Geoneutrinos

Livia Ludhova

for Borexino collaboration

Clermont Ferrand

April 19th, 2012

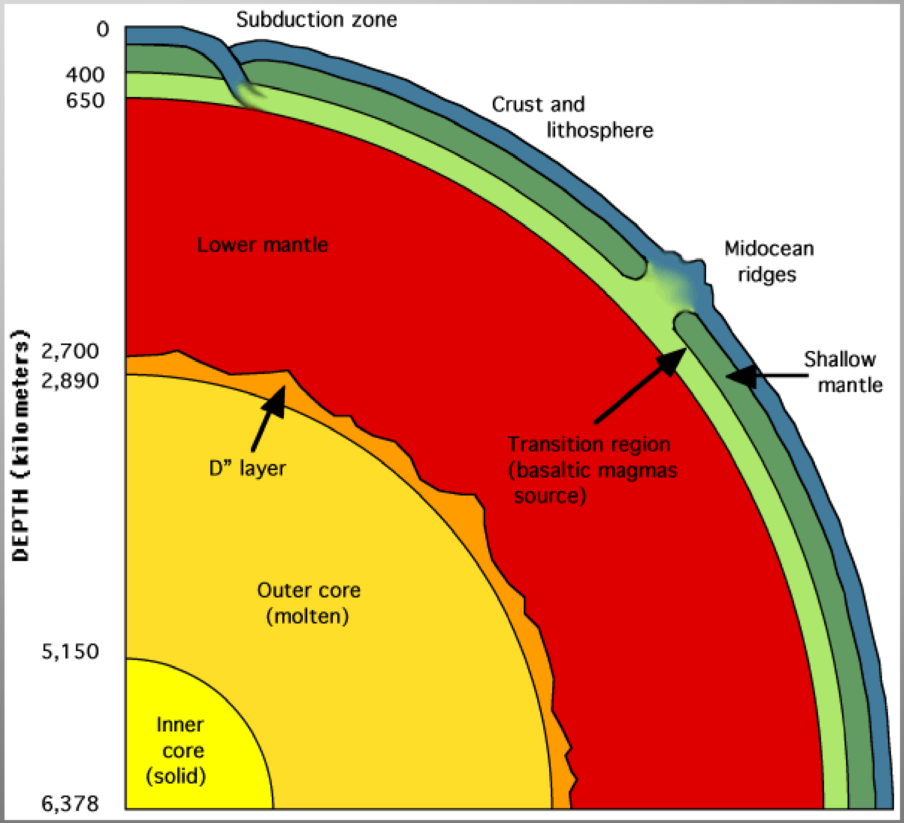
Outline

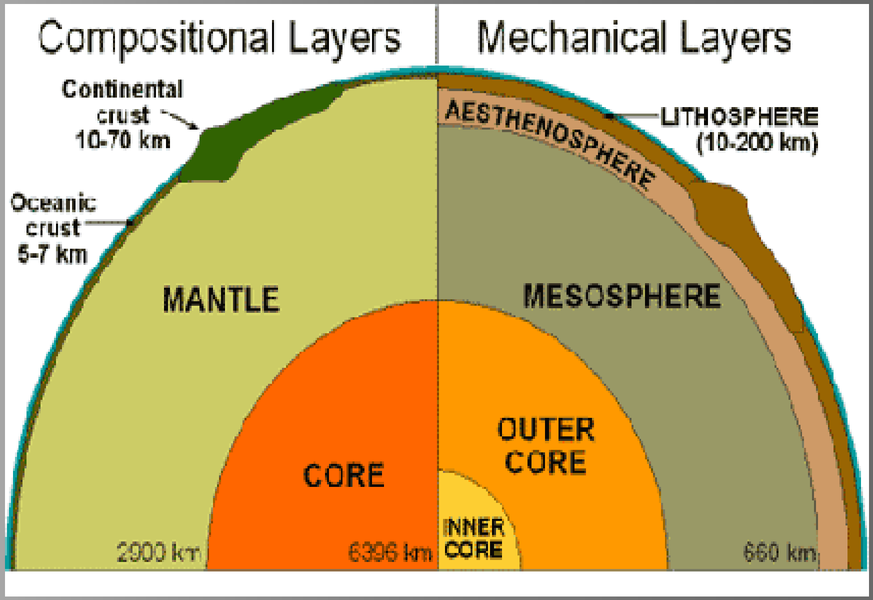
- **The Earth** (mostly for physicists)
- **Neutrinos and anti-neutrinos** (mostly for geologists)
- **Geoneutrinos**
- **Latest geoneutrino experimental results**
- **Future**

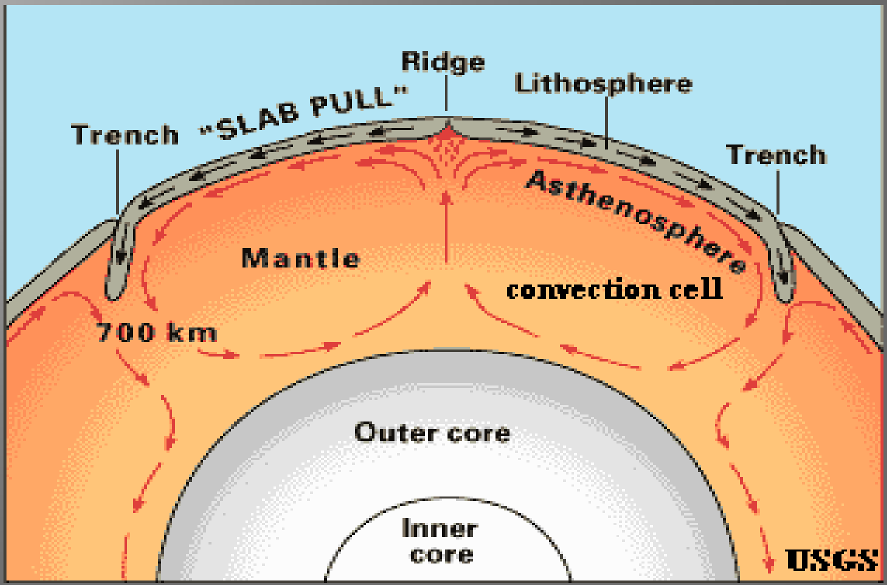
Outline

- **The Earth (mostly for physicists)**
- **Neutrinos and anti-neutrinos (mostly for geologists)**
- **Geoneutrinos**
- **Latest geoneutrino experimental results**
- **Future**

Earth structure



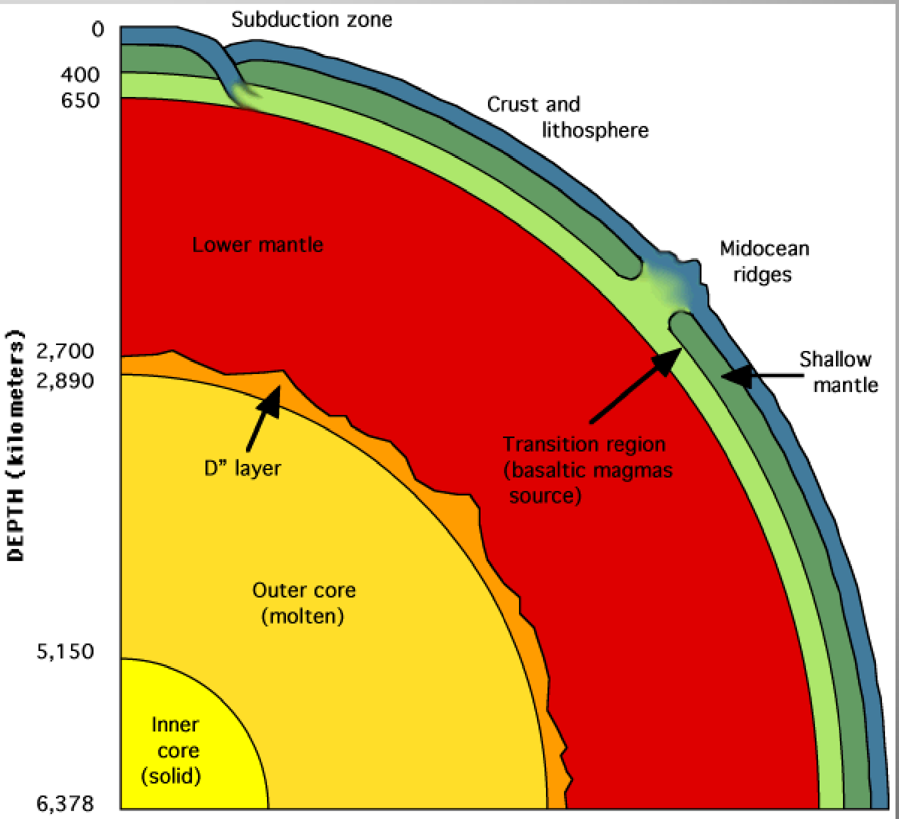




Clermont Ferrand, April 19th, 2012

Livia Ludhova

Earth structure



Inner Core - SOLID

- about the size of the Moon;
- Fe – Ni alloy;
- **solid** (high pressure ~ 330 GPa);
- temperature ~ 5700 K;

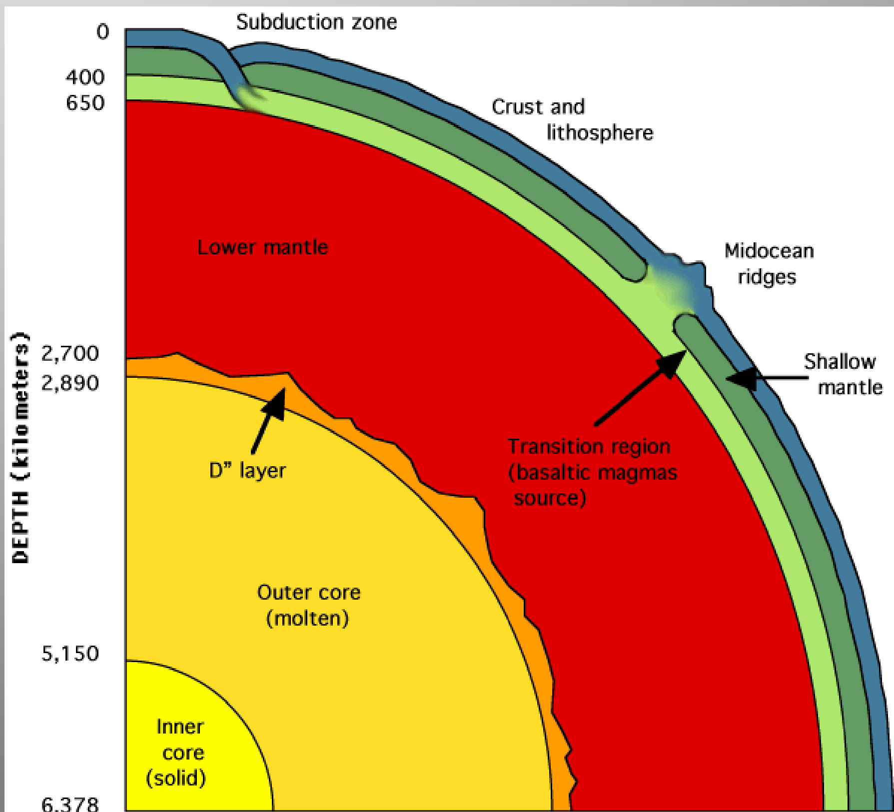
Outer Core - LIQUID

- 2260 km thick;
- FeNi alloy + 10% light elem. (S, O?);
- **liquid;**
- temperature ~ 4100 – 5800 K;
- **geodynamo:** motion of conductive liquid within the Sun's magnetic field;

D" layer: mantle –core transition

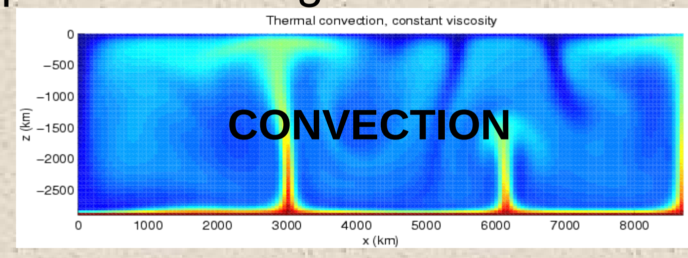
- ~200 km thick;
- seismic discontinuity;
- unclear origin;

Earth structure



Lower mantle (mesosphere)

- rocks: high Mg/Fe, < Si + Al;
- T: 600 – 3700 K;
- high pressure: solid, but viscose;
- "plastic" on long time scales:

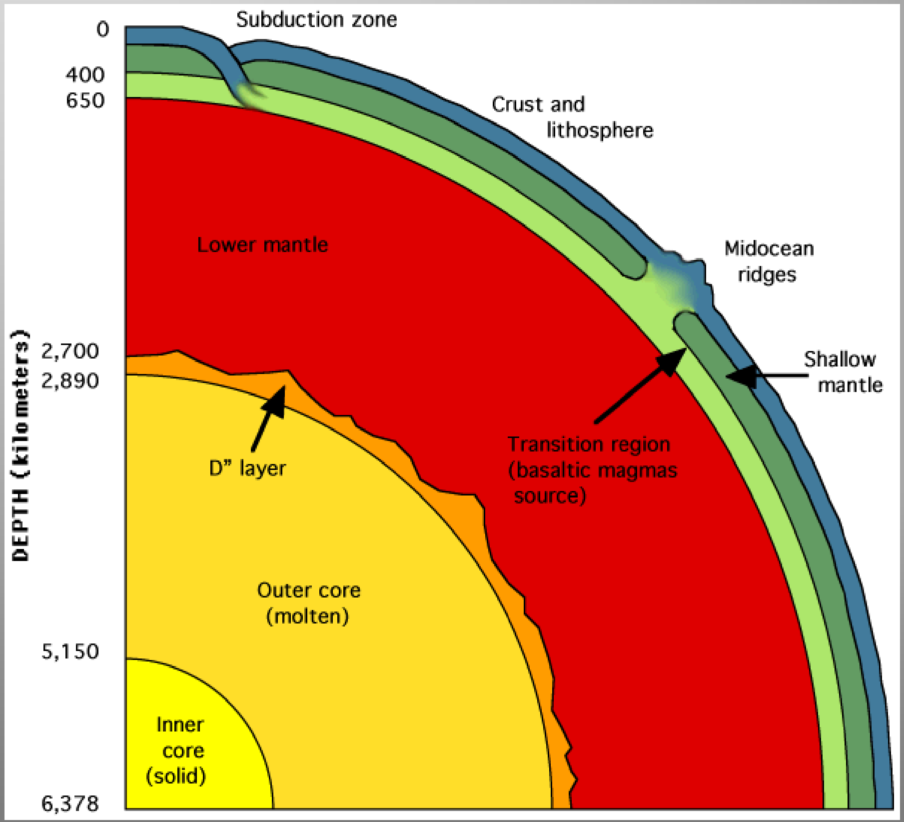


Transition zone (400 -650 km)

seismic discontinuity;

- mineral recrystallisation;
- : role of the latent heat?;
- partial melting: the source of mid-ocean ridges basalts;

Earth structure



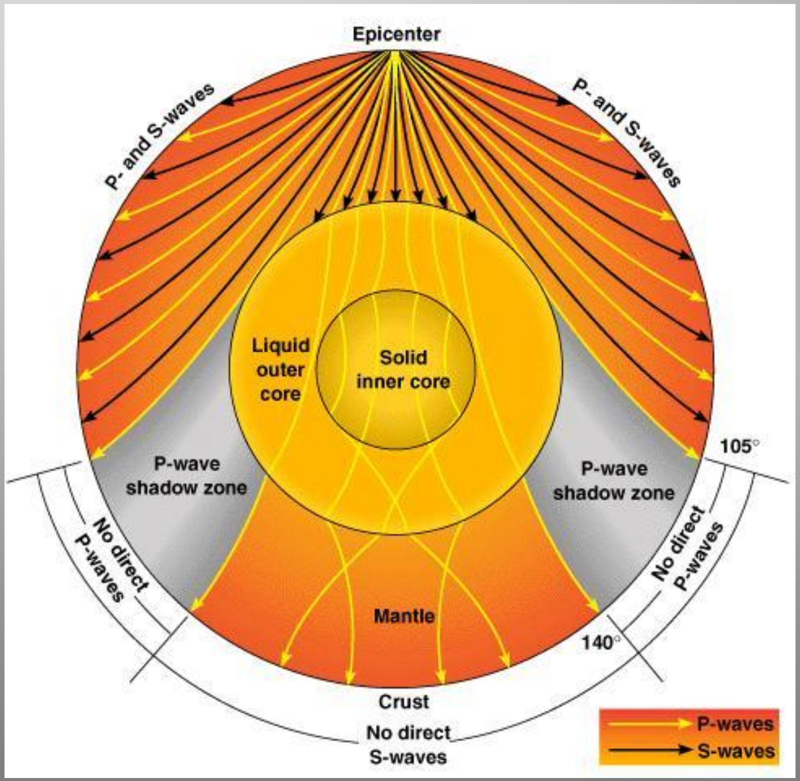
Upper mantle

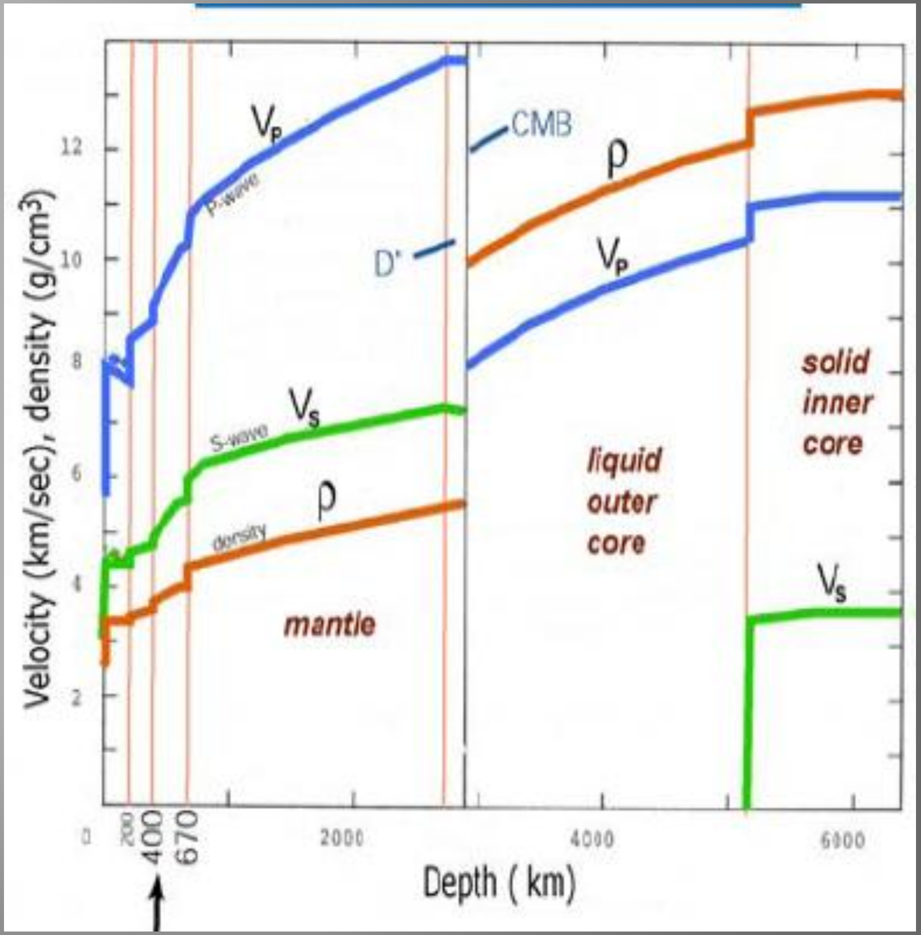
- composition: rock type peridotite
- includes highly viscose **astenosphere** on which are floating litospheric tectonic plates (**lithosphere** = more rigid upper mantle + crust);

Crust: the uppermost part

- **OCEANIC CRUST**:
- created at mid-ocean ridges;
- ~ 10 km thick;
- **CONTINENTAL CRUST**:
- the most differentiated;
- 30 – 70 km thick;
- igneous, metamorphic, and sedimentary rocks;
- obduction and orogenesis;

Seismology





P – primary, longitudinal waves
S – secondary, transverse/shear waves

Discontinuities in the waves propagation and the density profile but no info about the chemical composition of the Earth

Geochemistry

1) Direct rock samples

* surface and bore-holes (max. 12 km);

* mantle rocks brought up by tectonics and **vulcanism;**

BUT: POSSIBLE ALTERATION DURING THE TRANSPORT

2) Geochemical models:

– composition of direct rock samples + chondritic/enstatic meteorites + Sun;

Bulk Silicate Earth (BSE) models:

medium composition of the "re-mixed" crust + mantle,

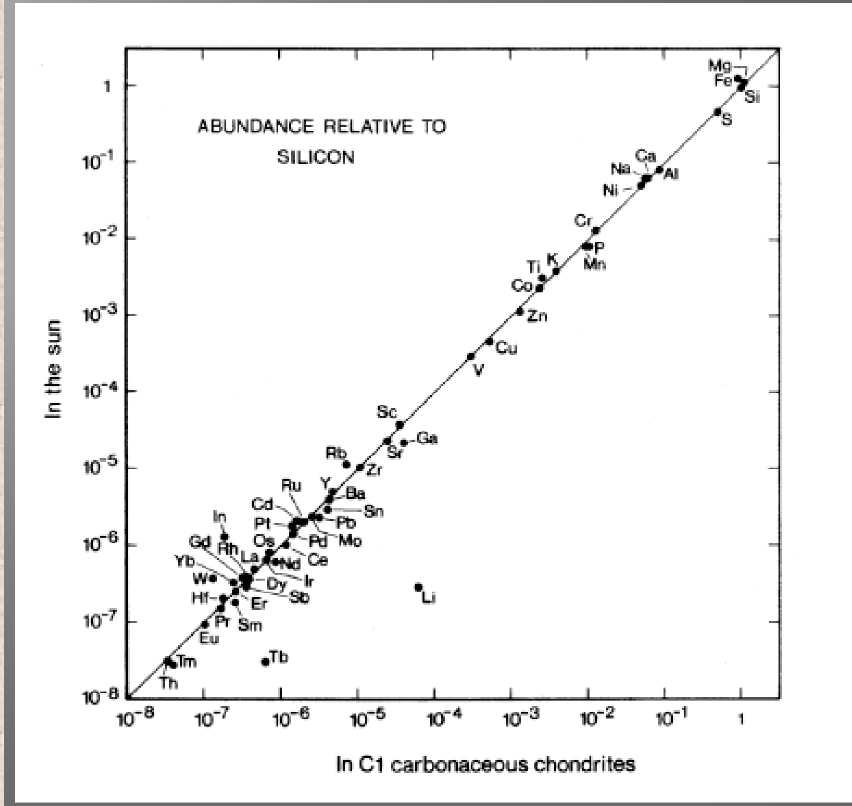
i.e., primordial mantle before the crust differentiation and after the Fe-Ni core separation;

(chondritic :McDonough & Sun 1995, Lyubetskaya & Korenaga 2007; enstatic: Javoy 2010)

ratios of element abundances more stable in different models with respect to absolute abundances:

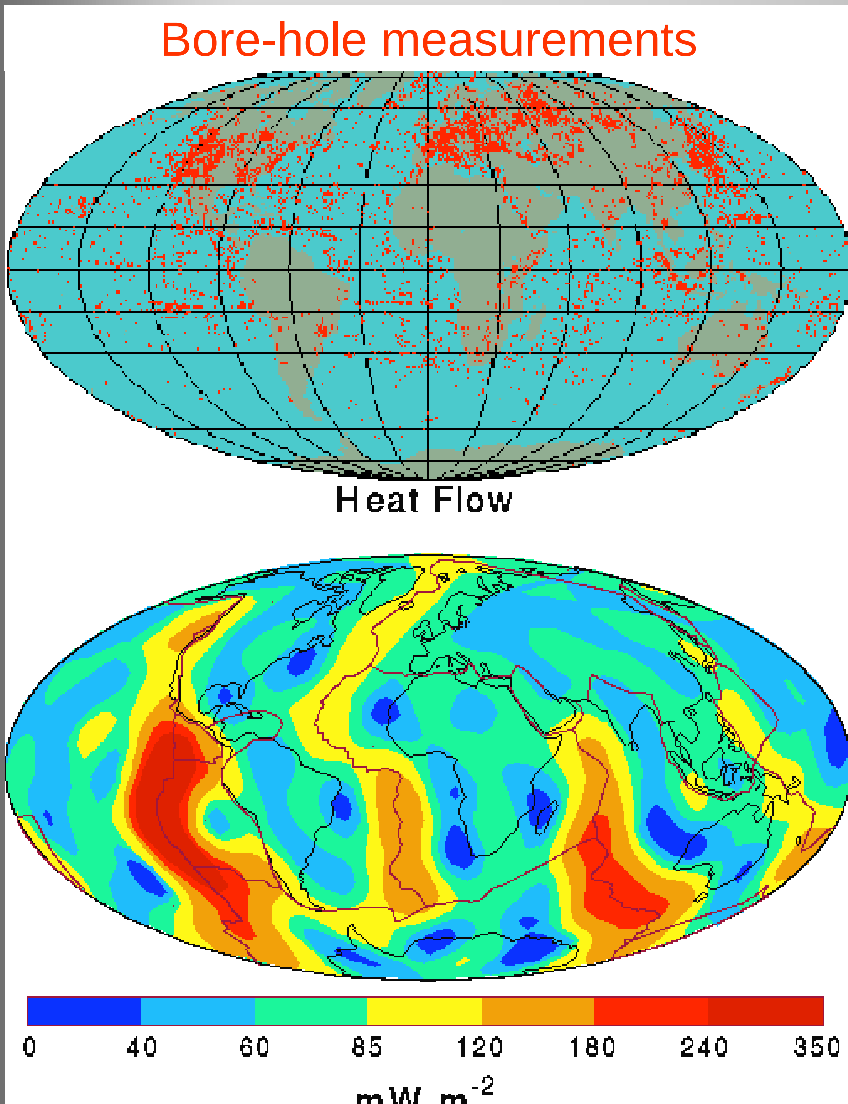
Th/U = 3.9

K/U = 1.14×10^4



Livia Ludhova

Surface heat flux



Global Heat Flow Data (Pollack *et al.*)

- Conductive heat flow from bore-hole temperature gradient;

- **Total surface heat flux:**

  31 ± 1 TW (Hofmeister&Criss 2005)

  46 ± 3 TW (Jaupart et all 2007)

  47 ± 2 TW (Davis&Davies 2010)

  (same data, different analysis)

SYSTEMATIC ERRORS

Different assumptions concerning the role of fluids in the zones of mid ocean ridges.

Sources of the Earth heat

- **Total heat flow ("measured"): 31±1 or 46±3 or 47±2 TW**
- **Radiogenic heat flow (BSE composition)**

  A) Chondritic : 17-21 TW, 19 TW (McDonough & Sun 1995)

  the main long-lived radioactive elements within the Earth:

  ^{238}U, ^{232}Th, and ^{40}K: 7 TW crust, 13 TW mantle, 0 TW core;B)

  B) Enstatic models: (Javoy 2010): 11 TW!!!
- **Other heat sources (possible deficit up to 47-11 = 36 TW!)**
  - **Residual heat: gravitational contraction and extraterrestrial impacts in the past;**
  - **^{40}K in the core;**
  - **nuclear reactor; (BOREXINO rejects a power > 3 TW at 95% C.L.)**
  - **mantle differentiation and recrystallisation;**

IMPORTANT MARGINS
FOR ALL DIFFERENT MODELS OF THE EARTH STRUCTUE

Outline

- **The Earth** **(mostly for physicists)**
- **Neutrinos and anti-neutrinos** **(mostly for geologists)**
- **Geoneutrinos**
- **Latest geoneutrino experimental results**
- **Future**

LEPTONS

particles - antiparticles

lepton number +1 | **lepton number -1**

e^-	ν_e	e^+	$\bar{\nu}_e$
μ^-	ν_μ	μ^+	$\bar{\nu}_\mu$
τ^-	ν_τ	τ^+	$\bar{\nu}_\tau$

3 flavors

ν_e produced in the nuclear reactions in the Sun;

Total flux ~10^{10} cm^{-2} s^{-1}

Detected via elastic scattering on e:

$$\sigma_{\nu_e e^- \rightarrow \nu_e e^-} \approx 9.5 E_\nu(MeV) \times 10^{-45} \mathrm{cm}^2$$

$\bar{\nu}_e$ produced in the nuclear power-plants (< 10 MeV) and from the Earth radioactivity (**geoneutrinos**) (< 3 MeV)

Total geonu flux ~10^6 cm^{-2} s^{-1}

$$\bar{\nu}_e + p \rightarrow e^+ + n.$$

$$\sigma_{\bar{\nu}_e p \rightarrow e^+ n} \approx 9.3 [E_\nu(MeV)]^2 \times 10^{-44} \mathrm{cm}^2,$$

Neutrino oscillations

Each (anti-) neutrino flavour, electron, muon, tau is a superposition of 3 mass eigenstates, 1, 2, and 3, in different and characteristics proportions.

An (anti-)neutrino of a given energy(momentum) has a periodically evolving mixture of mass eigenstates, thus a probability to observe a certain flavor does oscillate during its passage.

The probability to detect electron antineutrino (from nuclear power plant or geo-neutrino) oscillates:

$$P_{\overline{\nu}_e \to \overline{\nu}_e} \cong 1 - \sin^2(2\theta_{12}) \sin^2\left(1.27 \Delta m^2_{21} L / E_{\overline{\nu}_e}\right)$$

τ_{12}, $\Delta m_{12}{}^2$ … physical constants (oscillation parameters)
L… source – detection distance
E ….antineutrino energy in MeV
3 MeV antineutrino .. Oscillation length of ~100 km, so for geoneutrinos we can use average survival probability of 0.56 ± 0.02 (Enomoto et al 2007) , but for reactor antineutrinos not!

Outline

- The Earth (mostly for physicists)
- Neutrinos and anti-neutrinos (mostly for geologists)
- **Geoneutrinos**
- Latest geoneutrino experimental results
- Future

Geoneutrinos: antineutrinos from the Earth

- ^{238}U, ^{232}Th, ^{40}K chains ($T_{1/2}$ = (4.47, 14.0, 1.28) x 10^9 years, resp.):

  $^{238}U \rightarrow {}^{206}Pb + 8\,\alpha + 8\,e^- +$ 6 anti-neutrinos + 51.7 MeV

  $^{232}Th \rightarrow {}^{208}Pb + 6\,\alpha + 4\,e^- +$ 4 anti-neutrinos + 42.8 MeV

  $^{40}K \rightarrow {}^{40}Ca + e^- +$ 1 anti-neutrino + 1.32 MeV

Earth shines in antineutrinos: flux ~ 10^6 cm^{-2} s^{-1}
leaving freely and instantaneously the Earth interior
(to compare: solar neutrino flux ~ 10^{10} cm^{-2} s^{-1})

  – **released heat and anti-neutrinos flux in a well fixed ratio!**

- **Possible answers to the questions:**
  - What is the radiogenic contribution to the terrestrial heat??
  - What is the distribution of the radiogenic elements within the Earth?
    - how much in the crust and mantle
    - core composition: Ni+Fe and ^{40}K?? geo-reactor ? (Herndon 2001)
  - Is the BSE model compatible with geoneutrino data?

Geoneutrinos: antineutrinos from the Earth

- The main long-lived radioactive elements: ^{238}U, ^{232}Th, and ^{40}K

U, Th, K are refractory lithophile elements (RLE)

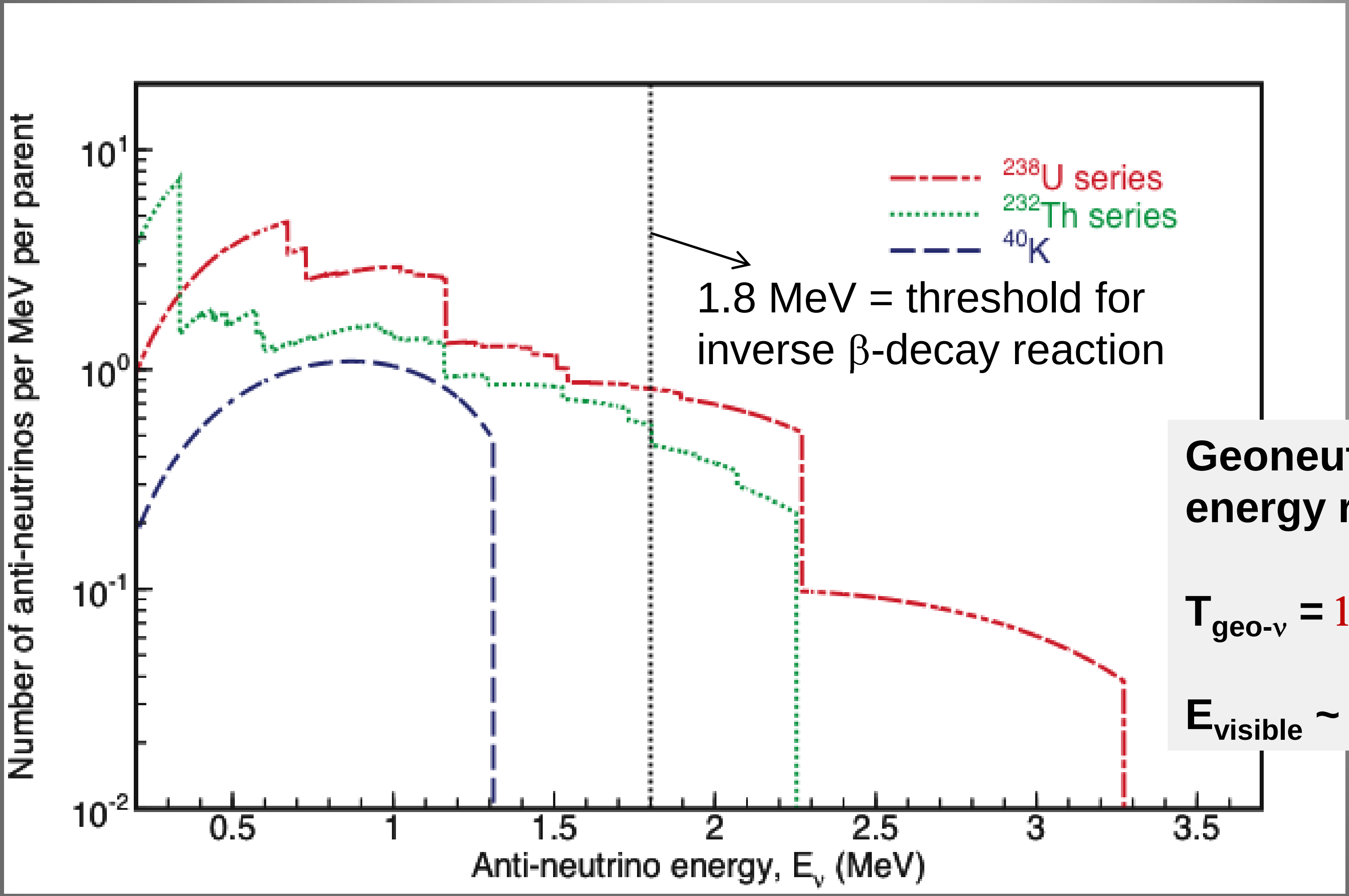
- **Volatile /Refractory:** Low/High condensation temperature
- **Lithophile** – like to be with silicates: during partial melting they tend to stay in the liquid part. The residuum is depleted. Accumulated in the continental crust. Less in the oceanic crust. Mantle even smaller concentrations. Nothing in core.
- absolute BSE abundances varies within 10% based on the model (chondritic models);
- ratios of BSE element abundances more stable in different calculations:
  - **Th/U = 3.9**
  - K/U = 1.14 x 10^4

concentration for ^{238}U (Mantovani *et al*. 2004)

upper continental crust:	2.5	ppm
middle continental crust:	1.6	ppm
lower continental crust:	0.63	ppm
oceanic crust:	0.1	ppm
upper mantle:	6.5	ppb
core	NOTHING	

BSE (primordial mantle) 20 ppb

Geoneutrinos energy spectra
(theoretical calculations)



Geoneutrinos energy range

$T_{geo-\nu}$ = 1.8 – 3.3 MeV

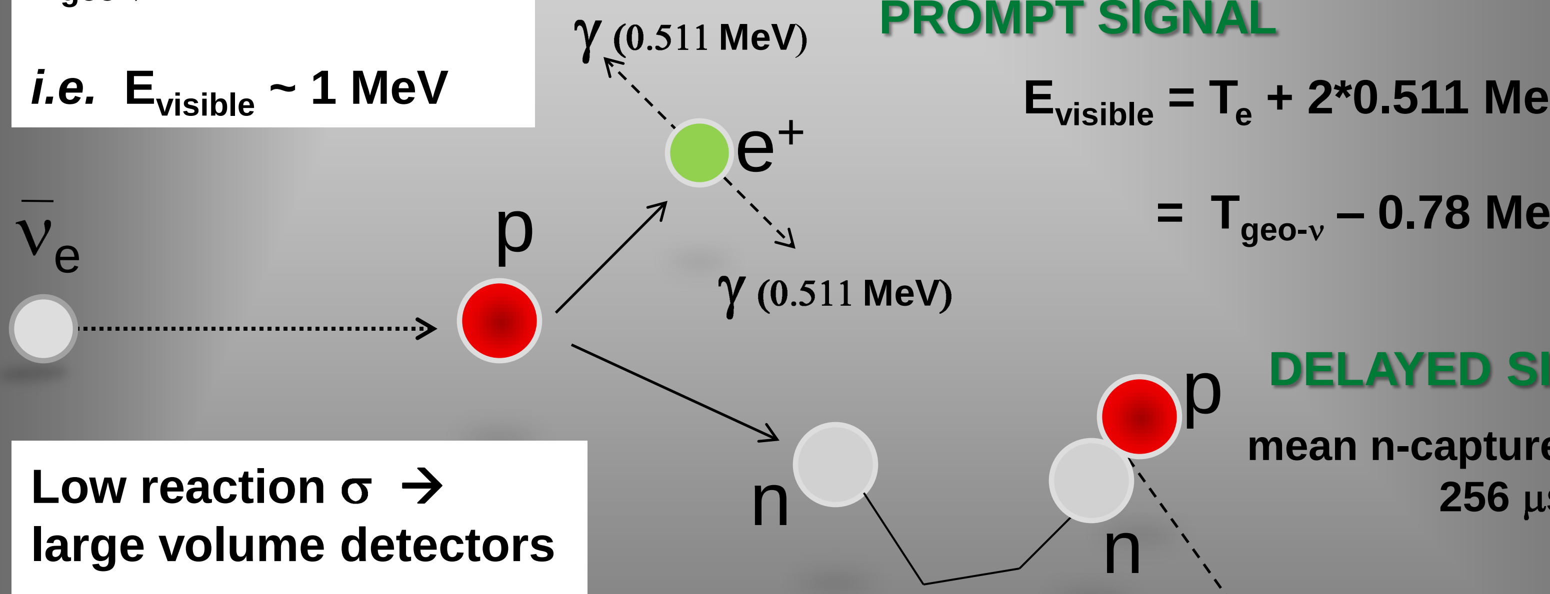
$E_{visible}$ ~ 1 – 2.5 MeV

Detecting geo-ν: inverse β-decay

Energy **threshold** of

$T_{geo-\nu}$ = 1.8 MeV

i.e. $E_{visible}$ ~ 1 MeV



PROMPT SIGNAL

$E_{visible} = T_e + 2{*}0.511\ \text{MeV} =$

$= T_{geo-\nu} - 0.78\ \text{MeV}$

DELAYED SIGNAL

mean n-capture time on p
256 μs

neutron thermalization
up to cca. 1 m

Low reaction σ → large volume detectors

Liquid scintillators

Radioactive purity & underground labs

Outline

- The Earth (mostly for physicists)
- Neutrinos and anti-neutrinos (mostly for geologists)
- Geoneutrinos
- **Latest geoneutrino experimental results**
- Future

- **only 2 running experiments measured geoneutrinos;**
- liquid scintilllator detectors;
- (Anti-)neutrinos have low interaction rates, therefore:
  - Large volume detectors needed;
  - High radiopurity of construction materials;
  - Underground labs to shield cosmic radiations;

KamLand in Kamioka, Japan

OCEANIC CRUST

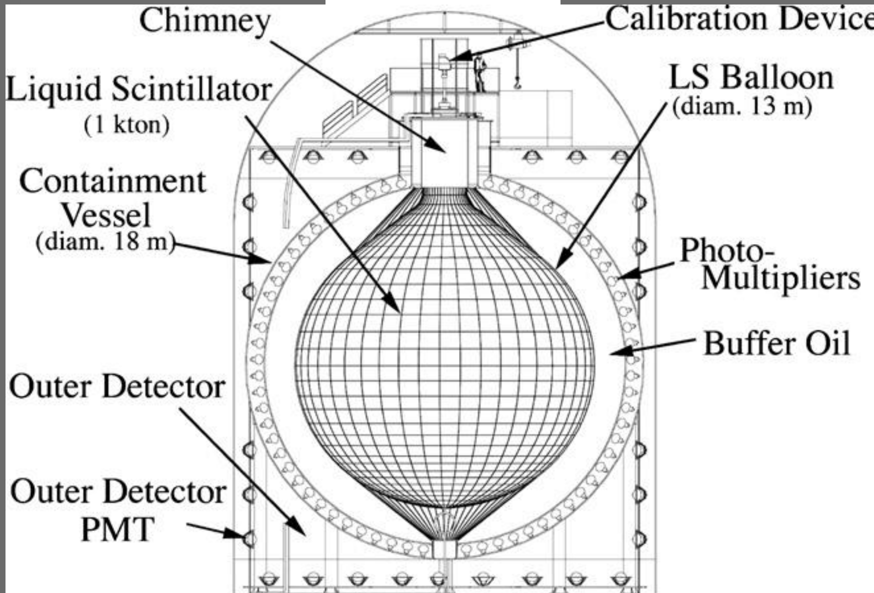
- originally build to measure reactor antineutrinos;
- 1000 tons;
- S(reactors)/S(geo) ~ 6.7 (2010)
- The first excess due to geoneutrinos measured in 2005 (Araki et al. Nature 436);
- high exposure: 99.997 CL observation in 2011 (Gando et al, Nature Geoscience 1205): 106^{+29}_{-28} geonu events detected;

Borexino in Gran Sasso, Italy

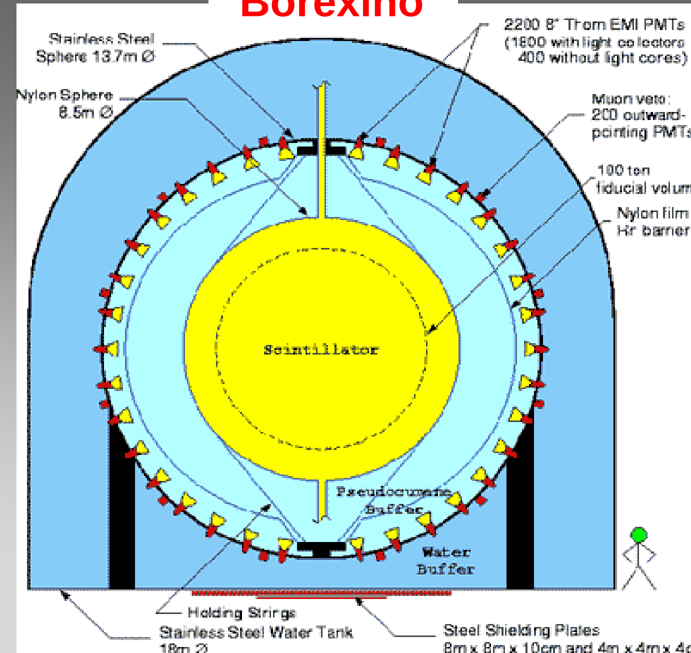
CONTINENTAL CRUST

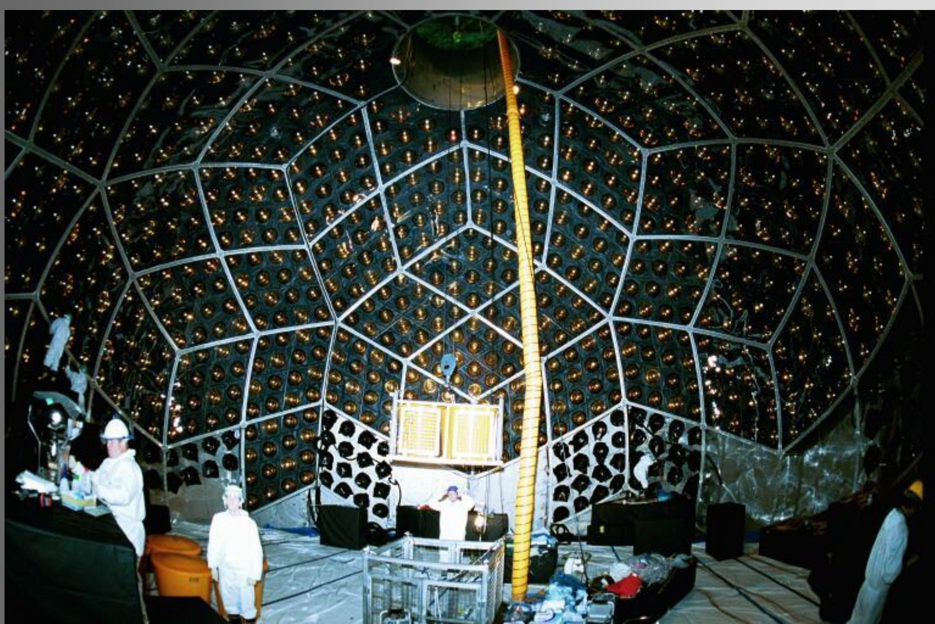
- originally build to measure neutrinos from the Sun – extreme radiopurity needed and achieved;
- 280 tons;
- S(reactors)/S(geo) ~ 0.3 !!! (2010)
- DAQ started in 2007;
- small exposure but low background level: observation at 99.997 CL in 2010 (Bellini et al, PLB 687): $9.9^{+4.1}_{-3.4}$ geonu events detected;
- active geo-reactor in the Earth core of power > 3 TW excluded at 95% CL;

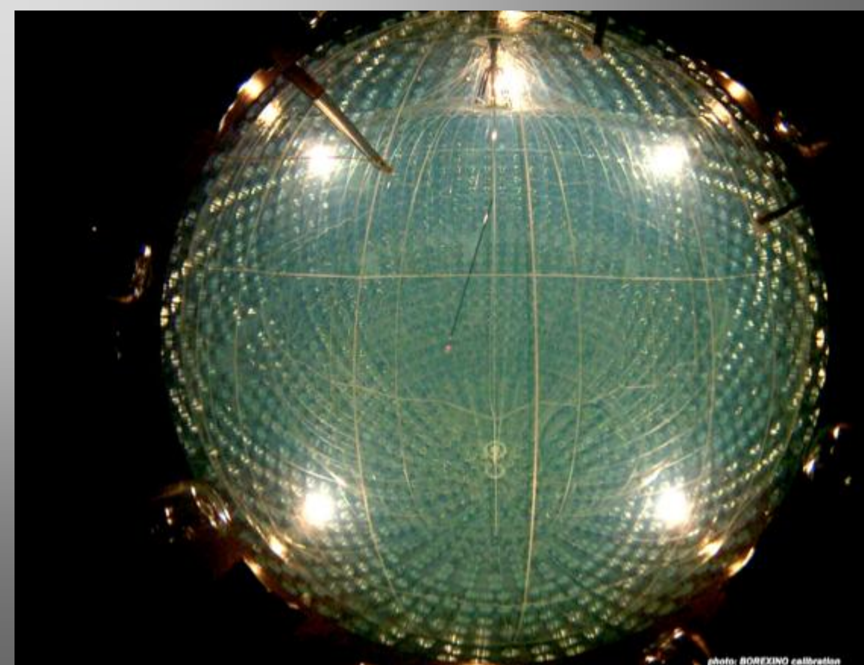
KamLand



Borexino

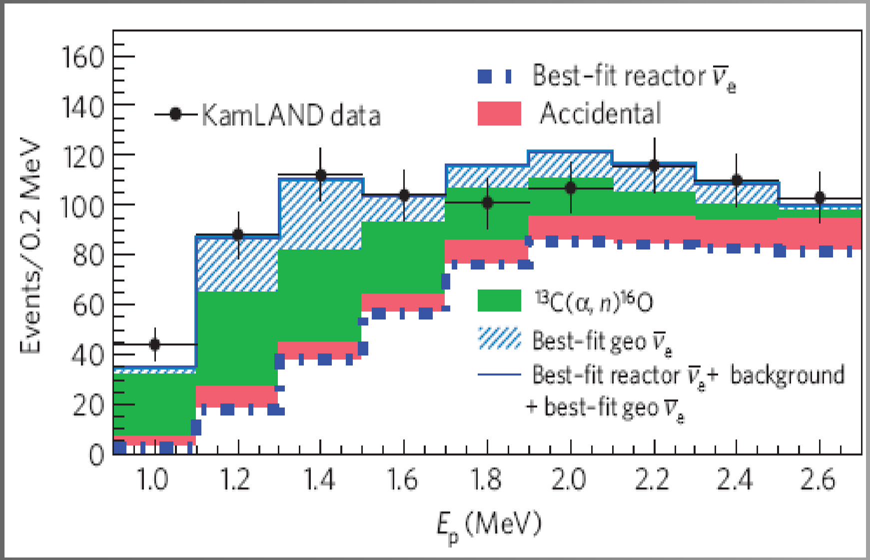


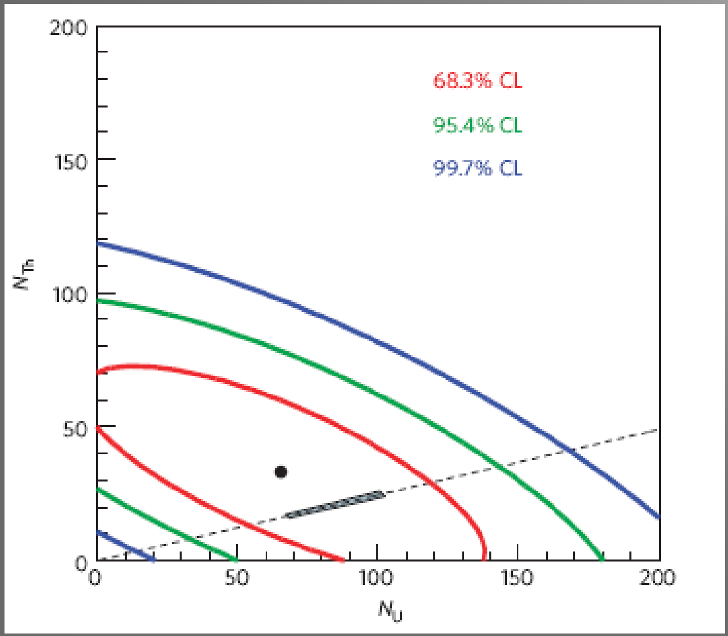




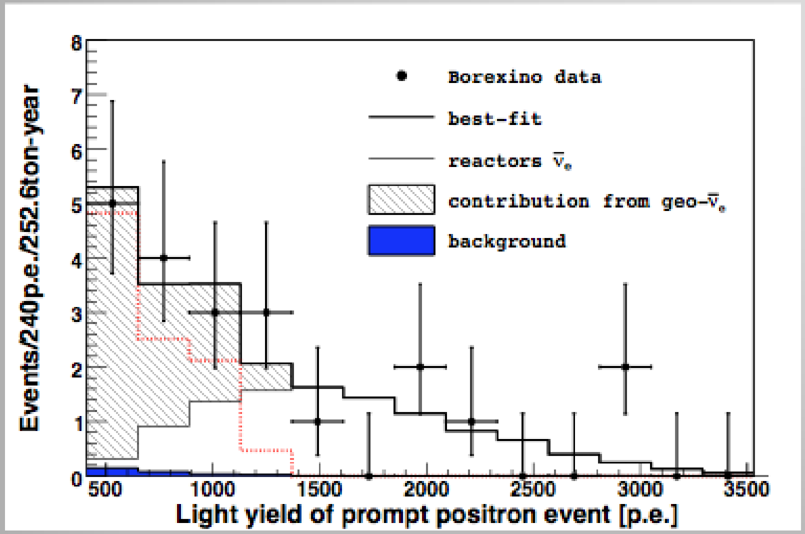
Clermont Ferrand, April 19th, 2012

KamLand





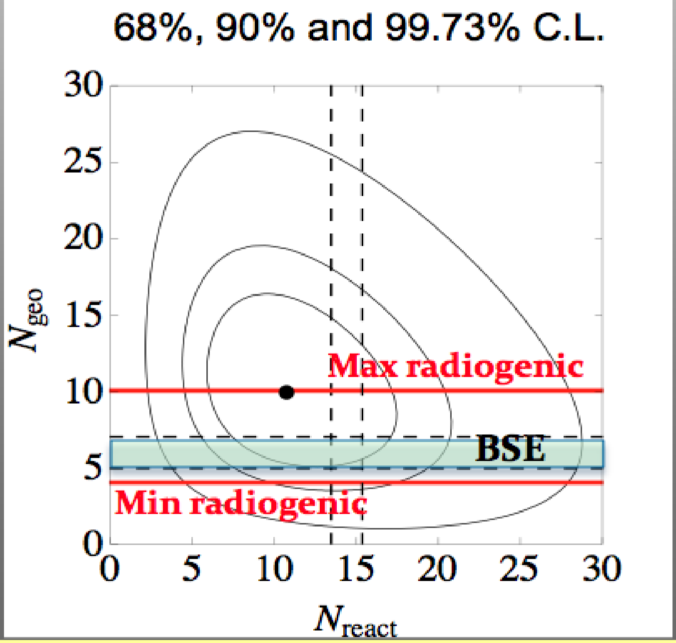
Borexino



~1 MeV

~3 MeV

~7 MeV

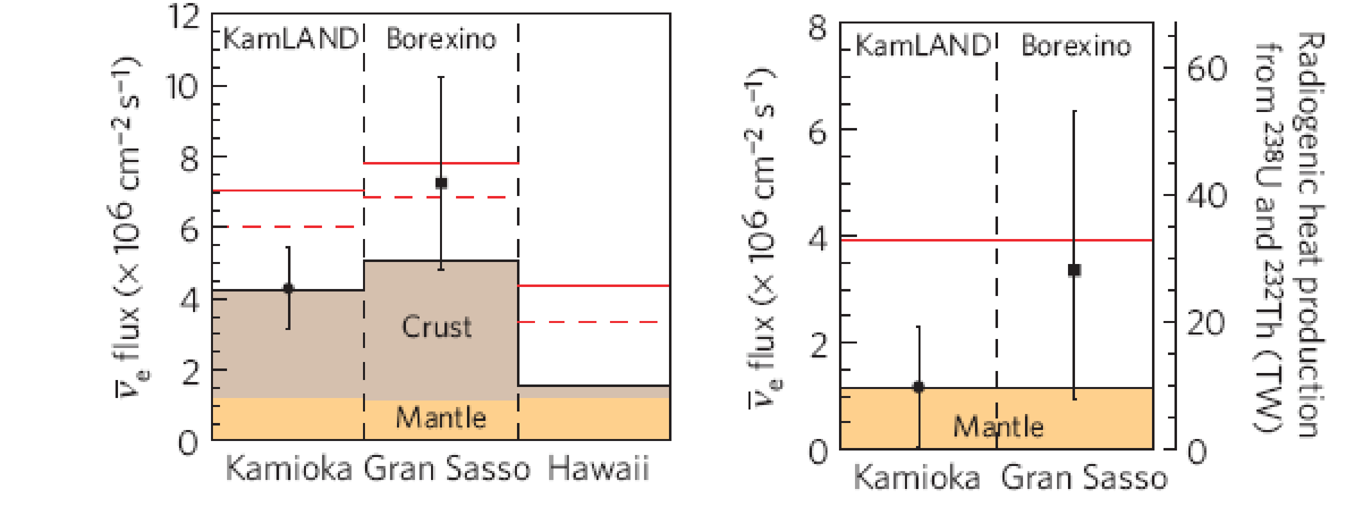


A. Gando *et al.*, Nature Geoscience **1205** (2011).

G. Bellini *et al.*, *PLB* **687** (2010) 299-304.

Combined analysis

A. Gando *et al*., Nature Geoscience **1205** (2011).



- **mantle contribution observed;**

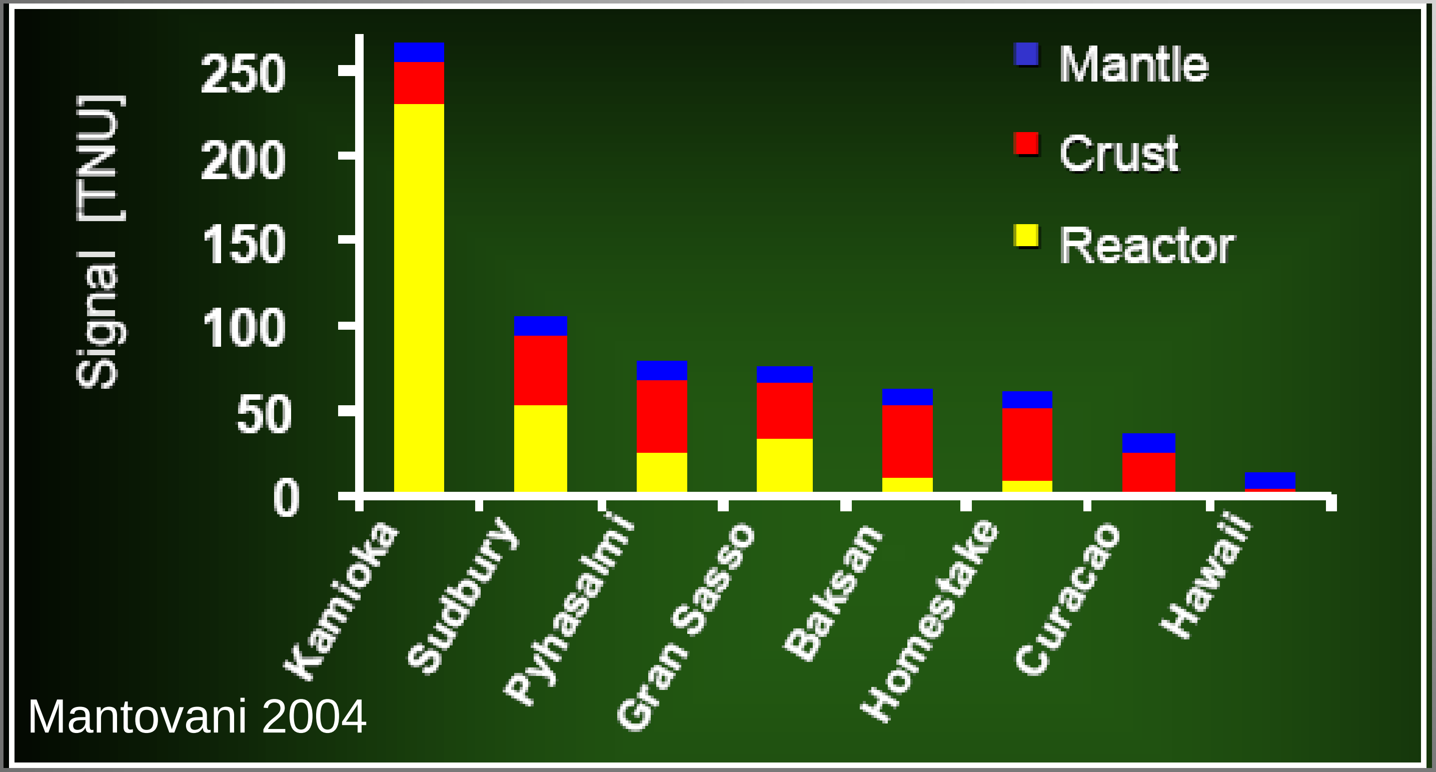
•**Fully radiogenic model excluded at 97% CL**

(combined KamLand + Borexino data: uranium-238 and thorium-232: $20.0^{+8.8}_{-8.6}$ TW, from geology: potassium-40 contributes 4 TW)

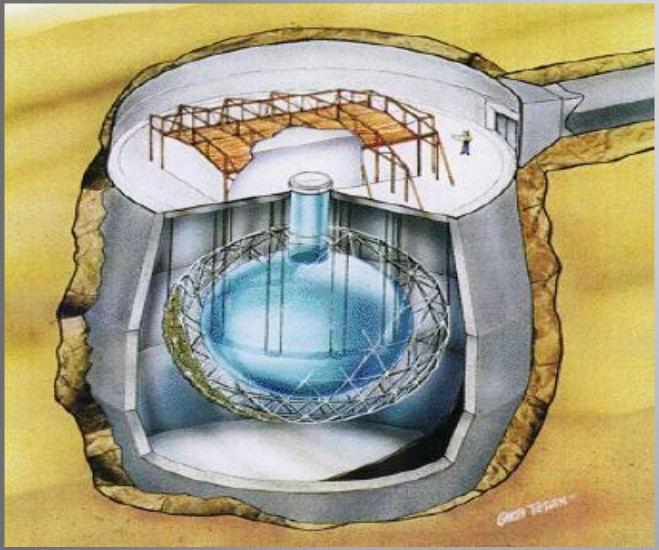
Outline

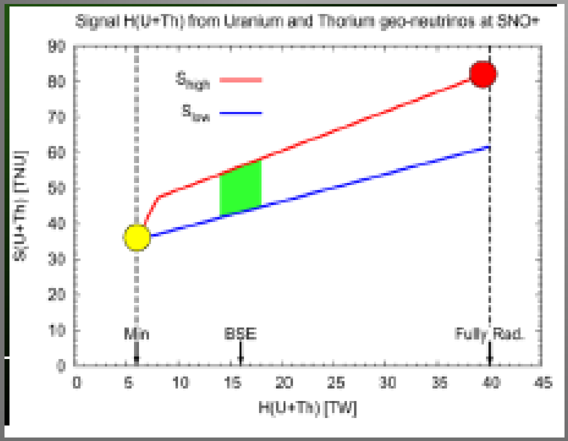
- The Earth (mostly for physicists)
- Neutrinos and anti-neutrinos (mostly for geologists)
- Geoneutrinos
- Current experimental results
- **Future**

Running and planned experiments
having geoneutrinos among their aims



SNO+ at Sudbury, Canada





Mantovani et al., TAUP 2007

SHOULD BE COMING SOON!

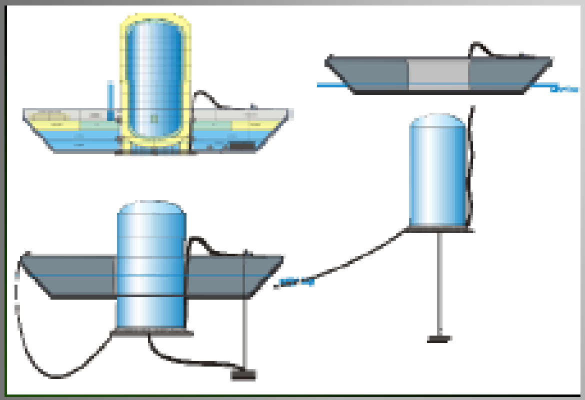
After SNO: D_2O replaced by 1000 tons of liquid scintillator
M. J. Chen, *Earth Moon Planets* **99**, 221 (2006)

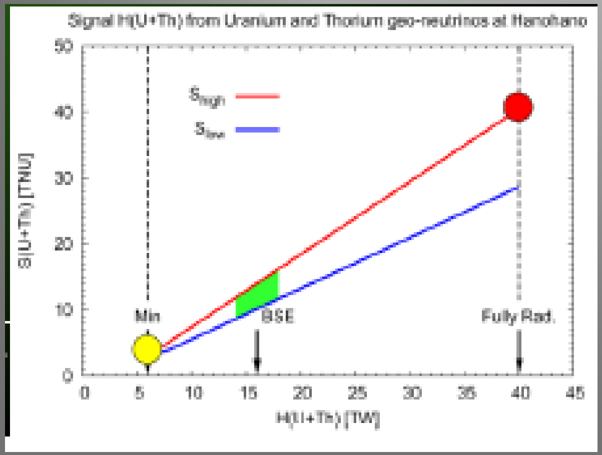
Placed on an old continental crust:
80% of the signal from the crust
(Fiorentini et al., 2005)

BSE: 28-38 events/per year

Hanohano at Hawaii

Hawaii Antineutrino Observatory (HANOHANO = "magnificent” in Hawaiian





Mantovani , TAUP 2007

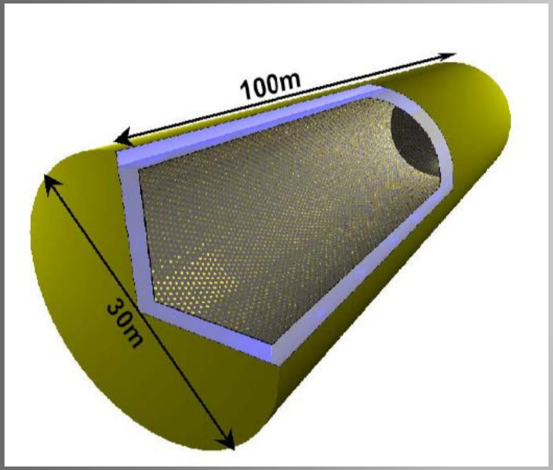
Project for a 10 kton liquid scintillator detector, movable and placed on a deep ocean floor

J. G. Learned et al., *XII International Workshop on Neutrino Telescopes*, Venice, 2007.

Since Hawai placed on the U-Th depleted oceanic crust
70% of the signal from the mantle!
Would lead to very interesting results!
(Fiorentini et al.)

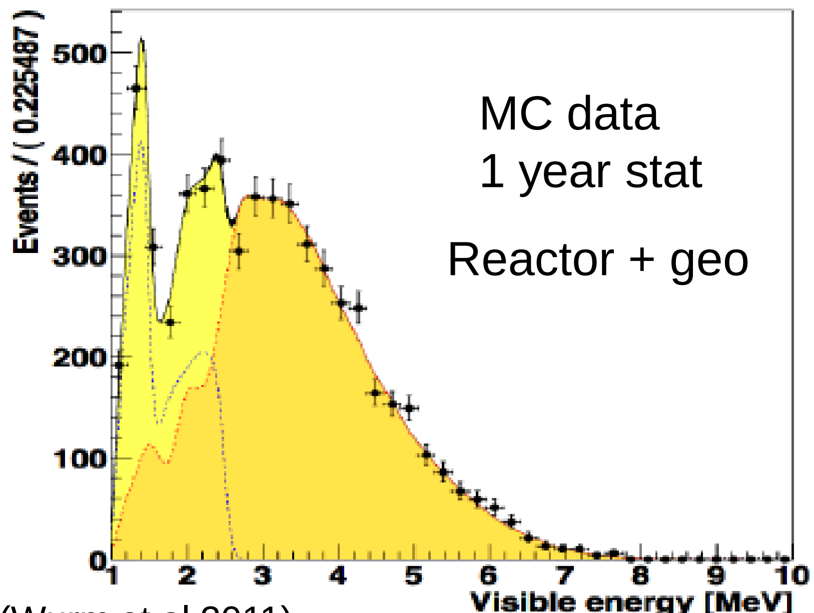
BSE: 60-100 events/per year

LENA at Pyhasalmi, Finland



Project for a 50 kton underground liquid scintillator detector (Hochmuth et al 2007)

80% of the signal from the continental crust (Fiorentini et al.)
BSE: 800-1200 events/per year



(Wurm et al 2011)

Within the first few years, the total geoneutrino flux could be measuered at few % precision

Strong potential in determining the U/Th ratio of the measured geonu flux

Summary

- The new interdisciplinary field is born;
- Collaboration among geologists and physicists is a must;
- The current experimental results confirm that geo-neutrinos can be successfully detected;
- Signal prediction and data interpretation: local geology around the experimental site must be studied;
- The combined results from different experimental sites have stronger impact – first geologically significant results start to appear;
- New measurements and the new generation experiments are needed for geologically highly significant results;

THANK YOU!!!

Clermont Ferrand, April 19th, 2012 Livia Ludhova