# First results on $^{7}$Be solar neutrinos from the Borexino real time detector



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# A touch of History

1990 A group of physicists started a project having as main goal the detection in real time of the solar ν below 2 MeV

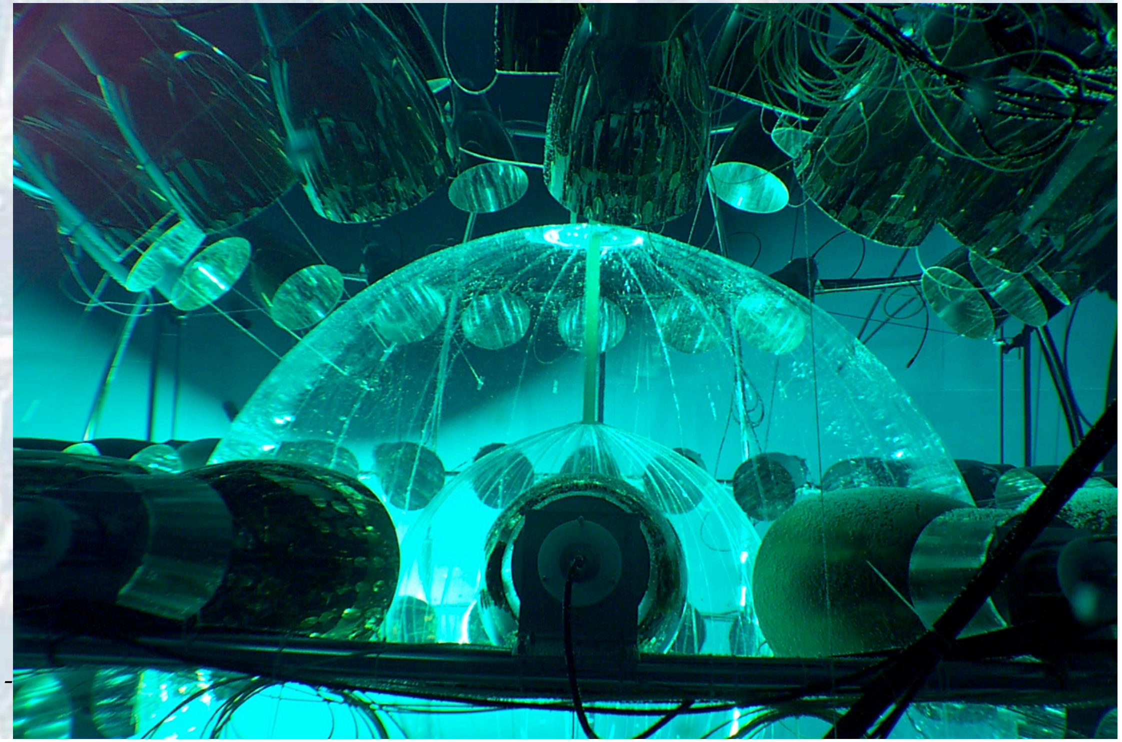
Main choice: use scintillator to have more light

Main problem: natural radioactivity

Main prescription at that time: rad. levels ≤ $10^{-16}$g/g : Th, U, eq.; $^{14}C/^{12}C \approx 10^{-18}$.

1992-1995

To check ultralow rad. levels we installed a very high sensitivity detector, the C.T.F.: sensitivity down to 5 $10^{-16}$g/g U,Th equiv.



1995 The CTF results showed the feasibility, in principle, of the project.(Borex, Coll.Phys.Letters,B422,1998;Astrop.Phys.8,1998; Astrop.Phys.18,2002)

1996-1998 Borexino approved by the funding Agencies

2002-2004 The project is stopped for the well known local problems

2005 Re-commissioning of all the set ups

Late spring 2006 Restart of all operations- detector filled with purified water

2007 Detector filled with purified scintillator (PC+1.5 g/l PPO), PC plus quencher(5.0 g/l),purified water

May 15th 2007- Borexino starts the data taking with the detector completely filled.

•Borexino is located under the Gran Sasso mountain which provides a shield against cosmic rays (4000 m water equivalent);

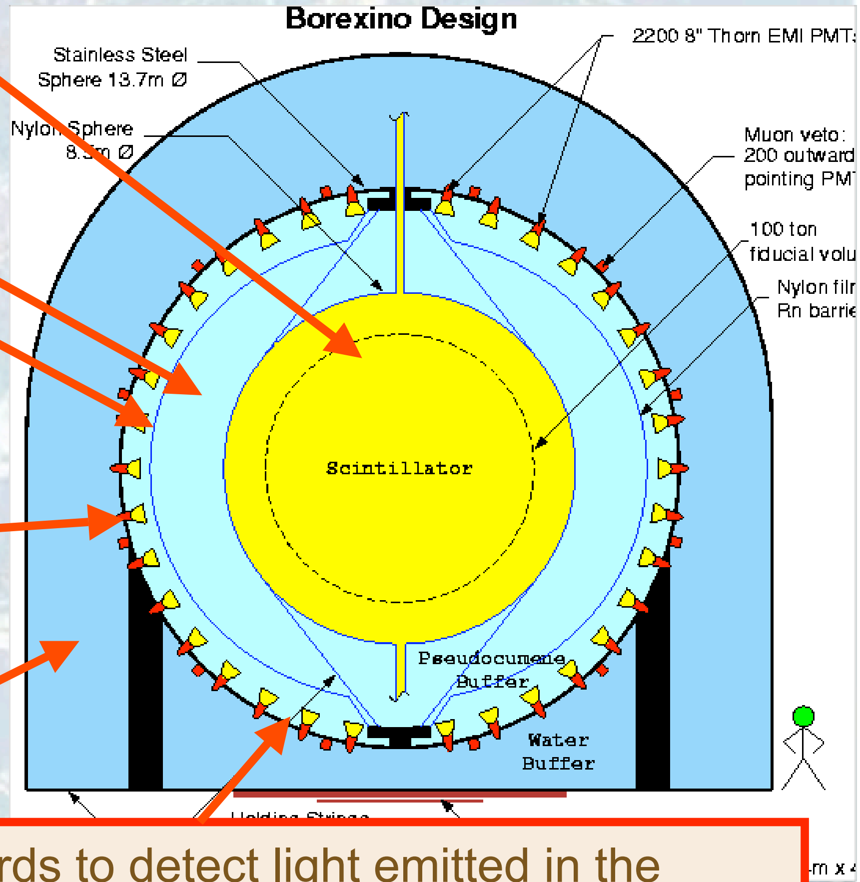
Core of the detector: 278 tons of liquid scintillator contained in a nylon vessel of 4.25 m radius (PC+PPO);

1st shield: 890 tons of ultra-pure buffer liquid (PC+quencher) contained in a stainless steel sphere of 6.75 m radius;

External nylon vessel; it is a barrier against Rn emitted by PMT and s.steel

2214 photomultipliers pointing towards the center to view the light emitted by the scintillator (1843 with opt. concentr.)

2nd shield: 2100 tons of ultra-pure water contained in a cylindrical dome;




200 PMTs mounted on the SSS pointing outwards to detect light emitted in the water by muons crossing the detector;

# The BOREXINO collaboration

- France
  - APC_ Paris
- Germany
  - Max-Planck Institute fuer Kernphysik _ Heidelberg
  - Technische Universitaet _ Muenchen
- Italy
  - INFN Laboratori del Gran Sasso-Assergi
  - INFN e Dipartimento di Fisica dell' Universita' _ Genova
  - INFN e Dipartimento di Fisica dell' Universita' _ Milano
  - INFN e Dipartimento di Chimica dell' Universita' _ Perugia
- Poland
  - Institute of Physics, Jagellonian University _ Cracow
- Russia
  - JINR _Dubna
  - Institute for Nuclear Research_Gatchina
  - Kurchatov Institute _Moscow
  - University of Moscow_Moscow
- USA
  - Virginia Tech,_Blacksburg
  - Princeton University _ Princeton

# TOOLS FOR A SUCCESS

(Borex.Coll.,Astrop.Phys.16,2002)

Cleaning scintillator : PC: water extraction,distillation (80 mbar,90-95 $^0$C),
nitrogen stripping, ultrafine filtration
: master solution cleaned separately

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

Purified water: U/Th equivalent:$10^{-14}$g/g,$^{222}$Rn<1 mBq/m$^3$,
$^{226}$Ra<0.8 mBq/m$^3$

Severe selection of all components: concrete s.steel, gaskets, only s.steel valves, Pmt glass and ceramic, sealing materials, pumps etc..

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

Tightness of all systems and plants: <$10^{-8}$ bar cm$^3$ s$^{-1}$ ( Rn underground 40-120 Bq/m$^3$)

All operations concerning the detector in clean rooms:classes 10, 100,1000; the detector itself maintained as a class 10000 clean room

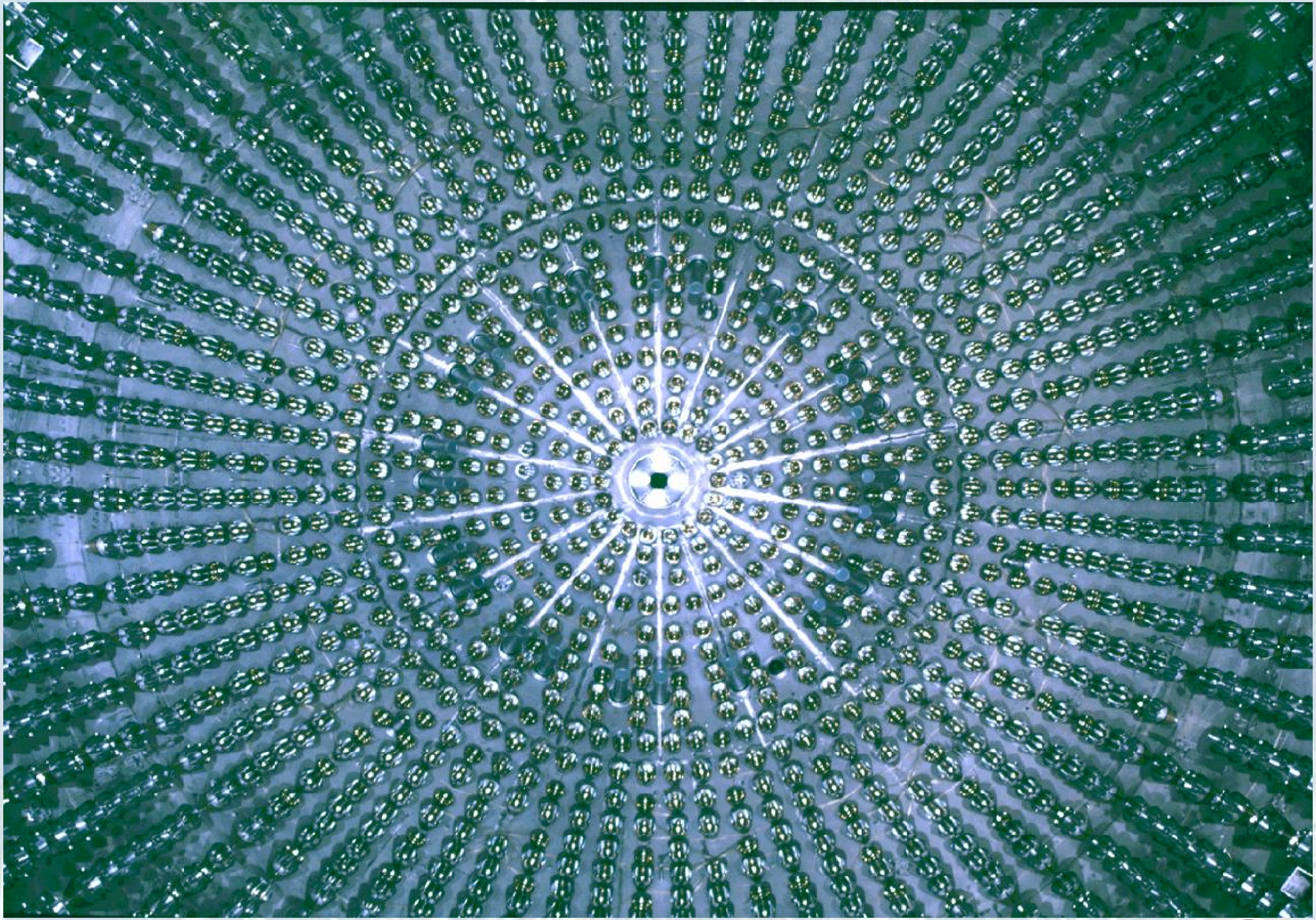
All operation concerning the auxiliary plants in $N_2$ atmosphere .

Precision cleaning: (detector, storage vessels, lines, components) with acids,detergents and purified water

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

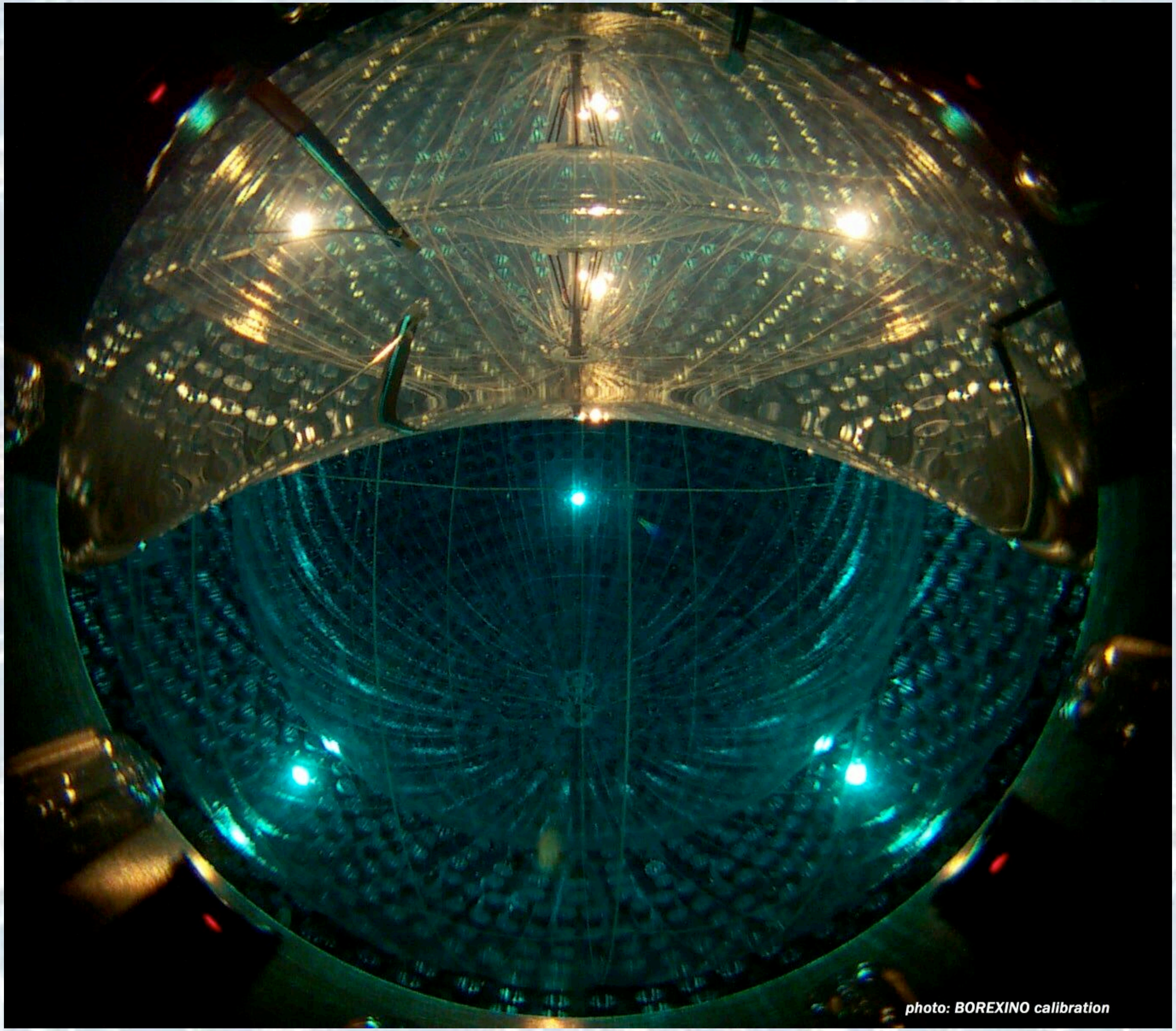
Extreme precaution in the fabrication and assembly of the Nylon Vessels: selection and extrusion of the materials in controlled area, construction in clean room with Rn control,special bags for shipping

Finally,last but not least, human strength, will and determination especially during the 3 years of stop!

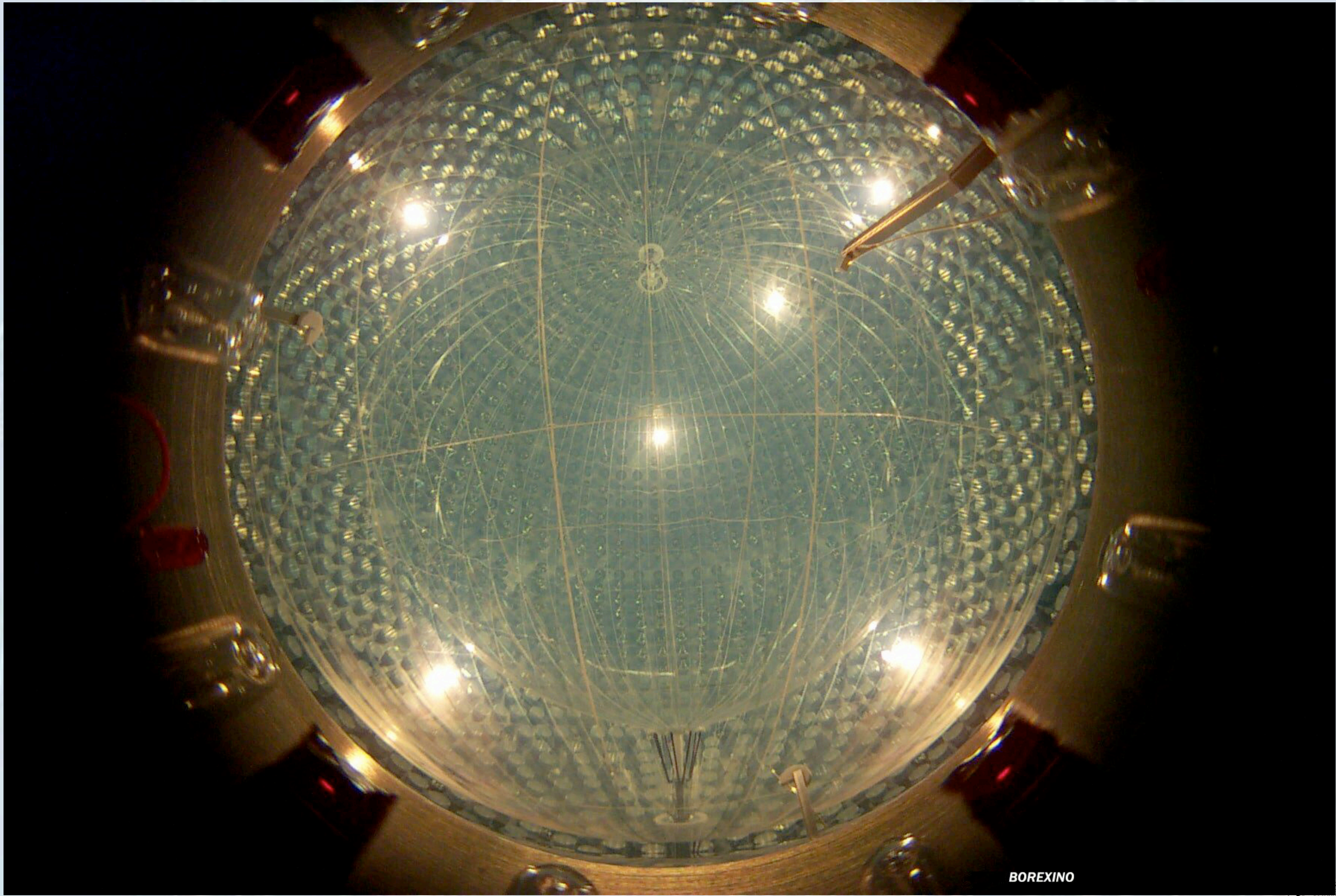


# During the water filling

# During the PC filling



# PC filling completed



# Data acquisition    ν-e scattering

- First tests with the detector filled with $N_2$ and water

- The data taking with the whole scintillator started may 15th, 2007

- First activity has been the electronics tuning

- The main trigger fires with ≥ 30 PMTs detecting each 1 p.e., at least , within 60 ns; En. threshold: ≈60 keV
  -the time and charge of each PMT, detected in 7.2μs, are recorded
- Typical triggering rate: 11 cps (dominated by $^{14}C$)

- The time is measured by a TDC (res.≈0.5 ns); the charge by 8 bits ADC

- The OD gives a veto when ≥ 6 PMT fire (99.8 %of probability of μ rejection)-- within 2 ms after a μ crossing the PC all events are rejected. The μ rate in scintillator plus buffer is 0.055 $s^{-1}$.

>> The time and the total charge are measured, and the position is reconstructed for each event . Absolute time is also provided( GPS)

>> The number of hit PMTs has been chosen to evaluate the total collected charge. Borexino has been designed in a way that, at energies lower than few MeV, the charge of each PMT corresponds in most cases to 1 p.e.

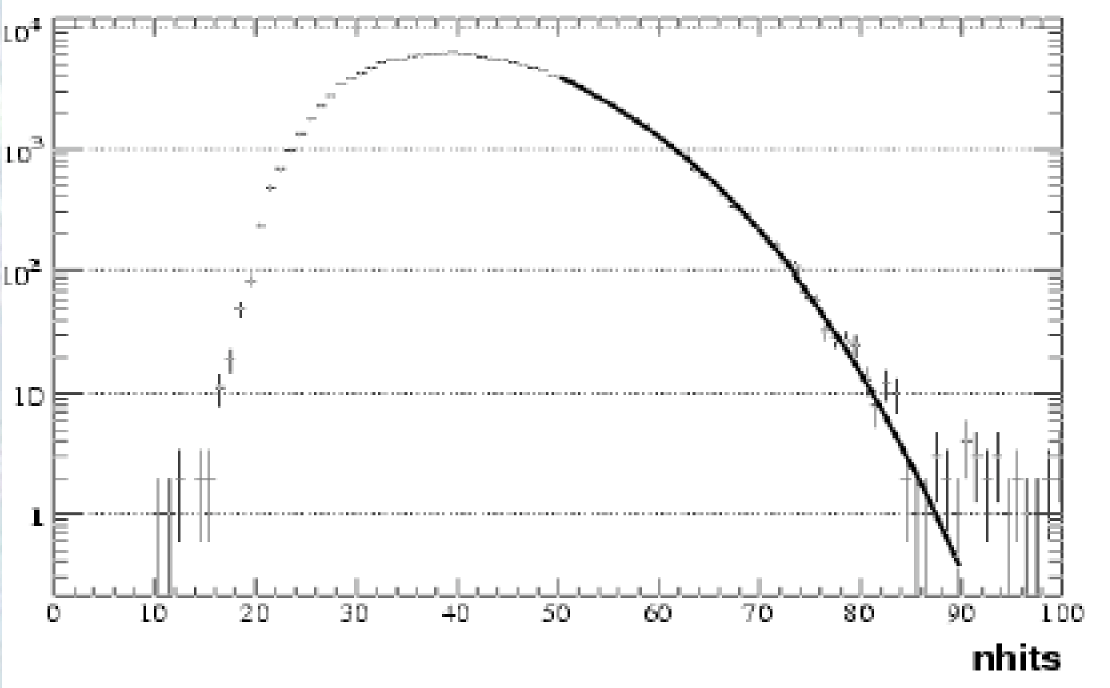
>> 47.4 live days of data taking

>>Two independent codes and analyses -->consistent results

>>The reconstruction programs not yet tuned with calibration sources -the tuning at present is based upon internal signals

# Light Yield

The Light Yield has been evaluated first fitting the $^{14}C$ spectrum.
( β decay-156 keV, end point)
Borex. Coll. NIM A440,2000




The light yield has been evaluated also by taking it as free parameter in a global fit on the total spectrum($^{14}C$,$^{210}Po$, $\sigma_{210Po}$,$^{7}Be$ ν Compton edge)

**LY≈500 p.e./MeV**
(taking into account the β quenching factor)

Spatial resolution: 16 cm at 500 keV
(scaling as $N_{p.e.}^{-1/2}$ )
Energy resolution: 10% at 200 keV
8% at 400 keV
6% at 1 MeV

# **Fiducial volume**- nominal 100 tons

about 1.25 m of scintillator in all directions assures a shielding for the background from the PMTs and the nylon of the vessel.

>the nominal Inner Vessel radius: 4.25m (278 tons of scintillator)

>the effective I.V. radius has been reconstructed using:

\# $^{14}C$ events # Thoron on the I.V. surface (emitted by the nylon-$\tau$=80s)

\# External background gamma # Teflon diffusers on the IV surface

>The F.V. is defined by considering a volume containing the 35.9% of the events - This corresponds to the ratio F.V./Total vol.
In addition a cut at z<1.8 m is applied on the north hemisphere due to a temporary presence of Radon, consequent to refilling operations.

Total effective fid. vol. -->87 tons ;

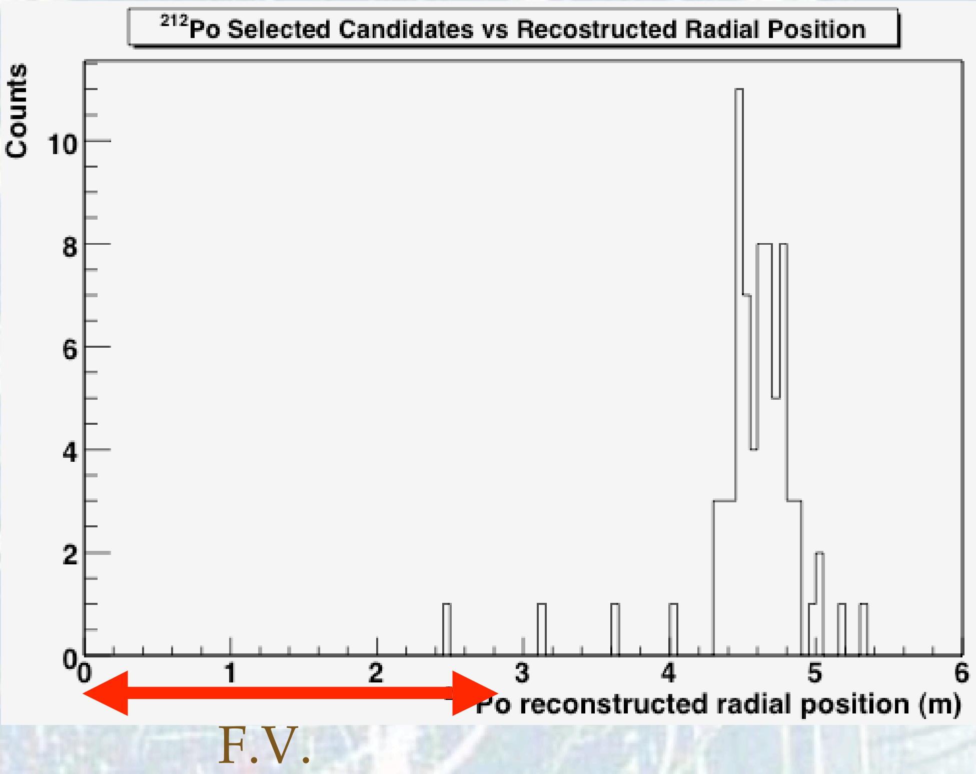
maximum uncertainty : 25%

# BACKGROUND

- $^{14}C$ ---------->> $2.7 \pm 0.6\ 10^{-18}$ $^{14}C/^{12}C$
- $^{232}Th$ family ---->> studied through the $^{220}Rn$ daughters
  - -assuming valid the secular equilibrium

Thoron ($^{220}Rn$)
Daughters $^{212}Bi$-$^{212}Po$
$\tau$=432.8 ns Eff.: 93%

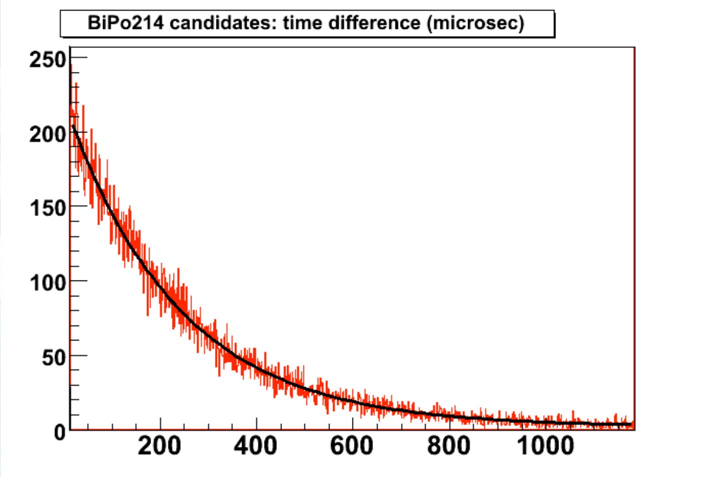
$< 6.6\ 10^{-18}$ g/g
$^{232}Th$ equivalent



# Background (cont.)

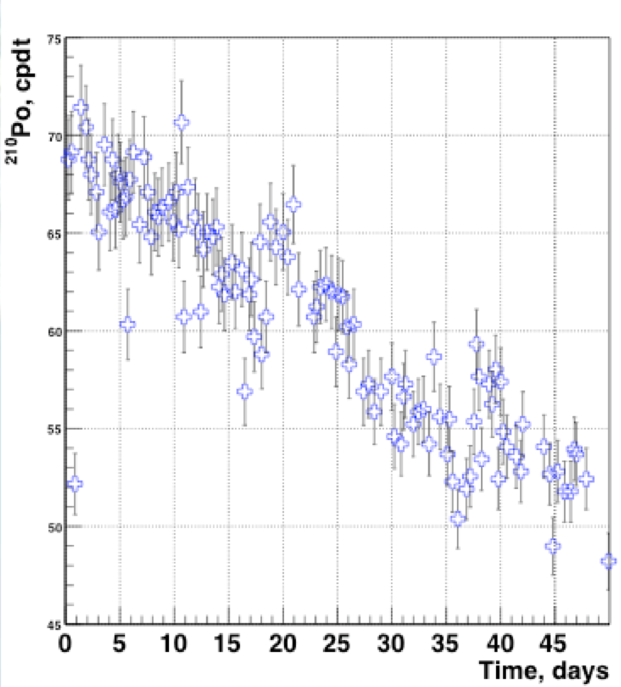
- $^{238}$**U** family- studied through the $^{222}$Rn daughters: $^{214}$Bi-$^{214}$Po coincidence (τ=236 μs)- <2 cpd/100 tons efficiency: 99.3%

---> < 2 $10^{-17}$ g/g $^{238}$U equivalent




Test during the filling

τ(exp)= 236±4μs




➢ $^{210}$**Po** (≈ 60 cpd/1ton) without a clear evidence of $^{210}$Bi
-it is decaying with a τ≈200 d
-removed via α/β discrimination

# Other contaminants

## $^{85}$Kr

@ β decay with an En. spectrum similar to the $^{7}$Be recoil electron

@ study of the decay

$$^{85}Kr \xrightarrow{\beta\text{-}173\ keV} {}^{85m}Rb \xrightarrow[1.46\ \mu s]{\gamma\text{–}514\ keV} {}^{85}Rb$$

BR: 0.43% 2 candidates in the IV in 47.4 d

Borex coll. Astrop.8,1998

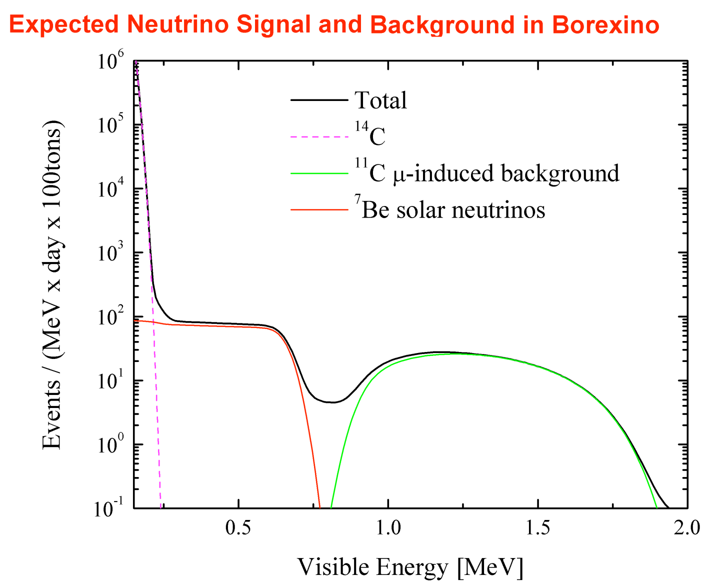
--------> upper limit < 35 cpd/100 tons (90% c.l.) for $^{85}$Kr decay

More statistics is needed---> Taken as free parameter in the total fit

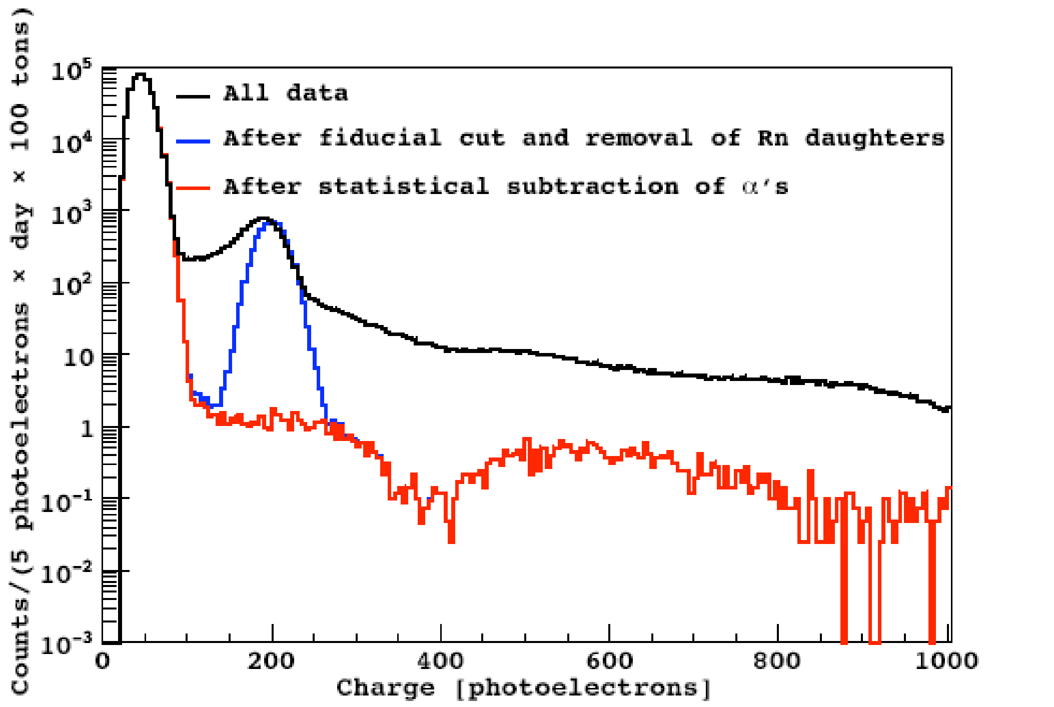
## $^{210}$Bi

@ no direct evidence----> free parameter in the total fit

cannot be disentangled, in the $^{7}$Be energy range, from the CNO




Expected energy spectrum
The unavoidable background is included: $^{14}C$, $^{11}C$




Raw p.e. charge spectrum after the basic cuts and subtr.

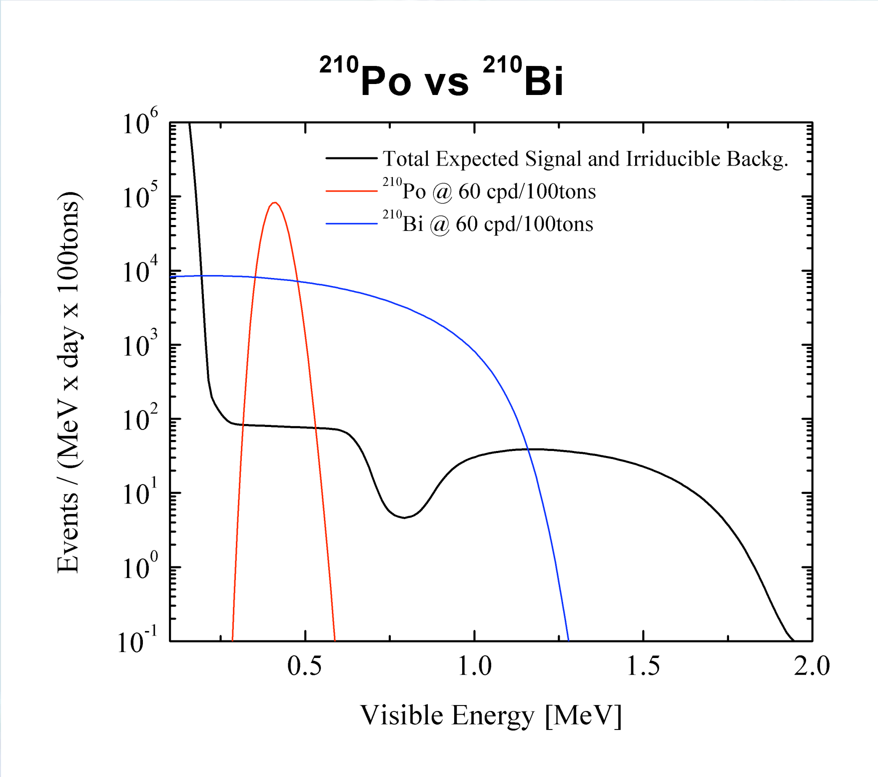
- -μ and μ–correlated activities
- -fiducial volume;
- -$^{222}$Rn daughters;
- –α

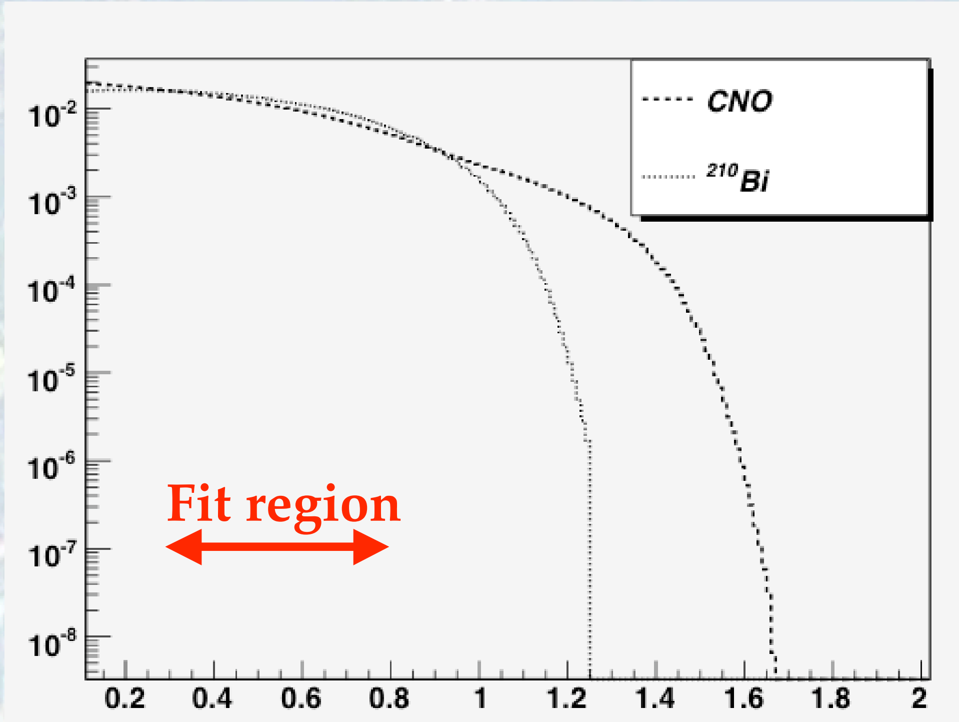
In these first weeks of data taking and analysis, we have focused our efforts on the $^{7}$Be region. We fit the energy spectrum in the window: 250-800 keV, once subtracted the identified $^{214}$Bi, $^{214}$Po, and a number of $^{214}$Pb equivalent to the $^{214}$Bi-$^{214}$Po coincidences.

Two different fits: one without $\alpha$ subtraction; a second one applying the statistical subtraction based upon the Gatti parameter ($\alpha/\beta$ discr.).

The statistical errors are determined by the $\chi^2$ profile. For the $^{7}$Be flux , its change, when in the fit the contribution of the $^{85}$Kr is fixed at its max. value (+ 3$\sigma$), is added to the statistical error.

The systematic errors are dominated by the uncertainty in the F.V. definition.



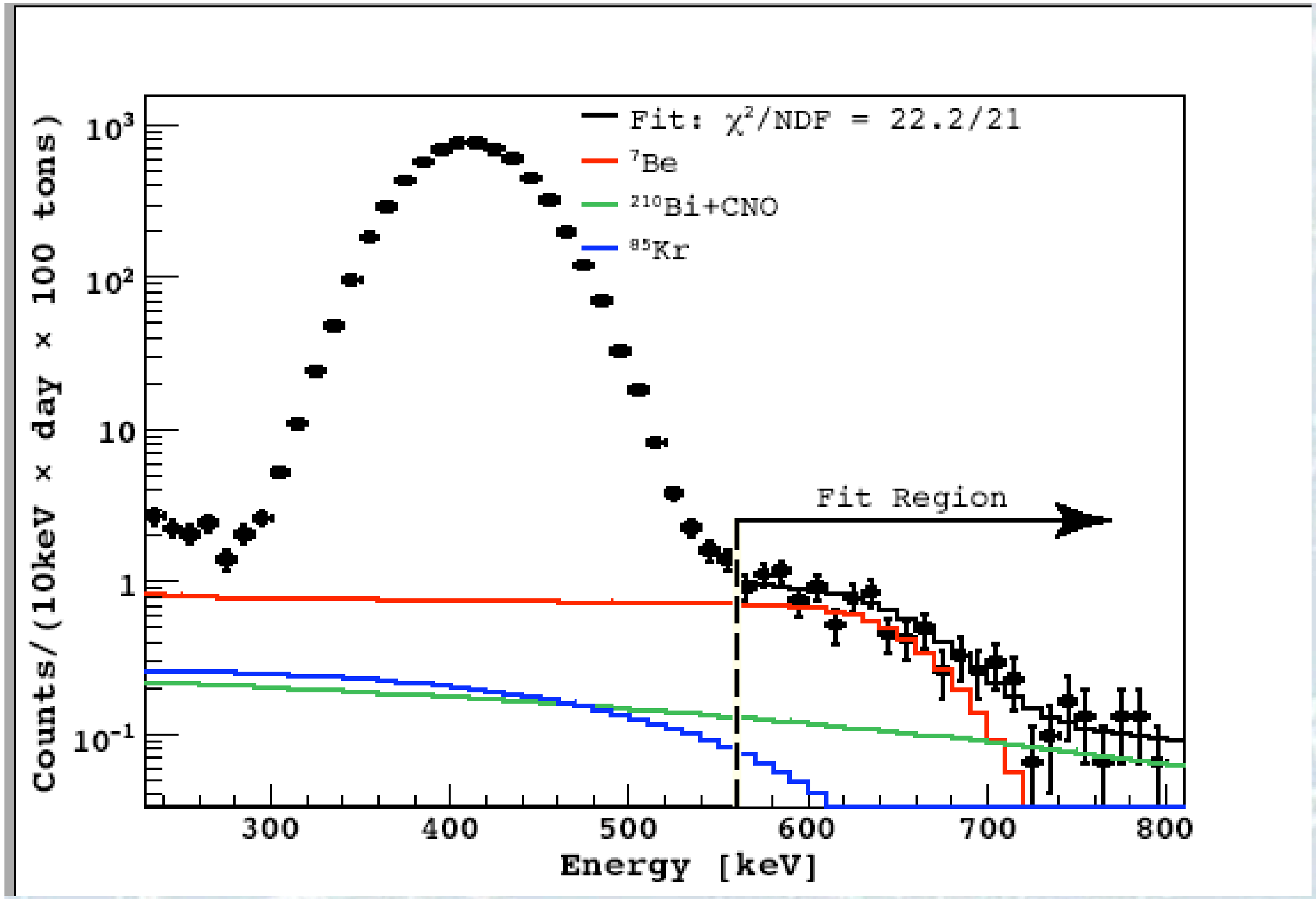




___ $^{210}$Po: 60 cpd / 1 ton

---- CNO

___ $^{210}$Bi: 60 cpd / 1ton

.... $^{210}$Bi




Cpd/100 tons

$^{7}$Be: 49 ± 7

$^{85}$Kr:16 ± 9

$^{210}$Bi+CNO: 19 ± 3

Syst.error: 25%

$\chi^2$/NDF: 22.2/21

Two steps : 1st fit on the En. region: 250-800 keV with LY,$^{210}$Po, $\sigma_{^{210}Po}$,$^{85}$Kr, CNO+$^{210}$Bi,$^{7}$Be, as free parameters

2nd fit: in 560-800 keV, with $^{7}$Be,CNO+$^{210}$Bi as free parameters ( the other parameters are fixed at the values obtained from the 1st fit)

# α/β discrimination- Gatti parameter

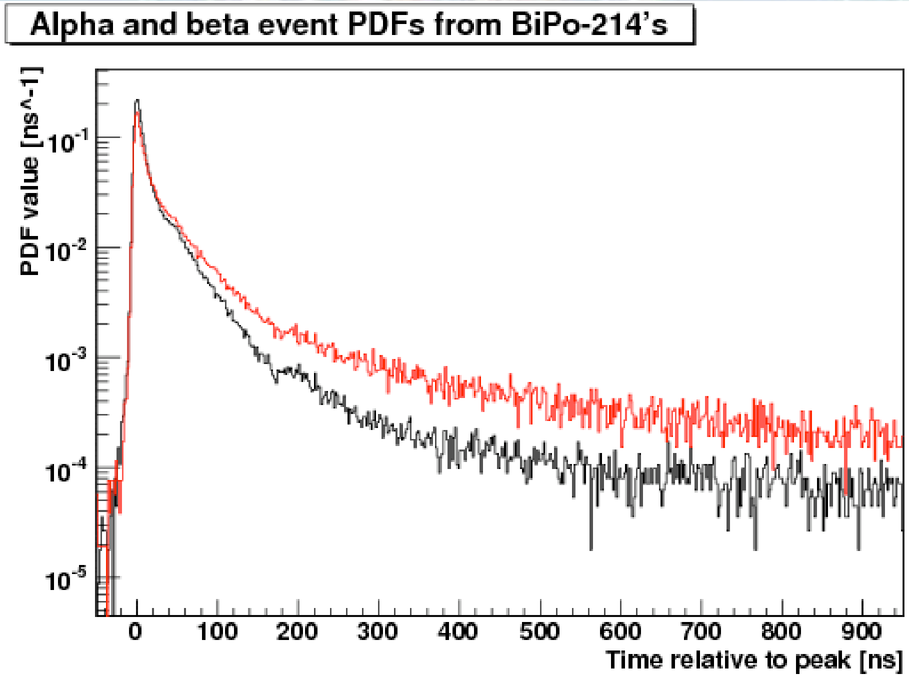
#Borex.Coll.N.I.M.A,in publ.

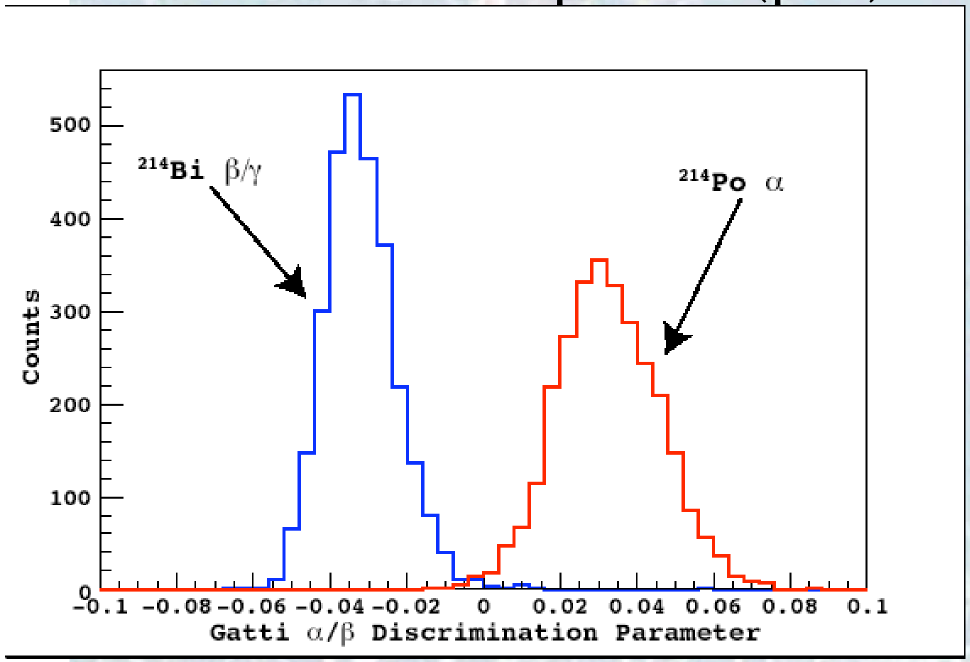
$G_\alpha = \sum_i P_i \beta_i$ $\alpha_\iota, \beta_\iota$ –>n. p.e. for the indiv. shape within a given Δt (2 ns)

$G_\beta = \sum_i P_i \alpha_i$

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

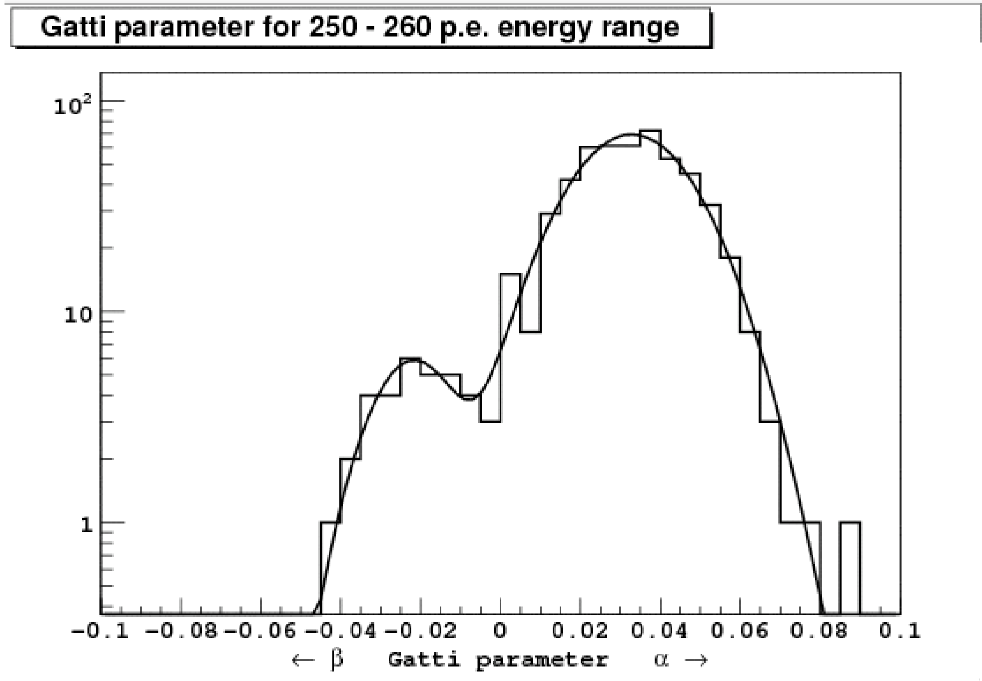
$\bar{\alpha}_i, \bar{\beta}_i$ –>av. shape of current pulses (pdf)

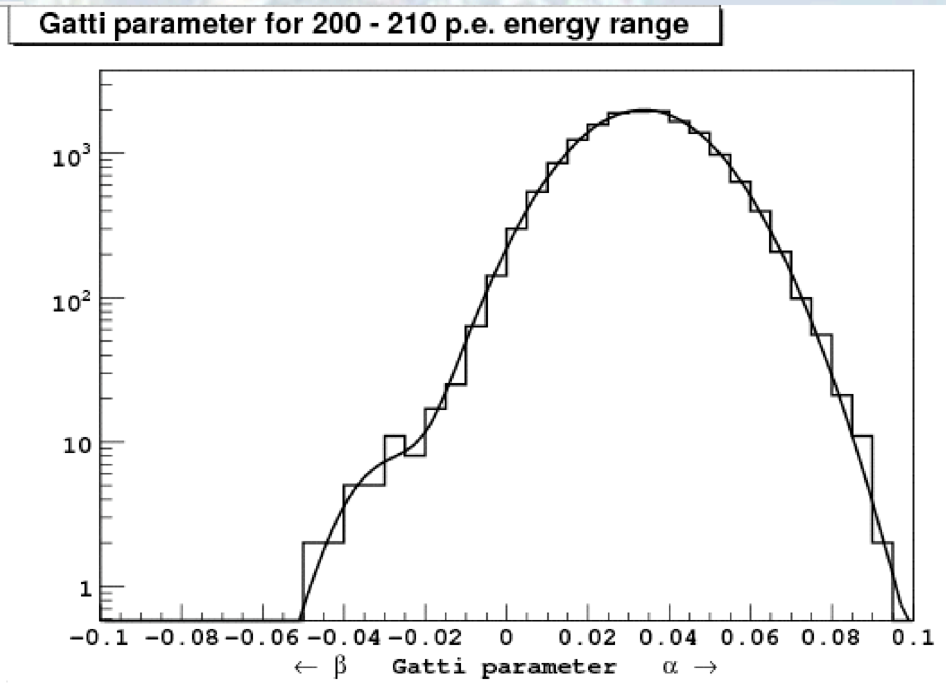



This analysis for the reference curves has been done during the filling period, when $^{222}$Rn was present

# GATTI Parameter applied to the range: 200-800keV for 20 keV bins-statistical subtraction

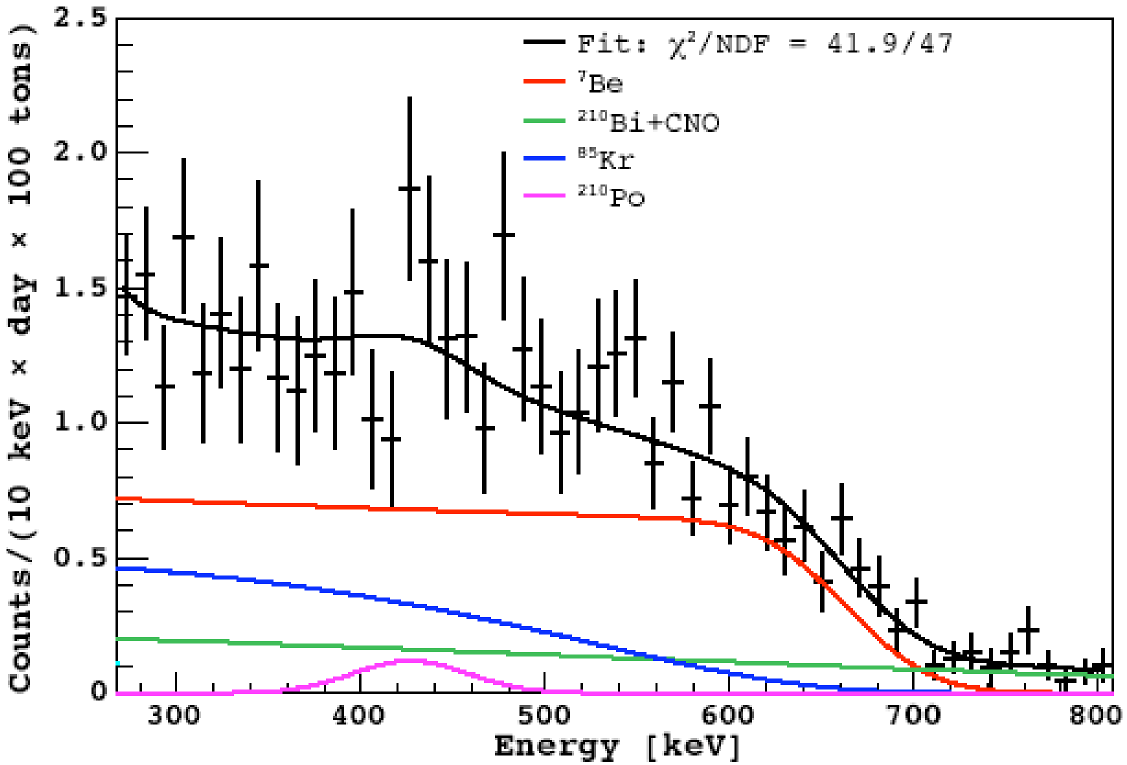



Efficiency ≈ 98.5%

@ the times of the PMT hits are compensated for the travel distance

@the pulse shapes does not depend on energy (test in CTF)




cpd / 100 tons

__$^{7}$Be: 47 ± 7

__$^{85}$Kr: 22 ± 7

__$^{210}$Bi+CNO:15 ± 4

__$^{210}$Po(res.): 0.9 ± 1.2

Syst error : 25%

Fit in the En. Range: 240-800 keV

Free parameters:$^{7}$Be, CNO+$^{210}$Bi,$^{85}$Kr, $^{210}$Po (residual)

$\chi^2$/NDF= 41.9 / 47

## $47 \pm 7_{stat}$ cpd / 100tons for 862 keV $^{7}$Be solar ν

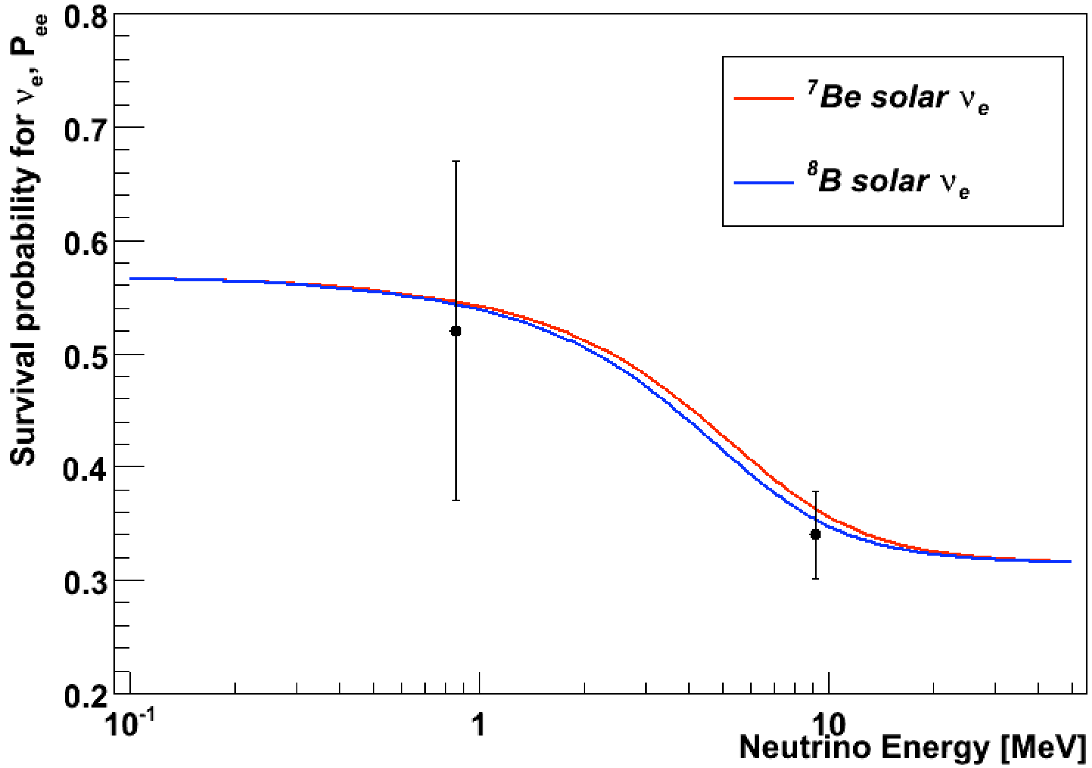
Syst. Error: 25%

Using LMA with:

$\delta m_{12}^2 = 7.92 \cdot 10^{-5}$ eV$^2$

$\sin^2\theta_{12} = 0.314$

and BPS07(GS98)



# What next

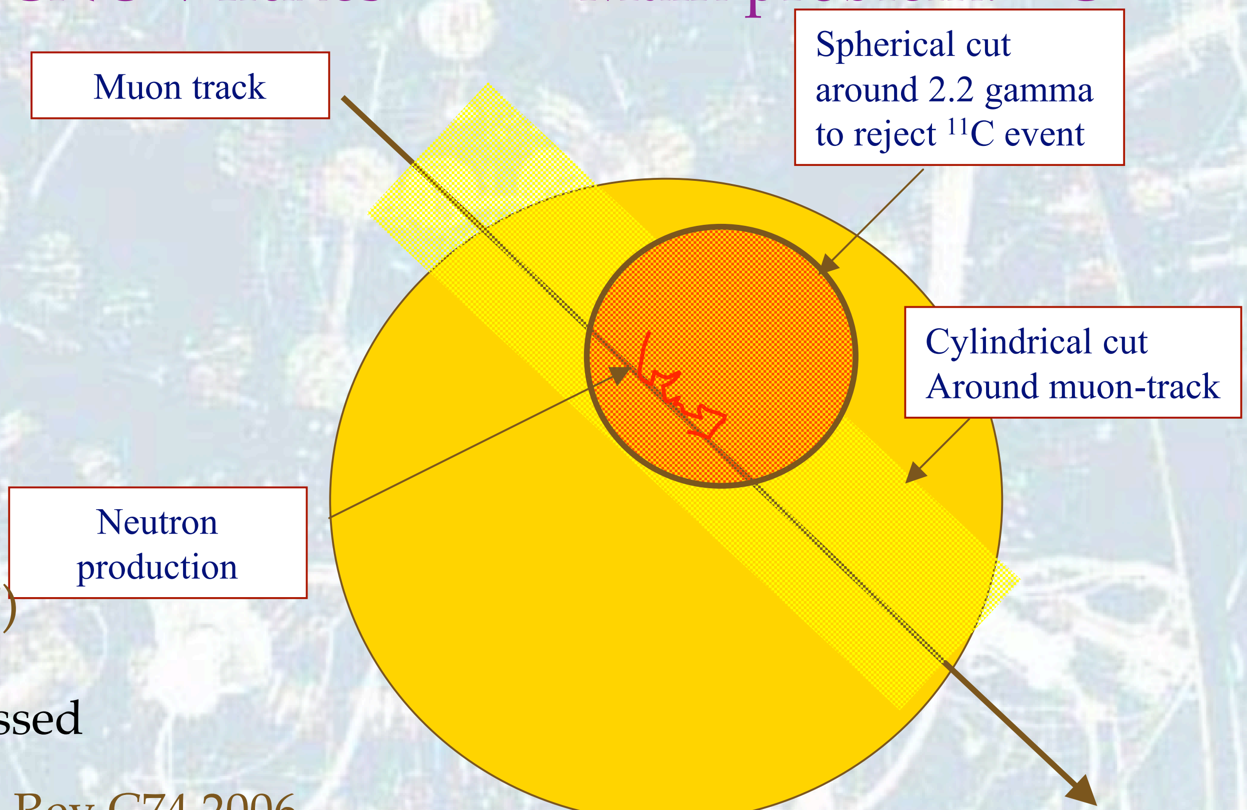
@ continue the efforts on $^{7}$Be ν to shrink errors below 5 % (more statistics, source calibration,etc)

@ pep and CNO ν fluxes     Main problem: $^{11}$C

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

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

n capture
γ (2.2 MeV)




≈ 14% of ν ev. are missed

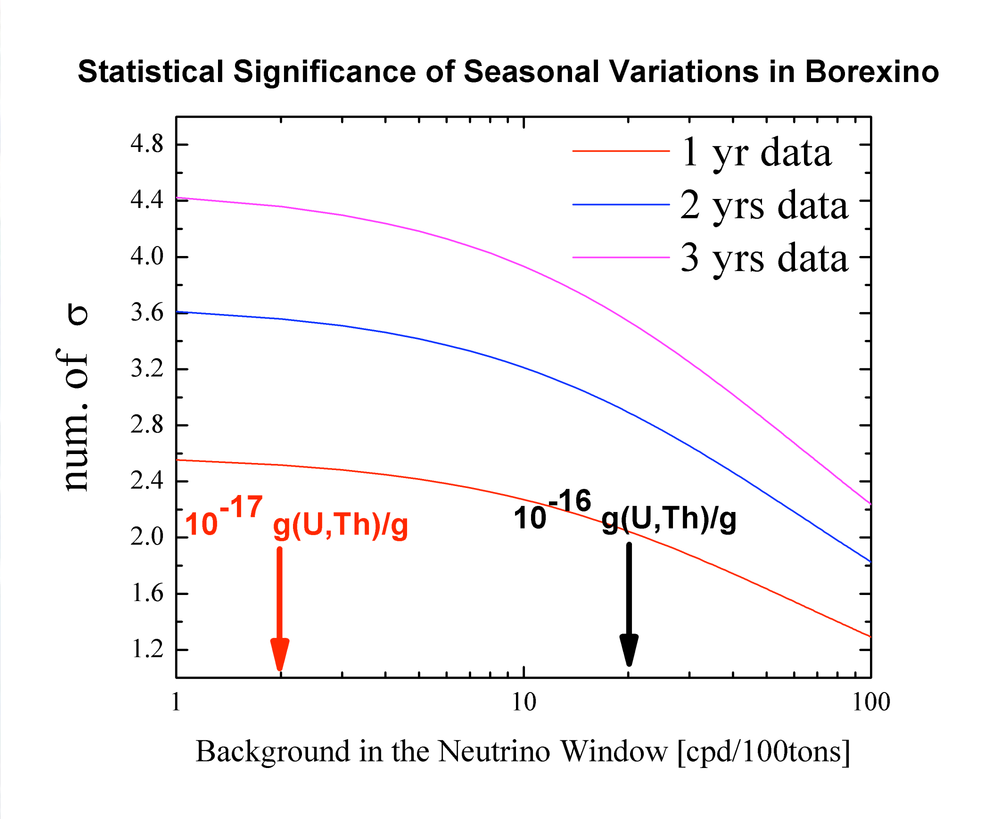
#Borex. Coll.Phys.Rev.C74,2006

# What next (cont.)

@ possibly p-p neutrinos

@ seasonal variations of the solar ν flux due to the eccentricity of the Earth orbit

250-800 keV En. window →



# What next (cont.)

@ search for antineutrinos (from Sun, Earth,reactors)

Borex. Coll. Eur. Phys.J. C47,2006

good tagging: $\bar{\nu}$ +p → n+e⁺ signal > 1 MeV

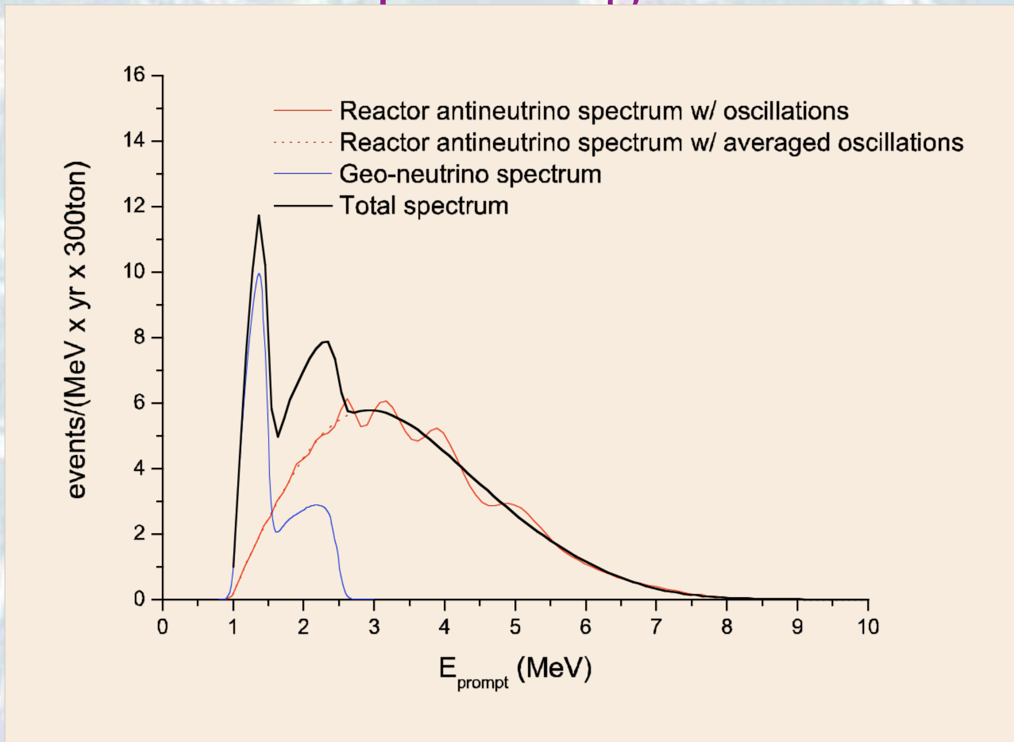
≈300μs

neutron capture: signal 2.2 MeV

--->> geoneutrinos

Main bckg: $\bar{\nu}$ from reactors
In 300 tons: 7- 17 ev/y
(BSE)- S/N=1

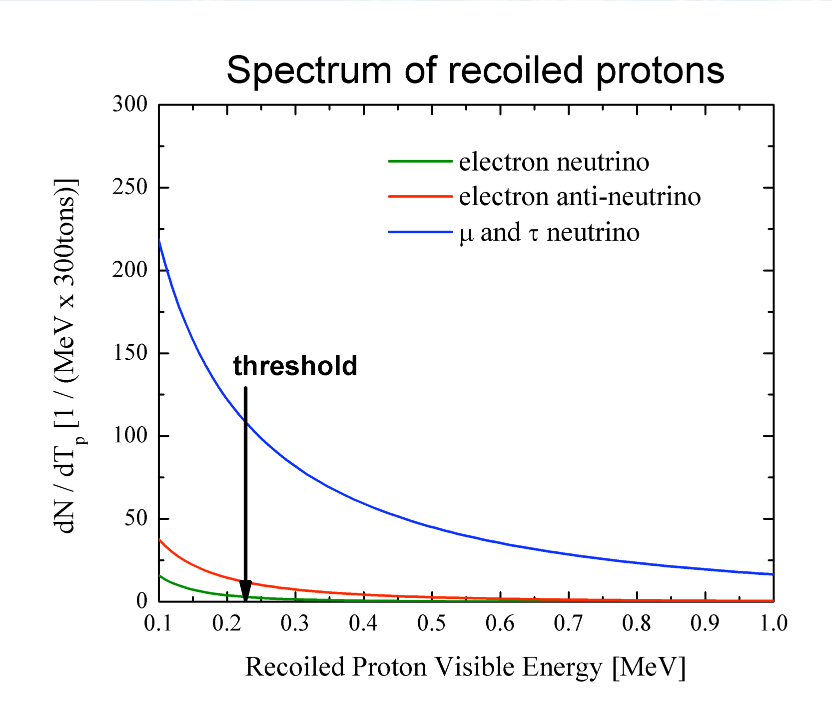
Antineutrinos from Reactors; long base line: ≈1000 km
Rate: ≈ 20 ev/y



# What next (cont.)

## @ Supernova

**Standard SN @ 10kpc**




| Detection channel | Any hierarchy |
|---|---|
| **Inverse-Beta Decay ($E_\nu$ > 1.8 MeV)** | 79 |
| **ν-p ES ($E_\nu$ > 0.25 MeV)** | 55 |
| **$^{12}C(\nu,\nu)^{12}C^*$ ($E\gamma$ = 15.1 MeV)** | 17 |

@ 2.5MCi $^{51}$Cr $\nu_e$ source

8.25m from detector's center

Monoenergetic neutrinos:

751 keV 9%

746 keV 81%

426 keV 9%

Limit to the magnetic moment :

5 $10^{-11}$ Bohr magnetons

$T_{1/2}$=27.7d

# CONCLUSIONS

>> Borexino just started the study of the various solar neutrino sources below 2 MeV, with a real time detection ( pp, $^{7}$Be, pep, CNO)

>> The program includes also the study of the antineutrinos (from Sun, Earth, Reactors)

>> Borexino in also a useful observatory for the Supernova

>>A study of the neutrino magnetic moment with an artificial source is also considered