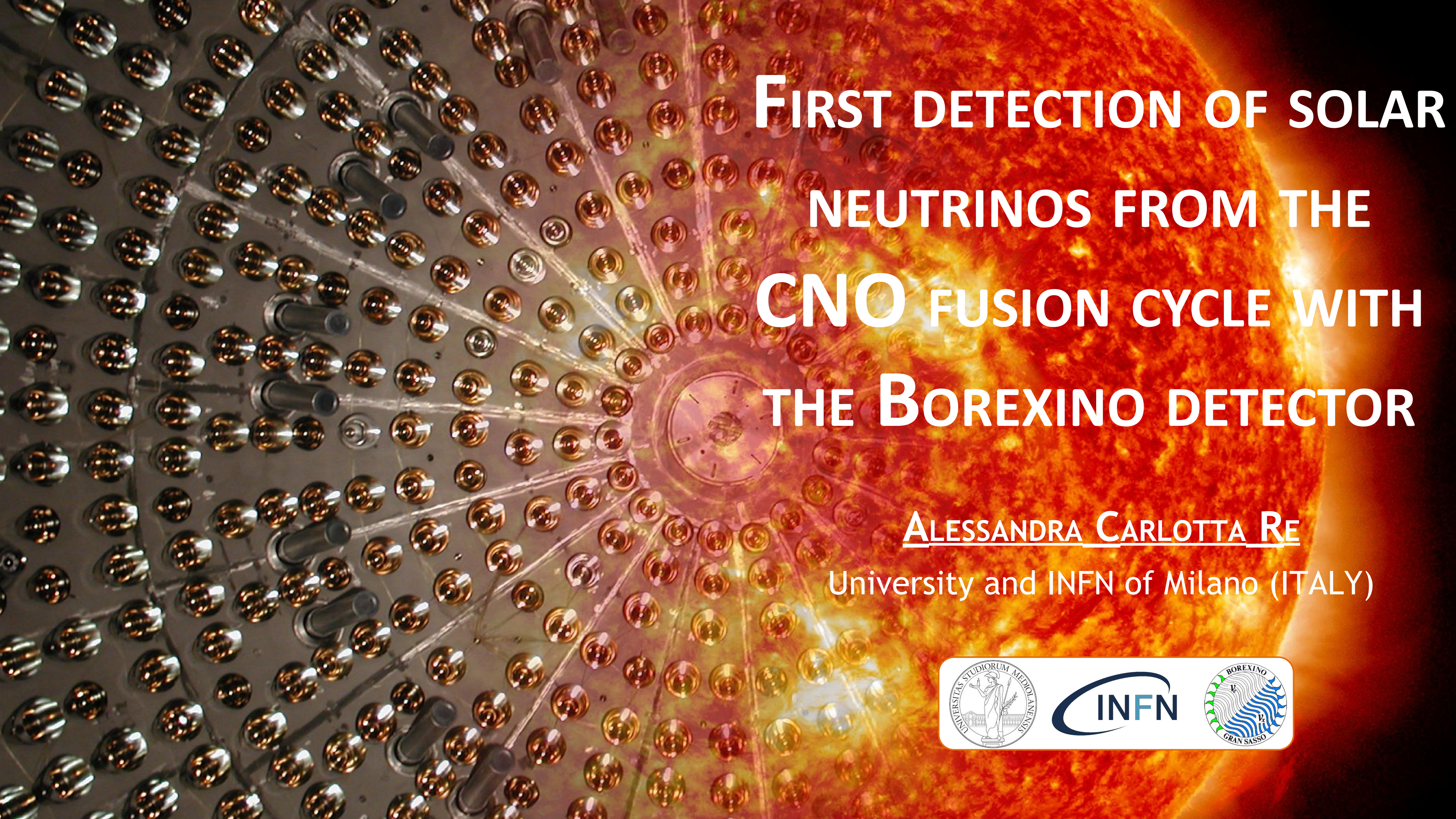


FIRST DETECTION OF SOLAR NEUTRINOS FROM THE CNO FUSION CYCLE WITH THE BOREXINO DETECTOR

ALESSANDRA CARLOTTA RE

University and INFN of Milano (ITALY)

STUDYING THE SUN WITH NEUTRINOS…

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

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

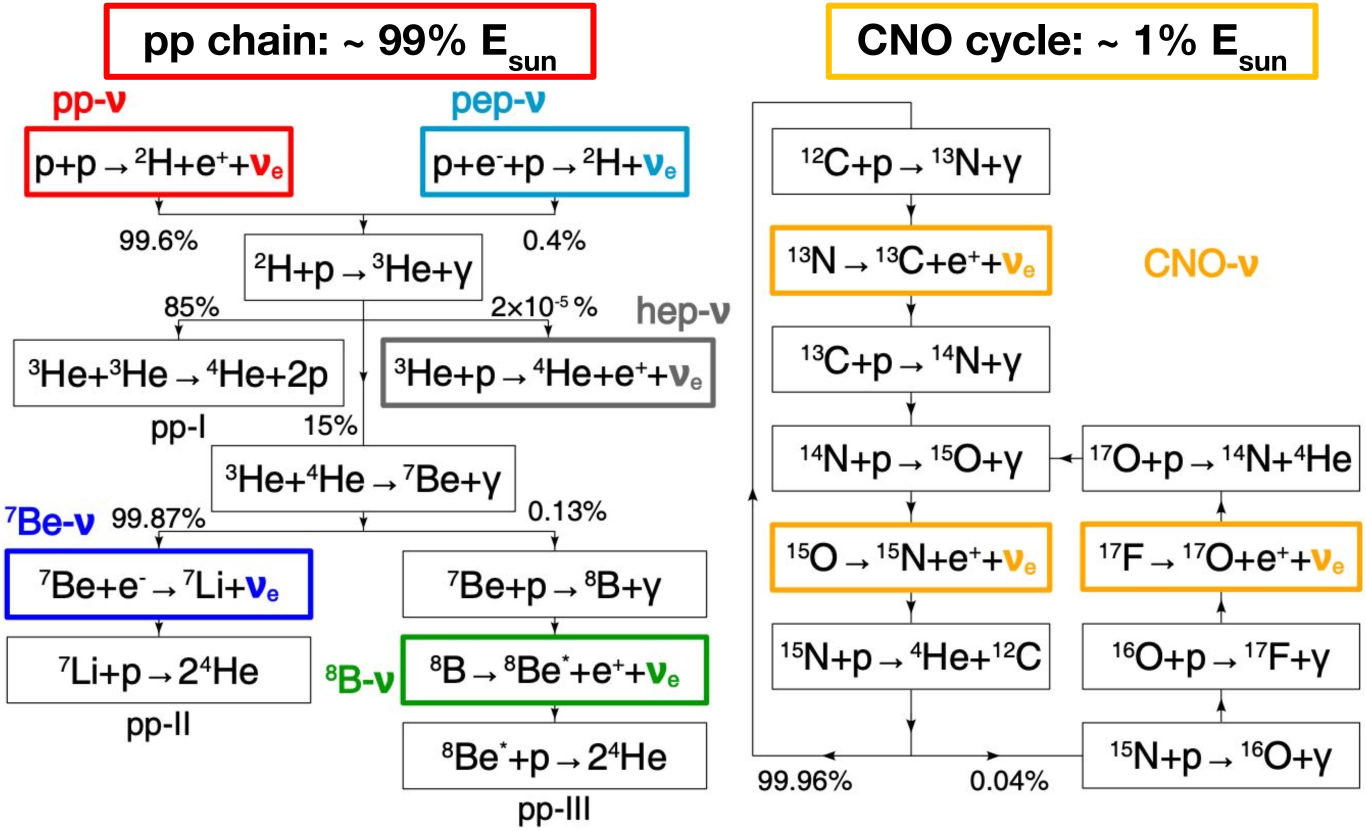
Neutrinos interacts through the weak-interaction only:

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

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?



pp chain: ~ 99% E_{sun}

CNO cycle: ~ 1% E_{sun}

pp-ν

$p+p \rightarrow {}^2H+e^++\nu_e$

pep-ν

$p+e^-+p \rightarrow {}^2H+\nu_e$

99.6%

0.4%

${}^2H+p \rightarrow {}^3He+\gamma$

85%

2×10^{-5} %

hep-ν

${}^3He+{}^3He \rightarrow {}^4He+2p$

${}^3He+p \rightarrow {}^4He+e^++\nu_e$

pp-I

15%

${}^3He+{}^4He \rightarrow {}^7Be+\gamma$

^{7}Be-ν

99.87%

0.13%

${}^7Be+e^- \rightarrow {}^7Li+\nu_e$

${}^7Be+p \rightarrow {}^8B+\gamma$

${}^7Li+p \rightarrow 2\,{}^4He$

pp-II

^{8}B-ν

${}^8B \rightarrow {}^8Be^*+e^++\nu_e$

${}^8Be^*+p \rightarrow 2\,{}^4He$

pp-III

${}^{12}C+p \rightarrow {}^{13}N+\gamma$

${}^{13}N \rightarrow {}^{13}C+e^++\nu_e$

CNO-ν

${}^{13}C+p \rightarrow {}^{14}N+\gamma$

${}^{14}N+p \rightarrow {}^{15}O+\gamma$

${}^{17}O+p \rightarrow {}^{14}N+{}^4He$

${}^{15}O \rightarrow {}^{15}N+e^++\nu_e$

${}^{17}F \rightarrow {}^{17}O+e^++\nu_e$

${}^{15}N+p \rightarrow {}^4He+{}^{12}C$

${}^{16}O+p \rightarrow {}^{17}F+\gamma$

${}^{15}N+p \rightarrow {}^{16}O+\gamma$

99.96%

0.04%

PP CHAIN VS CNO CYCLE

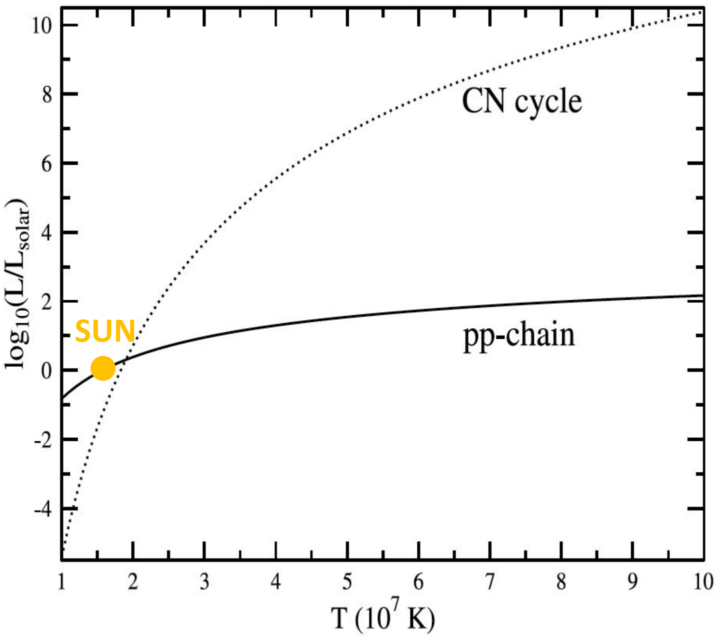
In the Sun, the CNO cycle is subdominant with respect to the pp-chain

BUT

In massive stars, having higher ($T \gtrsim 2 \times 10^7$ 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!

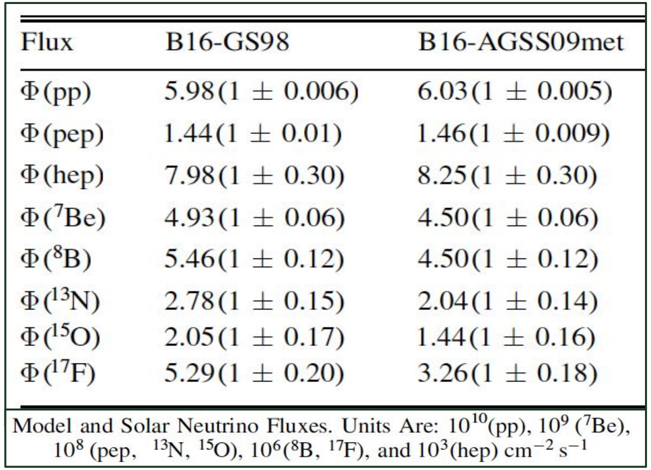
It was never directly observed before Borexino result in 2020.



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

THE STANDARD SOLAR MODEL

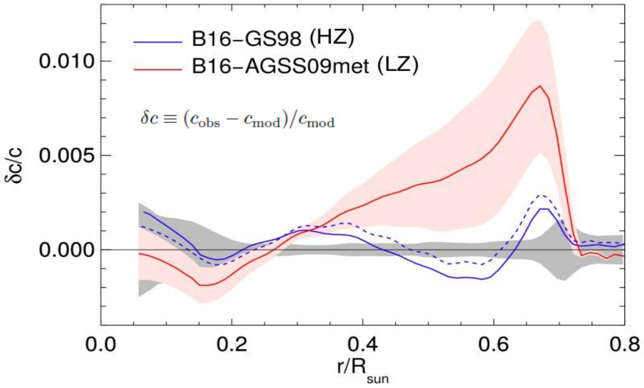
A Standard Solar Model (SSM) is a complex container where input parameters (such as Sun luminosity, age, mass, radius, chemical elements abundances, cross-sections, radiative opacity, metallicity….) are considered all together and result in expectations about the neutrino fluxes and helioseismology.



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

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}

The METALLICITY Puzzle



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

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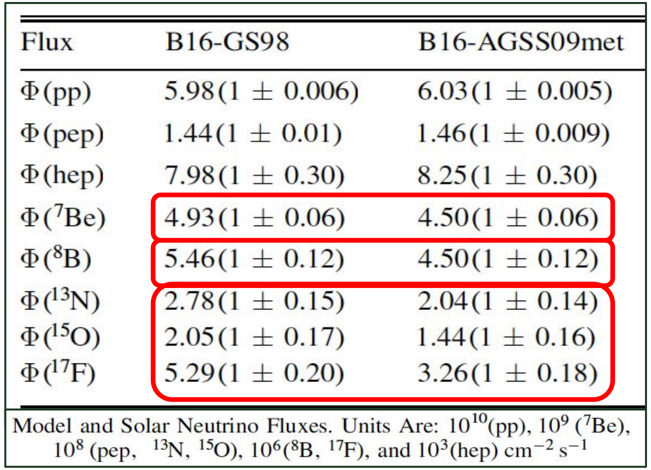

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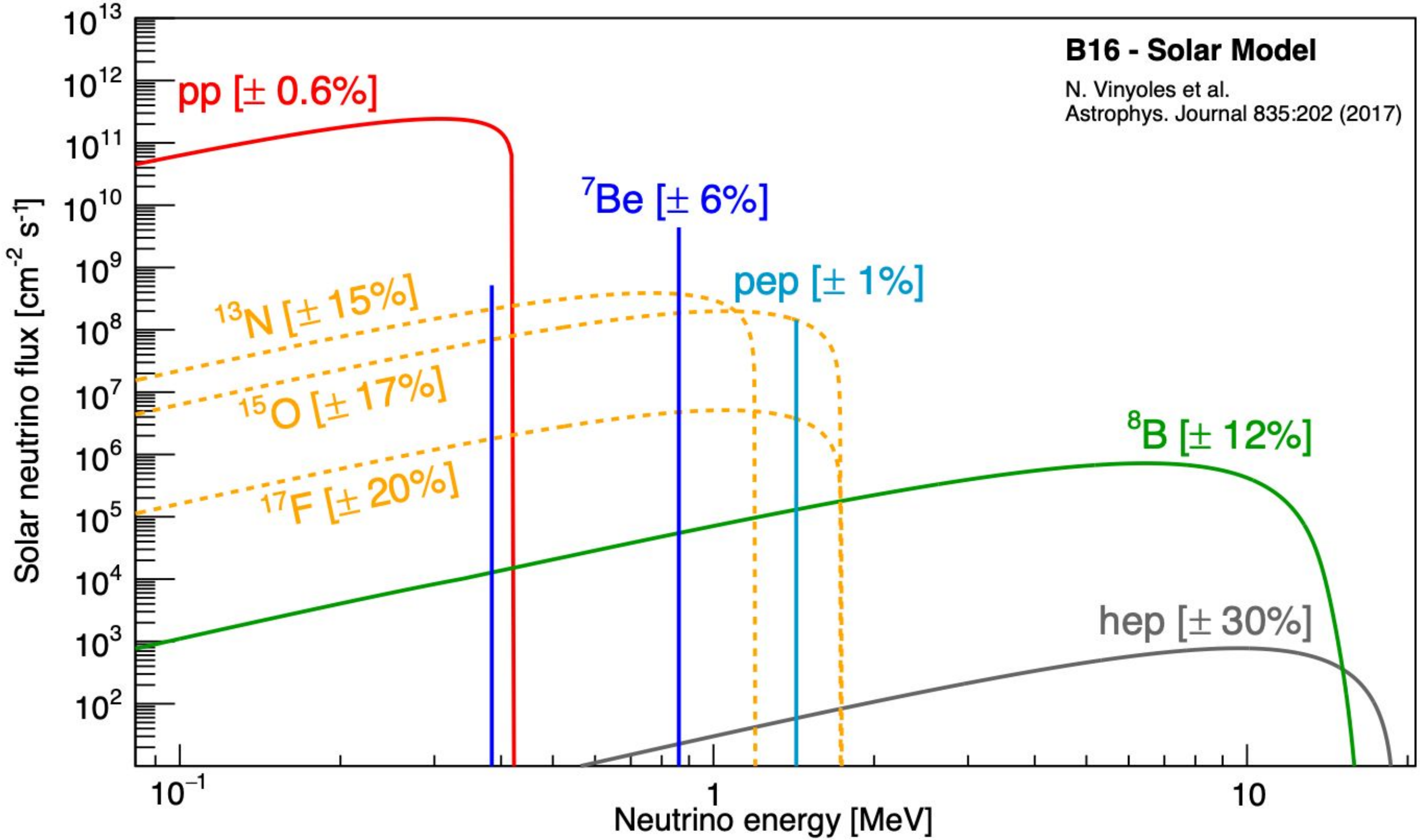
About 9% difference

About 18% difference

About 28% difference

THE SOLAR NEUTRINO SPECTRUM



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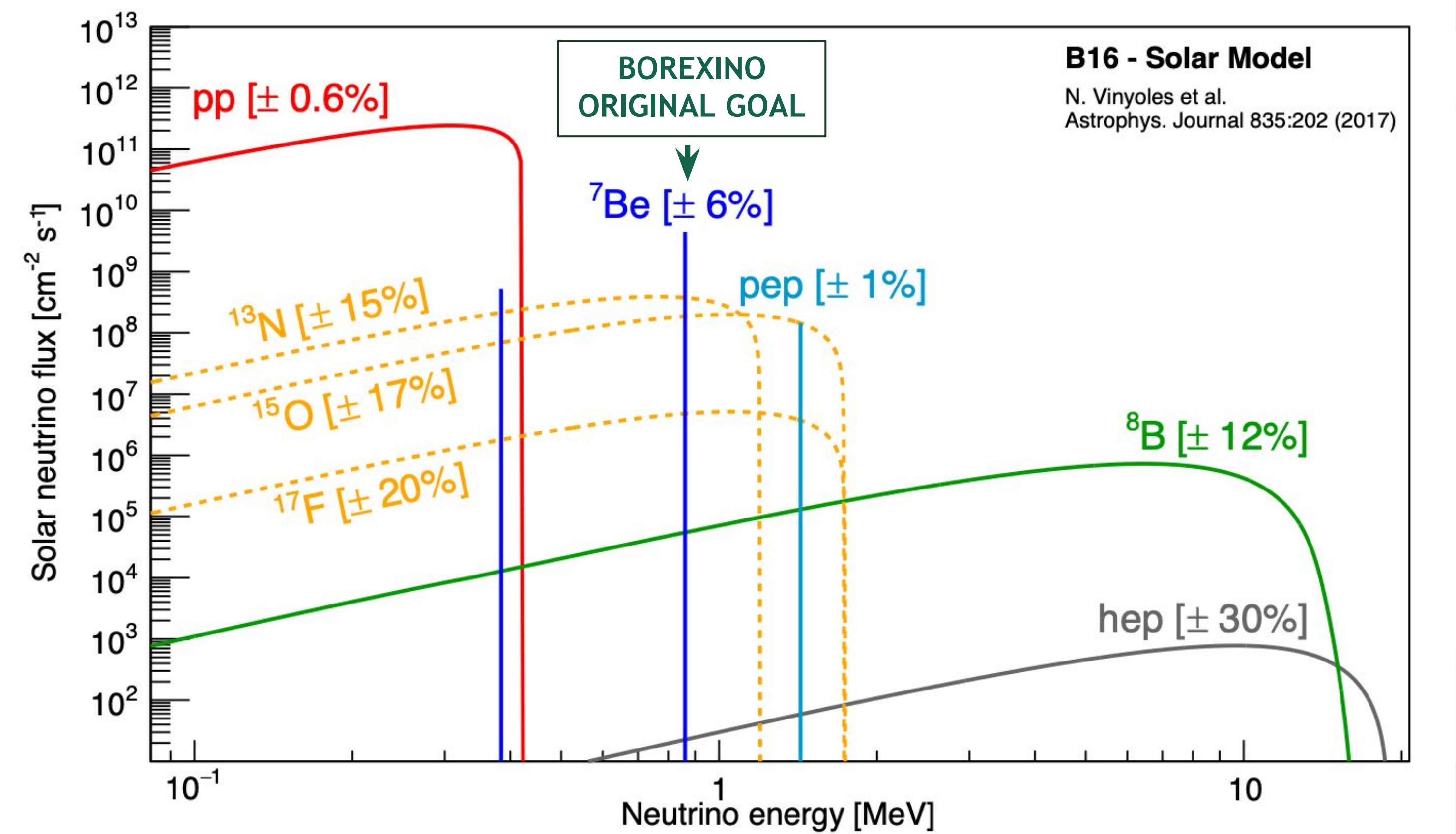
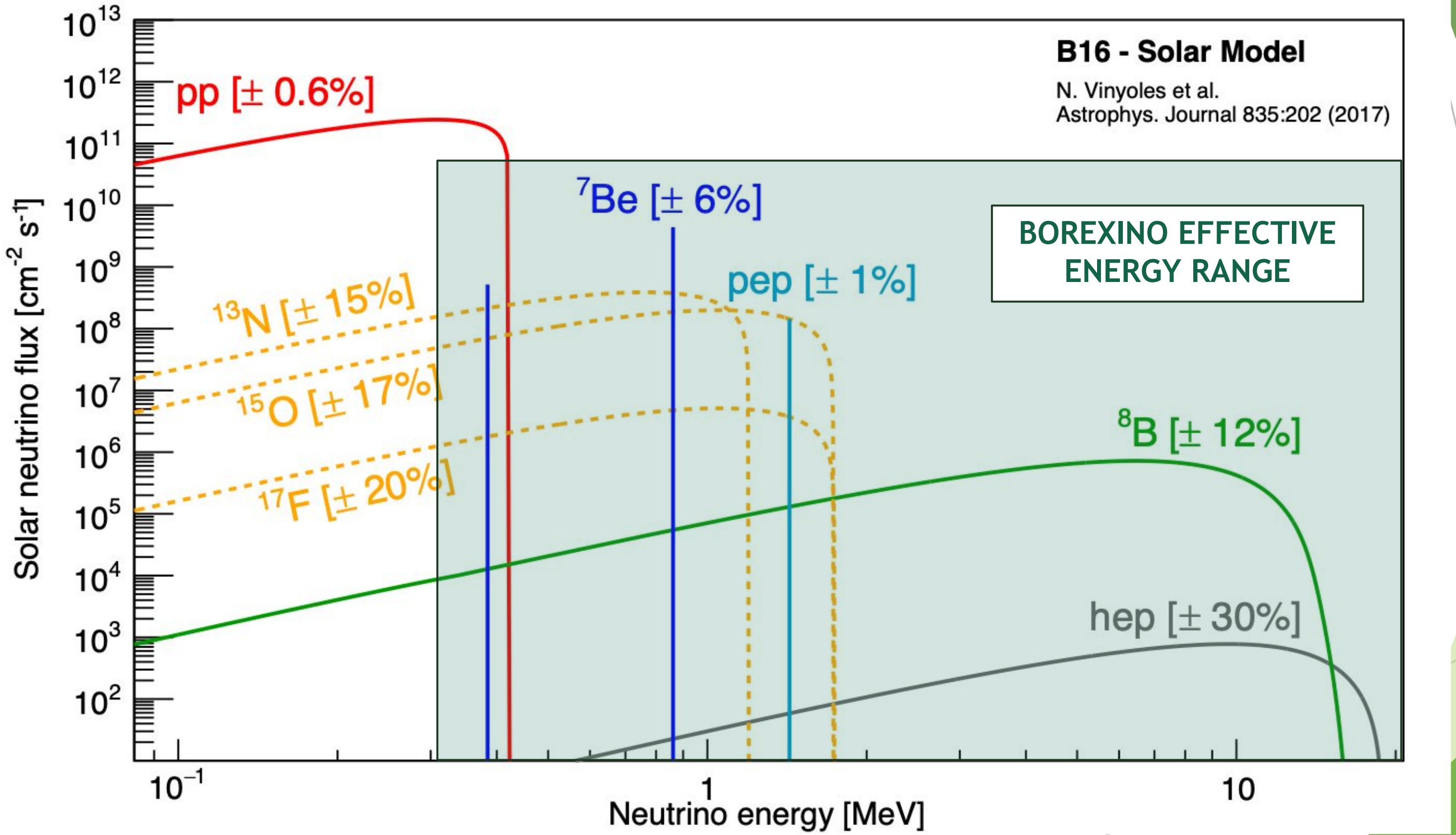
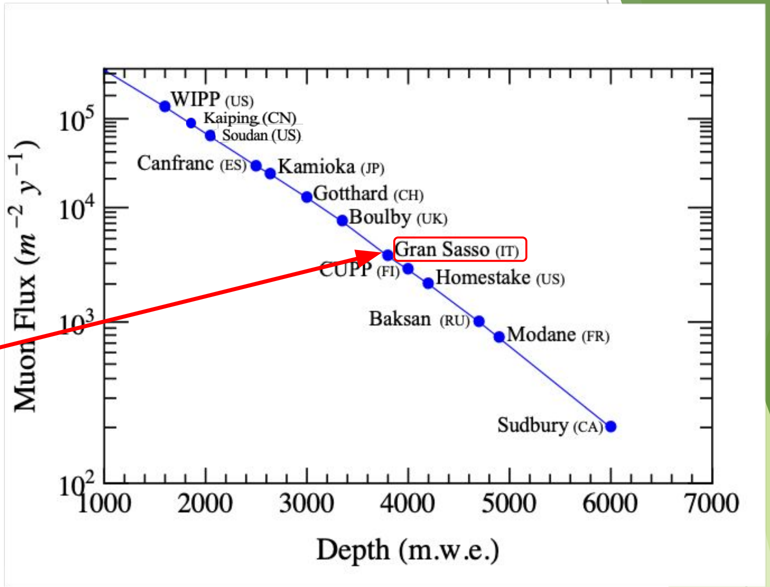


BOREXINO ORIGINAL GOAL

THE SOLAR NEUTRINO SPECTRUM



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 information.

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

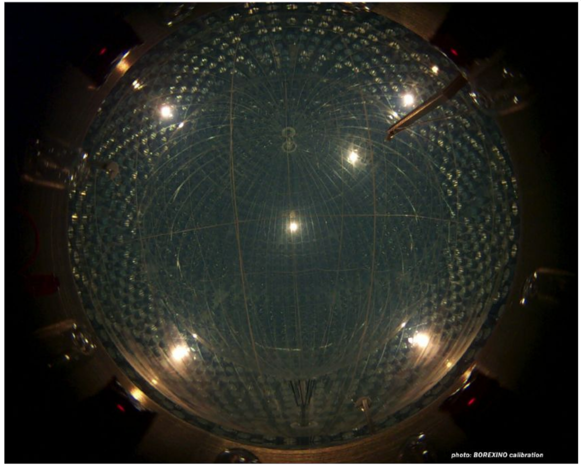
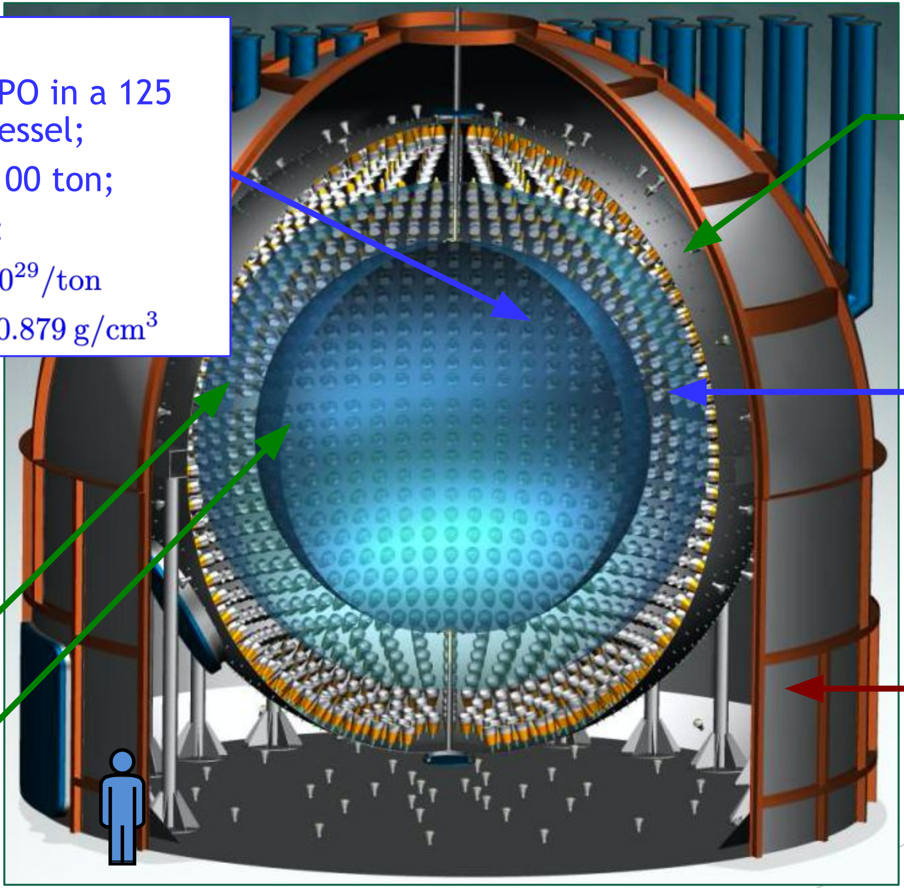


photo: BOREXINO calibration

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 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 ~ 100 ton;

Electron density:

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

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

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

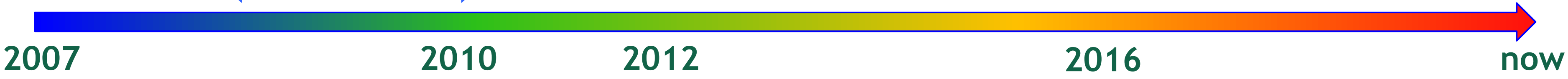
γ and n shield

μ water Č detector

208 PMTs in water

THE BOREXINO RESULTS... SO FAR

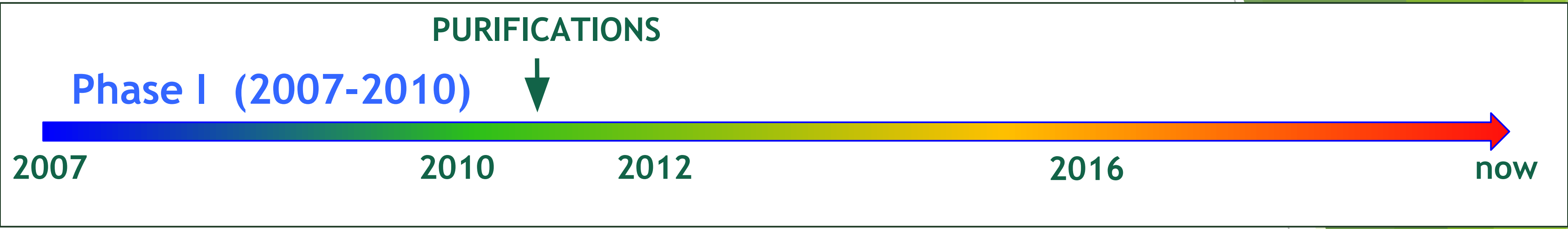
Phase I (2007-2010)



Direct measurements of

- ^{7}Be flux: 1st observation + precise measurement (5%);
- Absence of day/night asymmetry for ^{7}Be signal
  => MSW-LMA singled out (> 8.5σ);
- ^{8}B 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)

^{85}Kr: reduced by ~4.6 factor
^{210}Bi: reduced by ~2.3 factor
^{238}U: $< 9.4 \times 10^{-20}$ g/g (95% C.L.)
^{232}Th: $< 5.7 \times 10^{-19}$ g/g (95% C.L.)
^{210}Po: reduced by > 10 factor due to natural decay

→ **Further radiopurity improvement:**
A scintillator has never been so clean!

THE BOREXINO RESULTS… SO FAR

PURIFICATIONS

Phase I (2007-2010)

Phase II (2012-2016)

2007 2010 2012 2016 now

Direct measurements of

- pp flux: 1st direct measurement ;
- Geoneutrinos (> 5σ);
- 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 > 5σ).

THE BOREXINO RESULTS… SO FAR

Purifications

Thermal Insulation

Phase I (2007-2010)

Phase II (2012-2016)

2007

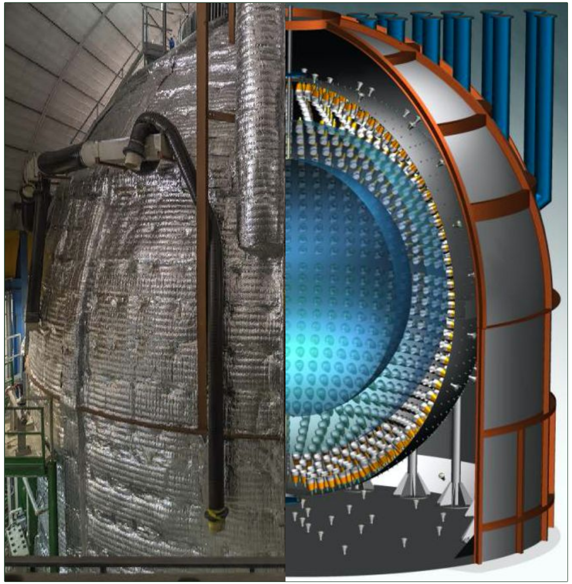
2010

2012

2016

now

A key-step towards the CNO measurement !



THE BOREXINO RESULTS… SO FAR

Purifications

Thermal Insulation

Phase I (2007-2010)

Phase II (2012-2016)

Phase III (2016-)

2007 2010 2012 2016 now

The international journal of science / 26 November 2020

outlook Multiple myeloma

nature

CATCHING THE RAYS

Neutrino detector secures evidence of the Sun's secondary fusion cycle

Coronavirus How Iceland subdued COVID-19 with science

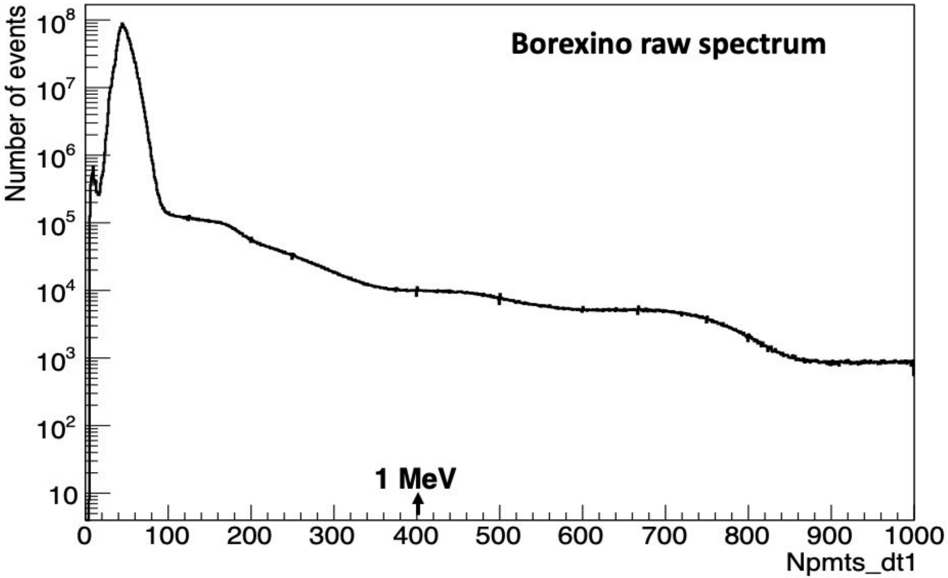
Family planning Research and invest in contraceptives that meet women's needs

Environment The effect of noise and light pollution on US bird populations

Phase III:
- FIRST DIRECT MEASUREMENT OF CNO SOLAR-ν

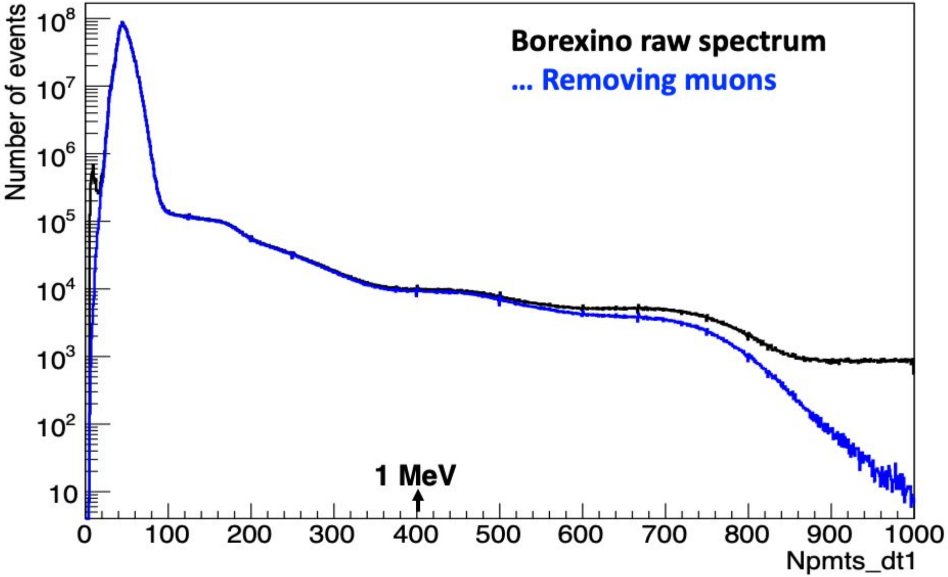
physicsworld TOP 10 BREAKTHROUGH 2020

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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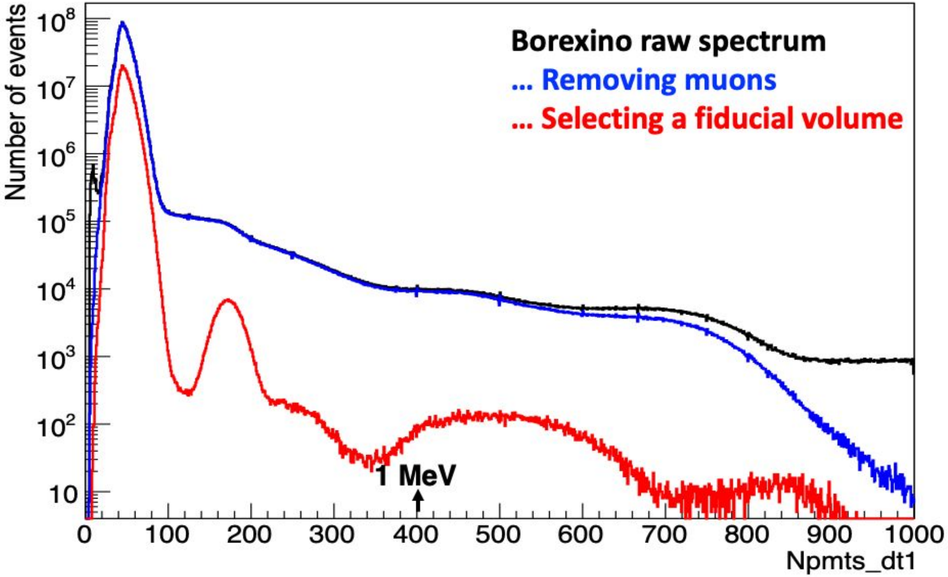

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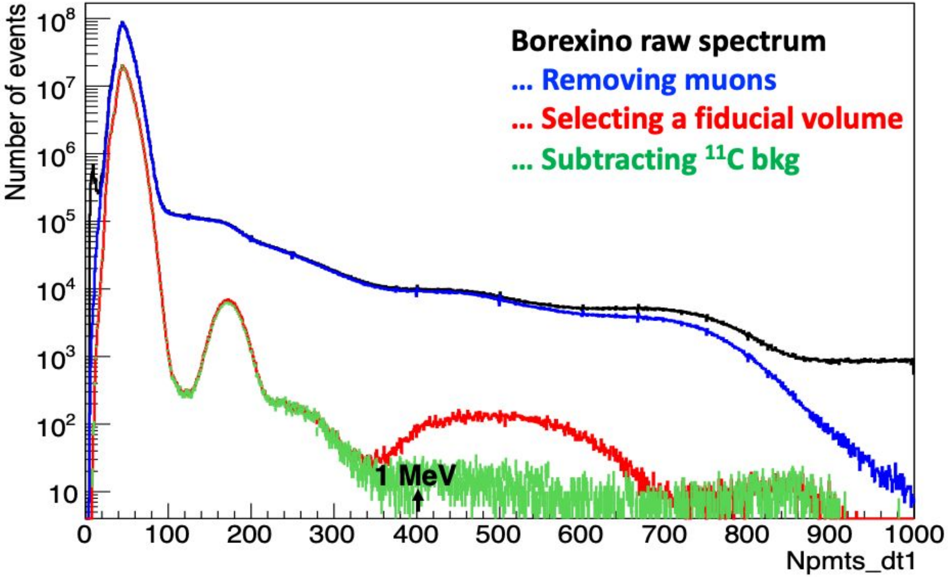

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THE THREE-FOLD COINCIDENCE TECHNIQUE

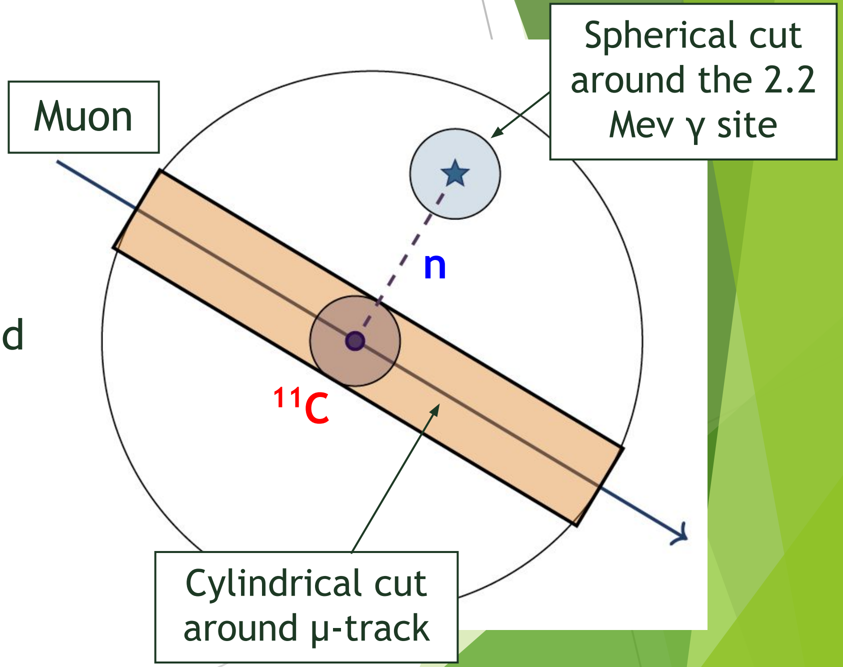
The TFC technique is foundamental to improve the fit capability to disantagle the ^{11}C contamination from the pep & CNO neutrino signals.

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

$$\boxed{\begin{array}{c}{}^{11}\mathrm{C} \rightarrow {}^{11}\mathrm{B} + \mathrm{e}^{+} + \nu_{\mathrm{e}} \\ \tau \sim 30\ \mathrm{min}\end{array}} \qquad \boxed{\begin{array}{c}\mathrm{n} + \mathrm{p} \rightarrow \mathrm{d} + \gamma \\ \tau \sim 250\ \mu\mathrm{s}\end{array}}$$

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.**

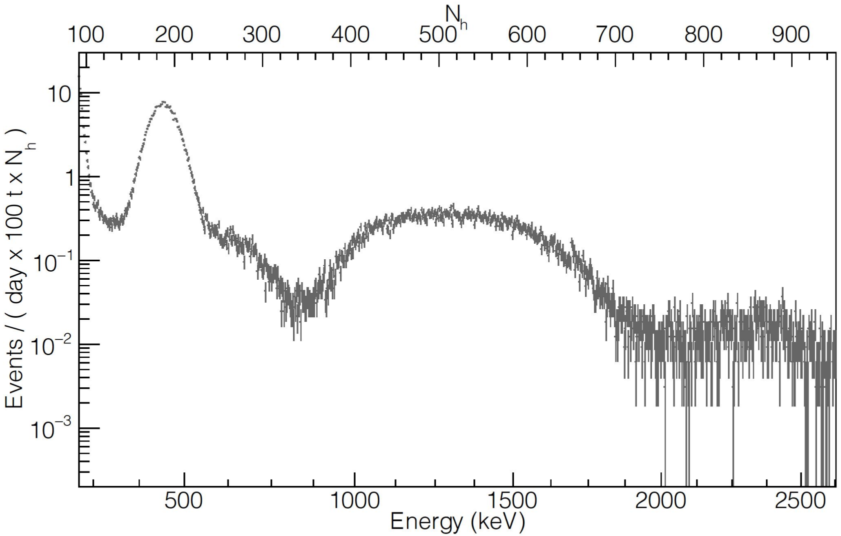
…. So all challenges at once!

For the first time we are able to perform a simultaneous fit on the whole solar neutrino energy region.

A COMPREHENSIVE SOLAR NEUTRINO SPECTROSCOPY WITH BOREXINO

THE PP-CHAIN SOLAR-ν MEASUREMENT

Nature 562 (2018) 505; Physical Review D 100, 082004 (2019)



Data-set: Phase-II (December 2011 - May 2016) --> Exposure: 1292 days x 71.3 t

LER Fit range: 0.19 – 2.93 MeV (Low Energy Region: pp, pep and ^{7}Be ν).

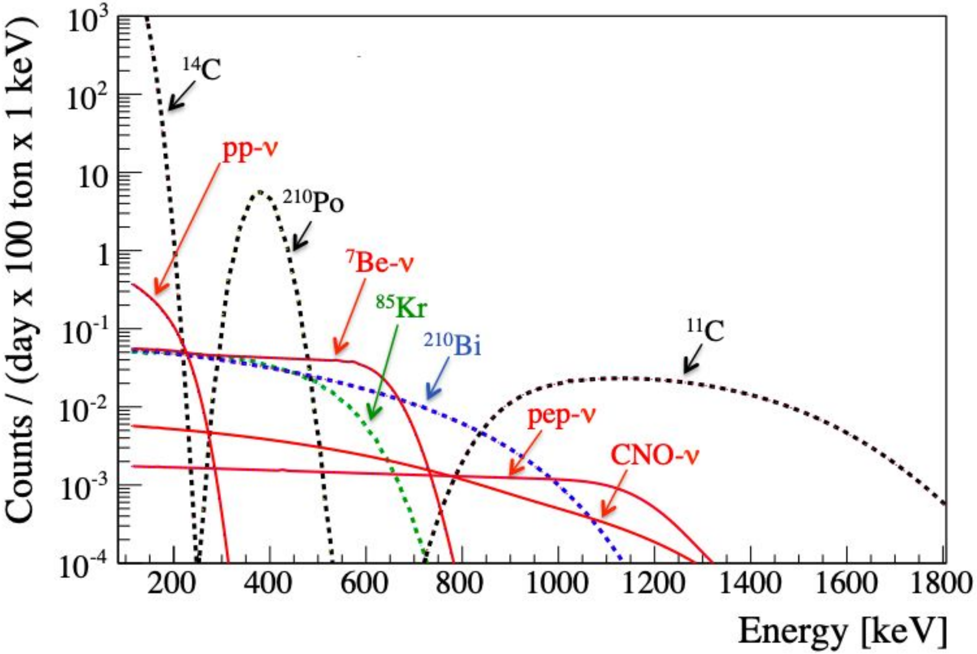
Software cuts: 1) Removing muons
2) Selecting a fiducial volume (r < 2.8 m, −1.8 m < z < 2.2 m)
3) Tagging/Subtracting ^{11}C background

THE PP-CHAIN SOLAR-ν MEASUREMENT (2)

Nature 562 (2018) 505; Physical Review D 100, 082004 (2019)

Main LER background sources:

- ^{14}**C**: irreducible background in any organic scintillator;
- ^{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;
- **pile-up** of events (mainly ^{14}C-^{14}C);



THE PP-CHAIN SOLAR-ν MEASUREMENT (3)

Nature 562 (2018) 505; Physical Review D 100, 082004 (2019)

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.

Two complementary fit methods

Analytical fit

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

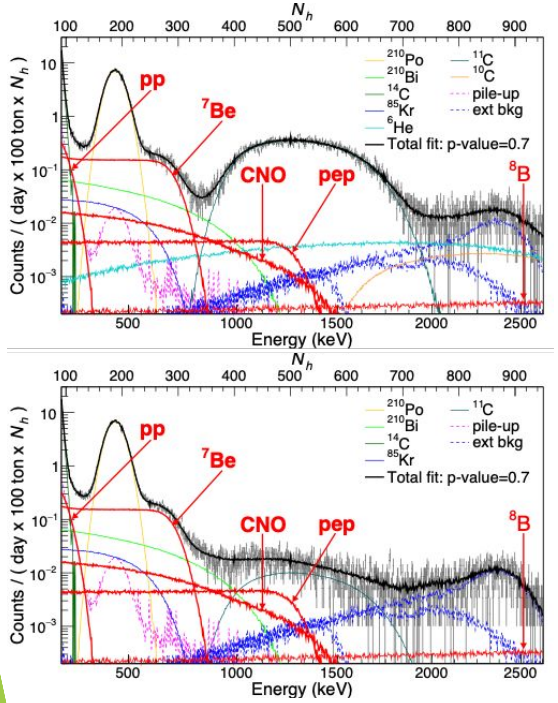
Monte Carlo fit

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

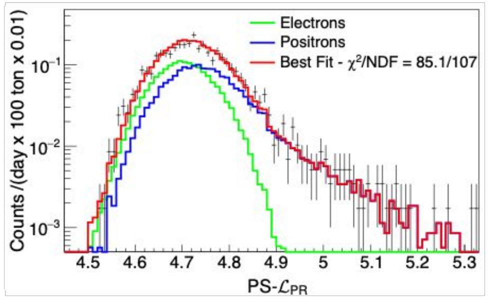
THE PP-CHAIN SOLAR-ν MEASUREMENT (4)

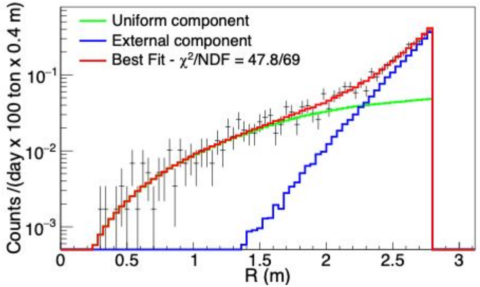
Nature 562 (2018) 505; Physical Review D 100, 082004 (2019)

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



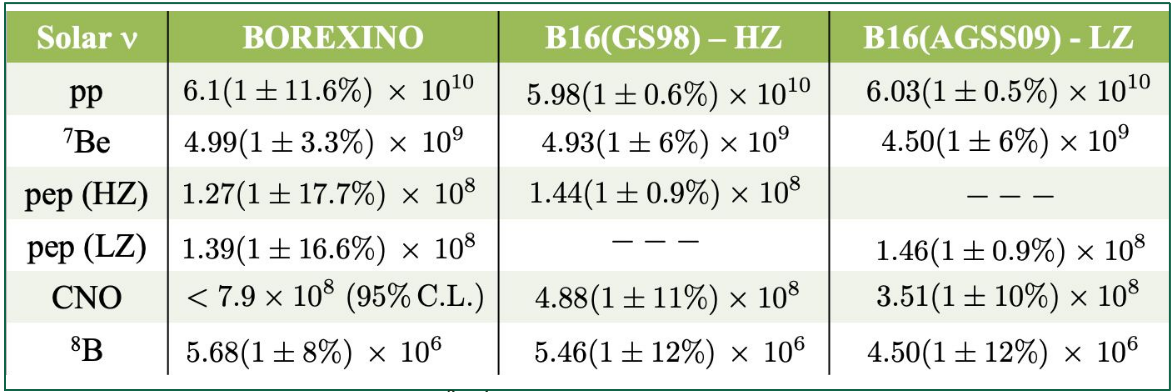
1. Energy spectra (TFC-tagged and TFC subtracted);
2. e^-/e^+ pulse-shape distribution PS-L_{PR};
3. Radial distribution.





THE PP-CHAIN SOLAR-ν MEASUREMENT (5)

Nature 562 (2018) 505; Physical Review D 100, 082004 (2019)



Solar ν	BOREXINO	B16(GS98) – HZ	B16(AGSS09) - LZ
pp	$6.1(1 \pm 11.6\%) \times 10^{10}$	$5.98(1 \pm 0.6\%) \times 10^{10}$	$6.03(1 \pm 0.5\%) \times 10^{10}$
^{7}Be	$4.99(1 \pm 3.3\%) \times 10^{9}$	$4.93(1 \pm 6\%) \times 10^{9}$	$4.50(1 \pm 6\%) \times 10^{9}$
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.)	$4.88(1 \pm 11\%) \times 10^{8}$	$3.51(1 \pm 10\%) \times 10^{8}$
^{8}B	$5.68(1 \pm 8\%) \times 10^{6}$	$5.46(1 \pm 12\%) \times 10^{6}$	$4.50(1 \pm 12\%) \times 10^{6}$

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

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

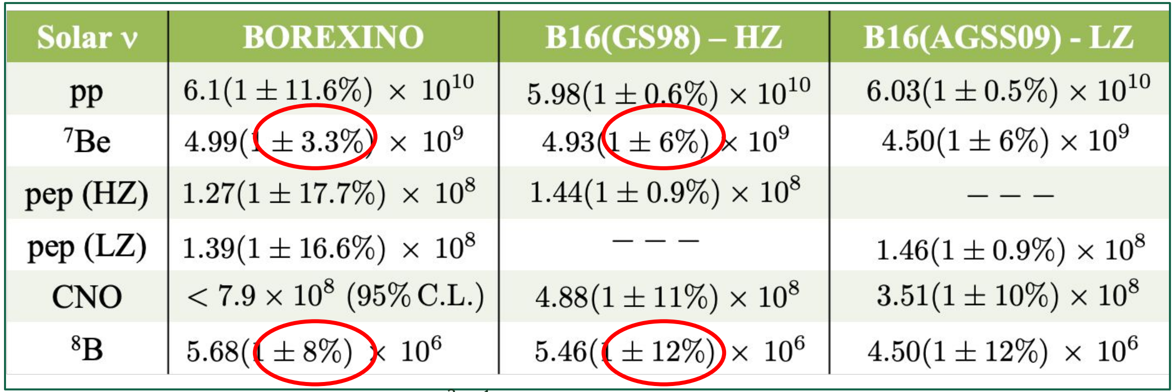
Neutrino oscillation parameters from: *I. Esteban et al., JHEP 01 (2017)*

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

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

THE PP-CHAIN SOLAR-ν MEASUREMENT (5)

Nature 562 (2018) 505; Physical Review D 100, 082004 (2019)



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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.)	$4.88(1 \pm 11\%) \times 10^{8}$	$3.51(1 \pm 10\%) \times 10^{8}$
^{8}B	$5.68(1 \pm 8\%) \times 10^{6}$	$5.46(1 \pm 12\%) \times 10^{6}$	$4.50(1 \pm 12\%) \times 10^{6}$

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

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

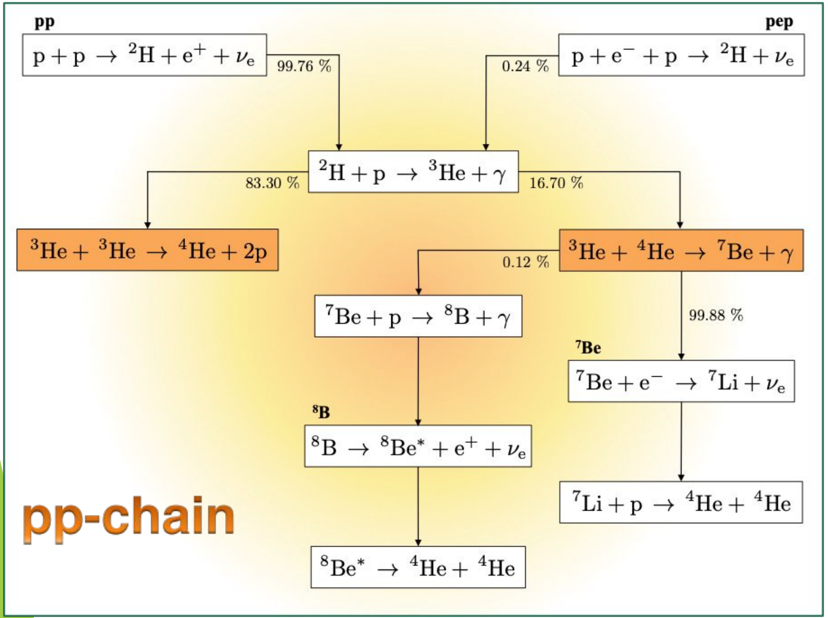
Neutrino oscillation parameters from: *I. Esteban et al., JHEP 01 (2017)*

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

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

THE PP-CHAIN SOLAR-ν MEASUREMENT: ASTROPHYSICAL IMPLICATIONS

Nature 562 (2018) 505; Physical Review D 100, 082004 (2019)



pp

$\mathrm{p + p \rightarrow {}^2H + e^+ + \nu_e}$

99.76 %

pep

$\mathrm{p + e^- + p \rightarrow {}^2H + \nu_e}$

0.24 %

$\mathrm{{}^2H + p \rightarrow {}^3He + \gamma}$

83.30 %

16.70 %

$\mathrm{{}^3He + {}^3He \rightarrow {}^4He + 2p}$

$\mathrm{{}^3He + {}^4He \rightarrow {}^7Be + \gamma}$

0.12 %

99.88 %

$\mathrm{{}^7Be + p \rightarrow {}^8B + \gamma}$

^{7}Be

$\mathrm{{}^7Be + e^- \rightarrow {}^7Li + \nu_e}$

^{8}B

$\mathrm{{}^8B \rightarrow {}^8Be^* + e^+ + \nu_e}$

$\mathrm{{}^7Li + p \rightarrow {}^4He + {}^4He}$

$\mathrm{{}^8Be^* \rightarrow {}^4He + {}^4He}$

pp-chain

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

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

B16-SSM expected values:

R = 0.180 ± 0.011 (HZ)

R = 0.161 ± 0.010 (LZ)

Borexino result:

$R = 0.178^{+0.027}_{-0.023}$

THE PP-CHAIN SOLAR-ν MEASUREMENT: ASTROPHYSICAL IMPLICATIONS (2)

Nature 562 (2018) 505; Physical Review D 100, 082004 (2019)


https://geographical.co.uk

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

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

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

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

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).

THE PP-CHAIN SOLAR-ν MEASUREMENT: ASTROPHYSICAL IMPLICATIONS (3)

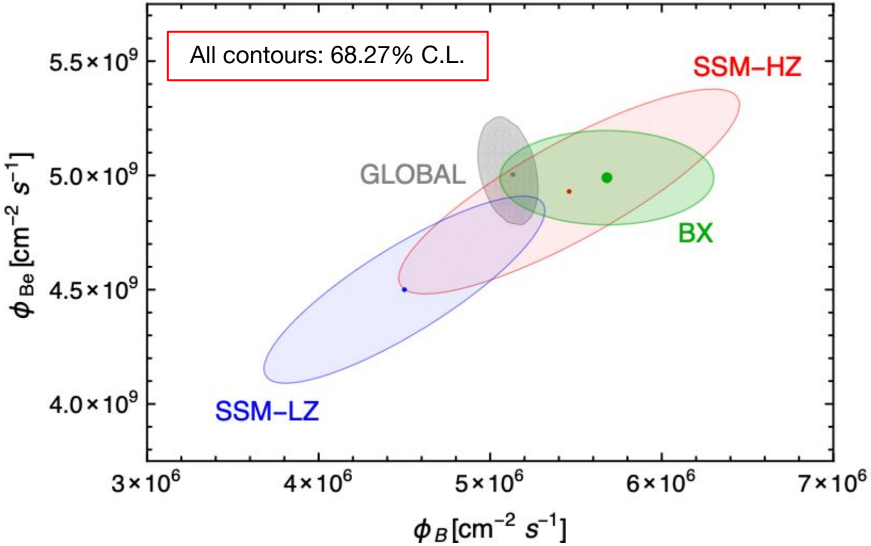
Nature 562 (2018) 505; Physical Review D 100, 082004 (2019)

The Metallicity Puzzle

The Borexino combined results on ^{7}Be and ^{8}B 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.

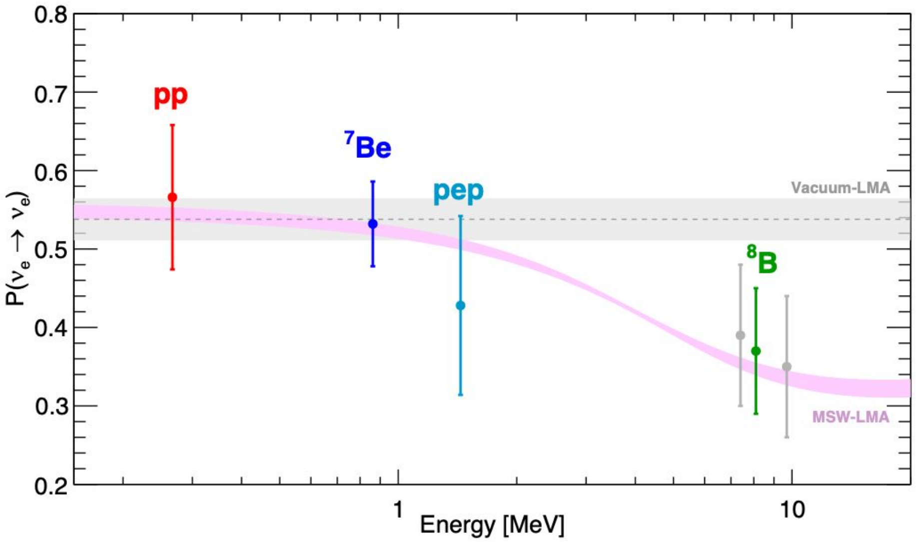


Global analysis performed over BX+SNO+SK+KL data, assuming SSM solar-ν fluxes from *N. Vinyoles et al., Astrophys. Journal 835:202 (2017)* and neutrino oscillation parameters from *I. Esteban et al., JHEP 01 (2017).*

The pp-chain solar-ν measurement: Neutrino Physics implication

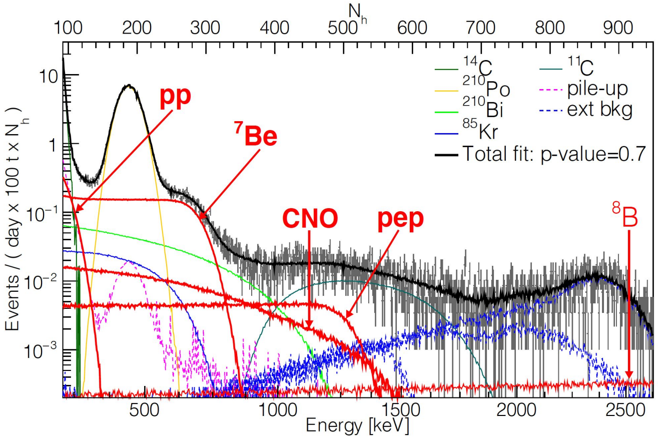
Nature 562 (2018) 505; Physical Review D 100, 082004 (2019)

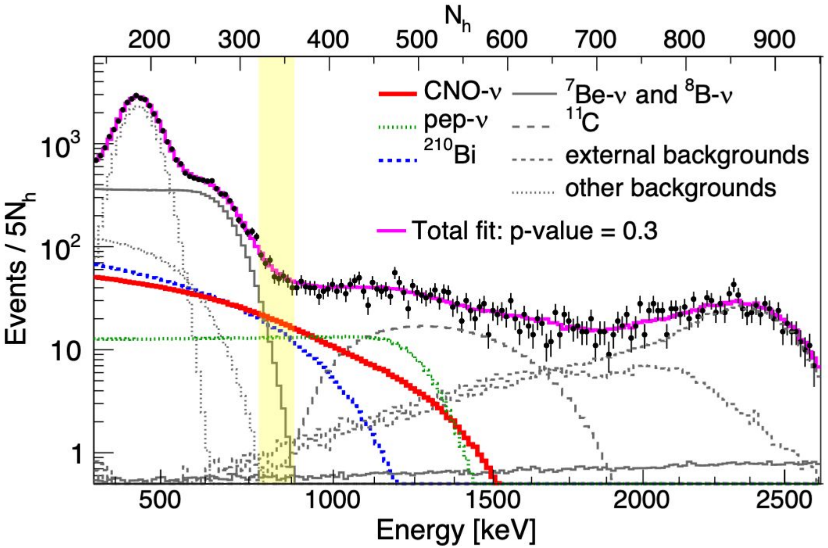
Studying the Sun with neutrinos... and studying neutrinos with the Sun:
testing the MSW-LMA scenario



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).*

FROM THE PP-CHAIN MEASUREMENT…
… TO THE CNO-CYCLE MEASUREMENT

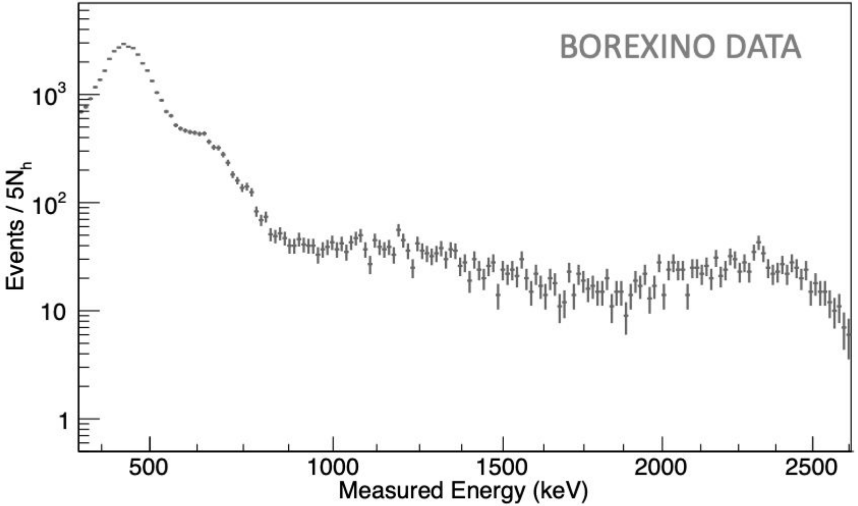




"Experimental evidence of neutrinos produced in the CNO fusion cycle in the Sun", ***Nature* 587 (2020) 577**

How to extract the CNO-ν signal?

Nature 587 (2020) 577



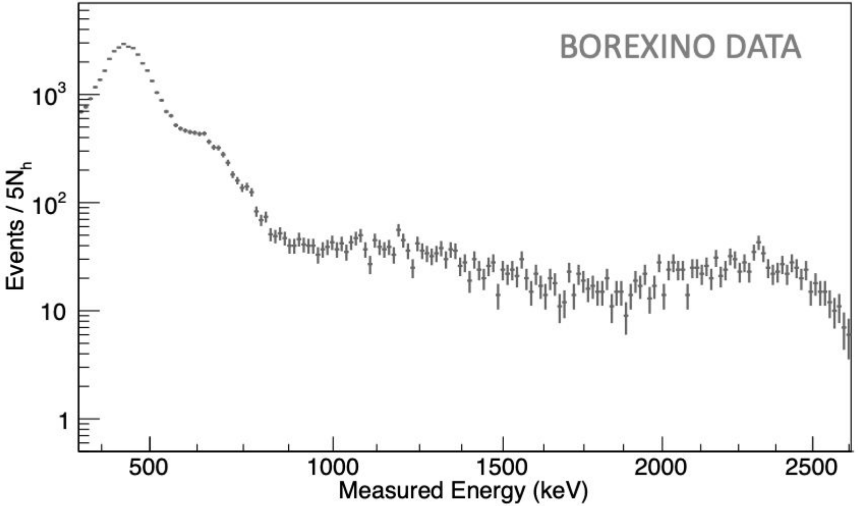
Data-set: Phase-III (July 2016 - February 2020) --> Exposure: 1072 days x 71.3 t

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?

Nature 587 (2020) 577



Where are CNO neutrinos?

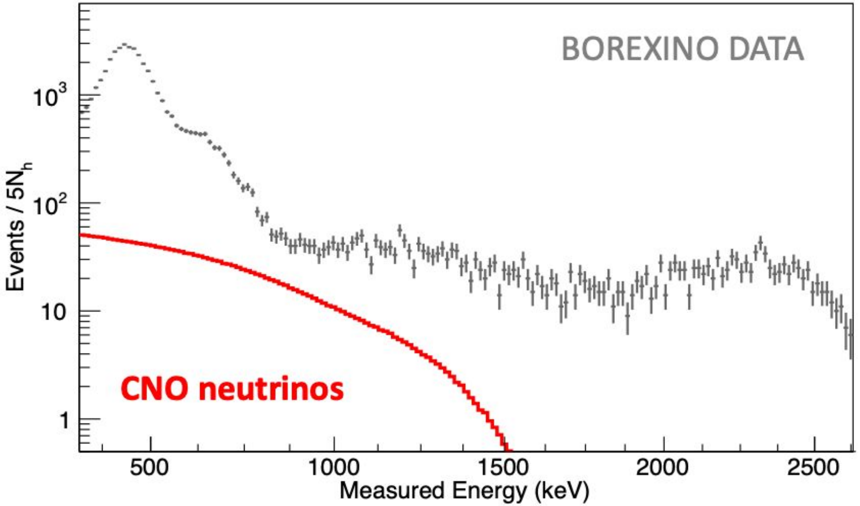
Data-set: Phase-III (July 2016 - February 2020) --> Exposure: 1072 days x 71.3 t

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?

Nature 587 (2020) 577



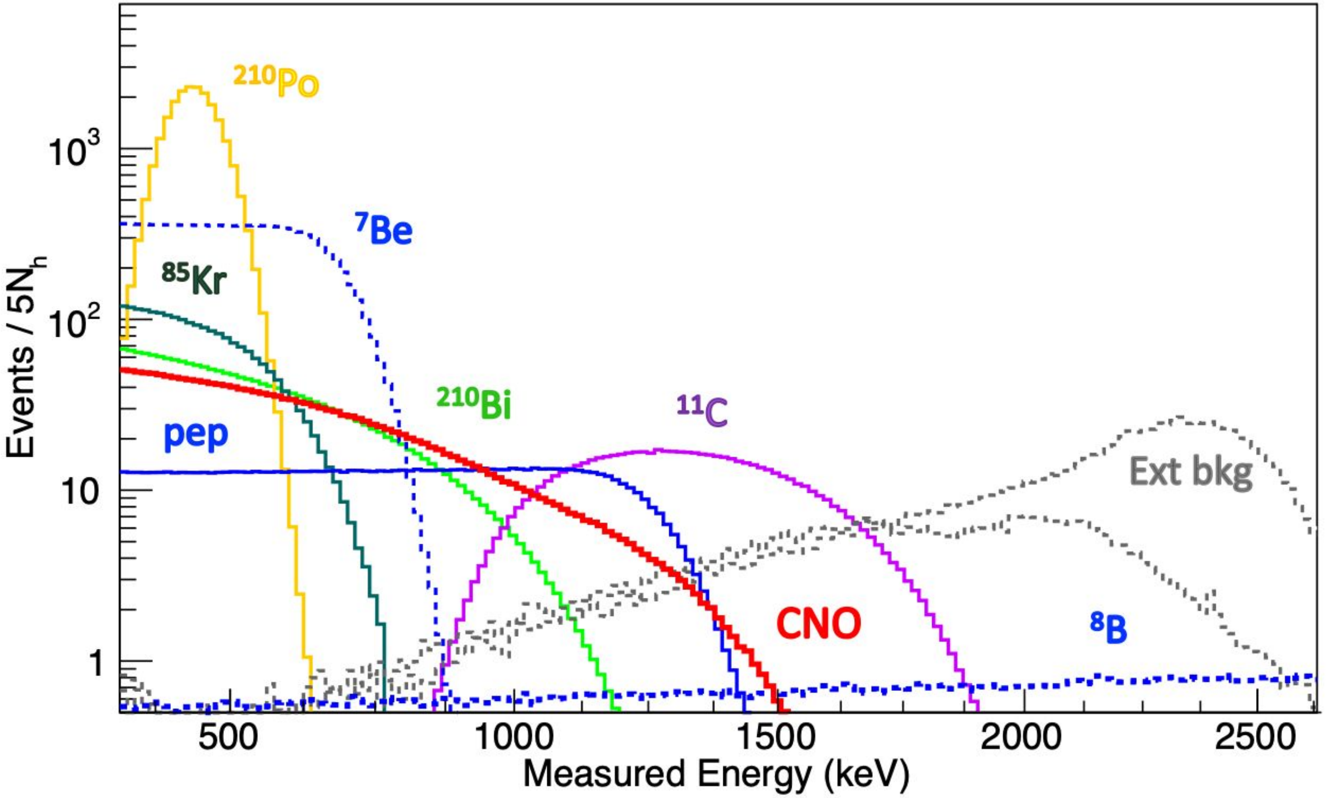
Strategy:

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

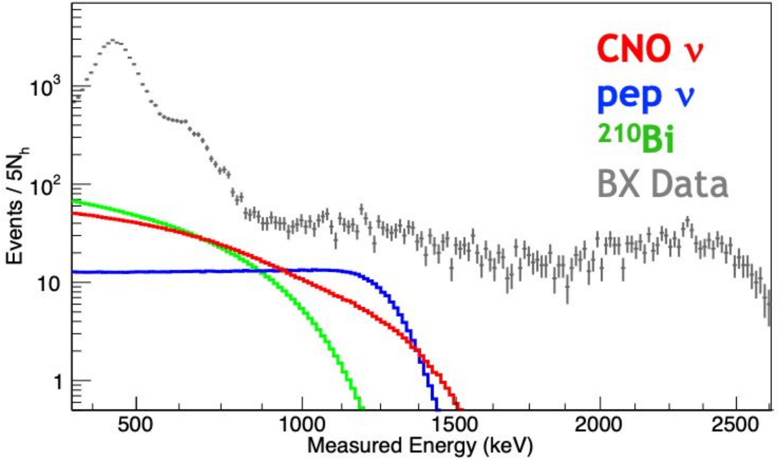
Nature 587 (2020) 577

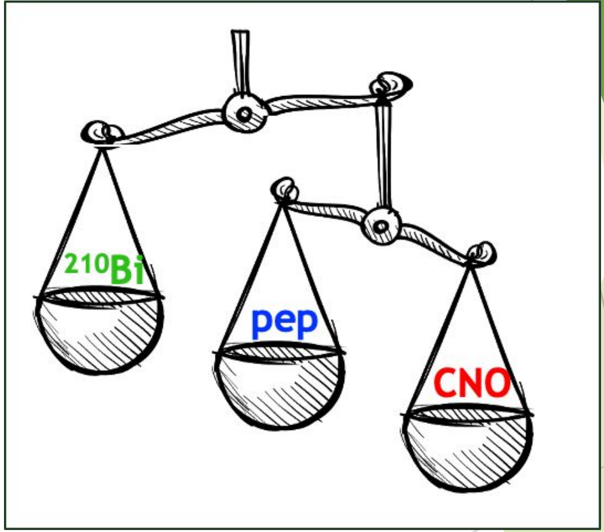


TOWARDS THE CNO-ν MEASUREMENT

Nature 587 (2020) 577

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



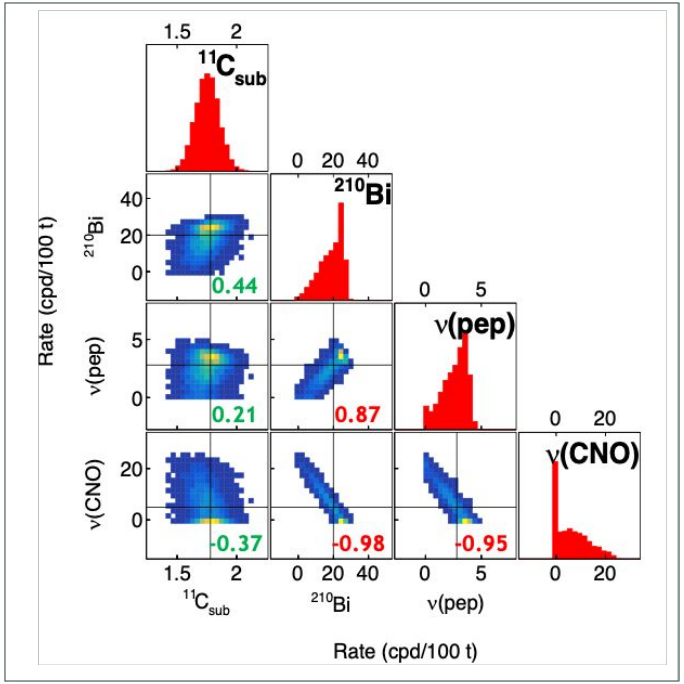


The predicted neutrino rates do not help:

- 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

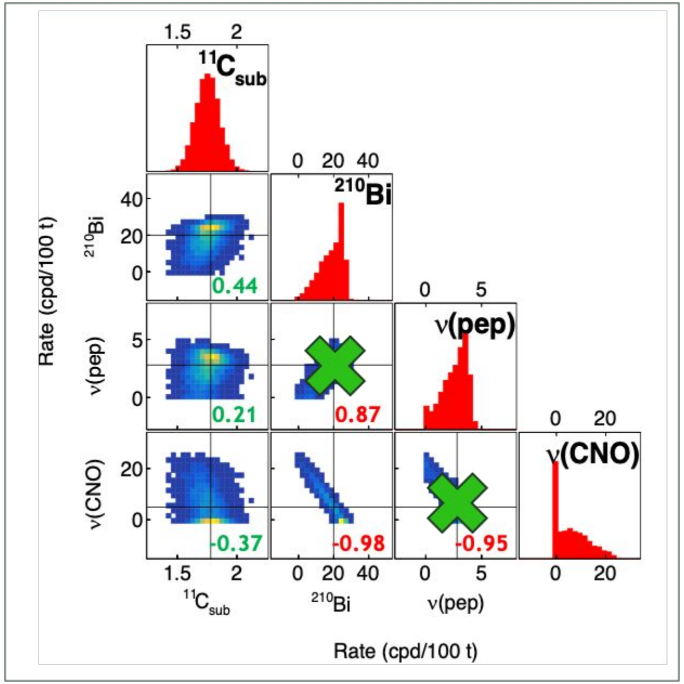
Nature 587 (2020) 577



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

Nature 587 (2020) 577

THE PP/PEP RATIO CONSTRAINT



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

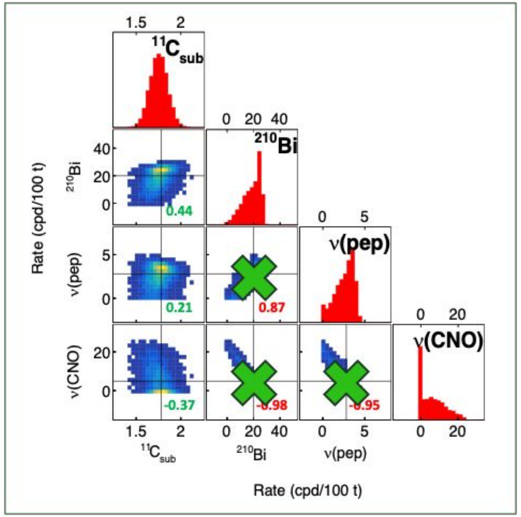
To reduce correlations we put a constraint on the pp/pep ratio following the theoretical predictions as described in *Nature 562 (2018), 505*.

THE BISMUTH-210 CONSTRAINT

Nature 587 (2020) 577

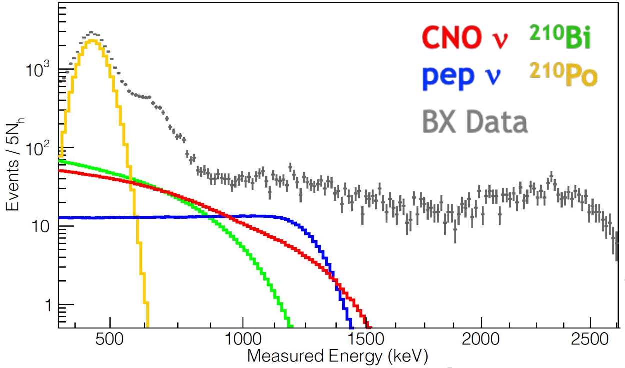
The ^{210}Bi spectrum is still quasi-degenerate with the CNO neutrino one…..
…. But the ^{210}Bi rate can be constrained by precisely (and indipendently) mapping the ^{210}Po rate!

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



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

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



TOWARDS THE CNO-ν MEASUREMENT (2)

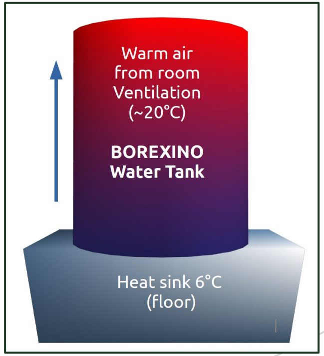
Unluckily, life is not that easy.

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 prevents convective motions



THE DETECTOR THERMAL INSULATION

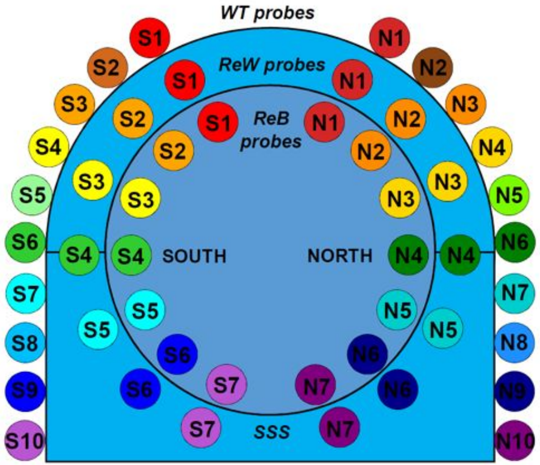
The Borexino detector is covered with a 20cm-thick layer of rock wool

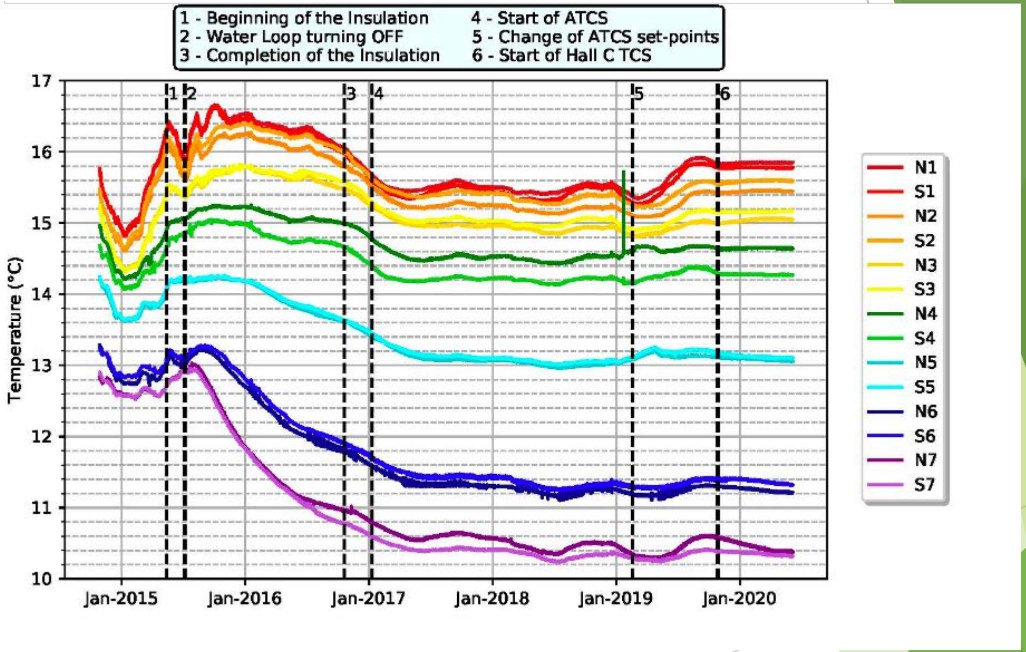
Before the thermal insulation
(Mid 2015)

After the thermal insulation
(Early 2016)

THE DETECTOR THERMAL INSULATION (2)

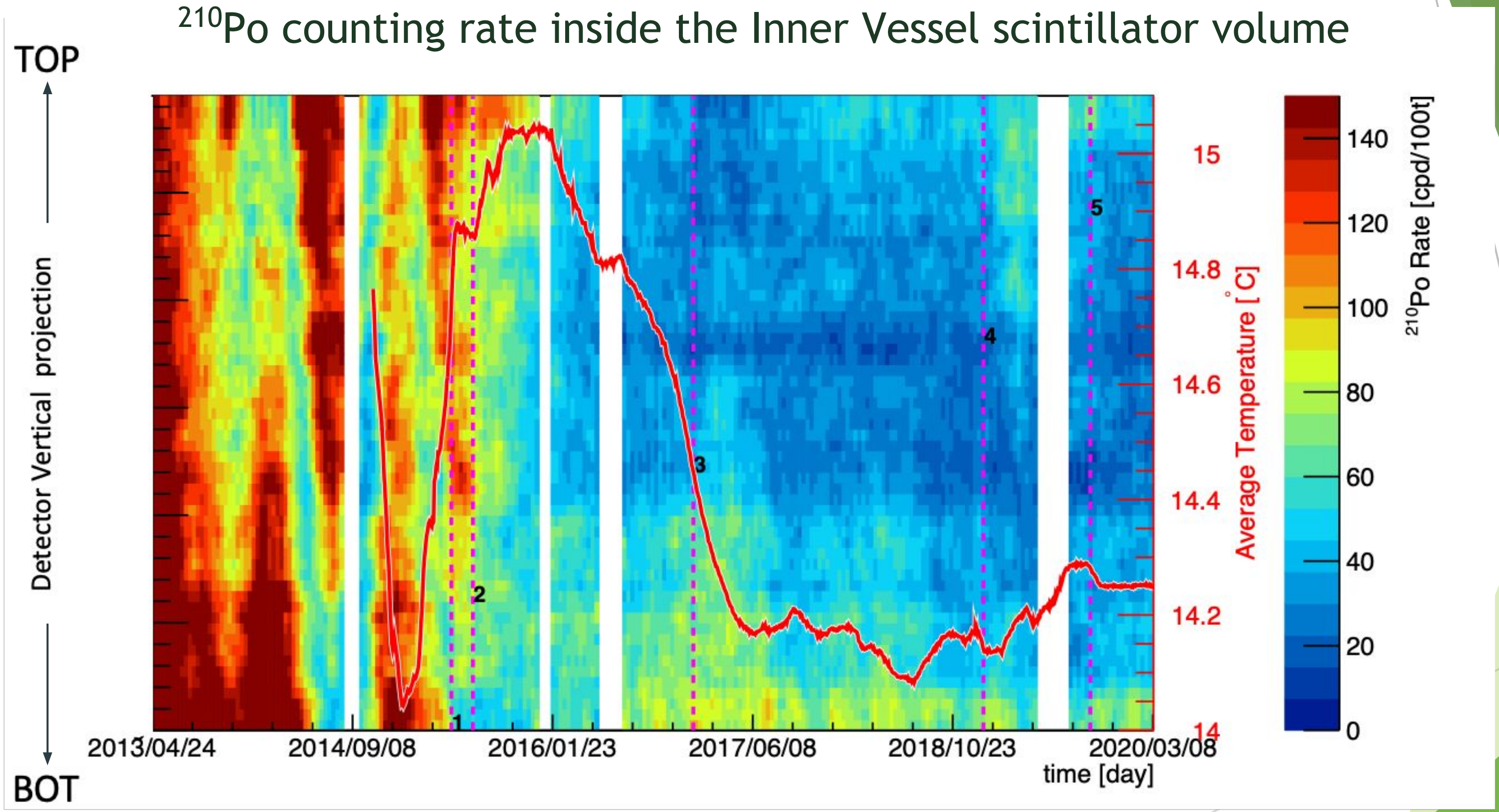
The Active Temperature Control System (ATCS)





EFFECTS ON POLONIUM-210

Nature 587 (2020) 577



THE LOW POLONIUM FIELD: LPOF

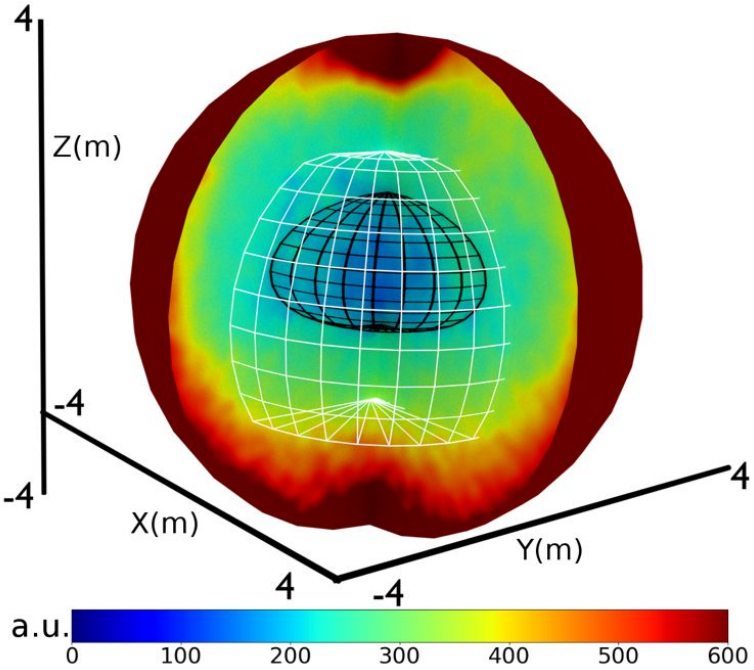
Nature 587 (2020) 577

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!

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



BISMUTH-210 UNIFORMITY

Nature 587 (2020) 577

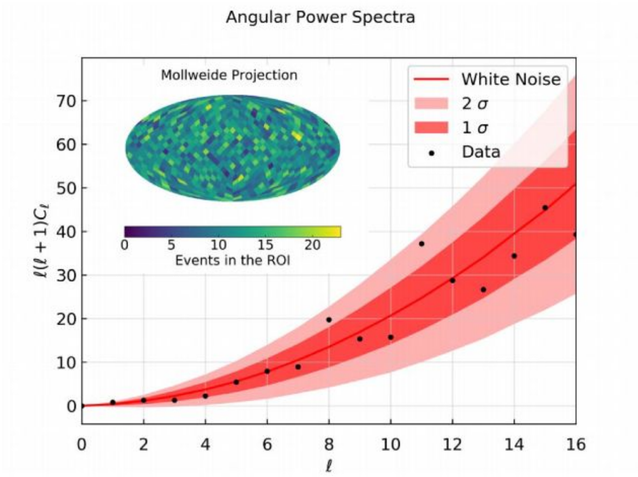
The ^{210}Bi upper limit can be extended over the full FV **<u>if and only</u>** ^{210}Bi is uniform both in the angular and radial distributions: it is found uniform within error!

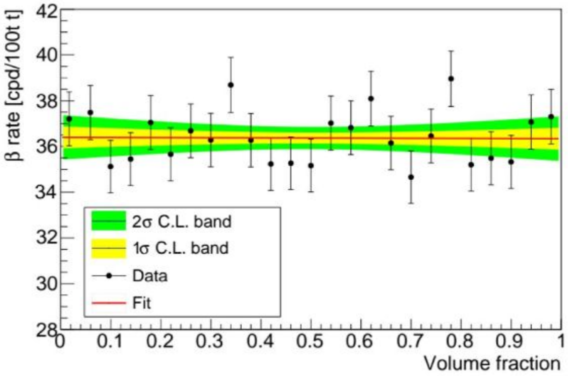
Systematic uncertainty: 0.78 cpd/100 t

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

Final constraint on ^{210}Bi:

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

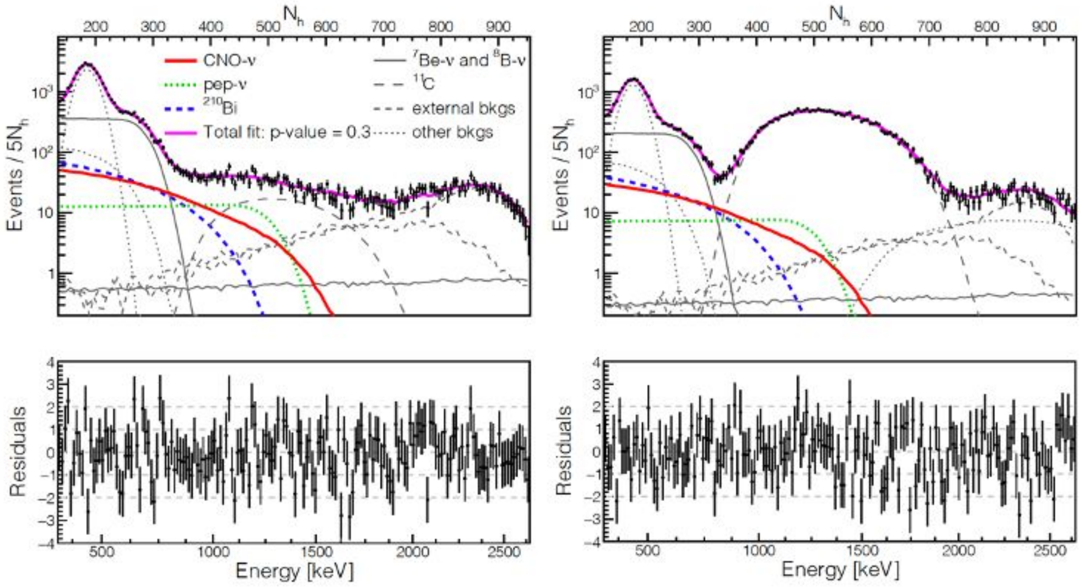




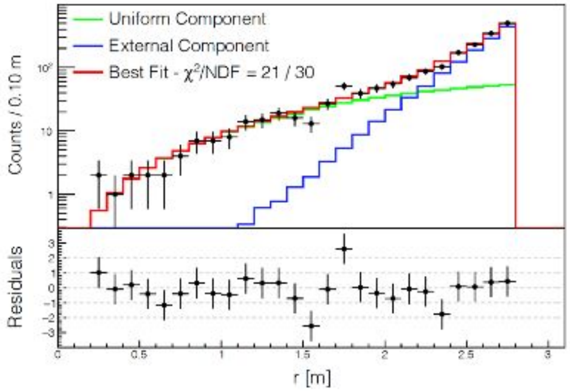
Nature 587 (2020) 577

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.

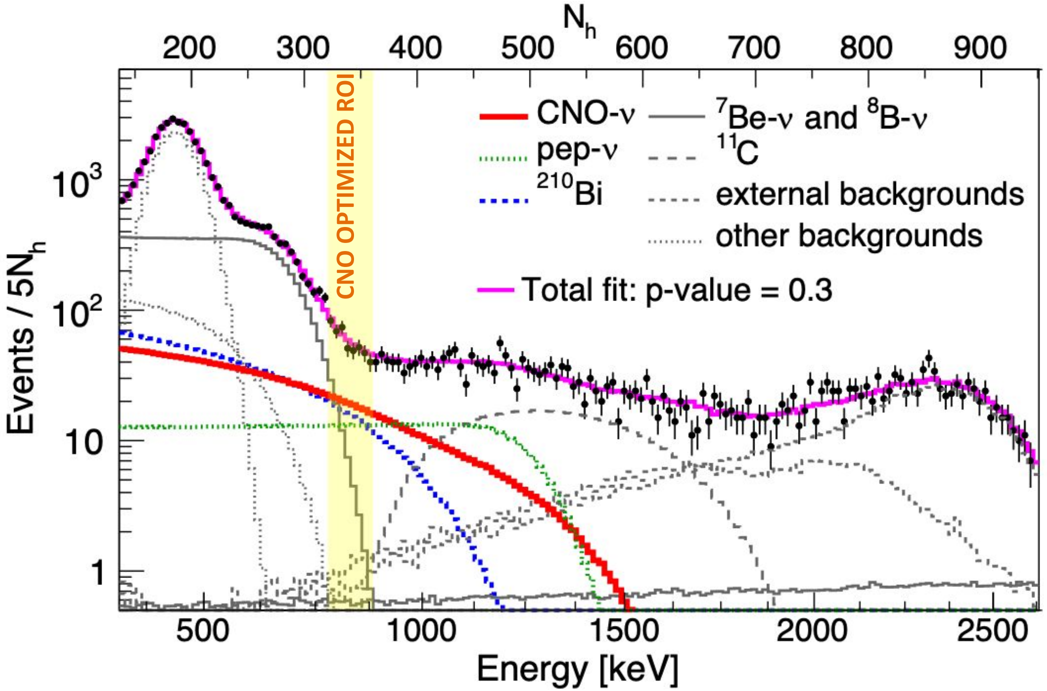


$$\mathcal{L}_{\mathrm{MV}} = \mathcal{L}_{^{11}\mathrm{C_{sub}}} \cdot \mathcal{L}_{^{11}\mathrm{C_{tag}}} \cdot \mathcal{L}_{\mathrm{rad}}$$



THE CNO MEASUREMENT: RESULTS

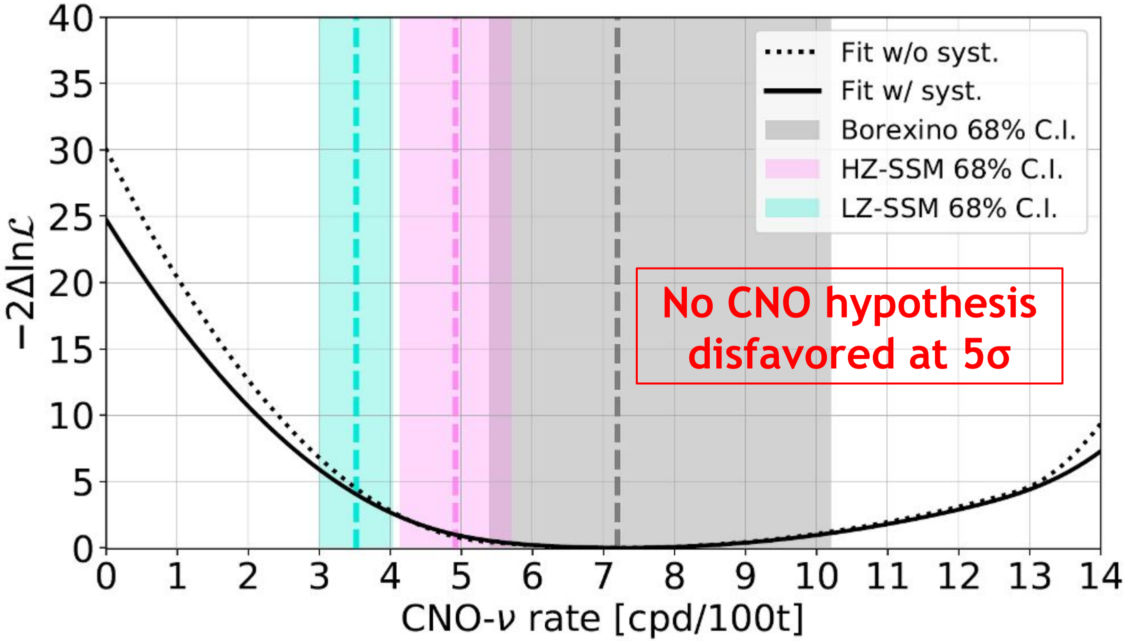
Nature 587 (2020) 577



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

THE CNO MEASUREMENT: RESULTS (2)

Nature 587 (2020) 577



No CNO hypothesis disfavored at 5σ

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

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

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.

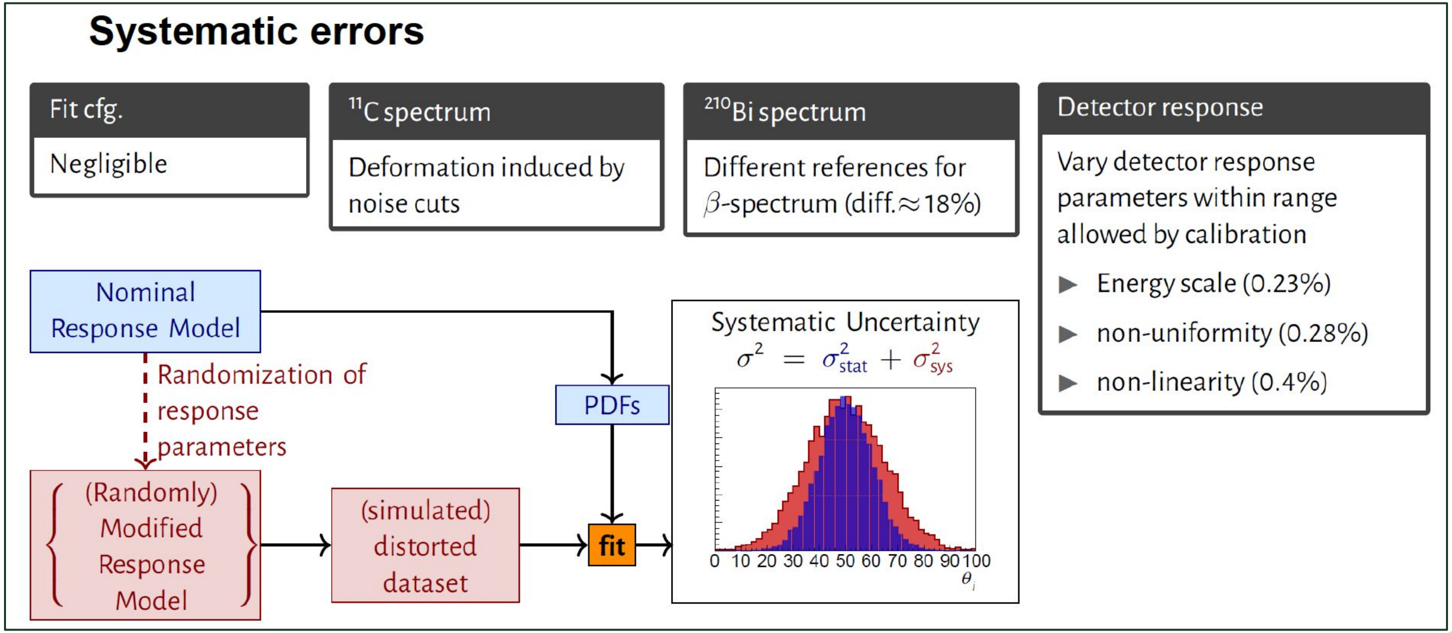
Borexino has mapped out the entire pp solar fusion chain with high precision and it has demonstrated the existence of CNO solar neutrinos for the first time (significance 5σ).

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 ^{7}Be and ^{8}B ν 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%)

Nominal Response Model

Randomization of response parameters

(Randomly) Modified Response Model

(simulated) distorted dataset

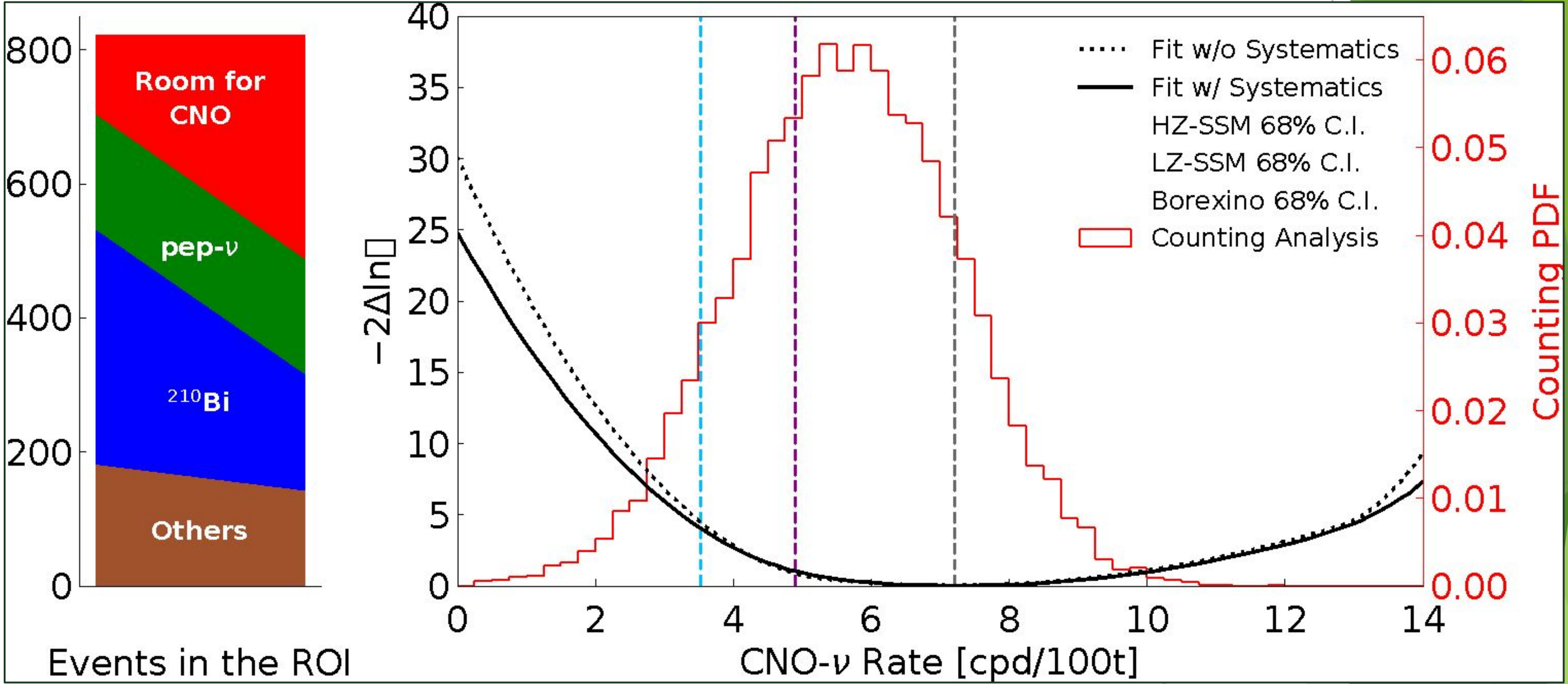
PDFs

fit

Systematic Uncertainty

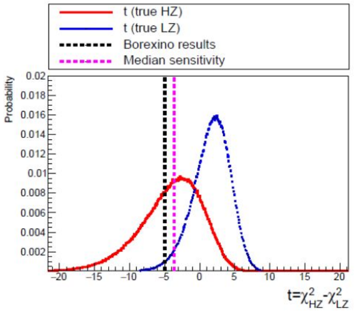
$$\sigma^2 = \sigma^2_{\text{stat}} + \sigma^2_{\text{sys}}$$

THE CNO MEASUREMENT: RESULTS (3)



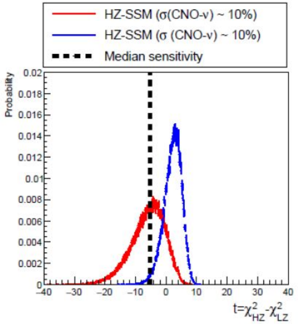
CNO ANALYSIS: LZ/HZ DISCRIMINATION

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



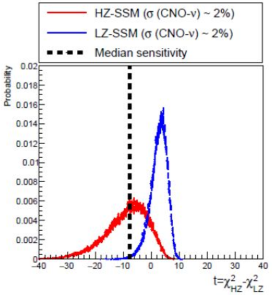
Esclusion of LZ at ~2.1 σ

FUTURE hypothetical result on CNO at 10% error



Esclusion of LZ at ~2.2 σ

FUTURE hypothetical result on CNO at 2% error



Esclusion of LZ at ~2.6 σ

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

^{7}BE-N FLUX SEASONAL MODULATIONS

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:

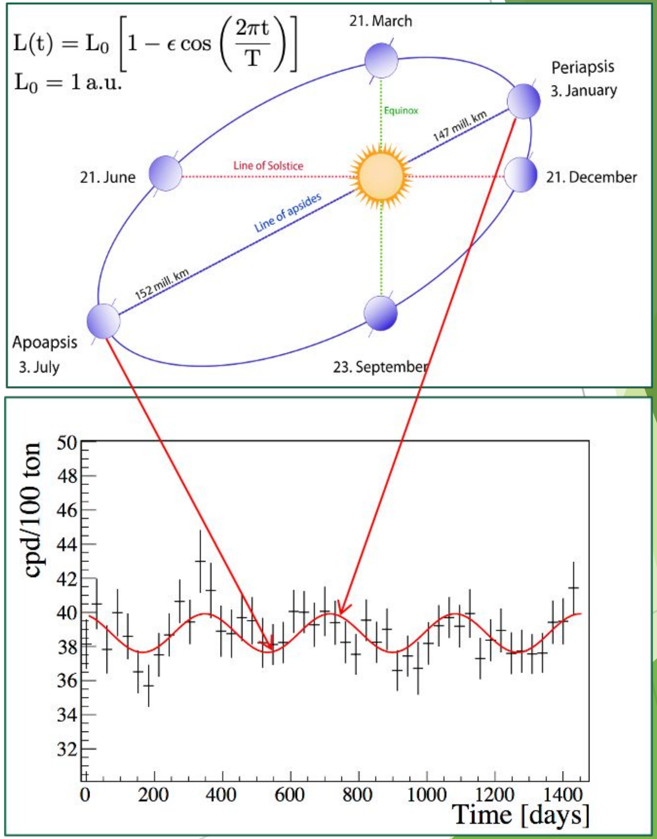
- T = 365.256 d
- ε = 0.0167

Different Data Analysis Method:

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

<u>**Borexino results**</u>:

- T = 367 ± 10 d
- ε = 0.0174 ± 0.0045



^{7}BE-N FLUX SEASONAL MODULATIONS

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Astronomical observations:

- T = 365.256 d
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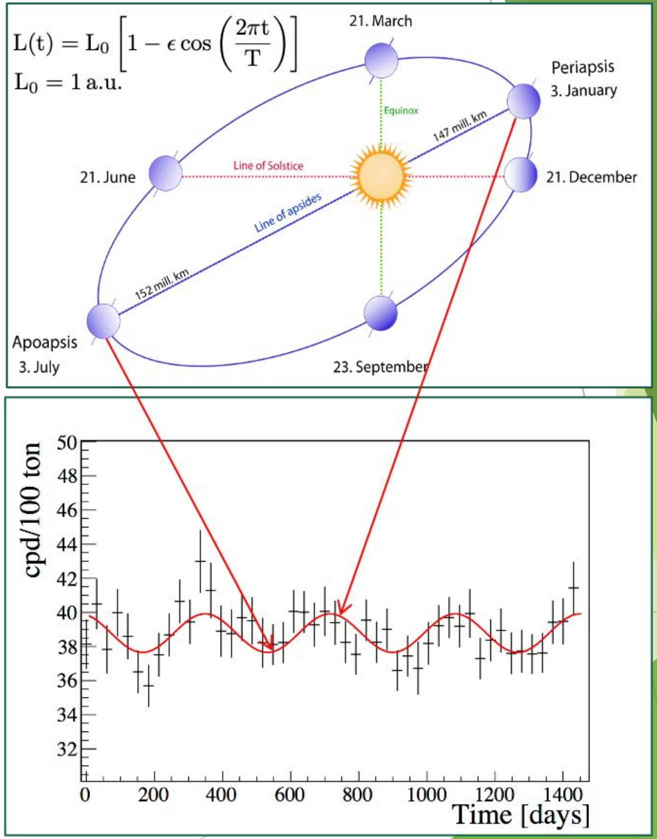
Borexino results:

- T = 367 ± 10 d
- **ε** = 0.0174 ± 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}Be neutrinos!**



$$L(t) = L_0 \left[1 - \epsilon \cos\left(\frac{2\pi t}{T}\right)\right]$$

$$L_0 = 1\,\mathrm{a.u.}$$

THE PP-CHAIN SOLAR-ν MEASUREMENT

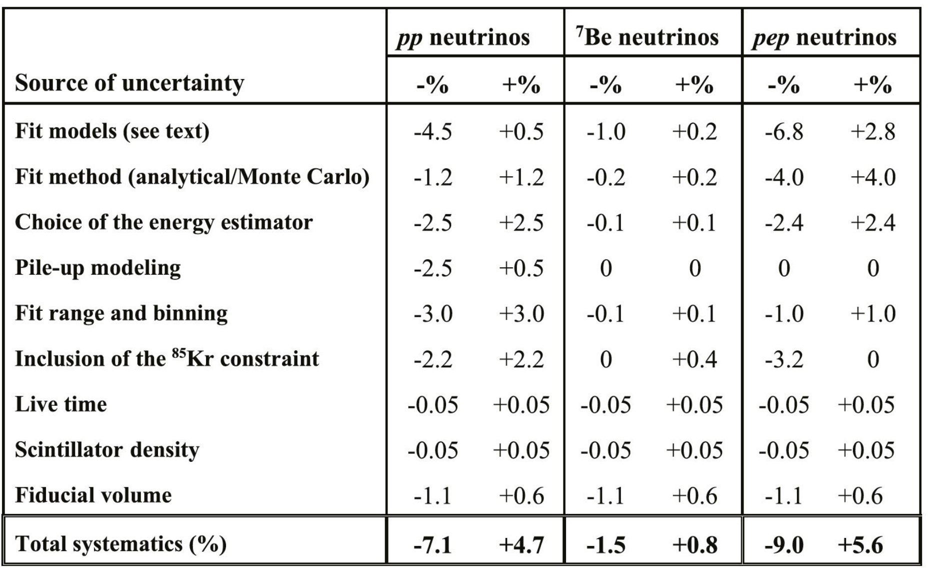
Nature 562 (2018) 505; Physical Review D 100, 082004 (2019)

LER ANALYSIS - SYSTEMATIC ERRORS

Two methods to take into account pile-up

Effects of non perfect modelling of the detector response;

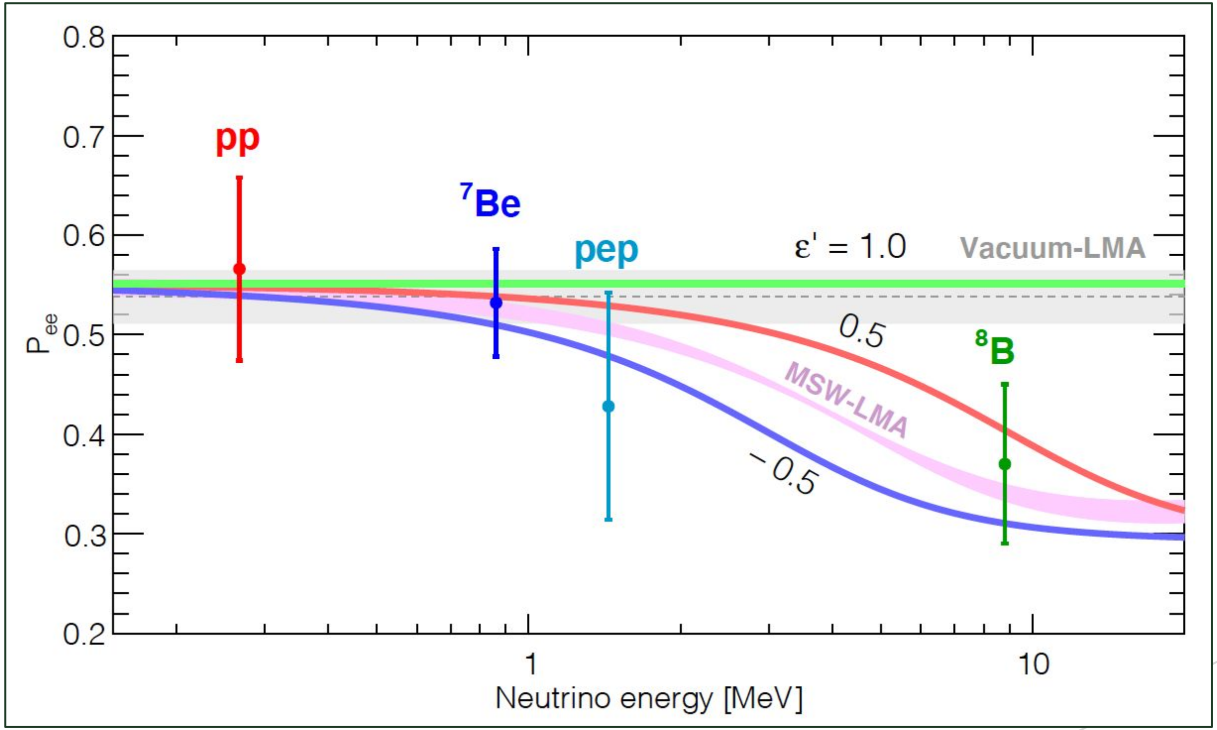
^{85}Kr constrained to be <7.5cpd/100t (95% C.L.) from Kr-Rb delayed coincidences



Source of uncertainty	*pp* neutrinos		^{7}Be neutrinos		*pep* 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**

NON STANDARD INTERACTION WITH BOREXINO

JHEP 2 (2020) 038



THE PP-CHAIN SOLAR-ν MEASUREMENT

Nature 562 (2018) 505

Main HER analysis features:

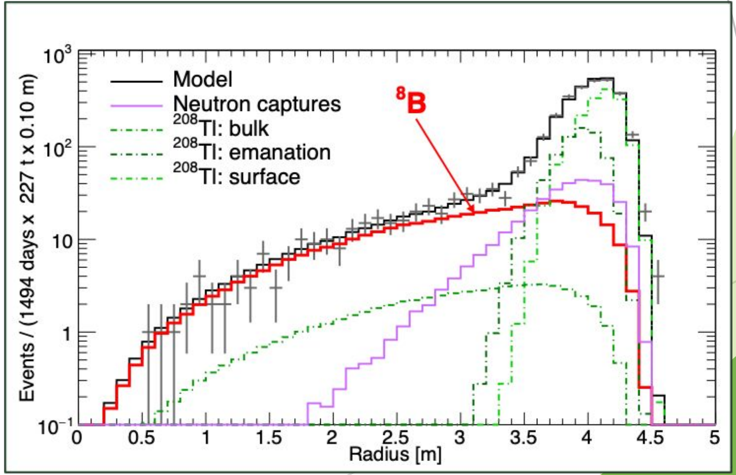
- Data-set: January 2008 - December 2016 (purification period excluded);
- Fiducial mass: extended to the entire active mass (from ~100 t to 300 t);
- Fit range: 3.2 -16 MeV;
- Total exposure: 1.5 kton x year (11.5-fold increase).

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).



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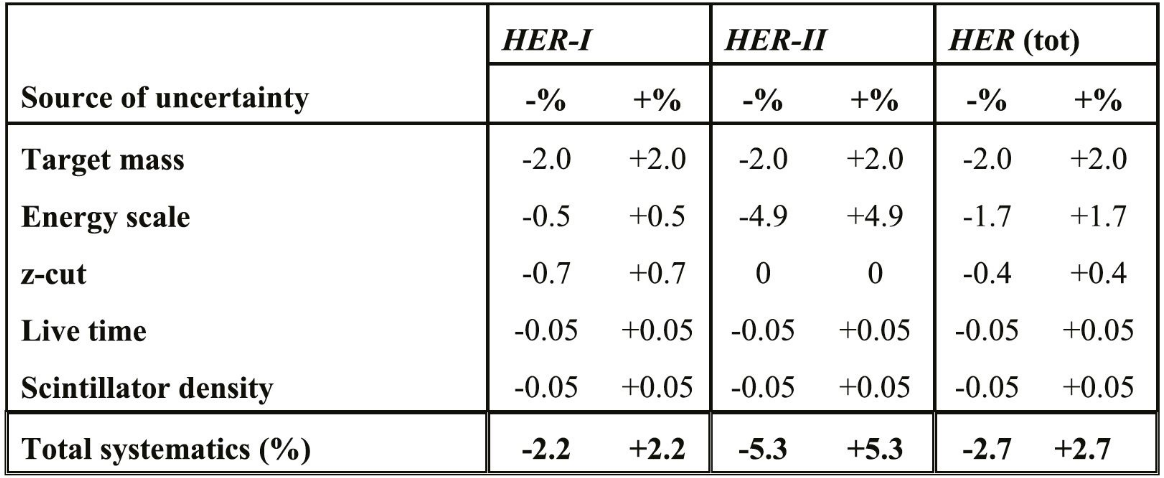
THE PP-CHAIN SOLAR-ν MEASUREMENT

HER ANALYSIS - SYSTEMATIC ERRORS



	HER-I		*HER-II*		*HER* (tot)	
Source of uncertainty	**-%**	**+%**	**-%**	**+%**	**-%**	**+%**
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**