Recent results on solar neutrinos with Borexino

PHYSUN – LNGS, 9 Oct 2012

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(on behalf of the Borexino collaboration)

Outlook

Borexino has started taking data in May 2007 and given since then many important results on solar neutrinos, geo-neutrinos, search for rare events;

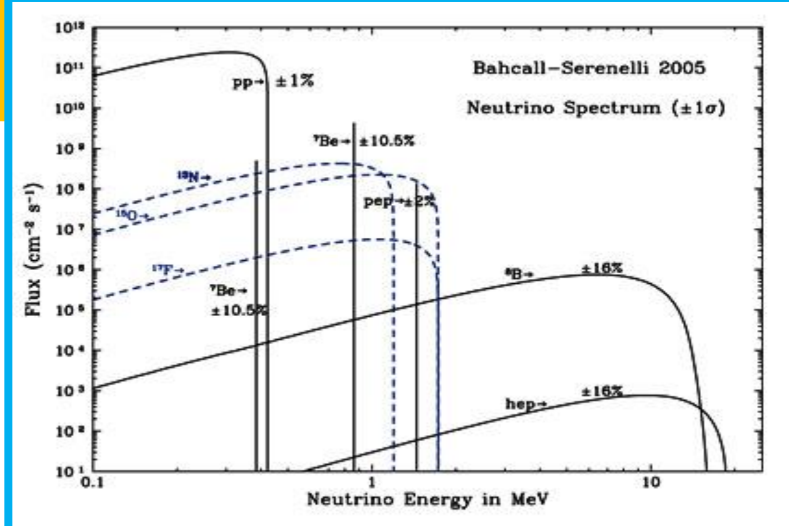
In this presentation I will focus on the results concerning solar neutrinos

- **^{7}Be neutrinos and their day-night asimmetry;**
- **^{8}B neutrinos;**
- **pep neutrinos and limits on CNO neutrinos;**
- **Global analysis of Borexino data;**

Solar neutrinos

Most recent update:
Serenelli, Haxton and Pena-Garay arXiV:1104.1639

J. Bahcall



pp CYCLE:
~99% of the sun energy

99.7%
$p+p \rightarrow D+e^{+}+\nu_e$
$E_\nu \leq 0.42\ MeV$

0.3%
$p+e^{-}+p \rightarrow D+\nu_e$
$E_\nu = 1.44\ MeV$

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

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

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

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

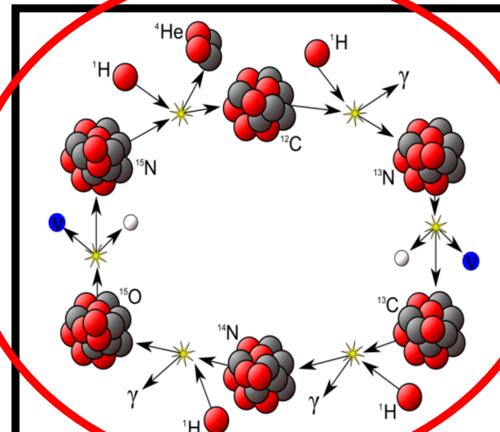
99.89%
${}^7Be+e^{-} \rightarrow {}^7Li+\nu_e$
$E_\nu = 0.863\ MeV$

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

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

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

CNO CYCLE:
<1% of the sun energy



Why study solar neutrinos?

Astrophysics:

Open issues: solar metallicity controversy

- Metallicity (the abundance of elements heavier than He) is used as input in the Standard Solar Model;
- The neutrino fluxes depend on it;
- Differences as large as 30-40% (for CNO);
- Differences of ~9% for ^{7}Be ν

Sources	$\Phi(\nu\ \sec^{-1}\ \mathrm{cm}^2)$ *high-metallicity*[?],[?]	$\Phi(\nu\ \sec^{-1}\ \mathrm{cm}^2)$ *low-metallicity*[?],[?]	Difference %
pp	$5.98(1\pm0.006)\times10^{10}$	$6.03(1\pm0.006)\times10^{10}$	0.8
pep	$1.44(1\pm0.012)\times10^{8}$	$1.47(1\pm0.012)\times10^{8}$	2.1
hep	$8.04(1\pm0.300)\times10^{3}$	$8.31(1\pm0.300)\times10^{3}$	3.3
^7Be	$5.00(1\pm0.070)\times10^{9}$	$4.56(1\pm0.070)\times10^{9}$	8.8
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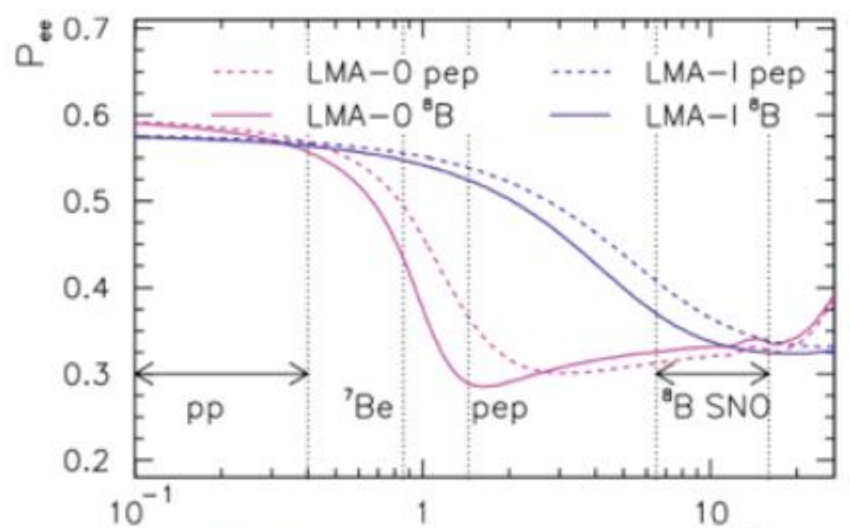
^{17}F	$5.52(1\pm0.170)\times10^{6}$	$3.40(1\pm0.160)\times10^{6}$	38.4

- **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

Neutrino oscillations:

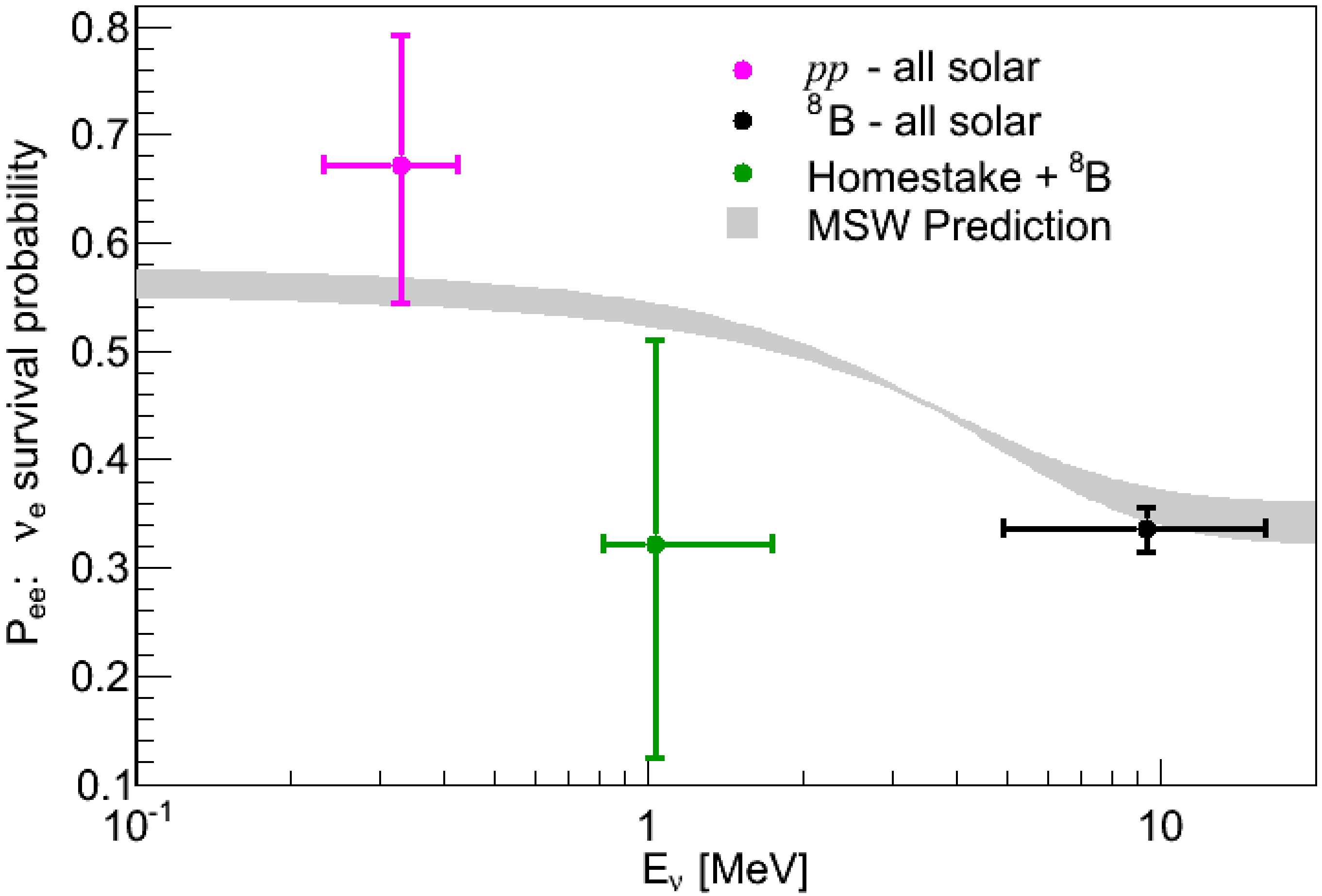
Precision measurements of solar neutrino sources at low energies probe P_{ee} in the vacuum to matter transition region which is sensitive to new physics



Friedland, et al PLB 594, 347 (2004)

Solar neutrino oscillations before Borexino

- Solar neutrinos undergo oscillations in their path from Sun to Earth;
- Preferred region of the oscillation parameter space is the so-called “LMA solution”: $\Delta m^2 = 7.6\times10^{-5}$ eV^2; tg$^2\theta$ = 0.468



Borexino

- **Main goal**: detecting low energies solar neutrinos, in particular ^{7}Be neutrinos;
- **Detection principle:** scattering of neutrinos on electrons $\nu_x + e^- \rightarrow \nu_x + e^-$
- **Detection technique**: large mass of organic liquid scintillator;
- **Technique advantages**: high light-yield (higher than Cerenkov)
- **Technique disadvantages**: no directional information (unlike Cerenkov);

Signal is indistinguishable from background: high radiopurity is a MUST!

- The expected rate of solar neutrinos in 100tons of BX scintillator is ~50 counts/day which corresponds to ~ 5 10^{-9} Bq/Kg;
- Just for comparison:
  - Natural water is ~ 10 Bq/Kg in ^{238}U, ^{232}Th and ^{40}K
  - Air is ~ 10 Bq/m^3 in ^{39}Ar, ^{85}Kr and ^{222}Rn
  - Typical rock is ~ 100-1000 Bq/m^3 in ^{238}U, ^{232}Th and ^{40}K

↓

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

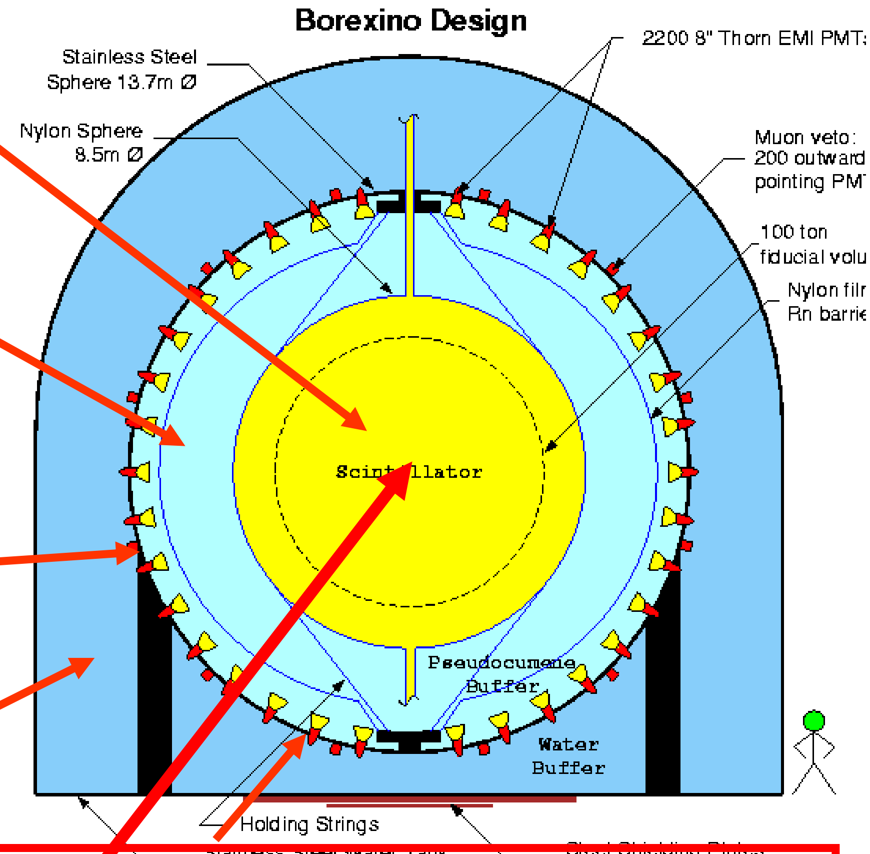
Borexino

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

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

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

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



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

Only the innermost part of the scintillator is considered in the analysis (FV selection), in order to further reduce the external background.

Background suppression: 15 years of work

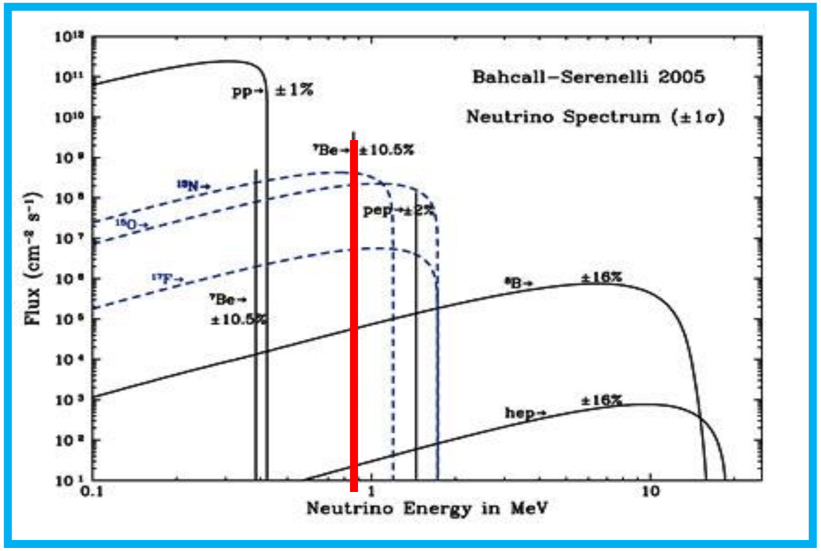
- **Internal background: contamination of the scintillator itself (^{238}U, ^{232}Th, ^{40}K, ^{39}Ar, ^{85}Kr, ^{222}Rn)**
  - Solvent purification (pseudocumene): distillation, vacuum stripping with low Argon/Kripton N2 (LAKN);
  - Fluor purification (PPO): water extraction, filtration, distillation,N_2 stripping with LAKN;
  - Leak requirements for all systems and plants < 10^{-8} mbar· liter/sec;
- **External background: γ and neutrons from surrounding materials**
  - Detector design: concentric shells to shield the inner scintillator;
  - Material selection and surface treatement;
  - Clean construction and handling;

Background suppression: achievements

•Contamination from ^{238}U and ^{232}Th chain are found to be in the range of ~10^{-17} g/g and ~5x×10^{-18} g/g respectively;

•**More than one order of magnitude better than specifications!**

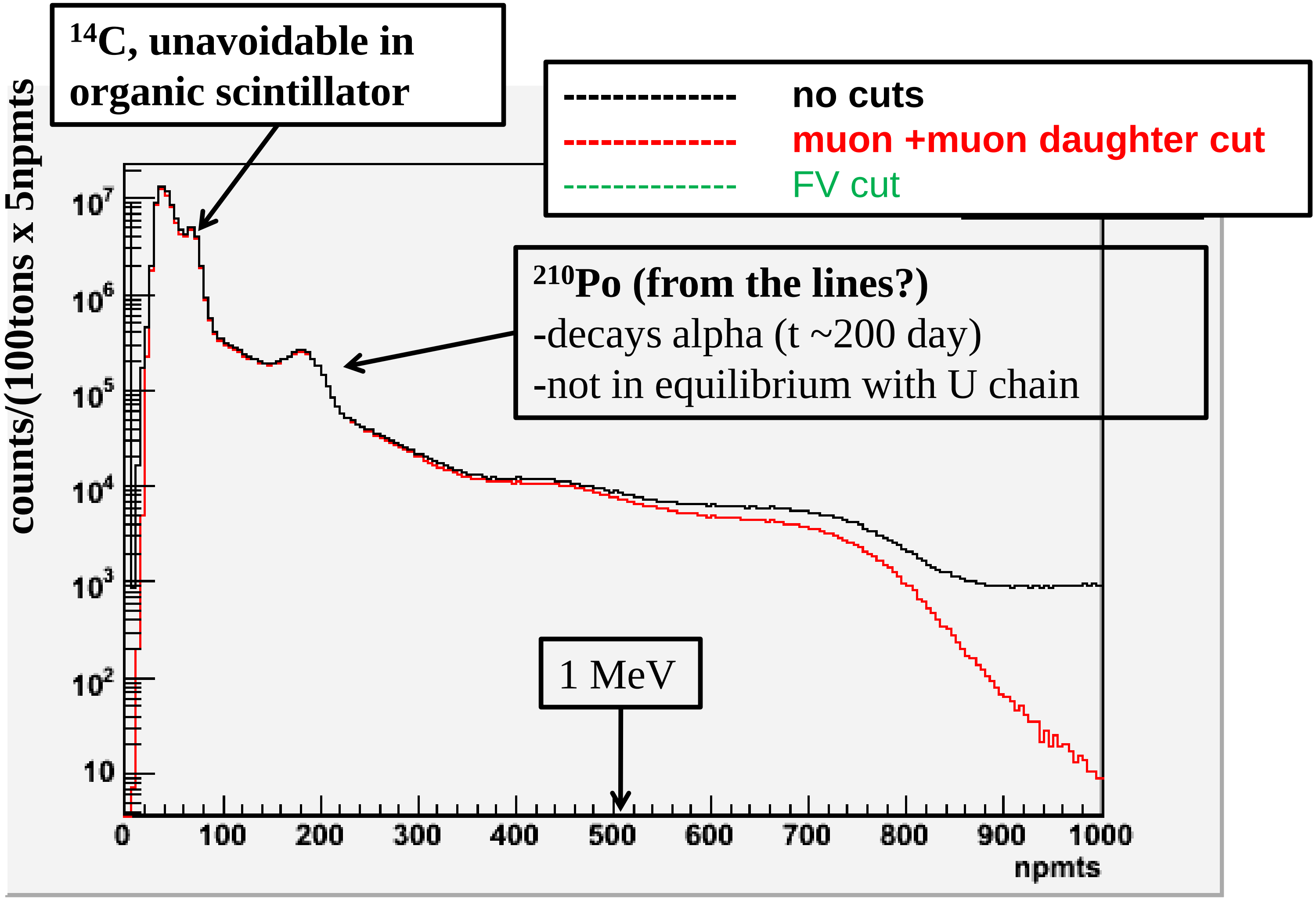
•Three backgrounds out of specifications: ^{210}Po, ^{210}Bi and ^{85}Kr.



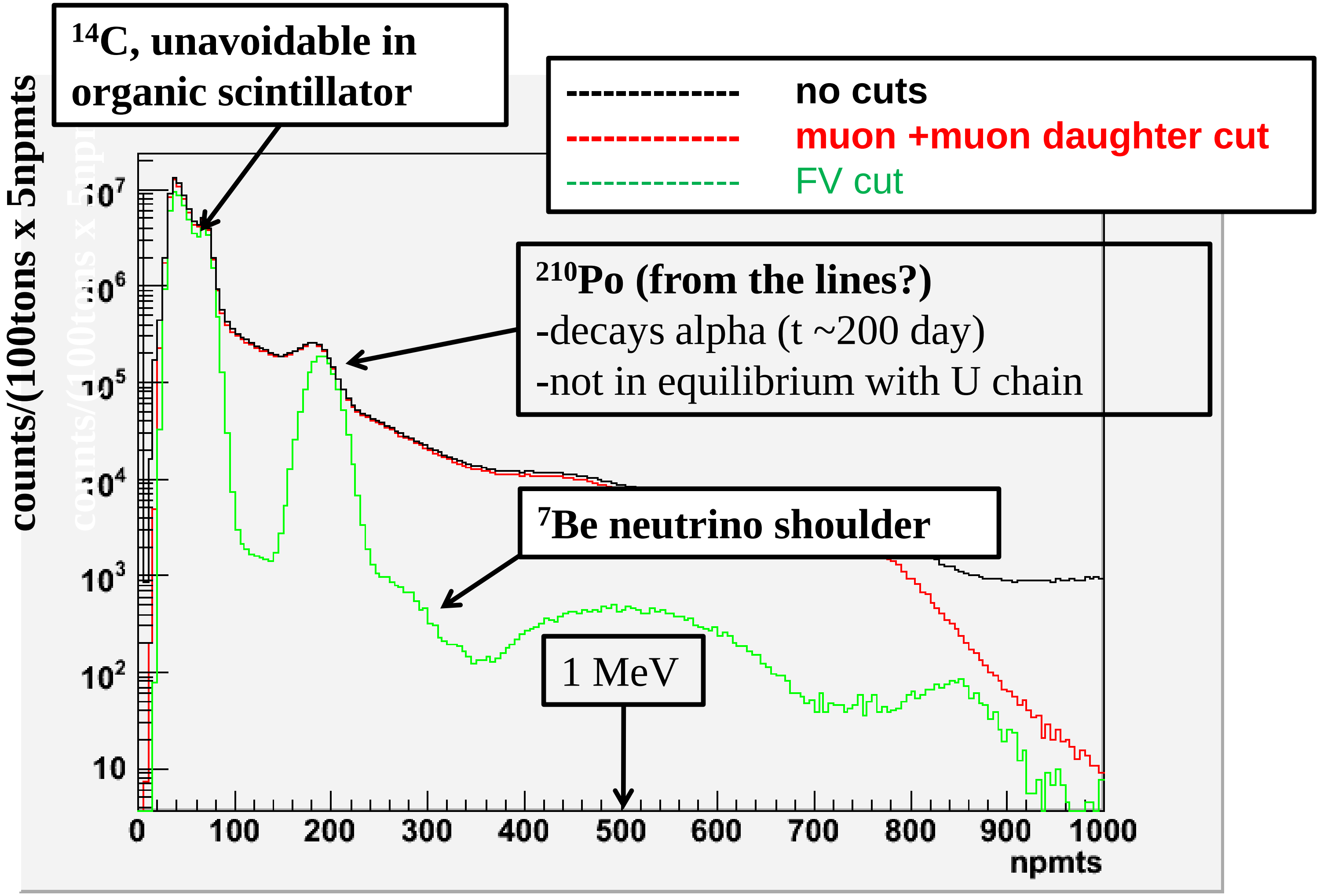
Be7 neutrinos and their day-night asymmetry

^{7}Be neutrinos: precision measurement

Data after 750 days (normalized to 100tons)

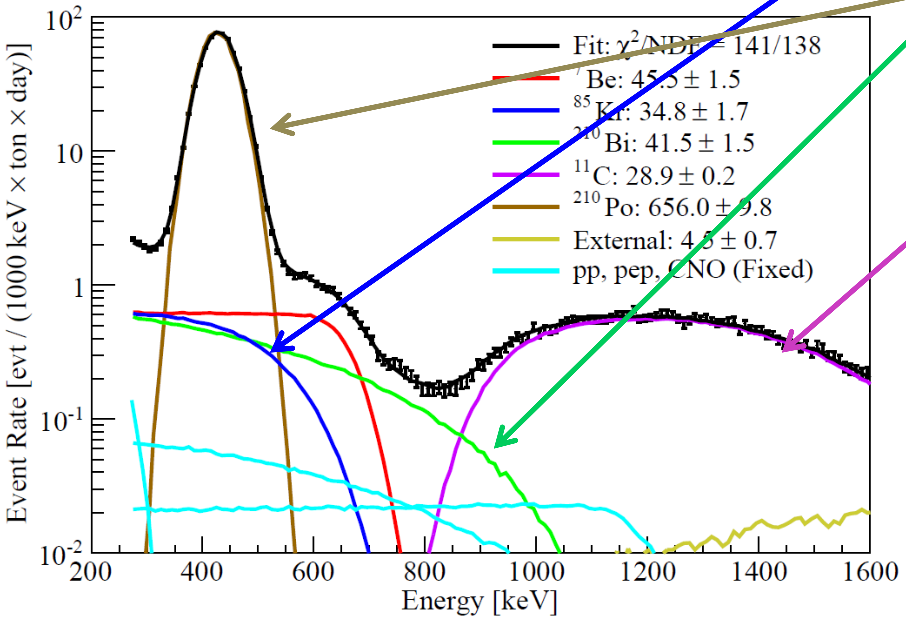


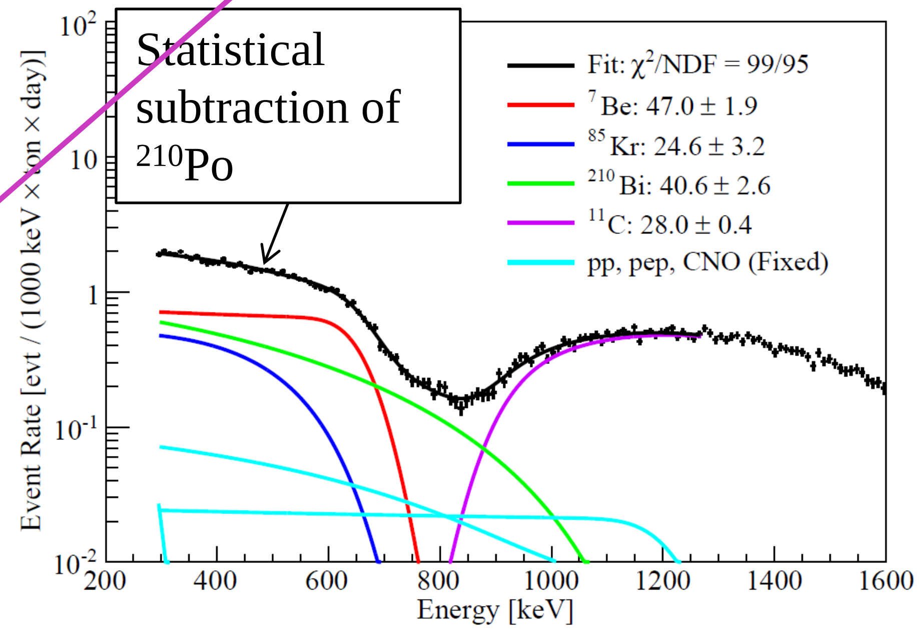
Data after 750 days (normalized to 100tons)



^{7}Be neutrinos: precision measurement

- Residual background components (^{85}Kr, ^{210}Bi, ^{210}Po, ^{11}C);





- Two independent methods to describe the shape of the components of the spectral fit: a MonteCarlo based one and an analytical one;
- Fit performed on the spectrum with and without statistical subtraction of the ^{210}Po alpha component;

$$^{7}\mathbf{Be-rate\,(862keV\,line) = 46.0 \pm 1.5\,(stat)\ counts/(day \times 100tons)}$$

^{7}Be neutrinos: precision measurement

Systematic error

- Main improvement on the systematic error with respect to previous measurement is on Fiducial Volume and Energy response;
- **This was possible thanks to the extensive calibration campaigns with radioactive sources performed between 2008 and 2009;**

Source	[%]
Trigger efficiency and stability	<0.1
Live time	0.04
Scintillator density	0.05
Sacrifice of cuts	0.1
Fiducial volume	$^{+0.5}_{-1.3}$
Fit methods	2.0
Energy response	2.7
Total Systematic Error	$^{+3.4}_{-3.6}$

Previously ±6% (Fiducial volume)

Previously ±6% (Energy response)

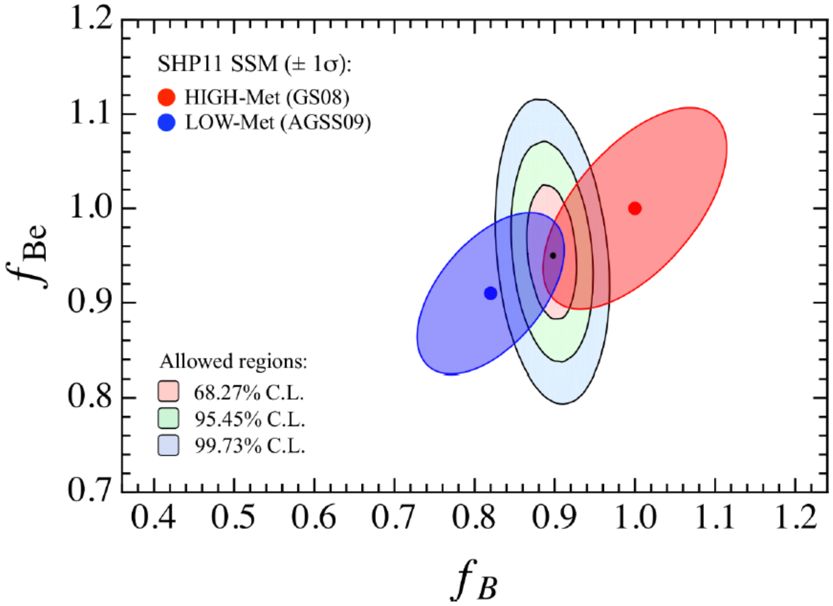
$$46.0 \pm 1.5(\mathrm{stat})^{+1.5}_{-1.6}(\mathrm{syst})\ \mathrm{counts}/(\mathrm{day}\cdot 100\ \mathrm{ton})$$

^{7}Be neutrinos: precision measurement

Implications on metallicity controversy

- ~9% difference for ^{7}Be flux
- ~20% difference for ^{8}B

•Fit to the available solar neutrino data including BX and leaving free $f_{Be} = \Phi_{Be}/\Phi_{Be}(SSM)$ and $f_B = \Phi_B/\Phi_B(SSM)$



BX measurement cannot discriminate between High and Low metallicity

Implications on other solar neutrino sources

•The result of BX +solar experiments +solar luminosity constraint allows to precisely determine pp flux and set a limit on CNO flux

•$f_{pp} = \Phi_{pp}/\Phi_{pp}(SSM)$

$f_{CNO} = \Phi_{CNO}/\Phi_{CNO}(SSM)$

$$f_{pp} = 1.013^{+0.003}_{-0.010}$$

$$f_{CNO} < 2.5 \text{ at } 95\% \text{ C.L.}$$

^{7}Be neutrinos: precision measurement

Implications on oscillation parameters

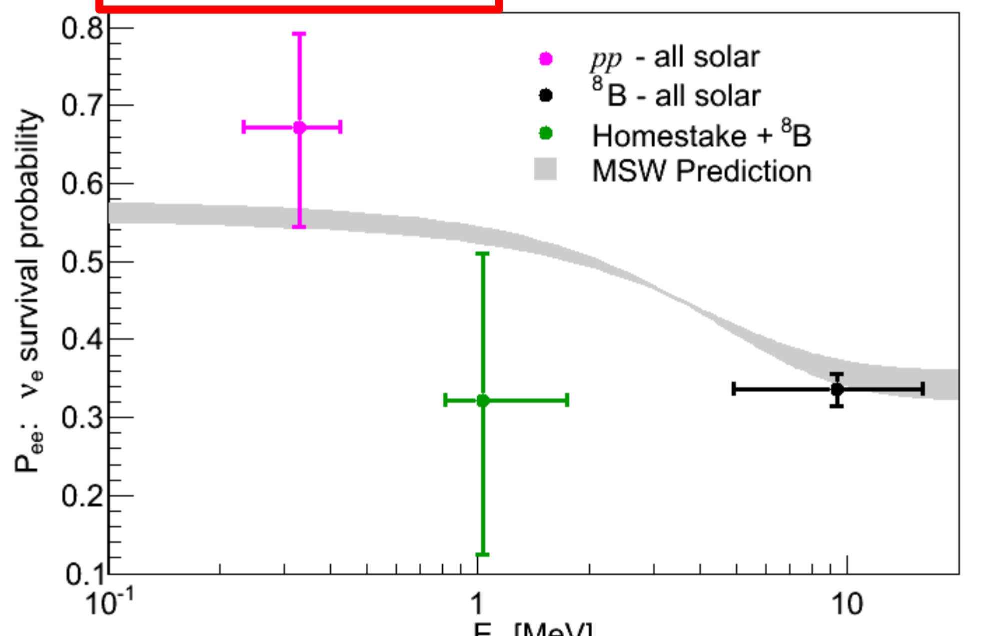
$$^{7}\text{Be rate (862 keV line)} = 46.0 \pm 1.5\,\text{(stat)}\,^{+1.5}_{-1.6}\,\text{(sys) cpd/100tons}$$

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

The hypothesis of no-oscillations is rejected at 5σ

Implications on ν_e survival probability P_{ee}

Before BX



^{7}Be neutrinos: precision measurement

Implications on oscillation parameters

$$^7\text{Be rate (862 keV line)} = 46.0 \pm 1.5\,(\text{stat})\,^{+1.5}_{-1.6}\,(\text{sys})\ \text{cpd}/100\text{tons}$$

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

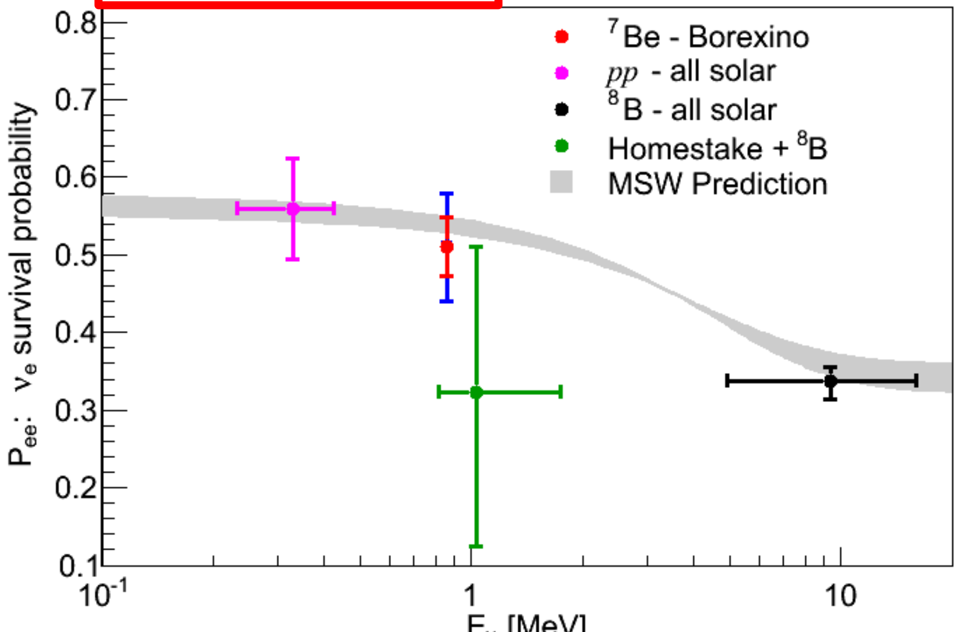
The hypothesis of no-oscillations is rejected at 5σ

Implications on ν_e survival probability P_{ee}

P_{ee} = 0.51 ± 0.07 (E=862 keV)

Note that Borexino total error (4.6%) is now smaller than the theoretical uncertainty on the 7Be flux prediction from SSM (7%);

After BX



^{7}Be neutrinos: day-night asymmetry

•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

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

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

•For the ^{7}Be energies and for parameters in the LMA region A_{dn} is expected to be very small (~0);

•In principle, A_{dn} could be different from zero for different values of the oscillation parameters: for example for the so-called LOW solution- Δm^2 (10^{-8}- 2×10^{-6})eV^2 - A_{dn} would be between 10% and 80%;

•Some exotic models, like Mass Varying neutrinos, foresee a large Day/Night asymmetry of the opposite sign (-23%)

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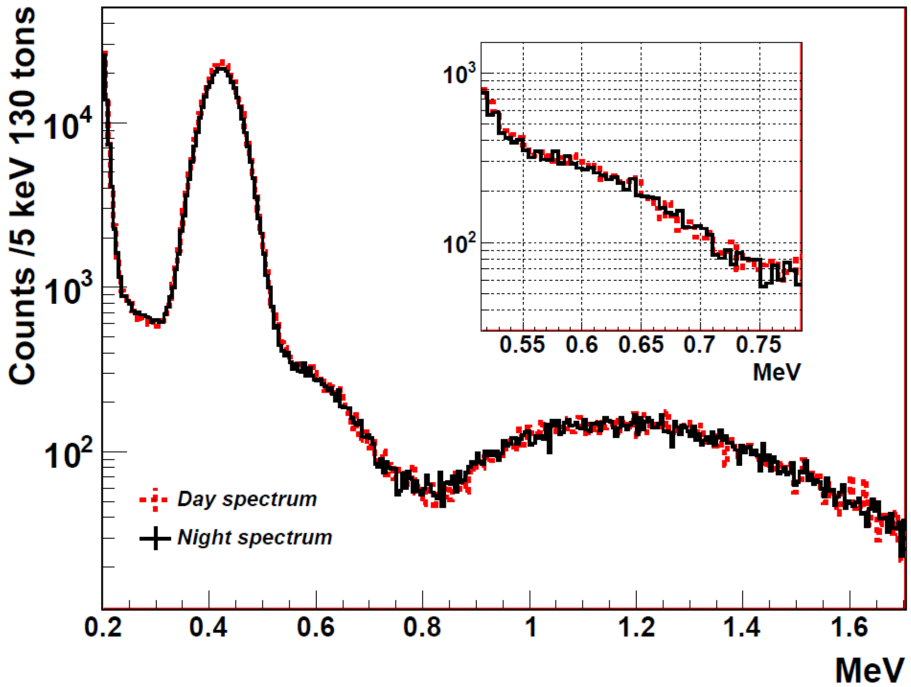
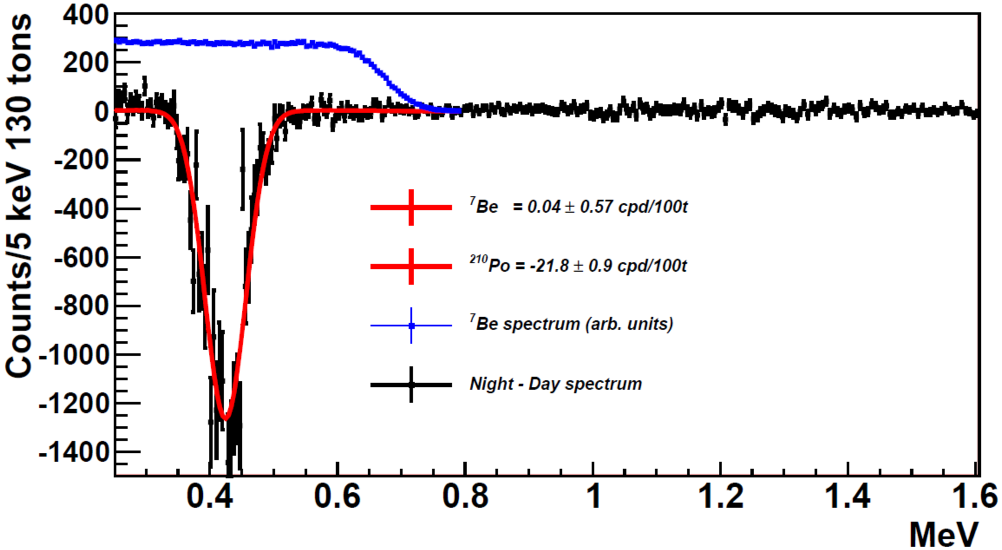
- It is important to study the Day/Night asymmetry at ^{7}Be energies

^{7}Be neutrinos: day-night asymmetry



- Divide spectrum in day and night (Day=360.35 d and Nights=380.63 d);
- Subtract day from night spectrum;
- Fit the residual spectrum with the ^{7}Be shoulder + constant;
- It is consistent with 0;



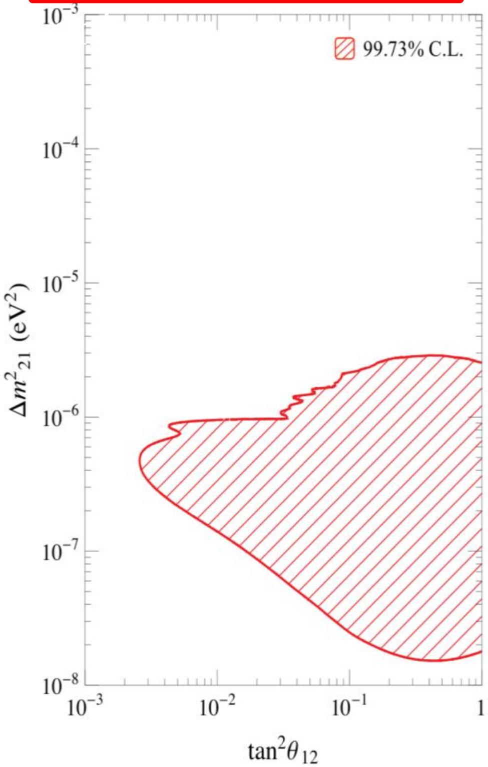
A_{dn} = 0.001 ± 0.012(stat) ± 0.007(sys)
No asymmetry within errors

Source of error	Error on A_{dn}
Live–time	$< 5 \cdot 10^{-4}$
Cut efficiencies	0.001
Variation of ^{210}Bi with time	± 0.005
Fit procedure	$\pm$ 0.005
Total systematic error	0.007

^{7}Be neutrinos: day-night asymmetry

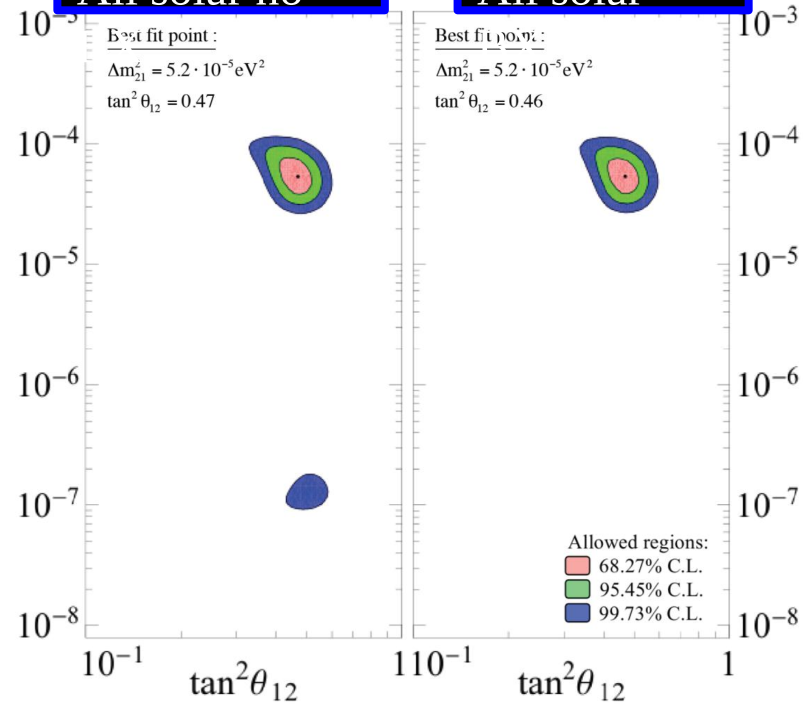
Strong confirmation of the LMA without relying on anti-neutrino kamLAND data

Fit to BX ADN



All solar no

All solar +



Low solution excluded at more than 8σ by Borexino data only

B. Cleveland *et al.* (the Homestake collaboration), *Astrophys. J.*, **496**, 505 (1998).

J. Abdurashitov *et al.* (the SAGE collaboration), *Phys. Rev. C*, **80**, 015807 (2009).

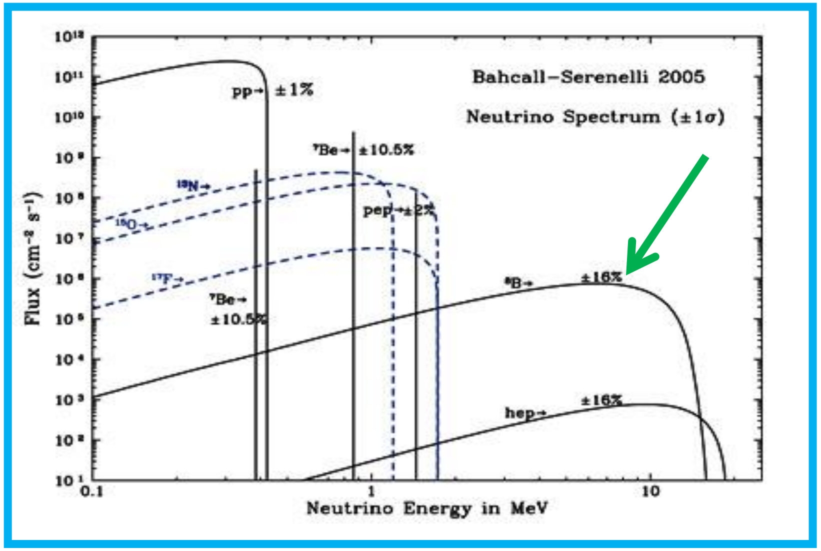
F. Kaether *et al.* (the GALLEX collaboration), *Phys. Lett. B*, **685**, 47 (2010).

B. Aharmim *et al.* (the SNO collaboration), *Phys. Rev. Lett.*, **101**, 111301 (2008).

B. Aharmin *et al.* (the SNO collaboration), *Phys. Rev. C*, **81**, 055504 (2010).

J. Hosaka *et al.* (the Super Kamiokande collaboration), *Phys. Rev. D*, **73**, 025503 (2006).

K. Abe *et al.* (the Super Kamiokande collaboration), *Phys. Rev. D*, **83**, 052010 (2011).



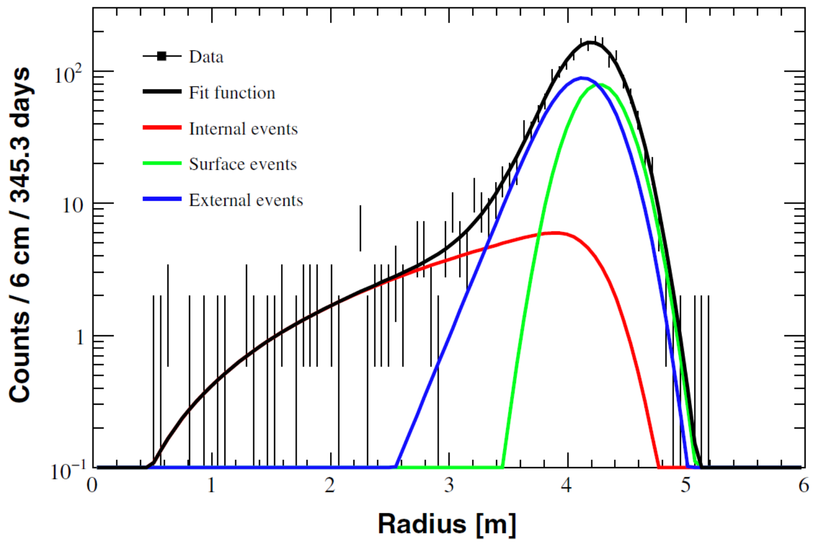
^{8}B solar neutrinos

^{8}B neutrinos with low energy threshold (T_e >3 MeV)

Analysis performed on 488 live days of data-taking (from Jul2007 to Aug 2009)

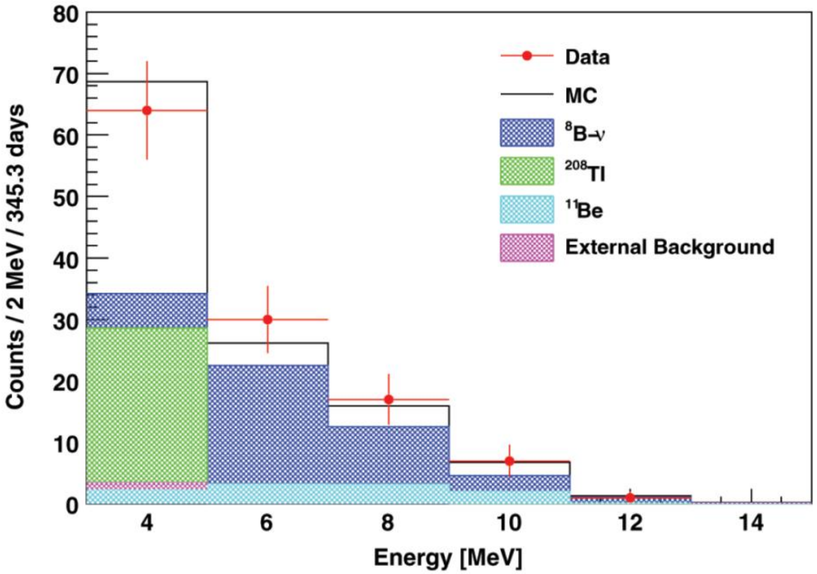
- Muon rejection;
- Fiducial Volume cut (R<3m)
- Rejection of cosmogenics by cutting 6.5 seconds after the muons (reduction of detecting efficiency by 29.4%);

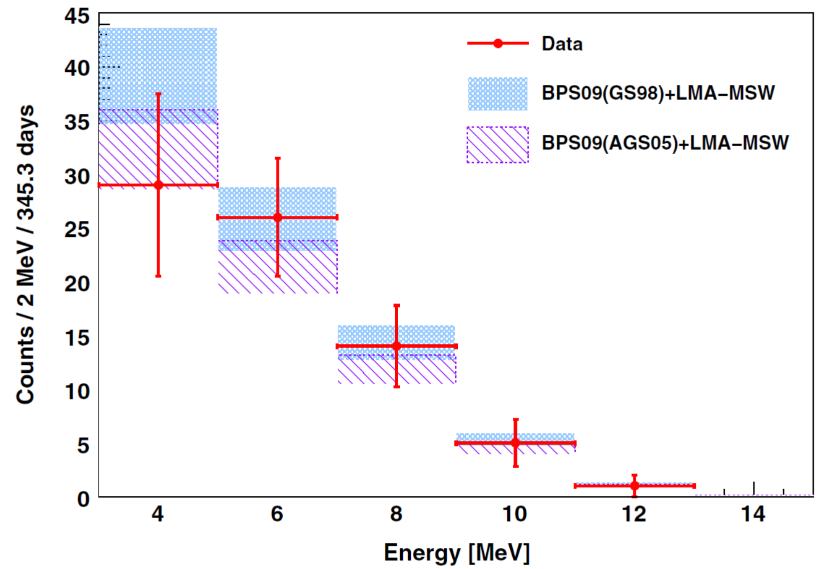
Cut	Counts 3.0–16.3 MeV	Counts 5.0–16.3 MeV
All counts	1932181	1824858
Muon and neutron cuts	6552	2679
FV cut	1329	970
Cosmogenic cut	131	55
^{10}C removal	128	55
^{214}Bi removal	119	55
^{208}Tl subtraction	90 ± 13	55 ± 7
^{11}Be subtraction	79 ± 13	47 ± 8
Residual subtraction	75 ± 13	46 ± 8
Final sample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



- Residual external contamination for R<3m contamination (6.4±0.2)x10^{-3} cpd/100tons

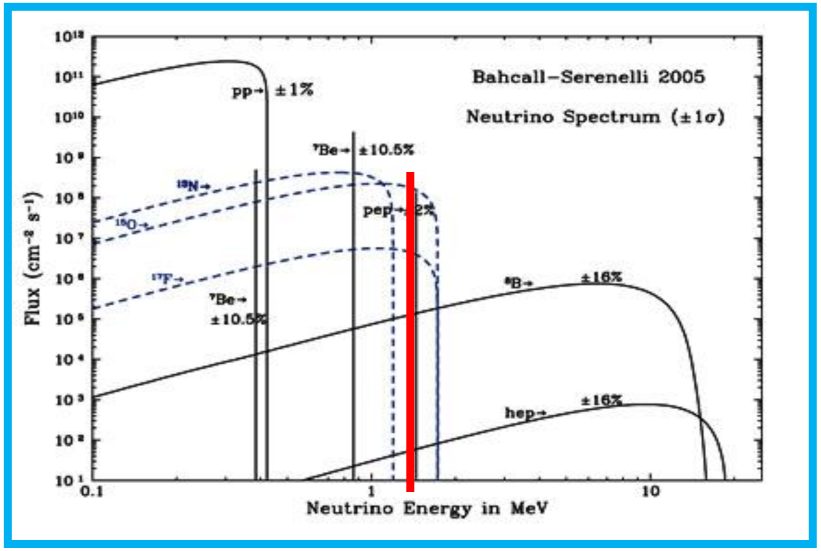
^{8}B neutrinos with low energy threshold (T_e >3 MeV)





Rate of ^{8}B neutrinos (E>3 MeV) = 0.22 ± 0.04 (stat) ± 0.01 (sys) cpd/100t

	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_{exp}^{ES} [10^6 cm^{-2} s^{-1}]	$2.4 \pm 0.4 \pm 0.1$	$2.7 \pm 0.4 \pm 0.2$
$\Phi_{exp}^{ES}/\Phi_{th}^{ES}$	0.88 ± 0.19	1.08 ± 0.23



First evidence of pep neutrinos and limits on CNO

First evidence of pep solar neutrinos and limit on CNO

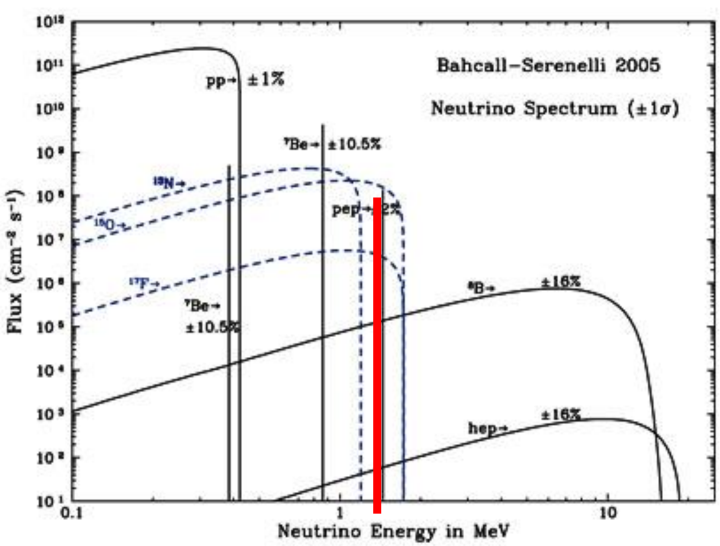
First Evidence of pep Solar Neutrinos by Direct Detection in Borexino PRL 108, 051302 (2012);

– The importance of this result induced APS to highlight the paper with a Synopsis on the Physics website

http://physics.aps.org/synopsis-for/10.1103/PhysRevLett.108.051302

Pep solar neutrinos

– Monocromatic line at E=1.44MeV;
– Ideal to test P_{ee} in the transition region;



CNO solar neutrinos

– Never directly observed;
– Optimal to study the solar metallicity controversy

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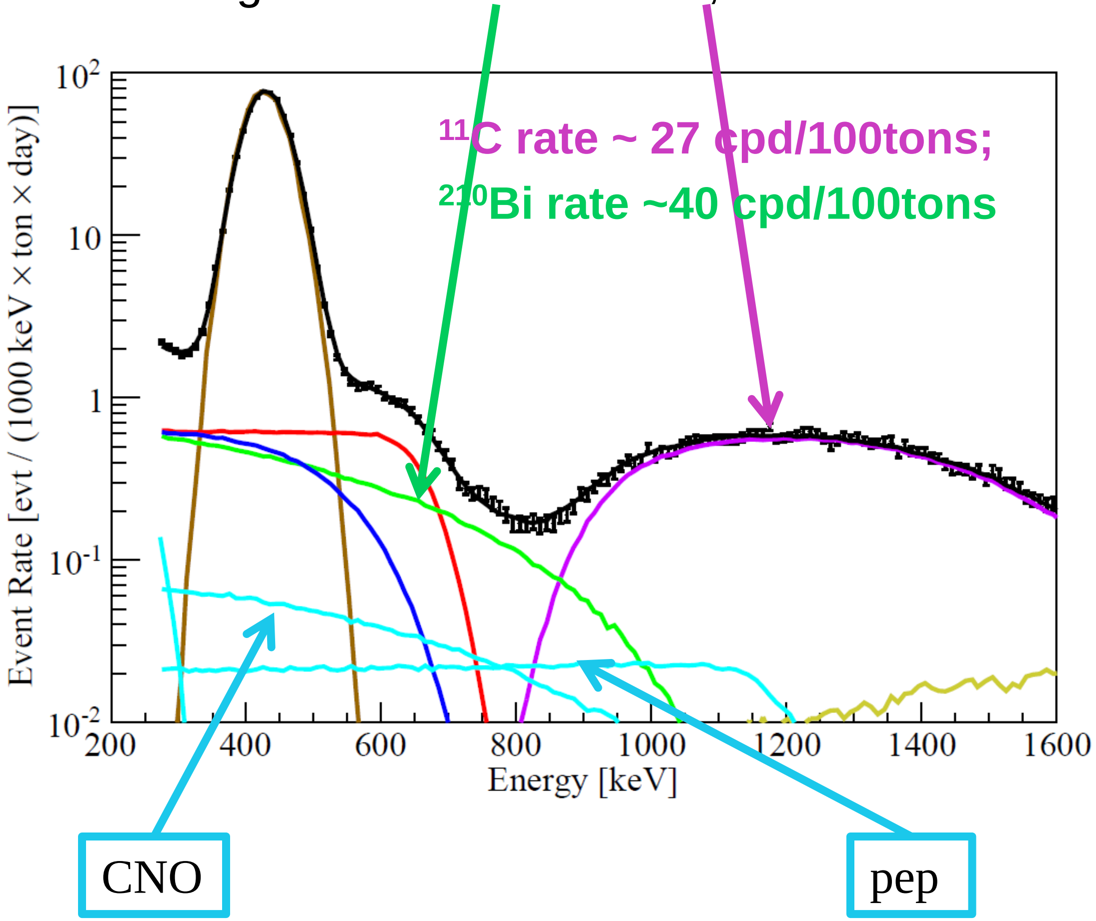
First evidence of pep solar neutrinos and limit on CNO

Backgrounds

- Difficulties of this analysis:
  - Very tiny rates (few counts /day/100tons);
  - Backgrounds: ^{210}Bi and ^{11}C;



It is possible to suppress the ^{11}C background by

- three-fold coincidence;
- pulse-shape discrimination;

First evidence of pep solar neutrinos and limit on CNO

Three-fold coincidence technique:

Space and time veto after the coincidence of a muon and a neutron

^{11}C is produced by muons crossing BX

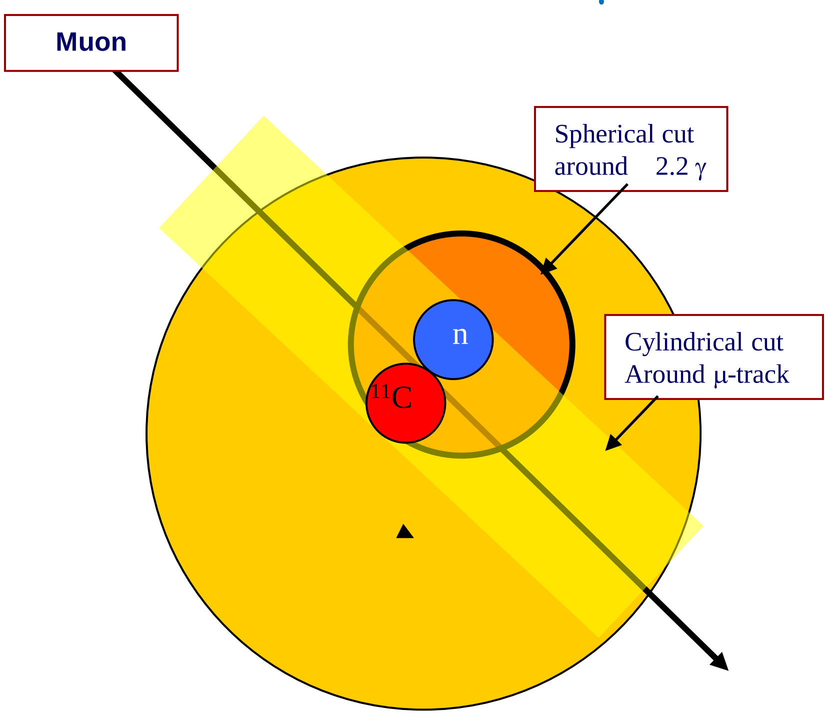
$\mu + {}^{12}C \rightarrow \mu + {}^{11}C + n$

$^{11}C \rightarrow {}^{11}B + e^+ + \nu_e$

t~30min

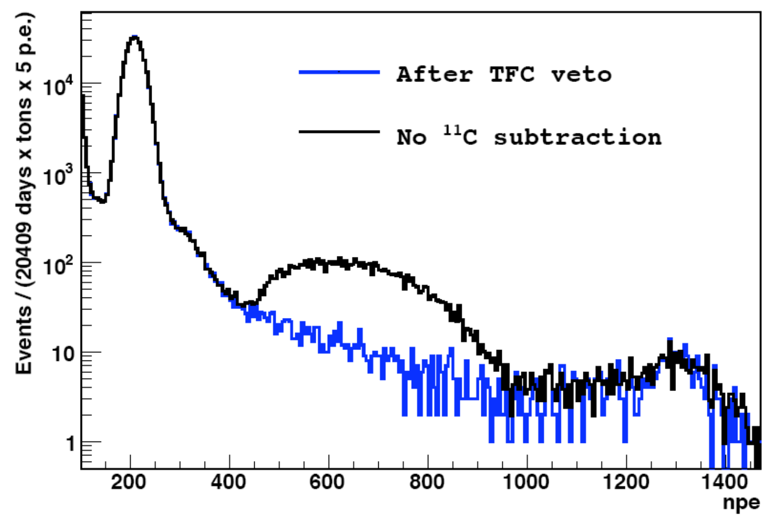
$n + p \rightarrow d + \gamma$

$\tau \sim 260 \mu s$



Optimal choice:

- Eliminates 91% of ^{11}C;
- Preserve 48.5% of livetime;

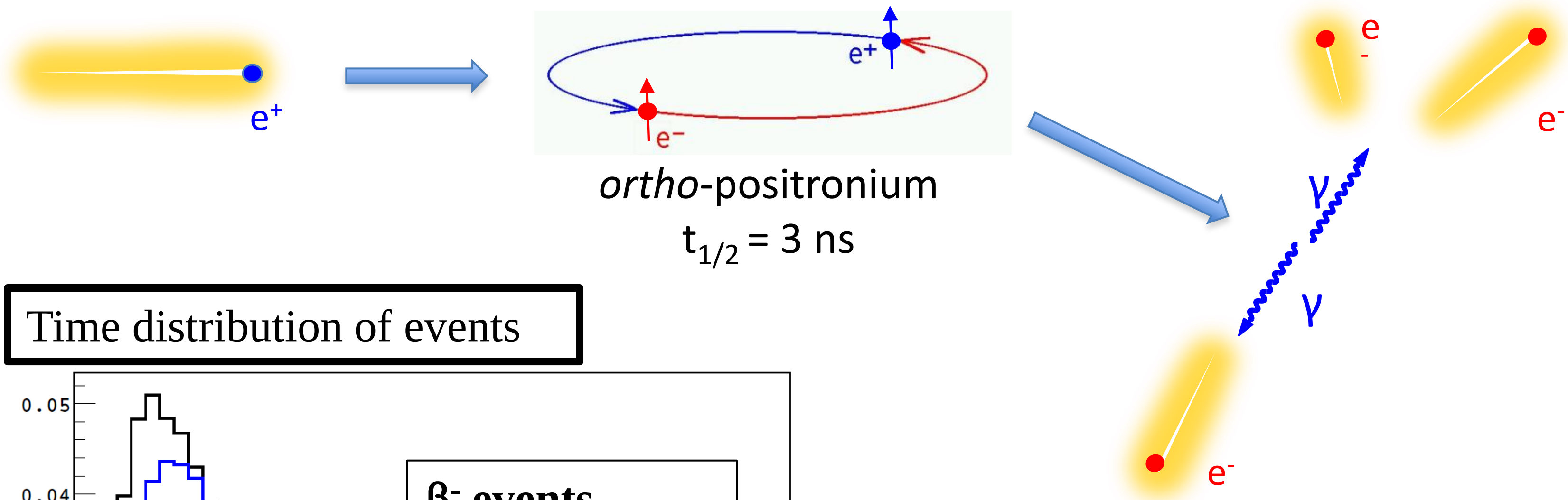


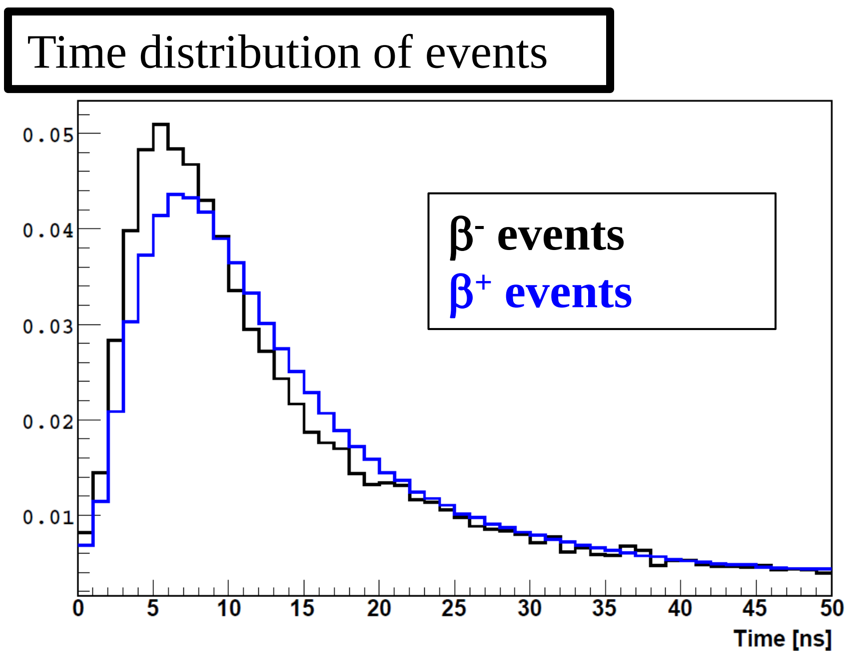
- ^{11}C from 27 counts/day/100tons to 2.5 counts/day/100tons

First evidence of pep solar neutrinos and limit on CNO

e+/e- pulse shape discrimination (PRC 83-015522 (2011))

- Based on the small differences in the time distribution of the scintillation signal coming from the ortho-positronium finite lifetime and the presence of annihilation γ rays.





- Boost decision tree to construct an optimized pulse-shape discrimination variable

First evidence of pep solar neutrinos and limit on CNO

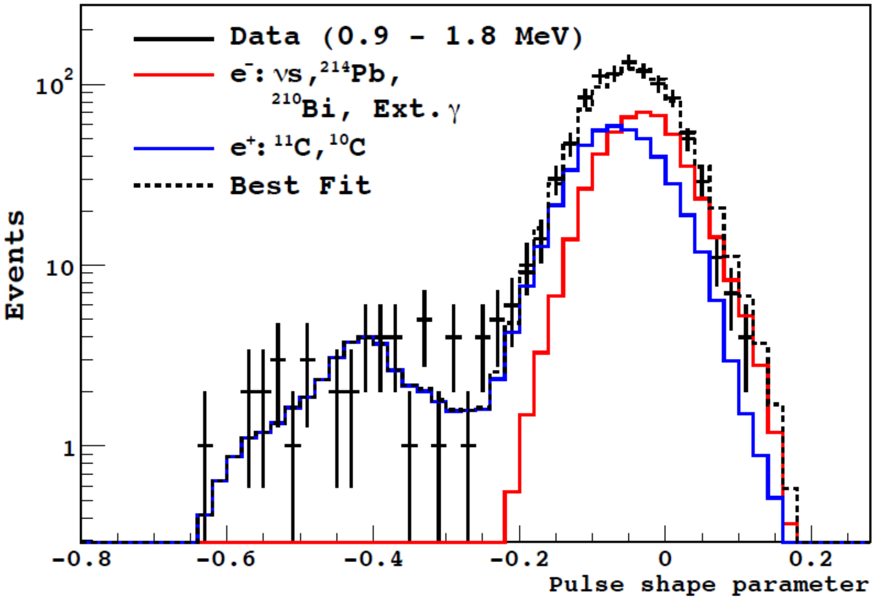
Multivariate analysis:

Fit simultaneously:

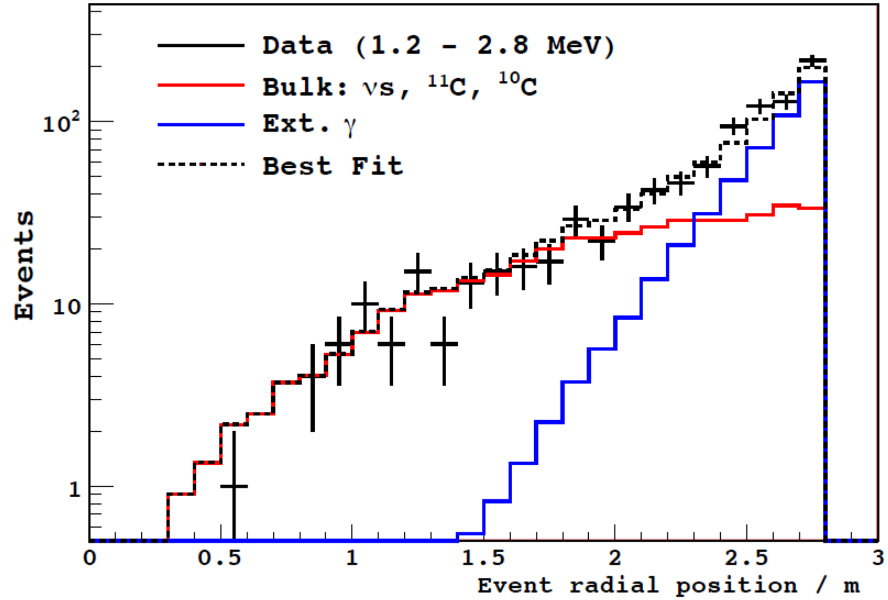
- Radial distribution of events;
- Energy distribution of events;
- Pulse-shape distribution of events;

Both pep and CNO rates are parameters of the fit

Pulse-shape variable distribution

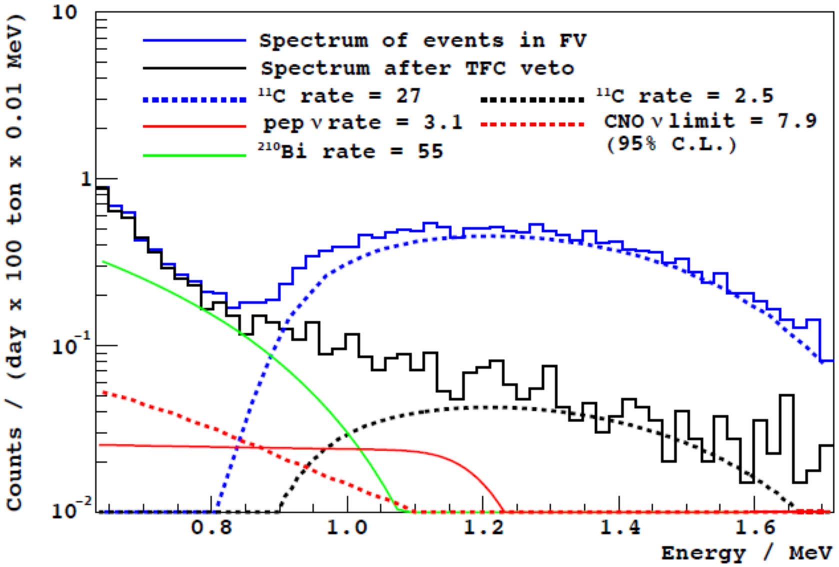


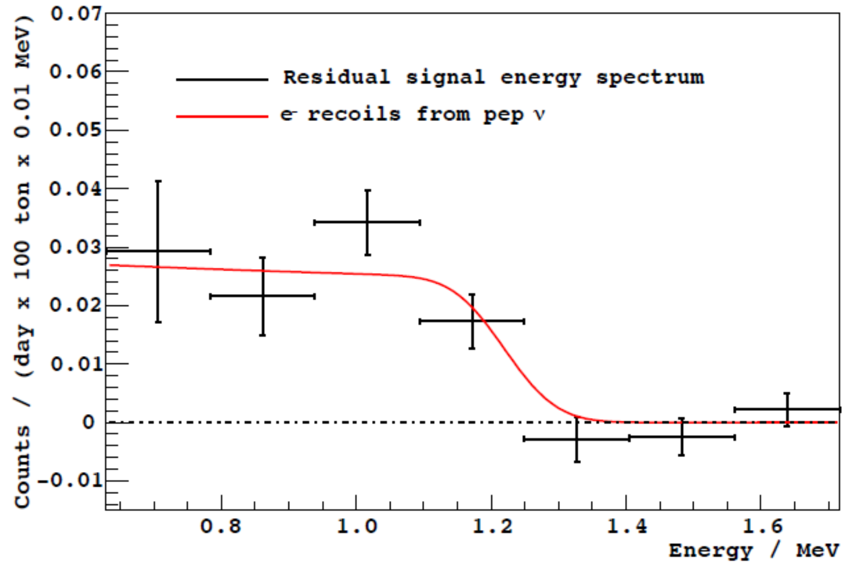
Radial distribution



First evidence of pep solar neutrinos and limit on CNO

Energy spectrum



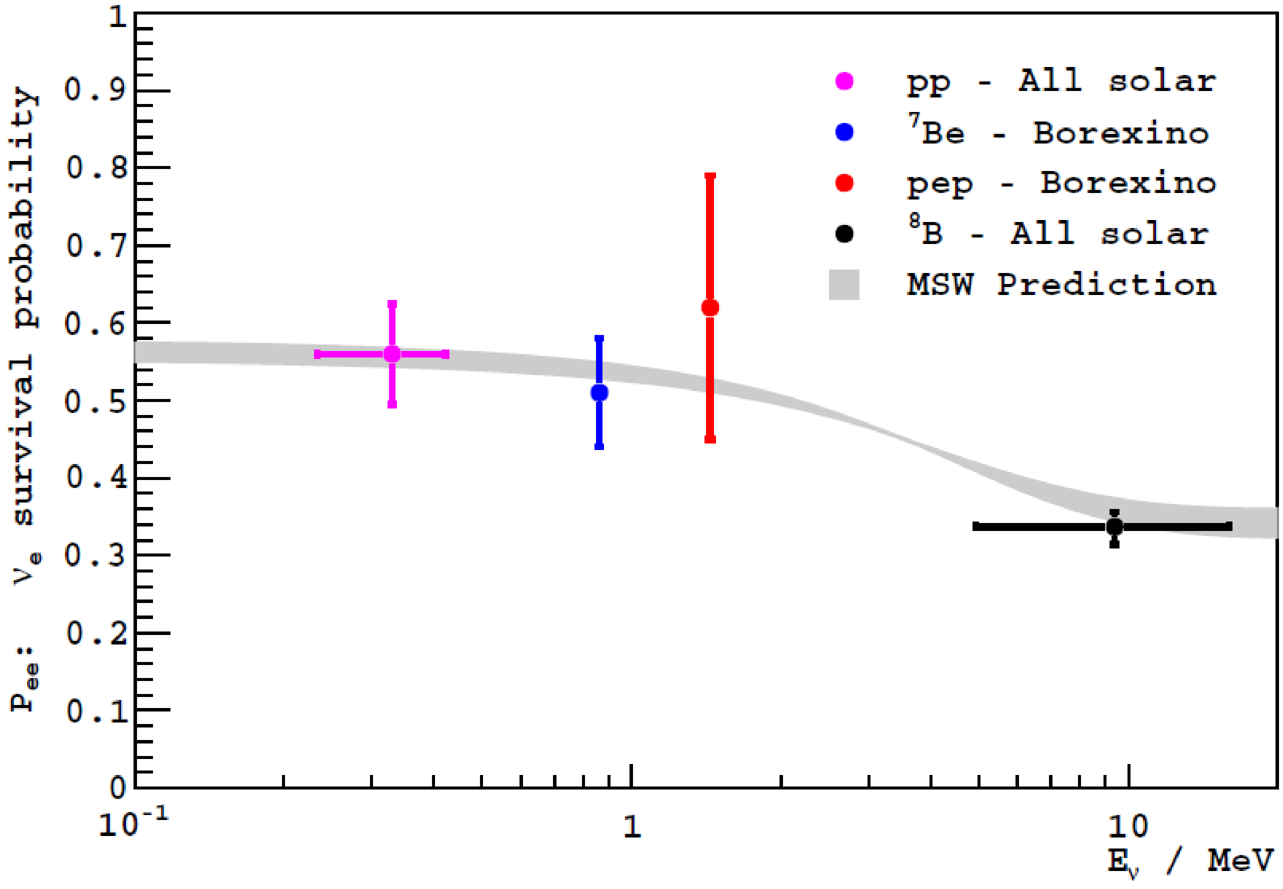


ν	Interaction rate [counts/(day · 100 ton)]	Solar-ν flux [10^8 cm^{-2} s^{-1}]	Data/SSM ratio
pep	$3.1 \pm 0.6_{stat} \pm 0.3_{syst}$	1.6 ± 0.3	1.1 ± 0.2

Source	[%]
Fiducial exposure	$^{+0.6}_{-1.1}$
Energy response	± 4.1
^{210}Bi spectral shape	$^{+1.0}_{-5.0}$
Fit methods	± 5.7
Inclusion of independent ^{85}Kr estimate	$^{+3.9}_{-0.0}$
γ rays in pulse-shape distributions	± 2.7
Statistical uncertainties in pulse-shape distributions	± 5
Total systematic uncertainty	± 10

First evidence of pep solar neutrinos and limit on CNO

Electron neutrino survival probability

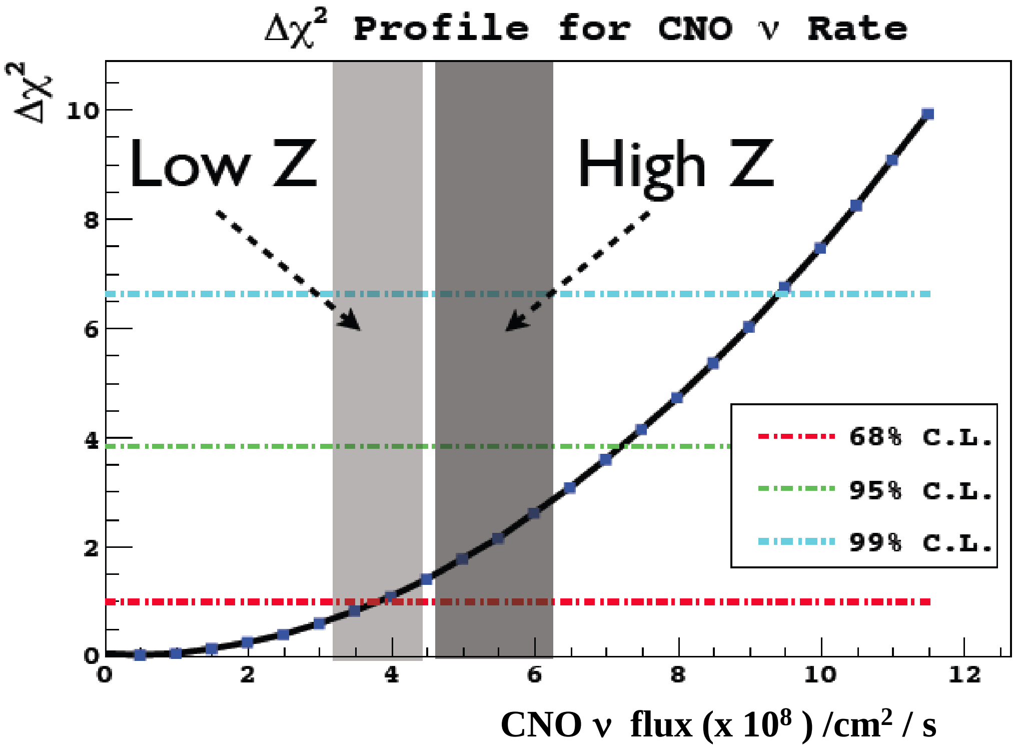


MSW-LMA prediction band is the 1σ range for oscillation parameters given in K.Nakamura et al. (Particle Data Group), J.Phys.G 37, 075021 (2010).

First evidence of pep solar neutrinos and limit on CNO

Limit on CNO flux

- ^{210}Bi backround is hard to disentangle from CNO signal→ only a limit can be quoted;
- Fixing the pep rate at the SSM prediction;
- CNO neutrino flux: < 7.9 (<$7.1_{\text{stat only}}$) x10^8 ν/cm^2 s (95% C.L);
- **Result consistent with both high and low metallicity rates;**

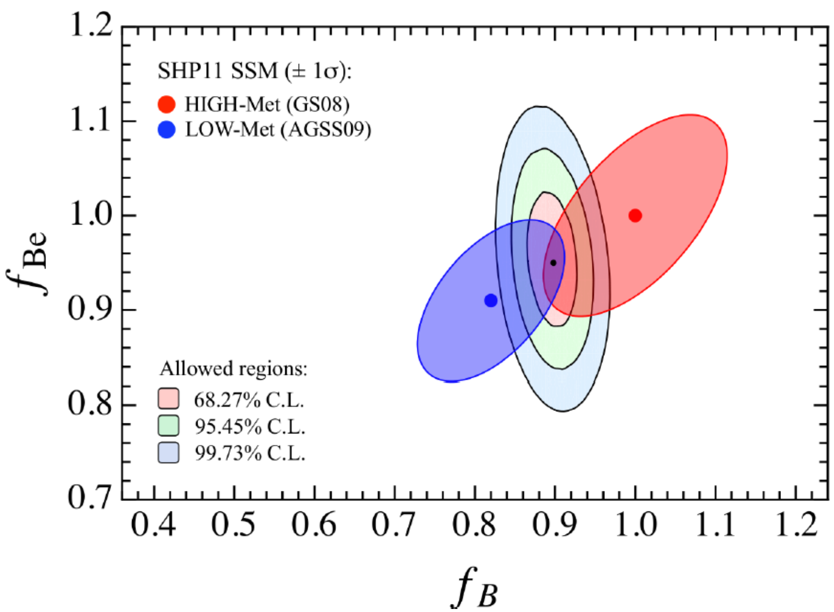


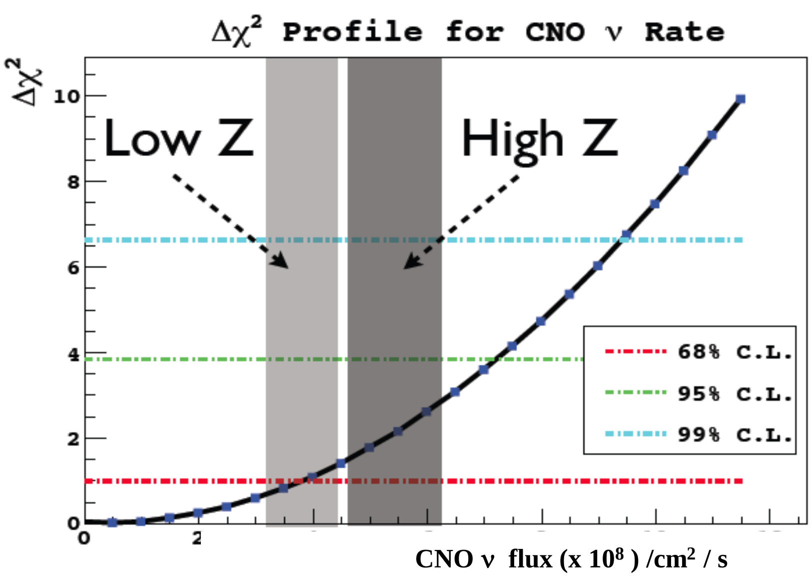
Summary and conclusions

Implications of Borexino data on solar physics

- **Borexino has provided a real-time spectroscopy of solar neutrinos:**
  - Precise measurement of ^{7}Be neutrino rate and null day/night asymmetry;
  - Measurement of ^{8}B neutrino rate with the lowest threshold (T_e >3 MeV);
  - First direct evidence of pep solar neutrinos;
  - Most stringent limit on the CNO neutrino flux;

- Unfortunately Borexino measurement cannot discriminate between high and low metallicity;

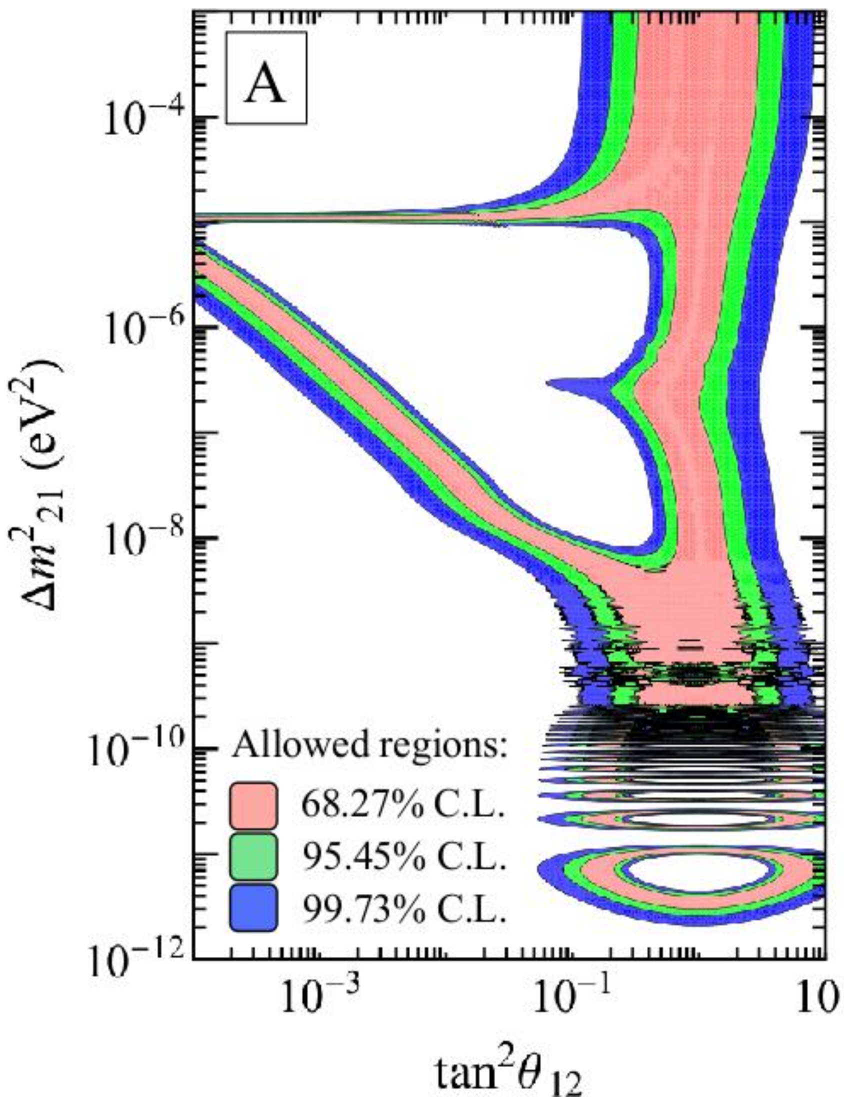




Implications of Borexino data on oscillation parameters

Analysis with Borexino data only

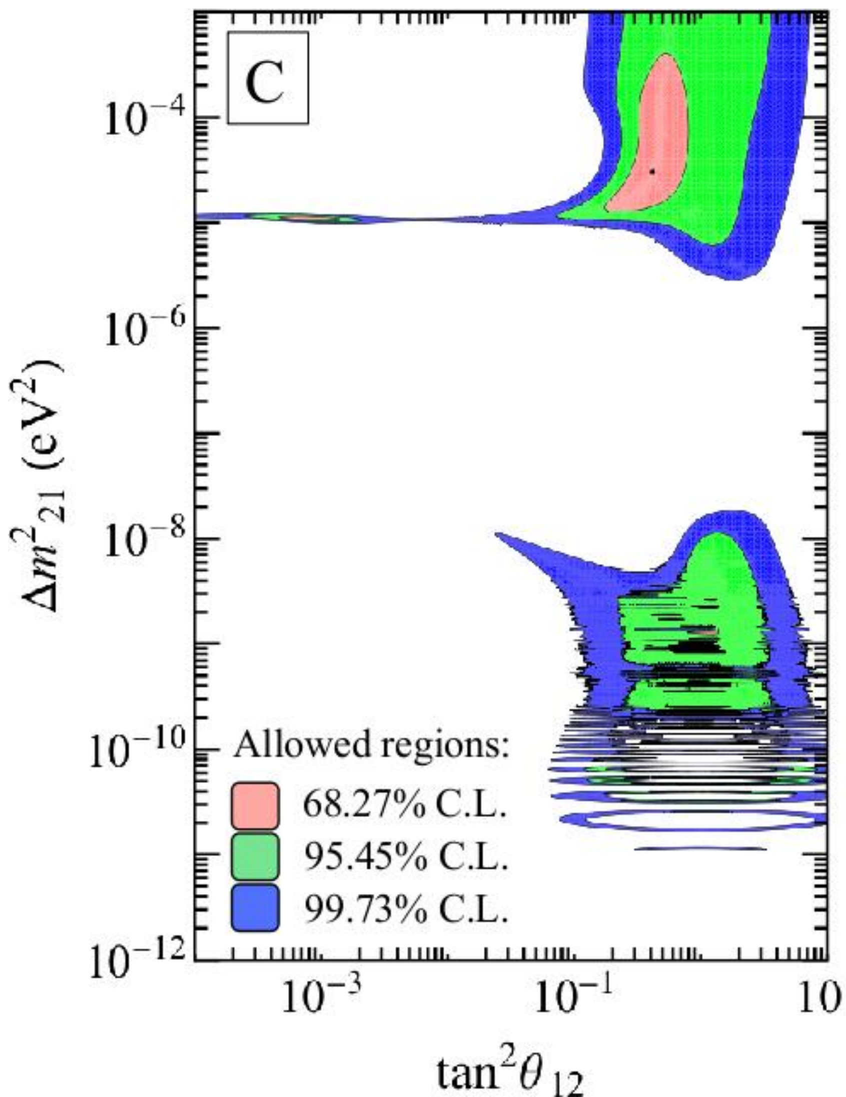
^{7}Be rate only



Implications of Borexino data on oscillation parameters

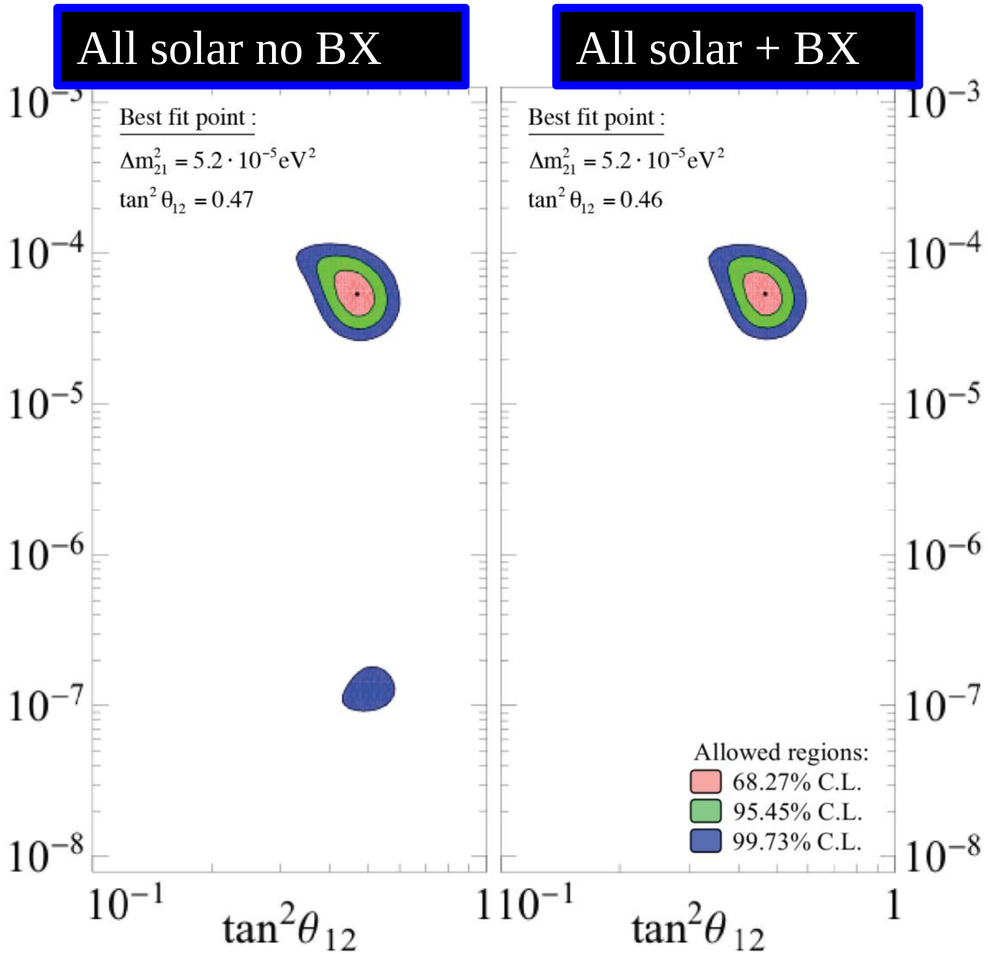
Analysis with Borexino data only

^{7}Be+^{8}B rate +ADN



Implications of Borexino data on oscillation parameters

Analysis with solar data and Borexino data

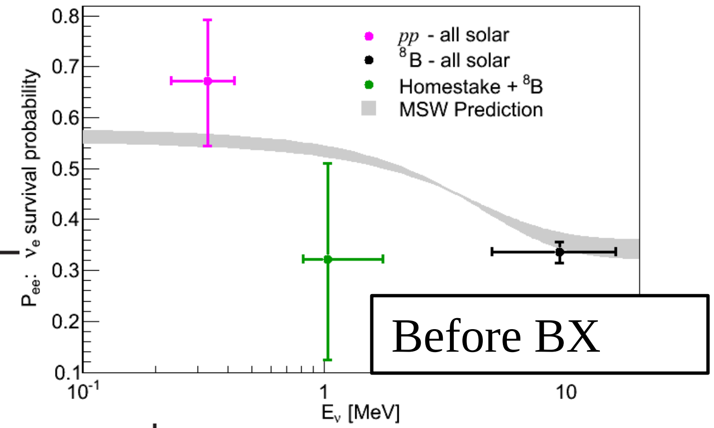


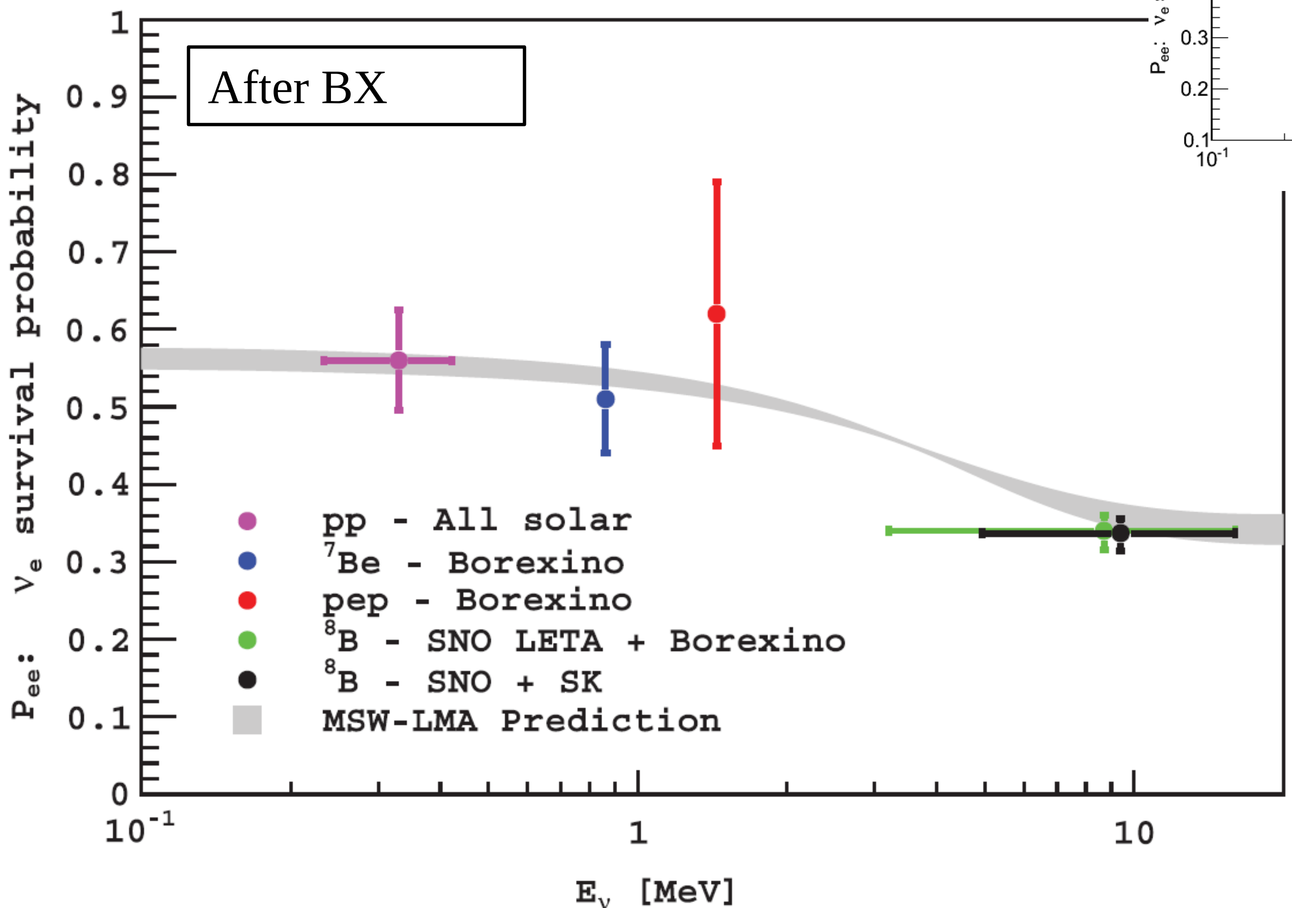
Strong confirmation of the LMA without relying on anti-neutrino kamLAND data

Implications of Borexino data on oscillation parameters

Analysis including all available information on solar+ kamLAND

Borexino has been able of probing Pee at different energies, giving a confirmation of the LMA hypothesis





Perspectives

- **We are not stopping here! Getting ready for Borexino Phase II:**
  - 6 purification cycles performed between May 2010 and August 2011
  - Exceptional levels of radiopurity: ^{85}Kr rate consistent with 0, ^{210}Bi reduced by a factor ~4, unprecedented levels of U and Th;

- **Future goals:**
  - pp neutrinos (very challenging!)
  - Improve precision on ^{7}Be neutrino rate (3% ?)
  - Improve significance of pep signal (3σ or more)
  - Improve limit on CNO neutrinos (observation ?)