

FIRST DETECTION OF SOLAR NEUTRINOS FROM THE CNO FUSION CYCLE WITH THE BOREXINO DETECTOR

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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:



Neutrinos interact through the weak-interaction only: $\sigma \approx 10^{-44} \text{ cm}^2$ @ 1MeV

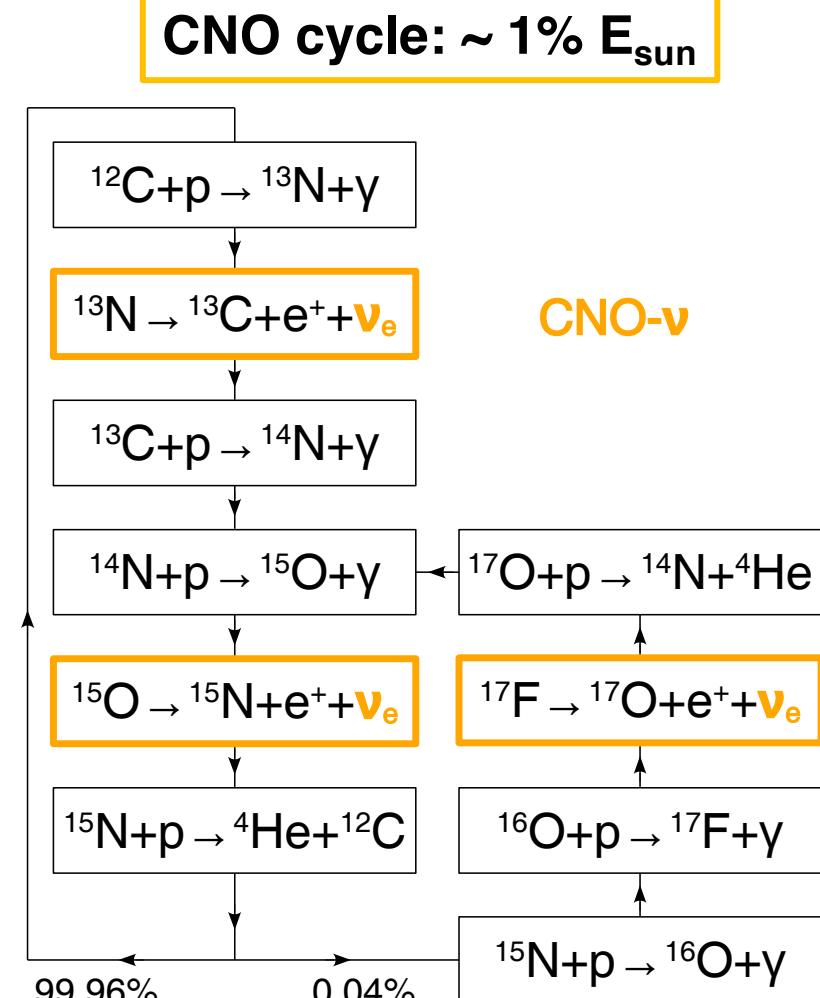
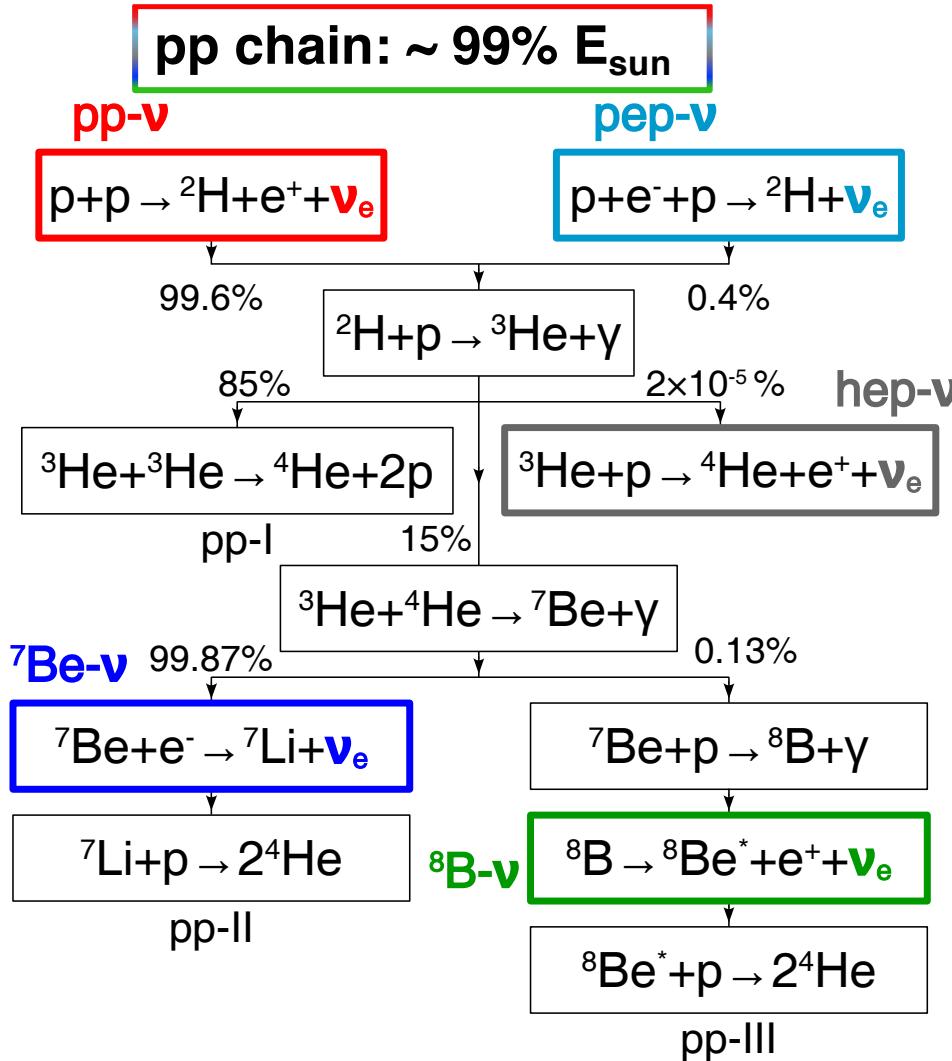
They are very elusive and thus, they are a very powerful tool to study astrophysical objects.

Photons massively interact with the solar plasma and take about 10^5 years to reach our star surface.

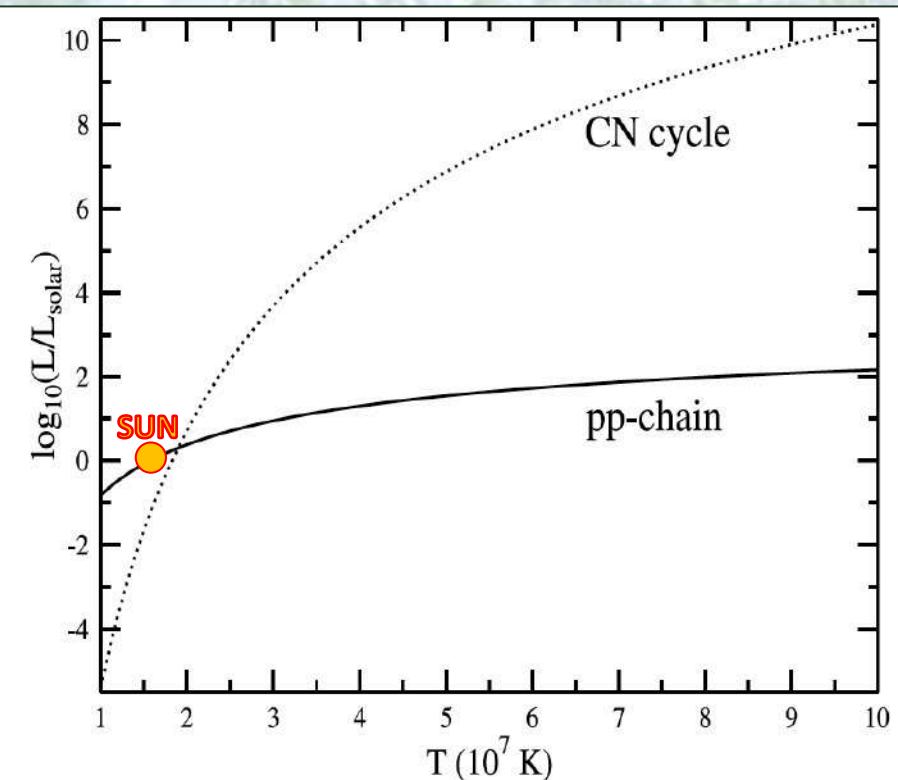
Instead, neutrinos only take about the famous 8 minutes to travel from their production site to the Sun surface and to the Earth.

→ 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?



PP CHAIN VS CNO CYCLE



W.C. Haxton and A. M. Serenelli, *Astrophys. Journal* 687:678 (2008)

In the Sun, the CNO cycle is subdominant with respect to the pp-chain

BUT

In massive stars, having higher ($T \gtrsim 2 \times 10^7 \text{ K}$) temperature in their cores, the CNO cycle is the dominant energy source.

the CNO fusion cycle the main Hydrogen-to-Helium conversion process in the stars!

It was never directly observed before Borexino result in 2020.

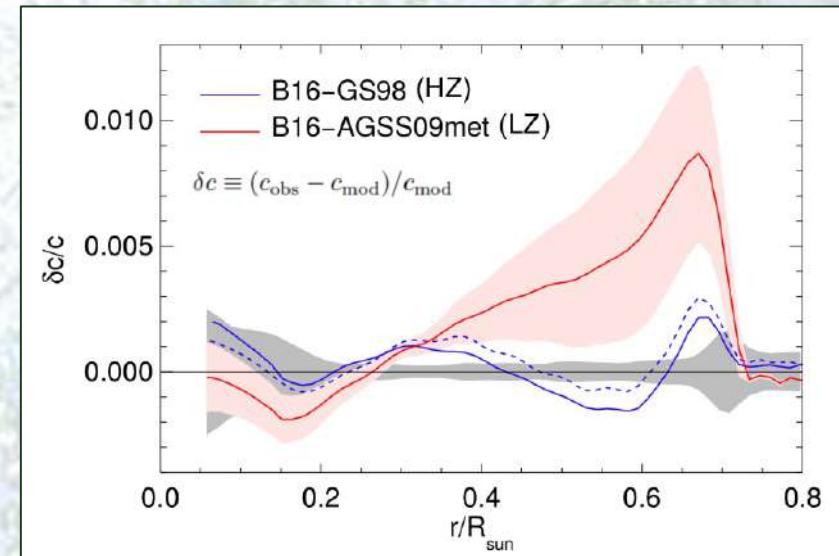
THE STANDARD SOLAR MODEL

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

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

The METALLICITY Puzzle



B16-SSM: N. Vinyoles et al., *Astrophys. Journal* 835:202 (2017)

THE STANDARD SOLAR MODEL

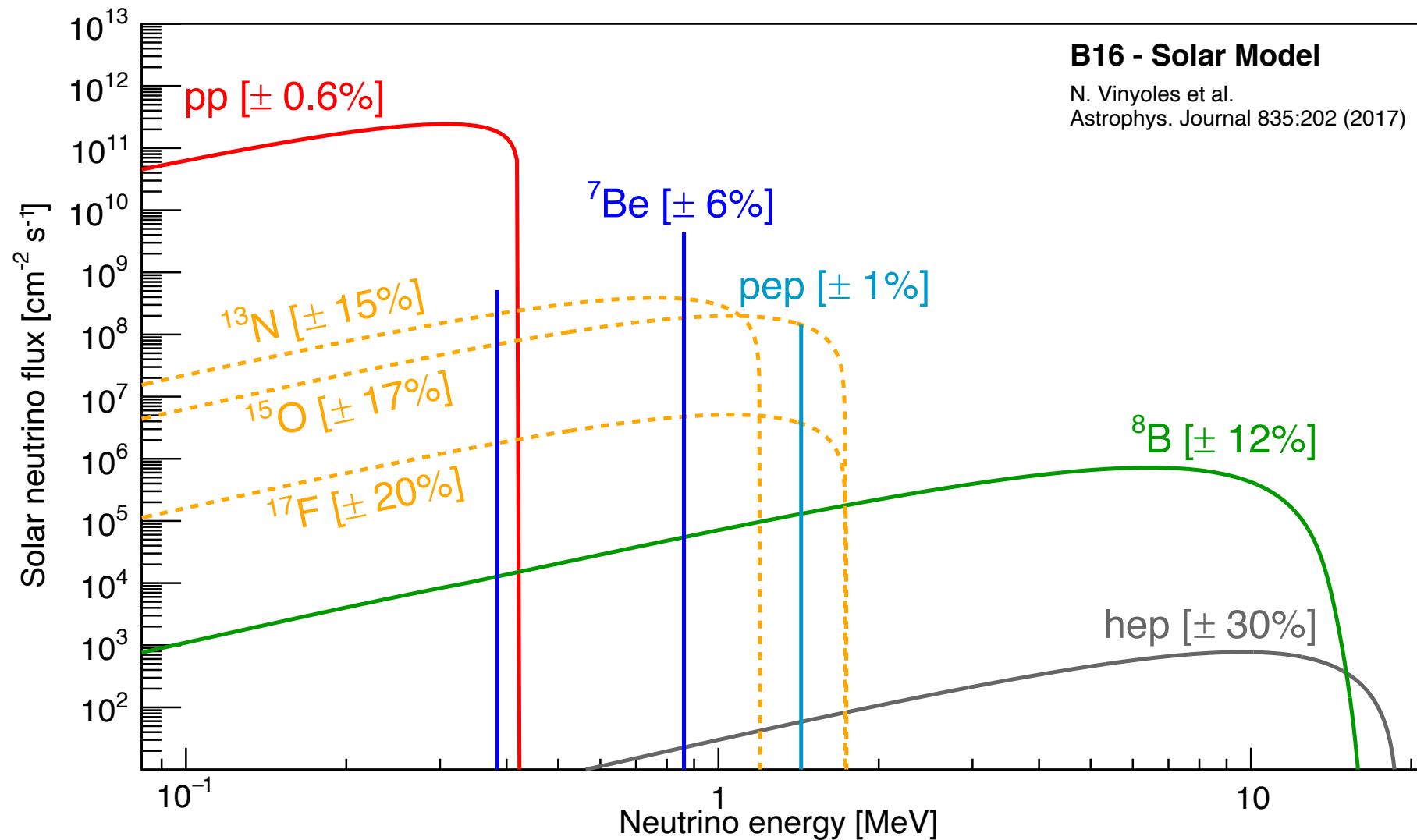
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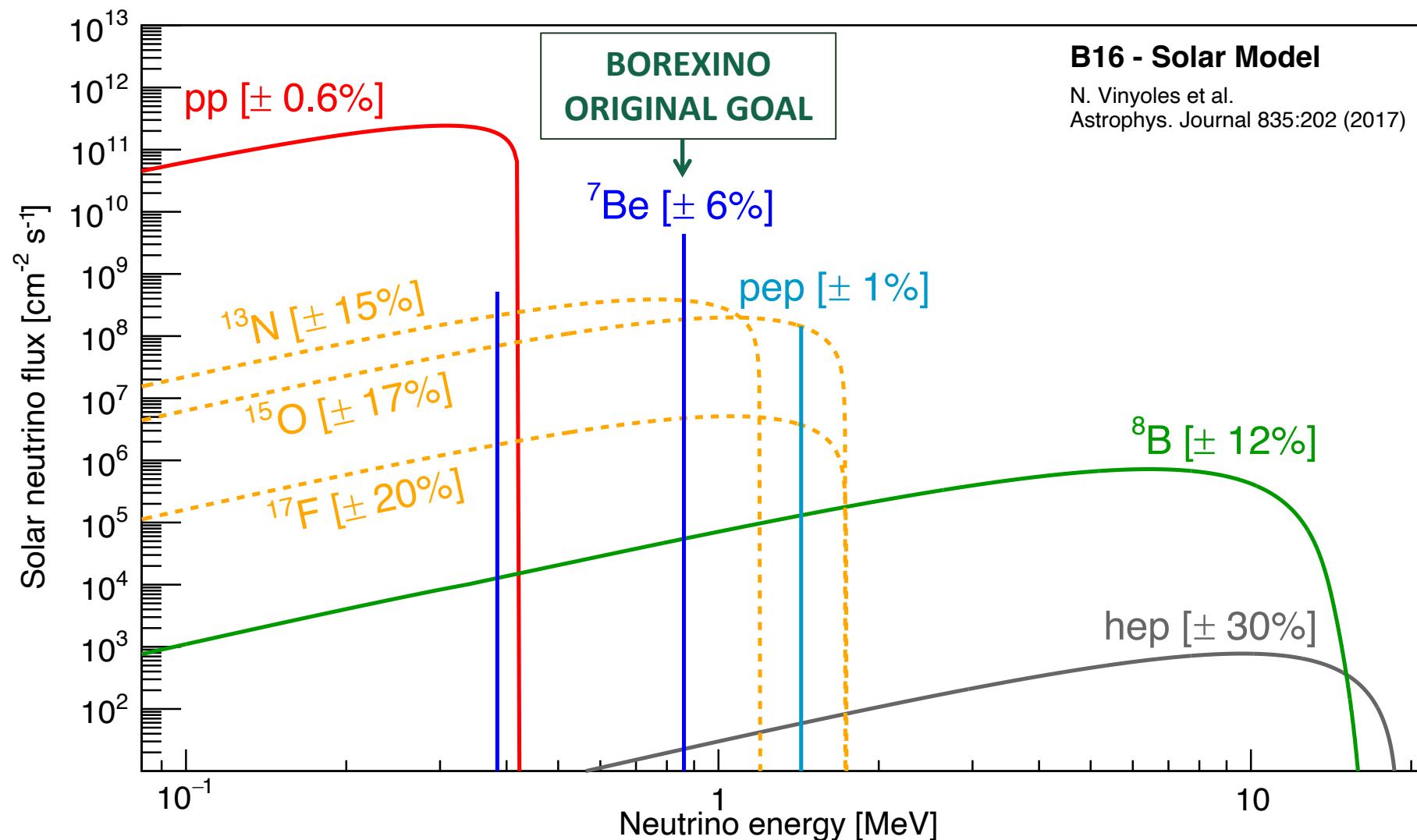
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→ About 9 % difference
→ About 18 % difference
} About 28 % difference

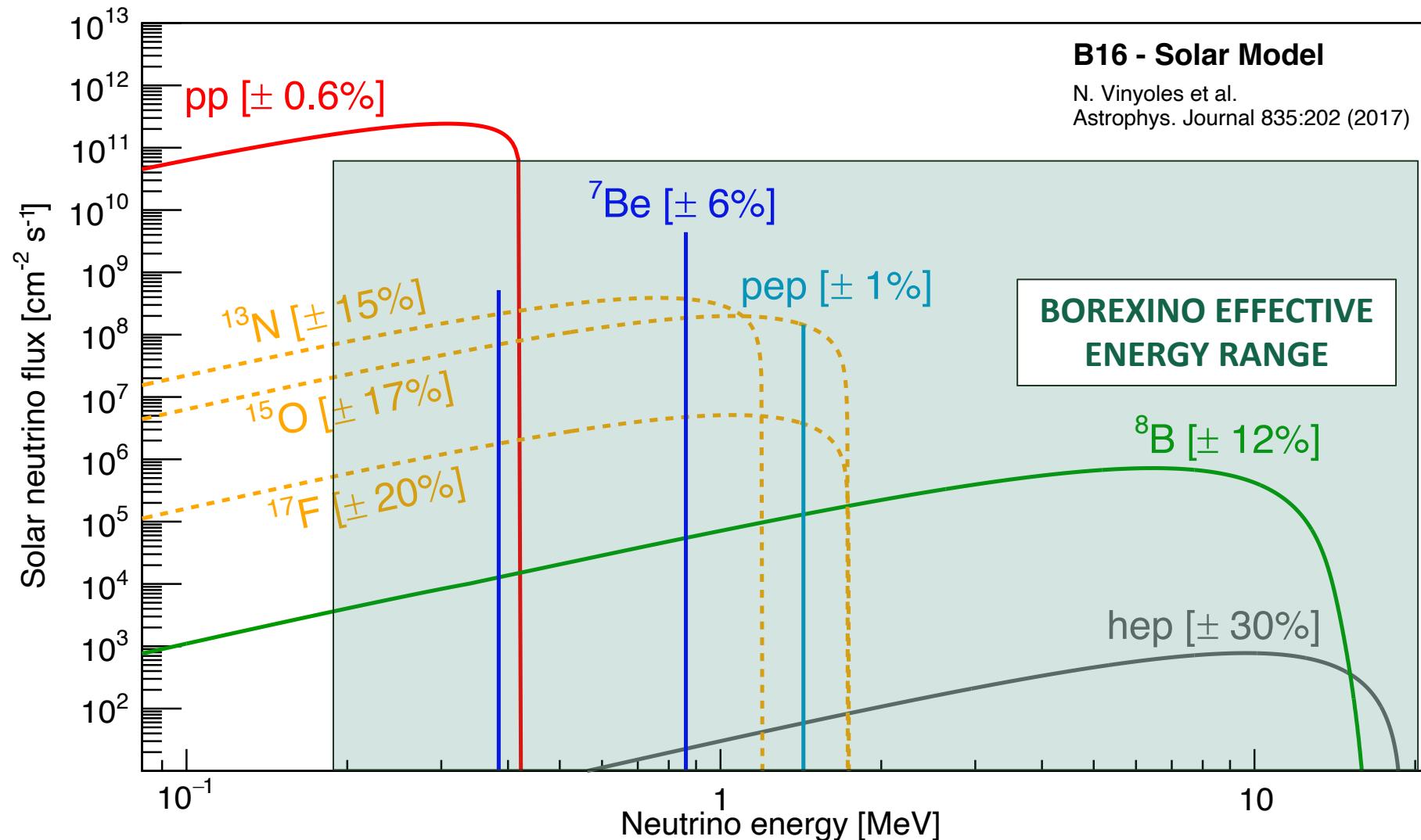
THE SOLAR NEUTRINO SPECTRUM



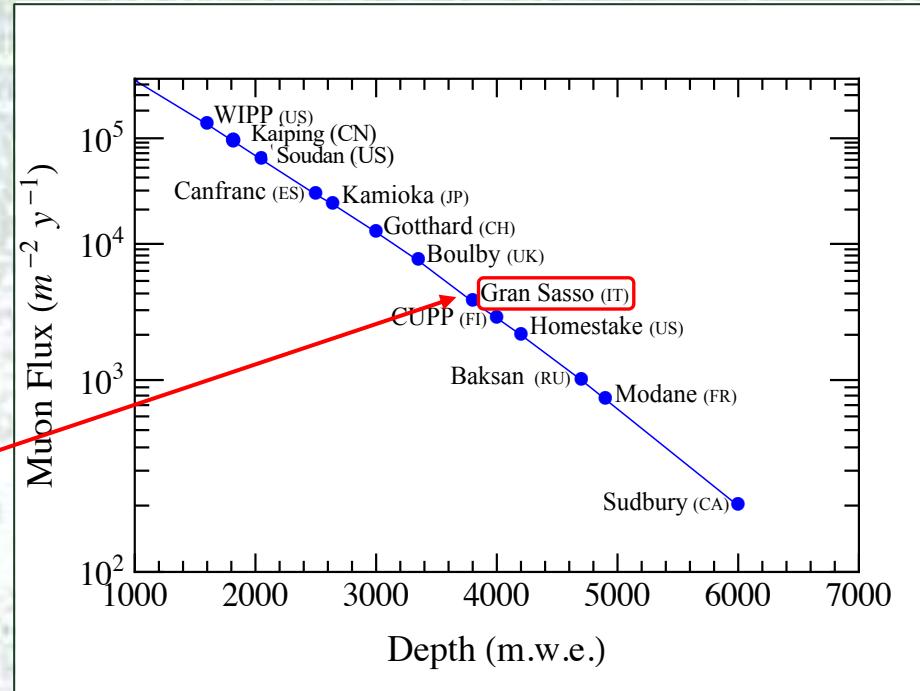
THE SOLAR NEUTRINO SPECTRUM



THE SOLAR NEUTRINO SPECTRUM



LABORATORI NAZIONALI GRAN SASSO (ITALY)



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. $\Phi(\mu) \sim 1 \mu/m^2/h$

THE BOREXINO EXPERIMENT

✧ **Original goal:** the detection of low energies solar neutrinos, in particular ^7Be neutrinos.

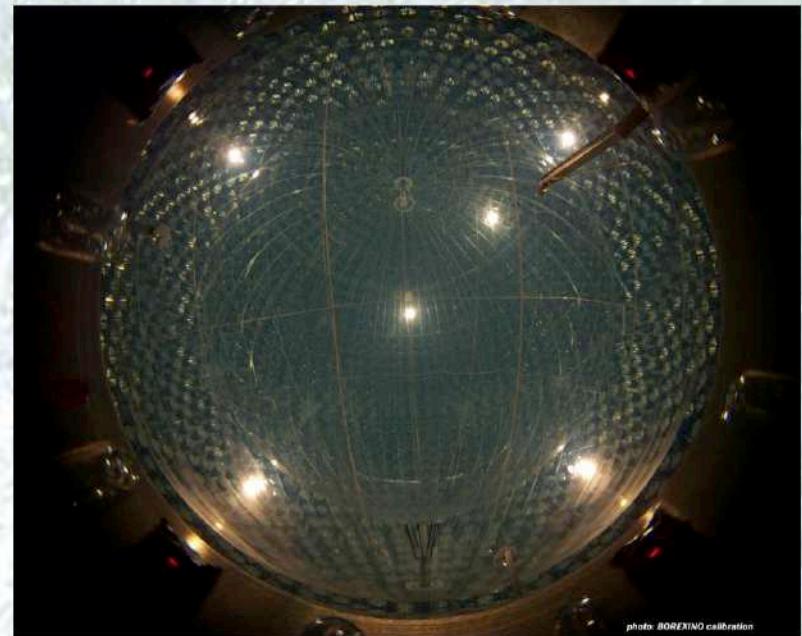
✧ **Detection method:** elastic scattering of neutrinos on electrons.

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

✧ **Detection medium:** large mass of organic liquid scintillator.

- Advantage: large light-yield;
- Disadvantage: no directional information.

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



The expected rate of ^7Be solar neutrinos 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 10 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 \sim 100 ton;

Electron density:

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

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

Stainless Steel Sphere:

2212 PhotoMultipliers



Nylon vessels:

Outer: 5.50 m

Inner: 4.25 m

Non-scintillating buffer:

900 ton of quenched scintillator

Water Tank:

2.8 kton of pure H_2O

γ and n shield

μ water Č detector

208 PMTs in water

THE BOREXINO RESULTS... SO FAR

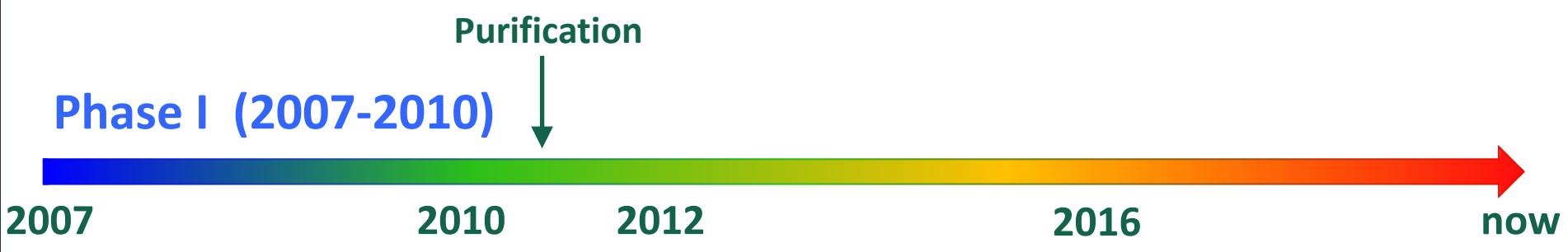
Phase I (2007-2010)



Direct measurements of

- ^7Be flux: 1st observation + precise measurement (5%);
- Absence of day/night asymmetry for ^7Be signal
=> MSW-LMA singled out ($> 8.5\sigma$);
- ^8B flux with low E threshold;
- pep flux: 1st observation;
- CNO upper limit (best to that date).

THE BOREXINO RESULTS... SO FAR



2011 – 2nd Purification (6 cycles)
Further radiopurity improvement

^{85}Kr : reduced by ~ 4.6 factor

^{210}Bi : reduced by ~ 2.3 factor

^{238}U : $< 9.4 \times 10^{-20} \text{ g/g}$ (95% C.L.)

^{232}Th : $< 5.7 \times 10^{-19} \text{ g/g}$ (95% C.L.)

^{210}Po : reduced by > 10 factor due
to natural decay

→ **The scintillator has never
been so clean!**

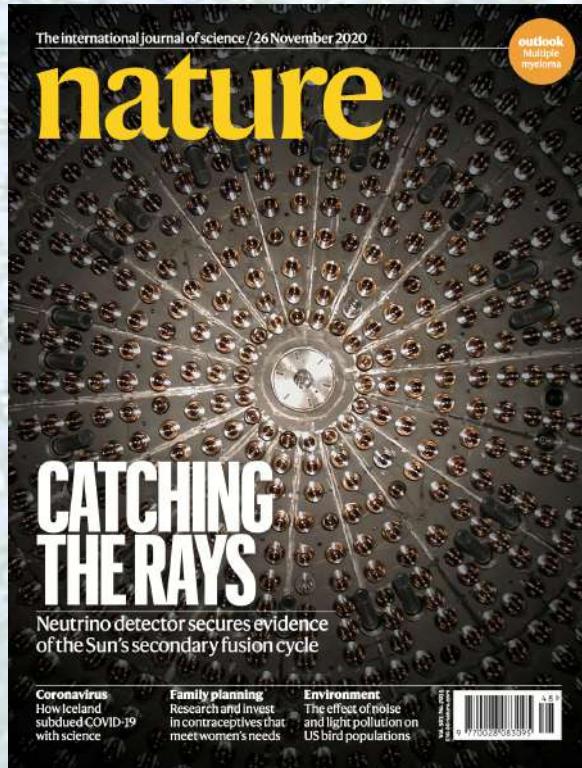
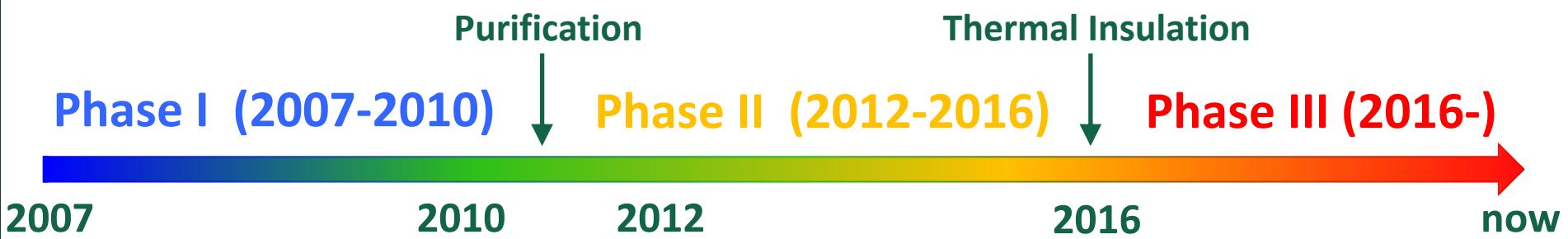
THE BOREXINO RESULTS... SO FAR



Direct measurements of

- pp flux: 1st direct measurement ;
- Geoneutrinos ($> 5\sigma$);
- Electric charge conservation (best limit to date);
- Gamma-ray burst corr.
- ^{7}Be flux seasonal modulation;
- New limit on neutrino magnetic moments;
- Comprehensive measurement of pp-chain solar neutrinos (pep signal $> 5\sigma$).

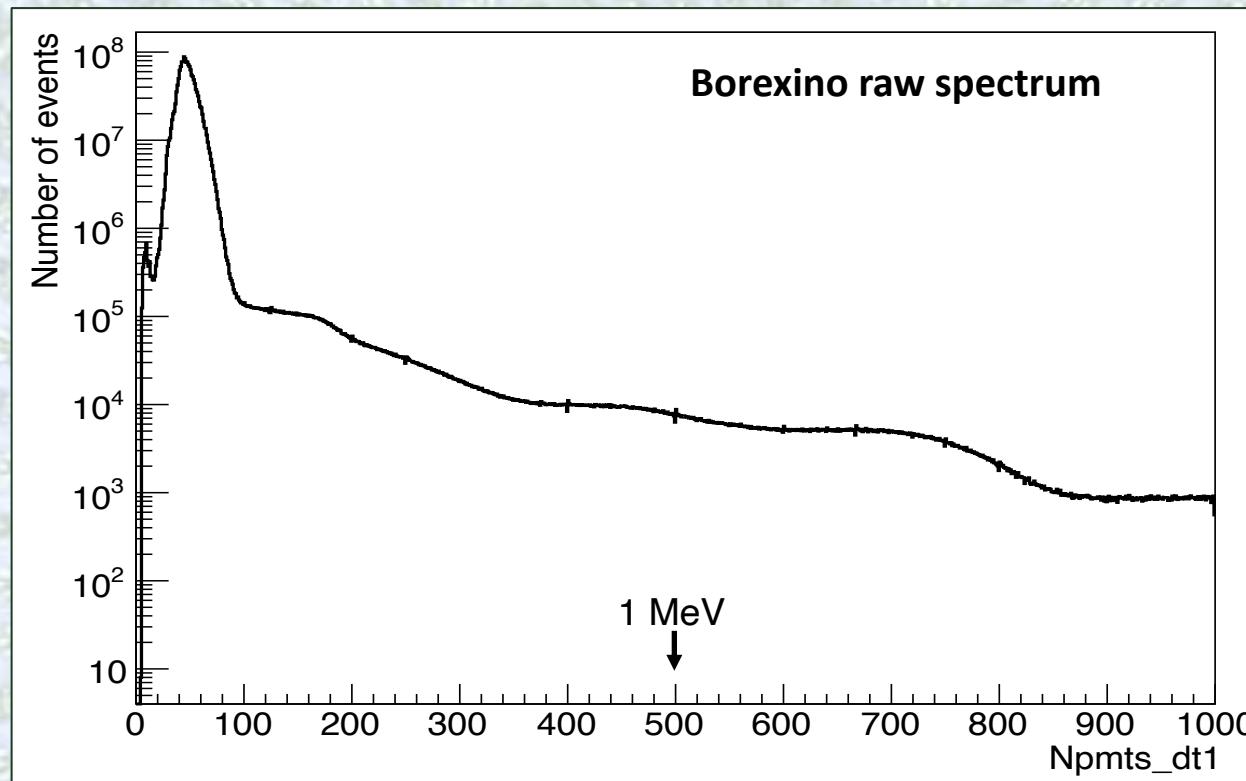
THE BOREXINO RESULTS... SO FAR



Phase III:

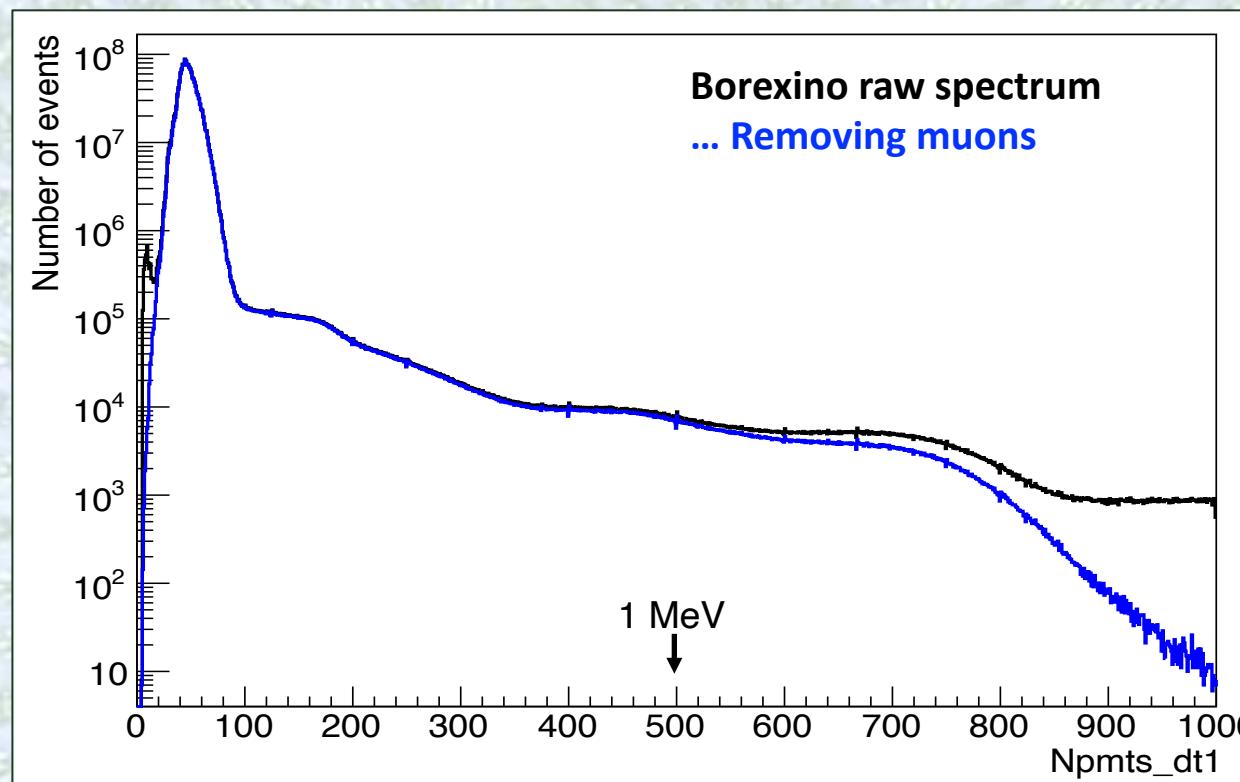
- Geoneutrinos measurement further improved;
- **FIRST DIRECT MEASUREMENT OF CNO SOLAR- ν**

HOW TO EXTRACT A NEUTRINO SIGNAL



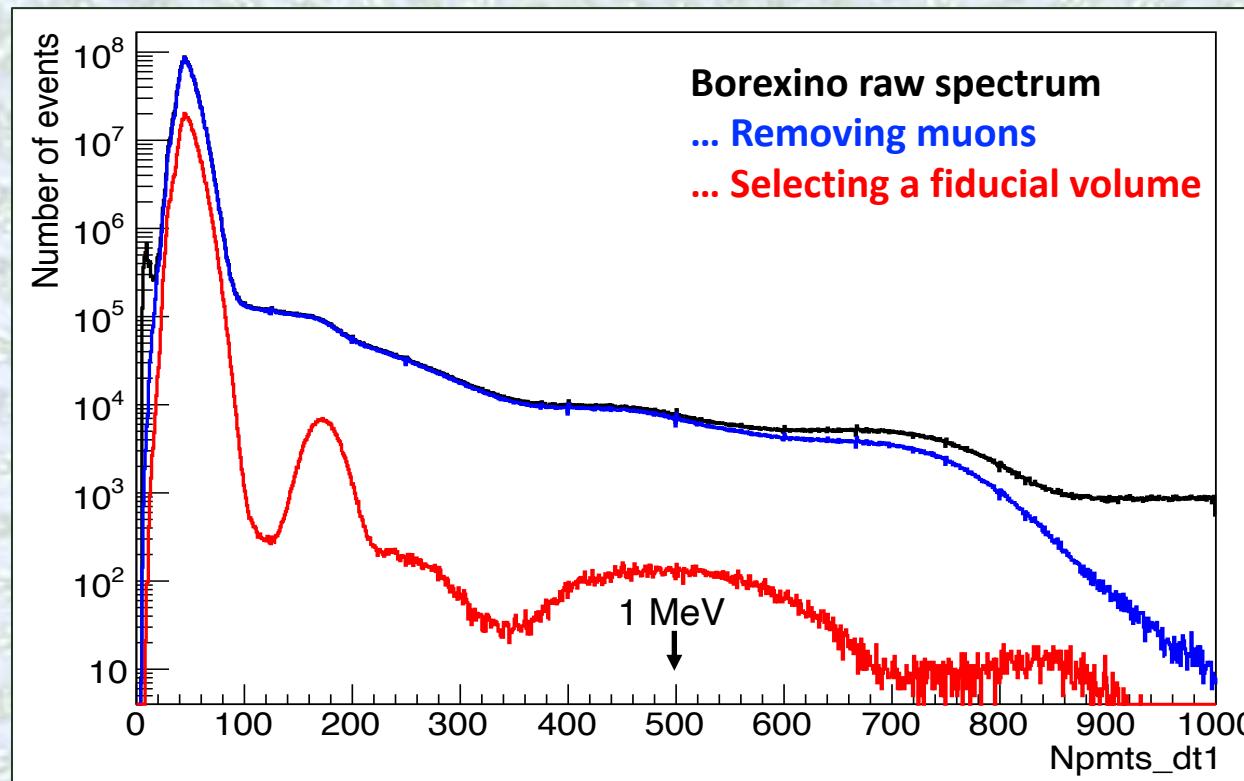
Even at the Borexino very high radiopurity conditions, we still have background events contaminating our solar neutrino signal and we need to apply software cuts to data, in order to remove as much background as possible. Furthermore, we need a powerful tool to separate the signal from the residual background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

HOW TO EXTRACT A NEUTRINO SIGNAL



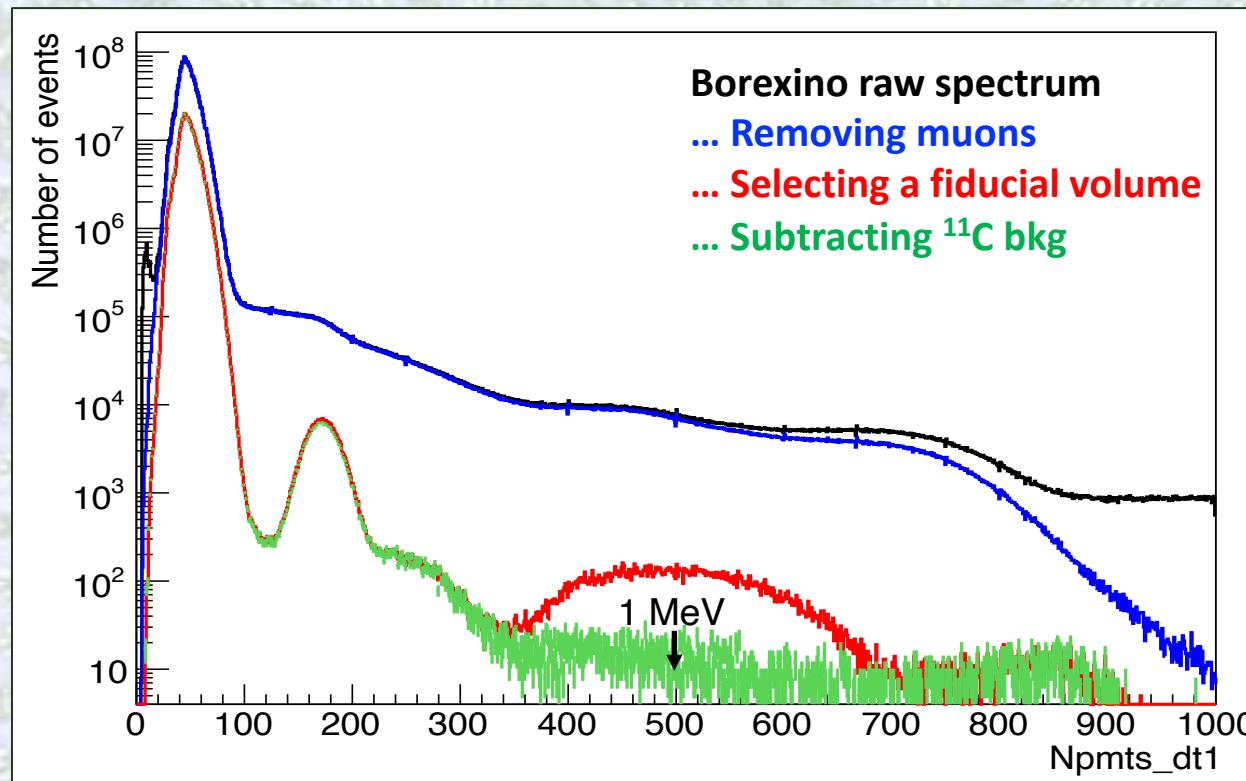
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COMPREHENSIVE SOLAR NEUTRINO SPECTROSCOPY

“Comprehensive measurement of pp-chain solar neutrinos”, *Nature* 562 (2018) 505

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 we were able to perform a simultaneous fit on the whole solar neutrino energy region.

The analysis is carried out on two energy ranges:

- **LER** (Low Energy Range) between (0.19 –2.93) MeV (pp, pep and ^7Be ν)
- **HER** (High Energy Range) between (2.3 -16) MeV (^8B and hep ν)

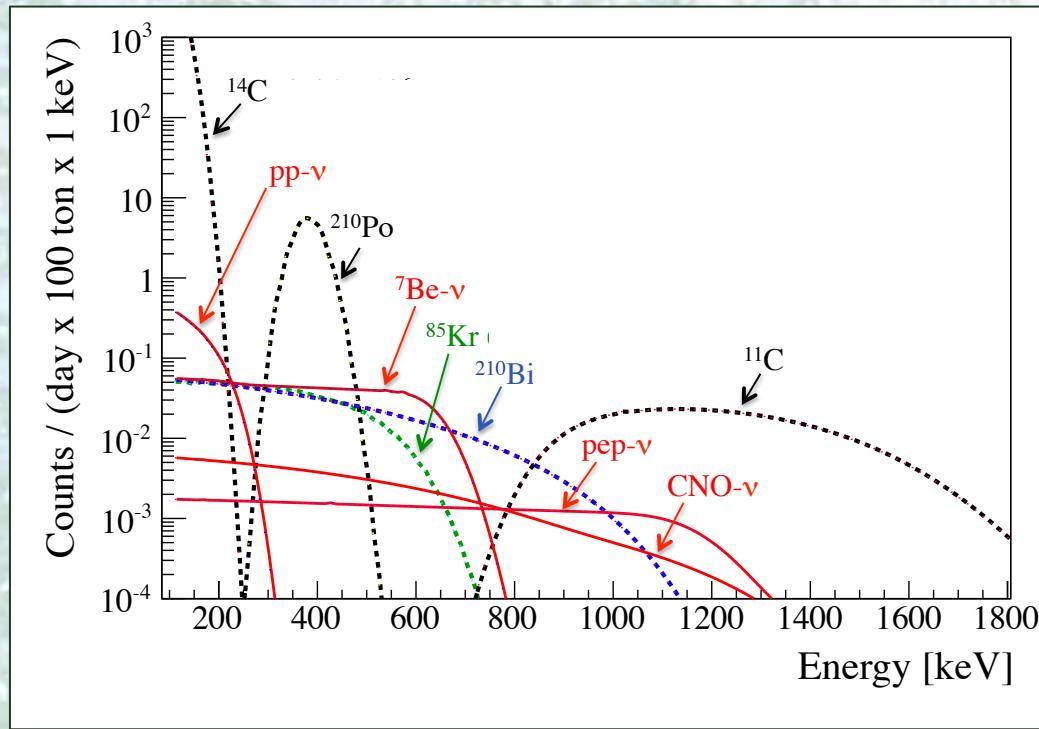
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LER analysis *Physical Review D* 100, 082004 (2019)

The analysis follows similar strategies in both the LER and HER but it is differently optimized in the two energy regions to comply with the different backgrounds affecting each specific energy range.

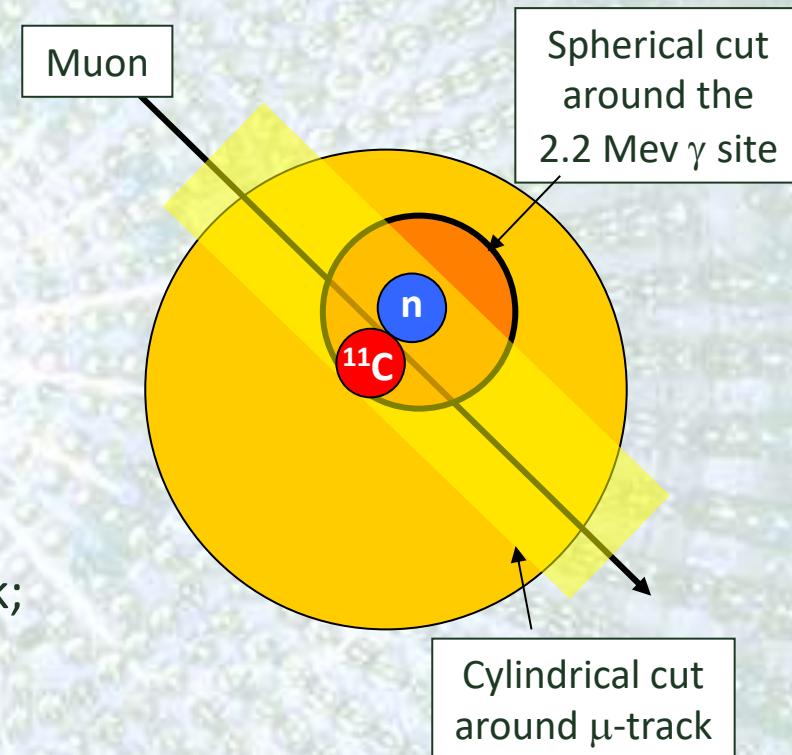
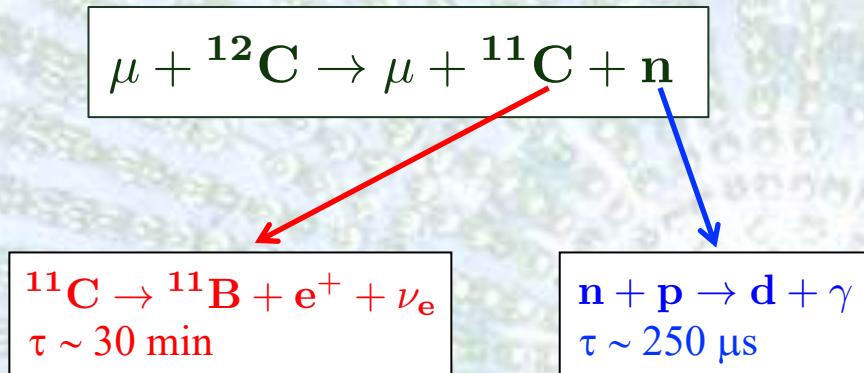
Main LER background sources:

- **^{14}C :** irreducible background in any organic scintillator;
- **pile-up** of events (mainly ^{14}C);
- **^{210}Bi :** comes from ^{210}Pb , is not in equilibrium with the ^{238}U chain;
- **^{210}Po :** comes from ^{210}Bi , is not in equilibrium with the ^{238}U chain;
- **^{85}Kr :** present in air;
- **^{11}C :** produced by μ .



THE THREE-FOLD COINCIDENCE TECHNIQUE (TFC)

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



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 in an event.

COMPREHENSIVE SOLAR NEUTRINO SPECTROSCOPY

"Comprehensive measurement of pp-chain solar neutrinos", *Nature* 562 (2018) 505
LER analysis *Physical Review D* 100, 082004 (2019)

Main LER analysis features:

- Data-set:
December 2011 - May 2016;
- Exposure: 1291.51 days x 71.3 t
→ Exposure 1.6 times the one used for the ^7Be 5% precision measurement;
- Fit range: 0.19 – 2.93 MeV.

Two complementary fit methods:

Analytical fit

- model of the detector response;
- possibility to describe unknown time variations;

Monte Carlo fit

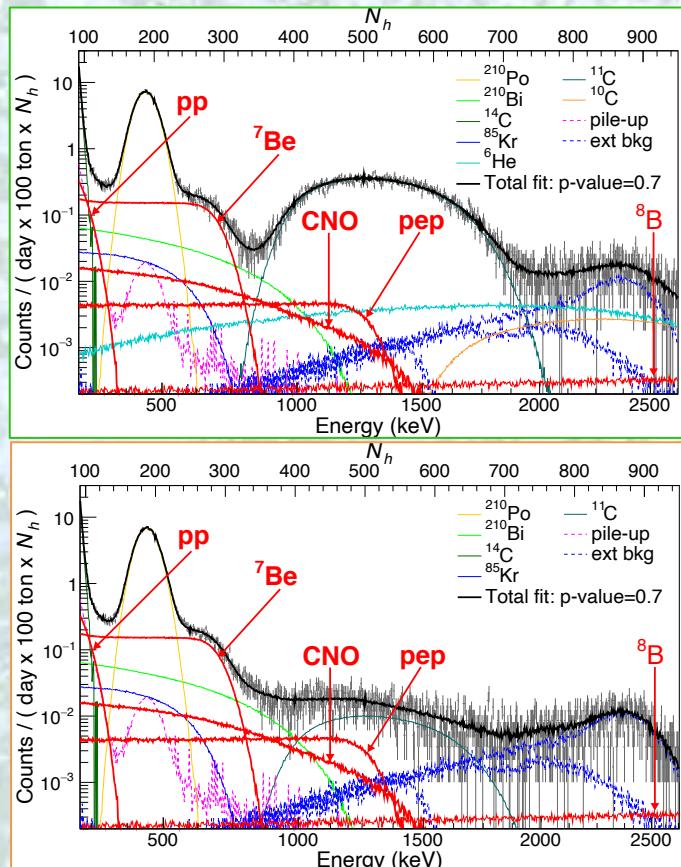
- detailed MC modeling tuned on calibrations data;
- sub% accuracy [Astr. Phys. 97 (2018) 136].

The data set is presented as two energy spectra: one with ^{11}C included (TFC-tagged) and one depleted in ^{11}C (TFC-subtracted) which are then simultaneously fit.

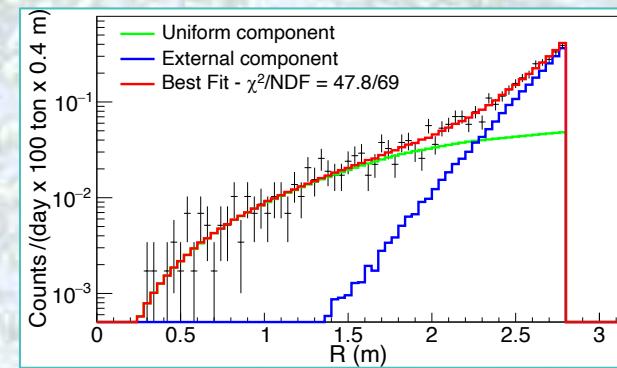
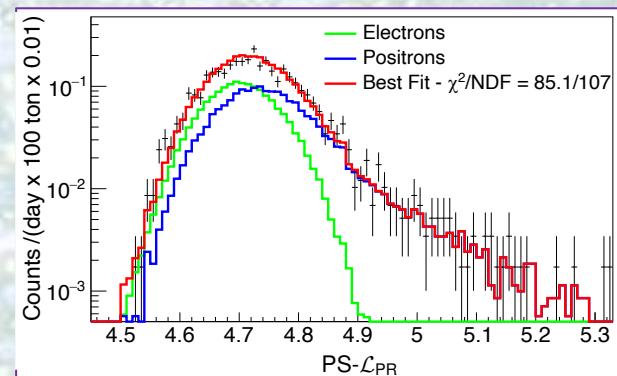
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LER analysis *Physical Review D* 100, 082004 (2019)

A Multivariate fit is performed and the neutrino interaction rates are obtained by maximizing a binned likelihood function which includes:



1. Energy spectra (TFC-tagged and TFC subtracted);
2. e^-/e^+ pulse-shape distribution PS- \mathcal{L}_{PR} ;
3. Radial distribution.



COMPREHENSIVE SOLAR NEUTRINO SPECTROSCOPY

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LER analysis *Physical Review D* 100, 082004 (2019)

Solar ν	BOREXINO	B16(GS98) – HZ	B16(AGSS09) - LZ
pp	$6.1(1 \pm 11.6\%) \times 10^{10}$	$5.98(1 \pm 0.6\%) \times 10^{10}$	$6.03(1 \pm 0.5\%) \times 10^{10}$
^7Be	$4.99(1 \pm 3.3\%) \times 10^9$	$4.93(1 \pm 6\%) \times 10^9$	$4.50(1 \pm 6\%) \times 10^9$
pep (HZ)	$1.27(1 \pm 17.7\%) \times 10^8$	$1.44(1 \pm 0.9\%) \times 10^8$	— — —
pep (LZ)	$1.39(1 \pm 16.6\%) \times 10^8$	— — —	$1.46(1 \pm 0.9\%) \times 10^8$
CNO	$< 7.9 \times 10^8$ (95% C.L.)	$4.88(1 \pm 11\%) \times 10^8$	$3.51(1 \pm 10\%) \times 10^8$
^8B	$5.68(1 \pm 8\%) \times 10^6$	$5.46(1 \pm 12\%) \times 10^6$	$4.50(1 \pm 12\%) \times 10^6$

All fluxes results are given in $\text{cm}^{-2} \text{s}^{-1}$.

B16 Neutrino theoretical fluxes from: *N. Vinyoles et al., Astrophys. Journal* 835:202 (2017)

Neutrino oscillation parameters from: *I. Esteban et al., JHEP* 01 (2017)

All rates and fluxes are fully compatible with and improve the uncertainty of the previously published Borexino results.

Solar ν	Uncertainty reduction ($\text{err}_{\text{new}}/\text{err}_{\text{old}}$)
pp	0.78
^7Be (862 keV)	0.57
pep	0.61
^8B	0.48

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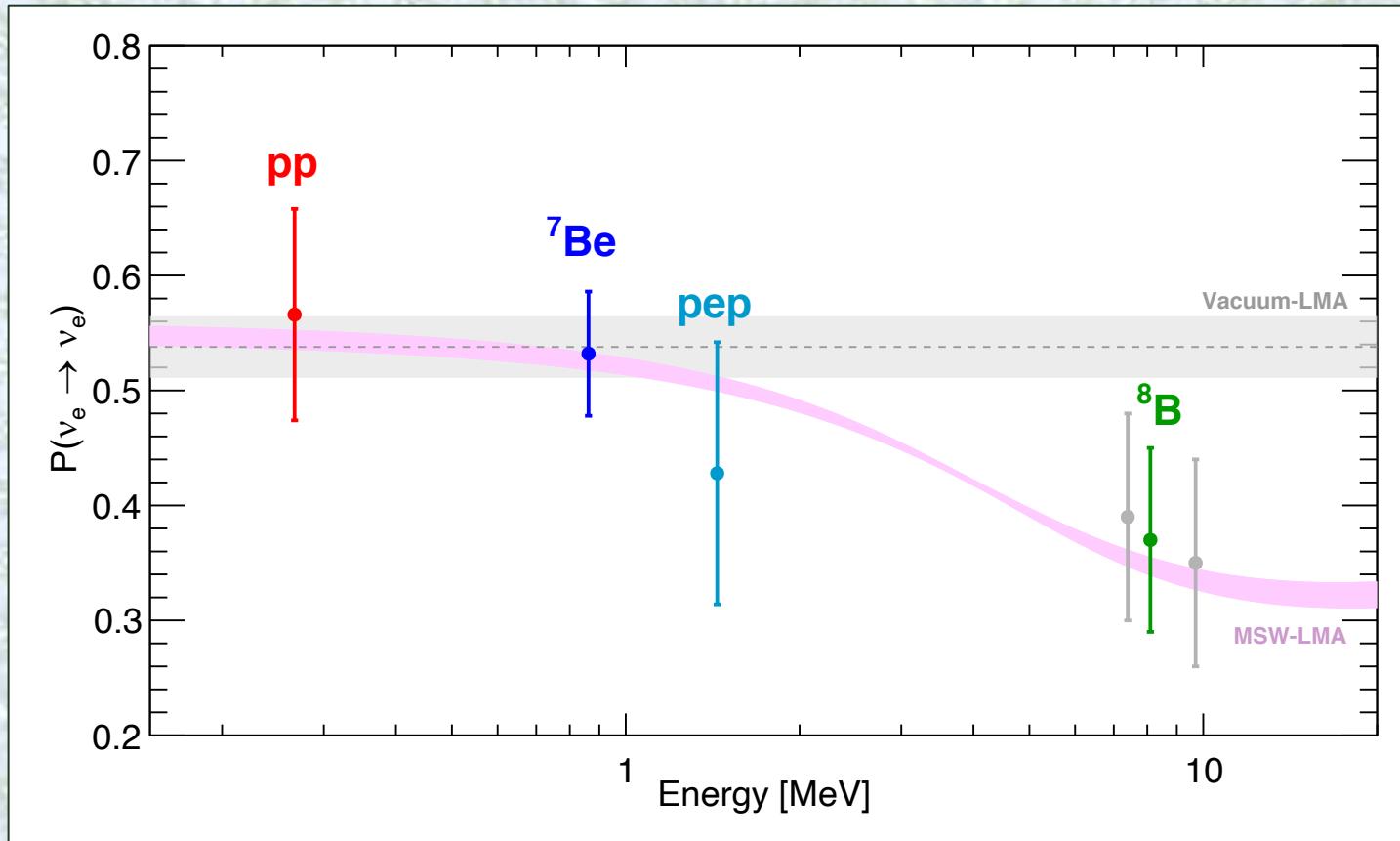
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STUDYING THE SUN WITH NEUTRINOS... ...STUDYING NEUTRINOS WITH THE SUN

Neutrino physics implications of the results: testing MSW-LMA



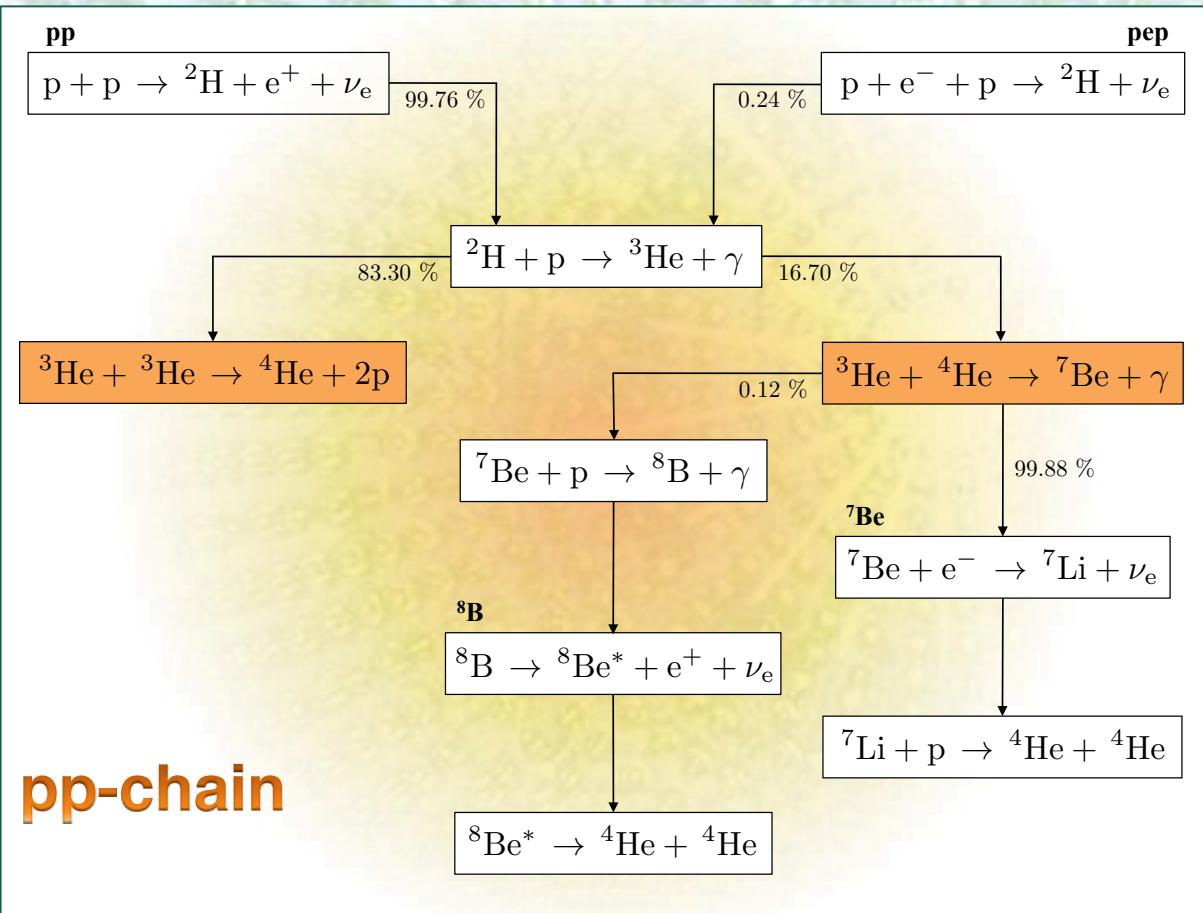
SSM-HZ solar-ν fluxes from *N. Vinyoles et al., Astrophys. Journal 835:202 (2017)*

Neutrino oscillation parameters from *I. Esteban et al., JHEP 01 (2017)*.

COMPREHENSIVE SOLAR NEUTRINO SPECTROSCOPY

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

Astrophysical implications of the results: probing solar fusion



Probing solar fusion by studying the two primary modes of terminating the pp-chain.

$$\mathcal{R} = \frac{2\Phi(^7\text{Be})}{[\Phi(pp) - \Phi(^7\text{Be})]}$$

B16-SSM expected values:

$$\mathcal{R} = 0.180 \pm 0.011 \text{ (HZ)}$$

$$\mathcal{R} = 0.161 \pm 0.010 \text{ (LZ)}$$

Borexino result:

$$\mathcal{R} = 0.178 \begin{array}{l} + 0.027 \\ - 0.023 \end{array}$$

COMPREHENSIVE SOLAR NEUTRINO SPECTROSCOPY

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

Astrophysical implications of the results: solar luminosity



<https://geographical.co.uk>

Using Borexino results only we can calculate the neutrino solar luminosity:

$$L_\nu = (3.89_{-0.42}^{+0.35}) \times 10^{33} \text{ erg s}^{-1}$$

which is found to be in agreement with the well measured photon value:

$$L_{\text{ph}} = (3.846 \pm 0.015) \times 10^{33} \text{ erg s}^{-1}$$

- This confirms the nuclear origin of the solar power!
- It proves that the Sun has been in thermodynamic equilibrium over the last 10^5 years (the time required for radiation to flow from the center to the surface of the Sun).

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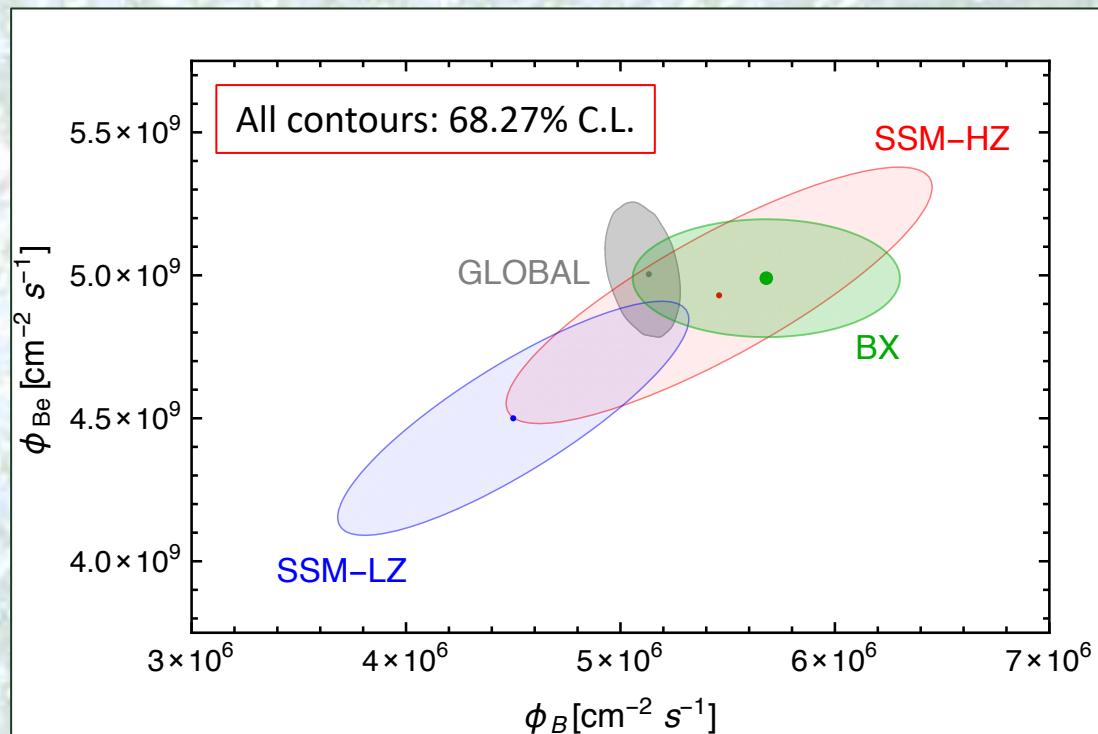
Astrophysical implications of the results: the metallicity puzzle

The Borexino combined results on ^7Be and ^8B neutrino fluxes seem to give an hint towards the High Metallicity scenario:

p-value (HZ) = 0.87

p-value (LZ) = 0.11

We are now largely dominated by the theoretical SSM errors.



Global analysis performed over BX+SNO+SK+KL data, assuming SSM solar- ν fluxes from *N. Vinyoles et al., Astrophys. Journal* 835:202 (2017) and neutrino oscillation parameters from *I. Esteban et al., JHEP* 01 (2017).

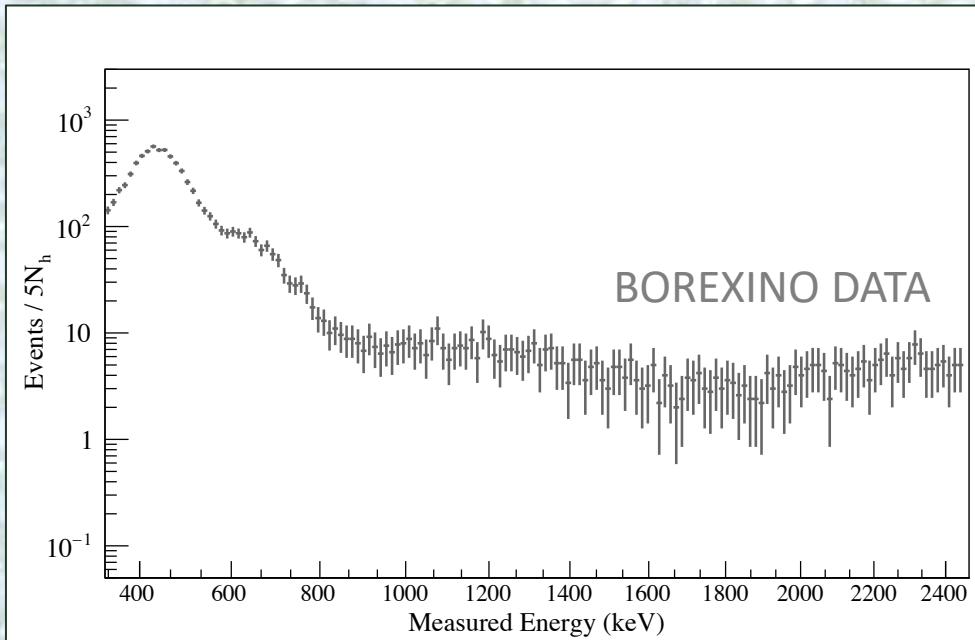
STILL, ONE MEASUREMENT WAS MISSING....

THE MEASUREMENT OF SOLAR NEUTRINOS FROM THE CNO FUSION CYCLE



“Experimental evidence of neutrinos produced in the CNO fusion cycle in the Sun”
Nature 587 (2020) 577

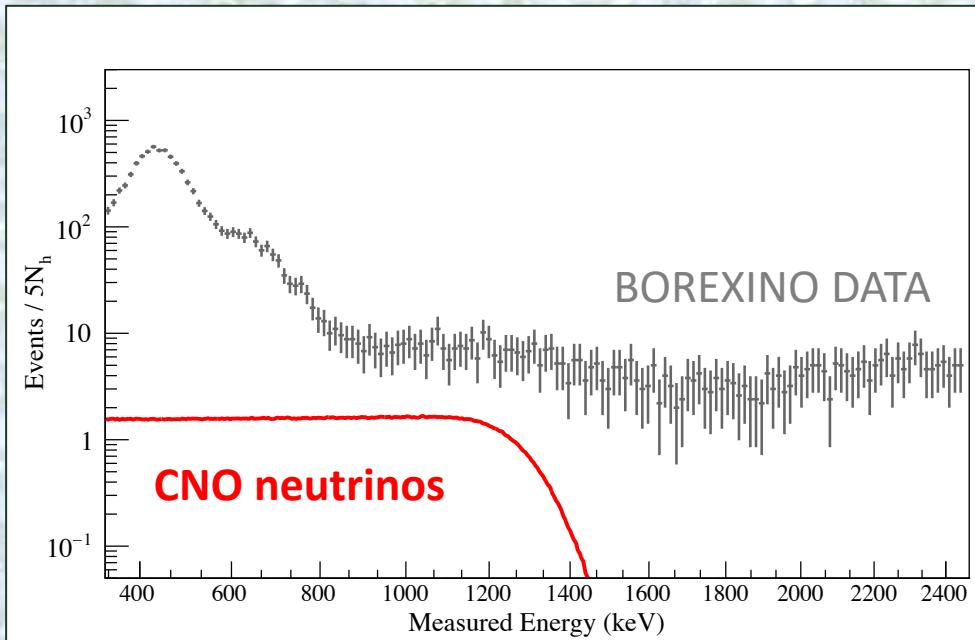
TOWARDS THE CNO- ν MEASUREMENT



Main CNO analysis features:

- Data-set: Phase-III
July 2016 - February 2020;
- Exposure: $1072 \text{ days} \times 71.3 \text{ t}$
- Fiducial volume
 $r < 2.8 \text{ m} \ \&\&$
 $-1.8 \text{ m} < z < 2.2 \text{ m}$
- Fit range: $0.32 - 2.64 \text{ MeV.}$
- ^{11}C background tagged/subtracted

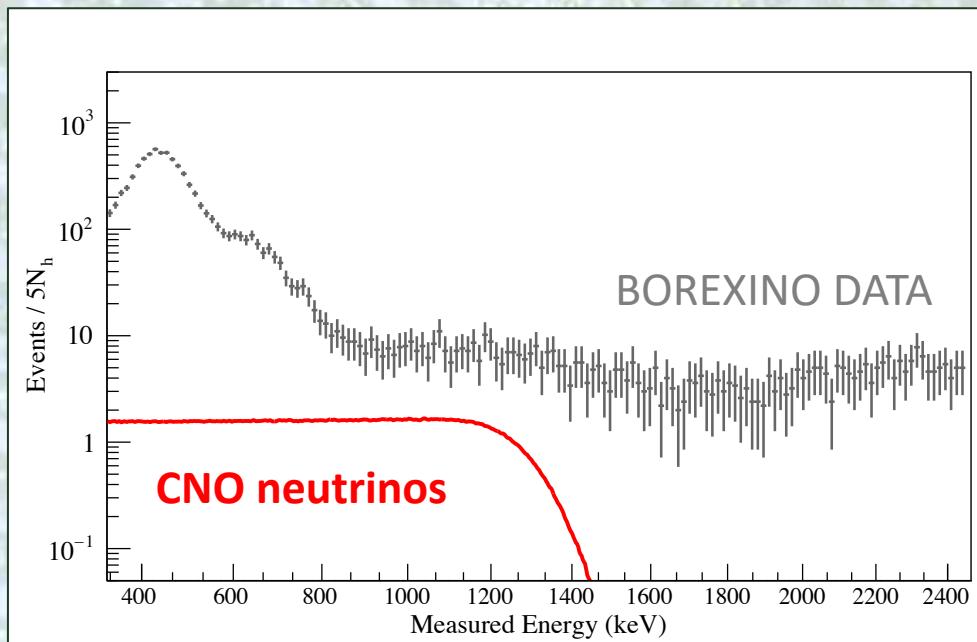
TOWARDS THE CNO- ν MEASUREMENT



Main CNO analysis features:

- Data-set: Phase-III
July 2016 - February 2020;
- Exposure: $1072 \text{ days} \times 71.3 \text{ t}$
- Fiducial volume
 $r < 2.8 \text{ m} \ \&\&$
 $-1.8 \text{ m} < z < 2.2 \text{ m}$
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 -1.8 m $< z < 2.2$ m
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Strategy to extract the CNO neutrino signal:

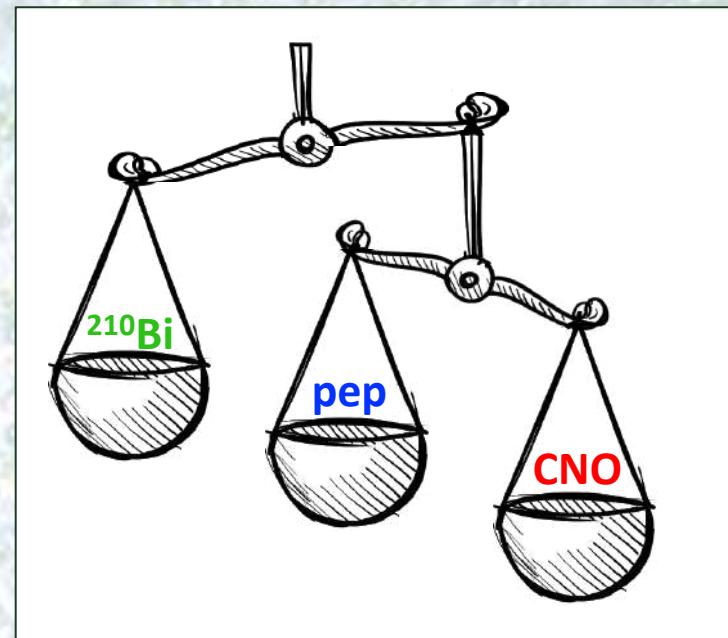
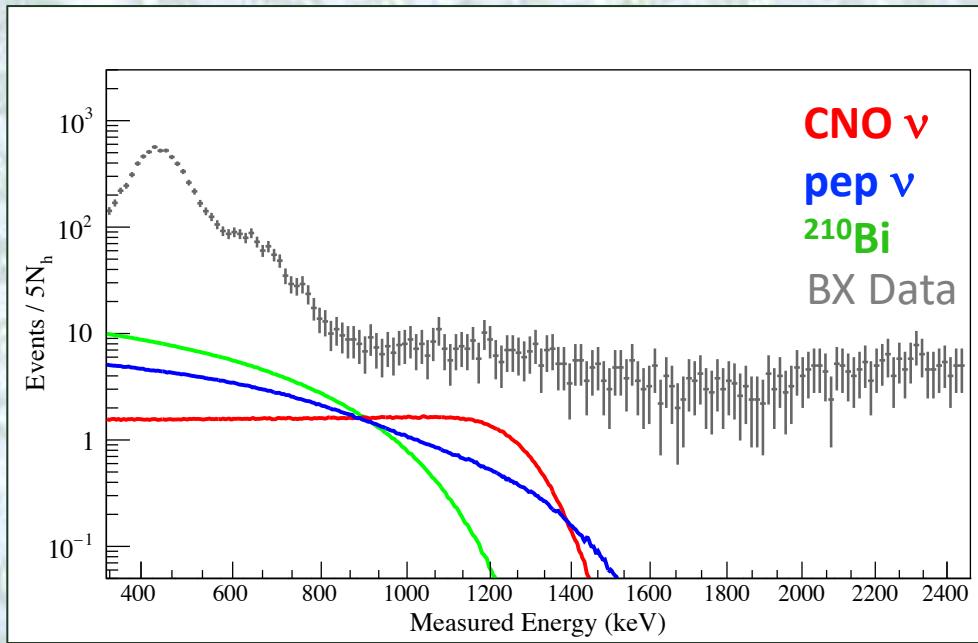
We exploit the difference in the energy distribution of signal and backgrounds to separate them.

The spectral shapes for both components of signal and backgrounds are generated in a Geant4 Borexino-tailored Monte Carlo framework.

THAT EASY?

TOWARDS THE CNO- ν MEASUREMENT (2)

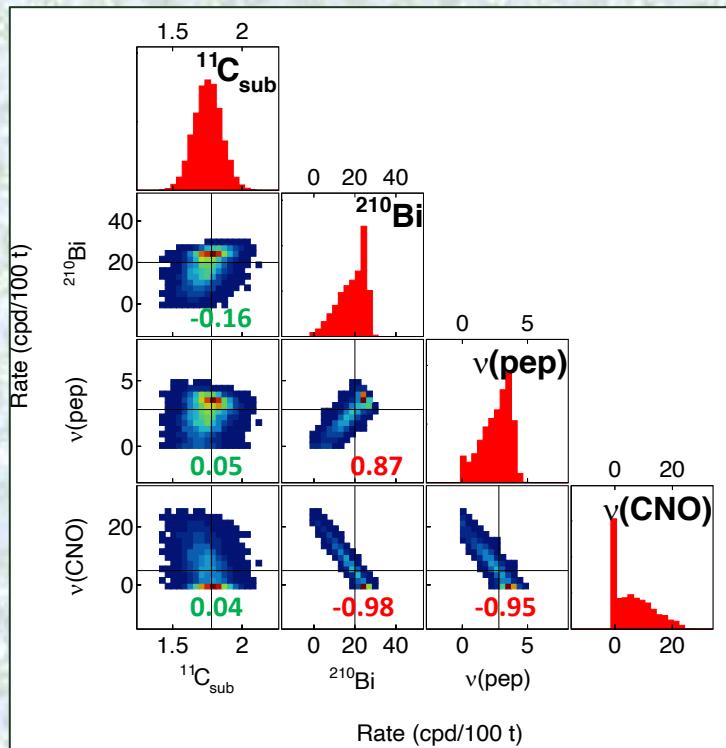
The similarity between the CNO, pep and ^{210}Bi spectral shapes limits the sensitivity of Borexino.



The predicted neutrino rates do not help:

- CNO ν $\sim 4\text{-}5 \text{ cpd}/100 \text{ ton}$
- pep ν $\sim 3 \text{ cpd}/100 \text{ ton}$
- ^{210}Bi $\sim 15\text{-}20 \text{ cpd}/100 \text{ ton}$

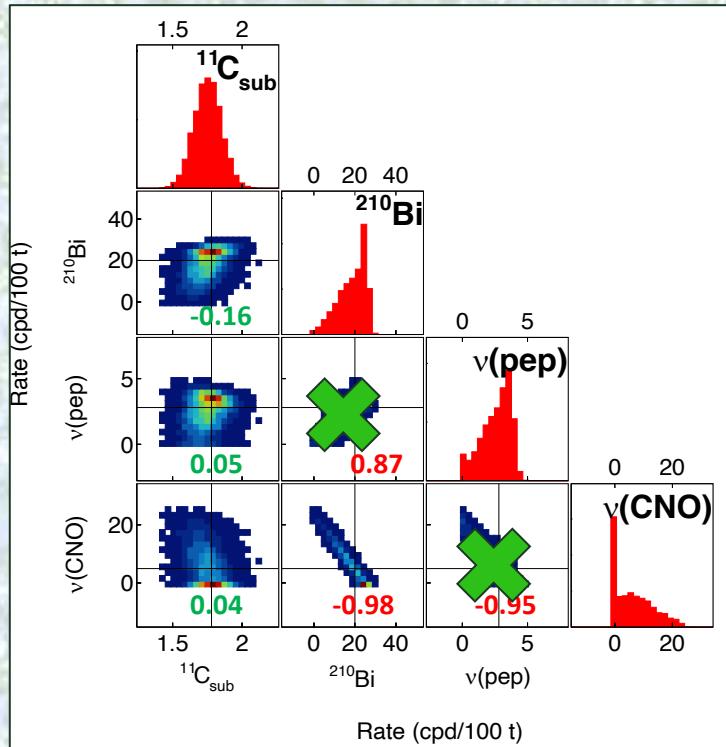
TOWARDS THE CNO- ν MEASUREMENT (3)



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

BUT the ^{210}Bi spectrum is still quasi-degenerate with the CNO neutrino one.....

TOWARDS THE CNO- ν MEASUREMENT (3)

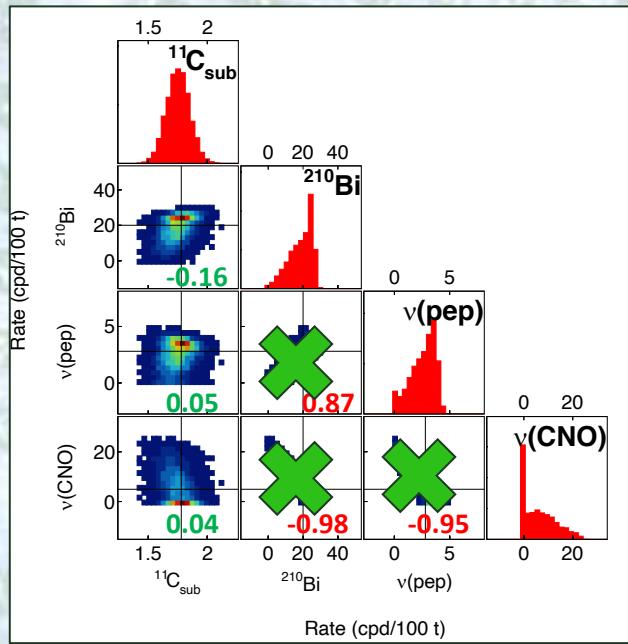


To reduce correlations we put a constraint on the pp/pep ratio following the theoretical predictions as described in *Nature 562 (2018) 505*.

BUT the ^{210}Bi spectrum is still quasi-degenerate with the CNO neutrino one.....

TOWARDS THE CNO- ν MEASUREMENT (4)

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



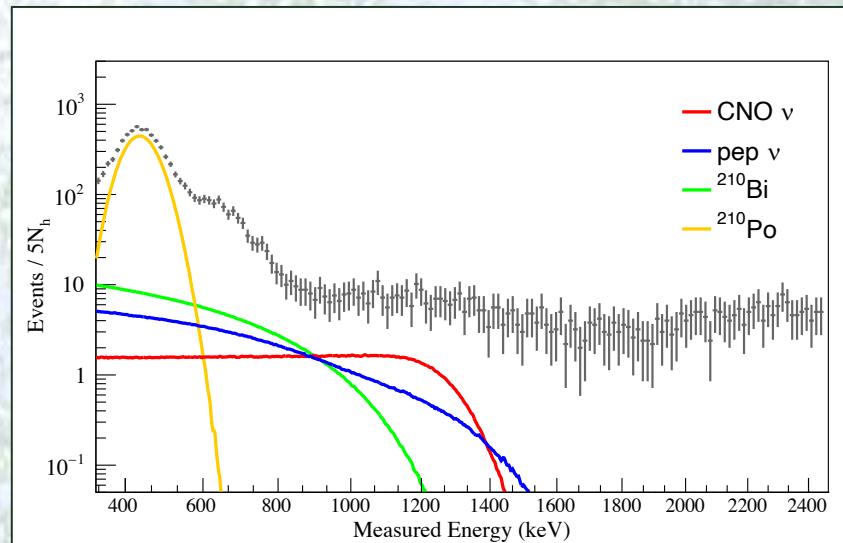
The ^{210}Bi spectrum is still quasi-degenerate with the CNO neutrino one.....

.... But the ^{210}Bi rate can be constrained by precisely (and independently) mapping the ^{210}Po rate!



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

- α decay \rightarrow pulse shape discrimination
- Monoenergetic \rightarrow “gaussian” peak



TOWARDS THE CNO- ν MEASUREMENT (5)

Unluckily, life is not that easy.

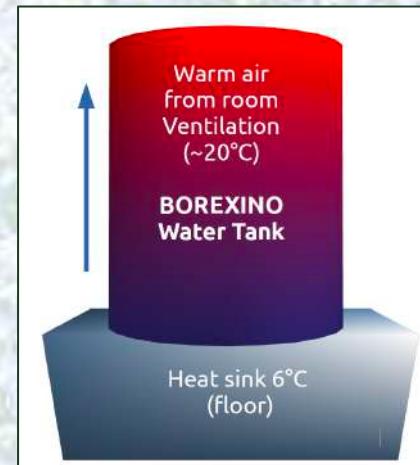
The convective motions triggered by seasonal changes in temperature bring inside the scintillator an unknown amount of ^{210}Po which has been present on the nylon Inner Vessel.

→ 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
prevents convective motions



THE DETECTOR THERMAL INSULATION

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

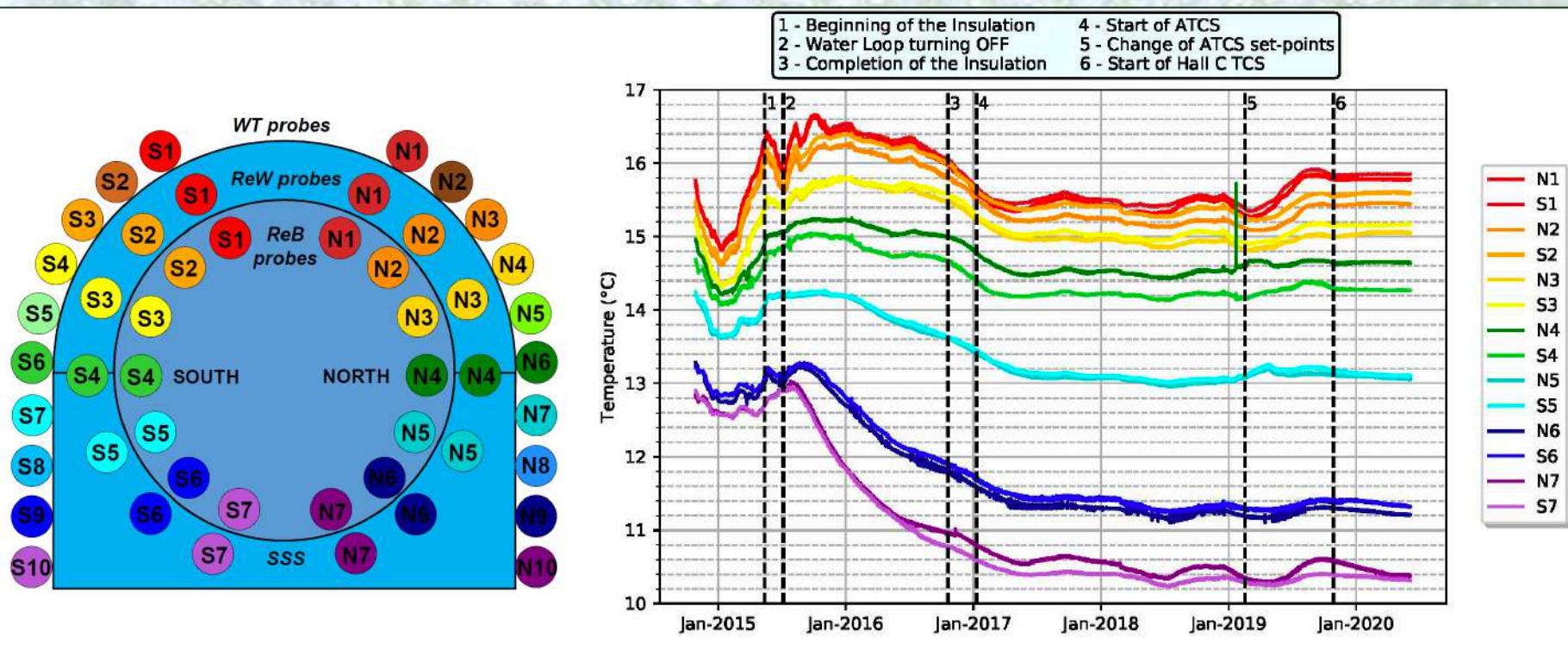


Before the thermal insulation
(Mid 2015)

After the thermal insulation
(Early 2016)

THE DETECTOR THERMAL INSULATION (2)

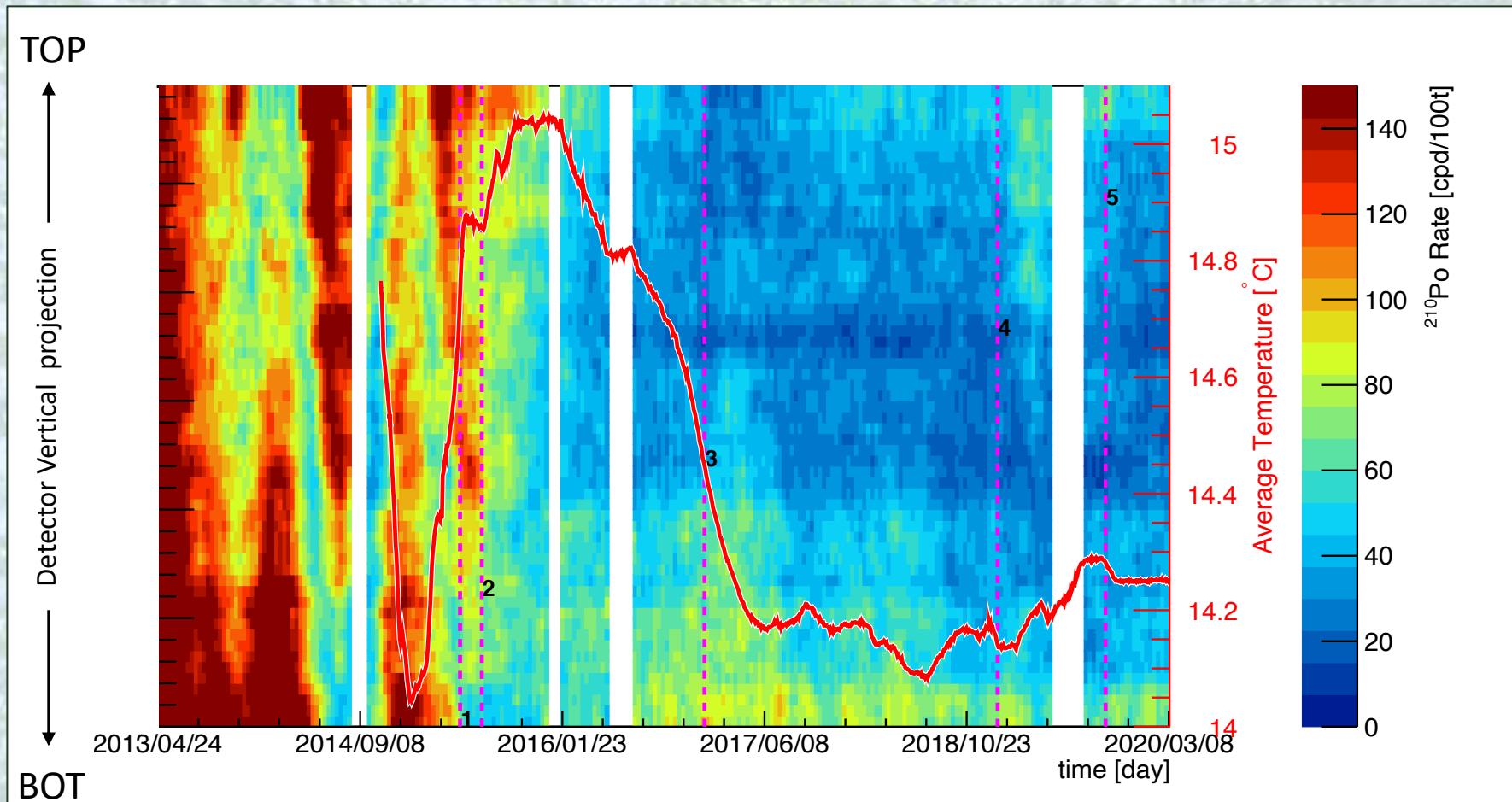
The Active Temperature Control System (ATCS)



T profile from probes closer to the inner detector

EFFECTS ON POLONIUM-210

^{210}Po counting rate inside the Inner Vessel scintillator volume



1: Beginning of the insulation program

2: Turning off of the water recirculation system in the water tank;

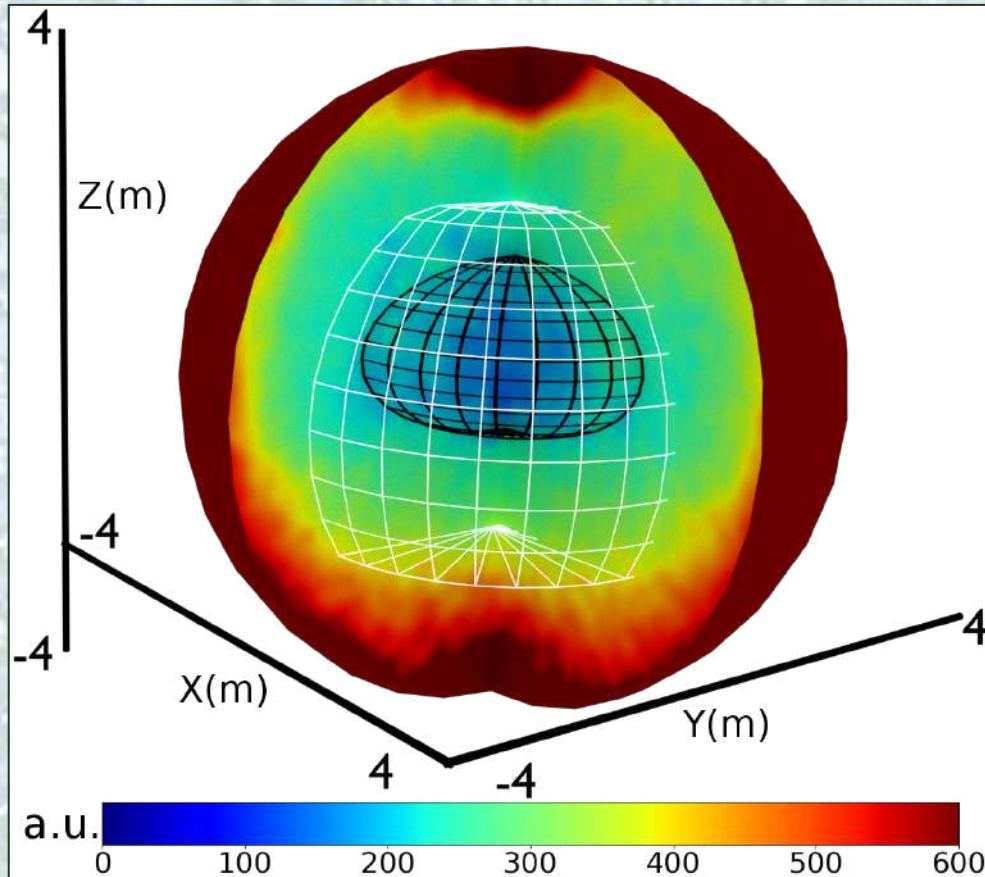
3: First operation of the active temperature control system;

4: Change of the active control set point

5: Installation and commissioning of the hall temperature

control system.

THE Low POLONIUM FIELD: LPoF



There is an innermost region almost free of convective currents: the Low Polonium Field (LPoF);

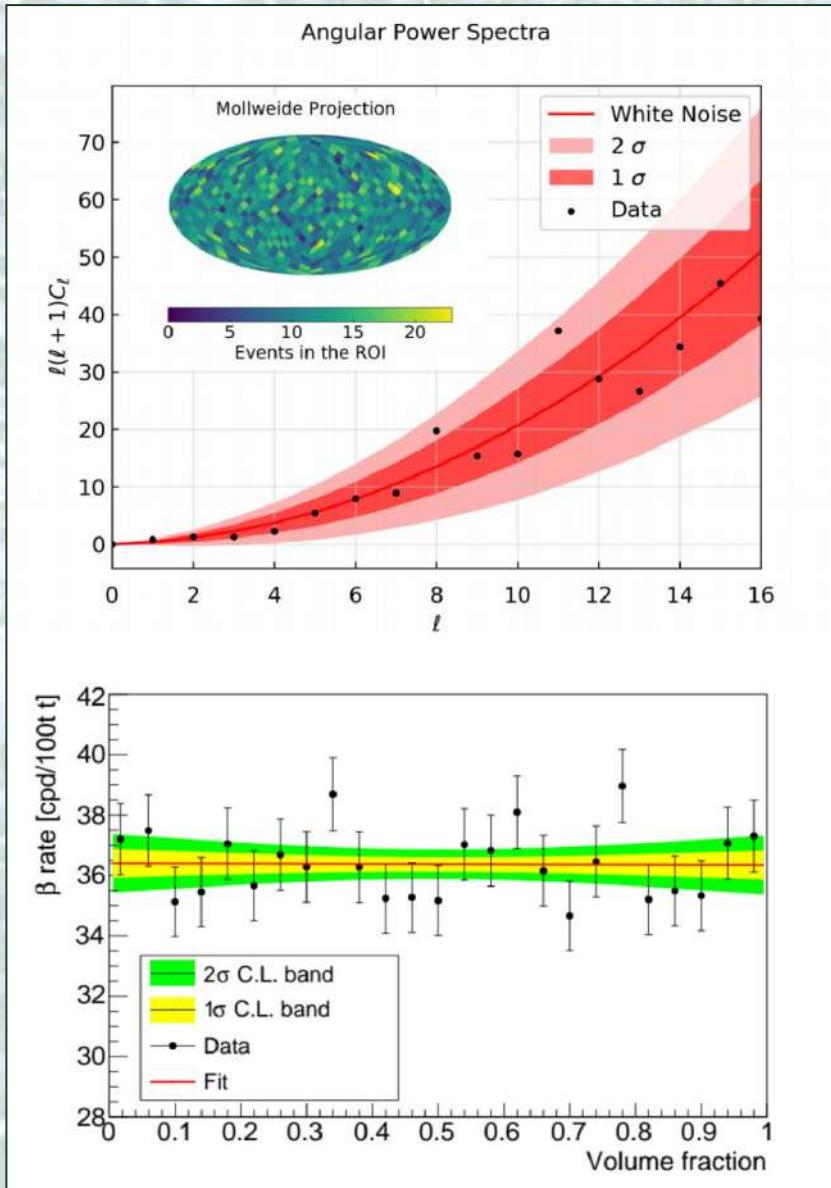
Cross-checked with numerical fluid-dynamics simulation.

In that region, the ^{210}Po rate can be 2D fit assuming a bulk+IV contributions:

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

$$R(^{210}\text{Bi}) < 11.5 \pm 1.04 \text{ cpd}/100t$$

^{210}Bi UNIFORMITY



The ^{210}Bi upper limit can be extended over the full FV if and only ^{210}Bi is uniform both in the angular and radial distributions: it is found uniform within error!

Systematic uncertainty: 0.78 cpd/100 t

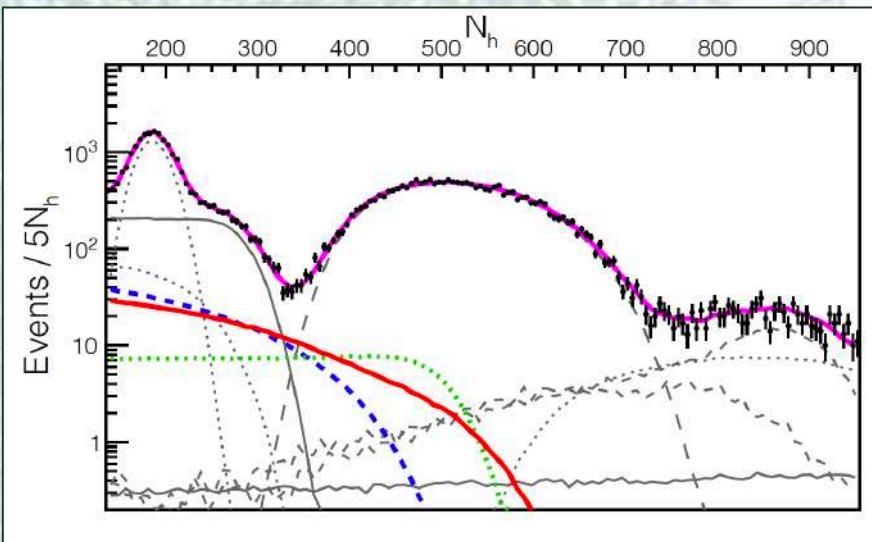
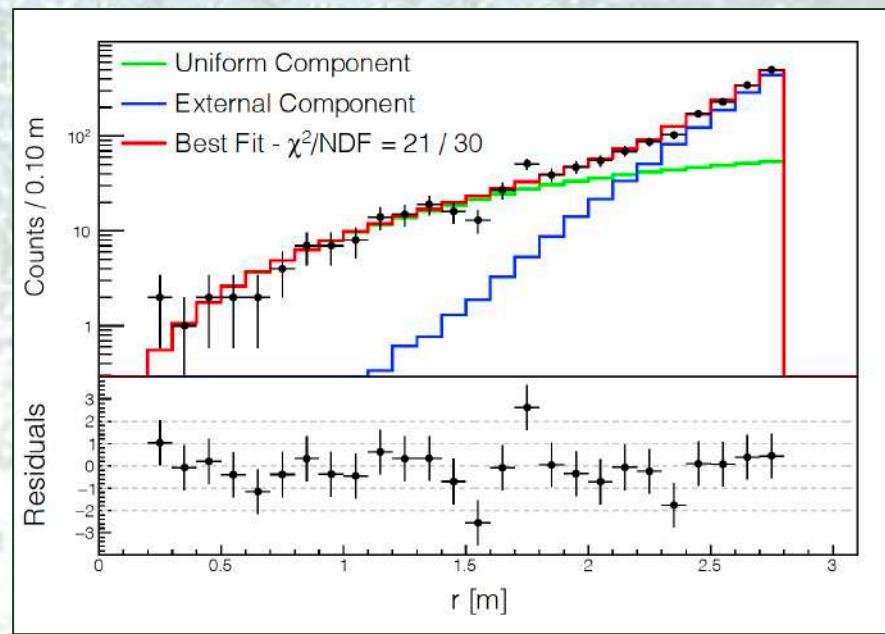
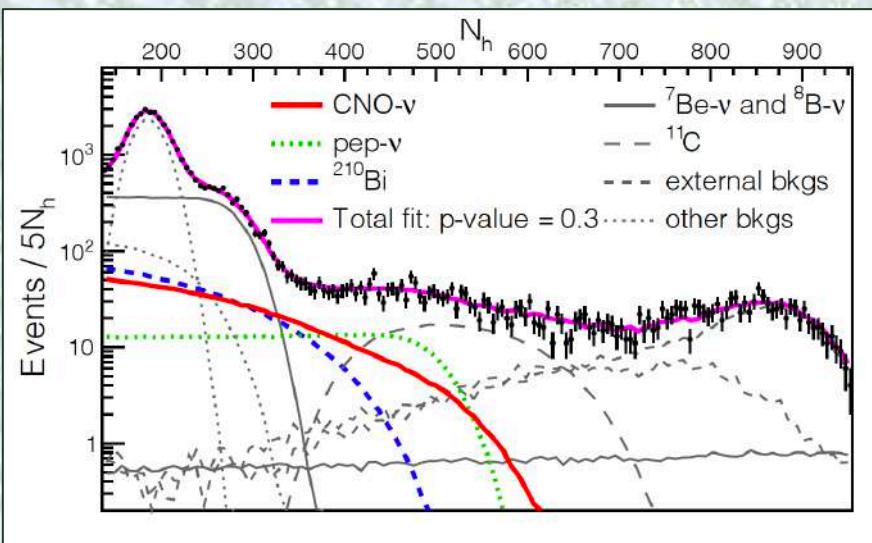
^{210}Bi stable in time \rightarrow ^{210}Pb leaching from the nylon vessel is negligible

Final constraint on ^{210}Bi :

$$R(^{210}\text{Bi}) < 11.5 \pm 1.3 \text{ cpd/100t}$$

CNO NEUTRINOS: THE MULTIVARIATE FIT

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



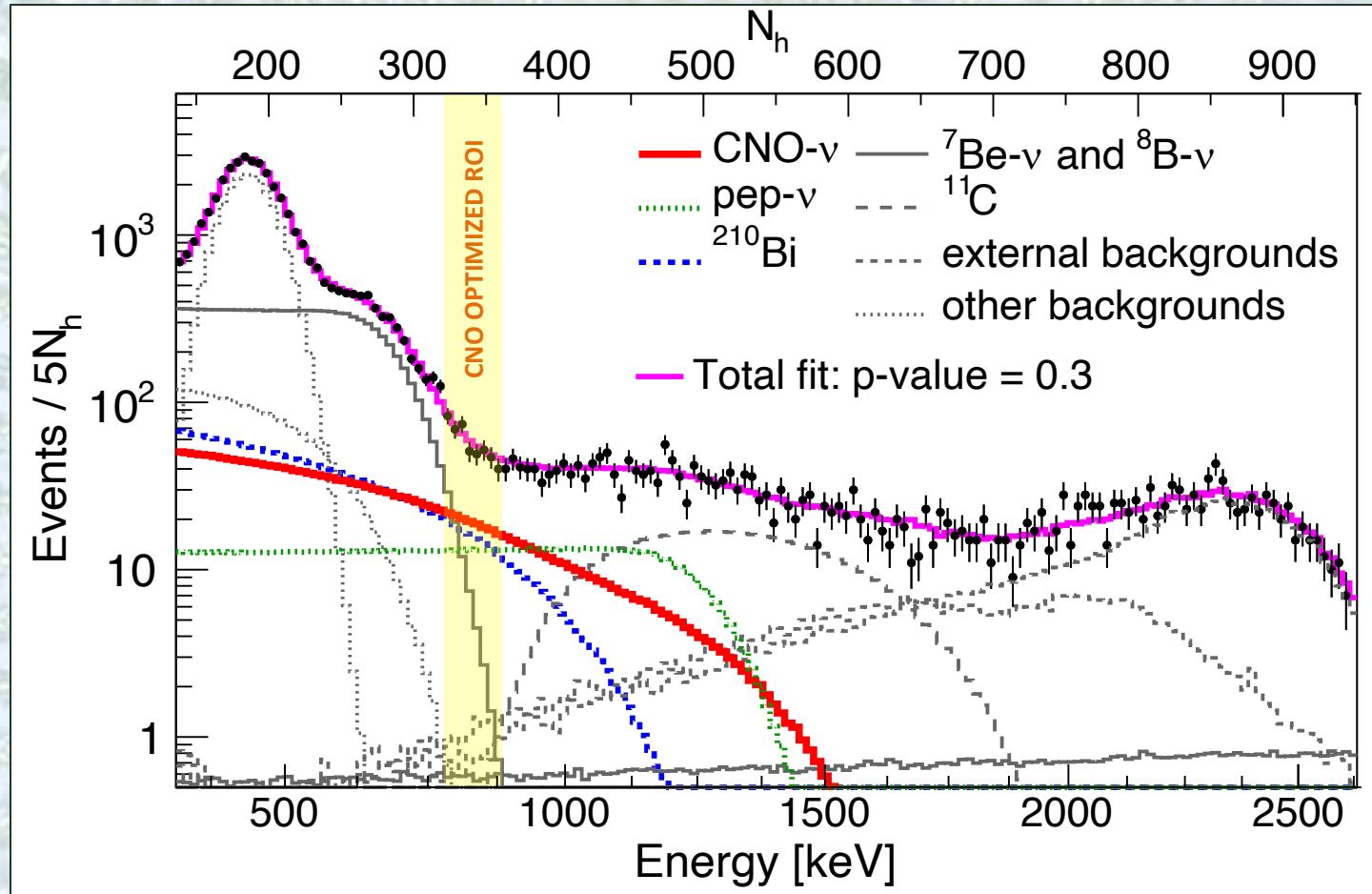
Multivariate fit likelihood:

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

The rate of signals and backgrounds are the free parameters of the fit with two discussed exception: ^{210}Bi and pep.

CNO NEUTRINOS: RESULTS

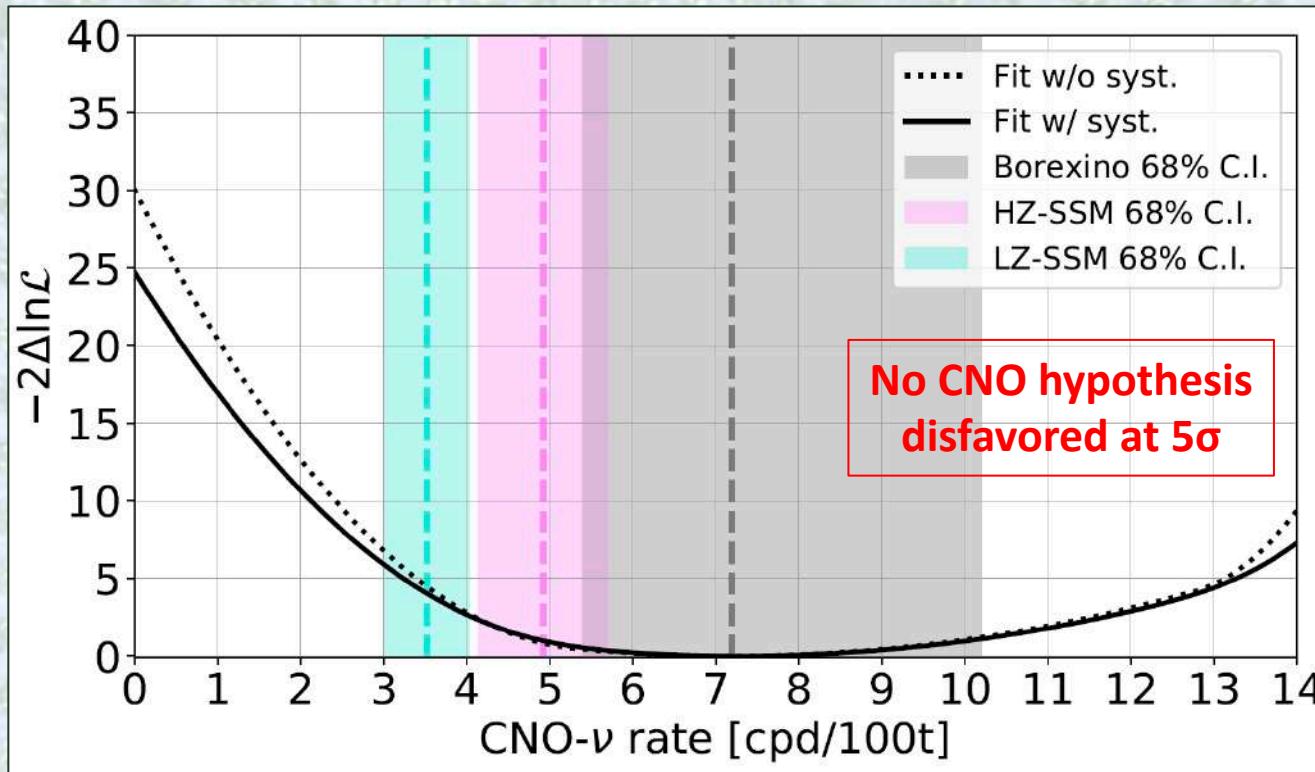
"Experimental evidence of neutrinos produced in the CNO fusion cycle in the Sun", *Nature* 587 (2020) 577



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

CNO NEUTRINOS: RESULTS

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



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

$$\Phi(\text{CNO}) = 7.2^{+3.0}_{-2.0} \times 10^8 \text{ } \nu/\text{cm}^2/\text{s (stat + sys)}$$

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).

Low-energy electron scattering can probe interesting new physics: we can simultaneously test the P_{ee} in the vacuum and matter dominated region.

The combination of the ^7Be and $^8\text{B} \nu$ measurements hints 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

CNO ANALYSIS: SYSTEMATICS

Systematic errors

Fit cfg.

Negligible

^{11}C spectrum

Deformation induced by
noise cuts

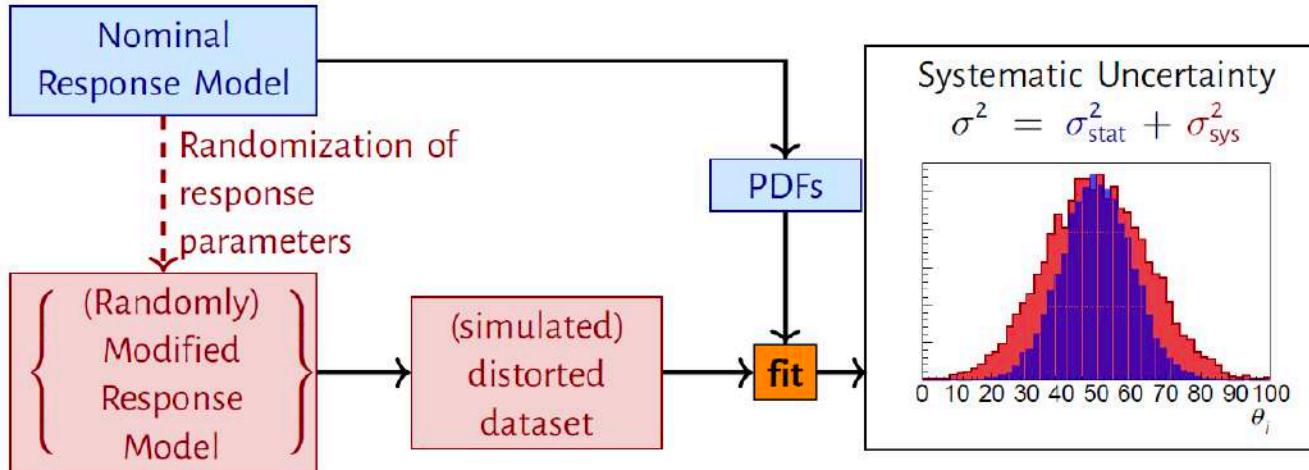
^{210}Bi spectrum

Different references for
 β -spectrum (diff. $\approx 18\%$)

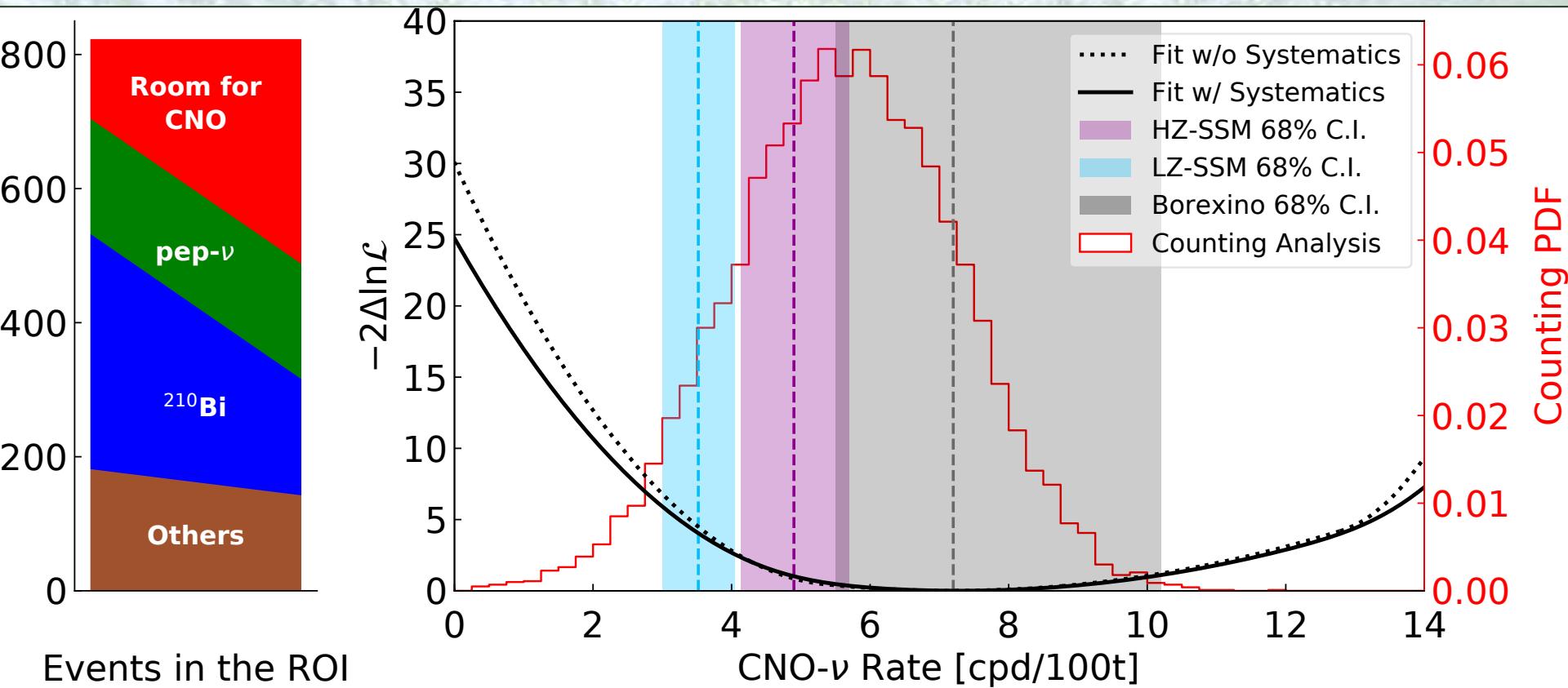
Detector response

Vary detector response
parameters within range
allowed by calibration

- ▶ Energy scale (0.23%)
- ▶ non-uniformity (0.28%)
- ▶ non-linearity (0.4%)

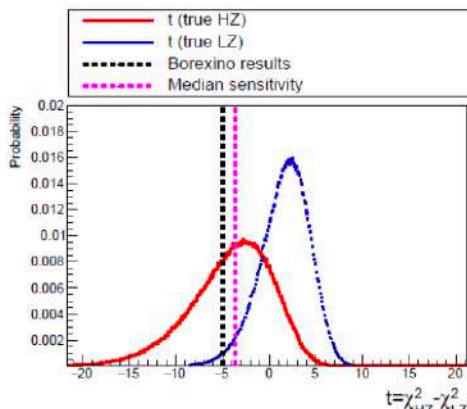


CNO ANALYSIS: RESULTS



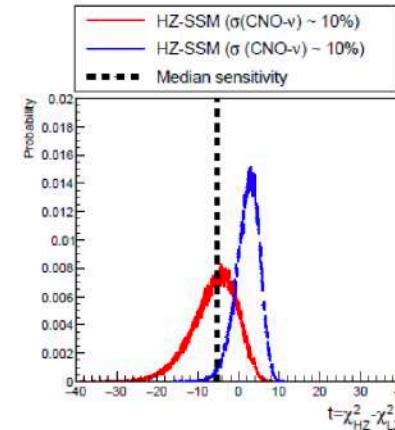
CNO ANALYSIS: LZ/HZ DISCRIMINATION

CURRENT: results of BX on Be7, 8B and CNO neutrinos



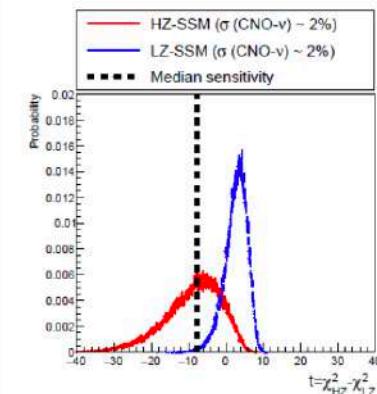
Exclusion of LZ at $\sim 2.1 \sigma$

FUTURE hypothetical result on CNO at 10% error



Exclusion of LZ at $\sim 2.2 \sigma$

FUTURE hypothetical result on CNO at 2% error

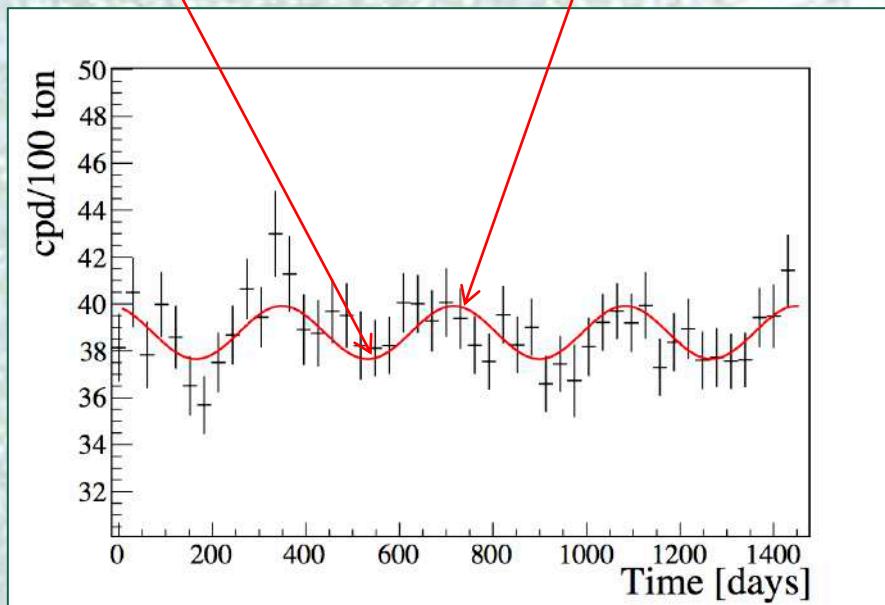
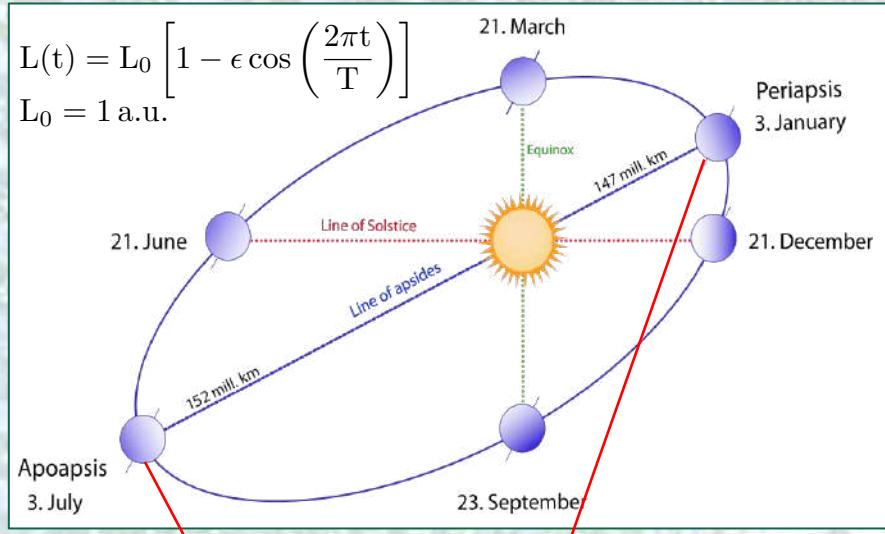


Exclusion of LZ at $\sim 2.6 \sigma$

Frequentist hypothesis test: even in the most optimistic case the discrimination power is small, due to large theoretical uncertainties

$^{7}\text{Be}-\nu$ FLUX SEASONAL MODULATION

"Seasonal modulation of the ^{7}Be solar neutrino rate in Borexino" - *Astr. Phys.* 92 (2017) 21



We searched for the seasonal variations of the neutrino interaction rate due to the varying distance $L(t)$ between Sun and Earth during the year.

Astronomical observations:

- $T = 365.256 \text{ d}$
- $\epsilon = 0.0167$

Different Data Analysis Method:

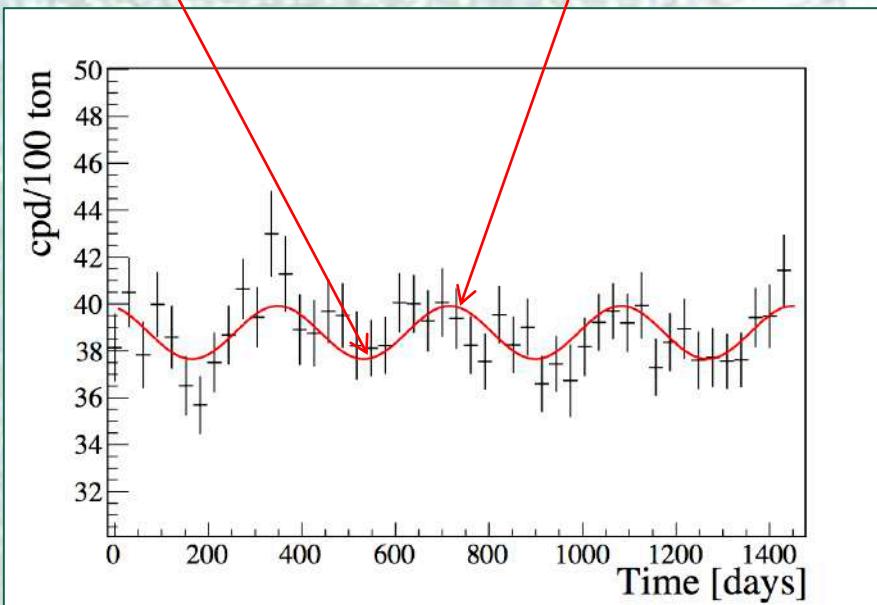
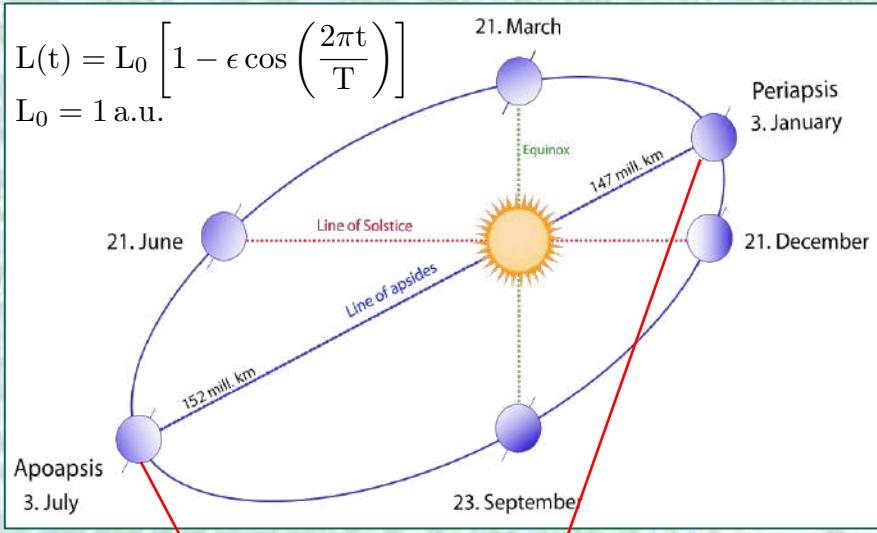
- Analytical Fit
- Lomb-Scargle (Fourier Transform)
- Empirical Mode Decomposition

Borexino results:

- ◆ $T = 367 \pm 10 \text{ d}$
- ◆ $\epsilon = 0.0174 \pm 0.0045$

${}^7\text{Be}-\nu$ FLUX SEASONAL MODULATION

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- ◆ $T = 367 \pm 10$ d
- ◆ $\epsilon = 0.0174 \pm 0.0045$

The absence of seasonal modulation is ruled out at 99.99% C.L. (3.91σ).

All approaches show
→ consistency with the solar origin
of ${}^7\text{Be}$ neutrinos!

NEUTRINO OPEN QUESTIONS

❖ Particles Physics:

- ✧ Non-Standard interactions?
- ✧ Number of neutrino species.
Any Sterile neutrino?
- ✧ Dirac or Majorana neutrino?
- ✧ Hierarchy:
Normal or Inverted?
- ✧ δ_{CP} value?

❖ AstroPhysics:

- ✧ Low/High metallicity: What is the correct hypothesis?
- ✧ How a star works/burns?
We only have infos from starlight spectroscopy.

❖ Earth Physics:

- ✧ Geoneutrinos: a unique direct probe of our planet's interior!

SIMULTANEOUS SOLAR NEUTRINO SPECTROSCOPY

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

LER ANALYSIS - SYSTEMATIC ERRORS

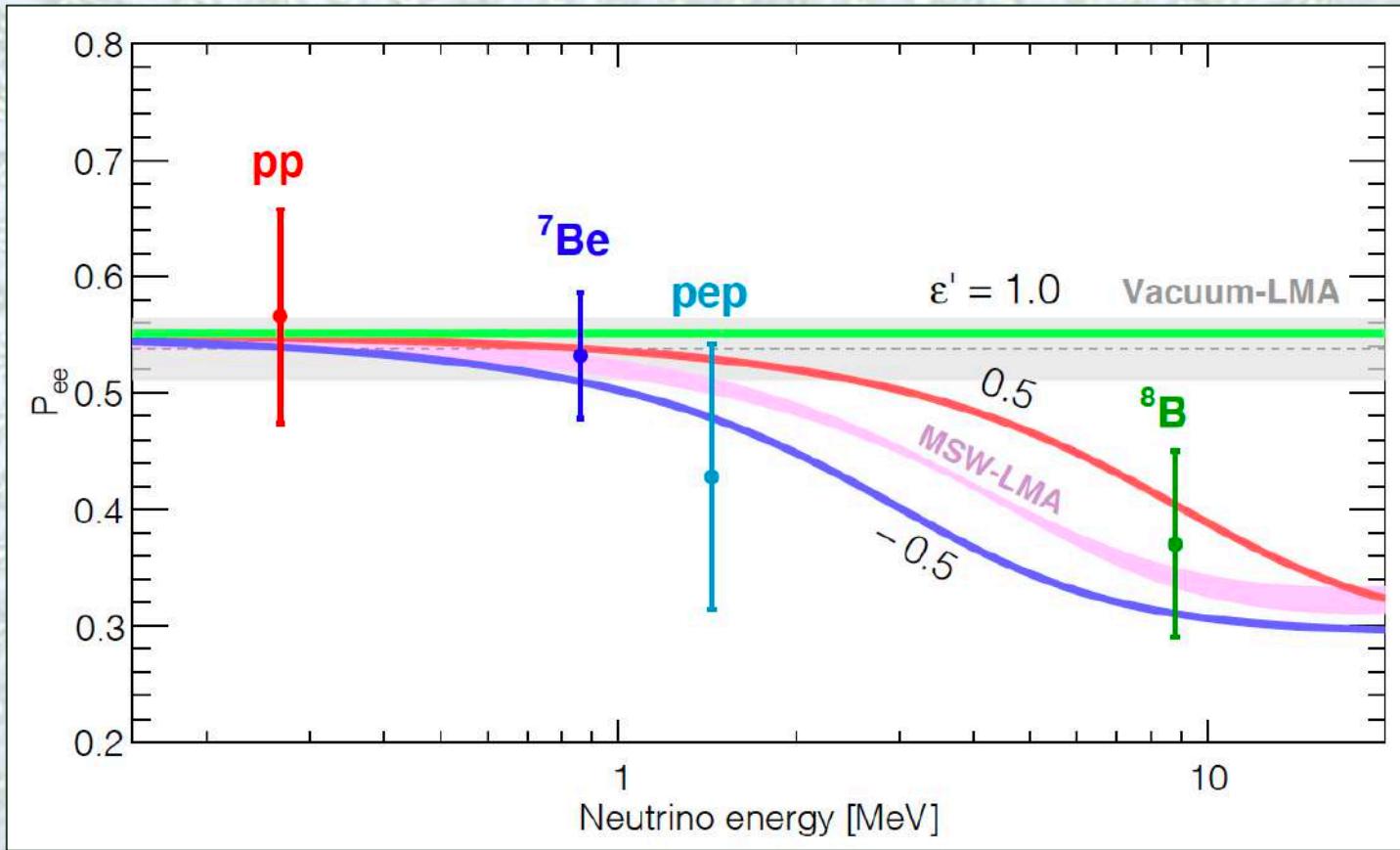
Two methods to take into account pile-up

- Effects of non perfect modelling of the detector response;
- Uncertainty on theoretical input spectra (^{210}Bi);
- ^{85}Kr constrained to be $< 7.5\text{cpd}/100\text{t}$ (95% C.L.) from Kr-Rb delayed coincidences

Source of uncertainty	<i>pp</i> neutrinos		^{7}Be neutrinos		<i>pep</i> neutrinos	
	-%	+	-%	+	-%	+
Fit models (see text)	-4.5	+0.5	-1.0	+0.2	-6.8	+2.8
Fit method (analytical/Monte Carlo)	-1.2	+1.2	-0.2	+0.2	-4.0	+4.0
Choice of the 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
Inclusion of the ^{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

STUDYING THE SUN WITH NEUTRINOS... ...STUDYING NEUTRINOS WITH THE SUN

Neutrino physics: Non Standard Interaction investigation



arXiv:1905.03512 [hep-ph] (2019) accepted for publication on JHEP

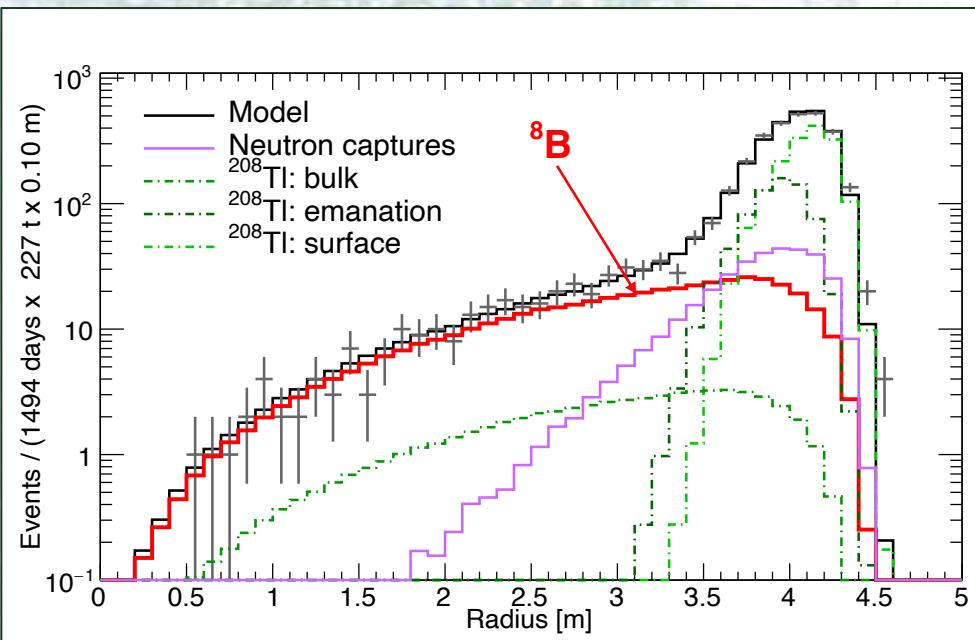
COMPREHENSIVE SOLAR NEUTRINO SPECTROSCOPY

"Comprehensive measurement of pp-chain solar neutrinos", *Nature* 562 (2018) 505
HER analysis arXiv: 1709.00756 [hep-ex] (2017)

Main HER analysis features:

- Data-set: January 2008 - December 2016 (purification period excluded);
- Fiducial mass: extended to the entire active mass (from about 100 t to 300 t);
- Fit range: 3.2 -16 MeV;
- Total exposure: 1.5 kton x year (11.5-fold increase).

New strategy! A MonteCarlo radial fit on Low Energy (HER-I: 3.2-5 MeV) and High Energy (HER-II: 5-16 MeV) sectors so to better handling the background.



Extracting the neutrino signal from data:

Residual backgrounds affecting the ^{8}B energy region are:

- ^{208}Tl (emanated from PMTs, from the vessel or internal);
- cosmogenic isotopes;
- ^{214}Bi (internal).

SIMULTANEOUS SOLAR NEUTRINO SPECTROSCOPY

“Comprehensive measurement of pp-chain solar neutrinos”, *Nature* 562 (2018) 505

HER ANALYSIS - SYSTEMATIC ERRORS

Source of uncertainty	HER-I		HER-II		HER (tot)	
	-%	+	-%	+	-%	+
Target mass	-2.0	+2.0	-2.0	+2.0	-2.0	+2.0
Energy scale	-0.5	+0.5	-4.9	+4.9	-1.7	+1.7
z-cut	-0.7	+0.7	0	0	-0.4	+0.4
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
Total systematics (%)	-2.2	+2.2	-5.3	+5.3	-2.7	+2.7