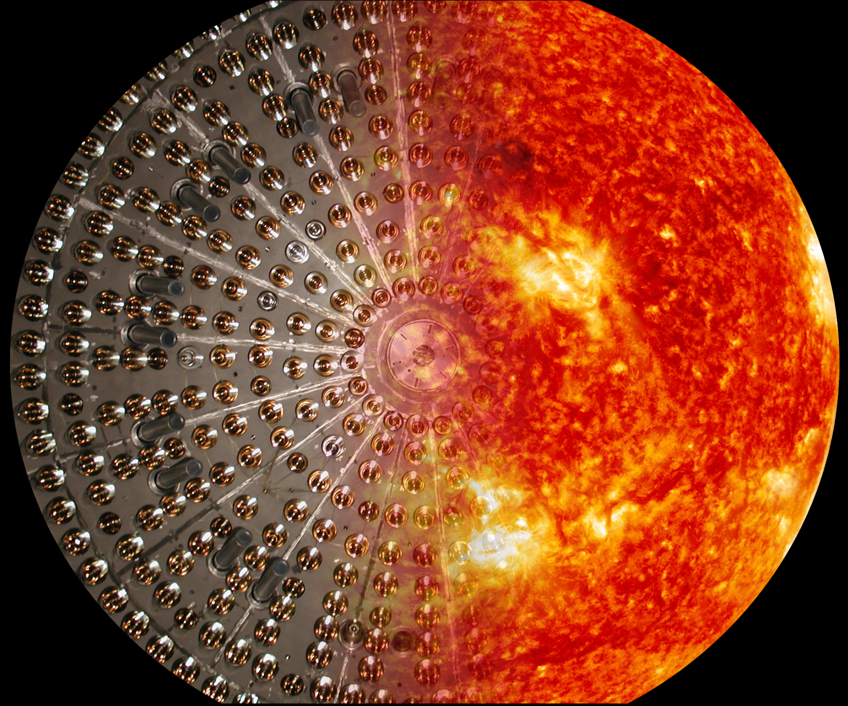


First direct detection of CNO neutrinos: the multivariate fitting strategy

Luca Pelicci on behalf of Borexino Collaboration

106° Congresso Nazionale della Società Italiana di Fisica
14-18 Settembre 2020

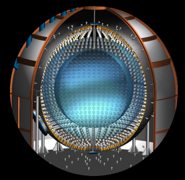
BOREXINO
GRAN SASSO

SOCIETÀ ITALIANA DI FISICA

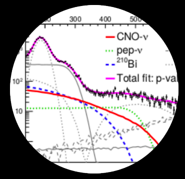
INFN
MILANO
Istituto Nazionale di Fisica Nucleare
Sezione di Milano

Outline

Solar neutrino physics



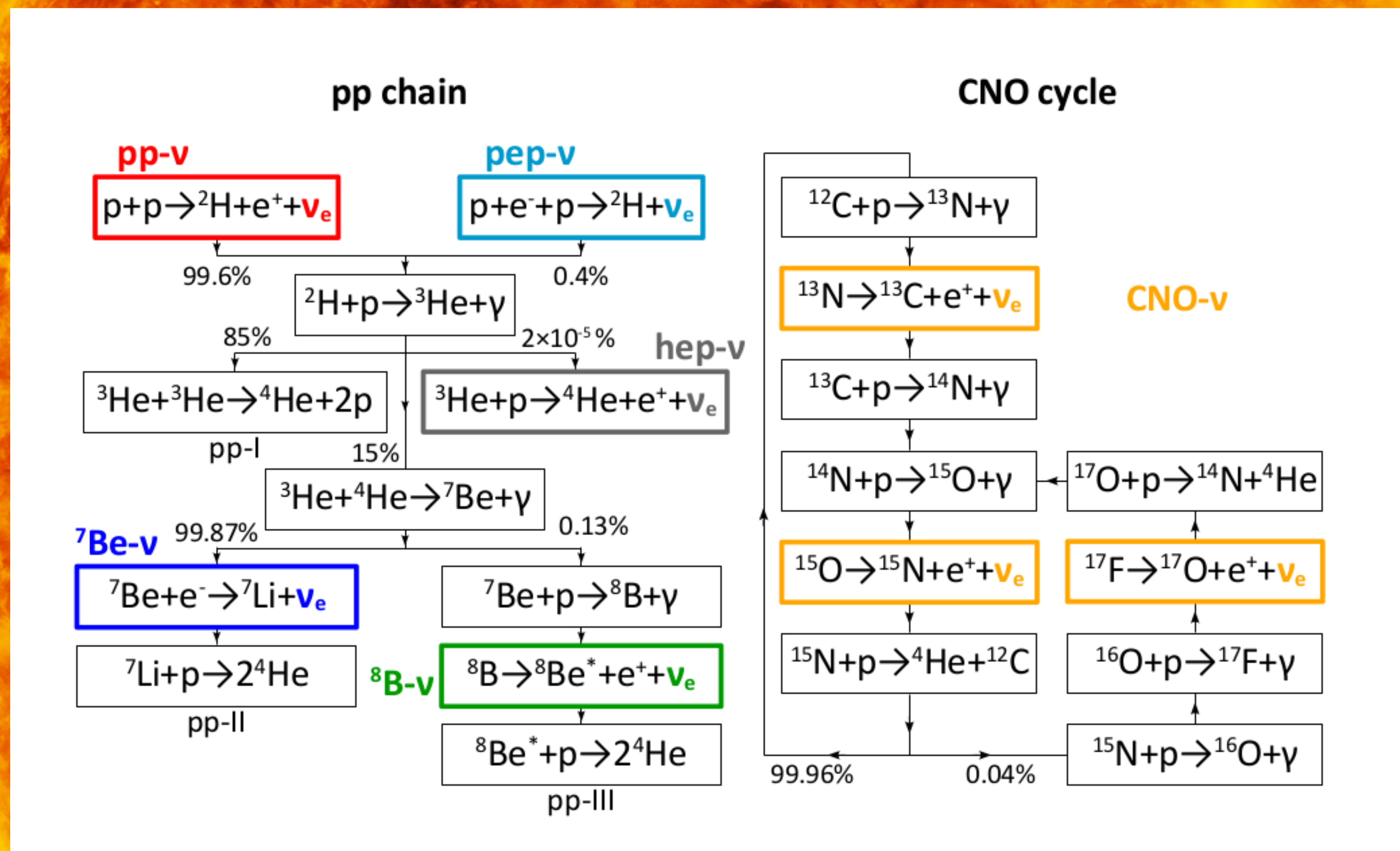
The Borexino detector



The multivariate analysis

Solar neutrino physics

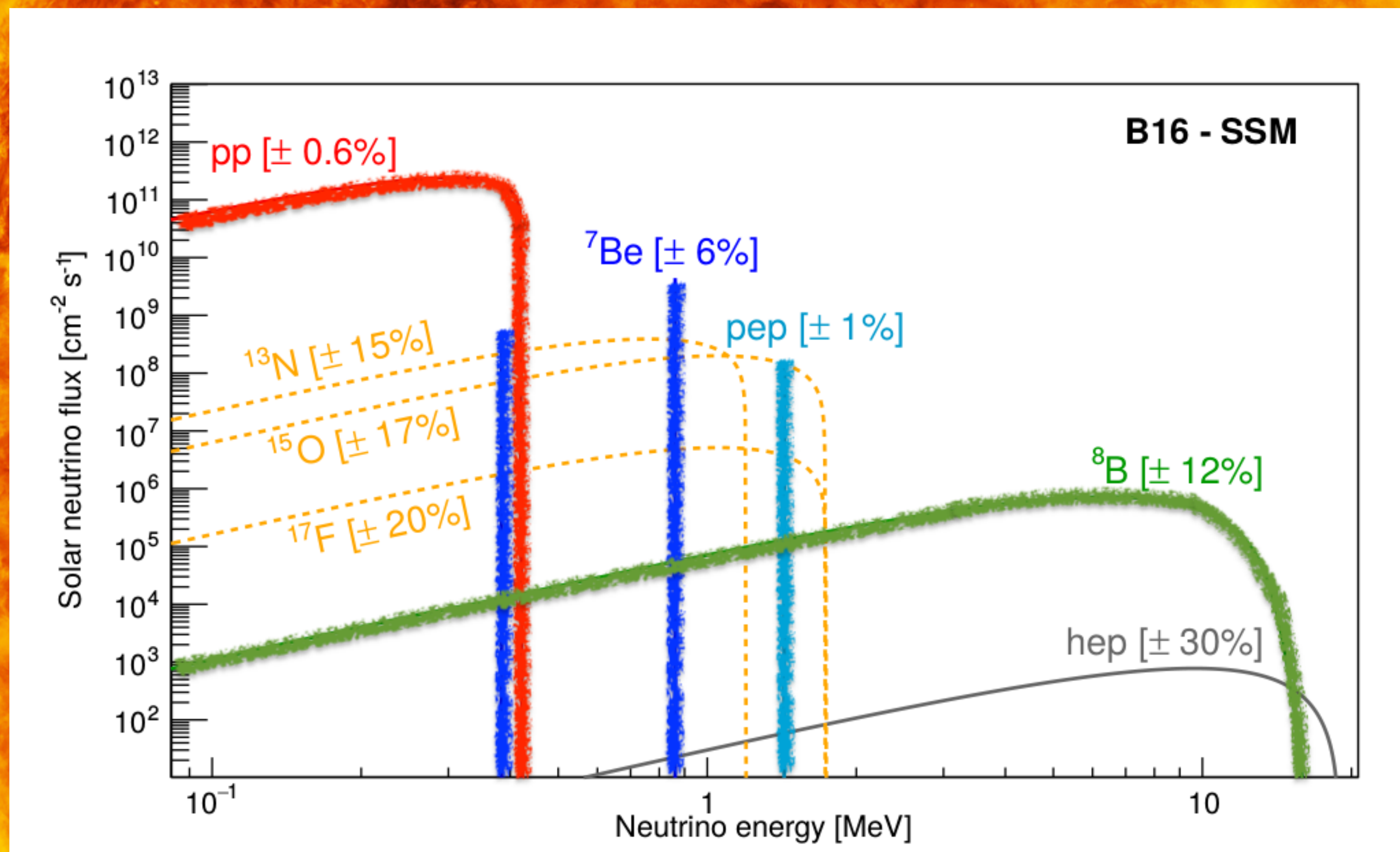
According to the Standard Solar Model
the Sun is powered by two sequences of thermonuclear reactions:



Reaction: $4p \rightarrow {}^4He + 2e^+ + 2\nu_e \qquad Q \approx 26.7 MeV$

Solar neutrino physics

In the last decades several issues in astroparticle physics have been addressed through solar neutrino detection:



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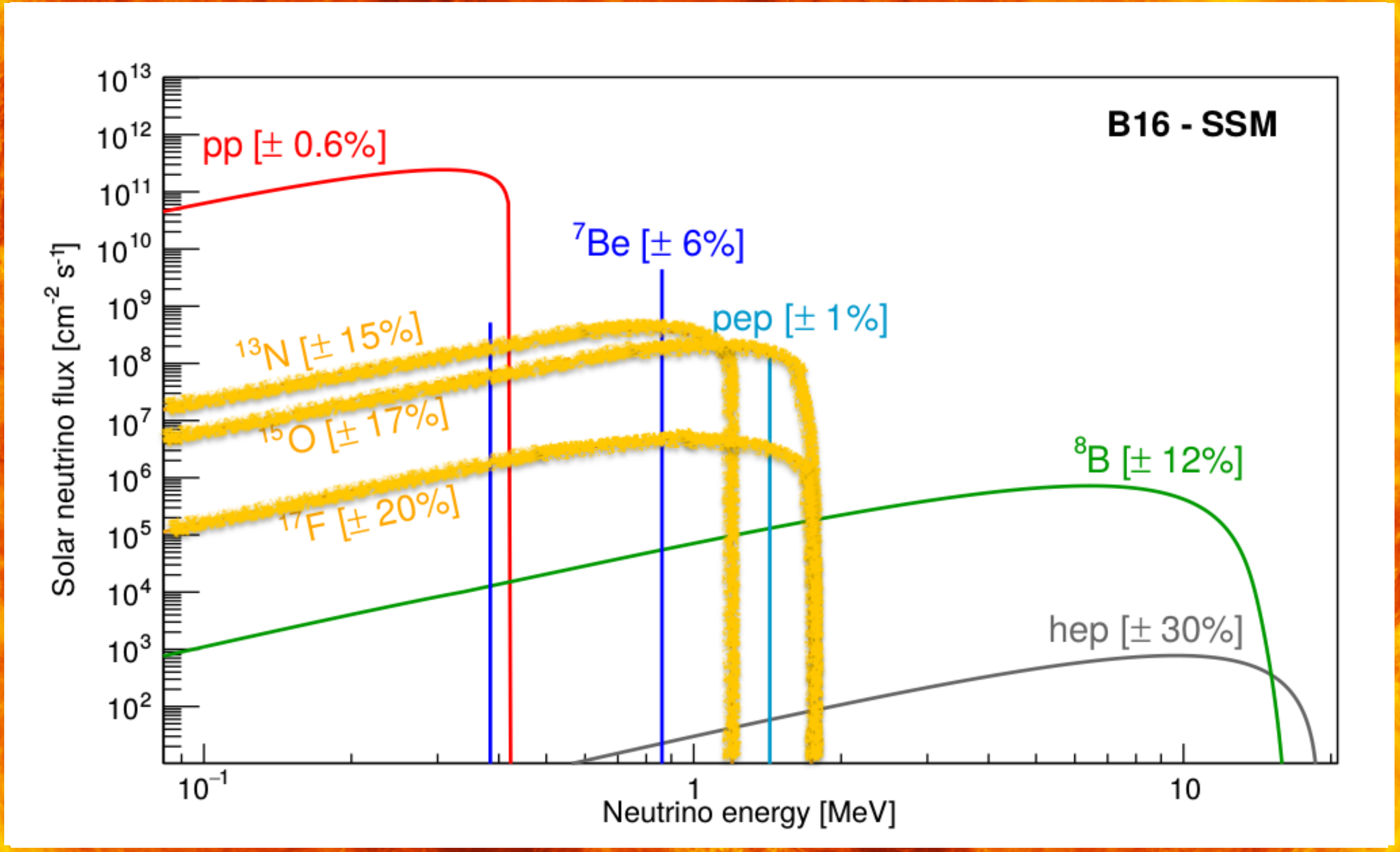


CNO cycle represents the missing piece for the complete understanding of the processes that make the Sun shine

The importance of CNO neutrinos

CNO neutrinos have never been detected so far:

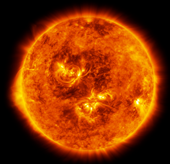
- Proof of energy production in the Sun via CNO cycle
- CNO cycle is xpected to be dominant for stars with $M \geq 1.5\ M_{\odot}$

Metallicity problem:

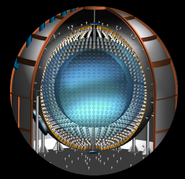
Inconsistencies beetween solar models based on high or low metallicity scenarios:

Φ^{SSM}_{CNO} differ at ~30% level using different metallicity scenarios
CNO neutrinos are the perfect candidates to solve the puzzle

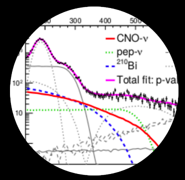
Outline



Solar neutrino physics



The Borexino detector



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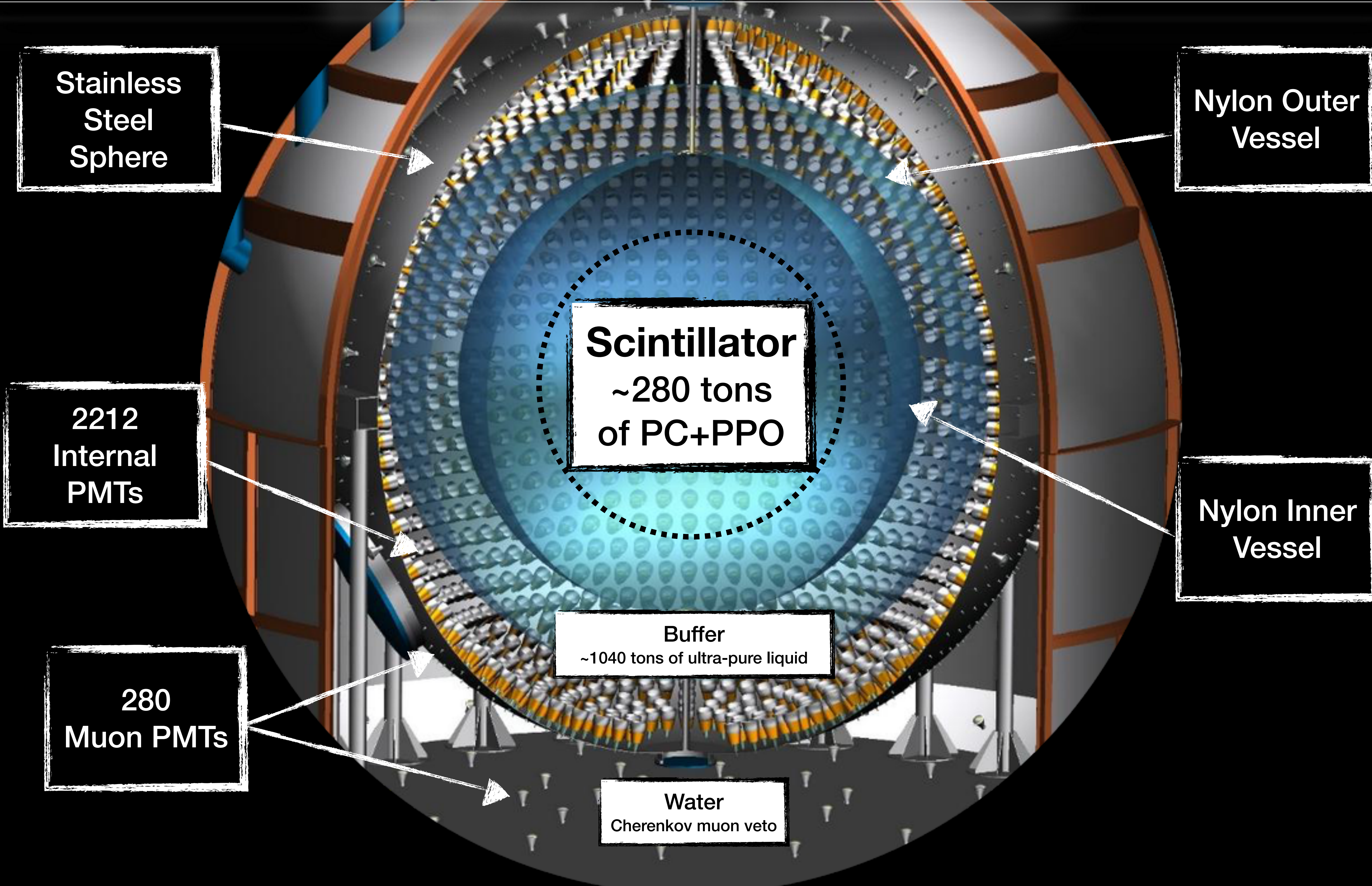
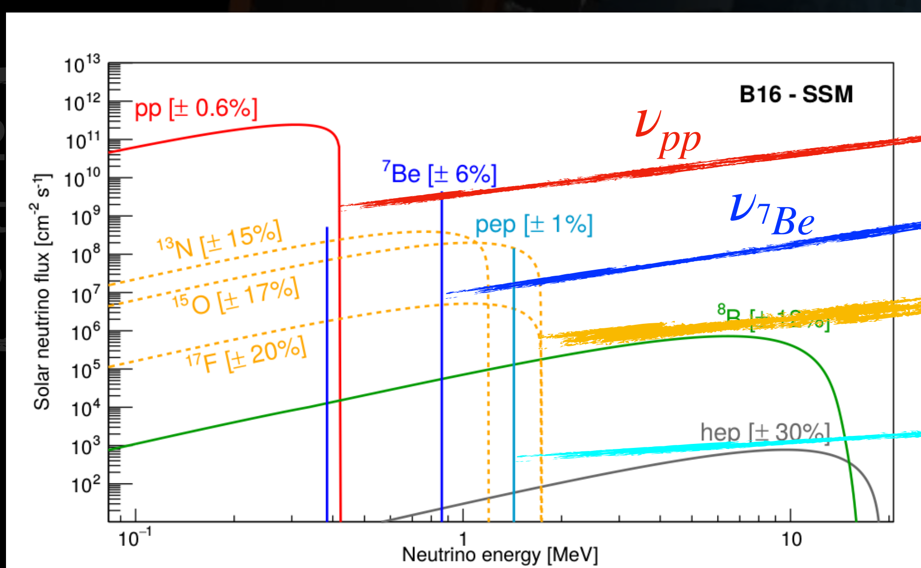


The Borexino detector

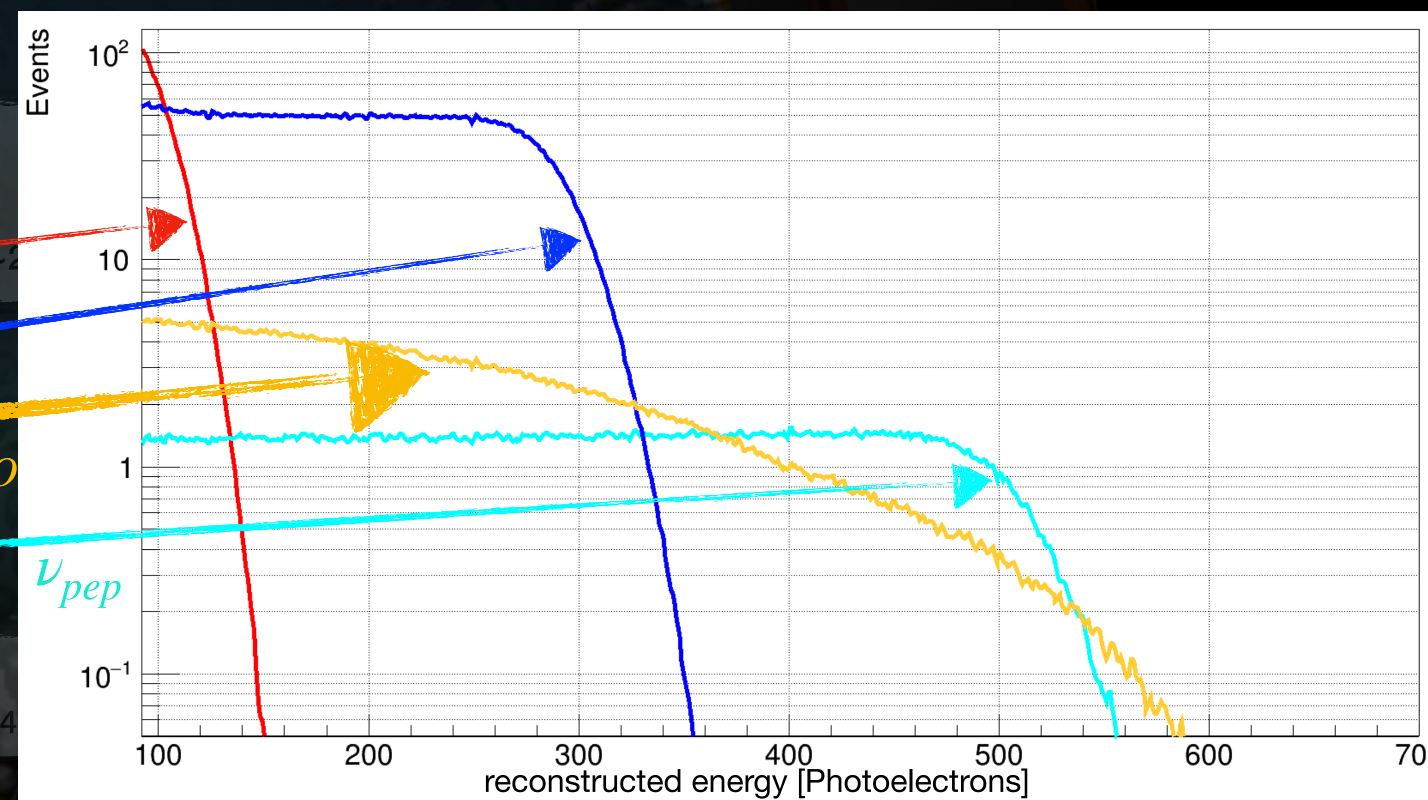
Detection method: elastic scattering of neutrinos on electrons

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

SSM prediction for solar neutrino fluxes



Neutrino-electron scattering spectrum in Borexino:



- ✅ High light yield (~10^4 photons/MeV)
- ✅ Low energy threshold
- ❌ No directional information

Unprecedented level of radiopurity

Borexino: a long story

2007

Phase-I:

Solar neutrinos:
- $^7Be\ \nu$: 1st observation (5%)+ absence of day/night asymmetry;
- pep ν: 1st observation;
- 8B ν with low threshold;
- CNO ν : best limit;

Other:
- Geo-ν evidence > 4.5σ;

2010

Purification campaign

2012

Phase-II:

Solar neutrinos:
- pp ν: 1st observation;
- $^7Be\ \nu$ flux seasonal modulation;
- Comprehensive measurement of of pp-chain (**Nature 2018**)

Other:
- New limit on neutrino magnetic moment
- Geo-ν evidence > 5σ;

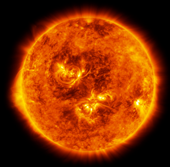
Thermal Insulation

2016 - 2020

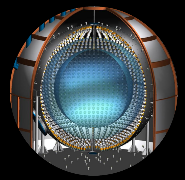
Phase-III:

- **New Results (this talk):** First direct experimental evidence of **CNO neutrinos**

Outline



Solar neutrino physics



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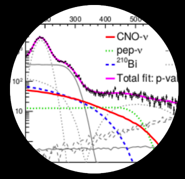


The multivariate analysis

Data selection - Backgrounds

Internal backgrounds

^{232}Th and ^{238}U are negligible ($\sim 10^{-19}\ g/g$) after purifications campaign
^{210}Bi reduced by a factor ~ 2, ^{85}Kr reduce by a factor ~ 5
^{210}Po identified via α/β discrimination

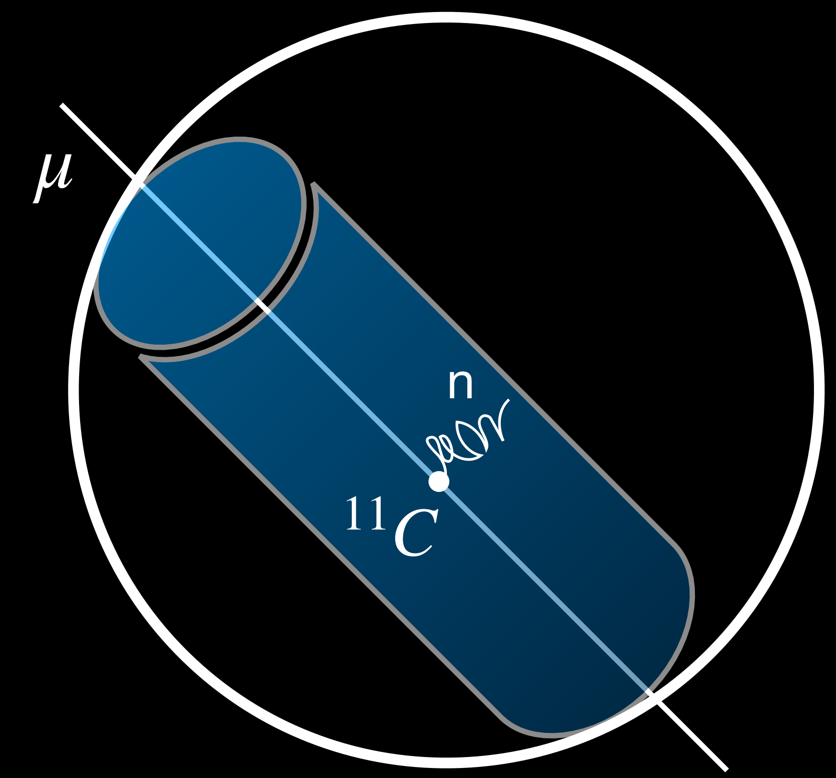
External backgrounds

γ's produced from ^{208}Tl , ^{214}Bi and ^{40}K radionuclides
Reduced with FV selection and exploiting radial dependence

Cosmogenic backgrounds

^{11}C produced by cosmic rays interaction
identified via three fold coincidence (TFC):

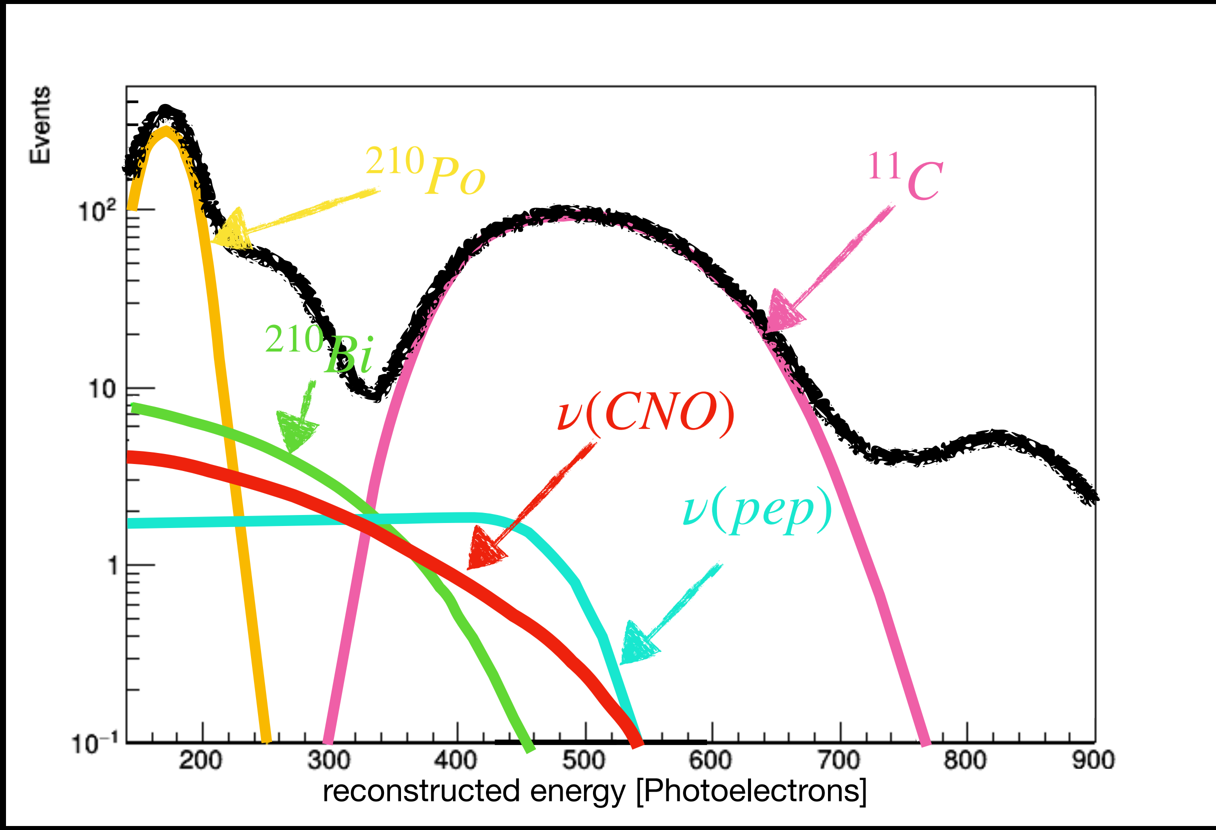
$$\mu + {}^{12}C \rightarrow \mu + {}^{11}C + n \begin{cases} {}^{11}C \rightarrow {}^{11}B + e^+ + \nu_e \\ n + p \rightarrow d + \gamma_{2.2\ MeV} \end{cases}$$



Data-set divided in two samples:
TFC-tagged (enriched in ^{11}C) and
TFC-subtracred (depleted in ^{11}C)

Challenges of CNO detection

The rate of $\nu(CNO)$ is marginal (expected 3-5 cpd/100ton) with respect to the backgrounds:



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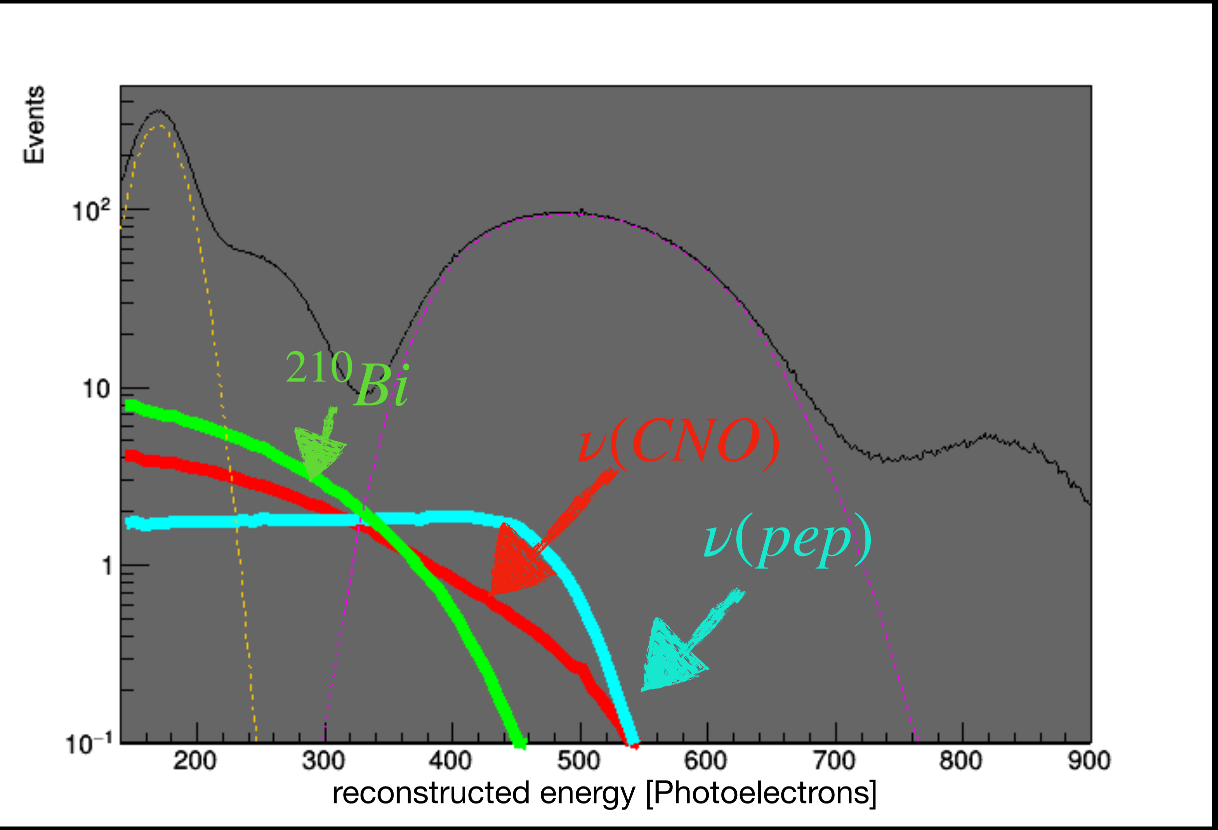


The degeneracy between $\nu(CNO)$, $\nu(pep)$ and ^{210}Bi spectral shapes limits Borexino sensitivity:

No sensitivity to $\nu(\mathrm{CNO})$ signal, but rather to the sum of the interaction rates

Strong correlation between $\nu(CNO)$, ^{210}Bi and $\nu(pep)$ require **independent constraint**:

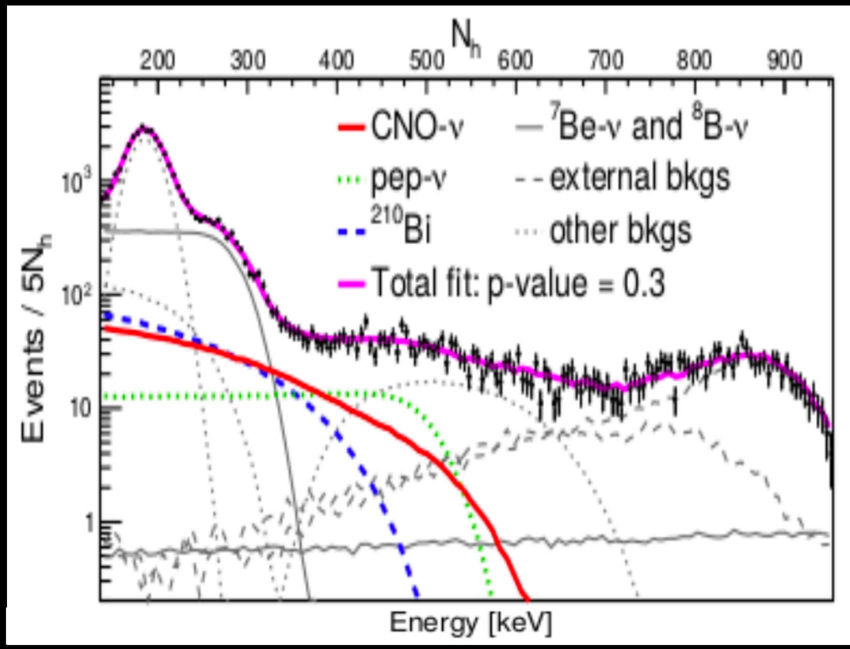
- $\nu(pep) = 2.74 \pm 0.04$ cpd/100t (solar luminosity constraint);
- $^{210}Bi \leq 11.5 \pm 1.3$ cpd/100t (**link with ^{210}Po, viable solution only in Phase-III**).

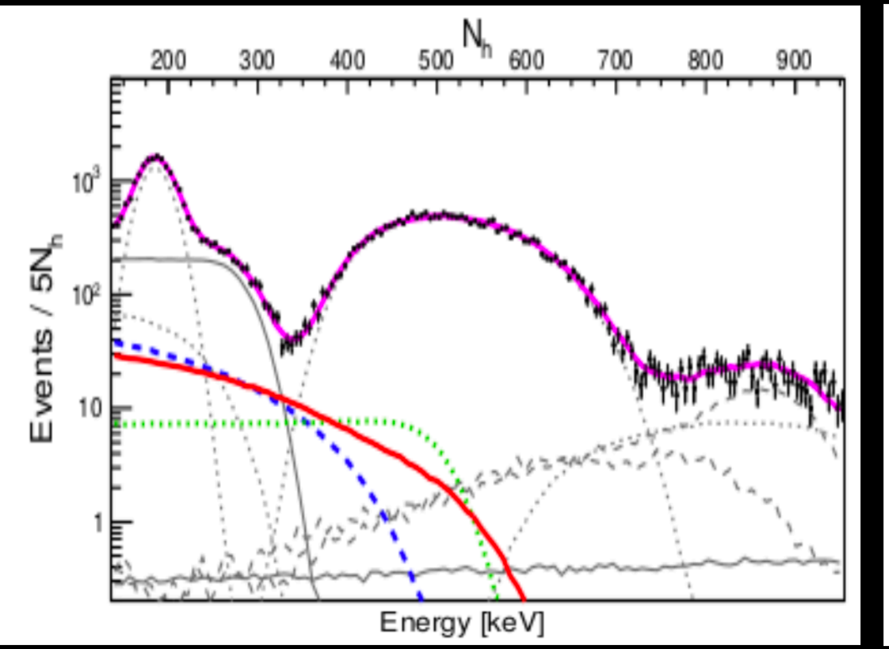
For more details see the presentation by Riccardo Biondi "*Strategy of detection for solar CNO neutrinos and temperature stabilization of the borexino detector*" (atticon12561)

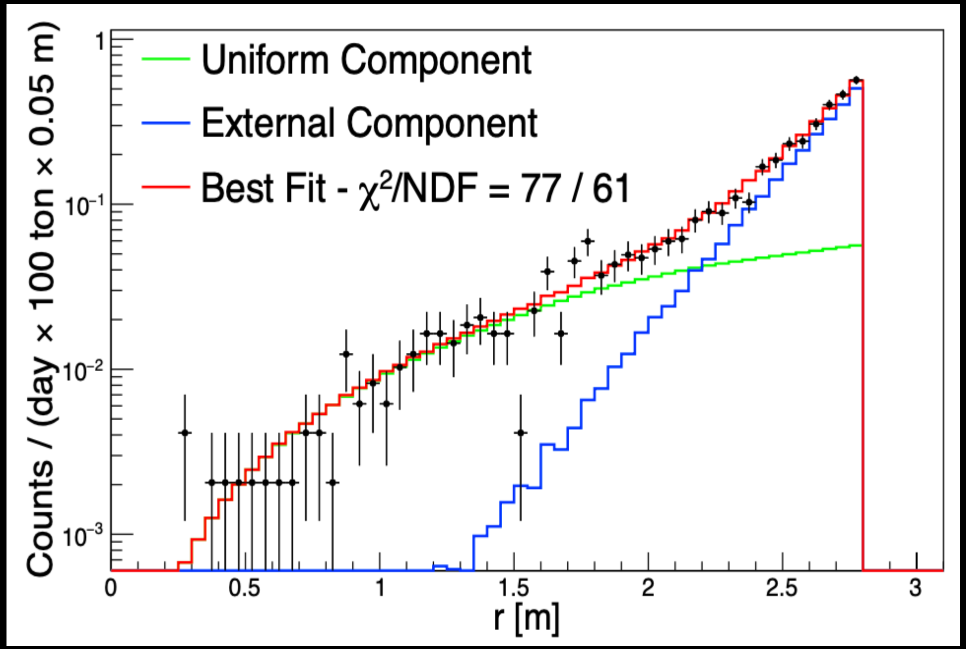
Multivariate fit

Simultaneous fit of data through the optimization of the binned maximum likelihood:

$$\mathscr{L}_{MV}(\vec{k} \mid \vec{\theta}) = \mathscr{L}_E^{TFC-sub}(\vec{k} \mid \vec{\theta}) \cdot \mathscr{L}_E^{TFC-tag}(\vec{k} \mid \vec{\theta}) \cdot \mathscr{L}_{Rad}(\vec{k} \mid \vec{\theta})$$







TFC-subtracted energy spectrum: 63.6% of exposure with 5.5% of ^{11}C

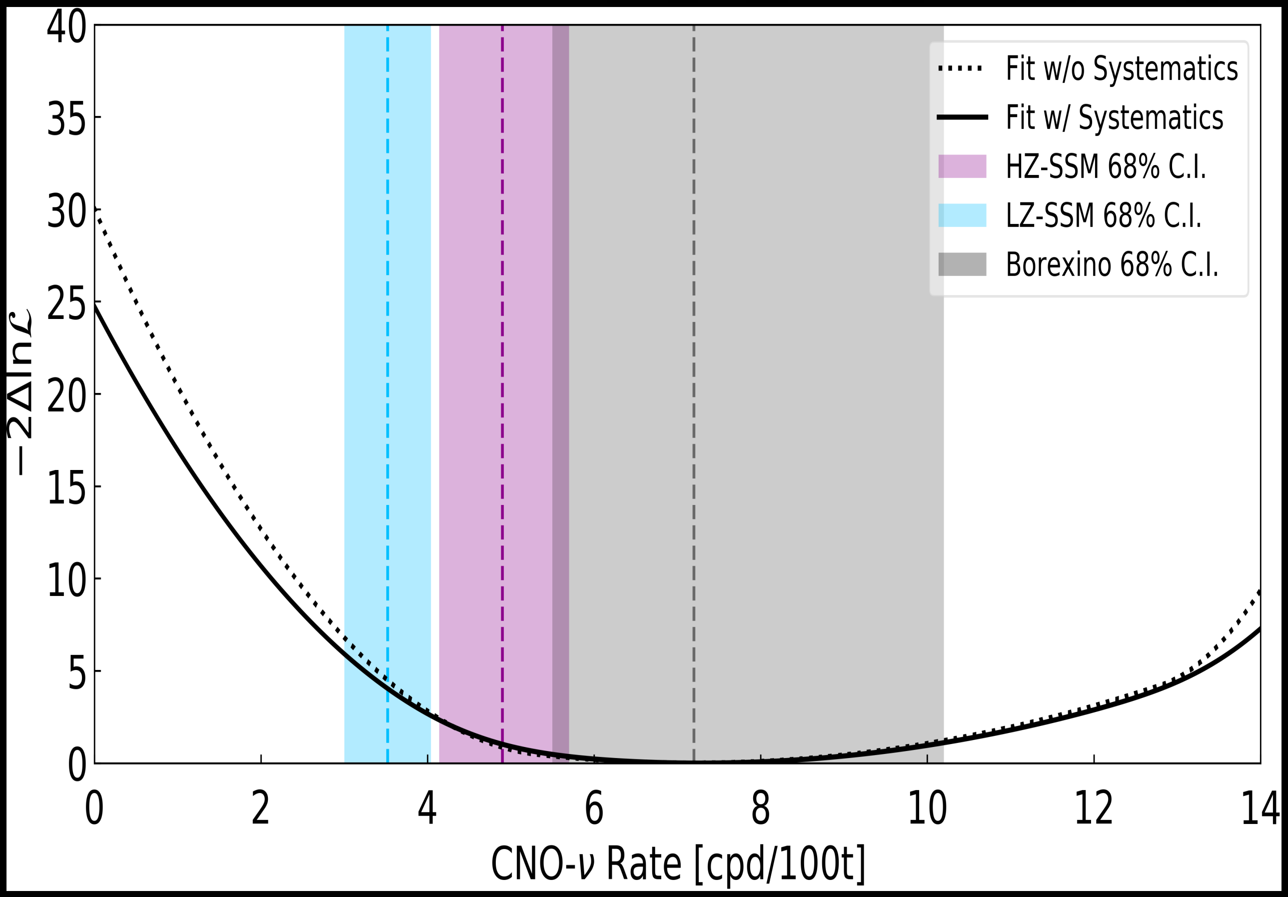
TFC-tagged energy spectrum: 36.4% of exposure with 94.5% of ^{11}C

Radial distribution: improve external backgrounds rejection

Multivariate analysis technical features:

- Energy window: 0.32 - 2.64 MeV
- Phase-III data-set: July 2016 - Feb 2020 (1072 days livetime)
- Fiducial Volume cut: $r < 2.8$ m & $-1.8m < z < 2.2m$)
- Three fold coincidence veto
- Free parameters: $\nu(CNO)$, $\nu(^7Be)$, ^{11}C, ^{85}Kr and externals
- Constrained parameters: $\nu(pep)$ and ^{210}Bi

Results and conclusions



$\nu(CNO)$ fit result: $7.2^{+2.9}_{-1.7}$ cpd/100t (stat only)

Main sources of systematics include: light yield, detector energy response, ^{210}Bi shape, noise cut efficiency and ^{11}C peak position

Final systematics: $X^{+0.6}_{-0.5}$

Best fit results: $7.2^{+3.0}_{-1.7}$ cpd/100 t (stat + syst)

The abscence of CNO signal is disfavored at 5σ

First direct detection ever of CNO solar neutrinos

Thank you for your attention

Borexino Collaboration

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