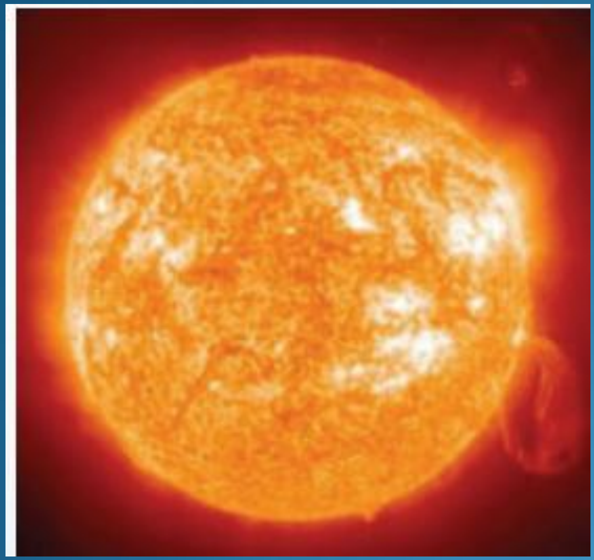
Solar Neutrino Physics With Borexino I



Livia Ludhova
INFN Milano, Italy
(on behalf of Borexino collaboration)

Borexino Collaboration

Milano

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Princeton University

Kurchatov Institute (Russia)

Heidelberg (Germany)

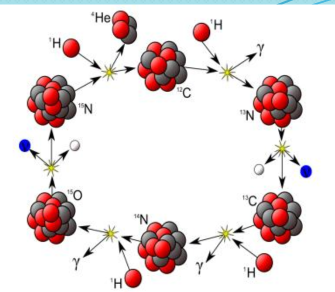
Virginia Tech. University

Jagiellonian U. Cracow (Poland)

Dubna JINR (Russia)

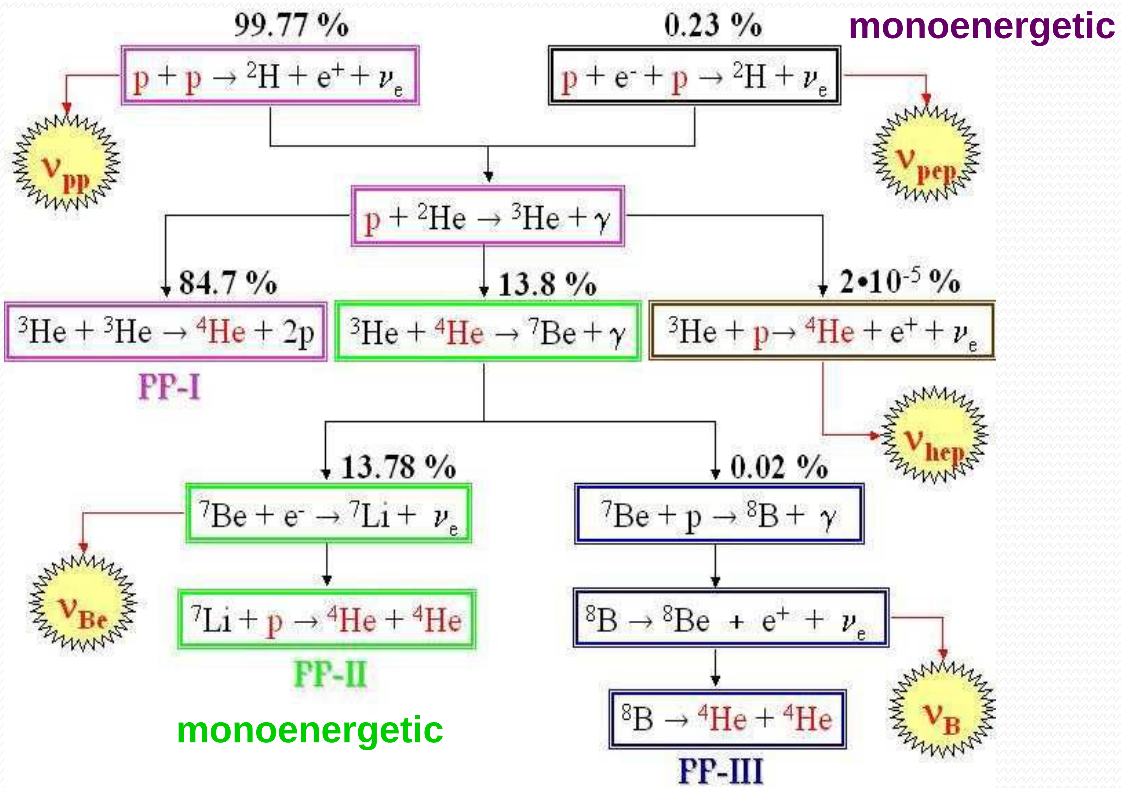
Munich (Germany)

APC Paris



Nuclear reactions in the Sun

PP cycle… 99% of energy

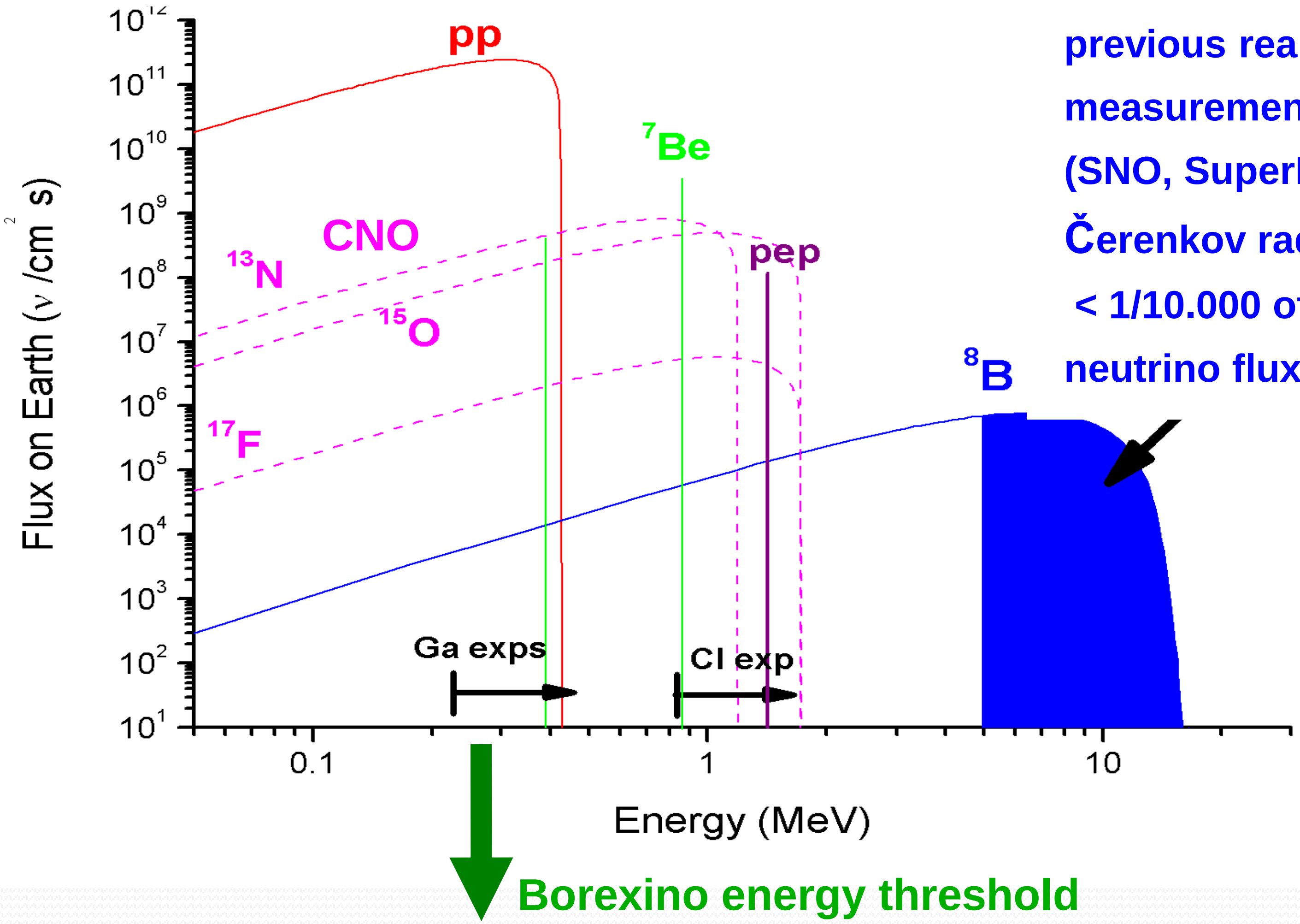


CNO cycle… <1% of energy

Poorly known
Not directly measured

$$^{12}C + {}^1H \rightarrow {}^{13}N + \gamma$$
$$^{13}N \rightarrow {}^{13}C + e^+ + \nu$$
$$^{13}C + {}^1H \rightarrow {}^{14}N + \gamma$$
$$^{14}N + {}^1H \rightarrow {}^{15}O + \gamma$$
$$^{15}O \rightarrow {}^{15}N + e^+ + \nu$$
$$^{15}N + {}^1H \rightarrow {}^{12}C + {}^4He$$
$$\rightarrow {}^{16}O + \gamma$$
$$^{16}O + {}^1H \rightarrow {}^{17}F + \gamma$$
$$^{17}F \rightarrow {}^{17}O + e^+ + \nu$$
$$^{17}O + {}^1H \rightarrow {}^{14}N + {}^4He$$

Solar-neutrino energy spectrum



previous real-time measurements (SNO, SuperKamiokande) Čerenkov radiation < 1/10.000 of the total solar neutrino flux

Borexino energy threshold

What can we learn from solar neutrinos (1) ?

Astrophysics: resolving "metallicity problem"

metallicity
abundance of the elements above He

New 3D Standard Solar Models -> lower metallicity -> discrepancy with helioseismology…
where is the problem?

Sources	$\Phi(\nu\ \mathrm{sec}^{-1}\ \mathrm{cm}^{2})$ *high-metallicity*	$\Phi(\nu\ \mathrm{sec}^{-1}\ \mathrm{cm}^{2})$ *low-metallicity*	Difference %
pp	$5.98(1\pm0.006)\times10^{10}$	$6.03(1\pm0.006)\times10^{10}$	0.8
pep	$1.44(1\pm0.012)\times10^{8}$	$1.47(1\pm0.012)\times10^{8}$	2.0
hep	$8.04(1\pm0.300)\times10^{3}$	$8.31(1\pm0.300)\times10^{3}$	3.3
^{7}Be	$5.00(1\pm0.070)\times10^{9}$	$4.56(1\pm0.070)\times10^{9}$	9.4
^{8}B	$5.58(1\pm0.140)\times10^{6}$	$4.59(1\pm0.140)\times10^{6}$	19.8
^{13}N	$2.96(1\pm0.140)\times10^{8}$	$2.17(1\pm0.140)\times10^{8}$	31.6
^{15}O	$2.23(1\pm0.150)\times10^{8}$	$1.56(1\pm0.150)\times10^{8}$	33.5
^{17}F	$5.52(1\pm0.170)\times10^{6}$	$3.40(1\pm0.160)\times10^{6}$	53.0

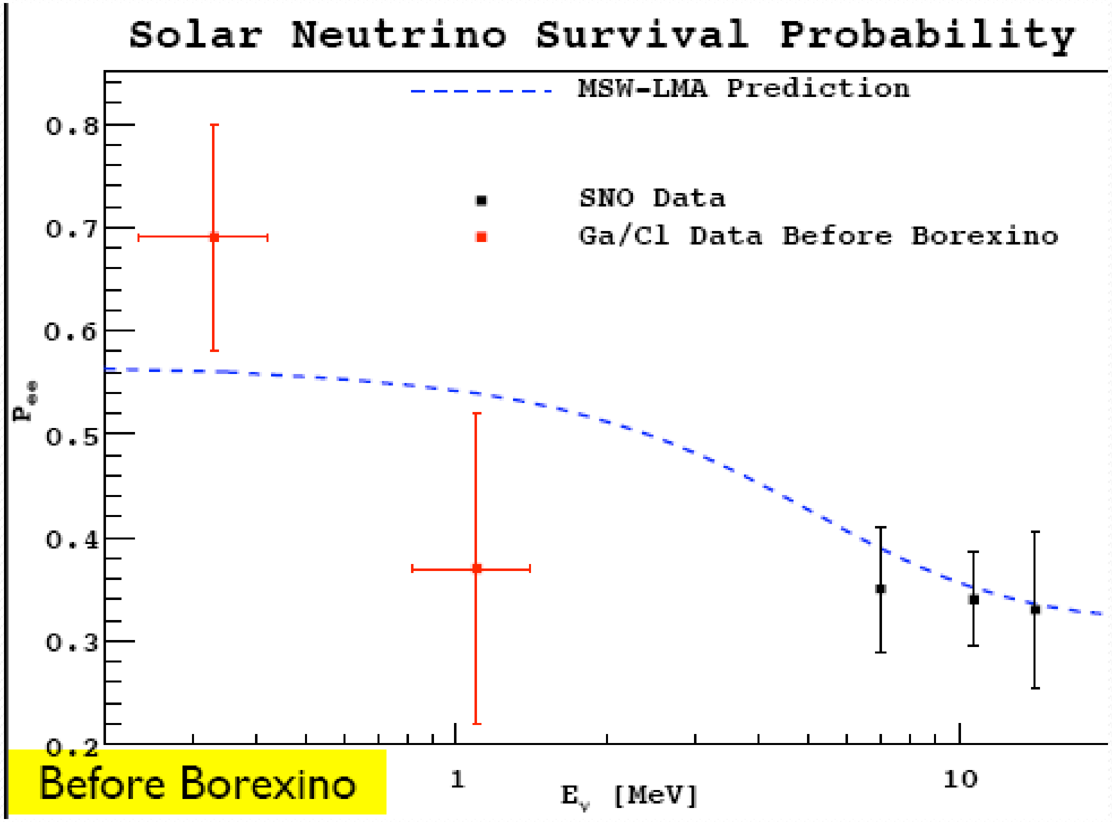
Solar neutrino fluxes depend on metallicity!

- **Solar Model:** Serenelli, Haxton and Pena-Garay arXiV:1104.1639
- **High metallicity GS98** = Grevesse et al. *S. Sci. Rev. 85,161 ('98);*
- ***Low metallicity AGS09*** = *Asplund, et al,* A.R.A.&A. 47(2009)481;

What can we learn from solar neutrinos (2) ?

Neutrino Physics: precision measurement of solar ν fluxes vs survival probability P_{ee}

Pee = electron neutrino survival probability from the Sun's core to the detector



Vacuum regime

Matter regime

Low energy neutrinos:
flavor change dominated
by vacuum oscillations;

High energy neutrinos:
Resonant oscillations in matter
(MSW effect):
Effective electron neutrino mass
is increased due to the charge
current interactions
with electrons of the Sun

Transition region:
Decrease of the ν_e survival
probability (P_{ee})

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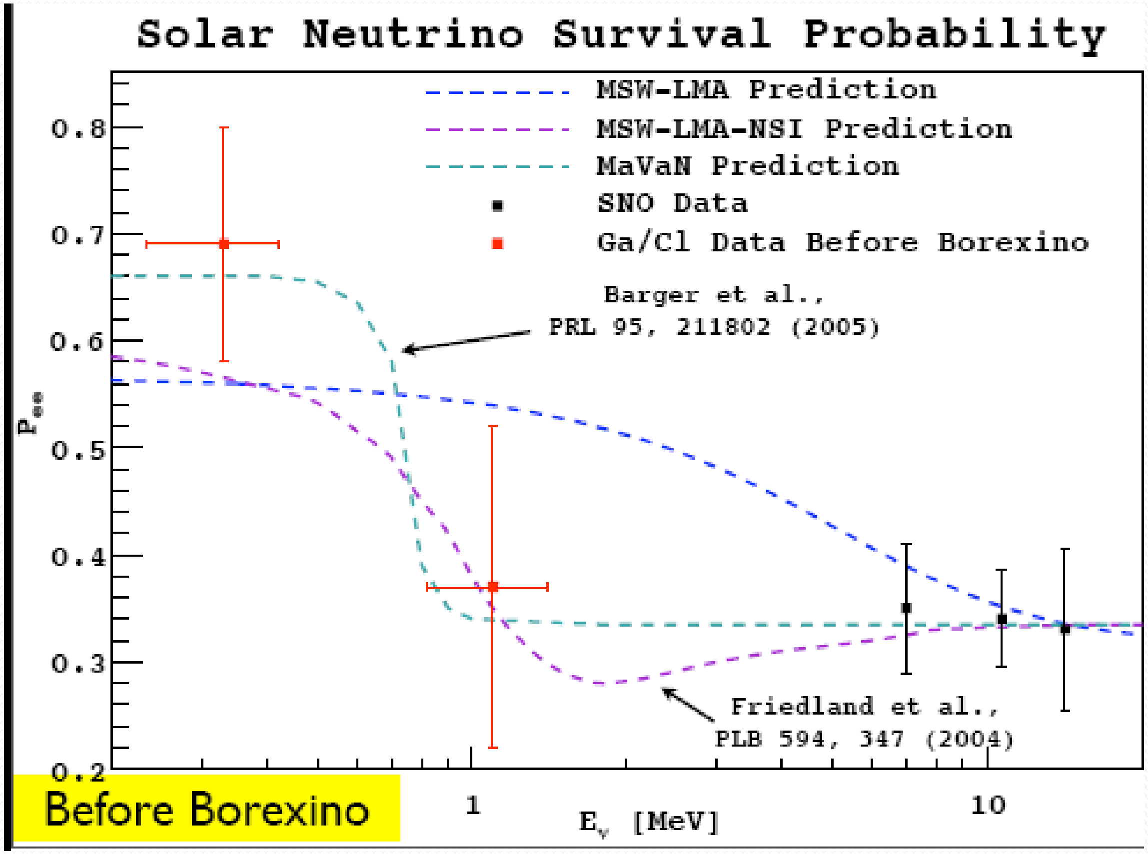

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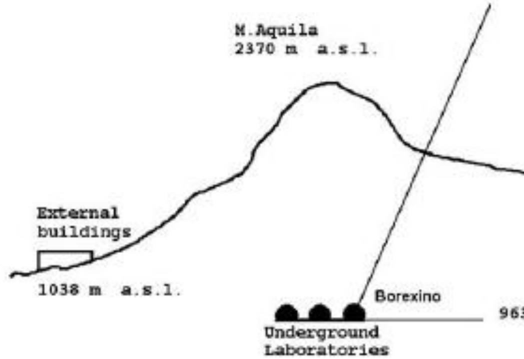
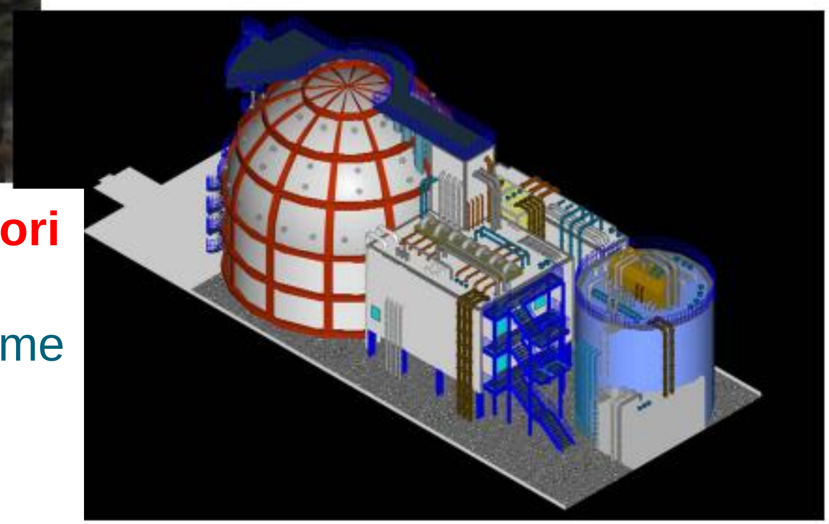
Borexino experimental site





Borexino is located at the **Laboratori Nazionali del Gran Sasso**, near L'Aquila, cca.120 km from Rome in Italy, shielded by 1400 m of limestone rocks
(3800 m water equivalent)

Borexino Collaboration: Nucl. Instr. Methods. Phys. Res. A 600 (2009) 568-593: Borexino detector at the Laboratori Nazionali del Gran Sasso.

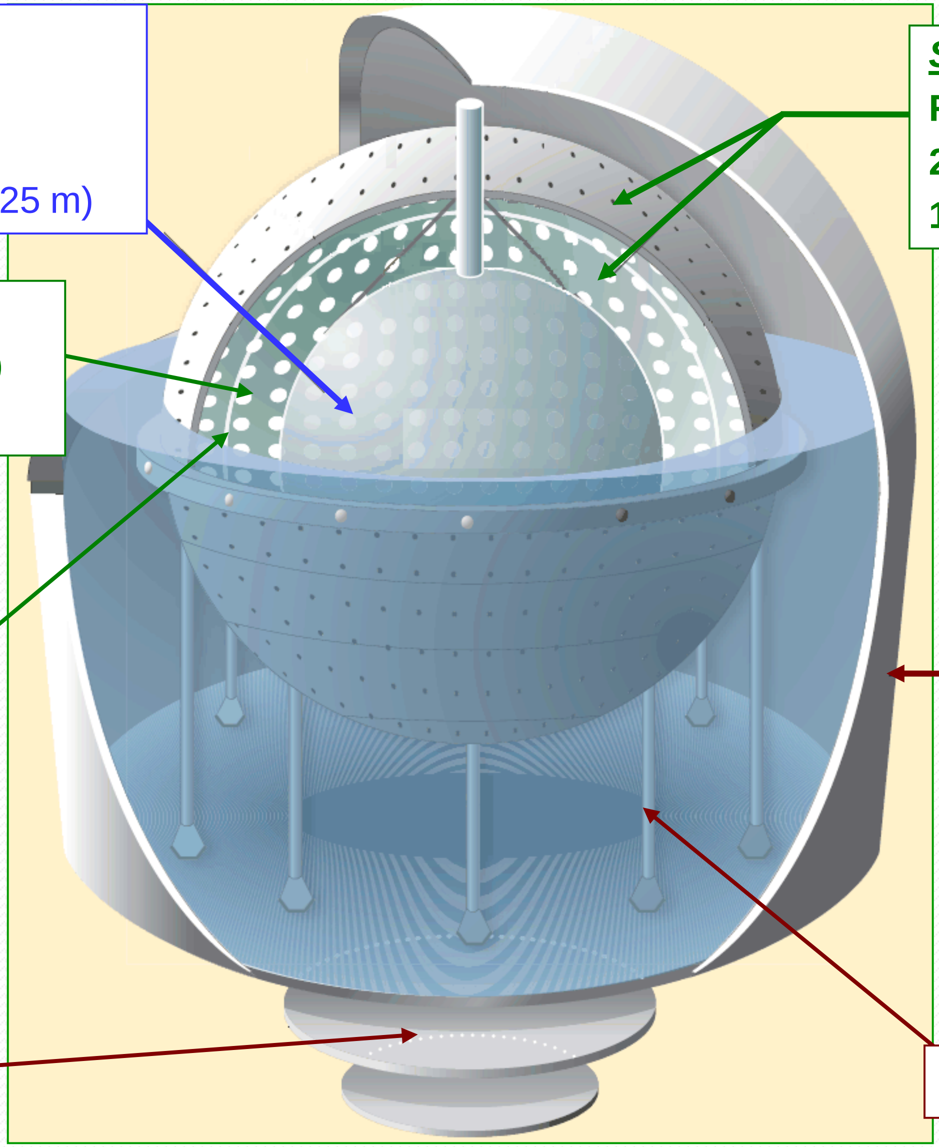
Borexino detector

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

Outer nylon vessel:
R = 5.50 m
(^{222}Rn barrier)

Carbon steel plates



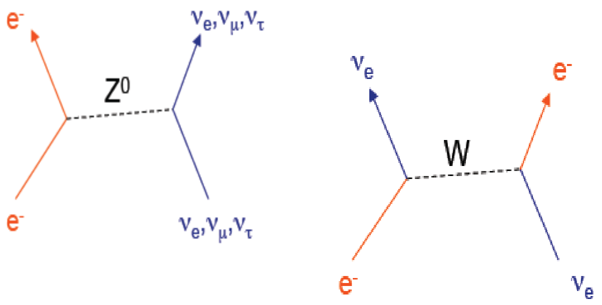
Stainless Steel Sphere:
R = 6.75 m
2212 PMTs
1350 m^3

Water Tank:
γ & neutron shield
μ Water Čerenkov detector
208 PMTs in water
2100 m^3

20 steel legs

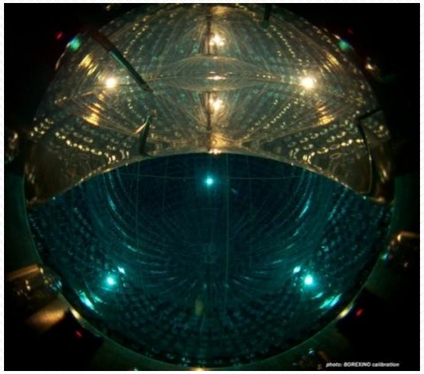
Detection principle

- Neutrino elastic scattering on electrons of liquid scintillator: **$e^- + \nu \rightarrow e^- + \nu$;**
- Scattered electrons cause the scintillation light production;
- **<u>Advantages</u>**:
  - Low energy threshold (~ 0.2 MeV);
  - High light yield and a good energy resolution;
  - Good position reconstruction;
- **<u>Drawbacks :</u>**
  - Info about the ν directionality is lost ;
  - ν-induced events can't be distinguished from the events of β/γ natural radioactivity;

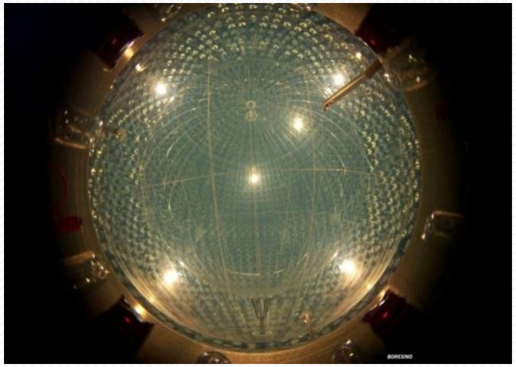


End October 2006

March 2007



May 2007



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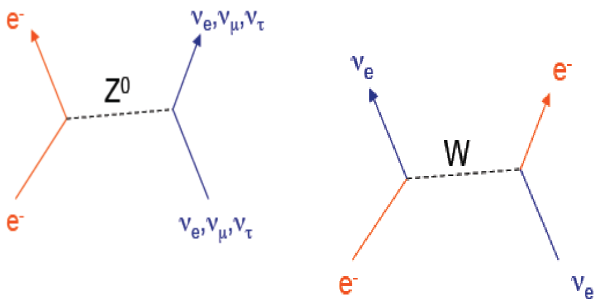
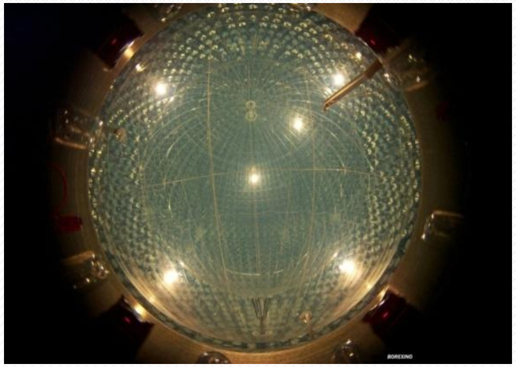


Extreme radiopurity is a must for a precision spectroscopy measurement!!!

DAQ STARTS : May 2007

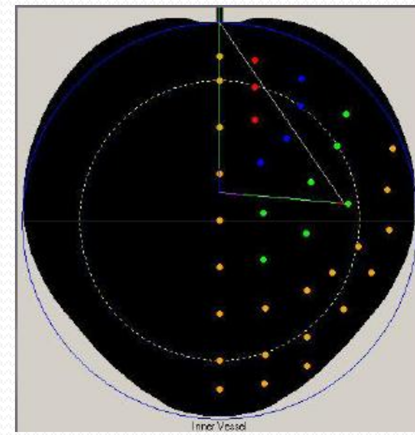


Rencontres de Moriond EW, La Thuile, 3-10 March 2012 Livia Ludhova (Borexino collaboration)

Calibration with radioactive sources

	γ								β		α	n (AmBe)		
	^{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

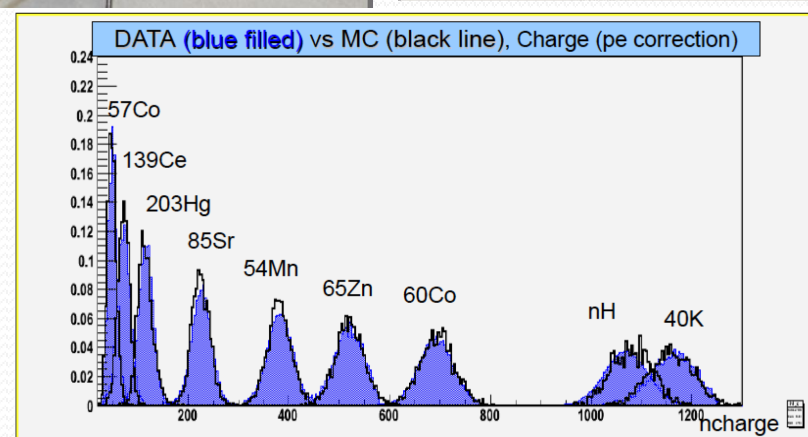
- Absolute source position: LED and CCD cameras (± 2cm);
- cca. 300 points through the whole scintillator volume;



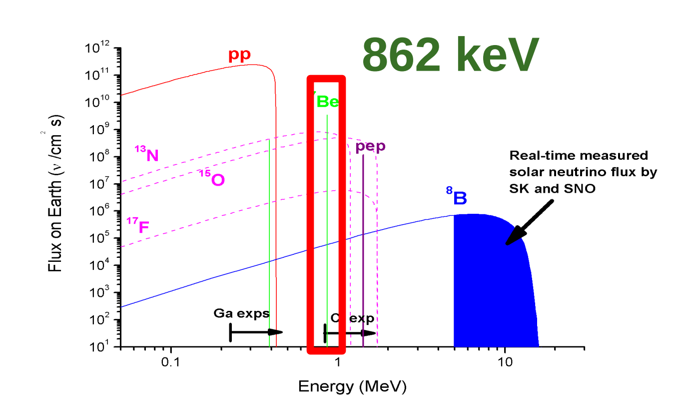
- **Detector response as a function of position;**
- **Fiducial volume definition and tuning of th spatial reconstruction algorithm;**
- **Energy scale definition**

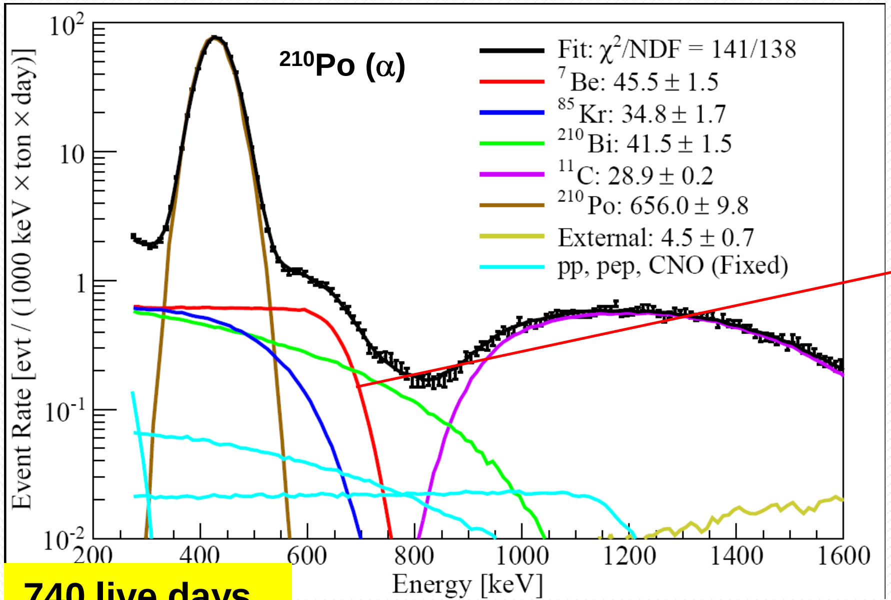
  precise calibration in the 0-7 MeV range.
- **Tuning of the full Monte Carlo simulation**

SYSTEMATIC ERROR REDUCTION
For ALL SOLAR NEUTRINO RESULTS



^{7}Be neutrino (862 keV) rate @ 4.6%
(SSM prediction @ 7%)



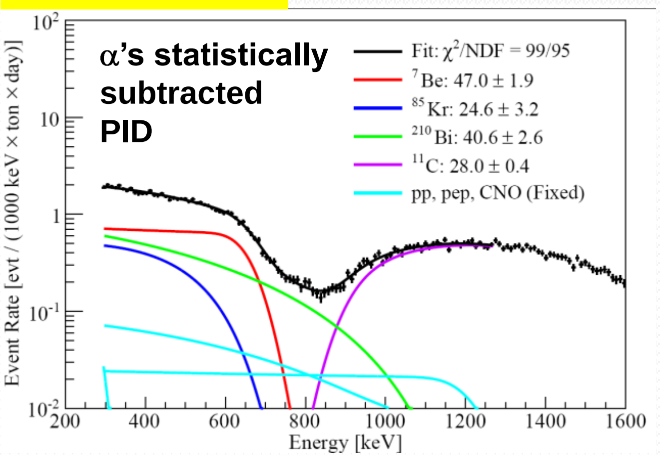


Spectral feature: compton-like edge from scattered electrons

$$46.0 \pm 1.5(\mathrm{stat})^{+1.5}_{-1.6}(\mathrm{syst})$$

cpd/100 tons

740 live days



1ton of LS = (3.307 ± 0.003) x 10^{29} electrons

- Spectral fit including neutrino signal + background components;
- Two independent methods: MC based and the analytical one;
- fit with and without α's statistical subtraction;

Implications of the ^{7}Be measurement

•comparing to non-oscillated SSM : **no oscillation excluded @ 5.0 σ**

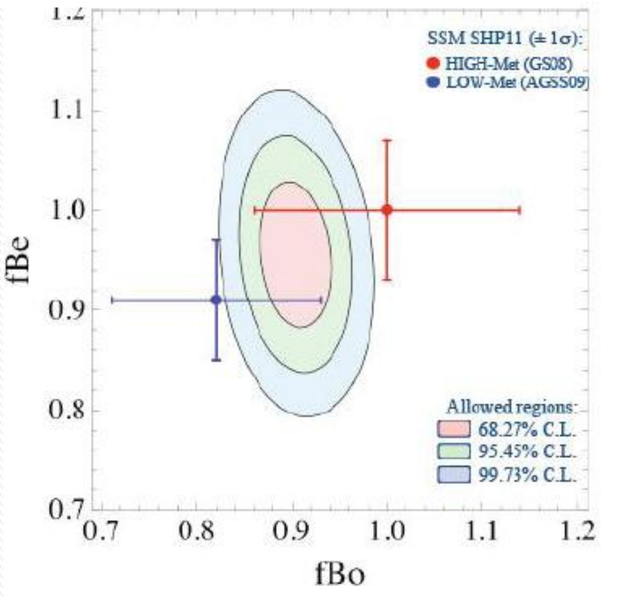
(electron equivalent flux (862 keV line): **(2.78 ± 0.13) x 10^9 cm^{-2} s^{-1})**

• assuming MSW-LMA: f (7Be) = measured flux / SSM = 0.97 + 0.09

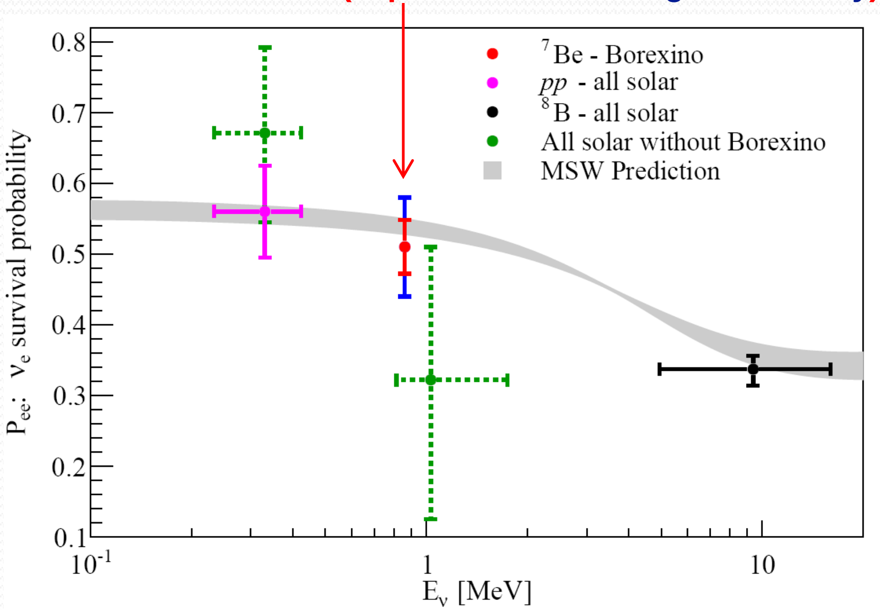
• **including all solar experiments + luminosity constrain:**

$$f_{pp} = 1.013^{+0.003}_{-0.010}$$
$$f_{CNO} < 2.5 \text{ at } 95\% \text{ C.L.}$$

no power to resolve low/high metallicity problem



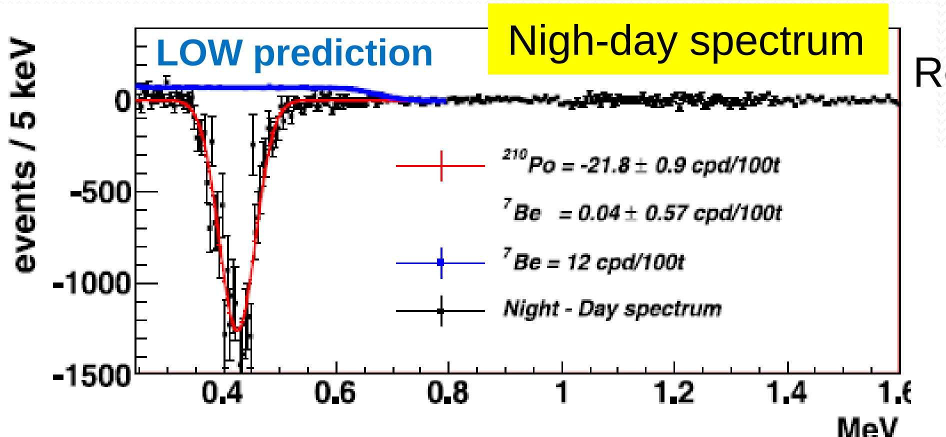
Pee = 0.51 + 0.07(experiment + SSM high metalilcity);



Absence of day-night asymmetry for ^{7}Be rate (R)

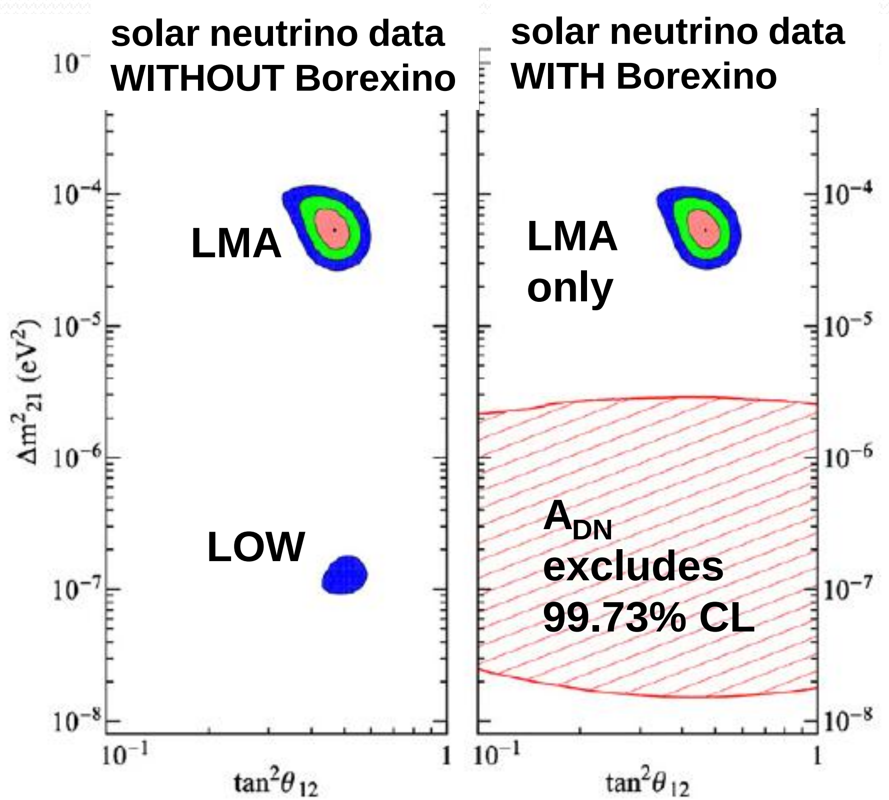
$$A_{dn} = 2\frac{R_N - R_D}{R_N + R_D} = \frac{R_{\rm diff}}{\langle R \rangle}$$

•MSW: a possible regeneration of electron neutrinos in the matter (within the Earth during night): effect depends on the oscillation parameters and on energy;



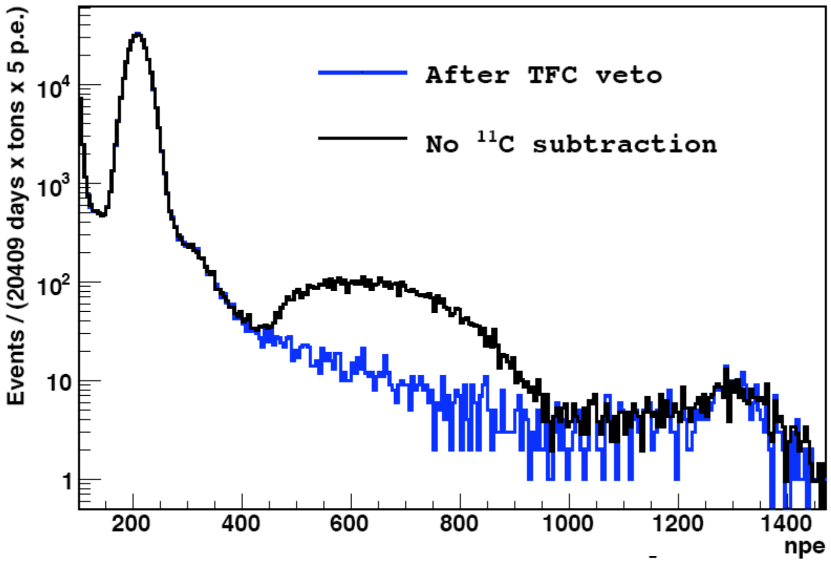
A_{DN}= 0.001 ± 0.012(stat) ± 0.007(syst)

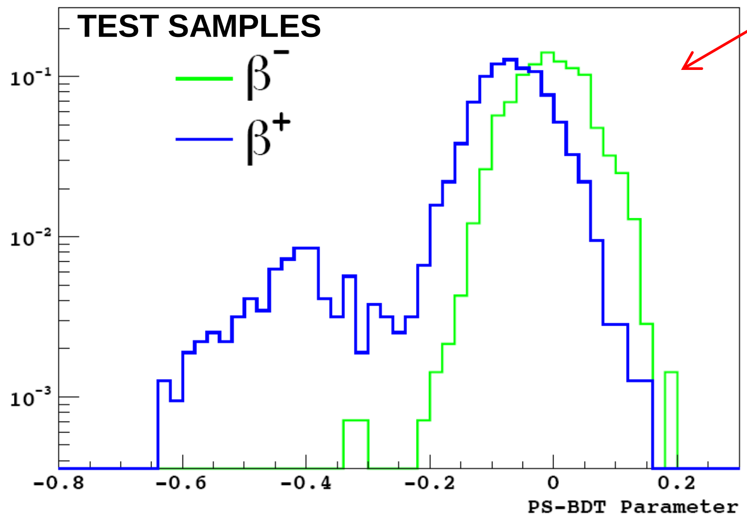
Regions allowed @ 68.27%, 95.45%, 99.73% CL



- in agreement with MSW-LMA;
- LOW region excluded at > 8.5 σ with solar neutrinos only: for the first time without the use of reactor ANTIneutrinos and therefore the assumption of CPT symmetry;
- constrains non standard interacitons (MaVaN in Holanda 2009 excluded)

First observation of pep neutrinos (1442 keV)





- Main background ^{11}C (e^+) with τ = 29.4 min:

1 2 3

$$\mu + {}^{12}C \longrightarrow \mu + n + {}^{11}C$$

Three Fold Coincidence (TFC):
space-time veto removes 90% of ^{11}C
payed with 50% loss of exposure

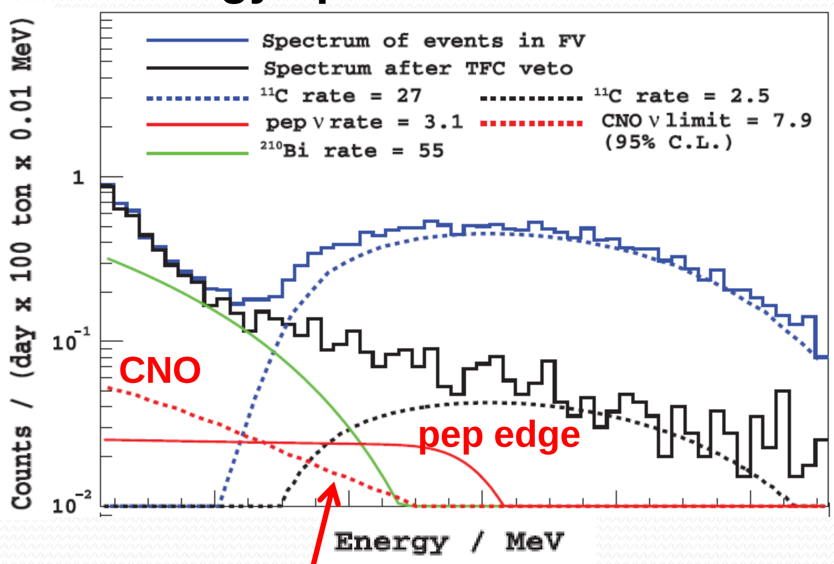
- **pulse-shape discrimination**:
positronium formation + annihilation

- **simultaneous fit in 3 parameter space**:
energy spectra, pulse shape, and radial distribution (sensitive to external background):

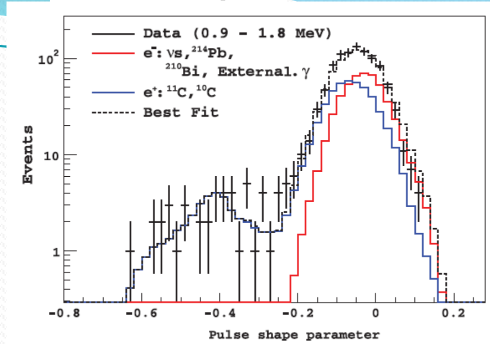
$$3.1 \pm 0.6_{stat} \pm 0.3_{syst} \text{ counts}/(\text{day} \cdot 100 \text{ ton})$$

$$(1.6 \pm 0.3) \times 10^8 \text{ cm}^{-2}\text{s}^{-1}$$ (assuming MSW-LMA)

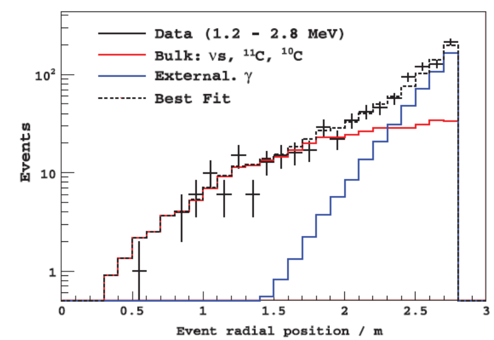
Energy spectral fit

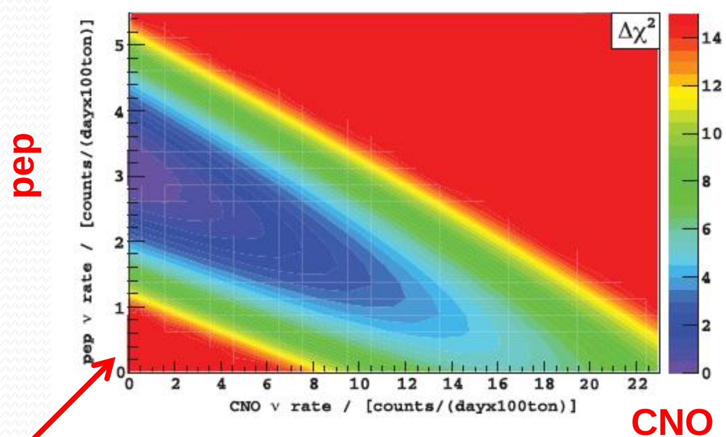


Pulse shape



Radial fit





Likelihood ratios for fits with fixed pep/CNO rates and the best fit

CNO neutrinos

- same analysis as for pep
- only limits, correlation with ^{210}Bi
- **the strongest limit to date**

<7.9 counts/(day · 100 ton) (95% C.L.)

$<7.7 \times 10^8$ cm^{-2} s^{-1} (95% C.L.) (assuming MSW-LMA)

- **not sufficient to resolve metallicity problem**

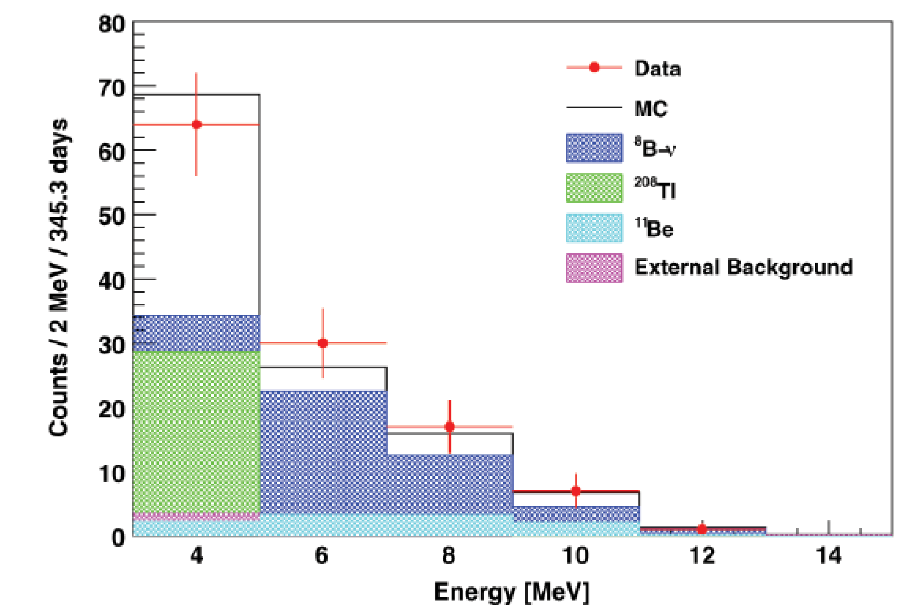
^{8}B neutrino rate with 3 MeV energy threshold

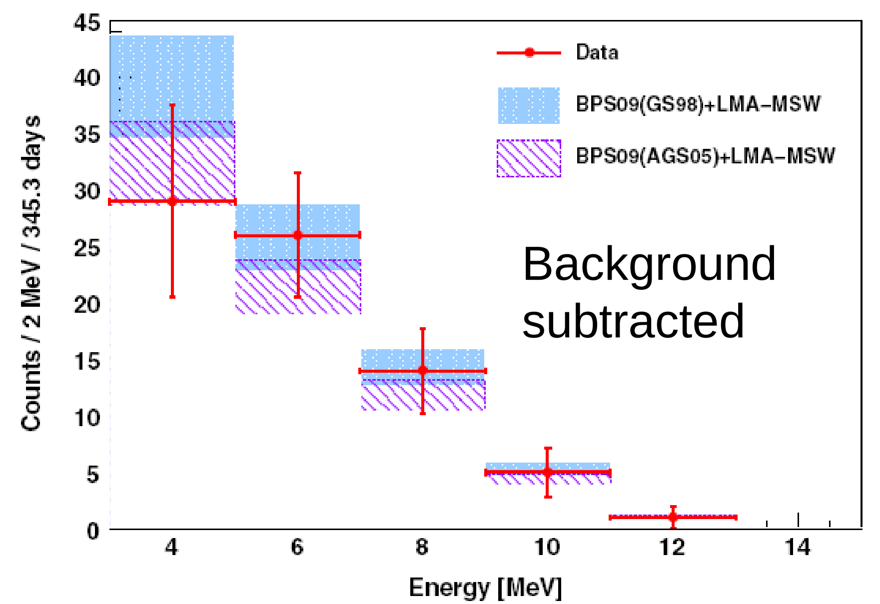
lower energies limited by ^{208}Tl

	3.0–16.3 MeV	5.0–16.3 MeV
Rate [cpd/100 t]	$0.22 \pm 0.04 \pm 0.01$	$0.13 \pm 0.02 \pm 0.01$
Φ^{ES}_{exp} [10^6 cm^{-2} s^{-1}]	$2.4 \pm 0.4 \pm 0.1$	$2.7 \pm 0.4 \pm 0.2$
$\Phi^{ES}_{exp}/\Phi^{ES}_{th}$	0.88 ± 0.19	1.08 ± 0.23

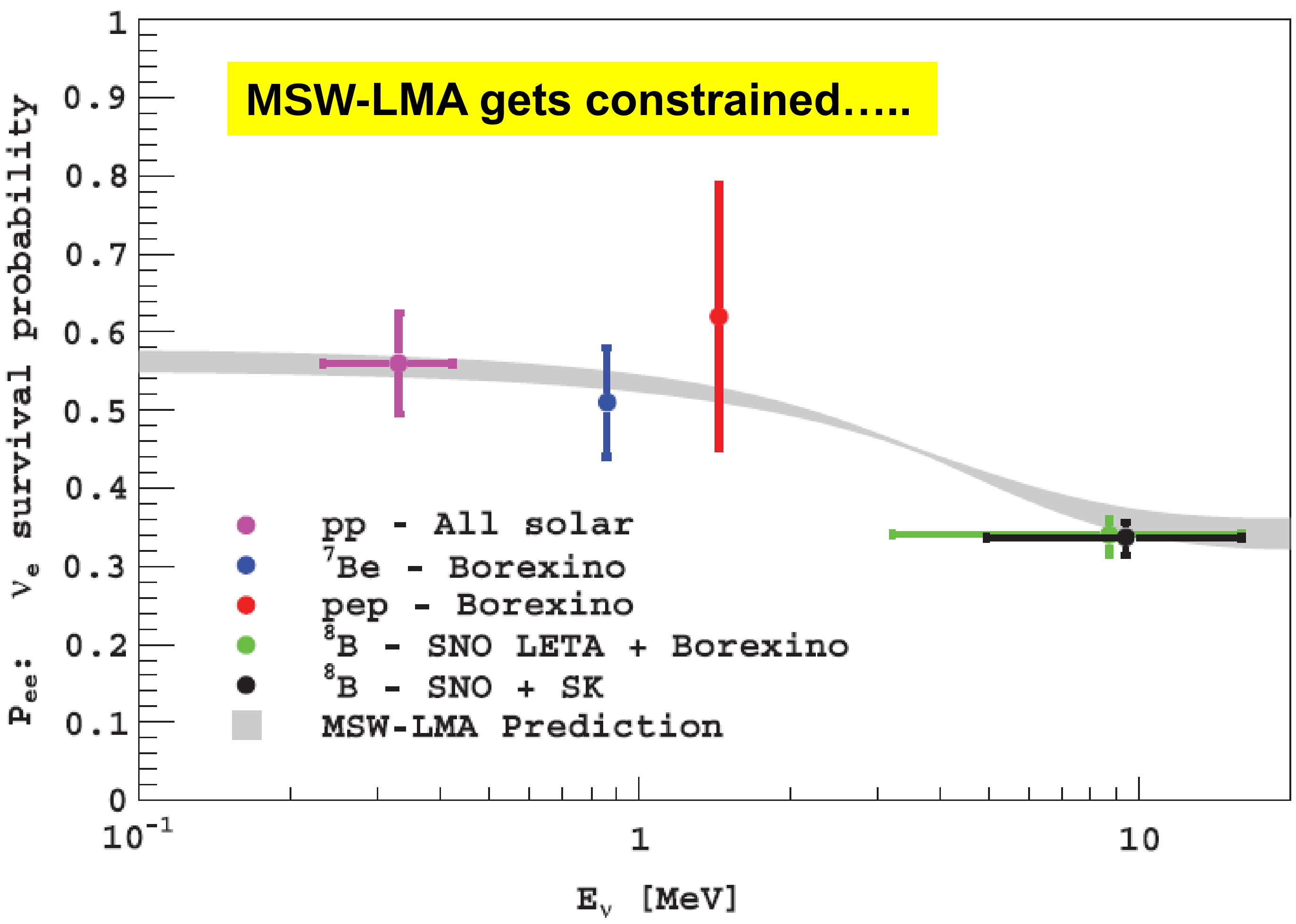
TABLE VI. Results on ^{8}B solar neutrino flux from elastic scattering, normalized under the assumption of the no-oscillation scenario reported by SuperKamiokaNDE, SNO, and Borexino.

	Threshold [MeV]	$\Phi^{ES}_{^8B}$ [10^6 cm^{-2} s^{-1}]
SuperKamiokaNDE I [3]	5.0	$2.35 \pm 0.02 \pm 0.08$
SuperKamiokaNDE II [2]	7.0	$2.38 \pm 0.05^{+0.16}_{-0.15}$
SNO D_2O [4]	5.0	$2.39^{+0.24}_{-0.23}$ $^{+0.12}_{-0.12}$
SNO Salt Phase [25]	5.5	$2.35 \pm 0.22 \pm 0.15$
SNO Prop. Counter [26]	6.0	$1.77^{+0.24}_{-0.21}$ $^{+0.09}_{-0.10}$
Borexino	3.0	$2.4 \pm 0.4 \pm 0.1$
Borexino	5.0	$2.7 \pm 0.4 \pm 0.2$





To conclude, we put all together….. P_{ee} after Borexino I



Livia Ludhova (Borexino collaboration)

Future and Borexino phase II

• since July 2010 we have undertaken a series of purification campaigns to decrease radioactive background;

• Nitrogen stripping has been successful in removing 85Kr;

• moderate success at removing 210Pb/Bi by water extraction;

•210Po decreasing;

• Borexino phase II is about to start…
    • continue solar neutrino program;
    • more statistics for an update of geo-neutrino measurement;
    • another scientific goals under discussion

More about Borexino solar results in:

Pep & CNO limit : G. Bellini et al. : First Evidence of *pep* Solar Neutrinos by Direct Detection in Borexino, Phys. Rev. Lett. 108 (2012) 051302.

7Be Adn: G. Bellini at al. : Absence of day-night asymmetry of 862 keV ^{7}Be solar neutrino rate in Borexino and MSW oscillation parameters, Physics Letters B 707 (2012) 22-26.

7Be @ 5%: G. Bellini et al. : Precision measurement of the 0.862 MeV ^{7}Be solar neutrino interaction rate in Borexino, Phys. Rev. Lett. 107 (2011) 141302.

8B > 3 MeV: G. Bellini at al. (Borexino collaboration): Measurement of the solar ^{8}B neutrino rate with a liquid scintillator target and 3 MeV energy threshold in the Borexino detector. Phys. Rev. D 82 (2010) 033006.

Solar antinu limits: G. Bellini at al.: Study of solar and other unknown anti-neutrino fluxes with Borexino at LNGS., Phys. Lett. B 696 (2011) 191-196.

7Be @ 10%: C. Arpesella *at al*. (Borexino collaboration): Direct measurement of the ^{7}Be solar neutrino flux with 192 days of Borexino data, Phys. Rev. Lett. 101 (2008) 091302.

7Be @ 17%: C. Arpesella *at al.* (Borexino collaboration): First real time detection of ^{7}Be solar neutrinos by Borexino, Phys. Lett. B 658 (2008) 101-108

Thank you!

Backup

The internal background in Borexino i

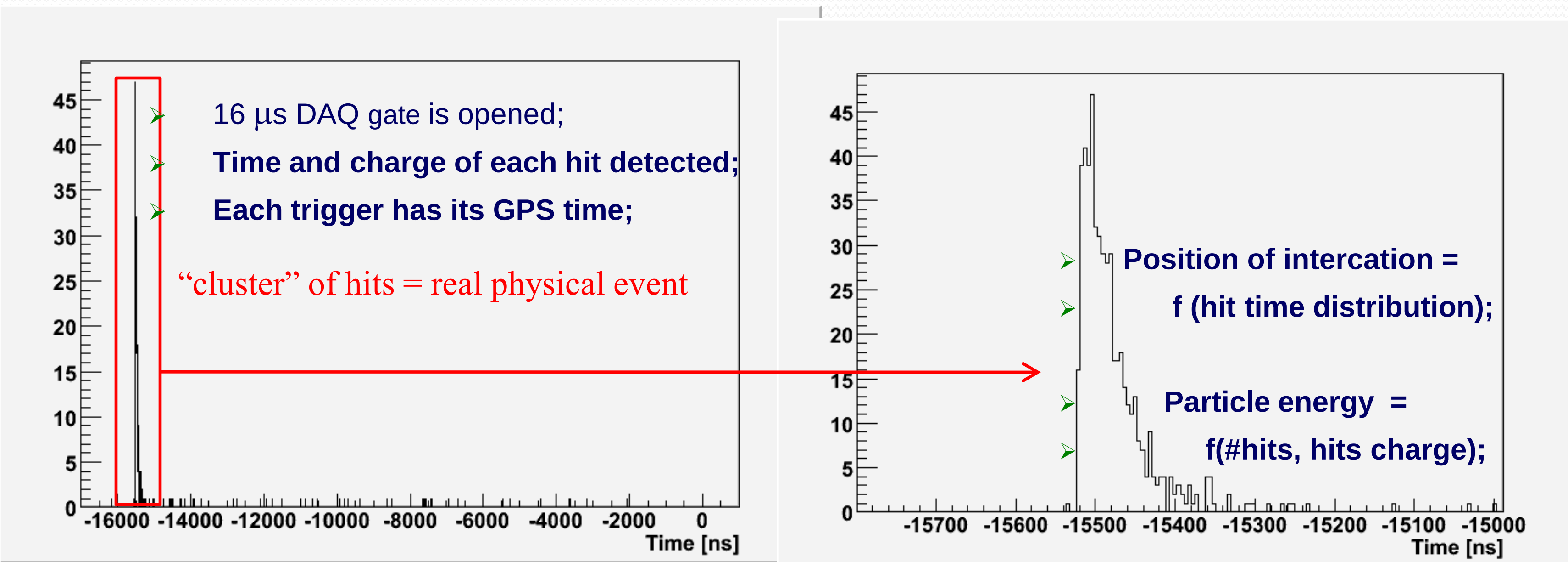
- Careful selection of the construction materials and operational procedures;
- Special procedures for fluid procurement;
- Scintillator and buffer purification during the filling;
- Sparging with high purity N2;
- **More than 15 years of work…**

Extreme radiopurity is a must!!!

Background	Typical abundance (source)	Goal	Measured
$^{14}C/^{12}C$	10^{-12} (cosmogenic) g/g	10^{-18} g/g	~2 x 10^{-18} g/g
^{238}U (by ^{214}Bi-^{214}Po)	2 x10^{-5} (dust) g/g	10^{-16} g/g	(1.6 $\pm$ 0.1) x 10^{-17} g/g
^{232}Th (by ^{212}Bi-^{212}Po)	2 x 10^{-5} (dust) g/g	10^{-16} g/g	(5 $\pm$ 1) x 10^{-18} g/g
^{222}Rn (by ^{214}Bi-^{214}Po)	100 atoms/cm^3 (air) emanation from materials	10^{-16} g/g	~ 10^{-17} g/g (~1 count /day/100t)
^{210}Po	Surface contamination	~1 c/day/t	May 2007: 70 c/d/t Sep 2008: 7 c/d/t
^{40}K	2 x 10^{-6} (dust) g/g	~10^{-18} g/g	< 3 x 10^{-18} (90%) g/g
^{85}Kr	1 Bq/m^3 (air)	~1 c/d/100t	(28 $\pm$ 7) c/d/100t (fast coinc.)
^{39}Ar	17 mBq/m^3 (air)	~1 c/d/100t	<< ^{85}Kr

Data structure and detector performance

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



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

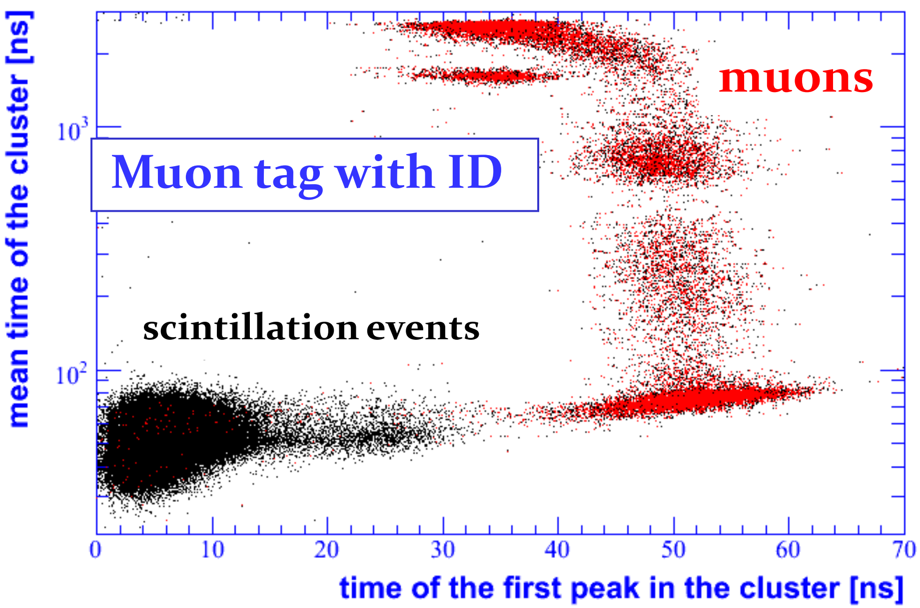
Light yield: (500 ± 12) p.e./MeV
taking into account quenching factor

Spatial resolution: 35 cm @ 200 keV
(scaling as $N_{p.e.}^{-1/2}$) 16 cm @ 500 keV

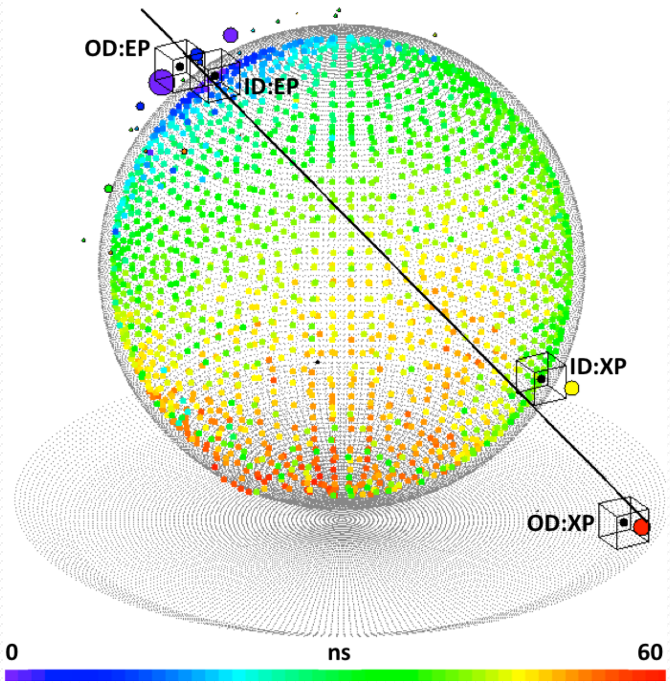
Energy resolution (s): 10% @ 200 keV
8% @ 400 keV
6% @ 1000 keV

Muon and neutron detection

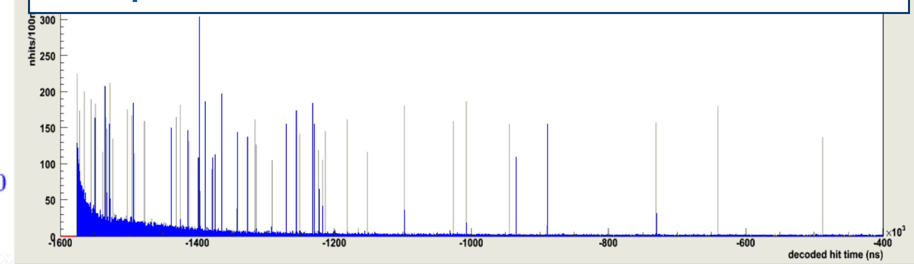
- μ are identified by the OD and by the ID
  - OD eff: > 99.28%
  - ID analysis based on pulse shape variables
    - Cluster mean time, peak position in time
  - **Combined overall efficiency > 99.992%**
  - **After cuts, μ not a relevant background for ^{7}Be**
    - **Residual background: < 1 count /day/ 1 00 t**



Muon track reconstruction

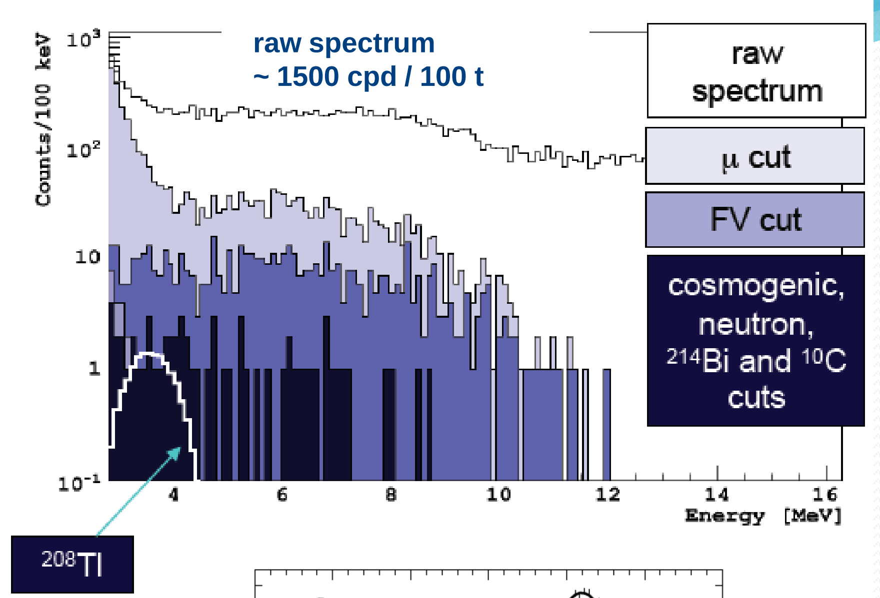


After each μ, 1.6 ms gate opened to detect neutrons: example with several tens of neutrons.



NEW: Muon and Cosmogenic Neutron Detection in Borexino.
Sent to JINST 2 weeks ago, arXiv:1101.3101

^{8}B analysis details

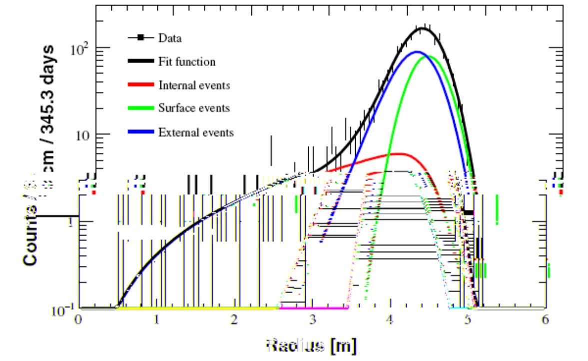


External backgrounds (FV CUT):

- High energy γ from neutrons
- ^{214}Bi and ^{208}Tl from Rn emanated from nylon or detector

Internal radiocative backgrounds:

- ^{214}Bi (^{238}U chain) via ^{214}Bi-^{214}Po coincidences;
- ^{208}Tl (^{232}Th chain) from bulk: stat. subtr.;



Cosmogenic background rejection:

- ***FAST COSMOGENIC CUT:*** 6.5 s dead time after all ID muons to reject fast cosmogenic isotopes; (29.2 % dead time,, 4300 muons/day passing ID)
- ***NEUTRON REJECTION***: 2 ms after all muons (neutron capture time 256 μs , AmBe source);
- ***^{10}C SUBTRUCTION:*** 3-fold coincidence with parent muon and neutron;
- ***^{11}Be STATISTICAL SUBTRUCTION;***

Background: ^{232}Th and ^{238}U content

Assuming secular equilibrium:

^{232}Th chain

τ = 432.8 ns

$^{212}Bi \xrightarrow{\beta} {}^{212}Po \xrightarrow{\alpha} {}^{208}Pb$

2.25 MeV ~800 keV eq.

^{238}U chain

τ = 236 μs

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

3.2 MeV ~700 keV eq.

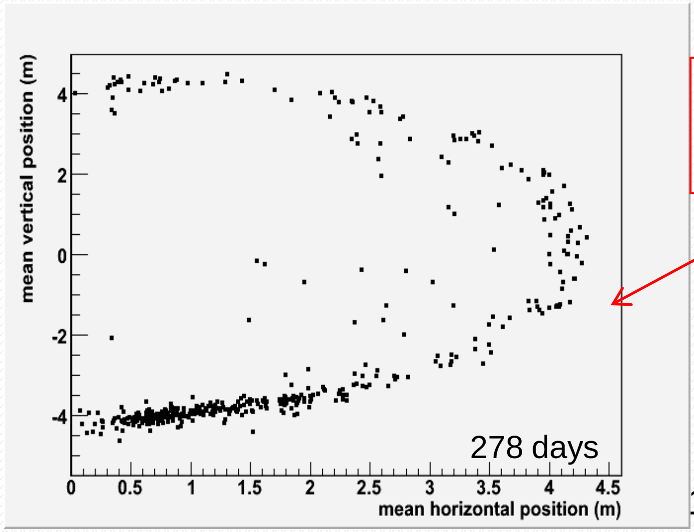
Bulk contamination

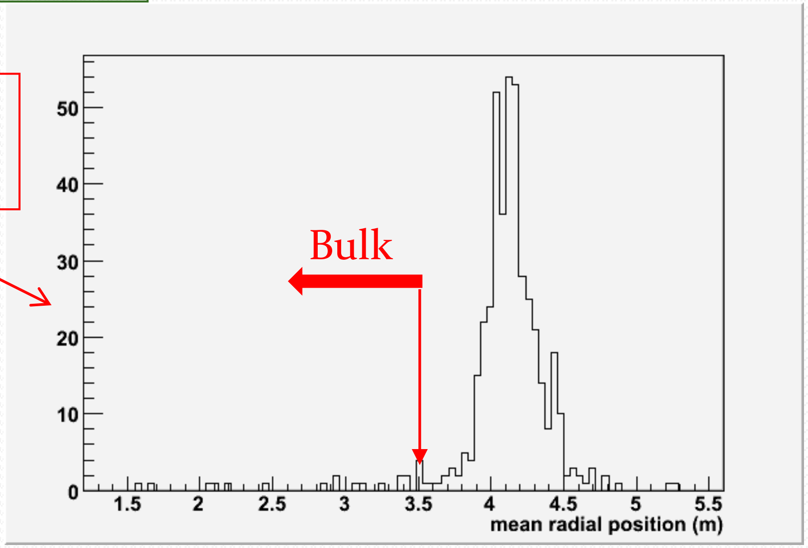
(6.8±1.5) 10^{-18} g(Th)/g

(1.6 0.1) 10^{-17} g(U)/g

Only few bulk candidates

^{212}Bi-^{212}Po centre of mass position distribution





Background: ^{210}Po and ^{85}Kr

^{210}Po: end of ^{238}U chain :

	^{210}Pb	$\xrightarrow{\beta^-(61\ keV)}$	^{210}Bi	$\xrightarrow{\beta^-(1.2MeV)}$	^{210}Po	$\xrightarrow{\alpha}$	^{206}Pb
$t_{1/2}$	22.3 y		5.01 d		138.38 d		stable

- The bulk ^{238}U and ^{232}Th contamination is **negligible**
- The ^{210}Po background is **NOT related** neither to ^{238}U nor to ^{210}Pb contamination
- **May 2007 ~80 counts/day/ton, τ=204.6 days**
- **^{210}Bi no direct evidence** ---> free parameter in the total fit, cannot be disentangled, in the ^{7}Be energy range, from the CNO

^{85}Kr β-decay energy spectrum similar to the ^{7}Be recoil electron

$$^{85}Kr \xrightarrow[687\ keV]{\beta} {}^{85}Rb$$

τ = 10.76 y - BR: 99.56%

^{85}Kr is studied through :

$$^{85}Kr \xrightarrow[173\ keV]{\beta} {}^{85m}Rb \xrightarrow[514\ keV]{\gamma} {}^{85}Rb$$

τ = 1.46 ms - BR: 0.43%

PRELIMINARY: the ^{85}Kr contamination **(30±5) counts/day/100 ton**