Geoneutrinos and Borexino

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for the Borexino collaboration

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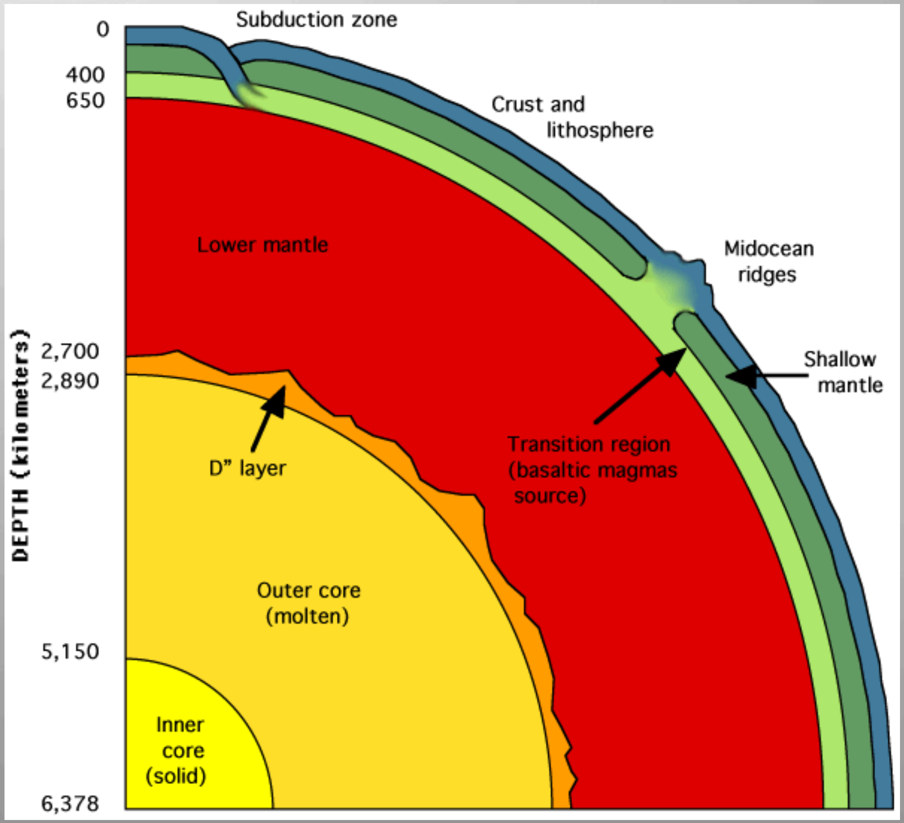
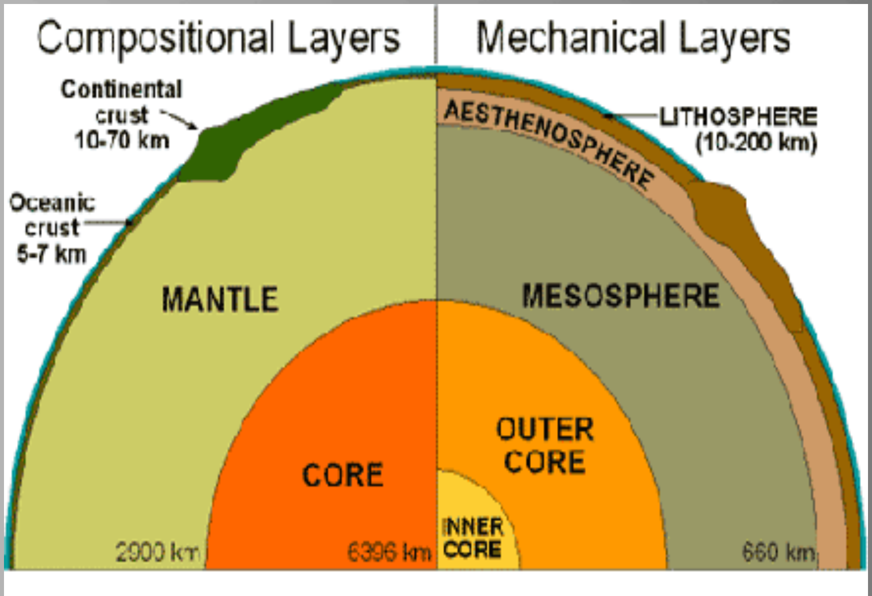
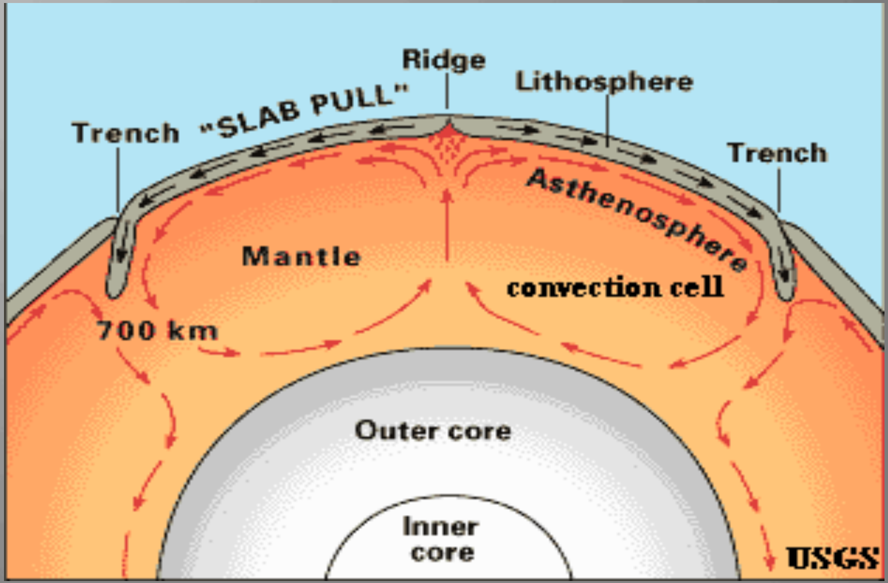
Outline

- The Earth
- Geoneutrinos
- Borexino geoneutrino results
- Future prospects

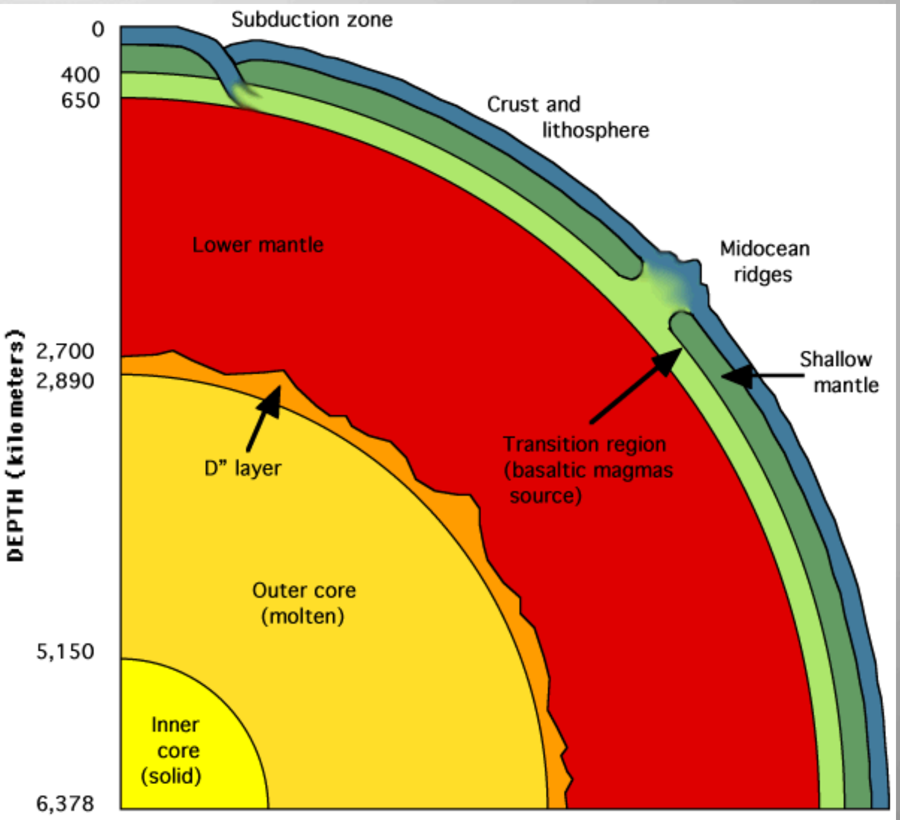
Earth structure







Earth structure



Inner Core - SOLID

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

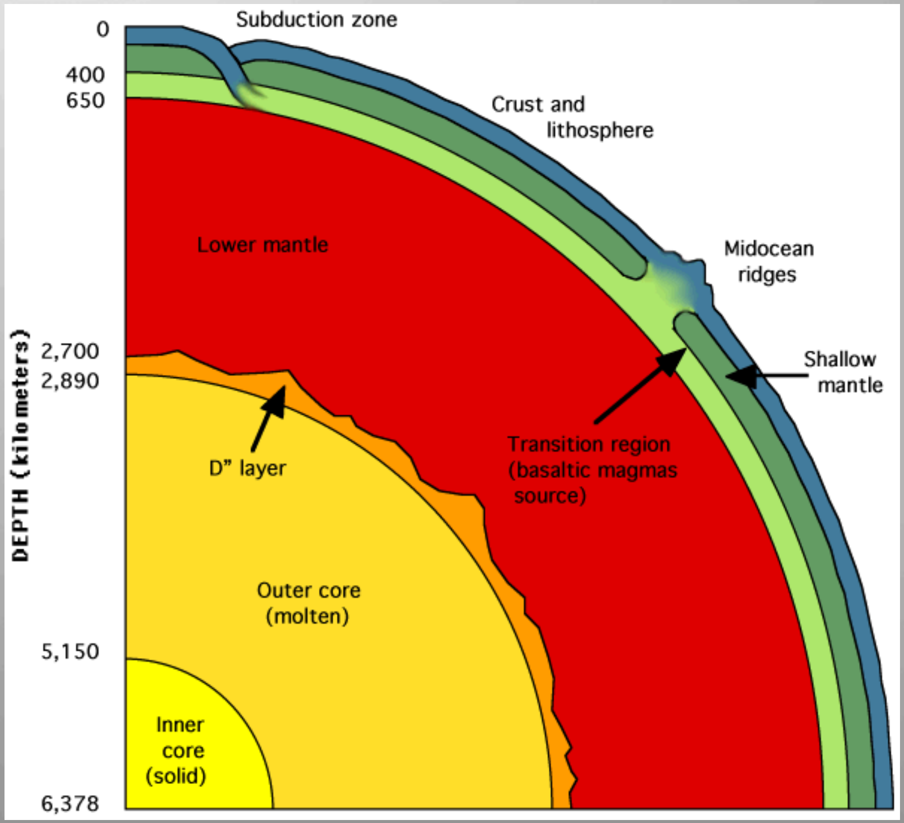
Outer Core - LIQUID

- 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

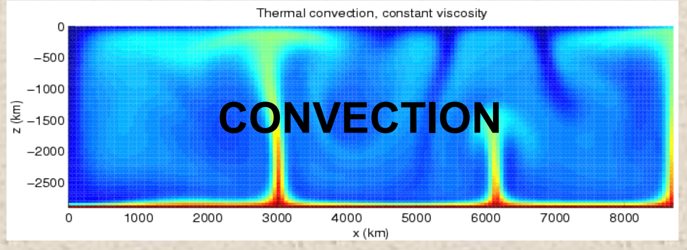
- ~200 km thick;
- seismic discontinuity;
- unclear origin;

Earth structure



Lower mantle (mesosphere)

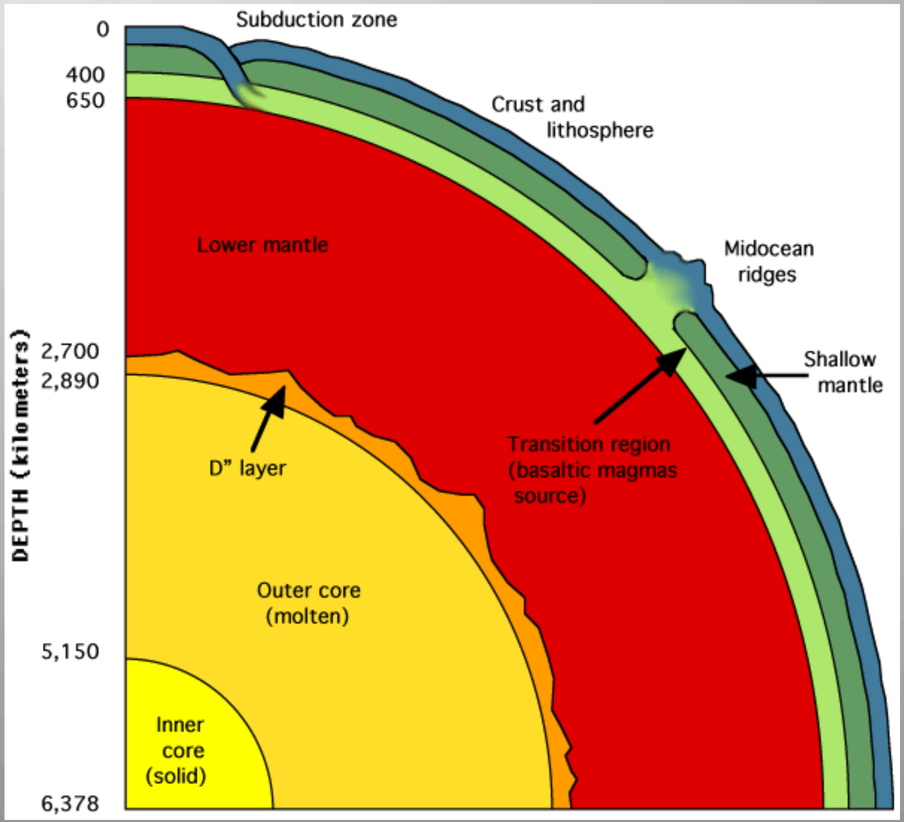
- rocks: high Mg/Fe, < Si + Al;
- T: 600 – 3700 K;
- high pressure: solid, but viscose;
- "plastic" on long time scales:



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



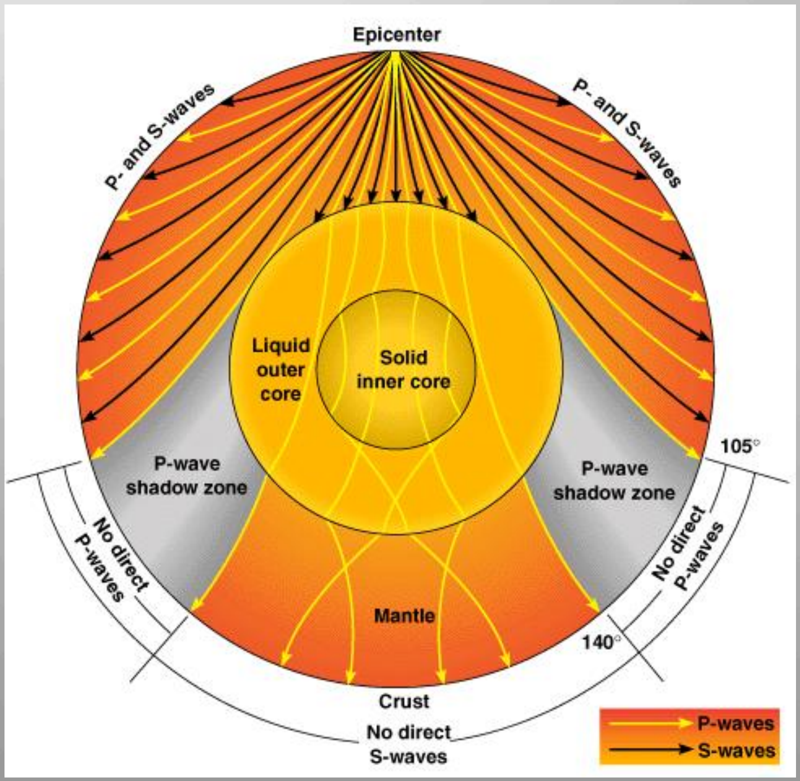
Upper mantle

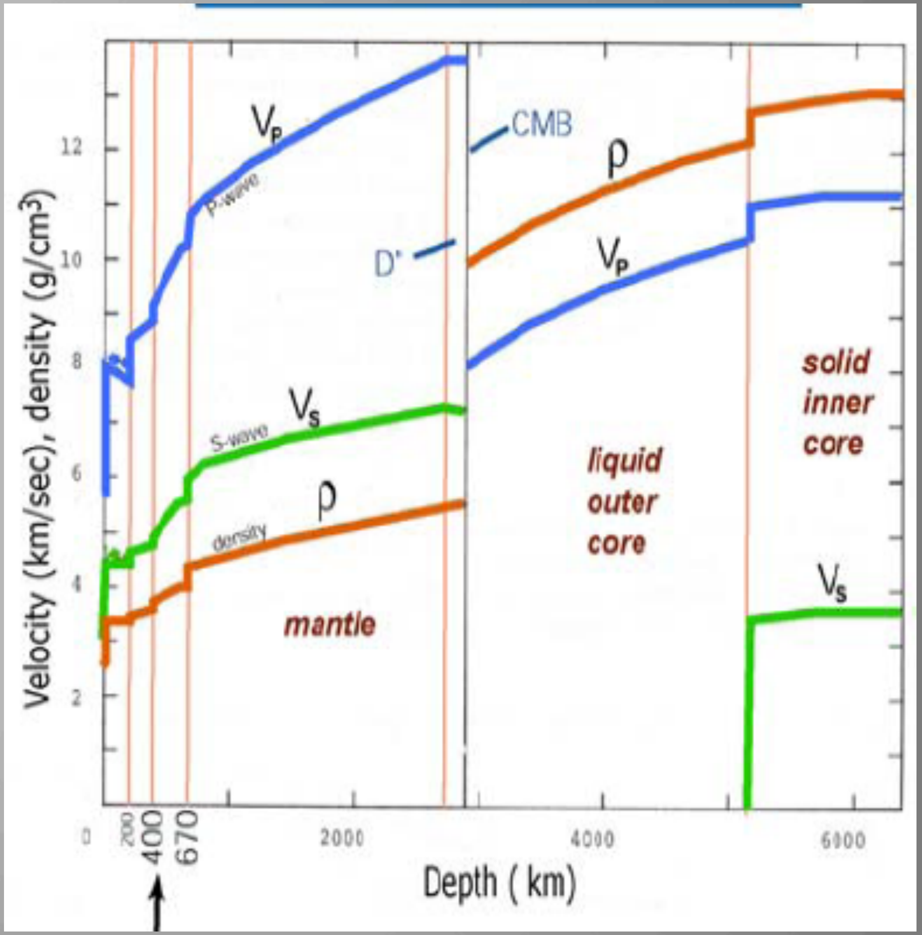
- composition: rock type peridotite
- includes highly viscose **astenosphere** on which are floating litospheric tectonic plates (**lithosphere** = more rigid upper mantle + crust);

Crust: the uppermost part

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

Seismology



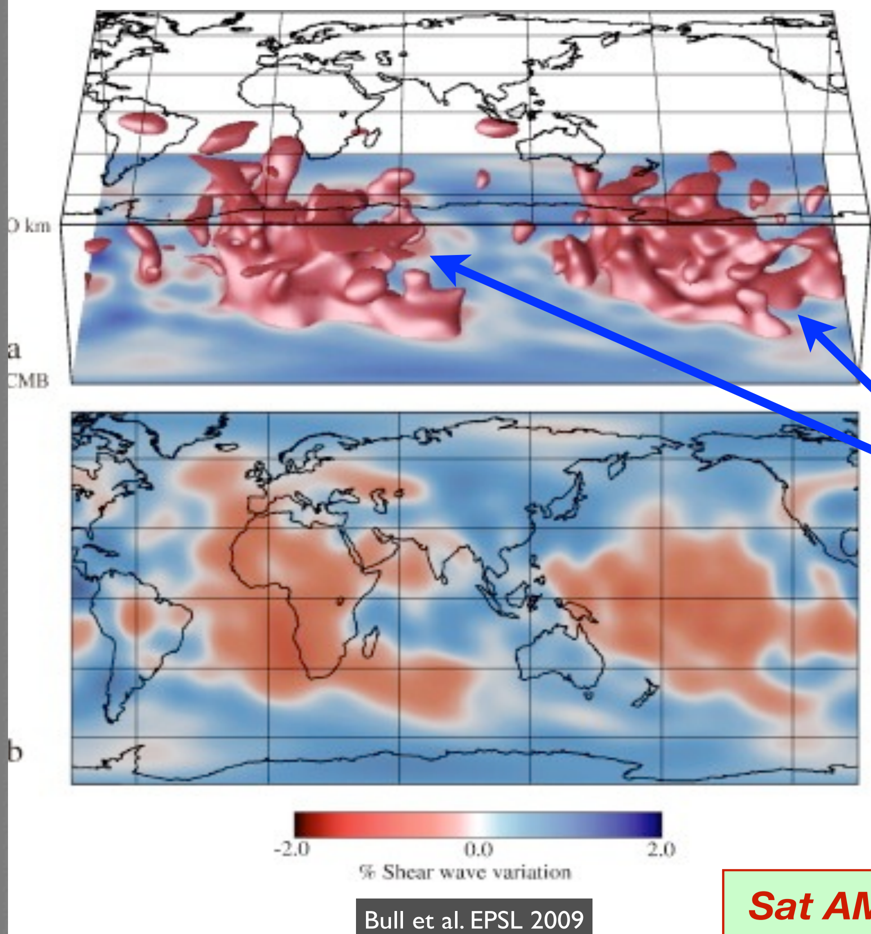


P – primary, longitudinal waves
S – secondary, transverse/shear waves

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

Seismic tomography image of present-day mantle

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



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**

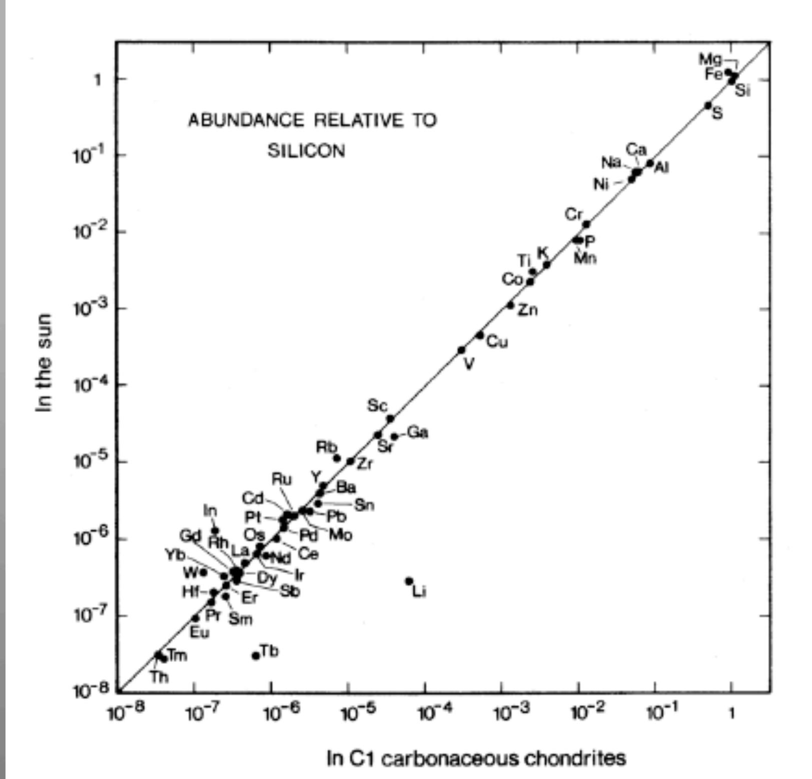
* surface and bore-holes (max. 12 km);

- Lower crust and upper 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;



From Sramek @ Neutrino Geoscience 2013

U Th K

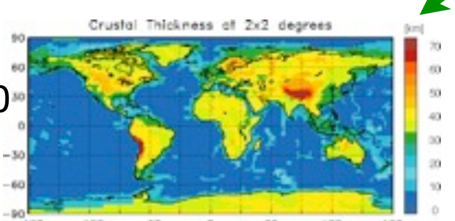
Composition of Silicate Earth (BSE)

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

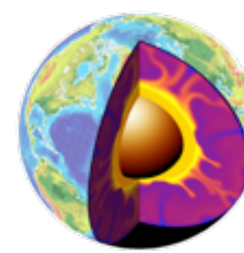
CRUST2.0 thickness



Oceanic: 0.22 ± 0.03 TW

Continental: 7.8 ± 0.9 TW

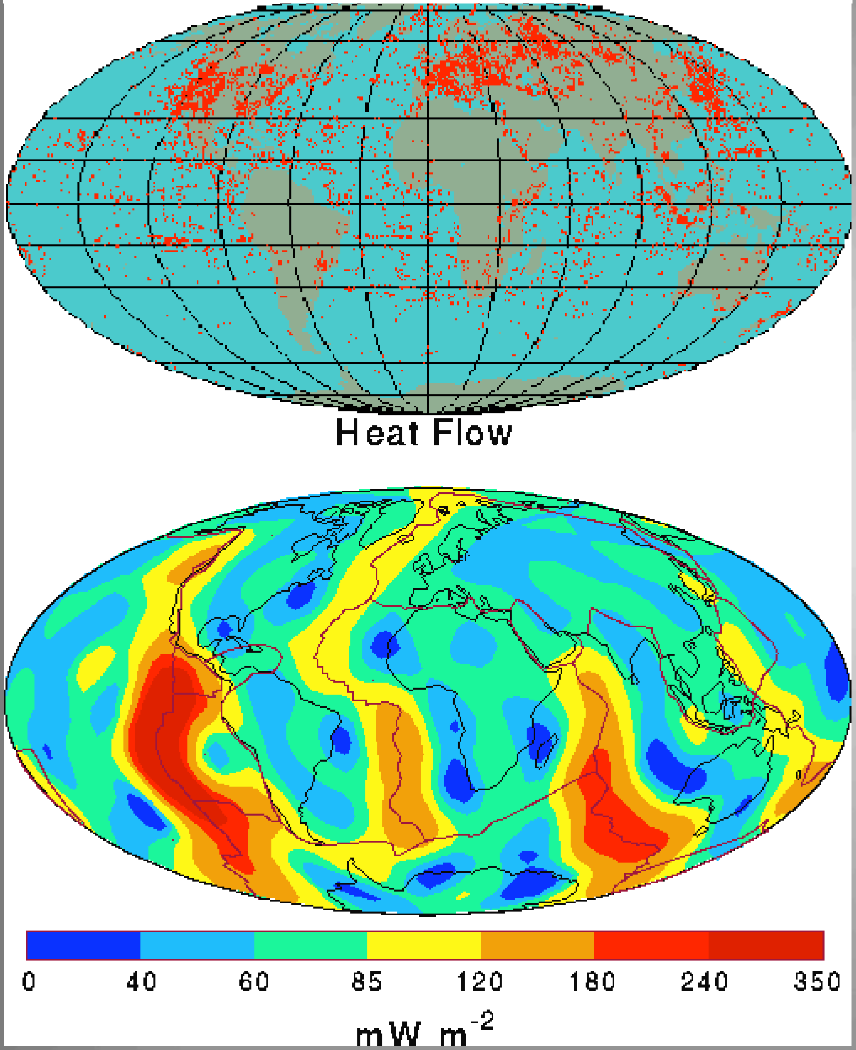
?



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

Surface heat flux

Bore-hole measurements



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

- Conductive heat flow from bore-hole temperature gradient;

- **Total surface heat flux:**
  31 $\pm$ 1 TW (Hofmeister&Criss 2005)
  46 $\pm$ 3 TW (Jaupart et all 2007)
  47 $\pm$ 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's heat

- **Total heat flow ("measured"): 31$\pm$1 or 46$\pm$3 or 47$\pm$2 TW**
- ***Radiogenic heat = from decays of radioactive elements***

  BIG SPREAD: 11 – 33 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, HISTORY, AND COMPOSITION

Geo-neutrinos: antineutrinos from the Earth

- ***Electron antineutrinos from the decays of long lived radioactive isotopes naturally present in the Earth;***
- ^{238}U and ^{232}Th chains and ^{40}K ($T_{1/2}$ = (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})

the only direct probe of the deep Earth

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

measure geoneutrino flux = (in principle) = get radiogenic heat

in practice (as always) more complicated…..

Where are concentrated U,Th, and K?

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

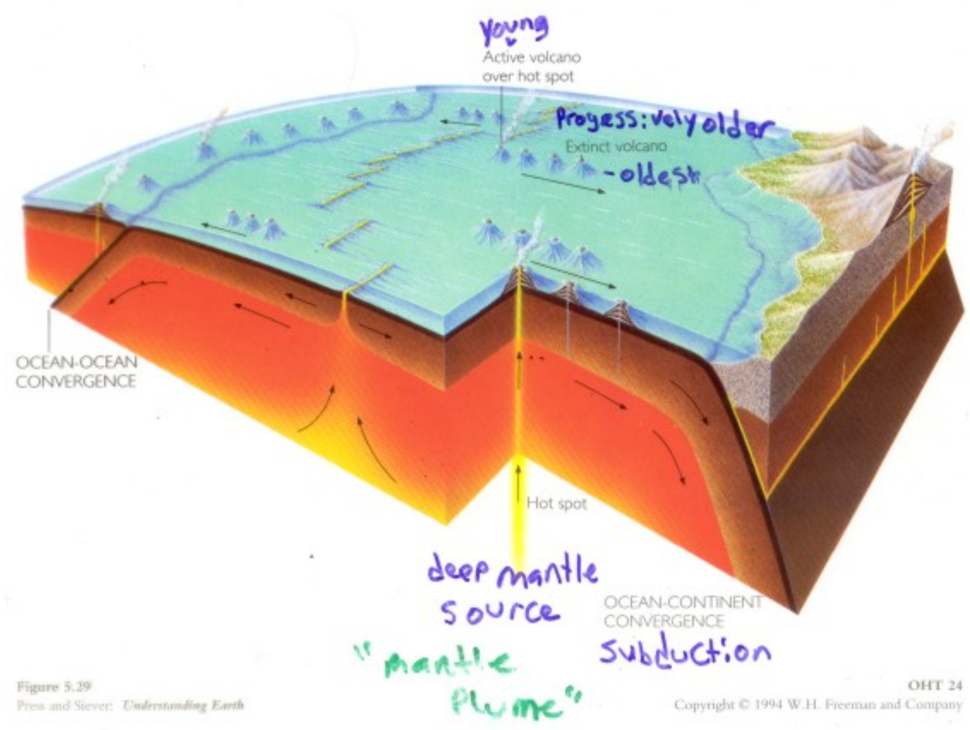
U, Th, K are refractory lithophile elements (RLE)

– **Volatile /Refractory:** *Low/High condensation temperature*

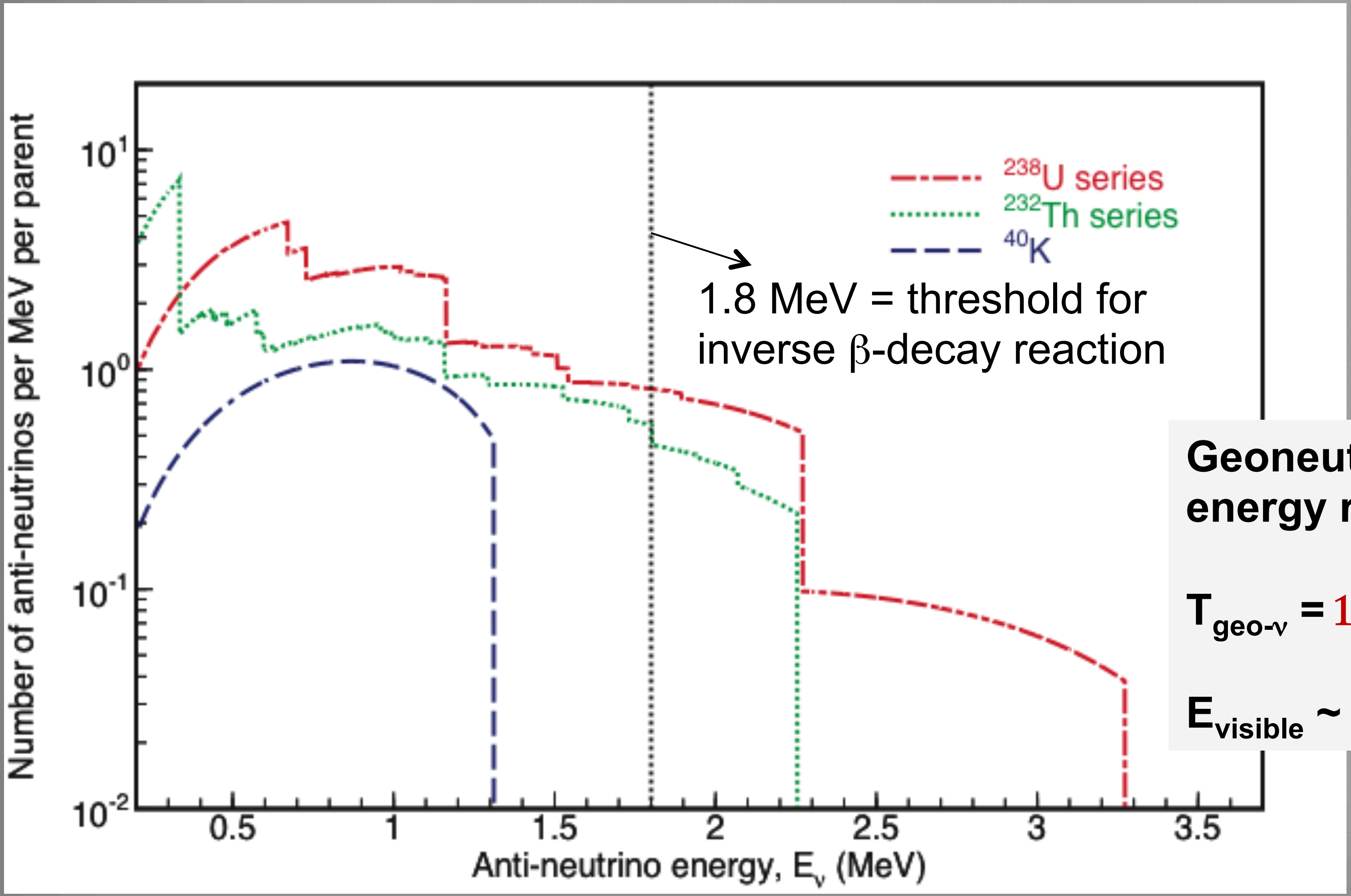
– **Lithophile** – *like to be with silicates: during partial melting they tend to stay in the liquid part. The residuum is depleted. Accumulated in the continental crust. Less in the oceanic crust. Mantle even smaller concentrations. Nothing in core.*

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	



Geoneutrino energy spectra: theoretical calculations



Geoneutrinos energy range

$T_{geo-\nu}$ = 1.8 − 3.3 MeV

$E_{visible}$ ~ 1 – 2.5 MeV

Geo-neutrinos: why to study them?

- **Possible answers to the questions**
  - What is the radiogenic contribution to the terrestrial heat??
  - Are there any other heat sources or not?
  - What is the distribution of the long-lived radioactive elements within the Earth?
    - how much of them is in the crust and in the mantle;
    - Is their distribution in the mantle homogeneous or not;
    - are they present in the core;
    - is there a geo-reactor (Herndon 2001);
  - Are the BSE models compatible with geoneutrino data?
  - Discrimination among different BSE models;
  - What is the bulk Th/U ratio;

All these info would give significant margins to many geochemical and geophysical models and insights into the models of the Earth's formation.

Neutrino oscillations

The probability to detect electron antineutrino (geo-neutrino or antineutrinos from nuclear power plants, an important background source for geoneutrino measurement) oscillates :

$$P_{ee} = P\left(\overline{\nu}_e \longrightarrow \overline{\nu}_e\right) = \sin^4\theta_{13} + \cos^4\theta_{13}\left(1 - \sin^2 2\theta_{12}\sin^2\left(\frac{1.267\Delta m^2_{21}\boxed{L}}{4\boxed{E}}\right)\right)$$

- Assuming $\Delta m^2_{31} \sim \Delta m^2_{32} \gg \Delta m^2_{21}$
- θ_{12}, θ_{13}, Δm_{12}^2 … neutrino oscillation parameters

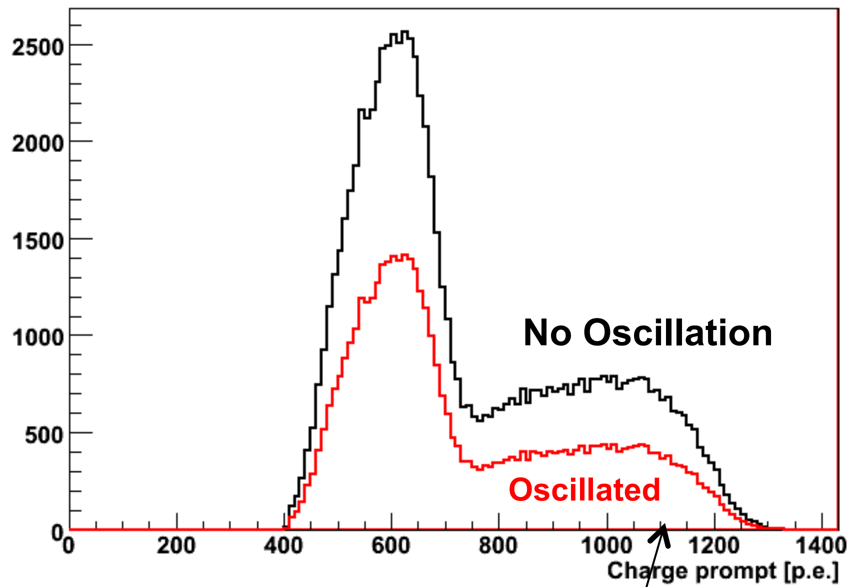
L… source – detector distance;

E ….antineutrino energy in MeV;

- Oscillation length L_0: $L_o \sim \pi c\hbar \dfrac{4E}{\Delta m^2_{21}}$.

3 MeV antineutrino ..
Oscillation length of ~100 km
Earth radius ~6370 km

Geoneutrinos



for geoneutrinos we can use average survival probability:

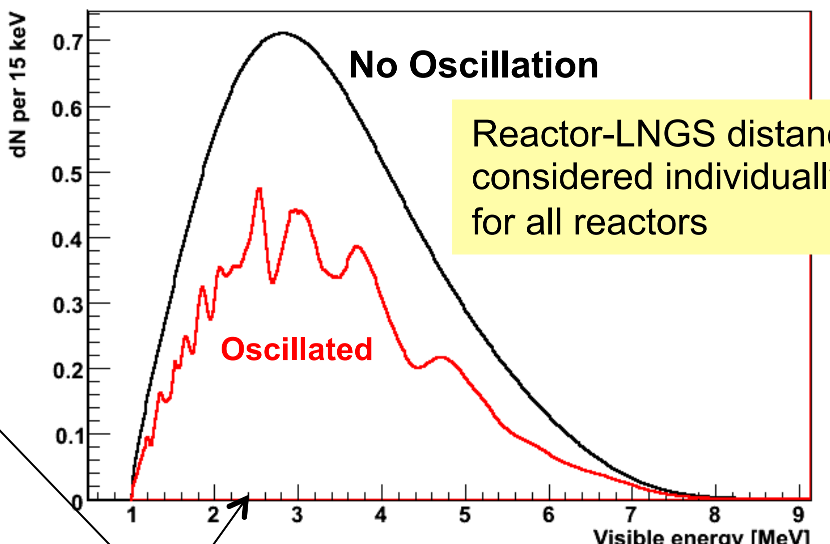
$$\langle P_{ee} \rangle \simeq \cos^4\theta_{13}\left(1 - \frac{1}{2}\sin^2 2\theta_{12}\right) + \sin^4\theta_{13}$$

0.551 ± 0.015
(Fiorentini et al 2012),

but for reactor antineutrinos not!

E_antinu = 3 MeV

Reactor antineutrinos at LNGS

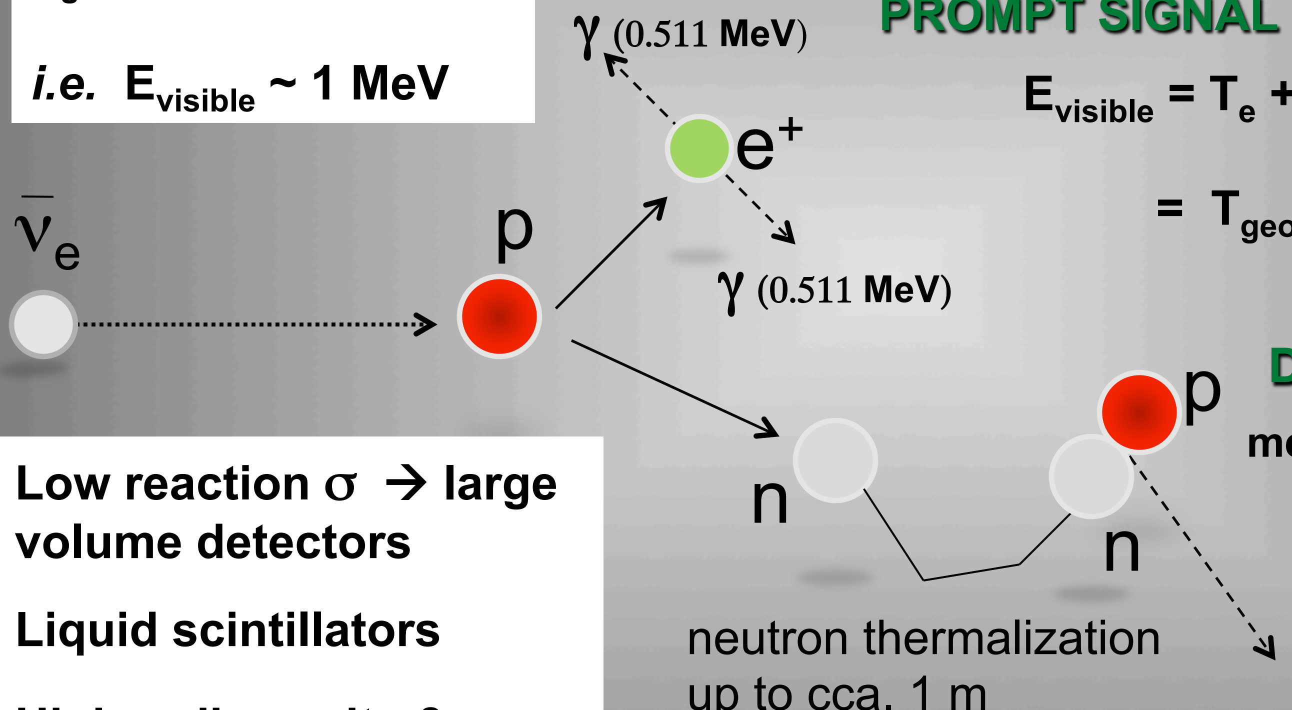


Detecting geo-ν: inverse β-decay

Energy threshold of

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

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



PROMPT SIGNAL

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

$= T_{geo\text{-}\nu} - 0.784$ MeV

DELAYED SIGNAL

mean n-capture time on p
256 μs

Low reaction σ → large volume detectors

Liquid scintillators

High radio-purity & underground labs to shield from cosmic rays

Geo-neutrino signal prediction

Signal = function (amount and distribuiton of U and Th in the Earth)

1 Terrestrial Neutrino Unit **(TNU)** = 1 event / year / 10^{32} protons (~ 1kton scitnillator)

$$S\left({}^{232}\mathrm{Th}\right)\ [\mathrm{TNU}] = 4.07 \cdot \phi\left({}^{232}\mathrm{Th}\right),$$

$$S\left({}^{238}\mathrm{U}\right)\ [\mathrm{TNU}] = 12.8 \cdot \phi\left({}^{238}\mathrm{U}\right).$$

Fogli at al. 2010

Conversion between the measured rate in TNU and the oscillated, electron-flavor flux Φ, (considering geoneutrino energy spectrum and cross-section of the detection interaction)

Crustal signal = relatively well known (LOC and ROC from Fiorentini et al. 2012)
LOC (Local Crust) = area of few hundreds km around the site… up to 50% of signal!
ROC(Rest Of the Crust) = latest Huang et al. 2013; 3D tiles of 1°x1°

Mantle signal is THE UNKNOWN:
U+Th mass (Mantle) = BSE geological model – crust
Different distributions of U and Th in the mantle:

a) **Homogeneous mantle** (maximal geonu signal)
b) **Sunken layer close to the core** (minimal geonu signal)
c) **Depleted mantle + Enriched Layer** (intermediate geonu signal)

- **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;
- data since 2002;
- 2700 meters water equivalent shielding;

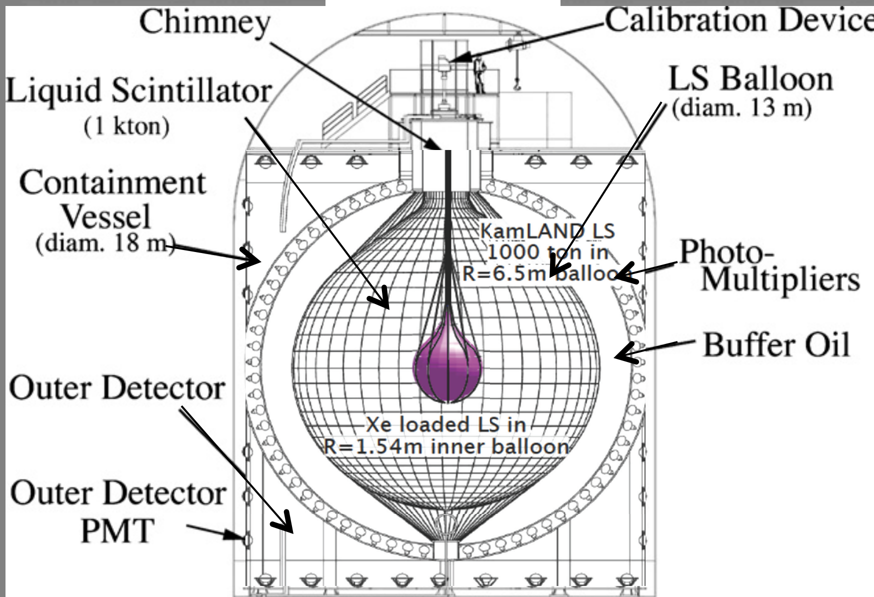
Monday talk of A. Kozlov (Kavli IPMU): Current status of the KamLAND physics program

Borexino in Gran Sasso, Italy
CONTINENTAL CRUST

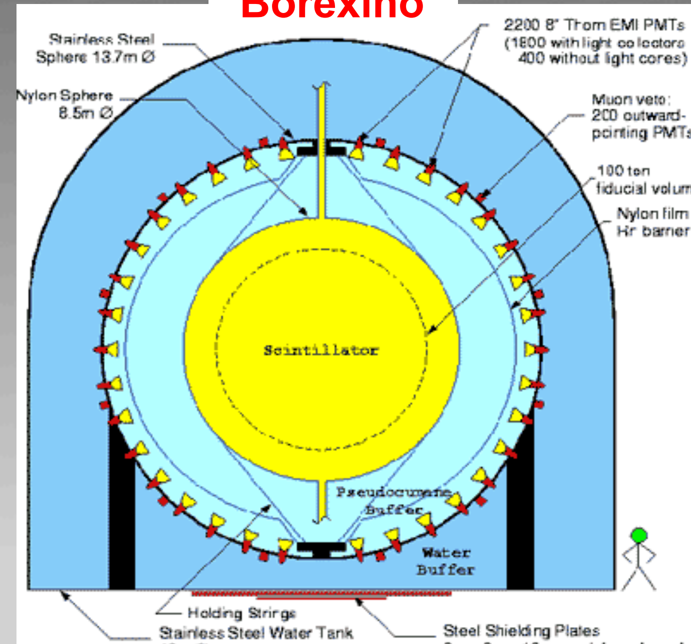
THIS TALK

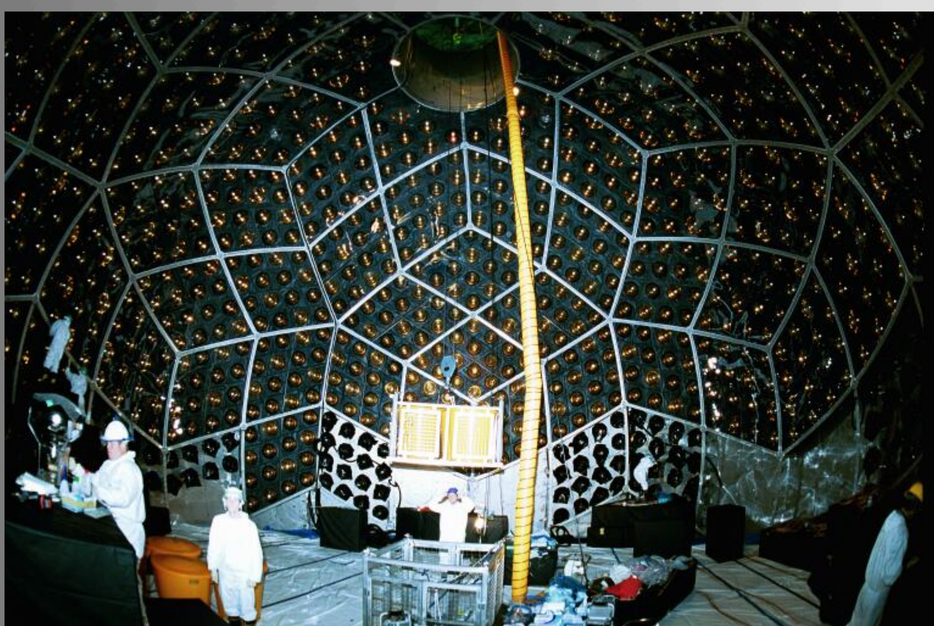
- originally build to measure neutrinos from the Sun – extreme radiopurity needed and achieved;
- 280 tons;
- DAQ started in 2007;
- 3600 m.w.e. shielding;

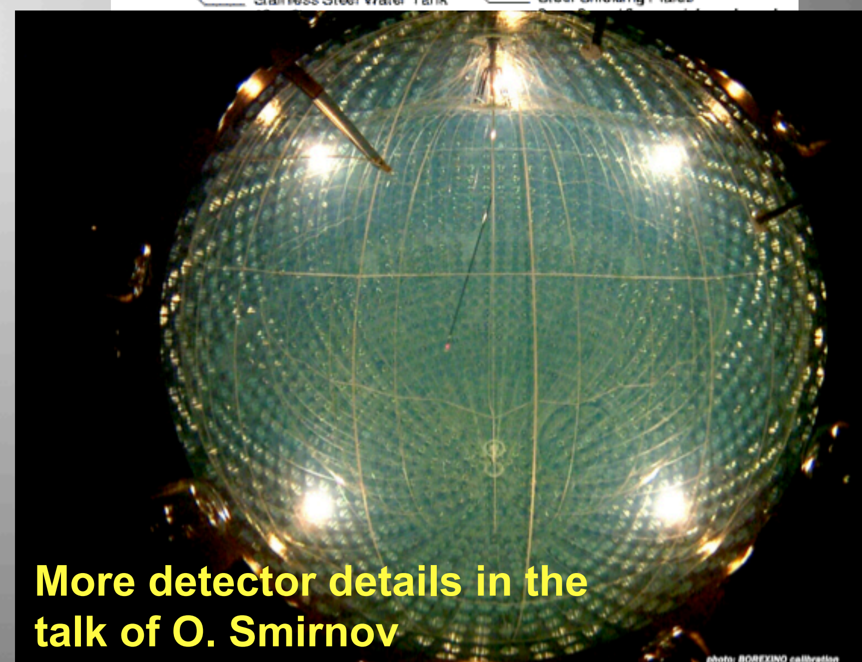
KamLand



Borexino







Geo-neutrino experimental results

KamLand

- 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
- **Phys. Rev. D 88 (2013) 033001**
  116^{+28}_{-27} geonu events ;
  (March 2002 – November 2012)
  4.9 x 10^{32} target-proton year
  0-hypothesis @ 2 x 10^{-6}

Borexino

- 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;
(December 2007 – December 2009)
Exposure 1.5 x 10^{31} target-proton year

- **Phys. Lett. B 722 (2013) 295-300**
  14.3 +- 4.4 geonu events;
  (December 2007 – August 2012)
  3.69 x 10^{31} target-proton year after cuts
  0-hypothesis @ 6 x 10^{-6}

Geo-neutrino detection basics

antineutrino + proton → positron + neutron

E (prompt) = E(antineutrino) – 0.784 MEV

Edelayed = 2.2 MeV gamma

Δ time
Δ R

- **Charged particles produce scintillation light;**
- **Gamma rays from the positron annihilation and from the neutron capture are neutral particles but in the scintillator they interact mostly via Compton scattering producing electrons = charged particles;**
- **Scintillation light is detected by an array of phototubes (PMTs) converting optical signal to electrical signal;**
- **Number of hit PMTs = function (energy deposit) -> Eprompt, Edelayed**
- **Hit PMTs time pattern = position reconstruction of the event -> Δ R** of events
- Each trigger has its GPS time -> **Δ time** of events

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

- They can be due to:
  - Geo-neutrinos;
  - Reactor antineutrinos;
  - Other backgrounds;
- We need to estimate different contributions and then extract the number of measured geo-neutrinos by fitting the Eprompt energy spectrum;

Borexino 2013 geo-ν measurement

Phys. Lett. B 722 (2013) 295-300

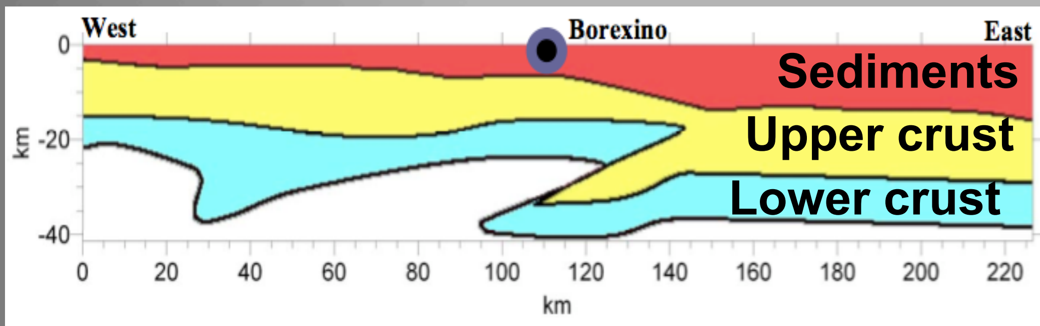
(14.3 $\pm$ 4.4) geoneutrino events

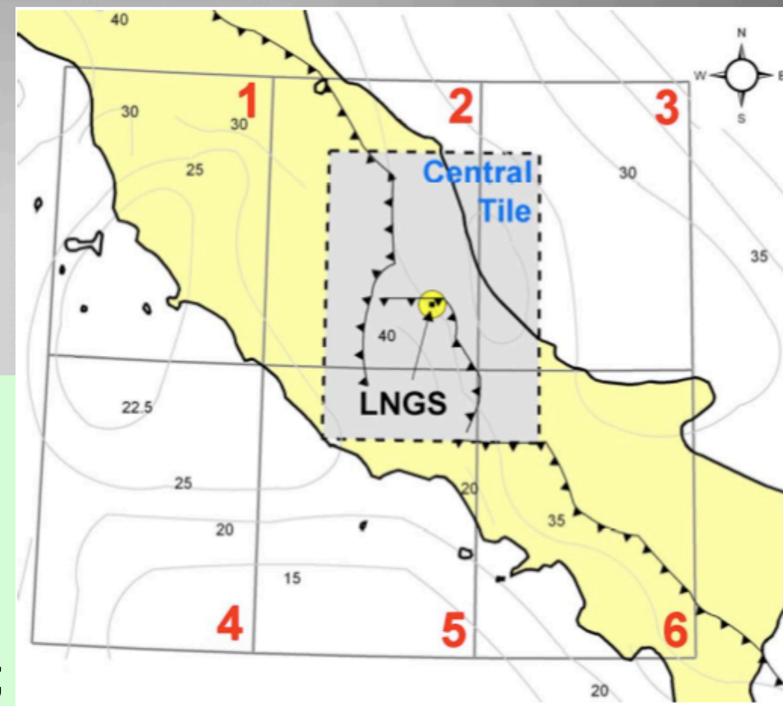
What do we expect?

LNGS local geology study

(Coltorti et al., Geo.Cosm. Acta 75(2011) 2271)

~50% of the expected signal is coming from R< 500 Km!!





- ✓U and Th abundances of samples belonging to sedimentary cover analized by means of ICP-MS and NaI(TI) gamma spectroscopy;
- ✓U and Th content in the upper and lower crust from Valsugana and Ivrea-Verbano area outcrops;

By using the available seismic profile as well stratigrafic records from a number of exploration wells, a 3 D model was developed down to the Moho depht for a total of 10^6 1 km^3 volume cells.

Expected geoneutrino signal at LNGS

Local crust contribution from the 6° x 4° area around the detector:

$S_{crust}(LOC) = (9.7 \pm 1.3)$ TNU (Coltorti et al .2011)

Total crustal contribibution, LOC + Rest Of the Crust (Huang et al (2013)

S_{crust} (LOC + ROC) = 23.4 ± 2.8 TNU

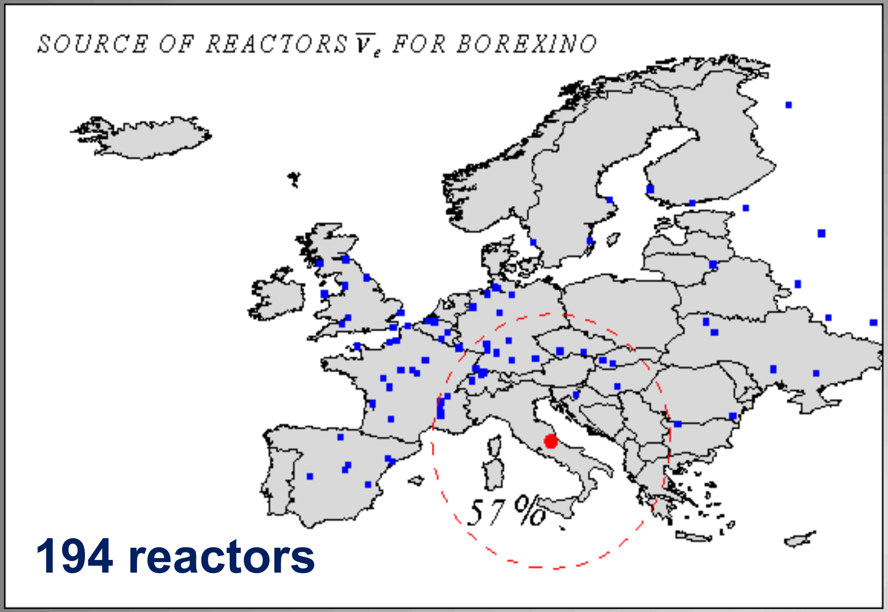
Mantle contribution is less well known. By considering, as an example, the mantle contribution quoted in Fiorentini et al (2012) for the BSE model by Mc. Donough and Sun (1995), the total expected geoneutrino signal at LNGS site is:

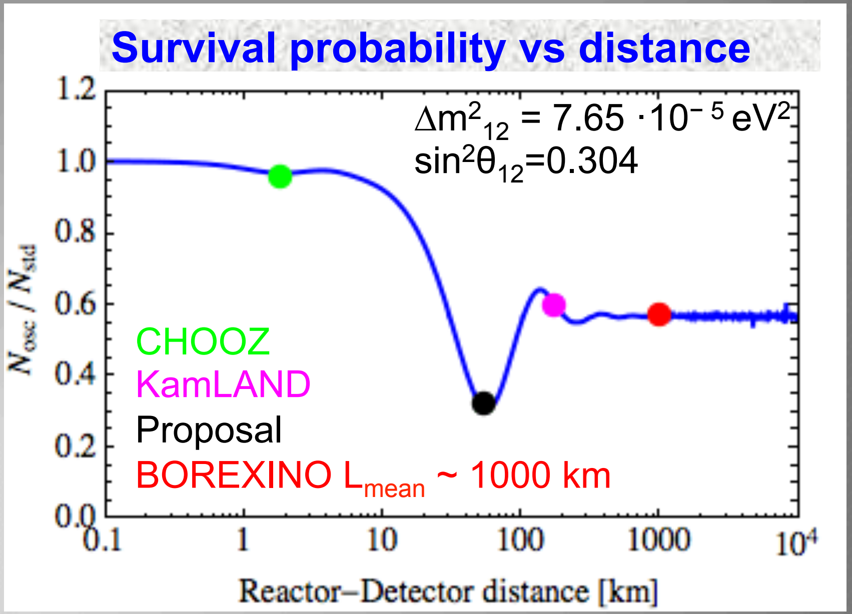
$S_{geo} = (33.2 \pm 4.8)$ TNU → $N_{geo} = (12.2 \pm 1.8)$ events!!

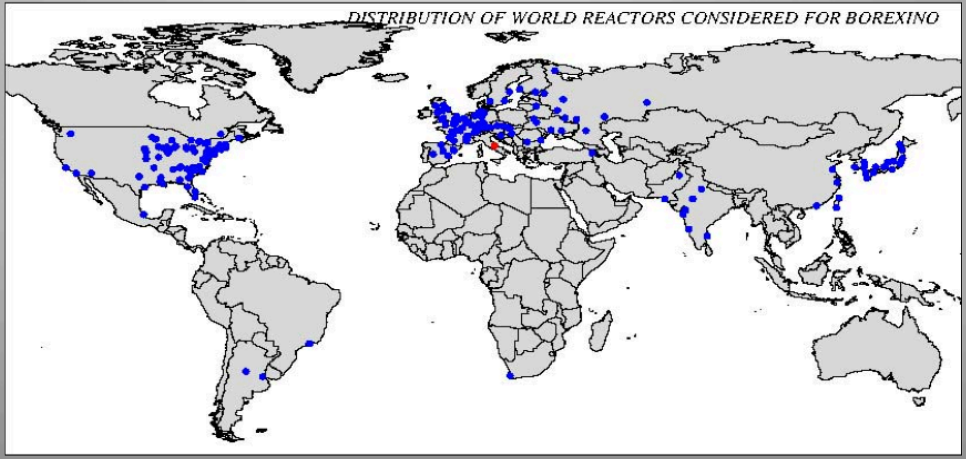
in 3.69×10^{31} target-proton year exposure (exposure of the 2013 Borexino data)

Ultra-pure detector mandatory !!!

Reactor antineutrinos







245 world non European reactors

Calculation of reactor anti-ν signal

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

- **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, Huber 2011, Mueller et al.2011, Huber-Schwetz 2004);
  - P_{ee}: oscillation survival probability;
- **Calculated as a f(detector):**
  - 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 (reactor core composition);

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

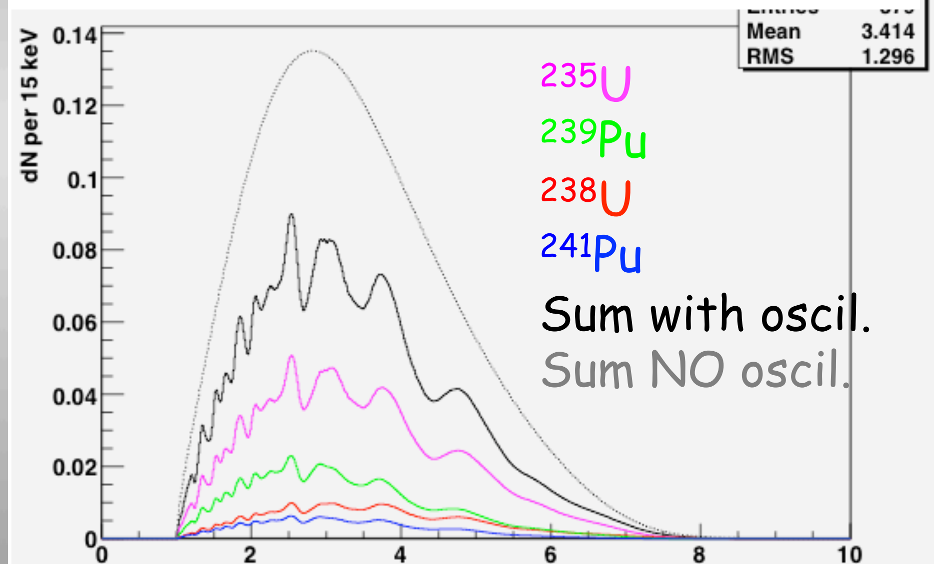
Expected reactor anti-neutrino signal and its error in Borexino

Expected number of events: (33.3±2.4) events in 613 ton x year exposure

Source of error	Error (%)
Oscillations: θ_{13}	±0.5%
Oscillations: δm^2	±0.02%
Oscillations: θ_{12}	**±2.3%**
Energy per fission of isotope i: E_i	±0.6%
Flux shape: $\Phi_i(E_\nu)$	**±3.5%**
Cross section: $\sigma(E)$	±0.4%
Thermal power: P_{rm}	**±2.0%**
Long lived isotopes in spent fuel	±1%
Fuel composition: f_{ri}	**±3.2%**
Reactor – Borexino distance L_r	±0.4%
TOTAL	**±5.8%**

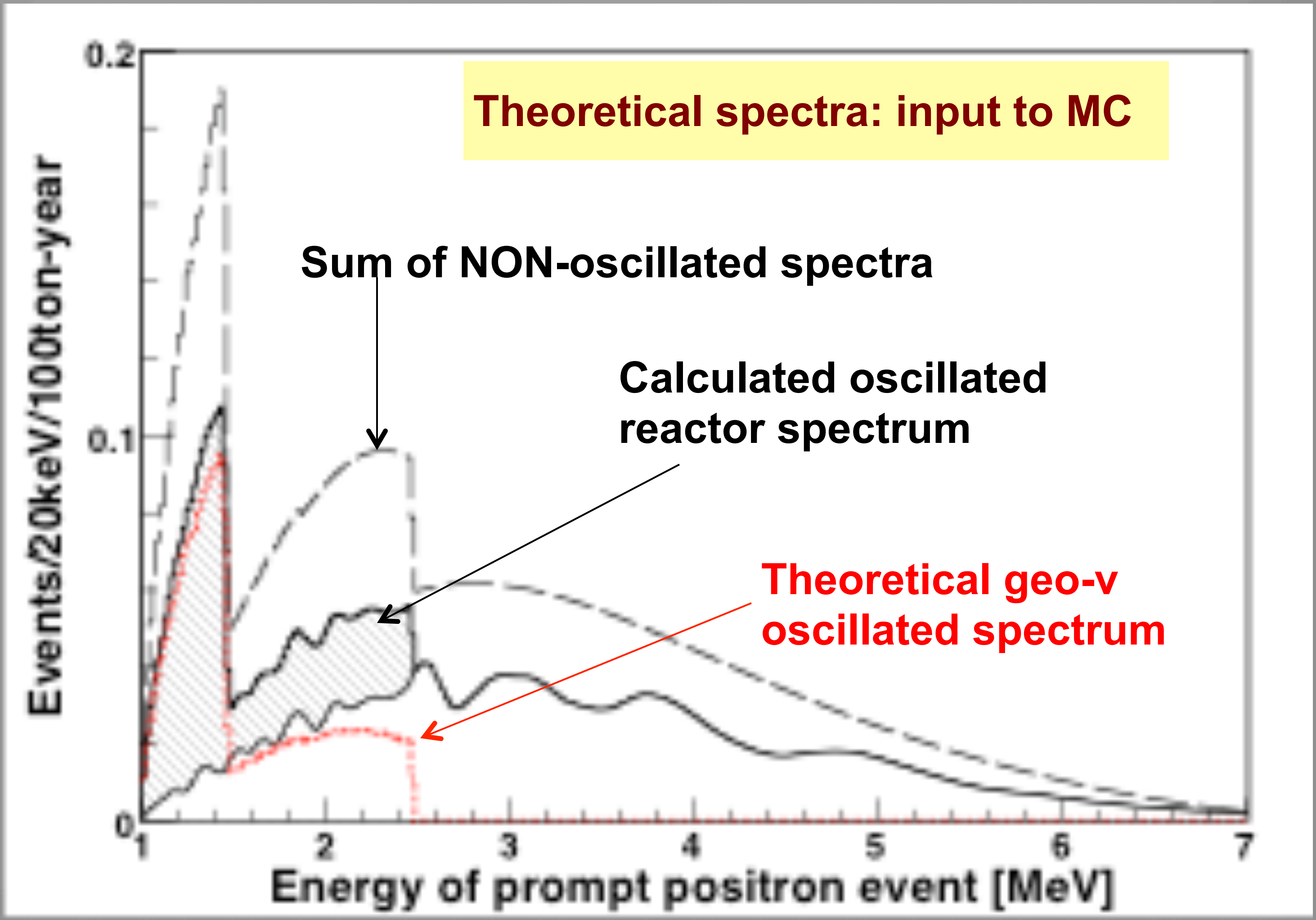
$\sigma \sim 10^{-44}$ cm^2 $N_{protons} = 6 \times 10^{30}$ in 100 tons

Energy spectrum of prompt events

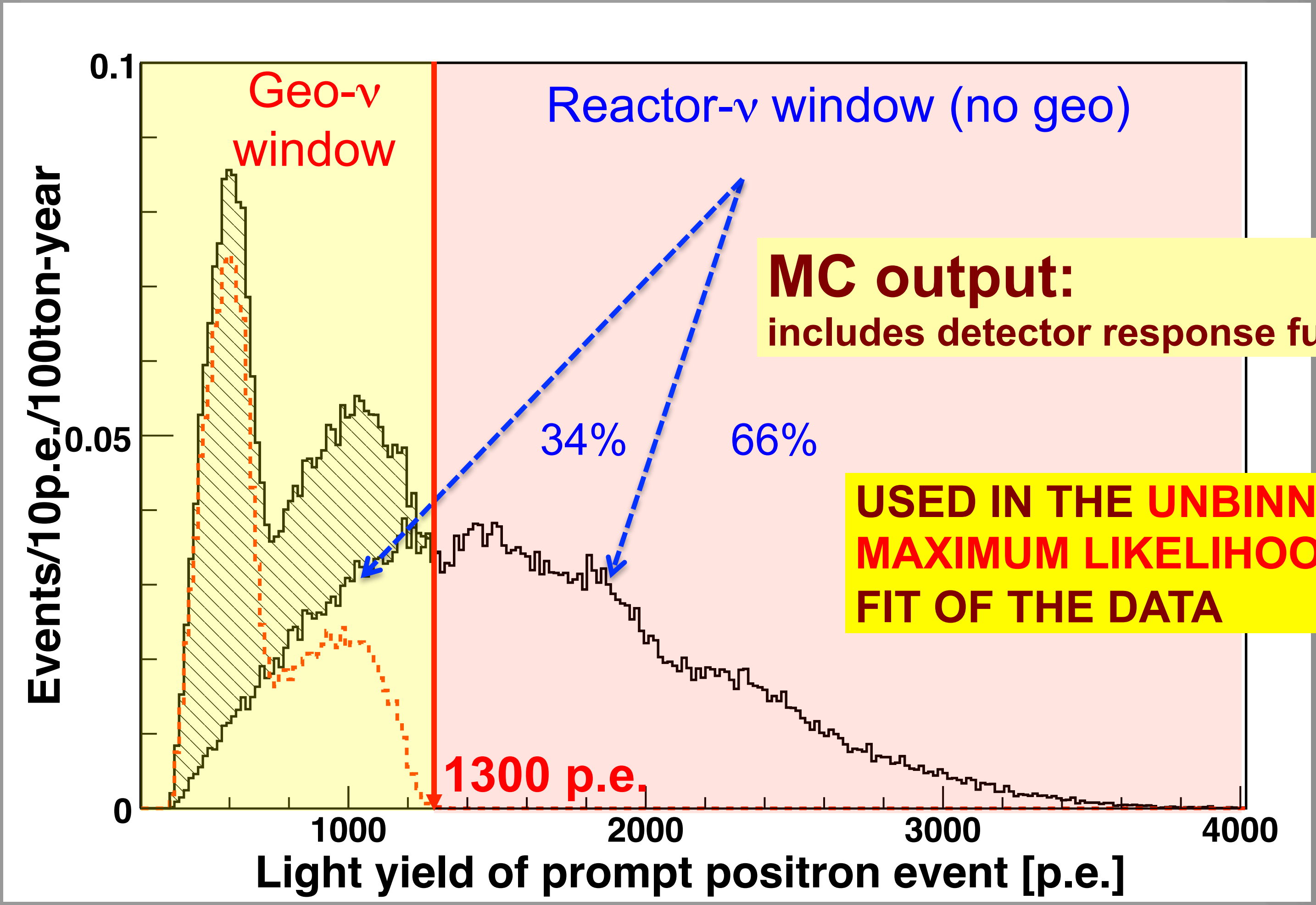


Ideal detector Prompt energy (MeV)

Expected prompt-event energy spectrum: theoretical shapes (in MeV)



Expected prompt-event spectrum: Monte Carlo result (in photoelectrons)



MC output:
includes detector response function

USED IN THE UNBINNED MAXIMUM LIKELIHOOD FIT OF THE DATA

Backgrounds mimicking the anti-ν interactions

Background source	Events in total exposure
Cosmogenic ^{9}Li and ^{8}He	0.25 ± 0.18
Fast neutrons from μ in Water Tank (measured)	< 0.07
Fast neutrons from μ in rock (MC)	< 0.28
Non-identified muons	0.080 ± 0.007
Accidental coincidences	0.206 ± 0.004
Time correlated background	0.005 ± 0.012
(γ,n) reactions	< 0.04
Spontaneous fission in PMTs	0.022 ± 0.002
(α,n) reactions in the scintillator [^{210}Po]	0.13 ± 0.01
(α,n) reactions in the buffer [^{210}Po]	< 0.43
TOTAL	0.70 ± 0.18

Anti-neutrino candidates and the results

Geo-ν: the selecting cuts

Selection cuts efficiency (estimated with MC): 0.84 $\pm$ 0.01

Energy cuts (ligh yield ~ 500 p.e./MeV):

- Prompt event light yield (above kinematic threshold) > 408 p.e.
- 860 p.e .< delayed event< 1300 p.e.

Time cuts :

- 20 μs < Δt < 1280 μs (neutron capture time ~255 μs)
- 2 s dead time after μ crossing the scintillator/buffer
- 2 ms dead time after μ crossing the Water Tank
- multiplicity cut: no neutron-like events in a $\pm$2 ms time

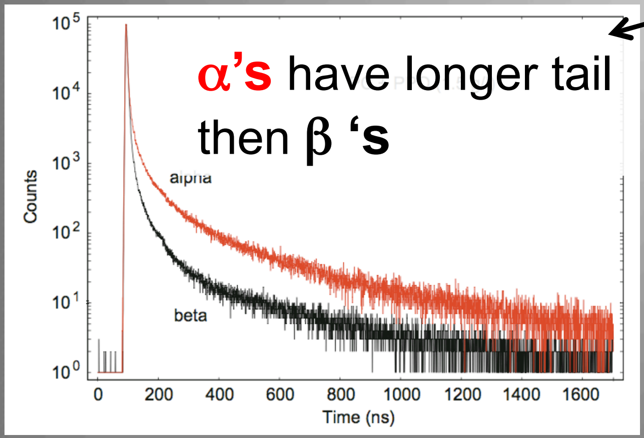
Spatial cuts:

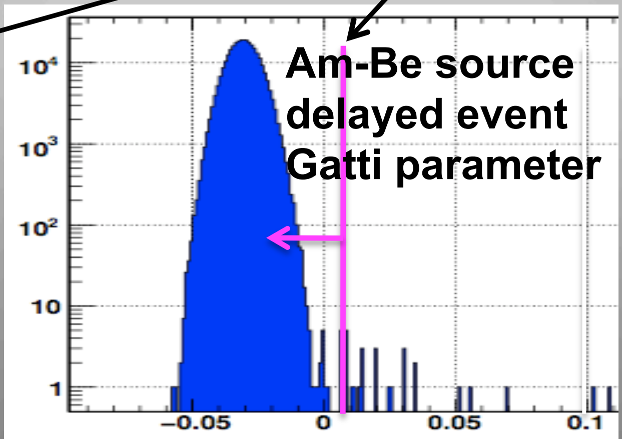
- ΔR < 1m
- D_{prompt} from the inner vessel > 0.25 m

Pulse-shape cuts :

- Delayed event Gatti parameter: G_{del} < 0.015

E. Gatti F. And De Martini Nuclear Electronics II (1962) 265

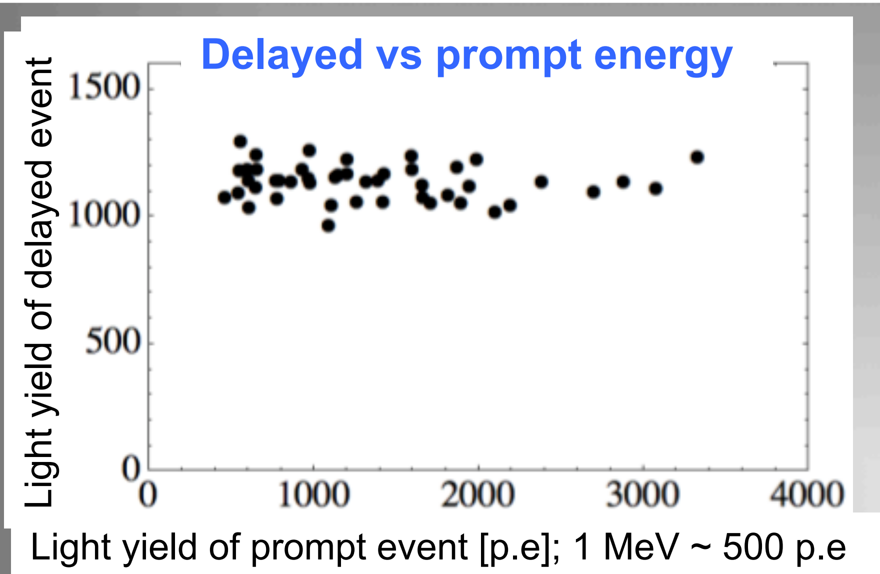


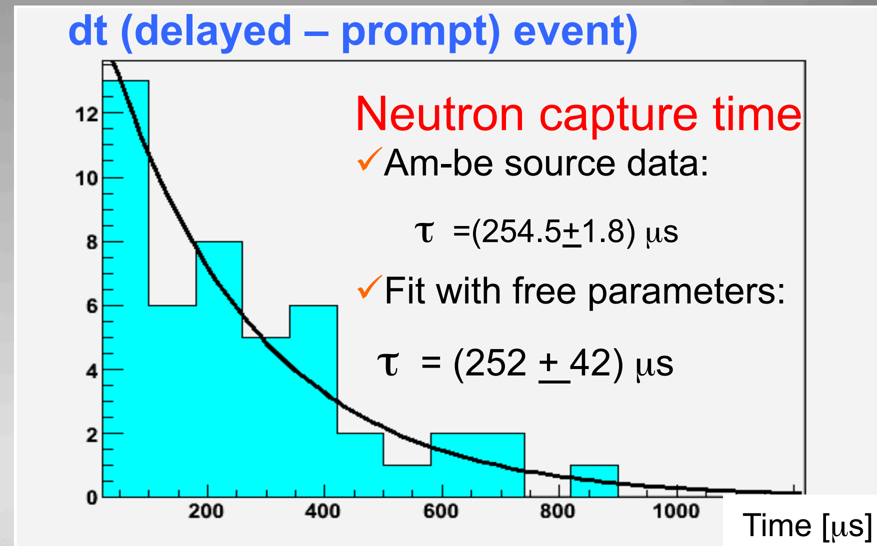


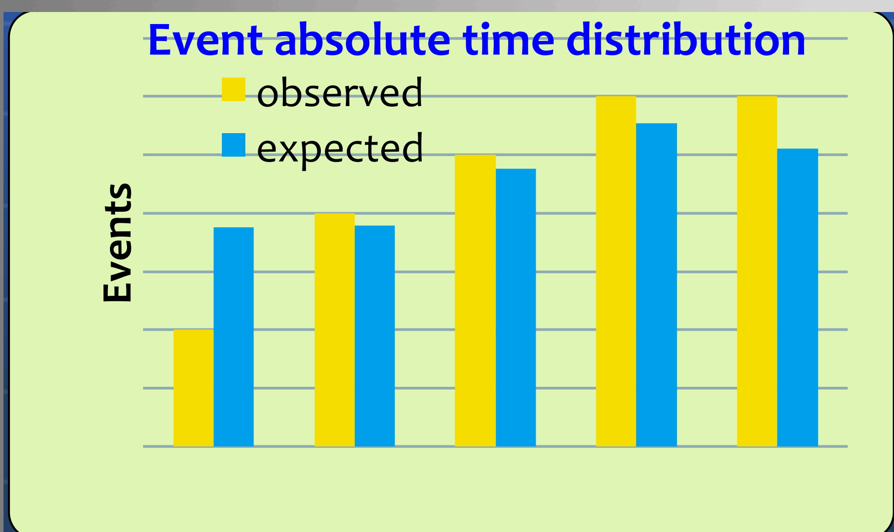
Mostly introduced to reject ^{214}Bi-^{214}Po background during purifications and coming from the 10^{-2} % $^{214}Po(\alpha+\gamma)$ decay branch

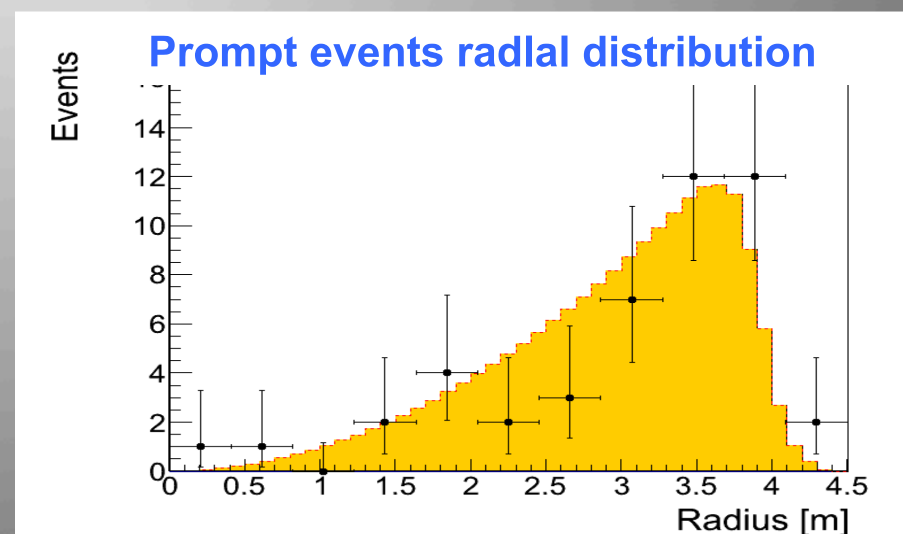
46 golden anti-neutrino candidates

(in 1198.9 days from Dec. 2007 to Aug.2012)







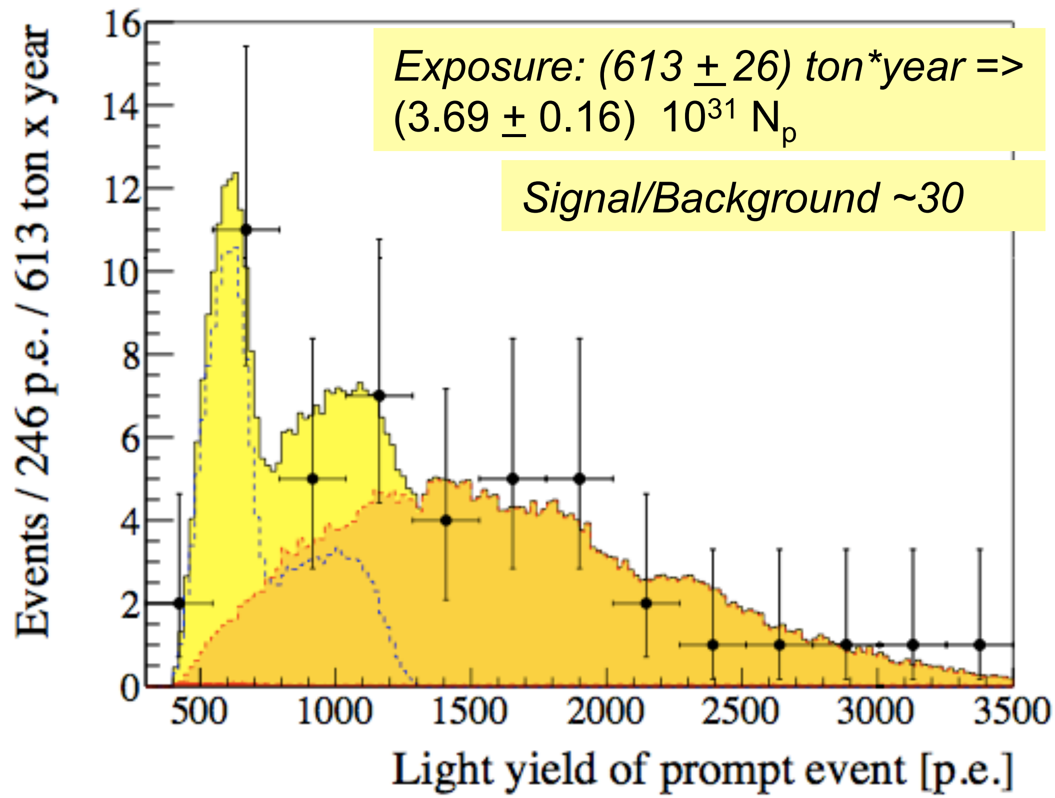


46 golden anti-neutrino candidates

(in 1198.9 days from Dec. 2007 to Aug.2012)

✓An unbinned maximal likelihood fit of the energy spectrum of the 46 prompt candidates has been performed;

✓Th/U mass ratio fixed to the chondritic value of 3.9;



*Exposure: (613 ± 26) ton*year =>*
(3.69 ± 0.16) 10^{31} N_p

Signal/Background ~30

Free fit parameters:

- N_{geo}
- N_{rea} (no dependence of the result on the reactor flux normalisation)
- Backgrounds constrained at their ±1σ expectation values

N_{geo} =(14.3 ± 4.4)

N_{rea} = $(31.2\ ^{+7.0}_{-6.1})$

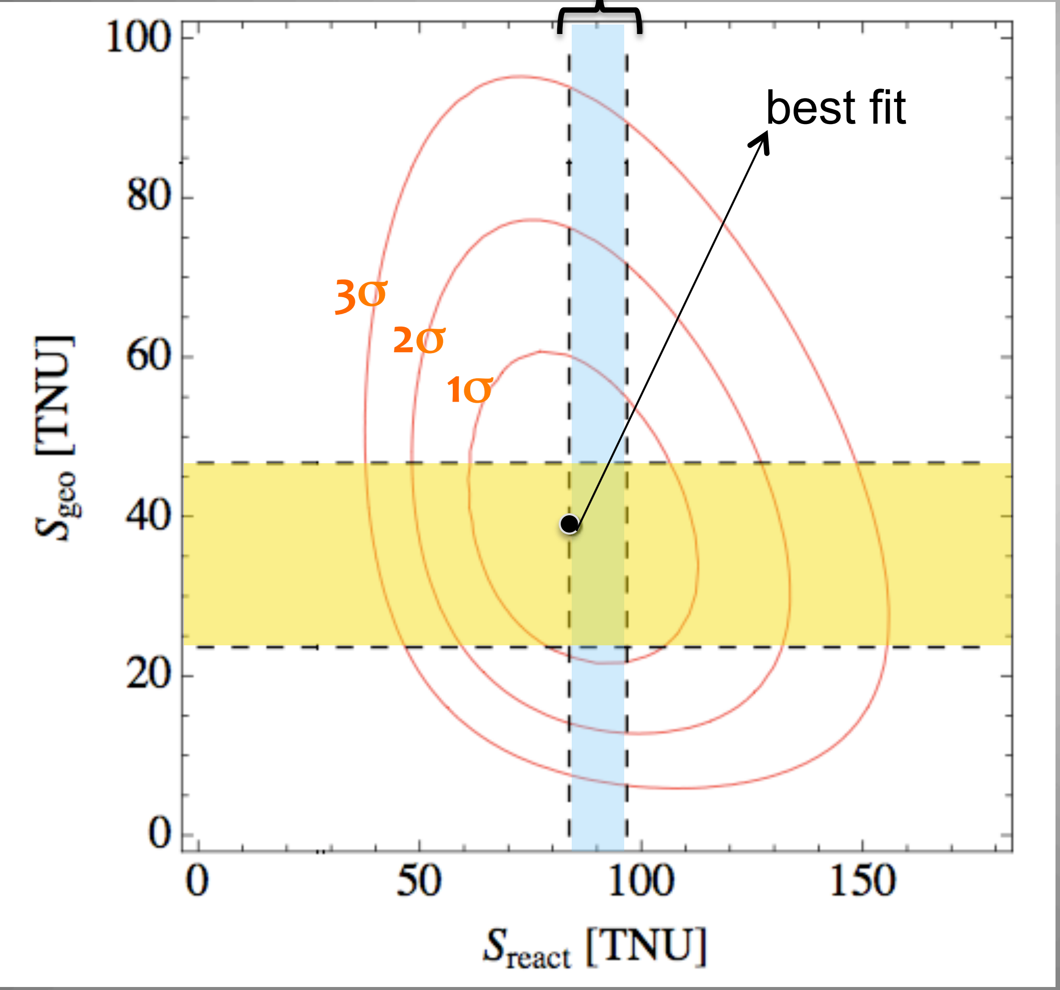
S_{geo}= 0: probability of 6 10^{-6}

Evidence for geo-ν at 4.5σ C.L.

Comparison with expectations

Contour plot for geo-ν and reactor antineutrino signal rate

1σ expectation band of S_{rea}: (83.2-97.3) TNU



Observed number of reactor antineutrinos is consistent with expectations

Observed number of geo-neutrinos falls within the range expected by geological models

1σ expectation band of S_{geo}=(26.3-46.6)TNU for different geo-models

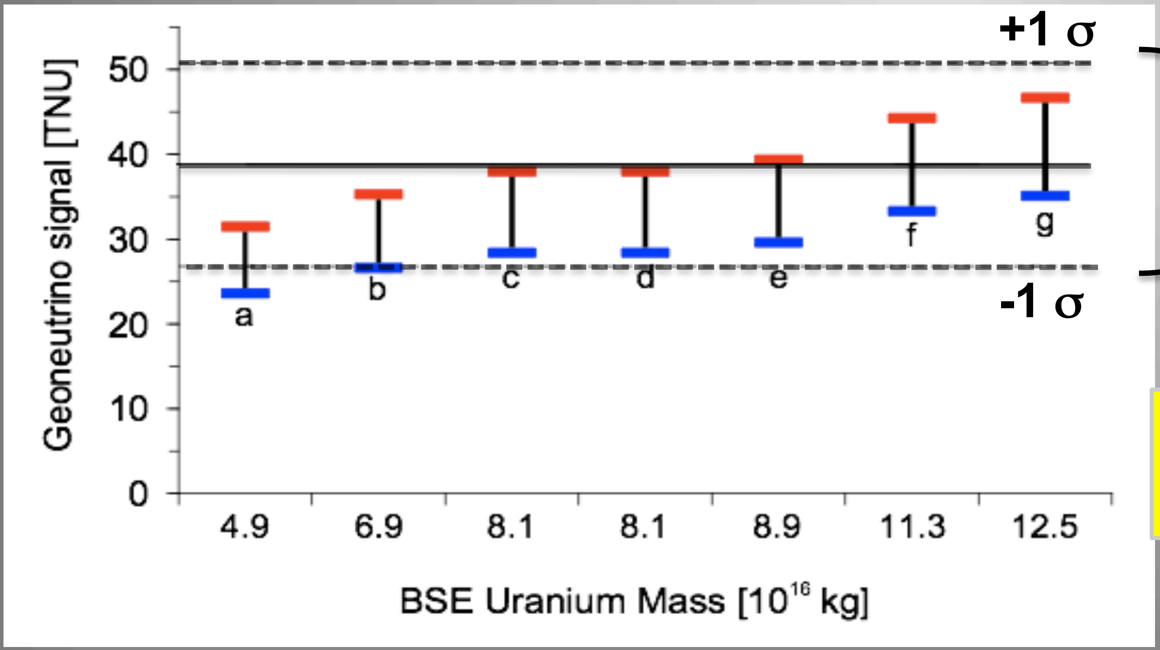
Geo-ν signal vs BSE geological models

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)

$S^{BX}_{geo} = (38.8 \pm 12.0\ )$ TNU

High signal = homogeneous mantle, crustal signal + 1 σ error

Low signal = U and Th concentrated close to the core-mantle boundary, crustal signal -1σ error

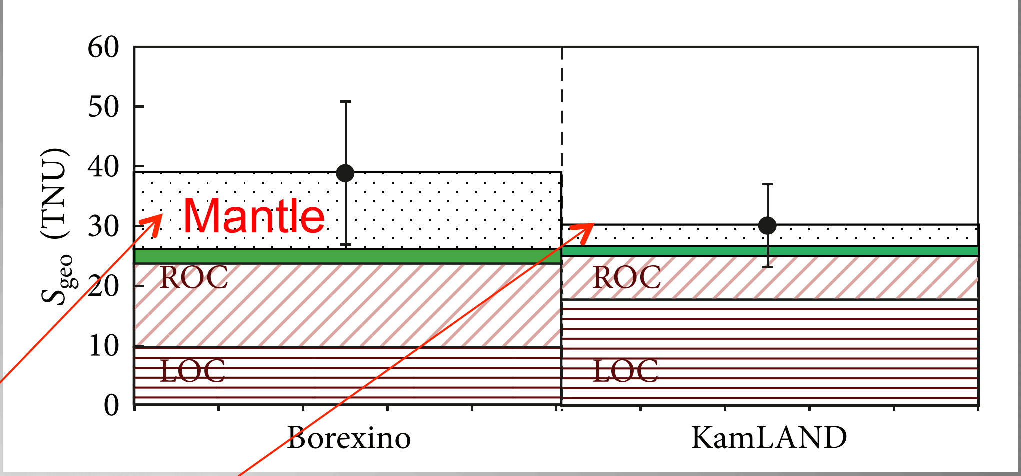


1 σ band for the BX results

BX result in agreement with
- the available BSE models

Mantle geo-neutrinos

$S_{geo} = S(crust) + S(mantle)$



Ludhova and Zavatarelli, Hindavi Publishong Corporation, Advances in High Energy Physics, 2013.

BOREXINO alone

S^{BX}_{geo} (Total) =(38.8 ± 12.0) TNU

S^{BX}_{geo} (Crust) =(23.4 ± 2.8) TNU

S^{BX} (mantle) =(15.4 ± 12.3) TNU

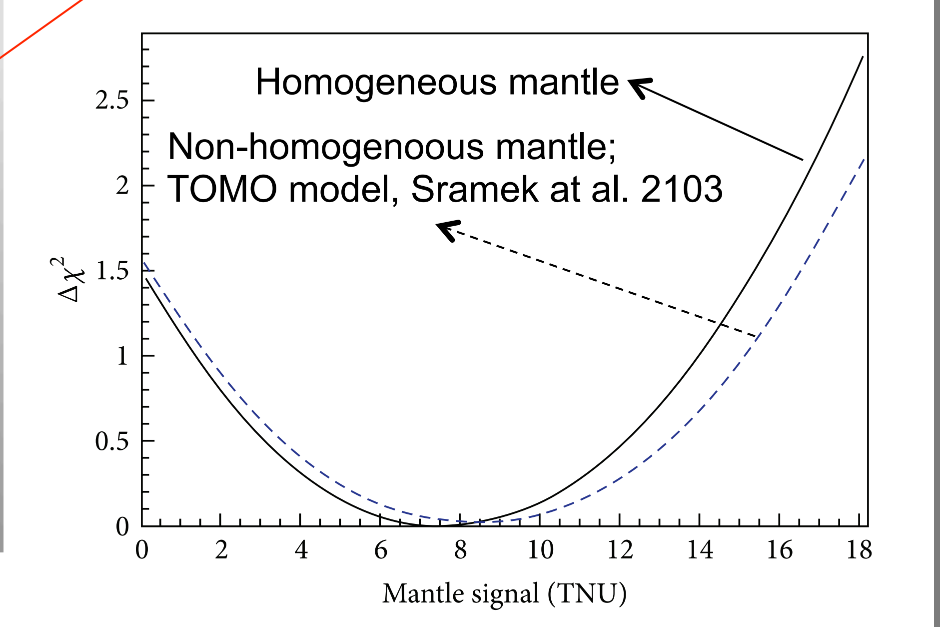
KAMLAND alone, Data from PRD 88 (2013) 033001

S^{BX} (mantle) =(5.0 ± 7.3) TNU

Combined analysis BX + KL:

S^{SYM}_{BX+KL} (mantle) =(7.7 ± 6.2) TNU

S^{TOMO}_{BX+KL} (mantle) = $(8.4^{+6.6}_{-6.7})$ TNU

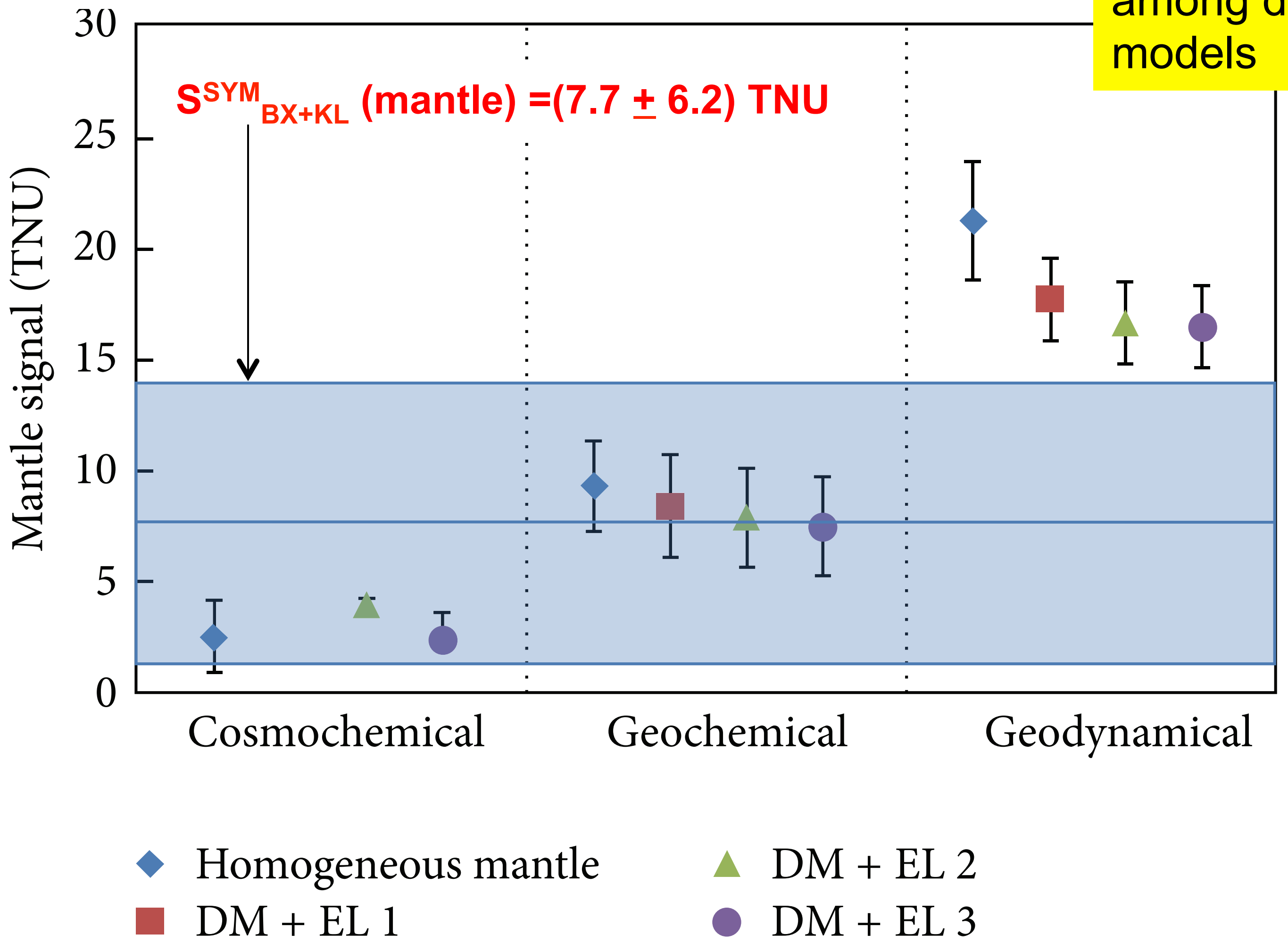


Ludhova and Zavatarelli, Hindavi Publishong Corp., Advances in High Energy Physics, 2013.

Mantle geo-neutrinos

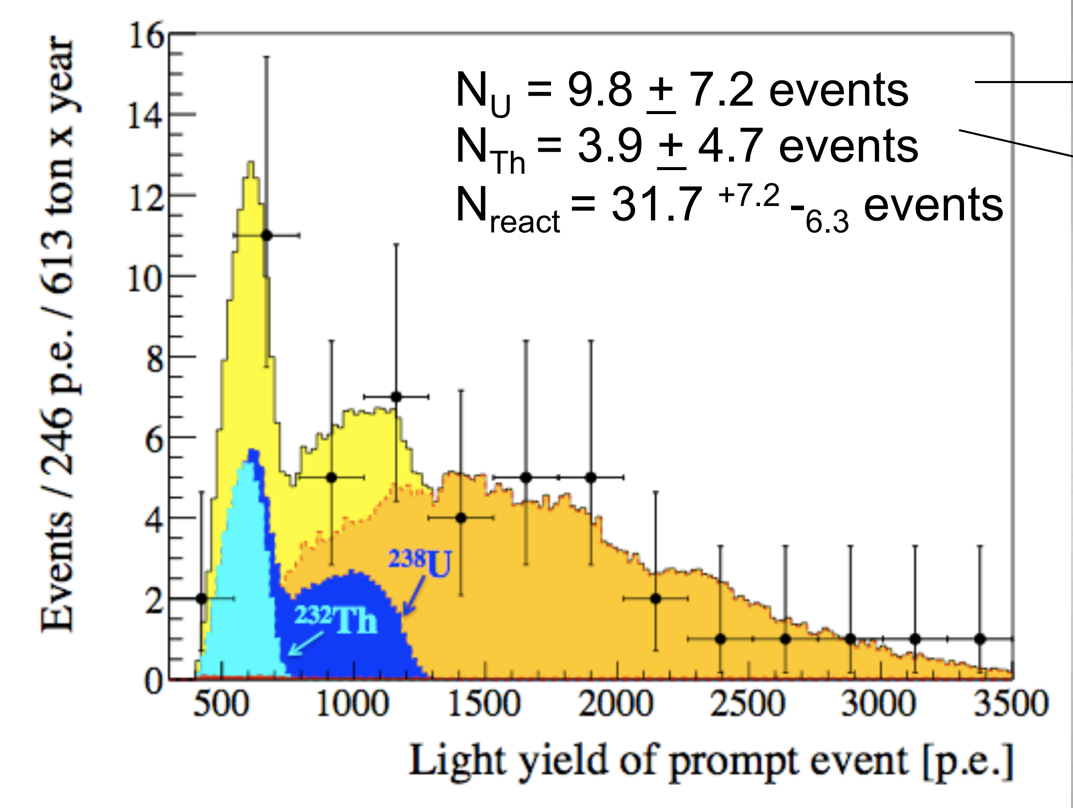
Current measurements cannot discriminate among different BSE models

Ludhova and Zavatarelli, Hindavi Publishong Corporation, Advances in High Energy Physics, 2013.



Fit with free U/Th ratio

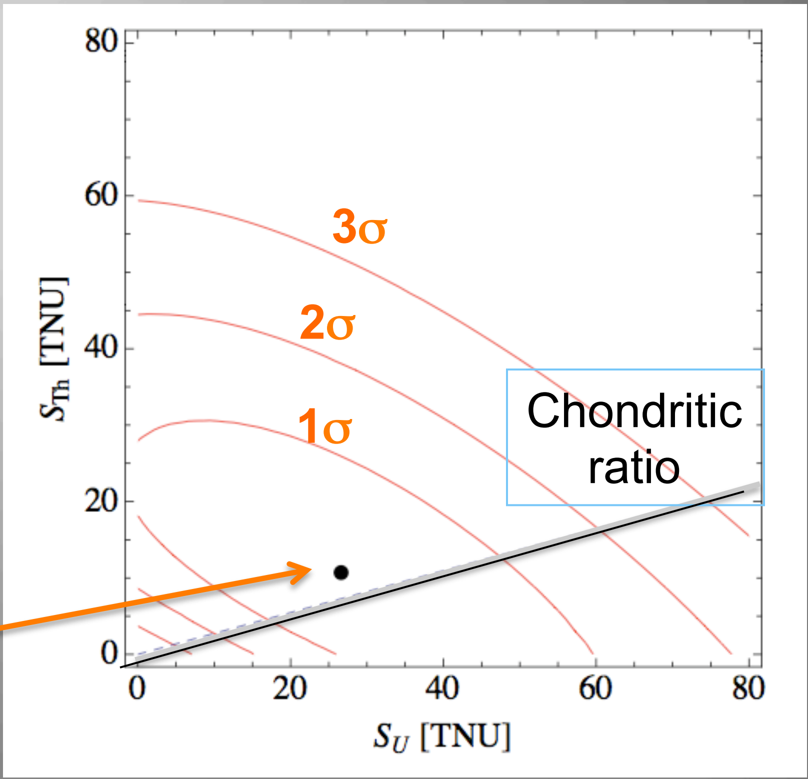
U and Th spectra have been fit as two independent PDF's.



N_U = 9.8 $\pm$ 7.2 events
N_{Th} = 3.9 $\pm$ 4.7 events
N_{react} = 31.7 $^{+7.2}_{-6.3}$ events

S_U = (26.5 $\pm$ 19.5) TNU

S_{Th} = (10.6 $\pm$12.7) TNU



Best fit result (black point) in good agreement with chondritic value

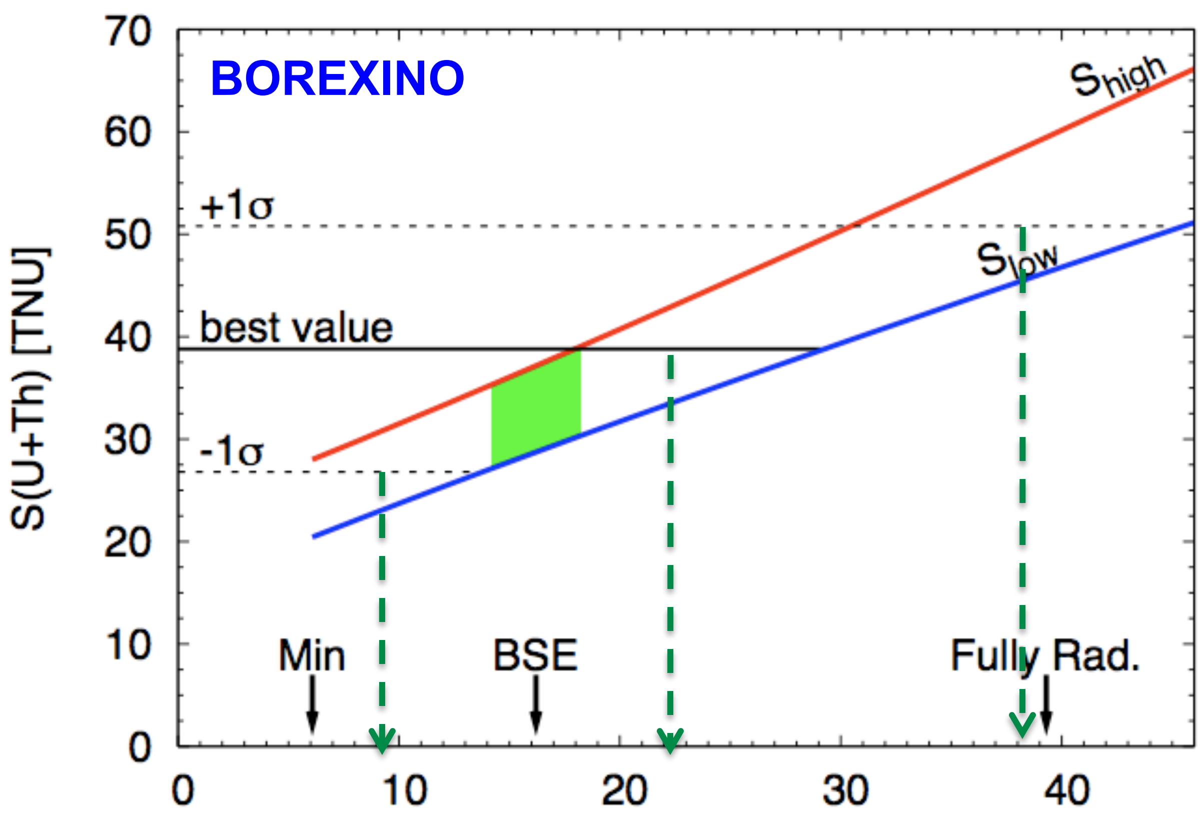
Earth radiogenic heat power

M(U) = (0.8 $\pm$ 0.1) 10^{17} Kg
Th/U = 3.9
K/U = 12000

Red line: ROC + LOC +1σ, mantle homogeneous

Blue line: ROC + LOC -1σ, HPE's at the mantle-core boundary

$S_{BX}^{crust} = (23.4 \pm 2.8)$ TNU

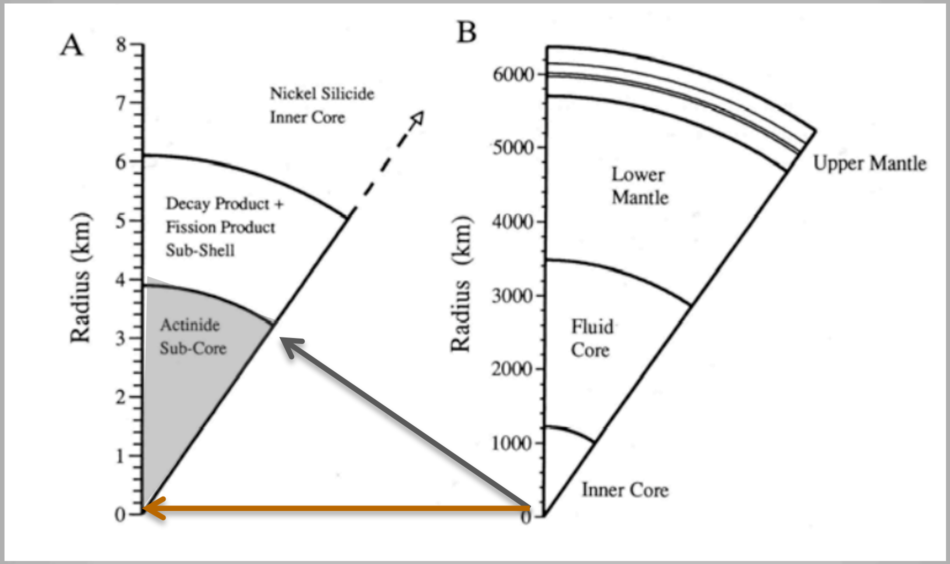


Min = only crustal HPE's

Fully Rad = MAX:
Tot. Heat = (47 $\pm$ 2) TW
=> $H_U + H_{Th} = 39.3$ TW

Geo-reactor

- Herndon et al: Geo-reactor with thermal power < 30 TW in the central part of the core within a radius of about 4 km
- Suggested composition $^{235}U : ^{238}U$: other = 0.76 : 0.23 : 0.01

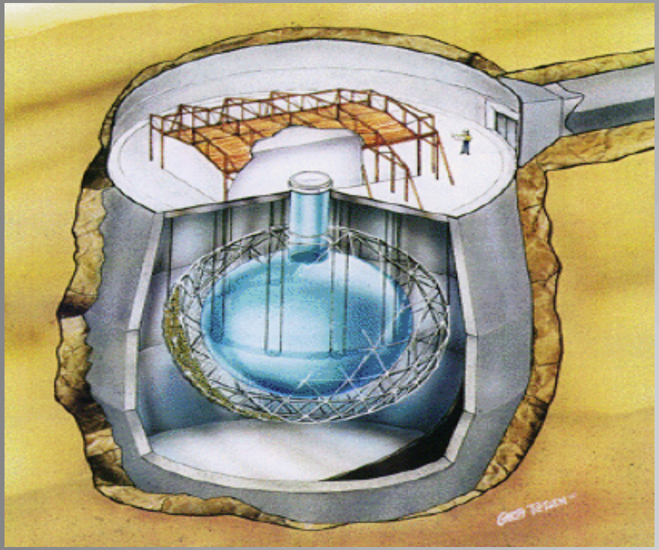


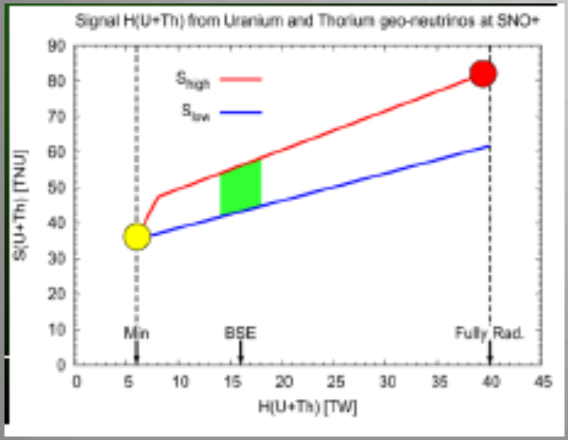
Unbinned maximal likelihood fit of BX data: adding the PDF for geo-reactor signal and constraining the signal from nuclear power plants to the expectation band.

Geo-reactor power < 4.5 TW at 95% C.L.

A window towards the future

SNO+ at Sudbury, Canada





Mantovani et al., TAUP 2007

SHOULD BE COMING SOON!

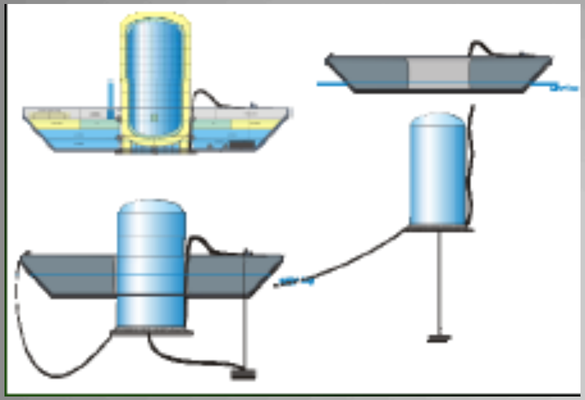
After SNO: D_2O replaced by 1000 tons of liquid scintillator
M. J. Chen, *Earth Moon Planets* **99**, 221 (2006)

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

BSE: 28-38 events/per year

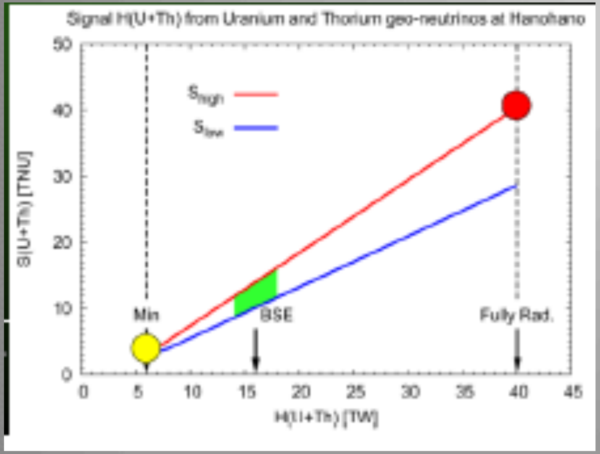
Hanohano at Hawaii

Hawaii Antineutrino Observatory (HANOHANO = "magnificent" in Hawaiian



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.



Mantovani , TAUP 2007

Since Hawai placed on the U-Th depleted oceanic crust

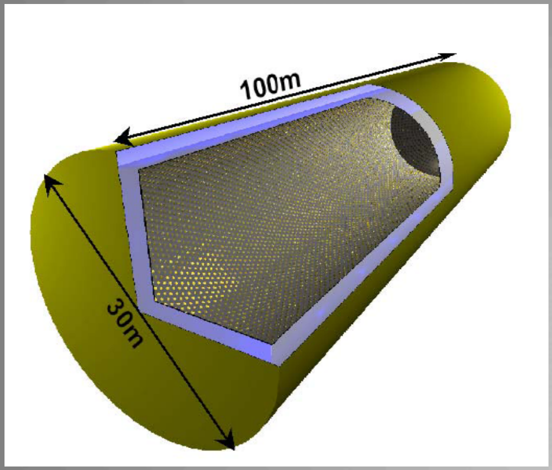
70% of the signal from the mantle!

Would lead to very interesting results!

(Fiorentini et al.)

BSE: 60-100 events/per year

LENA at Pyhasalmi, Finland

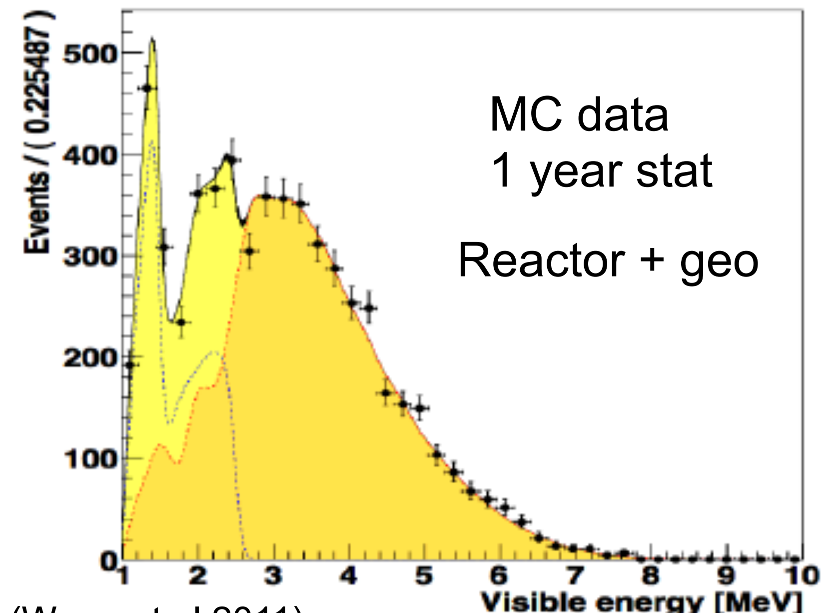


Project for a 50 kton underground liquid scintillator detector (Hochmuth et al 2007)

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

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



(Wurm et al 2011)

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!!!

BACKUP SLIDES

Background sources

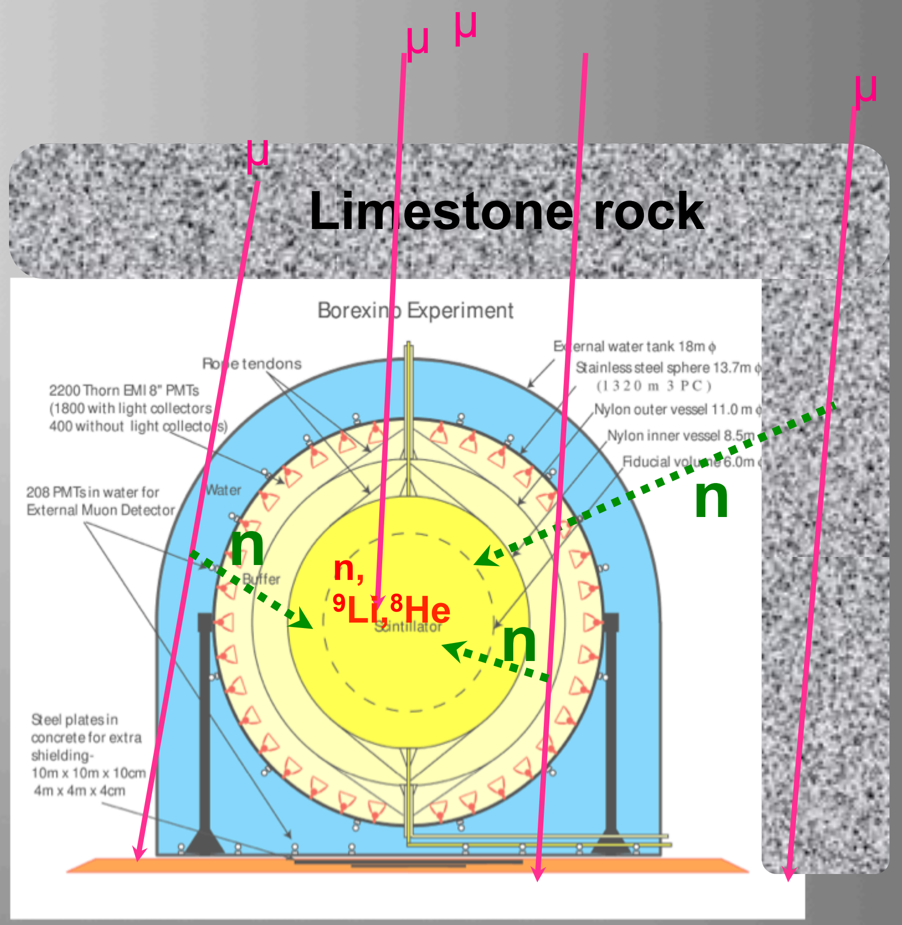
Reactions which can mimick the golden coincidence:

1) <u>Cosmogenic-muon induced:</u>

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

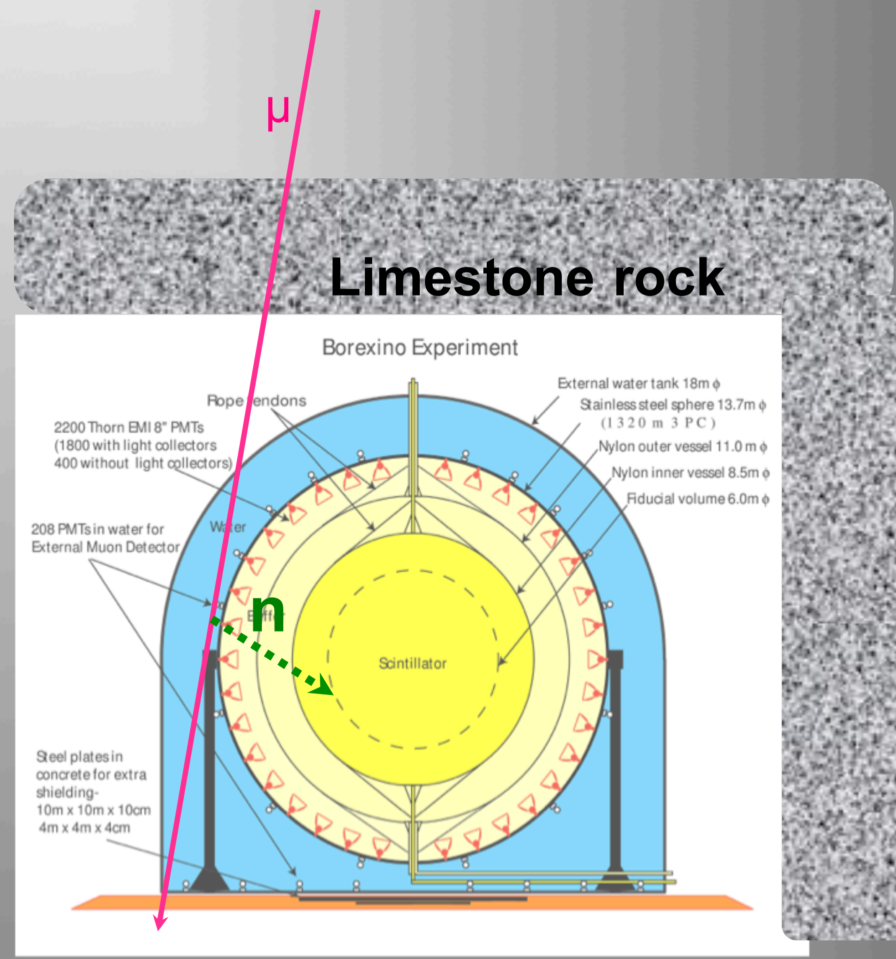
2) <u>Accidental coincidences</u>;

3) <u>Due to the internal radioactivity</u>: (α,n) and (γ,n) reactions



Muons crossing the OD

- To remove **fast neutrons** originated in the Water Tank we apply a 2 ms (~ 8 neutron capture livetimes) veto after each detected muon by the OD;
- In correlation with OD tagged muons we have observed 2 fake anti-ν candidates;
- The inefficiency of OD muon veto is 5×10^{-3};
- For this background we can set an upper limit of **< 0.28 events / data set at 90% C.L.**



^{9}Li-^{8}He background

Isotope	$T_{1/2}$ [ms]	Decay mode	BR [%]	Q_β [MeV]
^{8}He	119.0	β + n	16	5.3, 7.4
^{9}Li	178.3	β + n	51	1.8, 5.7, 8.6, 10.8, 11.2

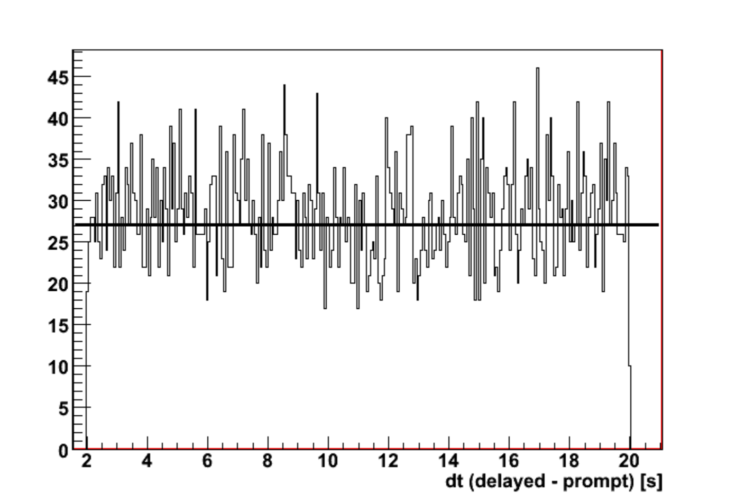
- induced by cosmogenic muons;
- we apply 2 s dead time (several livetimes) after each internal μ;
- from this cut is implied 10% reduction of live time (muon flux ~ 4300/day);
- as a background for geoν we calculate the exponential tail at time > 2 s;

- 148 candidates found within 2 s after muons that satisfy all other selection cuts;
- The energy spectrum consistent with MC predictions

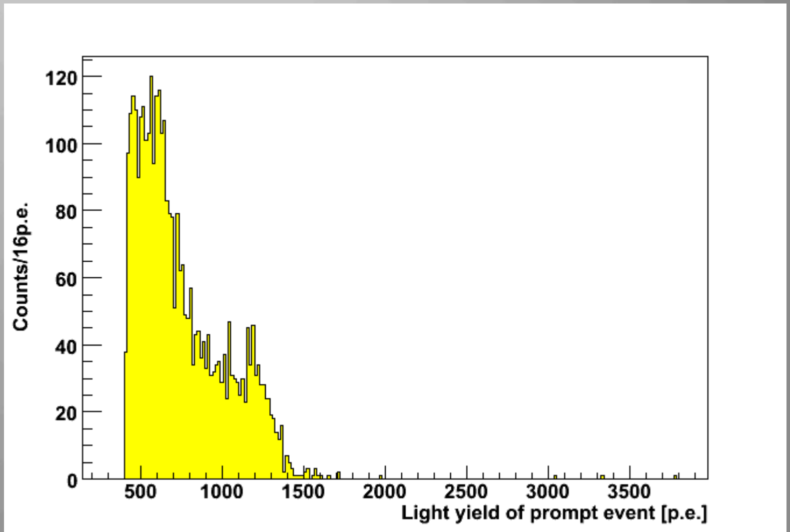
Bgr for geonu:
< 0.25± 0.18 ev/data set

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;



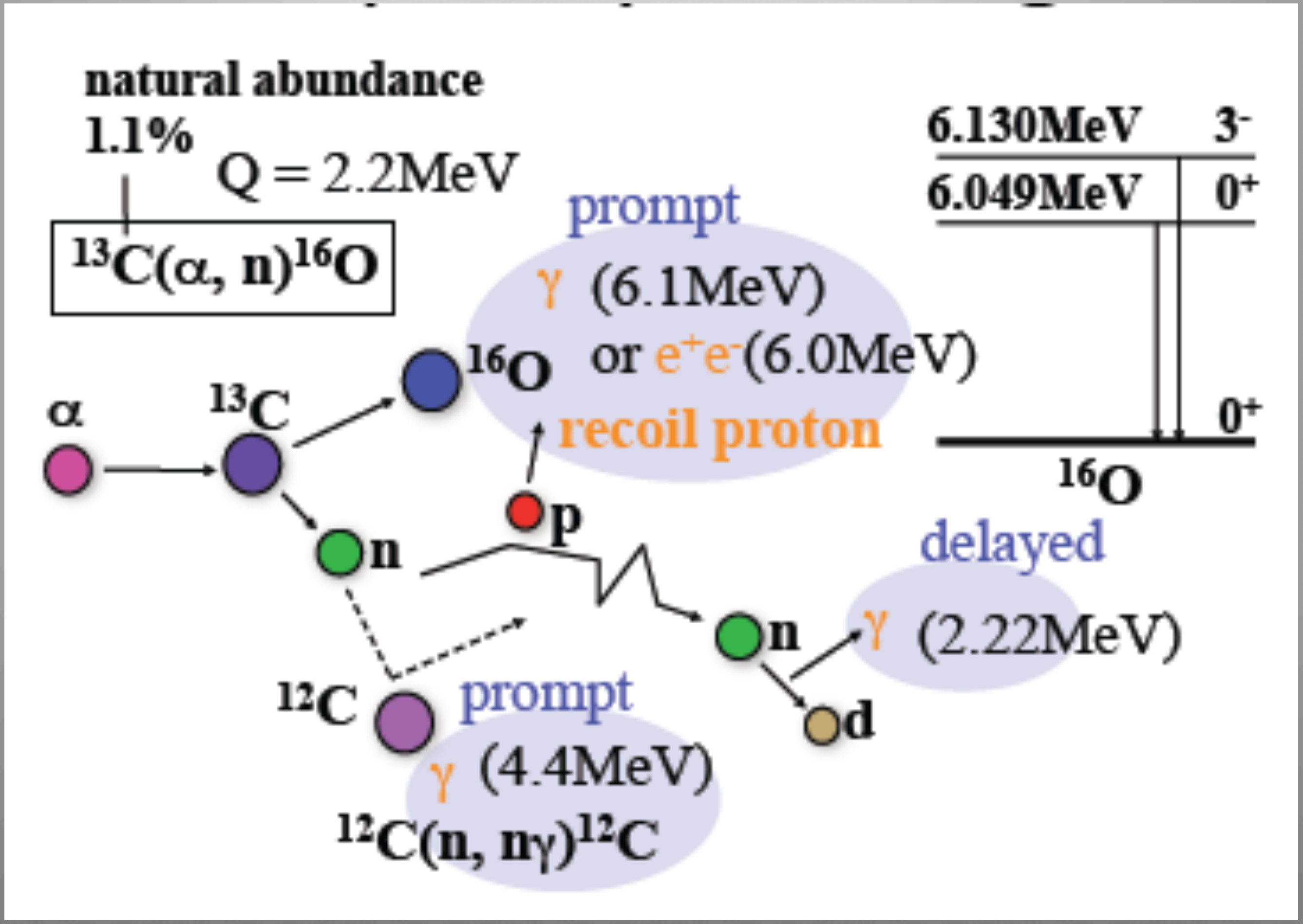
Visible energy of the prompt event



0.206 ± 0.004 events/data set

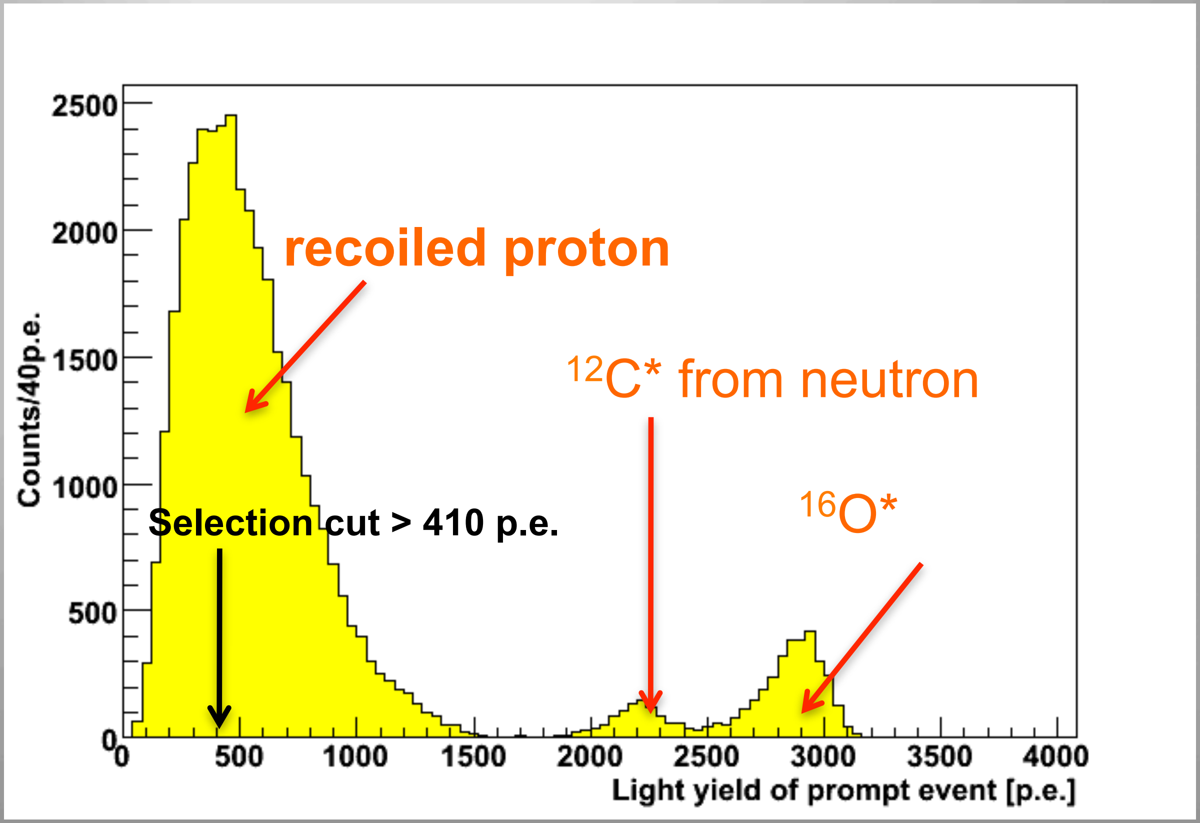
$^{13}C(\alpha,n)^{16}O$

1) Isotopic abundance of ^{13}C: 1.1%
2) ^{210}Po contamination: A_{Po}~ 12 cpd/ton



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

Probability for ^{210}Po nucleus to give (α,n) in pure ^{13}C $(6.1\pm0.3)\ 10^{-6}$ (Mc Kee 2008).
In PC it corresponds to $(5.0\pm0.8)10^{-8}$



(0.13 ± 0.01) events/exposure

Running and planned experiments
having geoneutrinos among their aims