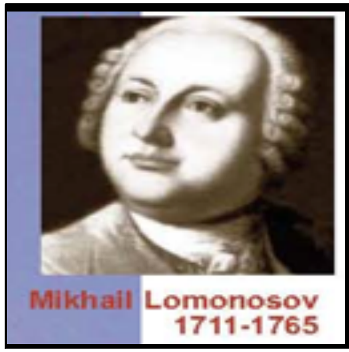


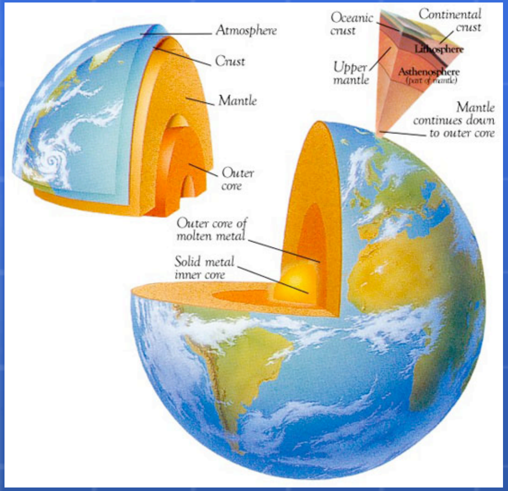
# Geo-Neutrinos

Sandra Zavatarelli INFN Genova (Italy)

# Geo-ν as probes for the deep Earth

*Thanks to neutrinos we were able to get closer insights into deep stellar core…*

*Why do not extend this approach to the Earth study?*



→ **NEUTRINO GEOSCIENCE**

**The Earth shines in anti-ν ($\Phi_\nu \sim 10^6$ cm$^{-2}$ s$^{-1}$)**

$^{232}$Th → $^{208}$Pb + 6 α + 4 $e^-$ + **4 $\bar{\nu}_e$** + 42.8 MeV

$^{238}$U → $^{206}$Pb + 8 α + 8 $e^-$ + **6 $\bar{\nu}_e$** + 51.7 MeV

$^{235}$U → $^{207}$Pb + 7 α + 4 $e^-$ + **4 $\bar{\nu}_e$** + 46.4 MeV

$^{40}$K → $^{40}$Ca + $e^-$ + **1 $\bar{\nu}_e$** + 1.32 MeV (89.3%)

$^{40}$K + e → $^{40}$Ar + $e^+$ + **1 $\nu_e$** + 1.505 MeV (10.7%)

Heat Producing Elements

HPE's

✓ **Released heat and anti-neutrinos flux in a well fixed ratio!**

*Geo-ν as probes for the deep Earth : feasible because of the progresses on understanding neutrino properties and propagation and because of the existence of extremely low background scintillation detector( expected rates ~ few tens events/year, detection reaction: $\bar{\nu}_e$+p->$e^+$+n),*

# Talk Outline

✓ The Earth: what we know and what the geo-ν could help to undestand:

- Energy budget;
- Composition and Structure;

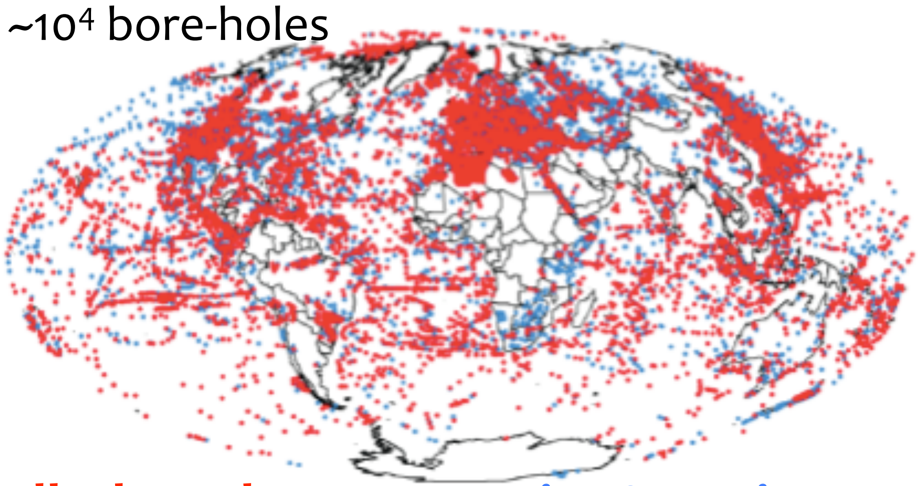
✓ Geo-ν: the energy spectra, the expected fluxes and the detection techniques…

✓ Two experiments measuring geo-ν, Borexino and Kamland: new results released in March '13

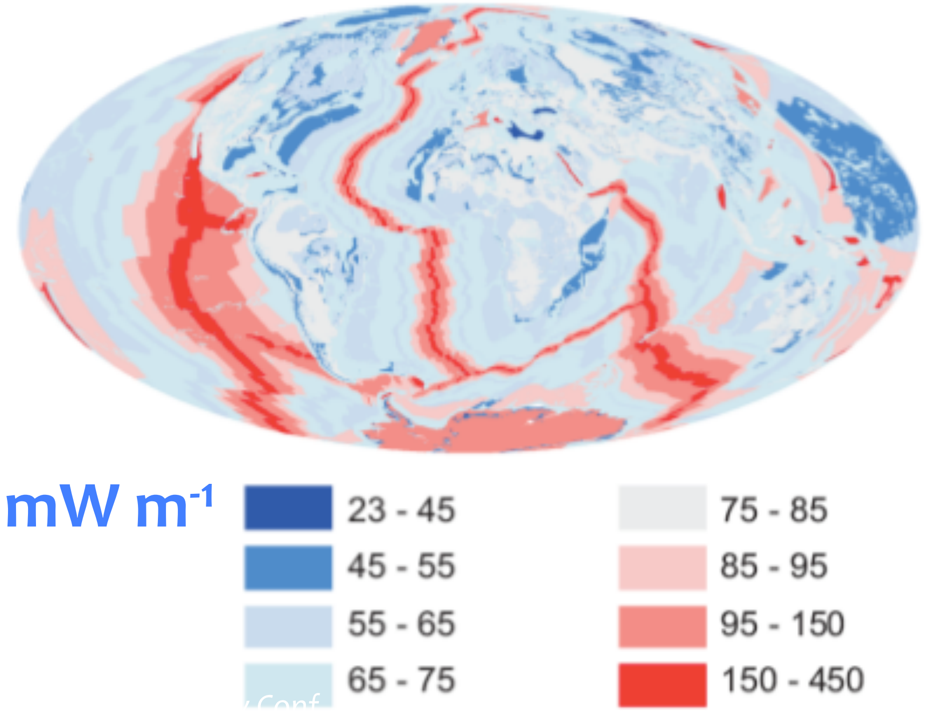
✓ Combined analysis

✓ The future

# Sources of Earth heat: an open issue!!



**Pollack et al., 1993 + Davies & Davies 2010**



## Heat flux: 47 ± 2 TW

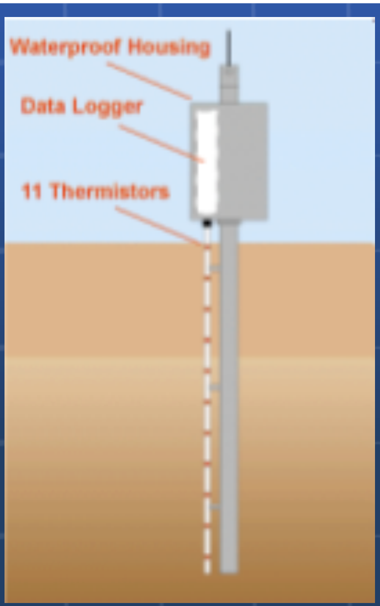
*(Davies and Davies 2010)*

Understanding of Earth energetics is a key point to define:

- the energy available to drive the plate tectonics;
- the power substaining the geo dynamo, the source of the Earth magnetic field…

Cond. heat flow law:

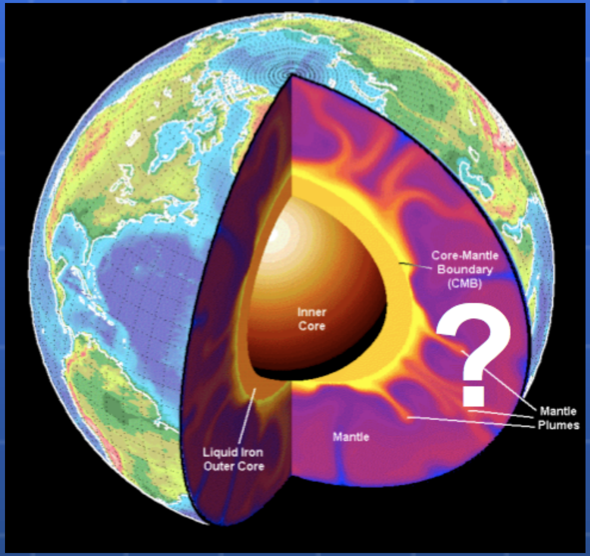
*Q=-k dT/dx*



# Sources of Earth heat: an open issue!!

Necessary energy supply: U = H (heat flow) x t (Earth age)~ $5\ 10^{30}$ J

$U_G \sim GM^2/R \sim 4\ 10^{32}$ J, $U_{chem} \sim 0.1$ eV x $N_{at} \sim 6\ 10^{31}$ J, $U_{nucl} \sim 1$ MeV x $N_{nucl} \sim 6\ 10^{30}$ J => All ok!!!!!



- **Total heat flow ("measured"):**
  **47±2 TW (**
- **Internal heating ?** Radiogenic power: 10-30 TW
  (different Earth models..)
  ~20% escapes to space as geo-ν
  ~80% remains to heat planet

Geo-ν fluxes => HPE's abundances => Radiogenic heat

- Other heat sources:
  - Residual heat and secular cooling;
  - gravitational contraction and extraterrestrial impacts in the past;
  - mantle differentiation and recrystallisation…

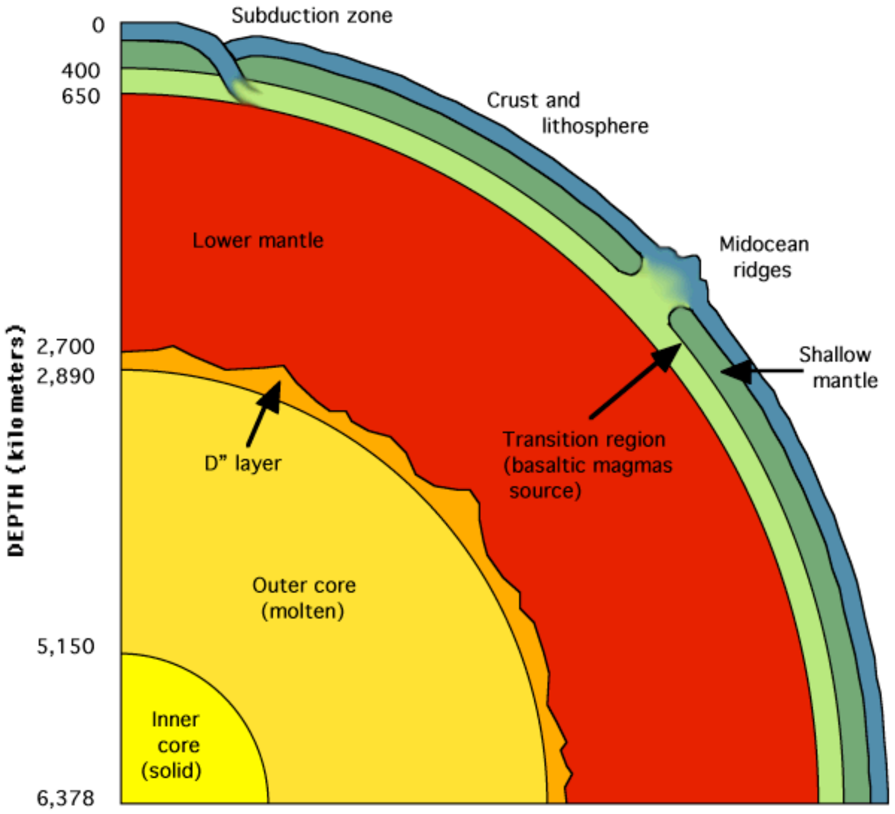
**IMPORTANT MARGINS**
**FOR ALL DIFFERENT MODELS OF THE EARTH HEAT SOURCES**

# The Earth: Composition

## Sismology -> Mechanical layers

**Discontinuities in the waves propagation and velocity -> structure & density profile**

No info about the chemical composition of the Earth



How do we know the Earth composition ??

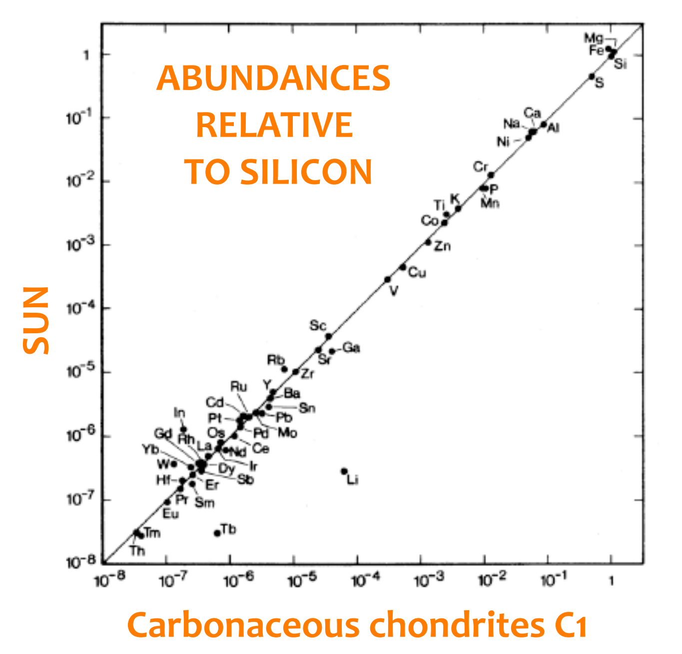
**Direct rock samples**

- surface and bore-holes (max. 12 km)
- mantle rocks brought up by tectonics and **vulcanism**

BUT: POSSIBLE ALTERATION DURING THE TRANSPORT

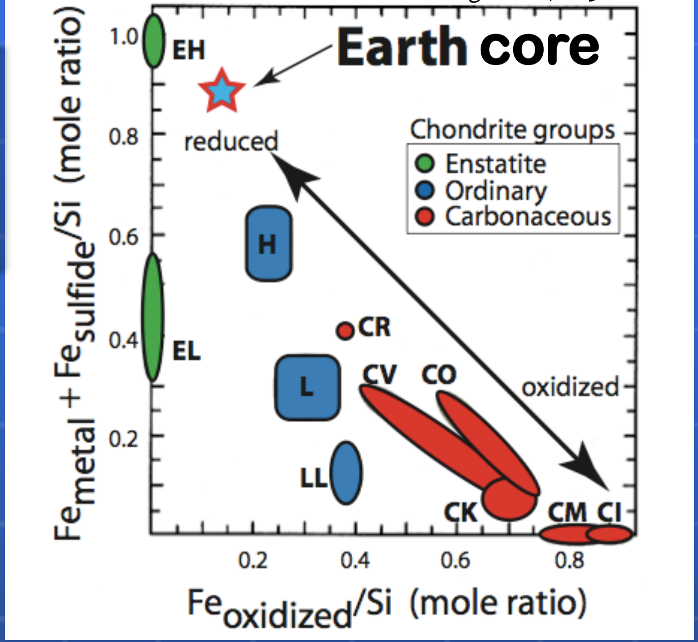
The Crust and Upper Mantle composition are quite known but what about the Lower Mantle and Core composition?

# Cosmochemistry and BSE Models



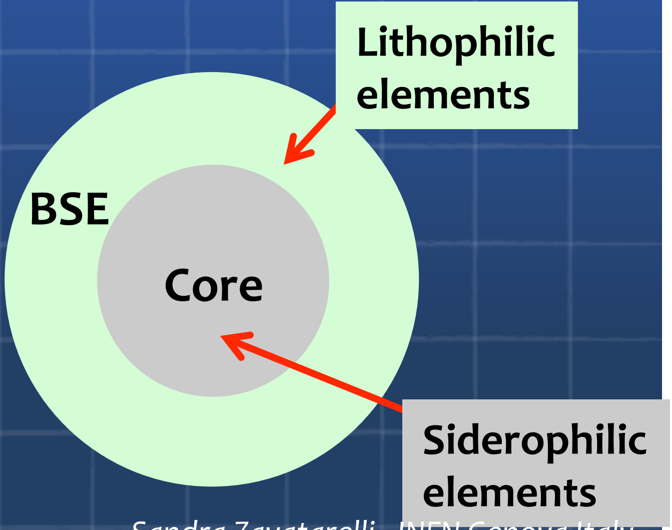
Chondrites are the essential building blocks of the Earth

Many chondrites...
many Earth models!



*W. Mc Donough et al.,2013*

- ✓ Earth core formation occurred after ~ 10 millions of years;
- ✓ The BSE models describes the primordial non metallic Earth that followed planetary accretion and core separation prior to its differentiation into a mantle and crust.



**Lithophilic elements**

**BSE**

**Core**

**Siderophilic elements**

# BSE models

**Three classes of BSE compositional models:**

- ✓ Cosmochemical (enstatite chondrites, collisional erosion)
- ✓ Geochemical (carbonaceous chondrites+terrestrial samples)
- ✓ Geodynamical (mantle convection energetics+surface heat loss)

Strong differences on HPE abundances predictions:

| **Ref. O. Šrámek et al (1)** | **Cosmochem.** | **Geochem.** | **Geodyn.** |
|---|---|---|---|
| $A_U$ (ppb) | 12 ±2 | 20±4 | 35±4 |
| $A_{Th}$ (ppb) | 43±4 | 80±13 | 140±14 |
| $A_K$ in ppm | 146±29 | 280±60 | 350±35 |
| Th/U | 3.5 | 4.0 | 4.0 |
| K/U | 12000 | 14000 | 10000 |
| Tot. Power (TW) | 11±2 | 20+4 | 33±3 |
| Mantle Urey ratio | 0.08±0.05 | 0.3±0.1 | 0.7±0.1 |
| Mantle power (TW) | 3.3±2.0 | 12±4 | 25±3 |

factor 3

factor 10!!

*(1) O. Šrámek et al. Earth. Plan. Sci. Letters 361 (2013)356-366*

# Geo-ν a unique direct probe of the Earth interior

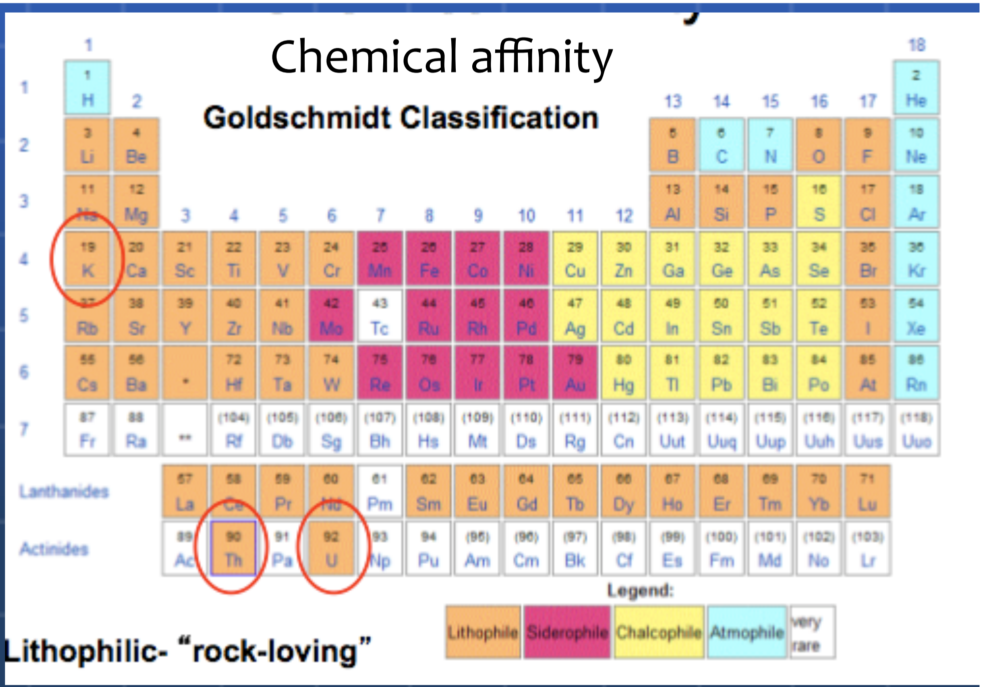
**The geo-ν could help to answer to the following open questions:**

- *What is radiogenic contribution to the Earth energy budget?*
- *Which models (BSE?) are correct?*
- *Earth composition: which are the absolute HPE’s abundances? How their are distributed?*
- *Is the Th/U ~ 3.9 like in chondrites?*

U, Th and K are refractory-lithophilic elements, so they are concentrated in the crust & mantle

| **Ref . Y. Huang et al*** | **M $10^{21}$ Kg** | **U Abundance μg/g** | **U Mass μg/g** |
|---|---|---|---|
| Continental Upper Crust | 6.7 ± 0.8 | 2.7 ± 0.6 | $18.2^{+4.8}_{-4.3}$ |
| Ocean.Crust | 6.3 ± 2.2 | 0.07 ± 002 | 0.4 ± 0.2 |
| Depleted Mantle | 3207 | 0.008 | 25.7 |
| Enriched Mantle | 704 | 0.034 | 24.0 |

*(*) Huang et al., DOI: 10.1002/ggge.20129,2013*



Chemical affinity

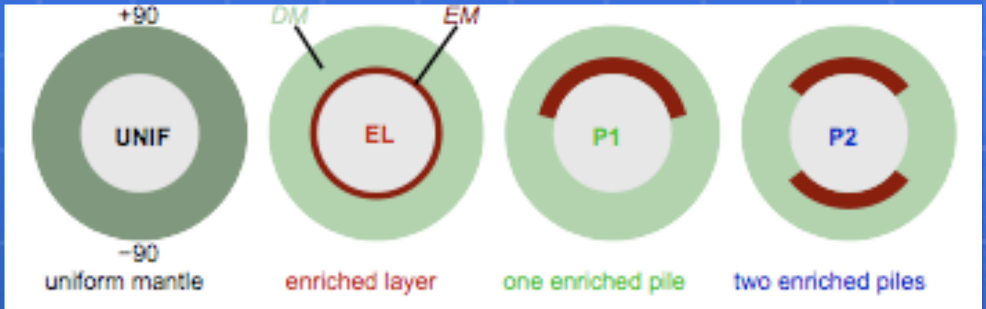
Goldschmidt Classification

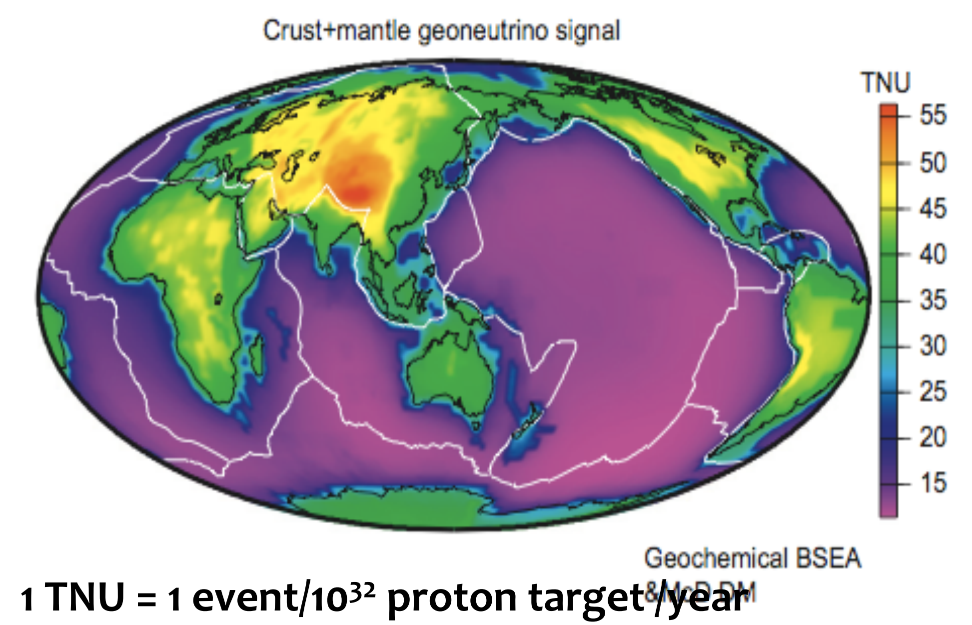
Lithophilic- “rock-loving”

# The importance of multi-site measurements:

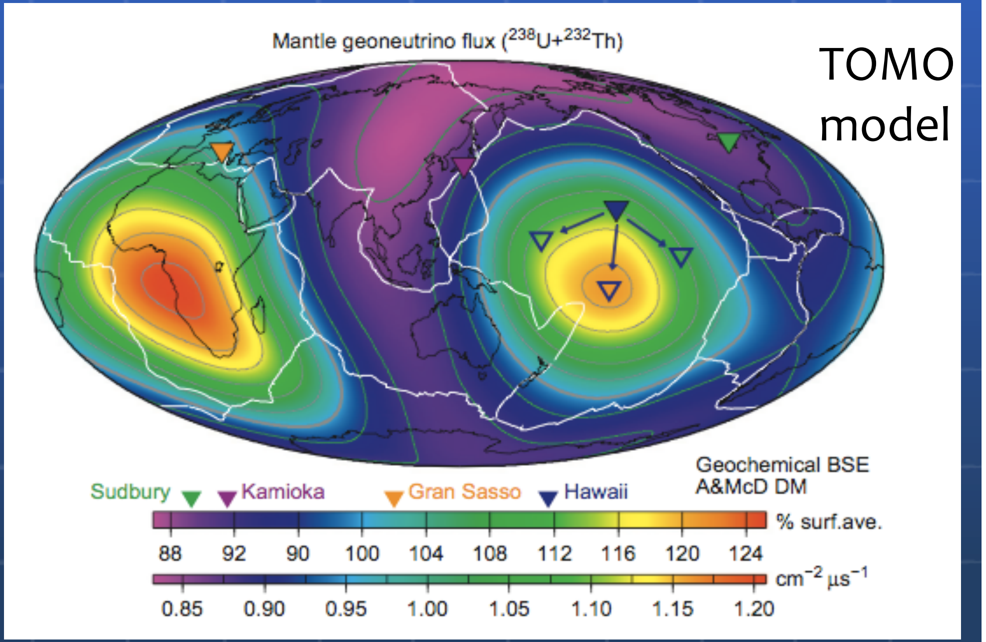
Geo-ν fluxes not homogeneous!! Seismic tomography reveals superplumes at the base of the mantle beneath Africa and the Pacific => evidences for a not homogeneous mantle…

Plots from
O. Šrámek et al (2013)





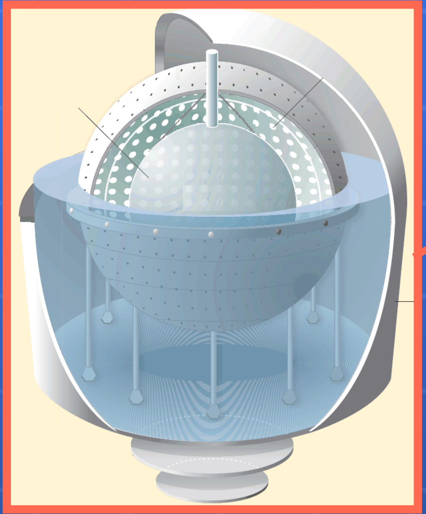
1 TNU = 1 event/$10^{32}$ proton target/year

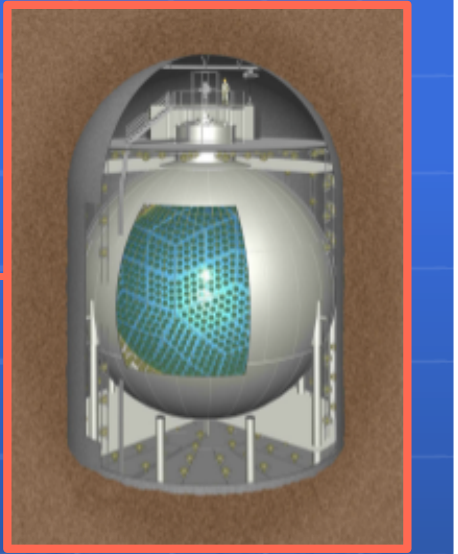


TOMO model

**A one site measurement even if very precise cannot say the whole story: join effort!**

# Experiments measuring geo-ν





## Borexino

Lab. Naz. Gran Sasso (Italy)

Continental crust

Latitude ~ 40° N
Longitude: 13.57° E (LNGS)
137.31° E Kamioka

## KamLAND

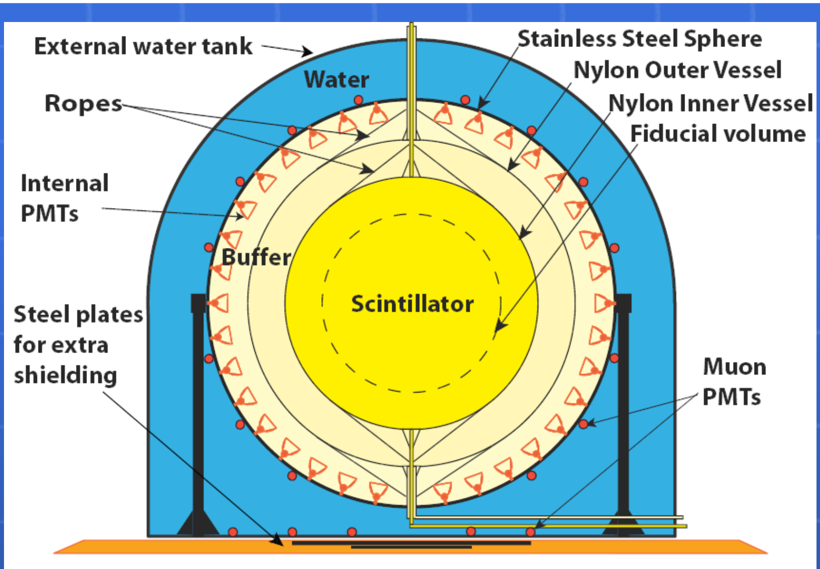
Kamioka (Japan)

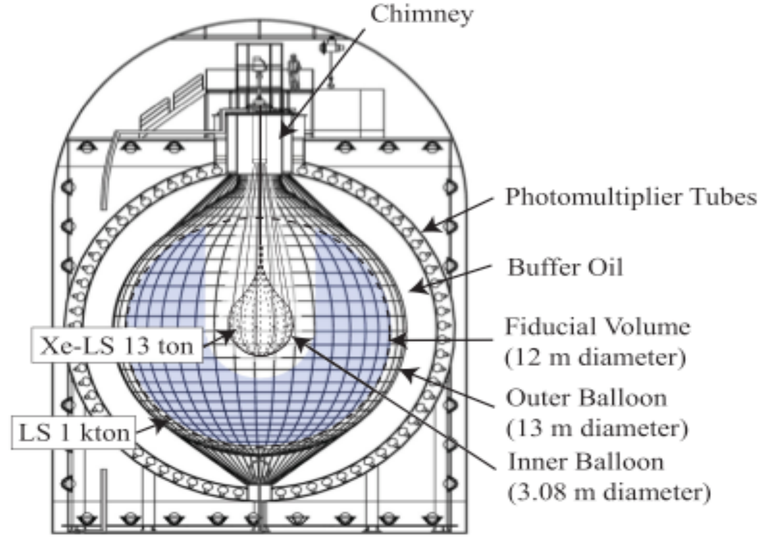
Contin. + oceanic crust

- DAQ started in 2007;
- Observation at 99.997 C.L. in 2010 (Bellini et al, PLB 687) in 252.6 ton y:
- 2013: new data release based on a statistics of 3.7 $10^{31}$ prot/year.

- The first excess due to geoneutrinos measured in 2005 (Araki et al. Nature 436);
- 99.997 C.L. observation in 2011 (Gando et al, Nature Geoscience 1205) in 4132 ton y:
- 2013: new data release based on a statistics of 4.9 $10^{32}$ prot/year

# KamLAND & Borexino





**Borexino**:

- originally build to measure solar neutrinos, extreme radiopurity needed and achieved;
- 280 tons of PC+ 1.5 g/l PPO;
- 3600 m.w.e. depht, $\Phi\mu \sim 1 m^{-2} h^{-1}$;
- mean reactors distance ~ 1170 km

**Kamland:**

- originally build to measure reactor anti-ν;
- 1 kton of 80% dodec., 20% PC + 1.4 g/l PPO;
- 2700 m.w.e. depht; $\Phi\mu \sim 5.4\ m^{-2}\ h^{-1}$;
- mean reactors distance ~ 80 km.

# Geo-ν detection

**Prompt:**

$\nu + p \rightarrow n + e^+$

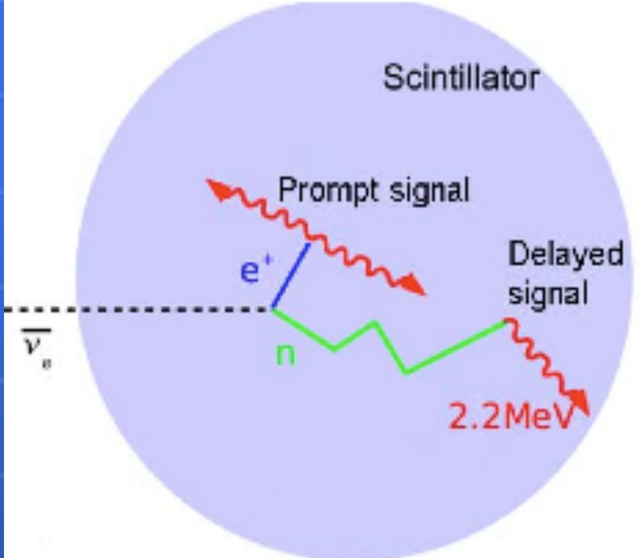
$E_{thr}=1.8$ MeV

*Minimum det. energy: 2x 511 keV*

$E_{prompt}=E_\nu - 0.784$ MeV

**Expected rate:**

~ 2 cpy/100 t

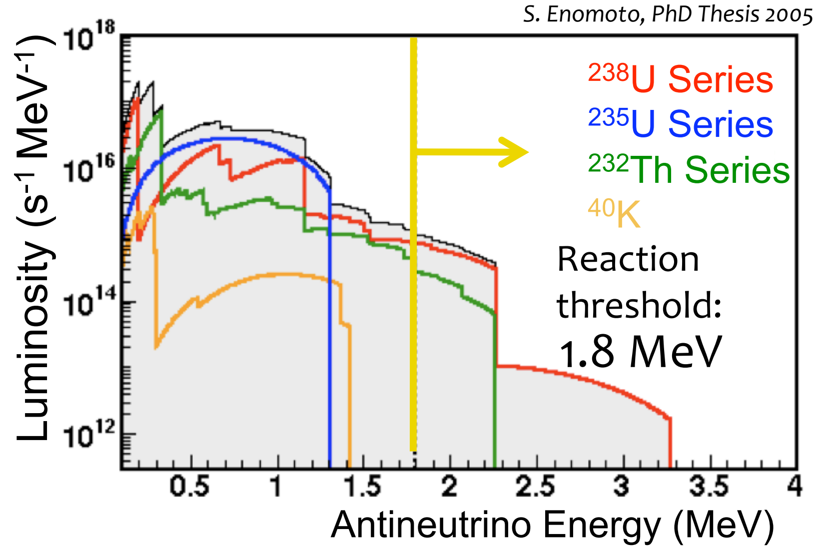


**Delayed (τ~254 μs):**

**$n + p \rightarrow d + \gamma$**

*Detected energy: 2.2 MeV*

*Geo-ν energy spectrum*



A(Th)/A(U)=3.9

S(Th)/S(U) =0.27

# Geoneutrinos energy spectra

The probability to detect electron antineutrino :

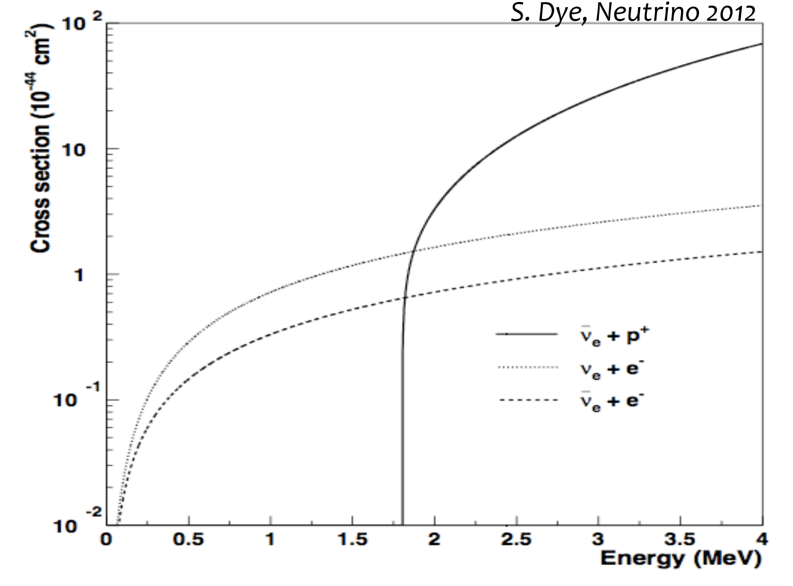
$$P_{ee} = P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = \cos^4\theta_{13}\left(1 - \sin^2 2\theta_{12}\sin^2\left(\frac{\delta m^2 L}{4E}\right)\right) + \sin^4\theta_{13}$$

For geoneutrinos we can use average survival probability:

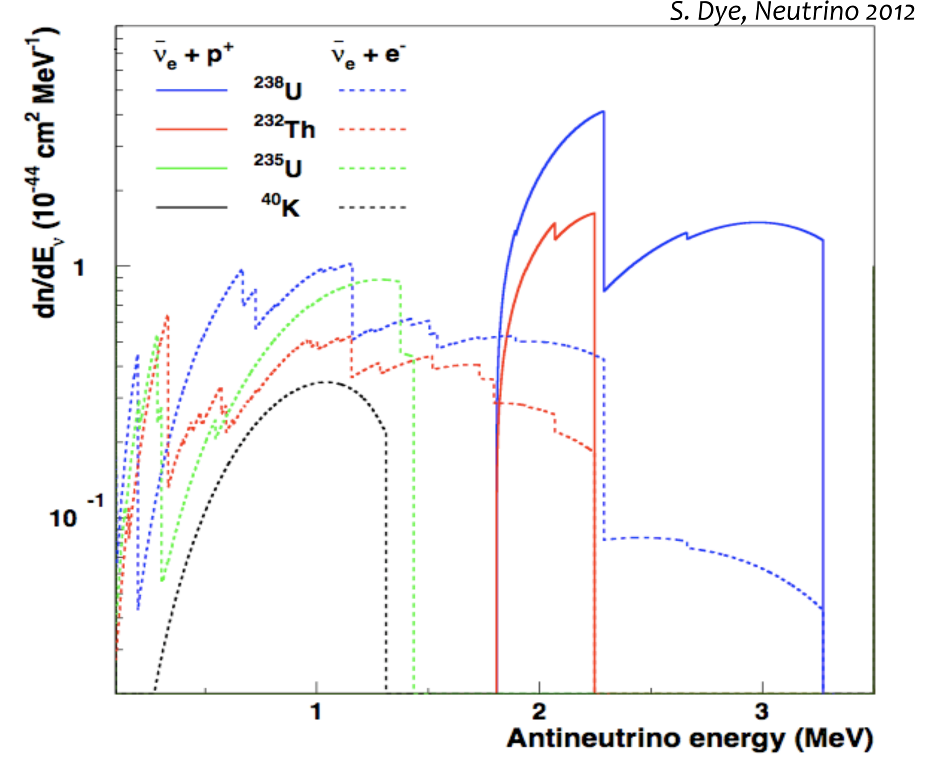
**Pee (3 flavors) ~ 0.54 (in vacuum) -> 0.55 (matter effect)**

$\theta_{13} : 0° \rightarrow 10°$

$<P_{ee}> : 0.58 \rightarrow 0.54$



S. Dye, Neutrino 2012

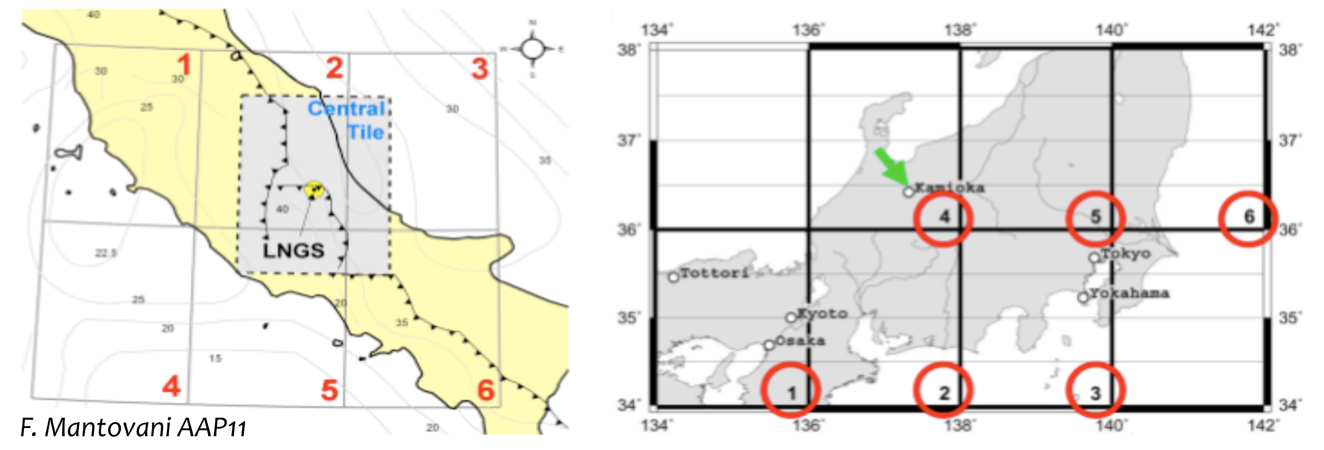


S. Dye, Neutrino 2012

# The importance of the local geology

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

***3 D models of the crust composition up to the Moho depht over an area of six 2° x 2° cells around the detector site => contribution of local crust (LOC)***



*F. Mantovani AAP11*

$S_{tot} = S_{crust} + S_{mantle}$

$S_{crust} = S_{LOC} + S_{ROC}$

1 TNU= 1 event /$10^{32}$ target protons/ year

| | **Borexino [TNU]** | **KamLand [TNU]** |
|---|---|---|
| Local crust (LOC) | 9.7 ± 1.3 | 17.7 ± 1.4 |
| Rest of Crust (ROC) | $13.7^{+2.8}_{-2.3}$ | $7.3^{+1.5}_{-1.2}$ |
| Total crust | $23.4^{+3.1}_{-2.6}$ | $25.0^{+2.1}_{-1.8}$ |
| Lithospheric mantle | $2.2^{+3.1}_{-1.3}$ | $1.6^{+2.2}_{-1.0}$ |
| Mantle | 8.7 | 8.8 |
| Total | $34.4^{+4.4}_{-2.9}$ | $35.4^{+3.0}_{-2.1}$ |

← *G. Fiorentini et al., Phys. Rev. D 86 (2012) 033004*

← *Y. Huang et al., DOI:10.1002/ggge.20129, 2013*

← *W. McDonough and S. Sun, Chem. Geol. 120 (1995) 223*

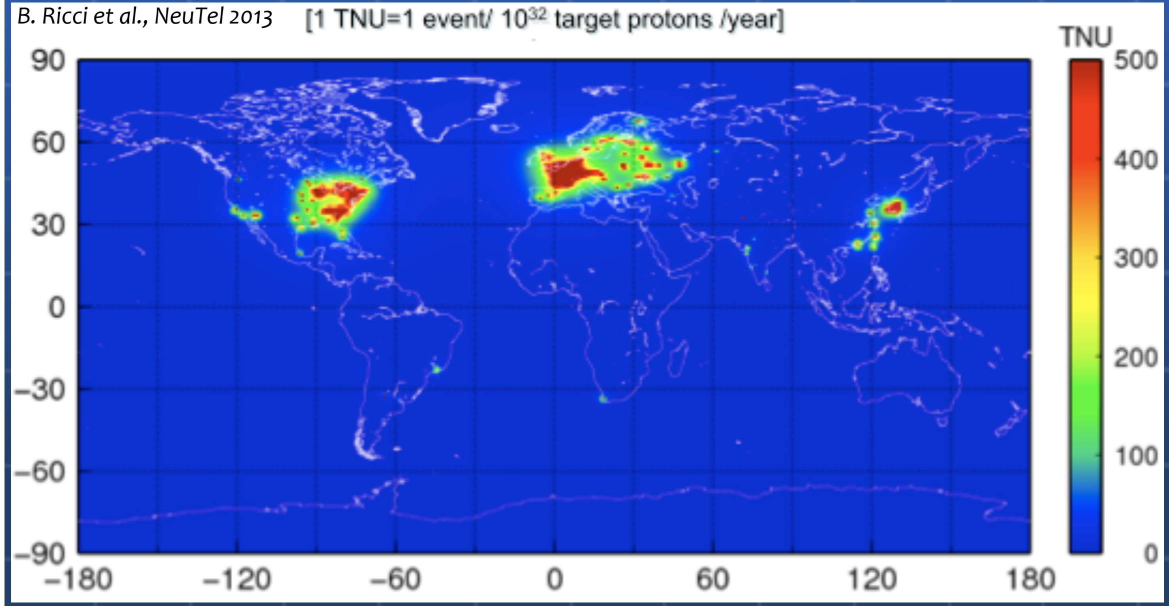
# The most important backgrounds

## Reactor antineutrinos

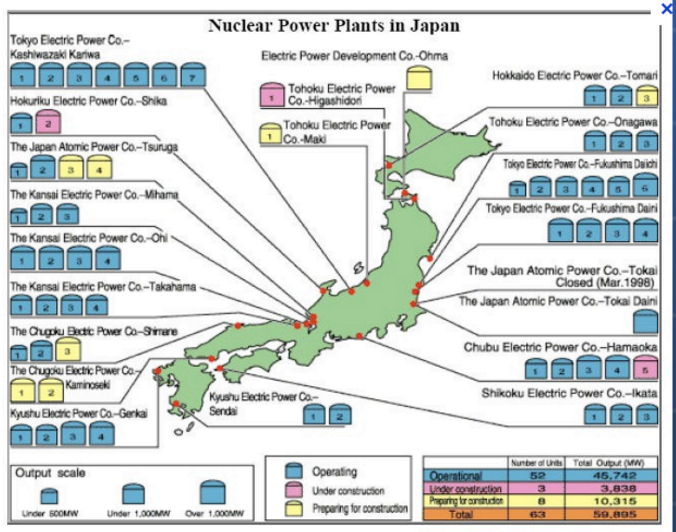
The two collaborations are in contact respectively with with IAEA and EDF (BX) and the the Consortium of Japanese electric power companies *to get info about thermal powers, the reactors operation records,, fuel burn-up and exchange andenrichments log : fluxes evaluated with a dedicated code*

-S(reactors)/S(geo) ~ 0.4 at LNGS

S(reactors)/S(geo) ~ 5 in geo-ν window at Kamioka

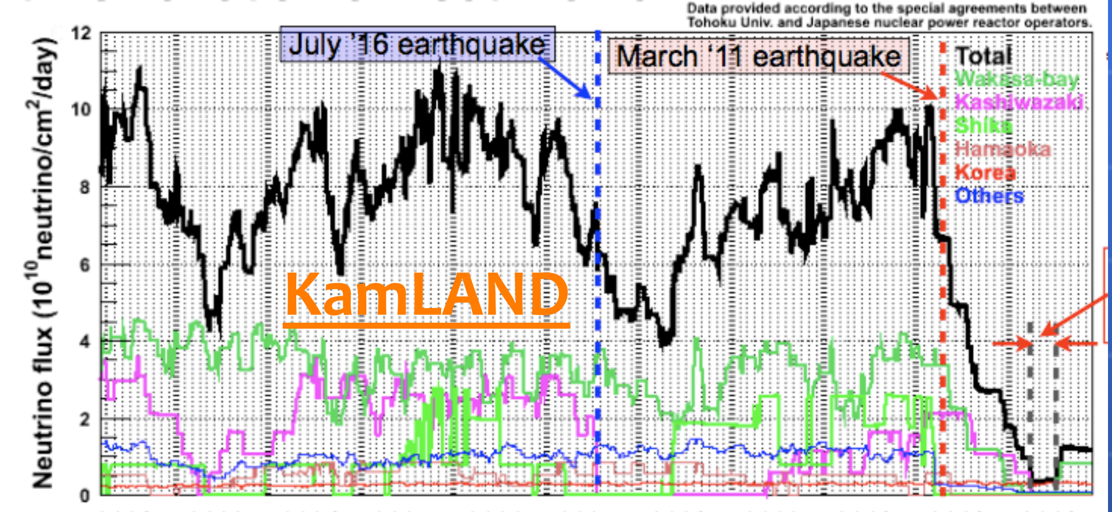

*B. Ricci et al., NeuTel 2013*

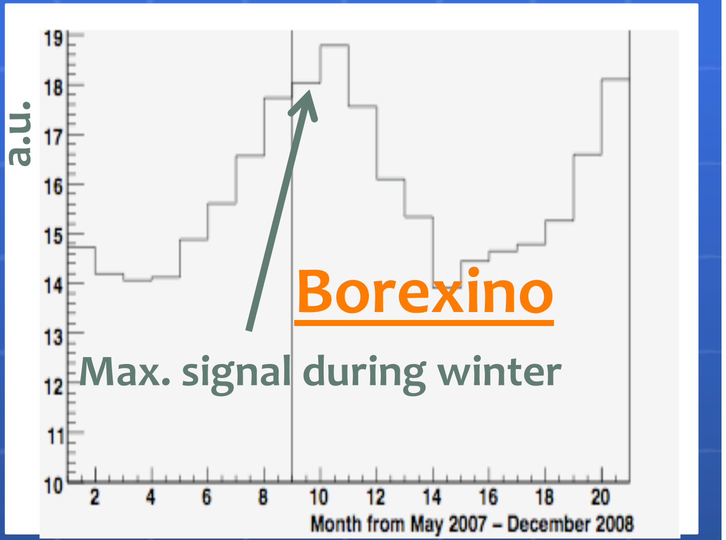
[1 TNU=1 event/ $10^{32}$ target protons /year]



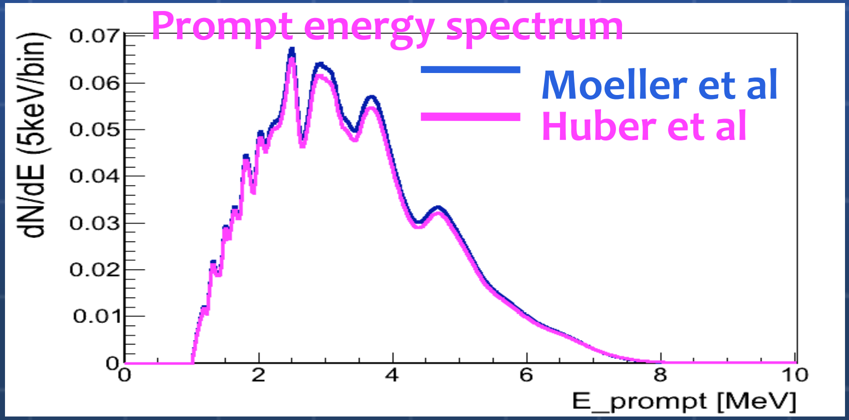
# The most important backgrounds

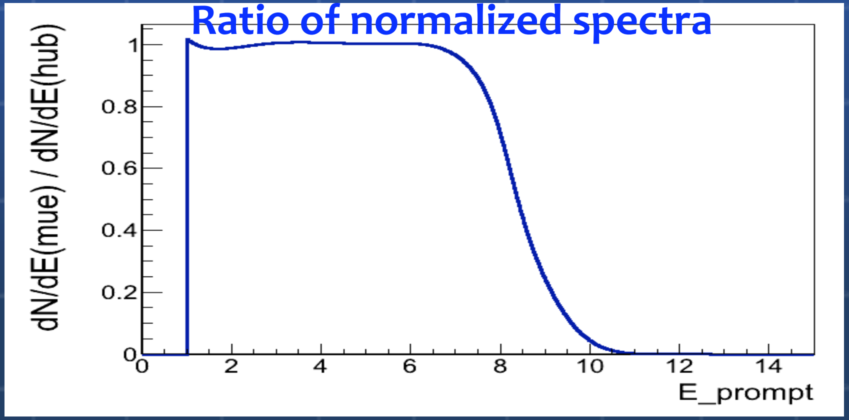
## Reactor antineutrinos: reactors signal vs time





2011: effect of new spectra parametrization => flux increase of ~ 3%





# The most important backgrounds

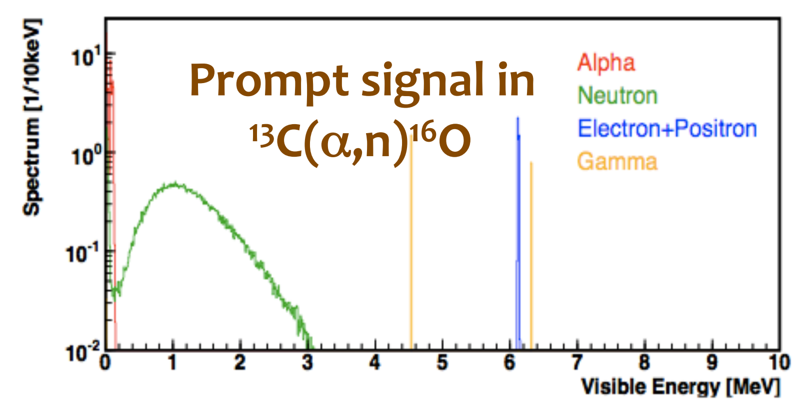
## Background mimicking the anti-ν interactions:

### Internal contamination: $^{13}C(\alpha,n)^{16}O$

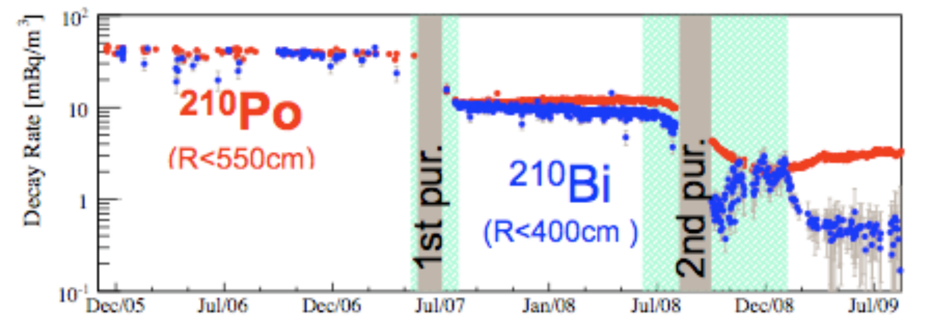
- α particles are emitted in the U an Th chains
- $^{210}$Po α emitter

(KL ~ 5000 cpd/t, now~250 cpd/t, BX~12 cpd/t)

- $^{13}$C low abundance: $^{13}C/^{12}C$~1.1 %
- KL: S(α,n)/S(geo)~ 1.5 ; BX: 1%



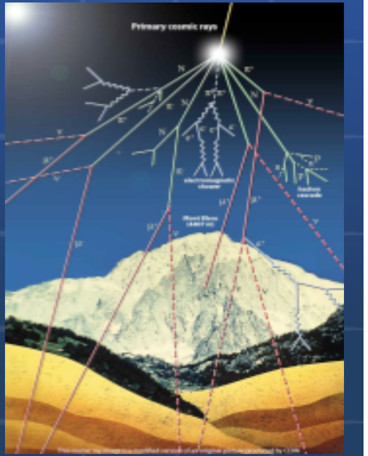
*S. Enomoto PhD Thesis 2005*



*H. Watanabe NGS 2013*

### Random coincidences

- Mostly due to U/Th chains high energy decays and external backgrounds;
- KL: S(rnd)/S(geo)~ 1 ; BX: S(rnd)/S(geo)~1.5%.



### Muon correlated events: fast neutrons & cosmogenic $^9$Li and $^8$He decay via *β-n reactions*

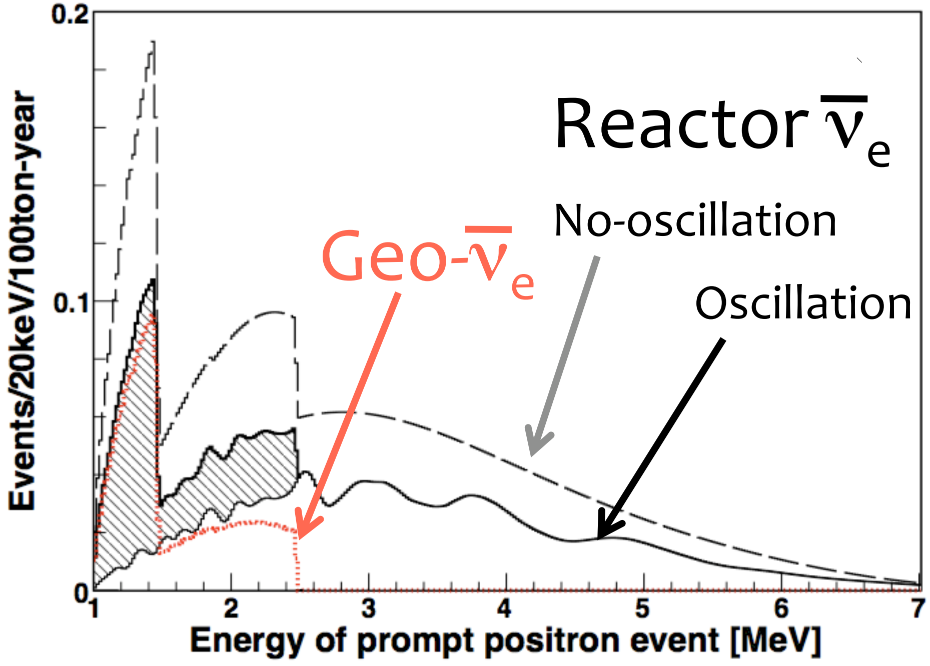
$^9Li \to 2\alpha + e^- + n + \nu$; $^8He \to {}^7Li + n + e^- + \gamma$

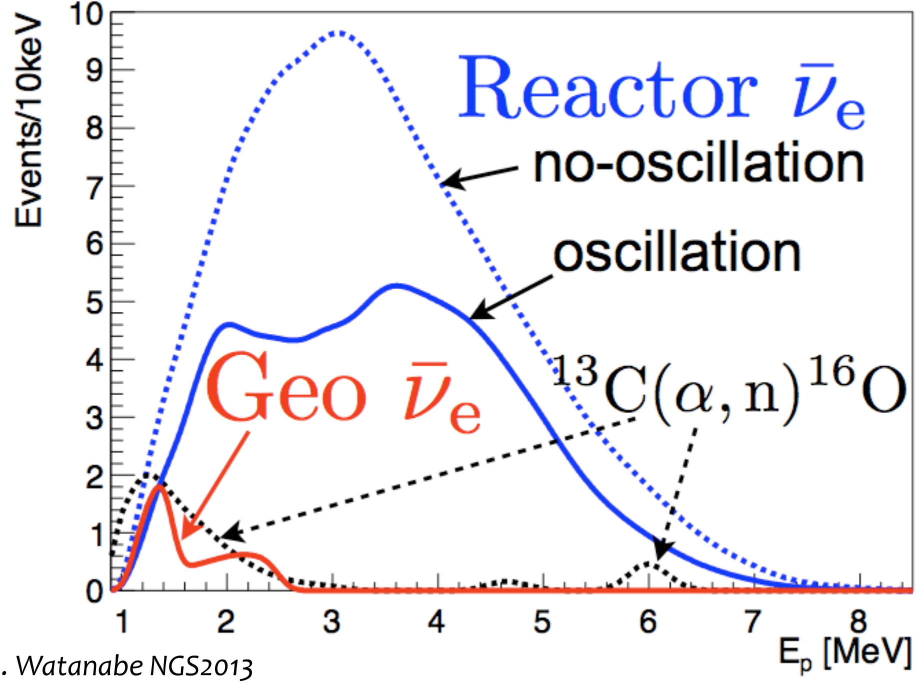
τ~ 150 ms=> 2 s detector veto after scintillator muons-> negligible!!

# The expected signal + background in BX and KL

## Borexino

## KamLAND





*H. Watanabe NGS2013*

$S(reactors)/S(geo) \sim 0.7$ at $E_{prompt} < 2.6$ MeV

$S(\alpha,n)/S(geo) \sim 1\%$

$S(random)/S(geo) \sim 1\%$

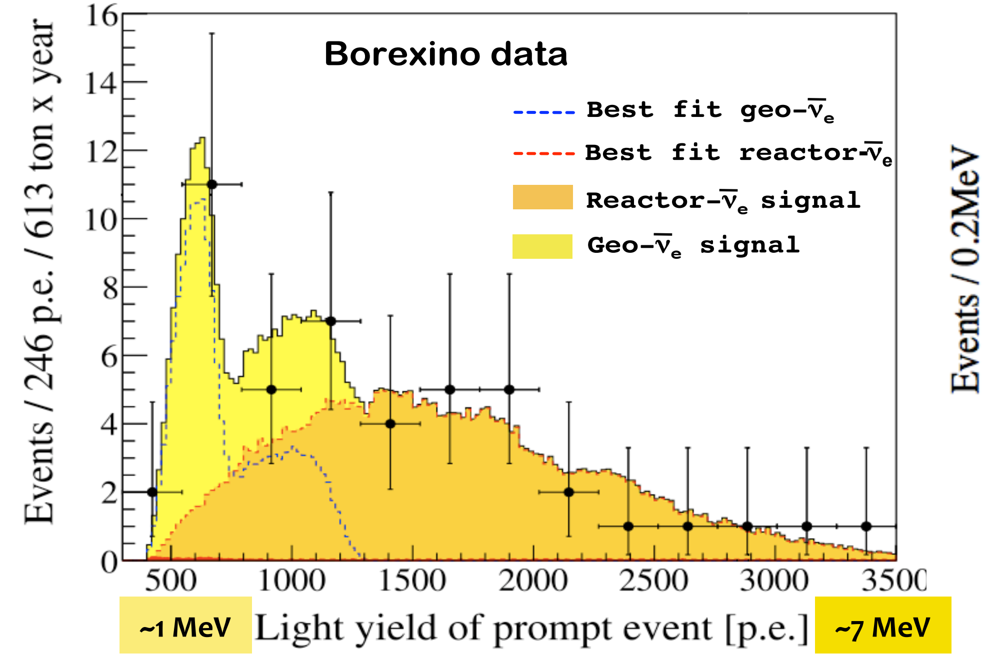
$S(reactors)/S(geo) \sim 5 - 6$ at $E_{prompt} < 2.6$ MeV

$S(\alpha,n)/S(geo) \sim 1.5$

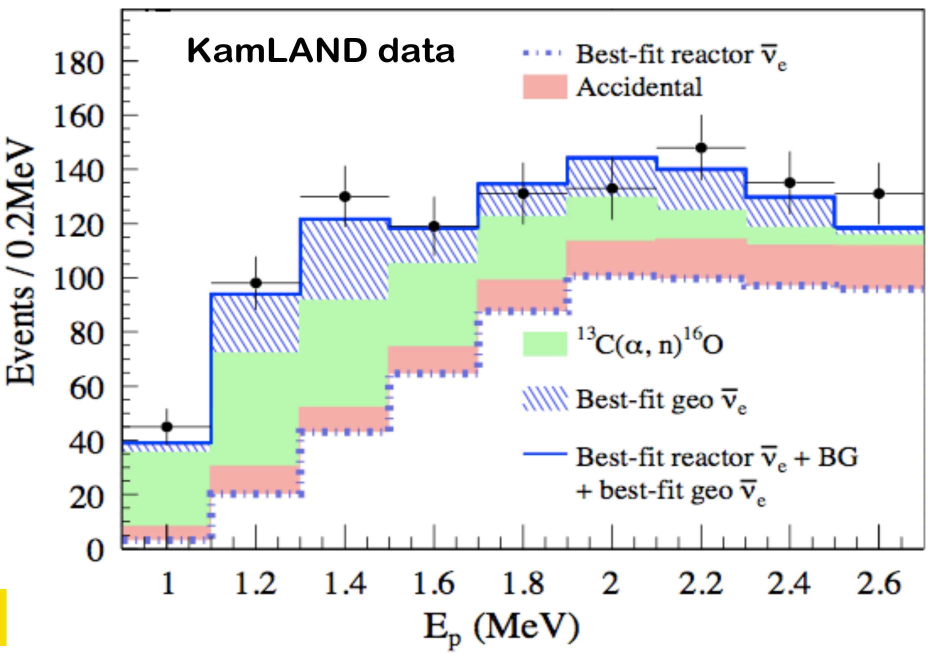
$S(random)/S(geo) \sim 1$

# New results of 2013!

Bellini et al Phys. Lett. B, 722 (2013) 295



A. Gando, Phys. Rev. D 88 (2013) 033001

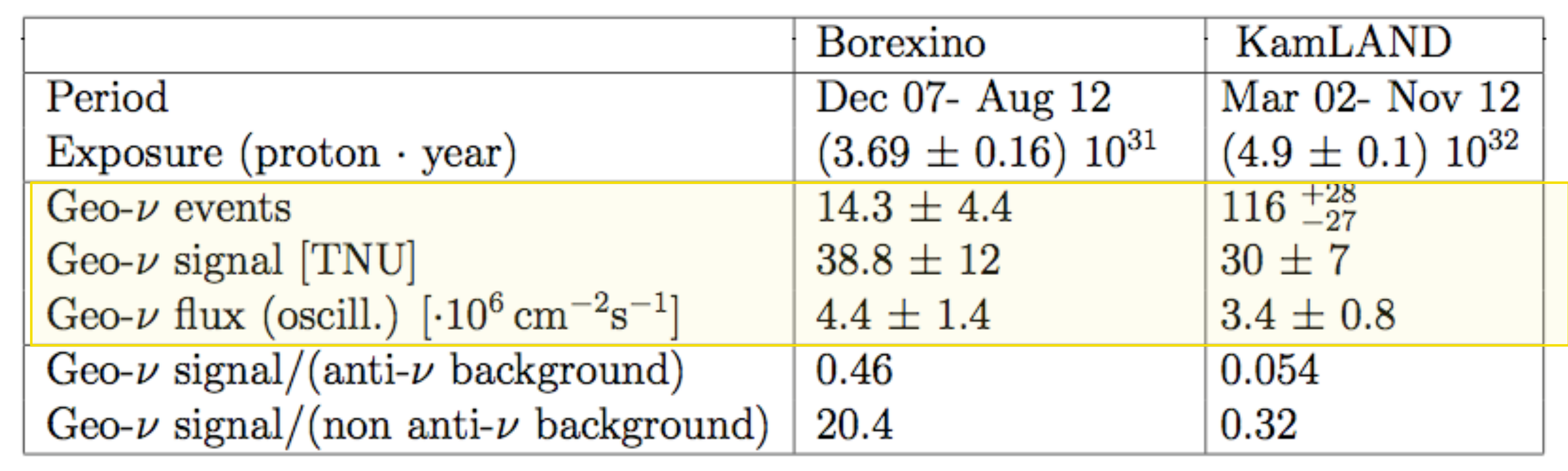


| **Period** | **Aug.07 – Aug.12**<br>**(3.69 ± 0.16) $10^{31}$ prot*y** |
|---|---|
| Tot ev [full sp.] | 46 |
| Reactors ev. | $31.2_{-6.1}^{+7.0}$ (all spectrum) |
| Geo-ν ev. | 14.3 ± 4.4 |
| Background ev. | 0.70 ±0.18 |

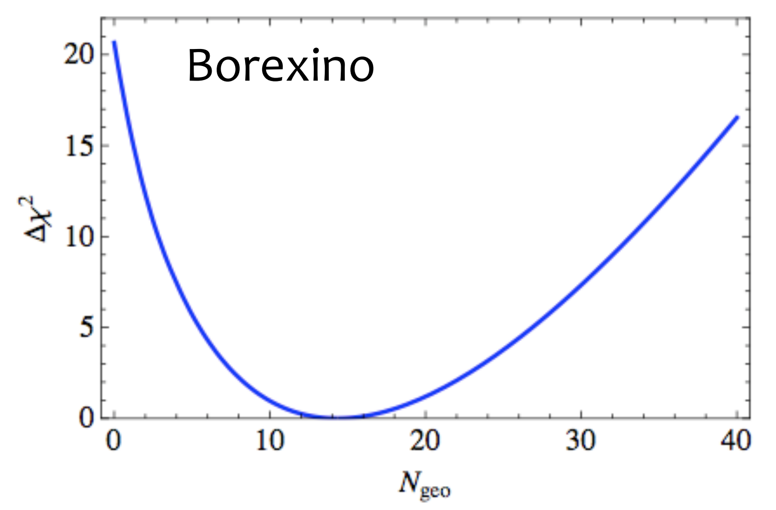
| **Period** | **Mar 02- Nov. 12**<br>**(4.9 ± 0.1) $10^{32}$ prot*y** |
|---|---|
| Tot. Ev. [gν e.w.] | 2611 |
| Reactors ev. | 2131 ± 41 (all spectrum) |
| Geo-ν ev | $116_{-27}^{+28}$ |
| $^{13}$C $(\alpha,n)^{16}$O | 207.1 ± 21.4 |
| Accidental ev. | 125.5 ± 0.1 |

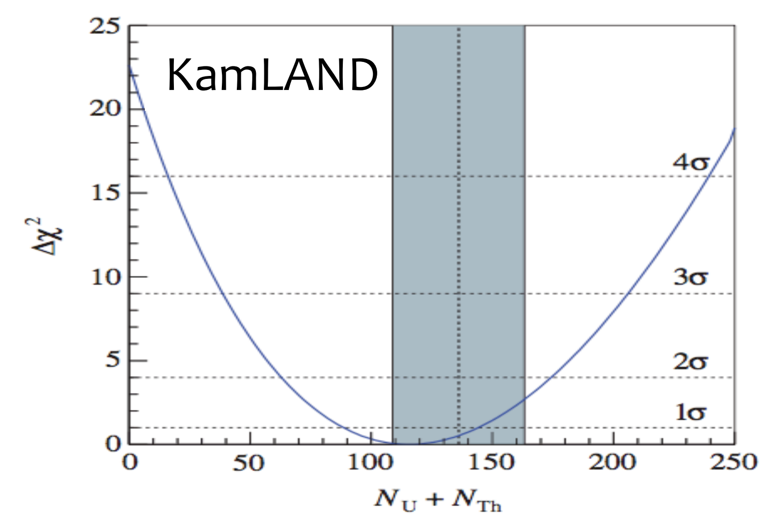
Th/U =3.9

# Geo-ν: the energy spectrum and fit



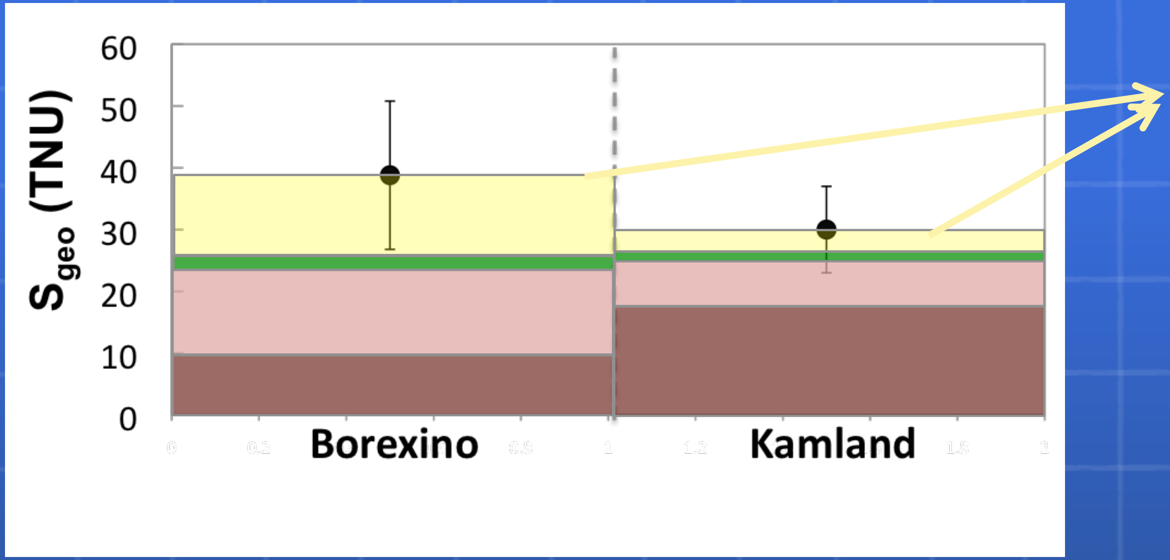
| | Borexino | KamLAND |
|---|---|---|
| Period | Dec 07- Aug 12 | Mar 02- Nov 12 |
| Exposure (proton · year) | $(3.69 \pm 0.16)\ 10^{31}$ | $(4.9 \pm 0.1)\ 10^{32}$ |
| Geo-$\nu$ events | $14.3 \pm 4.4$ | $116\ ^{+28}_{-27}$ |
| Geo-$\nu$ signal [TNU] | $38.8 \pm 12$ | $30 \pm 7$ |
| Geo-$\nu$ flux (oscill.) $[\cdot 10^6\,\mathrm{cm}^{-2}\mathrm{s}^{-1}]$ | $4.4 \pm 1.4$ | $3.4 \pm 0.8$ |
| Geo-$\nu$ signal/(anti-$\nu$ background) | 0.46 | 0.054 |
| Geo-$\nu$ signal/(non anti-$\nu$ background) | 20.4 | 0.32 |





- The null hyphotesis ( $S_{geo}$=0) has a probability of few $10^{-6}$
- Evidence for geo-ν observation at 4.5σ C.L.

# Comparison with expectations



Excess =
Lower+Upper
mantle
signal???

|  | **Borexino [TNU]** | **KamLand [TNU]** |
|---|---|---|
| Local crust (LOC) | $9.7 \pm 1.3$ | $17.7 \pm 1.4$ |
| Rest of Crust (ROC) | $13.7^{+2.8}_{-2.3}$ | $7.3^{+1.5}_{-1.2}$ |
| Total crust | $23.4^{+3.1}_{-2.6}$ | $25.0^{+2.1}_{-1.8}$ |
| Lithospheric mantle | $2.2^{+3.1}_{-1.3}$ | $1.6^{+2.2}_{-1.0}$ |

Mantle inhomogeneity???

# Mantle geo-ν

$S_{geo}$=S(Crust) + S(Mantle)

BOREXINO

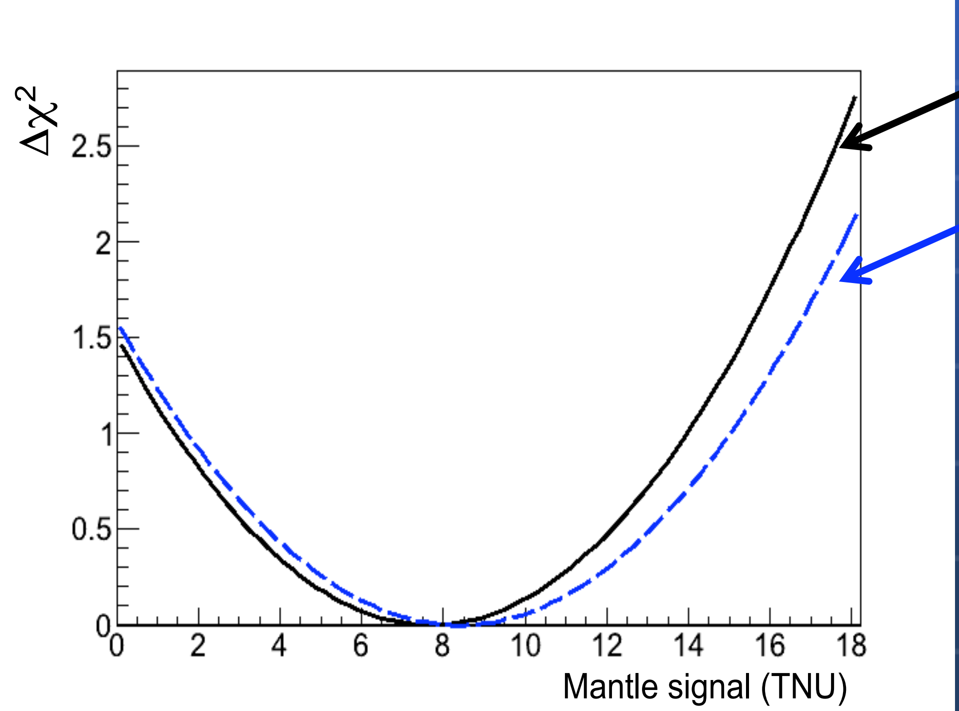
$S^{BX}_{geo}$ (Total) =(38.8 ± 12.0) TNU

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

KamLAND:

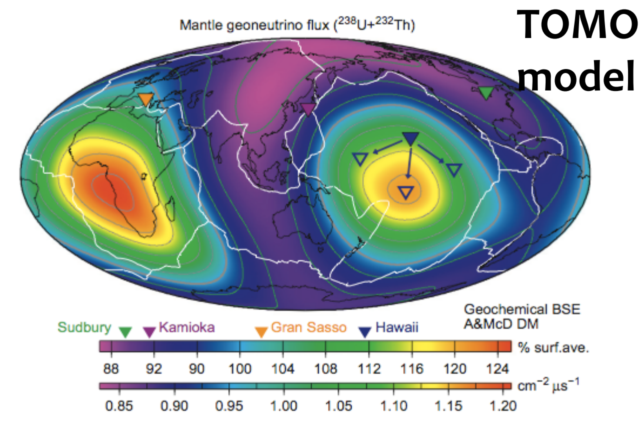
$S^{KL}_{geo}$(Total)=(30 ± 7) TNU

$S^{KL}_{geo}$(Crust)=(25 ± 2) TNU



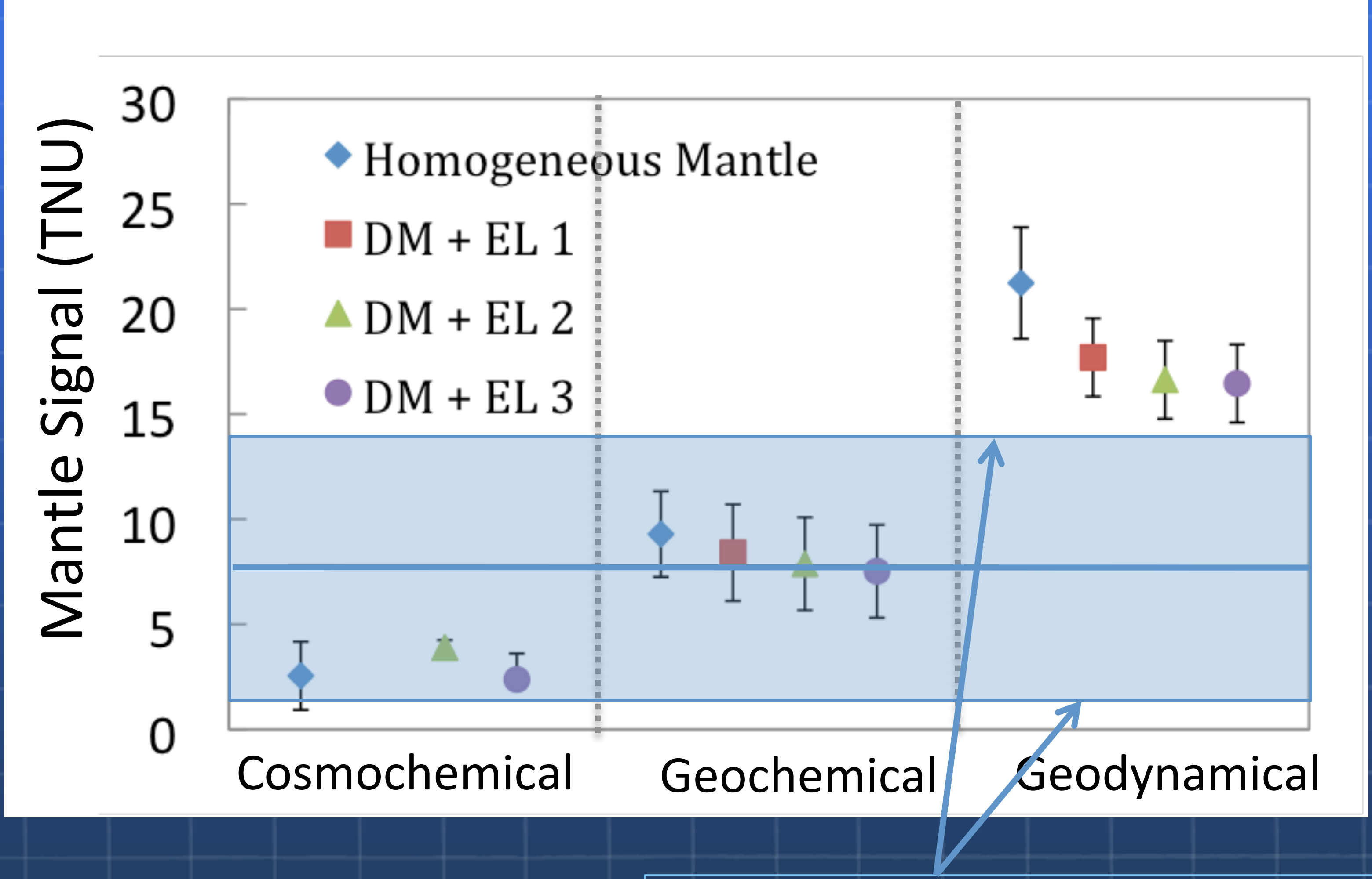
$S_{SYM}$(**Mantle**) = (7.7 ± 6.2) TNU

$S_{TOMO}$(Mantle) = ($\mathbf{8.4}^{+6.6}_{-6.7}$) TNU

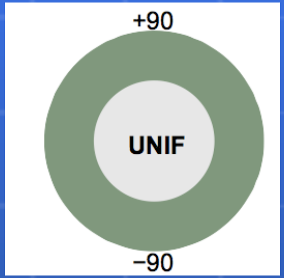


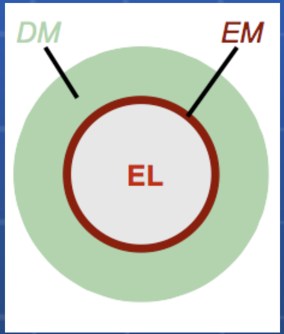
# Mantle geo-ν: comparison with BSE models

Data from O. Šrámek et at (2013)



Uniform distribution



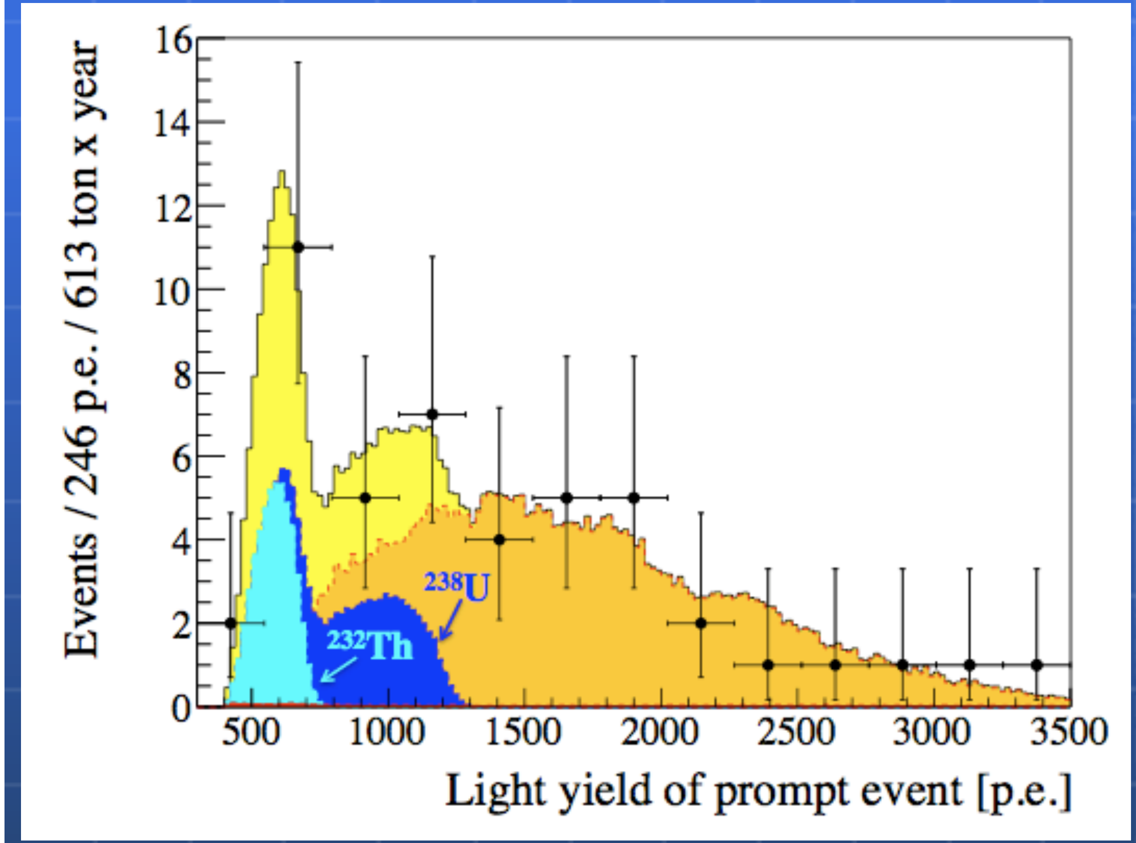


Enriched layer

**Band for the mantle signal (combined analysis)**

# Borexino: fit with free U/Th components

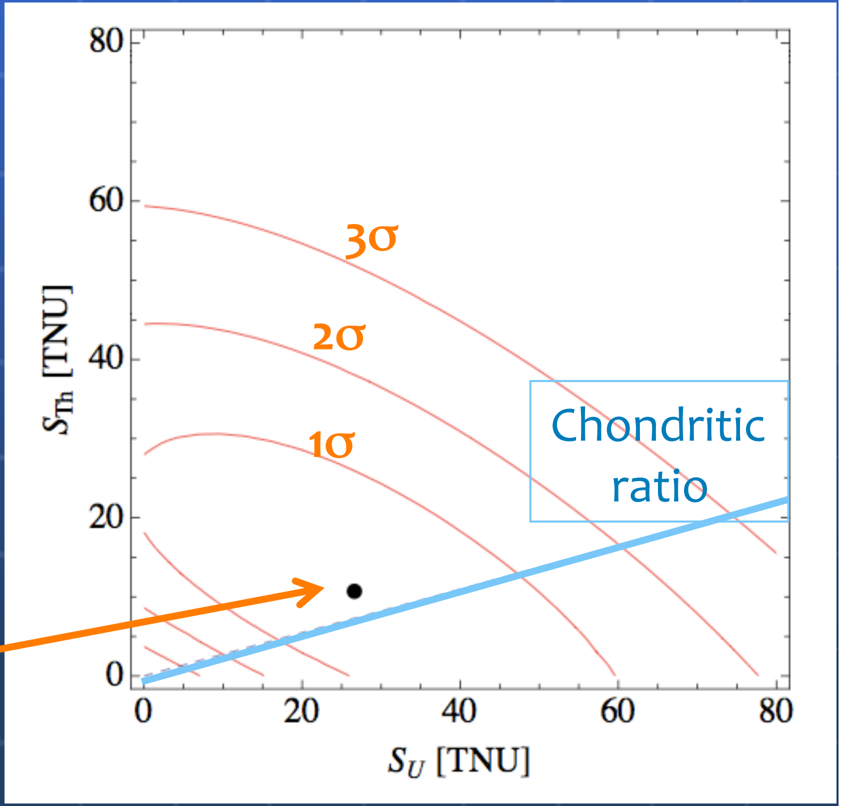
U and Th spectra have been fit as two independent PDF's.



$N_U$ = 9.8 ± 7.2 events

$N_{Th}$=3.9 ± 4.7 events

$N_{react}$=31.7 $^{+7.2}{}_{-6.3}$ events

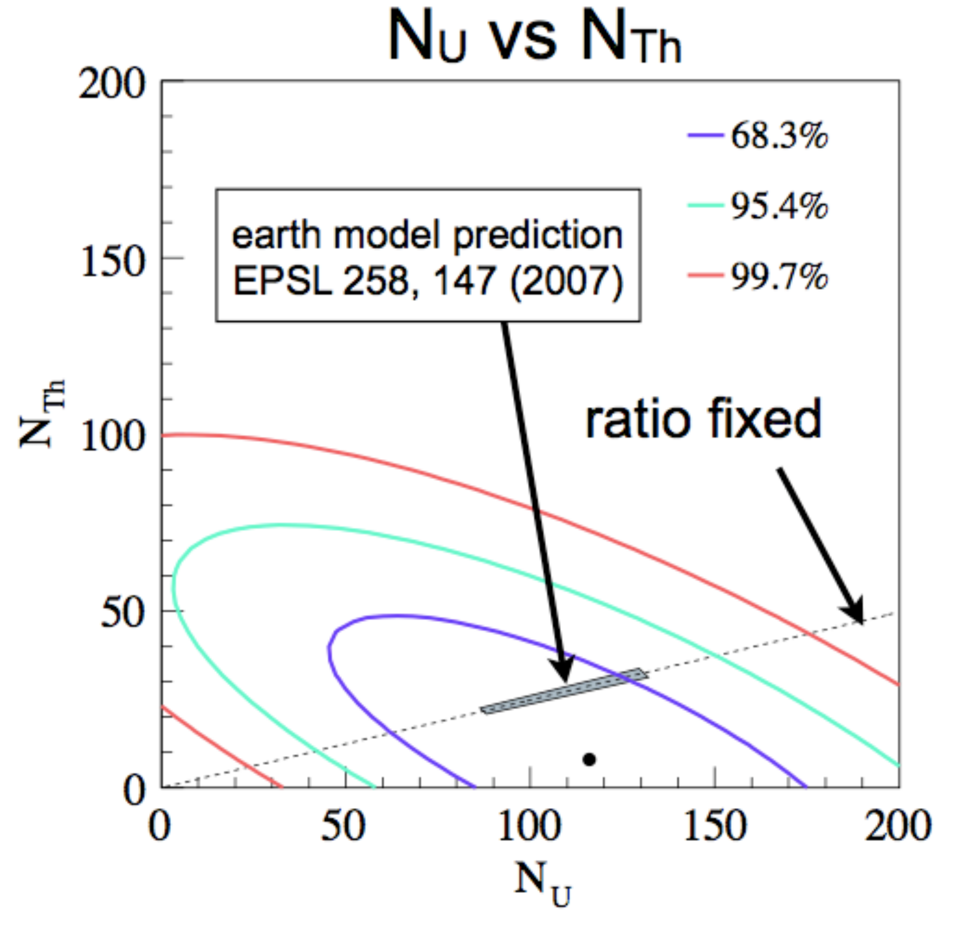


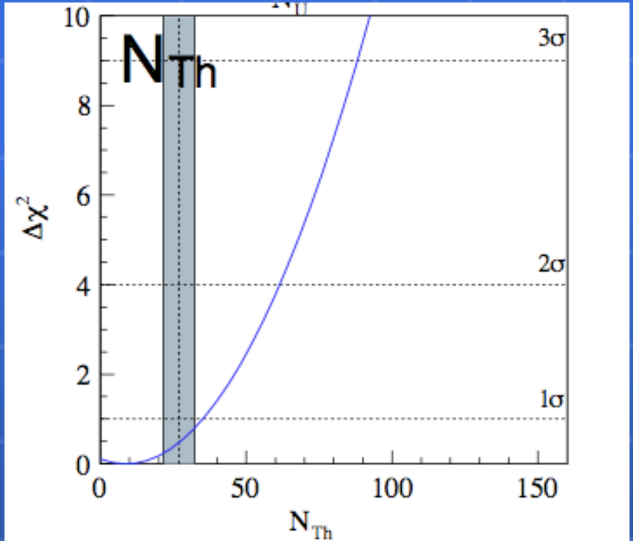
$S_U$ =( 26.5 ± 19.5) TNU $S_{Th}$=(10.6 ±12.7) TNU

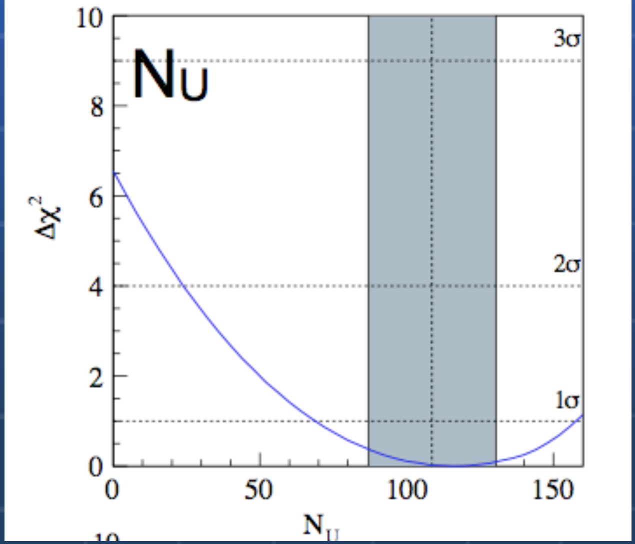
Best fit result (black point) in good agreement with chondritic value

# KamLAND: fit with free U/Th components

*H. Watanabe, NGS 2013*







Best fit : $N_U$=116, $N_{Th}$=8

Null U signal rejected at 90 % C.L. (2.6 σ)

# Earth radiogenic power

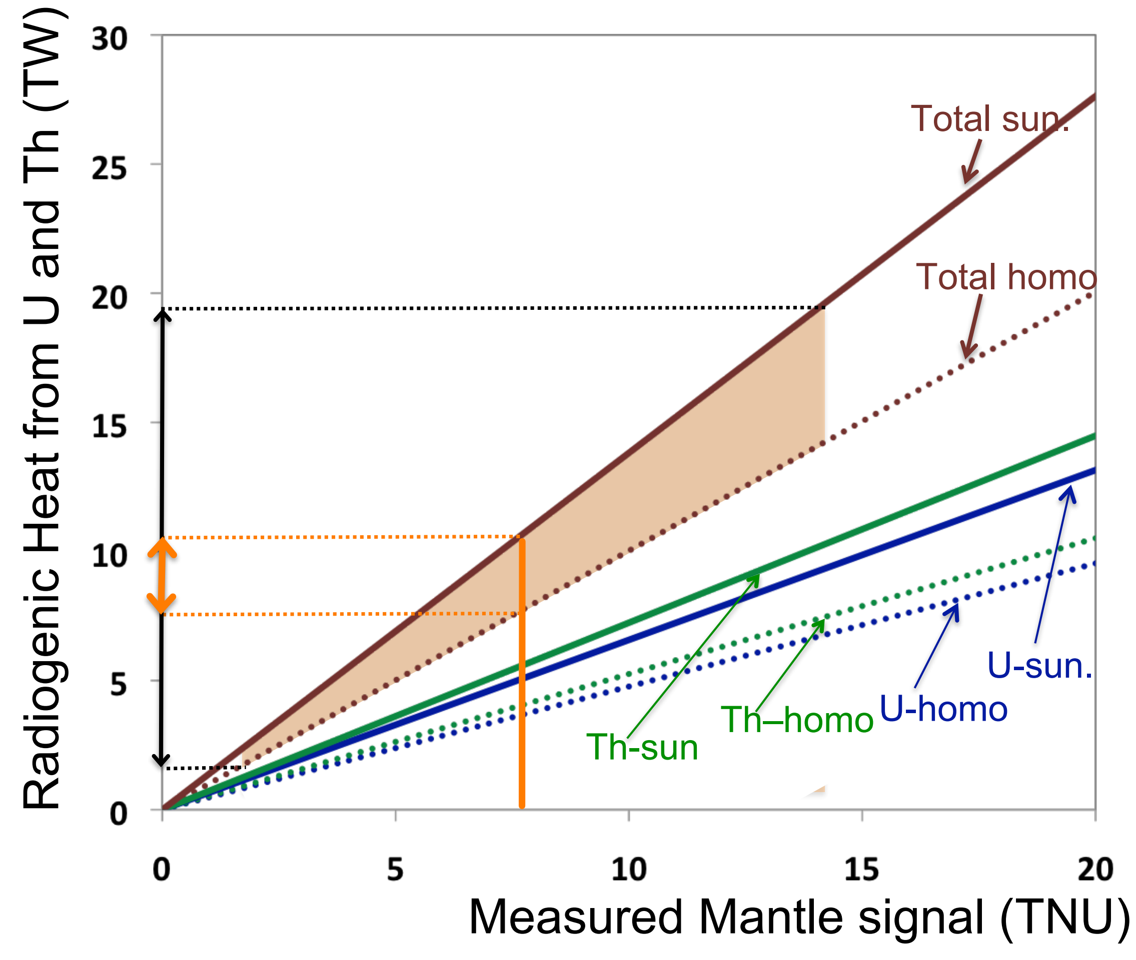
Th/U=3.9

$$L\,(10^{24}s^{-1})=7.64*\,m_U(10^{17}\,Kg)+1.62*\,m_{Th}(10^{17}\,Kg)$$

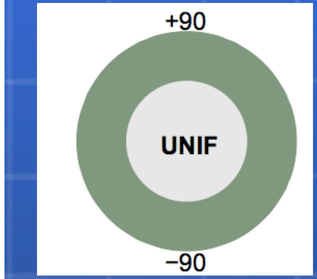
$$H_R(10^{12}W)=9.85*\,m_U(10^{17}\,Kg)+2.67*m_{Th}(10^{17}\,Kg)$$

Crust:

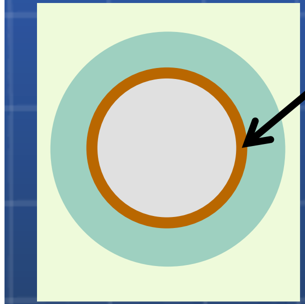
$m_U$:
(3.45±0.57) $10^{16}$ kg
$m_{Th}$:
(15.3±1.77) $10^{16}$ kg



Uniform distribution



All U & Th



Sunkern layer

# BSE models

**Three classes of BSE compositional models:**

- ✓ Cosmochemical (enstatite chondrites, collisional erosion)
- ✓ Geochemical (carbonaceous chondrites+terrestrial samples)
- ✓ Geodynamical (mantle convection energetics+surface heat loss)

Strong differences on HPE abundances predictions:

| Ref. O. Šrámek et al (1) | Cosmochem. | Geochem. | Geodyn. |
|---|---|---|---|
| $A_U$ (ppb) | 12 ±2 | 20±4 | 35±4 |
| $A_{Th}$ (ppb) | 43±4 | 80±13 | 140±14 |
| $A_K$ in ppm | 146±29 | 280±60 | 350±35 |
| Th/U | 3.5 | 4.0 | 4.0 |
| K/U | 12000 | 14000 | 10000 |
| Tot. Power (TW) | 11±2 | 20+4 | 33±3 |
| Mantle Urey ratio | 0.08±0.05 | 0.3±0.1 | 0.7±0.1 |
| Mantle power (TW) | 3.3±2.0 | 12±4 | 25±3 |

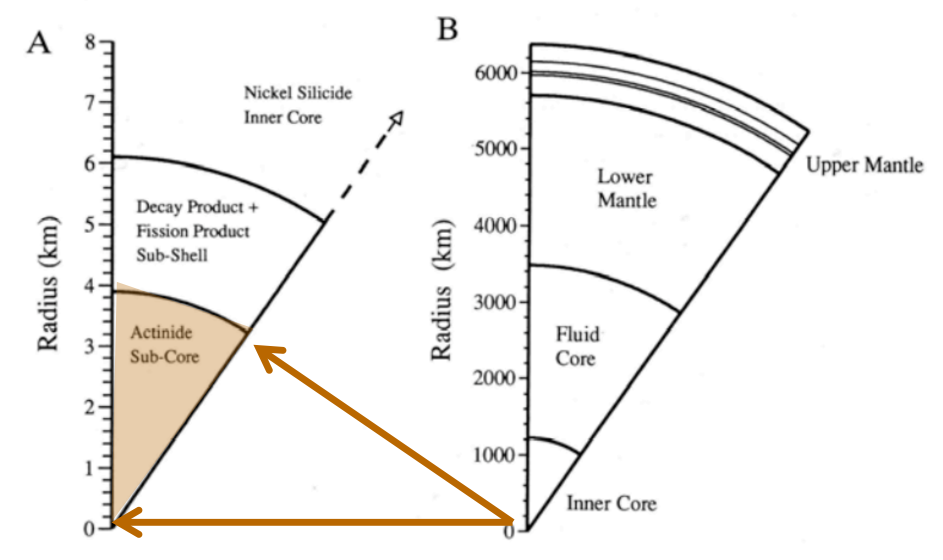
factor 3

factor 10!!

*(1) O. Šrámek et al. Earth. Plan. Sci. Letters 361 (2013)356-366*

# Geo-reactor

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



Unbinned maximal likelihood fit adding the PDF for geo-reactor signal and constraining the power plants reactor signal to the expectation band.

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

**KamLAND: Geo-reactor power < 3.7 TW at 95% C.L.**

# Summary

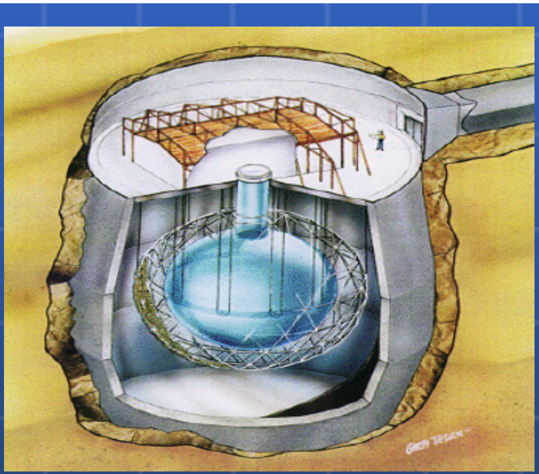
- ✓ Two independent geo-ν measurements from the Borexino and Kamland experiments have opened to door to a new interdisciplinary field, the Neutrino Geoscience, osservation at 4.5 σ C.L.;
- ✓ The combined results from different experimental sites have stronger impact –> multi-site measurements are crucial!
- ✓ The first indication of a geo-neutrino mantle signal has emerged;
- ✓ The first attempts to directly measure the Earth U/Th ratio have been performed, evidence at 2.6 s level for a positive U signal ;
- ✓ The data seems to prefer the geochemical or cosmochemical models, but probably the geo-dynamical are going to be revised and reconciled with the other ones;
- ✓ New measurements are mandatory: large mass detectors are surely more suited to study the geo-ν signal….

# Incoming experiments

- Geologically interesting results require
  - Large detector masses (~10 Ktons)
  - Suited experimental sites

Many incoming/future projects have geo-ν among their scientific goals…

## SNO+ at Sudbury, Canada



- Made of 780 tons of CH2 LAB +PPO
- Start of the data taking in 2014-15
- Rate ~20 geo-ν/year, geo-ν/reactor signal ~ 1.2
- Placed on an old & thick continental crust, mostly made of felsic rocks which are enriched in U/Th: strong LOC signal ~ 19 TNU
- A very detailed study of the local geology is mandatory to allow the measurement of the mantle signal.

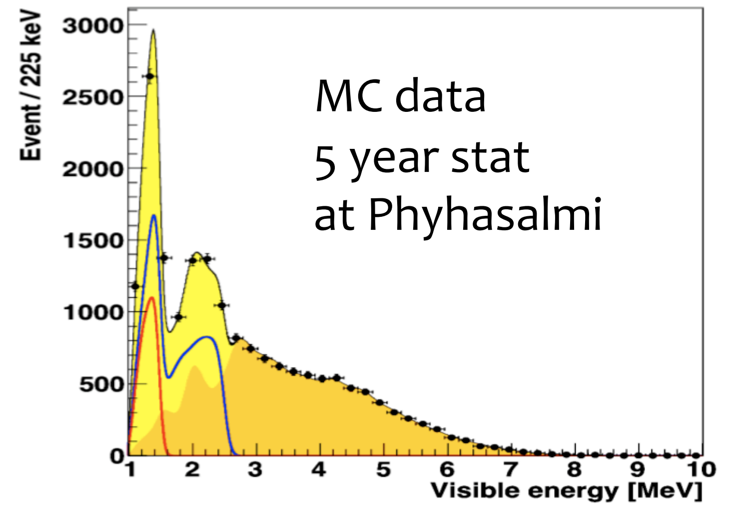
## DAYA BAY2 (China)

- Aimed to study the neutrino mass hierarchy: 20 kton, 400 geo-ν/year, but 40 reactors $\nu_e$ events/day and shallow depht -> challenge!!

# Future projects

## LENA at Phyhasalmi (FL) or Frejus (FR)

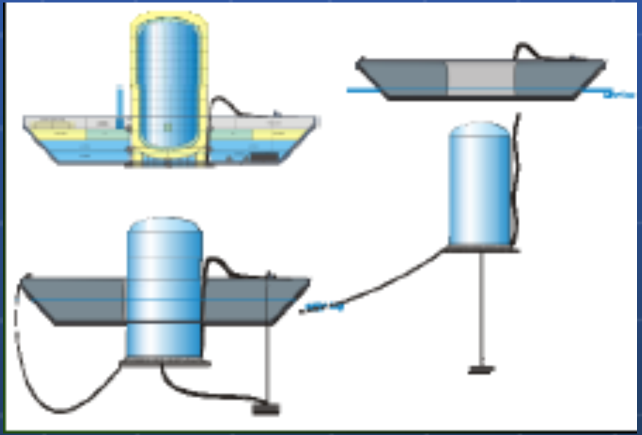
- Project for a 50 kton underground liquid scintillator detector (Wurm et al 2011);
- Rate= ~ 1000 geo-ν events/ year;
- Overall flux : a few % precision in a couple of years;
- U/Th ratio: 10 % precision in 3 years at Phyhasalmi, 20% at Frejus.



MC data
5 year stat
at Phyhasalmi

## HANOHANO at Hawaii

- Project for a 5-10 kton liquid scintillator detector, movable and placed on a deep ocean floor;
- Geo-ν/reactor signal > 10;
- Since Hawaii placed on the U-Th depleted oceanic crust 75% of the signal from the mantle!



# Conclusions

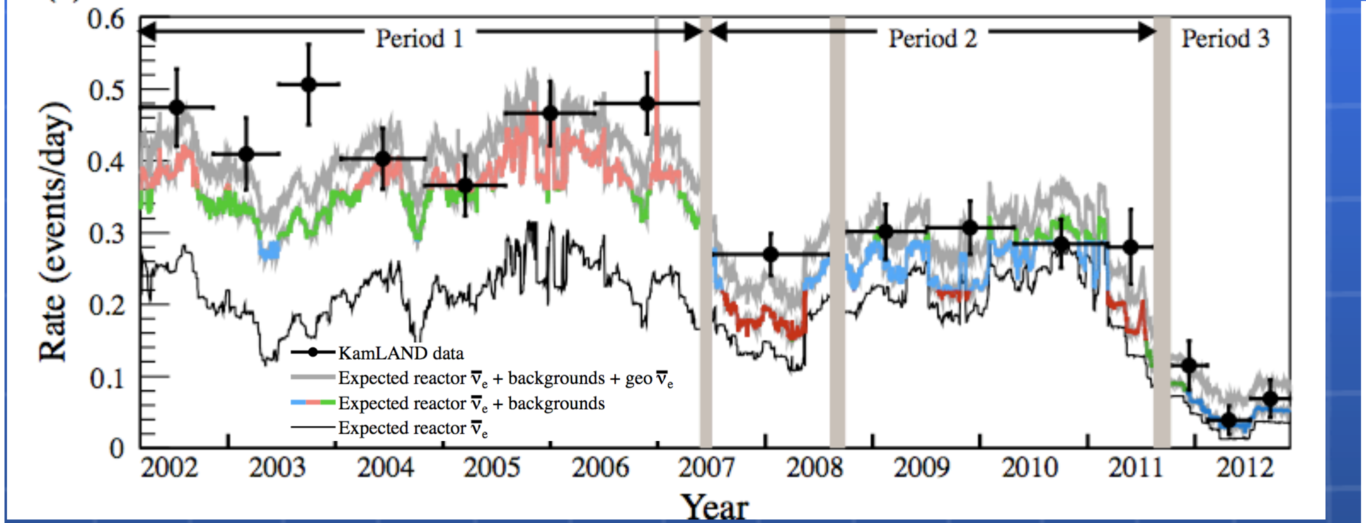
New experiments are going to join the geo-ν detectors network.
Borexino and KamLAND are going on to take data-> milestones towards an Earth tomography!

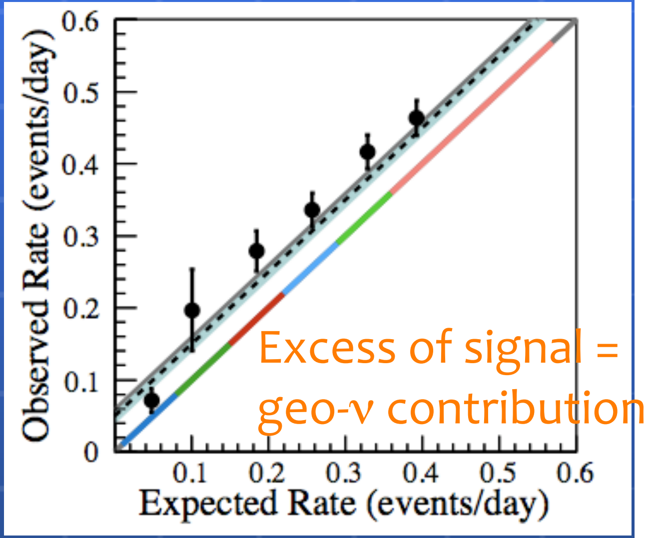
**THANK YOU!!!**

# Backup slides

# March 2013: Release of new results

KamLAND (Gando et al., Phys. Rev. D 88,2013, 033001) Statistics Mar 2002- Nov 2012
3 data-taking periods, different signal/backg. conditions (2002-2007) (2007-2011) (2011-2012)

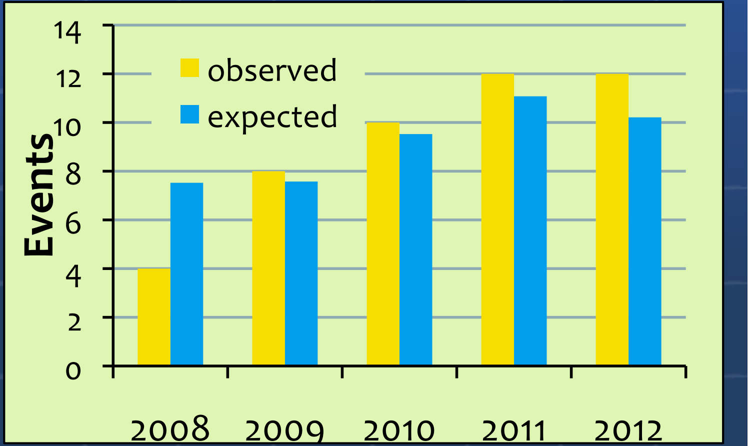




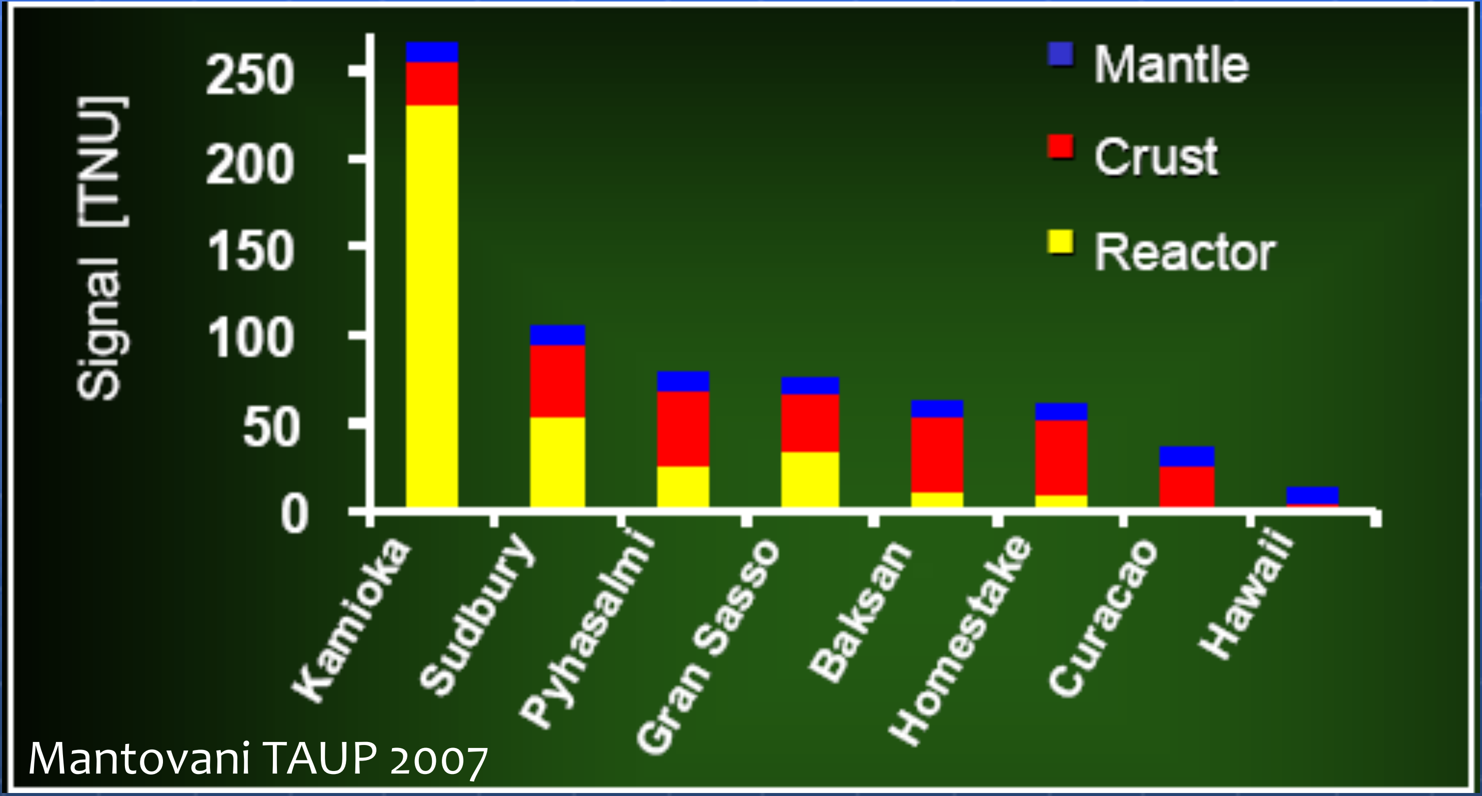
Excess of signal = geo-ν contribution

Borexino (Bellini et al.,Phys. Lett.B ,2013, 295-300)

Statistics: May 2007-Aug 2012, 613 ton* year
(previous= 252 tons*year)
2010-2012 six purification campaigns



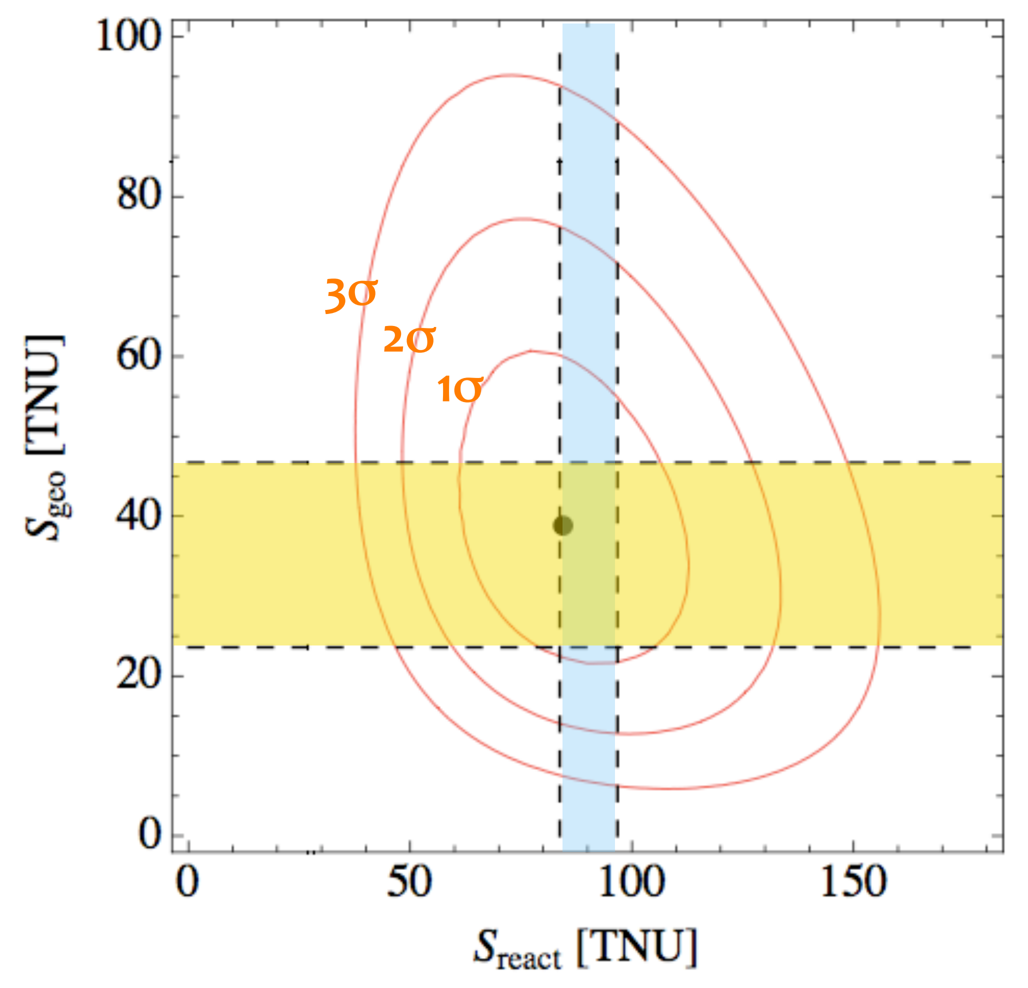
# Running and planned experiments



Mantovani TAUP 2007

# Comparison with expectations

Contour plot for geo-ν and reactor antineutrino signal rate: black point = best fit



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

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

# Geo-$\nu$: the background in BX

**Geo-$\nu$ expected signal (BSE) = 2.5 cpy/100 t**

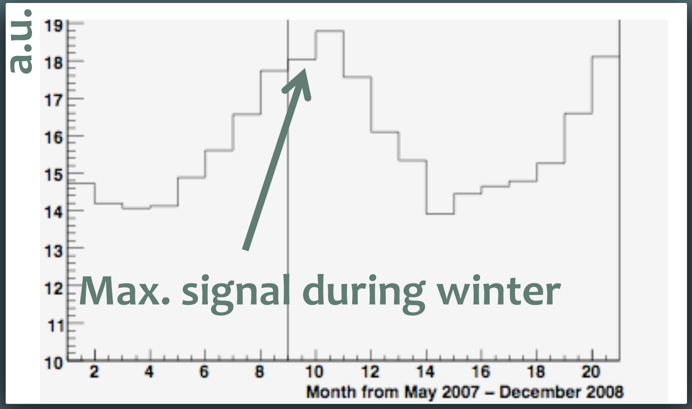
## Reactor antineutrinos

- ✓ Overall rate: 5.0 ± 0.3 cpy/100 t
- ✓ Rate in the GNW: 2.0 ±0.1 cpy/100 t

We are in contact with IAEA and EDF:

*-Thermal powers for each European reactors are known on a monthly base;*

*-Expected signal @ LNGS evaluated with a dedicated code ( sys. uncertainty: 5.4%)*



**Signal (BSE)/(Reactor background) ~ 1.25 In the GNW**

## Cosmogenic/enviromental background

- ✓ Overall rate: 0.14 ± 0.02 cpy/100 t
- ✓ Rate in the GNW: 0.12 ±0.01 cpy/100 t

### Muon correlated events

***Cosmogenic $^9$Li and $^8$He decay via $\beta$-n***

- $\tau$~ 150 ms
- 2 s detector veto after scintillator muons
- Residual background: 0.03±0.02 cpy/100 t

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

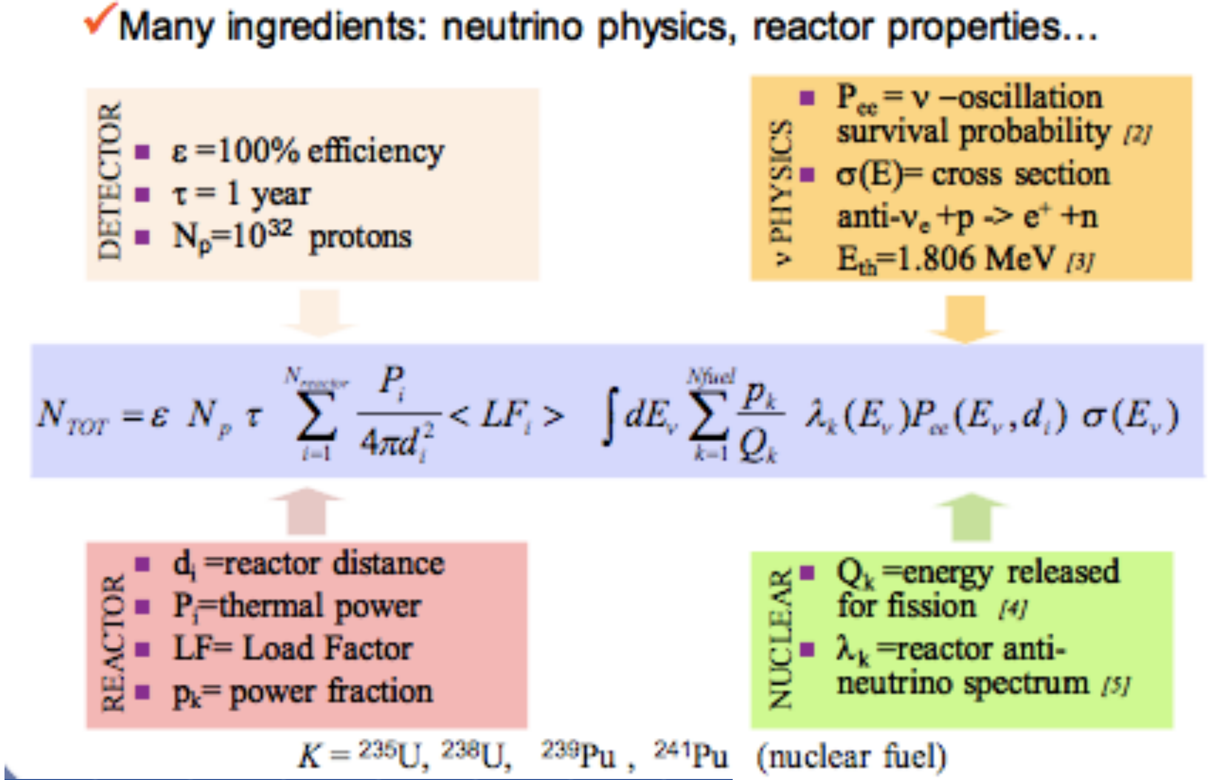
- $^{210}$Po a emitter: 12 cpd/100 t
- $^{13}$C low abundance: $^{13}$C/$^{12}$C~1.1 %
- Background: 0.014±0.001 cpy/100 t

### Random coincidences

Searching for events in a window of 2 ms-2 s: 0.080 ±0.001 cpy/100t

**Signal(BSE)/(non anti-$\nu$ Background) ~ 21**

# The reactors anti-ν expected signal



✓ Many ingredients: neutrino physics, reactor properties…

**DETECTOR**
- $\varepsilon$ =100% efficiency
- $\tau$ = 1 year
- $N_p$=$10^{32}$ protons

**ν PHYSICS**
- $P_{ee}$ = ν –oscillation survival probability [2]
- $\sigma(E)$= cross section anti-$\nu_e$+p -> $e^+$ +n $E_{th}$=1.806 MeV [3]

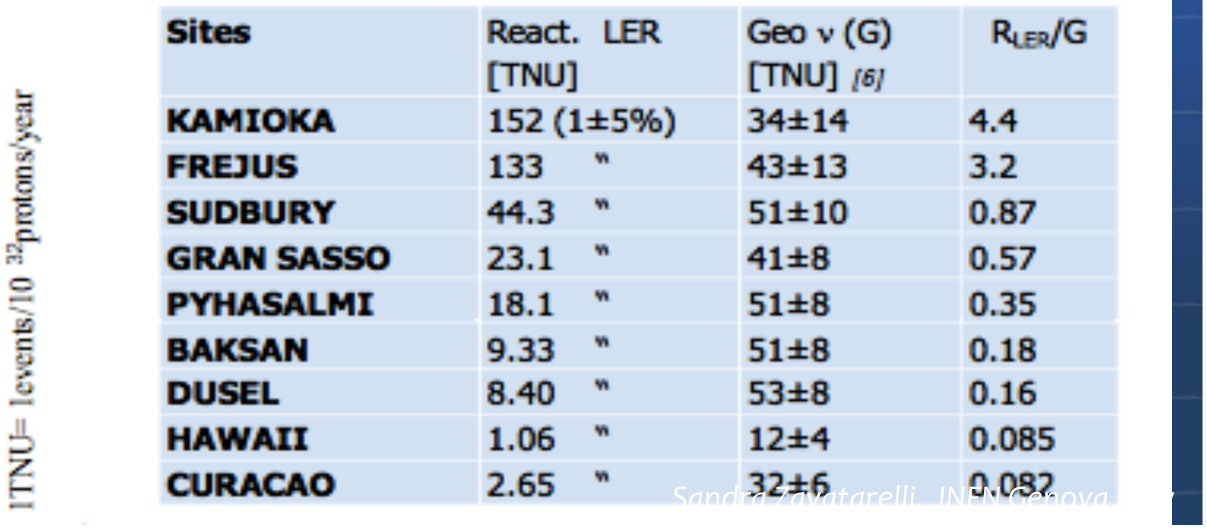
$$N_{TOT} = \varepsilon\ N_p\ \tau \sum_{i=1}^{N_{reactor}} \frac{P_i}{4\pi d_i^2} < LF_i > \int dE_\nu \sum_{k=1}^{Nfuel} \frac{p_k}{Q_k}\ \lambda_k(E_\nu) P_{ee}(E_\nu, d_i)\ \sigma(E_\nu)$$

**REACTOR**
- $d_i$ =reactor distance
- $P_i$=thermal power
- LF= Load Factor
- $p_k$= power fraction

**NUCLEAR**
- $Q_k$ =energy released for fission [4]
- $\lambda_k$ =reactor anti-neutrino spectrum [5]

$K = {}^{235}U,\ {}^{238}U,\ {}^{239}Pu\ ,\ {}^{241}Pu$ (nuclear fuel)

B. Ricci
TAUP 2012



1TNU= 1events/$10^{32}$protons/year

| Sites | React. LER [TNU] | Geo ν (G) [TNU] [6] | $R_{LER}$/G |
|---|---|---|---|
| **KAMIOKA** | 152 (1±5%) | 34±14 | 4.4 |
| **FREJUS** | 133 " | 43±13 | 3.2 |
| **SUDBURY** | 44.3 " | 51±10 | 0.87 |
| **GRAN SASSO** | 23.1 " | 41±8 | 0.57 |
| **PYHASALMI** | 18.1 " | 51±8 | 0.35 |
| **BAKSAN** | 9.33 " | 51±8 | 0.18 |
| **DUSEL** | 8.40 " | 53±8 | 0.16 |
| **HAWAII** | 1.06 " | 12±4 | 0.085 |
| **CURACAO** | 2.65 " | 32±6 | 0.082 |