First evidence of CNO neutrinos with Borexino

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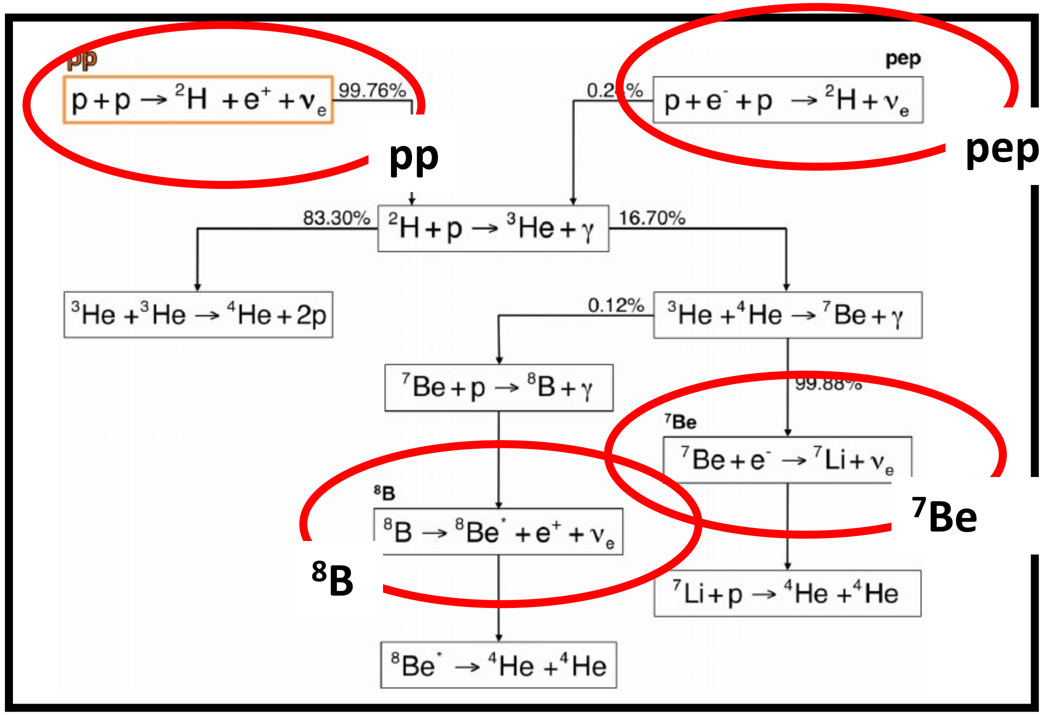
Studying Solar Neutrinos

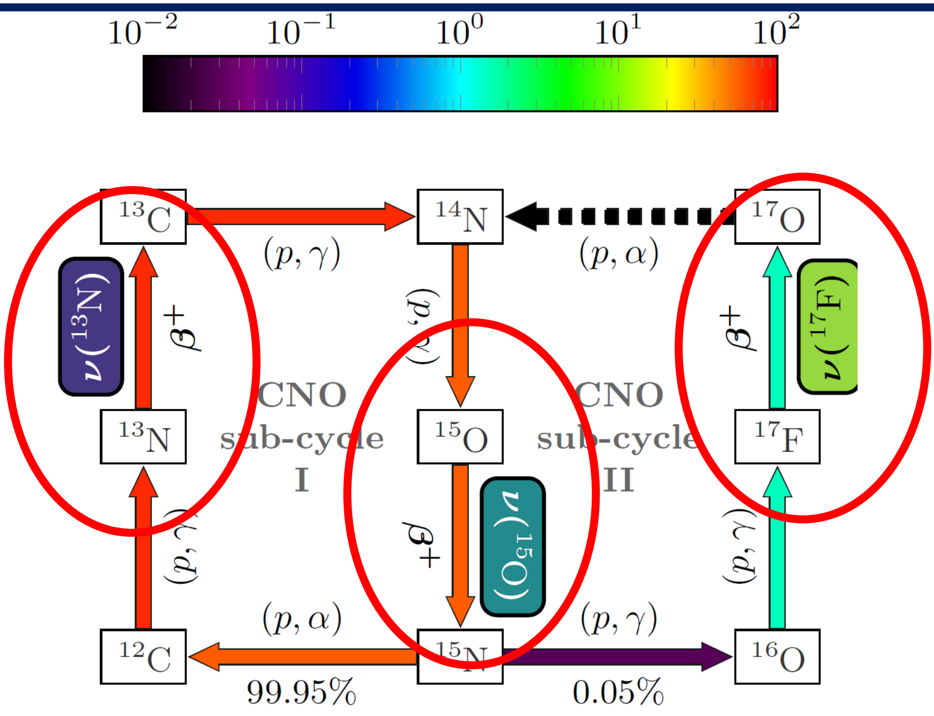
The Sun is powered by nuclear reactions occurring in its core

$4\,p \rightarrow \alpha + 2\,e^{+} + 2\nu$ (E released ~ 26 MeV)

pp CHAIN:
~99% of the Sun energy



CNO CYCLE:
<1% of the sun energy



Barbara Caccianiga (BX collaboration) ``First evidence of CNO neutrinos with Borexino''

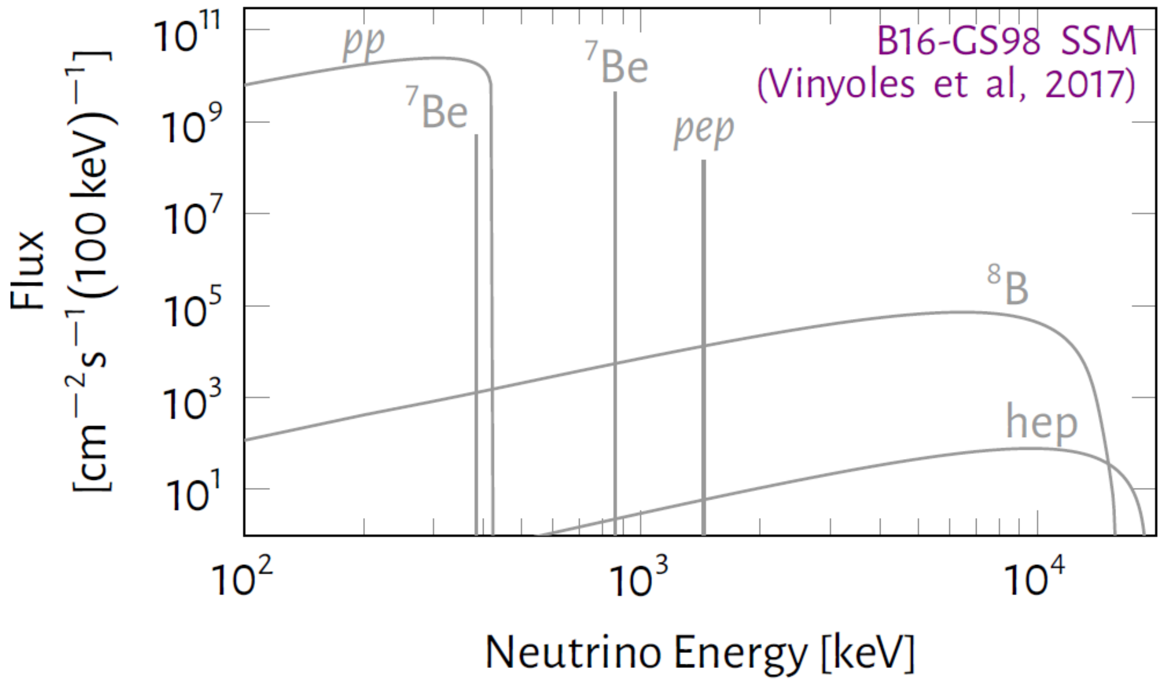
Studying Solar Neutrinos

- Neutrinos propagates from the core to the surface of the Sun in few seconds and then take only 8 minutes to reach the Earth;

➢ Unlike photons they provide a real time picture of the core of the Sun

Φ(proton-proton chain ν)
~6 x10 ^{10} ν /cm^2/sec

Solar neutrino spectrum



Studying Solar Neutrinos

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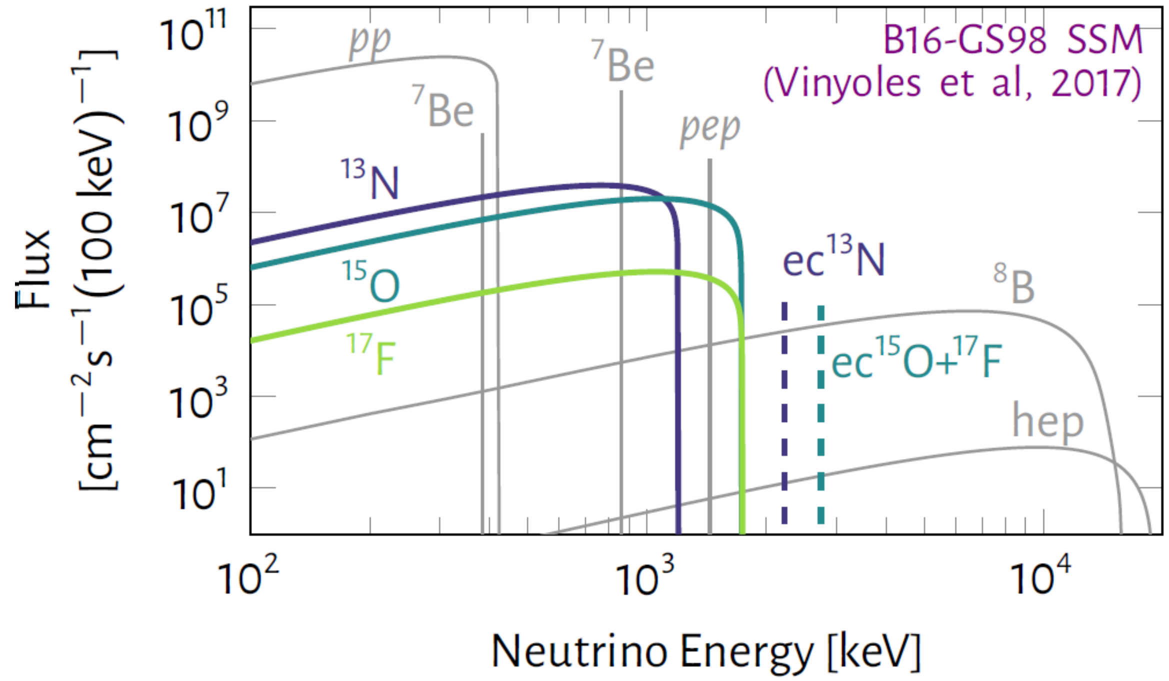
➢ Unlike photons they provide a real time picture of the core of the Sun

Φ(proton-proton chain ν)
~6 x10 ^{10} ν /cm^2/sec

Φ(CNO ν) (blue dotted line)
~5 x10 ^{8} ν /cm^2/sec

Solar neutrino spectrum



Studying Solar Neutrinos

The glorious past

Astrophysics

Original motivation of the first experiments on solar ν was to test Standard Solar Model (SSM);

Solar neutrino problem

Particle physics

Breakthrough! The solar neutrino problem provided one of the first hints towards the discovery of neutrino oscillations;

Study of the details of ν flux

Studying Solar Neutrinos

The challenging present

Astrophysics

Still open issues on our Sun;

- **Metallicity problem**
- **CNO neutrinos**

Particle physics

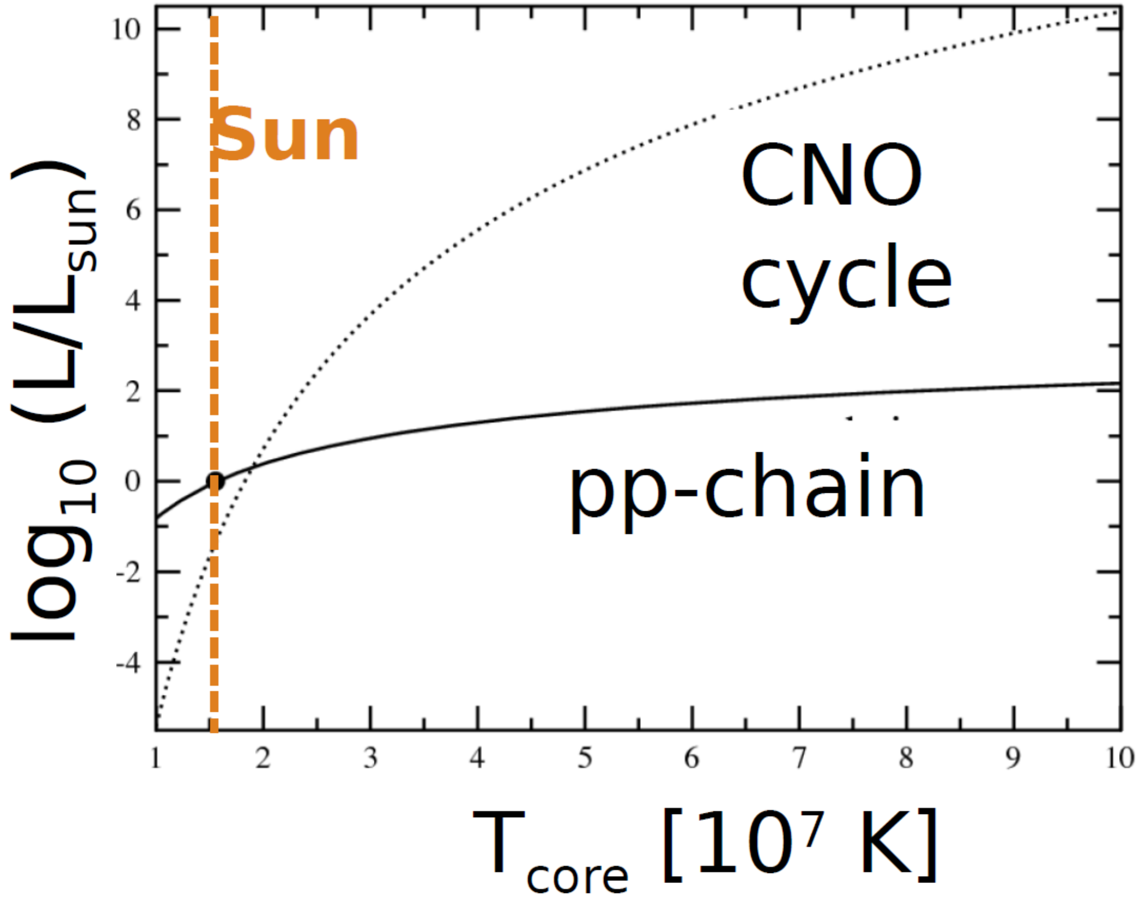
open issues on neutrino oscillations;

- **Non Standard Interactions of neutrinos**

Both astrophysics and particle physics can greatly profit from a detailed knowledge of the solar neutrino spectrum

Studying Solar Neutrinos

The importance of the CNO cycle



- In the Sun is subdominant; BUT
- It is dominant in more massive Stars

- A crucial process for energy production in the Stars;
- Never observed directly;

The experimental proof of the existence of the CNO cycle is important in itself

Studying Solar Neutrinos

The importance of the CNO cycle: the solar metallicity puzzle

- Metallicity of the Sun: content of elements with Z>2;
- Metallicity is a crucial input parameter of the Standard Solar Model;
- Metallicity is obtained from spectroscopic measurement of the photosphere;
- The most recent re-evaluation of metallicity leads to values lower than previously obtained;
- The Standard Solar Model which uses in input the low metallicity (LZ-SSM) gives output at odds with the measurement from helioseismology (helioseismology== study of propagation of sound waves on the Sun's surface);
- The Standard Solar Model which uses in input the older metallicity (HZ-SSM) gives output in agreement with the measurements from helioseismology;

Studying Solar Neutrinos

The importance of the CNO cycle: the solar metallicity puzzle

The predictions for CNO neutrinos depends on the input metallicity:

- Directly: CNO reactions depends directly on the content of C and N in the core of the Sun;
- Indirectly: CNO reactions (as pp-chain reactions) depends on temperature → which in turn depends on opacity → which in turn depends on metallicity

FLUX	High Metallicity (HZ)	Low Metallicity (LZ)	DIFF. (HZ-LZ)/HZ
pp (10^{10} cm^{-2} s^{-1})	5.98(1±0.006)	6.03(1±0.005)	-0.8%
pep (10^{8} cm^{-2} s^{-1})	1.44(1±0.01)	1.46(1±0.009)	-1.4%
^{7}Be (10^{9} cm^{-2} s^{-1})	4.94(1±0.06)	4.50(1±0.06)	8.9%
^{8}B (10^{6} cm^{-2} s^{-1})	5.46(1±0.12)	4.50(1±0.12)	17.6%
^{13}N (10^{8} cm^{-2} s^{-1})	2.78(1±0.15)	2.04(1±0.14)	26.6%
^{15}O (10^{8} cm^{-2} s^{-1})	2.05(1±0.17)	1.44(1±0.16)	29.7%
^{17}F(10^{6} cm^{-2} s^{-1})	5.29(1±0.20)	3.261±0.18)	38.3%

→

Measuring the flux of CNO neutrinos could provide a crucial input to solve the puzzle;

Borexino under the Gran Sasso mountain

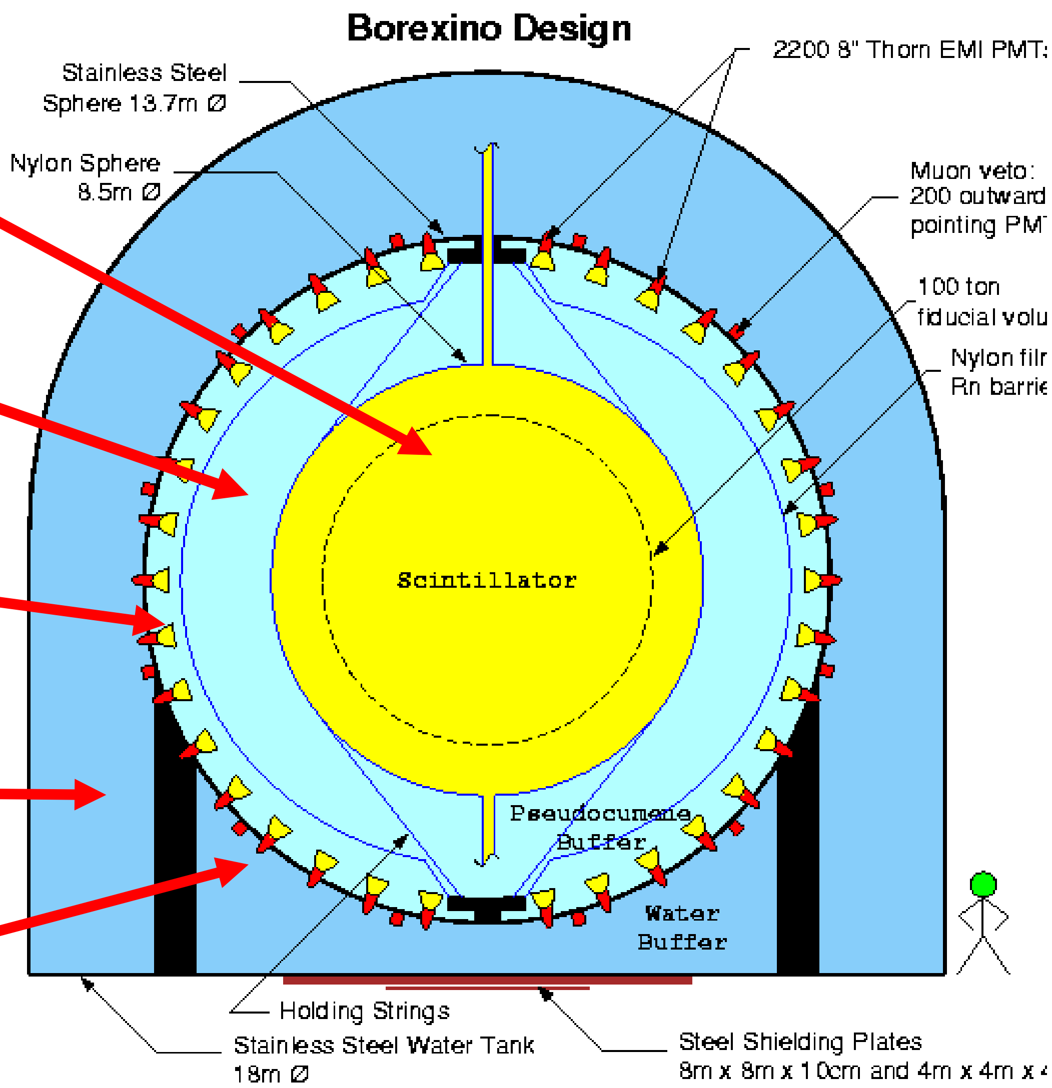
Core of the detector: 300 tons of liquid scintillator (PC+PPO) contained in a nylon vessel of 4.25 m radius;

1st shield: 1000 tons of ultra-pure buffer liquid (pure PC) contained in a stainless steel sphere of 7 m radius;

2214 photomultiplier tubes pointing towards the center to view the light emitted by the scintillator;

2nd shield: 2000 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;



Borexino: the long story..

PHASE 1 (2007-2010)

Solar neutrinos

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

Other

- geo-ν Evidence > 4.5σ
- Limit on rare processes
- Study on cosmogenics

Purifications

6 cycles of water extraction

PHASE 2 (2012-2016)

Solar neutrinos

- pp neutrinos (Nature 2014)
- seasonal modulations (2017)

``First simultaneous precision spectroscopy of pp, 7Be and pep solar ν with Borexino Phase-II"

- New results on ^{8}B neutrinos (see Davide Franco's talk)

Thermal insulation

PHASE 3 (2016-2020)

Solar neutrinos

First detection of CNO neutrinos

Borexino: essential ingredients (1)

For each scintillation event, we record

Number of collected photons (~ 500 p.e./MeV) → **Energy** $\frac{\sigma(E)}{E} \sim \frac{5\%}{\sqrt{E}}$

Time of arrival of collected photons @ each PMT → **Position** $\frac{\sigma(x)}{x} \sim \frac{10\text{cm}}{\sqrt{E}}$

Time of arrival of collected photons @ each PMT → **Pulse-shape discrimination** α, β^-, β^+

Borexino: essential ingredients (1)

For each scintillation event, we record

Number of collected photons (~ 500 p.e./MeV)

Time of arrival of collected photons @ each PMT

!

Actually much more complicated than this:

- Energy reconstruction is affected by non-linearities (for example, quenching effect) ; also it depends on position and on particle type;
- $\sigma(E)$ has non-Poissonian dependencies from E and also depends on position;
- Position reco and resolution are also energy and position dependent;

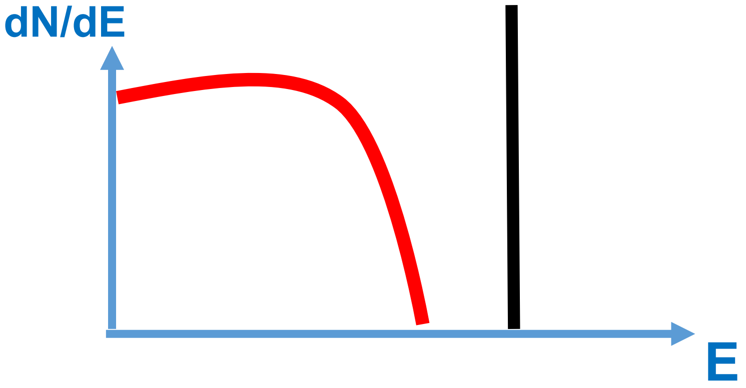
It is crucial to be able of modeling correctly these effects (either analytically or with MonteCarlo simulations)

Borexino: essential ingredients (2)

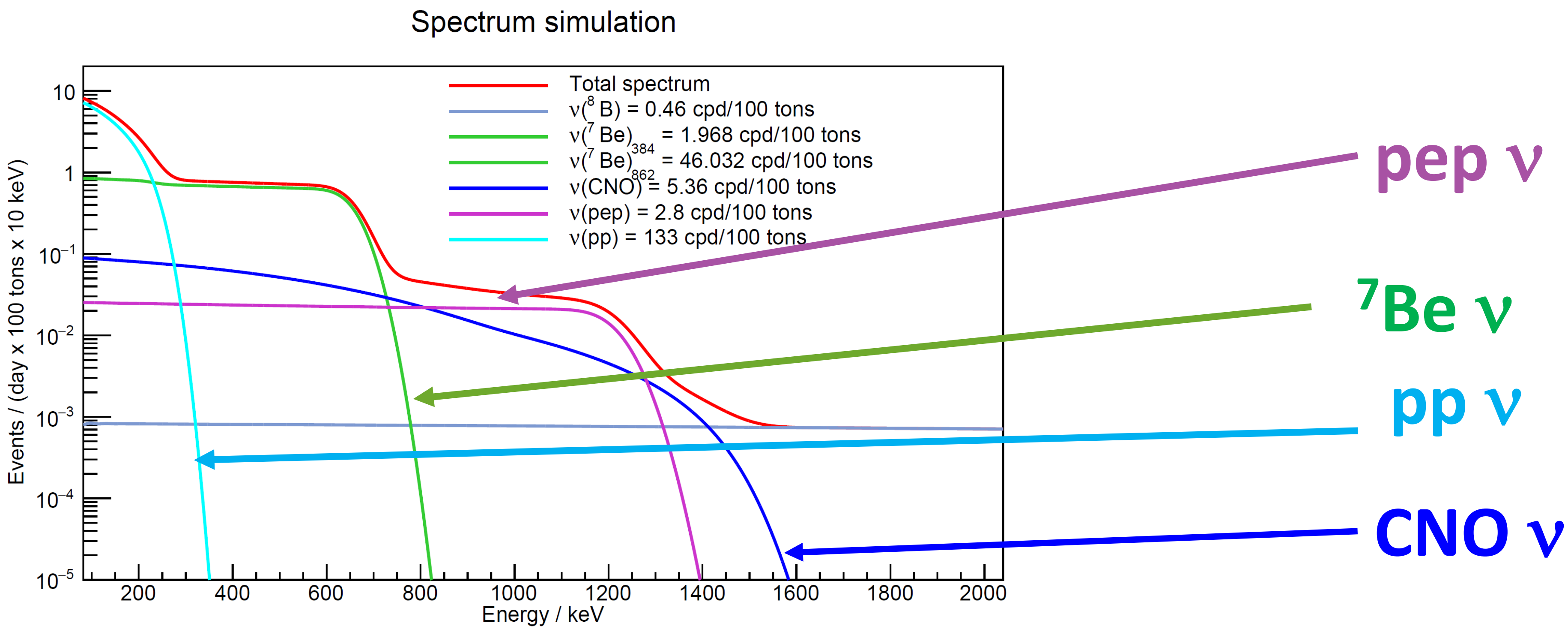
Borexino detects neutrinos through scattering on electrons

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

So, what we see is only the energy carried away by the electron NOT the total neutrino energy



Borexino: essential ingredients (2)



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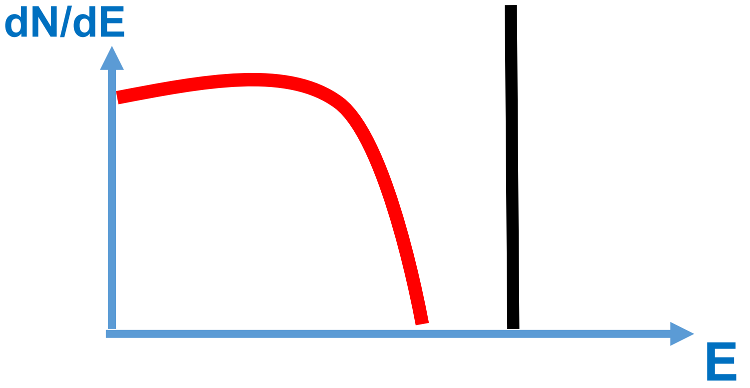


Borexino: essential ingredients (3)

pros

Relatively high light yield
(with respect, for example, to Cerenkov detectors)

Number of photons larger than random instrumental noise →

- Low energy threshold is possible
- Hardware threshold~ 50 keV

Relatively good energy resolution →

- Possibility to distinguish contributions from different signal/background in the energy spectrum;

Borexino: essential ingredients (4)

cons

Scintillator light is not directional

- Signal cannot be separated from background using correlation with the Sun position

- **Extreem radiopurity needed!**

Borexino: the quest for the radiopurity Grail

Requirements

- **The expected rate of solar neutrinos in BX is at most ~ 50 counts/day/100t which corresponds to ~ 5 10^{-9} Bq/Kg;**
- Just for comparison:
  - Natural water is ~ 10 Bq/Kg in ^{238}U, ^{232}Th and ^{40}K
  - Air is ~ 10 Bq/m^3 in ^{39}Ar, ^{85}Kr and ^{222}Rn
  - Typical rock is ~ 100-1000 Bq/m^3 in ^{238}U, ^{232}Th and ^{40}K

BX scintillator must be 9/10 order of magnitude less radioactive than anything on Earth!

Borexino: the quest for the radiopurity Grail

15 years of work

- **Internal background: contamination of the scintillator itself**

  (^{238}U, ^{232}Th, ^{40}K, ^{39}Ar, ^{85}Kr, ^{222}Rn)
  - Solvent purification (pseudocumene): distillation, vacuum stripping with low Argon/Kripton N2 (LAKN);
  - Fluor purification (PPO): water extraction, filtration, distillation,N_2 stripping with LAKN;
  - Leak requirements for all systems and plants < 10^{-8} mbar· liter/sec;
- **External background: γ and neutrons from surrounding materials**
  - Detector design: concentric shells to shield the inner scintillator;
  - Material selection and surface treatement;
  - Clean construction and handling;

Borexino: the quest for the radiopurity Grail

Achievements

Internal background: contamination of the scintillator itself

- Contamination from ^{14}C ~ $2x10^{-18}$ $^{14}C/^{12}C$ **OK!**
- Contamination from ^{238}U chain ~10^{-17} g/g and ^{232}Th chain ~$5x\times10^{-18}$ g/g; **OK!**
  More than one order of magnitude better than specifications!
- Contamination from ^{40}K not observed; **OK!**
- Contamination from ^{7}Be (cosmogenic) not observed; **OK!**
- Contamination from ^{39}Ar <<1 cpd/100t **OK!**
- Some backgrounds out of specifications: ^{210}Po, ^{85}Kr, ^{210}Bi, ^{11}C) ⟵ **See later**

External background: γ and neutrons from surrounding materials

- Contribution in the relevant energy window ~3 counts/day/100t

Borexino: the quest for the radiopurity Grail

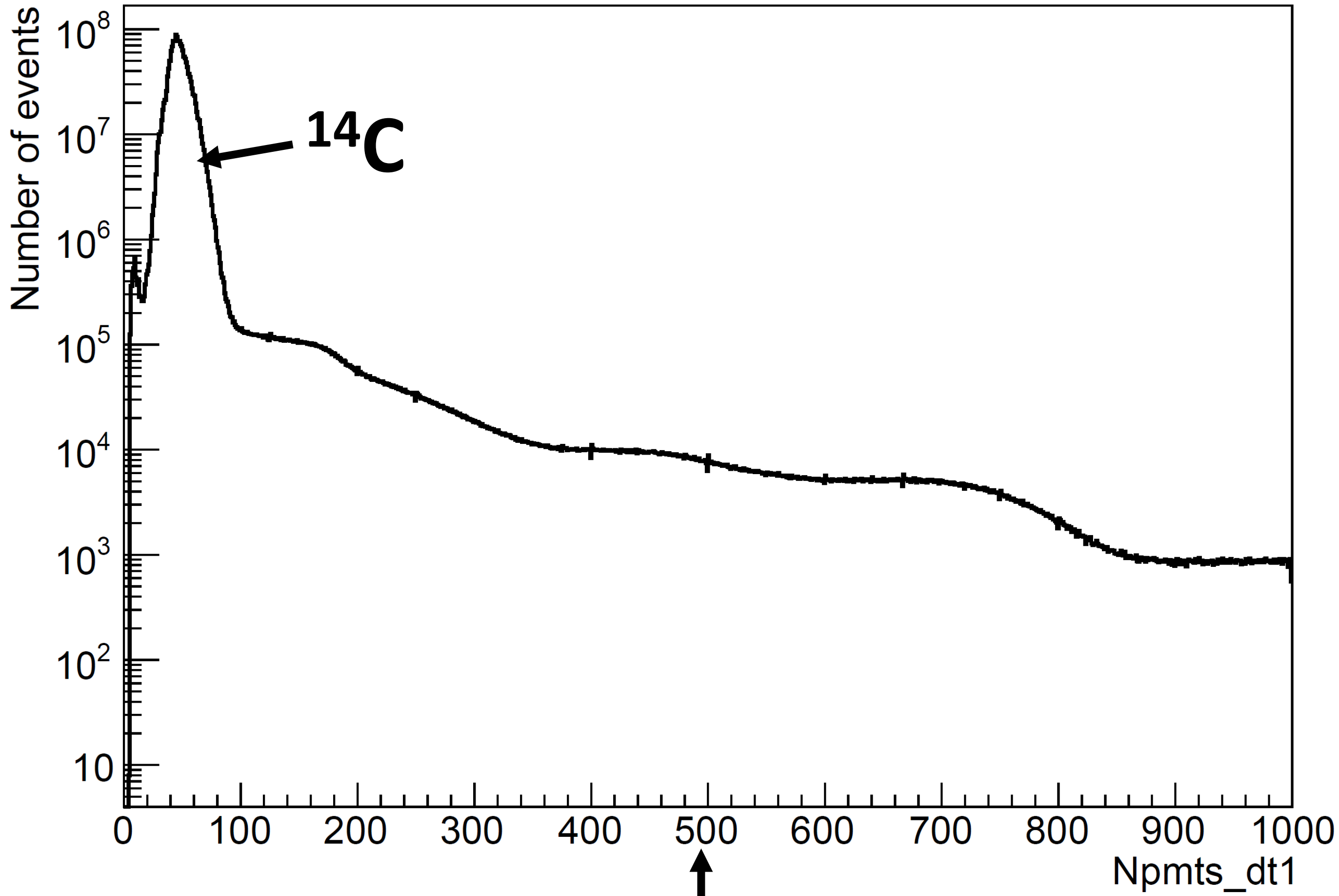
The fight against background is not over...

Even in these high radiopurity conditions, we still have background events contaminating our solar neutrino signal;

We need to apply software cuts to data, in order to remove as much background as possible;

Borexino: data selection

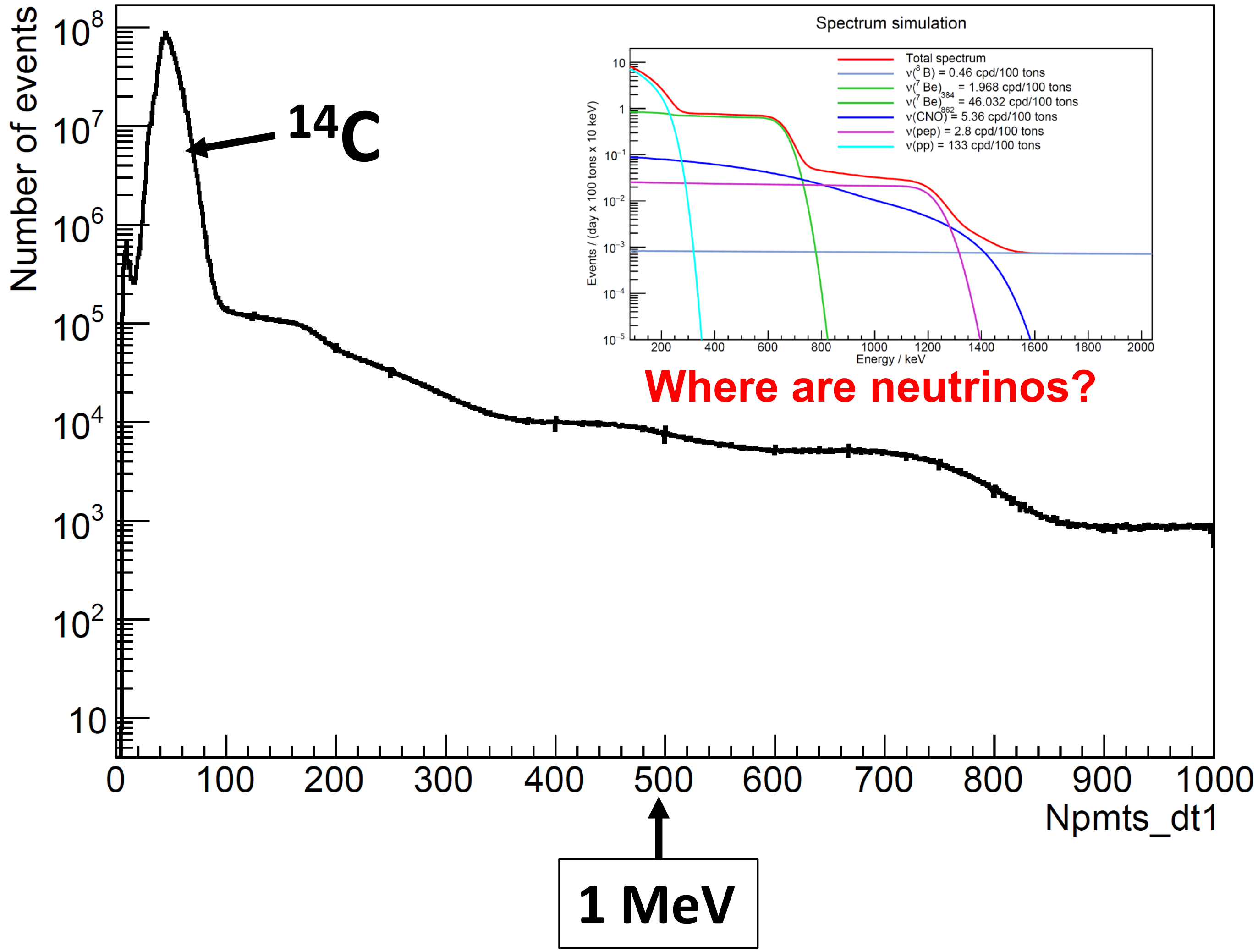
All data no cuts



1 MeV

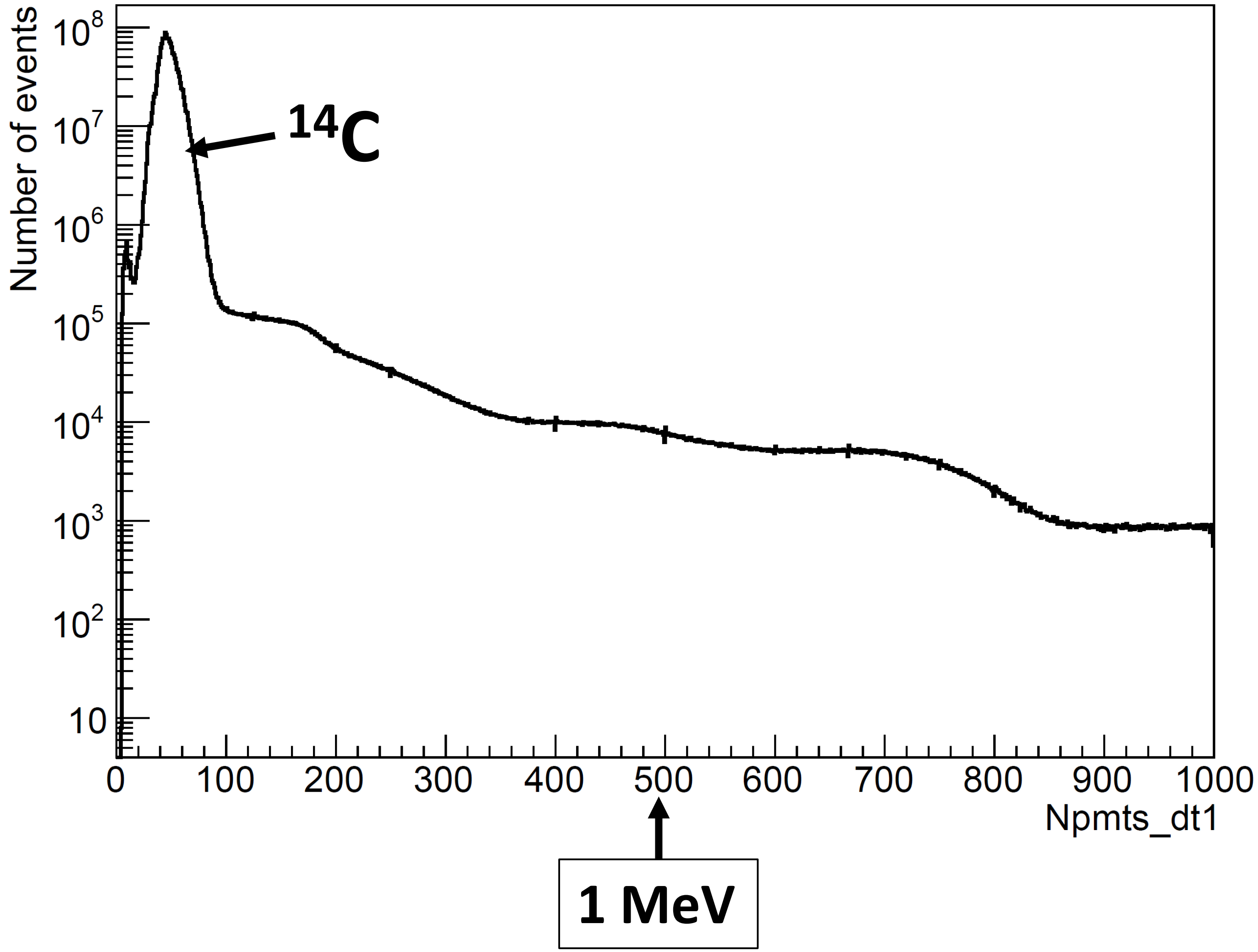
Borexino: data selection

All data no cuts



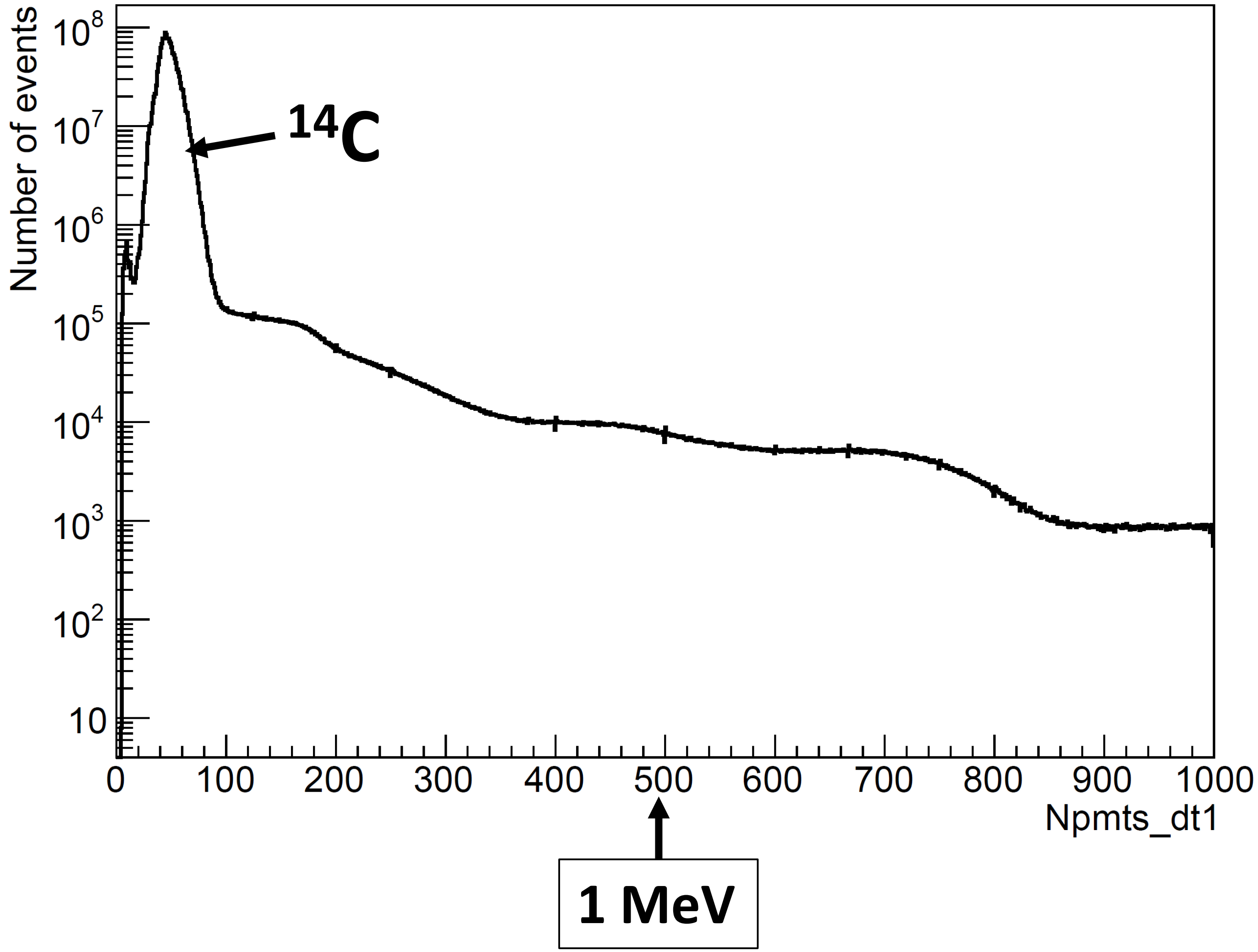
Borexino: data selection

All data
no cuts



Borexino: data selection

CUT 1
μ and μ-daughter

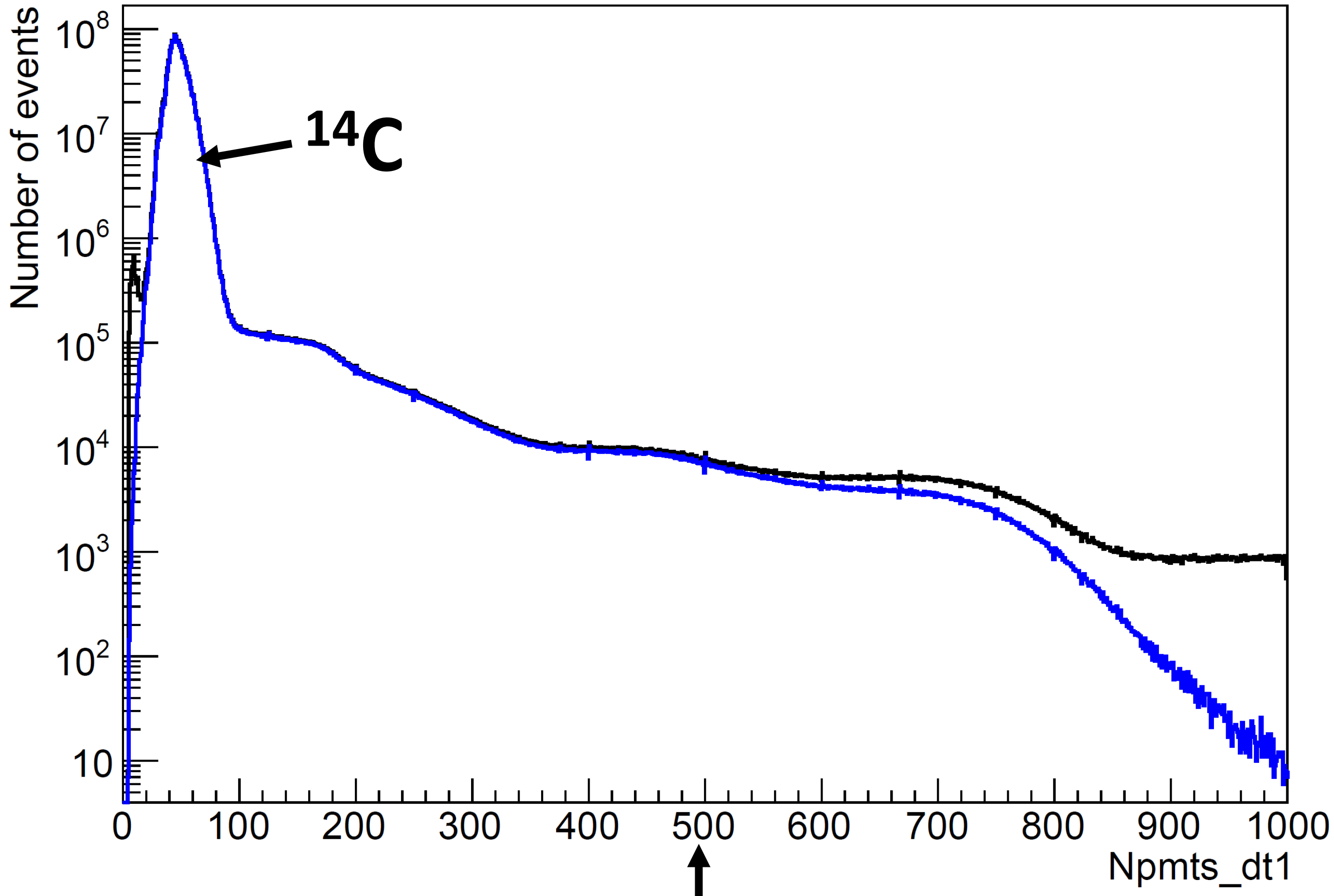


CUT 1

- μ rejected with the external water cerenkov veto and exploiting the fact that muon pulse are not point-like
- μ daughter rejected by vetoing 300 ms after each muon

Borexino: data selection

CUT 1
μ and μ-daughter



1 MeV

CUT 1

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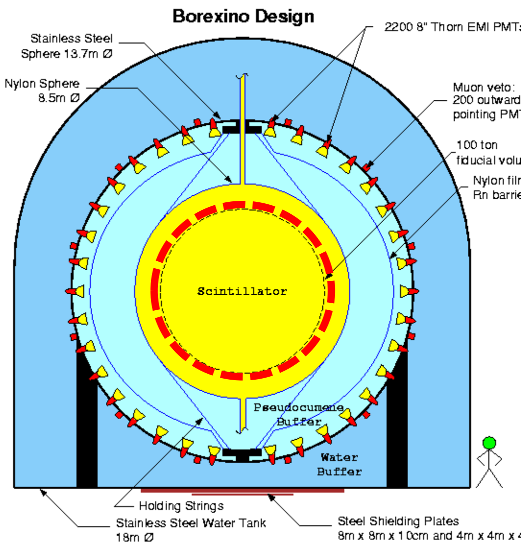
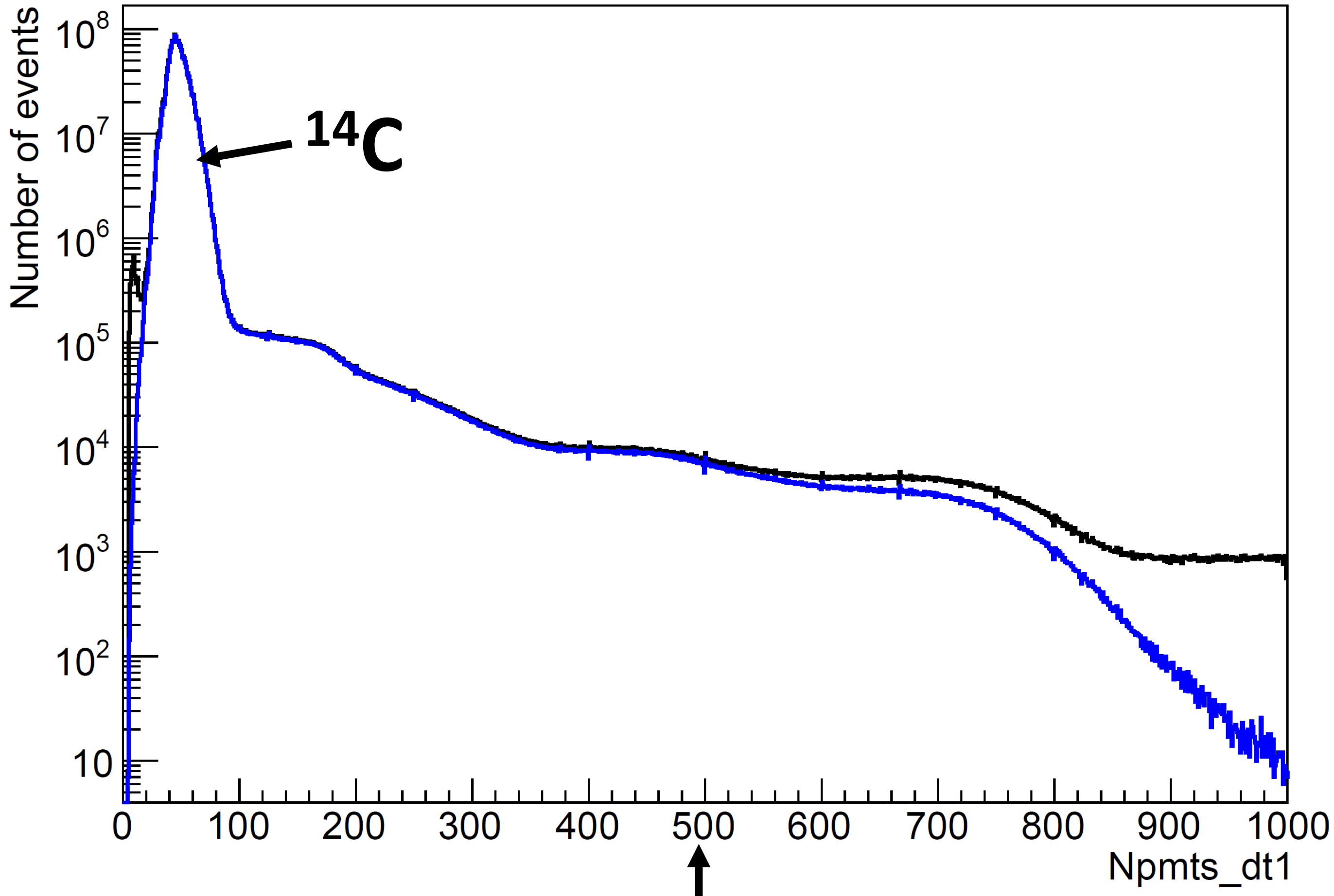
Borexino: data selection

CUT 2
FV cut





1 MeV

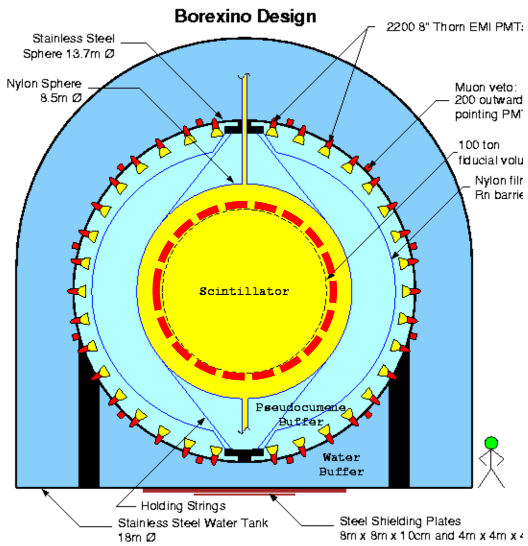
CUT 2
the innermost region of the scintillator is selected to reject external background

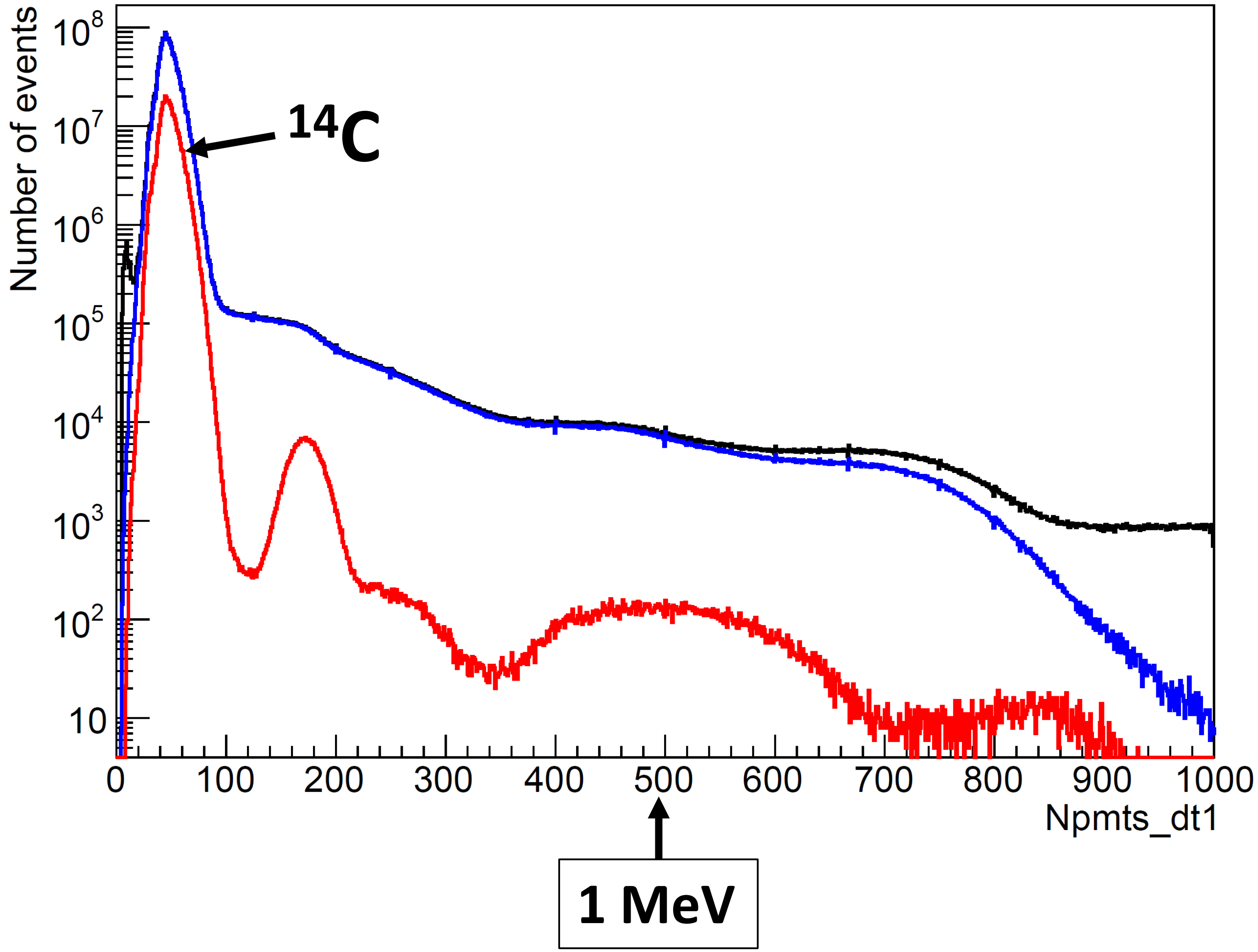
R<2.8 m

-1.8 m<z<2.2 m

Borexino: data selection

CUT 2
FV cut





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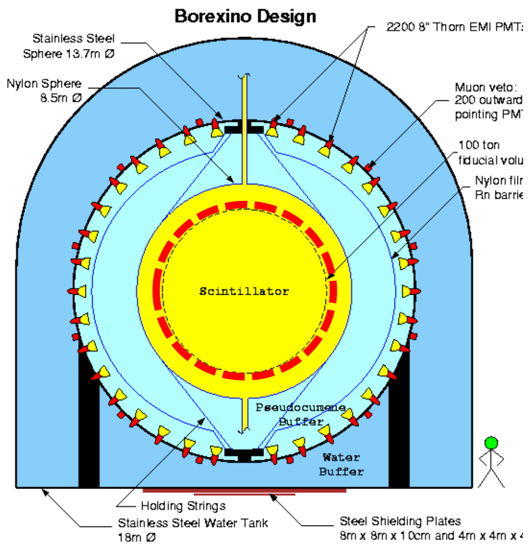

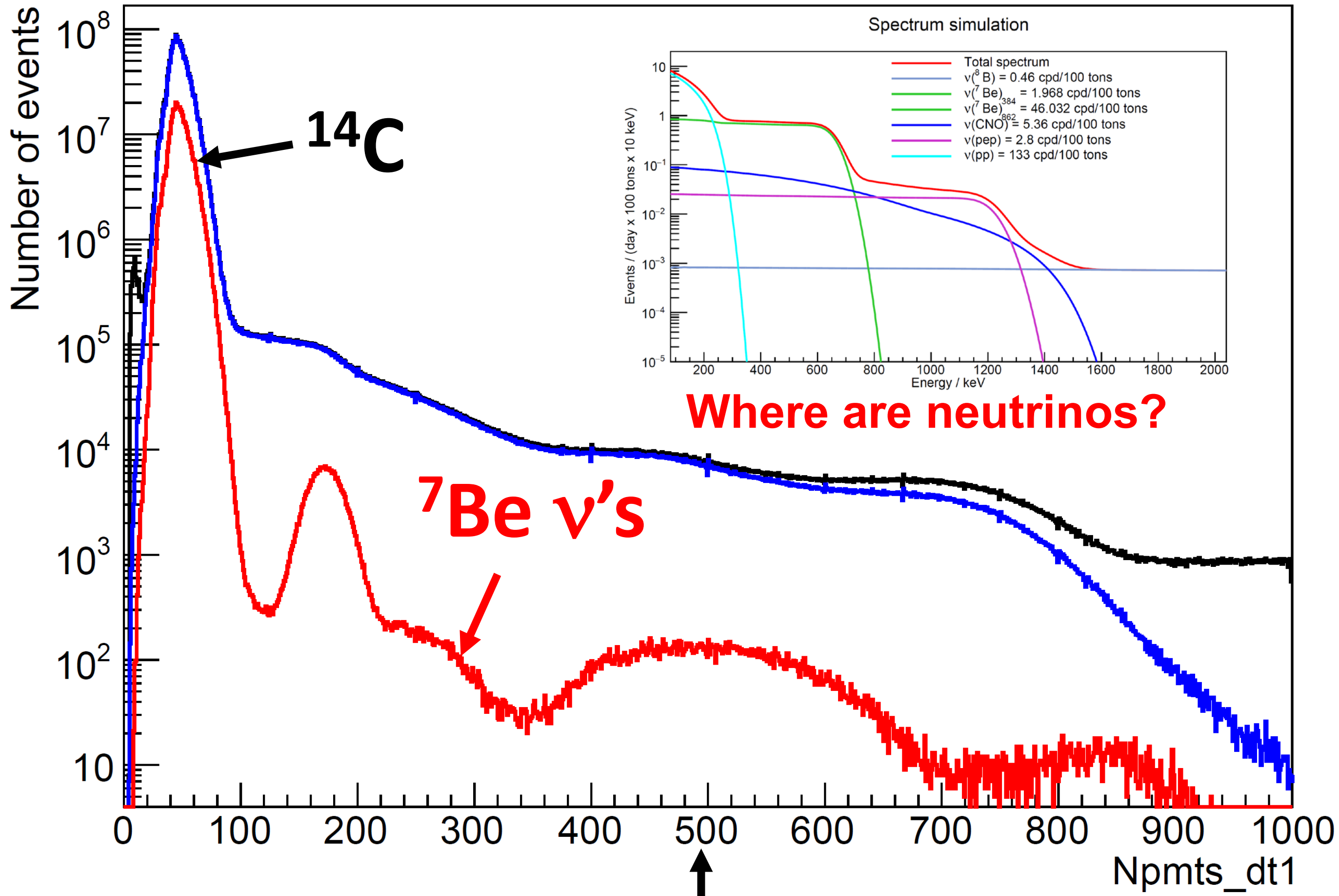

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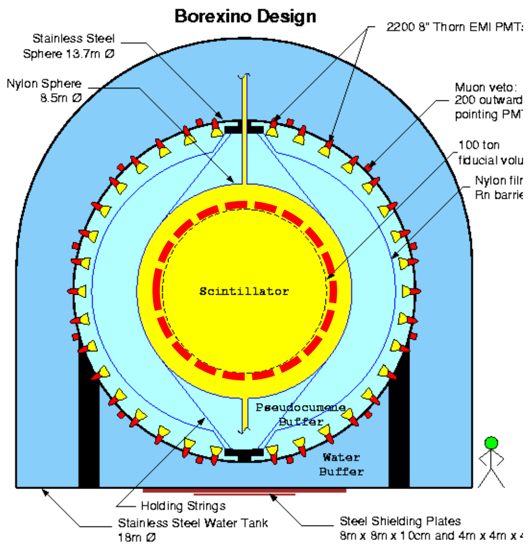

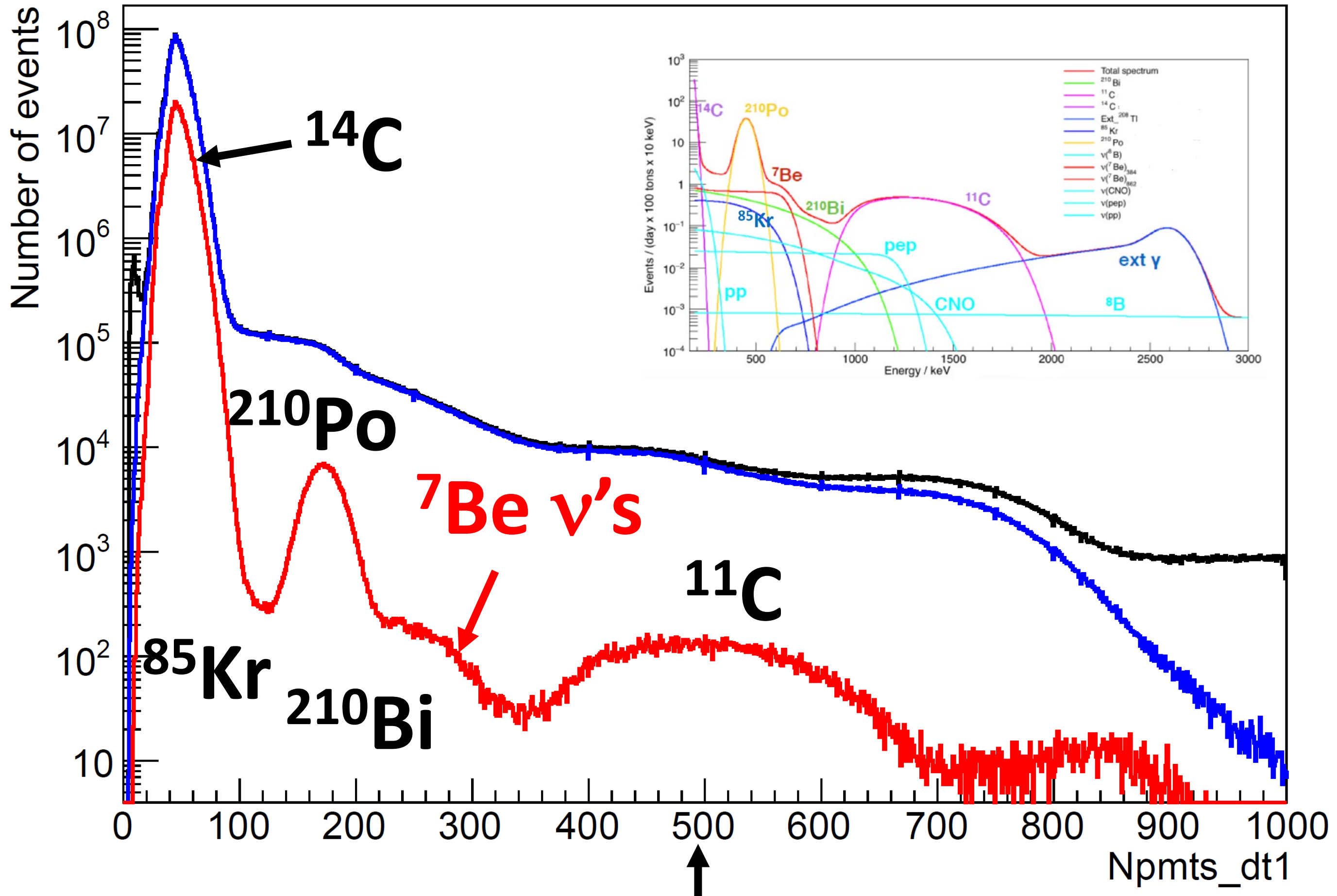

1 MeV

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Borexino: data selection

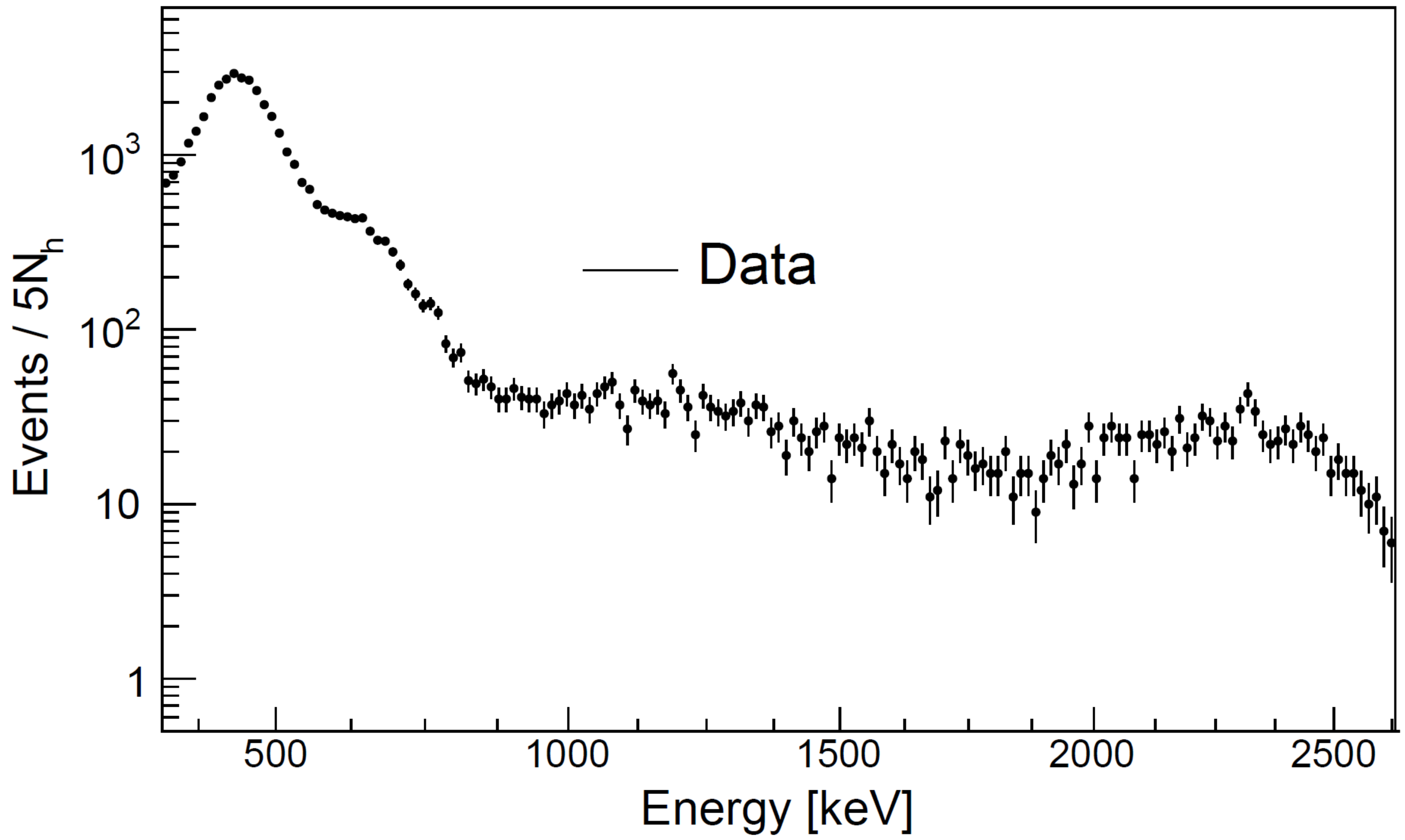
Residual backgrounds

- ^{14}**C**: irreducible background in an organic scintillator. It decays β^- with an end-point of 156 keV. It affects the low energy region (pp neutrinos);
- **pile-up** of events: it especially affects low-energies (pp neutrinos);
- ^{85}**Kr**: reduced in Phase-II by purifications (pp, ^{7}Be neutrinos);
- ^{210}**Bi**: reduced in Phase-II by purifications decays β^- with an end-point of 1160 keV (pp, ^{7}Be, pep and CNO neutrinos);
- ^{210}**Po**: reduced in Phase-II by natural decay ^{238}U chain nor with ^{210}Pb; it decays with its livetime of ~ 200 days) (pp, ^{7}Be, pep and CNO neutrinos);
- ^{11}**C**: produced by μ. It decays in 30 minutes → cannot be eliminated with the μ-daughter cut (pep and CNO neutrinos);

The search for CNO neutrinos

CNO neutrinos: the needle in a haystack

Extracting the CNO neutrino signal from data

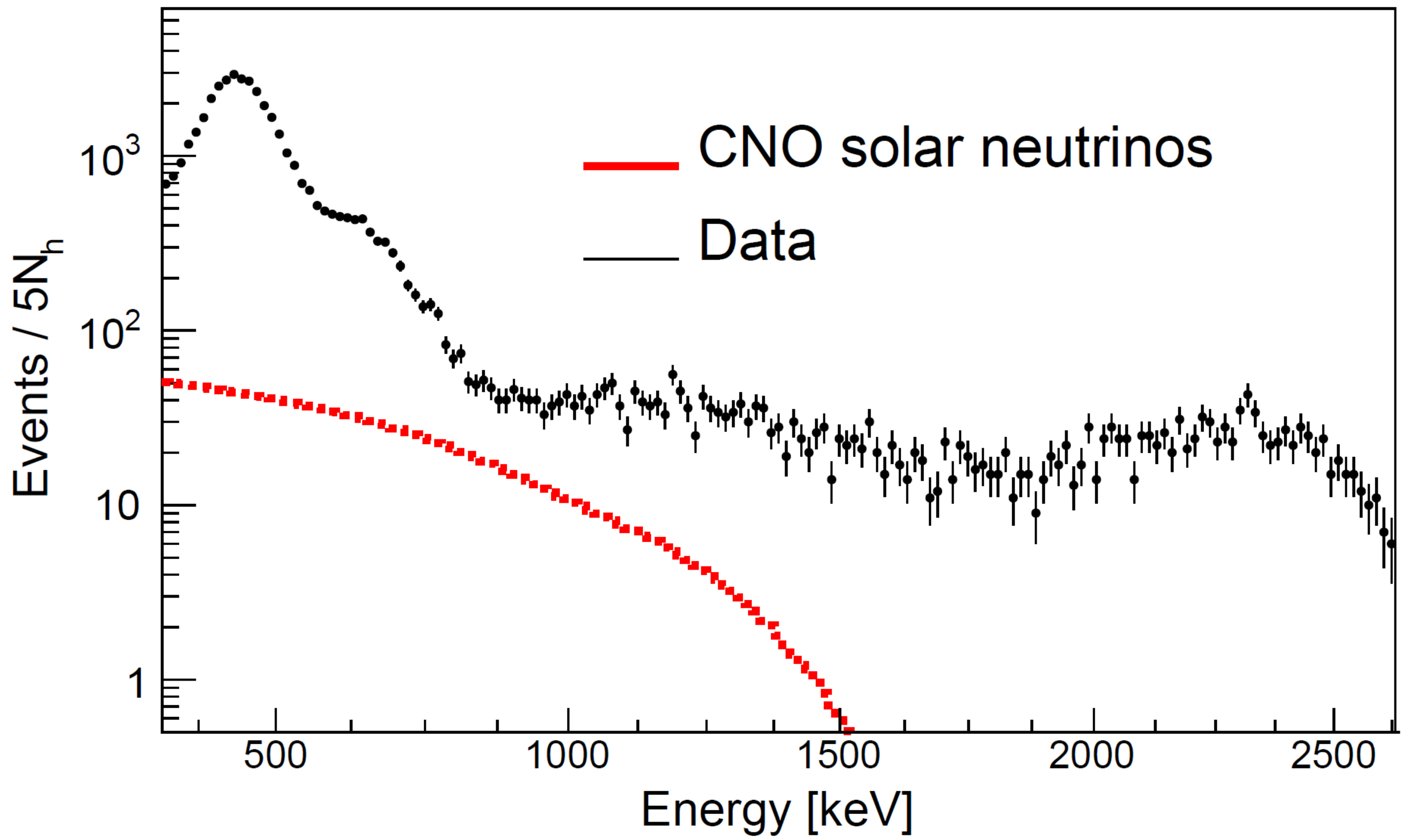


Data set
July 2016 – feb 2020
(after selection cuts)

Where are CNO neutrinos?

CNO neutrinos: the needle in a haystack

Strategy to extract the CNO neutrino signal from data (1)



Data set
July 2016 – feb 2020
(after selection cuts)

Where are CNO neutrinos?

They are submerged by residual backgrounds like a needle in a haystack

CNO neutrinos: the needle in a haystack

Strategy to extract the CNO neutrino signal from data (1)

- We exploit the difference in the energy distribution of signal and backgrounds to separate them;
- How do we know the spectral shapes for each components of signal and backgrounds? By MonteCarlo simulations

MonteCarlo g4bx

- Based on Geant4;
- Full simulation of all processes: energy deposition, light production (scintillator and Cerenkov), propagation and collection;
- All known materal properties included;
- Known time variations of the detector included (for example, number of live PMTs and electronics channels);
- Tuned on calibration data of Phase-I;

CNO neutrinos: the needle in a haystack

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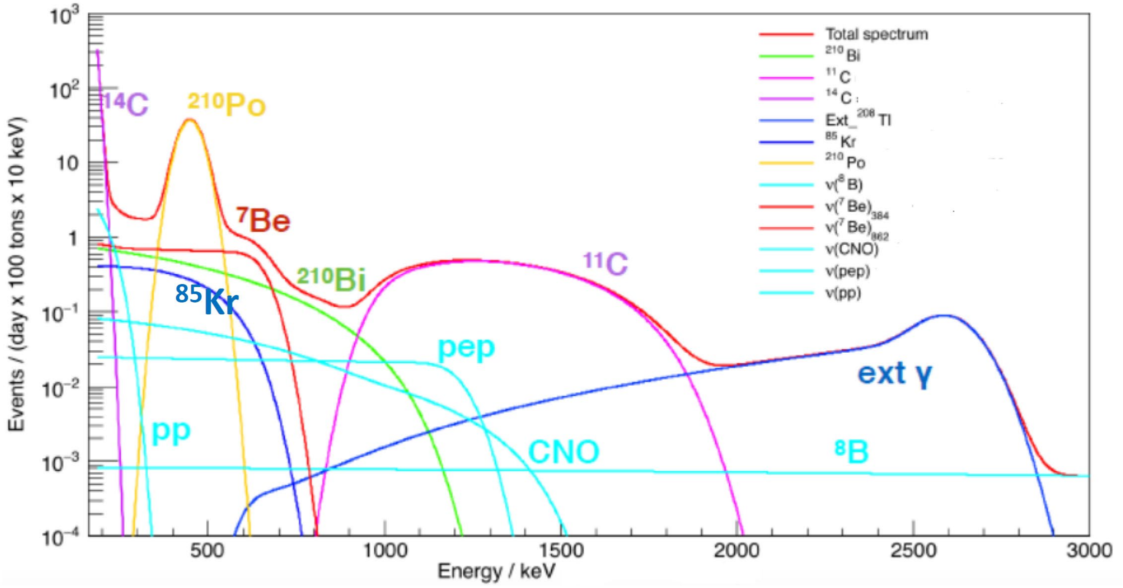


CNO neutrinos: the needle in a haystack

Strategy to extract the CNO neutrino signal from data (1)

- We exploit the difference in the energy distribution of signal and backgrounds to separate them;
- How do we know the spectral shapes for each components of signal and backgrounds? By MonteCarlo simulations

- A fit is performed to the energy dstribution of events assumed to be the sum of signal and backgrounds;
- The spectral shapes are those determined with MC simulations;
- **The rates of each species are the only free parameters of the fit;**

Strategy to extract the CNO neutrino signal from data (2)

In addition to the spectral shapes we exploit the Three Fold Coincidence method to tackle 11C

^{11}C is produced by muons together with neutron(s);

to improve the fit capability to disentangle ^{11}C

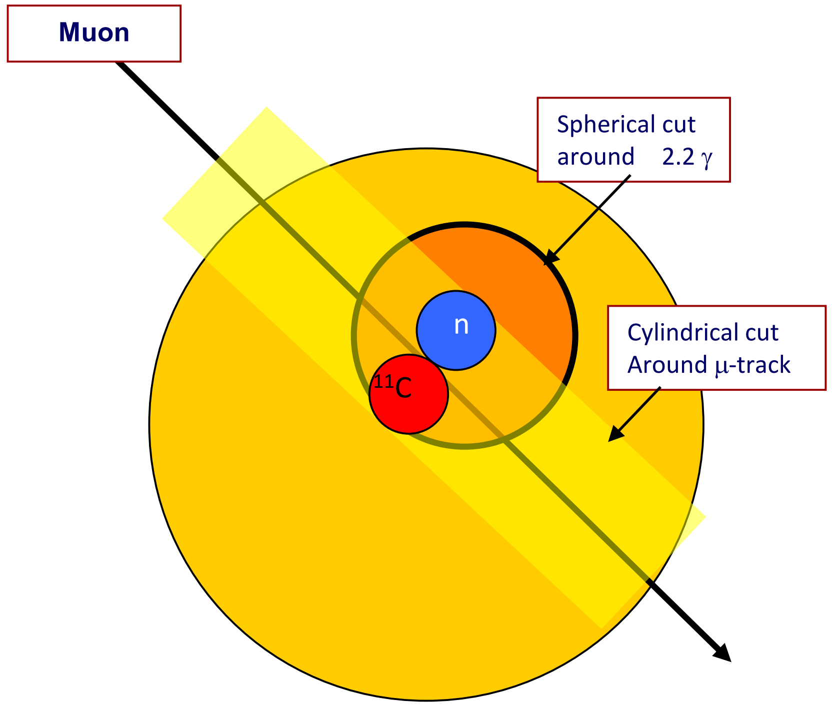
$$\mu + {}^{12}C \rightarrow \mu + {}^{11}C + n$$

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

t~30min

$$n + p \rightarrow d + \gamma$$

$\tau \sim 260 \mu s$



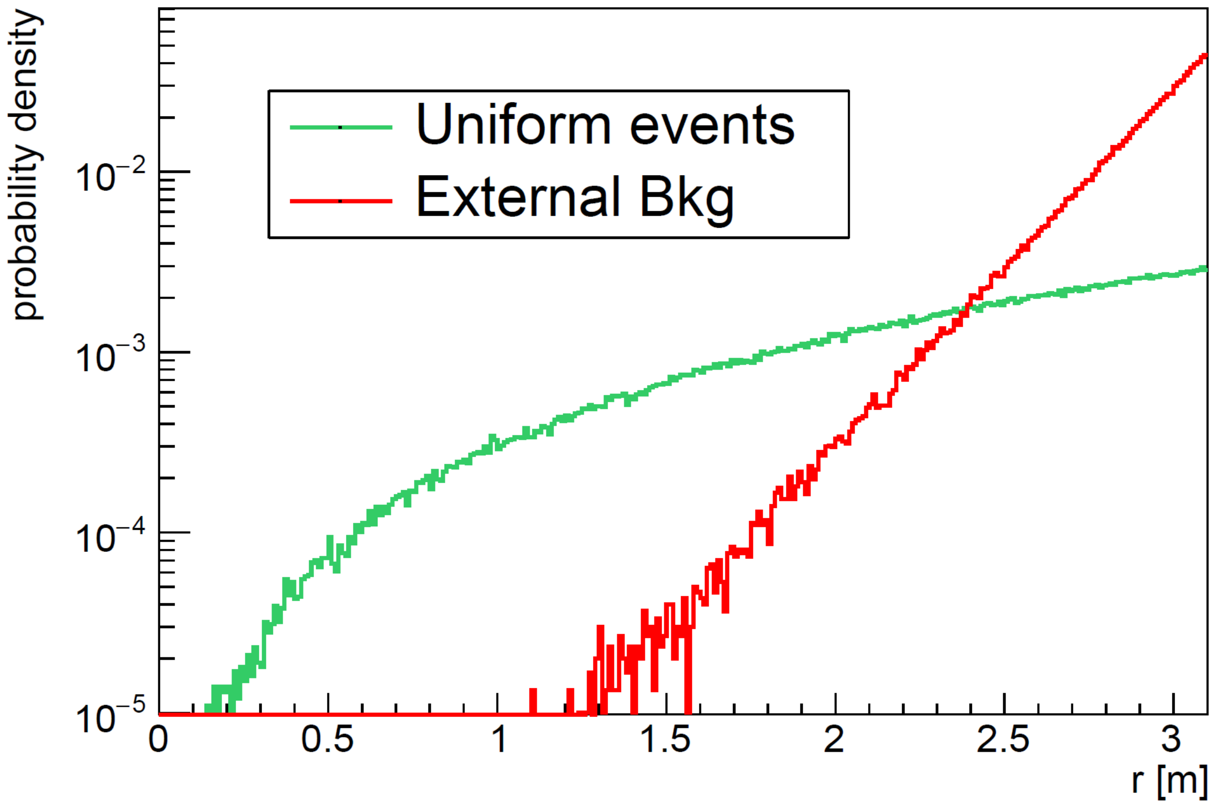
The data-set is divided in two samples: one depleted in ^{11}C (TFC-subtracted) and one enriched in ^{11}C (TFC-tagged) which are simultaneously fit;

CNO neutrinos: the needle in a haystack

Strategy to extract the CNO neutrino signal from data (3)

In addition, the radial distribution of events is included in the fit

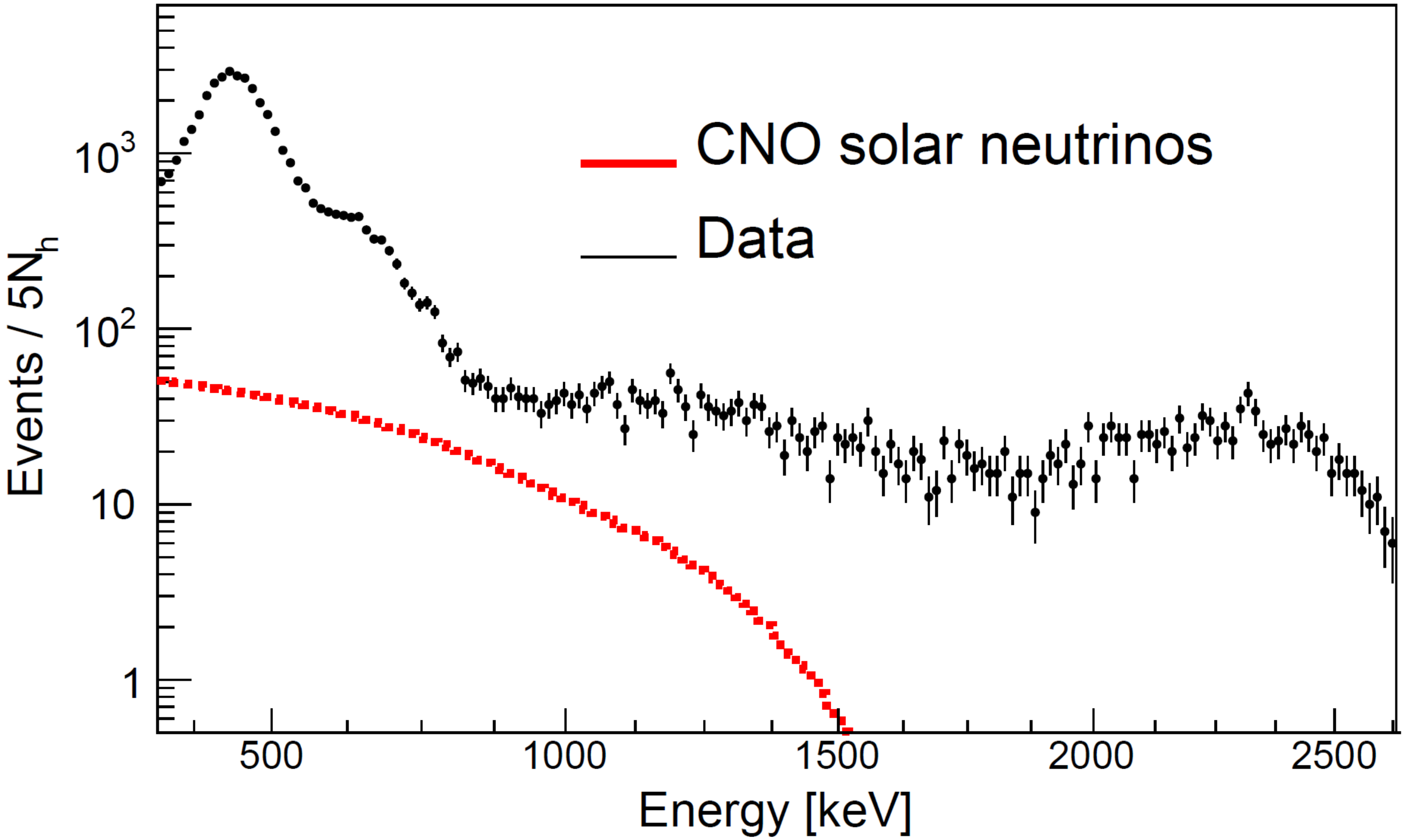
to improve the fit capability to disentangle external background



- The residual external background which is able of penetrating even inside the FV can be disentangled from events uniformly distributed in the volume by their radial distribution;

CNO neutrinos: the problem of ^{210}Bi

The main problem for the extraction of CNO neutrinos is ^{210}Bi;



THE PROBLEM

- The rate of CNO signal and ^{210}Bi is expected to be comparable;
- The spectral shape is very similar → the fit cannot disentangle the two contributions easily!

Need to determine the rate of ^{210}Bi independently in order to constrain it in the fit

CNO neutrinos: the problem of ^{210}Bi

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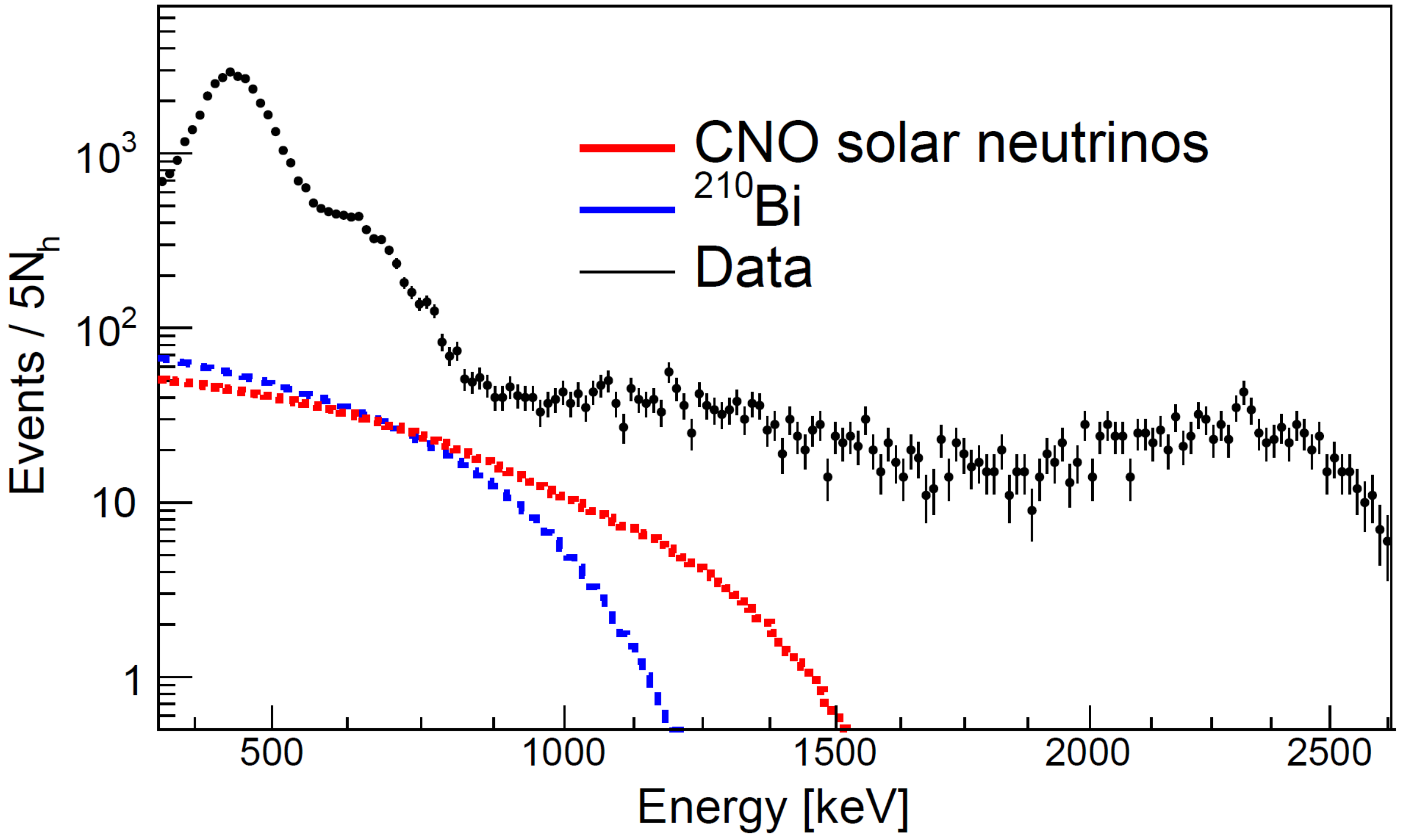

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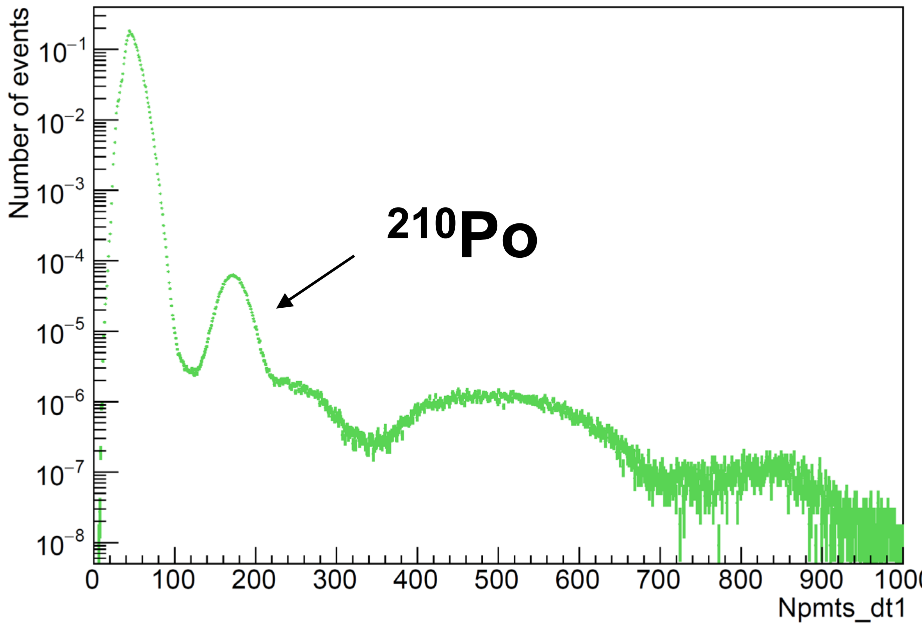
CNO neutrinos: the problem of ^{210}Bi

How can we measure the ^{210}Bi rate independently from the fit?

- ^{210}Bi comes from ^{210}Pb

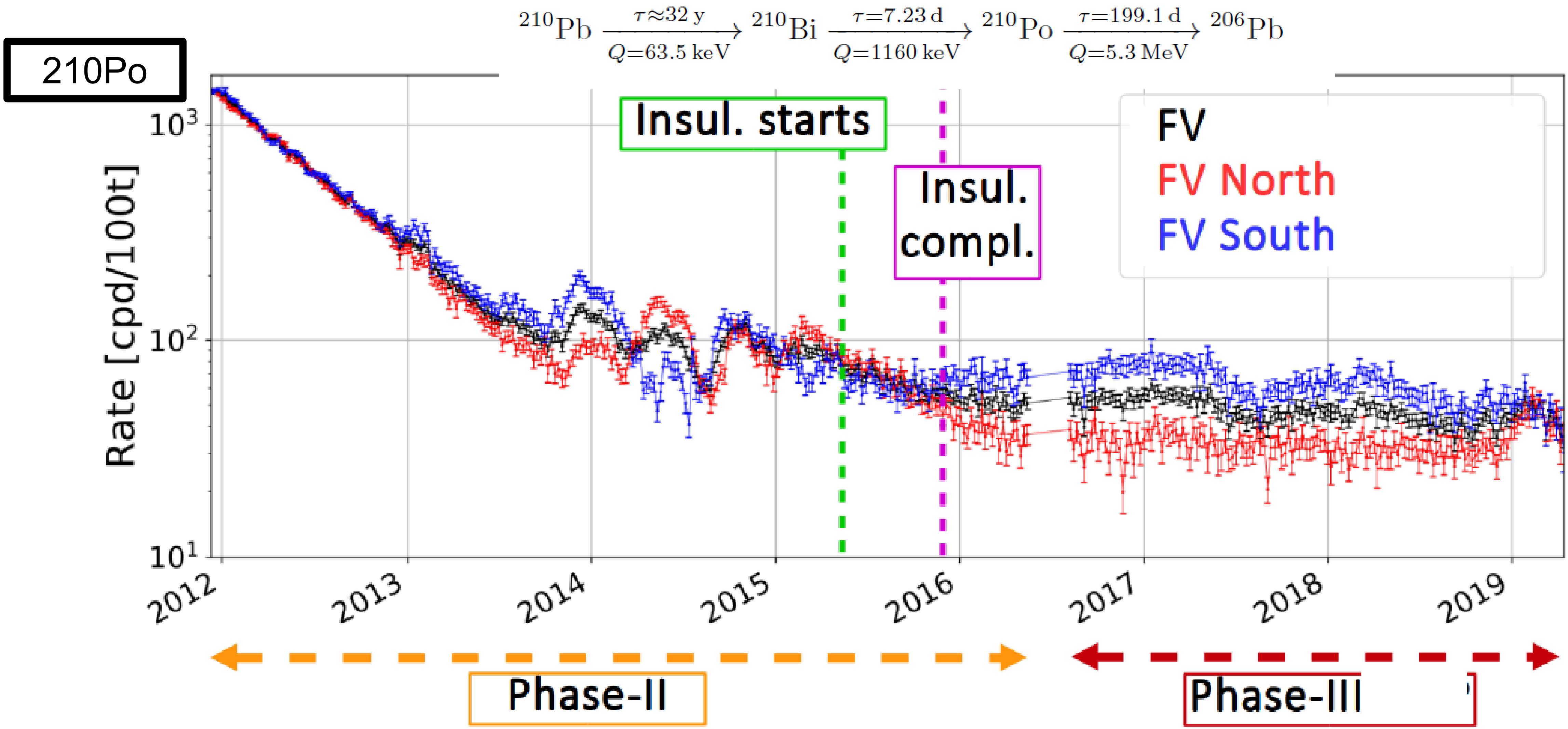
$^{210}Pb \rightarrow {}^{210}Bi + \beta^-$ (τ=33y)
$^{210}Bi \rightarrow {}^{210}Po + \beta^-$ (τ=7d)
$^{210}Po \rightarrow {}^{206}Pb + \alpha$ (τ=200d)



- At secular equilibrium, the rate of rate(^{210}Po) = rate(^{210}Bi);

- ^{210}Po is relatively easy to count since it is a peak and it is an alpha → pulse-shape discrimination methods can be used;

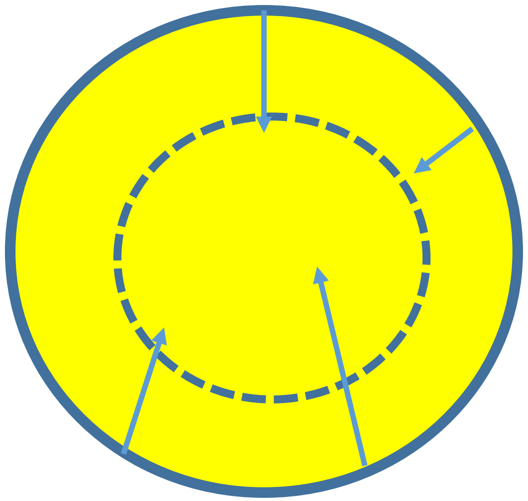
CNO neutrinos: tagging ^{210}Bi with ^{210}Po



Barbara Caccianiga (BX collaboration) ``First evidence of CNO neutrinos with Borexino''

CNO neutrinos: tagging ^{210}Bi with ^{210}Po

- What is causing the large instabilities of the ^{210}Po rate?
- We realized they are strongly correlated to temperature variations



- The vessel containing the scintillator is contaminated with ^{210}Pb;
- Temperature variations are causing convective motions which bring ^{210}Po from the vessel into the scintillator;

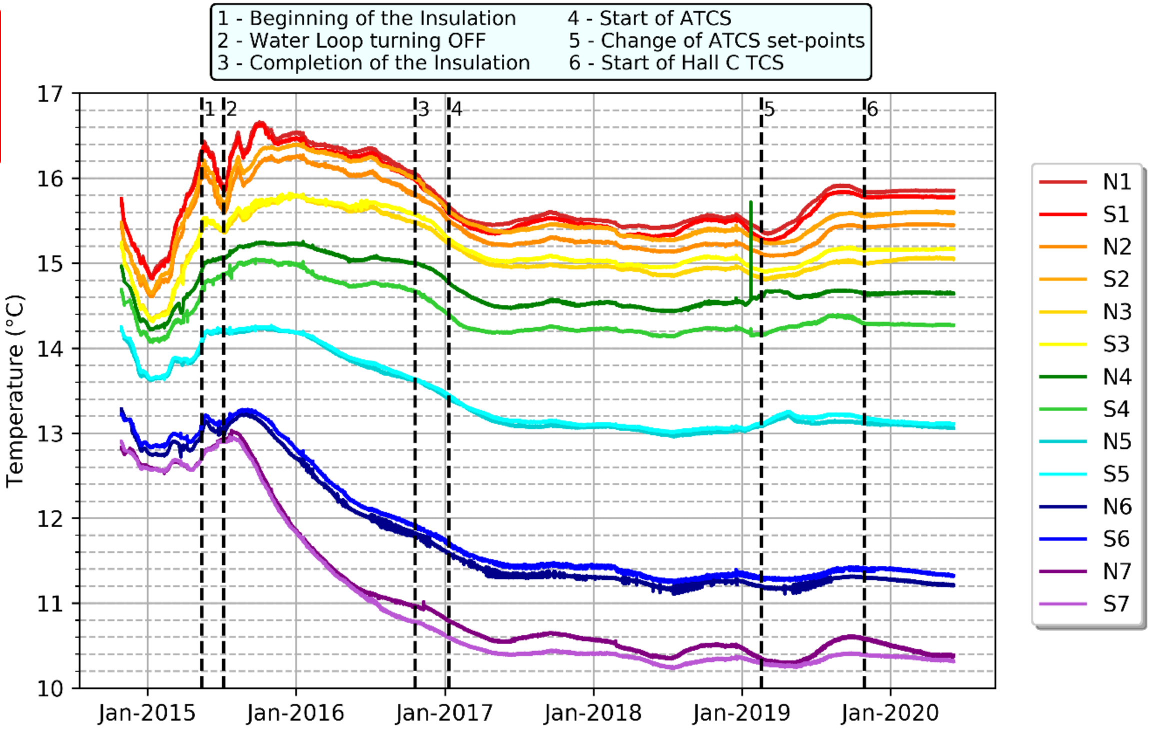
- In these conditions the secular equilibrium is broken and the tagging of ^{210}Bi with ^{210}Po gives misleading results, since ^{210}Po is the sum of two contributions:
- ^{210}Po from the ^{210}Pb chain (rate= ^{210}Bi)
- ^{210}Po from the vessel

CNO neutrinos: tagging ^{210}Bi with ^{210}Po

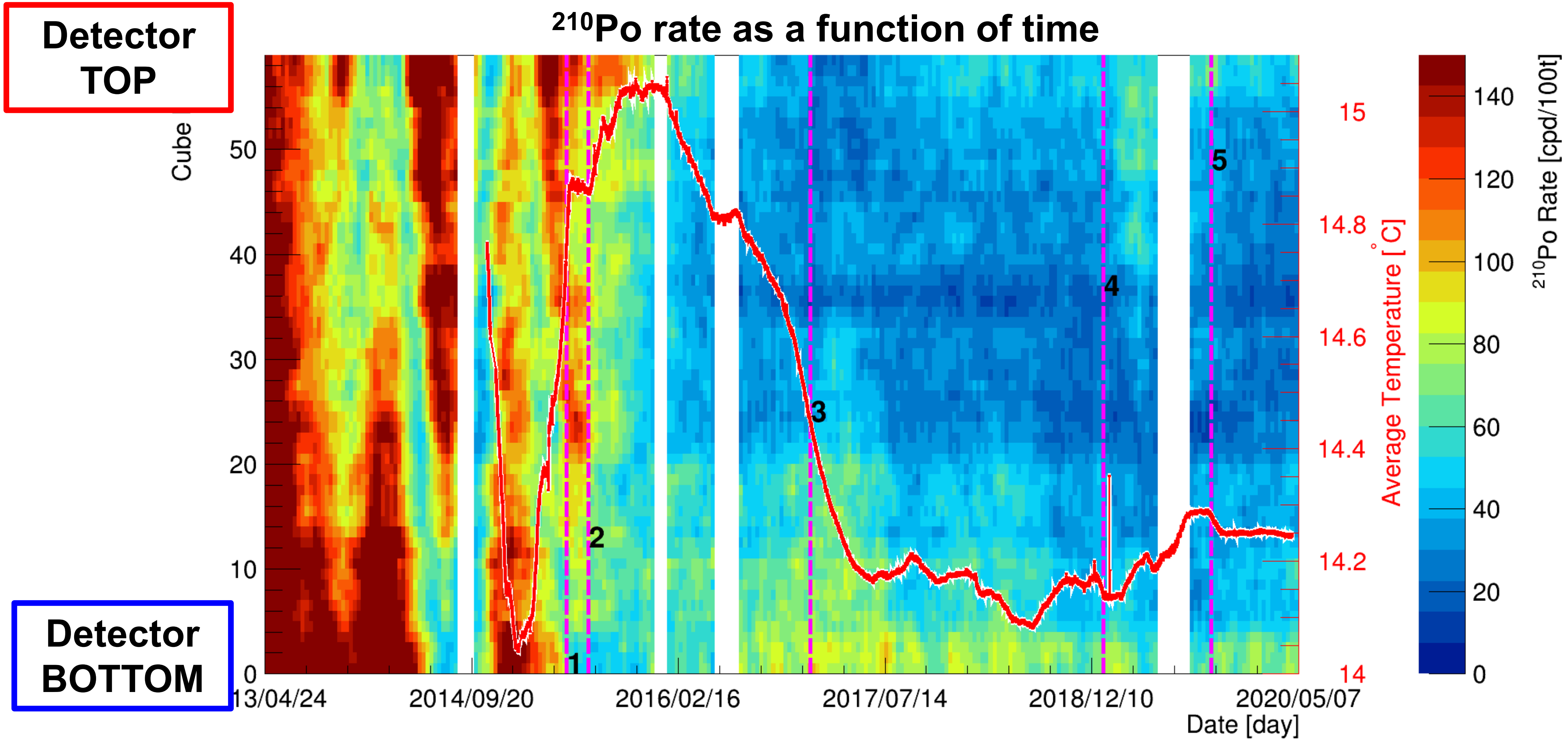
- **Need to thermally stabilize the detector**;
- Insulation of the detector with a 20cm-thick layer of rock wool (work completed in dec 2015)

Detector TOP

Detector BOTTOM

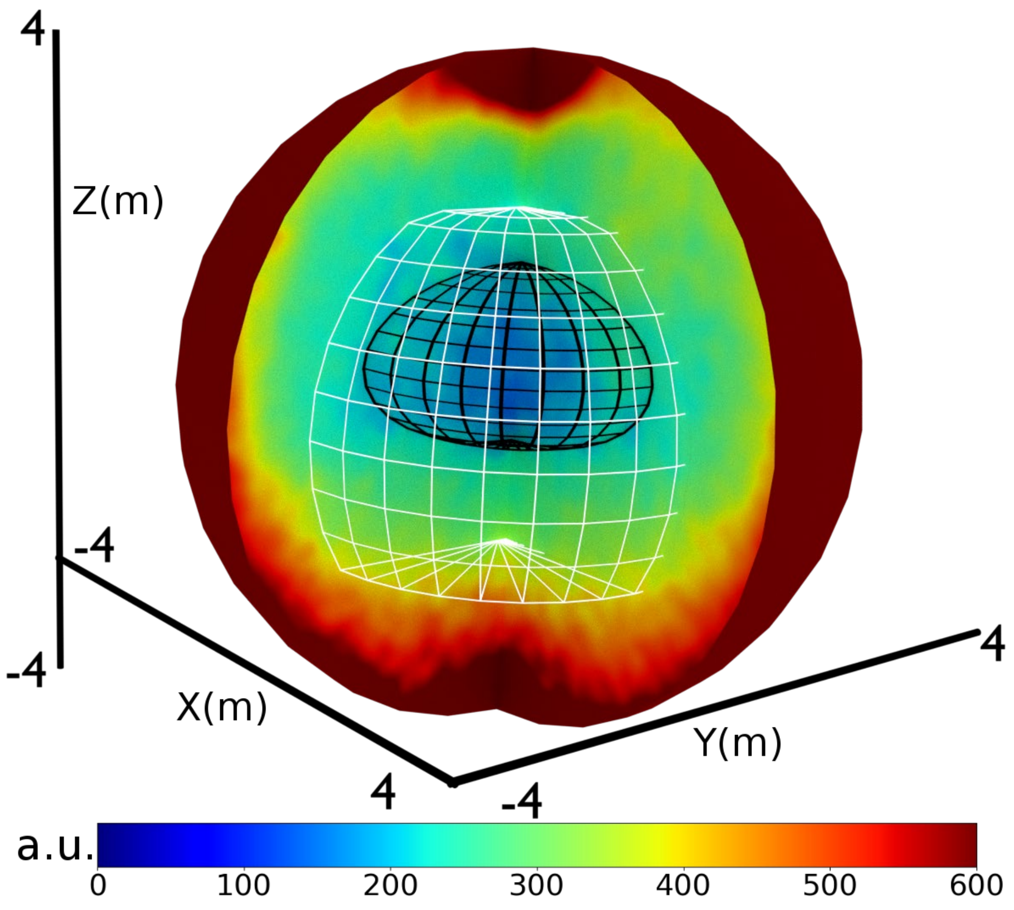


CNO neutrinos: tagging ^{210}Bi with ^{210}Po



Barbara Caccianiga (BX collaboration) ``First evidence of CNO neutrinos with Borexino''

CNO neutrinos: tagging ^{210}Bi with ^{210}Po



- Thanks to the insulation the convective currents are significantly reduced;
- There is an innermost region almost free of convective currents (Low Polonium Field-LPoF);
- 2D fit to the LPoF to find the minimum

$$R_{\mathrm{Po}}(\rho, z) = R^{b}_{\mathrm{Po}} \left[1 + \frac{\rho^2}{a^2} + \frac{(z - z_0)^2}{b^2}\right]$$

- This gives an upper limit of the ^{210}Bi rate

R (^{210}Bi) < 11.5 +/- 1.3 counts/day/100t

CNO neutrinos: results

We now have all the elements to extract CNO neutrinos from data;

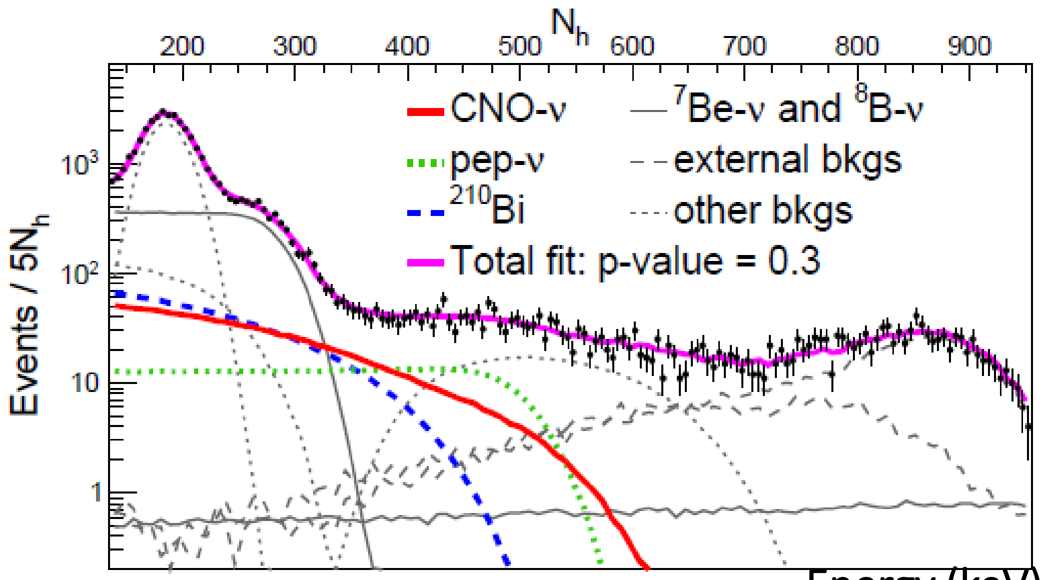
STEP 1
Apply selection cuts to the dataset (July 2016-Feb 2020)

- We have ~90000 events surviving the cuts in the energy region between 320 keV and 2.8 MeV

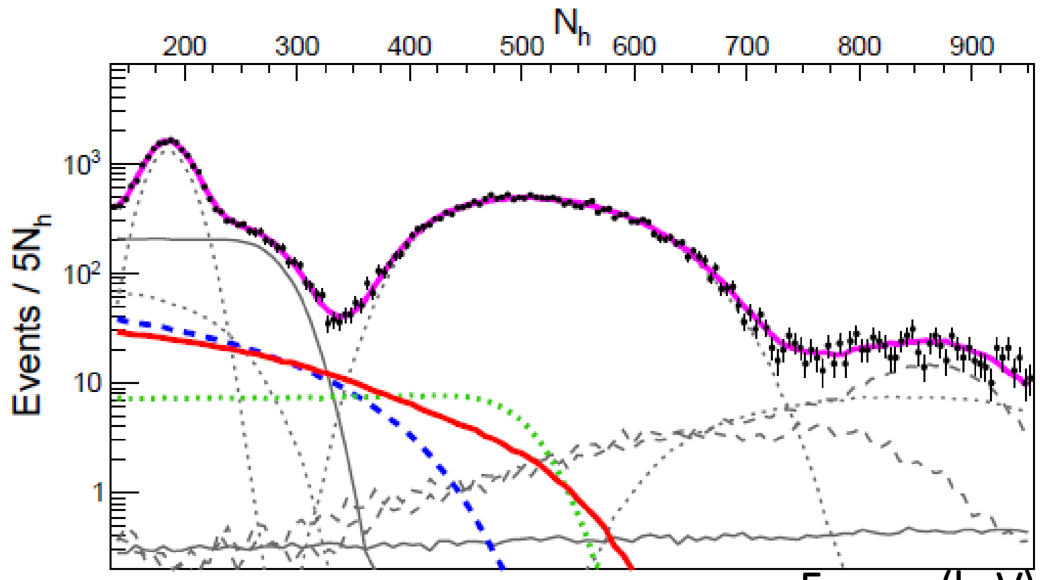
STEP 2
Multivariate fit including energy and radial distributions

- The rate of signal and backgrounds are the free parameters of the fit:
- Two exceptions:
  - ^{210}Bi: rate is costrained to the upper limit found by the ^{210}Po tag analysis (11.8 +/- 1.3 cpd/100t)
  - pep ν rate is constrained to the value found by a global anslysis of all solar experiments + luminosity constraint;

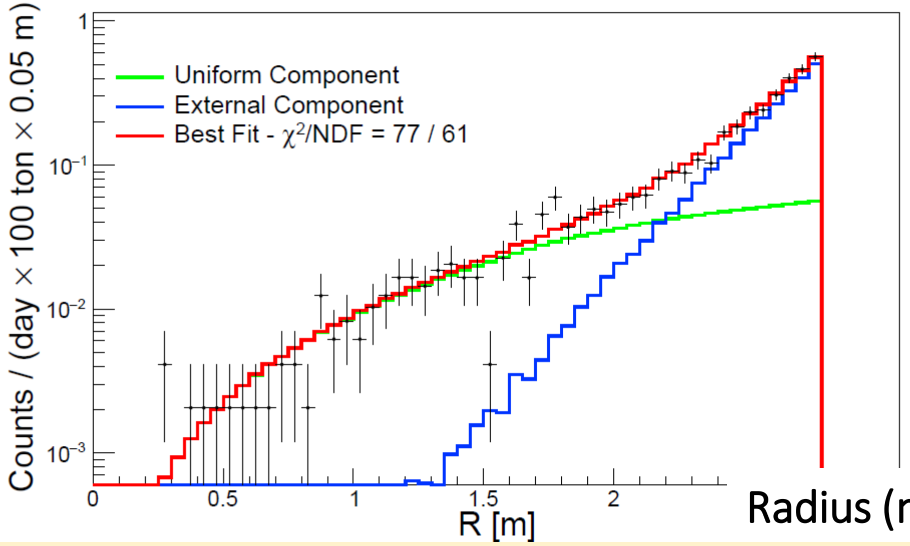
CNO neutrinos: results



Energy (keV)



Energy (keV)



Radius (m)

Best fit result

$$R(\mathrm{CNO}) = 7.2^{+2.9}_{-1.7}(\mathrm{stat})\ \text{cpd/100t}$$

Asymmetric C.I. due to ^{210}Bi upper limit

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CNO neutrinos: results

Systematic errors

Fit cfg.	^{11}C spectrum	^{210}Bi spectrum	Detector response
Negligible	Deformation induced by noise cuts	Different references for β-spectrum (diff. $\approx 18\%$)	Vary detector response parameters within range allowed by calibration ▶ Energy scale (0.23%) ▶ non-uniformity (0.28%) ▶ non-linearity (0.4%)

Nominal Response Model

Randomization of response parameters

(Randomly) Modified Response Model

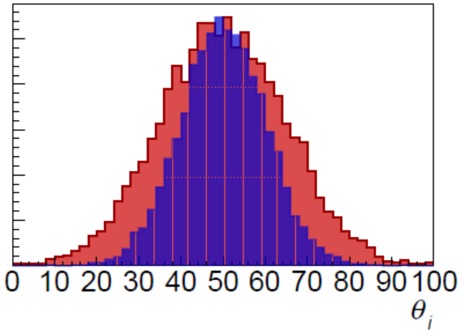
(simulated) distorted dataset

PDFs

fit

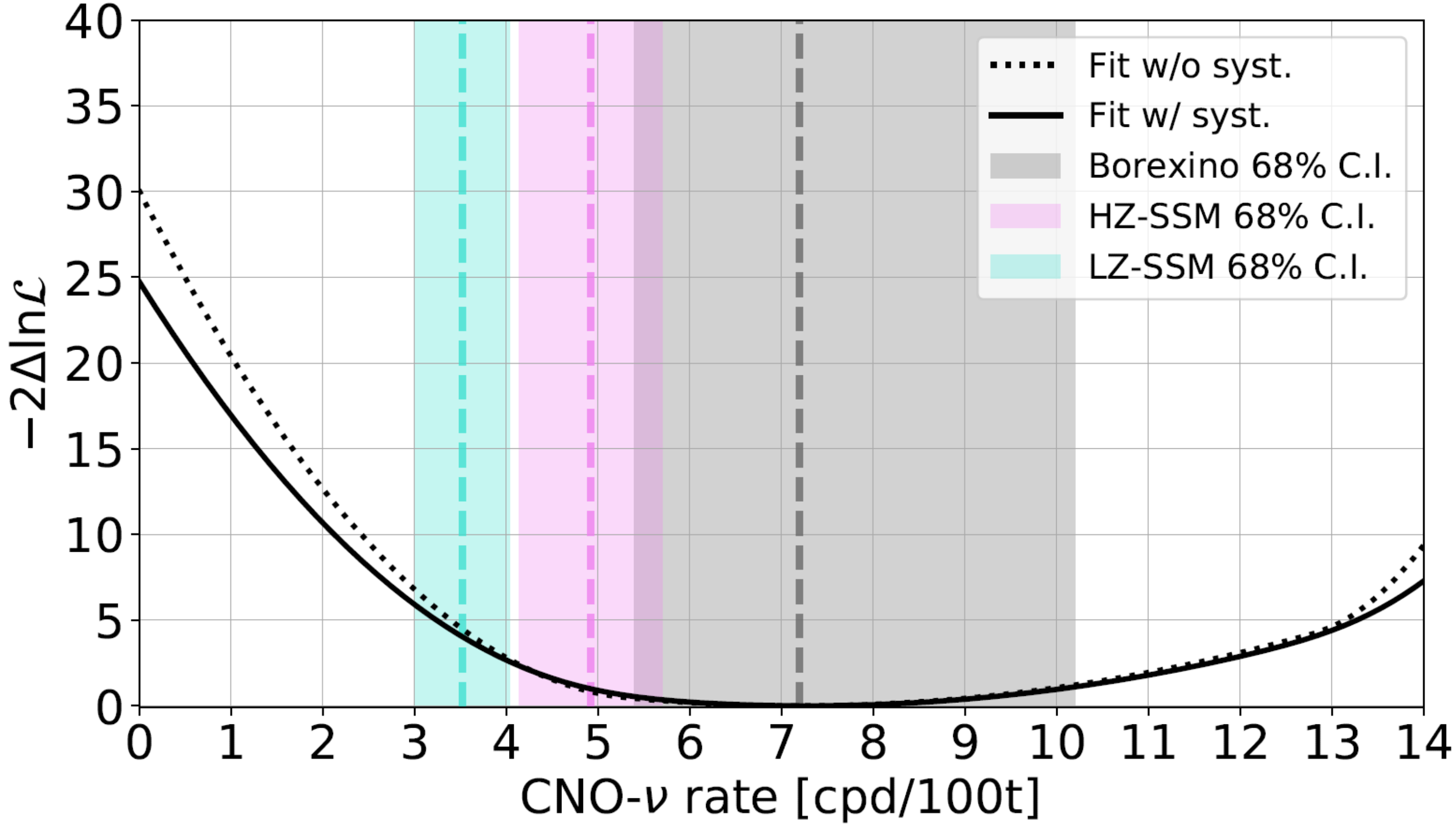
Systematic Uncertainty

$$\sigma^2 = \sigma^2_{stat} + \sigma^2_{sys}$$



$$R(\mathrm{CNO}) = 7.2^{+2.9}_{-1.7}(\mathrm{stat})^{+0.6}_{-0.5}(\mathrm{sys}) \quad \rightarrow \quad \Phi(\mathrm{CNO}) = 7.0^{+2.9}_{-1.9} \times 10^8\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

CNO neutrinos: results



Results (including sys errors)

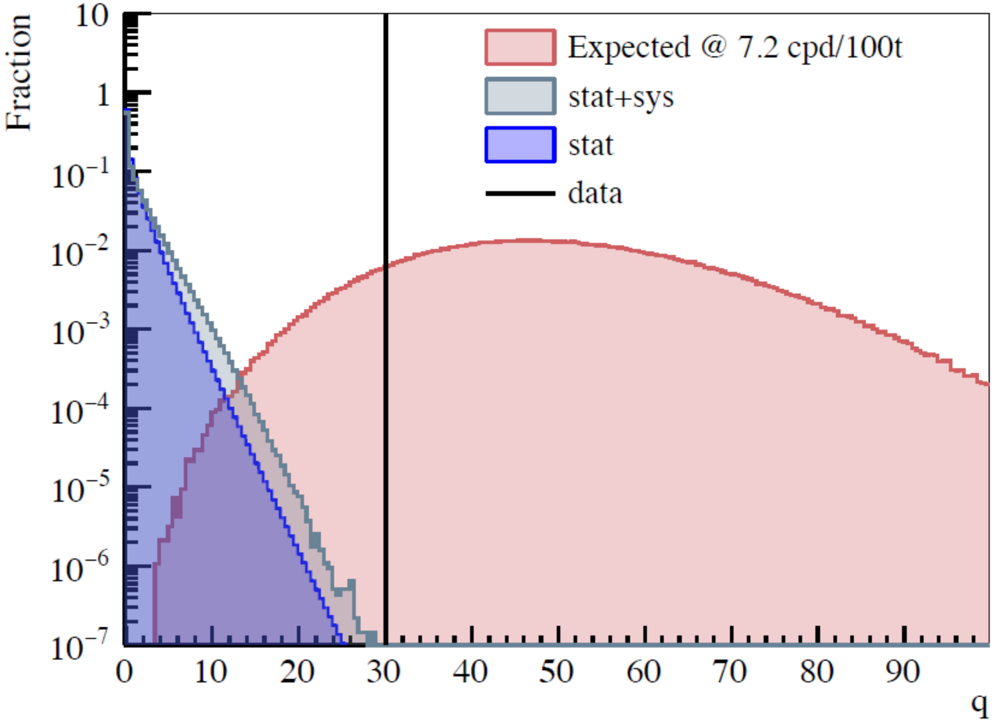
Rate(CNO)= $7.2^{+3.0}_{-1.7}$ cpd/100t

ϕ(CNO)= $7.2^{+3.0}_{-2.0} \times 10^{8}\ \nu\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$

- The results are consistent with both HZ and LZ predictions;
- At the moment we cannot discriminate between HZ and LZ;

CNO neutrinos: results

Significance of the CNO neutrino detection



Hypothesis test: signal vs background only

Profile Likelihood ratio test statistics:

$$q_0 = -2\log\frac{\mathcal{L}(CNO = 0, \hat{\hat{\theta}}_{\mathrm{bkg}})}{\mathcal{L}(CNO\ \mathrm{free}, \hat{\theta}_{\mathrm{bkg}})}$$

PDF obtained generating $\lesssim$ 15M "distorted" datasets with no CNO injected and analysed as regular data

$q_0(\mathrm{data}) = 30.05$ $\rightarrow$ No-CNO hypothesis disfavoured with $\geq 5\sigma$ significance (99% C.L.)

Borexino can claim the first detection of CNO solar neutrinos

Conclusions

After many years of hard work

Borexino has been able of detecting neutrinos from the CNO cycle in the Sun with a significance of 5σ

1) *With this result Borexino has completed the real time picture of the Sun, measuring both processes that sustain it: the* ***pp chain*** *and the* ***CNO cycle***

more generally

2) With this result Borexino has proved experimentally for the first time the existence of the cathalized hydrogen fusion mechanism envisaged in the '30s by Bethe and Weiszacker;

(We remind that the CNO cycle plays a crucial role in stellar physics, since it is believed to be dominant in Stars heavier than the Sun)

Thank you!

Borexino Collaboration

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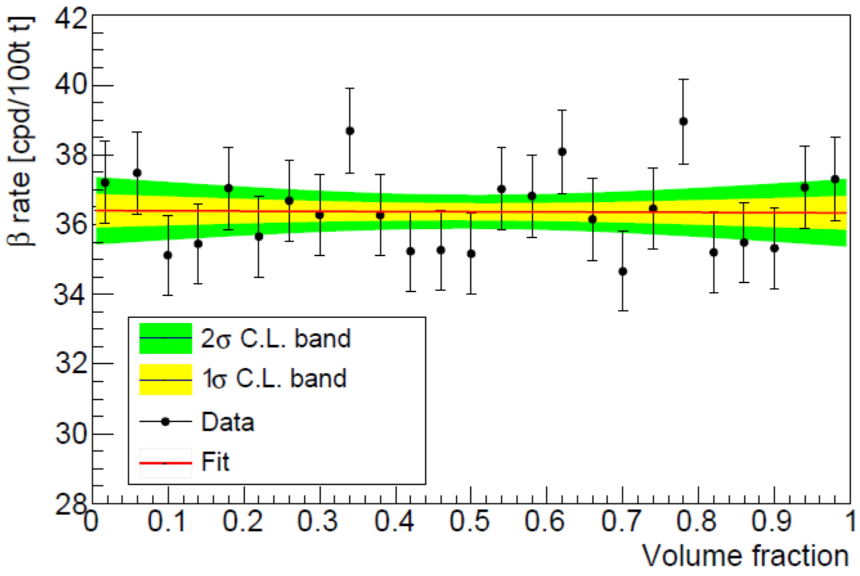
Backup slides

CNO neutrinos: tagging ^{210}Bi with ^{210}Po

- We have to prove the uniformity of ^{210}Bi in the entire volume

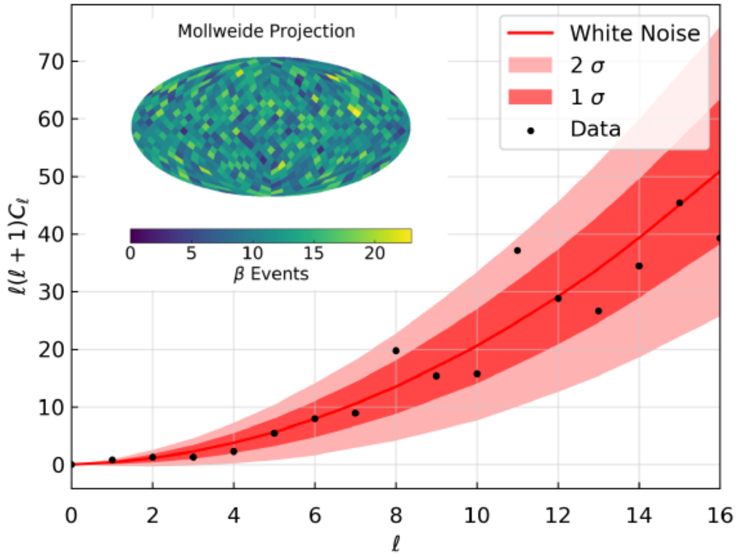
Radial distribution



Radial shell analysis

$\sigma^{\mathrm{sys}}(\mathrm{rad}) = 0.51\ \mathrm{cpd}/100\ \mathrm{t}$

Angular distribution



Spherical Harmonic decomposition

$\sigma^{\mathrm{sys}}(\mathrm{ang}) = 0.59\ \mathrm{cpd}/100\ \mathrm{t}$

The systematic error associated to ^{210}Bi uniformity is 0.78 counts/day/100t