Achievements in solar neutrino physics with the Borexino detector

STARS2015 - 3rd Caribbean Symposium on Cosmology, Gravitation, Nuclear and Astroparticle Physics

SMFNS2015 - 4th International Symposium on Strong Electromagnetic Fields and Neutron Stars

10-16 May 2015 L'havana and Varadero - Cuba

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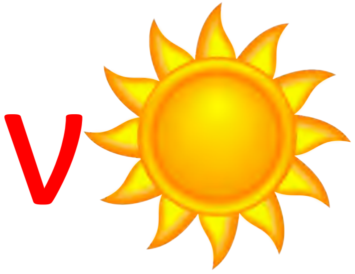
and

Istituto Nazionale di Fisica Nucleare
*(***on behalf of the Borexino Collaboration***)*

Why detecting solar neutrinos?



- **ASTROPHYSICS** (comparison with predictions of the SSM)

The standard Solar Model predicts the neutrino fluxes and their spectrum

…………. see later…..

- **PARTICLE PHYSICS** (neutrinos oscillations)

The "solar neutrino problem" has provided one of the first hints towards neutrino oscillations.

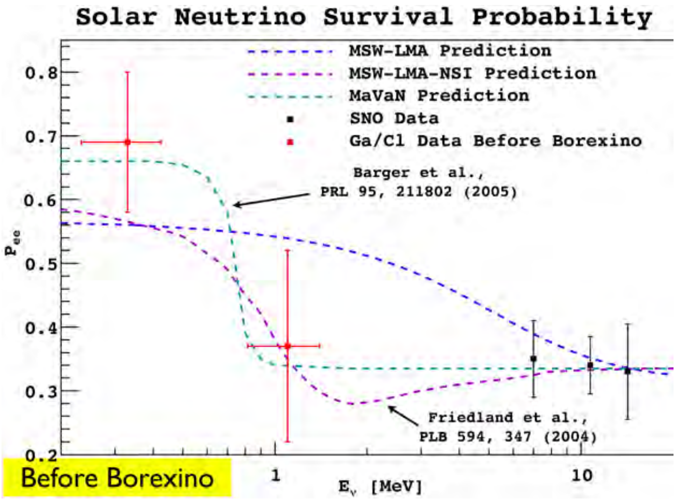
Now we know that neutrinos oscillate in their path from Sun to Earth

Open issues: precision measurements of solar neutrino sources at low energies probe P_{ee} in the vacuum to matter transition region which is sensitive to new physics;

$$"\textit{LMA Solution}"$$

$$\Delta m^2 = 7.6\cdot 10^{-5}\, eV^2$$

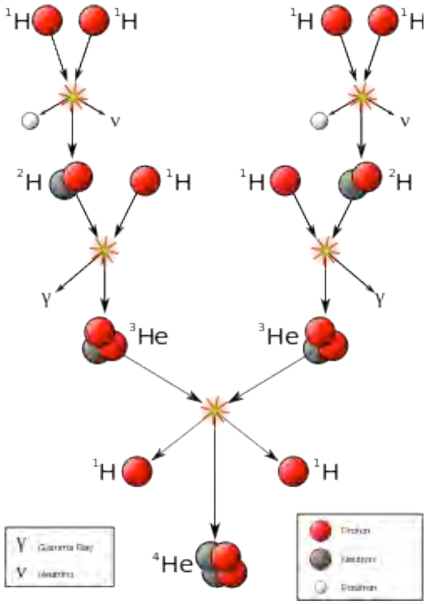
$$tg^2\vartheta = 0.468$$

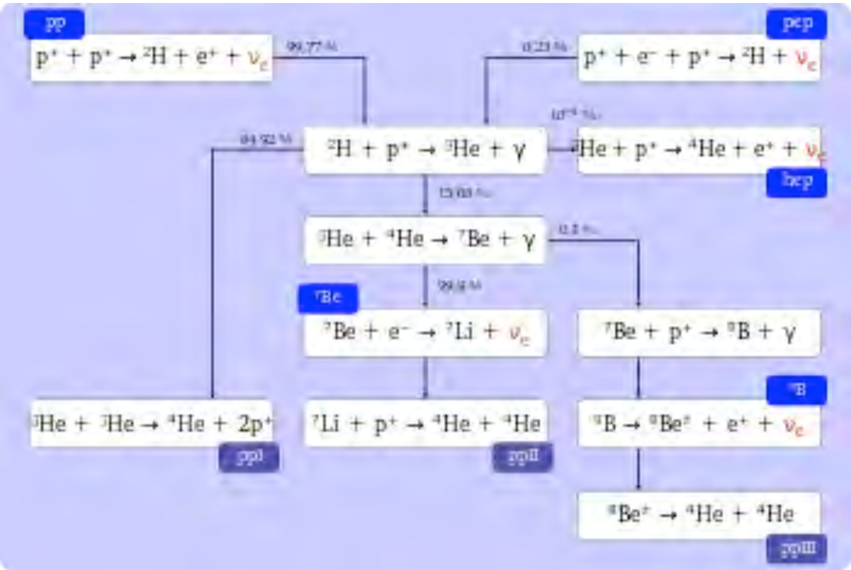


The Solar Standard Model and the Neutrino fluxes

proton-proton chain

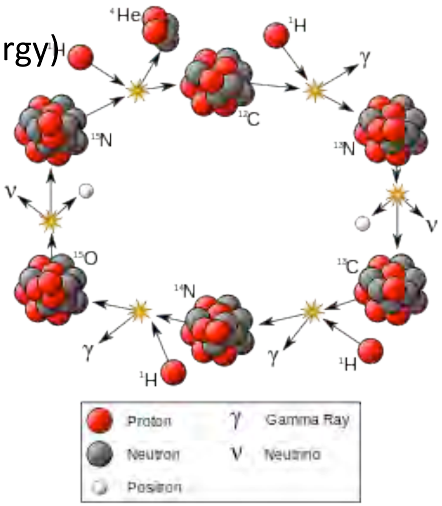
(~ 99% of the sun energy)





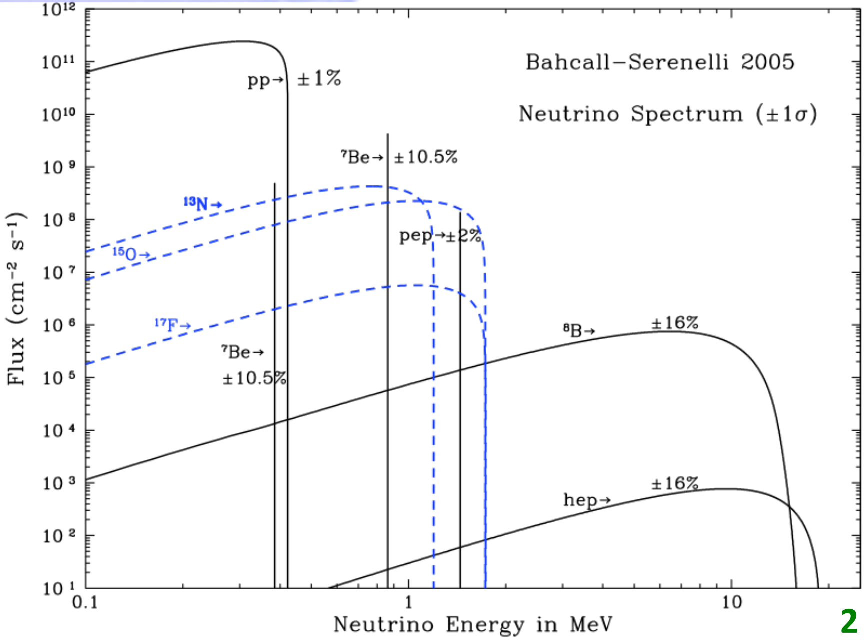
CNO cycle

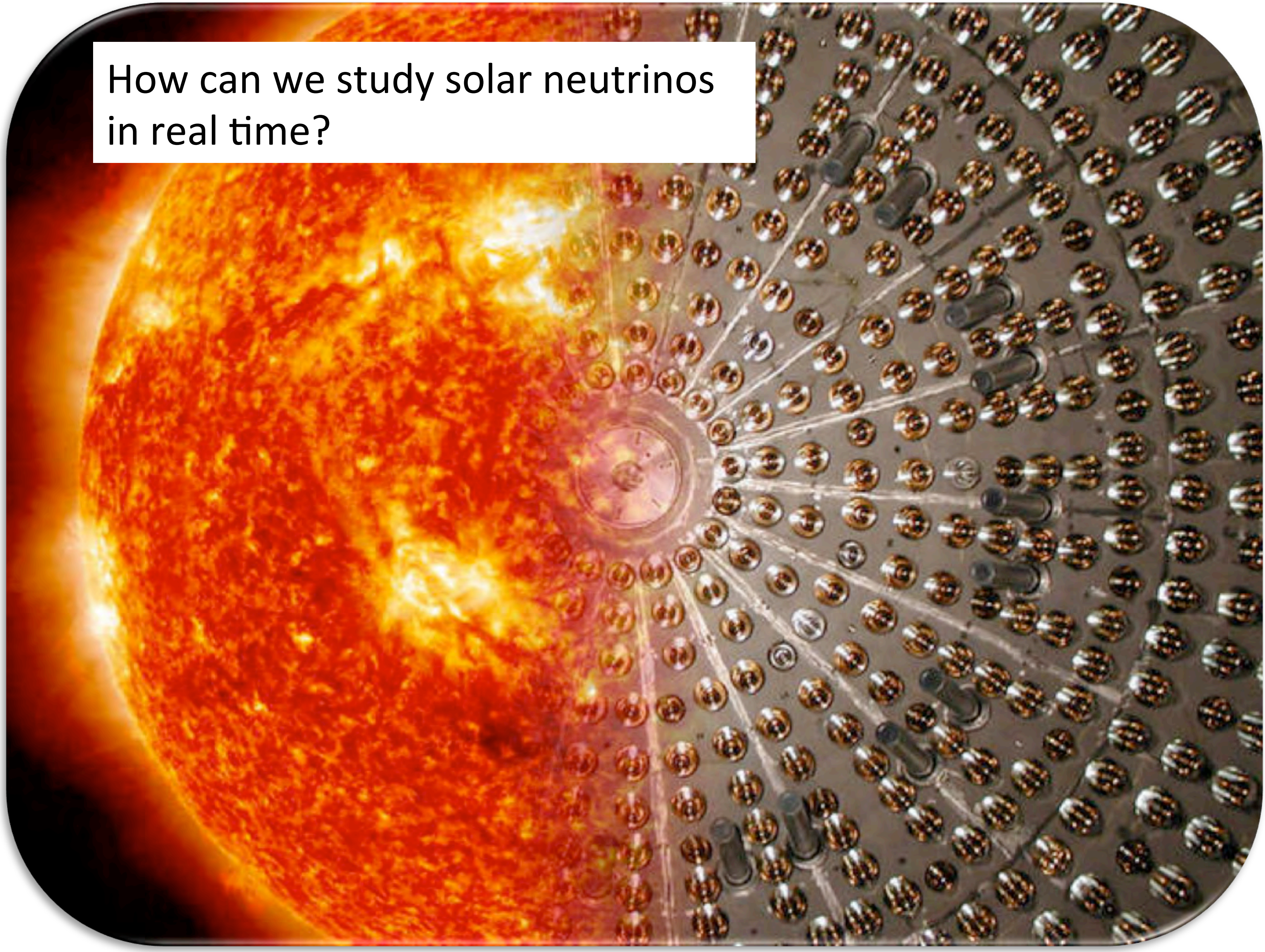
(≈1% of the sun energy)



Sources	Φ(ν sec^{-1} cm^2) *high-metallicity*	Φ(ν sec^{-1} cm^2) *low-metallicity*	Difference %
pp	$5.98(1\pm0.006)\times10^{10}$	$6.03(1\pm0.006)\times10^{10}$	0.8
pep	$1.44(1\pm0.012)\times10^{8}$	$1.47(1\pm0.012)\times10^{8}$	2.1
hep	$8.04(1\pm0.300)\times10^{3}$	$8.31(1\pm0.300)\times10^{3}$	3.3
^7Be	$5.00(1\pm0.070)\times10^{9}$	$4.56(1\pm0.070)\times10^{9}$	8.8
^8B	$5.58(1\pm0.140)\times10^{6}$	$4.59(1\pm0.140)\times10^{6}$	17.7
^{13}N	$2.96(1\pm0.140)\times10^{8}$	$2.17(1\pm0.140)\times10^{8}$	26.7
^{15}O	$2.23(1\pm0.150)\times10^{8}$	$1.56(1\pm0.150)\times10^{8}$	30.0
^{17}F	$5.52(1\pm0.170)\times10^{6}$	$3.40(1\pm0.160)\times10^{6}$	38.4

- **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





How can we study solar neutrinos in real time?

Borexino is a low energy threshold (~ 200 keV) real time experiment

Core of the detector

≈100 tons
Ultra high-purity liquid scintillator
PC+PPO

Detection principle

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

elastic scattering (ES) on electrons

It is possible to distinguish the different neutrino contributions: **Spectroscopy**

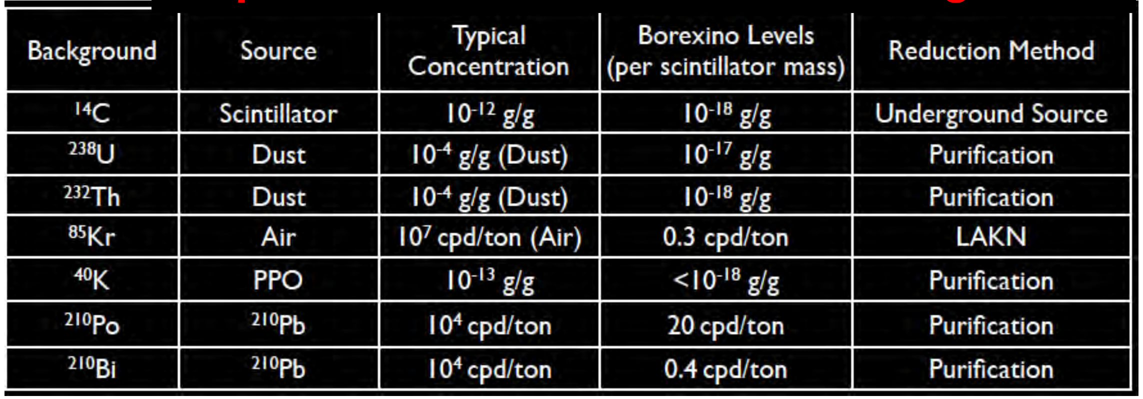
Unlike Cherenkov light, the scintillation **light is emitted isotropically**; this means that the ν induced events can't be distinguished from other γ/β events due to **natural radioactivity**.

Signal to noise ratio:
In order to have a signal to noise ratio on the order of 1, the ^{238}U (and ^{232}Th) intrinsic contamination can't exceed **10^{-16} g/g**! (*this means 9-10 orders of magnitude less radioactive then anything on Earth*)

Several techniques have been applied:

- Distillation,
- Water extraction,
- Nitrogen stripping,
- ecc…..

Unprecedented low levels of background



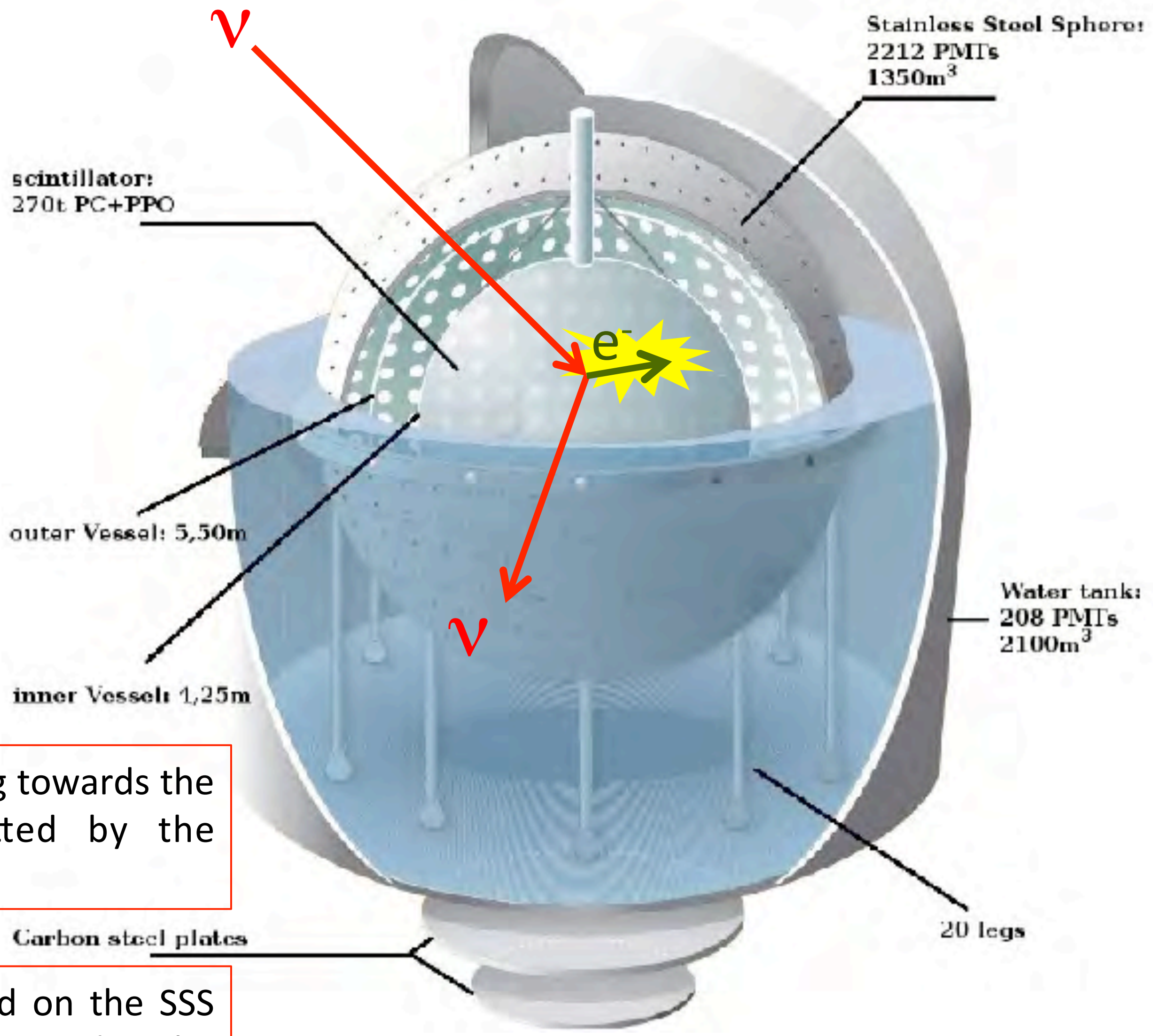
Background	Source	Typical Concentration	Borexino Levels (per scintillator mass)	Reduction Method
^{14}C	Scintillator	10^{-12} g/g	10^{-18} g/g	Underground Source
^{238}U	Dust	10^{-4} g/g (Dust)	10^{-17} g/g	Purification
^{232}Th	Dust	10^{-4} g/g (Dust)	10^{-18} g/g	Purification
^{85}Kr	Air	10^{7} cpd/ton (Air)	0.3 cpd/ton	LAKN
^{40}K	PPO	10^{-13} g/g	$<10^{-18}$ g/g	Purification
^{210}Po	^{210}Pb	10^{4} cpd/ton	20 cpd/ton	Purification
^{210}Bi	^{210}Pb	10^{4} cpd/ton	0.4 cpd/ton	Purification

Borexino al LNGS

300 tons of liquid scintillator (PC+PPO) *contained in a* ***nylon vessel*** *of 4.25 m radius*

1000 tons of ultra-pure buffer liquid (pure PC) *contained in a* ***stainless steel sphere*** *of 7 m radius*

2000 tons of ultra-pure water *contained in a* ***cylindrical dome***



2200 photomultiplier tubes pointing towards the center to view the light emitted by the scintillator

200 photomultiplier tubes mounted on the SSS pointing outwards to detect light emitted in the water by muon scrossing the detector

Laboratori Nazionali del Gran Sasso (LNGS)

Borexino Detector and Plants

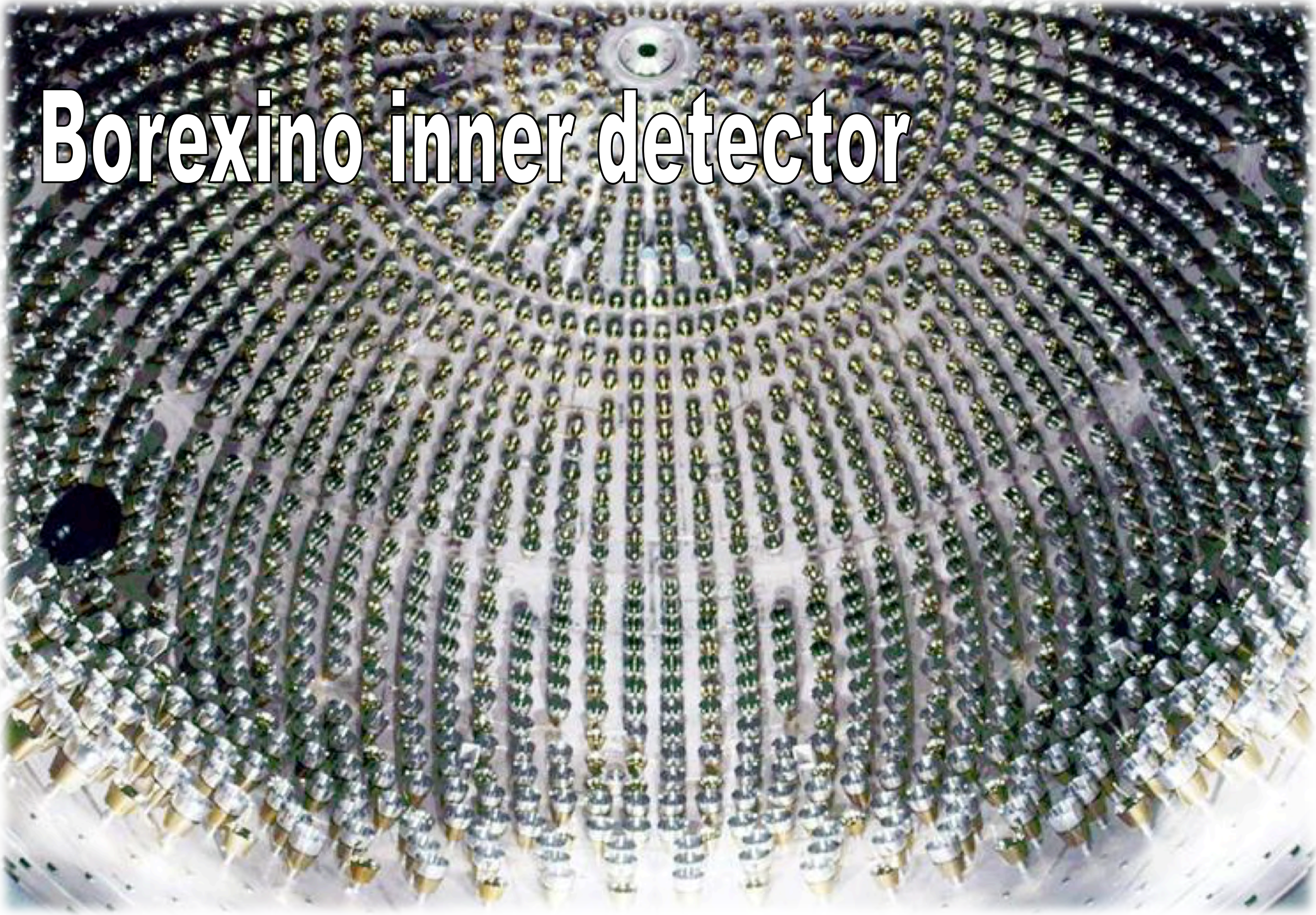
Experimental Hall C

External dome

18 m

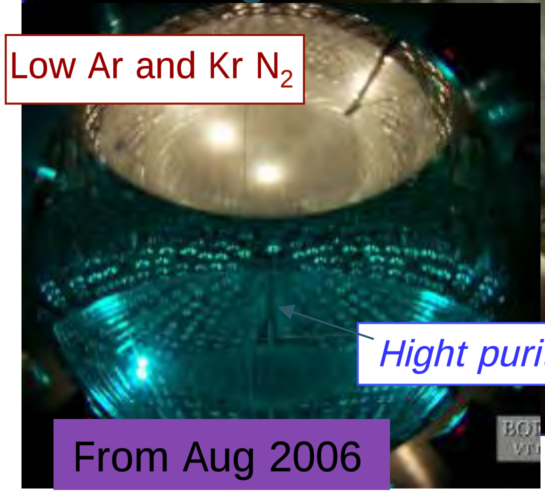
Stainless Steel Sphere (SSS)

Borexino inner detector



Nylon vessels inflated, filled with water and replaced with scintillator

water filling



Low Ar and Kr N_2

Hight purity water

From Aug 2006

Scintillator filling

Liquid scintillator

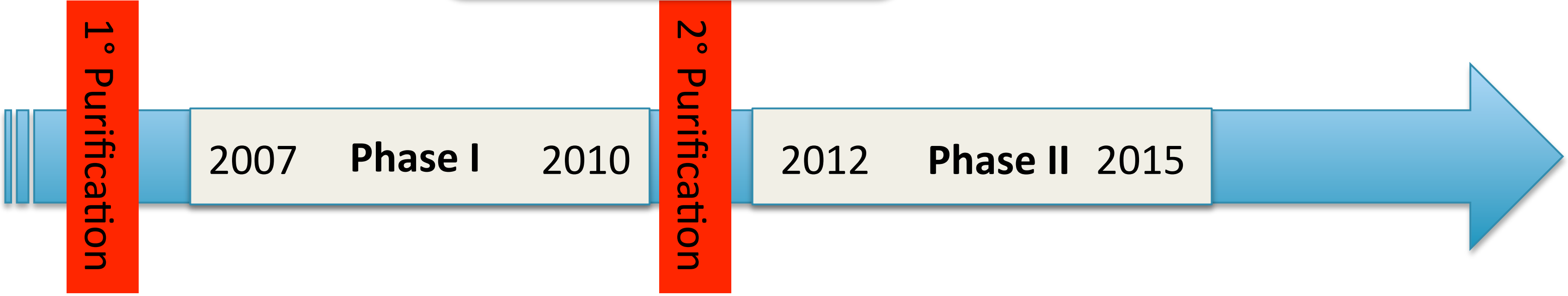
From Jan 2007

May 15th, 2007

Borexino’s history

Improved radiopurity

^{85}Kr rate compatible with 0
^{210}Bi reduced by a factor ≈ 3;
^{232}Th and ^{238}U negligible;



- ^{7}Be-ν: 1st observation and precise measurement (5%);
- Day/Night asymmetry;
- pep-ν: 1st observation;
- ^{8}B-ν at low threshold;
- CNO-ν: best limit

- pp-ν: 1st observation in real time
- Seasonal modulation of ^{7}Be signal

Results of Borexino Phase I

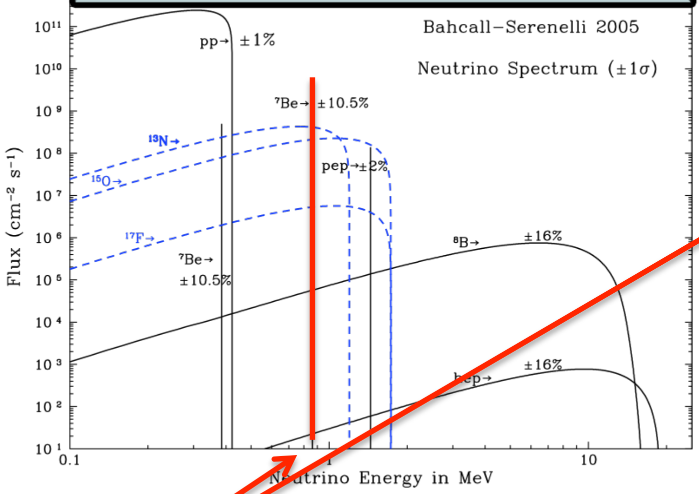
(above ^{14}C end-point)

From raw data to neutrino signal

Example of ^{7}**Be** neutrino line

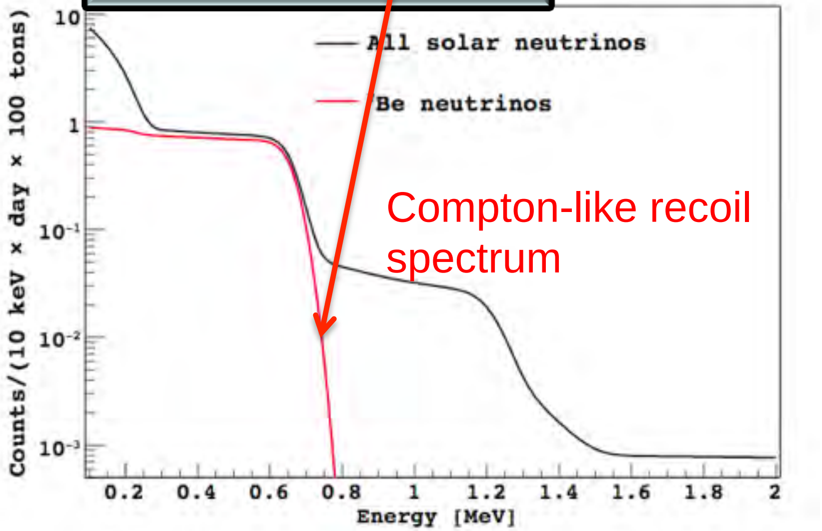
$$\nu_x + e^- \rightarrow \nu_x + e^-$$

ν flux as predicted by SSM



^{7}Be monochromatic line at 0.862 MeV

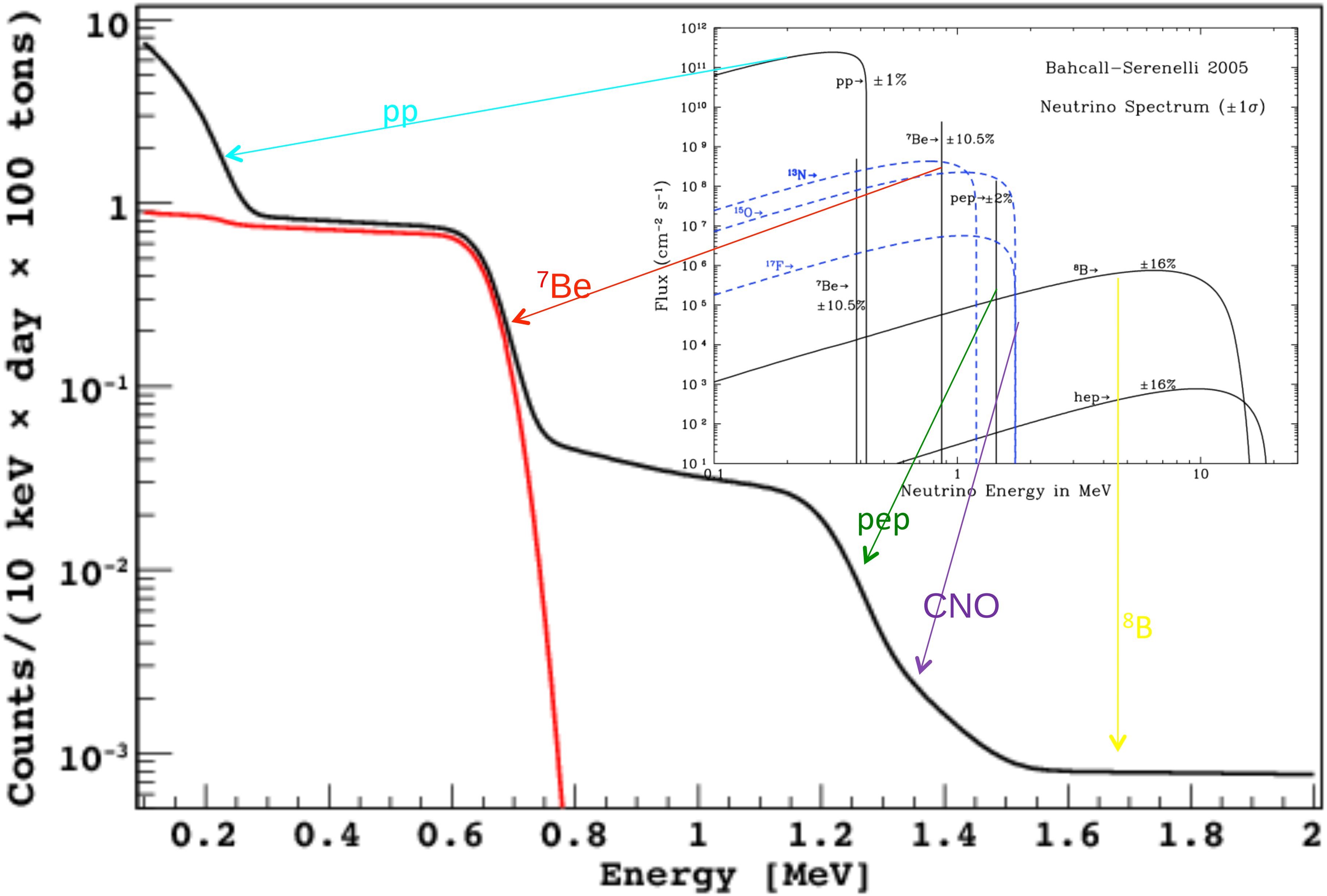
ν signal in Borexino



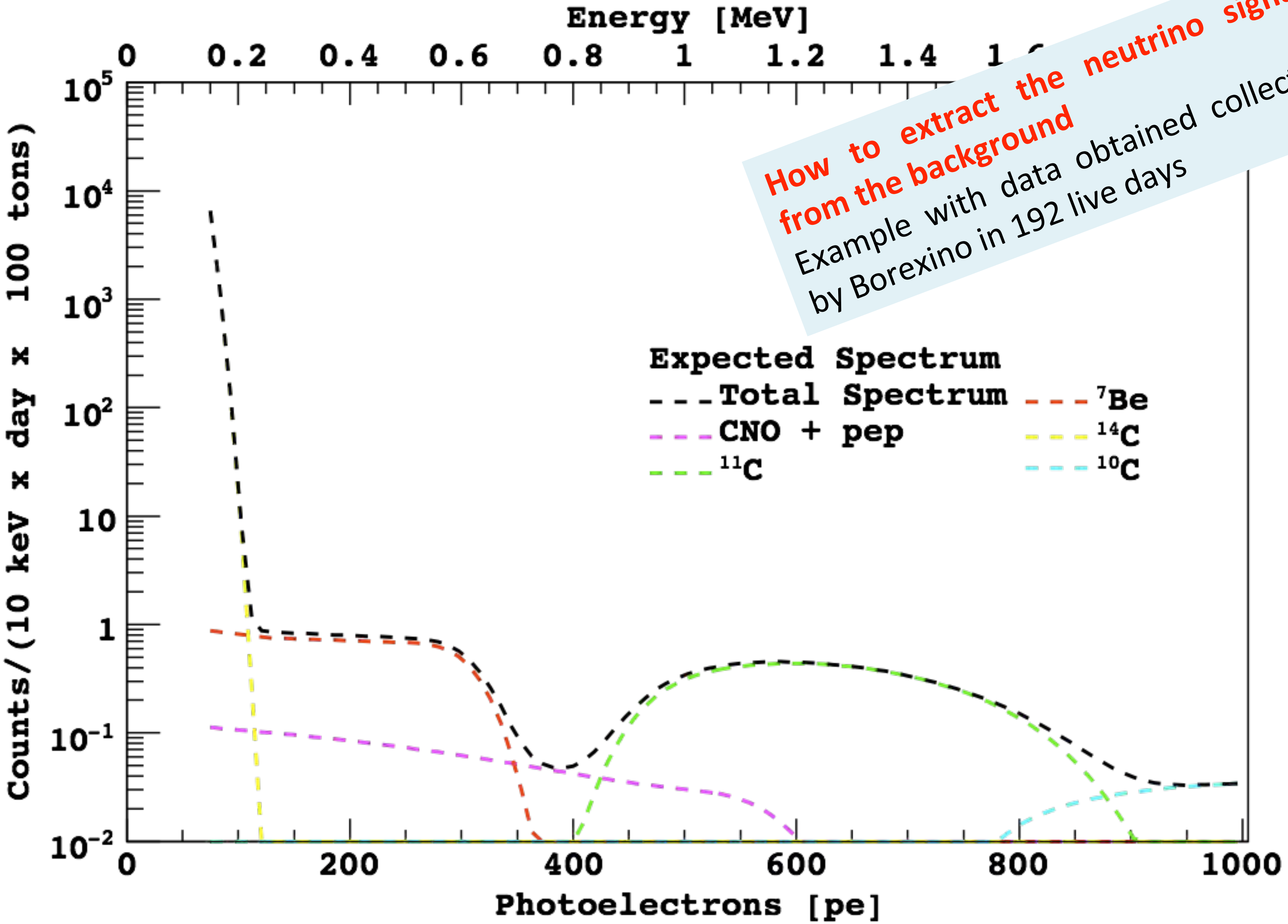
Compton-like recoil spectrum

Maximum ES of e^{-} 0.662 MeV

<u>Warning</u>: we have to take into account the energy resolution of the detector


Counts/(10 keV × day × 100 tons)
10
1
10-1
10-2
10-3
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Energy [MeV]
pp
7Be
pep
CNO
8B
Bahcall−Serenelli 2005
Neutrino Spectrum (±1σ)
Flux (cm-2 s-1)
Neutrino Energy in MeV
pp→ ±1%
7Be→ ±10.5%
13N→
15O→
17F→
pep→±2%
7Be→ ±10.5%
8B→ ±16%
hep→ ±16%
1012
1011
1010
109
108
107
106
105
104
103
102
101
0.1
1
10

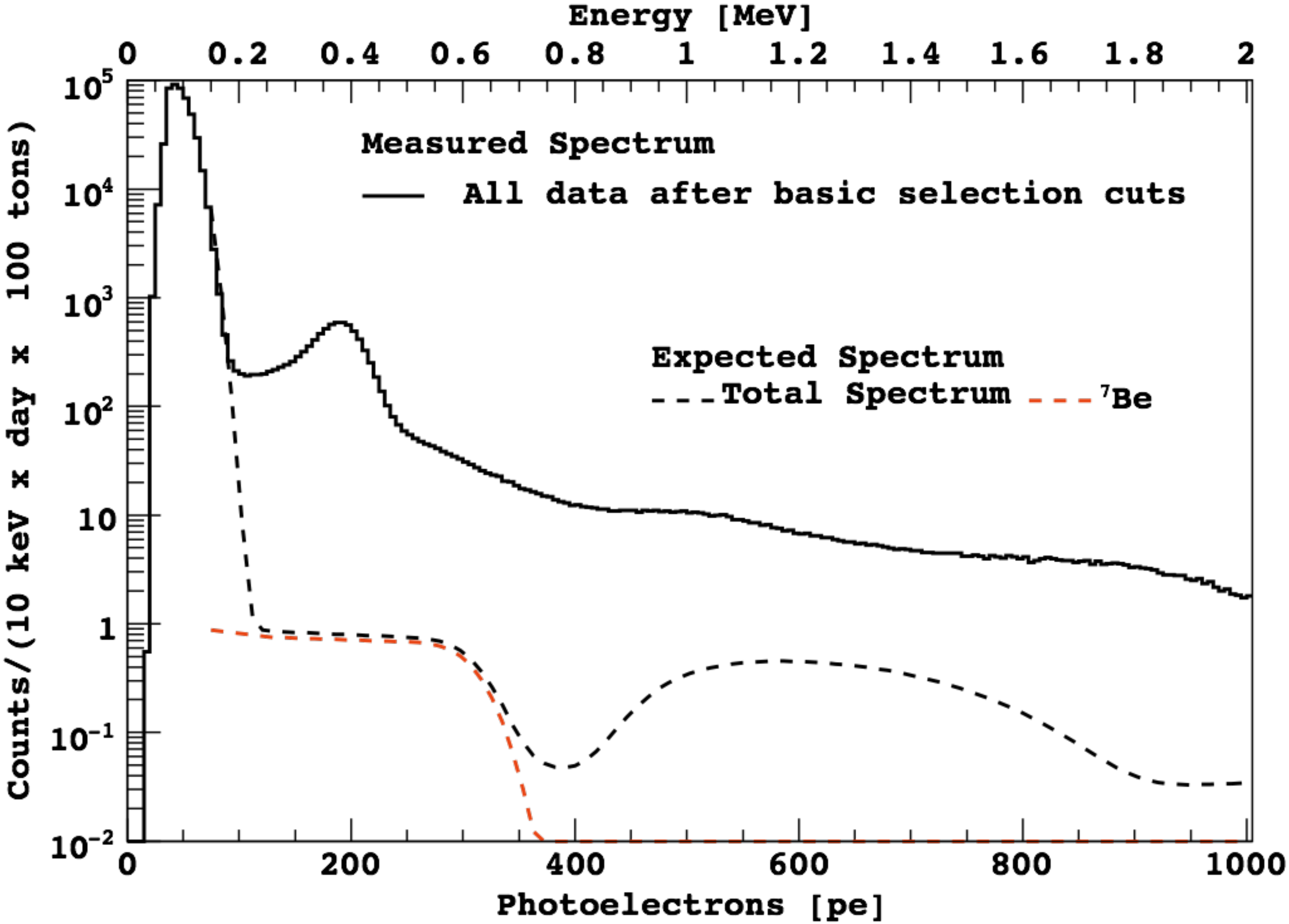
Expected Spectrum



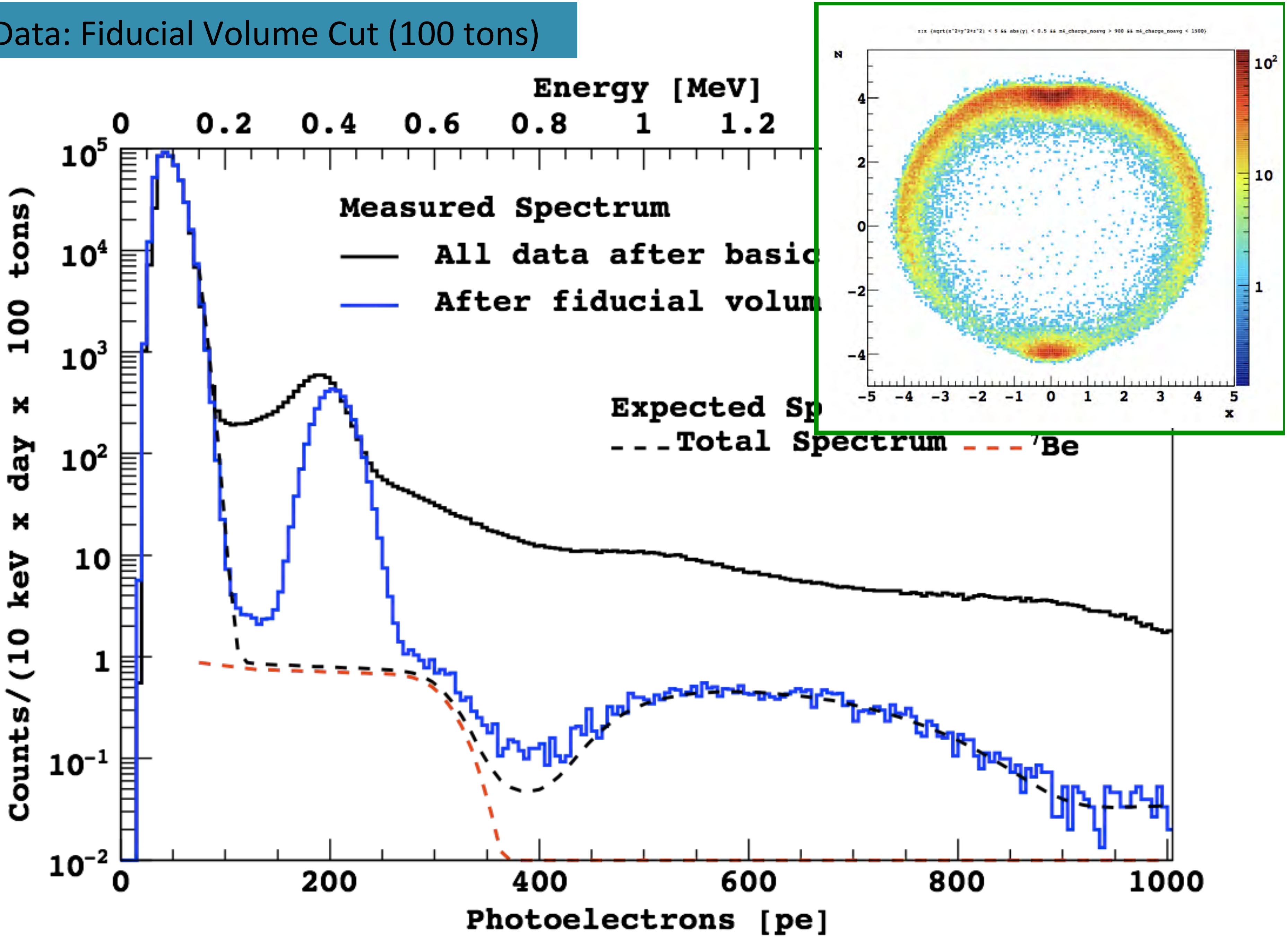
How to extract the neutrino signal from the background

Example with data obtained collected by Borexino in 192 live days

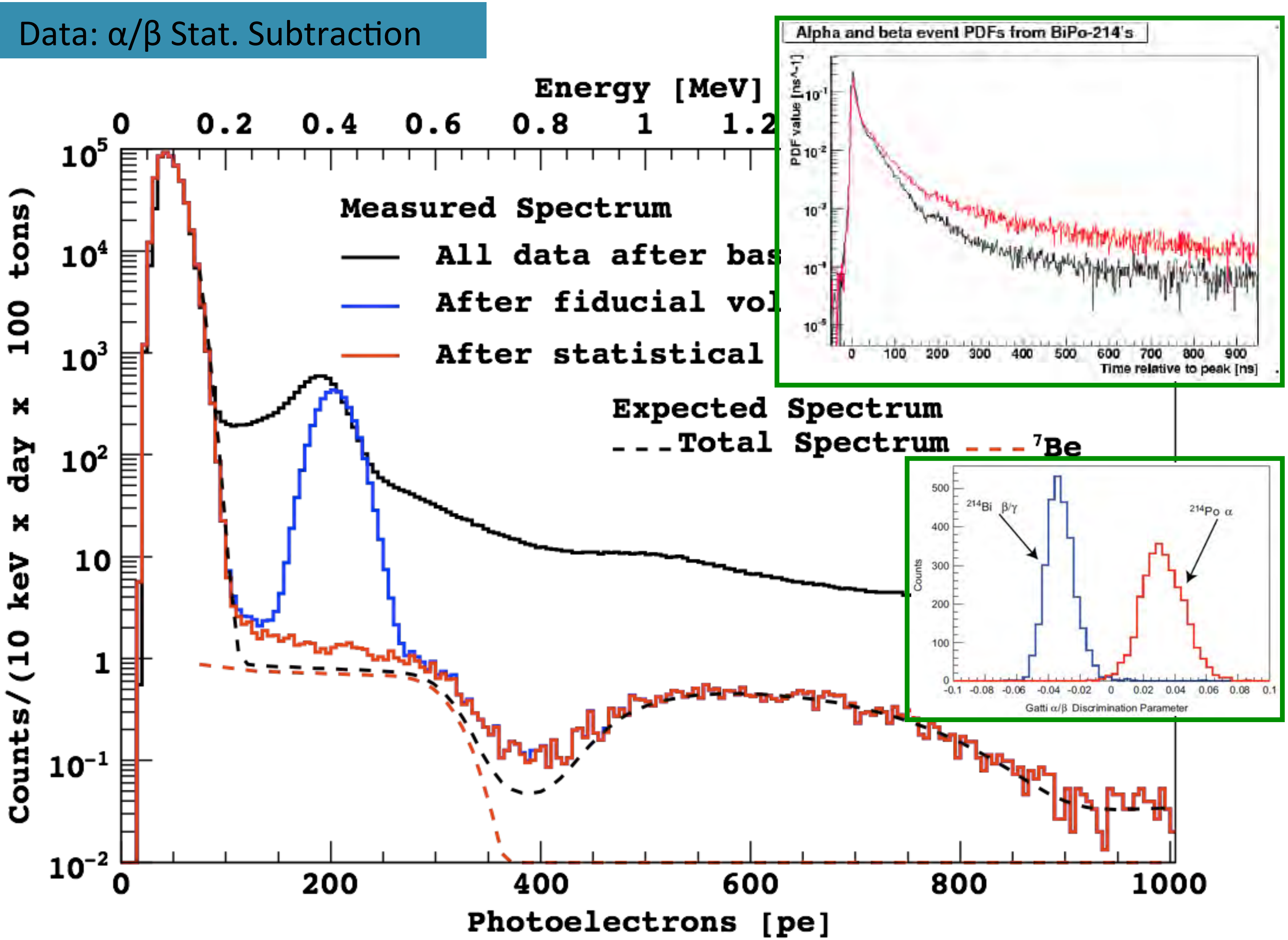
Data: Raw Spectrum (Before any Cuts)



Data: Fiducial Volume Cut (100 tons)

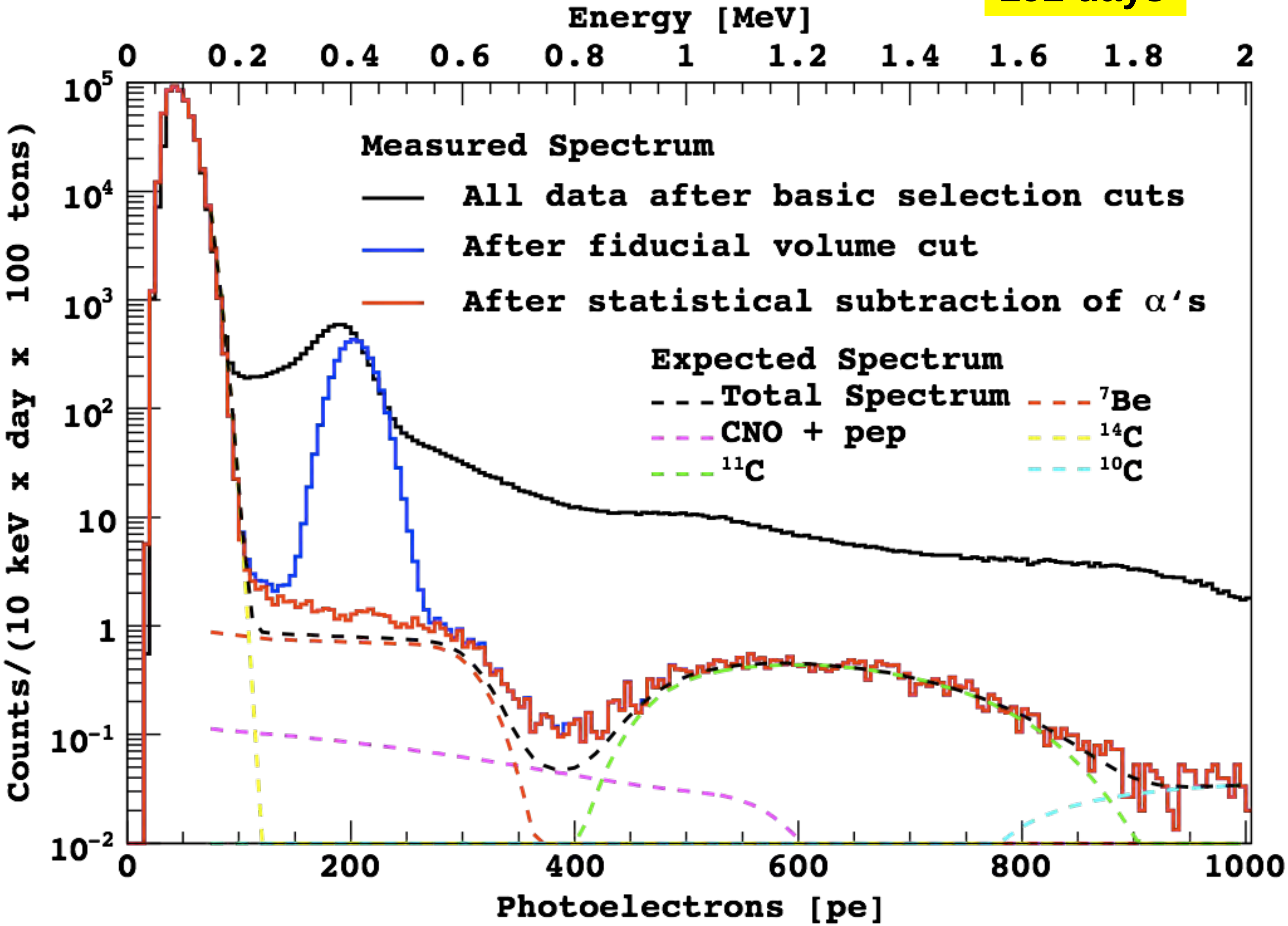


Data: α/β Stat. Subtraction

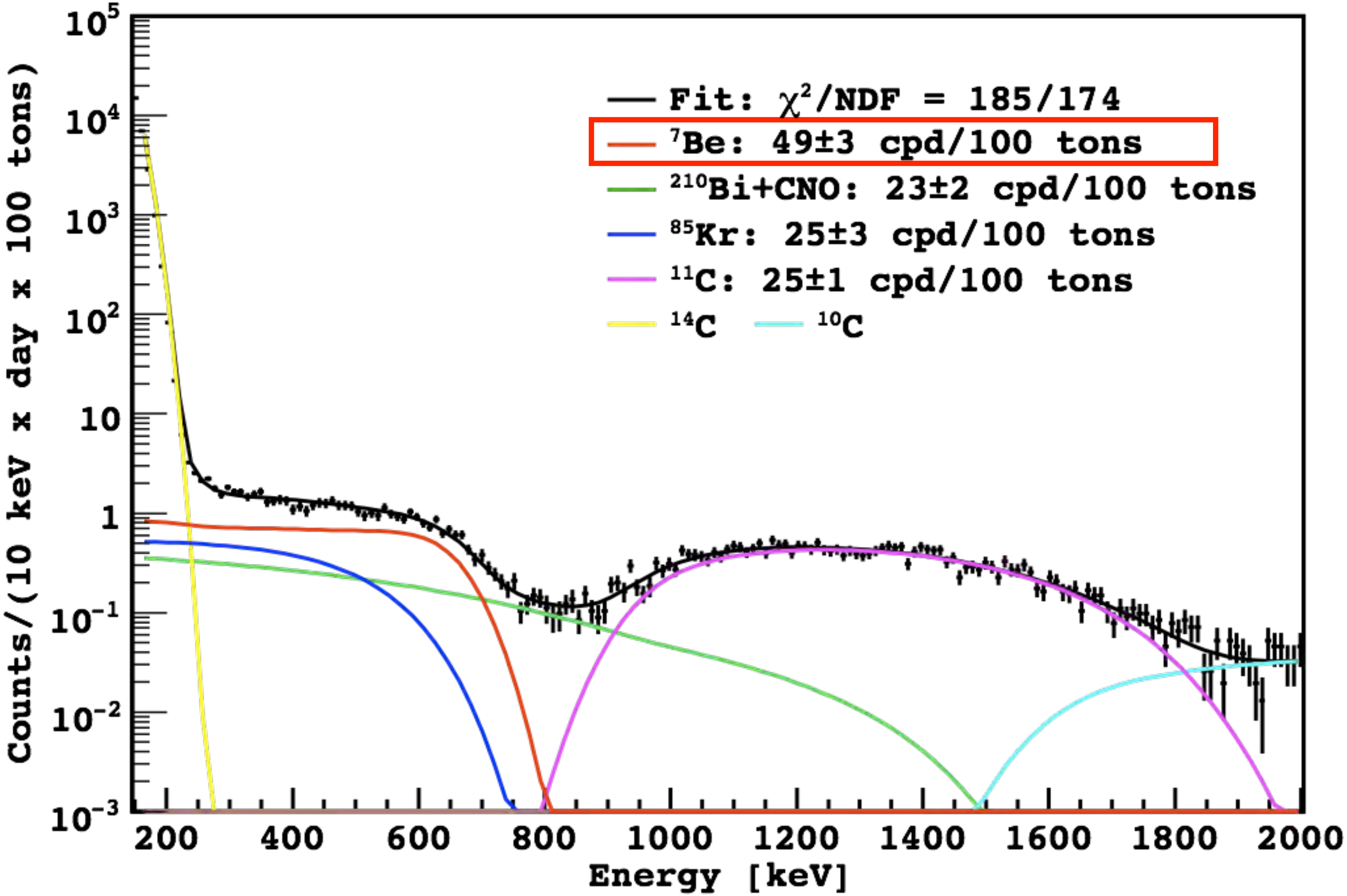


Data: Final Comparison

192 days

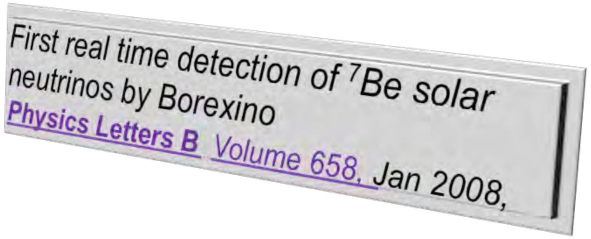


192 Days


Fit: χ²/NDF = 185/174
⁷Be: 49±3 cpd/100 tons
²¹⁰Bi+CNO: 23±2 cpd/100 tons
⁸⁵Kr: 25±3 cpd/100 tons
¹¹C: 25±1 cpd/100 tons
¹⁴C
¹⁰C
Counts/(10 keV x day x 100 tons)
10⁵
10⁴
10³
10²
10
1
10⁻¹
10⁻²
10⁻³
200
400
600
800
1000
1200
1400
1600
1800
2000
Energy [keV]

We have to add the systematic error:

$$\boxed{49 \pm 3_{stat} \pm 4_{syst} \quad cpd/100\ tons}$$


First real time detection of ^{7}Be solar neutrinos by Borexino
Physics Letters B Volume 658, Jan 2008,

Estimated 1σ Systematic Uncertainties* [%]

Total Scintillator Mass	0.2
Fiducial Mass Ratio	6.0
Live Time	0.1
Detector Resp. Function	6.0
Cuts Efficiency	0.3
Total	8.5

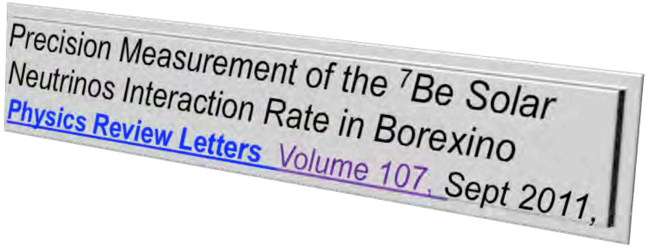
Expected ^{7}Be interaction rate for MSW-LMA oscillations:

$$\boxed{48 \pm 4 \quad cpd/100\ tons}$$ High Metallicity

$$\boxed{44 \pm 4 \quad cpd/100\ tons}$$ Low Metallicity

After 740 live days and a **calibration campaign** Borexino published the new result on **^{7}Be rate with a total error at 4.6%** (SSM prediction at 7%)

$$\boxed{46.0 \pm 1.5(stat) \begin{matrix} +1.5 \\ -1.6 \end{matrix} (syst) \quad cpd/100\ tons}$$


Precision Measurement of the ^{7}Be Solar Neutrinos Interaction Rate in Borexino
Physics Review Letters Volume 107, Sept 2011,

pep neutrinos (indirect constraint on pp neutrino flux)

CNO neutrinos (direct indication of metallicity in the Sun's core)

Cosmogenic ^{11}C

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

$^{11}C \rightarrow {}^{11}B + e^+ + \nu_e$
t~30min

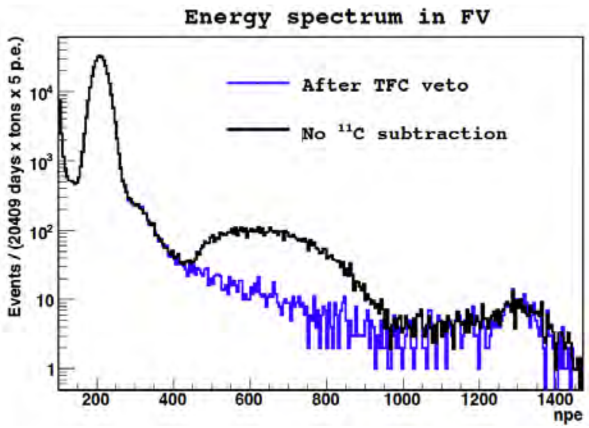
$n + p \rightarrow d + \gamma$
τ~260μs

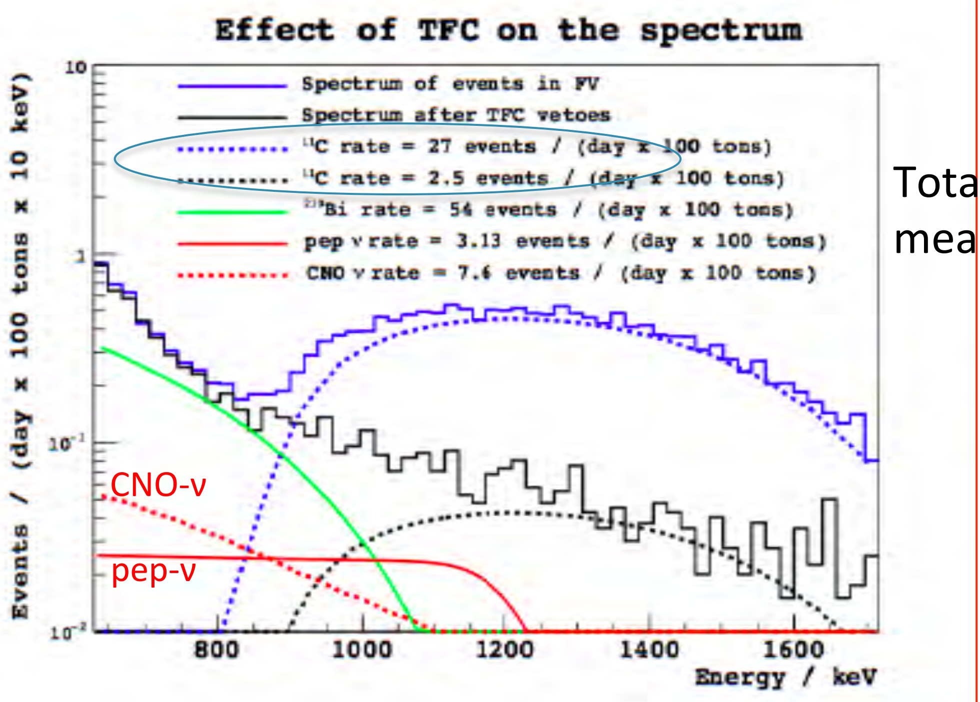
Three-fold coincidence (TFC) technique:

Using

space
time correlation with μ
n

to veto regions of the detector with higher ^{11}C background

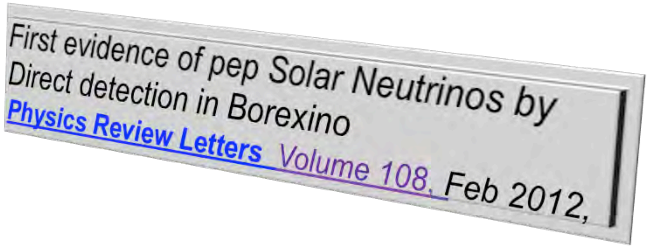




Total fluxes from direct measurement:

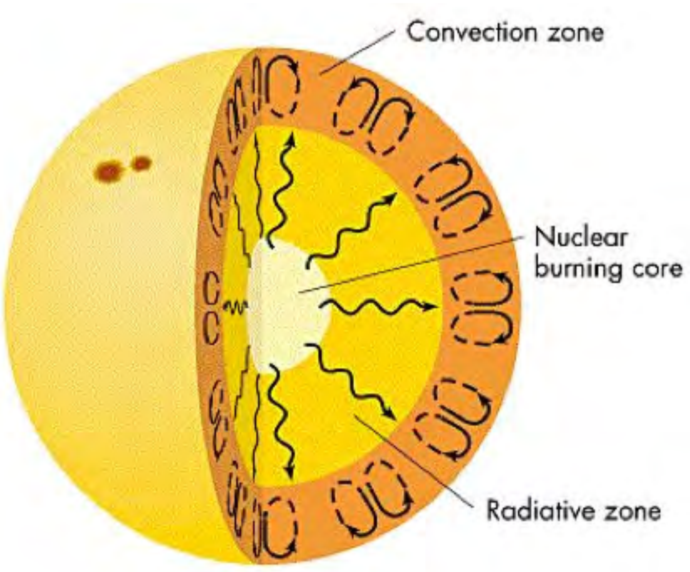
pep flux: $(1.6 \pm 0.3) \cdot 10^8$ cm^{-2}s^{-1}
CNO flux: $< 7.4 \cdot 10^8$ cm^{-2}s^{-1}

SSM pep flux: $(1.44 \pm 0.02) \cdot 10^8$ cm^{-2}s^{-1}


First evidence of pep Solar Neutrinos by Direct detection in Borexino
Physics Review Letters Volume 108, Feb 2012,

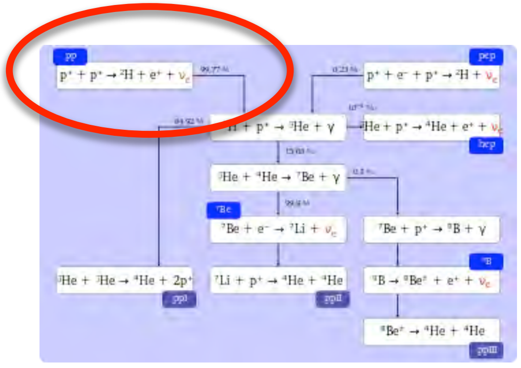
Results of Borexino Phase II

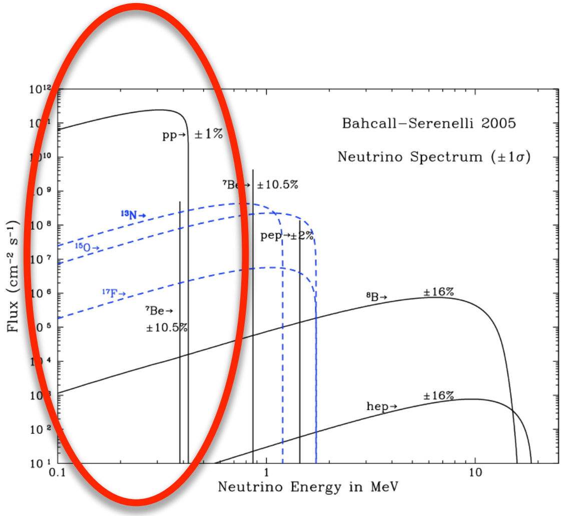
pp- neutrinos



Why studying pp neutrinos?

- they provide a direct glimpse into the main fusion process (produced in the primary nuclear reaction of the pp-cycle);
- they represent about 90% of the solar luminosity in neutrinos.





SOLAR (IN)VARIABILITY

photons take ≈ **10^5 years** to travel from the center of the Sun to the surface while **neutrinos** take only **few seconds**

γ vs. ν

This allow to verify the stability of the Sun on the 10^5 years time scale;

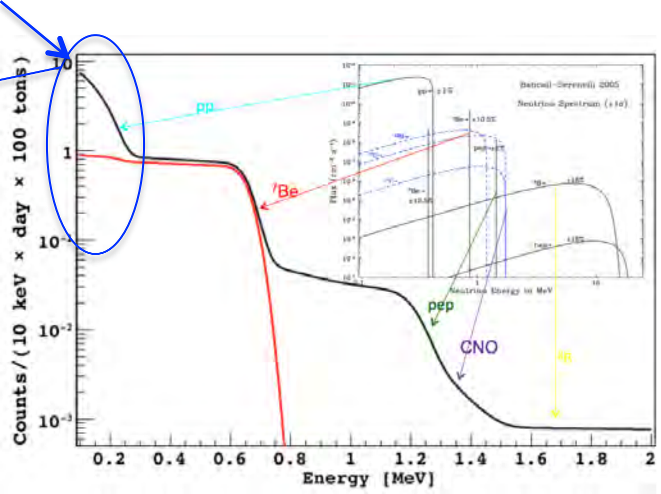
pp-neutrinos (0-0.42) MeV induce electron-recoils up to ≈ 300 keV

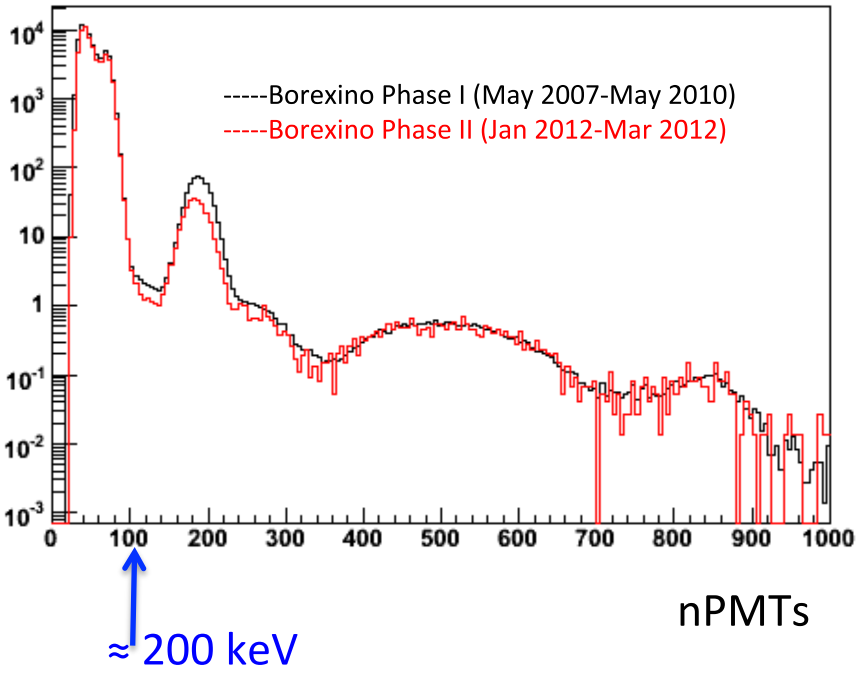
Region dominated by

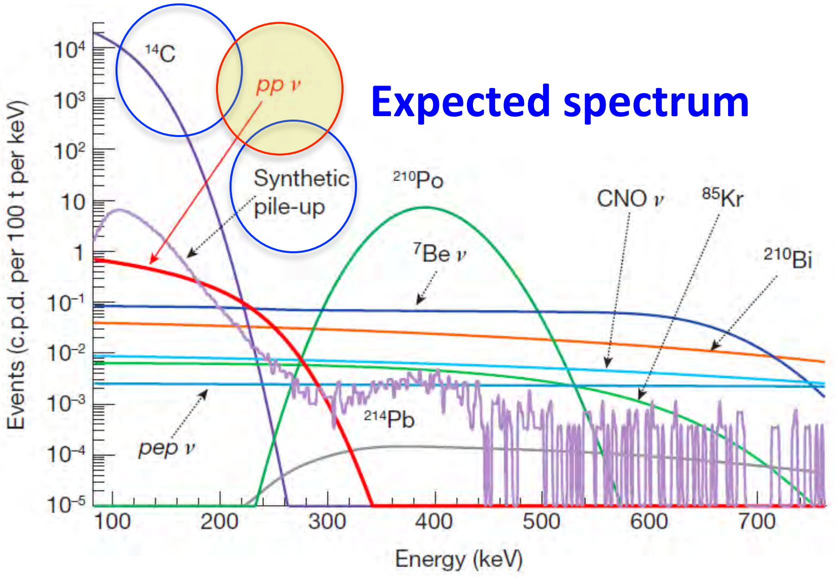
- **^{14}C** - Signal/Background ≈ 10^{-5}

  Below ≈150 keV (≈60 nPMTs) ^{14}C is overwhelming

- **Pile-up** of **^{14}C**

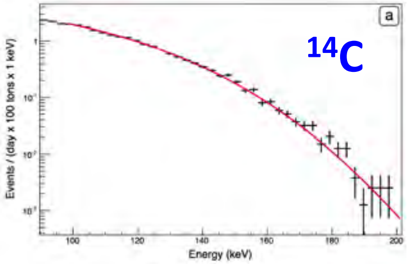




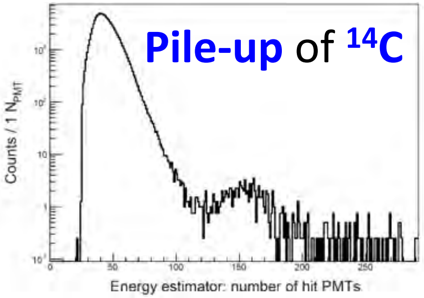

Expected spectrum

In order to disentangle the signal from the background we need a spectral fit

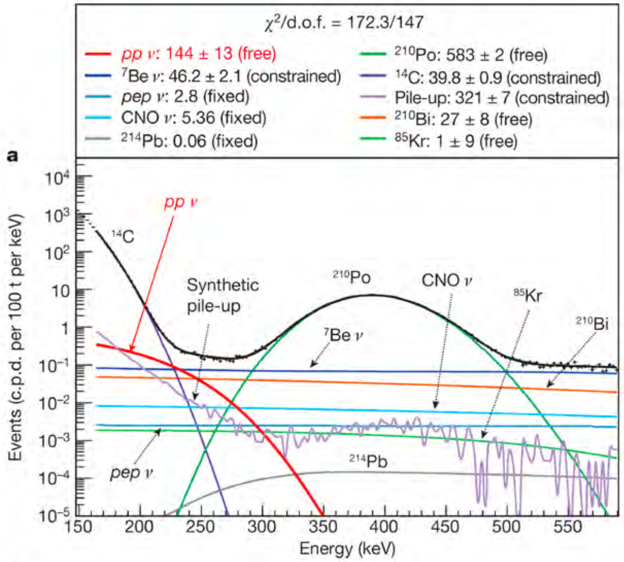
We have to determine independently the rate of the two main backgrounds (^{14}C and pile-up of ^{14}C) in order to constrain them in the fit procedure.



- **^{14}C** rate determined from an independent class of events less affected by the trigger threshold; ^{14}C rate = (40 ±1) Bq/100tons

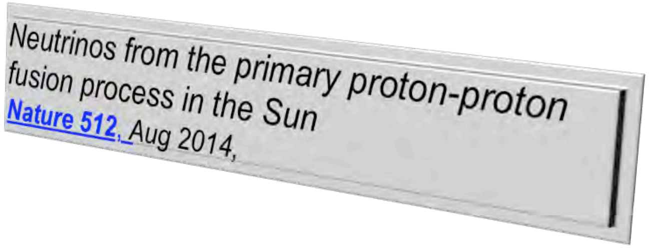


- **Pile-up** of **^{14}C** rate and shape determined by a data-driven method (synthetic pile-up); $Pile-up \text{ rate } (^{14}\text{C-}^{14}\text{C}) = (154 \pm 10)\ cpd/100\text{tons}$



$$\boxed{pp-\nu\ rate = 144 \pm 13(stat) \pm 10(sys) \quad cpd/100tons}$$

$$\boxed{predicted\ rate\ SSM(HM) + MSW(LMA) = 132 \pm 2 \quad cpd/100tons}$$



Neutrinos from the primary proton-proton fusion process in the Sun
Nature 512, Aug 2014,

what next?

A **new calibration campaign** will take place this year for a complete analysis of Phase II in order to further reduce systematic uncertainties

- **Improve measurements** (reduced errors) obtained so far;
- Attempt to measure neutrino from **CNO**-cycle;
- Plus others **non-solar neutrinos** measurements (Geo-neutrinos. Artificial ν-sources).

Thank you

for your attention