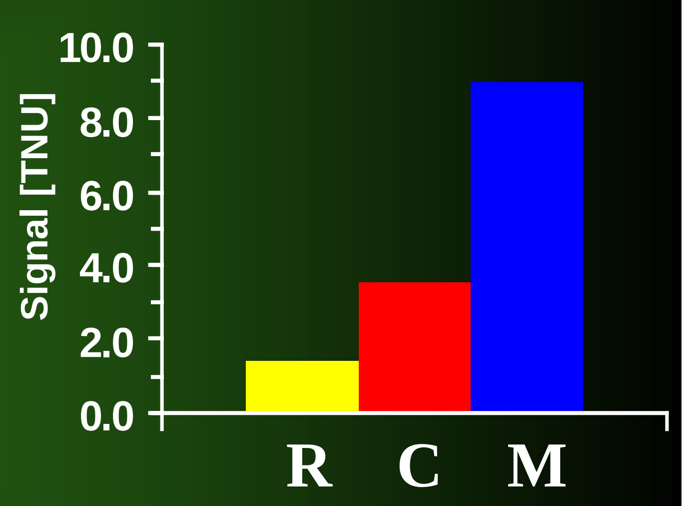


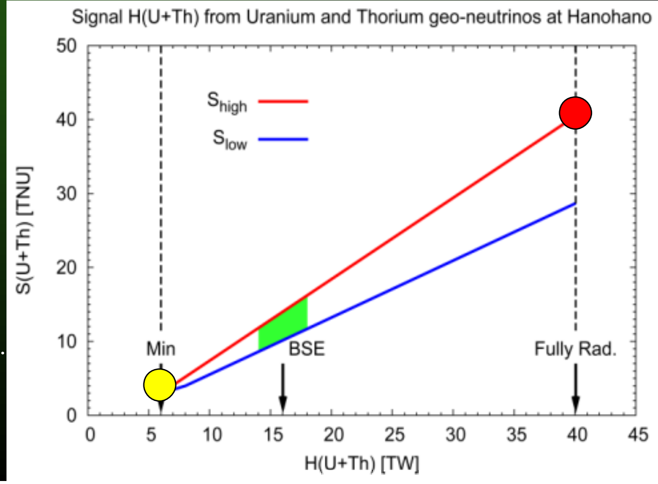
Chen, M. C., 2006, Earth Moon Planets 99, 221.

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

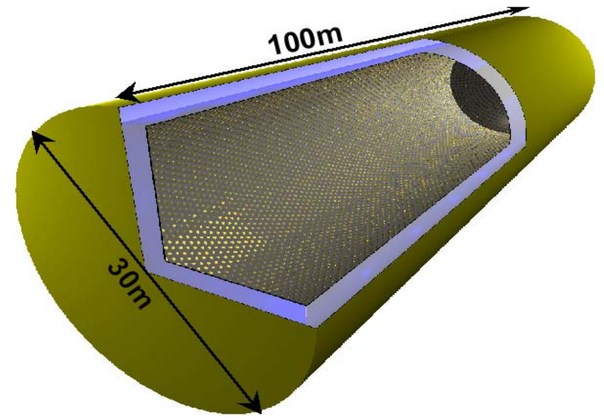
J. G. Learned et al. – ``XII-th International Workshop on Neutrino Telescope", Venice, 2007

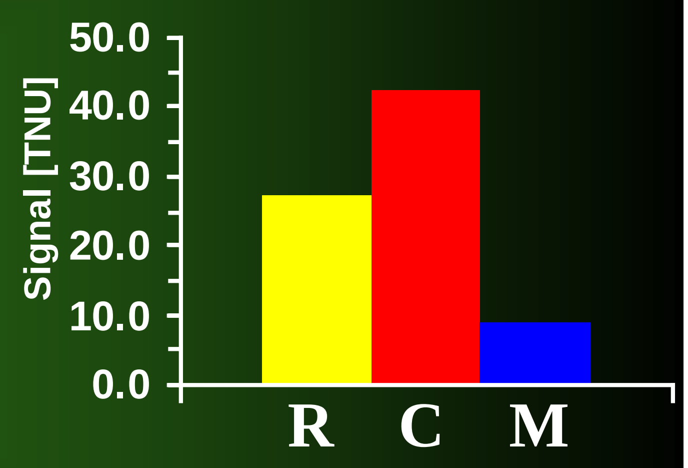
LENA at Pyhasalmi

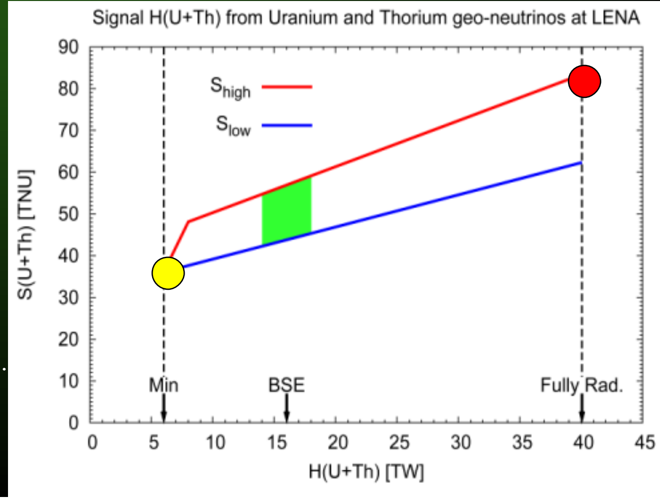
- Project of a **50** kiloton underground liquid scintillator detector in Finland
- 80% of the signal comes from the crust
- From BSE expect **800 – 1200** events/year*
- LS is loaded with 0.1% Gd which provides:
  - better neutron identification
  - moderate **directional** information

* 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?

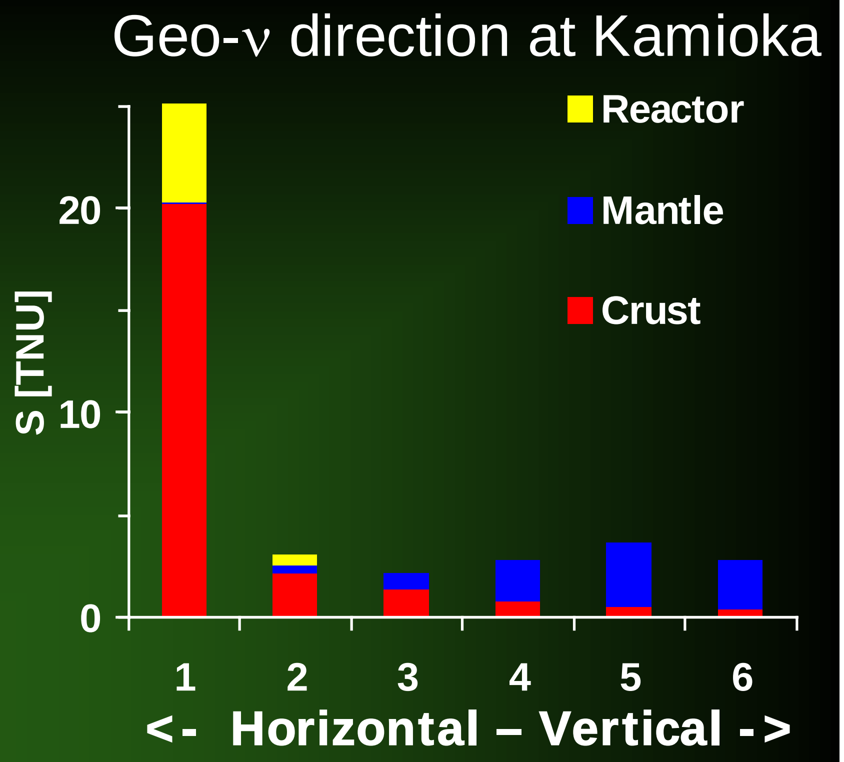
- Geo-ν direction knows if it is coming from reactors, crust, mantle…

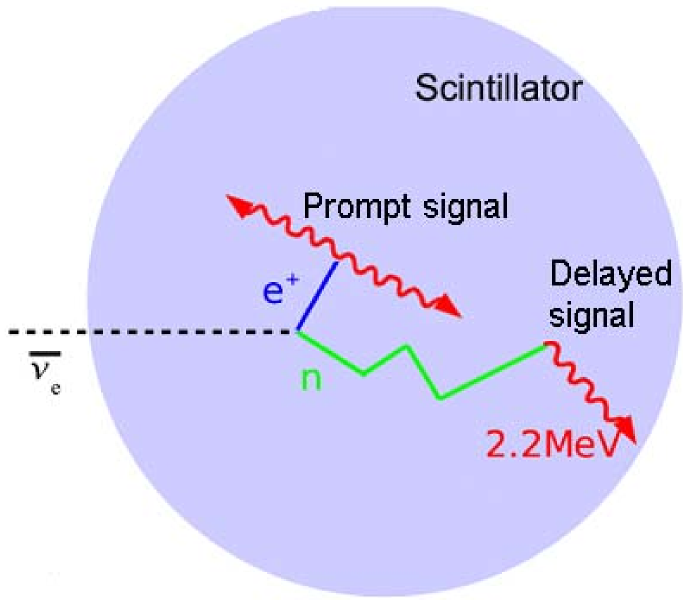
- Even a moderate directional information would be sufficient for source discrimination.

- $\vec{P}$ 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…



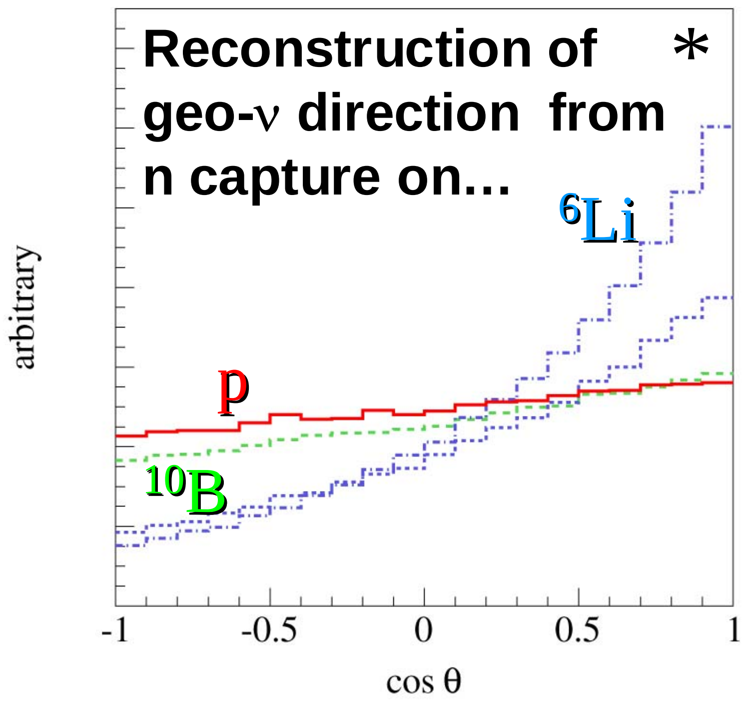


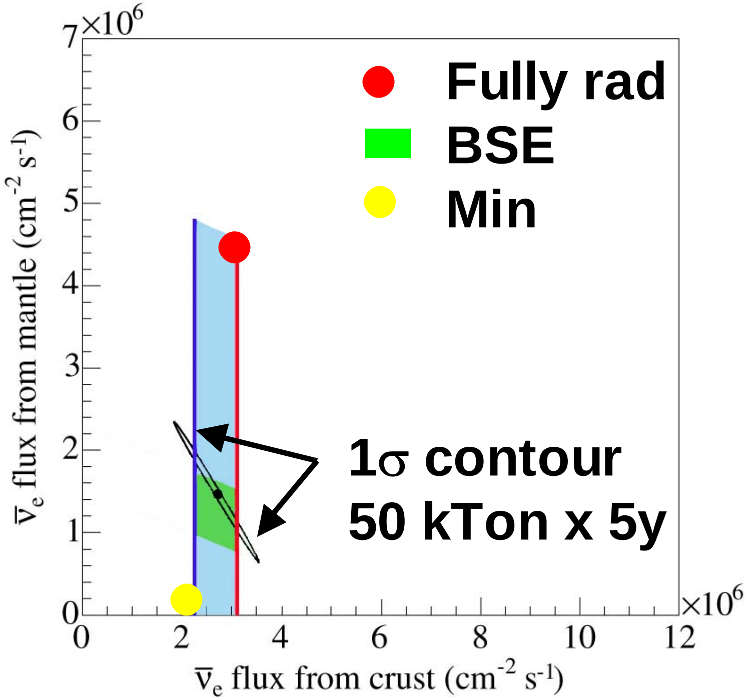
A shortcut in the roadmap?

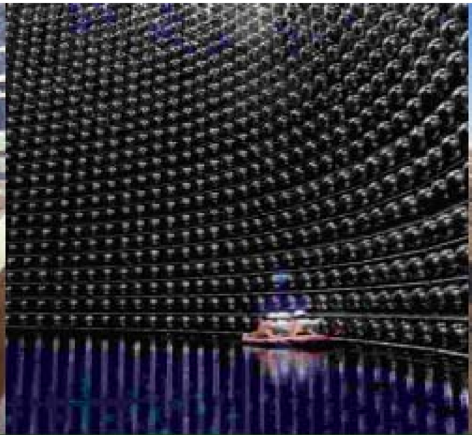
- Reconstruction of geo-ν direction with Gd, Li and B loaded LS is being investigated by several groups. (See Shimizu*, Domogatsky et al., Hochmuth et al., Poster @ TUAP 07)

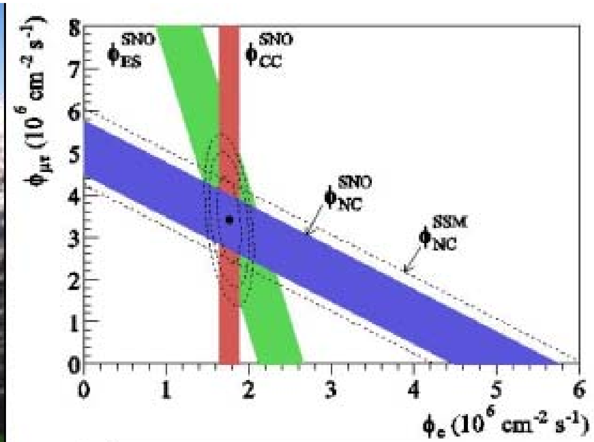
- A 50 kTon 1.5% ^{6}Li loaded LS in 5 years could discriminate crust and mantle contribution at the level of BSE prediction.

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





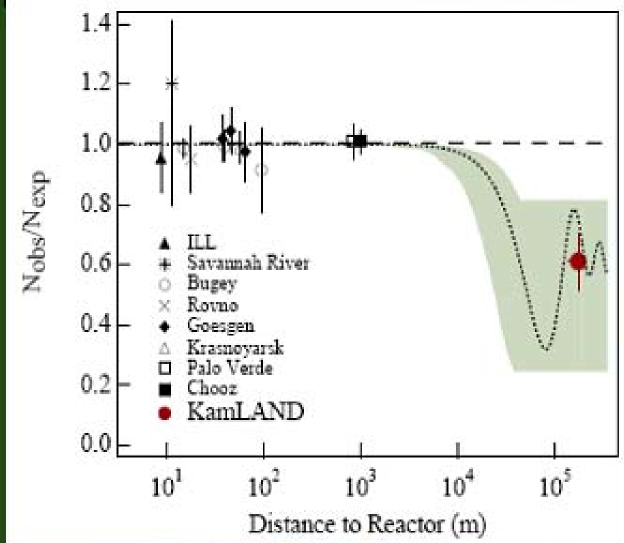


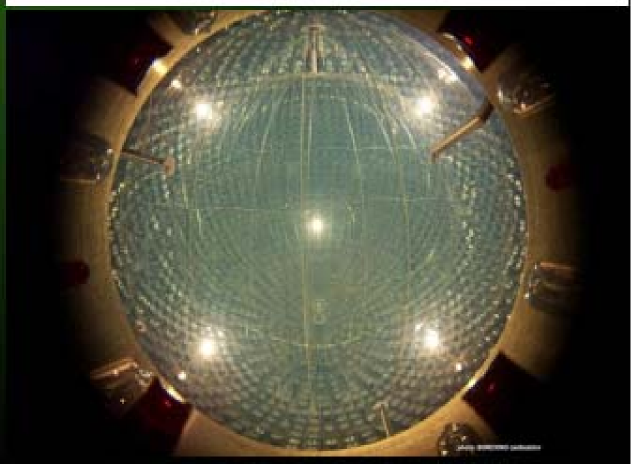
The lesson of solar neutrinos

✓ 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…

Extra slides

Where is Potassium?

$$^{40}K \rightarrow {}^{40}Ca + e + \bar{\nu}$$

- **BSE predicts a ^{40}K contribution ~ 4 TW to radiogenic heat.**
- **BSE assumes Earth (crust + mantle) is depleted in K content with respect to most primitive meteorites (factor ~ 7)***
- **Others speculate that missing K is hidden in the Earth core, providing additional r.h. (~ 24 TW), an energy source for the terrestrial dynamo and the light element "needed" in the Fe-Ni core for getting the right density.**
- **^{40}K geo-neutrino flux could reach $10^8 cm^{-2} s^{-1}$, however E_{max} = 1.3 MeV is below threshold for I.β on free protons and other detection methods are needed…**
- **A possibility considered by M. Chen is I.β on ^{106}Cd, yielding few $\beta^+ \beta^+$ events per year and ^{106}Cd kiloton…**

***Most K should have escaped (volatilized) during planetesimal accretion, preceding Earth formation.**

Un-orthodox or even heretical views

- Herndon (2001) proposed that a large fraction of Uranium has been collected at the center of the Earth, forming a natural 3-6 TW reactor. Fission should provide the energy source for mag. field, a contribution to missing heat, and the source of "high" 3He/4He flow from Earth.
- Emitted electron anti-neutrinos could be detected by the Kamioka liquid scintillator anti-neutrino detector (KamLAND) (Raghavan 2002 – Fogli et al. 2003).
- Time dependence of man made reactor signal could be exploited.

Experimental Status of Geo-reactor Search with KamLAND Detector

Earth, Moon, and Planets (2006) 99:147–153

JELENA MARICIC for KAMLAND COLLABORATION

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Here we present the first attempt to measure the geo-reactor power. Based on a 776 ton-year exposure of KamLAND to electron anti-neutrinos, the detected flux corresponds to (6 ± 6) TW. The upper limit on the geo-reactor power at 90% confidence level is 18 TW, which is below the lower limit of the total Earth's radiogenic heat, estimated to be between 19 and 31TW (Anderson, 2003).

^{235}U?

TABLE I Properties of ^{238}U, ^{232}Th, ^{40}K, ^{235}U, and ^{87}Rb and of their (anti)neutrinos. For each parent nucleus the table presents the natural isotopic mass abundance, half-life, antineutrino maximal energy (or neutrino energy), Q value, $Q_{\rm eff} = Q - \langle E_{(\nu,\bar\nu)} \rangle$, antineutrino and heat production rates for unit mass of the isotope ($\varepsilon_{\bar\nu}$, ε_H), and for unit mass at natural isotopic composition ($\varepsilon'_{\bar\nu}$, ε'_H). Note that antineutrinos with energy above threshold for inverse beta decay on free proton ($E_{th} = 1.806$ MeV) are produced only in the firsts two decay chains.

Decay	Natural isotopic abundance	$T_{1/2}$ [10^9 yr]	$E_{\rm max}$ [MeV]	Q [MeV]	$Q_{\rm eff}$ [MeV]	$\varepsilon_{\bar\nu}$ [kg^{-1}s^{-1}]	ε_H [W/kg]	$\varepsilon'_{\bar\nu}$ [kg^{-1}s^{-1}]	ε'_H [W/kg]
$^{238}U \to {}^{206}Pb + 8\,{}^4He + 6e + 6\bar\nu$	0.9927	4.47	3.26	51.7	47.7	7.46×10^7	0.95×10^{-4}	7.41×10^7	0.94×10^{-4}
$^{232}Th \to {}^{208}Pb + 6\,{}^4He + 4e + 4\bar\nu$	1.0000	14.0	2.25	42.7	40.4	1.62×10^7	0.27×10^{-4}	1.62×10^7	0.27×10^{-4}
$^{40}K \to {}^{40}Ca + e + \bar\nu$ (89%)	1.17×10^{-4}	1.28	1.311	1.311	0.590	2.32×10^8	0.22×10^{-4}	2.71×10^4	2.55×10^{-9}
$^{40}K + e \to {}^{40}Ar + \nu$ (11%)	1.17×10^{-4}	1.28	0.044	1.505	1.461	=	0.65×10^{-5}	=	0.78×10^{-9}
$^{235}U \to {}^{207}Pb + 7\,{}^4He + 4e + 4\bar\nu$	0.0072	0.704	1.23	46.4	44	3.19×10^8	0.56×10^{-3}	2.30×10^6	0.40×10^{-5}
$^{87}Rb \to {}^{87}Sr + e + \bar\nu$	0.2783	47.5	0.283	0.283	0.122	3.20×10^6	0.61×10^{-7}	8.91×10^5	0.17×10^{-7}

The energy of ^{87}Rb neutrinos is so low that it is very unlikely that its flux could be measured. Also heat production from ^{87}Rb is at the level of 1% of the total[5]. For these reasons, from now on we shall consider only U, Th, and ^{40}K and refer to these three elements as the Heat Generating Elements (HGEs) and to the antineutrinos from their decay (chains) as geo-neutrinos.

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[3] Isotopes in the list have abundances and decay rates sufficiently large to give contributions of order 1% or more to the estimated radiogenic heat production: other radioactive elements such as ^{176}Lu, ^{147}Sm, ^{187}Ru, give contributions of order 10^{-4} or less.

[4] In the Table and in the rest of the paper, unless differently specified, nuclear data are taken from (Firestone and Shirley, 1996).

[5] This estimate is obtained assuming an abundance of ^{87}Rb about 50 times the one of uranium.