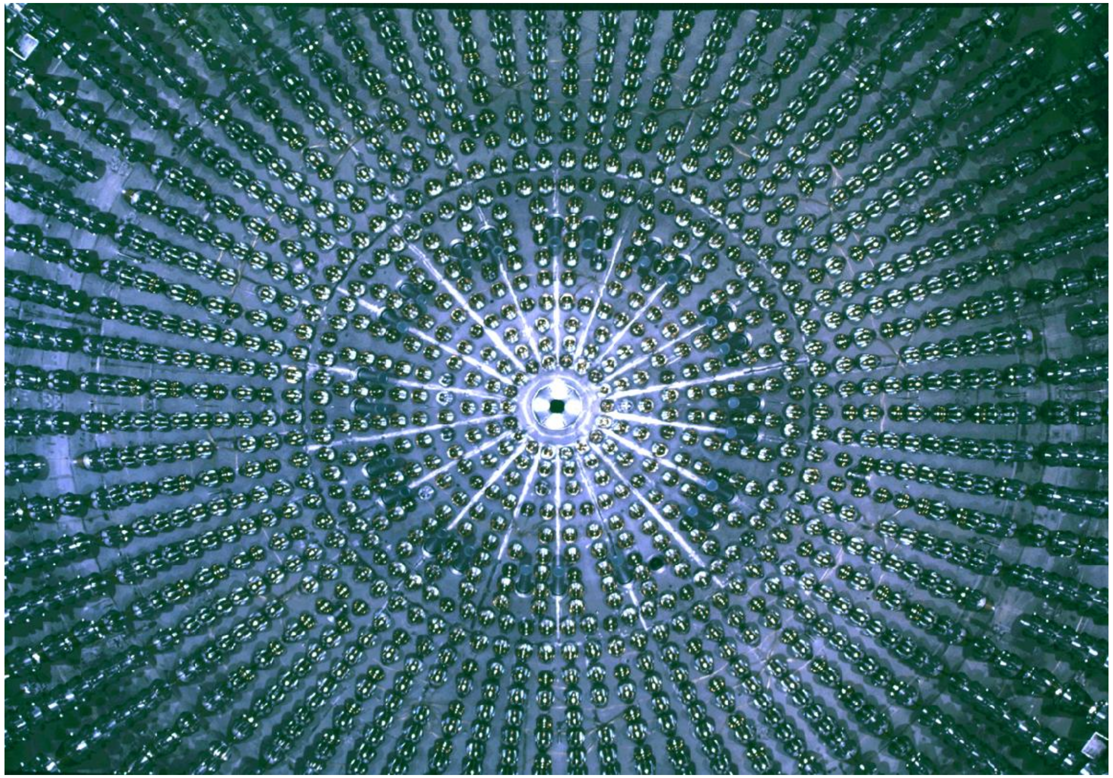
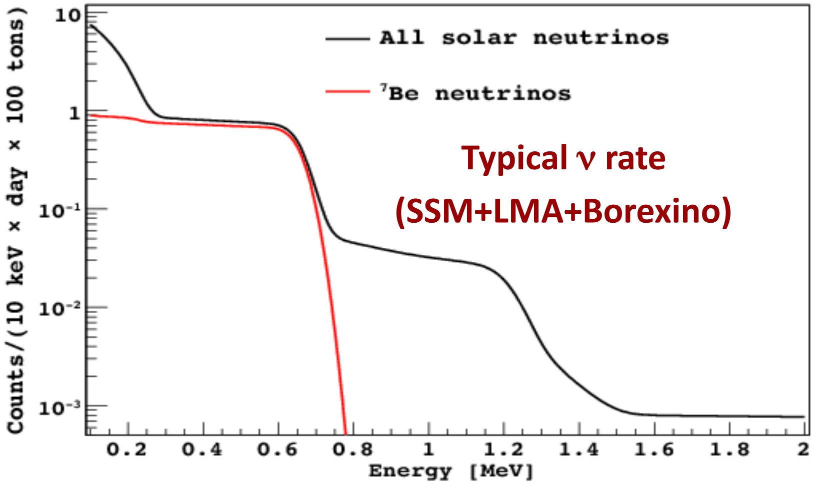
Neutrino Physics with the Borexino experiment



Emanuela Meroni
On behalf of the Borexino Collaboration

Physics and detection principles

- Borexino aims to measure low energy solar neutrinos in **real time** by elastic neutrino-electron scattering in a volume of **highly purified liquid scintillator**
  - Mono-energetic 0.862 MeV ^{7}Be ν is the main target
  - ^{8}B, pep, CNO and possibly pp ν
  - Geoneutrinos
  - Supernova ν

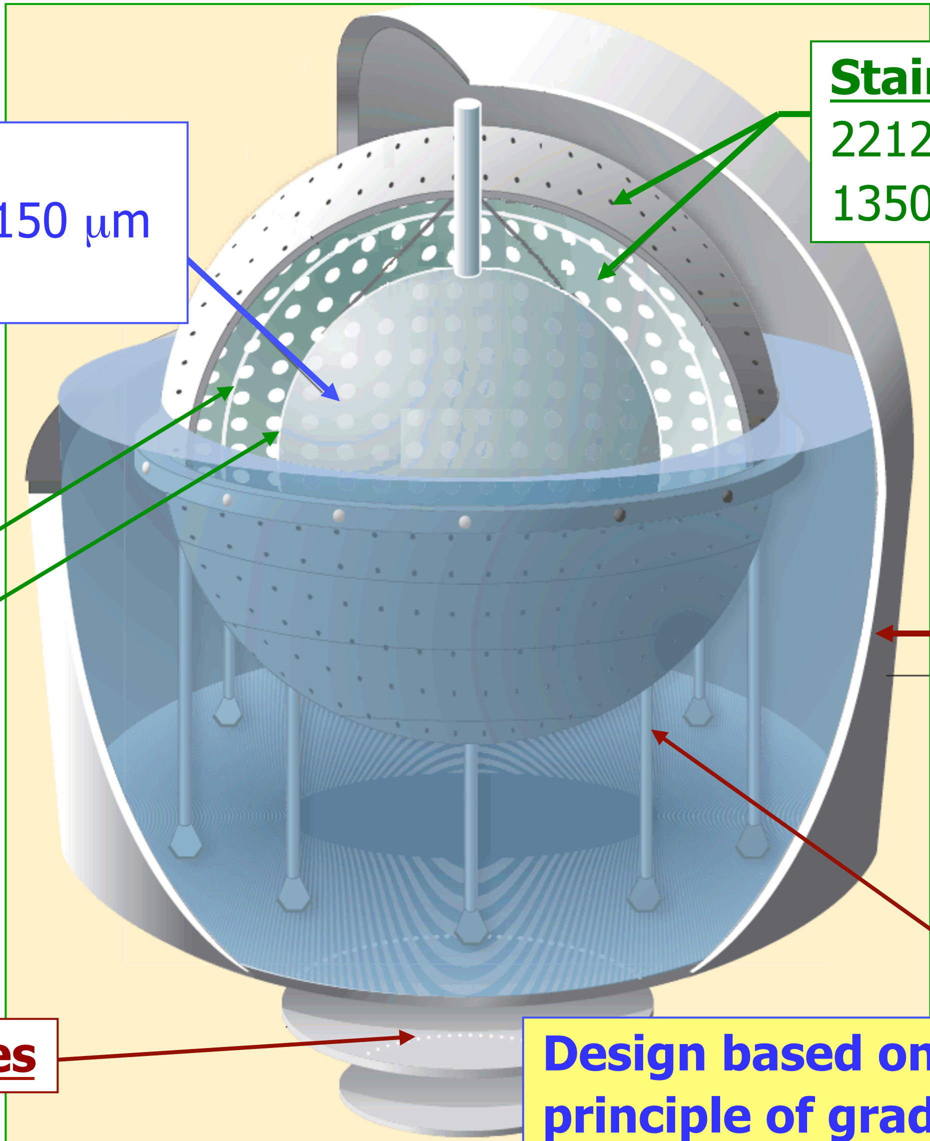


- Detection via scintillation light
  - Very low energy threshold
  - Good position reconstruction
  - Good energy resolution
- Drawbacks:
  - No direction measurements
  - ν induced events can't be distinguished from β-decay due to natural radioactivity

Extreme radiopurity of the scintillator

Detector design and layout

Borexino detector at LNGS



Scintillator:
270 t PC+PPO in a 150 μm thick nylon vessel

Stainless Steel Sphere:
2212 photomultipliers
1350 m^3

Nylon vessels:
Inner: 4.25 m
Outer: 5.50 m

Water Tank:
γ and *n* shield
μ water č detector
208 PMTs in water
2100 m^3

20 legs

Carbon steel plates

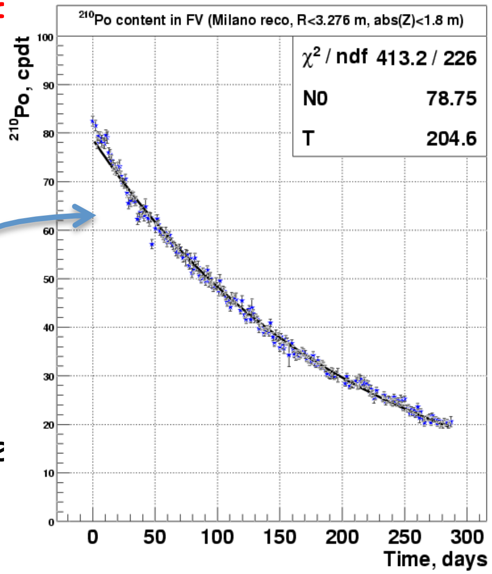
Design based on the principle of graded shielding

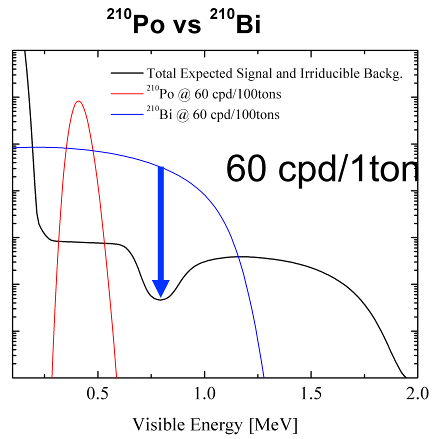
Background suppression: achievements

Radioisotopes	Typical	Goal	Achieved in Bx	detection
^{238}U	~10^{-5} - 10^{-6} g/g	10^{-16} g/g	1.9 x 10^{-17} g/g	^{214}Bi-Po (τ=236μs)
^{232}Th	~10^{-5} - 10^{-6} g/g	10^{-16} g/g	6.8 x 10^{-18} g/g	^{212}Bi-Po (τ=433ns)

➪ 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 decays away with its lifetime (200d)
  - It is NOT in equilibrium with ^{238}U nor ^{210}Pb;





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

^{85}Kr β decay : (β decay has an energy spectrum similar to the ^{7}Be recoil electron)

^{85}Kr $\xrightarrow{\beta}$ ^{85}Rb

687 keV

τ = 10.76 y - BR: 99.56%

^{85}Kr is studied through :

^{85}Kr $\xrightarrow{\beta}$ ^{85m}Rb $\xrightarrow{\gamma}$ ^{85}Rb

173 keV — 514 keV

τ= 1.46 μs - BR: 0.43%

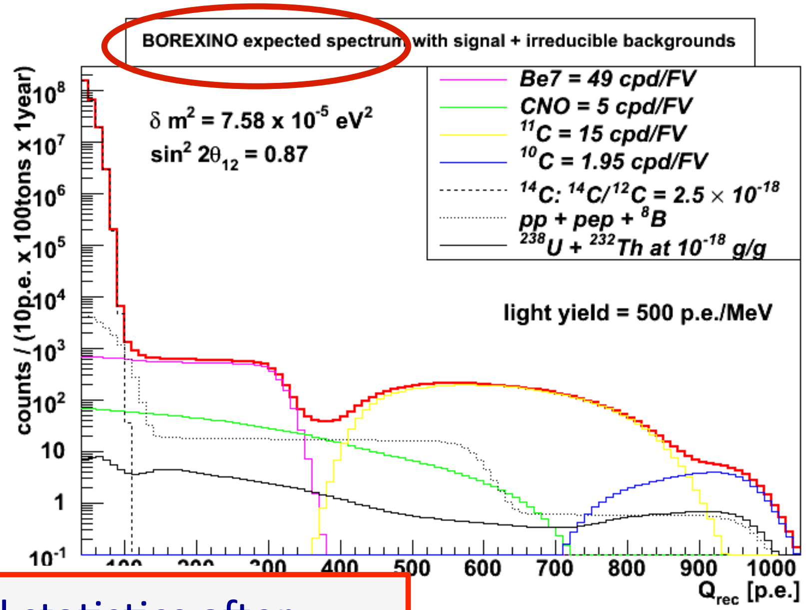
Measured with 751 days of statistics
32 candidate events in final sample

➘ Result on ^{85}Kr contamination (main β decay to ^{85}Rb ground state)

30 ± 5 c / (dayx100 t)

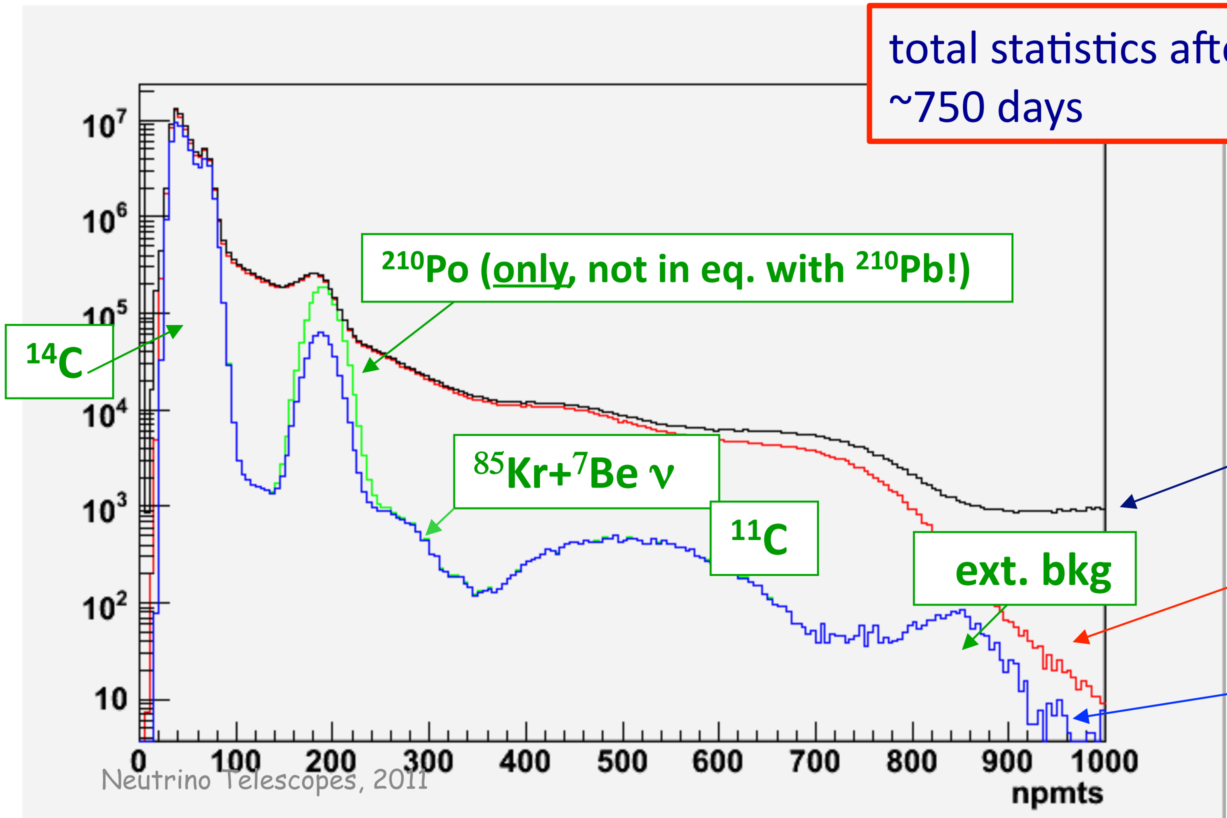
---> Taken as free parameter in the total fit

Selection criteria to obtain the final spectrum



Understanding the final spectrum: main components

total statistics after ~750 days



No cuts

After μ + Muon daughter cut

After FV cuts
Soft α/β cut

Borexino started taking data on May 15th 2007
Published results on ^{7}Be solar neutrinos

First real-time detection of ^{7}Be solar neutrinos by Borexino. PLB 658 2008

(47.4 live days between May and July 2007)

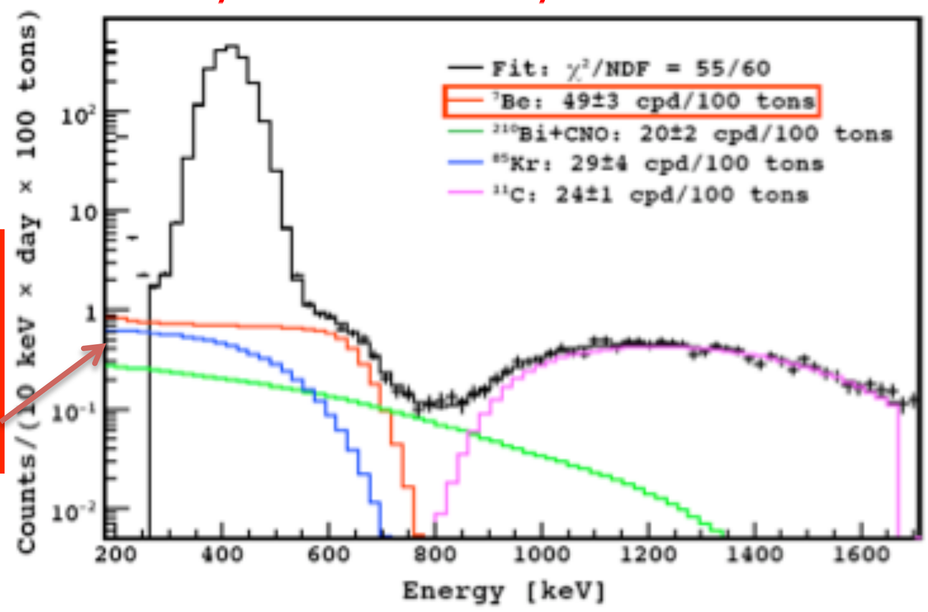
^{7}Be ν Rate: **47 ± 7$_{STAT}$ ± 12$_{SYS}$** c/(dx100 t)

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

^{7}Be ν Rate : **49 ± 3$_{STAT}$ ± 4$_{SYS}$** c/(dx100 t)

Source	Syst, error 1σ
Tot. Scint. mass	±0.2 %
Live time	±0.1 %
Efficiency of Cuts	±0.3 %
Detector resp. func	±6 %
Fiducial mass	±6 %
TOT	±8.5 %

May 2008: 192 days of statistics

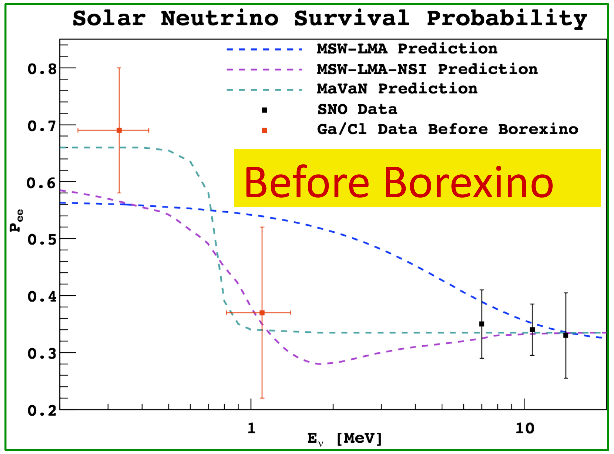


In this talk we give the new preliminary result of the ^{7}Be rate with error reduced to 4.3%

^{7}Be ν Rate:
46 ± 1.5$_{STAT}$ ± 1.3$_{SYS}$ c/d/100 t
in 750 days of data

Why measure Solar νs ?

- **MSW-LMA** scenario is our current understanding of solar νs and ν oscillations
  - ✗ Mainly from ^{8}B neutrinos + plus radiochemical experiments + reactor
    - ✗ **Pee very poorly constrained !**



- Borexino alone aims to independently confirm the **MSW-LMA** scenario with:
  - ✓ ^{7}Be neutrino rate with a total error < 5%
  - ✓ DayNight asymmetry study (in progress)
  - ✓ ^{8}B neutrino

- **Solar Physics**:
  - ✓ Sub-MeV Solar ν flux
  - ✓ Metallicity controversy
    - ✓ The abundance of elements heavier than helium (metallicity) is used as inputs in the Standard Solar Model
      - – the neutrino fluxes depend on metallicity

^{7}**Be** may yield useful infos if precision is good enough **(5%)**

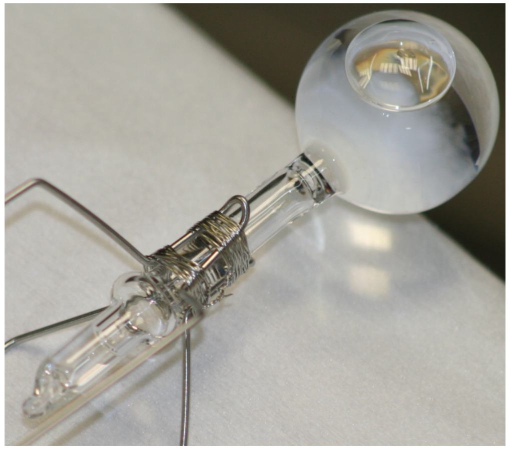
	Φ(n s^{-1} cm^{-2}) High-metallicity GS98	Φ(n s^{-1} cm^{-2}) Low-metallicity AGS05	$\Delta\Phi$
pp	5.97×10^{10}	6.04×10^{10}	
pep	1.41×10^{8}	1.45×10^{8}	
hep	7.90×10^{3}	8.22×10^{3}	
^{7}Be	5.07×10^{9}	4.55×10^{9}	10%
^{8}B	5.94×10^{6}	4.72×10^{6}	21%
^{13}N	2.88×10^{8}	1.89×10^{8}	31%
^{15}O	2.15×10^{8}	1.34×10^{8}	31%
^{17}F	5.84×10^{6}	3.25×10^{6}	44%

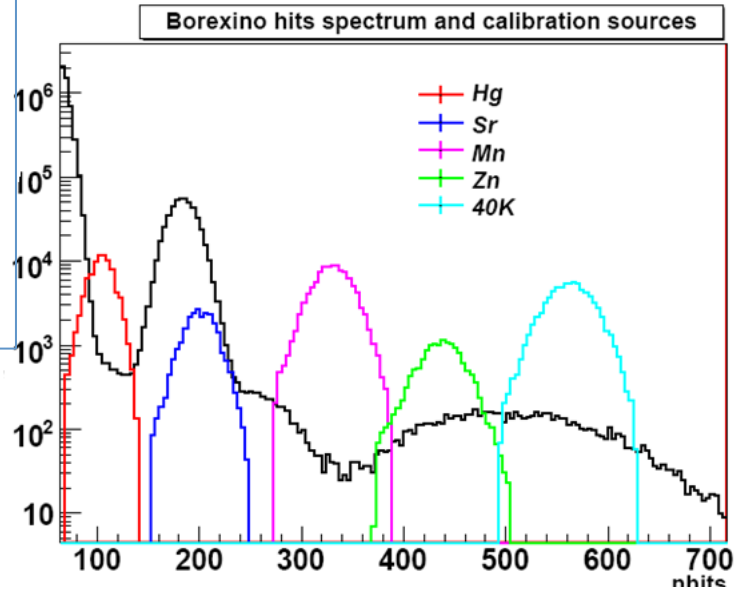
$\Phi_{SNO}(^{8}B) = 4.94 \times 10^{6}\ cm^{-2}\ s^{-1}$

Calibrations of the detector

In 2009 we have performed an extensive and detailed calibration campaign with internal α,β,γ, and neutron sources

1. Calibration of the detector with internal (and external) radioactive sources
   - Measure the accuracy of the position reconstruction
   - Measure the resolution of the position Reconstruction
   - Check the energy scale
2. Reproduce the calibration data with a Full simulation (MonteCarlo) code
   - Use the MC code to model and reproduce the whole detector response function
   - Use the MC to analyze the real data





- α,β : 222Rn loaded liquid scintillator vial
  - Clean α,β tag from 214Bi-214Po fast coincidence
- γ: dopant dissolved in small water vial
  - ^{57}Co, ^{139}Ce, ^{203}Hg, ^{85}Sr, ^{54}Mn, ^{65}Zn, ^{60}Co, ^{40}K
- neutrons:
  - Am-Be source

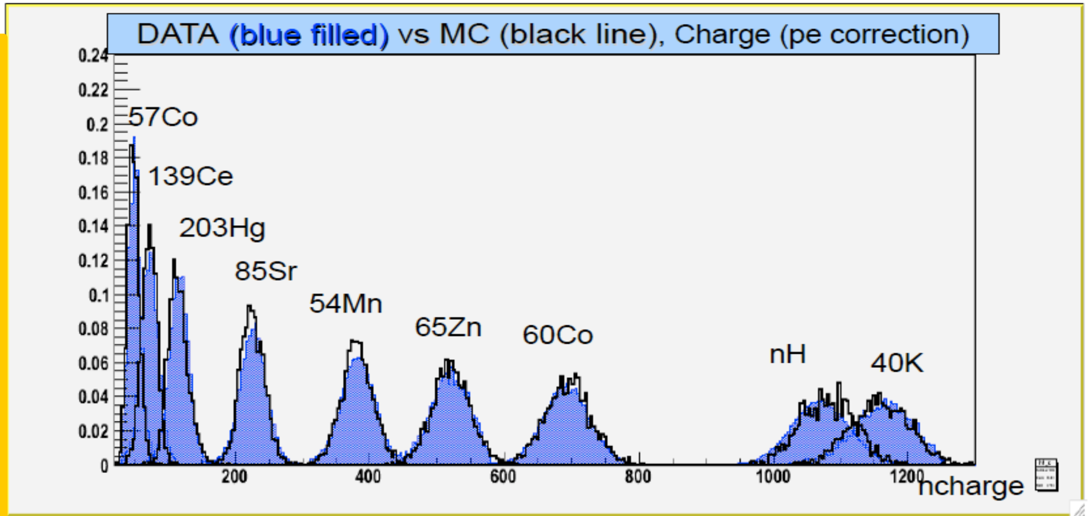
	γ								β		α	n		
	^{57}Co	^{139}Ce	^{203}Hg	^{85}Sr	^{54}Mn	^{65}Zn	^{60}Co	^{40}K	^{14}C	^{214}Bi	^{214}Po	n-p	n $+^{12}C$	n+Fe
energy (MeV)	0.122	0.165	0.279	0.514	0.834	1.1	1.1, 1.3	1.4	0.15	3.2		2.226	4.94	~7.5

Energy scale and energy resolution

- Before calibrating the energy scale was determined by means of internal contaminants (^{14}C , ^{11}C, …);
- 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:

- Precise calibration in the 0-7 MeV range
- the uncertainty on the energy scale between 0-2MeV is less than 1.3%;
- study of the uniformity of detector response as a function of position



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

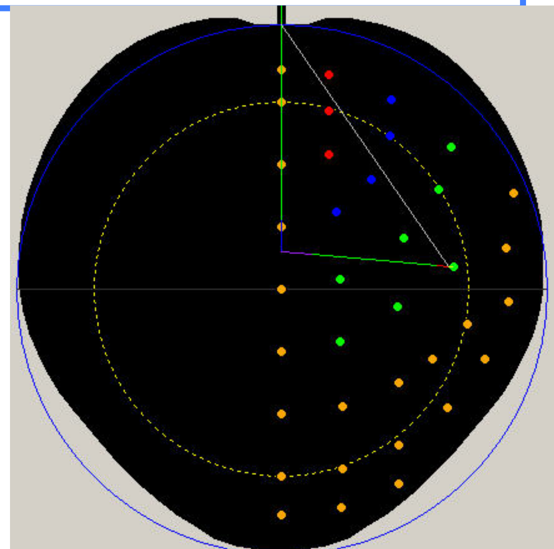
- This high light-yield leads to a good energy resolution
- $\sigma(E)/E = 5\%$ at 1MeV;

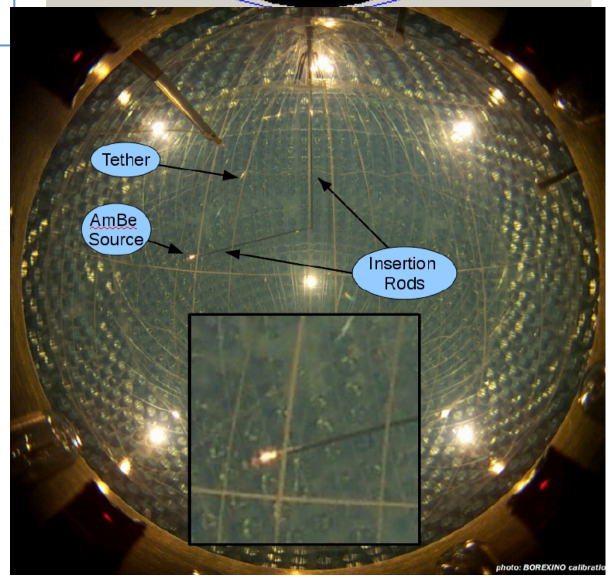
Position reconstruction and FV definition

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

Calibrations:

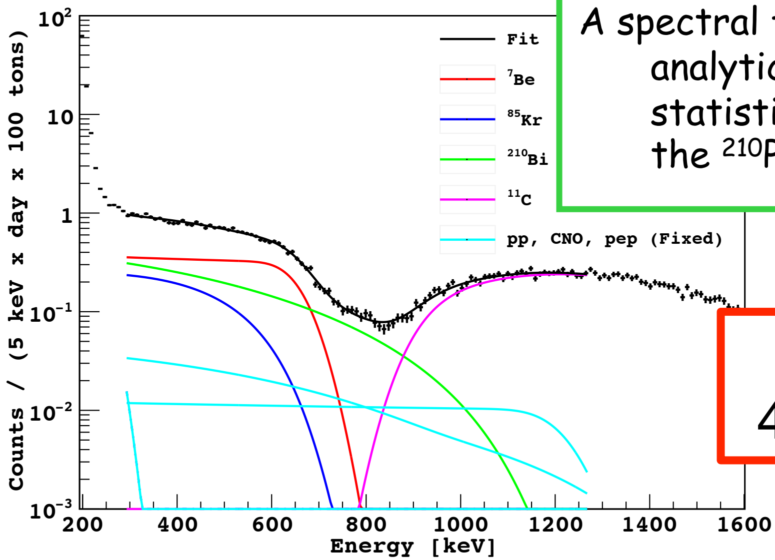
- Absolute position of the source determined by means of a LED and cameras with a precision of 2cm
- allowed to fine-tune the position reconstruction algorithm
- max difference between reconstructed and measured position = 2 cm !
- Position resolution is $\sigma \sim 10$ cm at 1 MeV





systematic error on the Fiducial Volume determination from 6% down to 1.3%

New result on ^{7}Be rate (preliminary)

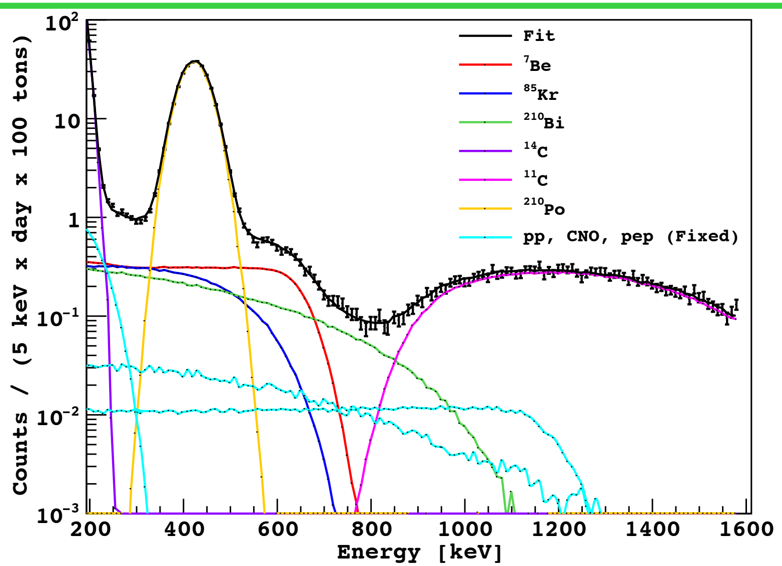


A spectral fit based on an analytical model with statistical subtraction of the ^{210}Po alpha component

~750 days of data

^{7}Be rate (E=862 keV line)
46.0 ± 1.5 (stat) ± 1.3 (sys) counts/(day x 100t)

A spectral fit based on MonteCarlo



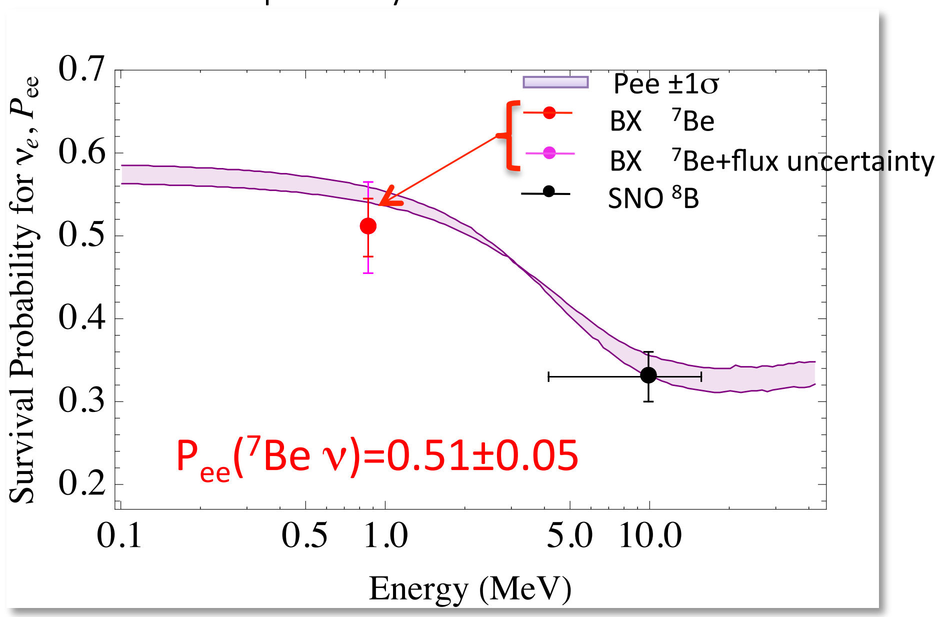
Source	Syst, error 1σ
Tot. Scint. mass	±0.3 %
Live time	±0.1 %
Fraction of good events removed by cuts	±0.6 %
Energy scale	±1.3 %
Fiducial mass	±1.3 %
Fit method (α/β subtraction)	±1.0 %
Fit assumption	±1.7 %
Total syst. error	±2.73 %

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

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

46.0 ± 1.5 (stat) ± 1.3 (sys)

Survival probability for solar neutrinos



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:

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

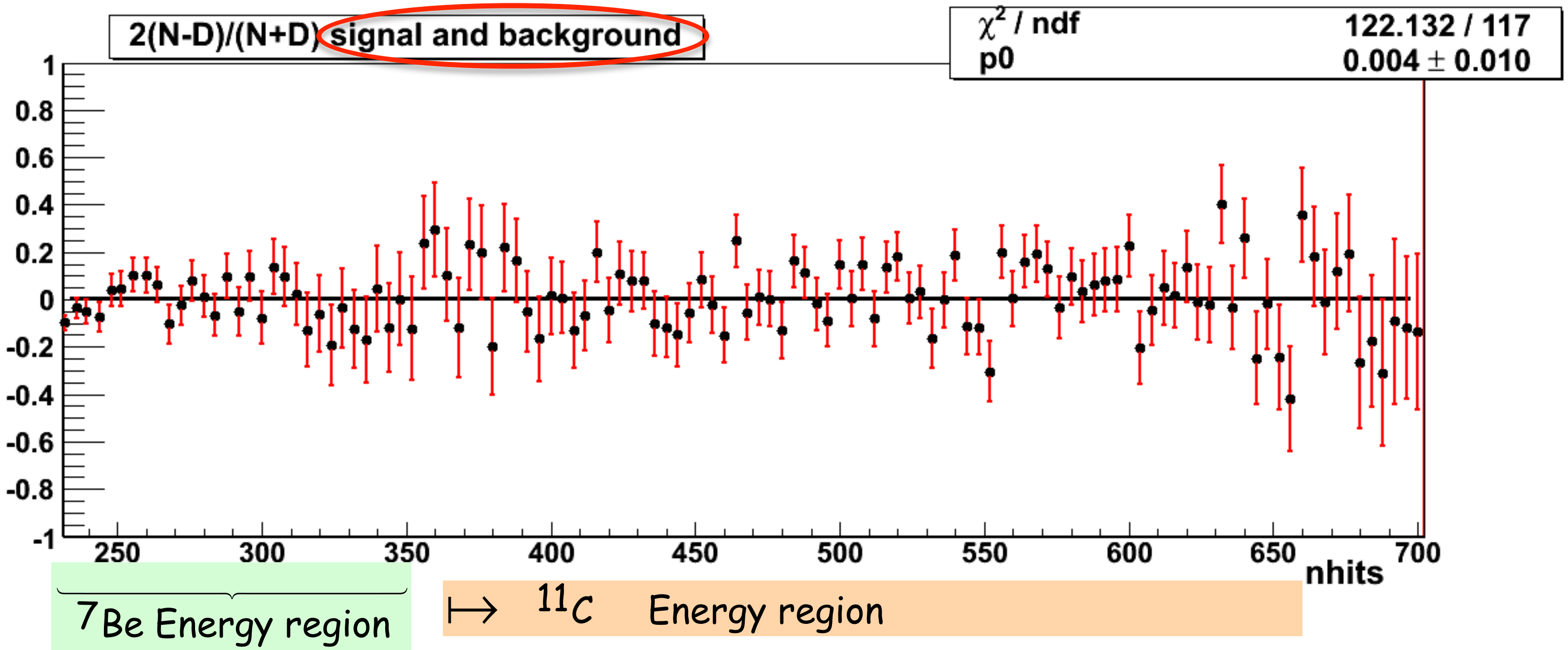
A_{dn} depends on the value of the oscillation parameters and on the neutrino energy.

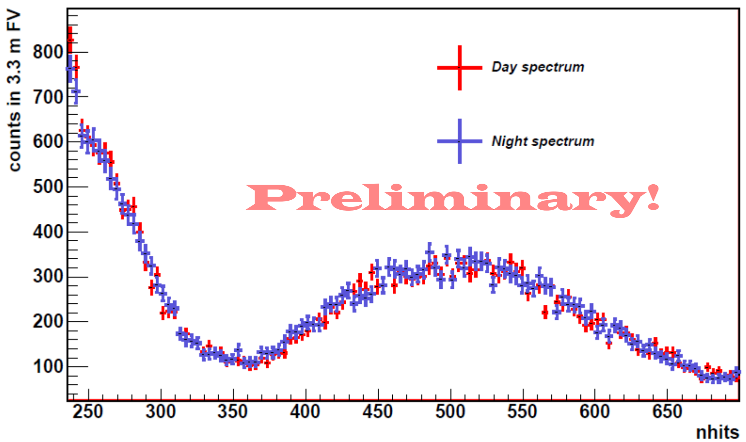
J. Bahcall JHEP07(2002)054

Observable	LMA	LOW $\Delta m^2 \approx 10^{-7}\ eV^2$
^{7}Be	0.64±0.07	0.58±0.05
ADN	~0%	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

The day night preliminary result





^{7}Be Day spectrum	387.46 days
^{7}Be Night spectrum	401.57 days
Statistical error	2.3 c/(dx100t)

The day night preliminary result

- The ^{7}Be flux is obtained from the separated full fit of the day and night spectra
- Preliminary (and conservative) result: $A_{DN} = 2\frac{\Phi_n - \Phi_d}{\Phi_n + \Phi_d} = 0.007 \pm 0.073(stat)$

- A_{DN} is well consistent with zero: further confirmation of the LMA!
- Unique measurement for solar ^{7}Be neutrinos

- Result not sensitive to many systematic effect influencing the ^{7}Be absolute measurement

⇨ More refined analysis is in progress aiming to reduce the error

^{8}B ν at 3 MeV energy threshold

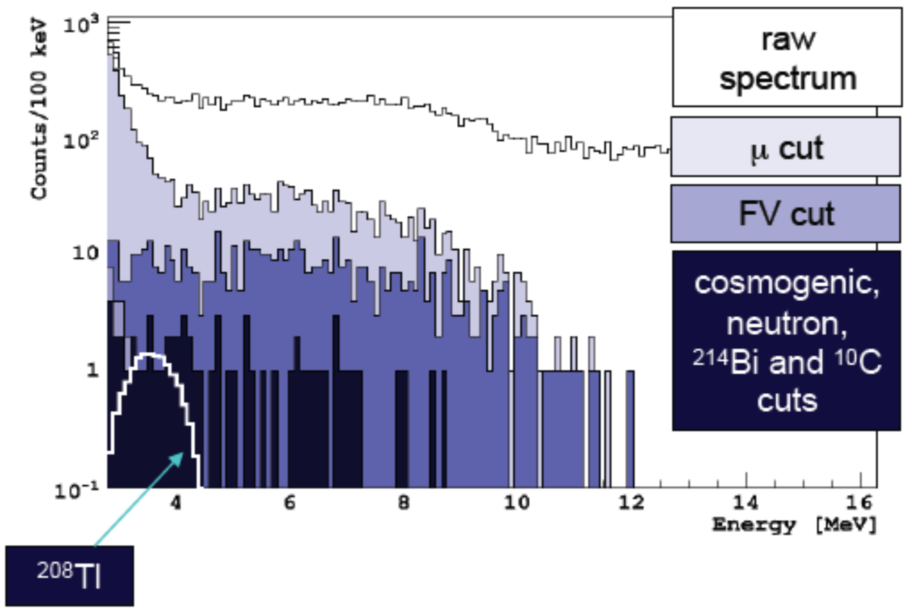
Measurement of the ^{8}B neutrino rate with a liquid scintillator target and 3 MeV energy threshold in the Borexino detector
Physical Review **D 82**, 033006 (2010)

- 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;

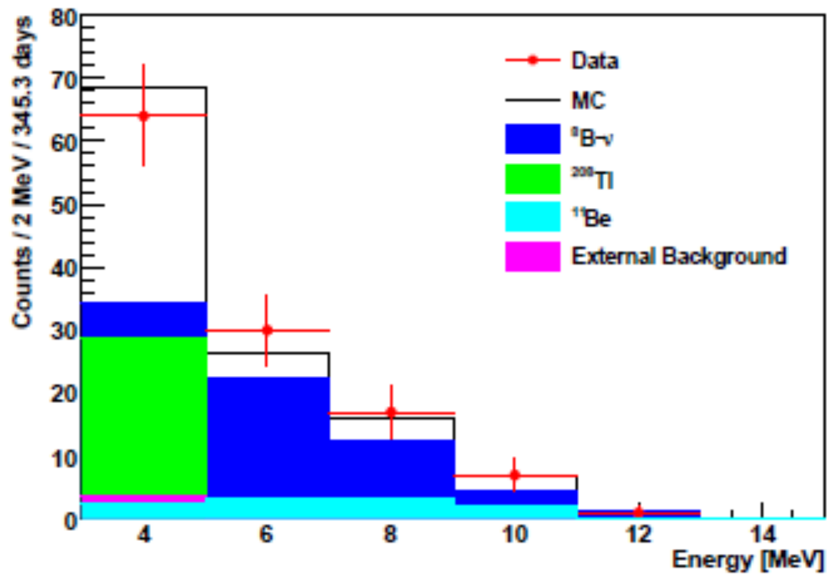
Main contribution to background
- Muons;
- External background;
- Muon daughters;

- Statistics collected in 345.3 days of livetime;

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



Systematic errors

Source	E>3 MeV σ_+	E>3 MeV σ_-	E>5 MeV σ_+	E>5 MeV σ_-
Energy threshold	3.6%	3.2%	6.1%	4.8%
Fiducial mass	3.8%	3.8%	3.8%	3.8%
Energy resolution	0.0%	2.5%	0.0%	3.0%
Total	5.2%	5.6%	7.2%	6.8%

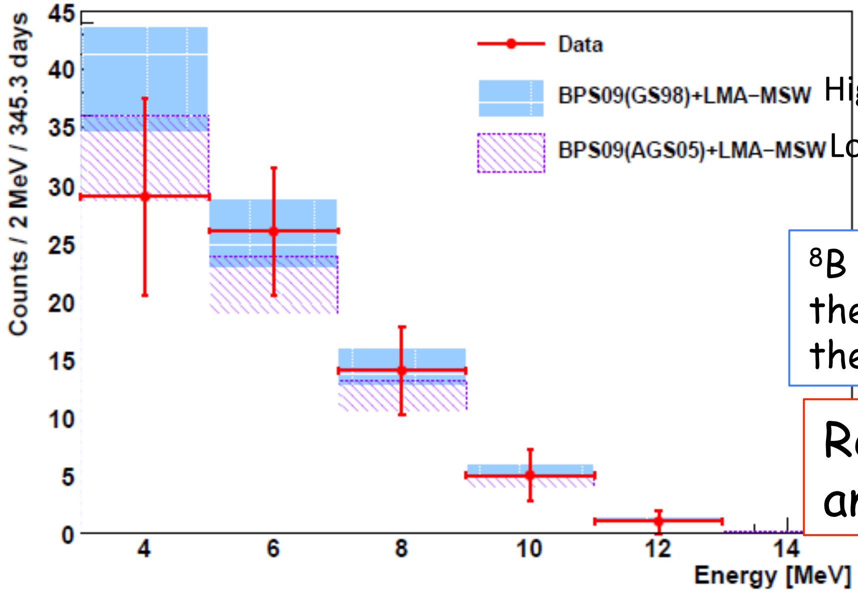
Energy threshold: $^{241}Am^{9}Be$ neutron source, n capture on ^{1}H (2.2 MeV γ), on ^{14}C (4.9MeV γ), on ^{56}Fe (7.6MeV γ), on ^{56}Fe (9.3MeV γ)

Fiducial mass: off-axis source insertion system to place sources at several locations

^{8}B rate in BX above 3 MeV

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

^{8}B ν with 3 MeV energy threshold in Borexino

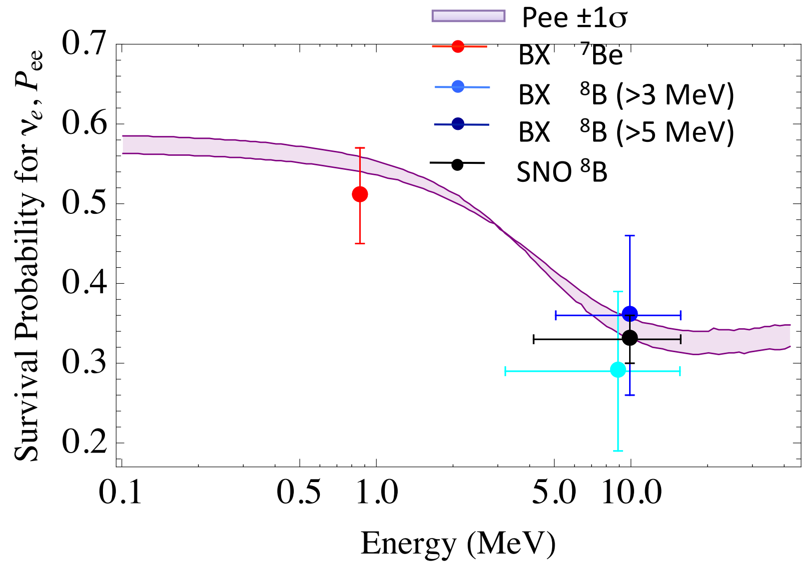


High metallicity

Low metallicity

^{8}B solar neutrinos: electron recoil spectrum after the background subtraction and comparison with the models

Results in agreement with LMA-MSW and solar models



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

Observation of Geo-neutrinos

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

Anti-neutrino detection: inverse β-decay

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

E_{th}=1.8 MeV

Delayed signal (n) | Prompt signal (e^+)

- **Prompt signal:** positron kinetic energy + 1.022 MeV of annihilation gammas
- **Delayed signal:** neutron is captured by proton (τ~256 μsec) and emits 2.2MeV γ

- Delayed coincidence reaction is a very strong signature: small background
- Main background is due to reactor neutrinos (large distance);

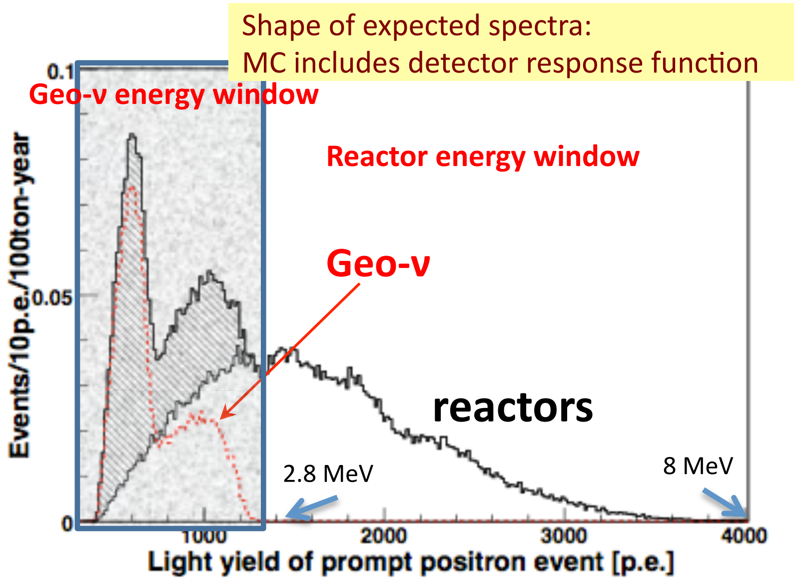
Measuring anti-neutrinos from Earth

-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;

–Borexino is on continental crust

–Complementary information compared to KamLand



Backgrounds (besides reactors)

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

Muon correlated events (τ = 150 ms)
- Removed with 2 s detector veto after each muon in Inner Detector

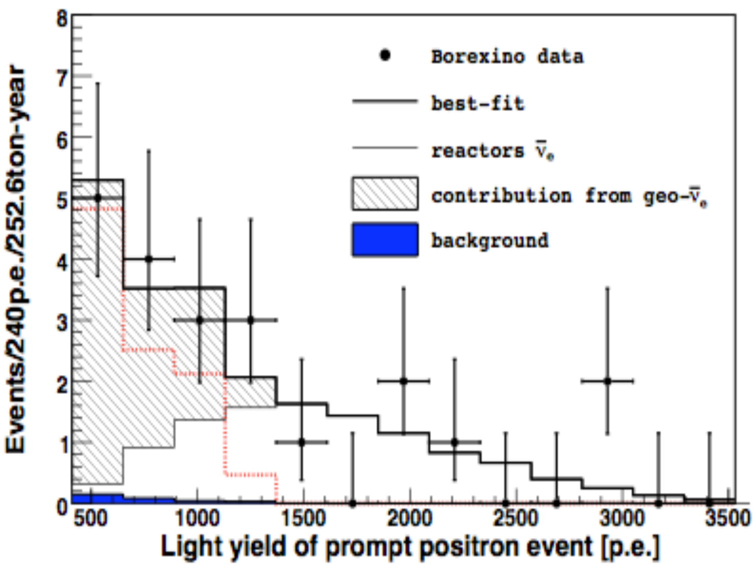
Fast neutrons generated by muons outside IV
- 2 ms veto

Radiogenic $^{13}C(\alpha,n)^{16}O$
- From ^{210}Po as α emitter: 12 c/(ton day) on average
- ^{13}C / ^{12}C abundance is low: 1.1 %

To be compared: 2.5 geo-ν/100 ton-year assuming BSE)

GeoNeutrino Results:

- 21 candidates selected
- exposure= 483 live days (252.6 ton-year after all cuts) December 07 – December 09



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

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

68.3 % 99.7%

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

- 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;
- confirmation of oscillations (reactor antinu) at 1000 km @ 2.9σ;
- georeactor in the Earth core with > 3 TW rejected at 95% C.L.;

Conclusions

- Borexino has been running successfully since May 2007

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

THE FUTURE

- Search for pep neutrinos
- pp neutrinos (?)

⇨ For this a new purification campaigns is in progress to reduce Kr and Bi
  - Purification with Water Extraction + N_2 stripping is in progress
- If successful, a new phase will start with the goal of observing other solar neutrino components, improve geo-neutrino measurement

Borexino collaboration

Genova

Milano

Perugia

Princeton University

Virginia Tech. University

Umass Amherst

APC Paris

Dubna JINR (Russia)

Kurchatov Institute (Russia)

Jagiellonian U. Cracow (Poland)

Heidelberg (Germany)

Munich (Germany)

St. Petersburg