Results and strategy of Borexino

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(on behalf of the Borexino collaboration)

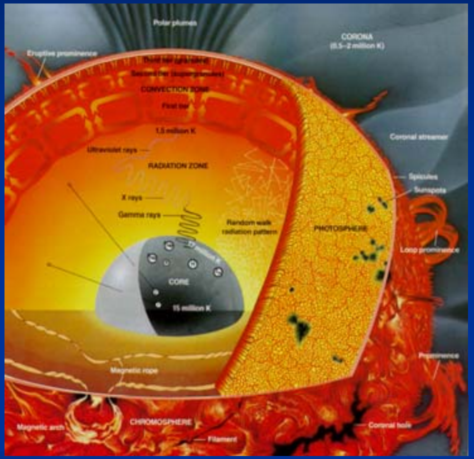
La Thuile 2nd March 2010

Neutrino as a messenger

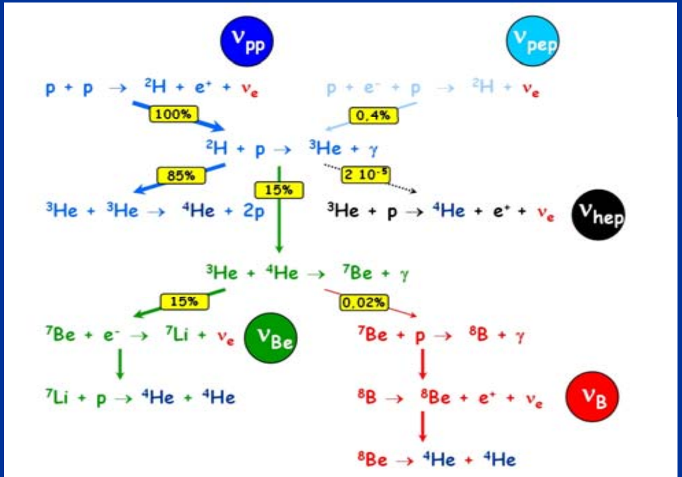
Standard Solar Model – collects our present knowladge about the Sun.

SSM calculations aim to describe the evolution of the Sun from its origin up to the present day.

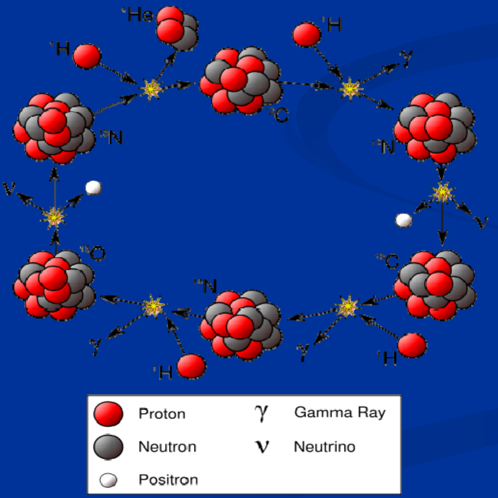
SSM predicts the neutrino fluxes, one of the outputs of the model.



pp cycle: *pp*(~92%), *pep*, *hep*, ^{7}Be(~8%), ^{8}B



CNO cycle: ^{13}N, ^{15}O, ^{17}F

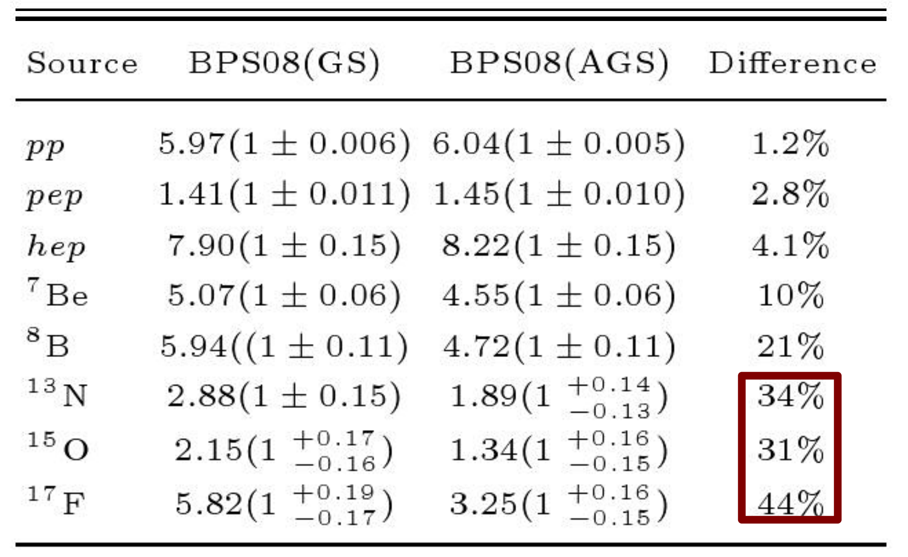


Neutrinos are the direct messengers from the core of the Sun

Solar Metallicity

Abundance of the elements (Z>4) in the Sun (*solar metallicity*) play a crucial role in our understanding of the star.

<u>Old abundances</u>, *recommended by Grevesse & Saurval* ***1998*** *(GS98)*, leads to the perfect agreemnt between the helioseismological observation and the SSM predictions;
<u>New abundances</u>, *recommented by Asplund et al.* ***2005*** *(AGS05)*, breaks this agreement and changes the solar neutrino fluxes:



Source	BPS08(GS)	BPS08(AGS)	Difference
pp	$5.97(1 \pm 0.006)$	$6.04(1 \pm 0.005)$	1.2%
pep	$1.41(1 \pm 0.011)$	$1.45(1 \pm 0.010)$	2.8%
hep	$7.90(1 \pm 0.15)$	$8.22(1 \pm 0.15)$	4.1%
^{7}Be	$5.07(1 \pm 0.06)$	$4.55(1 \pm 0.06)$	10%
^{8}B	$5.94((1 \pm 0.11)$	$4.72(1 \pm 0.11)$	21%
^{13}N	$2.88(1 \pm 0.15)$	$1.89(1\ ^{+0.14}_{-0.13})$	34%
^{15}O	$2.15(1\ ^{+0.17}_{-0.16})$	$1.34(1\ ^{+0.16}_{-0.15})$	31%
^{17}F	$5.82(1\ ^{+0.19}_{-0.17})$	$3.25(1\ ^{+0.16}_{-0.15})$	44%

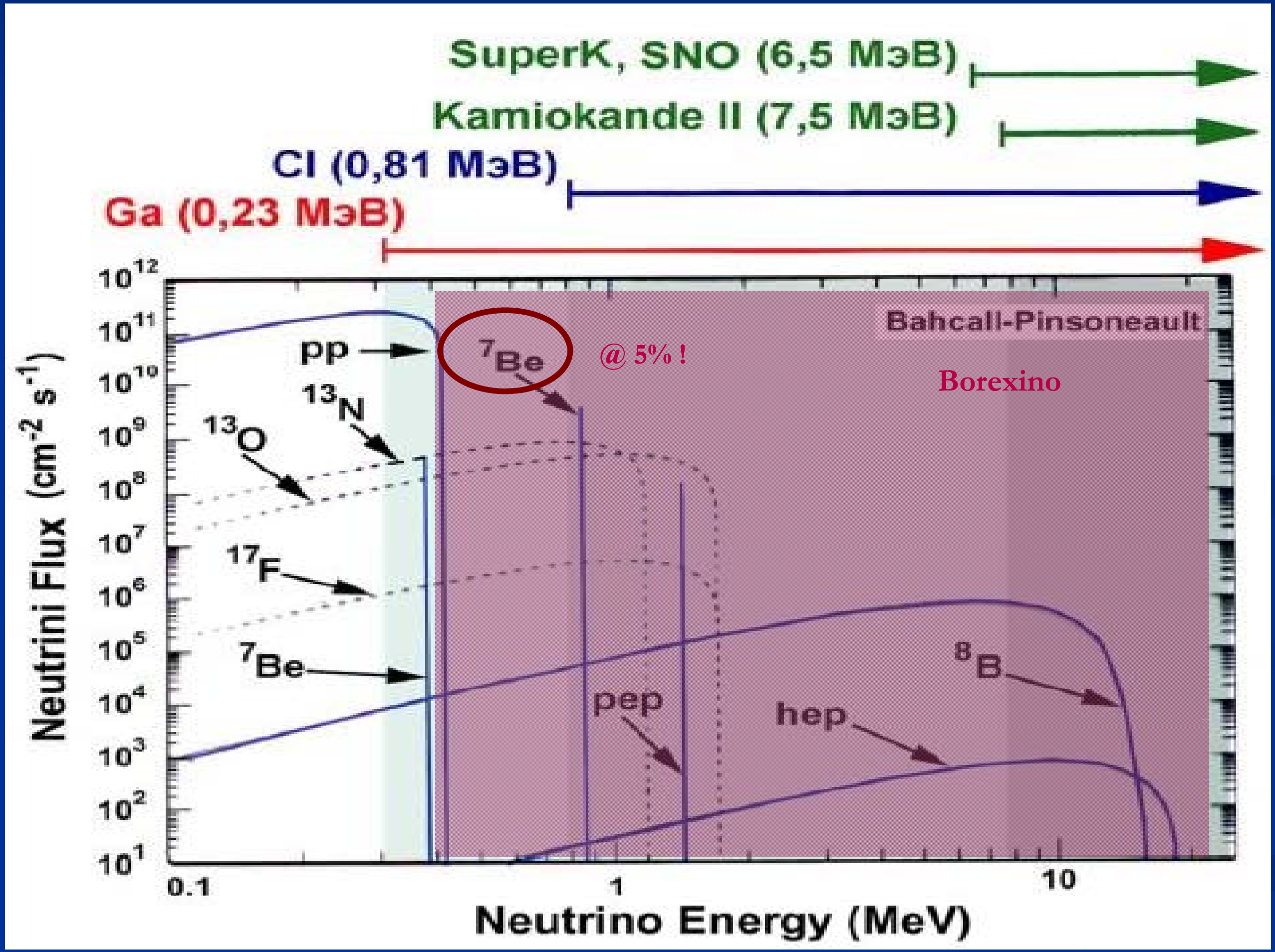
arXiv:0811.2424v1 [astro-ph] C.Pena-Garay & A.M.Serenelli 2008

Solar neutrinos can help to solve the problem (in particular CNO)

Precise measurements of the ^{7}Be solar neutrino flux (3%) is needed!

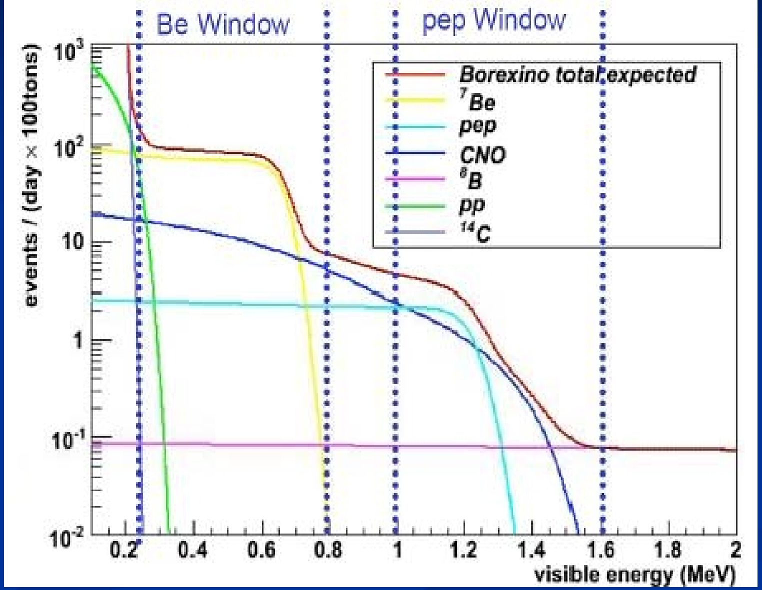
State of the Art

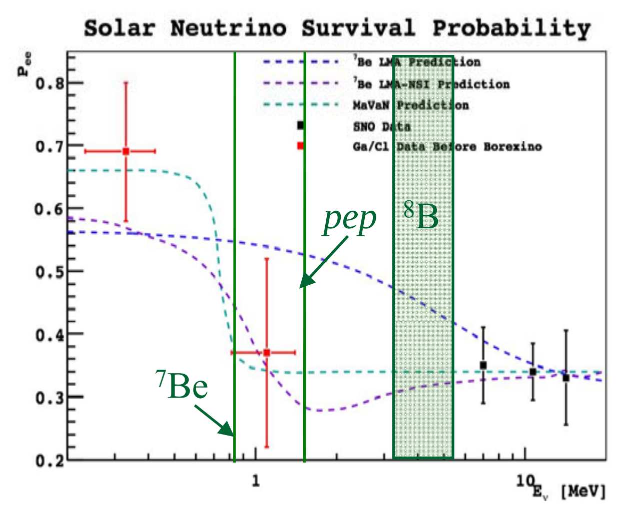
99.994% of the solar neutrino spectrum in Not yet measured in the real time!



Borexino goals

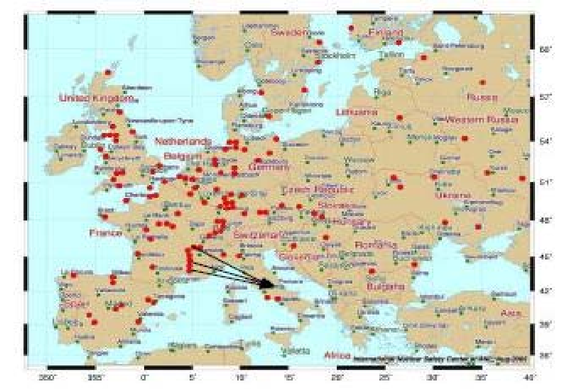
- First real time observation of the sub-MeV solar neutrinos (mainly from *^{7}Be*);
- Low threshold measurements of the *^{8}B* neutrinos;
- Study of Solar spectroscopy: *CNO* (test of the solar metallicity), *pp* tail and possibly *pep*;





- Test of the *matter-vacuum transition* of the neutrino oscillations with *^{7}Be, ^{8}B* and possibly *pep* neutrinos;

Map of reactors in Europe



- Study of the neutrino effective magnetic moment;
- SNEWS network;

- First evidence of the geoneutrino signal (**3 σ**)

Borexino collaboration

About 160 collaborators from Italy, USA, Russia, Germany, France and Poland

Milano

Genova

Perugia

APC Paris

Dubna JINR (Russia)

Princeton University

Virginia Tech. University

Kurchatov Institute (Russia)

Munich (Germany)

Heidelberg (Germany)

Jagiellonian U. Cracow (Poland)

Detection principles

Elastic scattering off target electrons as the solar neutrino detection reaction.

Scintillation light as the detection mechanism:

- Low threshold (limited by ^{14}C);
- Good energy resolution;
- Good position resolution;

However!

- No direction information (unlike in the Cherenkov detectors);
- The neutrino induced events can't be distinguished from the β's and γ's of natural radioactivity.

The extreme purity of the detector is crucial for the success of the project!

Expected in Borexino rate of (^{7}Be) neutrino: ~50 cpd /100 tons (**~5x10^{-9} Bq/kg**)

Drinking water	~10 Bq/kg (^{238}U,^{232}Th and ^{40}K)
Air	~10 Bq/m^3 (^{238}U,^{232}Th and ^{40}K)
Typical rock	~100 -1000 Bq/kg (^{222}Rn, ^{39}Ar and ^{85}Kr)

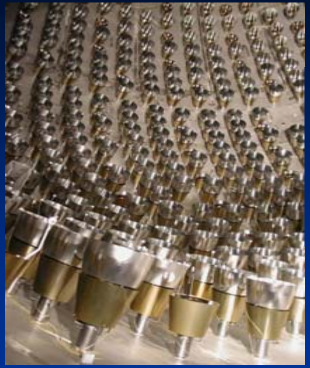
Borexino detector must be 9-10 orders of magnitude less radioactive then *anything* on Earth

Borexino design

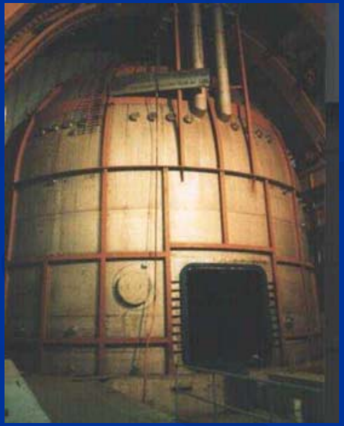
Two Nylon balloons:

Inner Vessel
(8.5 m, V = 340 m^3) filled with 278 tons of scintillator (PC + 1.5 g/l of PPO)

***Inner Buffer** (11.5 m)*
filled with PC + DMP



2212** 8" ETL 9351 **PMTs
mounted inside the SSS



Water Tank
(d=18 m, V = 2400 m^3)
Sheilding form γ and n. Water Cerenkov detector (Muon Veto) 208 PMTs

Steinless Steel Sphere
***(d= 13.7 m, Volume =** 1340 m^3)*

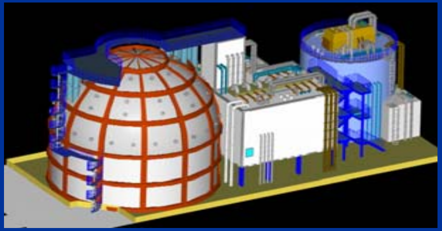
20 supporting legs

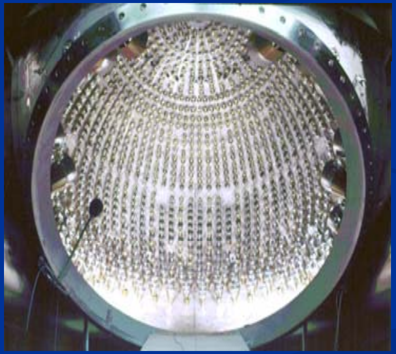
Borexino plants

Laboratori Nazionali del Gran Sasso

Assergi (AQ), Italy

- Water Plant;
- Purification Skids;
- Filling Station;
- Storage Area;
- Unloading station;
- Low Ar-Kr N_2 plant;
- Hot oil system;
- Cooling (water) system.
- CTF





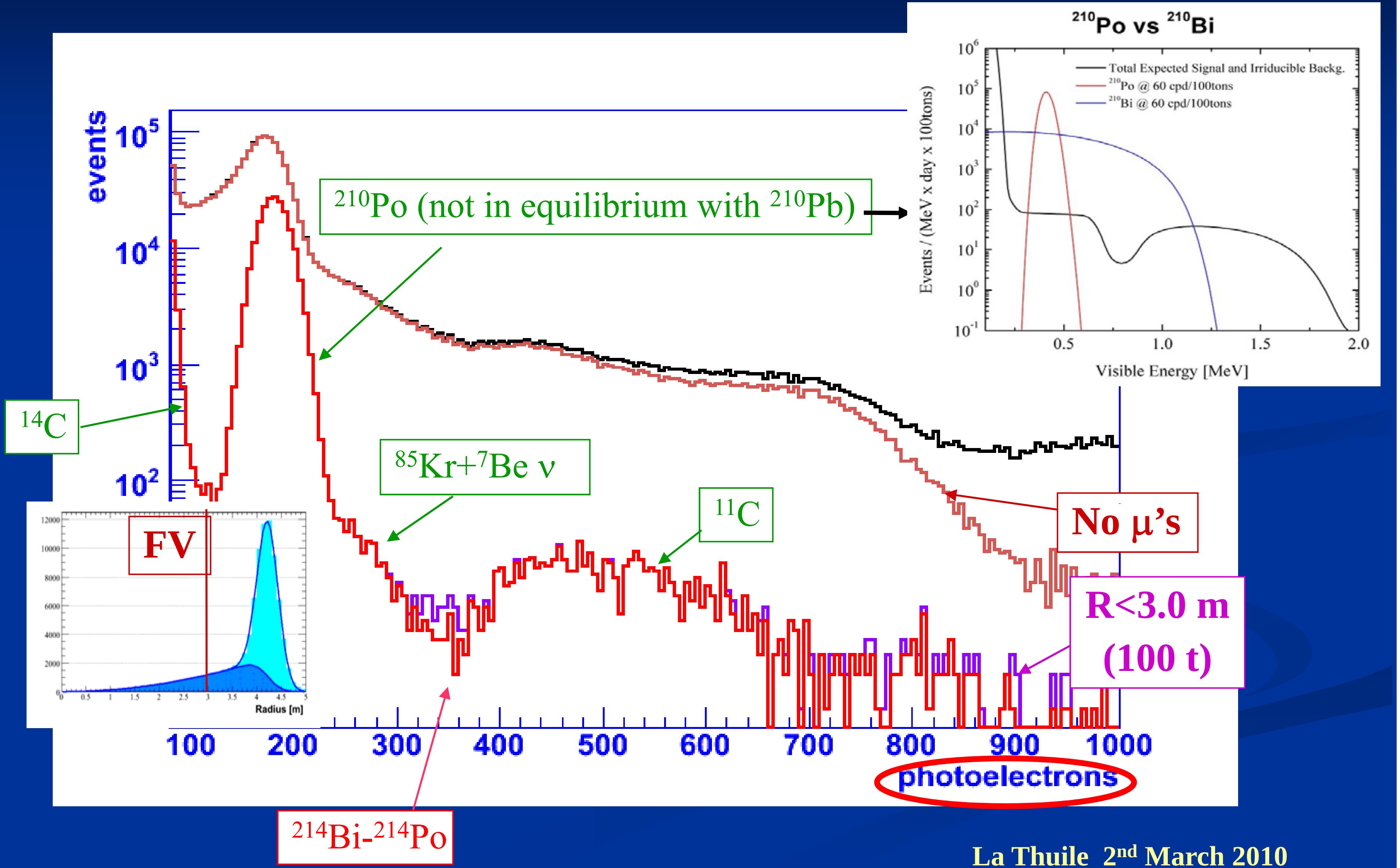
~ 1000 m^2 total footprint of the experiment

LS radiopurity in Borexino

15 years of work! Outstanding purity of the detector!

Background	Typical abundance (source)	Borexino goals	Borexino measured
^{14}C/^{12}C	10^{-12} (cosmogenic) g/g	**10^{-18} g/g**	~ 2 10^{-18} g/g
^{238}U (by ^{214}Bi-^{214}Po)	2 10^{-5} (dust) g/g	**10^{-16} g/g**	**(1.6±0.1) 10^{-17} g/g**
^{232}Th (by ^{212}Bi-^{212}Po)	2 10^{-5} (dust) g/g	**10^{-16} g/g**	**(5±1) 10^{-18} g/g**
^{222}Rn (by ^{214}Bi-^{214}Po)	100 atoms/cm^3 (air) emanation from materials	**10^{-16} g/g**	~ 10^{-17} g/g (~1 cpd/100t)
^{210}Po	Surface contamination	~1 c/d/t	May 07 : 70 c/d/t Sep08 : 7 c/d/t
^{40}K	2 10^{-6} (dust) g/g	~ 10^{-18} g/g	< 3 10^{-18} (90%) g/g
^{85}Kr	1 Bq/m^3 (air)	~1 c/d/100t	(28±7) c/d/100t (fast coinc.)
^{39}Ar	17 mBq/m^3 (air)	~1 c/d/100t	<< ^{85}Kr

Detector performance



^{210}Po (not in equilibrium with ^{210}Pb)

^{14}C

^{85}Kr+^{7}Be ν

^{11}C

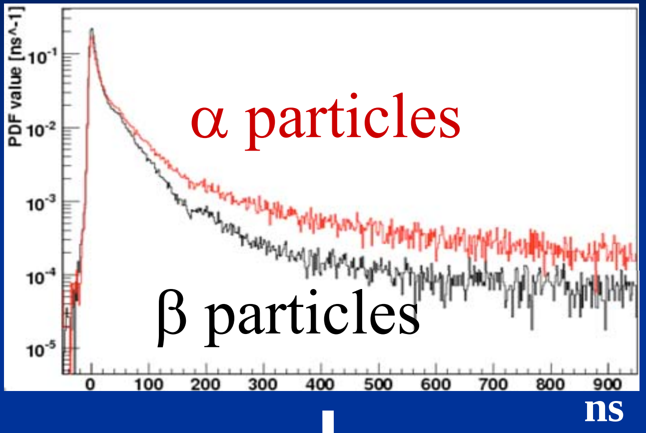
No μ's

R<3.0 m (100 t)

FV

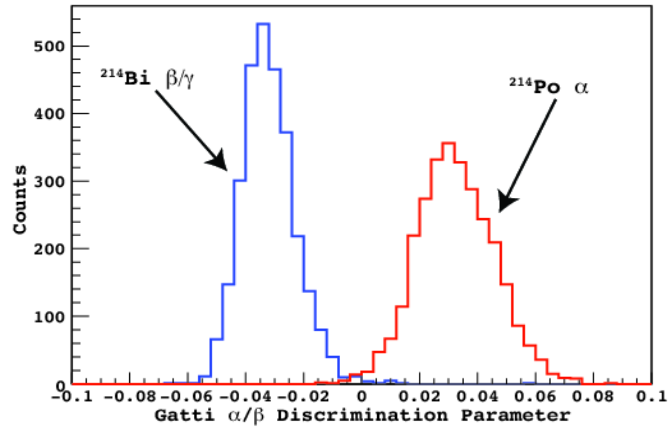
^{214}Bi-^{214}Po

α/β discrimination

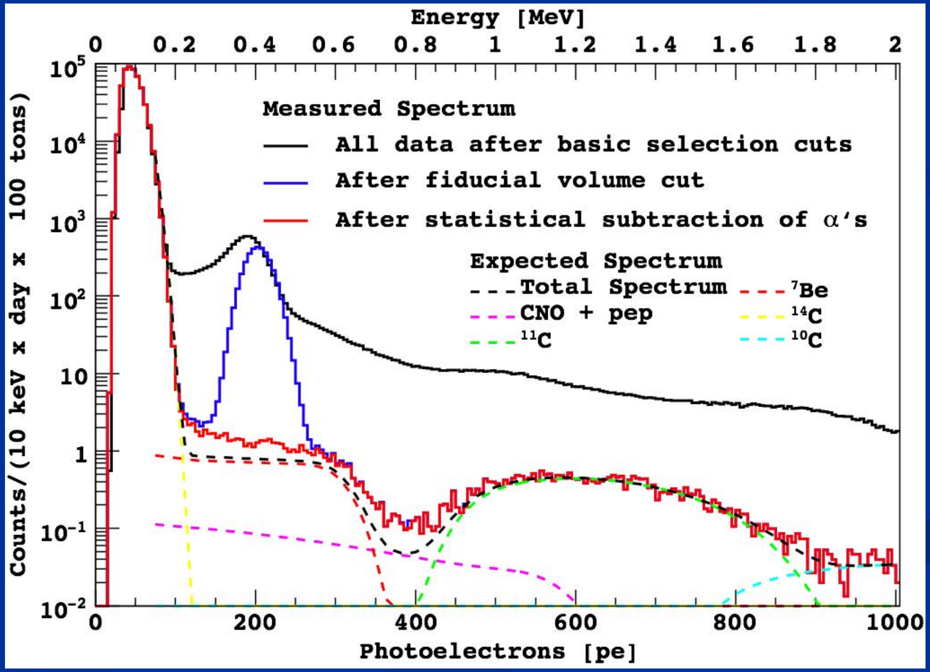


α/β discrimination is based on the different flourescence time profile for α and β scintillation events.

Optimal Gatti filter (E. Gatti, F. De Martini Nuclear Electronics, vol. 2, IAEA, Wien, 1962, pp. 265–276.)



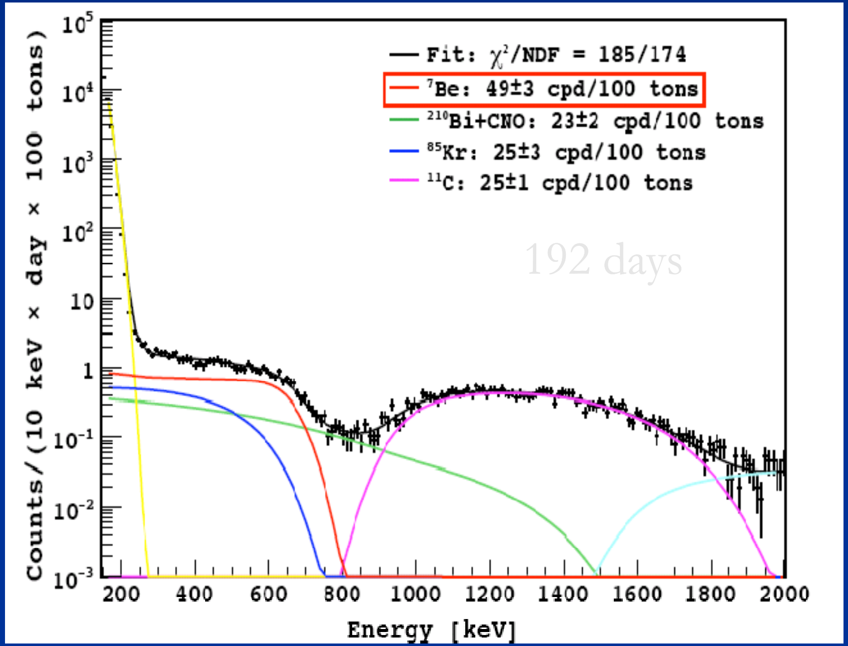
Full separation at the energy of 800 keV.

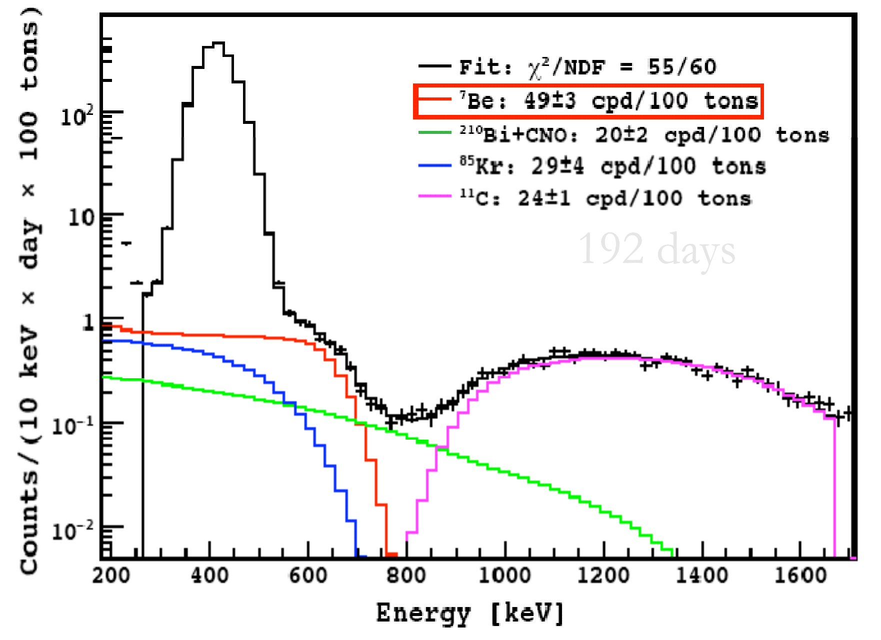


“Direct Measurement of the ^{7}Be Solar Neutrino Flux”

PRL 101, 091302 (2008)

Spectral fit with and without alpha subtraction – two codes, consistent results!





- **Light yield** left as a free parameter of the fit;
- Weights of **^{210}Bi, ^{85}Kr, ^{11}C** are left free, other contributions are fixed;
- Quenching effect is taken into account (Birk's parameterization).

^{7}Be results summary

Expected in Borexino:

	NO oscillations BPS07 (High-Z)	BPS07(GS98) High-Z	BPS07(AGS05) Low-Z
Expected rate (cpd/100 t)	74 ± 4	48 ± 4	44 ± 4

Measured in Borexino ^{7}Be solar neutrino rate:

$$\boxed{R(^{7}Be) = 49 \pm 3_{stat} \pm 4_{sys} \text{ cpd/100 ton } [\pm 10\%]}$$

Correspondig flux:

$\Phi(^{7}Be) = (5.18 \pm 0.51) x\ 10^{9}\ cm^{-2}\ s^{-1}$

$\Phi(^{7}Be)^{exp} / \Phi(^{7}Be)^{SSM} = 1.02 \pm 0.10$

No Oscillation hypothesis is rejected at 4 σ level

Present level of the accuracy is 10% → not possible to resolve the solar metallicity problem (High Z or Low Z).

The main problem - the systematic error of 8% because of FV uncertainty (6%) and ^{7}Be-^{85}Kr anticorrelation in the spectral fit.

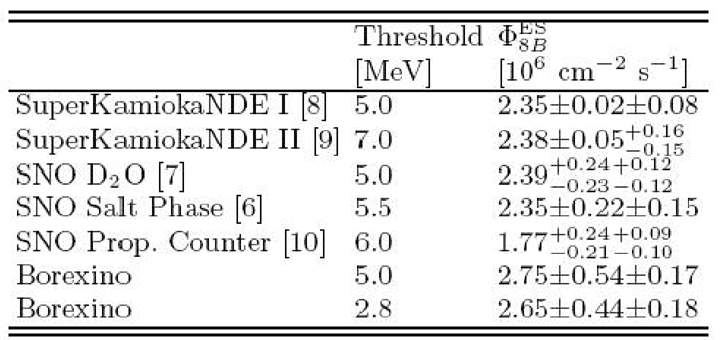
^{8}B solar neutrinos

First measurement of the ^{8}B solar neutrino with a LS detector at the threshold of 2.8 MeV.

*Measurement of the solar ^{8}B neutrino flux with **246** live days of Borexino and observation of the MSW vacuum-matter transition*
(*Borexino coll. arXiv:astro/ph 0808.2868v1*)

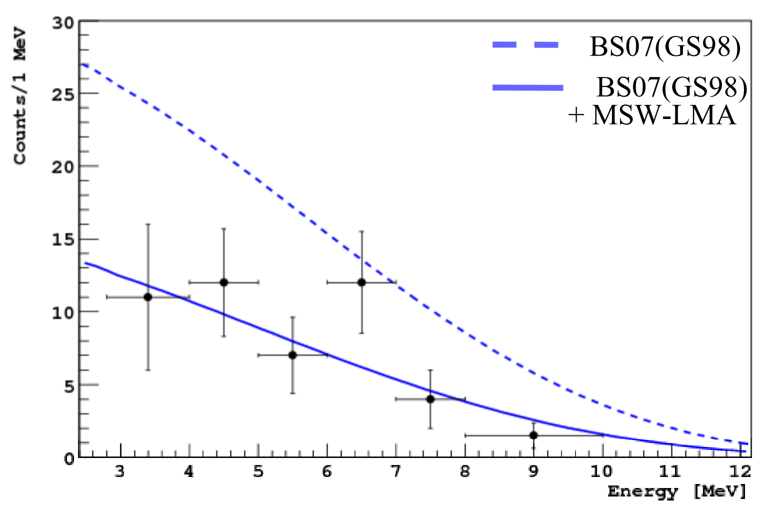
R(^{8}B) =0.26±0.04$_{stat}$±0.02$_{svs}$ cpd/100 t

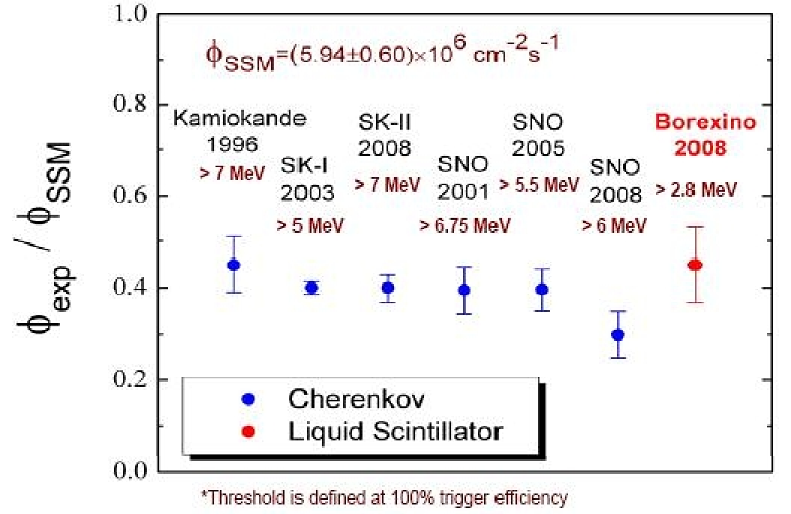
Neutrino oscillation is confirmed at 4.2 σ , including the theoretical uncertainty (10%) on the ^{8}B flux from the Standard Solar Model



	Threshold [MeV]	Φ^{ES}_{8B} [10^6 cm^{-2} s^{-1}]
SuperKamiokaNDE I [8]	5.0	$2.35\pm0.02\pm0.08$
SuperKamiokaNDE II [9]	7.0	$2.38\pm0.05^{+0.16}_{-0.15}$
SNO D_2O [7]	5.0	$2.39^{+0.24+0.12}_{-0.23-0.12}$
SNO Salt Phase [6]	5.5	$2.35\pm0.22\pm0.15$
SNO Prop. Counter [10]	6.0	$1.77^{+0.24+0.09}_{-0.21-0.10}$
Borexino	5.0	$2.75\pm0.54\pm0.17$
Borexino	2.8	$2.65\pm0.44\pm0.18$

New results based on ~500 days statistics are coming!





*Threshold is defined at 100% trigger efficiency

La Thuile 2nd March 2010

Survival probability

For the first time the **same detector** obtained **two values** of the neutrino electron survival probability: P_{ee} (^{7}Be) (transition zone) and P_{ee} (^{8}B) (matter oscillations)

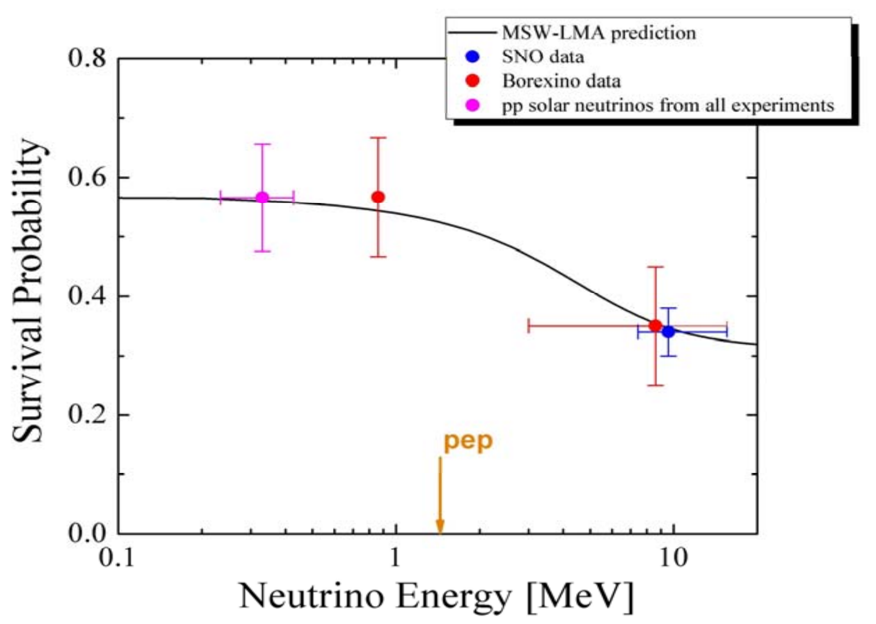
Under the assumption of the high Z SM

P_{ee} (^{7}Be) = 0.56 ± 0.10 (0.862 MeV)
P_{ee} (^{8}B) = 0.35 ± 0.10 (8.6 MeV)

$\boxed{P_{ee}(^7Be) / P_{ee}(^8B) \neq 1}$ @ 1.8 σ

Borexino confirms @ 1.8 **σ** the presence of the transition zone between the low energy vacuum-driven and high-energy matter-driven solar neutrino oscillations predicted by the MSW-LMA.

Borexino measurement confirms the MSW-LMA solution.



Day-Night asymmetry

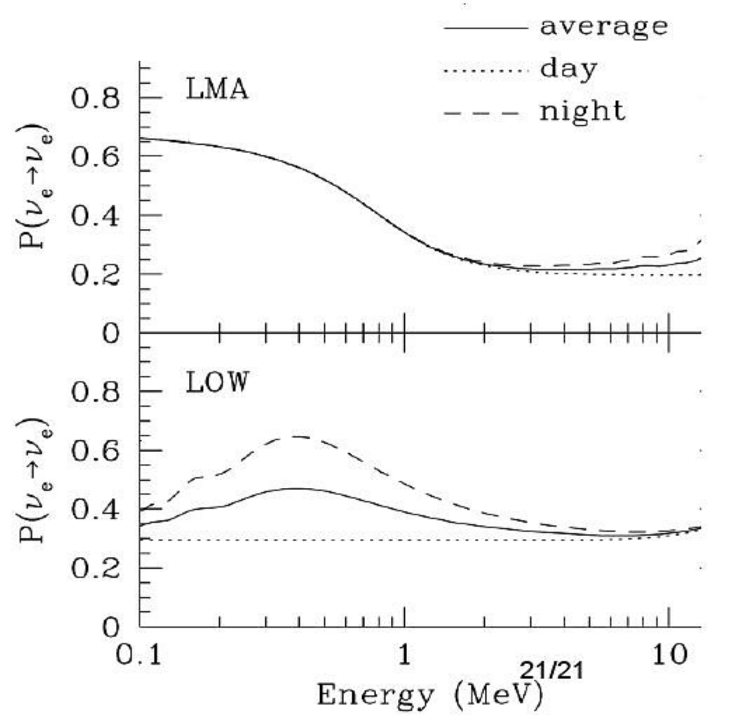
MSW mechanism can lead to the neutrino regeneration in the Earth matter. In this case more neutrinos should be observed during the night than during the day → day-night asymmetry.

MSW-LMA predicts the lack of the of day-night asymmetry in the solar neutrino fluxes.

Preliminary result on the day-night asymmetry with 422 days of statistics (213 "nights" + 209 "days") is in agreement with MSW-LMA predictions.

$$ADN = \frac{N-D}{N+D} = 0.02 \pm 0.04$$

(*see G.Testera's talk at Neutrino Telescopes in March 2009*)



Neutrino $\mu_{\nu\,\mathrm{eff}}$

The shape of the solar neutrino spectrum is sensitive to the possible presence of non-null magnetic moment.

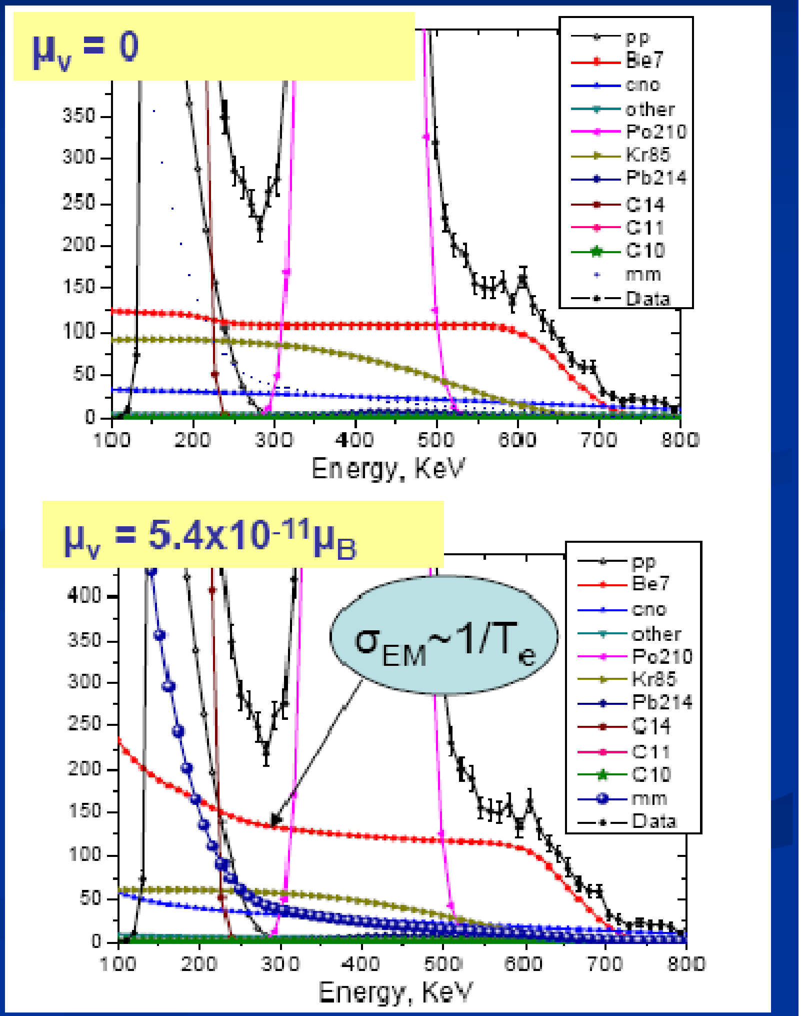
The electroweak cross section:

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

Non zero neutrino mass gives rise to the additional electromagnetic term in the cross section expression. Sensitivity is enhanced at low energy (1/T):

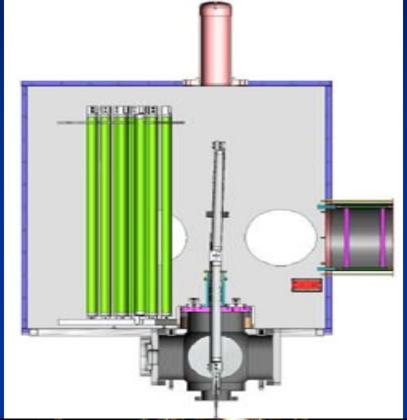
$$\left(\frac{d\sigma}{dT}\right)_{EM} = \mu_\nu^2 \frac{\pi\alpha_{em}^2}{m_e^2}\left(\frac{1}{T}-\frac{1}{E_\nu}\right)$$

Estimate	Method	10^{-11} μ_B
SuperK	^{8}B	<11
Montanino et al.	^{7}Be	<8.4
GEMMA	**Reactor**	**<3.2**
Borexino	**^{7}Be**	**<5.4**



Calibrations 2008-2009

Detailed study of the detector. Over 300 *on-axis* and *off-axis* positions.



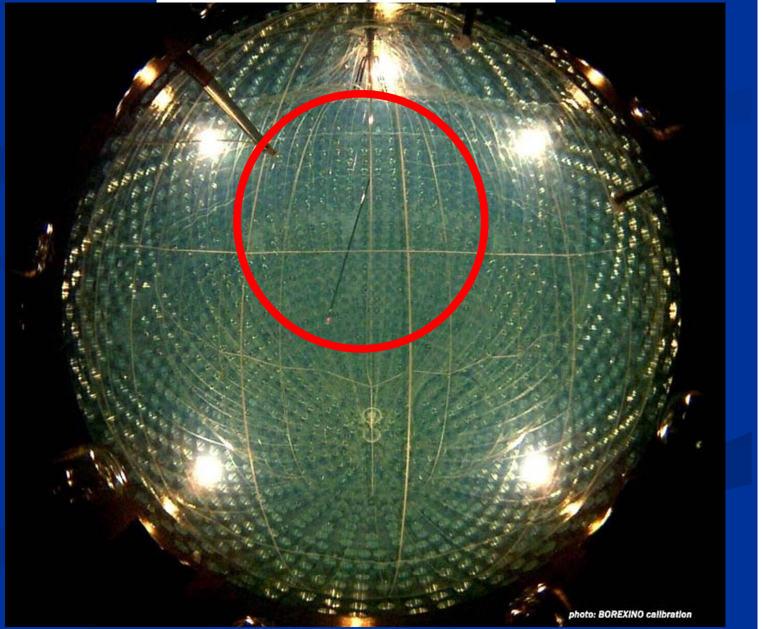


photo: BOREXINO calibration

Detector response vs position:

100 Bq $^{14}C+^{222}Rn$ in scintillator in >100 positions.

Improved position reconstruction. We *plan to reduce the error on the FV down to 1-2%* (old value 6%)

Energy scale and quenching:

α : ^{14}C, ^{222}Rn in scintillator

β : ^{222}Rn in scintillator

γ : ^{139}Ce, ^{57}Co, ^{60}Co, ^{203}Hg, ^{65}Zn, ^{40}K, ^{85}Sr, ^{54}Mn

Neutron: ^{241}Am-^{9}Be (protons recoil study)

Improved understanding of energy scale:
(from **120 keV** up to **9.3 MeV**);
PRELIMINARY: uncertainty in energy scale <1%.
Monte Carlo code tuned to take into account non-linearities of the energy scale (ionization quenching, electronics);

New results on ^{7}Be and ^{8}B will be relised soon…

Anti-ν detection

The unprecedentedly low intrinsic radioactivity of Borexino, the high photon yield and large number of free target protons (~ 1.8×10^{31}) offer a unique tool for the anti-ν study.

Inverse beta decay reaction. Correlated in space and time pair of signals.

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

$E_{th}=1.806$ MeV

1) *Prompt signal:* Positron + 2 γ from annihilation with e^-, ***E_γ=0.511 MeV***

After t~250μs

2) *Delayed signal:* Neutron capture on Hydrogen - γ of ***E_γ=2.2 MeV***

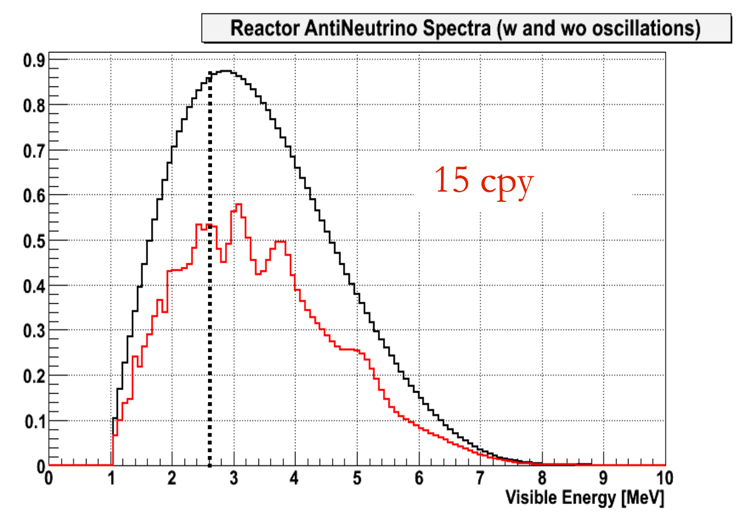
The expected anti-ν signal comes mainly from the reactors and from the β decays of long-lived radioactive isotopes (^{238}U, ^{232}Th) naturally present in the Earth's interior (geo-neutrinos).

Geo-neutrinos are able to shed light on the radioactive element abundances and their distribution in the Earth and on the possible radiochemical contribution to the Earth’s heat flow.

Reactor anti-ν

Study of the reactor anti-neutrino spectrum.
Main contribution from ~190 European nuclear plants.
245 from the rest of the world give 2.5 %.

3 most powerful power plants in France
give 13% of the total signal.



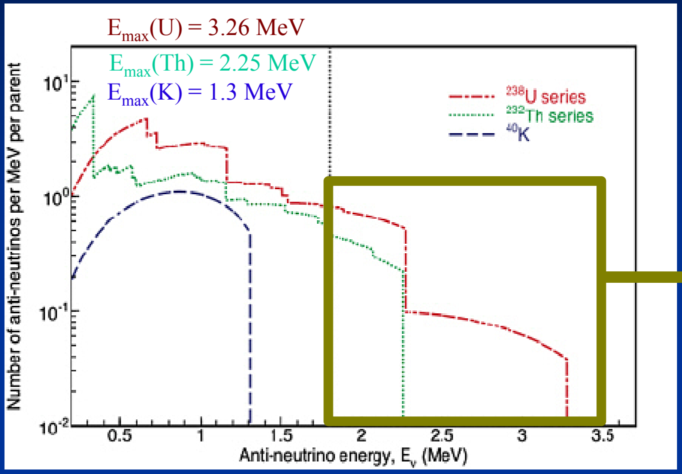
Knowledge of the exact duty cycle and the fuel composition of the nuclear plants is of the crucial importance!

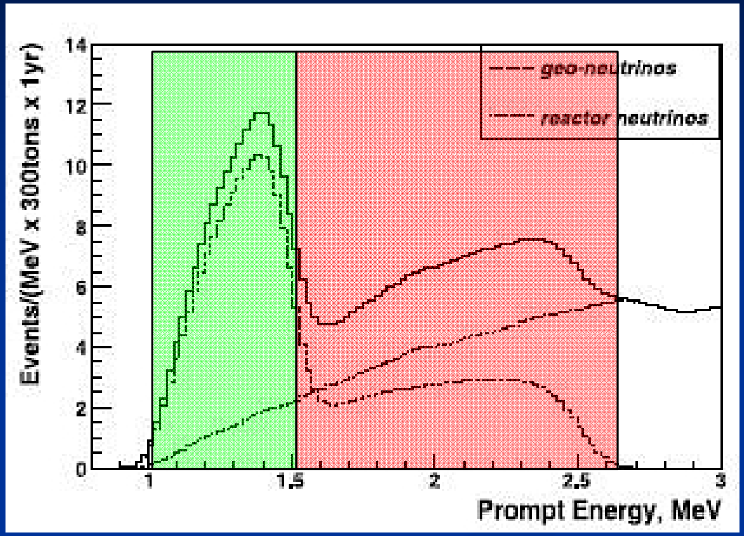
Constant up-date from the IEAE and EDF.

Expected in Borexino:

~15 cpy in the whole spectrum (up to 8 MeV), in case of 100% detection efficiency and 80% of the reactors duty cycle.

Geo-ν study





Precise measurement of the reactor anti-nu spectrum allow to separate the geo-neutrino signal!

Cosmogenic background (^{9}Li, ^{8}He) is effectively reduced by the muon veto (2s after each muon, cost - 10% of statistics).

Other sources of the background are negligible.

S/B > 1 in the whole geo-ν window

Expected geo-neutrino signal: ~5 cpy

	1-1.5	1.5-2.6	2.6-10
Geo ^{232}Th	1.2	0	0
Geo ^{238}U	2.1	2.3	0
Reactor	*0.5*	*3.3*	*8.5*
Total	*3.8*	*5.6*	*8.5*
Random	0.3	0.2	0.0

Expected in 300 t in 1 year

Results Summary

(I) First Real time measurement of ^{7}Be solar neutrino flux with accuracy of 10% -
R(^{7}Be) = 49 ± 3_{stat} ± 4_{sys} cpd /100 ton.

(II) First measurement with LS detector of the solar ^{8}B neutrino flux with the lowest threshold achieved so far (2.8 MeV). R(^{8}B) = 0.26 ± 0.04_{stat} ± 0.02_{sys} cpd /100 ton.

(III) Simultaneous observation of both the vacuum (^{7}Be) and matter-enhanced dominated oscillation regimes (^{8}B). Borexino results are compatible with MSW-LMA . No oscillation hypothesis is rejected at 4 σ C.L.

(IV) Best current limit on the effective neutrino magnetic moment: $\mu_{eff} < 5.4 \cdot 10^{-11}\ \mu_B$

Future plans

New purification campaign (March 2010);

New improved results on the ^{7}Be and ^{8}B fluxes after the calibrations will be released in 2010!

More precise measurements of the survival probability (P_{ee} (^{7}Be), P_{ee} (^{8}B));

Further study of Day-Night asymmetry and seasonal variations in the neutrino fluxes;

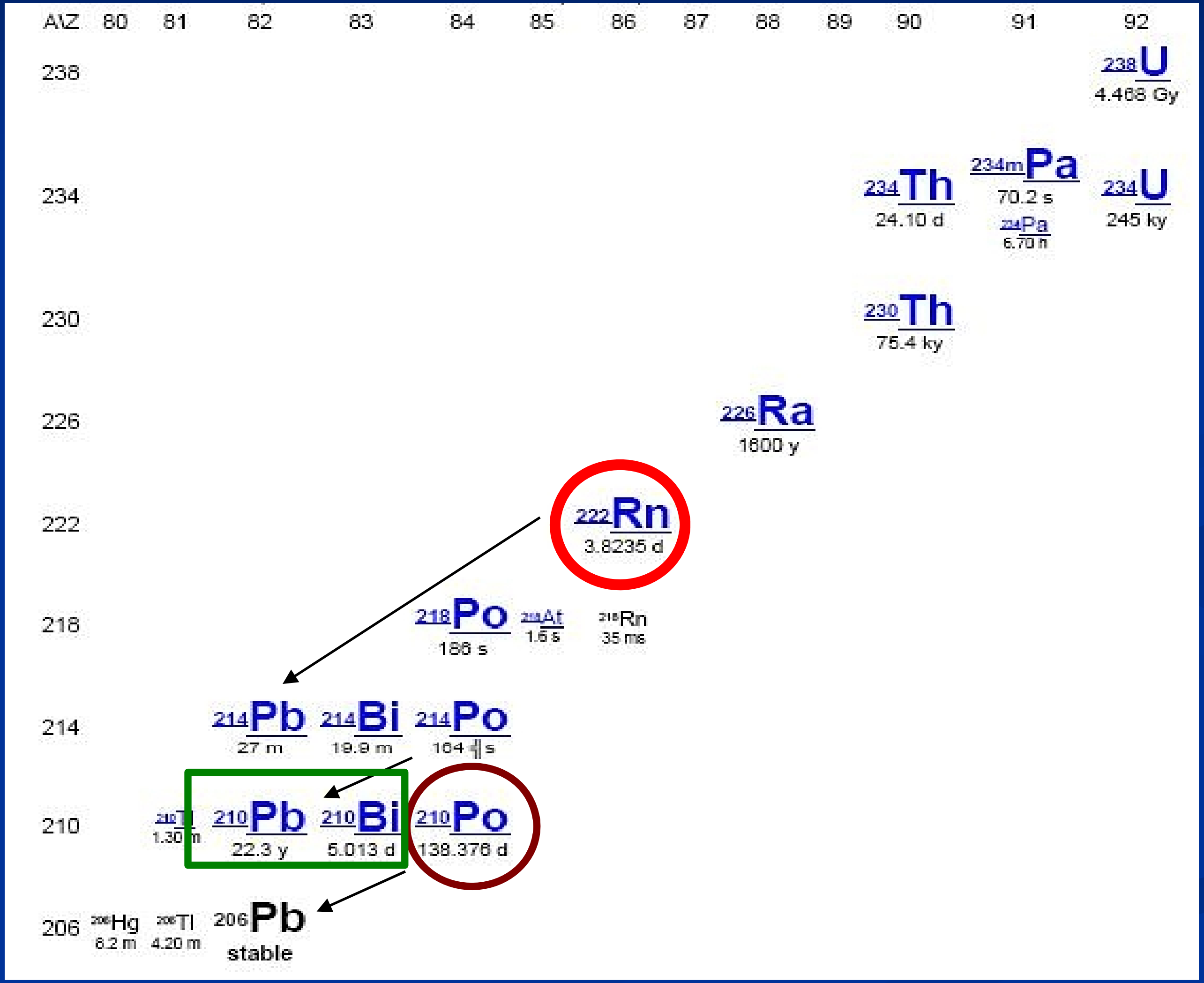
Study of the CNO flux;

Feasibility of the pp and pep neutrinos measurements is under investigation;

Anti-neutrino measurement: reactor anti-neutrinos, geo-neutrinos!

The End

^{210}Po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234mPa
70.2 s
234Pa
6.70 h
234U
245 ky
230Th
75.4 ky
226Ra
1600 y
222Rn
3.8235 d
218Po
186 s
218At
1.6 s
218Rn
35 ms
214Pb
27 m
214Bi
19.9 m
214Po
104 μs
210Tl
1.30 m
210Pb
22.3 y
210Bi
5.013 d
210Po
138.376 d
206Hg
8.2 m
206Tl
4.20 m
206Pb
stable

Detector performance

Light Yield: 500 p.e. from the study of the *"internal sources"* ^{14}C,^{11}C,^{210}Po, and global fit.

Energy resolution: 6% @ 1000 keV
8% @ 400 keV
10% @ 200 keV

Spatial resolution: 14 cm @ 800 keV
41 cm @ 100 keV

Fiducial volume definition:

Before Calibration: FV 100 tons - defined by means of the background component (^{14}C) which is uniform in the scintillator volume

Calibrations: 3D mapping of the detector (more then 100 positions!) with the (^{14}C+^{222}Rn) radioactive source

Data selection

One cluster : all events must have the unique time cluster of the PMTs hits;

Muon cut : muons and all events within 2ms after muons are rejected;

Correlated events : Decays due to radon daughters (events occuring closer than 1.5 m in the 2 ms are rejected);

Fiducial valume cut : All events must be reconstrutced within a FV (R<3m), additional requirement |z| < 1.7m → FV mass of 78.5 tonns.