The latest Borexino results on the CNO neutrino studies

I. Drachnev on behalf of the Borexino collaboration

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The Borexino Collaboration

Borexino Collaboration

Università degli Studi di Milano

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LNGS

Princeton University

Università degli Studi di Genova

National Research Center "Kurchatov Institute"

St. Petersburg Nuclear Physics Inst.

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University of Houston

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Gran Sasso Science Institute — Center for Advanced Studies, Istituto Nazionale di Fisica Nucleare

Università degli Studi di Ferrara

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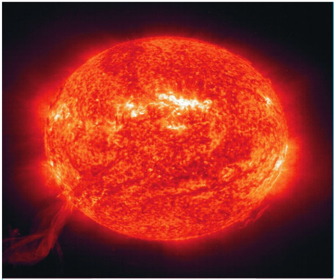
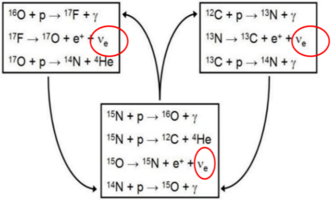
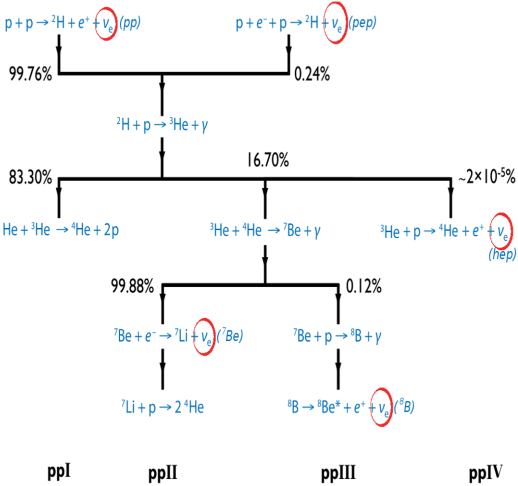
Solar neutrino sources







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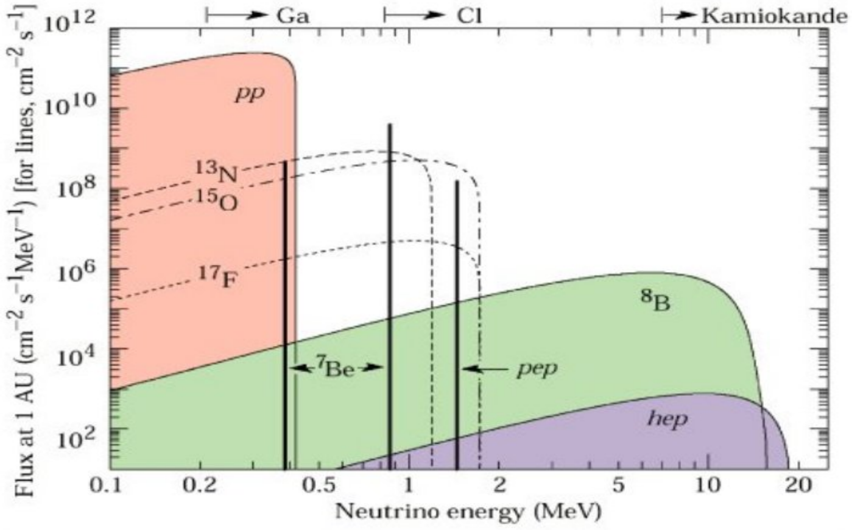
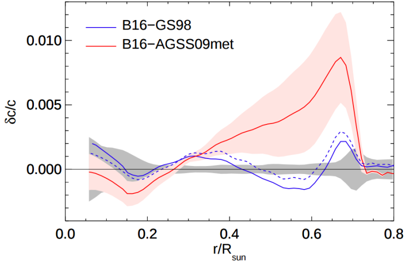


Solar neutrino problem: Solar models

Element	GS98	AGSS09met
C	8.52 ± 0.06	8.43 ± 0.05
N	7.92 ± 0.06	7.83 ± 0.05
O	8.83 ± 0.06	8.69 ± 0.05
Ne	8.08 ± 0.06	7.93 ± 0.10
Mg	7.58 ± 0.01	7.53 ± 0.01
Si	7.56 ± 0.01	7.51 ± 0.01
S	7.20 ± 0.06	7.15 ± 0.02
Ar	6.40 ± 0.06	6.40 ± 0.13
Fe	7.50 ± 0.01	7.45 ± 0.01
$(Z/X)_\odot$	0.02292	0.01780

(from N. Vinyoles et al. The Astrph. Journ. 835 1 (2017))



Flux	B16-GS98	B16-AGSS09met	Solar[a]	Chg.
$\Phi(pp)$	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.005)$	$5.97^{(1+0.006)}_{(1-0.005)}$	0.0
$\Phi(pep)$	$1.44(1 \pm 0.01)$	$1.46(1 \pm 0.009)$	$1.45^{(1+0.009)}_{(1-0.009)}$	0.0
$\Phi(hep)$	$7.98(1 \pm 0.30)$	$8.25(1 \pm 0.30)$	$19^{(1+0.63)}_{(1-0.47)}$	-0.7
$\Phi(^7Be)$	$4.93(1 \pm 0.06)$	$4.50(1 \pm 0.06)$	$4.80^{(1+0.050)}_{(1-0.046)}$	-1.4
$\Phi(^8B)$	$5.46(1 \pm 0.12)$	$4.50(1 \pm 0.12)$	$5.16^{(1+0.025)}_{(1-0.017)}$	-2.2
$\Phi(^{13}N)$	$2.78(1 \pm 0.15)$	$2.04(1 \pm 0.14)$	≤ 13.7	-6.1
$\Phi(^{15}O)$	$2.05(1 \pm 0.17)$	$1.44(1 \pm 0.16)$	≤ 2.8	-8.1
$\Phi(^{17}F)$	$5.29(1 \pm 0.20)$	$3.26(1 \pm 0.18)$	≤ 85	-4.2

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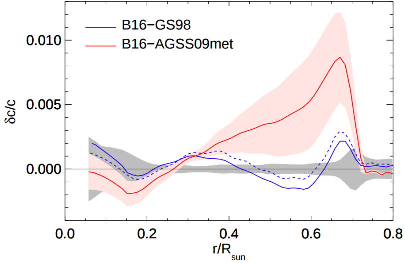

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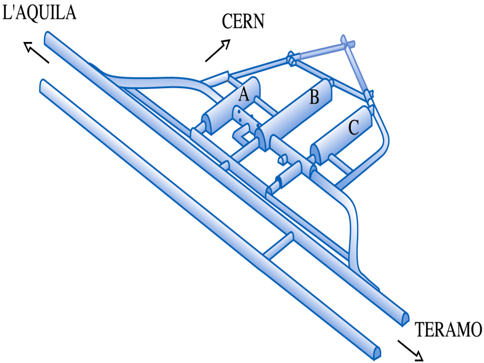
Borexino detector

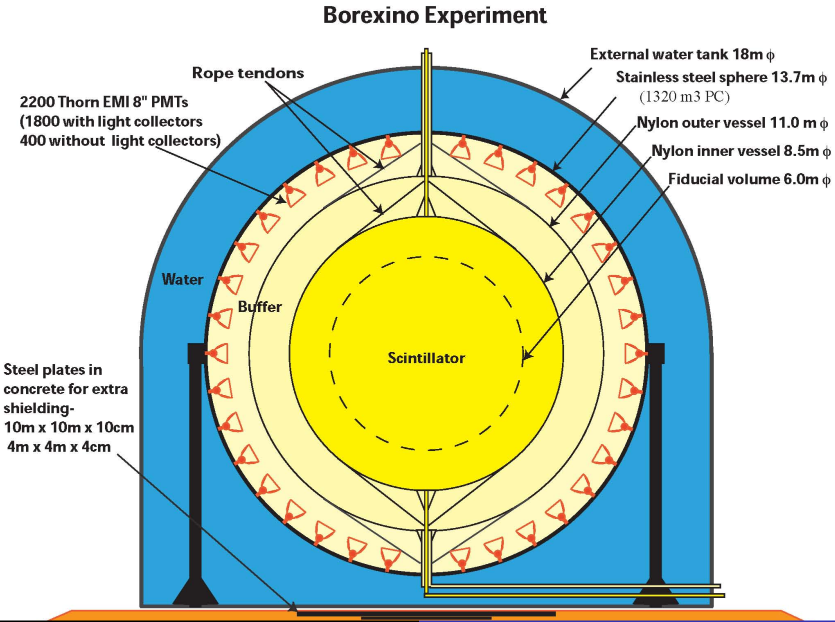
Borexino is a liquid scintillator neutrino detector, located in Hall C of Gran Sasso National Laboratory (LNGS)



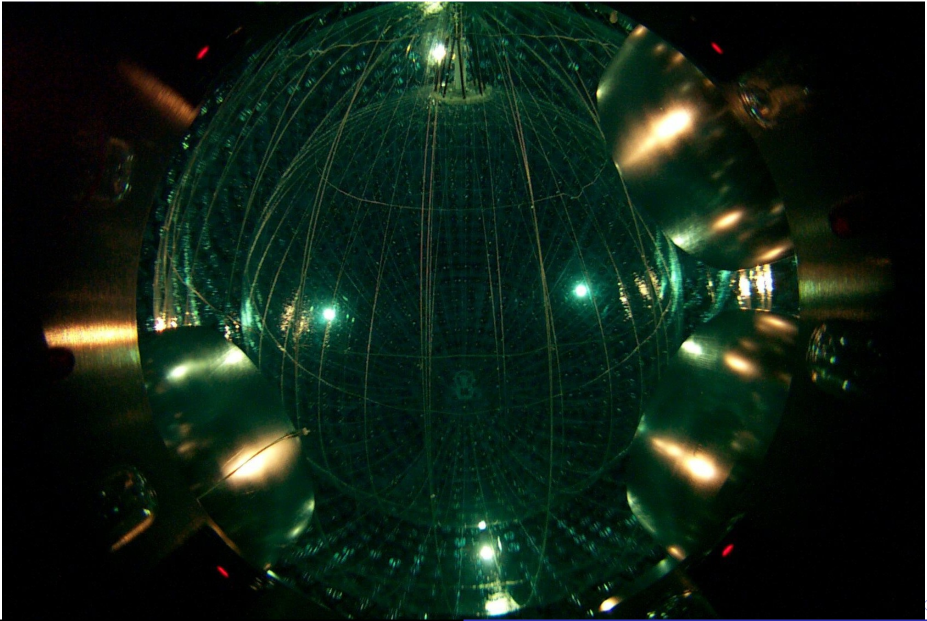
LNGS tunnels

Borexino detector

Borexino construction



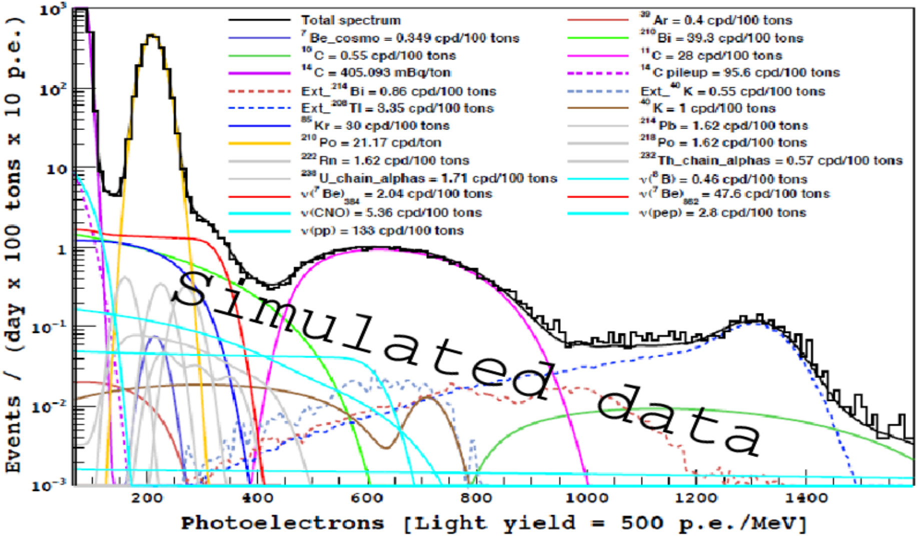
Borexino construction



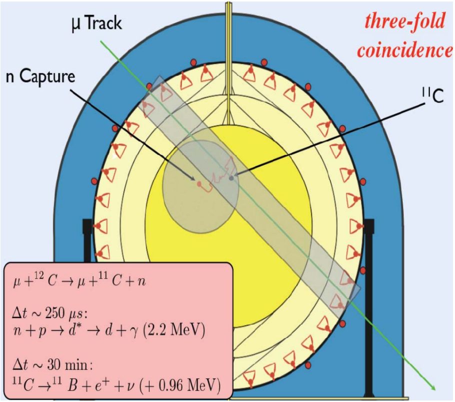
Radiopurity of the detector

Isotope	Typical abundance (source)	Borexino goals	Borexino-I	Borexino-II
^{14}C / ^{12}C, g/g	10^{-12} (cosmogenic)	$\sim 10^{-18}$	$2.7 \cdot 10^{-18}$	$2.7 \cdot 10^{-18}$
^{238}U, g/g (^{214}Bi-^{214}Po)	10^{-6}-10^{-5} (dust)	$\sim 10^{-16}$ (1 µBq/т)	$(1.6 \pm 0.1) \cdot 10^{-17}$	$< 9.4 \cdot 10^{-20}$ (95%)
^{232}Th, g/g (^{212}Bi-^{212}Po)	10^{-6}-10^{-5} (dust)	$\sim 10^{-16}$	$(6.8 \pm 1.5) \cdot 10^{-18}$	$< 5.7 \cdot 10^{-19}$ (95%)
^{222}Rn (^{238}U), ev/d/100 t	100 atoms/cm^3 (air)	10	1	0.1
^{40}K, g[K_{nat}]/g	$2 \cdot 10^{-6}$ (dust)	$\sim 10^{-15}$	$< 1.7 \cdot 10^{-15}$ (95%)	---
^{210}Po, ev//d/t	Surface contamination	$\sim 10^{-2}$	80 (initial), $T_{1/2}$=134 days;	2
^{210}Bi, ev/d/100 t	Inequilibrium with ^{222}Rn or ^{210}Pb	Not specified	20-70	~20
^{85}Kr ev/d/100 t	1 Bq/m^3 (technogenic, air)	~1	30.4±5 cpd/100t	< compatble with 0
^{39}Ar ev/d/100 t	17 mBq/m^3 (cosmogenic in air)	~1	<<^{85}Kr	

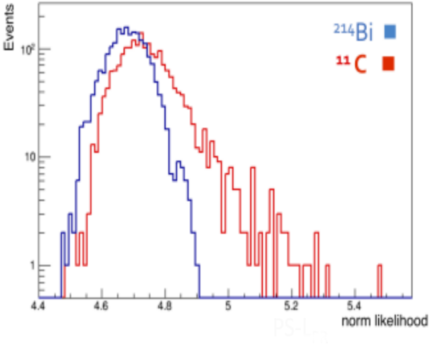
Borexino backgrounds



^{11}C discrimination

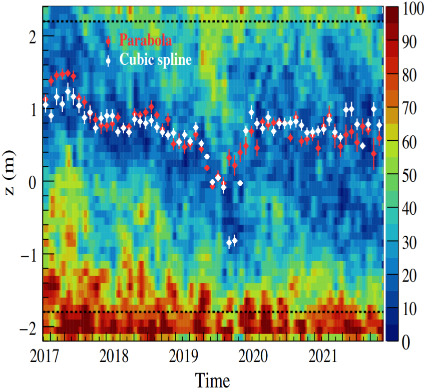


TFC algorithm gives efficiency of 92.4 $\pm$ 4% for the price of 36 % live time loss



Normalized likelihood of TOF position reconstruction gives additional information on e^+/e^- content

^{210}Bi upper limit

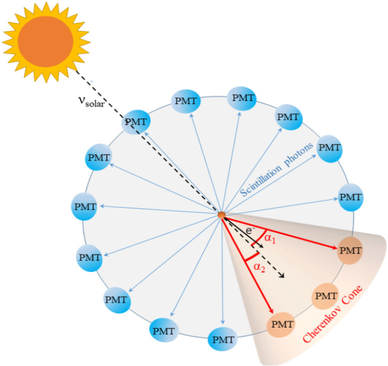


^{210}Po evolution fitted by 10 cm z-slices within $x^2 + y^2 < 2$ m^2 on monthly basis

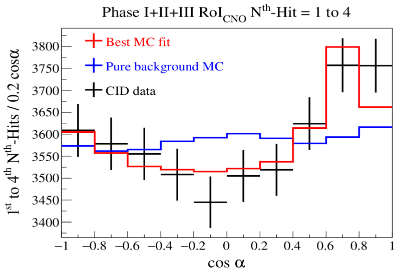
The final LPoF fit is then performed on the aligned dataset in 20 - 25 tonnes, depending on the method, on approximately 6000 - 9000 ^{210}Po events. The final ^{210}Bi upper limit including all systematic uncertainties is

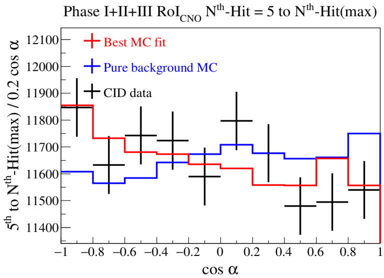
10.8 $\pm$ 1 counts/day/100 tonnes.

Directional sensitivity

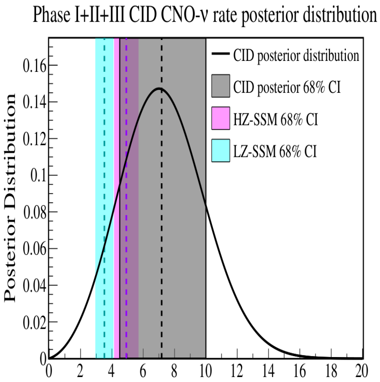


Čerenkov light unlike the scintillation is correlated with the direction to the Sun and could be discriminated temporally





Directional sensitivity



The angular distribution could be fitted with uniform MC background and a neutrino component giving a result on the CNO rate.
The likelihood obtained could be used independently or be injected in a standard spectral fit.

Detector response modelling

The detector response is described with two approaches:

Monte-Carlo simulation:

- High-precision simulation (Borexino Coll. arXiv:1704.02291 (2017).)
- Rigid response without free parameters
- Some of effects could be out of scope

Analytical modeling

- Dedicated response model (O. Ju. Smirnov. Instruments and Experimental Techniques No.2 (2003))
- Free parameters allowing to follow detector evolution
- More event flux correlations

The two approaches were used for cross-checks

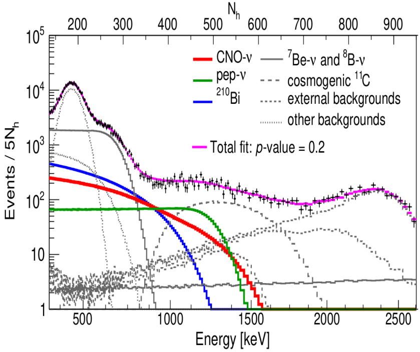
analysis approach

The analysis is based on spectral fit with binned maximum likelihood method:

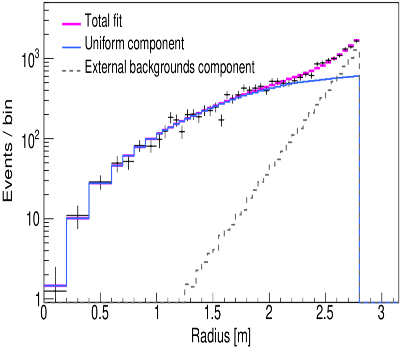
$$\mathcal{L} = \mathcal{L}_{sub} \times \mathcal{L}_{enh} \times \mathcal{L}_{radial} \times \mathcal{L}_{pos\_lik} \times \mathcal{L}_{CID} \times \mathcal{L}_{Bi\_pull}$$

Additional information is provided through radial, pulse-shape and CID distribution fits as well as through pull terms for values estimated independently (e.g. ^{210}Bi)

Spectral fit results

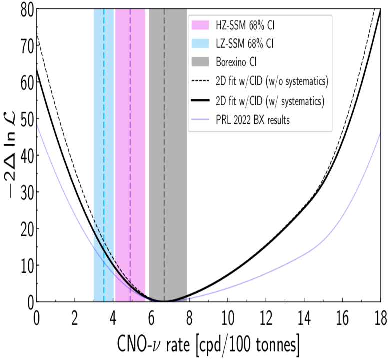


Fit of the subtracted Borexino spectrum according to the full procedure



fit of the radial event distribution performed with MC PDFs

Spectral fit results



Results of the Borexino CNO measurement

The outcoming measurements of the CNO rate are

- $7.2^{+2.8}_{-2.7}$ counts/day/100 tonnes without Bi constraint; no-CNO hypothesis including the pep constraint only is rejected at 5.3σ level
- $6.7^{+1.2}_{-0.8}$ counts/day/100 tonnes with Bi constraint; no-CNO hypothesis including the pep constraint is rejected at $\approx 8\ \sigma$ level

Conclusions

- The updated CNO measurements have been performed
- $7.2^{+2.8}_{-2.7}$ counts/day/100 tonnes are obtained **without Bi constraint**; no-CNO hypothesis is rejected at 5.3σ level
- $6.7^{+1.2}_{-0.8}$ counts/day/100 tonnes is the ultimate result; no-CNO hypothesis is rejected at $\approx 8\ \sigma$ level

References

- Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment Volume 600, Issue 3, 11 March 2009, Pages 568-593.
- Improved Measurement of Solar Neutrinos from the Carbon-Nitrogen-Oxygen Cycle by Borexino and Its Implications for the Standard Solar Model Phys. Rev. Lett. 129, 252701 (2022) [DOI:10.1103/PhysRevLett.129.252701]
- Final results of Borexino on CNO solar neutrinos, arXiv:2307.14636v1 [hep-ex] 27 Jul 2023
- First Directional Measurement of Sub-MeV Solar Neutrinos with Borexino Phys. Rev. Lett. 128, 091803 [doi:10.1103/PhysRevLett.128.091803]

Thank You for Your attention