Geo neutrinos

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Outline…

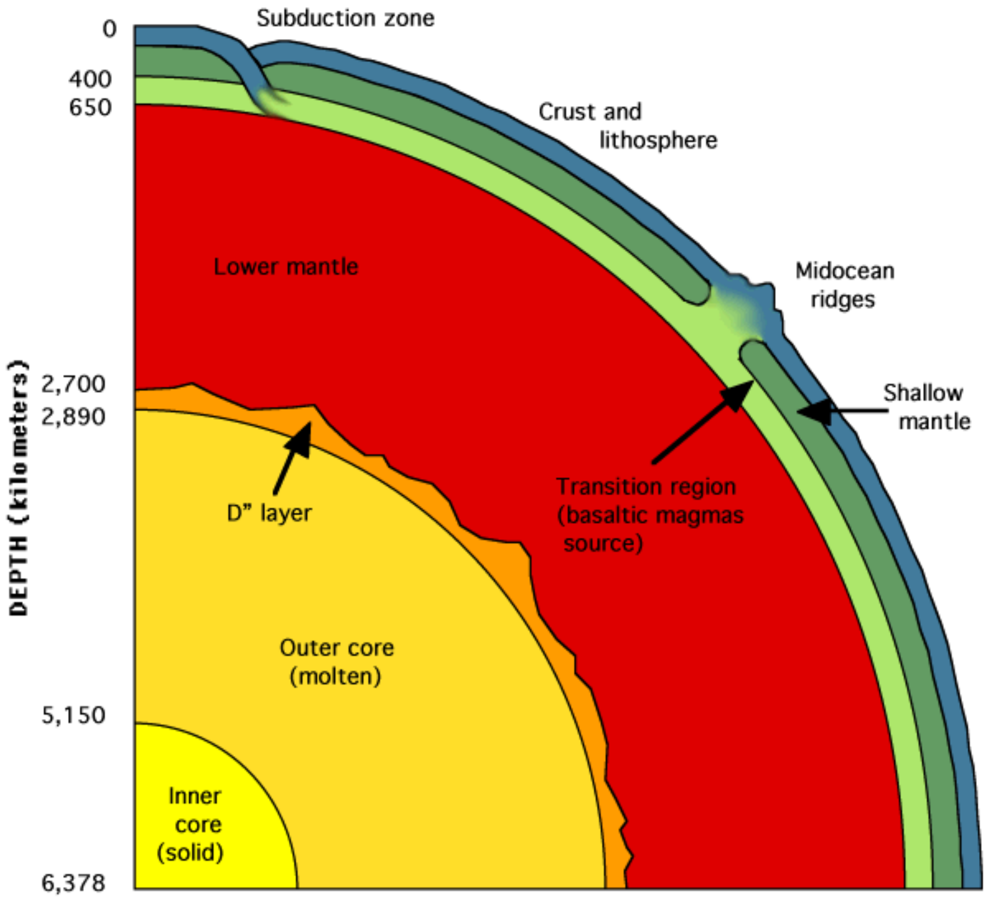
1. The Earth;

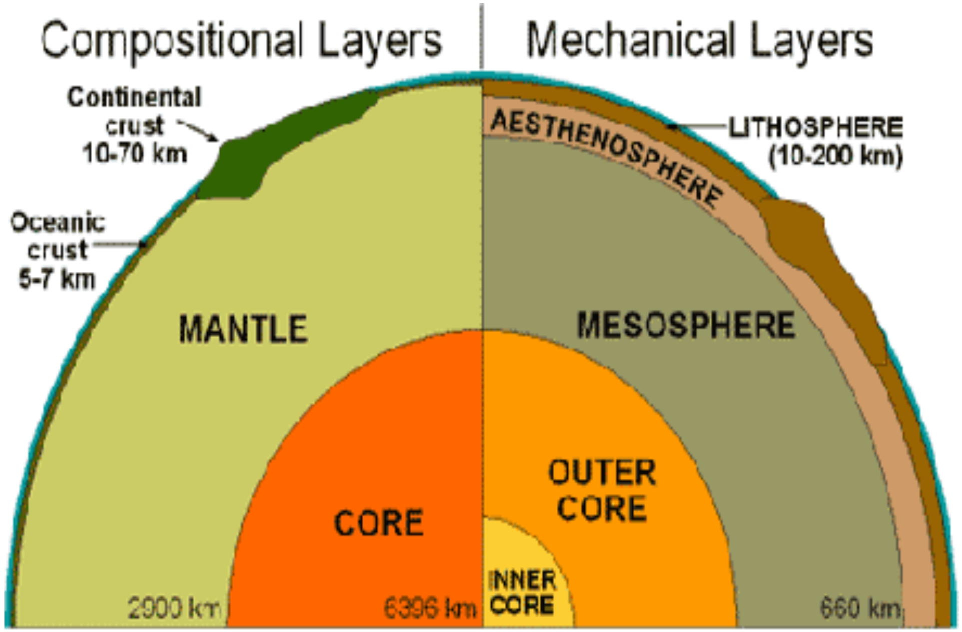
2. Geoneutrinos;

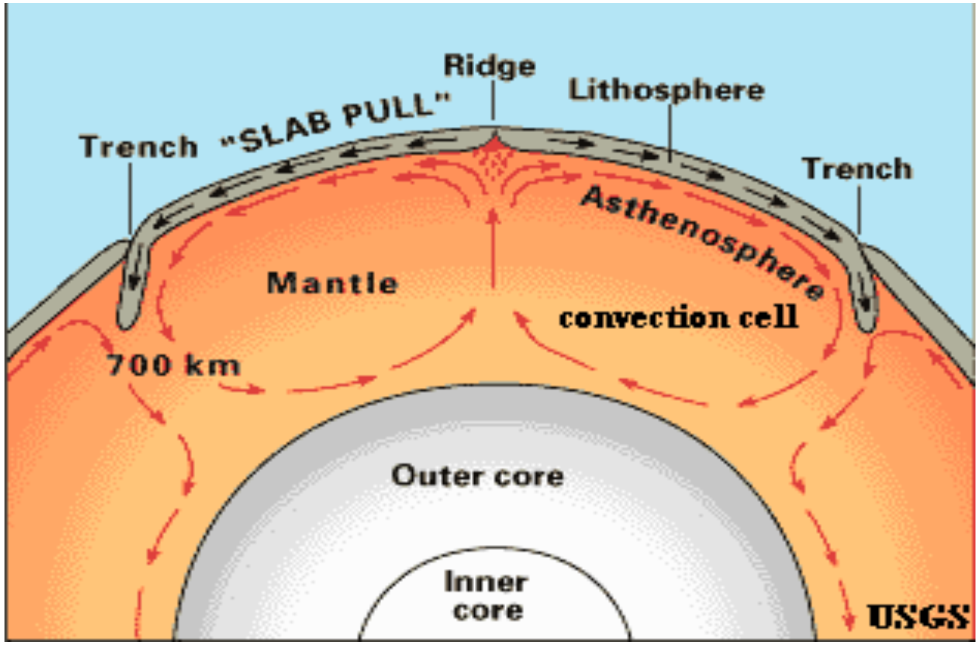
3. Experimental results;

4. Future and perspectives;

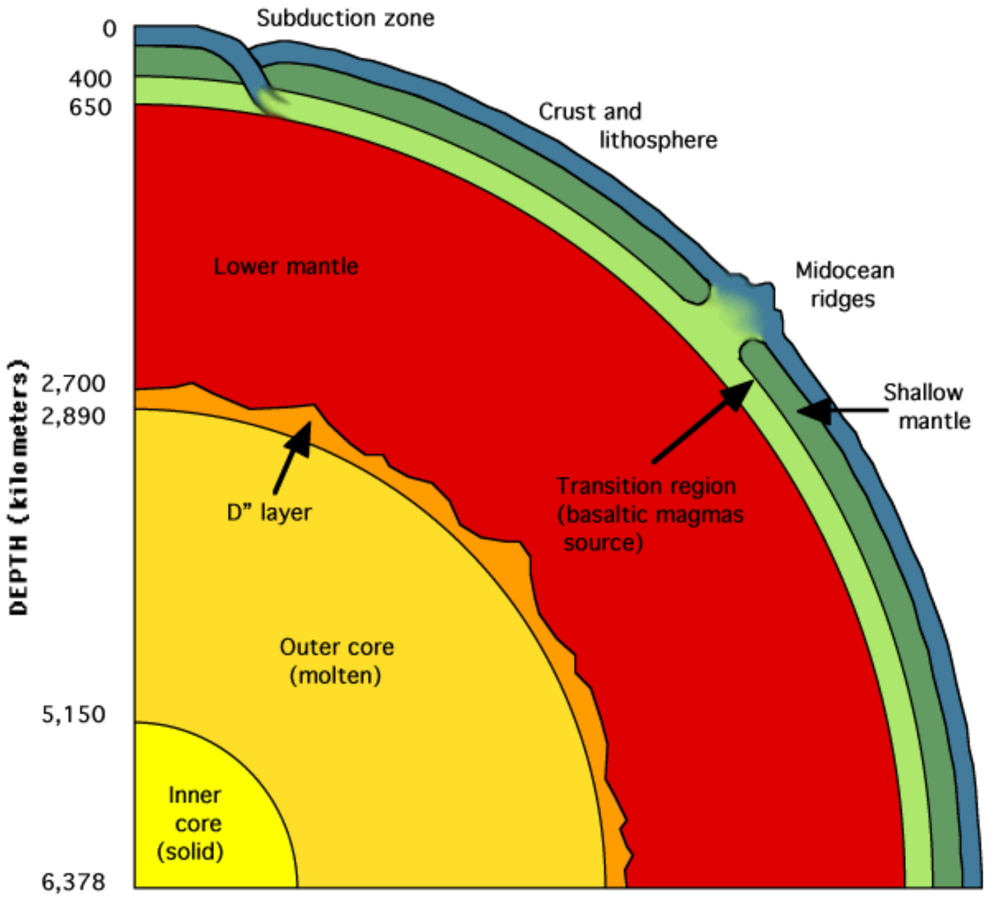
Earth structure







Earth structure



Inner Core - SOLID

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

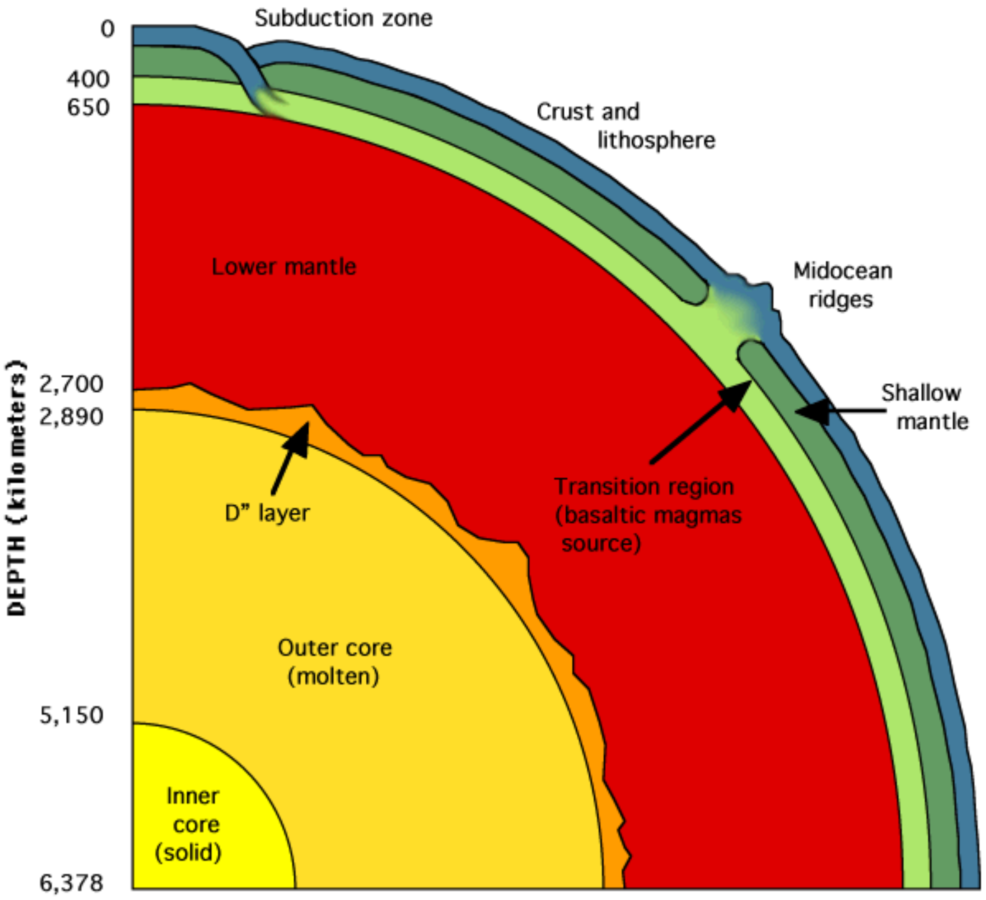
Outer Core - LIQUID

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

D" layer: mantle –core transition

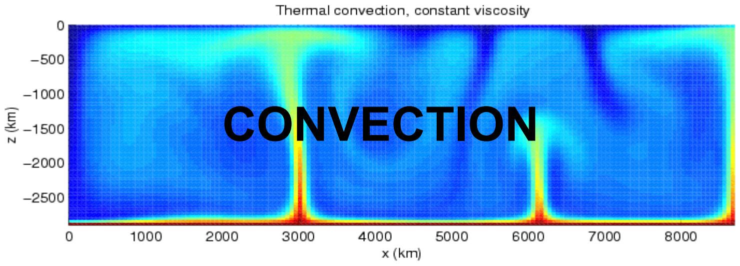
- ~200 km thick;
- seismic discontinuity;
- unclear origin;

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:

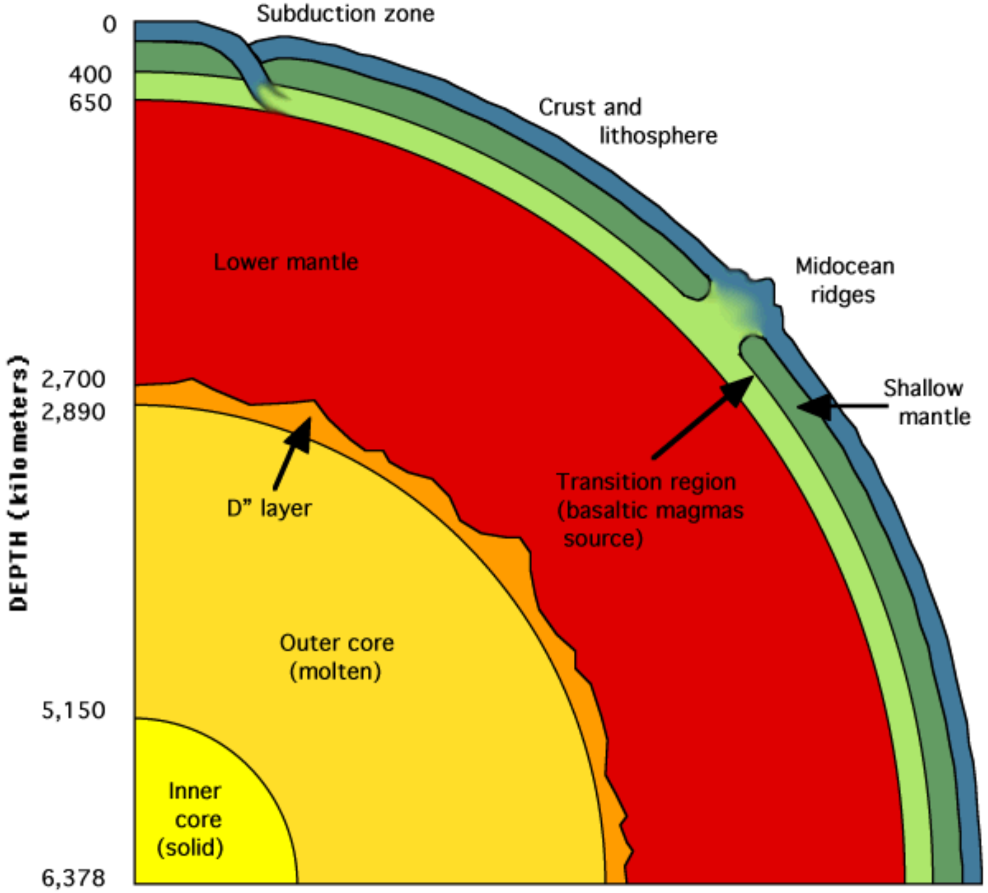


Transition zone (400 -650 km)

seismic discontinuity;

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

Earth structure



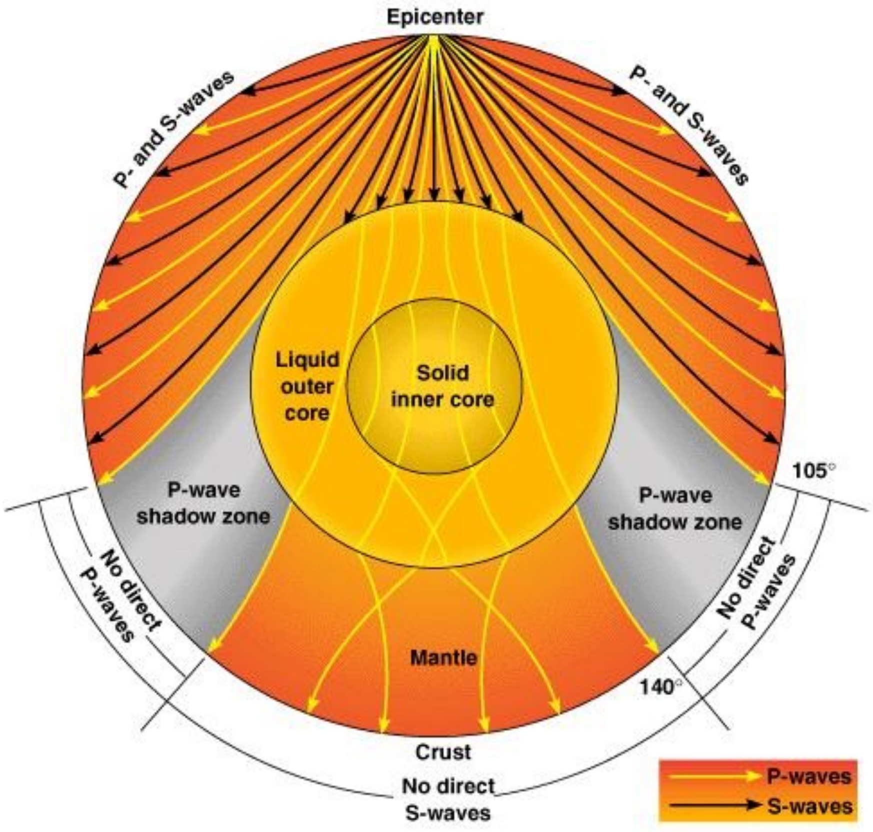
Upper mantle

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

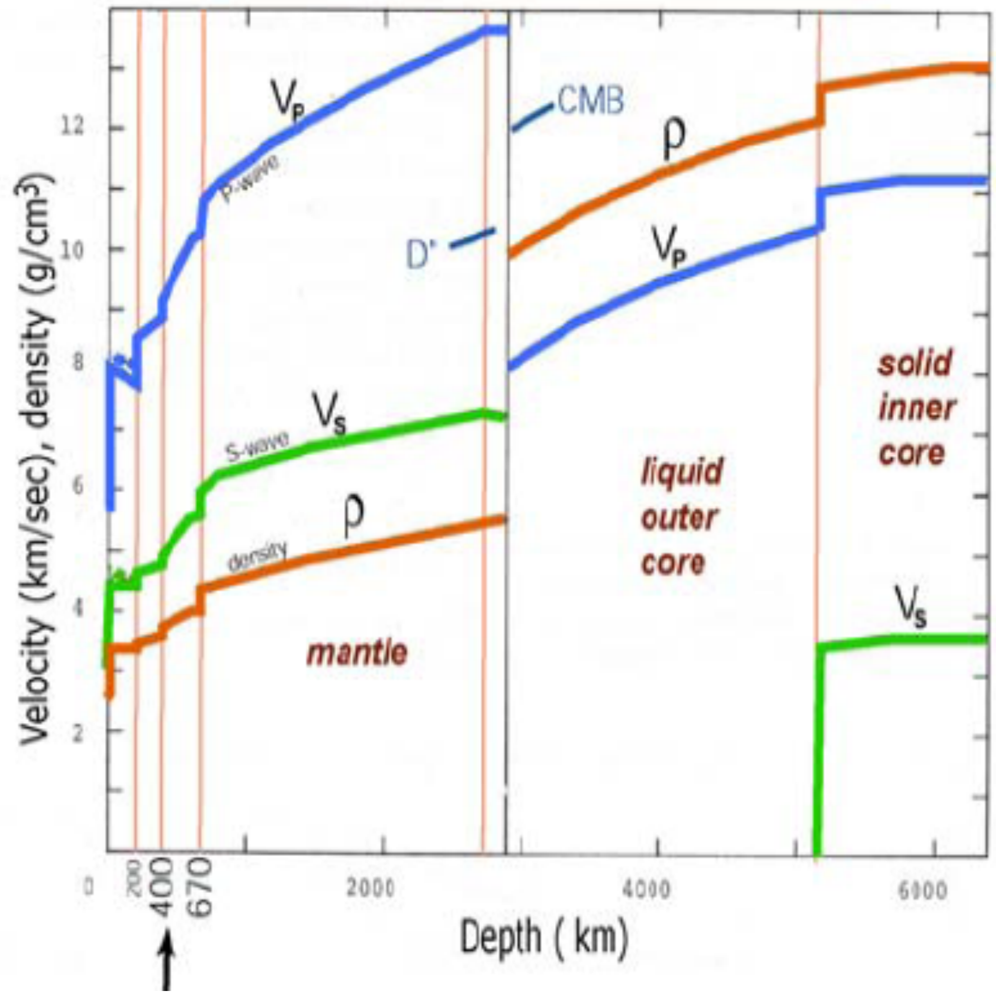
Crust: the uppermost part

- **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



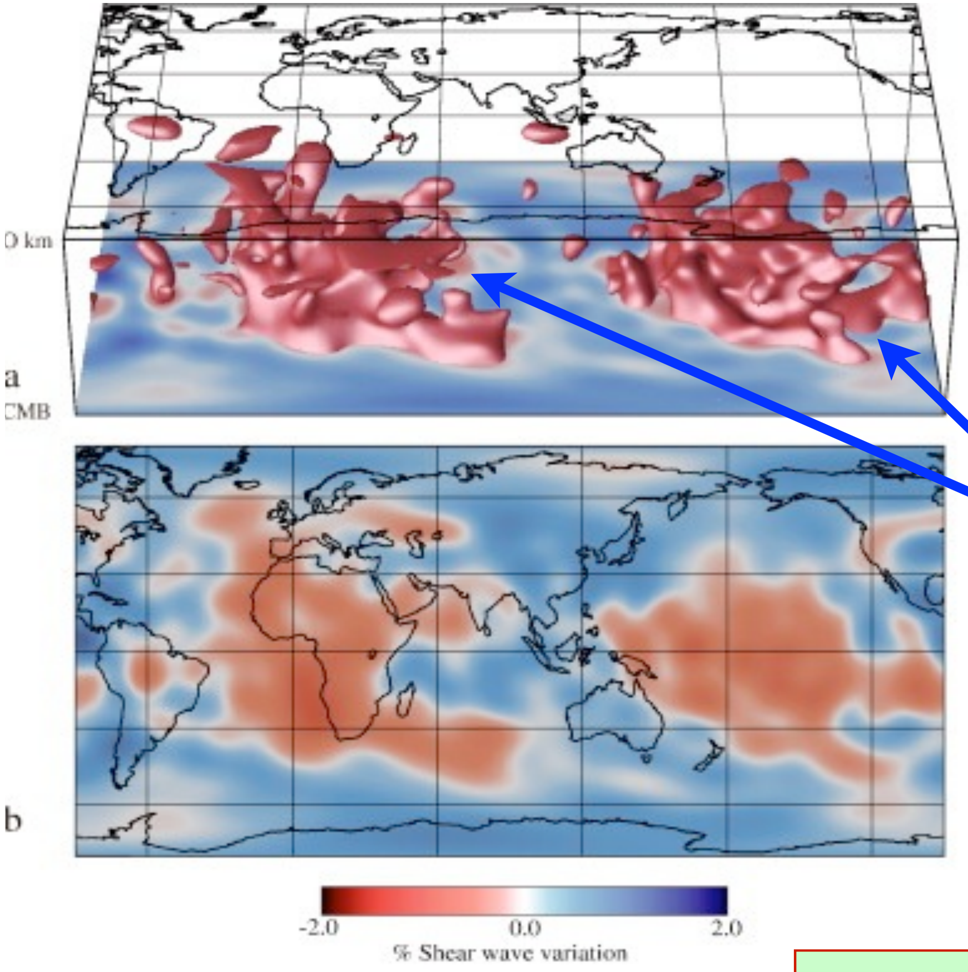
Discontinuities in the waves propagation and the density profile but no info about the chemical composition of the Earth

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

Geochemistry

1) **Direct rock samples**

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

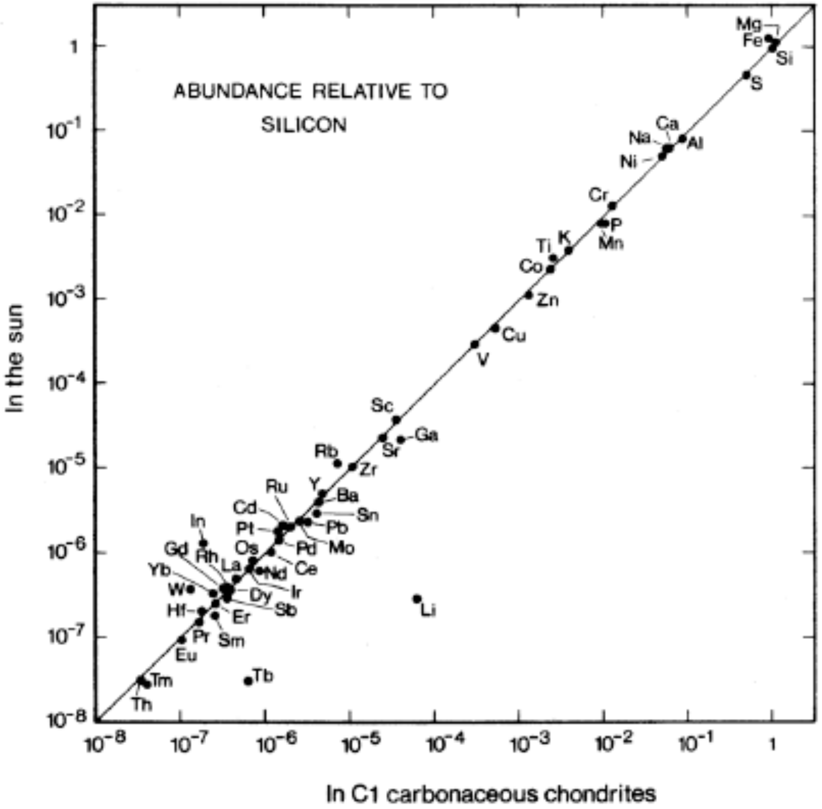
* mantle rocks brought up by tectonics and **vulcanism;**

BUT: POSSIBLE ALTERATION DURING THE TRANSPORT

2) **Geochemical models:**

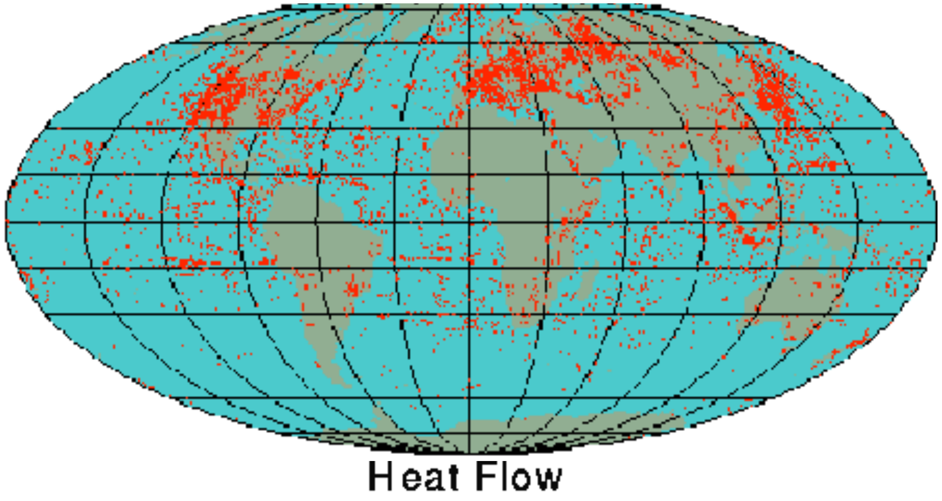
composition of direct rock samples +
C1 carbonaceous chondrites meteorites +
Sun's photosphere;

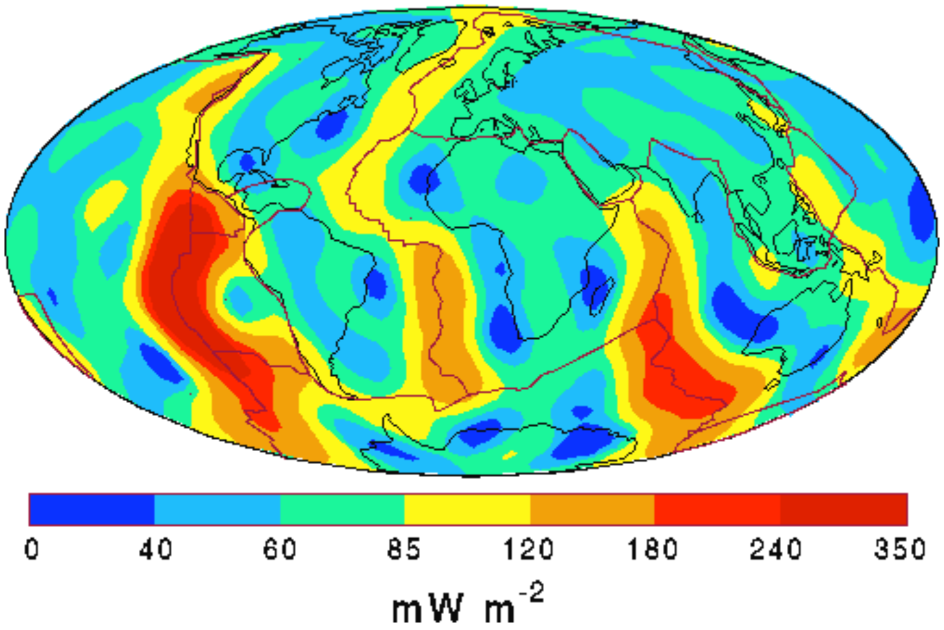
Bulk Silicate Earth (BSE) models (several!):
medium composition
of the "re-mixed" crust + mantle,
i.e., primordial mantle before the crust differentiation and after the Fe-Ni core separation;



Surface heat flux

Bore-hole measurements





- 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)

SYSTEMATIC ERRORS

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

Sources of the Earth's heat

- Total heat flow ("measured"): latest results: 47±2 TW
- *Radiogenic heat = from decays of long-lived radioactive elements (U,Th chains + ^{40}K)*

  A) C1 carbonaceous chondrites : 17-21 TW from which

  ~9 TW from the crust and 0 from the core (the rest is in the mantle);

  B) Enstatic-chondrites models: (Javoy 2010): only 11 TW!!!

  C) Geodynamical models: >30 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.)

IMPORTANT MARGINS
FOR ALL DIFFERENT MODELS OF THE EARTH STRUCTUE

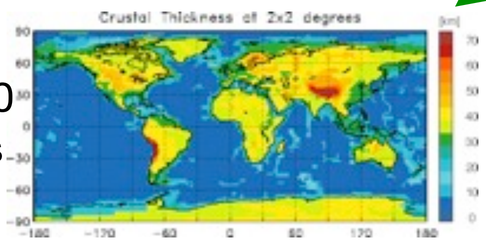
From Sramek @ Neutrino Geoscience 2013

U Th K Composition of Silicate Earth (BSE)

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



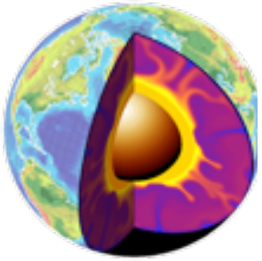
CRUST2.0 thickness

Oceanic: 0.22 ± 0.03 TW

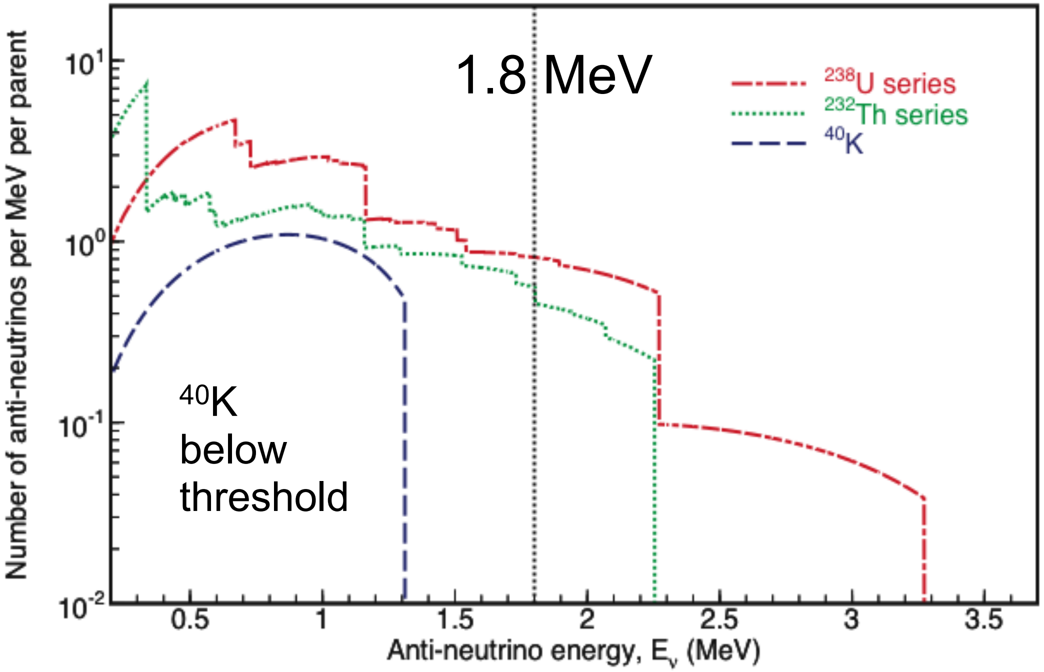
Continental: 7.8 ± 0.9 TW

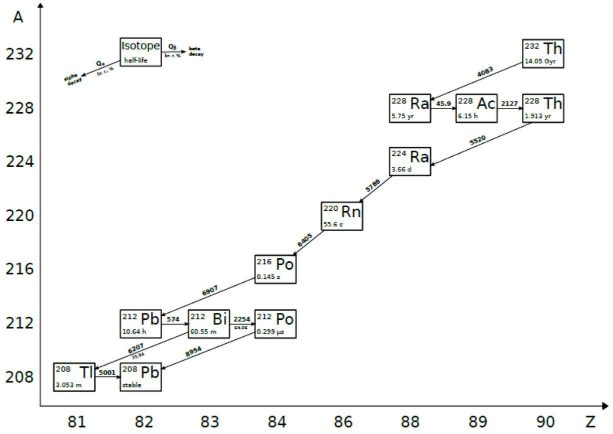
Tomorrow: New crustal model by Yu Huang et al.
CC = 6.8 (+1.4/-1.1) TW

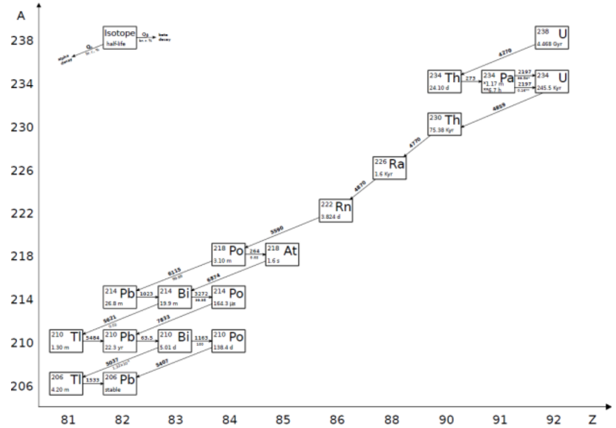
?



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







Half life

$$\boxed{\begin{array}{c}{}^{238}\mathrm{U}\\ 4.47\ \mathrm{Gy}\end{array}} \xrightarrow[100\%]{} {}^{206}\mathrm{Pb} + 8\,{}^{4}\mathrm{He} + 6e^{-} + \underline{6\bar{\nu}_e} + 51.7\ [\mathrm{MeV}]$$

$$\boxed{\begin{array}{c}{}^{232}\mathrm{Th}\\ 14.05\ \mathrm{Gy}\end{array}} \xrightarrow[100\%]{} {}^{208}\mathrm{Pb} + 6\,{}^{4}\mathrm{He} + 4e^{-} + \underline{4\bar{\nu}_e} + 42.7\ [\mathrm{MeV}]$$

$$\boxed{\begin{array}{c}{}^{40}\mathrm{K}\\ 1.28\ \mathrm{Gy}\\ {}^{40}\mathrm{K}\end{array}} \begin{array}{l}\xrightarrow[89.28\%]{} {}^{40}\mathrm{Ca} + e^{-} + \underline{\bar{\nu}_e} + 1.311\ [\mathrm{MeV}]\\ + e^{-} \xrightarrow[10.72\%]{} {}^{40}\mathrm{Ar} + \underline{\nu_e} + 1.505\ [\mathrm{MeV}]\end{array}$$

Geoneutrinos detection: inverse beta decay

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

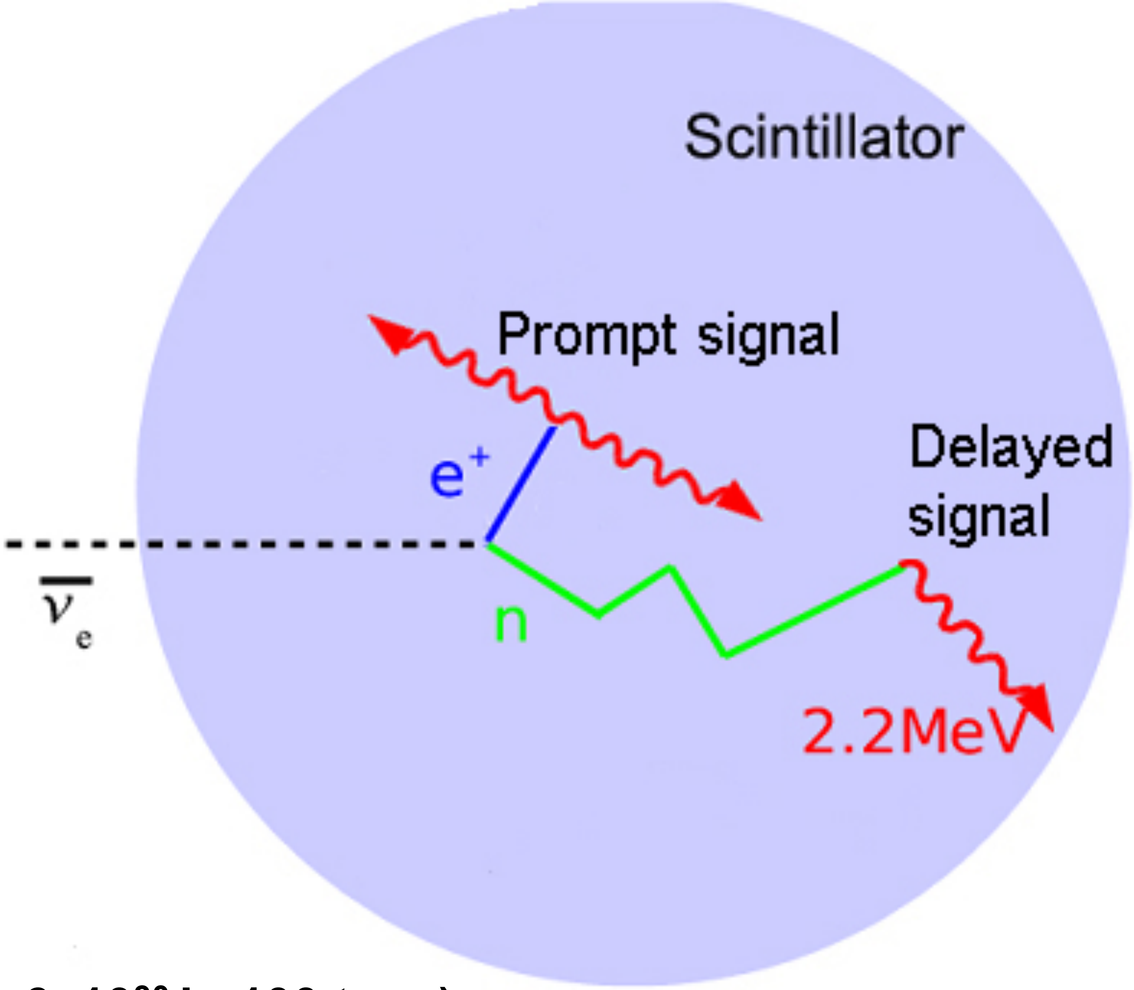
- "prompt signal"

e+: energy loss + annihilation

- "delayed signal"

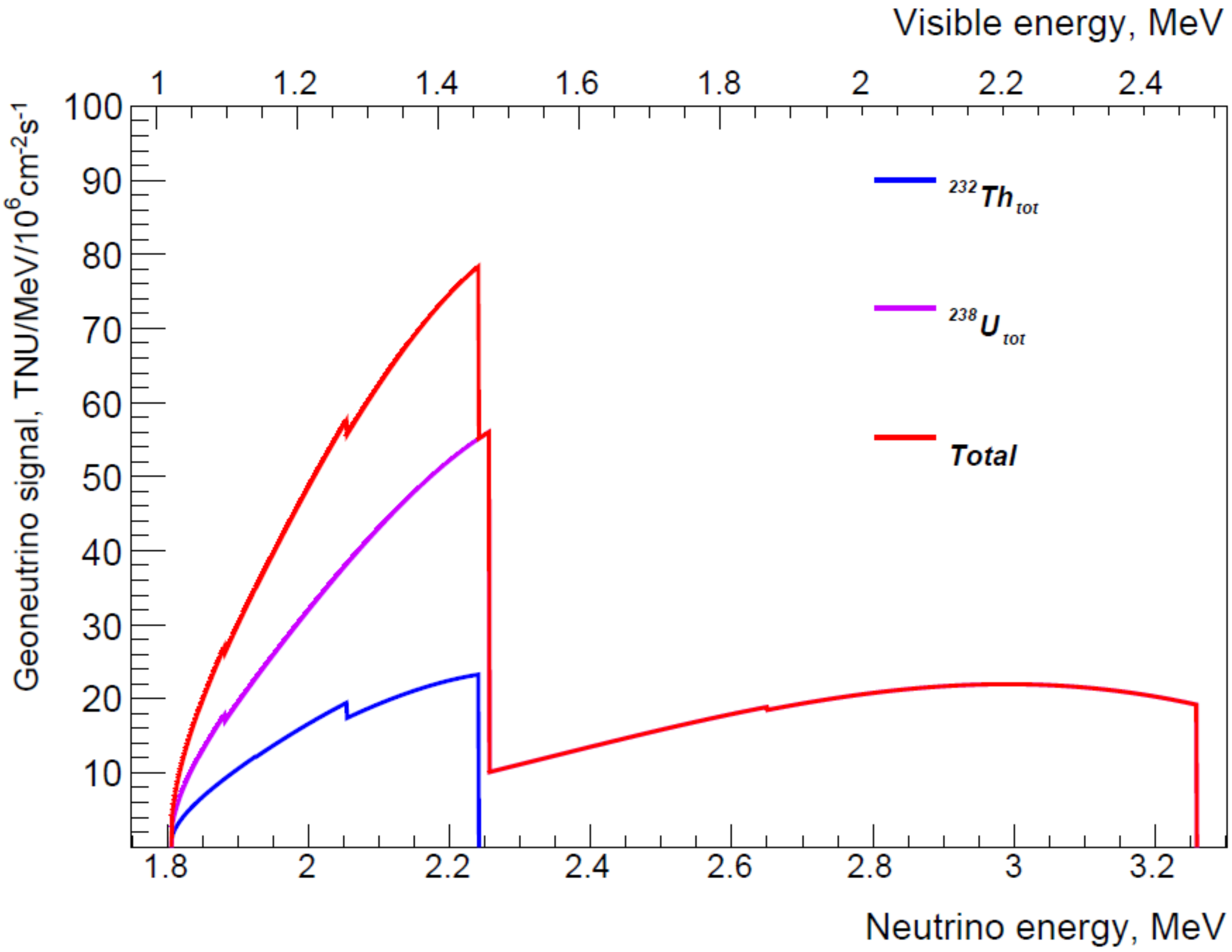
neutron capture on protons after thermalization 2.2 γ

$E_{\nu} > 1.8$ MeV



$\sigma \sim 10^{-44}$ cm^2 (in Borexino: $N_{protons} = 6 \times 10^{30}$ in 100 tons)

U/Th signal (no energy resolution)



From Oleg Smirnov @ Neutrino Geoscience 2015)

Why to study geoneutrinos?

- Abundance of radioactive elements fixes the amount of radiogenic heat (nuclear physics);
- Mass and distribution of radiogenic elements → geoneutrino flux (cca 10^6 cm^{-2} s^{-1});
- From measured geoneutrino flux to radiogenic heat a bit more complicated (U and Th distribution in the deep Earth is not known)….

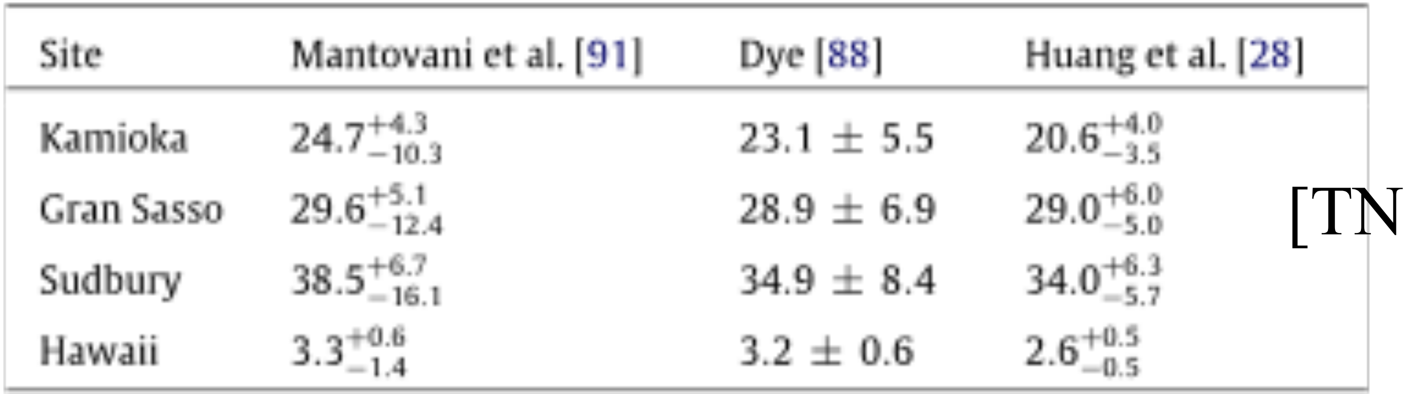
Main goal: determine the contribution of the **radiogenic heat to the total surface heat flux**, which is an important margin, test, and input at the same time for many geophysical and geochemical models of the Earth;

Further goals: tests and discrimination among geological models, study of the mantle homogeneity, insights to the processes of Earth'formation…..

Expected geoneutrino signal: geochemical approach

- **LOC: Local 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 based on CRUST 1);
- **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);

Borexino
KamLAND
SNO+
HanoHano



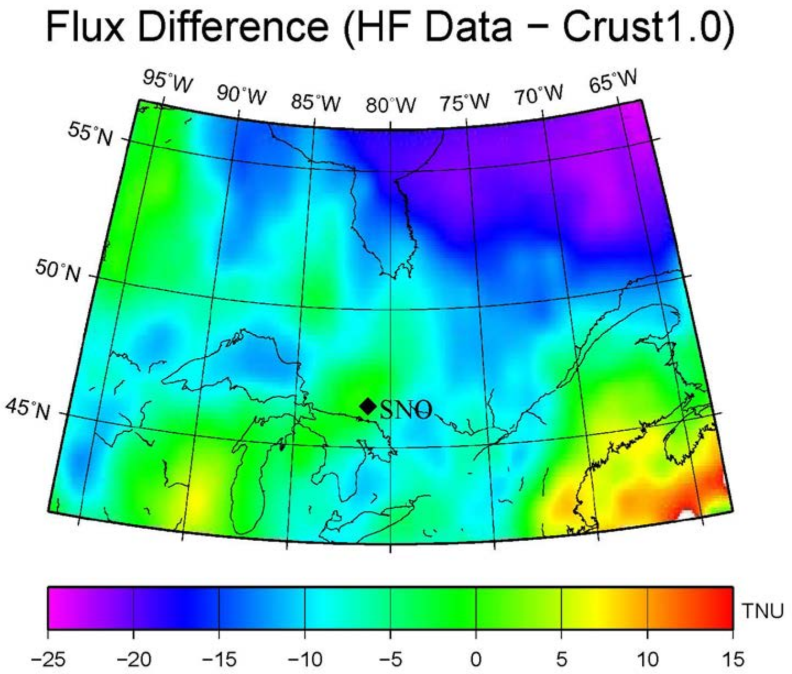
Site	Mantovani et al. [91]	Dye [88]	Huang et al. [28]
Kamioka	$24.7^{+4.3}_{-10.3}$	23.1 ± 5.5	$20.6^{+4.0}_{-3.5}$
Gran Sasso	$29.6^{+5.1}_{-12.4}$	28.9 ± 6.9	$29.0^{+6.0}_{-5.0}$
Sudbury	$38.5^{+6.7}_{-16.1}$	34.9 ± 8.4	$34.0^{+6.3}_{-5.7}$
Hawaii	$3.3^{+0.6}_{-1.4}$	3.2 ± 0.6	$2.6^{+0.5}_{-0.5}$

[TNU]

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

Expected geoneutrino signal: from the heat flux data

- Assumes steady state: can be applied old shields and cratons
- Ah these regions, flux across Moho 15 + 3 mW/m2
- Interpolates between data = heat flux measurements
- $Q_S = Q_m + \int_0^m H(z)dz$



- Differences can be very large (>20 TNU east of James Bay)
- BUT, difference ≈ 0 near Sudbury!!!
- Signal at SNO ≈ 27.5 TNU (oscillated)

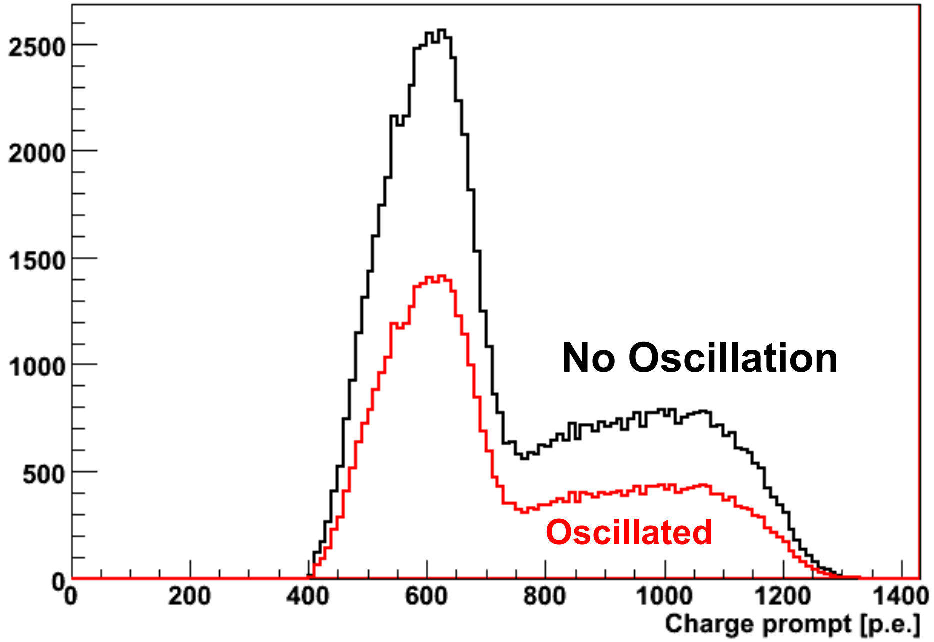
Mareschal and Jaupart, Neutrino Geoscience 2015

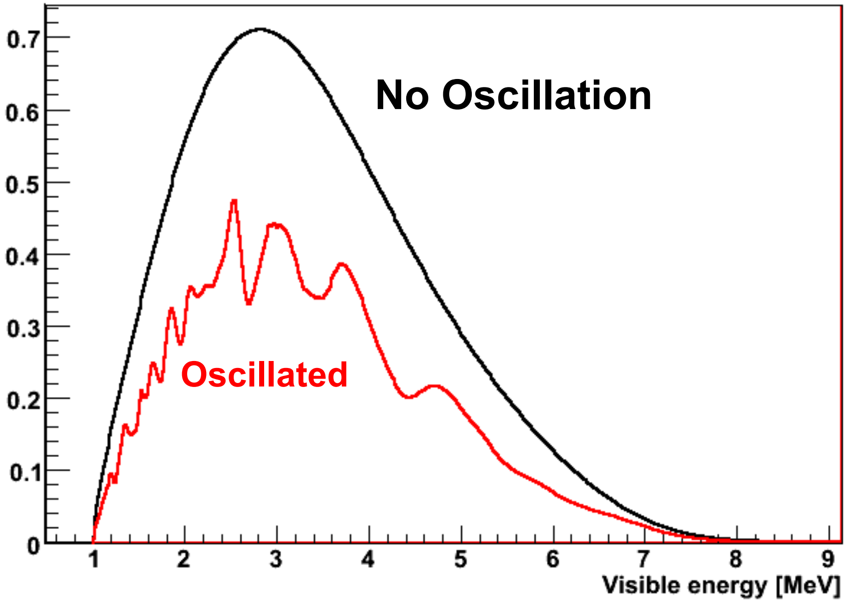
Effect of neutrino oscillations

$$P_{ee} = P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = \cos^4\theta_{13}\left(1-\sin^2 2\theta_{12}\sin^2\left(\frac{\delta m^2 L}{4E}\right)\right)+\sin^4\theta_{13}$$

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

- **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

- originally build to measure reactor antineutrinos;
- 1000 tons;
- S(reactors)/S(geo) ~ 6.7 (2010)
- after Fukushima Japanese reactors are off
- data since 2002;
- 2700 meters water equivalent shielding;

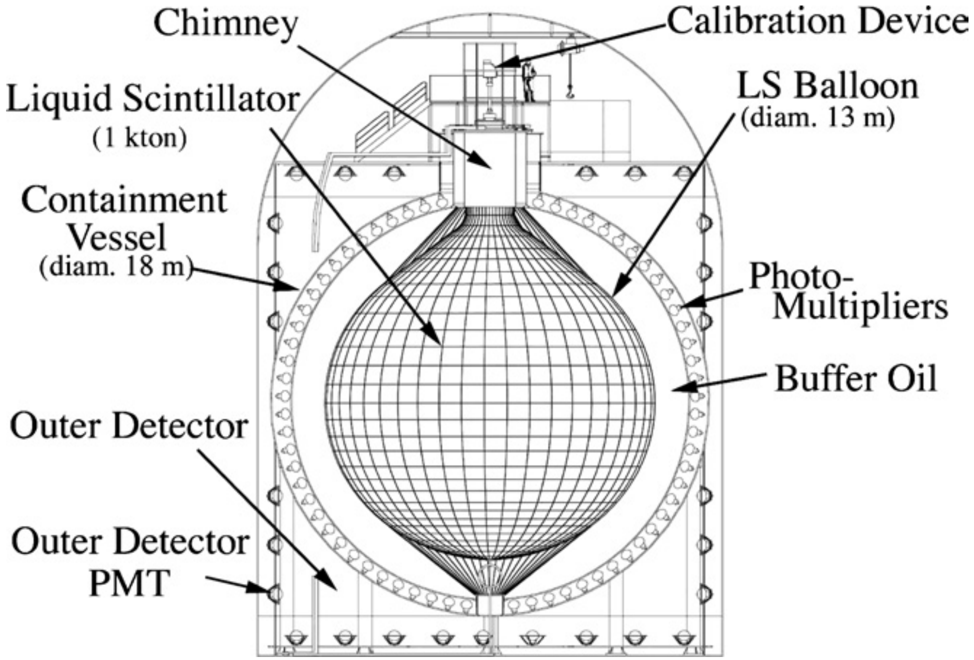
Borexino in Gran Sasso, Italy

CONTINENTAL CRUST

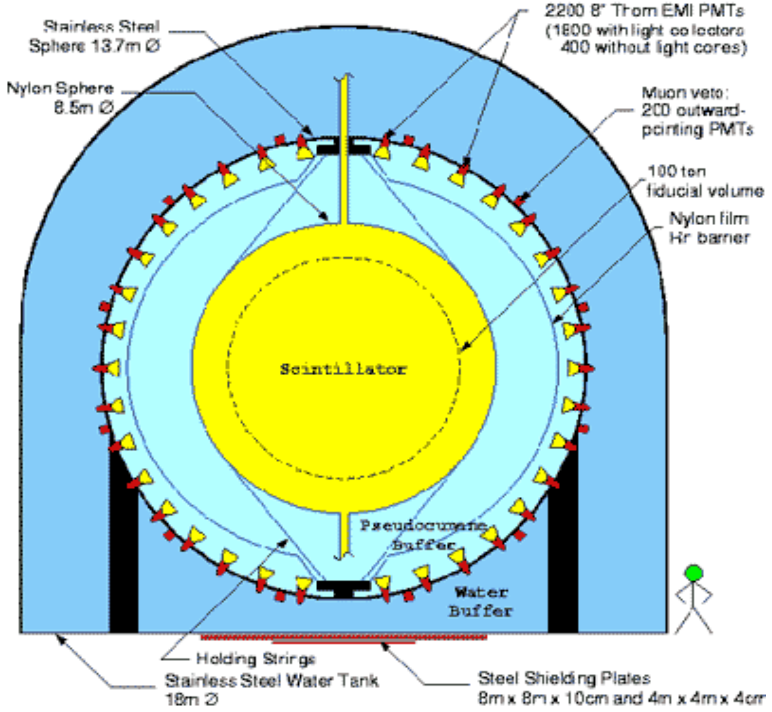
- originally build to measure neutrinos from the Sun – extreme radiopurity needed and achieved;
- 280 tons;
- S(reactors)/S(geo) ~ 0.3 !!! (2010)
- DAQ started in 2007;
- 3600 m.w.e. shielding;

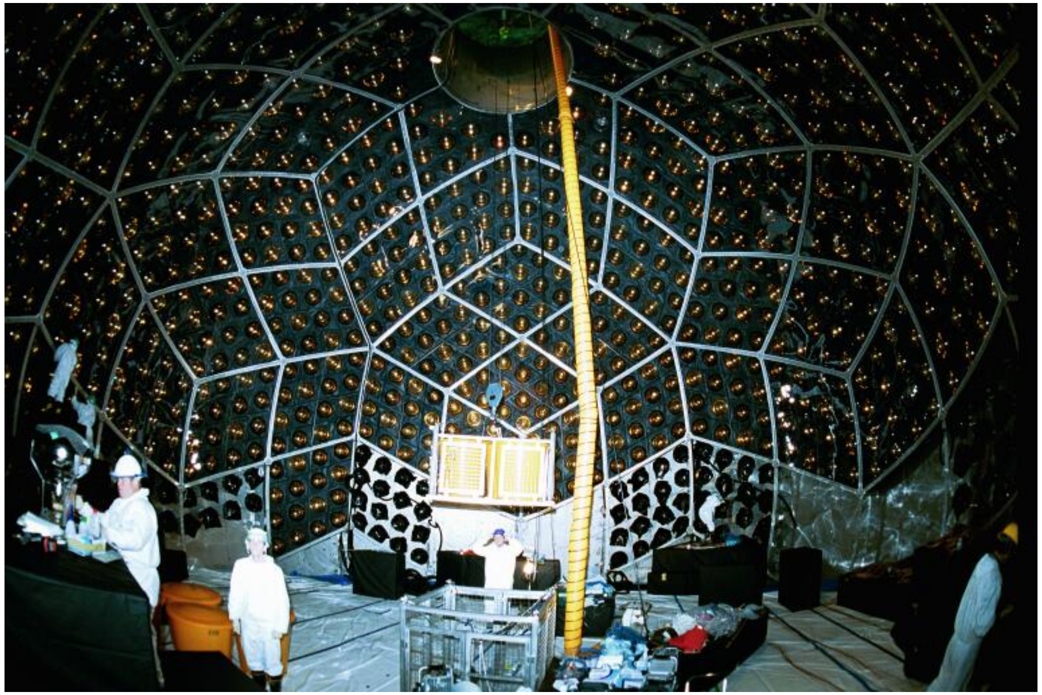
Experimental data

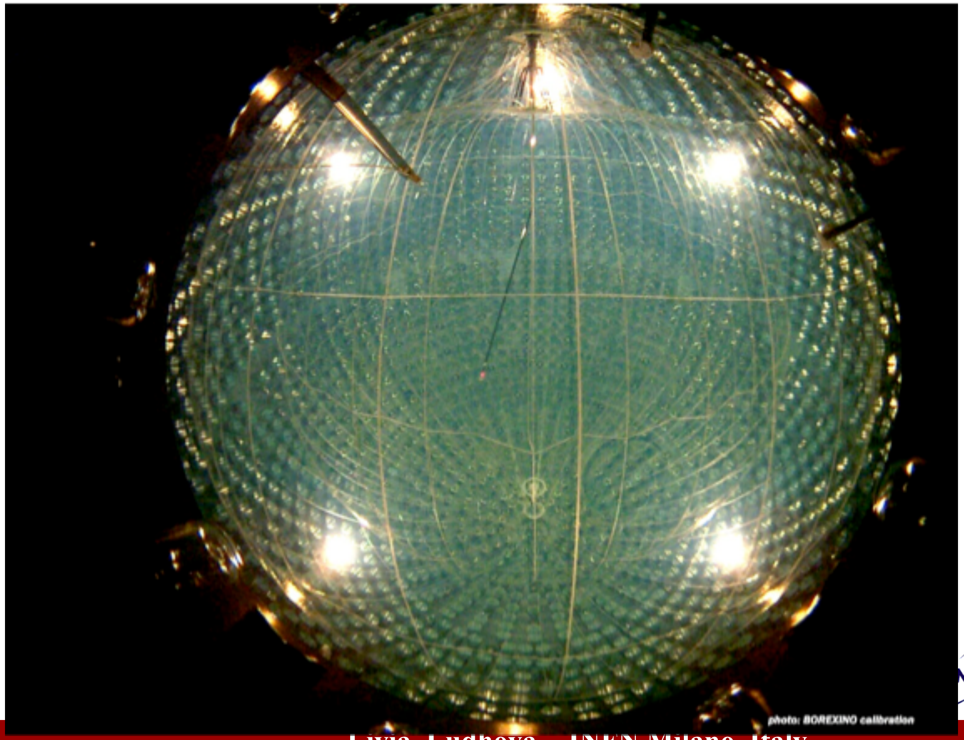
KamLand



Borexino







Geoneutrino experimental results

KamLand (Japan)

- The very first investigation in 2005 (Nature 436 (2005) 499): CL < 2 sigma;
- Update in PRL 100 (2008): 73 +- 27 geo events
- high exposure: 99.997 CL observation in 2011 (Gando et al, Nature Geoscience 1205)
  106 $^{+29}_{-28}$ geonu events detected;
  (March 2002 – April 2009)
  3.49 x 10^{32} target-proton year
- **PRD 88 (2013) 033001**
  116 $^{+28}_{-27}$ geonu events detected;
  (March 2002 – November 2012)
  4.9 x 10^{32} target-proton year
  0-hypothesis @ 2 x 10^{-6}

Borexino (Italy)

- small exposure but low background: observation at 99.997 CL in 2010 (Bellini et al, PLB 687):

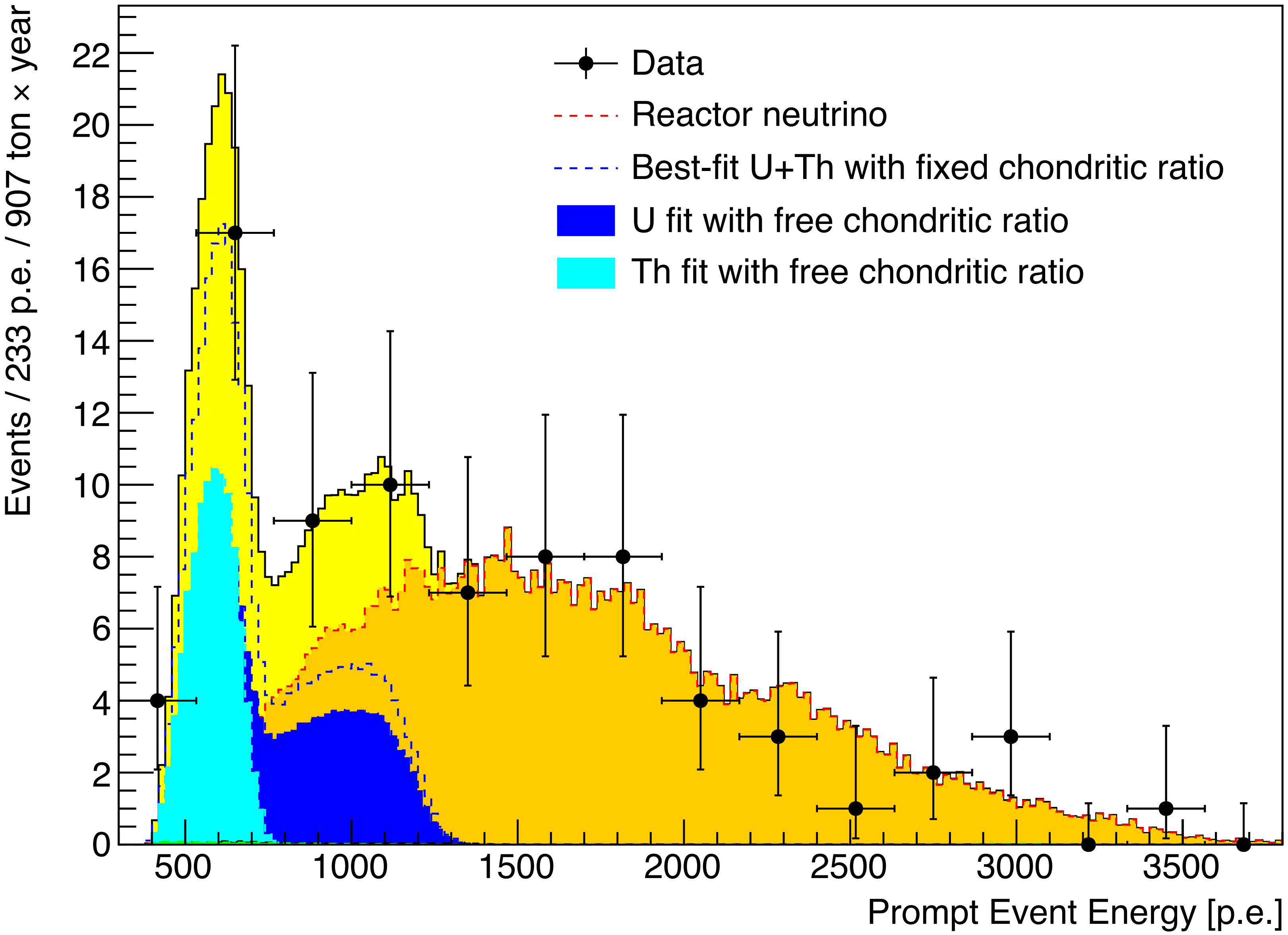
9.9 $^{+4.1}_{-3.4}$ geonu events detected;
(December 2007 – December 2009)
Exposure 1.5 x 10^{31} target-proton year

- **PLB 722 (2013) 295–300:**
  14.3 +- 4.4 geonu events;
  (December 2007 – August 2012)
  3.69 x 10^{31} target-proton year after cuts
- **NEW 2015: arXiv:1506.04610**
  23.7 +6.5- 5.7 geonu events;
  (December 2007 – March 2015)
  5.5 x 10^{31} target-proton year
  0-hypothesis @ 3.6 x 10^{-9}
  (5.9 sigma)

Borexino latest results

3 days old result!

- **arXiv:1506.04610**



Set of cuts

1. Prompt energy: $Q_{prompt} > 408$ p.e. (> kinematic threshold, resolution)
2. Delayed energy: $860 < Q_{delayed} < 1300$ p.e : 2.2 MeV γ peak
3. Distance: $\Delta R < 1$ m; (position reconstruction)
4. Time separation: : $20 < \Delta t < 1280$ μs (neutron capture time)
5. Pulse shape: $g_{\alpha\beta}$(delayed)<0.015 : selecting e-like events
6. Muon veto: $T_\mu > 2$ ms : fast neutrons after muon
7. Muon veto: $T_\mu > 2$ s for every muon passing through internal detector. Long-lived cosmogenic (β + neutron) isotopes. ~11% of live time loss.
8. Multiplicity cut: no n-like events in ±2 ms window
9. FV cut: $R_{IV}(\Theta,\varphi)-R_{prompt}(\Theta,\varphi)>0.30$ m : dynamical, follows shape of the inner vessel
10. FADC cut: independent check of pulse shapes with 400 MHz digitizing system

Total efficiency=84.2 ± 1.5% (MC). 77 candidates selected

These 77 candidates can be due to:

1. Geoneutrinos
2. Antineutrino background: reactor neutrinos
3. Non antineutrino background

Calculation of reactor anti-ν signal

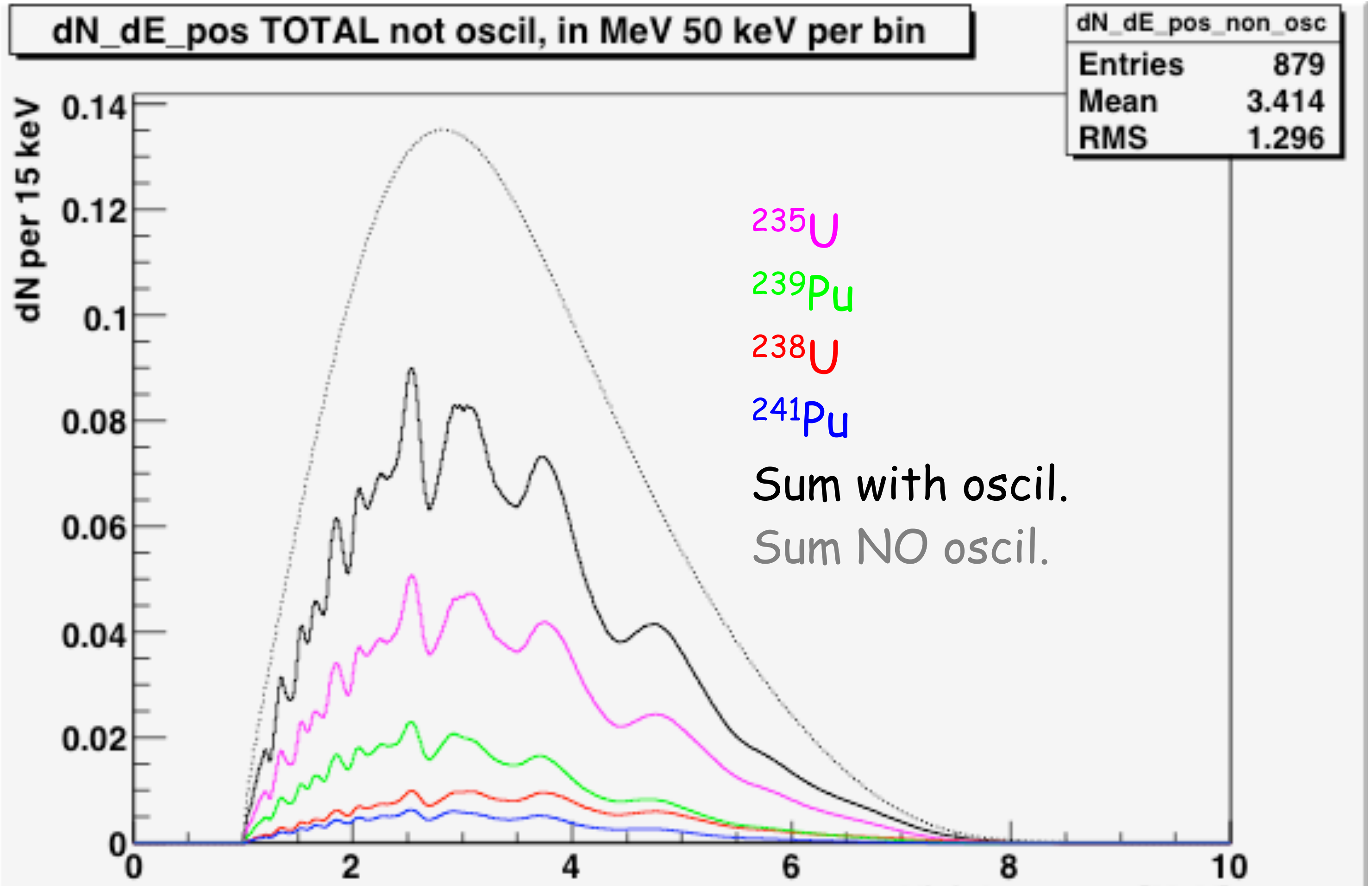
$$\Phi(E_{\bar{\nu}_e}) = \sum_{r=1}^{N_{react}} \sum_{m=1}^{N_{month}} \frac{T_m}{4\pi L_r^2} P_{rm} \sum_{i=1}^{4} \frac{f_{ri}}{E_i} \Phi_i(E_{\bar{\nu}_e}) P_{ee}(E_{\bar{\nu}_e}; \hat{\vartheta}, L_r)$$

- **From the literature:**
  - **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;
- **Calculated:**
  - **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

Expected reactor anti-neutrino signal and its error in Borexino

Expected reactor signal: (87 ± 4) TNU



Prompt energy (MeV)

Ideal detector

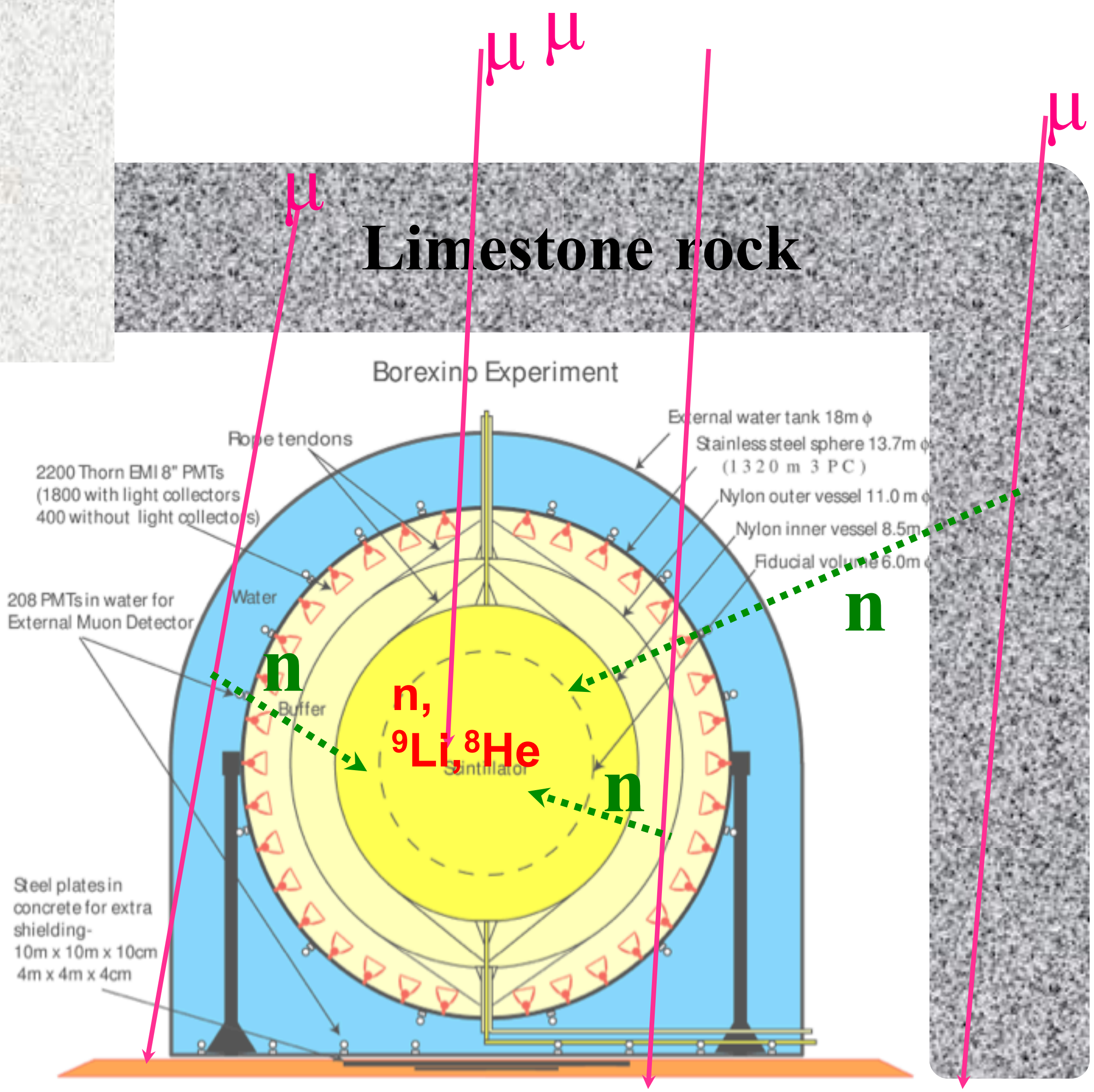
Non-antineutrino background sources

Source	Events
Cosmogenic ^{9}Li and ^{8}He	$0.194^{+0.125}_{-0.089}$
Fast neutrons from μ in Water Tank	< 0.01 (90% CL) (measured)
Fast neutrons from μ in rock	< 0.43 (90% CL) (MC)
Non-identified muons	0.12 ± 0.01
Accidental coincidences	0.221 ± 0.004
Time correlated background	$0.035^{+0.029}_{-0.028}$
Spontaneous fission in PMTs	0.032 ± 0.003
(α,n) reactions in the scintillator [^{210}Po]	0.165 ± 0.010
(α,n) reactions in the buffer [^{210}Po]	< 0.51 (90% CL)
^{214}Bi-^{214}Po	0.009±0.013
TOTAL	$0.78^{+0.13}_{-0.10}$ <0.65 (combined)

Cosmogenic background

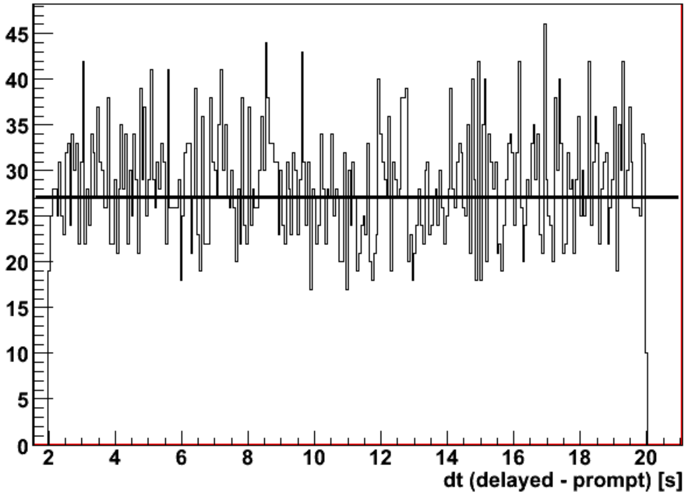
1) Cosmogenic-muon induced:

- **^{9}Li and ^{8}He** decaying β-n;
- **neutrons** of high energies;
  - neutrons scatters proton = prompt;
  - neutron is captured = delayed;
- Non-identified muons;

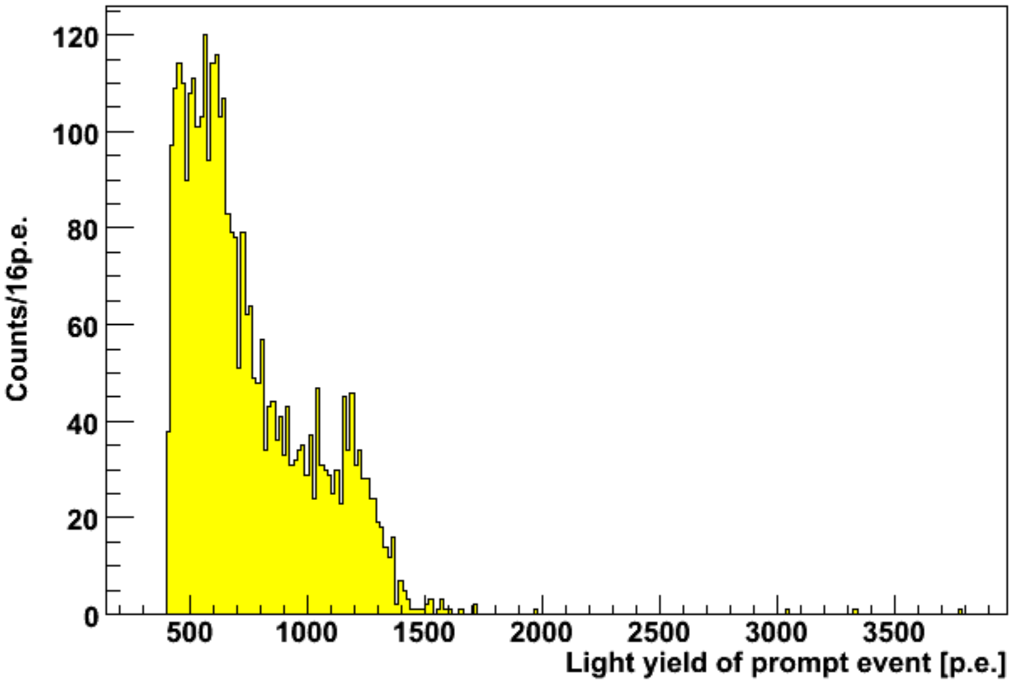


Accidental coincidences

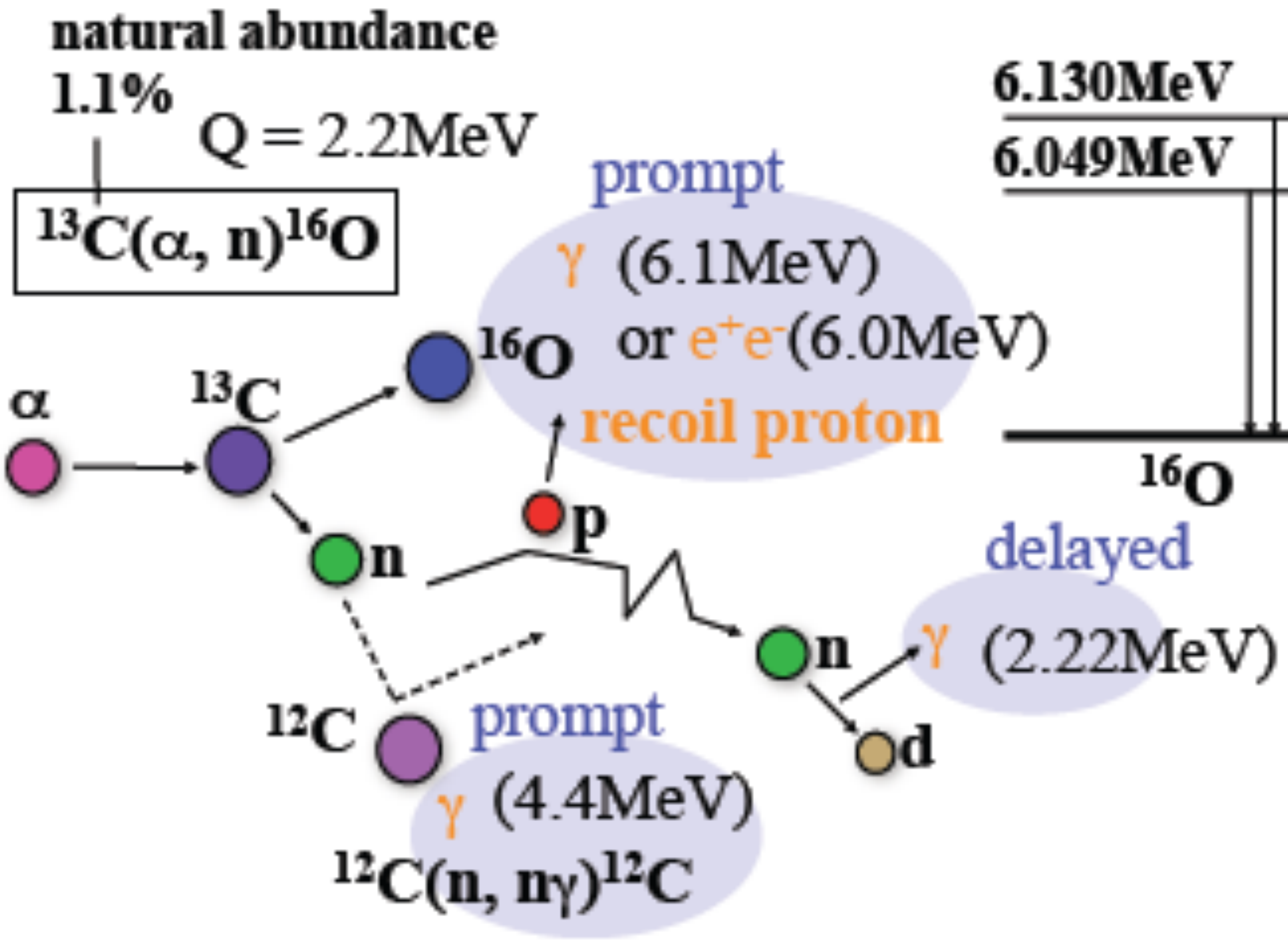
- Same cuts, just dt instead of 20-1280 μs is 2-20 s in order to maximise the statistics and so minimise the error;



Visible energy of the prompt event



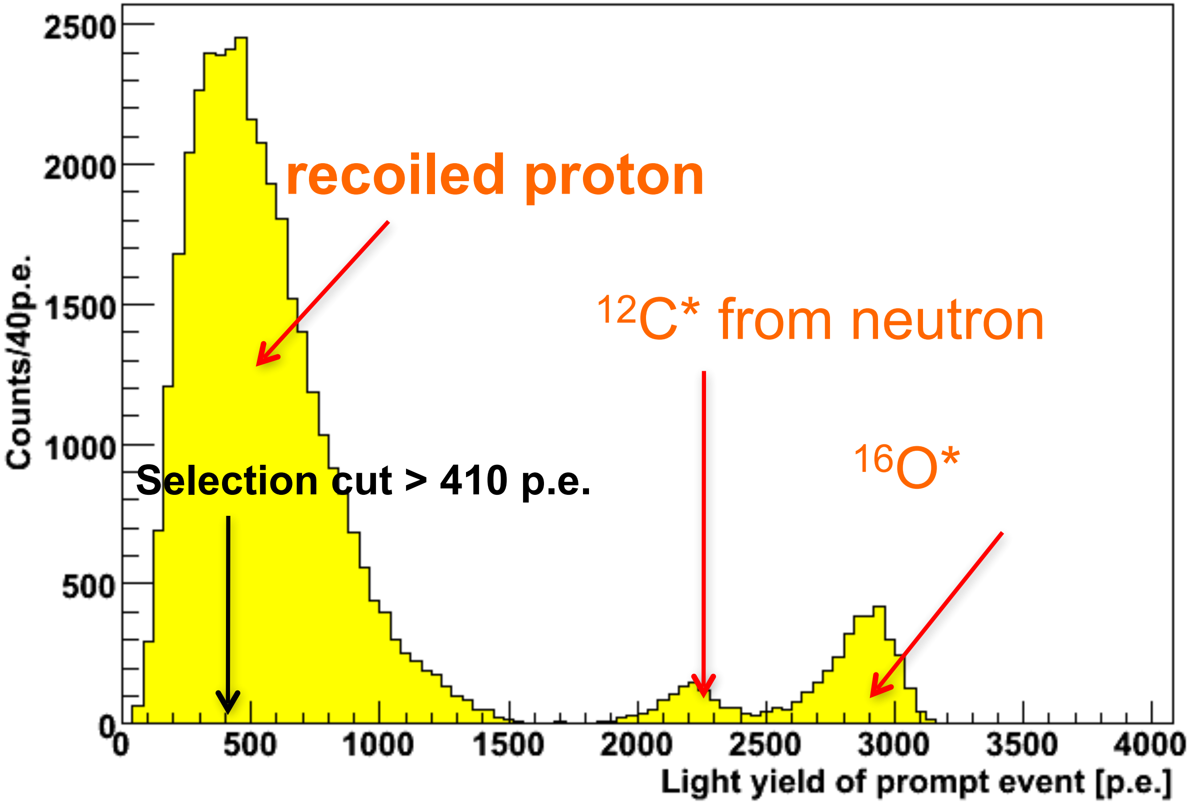
$^{13}C(\alpha,n)^{16}O$



MC for $^{13}C\ (\alpha,n)^{16}O$

Probability for ^{210}Po nucleus to give (a,n) in pure ^{13}C (6.1±0.3) 10^{-6} (Mc Kee 2008).
In PC it corresponds to (5.0±0.8)10^{-8}

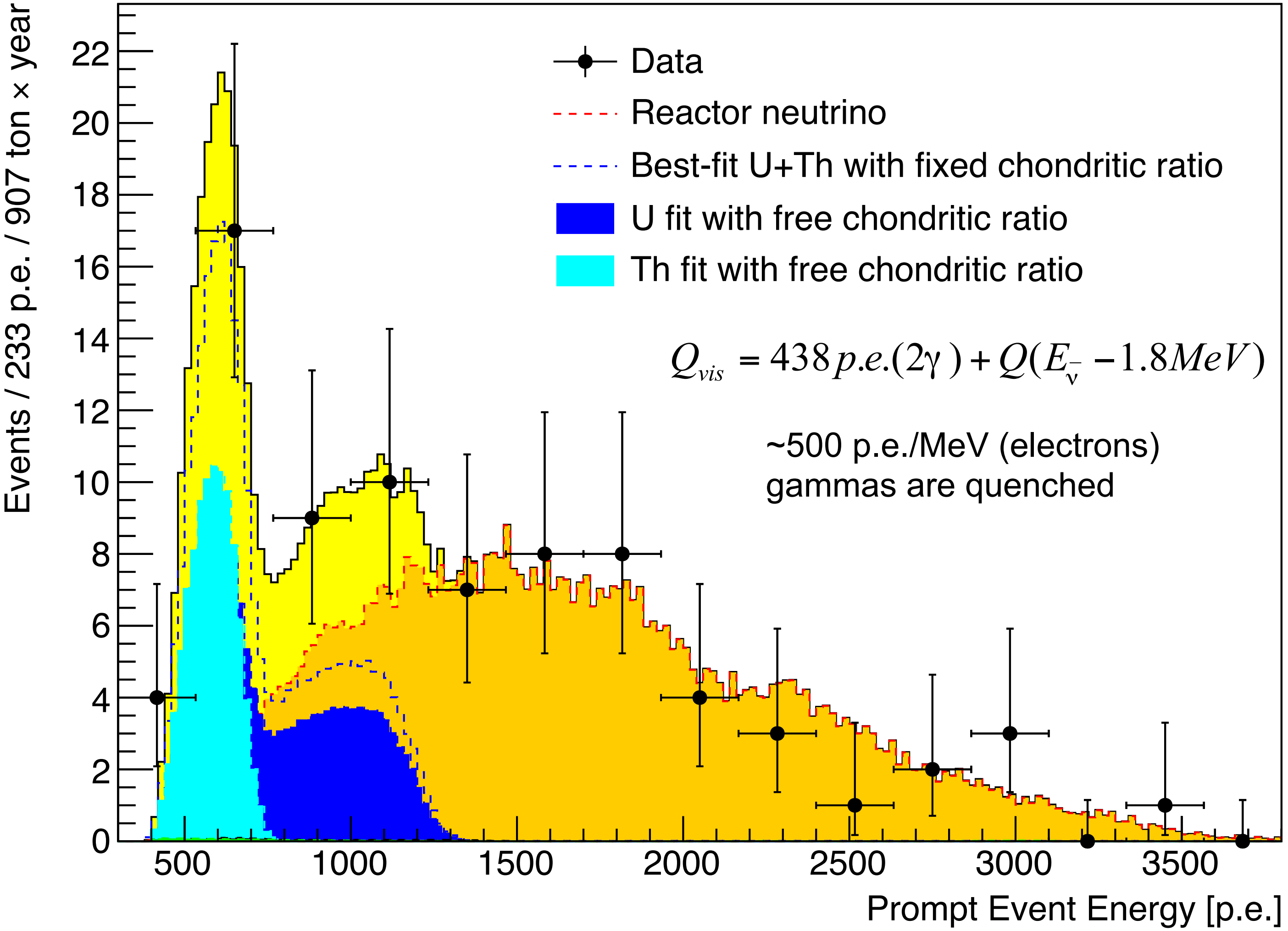
1) Isotopic abundance of ^{13}C: 1.1%
2) ^{210}Po contamination



Unbinned maximal likelihood fit:

Free: ***geoneutrino*** (T/Th constrained to chondritic value OR separate U and Th contributions)
reactor antineutrino (different parametrsations differ in rate and not that much in shape)

Constrained: **other backgrounds** (almost negligible)



$$Q_{vis} = 438\,p.e.(2\gamma) + Q(E_{\bar{\nu}} - 1.8MeV)$$

~500 p.e./MeV (electrons)
gammas are quenched

Fit results for fixed M(Th)/M(U)=3.9

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

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

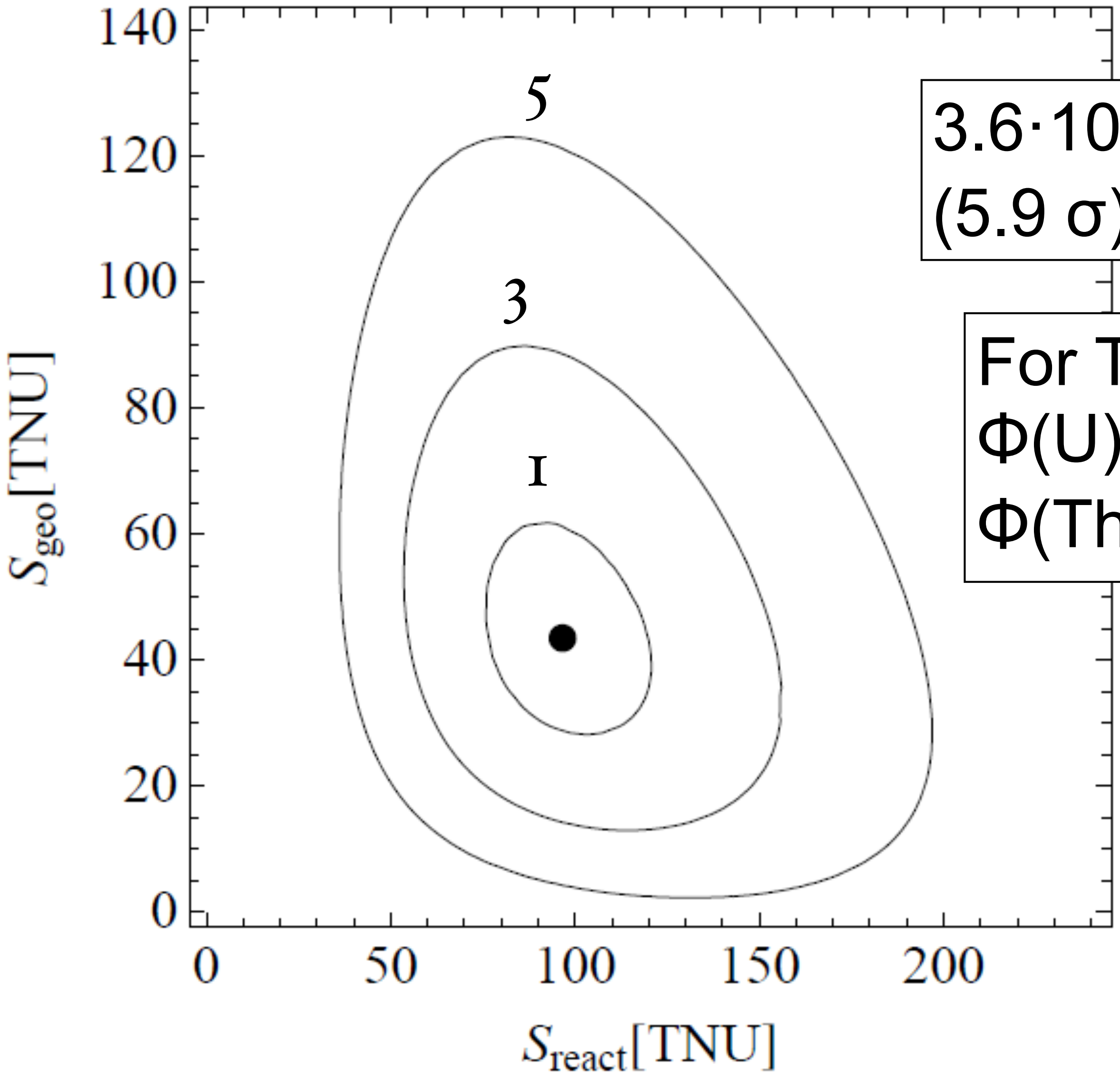
- $N_{react}=52.7^{+8.5}_{-7.7}(\text{stat})^{+0.7}_{-0.9}(\text{syst})$ events

  $S_{react}=96.5^{+15.6}_{-14.2}(\text{stat})^{+4.9}_{-5.0}(\text{syst})$ TNU

Predicted reactor signal 87 ± 4 TNU

- Systematics: 4.8% on FV and 1% on the energy scale
- *1 TNU = 1 event on 10^{32} protons in 1 yr (~1 kt of LS)

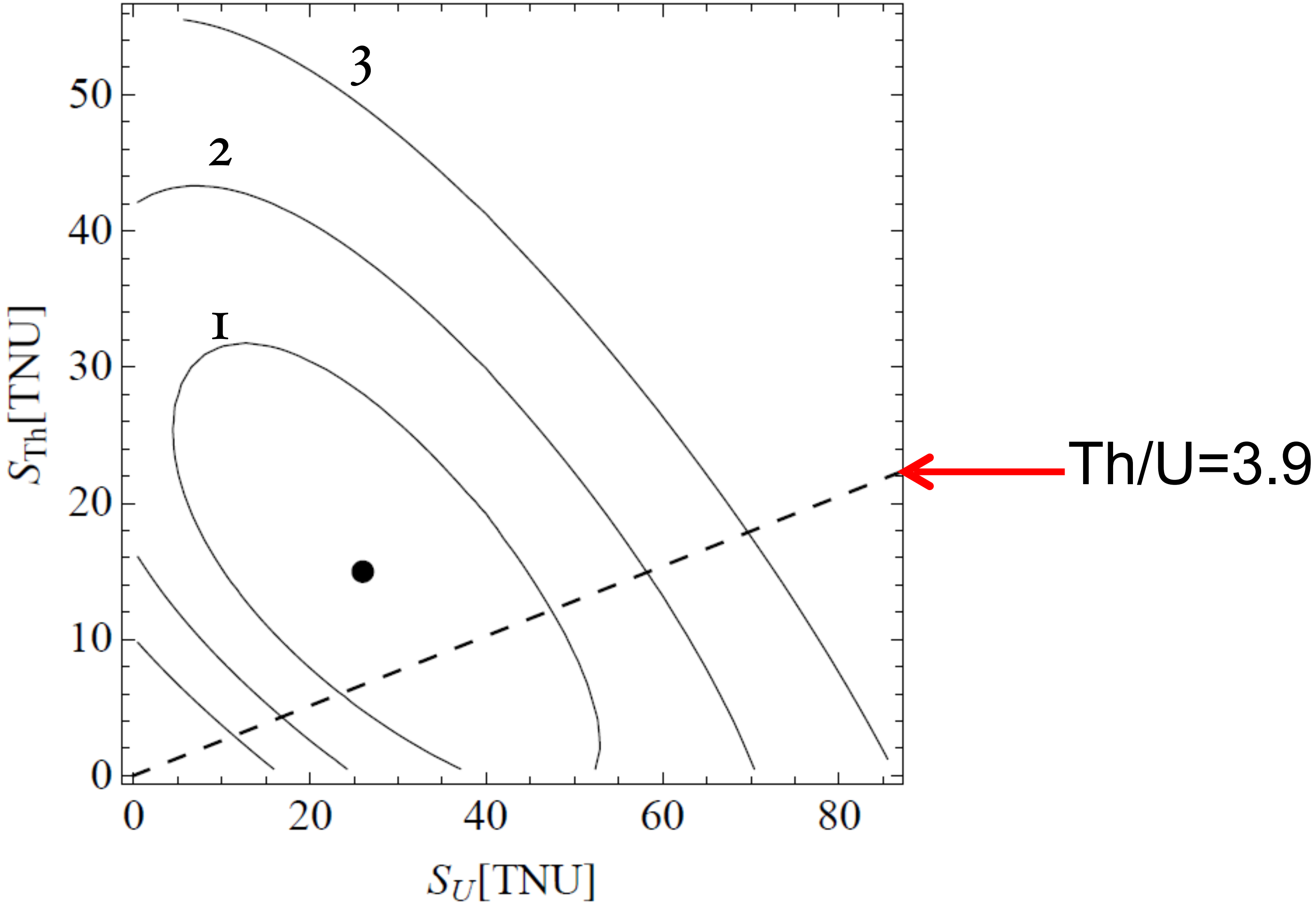
S_{geo}:S_{react} for fixed M(Th)/M(U)=3.9



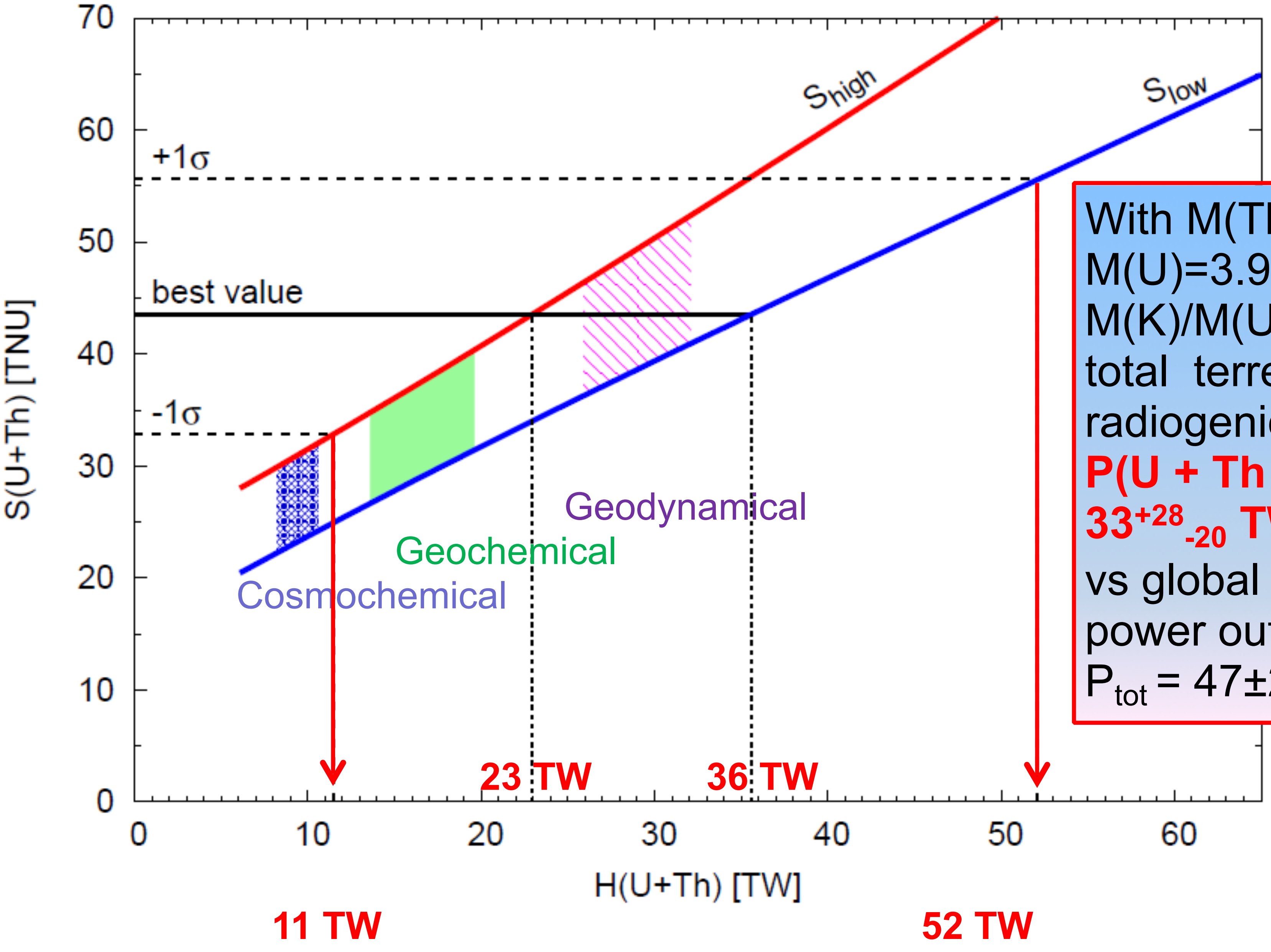
$3.6 \cdot 10^{-9}$ probability of $N_{geo}=0$ (5.9 σ)

For Th/U=3.9 :
$\Phi(U)=(2.7^{+0.8}_{-0.7})\mathrm{x}10^{6}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
$\Phi(Th)=(2.3^{+0.7}_{-0.6})\mathrm{x}10^{6}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

Unconstrained M(U)/M(Th) fit



Radiogenic heat

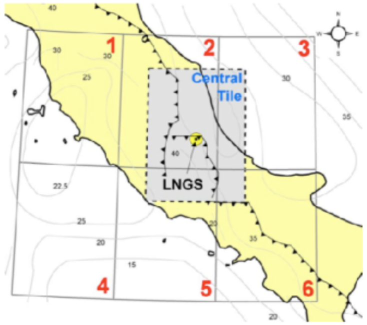


With M(Th)/M(U)=3.9 & M(K)/M(U) = 10^4 the total terrestrial radiogenic power :

P(U + Th + K) = 33^{+28}_{-20} TW,

vs global terrestrial power output P_{tot} = 47±2 TW

Signal from the mantle



- *Total contribution from the Earth crust (Coltorni et al.,* Huang et al.) *(LOC + ROC) is* S_{geo}*(Crust) = (23.4 ± 2.8) TNU -> 12.75 ±1.53 events (+stat.smearing)*

- **subtraction of probability distributions for the total signal (from the fit) and pdf for crust (normal approximation). Non-physical values of difference are excluded and final p.d.f. renormalized to unity.**

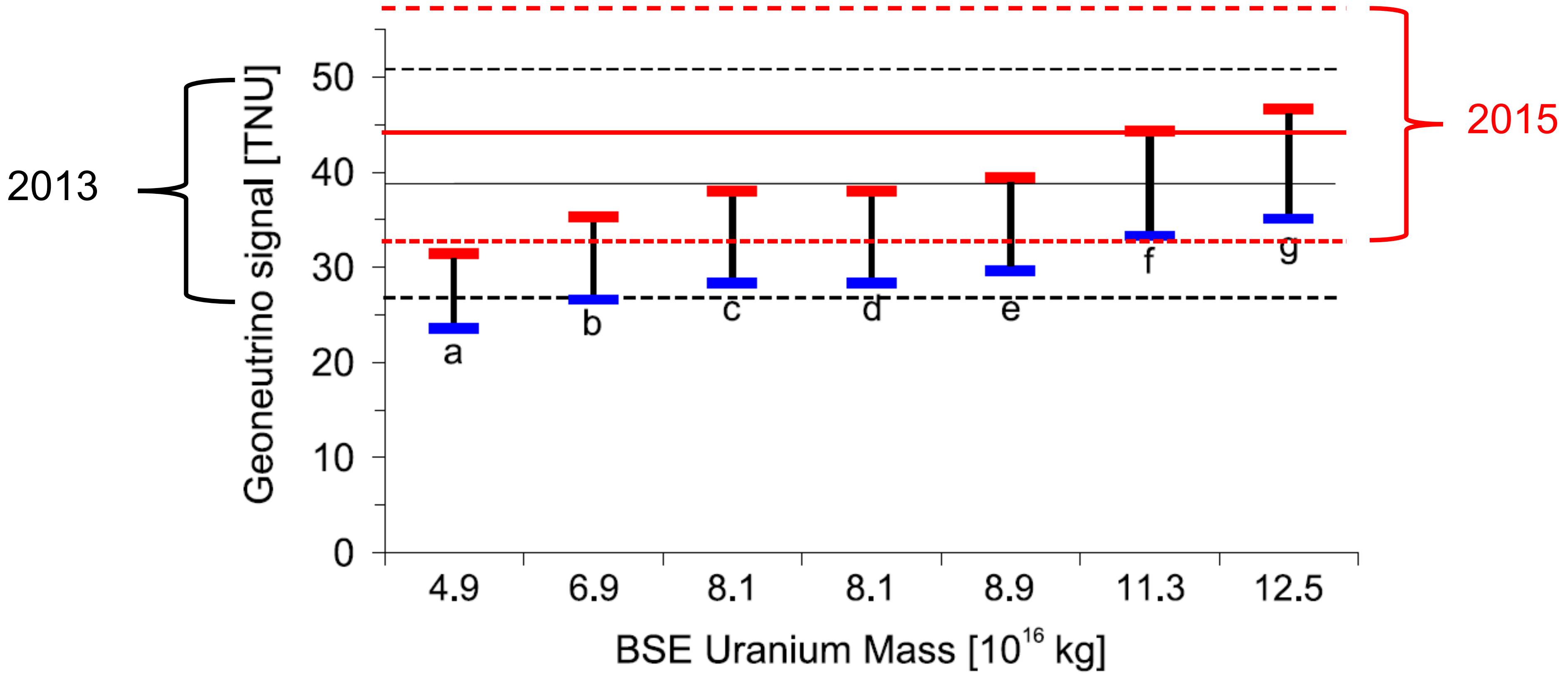
p.d.f.(Mantle) = p.d.f. (Geo Signal) - p.d.f.(Crust) :

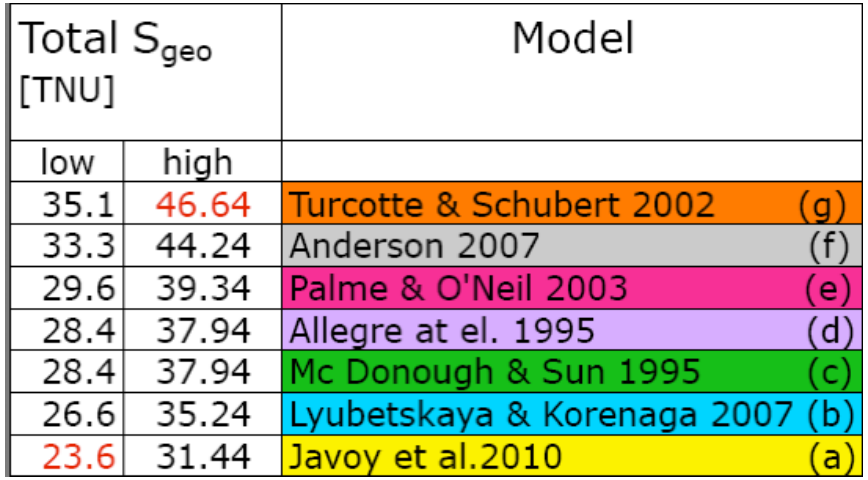
$$S_{geo}(Mantle) = 20.9^{+15.1}_{-10.3}\ \text{TNU}$$

with a probability of 98% we observe at least 1 event from the mantle

- Note:
  - Mean value is bigger compared to a simple difference $<S_{geo}> - <S(Crust)> = 43.5 - 23.4 = 20.1$ as a result of excluding non-physical values from p.d.f.
- LOC: M. Coltorti et al., Earth Planet. Sci. Lett. 293 (2010) 259.
- ROC: Y. Huang et al. Geochemistry, Geophysics, Geosystems 14, 2003 (2013).

Comparison with BSE models





Total S_{geo} [TNU]		Model
low	high	
35.1	46.64	Turcotte & Schubert 2002 (g)
33.3	44.24	Anderson 2007 (f)
29.6	39.34	Palme & O'Neil 2003 (e)
28.4	37.94	Allegre at el. 1995 (d)
28.4	37.94	Mc Donough & Sun 1995 (c)
26.6	35.24	Lyubetskaya & Korenaga 2007 (b)
23.6	31.44	Javoy et al.2010 (a)

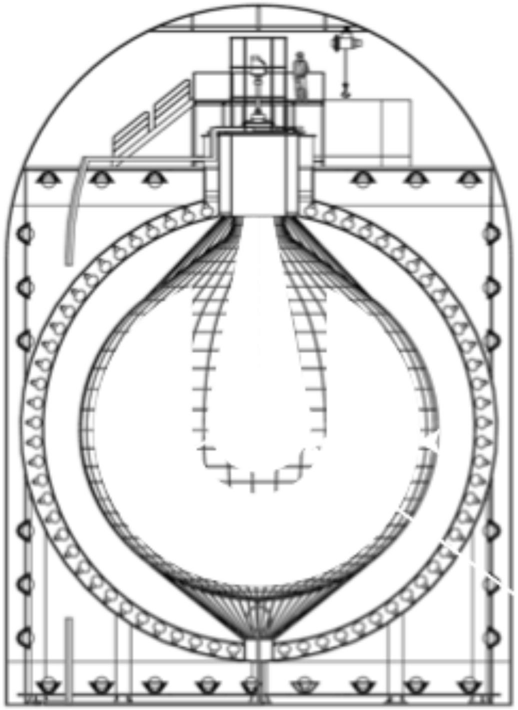
x-axis : total U mass in corresponding BSE model

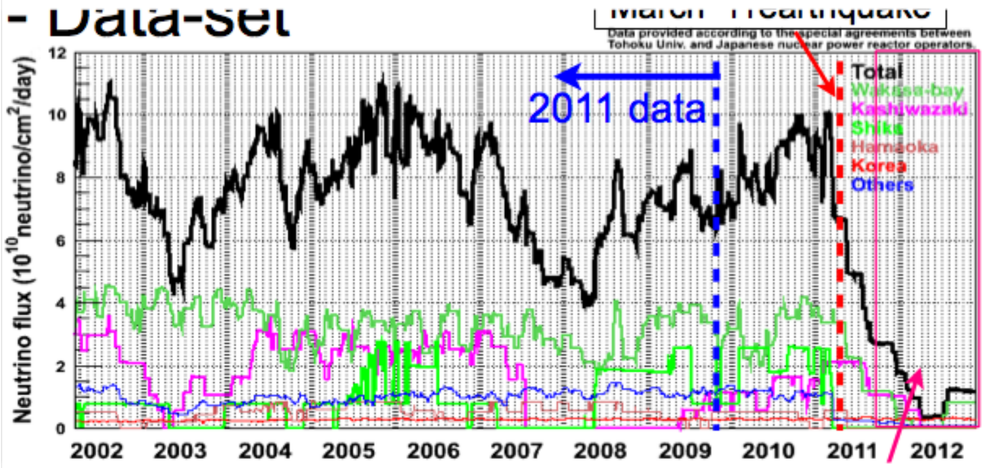
Red upper - “maximal” models : max. possible amount of radiogenic material, uniformly distributed in the mantle (+1σ).

Blue lower -“minimal” models : min.possible amount of radiogenic material in thin layer at the bottom of the mantle (-1σ).

KamLAND 2013 results

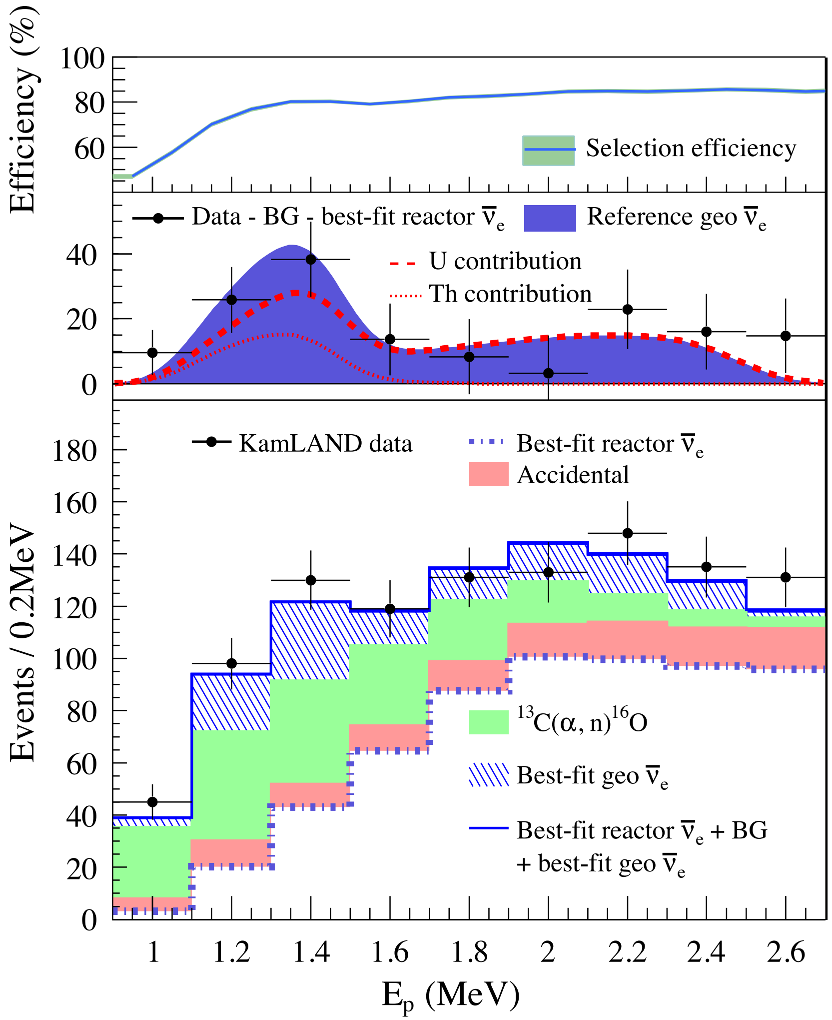
PRD 88 (2013) 033001

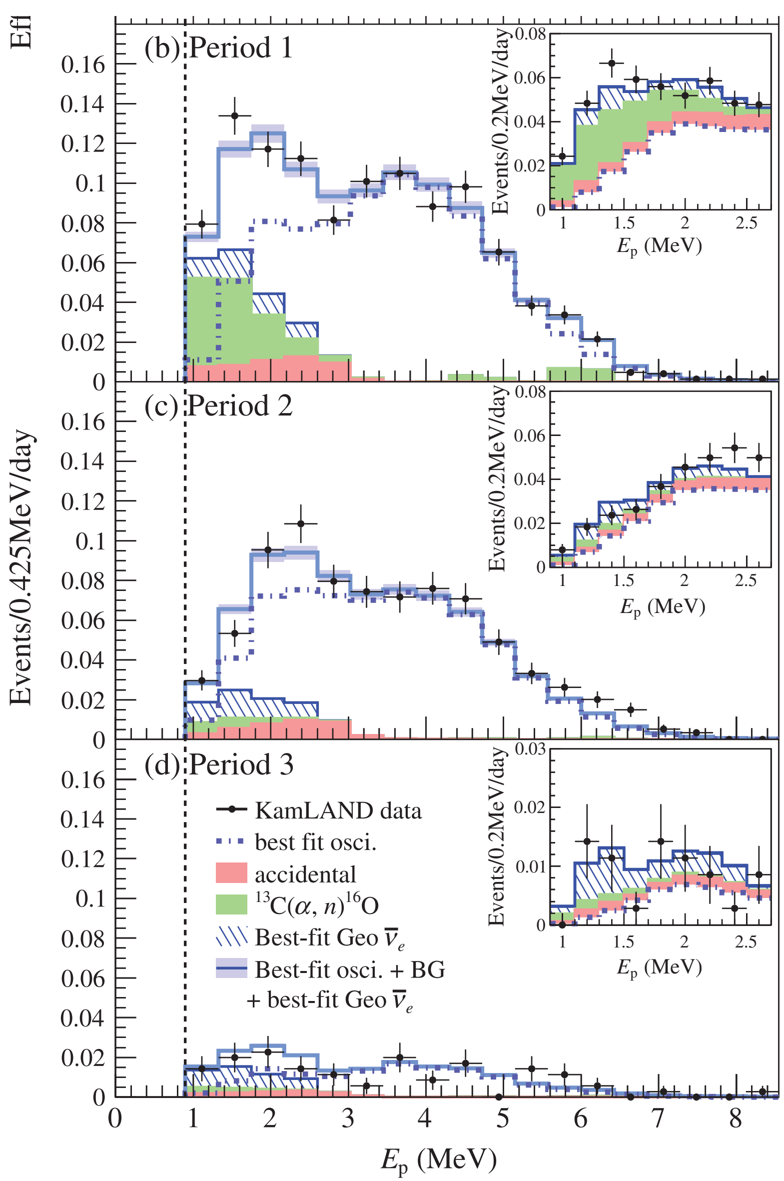




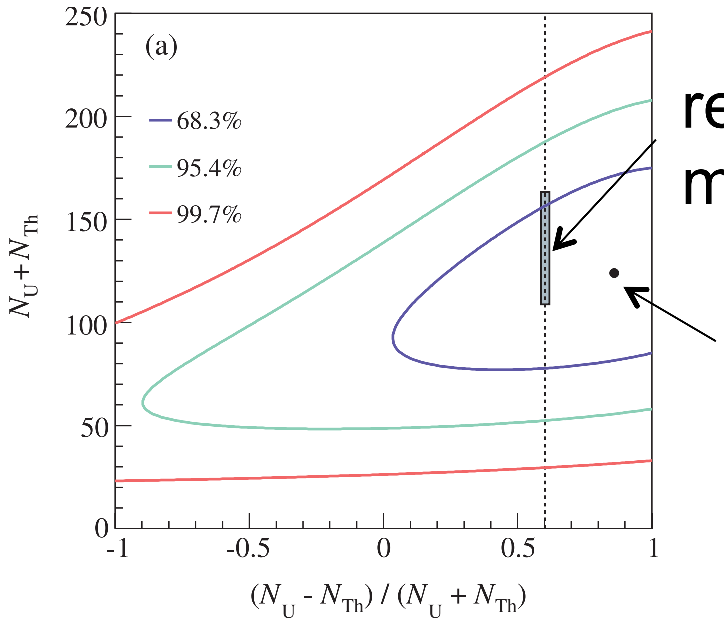
KamLAND (2013) geoneutrino results

▸Analysis : Energy Spectrum (0.9-2.6 MeV)



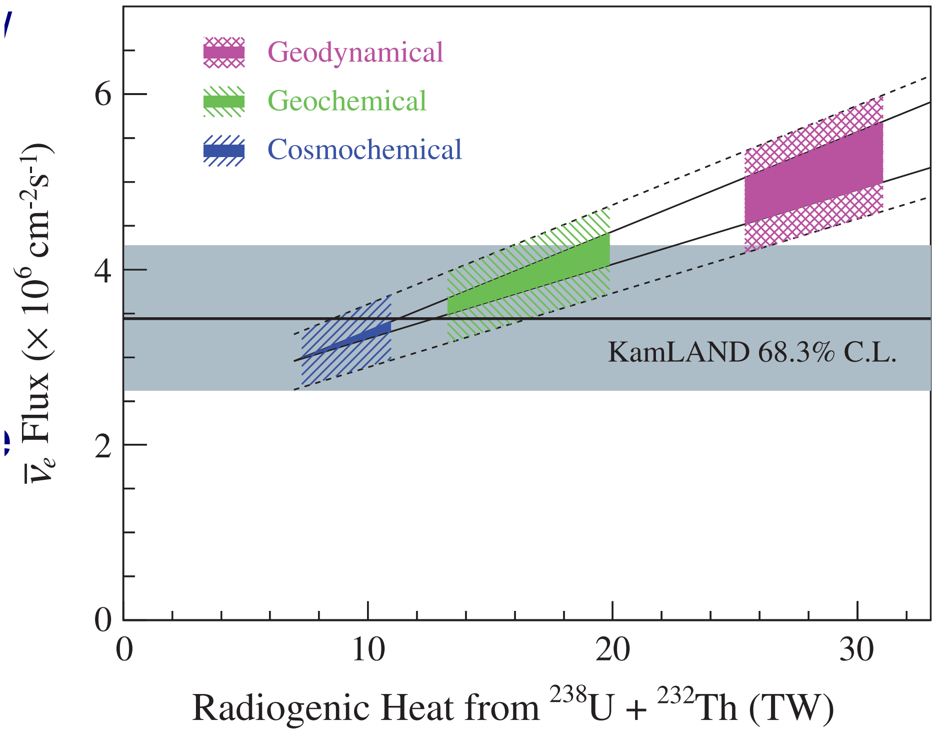


From KamLAND talk of H. Watanabe @ Neutrino Geoscience 2013



reference model

best fit



- Fully radiogenic model (homogeneous mantle) is excluded with 98 % C.L. (total heat flow 46±3 TW (Jaupart et al. 2007) assumed)

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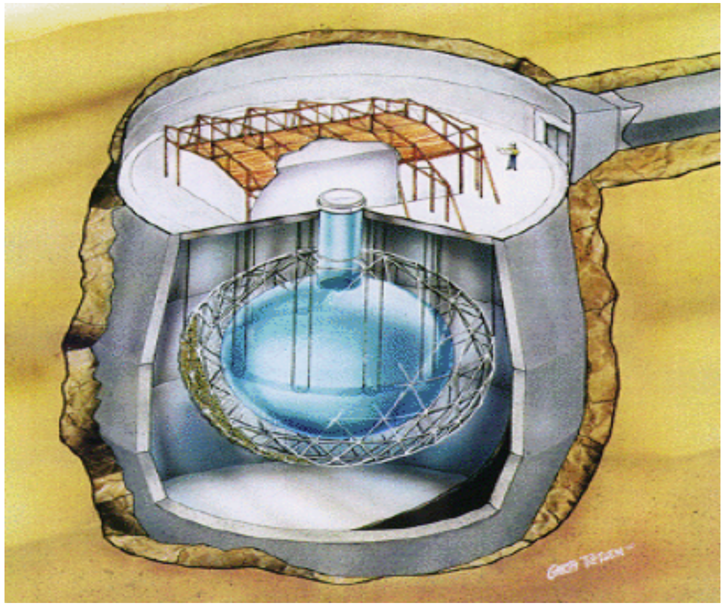
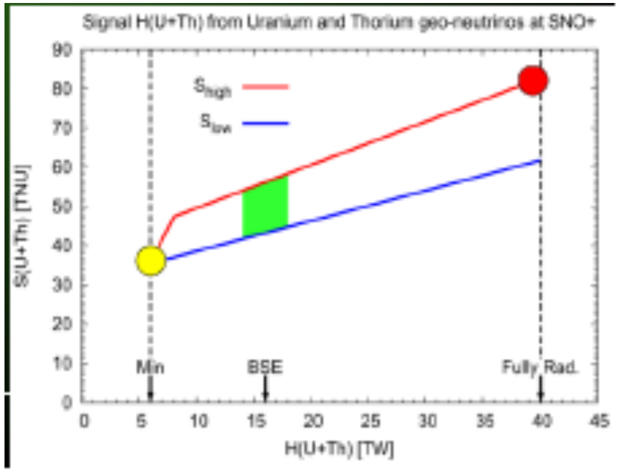
Future projects

SNO+ at Sudbury, Canada





SHOULD BE COMING SOON!

After SNO: D_2O replaced by 1000 tons of liquid scintillator

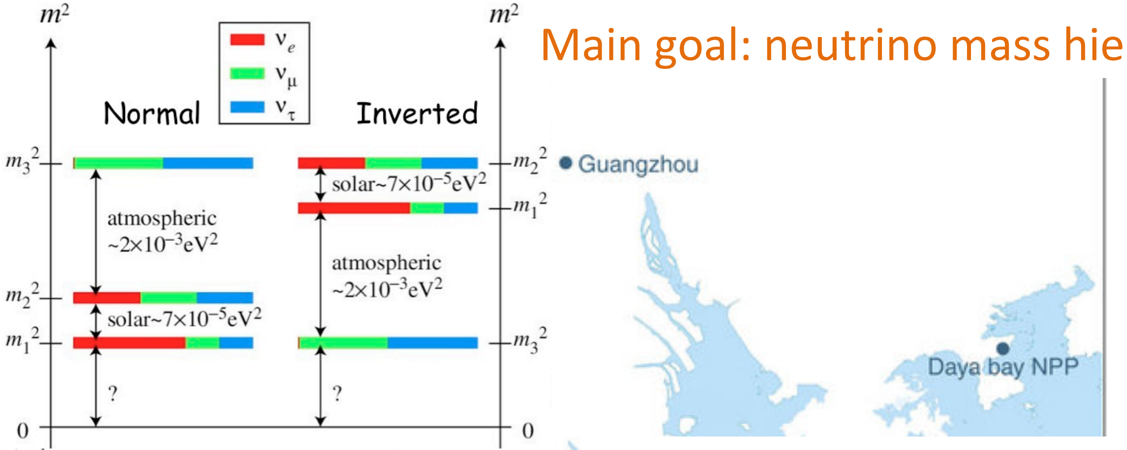
M. J. Chen, *Earth Moon Planets* **99**, 221 (2006)

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

BSE: 28-38 events/per year

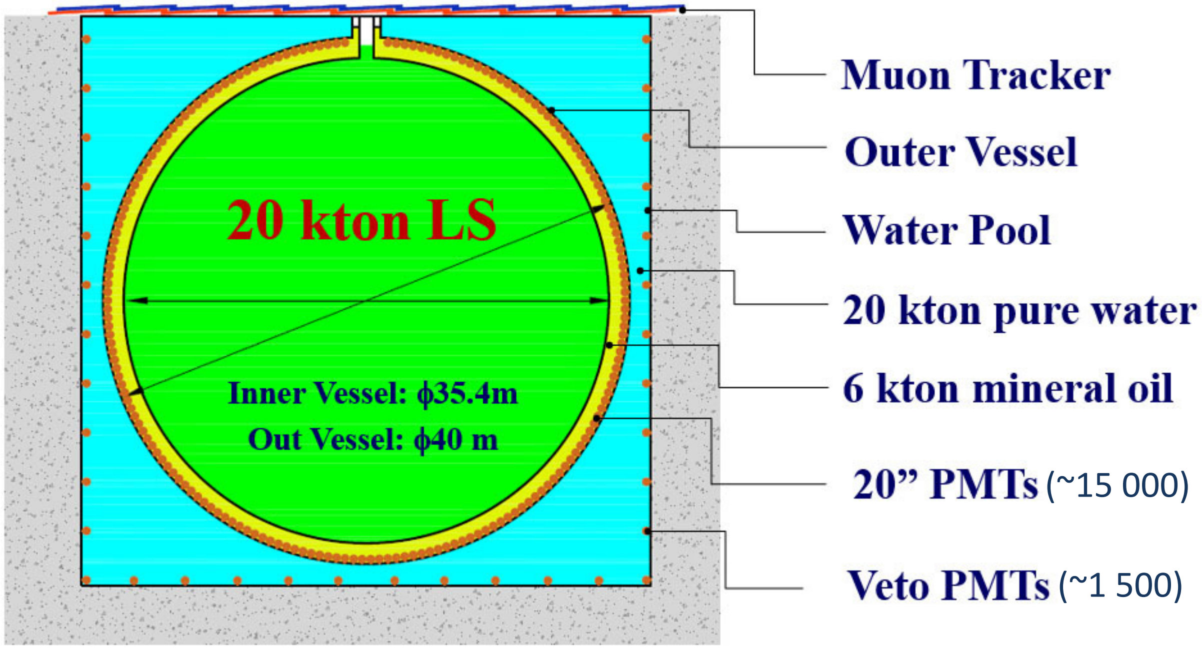
JUNO at Jiangmen, China

Main goal: neutrino mass hierarchy



Challenges:

- Large mass (20 kton)
- Excellent energy resolution of 3% @ 1 MeV
- Great control of energy scale linearity
- High light yield 1200 pe/MeV

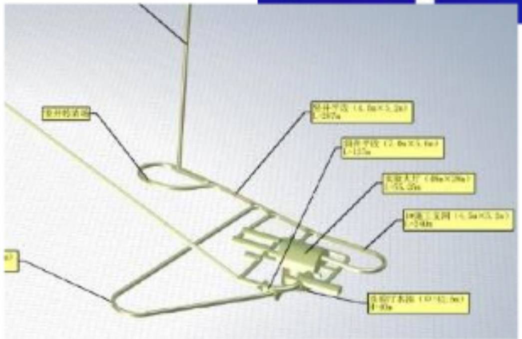


江门中微子实验建设启动会

Jiangmen Underground Neutrino Observatory
Construction Start-up Meeting

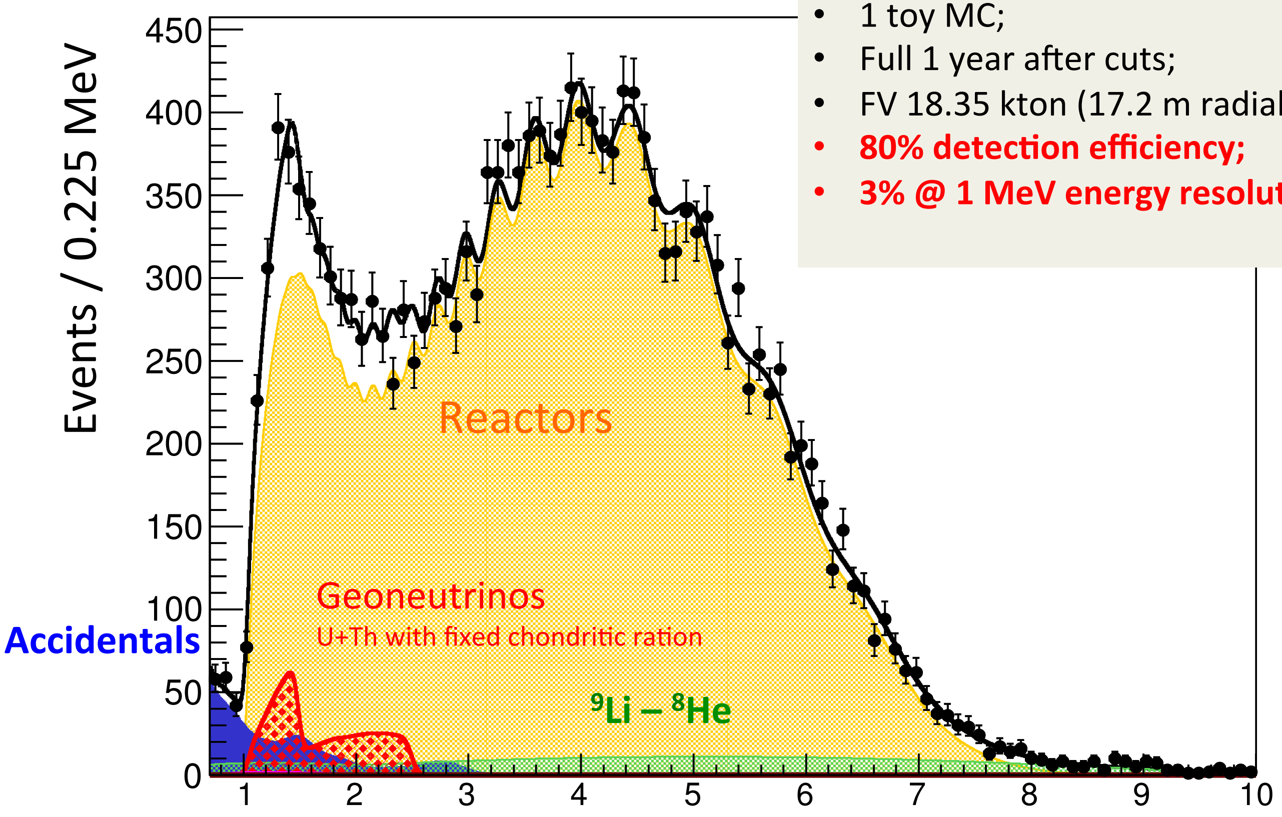
广东省.开平市.金鸡镇
2015.1.10.

Jan. 10, 2015



600 m vertical shaft
1300-m long tunnel(40% slope)
50-m diameter, 80-m high cavern

JUNO sensitivity to geoneutrinos with toy MC



- 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**

- Scintillator:
  i) 10^{-15} g/g for U and Th
  (~3 orders of magnitude worse than Borexino)
  ii) ^{40}K 10^{-16} g/g
  iii) ^{210}Pb 10^{-22} g/g
- Acrylic vessel:
  ^{238}U 10 ppt, ^{232}Th: 10 ppt
- Baloon:
  ^{238}U 2 ppt, ^{232}Th: 4 ppt

Source	Events/year
Geoneutrinos	408 ± 60
U chain	311 ± 55
Th chain	92 ± 37
Reactors	16100 ± 900
Fast neutrons	36.5 ± 36.5
^{9}Li - ^{8}He	657 ± 130
$^{13}C(\alpha,n)^{16}O$	18.2 ± 9.1
Accidental coincidences	401 ± 4

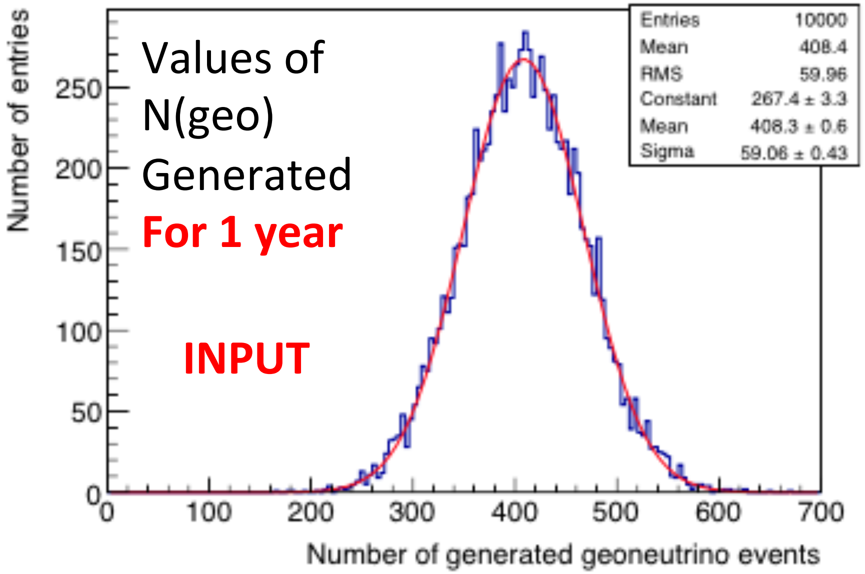
Background type	Rate after IBD+ muon cuts [events/day]	Uncertainty in Rate [%]	Uncertainty in Shape [%]
^{9}Li – ^{8}He (β + neutron decays)	1.8	20	10
Fast neutrons	0.1	100	20
Accidental events	1.1	1	negl.
$^{13}C(\alpha,n)^{16}O$ (acrylic vessel)	0.05	50	50
$^{13}C(\alpha,n)^{16}O$ (balloon)	0.01	50	50

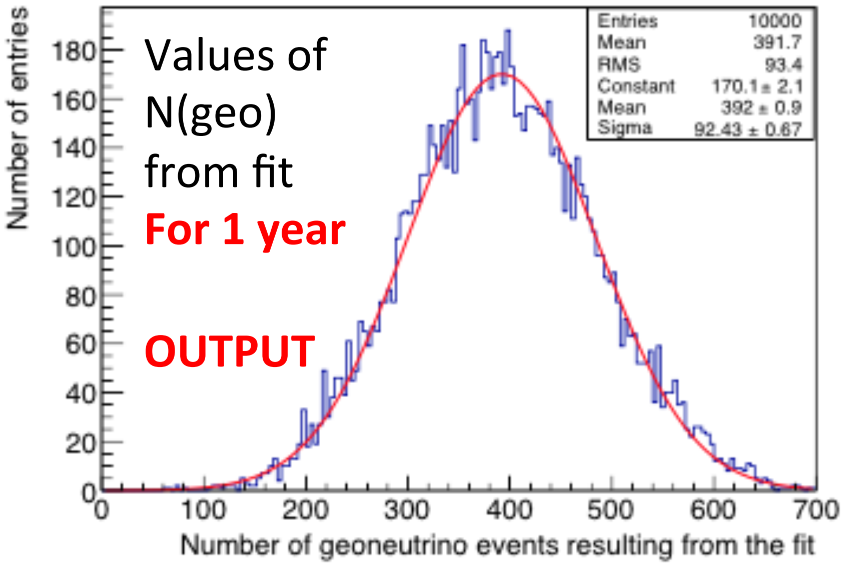
Cosmogenic production, veto along muon tracks etc.. Reduced Li-He bgr from 80 to 1.8 events/day,
BUT 17% dead time

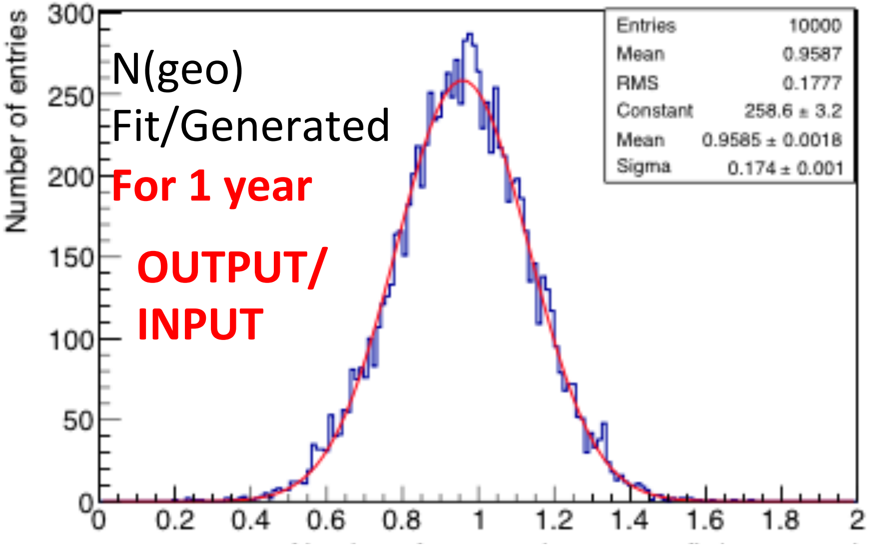
Toy MC was repeated 10 000 times for 1, 3, 5, and 10 years statistics

- Maximal likelihood fit;
- Geo and reactor signal free;
- Other backgrounds

constrained within 1σ range;







Final results on the precision of JUNO geoneutrino measurement

Number of years	U + Th (fixed chondritic Th/U ratio)
1	0.96 ± 0.17
3	0.96 ± 0.10
5	0.96 ± 0.08
10	0.96 ± 0.06

Better than the current data:
Borexino ~30%
KamLAND: ~25%

Mean and RMS of the Gaussian N(geo) fit/generated

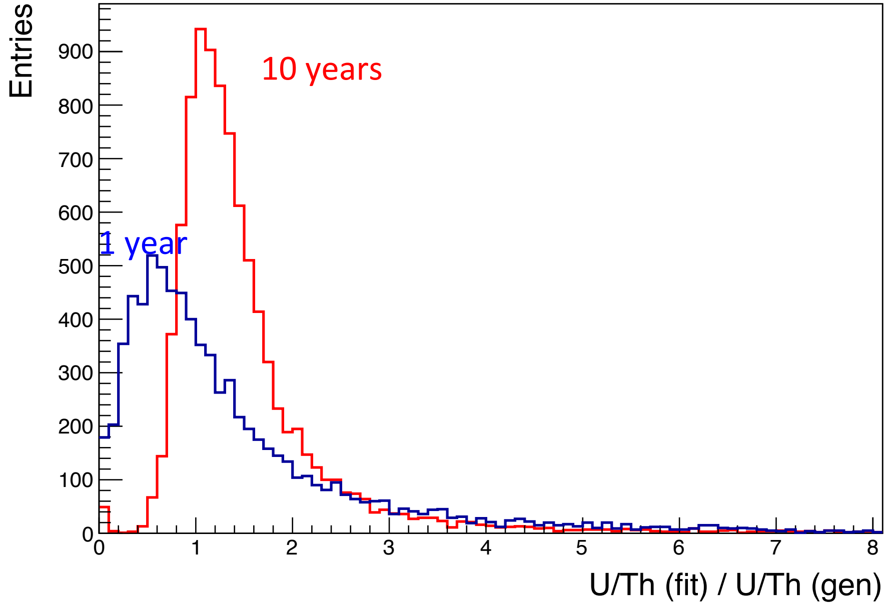
The systematic shift of -4%
is mostly due to the correlations
with reactor antineutrino background
And does not disappear with increased statistics

Precision of the reconstruction of the U and Th signals

Number of years	U (free)	Th (free)
1	1.02 ± 0.32	0.83 ± 0.60
3	1.03 ± 0.20	0.80 ± 0.38
5	1.03 ± 0.16	0.80 ± 0.28
10	1.03 ± 0.11	0.80 ± 0.19

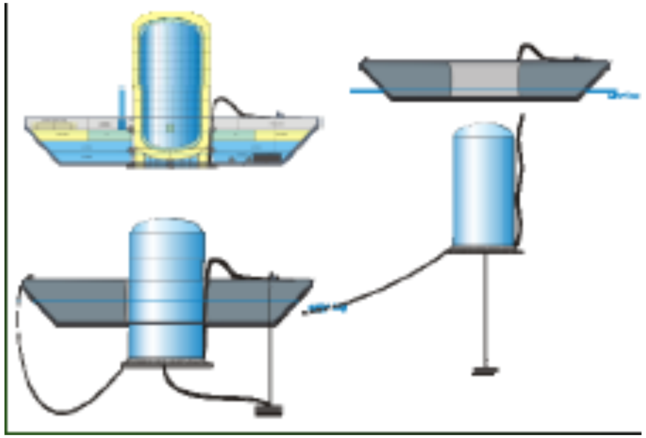
- 1 year poor precision but the RMS improves with statistics;
- Systematic 1-3% overestimation of the U signal;
- Systematic 20% underestimation of the Th signal;
- Systematics is due to the correlations;

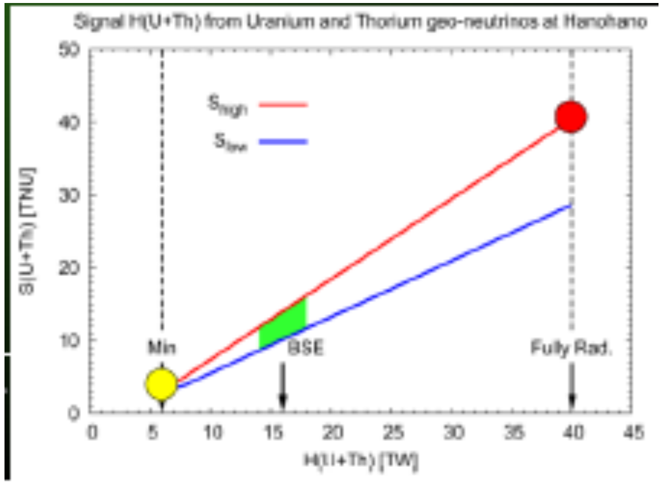
Reconstruction of U/Th ratio



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 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:
- Borexino and KamLAND continue to take data;
- SNO+ in Canada (1 kton) should provide data in not that far future;
- JUNO in China (20 kton): big reactor and cosmogenic background, but large statistics compensates: interesting results to come after 2020;
- The BEST would be HanoHano in Hawaii, underwater, on the eceanic crust, ~80% of signal from the mantle! (no money ☹)

THANK YOU!