Taking snapshots of our Sun with the Borexino experiment

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Studying the Sun with Neutrinos...

Our Sun emits a tremendous number of neutrinos due to the fusion reactions occurring in its core:

$$4\,\mathbf{p} \rightarrow \alpha + \mathbf{2\,e^+} + \mathbf{2}\,\nu_\mathbf{e} \qquad \mathbf{E_{released}} \sim \mathbf{26\,MeV}$$

Neutrinos interacts through the weak-interaction only:

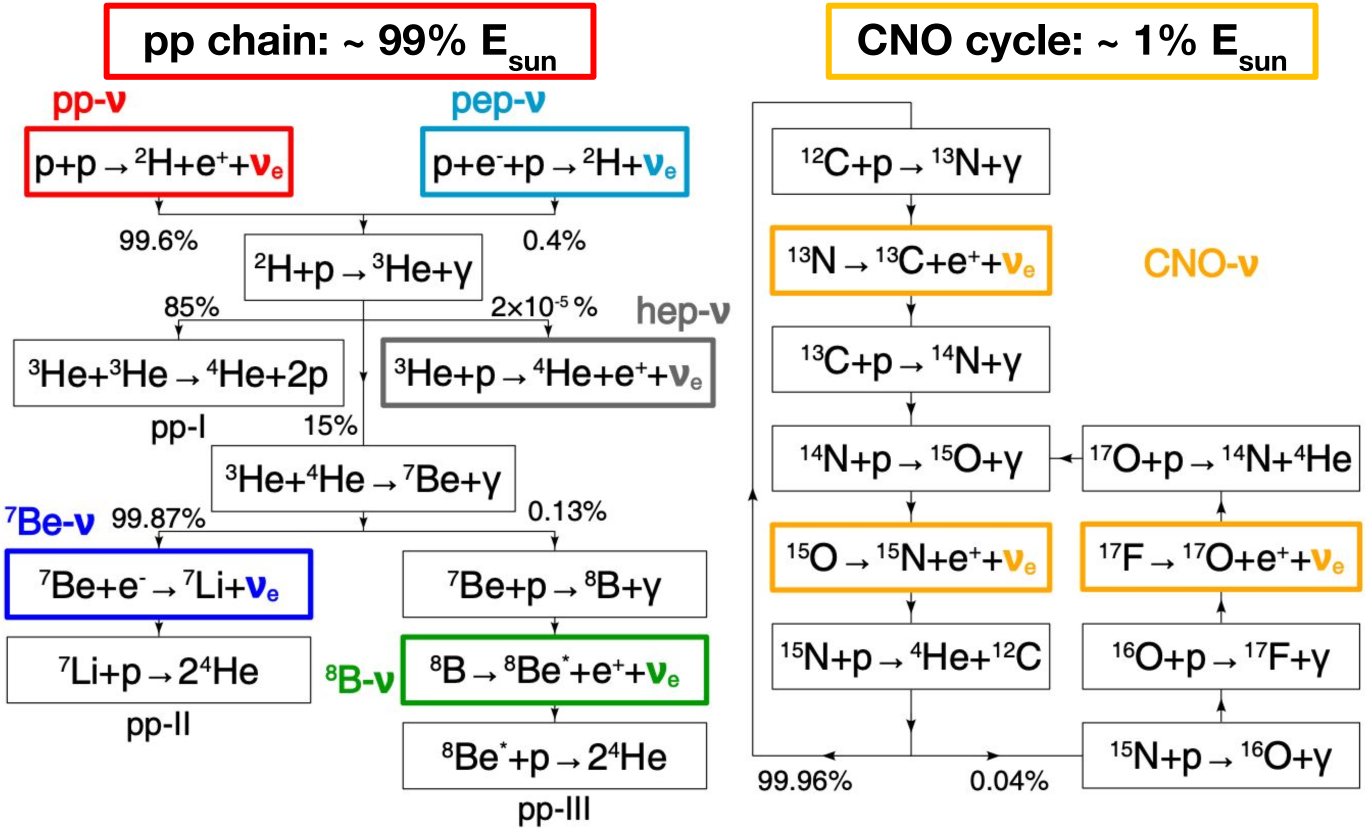
$$\sigma \approx \mathbf{10^{-44}\,cm^2} \quad @\,\mathbf{1\,MeV}$$

They are very elusive and thus, they are a very powerful tool to study astrophysical objects.

Photons massively interact with the solar plasma and take about 10^5 years to reach our star surface.
Instead, neutrinos only take about the famous 8 minutes to travel from their production site to the Sun surface and to the Earth.

→ Performing solar neutrino spectroscopy is the only way to get a real snap-shot of the Sun and (true) real time informations.

What are solar neutrinos?



The Standard Solar Model

A Standard Solar Model (SSM) is a complex container where input parameters (such as Sun luminosity, age, mass, radius, chemical elements abundances, cross-sections, radiative opacity, metallicity….) are considered all together and result in expectations about the neutrino fluxes and helioseismology.

Flux	B16-GS98	B16-AGSS09met
$\Phi(pp)$	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.005)$
$\Phi(pep)$	$1.44(1 \pm 0.01)$	$1.46(1 \pm 0.009)$
$\Phi(hep)$	$7.98(1 \pm 0.30)$	$8.25(1 \pm 0.30)$
$\Phi(^7Be)$	$4.93(1 \pm 0.06)$	$4.50(1 \pm 0.06)$
$\Phi(^8B)$	$5.46(1 \pm 0.12)$	$4.50(1 \pm 0.12)$
$\Phi(^{13}N)$	$2.78(1 \pm 0.15)$	$2.04(1 \pm 0.14)$
$\Phi(^{15}O)$	$2.05(1 \pm 0.17)$	$1.44(1 \pm 0.16)$
$\Phi(^{17}F)$	$5.29(1 \pm 0.20)$	$3.26(1 \pm 0.18)$

Model and Solar Neutrino Fluxes. Units Are: 10^{10}(pp), 10^9 (^{7}Be), 10^8 (pep, ^{13}N, ^{15}O), 10^6(^{8}B, ^{17}F), and 10^3(hep) cm^{-2} s^{-1}

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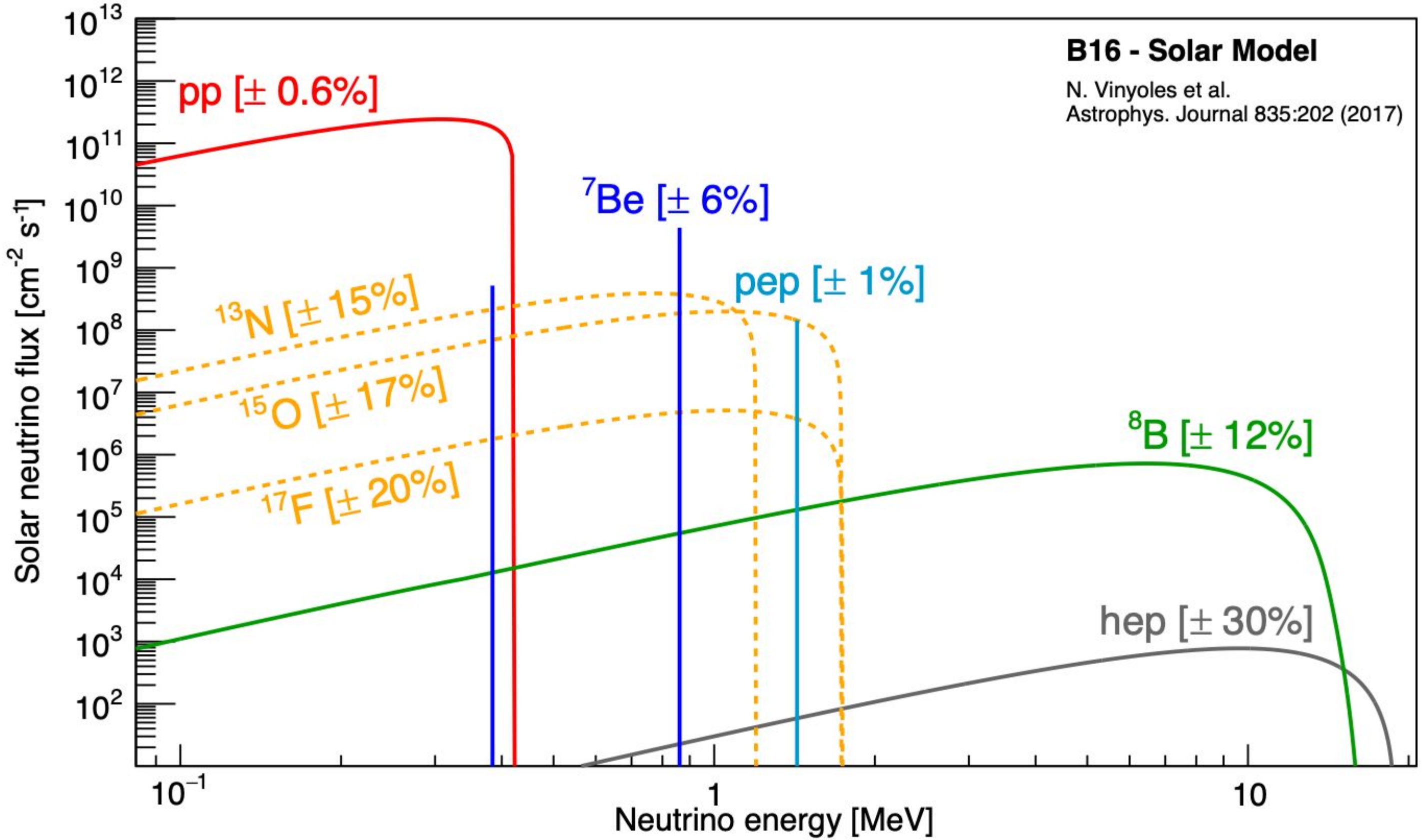
About 9% difference

About 18% difference

<u>About 28% difference</u>

The Solar Neutrino Spectrum



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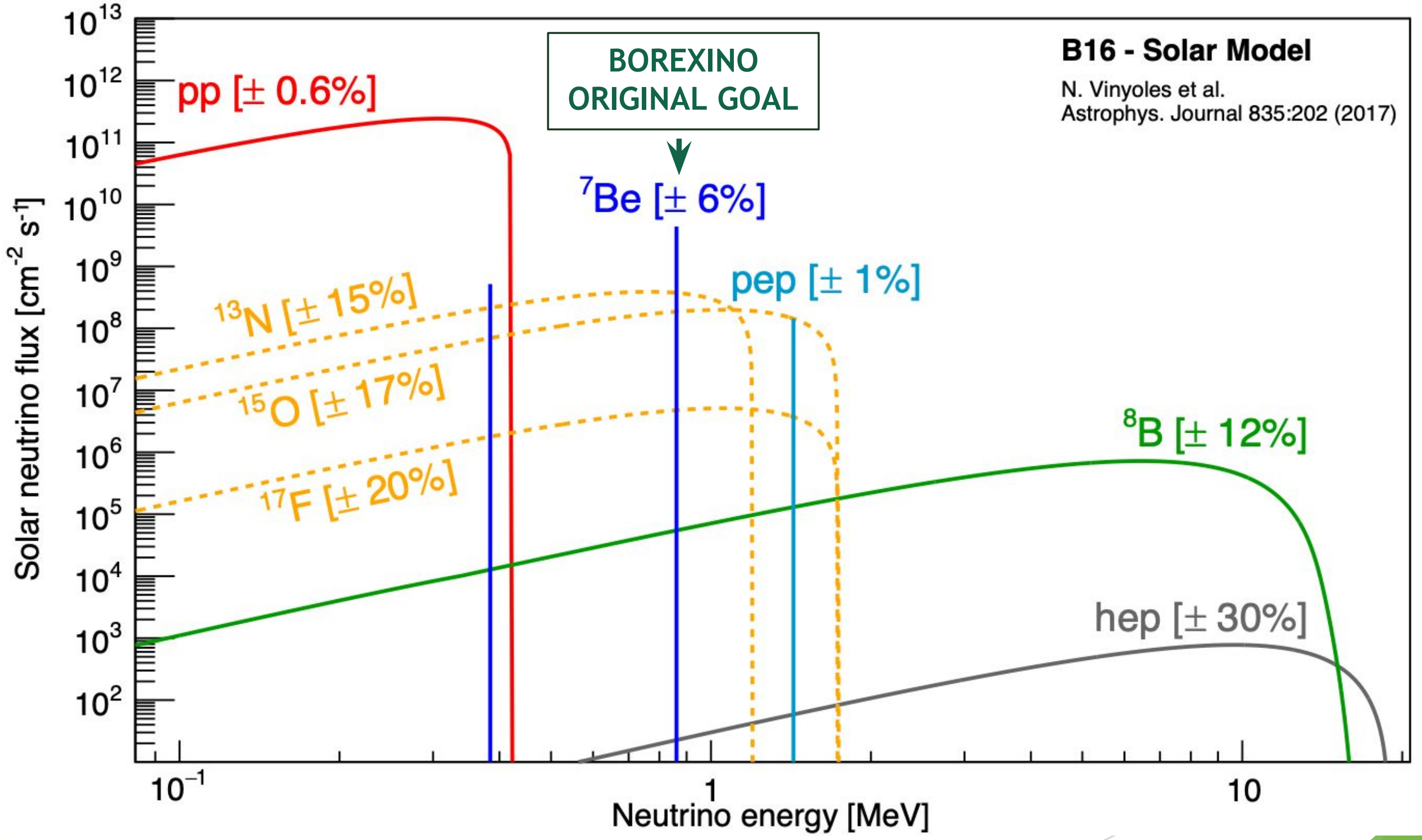

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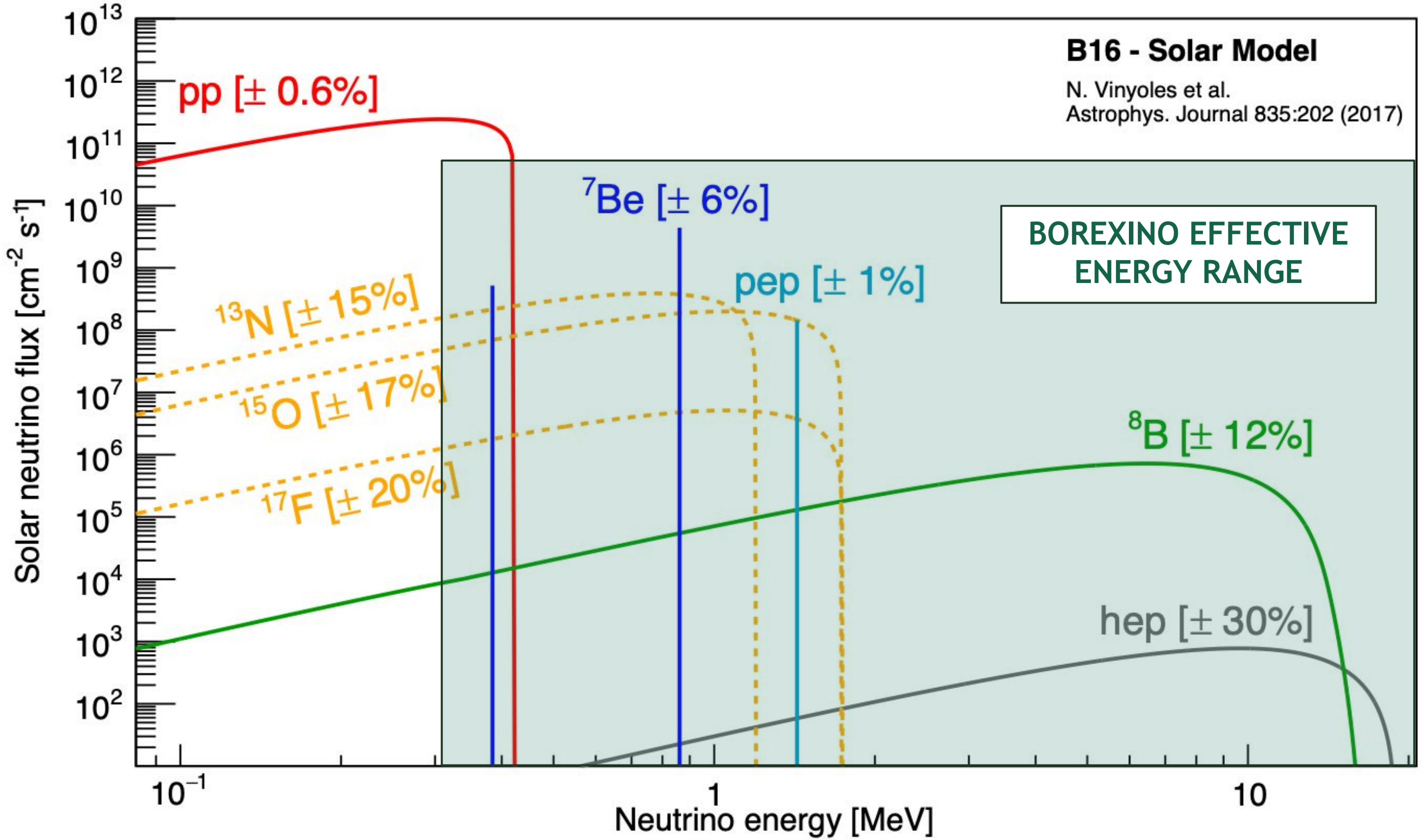
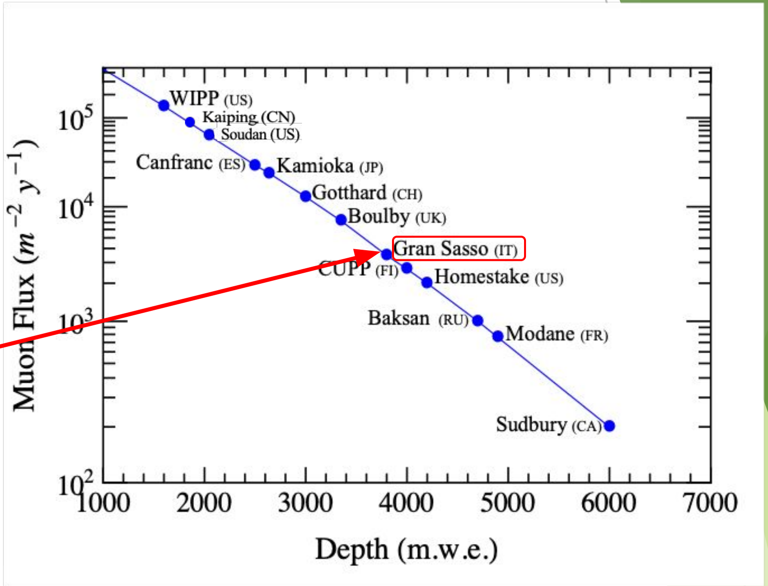


Laboratori Nazionali del Gran Sasso



The **LNGS** altitude is 963 m and the average rock cover is about 1400 m.
The shielding capacity against cosmic rays is about 3800 m.w.e.:

→ in Borexino the muon flux is reduced by a factor 10^6 with respect to the surface. $\Phi(\mu) \approx 1\,\mu/\mathrm{m}^2/\mathrm{h}$

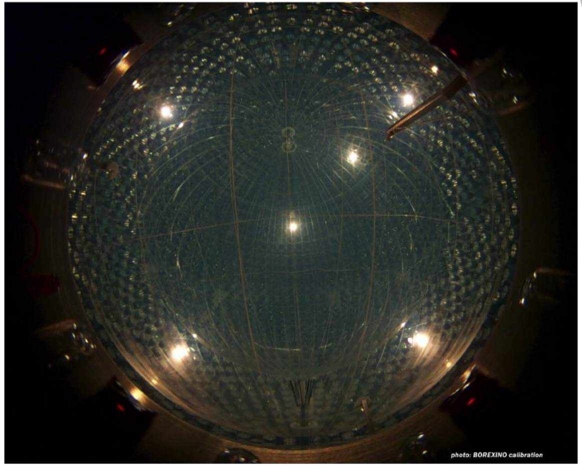
THE BOREXINO EXPERIMENT

- **Original goal**: the detection of low energies solar neutrinos, in particular ^{7}Be neutrinos.
- **Detection method**: elastic scattering of neutrinos on electrons.

$$\nu_x + e \rightarrow \nu_x + e \quad x = e, \mu, \tau$$

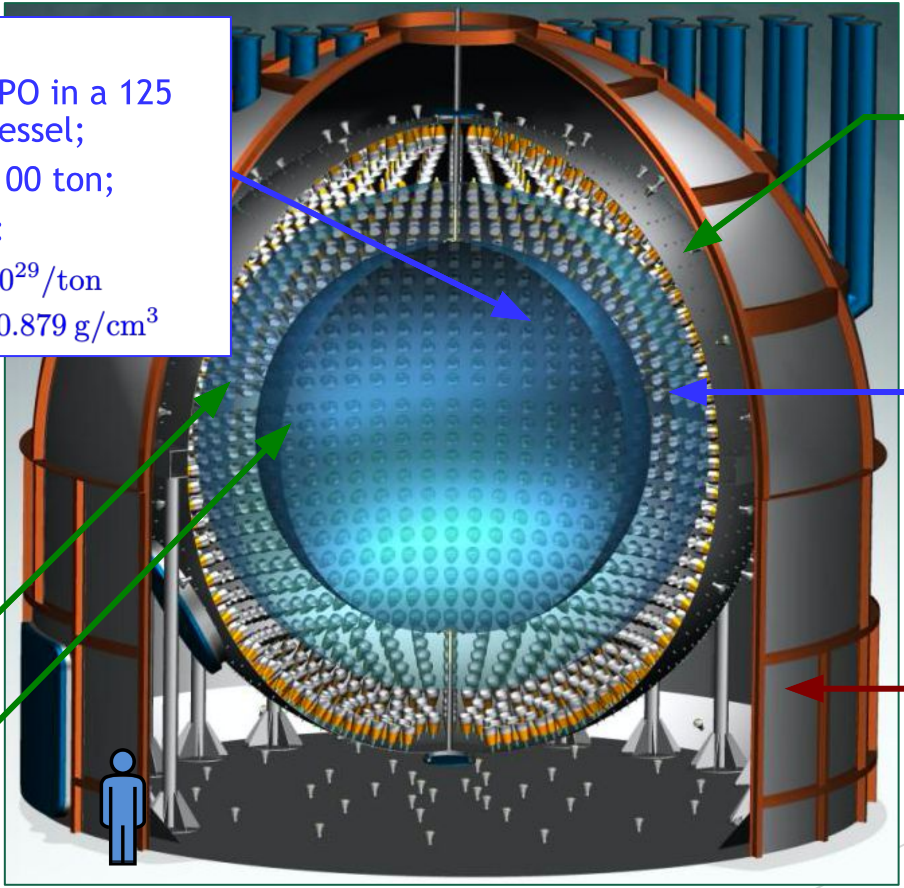
- **Detection medium**: large mass of organic liquid scintillator.
  - Advantage: large light-yield;
  - Disadvantage: no directional informations.

Signal is indistinguishable from background: high radiopurity is a MUST!



The expected rate of ^{7}Be solar-ν in 100 ton of BX scintillator is about 50 counts/day which corresponds to 10^{-9} Bq/Kg.
Just for comparison, natural water is about 1 Bq/Kg in ^{238}U, ^{232}Th and ^{40}K.

The Borexino Experiment (2)



Scintillator:

280 ton of PC+PPO in a 125 μm thick nylon vessel;

Fiducial mass ~ 100 ton;

Electron density:

$(3.307 \pm 0.003) \times 10^{29}/\mathrm{ton}$

Mass density: $\simeq 0.879\,\mathrm{g/cm^3}$

Stainless Steel Sphere:

2212 PhotoMultipliers

Non-scintillating buffer:

900 ton of quenched scintillator

Nylon vessels:

Outer: 5.50 m

Inner: 4.25 m

Water Tank:

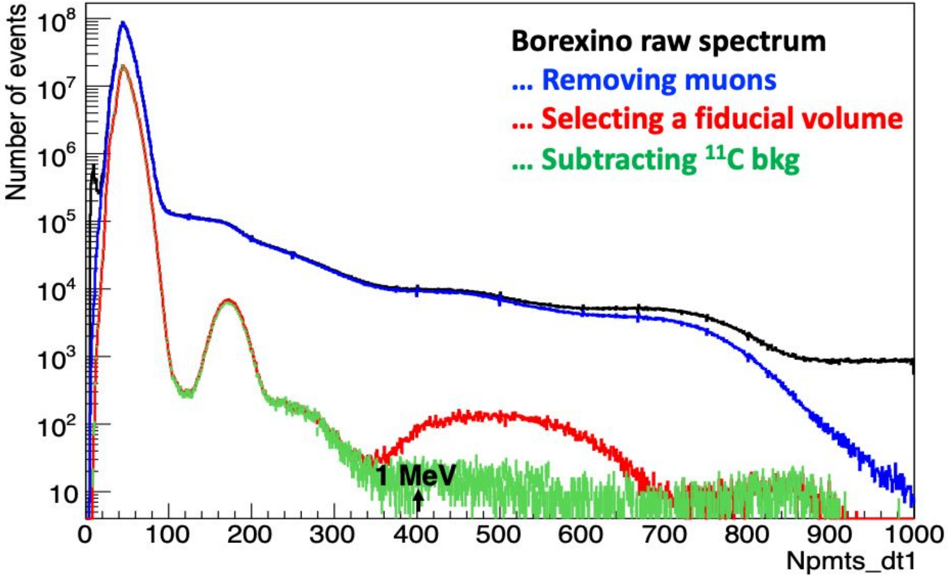
2.8 kton of pure H_2O

γ and n shield

μ water Č detector

208 PMTs in water

How to extract a neutrino signal?



Even at the Borexino very high radiopurity conditions, we still have background events contaminating our solar neutrino signal and we need to apply software cuts to data, in order to remove as much background as possible. Furthermore, we need a powerful tool to separate the signal from the residual background components.

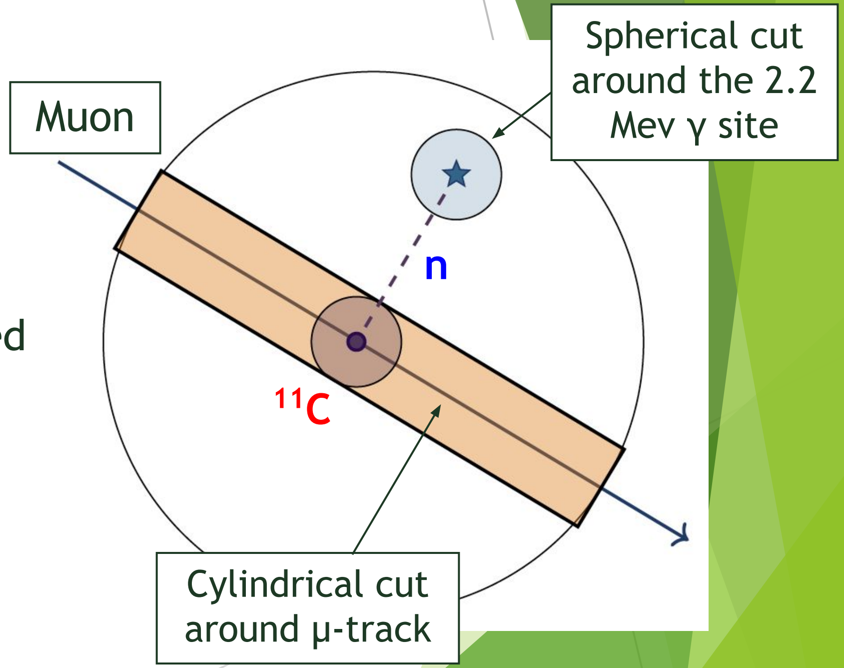
The Three-Fold Coincidence technique

The TFC technique is fundamental to improve the fit capability to disantagle the ^{11}C contamination from the pep & CNO neutrino signals.

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

$$^{11}\mathbf{C} \rightarrow {}^{11}\mathbf{B} + \mathbf{e}^+ + \nu_e \quad \tau \sim 30 \text{ min}$$

$$\mathbf{n} + \mathbf{p} \rightarrow \mathbf{d} + \gamma \quad \tau \sim 250\ \mu\text{s}$$



The likelihood that a certain event is ^{11}C is obtained using:

- Distance in space and time from the μ-track;
- Distance from the neutron;
- neutron multiplicity;
- Muon dE/dx and number of muon clusters per event.

A comprehensive solar neutrino spectroscopy with Borexino

The Borexino experiment has never been so performing…

1. **Improved radiopurity**, because of the purification campaign;
2. **Increased statistics;**
3. **Increased stability** of the detector;
4. **Better comprehension of the details of the energy scale and detector response.**

.... So all challenges at once!

For the first time it was possible to perform a simultaneous fit on the whole solar neutrino energy region.

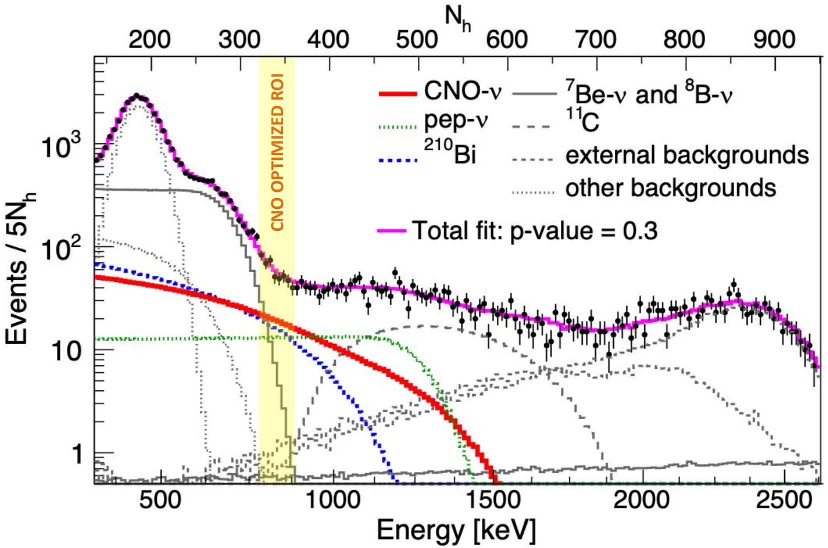
The PP-CHAIN solar neutrinos measurement with Borexino

"Comprehensive measurement of pp-chain solar neutrinos",
Nature 562 (2018) 505

LER (Low Energy Region) Analysis:
Physical Review D 100, 082004 (2019)

HER (High Energy Region) Analysis:
Physical Review D 101, 062001 (2020)

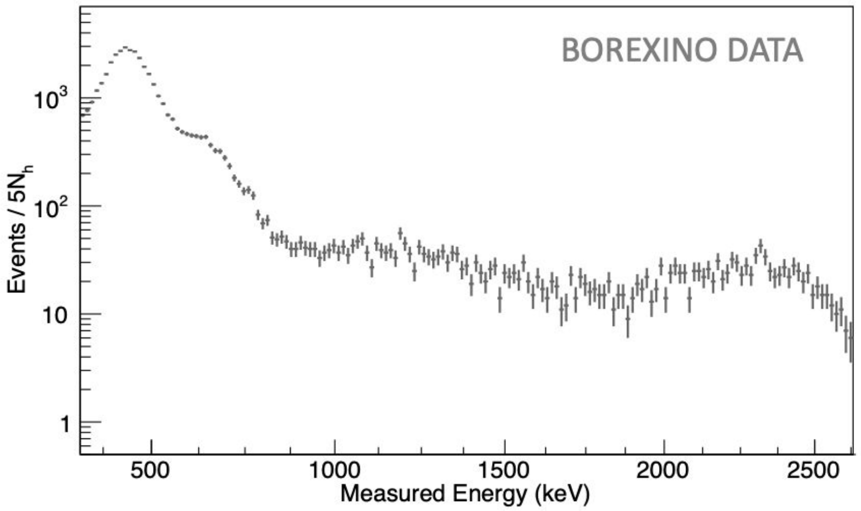
The CNO solar neutrinos measurement with Borexino



"Experimental evidence of neutrinos produced in the CNO fusion cycle in the Sun", ***Nature 587 (2020) 577***

physicsworld TOP 10 BREAKTHROUGH 2020

HOW TO EXTRACT THE CNO-ν SIGNAL?

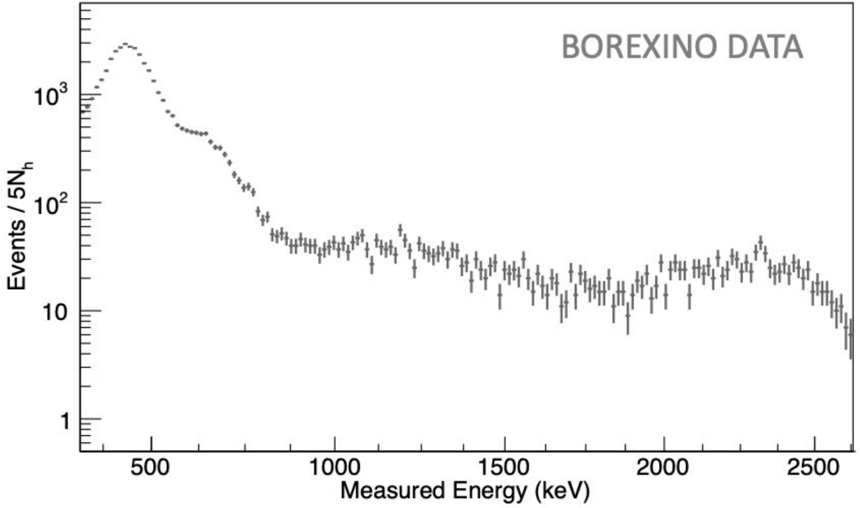


Data-set: Phase-III (July 2016 - February 2020) --> Exposure: 1072 days x 71.3 t

Fit range: 0.32 – 2.64 MeV.

Software cuts: 1) Removing muons
2) Selecting a fiducial volume ($r < 2.8$ m, -1.8 m $< z < 2.2$ m)
3) Tagging/Subtracting ^{11}C background

HOW TO EXTRACT THE CNO-ν SIGNAL?



Where are CNO neutrinos?

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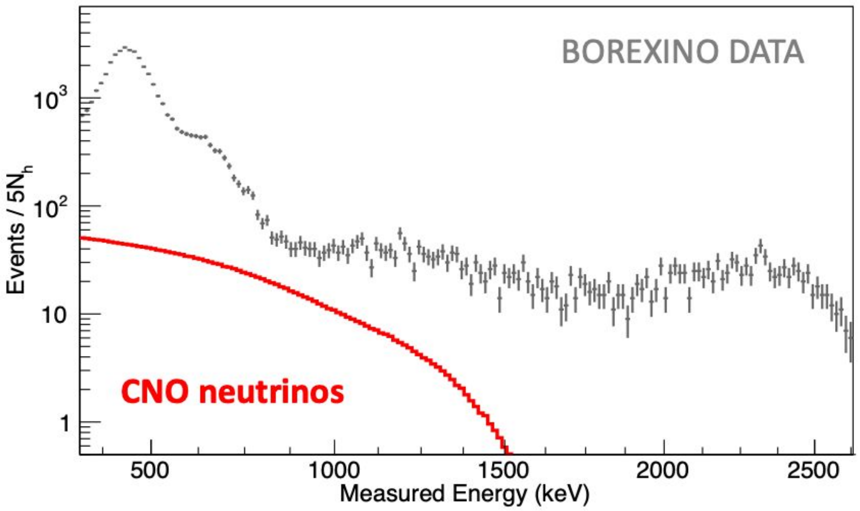
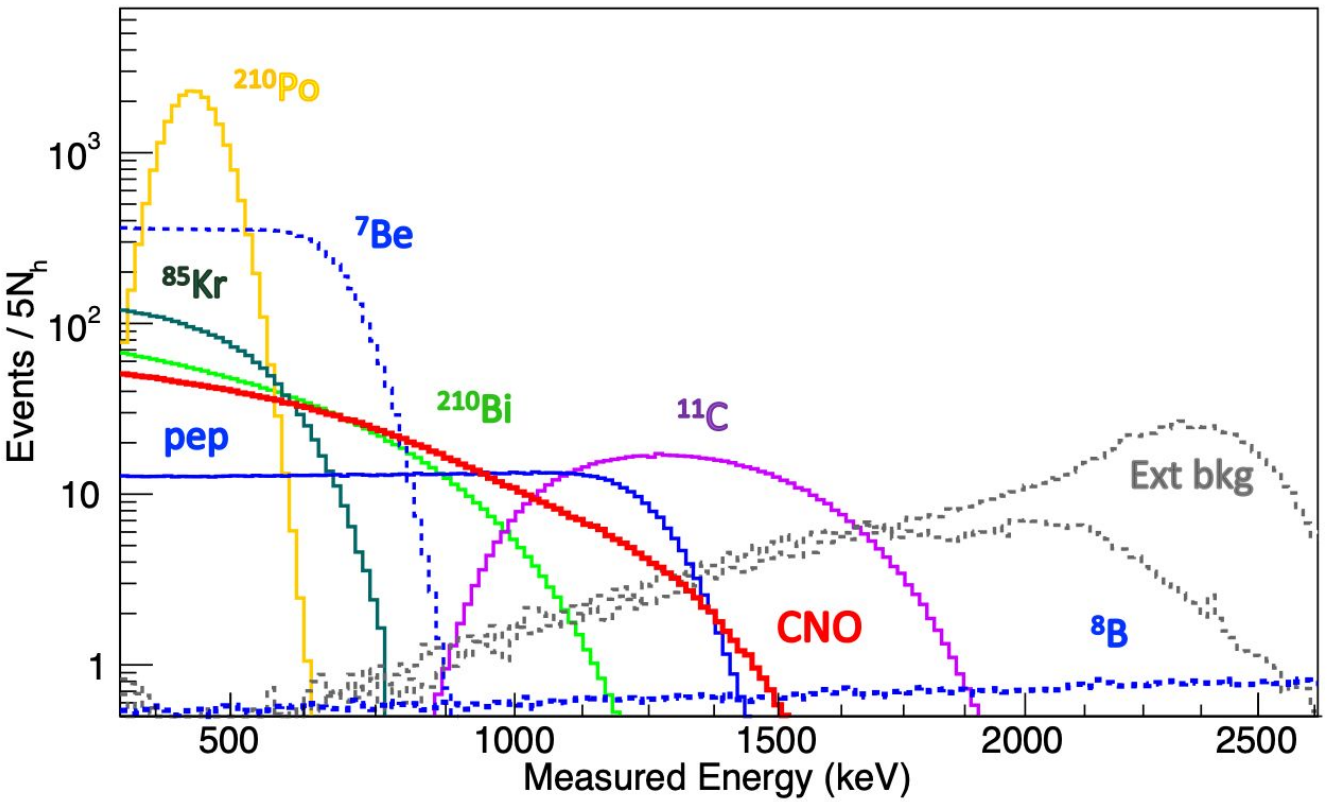


Strategy:
Exploiting the difference in the energy distribution of signal and backgrounds to separate them.

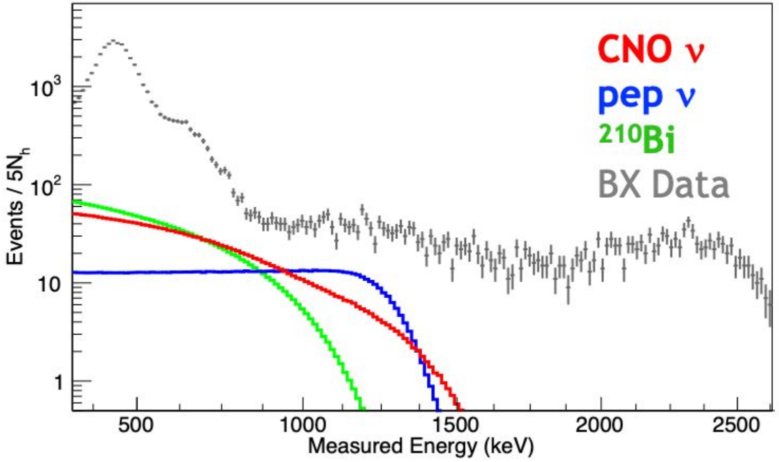
→ The spectral shapes for both components are generated in a Borexino-tailored Geant4 Monte Carlo framework.

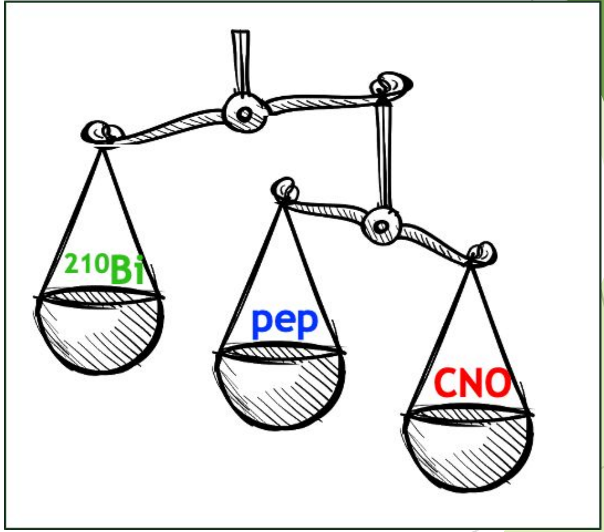
The BX predicted spectral shapes



TOWARDS THE CNO-ν MEASUREMENT

The similarity between the CNO, pep and ^{210}Bi spectral shapes limits the sensitivity of Borexino.

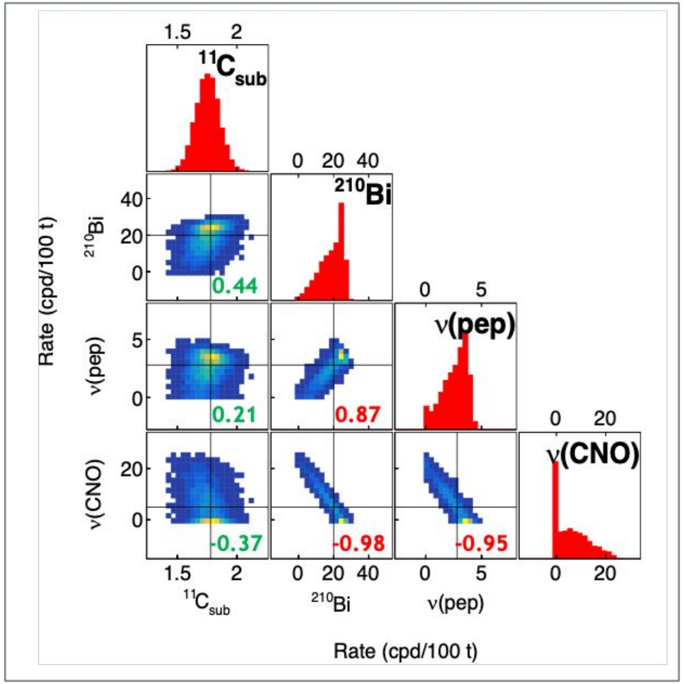




The predicted neutrino rates do not help:

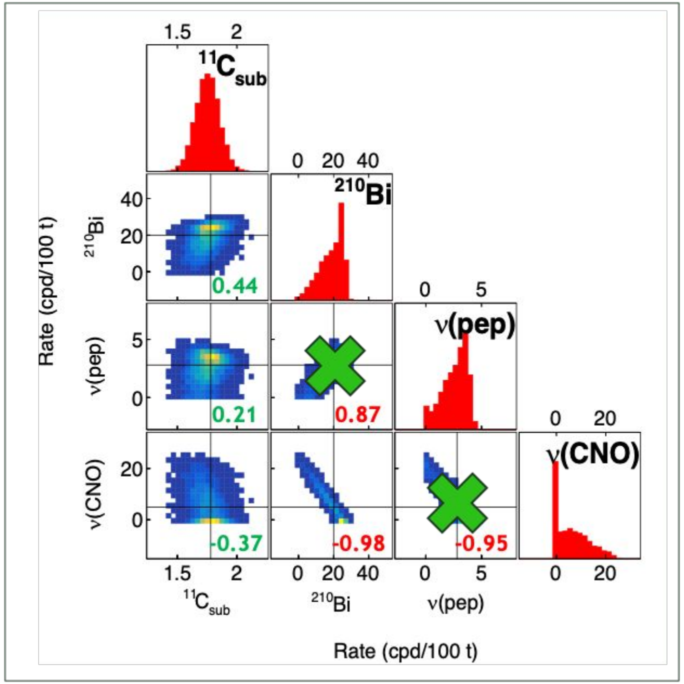
- CNO ν ~ 4-5 cpd/100 ton
- pep ν ~ 3 cpd/100 ton
- ^{210}Bi ~ 15-20 cpd/100 ton

THE PP/PEP RATIO CONSTRAINT



To reduce correlations we put a constraint on the pp/pep ratio following the theoretical predictions as described in *Nature 562 (2018), 505*.

The pp/pep ratio constraint



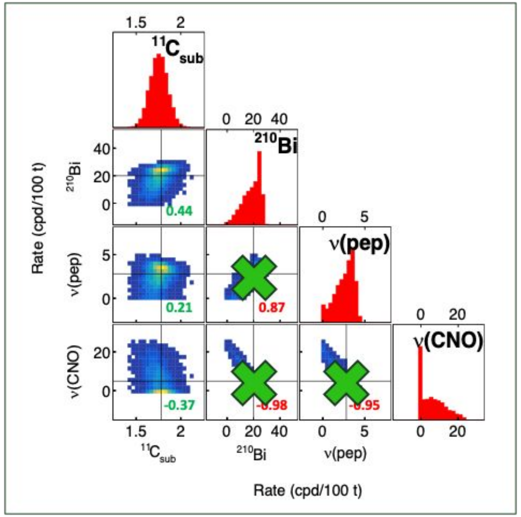
Still, the ^{210}Bi spectrum is quasi-degenerate with the CNO neutrino one…..

To reduce correlations we put a constraint on the pp/pep ratio following the theoretical predictions as described in *Nature 562 (2018), 505*.

THE BISMUTH-210 CONSTRAINT

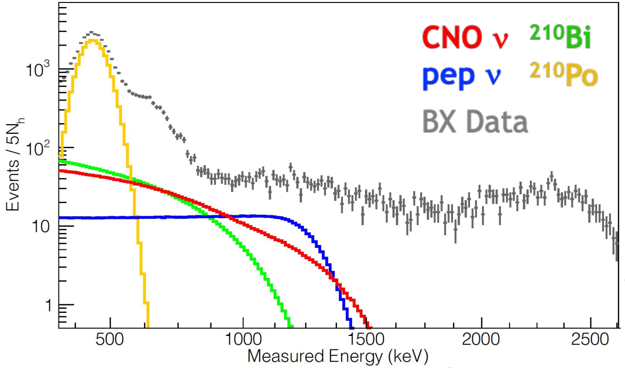
The ^{210}Bi spectrum is still quasi-degenerate with the CNO neutrino one...
… But the ^{210}Bi rate can be constrained by precisely (and independently) mapping the ^{210}Po rate!

$$^{210}\mathrm{Pb} \xrightarrow[23\,y]{\beta^-} {}^{210}\mathrm{Bi} \xrightarrow[5\,d]{\beta^-} {}^{210}\mathrm{Po} \xrightarrow[138\,d]{\alpha} {}^{206}\mathrm{Pb}\ (\mathrm{stable})$$



^{210}Po is "easier" to identify than ^{210}Bi:

- α decay → pulse shape discrimination
- Monoenergetic "gaussian" peak



TOWARDS THE CNO-ν MEASUREMENT (2)

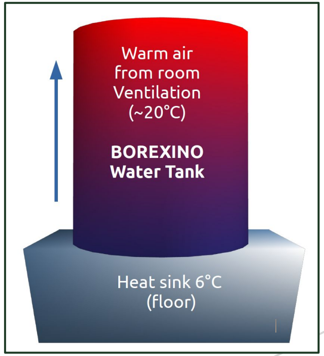
Unluckily, life is not that easy.

The convective motions triggered by seasonal changes in temperature bring inside the scintillator an unknown amount of ^{210}Po which has been present on the nylon Inner Vessel.

→ This breaks the secular equilibrium of the ^{210}Pb chain!

Before performing any counting analysis, we had to thermally insulate the detector to stop convective motions!

MAIN CONCEPT:
Strong and stable vertical gradient to prevent convective motions



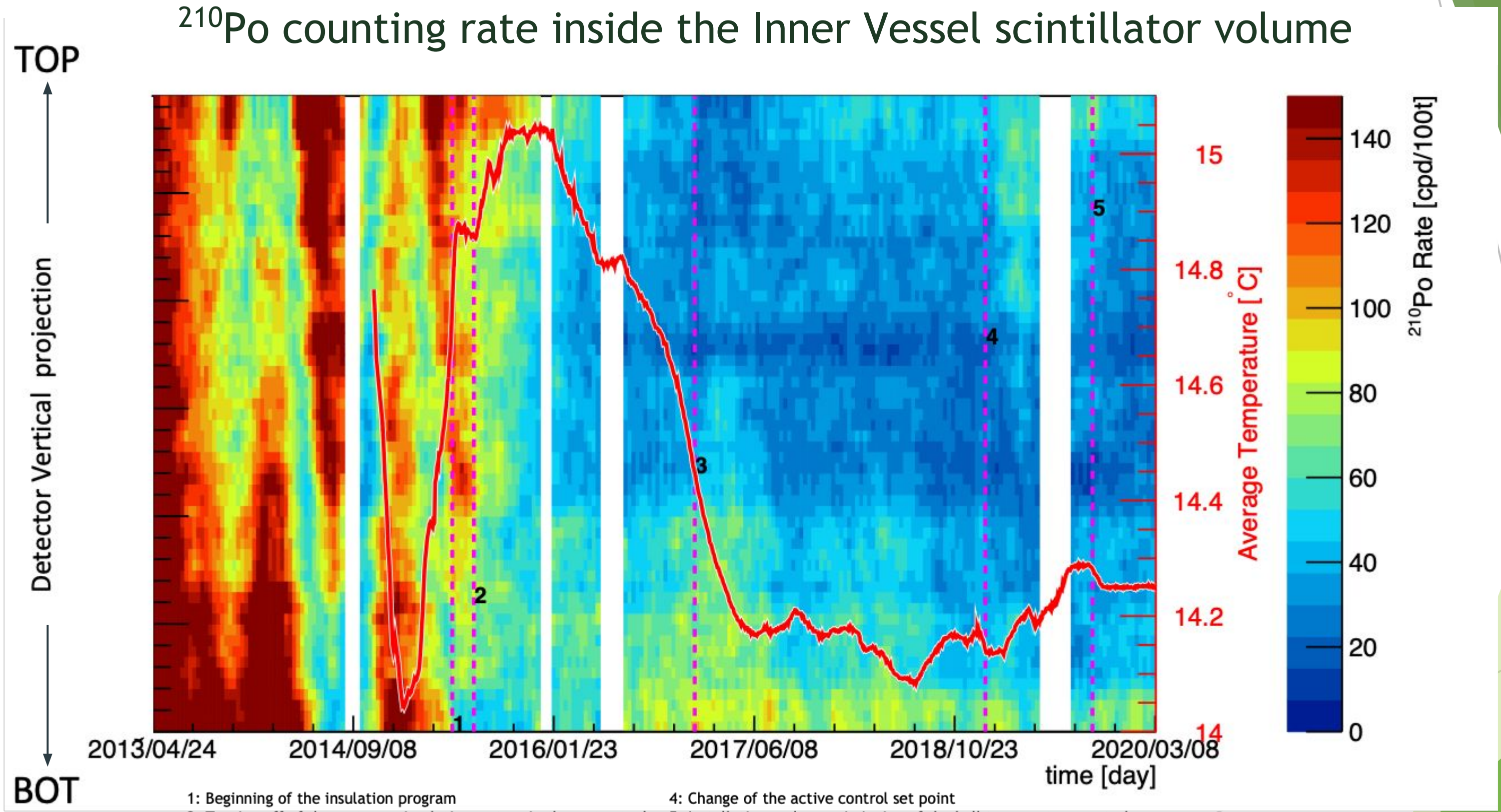
The Detector Thermal Insulation

The Borexino detector is covered with a 20cm-thick layer of rock wool

Before the thermal insulation
(Mid 2015)

After the thermal insulation
(Early 2016)

Effects on Polonium-210



1: Beginning of the insulation program
2: Turning off of the water recirculation system in the water tank;
3: First operation of the active temperature control system;
4: Change of the active control set point
5: Installation and commissioning of the hall temperature control system.

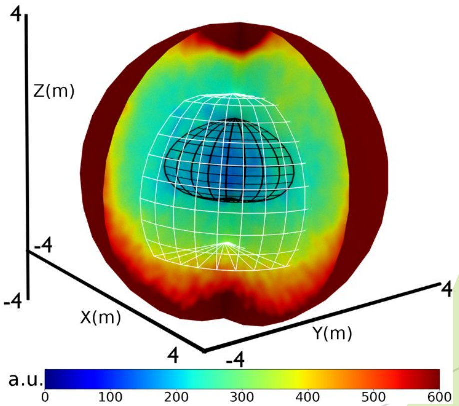
The Bismuth-210 constraint

There is an innermost region of the scintillator which is almost free of convective currents: the ^{210}Po rate can be there fitted assuming a bulk+IV contributions.

→ We get a minimum for the ^{210}Po rate and an upper limit for the ^{210}Bi rate!

This ^{210}Bi upper limit can be extended over the full FV **<u>if and only</u>** ^{210}Bi is found, within error, uniform both in the angular and radial distributions

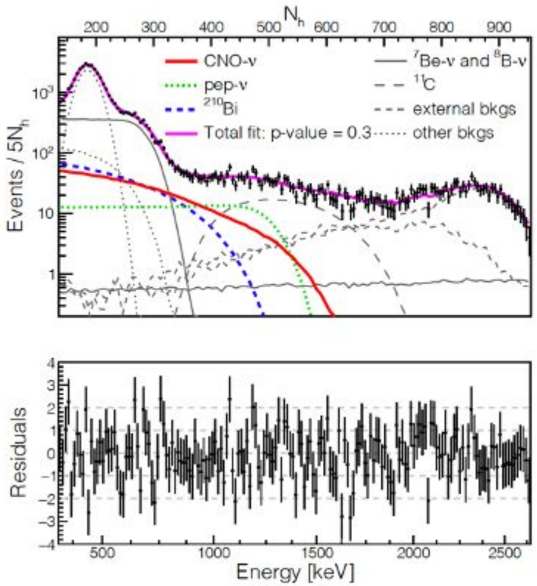
^{210}Bi stable in time → ^{210}Pb leaching from the nylon vessel is negligible.

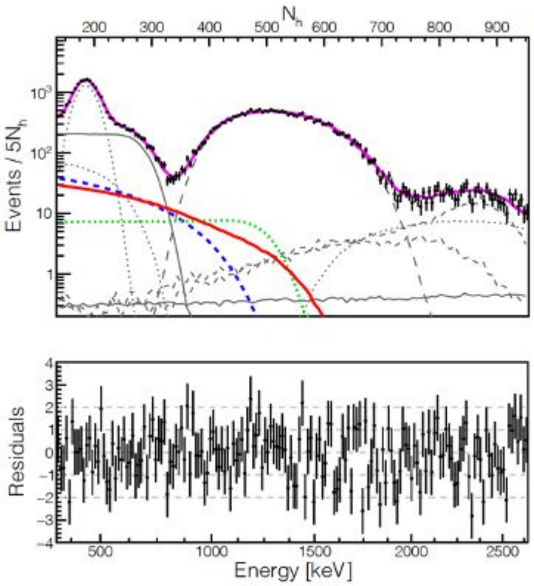


R(^{210}Bi) < 11.5 ± 1.3 cpd/100t

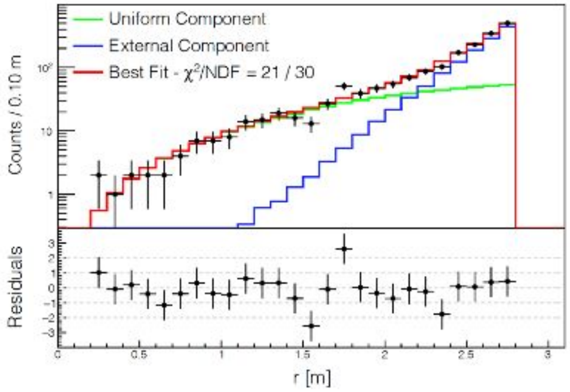
Towards the CNO-ν measurement (3)

A Multivariate fit is performed and the neutrino interaction rates are obtained by maximizing a binned likelihood function which includes both the ^{11}C-subtracted and ^{11}C-tagged energy spectrum, as well as the radial distribution. The rate of signals and backgrounds are left free parameters of the fit with the two discussed exceptions: ^{210}Bi and pep.

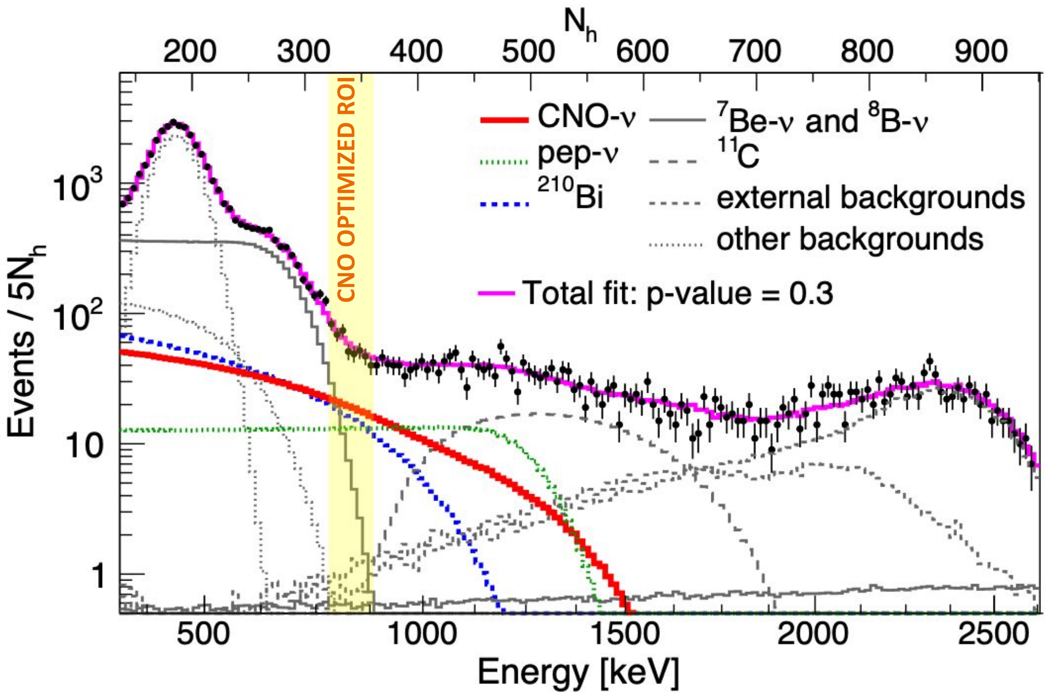




$$\mathcal{L}_{MV} = \mathcal{L}_{^{11}C_{sub}} \cdot \mathcal{L}_{^{11}C_{tag}} \cdot \mathcal{L}_{rad}$$



The CNO measurement: Results

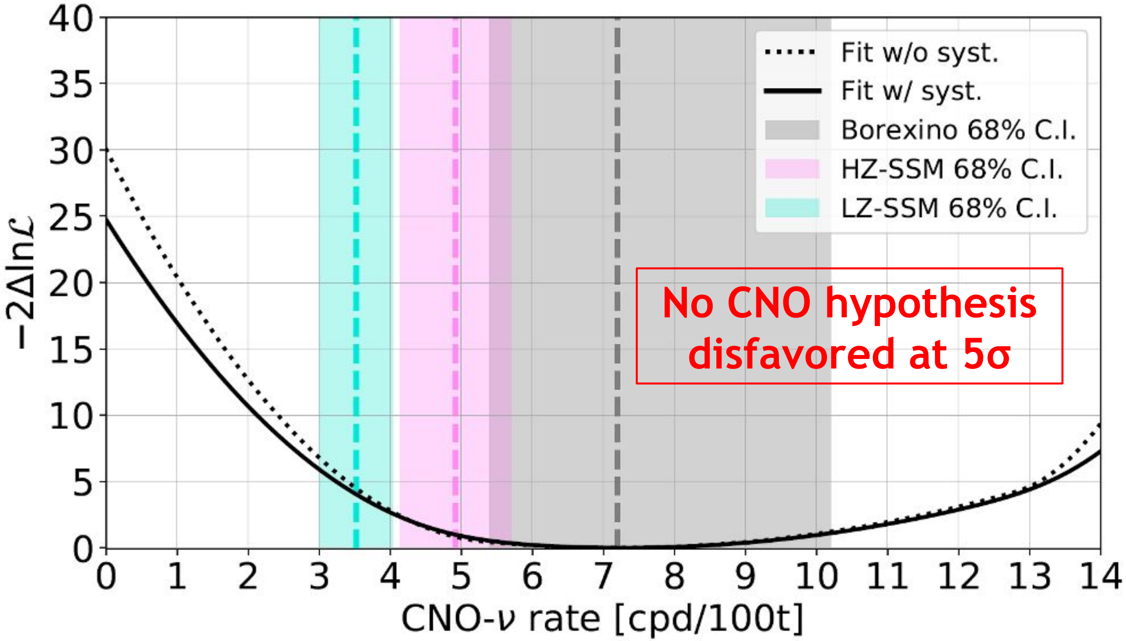


$$\mathcal{R}(\mathrm{CNO}) = \mathbf{7.2}^{+\mathbf{2.9}}_{-\mathbf{1.7}}\ \mathrm{cpd}/100\,\mathrm{t}\ (\mathrm{stat})$$

***Nature* 587 (2020) 577**

"Experimental evidence of neutrinos produced in the CNO fusion cycle in the Sun".

THE CNO MEASUREMENT: RESULTS (2)



Nature 587 (2020) 577

"Experimental evidence of neutrinos produced in the CNO fusion cycle in the Sun".

$$\mathcal{R}(\mathrm{CNO}) = \mathbf{7.2^{+3.0}_{-1.7}}\ \mathrm{cpd/100\,t\ (stat + sys)}$$

$$\Phi(\mathrm{CNO}) = \mathbf{7.0^{+3.0}_{-2.0}} \times \mathbf{10^8}\ \nu/\mathrm{cm}^2/\mathrm{s\ (stat + sys)}$$

Conclusions and Perspectives

Solar neutrinos were and still are essential in proving how the Sun shines and in discovering and studying the physics of neutrino oscillations.

Borexino has mapped out the entire pp solar fusion chain with high precision and it has demonstrated the existence of CNO solar neutrinos for the first time (significance 5σ).

The combination of the ^{7}Be and ^{8}B neutrino fluxes measurements have shown a mild preference towards the SSM High Metallicity scenario.

A more precise measurement of CNO neutrinos rate could give us key knowledge of the Sun's metallicity and of how the massive stars burns.


THE BOREXINO COLLABORATION