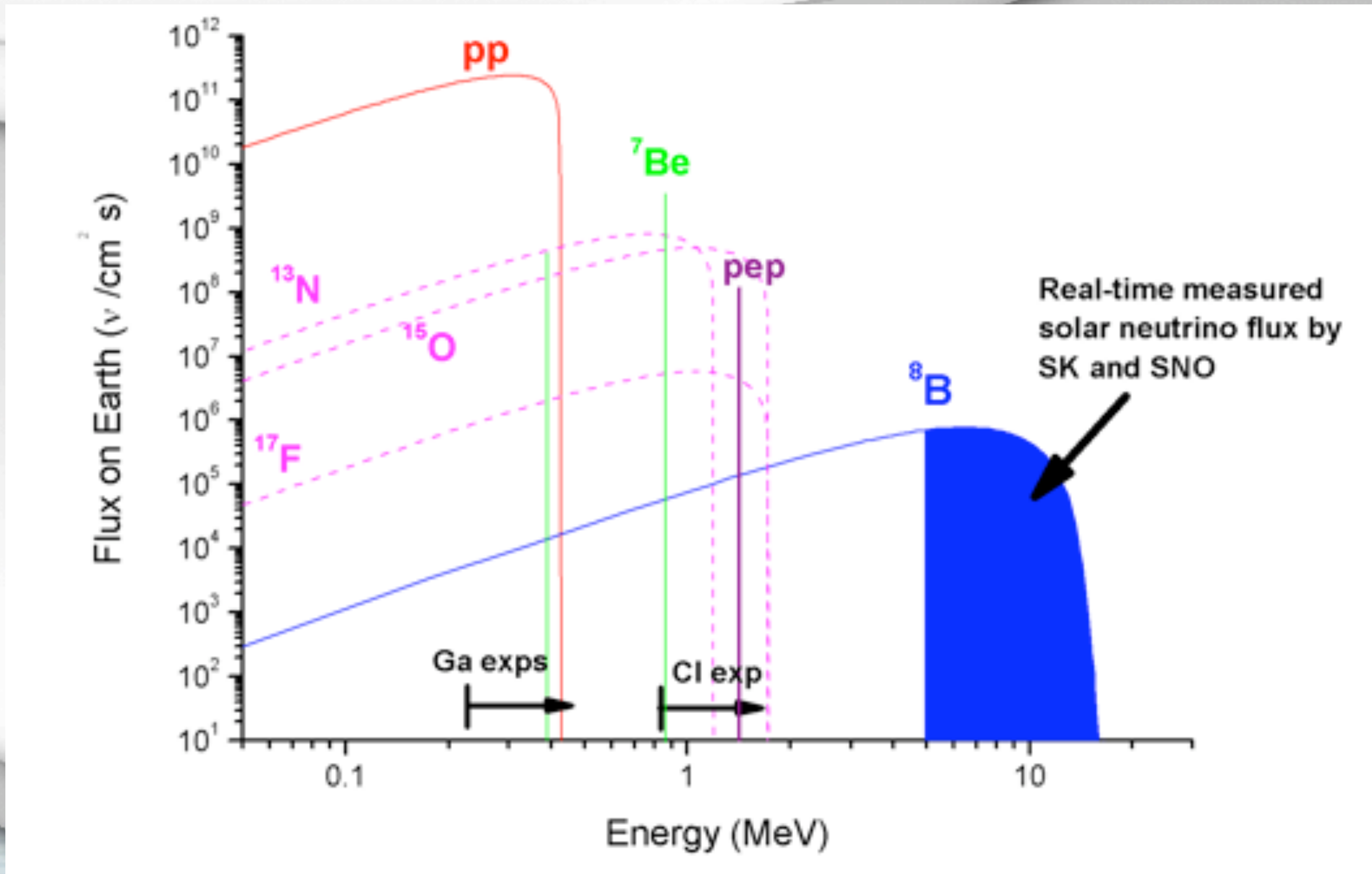
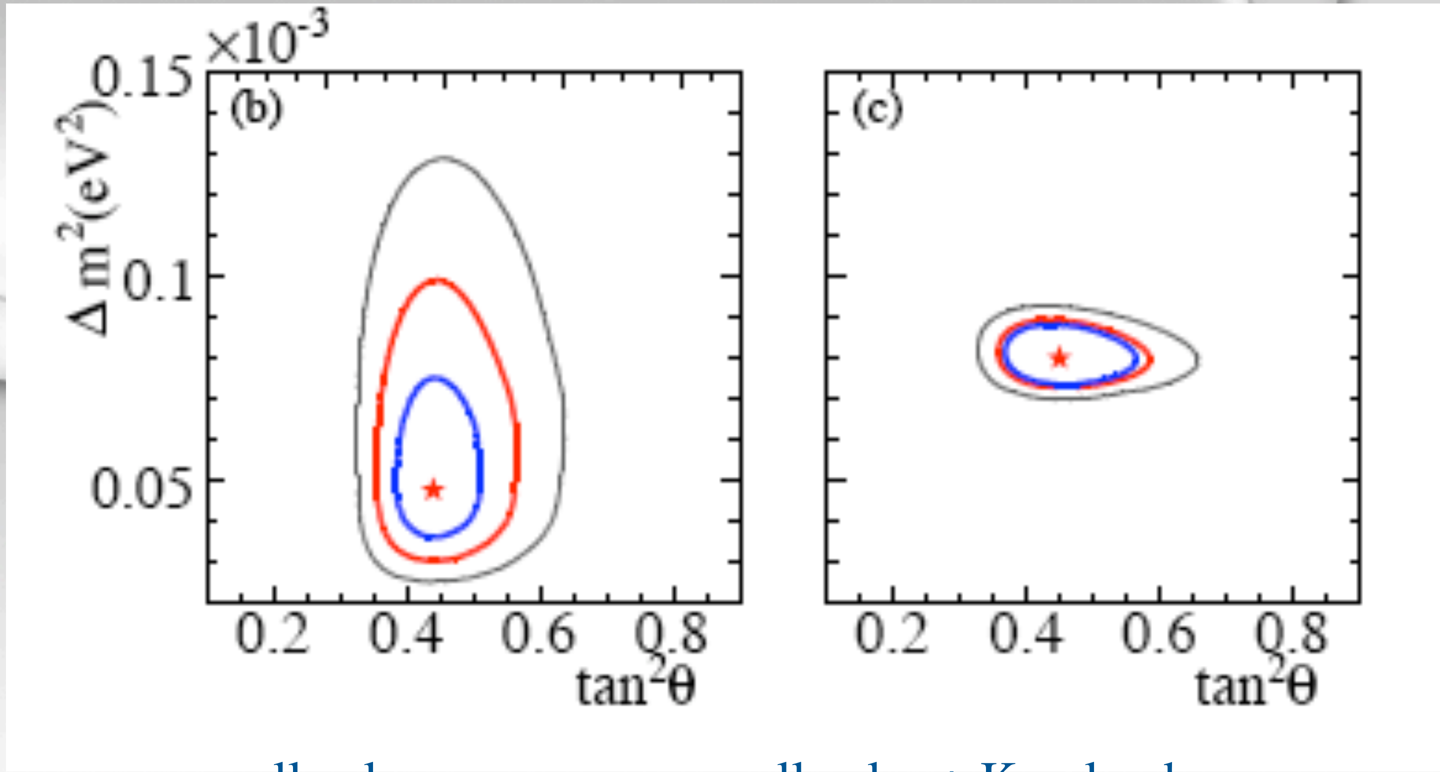
Study of neutrino interactions over 200 keV lower threshold

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

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



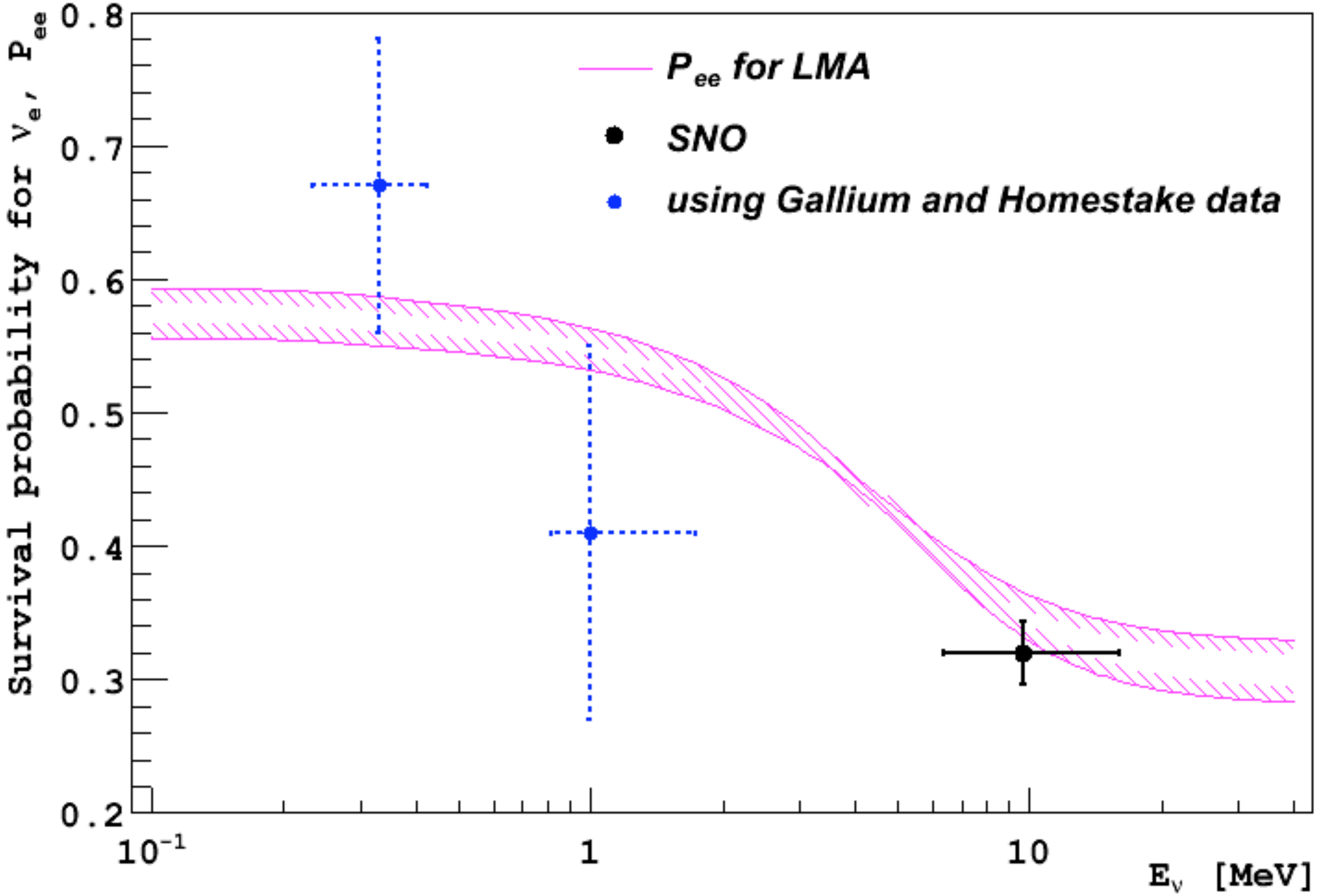


all solar

all solar + Kamland

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

Current MSW-LMA model-



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.

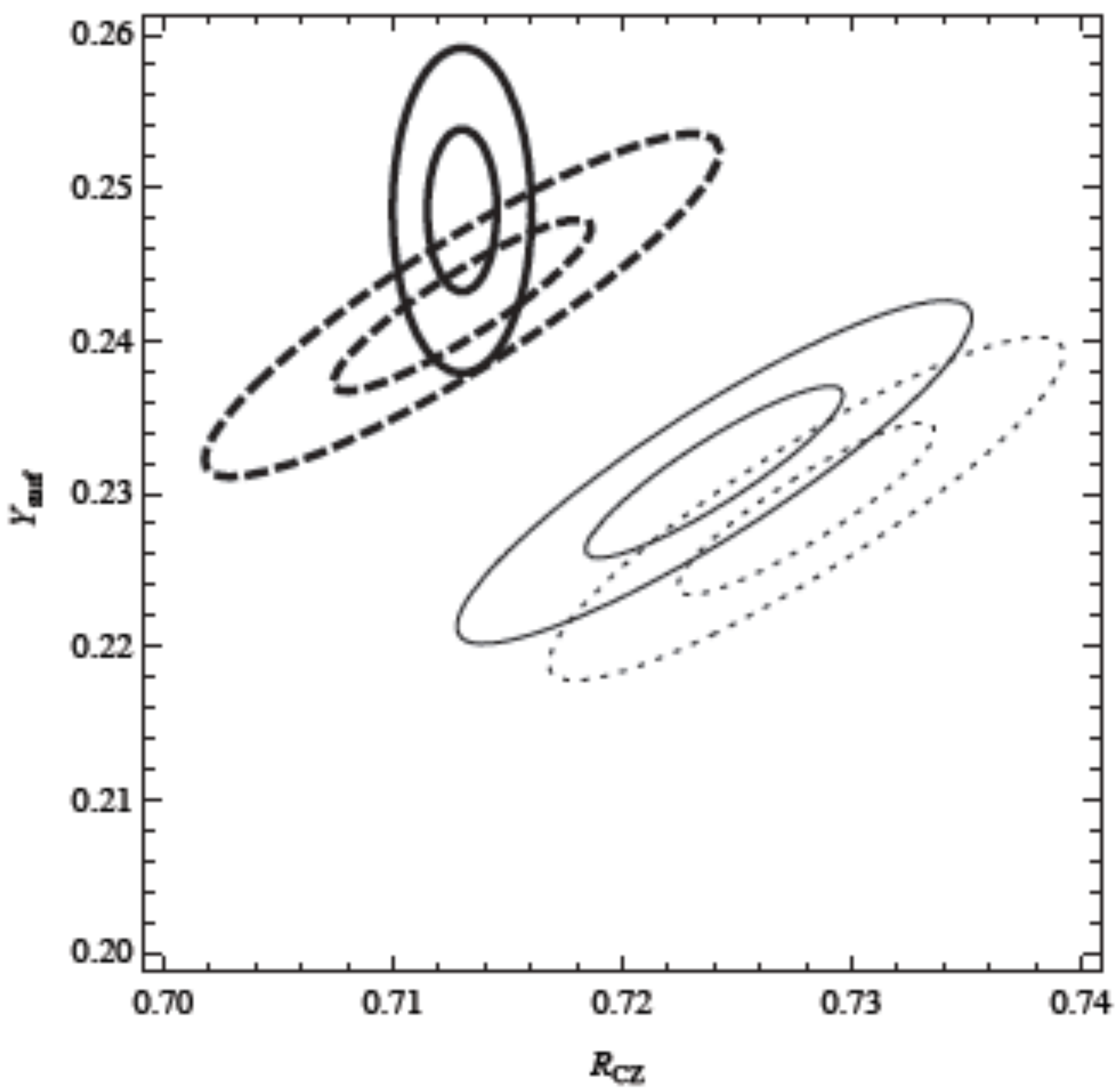
A much improved 3D model of the solar atmosphere has been developed, which better reproduces line profiles and brings the Solar abundances into better agreement with other stars in the neighborhood (AGS05)-bad agreement with helioseismology

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

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

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



Δ(rate) for ^{7}Be reduced to 8.7%

M. Asplund, N Grevesse, J. Sauval and P. Scott http://arjournals.annualreviews.org/toc/astro/47/1

Borexino: low energy real time detection

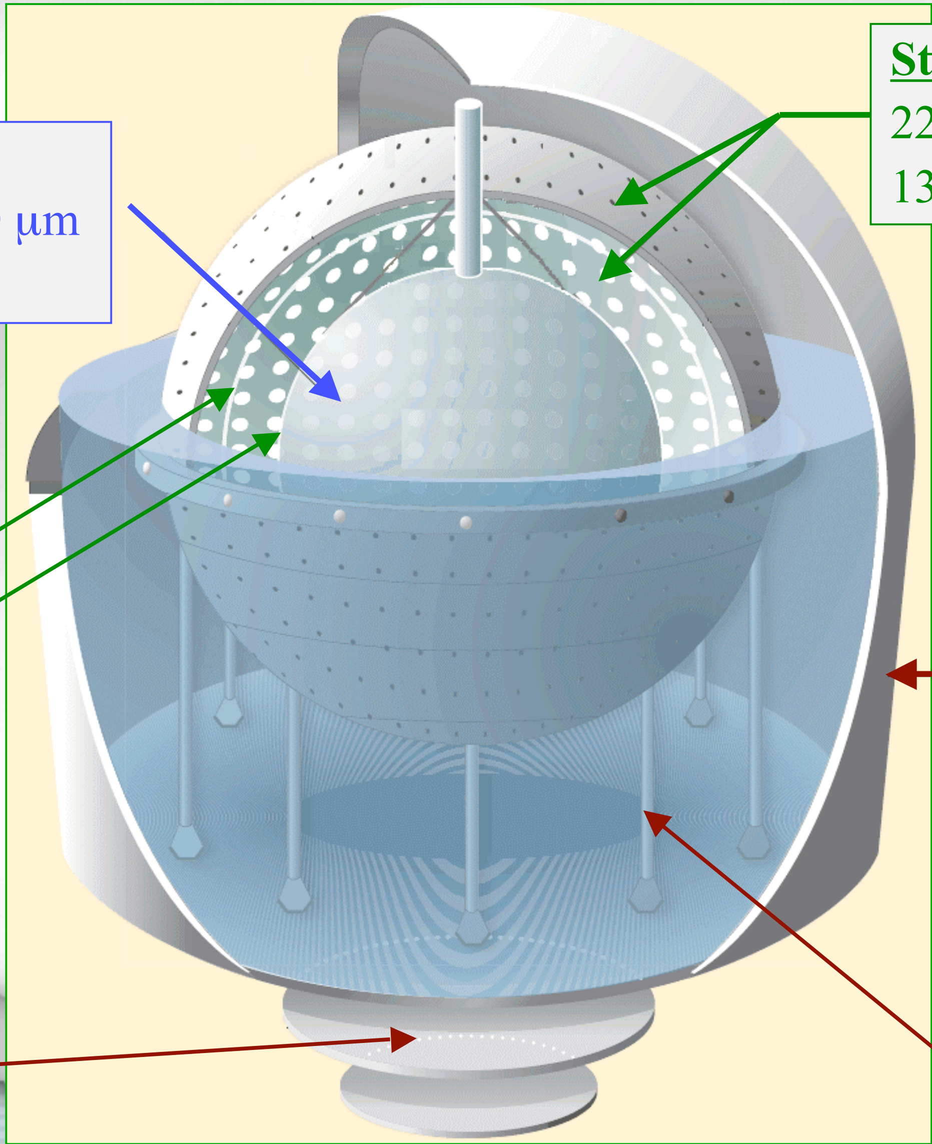
Scintillator:
270 t PC+PPO in a 150 μm thick nylon vessel

Nylon vessels:
Inner: 4.25 m
Outer: 5.50 m

Neutrino electron scattering

ν e –> ν e

Carbon steel plates



Stainless Steel Sphere:
2212 photomultipliers
1350 m^3

Design based on the principle of graded shielding

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

20 legs

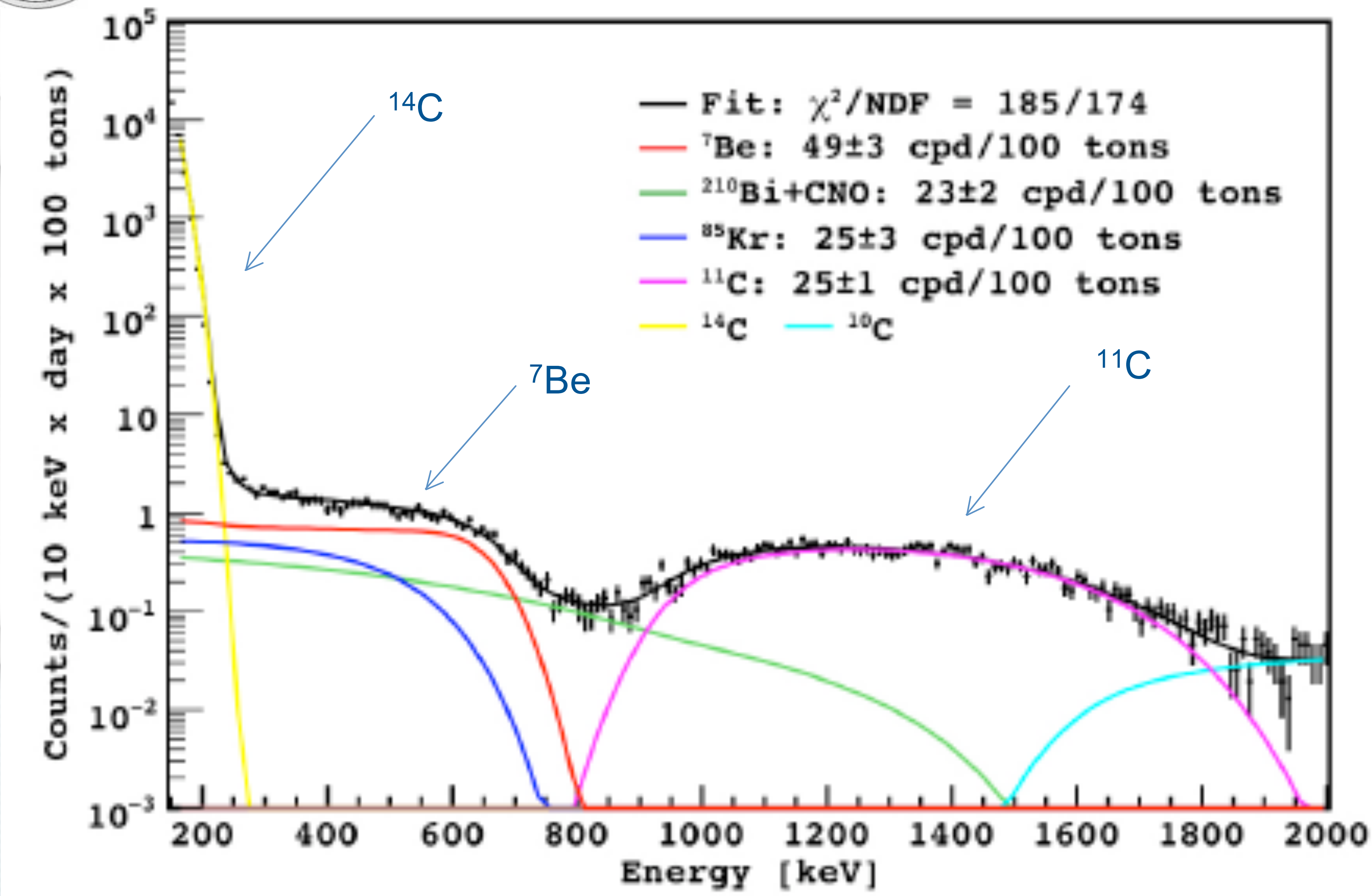
Filled detector

Records in the radiopurity achieved by Borexino

	Material	Typical conc. of the unpurified materials	Radiopurity levels in the Bx scintillator
^{14}C	scintillator	$^{14}C/^{12}C<10^{-12}$	$^{14}C/^{12}C \cong 2 \cdot 10^{-18}$
^{238}U, ^{232}Th equiv.	- Hall C dust - stainless. steel - nylon	~1 ppm ~1ppb ~1ppt	$10^{-17} - 10^{-18} g/g$
K_{nat}	Hall C dust	~1 ppm	$< 10^{-14} g/g$
^{222}Rn	- external air. - air underground	~20 Bq/m^3 ~40-100 Bq/m^3	$< 1\ \mu Bq/m^3$
^{85}Kr ^{39}Ar	in N_2 for stripping	~1.1 Bq/m^3 ~13 mBq/m^3	$\sim 0.16\ mBq/m^3$ $\sim 0.5\ mBq/m^3$
- ^{222}Rn - ^{238}U, ^{232}Th equiv.	LNGS - Hall C water	~50 Bq/m^3 ~10^{-10} g/g	Water $\sim 30\ \mu Bq/m^3$ $\sim 10^{-14}\ g/g$

BOREXINO: 192 days-free parameters:^{7}Be,^{14}C, CNO+^{210}Bi,^{11}C,^{85}Kr;

-fixed at the SSM values:pp, pep

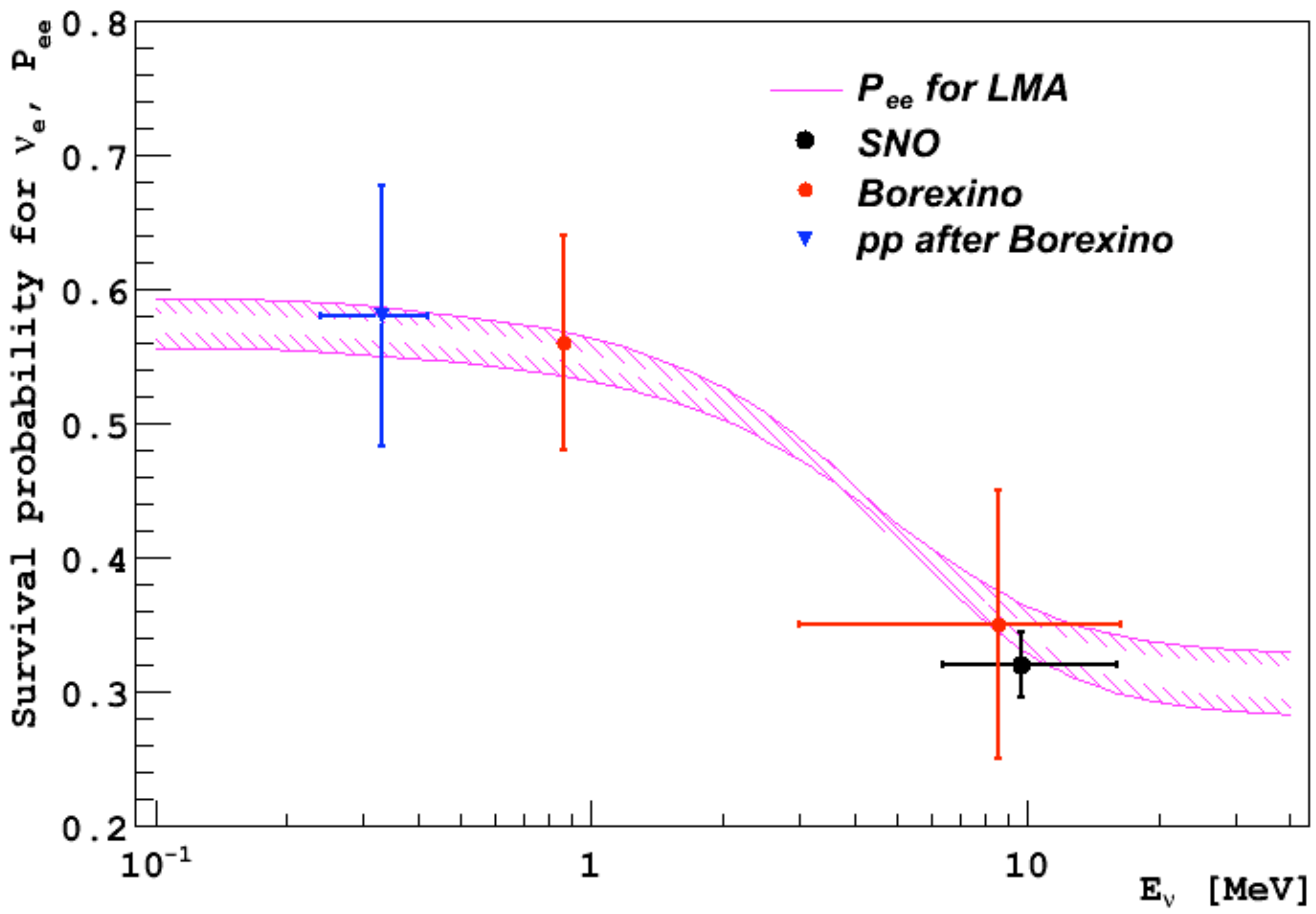


$49 \pm 3_{stat} \pm 4_{syst}$ cpd / 100tons for 862 keV ^{7}Be solar ν

$\Phi(^7Be)=(5.12 \pm 0.51)\times 10^9 cm^{-2}s^{-1}$ SSM; H.M.$(5.08\pm0.56)\times 10^9 cm^{-2}s^{-1}$

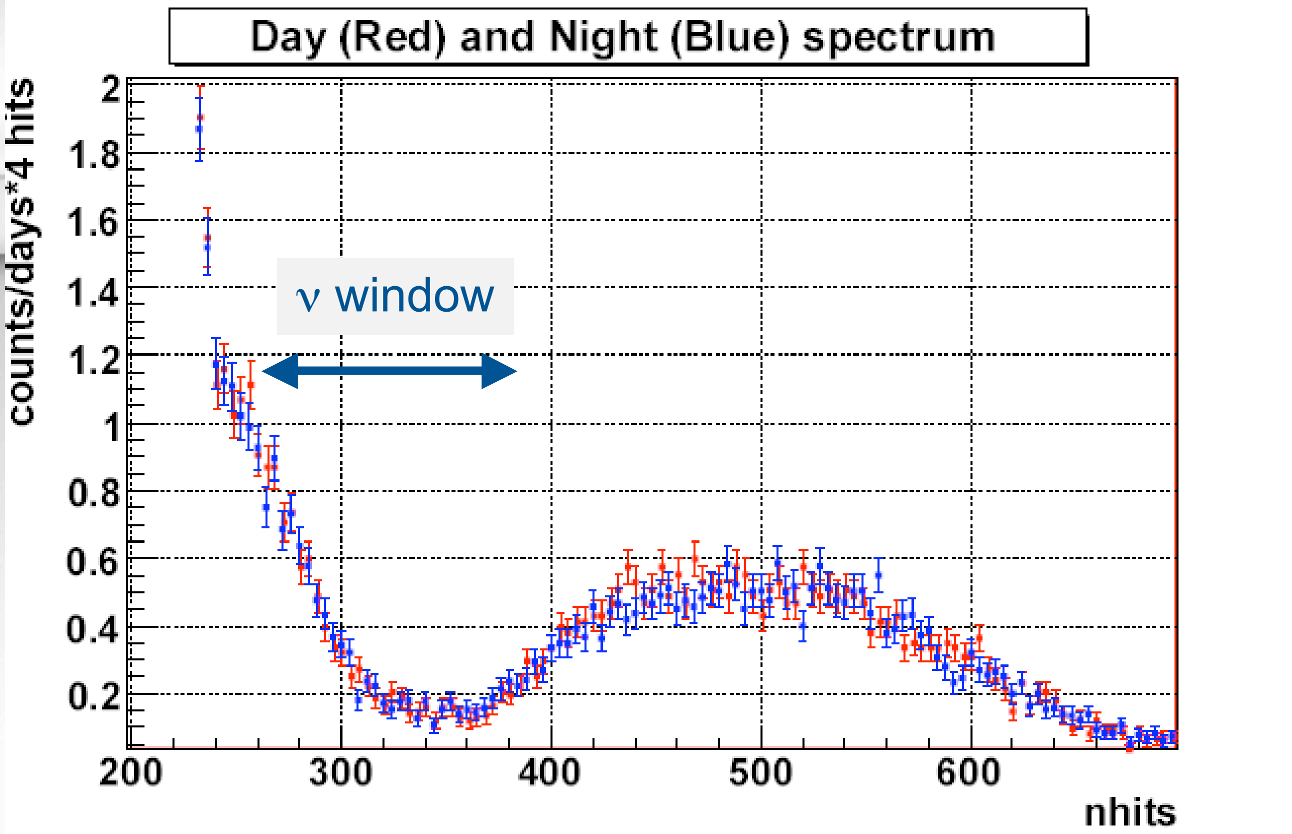
L.M.$(4.55 \pm 0.5)\times 10^9 cm^{-2}s^{-1}$

First experimental evidence of the vacuum regime



Day night asymmetry for ^{7}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)

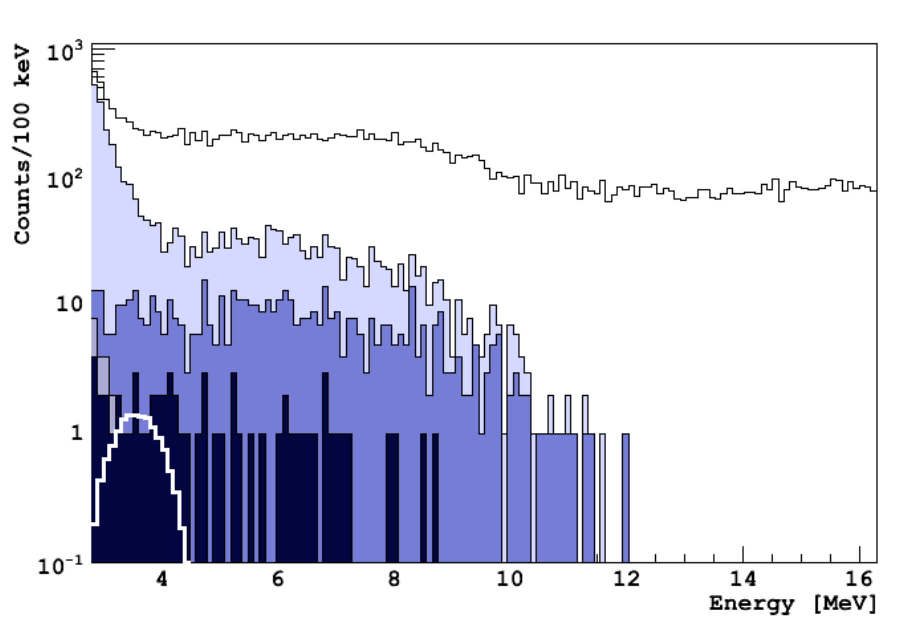


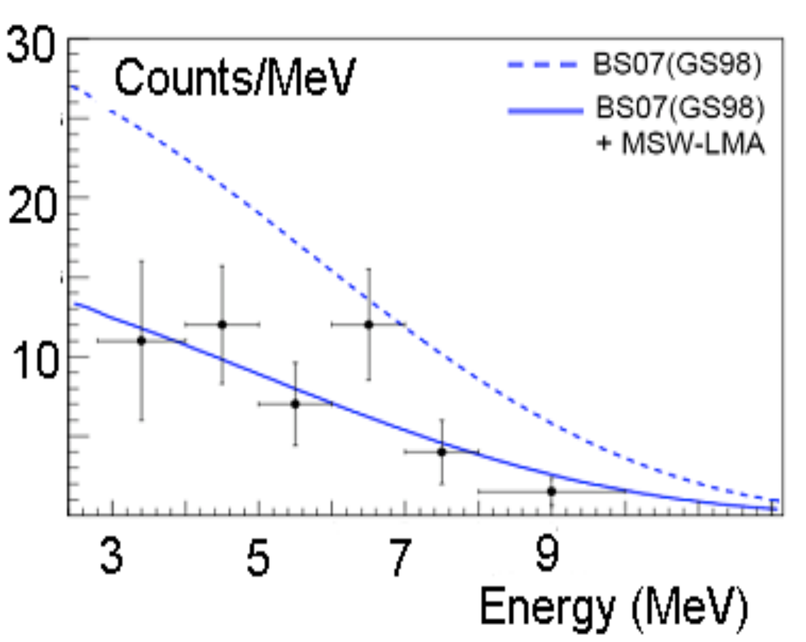
$$ADN^{\upsilon} = 0.02 \pm 0.04_{stat}$$

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

^{8}B-ν 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}C);
6) Bulk ^{232}Th contamination (^{208}Tl);





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

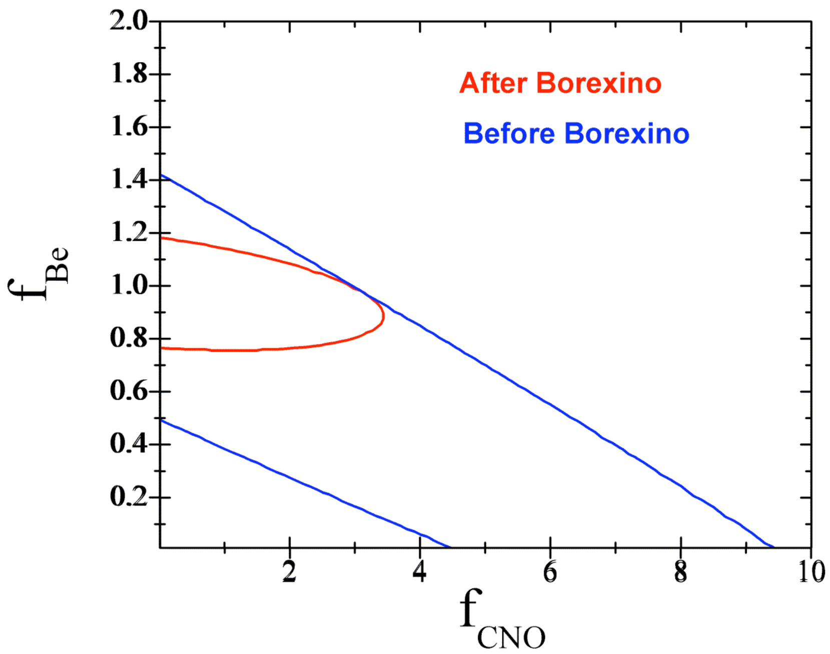
$$Rate_{>2.8MeV} = (0.26 \pm 0.04_{stat} \pm 0.02_{sys})\ \text{counts/day/100 tons}$$

	Threshold [MeV]	Φ^{ES}_{8B} [10^6 cm^{-2} 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_2O [7]	5.0	$2.39^{+0.24}_{-0.23}{}^{+0.12}_{-0.12}$
SNO Salt Phase [6]	5.5	$2.35 \pm 0.22 \pm 0.15$
SNO Prop. Counter [10]	6.0	$1.77^{+0.24}_{-0.21}{}^{+0.09}_{-0.10}$
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 →

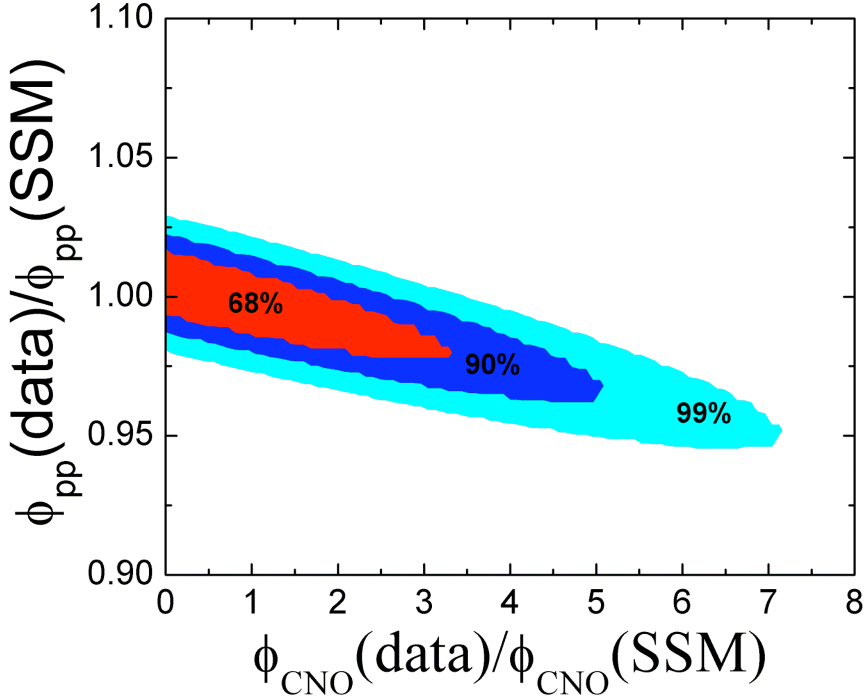
$$P_{ee}(^7Be)/P_{ee}(^8B) = 1.60 \pm 0.33$$

Signal/SSM



7Be vs CNO before Borexino

pp and CNO after 192 days of Borexino d.t.



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 σ

Spectral shape sensitive to μ_ν

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 ν from ^8B	<11
GEMMA	$\bar{\nu}_e$ from reactors	<3.2
Borexino	Solar ν from ^7Be	<5.4

Effective magn. moment → Borexino

We can write:

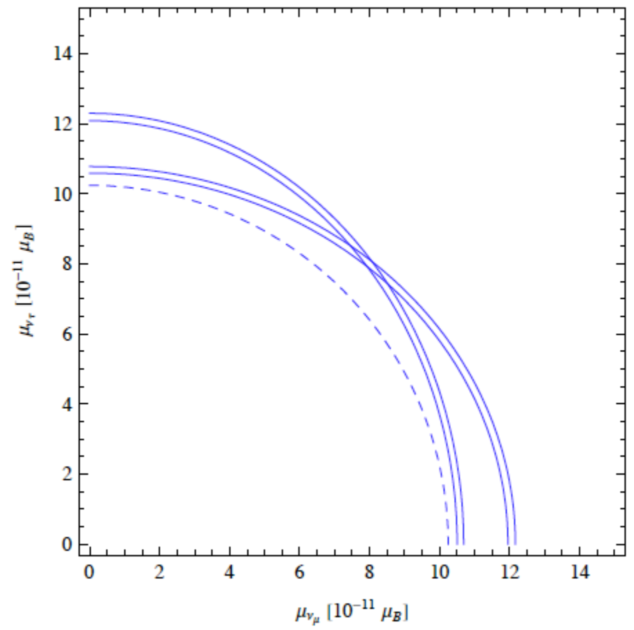
$$\mu_{eff}^2 = P_{ee} \cdot \mu_e^2 + (1 - P_{ee})(\cos^2\theta_{23} \cdot \mu_\mu^2 + \sin^2\theta_{23} \cdot \mu_\tau^2)$$

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

Present limits on the neutrino magnetic moments are:
μ_e < 3.2×10-11 μB by GEMMA (elastic scattering)
μ_μ < 68×10-11 μB by LSND (elastic scattering)
μ_τ < 39000×10-11 μB 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 μ_e=0 with uncertainties on P_{ee} and θ_{23}. Dashed line for $\mu_e = 3.2\times10^{-11}\ \mu_B$.

Pauli principle violation- 350 days of data taking

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

decay	δ^2	Previous limit	
γ	$2.2\ 10^{-57}$	$2.3\ 10^{-57}$	Kamiokande (^{16}O)
N(n,p)	$9.6\ 10^{-60}$	$3.5\ 10^{-55}$	DAMA (NaI)
(e,ν)	$2.1\ 10^{-35}$	$6.5\ 10^{-34}$	LSD (^{12}C)

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}Be flux (0.862 MeV) and good limit on the pp ν 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 ν_e survival probabilities in vacuum and in matter: 1.6 ± 0.33 (from the ^{7}Be flux and the ^{8}B flux, this last measured with a threshold down to 2.8 MeV).

3. Measurement of the day/night effect for ν at very low energy:

$$ADN = \frac{N - D}{N + D} = 0.02 \pm 0.04$$ 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}Be flux with a total error ≤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}C muon produced.

D. Determination of the survival probability ratio, day/night effect, etc. with strongly reduced errors.

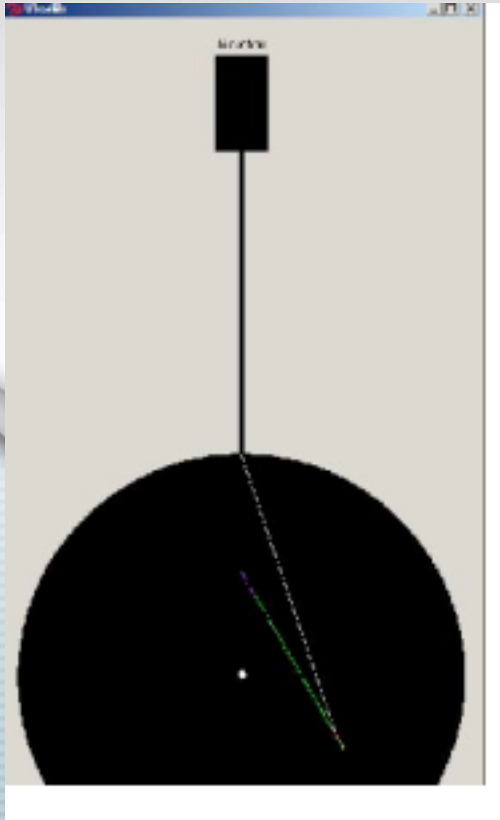
E. Measurements of the geo-neutrinos (the Gran Sasso region is especially favored due to the low background of reactor $\bar{\nu}_e$)

F. Better limits for rare phenomena: ν magnetic moment, Pauli Principle violation, electron decay (e->n+g)..

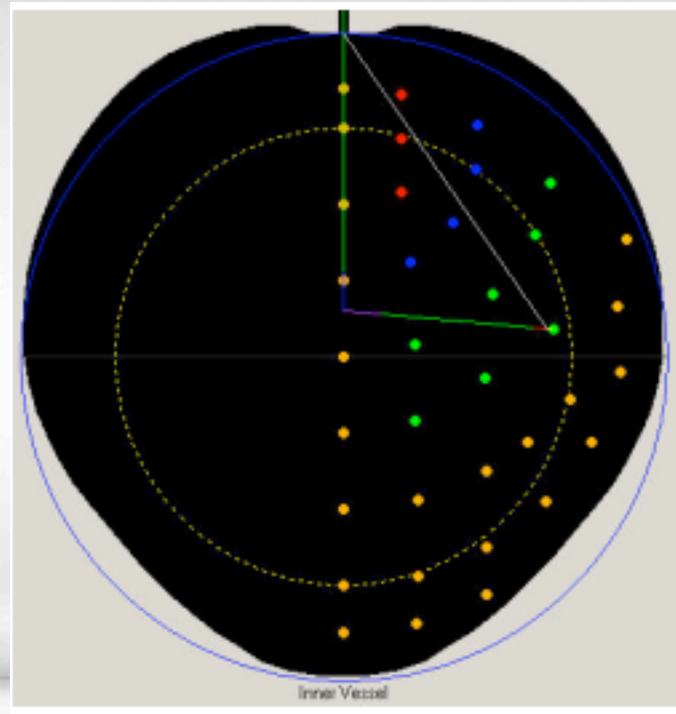
Calibration campaigns 2008-2009

On-axis and off -axis

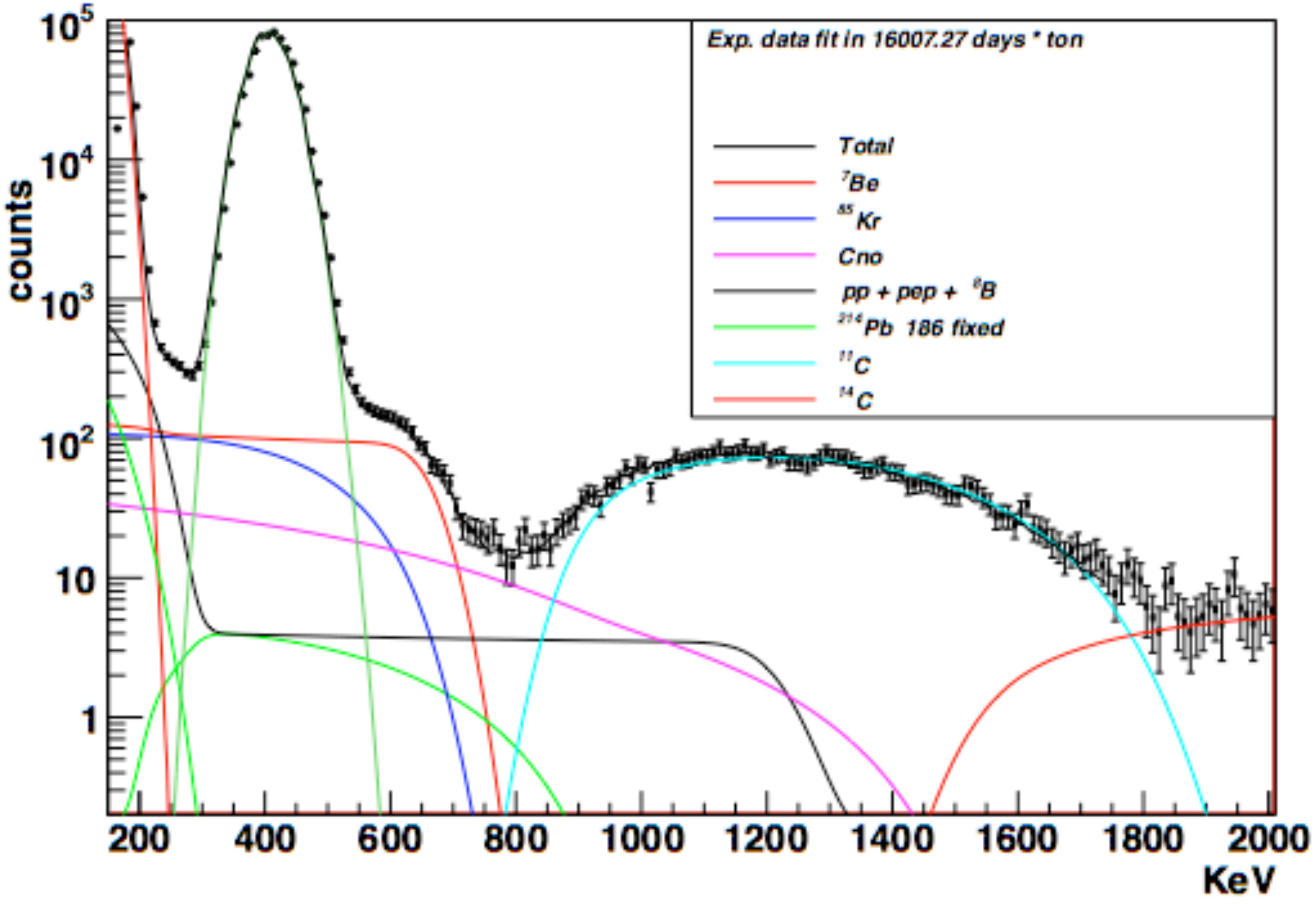
- Rn source: position reconstruction (FV definition), detector response as function of the position
- Gamma source (8 sources from 122 keV to 1.4 MeV): energy scale
- AmBe source: FV at high energies , proton recoil calibrations (for antineutrino)



•Laser diffuser: check PMT alignment



Study of pep and CNO fluxes



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

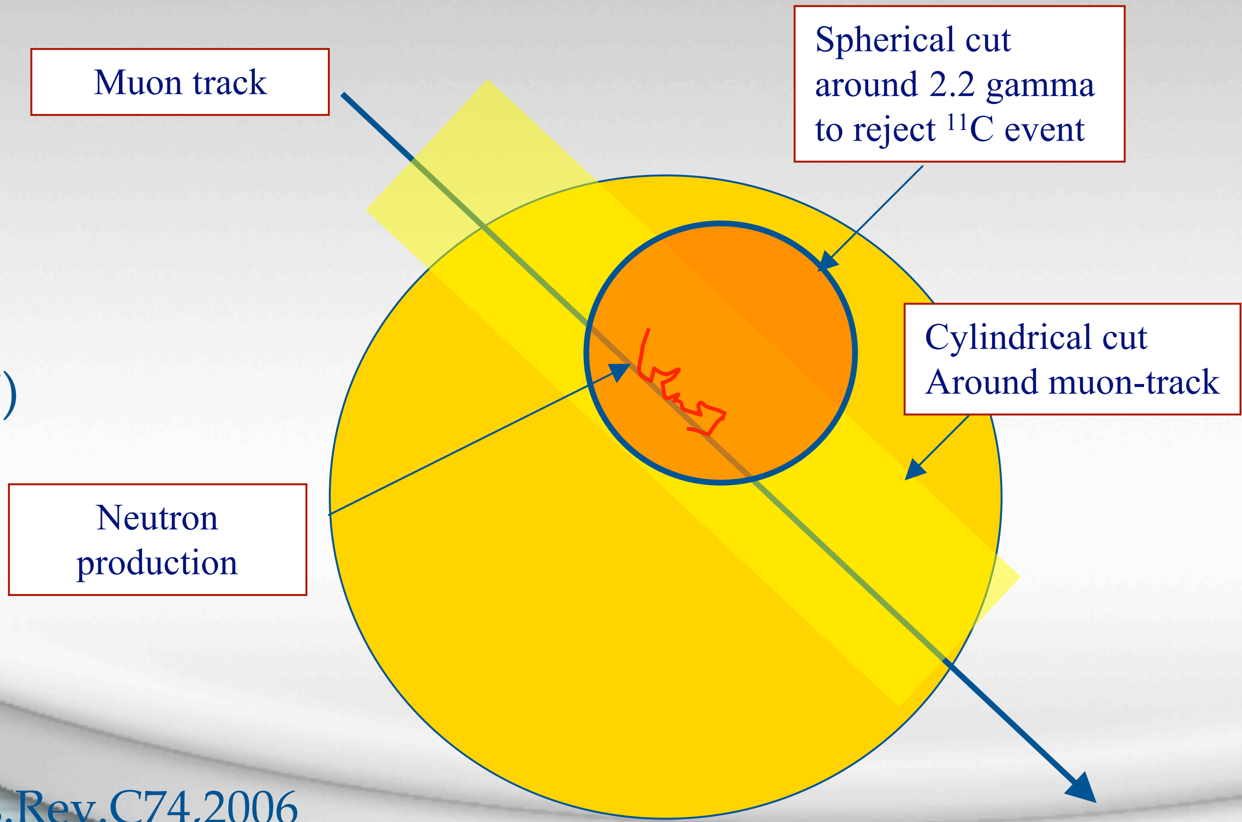
→ CNO:≈ 5 cpd/100 tons

→ pep:≈ 2 cpd/100 tons ← Expected from SSM with oscil.

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

↓ $^{11}B + e^+ + \nu_e$

↓ n capture
γ (2.2 MeV)

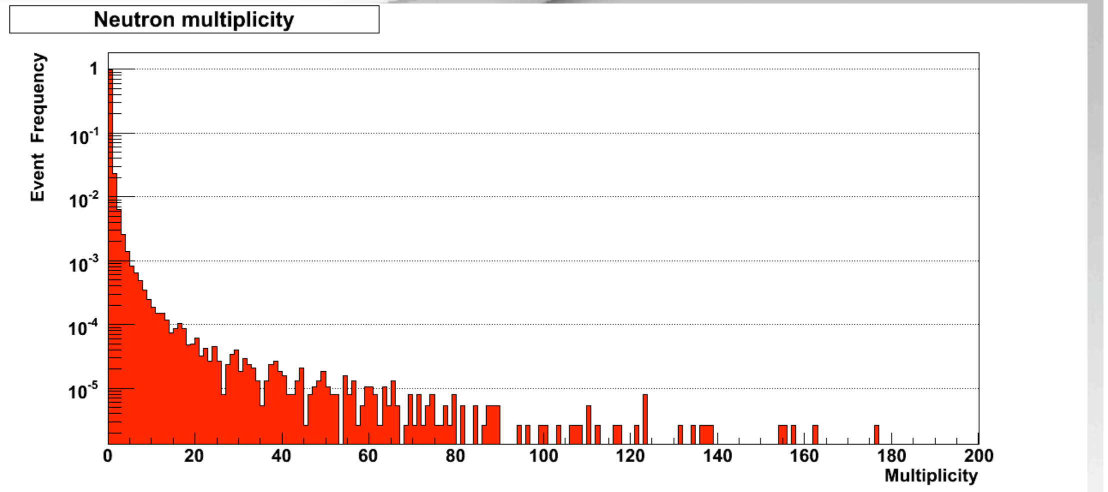


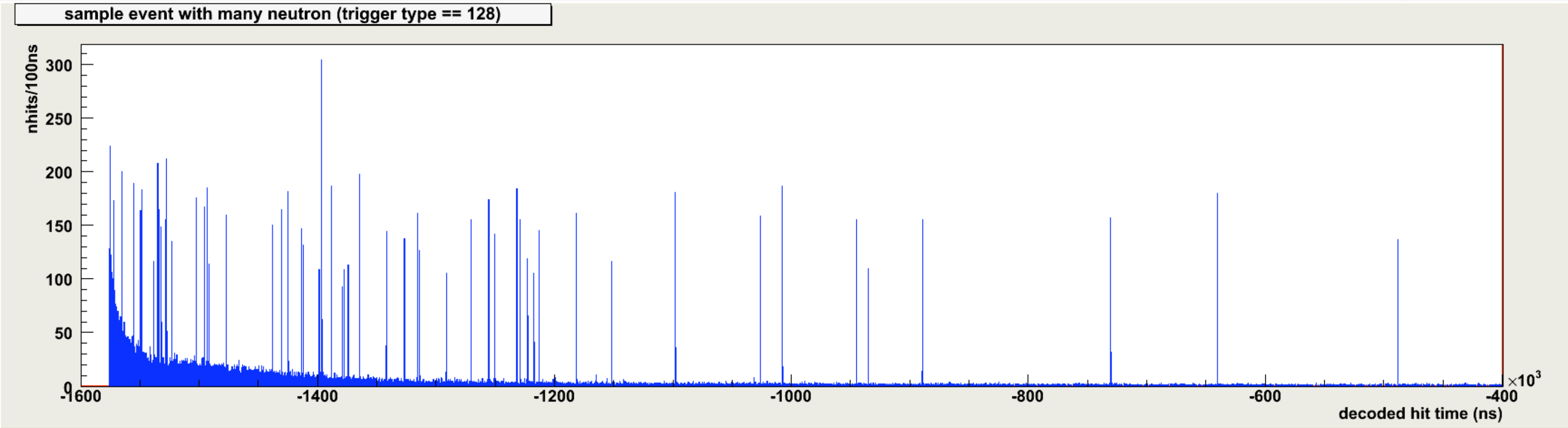
#Borex. Coll.Phys.Rev.C74,2006

^{11}C and neutrons after muons

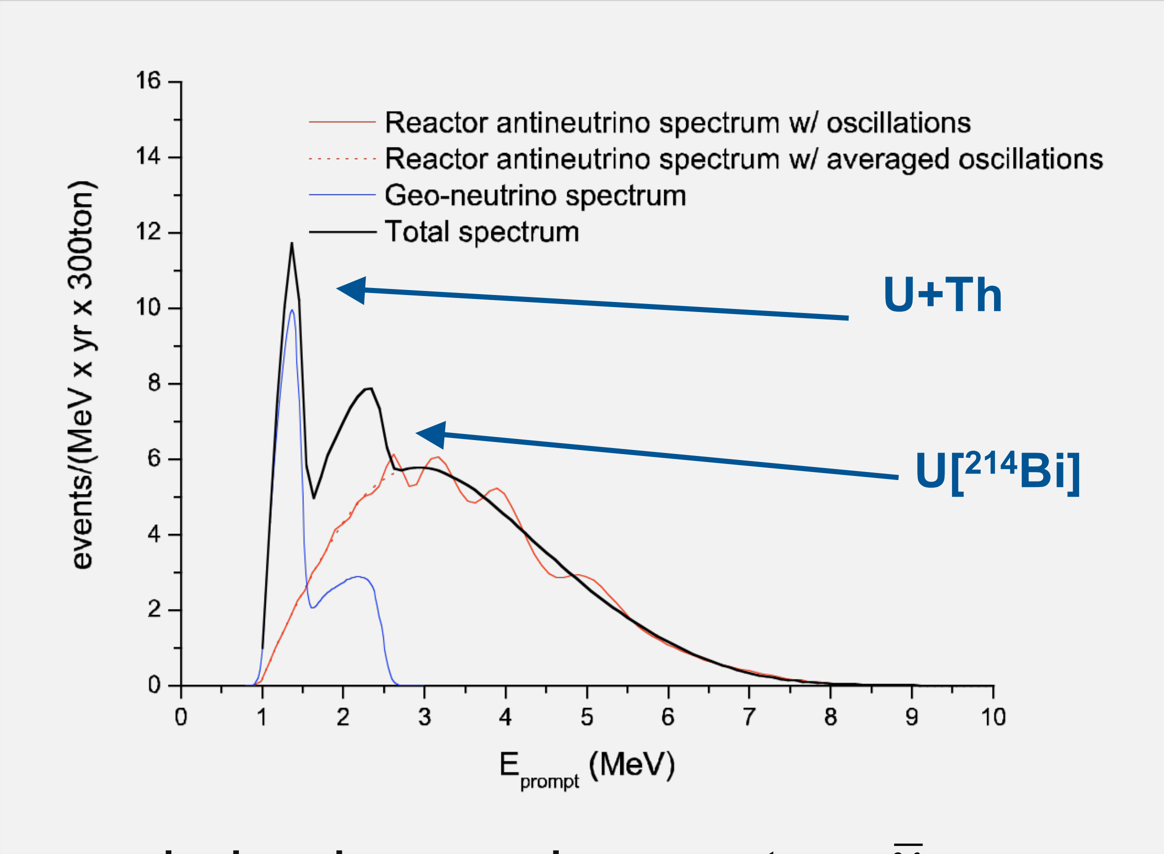
Now: 87% rejection

Still in progress





Geoneutrinos in Borexino



- good tagging: inverse beta decay

$$\overline{\nu}_e + p \rightarrow e^+ + n$$

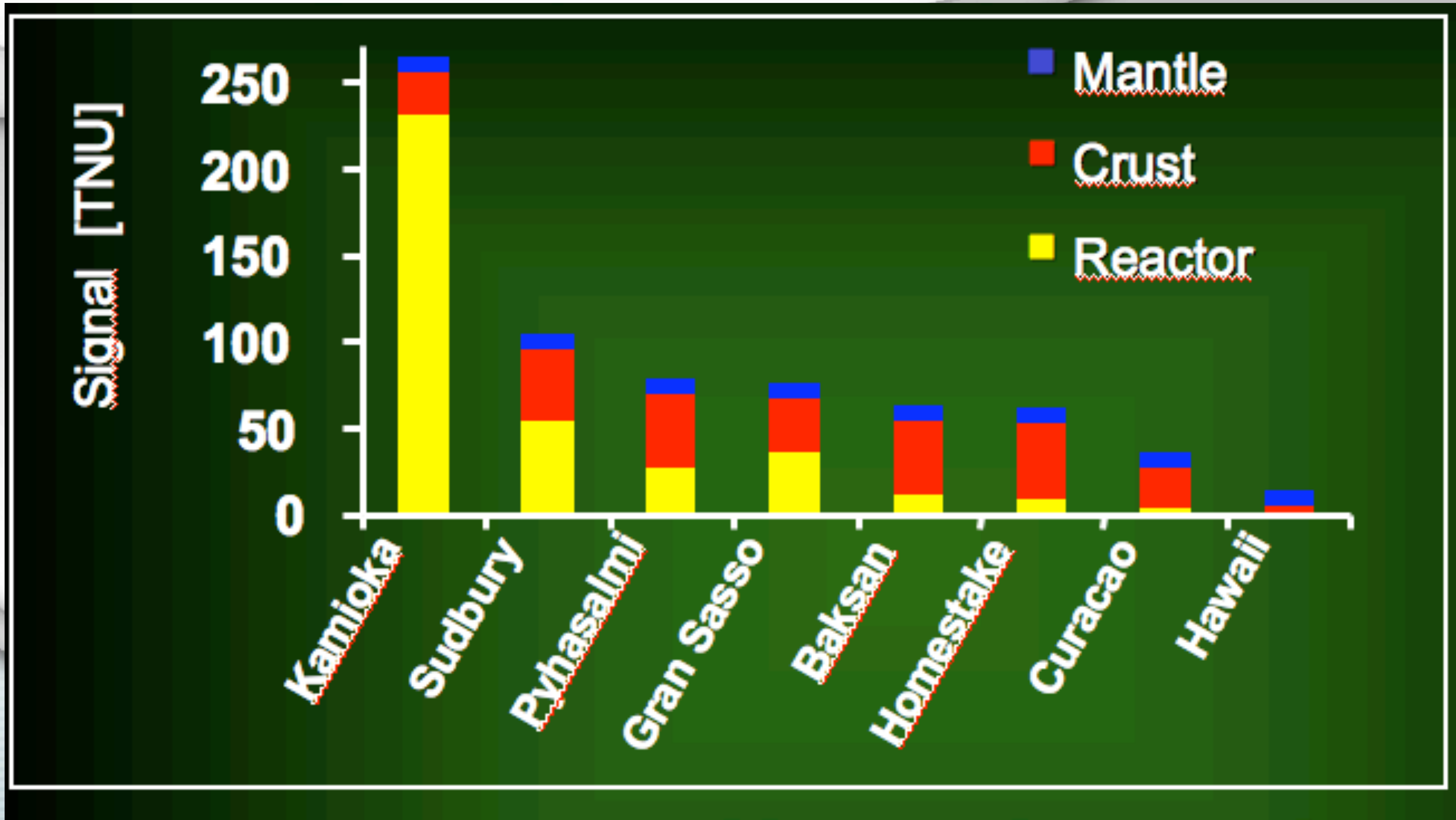
$$n + p \rightarrow d + \gamma(2.2\ \text{MeV})$$

- 280 tons target mass

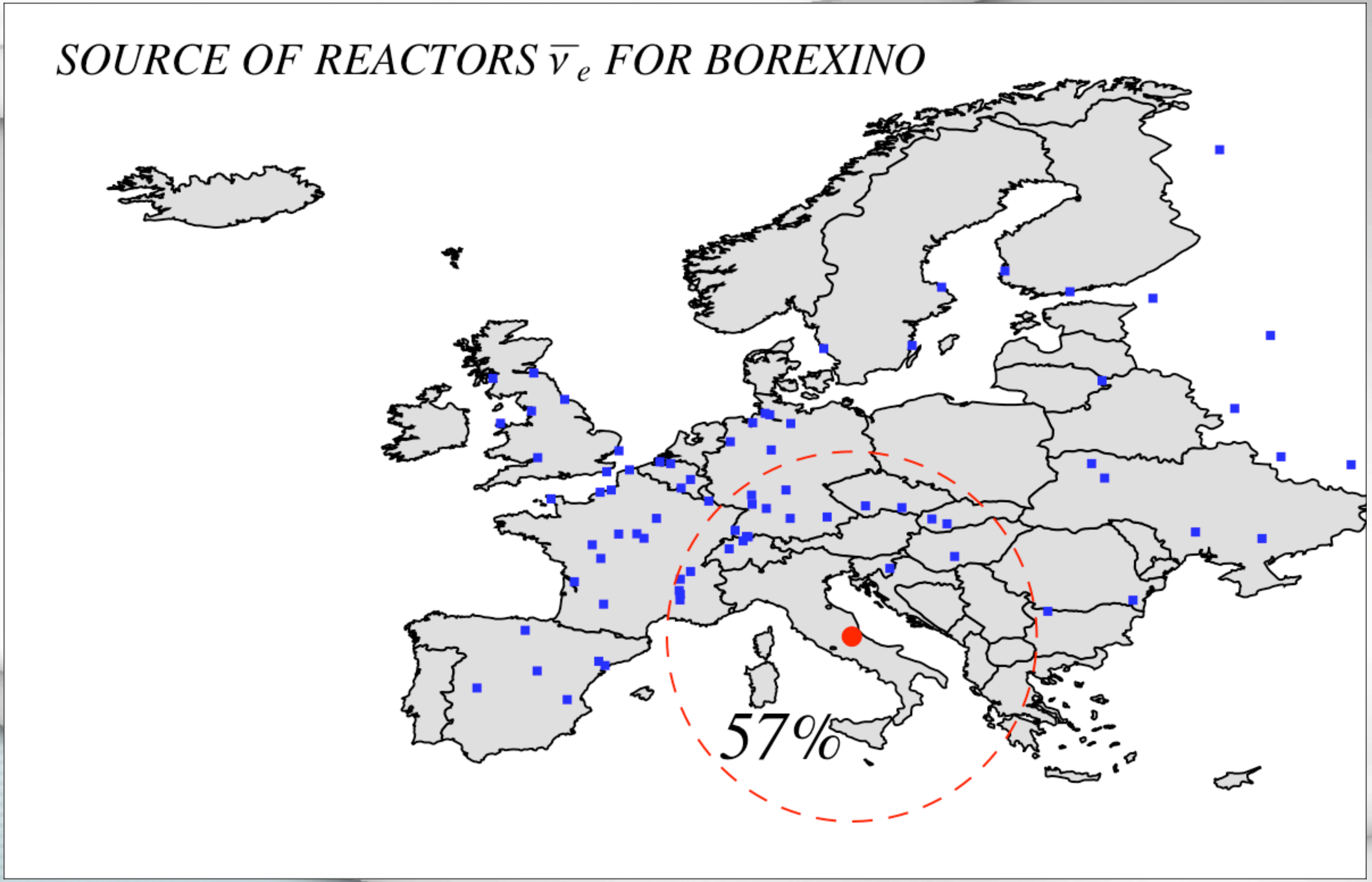
•main background: - reactors $\overline{\nu}_e$;

- (α,n), (γ,n), fast neutrons (γ and n from ext.backg); negligible due the following tools: p/β discrimination; p recoil energy (AmBe source calib.)

Antineutrino fluxes in the various sites



European Reactors (using IAEA database)



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

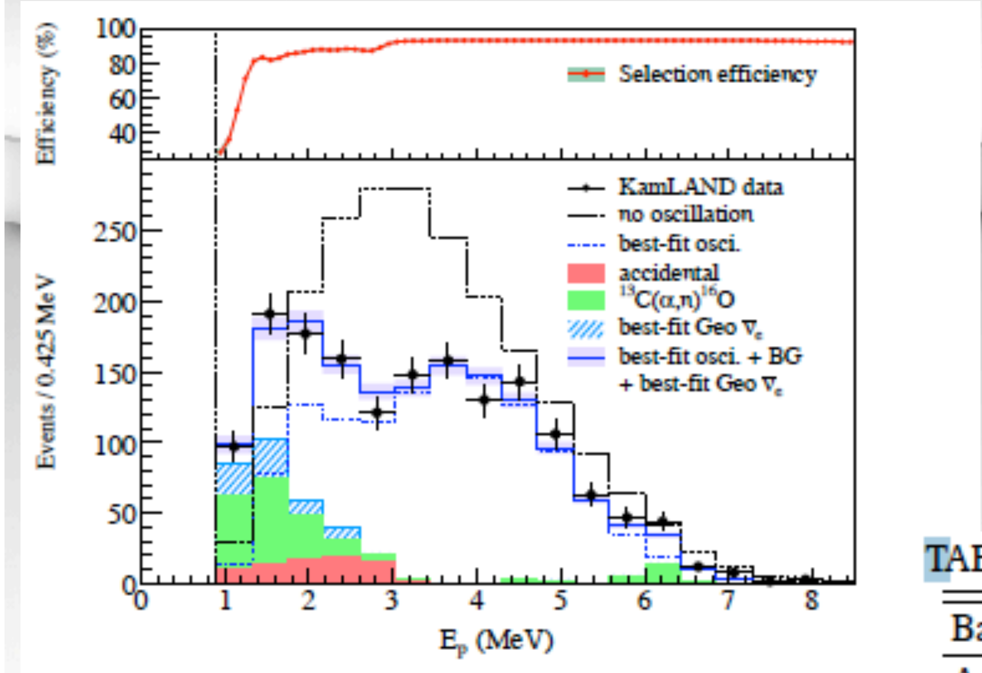
MeV	1.-1.5	1.5-2.6	>2.6
Reactors	0.5	4	10
Geo (BSE)	4	3	0

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±27 ev.

TABLE II: Estimated backgrounds after selection efficiencies.

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

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}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