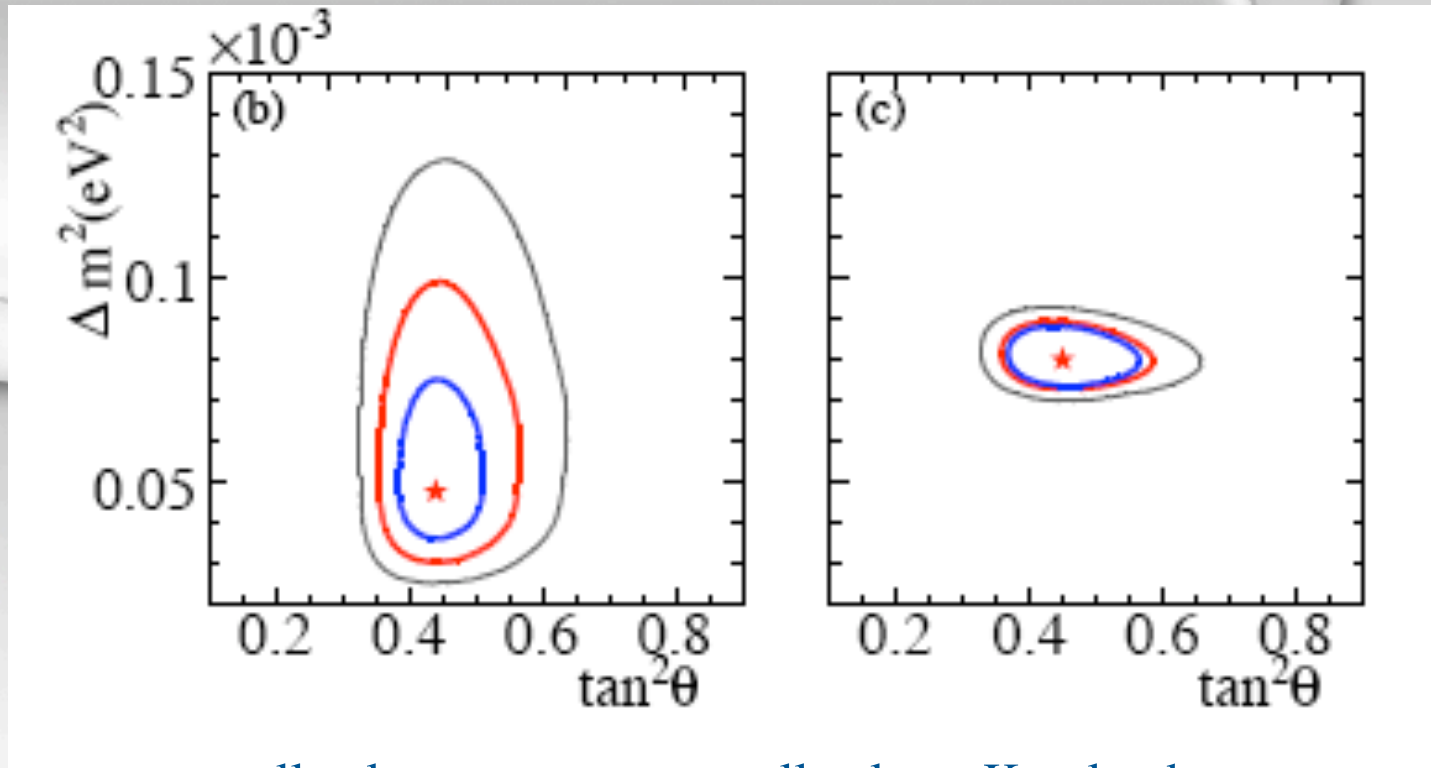


# Study of neutrino interactions over 200 keV lower threshold

- @ open problems in the solar neutrinos
- @ first results obtained by Borexino
- @ what we can expect in the near future
- @ study of the geo-neutrinos

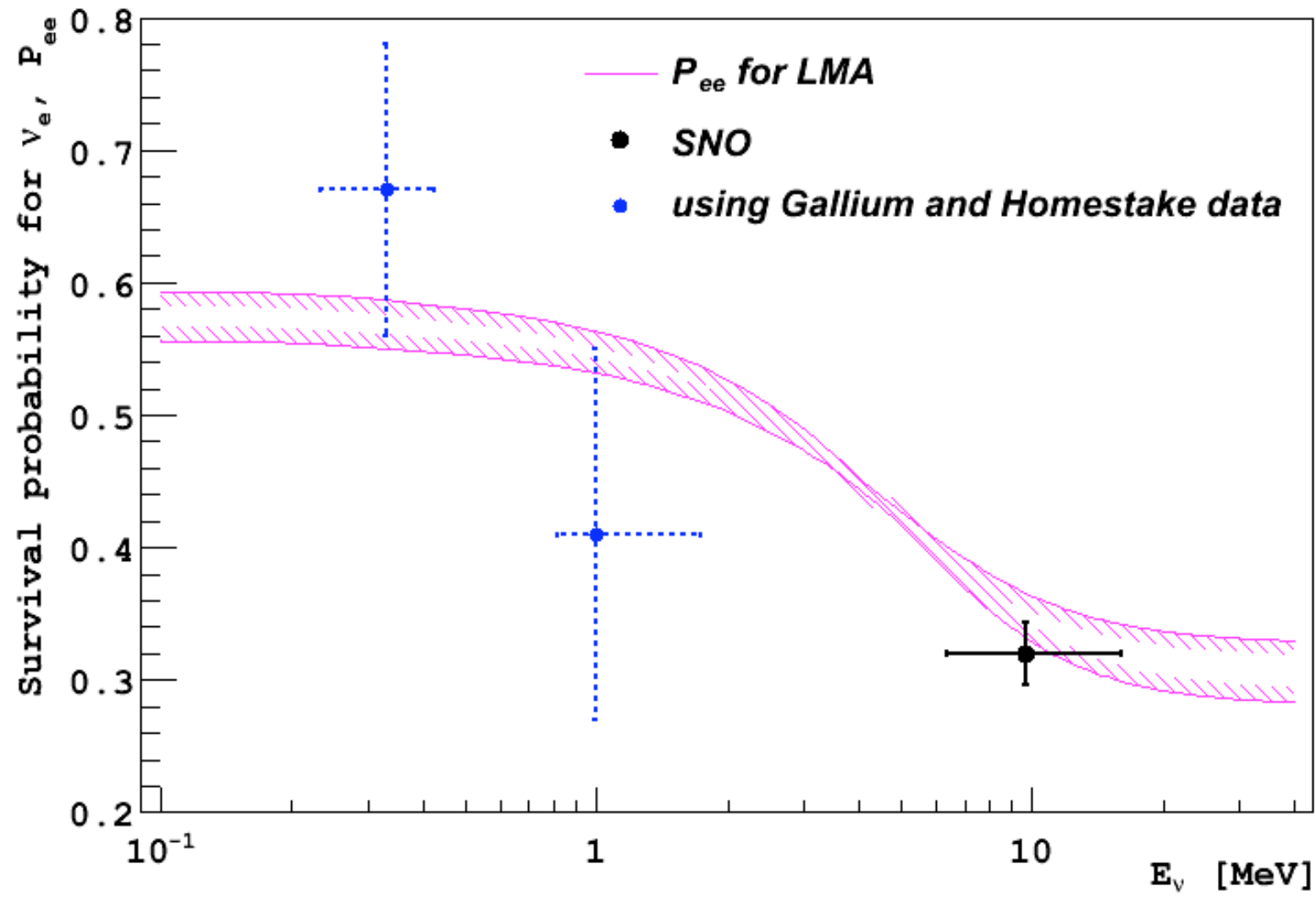


all solar

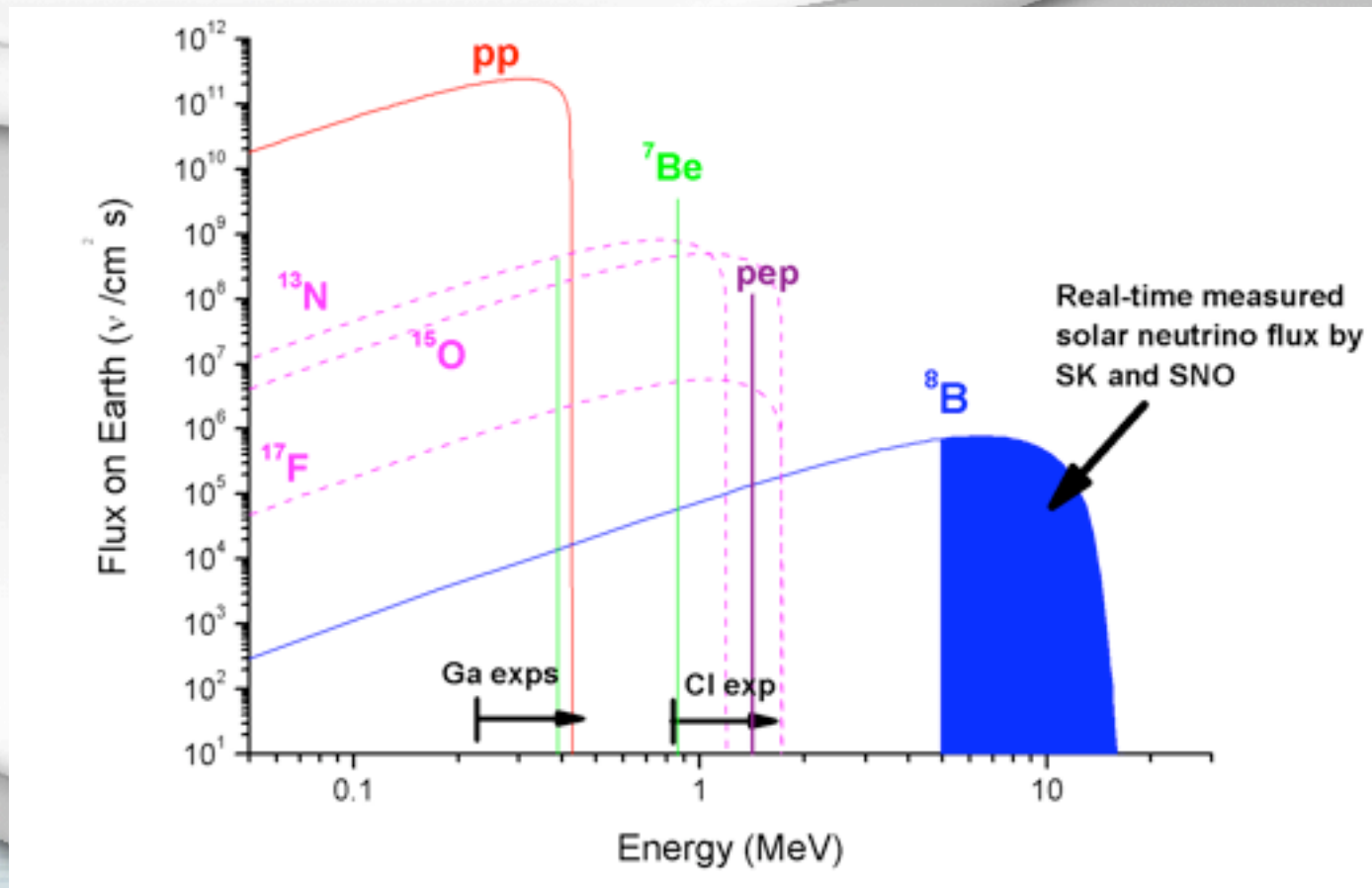
all solar + Kamland

$$\Delta m^2 = 7.65^{+0.23}_{-0.20} \cdot 10^{-5} \text{ eV}^2 \quad \tan^2 \theta = 0.437^{+0.047}_{-0.032}$$

## Current MSW-LMA model-



> 99% of solar neutrino spectrum is not measured in real time mode before Borexino





# Metallicity

Solar surface abundances are determined from analyses of photospheric atomic and molecular spectral lines.

The associated solar atmosphere modeling has been done in one dimension in a time-independent hydrostatic analysis that incorporates convection (GS98)-good agreement with helioseis.

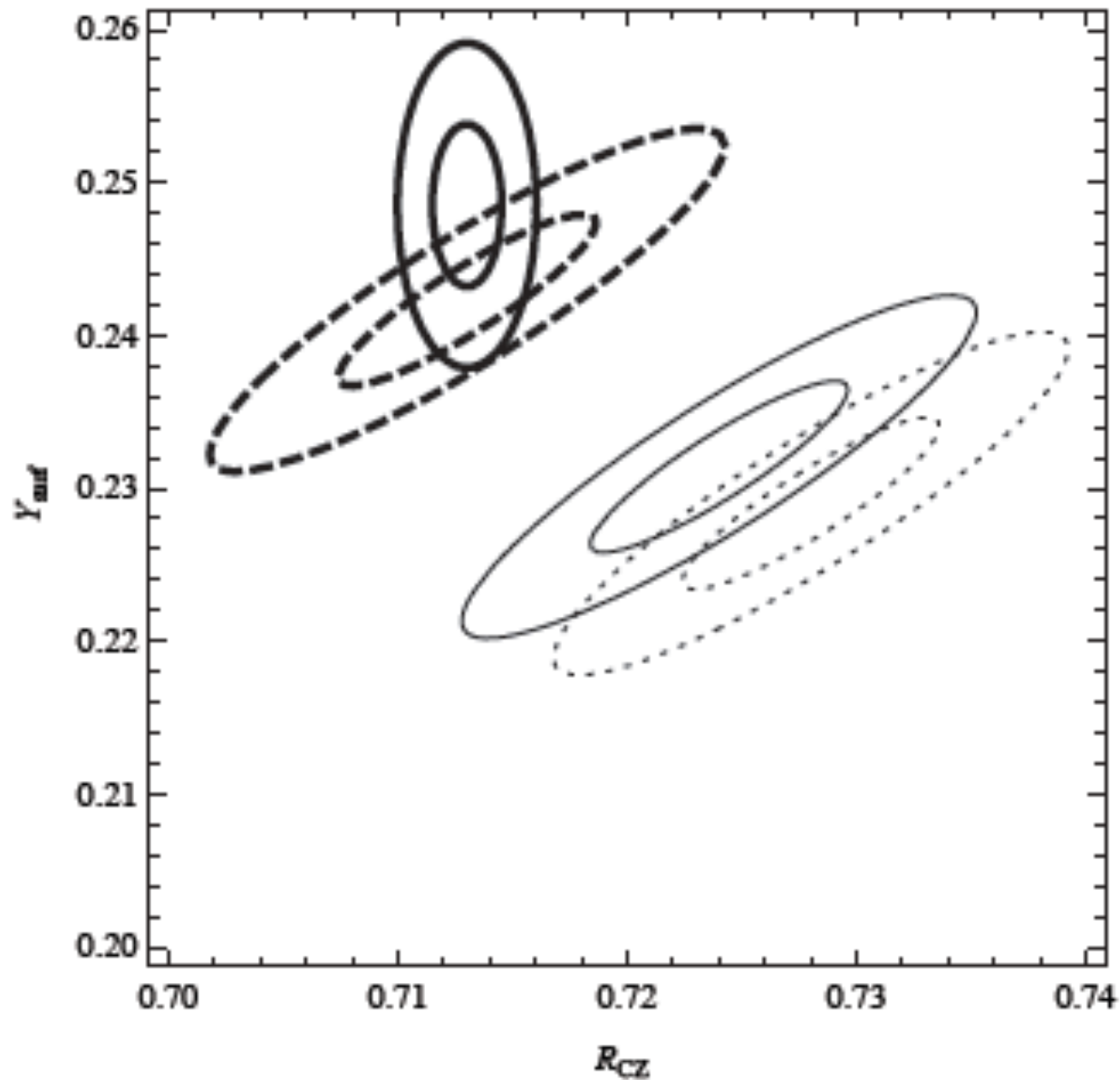
A much improved 3D model of the solar atmosphere has been developed, which better reproduces line profiles and brings the Solar abundances into better agreement with other stars in the neighborhood (AGS05)-bad agreement with helioseismology

Due to this improved analysis, the solar surface contains 30-40% less carbon, nitrogen, oxygen, neon and argon than previously believed.

Source	$BPS_{highZ}$	$BPS_{lowZ}$	Difference
$pp$	$5.97(1 \pm 0.007)$	$6.04(1 \pm 0.007)$	$0.07 \pm 0.06$
$pep$	$1.41(1 \pm 0.011)$	$1.45(1 \pm 0.011)$	$0.04 \pm 0.02$
$hep$	$7.90(1 \pm 0.16)$	$8.22(1 \pm 0.16)$	$0.30 \pm 1.70$
${}^7\text{Be}$	$5.08(1 \pm 0.05)$	$4.55(1 \pm 0.05)$	$0.53 \pm 0.35$
${}^8\text{B}$	$5.95(1^{+0.10}_{-0.09})$	$4.72(1^{+0.10}_{-0.09})$	$1.2 \pm 0.8$
${}^{13}\text{N}$	$2.93(1^{+0.15}_{-0.13})$	$1.93(1^{+0.15}_{-0.13})$	$1.0 \pm 0.6$
${}^{15}\text{O}$	$2.20(1^{+0.17}_{-0.14})$	$1.37(1^{+0.17}_{-0.14})$	$0.8 \pm 0.4$
${}^{17}\text{F}$	$5.82(1^{+0.17}_{-0.14})$	$3.25(1^{+0.17}_{-0.14})$	$2.6 \pm 1.2$

Units:  $10^{10}$  (pp),  $10^9$  ( ${}^7\text{Be}$ ),  $10^8$  (pep,  ${}^{13}\text{N}$ ,  ${}^{15}\text{O}$ ),  $10^6$  ( ${}^8\text{B}$ ,  ${}^{17}\text{F}$ ),  $10^3$  (hep)  $\text{cm}^{-2}, \text{s}^{-1}$

Precise measurements of the Solar neutrino Fluxes can help in fixing Z/X



$\Delta(\text{rate})$  for  ${}^7\text{Be}$   
reduced to 8.7%





# Borexino: low energy real time detection

## Scintillator:

270 t PC+PPO in a 150  $\mu\text{m}$  thick nylon vessel

## Nylon vessels:

Inner: 4.25 m  
Outer: 5.50 m

Neutrino electron scattering



Carbon steel plates

## Stainless Steel Sphere:

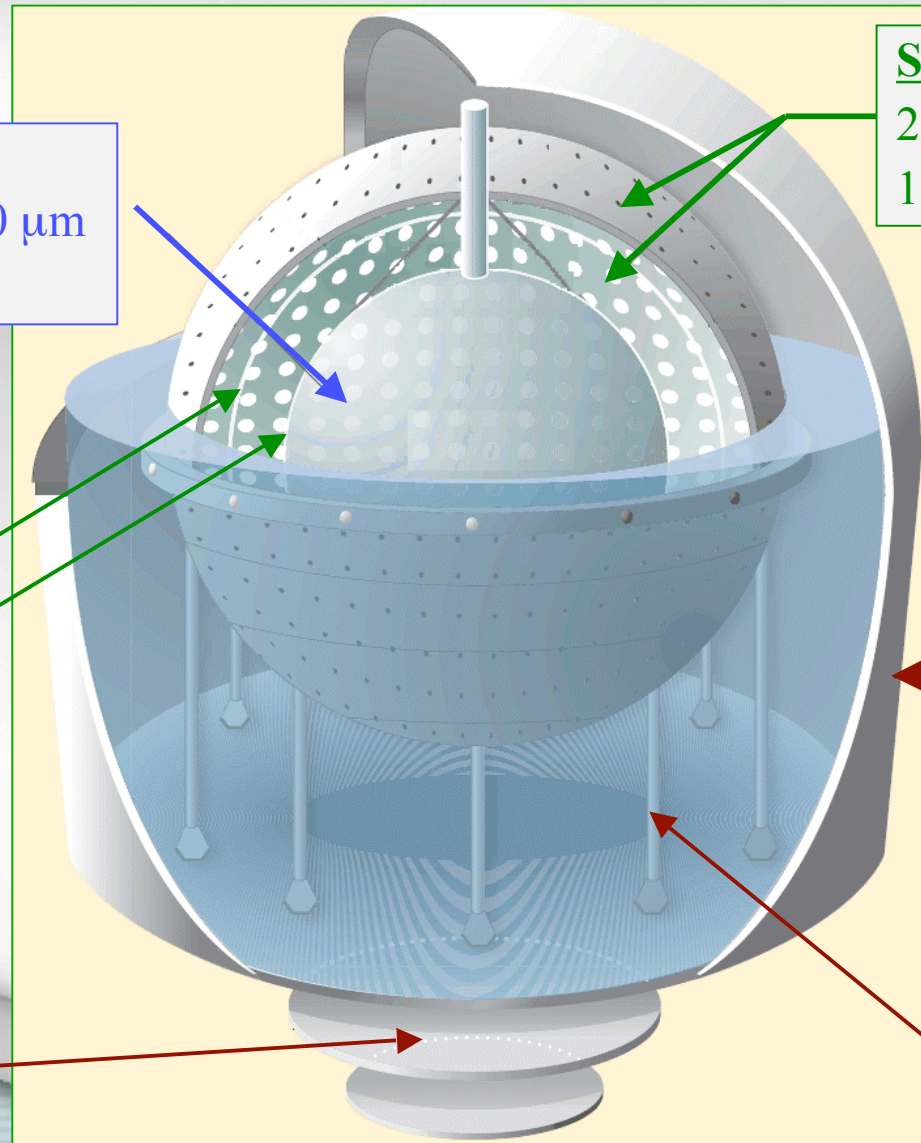
2212 photomultipliers  
1350 m<sup>3</sup>

Design based on the principle of graded shielding

## Water Tank:

$\gamma$  and n shield  
 $\mu$  water  $\checkmark$  detector  
208 PMTs in water  
2100 m<sup>3</sup>

20 legs





# Filled detector

PC filling completed  
May 15th, 2007





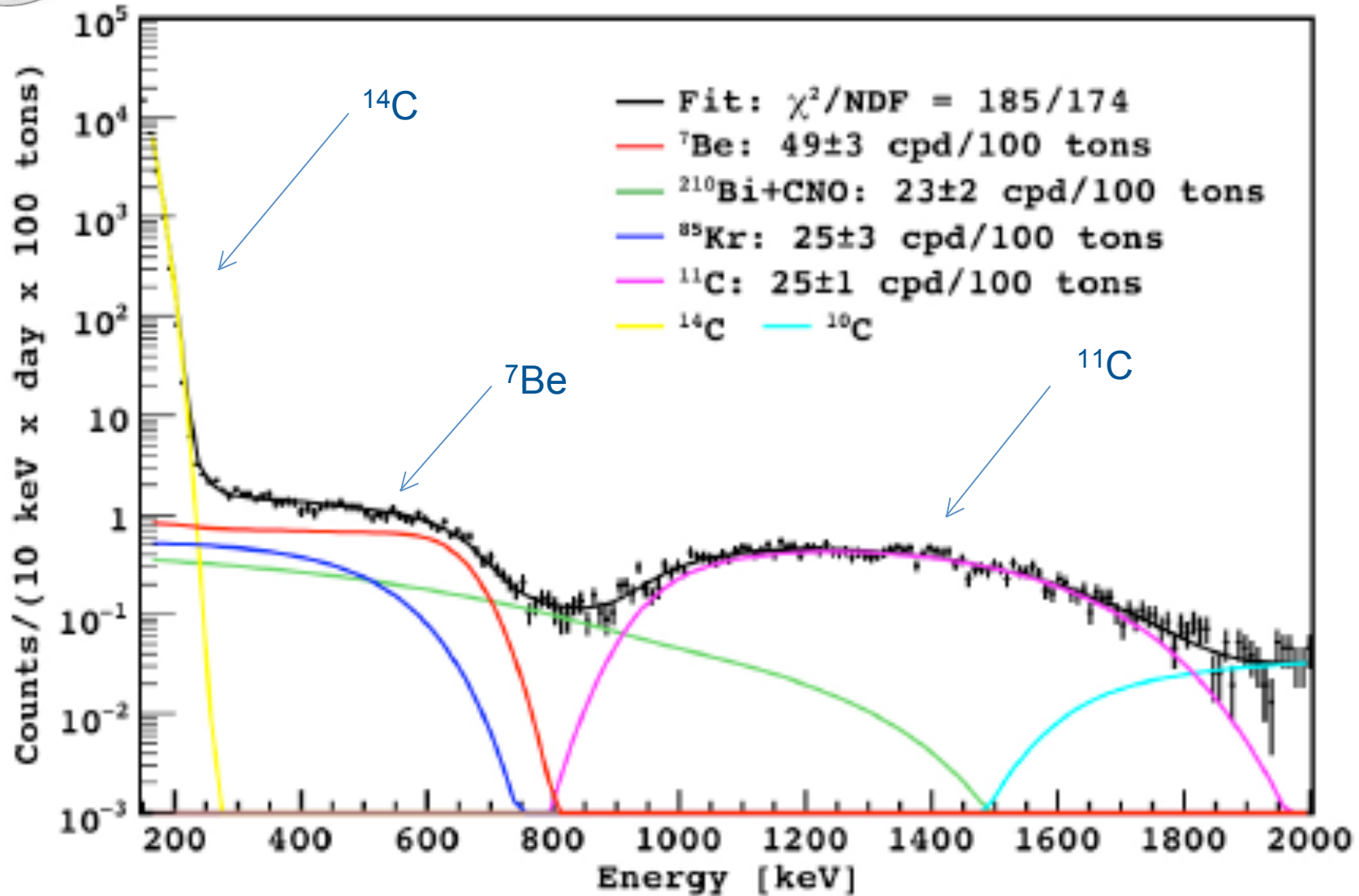
## Records in the radiopurity achieved by Borexino

	Material	Typical conc. of the unpurified materials	Radiopurity levels in the Bx scintillator
$^{14}\text{C}$	scintillator	$^{14}\text{C}/^{12}\text{C} < 10^{-12}$	$^{14}\text{C}/^{12}\text{C} \cong 2 \cdot 10^{-18}$
$^{238}\text{U}, ^{232}\text{Th}$ equiv.	- Hall C dust - stainless. steel - nylon	$\sim 1$ ppm $\sim 1$ ppb $\sim 1$ ppt	$10^{-17} - 10^{-18} \text{ g/g}$
$\text{K}_{\text{nat}}$	Hall C dust	$\sim 1$ ppm	$< 10^{-14} \text{ g/g}$
$^{222}\text{Rn}$	- external air. - air underground	$\sim 20 \text{ Bq/m}^3$ $\sim 40-100 \text{ Bq/m}^3$	$< 1 \mu\text{Bq/m}^3$
$^{85}\text{Kr}$ $^{39}\text{Ar}$	in $\text{N}_2$ for stripping	$\sim 1.1 \text{ Bq/m}^3$ $\sim 13 \text{ mBq/m}^3$	$\sim 0.16 \text{ mBq/m}^3$ $\sim 0.5 \text{ mBq/m}^3$
- $^{222}\text{Rn}$ - $^{238}\text{U}, ^{232}\text{Th}$ equiv.	LNGS - Hall C water	$\sim 50 \text{ Bq/m}^3$ $\sim 10^{-10} \text{ g/g}$	<b>Water</b> $\sim 30 \mu\text{Bq/m}^3$ $\sim 10^{-14} \text{ g/g}$



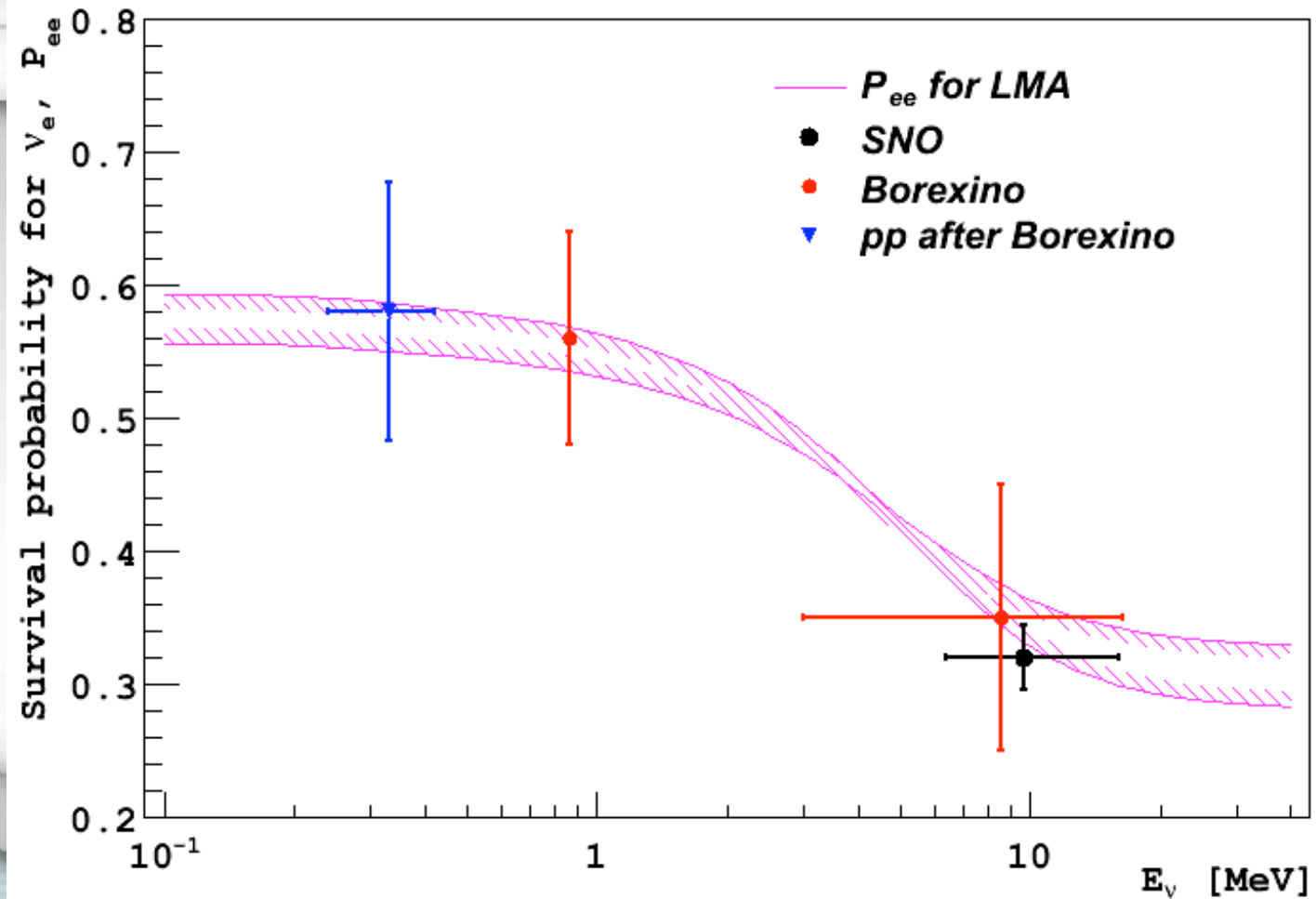


**BOREXINO: 192 days**-free parameters: ${}^7\text{Be}$ , ${}^{14}\text{C}$ , CNO+ ${}^{210}\text{Bi}$ , ${}^{11}\text{C}$ , ${}^{85}\text{Kr}$ ;  
-fixed at the SSM values:pp, pep



$49 \pm 3_{\text{stat}} \pm 4_{\text{syst}} \text{ cpd}/100\text{tons}$  for  $862 \text{ keV } ^7\text{Be}$  solar  $\nu$   
 $\Phi(^7\text{Be}) = (5.12 \pm 0.51) \times 10^9 \text{ cm}^{-2} \text{ s}^{-1}$  SSM; H.M.  $(5.08 \pm 0.56) \times 10^9 \text{ cm}^{-2} \text{ s}^{-1}$   
 L.M.  $(4.55 \pm 0.5) \times 10^9 \text{ cm}^{-2} \text{ s}^{-1}$

First  
 experimental  
 evidence of  
 the vacuum  
 regime





# Day night asymmetry for $^7\text{Be}$ solar neutrinos

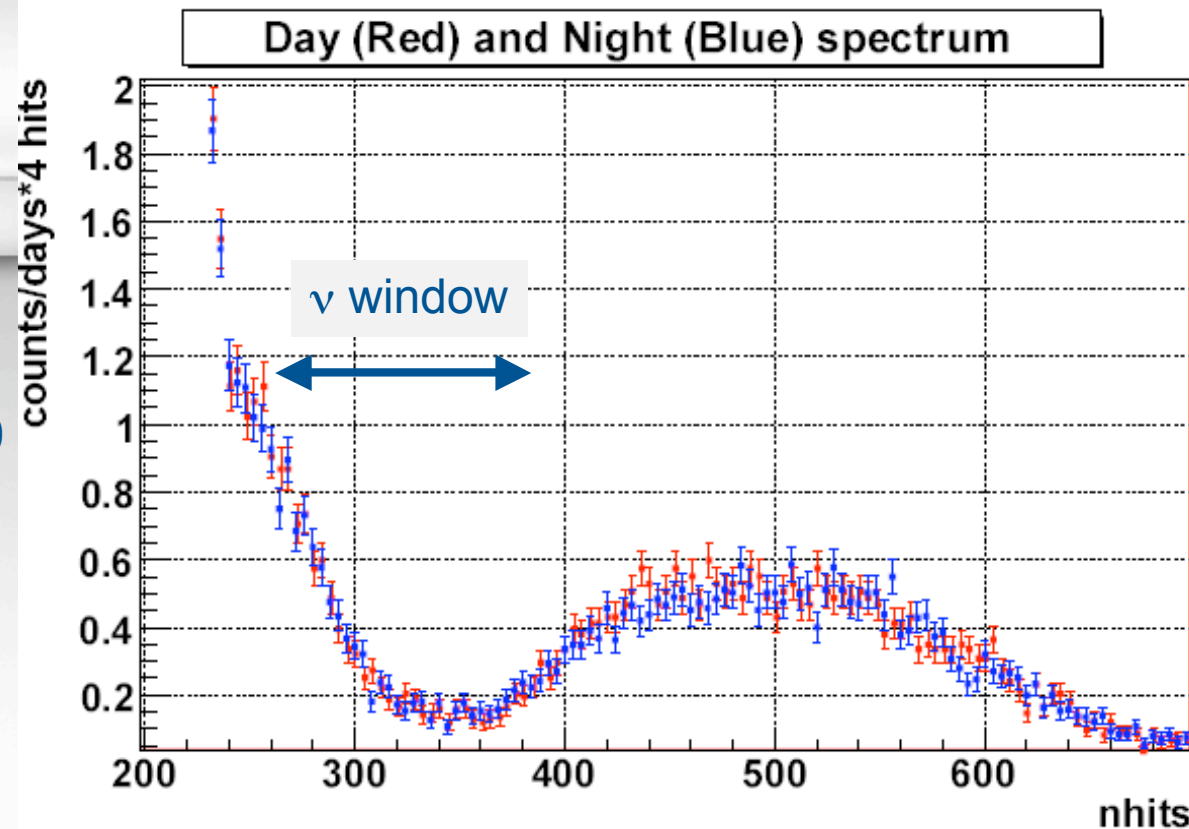
422.12 days total live time

Night 212.87 days

Day 209.25 days

Day: Sun Altitude  $\alpha > 0$   
(zenith  $< 90$  deg)

Night: Sun Altitude  $\alpha < 0$   
(zenith  $> 90$  deg)



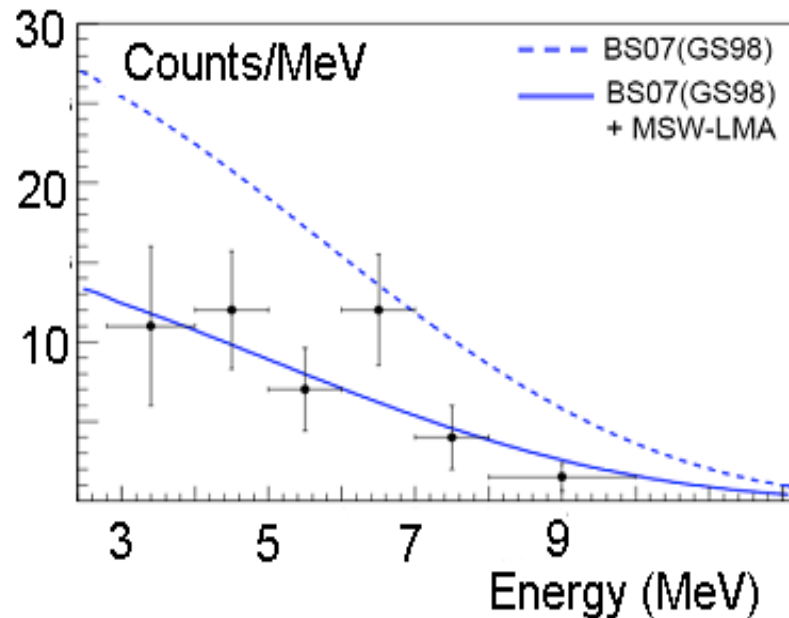
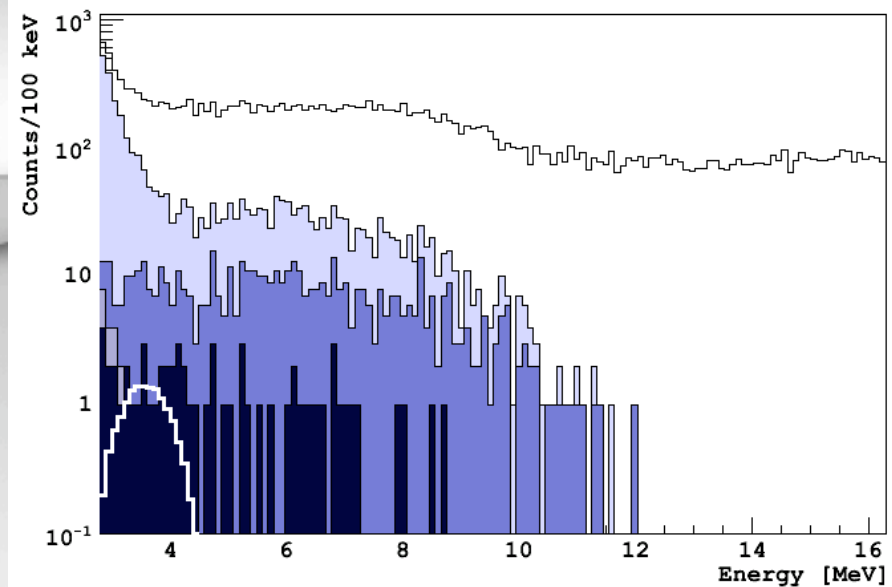
$$ADN^\nu = 0.02 \pm 0.04_{stat}$$

→ As expected by the MSW-LMA oscillation model previsions.

# $^8\text{B}$ - $\nu$ analysis with a lower threshold down to 2.8 MeV

## Major background sources:

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



- $^7\text{Be}$  and  $^8\text{B}$  flux measured with the same detector
- Borexino  $^8\text{B}$  flux above 5 MeV agrees with existing data
- Neutrino oscillation is confirmed for the  $^8\text{B}$  with Borexino at 4.2 sigma

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

	Threshold [MeV]	$\Phi_{8B}^{ES}$ [ $10^6 \text{ cm}^{-2} \text{ s}^{-1}$ ]
SuperKamiokaNDE I [8]	5.0	$2.35 \pm 0.02 \pm 0.08$
SuperKamiokaNDE II [9]	7.0	$2.38 \pm 0.05^{+0.16}_{-0.15}$
SNO D <sub>2</sub> O [7]	5.0	$2.39^{+0.24+0.12}_{-0.23-0.12}$
SNO Salt Phase [6]	5.5	$2.35 \pm 0.22 \pm 0.15$
SNO Prop. Counter [10]	6.0	$1.77^{+0.24+0.09}_{-0.21-0.10}$
Borexino	5.0	$2.75 \pm 0.54 \pm 0.17$
Borexino	2.8	$2.65 \pm 0.44 \pm 0.18$

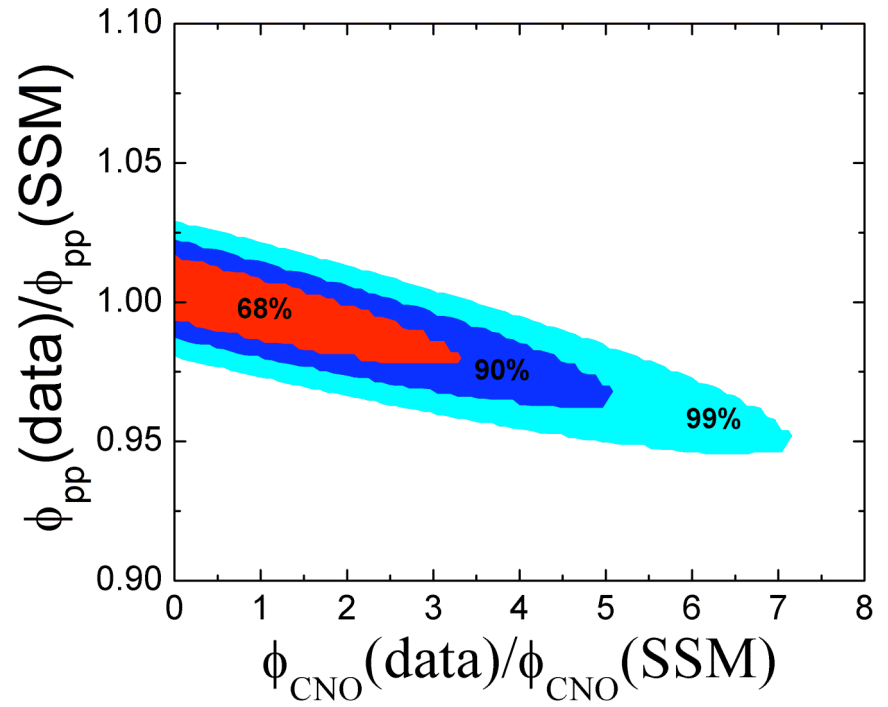
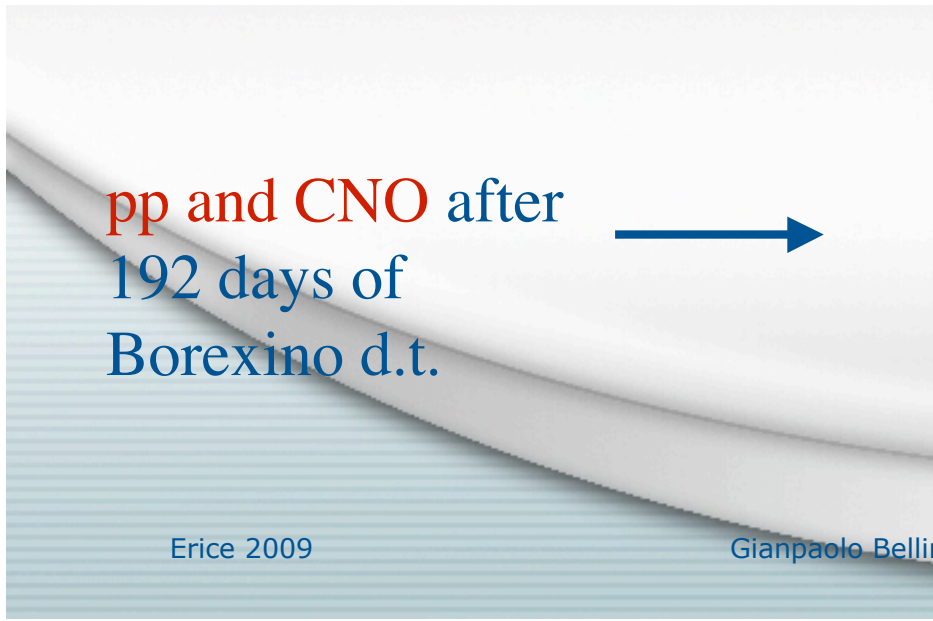
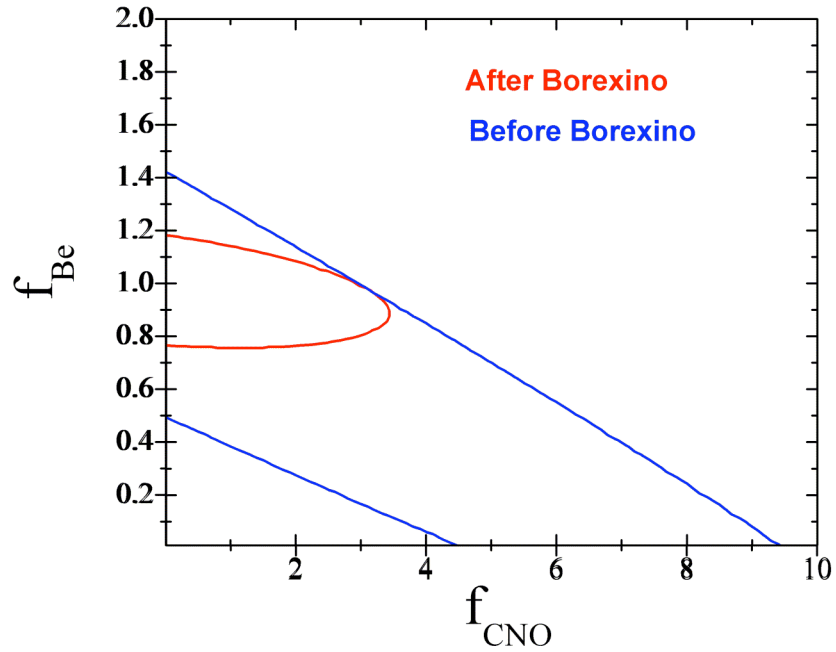
Preliminary measurement  
of the ratio between the  
survival probabilities in  
vacuum and in matter



$$P_{ee}(^7\text{Be})/P_{ee}(^8\text{B}) =$$

$$1.60 \pm 0.33$$







# Neutrino Magnetic Moment

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

EM current affects cross section  $\sigma$   
 Spectral shape sensitive to  $\mu_\nu$   
 Sensitivity enhanced at low energies ( $\sigma \approx 1/T$ )

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

Estimate	Source	$10^{-11} \mu_B$ 90% C.L.
Superk	Solar $\nu$ from $^8\text{B}$	<11
GEMMA	$\bar{\nu}_e$ from reactors	<3.2
Borexino	Solar $\nu$ from $^7\text{Be}$	<5.4

Effective magn.  
moment

We can write:

$$\mu_{\text{eff}}^2 = P_{ee} \cdot \mu_e^2 + (1 - P_{ee})(\cos^2\theta_{23} \cdot \mu_\mu^2 + \sin^2\theta_{23} \cdot \mu_\tau^2)$$

where  $P_{ee} = 0.552 \pm 0.016$  is the survival probability at Earth for  ${}^7\text{Be}$  neutrinos at 0.863 MeV,  $\sin^2\theta_{23} = 0.5^{+0.07}_{-0.06}$  and  $\mu_x$  are the neutrino magnetic moments.

Present limits on the neutrino magnetic moments are:

$\mu_e < 3.2 \times 10^{-11} \mu_B$  by GEMMA (elastic scattering)

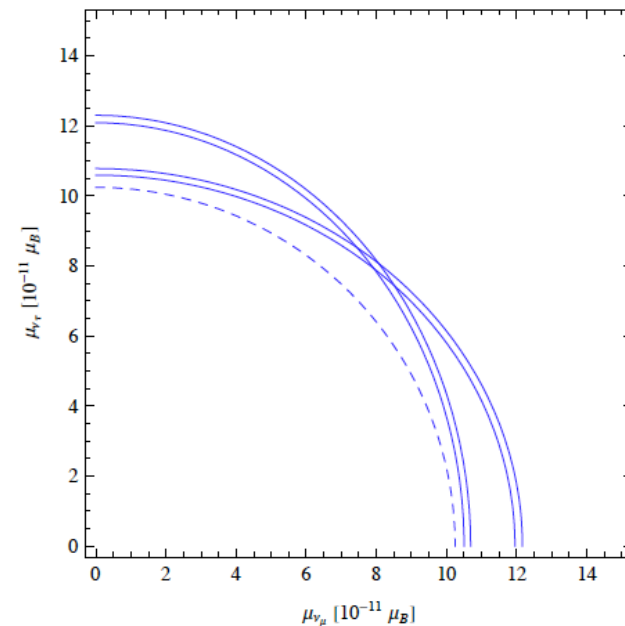
$\mu_\mu < 68 \times 10^{-11} \mu_B$  by LSND (elastic scattering)

$\mu_\tau < 39000 \times 10^{-11} \mu_B$  by DONUT (elastic scattering)

**New Borexino limits:**

$$\mu_\mu < 12 \cdot 10^{-11} \mu_B$$

$$\mu_\tau < 12.5 \cdot 10^{-11} \mu_B$$



Solid lines for  $\mu_e=0$  with uncertainties on  $P_{ee}$  and  $\theta_{23}$ . Dashed line for  $\mu_e=3.2 \times 10^{-11} \mu_B$ .

## Pauli principle violation- 350 days of data taking

Channel	Detectable En. (MeV)	Borexino $\tau_{lim}, \gamma$	Previous limits
$^{12}\text{C} \rightarrow ^{12}\text{C}^{\text{NP}} + \gamma$	16.4-19.	$2.6 \cdot 10^{31}$	$4.2 \cdot 10^{24}$ NEMO-II
$^{12}\text{C} \rightarrow ^{11}\text{B}^{\text{NP}} + p$	4.6-8.3	$7.1 \cdot 10^{29}$	$1.7 \cdot 10^{25}$ NaI Elegant $1.9 \cdot 10^{25}$ NaI DAMA
$^{12}\text{C} \rightarrow ^{11}\text{C}^{\text{NP}} + n$ (n capture with 2.2 MeV $\gamma$ emission)	recoil proton + 2.2	$3.4 \cdot 10^{30}$	$1.0 \cdot 10^{20}$ Kishimoto et al
$^{12}\text{C} \rightarrow ^{12}\text{N}^{\text{NP}} + e^- + \bar{\nu}_e$	18.9 lower end point	$3.1 \cdot 10^{30}$	$3.1 \cdot 10^{24}$ NEMO II $9.5 \cdot 10^{27}$ LSD
$^{12}\text{C} \rightarrow ^{12}\text{B}^{\text{NP}} + e^+ + \nu_e$	16.8 lower end point	$2.1 \cdot 10^{30}$	$2.6 \cdot 10^{24}$ NEMO-II

To compare the results for different nuclei and different energy threshold one have to estimate the rate of normal transitions.



We can calculate the limits  $\delta^2$  of relative strenght of non Paulian transitions to the normal one. In this way we can compare the experimental limits on lifetime obtained for different nuclei and atoms.

In the case of the non Paulian transitions in  $^{12}\text{C}$  nuclei we obtain:

decay	$\delta^2$	Previous limit	
$\gamma$	$2.2 \cdot 10^{-57}$	$2.3 \cdot 10^{-57}$	Kamiokan de ( $^{16}\text{O}$ )
N(n,p)	$9.6 \cdot 10^{-60}$	$3.5 \cdot 10^{-55}$	DAMA (NaI)
(e, $\nu$ )	$2.1 \cdot 10^{-35}$	$6.5 \cdot 10^{-34}$	Kekez-1990 Aglietta- 1986



## Conclusion after 192 days

1. First direct experimental evidence of the vacuum regime in the neutrino oscillation at very low energy: measurement of the  ${}^7\text{Be}$  flux ( 0.862 MeV) and good limit on the pp  $\nu$  flux. In this way a first validation of the MSW-LMA model in the vacuum regime has been obtained within a total error in the range of 10%.
2. First preliminary determination of the ratio between the  $\nu_e$  survival probabilities in vacuum and in matter:  $1.6 \pm 0.33$  (from the  ${}^7\text{Be}$  flux and the  ${}^8\text{B}$  flux, this last measured with a threshold down to 2.8 MeV).
3. Measurement of the day/night effect for  $\nu$  at very low energy:

$$ADN = \frac{N - D}{N + D} = 0.02 \pm 0.04 \quad \text{as predicted by the MSW-LMA model.}$$

4. Good limits for CNO flux, Pauli principle violation, neutrino magnetic moment

## What Next

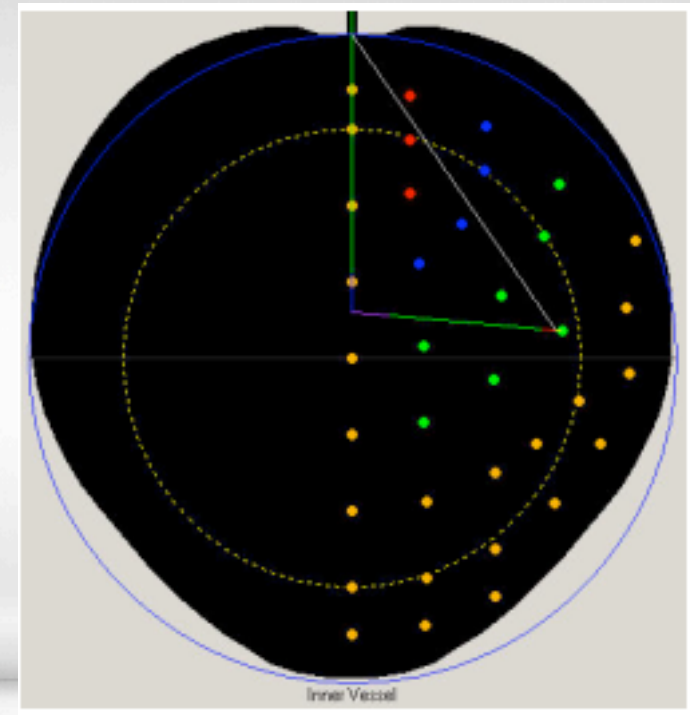
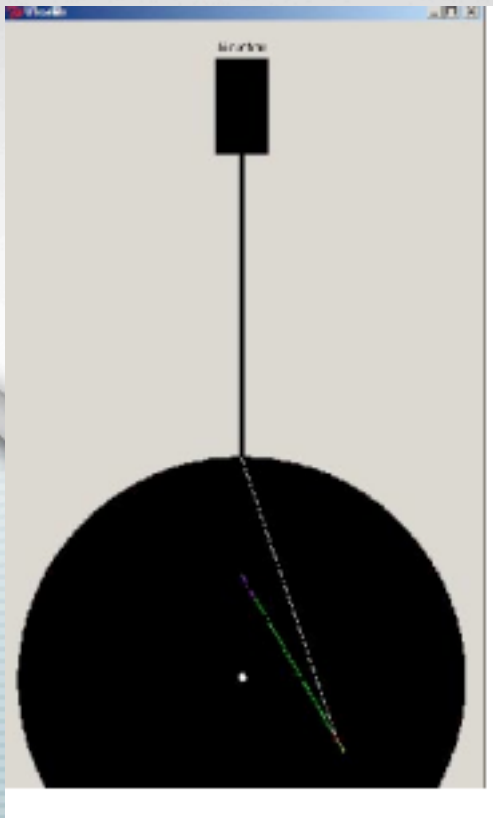
- A. Measurement of the  ${}^7\text{Be}$  flux with a total error  $\leq 5\%$  (hopefully  $3\%$ ): final validation of the MSW-LMA model; important insight for the Standard Solar Model metallicity puzzle and stronger limits on the pp flux and CNO.
- B. Possible direct measurement of the pp flux in the window: 190-230 keV
- C. Study of the pep region (energy spectrum in the range 0.9-1.5 MeV) with the suppression of the  ${}^{11}\text{C}$  muon produced.
- D. Determination of the survival probability ratio, day/night effect, etc. with strongly reduced errors.
- E. Measurements of the geo-neutrinos (the Gran Sasso region is especially favored due to the low background of reactor  $\bar{\nu}_e$  )
- F. Better limits for rare phenomena:  $\nu$  magnetic moment, Pauli Principle violation, electron decay ( $e \rightarrow n + g$ )..



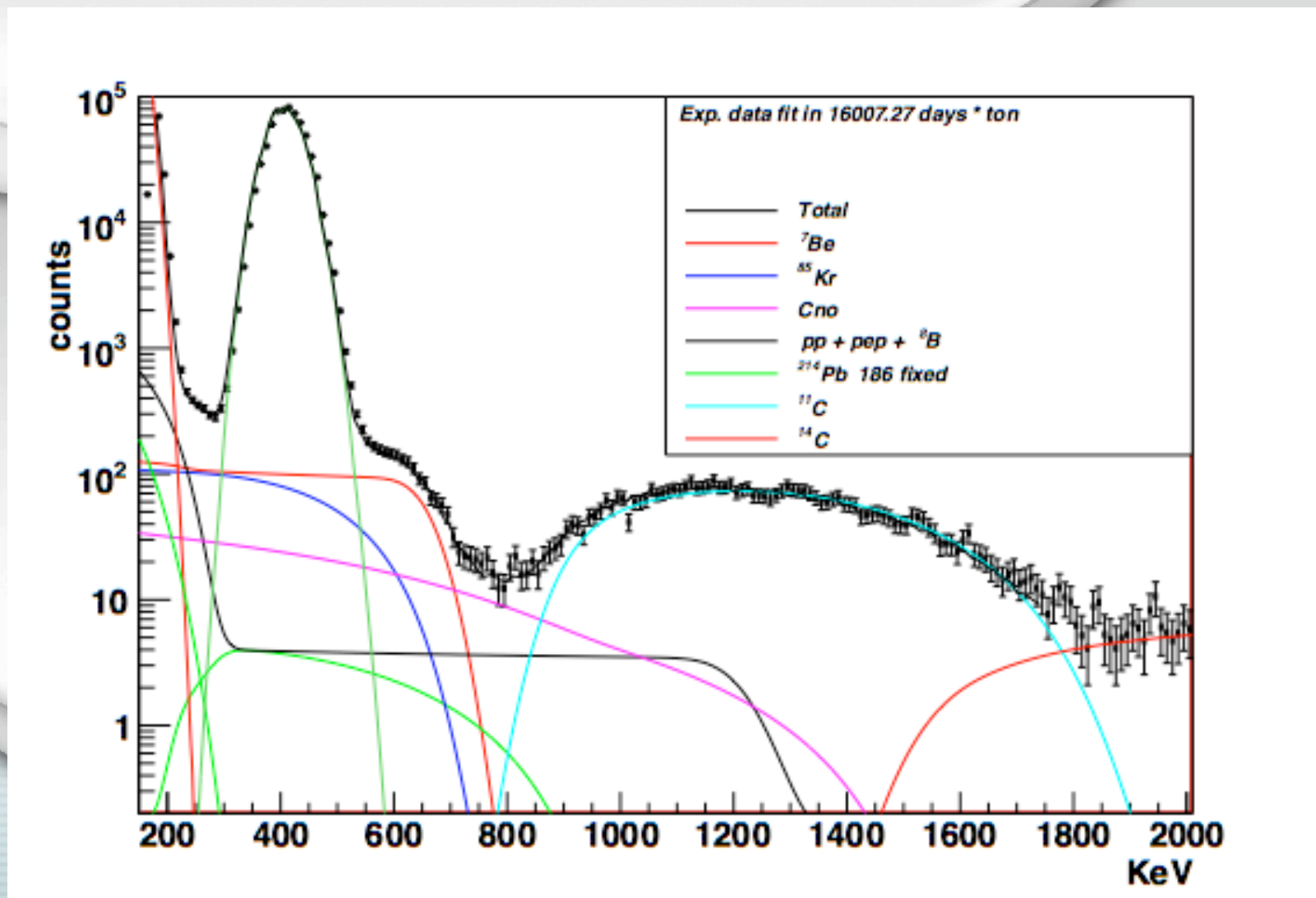
# Calibration campaigns 2008-2009

## On-axis and off-axis

- Rn source: position reconstruction (FV definition), detector response as function of the position
- Gamma source (8 sources from 122 keV to 1.4 MeV): energy scale
- AmBe source: FV at high energies , proton recoil calibrations (for antineutrino )
- Laser diffuser: check PMT alignment



## Study of pep and CNO fluxes



Best estimate for cosmogenic  $^{11}\text{C}$  is 25 cpd/100 tons ( $1.1 \mu \text{ m}^{-2}\text{h}^{-1}$ ,  $\langle E_{\mu} \rangle 325 \text{ GeV}$ )

→ CNO:  $\approx 5 \text{ cpd}/100 \text{ tons}$

→ pep:  $\approx 2 \text{ cpd}/100 \text{ tons}$

Expected from SSM with oscill.



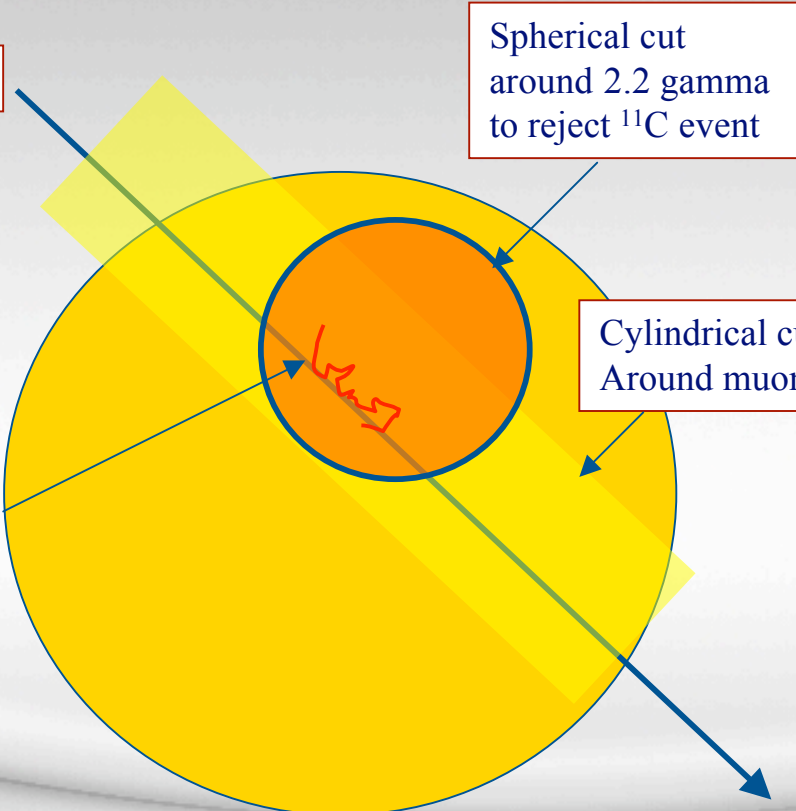
n capture  
 $\gamma$  (2.2 MeV)

Muon track

Neutron production

Spherical cut  
around 2.2 gamma  
to reject  $^{11}\text{C}$  event

Cylindrical cut  
Around muon-track

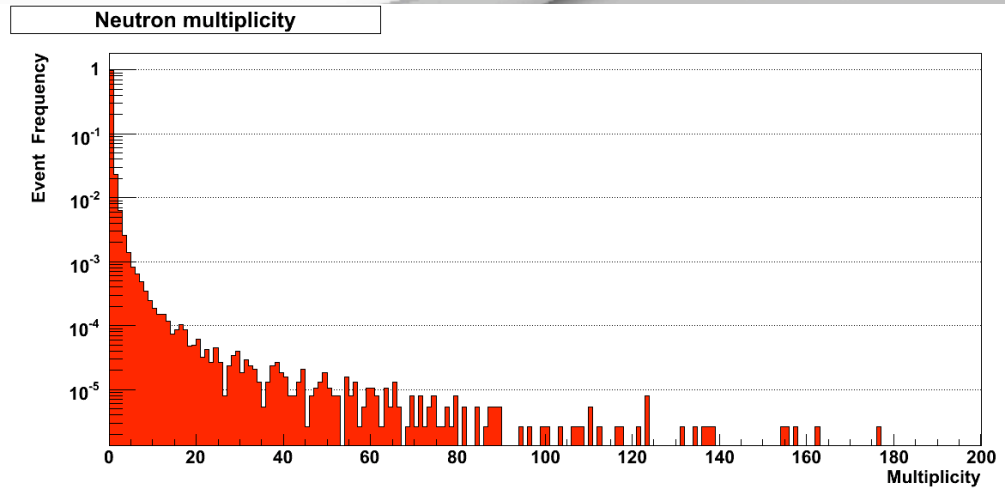


#Borex. Coll.Phys.Rev.C74,2006

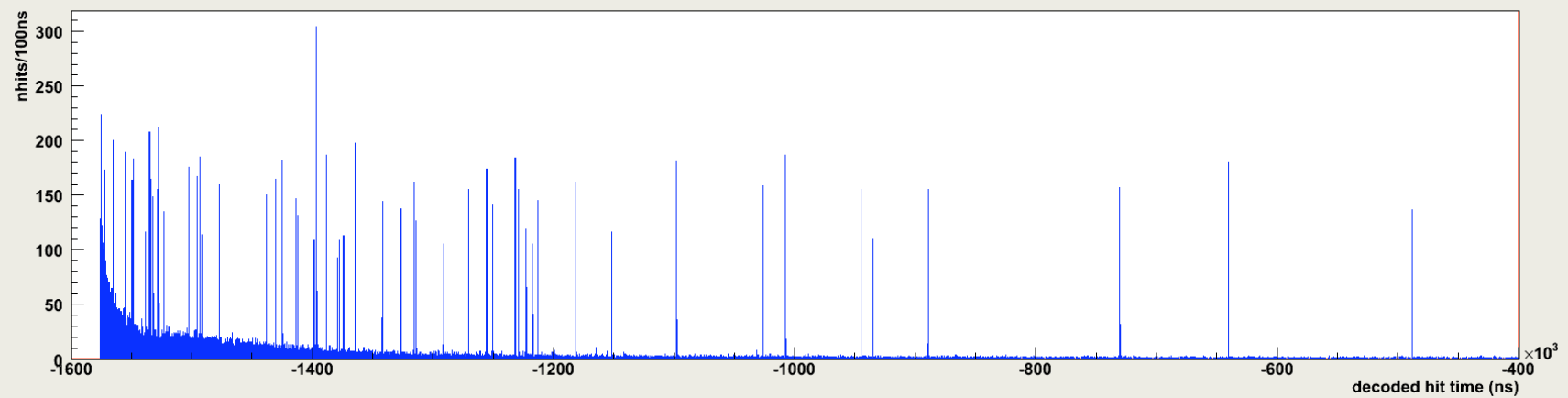
# $^{11}\text{C}$ and neutrons after muons

Now: 87% rejection

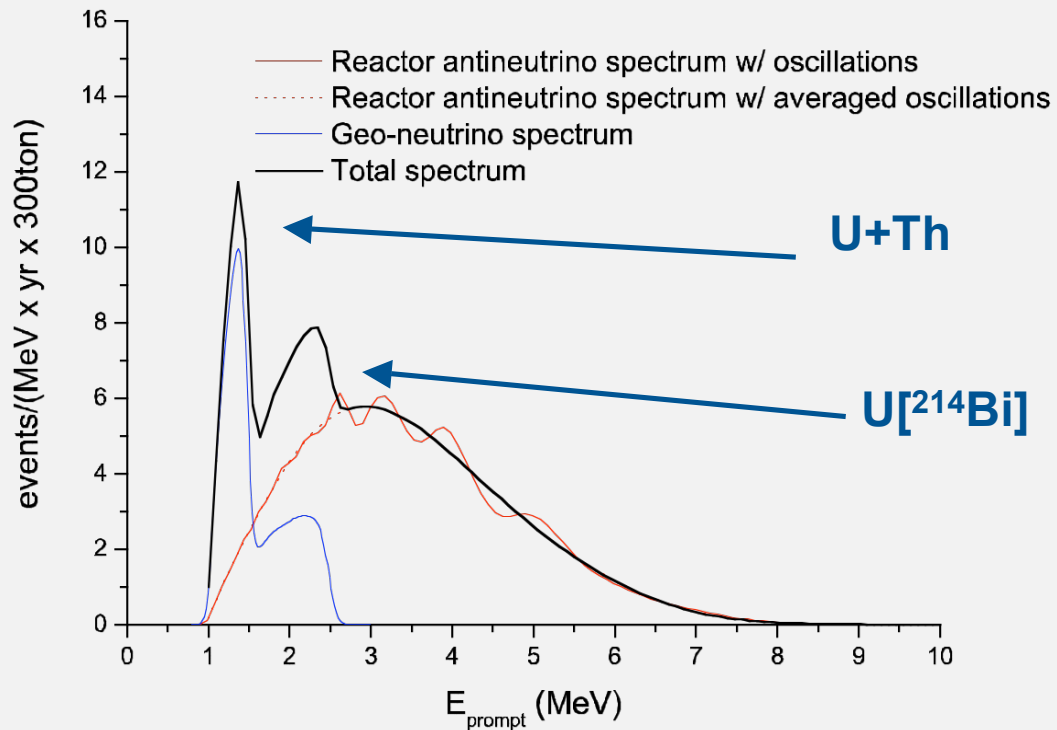
Still in progress



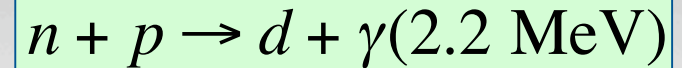
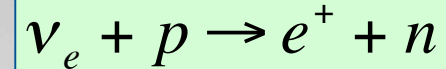
sample event with many neutron (trigger type == 128)



# Geoneutrinos in Borexino



- good tagging: inverse beta decay

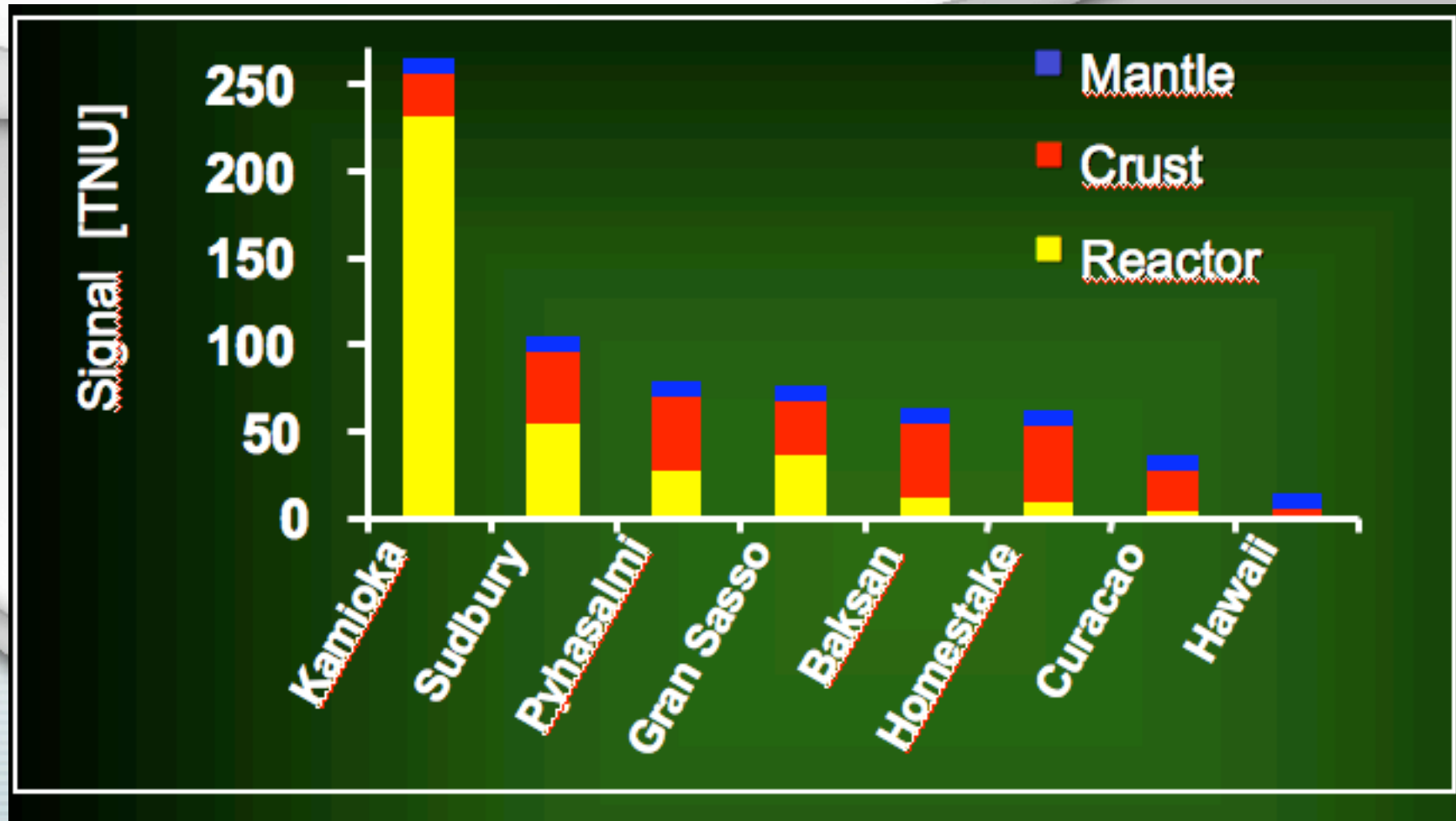


- 280 tons target mass

- main background: - reactors  $\bar{\nu}_e$  ;  
-  $(\alpha, n)$ ,  $(\gamma, n)$ , fast neutrons ( $\gamma$  and  $n$  from ext.backg); negligible due the following tools: p/ $\beta$  discrimination; p recoil energy (AmBe source calib.)



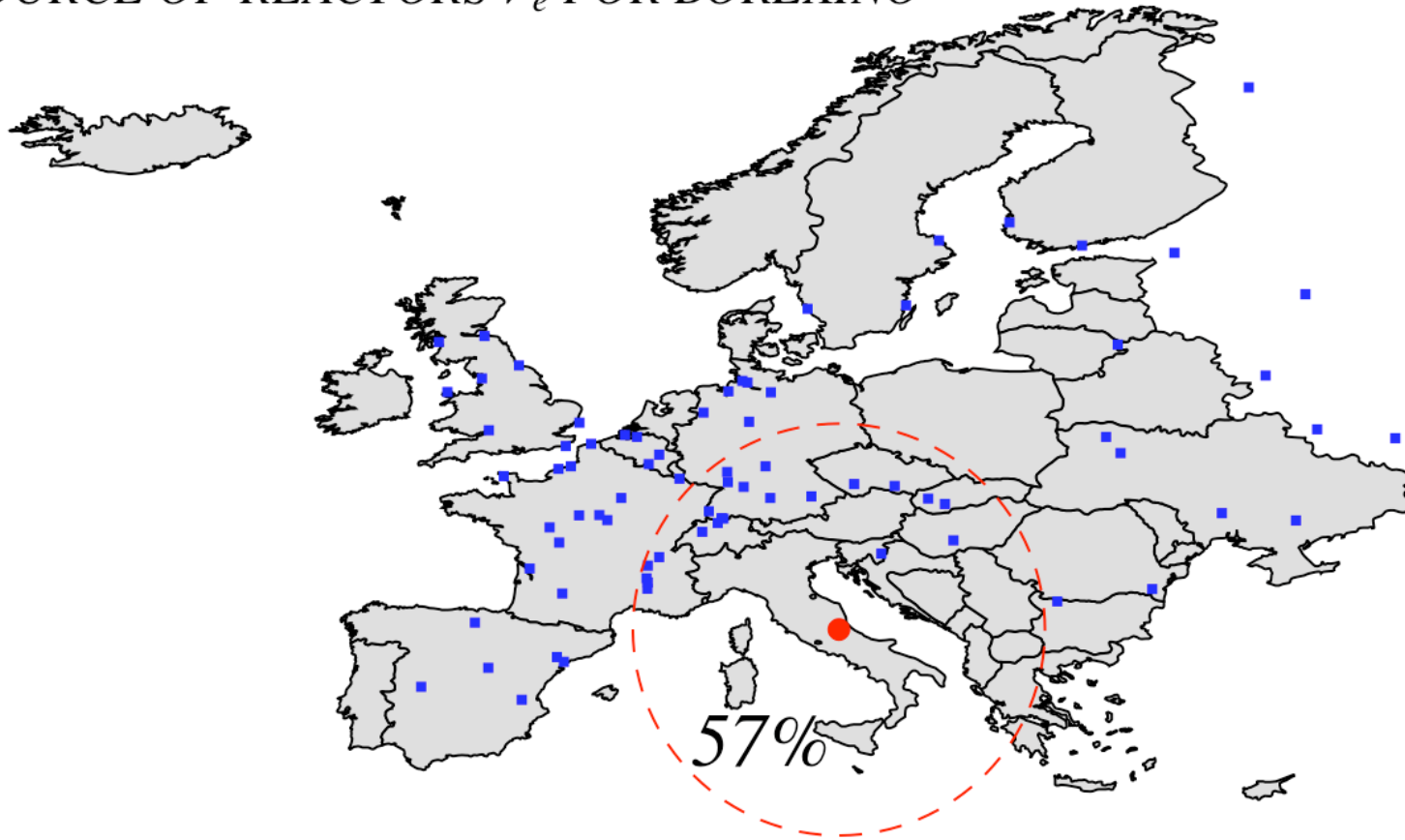
## Antineutrino fluxes in the various sites





# European Reactors (using IAEA database)

*SOURCE OF REACTORS  $\bar{\nu}_e$  FOR BOREXINO*



## Expected signal $\bar{\nu}_e$ in Borexino (1 year of data taking)

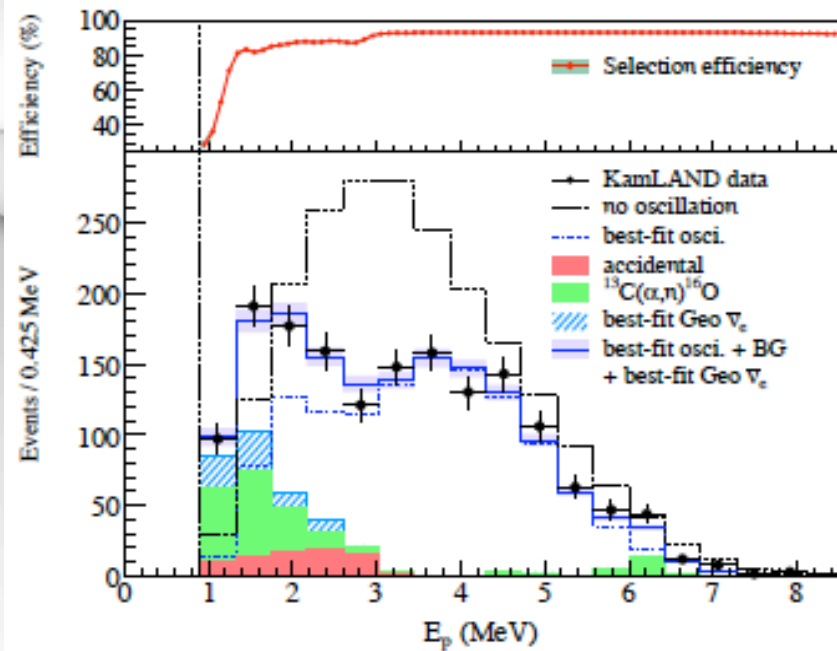
MeV	1.-1.5	1.5-2.6	>2.6
Reactors	0.5	4	10
Geo (BSE)	4	3	0

S/N~1.5

Measurement of the sediment radioactivity in the Gran Sasso region.  
The contribution is very small.

Borexino planes a first release of the data by the early summer 2010.

# Kamland



Signal =  $73 \pm 27$  ev.

TABLE II: Estimated backgrounds after selection efficiencies.

Background	Contribution
Accidentals	$80.5 \pm 0.1$
${}^9\text{Li}/{}^8\text{He}$	$13.6 \pm 1.0$
Fast neutron & Atmospheric $\nu$	$< 9.0$
${}^{13}\text{C}(\alpha, n){}^{16}\text{O}$ G.S.	$157.2 \pm 17.3$
${}^{13}\text{C}(\alpha, n){}^{16}\text{O}$ ${}^{12}\text{C}(n, n\gamma){}^{12}\text{C}$ (4.4 MeV $\gamma$ )	$6.1 \pm 0.7$
${}^{13}\text{C}(\alpha, n){}^{16}\text{O}$ 1 <sup>st</sup> exc. state (6.05 MeV $e^+e^-$ )	$15.2 \pm 3.5$
${}^{13}\text{C}(\alpha, n){}^{16}\text{O}$ 2 <sup>nd</sup> exc. state (6.13 MeV $\gamma$ )	$3.5 \pm 0.2$
<b>Total</b>	<b><math>276.1 \pm 23.5</math></b>

In the geo neutrino energy region; S/N ~ 0.4

# Conclusions

- Borexino is validating (or disproving ) the current MSW-LMA oscillation model in the vacuum regime
- It is also trying to measure directly the pp and the pep fluxes (producing an experimental point in the transition region)
- For CNO Borexino would establish good upper limits
- A measurement of the  ${}^7\text{Be}$  flux with a 3% of total error will give an important contribution to the solution of the SSM metallicity puzzle
- Borexino is close to release experimental data on the geo-neutrinos with a very small background