NEUTRINO PHYSICS WITH THE BOREXINO EXPERIMENT

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On behalf of the Borexino collaboration

Borexino

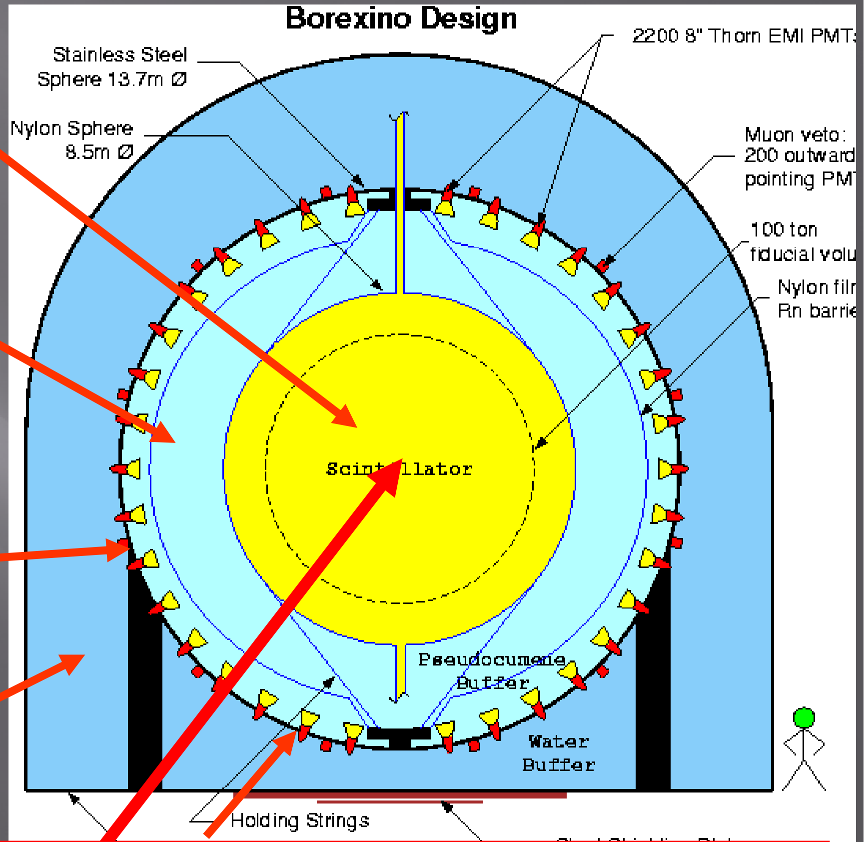
•Borexino is located under the Gran sasso mountain which provides a shield against cosmic rays (residual flux = 1 m /m^2 hour);

Core of the detector: 300 tons of liquid scintillator contained in a nylon vessel of 4.25 m radius (PC+PPO);

1st shield: 1000 tons of ultra-pure buffer liquid (pure PC) contained in a stainless steel sphere of 7 m radius;

2214 photomultiplier tubes pointing towards the center to view the light emitted by the scintillator;

2nd shield: 2000 tons of ultra-pure water contained in a cylindrical dome;

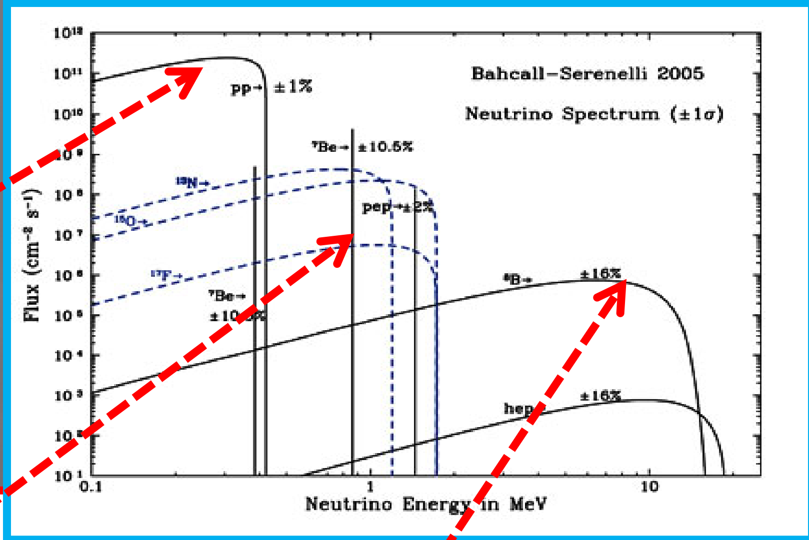


200 PMTs mounted on the SSS pointing outwards to detect light emitted in the water by muons crossing the detector;

Only the innermost 100tons of scintillator (R<3m) are considered in the analysis, in order to further reduce the external background.

Solar neutrinos

Solar neutrinos:
The Standard Solar Model



PROTON-PROTON CYCLE:
~99% of the sun energy

pp (99.7%): $p + p \rightarrow D + e^+ + \nu_e$, $E_\nu \leq 0.42\ MeV$

pep (0.3%): $p + e^- + p \rightarrow D + \nu_e$, $E_\nu = 1.44\ MeV$

100%: $D + p \rightarrow {}^3He + \gamma$

85%: ${}^3He + {}^3He \rightarrow \alpha + 2p$

15%: ${}^3He + \alpha \rightarrow {}^7Be + \gamma$

Hep: ${}^3He + p \rightarrow \alpha + e^+ + \nu$, $E_\nu \leq 18.8\ MeV$

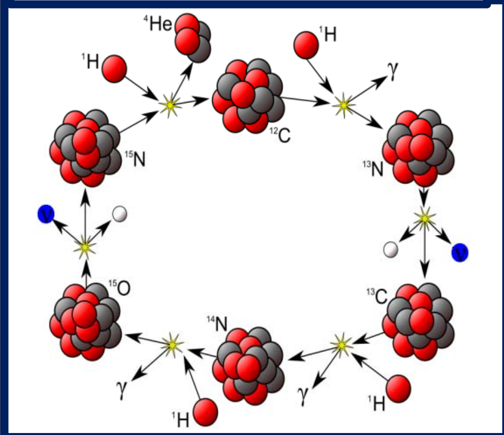
Be (99.89%): ${}^7Be + e^- \rightarrow {}^7Li + \nu_e$, $E_\nu = 0.863\ MeV$

${}^7Li + p \rightarrow 2\alpha$

0.11%: ${}^7Be + p \rightarrow {}^8B + \gamma$

B: ${}^8B \rightarrow 2\alpha + e^+ + \nu_e$, $E_\nu \leq 15\ MeV$

CNO CYCLE:
<1% of the sun energy

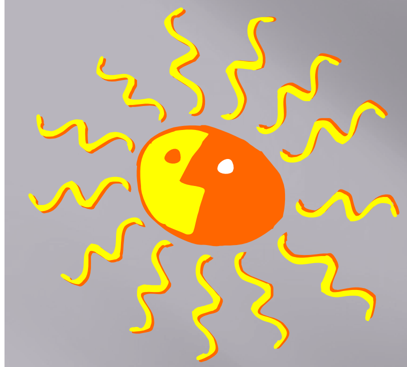


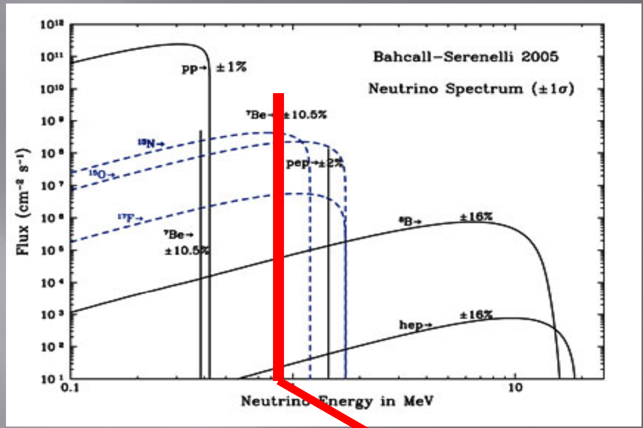
The solar metallicity controversy

- The abundance of elements heavier than helium (metallicity) is used as input in the Standard Solar Model;
- The neutrino fluxes depend on metallicity;

- **High metallicity GS98** = Grevesse and Sauval *Space Sci. Rev. 85, 161 (1998);*
- ***Low metallicity AGS05*** = *Asplund, Grevesse, Sauvall* Asplund, Nucl. Phys. A **777, 1** (2006);

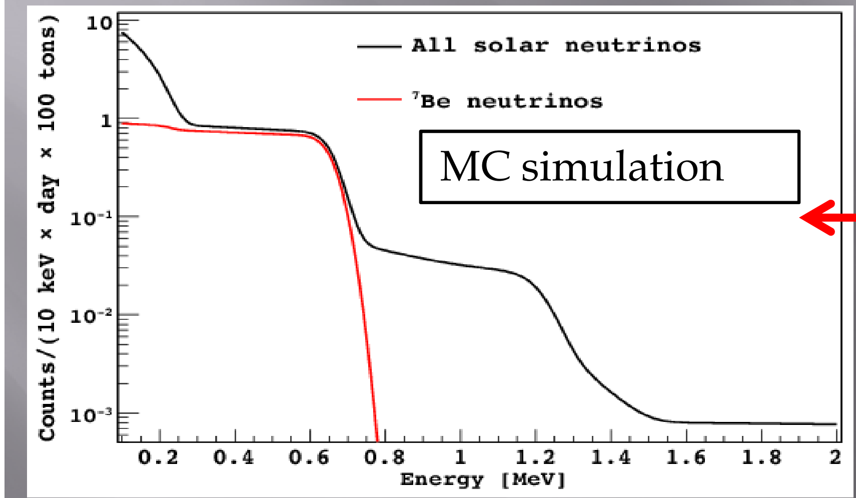
Sources	Φ (ν sec-1 cm-2) High-metallicity GS98	Φ (ν sec-1 cm-2) Low-metallicity AGS05	Difference
Pp	5.97×10^{10}	6.01×10^{10}	1.2%
Pep	1.41×10^{8}	1.45×10^{8}	2.8%
Hep	7.90×10^{3}	8.22×10^{3}	4.1%
^{7}Be	5.07×10^{9}	4.55×10^{9}	10%
^{8}B	5.94×10^{6}	4.72×10^{6}	21%
^{13}N	2.88×10^{8}	1.89×10^{8}	31%
^{15}O	2.15×10^{8}	1.34×10^{8}	31%
^{17}F	5.82×10^{6}	3.25×10^{6}	44%



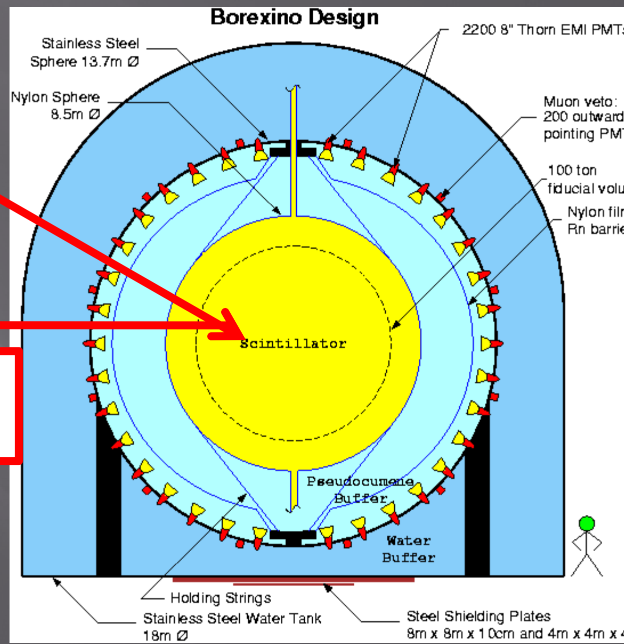


•Main goal: neutrinos from 7Be E=862 keV;
•Also measured 8B;
•Pep, CNO work in progress;

$\nu_e \to \nu_x$



$\nu_x + e^- \to \nu_x + e^-$



•Technique liquid scintillator → high light-yield (higher than Cerenkov)
•Technique liquid scintillator → no directional information (unlike Cerenkov);
•Signal is indistinguishable from background: high radiopurity is a MUST!

Radiopurity: the key issue for Borexino

The expected rate of solar neutrinos in 100tons of scintillator is ~50 counts/day;

It corresponds to ~ 5 10^{-9} Bq/Kg;

Just for comparison

- Natural water is ~ 10 Bq/Kg in ^{238}U, ^{232}Th and ^{40}K
- Air is ~ 10 Bq/m^3 in ^{39}Ar, ^{85}Kr and ^{222}Rn
- Typical rock is ~ 100-1000 Bq/m^3 in ^{238}U, ^{232}Th and ^{40}K

BX scintillator must be 9/10 order of magnitude less radioactive than anything on earth!

Background suppression: 15 years of

- **Internal background: contamination of the scintillator itself (^{238}U, ^{232}Th, ^{40}K, ^{39}Ar, ^{85}Kr, ^{222}Rn)**
  - Solvent purification (pseudocumene):
    - Distillation (6 stages distillation, 80 mbar, 90 °C);
    - Vacuum Stripping by Low Argon/Kripton N_2 (LAKN);
  - Fluor purification (PPO):
    - Water extraction (5 cycles);
    - Filtration;
    - Single step distillation;
    - N_2 stripping with LAKN;
  - Leak requirements for all systems and plants < 10^{-8} mbar· liter/sec;
    - Critical regions (pumps, valves, big flanges) were protected with additional nitrogen blanketing;

- **External background: γ and neutrons from surrounding materials**
  - Detector design: concentric shells to shield the inner scintillator;
  - Material selection and surface treatment;
  - Clean construction and handling;

Background suppression: achievements

Radioisotopes	Typical	Goal
^{238}U	~10^{-5} - 10^{-6} g/g	10^{-16} g/g
^{232}Th	~10^{-5} - 10^{-6} g/g	10^{-16} g/g

There are two backgrounds which are out of specifications:

•^{210}Po: started out at 6000 counts/day/100t (the origin of the contamination is not known);

- It is NOT in equilibrium with ^{238}U nor ^{210}Pb;
- It decays away with its lifetime (200d);
- Can be rejected by pulse/shape discrimination methods;

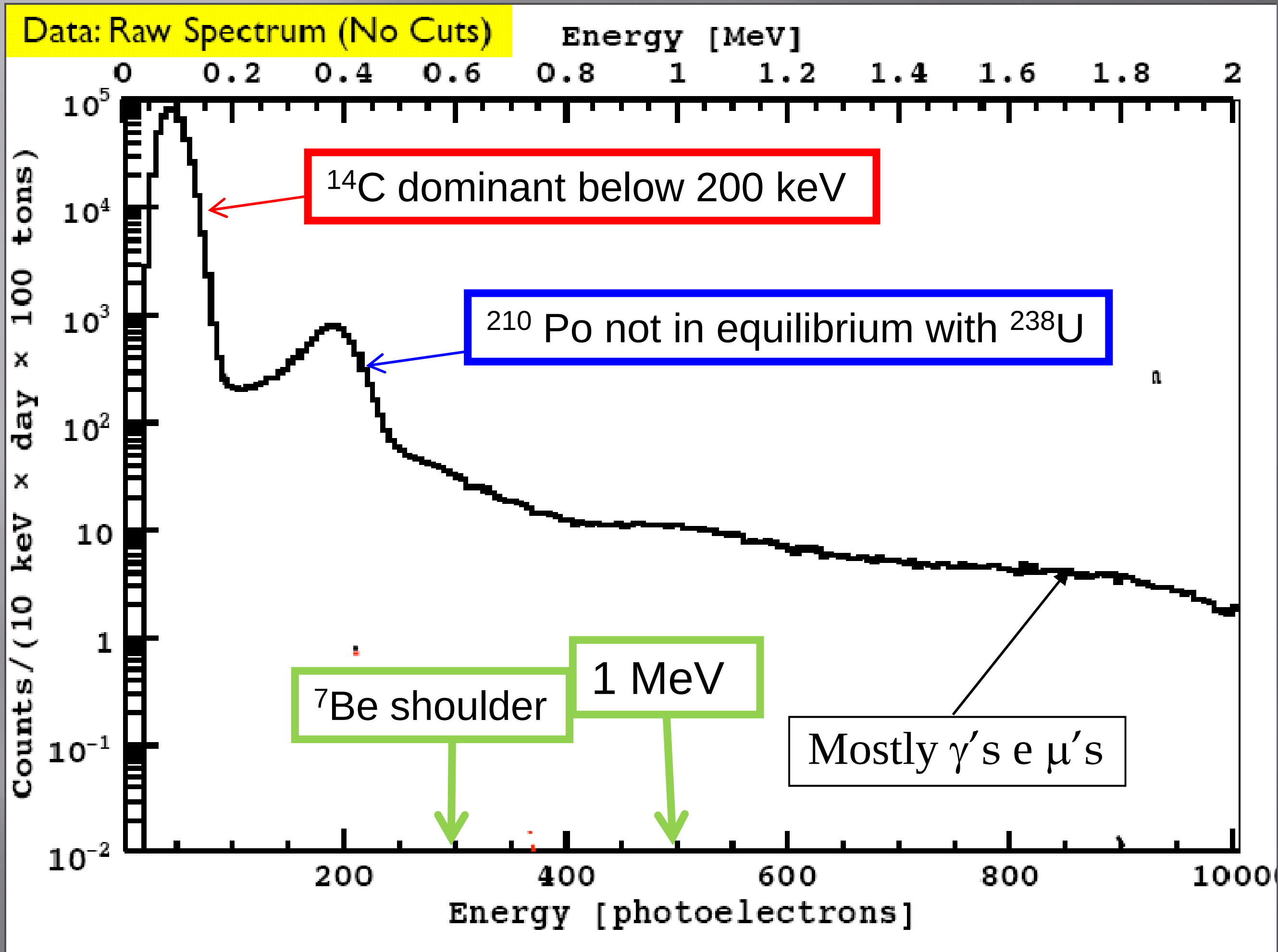
•^{85}Kr : ~30 counts/day/100tons (probably because of a few liters air leak which happened during filling);

- It decays beta with an end-point of ~687 keV→ very annoying for neutrino analysis;
- It is long-lived (31 years);
- Its amount can be estimated independently via a rare channel decay;
- Its amplitude is also left free in the global fit;

^{7}Be neutrinos

Direct measurement of the ^{7}Be solar neutrino flux with 192 days of Borexino data PRL 101 2008

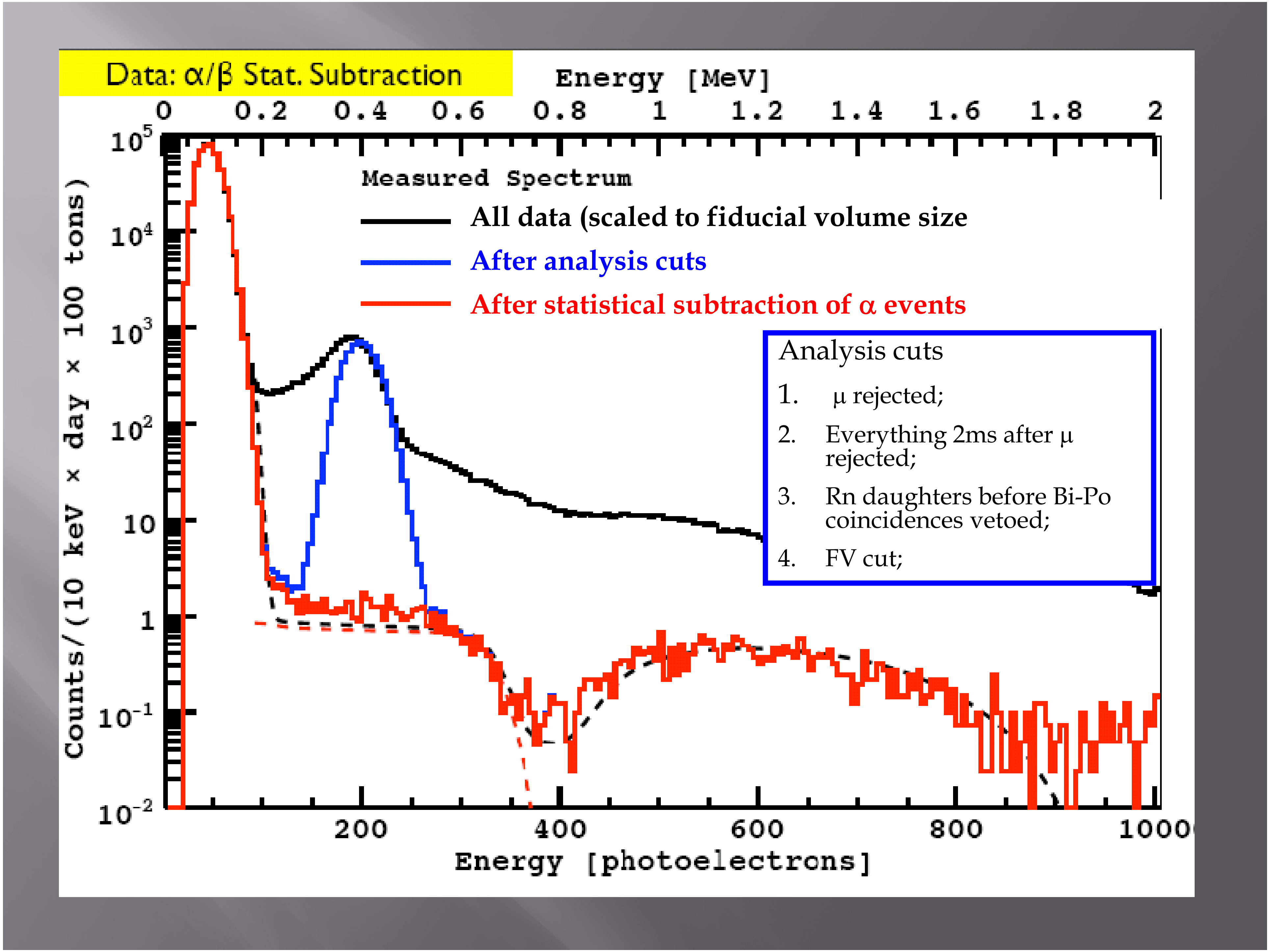
How does the Borexino spectrum look like?



- ^{14}C is an unavoidable background in an organic scintillator;
- It is responsible for most of the counting rate in Borexino (~20cnts);

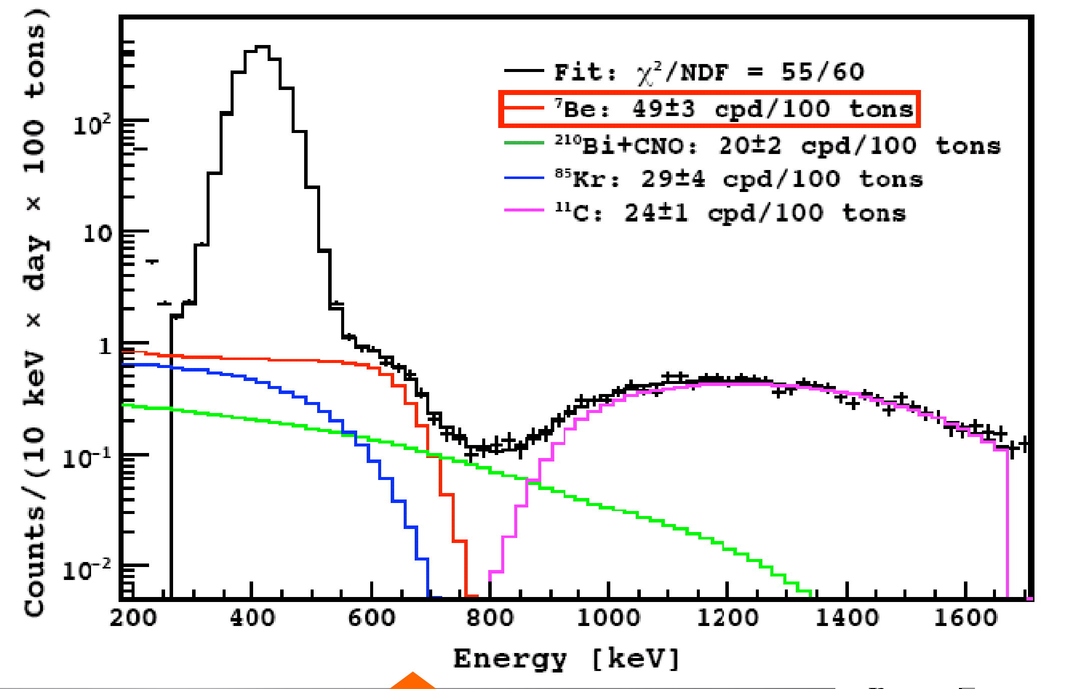
The crucial information collected for each event are

- Number of photons → energy of the event
- Time of arrival of each photon at each PMT → position of the event



Data: α/β Stat. Subtraction
Energy [MeV]
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
Measured Spectrum
All data (scaled to fiducial volume size
After analysis cuts
After statistical subtraction of α events
Analysis cuts
1. μ rejected;
2. Everything 2ms after μ rejected;
3. Rn daughters before Bi-Po coincidences vetoed;
4. FV cut;
Counts/(10 keV × day × 100 tons)
10^5 10^4 10^3 10^2 10 1 10^-1 10^-2
200 400 600 800 1000
Energy [photoelectrons]

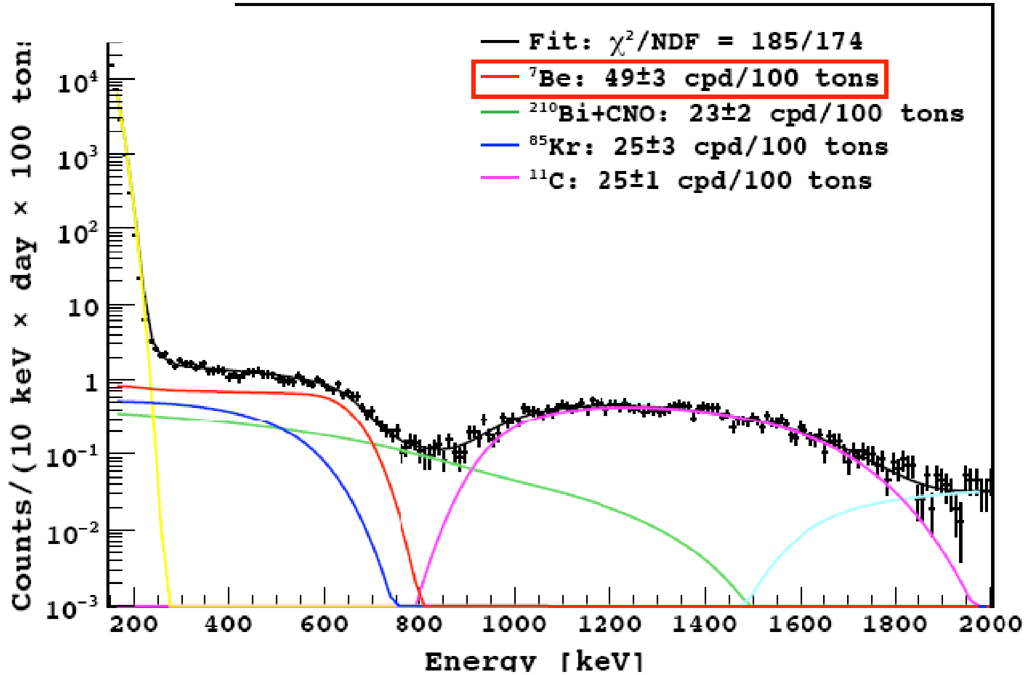
Fit to the spectrum



- Fit between 100-800p.e.
- Light yield is a free parameter of the fit;
- Light quenching is included according to the Birks' parametrization;
- ^{14}C, ^{11}C and ^{85}Kr are left as free parameters of the fit

- Fit to the spectrum with and without alpha subtraction is performed giving consistent results

^{7}Be: 49±3 cpd/100 tons



Systematic errors

Source	Syst.error (1σ)
Tot. scint. mass	± 0.2%
Live Time	± 0.1%
Efficiency of Cuts	± 0.3%
Detector Resp.Function	± 6%
Fiducial Mass	± 6%
TOT	± 8.5%

Rate of ^{7}Be neutrinos

49 ± 3 (stat) ± 4 (sys) counts/(day×100t)

- Total statistic+systematic error~10%
- In the new analysis significantly reduced thanks to enlarged statistics and to calibrations;

Hypothesis	Expected rate (cpd/100t)
No osc +High Metallicity	74±4
No osc + Low Metallicity	67±4
Osc. MSW + High Metallicity	48±4
Osc. MSW + Low Metallicity	44±4

BX measurement confirms oscillations but cannot discriminate between High and Low metallicity hypothesis

Day/Night asymmetry of 7Be neutrinos

•In the MSW framework, the neutrino rate at Night (when neutrinos cross Earth) could be significantly larger than the rate during the Day, because of regeneration effect;

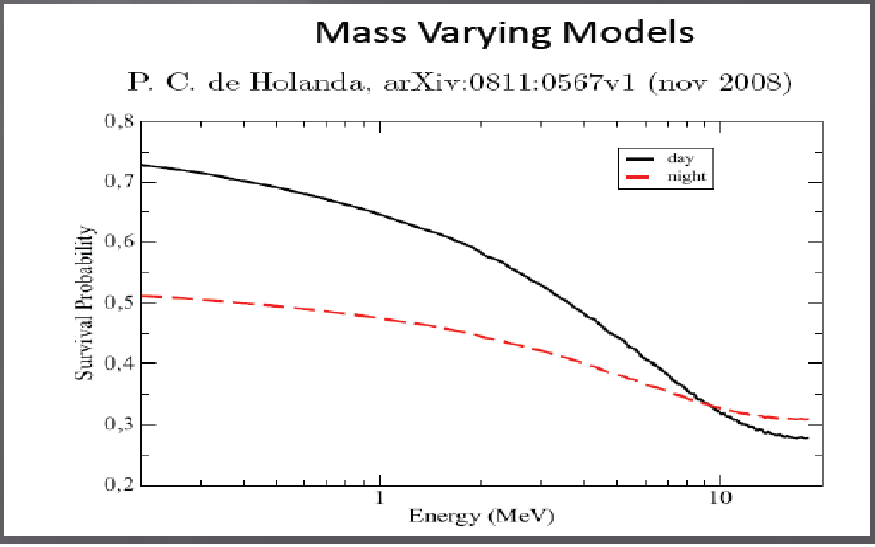
If we define

$$A_{dn} = 2\frac{\Phi_n - \Phi_d}{\Phi_n + \Phi_d}$$

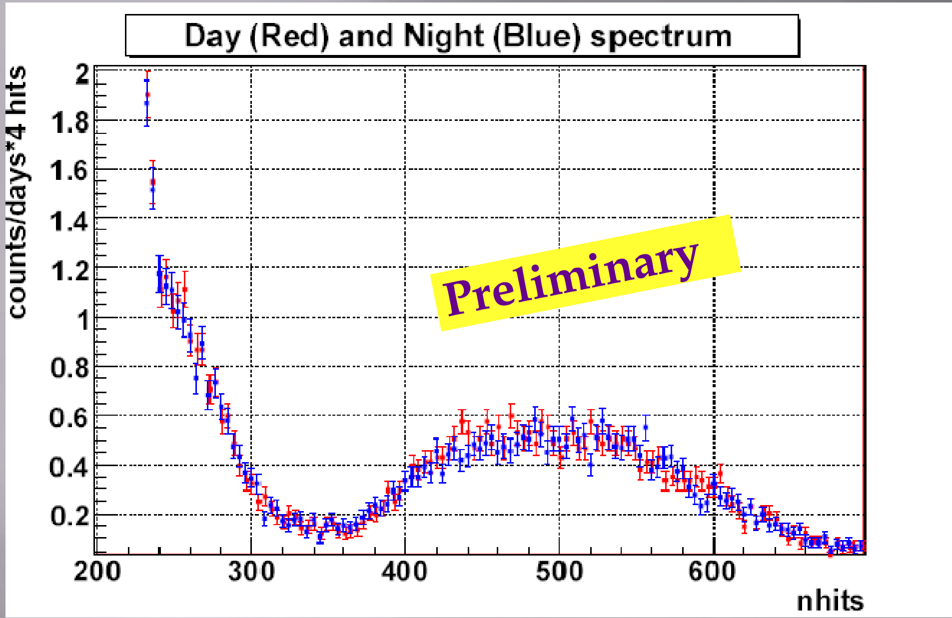
•A_{dn} depends on the value of the oscillation parameters and on the neutrino energy.
•For the 7Be energies
LMA-→ A_{dn} very small (~0);
LOW → A_{dn} very large (23 ±11)%;

•Therefore A_{dn} is a good probe to exclude the LOW solution;
•We recall that the LOW solution is significantly excluded only by reactor anti-neutrino data;
•It is important to independently exclude it with neutrino data;

•Some models like Mass Varying neutrinos foresee a large Day/Night asymmetry of the opposite sign (-23%);
•Test of new physics

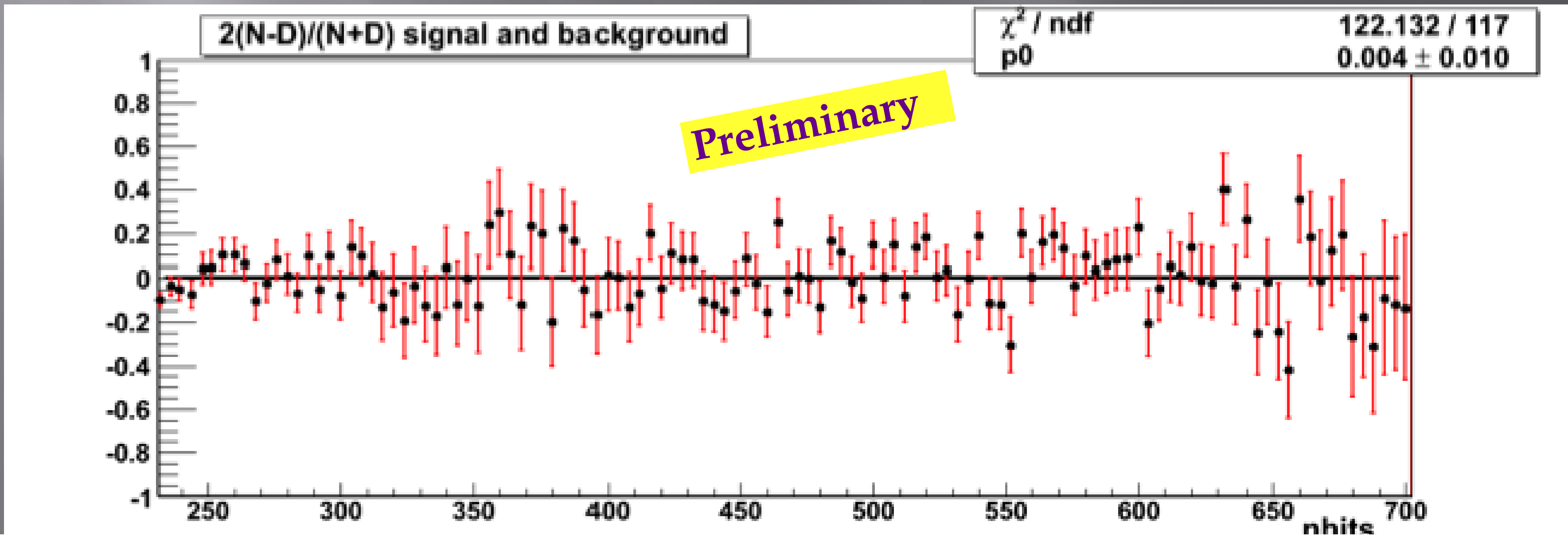


Day/Night asymmetry of 7Be neutrinos (preliminary) on 422 days of data



$A_{dn}=0.007\pm0.073(stat)$

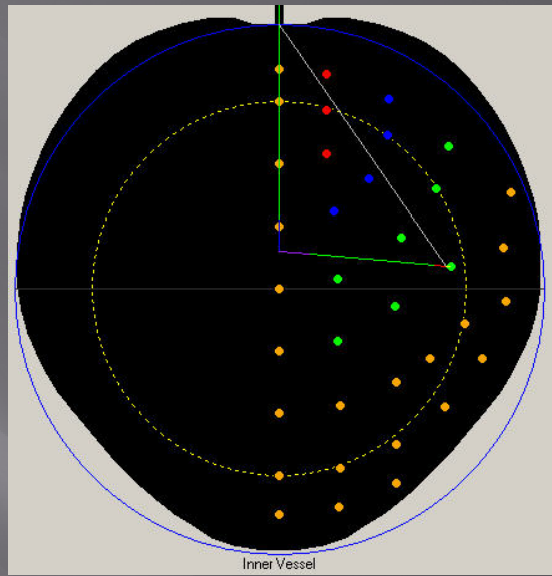
- The A_{dn} is consistent with zero within errors;
- Confirmation of the LMA solution;
- MaVan excluded at 3σ;
- More precise measurement will be published soon;



Toward the precision measurement of the ^{7}Be rate

Calibrations of the detector

Two calibration campaigns performed in 2009 inserting several type of sources (α, β, γ) in over 300 positions;



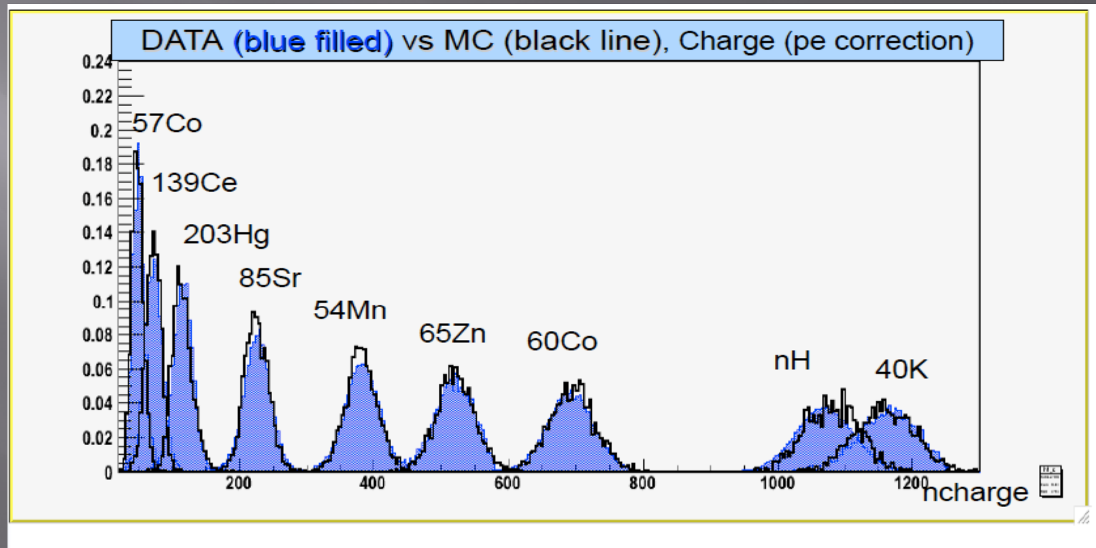
	γ								β		α	neutron		
	^{57}Co	^{139}Ce	^{203}Hg	^{85}Sr	^{54}Mn	^{65}Zn	^{60}Co	^{40}K	^{14}C	^{214}Bi	^{214}Po	n-p	n+^{12}C	n+Fe
energy (MeV)	0.122	0.165	0.279	0.514	0.834	1.1	1.1, 1.3	1.4	0.15	3.2	7.6	2.226	4.94	~7.5

Different particle types allows to tune the algorithms for particle identification (like α/ β discrimination)

Energy scale and energy resolution

- Before calibrating the energy scale was determined by means of internal contaminants (^{14}C , 11C, …);
- WARNING: life is not simple. Light quenching introduces non-linearities in the energy scale: this makes it crucial to have several calibrating points throughout the entire energy window of interest;

- Thanks to the calibration campaigns the uncertainty on the energy scale between (0,2)MeV is less than1.5%;



Calibrations were also fundamental to fine-tune the MonteCarlo simulation inputs;

The light yield is in the range of ~ 500 p.e./MeV

- This high light-yield leads to a good energy resolution
- $\sigma(E)/E$ = 5% at 1MeV;

Calibrations allowed to study the uniformity of detector response as a function of position;

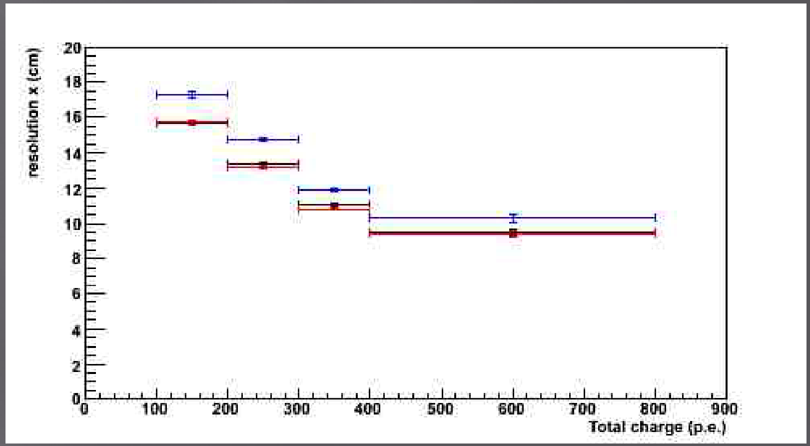
Position reconstruction and FV definition

- Position reconstruction is needed to select an inner fiducial region of the detector free from external background

- Position is obtained by a maximum-likelihood fit to the photon arrival time distribution;
- It relies on the precise time-alignment of all the 2200 PMTs (within 1.5nsec);
- The algorithm was tuned on internal contamination events;
- **Calibrations allowed to check the performance of the algorithm: the position of the source is determined independently by a CCD camera system with a precision of 2cm**

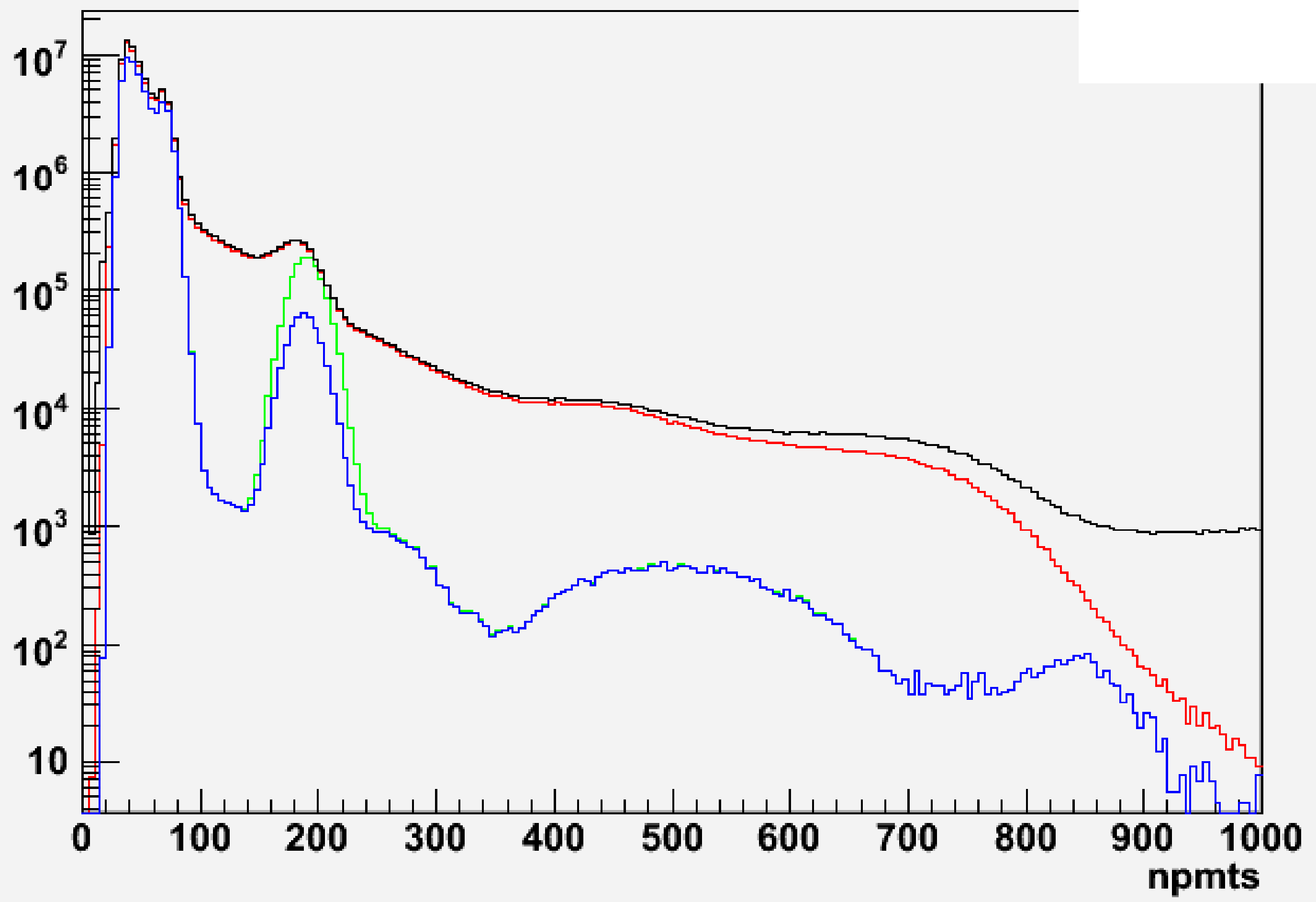
- Calibrations allowed to fine-tune the position reconstruction algorithm and to reduce the systematic error on the Fiducial Volume determination from 6% down to 1%;

- Position resolution is
- $\sigma \sim 10$ cm at 1 MeV;



New results with improved errors to be released soon!

New spectrum of Borexino : statistics of ~750 days



^{8}B neutrinos

Physical Review **D 82**, 033006 (2010)

``Measurement of the ^{8}B neutrino rate with a liquid scintillator target and 3 MeV energy threshold in the Borexino detector''

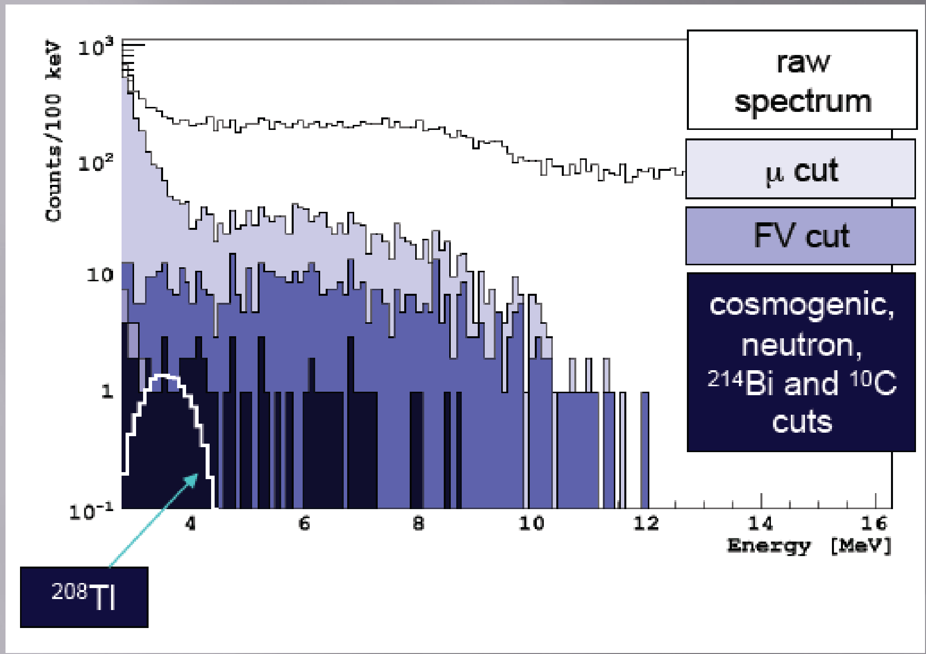
- The very low intrinsic contamination of the scintillator has made it possible (almost unexpectedly) to measure ^{8}B ν ;
- In particular the low content in ^{232}Th has made it possible to lower the threshold for the ^{8}B analysis down to 3.0 MeV;
- First measurement in real-time below 5 MeV;

Statistics collected in 345.3 days of livetime;

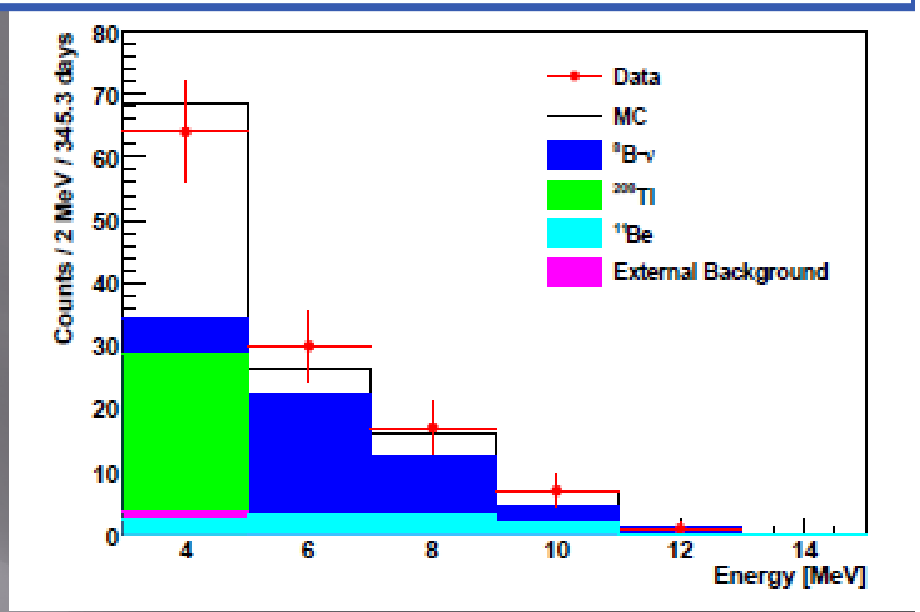
Main contribution to background

- Muons;
- External background;
- Muon daughters;

Cut	Counts 3.0–16.3 MeV	Counts 5.0–16.3 MeV
All counts	1932181	1824858
Muon and neutron cuts	6552	2679
FV cut	1329	970
Cosmogenic cut	131	55
^{10}C removal	128	55
^{214}Bi removal	119	55
^{208}Tl subtraction	90±13	55±7
^{11}Be subtraction	79±13	47±8
Residual subtraction	75±13	46±8
Final sample	75±13	46±8
BPS09(GS98) ^{8}B ν	86±10	43±6
BPS09(AGS05) ^{8}B ν	73±7	36±4



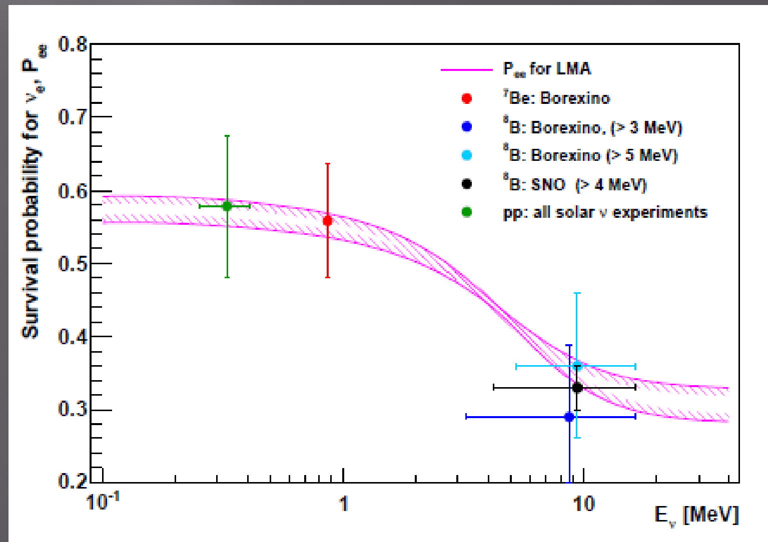
Energy spectrum of events surviving cuts



^{8}B rate in BX above 3 MeV

0.217 ± 0.038 (stat) ± 0.008 (sys) counts/(day × 100t)

- Probing for the first time with the same experiment the Pee in the vacuum regime (7Be neutrinos) and in the matter-enhanced regime (8B neutrinos);



Anti-neutrinos from earth: geoneutrinos

Physics Letters **B 687**, (2010) *299 ``Observation of geo-neutrinos''*

Anti-neutrino detection: inverse β-decay

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

E_{th}=1.8 MeV

Delayed signal

Prompt signal

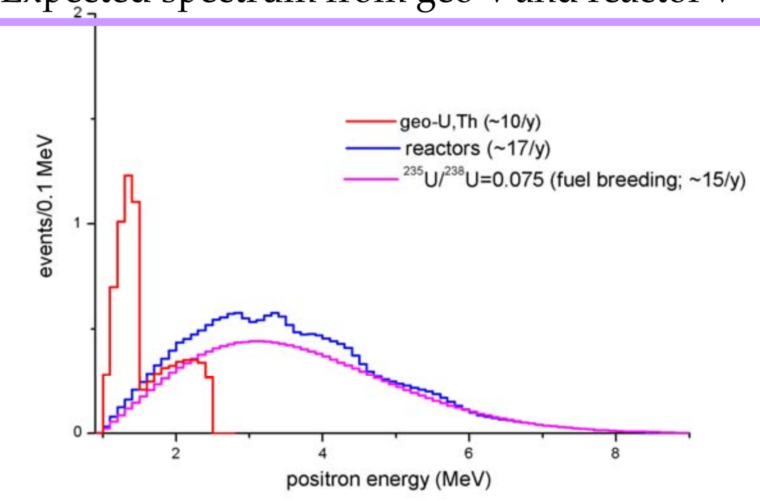
- **Prompt signal:** positron kinetic energy + 1.022 MeV of annichilation gammas;
- **Delayed signal:** neutron is captured by proton (t~256 μsec)and emits 2.2 MeV γ;
- Delayed coincidence reaction is a very strong signature: small background;
- Main backround is due to reactor neutrinos;

Measuring anti-neutrinos from Earth

-spectroscopy of geo-neutrinos provides information on the radiochemical composition of Earth;

-main contribution to radiogenic heat are expected to come from U,Th chains and K;

Expected spectrum from geo-ν and reactor ν

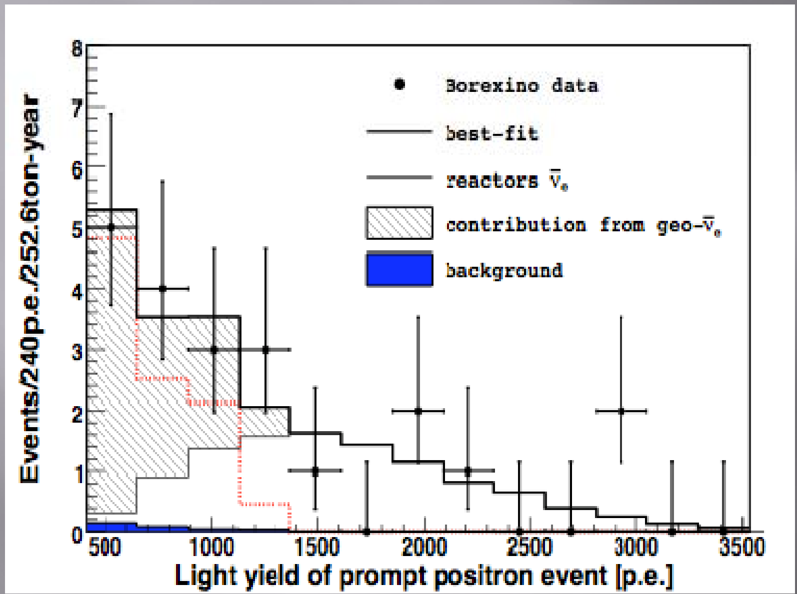


Results: 21 candidates selected December 2007 – December 2009

exposure= 483 live days (252.6 ton-year after all cuts

Estimated backgrounds reactor ν (oscillated) = 17.9 ±0.9

Other residual backgrounds 0.44 ± 0.06



Extract signal with an unbinned maximum likelihood fit using reference MonteCarlo shapes for both geo-neutrinos and reactor neutrinos;

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

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

- the first clear observation of geoneutrinos at 4.2σ ;
- the rate is measured with 40% precision;
- confirmation/exclusion of geological models limited by the statistics;
- the first measurement of oscillations (reactor antinu) at 1000 km @ 2.9s;
- georeactor in the Earth core with > 3 TW rejected at 95% C.L.;

Conclusions

•Borexino has been running successfully since May 2007;

THE PAST

•Measurement of 7Be rate with a total error of 10%;
•Measurement of 8B rate down to 3 MeV;
•Observation of geo-neutrinos;
•Limits on neutrino magnetic moments;
•Limits on forbidden processes (Pauli esclusion principle);

THE PRESENT

•New measurement of 7Be rate with a reduced error to be published soon;
•Measurement of Day/Night asymmetry of 7Be neutrinos with reduced error to be published soon;

THE FUTURE

•Search for pep and CNO neutrinos
• pp neutrinos (?)
•For this a new purification campaigns is in progress to reduce Kr and Bi