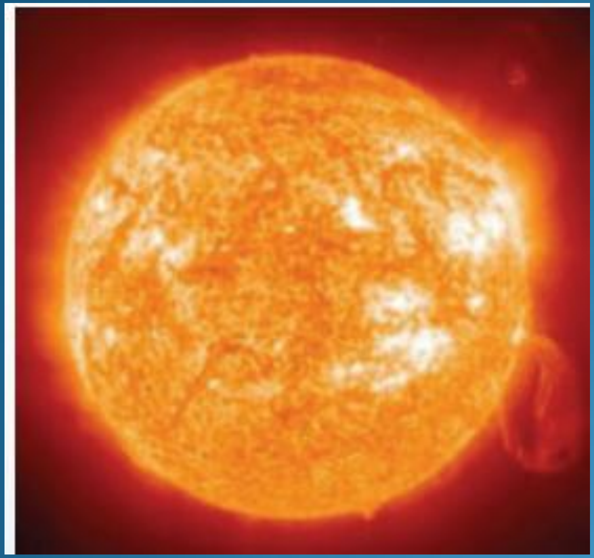
Solar Neutrino Physics With Borexino I



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

Borexino Collaboration

Milano

Genova

Perugia

Princeton University

Kurchatov Institute (Russia)

Heidelberg (Germany)

Virginia Tech. University

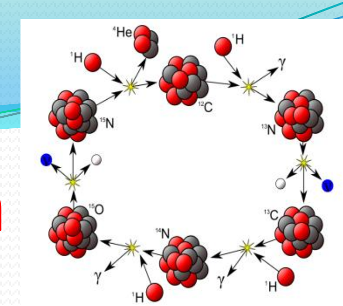
Jagiellonian U. Cracow (Poland)

APC Paris

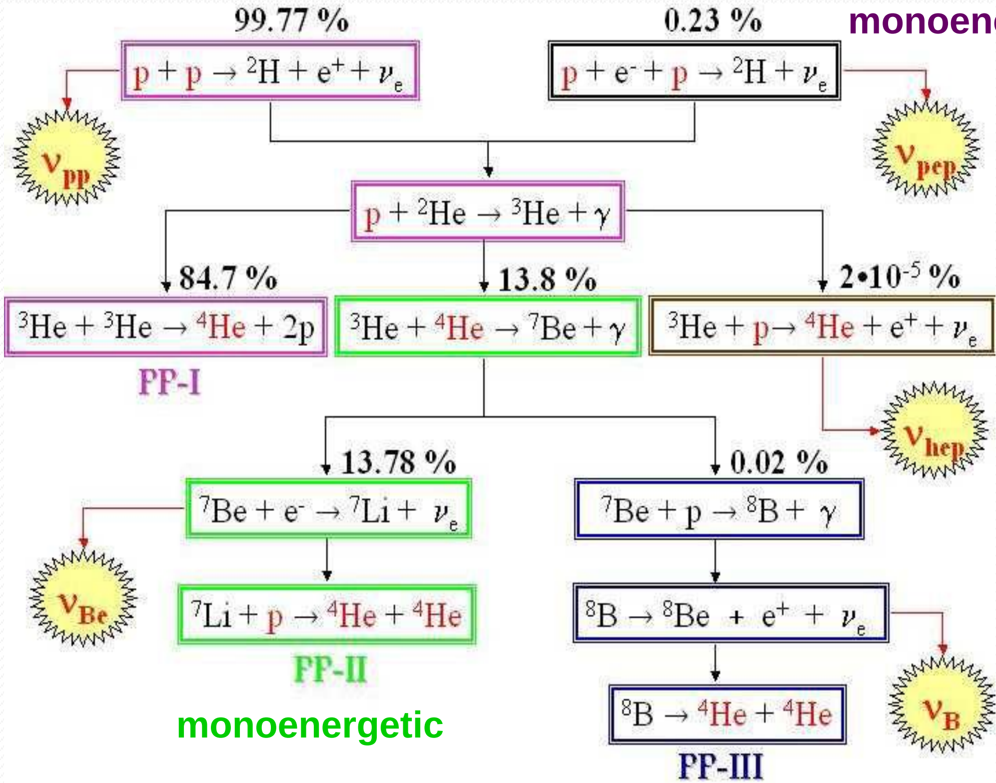
Dubna JINR (Russia)

Munich (Germany)

Neutrinos && Nuclear reactions in the Sun



PP cycle… 99% of energy

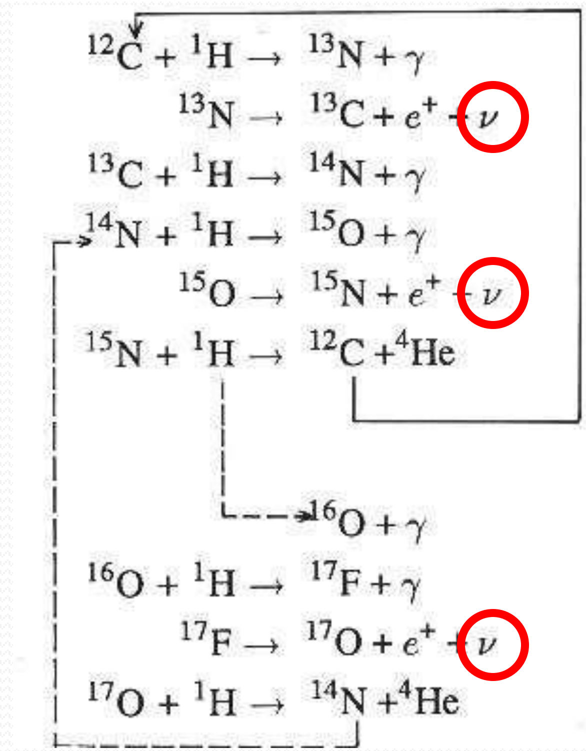


monoenergetic

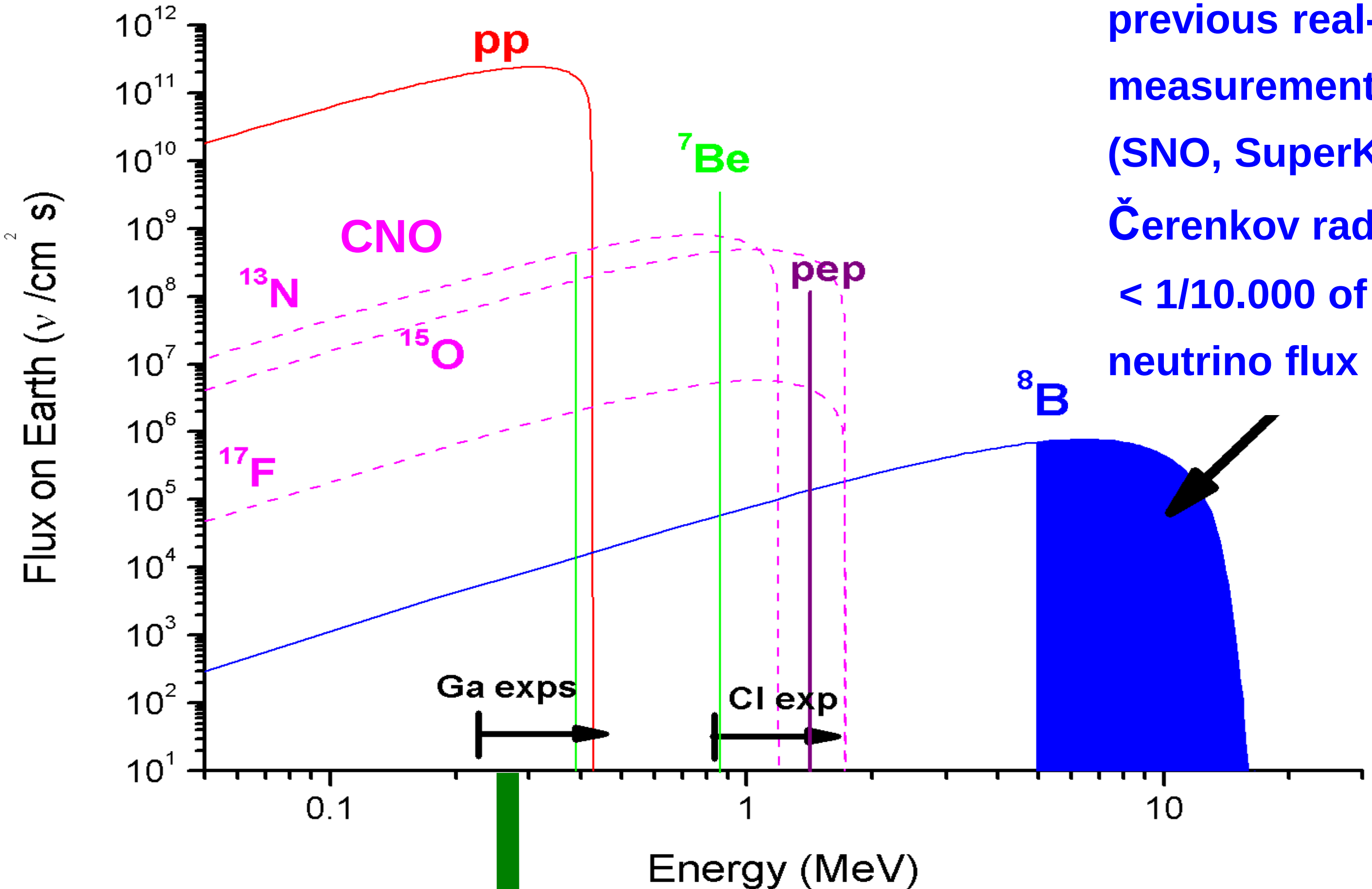
monoenergetic

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) ?

Astrophysics: resolving "metallicity problem"

metallicity
abundance of the elements above He

New 3D Standard Solar Models -> lower metallicity -> discrepancy with helioseismology…
where is the problem?

Sources	$\Phi(\nu\ \sec^{-1}\ \mathrm{cm}^2)$ *high-metallicity*	$\Phi(\nu\ \sec^{-1}\ \mathrm{cm}^2)$ *low-metallicity*	Difference %
pp	$5.98(1\pm0.006)\times10^{10}$	$6.03(1\pm0.006)\times10^{10}$	0.8
pep	$1.44(1\pm0.012)\times10^{8}$	$1.47\boxed{(1\pm0.012)}\times10^{8}$	2.0
hep	$8.04(1\pm0.300)\times10^{3}$	$8.31(1\pm0.300)\times10^{3}$	3.3
^{7}Be	$5.00(1\pm0.070)\times10^{9}$	$4.56\boxed{(1\pm0.070)}\times10^{9}$	9.4
^{8}B	$5.58(1\pm0.140)\times10^{6}$	$4.59(1\pm0.140)\times10^{6}$	19.8
^{13}N	$2.96(1\pm0.140)\times10^{8}$	$2.17(1\pm0.140)\times10^{8}$	31.6
^{15}O	$2.23(1\pm0.150)\times10^{8}$	$1.56(1\pm0.150)\times10^{8}$	33.5
^{17}F	$5.52(1\pm0.170)\times10^{6}$	$3.40(1\pm0.160)\times10^{6}$	53.0

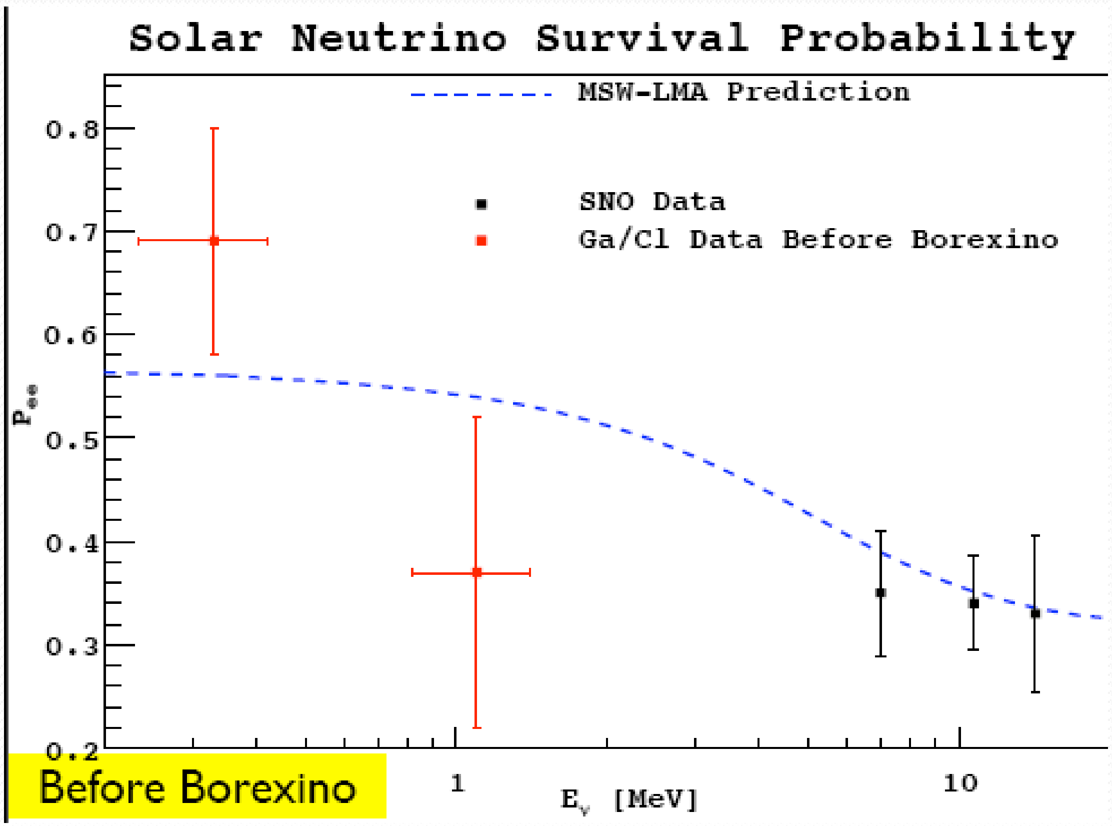
Solar neutrino fluxes depend on metallicity!

- **Solar Model:** Serenelli, Haxton and Pena-Garay arXiV:1104.1639
- **High metallicity GS98** = Grevesse et al. *S. Sci. Rev. 85,161 ('98);*
- ***Low metallicity AGS09** = Asplund, et al,* A.R.A.&A. 47(2009)481;

What can we learn from solar neutrinos (2) ?

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

Pee = electron neutrino survival probability from the Sun's core to the detector



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

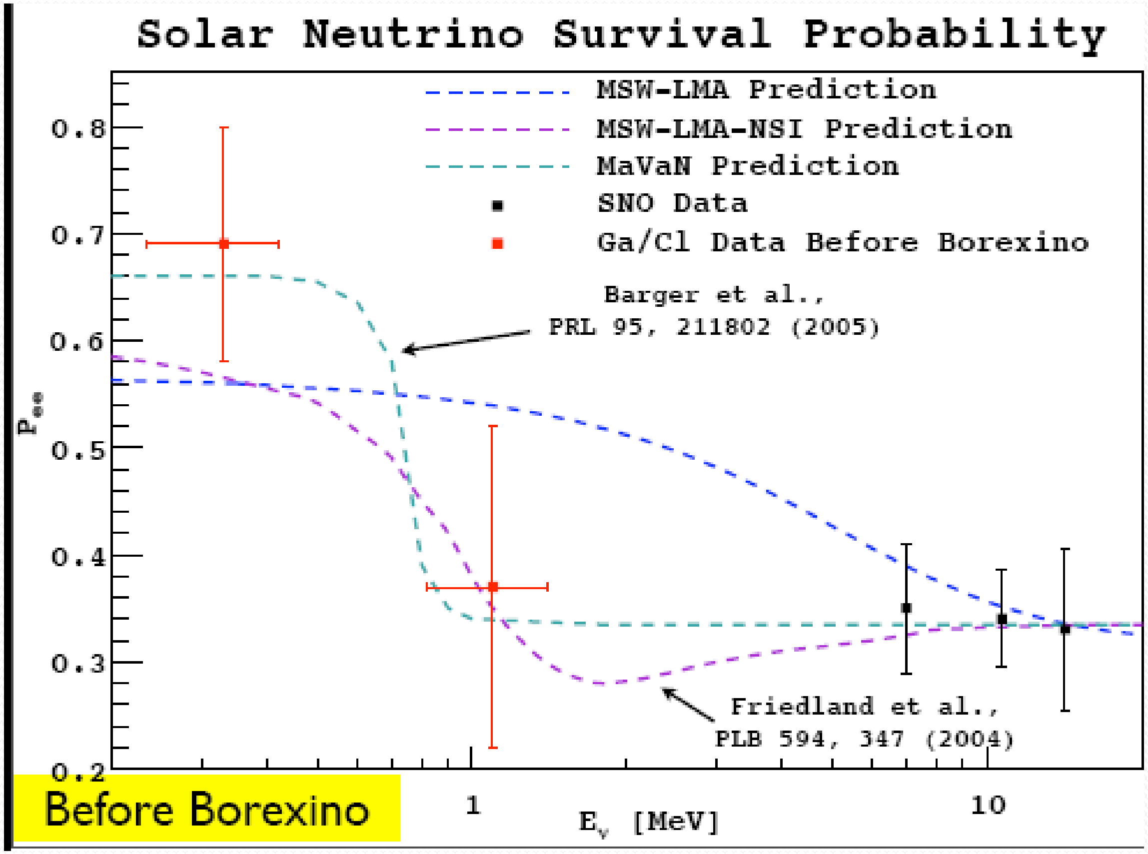
Transition region:
Decrease of the ν_e survival
probability (P_{ee})

Vacuum regime

Matter regime

What can we learn from solar neutrinos (2) ?

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



Vacuum regime

Matter regime

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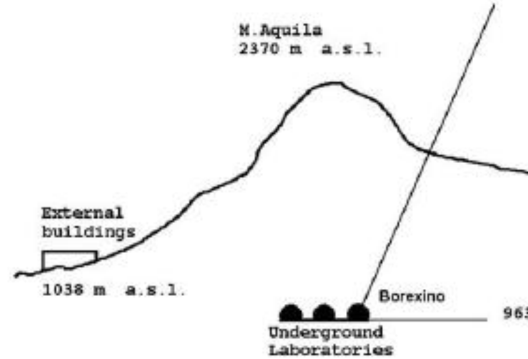
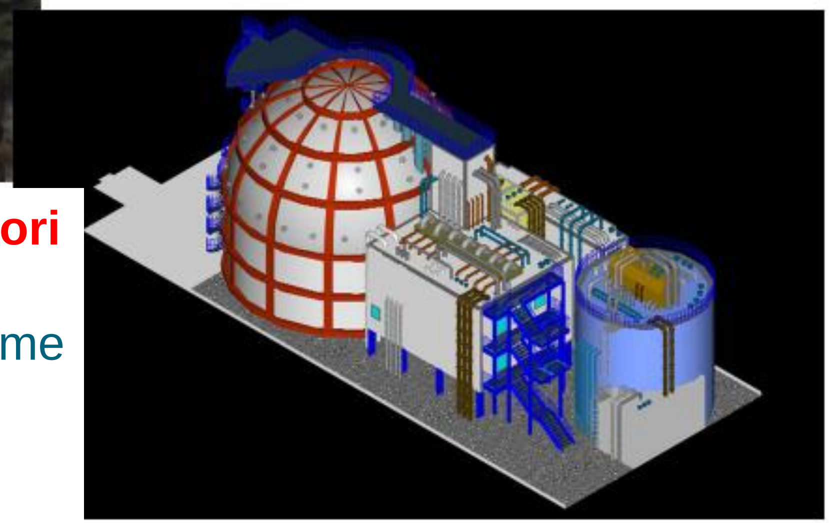
Borexino experimental site





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.

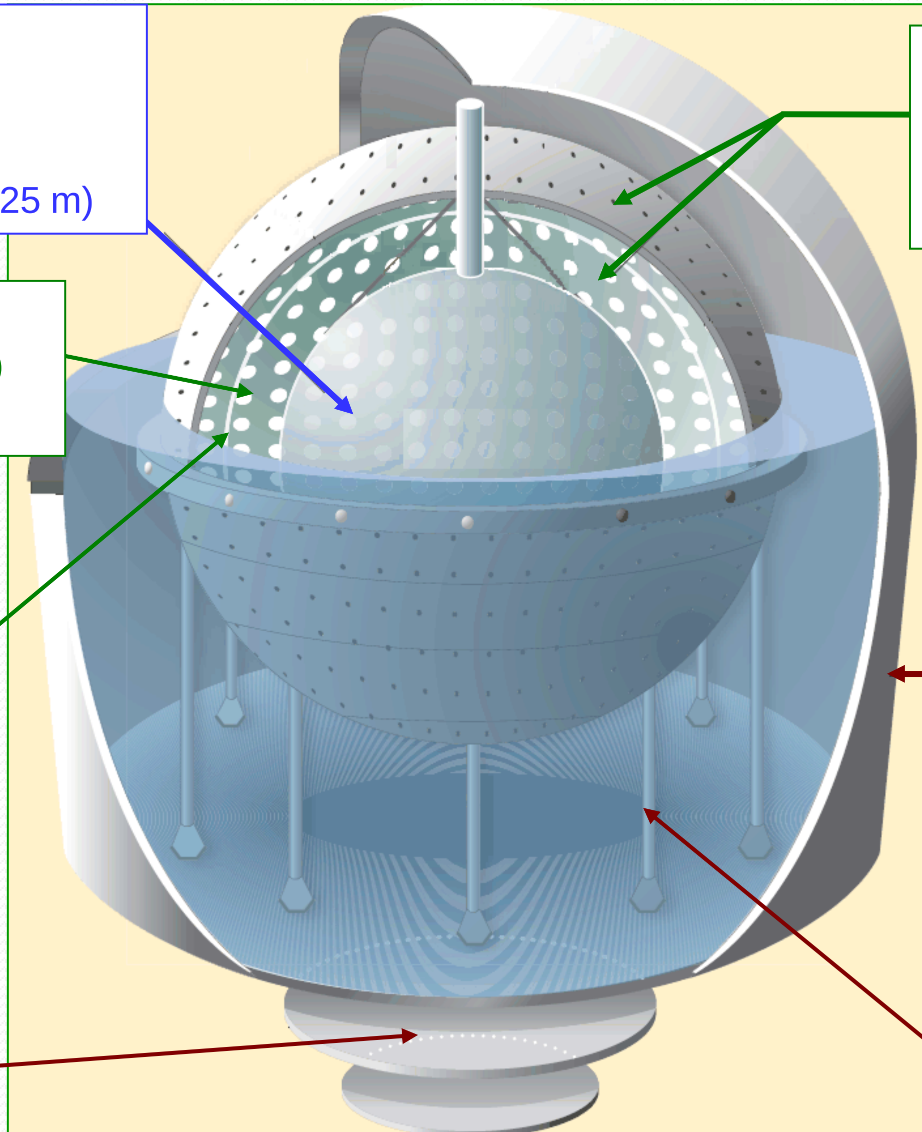
Borexino detector

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

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

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

Carbon steel plates



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

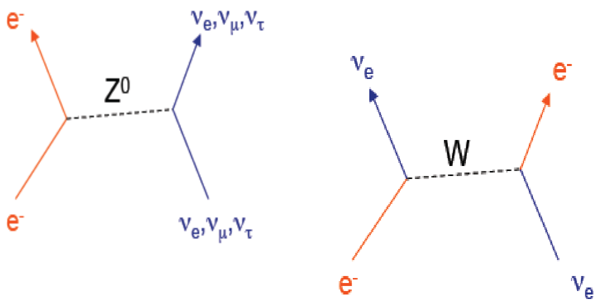
Water Tank:
γ & neutron shield
μ Water Čerenkov detector
208 PMTs in water
2100 m^3

20 steel legs

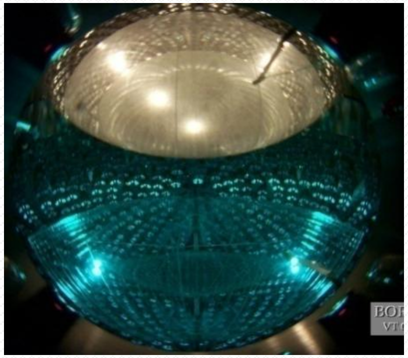
Detection principle

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

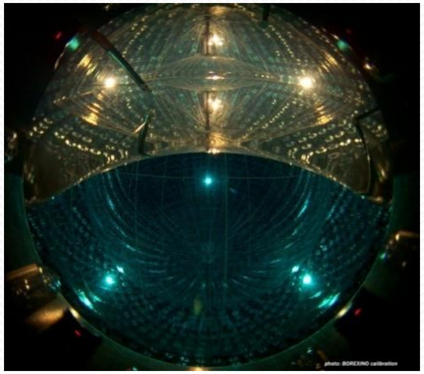
- Neutrino elastic scattering on electrons of liquid scintillator: $\mathbf{e^- + \nu \rightarrow e^- + \nu}$;
- Scattered electrons cause the scintillation light production;
- **Advantages**:
  - Low energy threshold (~ 0.2 MeV);
  - High light yield and a good energy resolution;
  - Good position reconstruction;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



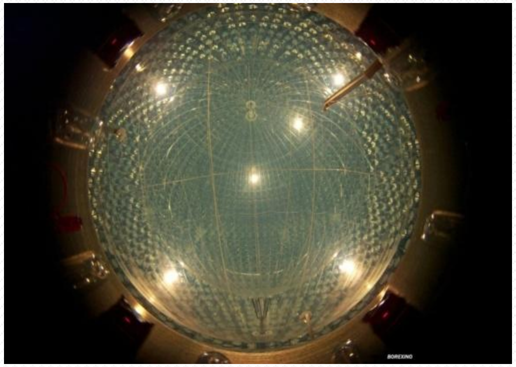
End October 2006



March 2007



May 2007



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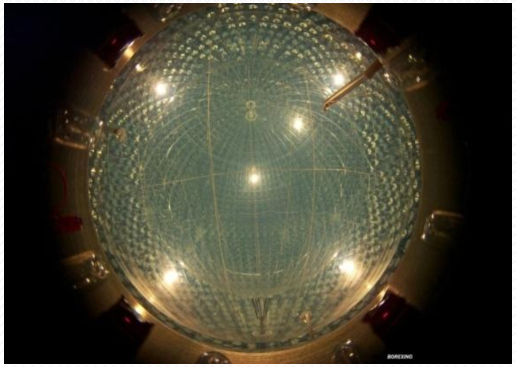
ENERGY RESOLUTION
10% @ 200 keV
8% @ 400 keV
6% @ 1 MeV

SPATIAL RESOLUTION
35 cm @ 200 keV
16 cm @ 500 keV

Extreme radiopurity is a must for a precision spectroscopy measurement!!!

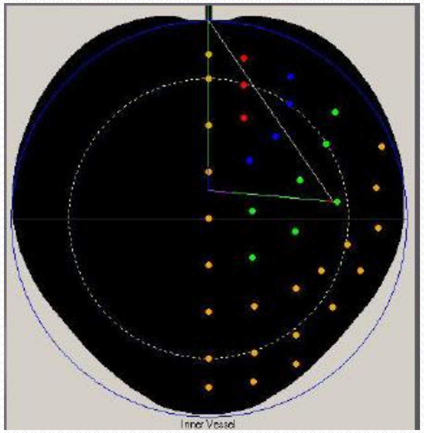
DAQ STARTS : **May 2007**



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

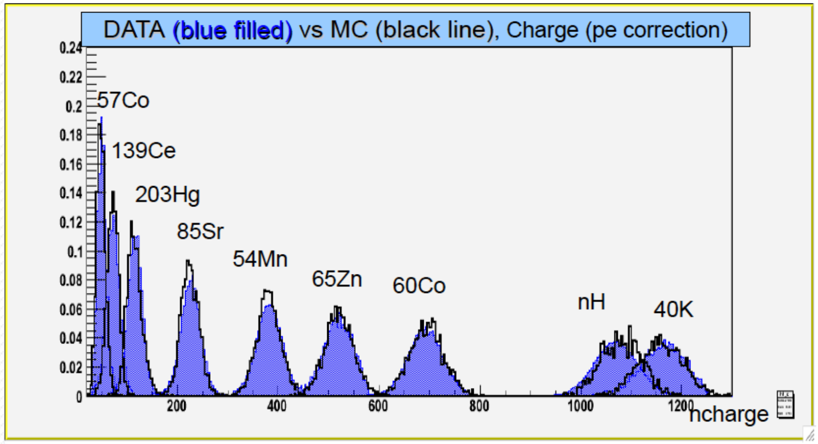
- Absolute source position: LED and CCD cameras (± 2cm);
- cca. 300 points through the whole scintillator volume;



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

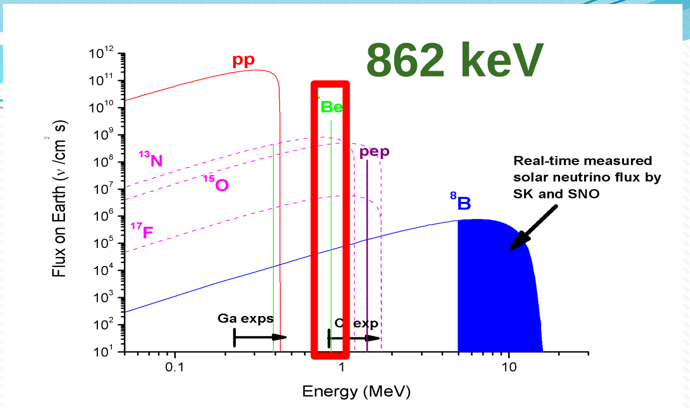
  precise calibration in the 0-7 MeV range.
- **Tuning of the full Monte Carlo simulation**

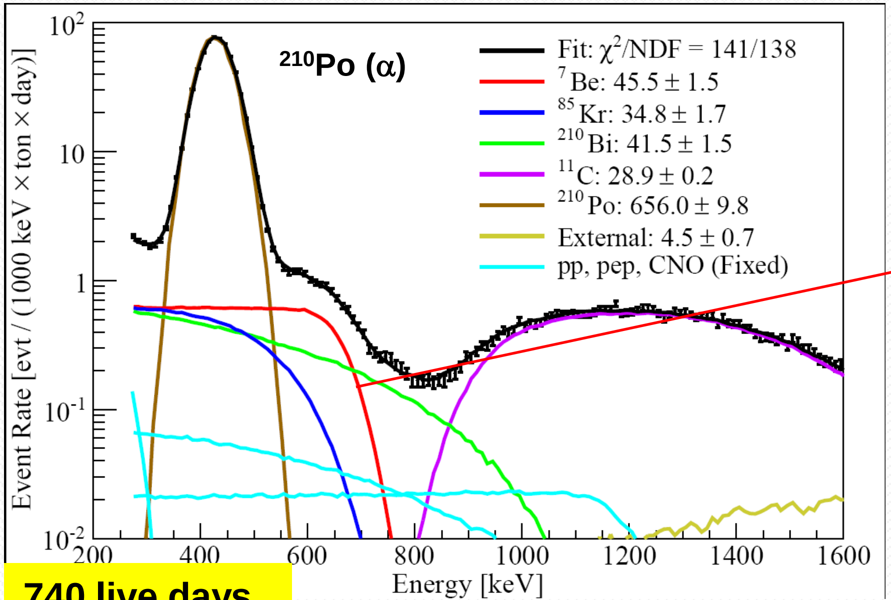
SYSTEMATIC ERROR REDUCTION
For ALL SOLAR NEUTRINO RESULTS



ICHEP 2012, Melbourne, 4-11 July 2012

^{7}Be neutrino (862 keV) rate @ 4.6%
(SSM prediction @ 7%) Phys. Rev. Lett. 107, (2011) 141302





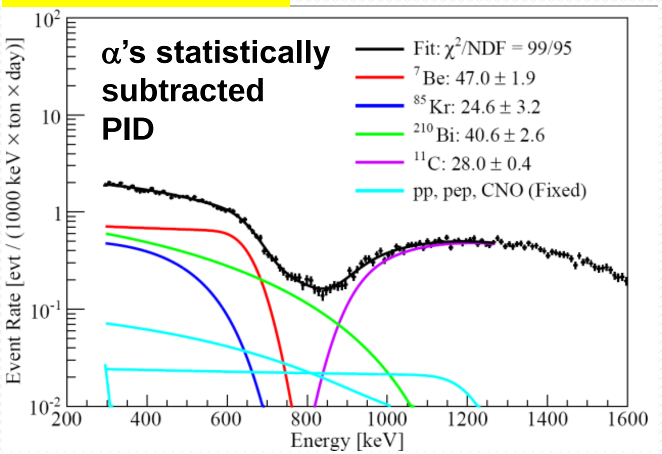
740 live days

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



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

Implications of the ^{7}Be measurement

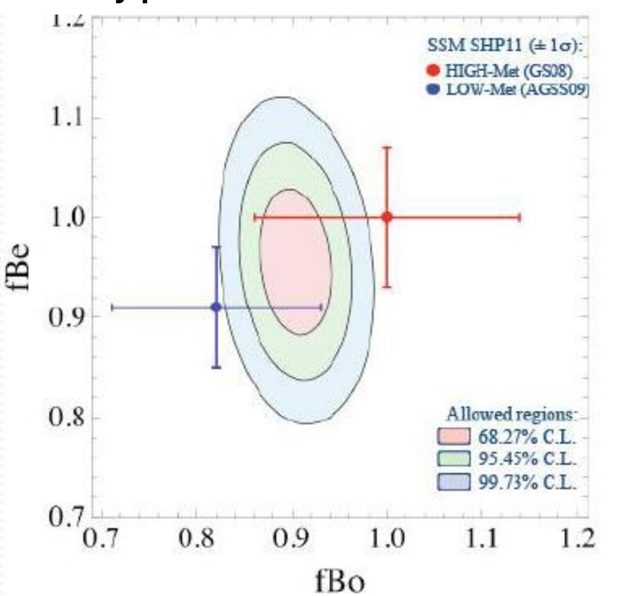
- comparing to non-oscillated SSM : **no oscillation excluded @ 5.0 σ**

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

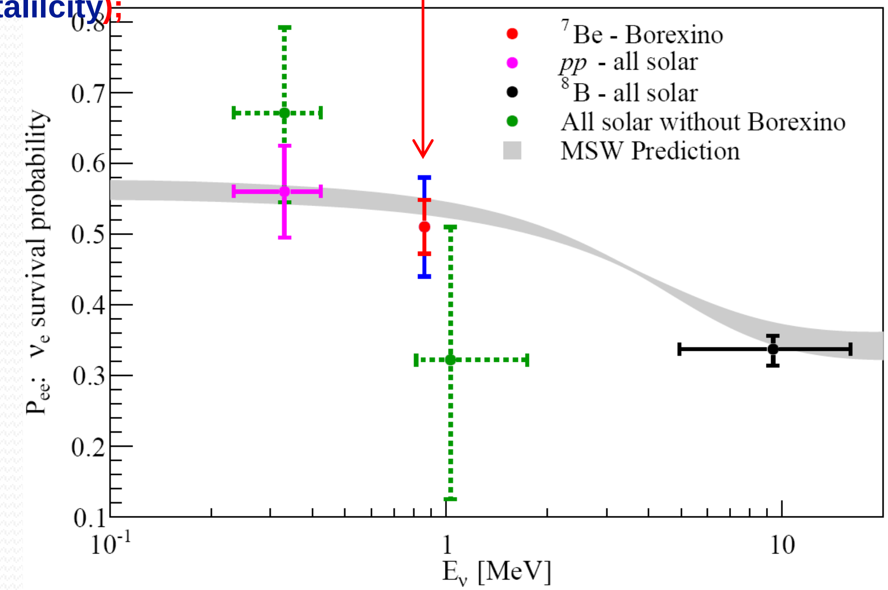
- assuming MSW-LMA: f (7Be) = measured flux / SSM = 0.97 $\pm$ 0.09
- **including all solar experiments + luminosity constrain:**

$$\boxed{\begin{aligned} f_{pp} &= 1.013^{+0.003}_{-0.010} \\ f_{CNO} &< 2.5 \text{ at } 95\% \text{ C.L.} \end{aligned}}$$

no power to resolve low/high metallicity problem



Pee = 0.51 $\pm$ 0.07 @ 867 keV (experiment + SSM high metalilcity);

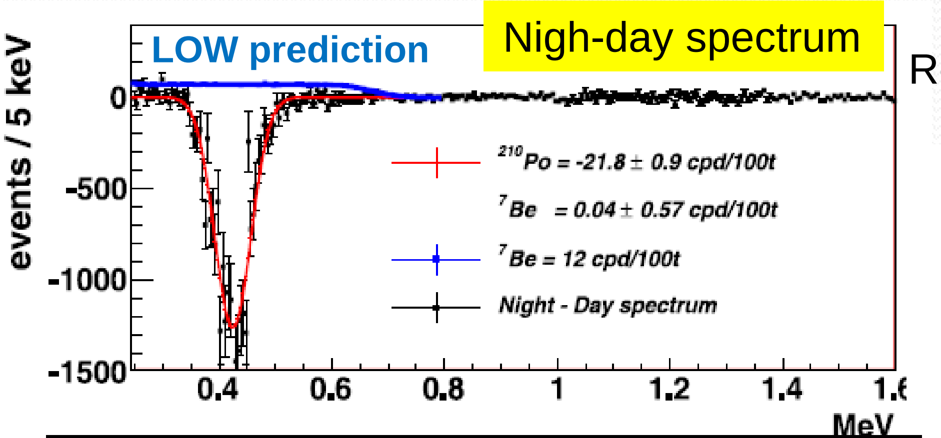


Absence of day-night asymmetry for ^{7}Be rate (R)

Phys. Lett. B 707 (2012) 22–26

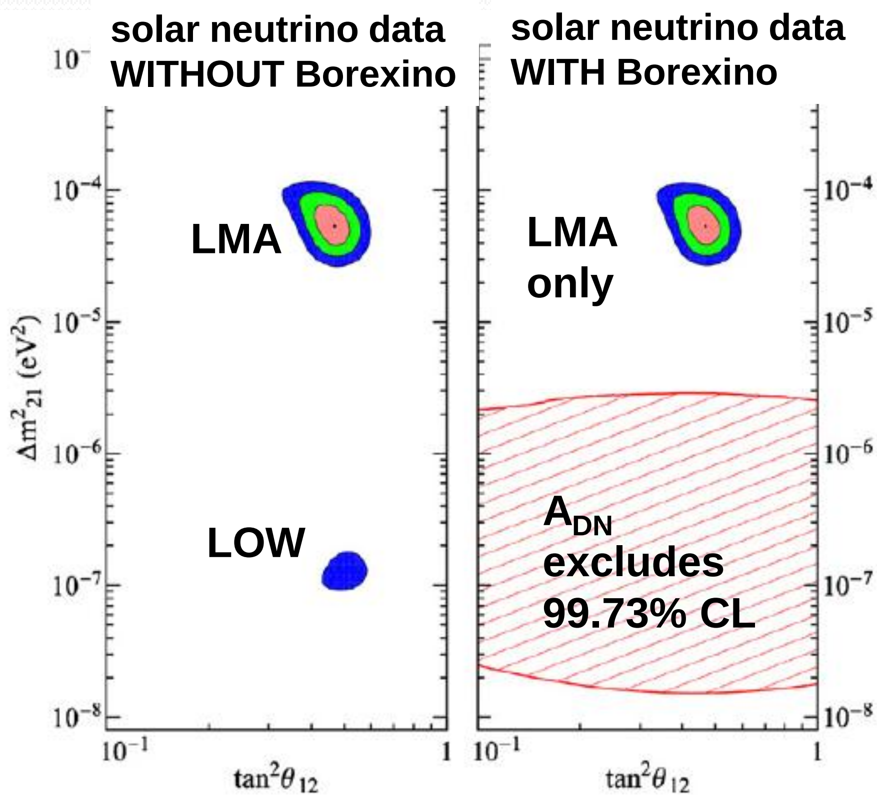
$$A_{dn} = 2\frac{R_N - R_D}{R_N + R_D} = \frac{R_{\text{diff}}}{\langle R \rangle}$$

•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)

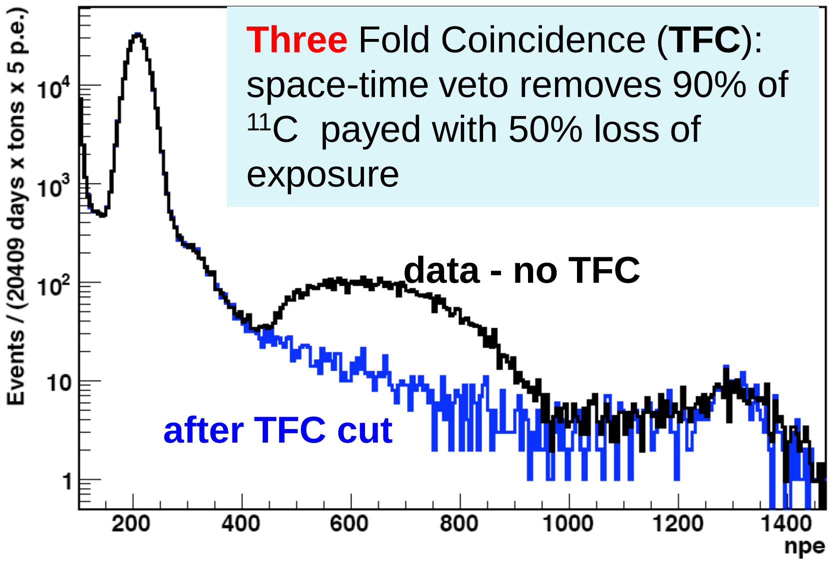
Regions allowed @ 68.27%, 95.45%, 99.73% CL



- 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)

PHYSICAL REVIEW C 74, 045805 (2006)



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

1 2 3

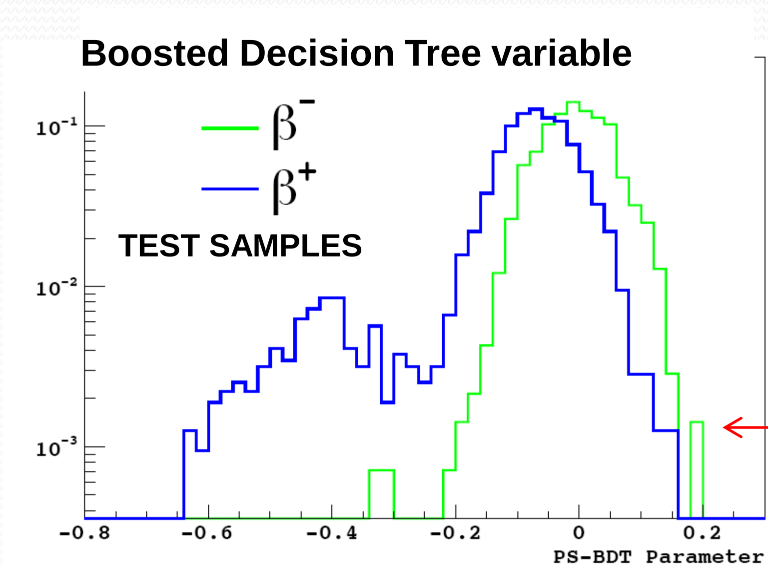
$$\mu + {}^{12}C \longrightarrow \mu + n + {}^{11}C$$

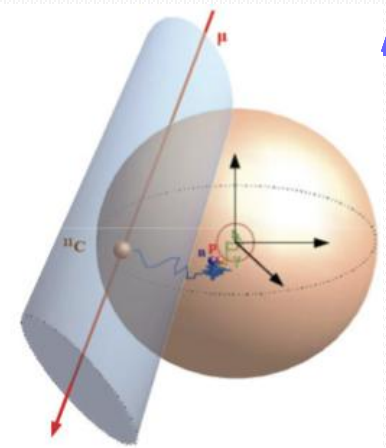
236 μs
Quick neutron thermalization and capture yields clear tag

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

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

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

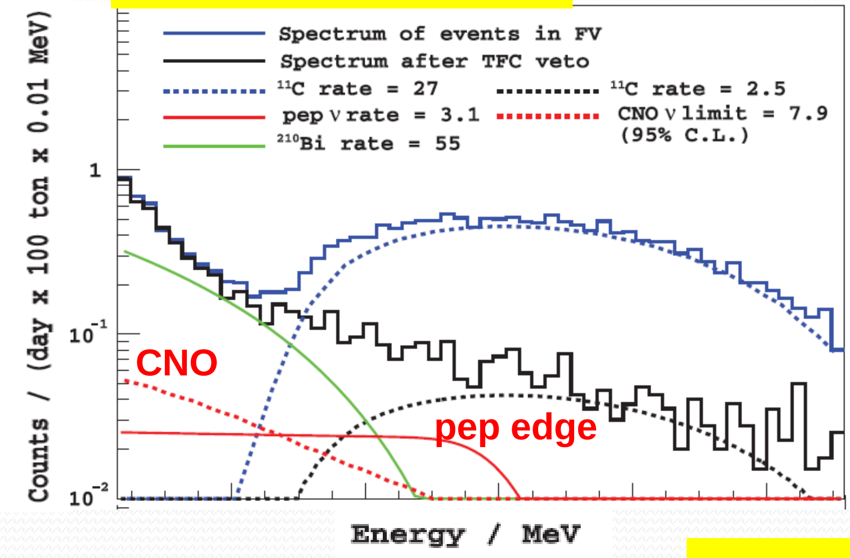




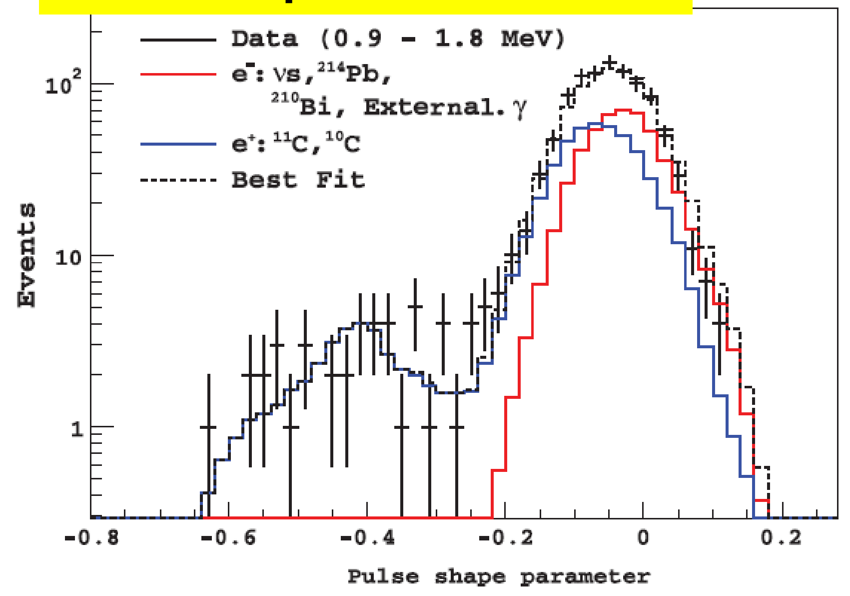
- **β^+/ β^- pulse-shape discrimination**: positronium formation + annihilation

Multivariate maximum likelihood fit

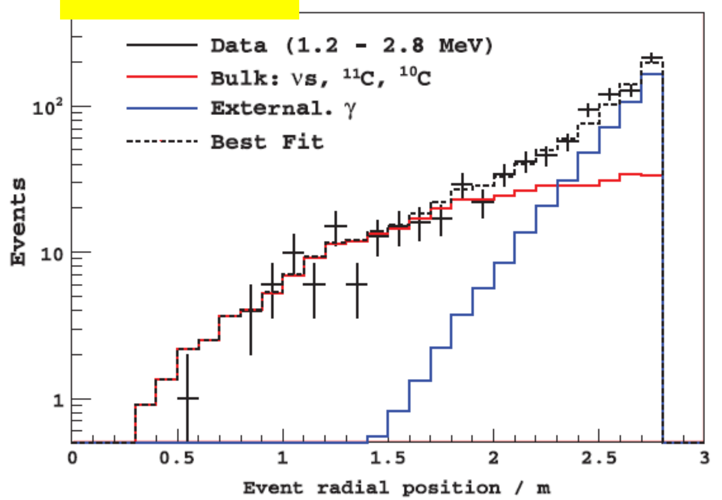
Energy spectral fit



Pulse shape variable



Radial fit



First observation of pep neutrinos II.

- <u>**Pep rate: 3.1 ± 0.6$_{(stat)}$ ± 0.3$_{(sys)}$ cpd/100 t**</u>
- Assuming MSW-LMA: $\Phi_{pep} = 1.6 \pm 0.3\ 10^8\ cm^{-2}$
- No oscillations excluded at **97% c.l.**
- Absence of pep solar ν excluded at 98%

CNO neutrinos

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

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

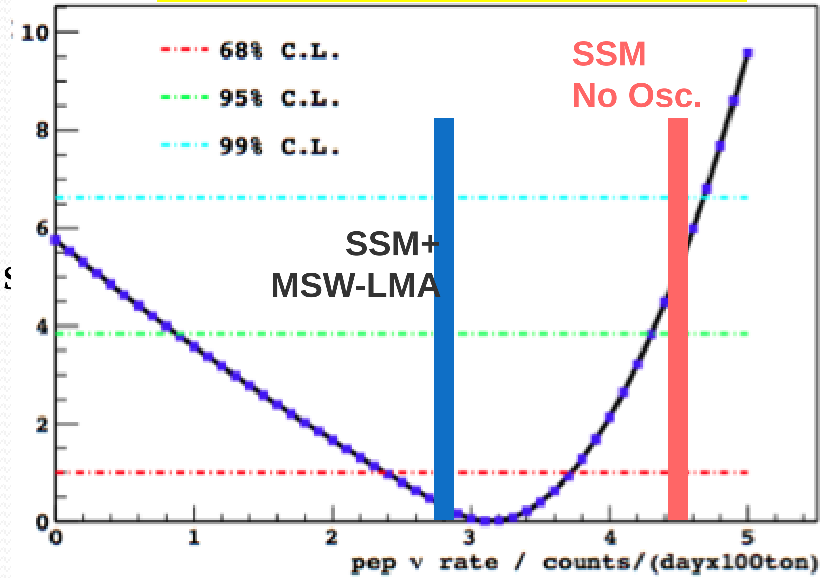
- Assuming MSW-LMA:

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

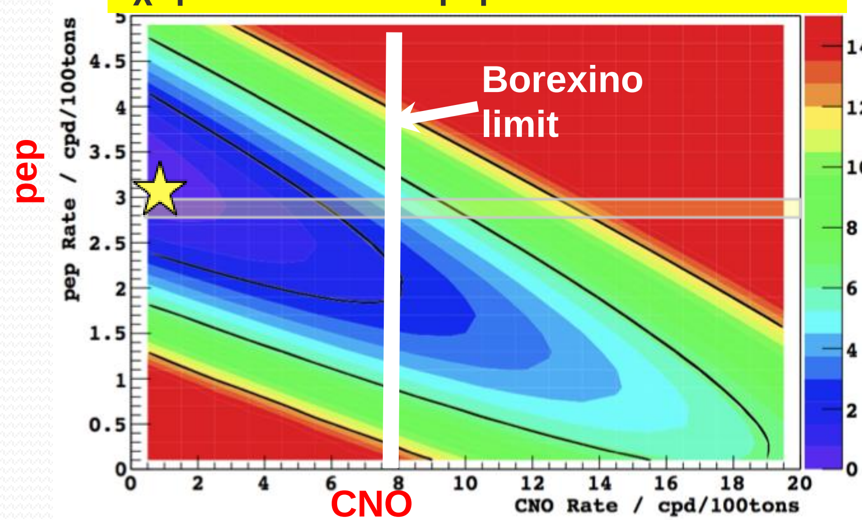
the strongest limit to date

not sufficient to resolve metallicity problem

$\Delta\chi^2$ profile for pep ν rate



$\Delta\chi^2$ profile for fixed pep and CNO rates



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

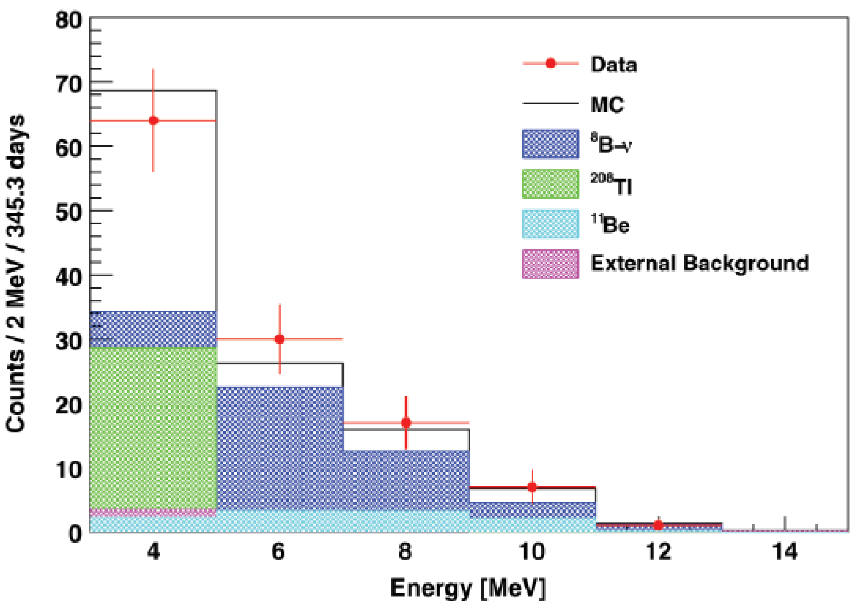
Phys. Rev. D 82 (2010) 033006 … to recall

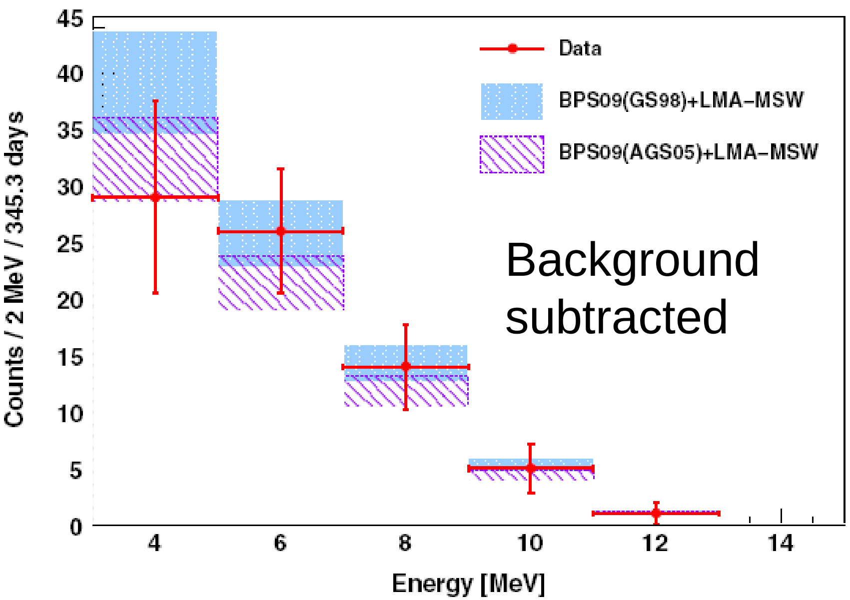
lower energies limited by ^{208}Tl

	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.

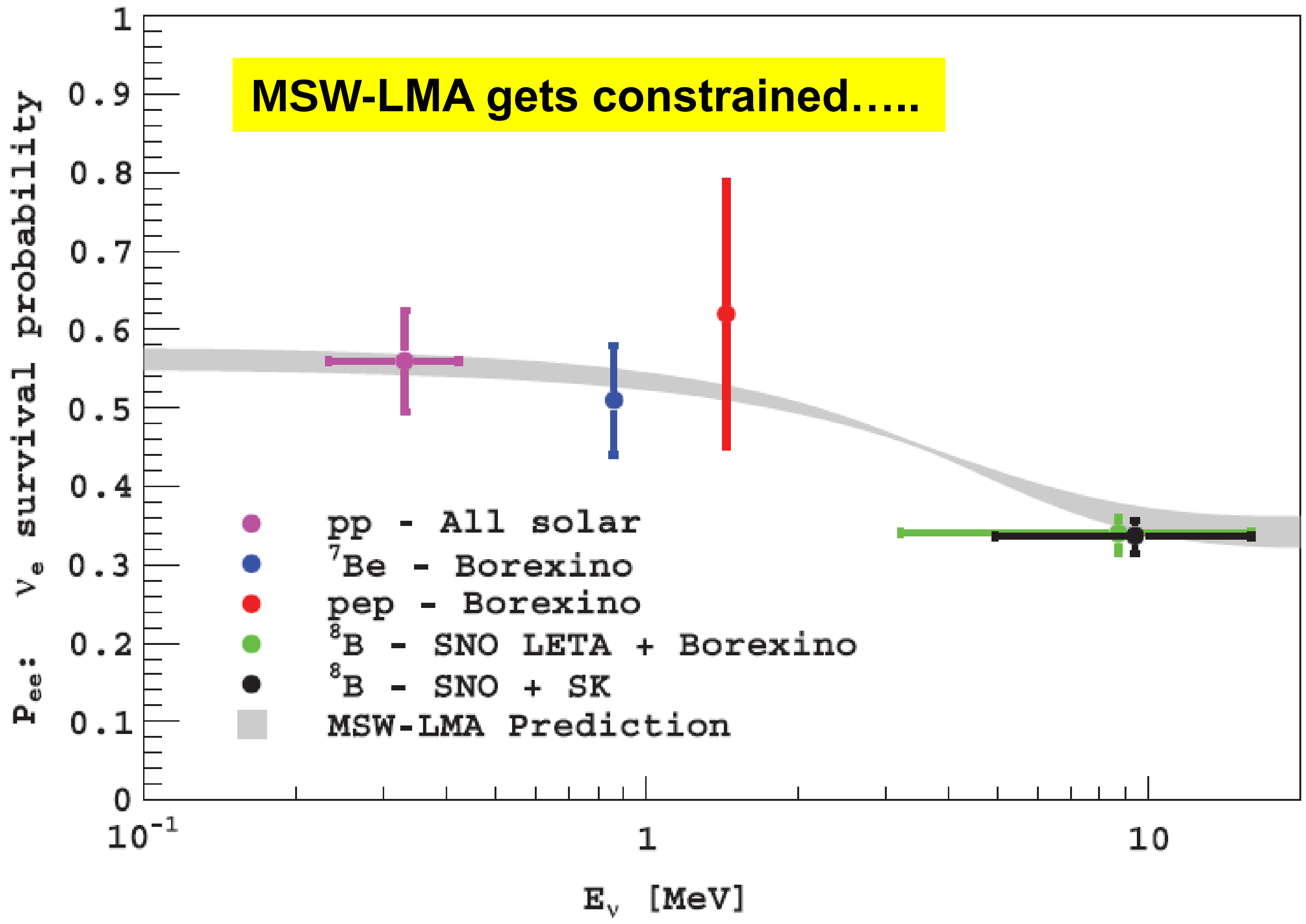
	Threshold [MeV]	$\Phi^{ES}_{^8B}$ [10^6 cm^{-2} s^{-1}]
SuperKamiokaNDE I [3]	5.0	$2.35 \pm 0.02 \pm 0.08$
SuperKamiokaNDE II [2]	7.0	$2.38 \pm 0.05^{+0.16}_{-0.15}$
SNO D_2O [4]	5.0	$2.39^{+0.24}_{-0.23}{}^{+0.12}_{-0.12}$
SNO Salt Phase [25]	5.5	$2.35 \pm 0.22 \pm 0.15$
SNO Prop. Counter [26]	6.0	$1.77^{+0.24}_{-0.21}{}^{+0.09}_{-0.10}$
Borexino	3.0	$2.4 \pm 0.4 \pm 0.1$
Borexino	5.0	$2.7 \pm 0.4 \pm 0.2$





Background subtracted

To conclude, we put all together….. P_{ee} after Borexino I



Livia Ludhova (Borexino collaboration)

Future and Borexino phase II

- since July 2010 we have undertaken a series of purification campaigns to decrease the radioactive background;
  - Nitrogen stripping has been successful in removing ^{85}Kr:

    ^{85}Kr < 8.8 cpd / 100 t (2007-2010: 31.2 ± 5)
  - moderate success at removing ^{210}Bi by water extraction:

    ^{210}Bi : (16 ± 4) cpd / 100 t (2007-2010: 41.0 ± 2.8)
  - unprecedented purity in ^{238}U and ^{232}Th:

    ^{238}U < 9.7 10^{-19} g/g and ^{232}Th < 2.9 10^{-18} g/g
  - ^{210}Po decreasing, ~5 cpd / t ;
- Borexino phase II just started…
  - continue solar neutrino program:

    - Improve ^{7}Be, ^{8}B → test of MSW

    - Confirm pep at more than 3σ and reduce error

    - Improve upper limit on CNO → probe metallicity

    -Attempt direct pp measurement
  - more statistics for an update of geo-neutrino measurement;
  - another long-term scientific goals under discussion.

More about Borexino solar results in:

Pep & CNO limit : G. Bellini et al. : First Evidence of *pep* Solar Neutrinos by Direct Detection in Borexino, Phys. Rev. Lett. 108 (2012) 051302.

7Be Adn: G. Bellini at al. : Absence of day-night asymmetry of 862 keV ^{7}Be solar neutrino rate in Borexino and MSW oscillation parameters, Physics Letters B 707 (2012) 22-26.

7Be @ 5%: G. Bellini et al. : Precision measurement of the 0.862 MeV ^{7}Be solar neutrino interaction rate in Borexino, Phys. Rev. Lett. 107 (2011) 141302.

8B > 3 MeV: G. Bellini at al. (Borexino collaboration): Measurement of the solar ^{8}B neutrino rate with a liquid scintillator target and 3 MeV energy threshold in the Borexino detector. Phys. Rev. D 82 (2010) 033006.

Solar antinu limits: G. Bellini at al.: Study of solar and other unknown anti-neutrino fluxes with Borexino at LNGS., Phys. Lett. B 696 (2011) 191-196.

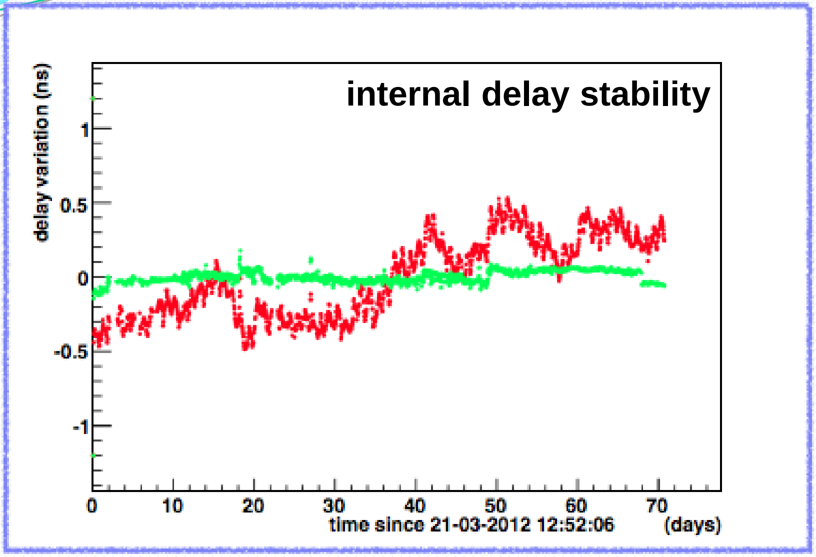
7Be @ 10%: C. Arpesella *at al*. (Borexino collaboration): Direct measurement of the ^{7}Be solar neutrino flux with 192 days of Borexino data, Phys. Rev. Lett. 101 (2008) 091302.

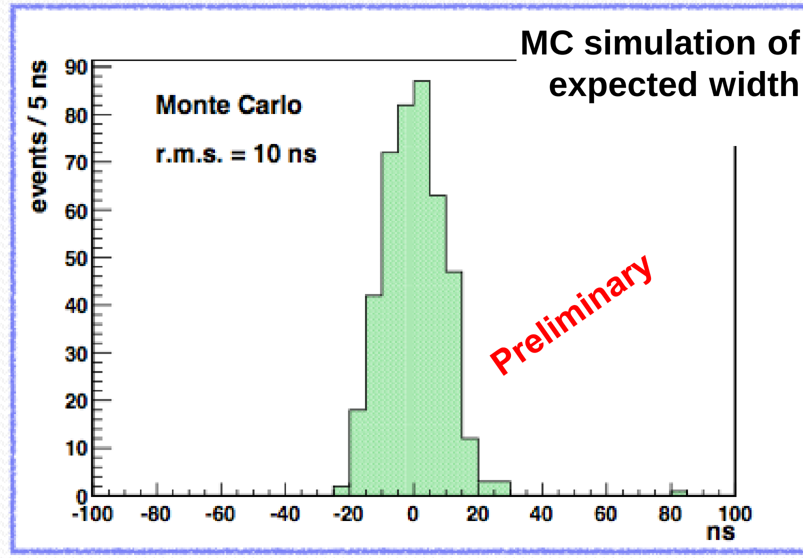
7Be @ 17%: C. Arpesella *at al.* (Borexino collaboration): First real time detection of ^{7}Be solar neutrinos by Borexino, Phys. Lett. B 658 (2008) 101-108

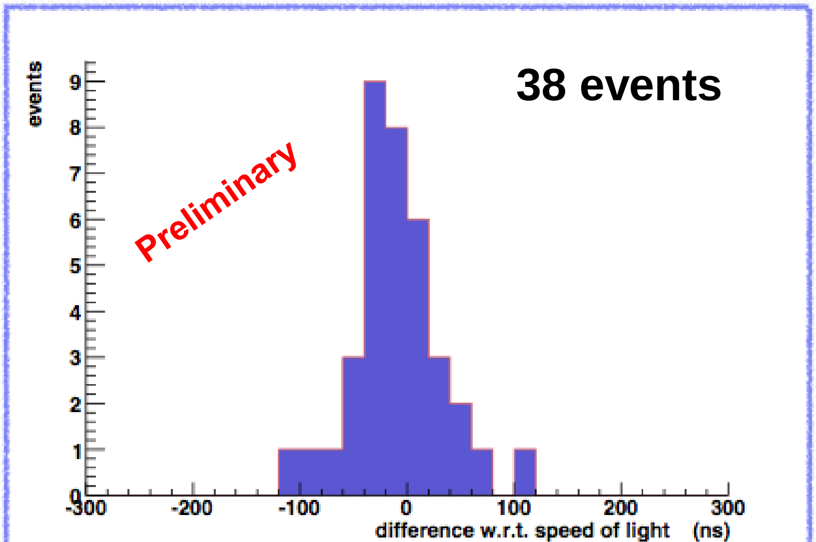
Thank you!

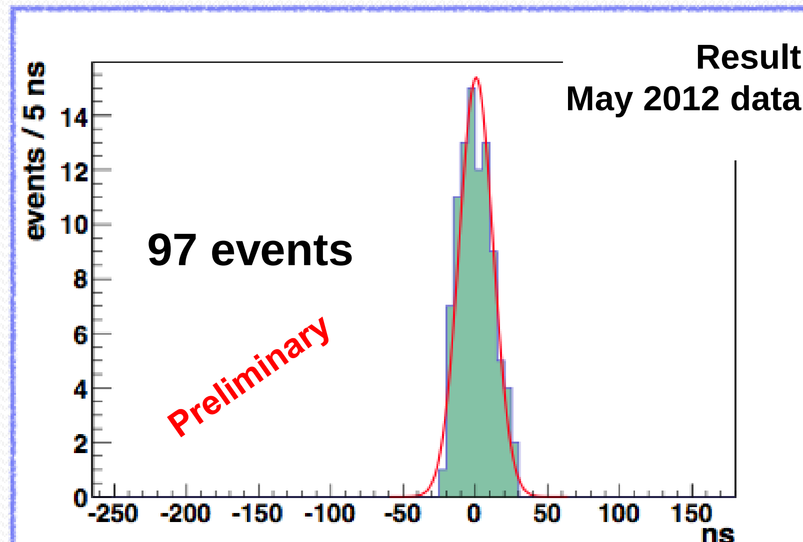
Backup

NEuTRINO SPEED - Preliminary RESULTS



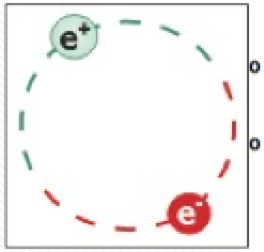


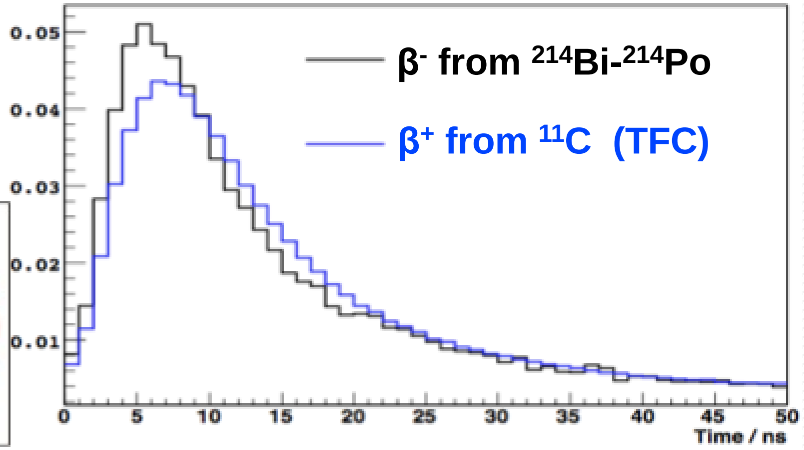


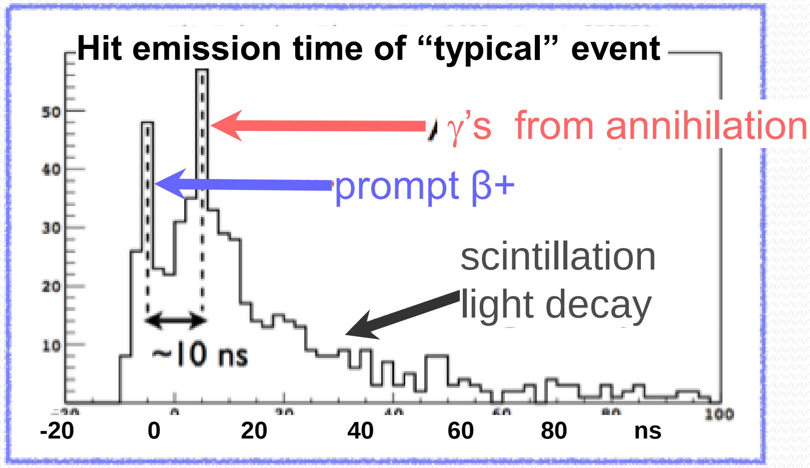


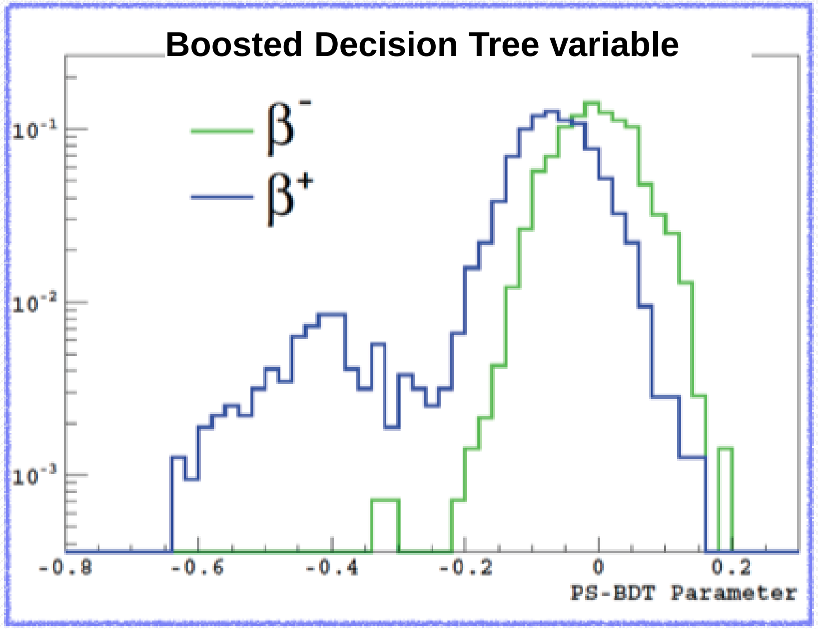
β+ - β- discrimination

- 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

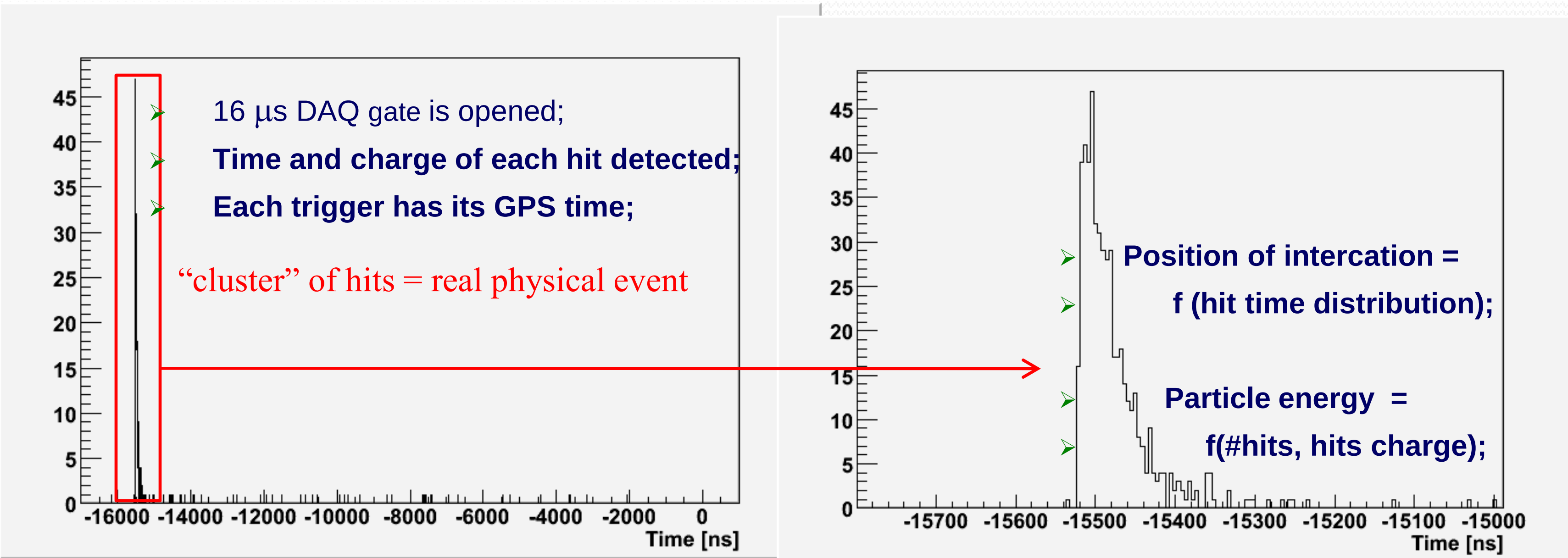
- Careful selection of the construction materials and operational procedures;
- Special procedures for fluid procurement;
- Scintillator and buffer purification during the filling;
- Sparging with high purity N2;
- **More than 15 years of work…**

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 $\pm$ 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 $\pm$ 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 $\pm$ 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 $\pm$ 12) p.e./MeV
taking into account quenching factor

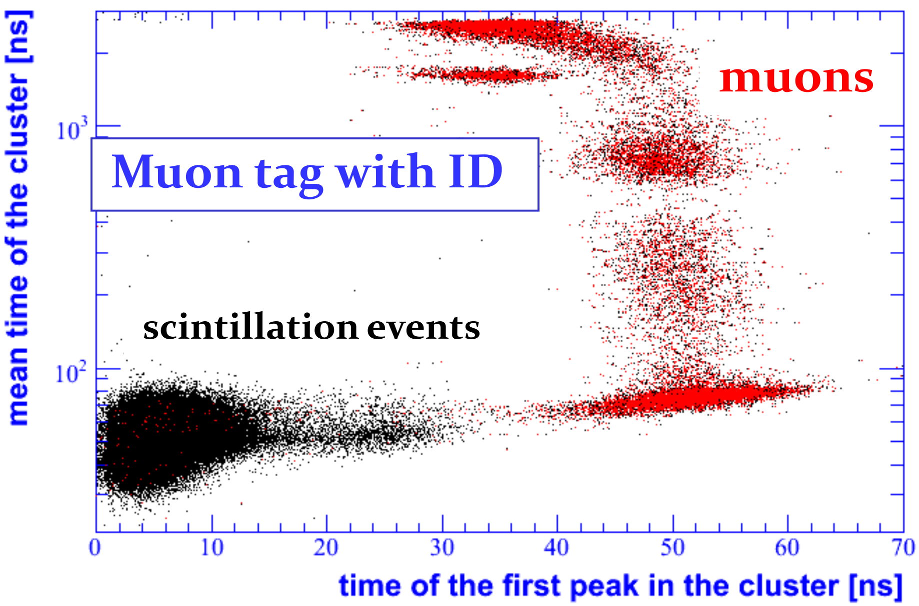
Spatial resolution: 35 cm @ 200 keV
(scaling as $N_{p.e.}^{-1/2}$) 16 cm @ 500 keV

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

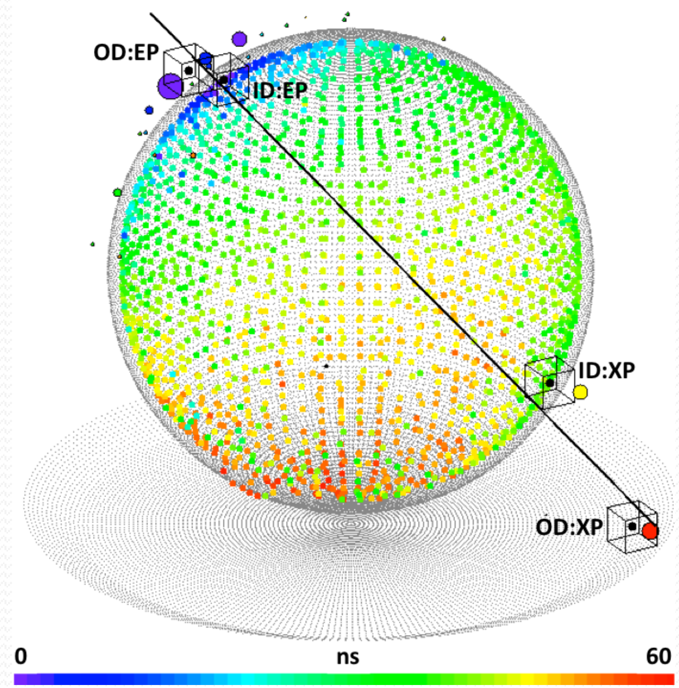
Livia Ludhova (Borexino collaboration)

Muon and neutron detection

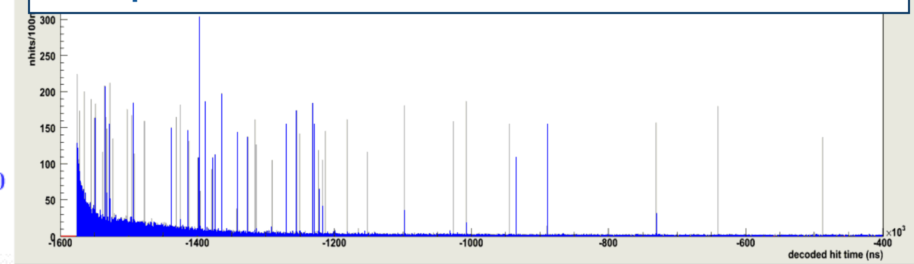
- μ are identified by the OD and by the ID
  - OD eff: > 99.28%
  - ID analysis based on pulse shape variables
    - Cluster mean time, peak position in time
  - **Combined overall efficiency > 99.992%**
  - **After cuts, μ not a relevant background for ^{7}Be**
  - **Residual background: < 1 count /day/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



Muon track reconstruction

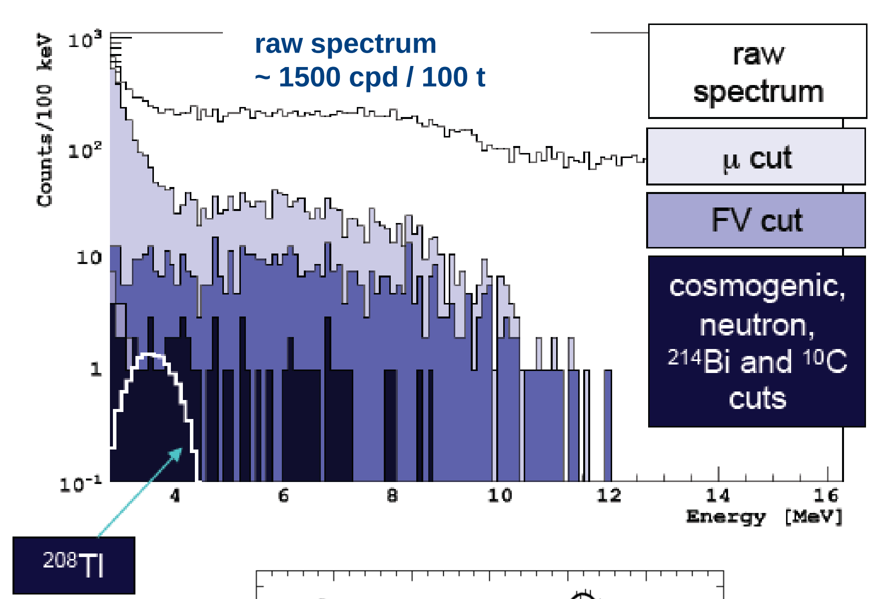


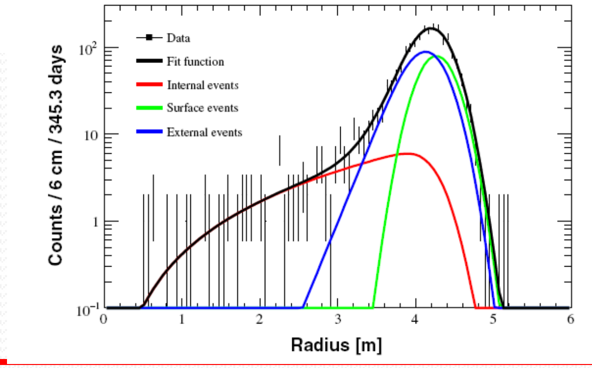
After each μ, 1.6 ms gate opened to detect neutrons: example with several tens of neutrons.



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

$\tau = 432.8$ ns

$^{212}Bi \xrightarrow[2.25\ MeV]{\beta} {}^{212}Po \xrightarrow[\sim 800\ keV\ eq.]{\alpha} {}^{208}Pb$

^{238}U chain

$\tau = 236\ \mu s$

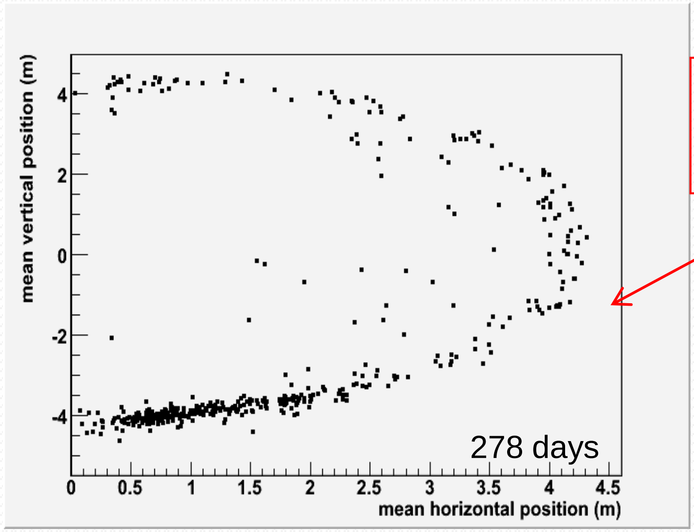
$^{214}Bi \xrightarrow[3.2\ MeV]{\beta} {}^{214}Po \xrightarrow[\sim 700\ keV\ eq.]{\alpha} {}^{210}Pb$

$(6.8 \pm 1.5) \times 10^{-18}$ g(Th)/g

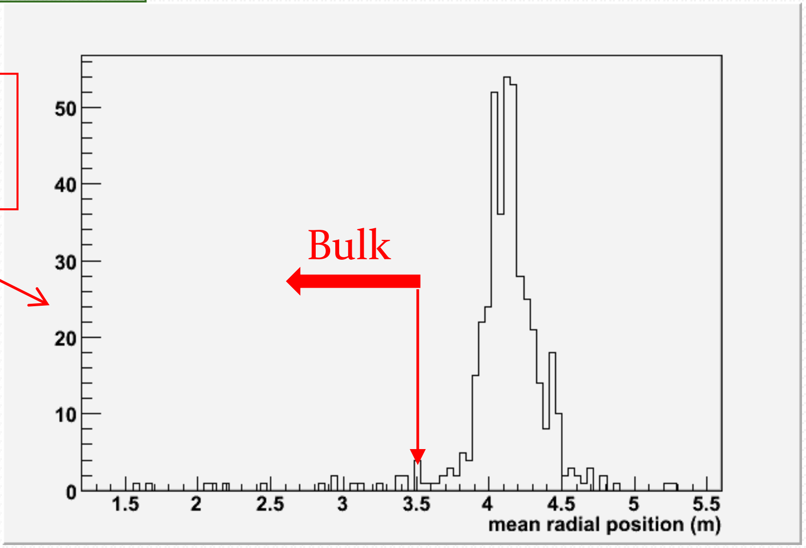
Bulk contamination

$(1.6 \pm 0.1) \times 10^{-17}$ 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 :

$$^{210}Pb \xrightarrow{\beta^-(61\ keV)} {}^{210}Bi \xrightarrow{\beta^-(1.2 MeV)} {}^{210}Po \xrightarrow{\alpha} {}^{206}Pb$$

	^{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

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

τ = 10.76 y - BR: 99.56%

^{85}Kr is studied through :

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

τ = 1.46 ms - BR: 0.43%

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