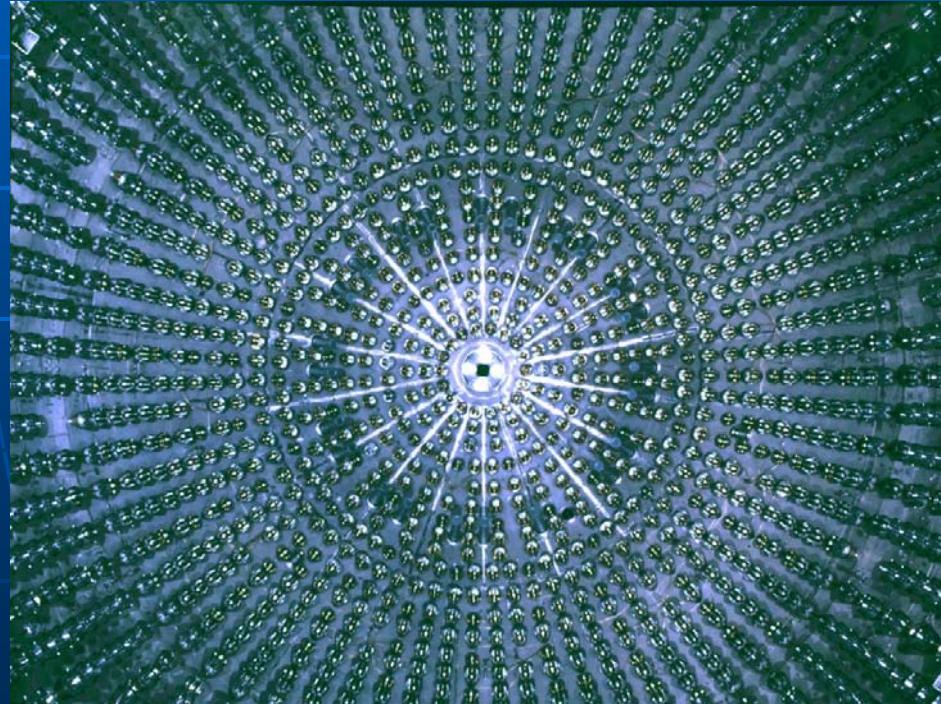


Measurement of ${}^7\text{Be}$ and ${}^8\text{B}$ solar neutrinos with BOREXINO



S. Zavatarelli
INFN Genova
(on behalf of Borexino collaboration)



La Thuile 2009

Sandra Zavatarelli Univ. & INFN Genova Italy

BOREXINO Collaboration



Genova



Perugia

Milano



APC Paris



Princeton University



Virginia Tech. University



Dubna JINR
(Russia)



Kurchatov
Institute
(Russia)



Jagiellonian U.
Cracow
(Poland)



Heidelberg
(Germany)



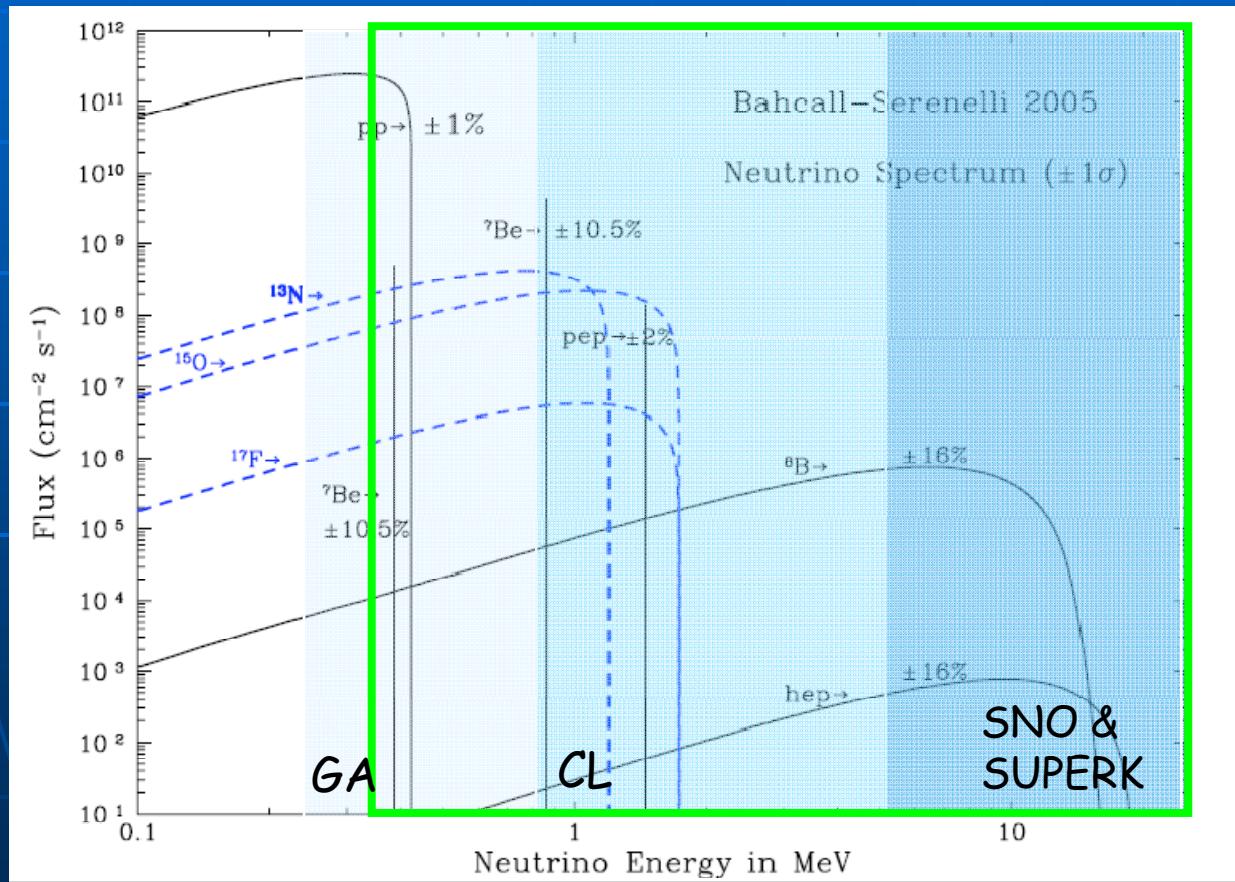
Munich
(Germany)



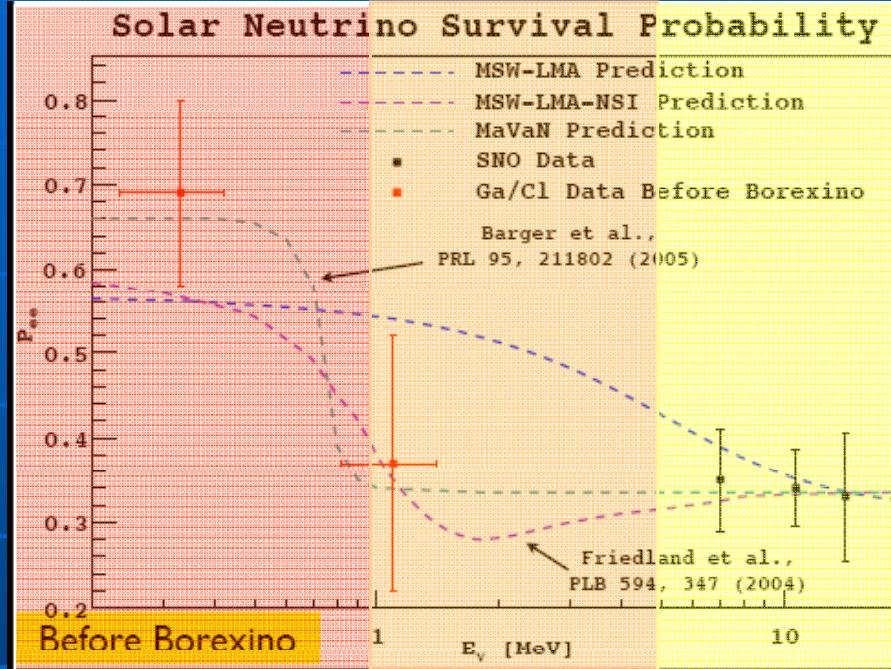
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BOREXINO : capability to measure in real time and separately the different components of the solar- ν spectrum



Importance of low/medium energies neutrinos precise flux measurements



MSW-LMA (arXiv:0806.2649):
 • $\Delta m^2 = 7.69 \times 10^{-5} \text{ eV}^2$
 • $\tan^2 \theta = 0.45$

MSW-LMA theory: neutrino oscillations are dominated by:

- resonant matter-enhanced oscillations at higher energies ($>5 \text{ MeV}$)
- vacuum oscillation at low energies ($<1 \text{ MeV}$)
- a smooth transition is expected between the two different regimes:
VERY IMPORTANT in order to confirm MSW-LMA or exploit possible traces of non-standard neutrino-matter interaction / presence of mass varying ν 's

Importance of low/medium energies neutrinos precise flux measurements: high/low metallicity Solar Models controversy



ν fluxes vs metallicity :

Φ (cm $^{-2}$ s $^{-1}$)	pp (x 10 10)	pep (x 10 8)	^7Be (x 10 9)	^8B (x 10 6)	$^{13}\text{N:CNO}$ (x 10 8)	$^{15}\text{O:CNO}$ (x 10 8)	$^{17}\text{F:CNO}$ (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 metallicity model GS98: Grevesse & Sauval, Space Sci. Rev. 85, 161 (1998)

⁽³⁾Based on new low metallicity model AGS05:

Asplund, Grevesse & Sauval 2005, Nucl. Phys. A 777, 1 (2006).

BUT: incompatible with helioseismological measurements

BOREXINO: Detection principles and ν signature



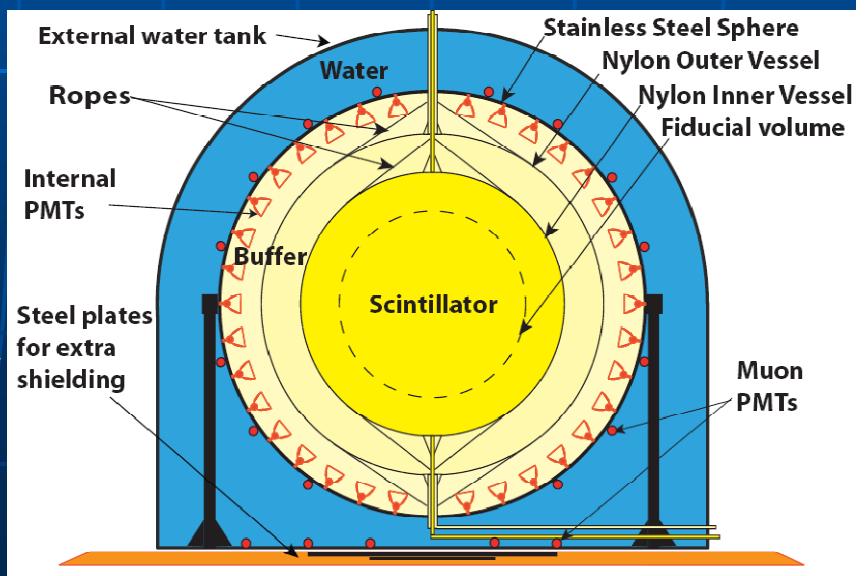
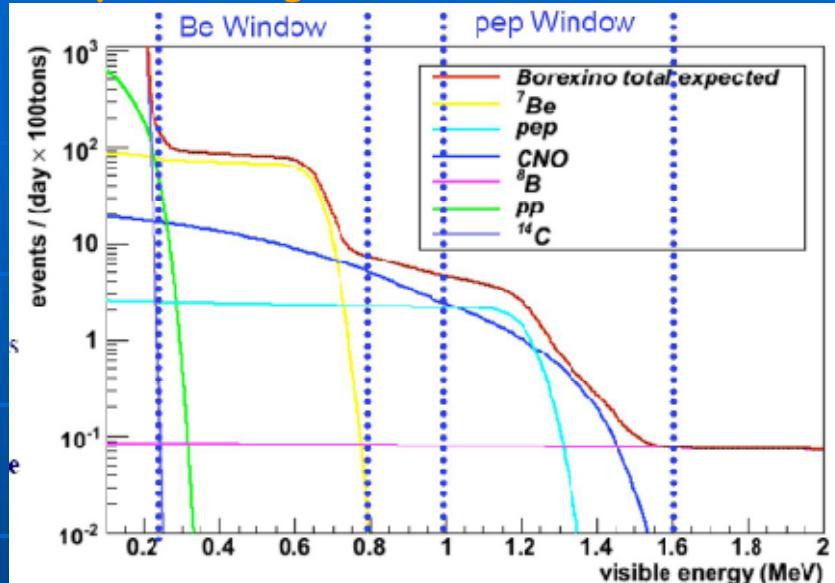
- Borexino detects solar ν in real time via their elastic scattering off electrons in a volume of highly purified liquid scintillator
- **Detection via scintillation light:**
 - Very low energy threshold
 - Good position reconstruction
 - Good energy resolution
- **BUT...**
 - No direction measurement
 - The ν induced events can't be distinguished from other β events due to natural radioactivity

Extreme radiopurity of scintillator
= 15 years of work !!!

Principle of graded shielding against
external radioactivity

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Expected signal



Liquid scintillator radiopurity



Background	Typical abundance (source)	Borexino goals	Borexino measured
$^{14}\text{C}/^{12}\text{C}$	10^{-12} (cosmogenic) g/g	10^{-18} g/g	$\sim 2 \cdot 10^{-18}$ g/g
^{238}U (by ^{214}Bi - ^{214}Po)	$2 \cdot 10^{-5}$ (dust) g/g	10^{-16} g/g	$(1.6 \pm 0.1) \cdot 10^{-17}$ g/g
^{232}Th (by ^{212}Bi - ^{212}Po)	$2 \cdot 10^{-5}$ (dust) g/g	10^{-16} g/g	$(5 \pm 1) \cdot 10^{-18}$ g/g
^{222}Rn (by ^{214}Bi - ^{214}Po)	100 atoms/cm ³ (air) emanation from materials	10^{-16} g/g	$\sim 10^{-17}$ g/g $(\sim 1 \text{ cpd}/100t)$
^{210}Po	Surface contamination	~ 1 c/d/t	May 07 : 70 c/d/t Sep 08 : 7 c/d/t
^{40}K	$2 \cdot 10^{-6}$ (dust) g/g	$\sim 10^{-18}$ g/g	$< 3 \cdot 10^{-18}$ (90%) g/g
^{85}Kr	1 Bq/m ³ (air)	~ 1 c/d/100t	(28 ± 7) c/d/100t (fast coinc.)
^{39}Ar	17 mBq/m ³ (air)	~ 1 c/d/100t	$\ll 85\text{Kr}$

Detector performance



Light yield

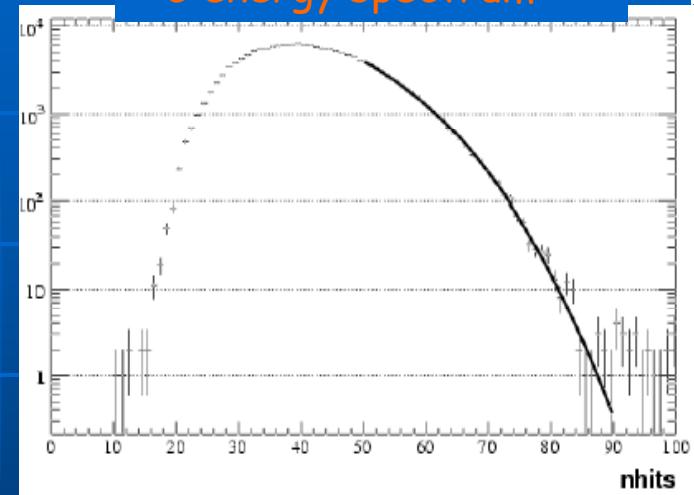


(500 ± 12) p.e./MeV

taking into account quenching factor

- 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 , ^7Be edge);

^{14}C energy spectrum



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

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

Fiducial volume definition (before calibration)

- 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)

BOREXINO: phase I (May07-Oct08) (before calibration campaigns)



Data from more than 1 year of detector live-time are available

3 main goals reached so far:

- (I) Real time measurement of ${}^7\text{Be}$ solar neutrino flux;
- (II) Direct measurement of the solar ${}^8\text{B}$ neutrino flux with the lowest threshold achieved so far (2.8 MeV) by a real time detector , observing simultaneously both the vacuum (${}^7\text{Be}$) and matter-enhanced dominated oscillation regimes (${}^8\text{B}$);
- (III) Best current limit on the neutrino magnetic moment.

(I) ^7Be analysis: Data Selection



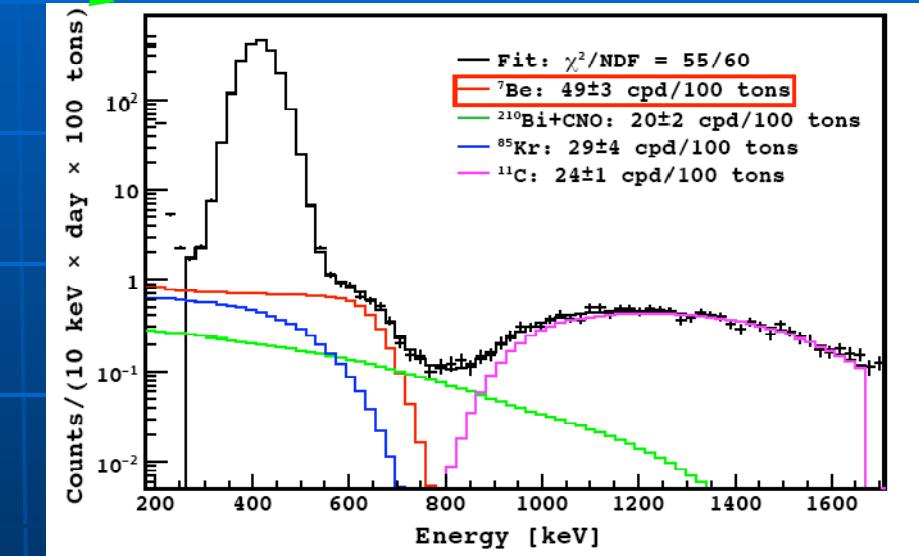
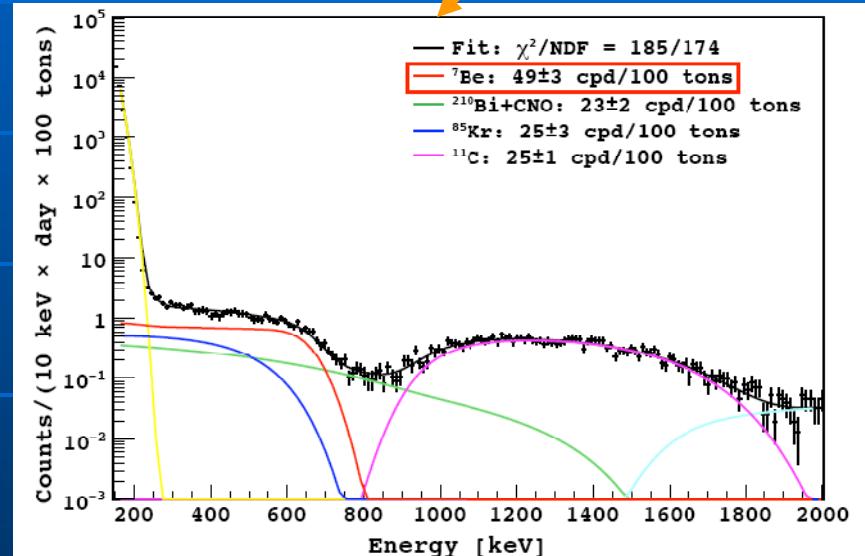
- **Muon & muon daughters are rejected:** events associated with muons are removed; 2 ms veto is applied after each muon (removing afterpulses and spurious events); the measured muon rate in Borexino is $0.055 \pm 0.002 \text{ s}^{-1}$, the dead time introduced by this cut is negligible.
- **Only 1 cluster events are accepted:** the event must have a unique reconstructed cluster in the gate time window ($16 \mu\text{s}$) in order to reject pile-up and fast coincident events ($\epsilon \approx 100\%$).
- **Space & time correlated events are rejected:** events occurring within 2ms at the same place ($\Delta R < 1.5 \text{ m}$) are removed; the Rn daughters occurring before the $^{214}\text{Bi}-^{214}\text{Po}$ delayed coincidences are eliminated by vetoing events up to three hours before a coincidence. The total loss of fiducial exposure due to this cuts is 0.7%.
- **Fiducial volume cut:** Software-defined FV cut ($R < 3\text{m} + |Z| < 1.7 \text{ m}$ in order to cut out the regions close to the poles with very different detector's response) resulting in a nominal fiducial mass of 78.5 t, for the moment the main source of systematics.
- **α subtraction :** Beta and alpha particles could be discriminated on the base of the different time pulse shape

(I) ^7Be analysis: Physical results



Last published result: Direct measurement of the ^7Be Solar neutrino flux with 192 days of Borexino data PRL 101 2008 errors reduced to 10% (our goal is 5%);

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



$$R_{^7\text{Be}} = 49 \pm 3_{\text{stat}} \pm 4_{\text{sys}} \text{ cpd}/100 \text{ tons} \text{ (192 days)}$$

(I) ^7Be analysis: Physical results and uncertainties



$$R_{^7\text{Be}}: (49 \pm 3_{\text{stat}} \pm 4_{\text{sys}}) \text{ cpd/100 tons (192 days)}$$

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

No-oscillation hypothesis rejected at 4σ level

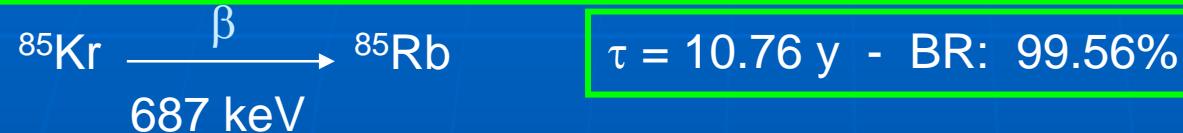
Need for
Calibrations!!!

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

(I) ^{7}Be analysis: ^{85}Kr contamination

Important source of uncertainty in the $^{7}\text{Be}-\nu$ flux determination

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



^{85}Kr contamination can be measured through a very rare branch which gives a fast coincidence:



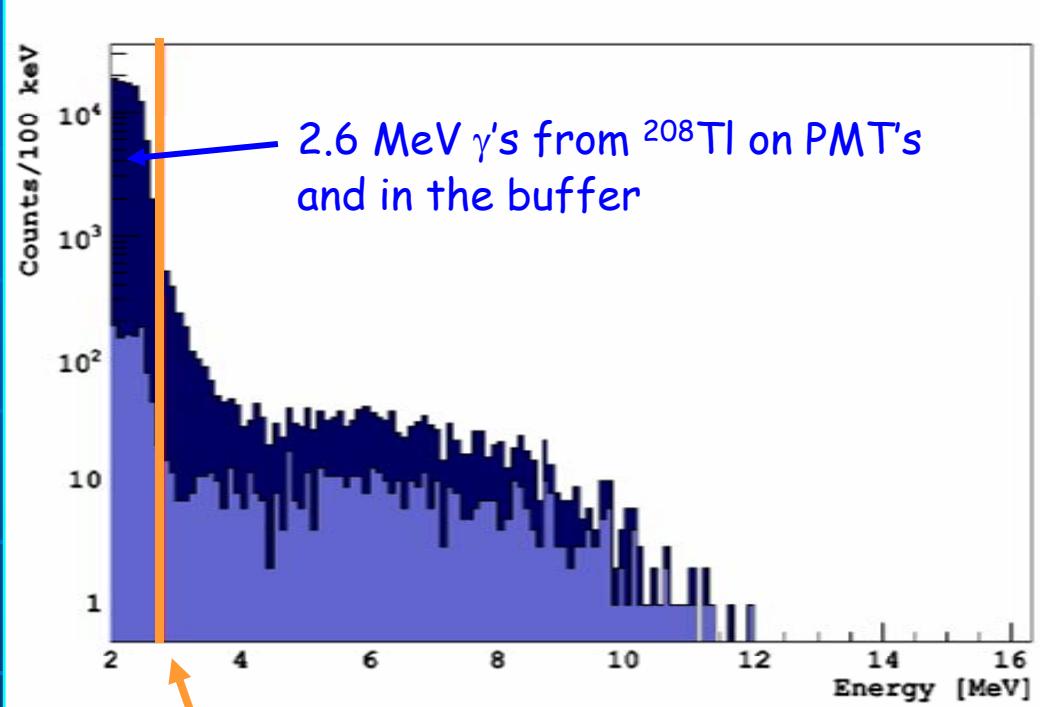
Last published result (PRL 101 2008): Only 8 (β - γ) coincidences selected in the inner vessel in 192 days : ^{85}Kr contamination (29 ± 14) counts/day/100 ton

Taken as a free parameter in the total fit

NOW: ~ 1 y lifetime, the uncertainty has been reduced by 50%:
 (28 ± 7) counts/day/100 ton

=> IT IS POSSIBLE to constrain the ^{85}Kr content in the total fit

(II) ${}^8\text{B}$ neutrinos: Analysis threshold



MSW-LMA prediction:
expected ${}^8\text{B}$ ν rate in 100 tons of liquid scintillator above 2.8 MeV:

$0.26 \pm 0.03 \text{ c/d/100 tons}$

Energy spectrum in Borexino

- muons cut
- FV cut

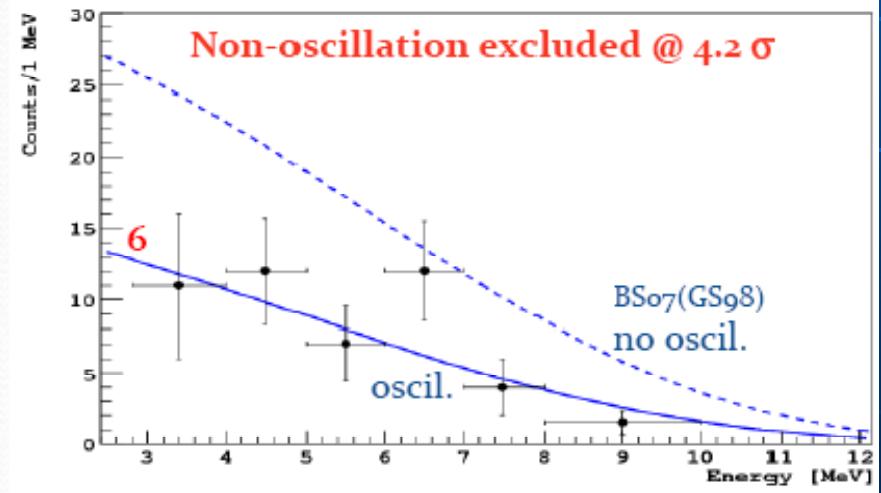
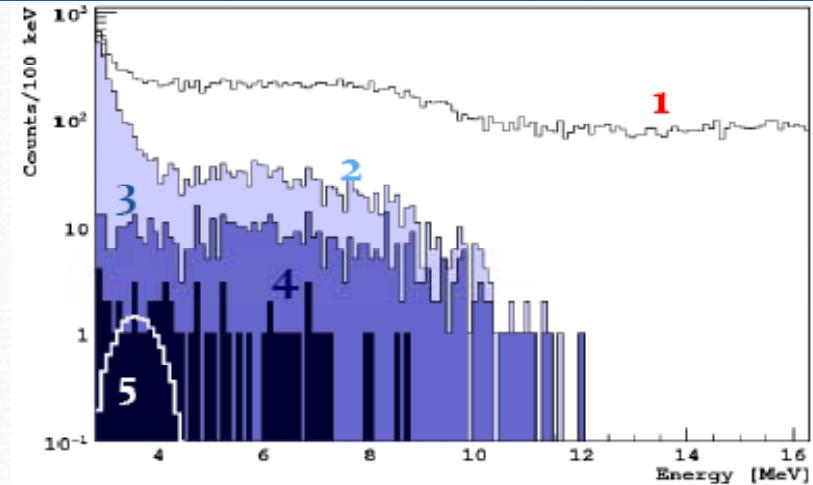
$E_{\text{thr}} = 2.8 \text{ MeV} > 5\sigma$ distant from the 2.6 MeV γ peak

(II) ${}^8\text{B}$ neutrinos: Selection cuts and spectrum



Cut	Counts 2.8-16.3 MeV	Counts 5.0-16.3 MeV	Idx
None	20449	14304	1
Muon cut	3363	1135	2
Neutron cut	3280	1114	
FV cut	567	372	3
Cosmogenic cut	71	26	
${}^{10}\text{C}$ removal	65	26	
${}^{214}\text{Bi}$ removal	62	26	4
Expected ${}^{208}\text{Tl}$	14 ± 3	0	5
Measured ${}^8\text{B}-\nu$	48 ± 8	26 ± 5	6
BSo7(GS98) ${}^8\text{B}-\nu$	50 ± 5	25 ± 3	
BSo7(AGSo5) ${}^8\text{B}-\nu$	40 ± 4	20 ± 2	

Livetime: 188 d

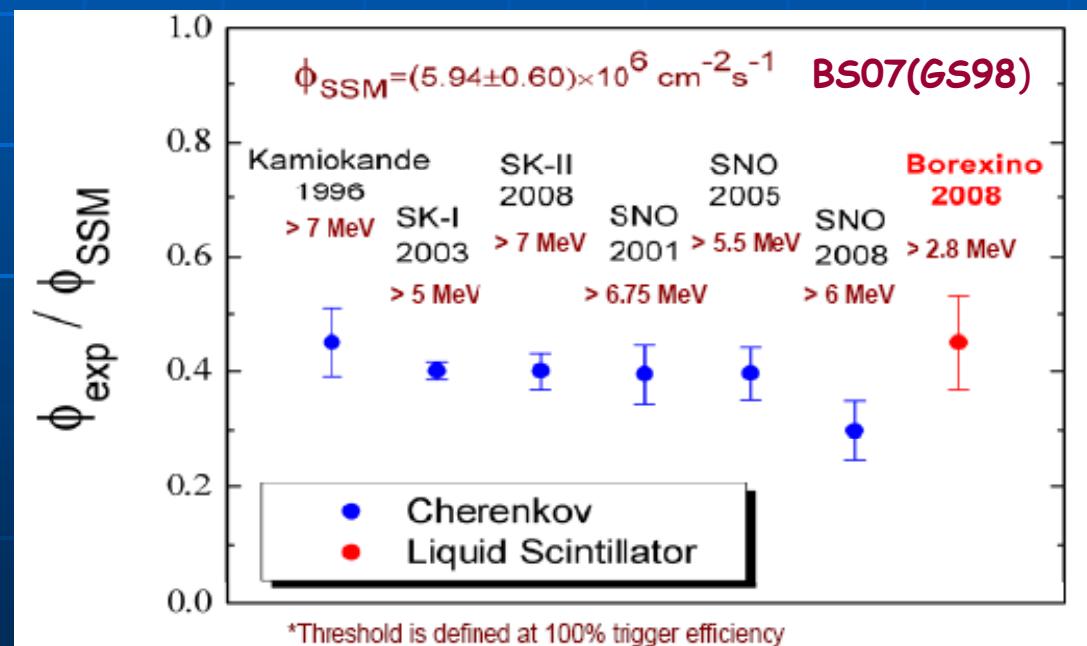


(II) ${}^8\text{B}$ neutrinos: equivalent ν flux



First real-time measurement above $T_e = 2.8 \text{ MeV}$:

$$\Phi_{\text{exp}}^{\text{ES}} = (2.65 \pm 0.44 \pm 0.18) 10^6 \text{ cm}^{-2} \text{ s}^{-1}$$



Systematic errors:

- ★ 6% from the determination of the fiducial mass
- ★ 3% (2%) uncertainty in the ${}^8\text{B}$ rate above 2.8 MeV (5.0 MeV) from the determination of the detector energy response



Need for calibrations

(II) ${}^8\text{B}$ / ${}^7\text{Be}$ neutrinos: Electron Neutrino Survival Probability



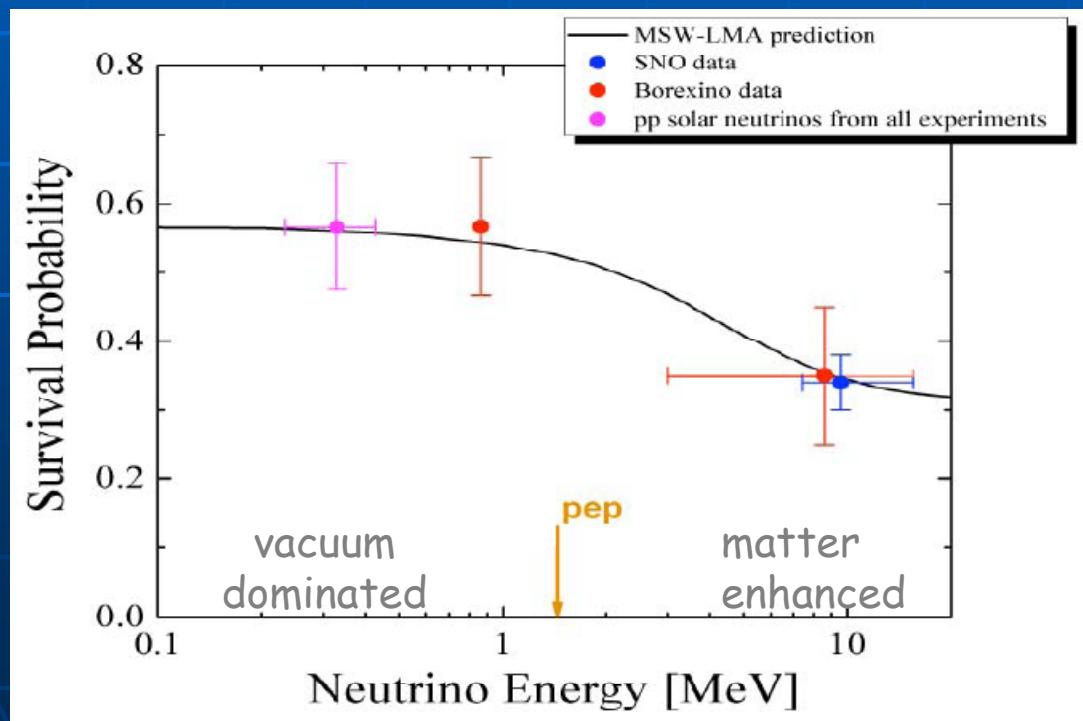
\overline{P}_{ee} is defined such that:

$$R = \int_{T_e > T_0} dT_e \int_{E_\nu > E_0} dE_\nu \left(\overline{P}_{ee} \cdot \frac{d\sigma_e}{dT_e}(E_\nu, T_e) + (1 - \overline{P}_{ee}) \cdot \frac{d\sigma_{\mu-\tau}}{dT_e}(E_\nu, T_e) \right) N_e \cdot \frac{d\Phi_e}{dE_\nu}(E_\nu)$$

R: measured rate

E_ν and T_e : neutrino and recoiled electron energies

$T_0 = 2.8$ MeV: energy threshold



$\overline{P}_{ee}({}^8\text{B}) = 0.35 \pm 0.10$ (8.6 MeV)
 $\overline{P}_{ee}({}^7\text{Be}) = 0.56 \pm 0.10$ (0.862 MeV)

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

Borexino data are in agreement
with the prediction of the
MSW-LMA solution for solar ν

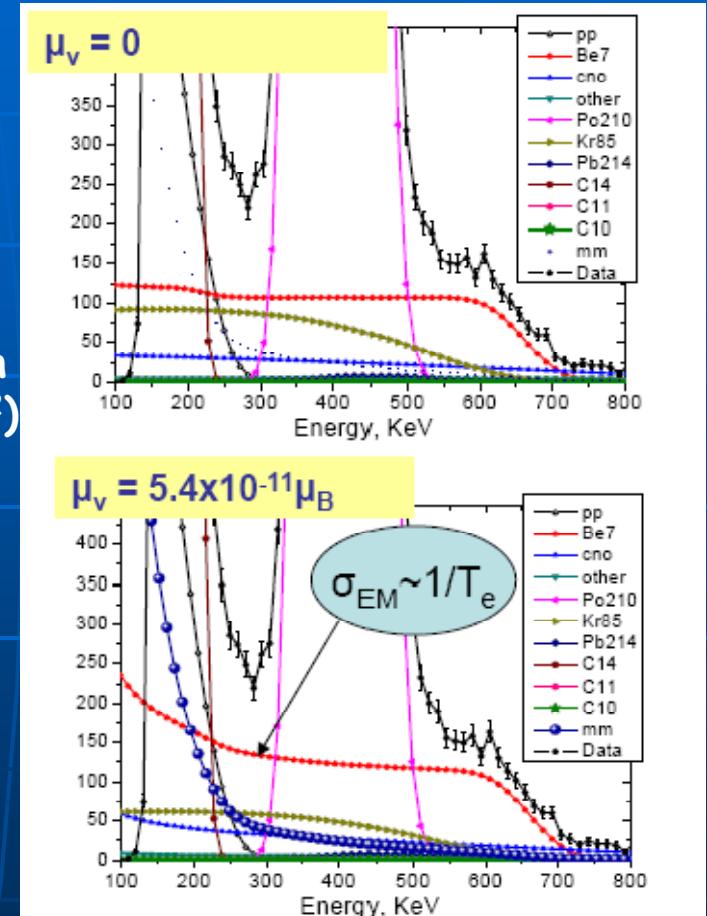
(III) Limit on the neutrino effective magnetic moment

If $m_\nu > 0$: $\mu_\nu > 0$, additional EM term influencing the ν scattering cross section off electrons and thus the spectral shape:

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

- The limit on the neutrino effective magnetic moment has been obtained studying the χ^2 profile as a function of the hypothetical EM contribution (proportional to μ_ν^2)
- Model-independent analysis, defined only by the shape of the spectra (no systematics attributed to the uncertainty of the FV).

Exp.	Method	90% C.L. ($10^{-11} \mu_B$)
SuperK	8B above 5 MeV	< 11
GEMMA	Reactor ν	< 5.8
Borexino	7Be	< 5.4



Best limit so far !

DONE:



Borexino performed the first real-time measurement of solar- ν below the barrier of natural radioactivity (4 MeV);

- The measurement reported for ${}^7\text{Be}-\nu$ favors MSW-LMA solution;
- The first real-time measurement of ${}^8\text{B}-\nu$ below 5 MeV (above 2.8 MeV) ;
- The first simultaneous measurement of solar neutrinos from the vacuum region (${}^7\text{Be}-\nu$) and from the matter-enhanced oscillation region (${}^8\text{B}-\nu$) ;
- Best current limit on neutrino magnetic moment

IN PROGRESS:

- Calibration campaigns (Oct08, Jan/Feb09, next scheduled: May09 ?)
- Borexino Outer/Inner Buffer distillation (Feb09-Mar09) in order to remove the PPO from the leak and reduce the quencher (DMP) concentration => small density gradient between OB/IB and Inner Vessel to stabilize IV shape.
- Inner Vessel Purification (?)

Detector Calibration



Main Goals:

- ★ Fix the FV volume and verify the detector Response vs Position:

100 Hz $^{14}\text{C} + ^{222}\text{Rn}$ source diluted in PC has been deployed in more than 100 positions inside the Borexino inner vessel

- ★ Fix the energy scale (precise determination of quenching parameters for different particles):

Beta sources: ^{14}C , ^{222}Rn diluted in scintillator

Alpha source: ^{222}Rn diluted in scintillator

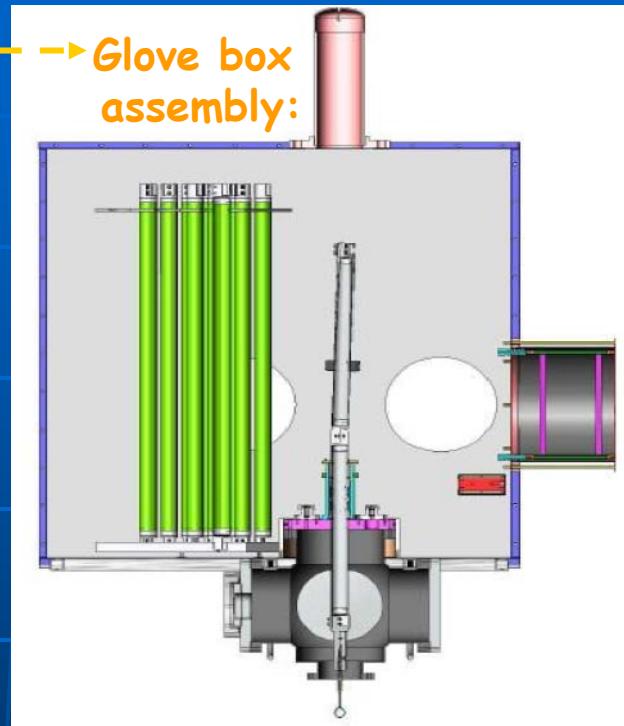
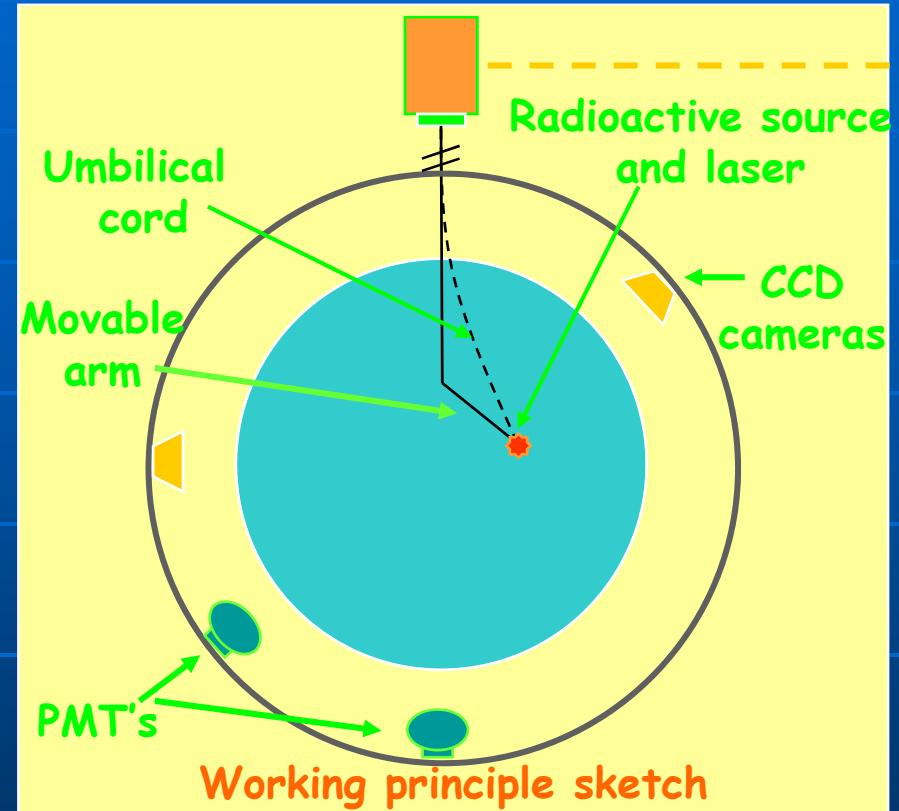
Gamma sources: ^{54}Mn , ^{85}Sr , ^{222}Rn in air

Neutron sources: AmBe

Detector Calibration

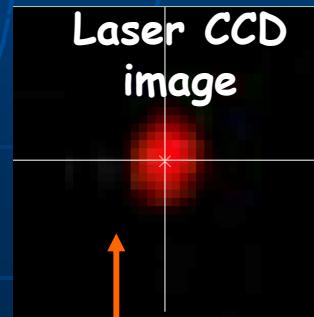
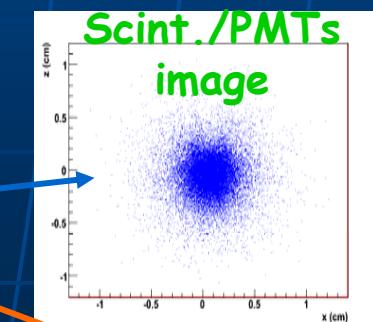


⇒ A movable arm insertion system has been developed by the Virginia Tech Group

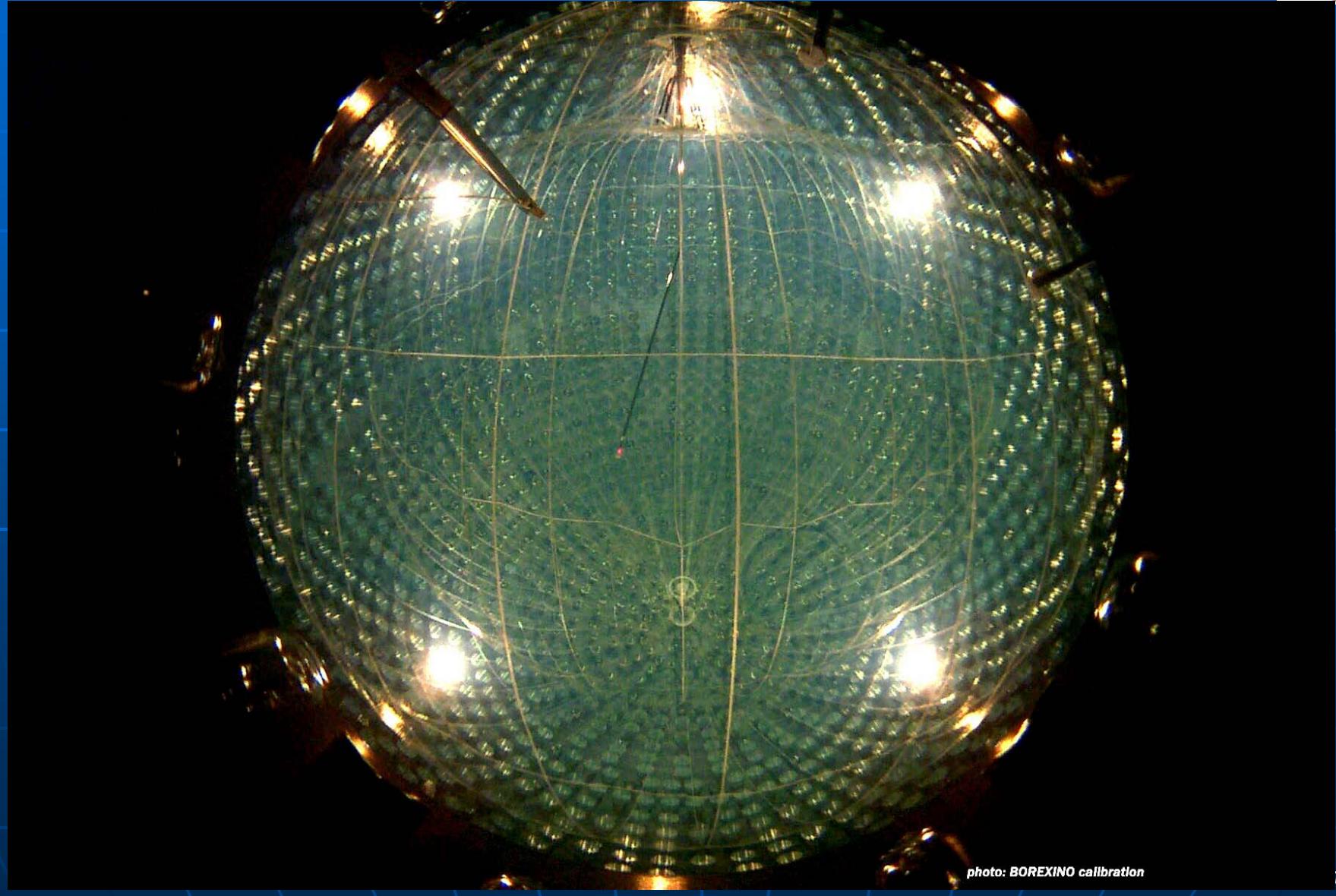


Source positions reconstruction:

- Source decays induced scintillation light/PMT's
- Red laser light/CCD cameras (accuracy: < 2 cm)

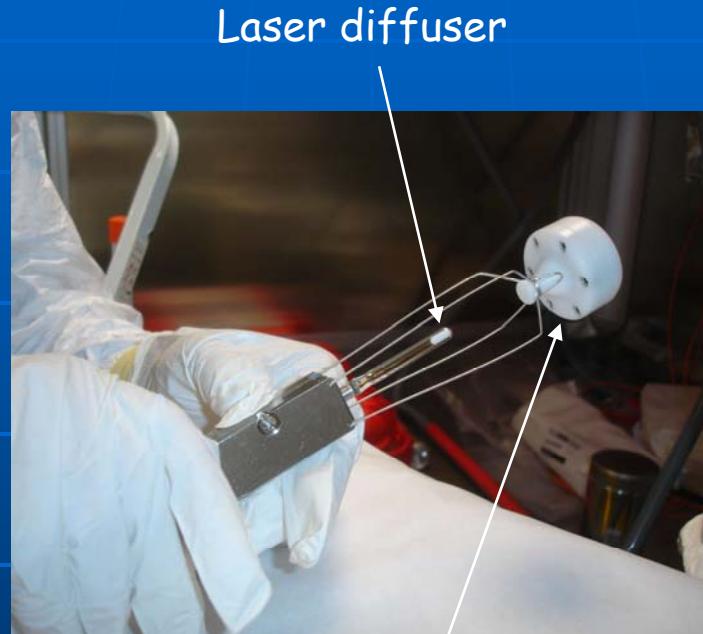


Detector Calibration: the AmBe source inside Borexino



roma Italy

Detector Calibration: source mounting and insertion



Laser diffuser

Am-Be source
housing



Source insertion in the cross

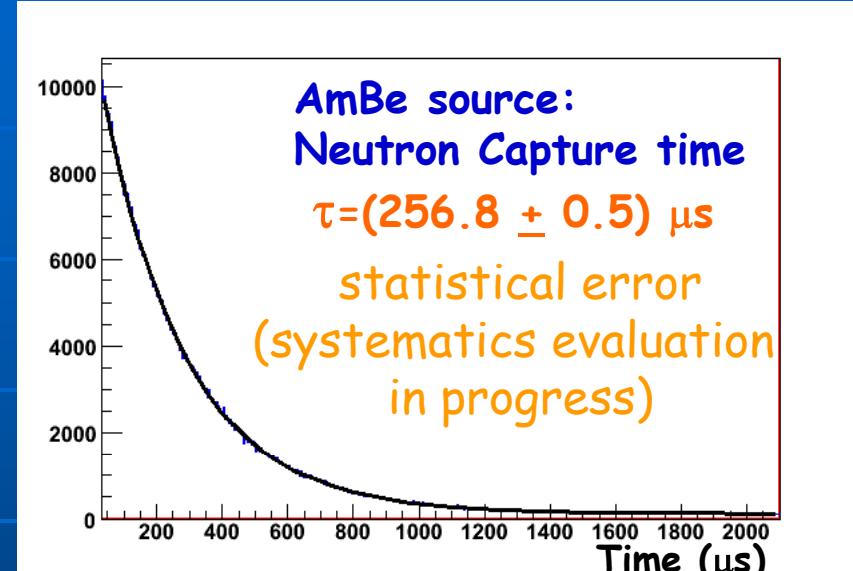
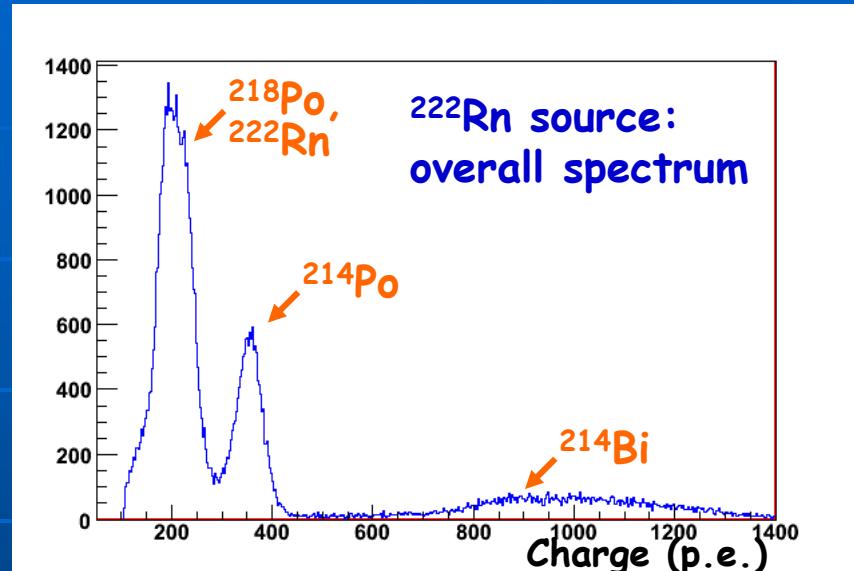


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Detector Calibration



Two examples:



Overall analysis in progress : results in the next months!!!

What's next (1-5 years)?



Precise measure of ${}^7\text{Be}$ neutrino flux coming in the next months:

- Fiducial volume and energy response fixed by calibrations;
- ${}^{85}\text{Kr}$ constrained by delayed coincidence measurement;
- Scintillator purification (?): ${}^{85}\text{Kr}$ effectively removed by nitrogen stripping.

More precise measurement of the oscillation probability in the transition region:

- Fiducial volume and energy response fixed by calibrations;
- More statistics (measure time + increase of FV mass)

Day/Night and Seasonal variations of the neutrino fluxes:

- D/N for ${}^7\text{Be}$ coming soon;
- Seasonal variations need more statistics;

CNO and pep-neutrino fluxes measurements:

- cosmogenic ${}^{11}\text{C}$ tagging already improved;
- ${}^{210}\text{Bi}$ content could be reduced through PC purification.

Antineutrino studies: geo- ν (expected 7-10/yr), reactor (20/yr), supernova.

- The study of geoneutrinos is promising due to the fact that Borexino is located far away from any of the European reactors. A set of candidates has been already collected but requires statistics in order to get evidence for a signal at the 3σ level

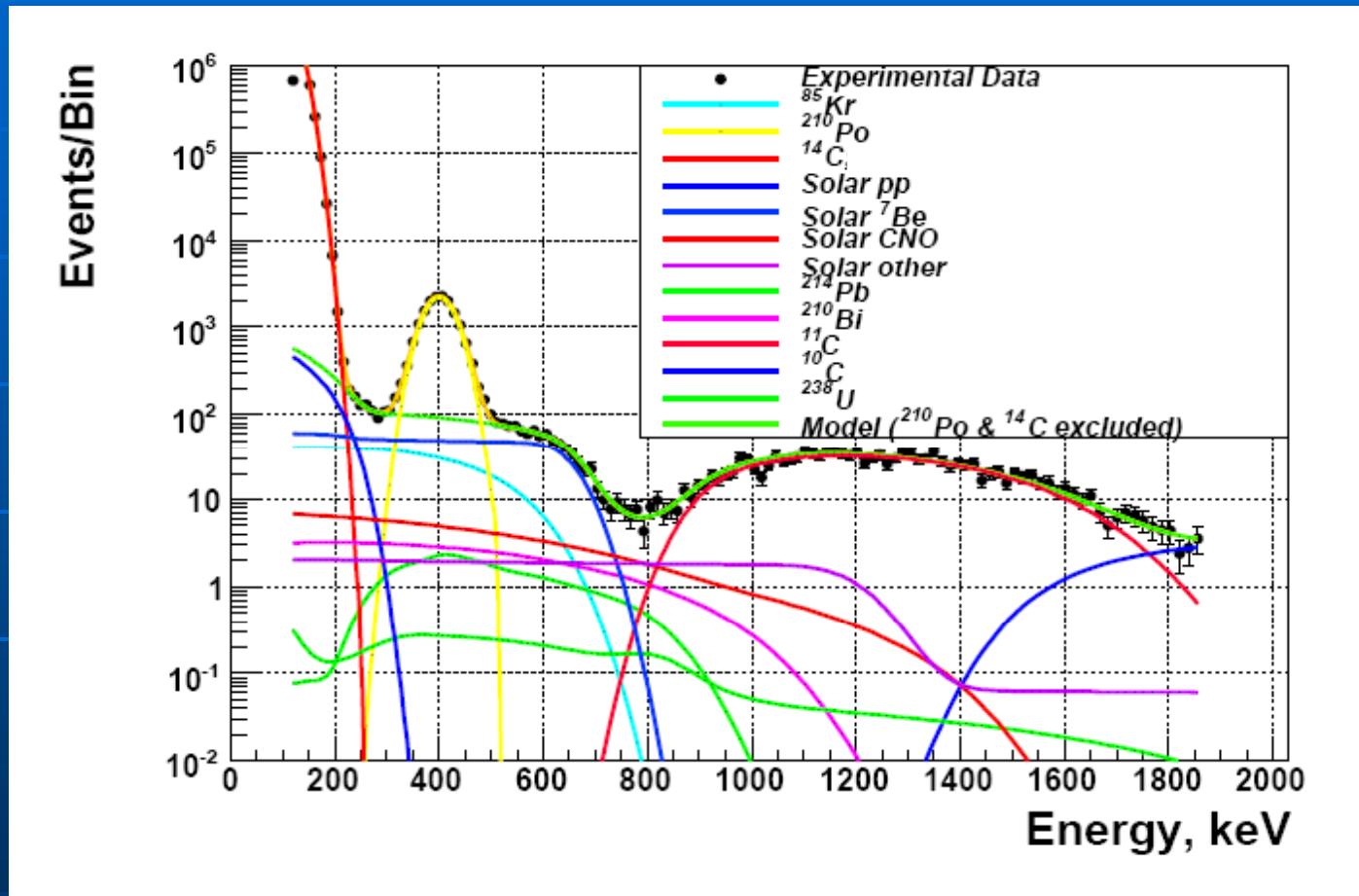
Backup slides

(I) ^7Be analysis: Physical Model used to fit the data



- ^{14}C free (with fixed shape factor);
- ^{85}Kr free; in principle can be bounded (correlated with ^7Be)
- ^{210}Po ; free (in another approach removed by statistical α/β subtraction)
- ^{214}Pb fixed at the value found for the number of ^{222}Rn events
- ^{210}Bi ; free
- ^7Be ; free normalization for MSW(LMA) parameters
- ^{11}C ; free
- CNO fixed @ SSM+MSW(LMA) (highly correlated with ^{210}Bi);
- fix pp and other solar neutrino contributions @ SSM+MSW(LMA)
- Other contributions (still not completely excluded ^{40}K ; isotopes from ^{238}U and ^{232}Th decay chains in secular equilibrium) are found to be negligible
- Light yield + one energy resolution parameter are free;
- Birks' quenching model with parameter k_B fixed at the (best-fit) value found with CTF

Example of spectral analysis



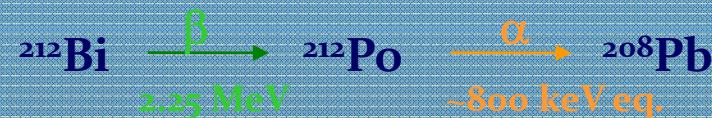
Background: ^{232}Th and ^{238}U content



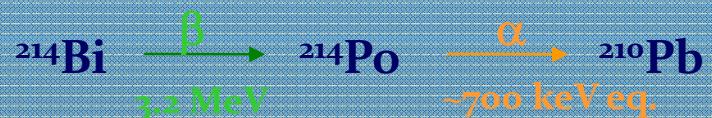
Assuming secular equilibrium:

^{232}Th chain ^{238}U chain

$$\tau = 432.8 \text{ ns}$$



$$\tau = 236 \mu\text{s}$$

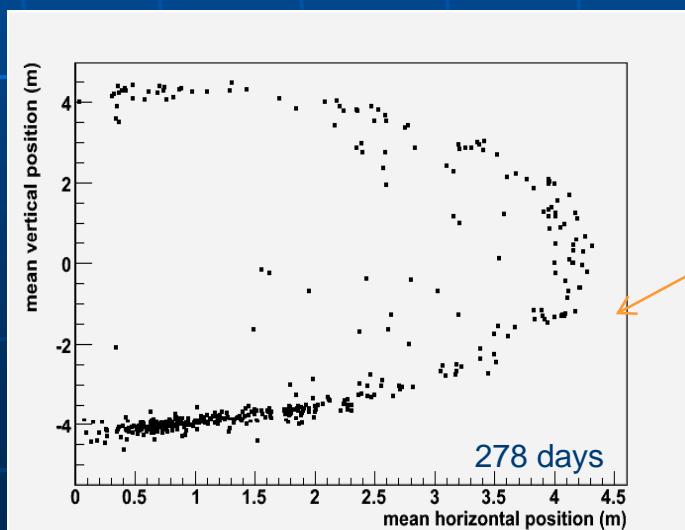


$$(5 \pm 1) \times 10^{-18} \text{ g(Th)/g}$$

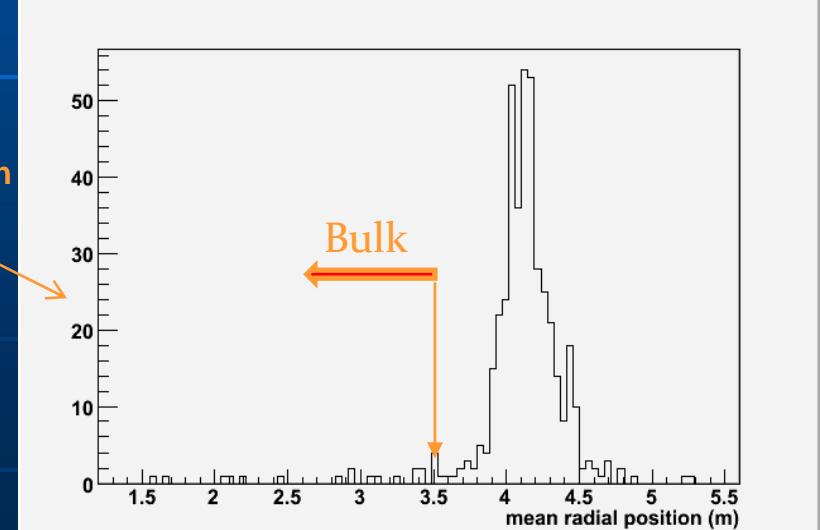
Bulk contamination

$$(1.6 \pm 0.1) \times 10^{-17} \text{ g(U)/g}$$

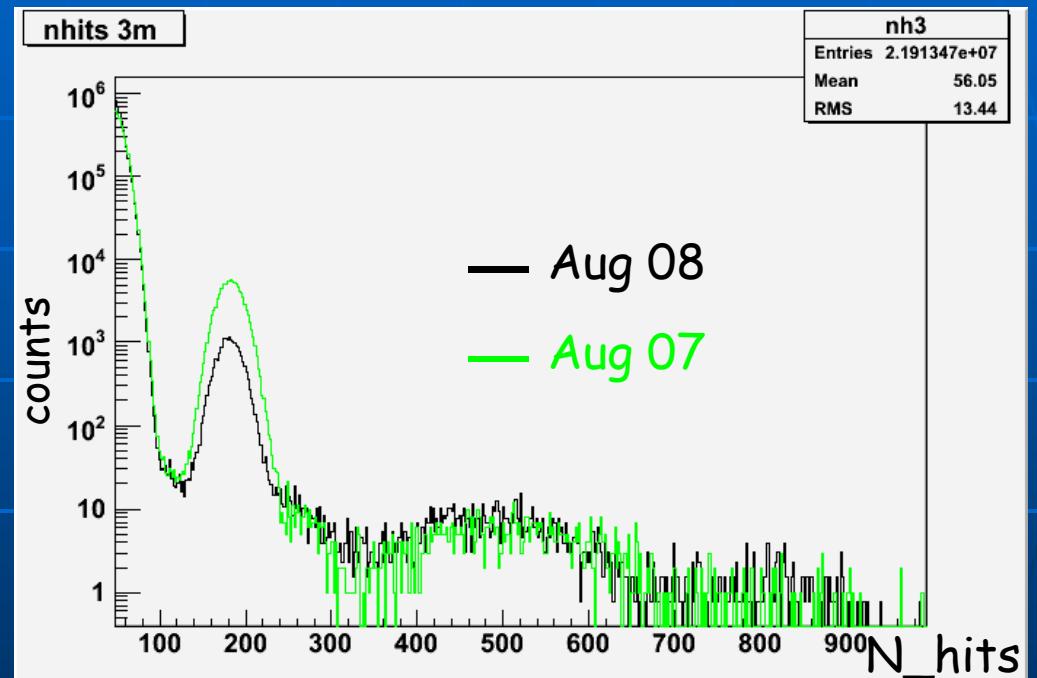
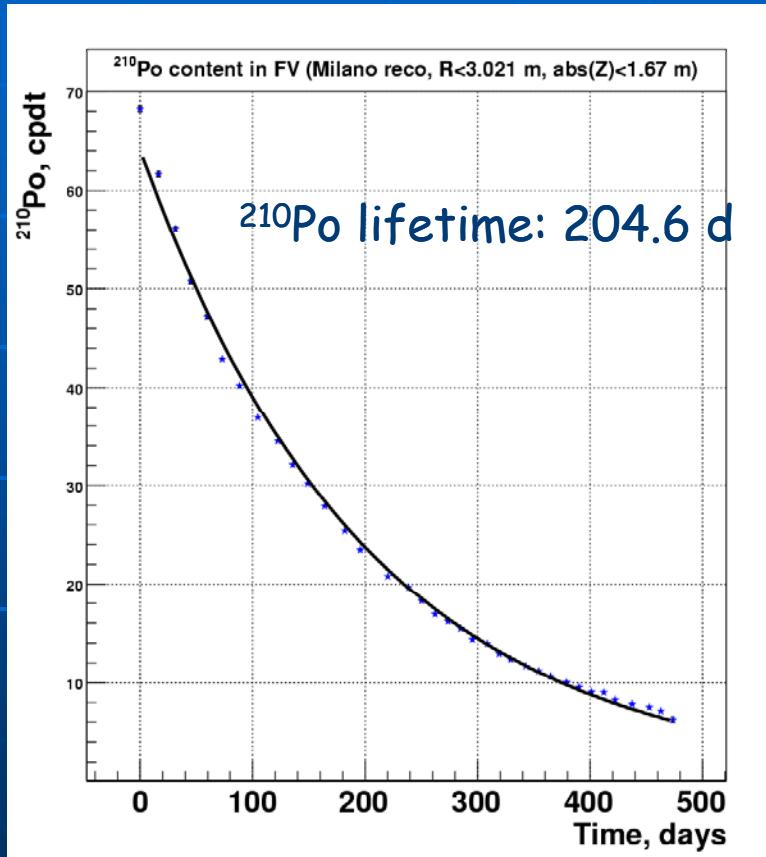
Only few bulk candidates



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



^{210}Po : time decay



May 2007 : 70 c/d/t
Sep. 2008: 7 c/d/t

It decays as expected

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



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

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

k = Homestake, Gallex

i = pp, pep, CNO, ${}^7\text{Be}$, ${}^8\text{B}$

$$f_i = \frac{\phi_i (\text{measured})}{\phi_i (\text{predicted})}$$

$R_{i,k}$ = expected rate of source "i" in experiment "k" (no oscill.)

$P_{ee}^{i,k}$ = average survival probability for source "i" in experiment "k"

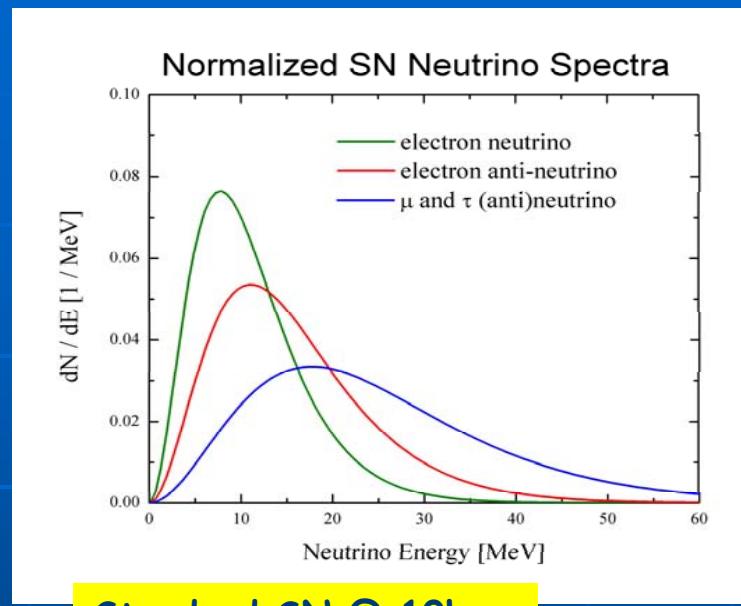
- $R_{i,k}$ and $P_{ee}^{i,k}$ are calculated in the hypothesis of **high-Z SSM and MSW LMA**;
- R_k are the rates actually measured by Chlorine and Gallium experiments;
- $f_{{}^8\text{B}} = 0.87 \pm 0.07$, measured by SNO and SuperK;
- $f_{{}^7\text{Be}} = 1.02 \pm 0.10$ is given by **Borexino results**;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

$$f_{pp} = 1.005^{+0.008}_{-0.020} \quad (1\sigma)$$

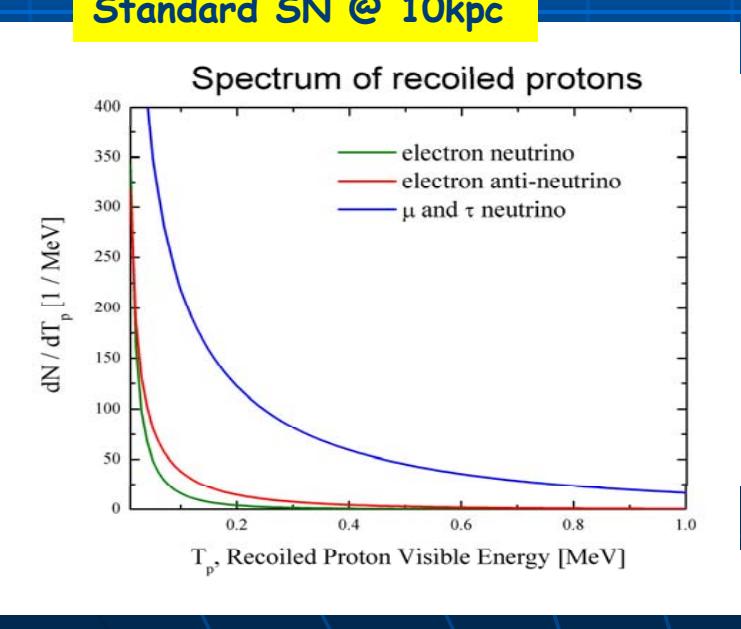
$$f_{CNO} < 3.80 \quad (90\% \text{ C.L.})$$

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

Borexino potential on supernovae neutrinos



Standard SN @ 10kpc



La Thuile 2009

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

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

Can be used as an early alarm

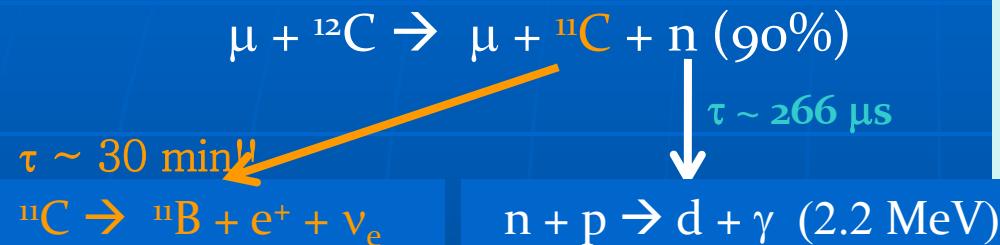
Borexino plans to enter SNEWS

Sandra Zavatarelli Univ. & INFN Genova Italy

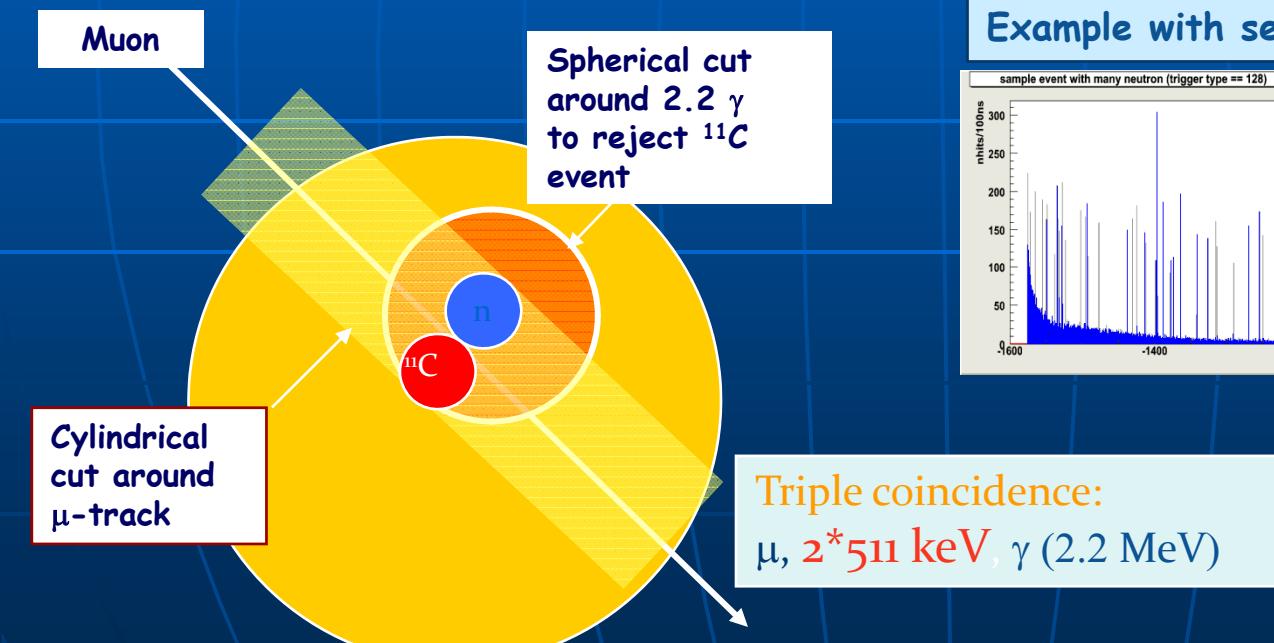
Pep- and CNO- ν fluxes



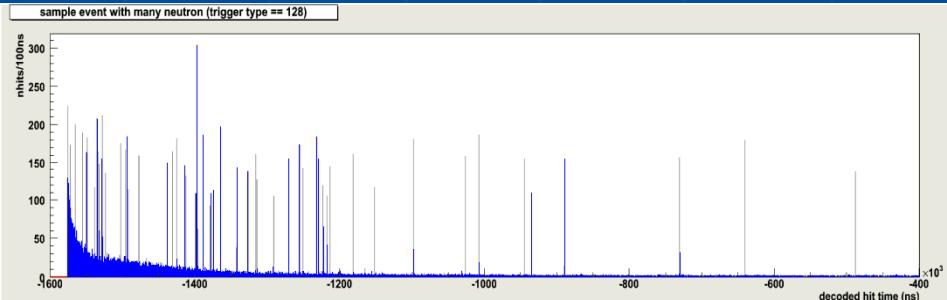
The main background for pep and CNO analysis is ^{11}C



- 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;

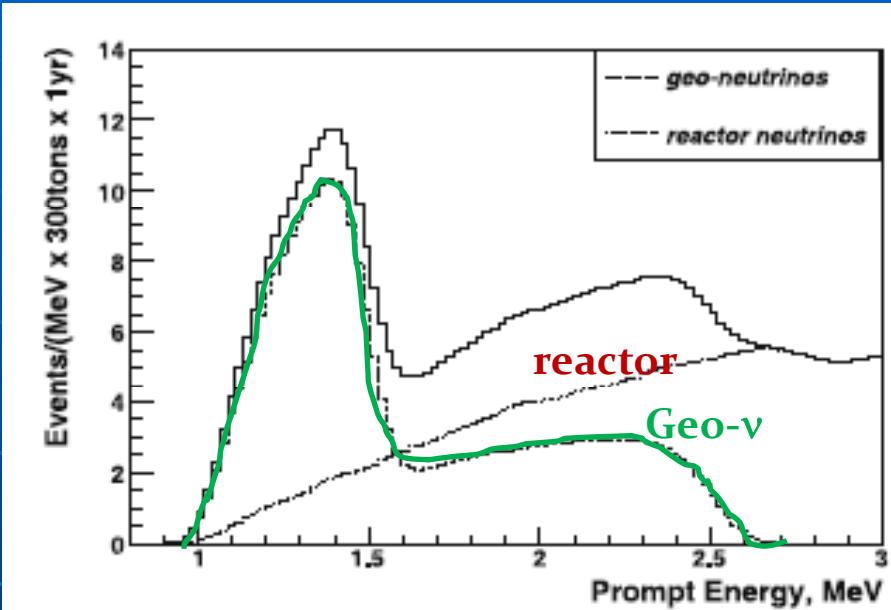


Example with several tens of neutrons detected:



Borexino potential on geo- ν

Prompt signal energy spectrum (model)



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

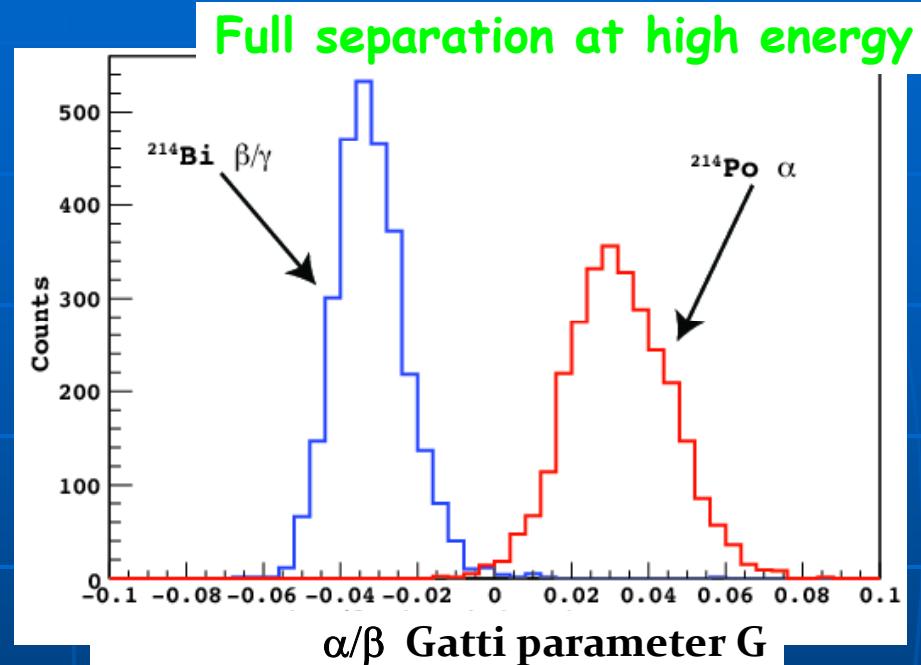
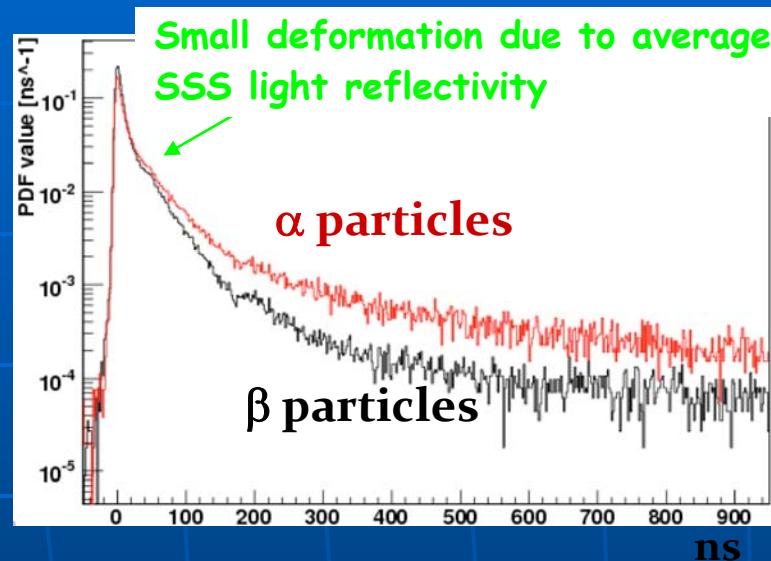
BSE: 6.3 events from geoneutrinos

(per year and 300 tons, $\varepsilon = 80\%$, 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

α/β discrimination



$$\bar{\alpha}_i, \bar{\beta}_i$$

\rightarrow average pulse shapes

$$P_i = \frac{(\bar{\alpha}_i - \bar{\beta}_i)}{(\bar{\alpha}_i + \bar{\beta}_i)}$$

\rightarrow for i-time interval of 2 ns

$$G = \sum_i P_i S_i$$

$S_i \rightarrow$ signal shape within a given Δt (2 ns)