Geoneutrinos and Borexino

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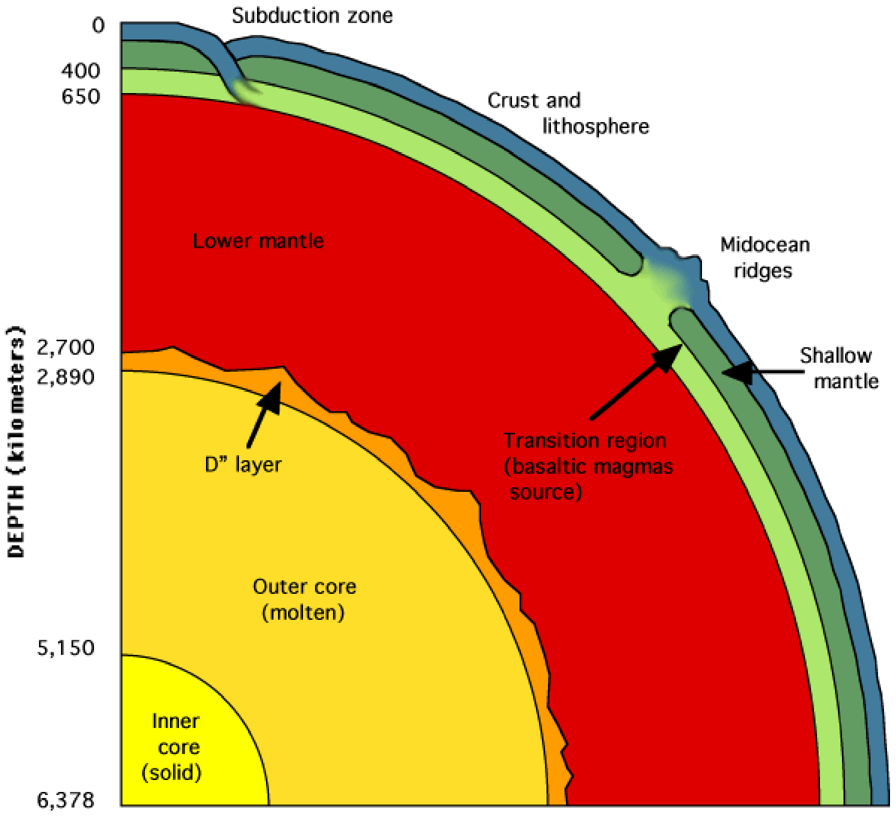
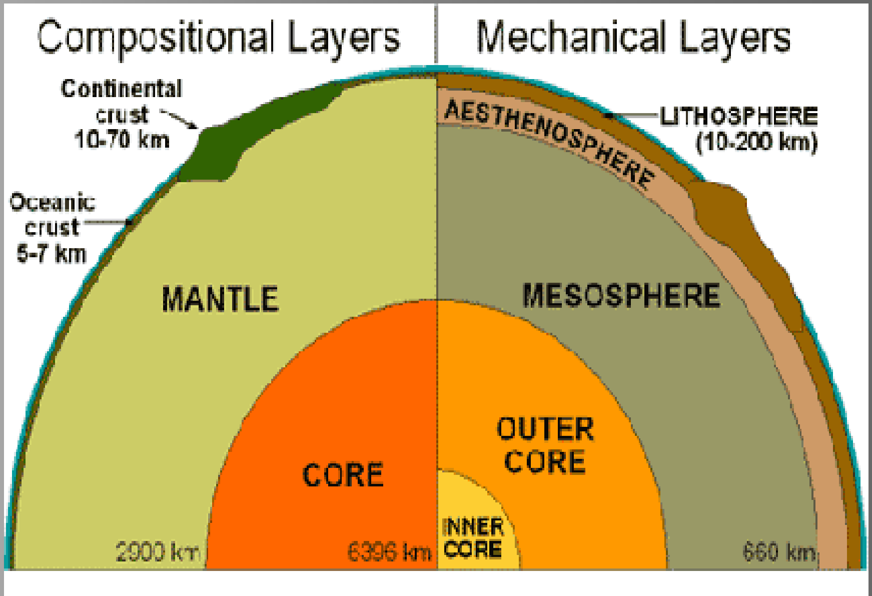
for Borexino collaboration

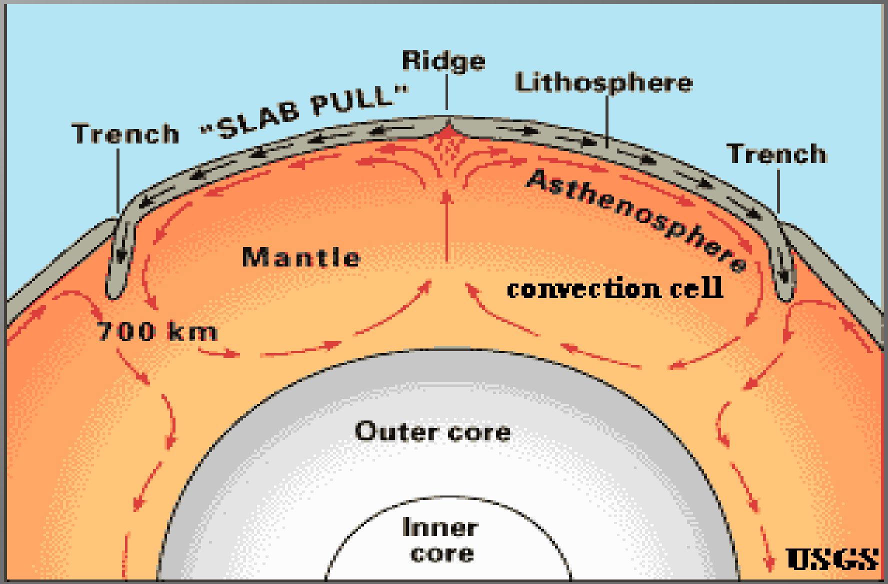
Outline

- **The Earth**
  - structure and composition ;
  - sources of knowledge (geophysics, geology, and geochemistry);
- **Geoneutrinos:**
  - what are they and to what questions they can answer;
- **Borexino:**
  - experimental techniques and the detector;
- **Antineutrino detection in Borexino:**
  - the background sources and reactor antineutrinos;
  - the geoneutrino signal;
- **Geoneutrino flux measurement:**
  - the results;
  - implications and perspectives in Borexino and in the world;

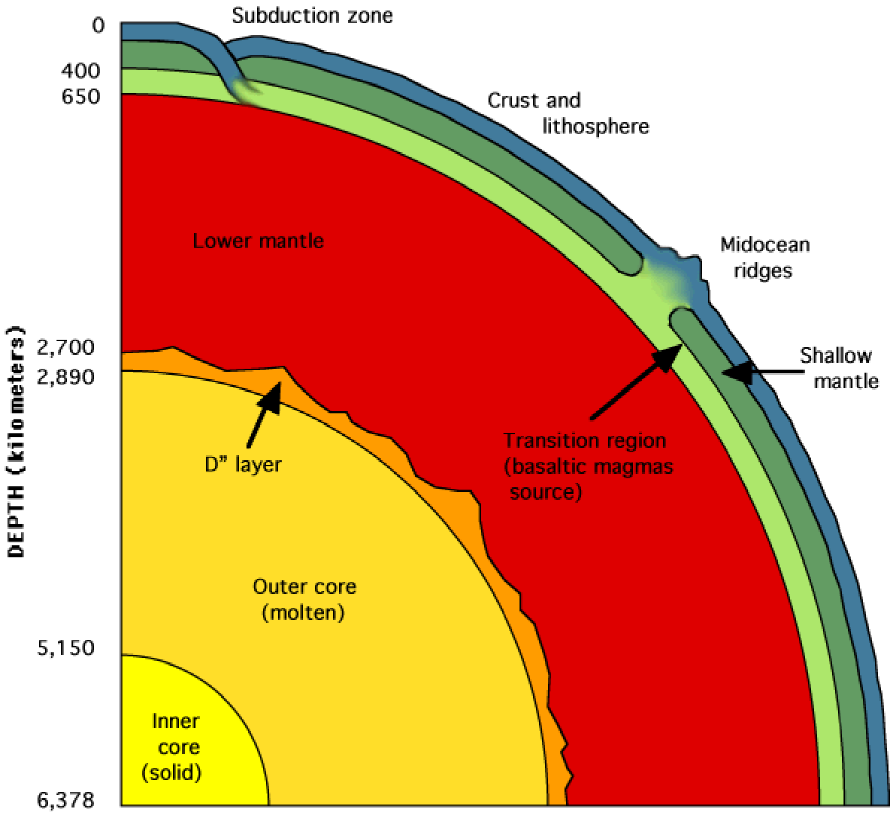
Earth structure







Earth structure



Inner Core - SOLID

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

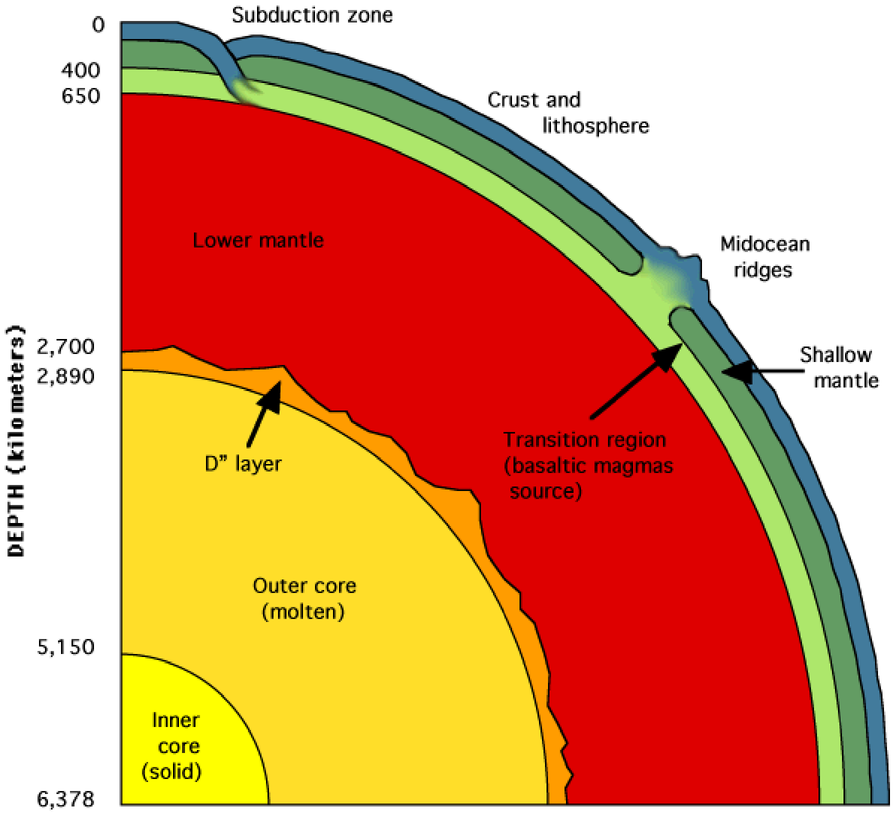
Outer Core - LIQUID

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

D” layer: mantle –core transition

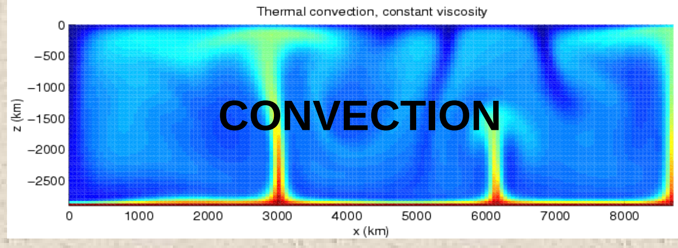
- ~200 km thick;
- seismic discontinuity;
- unclear origin;

Earth structure



Lower mantle (mesosphere)

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

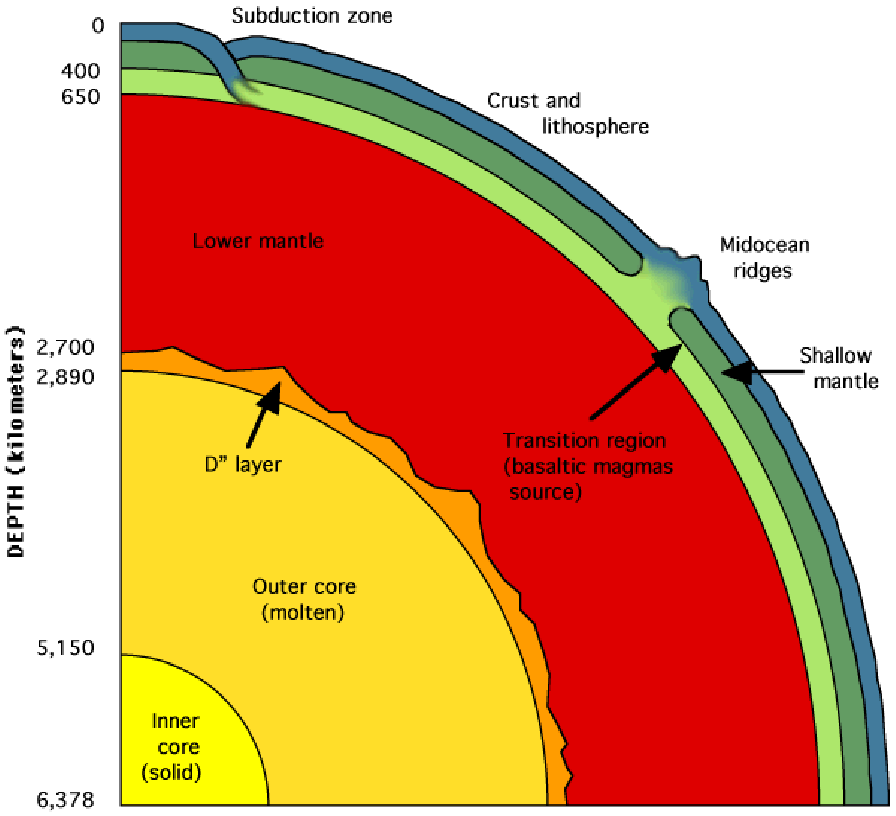


Transition zone (400 -650 km)

seismic discontinuity;

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

Earth structure



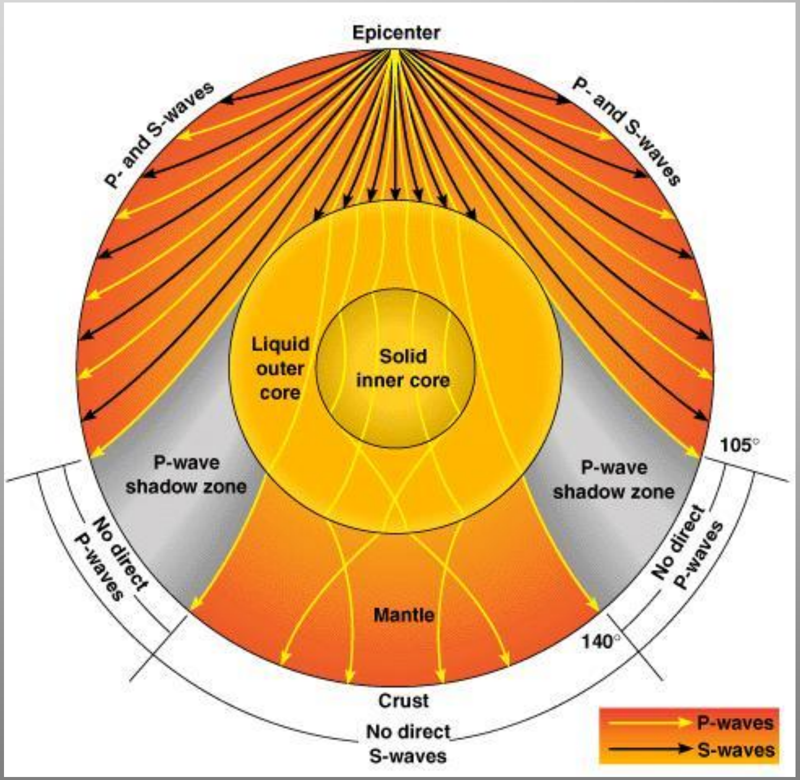
Upper mantle

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

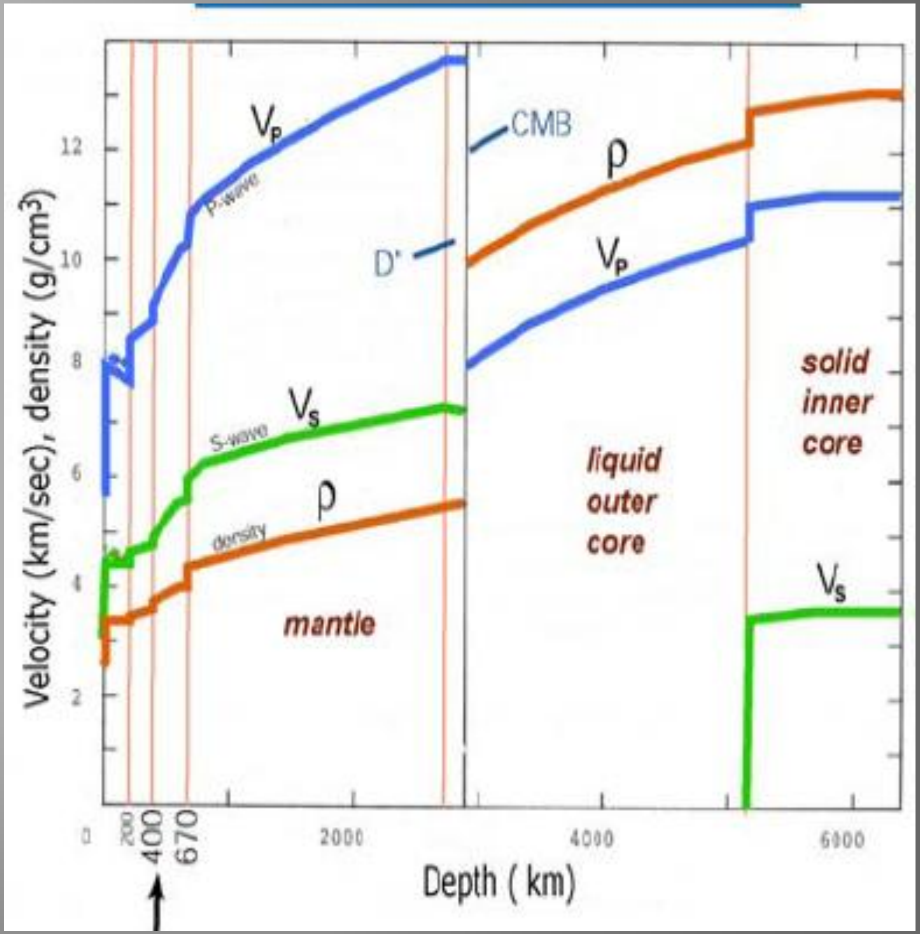
Crust: the uppermost part

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

Seismology



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



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

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 + chondritic meteorites + Sun;

Bulk Silicate Earth (BSE) models:

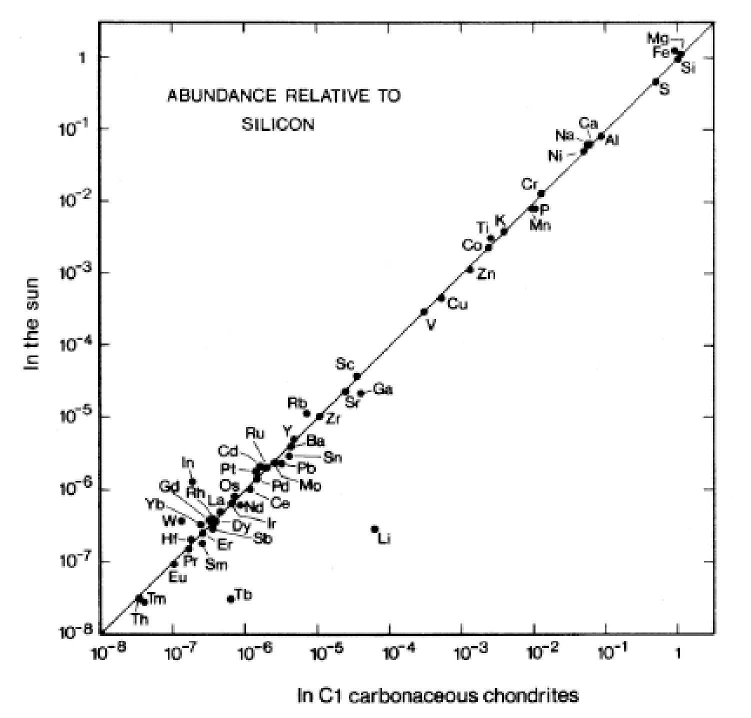
medium composition

of the "re-mixed" crust + mantle,

i.e., primordial mantle before the crust differentiation and after the Fe-Ni core separation;

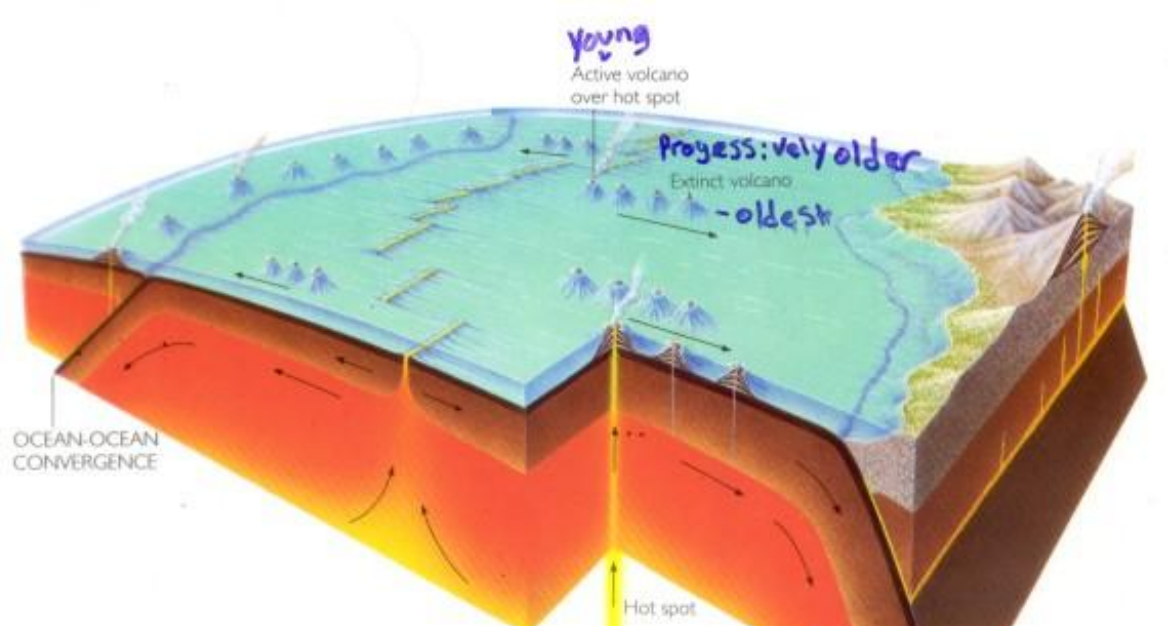
(original: McDonough & Sun 1995)

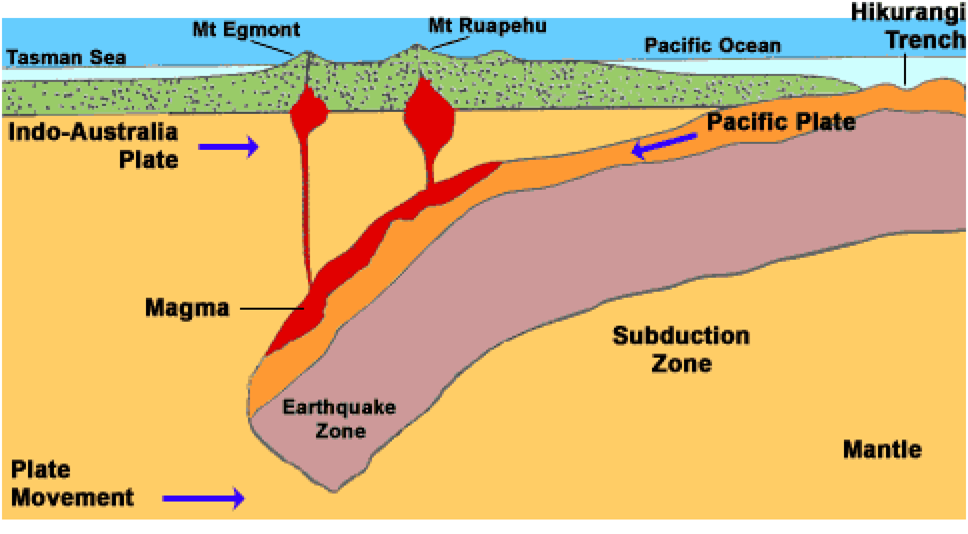
- absolute BSE abundances varies within 10% based on the model;
- ratios of BSE element abundances more stable in different calculations:
  - Th/U = 3.9
  - K/U = 1.14 x 10^4



Types of vulcanism:

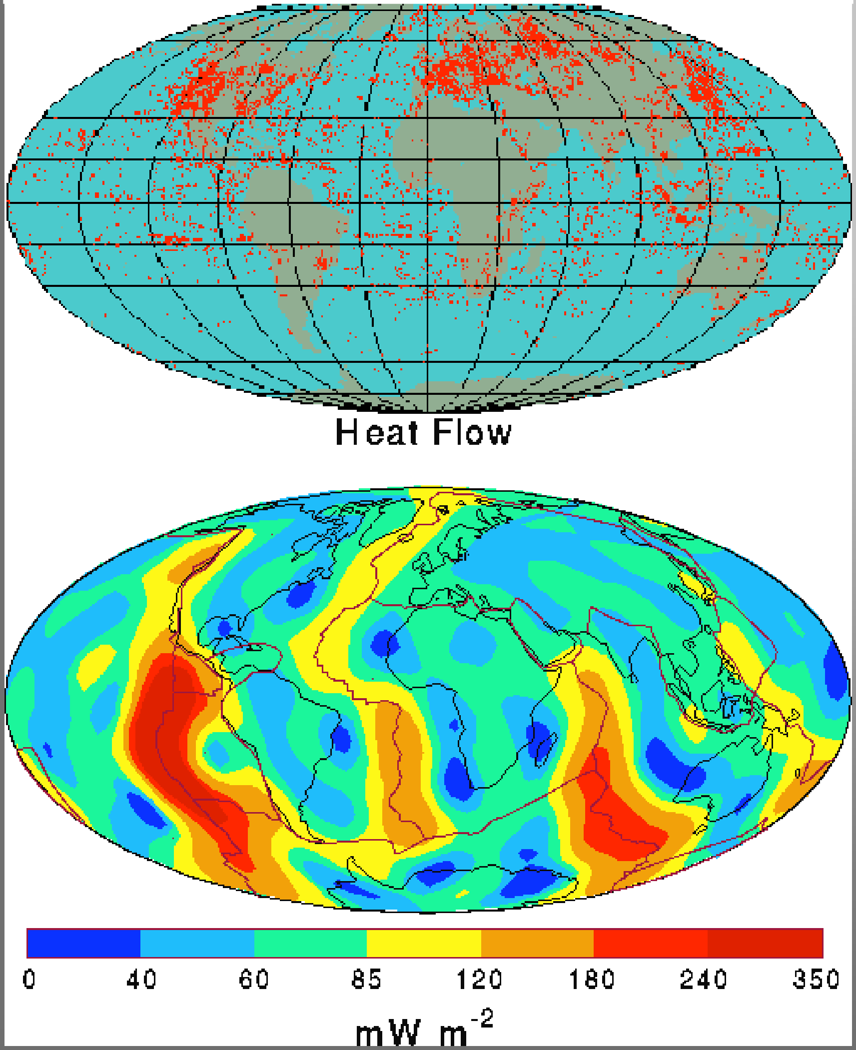
mid-ocean ridges
subduction zones (Ands)
island arcs (Japan)
hot spots (Hawaii, Iceland, Yellowstone)





Earth heat flow

Bore-hole measurements



- Conductive heat flow from bore-hole temperature gradient;

- **Total heat flow :**

  31+1 TW or **44+1 TW**

  (same data, different analysis)

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

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

Sources of the Earth heat

- Total heat flow ("measured"): 31±1 or 44±1 TW
- Radiogenic heat flow (BSE composition) cca. 19 TW

  the main long-lived radioactive elements within the Earth:

  ^{238}U, ^{232}Th, and ^{40}K

  9 TW crust (mainly continental), 10 TW mantle, 0 TW core;
- Other heat sources (possible deficit of 44-19 = 25 TW!)
  - Residual heat: gravitational contraction and extraterrestrial impacts in the past;
  - ^{40}K in the core;
  - nuclear reactor; (BOREXINO rejects a power > 3 TW at 95% C.L.)
  - mantle differentiation and recrystallisation;

IMPORTANT MARGINS

FOR ALL DIFFERENT MODELS OF THE EARTH STRUCTUE

Geoneutrinos: antineutrinos from the Earth

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

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

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

- absolute BSE abundances varies within 10% based on the model;
- ratios of BSE element abundances more stable in different calculations:
  - **Th/U = 3.9**
  - K/U = 1.14 x 10^4

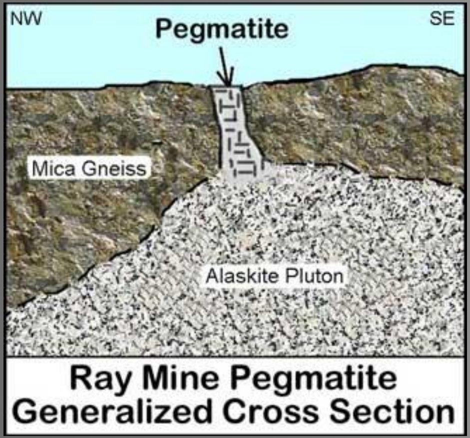
concentration for ^{238}U (Mantovani *et al*. 2004)

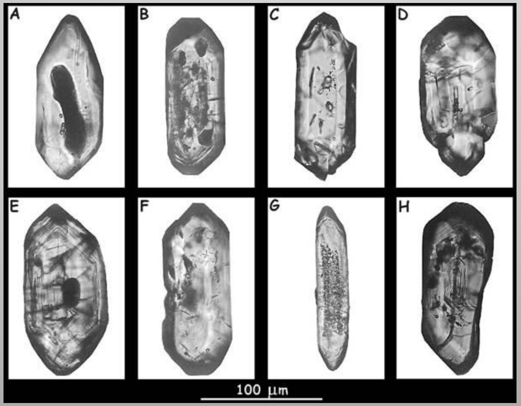
upper continental crust: 2.5 ppm
middle continental crust: 1.6 ppm
lower continental crust: 0.63 ppm
oceanic crust: 0.1 ppm
upper mantle: 6.5 ppb
core NOTHING

BSE (primordial mantle) 20 ppb

Where is concentrated U and Th?

refractory lithophile elements – accumulation in the melt (pegmatites, monazite)





accessories minerals in igneous rocks (zircon)

Uraninit (oxides of U) + secondary minerals phosphates, lignit (brown coal)

Heavy grains: accumulation in sandstones;

U: can be dissolved in water!!!! Mobility!!!

Geoneutrinos: antineutrinos from the Earth

- ^{238}U, ^{232}Th, ^{40}K chains (T$_{1/2}$ = (4.47, 14.0, 1.28) x 10^{9} years, resp.):

  ^{238}U → ^{206}Pb + 8 α + 8 e^- + 6 anti-neutrinos + 51.7 MeV

  ^{232}Th → ^{208}Pb + 6 α + 4 e^- + 4 anti-neutrinos + 42.8 MeV

  ^{40}K → ^{40}Ca + e^- + 1 anti-neutrino + 1.32 MeV

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

leaving freely and instantaneously the Earth interior

(to compare: solar neutrino flux ~ 10^{10} cm^{-2} s^{-1})

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

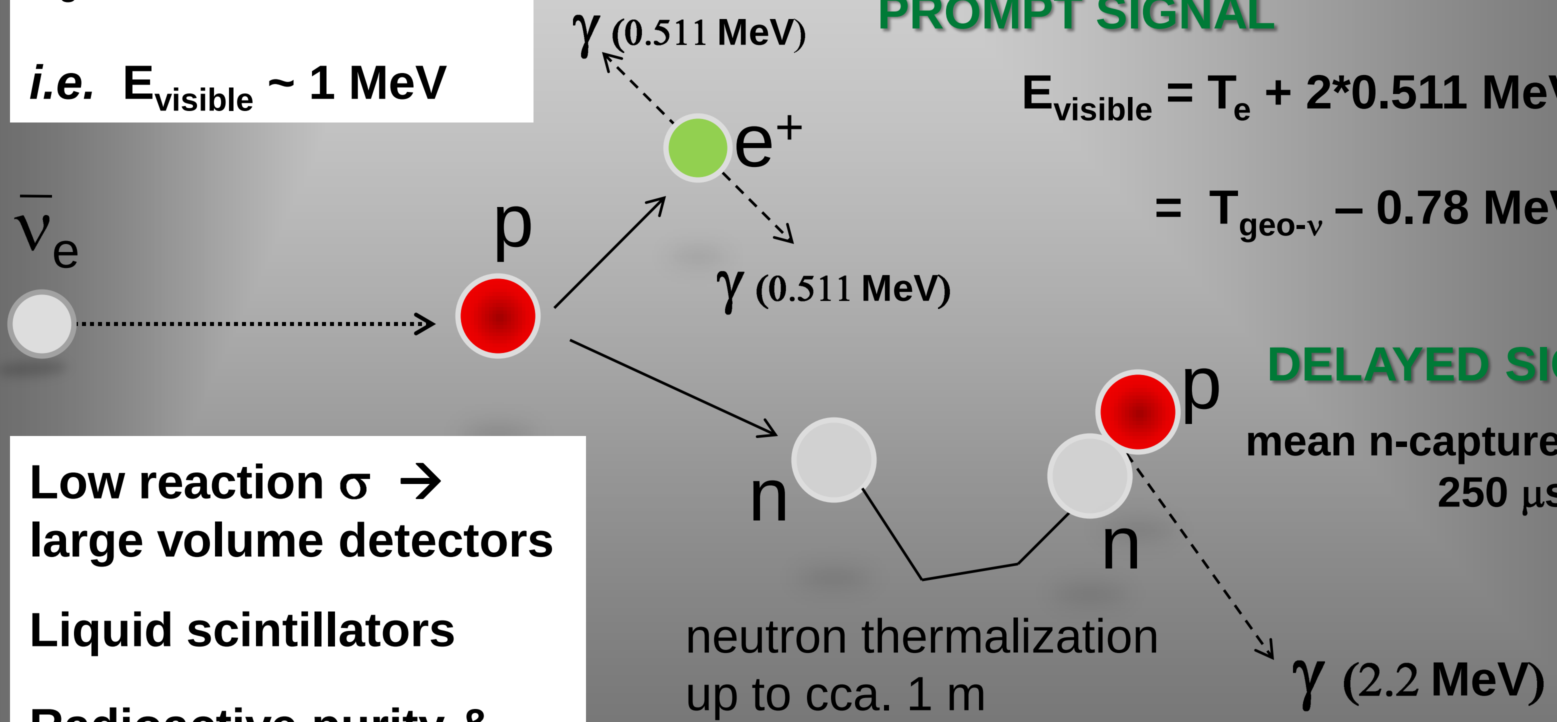
- **Possible answers to the questions:**
  - What is the radiogenic contribution to the terrestrial heat??
  - What is the distribution of the radiogenic elements within the Earth?
    - how much in the crust and mantle
    - core composition: Ni+Fe and ^{40}K?? geo-reactor ? (Herndon 2001)
  - Is the BSE model compatible with geoneutrino data?

Detecting geo-ν: inverse β-decay

Energy threshold of

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

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



PROMPT SIGNAL

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

$$= T_{geo\text{-}\nu} - 0.78\ \text{MeV}$$

DELAYED SIGNAL

mean n-capture time on p
250 μs

neutron thermalization
up to cca. 1 m

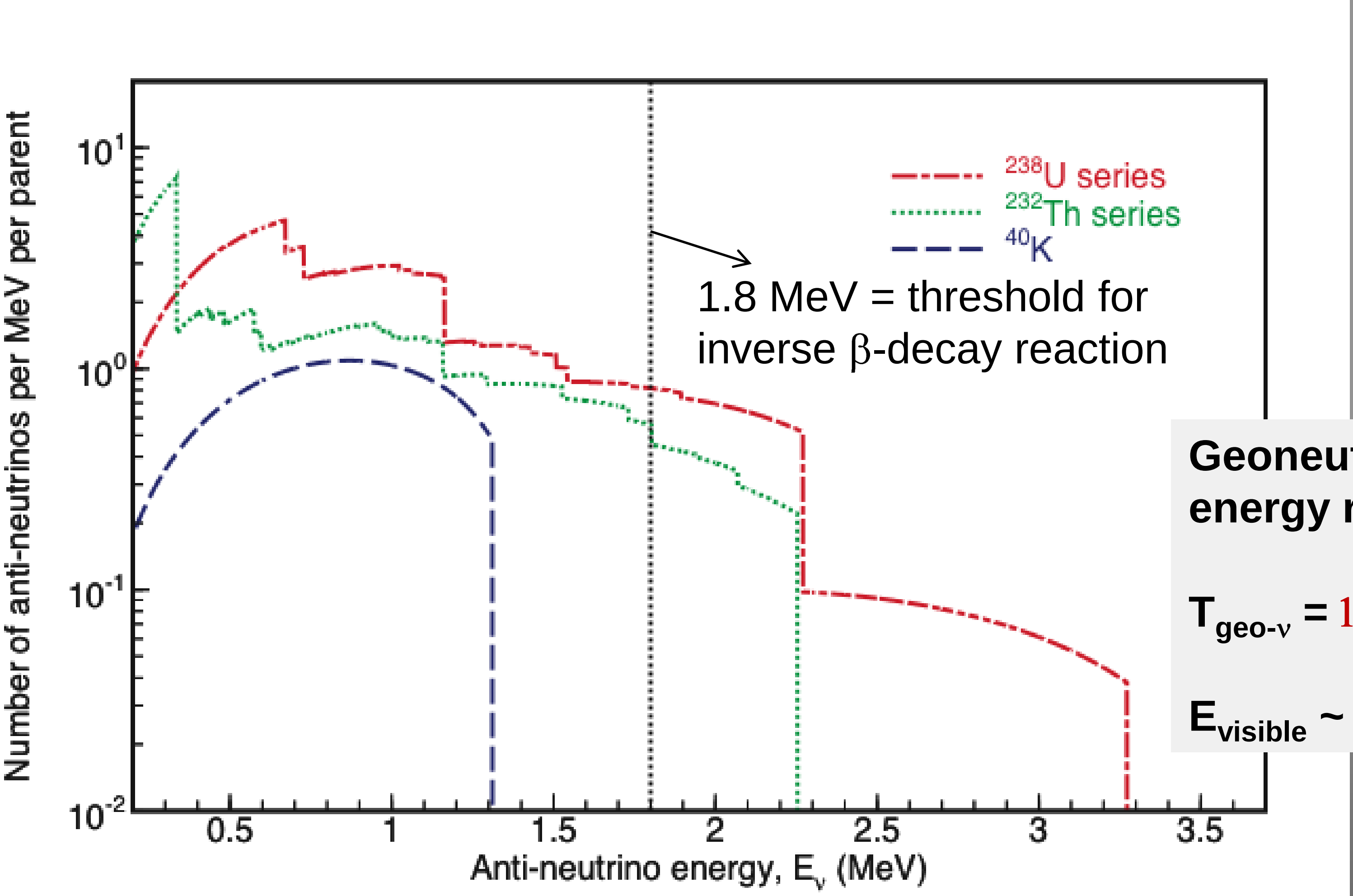
Low reaction σ → large volume detectors

Liquid scintillators

Radioactive purity & underground labs

Geoneutrinos energy spectra

(theoretical calculations)



1.8 MeV = threshold for inverse β-decay reaction

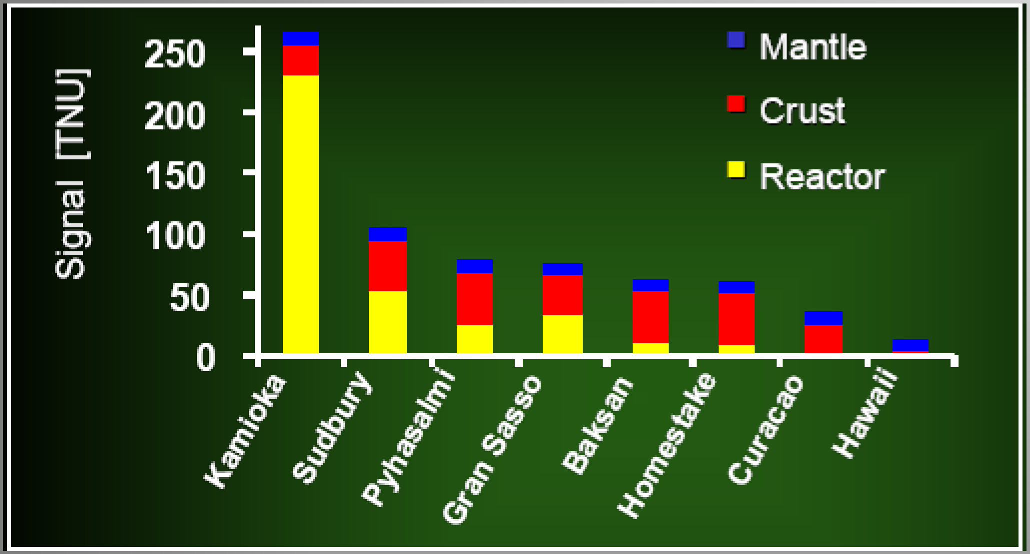
Geoneutrinos energy range

$T_{geo\text{-}\nu}$ = 1.8 – 3.3 MeV

$E_{visible}$ ~ 1 – 2.5 MeV

Running and planned experiments

having geoneutrinos among their aims



Mantovani et al., TAUP 2007

Only 2 running experiments having a potential to measure geoneutrinos

KamLand in Kamioka, Japan
S(reactors)/S(geo) ~ 6.7
OCEANIC CRUST

Borexino in Gran Sasso, Italy
S(reactors)/S(geo) ~ 0.3 !!! (2010)
CONTINENTAL CRUST

Expected geoneutrino signal at Borexino site

Allowed region – consistent with geophysical & geochemical data

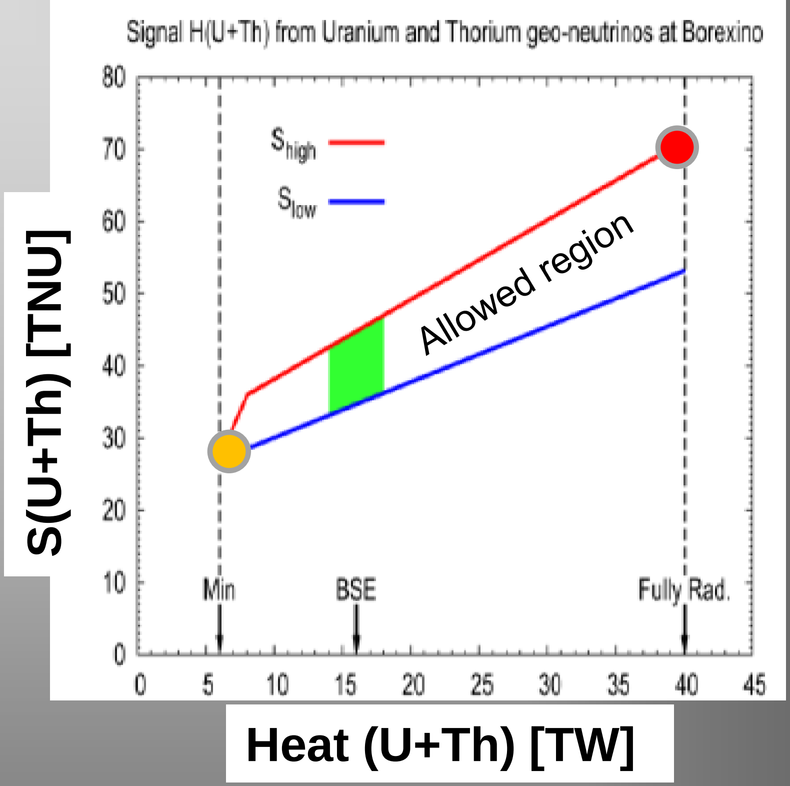
Slope – fixed by the reactions energetics

Intercept + width – site dependent, U+Th distribution

🟩 Region allowed by the BSE geochemical model

🟡 Minimum from known U+Th concentrations in the crust

🔴 Maximum given by the total Earth heat flow



for LNGS Mantovani et al., TAUP 2007

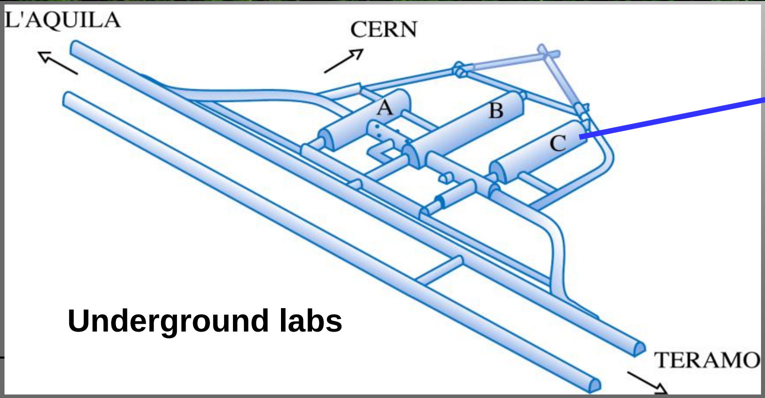
1 TNU (Terrestrial Neutrino Unit) = 1 event/ 10^{32} protons/year

Important local geology: cca. half of the signal comes from within 200 km range!!

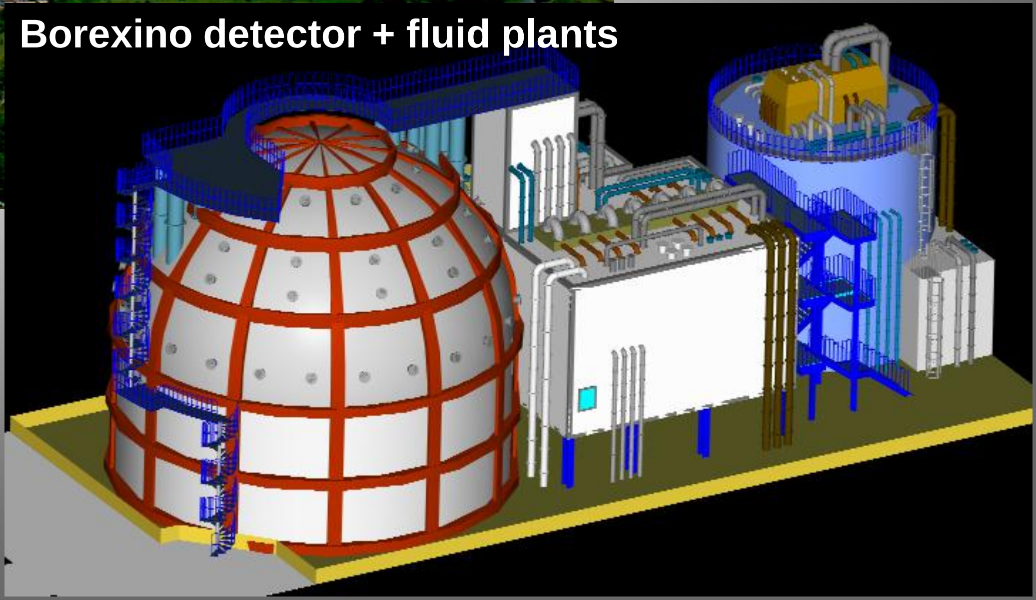
Abruzzo
120 Km from Rome

Laboratori Nazionali del Gran Sasso

Assergi (AQ)
Italy
~3500 m.w.e

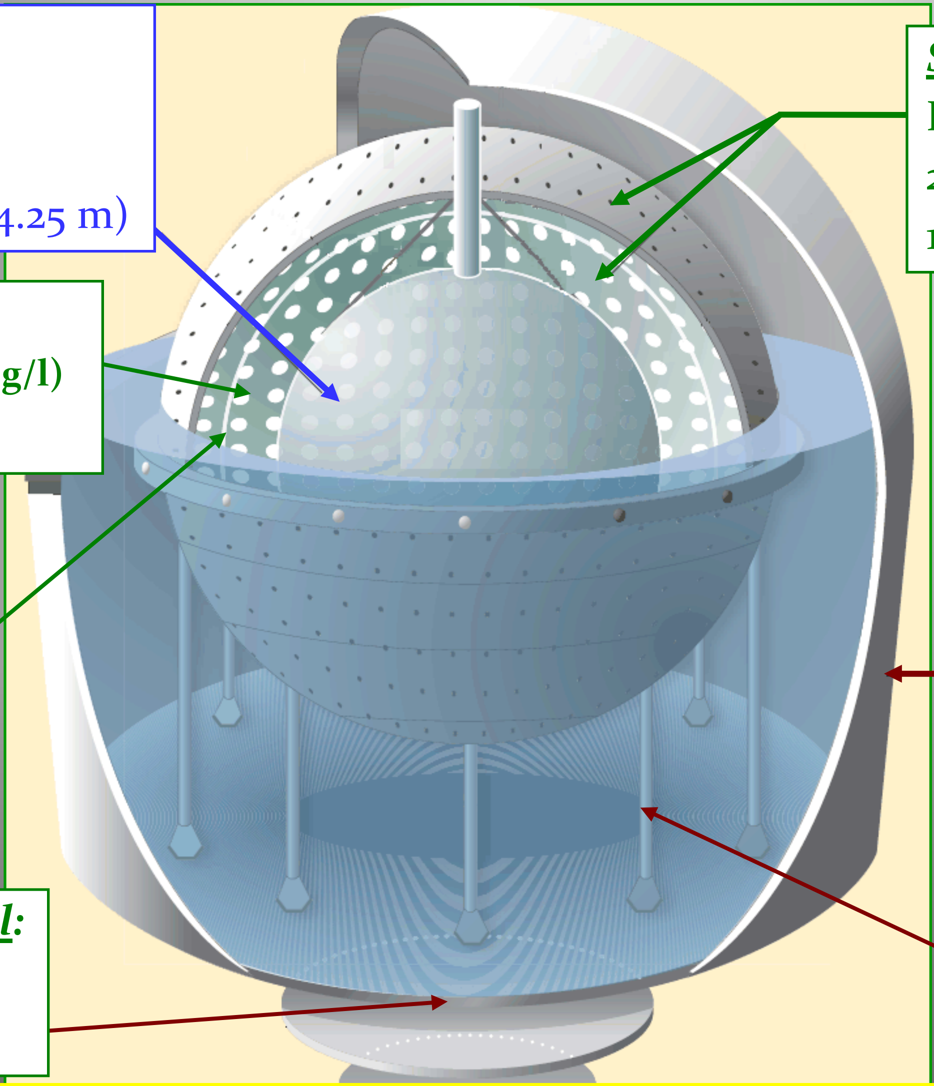


Underground labs



Borexino detector + fluid plants

Borexino Detector



Scintillator:

270 t PC+PPO (1.5 g/l)
in a 150 μm thick
inner nylon vessel (R = 4.25 m)

Buffer region:

PC+DMP quencher (5 g/l)
4.25 m < R < 6.75 m

Stainless Steel Sphere:

R = 6.75 m
2212 PMTs
1350 m^3

Water Tank:

γ and n shield
μ water Č detector
208 PMTs in water
2100 m^3

20 steel legs

C

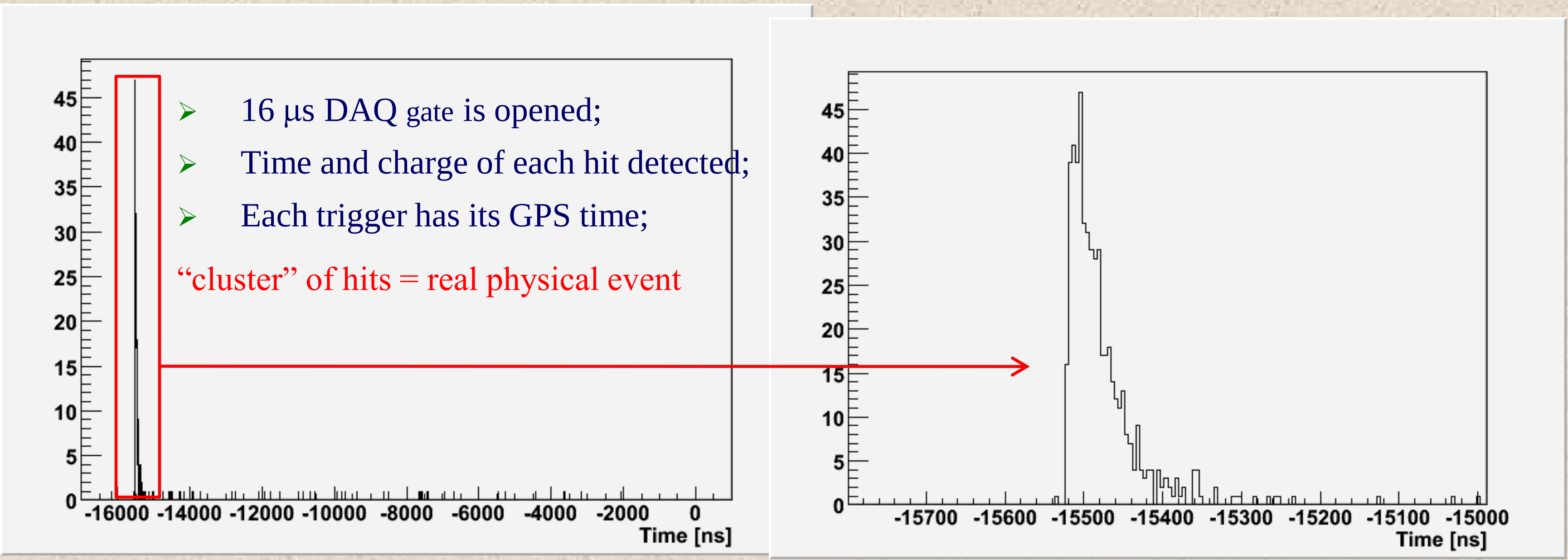
Outer nylon vessel:

R = 5.50 m
(^{222}Rn barrier)

the smallest radioactive background in the world:
9-10 orders of magnitude smaller
than the every-day environment

Data acquisition and data structure

- Charged particles and γ produce scintillation light: photons hit inner PMTs;
- DAQ trigger: > 25 inner PMTs (from 2212) are hit within 60-95 ns:



- 16 μs DAQ gate is opened;
- Time and charge of each hit detected;
- Each trigger has its GPS time;

"cluster" of hits = real physical event

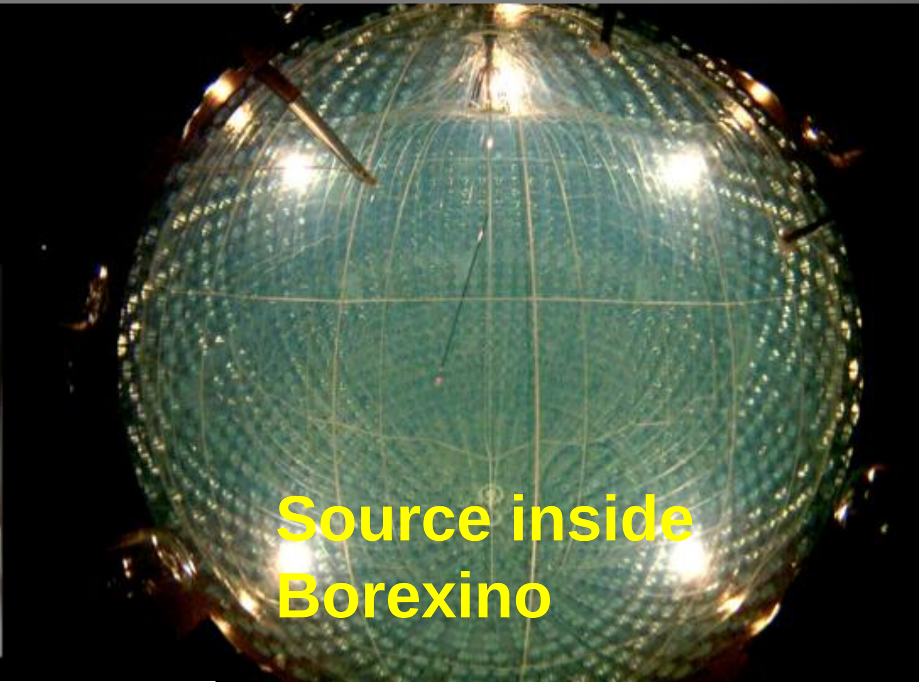
- Outer detector gives a muon veto if at least 6 outer PMTs (from 208) fire;

Calibration

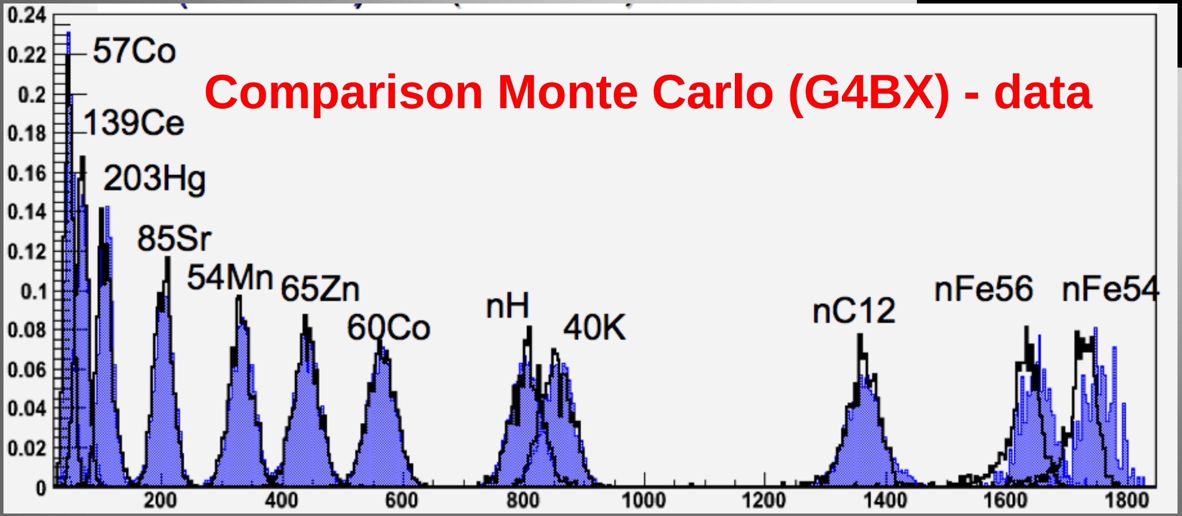
With α,β,γ and neutron sources in 300 positions on and off axis

Insertion

Am-Be source



Source inside Borexino



Comparison Monte Carlo (G4BX) - data

Energy resolution

10% @ 200 keV

8% @ 400 keV

6% @ 1 MeV

Spatial resolution

35 cm @ 200 keV

16 cm @ 500 keV

Event selection

An anti-neutrino candidate is selected using the following cuts

1) Light yield of prompt signal **> 410 p.e.**

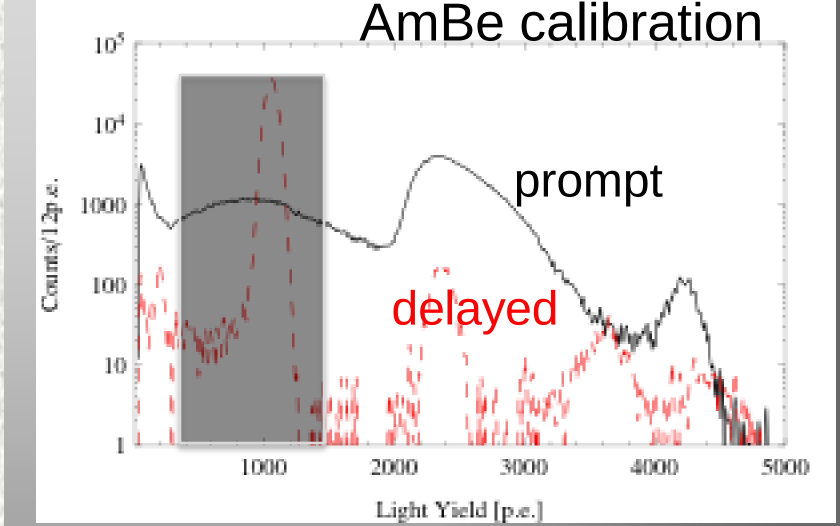
2) Light yield of delayed signal:
$700\text{p.e.} \leq Q_{\text{delayed}} \leq 1250\text{p.e.}$

3) Correlated time: **$2\ \mu\text{s} \leq \Delta t \leq 1280\ \mu\text{s}$**

4) Correlated distance **$\Delta R < 1\text{m}$**

5) Reconstructed vertex of prompt signal:
$R_{\text{InnerVessel}} - R_{\text{prompt}} \geq 25\text{ cm}$

Total detection efficiency determined by MC simulations: 0.85   0.01

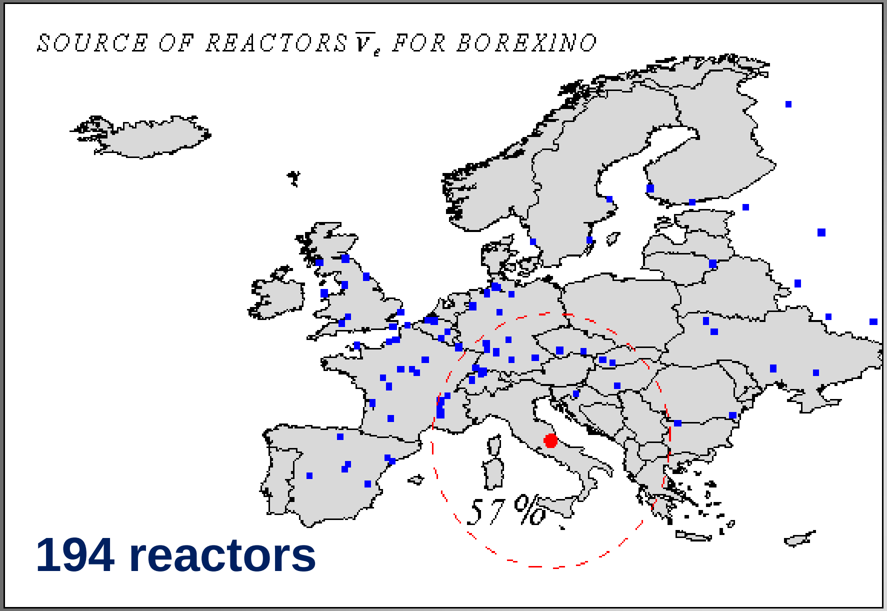


Selected events can be due to:

- geoneutrinos;
- reactor antineutrinos;

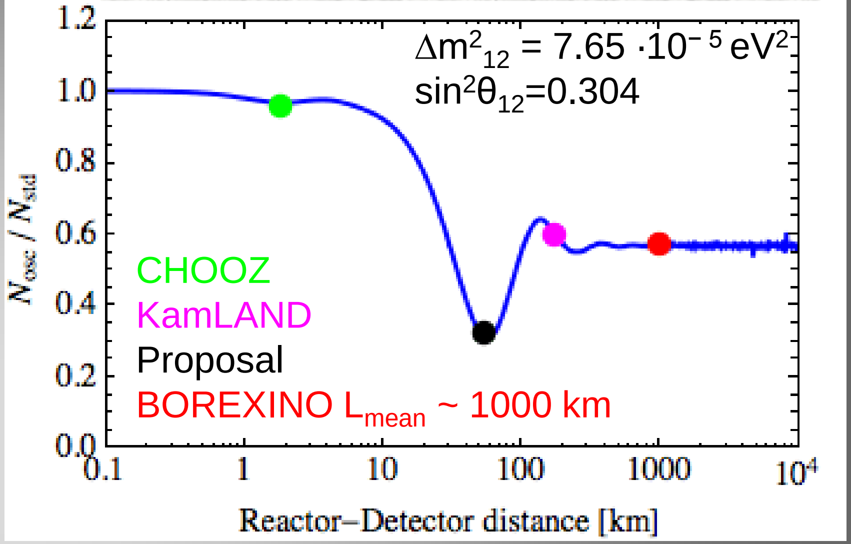
- background ;

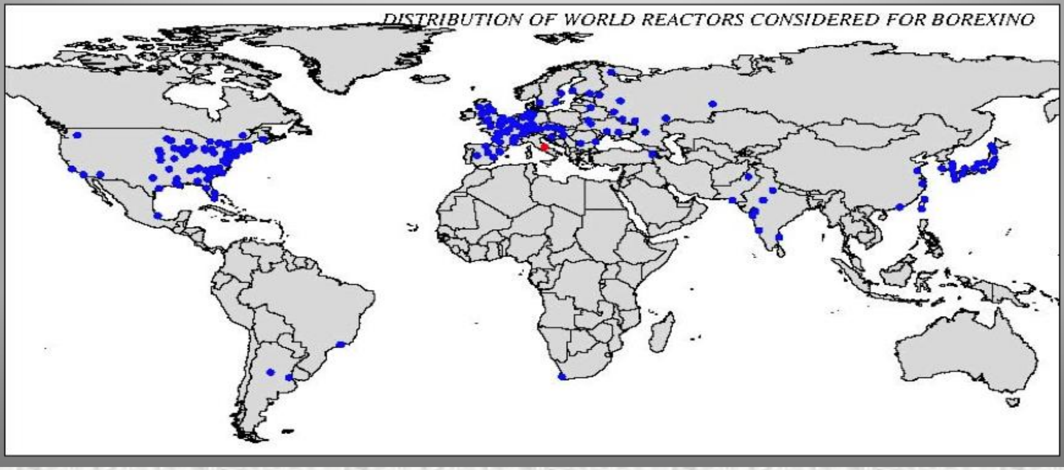
Reactors



194 reactors

Survival probability vs distance





245 world non European reactors: ~2% contribution

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 parametrisation, H-Sch'04);
  - **P_{ee}:** oscillation survival probability;
- **Calculated:**
  - **T_m:** live time during the month m;
  - **L_r:** reactor r – Borexino 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;

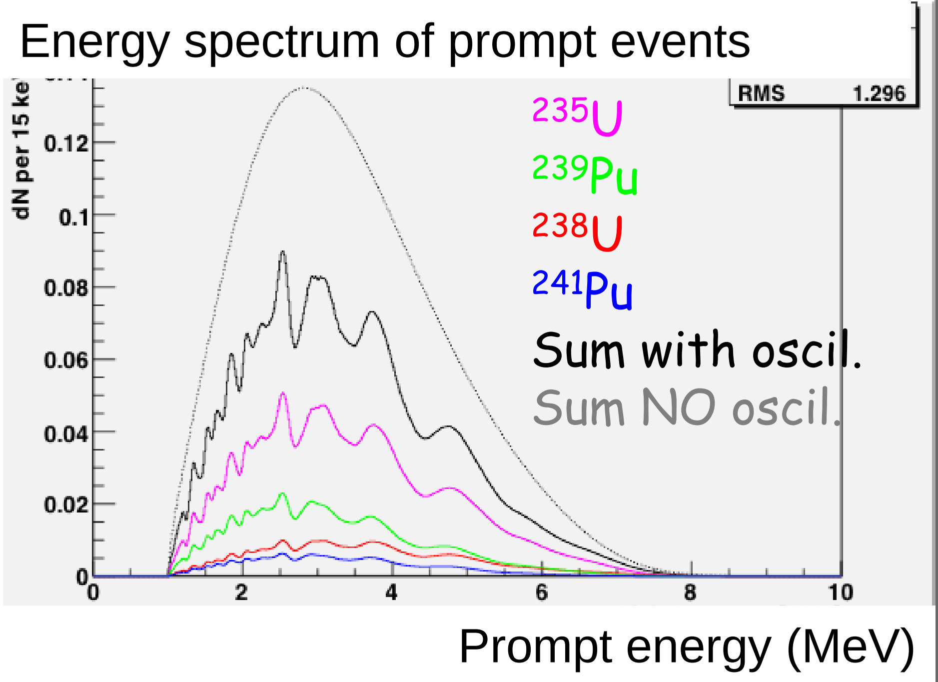
^{235}U
^{239}Pu
^{238}U
^{241}Pu

Expected signal and its error

Φ_ν (E_ν>1.8 MeV)= (9.0 ±0.5)10^4 $cm^{-2}s^{-1}$ → **(5.7±0.3) events/yr/100 t**

Source of error	Error (%)
Oscillations: Δm^2	±0.02%
Oscillations: ϑ_{12}	**±2.6%**
Energy per fission of isotope i: E_i	±0.6%
Flux shape: $\Phi_i(E_\nu)$	**±2.5%**
Cross section: σ(E)	±0.4%
Thermal power: P_{rm}	**±2%**
Long lived isotopes in spent fuel	±1%
Fuel composition: f_{ri}	**±3.2%**
Reactor – Borexino distance L_r	±0.4%
TOTAL	**±5.38%**

σ~10^{-44} cm^2 ;
$N_{protons}$ = 6x10^{30} in 100 tons;



Background sources

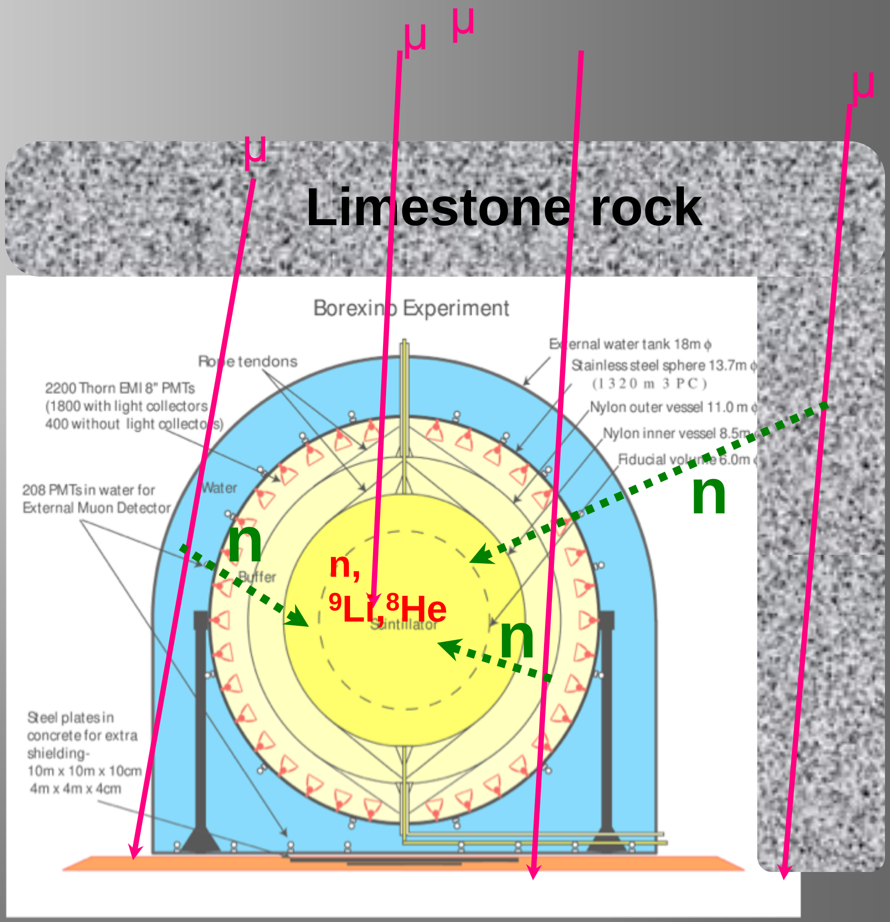
Reactions which can mimick the golden coincidence:

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

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

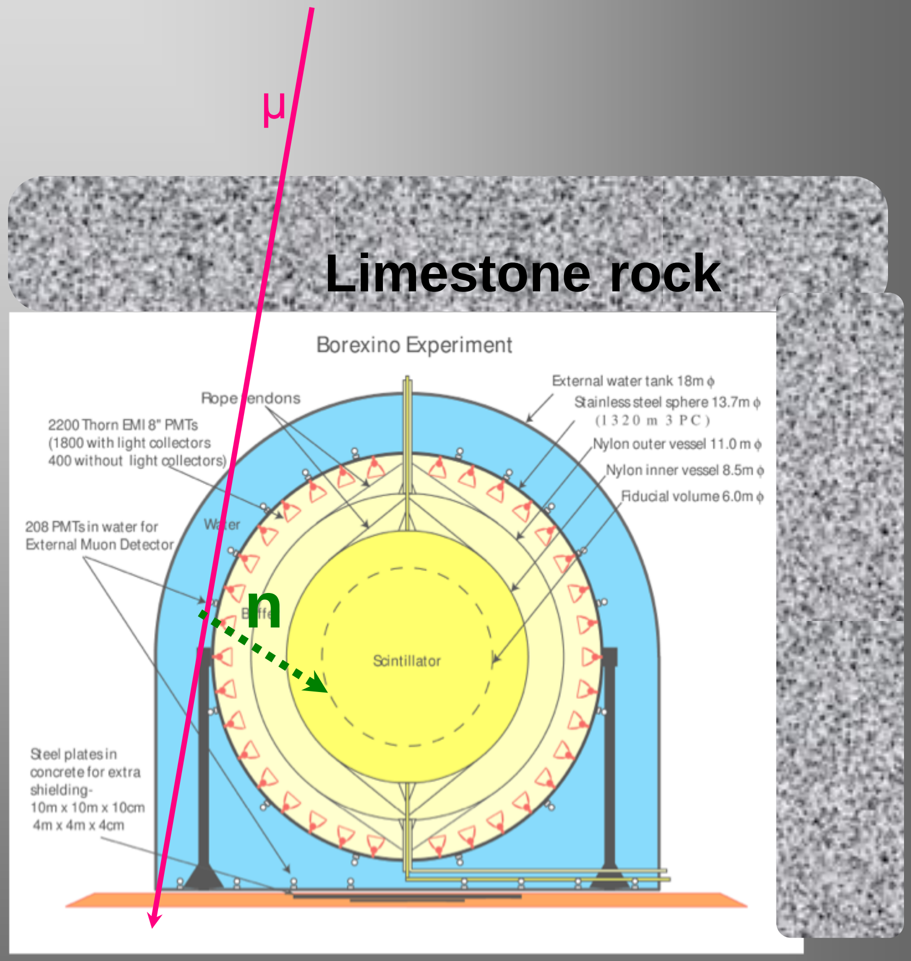
2) <u>Accidental coincidences</u>;

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



Muons crossing the OD

- To remove fast neutrons originated in the Water Tank we apply a 2 ms (~ 8 neutron capture livetimes) veto after each detected muon by the OD;
- In correlation with OD tagged muons we have observed 2 fake anti-ν candidates;
- The inefficiency of OD muon veto is $5\ \ 10^{-3}$;
- For this background we can set an upper limit of **< 0.01 events/(100 ton-year) at 90% C.L.**



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

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

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

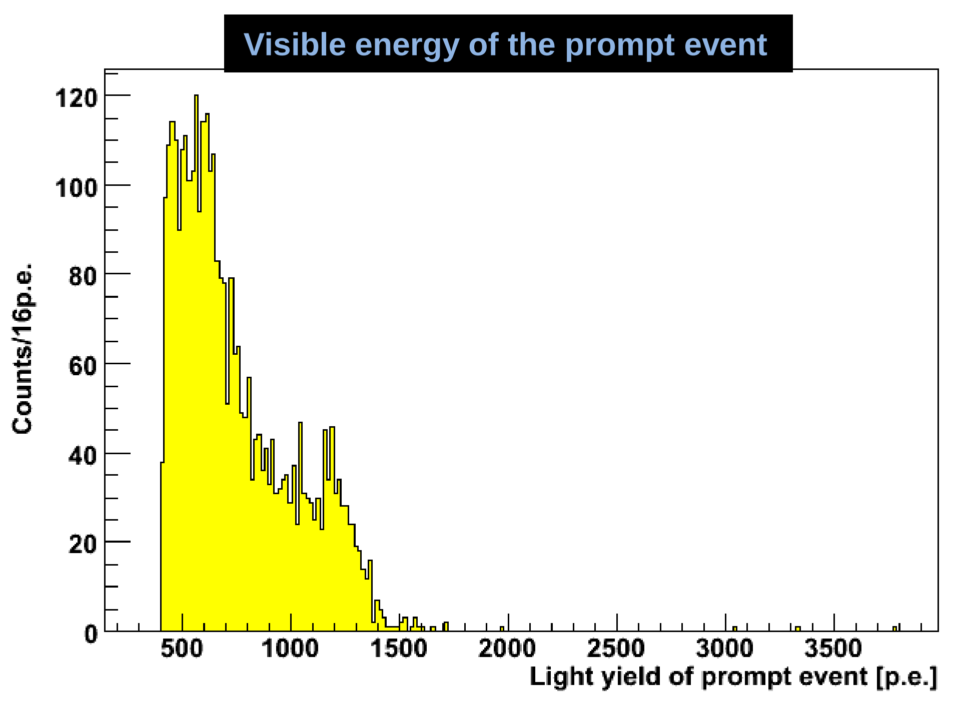
51 candidates

Rate of coincodences:
15.4 events/100 tons/year

Bgr for geonu:
< 0.03± 0.02 ev/100 tons/year

Accidental coincidences

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



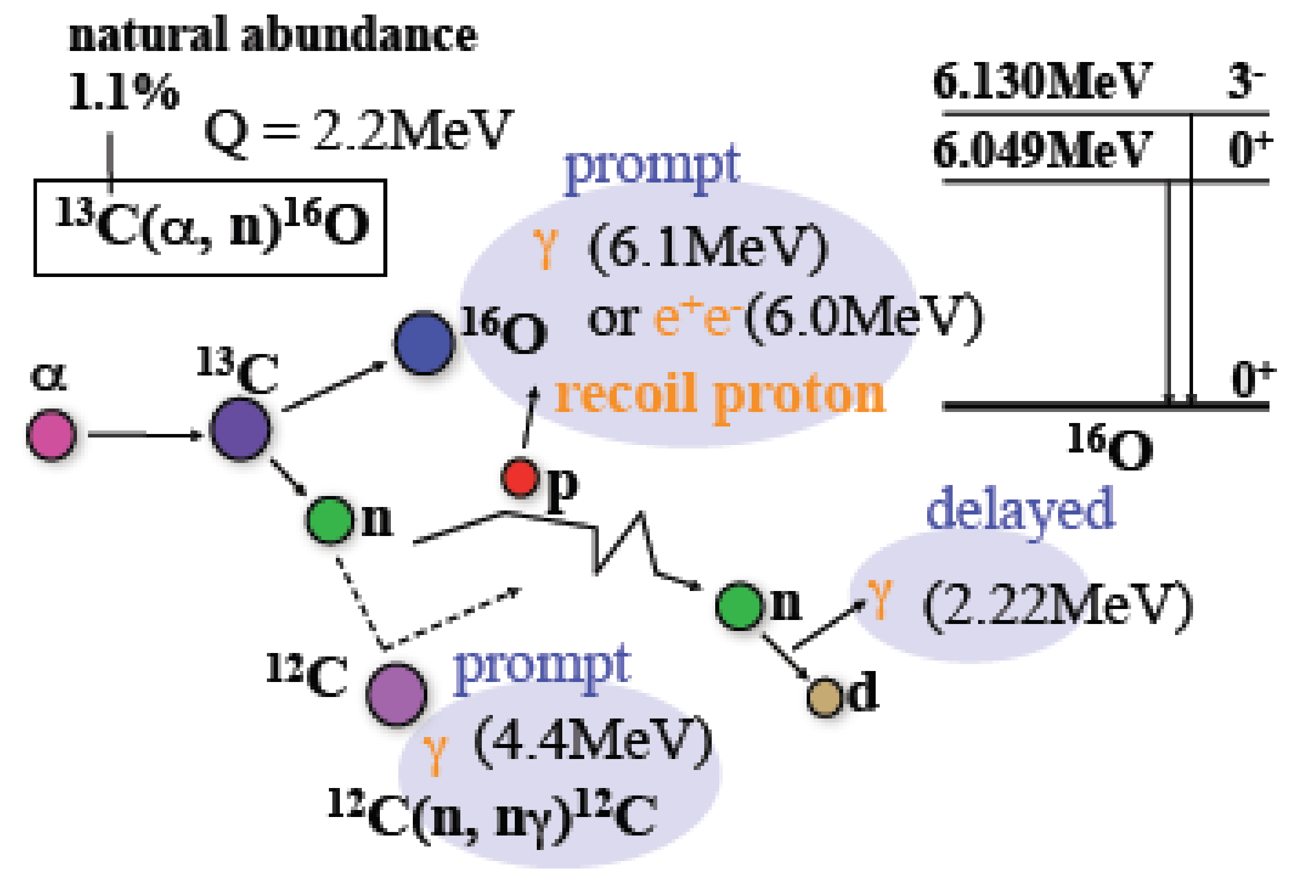
0.080 0.001 events/(100ton-year)

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

2) Isotopic abundance of ^{13}C: 1.1%

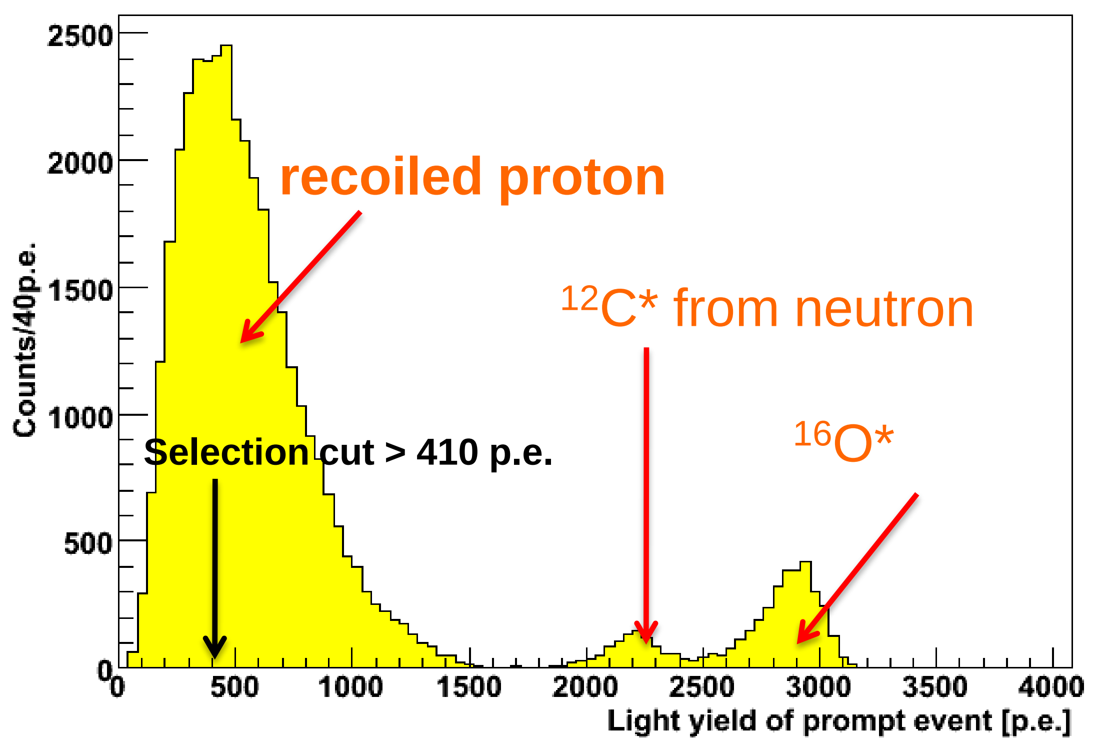
3) ^{210}Po contamination: **A_{Po}~ 12 cpd/ton**

4) E_α=5.3 MeV: $E_{neutrone}$ ≤ 7.29 MeV for transition to the ground state



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

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



(0.014±0.001) events/(100 tons yr)

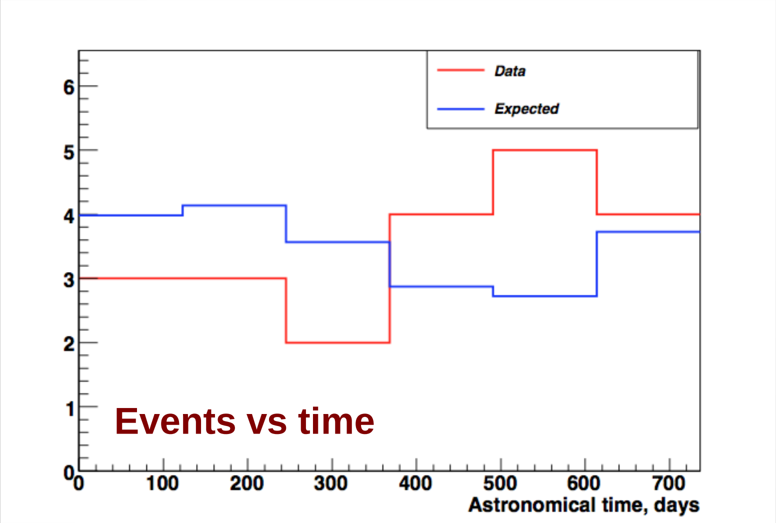
Summary of backgrounds

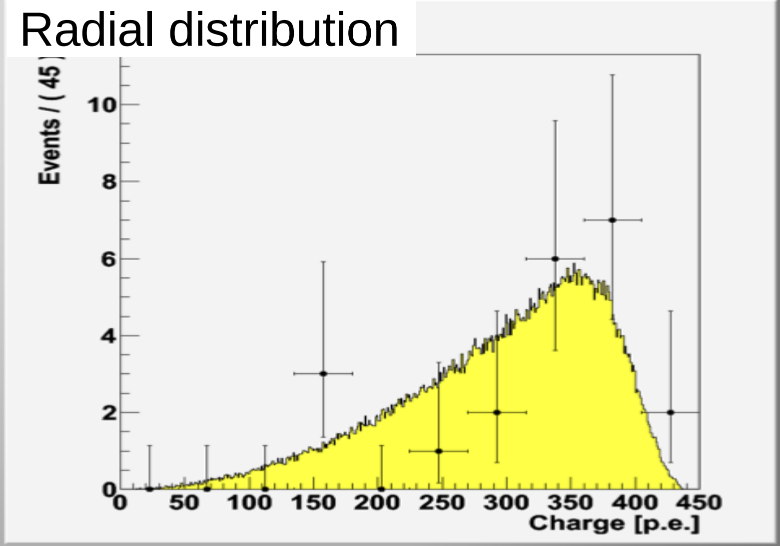
Background source	events/(100 ton-year)
Cosmogenic ^{9}Li and ^{8}He ✖	0.03 ± 0.02
Fast neutrons from μ in Water Tank (measured)	< 0.01
Fast neutrons from μ in rock (MC)	< 0.04
Non-identified muons	0.011 ± 0.001
Accidental coincidences ✖	0.080 ± 0.001
Time correlated background	< 0.026
(γ,n) reactions	< 0.003
Spontaneous fission in PMTs	0.003 ± 0.0003
(α,n) reactions in the scintillator [^{210}Po] ✖	0.014 ± 0.001
(α,n) reactions in the buffer [^{210}Po]	< 0.061
TOTAL	**0.14 ± 0.02**

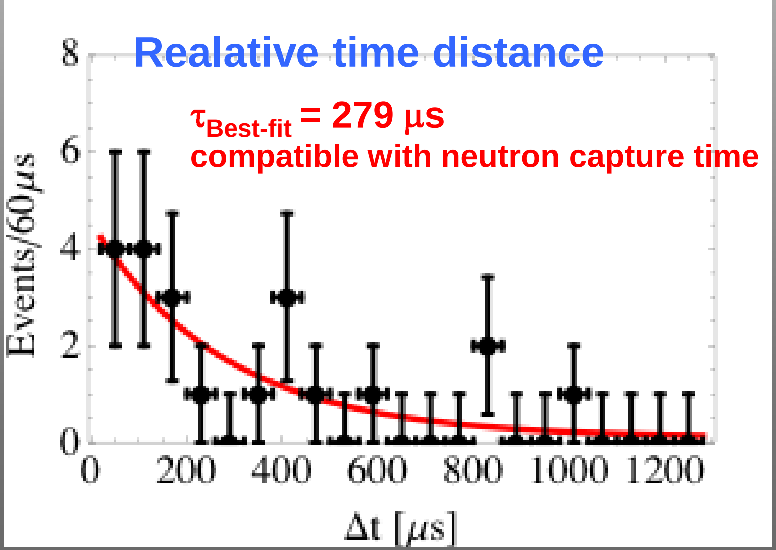
Aspettiamo: 2.5 geo-ν/(100ton-year) (assuming BSE)

Results: 21 candidates selected

in 483 live days (252.6 ton-year after all cuts)





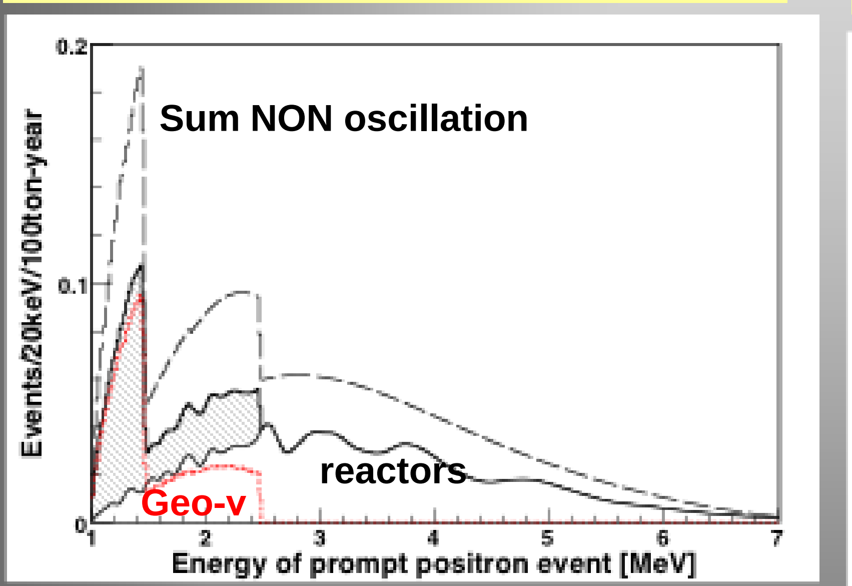


$\tau_{\text{Best-fit}}$ = 279 μs

compatible with neutron capture time

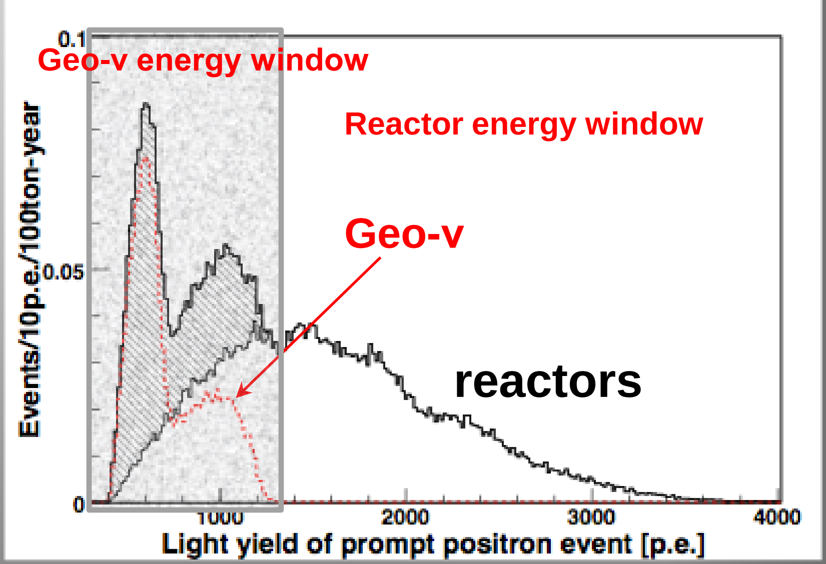
Shape of the expected spectra

Theoretical spectra: input to MC



MC output:

includes detector response function

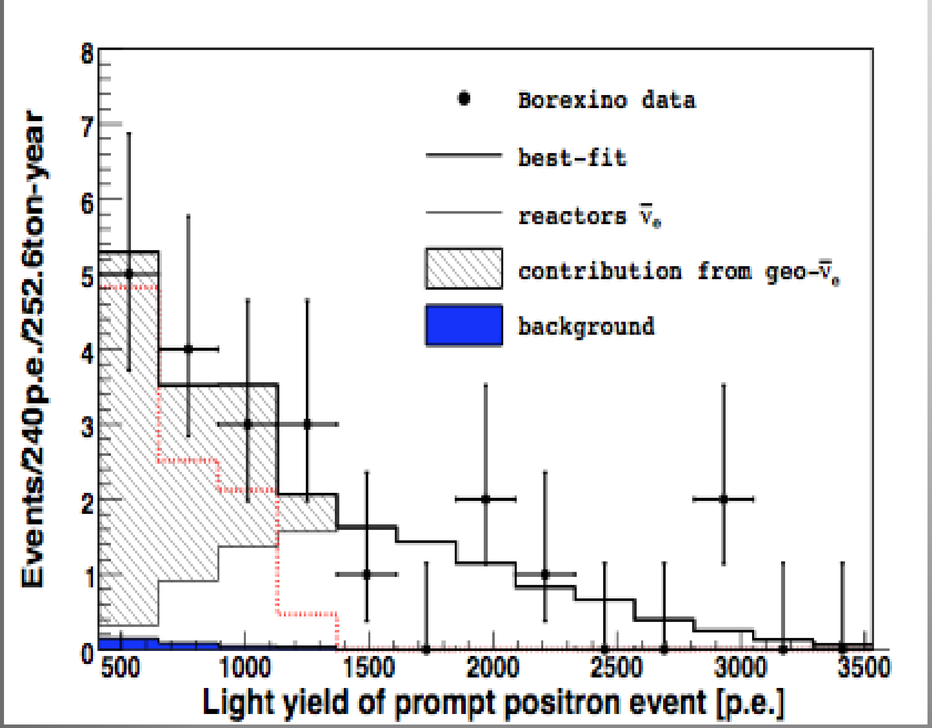


USED IN THE UNBINNED MAXIMUM LIKELIHOOD FIT OF THE DATA

Candidates vs Poisson probabilities

	Predicted from reactors	Background	Observed	Probability to get $N \geq N_{obs}$	Probability to get $N \leq N_{obs}$
Geo-ν window	5.0 0.3	0.31 0.05	15	$5\ \ 10^{-4}$ (3.5σ)	
Reactor-ν window without oscillations	16.3 1.1	0.09 0.06	6		$5\ \ 10^{-3}$ (2.9σ)

Unbinned max. likelihood fit of data



- unbinned since small statistics;
- just the result is plot in a binned spectrum;
- result of the fit: amplitudes of the geo and reactor anti-ν spectra;

68.3 % 99.7%

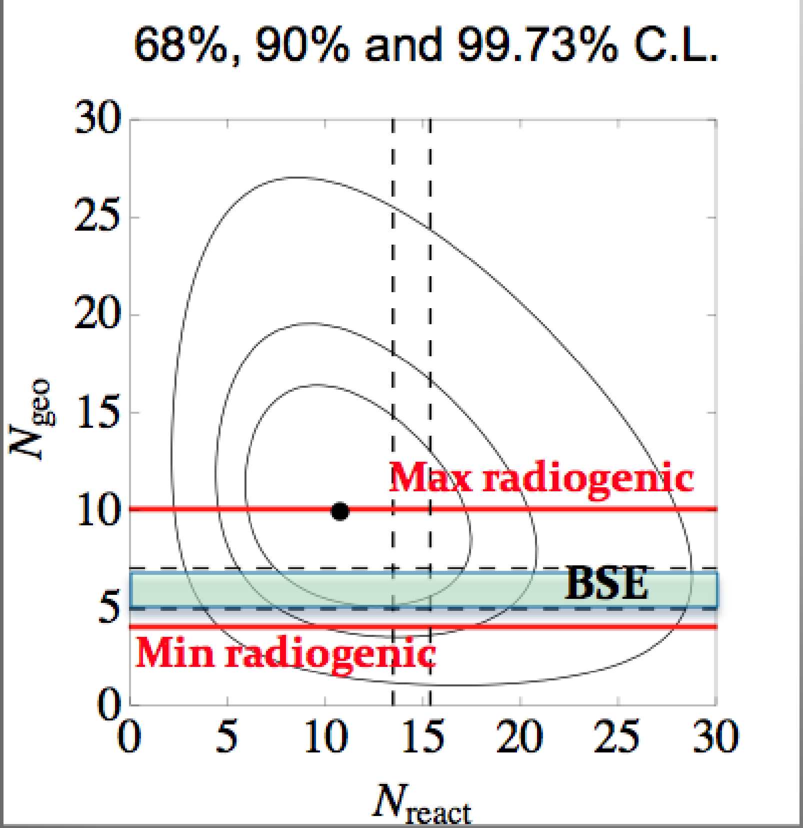
$$N_{geo} = 9.9^{+4.1}_{-3.4}{}^{+14.6}_{-8.2}$$

68.3 % 99.7%

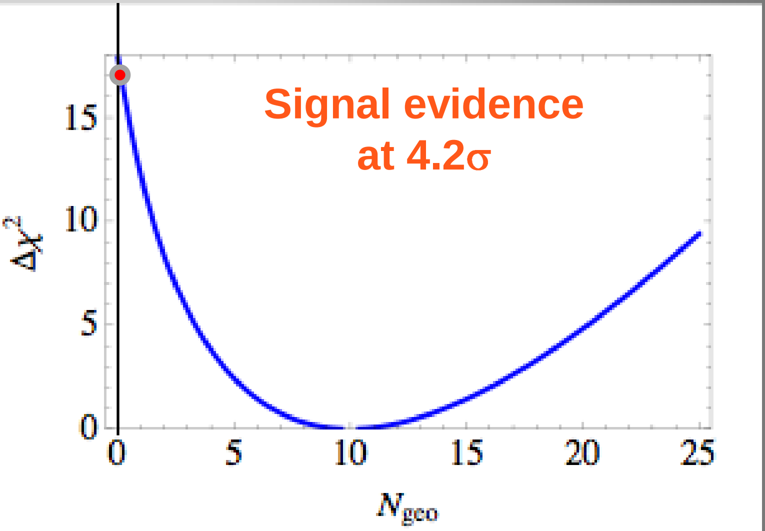
$$N_{react} = 10.7^{+4.3}_{-3.4}{}^{+15.8}_{-8.0}$$

Statistical significance of the result

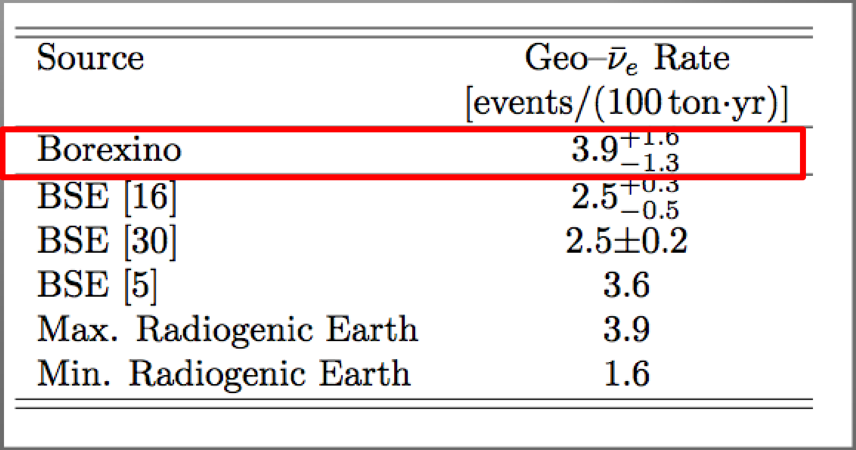
G. Bellini *et al.*, *PLB* **687** (2010) 299-304.



68%, 90% and 99.73% C.L.



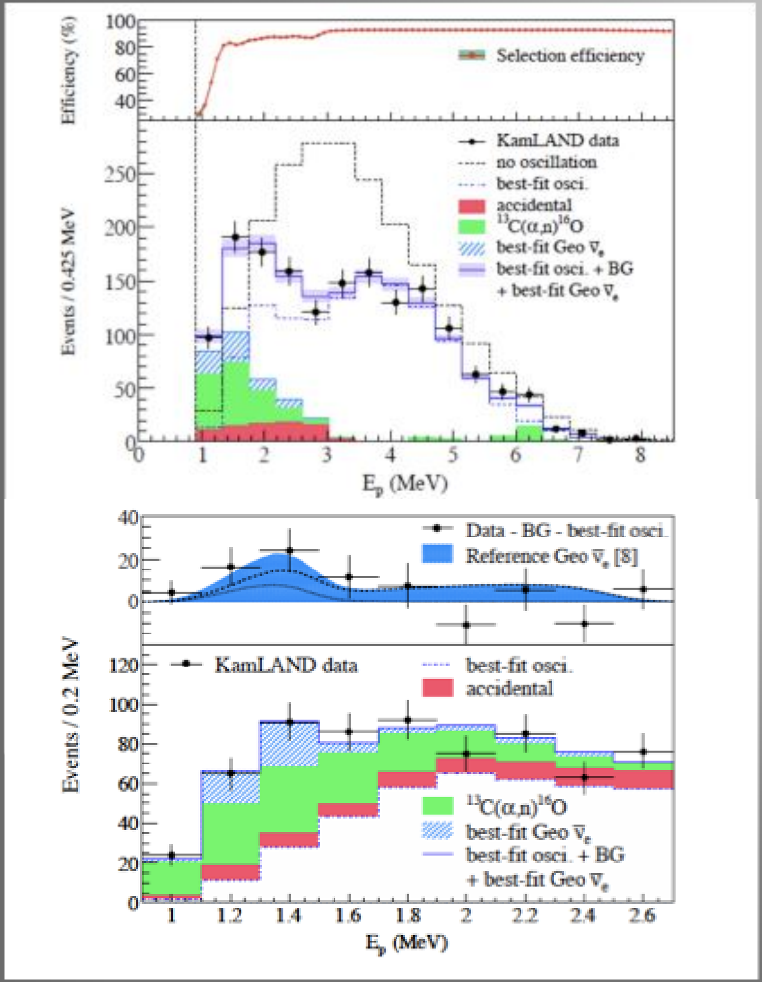
Signal evidence at 4.2σ



Source	Geo–$\bar{\nu}_e$ Rate [events/(100 ton·yr)]
Borexino	$3.9^{+1.6}_{-1.3}$
BSE [16]	$2.5^{+0.3}_{-0.5}$
BSE [30]	2.5 ± 0.2
BSE [5]	3.6
Max. Radiogenic Earth	3.9
Min. Radiogenic Earth	1.6

KamLand

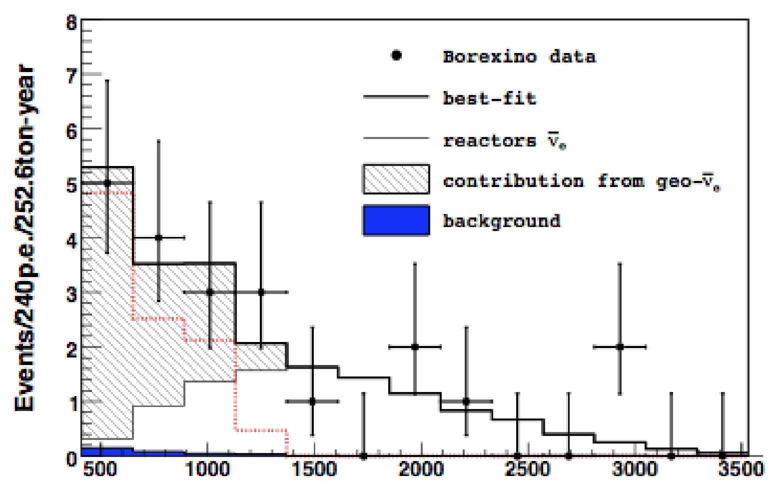
”indication” at 2.5σ



S. Abe *et al*., *PRL* **100** (2008) 221803.

Borexino

“observation” at 99.997% C.L.



G. Bellini *et al*., *PLB* **687** (2010) 299-304.

Competition?

In fact it is **complementarity**!!

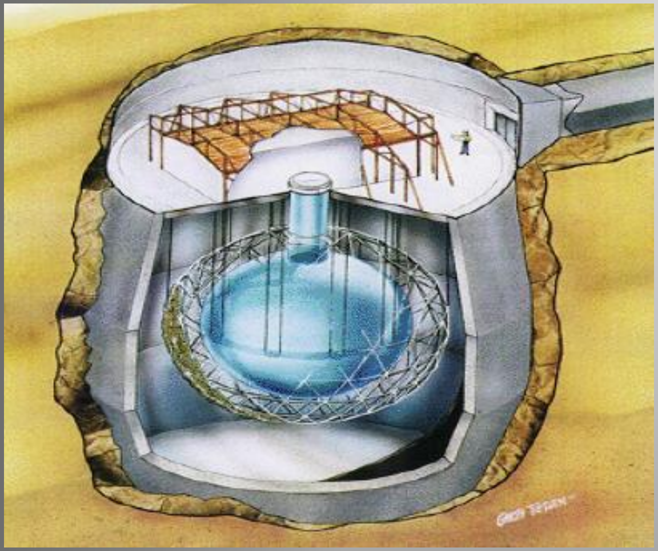
KamLand: oceanic crust
Borexino: continental crust

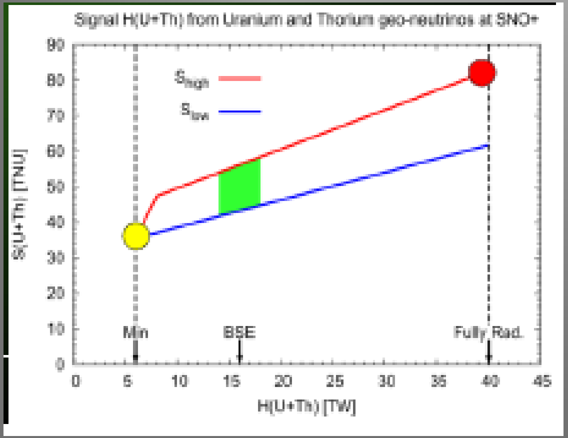
Summary of results and perspectives

- **Borexino results on geoneutrinos:**
  - **the first clear observation of geoneutrinos at 4.2σ ;**
  - the first measurement of oscillations (reactor antinu) at 1000 km @ 2.9σ;
  - georeactor in the Earth core with > 3 TW rejected at 95% C.L.;
- **Perspectives with Borexino:**
  - **accumulating statistics …. confirmation of BSE/fully radiogenic Earth??**
  - **spectroscopy U/Th ratio???**
- **Perspectives in the world:**
  - **future big experiments (LENA, 1000 events/year!!)**
  - **contribution from the mantle** (directionality measurement, Hanohano with 10 kton on the ocean floor, measurements at different sites);

Future experiments

SNO+ at Sudbury, Canada





Mantovani et al., TAUP 2007

After SNO: D_2O replaced by 1000 tons of liquid scintillator

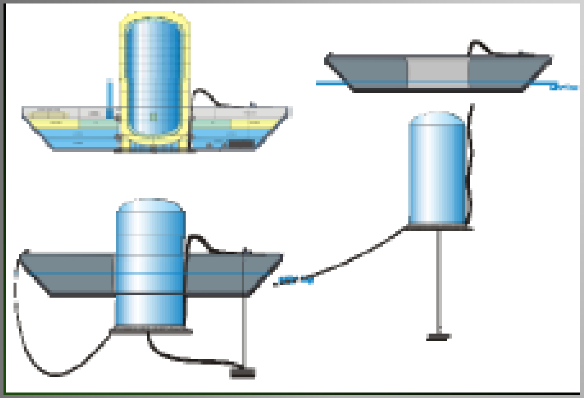
M. J. Chen, *Earth Moon Planets* **99**, 221 (2006)

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

BSE: 28-38 events/per year

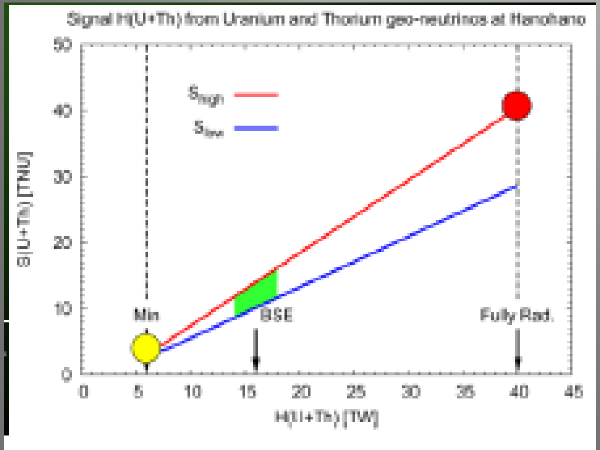
Hanohano at Hawaii

Hawaii Antineutrino Observatory (HANOHANO = "magnificent" in Hawaiian



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

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

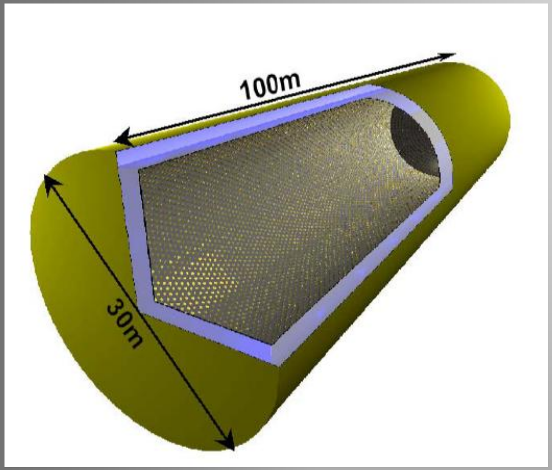


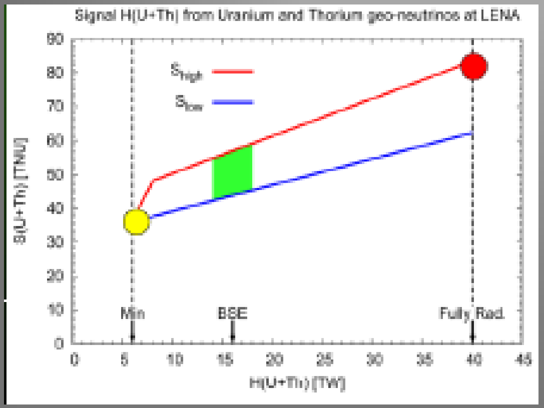
Mantovani , TAUP 2007

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

BSE: 60-100 events/per year

LENA at Pyhasalmi, Finland





Mantovani , TAUP 2007

Project for a 50 kton underground liquid scintillator detector

K.A. Hochmuth et al. – Astropart. Phys. 27, 2007.

80% of the signal from the continental crust (Fiorentini et al.)

BSE: 800-1200 events/per year

Scintillator loaded with 0.1% Gd:

- better neutron detection
- moderate **directionality** information

THANK YOU!!!

Milano

Genova

Perugia

Dubna JINR
(Russia)

Kurchatov
Institute
(Russia)

APC Paris

Princeton University

Virginia Tech. University

Jagiellonian U.
Cracow
(Poland)

Munich
(Germany)

Heidelberg
(Germany)

Directionality of geoneutrinos

•Momentum conservation → neutron starts “moving forwards”
angle (geoneutrino, neutron) < 26^o

• directionality degraded during the neutron thermalization

• even a minimal directional information would be sufficient for the source discrimination

•Reactor & crust antineutrinos→ horizontal
•Mantle antineutrinos→ vertical

Gd, Li and B loaded liquid scintillators with which directional measurement might be possible are under investigation by several groups

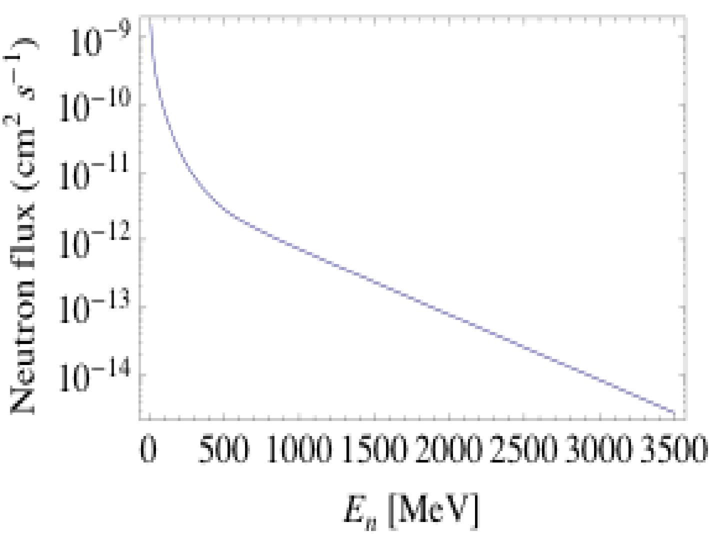
Muon-induced neutrons from the rocks

$\Phi(E_n > 10\ \text{MeV}) = 7.3\ 10^{-10}\ \text{cm}^{-2}\text{s}^{-1}$

$\langle E_n \rangle \sim 90$ MeV

Borexino shielding:
2m of water
2.5m of PC buffer
$\lambda_{PC}(100\ \text{MeV}) \cong 70$ cm
$\lambda_{PC\text{-}ES}(100\ \text{MeV}) \cong 110$ cm

Use neutron spectrum as input for MC simulation:
a) 5 10^6 events simulated
b) simulated statistics corresponds to 23 years;
c) 160 events inside Inner Vessel
d) 1 fake anti-ν found with 9000p.e.



<0.04 events/(100ton-year) 90% C.L.

We use the following likelihood:

$$L(N_{geo},N_{reac},S_{reac},S_{FV}) = e^{-\int_{E_{\min}}^{E_{\max}} dE\, \mathrm{f}_{\nu}(E;N_{geo},N_{reac},S_{reac},S_{FV})} \times \prod_{i=1}^{N_{obs}} \left[\mathrm{f}_{\nu}(E_i;N_{geo},N_{reac},S_{reac},S_{FV}) + f_B(E_i) \right] \times e^{-\frac{1}{2}\left(\frac{S_{reac}}{\sigma_{reac}}\right)^2} \times e^{-\frac{1}{2}\left(\frac{S_{FV}}{\sigma_{FV}}\right)^2}$$

with

f_{ν}= spectrum of geo + reactor anti-neutrinos (assumes chondritic Th/U ratio)

f_B= spectrum of backgrounds

$\sigma_{react}=0.0538$ and $\sigma_{FV}=0.038$

- **Il fondo radioattivo al livello piu' basso mai raggiunto**
  - 15 anni per **selezionare i materiali,**
  imparare a **purificare** lo scintillatore liquido e l'acqua fino al livello necessario;
  - Con **100 t** di massa bersaglio, ci si attendono **~ 45 c/d** attesi dai neutrini solari
    - ~ 45 / 86400 s/ 100000 kg = **~ 5 10^{-9} Bq/kg**
    Poiché un evento di diffusione v-e è indistinguibile da un decadimento β nucleare o dallo scattering compton di un γ,
    la radioattività naturale intrinseca dello scintillatore deve essere più bassa di questo numero
  - MA:

Acqua minerale naturale:	**10 Bq/kg**	**^{40}K, ^{238}U, ^{232}Th**
Aria:	**10 Bq/m^3**	**^{222}Rn, ^{85}Kr, ^{39}Ar**
Roccia qualunque:	**100-1000 Bq/Kg**	**^{40}K, ^{238}U, ^{232}Th …**

**Lo scintillatore di Borexino DEVE essere
(e fortunatamente è) 9-10 ordini di grandezza
MENO RADIOATTIVO di qualunque cosa sulla Terra**

- I problemi da affrontare
  - ^{14}C (β ~160 KeV): **dentro il PC**
    - Selezione scintillatore
  - **^{39}Ar (β), ^{85}Kr(β−γ), ^{222}Rn(α,β,γ)** : **aria**
    - Sviluppo di N_2 ultrapuro
    - Tenuta alto vuoto ovunque
  - **^{238}U(α,β,γ), ^{232}Th(α,β,γ), ^{210}Pb(α,β), ^{210}Po(α): ovunque**
    - Purificazioni, selezione materiali
    - Sviluppo tecniche di lavaggio, risciaquo, asciugatura
  - **γ** dalla **roccia** e dai materiali
    - Schermature, Selezione materiali
  - **μ** dai Raggi cosmici e cosmogenici
    - Laboratorio sotterraneo
    - Identificazione dei μ con il rivelatore