Drawing by Alina Vishneva

New Borexino CNO result with full Phase-III dataset

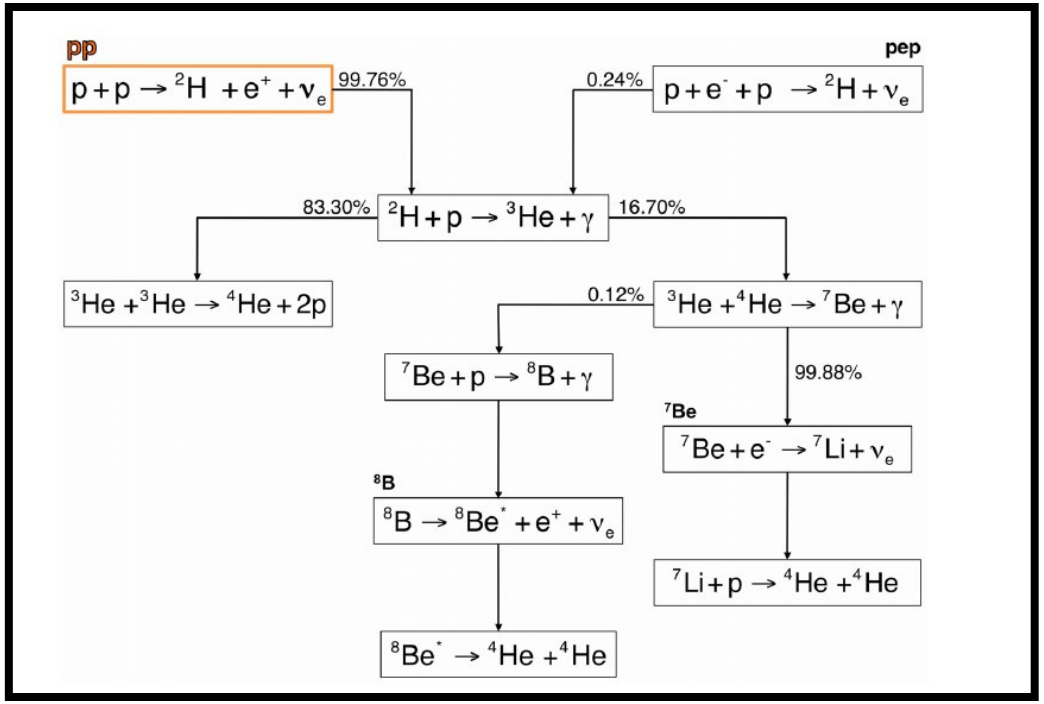
Barbara Caccianiga-
INFN and University of Milano
(on behalf of the Borexino Collaboration)

The CNO cycle

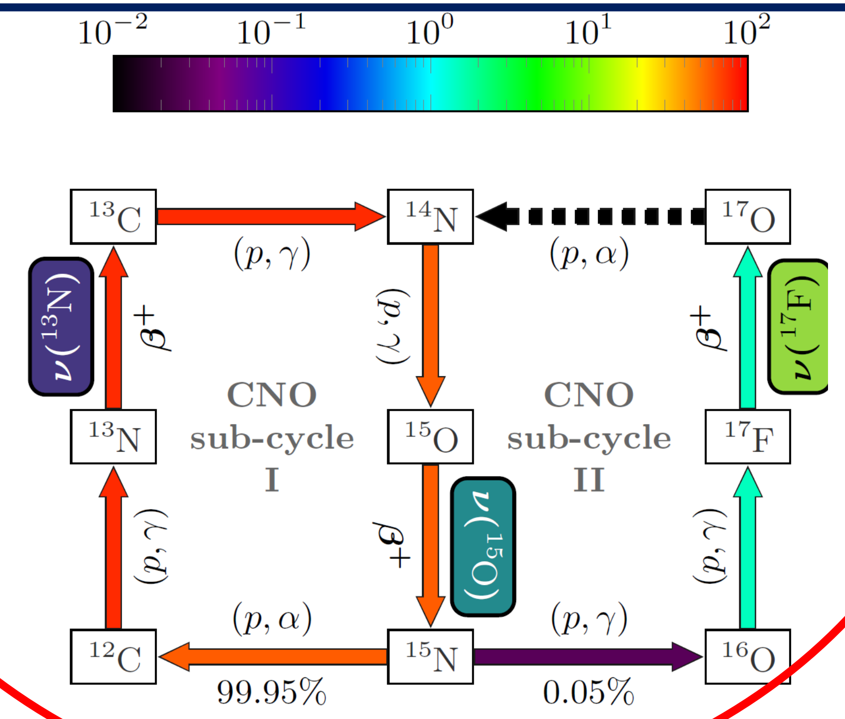
The Sun is powered by nuclear reactions occurring in its core

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

pp CHAIN:
~99% of the Sun energy

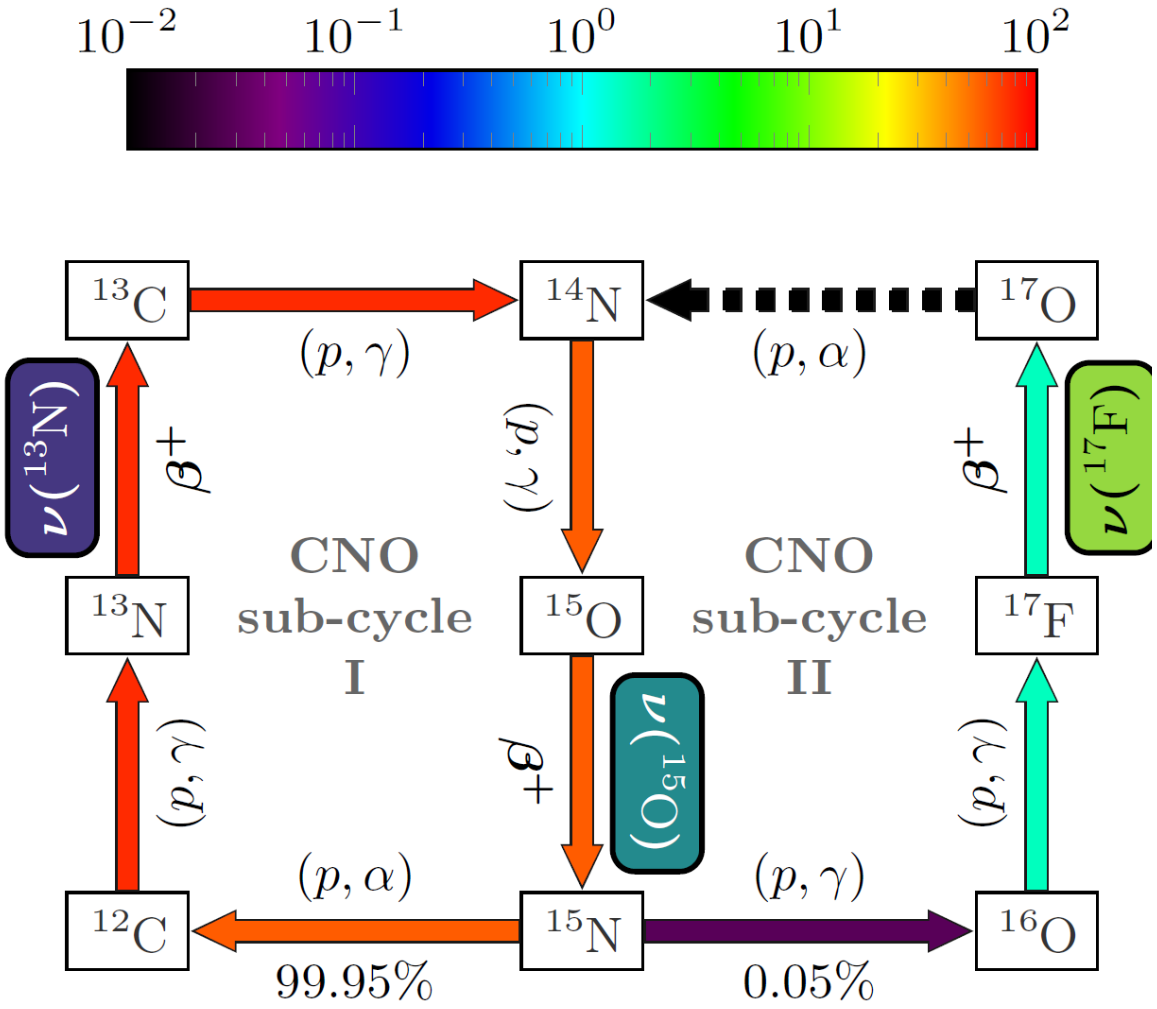


CNO CYCLE:
<1% of the sun energy

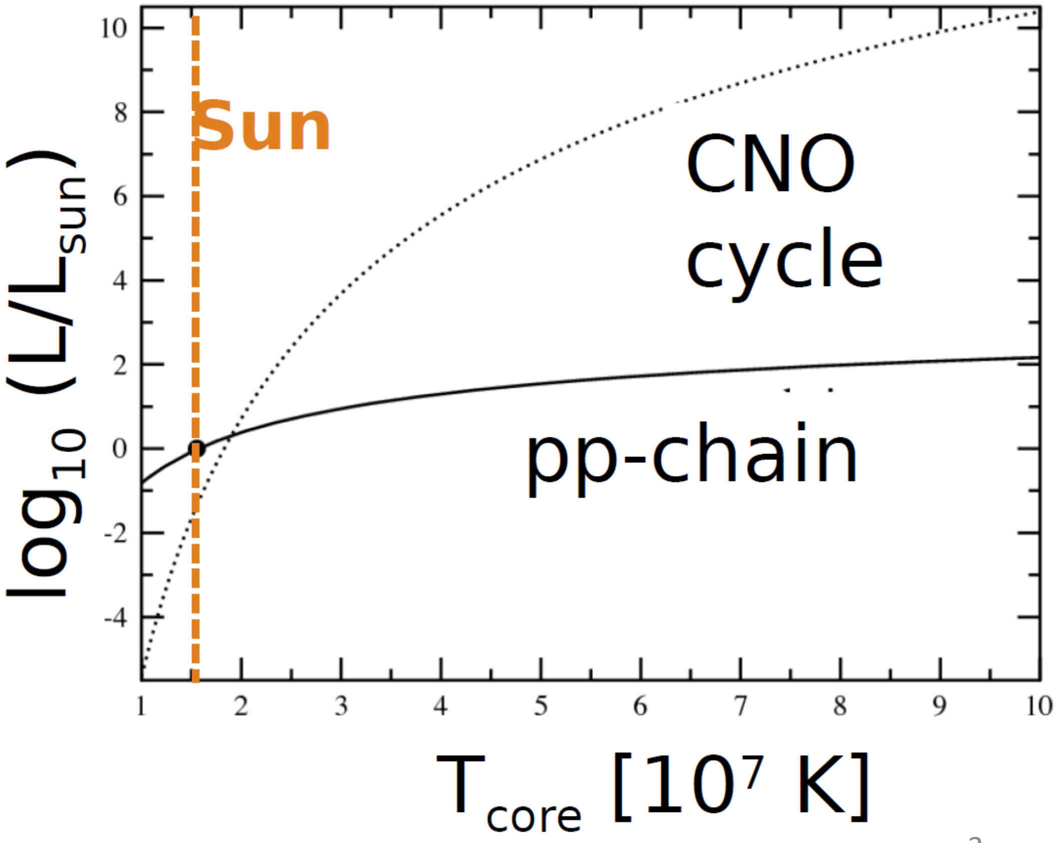


The CNO cycle

$$4\,p \rightarrow \alpha + 2\,e^{+} + 2\nu$$

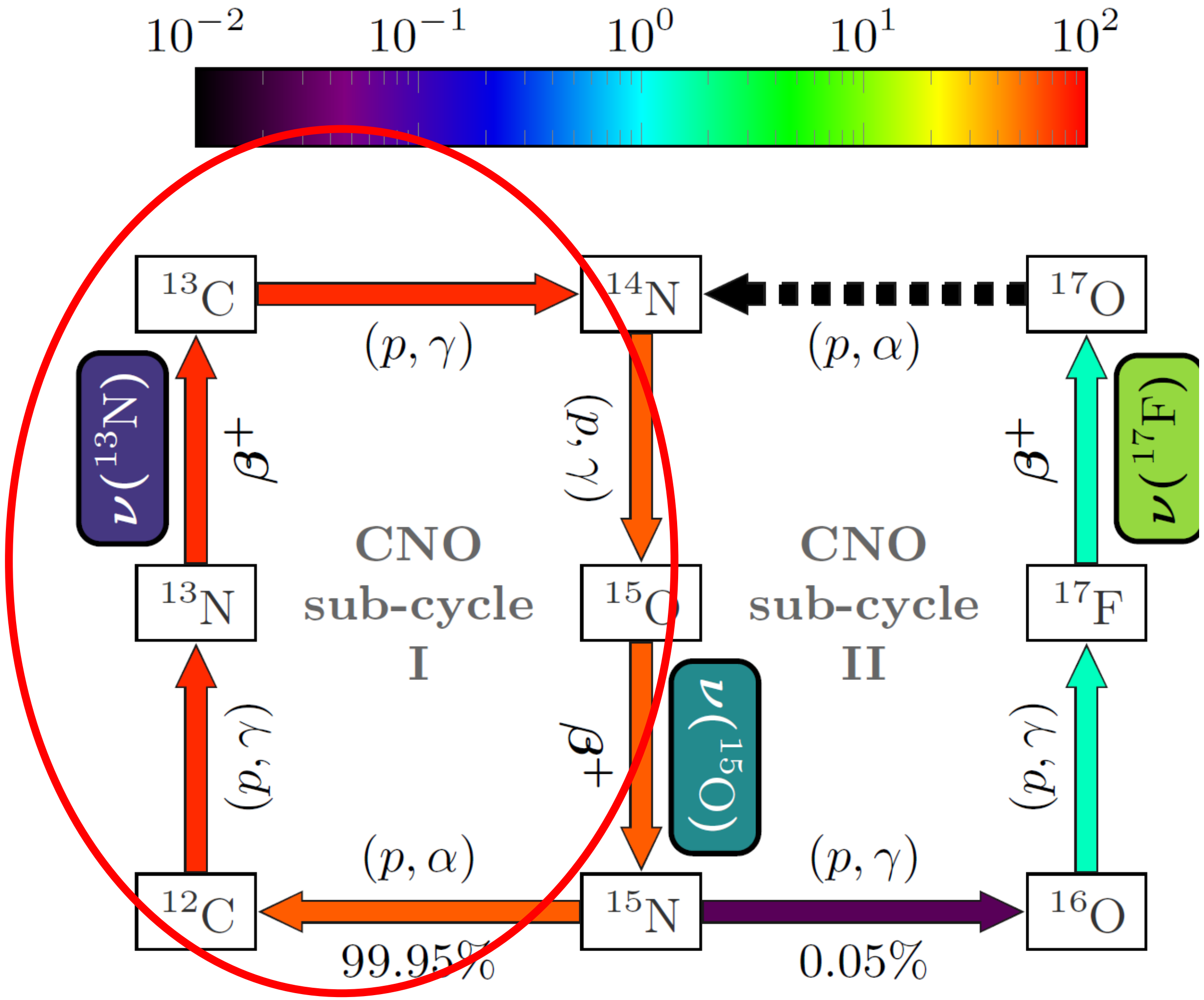


- The CNO cycle is sub-dominant in the Sun;
- It is dominant in more massive Stars;



The CNO cycle

$4p \rightarrow \alpha + 2e^+ + 2\nu$

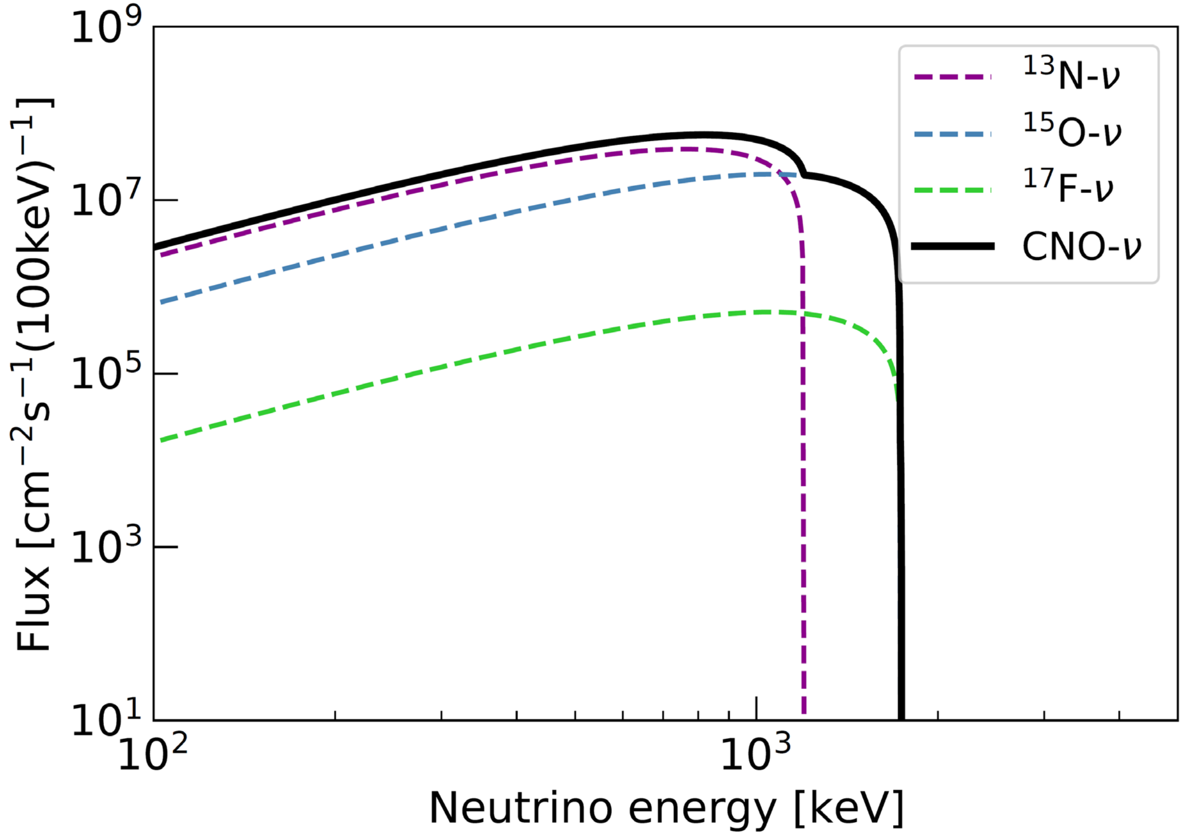


- Sub-cycle I (involving CN) is dominant over sub-cycle II (involving NO);
- Neutrinos are emitted in two reactions:

$^{13}N \rightarrow {}^{13}C + e^+ + \nu_e$ (E_{max} = 1.20 MeV)

$^{15}O \rightarrow {}^{15}N + e^+ + \nu_e$ (E_{max} = 1.74 MeV)

The CNO cycle



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Note that in Borexino we cannot disentangle the N from O. We fix the relative ratio between the two according to the SSM predictions;

The importance of studying CNO

- The experimental proof of the existence of the CNO cycle is important in itself, since CNO is a crucial process for energy production in Stars and was never observed experimentally before 2020;
- First evidence (5σ) presented by Borexino in 2020;

NEW!
Evidence reinforced in this new publication

Moreover

- Unlike the proton-proton chain, CNO depends directly on the content of pre-existing element C - N - O catalyzing the reaction;

NEW!
Info on solar metallicity in this new publication

Studying CNO will give direct experimental information on the solar metallicity;

The importance of studying CNO

The solar metallicity puzzle

- Metallicity of the Sun: abundance of elements with Z>2 (C, N, O, Ne, Mg, Si, S,Ar, Fe…);
- Metallicity is obtained from spectroscopic measurement of the photosphere and from studies of meteorites;
- Metallicity is an input of the Standard Solar Models (SSMs are calibrated on it);
- Metallicity influence significantly the outputs of SSM (influences→ opacity→Temperature)

Two observables to cross-check SSM

Helioseismology

Study of the sound wave propagation on the surface of the Sun;

Solar neutrinos

Study of the flux of solar neutrinos from the different nuclear reactions

The importance of studying CNO

The solar metallicity puzzle

1998

GS98*: **high metallicity**

Uses 1D hydrodynamical model of solar atmosphere

Z/X= 0.023

Helioseismology: ok

Grevesse et al.,Space Sci.Rev.* *(1998***)*85]*

→

2009

AGS09met*: **low metallicity**

Uses 3D hydrodynamical model of solar atmosphere

Z/X= 0.018

Helioseismology: ko

**A. Serenelli er al., Astr. J. 743,(2011)24*

→

2011

Caffau11*: **low metallicity**

Uses 3D hydrodynamical model of solar atmosphere

Z/X= 0.0209

Helioseismology: ko

**E.Caffau et al., Sol.Phys. (2011) 268*

→

2021

AGG21*: **low metallicity**

Uses 3D hydrodynamical model of solar atmosphere

Z/X= 0.0187

Helioseismology: ko

**Asplund et al .Rev.Astr.Astr A&A (2021) 653*

→

2022

MB22*: **high metallicity**

Uses 3D hydrodynamical model of solar atmosphere

Z/X= 0.0225

Helioseismology: ok

Magg et al., arXiV:2203.02255

The importance of studying CNO

The predictions for solar neutrinos depends on the input metallicity:

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

	FLUX	Dependence on T	SSM-/HZ (1)	SSM-/LZ(2)	DIFF. (HZ-LZ)/HZ
pp chain	pp (10^{10} cm^{-2} s^{-1})	$T^{-0.9}$	5.98(1±0.006)	6.03(1±0.005)	-0.8%
	pep (10^{8} cm^{-2} s^{-1})	$T^{-1.4}$	1.44(1±0.01)	1.46(1±0.009)	-1.4%
	^{7}Be (10^{9} cm^{-2} s^{-1})	T^{11}	4.94(1±0.06)	4.50(1±0.06)	8.9%
	^{8}B (10^{6} cm^{-2} s^{-1})	T^{24}	5.46(1±0.12)	4.50(1±0.12)	17.6%
CNO cycle	^{13}N (10^{8} cm^{-2} s^{-1})	T^{18}	2.78(1±0.15)	2.04(1±0.14)	26.6%
	^{15}O (10^{8} cm^{-2} s^{-1})	T^{20}	2.05(1±0.17)	1.44(1±0.16)	29.7%

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

(1) *SSM-HZ= B16-GS98: Vinyoles et al. Astr.J. 835 (**2017**) 202 + Grevesse et al.,Space Sci.Rev. (**1998**)85*
(2) *SSM-LZ= B16-AGSS09met: Vinyoles et al. Astr.J. 835 (**2017**) 202 + A. Serenelli er al., Astr. J. 743,(2011)24*

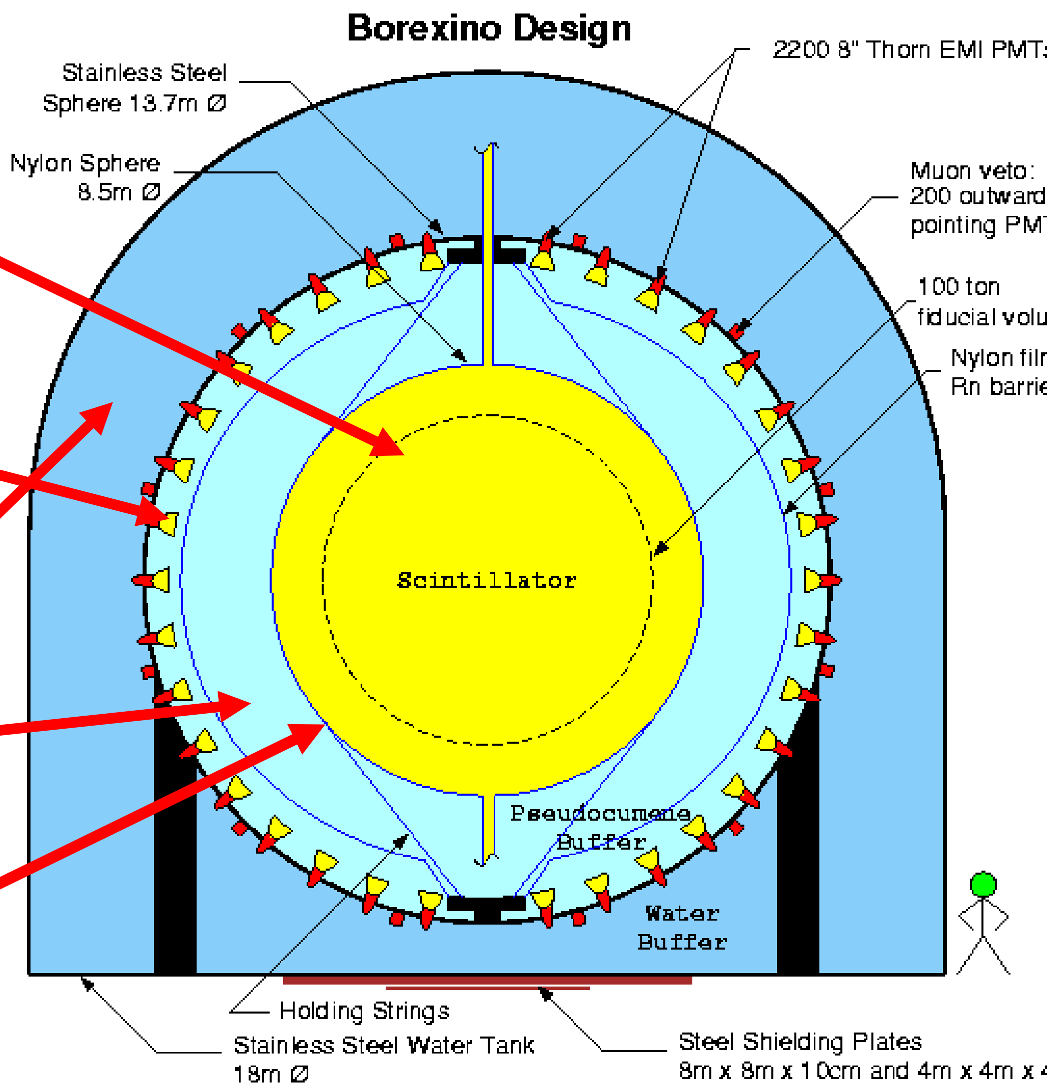
Borexino under the Gran Sasso mountain

Core of the detector: 300 tons of liquid scintillator (PC+PPO)

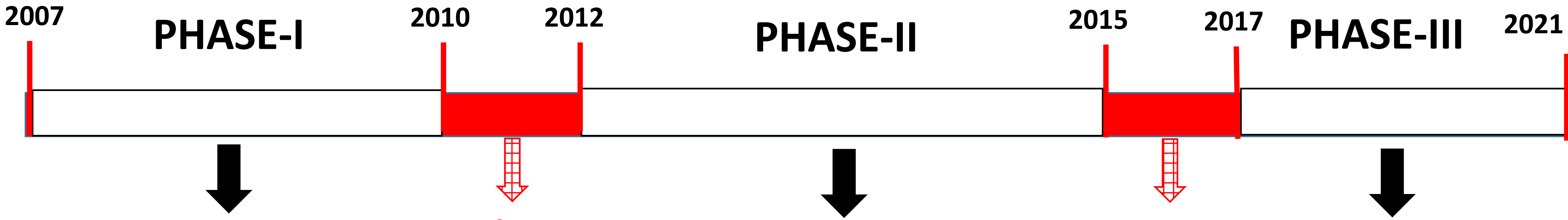
2214 photomultiplier tubes pointing towards the center to view the light emitted by the scintillator;

Shields to protect the scintillator from external background

Nylon Vessel: 4.25m spherical nylon vessel which contains the scintillator



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

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

PHASE 3 (2017-2021)

Solar neutrinos

2020: First detection of CNO neutrinos

October 2021: End of Borexino data-taking

Borexino: the long story..

2007 — PHASE-I — 2010 — 2012 — PHASE-II — 2015 — 2017 — PHASE-III — 2021

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;
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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 (2017-2021)

Solar neutrinos

2020: First detection of CNO neutrinos

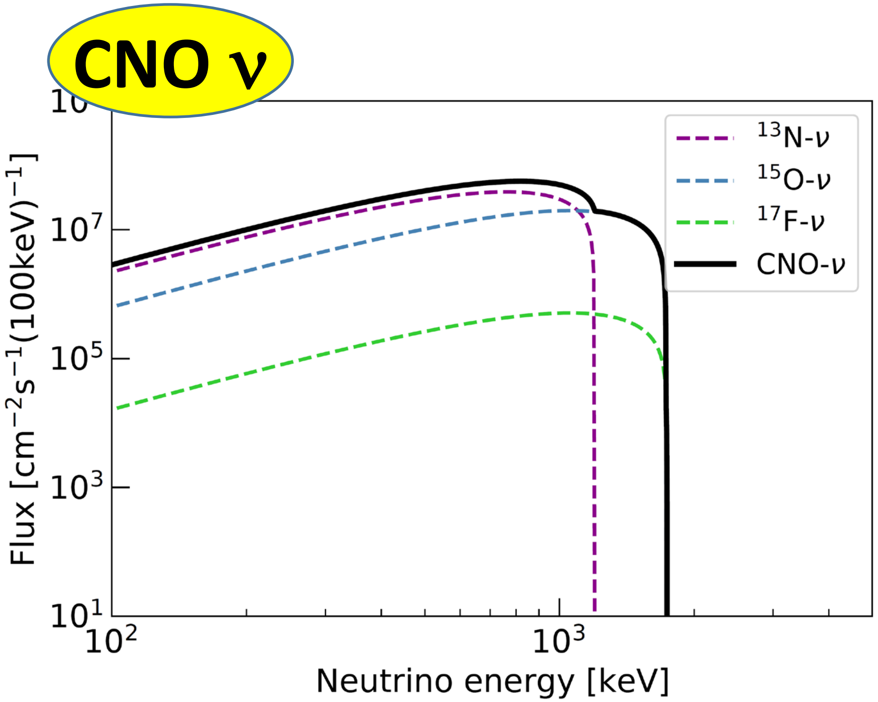
TODAY: New more precise result on CNO neutrinos

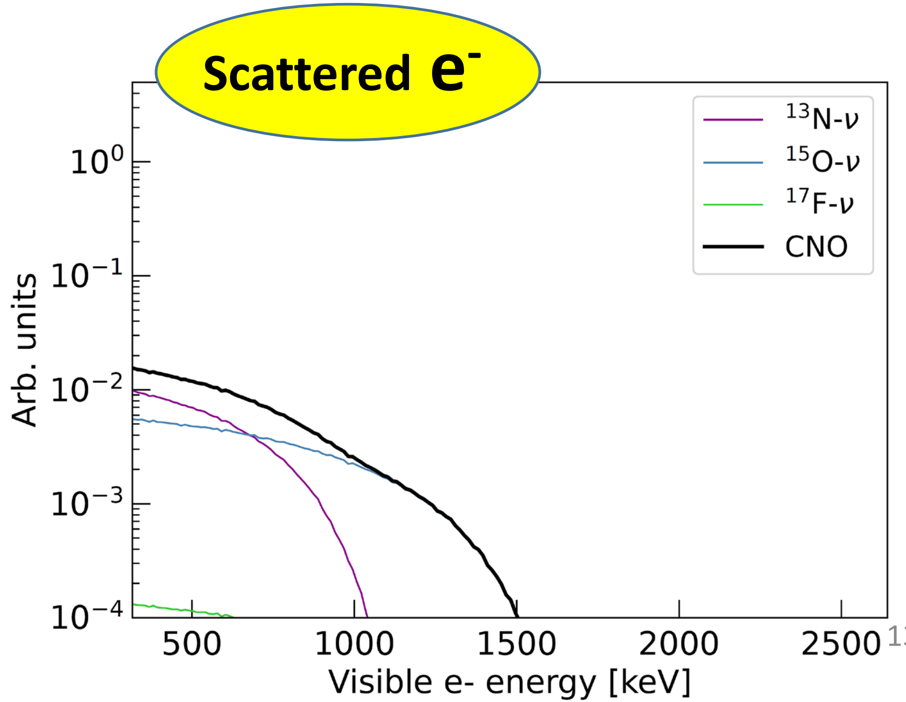
October 2021: End of Borexino data-taking

Borexino: essential ingredients (1)

Borexino detects neutrinos through scattering on electrons

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





Borexino: essential ingredients (2)

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 (3)

cons

Scintillation light is not directional

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

- **Extreme radiopurity needed!**

Borexino: the quest for the radiopurity Grail

15 years of work

- Purification of the scintillation (distillation, vacuum stripping with low Ar/Kr N2);
- Detector design: concentric shells to shield the inner scintillator from external background
- Material selection and surface treatment, clean construction and handling;

Achievements

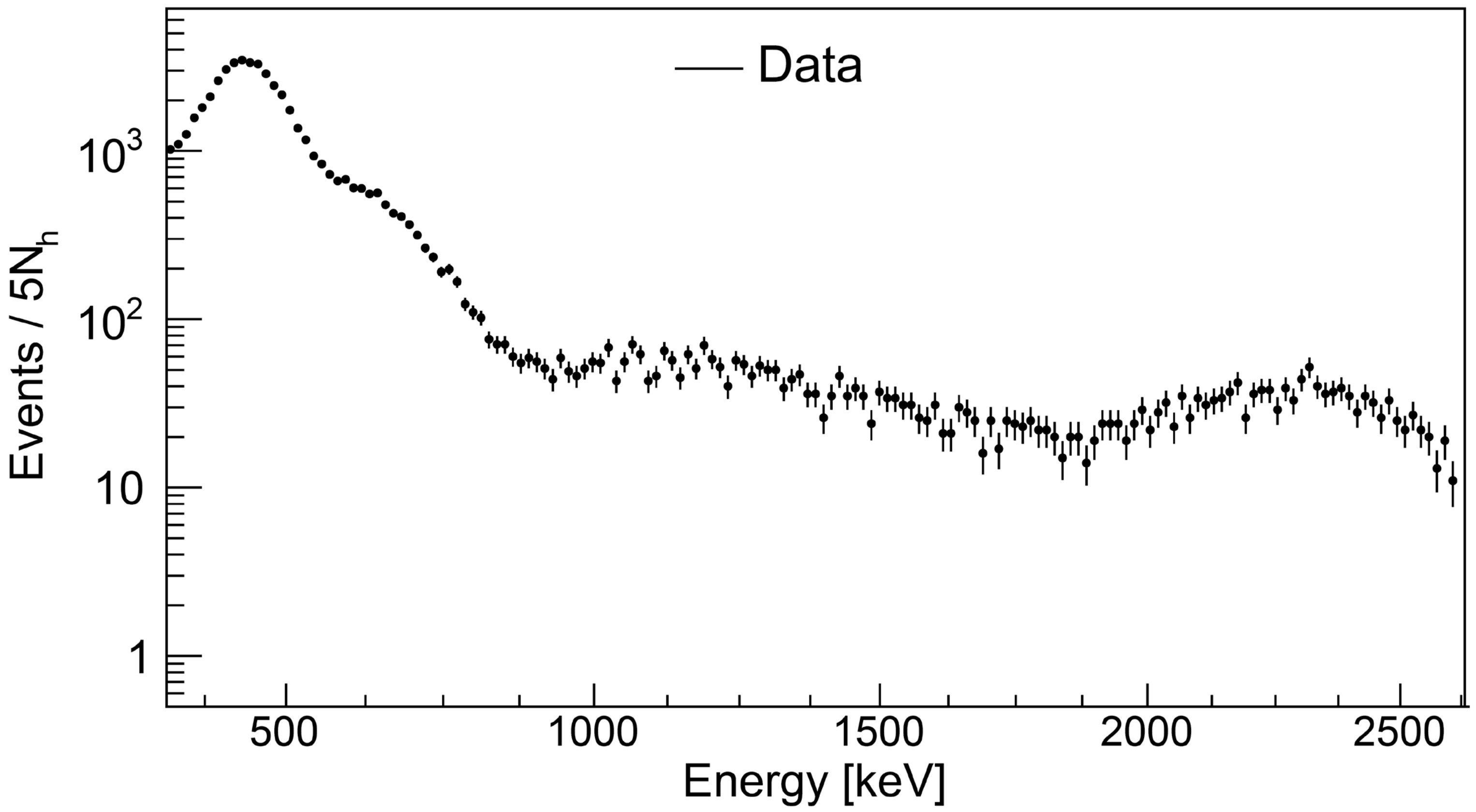
- Radiopurity even exceed design goals in some cases ^{238}U chain $<9.4x10^{-20}$ g/g and ^{232}Th chain $<5.7x\times10^{-19}$ g/g;
- Some background out of specifications (^{210}Po, ^{85}Kr, ^{210}Bi) ← **see later**

The search for CNO neutrinos

CNO neutrinos: the needle in a haystack

Extracting the CNO neutrino signal from data

Final Phase-III dataset: Jan 2017-Sep 2021; N_{ev}= 110000



Data set
Jan 2017 – sep 2021
(after selection cuts)

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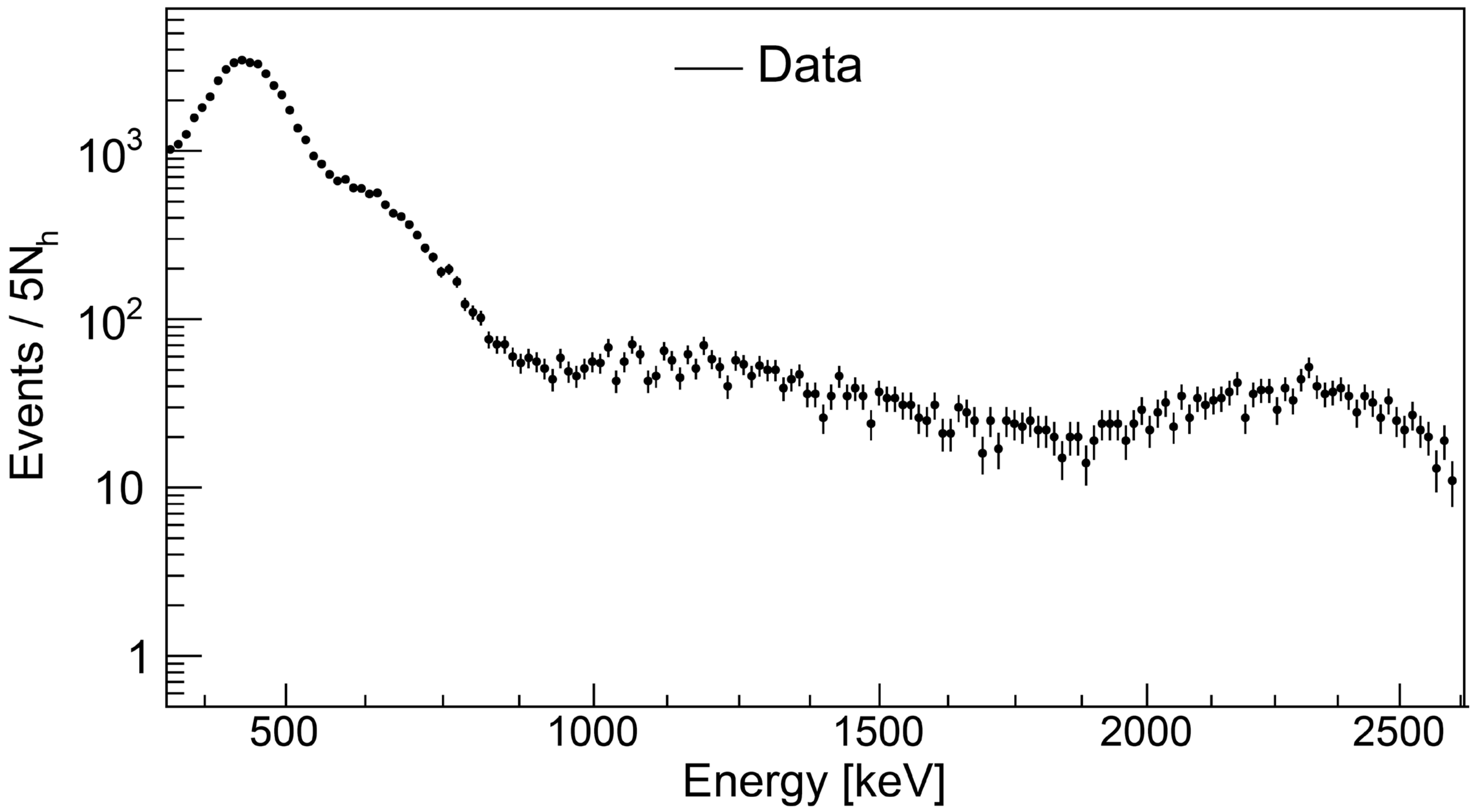

Data set
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(after selection cuts)

Where are CNO neutrinos?
only 5 counts/day/100t !

CNO neutrinos: the needle in a haystack

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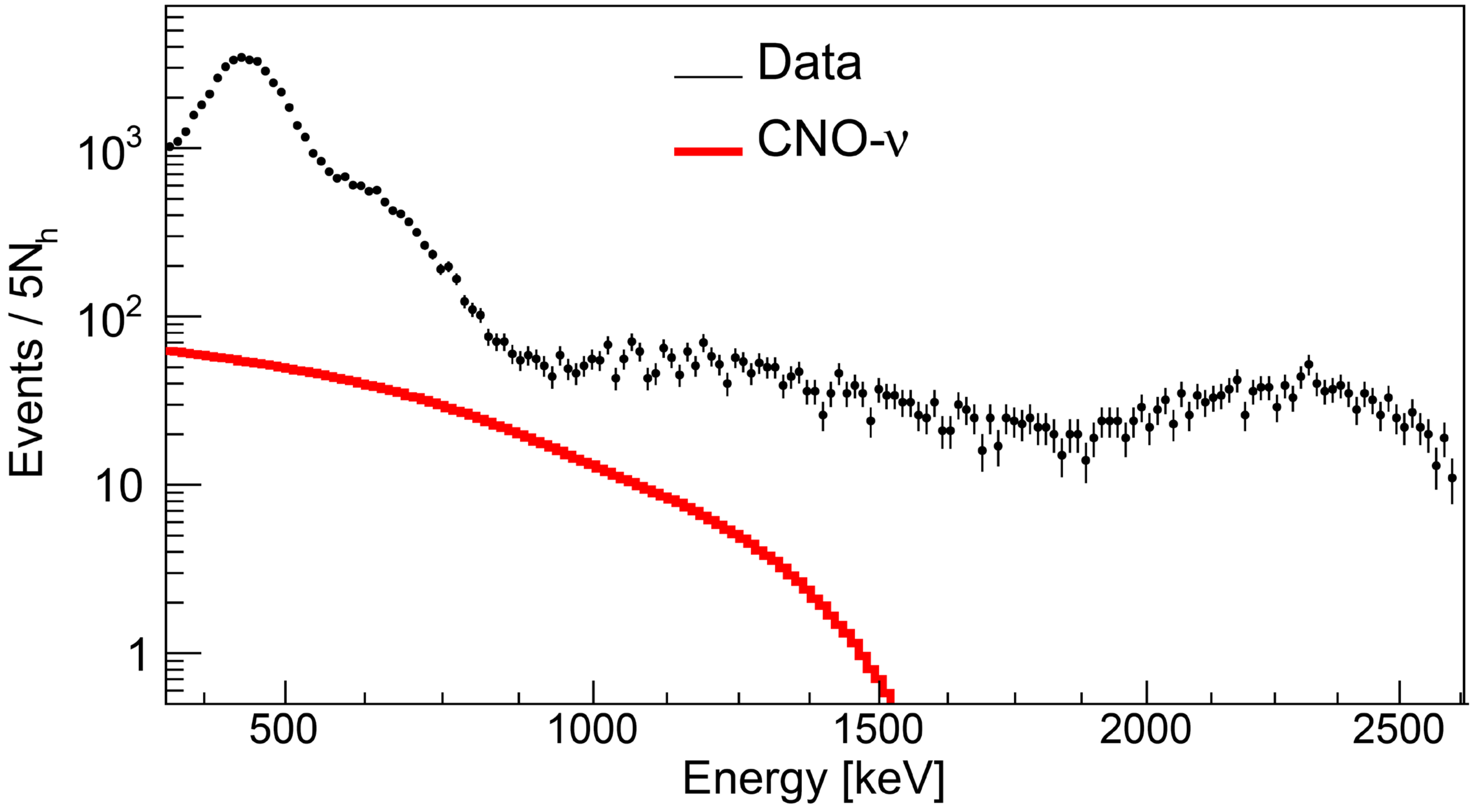

Data set
Jan 2017 – sep 2021
(after selection cuts)

Where are CNO neutrinos?
only 5 counts/day/100t !

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 and the radial 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 material 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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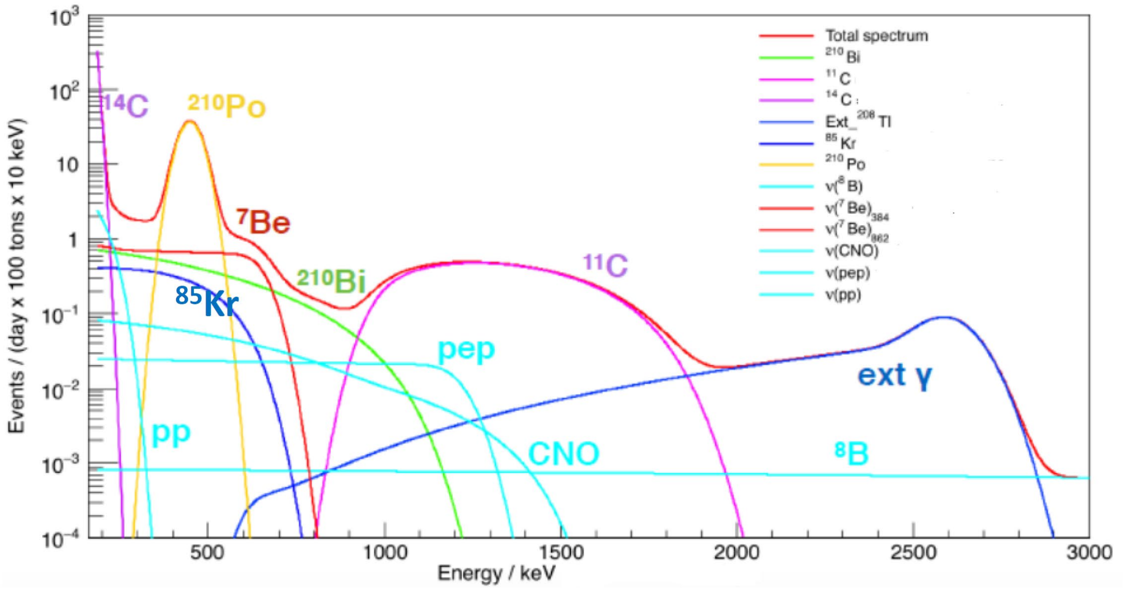


CNO neutrinos: the needle in a haystack

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

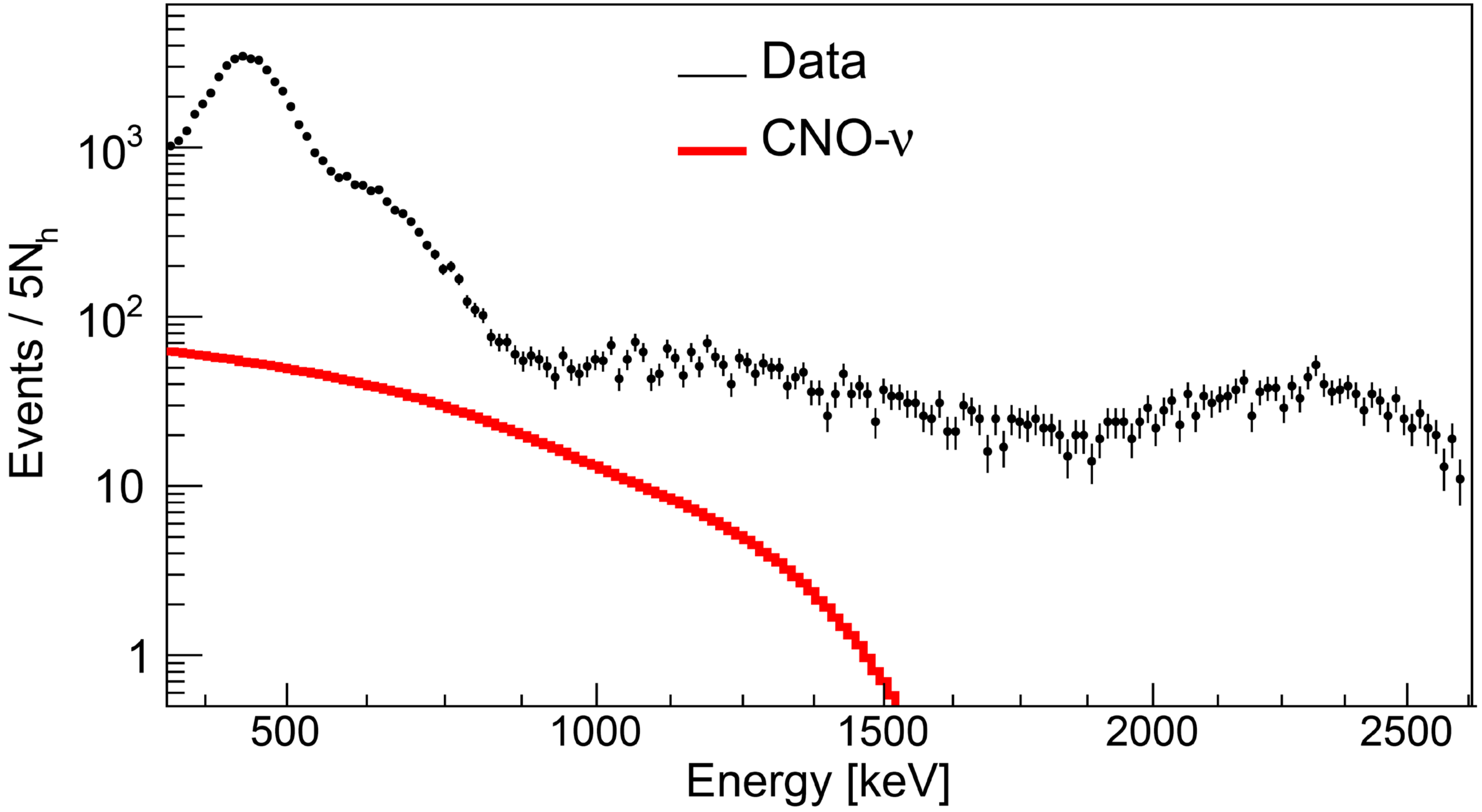
- A fit is performed to the energy distribution of events assumed to be the sum of signal and backgrounds;
- The spectral shapes are those determined with MC simulations;
- We include in the fit also the radial distribution of events to separate external backgrounds;
- **The rates of each species are the only free parameters of the fit;**

The problem of ^{210}Bi

CNO neutrinos: the problem of ^{210}Bi

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

Final Phase-III dataset: Jan 2017-Sep 2021; N_{ev}= 110000



THE PROBLEM

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

CNO neutrinos: the problem of ^{210}Bi

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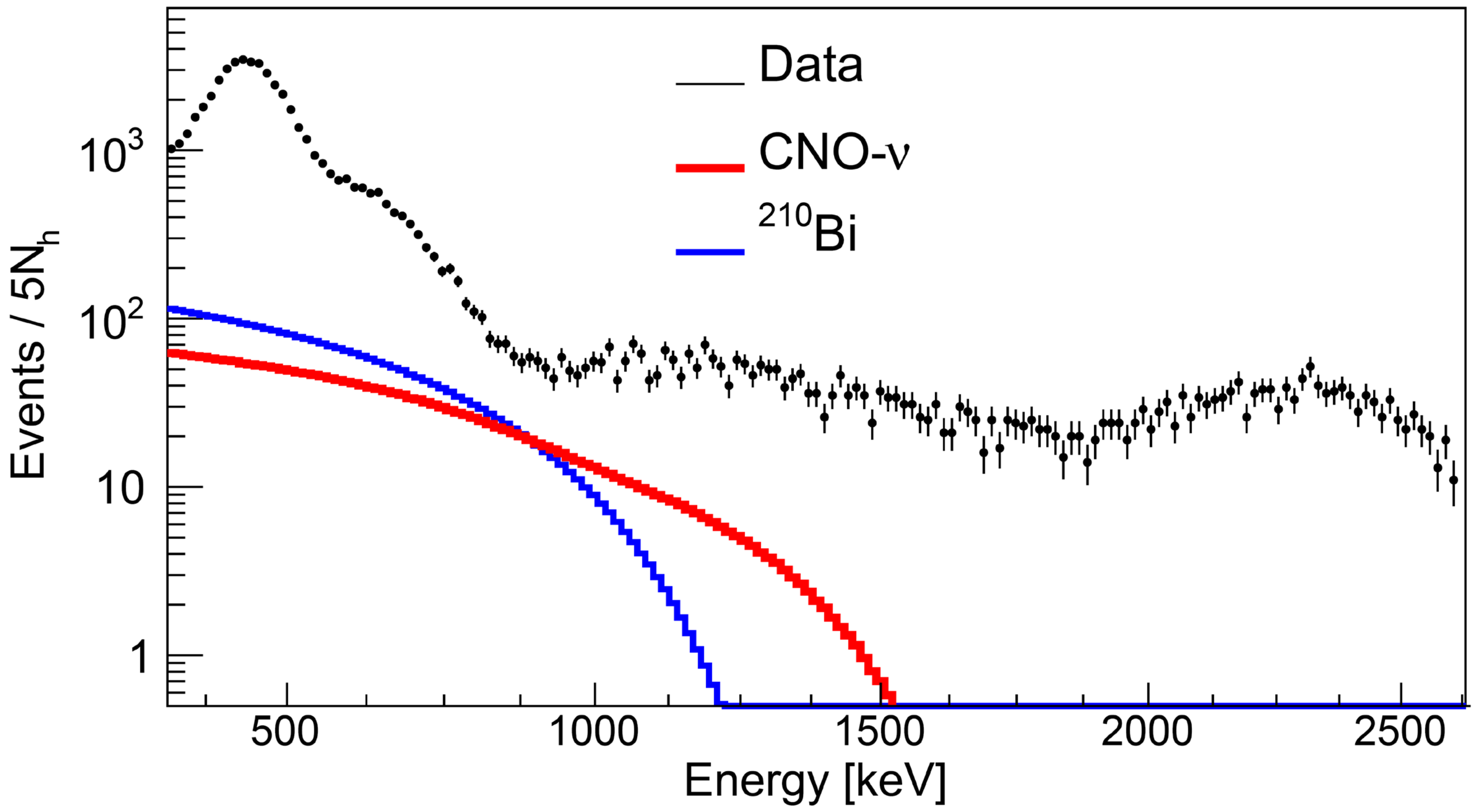
Final Phase-III dataset: Jan 2017-Sep 2021; N_{ev}= 110000



THE PROBLEM

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

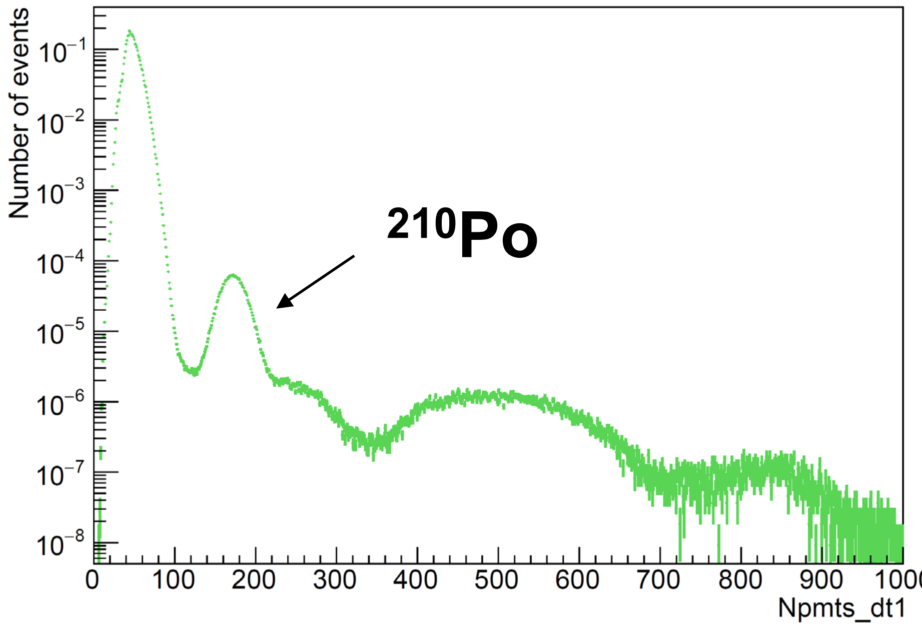
Need to determine the rate of ^{210}Bi independently in order to constrain it in the fit

CNO neutrinos: the problem of ^{210}Bi

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

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

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



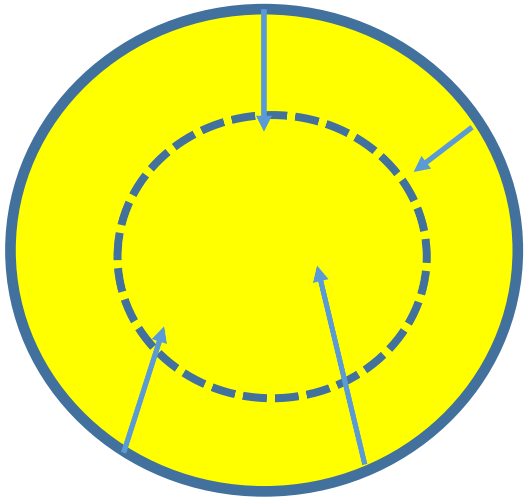
- At secular equilibrium, the rate of rate(^{210}Po) = rate(^{210}Bi);

- ^{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

PROBLEM

- We found 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;

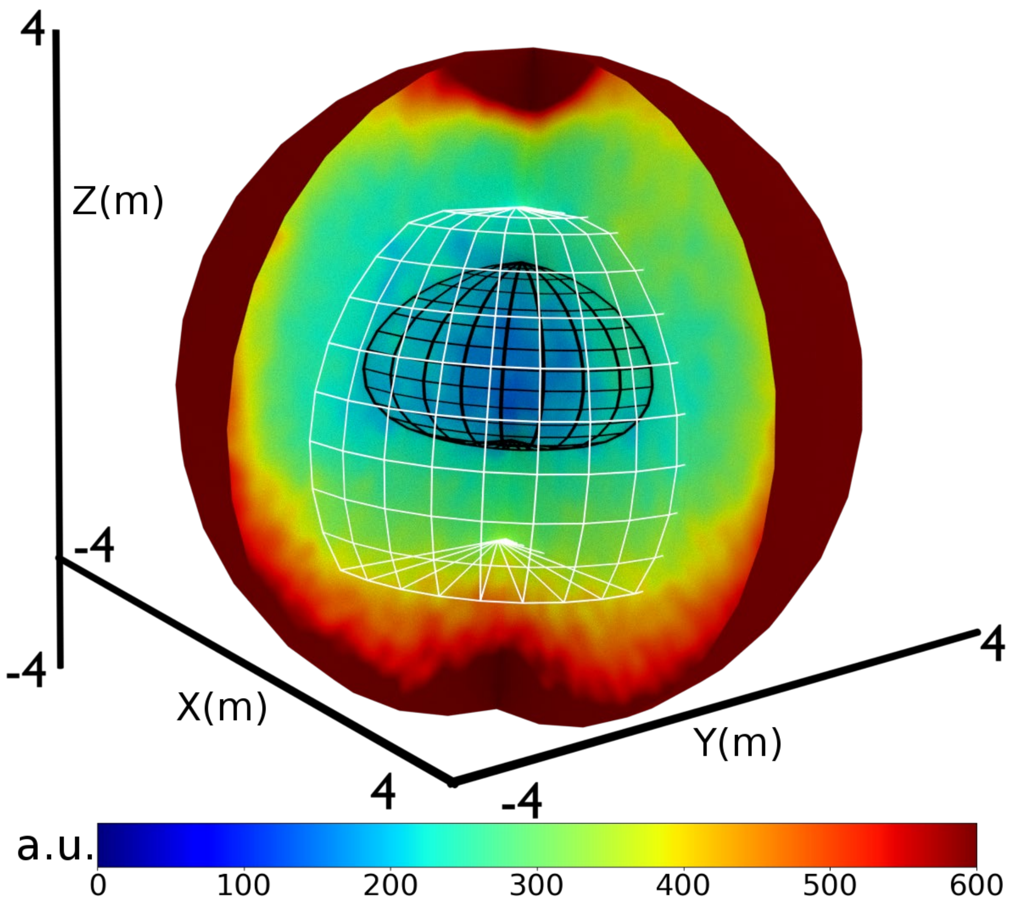
- In these conditions the secular equilibrium is broken and the tagging of ^{210}Bi with ^{210}Po gives misleading results, since ^{210}Po is the sum of two contributions:
- ^{210}Po from the ^{210}Pb chain (rate= ^{210}Bi)
- ^{210}Po from the vessel

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);
- Active temperature control system on the top of the tank to stabilize the Top/Bottom gradient (2016)

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

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

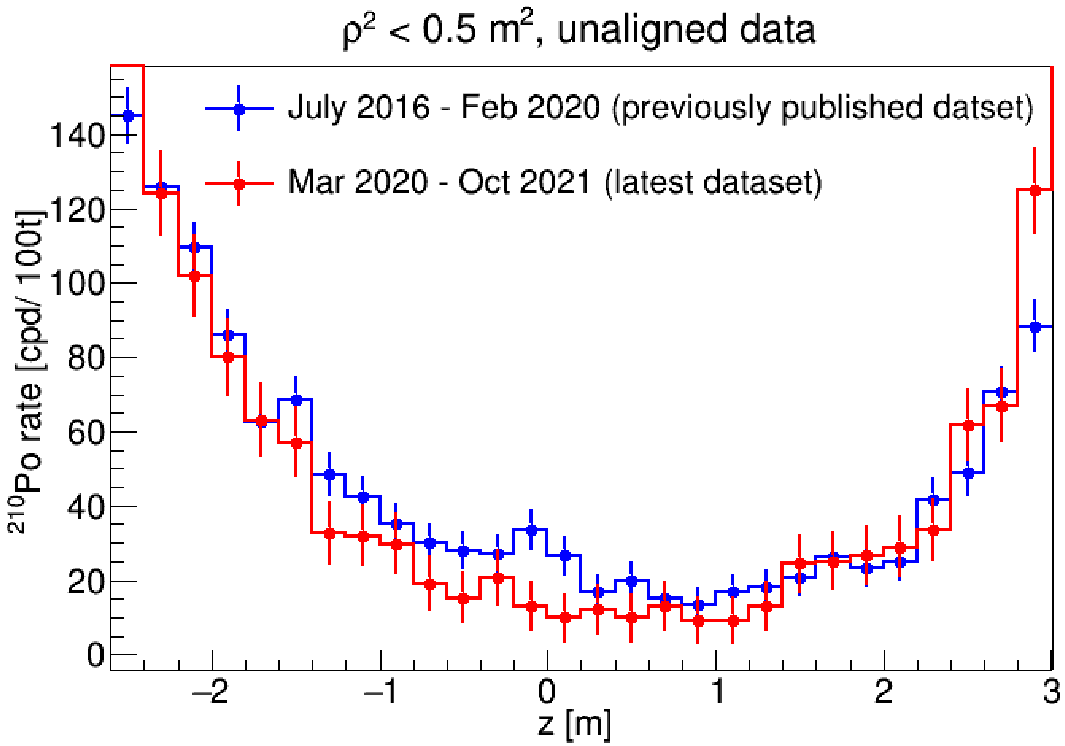
This provides an upper limit of ^{210}Bi rate

New results on CNO neutrinos

New results on CNO neutrinos: what's new?

What is new with respect to the previous publication (2020)?

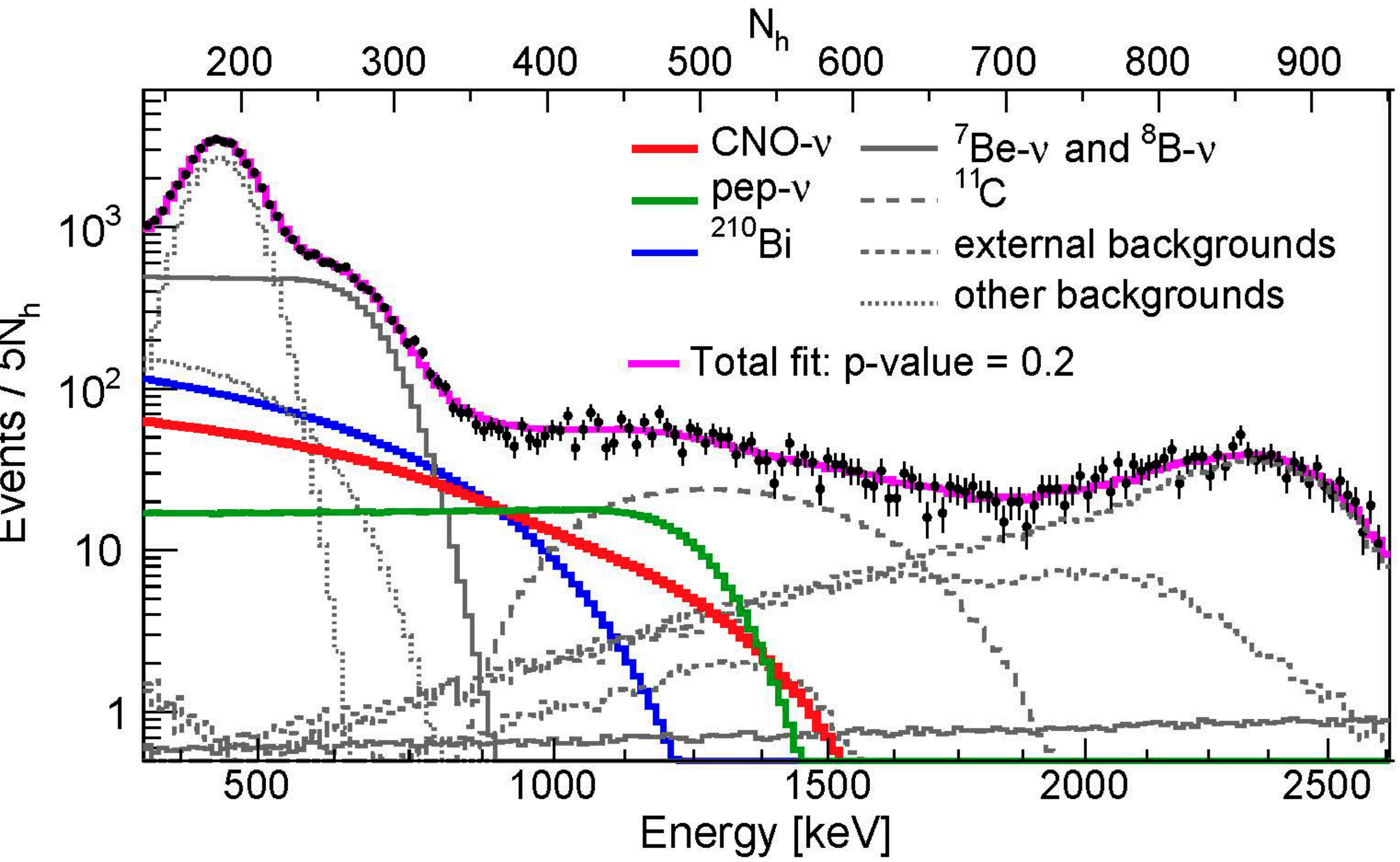
- Improvement of the MC wich gives the reference shapes for the fit;
- Exposure increased by ~ 33%
- Cleaner dataset: we removed the last 6 months of 2016 where contamination from unsupported ^{210}Po was still high;
- More stable temperature → less unsupported ^{210}Po → larger Low Polonium Field (LoPF) region;
- **This allows us to set a more stringent limit on ^{210}Bi;**



R (^{210}Bi) < 10.8+/- 1.0 counts/day/100t

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

New results on CNO neutrinos



Results (statistical errors only)

Rate(CNO)= $6.6\ ^{+2.0}_{-0.7}$ cpd/100t

New results on CNO neutrinos

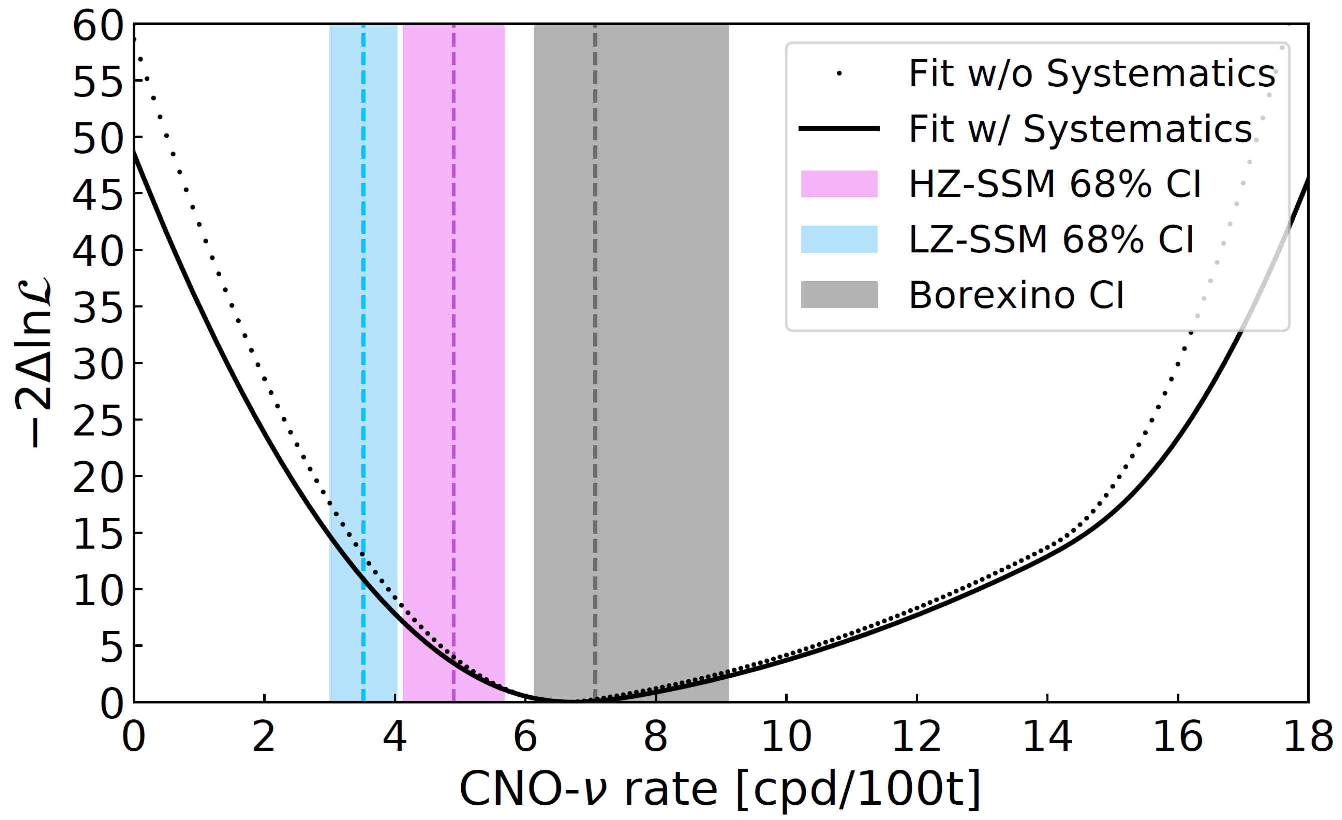
Systematic errors

We have investigated many sources of systematic errors:

- **Systematics on the method to extract the ^{210}Bi upper limit** (included in the error of the constraint);
- **Systematics on uniformity of ^{210}Bi** (included in the error on the constraint);
- **Fit condition:** we have performed the fit in ~700 different conditions → negligible;
- **Ratio between O and N neutrinos:** Systematics due to the fact that we fix the N/O ratio in the CNO spectral shape→negligible;
- **Systematic associated to non perfect knowledge of the energy response: -0.4 +0.5 cpd/100t:** stability in time of light yield (estimated with neutrons), linearity (from calibrations), non-uniformity (from calibrations and neutrons), systematic on the ^{210}Bi spectral shape;

New results on CNO neutrinos

Log-likelihood profile for CNO



Results (including sys errors)

Rate(CNO)= $6.7^{+2.0}_{-0.8}$ cpd/100t

ϕ(CNO)= $6.6^{+2.0}_{-0.9} \times 10^8\ \nu\ cm^{-2}\ s^{-1}$

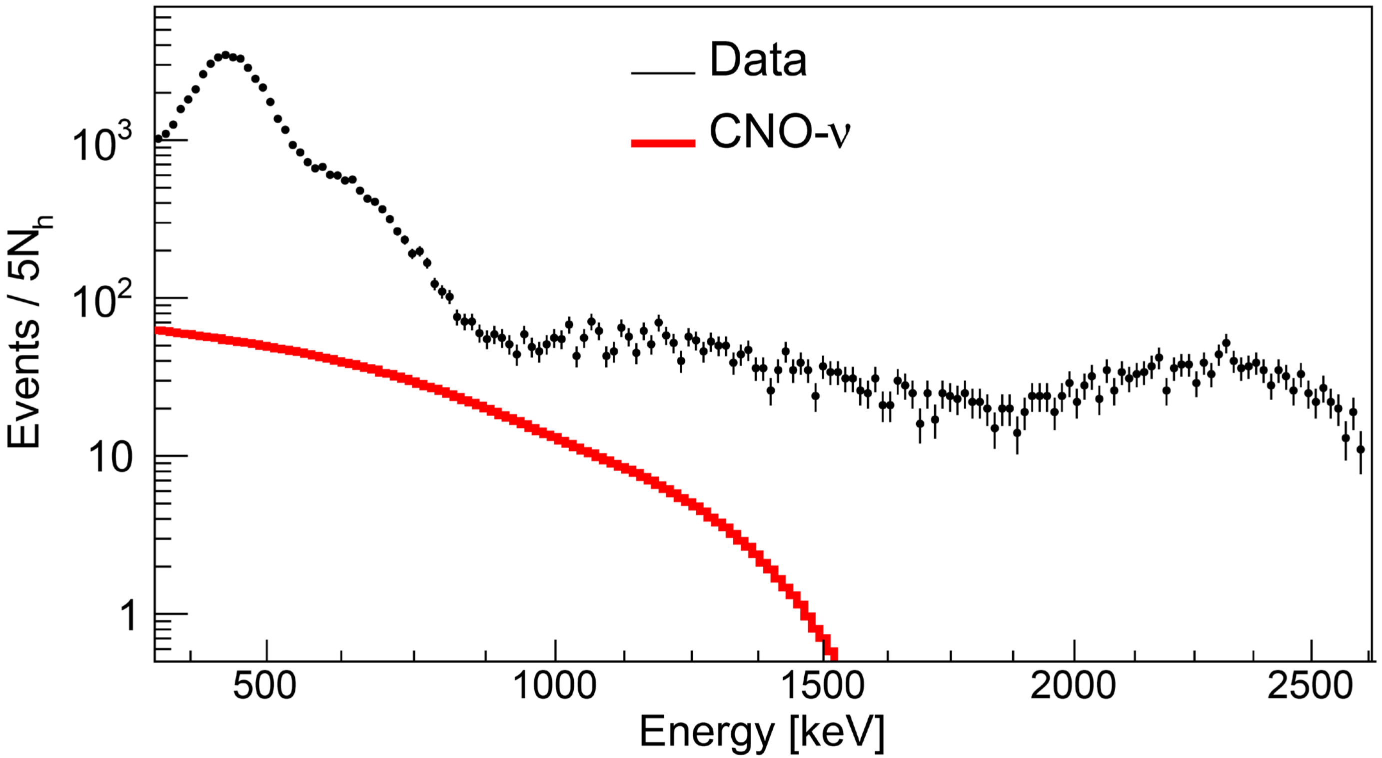
We disfavor the hypothesis CNO=0 with ~ 7σ significance

More details about the CNO analysis on Davide Basilico's poster #612

New results on CNO neutrinos: CNO energy spectrum

Are we really seeing CNO neutrinos?

We subtract from the data histogram the backgrounds obtained independently (assuming their spectral shapes)



- ^{7}Be ν: rate measured from Phase-II measurement by BX;
- Pep ν: rate measured from global fit;
- ^{85}Kr: rate measured from fast coincidences;
- ^{210}Po: rate measured with the help of pulse-shape discrimination;
- ^{210}Bi: optained from LPoF analysis;
- External background +^{11}C: rate obtained by a multivariate fit performed only above 1.5 MeV

New results on CNO neutrinos: CNO energy spectrum

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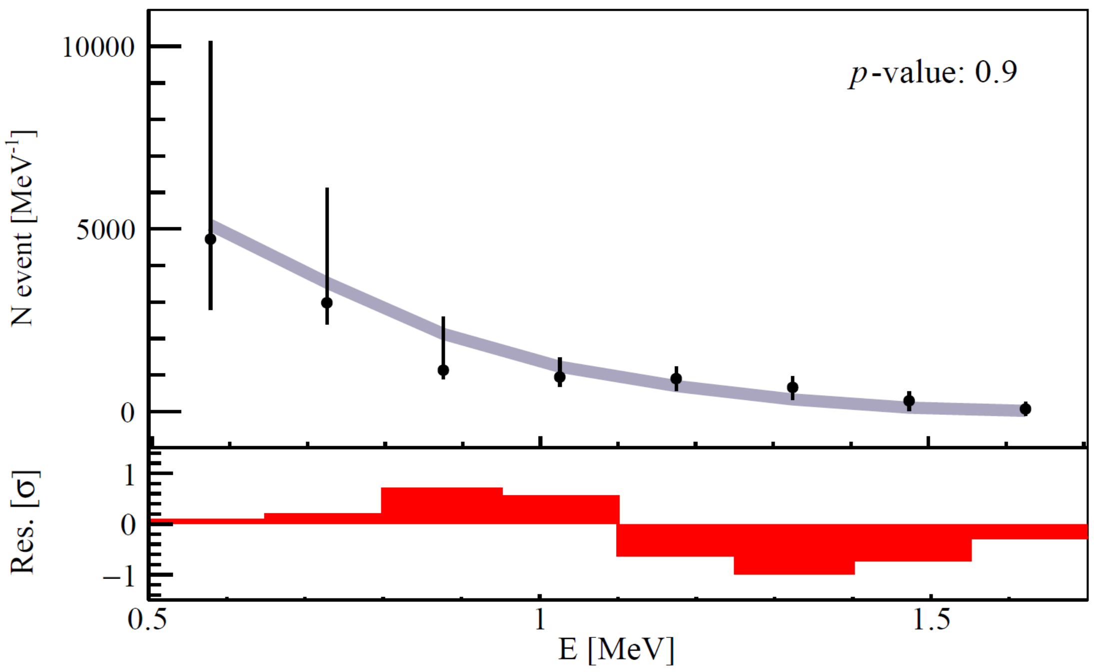

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- ^{210}Bi: optained from LPoF analysis;
- External background +^{11}C: rate obtained by a multivariate fit performed only above 1.5 MeV

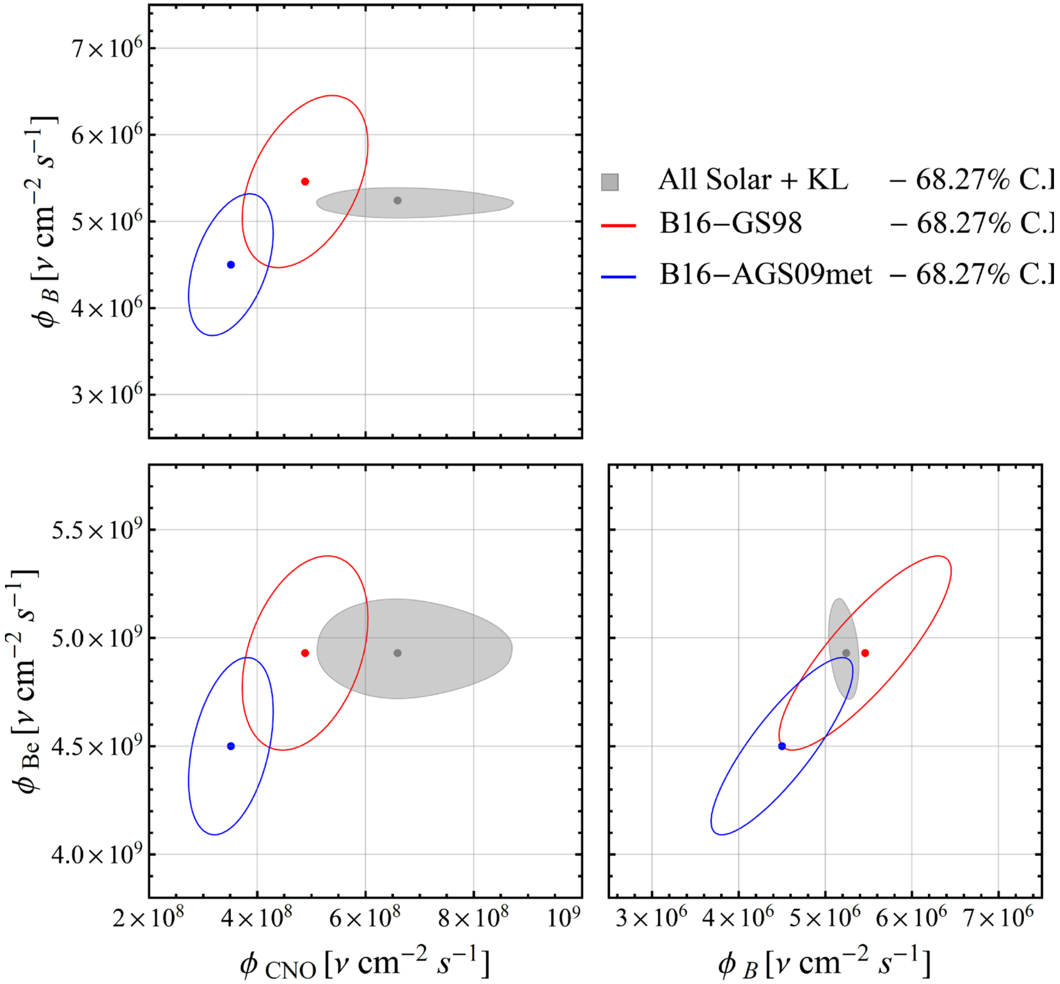
Shape compatible with the energy distribution of electrons scattered by CNO neutrinos

Implications of the new result

Comparison with predictions of SSM: global analysis

Global Analysis

- **We include the CNO result in a global analysis of all solar neutrino data+KamLAND;**
- Φ(Be), Φ(B) and Φ(CNO), together with θ_{12} and Δm^2_{12} are free parameter of the fit;
- The results agree well with the output of SSM-HZ (1) model, while feature a small tension with the SSM-LZ (2) model (p= 0.028);
- This small tension is created by the addition of the CNO result (p-value goes from 0.327 → 0.028)



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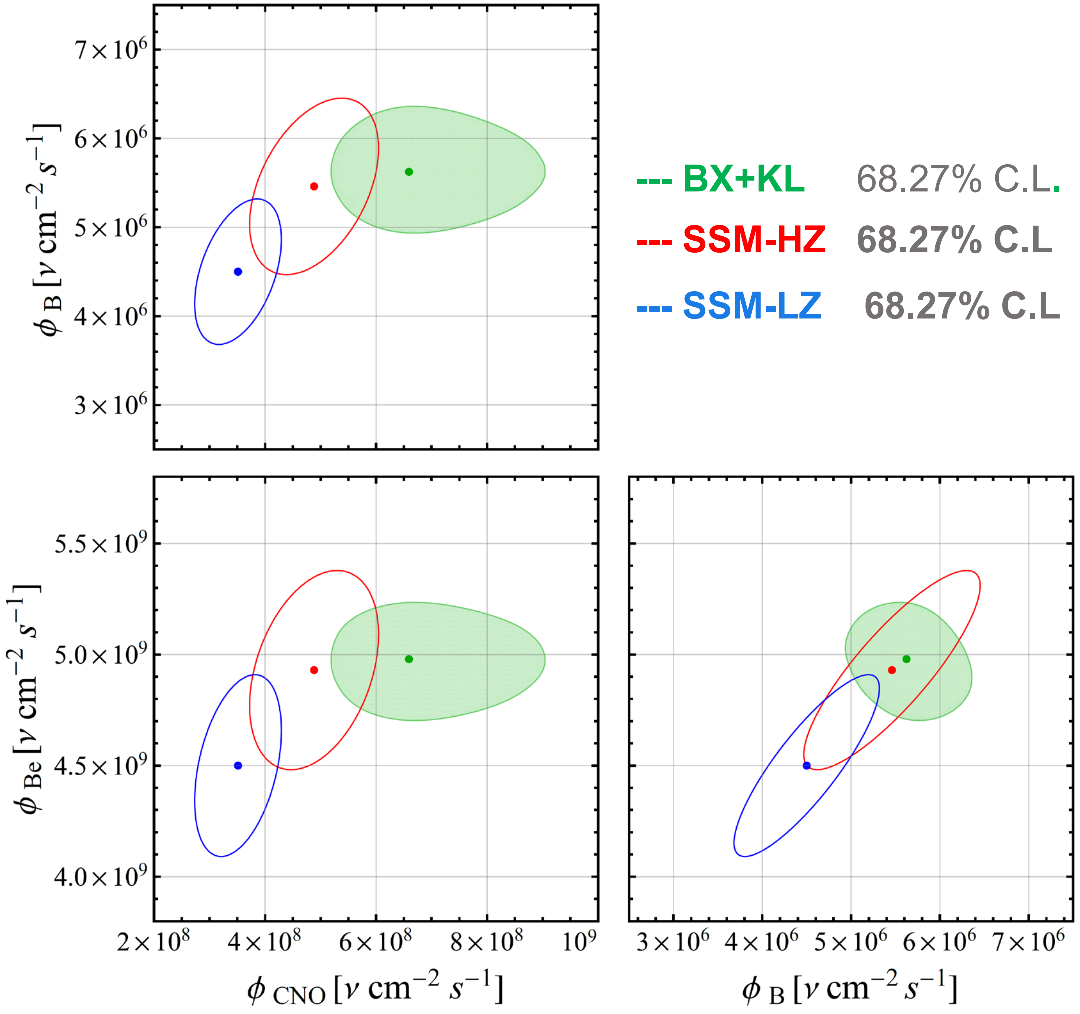
*(2) SSM-LZ= B16-AGSS09met: Vinyoles et al. Astr.J. 835 (**2017**) 202 + A. Serenelli er al., Astr. J. 743,(2011)24*

Comparison with predictions of SSM: BX only

Borexino only (+KL)

- **We include only Borexino results, (8B, 7Be,CNO) +KamLAND**;
- Φ(Be), Φ(B) and Φ(CNO), together with θ_{12} and Δm^2_{12} are free parameter of the fit;
- The results agree well with the output of SSM-HZ(1) model, while feature a small tension with the SSM-LZ (2) model (p= 0.018);
- This small tension is created mostly (but not only) by the addition of the CNO result (p-value goes from 0.196 → 0.018);



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(2) *SSM-LZ= B16-AGSS09met: Vinyoles et al. Astr.J. 835 (**2017**) 202 + A. Serenelli er al., Astr. J. 743,(2011)24*

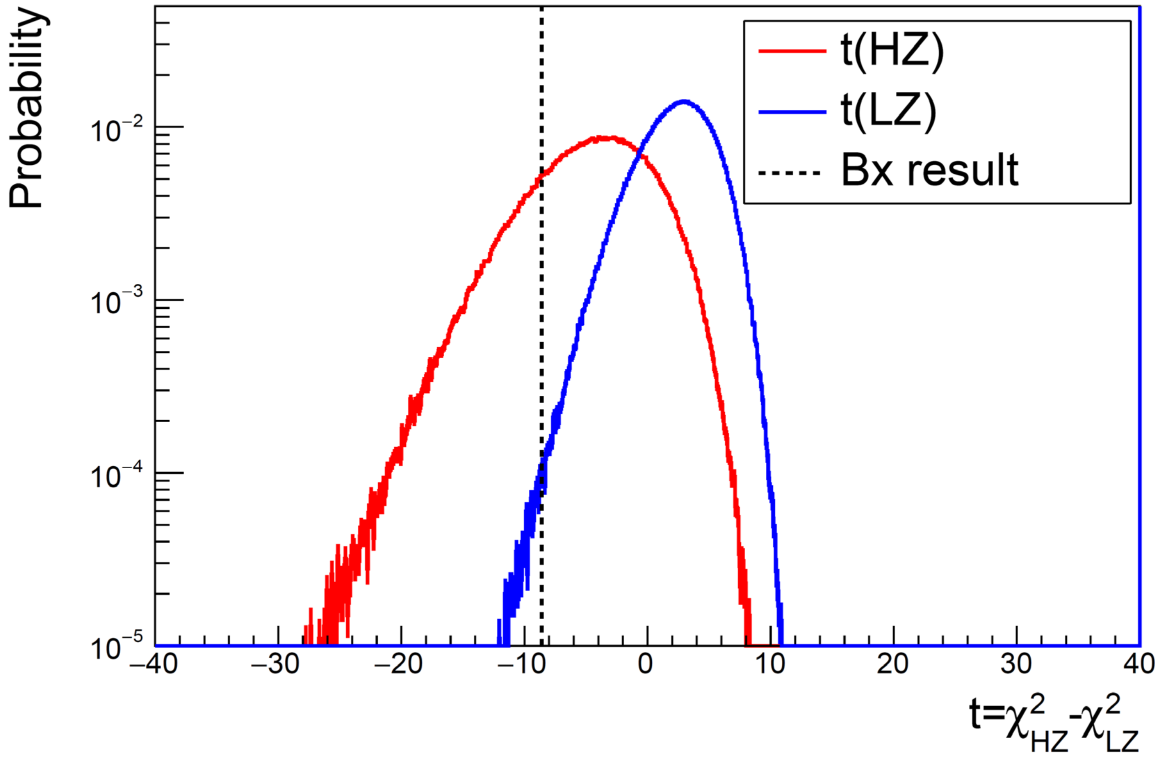
Comparison with predictions of SSM: SSM-HZ vs SSM-LZ

SSM-HZ[(1)] vs SSM-LZ [(2)]

We perform a frequentist hypothesis test based on a likelihood-ratio test statistics (SSM-HZ vs SSM-LZ);

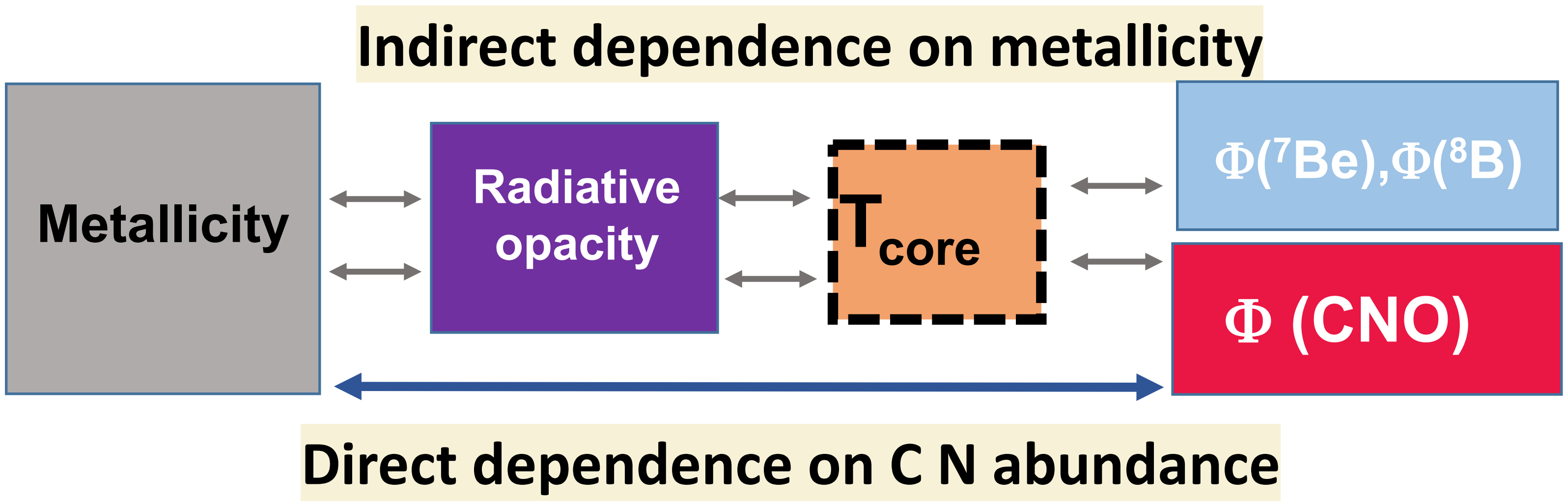
We build the test statistics *t* including ^{7}Be, ^{8}B and CNO flux predictions;

Assuming SSM-HZ, Borexino results on ^{7}Be, ^{8}B and CNO neutrinos disfavours SSM-LZ with a p-value of 9.1×10^{-4} ($\sim 3.1\sigma$)



(1) *SSM-HZ= B16-GS98: Vinyoles et al. Astr.J. 835 (**2017**) 202 + Grevesse et al.,Space Sci.Rev. (**1998**)85*
(2) *SSM-LZ= B16-AGSS09met: Vinyoles et al. Astr.J. 835 (**2017**) 202 + A. Serenelli er al., Astr. J. 743,(2011)24*

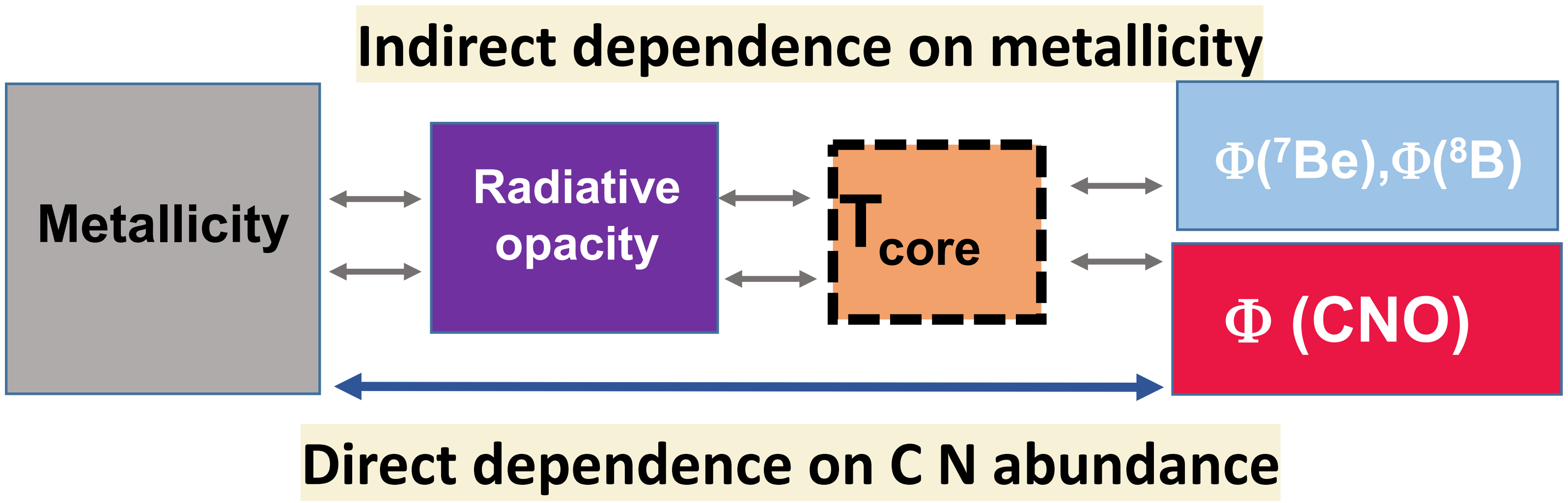
Determining C and N abundance from CNO measurement



$$\Phi_B/\Phi_B^{SSM} \propto (T_c/T_c^{SSM})^{\tau_B} \qquad \tau_B = 24$$

$$\Phi_O/\Phi_O^{SSM} \propto \frac{n_{CN}}{n_{CN}^{SSM}} \times (T_c/T_c^{SSM})^{\tau_O} \qquad \tau_O = 20$$

Determining C and N abundance from CNO measurement



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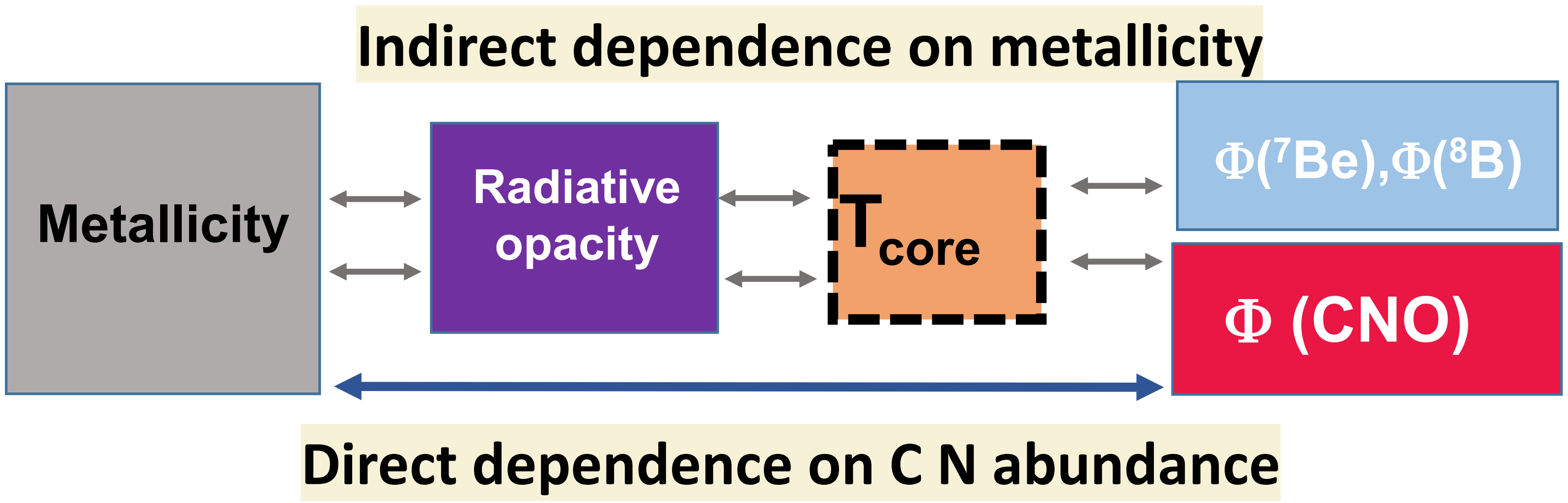
- The precise measurement of Φ (^{8}B) can be used as a ``thermometer'' of the solar core temperature;
- By taking the ratio between the $\Phi(^{15}\mathrm{O})/\ \Phi(^8\mathrm{B})$ with an appropriate factor *k* we can minimize the uncertainties due to opacity and other input parameters of SSM

$$\frac{(\Phi_O/\Phi_O{}^{SSM})}{(\Phi_B/\Phi_B{}^{SSM})^k} \propto \frac{n_{CN}}{n_{CN}^{SSM}} \left(\frac{T_c}{T_c{}^{SSM}}\right)^{\tau_O - k\tau_B}$$

- Naively $k = \tau_O/\tau_B = 0.83$

Determining C and N abundance from CNO measurement



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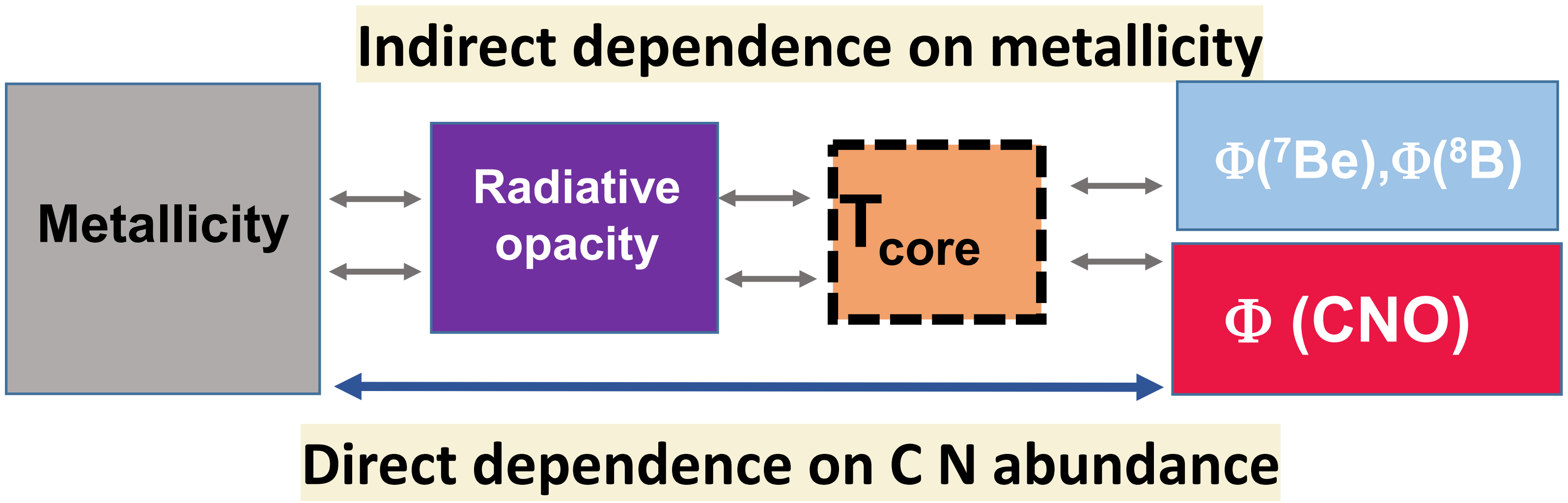
- The reality is more complicated: we need to propagate the uncertainties of SSM input parameters on the fluxes of ^{15}O and ^{8}B by means of partial derivatives;

More details about the CN determination on Daniele Guffanti and Xuefeng Ding's poster #659

Determining C and N abundance from CNO measurement



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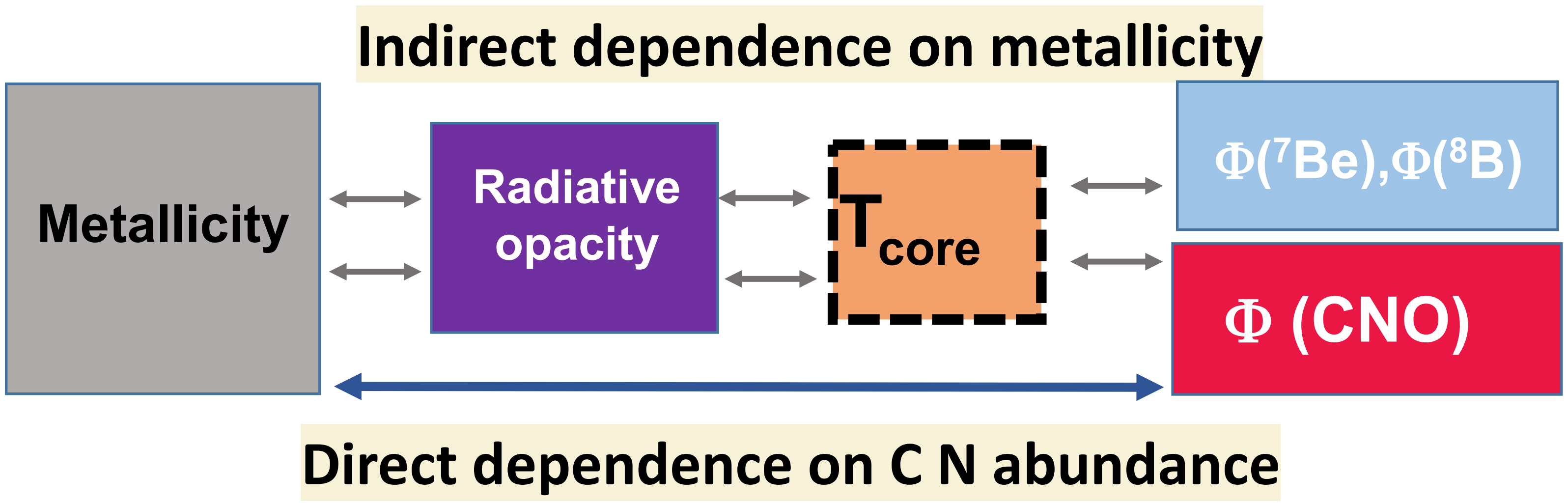
$$\frac{N_{CN}}{N_{CN}^{SSM}} = \frac{(\Phi_O/\Phi_O^{SSM})}{(\Phi_B/\Phi_B^{SSM})^{0.769}}$$

- The optimal *k* is found to be 0.769

Determining C and N abundance from CNO measurement



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Abundace on the surface

$$\frac{N_{CN}}{N_{CN}^{SSM}} = \frac{(\Phi_O/\Phi_O^{SSM})}{(\Phi_B/\Phi_B^{SSM})^{0.769}}$$

- N.B.: with this procedure we extract directly the abundance on the surface;
- In fact, the procedure relies on partial derivatives with respect to the photosphere composition;

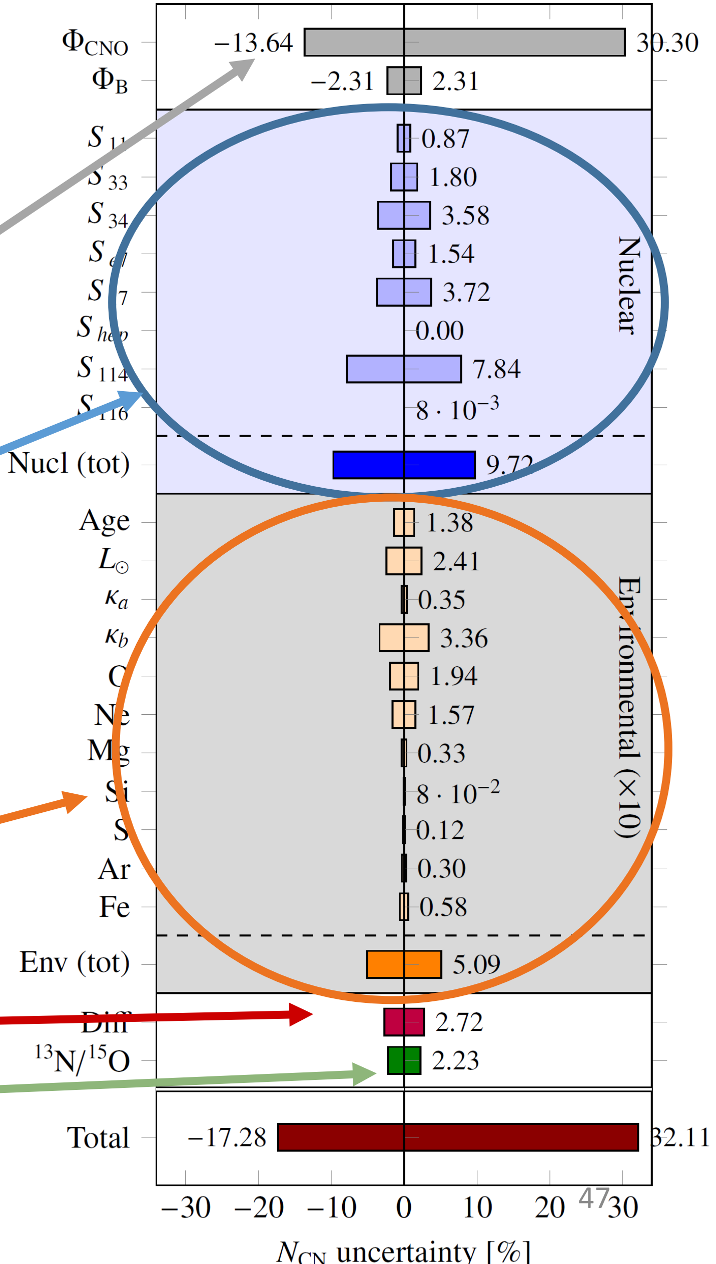
Determining C and N abundance from CNO measurement

- Inserting Φ_B from the global analysis
- Calculating Φ_O from the CNO flux, assuming the SSM N/O neutrino ratio

$$N_{CN} = (5.78^{+1.85}_{-1.00}) \times 10^{-4}$$

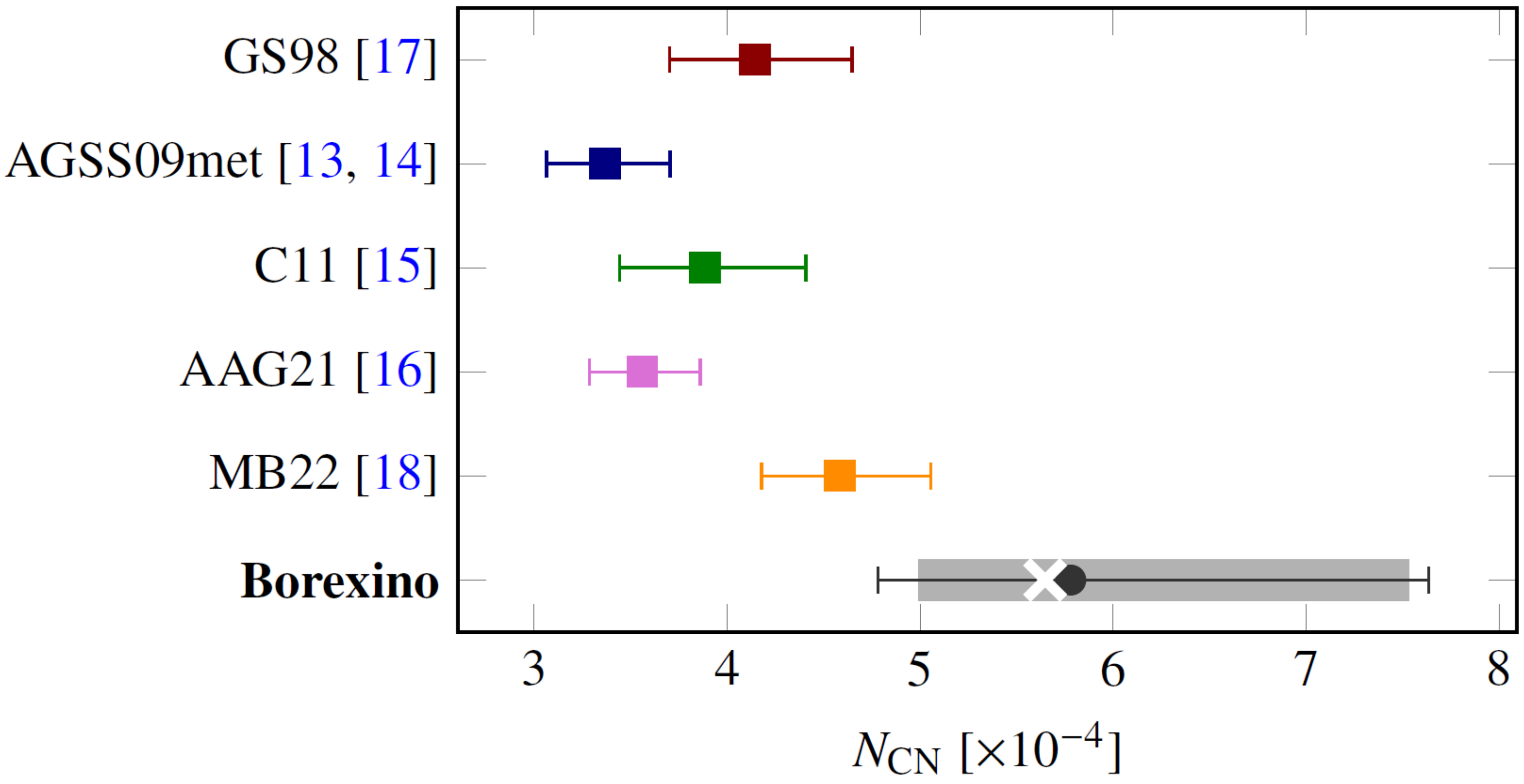
Contributions to the error:

- CNO measurement: +30% - 14%;
- ^{8}B flux: +/-2.3%
- Nuclear: +/- 9.7%
- Environm: 0.5% (small by construction)
- Diffusion: 2.7%
- N/O ratio: 2.2%



Determining C and N abundance from CNO measurement

- This is the first direct measurement of the C and N abundance (with respect to H) from solar neutrinos and can be compared directly with the measurements derived from the solar photosphere;



N.B.: we use as reference SSM B16-GS98, but by construction the method is only weakly dependent on it

Our measurement agrees nicely with the High Metallicity ones, while features a ~2σ tension with the low metallicity measurements

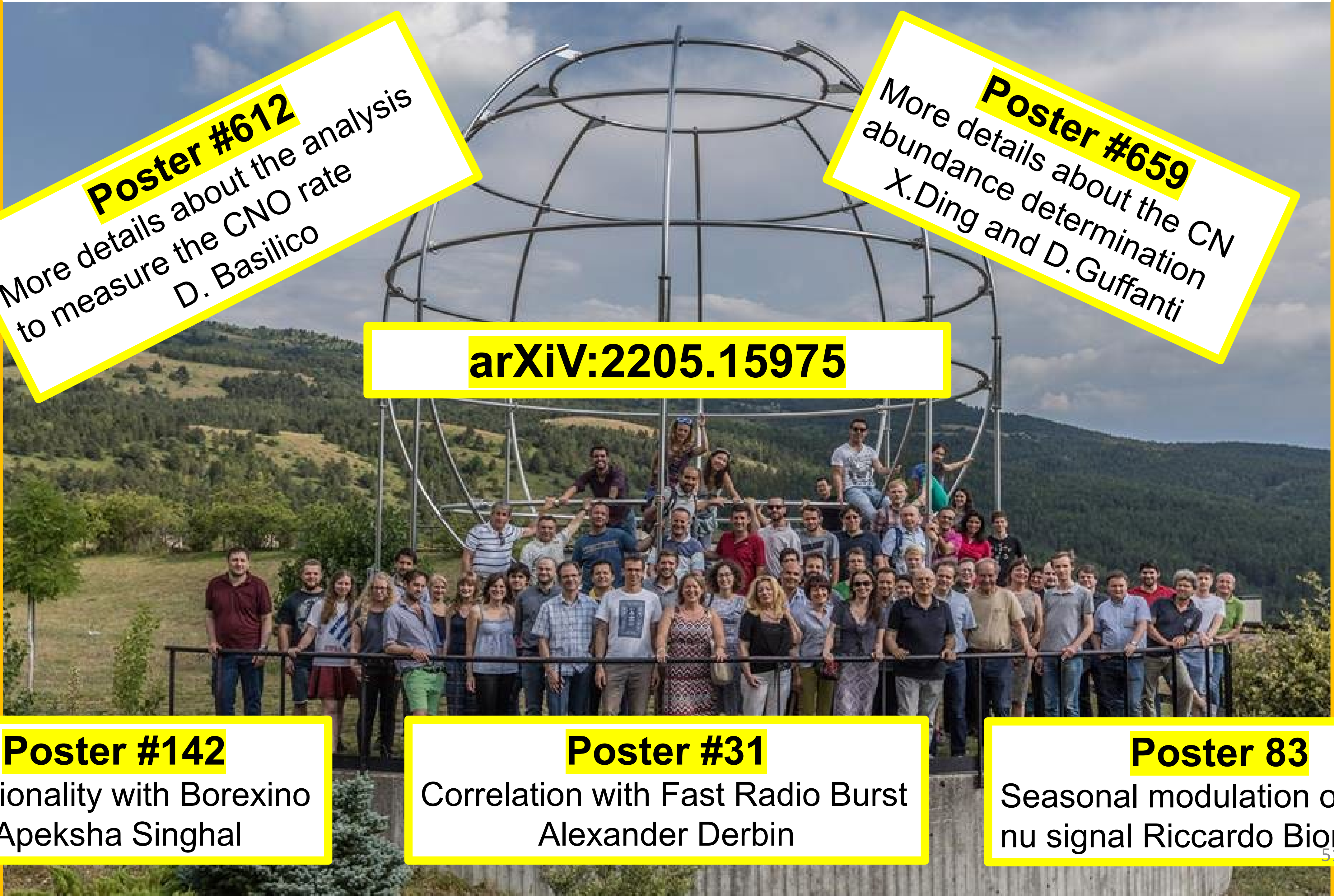
Conclusions

- **CNO-null hypothesis excluded at ~ 7σ:** Borexino has provided a new improved measurement of the CNO rate which reinforces the results previously obtained, excluding the CNO null-hypothesis at ~ 7σ;
- **We measure N_{NC} in the Sun for the first time with solar neutrinos:** the CNO measurement, combined with the 8B flux obtained from the global analysis is used to determine the abundance of C and N in the Sun;
- **N_{NC} in good agreement with HZ photospheric measurements; ~2σ tension with the LZ photospheric measurements**;
- **CNO+^{7}Be+^{8}B neutrino flux results from BX disfavor SSM-LZ at 3.1σ (when compared to HZ-SSM)** (assuming SSM-HZ to be true and using a frequentist analysis based on a likelihood-ratio test statistics);

Thank you!

Borexino Collaboration

Thank you!



Poster #612
More details about the analysis to measure the CNO rate
D. Basilico

Poster #659
More details about the CN abundance determination
X.Ding and D.Guffanti

arXiV:2205.15975

Borexino Collaboration

Poster #142
Directionality with Borexino
Apeksha Singhal

Poster #31
Correlation with Fast Radio Burst
Alexander Derbin

Poster 83
Seasonal modulation of solar nu signal Riccardo Biondi