Detection of solar neutrinos from the CNO cycle with Borexino

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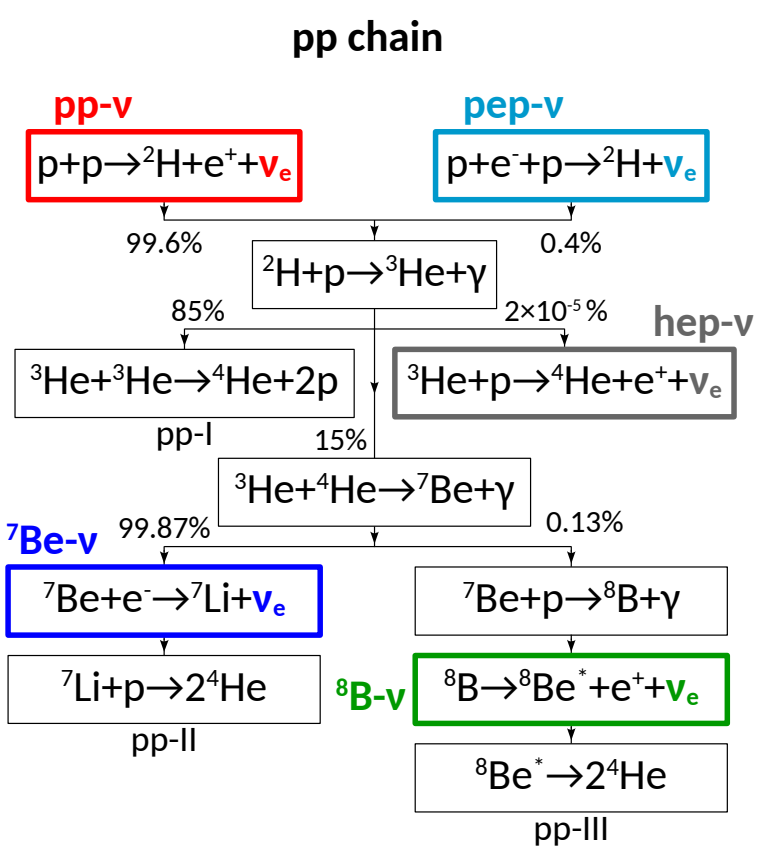
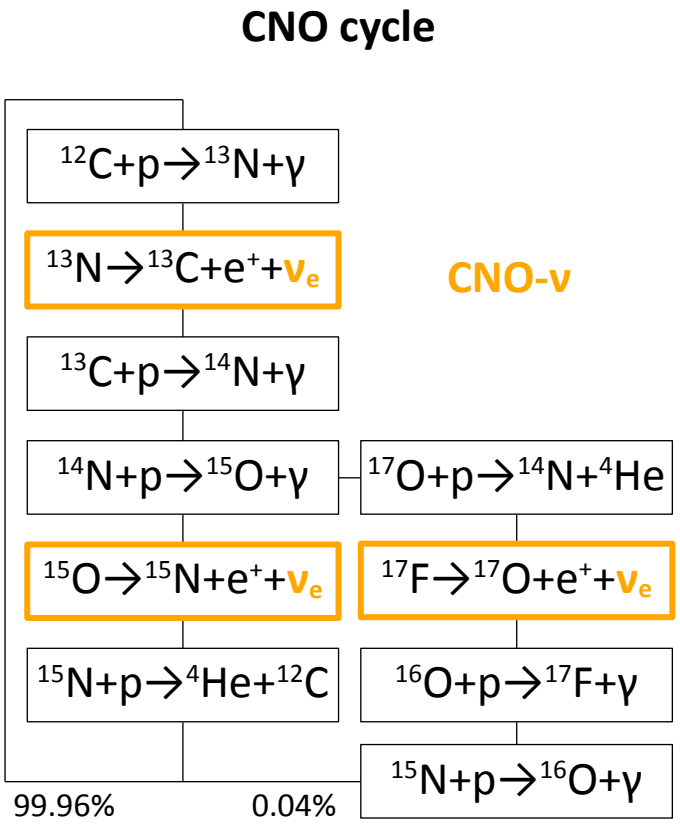
Solar neutrinos

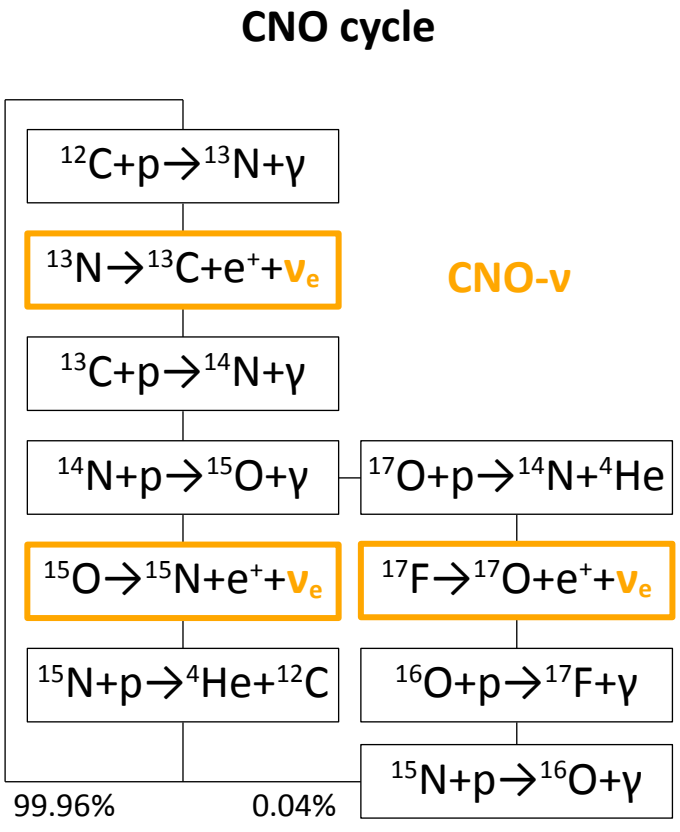




Solar neutrinos: CNO cycle

Produces ~ **1% of solar energy**, but expected to be dominant in heavier stars compared to the Sun

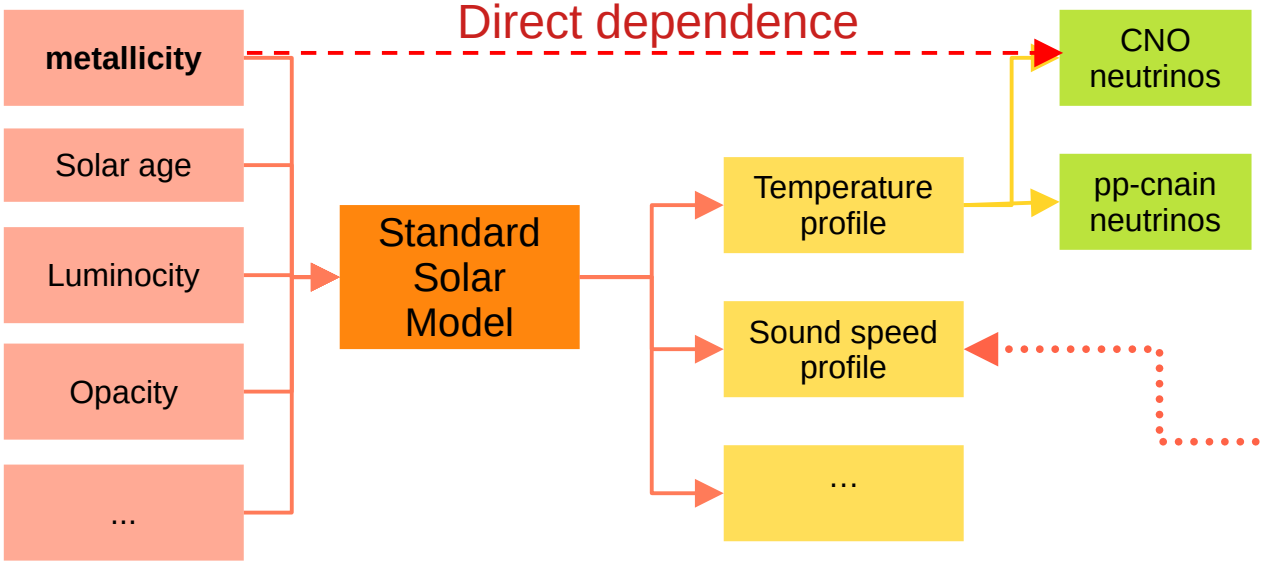
Direct probe of **solar metallicity** – abundance of heavy elements in the Sun



Solar metallicity problem

Metallicity is the abundance of elements heavier than helium (including **C**, **N**, **O**)

One of key inputs of the **Standard Solar Model**



Measurement of CNO neutrino flux can be an independent probe of solar metallicity

Spectroscopic measurements of solar metallicity:

High metallicity (HZ)

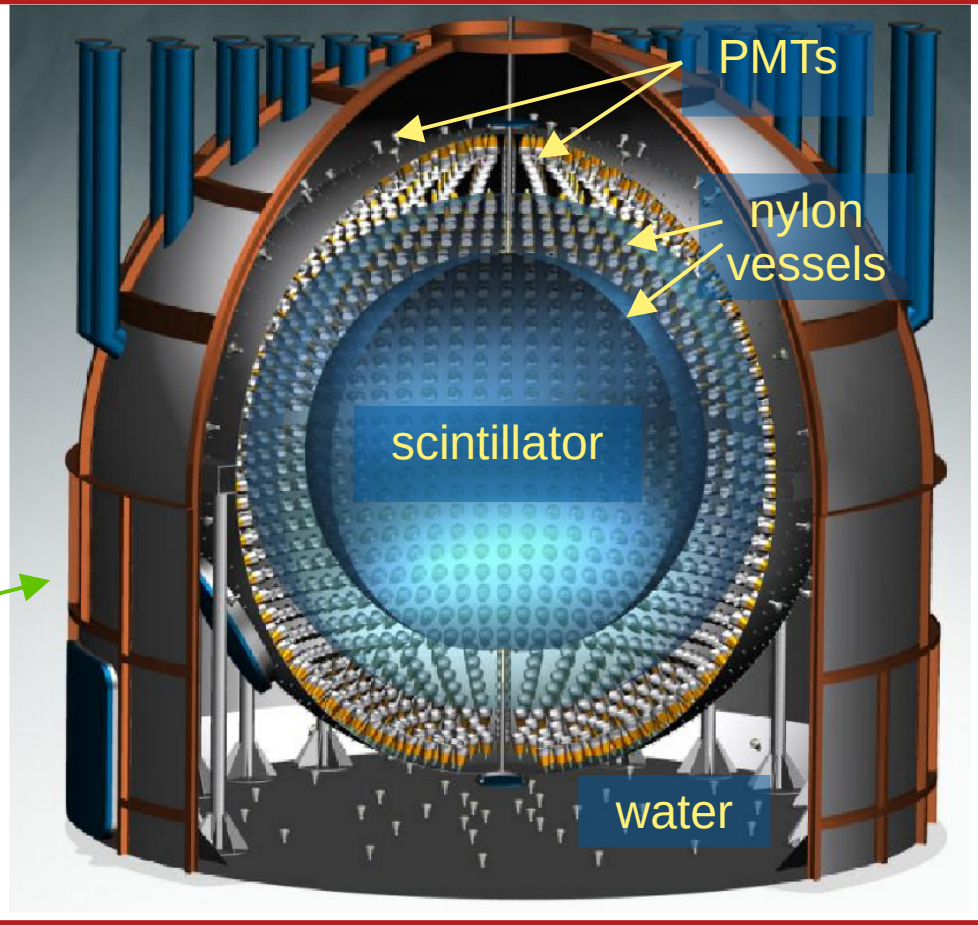
- **GS98** *N. Grevesse and A. Sauval*, Space Sci. Rev. 85 (1998)
- **MB22** *E. Magg et al.*, A&A 661, A140 (2022)

Low metallicity (LZ)

In disagreement with helioseismology

- **AGSS09** *M. Asplund et al.*, Annu. Rev. Astron. Astrophys. 47 (2009)
- **C11** *E. Caffau et al.*, Sol. Phys. 268 (2011)
- **AAG21** *M. Asplund et al.*, A&A 653 (2021)

Borexino experiment



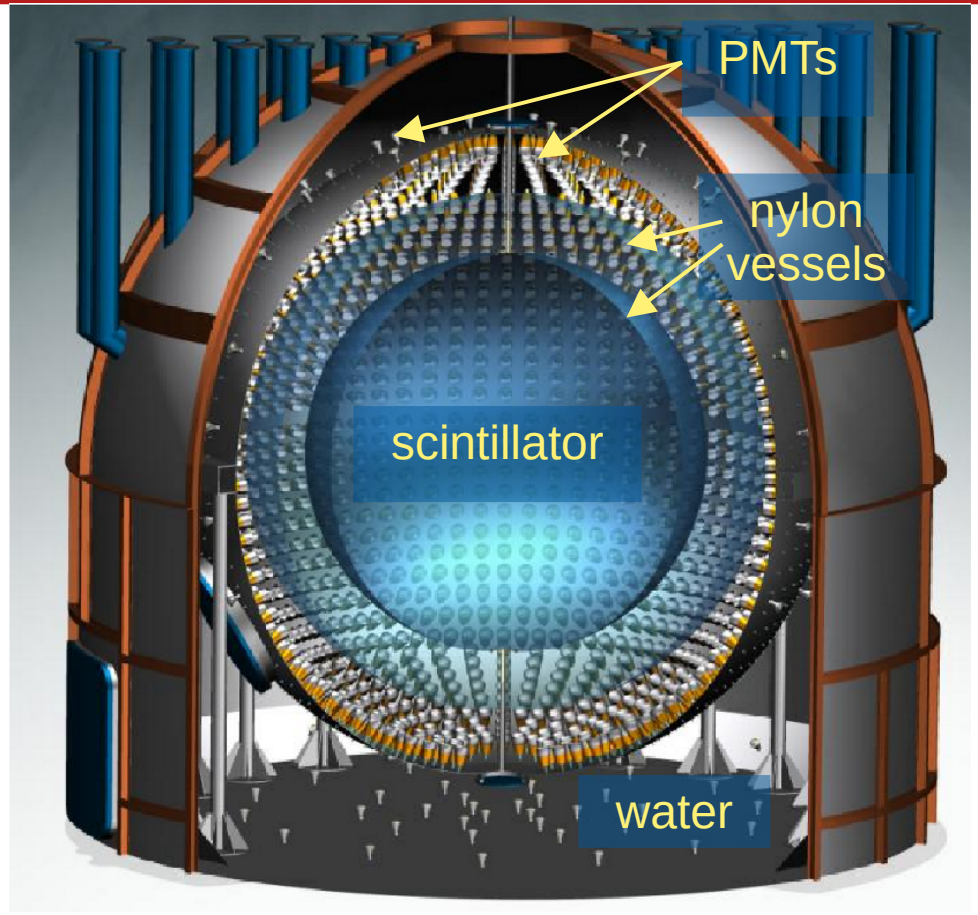
Borexino experiment

Inner detector

- 278 tonnes of liquid scintillator
- Extremely radiopure: ^{238}U and ^{232}Th contamination ~10^{-18} g/g
- Light yield ~500 p.e./MeV
- Energy resolution @ 1 MeV: ~5%
- Spatial resolution @ 1 MeV: ~10 cm

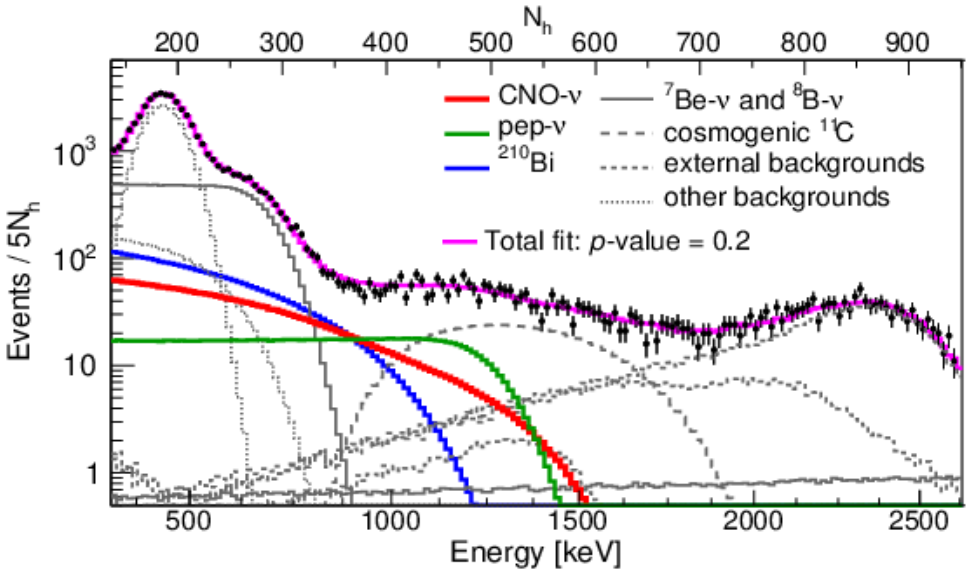
Outer detector

- 2.1 kt of ultra-pure water
- Active muon veto system



CNO measurement challenge

Similar spectral shapes of CNO, pep and ^{210}Bi background → strong anti-correlation



pep neutrino constraint

- pp/pep production rate ratio is well known from nuclear physics
- Global analysis of solar neutrino data with solar luminocity constraint:

J. Bergstrom et al., J. High Energy Phys 2016, 132 (2016)

R(pep) = 2.74±0.04 counts/day/100 t

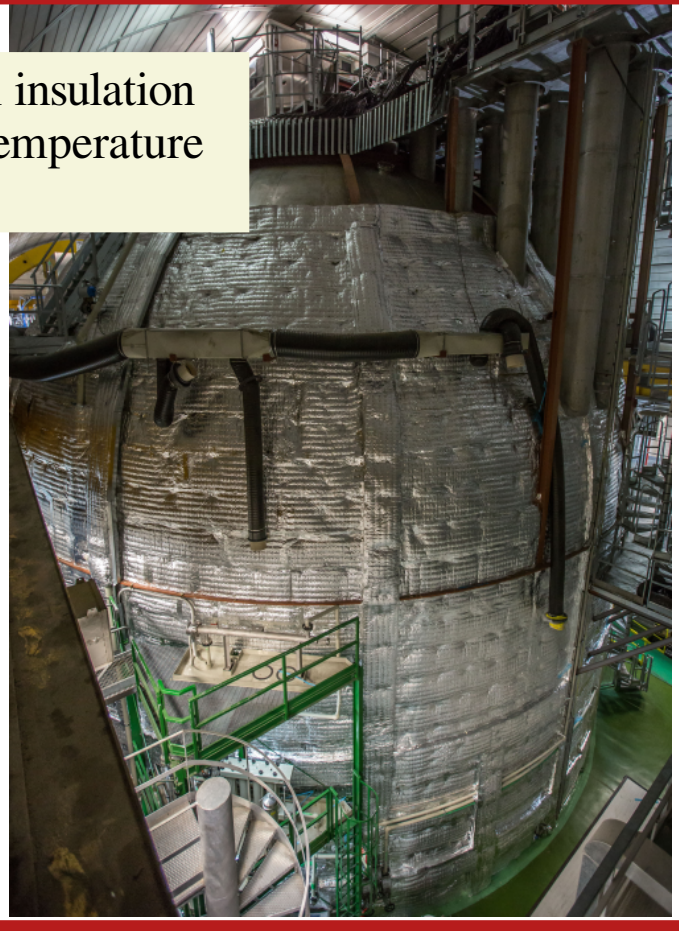
^{210}Bi constraint

$^{210}Pb \rightarrow {}^{210}Bi \rightarrow {}^{210}Po \rightarrow {}^{206}Pb$

Beta decay
Cannot be distinguished event by event

Alpha decay
Can be identified via pulse shape discrimination

Dec 2015: thermal insulation
Jan 2016: active temperature control system



Rate of ^{210}Po in fiducial volume:

$$R(^{210}Po)_{FV} = R(^{210}Bi)_{FV} + R(^{210}Po)_{vessel}$$

Due to thermal instabilities inside the detector additional ^{210}Po is brought inside the fiducial volume by convection

Thermal stabilization is needed

^{210}Bi constraint

^{210}Pb → ^{210}Bi → ^{210}Po → ^{206}Pb

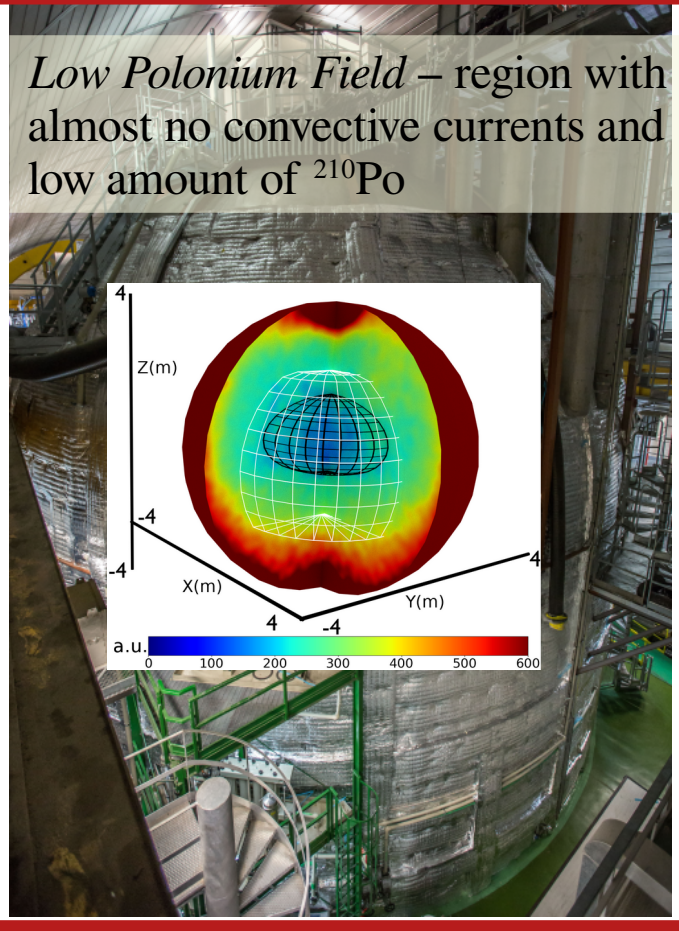
Beta decay
Cannot be distinguished event by event

Alpha decay
Can be identified via pulse shape discrimination

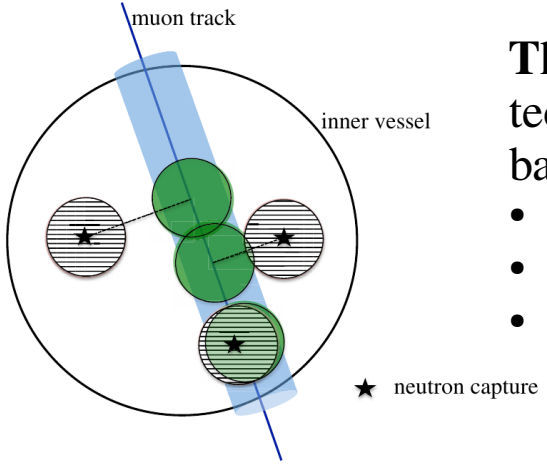
2D fit to obtain the ^{210}Po rate:

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

R(^{210}Bi)≤R(^{210}Po) = 10.8±1.0 counts/day/100 t



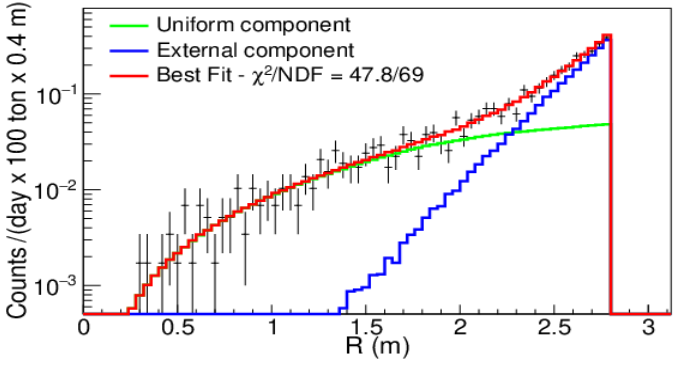
Spectral analysis technique



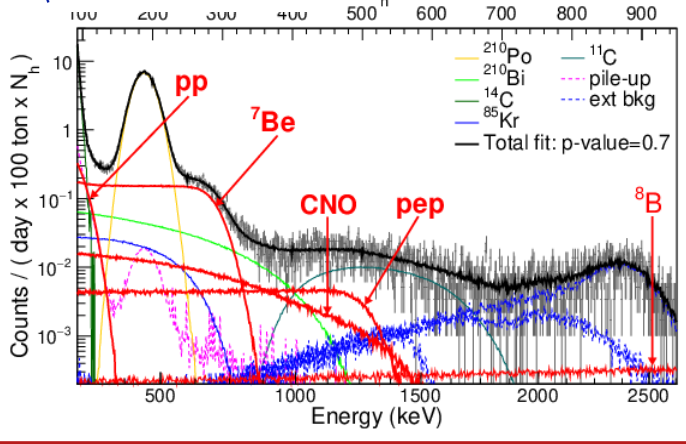
Three-**F**old **C**oincidence technique to suppress ^{11}C background:

- Muon
- Neutron capture
- β^+ decay of ^{11}C

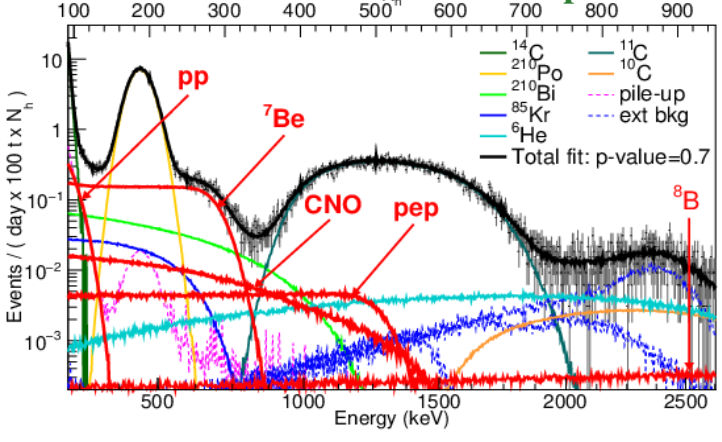
Radial distribution



TFC subtracted

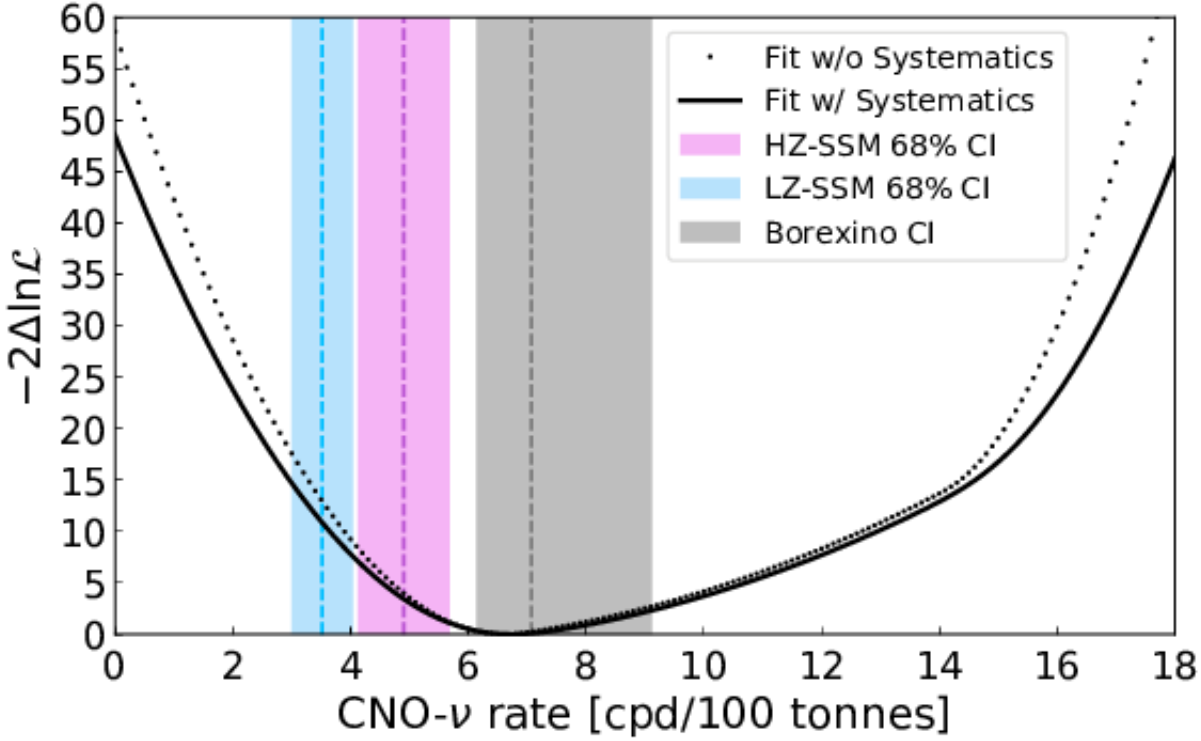


TFC complementary



CNO neutrino flux

First observation: Nature 587 (2020) 577-582
New measurement: arXiv:2205.15975 [hep-ex]



Dataset: Jan 2017 – Oct 2021 (Phase III)

Model presictions:
HZ-SSM rate: 3.52±0.52 cpd/100 t
LZ-SSM rate: 4.92±0.78 cpd/100 t

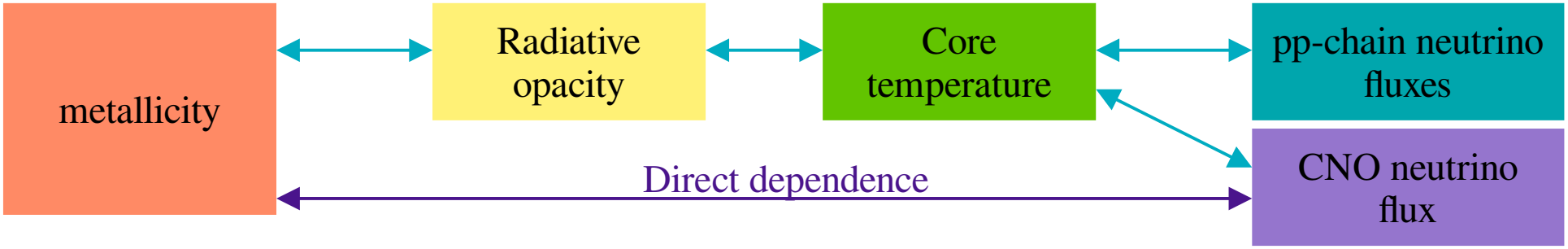
Rate: $6.7^{+2.0}_{-0.8}$ cpd/100 tonnes

Flux: $6.6^{+2.0}_{-0.9}\times10^{8}$ cm^{-2} s^{-1}

7σ significance of CNO observation!

Tension with LZ model ~ 2σ

Solar metallicity



Temperature dependence:

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

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

direct dependence on metallicity

Borexino result

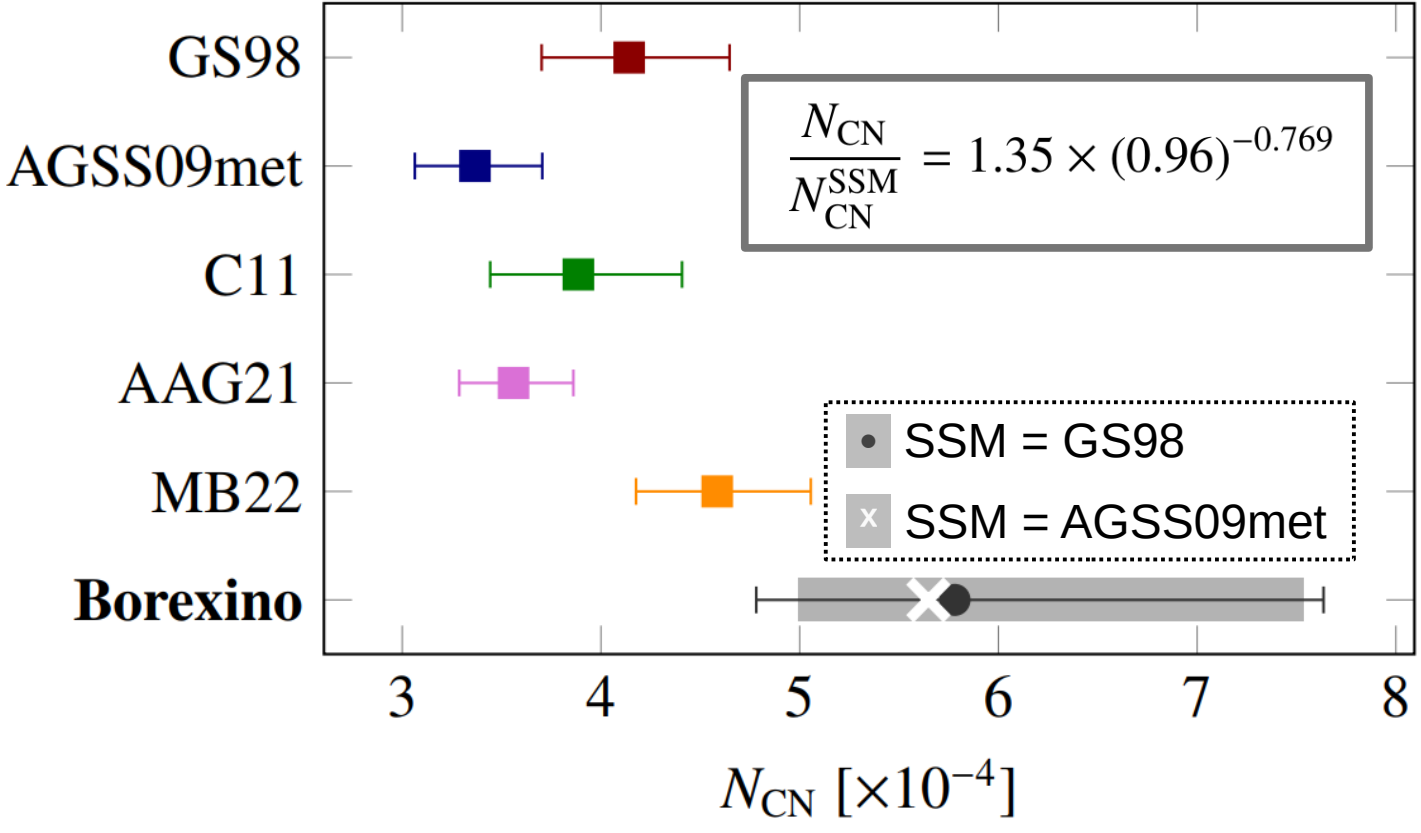
$$\frac{(\Phi_O/\Phi_O^{SSM})}{(\Phi_B/\Phi_B^{SSM})^k} \propto \frac{n_{CN}}{n_{CN}^{SSM}} \left(\cancel{\frac{T_c}{T_c^{SSM}}}\right)^{\tau_O - k\tau_B}$$

Global analysis

This coefficient value is chosen to minimize the uncertainty related to opacity and other inputs

Solar metallicity

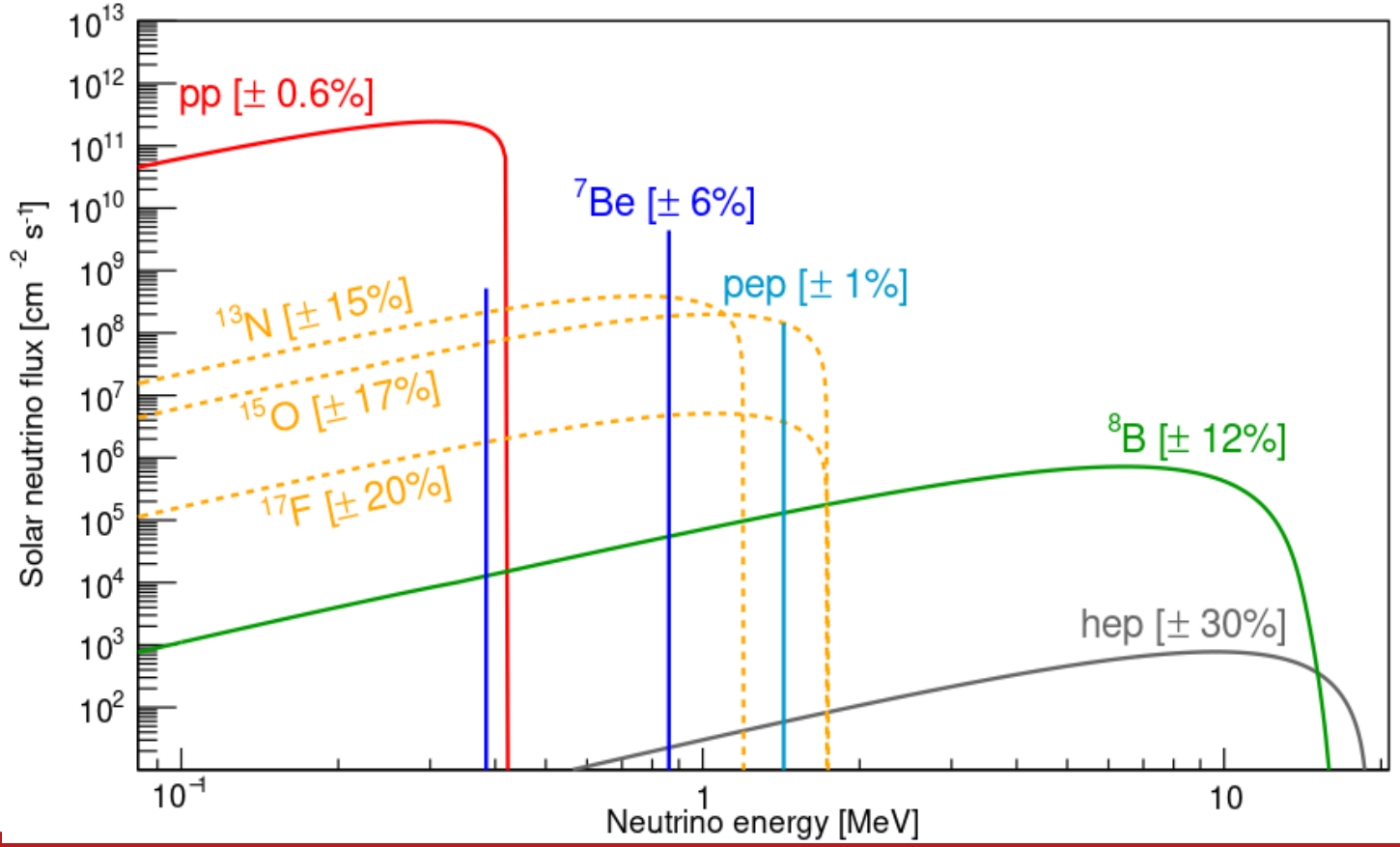
arXiv:2205.15975 [hep-ex]



Thank you for your attention!

Backup

Solar neutrino spectra



Signal and background sources

Neutrinos are detected via (ν-e) elastic scattering

Main selection criteria:

- Muon veto
- Fiducial volume