200 days of Borexino data

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(on behalf of Borexino collaboration)

Borexino Collaboration

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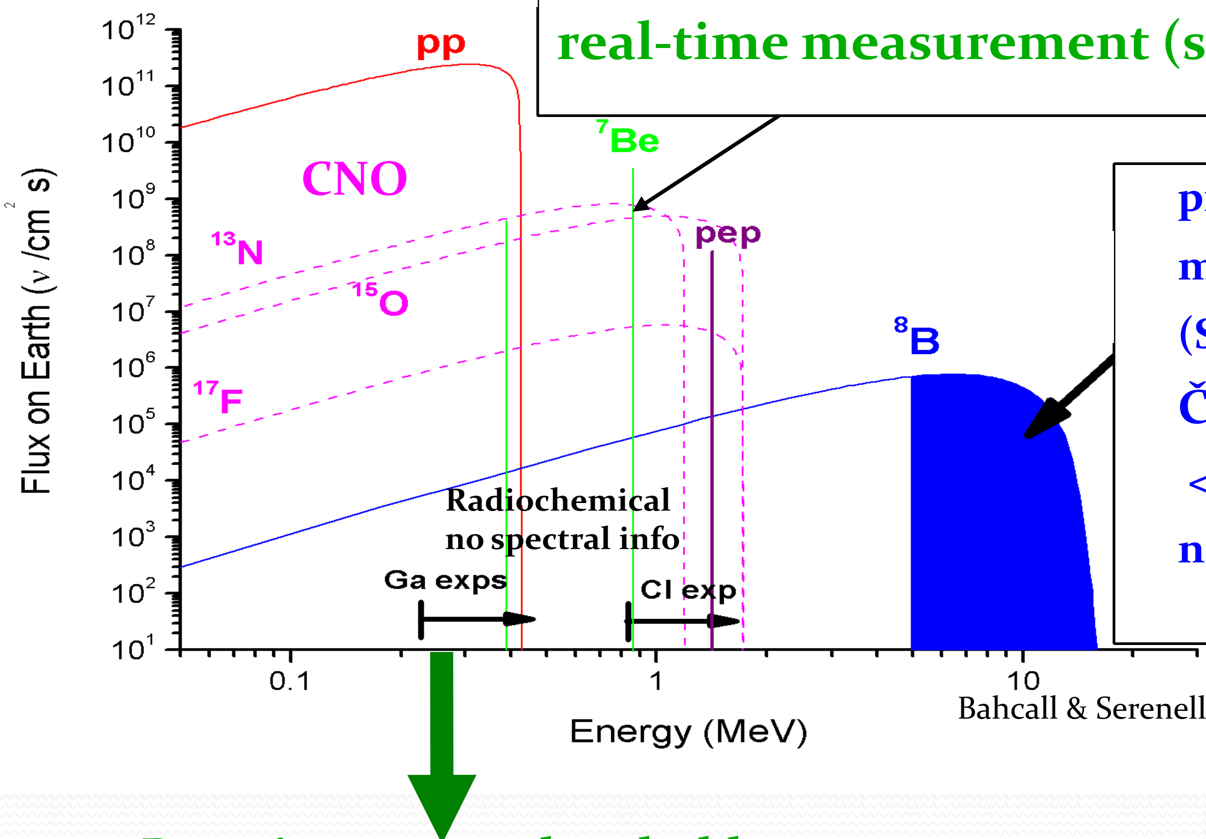
Solar neutrino energy spectrum

mono-energetic 0.862 MeV ^{7}Be-ν
real-time measurement (scintillation light)



Bahcall & Serenelli 2005

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

Borexino energy threshold

Standard Solar Model: Neutrino fluxes vs solar metallicity

(metallicity – abundance of the elements above Helium)

Φ ($cm^{-2}s^{-1}$)	pp ($x\,10^{10}$)	pep ($x\,10^{8}$)	^{7}Be ($x\,10^{9}$)	^{8}B ($x\,10^{6}$)	^{13}N:CNO ($x\,10^{8}$)	^{15}O:CNO ($x\,10^{8}$)	^{17}F:CNO ($x\,10^{6}$)
BS05 (1) GS 98 (2)	5.99	1.42	4.84	5.69	3.07	2.33	5.84
BS05 (1) AGS05(3)	6.06	1.45	4.34	4.51	2.01	1.45	3.25
Δ	+1%	+2%	-10%	-21%	-35%	-38%	-44%

(1)BS05: Bahcall, Serenelli & Basu, AstropJ 621 (2005) L85

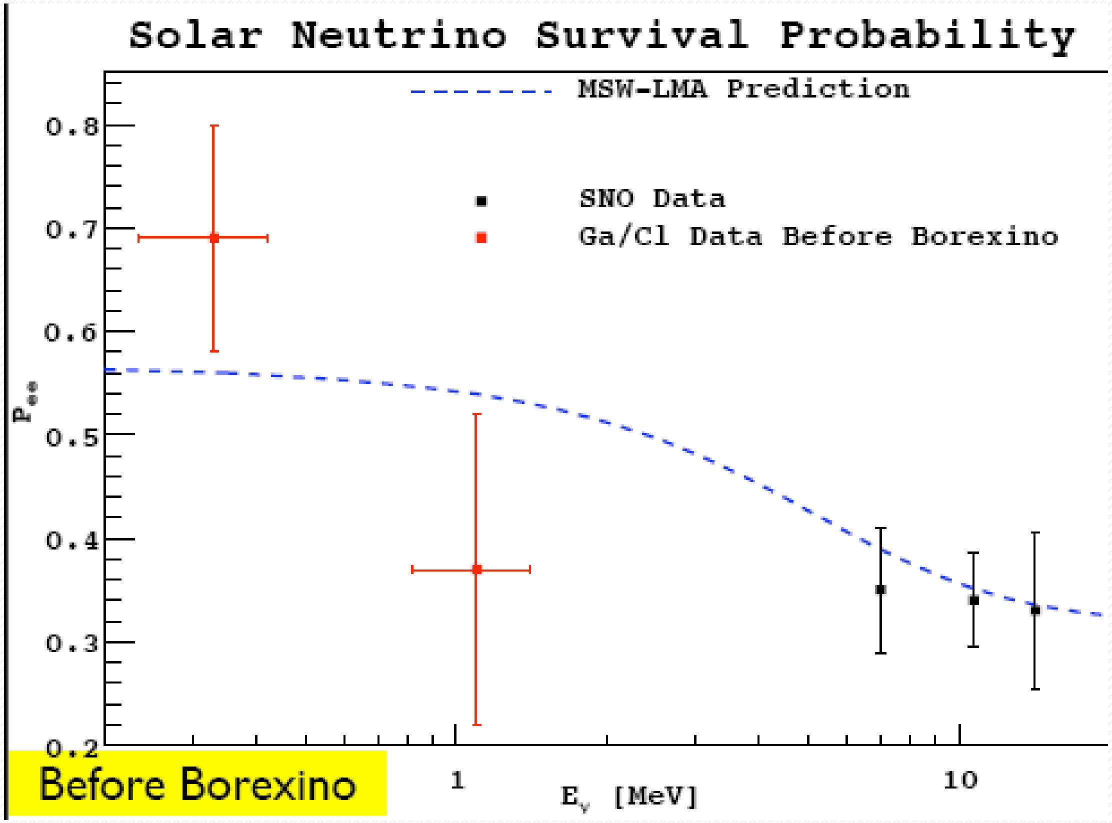
(2)Based on **high metalicity model** GS98: Grevesse & Sauval, Space Sci. Rev. **85, 161 (1998)**

(3)Based on new **low metalicity model** AGS05:
Asplund ,Grevesse & Sauval 2005, Nucl. Phys. A **777, 1** (2006).
BUT: incompatible with helioseismological measurements

Both (2) and (3) use Opacity Project opalicity

MEASURING for the first time the CNO-neutrino fluxes would help to resolve the controversy!

Solar –ν survival probability <u>BEFORE BOREXINO</u>



Vacuum regime

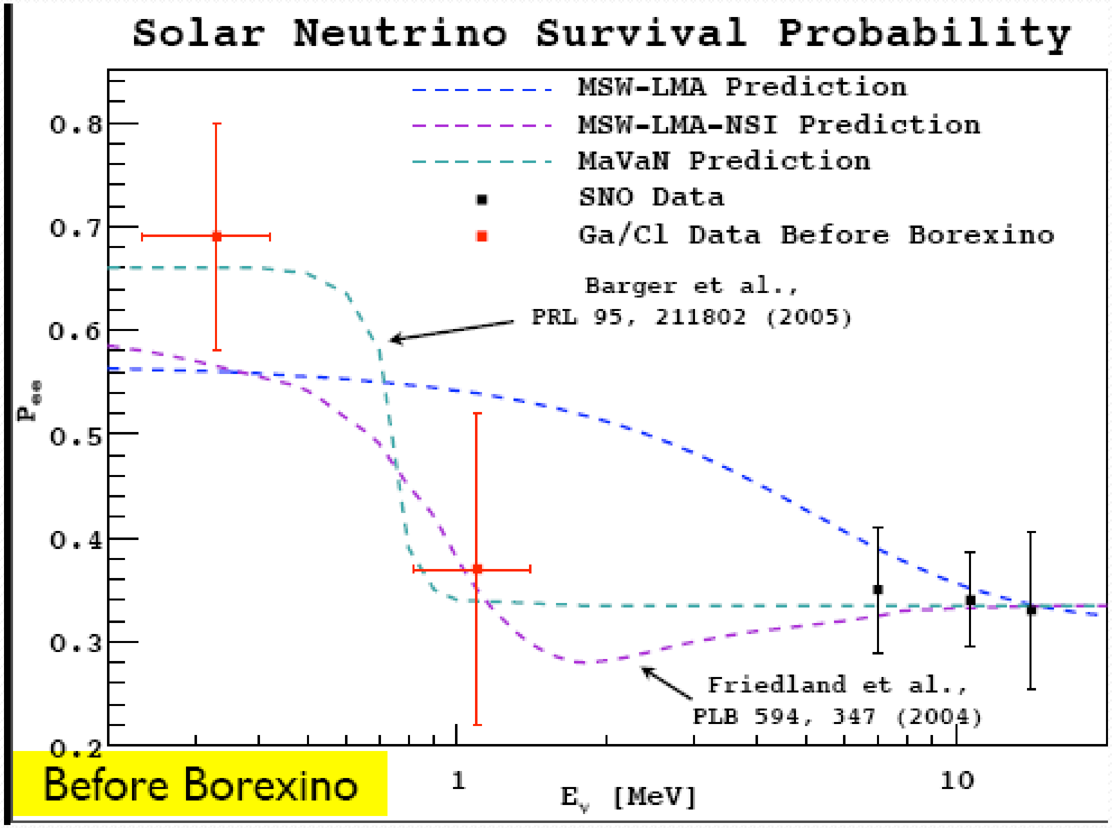
Matter regime

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})

Solar –ν survival probability BEFORE BOREXINO



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

Scientific goals of Borexino

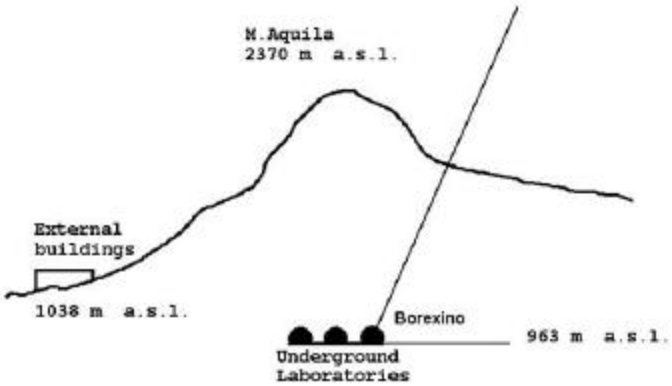
- **The first real-time measurement of sub-MeV solar neutrinos;**
- The first simultaneous measurement of solar neutrinos from the vacuum dominated region (**^{7}Be-ν – two measurements published**) and from the matter-enhanced oscillation region (**^{8}B-ν – the first measurement below 5 MeV recently submitted**, **see also talk of D. Franco in paralel session**)
- Precision measurement (at or below the level of 5%) of the ^{7}Be-ν rate: to test the SSM and MSW-LMA solution of the Standard Solar Problem and look for indications of the mass varying neutrinos or non-standard neutrino-matter interactions influencing P_{ee};
- To test the balance between the neutrino and photon luminosity of the Sun;
- Check the 7% **seasonal variation** of the neutrino flux (confirm solar origin);
- Under study: first measurement of the **CNO** neutrinos (sun metallicity controversy);
- Under study: ***pep*** neutrinos – indirect constrain on the pp-flux;
- High energy tail of ***pp*** neutrinos ?
- Antineutrinos and **geoneutrinos**;
- **Supernovae** neutrinos and antineutrinos;

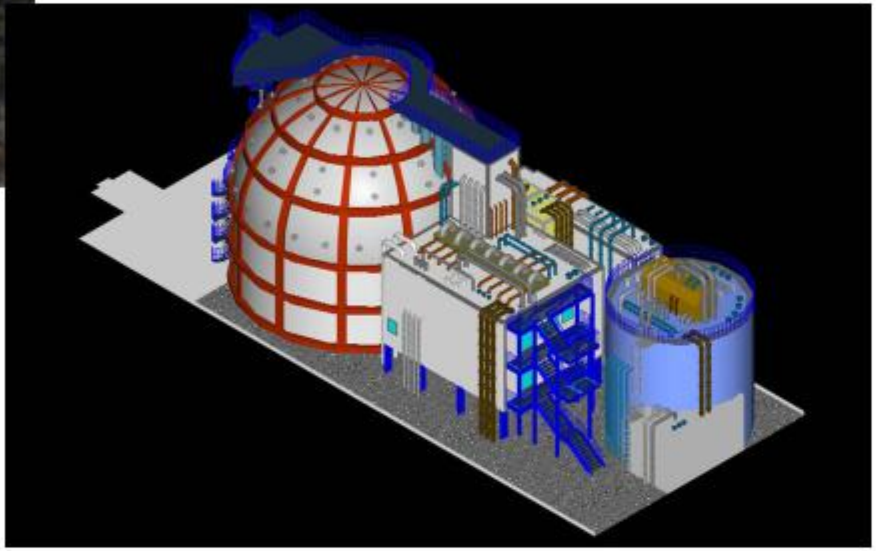
Detection principles in Borexino

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

Extreme radiopurity is a must!!!

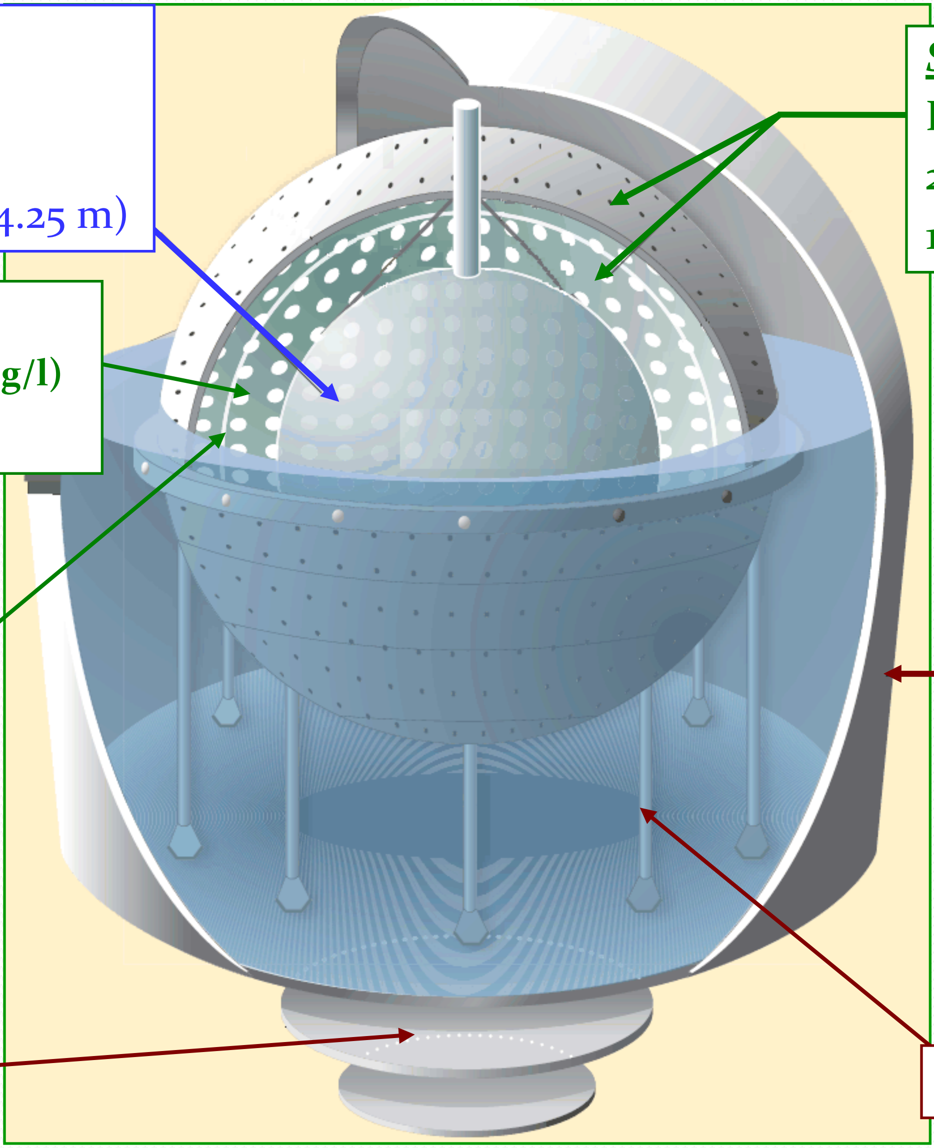
Experimental site





Borexino is located at the **Laboratori Nazionali del Gran Sasso**, near L'Aquila, shielded by 1400 m of Rocks (3500 m water equivalent)

Borexino Detector



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

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

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

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

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

Carbon steel plates

20 steel legs

Filling 1/3

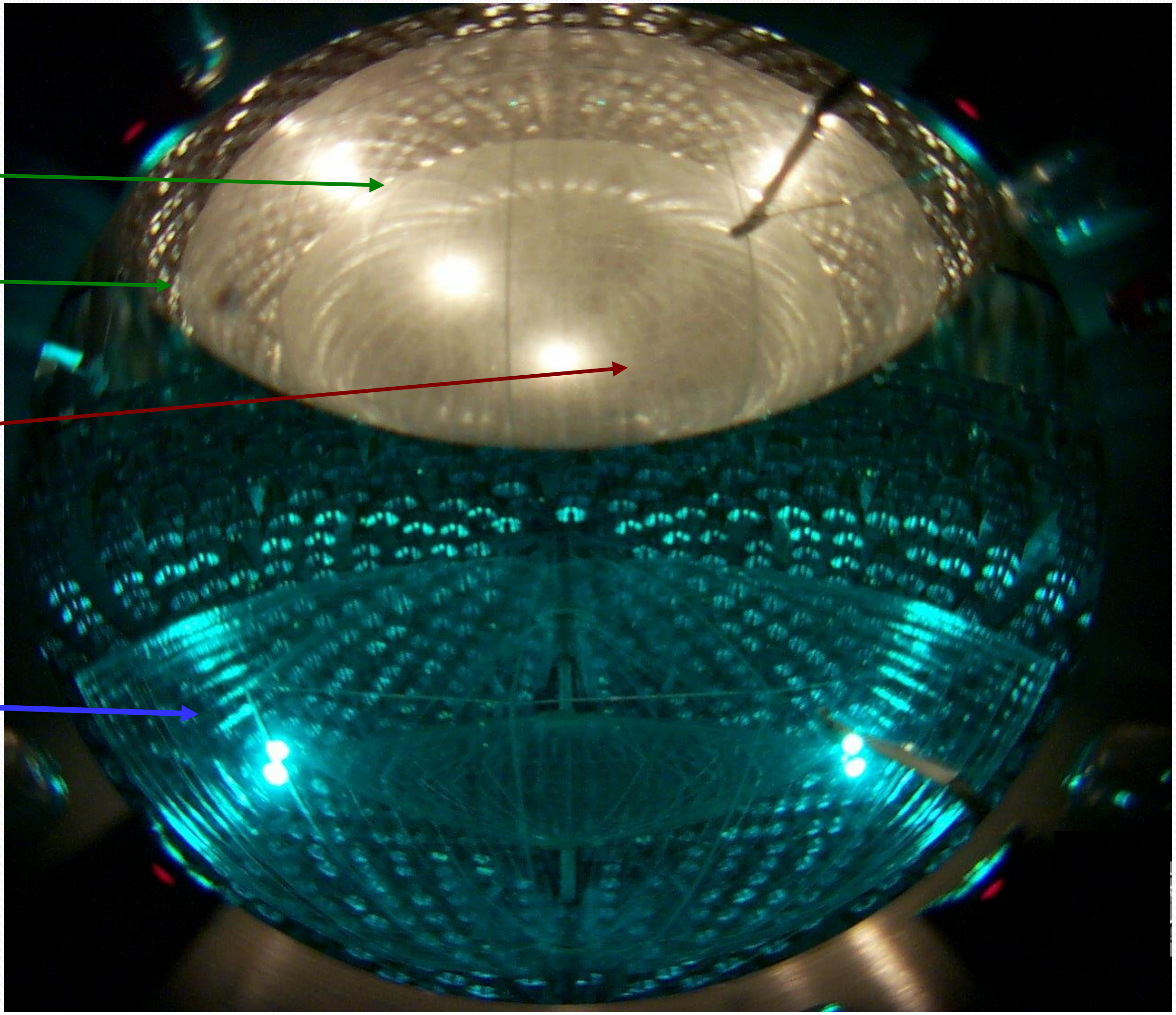
End October 2006

Nylon Vessels
Inner: 8.5 m
Outer: 11.0 m

LAKN – Low Argon and Krypton Nitrogen

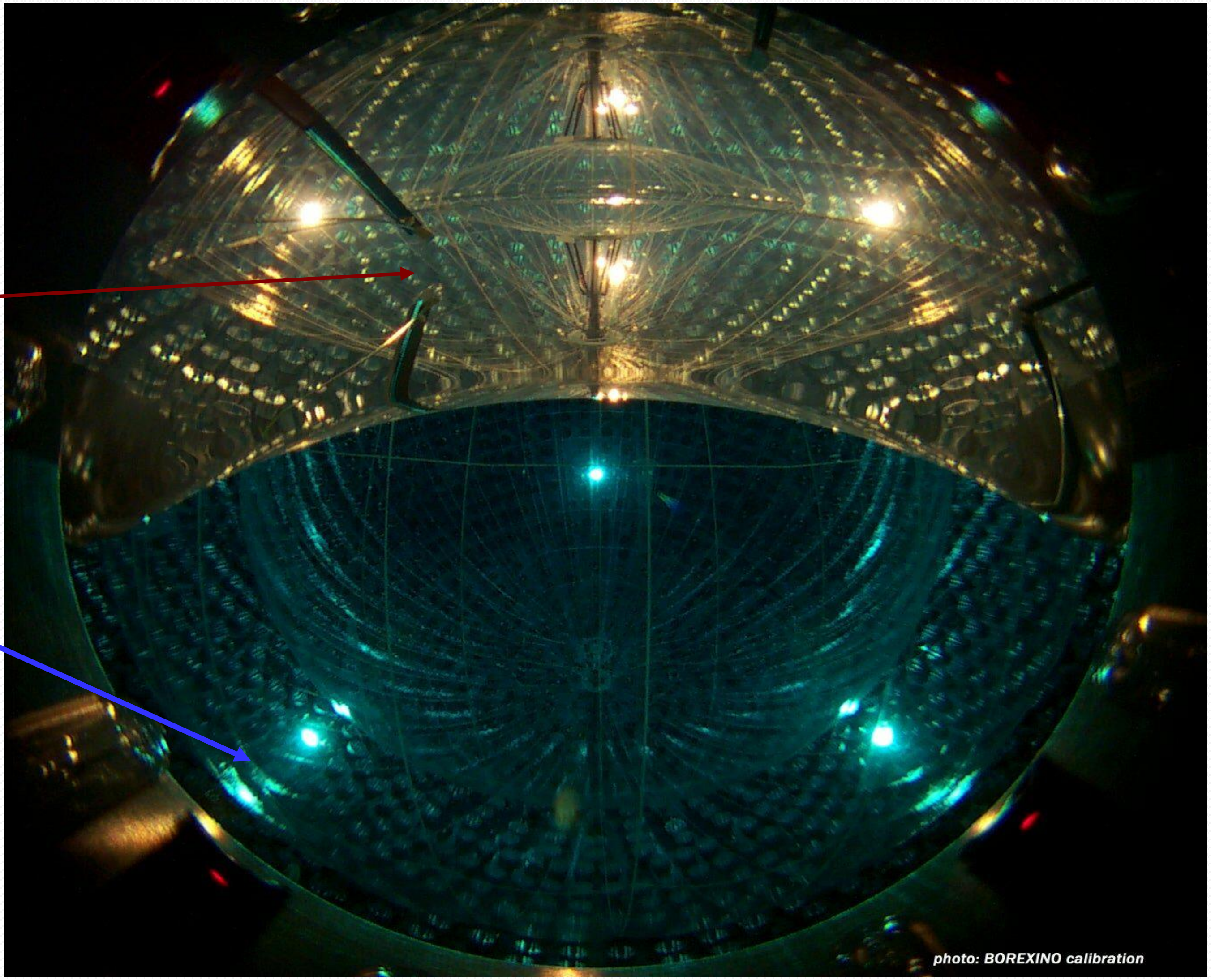
Ultra-pure water

Foto taken with one of 7 CCD cameras placed inside the detector



Filling 2/3

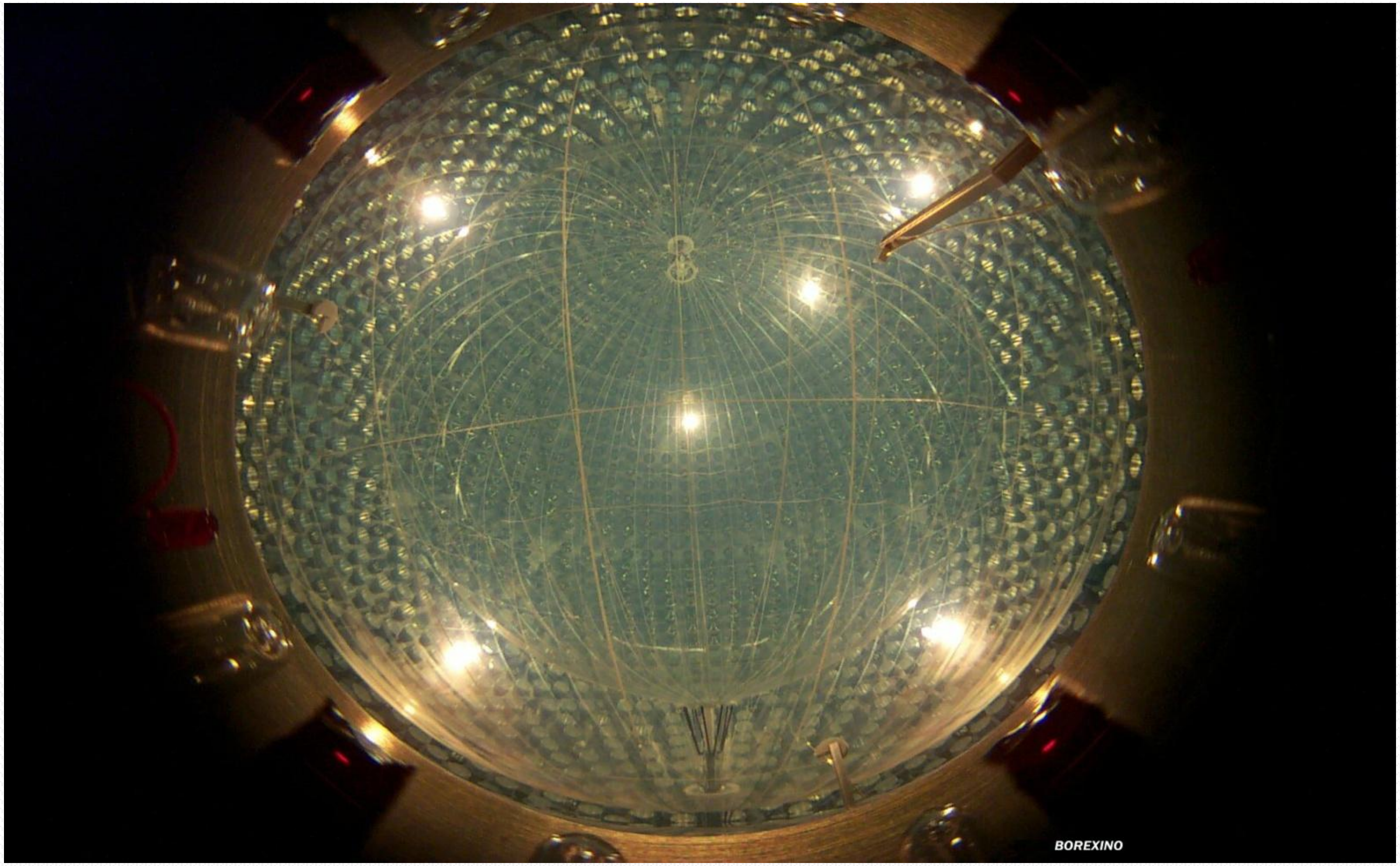
March 2007



Liquid scintillator

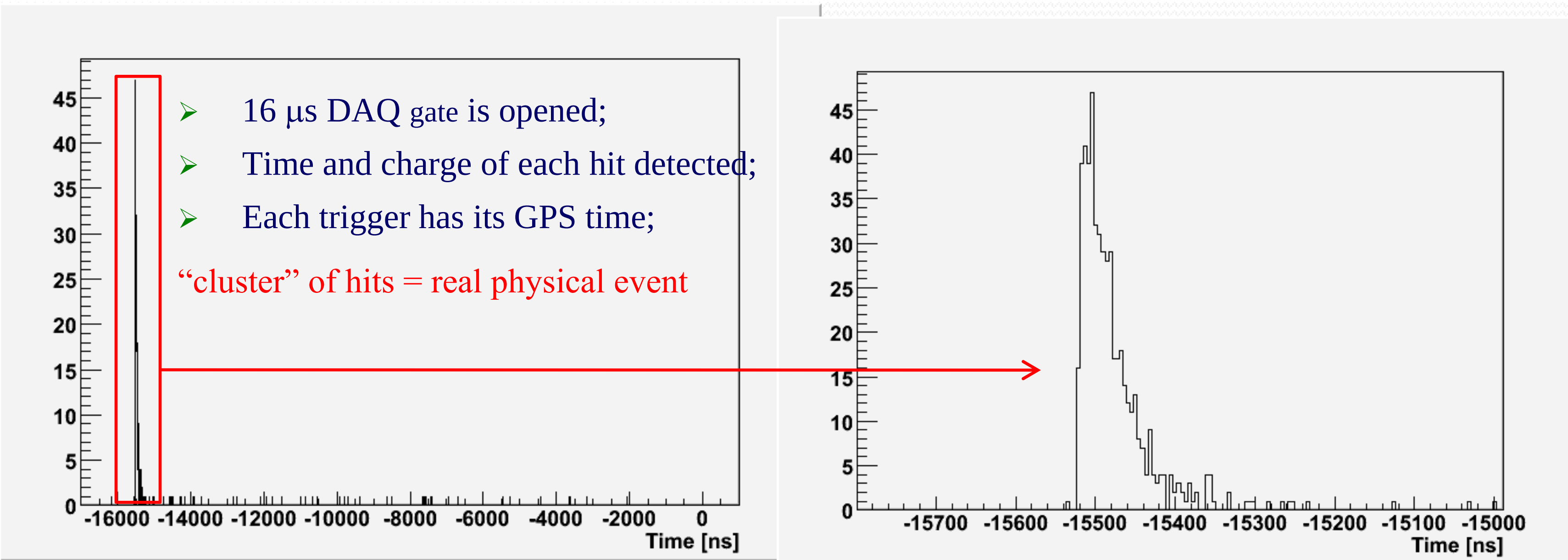
Ultra-pure water

Detector fully filled on May 15^{th,} 2007
DAQ STARTS



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:



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

Detector performances

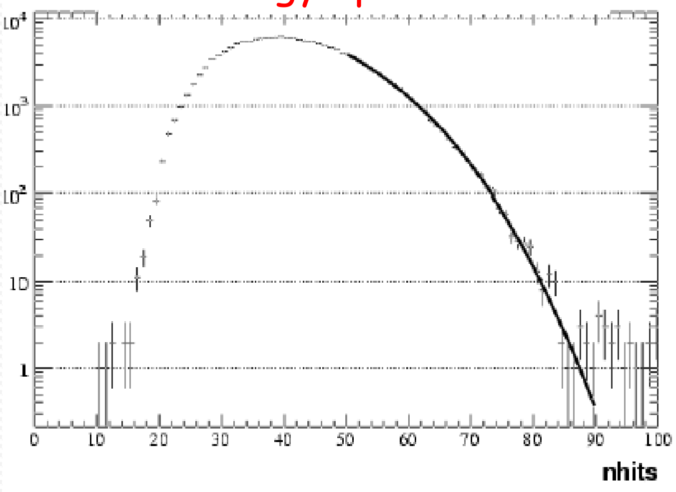
Lighth yield

1) ^{14}C spectrum, β^- decay 156 keV end point;
2) ^{11}C spectrum, β^+ decay 960 keV, triple coincidence with muon and neutron;
3) Global spectral fit (^{14}C, ^{210}Po, ^{7}Be edge);

(500 $\pm$ 12) p.e./MeV

taking into account quenching factor

^{14}C energy spectrum



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

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

Fiducial volume definition

- the nominal Inner Vessel radius: 4.25 m (278.3 tons of scintillator)
- how to define fiducial volume of 100 tons?

1) rescaling background components known to be uniformly distributed within the scintillator (^{14}C bound in scintillator itself, capture of μ-produced neutrons on protons)

2) using the sources with known position: (Th emitted by the IV-nylon, γ external background, teflon diffusers on the IV surface)

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

Assuming secular equilibrium:

^{232}Th chain

τ = 432.8 ns

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

2.25 MeV ~800 keV eq.

^{238}U chain

τ = 236 µs

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

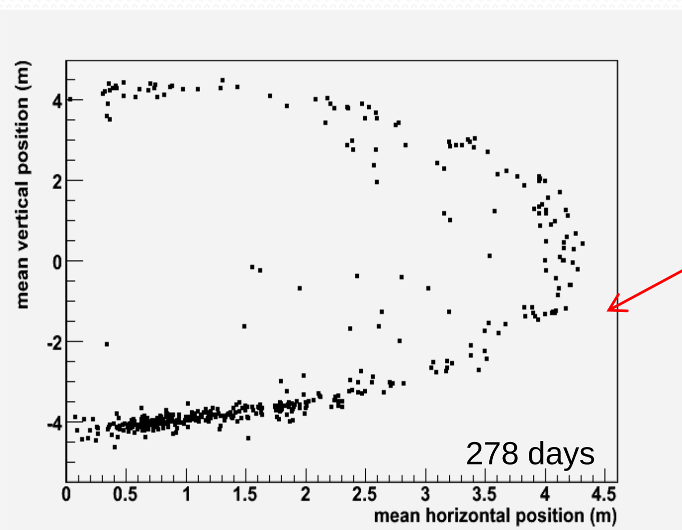
3.2 MeV ~700 keV eq.

Bulk contamination

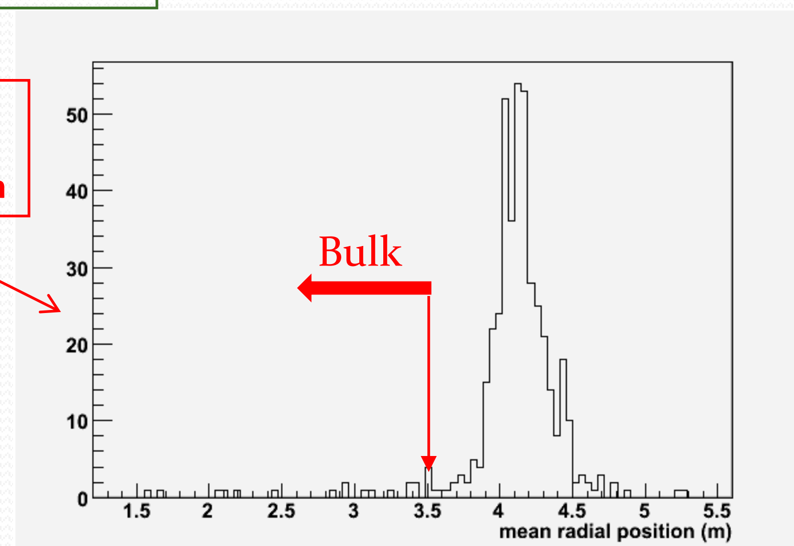
(6.8±1.5) 10^{-18} g(Th)/g

(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 :

	β⁻(61 keV)		β⁻(1.2MeV)		α	
	^{210}Pb	->	^{210}Bi	->	^{210}Po	-> ^{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

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

τ = 10.76 y - BR: 99.56%

^{85}Kr is studied through :

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

τ = 1.46 ms - BR: 0.43%

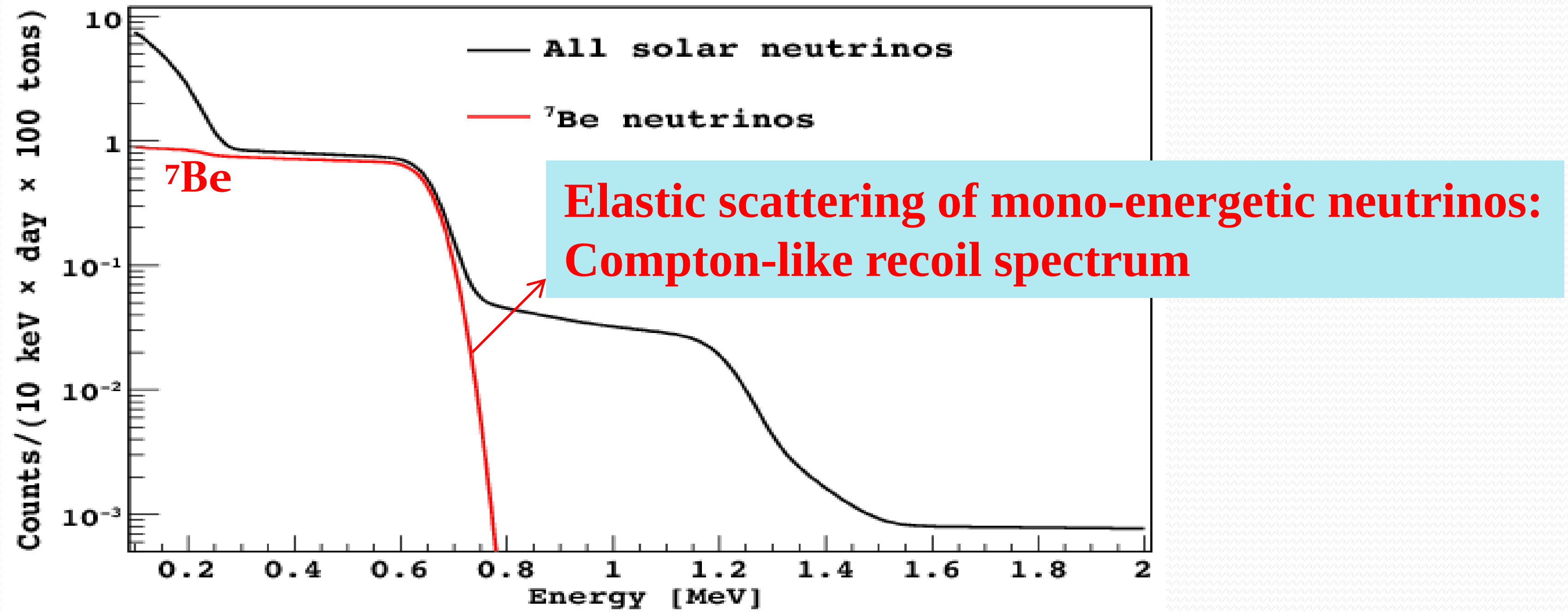
Only 8 (β–γ) coincidences selected in the inner vessel in 192 days

the ^{85}Kr contamination **(29±14) counts/day/100 ton**

More statistics is needed → taken as a free parameter in the total fit

Simulated spectrum of solar neutrinos

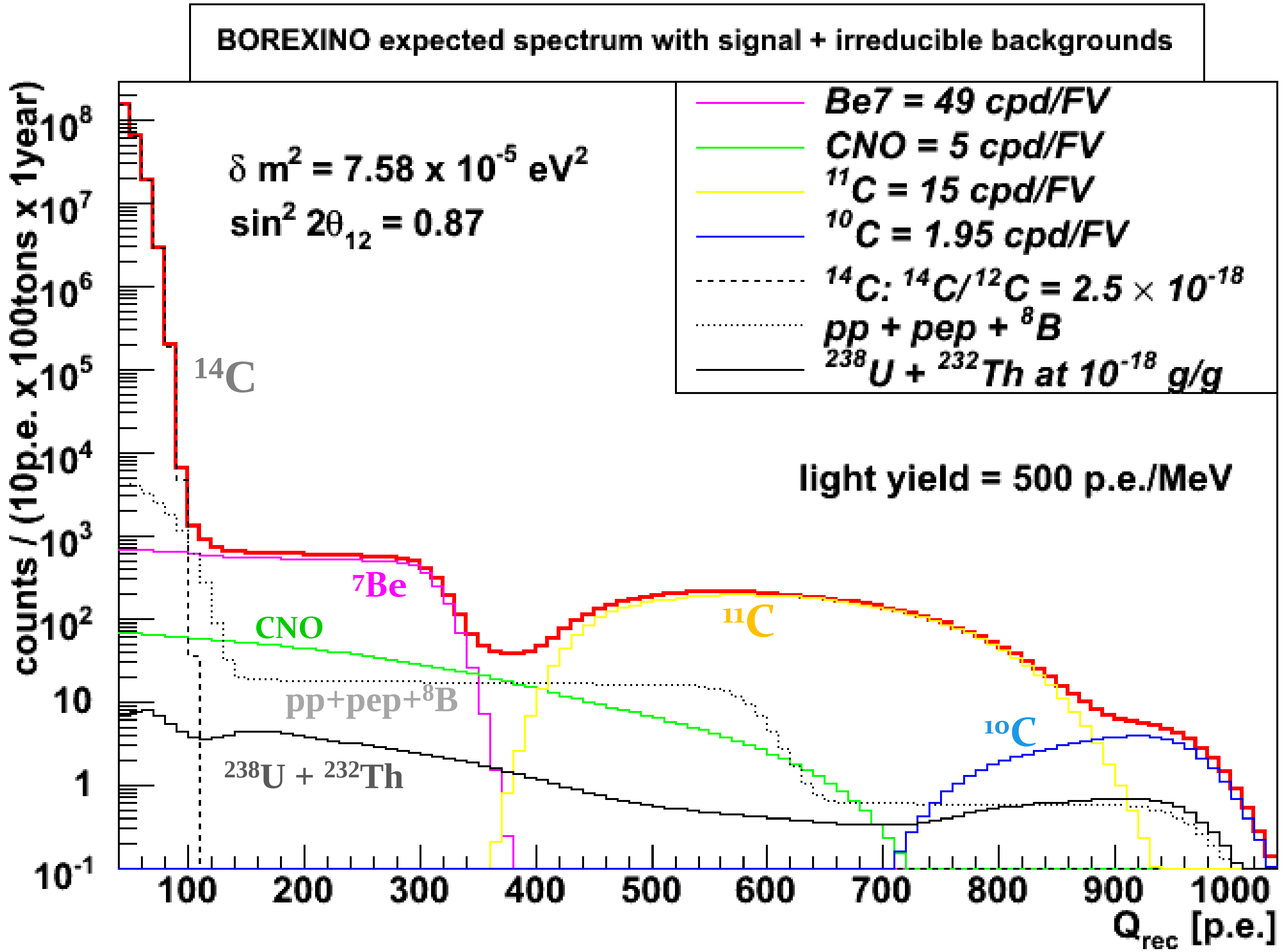
(detected via elastic scattering off electrons)

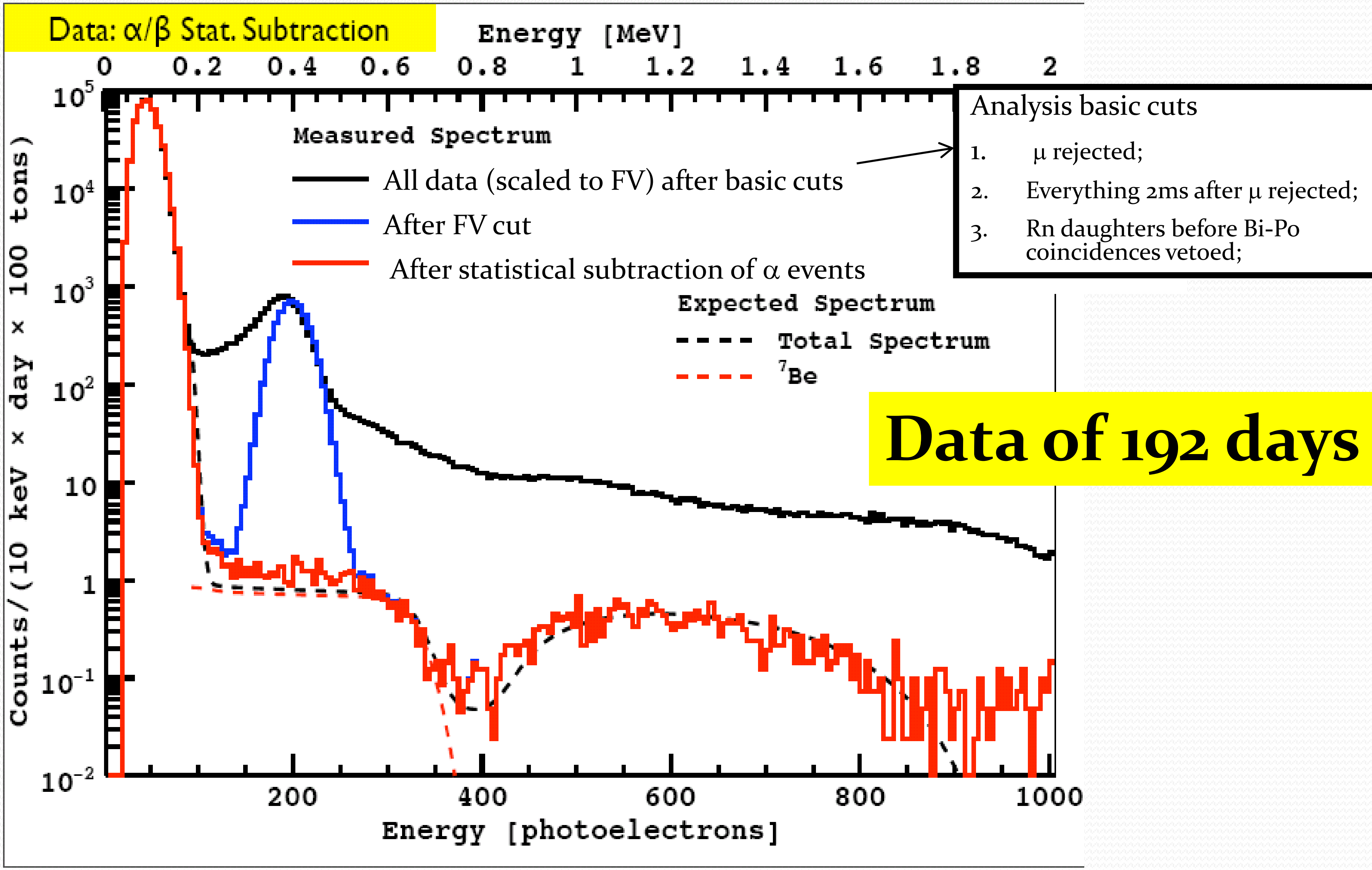


A measured neutrino flux depends on:

- neutrino flux produced in the Sun (**SSM: Standard Solar Model**)
- **neutrino survival probability**
  (LMA – Large Mixing Angle solution in the $\Delta m^2 - \sin^2 2\theta$ parameter space)
- **interaction cross section** (cca. 10^{-44} cm^2!!)

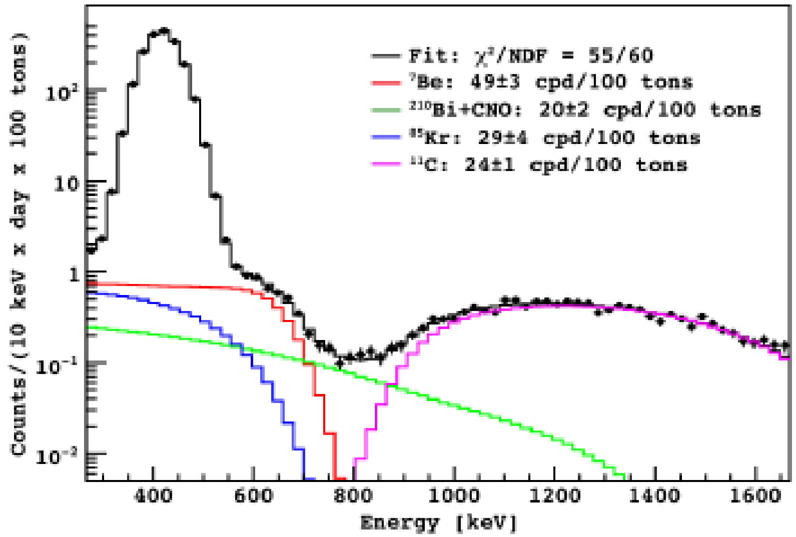
Expected MC spectrum: signal+irreducible background





Data of 192 days

Spectral fit

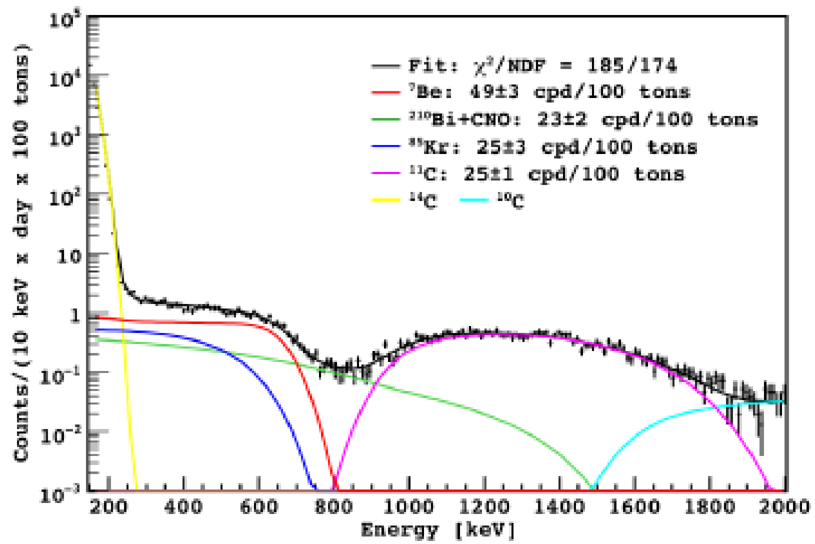


Fit region 260-1670 keV

- Light yield: a free fit parameter;
- Light quenching included Birks' parametrization;
- ^{14}C, ^{11}C and ^{85}Kr free fit parameters;

^{7}Be: (49 3_{STAT}) cpd/100 tons

- Fit to the spectrum **without** and **with** α–subtraction is performed giving consistent results



Fit region 160-2000 keV

Systematic uncertainties

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%

$49 \pm 3_{stat} \pm 4_{sys}$ cpd/100 tons

	Expected rate (cpd/100 t)
No oscillation	75 ± 4
BPS07(GS98) HighZ	48 ± 4
BPS07(AGS05) LowZ	44 ± 4

No-oscillation hypothesis rejected at 4σ level

Neutrino magnetic moment

SM with $m_\nu = 0$: $\mu_\nu = 0$

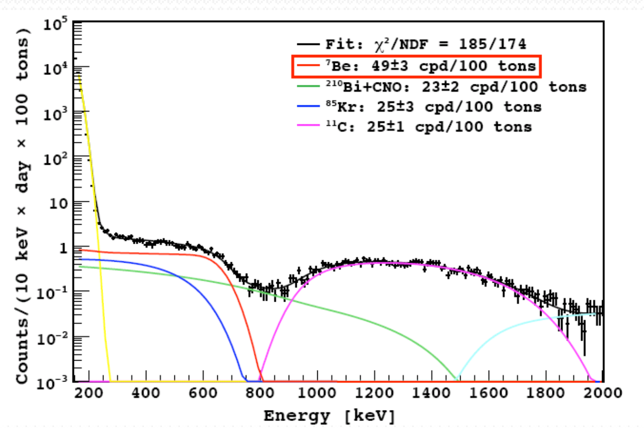
T – kinetic energy of scattered e
E_ν – neutrino energy

$$\left(\frac{d\sigma}{dT}\right)_W = \frac{2G_F^2 m_e}{\pi}\left[g_L^2 + g_R^2 + \left(1 - \frac{T}{E_\nu}\right)^2 - g_L g_R \frac{m_e T}{E_\nu^2}\right]$$

SM with $m_\nu > 0$: $\mu_\nu > 0$, additional EM term influencing the cross section and thus the spectral shape

$$\left(\frac{d\sigma}{dT}\right)_{EM} = \mu_\nu^2 \frac{\pi\alpha_{em}^2}{m_e^2}\left(\frac{1}{T} - \frac{T}{E_\nu}\right)$$

Sensitivity enhanced @ low energies



Estimate8	Method	90% C.L. 10^{-11} μ_B
SuperK	^{8}B above 5 MeV	< 11
Montanino *et al.*	^{7}Be (Borexino data)	< 8.4
GEMMA	Reactor anti-ν	< 5.8
Borexino	**^{7}Be**	**< 5.4**

Currently the best experimental limit!

Constraints on *pp*- & CNO-ν fluxes after the ^{7}Be measurement

- It is possible to combine the results obtained by Borexino on ^{7}Be flux with those obtained by other experiments to constraint the fluxes of pp and CNO ν_e;
- The measured rate in Clorine and Gallium experiments can be written as:

$$\boxed{R_k = \sum_{i,k} f_i R_{i,k} P_{ee}^{i,k}}$$

$$\boxed{\begin{aligned} &k = \text{Homestake, Gallex} \\ &i = pp, pep, CNO, {}^7Be, {}^8B \end{aligned}}$$

$$\boxed{\begin{aligned} &f_i = \frac{\phi_i(\text{measured})}{\phi_i(\text{predicted})} \\ &R_{i,k} = \text{expected rate of source "i" in experiment "k" (no oscill.)} \\ &P_{ee}^{e,k} = \text{average survival probability for source "i" in experiment "k"} \end{aligned}}$$

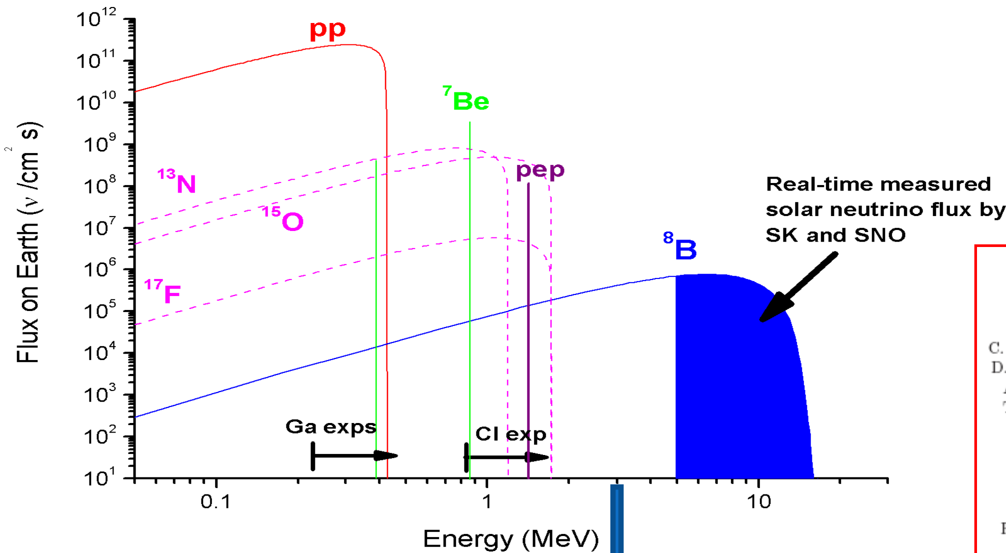
- $R_{i,k}$ and $P_{ee}^{i,k}$ are calculated in the hypothesis of **high-Z SSM and MSW LMA**, ;
- R_k are the rates actually measured by Clorine and Gallium experiments;
- **f_{8B} = 0.87 ± 0.07**, measured by **SNO** and **SuperK;**
- **f_{7Be} = 1.02 0.10** is given by **Borexino results**;
- Performing a χ^2 based analysis with the additional luminosity constraint;

$$\boxed{\begin{aligned} &f_{pp} = 1.005^{+0.008}_{-0.020}\ (1\sigma) \\ &f_{CNO} < 3.80\ (90\%\,C.L.) \end{aligned}}$$

Which is the best determination of pp flux (with luminosity constraint)

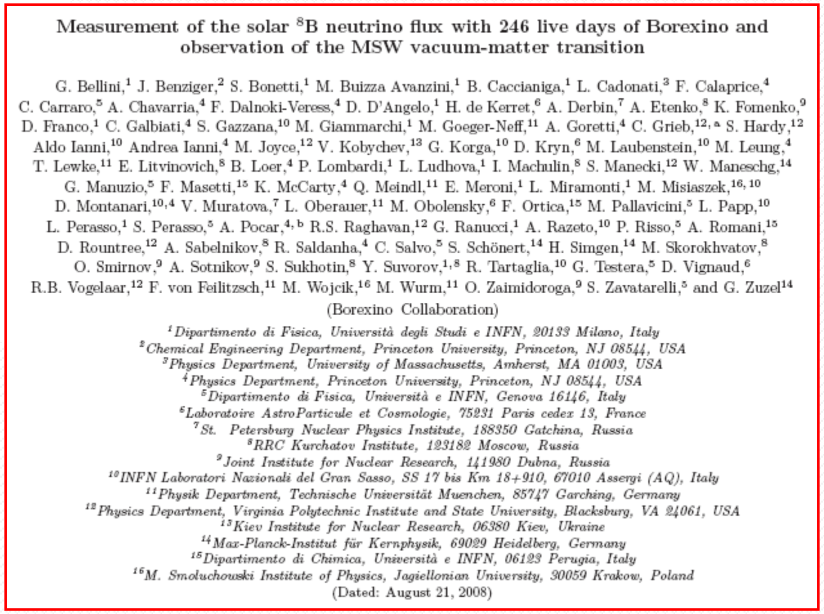
^{8}B-ν fluxes (see talk of D. Franco & arXiv 0808.2868 for details)

- The first simultaneous measurement of solar–ν from the **vacuum region** (**^{7}Be-ν**) and from **the matter-enhanced oscillation region (^{8}B-ν);**
- The first measurement of **^{8}B-ν in real time below 5 MeV;**



Borexino threshold for ^{8}B measurement

recently submitted to PRL



Measurement of the solar ^{8}B neutrino flux with 246 live days of Borexino and observation of the MSW vacuum-matter transition

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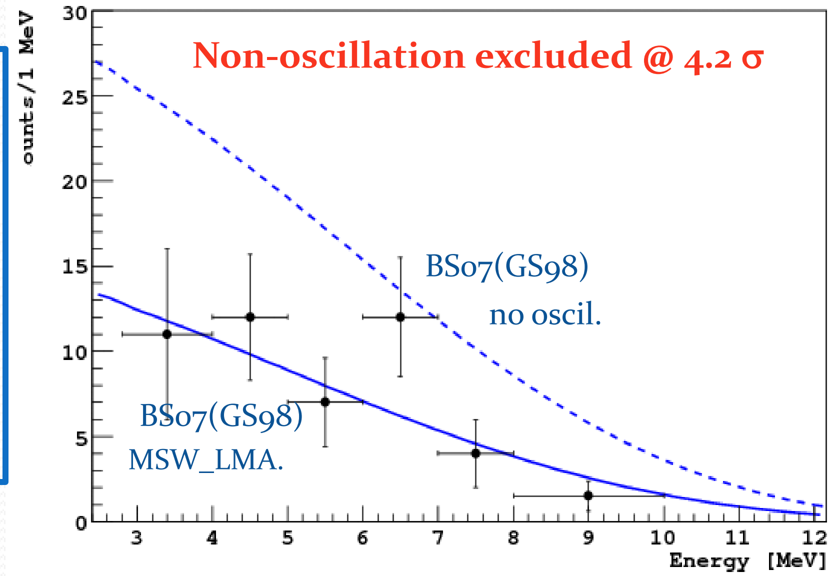
(Dated: August 21, 2008)

^{8}B-ν fluxes (see talk of D. Franco & arXiv 0808.2868 for details)

Major background sources:

1) Muons;
2) Gammas from neutron capture;
3) Radon emanation from the nylon vessel;
4) Short lived ($\tau < 2$ s) cosmogenic isotopes;
5) Long lived ($\tau > 2$ s) cosmogenic isotopes (^{10}C);
6) Bulk ^{232}Th contamination (^{208}Tl);



First real-time measurement above 2.8 MeV:

$$Rate_{>2.8MeV} = (0.26 \pm 0.04_{stat} \pm 0.02_{sys})\ \text{counts/day/100 tons}$$

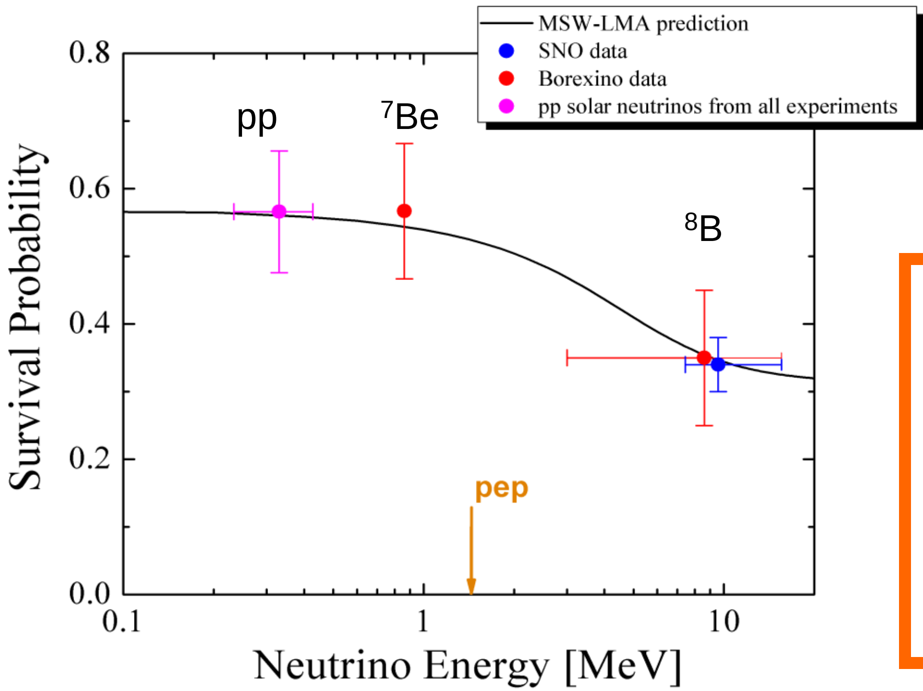
$$\left(\Phi_{exp}^{ES} / \Phi_{th}^{ES}\right)_{>2.8\,\text{MeV}} = (0.96 \pm 0.19)$$

Above 5 MeV in agreement with SNO and SuperK:

$$Rate_{>5MeV} = (0.14 \pm 0.03_{stat} \pm 0.01_{sys})\ \text{counts/day/100 tons}$$

$$\left(\Phi_{exp}^{ES} / \Phi_{th}^{ES}\right)_{>5\,\text{MeV}} = (1.02 \pm 0.23)$$

Survival probability after Borexino



First simultaneous measurement in both vacuum-dominated and matter-enhanced regions

Assuming high-Z SSM (BPS 07), the ^{7}Be rate measurement corresponds to

P_{ee} (^{7}Be) = 0.56   0.10 (1σ)

which is consistent with the number derived from the global fit to all solar and reactor experiments (S. Abe et al., arXiv: 0801.4589v2)

P_{ee} (^{7}Be) = 0.541   0.017

Assuming high-Z SSM (BPS 07) the ^{8}B rate measurement corresponds to

P_{ee} (^{8}Be) = 035   0.10 @ 8.6 MeV mean energy

We determine the survival probability for ^{7}Be and pp-ν_e, assuming BPS07 and **using input from all solar experiments** (Barger *et al.*, PR (2002) 88, 011302)

P_{ee} (^{7}Be) = 0.56   0.08

P_{ee} (pp) = 0.57   0.09

Future: pep- and CNO-ν fluxes

The main background for pep and CNO analysis is ^{11}C

$$\mu + {}^{12}C \rightarrow \mu + {}^{11}C + n \; (90\%)$$

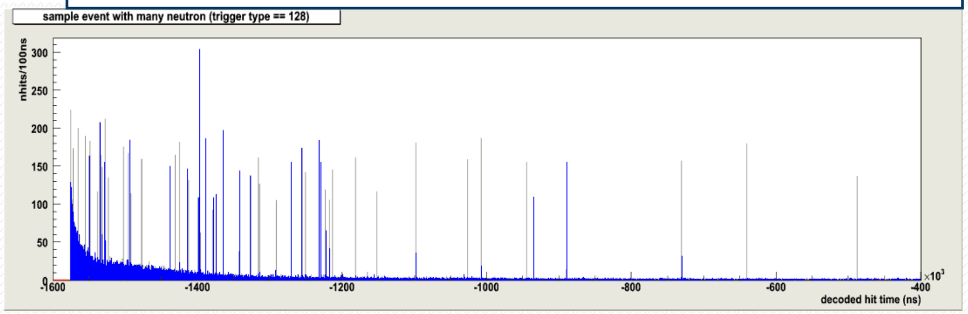
$\tau \sim 30$ min!!

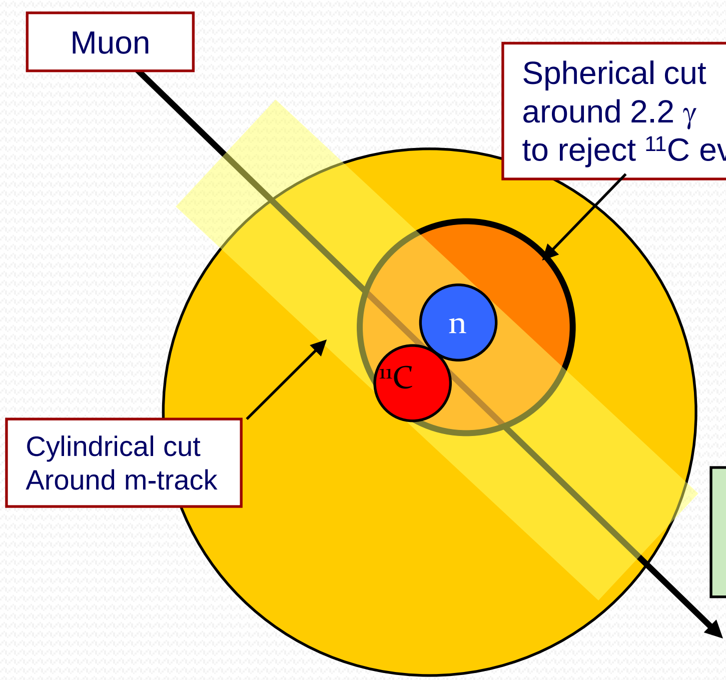
$\tau \sim 260\ \mu s$

$${}^{11}C \rightarrow {}^{11}B + e^{+} + \nu_e \qquad n + p \rightarrow d + \gamma \; (2.2\ \text{MeV})$$

- electronics improvement to detect all the neutrons produced by a muon
  - Changes in the electronics (Dec 07): after each muon, **1.6 ms gate opened**
  - FADC implementation in parallel;

Example with several tens of neutrons detected:



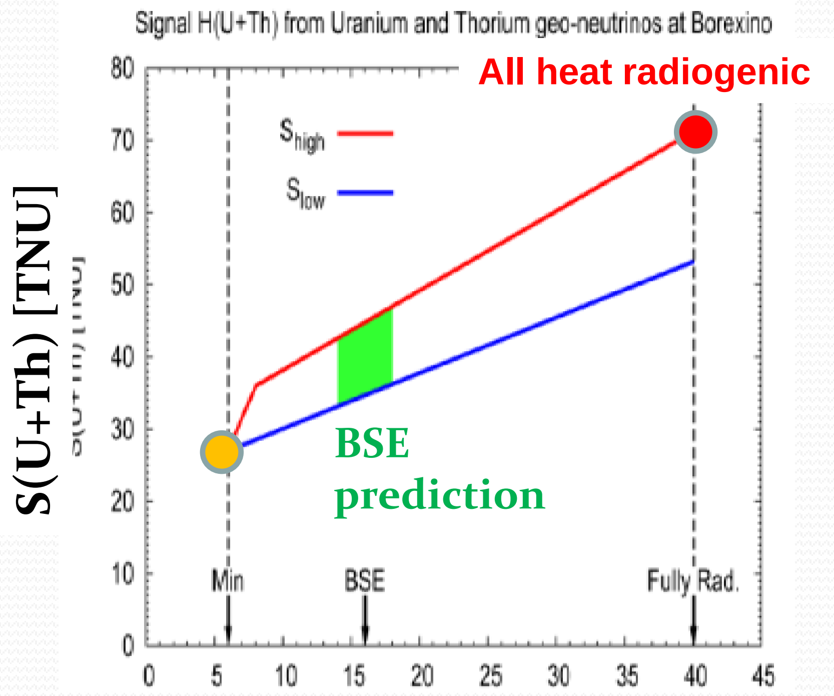


Triple coincidence:

μ, 2*511 keV, γ (2.2 MeV)

Borexino potential on geo-ν

(antineutrinos from the Earth, chains of U & Th, and K)

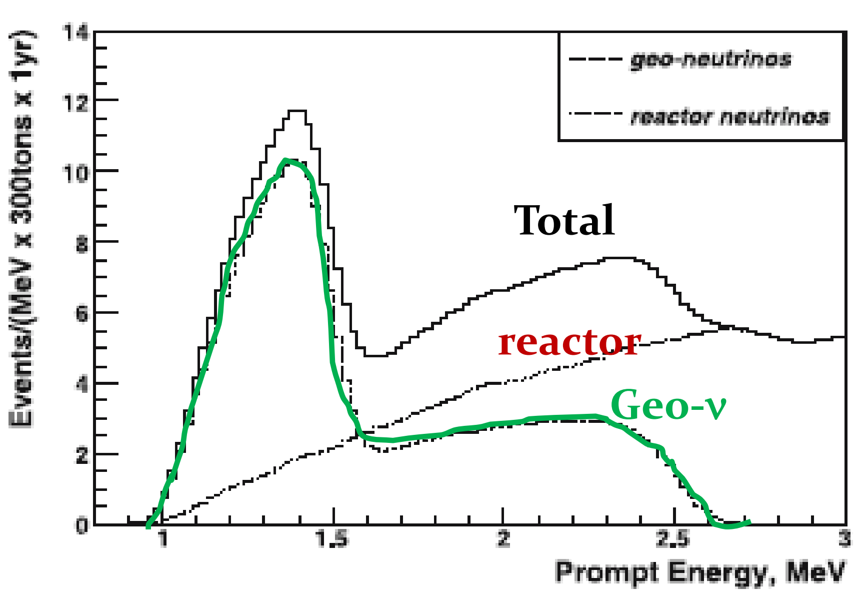


Mantovani et al., TAUP 2007

TNU = 1 event / 10^{32} target proton / year

Np (Borex) = 1.8 10^{31} target proton

Prompt signal energy spectrum (model)



5.7 events from reactors (in geo-ν E range)

BSE: 6.3 events from geoneutrinos

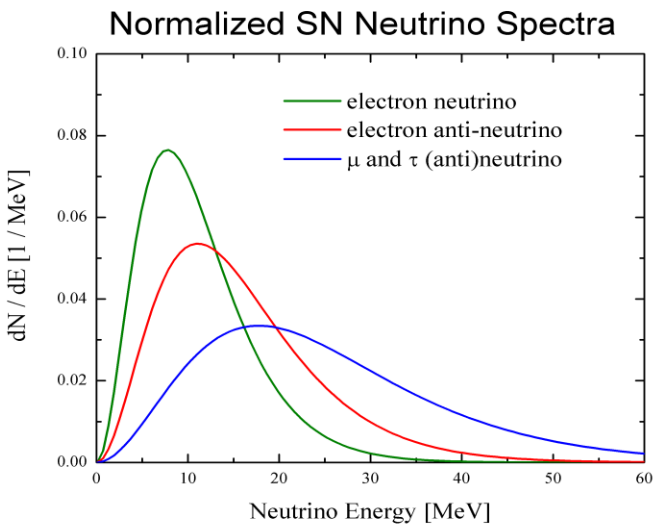
(per year and 300 tons, ε = 80%, 1-2.6 MeV)

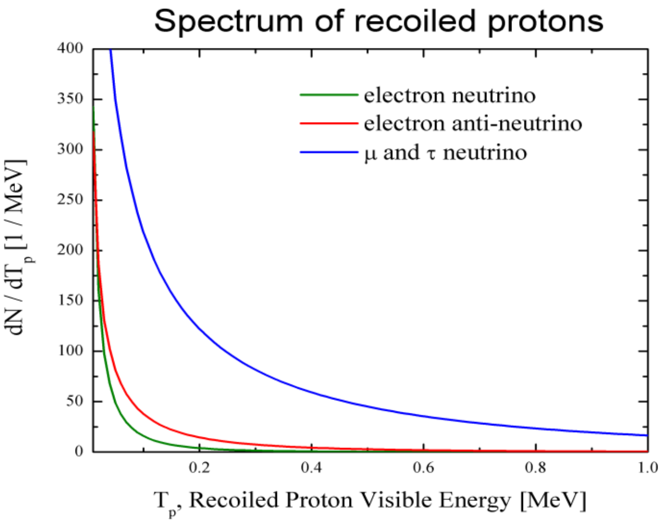
(Balata *et al.*, 2006, ref. model Mantovani *et al.*, 2004)

BSE: 3σ evidence of geoneutrinos expected in 4 years of data

Borexino potential on supernovae neutrinos

Standard SN @ 10kpc





Borexino E_{tresh} = 0.25 MeV
target mass 300 t

Detection channel	N events
ES ($E_\nu > 0.25$ MeV)	5
Electron anti-neutrinos ($E_\nu > 1.8$ MeV)	78
ν-p ES ($E_\nu > 0.25$ MeV)	52
$^{12}C(\nu,\nu)^{12}C^*$ ($E\gamma = 15.1$ MeV)	18
$^{12}C(\text{anti-}\nu,e^+)^{12}B$ ($E_{\text{anti-}\nu} > 14.3$ MeV)	3
$^{12}C(\nu,e^-)^{12}N$ ($E_\nu > 17.3$ MeV)	9

Can be used as an early alarm

Borexino plans to enter SNEWS

Livia Ludhova (Borexino collaboration)

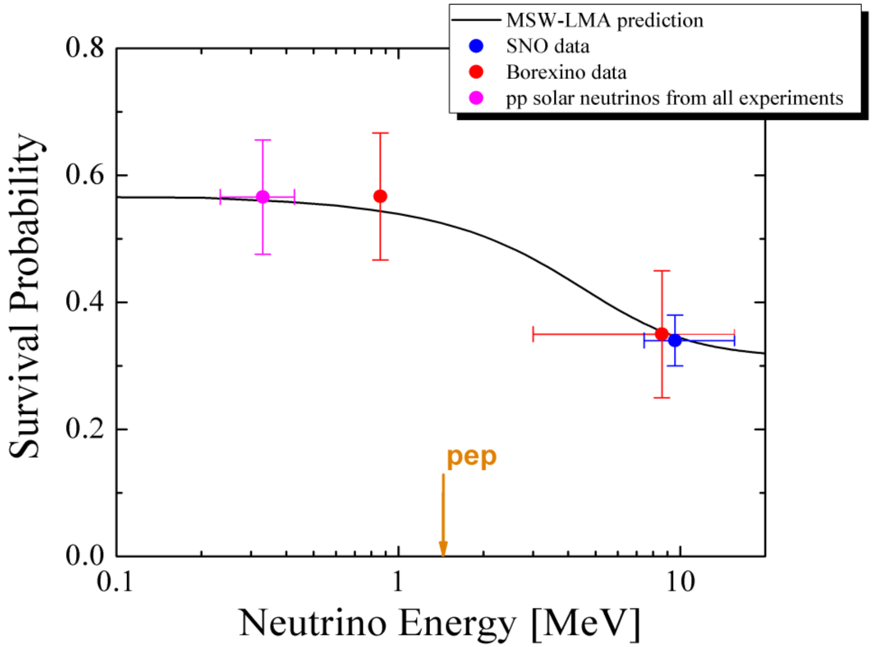
Conclusions

DONE

- Borexino performed the first real-time measurement **of solar-ν below the barrier of natural radioactivity** (4 MeV);
- The two measurements reported for **^{7}Be-ν** favor MSW-LMA solution;
- The first real-time measurement of **^{8}B-ν above 2.8 MeV** ;
- The first **simultaneous** measurement of solar neutrinos from the **vacuum region** (^{7}Be-ν) and from **the matter-enhanced oscillation region** (^{8}B-ν);
- **Best limits for pp- and CNO-ν,** combining information from all solar and reactor experiments;

TO BE DONE

- Precision measurement (at or below the level of 5%) of the ^{7}Be-ν rate;
- Check the 7% seasonal variation of the neutrino flux (confirm solar origin);
- Under study: measurement of the CNO, pep and high-energy pp neutrinos;
- Strong potential in antineutrinos (geoneutrinos, reactor, from the Sun) and in supernovae neutrinos and antineutrinos;

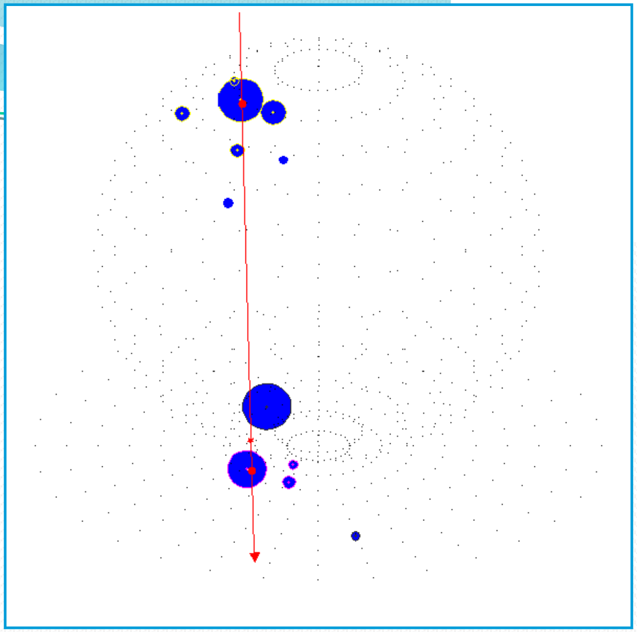

MSW-LMA prediction
SNO data
Borexino data
pp solar neutrinos from all experiments
Survival Probability
0.0
0.2
0.4
0.6
0.8
0.1
1
10
pep
Neutrino Energy [MeV]

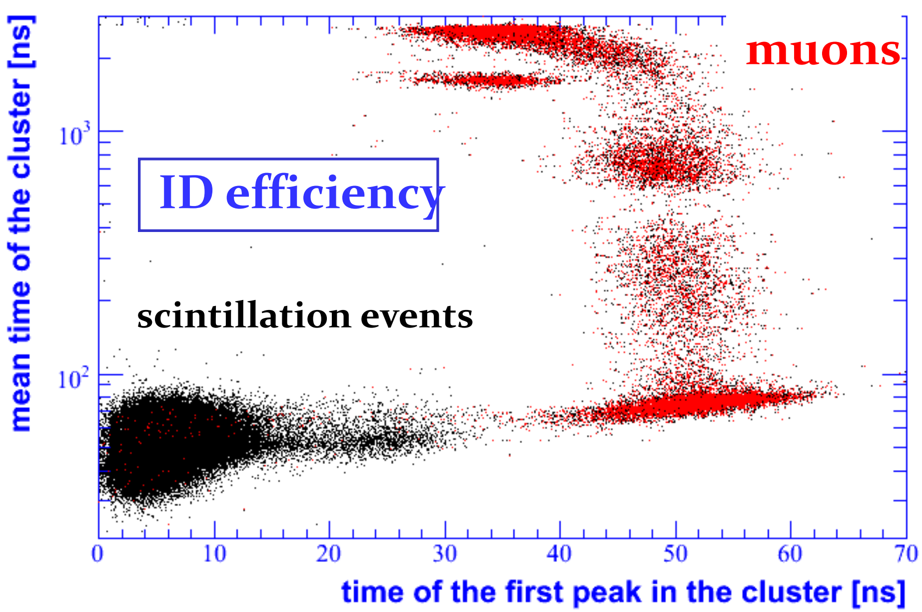
Thank you!!

Additional slides

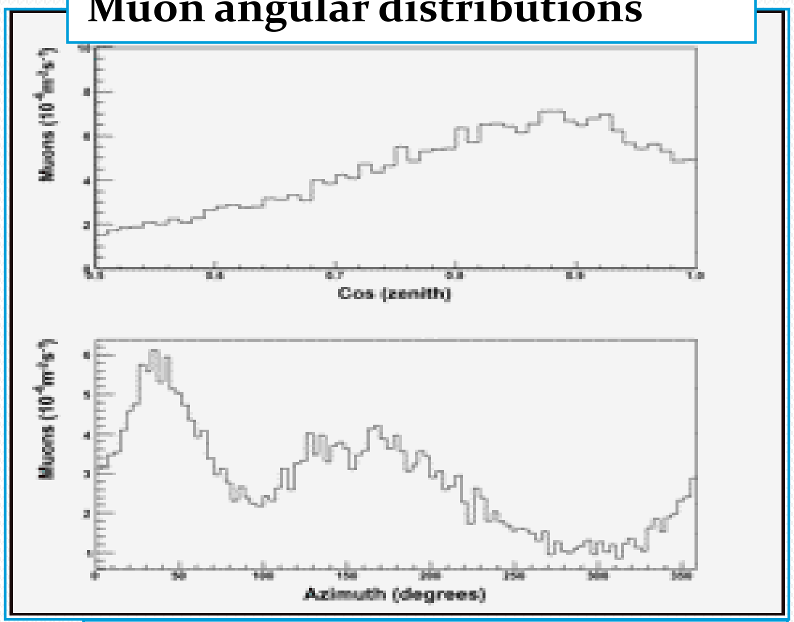
Cosmic μ's

- **μ are identified by the OD and by the ID**
  - OD eff: ~ 99%
  - ID analysis based on pulse shape variables
    - Deutsch variable: ratio between light in the concentrator and total light
    - Cluster mean time, peak position in time
  - Estimated overall rejection factor > 10^4 (still preliminary)
- **After cuts, m not a relevant background for ^{7}Be**
  - **Residual background: < 1 count /day/ 1 00 t**





Muon angular distributions

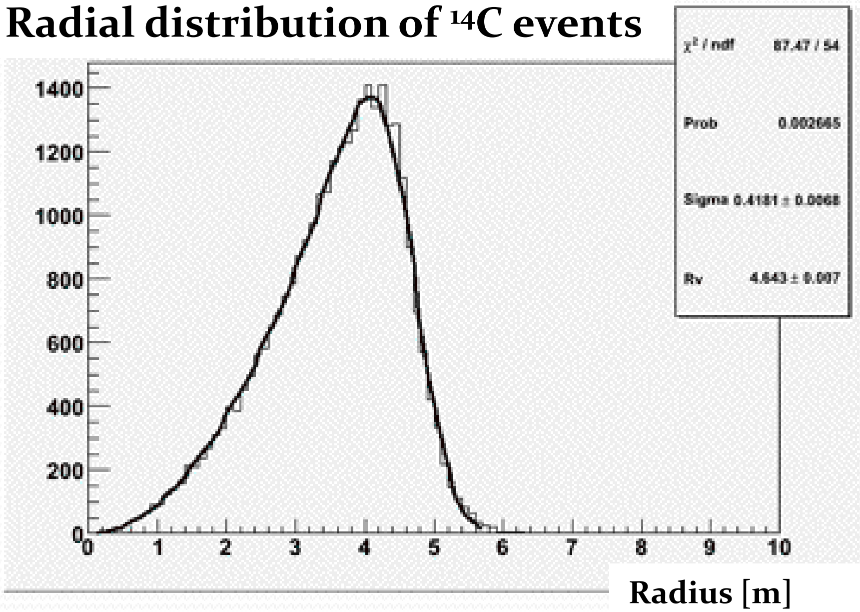


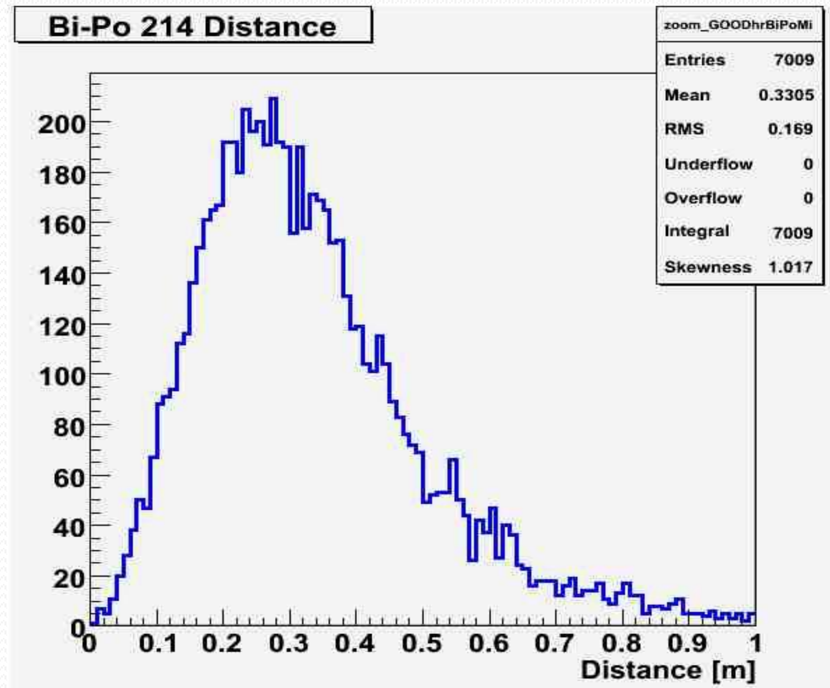
Muon flux:(1.21±0.05)$h^{-1}m^{-2}$

Position reconstruction algorithms

- Base on time of flight fit to hit-time distribution
- developed with MC, tested and validated in Borexino prototype CTF
- cross checked and tuned in Borexino on selected events (^{14}C, ^{214}Bi-^{214}Po, ^{11}C)

Radial distribution of ^{14}C events

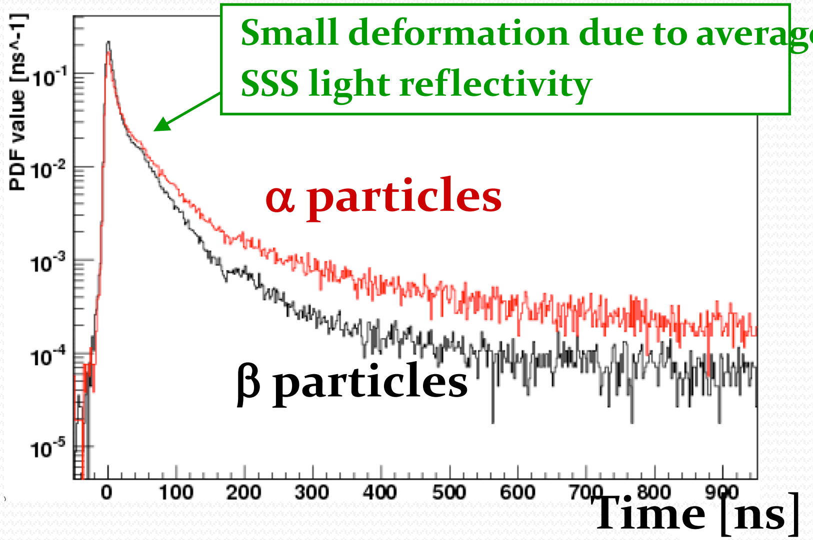


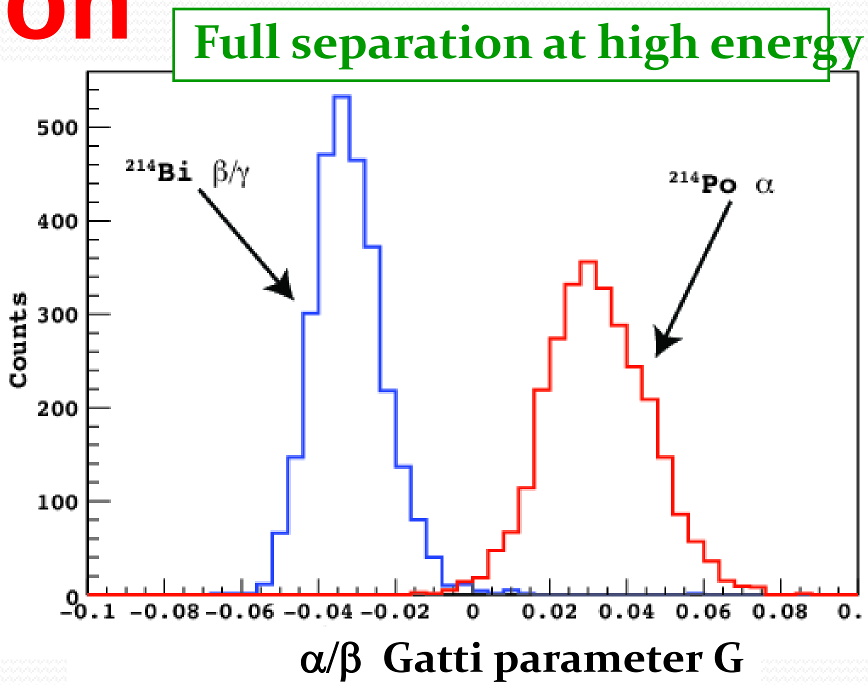


^{14}C "bound" in the scintillator: homogeneous
The fit is compatible with the expected
r^2-like shape with R=4.25m.

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

α/β discrimination





$\overline{\alpha}_i, \overline{\beta}_i$ –> average pulse shapes

$$P_i = \frac{(\overline{\alpha}_i - \overline{\beta}_i)}{(\overline{\alpha}_i + \overline{\beta}_i)}$$ –> for i-time interval of 2 ns

$$G = \sum_i P_i S_i$$

S_i –> signal shape within a given Δt (2 ns)

Techinques towards low-radioactivity

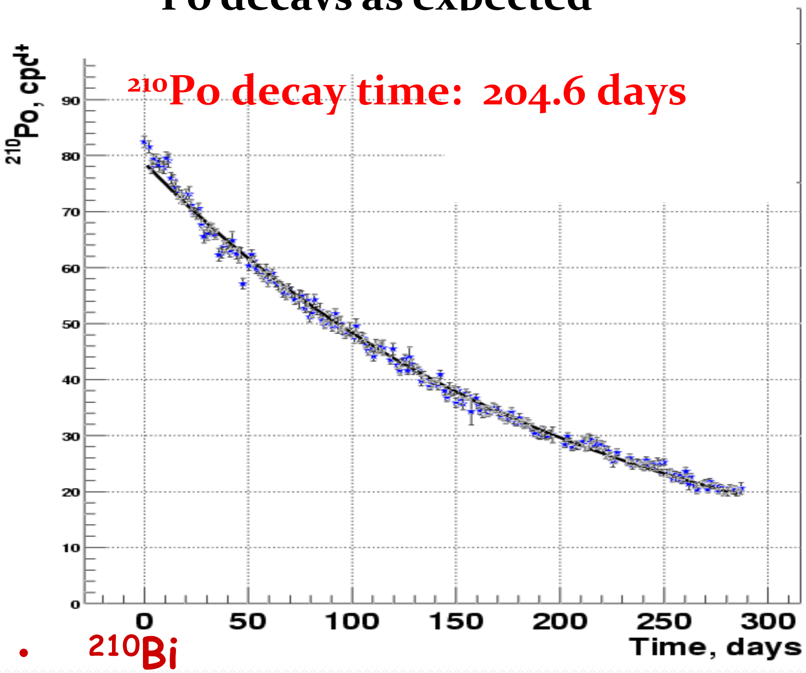
- Low background nylon vessel fabricated in hermetically sealed low radon clean room (~1 yr)
- Rapid transport of scintillator solvent (PC) from production plant to underground lab to avoid cosmogenic production of radioactivity (^{7}Be)
- Underground purification plant to distill scintillator components.
- Gas stripping of scintlllator with special nitrogen free of radioactive ^{85}Kr and ^{39}Ar from air
- All materials electropolished SS or teflon, precision cleaned with a dedicated cleaning module

Background: ^{210}Po

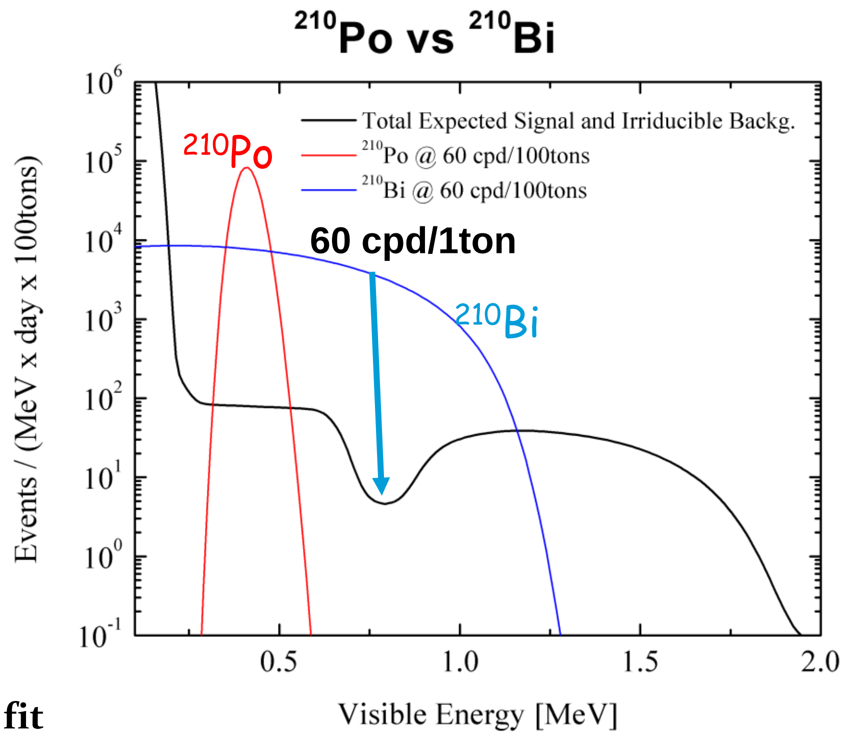
End of ^{238}U chain :

		β^-(61 keV)		β^-(1.2MeV)		α	
	^{210}Pb	->	^{210}Bi	->	^{210}Po	->	^{206}Pb
$t_{1/2}$	22.3 y		5.01 d		138.38 d		stable

- Not in equilibrium with ^{210}Pb !
- ^{210}Po decays as expected



- 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

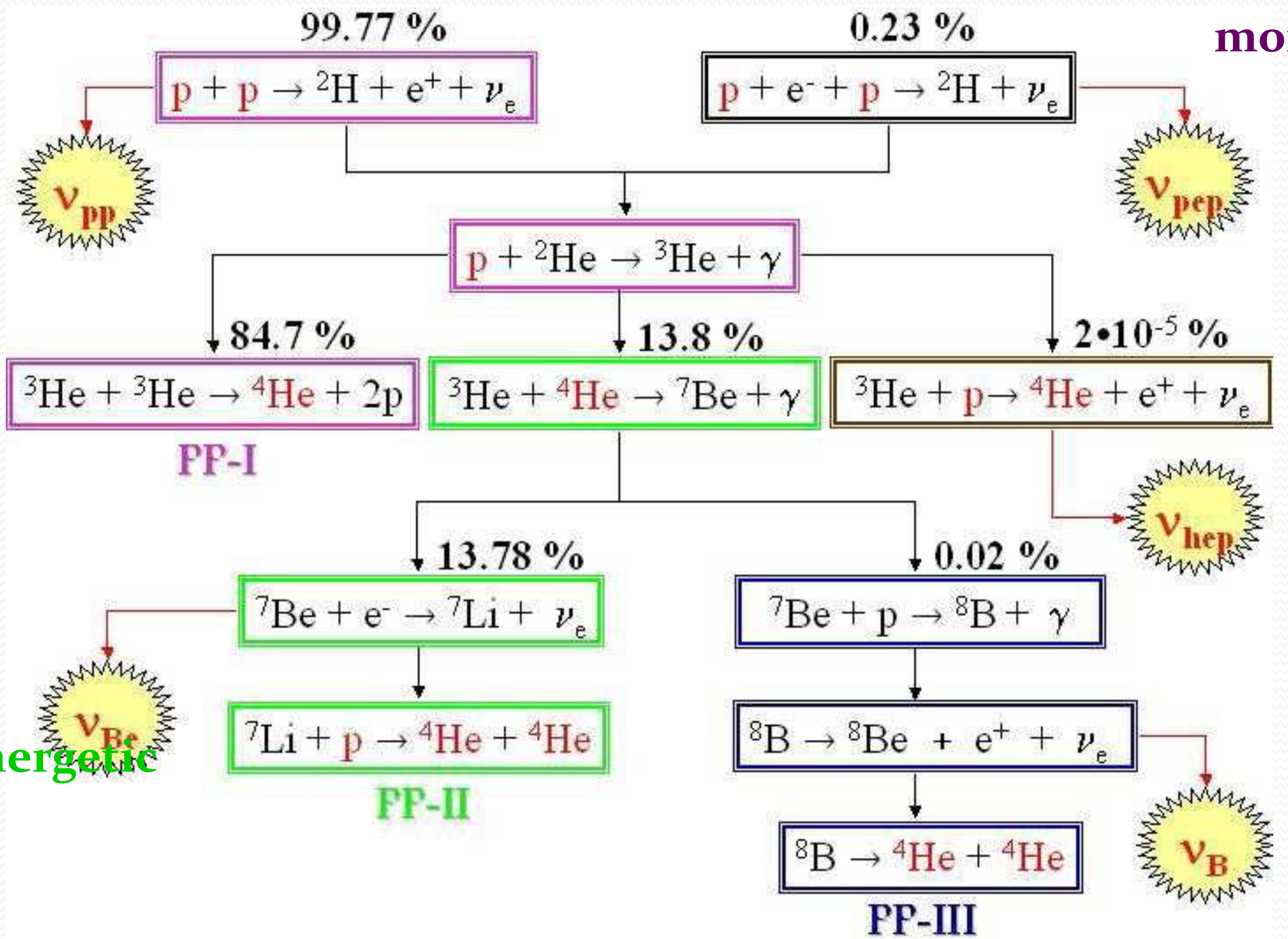


- ^{210}Bi

no direct evidence----> free parameter in the total fit

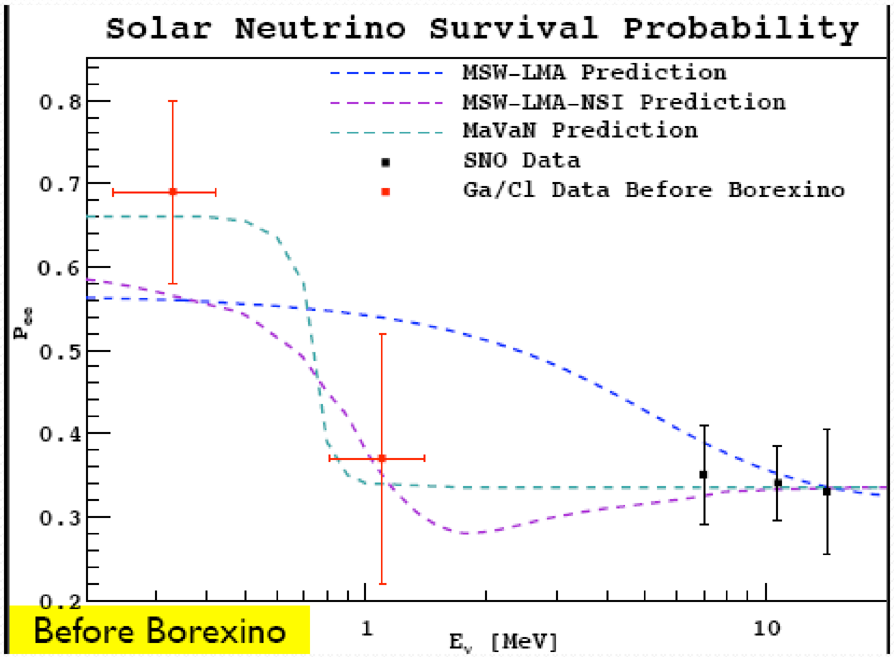
cannot be disentangled, in the ^{7}Be energy range, from the CNO

Proton-proton cycle: the main energy source in the Sun



monoenergetic

monoenergetic



Under the assuptions of High-Z SSM (BPS 07) the ^{7}Be rate measurement corresponds to

P_{ee} (^{7}Be) = 0.56 0.1 (1σ)

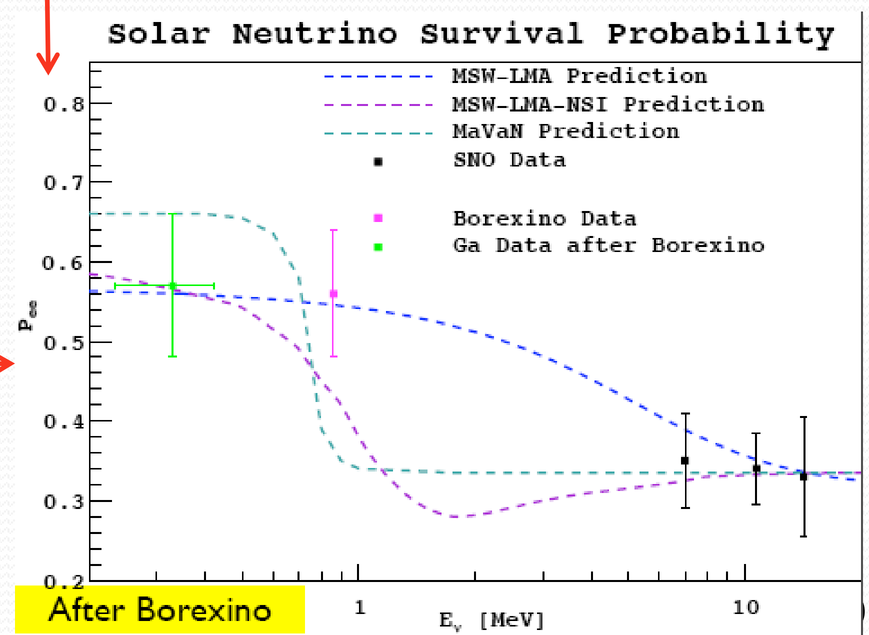
which is consistent with the number derived from the global fit to all solar and reactor experiments (S. Abe et al., arXiv: 0801.4589v2)

P_{ee} (^{7}Be) = 0.541 0.017

We determine the survival probability for ^{7}Be and pp-ν_e, assuming BPS07 and **using input from all solar experiments** (Barger *et al.*, PR (2002) 88, 011302)

P_{ee} (^{7}Be) = 0.56 0.08

P_{ee} (pp) = 0.57 0.09



What can Borexino say about other solar ν sources?