Geoneutrinos

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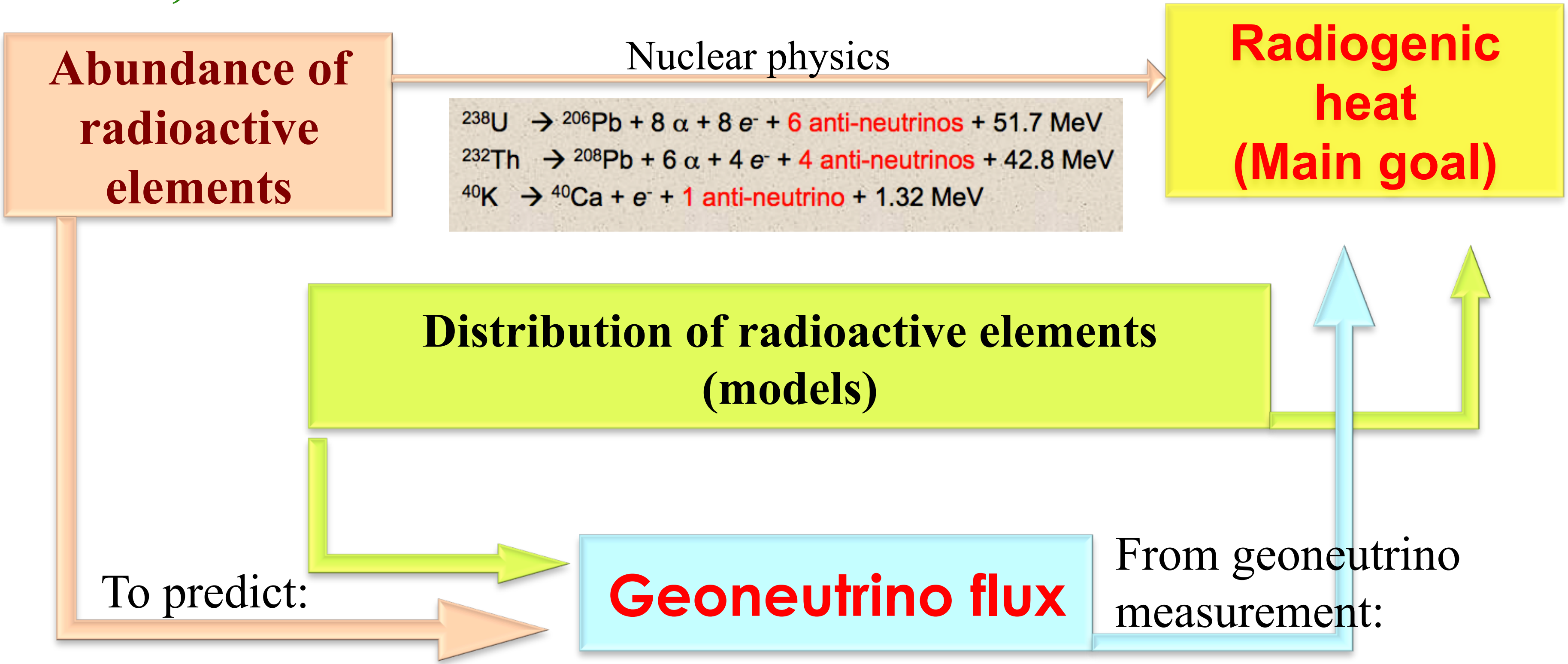
GDR Neutrino, June 2016

LPSC Grenoble

Geoneutrinos: antineutrinos from the decay of ^{238}U, ^{232}Th, and ^{40}K in the Earth



Abundance of radioactive elements

Nuclear physics

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

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

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

Radiogenic heat (Main goal)

Distribution of radioactive elements (models)

To predict:

Geoneutrino flux

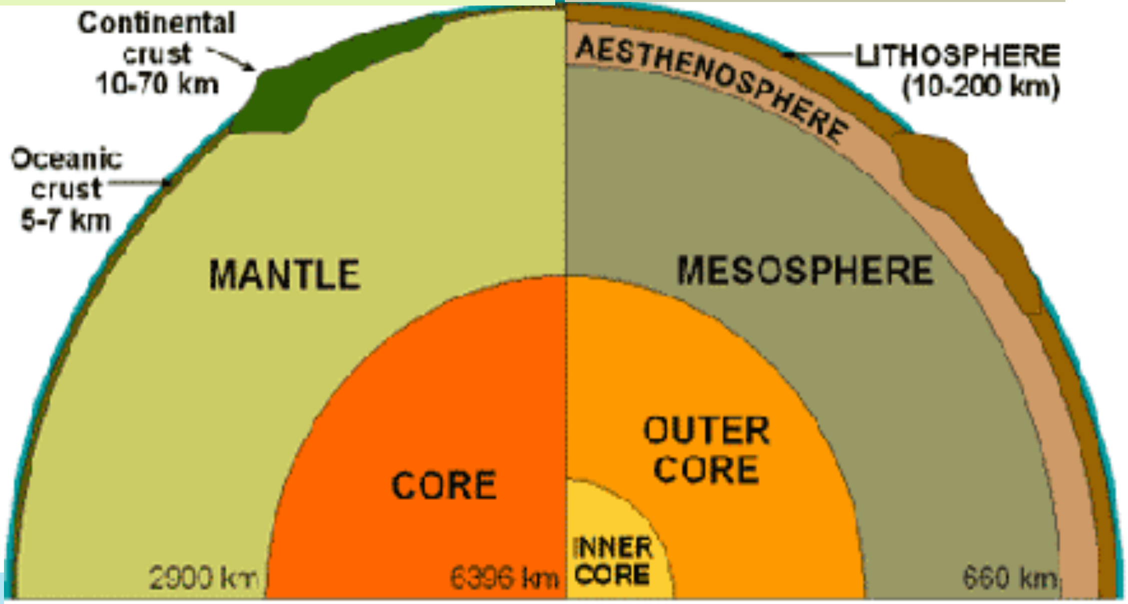
From geoneutrino measurement:

- **Main goal:** determine the contribution of the **radiogenic heat to the total surface heat flux**, which is an important margin, test, and input at the same time for many geophysical and geochemical models of the Earth;
- **Further goals:** tests and discrimination among geological models, study of the mantle homogeneity, insights to the processes of Earth'formation…..

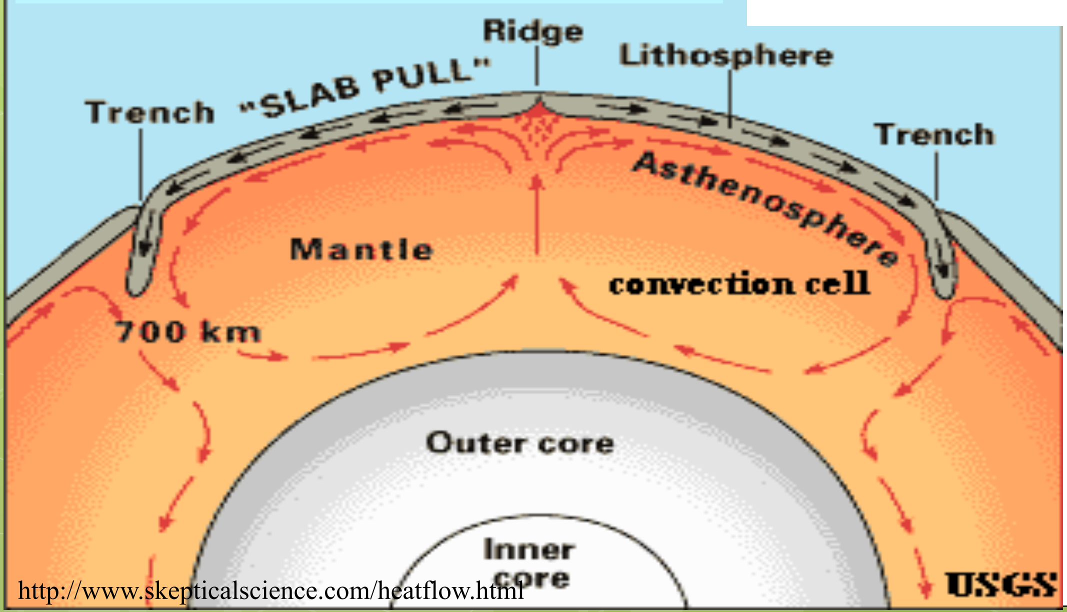
Earth's interior

Compositional layers

Mechanical layers



Dynamical picture



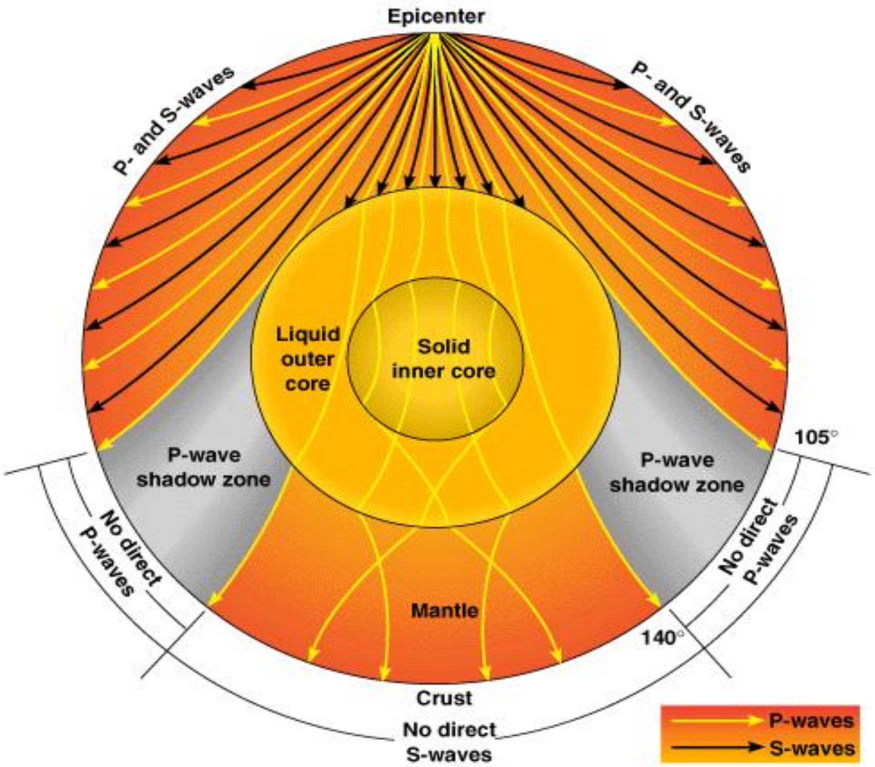
http://www.skepticalscience.com/heatflow.html

U, Th, K: refractory lithophile elements

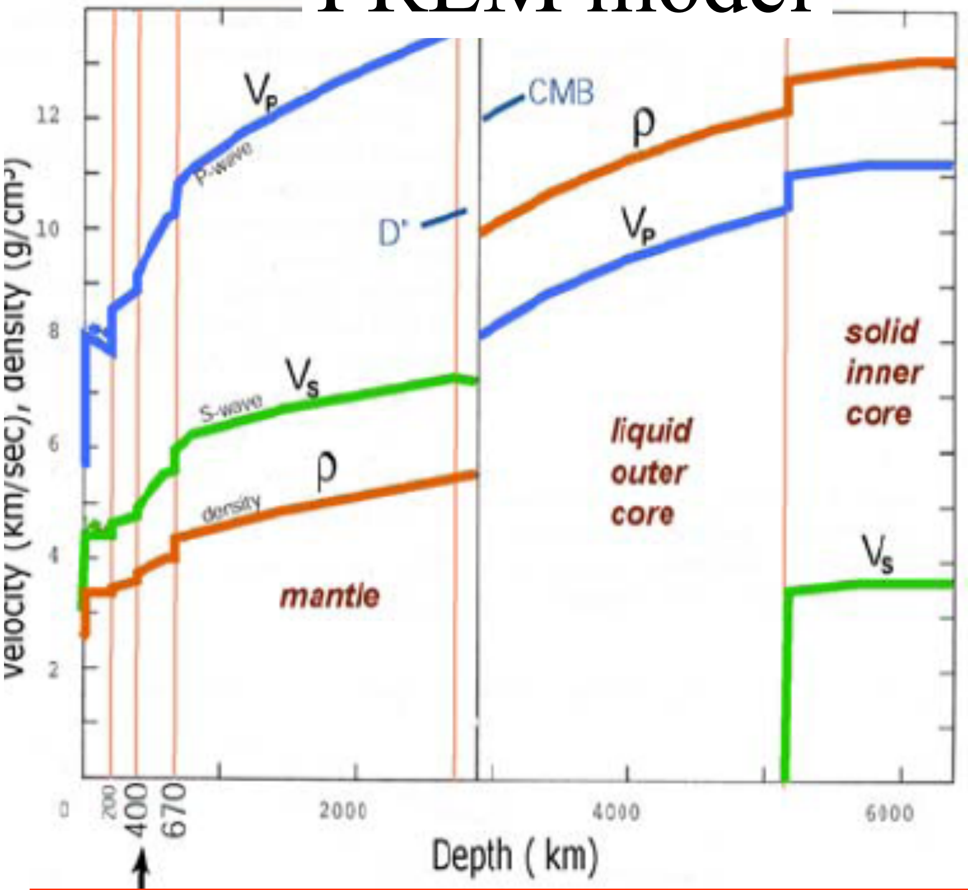
concentration for ^{238}U (Mantovani *et al.* 2004)

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

Seismology



PREM model



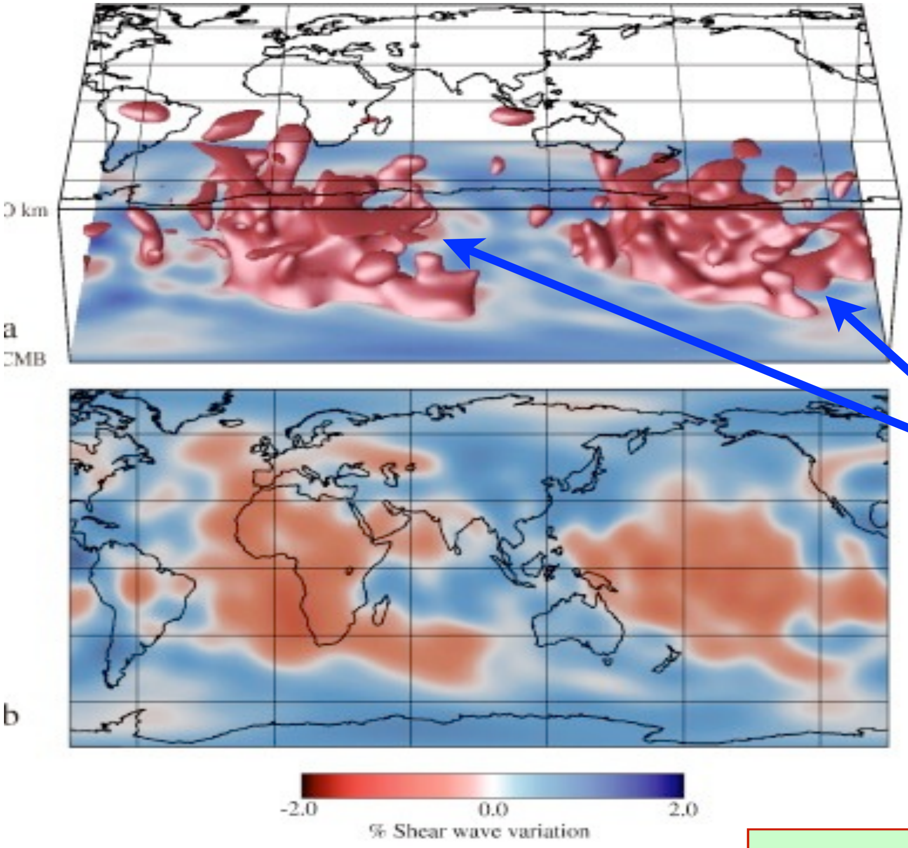
P – primary, longitudinal waves
S – secondary, transverse/shear waves

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

From the talk of Sramek at Neutrino Geoscienece 2013

Seismic tomography image of present-day mantle

Seismic shear wave speed anomaly
Tomographic model S20RTS (Ritsema et al.)



Bull et al. EPSL 2009

Two large scale seismic speed anomalies – below Africa and below central Pacific

Anti-correlation of shear and sound wavespeeds + sharp velocity gradients suggest a **compositional component**

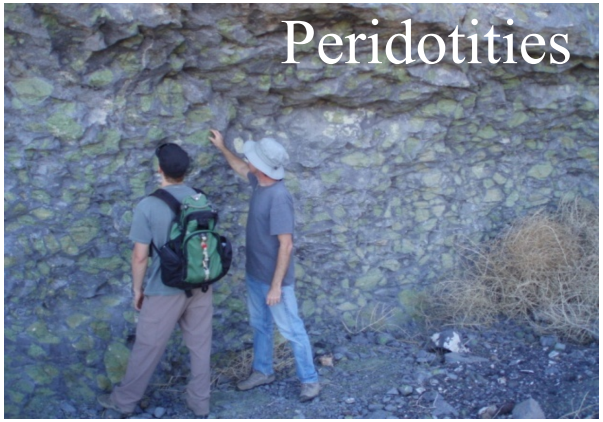
“piles” or “LLSVPs” or “superplumes”

Candidate for an distinct chemical reservoir

Sat AM: Ed Garnero

Geo-chemistry

Xenolite



Peridotities

1) **Direct rock samples**

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

* mantle rocks brought up by tectonics

BUT: POSSIBLE ALTERATION DURING THE TRANSPORT

2) **Geochemical models:**

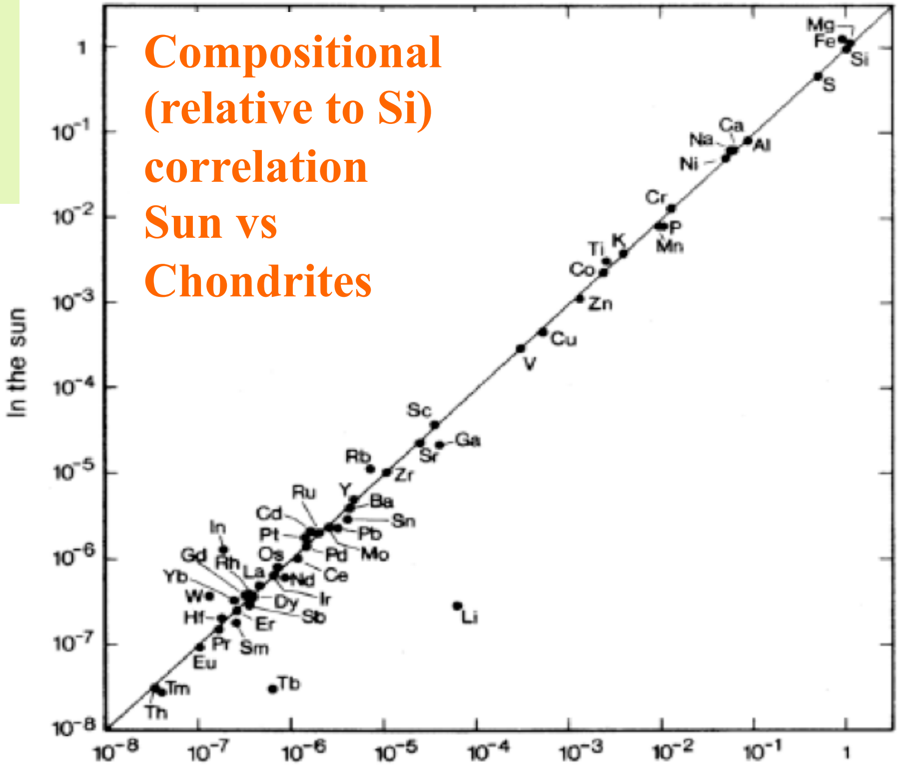
rock samples + meteorites + Sun

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



Compositional (relative to Si) correlation Sun vs Chondrites

BSE models (classification according Sramek at al.)

TW radiogenic power

BSE **Mantle**

- **“Geochemical”** estimate
  - – Ratios of RLE abundances constrained by C1 chondrites
  - – Absolute abundances inferred from Earth rock samples
  - – *McDonough & Sun (1995), Allègre (1995), Hart & Zindler (1986), Palme & O’Neill (2003),* ***Arevalo et al. (2009)***

20±4 **12±4**

- **“Cosmochemical”** estimate
  - – Isotopic similarity between Earth rocks and E-chondrides
  - – Build the Earth from E-chondrite material
  - – ***Javoy et al. (2010)***
  - – also “collisional erosion” models (*O’Neill & Palme 2008*)

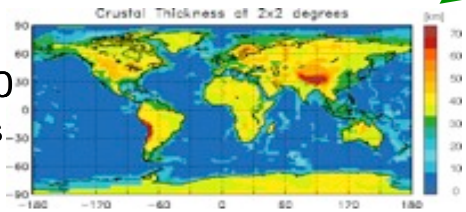
11±2 **3±2**

- **“Geodynamical”** estimate
  - – Based on a classical parameterized convection model
  - – Requires a high mantle Urey ratio, i.e., high U, Th, K

33±3 **25±3**

BSE = Mantle + Crust

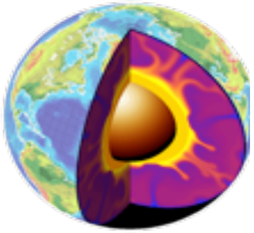
CRUST2.0
thickness



Oceanic: 0.22 ± 0.03 TW

Continental: 7.8 ± 0.9 TW

?



Tomorrow: New crustal model by Yu Huang et al.
CC = 6.8 (+1.4/-1.1) TW

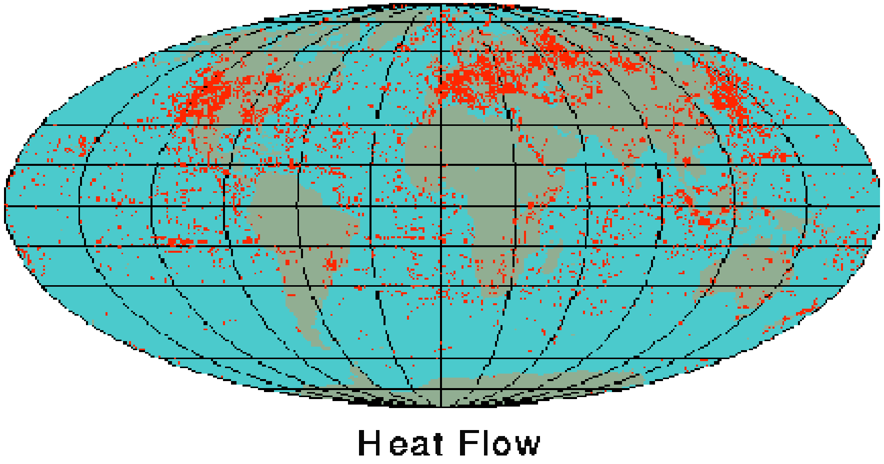
Surface heat flux

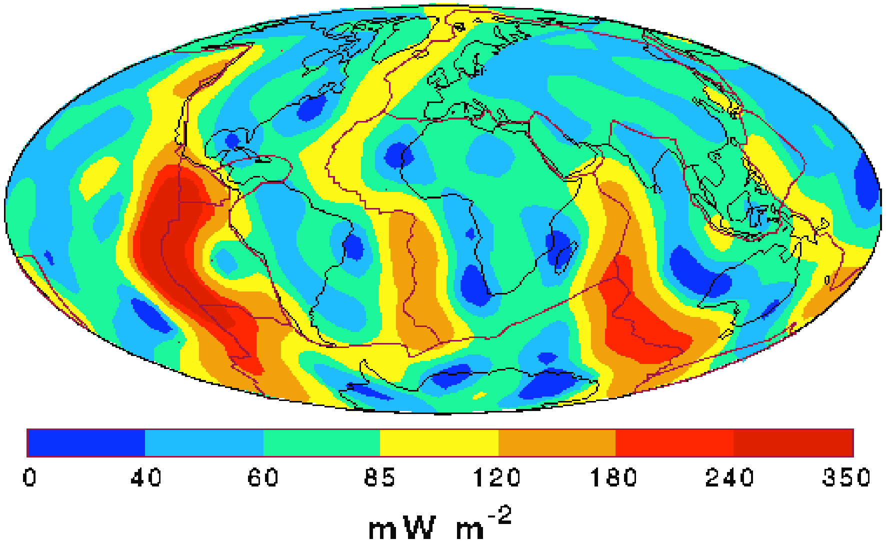
Bore-hole measurements →

47 ± 2 TW

(Davies & Davies 2010)

Sources





Radiogenic heat: (Geoneutrinos)!!!!!

BSE models predictions:

- ✓ Geochemical BSE:17-21 TW
- ✓ Cosmochemical BSE: 11 TW
- ✓ Geodynamical BSE: > 30 TW

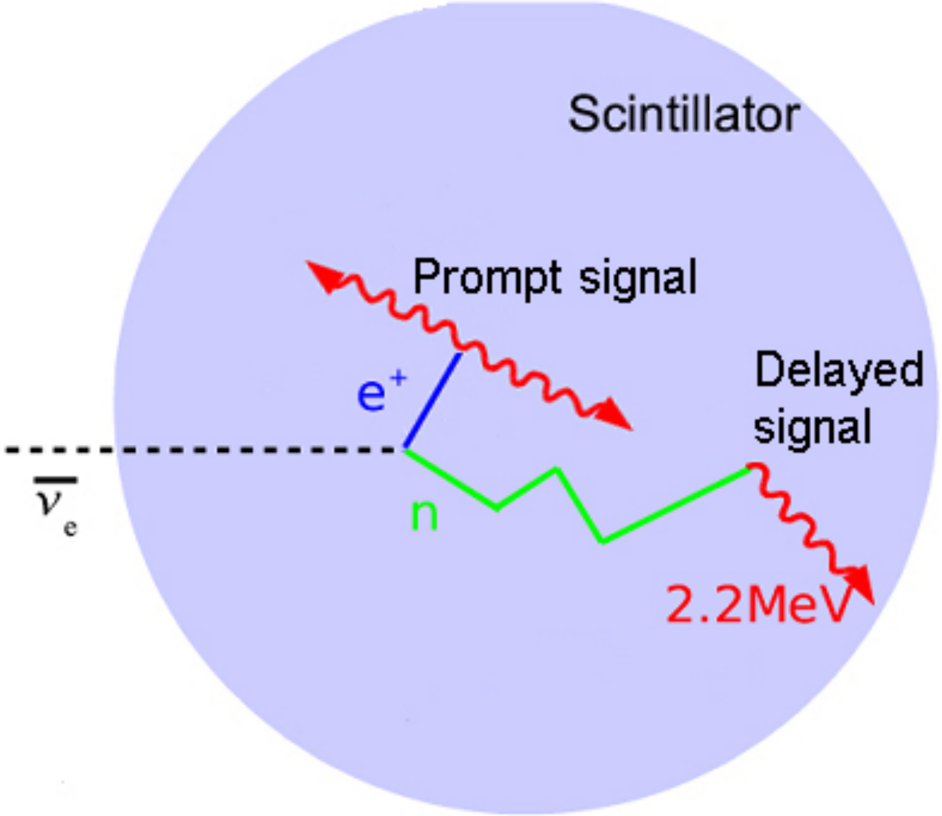
Other sources:

1) Residual heat from the past
2) ^{40}K in the core?
3) Nuclear reactor in the core?
4) Very minor (phase transitions, tidal etc..)

Geoneutrino detection

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

Inverse **B**eta **D**ecay



"prompt signal"

e^+: energy loss T_{e+}+ annihilation (2 x 0.511 MeV)

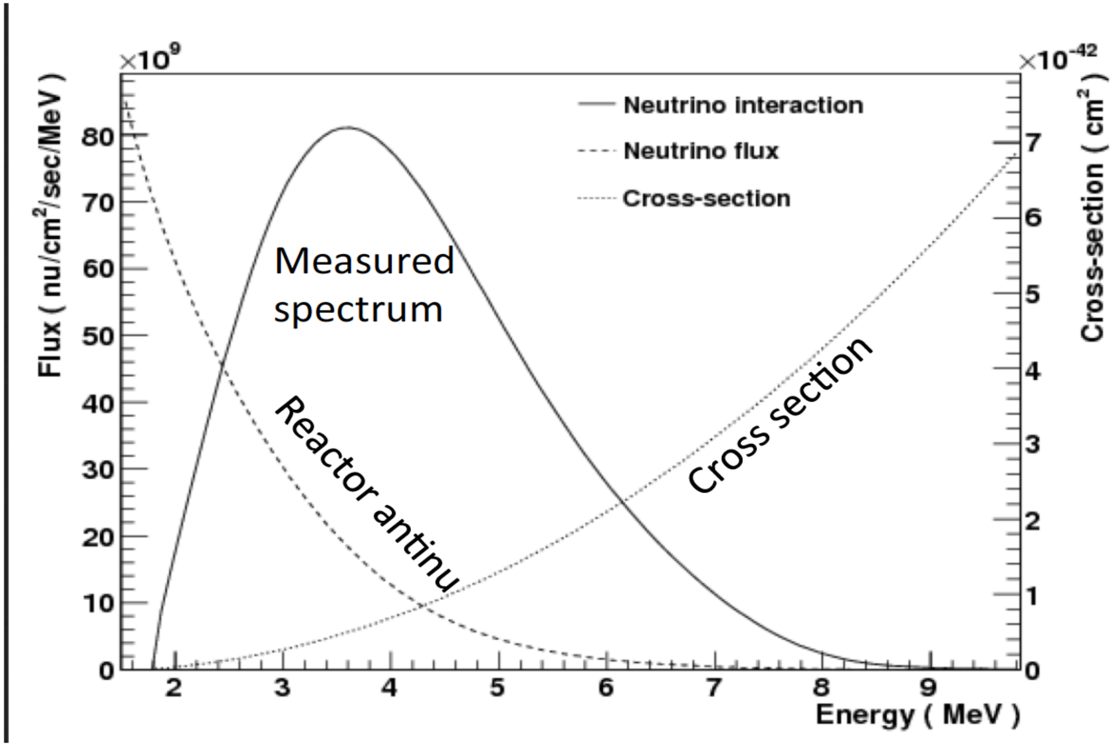
$E_{prompt} = E_{geonu} - 0.784$ MeV

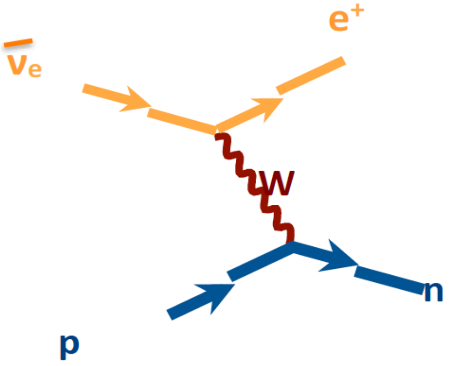
"delayed signal"

neutron thermalisation & capture on protons,
emission of **2.2 MeV γ**

IBD cross section

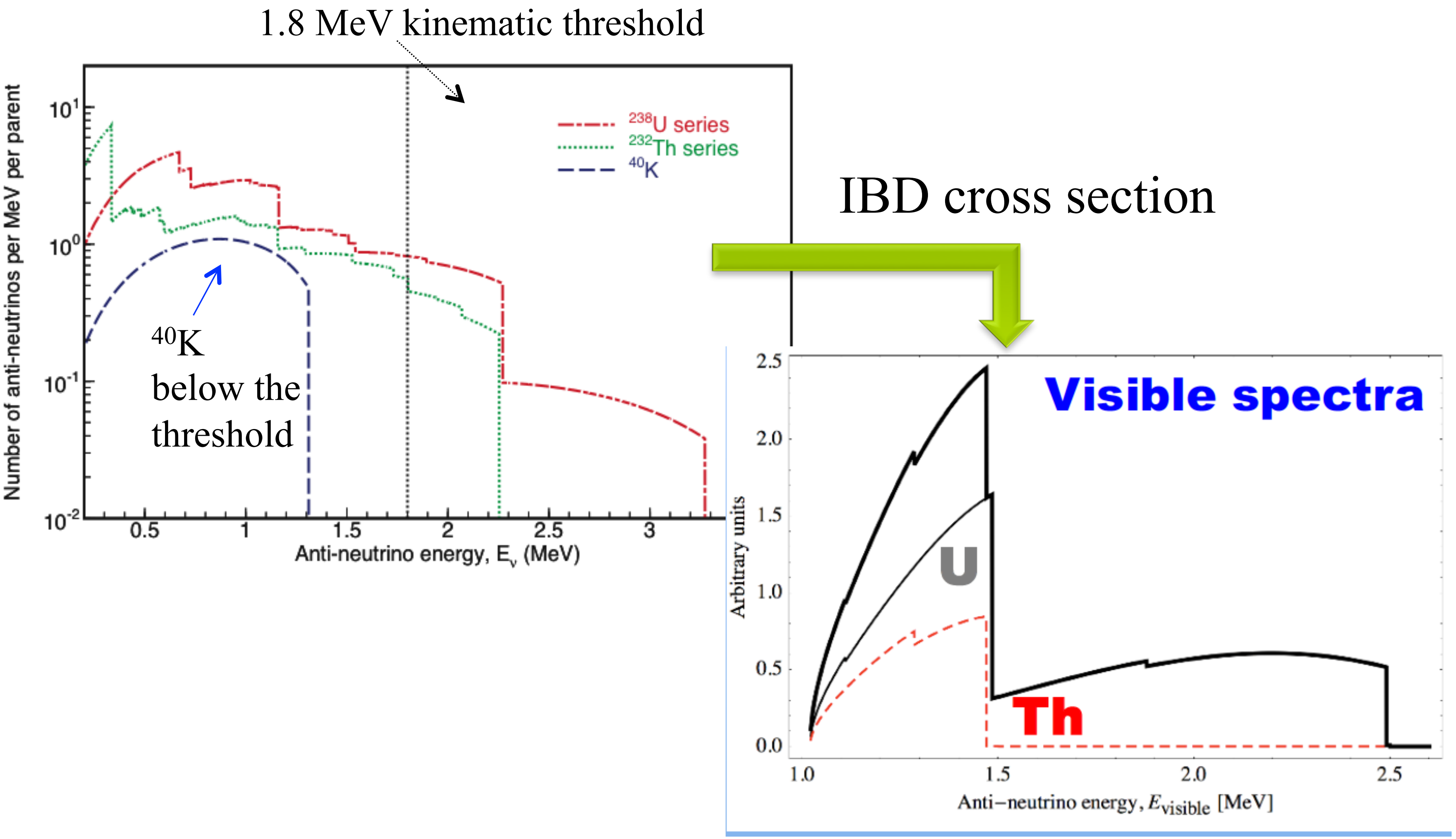
Energy threshold = 1.8 MeV
@ few MeV for electron flavour: ~10^{-42} cm^2 (~100 x more than scattering)





CC interaction

Geoneutrino spectrum



1.8 MeV kinematic threshold

^{40}K
below the
threshold

IBD cross section

We have then golden candidates found as time and spatial coincidences:

- They can be due to:
  - ✓ **Geo-neutrinos;**
  - ✓ **Reactor antineutrinos;**
  - ✓ **Non-antineutrino backgrounds;**
- We need to estimate different contributions and then extract the number of measured geo-neutrinos by fitting the E_{prompt} energy spectrum;

Expected geoneutrino signal

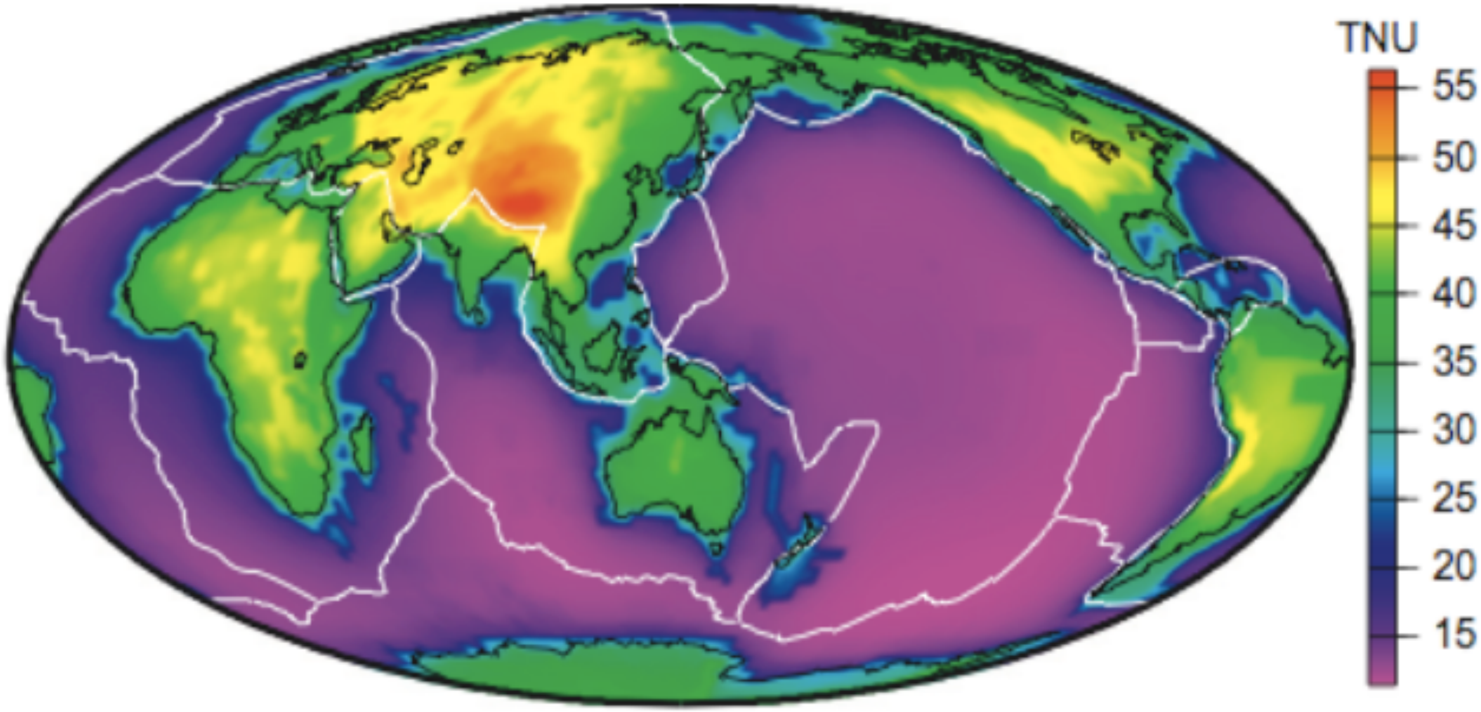
- **LOC: Local crust: on the continental crust:** about 50% of the expected geoneutrino signal comes from the crust within 500-800 km around the detector, thus local geology has to be known (for LNGS Coltorti et al. 2011);
- **ROC: Rest of the crust:** further crust is divided in 3D voxels, volumes for upper, middle, lower crust and sediments are estimated and a mean chemical composition is attributed to these volumes (Huang et al. 2013);
- **Mantle = BSE – (LOC + ROC):** this is the real unknown, different BSE models are considered and the respective U + Th mass is distributed either homogeneously (maximal signal) or it is concentrated near to the core-mantle boundary (minimal signal);

	Site	Mantovani et al. [91]	Dye [88]	Huang et al. [28]
Borexino	Kamioka	$24.7^{+4.3}_{-10.3}$	23.1 ± 5.5	$20.6^{+4.0}_{-3.5}$
KamLAND	Gran Sasso	$29.6^{+5.1}_{-12.4}$	28.9 ± 6.9	$29.0^{+6.0}_{-5.0}$
SNO+	Sudbury	$38.5^{+6.7}_{-16.1}$	34.9 ± 8.4	$34.0^{+6.3}_{-5.7}$
HanoHano	Hawaii	$3.3^{+0.6}_{-1.4}$	3.2 ± 0.6	$2.6^{+0.5}_{-0.5}$

[TNU]

1 TNU = 1 event / 10^{32} target protons / year
Cca 1 event / 1 kton / 1 year with 100% detection efficiency

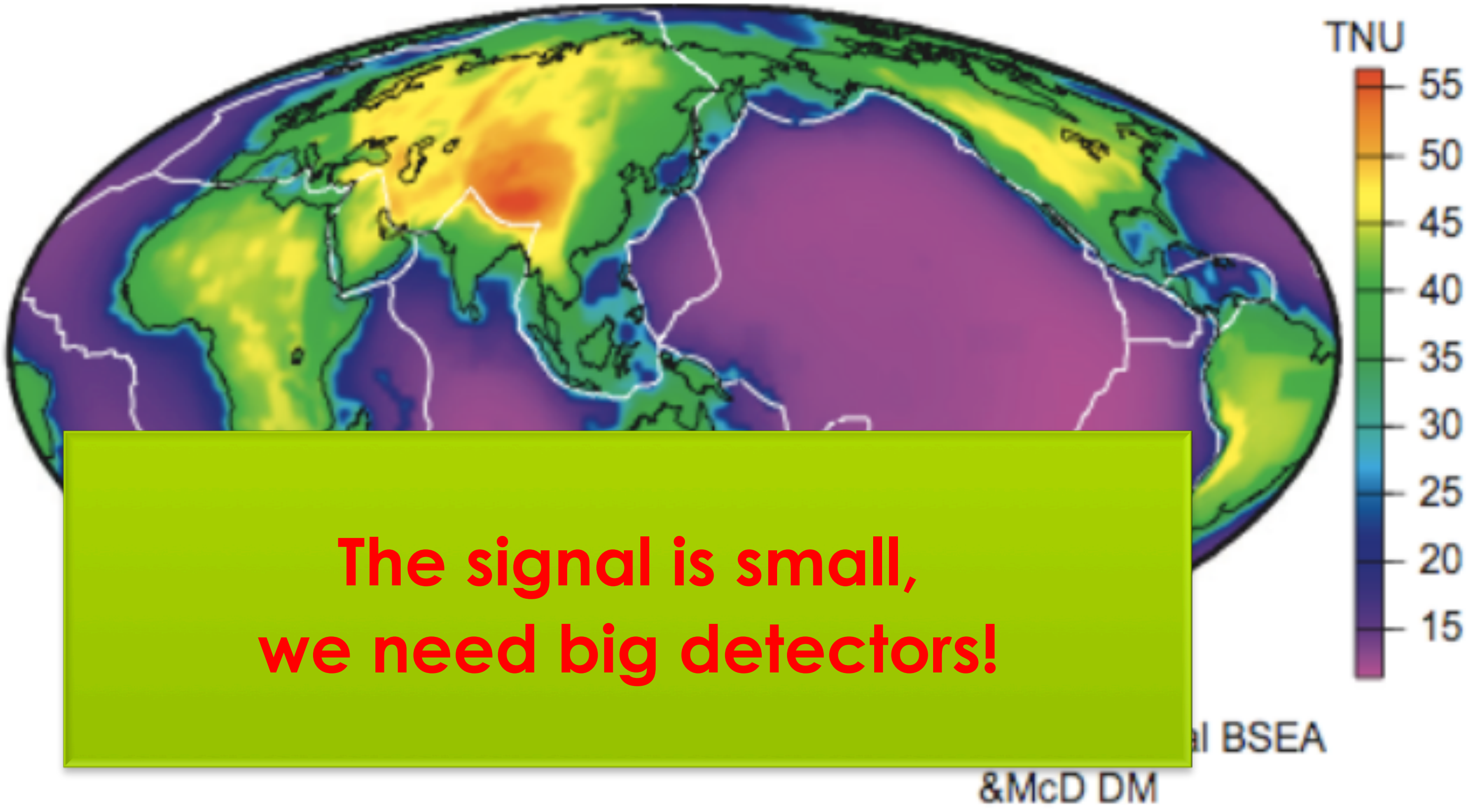
Crust + mantle geo-ν signal (U+Th)



Geochemical BSEA
&McD DM

1 TNU = 1 event / 10^{32} target protons / year
Cca 1 event / 1 kton / 1 year with 100% detection efficiency

Crust + mantle geo-ν signal (U+Th)

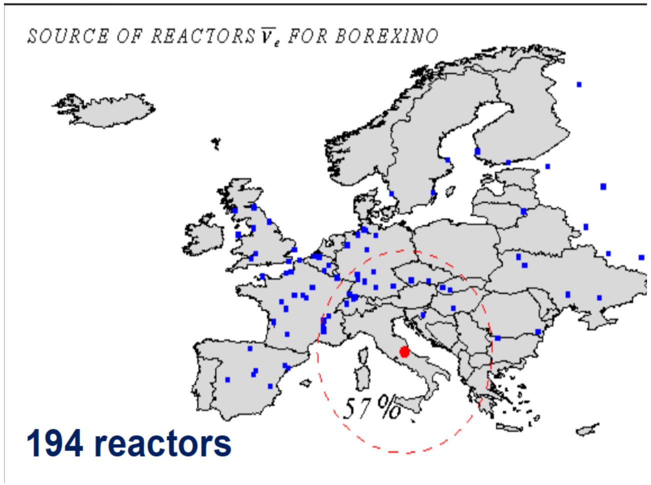


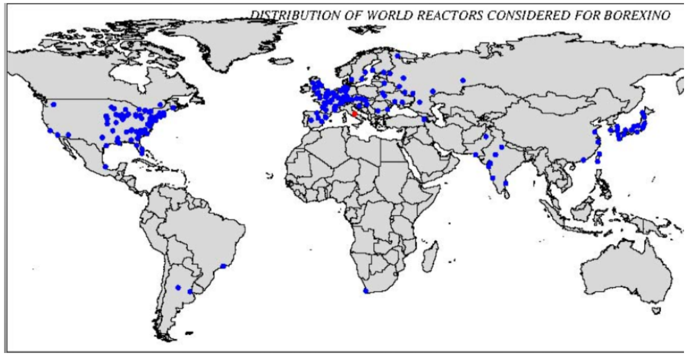
The signal is small,
we need big detectors!

1 TNU = 1 event / 10^{32} target protons / year
Cca 1 event / 1 kton / 1 year with 100% detection efficiency

Background sources

Reactor antineutrinos





Non-antineutrino background

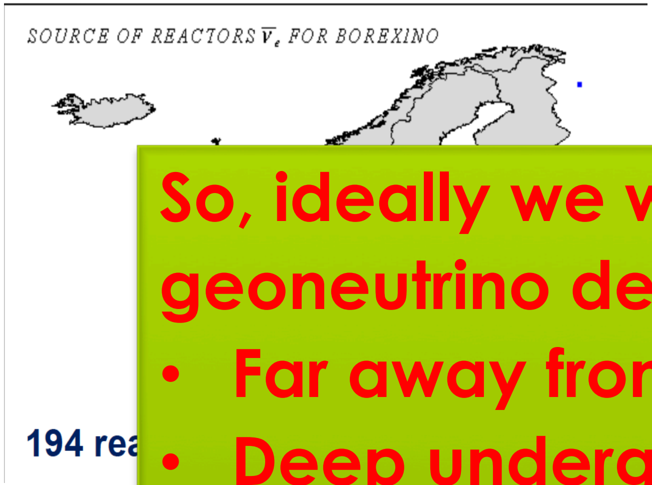
1) Cosmogenic background

2) Accidental coincidences

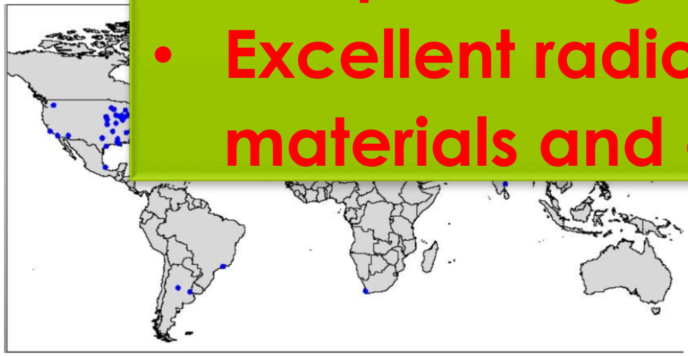
3) Due to the internal radioactivity: (α,n) reactions

Background sources

Reactor antineutrinos



194 rea



Non-antineutrino background

1) Cosmogenic background

s

So, ideally we would like to have our geoneutrino detector:

- Far away from reactors
- Deep underground
- Excellent radiopurity of construction materials and of the liquid scintillator

Calculation of reactor anti-ν signal

$$\Phi(E_{\bar{\nu}_e}) = \sum_{r=1}^{N_{react}} \sum_{m=1}^{N_{month}} \frac{T_m}{4\pi L_r^2} P_{rm} \sum_{i=1}^{4} \frac{f_{ri}}{E_i} \Phi_i(E_{\bar{\nu}_e}) P_{ee}(E_{\bar{\nu}_e}; \hat{\vartheta}, L_r)$$

- **Flux parameterization + neutrino oscillation survival probability:**
  - **E_i :** energy release per fission of isotope i (Huber-Schwetz 2004);
  - **Φ_i:** antineutrino flux per fission of isotope i (polynomial parametrization, Mueller et al.2011, Huber-Schwetz 2004);
  - **P_{ee}:** oscillation survival probability;
- **Detector related:**
  - **T_m:** live time during the month m;
  - **L_r:** reactor r – detector distance;
- **Data from nuclear agencies:**
  - **P_{rm}:** thermal power of reactor r in month m (IAEA , EDF, and UN data base);
  - **f_{ri}:** power fraction of isotope i in reactor r;

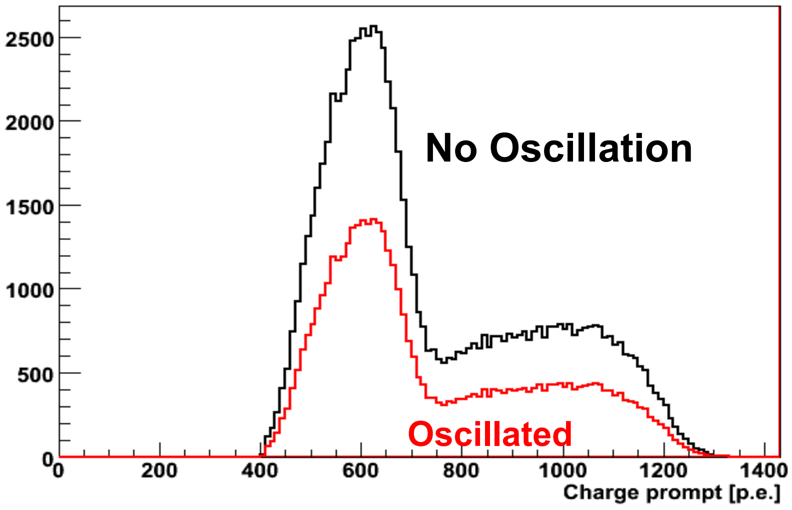
^{235}U
^{239}Pu
^{238}U
^{241}Pu

Effect of neutrino oscillations

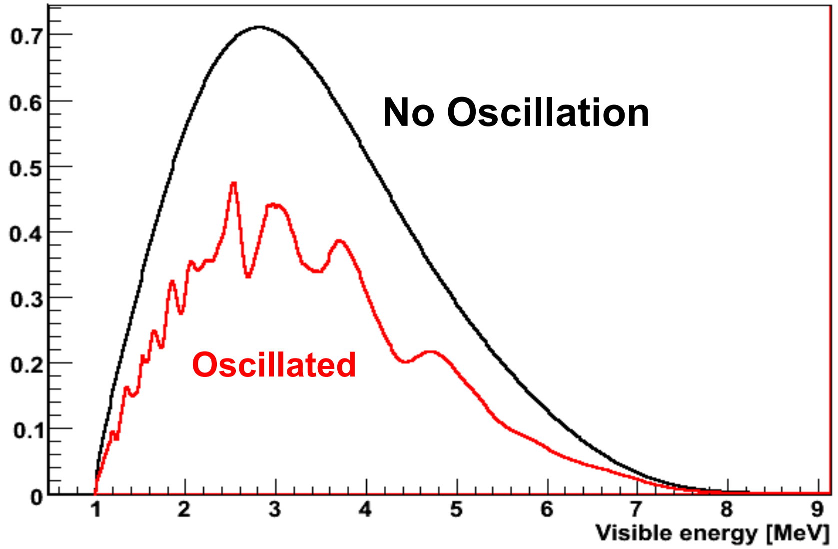
$$P(\overline{\nu}_e \to \overline{\nu}_e) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}),$$

3 MeV antineutrino ..
Oscillation length of ~100 km

for geoneutrinos we can use average survival probability of 0.551 + 0.015 (Fiorentini et al 2012), but for reactor antineutrinos not!



Geoneutrinos



Reactor antineutrinos at LNGS

Non-antineutrino background sources

1) Cosmogenic background

- ^{9}Li and ^{8}He ($T_{1/2}$ = 119/178 ms) decay: β(prompt) +neutron (delayed);
- **fast neutrons**

  scattered protons (prompt)

Estimated by studying coincidences detected AFTER muons

2) Accidental coincidences;

Estimated by studying

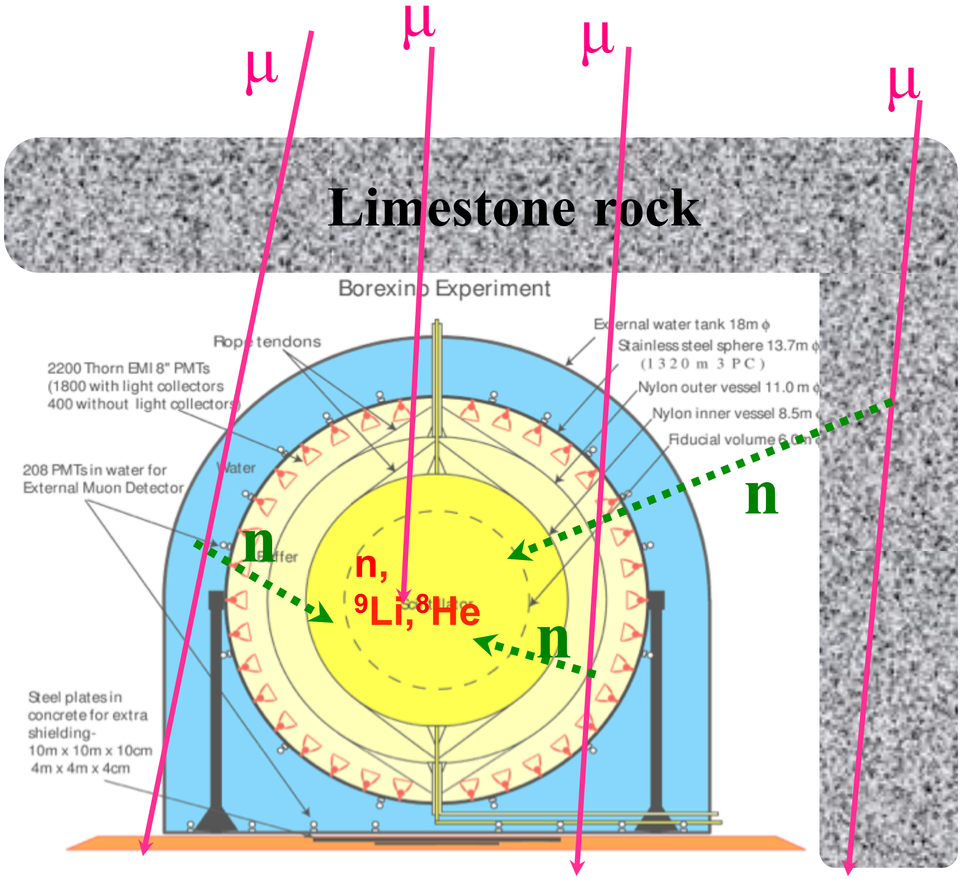
OFF-time coincidences

3) Due to the internal radioactivity: (α, n) reactions: $^{13}C(\alpha, n)^{16}O$

Prompt: scattered proton, ^{12}C(4.4 MeV) and ^{16}O (6.1 MeV) deexcitation gammas

Estimated by studying

^{210}Po(α) and ^{13}C contaminations



- **only 2 running experiments have 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

Border bewteen
OCEANIC AND CONTINENTAL CRUST

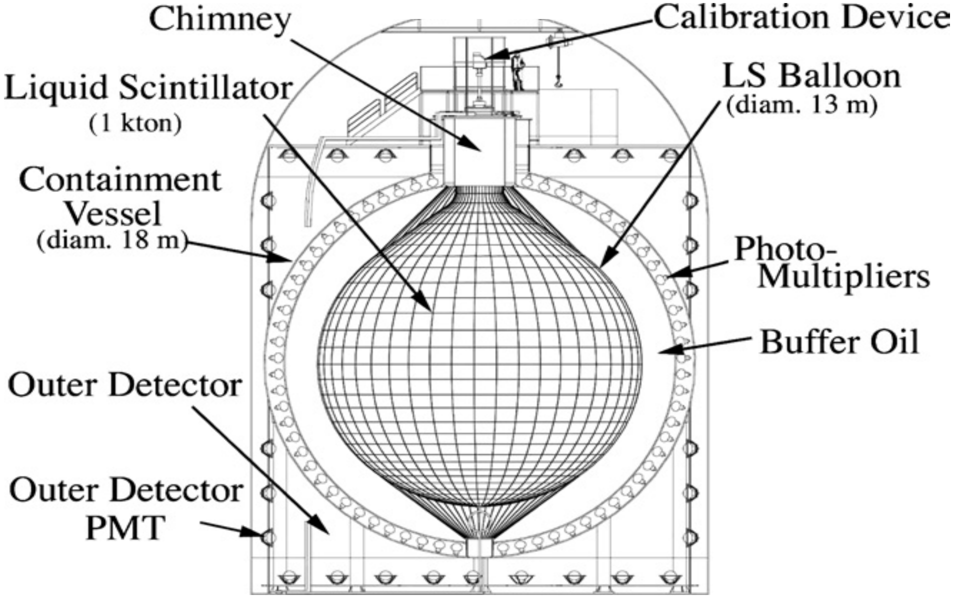
- build to detect reactor anti-ν;
- 1000 tons;
- S(reactors)/S(geo) ~ 6.7 (2010)
- After the Fukushima disaster (March 2011) many reactors OFF!
- data since 2002;
- 2700 m water equivalent shielding;

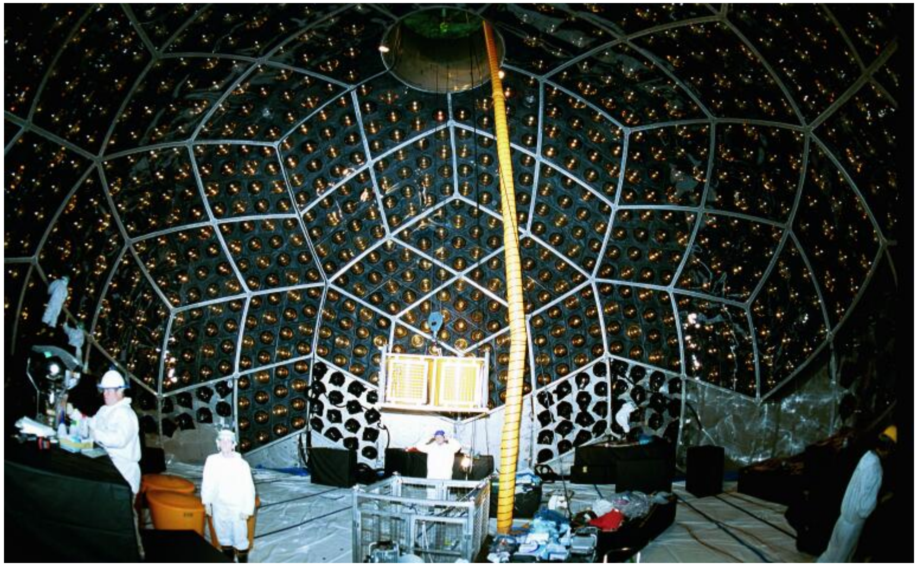
Borexino in Gran Sasso, Italy

CONTINENTAL CRUST

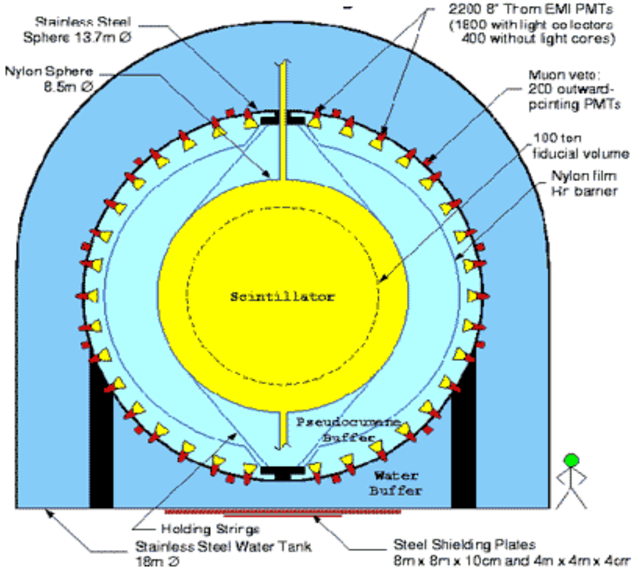
- originally build to measure neutrinos from the Sun – extreme radiopurity needed and achieved;
- 280 tons;
- S(reactors)/S(geo) ~ 0.3 !!! (2010)
- DAQ started in 2007;
- 3600 m.w.e. shielding;

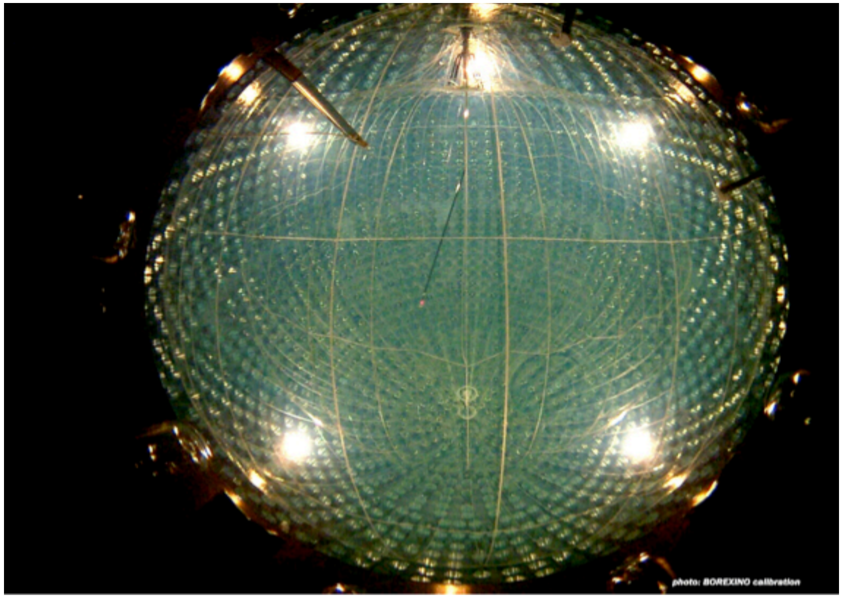
KamLAND





Borexino





Geoneutrino experimental results

KamLAND (Japan)

- **The first investigation in 2005**

  CL < 2σ

  Nature 436 (2005) 499

- **Update in 2008**

  73 ± 27 geonu's

  PRL 100 (2008) 221803

- **99.997 CL observation in 2011**

  106^{+29}_{-28} geonu's

  (March 2002 – April 2009)
  3.49×10^{32} target-proton year
  Nature Geoscience 4 (2011) 647

- **Latest result in 2013**

  116^{+28}_{-27} geonu's

  (March 2002 – November 2012)
  4.9×10^{32} target-proton year
  0-hypothesis @ 2×10^{-6}
  PRD 88 (2013) 033001

Borexino (Italy)

- **99.997 CL observation in 2010**

  $9.9^{+4.1}_{-3.4}$ geonu's

  small exposure but low background level
  (December 2007 – December 2009)
  1.5×10^{31} target-proton year
  PLB 687 (2010) 299

- **Update in 2013**

  14.3 ± 4.4 geonu's

  (December 2007 – August 2012)
  3.69×10^{31} target-proton year
  0-hypothesis @ 6×10^{-6}
  PLB 722 (2013) 295–300

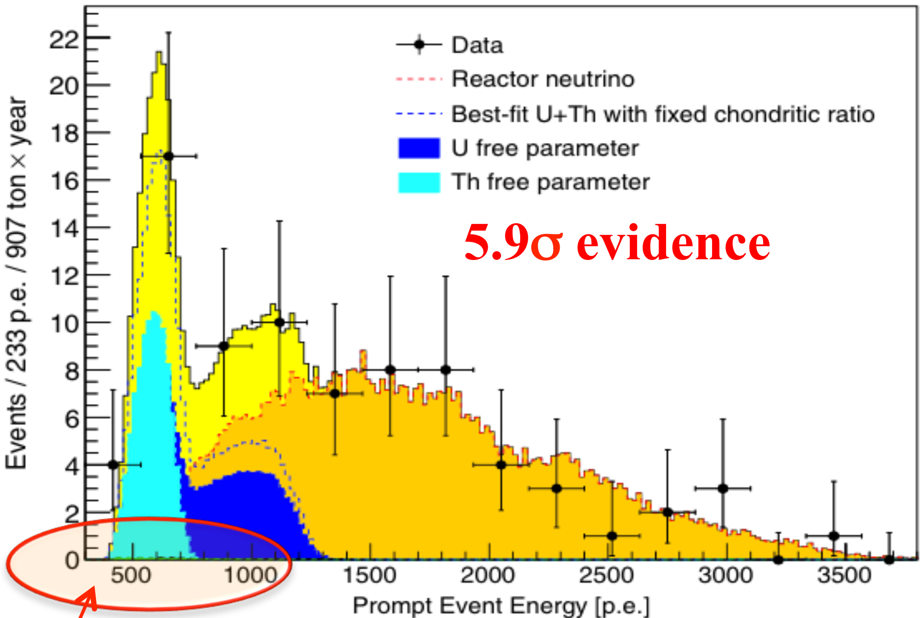
- **NEW in June 2015: 5.9σ CL**

  $23.7^{+6.5}_{-5.7}$ (stat) $^{+0.9}_{-0.6}$ (sys) geonu's

  (December 2007 – March 2015)
  5.5×10^{31} target-proton year
  0-hypothesis @ 3.6×10^{-9}
  PRD 92 (2015) 031101 (R)

Latest geoneutrino results

Borexino 2015: **23.7 $^{+6.5}$ (stat) $^{+0.9}$ (sys)** geonu's



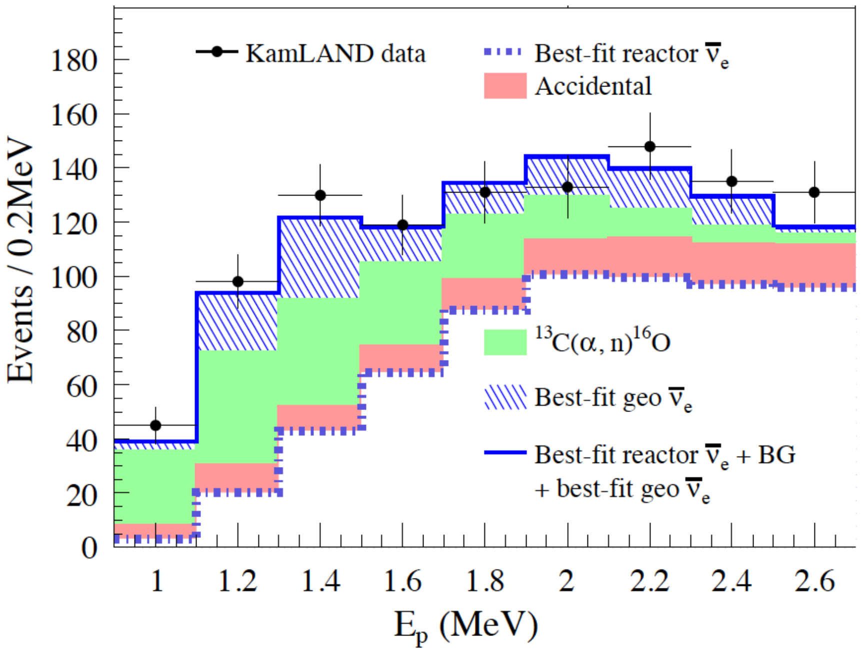
5.9σ evidence

~1 MeV

~7 MeV

PRD 92 (2015) 031101 (R)

KamLAND 2013: **116 $^{+28}_{-27}$** geonu's



Phys. Rev. D 88 (2013) 033001

- ✓ Non antineutrino background almost invisible!
- ✓ 5.5 x 10^{31} target-proton year
- ✓ 0-hypothesis @ 3.6 x 10^{-9}

- ✓ 4.9 x 10^{32} target-proton year
- ✓ 0-hypothesis @ 2 x 10^{-6}

PRD 92 (2015) 031101 (R)

Borexino geoneutrino analysis

Unbinned maximal likelihood fit:

- Geoneutrinos free
- Reactor antineutrinos free
- Other backgrounds ($0.78^{+0.78}_{-0.10}$ events total) constrained

Period	Dec.07 – Mar15 (5.5 ± 0.3) 10^{31} prot*y
Tot ev [full sp.]	77
Reactors ev.	$52.7\ _{-7.7}^{+8.5}$ (stat) $_{-0.9}^{+0.7}$ (sys)
Background ev.	$0.78_{-0.10}^{+0.13}$
Geo-ν ev.	$23.7\ _{-5.7}^{+6.5}$ (stat) $_{-0.6}^{+0.9}$ (sys))
Geo-ν signal **(TNU)**	$43.5\ _{-10.4}^{+11,8}$ (stat) $_{-2.4}^{+2.7}$ (sys)

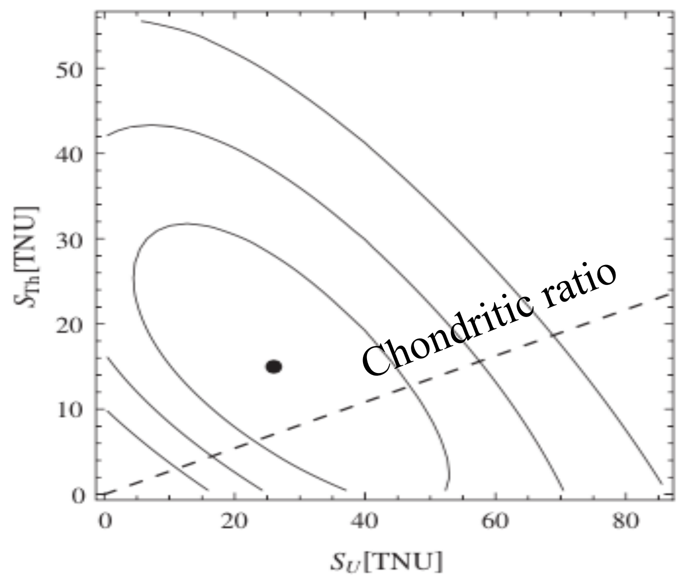
Two types of fits:

1) Th/U mass ratio fixed to chondritic value of 3.9

$N_{geo} = 23.7\ ^{+6.5}_{-5.7}(\text{stat})^{+0.9}_{-0.6}(\text{sys})$ events

$S_{geo} = 43.5\ ^{+11.8}_{-10.4}(\text{stat})^{+2.7}_{-2.4}(\text{sys})$ TNU[1]

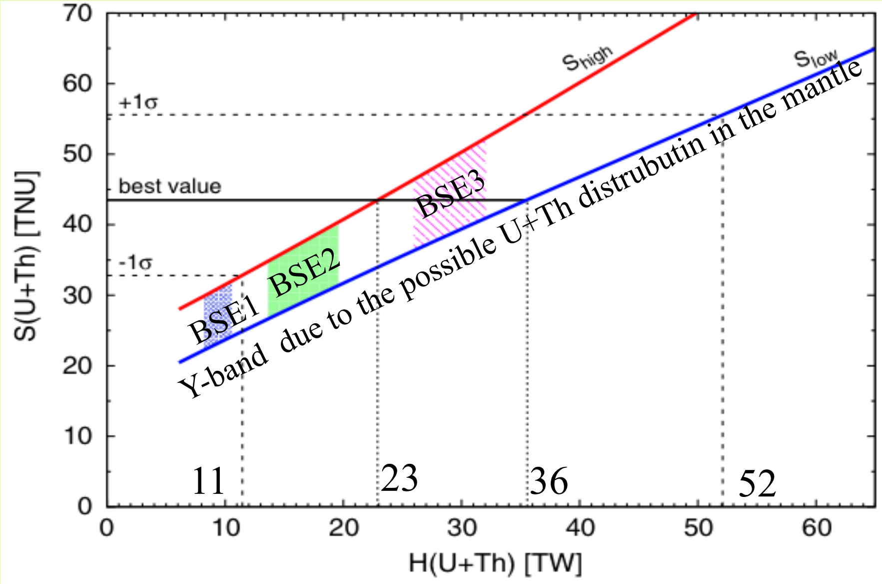
2) U and Th free fit paramters



PRD 92 (2015) 031101 (R)

Geological implications of the new Borexino results

Radiogenic heat



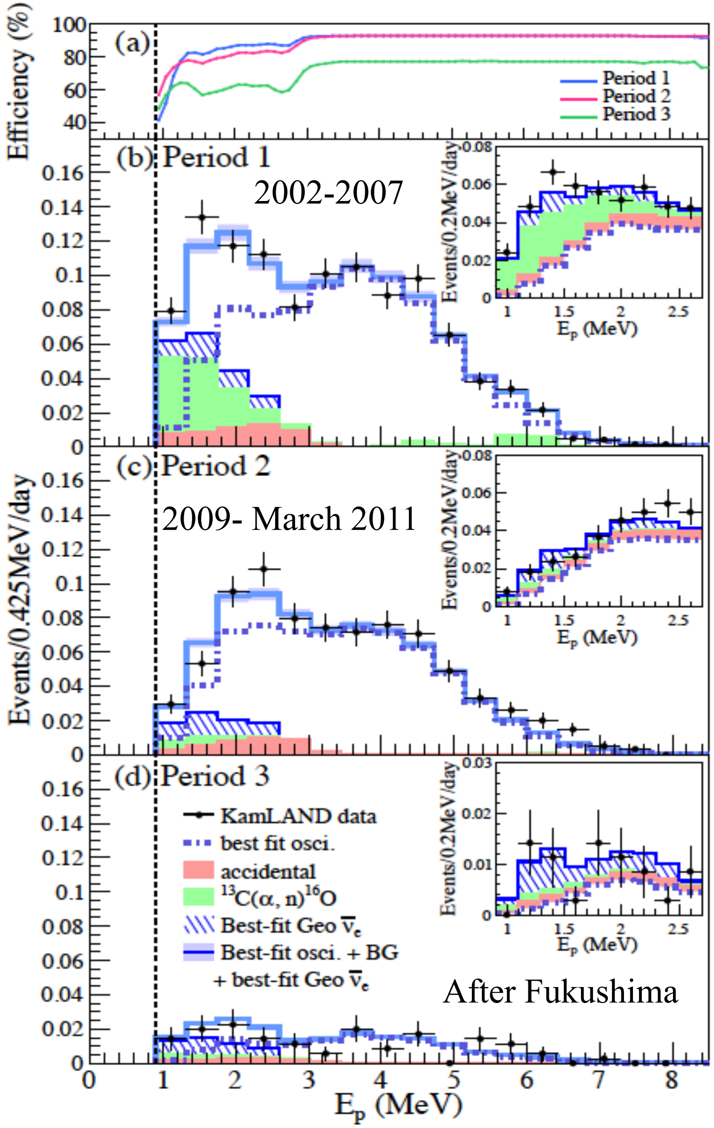
- Radiogenic heat (U+Th): 23-36 TW for the best fit and 11-52 TW for 1σ range
- Considering chondritic mass ratio Th/U=3.9 and K/U = 10^4 : Radiogenic heat
  (U + Th + K) = 33^{+28}_{-20} TW
  to be compared with 47 ± 2 TW of the total Earth surface heat flux (including all sources)

Mantle signal

- $S_{Mantle} = S_{measured} - S_{crust}$
- Crustal signal at LNGS “known”
  $S_{Crust} = (23.4 \pm 2.8)$ TNU
- Non-0 mantle signal at 98% CL
  $S_{mantle} = 20.9^{+15.1}_{-10.3}$ TNU

PRD 88 (2013) 033001

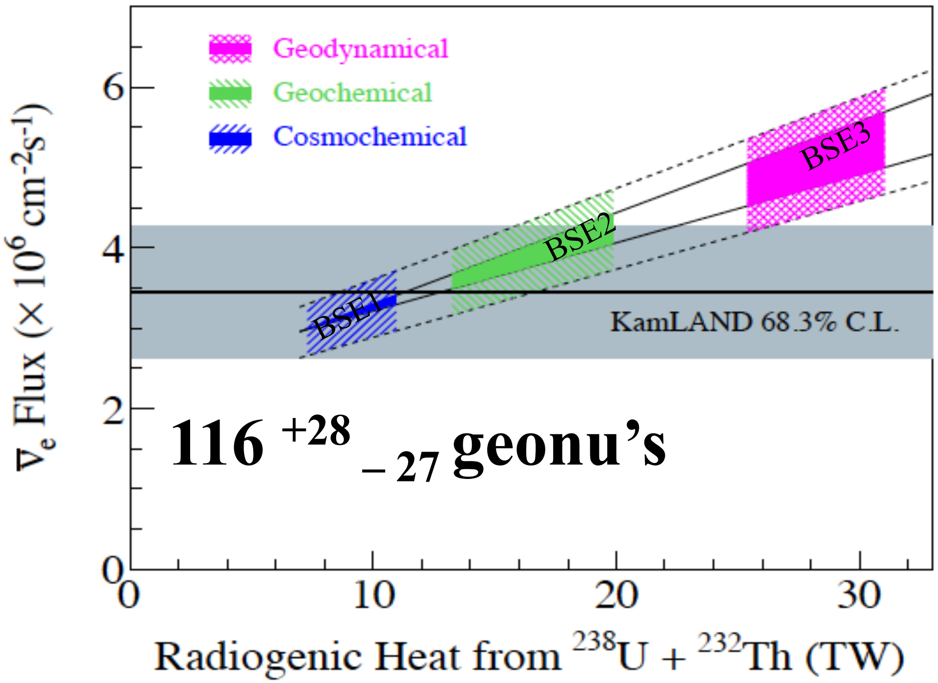
Latest KamLAND geoneutrino results



2002-2007

2009- March 2011

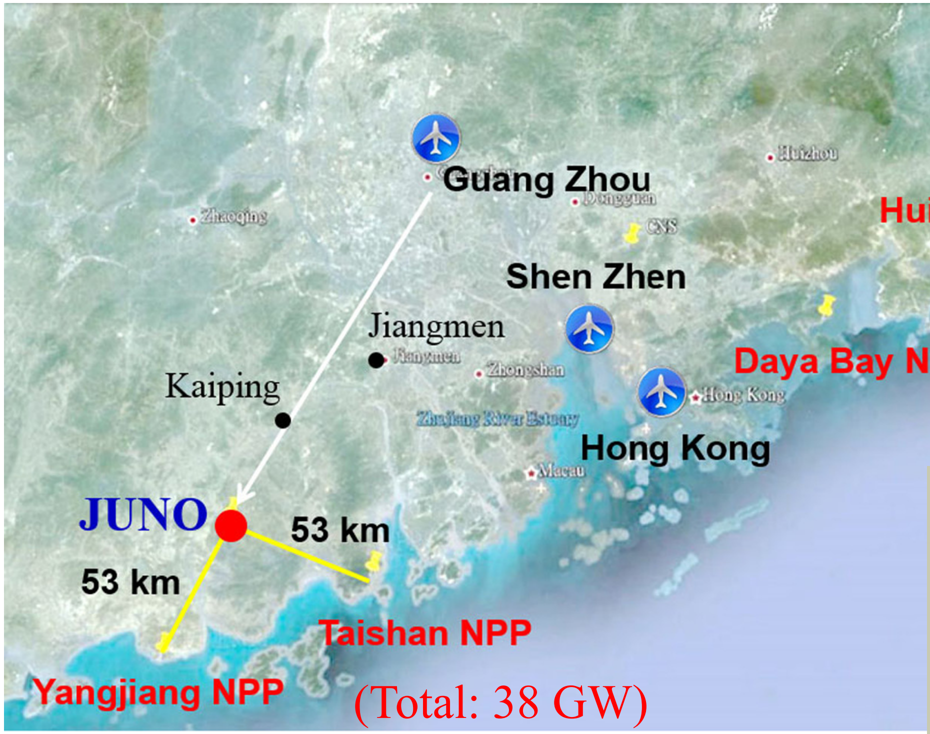
After Fukushima



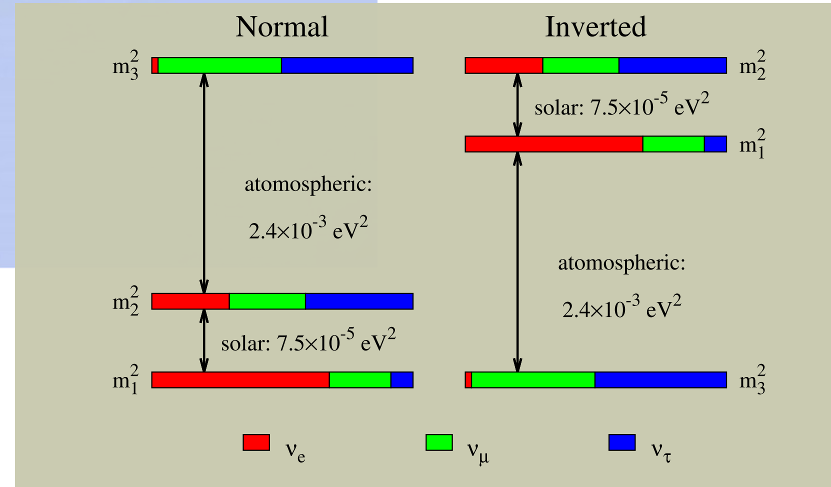
116^{+28}_{-27} geonu's

- After Fukushima, Japanese reactors off
- Plan to refurbish outer detector in Jan' 16.. new update expected then!

JUNO in Jiangmen, China

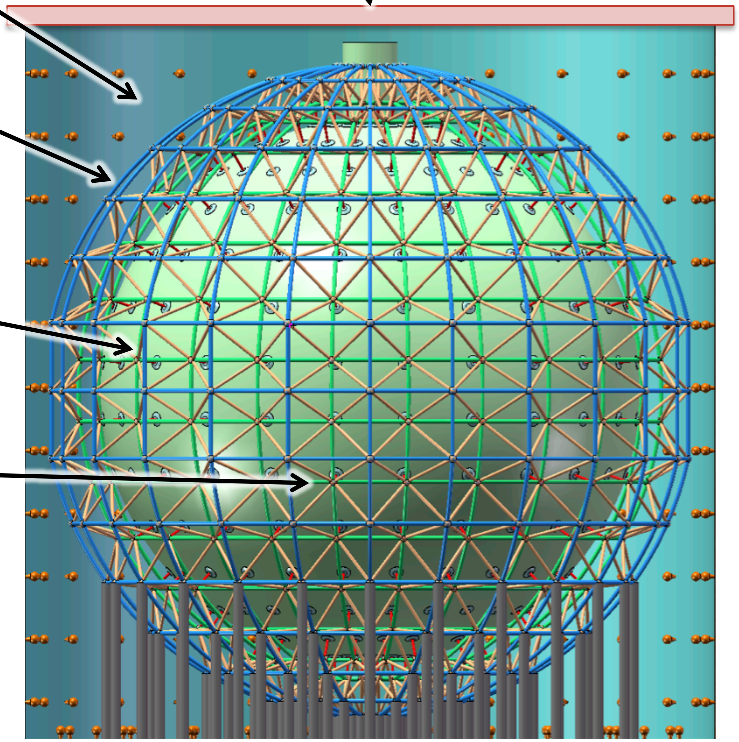


Main goal: neutrino mass hierarchy



JUNO detector: the first multi-kton liquid scintillator detector ever

- 700 m rock overburden
- 3% @ 1 MeV resolution
- LY = 1100 pe / MeV
- Non-linearities well known



Top muon veto
Scintillator panels

Outer water tank
Muon Cherenkov veto

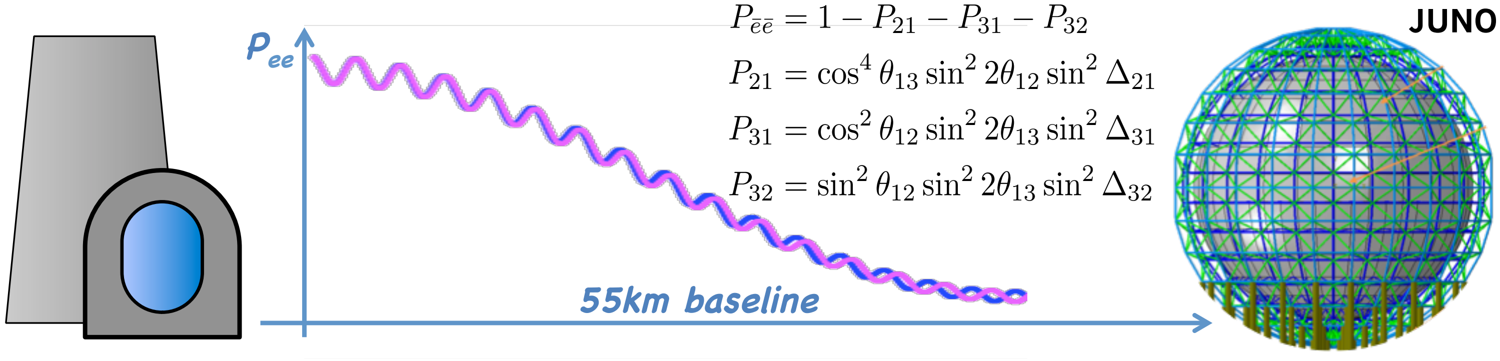
Steel structure
20,000 PMTs (20'')
optical separation

Acrylic sphere
diameter: 35.4m

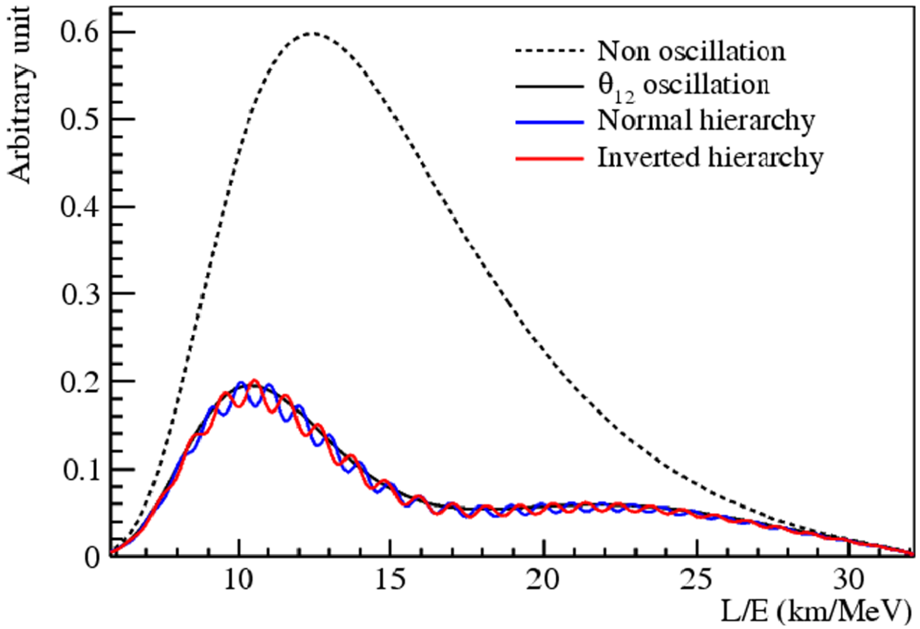
Liquid scintillator
20 kt of LAB

20 kton liquid scintillator target

Principle of the mass-hierarchy measurement

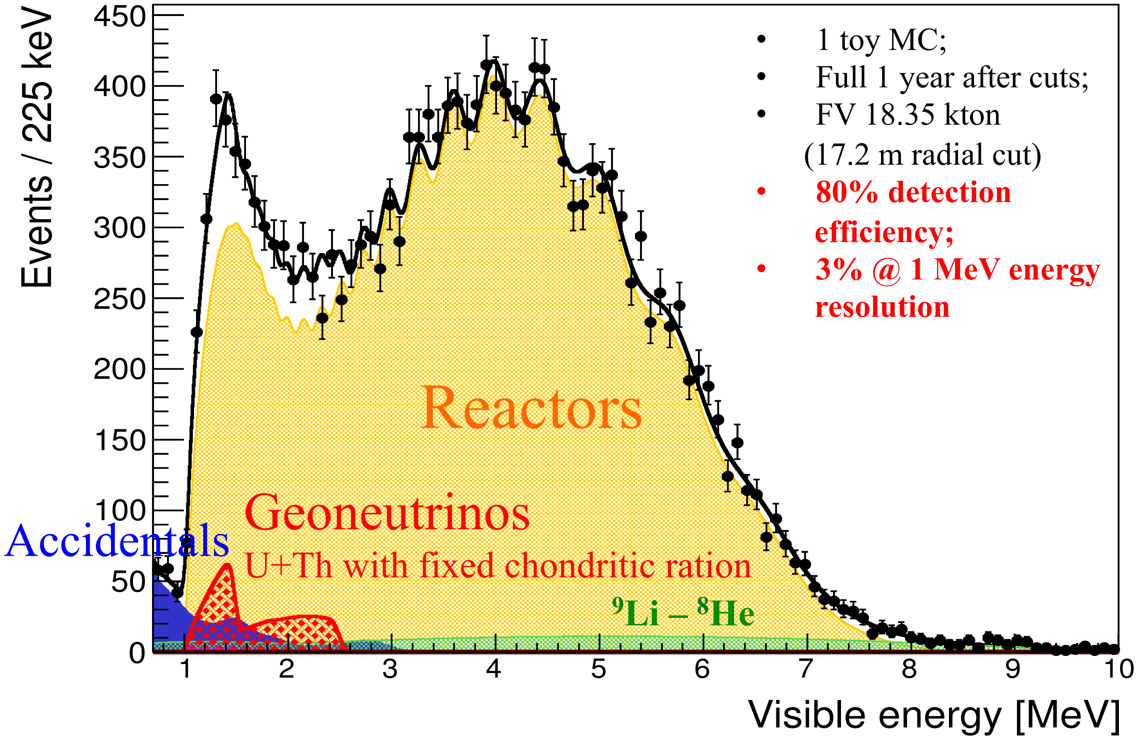


$$P_{\bar{e}\bar{e}} = 1 - P_{21} - P_{31} - P_{32}$$
$$P_{21} = \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$
$$P_{31} = \cos^2\theta_{12}\sin^2 2\theta_{13}\sin^2\Delta_{31}$$
$$P_{32} = \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2\Delta_{32}$$



After 6 years of running
3-4 σ CL

JUNO potential to measure geoneutrinos



- 1 toy MC;
- Full 1 year after cuts;
- FV 18.35 kton (17.2 m radial cut)
- **80% detection efficiency;**
- **3% @ 1 MeV energy resolution**

Big advantage:

- ✓ Big volume and thus high statistics (400 geonu / year)!

Main limitations:

- ✓ Huge reactor neutrino background;
- ✓ Relatively shallow depth – cosmogenic background;

Critical:

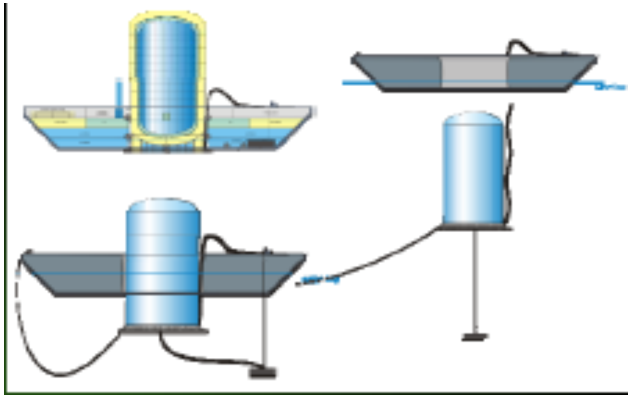
- ✓ Keep other backgrounds (^{210}Po contamination!) at low level and under control;

JUNO can provide another geoneutrino measurement with a comparable or even a better precision than existing results at another location in a completely different geological environment;

Would be the ultimate geoneutrino project

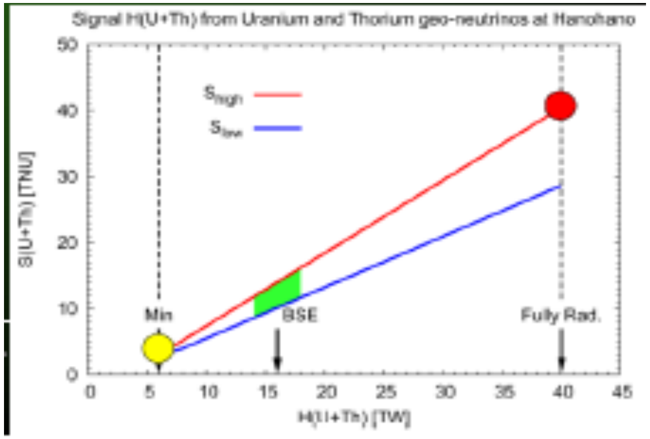
Hanohano at Hawaii

Hawaii Antineutrino Observatory (HANOHANO = "magnificent" in Hawaiian



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

Geoneutrino future

- **Borexino** will switch to SOX in 2017 –
  closure of geoneutrino dataset;
- **KamLAND**: next update with low reactor-background data expected in 2016;
- **SNO+** (Canada): 780 ton & DAQ start in 2017;
  detector should be able to provide geoneutrino results;
- **JUNO** (China): 20 kton & DAQ start in 2020; If non antineutrino background low and under control, JUNO will soon beat the precision of existing measurements;
- **HanoHano** (Hawaii): 10 kton underwater detector with ~80% mantle contribution:
  "**THE" GEONU DETECTOR: MISSING FUNDING!**

- New interdisciplinary field established: **NEUTRINO GEOSCIENCE** conference every two years
- Importance of multi-site measurements at geologically different environments

Thank You!