Hunting for geoneutrinos

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Outlook

1. **Geoneutrinos: what they are and the current measurements in a nutshell**

2. **Why to measure geoneutrinos?**

3. **What are neutrinos?**

4. **How to detect neutrinos?**

5. **Borexino and KamLAND geoneutrino analysis**

6. **Borexino and KamLAND experiments**

7. **Future perspective**

Geoneutrinos: electron antineutrinos

from the decays of long lived radioactive isotopes naturally present in the Earth (^{238}U and ^{232}Th chains and ^{40}K)

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^{235}U (0.7205% of natural U) → $^{207}Pb + 7\,\alpha + 4\,e^{-}$ + 4 anti-neutrinos + **46.4 MeV**
^{40}K (0.012% of natural K) → $^{40}Ca + e^{-}$ + 1 anti-neutrino + **1.32 MeV** (89.3 %)
$^{40}K + e^{-}$ → ^{40}Ar + 1 neutrino + **1.505 MeV** (10.7 %)

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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…..

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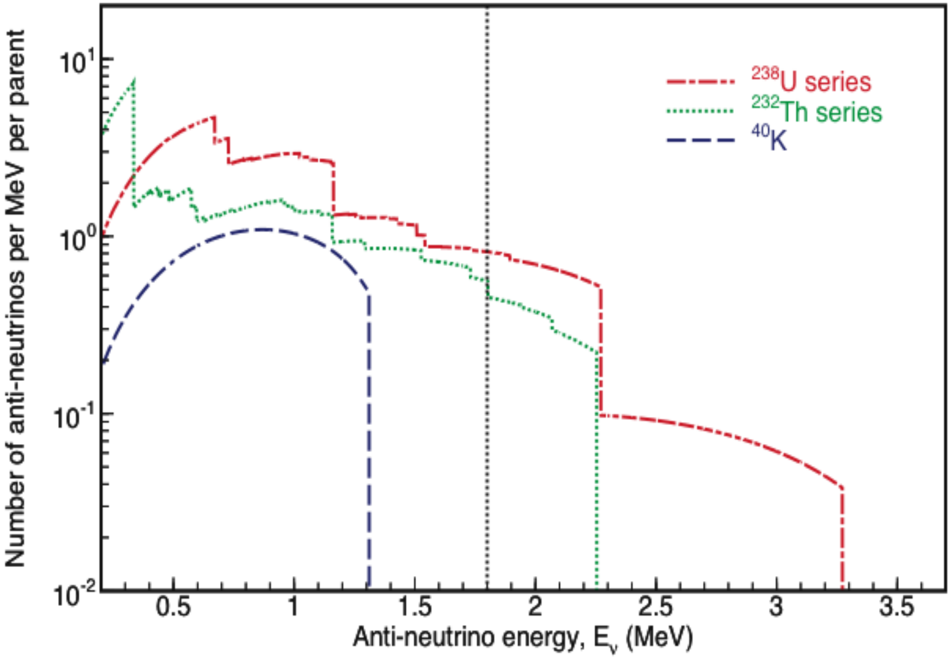
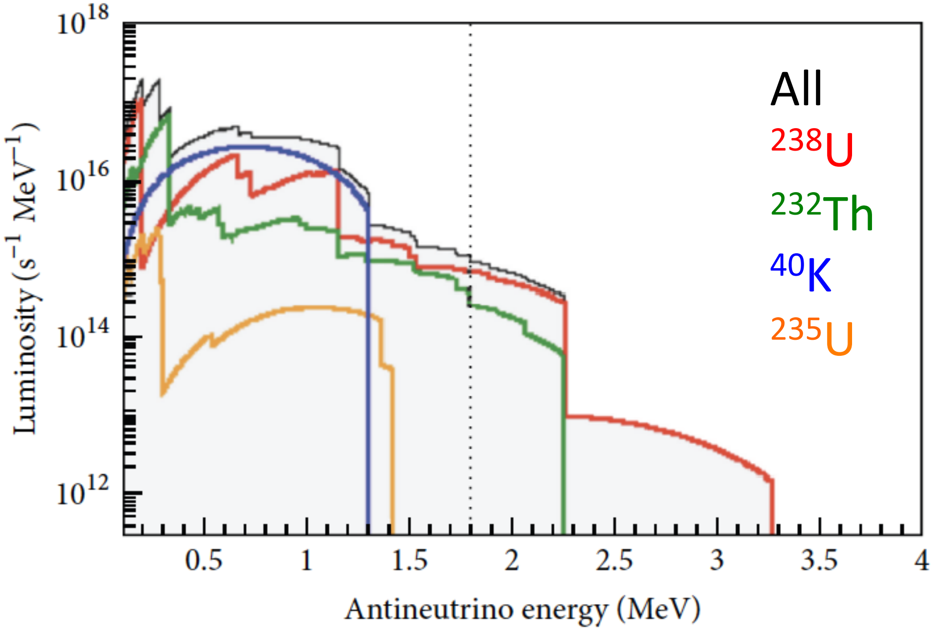
Earth shines in antineutrinos: flux ~ 10^6 cm^{-2} s^{-1}

leaving freely and instantaneously the Earth interior

(to compare: solar neutrino (NOT antineutrino!) flux ~ 10^{10} cm^{-2} s^{-1})

Decay	$T_{1/2}$ [10^9 yr]	E_{max} [MeV]	Q [MeV]	$\varepsilon_{\bar{\nu}}$ [$kg^{-1}s^{-1}$]	ε_H [W/kg]
$^{238}U \rightarrow {}^{206}Pb + 8\,{}^4He + 6e + 6\bar{\nu}$	4.47	3.26	51.7	7.46×10^7	0.95×10^{-4}
$^{232}Th \rightarrow {}^{208}Pb + 6\,{}^4He + 4e + 4\bar{\nu}$	14.0	2.25	42.7	1.62×10^7	0.27×10^{-4}
$^{40}K \rightarrow {}^{40}Ca + e + \bar{\nu}$ (89%)	1.28	1.311	1.311	2.32×10^8	0.22×10^{-4}





•Radiogenic heat is related to the neutrino flux:

H_R = 9.5 M(U) + 2.7 M(Th) + 3.6 M(^{40}K)

L_ν = 7.4 M(U) + 1.6 M(Th) + 27 M(^{40}K)

- only **2 running experiments** have measured geoneutrinos;
- liquid scintilllator detectors;
- (Anti-)neutrinos have low interaction rates, therefore:
    - Large volume detectors needed;
    - High radiopurity of construction materials;
    - Underground labs to shield cosmic radiations;

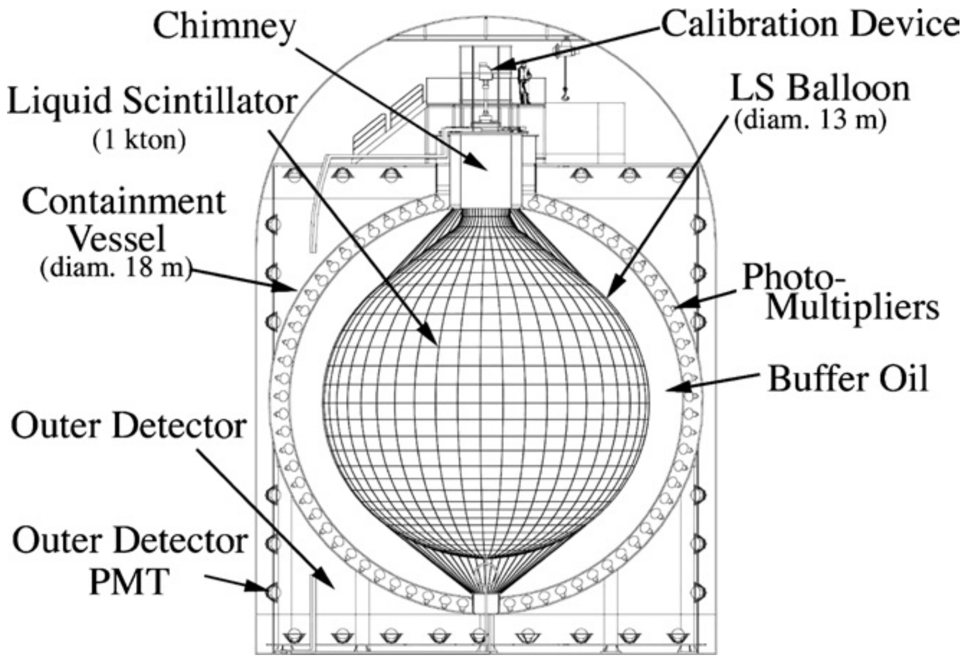
KamLand in Kamioka, Japan
Border bewteen
OCEANIC AND CONTINENTAL CRUST

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

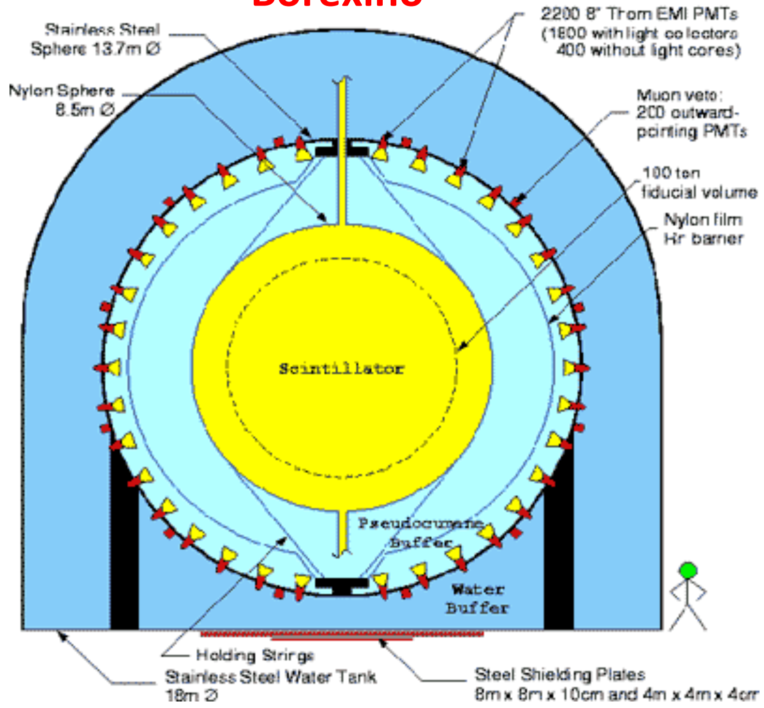
Borexino in Gran Sasso, Italy
CONTINENTAL CRUST

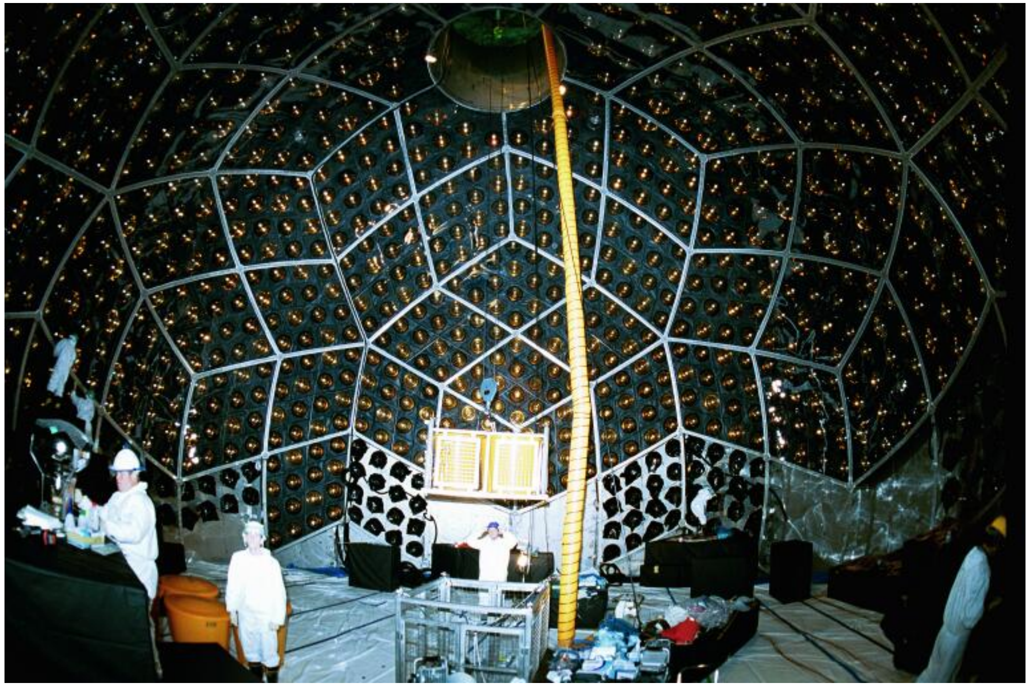
- originally build to measure neutrinos from the Sun – extreme radiopurity needed and achieved;
- 280 tons;
- S(reactors)/S(geo) ~ 0.3 !!! (2010)
- DAQ started in 2007;
- 3600 m.w.e. shielding;

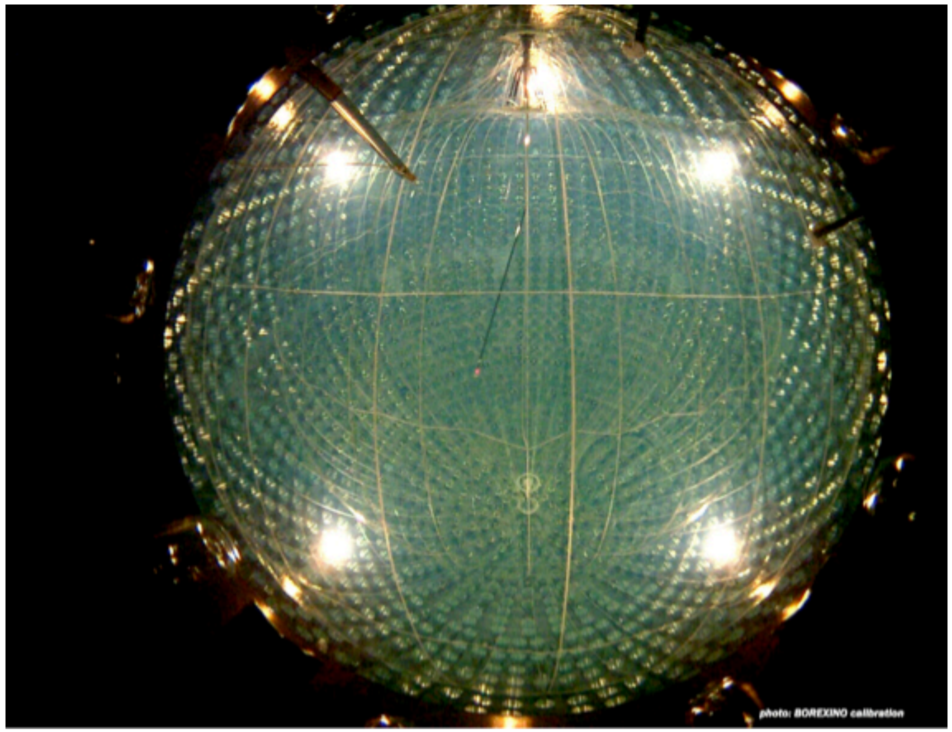
KamLand



Borexino

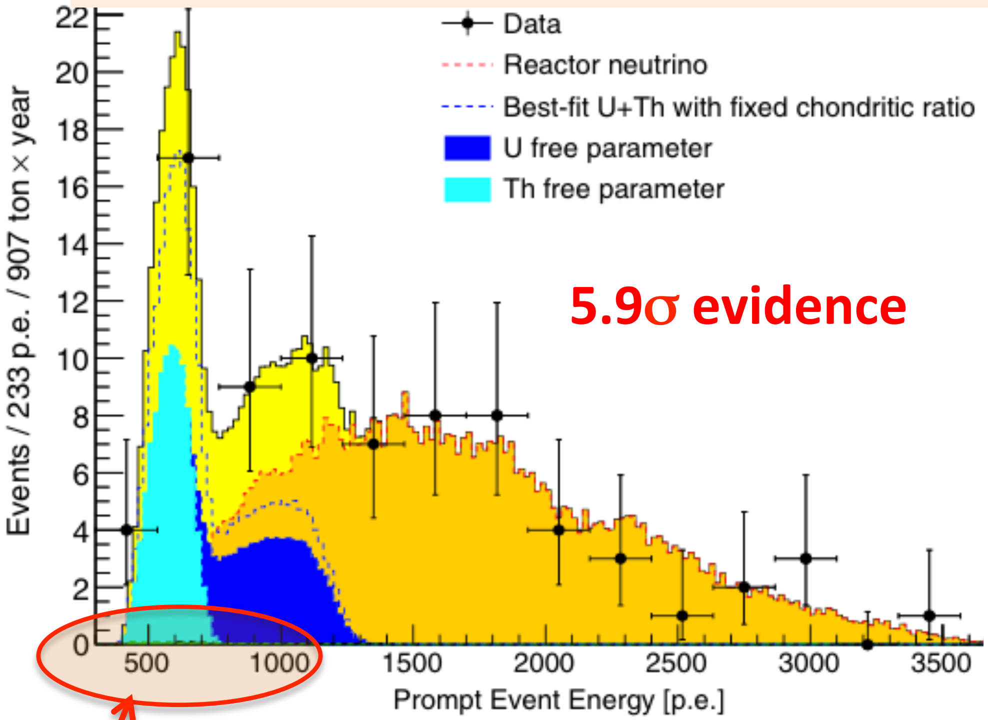






Latest geoneutrino results

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

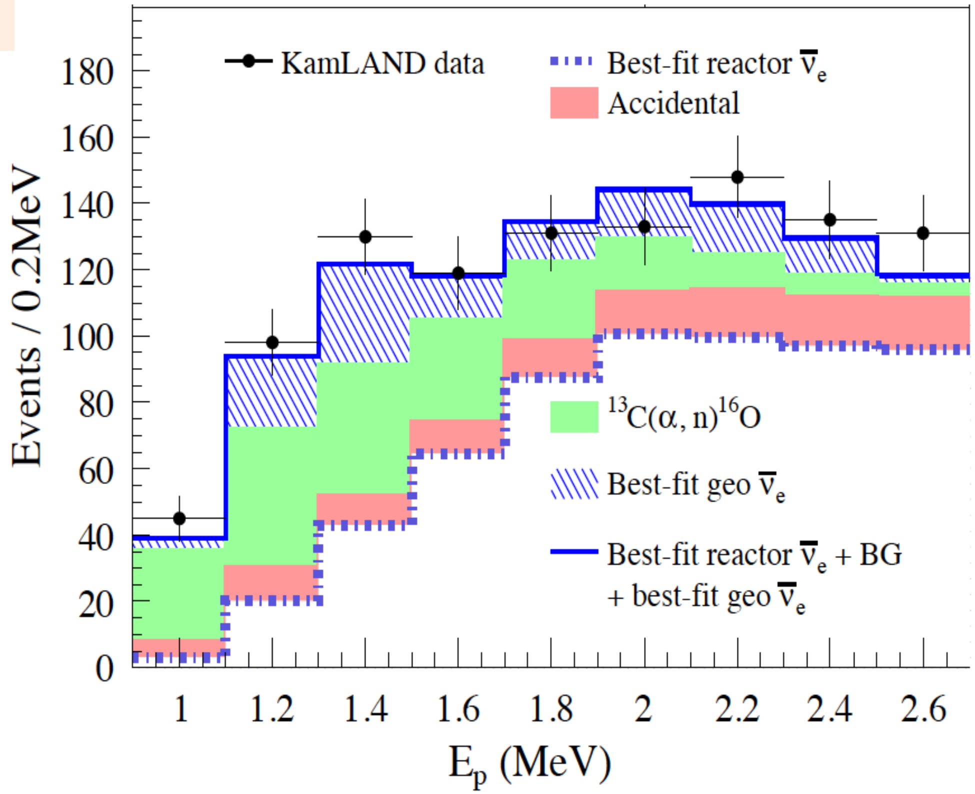


~1 MeV

PRD 92 (2015) 031101 (R)

~7 MeV

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



Phys. Rev. D 88 (2013) 033001

✓ Non antineutrino background almost invisible!

✓ 5.5 x 10^{31} target-proton year

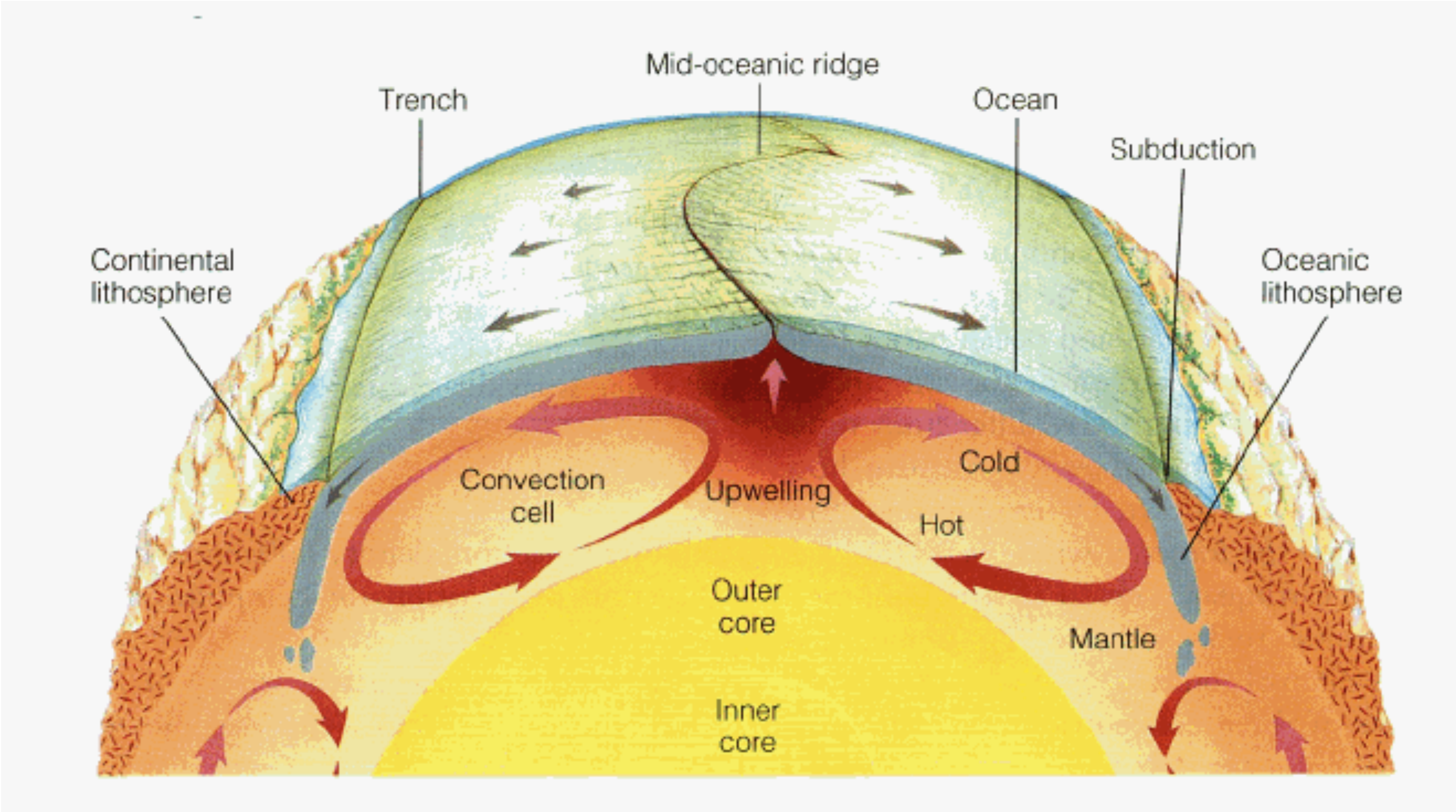
✓ 0-hypothesis @ 3.6 x 10^{-9}

✓ 4.9 x 10^{32} target-proton year

✓ 0-hypothesis @ 2 x 10^{-6}

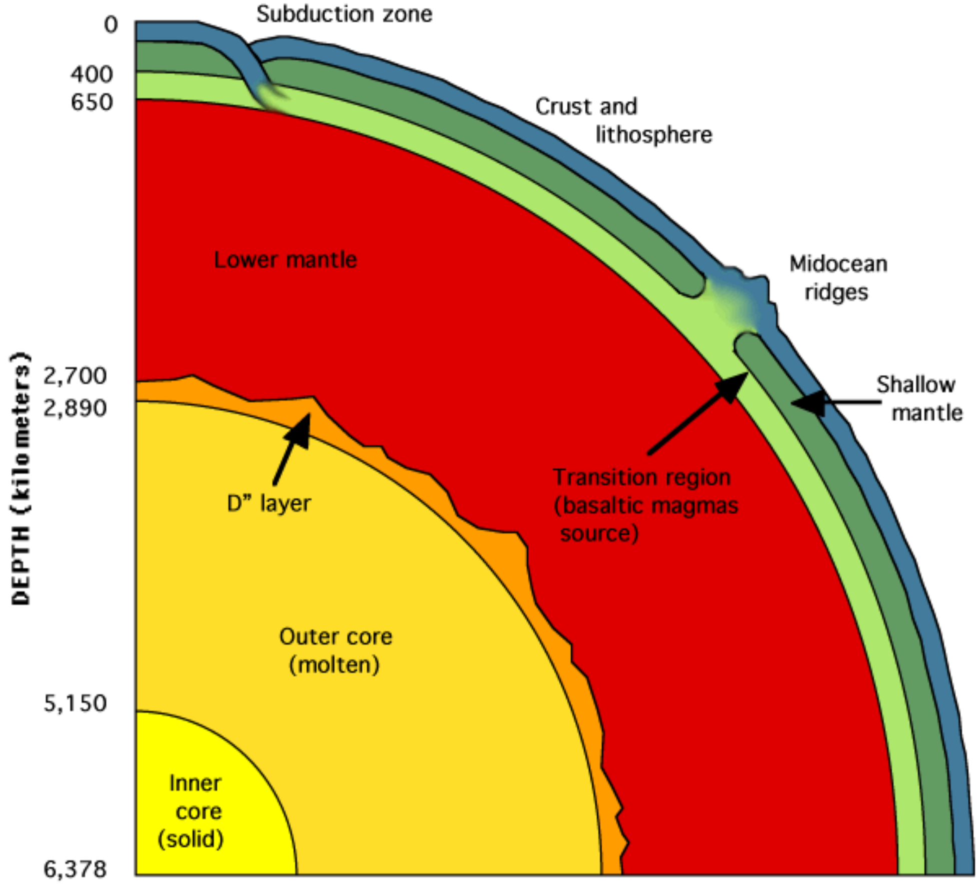
Why to study geoneutrinos?

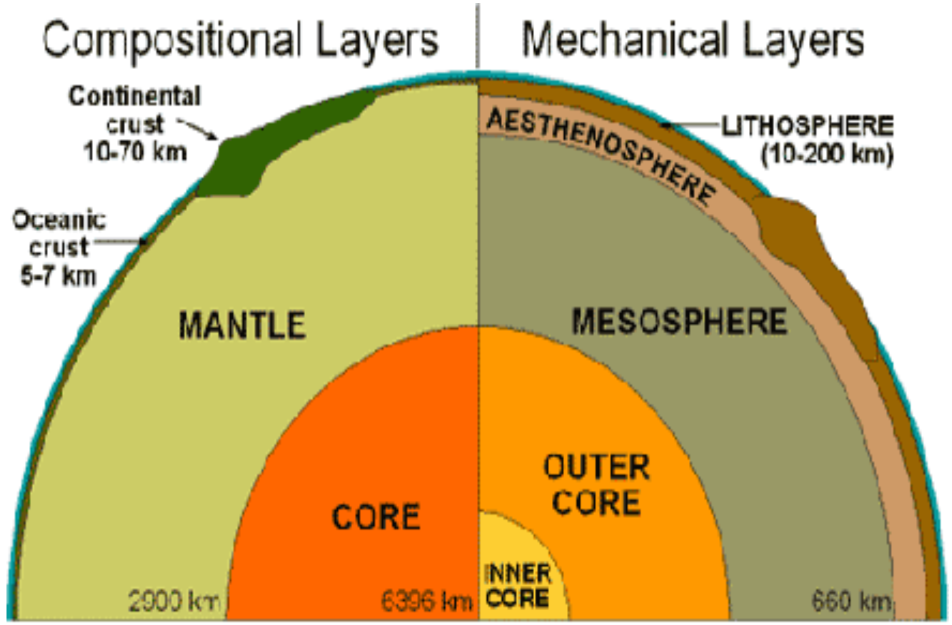
Earth structure

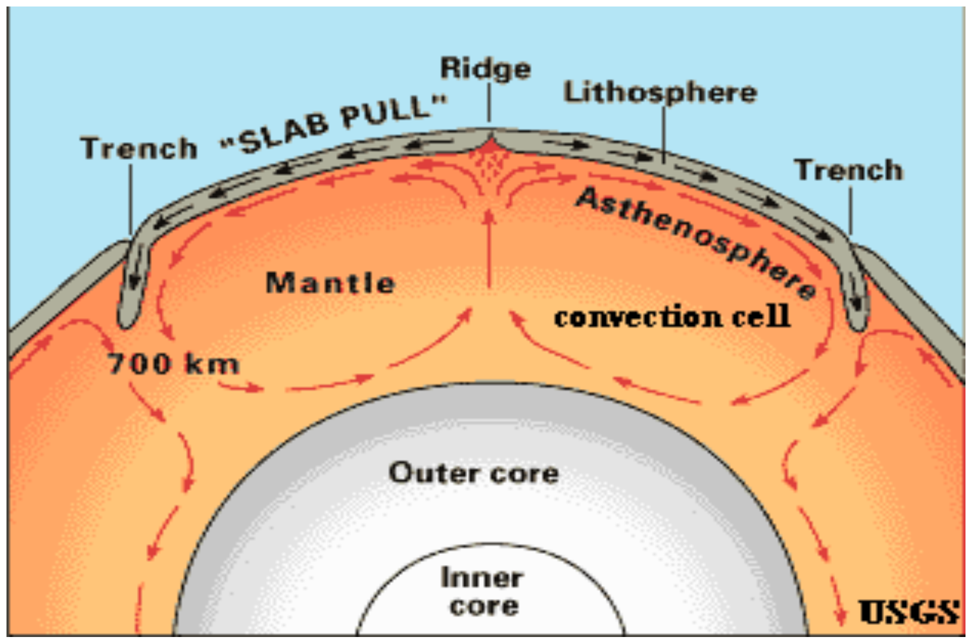


http://www.dstu.univ-montp2.fr/PERSO/bokelmann/convection.gif

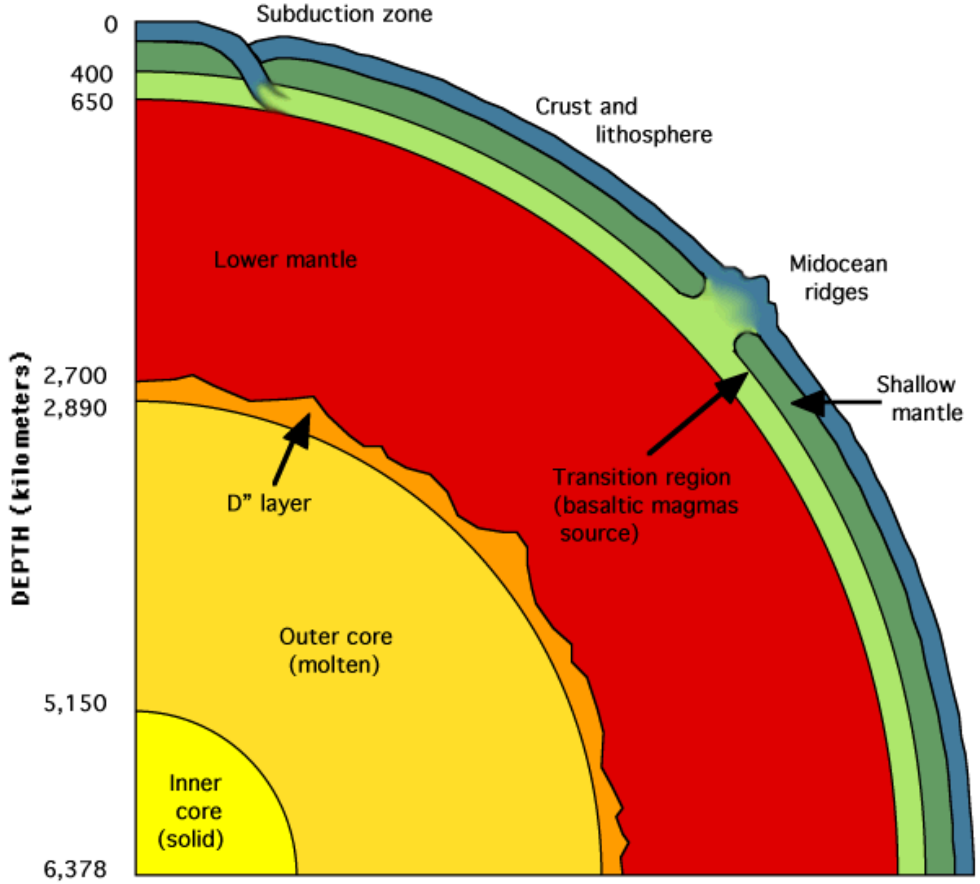
Earth structure







Earth structure



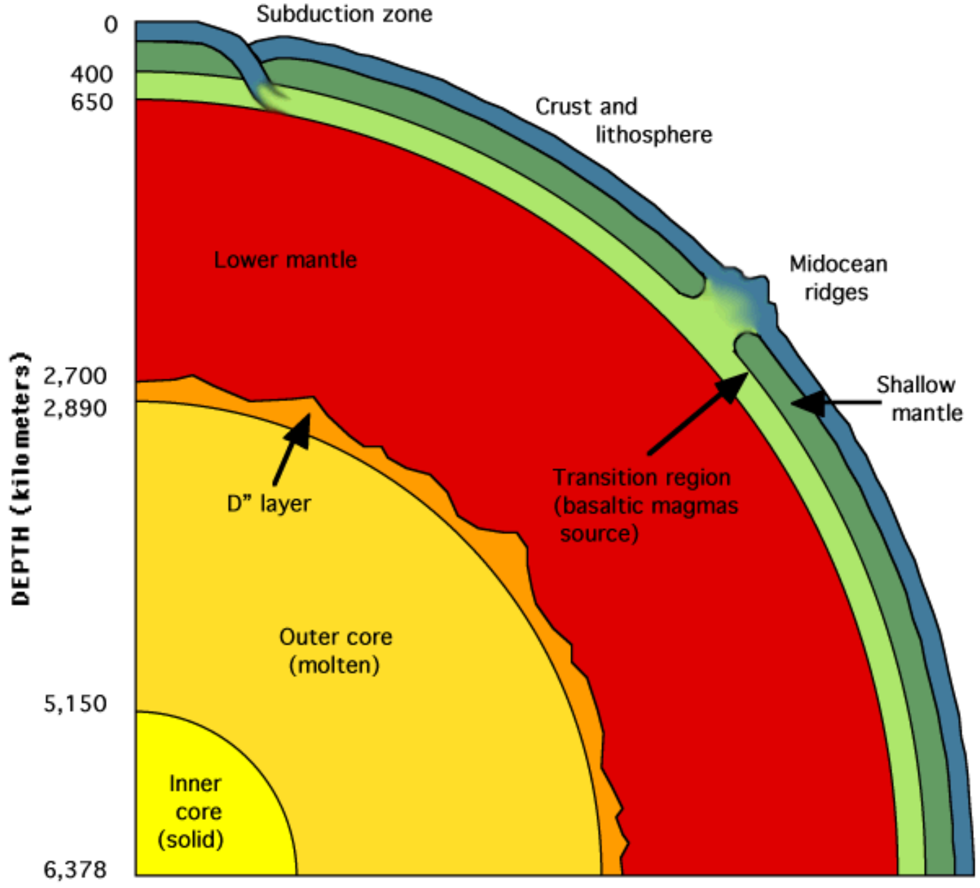
Inner Core - SOLID

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

Outer Core - LIQUID

- 2260 km thick;
- Fe – Ni alloy + + 10% light elements (S, O?);
- **liquid;**
- temperature ~ 4100 – 5800 K;
- **geodynamo:** motion of conductive liquid within the Sun's magnetic field;

Earth structure

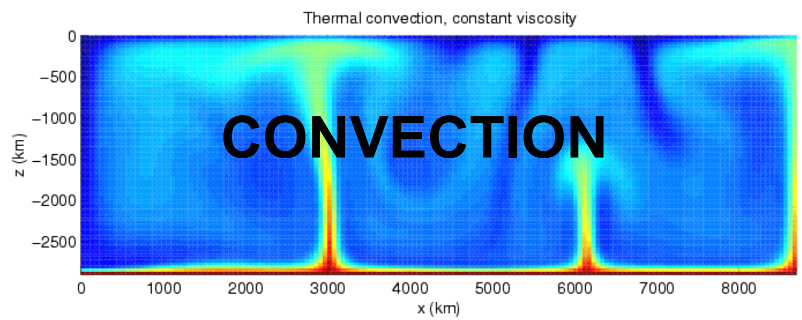


D'' layer: mantle –core transition

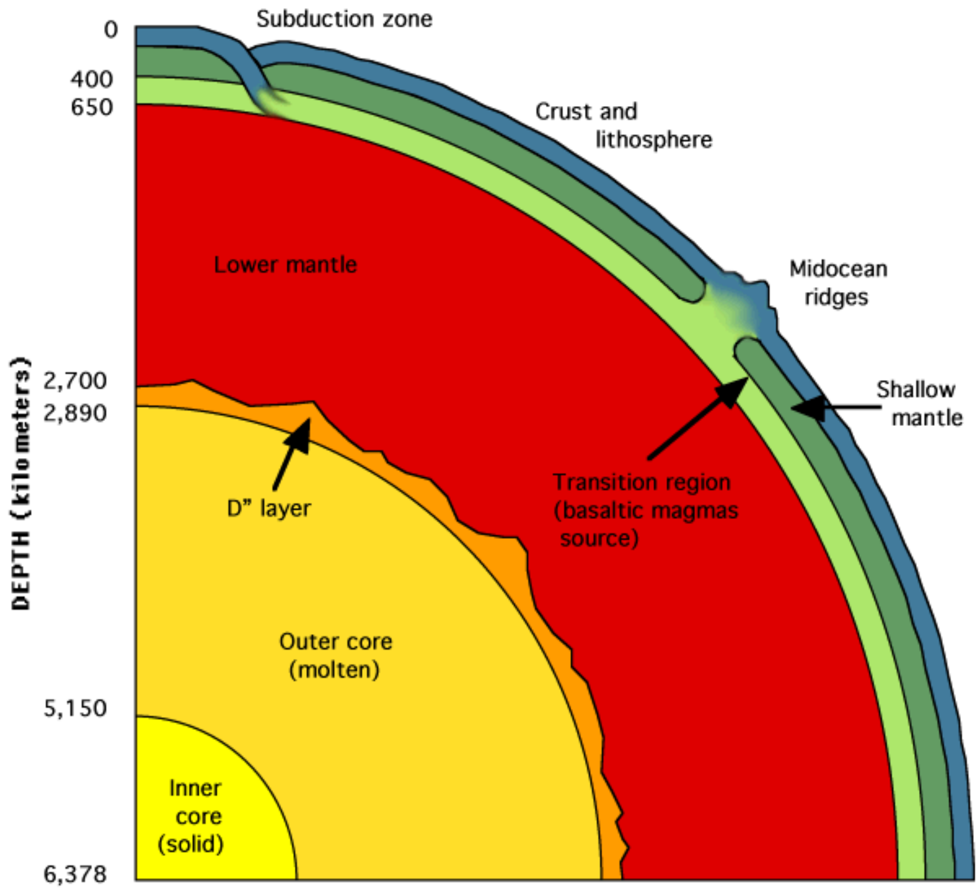
• ~200 km thick;
•seismic discontinuity;
• many different ideas around;
(mineral recrystallisation, material brought here from the subduction zones…)

Lower mantle (mesosphere)

• rocks: high Mg/Fe ratio, less Si + Al than in the crust;
• T: 600 – 3700 K;
• high pressure: solid, but viscose, no brittle faulting;
• "plastic" on long time scales:



Earth structure

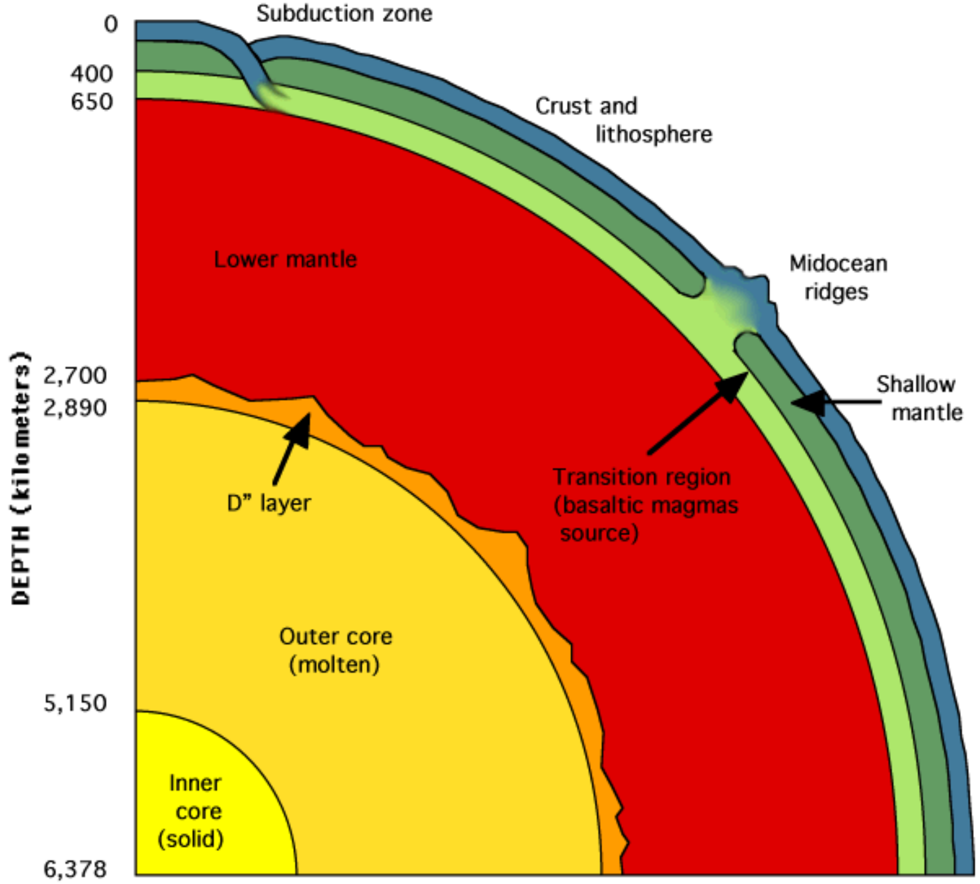


Transition zone (400 -650 km)

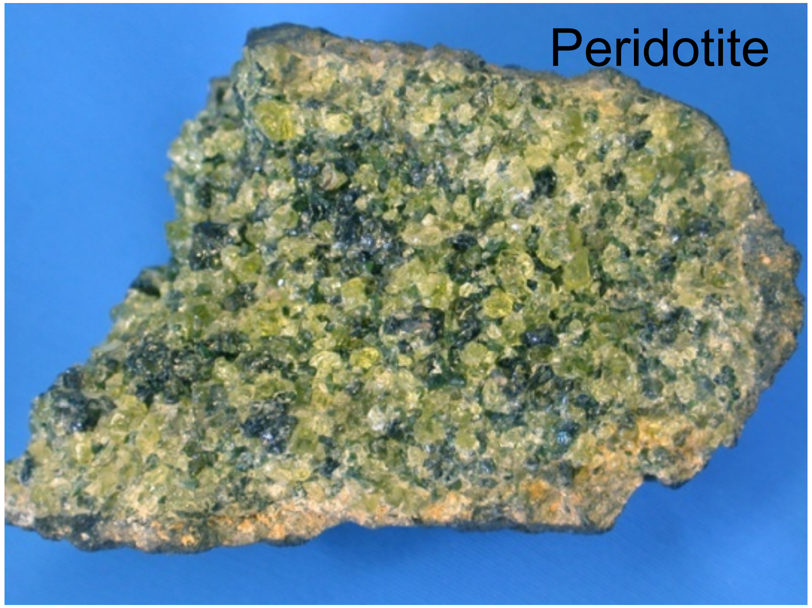
seismic discontinuity;
• mineral recrystallisation;
•: role of the latent heat?;
• partial melting: the source of mid-ocean ridges basalts;

Earth structure

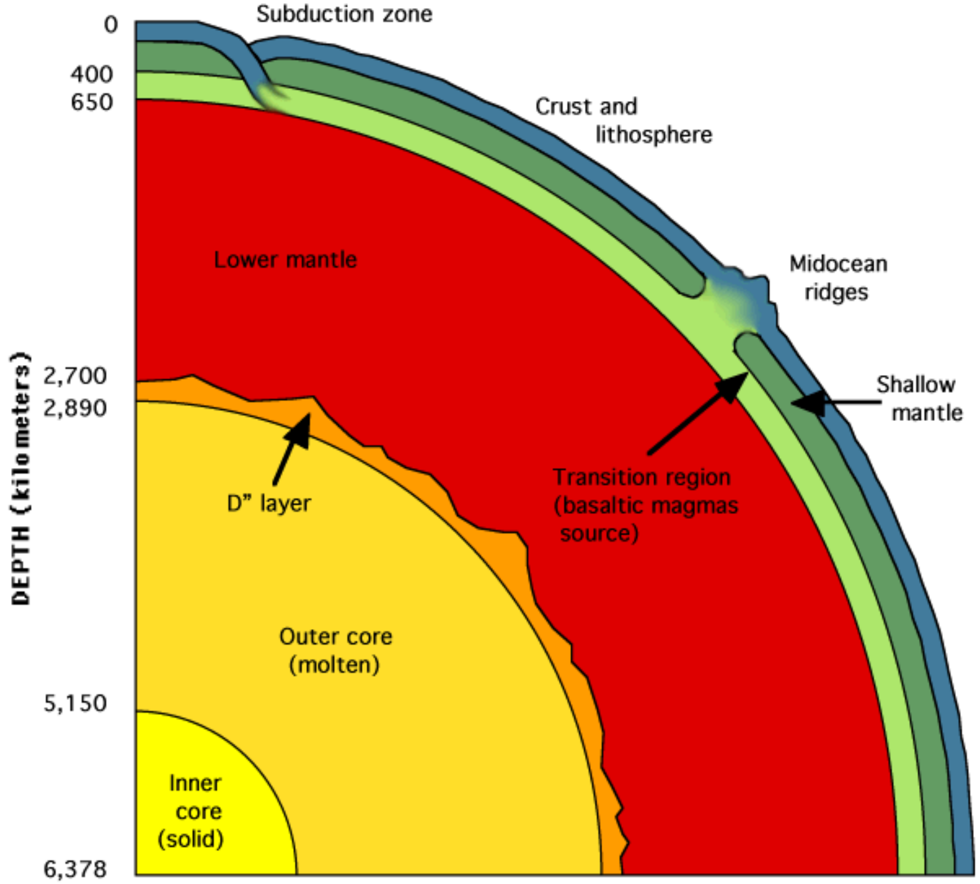
Upper mantle



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

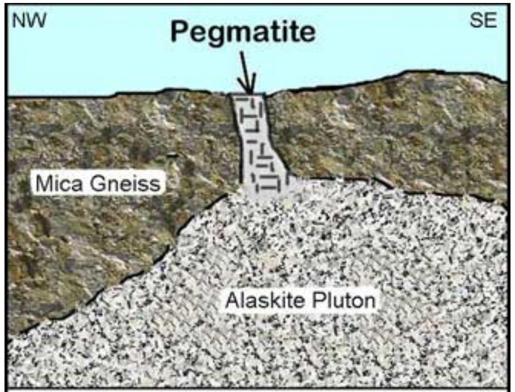


Earth structure



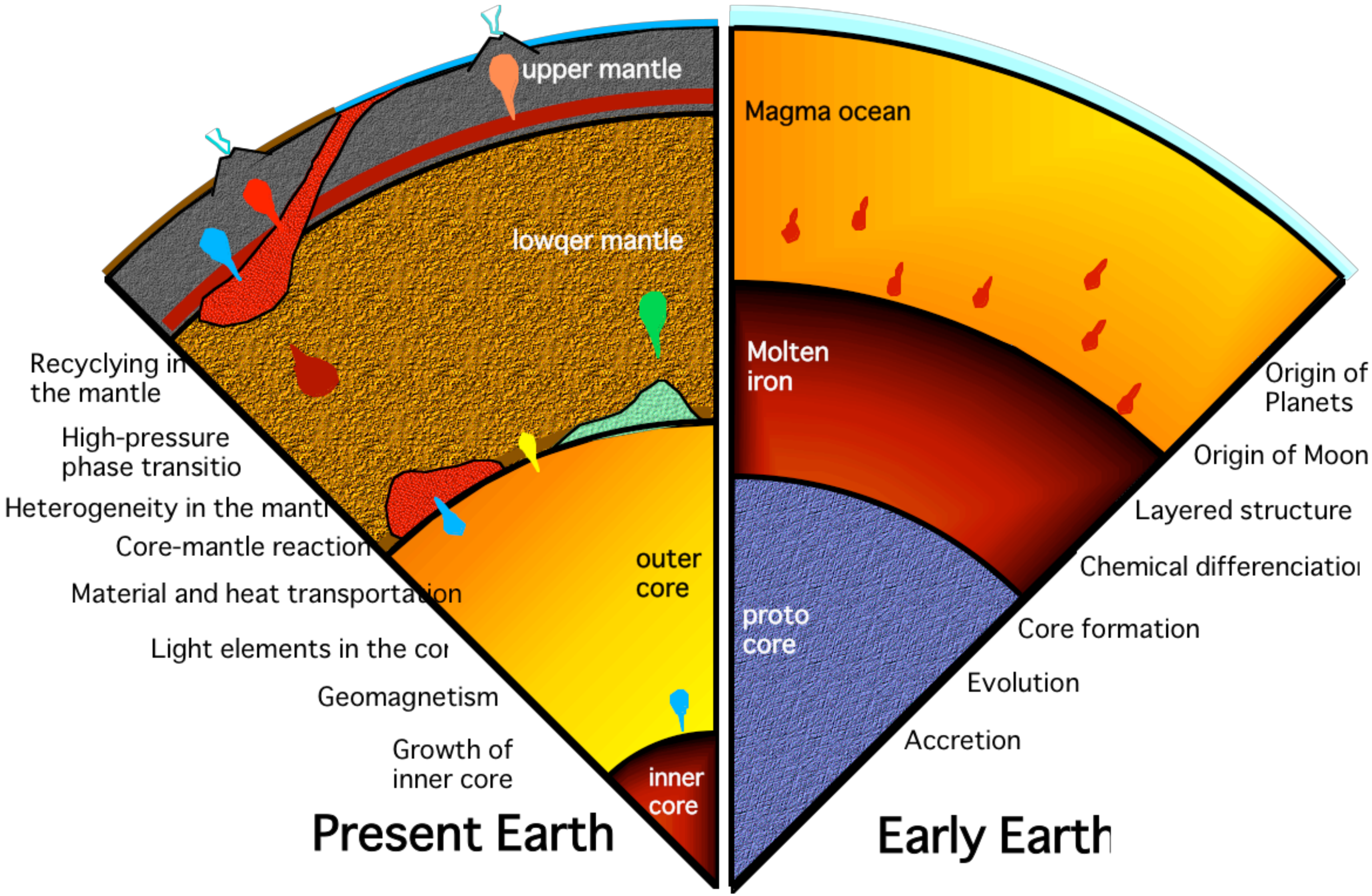
Crust: the uppermost part

- **<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;



Ray Mine Pegmatite
Generalized Cross Section

Earth's profile in time



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

Where are concentrated U, Th, and K ?

- The main long-lived radioactive elements: $^{238/235}$U, ^{232}Th, and ^{40}K

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

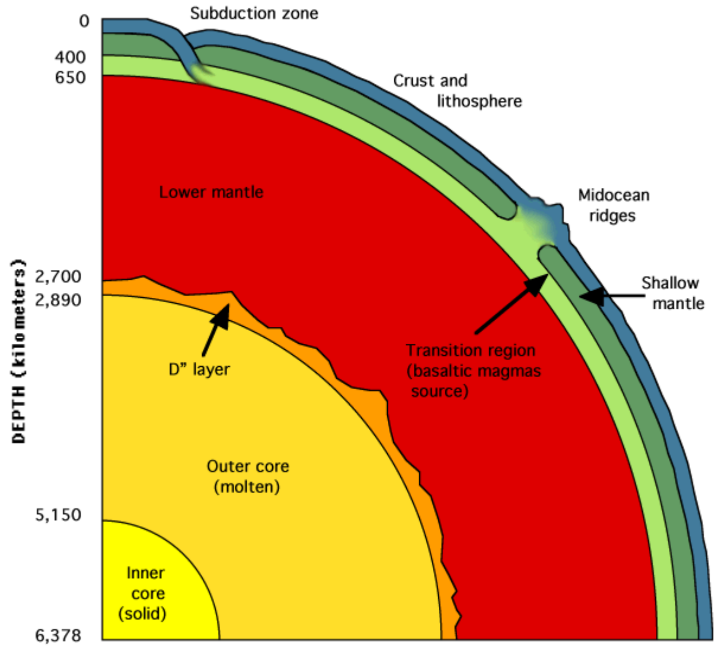
– **Volatile /Refractory:** *Low/High condensation temperature*

– **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)

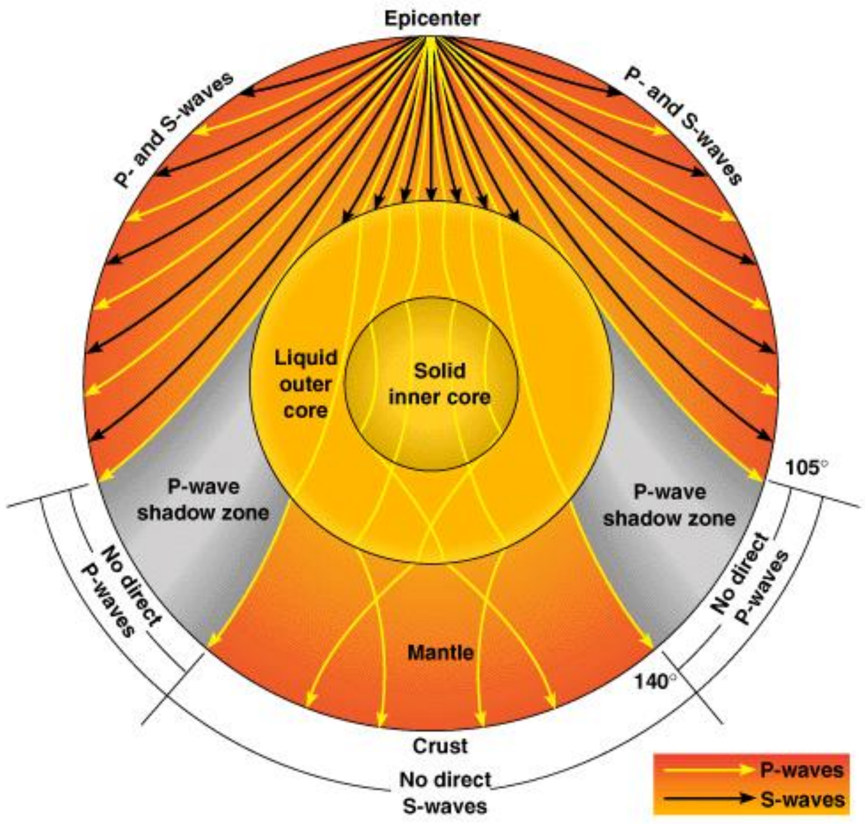
upper continental crust:	2.5 ppm
middle continental crust:	1.6 ppm
lower continental crust:	0.63 ppm
oceanic crust:	0.1 ppm
upper **mantle**:	6.5 **ppb**
core	NOTHING

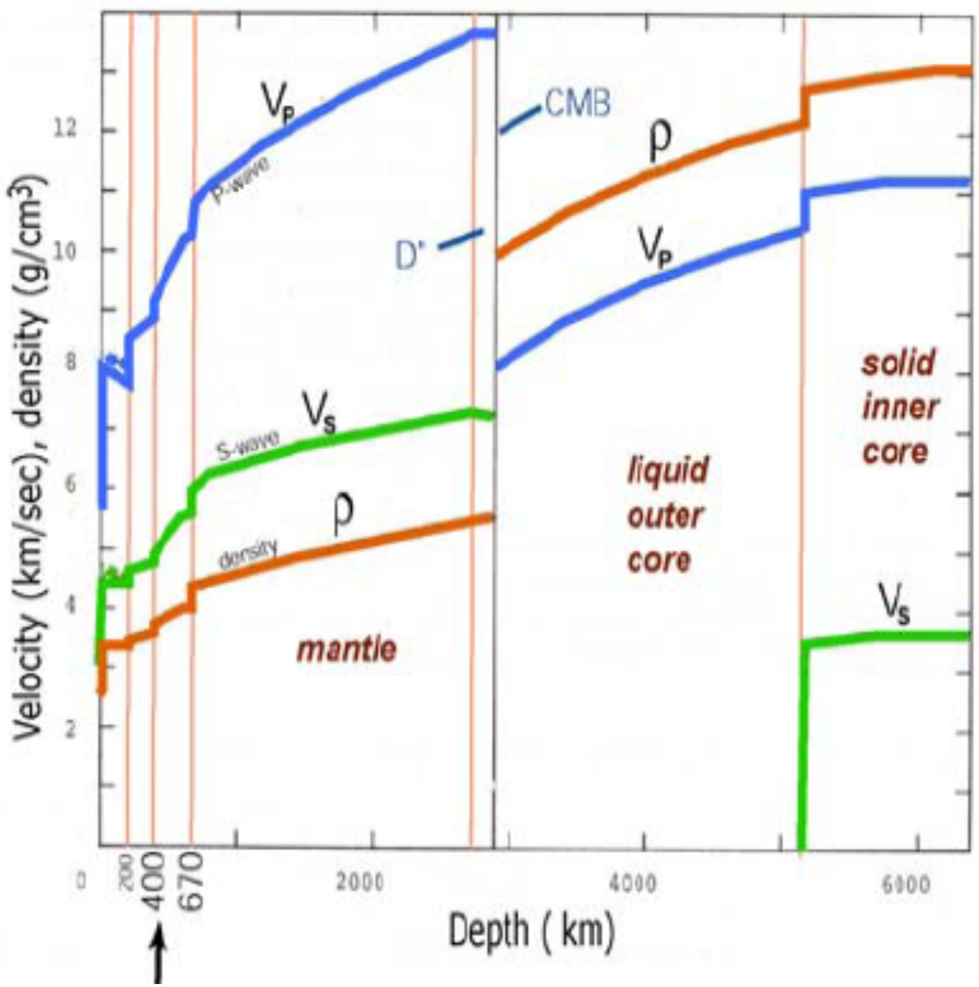
?^{40}K in the core???



How do we get information about the Earth interior ?

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

Geochemistry

1) **Direct rock samples**

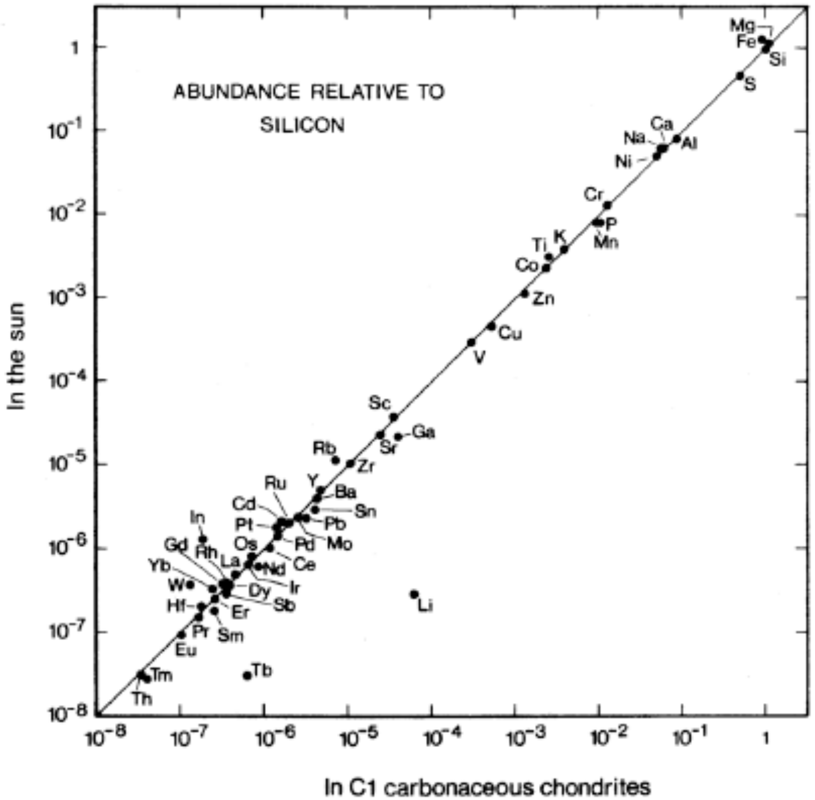
* surface and bore-holes (max. 12 km);
* mantle rocks brought up by tectonics and **vulcanism;**

BUT: POSSIBLE ALTERATION DURING THE TRANSPORT

2) **Geochemical models:**

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

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



From Sramek @ Neutrino Geoscience 2013

U Th K

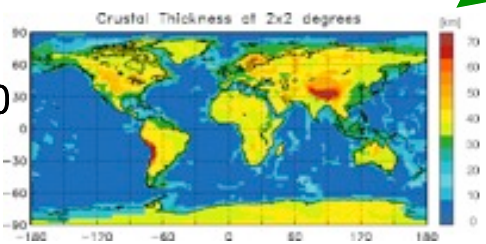
Composition of Silicate Earth (BSE)

	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

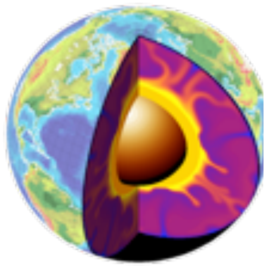
CRUST2.0 thickness



Oceanic: 0.22 ± 0.03 TW

Continental: 7.8 ± 0.9 TW

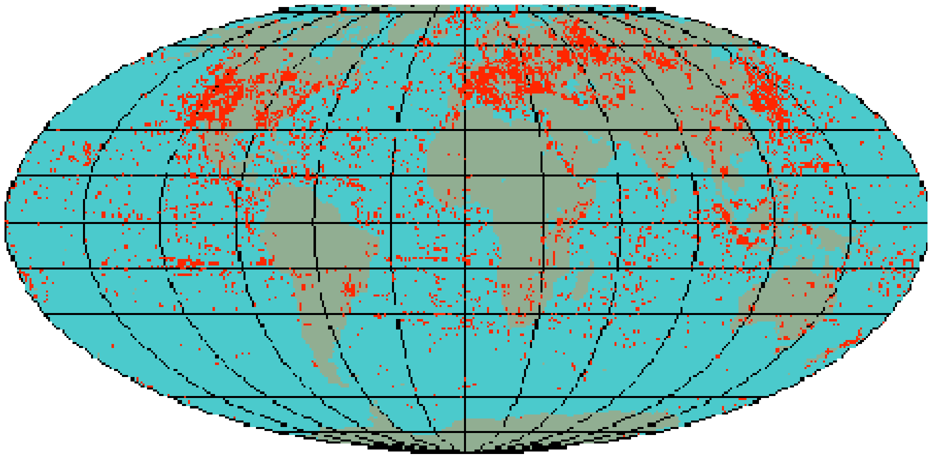
?



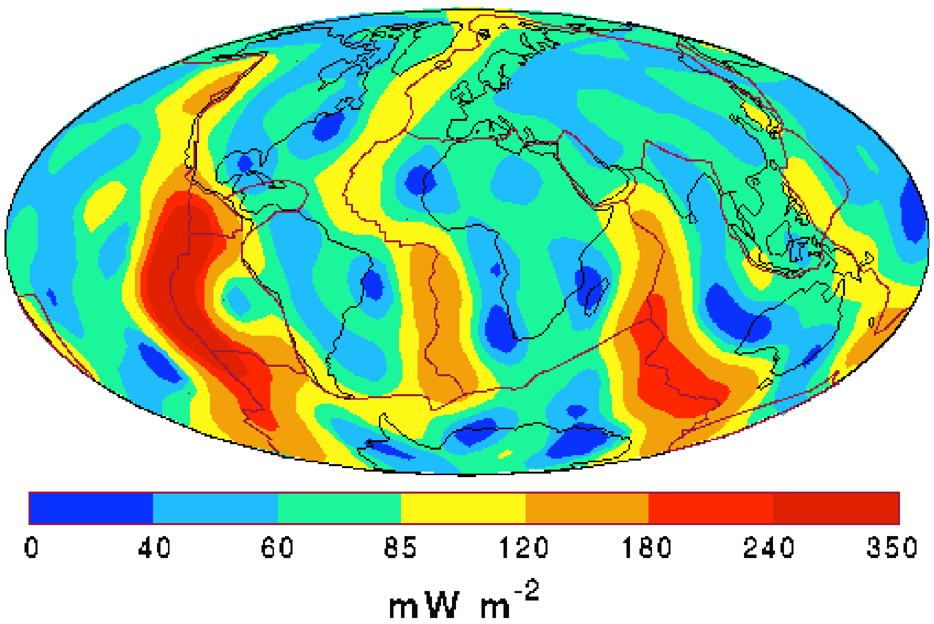
Tomorrow: New crustal model by Yu Huang et al.
CC = 6.8 (+1.4/-1.1) TW

Surface heat flux

Bore-hole measurements



Heat Flow



- Conductive heat flow from bore-hole temperature gradient;

- **Total surface heat flux:**
  31 + 1 TW (Hofmeister&Criss 2005)
  46 + 3 TW (Jaupart et all 2007)
  47 + 2 TW (Davis&Davies 2010)

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

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

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

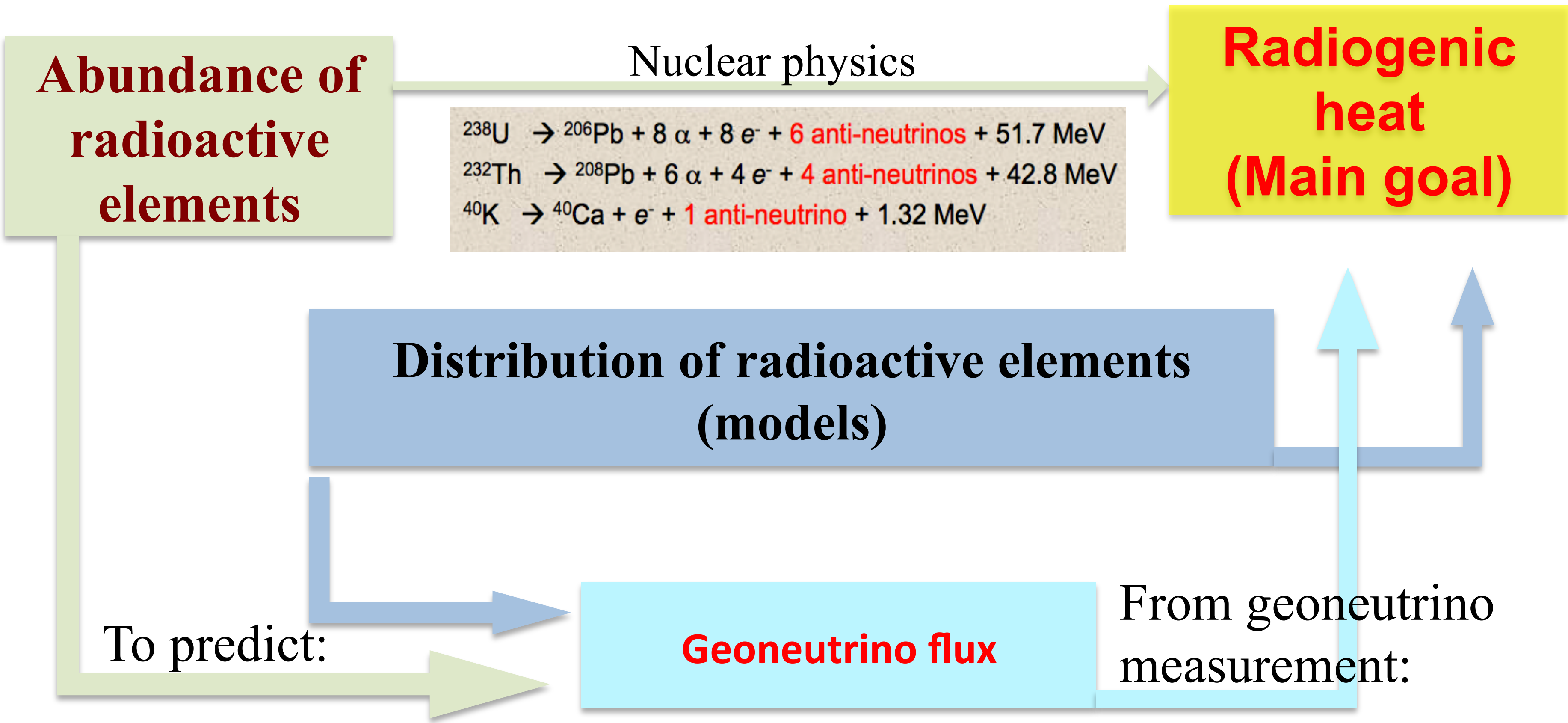
  B) Enstatic-chondrites models: (Javoy 2010): only 11 TW!!!

  C) Geodynamical models: >30 TW!!!

- Other heat sources (possible deficit up to 47-11 = 36 TW!)
  - Residual heat: gravitational contraction and extraterrestrial impacts in the past;
  - ^{40}K in the core;

IMPORTANT MARGINS
FOR ALL DIFFERENT MODELS OF THE EARTH STRUCTUE

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



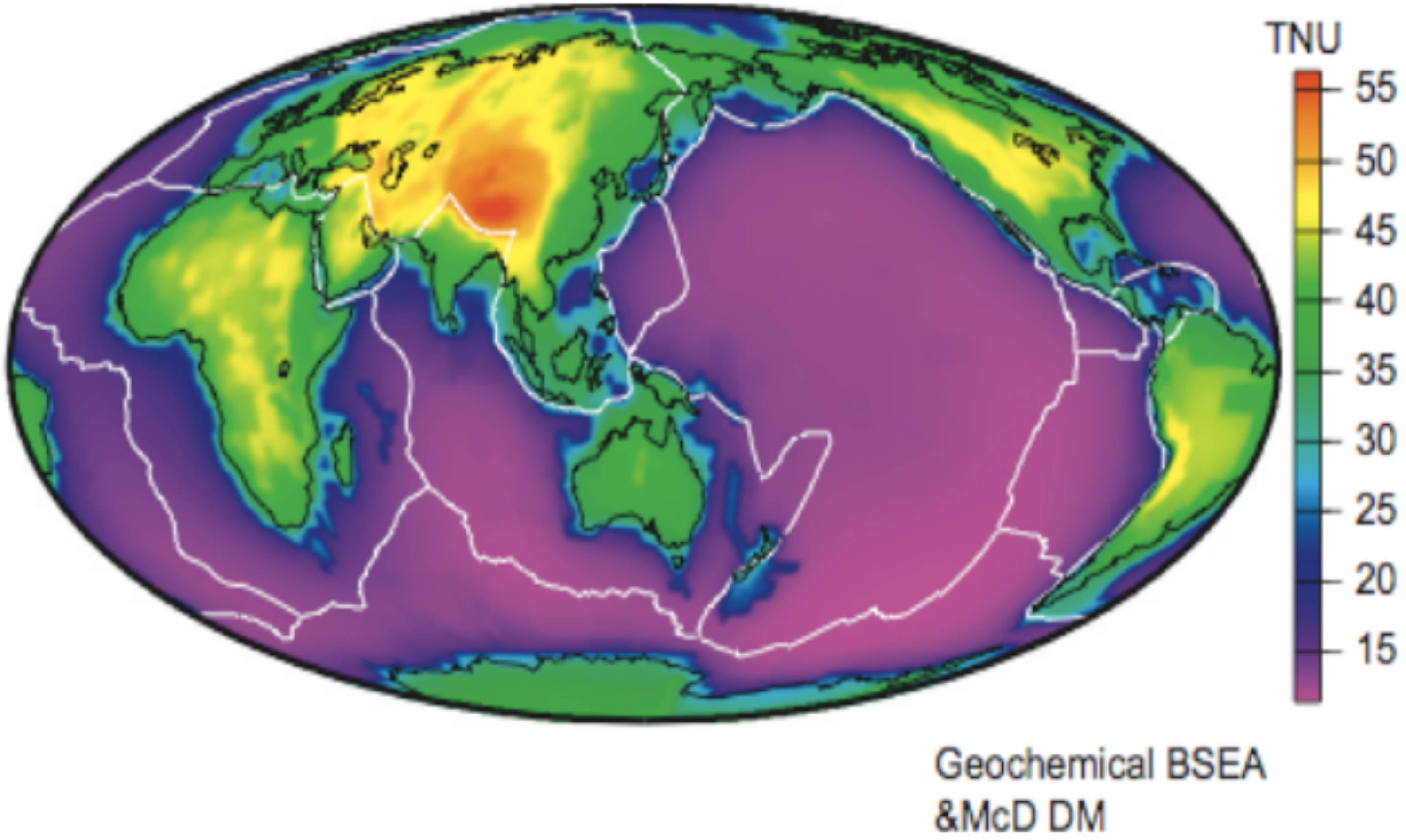
Expected geoneutrino signal

- **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	$29.0^{+6.0}_{-5.0}$	[TNU]
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	$2.6^{+0.5}_{-0.5}$	

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

Crust + mantle geo-ν signal (U+Th)

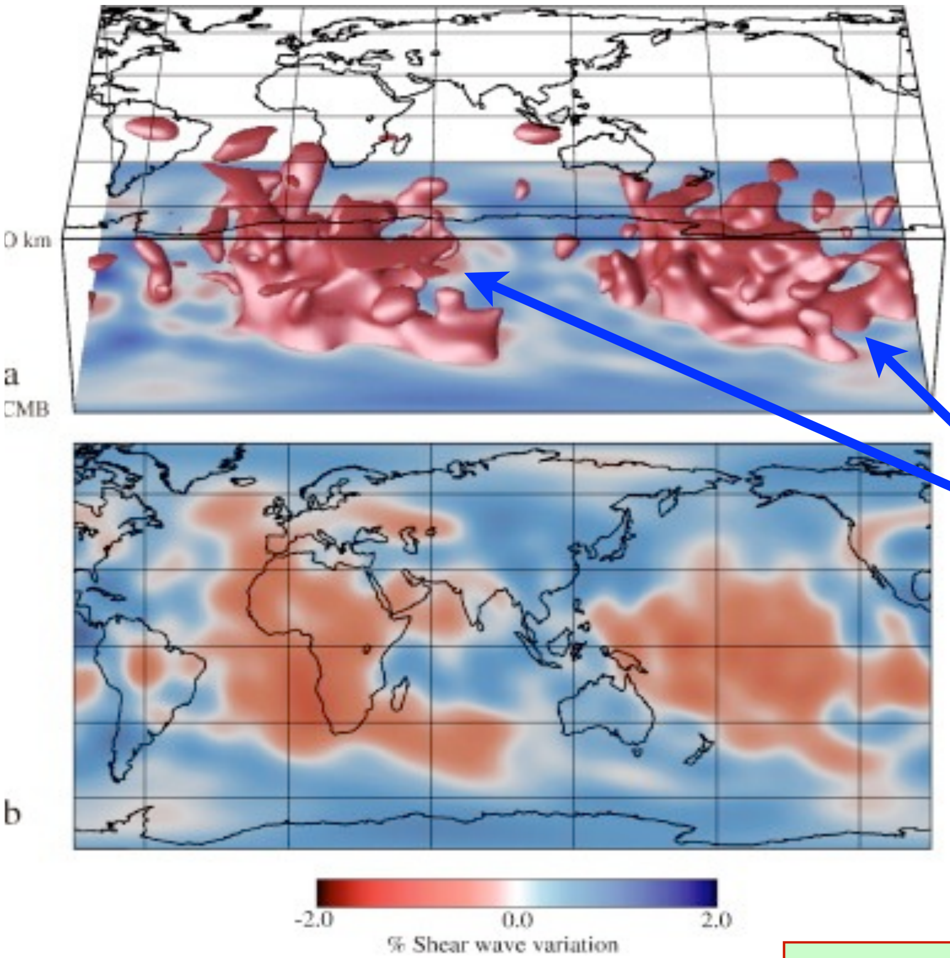


O. Šrámek et al. / Earth and Planetary Science Letters 361 (2013)

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**

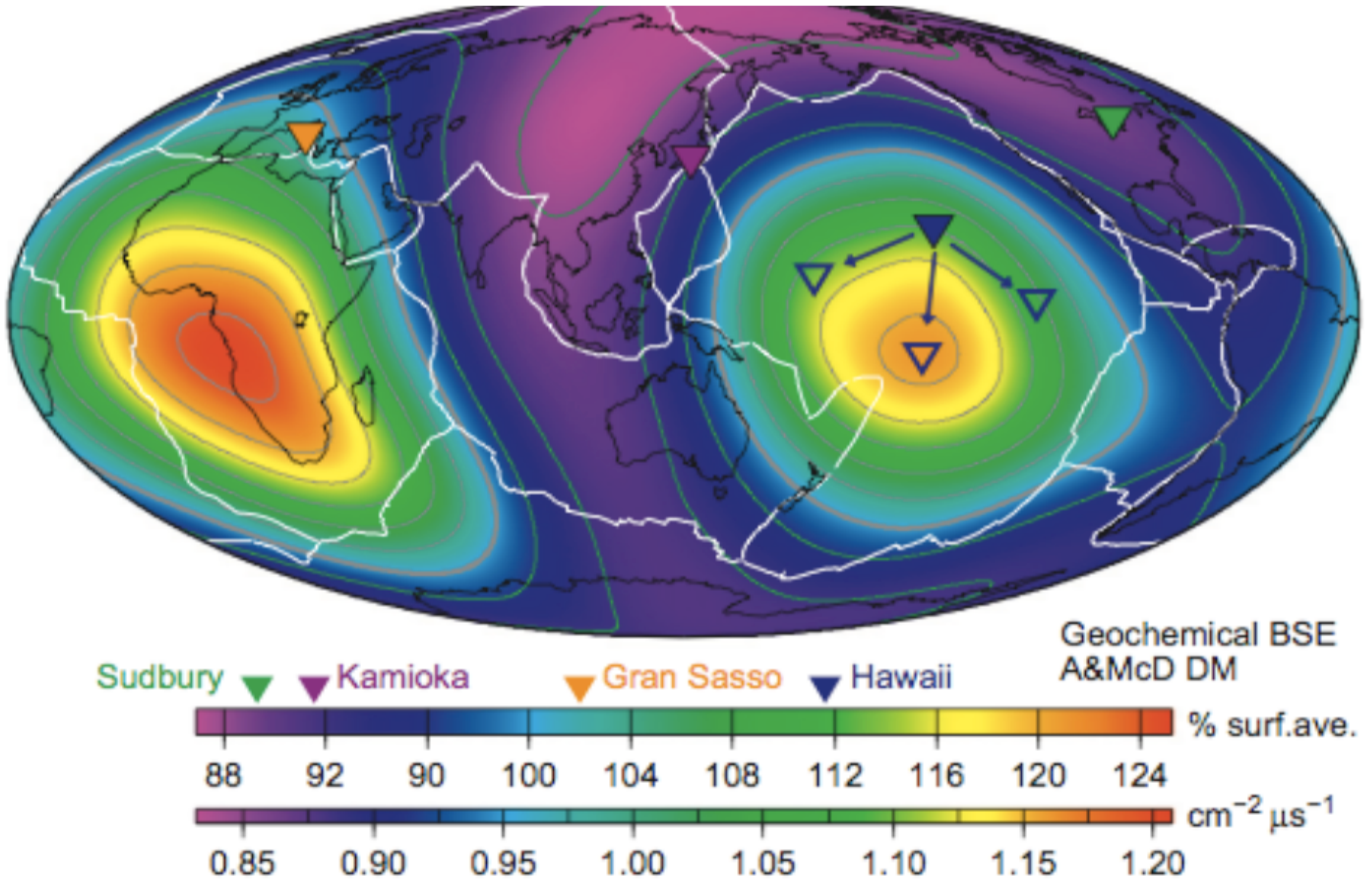
“piles” or “LLSVPs” or “superplumes”

Candidate for an distinct chemical reservoir

Sat AM: Ed Garnero

Is the mantle chemically homogenous? We do not know!!

Mantle geo-ν signal in the TOMO model



O. Šrámek et al. / Earth and Planetary Science Letters 361 (2013)

Geoneutrinos: why to study them

Possible answers to the questions

- **Main goal:**

  What is the radiogenic contribution to the terrestrial total surface heat flux

- 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;
- insights to the processes of the Earth'formation…

Geoneutrinos: why to study them

Possible answers to the questions

– **Main goal:**

What is the radiogenic contribution to the terrestrial total surface heat flux

–

– hin the

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

– Are the BSE models compatible with geoneutrino data?

– Discrimination among different BSE models;

– What is the bulk Th/U ratio;

– insights to the processes of the Earth'formation…

What are neutrinos?

Neutrino basics....

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

Elementary particles of the SM

- Originally, in the SM neutrinos have exactly zero mass, all neutrinos are left-handed and all antineutrinos are right handed;
- Experimental evidences for **neutrino oscillations**: **non-zero mass** required!
- Non-zero mass requires at least a minimal extension of the SM;
- Dirac or Majorana particles?
- If Majorana, then lepton-flavor violation by 2 and $0\nu-\beta\beta$ –decay possible: a big experimental effort is ongoing!

Neutrino mixing

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

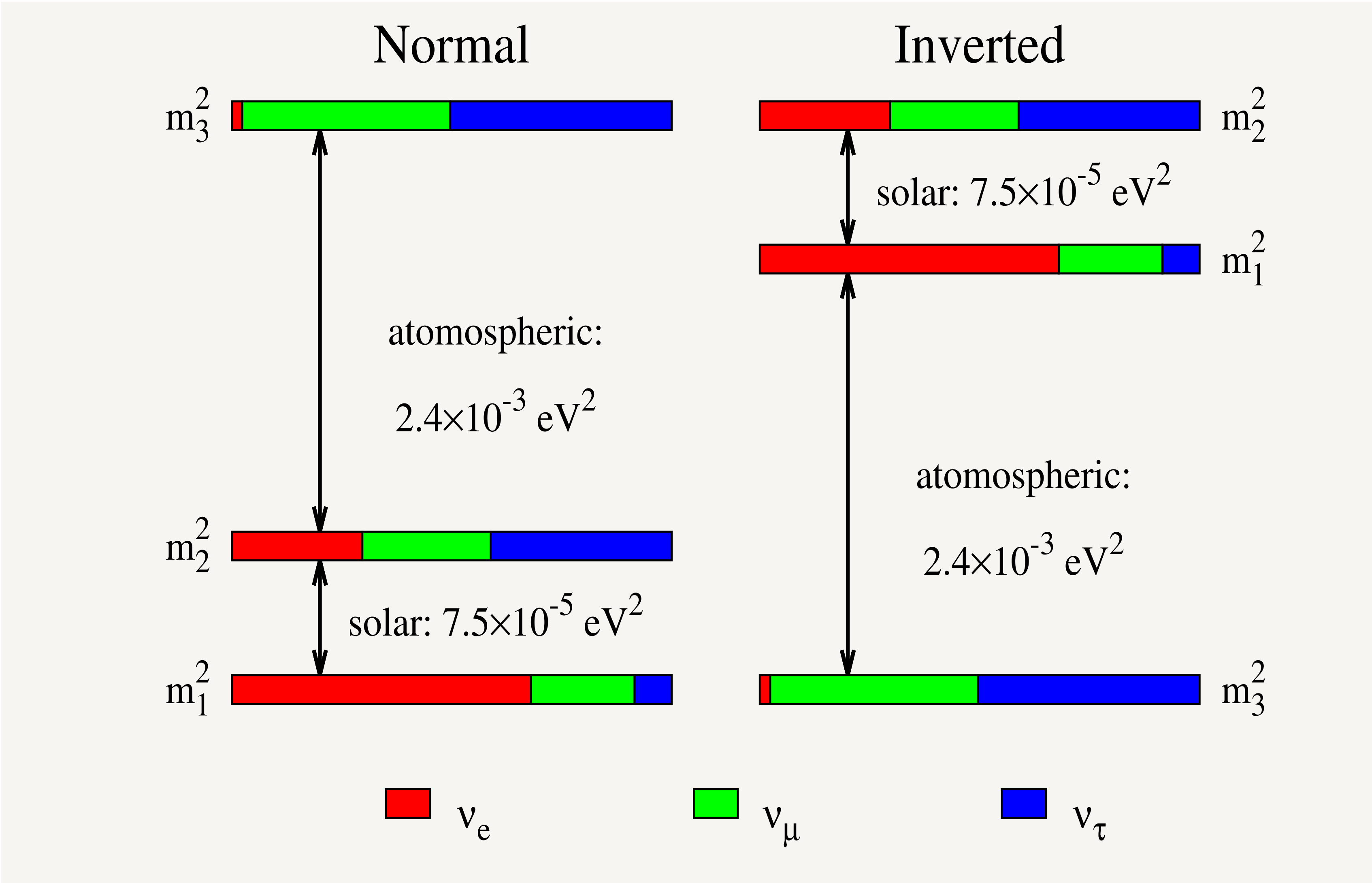
Atmospheric | Reactor | Solar | ? Majorana phases ?

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

$\theta_{23} \approx 45°$ $\theta_{13} \approx 9°$ $\theta_{12} \approx 33°$

- **3 mixing angles θ_{ij}:** measured (in which quadrant is θ_{23}?);
- Non-zero θ_{13} confirmed only in 2012 by Daya Bay in China!
- **Majorana phases $\alpha 1$, $\alpha 2$** and **CP-violating phase δ** unknown;

Mass hierarchy



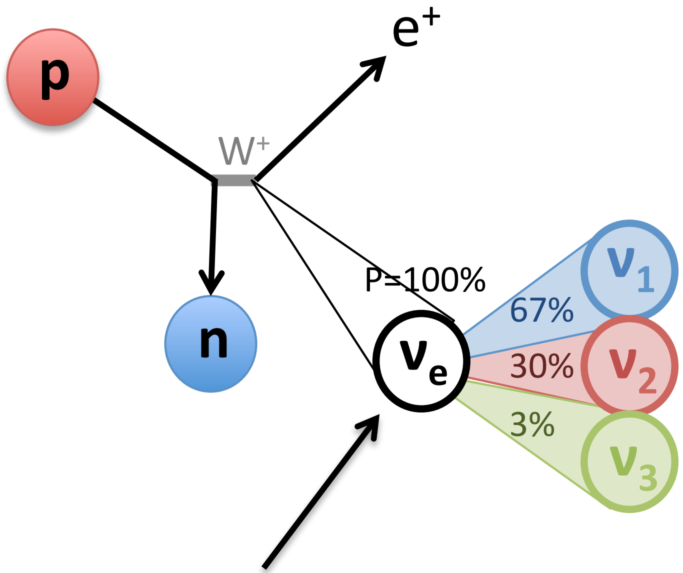
- $\Delta m_{21}^2 \equiv \Delta m_{sol}^2 = 7.53\,^{+0.18}_{-0.18} \times 10^{-5}$ eV^2[21]
- $|\Delta m_{31}^2| \approx |\Delta m_{32}^2| \equiv \Delta m_{atm}^2 = 2.44\,^{+0.06}_{-0.06} \times 10^{-3}$ eV^2 (normal mass hierarchy)[21]

PDG 2104

Neutrino Oscillations

ν production

e.g. β⁺-decay



Weak interaction creates neutrino in **flavor-eigenstate**.

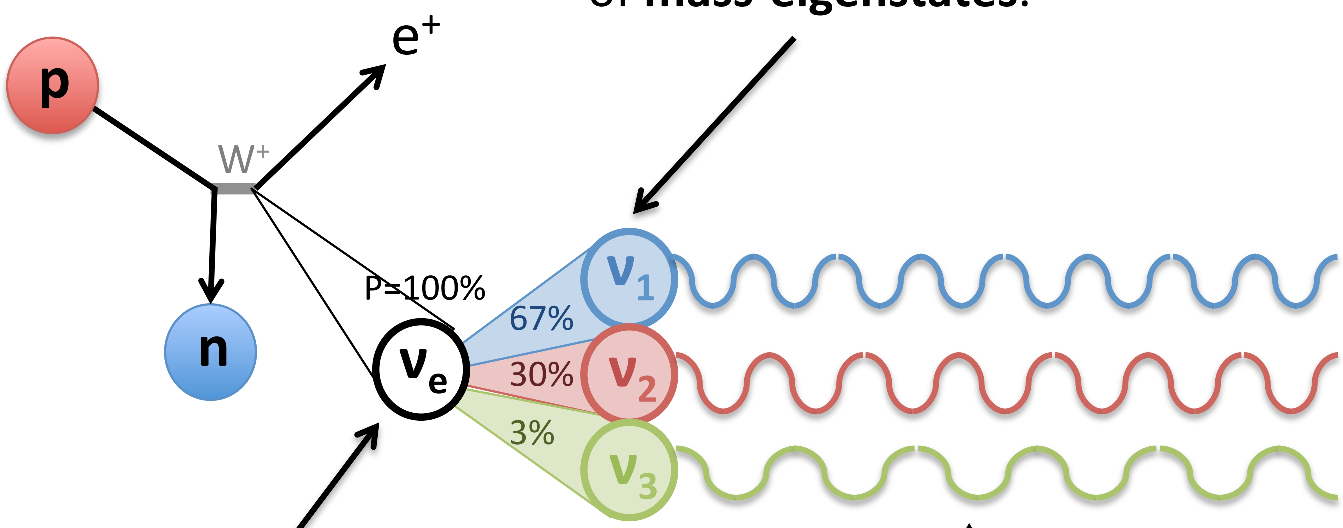
Neutrino Oscillations

ν production

ν propagation

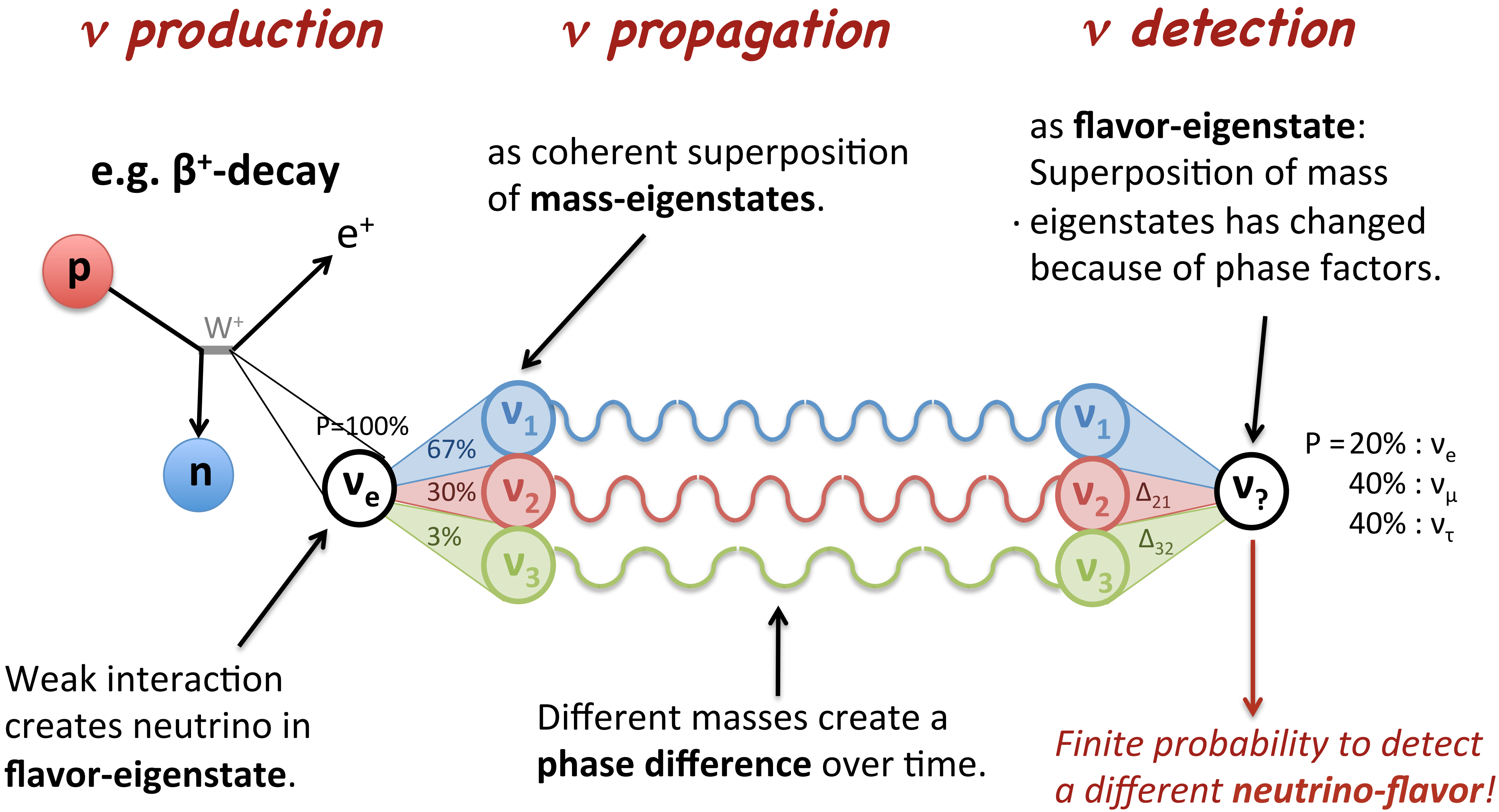
e.g. β^+-decay

as coherent superposition of **mass-eigenstates**.



Weak interaction creates neutrino in **flavor-eigenstate**.

Different masses create a **phase difference** over time.



Michael Wurm (JGU Mainz)

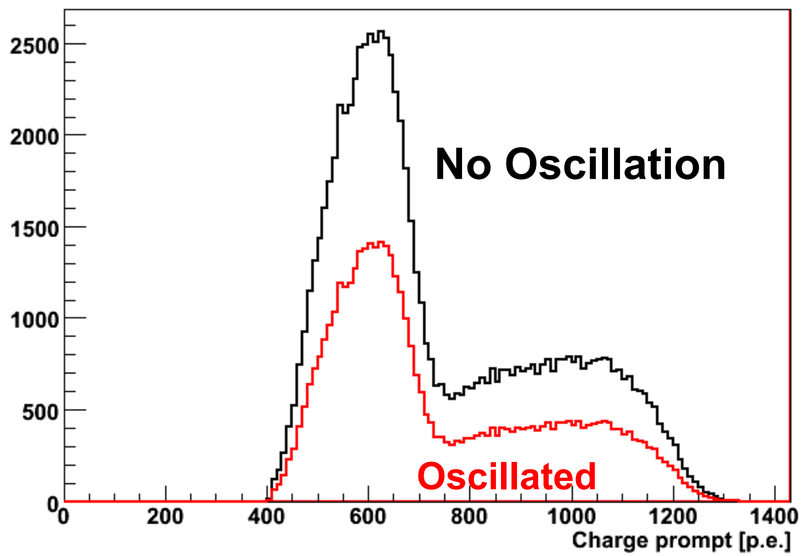
Effect of neutrino oscillations

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

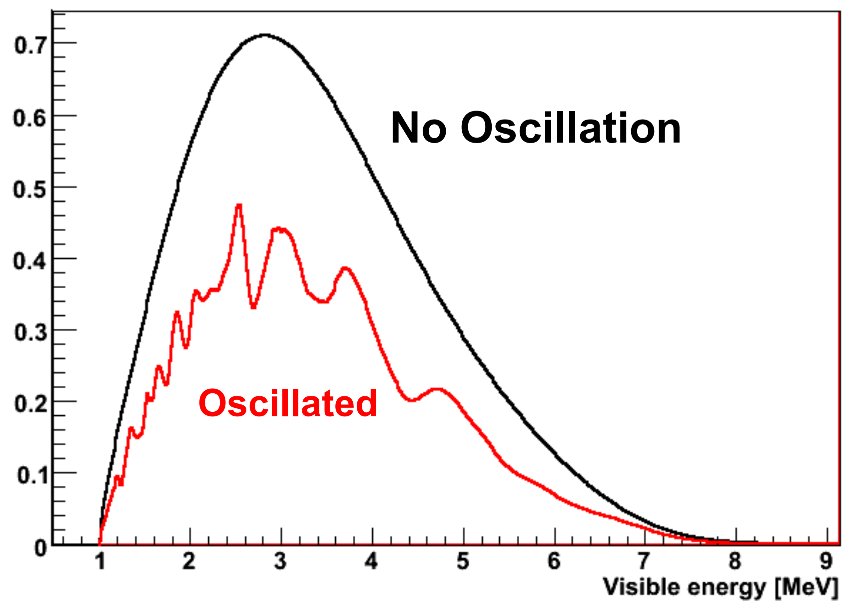
3 MeV antineutrino ..
Oscillation length of ~100 km

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

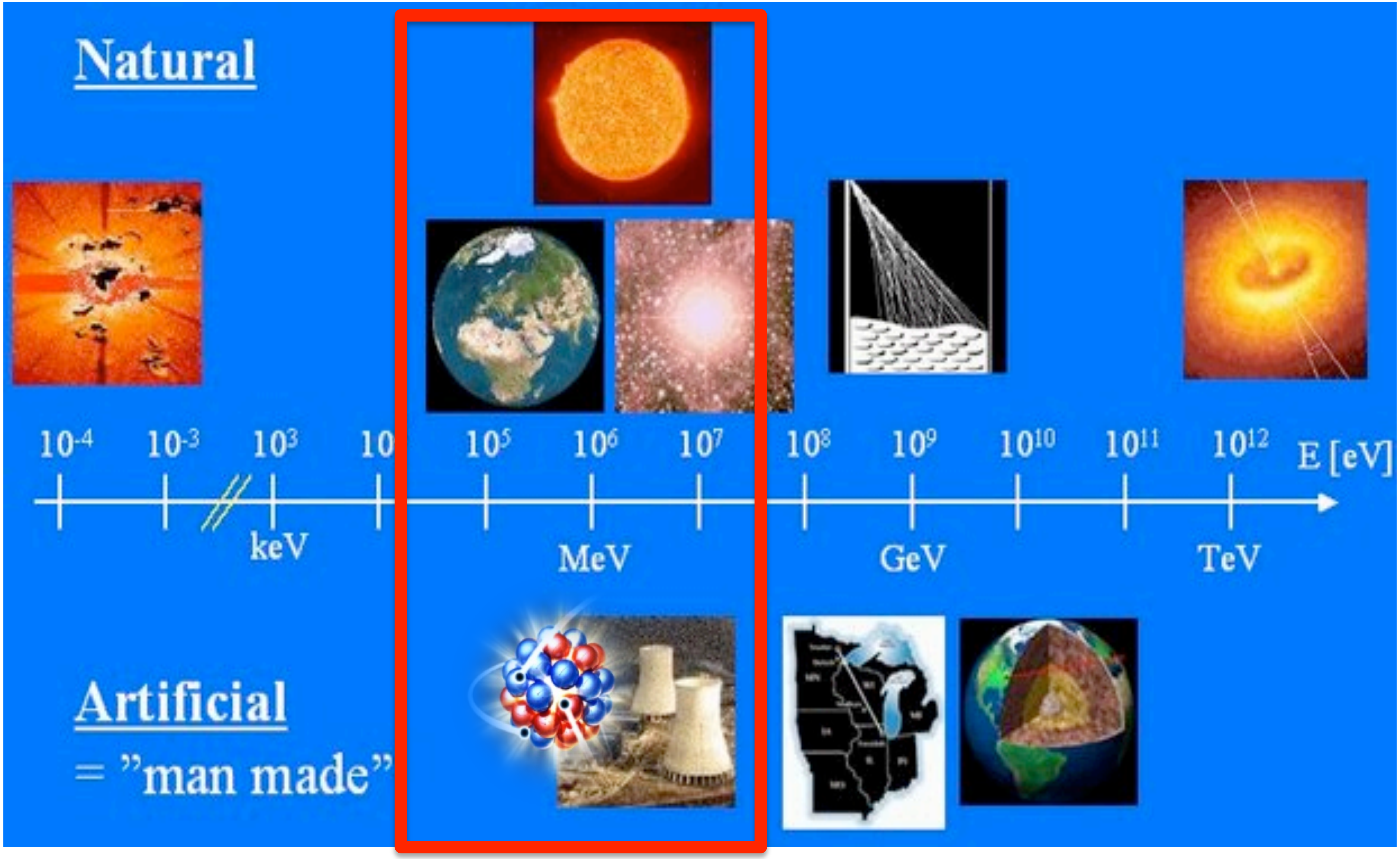
Geoneutrinos



Reactor antineutrinos at LNGS

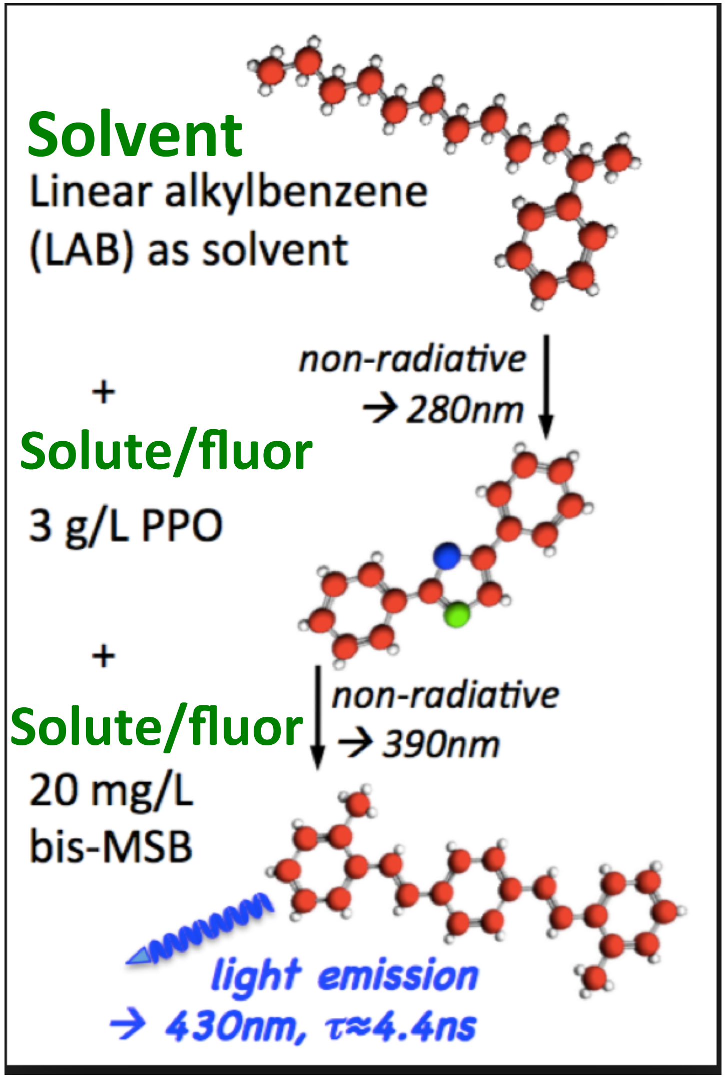


Neutrino sources



So how to detect geoneutrinos?

Scintillation based detection



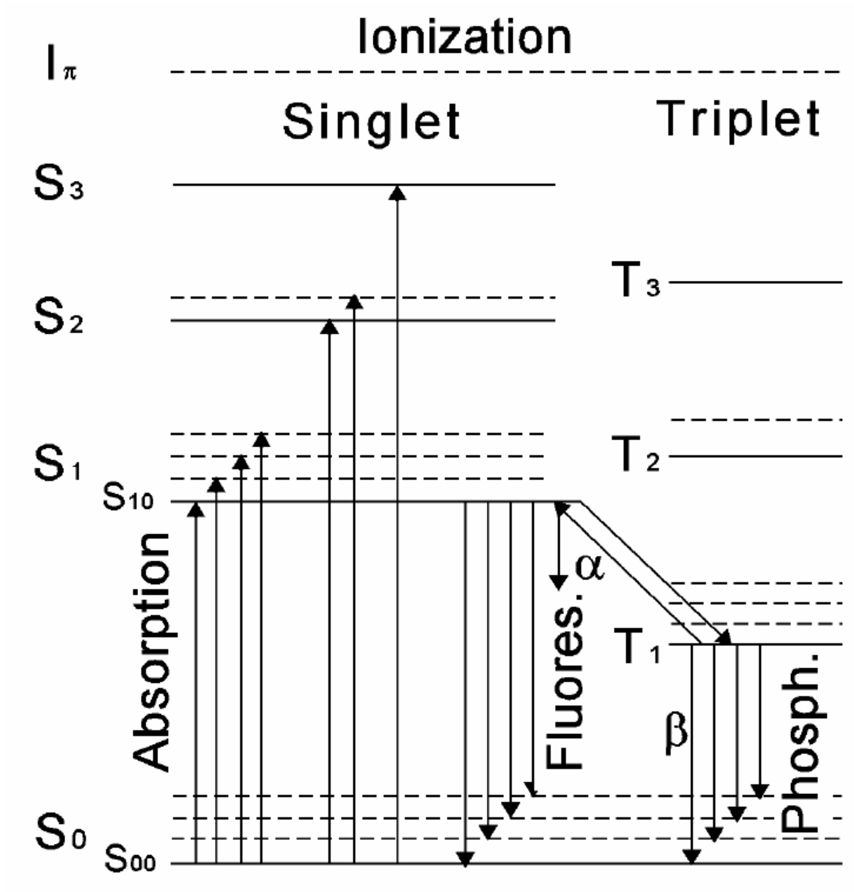
Scintillator cocktail for the JUNO experiment (picture Uni Mainz)

Detection of ionizing radiation through the scintillation light induced in special organic or inorganic materials = scintillators

Addition of the solutue/fluor serves as:

- ✓ efficient non-radiative tranfer of excitation energy from the solvent to fluor
- ✓ wavelength shifter to longer wavelengths to match quantum efficiency of the phototubes and decrease self-absorption
- ✓ Fast decay times

Scintillation based detection



Molecular states in aromatic carbohydrates π bonds

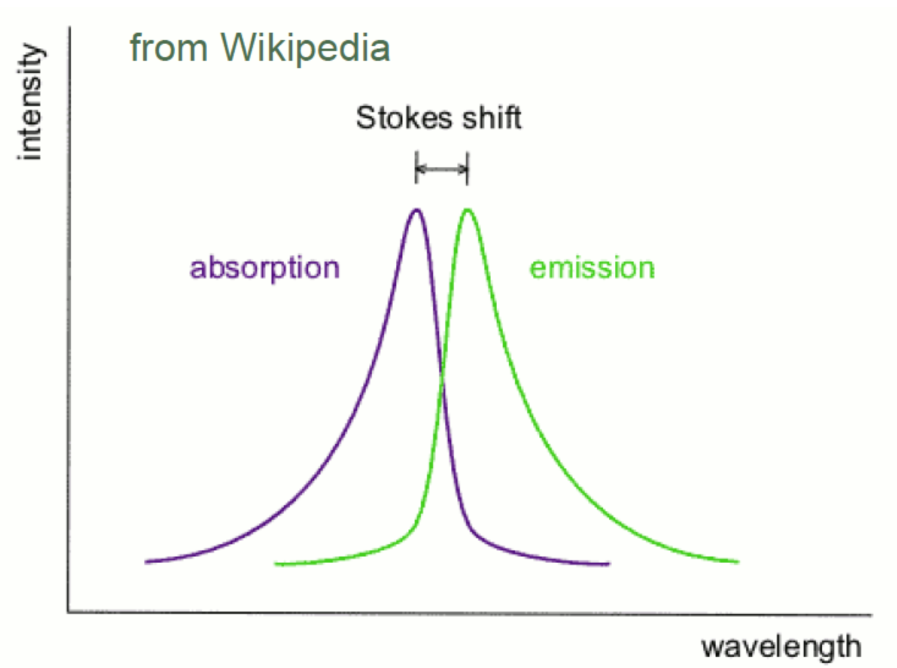
Absorption higher frequencies and smaller wavelengths than emission

Fast fluorescence has higher frequencies and smaller wavelengths than emission than **slower phosphorescence**

Stokes shift

an important, general concept to keep in mind for all scintillators

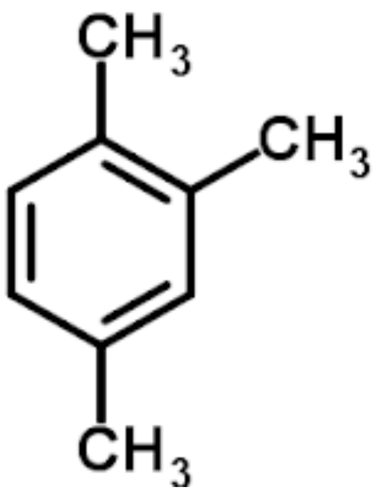
- emitted photons are at longer wavelengths (smaller energies) than the energy gap of the excitation
- the processes that produce this "Stokes shift" are different in different scintillating materials
- this allows the scintillation light to propagate through the material
  - emitted photons can't be self-absorbed by exciting the material again



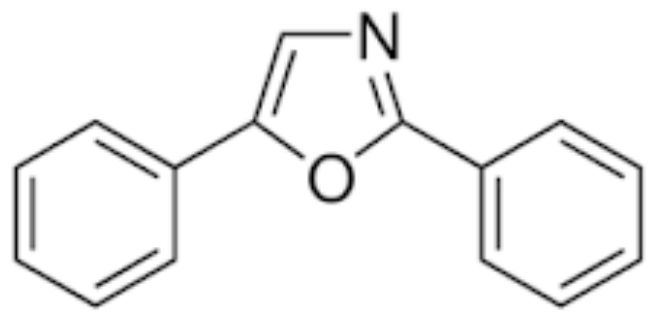
From M. Chen

Scintillator cocktail in Borexino

Pseudocumene (PC) as a solvent
1,2,4-trimethylbenzene



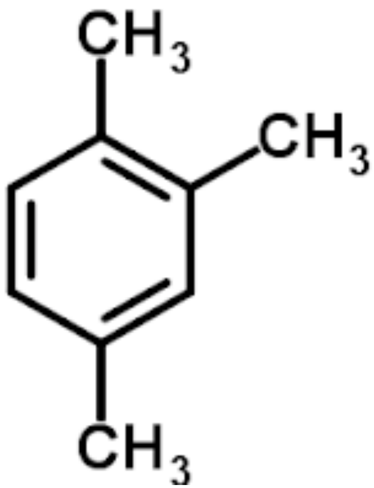
Called fluor / solute
PPO as a solute (~1.5 g/l)
2,5-diphenyloxazol



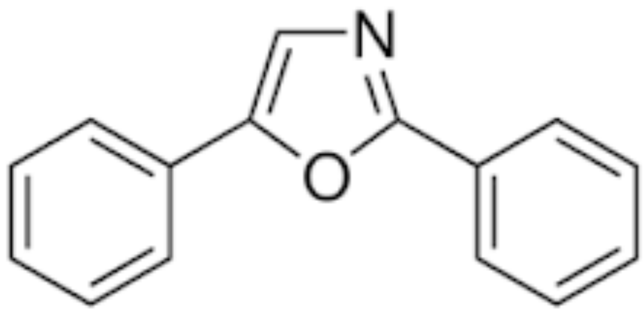
Aromatic carbohydrates:
"the cloud" of 6 p_z electrons
from double covalent bounds and
their excited molecular states play
an important role in the generation
of scintillation light

Scintillator cocktail in KamlAND

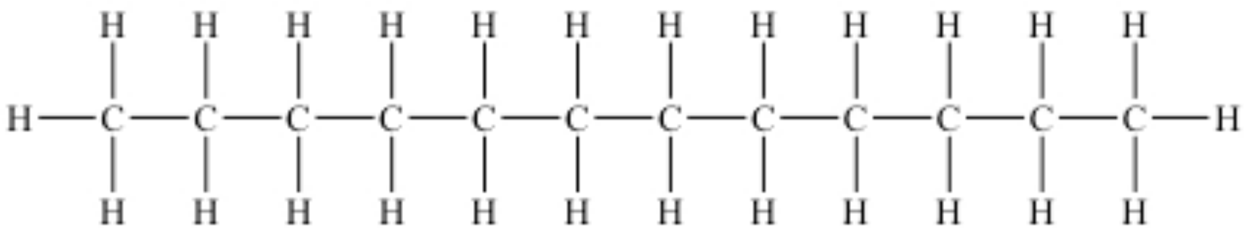
20% Pseudocumene (PC)
1,2,4-trimethylbensene



1.52 g/l PPO / solute
2,5-diphenyloxazol



80% Dodecane (mineral oil)

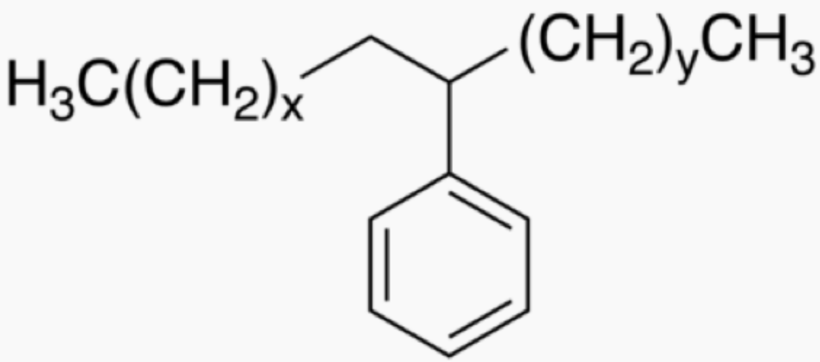


Non-aromatic carbohydrates:
for higher H/C ratio (neutron capture for antineutrino detection), better transparency, safety, and stability but some reduction of the light output

LAB solvent

LAB
linear-alkylbenzene

- Developed by SNO+
- Used in Daya Bay
- Planned for JUNO



Compared to pseudocumene:
- Non toxic
- High flash point
- Cheap
- Worse particle discrimination
- Compatible with acrylic
- Excellent transparency

Quenching

- quenching is an external process that de-excites the scintillator without fluorescence
- Impurity quenching: Oxygen!
- Ionisation quenching: high ionization density quenches

the excited π-electrons

Three important consequences:

1) non-linearity in energy response

2) heavy particles with **higher dE/dx (e.g. α) produce less light** for the same energy deposit, (by a factor of >10 for α in liquids)

3) the scintillation **pulse shape (fast/slow components) is different**

Need to calibrate the detectors with radioactive sources!

Scintillation based detection

Important characteristics:

- Fast pulses (short decay time of the scintillation light production)
- High scintillation efficiency and high light yield
- High transparency
- Good energy and position resolution
- Low energy threshold
- No directionality in current detectors
- Quenching: non-linearities between energy deposit and produced light
- Pulse shape discrimination (alpha/beta, positron/electron)

✓ elastic scattering: T ~200 keV for neutrino

✓ IBD: T = 1.8 keV for antineutrino

✓ **real- time technique: E_ν spectrum!**

We learned now
that charged particles can be detected in liquid scintillators

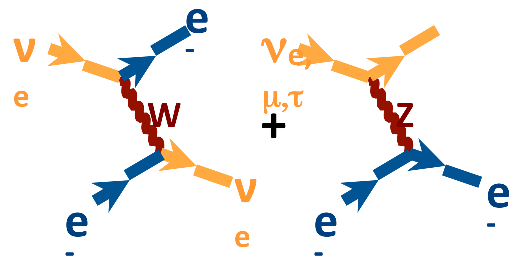
But neutrinos do not have any charge

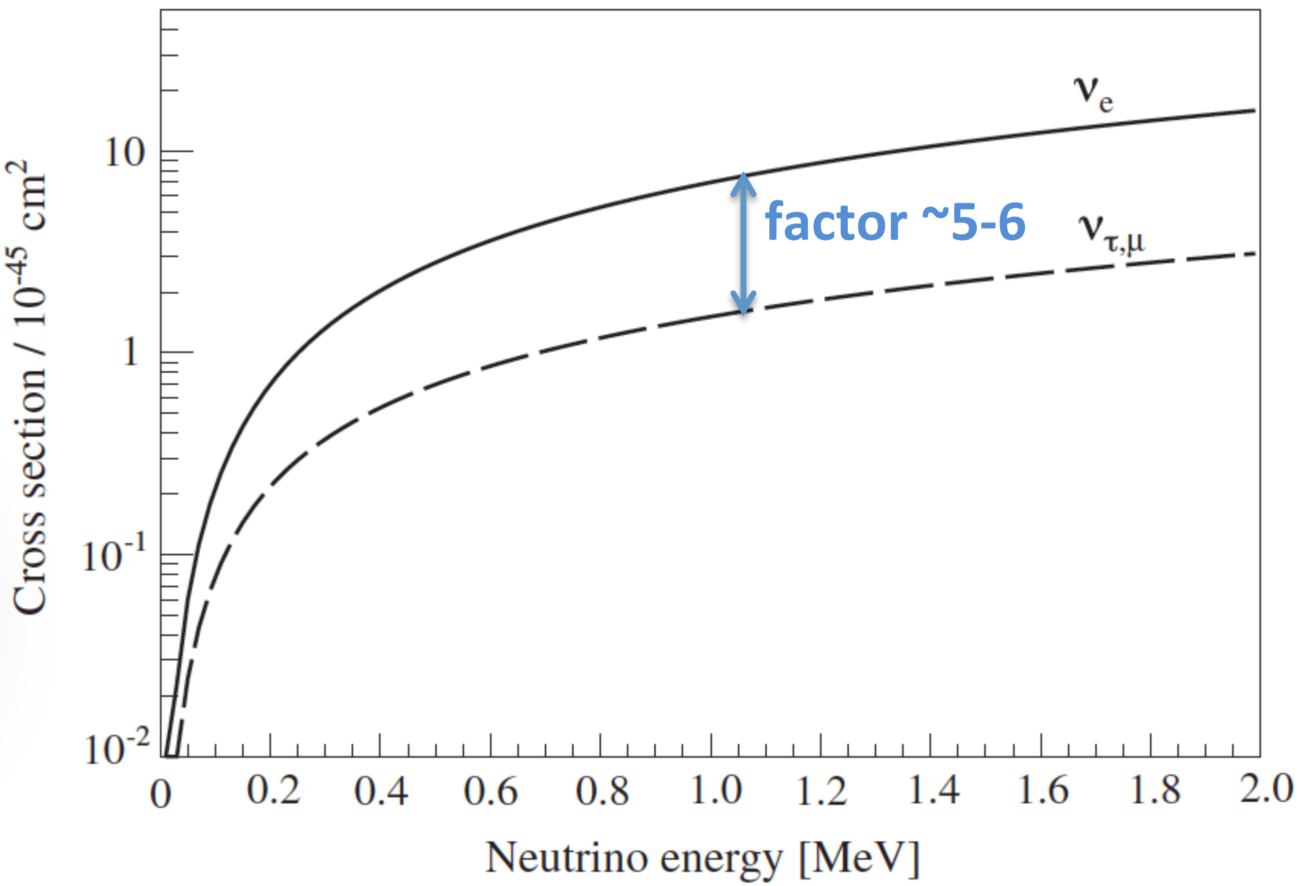
So how they are detected there???

Neutrinos detected through the elastic scattering: singles

@ 1-2 MeV for electron flavour: ~10^{-44} cm^2

for μ,τ flavours about 5-6 x smaller cross section





Eenergy spectrum of a scattered electron for 10 MeV (anti)-neutrino

Curtsey A. Derbin

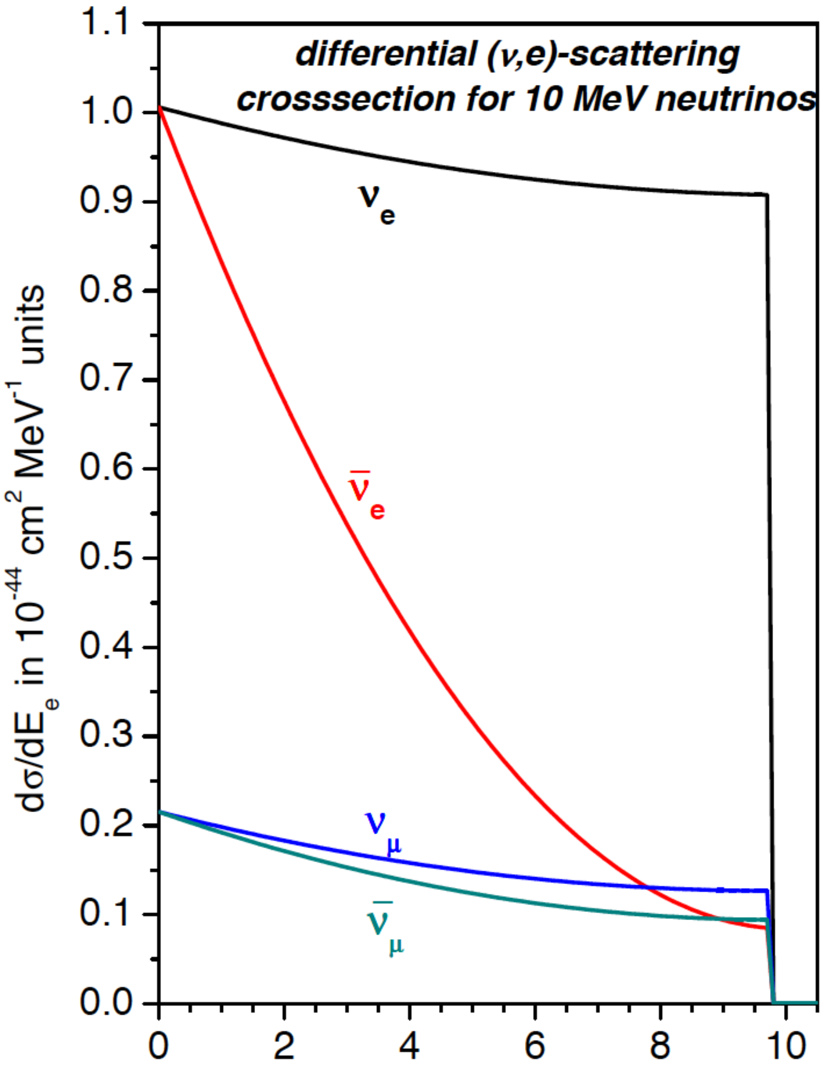
$$T_e^{max} = 2E_\nu^2/(m_e + 2E_\nu)$$

T_e^{max} (for 10 MeV neutrino) = 9.75 MeV

If you would have the same flux of

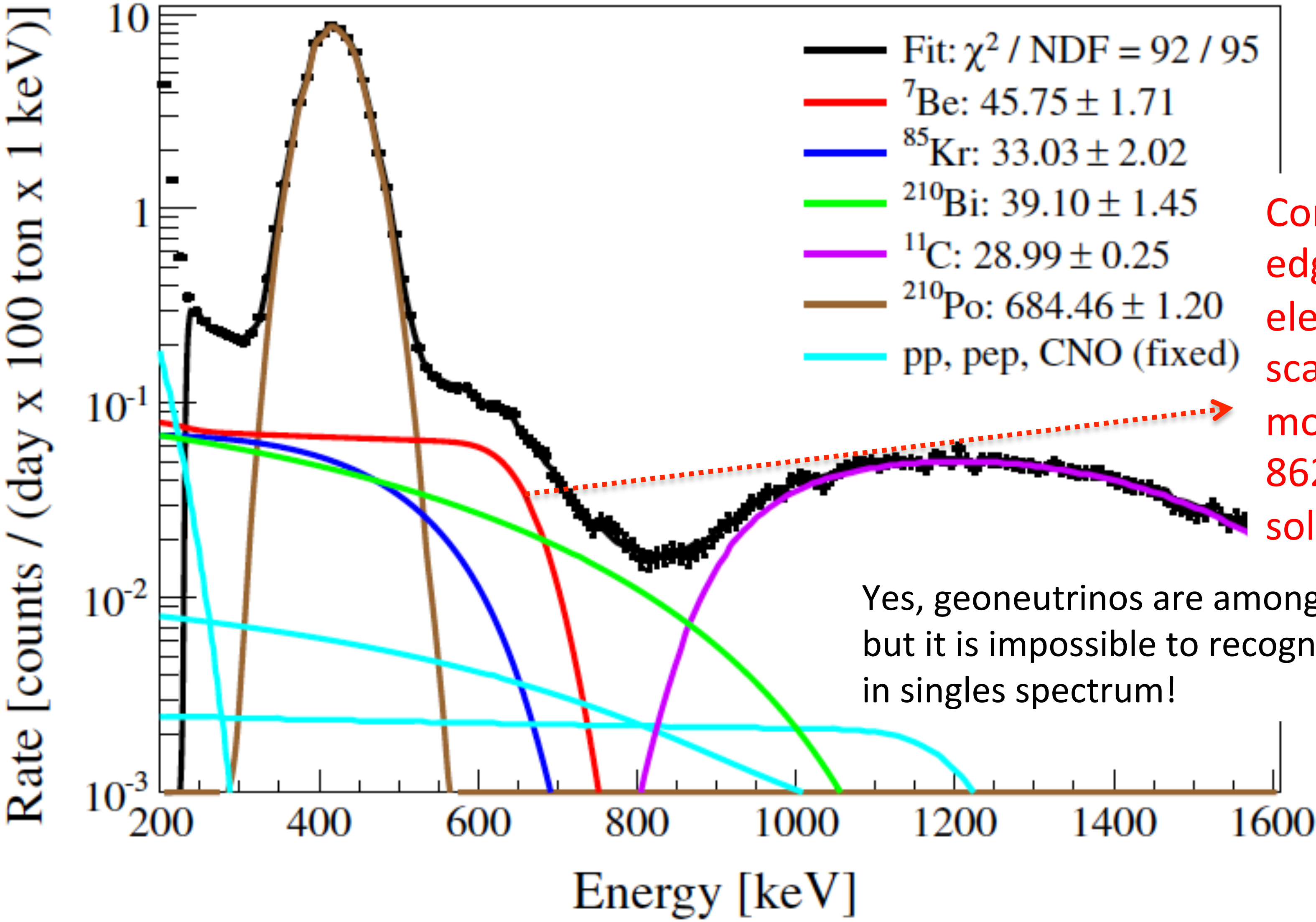
Electron neutrinos
Electron antineutrinos
Mu/tau neutrinos
Mu/tau antineurinos

You would measure these spectra trhough the scaterring channels



Energy of scattered electron T_e [MeV]

Borexino singles spectrum



Compton-like edge of electrons scattered off monoenergetic 862 keV ^{7}Be solar neutrinos

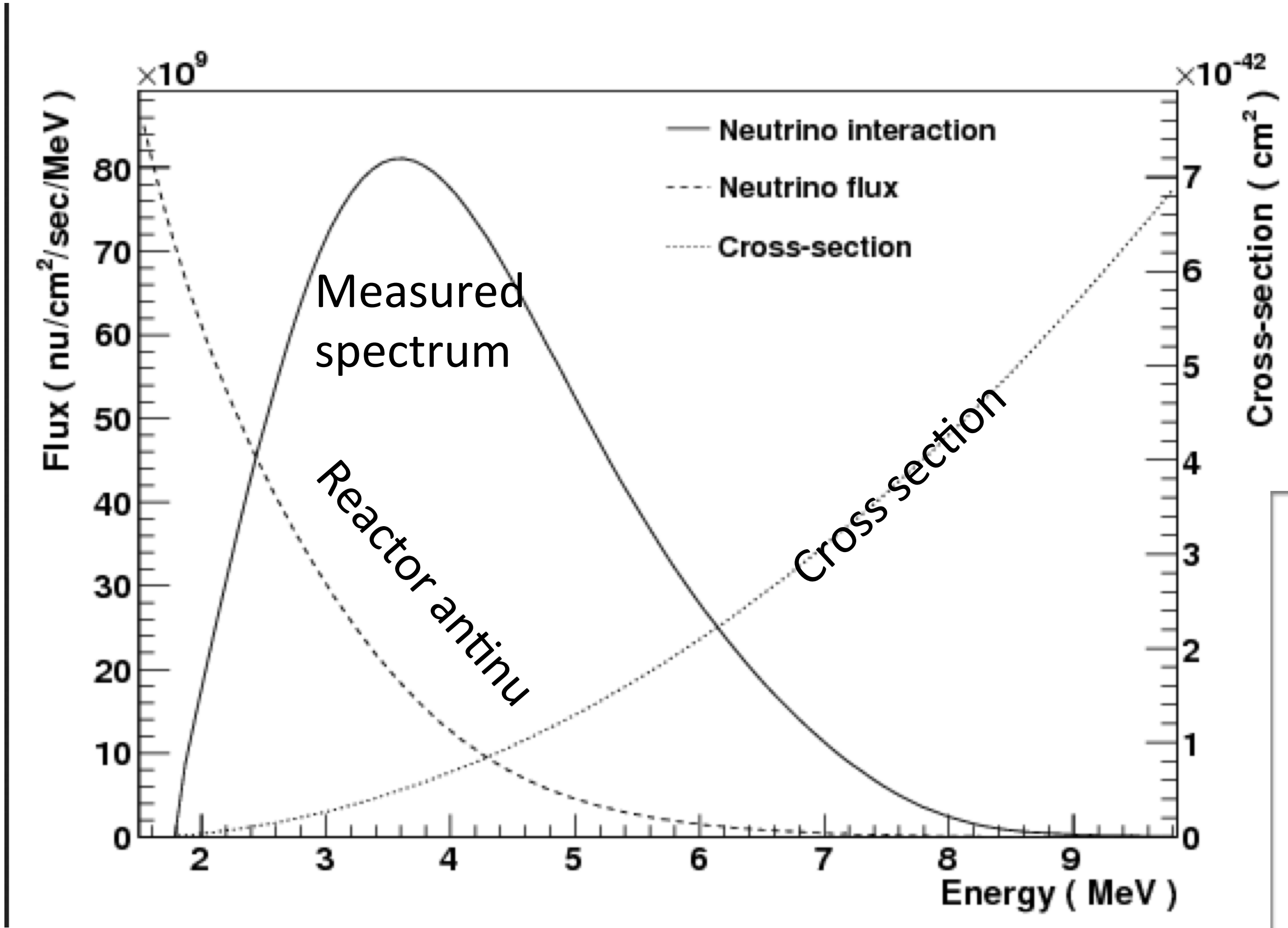
Yes, geoneutrinos are among these events, but it is impossible to recognize them in singles spectrum!

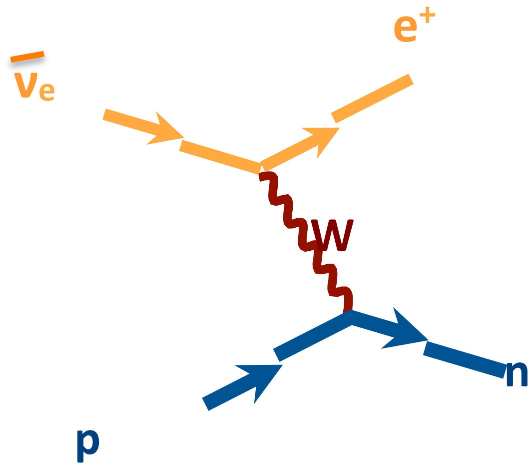
Borexino spectrum: different components extracted by a spectral fit

Electron antineutrinos detected through IBD (Inverse Beta Decay interaction)

Charge current, only anti-ν_e

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





Low reaction σ → large volume detectors

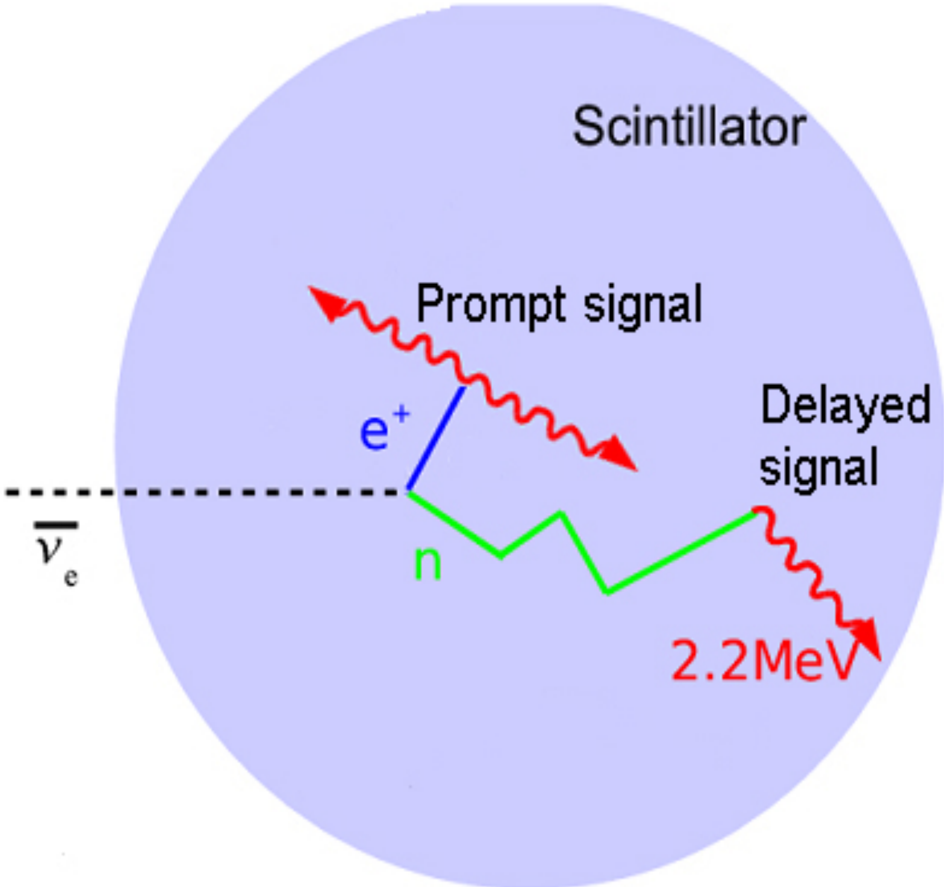
Liquid scintillators

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

Inverse Beta Decay interaction

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

Only in liquid scintillators



"prompt signal"

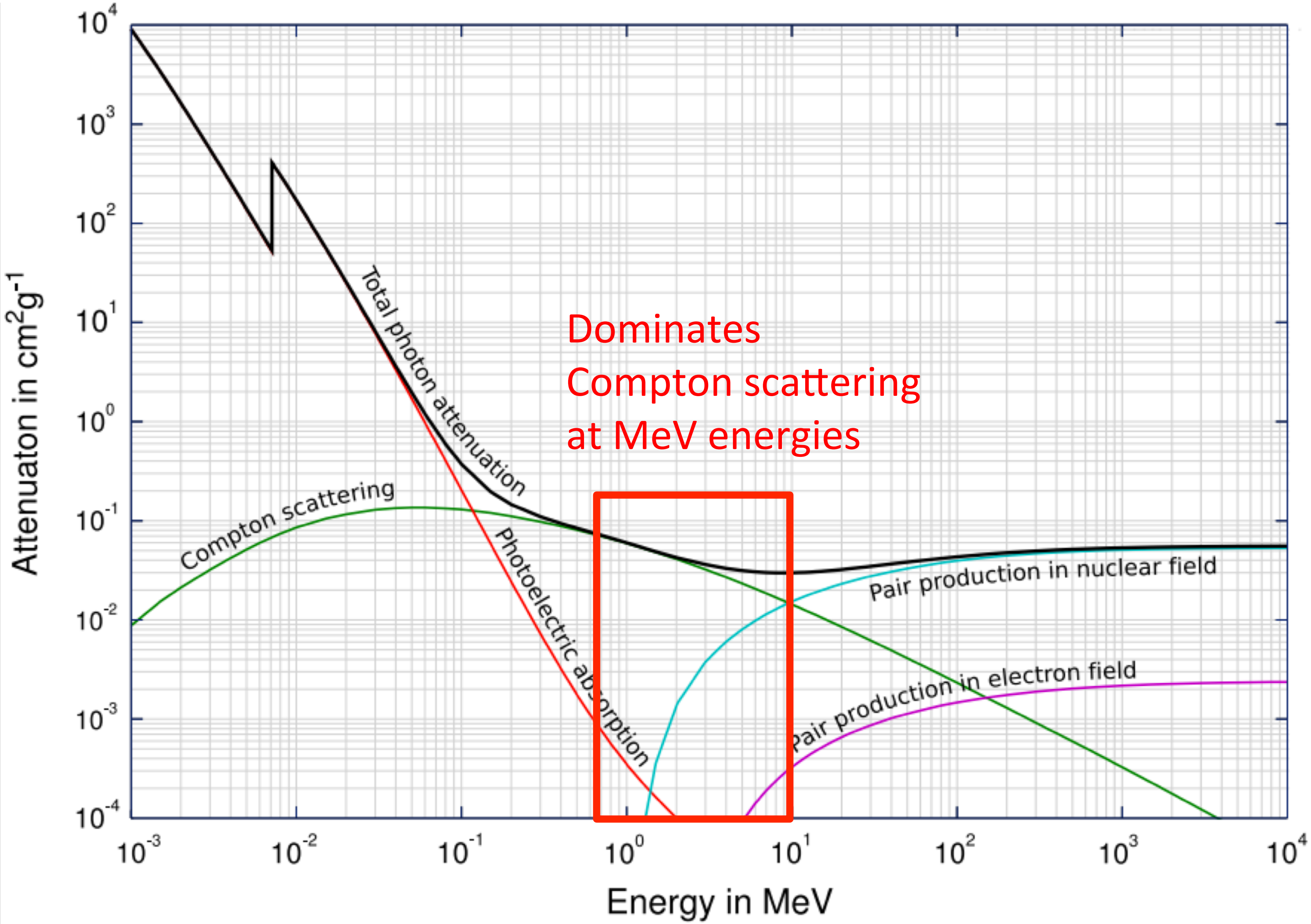
e^{+}: energy loss T_{e+} + annihilation (2 x 0.511 MeV)

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

"delayed signal"

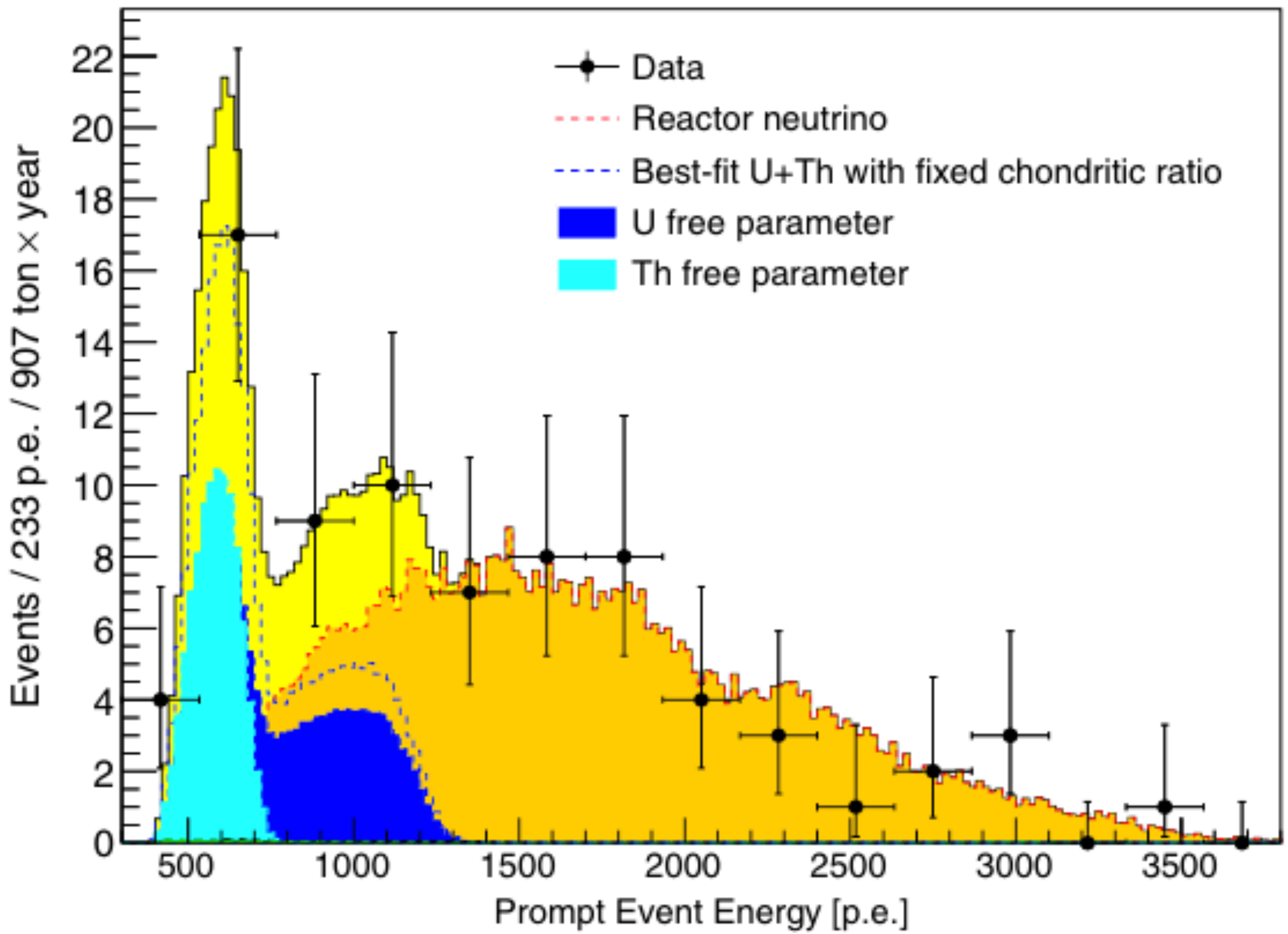
neutron thermalisation & capture on protons, emission of **2.2 MeV γ**

Cross section of gamma rays interactions



Electron antineutrinos detected in Borexino through IBD

Only 77 candidates since 2008!!

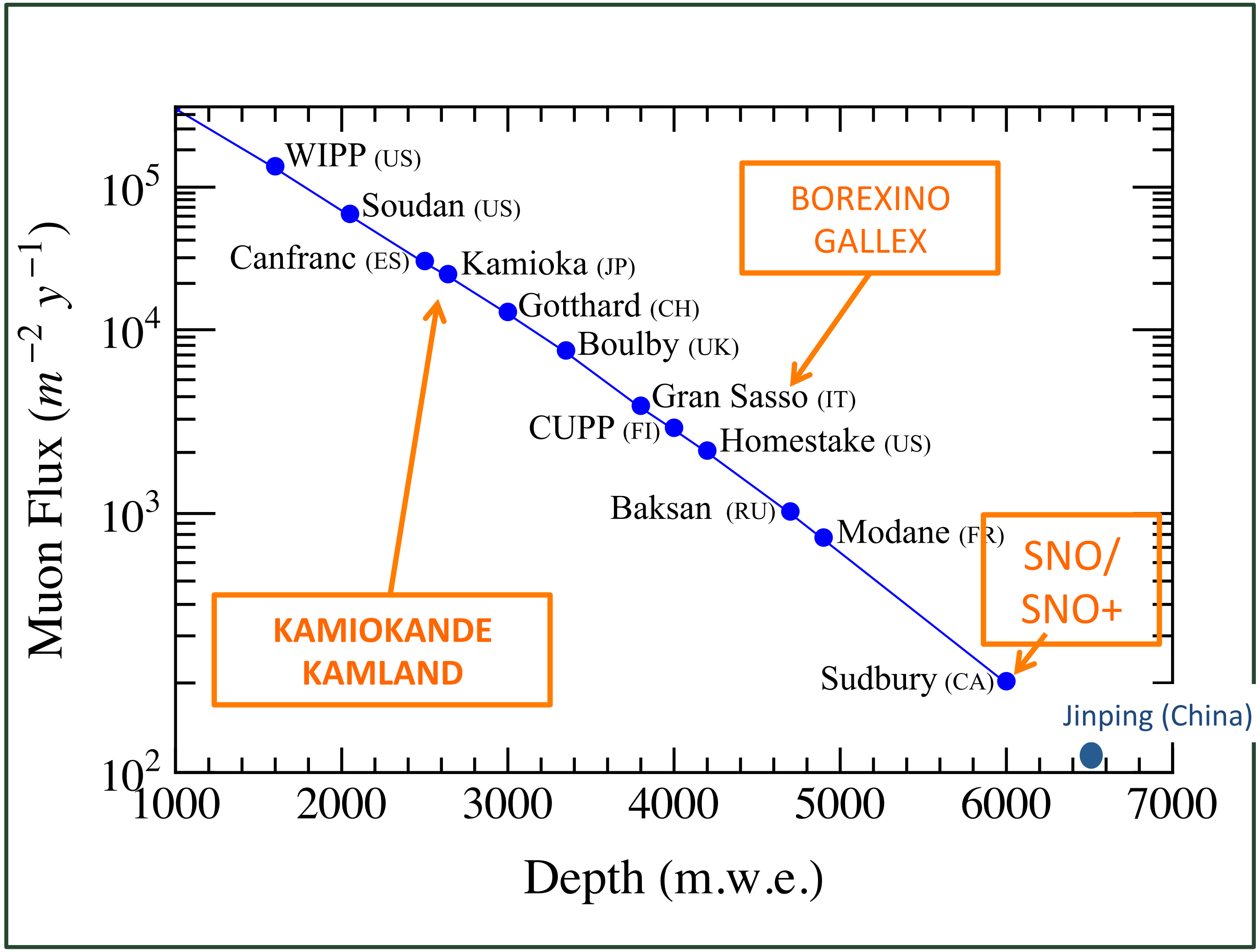


Neutrino detection is special

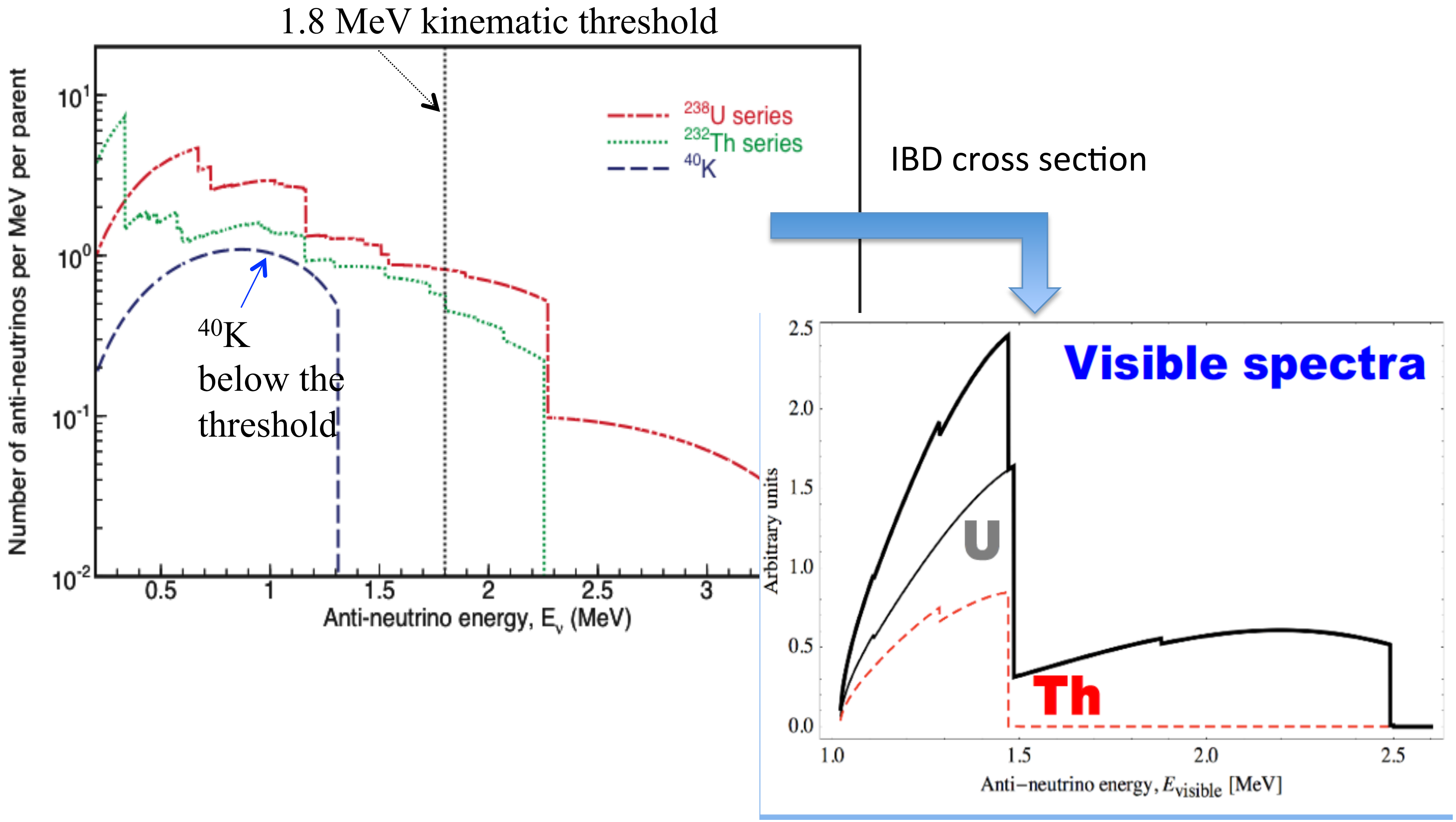
Cosmogenic background -> underground laboratories

Small neutrino interaction rates → shielding against cosmic rays

Muon flux in undeground laboratories



Geoneutrino energy spectrum



IBD in a nutshell

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;

Geoneutrino analysis

Geoneutrino experimental results

KamLAND (Japan)

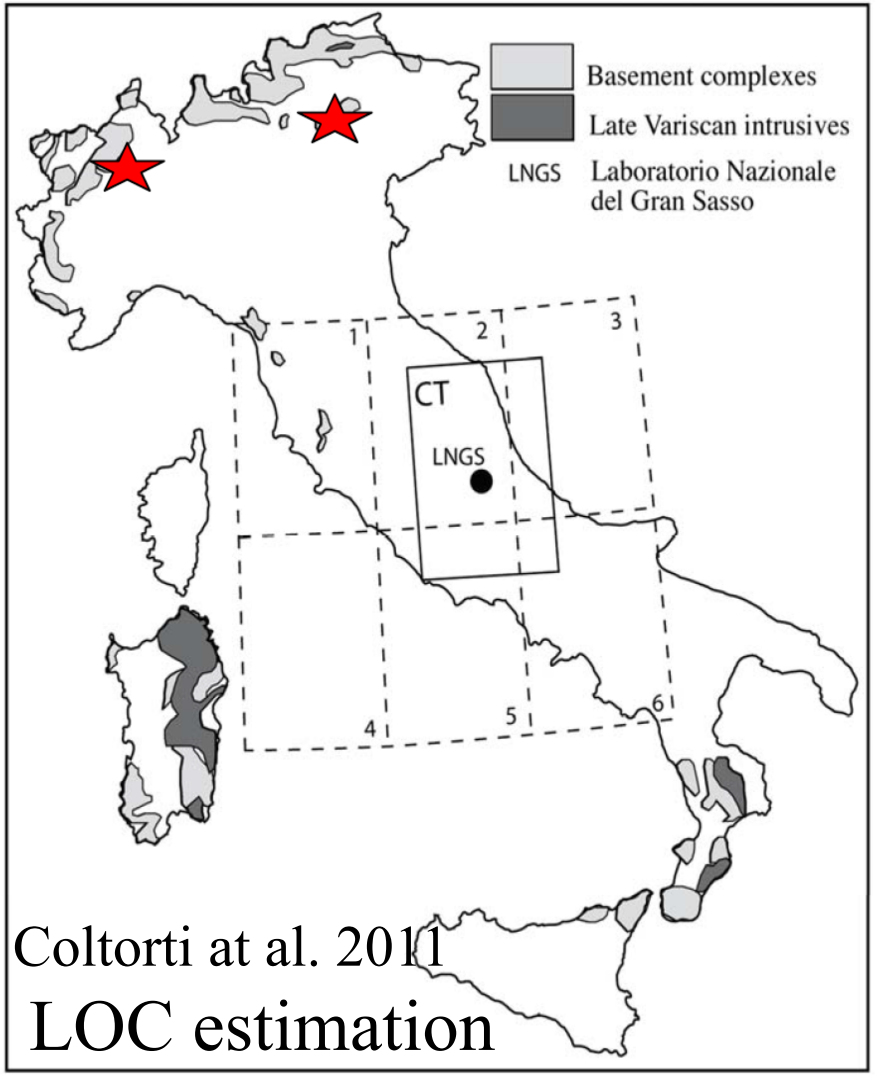
- **The first investigation in 2005**
  CL < 2σ
  Nature 436 (2005) 499
- **Update in 2008**
  73 ± 27 geonu's
  PRL 100 (2008) 221803
- **99.997 CL observation in 2011**
  106^{+29}_{-28} geonu's
  (March 2002 – April 2009)
  3.49 x 10^{32} target-proton year
  Nature Geoscience 4 (2011) 647
- **Latest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

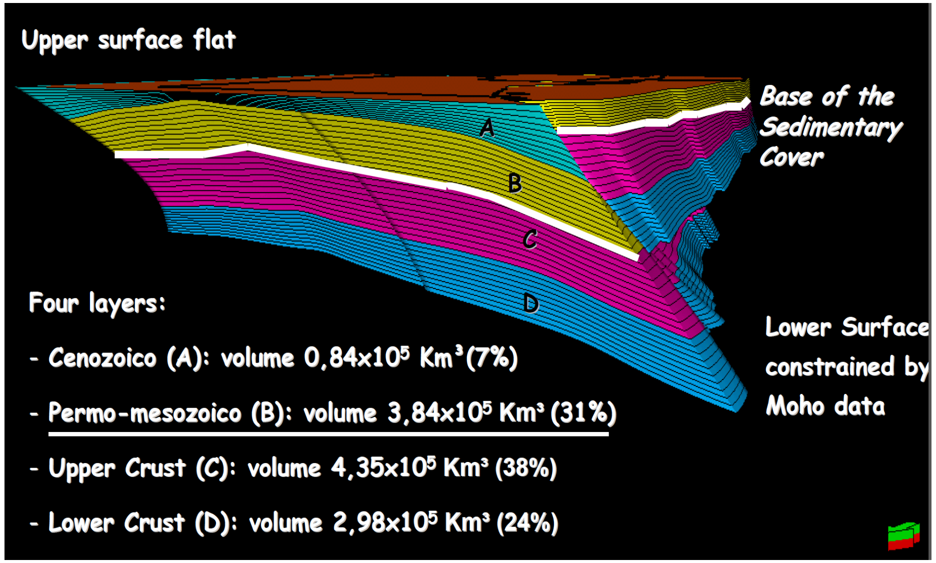
- **99.997 CL observation in 2010**
  $9.9^{+4.1}_{-3.4}$ geonu's
  small exposure but low background level
  (December 2007 – December 2009)
  1.5 x 10^{31} target-proton year
  PLB 687 (2010) 299
- **Update in 2013**
  14.3 ± 4.4 geonu's
  (December 2007 – August 2012)
  3.69 x 10^{31} target-proton 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)

Borexino analysis and results

Expected crustal signal at LNGS



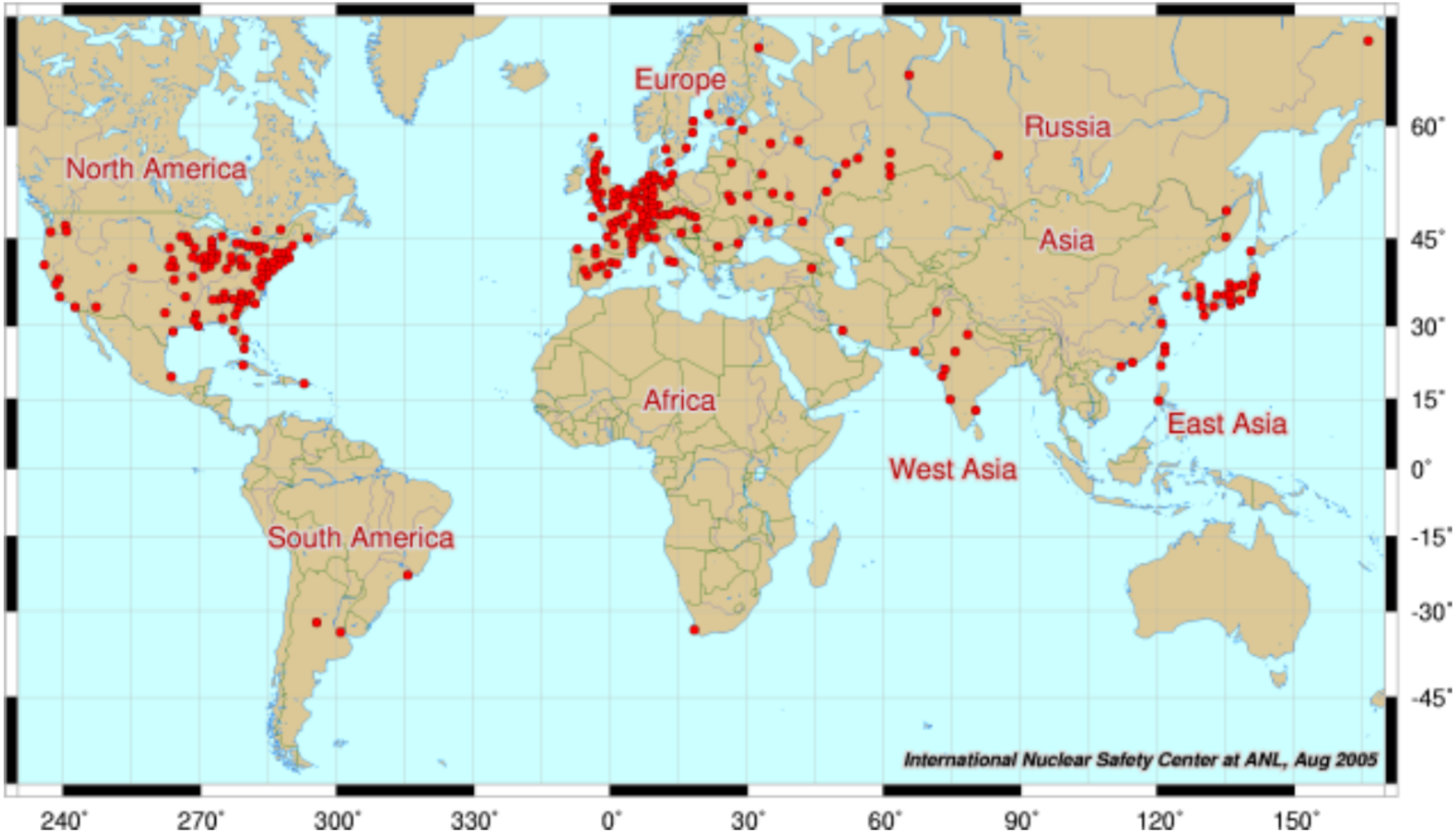
Coltorti at al. 2011
LOC estimation



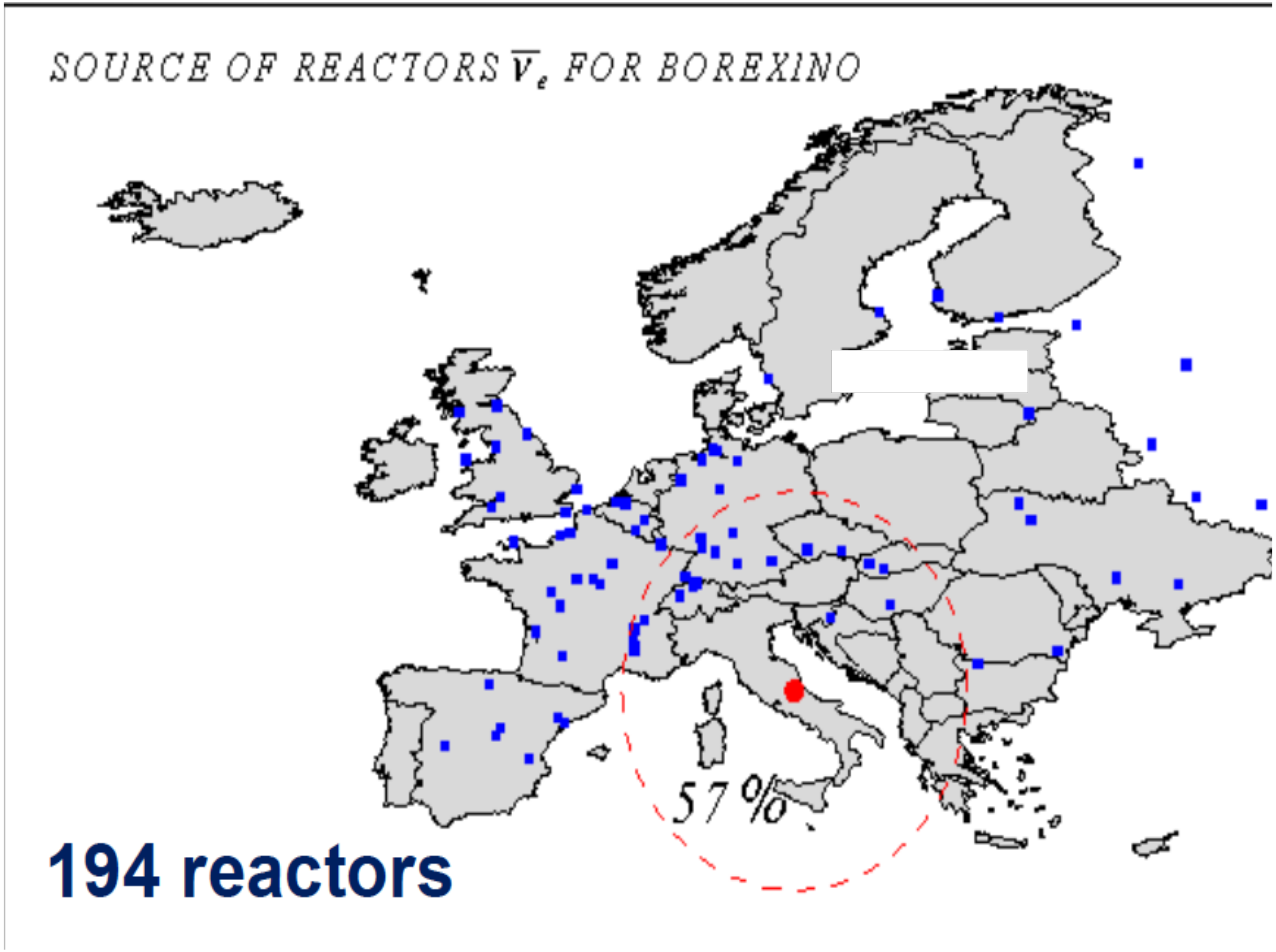
Expected crustal signal
local LOC + Rest-Of-the Crust
23.4 $\pm$ 2.8 TNU

A typical reactor emits every second about 10^{20} electron flavour antineutrinos (E > 1.8 MeV = detectable with present day technology)

World distribution of reactors



Reactors around LNGS



Calculation of reactor anti-ν signal

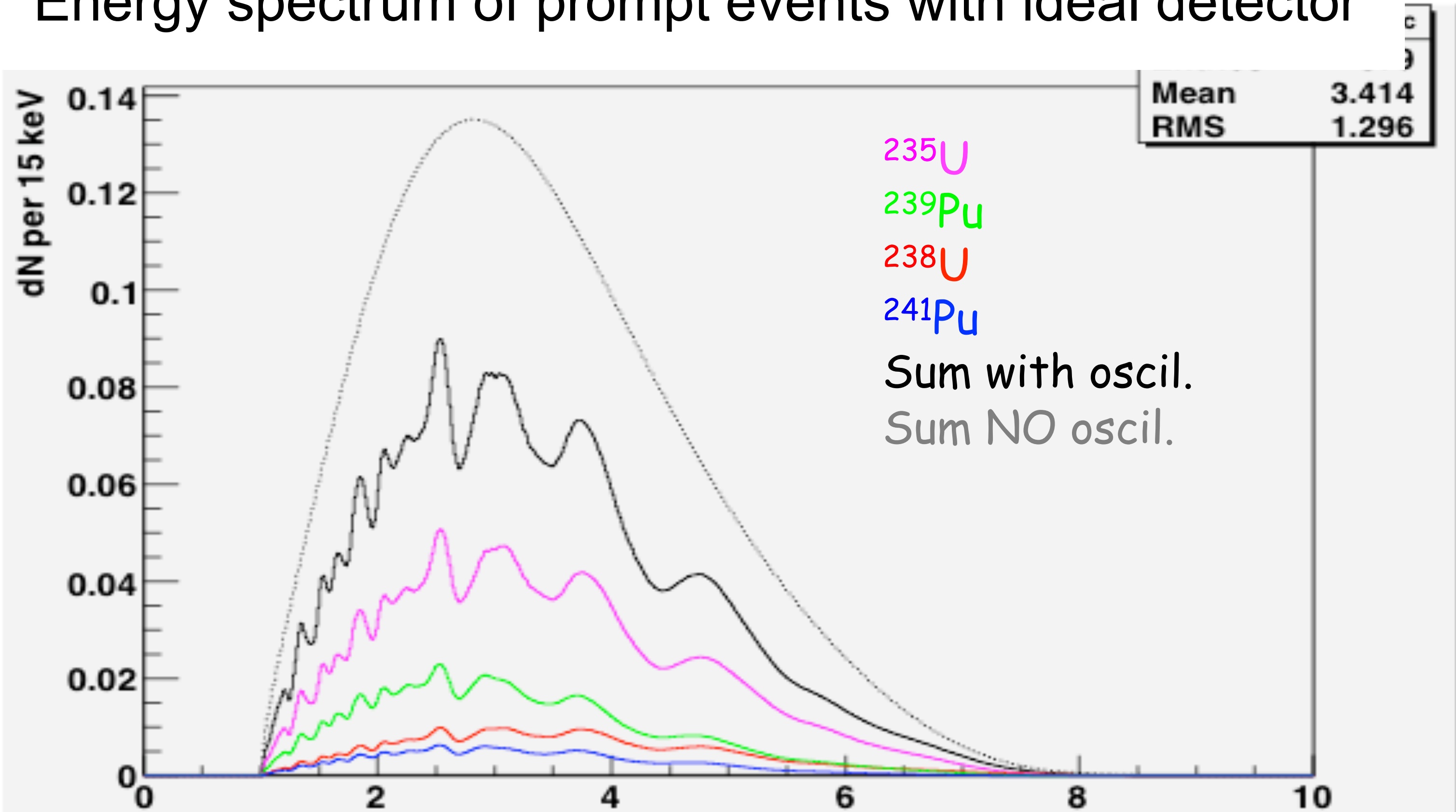
$$\Phi\left(E_{\bar{\nu}_e}\right)=\sum_{r=1}^{N_{react}}\sum_{m=1}^{N_{month}}\frac{T_m}{4\pi L_r^2}P_{rm}\sum_{i=1}^{4}\frac{f_{ri}}{E_i}\Phi_i\left(E_{\bar{\nu}_e}\right)P_{ee}\left(E_{\bar{\nu}_e};\hat{\vartheta},L_r\right)$$

- **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, Mueller et al.2011, Huber-Schwetz 2004);
  - P_{ee}: oscillation survival probability;
- **Calculated:**
  - T_m: live time during the month m;
  - L_r: reactor r – detector distance;
- **Data from nuclear agencies:**
  - P_{rm}: thermal power of reactor r in month m (IAEA , EDF, and UN data base);
  - f_{ri}: power fraction of isotope i in reactor r;

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

Expected reactor signal at LNGS

Energy spectrum of prompt events with ideal detector



Prompt energy (MeV)

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 (electron) + neutron;
- **neutrons** of high energies;

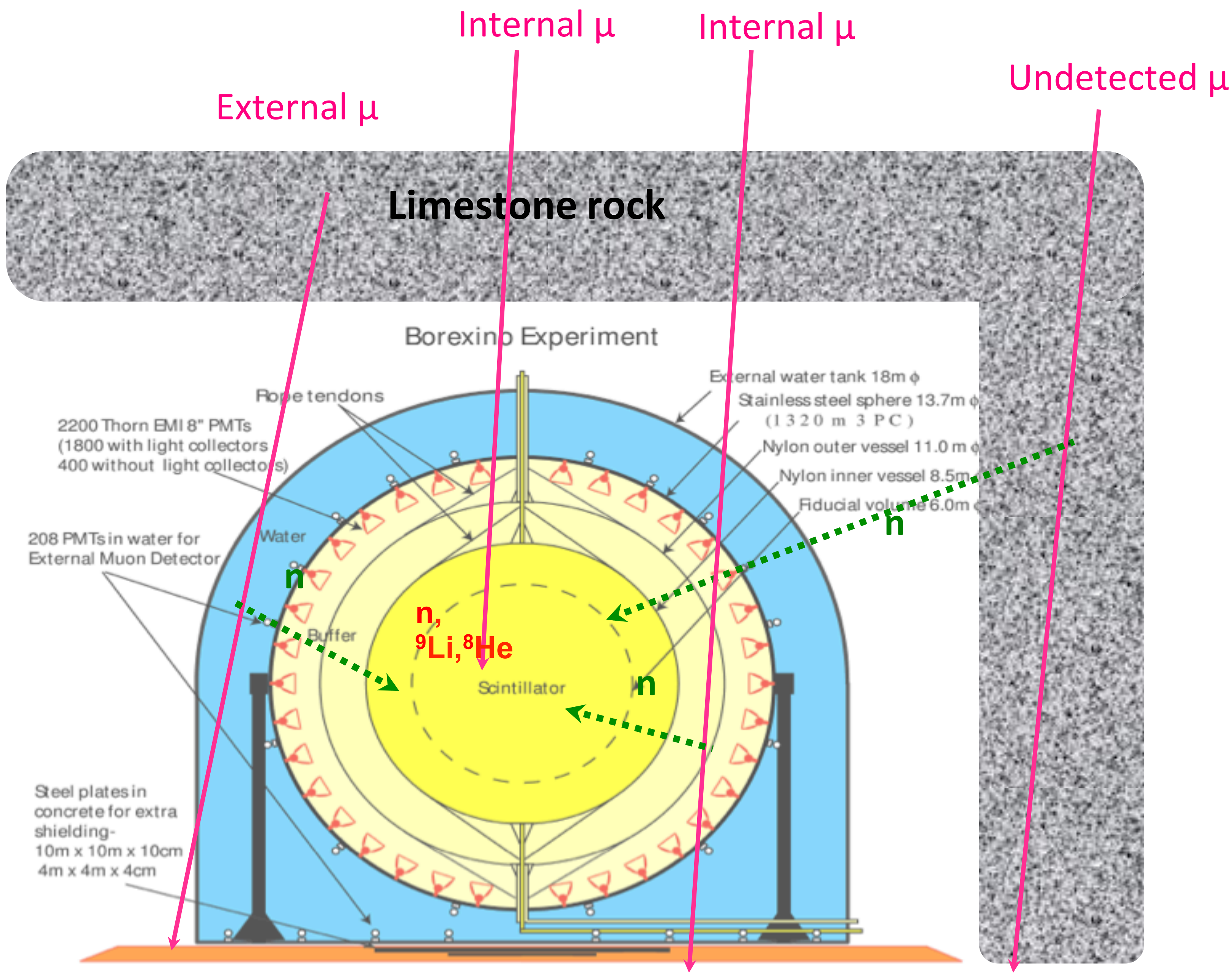
  neutrons scatters proton = prompt signal;

  neutron is captured = delayed signal;
- Non-identified muons;

2) Accidental coincidences;

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

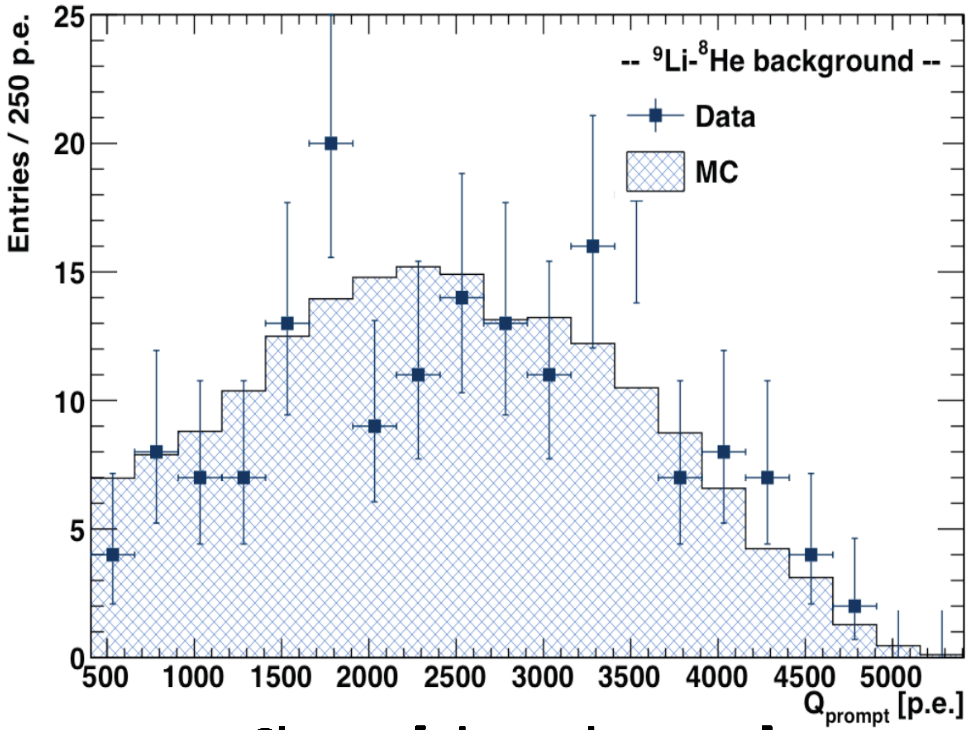
Cosmogenic background



^{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

Prompt-energy spectrum of LiHe candidates



Charge [photoelectrons]

Monte Carlo simulation does reproduce the measured LiHe spectrum

^{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
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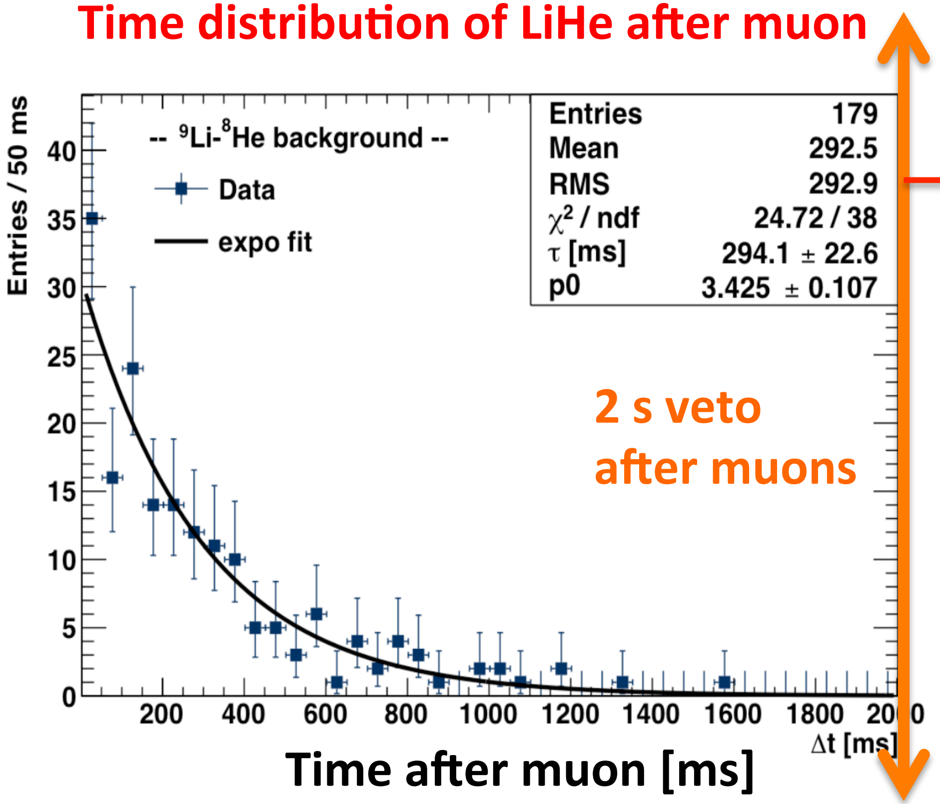
Time distribution of LiHe after muon



Time from the last muon > 2 s

Only candidates from this time window can appear in the final spectrum used in the geoneutrino analysis

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

Isotope	$T_{1/2}$ [ms]	Decay mode	BR [%]	Q_β [MeV]
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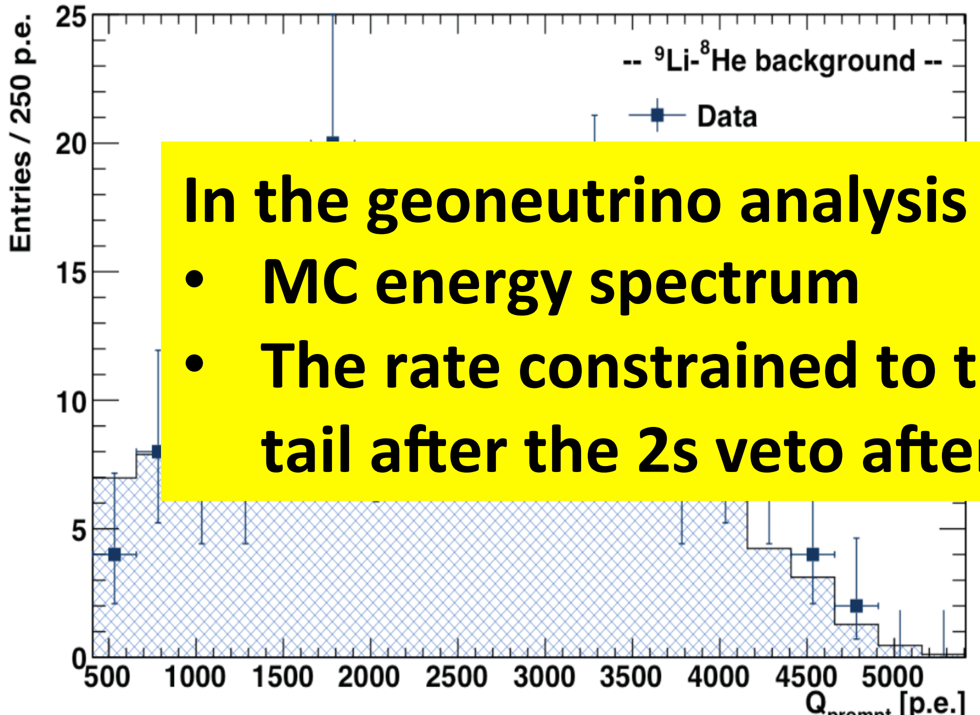
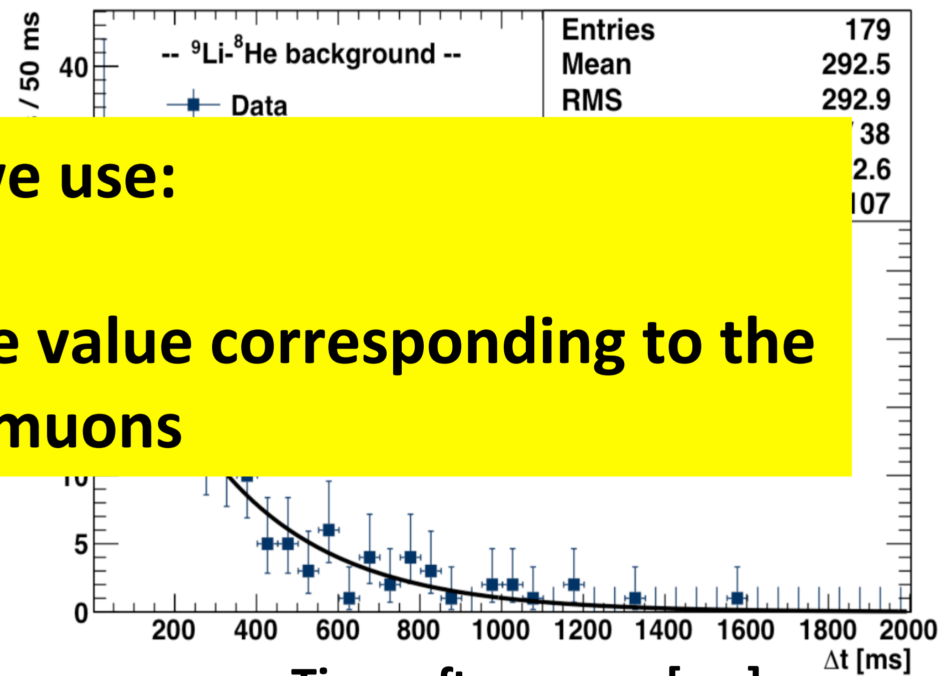
Prompt-nergy spectrum of LiHe candidates



Charge [photoelectrons]

Time distribution of LiHe after muon



Time after muon [ms]

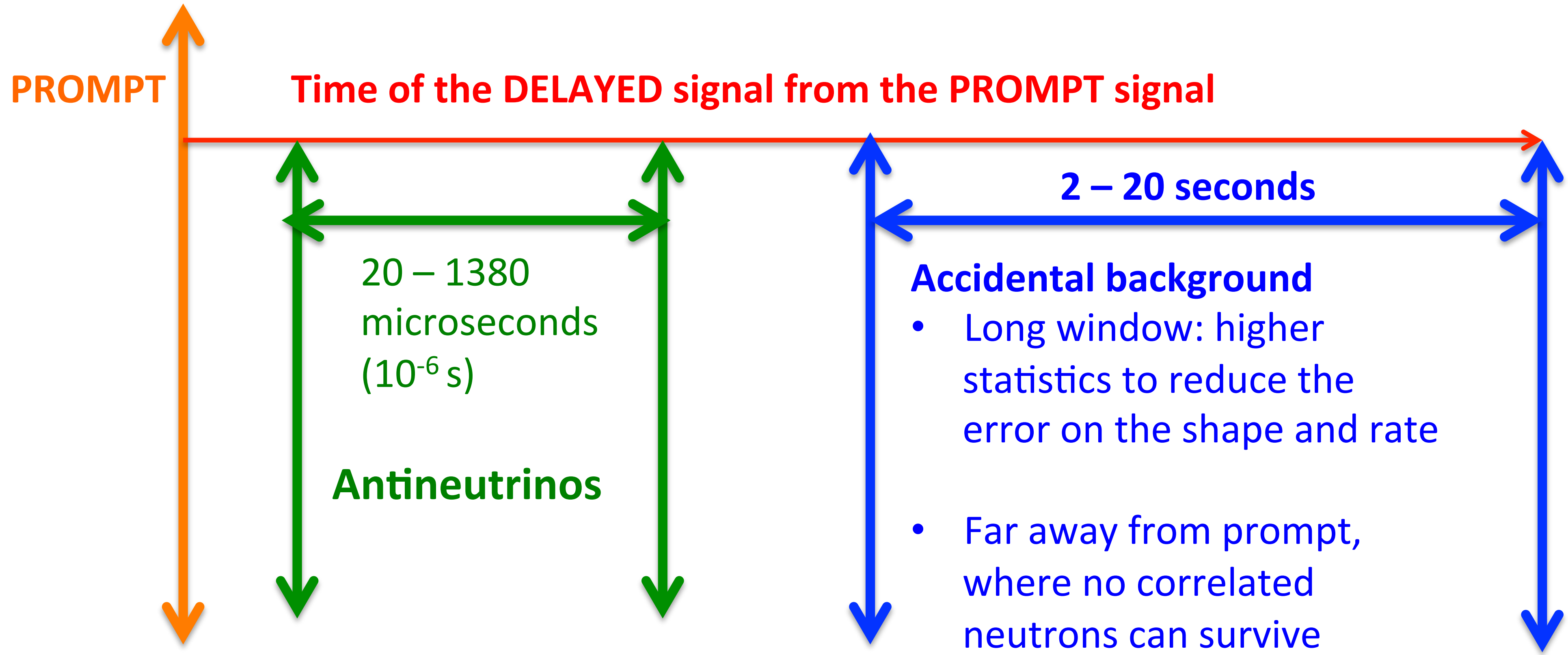
In the geoneutrino analysis we use:

- **MC energy spectrum**
- **The rate constrained to the value corresponding to the tail after the 2s veto after muons**

Accidental background

Pairs of uncorrelated signals occurring close to each other in space and time accidentally

Search for coincidences in the off-time window Δt (2 s – 20 s)
OTHER SELECTION CUTS KEPT THE SAME

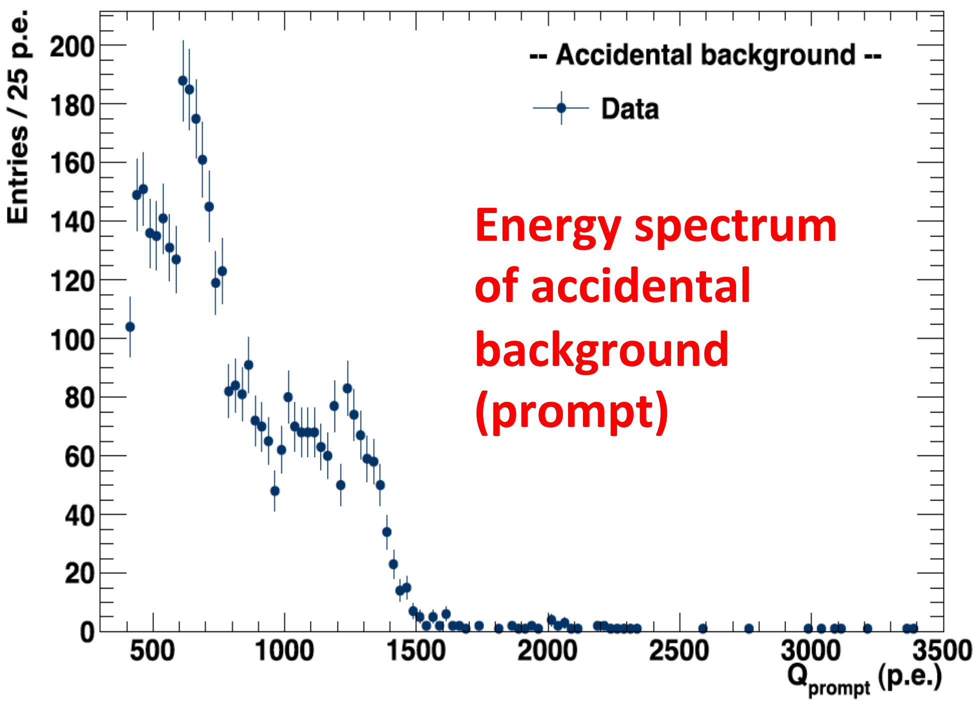


Rate observed in the 18 s time window, just scale back to the 1360 μs window

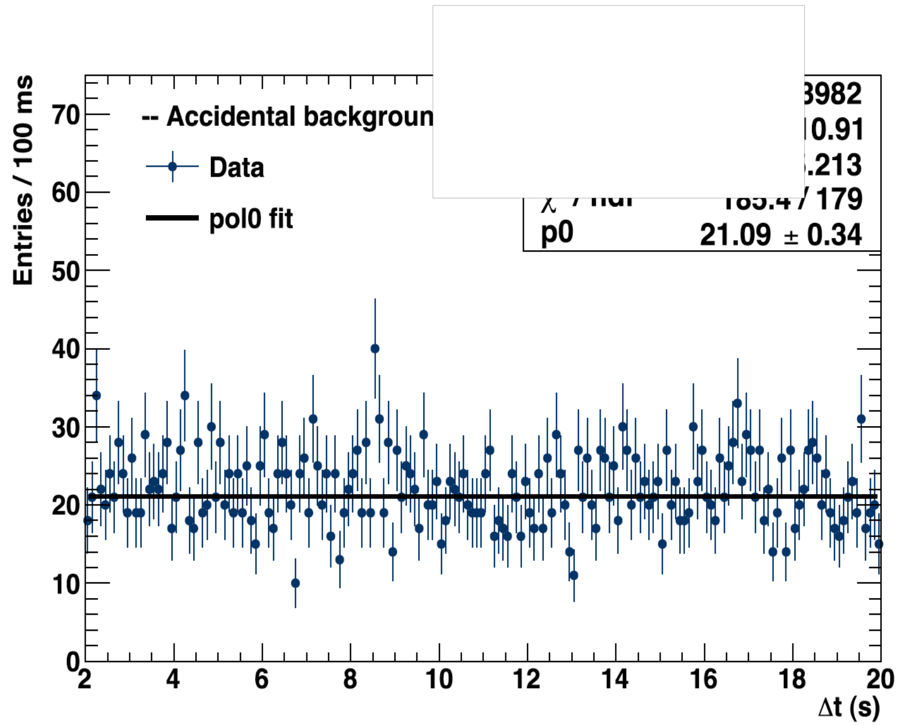
Accidental background

Pairs of uncorrelated signals occurring close to each other in space and time accidentally

Search for coincidences in the off-time window Δt (2 s – 20 s)
OTHER SELECTION CUTS KEPT THE SAME



Charge [photoelectrons]

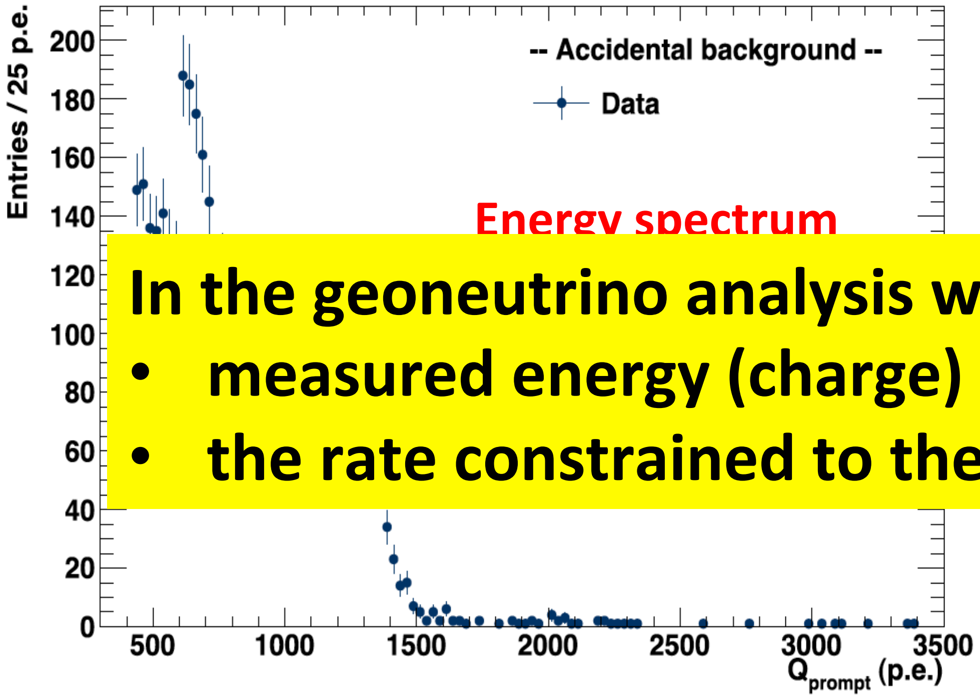


Time delayed - prompt [s]

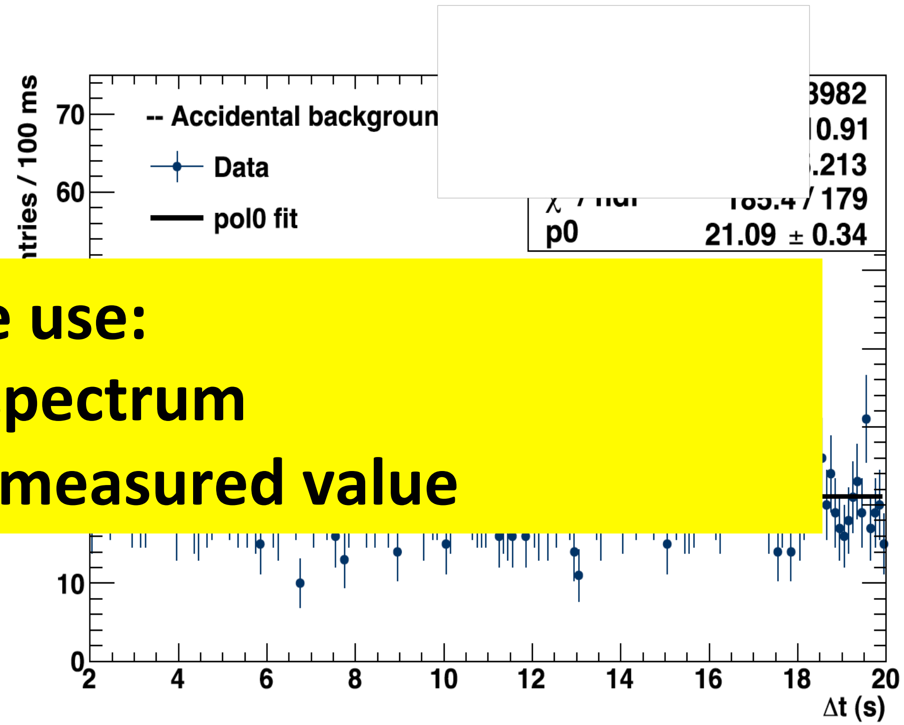
Accidental background

Pairs of uncorrelated signals occurring close to each other in space and time accidentally

Search for coincidences in the off-time window Δt (2 s – 20 s)
OTHER SELECTION CUTS KEPT THE SAME



Charge [photoelectrons]



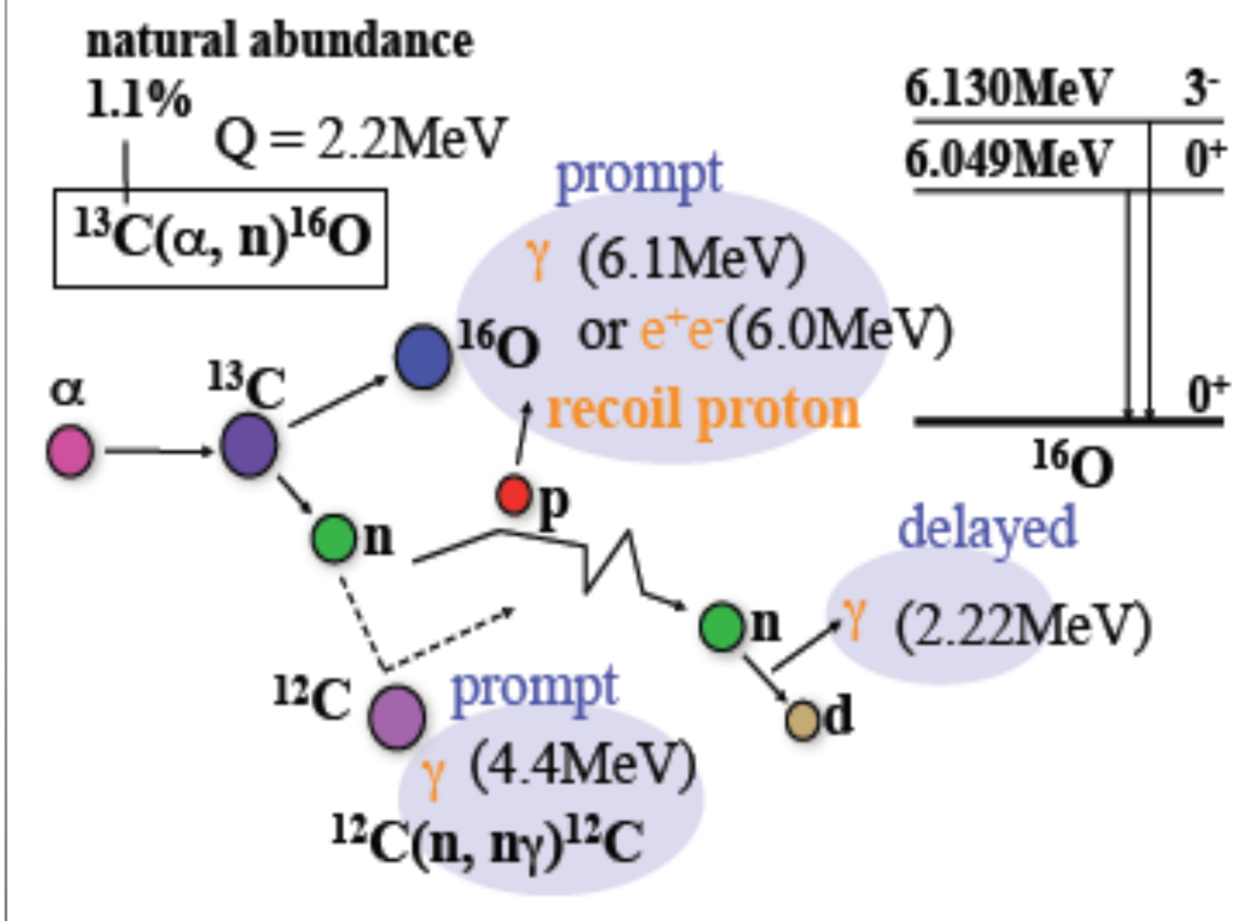
Time delayed - prompt [s]

In the geoneutrino analysis we use:

- **measured energy (charge) spectrum**
- **the rate constrained to the measured value**

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

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



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

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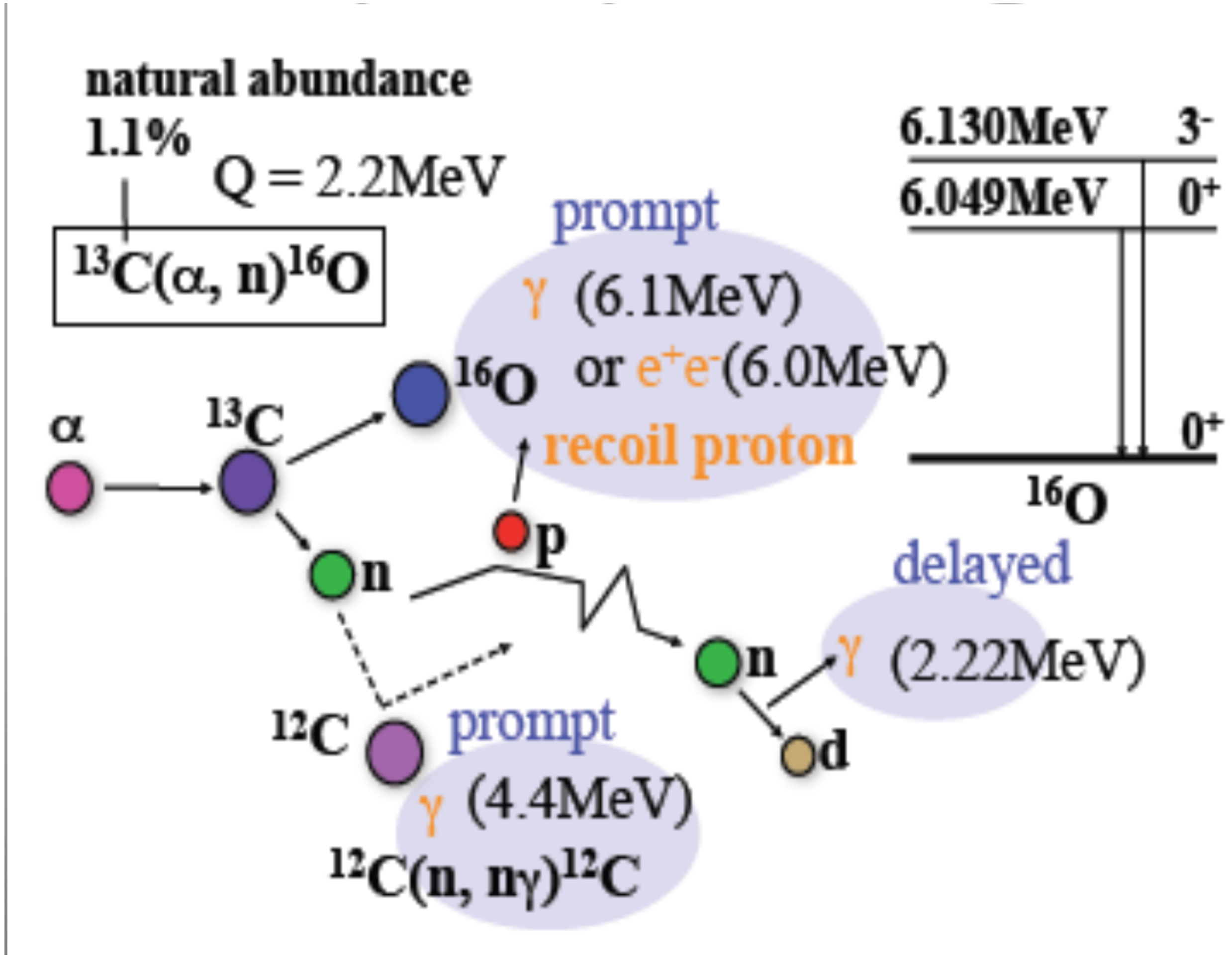


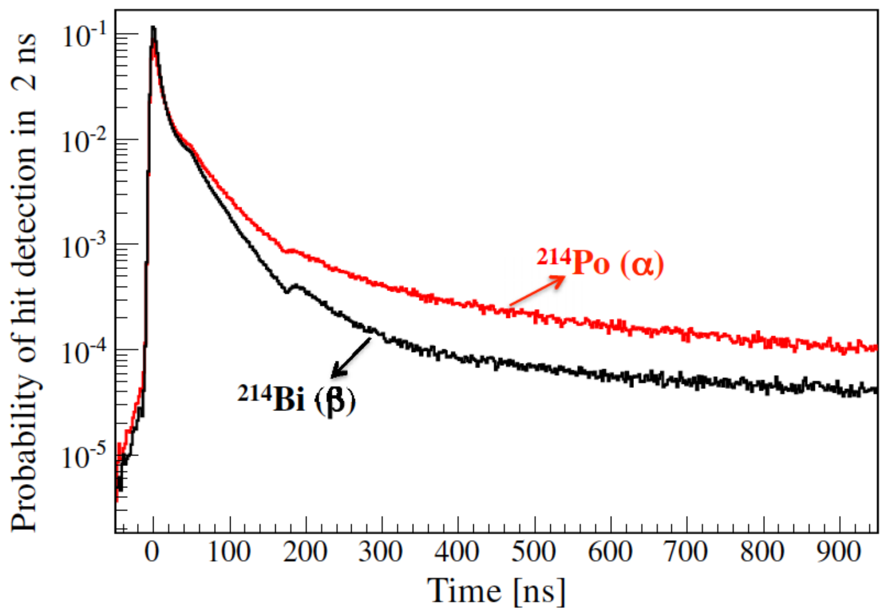
1. How do we know how much ^{210}Po (alpha) we have?

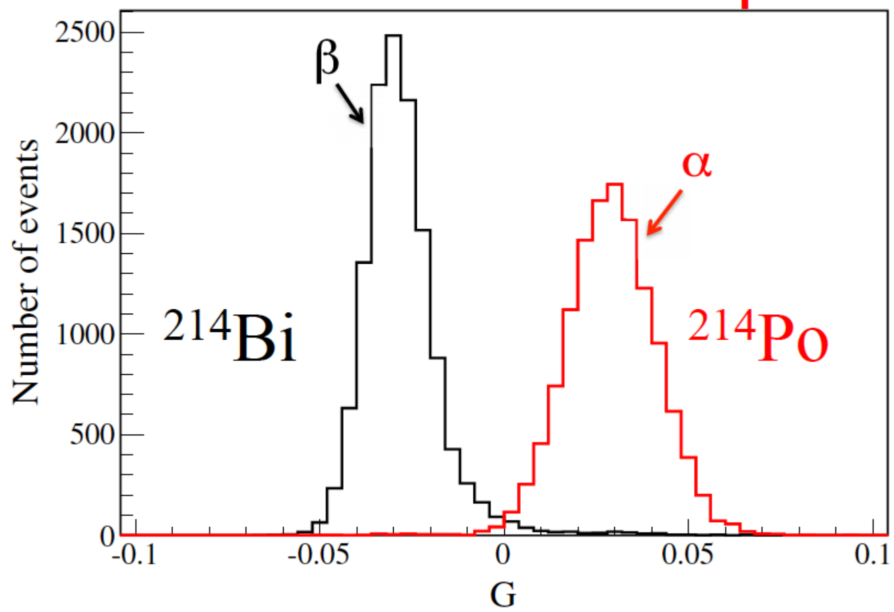
2. We can separate alphas from betas!

3. How?

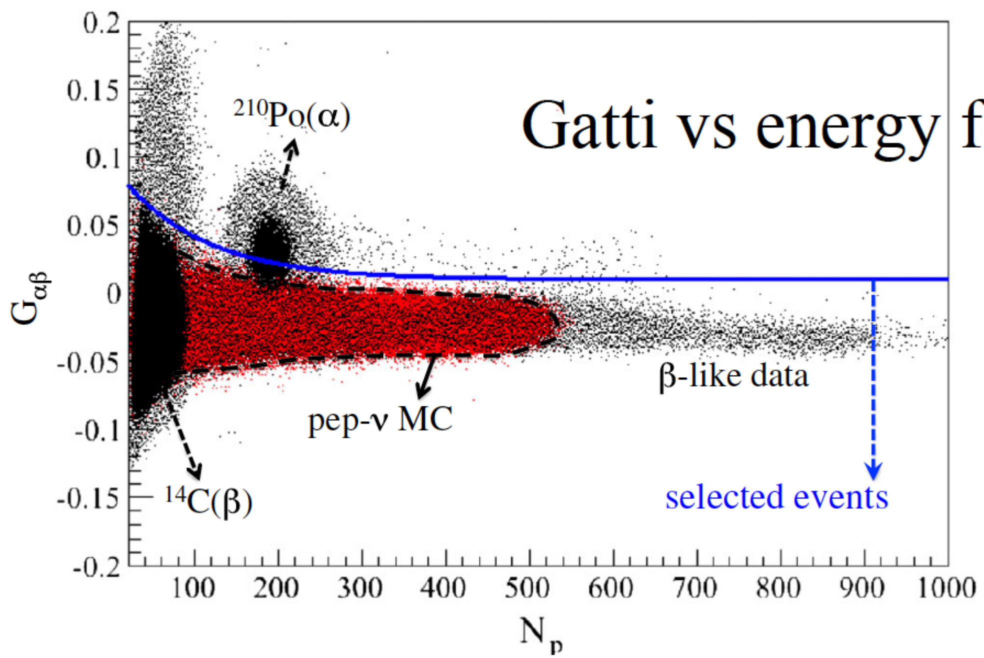
α/β discrimination

Gatti variable tuned on αβ samples



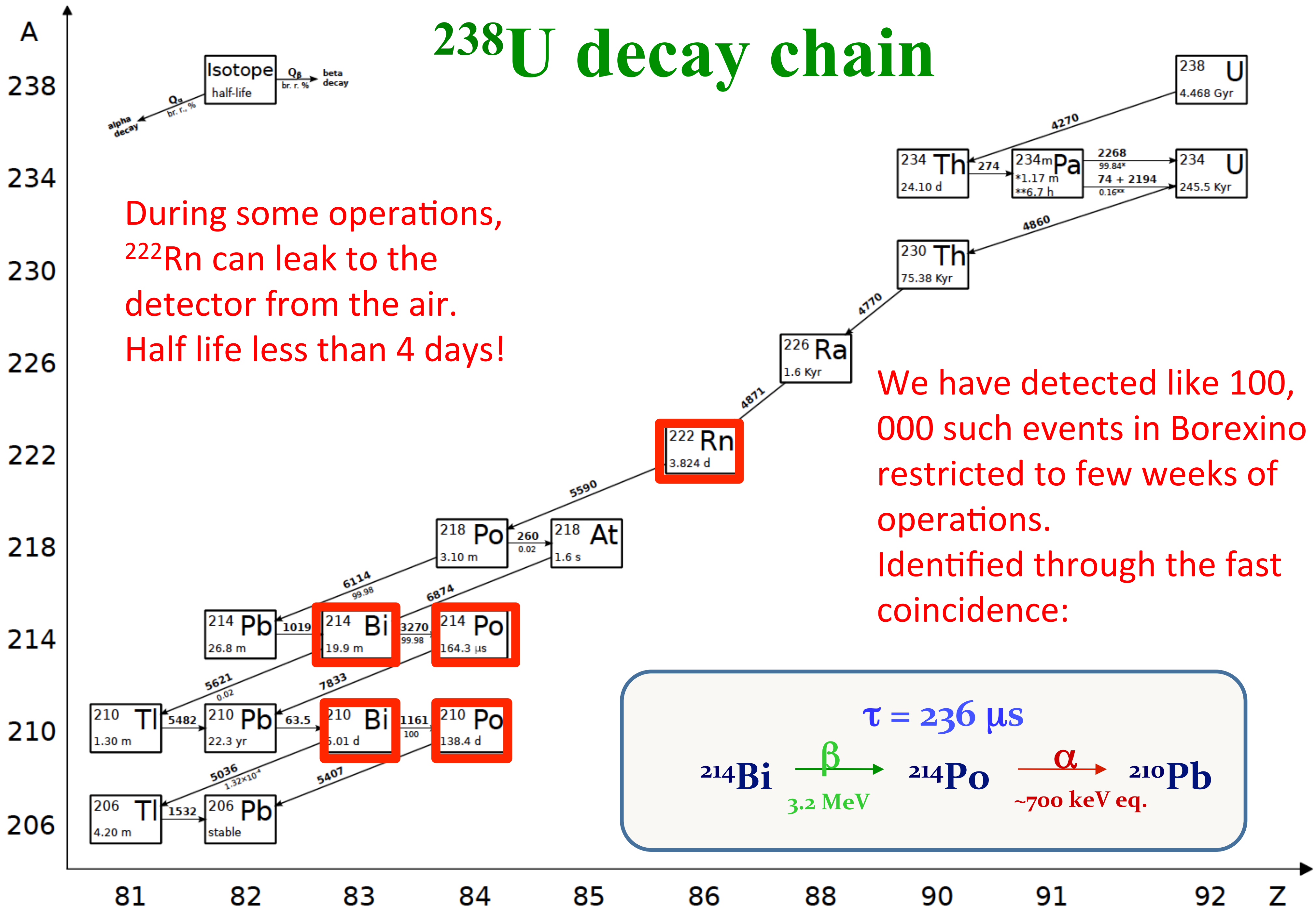


Gatti vs energy for normal data



Borexino data

^{238}U decay chain



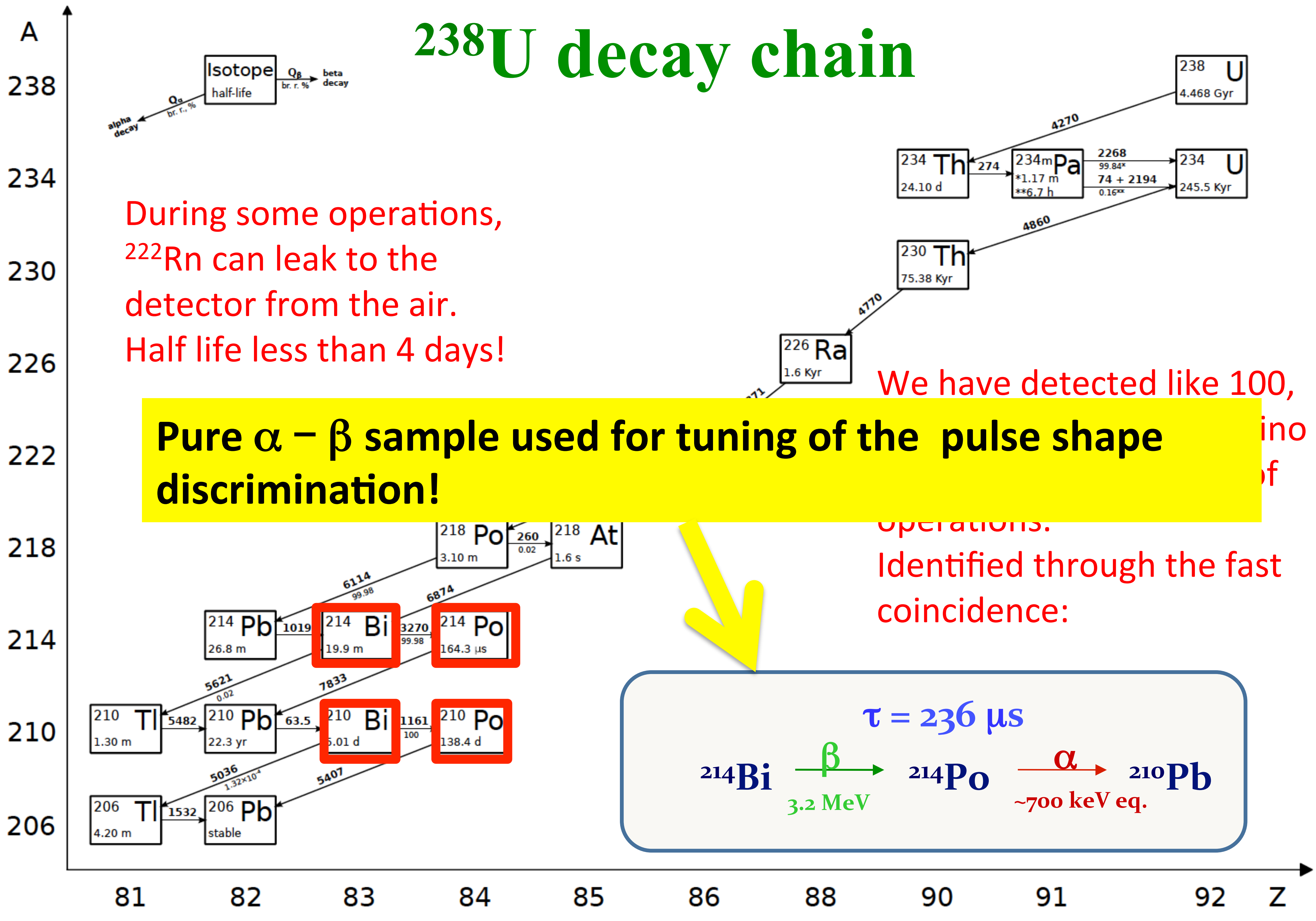
During some operations, ^{222}Rn can leak to the detector from the air.
Half life less than 4 days!

We have detected like 100, 000 such events in Borexino restricted to few weeks of operations.
Identified through the fast coincidence:

$$\tau = 236\ \mu s$$

$$^{214}\mathrm{Bi} \xrightarrow[3.2\ \mathrm{MeV}]{\beta} {}^{214}\mathrm{Po} \xrightarrow[\sim 700\ \mathrm{keV\ eq.}]{\alpha} {}^{210}\mathrm{Pb}$$

^{238}U decay chain



During some operations, ^{222}Rn can leak to the detector from the air.
Half life less than 4 days!

We have detected like 100, ...ino ...f ...operations.
Identified through the fast coincidence:

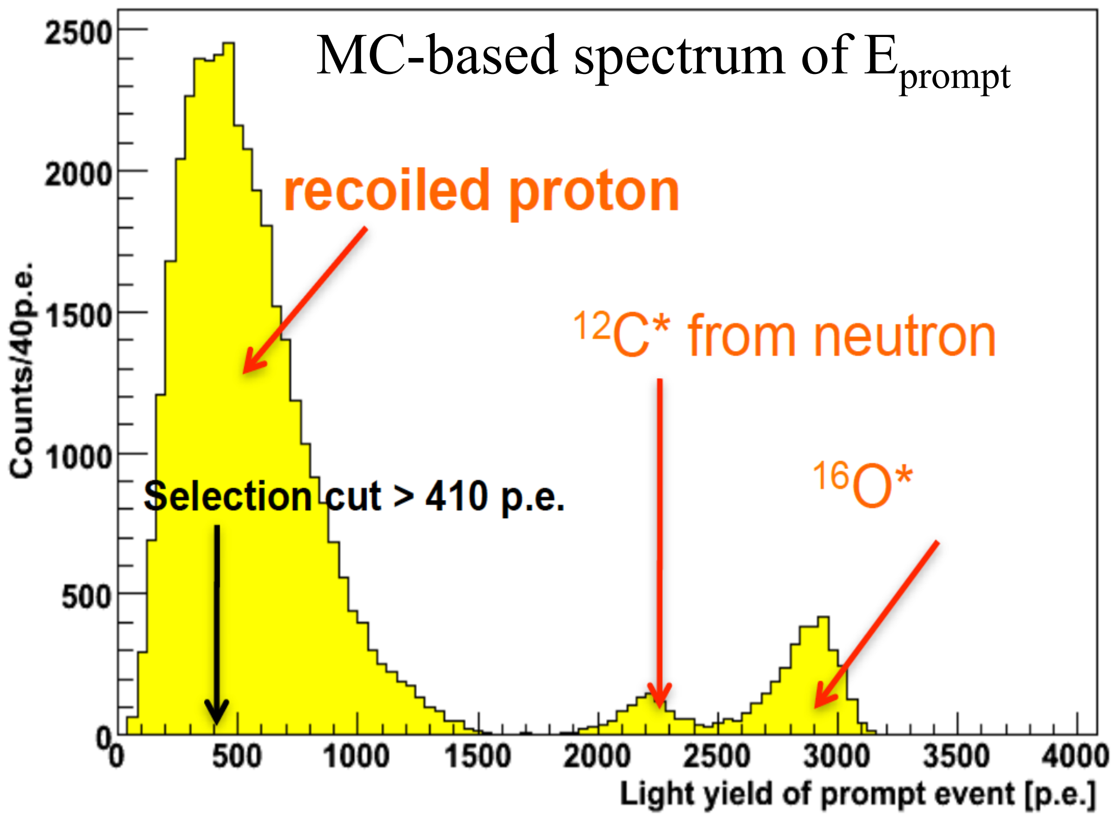
Pure α – β sample used for tuning of the pulse shape discrimination!

$\tau = 236\ \mu s$

$^{214}Bi \xrightarrow{\beta} {}^{214}Po \xrightarrow{\alpha} {}^{210}Pb$

3.2 MeV ~700 keV eq.

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



In the geoneutrino analysis we use:

- Monte Carlo based energy (charge) spectrum
- the rate constrained to the calculated value based on measured ^{210}Po contamination

Summary of non-antineutrino backgrounds in Borexino

Number of events among all 77 antineutrino candidates

^{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)	

Selection cuts

1. E_{prompt} > E_{prompt} @ **IBD threshold considering energy resolution: charge > 408 pe**

When geoneutrino has its minimal possible energy to trigger the IBD interaction (1.8 MeV),
the created positron has no kinetic energy.
Thus, the prompt signal has a visible energy of 2 annihilation gammas 2 x 511 keV = 1.022 MeV

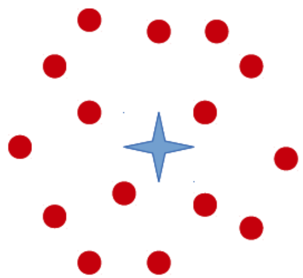
In Borexino: 1 MeV = 500 photoelectrons in the center of the detector

Statistical fluctuation: sqrt(500) = 22 photoelectrons

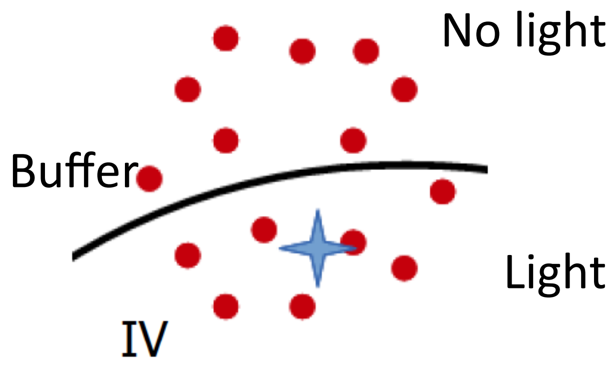
The lower energy limit on the prompt signal is 4-5 sigma below the central expected value

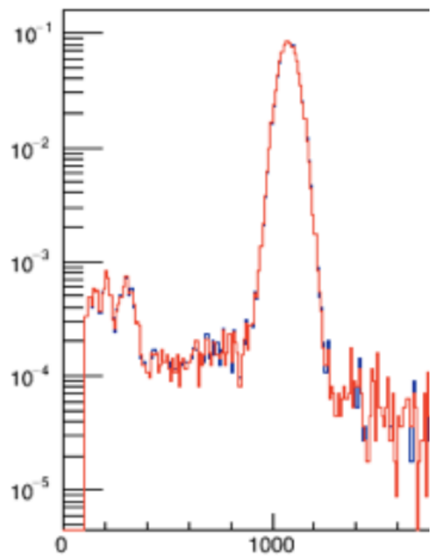
Selection cuts

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**



Compton electrons from gamma interaction

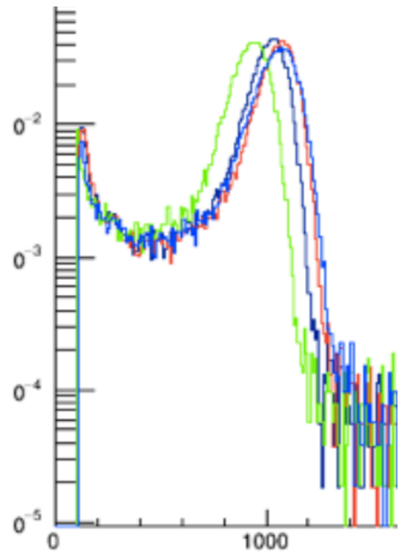




At the border of the detector →

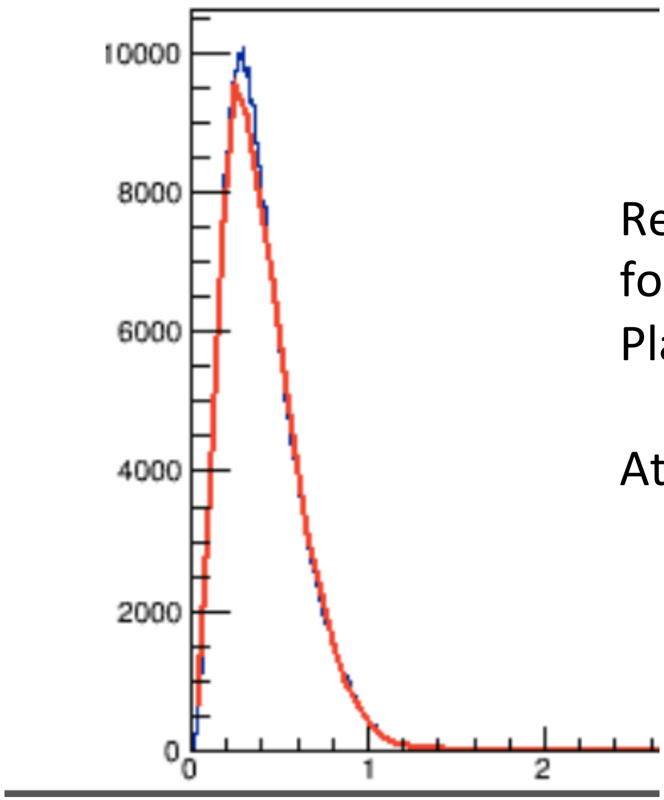
The 2.2 MeV peak is:

- shifted to lower energies
- has a low-energy tail



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**



Radius [m]

Reconstructed radius of the delayed signal, for the AmBe neutron calibration source Placed at the detector center

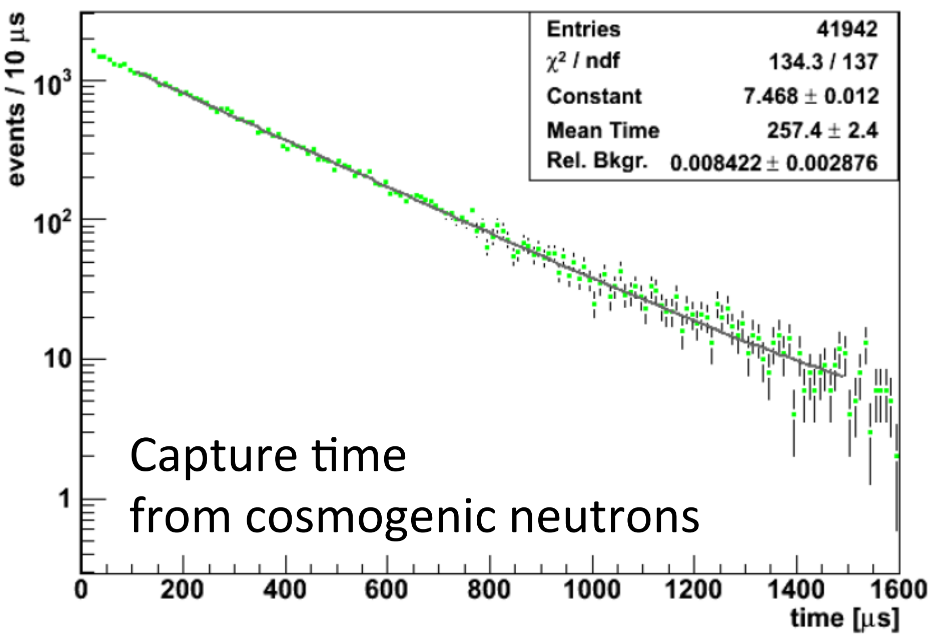
At the border slightly worsened

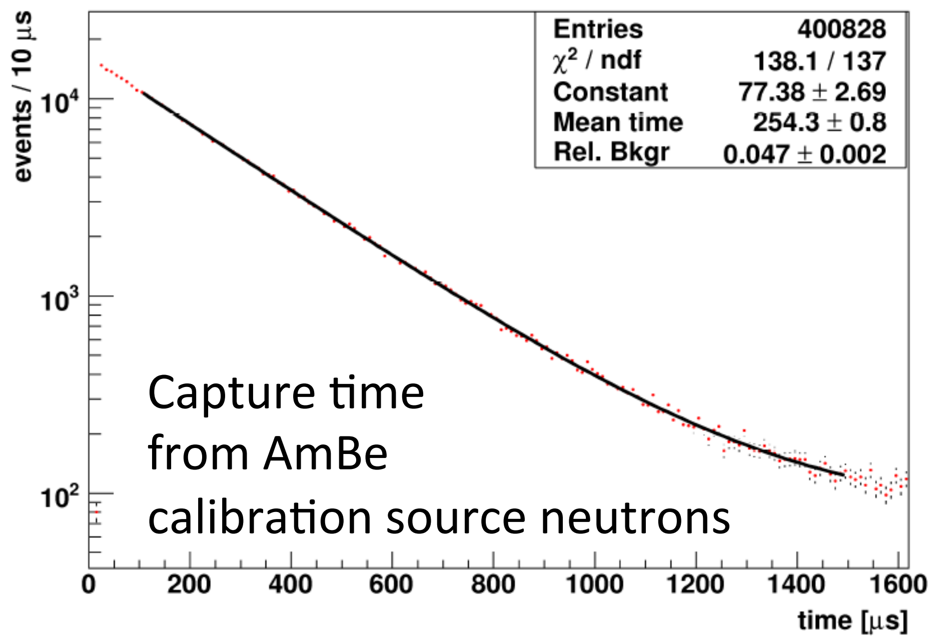
Selection cuts

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 between prompt and delayed :**

20 < Δt <1280 μs: 4.8 x neutron capture time

$$\tau = (257.4 \pm 2.4)\ \mu s$$





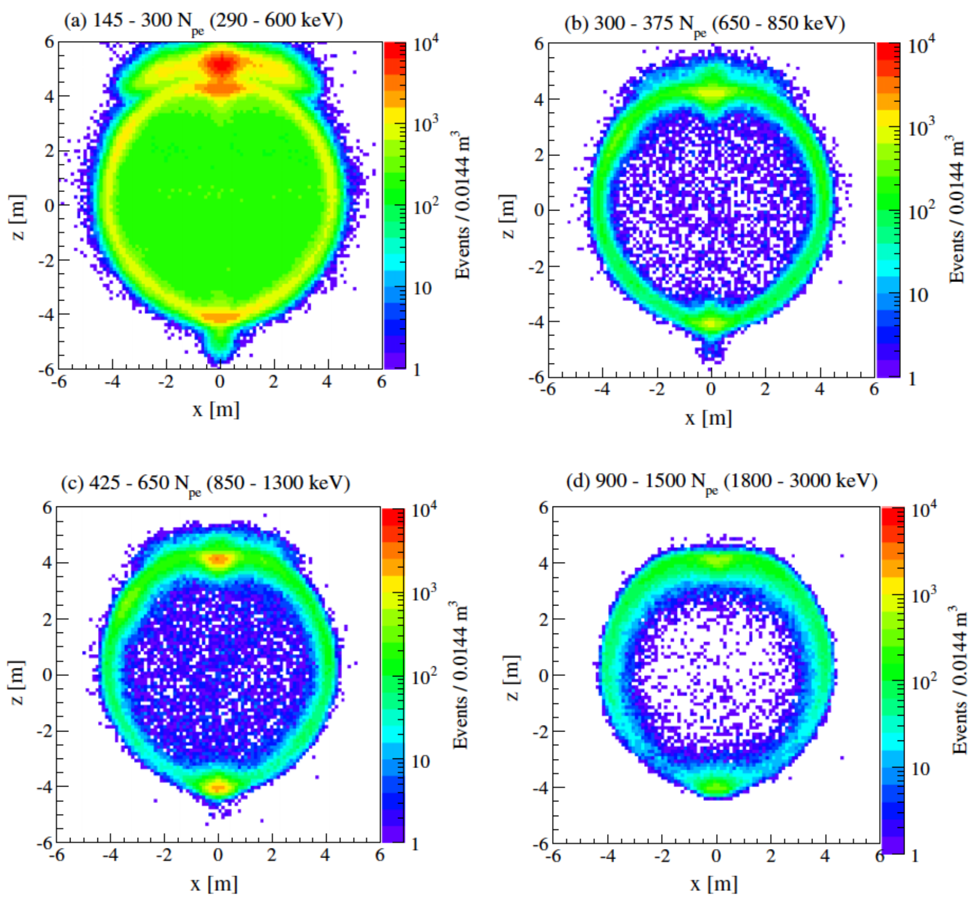
Selection cuts

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 veto:**
   - ✓ **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 (avoid non-detected muons with multiple neutrons)**

Selection cuts

6) Fidutial Volume cut:

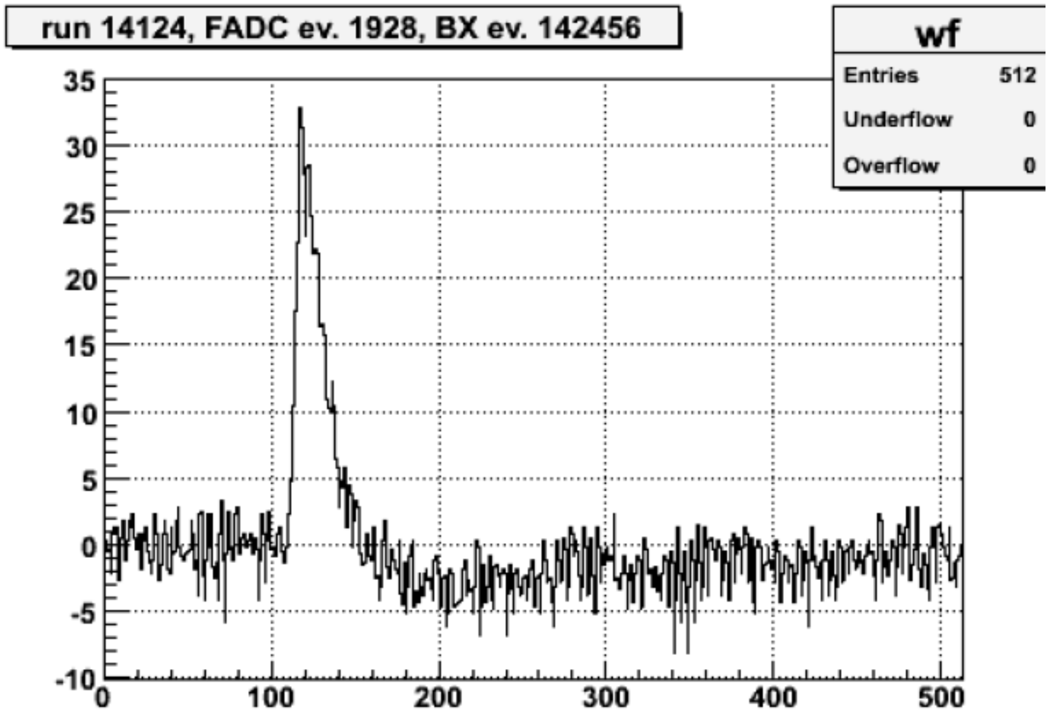
$R_{IV}(\Theta,\varphi) - R_{prompt}(\Theta,\varphi) > 0.30$ m : dynamical, follows Inner Vessel shape



- To avoid possible backgrounds originating in the vessel or in the buffer
- Our vessel (nylon balloon) holding the scintillator has a small leak, it is deformed and changes its shape in time
- We reconstruct the vessel shape based on the events from its radioactive contaminants based on 3 weeks of data

Selection cuts

7) FADC cut: **independent pulse shape check with 400 MHz digitizing system against noise events**



Summed signal from all PMTs

Example of a normal event

All candidates checked by eye and a specially developed noise filter based on a Fourier transform

Selection cuts

8) Pulse shape: require β-like signal for the delayed with $Gatti_{\alpha\beta} < 0.015$

To suppress ^{222}Rn-decay with 10^{-4} Branching Ratio

Prompt event: ^{214}Bi(β)
Delayed event: ^{214}Po(α + γ)

γ is less quenched than α
^{214}Po(α + γ) has higher visible energy than ^{214}Po(α)
can be still recognized as α−like with

Decay mode	Branching ratio [%]	Energy [keV]	Number of expected events (110k Bi-Po)
Alpha	99.99	E(alpha) = 7833.46	110k
Alpha + Gamma	1.04 x 10-4	E(alpha) = 7033.76 E(gamma) = 799.7	11
Alpha + Gamma	6.0 x 10-7	E(alpha) = 6735.76 E(gamma) = 1097.7	0.066

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 veto**
6. **FV cut:** $R_{IV}(\Theta,\varphi) - R_{prompt}(\Theta,\varphi) > 0.30$ m : dynamical, follows IV shape
7. **FADC cut:** independent pulse shape check with 400 MHz digitizing system
8. **Pulse shape delayed:** ^{222}Rn-decay (10^{-4} BR) ^{214}Bi(β)-^{214}Po(α+γ): $Gatti_{\alpha\beta}$ < 0.015

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

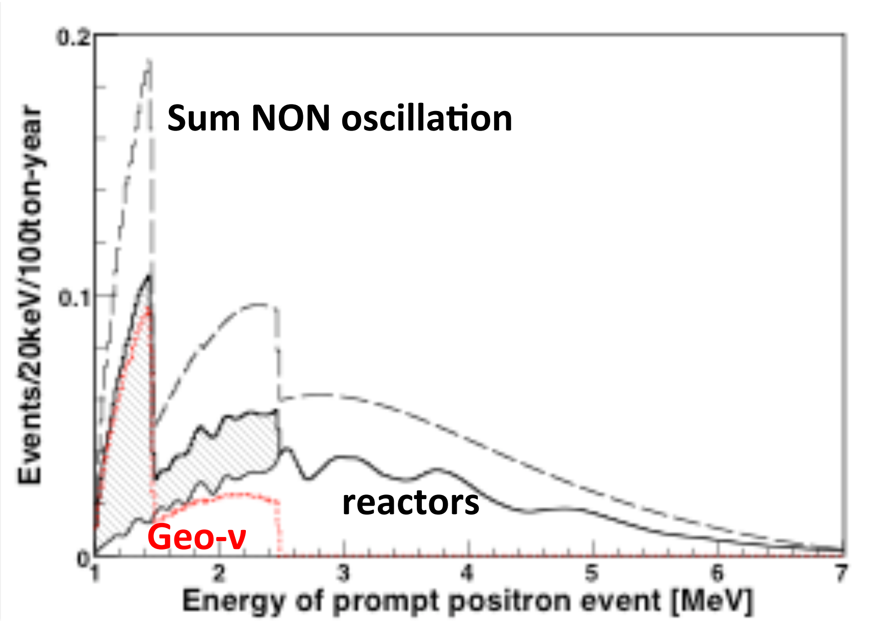
Spectral fit of E_{prompt}(photoelectrons, pe)

Unbinned maximal likelihood fit

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

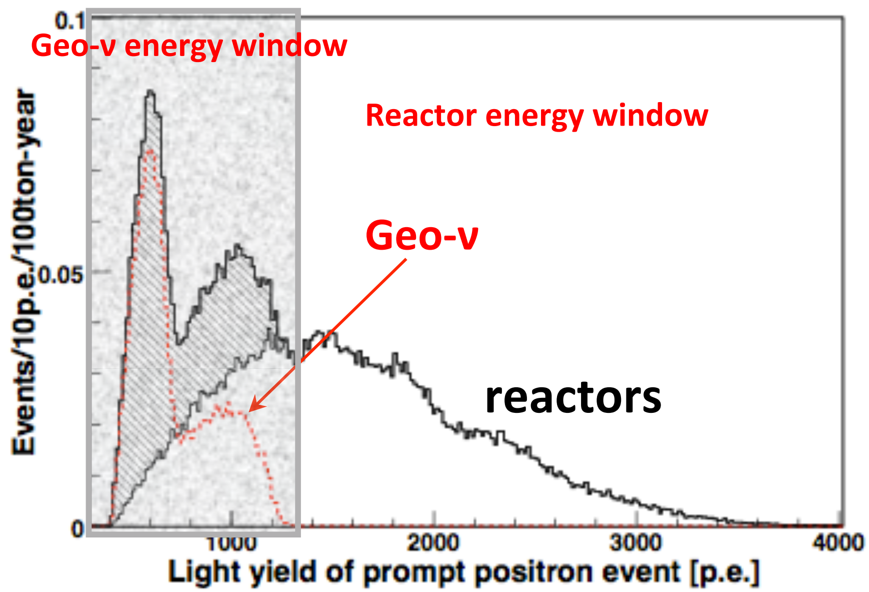
Shape of the expected spectra

Theoretical spectra: input to MC



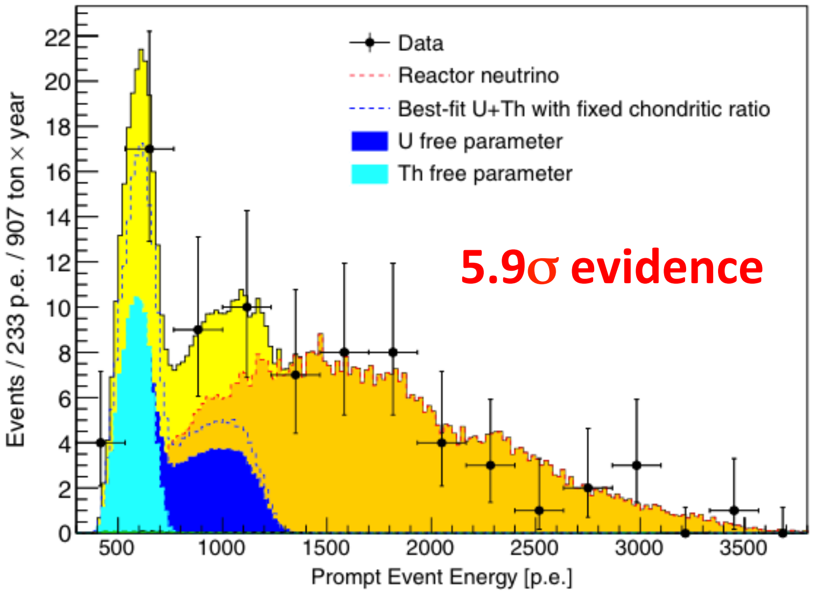
MC output:

includes detector response function



USED IN THE UNBINNED MAXIMUM LIKELIHOOD FIT OF THE DATA

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) $m(^{232}Th)/m(^{238}U) = 3.9$ (CI chondrites)

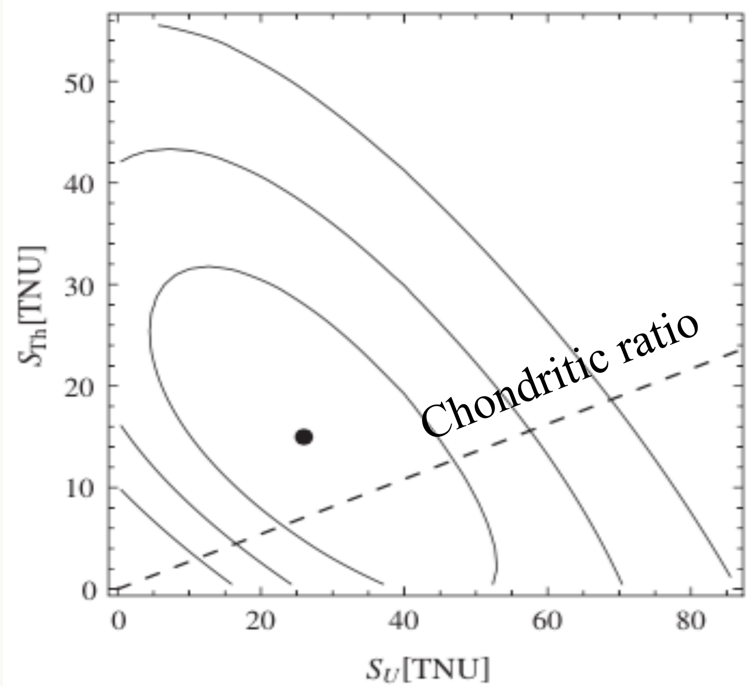
$S(^{232}Th)/S(^{238}U) = 0.27$

$S(^{238}U)/S(^{232}Th) = 3.7$

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

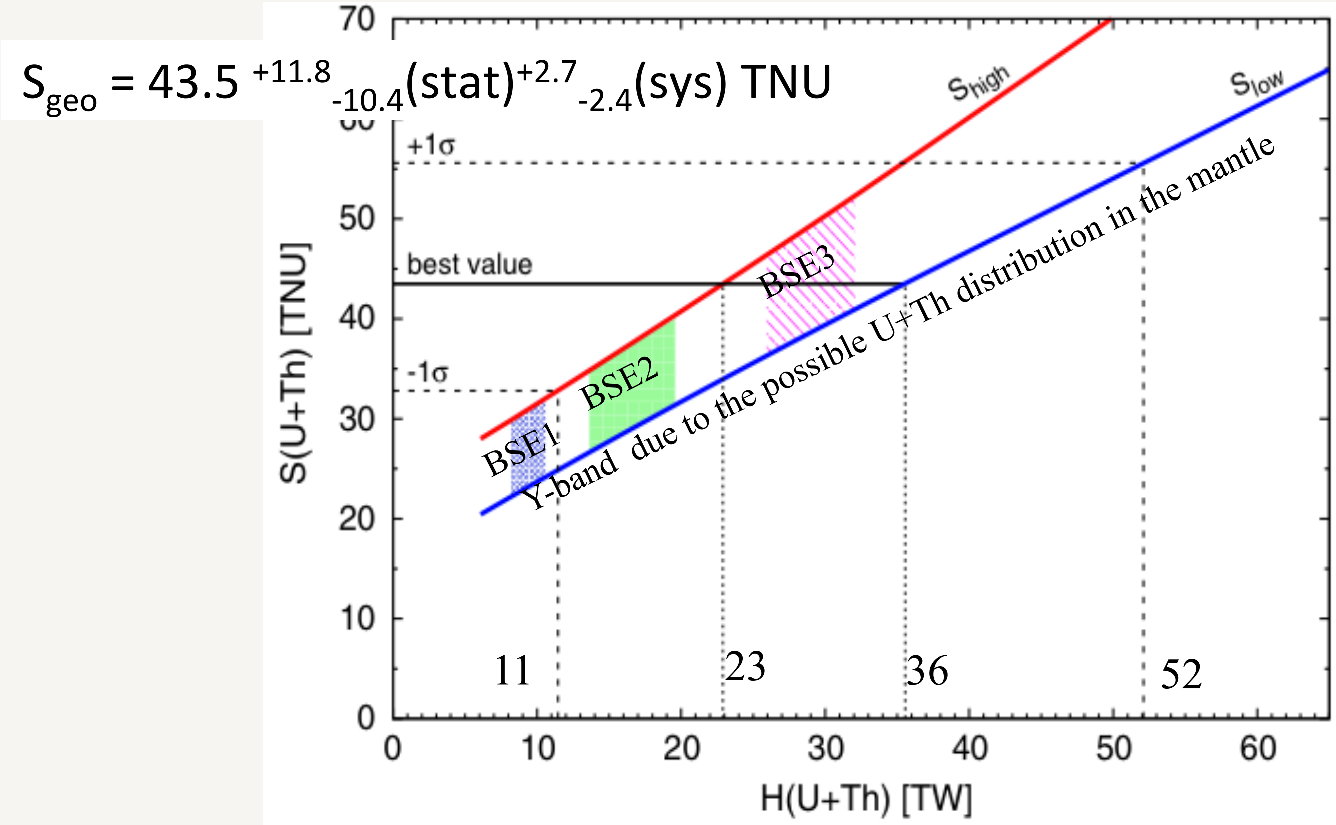
$S_{geo} = 43.5\ ^{+11.8}_{-10.4}(stat)^{+2.7}_{-2.4}(sys)$ TNU

2) U and Th free fit paramters



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)

Geological implications of the new Borexino results

Mantle signal

- $S_{Mantle} = S_{measured} - S_{crust}$
- $S_{measured} = 43.5\ ^{+11.8}_{-10.4}(stat)^{+2.7}_{-2.4}(sys)$ TNU
- Crustal signal at LNGS "known"

  ROC (Huang at al.) + LOC (Coltorti at al.)

  $S_{Crust} = (23.4 \pm 2.8)$ TNU
- Non-0 mantle signal at 98% CL

  $S_{mantle(Borexino)} = 20.1^{+15.1}_{-10.3}$ TNU

  (taking the central values: 23.7 events distributed as ~13 from the crust and 11 from the mantle)
- $S_{mantle\ (KamLAND)} = 5.0 \pm 7.3$ TNU

KamLAND analysis and results

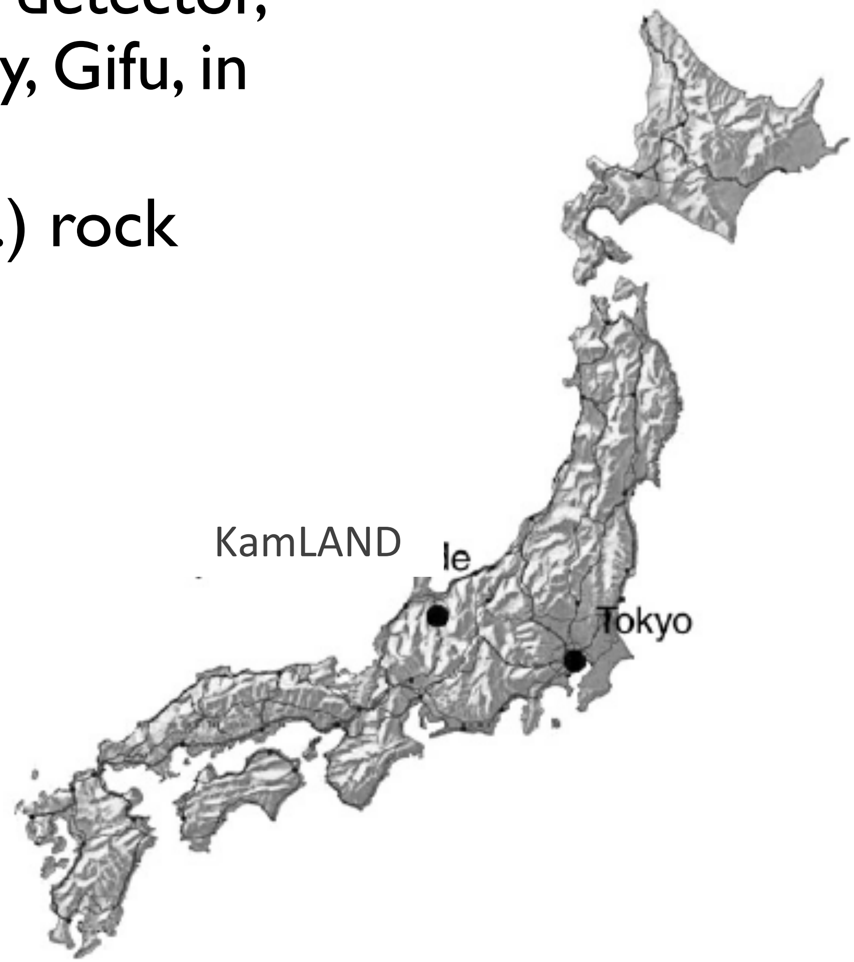
KamLAND

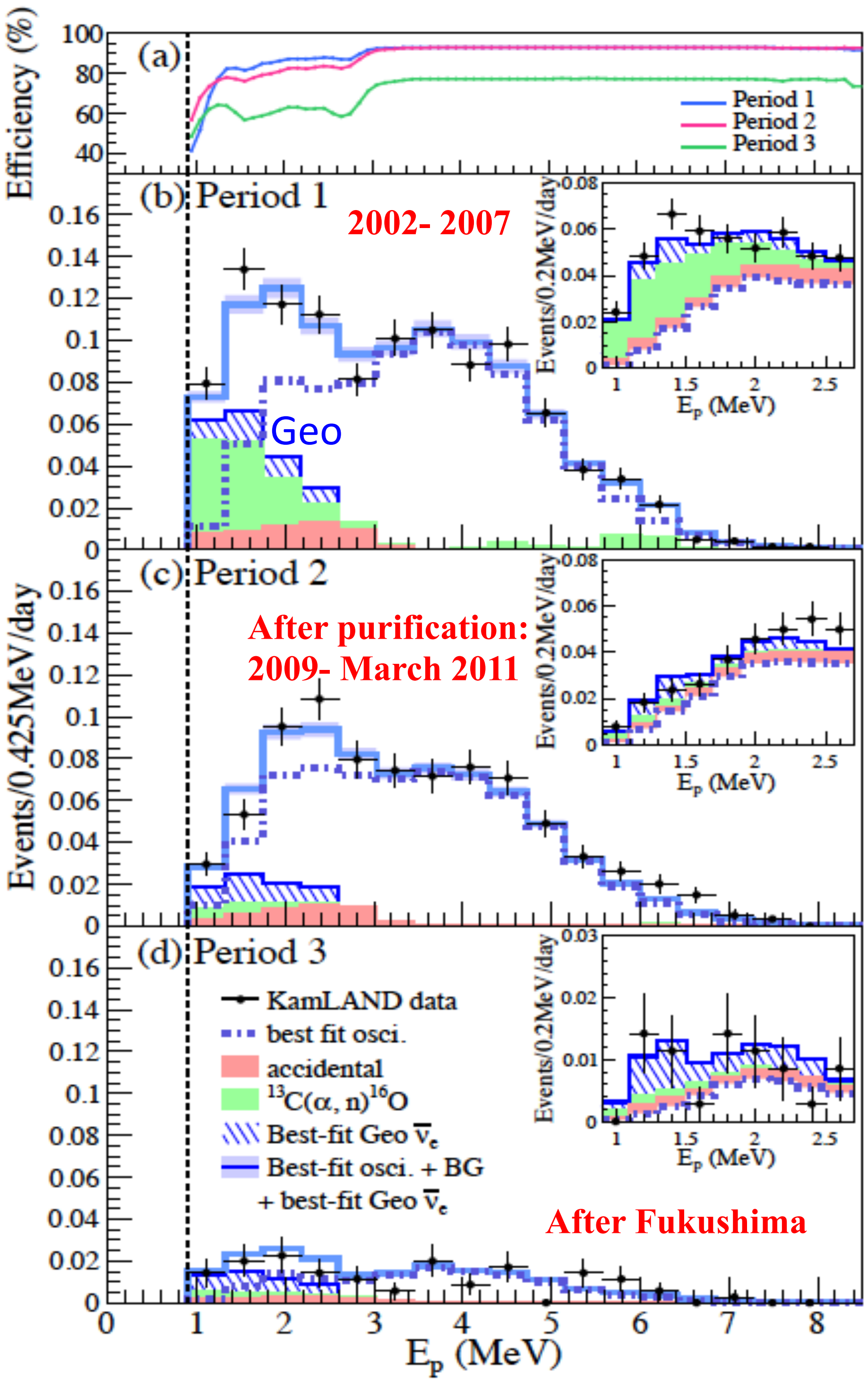
Kamioka Liquid Scintillator Antineutrino Detector

The world largest liquid scintillator detector, located in Kamioka mine, Hida-city, Gifu, in Japan,
under 1km (2.7 km-water-equiv.) rock overburden

DAQ started in 2002

130 people and about 35 institutes from Japan, the United States, Korea, China, Poland, Spain, Canada and UK.



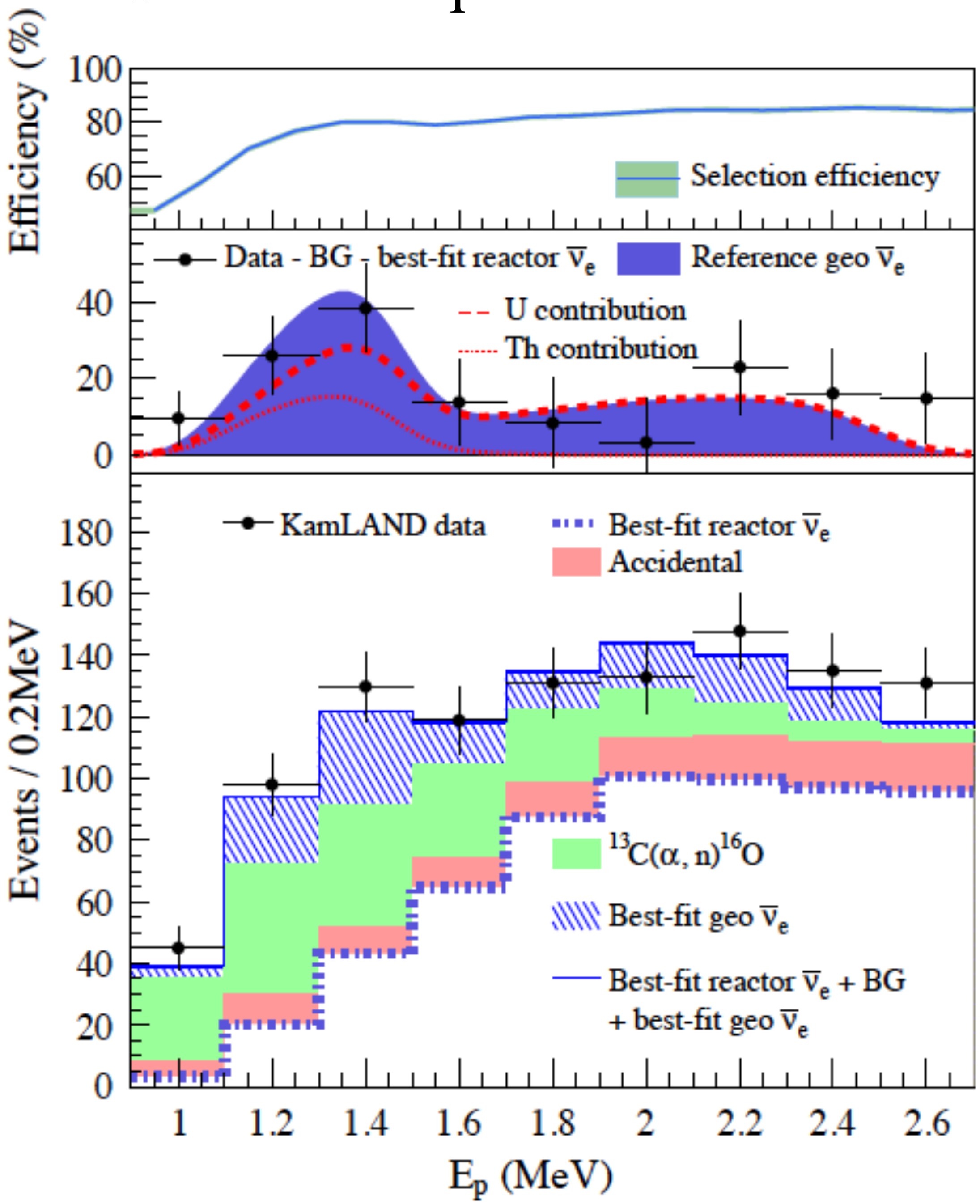


KamLAND-Phases

- ✓Period 1: 2002 – 2007
- ✓Period 2 (After a long purification campaign) 2009 – March 2011
- ✓Period 3 – After Fukushima when many of the nuclear reactors were switched off

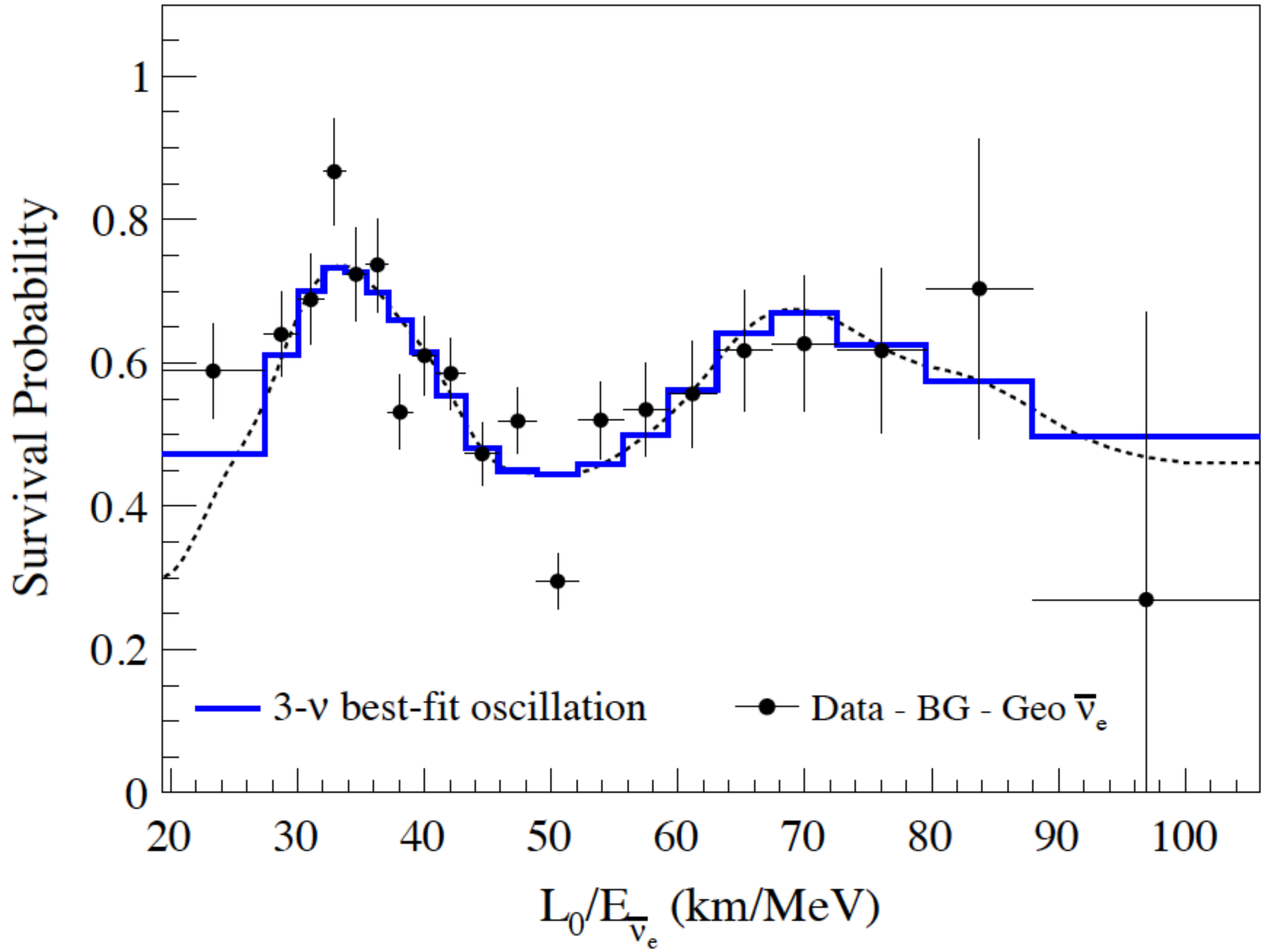
2013 results
PRD 88 (2013) 033001

Sum of all 3 periods 2002-2013



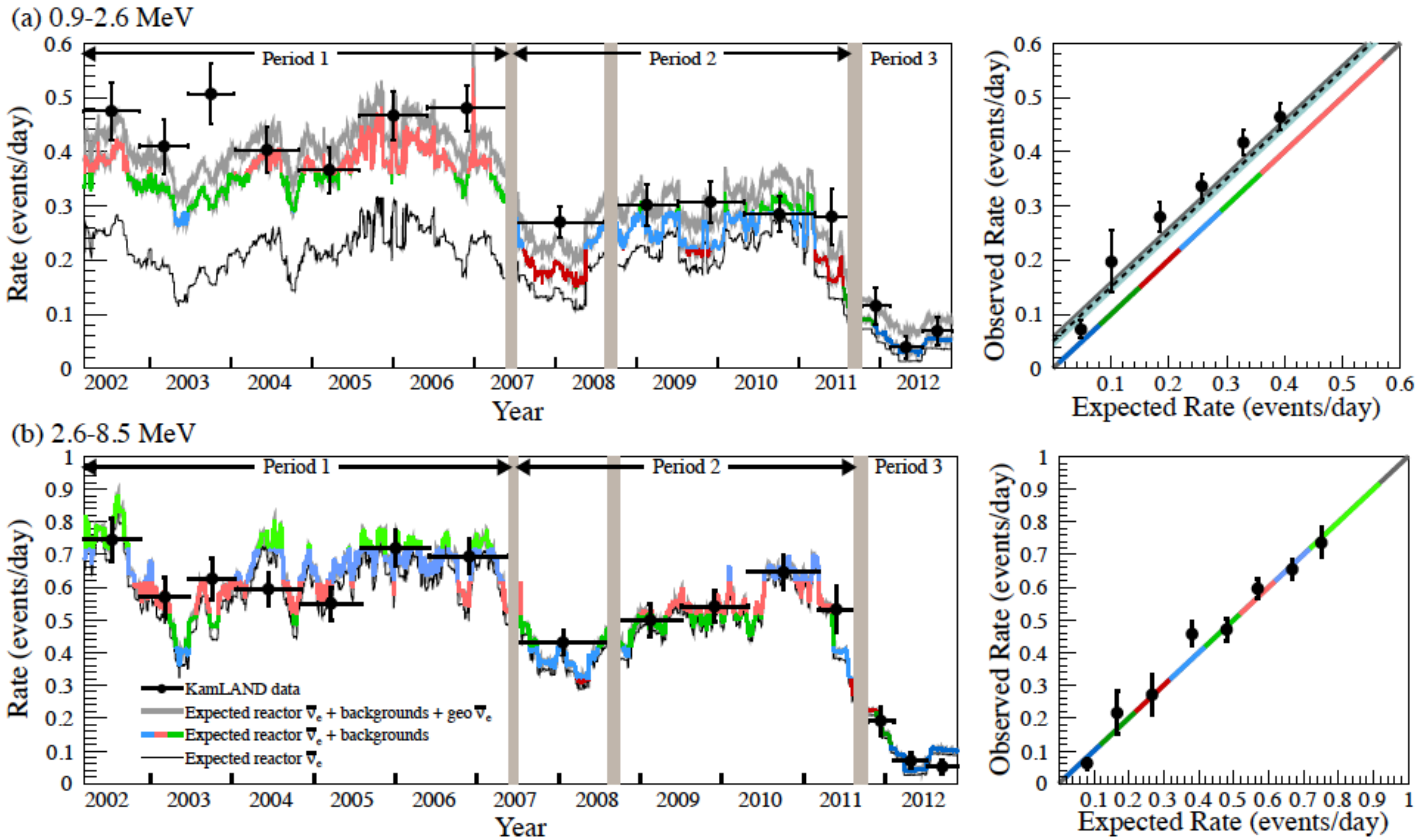
”Solar” sector: oscillation pattern f(L/E)

L = 180 km (power weighted average), E = 1.8 - ~10 MeV)



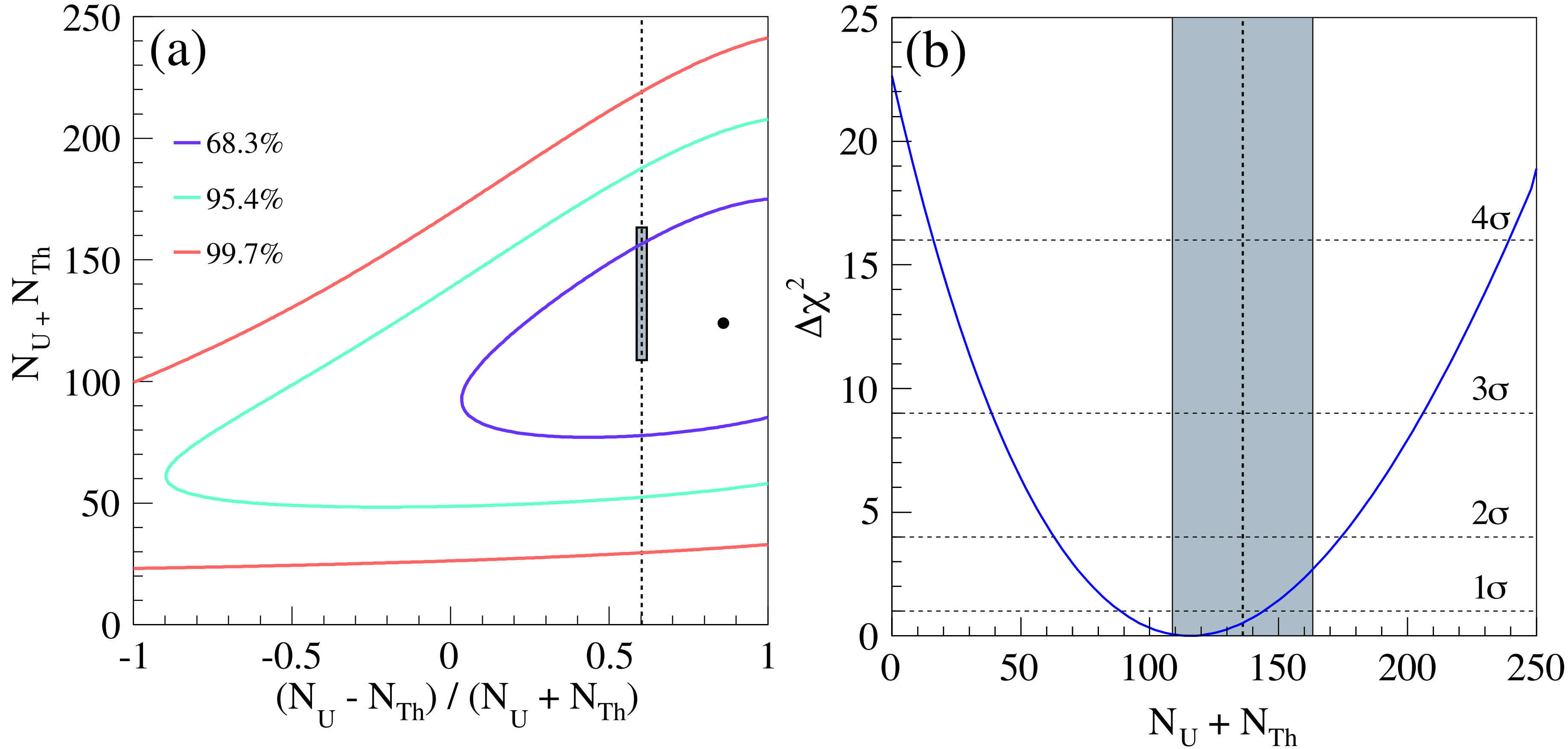
(2013)

Geoneutrinos: time-independent rate



▸Analysis - Rate+Shape+Time Analysis (2)

$N_U + N_{Th}$



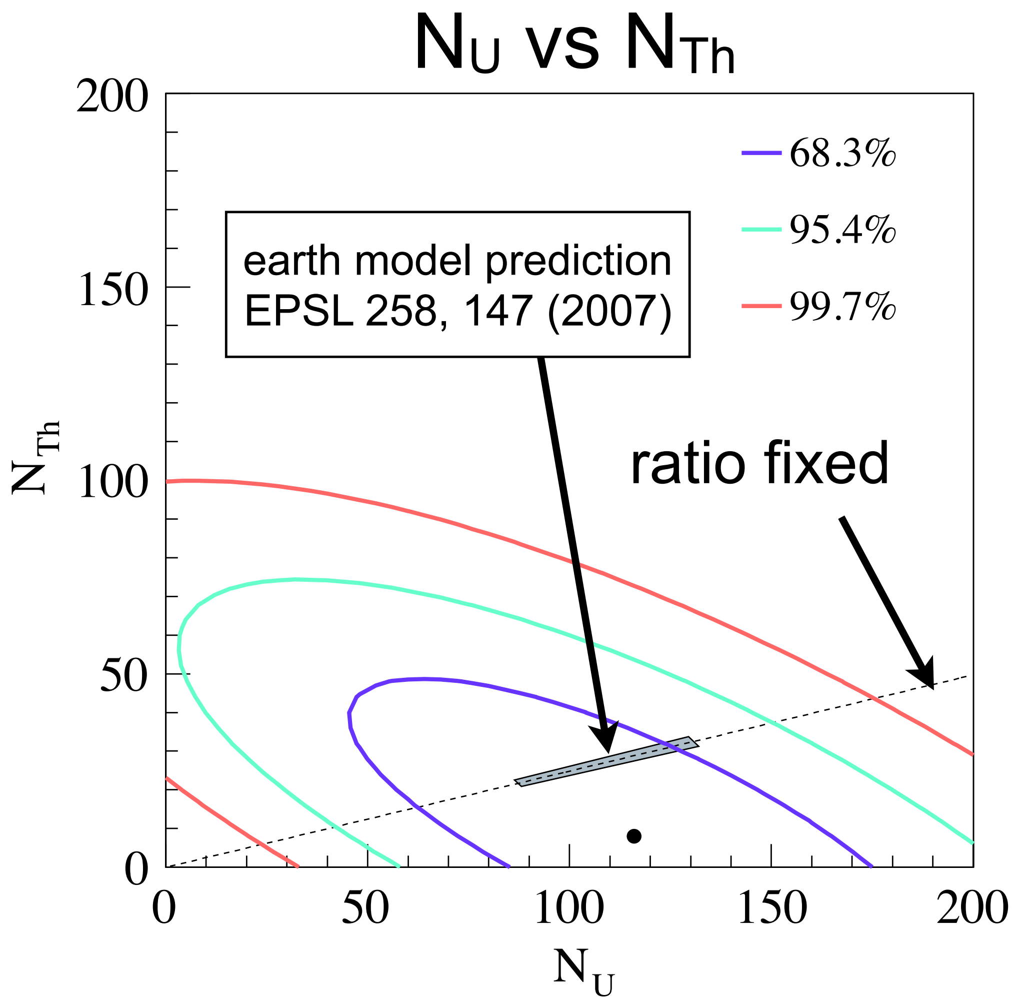
best-fit $N_U+N_{Th} = 116^{+28}_{-27}$

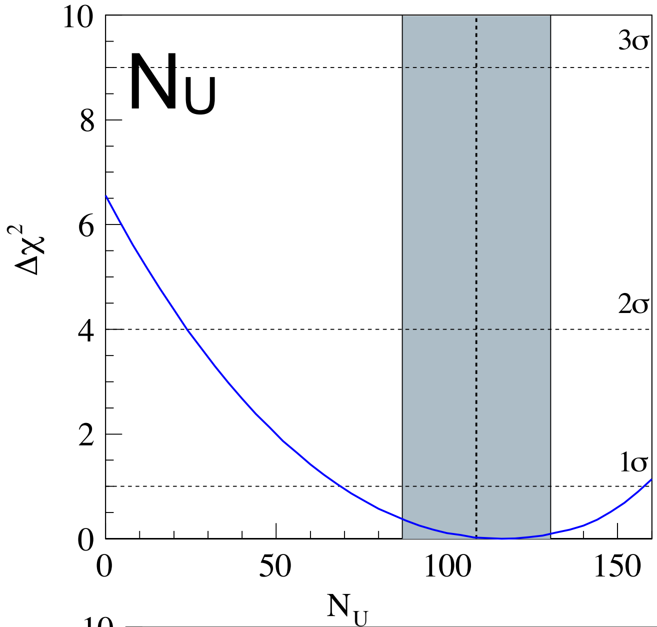
Flux : $3.4^{+0.8}_{-0.8} \times 10^6$ $cm^{-2}s^{-1}$

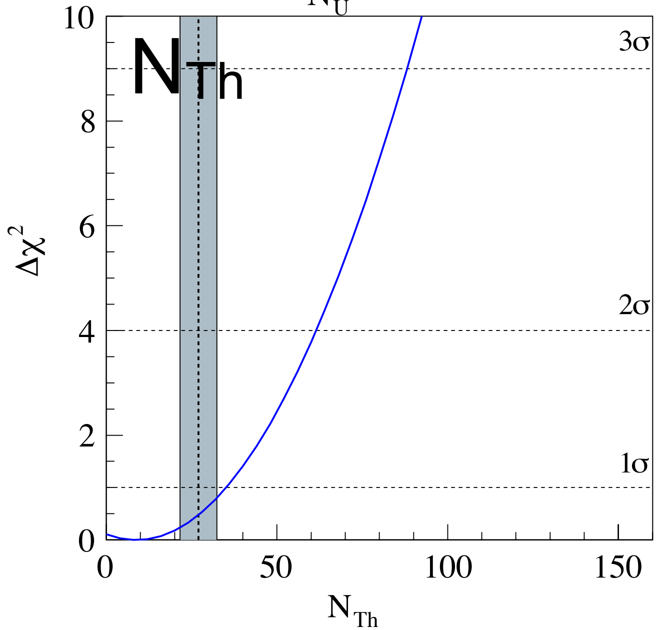
0 signal rejected at 99.9998% C.L. (2×10^{-6})

From KamLAND talk of H. Watanabe @ Neutrino Geoscience 2013

Analysis - Rate+Shape+Time Analysis (1)







best-fit (N_U, N_{Th}) = (116,8)

N_U 0 signal : rejected at 2.6σ (99.0%)

From KamLAND talk of H. Watanabe @ Neutrino Geoscience 2013

PRD 88 (2013) 033001

Latest KamLAND geoneutrino results