# New results on low energy neutrino physics

## Developments in solar and terrestrial neutrinos

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# Content

1- New results on solar neutrinos below 2 MeV;

2- Improvements in the experimental study of the solar neutrino flux from $^{8}B$;

3- Impact of these results on the low energy neutrino physics

4-Status of the study of the geo-neutrinos.

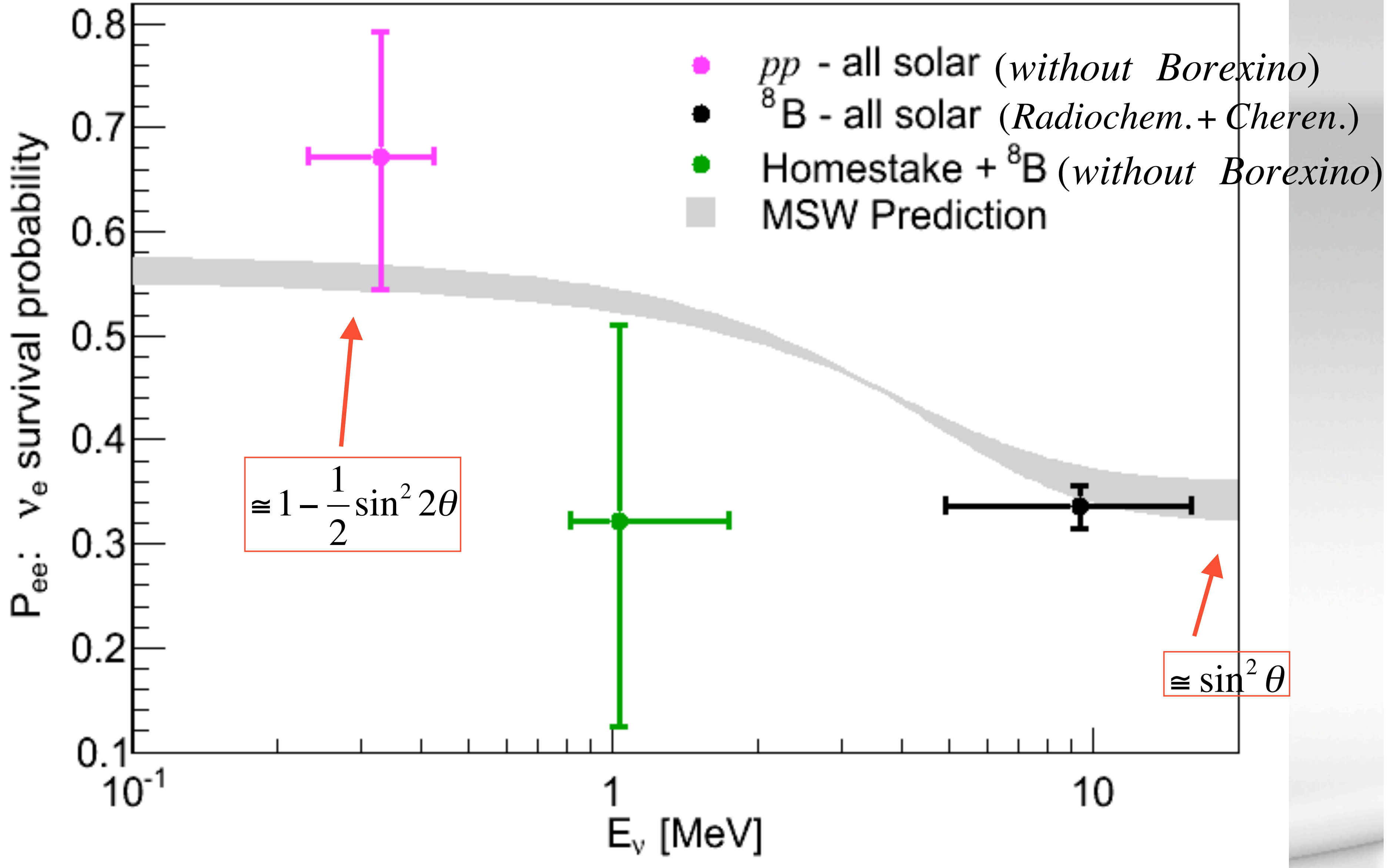
# Solar Neutrino Fluxes- metallicity problem

| $\nu$ flux | GS98 | AGS09 | $cm^{-2}\ s^{-1}$ |
|---|---|---|---|
| pp | 5.98 (1±0.006) | 6.03 (1±0.006) | x $10^{10}$ |
| pep | 1.44 (1±0.012) | 1.47(1±0.012) | x $10^{8}$ |
| hep | 8.04 (1±0.30) | 8.31 (1±0.30) | x $10^{3}$ |
| $^{7}$Be | 5.00 (1±0.07) | 4.56 (1±0.07) | x $10^{9}$ |
| $^{8}$B | 5.58 (1±0.14) | 4.59 (1±0.14) | x $10^{6}$ |
| $^{13}$N | 2.96 (1±0.14) | 2.17 (1±0.14) | x $10^{8}$ |
| $^{15}$O | 2.23 (1±0.15) | 1.56 (1±0.15) | x $10^{8}$ |
| $^{17}$F | 5.52 (1±0.17) | 3.40 (1±0.16) | x $10^{6}$ |

SHP11:
A.M. Serenelli, W. C.Haxton and C. Pena-Garay, arXiv:1104.16.39v1 [astro-ph]

@ GS98 (high metallicity)-solar atmosphere modeling in one dimension starting from the solar surface abundances (via spectroscopy)-excellent agreement with the helioseismology (sound speed)

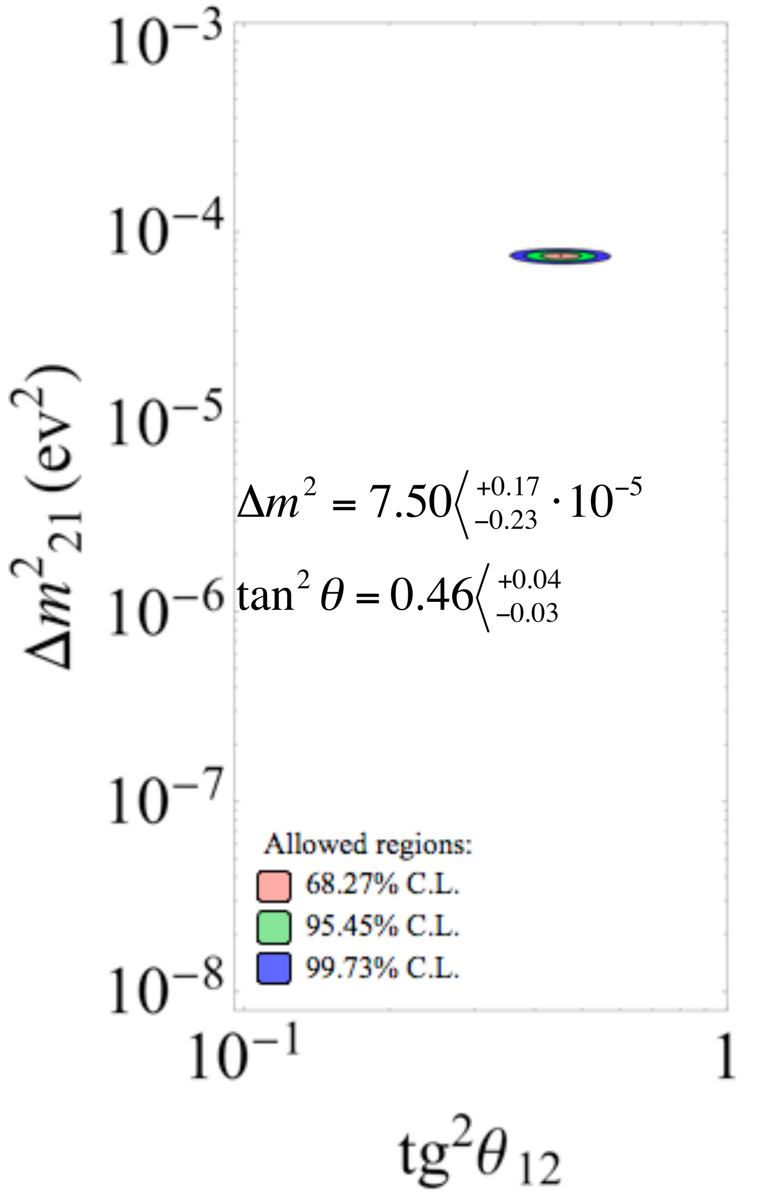
@ AGS09 ( low metallicity)- 3D modeling- less carbon, nitrogen, oxygen, neon and argon - disagreement with the helioseismology



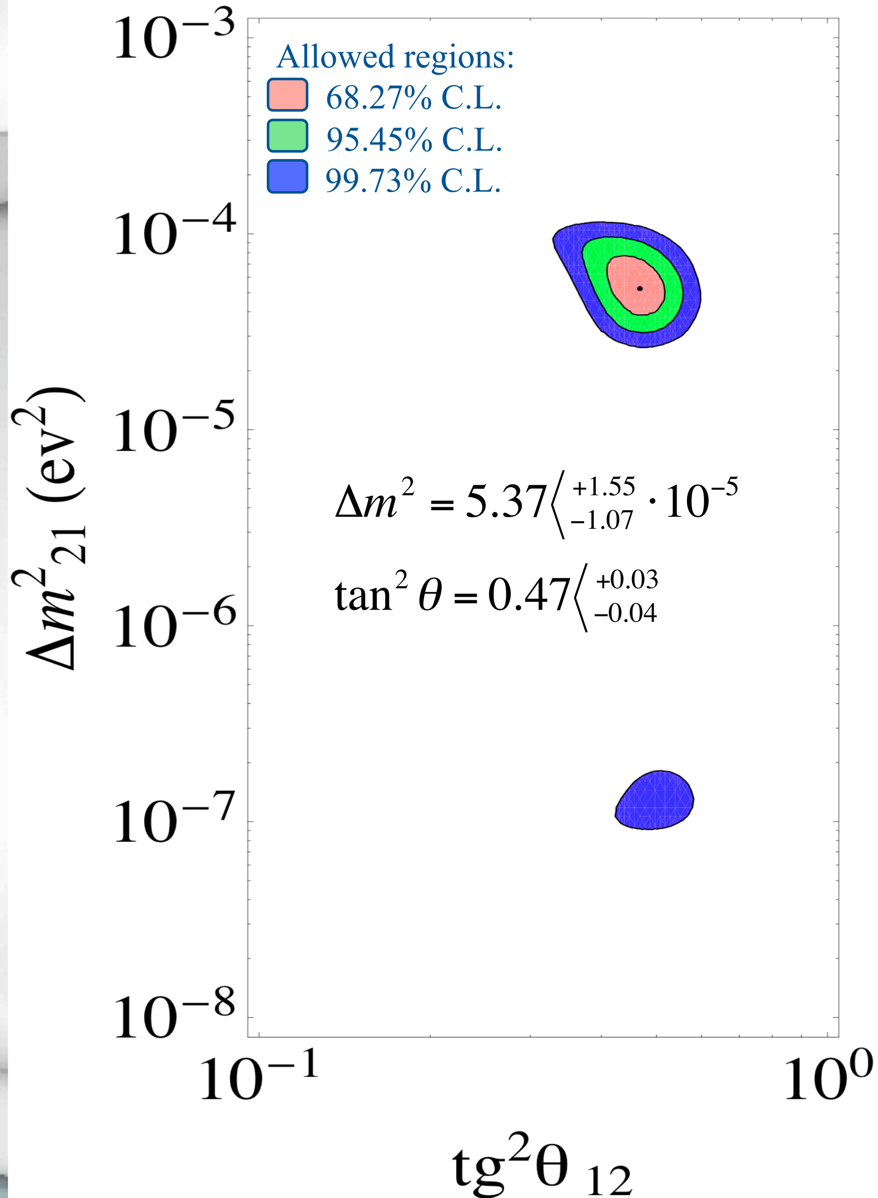
*pp* - all solar (*without Borexino*)
$^8$B - all solar (*Radiochem.+ Cheren.*)
Homestake + $^8$B (*without Borexino*)
MSW Prediction
$P_{ee}$: $\nu_e$ survival probability
$E_\nu$ [MeV]
$\cong 1 - \frac{1}{2}\sin^2 2\theta$
$\cong \sin^2\theta$
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
$10^{-1}$
1
10

# Global fit (without Borexino)

Solar + Kamland




Only solar



# Solar $\nu$

New data from Borexino, Kamland, SNO-LETA, Superkamiokande

- Borexino data concern: $^{7}$Be (flux and day/night) at 862 keV, pep at 1442 keV, $^{8}$B with the lower threshold down to 3 MeV($E_{\nu}$=3.2) - upper limit on CNO
- Kamland: $^{8}$B flux measurements over 5.5 MeV ($E_{\nu}$=5.8)
- SNO-LETA: $^{8}$B with the lower threshold down to 3.5 MeV ($E_{\nu}$=3.8 or 4.9)
- SuperK III.: lower errors $^{8}$B flux measurements over 5 MeV ($E_{\nu}$=5.3)

# Geo-antineutrinos

- New results from Kamland and joint treatment of Kamland and Borexino data.

# Solar and geo-neutrinos

Borexino.300 m$^3$ of liquid scintillator; F.V.:  86 m$^3$ for solar, 300  m$^3$  for geo-;light yield: 500 p.e./MeV

@ world record radiopurity: lower threshold: 60 keV (hardware), ~ 200 keV (software) electron energy

@ 4330/day on detector- $\mu$ veto

@ elastic scattering $\nu-e$

@ energy, position, isotropy, $\alpha/\beta$ discrimination;

Kamland.1000 tons of l.s.; F.V.:176.4 m$^3$;

@ 17107 $\mu$/day

@ elastic scattering

@ position and energy

SNO (LETA).1000 tons $D_2O$ ; Cherenkov light; F.V.: R<5.5 m

@  only 3 $\mu$/day in total

@  ES (elastic scatt.), CC ( $\rightarrow$ p+p+e$^-$- induced only by $\nu_e$), NC ($\rightarrow$ p+n+$\nu_x$- induced by every $\nu$)

@  $T_{eff}$ ,radial position, isotropy, $\theta_{solar}$

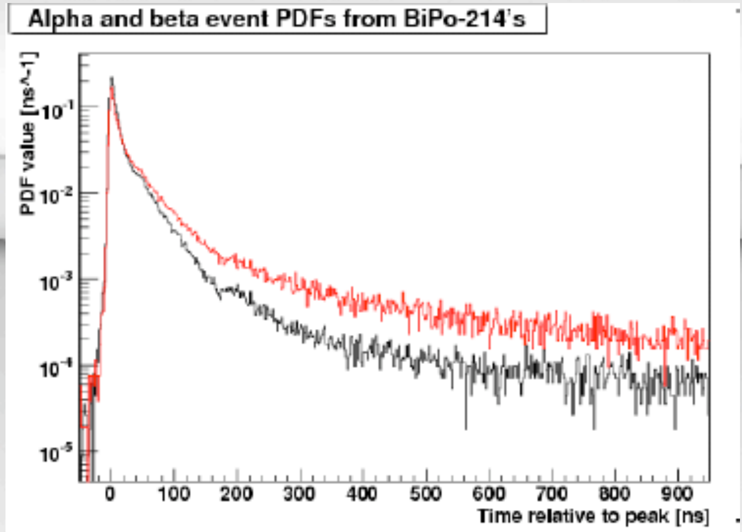
@  lower threshold:LETA: 3.5 MeV

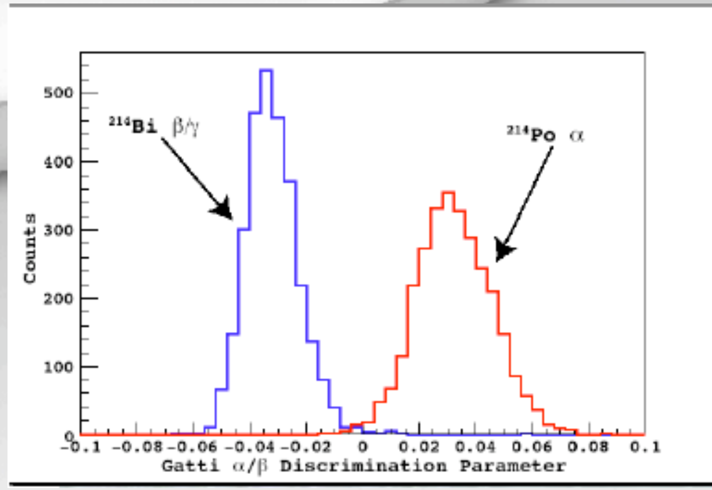
SuperK. III 50 ktons water; Cherenkov light; F.V. 13.3 ktons for 5.0-5.5 MeV; 22.5 ktons for 5.5-20.MeV.

@ energy,position, $\nu$ direction

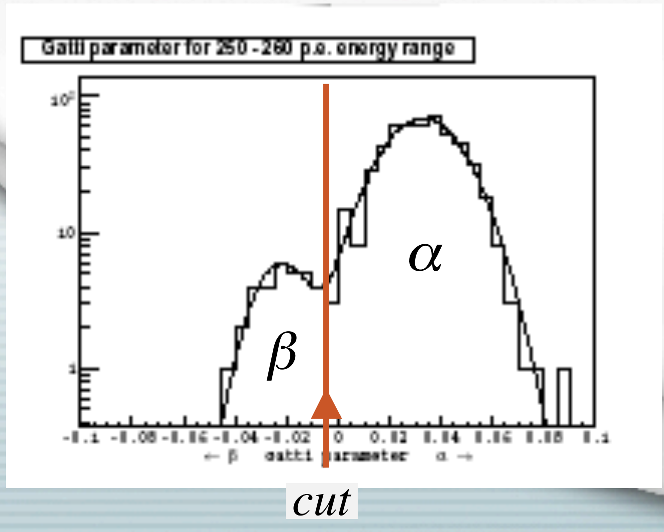
Borexino

## α/β discrimination- Gatti parameter




The analysis for the reference curves has been done from $^{222}$Rn
MC builds itself the references curves from the scintillator PDFs



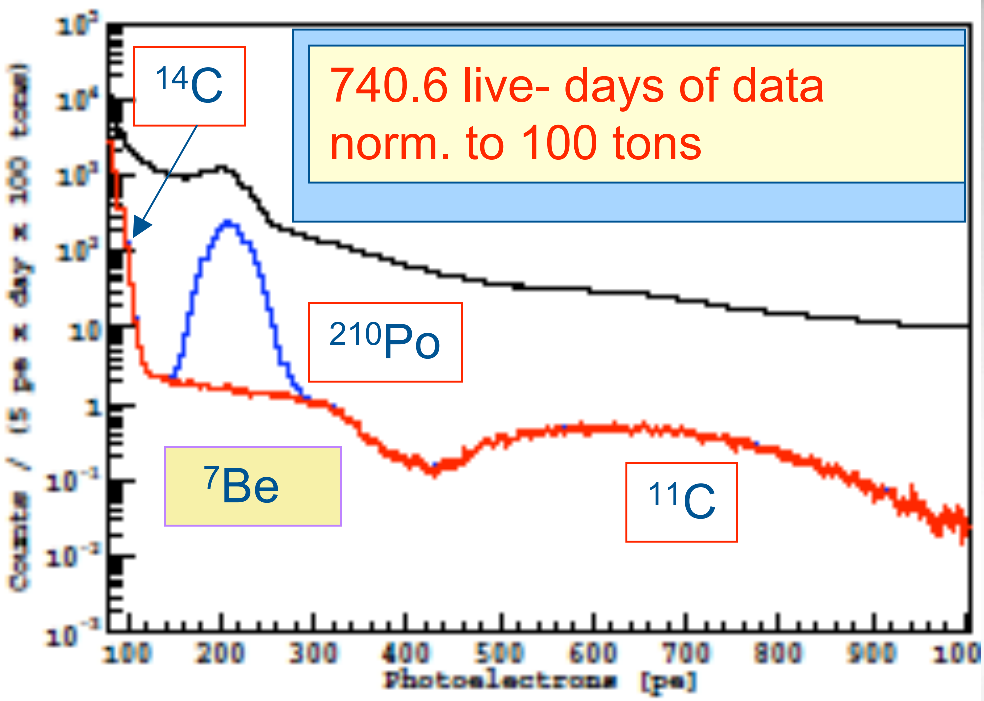

So called "soft cut"
The cut is chosen to not reject
β particles- done bin per bin
Reduction to 60%
It removes also noise events

So called "statistical subtraction-reduction close to 100%
Bin per bin the area below the α curve is evaluated and
then the equivalent number of events is subtracted

row data

$\mu$, $\mu$ induced events and FV cuts

$\alpha$ statistical subtraction




**$^{14}$C**-$\beta$ emitter-156 keV end point threshold 160 keV

**$^{210}$Po**– $\alpha$ emitter- embedded in the inner walls of the lines- $\tau$ =200 days

**$^{11}$C**- $\beta^+$ emitter -cosmogenic- 1.2 $\mu$/ m$^2$ h- $\tau$=29.4 minutes

## $^{85}$Kr

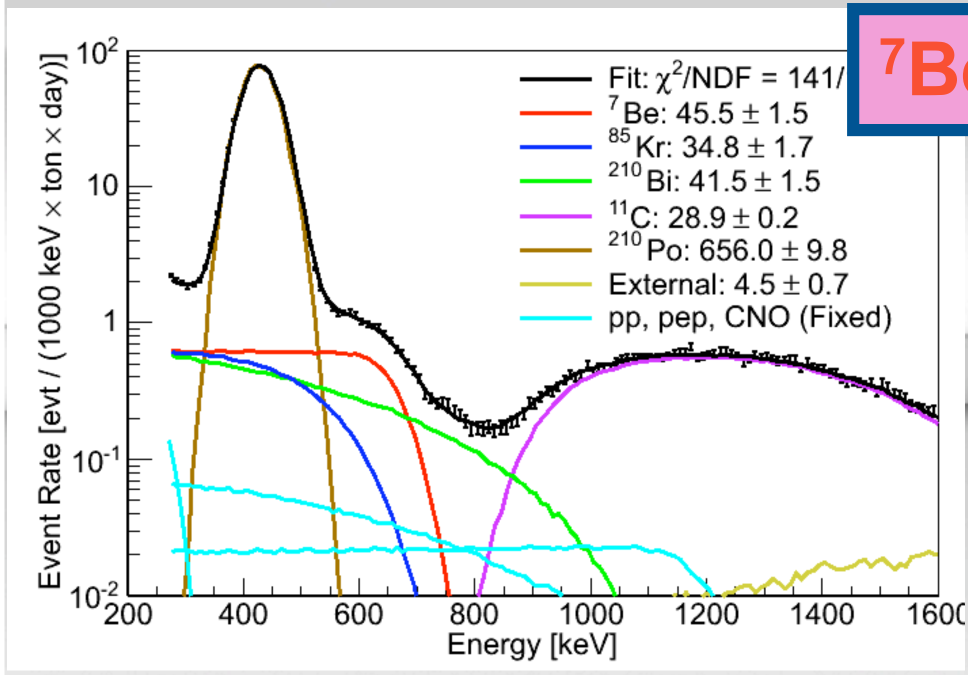
$$^{85}\mathrm{Kr} \xrightarrow[\tau\,=\,1.464\ \mu\mathrm{s}]{\beta\ 173\ \mathrm{keV}} {}^{85}\mathrm{Rb}^* \xrightarrow{\gamma\ 514\ \mathrm{keV}} {}^{85}\mathrm{Rb}$$

B.R. 0.46% ~ 750 l. days

33 candidates

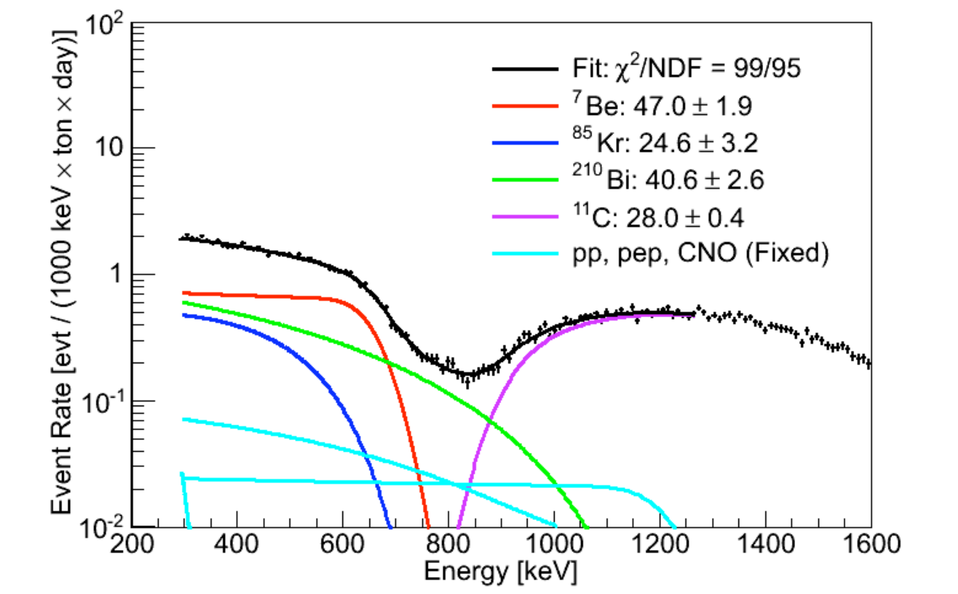
30.4±5.3±1.5 cpd/100 t

# $^{7}$Be-flux




MC- fit range: 250-1600 keV
Soft $\alpha$ subtraction

# pp, pep, CNO fixed, according MSW-LMA high metallicity
# free parameters: $^{7}$Be, $^{85}$Kr, $^{210}$Bi ( $\beta$ emitter) , $^{11}$C, $^{210}$Po ($\alpha$ emitter), $^{214}$Pb ($\beta$ emitter)




Analytical- fit range 300-1250 keV
statistical $\alpha$ subtraction

$\Phi(^{7}Be)=(4.87\pm0.24)$ $\times10^{9}\ cm^{-2}s^{-1}$

$f_{Be}=0.97\pm0.05\pm0.07$

**46±1.5 (stat.)± $\boxed{\left\langle{+1.6 \atop -1.5}\right.}$ (syst)cpd/100 tons**

# Main cuts for the $^{7}$Be search

Muons: # detection in the ID and veto of 300 *ms* (cosmogenic *n capture*); # detection in the OD only (Cherenkov) and veto of 2 ms; Fiducial volume ; Coincidences within 2 ms and events within 1.5 m of dist. are rejected: correlated events and $^{214}$Bi-$^{214}$Po ($\lambda$:238.1 $\mu$s); Check the charge - $0.6 < \frac{C}{q_{\exp}} < 1.6$ ($q_{exp}$ is the expected mean charge

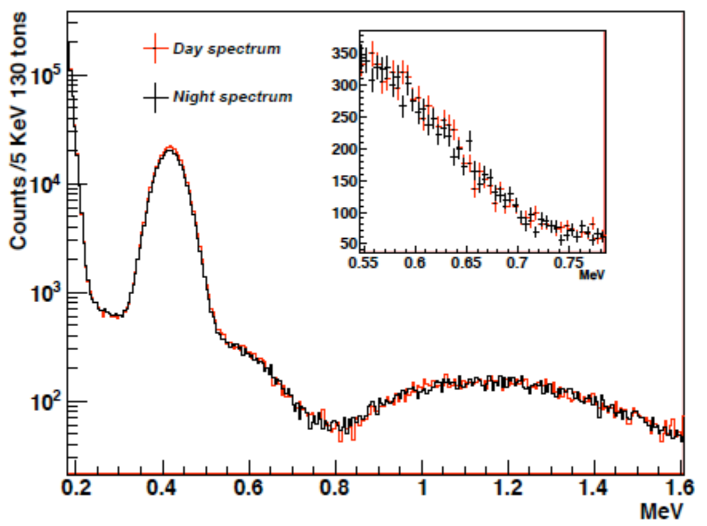
for single hit); Isotropic emission of the scintillation light around the interaction point; Rejected: pile-up of multiple events in the same DAQ gate( random,fast coincidences, etc.). Only 0.6% of live-time is missed

## Main systematics (%)

Energy scale: 2.7; Fit methods: 2. ; Position reconstruction: $\left\langle \begin{matrix} +0.5 \\ -1.3 \end{matrix} \right.$

# $^{7}$Be-Day/Night

Day (positive Sun altitude) 385.5 days
Night (negative Sun altitude) 363.6 days




# F.V. R < 3.0 or <3.3 m (130 t) and -1,67<Z<1.67
# $\nu$ *energy window*: 550-715 keV
# Exp. Function corrected for the geometrical seasonal variation (± 3%)

Asym. param. $$A_{dn} = 2\frac{R_n^{^7Be} - R_d^{^7Be}}{R_n^{^7Be} + R_d^{^7Be}} = \frac{R_{diff}}{R}$$

**First approach**: fit in the standard F.V. the D and N spectra separately to obtain $R_D$ and $R_N$.

$A_{dn}$= 0.007±0.073 (syst.error negligible)

**Second approach:** 1) subtract *D* and *N* spectra, normalized to the day live time.

F.V.< 3.3 m 2) search for a residual component having the shape of the electron recoil spectrum due to the $^{7}$Be $\nu$.

The difference between the two procedures quoted as systematic error.

**$A_{ND}$= -0.001±0.012(stat.)±0.007(syst)**

**pep** → monochromatic at 1442 keV → Compton edge as for $^{7}$Be

@ similar analysis as for $^{7}$Be, but with some important differences

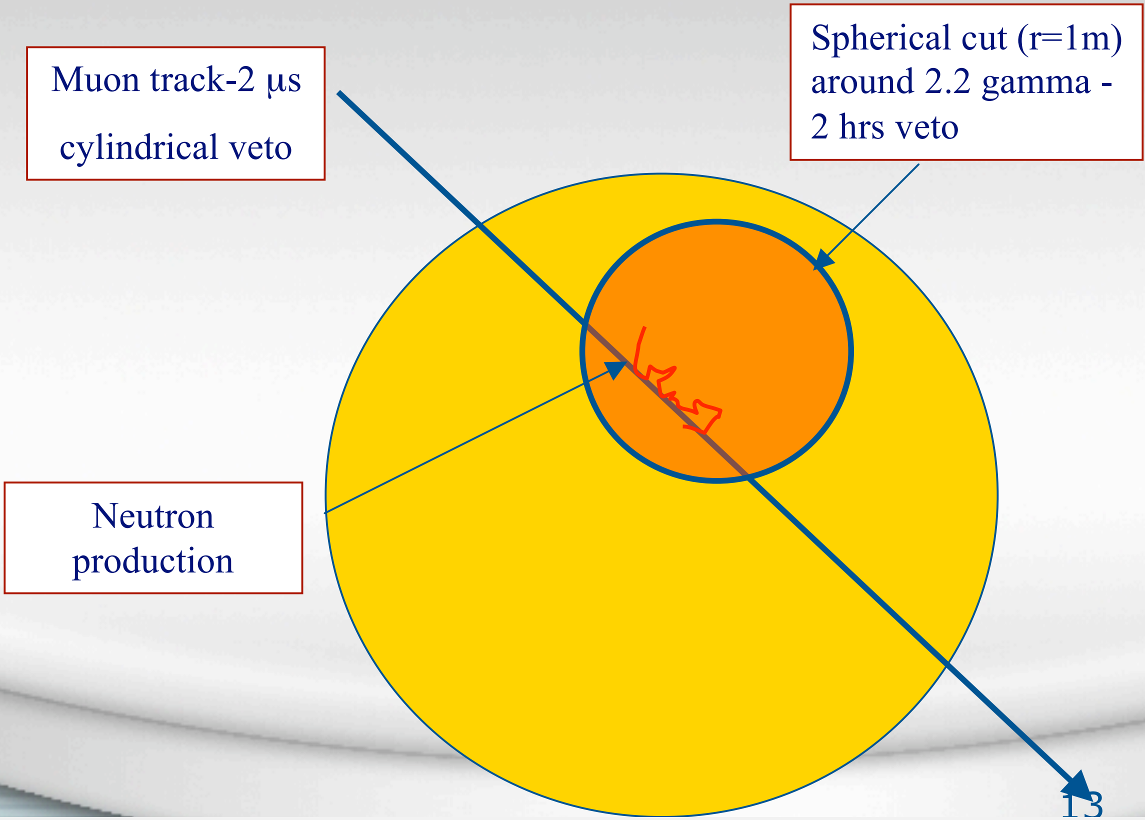
# cosmogenic $^{11}$C : rate of 28.5±0.2±0.7 cpd/100 tons, $\tau$=29.4'
# external $\gamma$s from $^{208}$Tl (2.61 keV) and $^{214}$Bi (3.27 keV)
# spectra of CNO $\nu$s and of $^{210}$Bi (background)

**TFC**

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

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

$n$ capture $\rightarrow$ $\gamma$ (2.2 MeV)



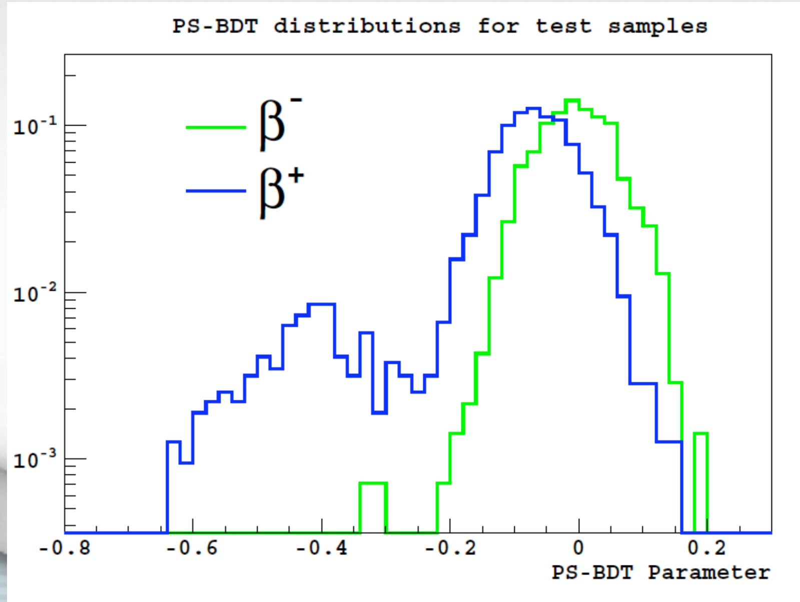

# optimal compromise: ~90% rejection; 48.5% residual exposure ( MC-$^{210}$Po)

# BDT Boosted Decision Tree

# 10% of $^{11}C$ still a significant background - $e^{+}/e^{-}$ pulse shape discrimination

# $e^+$ prior the annihilation may form a bound state with $e^-$ :positronium; the ortho-positronium (spin triplet state- S=0, $M_s$ =0) has $\tau \approx 140$ ns, reduced in the scintillator to 3 ns- 50% formation probability- during the annihilation emission of two $\gamma$ shower
delay and diffuse geometry of the events

# training on the $e^+$ distribution from $^{11}C$, tagged via TFC, and on $e^-$ from $^{214}Bi$ (tagged via $^{214}Bi^{214}Po$ coinc.) - checks via MC.




α/β # Statistical subtraction

## External Background

- Calibration with external source; ~5MBq $^{228}$Th in two position close to SSS
- Comparison with Mc-agreement at 99.5%on the reconstructed position.

## Multidimensional fitting strategy

@ Binned maximum likelihood fit on the events surviving the TFC veto- it takes into account simultaneously the energy spectrum, the radial distribution and the pulse shape BDT parameter ( with different fitting ranges).

@ Species left free in the fit: $^{210}$Bi, $^{10}$C, $^{11}$C,$^{6}$He,$^{40}$K,$^{85}$Kr,$^{234m}$Pa (internal background ) ,$^{208}$ Tl, $^{214}$Bi,$^{40}$K (external background), $^{7}$Be, pep, CNO. pp is fixed at the SSM prediction, $^{8}$B at the average experimental results.

@ The fit is carried out on the events surviving the TFC vetoes and to the energy spectrum of the events rejected, constraining the non-cosmogenic species to be the same (uncorrelated with the vetoes).

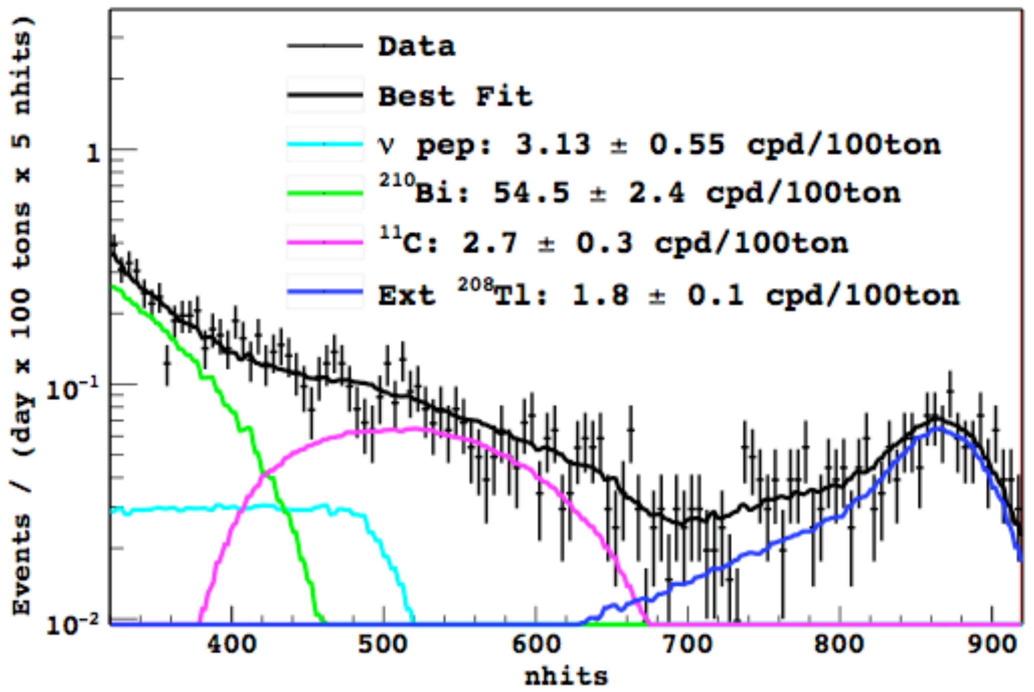
@ Checks with hundreds of fits to simulated events: p-value =0.3

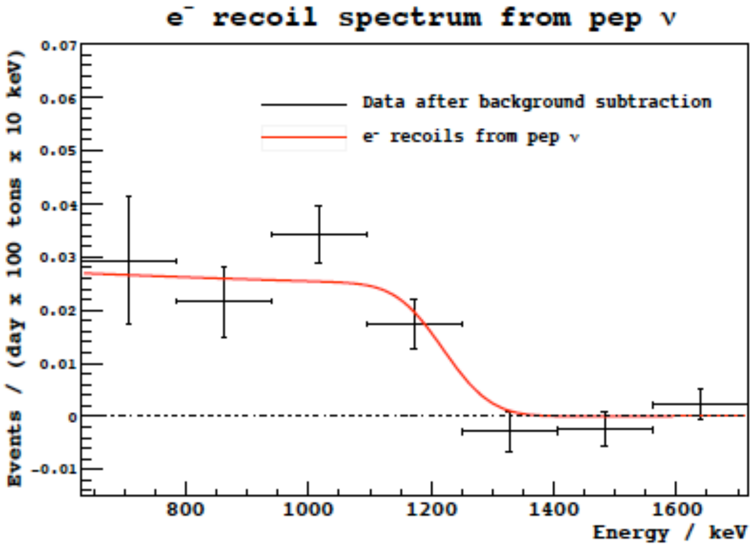
@ Further fit done fixing the pep value at SSM to improve the CNO limit (interference from the very similar $^{210}$Bi spectrum).

@ very good consistency with independent estimates for $^{10}$C, $^{6}$He,$^{85}$Kr,$^{234m}$Pa and of $^{11}$C and $^{7}$Be (previous analysis).

# pep: 3.13±0.55(stat.)±0.23(syst) cpd/100 tons
# CNO: <7.6 cpd/100 tons

$\Phi$(pep)= 1.6±0.3 $10^{8}$ $cm^{-2}\,s^{-1}$ $f_{pep}$(GS98)=1.1±0.2 $\Phi$(CNO)<7.4 $10^{8}$ $cm^{-2}\,s^{-1}$ $f_{CNO}$(GS98)<1.4




Main systematic: fit configuration and energy scale

## $^{8}B$

## Borexino

Similar analysis as in $^{7}Be$, but with further cuts for further background- ~ 688 live-days reduced of 30% due to cuts- F.V.: 86 $m^3$ - radial fit (possible distortion $^{8}B$ en.spect)- range; **3.0-16.3 MeV**

### Additional background

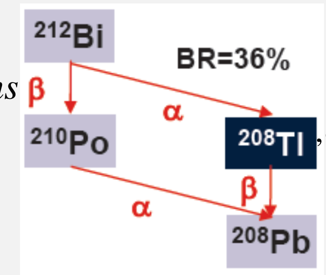
- $^{208}Tl$ (Q=5. MeV) and $^{214}Bi$ emanated from nylon vessel and in the bulk
- cosmogenic isotopes

Main systematic e.: energy threshold, fiducial volume

### Further cuts

- **Muon** induced radioactive **nuclides:** 6.5 s veto after each crossing muon (~30% dead time)-$^{10}C$ ($\tau$=27.8 s) tagged with the **Three-fold coincidence**-$^{11}Be$ ($\tau$=19.9 s) statistically subtracted
- $^{214}Bi$-$^{214}Po$ coincidences rejected ($\tau$=237 $\mu$s- $^{222}Rn$ daughter)
- $^{208}Tl$ :from $^{212}Bi$-$^{210}Po$ the $^{208}Tl$ production is evaluated:

$B.R.\ 64\%, 431\ ns$




$,4.47\,\text{min}$

### Results

| | 3.0–16.3 MeV | 5.0–16.3 MeV |
|---|---|---|
| Rate [cpd/100 t] | 0.22±0.04±0.01 | 0.13±0.02±0.01 |
| $\Phi^{ES}_{exp}$ [$10^6$ cm$^{-2}$s$^{-1}$] | 2.4±0.4±0.1 | 2.7±0.4±0.2 |
| $\Phi^{ES}_{exp}/\Phi^{ES}_{th}$ | 0.88±0.19 | 1.08±0.23 |

Kamland

Live days 1432 reduced of 62% due to cuts-FV:176.4 $m^3$-
direct identification of e.s.-independent fit on en. spec.- **5.5-20 MeV**

With respect to Borexino more cosmic $\mu$s and higher radio-contamination

- reduced fiducial volume for the external $\gamma$s
- lower threshold at 5.5 MeV for $^{208}$Tl (Q=5. MeV; $\tau$=3.05 minutes)-

Main systematic uncertainties

- $\mu$ spallation products
- external $\gamma$
- detection efficiency

$\Phi^{ES}$= 2.17±0.26±0.39 $10^6$ $cm^{-2}$ $s^{-1}$

Fit on energy spectrum:

2.77±0.26±0.32 $10^6$ $cm^{-2}$ $s^{-1}$

Super-K III

298.2 live days for the range 5.0-6.5 MeV; 547.9 days for the range 6.5-20 MeV. Also two different FV: 13.3 ktons (5.0-5.5 MeV), 22.5 ktons (5.5-20. MeV)

Main backgrounds:

- $\mu$s, $\mu$'s spallation and cosmogenic
- external events

$\Phi$ ($^8$B)= 2.32±0.04±0.05 $10^6$ $cm^{-2}$ $s^{-1}$

Main systematic sources:

- energy scale,angular resolution, fiducial volume, fit on solar angle , trigger efficiency

## SNO-LETA

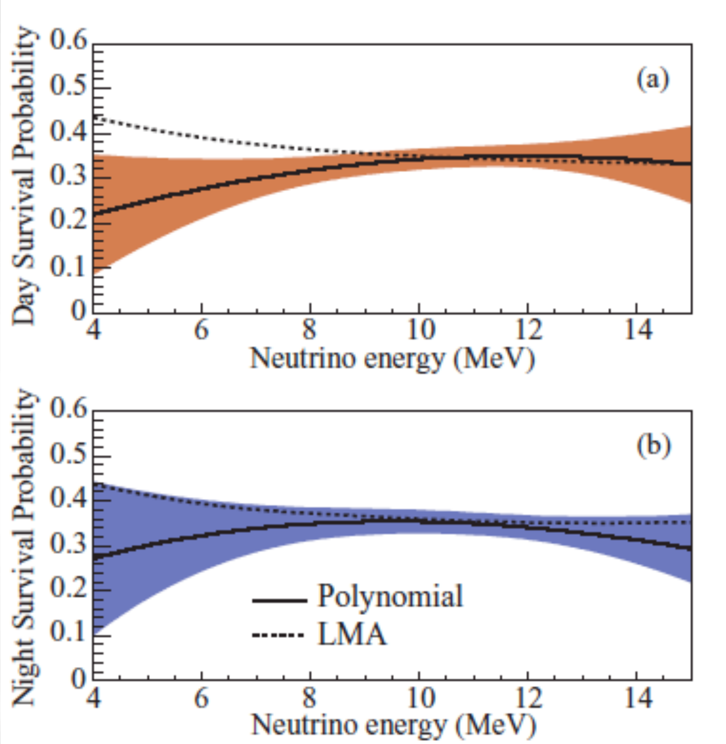
Various improvements in comparison to previous SNO analyses: Energy recon., quality cuts, selected runs- 668.8 live days- range: **3.5-20 MeV**

M.L. based on four parameters:energy,radial position, $\cos\theta_{Sun}$ ,isotropy- Fit on CC,ES,NC events + 17 background types:

- unconstrained fit with CC and ES spectra without model constraints
- extract the total $^{8}B$ $\nu$ flux and the survival probability $P_{ee}$ vs energy

TABLE X. The sources of physics-related background events in the LETA analysis.

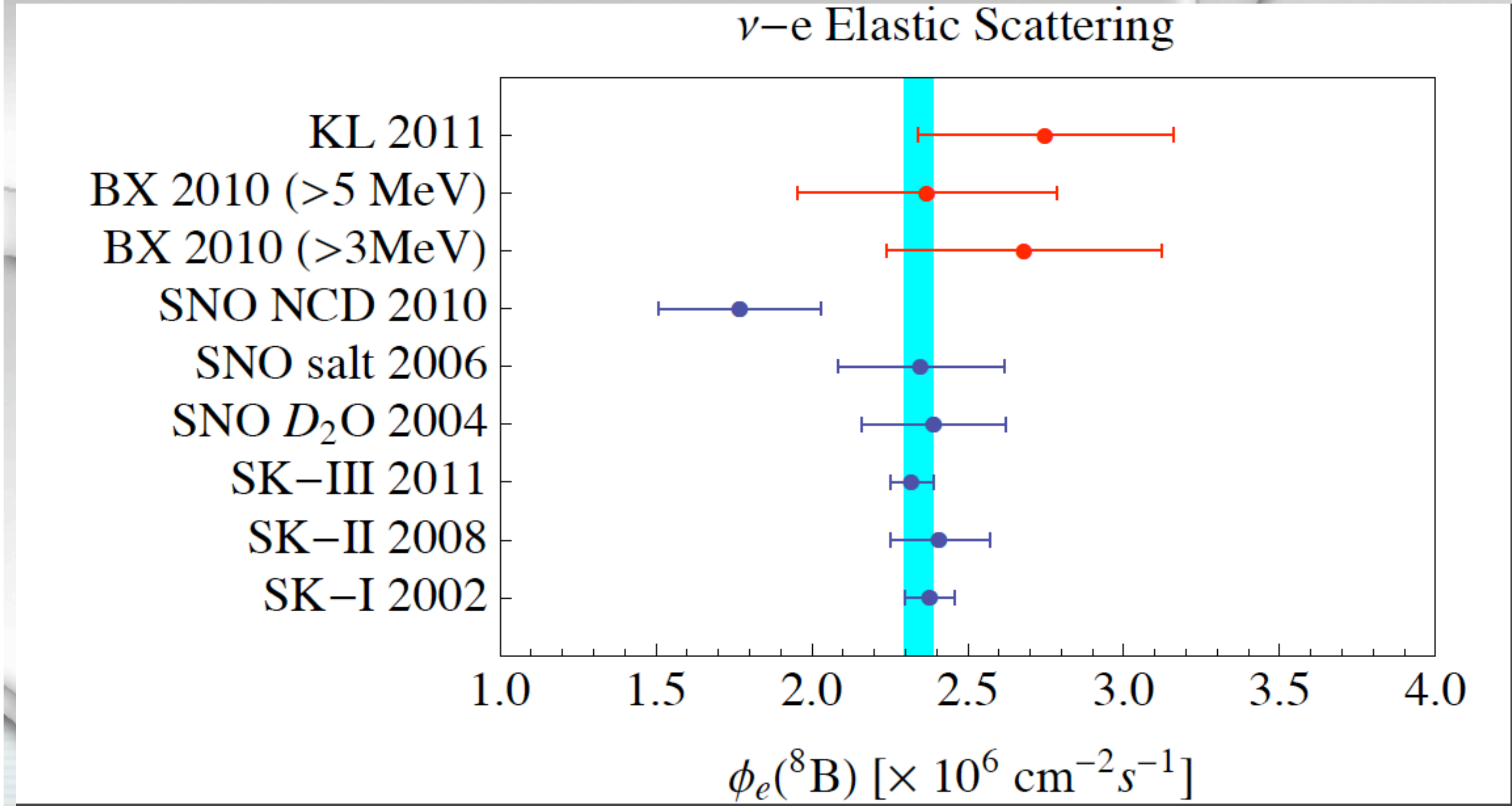
| Detector region | Phase I | Phase II |
|---|---|---|
| $D_2O$ volume | Internal $^{214}Bi$<br>Internal $^{208}Tl$ | Internal $^{214}Bi$<br>Internal $^{208}Tl$<br>$^{24}Na$ |
| Acrylic vessel | Bulk $^{214}Bi$<br>Bulk $^{208}Tl$<br>Surface $(\alpha,n)$ $n$s | Bulk $^{214}Bi$<br>Bulk $^{208}Tl$<br>Surface $(\alpha,n)$ $n$s |
| $H_2O$ volume | External $^{214}Bi$<br>External $^{208}Tl$<br>PMT $\beta$-$\gamma$s | External $^{214}Bi$<br>External $^{208}Tl$<br>PMT $\beta$-$\gamma$s |




$$\Phi_{NC} = 5.140\left\langle{}^{+0.160+0.132}_{-0.158-0.117}\right.$$ unconstrained fit

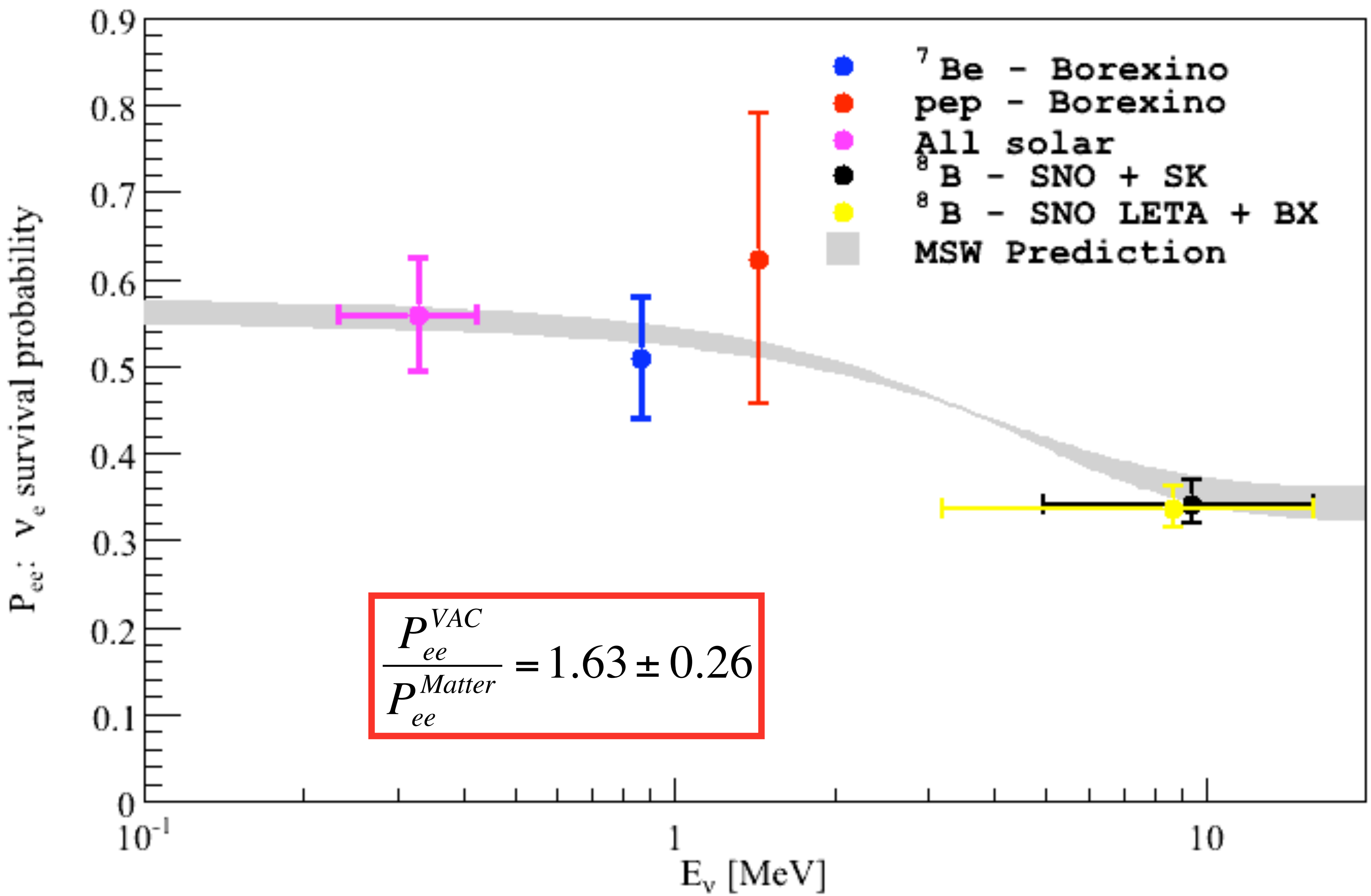
$$\Phi_{^8B} = 5.046\left\langle{}^{+0.20+0.107}_{-0.152-0.123}\right.$$ with $P_{ee}$

$A_{D/N}=0.037\pm0.040$

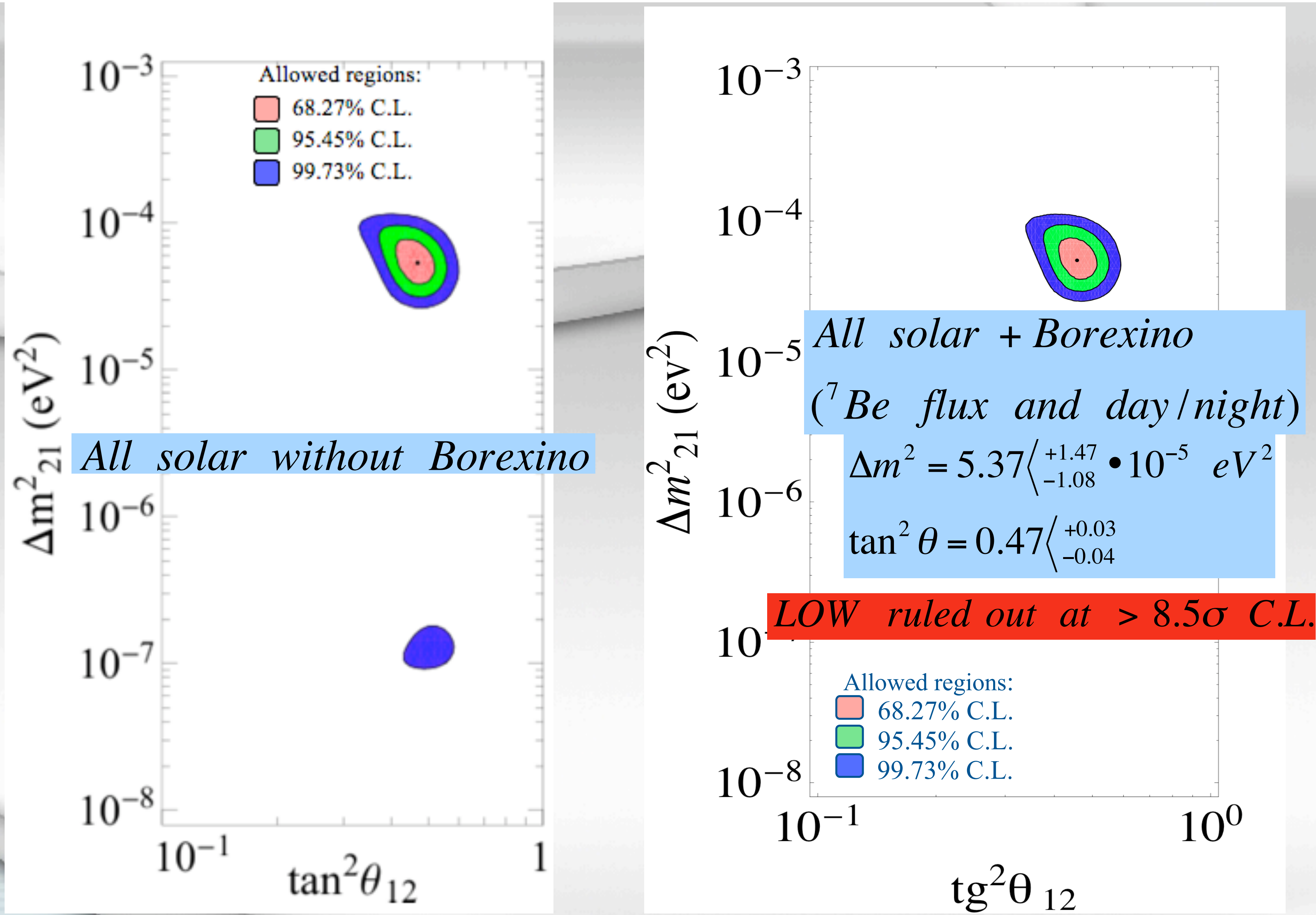



Average: $2.33 \pm 0.05\ 10^{6}\ cm^{-2}\ s^{-1}$

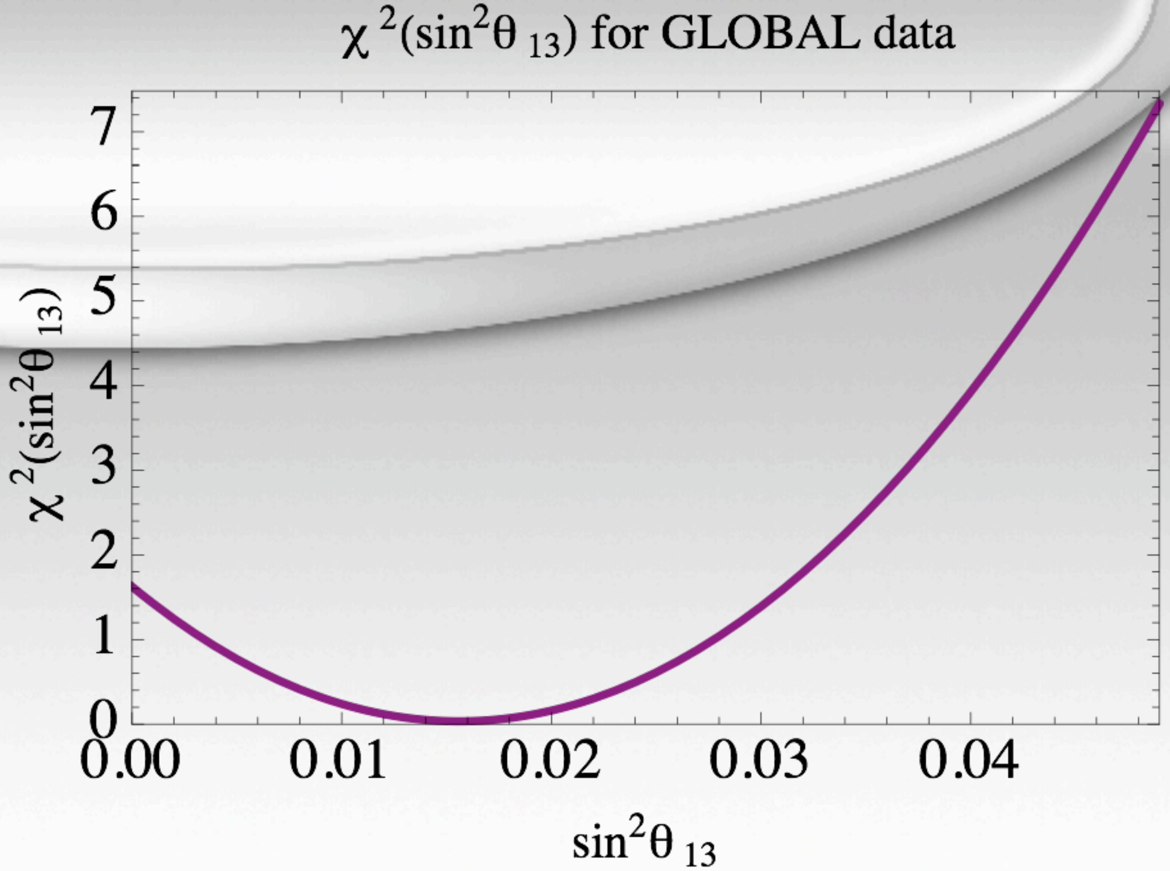
| $\nu$ flux | GS98 | AGS09 | $cm^{-2}\ s^{-1}$ | Experim. results |
|---|---|---|---|---|
| **pep** | 1.44 (1±0.012) | 1.47 (1±0.012) | x $10^8$ | 1.6±0.3 Borexino |
| **$^7$Be** | 5.00 (1±0.07) | 4.56 (1±0.07) | x $10^9$ | 4.87±0.24 Borexino |
| **$^8$B** | 5.58 (1±0.14) | 4.59 (1±0.14) | x $10^6$ | 5.2±0.3 SNO+SK+Borex+Kamland<br>$5.14\ \left(^{+0.21}_{-0.20}\right)$ SNO-LETA N.C.<br>$5.05\ \left(^{+0.19}_{-0.20}\right)$ LETA $^8$B total |
| **$^{13}$N**<br>**$^{15}$O**<br>**$^{17}$F** | 2.96 (1±0.14)<br>2.23 (1±0.15)<br>5.52 (1±0.17) | 2.17 (1±0.14)<br>1.56 (1±0.15)<br>3.40 (1±0.16 | x $10^8$ | <7.4 Borexino |




$^7$Be experimental errors lower than the SSM uncertainty




Then solar neutrino results with the addition of Borexino can isolate the LMA region without the Kamland antineutrino data




$$\sin^2\theta_{13} < 0.04 \ \ (2\sigma)$$

$T2K \quad \sin^2 2\theta_{13} = 0.1$

*null hypothesys rejected at* $2.5\sigma$ *C.L.*

# Geo-$\nu$

@ The radioactive decays are an important source of the terrestrial heat; they are present in the crust and in the mantle,but probably not in the core (chemical affinity).

@ The geo-thermical gradient estimates the global heat loss in the range 40 – 47 TW, but a global power of 30 TW is not excluded. The expected amount of radioactive decays in the mantle are model dependent: the canonical model, the *Bulk Silicate Earth* (BSE), predicts about 19 TW, but one cannot exclude that the radioactivity in the present Earth would be enough to account for even the highest estimate of the total terrestrial heat. Other models report the existence of a geo-reactor of 3-6 TW induced by important amounts of U present around the core.

@ The geological measurements of the radioactive decays are limited to the crust, where the investigations are based upon drill-holes.

@ The distribution of heat in the mantle produces convective movements which are related to volcanic activities and tectonic plate movements.

# Two LS experiments: Borexino (280 t) and Kamland (600 t)

- $^{238}U$, $^{232}Th$, $^{40}K$ chains ($T_{1/2}$ = (4.47, 14.0, 1.28) x $10^9$ years, resp. contribute about 99% to the total radiogenic heat:

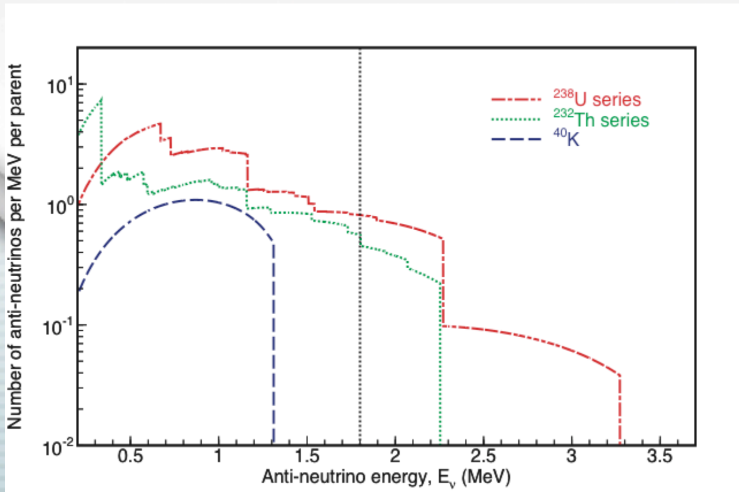
$^{238}U \rightarrow {}^{206}Pb + 8\,\alpha + 8\,e^- +$ 6 anti-neutrinos + 51.7 MeV

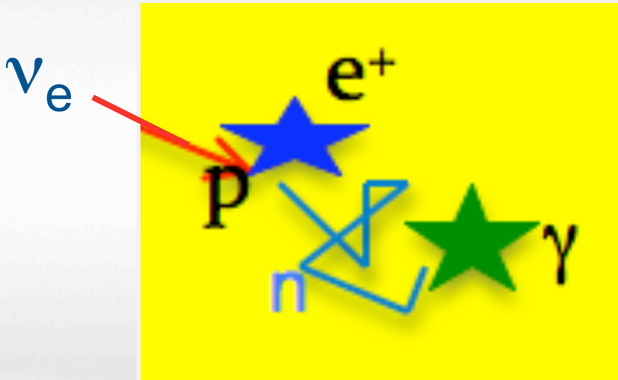
$^{232}Th \rightarrow {}^{208}Pb + 6\,\alpha + 4\,e^- +$ 4 anti-neutrinos + 42.8 MeV

$^{40}K \rightarrow {}^{40}Ca + e^- +$ 1 anti-neutrino + 1.32 MeV

$$\bar{\nu}_e + p \rightarrow e^+ + n - 1.806\,\mathrm{MeV}$$

**Energy threshold** $T_{geo\text{-}\nu}$ = 1.8 MeV

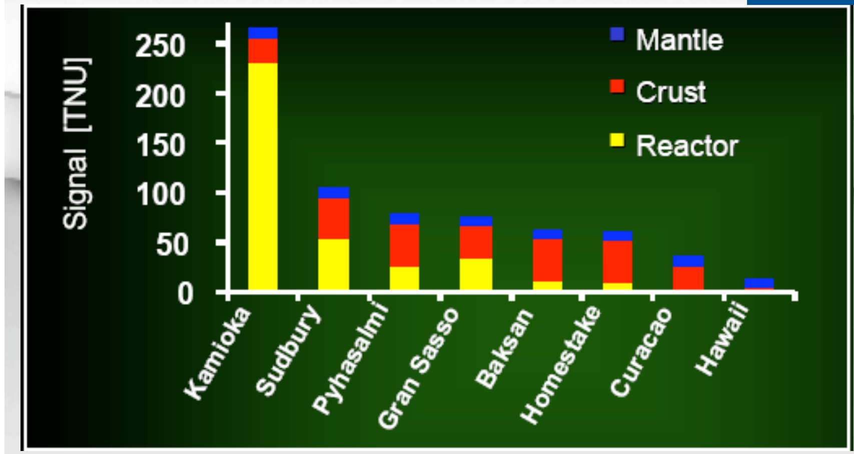



neutron thermalization up ~ 1 m; $\Delta t$~260 $\mu$s

# Background sources: reactor antineutrinos and inter. radioactivity

## Reactors




Flux calculation takes into account:

- Thermal power vs time
- Power fraction of isotopes
- Average distance to the detector
- $\bar{\nu}$ survival probability

**Borexino**

→ Dec.2007-Dec.2008-- 537.2 live-days
194 (Europe)+245(world-only 2.5%)
IAEA and EDF
→ Aver. Dist: 1000 km
@ Expected flux: 9.4±0.6 events

**Kamland**

→ March 2002-Nov.2009--2135 live-days
all Japan power stations
Japan electric power companies
→ Aver. Dist.: 200 km
@ Expected flux: 484.7±26.5 events

**Internal radioactivity: ($\alpha$,n), accidental coincidences, radioactive cosmogenic nuclides.**

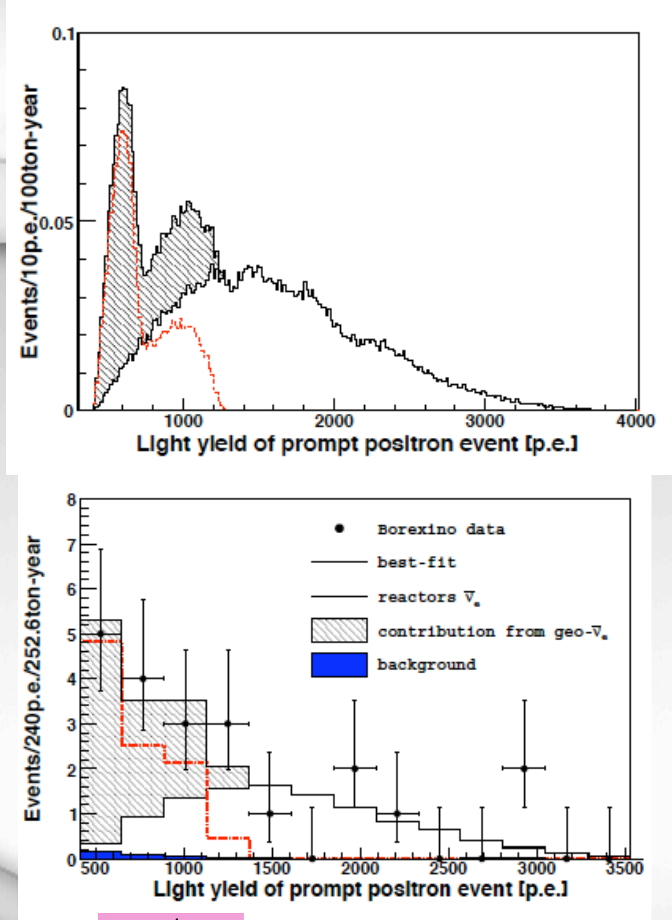
@ 0.42±0.56 events

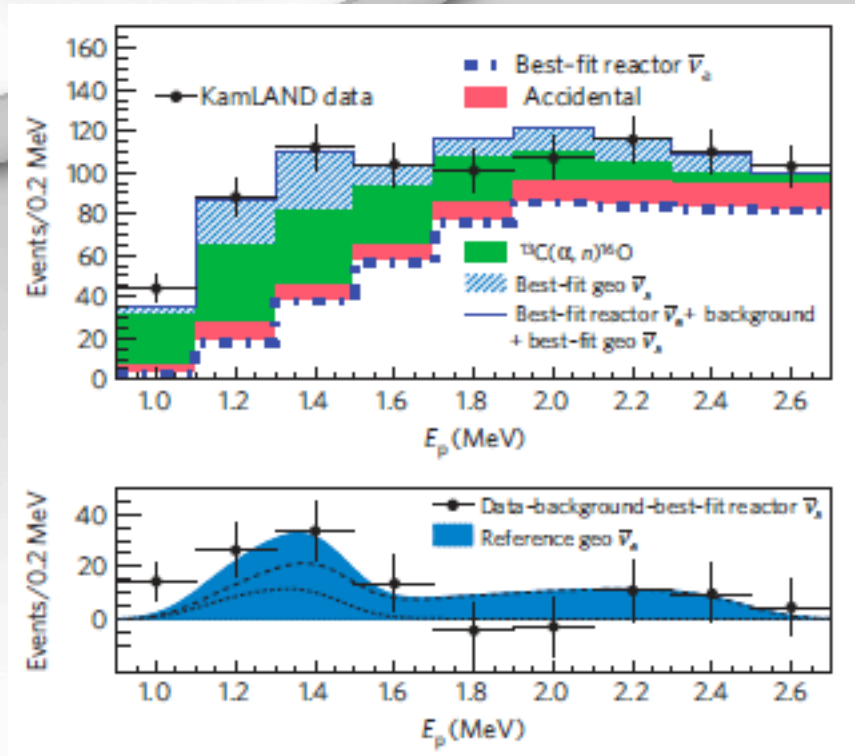
@ 244.7± 18.4 events

Continental crust

Oceanic crust

Different contribution from the crust and sediment; regional geology needed



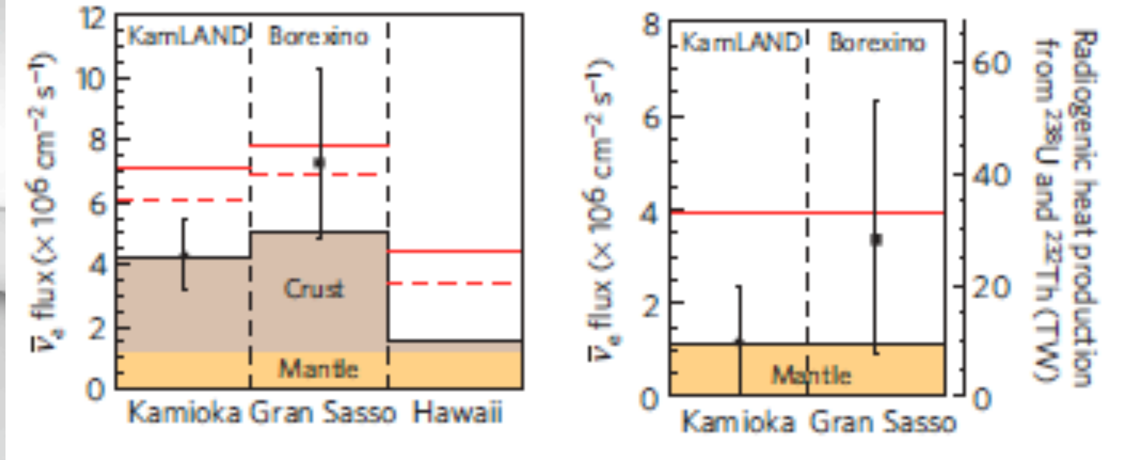




Geo$\nu$: $9.9\left\langle\begin{matrix}+4.1\\-3.4\end{matrix}\right.$

Geo$\nu$: $111\left\langle\begin{matrix}+45\\-43\end{matrix}\right.$

Null hypothesis disfavored at 4.2 $\sigma$ in both cases

Kamland has carried out a comparison between BSE and Kl and Bx results




Red lines: maximum radiogenic.
The uncertainties of the model are not included

Assumption in agreement with the BSE: Th:U=3.9 , composition of the Crust. U and Th distributed uniformly in the mantle.
@ From the composition of the two results we can obtain a prevision for the

radiogenic heat: $\boxed{20\langle^{8.8}_{-8.6} TW}$

More statistic is needed: Borexino with a s/n=3:1 in the geo-neutrino window and 5:1 in the region of the Th+U maximum has a large room to improve its sensitivity accumulating statistics. Already now the statistics is doubled with respect the results just shown.

# Conclusions

1. $^{7}Be$ and $^{8}B$ solar $\nu$ flux  measurements now well robust
2. First measurement of the pep flux, first limit on CNO and strong constraints on pp flux already achieved
3. MSW-LMA model now validated at low energy- the transition region needs more statistics measurements (NSI);
   LMA solution isolated by the solar $\nu$ only.
4. Experimental measurements not useful for the moment in helping to solve the metallicity puzzle.
5. Good determination of the Vacuum/Matter survival probabilities.
6. Evidence of geo-antineutrinos very robust. More statistics needed to obtain a clear determination of the radiogenic contribution to the terrestrial caloric energy
7. Borexino is doing a new purification campaign: results very promising
   The goal is the measurement of pep flux with reduced errors and hopefully the CNO flux