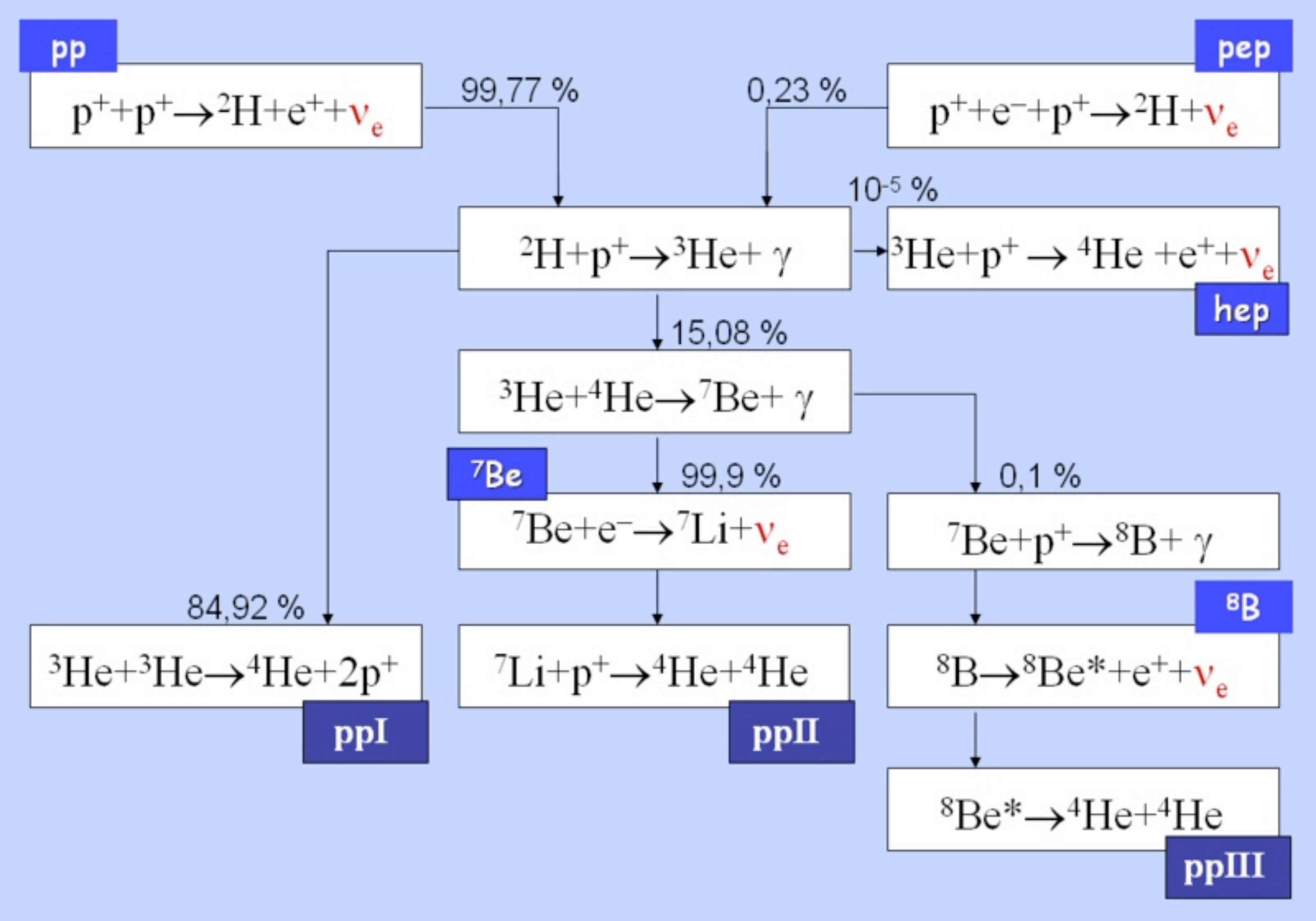
"Study in real time of the neutrino interactions, at a few MeV of Energy, with Borexino"

1. What Borexino is?
2. Results and perpectives on the ν physics
3. Results on the geoneutrinos

Gianpaolo Bellini
Universita' di Milano and Istituto Nazionale di Fisica Nucleare

Solar Standard Model



pp

$p^+ + p^+ \rightarrow {}^2H + e^+ + \nu_e$

99,77 %

pep

$p^+ + e^- + p^+ \rightarrow {}^2H + \nu_e$

0,23 %

$^2H + p^+ \rightarrow {}^3He + \gamma$

10^{-5} %

$^3He + p^+ \rightarrow {}^4He + e^+ + \nu_e$

hep

15,08 %

$^3He + {}^4He \rightarrow {}^7Be + \gamma$

7Be

99,9 %

$^7Be + e^- \rightarrow {}^7Li + \nu_e$

0,1 %

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

8B

84,92 %

$^3He + {}^3He \rightarrow {}^4He + 2p^+$

ppI

$^7Li + p^+ \rightarrow {}^4He + {}^4He$

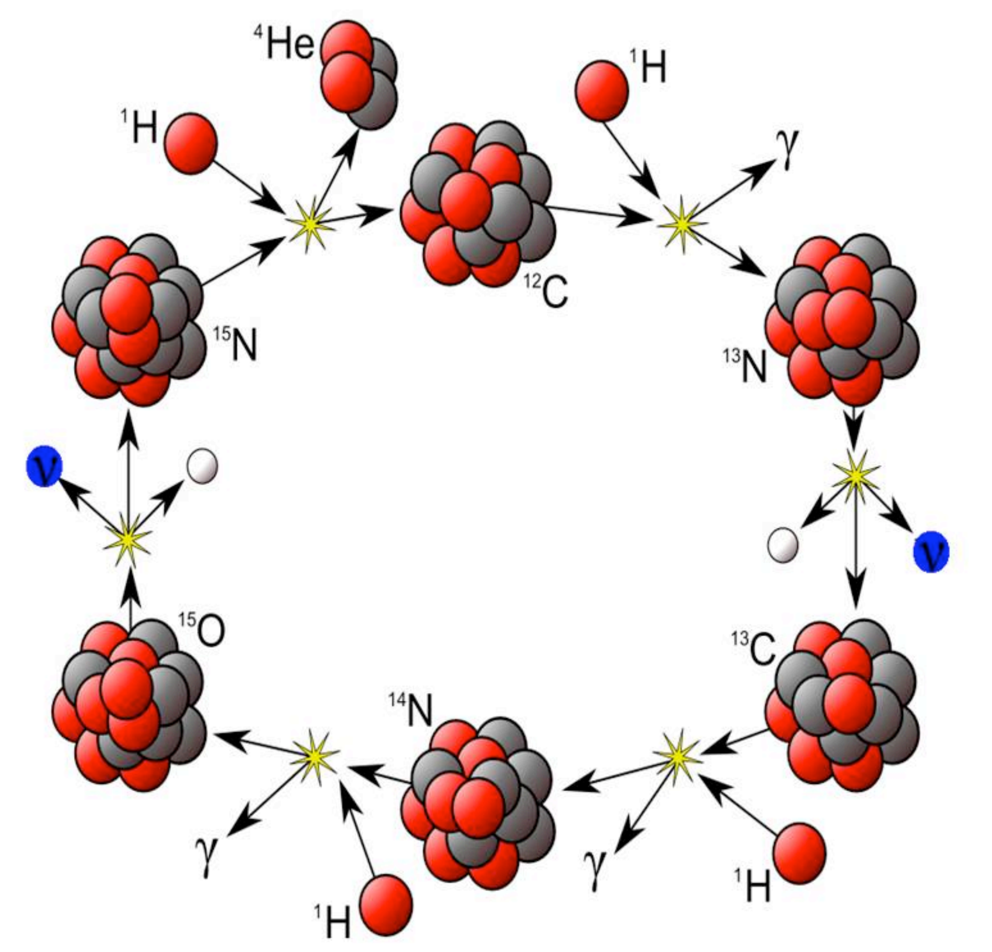
ppII

$^8B \rightarrow {}^8Be^* + e^+ + \nu_e$

$^8Be^* \rightarrow {}^4He + {}^4He$

ppIII

CNO chain



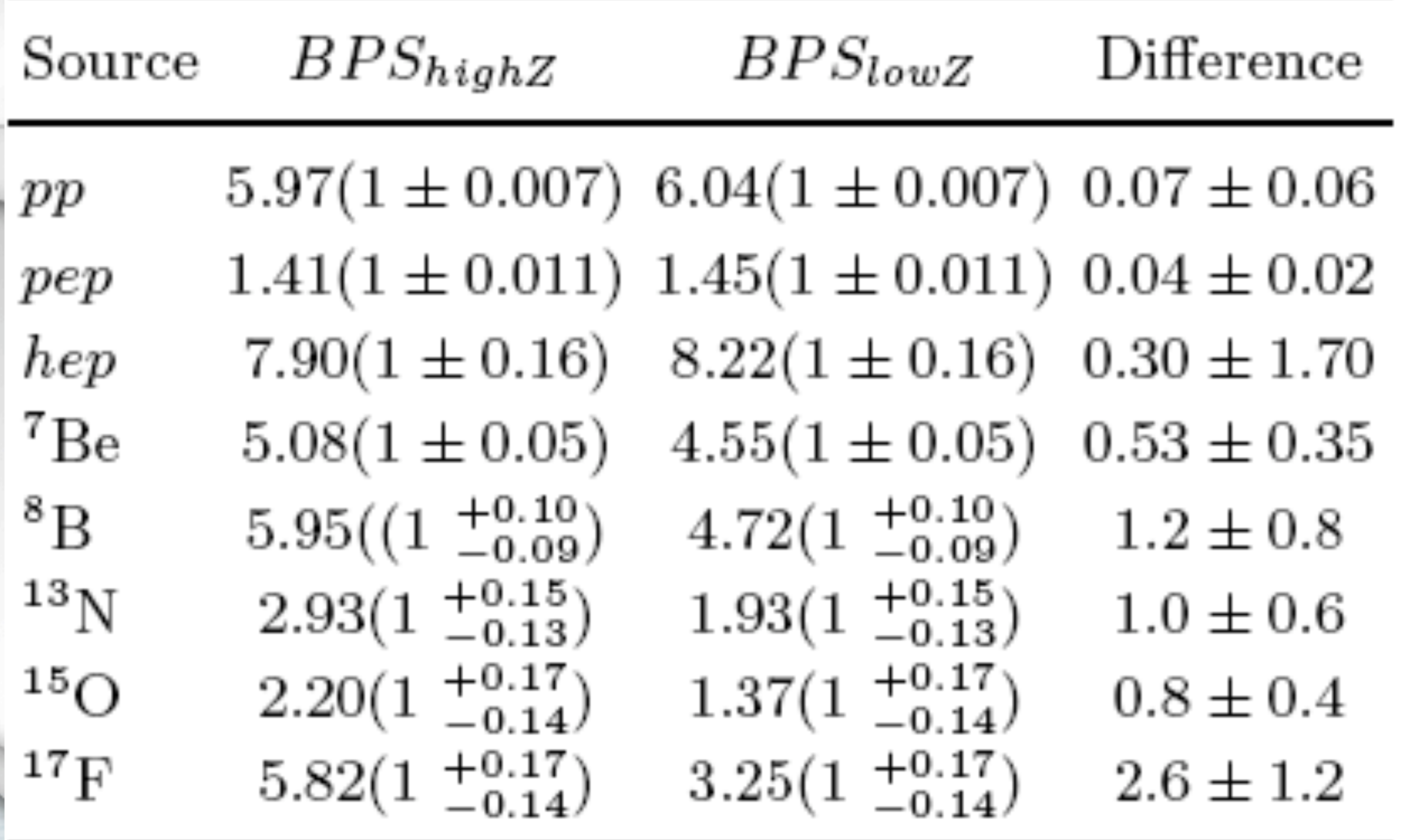
Metallicity

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.



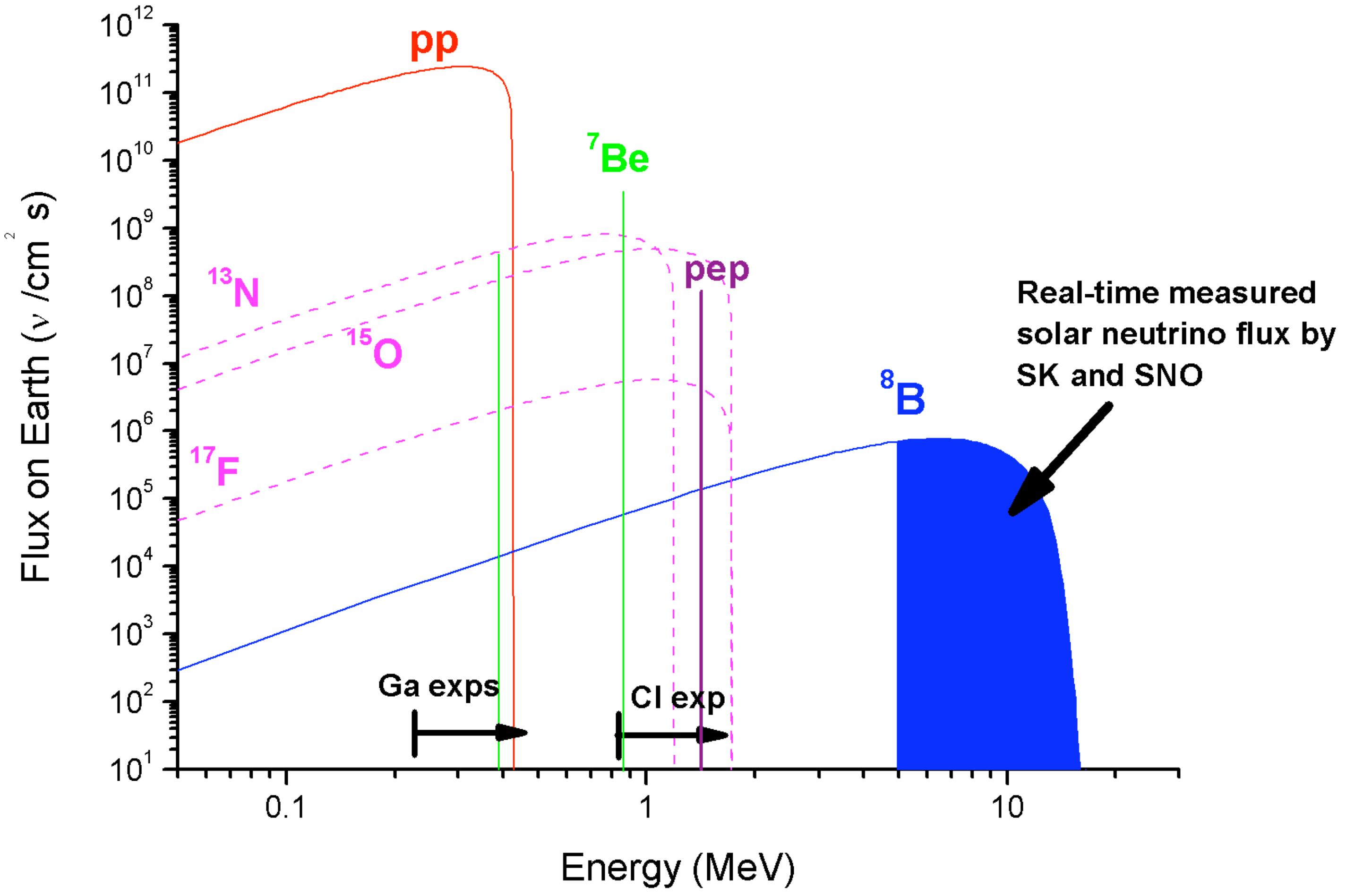
Source	BPS_{highZ}	BPS_{lowZ}	Difference
pp	$5.97(1 \pm 0.007)$	$6.04(1 \pm 0.007)$	0.07 ± 0.06
pep	$1.41(1 \pm 0.011)$	$1.45(1 \pm 0.011)$	0.04 ± 0.02
hep	$7.90(1 \pm 0.16)$	$8.22(1 \pm 0.16)$	0.30 ± 1.70
^{7}Be	$5.08(1 \pm 0.05)$	$4.55(1 \pm 0.05)$	0.53 ± 0.35
^{8}B	$5.95((1 \ {}^{+0.10}_{-0.09})$	$4.72(1 \ {}^{+0.10}_{-0.09})$	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

Before Borexino

99.994% of solar neutrino spectrum is NOT measured yet in real-time mode



Real-time measured solar neutrino flux by SK and SNO

Neutrino oscillations

$$|\nu_\alpha\rangle = \sum_i U_{\alpha,i}|\nu_i\rangle$$

ν_α, flavor eigenstates
ν_i, mass eigenstates
$U_{\alpha,i}$, mixing matrix

Two neutrino scenario

IN VACUUM

$$P(\nu_e \rightarrow \nu_\mu) = \sin^2 2\theta \cdot \sin^2\left(\Delta m^2 \frac{L}{4E}\right)$$

$$L_V = \frac{4\pi E}{\Delta m^2}$$

IN MATTER

ν_e interacts via charged current and neutral current
$\nu_{\mu,\tau}$ interact only via neutral current

A weak interacting potential $V_W = \sqrt{2}G_F n_e$ must be considered
n_e= electron density

$$P(\nu_e \rightarrow \nu_\mu) = \sin^2 2\theta_M \cdot \sin^2\left(\Delta m_M^2 \frac{L}{4E}\right)$$

$$\sin^2 2\theta_M = \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - X)^2}$$

If X=cos2θ -maximum mixing
$P(\nu_e \rightarrow \nu_\mu)$ increases-
resonance effect

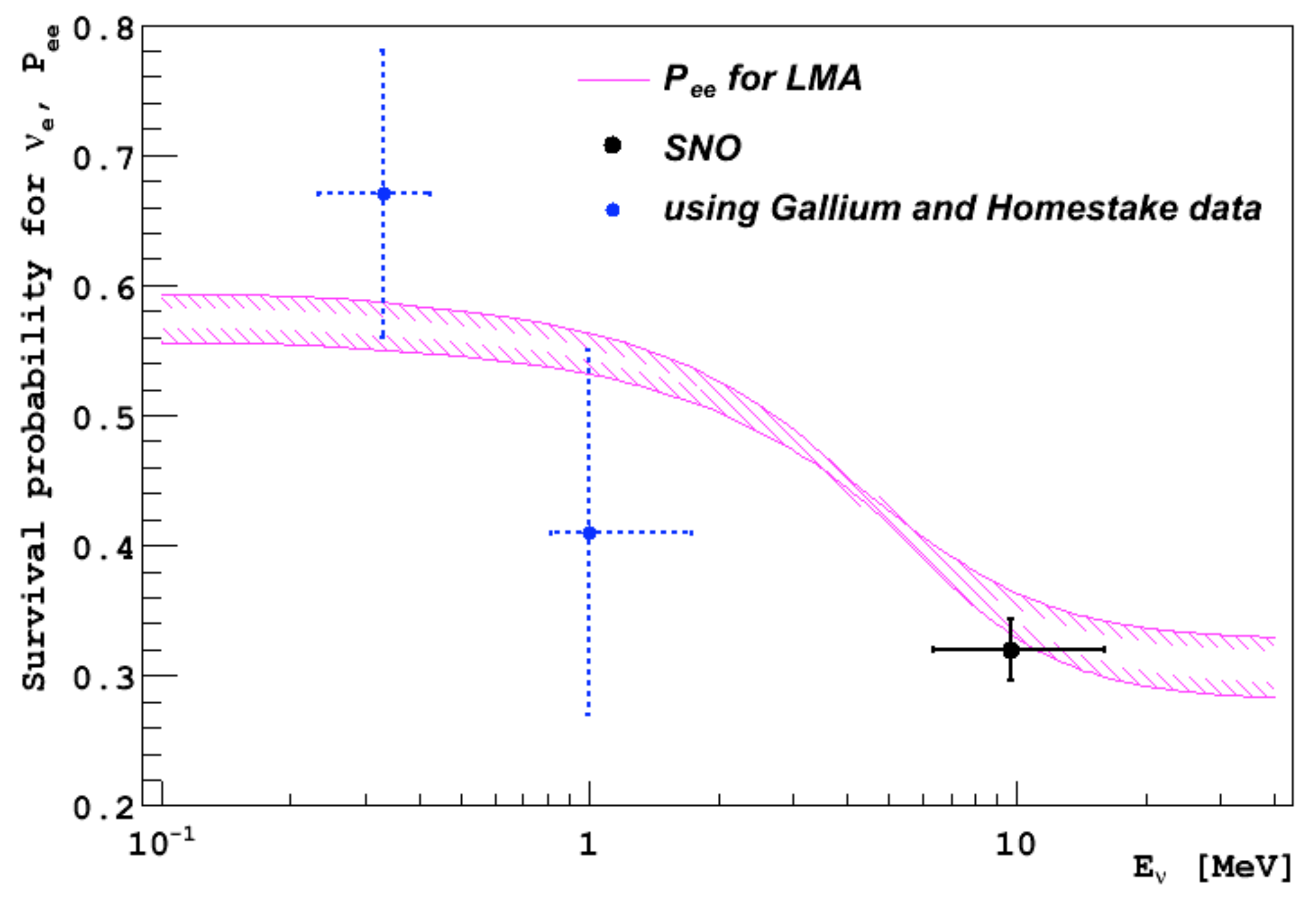
$4\pi E/\Delta m^2$

$$L_M = \frac{4\pi E}{\Delta m_M^2} = \frac{L_V}{\sqrt{\sin^2 2\theta + (\cos 2\theta - X)^2}}$$

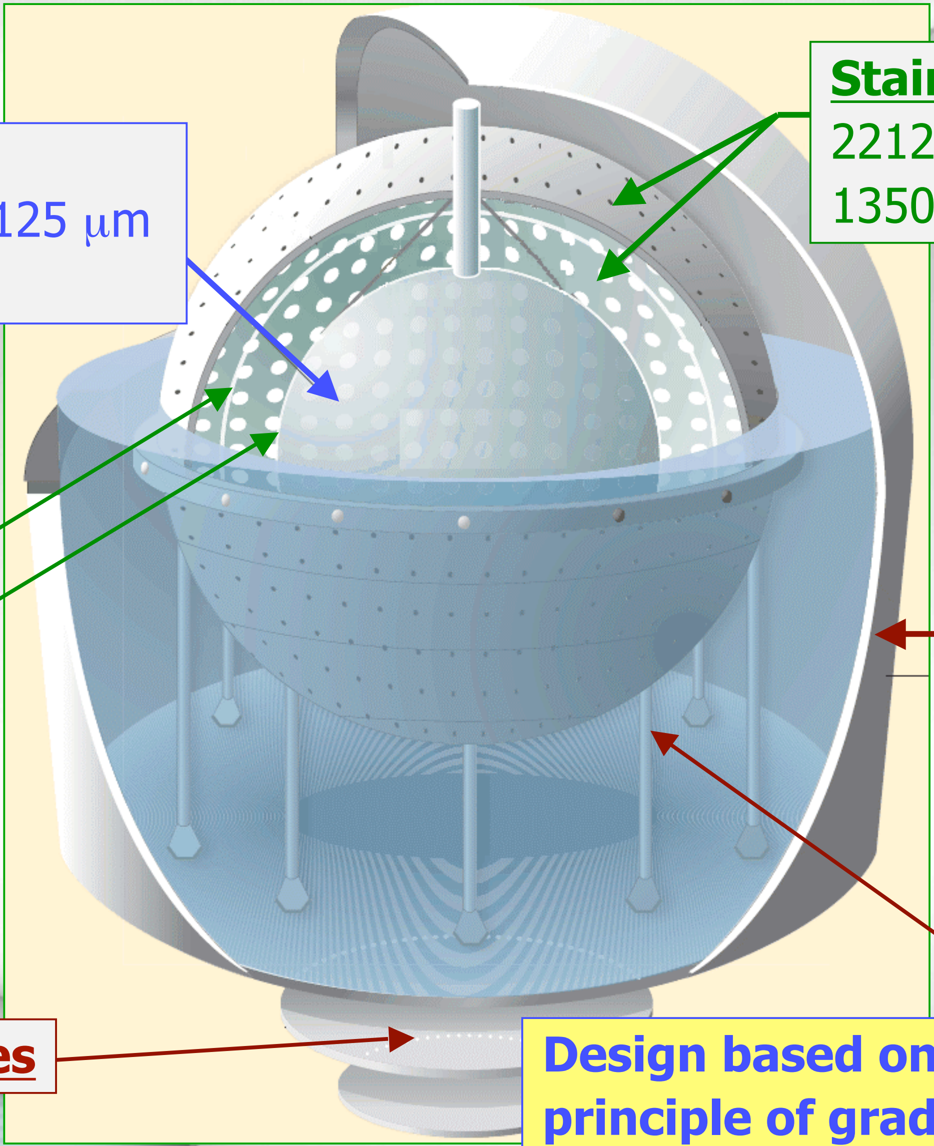
$$X = \frac{2\sqrt{2}G_F n_e E}{\Delta m^2}$$

Before Borexino

MSW-LMA $\Delta m^2 = 7.69 \cdot 10^{-5} eV^2$ $\tan^2\theta = 0.45$



Detector design and layout



Scintillator:
270 t PC+PPO in a 125 μm thick nylon vessel

Stainless Steel Sphere:
2212 photomultipliers
1350 m^3

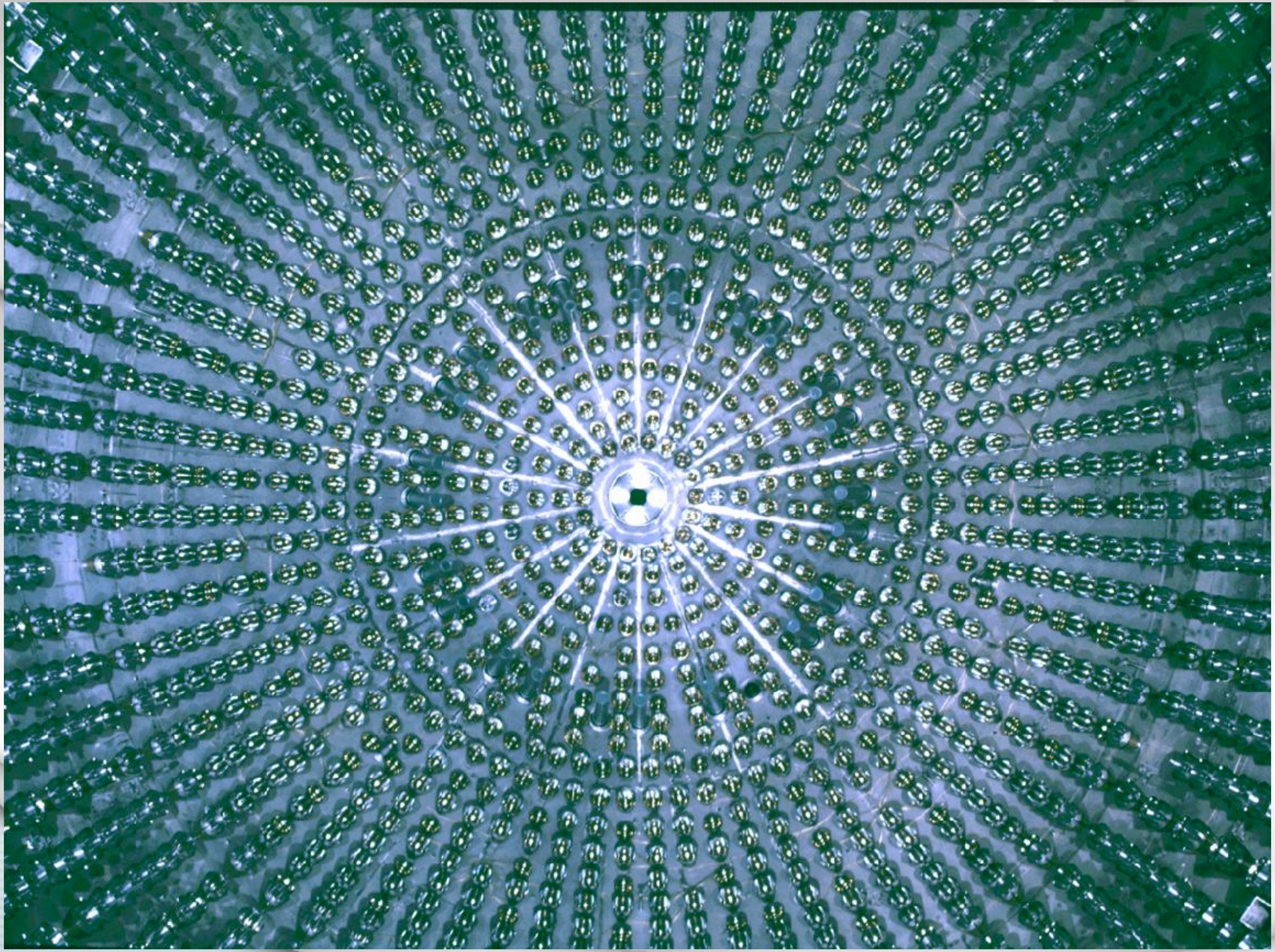
Nylon vessels:
Inner: 4.25 m
Outer: 5.50 m

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

20 legs

Carbon steel plates

Design based on the principle of graded shielding



Filled detector

PC filling completed
May 15th, 2007

Very high radiopurity- special methods and tools developed

>Cleaning scintillator : PC: water extraction,distillation (80 mbar,90-95 ^{0}C), nitrogen stripping, ultrafine filtration-master sol.

>Ultrapure N_2 for stripping: ultrapure Nitrogen: Rn< 0.1 μBq/m^3
LAK Nitrogen: 0.01 ppm Ar, 0.03 ppt Kr

>Special care in the PC procurement: old layers crude oil, special loading station directly connected to the production plant, special shipping vessels, special unloading station, rapid transport to the underground lab to avoid cosmogenic production of radioactive nuclides (^{7}Be)

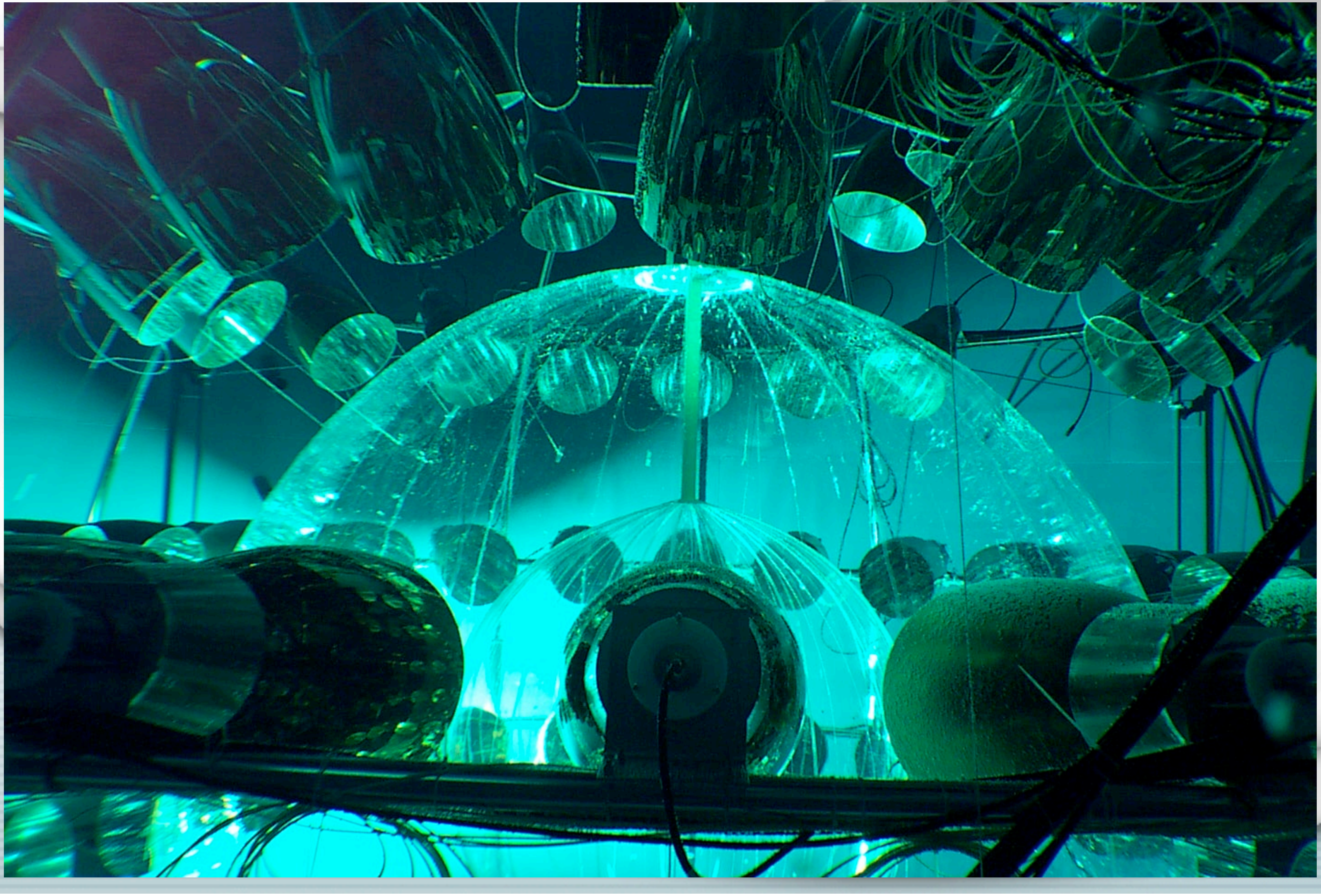
>Extreme precaution in the fabrication and assembly of the Nylon Vessels: selection and extrusion of the materials in controlled area, construction in clean room with Rn control,special bags for shipping

>All surfaces electropolished: detector components, lines, fittings,valves

>Special developments and selection of the components (as the PMTs),

>Any operation in clean room or in N_2, Ar atmosphere

To check ultra-low radioactive levels a very high sensitivity detector has has been installed -- sensitivity: down to 5 10^{-16}g/g U,Th equivalent; $\approx 10^{-18}\ {}^{14}C/{}^{12}C$



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 $\sim 30\ \mu Bq/m^3$ $\sim 10^{-14}\ g/g$

Solar neutrinos

Goals

1-To measure the various solar neutrinos fluxes: ^{7}Be,pep,pp,^{8}B (CNO is very difficult-try to measure a constraining limit),and other effects (day/night)

↓

Check the oscillation model in the vacuum regime and in the transition region (this one sensitive to possible non standard interactions)

2-Reproduce the seasonal variation of the solar flux (±3%)

Results already achieved

First measurement of the ^{7}Be flux and of the ^{8}B flux with a lower threshold down to 3.0 MeV

↓

First data confirming the vacuum regime- measure of the vacuum-matter survival probabilities

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

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

$\Phi(^{7}Be) = (5.12 \pm 0.51) \times 10^{9} cm^{-2} s^{-1}$ SSM; H.M.$(5.08 \pm 0.56) \times 10^{9} cm^{-2} s^{-1}$

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

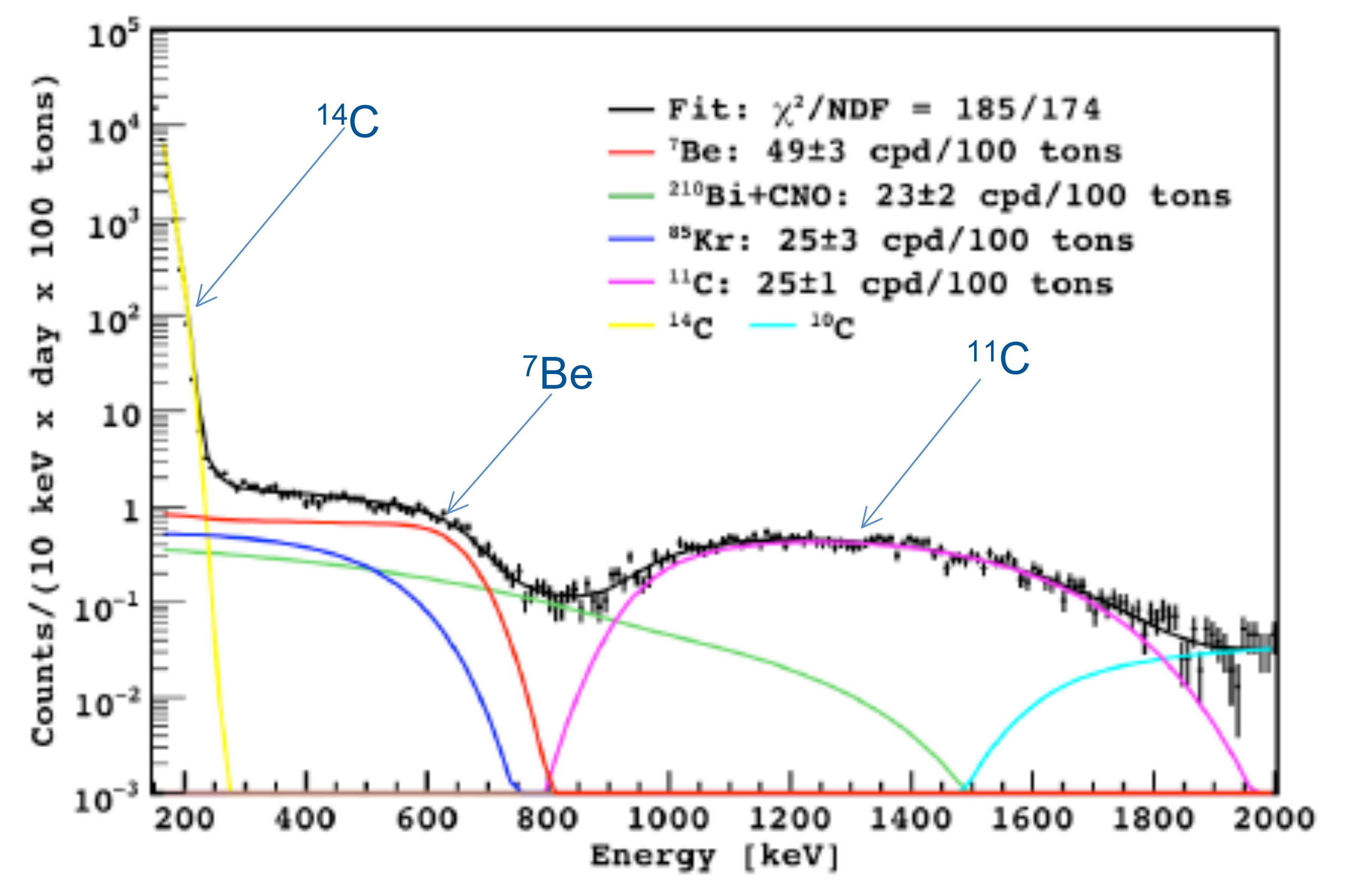
Main cuts:

-fiducial volume

–μ cut + 2 mms dead time

-^{214}Bi-^{214}Po rejection to cut ^{222}Rn

-α/β discrimination



P.Rev.Lett.101,2008

α/β discrimination- Gatti parameter

$G_\alpha = \sum_i P_i \beta_i$

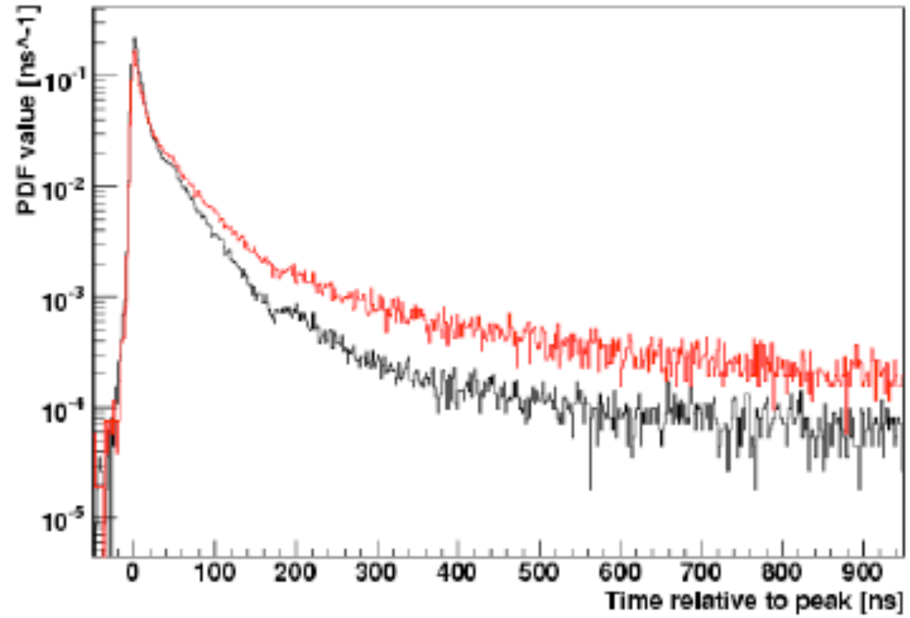
$G_\beta = \sum_i P_i \alpha_i$

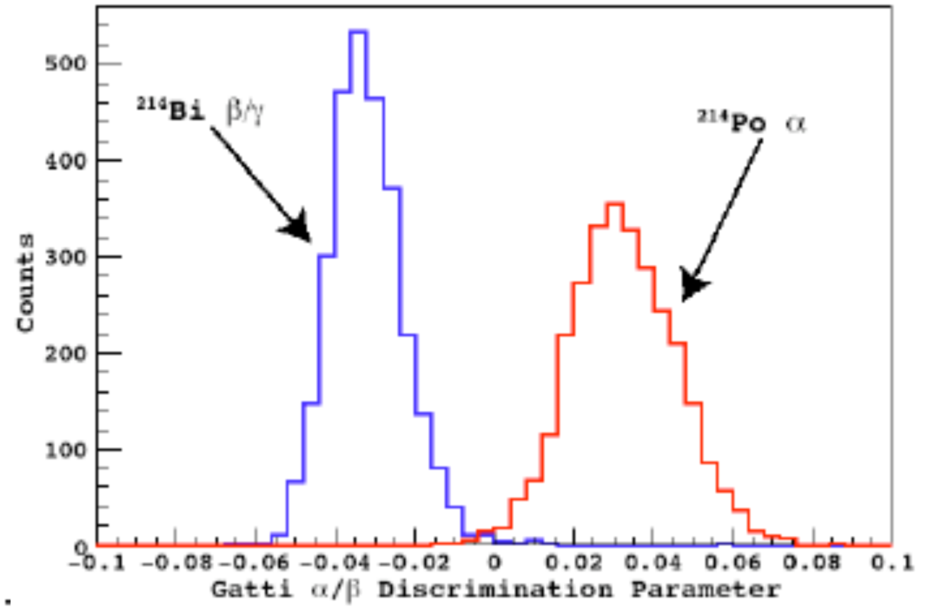
α_ι,β_ι–>n. p.e. for the indiv. shape within a given Δt (2 ns)

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

$\bar{\alpha}_i, \bar{\beta}_i$ –>av. shape of current pulses (pdf)

Alpha and beta event PDFs from BiPo-214's





This analysis for the reference curves has been done during the filling period, when ^{222}Rn was present

Next goal: @ measure the ^{7}Be flux with a total error < 5%
@ data from 390-750 live days of data taking

But the main gain is due to the reduction of the systematic errors (definition of the fiducial volume and energy scale)

Calibration campaign (in 2009)

External sources inserted in the detector at various positions:

8 gamma sources (^{57}Co,^{139}Ce,^{203}Hg,^{85}Sr,^{54}Mn,^{65}Zn,^{40}K,^{60}Co)

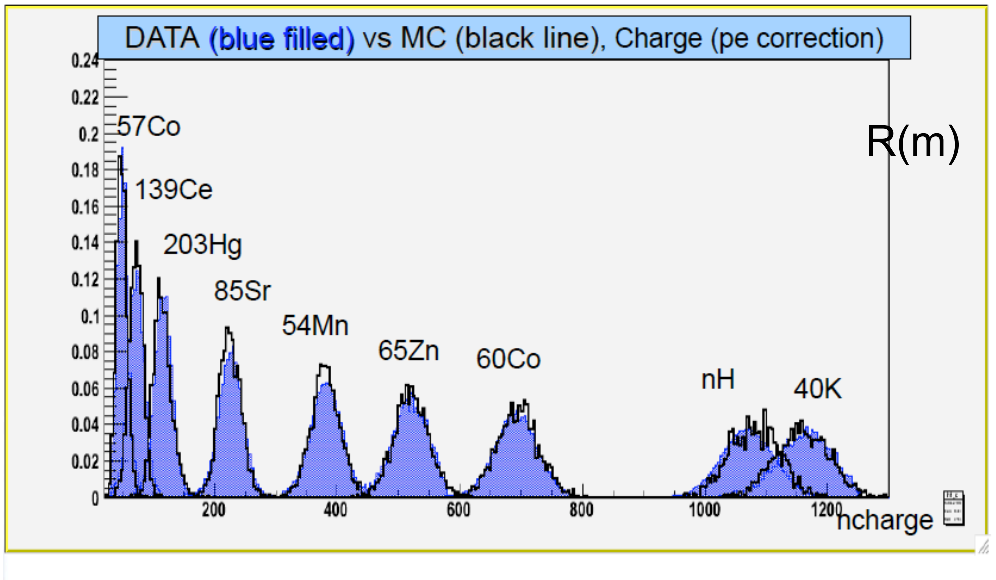
energy range up to 2 MeV

plus a neutron source (Am-Be) with capture gammas (H,^{12}C,^{56}Fe,^{54}Fe)

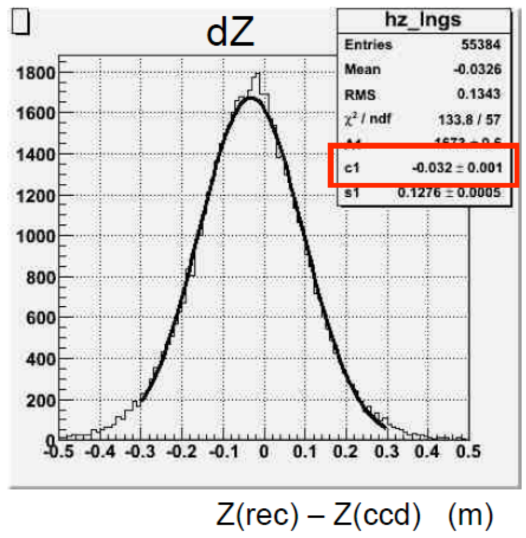
2-10 MeV

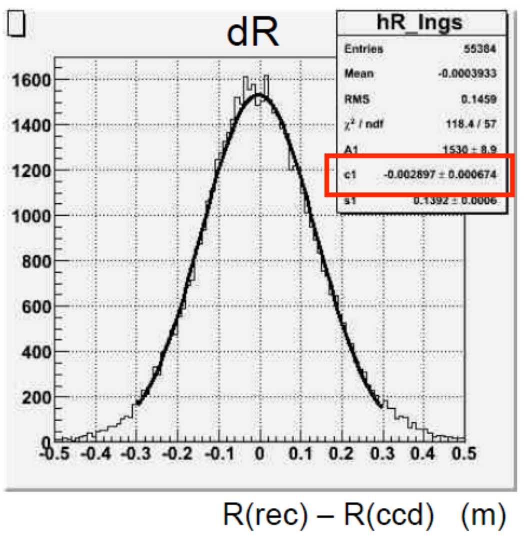
Checks of the reconstruction codes and MC tuning

Low energy (0.14-2 MeV)



Systematic errors-
± 1.5% for both the energy scale
and the fiducial volume
(from the previous ±6%)



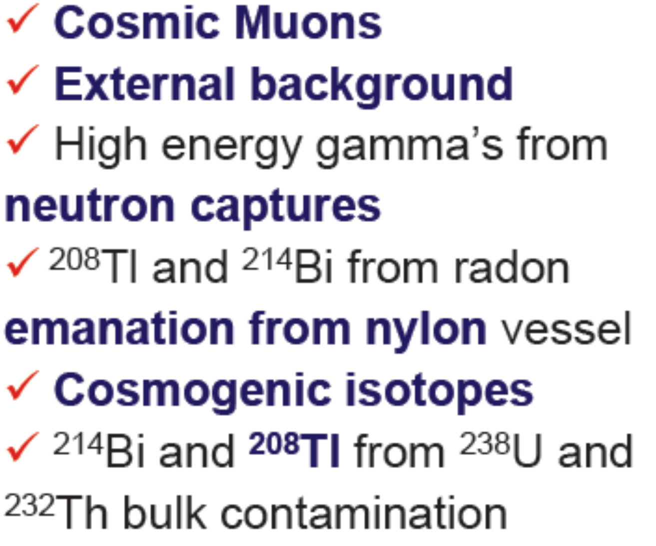


Over 2 MeV

A little worse due to the less accuracy in the calibration

^{8}B with lower threshold at 3 MeV (488 live days)

Background in the 3.0-16.5 MeV energy range



✓ **Cosmic Muons**

✓ **External background**

✓ High energy gamma's from **neutron captures**

✓ ^{208}Tl and ^{214}Bi from radon **emanation from nylon** vessel

✓ **Cosmogenic isotopes**

✓ ^{214}Bi and **^{208}Tl** from ^{238}U and ^{232}Th bulk contamination

Cuts

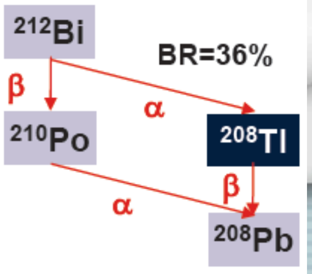
@**Muon cut + 2 mms** dead time to reject induced **neutrons** (240 μs)

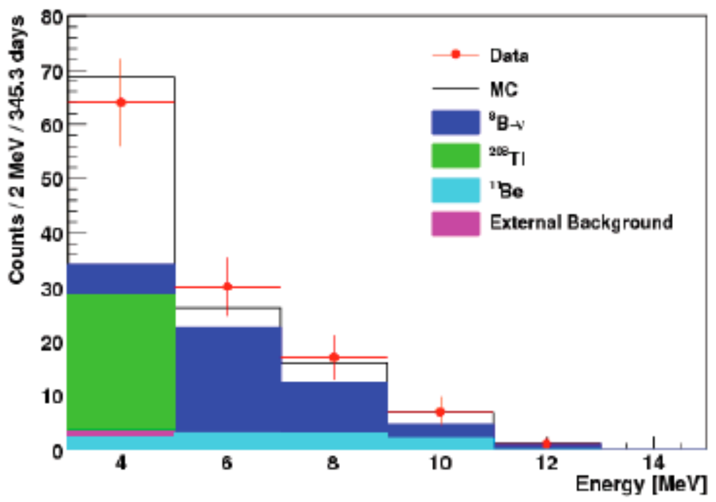
@**Fiducial volume**

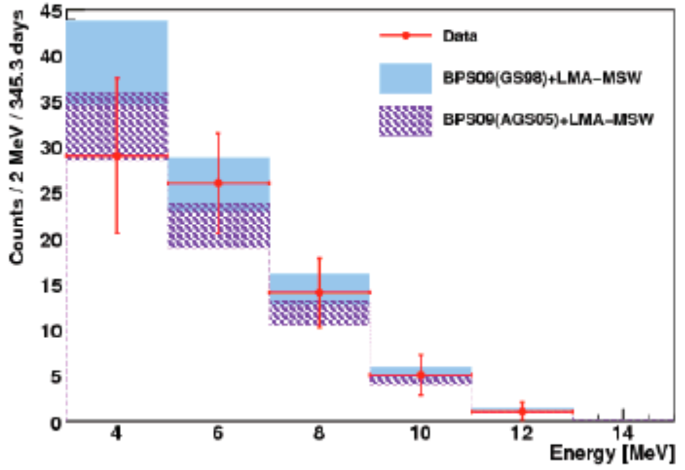
@**Muon** induced radioactive **nuclides:**6.5 s veto after each crossing muon (~30% dead time)-^{10}C (τ=27.8 s) tagged with the **Three-fold coincidence** with the μ parent and the neutron capture)-^{11}Be (τ=19.9 s) statistically subtracted

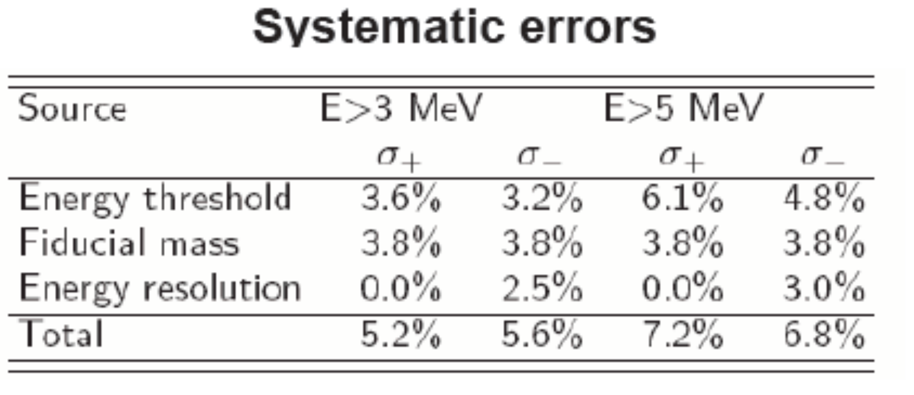
@^{214}Bi-^{214}Po coincidences rejected (τ=237 μs-^{222}Rn daughter)

@^{208}Tl from ^{212}Bi-^{212}Po (B.R.64%-τ=431ns)we evaluate the ^{208}Tl production via



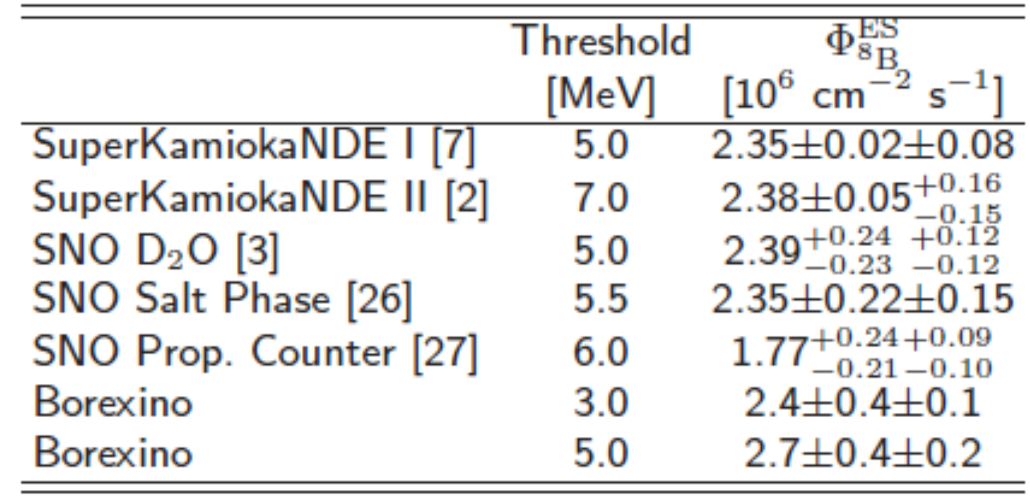






Systematic errors

Source	E>3 MeV		E>5 MeV	
	σ_+	σ_-	σ_+	σ_-
Energy threshold	3.6%	3.2%	6.1%	4.8%
Fiducial mass	3.8%	3.8%	3.8%	3.8%
Energy resolution	0.0%	2.5%	0.0%	3.0%
Total	5.2%	5.6%	7.2%	6.8%

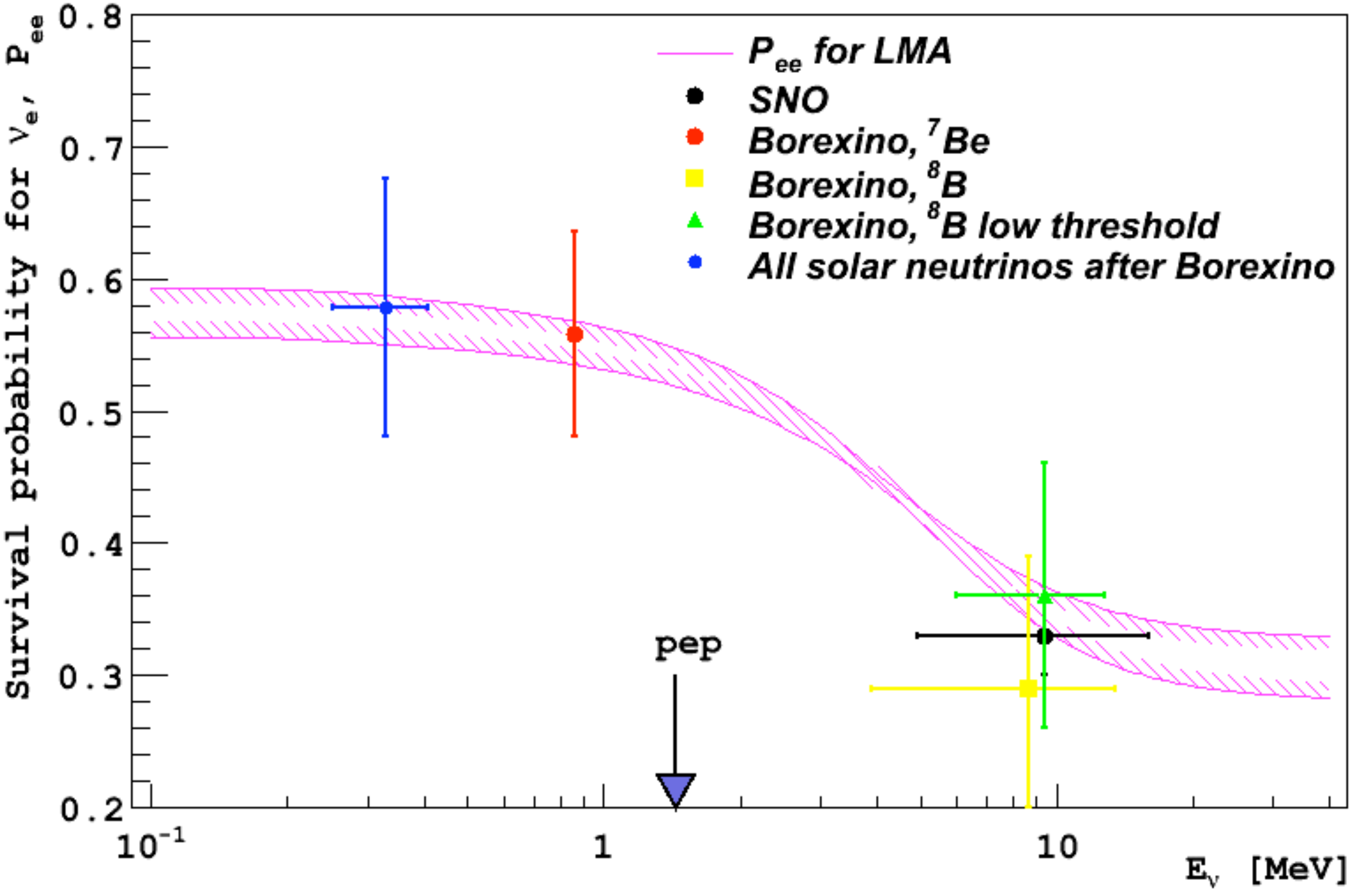


	Threshold [MeV]	$\Phi^{\mathrm{ES}}_{^8\mathrm{B}}$ [10^6 cm^{-2} s^{-1}]
SuperKamiokaNDE I [7]	5.0	$2.35 \pm 0.02 \pm 0.08$
SuperKamiokaNDE II [2]	7.0	$2.38 \pm 0.05^{+0.16}_{-0.15}$
SNO D_2O [3]	5.0	$2.39^{+0.24}_{-0.23}\ ^{+0.12}_{-0.12}$
SNO Salt Phase [26]	5.5	$2.35 \pm 0.22 \pm 0.15$
SNO Prop. Counter [27]	6.0	$1.77^{+0.24}_{-0.21}\ ^{+0.09}_{-0.10}$
Borexino	3.0	$2.4 \pm 0.4 \pm 0.1$
Borexino	5.0	$2.7 \pm 0.4 \pm 0.2$

SSM; H.M.(2.7±0.3) x10^{6}cm^{-2}s^{-1}
L.M.(2.2 ±0.2) x10^{6}cm^{-2}s^{-1}

To be published in Phys. Rev.D

After two years of Borexino data taking



P_{ee}(Vac) - P_{ee}(matter)= 0.27 (1.9σ)

The day night asymmetry in the ^{7}Be energy region

$$ADN = \frac{N-D}{(N+D)/2}$$

N = ν_e flux during night time (average over 1 year)
D = ν_e flux during day time (average over 1 year)

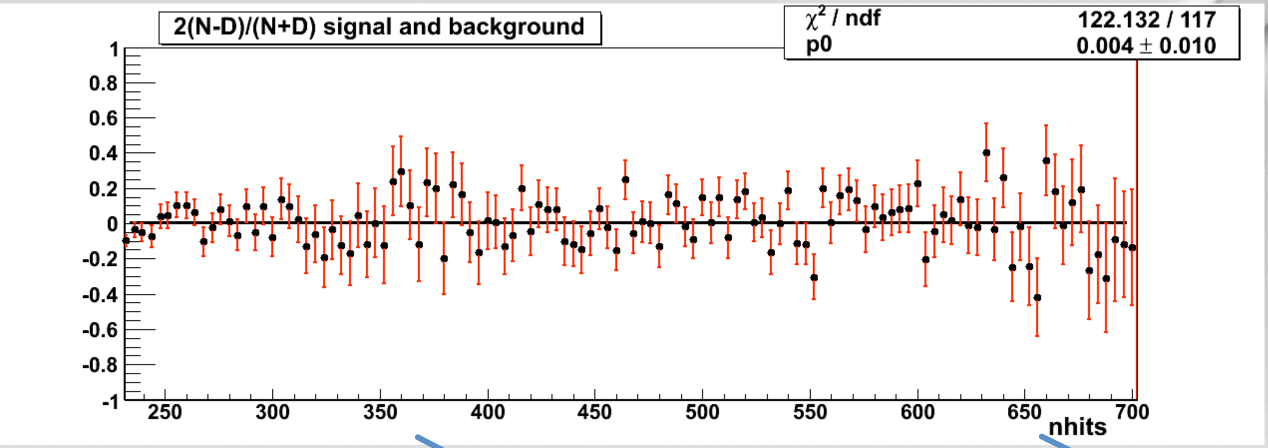
- MSW mechanism: ν_μ interaction in the Earth could lead to a ν_e regeneration effect
- Solar ν_e flux higher in the night than in the day ; the amount of the effect depends on the detector latitude, the oscillation parameter values and the energy of the neutrinos;
- Present LMA solution : a very small effect is expected

Analysis on Borexino

Be7 Day spectrum 387.46 days
Be7 Night spectrum 401.57 days
Statistical error 2.3 c/d100t
The 7Be flux is obtained from the separate full fits of the day and night spectra

$$ADN = \frac{N-D}{(N+D)/2} = 0.007 \pm 0.073\,(stat)$$

Study of systematic effects



Be7 signal region

Background dominated region

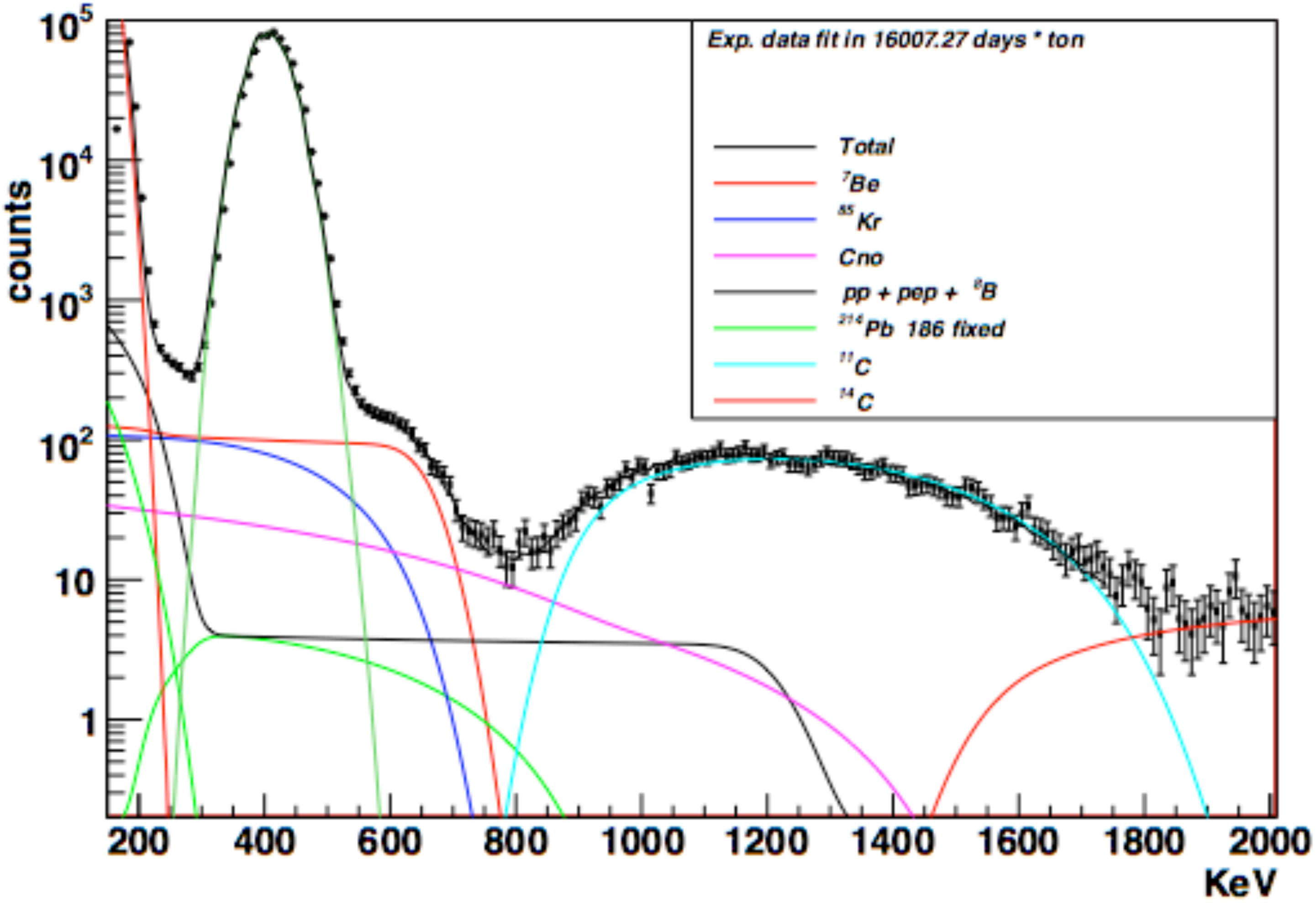
Good validation of the MSW-LMA solution in the vacuum regime from the Borexino analysis

•LMA and LOW predictions: large difference for the ADN effect and small difference for the 7Be flux; LOW is now already excluded, but Borexino alone could exclude a large portion of the LOW space parameters (without Kamland) .

- Some numbers from J. Bahcall et al., JHEP07(2002)05

Observable	**LMA (±3 σ)**	**LOW (± 3 σ)**
7Be ν-e scattering	$0.64_{-0.05}^{+0.09}$	0.58±0.05
ADN(%) 7Be	$0.0^{+0.1}_{-0.0}$	23^{+10}_{-13}

Study of pp, 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)

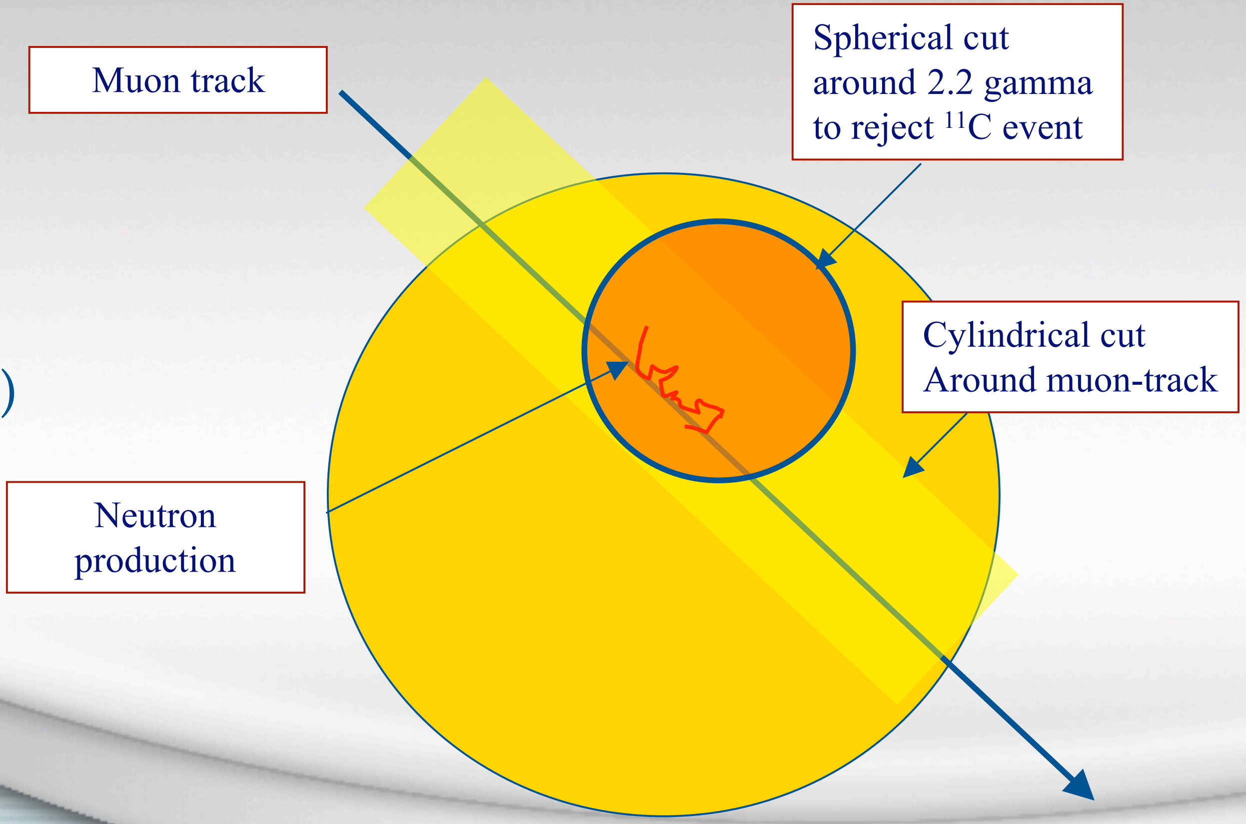
→ ^{11}C is identified at the 95% level- the analysis is still in progress

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

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

n capture

γ (2.2 MeV)



Muon track

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

Cylindrical cut
Around muon-track

Neutron
production

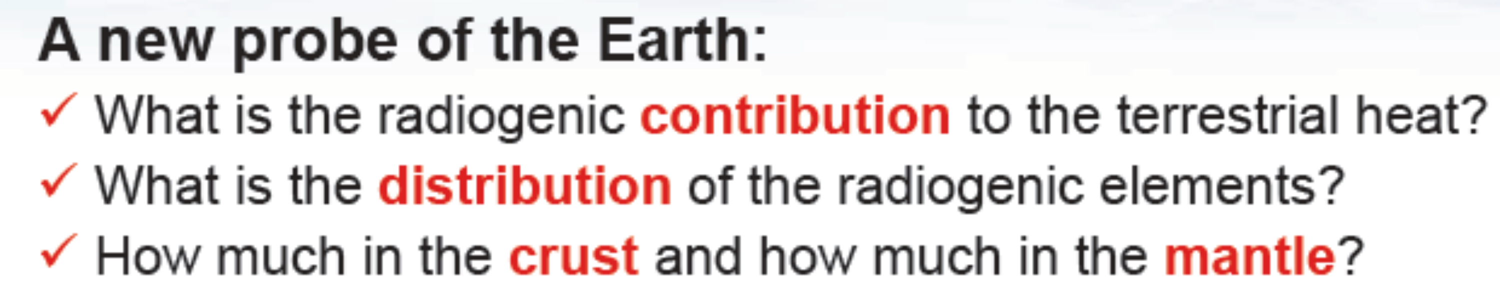
Goal: measure of the pep flux within the fall

The transition region is very sensitive to the effects of possible neutrino non standard interactions.
Then it is very important to measure the pep flux and possibly the ^{8}B flux at low energy.

Various models. Some of them can be already ruled out because they foresee important day/night effects already in the ^{7}Be region.

Geoneutrinos: first actual evidence from Borexino (4.2 σ)

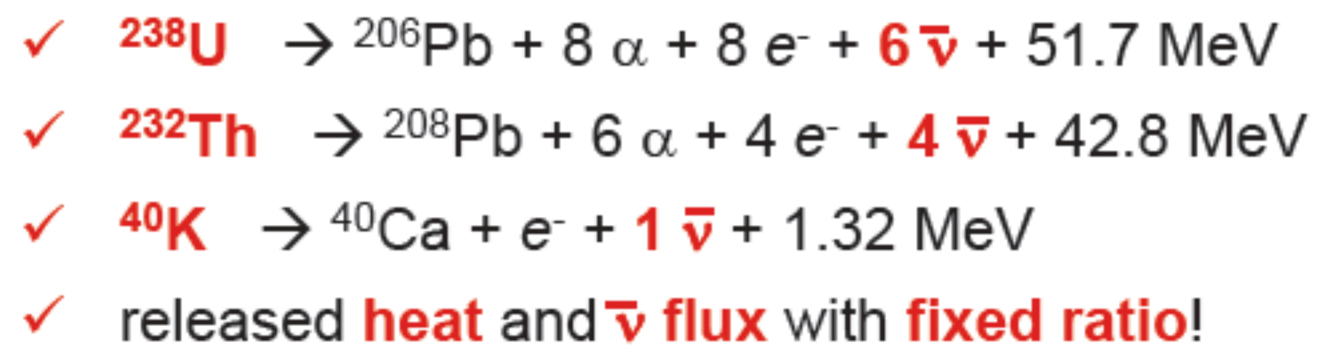
Why to study geo-neutrinos?



A new probe of the Earth:

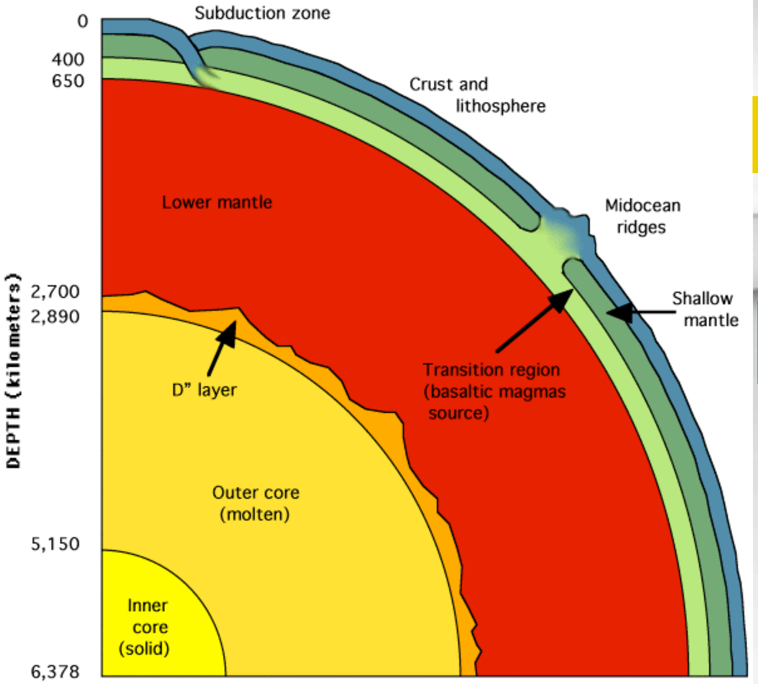
- ✓ What is the radiogenic **contribution** to the terrestrial heat?
- ✓ What is the **distribution** of the radiogenic elements?
- ✓ How much in the **crust** and how much in the **mantle**?

^{238}U, ^{232}Th chains, ^{40}K ($T_{1/2}$ = (4.47, 14.0, 1.28) x 10^9 years, resp.):



- ✓ $^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8\,\alpha + 8\,e^- + 6\,\bar{\nu} + 51.7\ \mathrm{MeV}$
- ✓ $^{232}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb} + 6\,\alpha + 4\,e^- + 4\,\bar{\nu} + 42.8\ \mathrm{MeV}$
- ✓ $^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + e^- + 1\,\bar{\nu} + 1.32\ \mathrm{MeV}$
- ✓ released **heat** and $\bar{\nu}$ **flux** with **fixed ratio**!

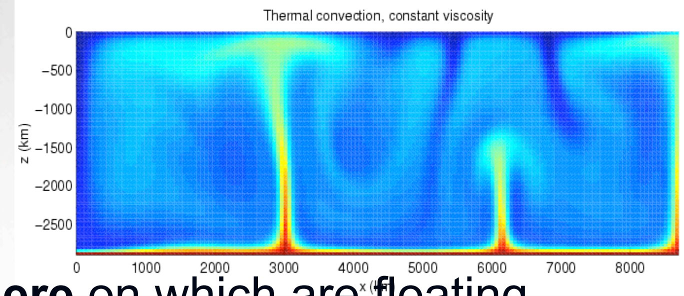
Earth structure



Inner Core- SOLID:
- •Fe – Ni alloy;
- •high pressure of ~ 330 Gpa and high temperature

Outer Core-LIQUID:
- Fe – Ni alloy + + 10% light elements(S, O?);
- temperature ~ 4100–5800 K;

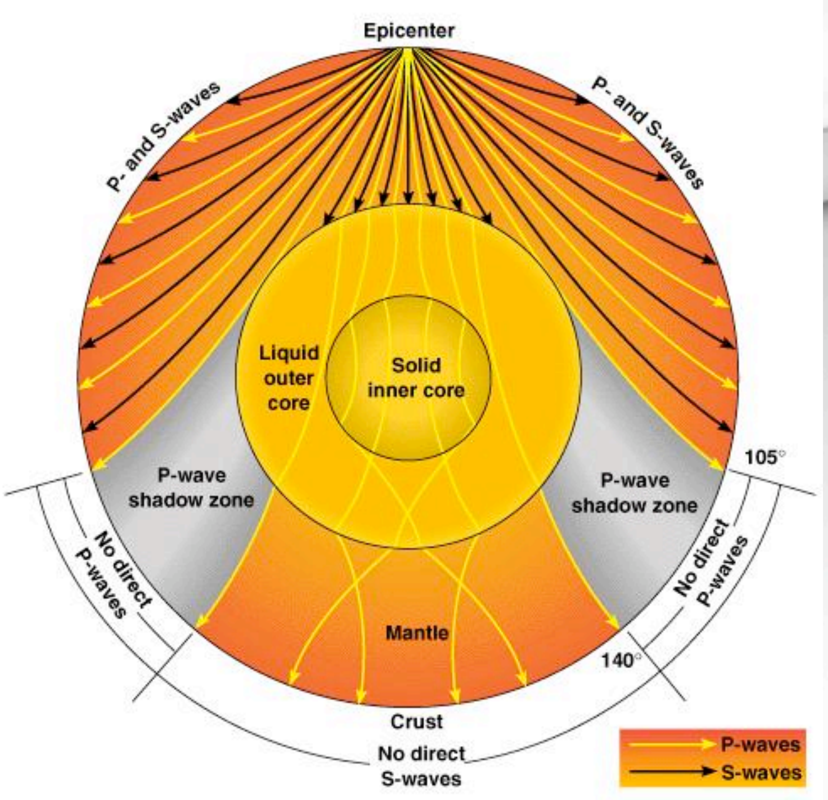
Lower mantle:
- rocks: high Mg/Fe ratio;
- T: 600 – 3700 K;
- high pressure: solid, but viscose; **CONVECTION**



Upper mantle: includes highly viscose **astenosphere** on which are floating litospheric tectonic plates

Crust:
- **OCEANIC CRUST**:created at mid-ocean ridges;~ 10 km thick;
- **CONTINENTAL CRUST**:the most differentiated;30 – 70 km thick; igneous, metamorphic, and sedimentary rocks.

Geophysics



P – primary, longitudinal waves
S – secondary, transverse/shear waves

Geochemistry

1) **Direct rock samples**
- bore-holes; max. 12 km (Russia) in continental crust;
- upper mantle (mid ocean ridges);
- mantle rocks brought up by tectonics and by the vulcanism

2) **Geochemical models:**
- composition of direct rock samples + chondritic meteorites + Sun;

Bulk Silicate Earth (BSE)
- primordial mantle before the crust differentiation and after the Fe-Ni core separation;

How detect the geo-neutrinos in Borexino

Prompt:

$\bar{\nu} + p \rightarrow n + e^+$

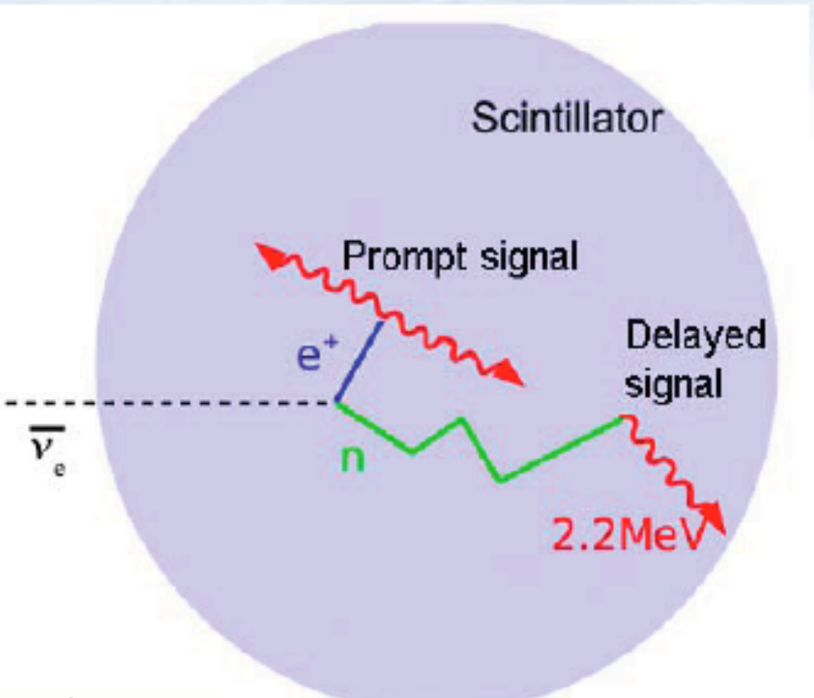
$E_{min}(n) = 1.8$ MeV

Minimum detected energy: **2x511 keV**

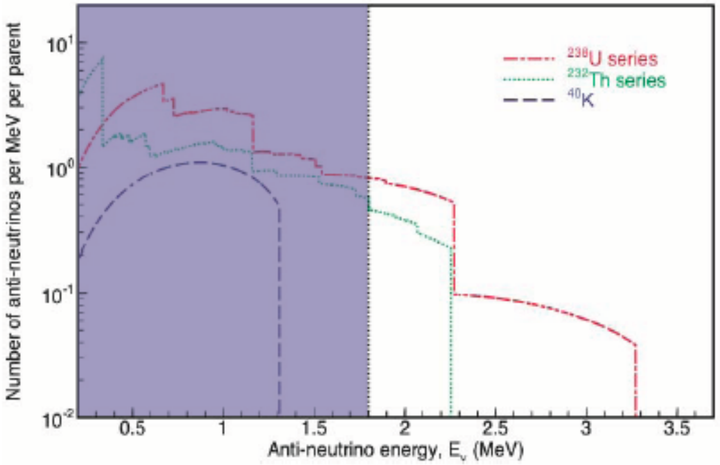
Delayed (τ ~250 μs):

$n + p \rightarrow d + \gamma$

Detected energy: **2.2 MeV**



Anti-neutrino energy spectrum

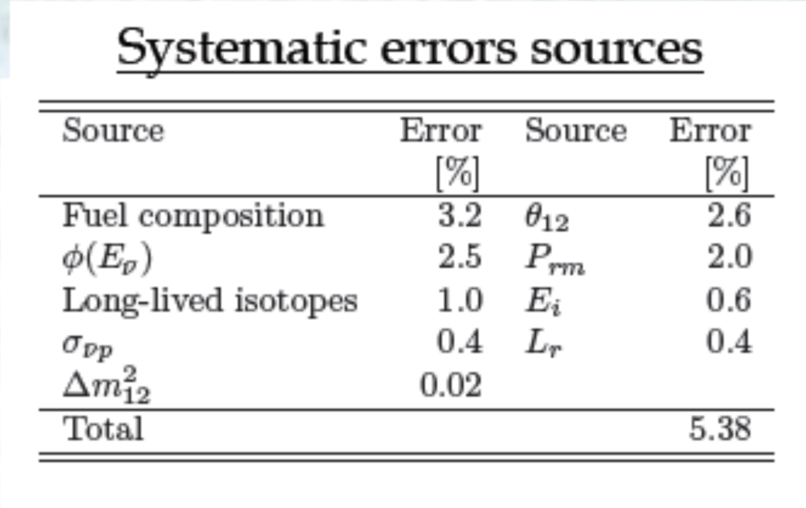


The main sources of background for the anti-neutrinos **are:**

1. **Distant reactors**

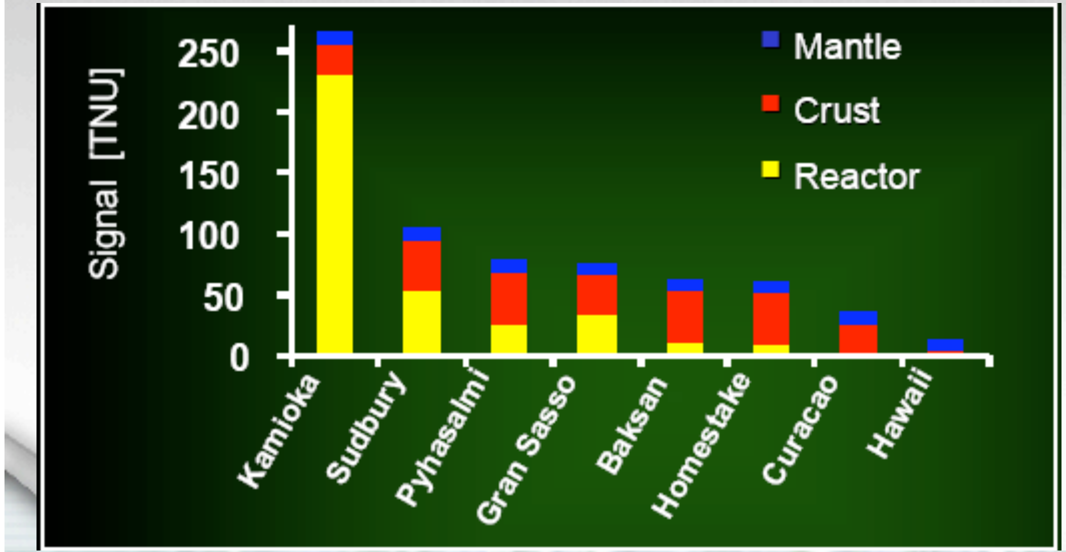
For reactors we have considered

194(Europe) + 245(World) power stations



Systematic errors sources

Source	Error [%]	Source	Error [%]
Fuel composition	3.2	θ_{12}	2.6
$\phi(E_{\bar{\nu}})$	2.5	P_{rm}	2.0
Long-lived isotopes	1.0	E_i	0.6
$\sigma_{\bar{\nu}p}$	0.4	L_r	0.4
Δm^2_{12}	0.02		
Total			5.38



P_{rm}: Thermal Power (IAEA, EDF);

f_{ri}: Power fraction of isotope $i = {}^{235}U, {}^{238}U, {}^{239}Pu, {}^{241}Pu$;

L_r: Distance reactor-detector;

T_m: Borexino livetime in months;

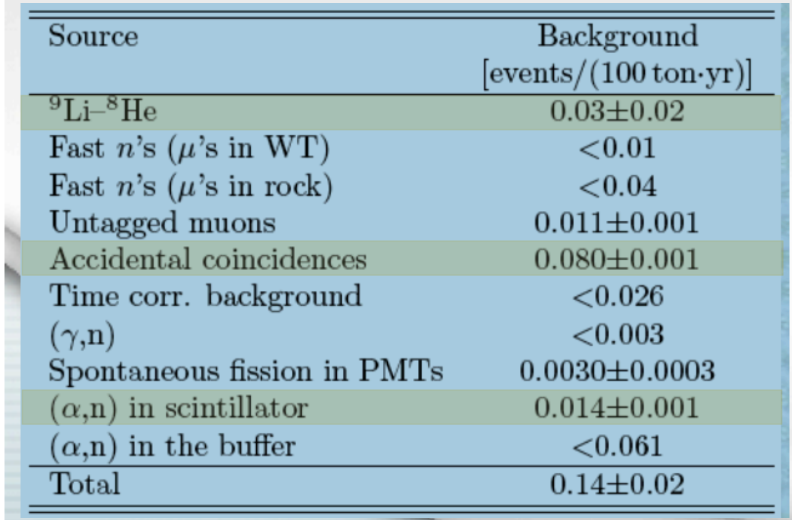
P_{ee}: anti-ν survival probability.

$$\boxed{\Phi\left(E_{\bar{\nu}_e}\right) = \sum_{r=1}^{N_{react}} \sum_{m=1}^{N_{month}} \frac{T_m}{4\pi L_r^2} P_{rm} \sum_{i=1}^{4} \frac{f_{ri}}{E_i} \Phi_i\left(E_{\bar{\nu}_e}\right) P_{ee}\left(E_{\bar{\nu}_e}; \vartheta_{12}, \Delta m^2_{21}, L_r\right)}$$

Loop over reactors, r Loop over months, m → Loop over isotopes, i

2.Background from other sources

Look for possible sources of *fake* anti-ν events
(prompt + delayed):



Source	Background [events/(100 ton·yr)]
^{9}Li–^{8}He	0.03±0.02
Fast n's (μ's in WT)	<0.01
Fast n's (μ's in rock)	<0.04
Untagged muons	0.011±0.001
Accidental coincidences	0.080±0.001
Time corr. background	<0.026
(γ,n)	<0.003
Spontaneous fission in PMTs	0.0030±0.0003
(α,n) in scintillator	0.014±0.001
(α,n) in the buffer	<0.061
Total	0.14±0.02

✓ Muon correlated events

Cosmogenic ^{8}Li and ^{8}He decay via β-n
τ ~ **150 ms**
2 s detector **veto** after each muon in the ID
Residual background: **0.03 ± 0.02 cpy/ 100 t**

Fast neutrons
Muon rejection efficiency with OD > **99.5%**
2 ms detector **veto** after each muon in the OD
Residual background: **<0.01 cpy/ 100 t** (90% C.L.)

✓ Radiogenic ^{13}C(α,n)^{16}O

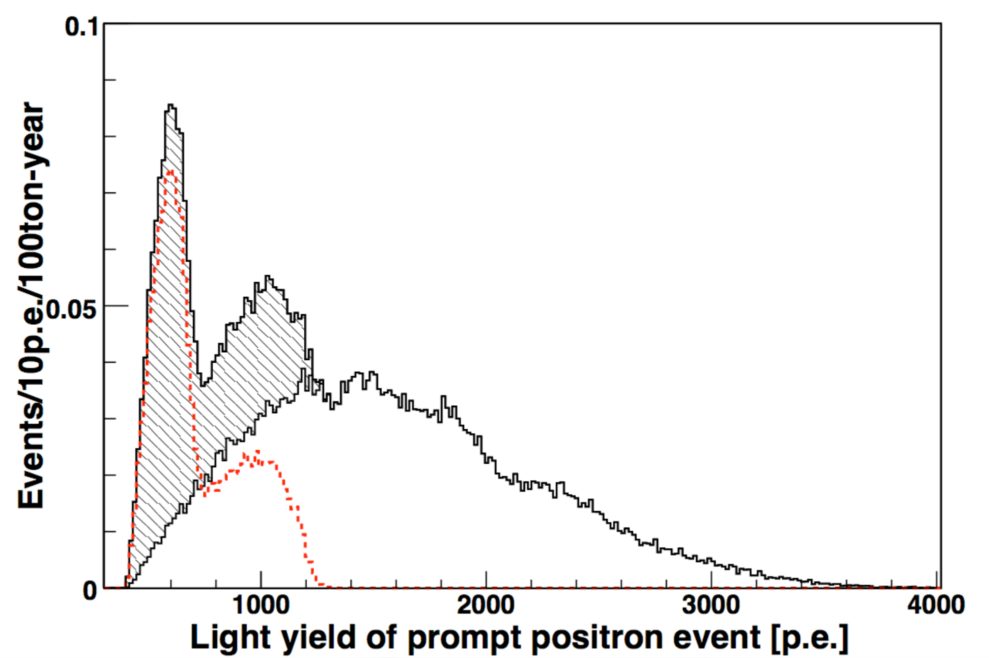
^{210}Po α emitter: **12 cpd/ 100 t**
^{13}C low abundance: **^{13}C/^{12}C ~ 1.1%**
Contamination: **0.021 ± 0.002 cpy/ 100 t**

✓ Random coincidences

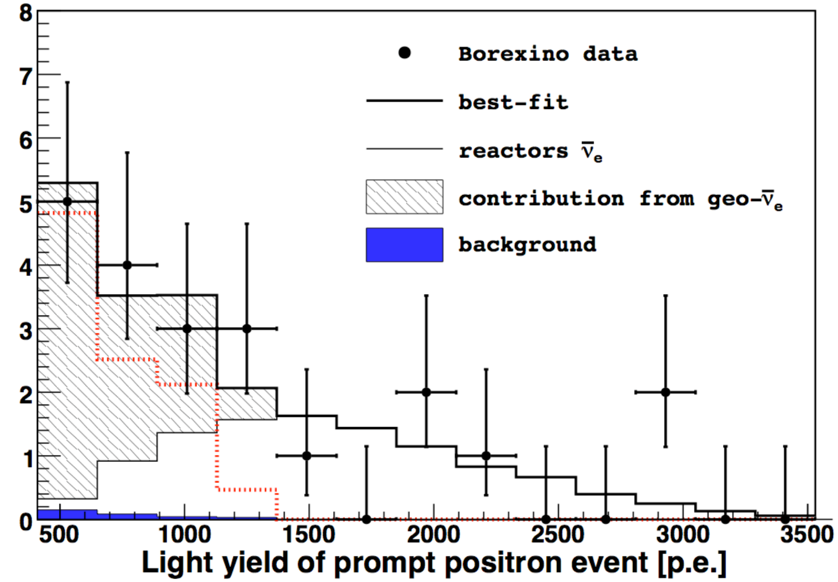
Searching for events in a window of 2ms - 2s:
<0.003 cpy/ 100 t (90% C.L.)

- Data set: from Dec 2007 to Dec 2009
- Total live time: **537.2 live days**
- Fiducial exposure after muon cuts and including detection efficiency: **252.6 ton-year**
- **21 anti-ν candidates selected**

MC spectra for likelihood function

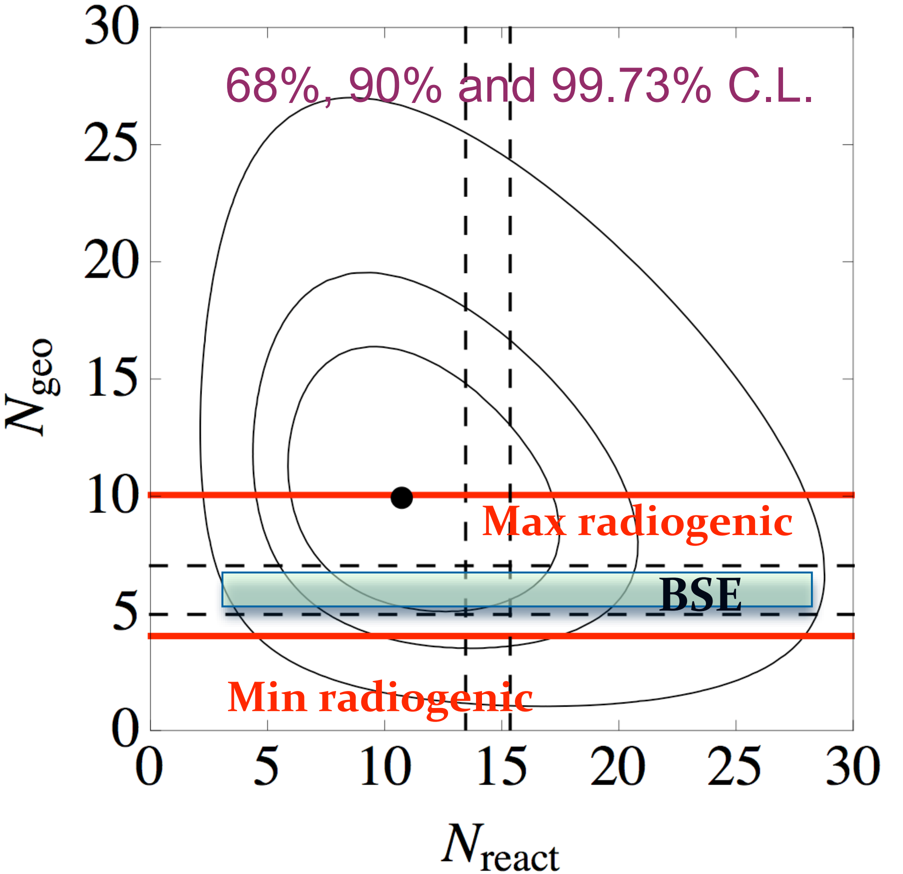


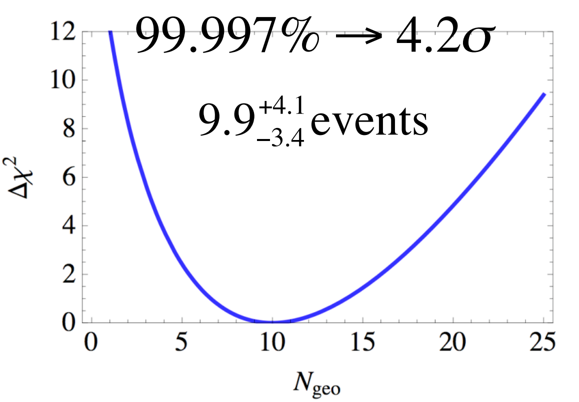
Unbinned ML best fit



Best-fit parameters from the likelihood analysis

- **Total heat flow :**
- **31±1 TW** or **44±1 TW**





$N_{react} = 10.7^{+4.3}_{-3.4}$

base line of 1000km
No oscillation rejected at 2.9σ

Phys. Letters B 687(2010)299

The non-Paulian (NP) transitions are searched for in ^{12}C nuclei in scintillator

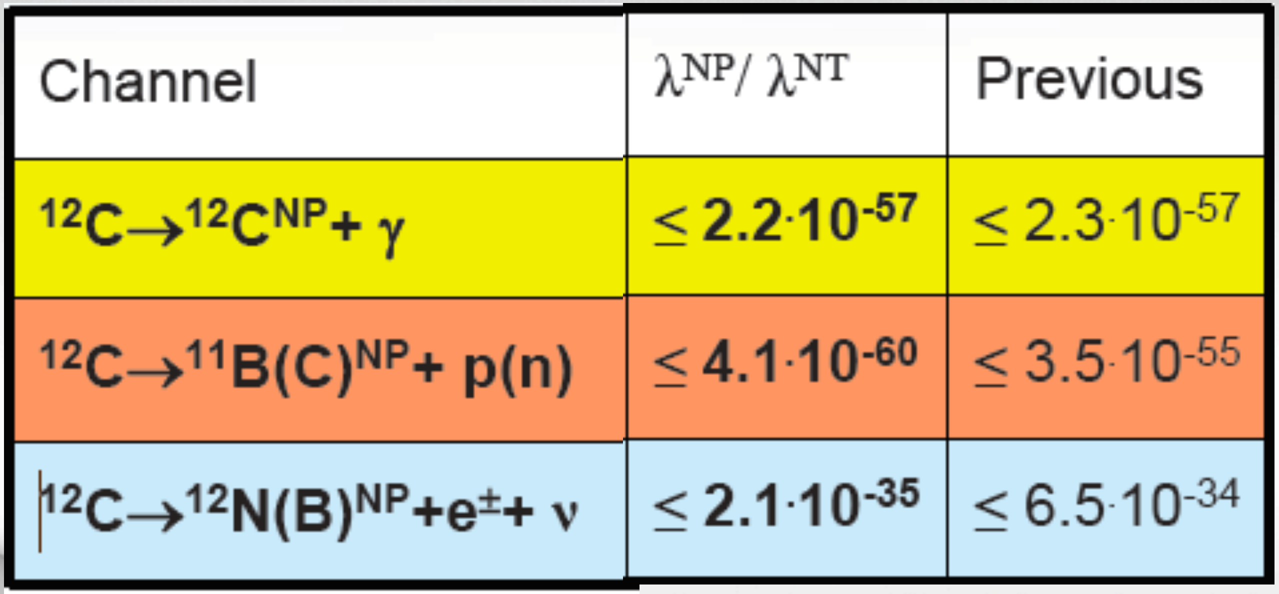
Channel	Q, MeV	E, MeV	
$^{12}C \to {}^{12}C^{NP} + \gamma$	16.4÷19.4	16.4÷19.4	E.M.
$^{12}C \to {}^{11}B^{NP} + p$	5.0÷9.0	4.6÷8.3	Strong
$^{12}C \to {}^{11}C^{NP} + n$	3.5÷7.9	3.2÷7.3	
$^{12}C \to {}^{8}Be^{NP} + \alpha$	3.0÷7.0	0.07÷0.25	
$^{12}C \to {}^{12}N^{NP} + e^- + \nu$	18.9 ±2	0.0÷18.9	Weak
$^{12}C \to {}^{12}B^{NP} + e^+ + \nu$	17.8 ±2	0.0÷17.8	

350 live days

Channel	E_0, MeV	τ_{lim}, y BOREXINO	τ_{lim}, y CTF	Previous experiments and limits
$^{12}C \to {}^{12}C^{NP} + \gamma$	17.5	$5.0 \cdot 10^{31}$	$2.1 \cdot 10^{27}$	$4.2 \cdot 10^{24}$ NEMO-II
$^{16}O \to {}^{16}O^{NP} + \gamma$	21.8	-	$2.1 \cdot 10^{27}$	$1.0 \cdot 10^{32}$ Kamiokande
$^{12}C \to {}^{11}B^{NP} + p$	4.8-8.2	$8.9 \cdot 10^{29}$	$5.0 \cdot 10^{26}$	$1.7 \cdot 10^{25}$ ELEGANT V. $6.9 \cdot 10^{24}$ DAMA (Na+I)
$^{12}C \to {}^{11}C^{NP} + n$	2.2	$3.4 \cdot 10^{30}$	$3.7 \cdot 10^{26}$	$1.0 \cdot 10^{20}$ Kishimoto et al
$^{12}C \to {}^{8}Be^{NP} + \alpha$	1.0-3.0	-	$6.1 \cdot 10^{23}$	-
$^{12}C \to {}^{12}N^{NP} + e^- + \nu_e$	18.9	$3.1 \cdot 10^{30}$	$7.6 \cdot 10^{27}$	$3.1 \cdot 10^{24}$ NEMO-II $\sim 8 \cdot 10^{27}$ LSD
$^{12}C \to {}^{12}B^{NP} + e^+ + \nu_e$	17.8	$2.1 \cdot 10^{30}$	$7.7 \cdot 10^{27}$	$2.6 \cdot 10^{24}$ NEMO-II

The relative strength of the NP transitions to the 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.



Channel	$\lambda^{NP}/\lambda^{NT}$	Previous
$^{12}C \rightarrow {}^{12}C^{NP} + \gamma$	$\leq 2.2 \cdot 10^{-57}$	$\leq 2.3 \cdot 10^{-57}$
$^{12}C \rightarrow {}^{11}B(C)^{NP} + p(n)$	$\leq 4.1 \cdot 10^{-60}$	$\leq 3.5 \cdot 10^{-55}$
$^{12}C \rightarrow {}^{12}N(B)^{NP} + e^{\pm} + \nu$	$\leq 2.1 \cdot 10^{-35}$	$\leq 6.5 \cdot 10^{-34}$

Phys. Rev.C 81 (2010) 034317

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

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

Spectral shape sensitive to μ_ν

Sensitivity enhanced at low energies ($\sigma \approx 1/T$)

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

Effective magn. moment →

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 $P_{ee}=0.552\pm0.016$ 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)

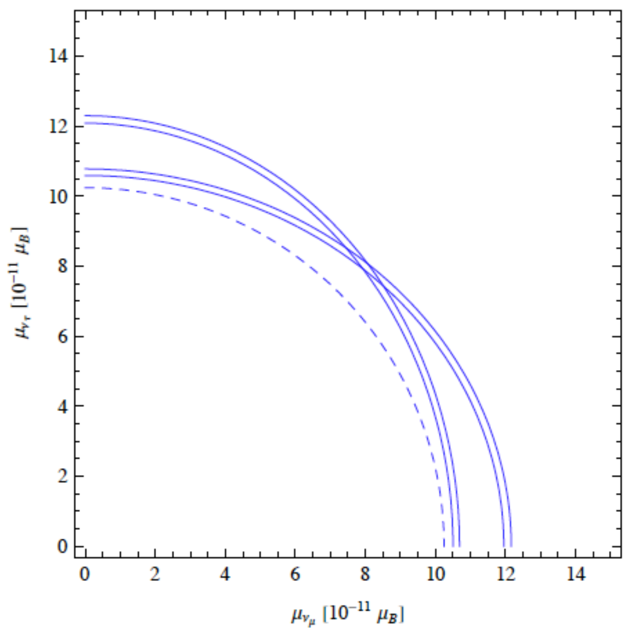
μ_μ < 68×10-11 μB by LSND (elastic scattering)

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 $\mu_e=3.2\times10^{-11}$ μ_B.

Conclusions

1. Borexino has succeeded in reaching very low radioactive levels and then to study the solar neutrino fluxes at very low energy (<1 MeV)
2. The vacuum regime in the neutrino oscillation phenomenon has been detected
3. The MSW-LMA oscillation model has been validated in the vacuum regime and the difference of the ν_e survival probabilities in vacuum and in matter has been measured in the same experiment.
4. The first actual evidence of the geo-neutrinos has been obtained.
5. The pep and the ^{8}B fluxes measurements (this last with a lower threshold down to 2 MeV) are in progress to study the transition region.
6. Important by-products have been already obtained or are under study

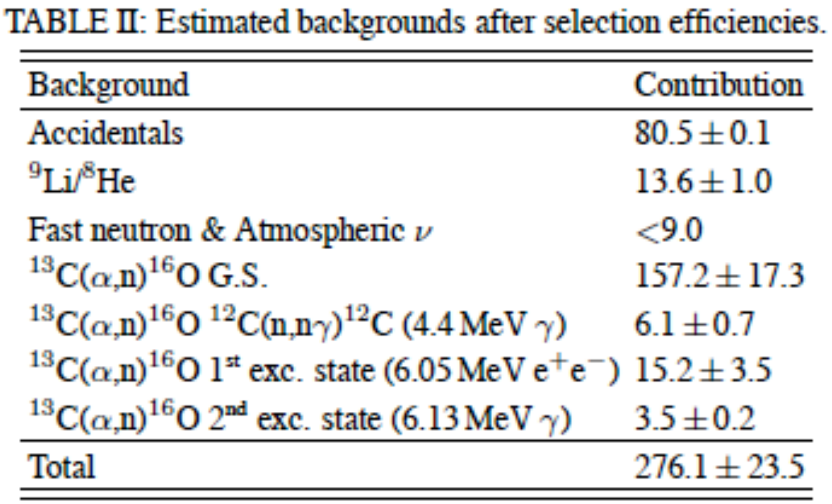
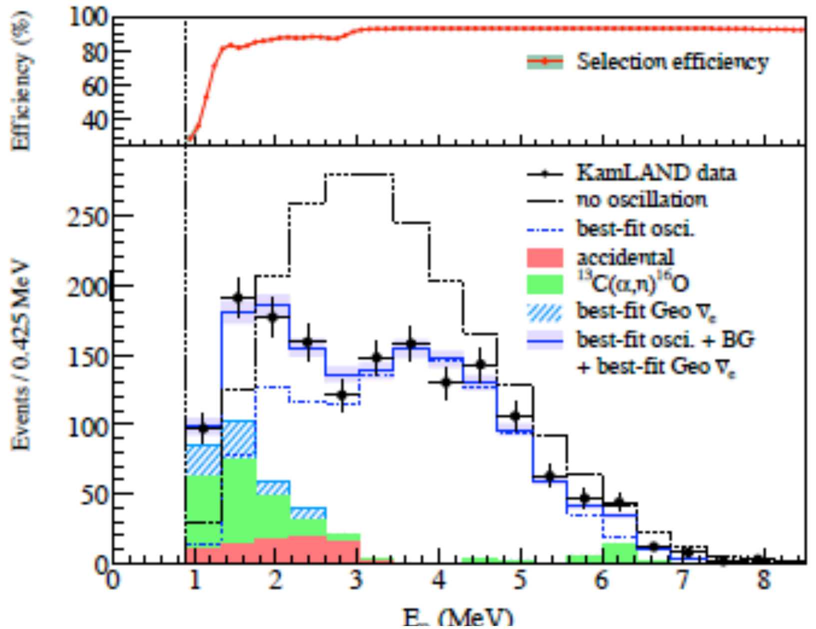


TABLE II: Estimated backgrounds after selection efficiencies.

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



N_{geo}=73±27

Signal/noise; BX 25/1
Kamland