Perspectives for CNO neutrino detection in Borexino

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on behalf of the Borexino Collaboration

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Gran Sasso Science Institute & INFN LNGS

5^{th} International Solar Neutrino Conference

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Outline

The Borexino experiment

- The Borexino spectrum and the role of CNO neutrinos
- The CNO challenge

Strategy

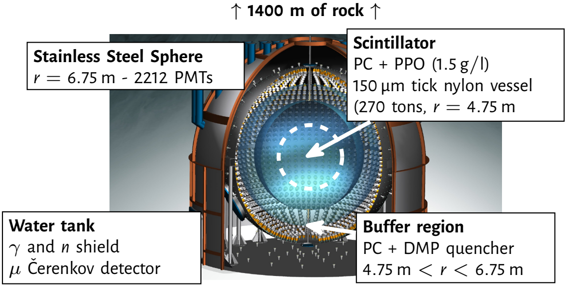
- The background in the CNO analysis
- Strategy for background constraints

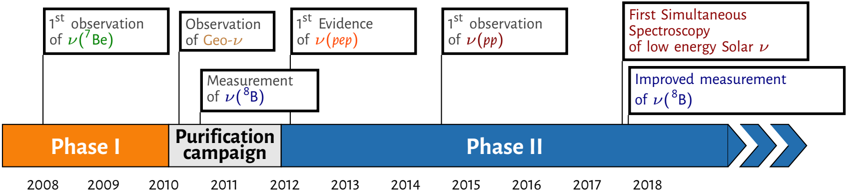
Projected sensitivity

- Uncertainty on CNO neutrino rate
- Statistical sensitivity for the detection of CNO neutrinos

The Borexino Experiment

Borexino is an **ultrapure liquid scintillator** experiment installed at the Gran Sasso National Laboratories of the Italian National Institute of Nuclear Physics

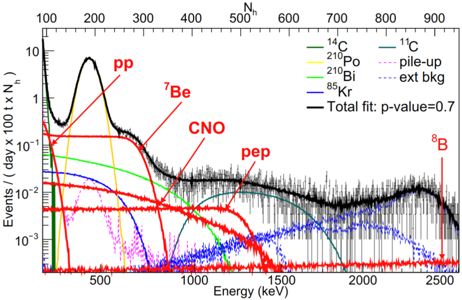




The Borexino spectrum and the role of CNO

arXiv:1707.09279[hep-ex]

Latest results from the solar neutrino analysis:
First Simultaneous Precision Spectroscopy of pp, pep, and ^{7}Be Solar Neutrinos



Dataset

Exposure: 905 days × 100tons
(1291.51 days from Dec. 2011 to May 2016)

Fit range: 0.19–2.93 MeV

Constrained parameters: ^{14}C, Pileup, ν(CNO)

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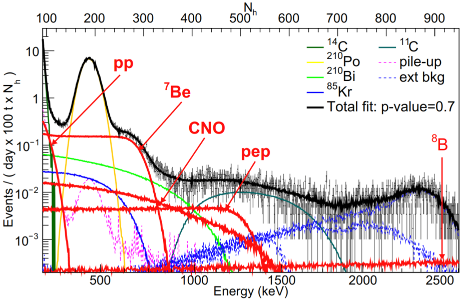

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External background

Gamma rays from ^{40}K, ^{214}Bi and ^{208}Tl
(mainly from steel, PMT glass and light concentrators)

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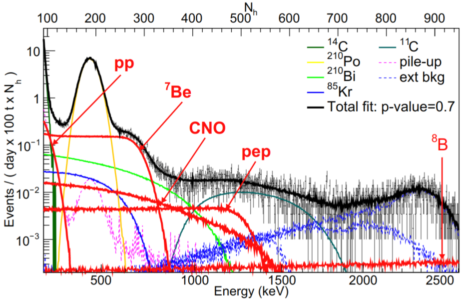

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^{11}C

Cosmogenic isotope (β^+, $\tau = 29.4$ min)

Produced by μ-induced showers with at least one neutron in 95% of the cases

μ track + neutron detection + space-time correlation → **tag** (92 ± 4% efficiency!)

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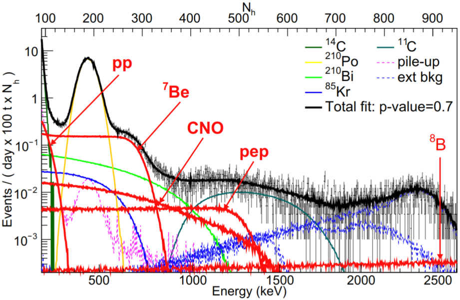

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^{210}Bi

Coming from ^{210}Pb dissolved in the scintillator

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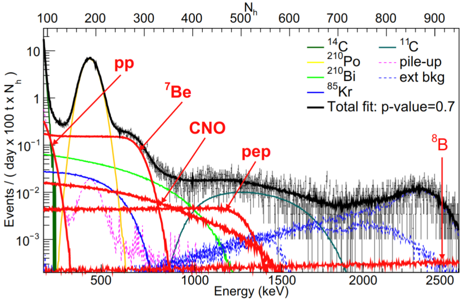

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^{210}Po

5 MeV alpha decay quenched by the liquid scintillator

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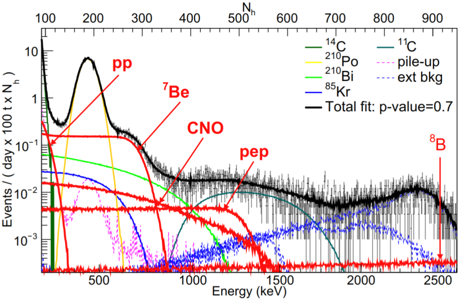

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Highlights

See M. Wurm talk!

- 22% improvement in $\Phi(pp)$ accuracy

$\nu(pp)$

Borexino:	$134 \pm 10(\text{stat})^{+6}_{-12}(\text{sys})$ cpd/100 ton
HZ Model:	131.0 ± 2.4 cpd/100 ton
LZ Model:	132.1 ± 2.3 cpd/100 ton

10% accuracy (22% improvement wrt to previous result)

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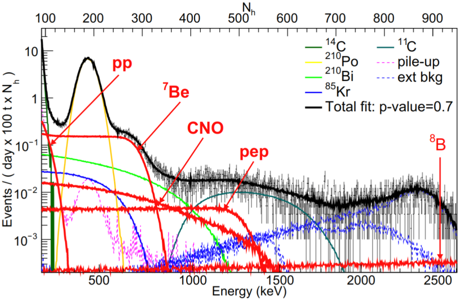

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- 22% improvement in $\Phi(pp)$ accuracy
- 3% accuracy on $\Phi(^{7}\text{Be})$

$\nu(^{7}\text{Be})$

Borexino:	$48.3 \pm 1.1(\text{stat})^{+0.4}_{-0.7}(\text{sys})$ cpd/100 ton
HZ Model:	47.8 ± 2.9 cpd/100 ton
LZ Model:	43.7 ± 2.6 cpd/100 ton

43% better precision wrt Borexino Phase I

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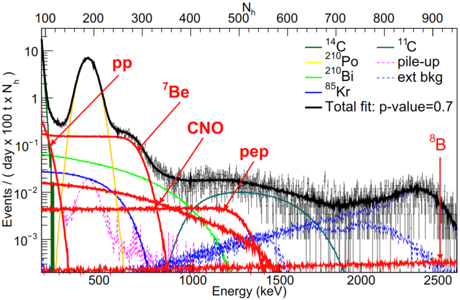

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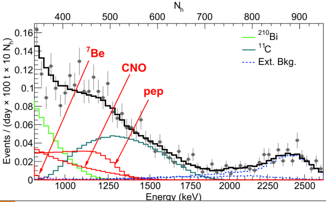
- Absence of $\nu(pep)$ rejected at more than 5σ

$\nu(pep)$

Borexino (HZ CNO):	$2.43 \pm 0.36(\text{stat})^{+0.15}_{-0.22}(\text{sys})$ cpd/100 ton
Borexino (LZ CNO):	$2.65 \pm 0.36(\text{stat})^{+0.15}_{-0.24}(\text{sys})$ cpd/100 ton
HZ Model:	2.74 ± 0.05 cpd/100 ton
LZ Model:	2.78 ± 0.05 cpd/100 ton



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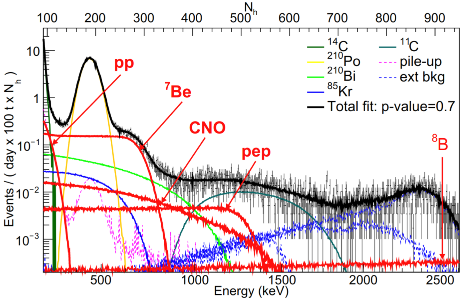

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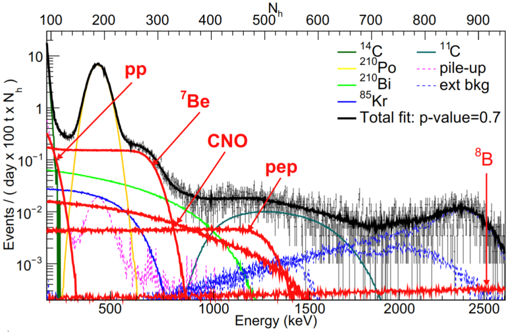
ν(CNO)

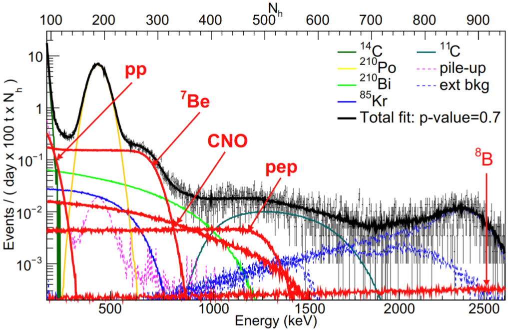
$$\Phi(\text{CNO}) < 7.9 \times 10^8\ \text{cm}^{-2}\text{s}^{-1}\ (95\%\ \text{C.L.})$$

The CNO challenge



The detection of CNO neutrinos in Borexino is made particularly challenging by

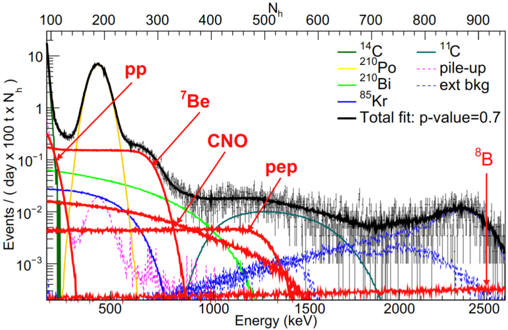
The CNO challenge



The detection of CNO neutrinos in Borexino is made particularly challenging by

- The low flux of CNO neutrinos
  (CNO cycle responsible of $\approx 1\%$ of the total Solar Power)

The CNO challenge



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- The low flux of CNO neutrinos
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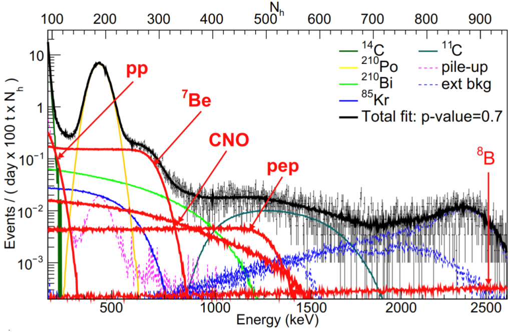
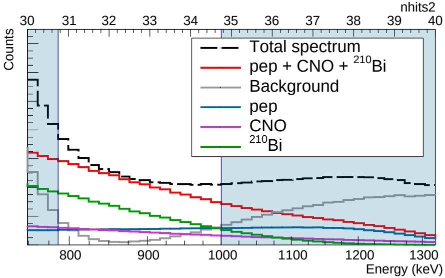
- The absence of prominent spectral features

The CNO challenge



The detection of CNO neutrinos in Borexino is made particularly challenging by

- The low flux of CNO neutrinos
  (CNO cycle responsible of $\approx$ 1% of the total Solar Power)
- The absence of prominent spectral features
- The presence of background with similar spectral shape

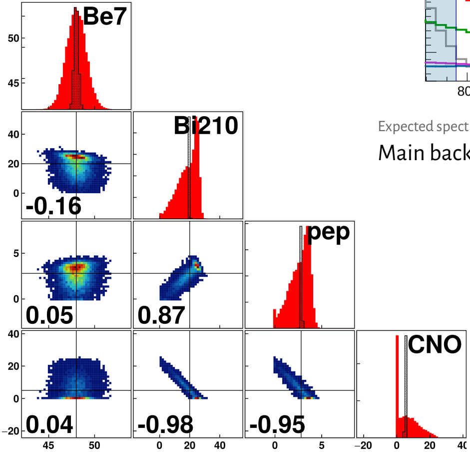


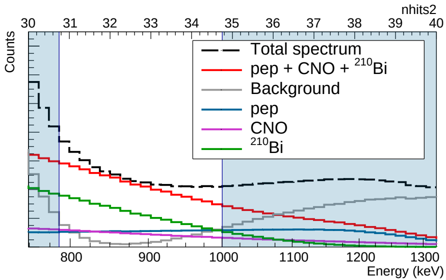
Expected spectrum [$\nu(CNO)$ HZ flux and other rates from last solar analysis]

Main background in the ROI: ^{210}Bi and $\nu(pep)$

$\hookrightarrow$ Strong correlation between $\nu(CNO)$-^{210}Bi-$\nu(pep)$

Toy-MC experiments parameters distribution





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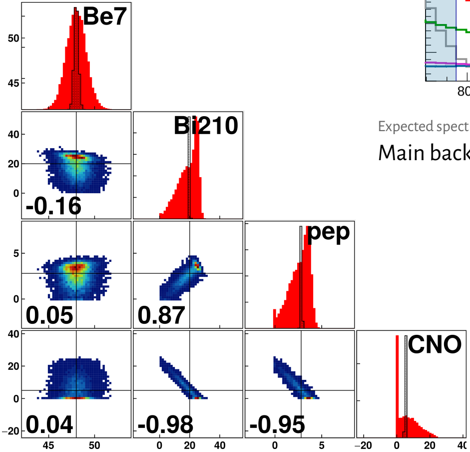

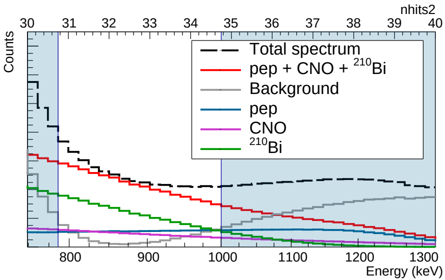

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Main background in the ROI: ^{210}Bi and $\nu(pep)$

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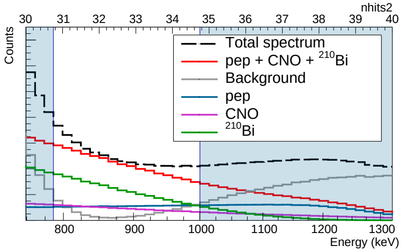
A spectral analysis of Borexino data without external constraints has almost no sensitivity to a CNO signal

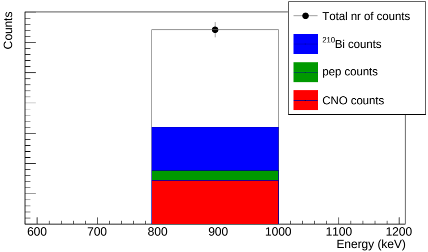
It is crucial to constrain the background for CNO

Very limited sensitivity to the ^{210}Bi/ν(CNO) **spectral information**

$\hookrightarrow$ **negligible** (in first approximation)



Expected spectrum assuming $\nu(CNO)$ HZ flux and other rates from last solar analysis



Expected counts in the 0.79–1 MeV energy window assuming $\nu(CNO)$ HZ flux and other rates from the last solar analysis

The total number of counts in the ROI is given by

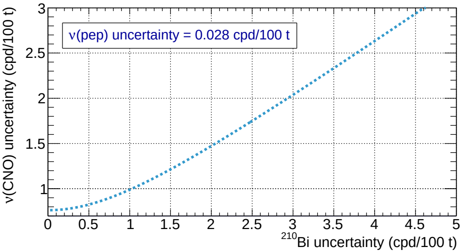
$$N_{\text{tot}} = (R_{\text{Bi210}} \cdot \varepsilon_{\text{Bi210}} + R_{pep} \cdot \varepsilon_{pep} + R_{\text{CNO}} \cdot \varepsilon_{\text{CNO}}) \cdot E$$

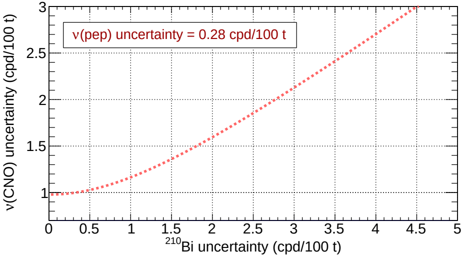
E = exposure, R_X = rate of X, ε_X = fraction of events in the ROI for X

CNO uncertainty depends mainly on the precision of external constraints

$$\sigma_{\mathrm{CNO}} = \frac{1}{E\cdot\varepsilon_{\mathrm{CNO}}}\sigma_{N_{tot}} \oplus \frac{\varepsilon_{\mathrm{Bi210}}}{\varepsilon_{\mathrm{CNO}}}\sigma_{\mathrm{Bi210}} \oplus \frac{\varepsilon_{pep}}{\varepsilon_{\mathrm{CNO}}}\sigma_{pep}$$

Evaluated w/ toy-MC | ^{210}Bi accuracy | *pep* accuracy





(Systematic uncertainties **not included**)

(B16)GS98 prediction

$R_{\mathrm{CNO}} = 4.92 \pm 0.55$ cpd/100 t

(B16)AGSS09 prediction

$R_{\mathrm{CNO}} = 3.52 \pm 0.37$ cpd/100 t

$\sigma(R_{\mathrm{CNO}}) \lesssim 2$ cpd/100 t $\leftrightarrow \sigma(R_{pep}) \lesssim 0.28$ cpd/100t $+ \sigma(R_{\mathrm{Bi\text{-}210}}) \lesssim 2.5$ cpd/100t

Constraining the $\nu(pep)$ flux

$\Phi(pp)/\Phi(pep)$ is known with sub-% accuracy (same nuclear matrix element)
$\hookrightarrow$ independent on the Solar Model (difference $< 1\%$)

Measurement of $\Phi(pp)$ with 10% uncertainty
$\hookrightarrow \Phi(pp)/\Phi(pep)$ constrained $\rightarrow \Phi(pep)$ constrained with 10% accuracy

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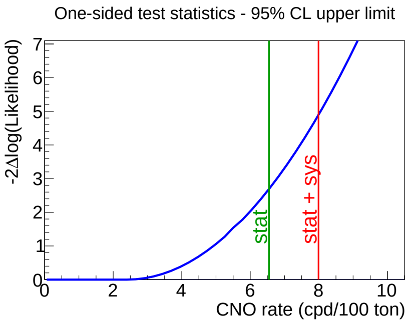
Measurement of $\Phi(pp)$ with 10% uncertainty
$\hookrightarrow$ $\Phi(pp)/\Phi(pep)$ constrained $\rightarrow$ $\Phi(pep)$ constrained with 10% accuracy

Φ(CNO) limit from latest solar analysis

$\Phi(\mathrm{CNO}) < 7.9 \times 10^8\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (95% C.L.)

B16-GS98 (HZ) $[\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	B16-AGSS09 (LZ) $[\mathrm{cm}^{-2}\mathrm{s}^{-1}]$
$4.88(1 \pm 0.11) \times 10^8$	$3.51(1 \pm 0.10) \times 10^8$



The Solar Luminosity constraint

John N. Bahcall, DOI: 10.1103/PhysRevC.65.025801
See F. Vissani talk!

Every neutrino emitted by the Sun marks a reaction

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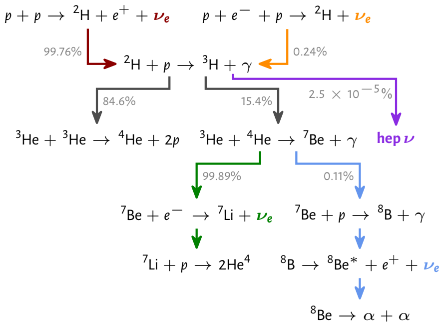
Every neutrino emitted by the Sun marks a reaction

$$\frac{L_\odot}{4\pi(\mathrm{A.U.})^2} = \varepsilon_{pp}\Phi(pp) + \varepsilon_{pep}\Phi(pep) + (\varepsilon_{34}+\varepsilon_{e7})\Phi(^7\mathrm{Be}) + (\varepsilon_{34}+\varepsilon_{p7})\Phi(^8\mathrm{B}) + \varepsilon_{hep}\Phi(hep) +$$

$$\frac{1}{2}\varepsilon_{33}\left[\Phi(pp)+\Phi(pep)-\Phi(hep)-\Phi(^7\mathrm{Be})-\Phi(^8\mathrm{B})\right] + \text{CNO terms}$$

ε_i = thermal energy released in the i process



Assumptions:

- The Sun is powered *only* by the processes of the *pp* chain and of the CNO cycle
- The Sun is in equilibrium
  ($L_\odot$ is constant over a $\sim 10^5$ yr time scale)
- ^{2}H and ^{3}He are in local kinetic equilibrium (creation rate = destruction rate)
  Reasonable since lifetime ^{2}H $\approx 10^{-8}$yr and ^{3}He $\approx 10^5$yr (proton lifetime $\approx 10^{10}$ yr)

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$$\frac{1}{2}\varepsilon_{33}\left[\Phi(pp) + \Phi(pep) - \Phi(hep) - \Phi(^7\mathrm{Be}) - \Phi(^8\mathrm{B})\right] + \text{CNO terms}$$

ε_i = thermal energy released in the i process

$$\downarrow$$

$$\frac{L_\odot}{4\pi(\mathrm{A.U.})^2} = \sum_{i=pp,pep,\ldots} \alpha_i \Phi_i$$

α_i = combination of ε_j

$L_\odot$ known at 0.4% precision, α_i uncertainty $\approx 10^{-5}$

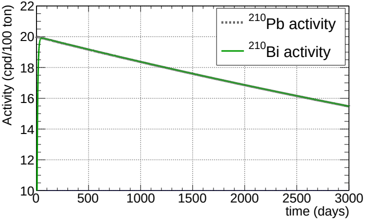
$$\downarrow$$

$\Phi(pp)$ uncertainty $< 1\%$

Constraining ^{210}Bi

F. Villante, A. Ianni, F. Lombardi, G. Pagliaroli, F. Vissani
DOI: 10.1016/j.physletb.2011.05.068

$$^{210}\text{Pb} \xrightarrow[32\text{ y}]{\tau_{\text{Pb-210}}} {}^{210}\text{Bi} \xrightarrow[7.23\text{ d}]{\tau_{\text{Bi-210}}}$$



^{210}Pb dissolved in the scintillator at the beginning of Phase II

Assuming no source of $^{210}\text{Pb} \rightarrow {}^{210}\text{Bi}$ in secular equilibrium

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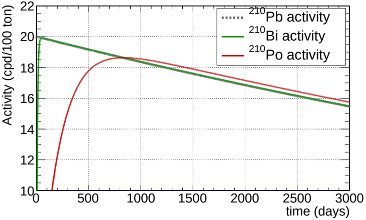
$$^{210}\text{Pb} \xrightarrow[32\text{ y}]{\tau_{\text{Pb-210}}} {}^{210}\text{Bi} \xrightarrow[7.23\text{ d}]{\tau_{\text{Bi-210}}} {}^{210}\text{Po} \xrightarrow[199.1\text{ d}]{\tau_{\text{Po-210}}} {}^{206}\text{Pb (stable)}$$



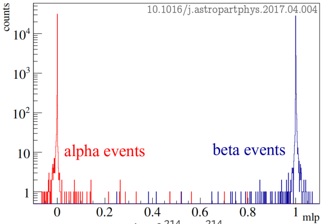
^{210}Pb dissolved in the scintillator at the beginning of Phase II

Assuming no source of ^{210}Pb $\rightarrow$ ^{210}Bi in secular equilibrium
$\hookrightarrow$ ^{210}Po in secular equilibrium too

^{210}Po α events tagged using Pulse-Shape Discrimination

Neural Network algorithm based on Multi Layer Perceptron (MLP)

- ▷ 13 input from pulse time structure
- ▷ Tagging efficiency > 99%



MLP test sample of ^{214}Bi - ^{214}Po events

- **^{210}Po from the nylon vessel**
  ^{210}Pb contaminations inside the nylon vessel

  $\hookrightarrow$ ^{210}Po daughter can diffuse through material
  ^{210}Po migration must be considered

  If ^{210}Po only diffuses inside the liquid scintillator is not critical

  Diffusion coefficient in hydrocarbon $D^{hc}_{\text{Po-210}} \approx 2 \times 10^{-5}\ \text{cm}^2/\text{s}$

  $\hookrightarrow$ diffusion length $\lambda = \sqrt{D^{hc}_{\text{Po-210}} \tau_{\text{Po-210}}} \approx 20\ \text{cm}$

  ^{210}Po decays before enetering the FV

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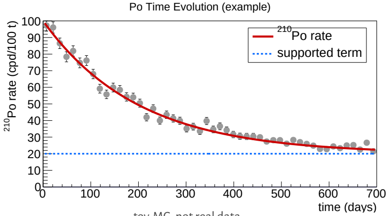
  ↪ diffusion length $\lambda = \sqrt{D^{hc}_{Po\text{-}210}\tau_{Po\text{-}210}} \approx 20$ cm
  ^{210}Po decays before enetering the FV

- **^{210}Po out of equilibrium**

$R_{Po\text{-}210} \approx 1400$ cpd/100ton
at beginning of Phase II (Dec. 2011)

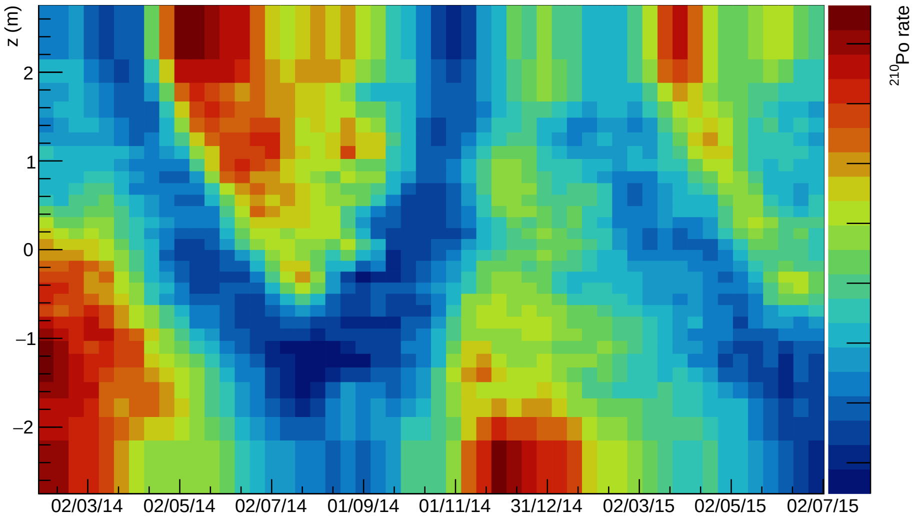
$$R_{Po\text{-}210}(t) = (A - B)e^{-t/\tau_{Po\text{-}210}} + B$$

A = unsupported term, B = supported term



toy-MC, not real data

Strong "seasonal" effect due to convective motions



31 iso-volume layers of a 2.75 m radius sphere

How to stop convective motions

10.1016/j.nima.2017.12.047
arXiv:1705.09658

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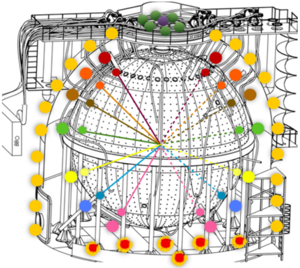
Understanding Borexino fluid dynamics

Temperature Monitoring System



Latitudinal Temperature Probe System

54 Temperature probes

Fluid dynamics simulation

Improve understanding of the detector fluid dynamics

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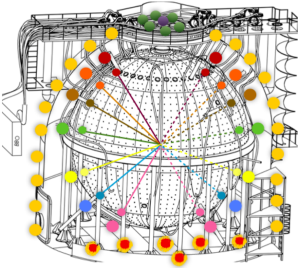

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Thermal Stabilization

Fix temperature gradient

Detector Insulation

Thermal Insulation System (TIS)

Double layer of mineral wool (20 cm)

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Understanding Borexino fluid dynamics

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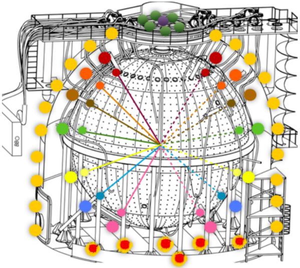

Latitudinal Temperature Probe System

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Fluid dynamics simulation

Improve understanding of the detector fluid dynamics

Thermal Stabilization

Fix temperature gradient

Detector Insulation

Thermal Insulation System (TIS)

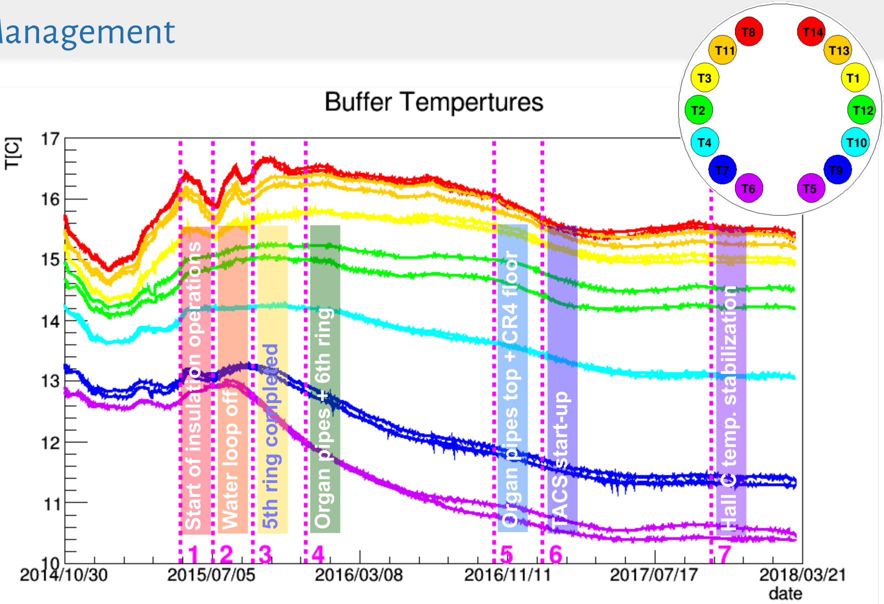
Double layer of mineral wool (20 cm)

Active Gradient Stabilization System (AGSS)

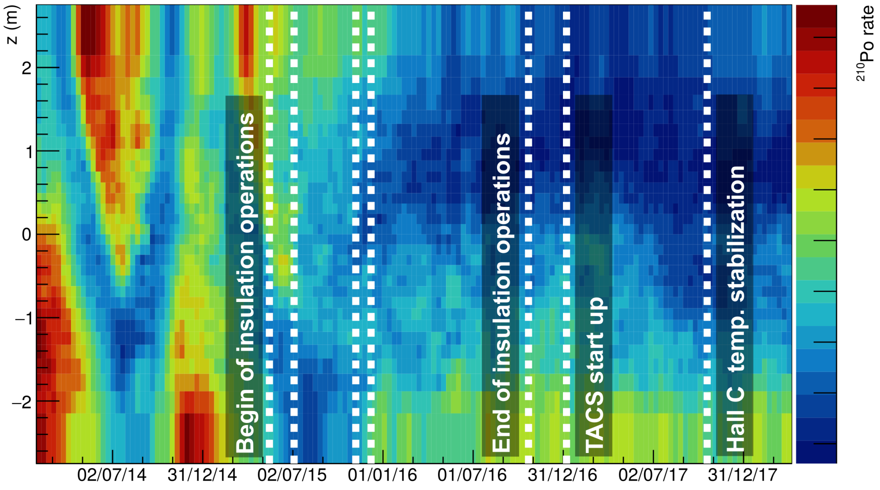
controlled temperature water loop circuits (uppermost dome “ring”)

Hall C Temperature Stabilization

Performance of the Borexino Thermal Monitor and Management



The impact of thermal stabilization on the ^{210}Po spatial distribution



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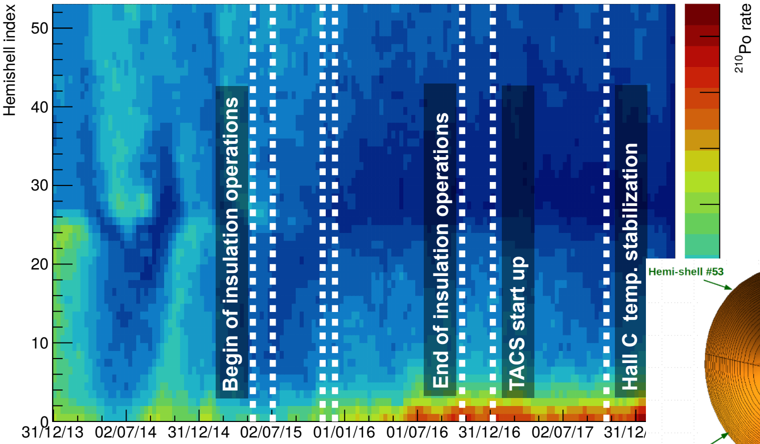
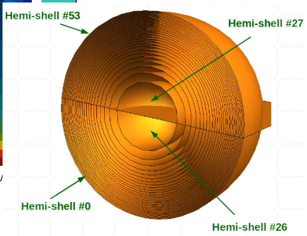
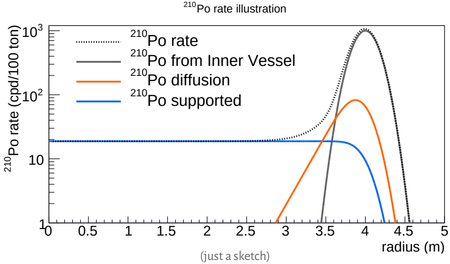




Very slow transition towards stabilization.

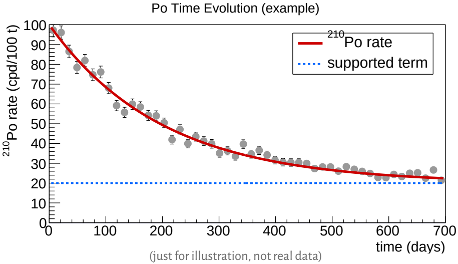
Stop of convective motions → Measurement of the ^{210}Bi supported rate

If no ^{210}Po out of equilibrium



(just a sketch)

If residual ^{210}Po out of equilibrium

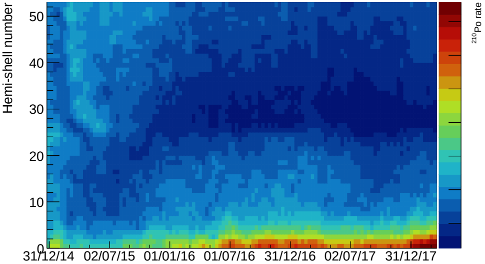


(just for illustration, not real data)

Very slow transition towards stabilization.

Stop of convective motions → Measurement of the ^{210}Bi supported rate

BUT if convection is still present in part of the detector…



"Clean" region selection

Region with constant ^{210}Po rate

Very slow transition towards stabilization.

Stop of convective motions → Measurement of the ^{210}Bi supported rate

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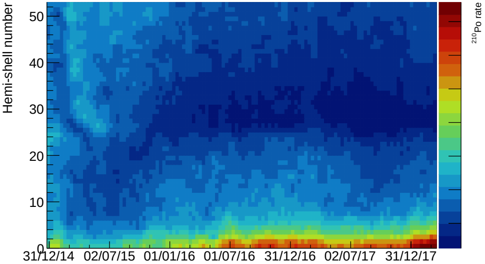

"Clean" region selection

Region with constant ^{210}Po rate

Precision depends on the selected volume mass and time of observation

Expected uncertainty of ν(CNO) rate

CNO uncertainty evaluated with a toy-MC method

Full multivariate analysis (energy + radial distribution)
Simultaneous fit of the ^{11}C sub./tagged datasets

Exposure:	Jul 2013 - May 2016
Variables:	`nhits`, r^3

	Inj. Rate
CNO	4.9 cpd/100t
^{210}Bi	17.5 cpd/100t
Remainder	See last solar analysis

pep and ^{210}Bi constraints folded in the analysis by adding to the likelihood two independent multiplicative Gaussian penalty terms on the ^{210}Bi and the $\nu(pep)$ rate.

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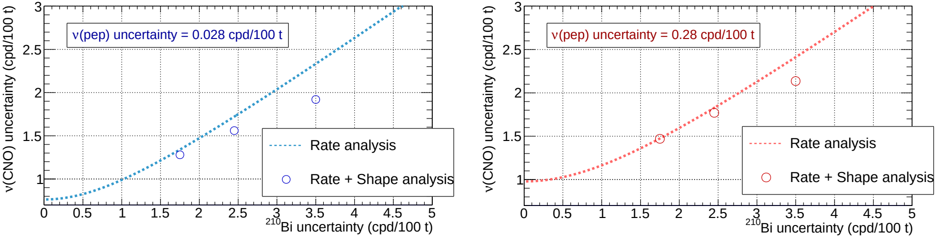
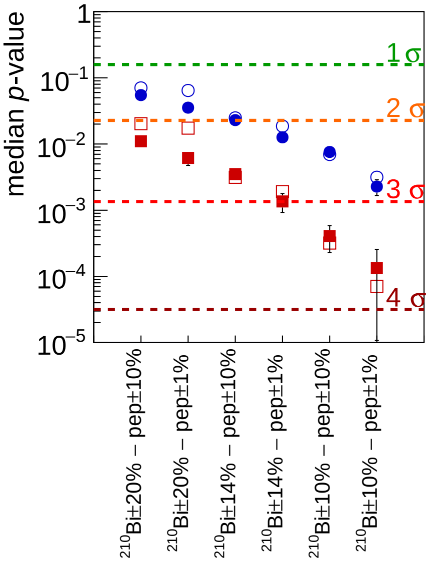


Shape information helps the CNO sensitivity if the ^{210}Bi constraint is weaker than 2.5 cpd/100t

(Systematic uncertainties not included)

Borexino median discovery power



Discovery power evaluated performing an hypothesis test based on a profile likelihood test statistics

- Results consistent with the expected uncertainty on the ν(CNO) rate.
- Stronger constraints
  $\hookrightarrow$ higher sensitivity to CNO signal
- Improvement due to shape information important only for relatively weak constraints

Conclusions and outlooks

- Borexino at the moment is the only **running experiment** being able to perform low energy Solar Neutrino spectroscopy
- A spectral analysis of Borexino data has no sensitivity to a CNO signal, the bulk of the **sensitivity** comes from a simple **counting analysis** and relies on independent measurement/estimation of the $\nu(pep)$ and ^{210}Bi rate
  - The spectral information plays a mild role
  - The uncertainty on the CNO rate is strongly connected to the precision of the *pep* and ^{210}Bi rate measurement
  - The rate of *pep* neutrinos can be constrained exploiting its connection with $\Phi(pp)$
  - Extracting the ^{210}Bi rate assuming ^{210}Po in secular equilibrium requires to prove that no source of ^{210}Po is present.
    - Thermal stabilization of the detector is ongoing
    - Will this be enough?

Backup slides

The Borexino MC full multivariate fit

The Borexino analysis

Analytical Fit

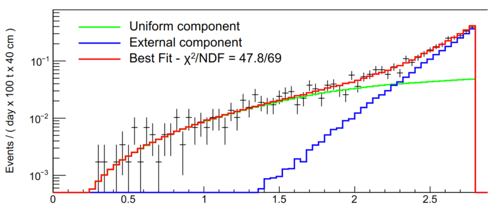
The detector response function is described by an analytical model taking into account quenching, Čerenkov effect,…

MC Fit

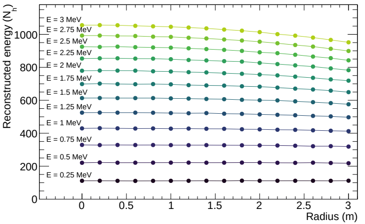
Background and ν's spectra are **simulated and processed as real data**, making up the PDF for each component.

Full multivariate MC fit

multidimensional PDFs filled with energy observable and distance from detector center



Uniform/External γ separation



Spatial dependance of detector response

Evaluation of the discovery power

CNO uncertainty gives indication about the CNO signal strength, but does not take into account the probability that fluctuation of the background can mimic the signal.

Discovery power from hypothesis test on profile likelihood test-statistic

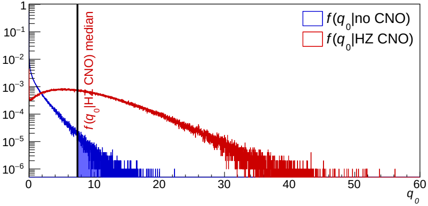
$$q_0 = -2\left[\ln L(0, \hat{\hat{\theta}}) - \ln L(\hat{\mu}, \hat{\theta})\right]$$

Minimized NLL assuming no CNO → $\ln L(0, \hat{\hat{\theta}})$

Minimized NLL w/ free CNO → $\ln L(\hat{\mu}, \hat{\theta})$

q_0 says how well a model with **no CNO** describes the data

1. Derive distribution of q_0 from pseudo-experiment with **no CNO injected** (null hypothesis, H_0)
2. Derive distribution of q_0 from pseudo-experiment with **CNO injected** according to HZ (HZ hypothesis, H_1)
3. Compute the **(median) discovery power** as the p-value of H_0 corresponding to the median value of H_1



Systematic uncertainty evaluation

Statistical sensitivity:
Build the parameters distributions from thousands of toy-MC experiments.

σ of the distribution = sensitivity
(Agreement with errors obtained on the data)

Model's Systematics:
Build the parameter distribution from thousands of **distorted** toy-MC experiments.
Including: energy scale, uniformity of detector response, shape of $\mathcal{L}_{PR}$ and **theoretical ^{210}Bi spectrum**

$$\sqrt{\sigma^2(\text{distorted}) - \sigma^2(\text{undistorted})} = \text{systematic uncertainty}$$