Spectral fit of Borexino Phase-III data for the detection of CNO solar neutrinos

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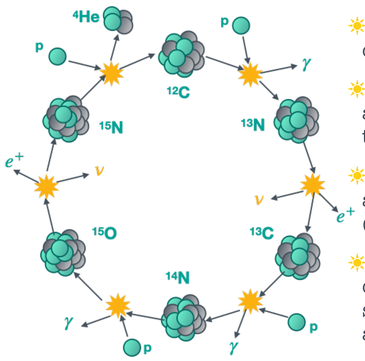
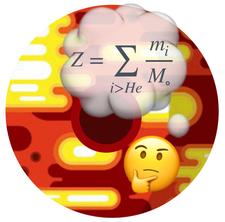
Why CNO solar neutrinos?



- **Proof of principle** of star energy production via carbon - nitrogen - oxygen (CNO) cycle
- Important for astrophysics studies of the Sun and heavier stars where the process is expected to be dominant
- Sensitive to **Sun core metallicity (Z) problem**: almost 30% difference in predictions from high (HZ) vs low (LZ) Standard Solar Models [1]
- Two-fold dependence on Z: indirectly through core temperature and opacity (as for the pp-chain solar neutrinos) + directly dependent on the amount of carbon and nitrogen.

Solar ν	Expected Flux (HZ)	Expected Flux (LZ)	Difference (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}]	4.93 (1± 0.06)	4.50 (1± 0.06)	8.7%
^{8}B [10^{6} cm^{-2} s^{-1}]	5.46 (1± 0.12)	4.50 (1± 0.12)	17.6%
CNO [10^{8} cm^{-2} s^{-1}]	4.88 (1± 0.11)	3.51(1± 0.11)	28.1%

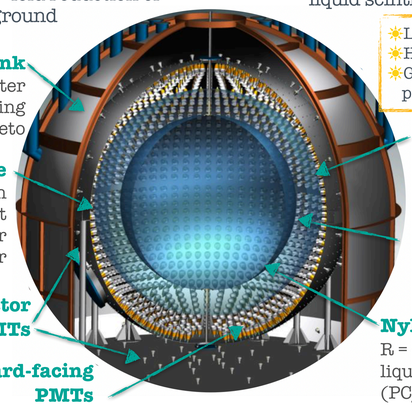


Borexino experiment

Laboratori Nazionali del Gran Sasso (LNGS) location: 10^6 fold reduction of the cosmogenic background

Purity: the most radiopure liquid scintillator

- Low-energy threshold
- High light yield
- Good energy and position resolution



Water tank
R = 9 m, 2.1 kt water
Shielding
Cherenkov muon veto

Stainless Steel Sphere
R = 6.85 m
PMTs support
Buffer + scintillator container

208 Outer Detector PMTs

2212 Inward-facing PMTs

Nylon Outer Vessel
R = 5.5 m
Barrier for ^{222}Rn from steel, PMTs etc.

Buffer
Pseudocumene (PC) + DMP quencher

Nylon Inner Vessel
R = 4.25 m, ~ 300 t of liquid scintillator (PC/PPO solution)

See Poster #297

Purification I → **Phase I (2007-2010)**: First observations of some low-energy solar neutrino components

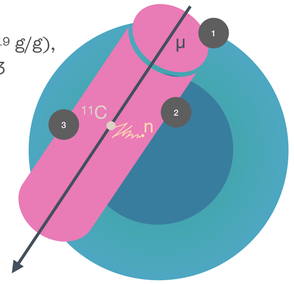
Purification II → **Phase II (2012-2016)**: Comprehensive measurement of all pp-chain solar neutrino components

Thermal insulation → **Phase III (2016-)**:
- Stabilized detector
- CNO detection

Signals and Backgrounds

Detection channel: neutrino electron elastic scattering

Internal backgrounds :
After purifications: ^{232}**Th** and ^{238}**U** negligible (~10^{-19} g/g), ^{85}**Kr** reduced by factor ~ 4.6; ^{210}**Bi** reduced by ~ 2.3
^{210}**Po** - the only α-decay background, key to its parent, ^{210}Bi, constraint

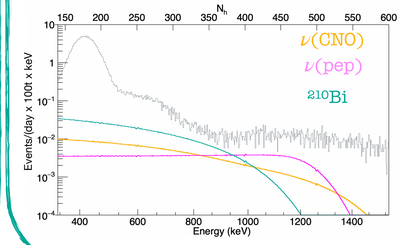


Cosmogenic background
Calculate for each event the likelihood to be ^{11}**C** through the three fold coincidence:

$$\mu + {}^{12}C \rightarrow \mu + {}^{11}C + n \quad (1)$$
$$n + p \rightarrow D + \gamma_{(2.2\ MeV)} \quad (250\ \mu s) \quad (2)$$
$$^{11}C \rightarrow {}^{11}B + e^+ + \nu_e \quad (\sim 30\ min) \quad (3)$$

External backgrounds
γs from ^{208}**Tl**, ^{214}**Bi**, ^{40}**K** - efficient reduction by fiducial volume selection + radial dependence

Solar neutrinos
Yesterday's signal = today's background:
pp-chain neutrinos: ν**(pp)**, ν**(**^{7}**Be)**, **and** ν**(pep)**



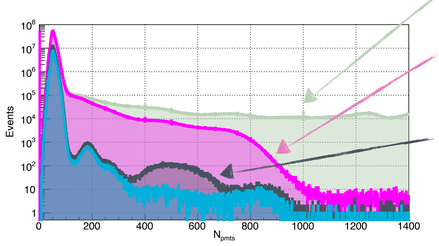
Example from Phase II

Challenges of CNO neutrinos detection
- Low rate of ν(CNO)
- Shape similar to ^{210}Bi and ν(pep)
- Strong correlations → need independent constraints:
  - ^{210}Bi: link with ^{210}Po
  - ν(pep): solar luminosity constraint

See Poster #212

Data Selection and Creation of PDFs

Dataset: July 2016 - February 2020
Exposure: 1071,95 days x 71.3 tons



Data selection main steps:

- All data
- muon and muon daughter cuts: 300 ms after crossing muons
- Fiducial volume (FV) cut: R<2.8 m; -1.8m <z<2.2m
- Three fold coincidence tag (^{11}C veto) -> ^{11}C depleted energy spectrum

Creation of Probability Density Functions (PDFs) :

Generating all species + uniform electrons (flat in energy) in the full Borexino Monte Carlo → Applying cuts on uniform electron sample → PDFs for uniform (MC e-) and external backgrounds radial distributions

Generating all species + uniform electrons (flat in energy) in the full Borexino Monte Carlo → Applying cuts on all components → PDFs for all neutrinos and backgrounds energy spectra

Scintillation light generation and propagation, electronics response, and energy and position reconstruction

See Poster #181

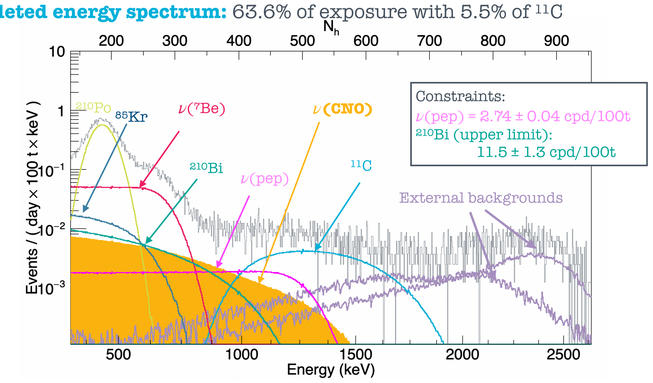
Normalised with the fraction of events passing the cuts to the number of events generated in FV

All set for the spectral fit!

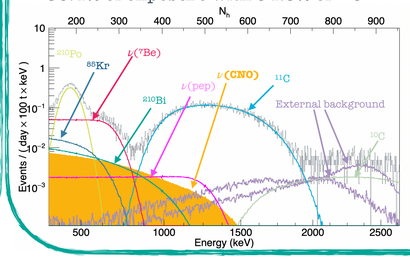
Spectral Fit of Phase-III data

A multivariate fit with the likelihood $\mathcal{L}_{MV}(\theta)=\mathcal{L}_{dep}(\theta)\cdot\mathcal{L}_{enr}(\theta)\cdot\mathcal{L}_{Rad}(\theta)$

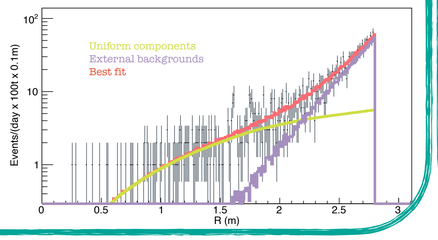
^{11}C depleted energy spectrum: 63.6% of exposure with 5.5% of ^{11}C



^{11}C enriched spectrum
36.4% of exposure with 94.5% of ^{11}C

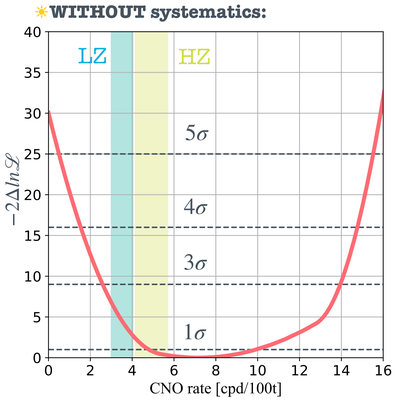


Radial distribution:
Improve disentanglement of external from the internal contaminants



Conclusions

WITHOUT systematics:



First detection of CNO neutrinos

- Building likelihood profile by performing multivariate spectral fits:
  - Best fit value: CNO = 7.2 cpd/100t
  - Significance without systematics: 5.48 σ
  - Significance with systematics: see the talk and [2]

See Talk by G. Ranucci

- Systematics include: light yield, non-uniformity, non-linearity of detector response, ^{210}Bi shape, ^{11}C peak position, event selection criteria

See Poster #438

- Counting analysis - compatible results

See Poster #93

- Discrimination between HZ and LZ not yet possible

References

[1] A New Generation of Standard Solar Models - Astrophys. J. 835, 2, 202 (2017)
[2] new Borexino arXiv submission
[3] Sensitivity to neutrinos from the solar CNO cycle in Borexino. arXiv:2005.12829
[4] Comprehensive measurement of pp-chain solar neutrinos Nature 562, p 496
[5] Simultaneous precision spectroscopy of pp, Be7, and pep solar neutrinos with Borexino PhaseII. Review D 100 p. 08200
[6] The Monte Carlo simulation of the Borexino detector Astroparticle Physics 97, p136