Geo-ν

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Outline

1. Basics of neutrino physics
2. The Earth
3. Geoneutrinos
4. Experimental results
5. Future prospects

Neutrino basics

- No electric charge
  = no elmag interactions;
- No color
  = no strong interactions;
- only weak interactions
  = very small cross sections;

particles		-	antiparticles	
lepton number +1			lepton number -1	
e^-	ν_e	3 flavors	e^+	$\bar{\nu}_e$
μ^-	ν_μ		μ^+	$\bar{\nu}_\mu$
τ^-	ν_τ		τ^+	$\bar{\nu}_\tau$

- Originally, in the Standard Model neutrinos have exactly zero mass, all neutrinos are left-handed and all antineutrinos are right handed;
- Experimental evidences for **neutrino oscillations (Nobel Prize 2015)**: **non-zero mass** required!
- Non-zero mass requires at least a minimal extension of the Standard Model;
- Dirac or Majorana particles?
- If Majorana: lepton-flavor violation by 2 and 0ν-$\beta\beta$ –decay. A big experimental effort ongoing to search for it (CUORE, Gedra, KamLAND-ZEN, SNO+)!

Discovery of neutrino oscillations

The Nobel Prize in Physics 2015

Photo © Takaaki Kajita

Takaaki Kajita

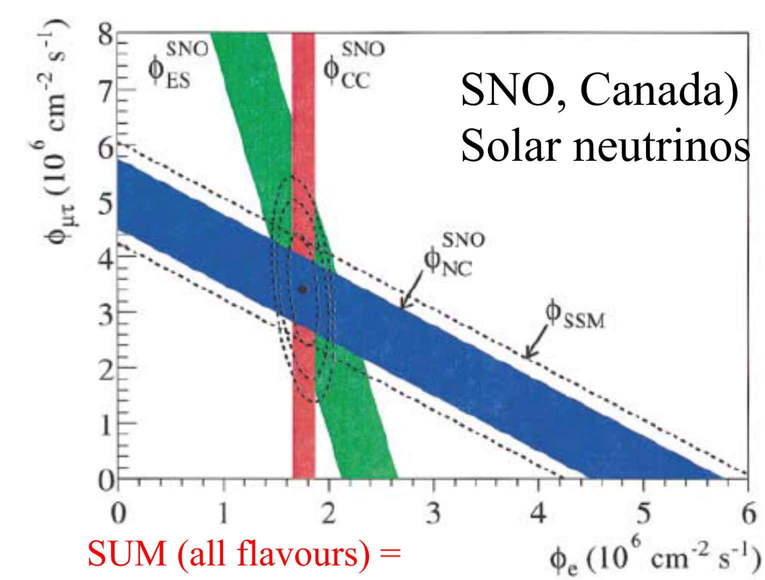
Prize share: 1/2

Photo: K. McFarlane. Queen's University /SNOLAB

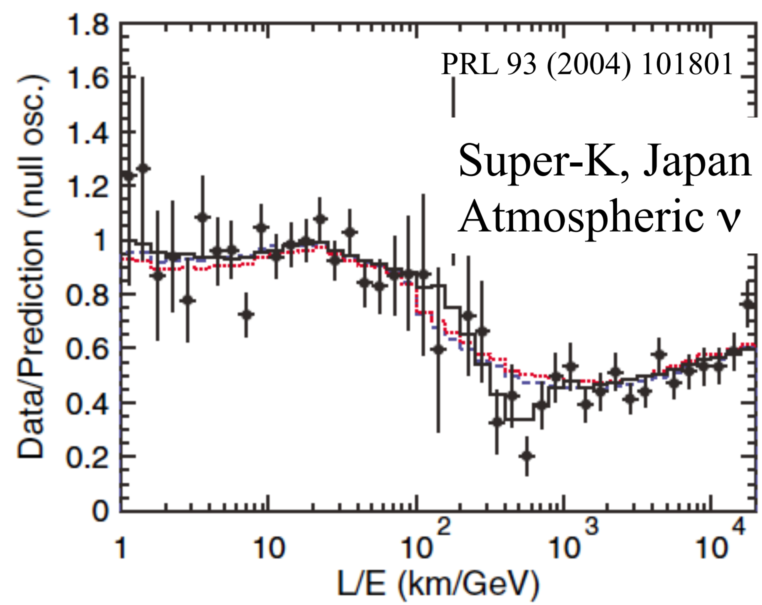
Arthur B. McDonald

Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*



SUM (all flavours) =
Standard Solar Model predictions



Neutrino oscillations I

α = e, μ, τ
Flavour eigenstates
INTERACTIONS

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i}\,|\nu_i\rangle$$

i = 1, 2, 3
Mass eigenstates
PROPAGATION

U: Pontecorvo – Maki – Nagawa – Sakata matrix

Atmospheric | Reactor | Solar | ? Majorana phases ?

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}\, e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}\, e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha 1/2} & 0 \\ 0 & 0 & e^{i\alpha 2/2} \end{pmatrix}$$

$\theta_{23} \approx 45°$ $\theta_{13} \approx 9°$ $\theta_{12} \approx 35°$

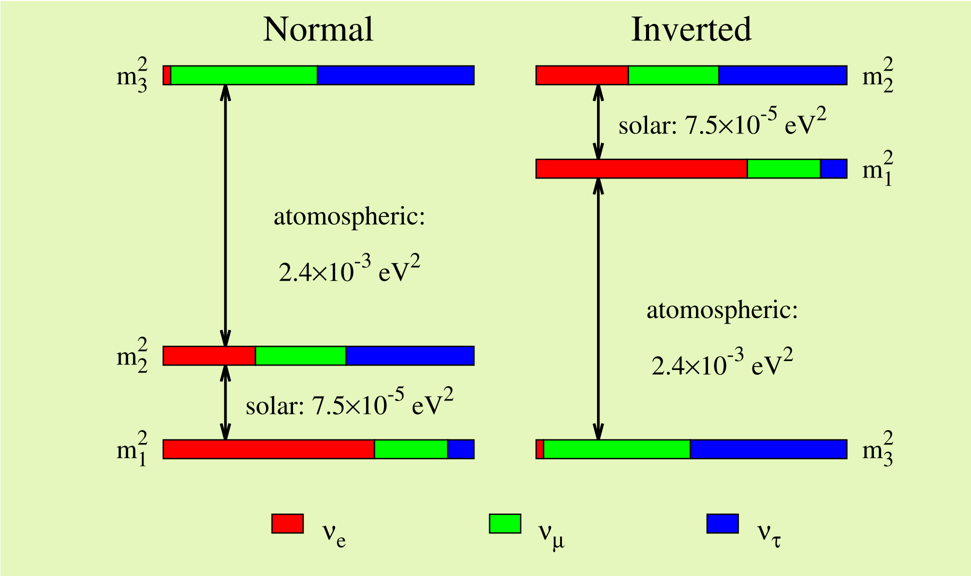
- **3 mixing angles θ_{ij}:** measured (bad precision for θ_{23});
- Non-zero θ_{13} confirmed only in 2012 by Daya Bay in China!
- **Majorana phases α1 , α2** and **CP-violating phase δ** unknown;

Neutrino oscillations II

Probability to measure neutrino of an original ***flavour α*** *as a* ***flavour β****:*

$$P_{\alpha\to\beta} = |\langle\nu_\beta|\nu_\alpha(t)\rangle|^2 = \left|\sum_i U^*_{\alpha i} U_{\beta i} e^{-i m_i^2 L/2E}\right|^2 .$$

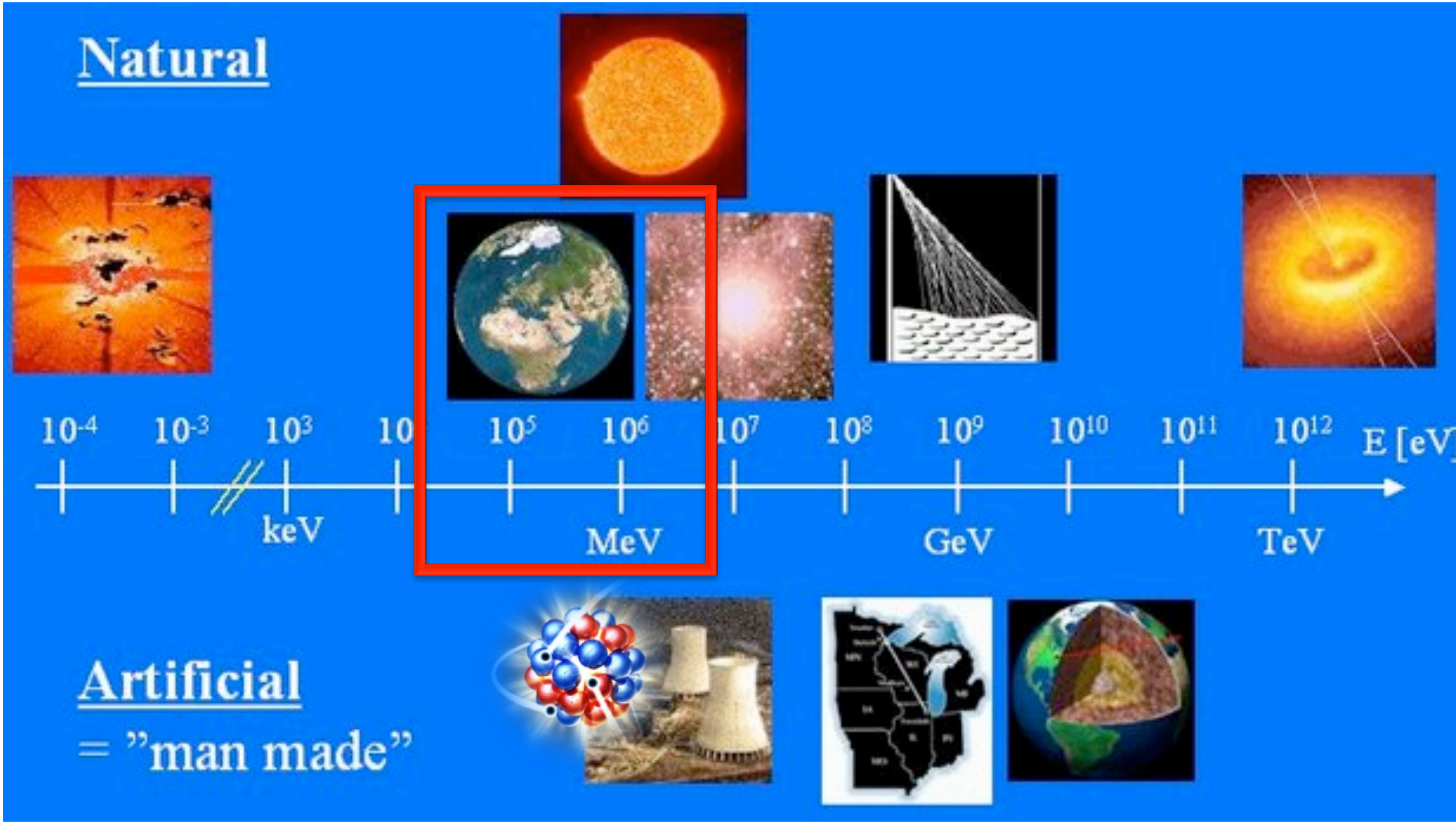
$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right) + 2\sum_{i>j} \mathrm{Im}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin\left(\frac{\Delta m^2_{ij} L}{2E}\right),$$



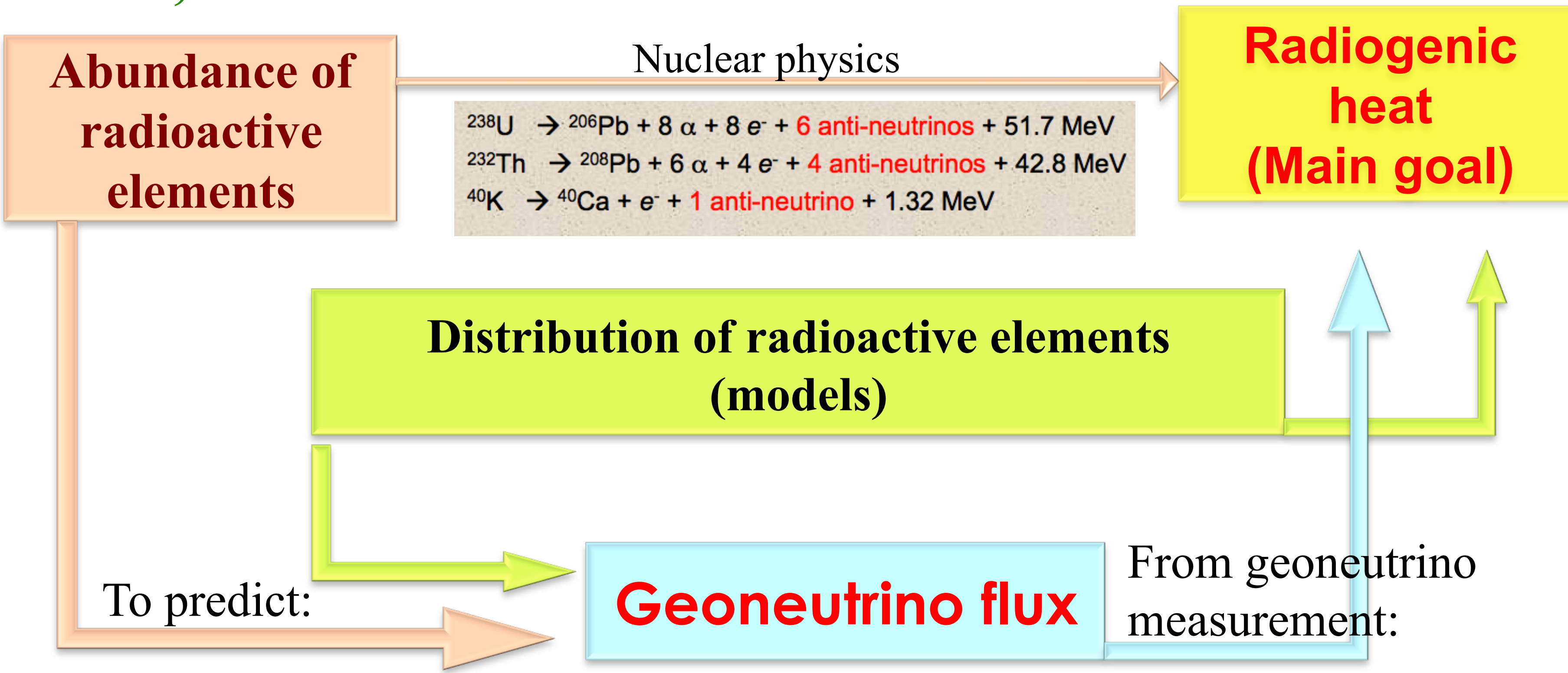
= f (E = energy, L = distance)

$$\Delta m^2_{ij} \equiv m_i^2 - m_j^2$$

Neutrino sources



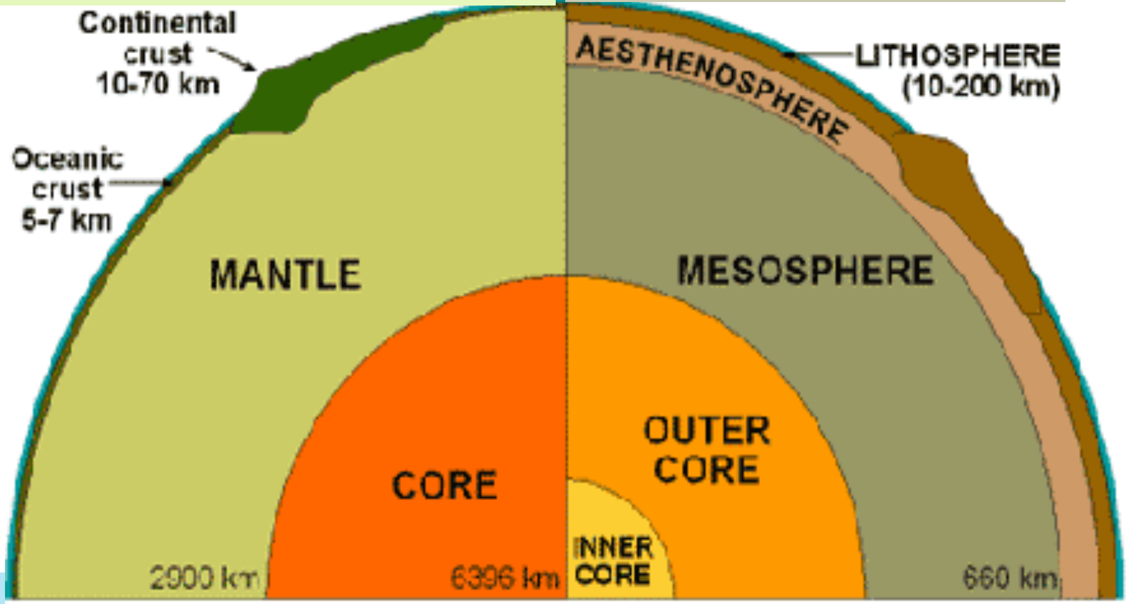
Geoneutrinos: antineutrinos from the decay of ^{238}U, ^{232}Th, and ^{40}K in the Earth



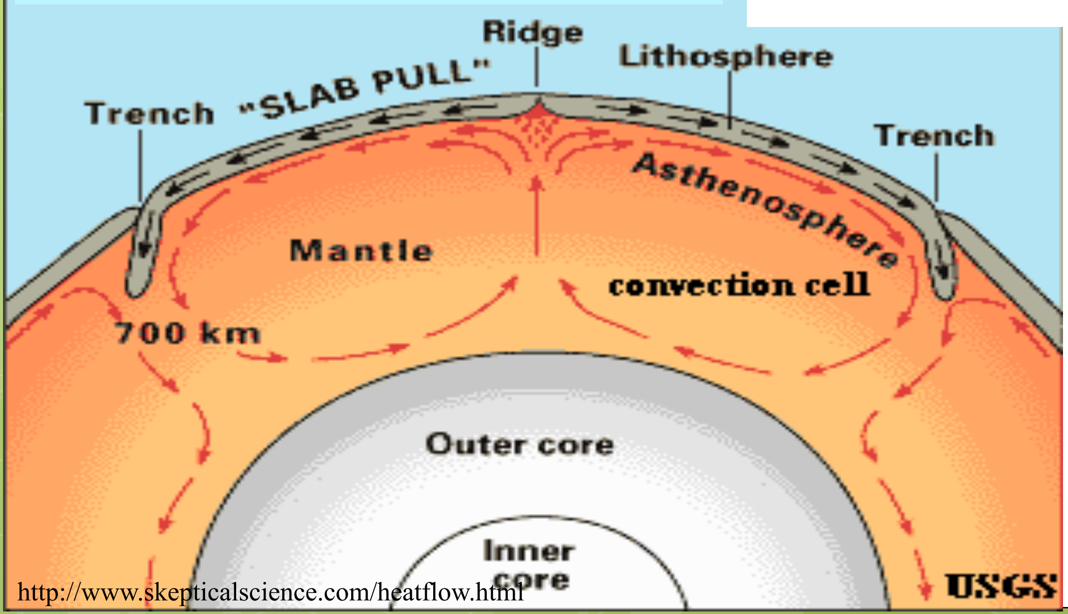
- **Main goal:** determine the contribution of the **radiogenic heat to the total surface heat flux**, which is an important margin, test, and input at the same time for many geophysical and geochemical models of the Earth;
- **Further goals:** tests and discrimination among geological models, study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

Earth's interior

Compositional layers | Mechanical layers



Dynamical picture



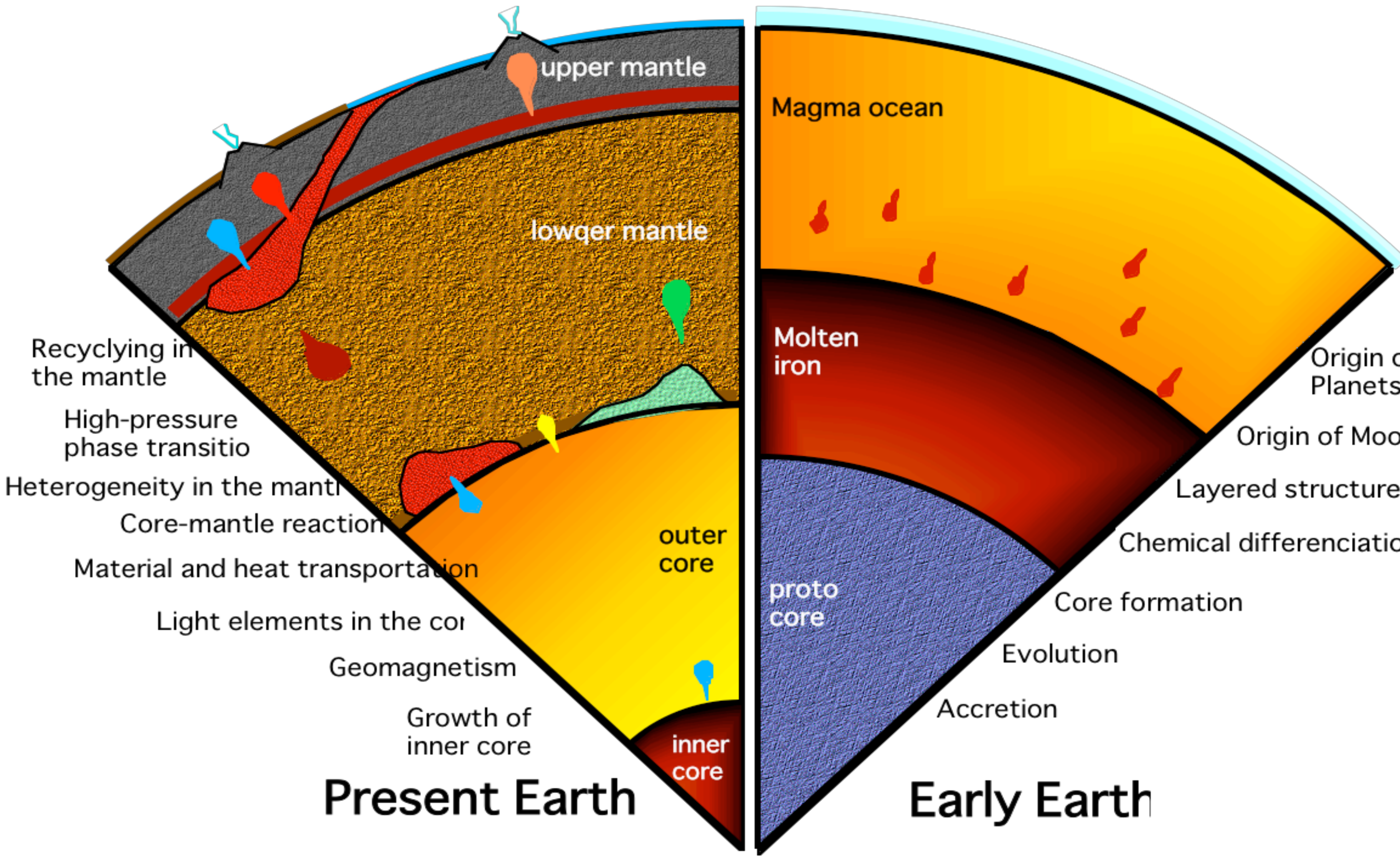
http://www.skepticalscience.com/heatflow.html

U, Th, K: refractory lithophile elements

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

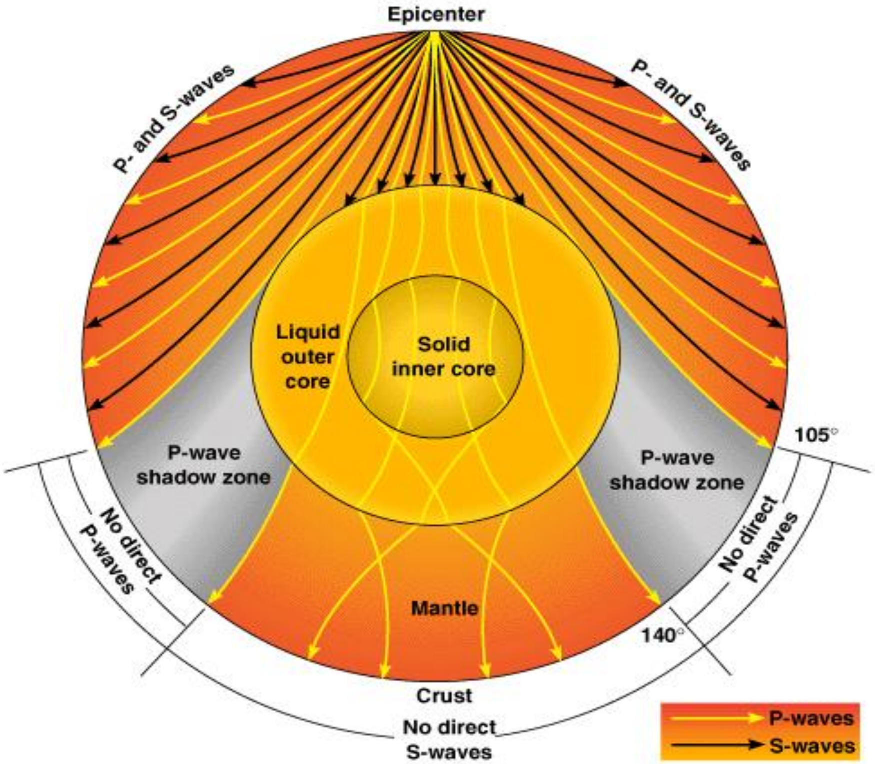
upper continental crust:	2.5 ppm
middle continental crust:	1.6 ppm
lower continental crust:	0.63 ppm
oceanic crust:	0.1 ppm
upper mantle:	6.5 ppb
core	NOTHING

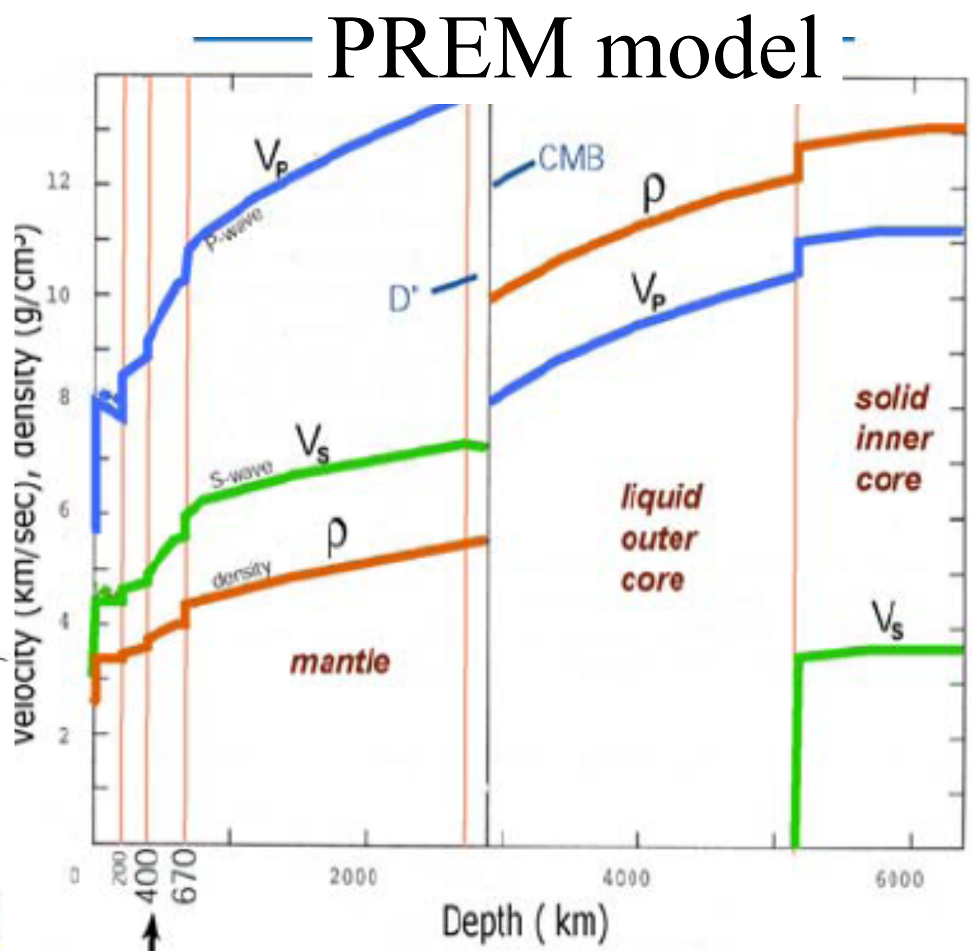
Earth’s profile in time



http://www.ess.sci.osaka-u.ac.jp/english/3_research/groups/g05kondo.html

Seismology





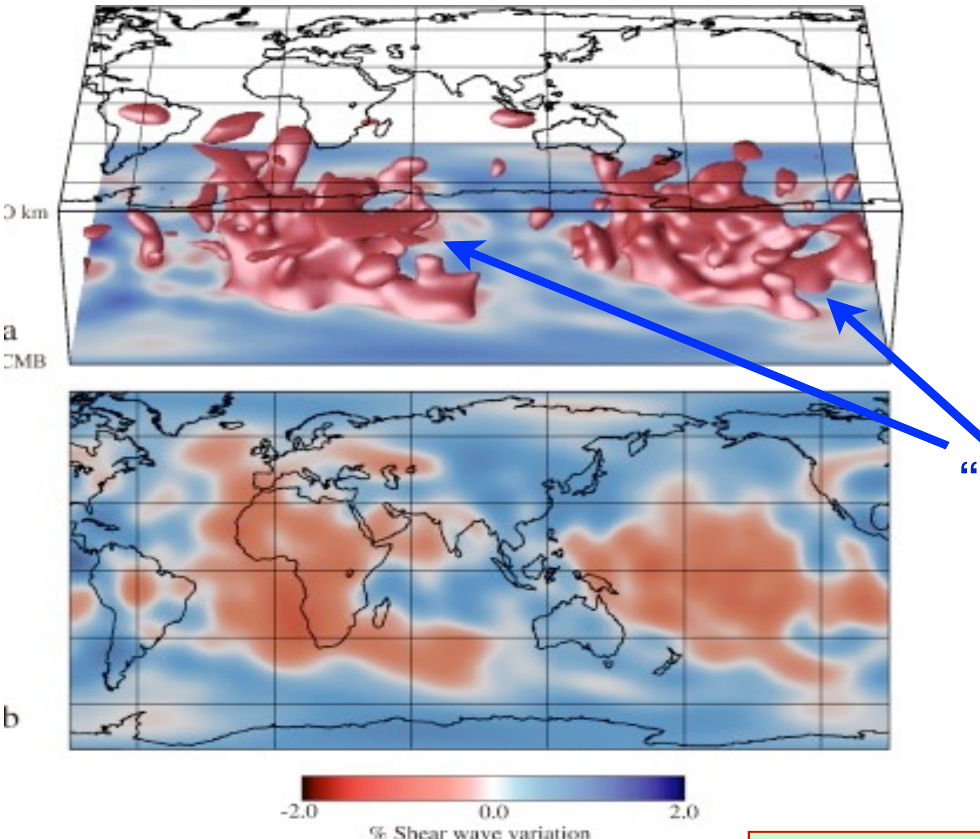
P – primary, longitudinal waves
S – secondary, transverse/shear waves

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

Geo-chemistry

1) **Direct rock samples**

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

BUT: <u>POSSIBLE ALTERATION DURING THE TRANSPORT</u>

2) Geochemical models:

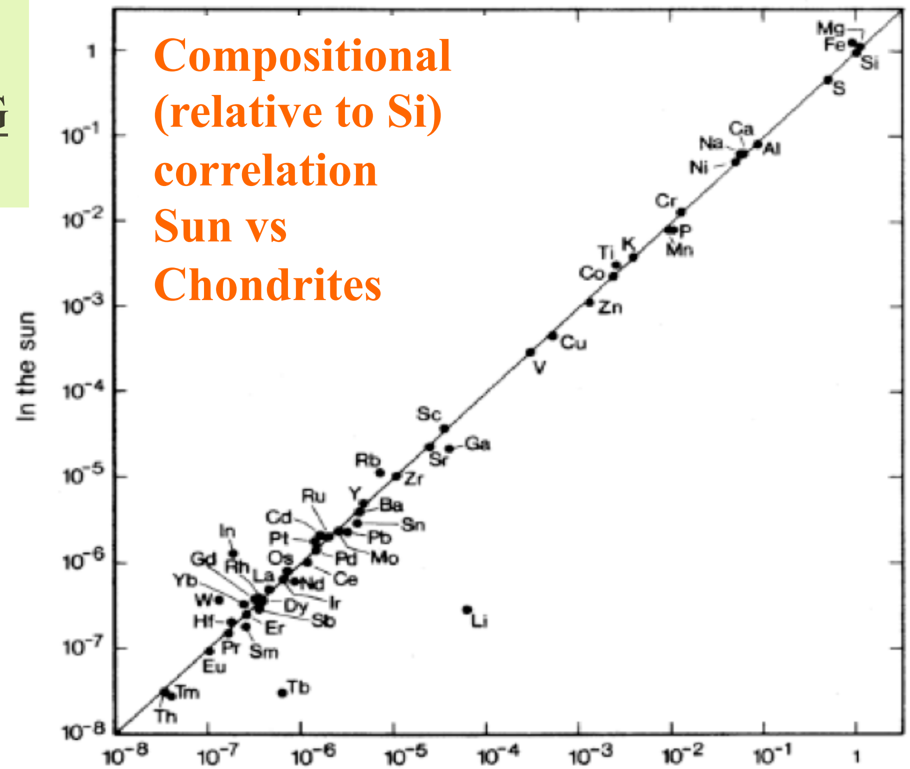
rock samples + meteorites + Sun

Bulk Silicate Earth (BSE) models medium composition

of the "re-mixed" crust + mantle,

i.e., primordial mantle before the crust

differentiation and after the Fe-Ni core separation



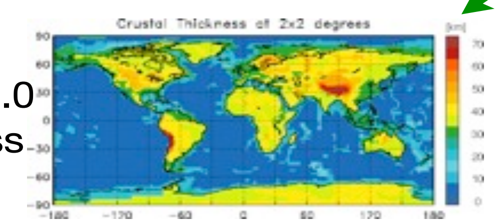
BSE models (classification according Sramek at al.)

Estimate	TW radiogenic power: BSE	TW radiogenic power: Mantle
"Geochemical" estimate	20±4	12±4
"Cosmochemical" estimate	11±2	3±2
"Geodynamical" estimate	33±3	25±3

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

BSE = Mantle + Crust

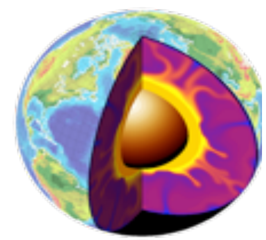
CRUST2.0 thickness



Oceanic: 0.22 ± 0.03 TW

Continental: 7.8 ± 0.9 TW

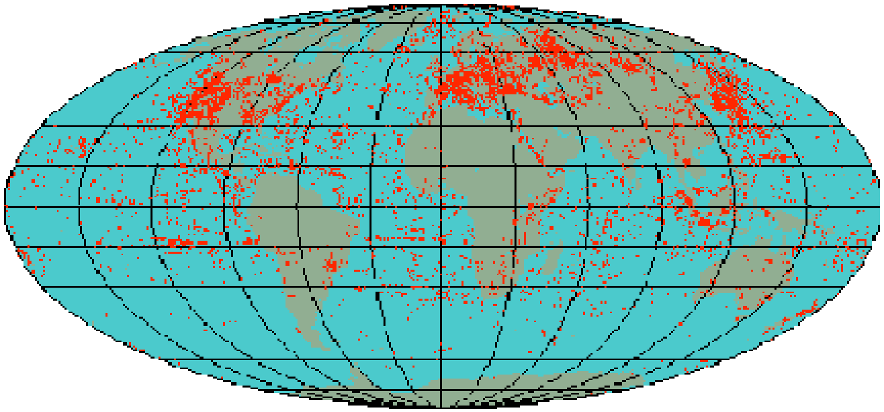
?



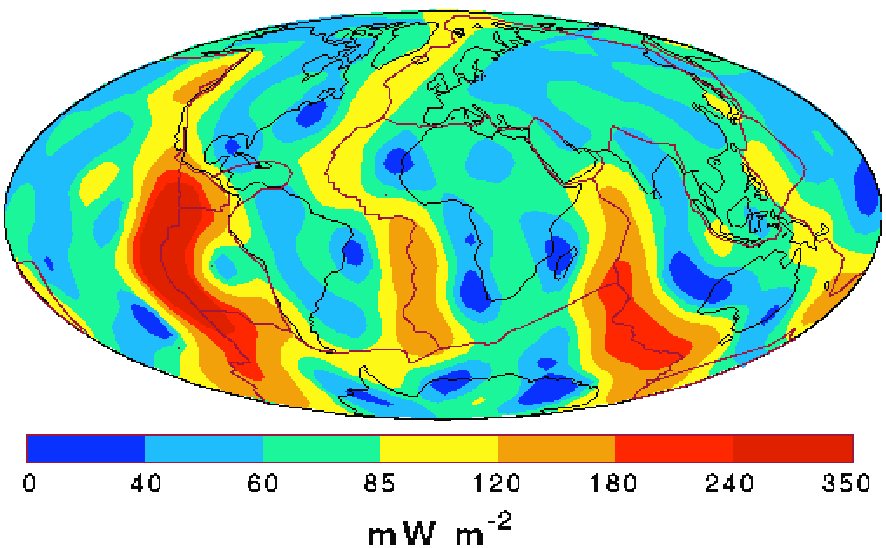
Tomorrow: New crustal model by Yu Huang et al.
CC = 6.8 (+1.4/-1.1) TW

Surface heat flux

Bore-hole measurements → **47 ± 2 TW** (Davies & Davies 2010)



Heat Flow



Sources

Radiogenic heat: (Geoneutrinos)!!!!!

BSE models predictions:

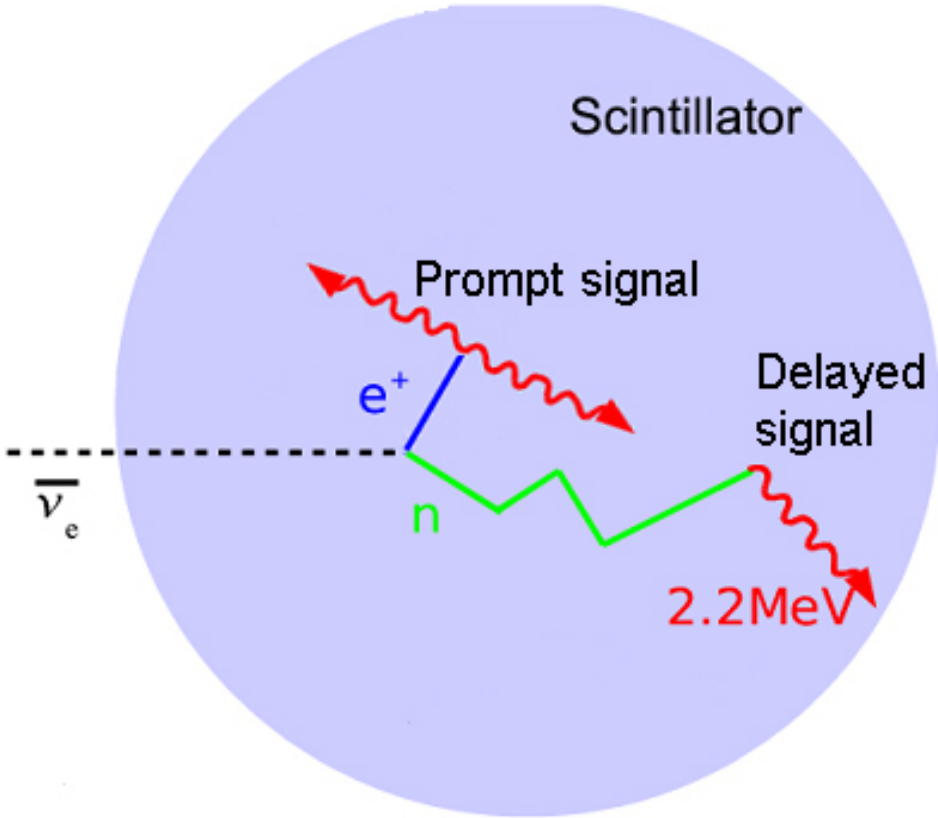
- ✓ Geochemical BSE:17-21 TW
- ✓ Cosmochemical BSE: 11 TW
- ✓ Geodynamical BSE: > 30 TW

Other sources:

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

Geoneutrinos detection

$\bar{\nu} + p \rightarrow n + e^{+}$ **I**nverse **B**eta **D**ecay

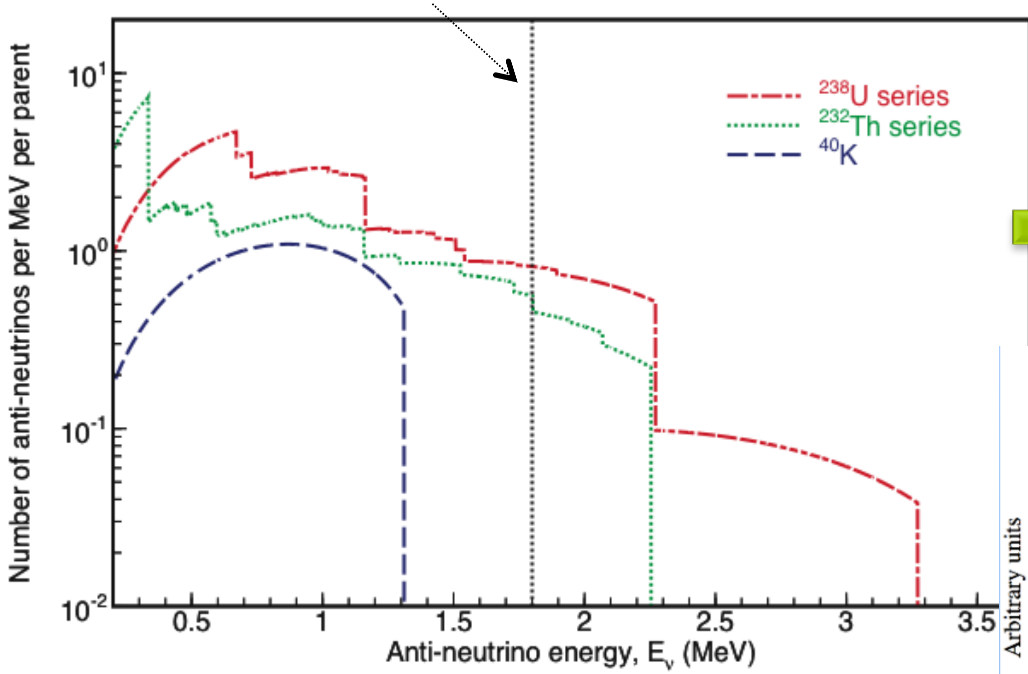


"prompt signal"
e^+: energy loss T_{e+}+
annihilation (2 x 0.511 MeV)
$\mathbf{E_{prompt} = E_{geonu} - 0.784\ MeV}$

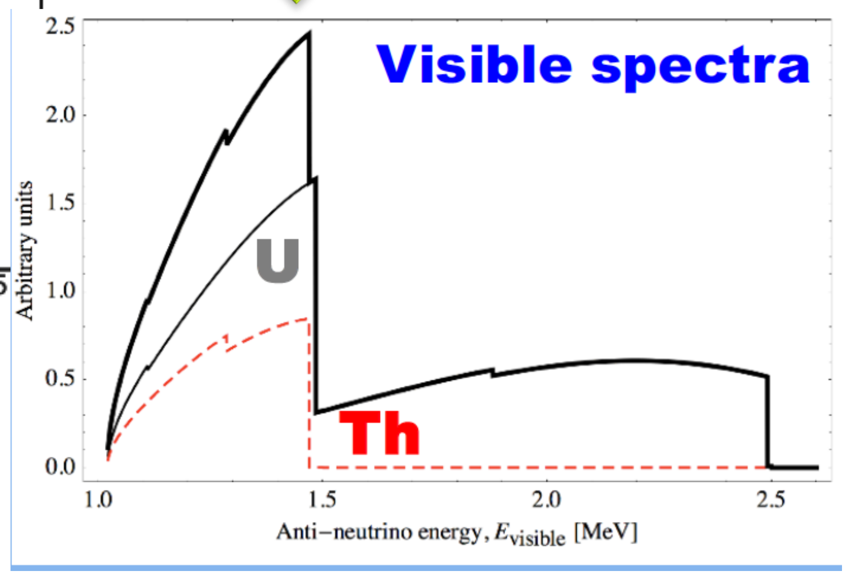
"delayed signal"
neutron thermalisation &
capture on protons,
emission of **2.2 MeV γ**

Geoneutrinos energy spectrum

1.8 MeV kinematic threshold



IBD cross section



Experimental principle

antineutrino + proton → positron + neutron

E_{prompt} = E(antineutrino) – 0.784 MEV

$E_{delayed}$ = 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;**
  - ✓ **Non-antineutrino backgrounds;**
- We need to estimate different contributions and then extract the number of measured geo-neutrinos by fitting the Eprompt energy spectrum;

Expected geoneutrino signal

- **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;
- **ROC: Rest of the crust:** further crust is divided in 3D voxels, volumes for upper, middle, lower crust and sediments are estimated and a mean chemical composition is attributed to these volumes (Huang et al. 2013);
- **Mantle = BSE – (LOC + ROC):** this is the real unknown, different BSE models are considered and the respective U + Th mass is distributed either homogeneously (maximal signal) or it is concentrated near to the core-mantle boundary (minimal signal);

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

[TNU]

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

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

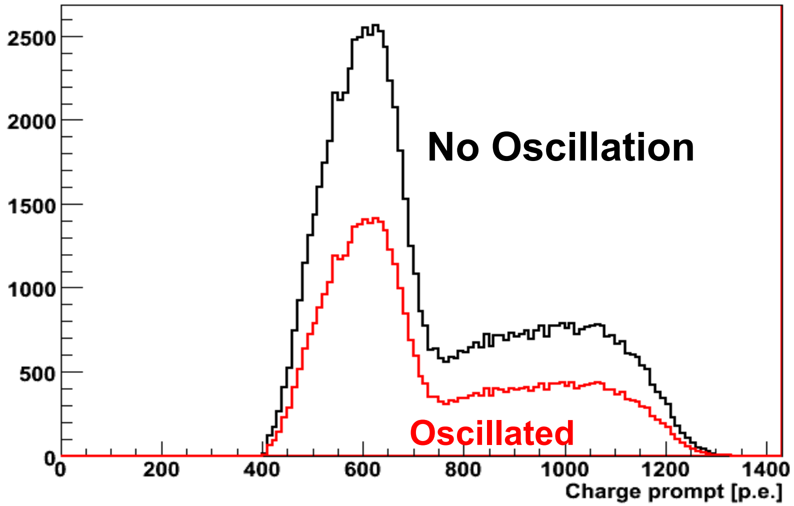
Effect of neutrino oscillations

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

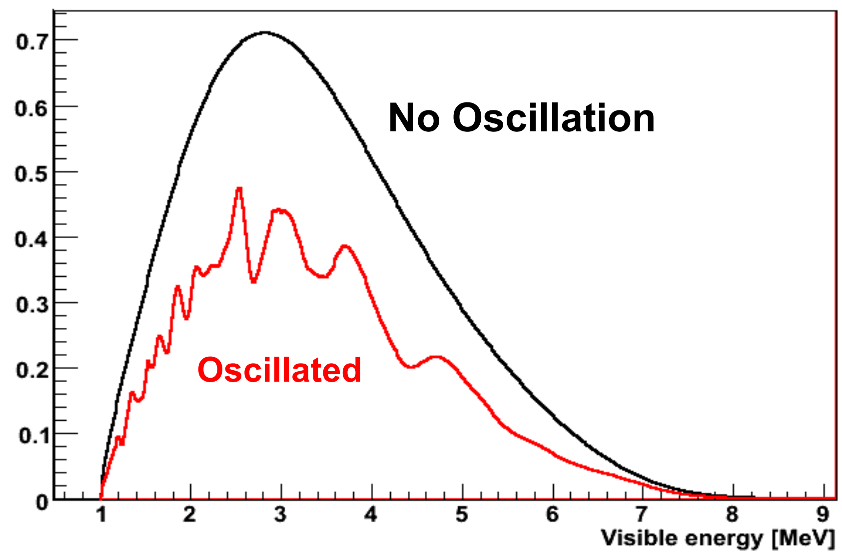
3 MeV antineutrino ..
Oscillation length of ~100 km

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

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

Borexino in Gran Sasso, Italy
CONTINENTAL CRUST

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

Geoneutrino experimental results

KamLAND (Japan)

- **The first investigation in 2005**
  CL < 2σ
  Nature 436 (2005) 499
- **Update in 2008**
  73 ± 27 geonu's
  PRL 100 (2008) 221803
- **99.997 CL observation in 2011**
  106^{+29}_{-28} geonu's
  (March 2002 – April 2009)
  3.49 x 10^{32} target-proton year
  Nature Geoscience 4 (2011) 647
- **Latest result in 2013**
  116^{+28}_{-27} geonu's
  (March 2002 – November 2012)
  4.9 x 10^{32} target-proton year
  0-hypothesis @ 2 x 10^{-6}
  PRD 88 (2013) 033001

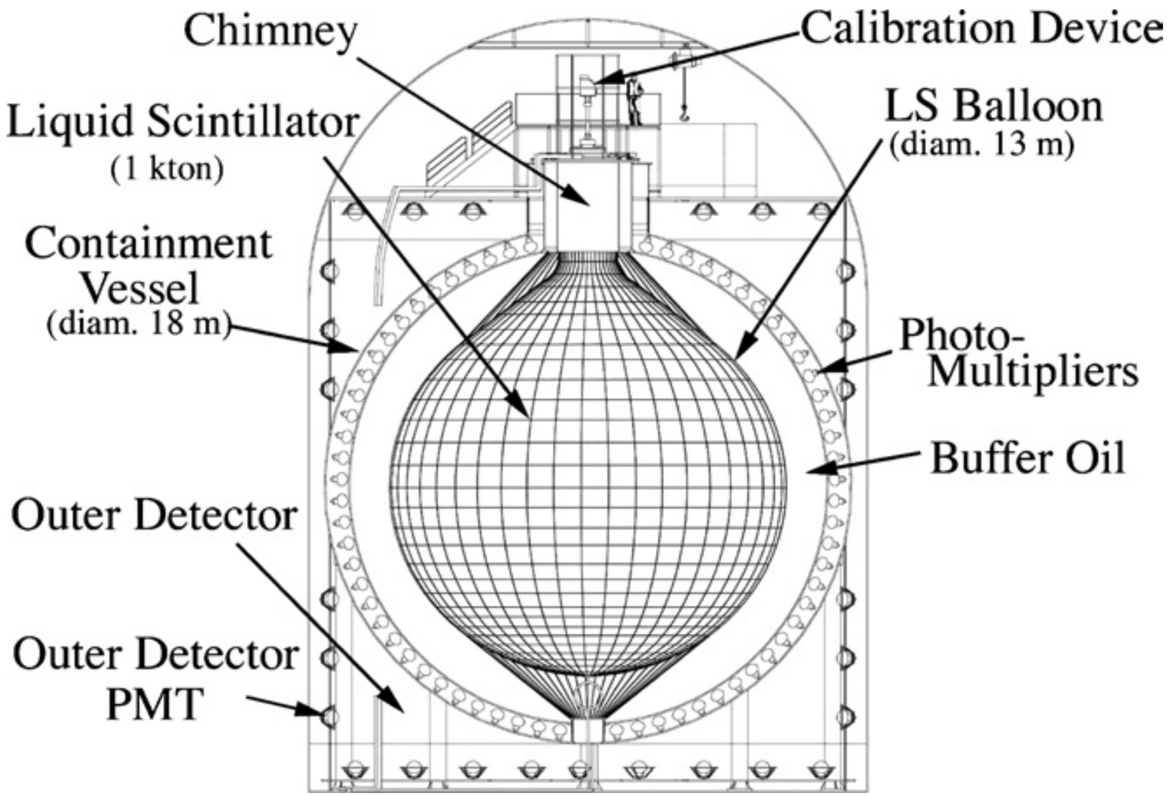
Borexino (Italy)

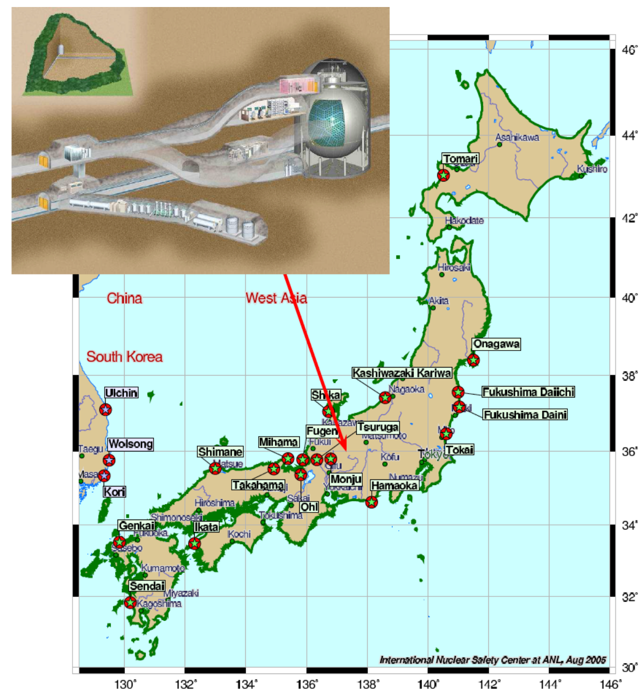
- **99.997 CL observation in 2010**
  $9.9^{+4.1}_{-3.4}$ geonu's
  small exposure but low background level
  (December 2007 – December 2009)
  1.5 x 10^{31} target-proton year
  PLB 687 (2010) 299
- **Update in 2013**
  14.3 ± 4.4 geonu's
  (December 2007 – August 2012)
  3.69 x 10^{31} target-proton year
  0-hypothesis @ 6 x 10^{-6}
  PLB 722 (2013) 295–300
- **NEW in June 2015: 5.9σ CL**
  $23.7^{+6.5}_{-5.7}$ (stat) $^{+0.9}_{-0.6}$ (sys) geonu's
  (December 2007 – March 2015)
  5.5 x 10^{31} target-proton year
  0-hypothesis @ 3.6 x 10^{-9}
  PRD 92 (2015) 031101 (R)

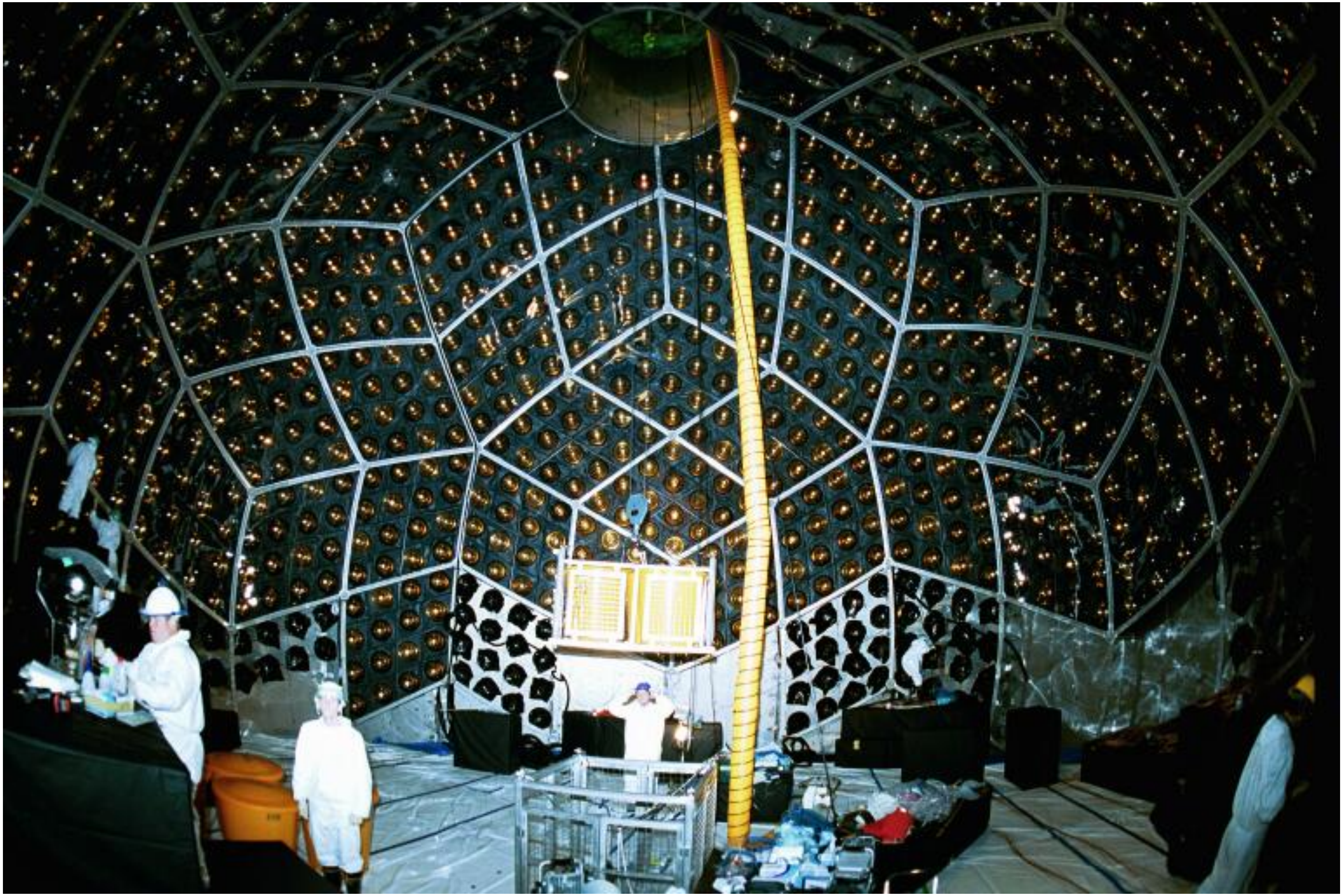
NEW

KamLAND

Principal goal:
neutrino oscillations
with reactor
antineutrinos
$L = 260$ km,
measurement of Δm^2_{12}

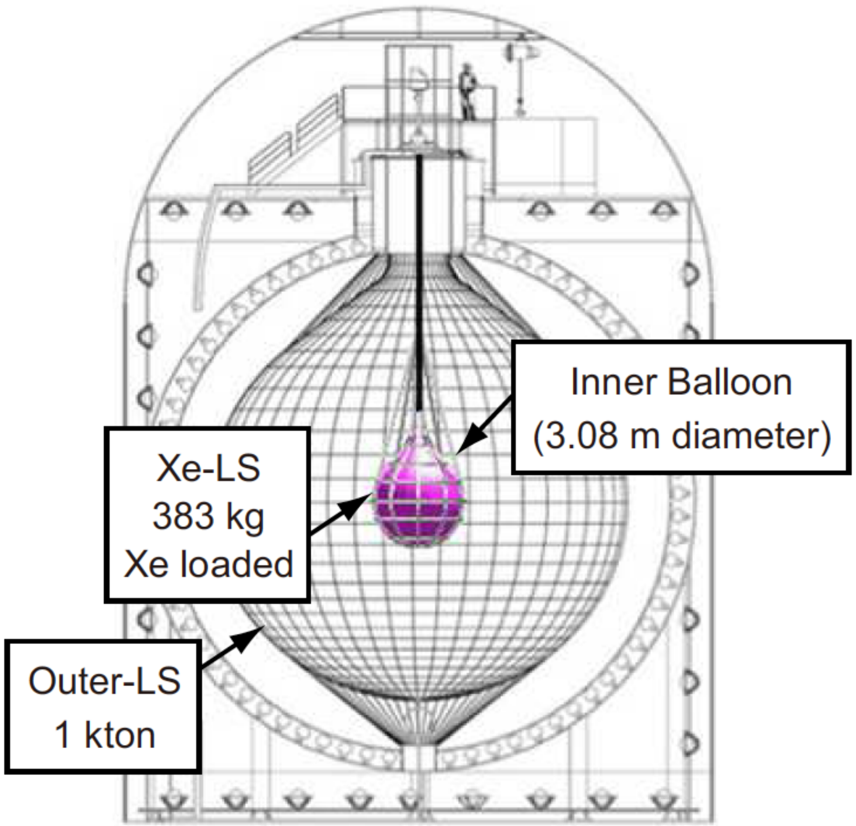






KamLAND-Zen: 0ν-ββ decay

Geoneutrinos
can be still measured in this phase

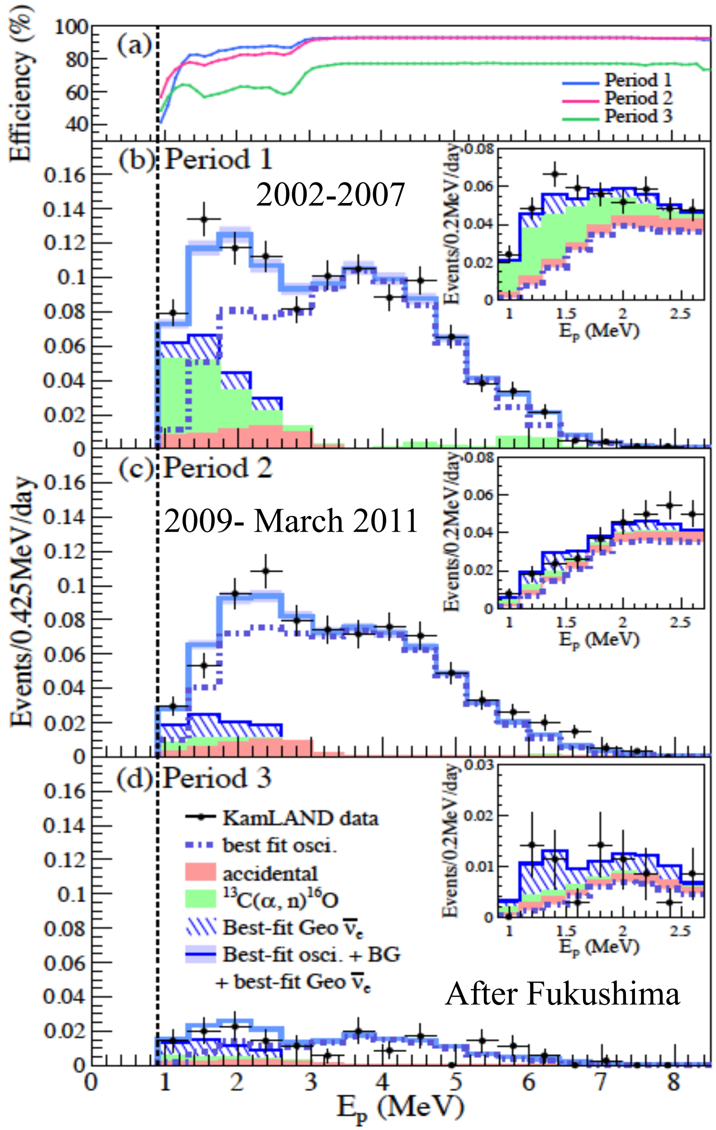


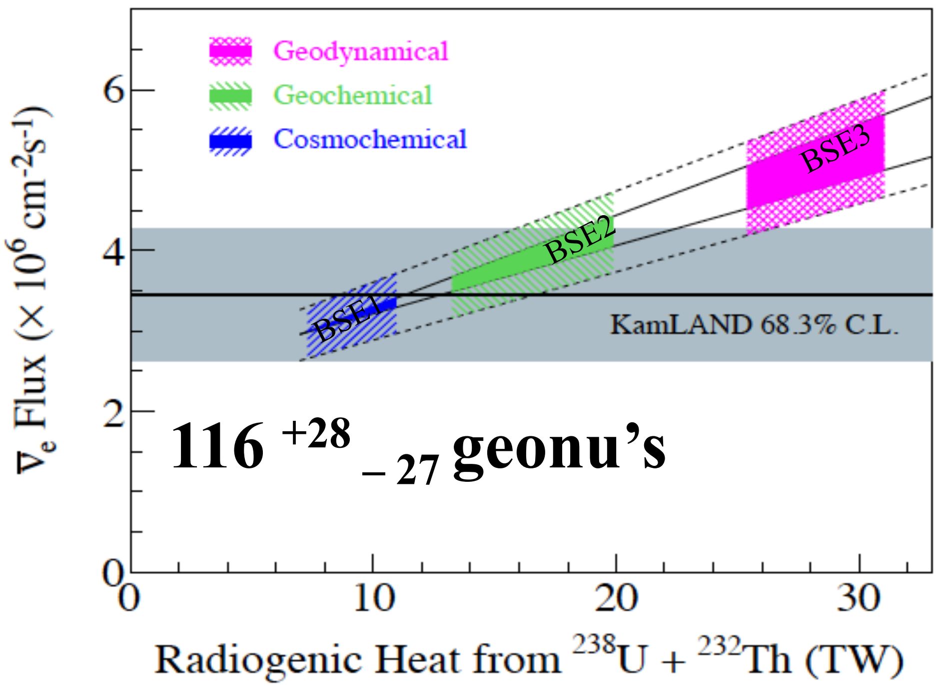
- ✓the first liquid scintillator based detector entering on the scene of 0ν-ββ decay experiments
- ✓ if this process would be observed: neutrinos Majorana particles
- ✓Start in 2011 (Phase 1): doping of the scintillator with ^{133}Xe
- ✓Problem with ^{110m}Ag contamination
- ✓2012-2013 long purification campaign and Dec 2013 Phase 2 (^{110m}Ag reduced by a factor 10)
- ✓ Refurbishing of the OD in 2016
- ✓competitive with other experiments (arXiv:1409.0077)

$$T^{0\nu}_{1/2} > 2.6 \times 10^{25} \text{ yr at } 90\% \text{ C.L.}$$

PRD 88 (2013) 033001

Latest KamLAND geoneutrino results



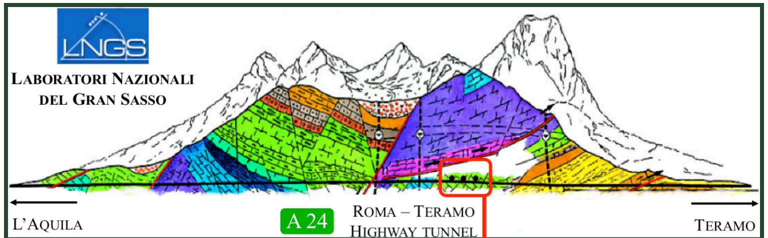


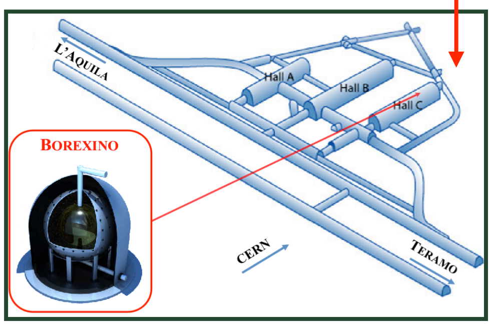
116 $^{+28}_{-27}$ geonu's

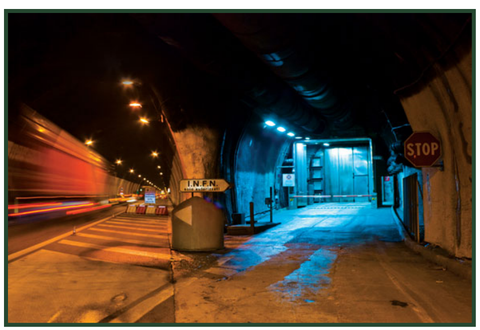
- After Fukushima, Japanese reactors off
- Plan to refurbish outer detector in Jan' 16.. new update expected then!

Borexino

Laboratori Nazionali del Gran Sasso, Italy



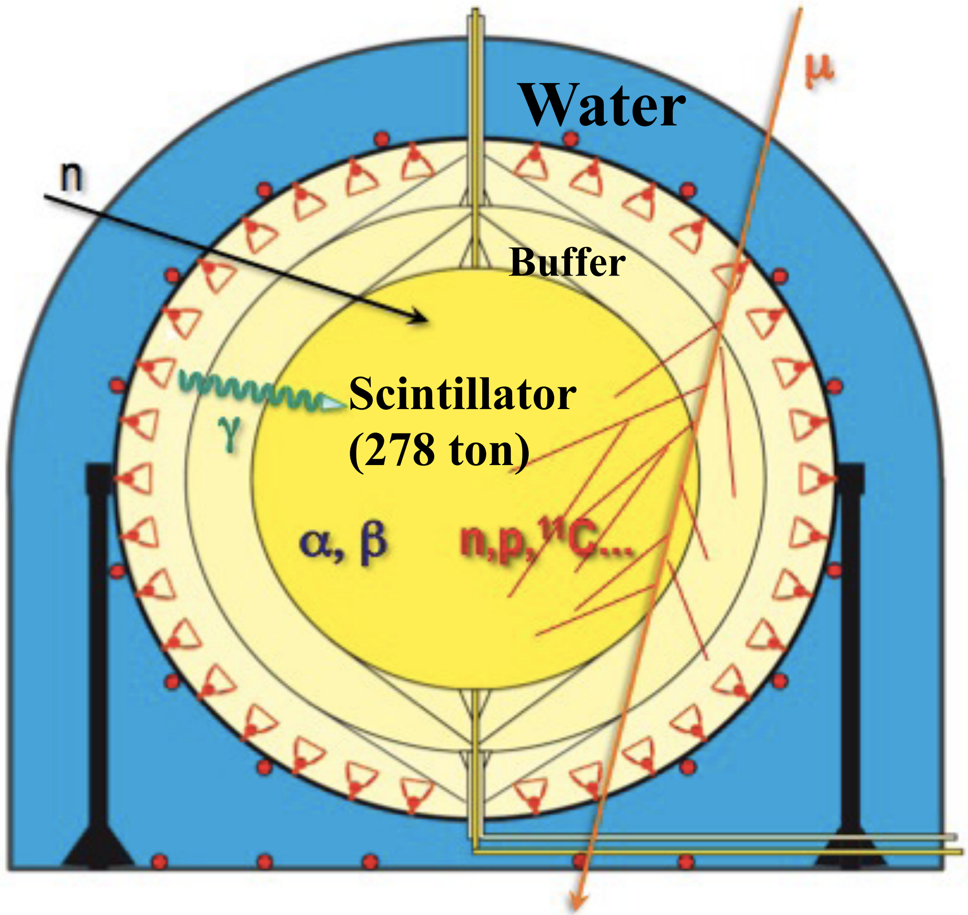




Principal goal: ^{7}Be solar-ν

BOREXINO
ν_e
ν_x
GRAN SASSO

Borexino detector



- ✓ Principle of **graded shielding:** materials get more pure towards the detector core
- ✓ **15 years of work to reach the required radio-purity**
- ✓ To reduce the background from natural radioactivity to the level of expected solar neutrino signal: reduction of 9-10 orders of magnitude required!

Backgrounds now : $^{238}U < 8\ 10^{-20}$ g/g at 95% C.L., $^{232}Th < 9\ 10^{-19}$ g/g at 95% C.L.

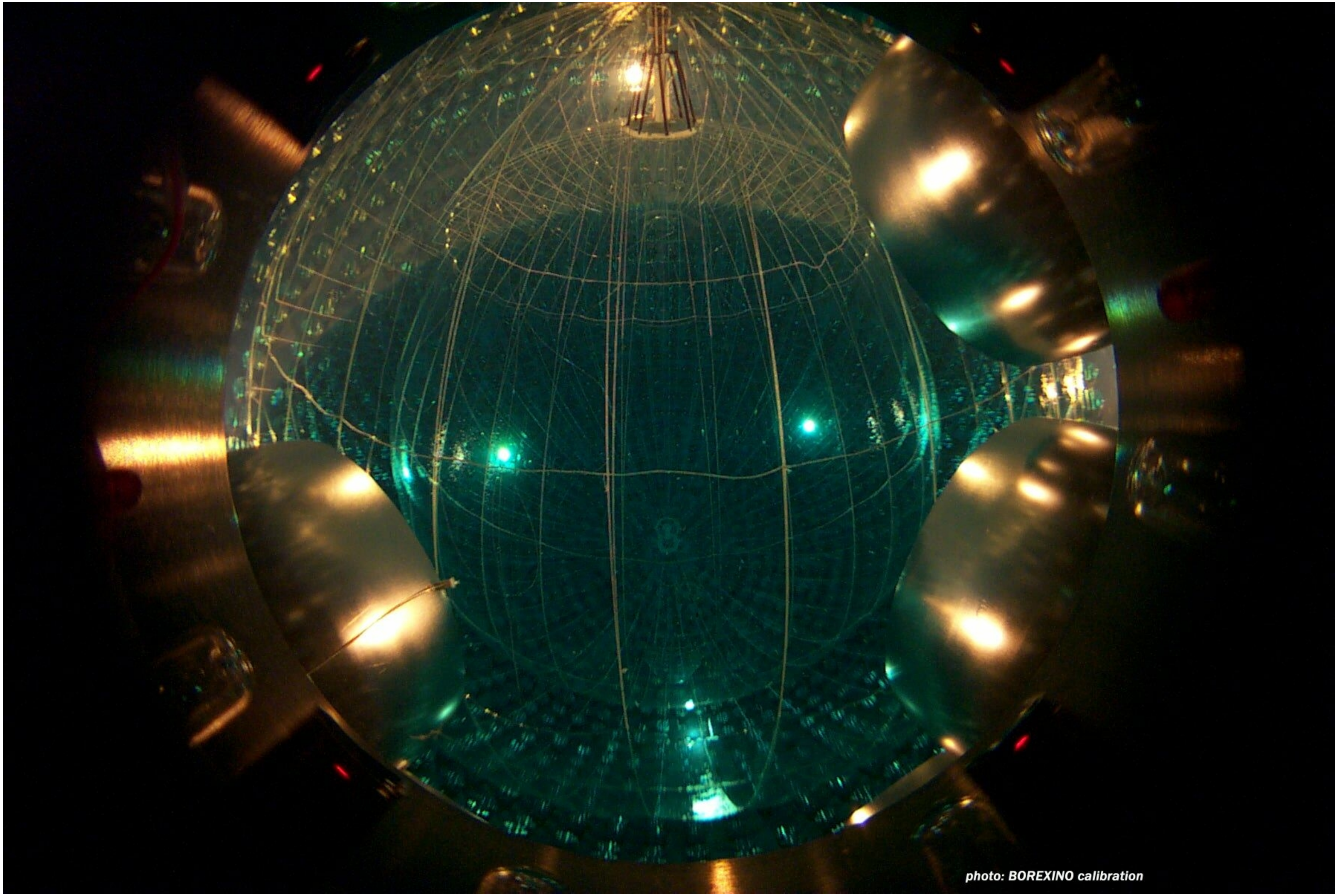
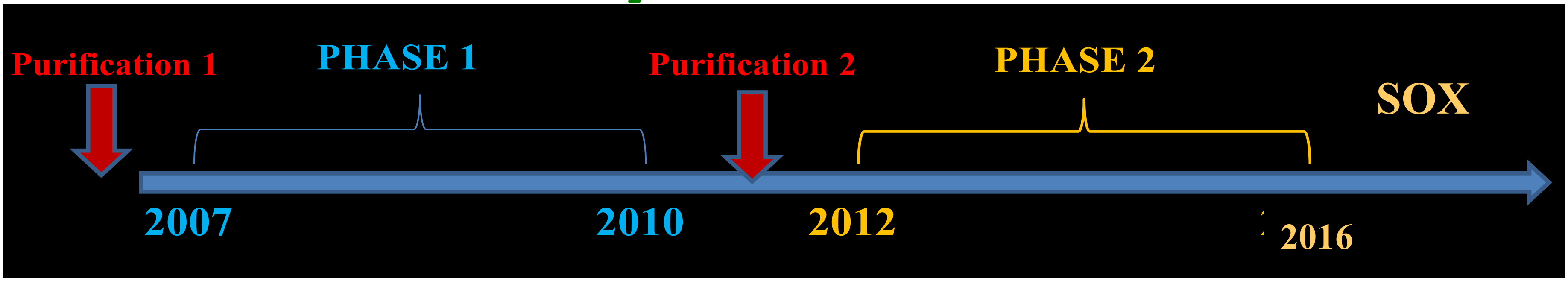


photo: BOREXINO calibration

Borexino history



PHASE 1 (2007-2010)

Solar neutrinos

- ^{7}Be ν : 1st observation+ precise measurement (5%); √
- Day/Night asymmetry; √
- pep ν: 1st observation; √
- ^{8}B ν; √
- CNO n: best limit √

Geo-neutrinos

- Evidence > 4.5σ √

- Limit on rare processes √
- Study on cosmogenics √

PHASE 2 (2012 – end 2016)

Improved radiopurity

- ^{85}Kr compatible with 0
- ^{210}Bi reduced (factor ~3)
- ^{232}Th and ^{238}U negligible

Solar neutrinos:

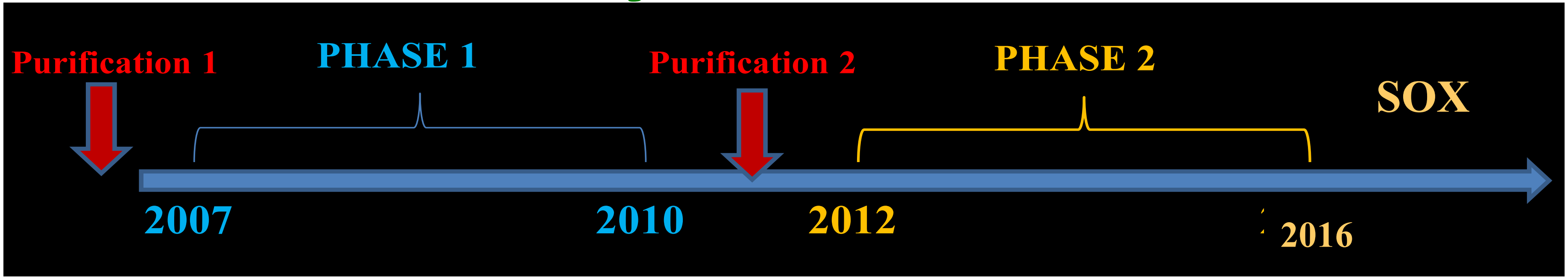
- pp-ν: first real time detection

Geo-neutrinos: 5.9 sigma C.L.

Rare processes:

- e$^-$ decay/charge conservation

Borexino history



What is going on now:

- update of **all solar neutrino** measurements (^{7}Be, pep, pp, ^{8}B)
- effort to measure **CNO neutrinos** (not easy…)
- Final update of **geoneutrino** measurements
- 3-4 months long calibration campaign ahead

SOX project:

- ✓ Short distance neutrino oscillations with Borexino
- ✓ insertion of a strong ^{144}Ce/^{144}Pr antineutrino generator at the end of 2016
- ✓ Search for a **sterile neutrino**

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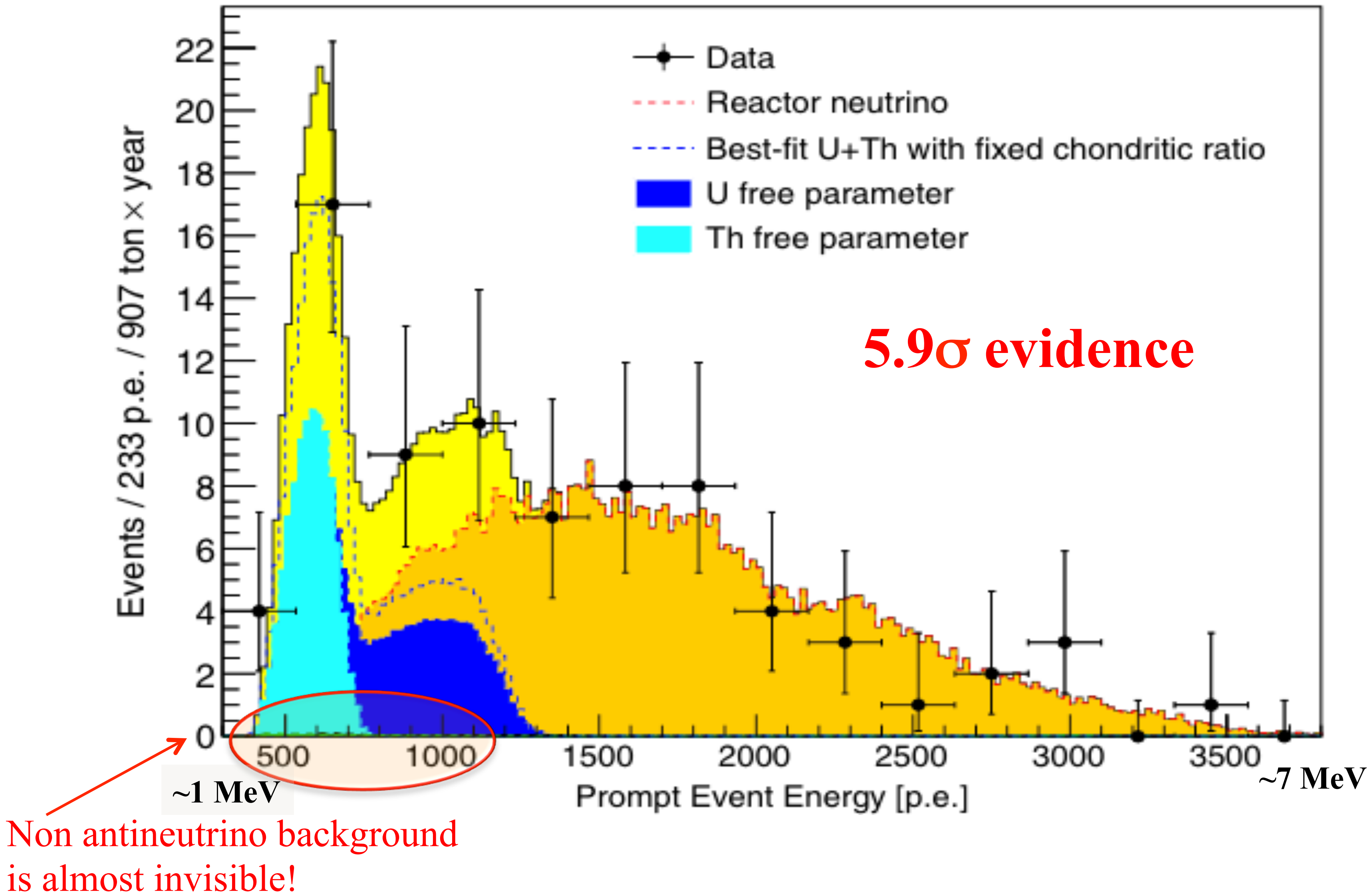
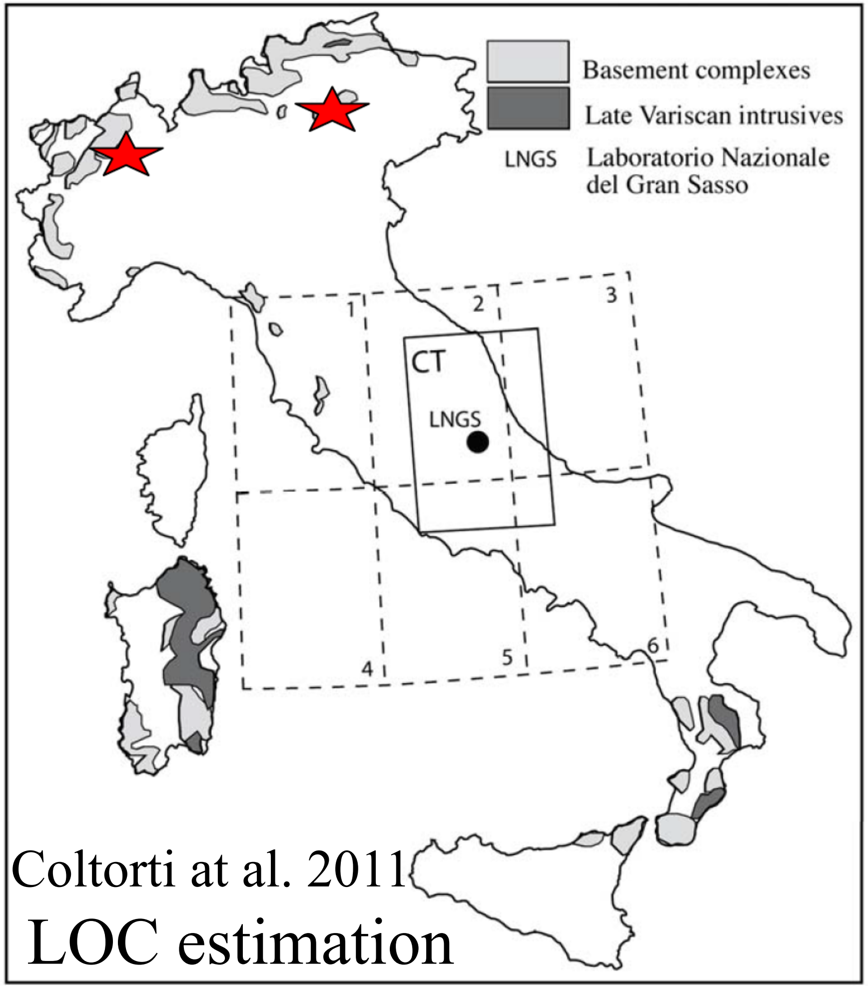
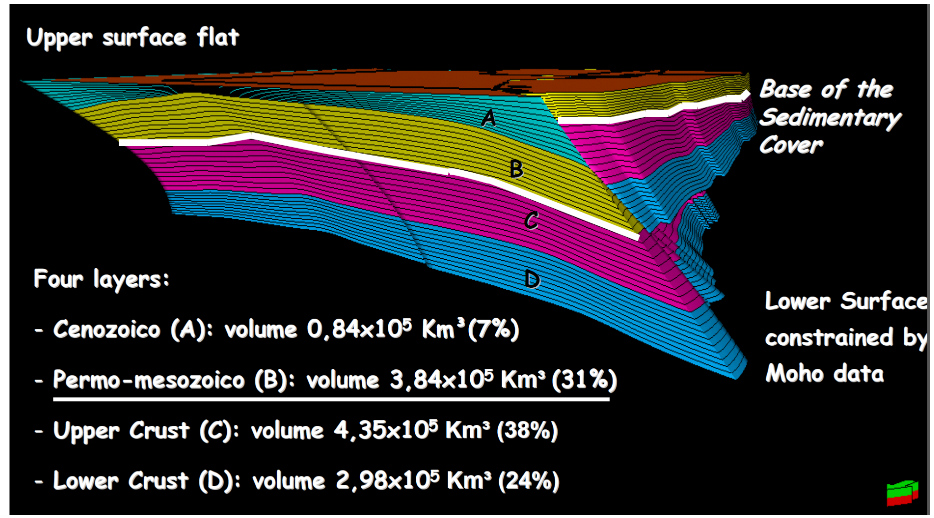
Latest Borexino geoneutrino results



Expected crustal signal at LNGS

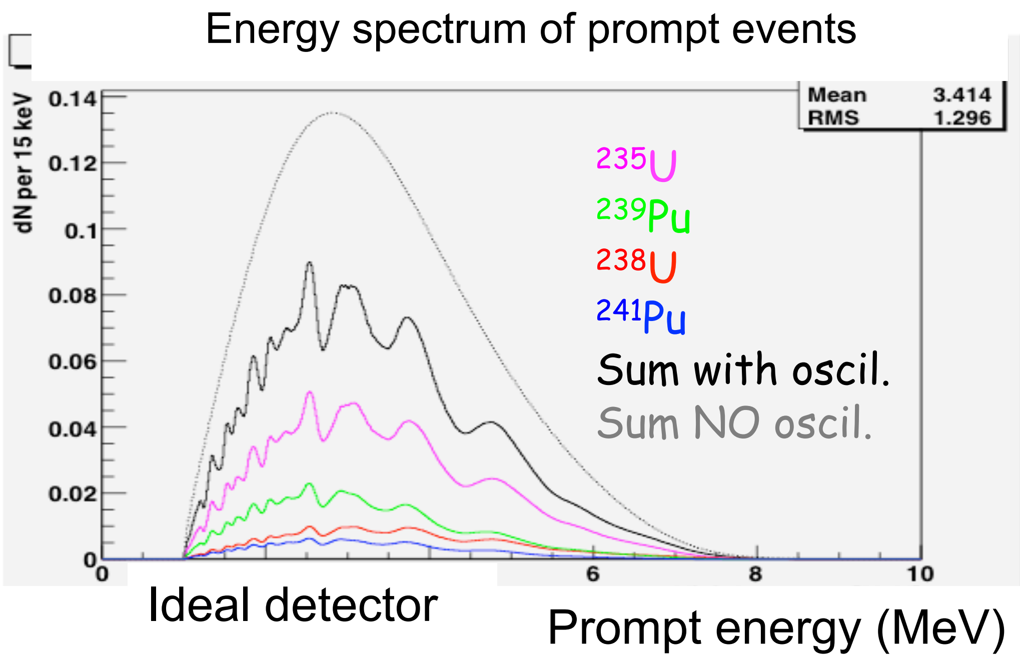


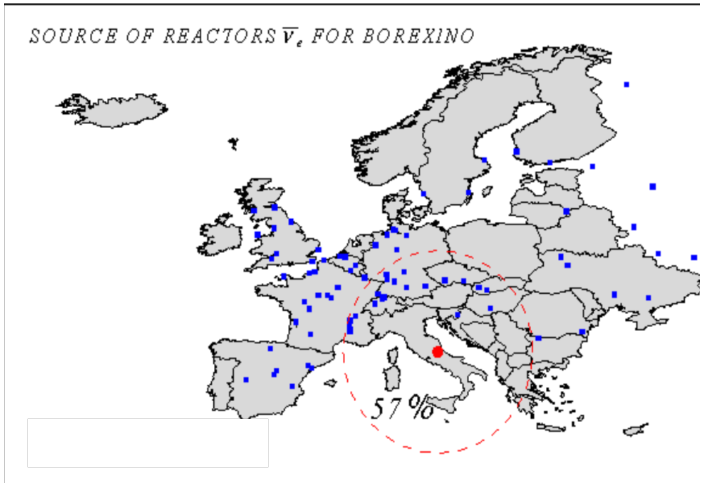
Coltorti at al. 2011
LOC estimation

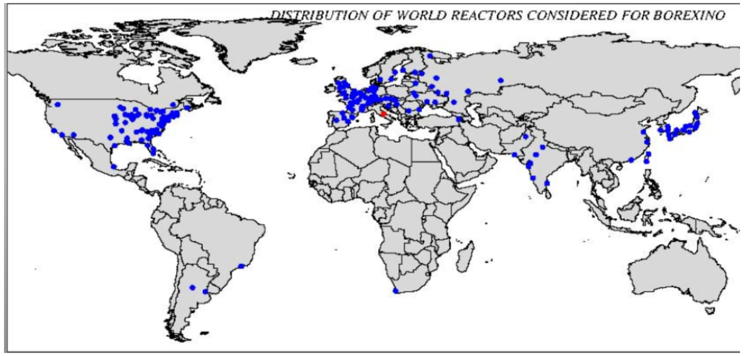


Expected crustal signal
local LOC + Rest-Of-the Crust
23.4 $\pm$ 2.8 TNU

Expected reactor signal at LNGS







Expected reactor signal

87 (1 ± 0.05) TNU

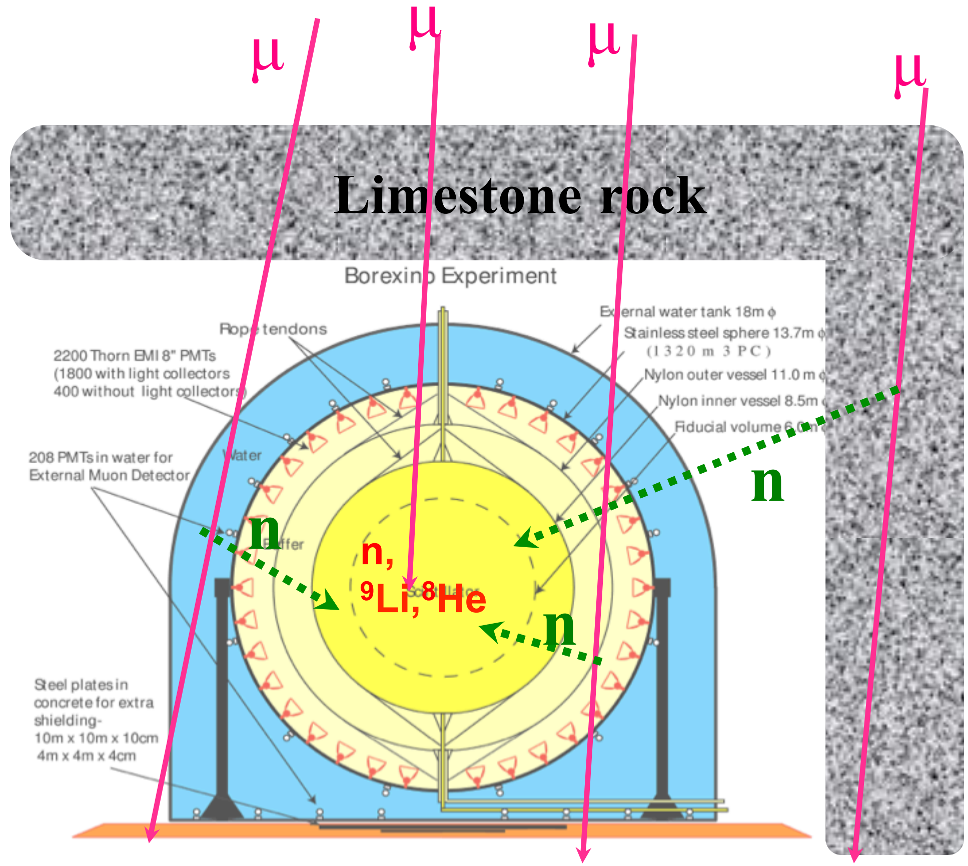
Non-antineutrino background sources

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

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

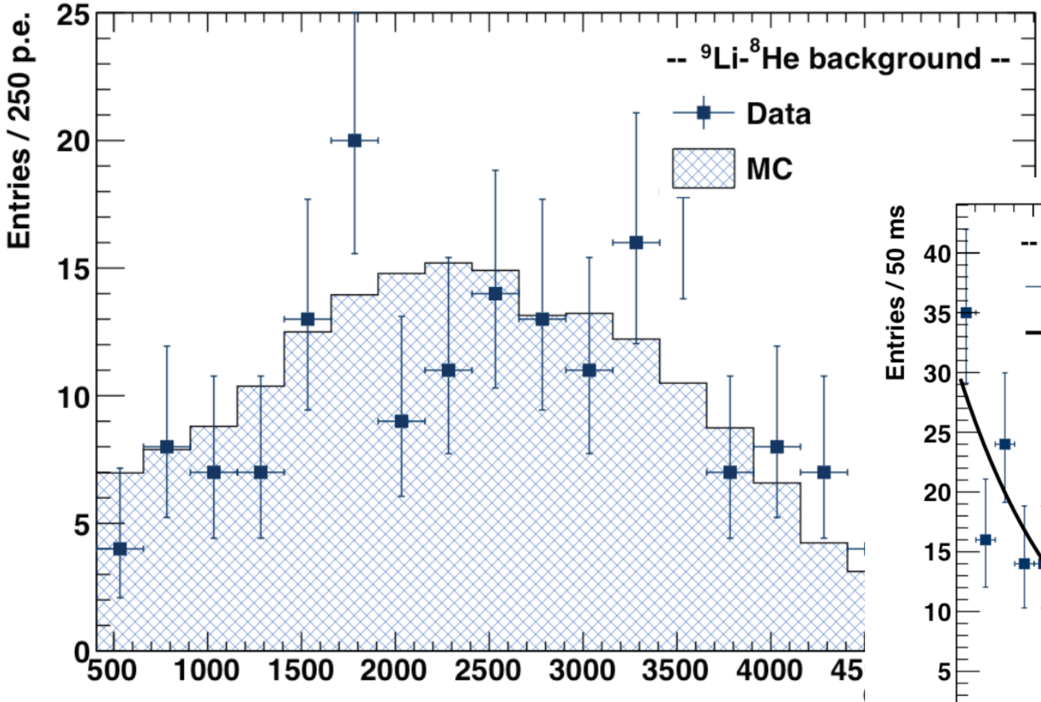
2) <u>Accidental coincidences;</u>

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

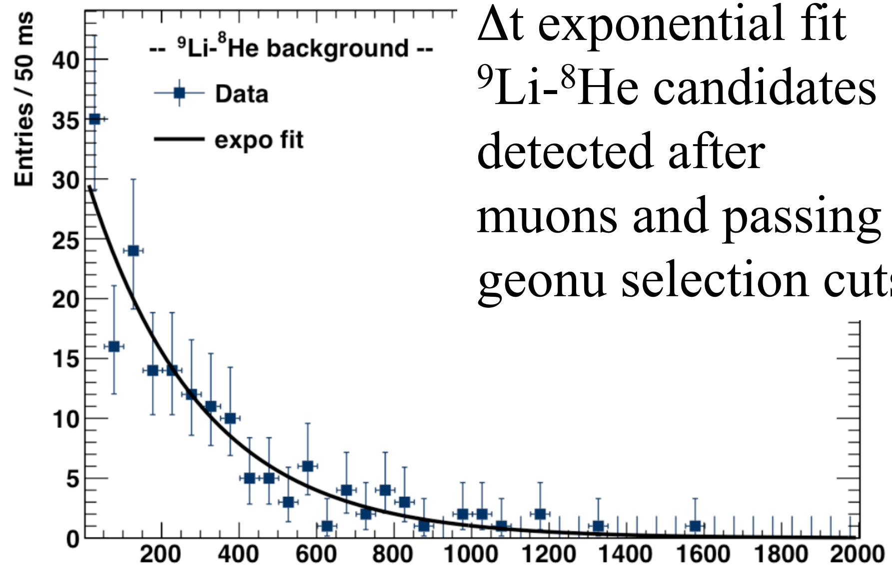


^{9}Li-^{8}He	$0.194^{+0.125}_{-0.089}$
Accidental coincidences	0.221 ± 0.004
Time correlated	$0.035^{+0.029}_{-0.028}$
(α, n) in scintillator	0.165 ± 0.010
(α, n) in buffer	<0.51
Fast n's (μ in WT)	<0.01
Fast n's (μ in rock)	<0.43
Untagged muons	0.12 ± 0.01
Fission in PMTs	0.032 ± 0.003
^{214}Bi-^{214}Po	0.009 ± 0.013
Total	$0.78^{+0.13}_{-0.10}$
	<0.65(combined)

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



Eenergy$_{prompt}$ [pe]

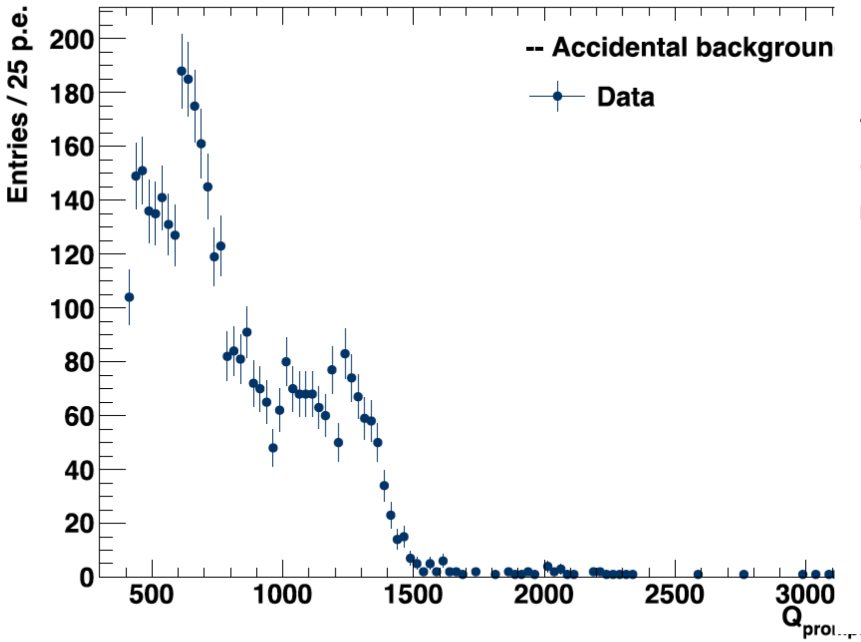


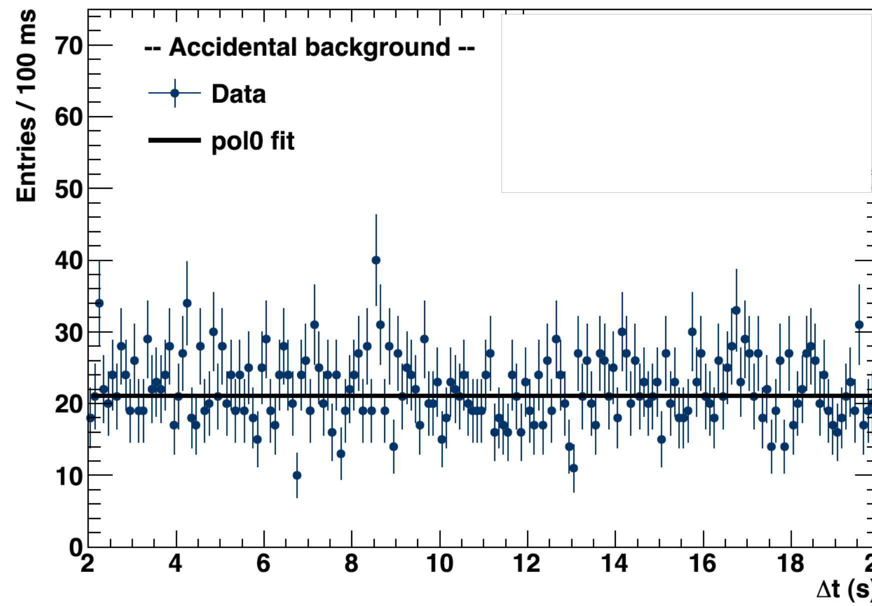
Δt (prompt – last muon) [ms]

Δt exponential fit
^{9}Li-^{8}He candidates detected after muons and passing geonu selection cuts

Accidental background

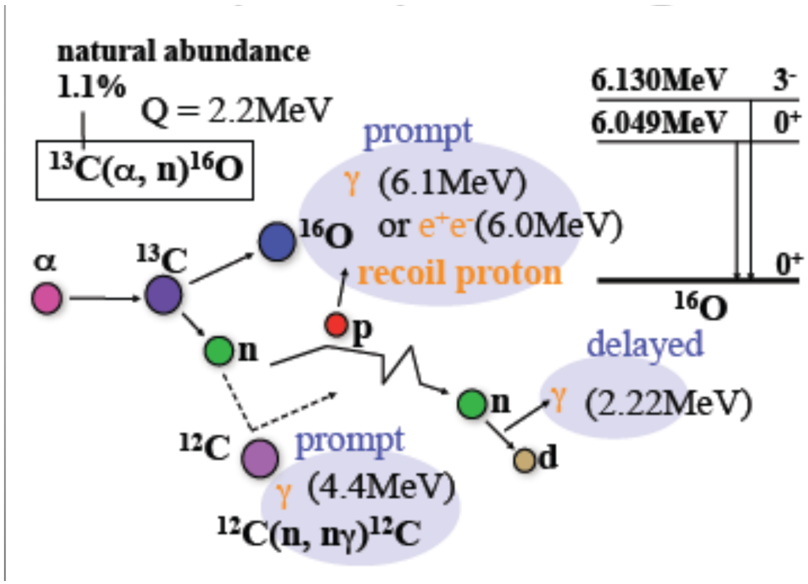
Search for coincidences in the off-time window Δt (2 s – 20 s)



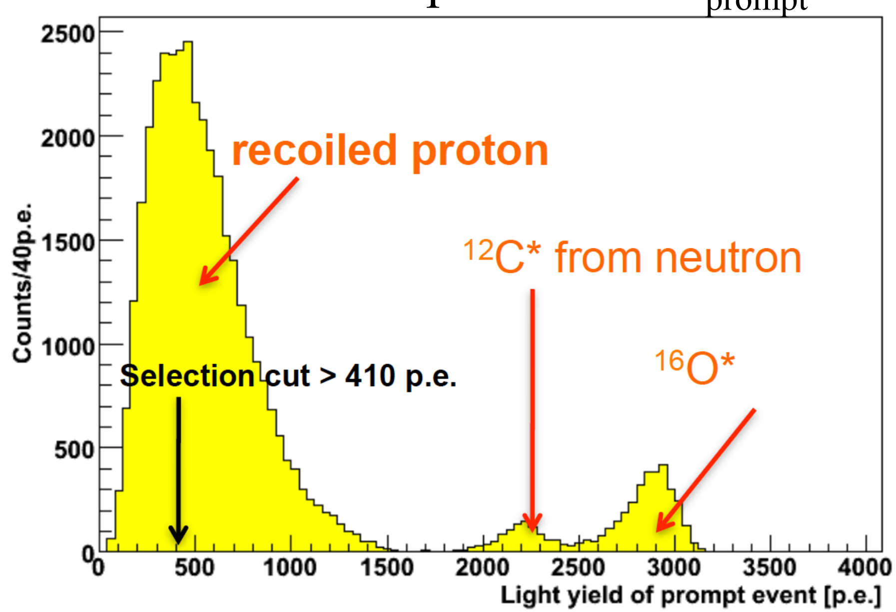


$^{13}C(\alpha, \text{neutron})^{16}O$ background

- Isotopic abundance of ^{13}C: 1.1%
- $^{210}Po(\alpha)$ = 14.1 cpd / ton (average value)



MC-based spectrum of E_{prompt}



Selection cuts

1. **E_{prompt}** > E_{prompt} @ IBD threshold considering energy resolution: Q > 408 pe
2. **$E_{delayed}$**: 2.2 MeV γ peak with low-energy tail at the border; 860 < Q < 1300 pe
3. **ΔR** < 1 m: optimized for signal/ accidental background
4. **Δt** : 4.8 x neutron capture time (20 < Δt <1280 μs)
5. **Muon correlated cuts:**
   - ✓ Remove muons (Water Cherenkov OD + pulse shape from ID)
   - ✓ To supress ^{9}Li-^{8}He cosmogenics: 2 s veto after internal muons: ~11% live time loss.
   - ✓ To supress fast neutrons: 2 ms veto after external muons
   - ✓ Multiplicity cut: no neutron-like events in ± 2 ms window (non-detected muons with multiple neutrons
6. **Pulse shape delayed:** ^{222}Rn-decay (10^{-4} BR) ^{214}Bi(β)-^{214}Po(α+γ): $Gatti_{\alpha\beta} < 0.015$
7. **FV cut:** $R_{IV}(\Theta,\varphi) - R_{prompt}(\Theta,\varphi) > 0.30$ m : dynamical, follows IV shape
8. **FADC cut:** independent pulse shape check with 400 MHz digitizing system

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

Spectral fit of E_{prompt}(pe)

Unbinned maximal likelihood fit

- **Geoneutrinos free**
  - ✓ theoretical spectra -> MC (detector response) -> E_{prompt} (pe) spectrum
  - ✓ U/Th ratio
    - o fixed to chondritic value
    - o Left free
- **Reactor antineutrinos free**
  - ✓ Calculated spectra -> MC (detector response) -> E_{prompt} (pe) spectrum
- **Other backgrounds constrained**
  - ✓ ^{9}Li-^{8}He spectra based on MC
  - ✓ Measured accidental background spectrum from off-time coincidences
  - ✓ MC-based (α, n) background shape

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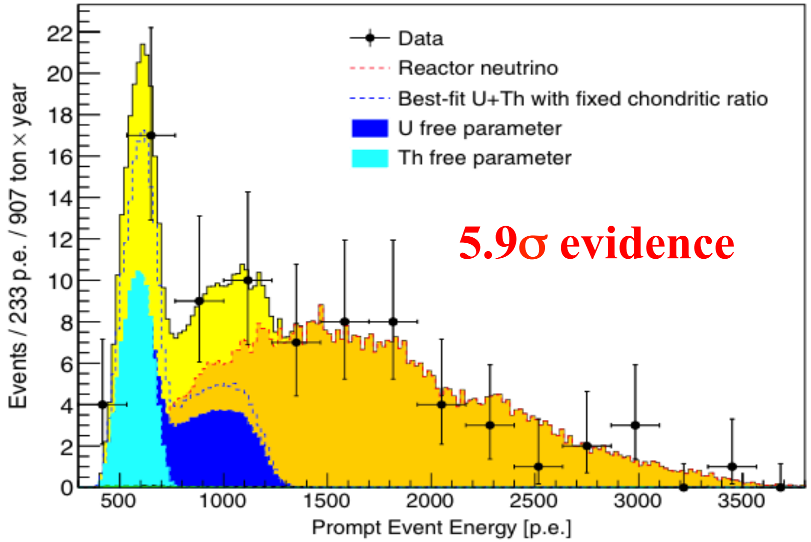
Latest Borexino geoneutrino results



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

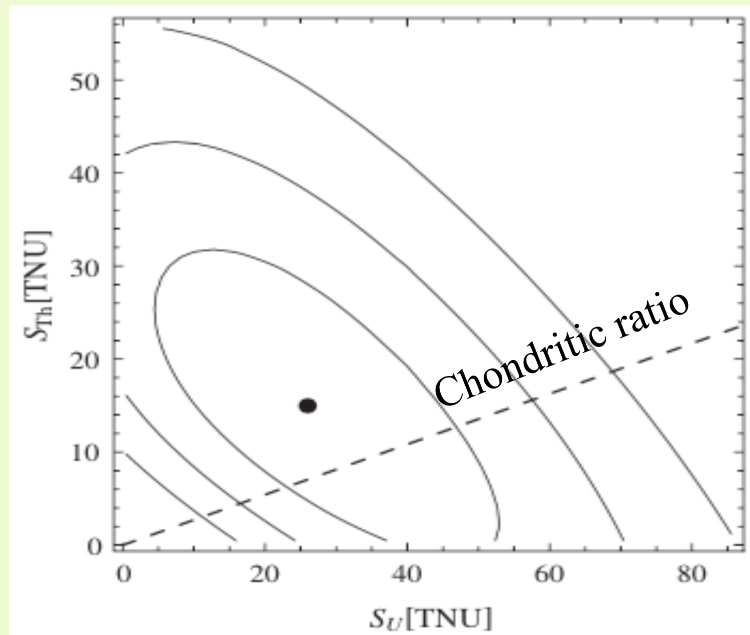
Two types of fits:

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

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

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

2) U and Th free fit paramters



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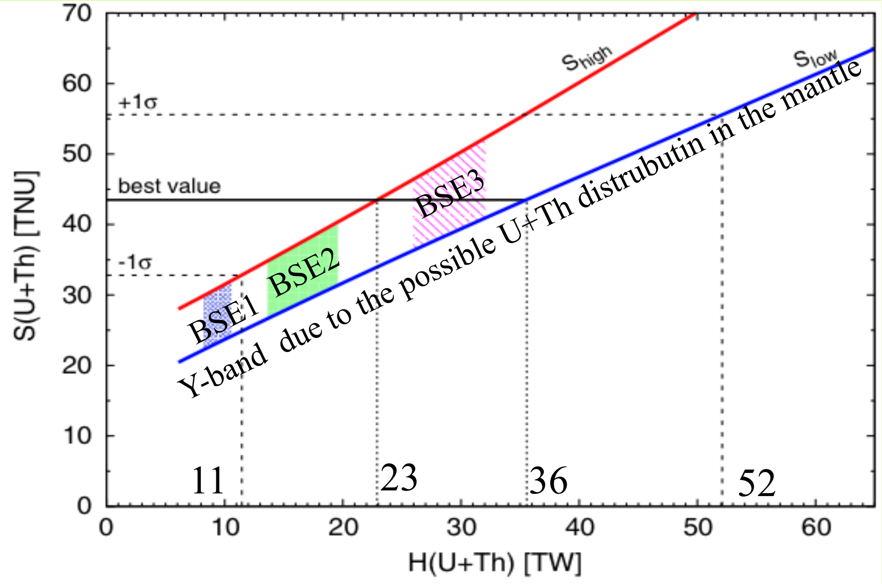
Geological implications of the new Borexino results

Radiogenic heat

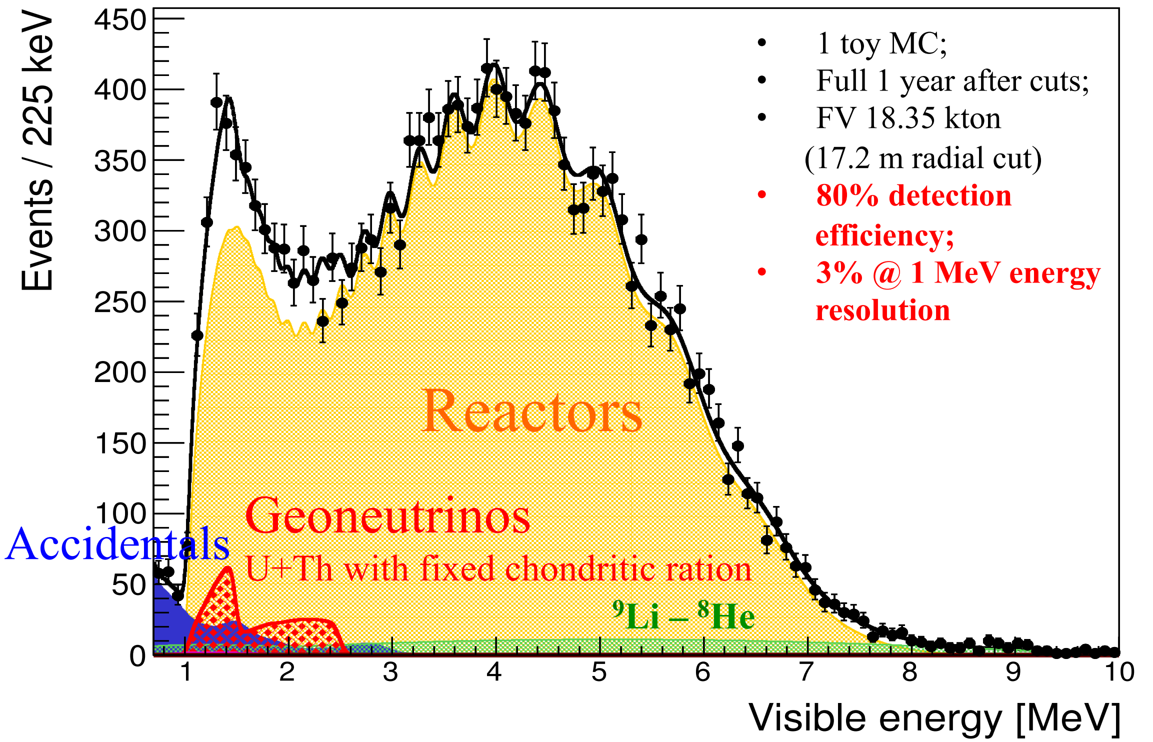


- Radiogenic heat (U+Th): 23-36 TW for the best fit and 11-52 TW for 1σ range
- Considering chondritic mass ratio Th/U=3.9 and K/U = 10^4 : Radiogenic heat
  (U + Th + K) = 33^{+28}_{-20} TW
  to be compared with 47 ± 2 TW of the total Earth surface heat flux (including all sources)

Mantle signal

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

JUNO potential to measure geoneutrinos



Big advantage:

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

Main limitations:

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

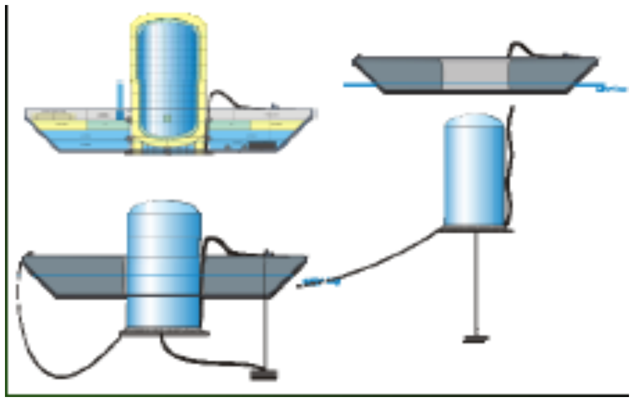
Critical:

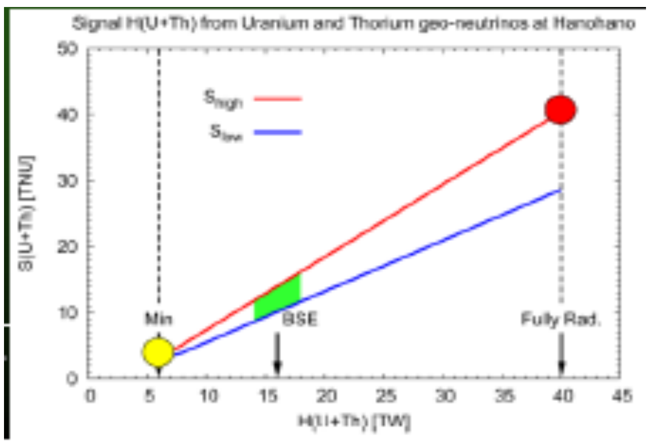
- ✓ Keep other backgrounds (^{210}Po contamination!) at low level and under control;

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

Hanohano at Hawaii

Hawaii Antineutrino Observatory (HANOHANO = "magnificent" in Hawaiian





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

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

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

BSE: 60-100 events/per year

Geoneutrino future

- **Borexino** will switch to SOX (see later) in late 2016 – closure of geoneutrino dataset;
- **KamLAND**: possible next update with low reactor-background data after the end of 2015;
- **SNO+** (Canada): 780 ton & DAQ start in 2017; detector should be able to provide geoneutrino results;
- **JUNO** (China): 20 kton & DAQ start in 2020; If non antineutrino background low and under control, JUNO will soon beat the precision of existing measurements;
- **HanoHano** (Hawaii): 10 kton underwater detector with ~80% mantle contribution: "**THE" GEONU DETECTOR: MISSING FUNDING!**

- New interdisciplinary field established: **NEUTRINO GEOSCIENCE** conference every two years
- Power of combined analysis and importance of multi-site measurements at geologically different environments

Thank you!