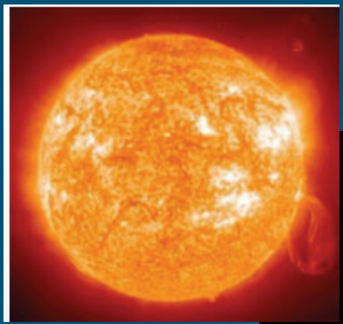
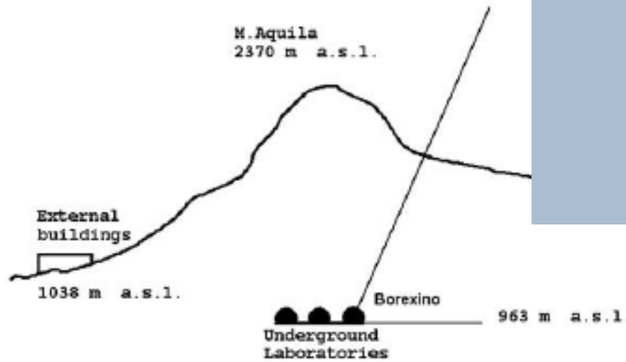
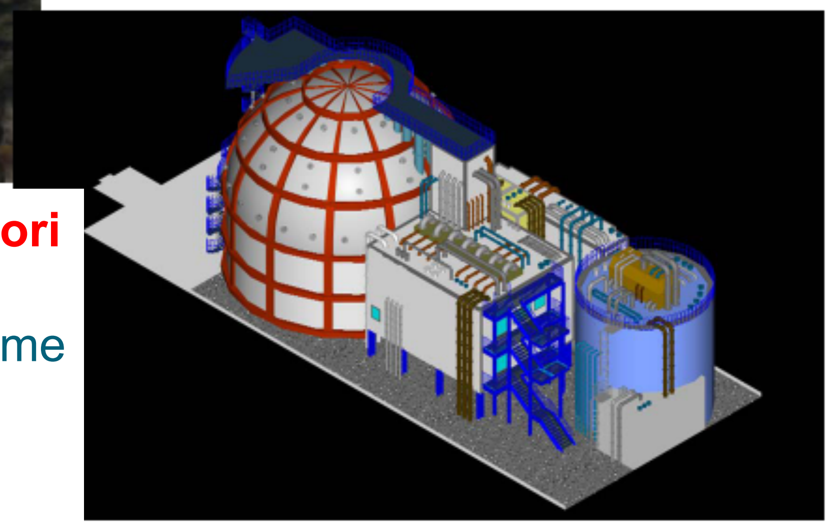
Recent Solar and Terrestrial Neutrino Results From Borexino



Livia Ludhova
INFN Milano, Italy
(on behalf of Borexino collaboration)

Borexino experimental site





Borexino is located at the **Laboratori Nazionali del Gran Sasso**, near L'Aquila, cca.120 km from Rome in Italy, shielded by 1400 m of limestone rocks (3800 m water equivalent)

Borexino Collaboration: Nucl. Instr. Methods. Phys. Res. A 600 (2009) 568-593: Borexino detector at the Laboratori Nazionali del Gran Sasso.

Borexino detector

Scintillator:
270 t PC+PPO (1.5 g/l)
in a 150 mm thick
inner nylon vessel (R = 4.25 m)

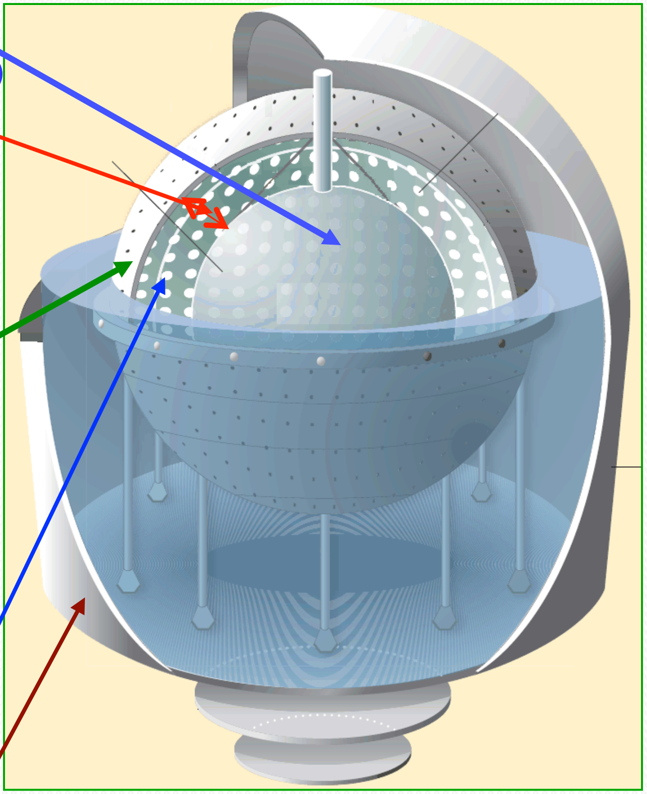
Buffer region:
PC+DMP quencher (5 g/l)
4.25 m < R < 6.75 m

Stainless Steel Sphere:
R = 6.75 m
2212 PMTs 1350 m^3

Outer nylon vessel:
R = 5.50 m
(^{222}Rn barrier)

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

Neutrino elastic scattering on electrons of liquid scintillator: $e^- + \nu \rightarrow e^- + \nu$;



# of photons → **energy**
time of flight → **position**
pulse shape → **α/β β$^+$/β$^-$**

- ~500 p.e/MeV (electron equivalent);
- Low energy threshold (~0.2 MeV);
- Calibration in situ with radioactive sources;
- Energy resolution 8% @ 400 keV;
- Space resolution 16 cm @ 500 keV;
- “wall less” Fiducial Volume;
- Accurate Monte Carlo modeling of the energy and time response function;

Drawback:
Info about the ν directionality is lost;

The smallest radioactive background in the world:
9-10 orders of magnitude smaller than the every-day environment

Borexino PHASE 1 and PHASE 2

Solar ν PHASE 1
Data taking and calibration

Scintillator purification

Solar ν PHASE 2

May 2007 — May 2010 — Aug. 2011 — Oct. 2011

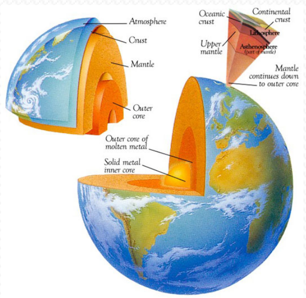
Within this period:

ν_e

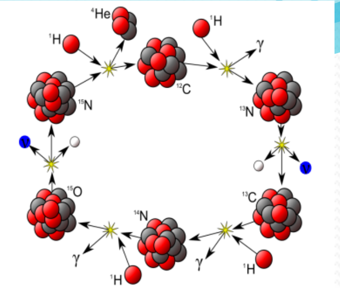
- First solar ^{7}Be-ν measurement;
- Absence of ^{7}Be-ν day-night asymmetry;
- Low-threshold ^{8}B-ν;
- First pep-ν detection;
- Best upper limit on CNO-ν;
- First geo-ν observation at > 4σ;
- Muon seasonal variations;
- Limits on rare processes;
- Neutrons and other cosmogenics;
- Evidence of ^{7}Be-ν seasonal modulation;

Updated geo-ν results:
Dec 2007 - Aug 2012

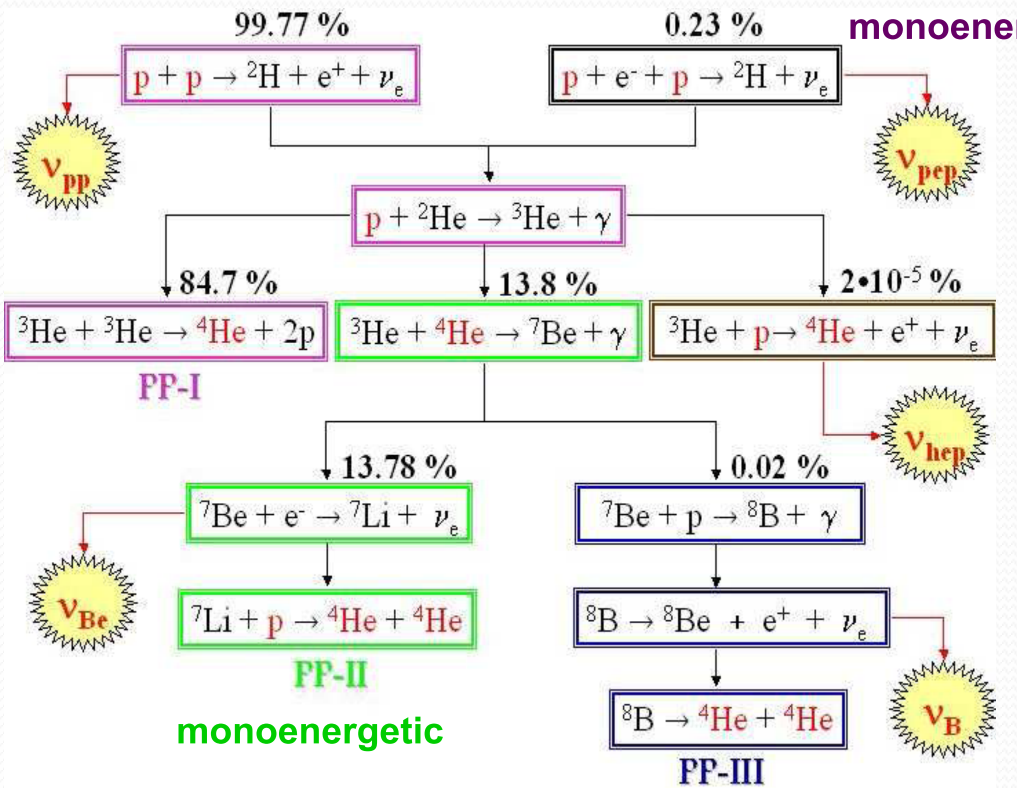
Released in 2013



Neutrinos && Nuclear reactions in the Sun

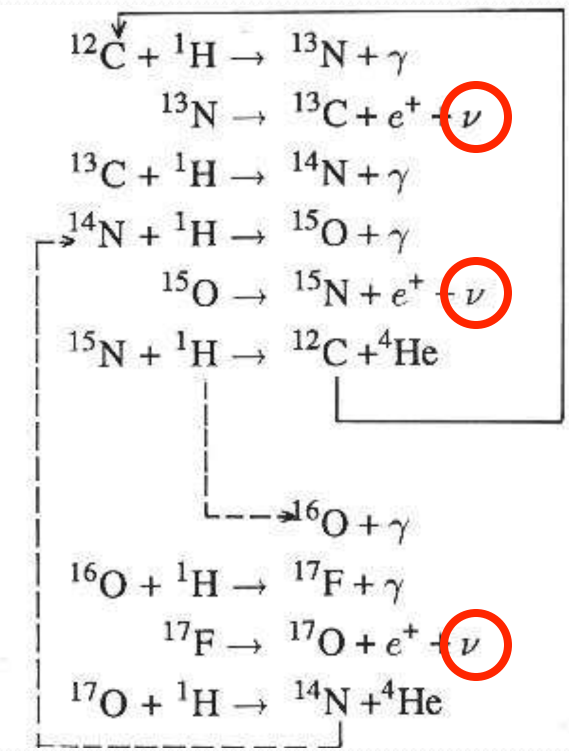


PP cycle… 99% of energy

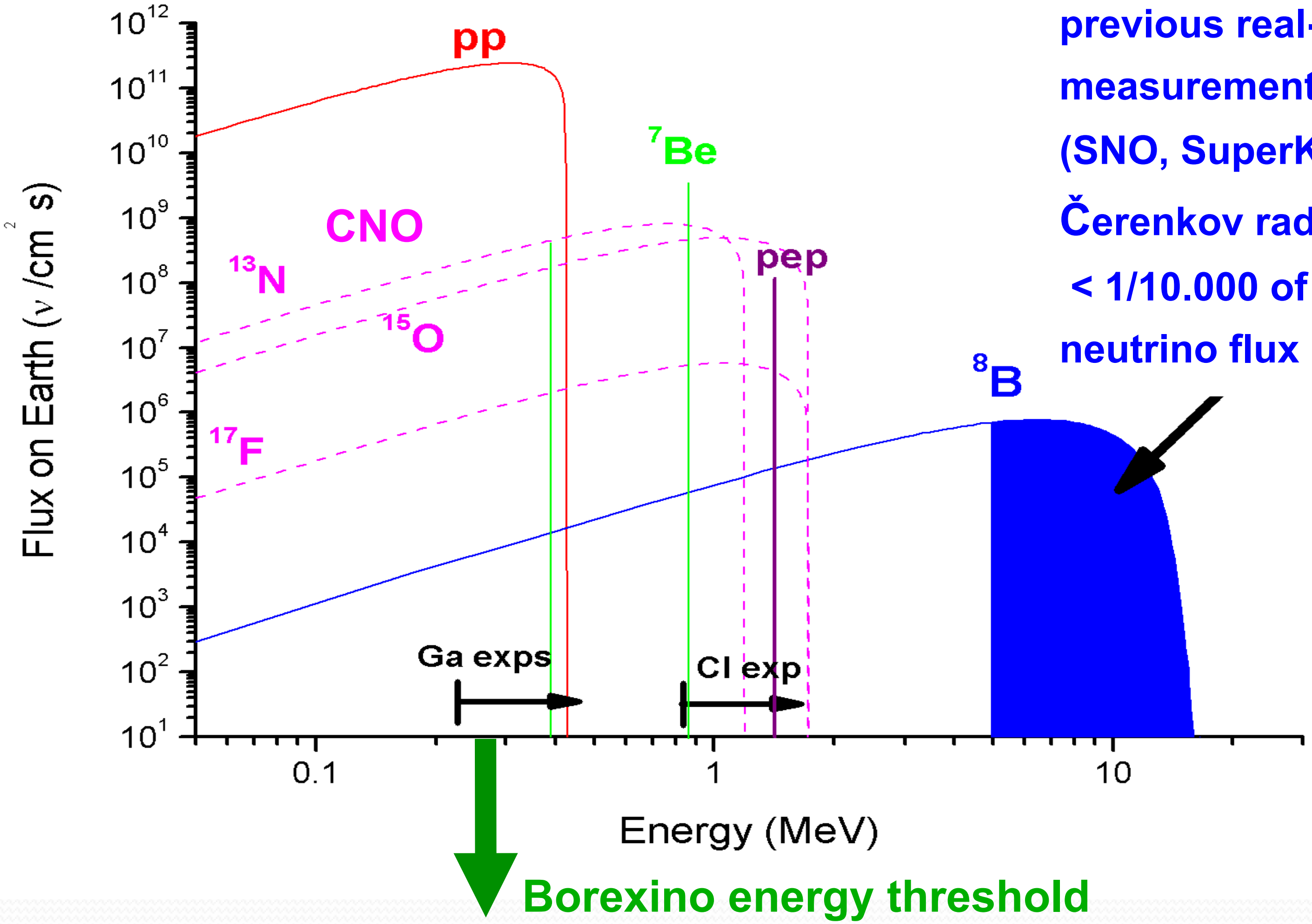


CNO cycle… <1% of energy

Poorly known
Not directly measured



Solar-neutrino energy spectrum



previous real-time measurements (SNO, SuperKamiokande) Čerenkov radiation < 1/10.000 of the total solar neutrino flux

Borexino energy threshold

What can we learn from solar neutrinos?

1) About the Sun: Solar model, SSM, flux prediction

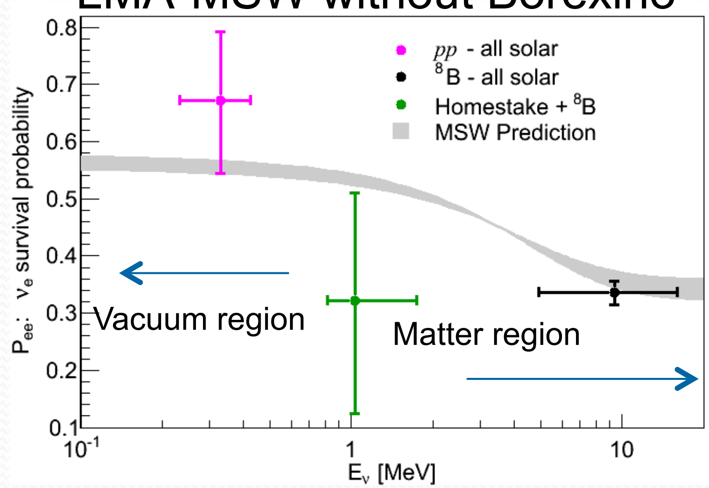
Metallicity: abundance of the elements above He

ν	Φ(ν sec^{-1} cm^{2}) High Metallicity	Φ(ν sec^{-1} cm^{2}) Low Metallicity	Diff %
pp	5.98 (1 ±0.006) 10^{10}	6.03 (1 ±0.006) 10^{10}	0.8
pep	1.44 (1 ±0.012) 10^{8}	1.47 (1 ±0.012) 10^{8}	2.1
^{7}Be	5.00 (1 ±0.070) 10^{9}	4.56 (1 ±0.070) 10^{9}	8.8
^{8}B	5.58 (1 ±0.14) 10^{6}	4.59 (1 ±0.14) 10^{6}	17.7
^{13}N	2.96 (1 ±0.14) 10^{8}	2.17 (1 ±0.14) 10^{8}	26.7
^{15}O (CNO)	2.23 (1 ±0.15) 10^{8}	1.56 (1 ±0.15) 10^{8}	30.0
^{17}F	5.52 (1 ±0.17) 10^{6}	3.40 (1 ±0.16) 10^{6}	38.4

Aldo M. Serenelli *et al.* 2011 *ApJ* **743** 24

2) **About ν-interactions:**

P_{ee} = ν_e survival probability:
LMA-MSW without Borexino

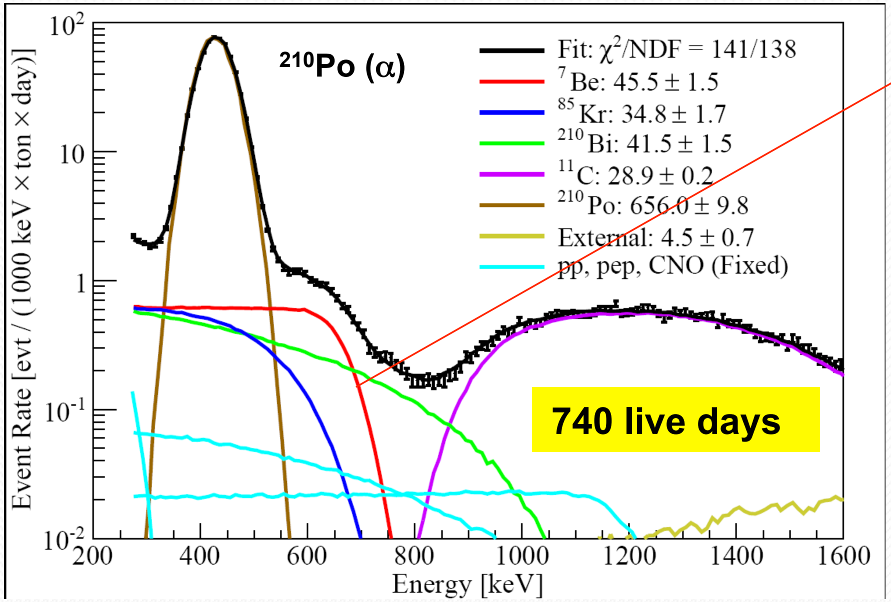


Non standard neutrino interaction:
P_{ee} (E) with different shape

Strong deviations in the transition region predicted by some models;

^{7}Be neutrino (862 keV) rate @ 4.6%

(SSM prediction @ 7%) Phys. Rev. Lett. 107, (2011) 141302



Spectral feature: Compton-like edge from scattered electrons

$46.0 \pm 1.5(\text{stat})^{+1.5}_{-1.6}(\text{syst})$

cpd/100 tons

1ton of LS = (3.307 ± 0.003) x 10^{29} electrons

- comparing to non-oscillated SSM flux: **no oscillation excluded @ 5.0 σ**

(electron equivalent flux (862 keV line): **(2.78 ± 0.13) x 10^{9} cm^{-2} s^{-1})**

- assuming MSW-LMA: f(^{7}Be) = measured flux / SSM (High Z) = 0.97 ± 0.09

Pee = 0.51 ± 0.07
(experiment + SSM high metalilcity);

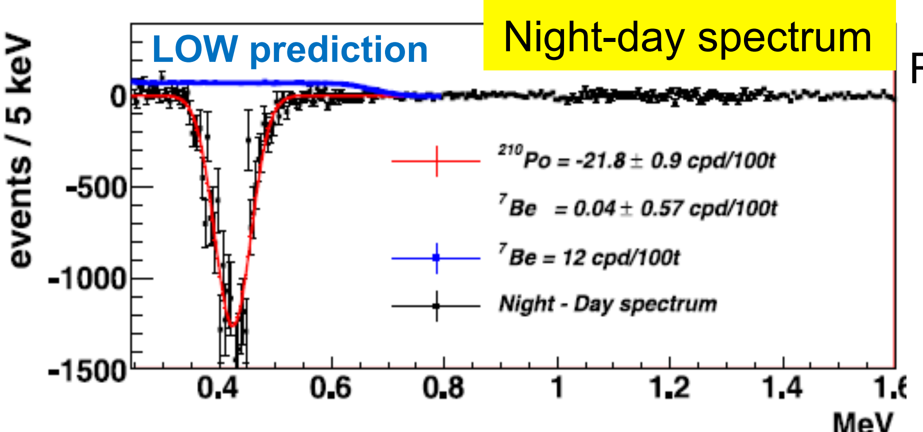
- Spectral fit including neutrino signal + background components;
- Two independent methods: MC based and the analytical one;
- fit with and without α' s statistical subtraction;

Absence of day-night asymmetry for ^{7}Be rate (R)

Phys. Lett. B 707 (2012) 22–26

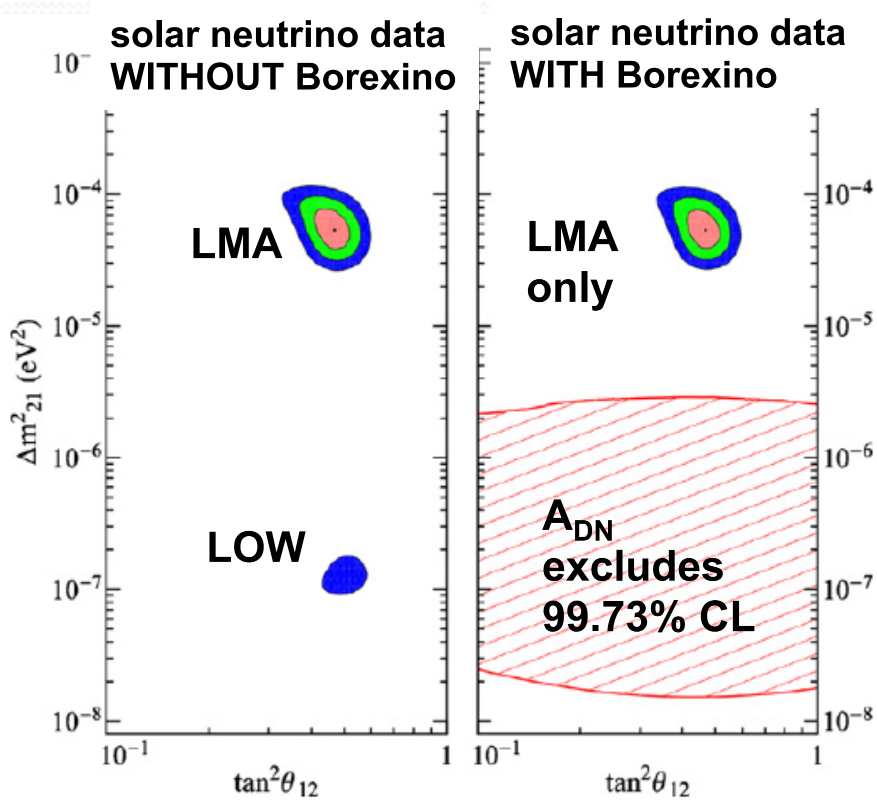
$$A_{dn} = 2\frac{R_N - R_D}{R_N + R_D} = \frac{R_{\text{diff}}}{\langle R \rangle}$$

•MSW: a possible regeneration of electron neutrinos in the matter (within the Earth during night): effect depends on the oscillation parameters and on energy;



A_{DN}= 0.001 ± 0.012(stat) ± 0.007(syst)

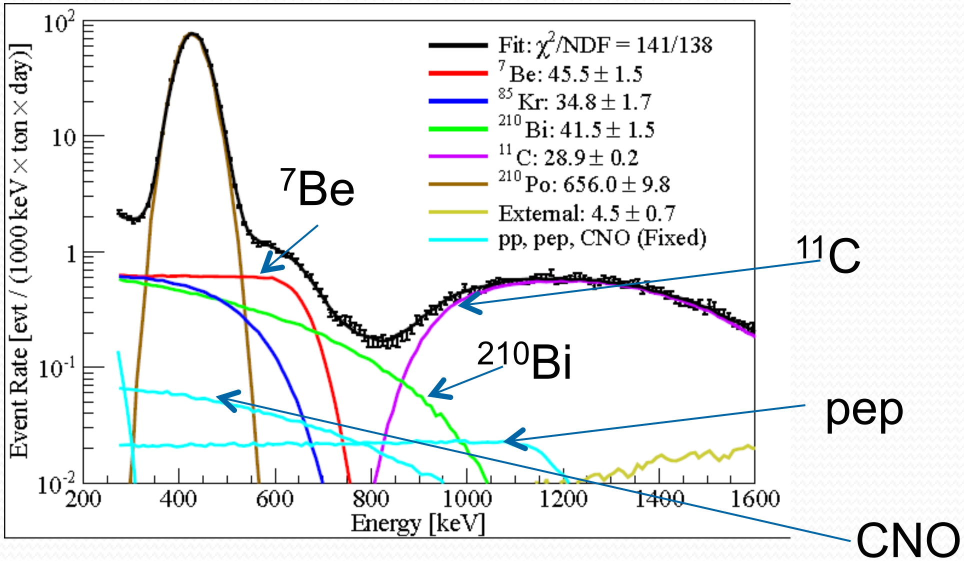
Regions allowed @ 68.27%, 95.45%, 99.73% CL



- in agreement with MSW-LMA;
- LOW region excluded at > 8.5 σ with solar neutrinos only: for the first time without the use of reactor ANTIneutrinos and therefore the assumption of CPT symmetry;
- constrains non standard interacitons (MaVaN in Holanda 2009 excluded)

First observation of pep neutrinos (1442 keV): multivariate analysis and novel background suppresion

Expected pep interaction rate: 2-3 cpd/100t



- Main background ^{11}C (e^+) with τ = 29.4 min:

1 2 3

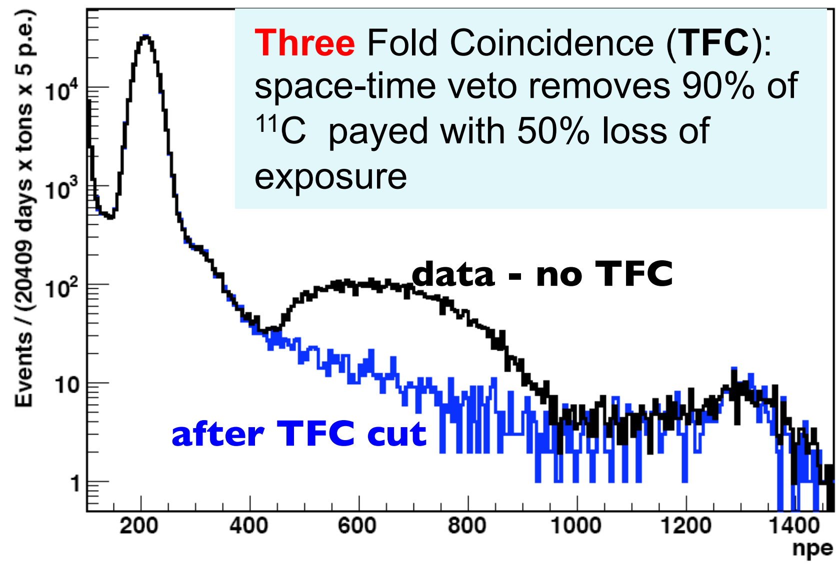
$\mu + {}^{12}C \longrightarrow \mu + n + {}^{11}C$

236 μs
Quick neutron thermalization and capture yields clear tag

$n + p \rightarrow D + \gamma$ (2.2 MeV)

29.4 min
No convection
^{11}C doesn't move

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

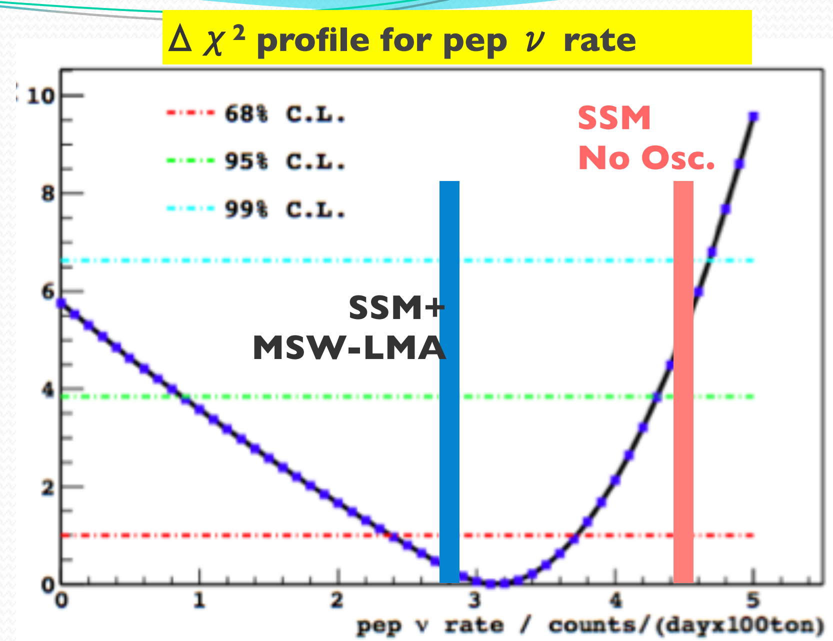


❑ **Novel β^+/ β^- pulse-shape discrimination**:
e^+ from ^{11}C decay forms Positronium having a few ns live-time in liquid scintillator (PRC 015522 2011);

❑ **Multivariate fit of:**
- the energy spectra;
- the radial distribution of the events
  (external background is not uniform, while signal is)
- pulse-shape parameter distrubution;

Pep-ν rate and CNO neutrinos

- **Pep rate: 3.1 ± 0.6$_{(stat)}$ ± 0.3$_{(sys)}$ cpd/100 t**
- Assuming MSW-LMA: Φ_{pep} = 1.6 ± 0.3 10^8 cm^{-2} s^{-1}
- No oscillations excluded at 97% c.l.
- Absence of pep solar ν excluded at 98%
- Data/SSM (high metallicity): 1.1 ± 0.2



CNO neutrinos

- only limits, correlation with ^{210}Bi;
- CNO limit obtained assuming pep @ SSM

CNO rate < 7.1 cpd/100 t (95% c.l.)

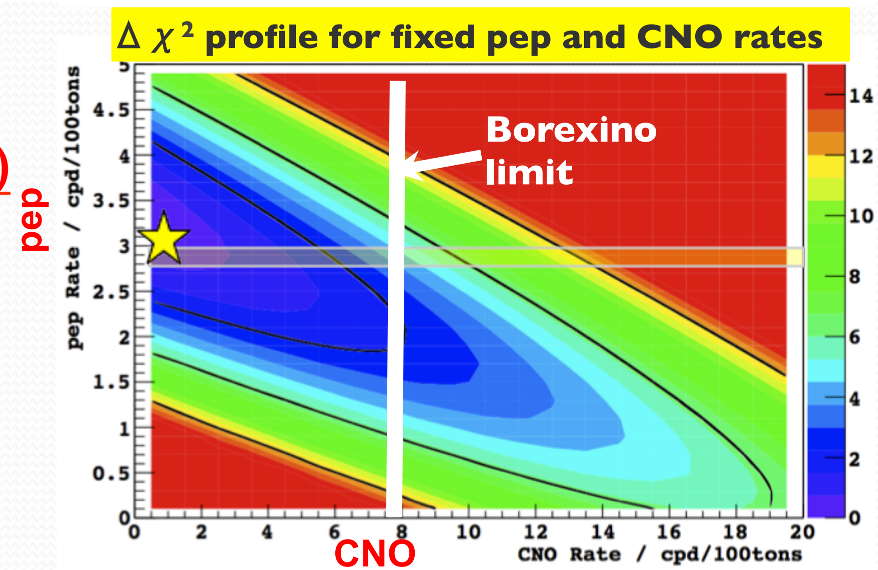
- Assuming MSW-LMA:

  Φ_{CNO} < 7.7 10^8 cm^{-2} s^{-1} (95% C.L.)

  Data/SSM (high metallicity): < 1.5

the strongest limit to date

not sufficient to resolve metallicity problem



^{8}B neutrino rate with 3 MeV energy threshold

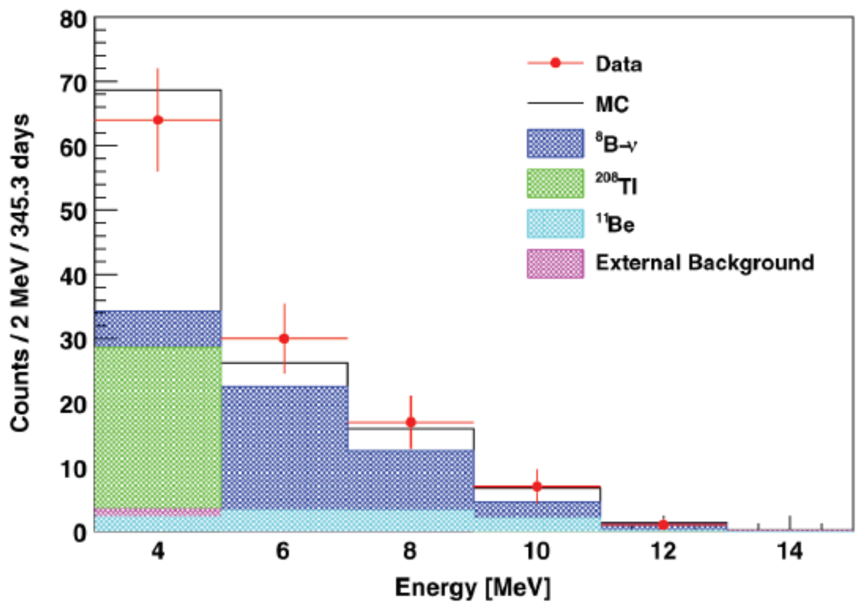
Phys. Rev. D 82 (2010) 033006 … to recall

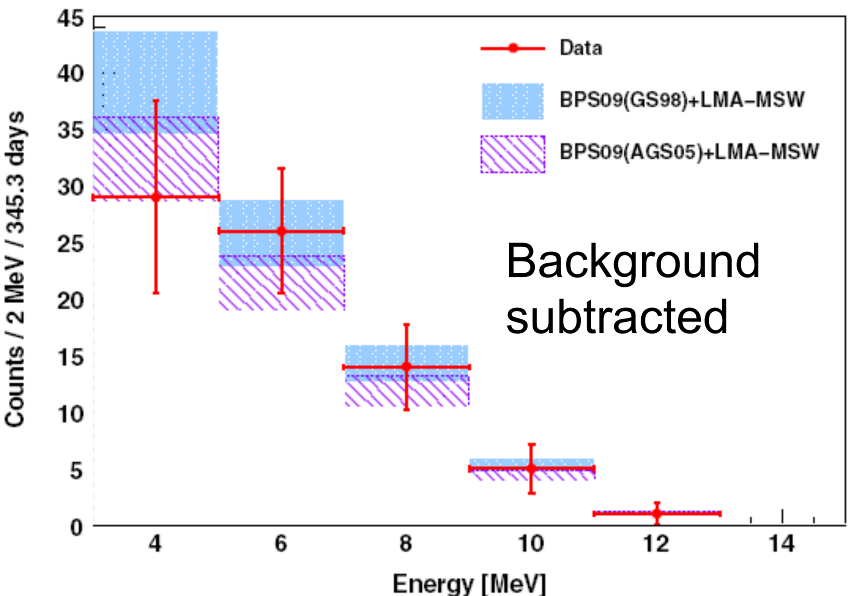
lower energies limited by ^{208}Tl

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

TABLE VI. Results on ^{8}B solar neutrino flux from elastic scattering, normalized under the assumption of the no-oscillation scenario reported by SuperKamiokaNDE, SNO, and Borexino.

	Threshold [MeV]	$\Phi^{ES}_{^8B}$ [10^6 cm^{-2} s^{-1}]
SuperKamiokaNDE I [3]	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 [4]	5.0	$2.39^{+0.24}_{-0.23}\ ^{+0.12}_{-0.12}$
SNO Salt Phase [25]	5.5	$2.35 \pm 0.22 \pm 0.15$
SNO Prop. Counter [26]	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	$2.7 \pm 0.4 \pm 0.2$



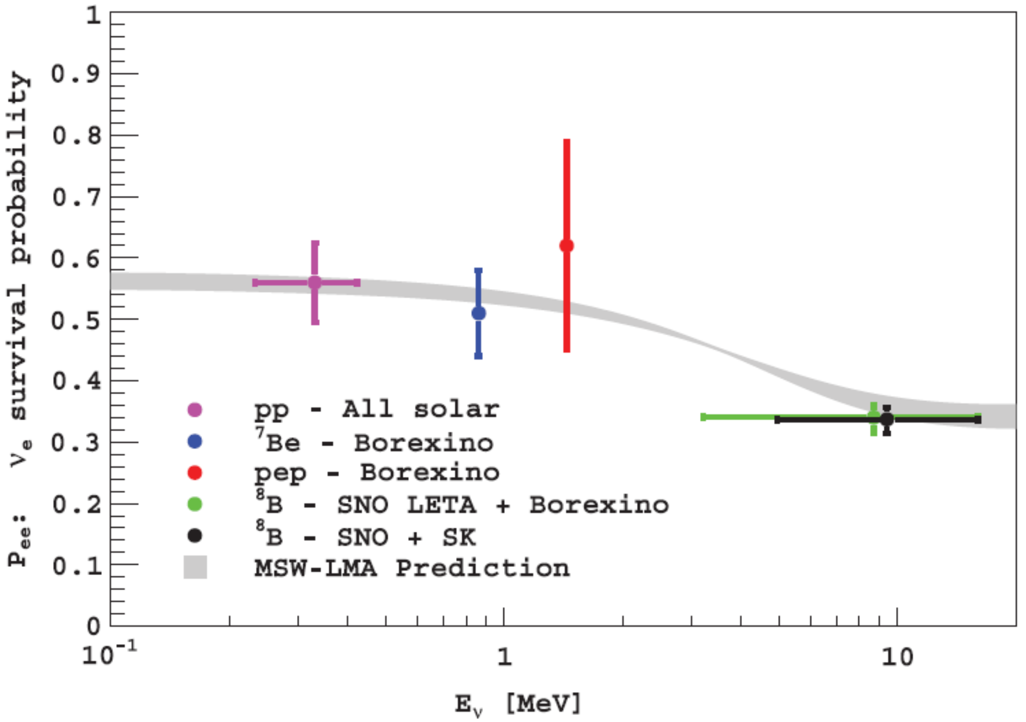


Background subtracted

Implications of Borexino solar neutrino measurements

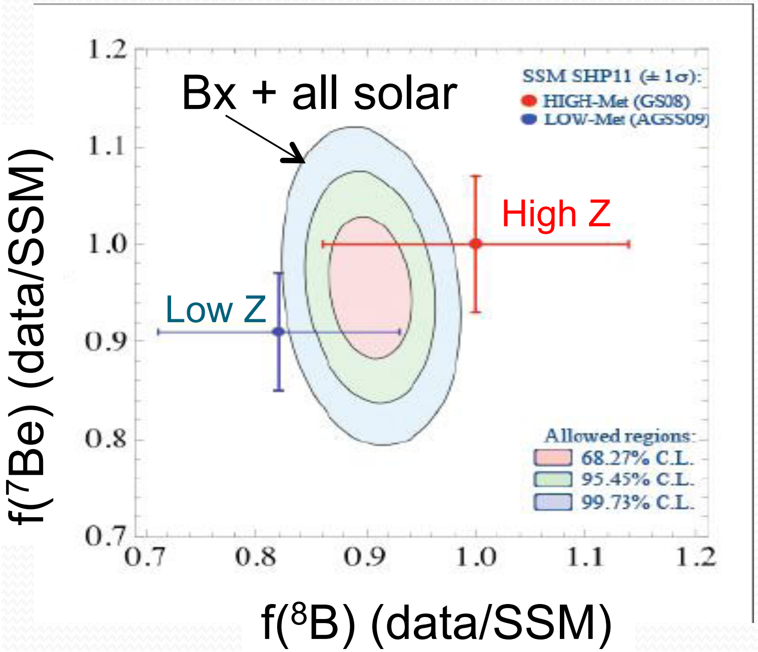
P_{ee} after Borexino I

MSW-LMA gets constrained…..



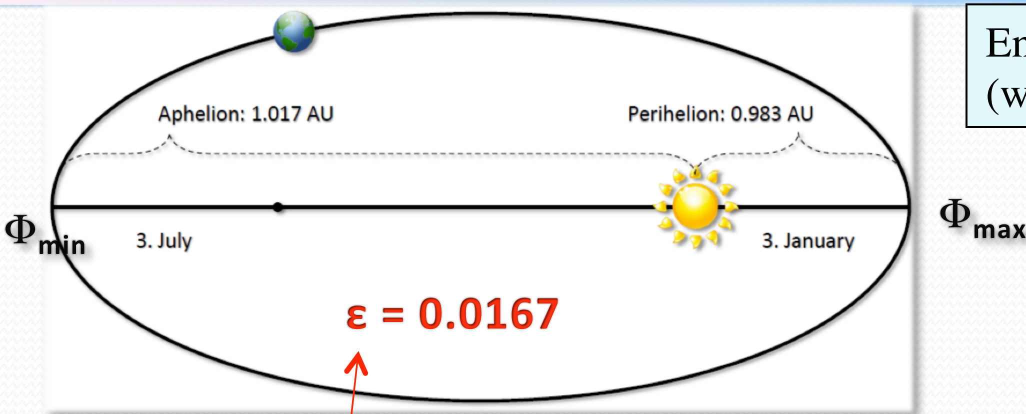
Final results of Borexino Phase-I on low-energy solar neutrino spectroscopy
arXive:1308.0443

And about the Sun?

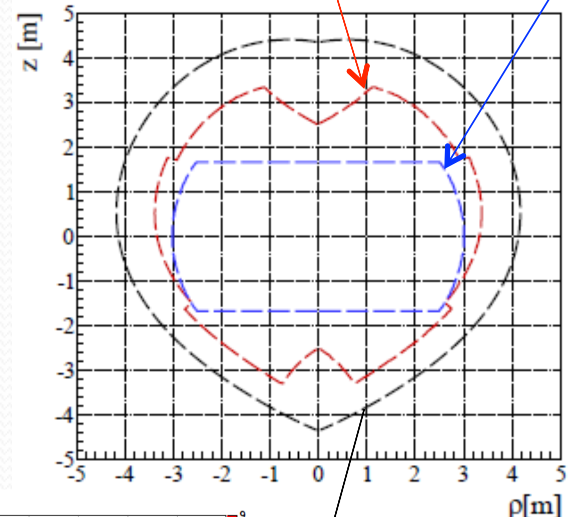


no power to resolve low/high metallicity problem

Latest solar-ν result: annual modulation of the ^{7}Be-ν signal



Enlarged, dynamic FV **(mean = 141.83 ton)**
(with respect to the ^{7}Be flux measur. (45.47 ton)

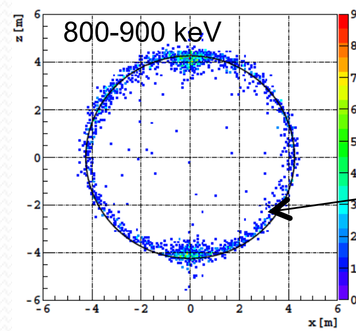


$$\Phi(t) = \Phi_0 \left(1 + 2\varepsilon \cos\left(\frac{2\pi t}{T} - \phi\right)\right)$$

$$\Phi_{max} - \Phi_{min} = 6.8\%$$

T = 1 year

Mean flux measured by Borexino: 46 ± 1.5 $^{+1.5}_{-1.5}$ cpd/100 ton



Reconstructed vessel shape = f (time, 1 week bin)

Based on ^{210}Bi on the vessel

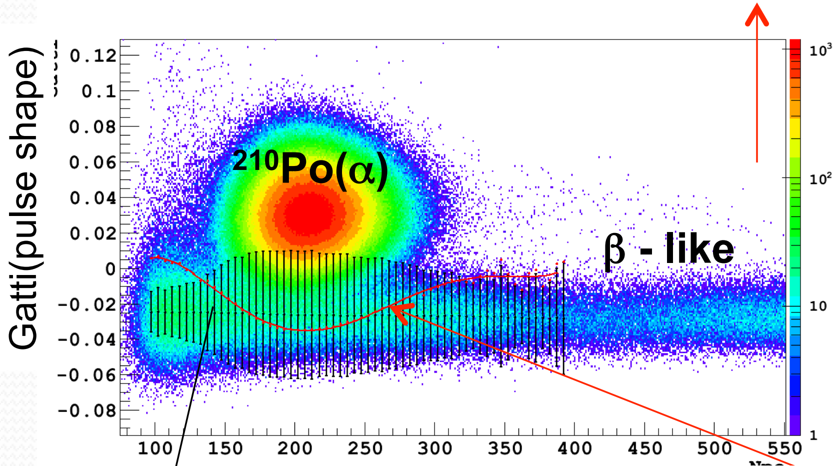
Spectral fit in sub-periods: too large stat. errors!

Rate analysis:
Select a proper energy region (optimize signal/bgr), group data in time bins and search for a periodical component;

Latest solar-ν result: annual modulation of the ^{7}Be-ν signal

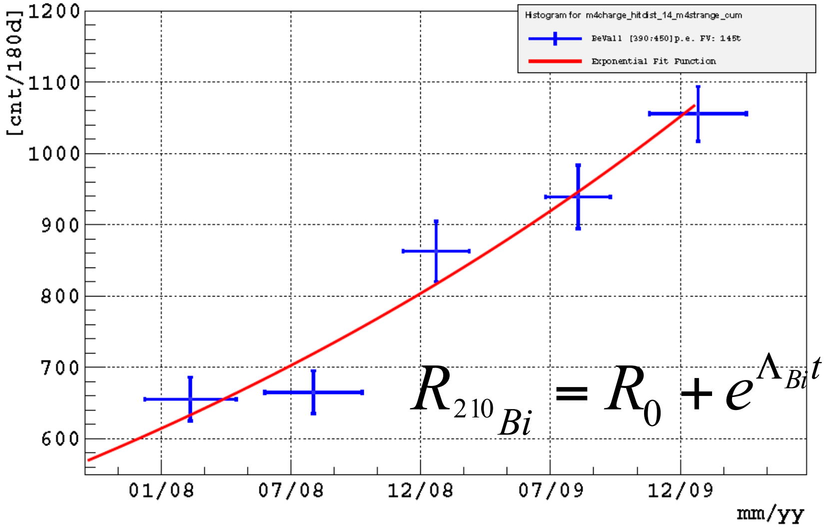
Problem: 210Bi contamination not stable in time;

Good: DETECTOR RESPONSE very stable!
(energy, position reco, pulse shape ident.)



mean β-Gatti with 99.9% interval

Counts in an energy region dominated by ^{210}Bi as a function of time



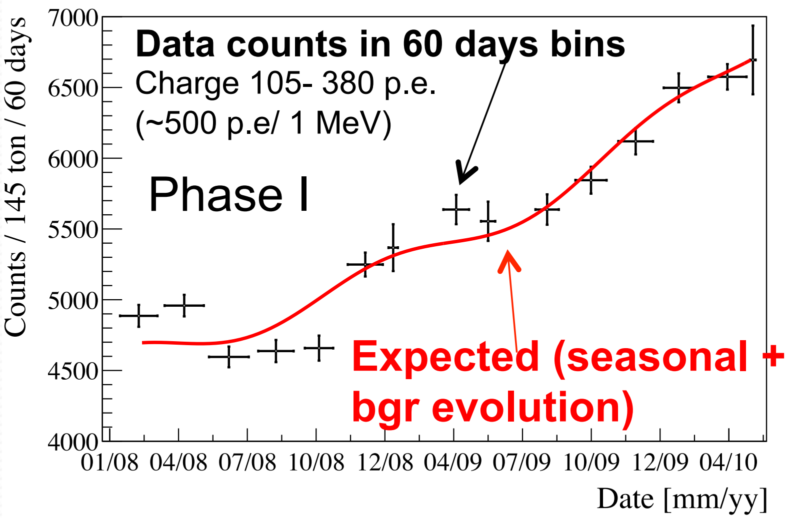
- ^{210}Po rate is also time dependent;
- Hard Gatti (pulse shape cut): removal of the events above the red line

Annual modulation of the ^{7}Be-ν signal: Results

arXive:1308.0443

3 analysis methods (consistent results)

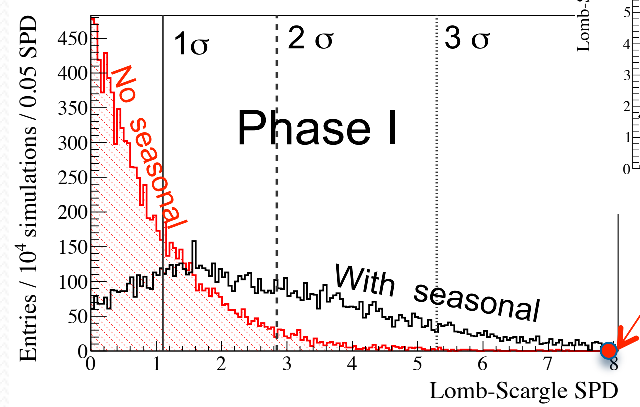
- Fit of the rate vs time;
- Lomb Scargle analysis;
- Empirical Mode Decomposition;

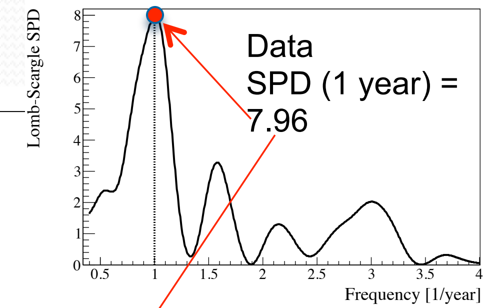


Within 2σ from expected values

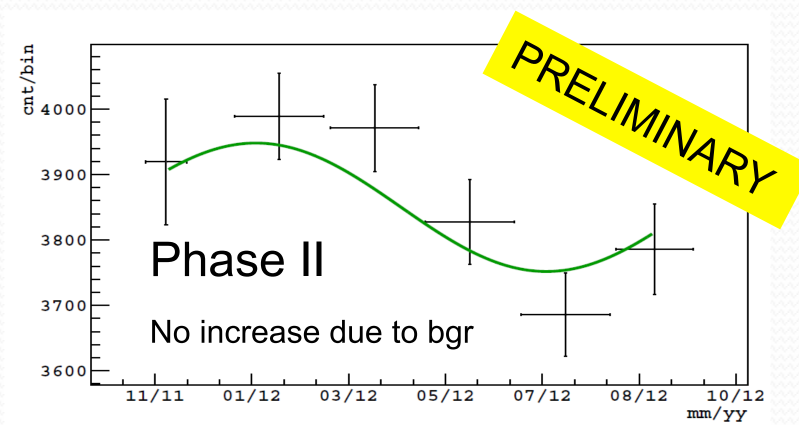
$$R = R_0 + e^{\Lambda_{Bi} t} + \overline{R}\left[1 + 2\varepsilon\cos\left(\frac{2\pi}{T} - \varphi\right)\right]$$

Monte Carlo distribution of the Spectral Power Density (SPD) With reak S/BGR ratio





No seasonal escluded at > 3σ

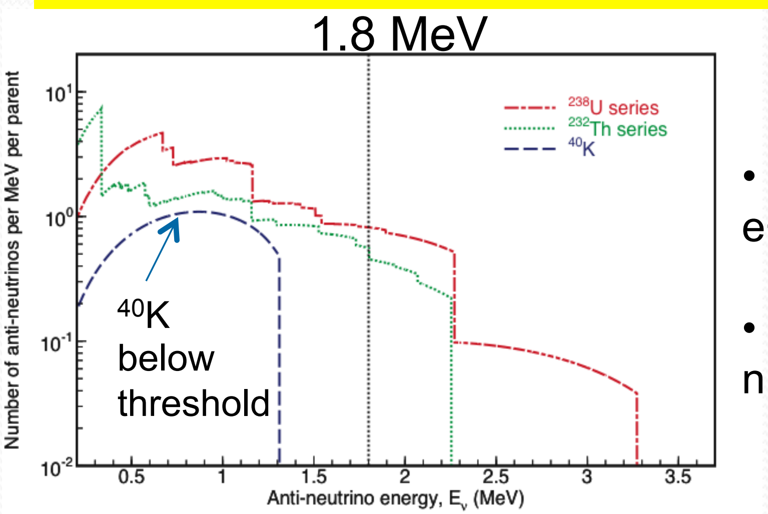


Geoneutrinos
antineutrinos from the decay of ^{238}U, ^{232}Th, ^{40}K in the Earth

Abundance of radioactive elements fixes the amount of radiogenic heat (nuclear physics);
Mass and distribution of radiogenic elements → geoneutrino flux (cca 10^6 cm^{-2} s^{-1});
From measured geoneutrino flux to radiogenic heat….

Main goal: determine the contribution of the **radiogenic heat to the total surface heat flux**, which is an important margin, test, and input at the same time for many gephysical and geochemical models of the Earth;

Further goals: tests and discrimination among geological models, study of the mantle homogeneity, insights to the processes of Earth'formation…..



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

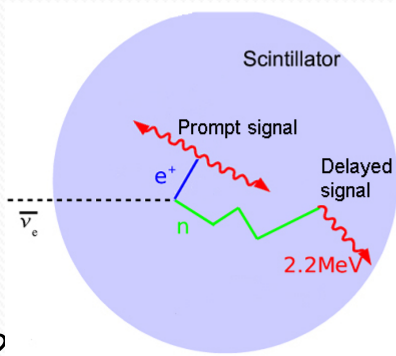
E_{ν}>1.8 MeV

- "prompt signal"

e+: energy loss + annihilation

- "delayed signal"

n capture after thermalization 2.2 γ



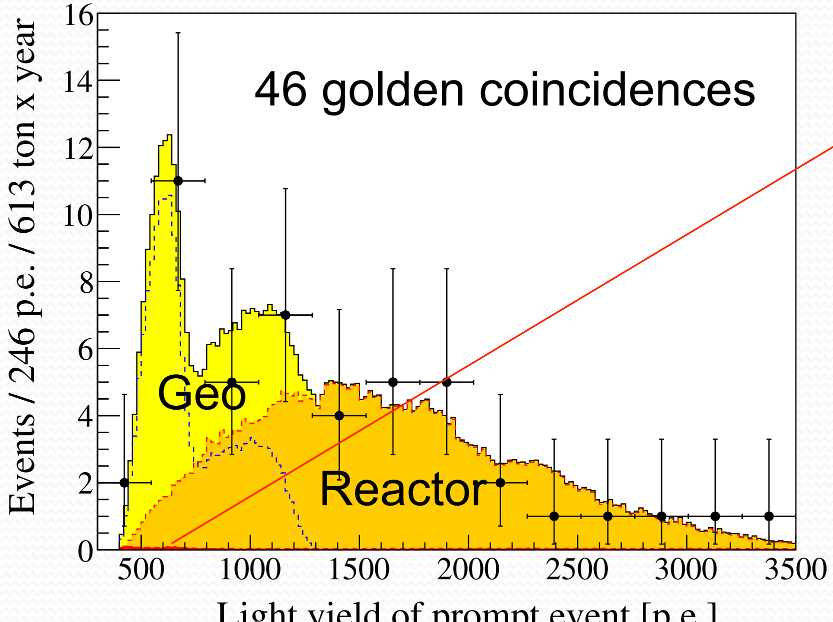
Geoneutrinos in Borexino

Previous result: G. Bellini et al. Phys. Lett. B 687 (2010) 299 with 252.6 ton-year exposure after cuts;

New result: G. Bellini et al. Phys. Lett. B 722 (2013) 295 with (613 ± 26) ton-year after cuts ;

Event selection (MC defined efficiency: 0.84 ± 0.01):

- Q_{prompt} > 480 p.e., $Q_{delayed}$ (860,1300), ΔR (promt-delayed) < 1m, Δt (promt-delayed) (20 – 1280 μs), $Gatti_{delayed}$ < 0.015 (must be "β-like")
- Large Fiducial Volume: distance from the vessel > 25 cm



Background not due to reactors is very small

Background source	Events
^9Li–^8He	0.25±0.18
Fast n's (μ's in WT)	<0.007
Fast n's (μ's in rock)	<0.28
Untagged muons	0.080±0.007
Accidental coincidences	0.206±0.004
Time corr. background	0.005±0.012
(γ,n)	<0.04
Spontaneous fission in PMTs	0.022±0.002
(α,n) in scintillator	0.13±0.01
(α,n) in the buffer	<0.43
Total	0.70 ± 0.18

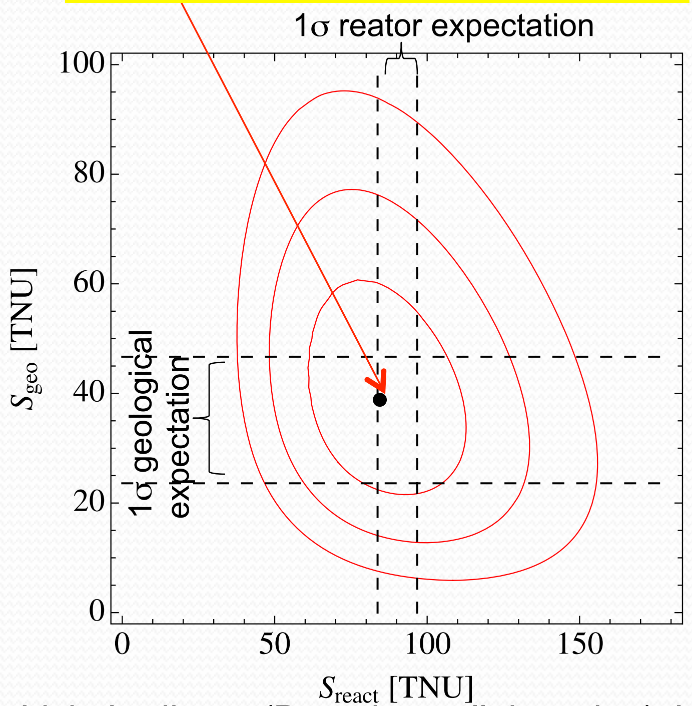
1 TNU = 1 event / 10^{32} target protons / year
Cca 1 event / 1 kton / 1 year with 100% eff

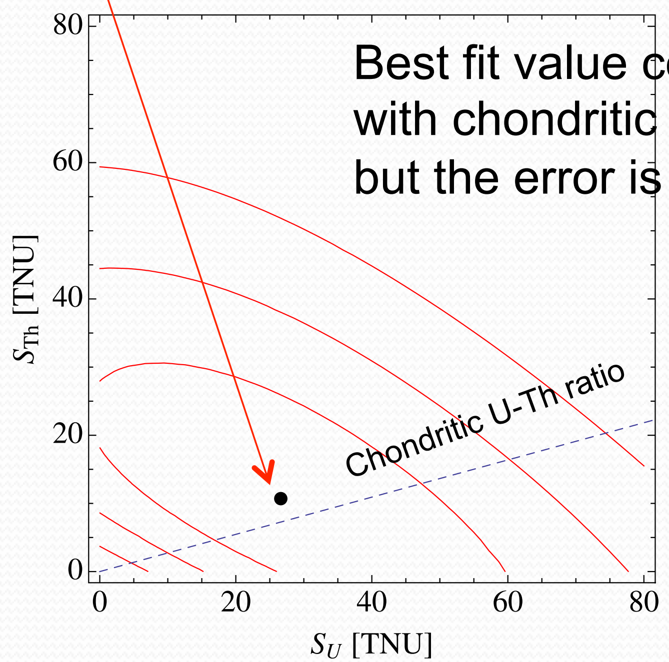
Geoneutrinos in Borexino: fit results

- Unbinned maximal likelihood fit with unconstrained geo and reactor component;
- $N_{reactor} = 31.2_{-6.1}^{+7}$ in agreement with expectation of 33.3 ± 2.4 events after oscillations;

Fixed Th/U mass ratio to chondritic value of 3.9:
N_{geo} = 14.3 ± 4.4 events
S_{geo} = 38.8 ± 12.0 TNU

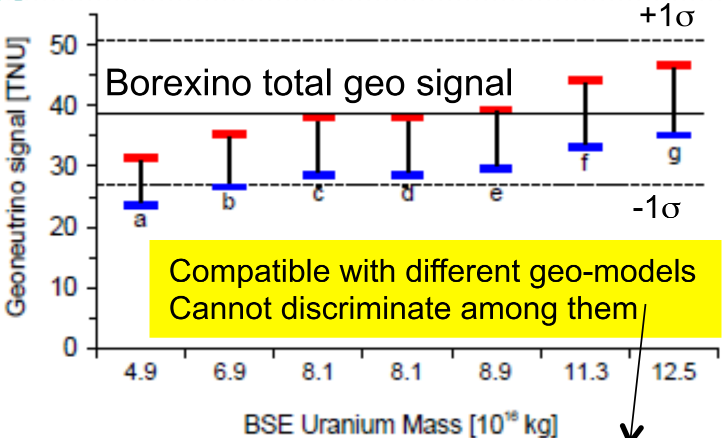
Th/U ratio free in the fit:
S(^{238} U)= 26.5 ± 19.5 TNU
S(^{232} T) = 10.6 ± 12.7 TNU



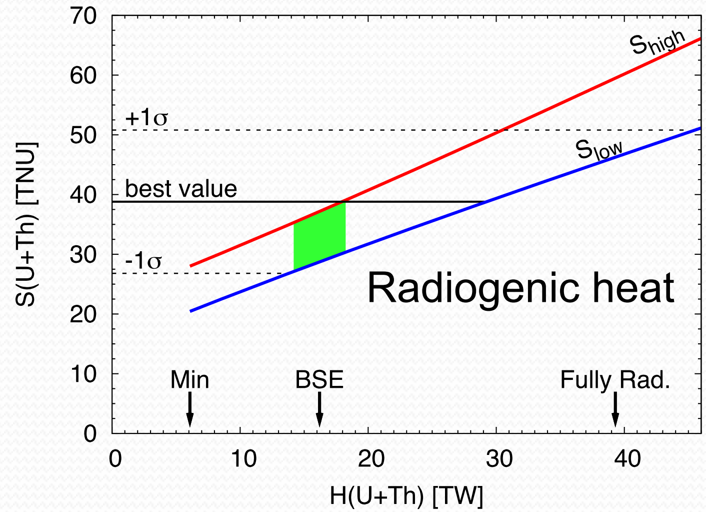


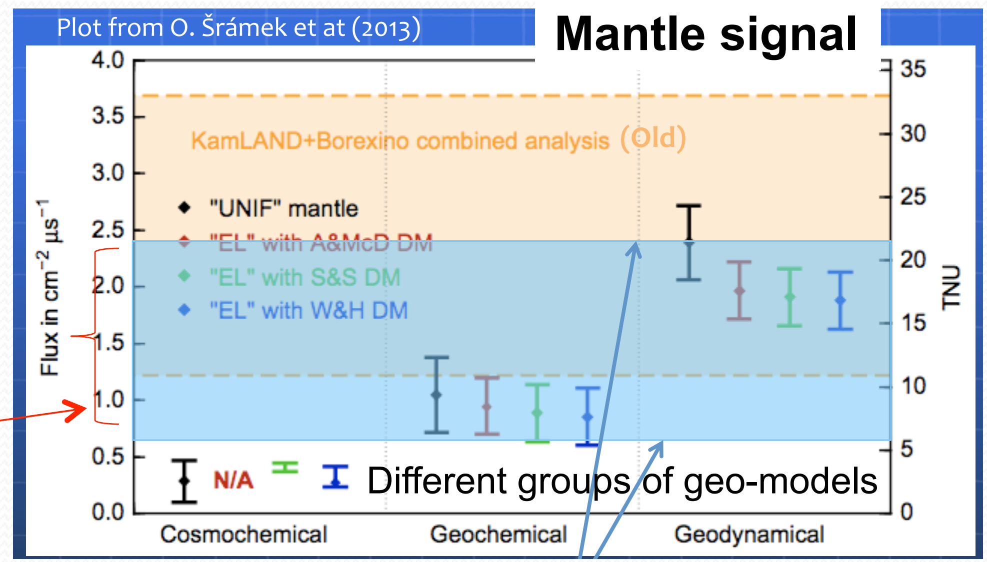
Best fit value compatible with chondritic value but the error is still large

Geoneutrinos in Borexino: implications



Turcotte & Schubert 2002	(g)
Anderson 2007	(f)
Palme & O'Neil 2003	(e)
Allegre at el. 1995	(d)
Mc Donough & Sun 1995	(c)
Lyubetskaya & Korenaga 2007	(b)
Javoy et al.2010	(a)





Mantle signal

= measured total – expected crustal (relatively well known)

Borex only: 15.4 + 12.3 TNU

Assuming homogeneous mantle:
Borex + KamLAND Nature Geoscience 4 (2011) 574

14.1 + 8.1 TNU

Borexino Phase II

Radiopurity after the purification of the scintillator:

1) Krypton: strongly reduced: consistent with zero cpd/100t from spectral fit
2) ^{210}Bi : from ~70 cpd/100 tons to 20 cpd/100tons) ;
3) ^{238}U (from ^{214}Bi - ^{214}Po tagging) < 9.7 10^{-19} g/g at 95% C.L.
4) ^{232}Th: < 1.2 10^{-18} g/g at 95% C.L. (2 events in ~600 days)
5) ^{210}Po decaying (200 cpd/100 tons in May 2013)
6) Radon: (5.4 $\pm$ 1.1) 10^{-19} g/g
7) Under study: estimation of the ^{210}Bi content from ^{210}Po evolution in time;

Physics goals of PHASE 2

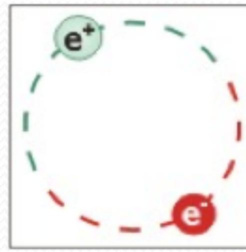
- Improve limit on CNO (observation?); (^{210}Bi suppression required);
- Improve significance of pep signal (3σ or more), ^{210}Bi suppression required;
- Search for pp neutrinos (^{85}Kr suppression helps);
- Improve precision on ^{7}Be neutrinos (^{210}Bi and ^{85}Kr suppression required);
- Collect statistics for geo-neutrino studies;

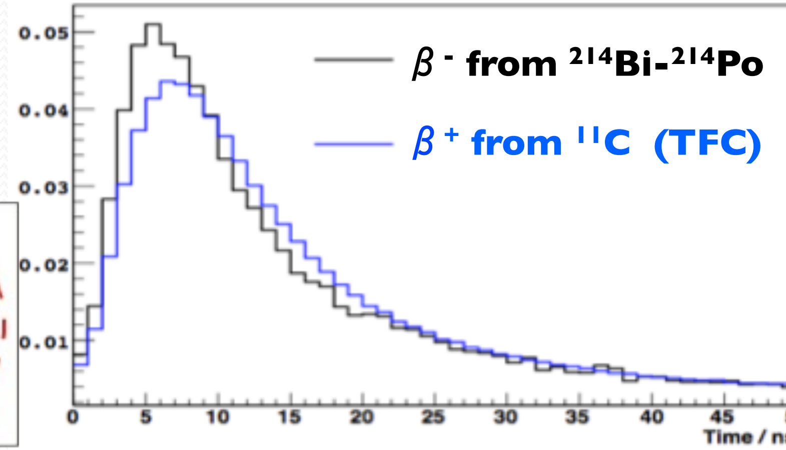

XXIV Workshop on Weak Interactions and Neutrinos
WIN 2013
Sep. 16 to 21, 2013 Natal, Brazil
Thank you!

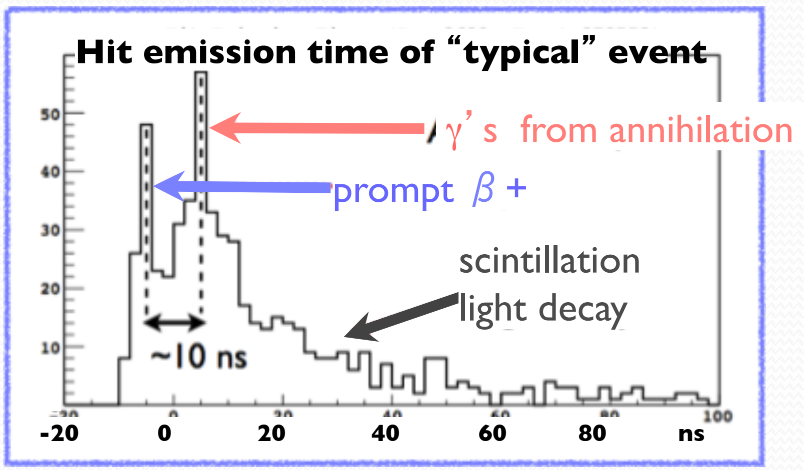
Backup

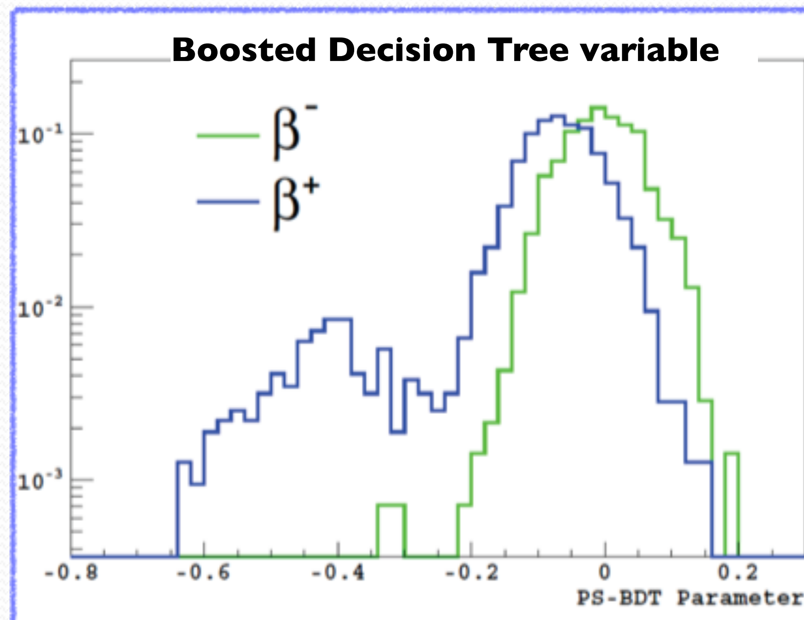
β+ - β- discrimination

- Positrons form **ortho-positronium** in ~ 50% of cases (in PC)
  - Scintillation signal **delayed** by ~ 3 ns
  - Pulse shape is different
  - Parameters measured in a dedicated experiment









- A Pulse Shape discriminating variable was developed, based on a **Boosted Decision Tree (BDT)**

The internal background in Borexino i

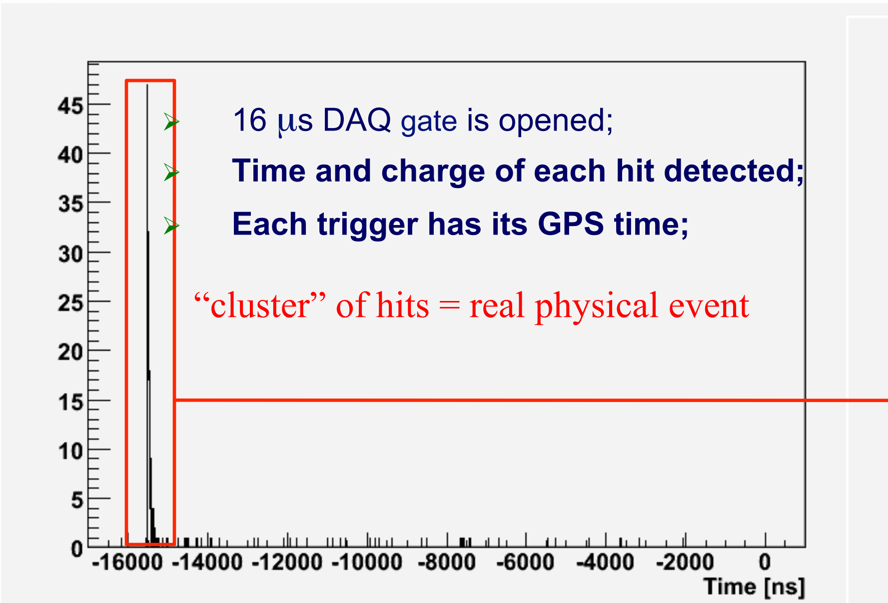
- Careful selection of the construction materials and operational procedures;
- Special procedures for fluid procurement;
- Scintillator and buffer purification during the filling;
- Sparging with high purity N2;
- **More than 15 years of work…**

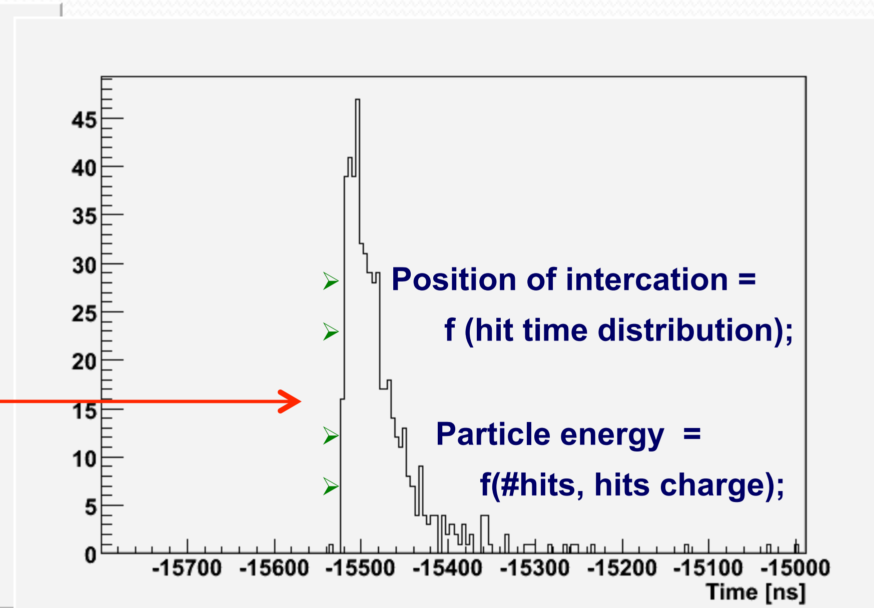
Extreme radiopurity is a must!!!

Background	Typical abundance (source)	Goal	Measured
$^{14}C/^{12}C$	10^{-12} (cosmogenic) g/g	10^{-18} g/g	~2 x 10^{-18} g/g
^{238}U (by ^{214}Bi-^{214}Po)	2 x10^{-5} (dust) g/g	10^{-16} g/g	(1.6 ± 0.1) x 10^{-17} g/g
^{232}Th (by ^{212}Bi-^{212}Po)	2 x 10^{-5} (dust) g/g	10^{-16} g/g	(5 ± 1) x 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 count /day/100t)
^{210}Po	Surface contamination	~1 c/day/t	May 2007: 70 c/d/t Sep 2008: 7 c/d/t
^{40}K	2 x 10^{-6} (dust) g/g	~10^{-18} g/g	< 3 x 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

Data structure and detector performance

- Charged particles and γ produce scintillation light: photons hit inner PMTs;
- DAQ trigger: > 25 inner PMTs (from 2212) are hit within 60-95 ns:





- Outer detector gives a muon veto if at least 6 outer PMTs (from 208) fire;

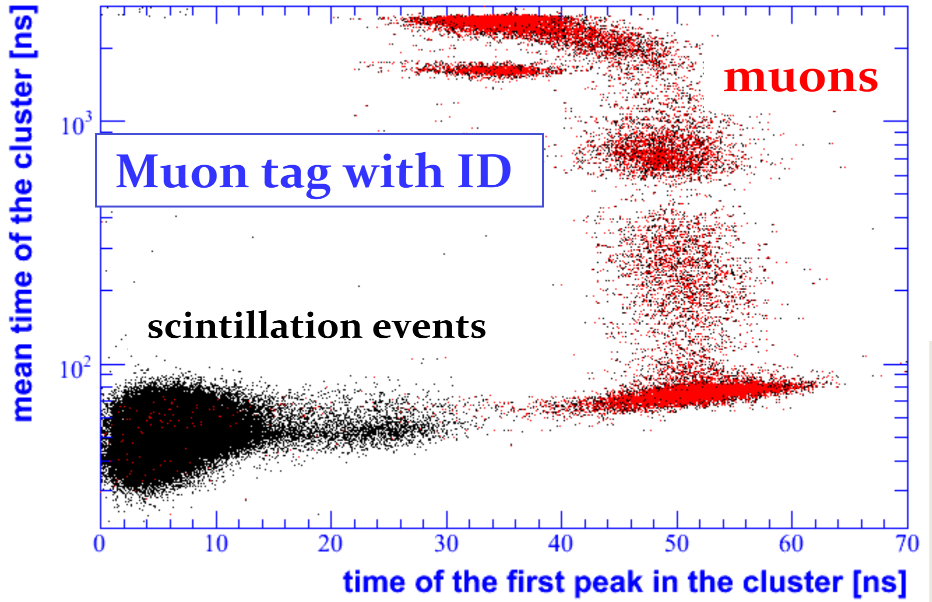
Light yield: (500 ± 12) p.e./MeV
taking into account quenching factor

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

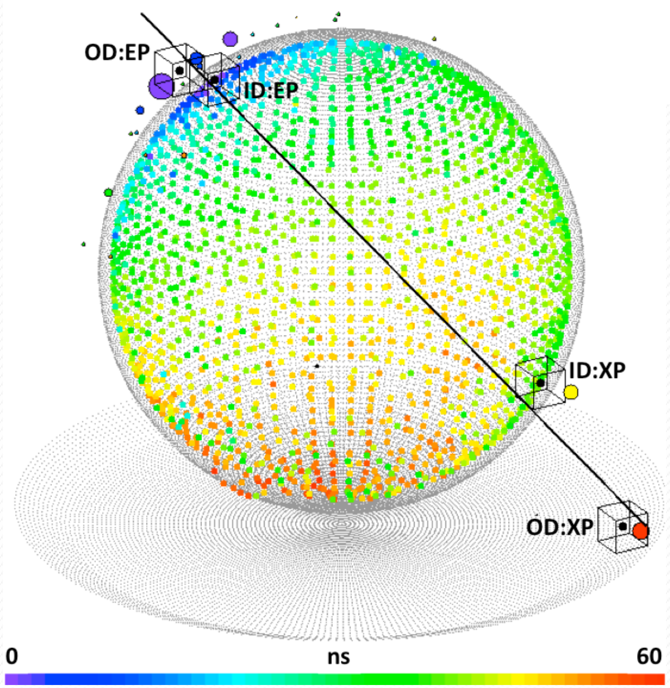
Spatial resolution: 35 cm @ 200 keV
(scaling as $N_{p.e.}^{-1/2}$) 16 cm @ 500 keV

Muon and neutron detection

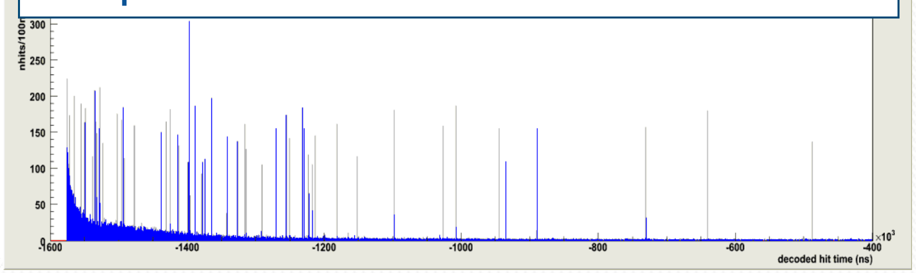
- μ are identified by the OD and by the ID
  - OD eff: > 99.28%
  - ID analysis based on pulse shape variables
    - Cluster mean time, peak position in time
  - **Combined overall efficiency > 99.992%**
  - **After cuts, μ not a relevant background for ^{7}Be**
  - **Residual background: < 1 count /day/ 1 00 t**



Muon track reconstruction



After each μ, 1.6 ms gate opened to detect neutrons: example with several tens of neutrons.



NEW: Muon and Cosmogenic Neutron Detection in Borexino. Sent to JINST 2 weeks ago, arXiv:1101.3101

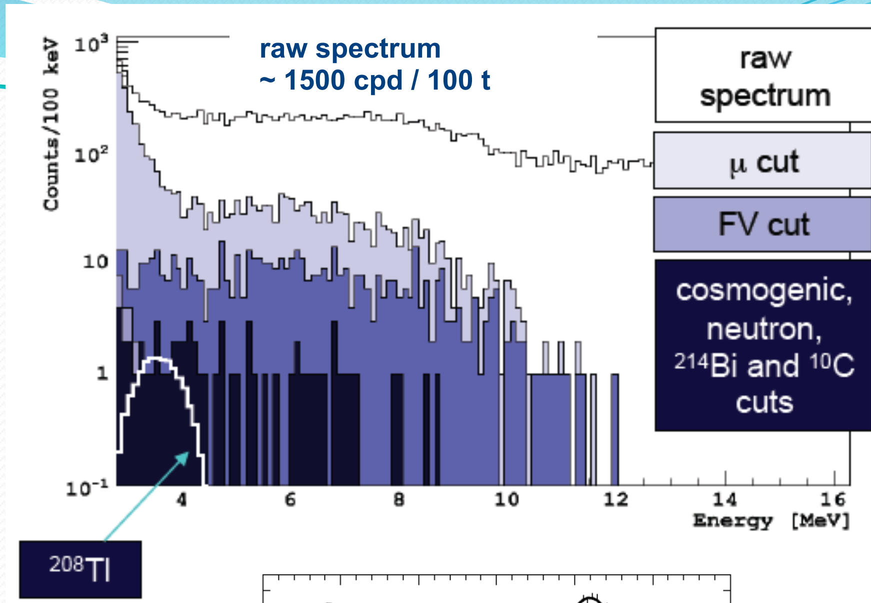
^{8}B analysis details

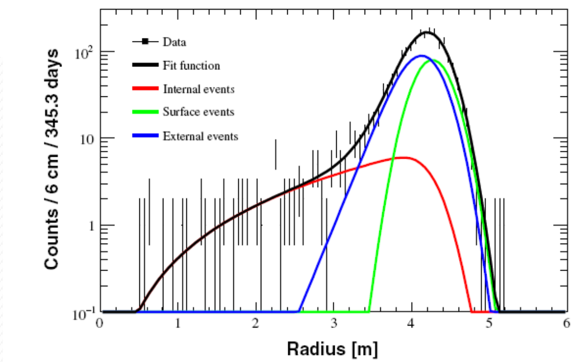
External backgrounds (FV CUT):

- High energy γ from neutrons
- ^{214}Bi and ^{208}Tl from Rn
  emanated from nylon or detector

Internal radiocative backgrounds:

- ^{214}Bi (^{238}U chain) via ^{214}Bi-^{214}Po coincidences;
- ^{208}Tl (^{232}Th chain) from bulk: stat. subtr.;





Cosmogenic background rejection:

- ***FAST COSMOGENIC CUT:*** 6.5 s dead time after all ID muons to reject fast cosmogenic isotopes; (29.2 % dead time,, 4300 muons/day passing ID)
- ***NEUTRON REJECTION***: 2 ms after all muons (neutron capture time 256 μs , AmBe source);
- ***^{10}C SUBTRUCTION:*** 3-fold coincidence with parent muon and neutron;
- ***^{11}Be STATISTICAL SUBTRUCTION;***

Background: ^{232}Th and ^{238}U content

Assuming secular equilibrium:

^{232}Th chain

τ = 432.8 ns

^{212}Bi $\xrightarrow{\beta}$ ^{212}Po $\xrightarrow{\alpha}$ ^{208}Pb

2.25 MeV ~800 keV eq.

^{238}U chain

τ = 236 μs

^{214}Bi $\xrightarrow{\beta}$ ^{214}Po $\xrightarrow{\alpha}$ ^{210}Pb

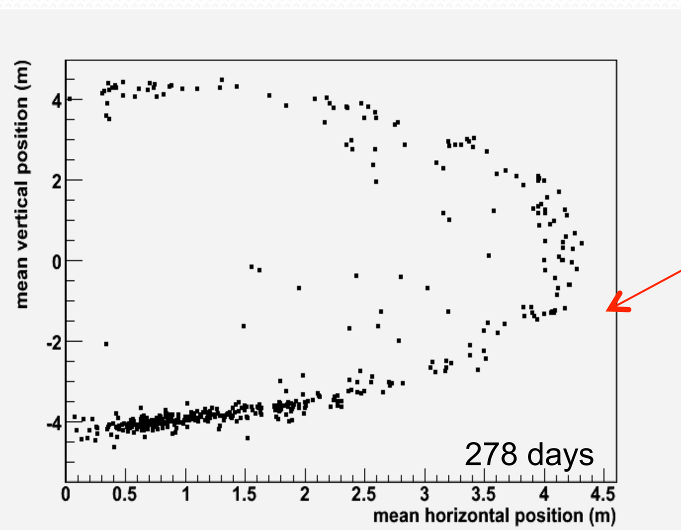
3.2 MeV ~700 keV eq.

(6.8±1.5) × 10^{-18} g(Th)/g

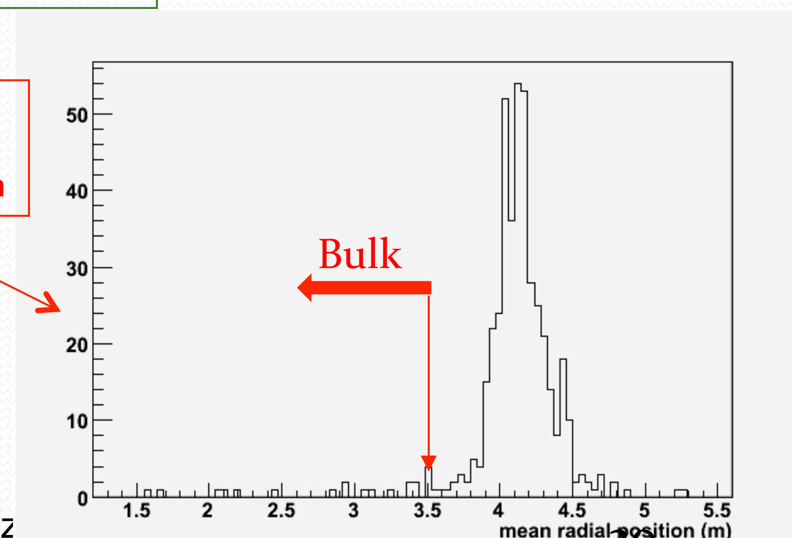
Bulk contamination

(1.6 ± 0.1) × 10^{-17} g(U)/g

Only few bulk candidates



^{212}Bi-^{212}Po centre of mass position distribution



Background: ^{210}Po and ^{85}Kr

^{210}Po: end of ^{238}U chain :

	β^-(61 keV)		β^-(1.2MeV)		α	
	^{210}Pb	->	^{210}Bi	->	^{210}Po	-> ^{206}Pb
$t_{1/2}$	22.3 y		5.01 d		138.38 d	stable

- The bulk **^{238}U and ^{232}Th** contamination is **negligible**
- The **^{210}Po** background is **NOT related** neither **to ^{238}U** nor to **^{210}Pb** contamination
- **May 2007 ~80 counts/day/ton, τ=204.6 days**
- **^{210}Bi no direct evidence** ---> free parameter in the total fit, cannot be disentangled, in the ^{7}Be energy range, from the CNO

^{85}Kr β-decay energy spectrum similar to the ^{7}Be recoil electron

$$^{85}\mathrm{Kr} \xrightarrow[687\ \mathrm{keV}]{\beta} {}^{85}\mathrm{Rb}$$

τ = 10.76 y - BR: 99.56%

^{85}Kr is studied through :

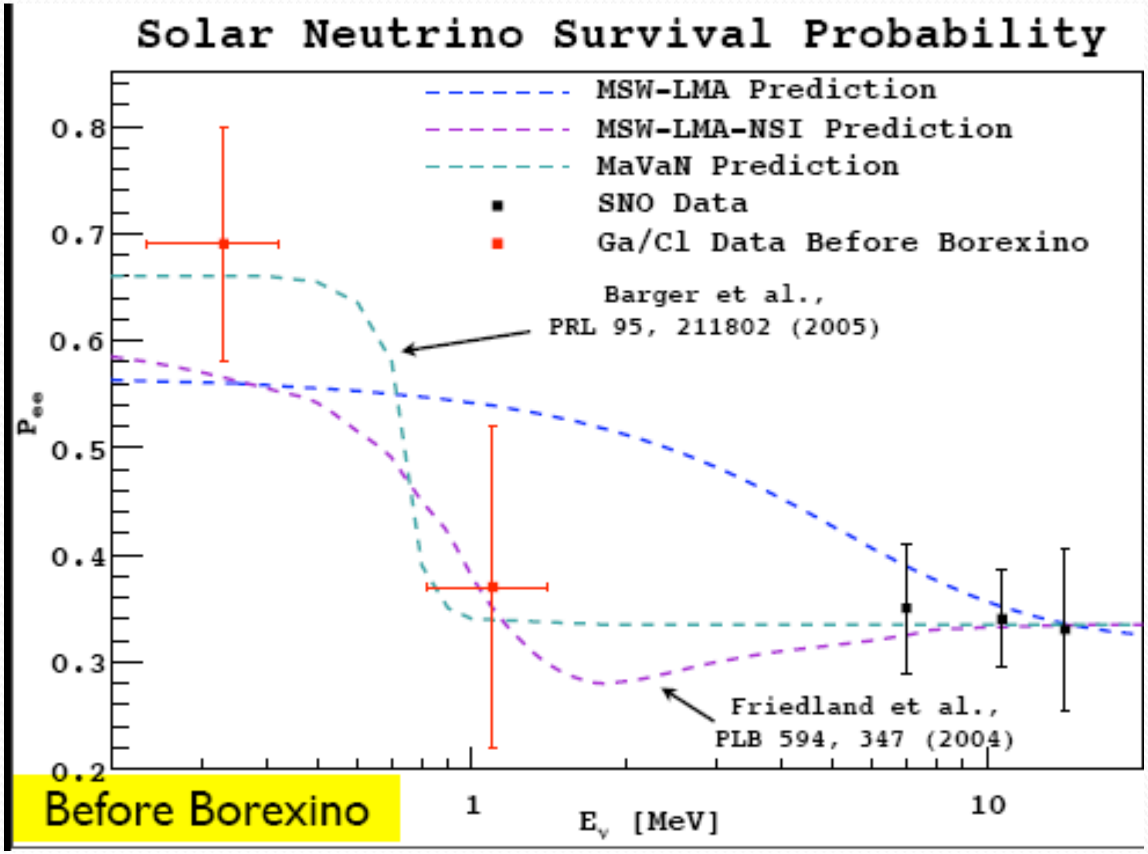
$$^{85}\mathrm{Kr} \xrightarrow[173\ \mathrm{keV}]{\beta} {}^{85m}\mathrm{Rb} \xrightarrow[514\ \mathrm{keV}]{\gamma} {}^{85}\mathrm{Rb}$$

τ = 1.46 ms - BR: 0.43%

PRELIMINARY: the ^{85}Kr contamination **(30$\pm$5) counts/day/100 ton**

What can we learn from solar neutrinos (2) ?

Neutrino Physics: precision measurement of solar ν fluxes vs survival probability P_{ee}



Low energy neutrinos:
flavor change dominated
by vacuum oscillations;

High energy neutrinos:
Resonant oscillations in matter
(MSW effect):
Effective electron neutrino mass
is increased due to the charge
current interactions
with electrons of the Sun

Transition region:
Decrease of the ν_e survival
probability (P_{ee})

Vacuum regime

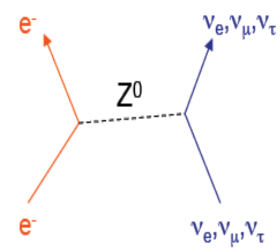
Matter regime

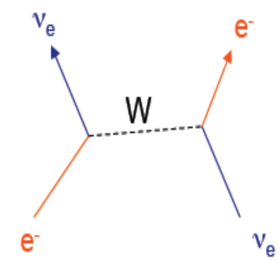
Livia Ludhova (Borexino collaboration), WIN 2013, Natal, Brazil, 16-21 September 2013

Detection principle

of photons → **energy**
time of flight → **position**
pulse shape → **α/β β^+/β^-**

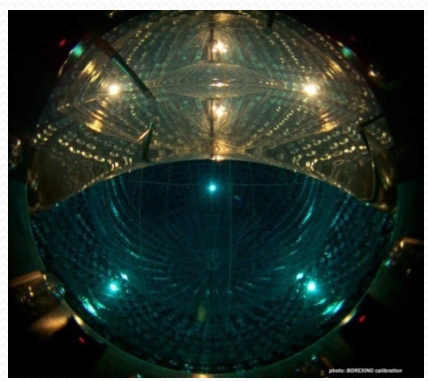
- Neutrino elastic scattering on electrons of liquid scintillator: **$e^- + \nu \rightarrow e^- + \nu$;**
- Scattered electrons cause the scintillation light production;
- **<u>Advantages</u>**:
  - Low energy threshold (~ 0.2 MeV);
  - High light yield and a good energy resolution;
  - Good position reconstruction;
- **<u>Drawbacks :</u>**
  - Info about the ν directionality is lost ;
  - ν-induced events can't be distinguished from the events of β/γ natural radioactivity;



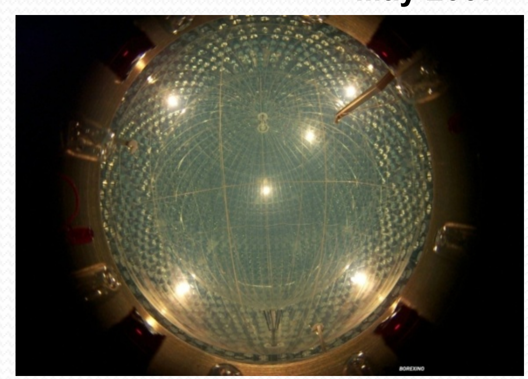


End October 2006

March 2007



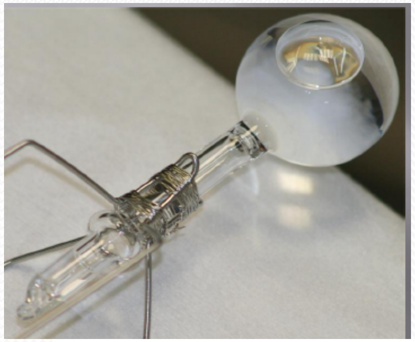
May 2007

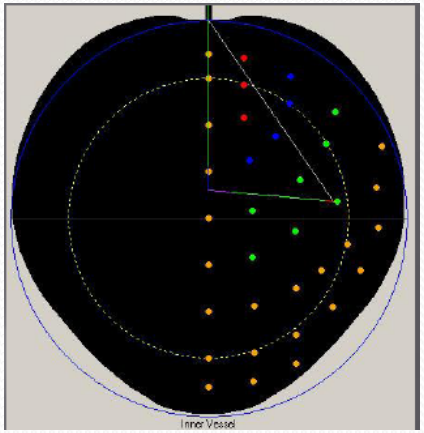


Calibration with radioactive sources

	γ								β		α	n (AmBe)		
	^{57}Co	^{139}Ce	^{203}Hg	^{85}Sr	^{54}Mn	^{65}Zn	^{60}Co	^{40}K	^{14}C	^{214}Bi	^{214}Po	n-p	n+^{12}C	n+Fe
energy (MeV)	0.122	0.165	0.279	0.514	0.834	1.1	1.1, 1.3	1.4	0.15	3.2		2.226	4.94	~7.5

- Absolute source position: LED and CCD cameras (± 2cm);
- cca. 300 points through the whole scintillator volume;

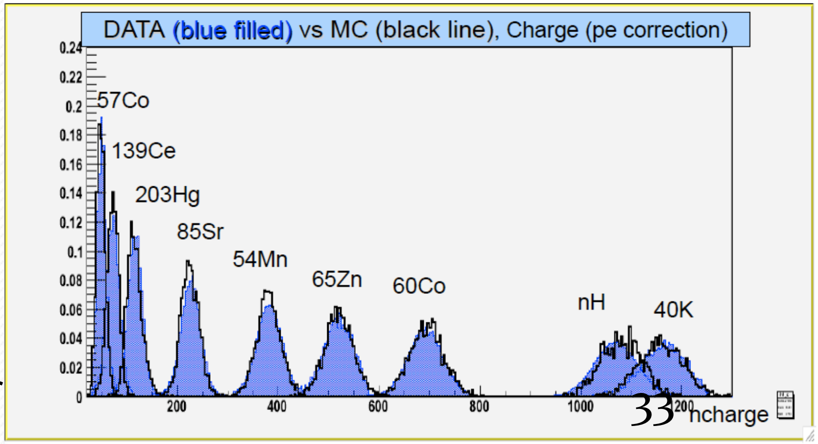




- **Detector response as a function of position;**
- **Fiducial volume definition and tuning of th spatial reconstruction algorithm;**
- **Energy scale definition**

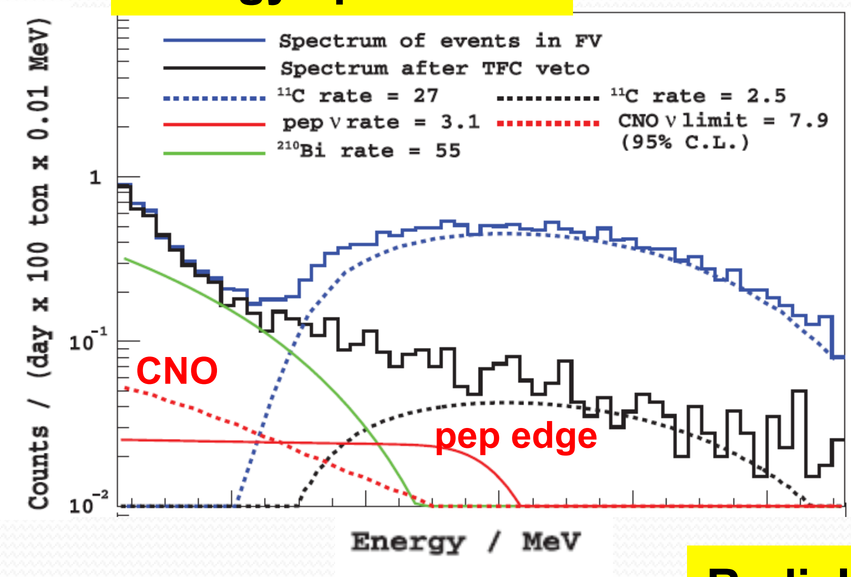
  precise calibration in the 0-7 MeV range.
- **Tuning of the full Monte Carlo simulation**

SYSTEMATIC ERROR REDUCTION
For ALL SOLAR NEUTRINO RESULTS

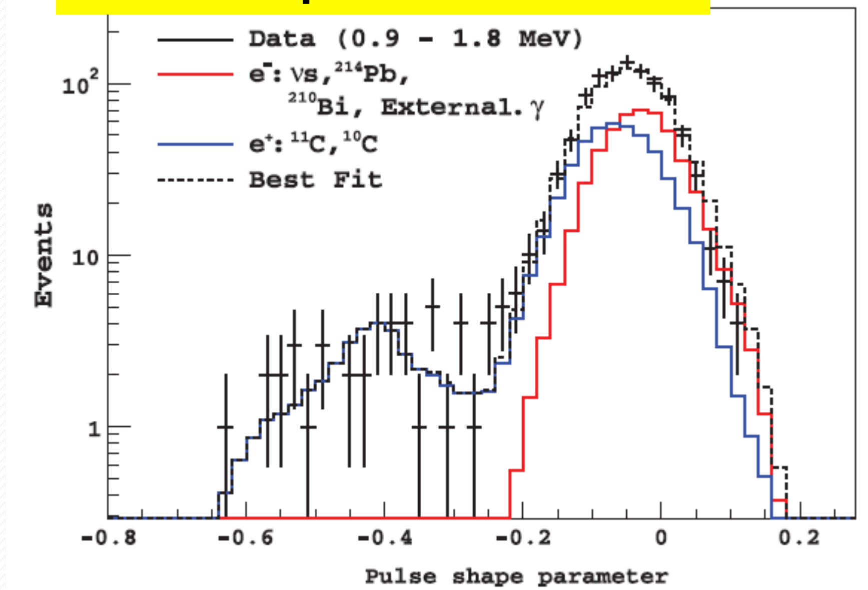


Multivariate maximum likelihood fit

Energy spectral fit



Pulse shape variable



Radial fit