Solar neutrino analysis with the Borexino detector

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on behalf of the Borexino collaboration

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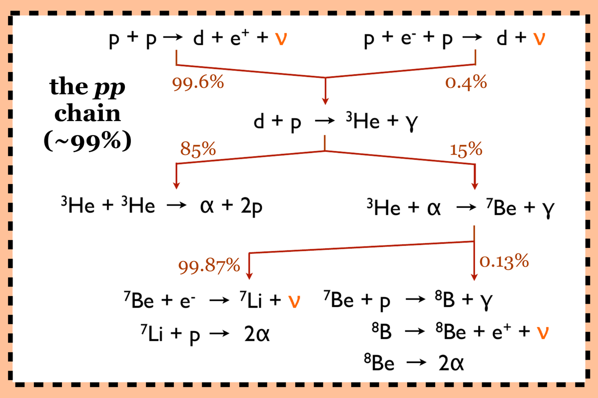
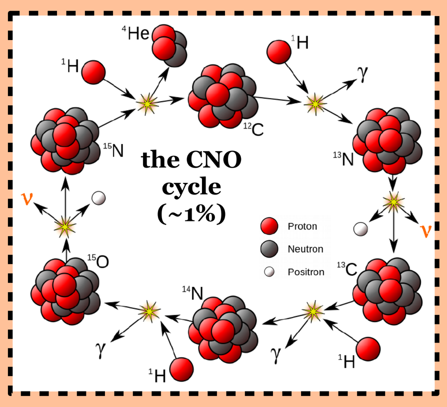
Solar neutrinos

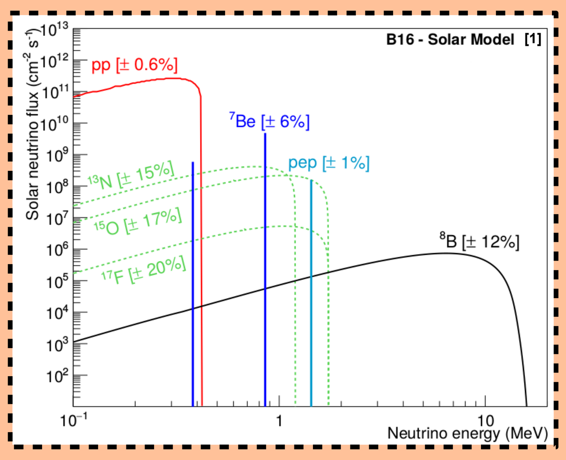


Neutrinos are the only carriers of the information about **nuclear fusion processes** occuring in the **core of the Sun**



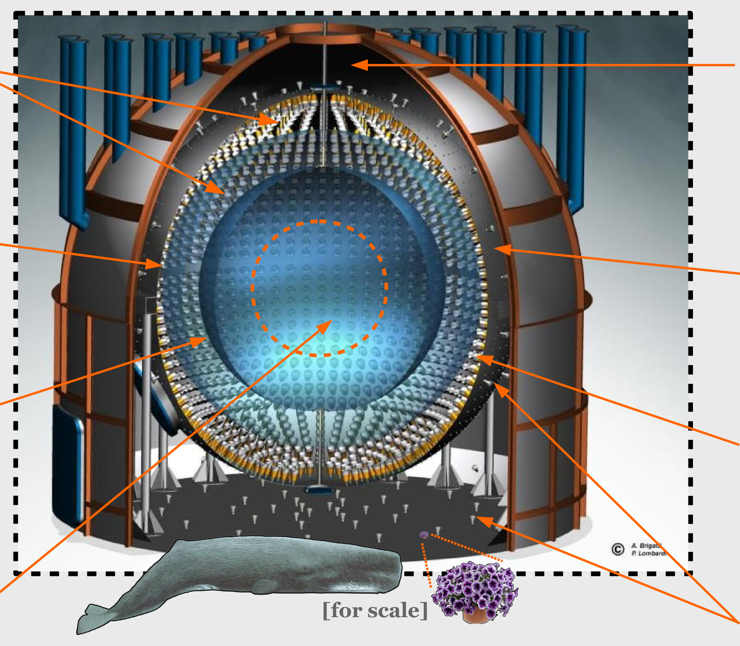
Study the Sun with neutrinos (**solar metallicity**)

Study neutrinos with the Sun (**neutrino oscillations**)



Low (**LZ**) and high (**HZ**) **metallicity models** predict the flux of the neutrinos produced

The Borexino Detector



Buffer
PC + DMP quencher

Nylon Outer Vessel
R = 5.5 m
Barrier for Rn

Nylon Inner Vessel
R = 4.25 m, ~300 t
Liquid scintillator: PC/PPO solution

Fiducial Volume
~70 t
Software cut

Water tank
R = 9 m, 2.1 kt water
Barrier for γ and n
μ Cherenkov detector

Stainless Steel Sphere
R = 6.85 m

Inner detector PMTs
~2000 PMTs
Mounted on SSS

Outer detector PMTs
~200 PMTs
Mounted on SSS, floor

Resolution:
~50 keV & ~10 cm @ 1 MeV

Neutrino detection:
$$\nu + e^- \to \nu + e^-$$

Phase II Results

Dataset: December 2011 to May 2016

Exposure: ~1300 days x 70 tons **Energy range: 0.19 ~ 2.93 MeV**

Constraining the rate of ν(CNO)

based on Standard Solar Model[1] HZ/LZ:

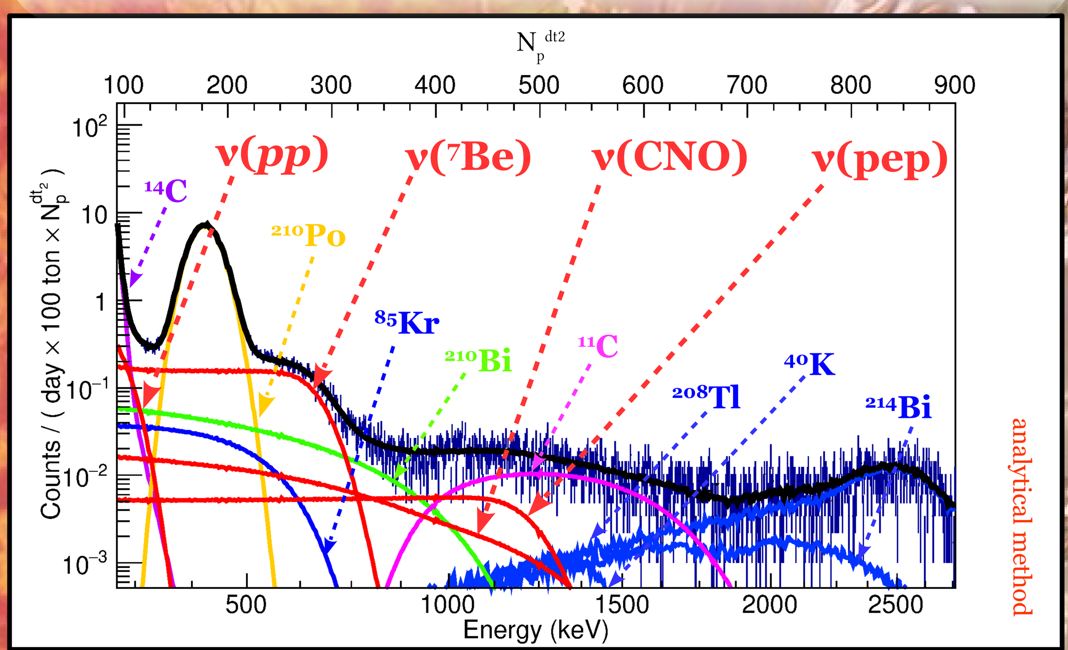
	Rate [cpd/100t]	Flux [cm^{-2} s^{-1}]
$\nu(pp)$	$134 \pm 10\ ^{+6}_{-10}$	$(6.1 \pm 0.5\ ^{+0.3}_{-0.5}) \times 10^{10}$
$\nu(^7\mathrm{Be})$	$48.3 \pm 1.1\ ^{+0.4}_{-0.7}$	$(4.99 \pm 0.13\ ^{+0.07}_{-0.10}) \times 10^{9}$
$\nu(pep)$ HZ	$2.43 \pm 0.36\ ^{+0.15}_{-0.22}$	$(1.27 \pm 0.19\ ^{+0.08}_{-0.12}) \times 10^{8}$
$\nu(pep)$ LZ	$2.65 \pm 0.36\ ^{+0.15}_{-0.24}$	$(1.39 \pm 0.19\ ^{+0.08}_{-0.13}) \times 10^{8}$

Constraining Rate(pp)/Rate(pep)

using MSW-LMA[2] + 2.5% error well-known from theory:

	Rate [cpd/100t]	Flux [cm^{-2} s^{-1}]
$\nu(\mathrm{CNO})$	< 8.1 (95% C.L.)	$< 7.9 \times 10^8$ (95% C.L.)

Multivariate fit result (example)



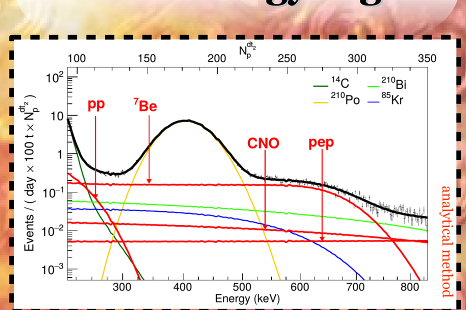
Systematic uncertainties

Source of uncertainty	pp −%	pp +%	^{7}Be −%	^{7}Be +%	pep −%	pep +%
Fit method (analytical/MC)	-1.2	1.2	-0.2	0.2	-4.0	4.0
Choice of energy estimator	-2.5	2.5	-0.1	0.1	-2.4	2.4
Pile-up modeling	-2.5	0.5	0	0	0	0
Fit range and binning	-3.0	3.0	-0.1	0.1	1.0	1.0
Fit models (see text)	-4.5	0.5	-1.0	0.2	-6.8	2.8
Inclusion of ^{85}Kr constraint	-2.2	2.2	0	0.4	-3.2	0
Live Time	-0.05	0.05	-0.05	0.05	-0.05	0.05
Scintillator density	-0.05	0.05	-0.05	0.05	-0.05	0.05
Fiducial volume	-1.1	0.6	-1.1	0.6	-1.1	0.6
Total systematics (%)	-7.1	4.7	-1.5	0.8	-9.0	5.6

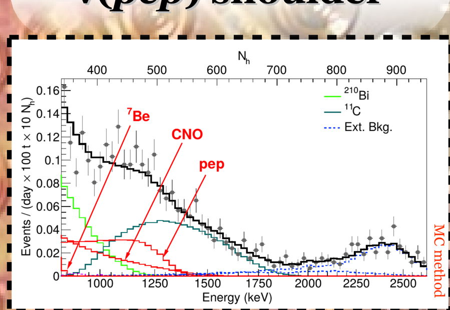
Highlights of the results

- updated **ν(*pp*)** measurement with **9.5%** precision
- **2.7%** precision measurement of **ν(⁷Be)**
- **>5σ** discovery of **ν(*pep*)**
- the most stringent upper limit on **ν(CNO)**

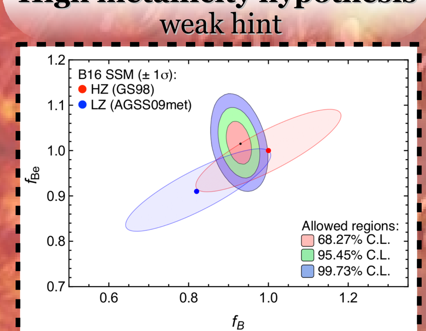
Lowest energy region



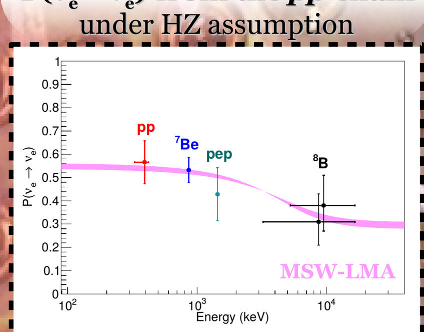
ν(*pep*) shoulder



High metallicity hypothesis
weak hint



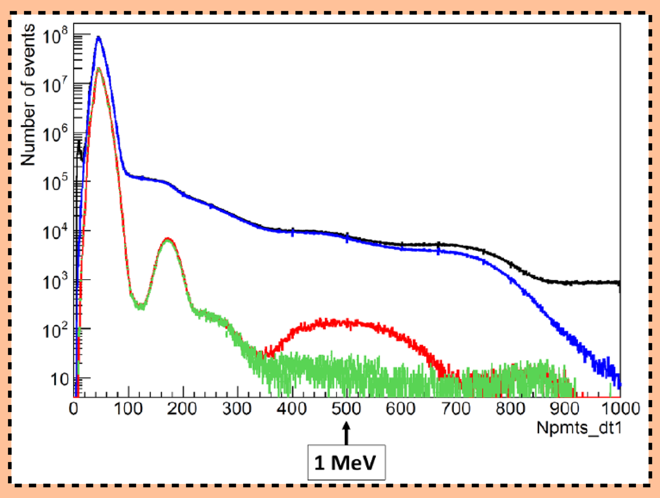
P($\nu_e \to \nu_e$) from the *pp* chain
under HZ assumption



Highlights of the systematics

- Fit procedure done with
  1) **Monte Carlo**
  2) **analytical** approach
- **Pile-up modelling**:
  1) convolution with each species
  2) synthetic pile-up
- **Compatible results** obtained with
  1) different FV and TFC methods
  2) fitting in charge variable

Data selection



no cuts
↓
μ and μ daughter cut
↓
FV cut
↓
TFC cut

Three-fold coincidence (TFC)

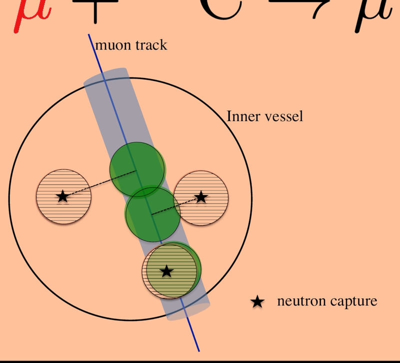
$$\mu + {}^{12}\mathrm{C} \to \mu + {}^{11}\mathrm{C} + n$$

(250 μs)

$$n + p \to D + \gamma$$

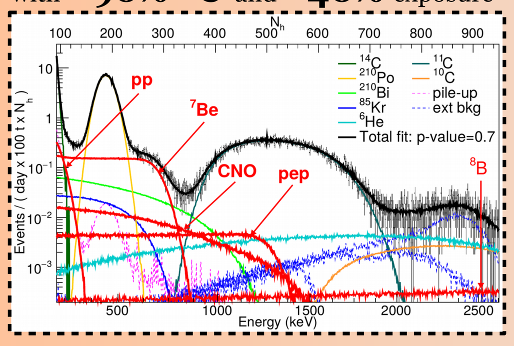
(29.4 min)

$$^{11}\mathrm{C} \to {}^{11}\mathrm{B} + e^+ + \nu_e$$

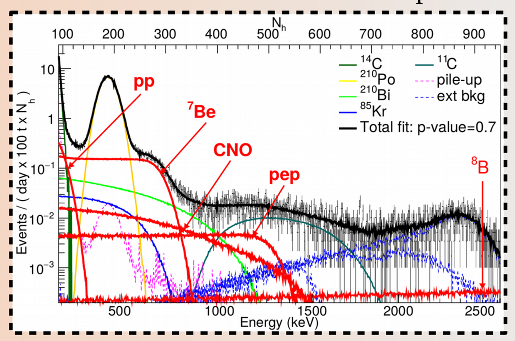


Multivariate Fit

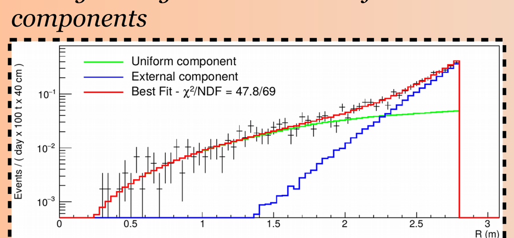
TFC-tagged spectrum with **~90% ¹¹C** and **~40%** exposure



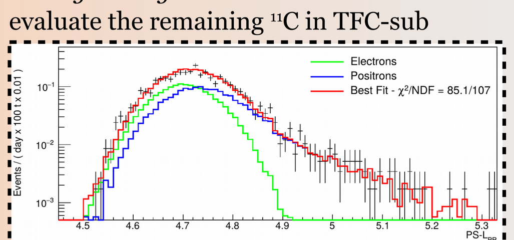
TFC-subtracted spectrum with **~10% ¹¹C** and **~60%** exposure



RD (radial distribution)
distinguishing external and uniform components



PS (pulse shape variable)
distinguishing e⁺ and e⁻
evaluate the remaining ¹¹C in TFC-sub



Multivariate likelihood

$$\mathcal{L}_{\mathrm{MV}}\left(\vec{\theta}\right) = \mathcal{L}_{\text{TFC-sub}}\left(\vec{\theta}\right) \cdot \mathcal{L}_{\text{TFC-tagged}}\left(\vec{\theta}\right) \cdot \mathcal{L}_{\mathrm{RD}}\left(\vec{\theta}\right) \cdot \mathcal{L}_{\mathrm{PS}}\left(\vec{\theta}\right)$$

Free parameters:
rates of all species, some detector response parameters, synthetic pile-up (optional)

Monte Carlo method ⟷ Analytical method

Detector response

Energy estimators

N_h	Total # of detected **hits (photons)**
N_{pe}	Total # of **photoelectrons (charge)**
N_p	Total # of **triggered PMTs** …within the first…

Used in the analytical fit:
$N_p^{dt_2}$ 230ns
$N_p^{dt_1}$ 400 ns

Analytical model

Deposited energy → photoelectrons

$$N_{pe}(E) = LY\left(Q(E) \cdot E + f_{Cher} \cdot Ch(E)\right)$$

light yield: energy → photons [# photons/MeV]
quenching: $\frac{1}{E}\int_0^E \frac{dE}{1 + k_B \frac{dE}{dx}}$
Cherenkov tuning parameter

Photoelectrons → number of PMTs

$$N_p(E) = N_{\mathrm{live}}\left(1 - e^{-\frac{N_{pe}}{N_{\mathrm{live}}}}\left[1 + p_t \frac{N_{pe}}{N_{\mathrm{live}}}\right]\right)\left(1 - g_C \frac{N_{pe}}{N_{\mathrm{live}}}\right)$$

average # **live PMTs** (dataset)
single e⁻ response (calibrations)
geometric correction (tuned with MC)

References:

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[5] G. Bellini et al. (Borexino Collaboration)
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