LATEST RESULTS OF THE BOREXINO EXPERIMENT ON SOLAR NEUTRINOS

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ON BEHALF OF THE BOREXINO COLLABORATION

La Thuile 2022 | March 8th, 2022

THE BOREXINO EXPERIMENT

- **Main goal**: the detection of low energies solar neutrinos, in particular ^{7}Be neutrinos.

- **Detection method**: elastic scattering off neutrinos on electrons.

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

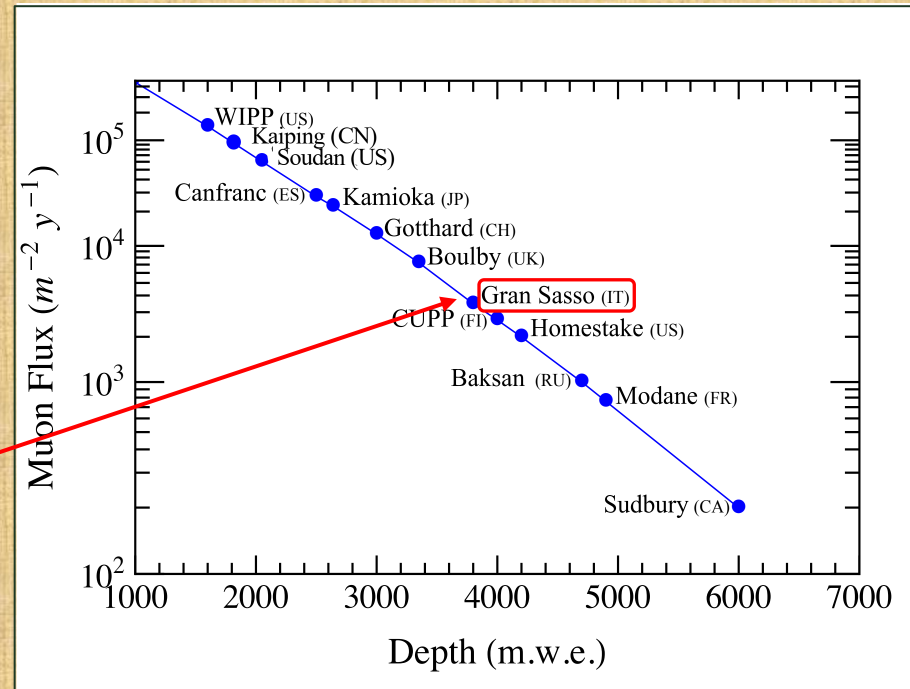
- **Location**: LNGS (Laboratori Nazionali del Gran Sasso)

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

The expected rate of ^{7}Be solar neutrinos in 100 ton of Borexino 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.
Huge effort to achieve extreme high radiopurity levels

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.

$$\Phi(\mu) \sim 1\ \mu/\mathrm{m}^2/\mathrm{h}$$

DETECTOR DESIGN

Scintillator:

280 ton of PC+PPO in a 125 μm thick nylon vessel;

Fiducial mass ~ 100 ton;

Electron density:

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

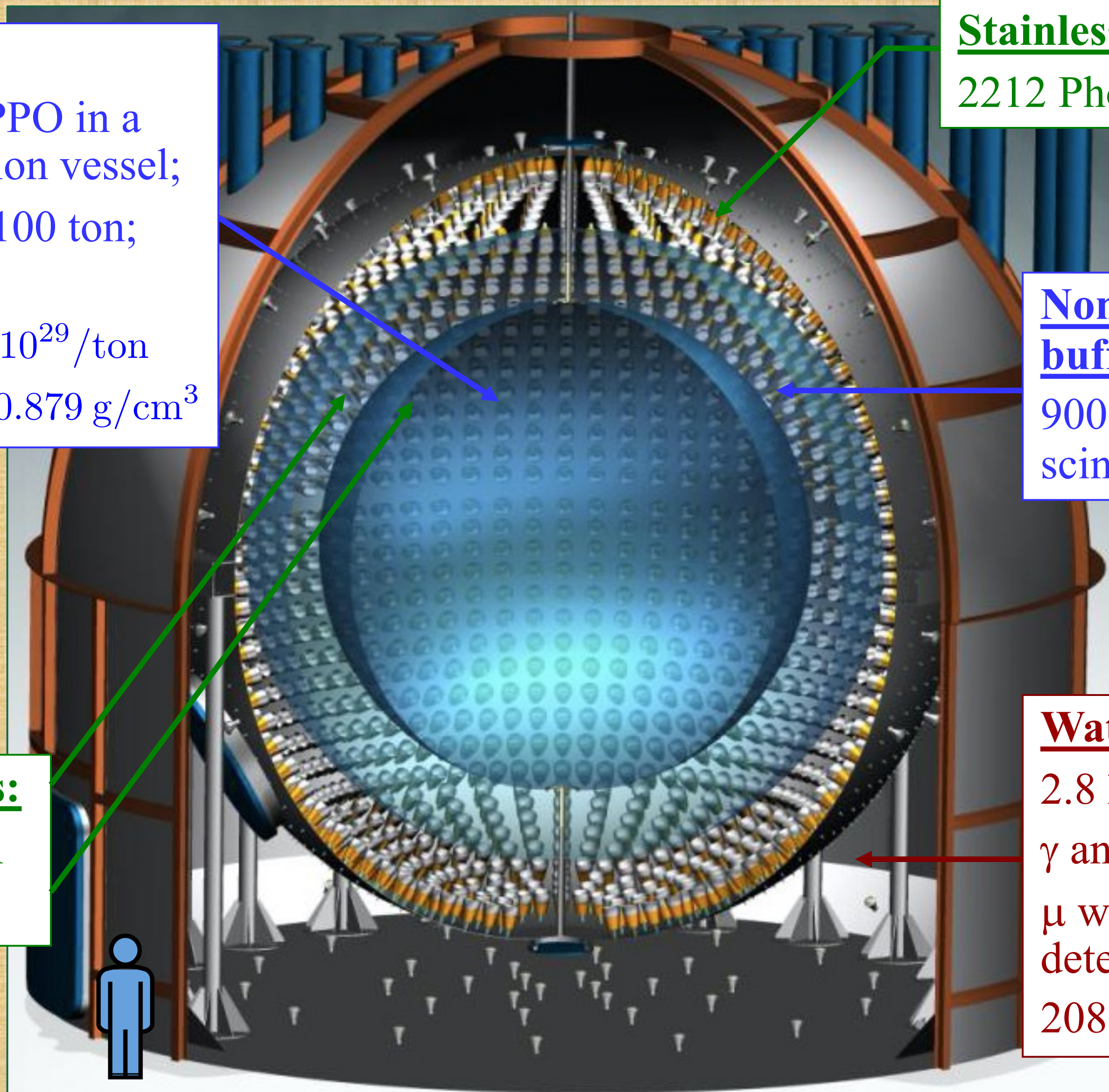
Mass density: $\simeq 0.879\ \text{g/cm}^3$

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 Čerenkov detector

208 PMTs in water

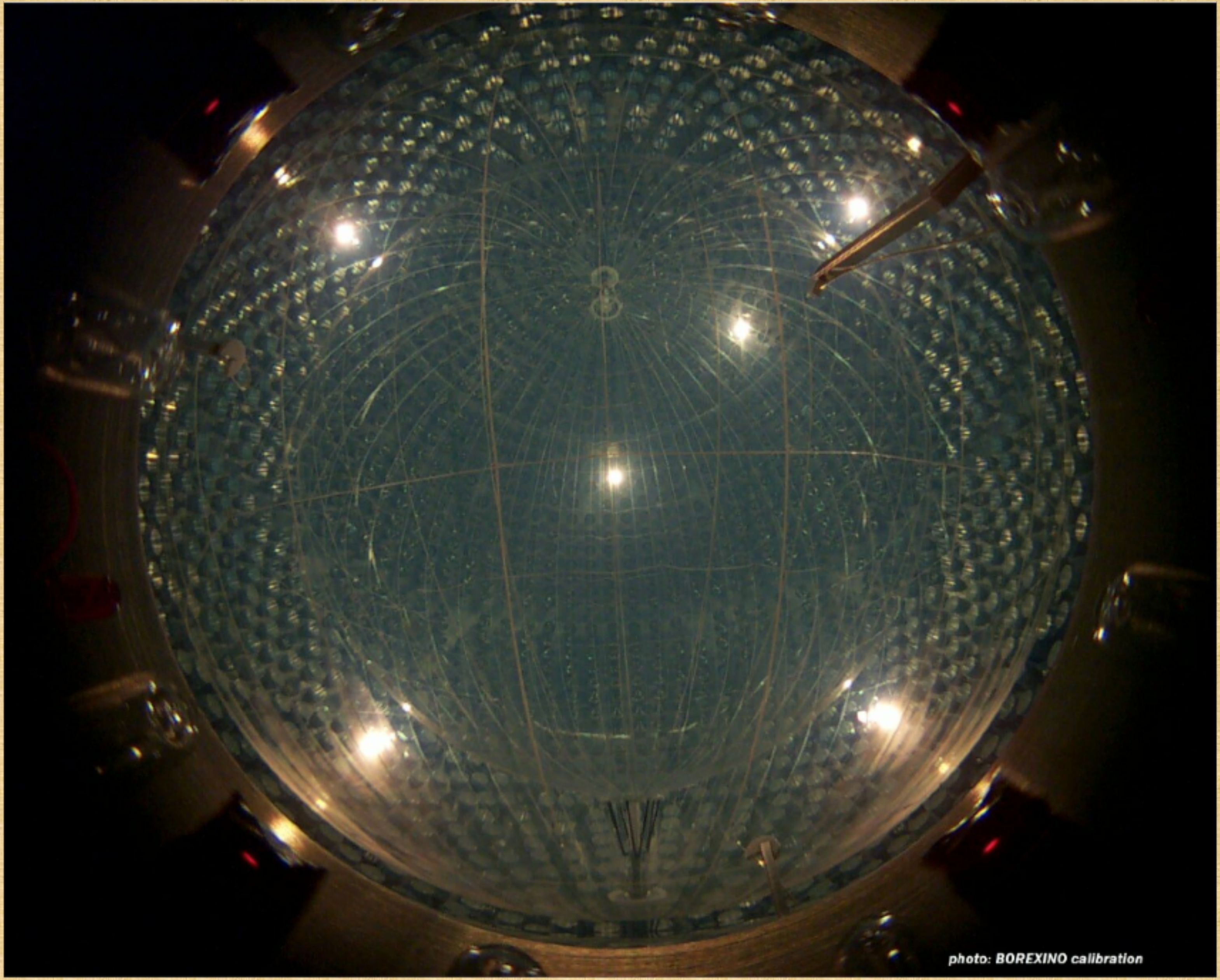


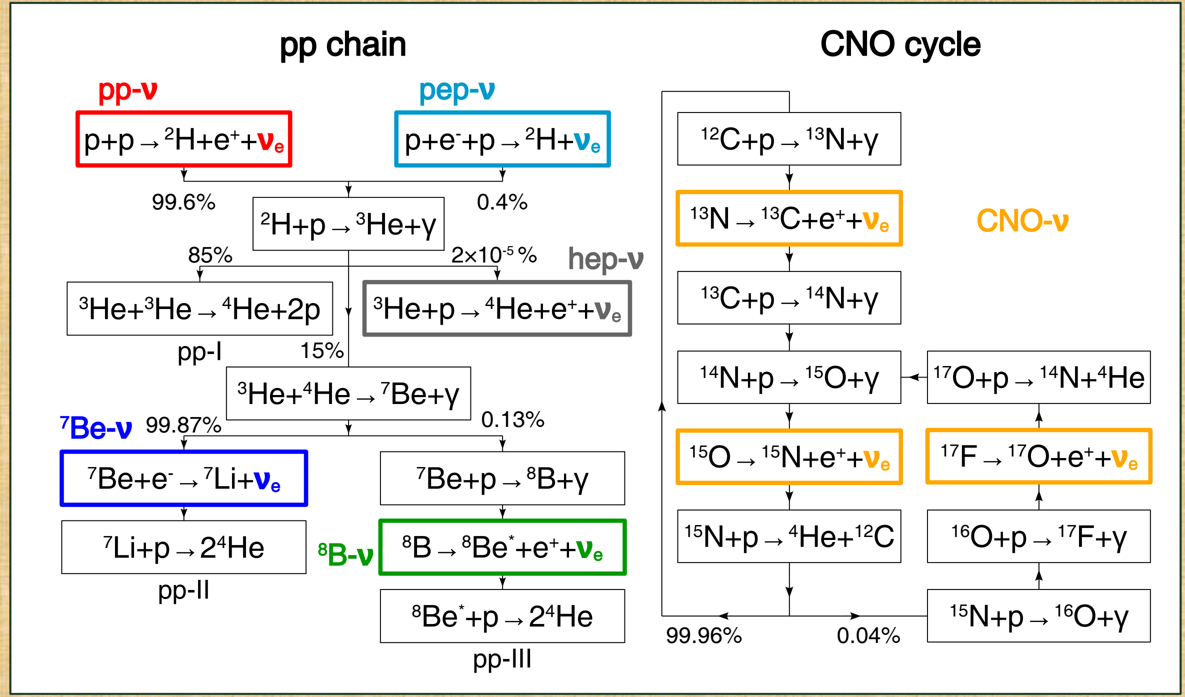
photo: BOREXINO calibration

STUDYING THE SUN WITH NEUTRINOS…

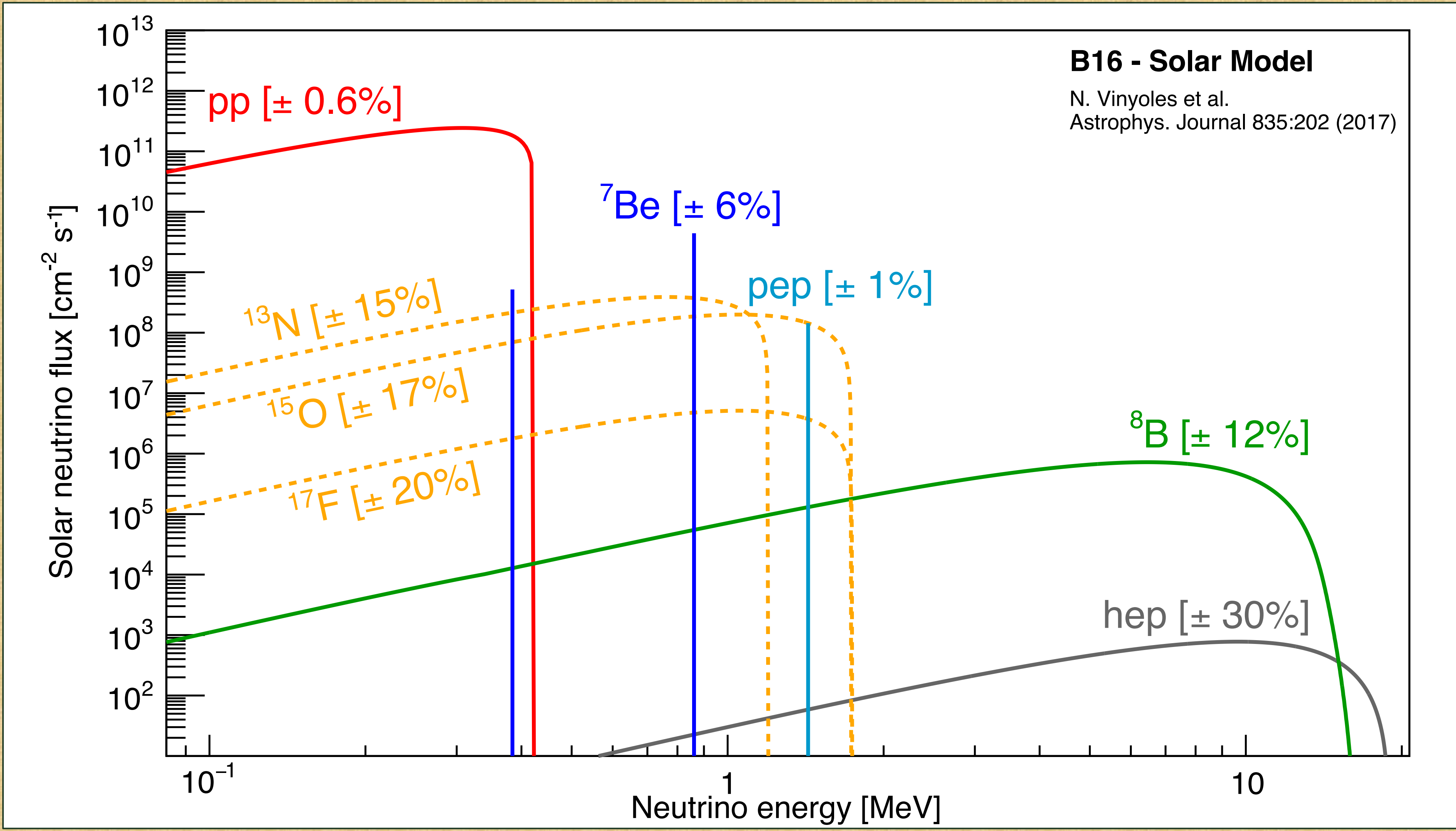
$$4\,\mathrm{p} \rightarrow \alpha + 2\,\mathrm{e}^{+} + 2\,\nu_{\mathrm{e}} \qquad \mathrm{E_{released}} \sim 26\,\mathrm{MeV}$$

-While γ massively interact with the solar plasma and take about 10^5 years to reach our star surface, neutrinos stream out the Sun and take just 8 minutes to reach the Earth

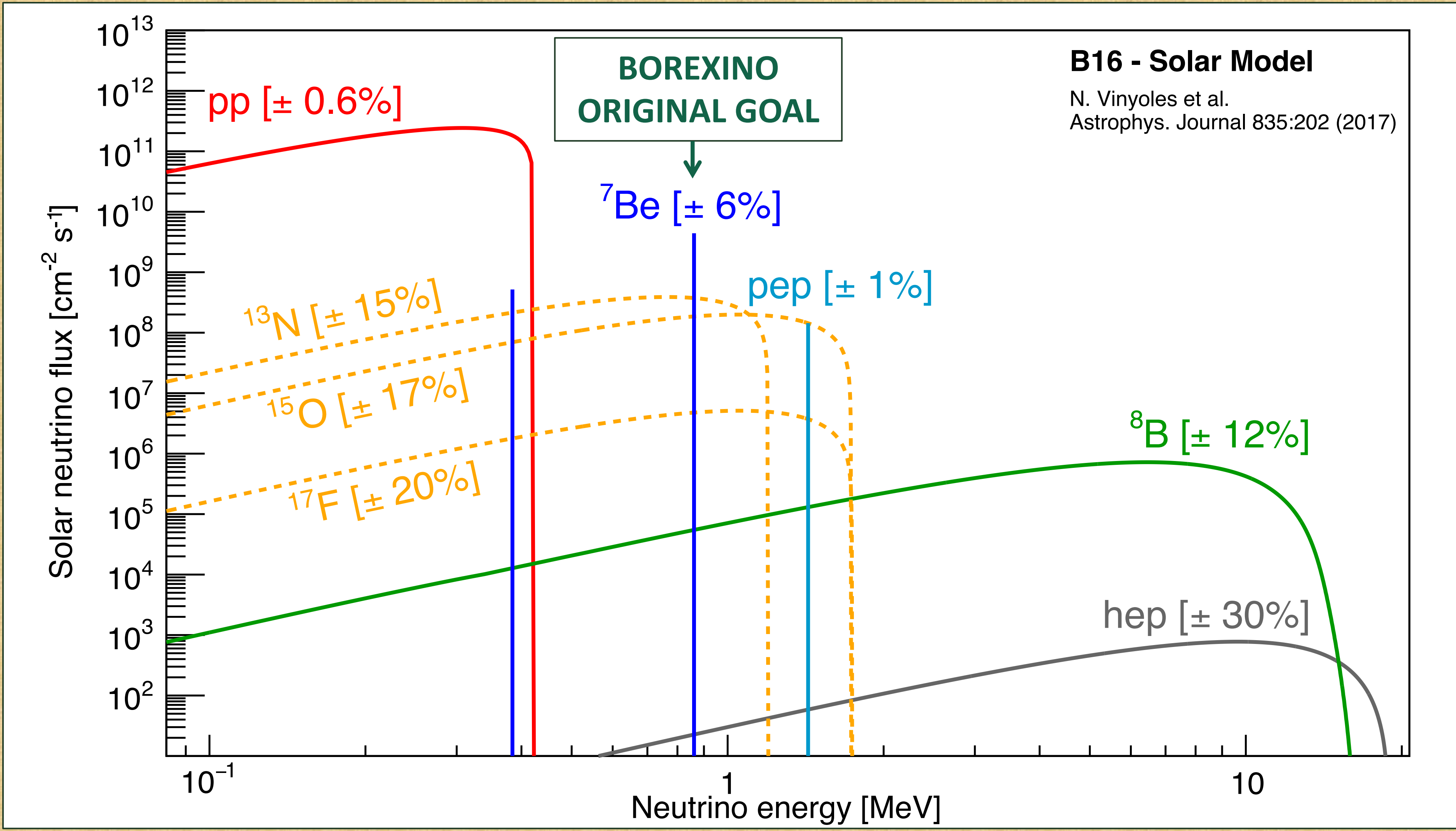
-Performing solar neutrino spectroscopy is the only way to get a real-time snap-shot of the nuclear processes inside the Sun



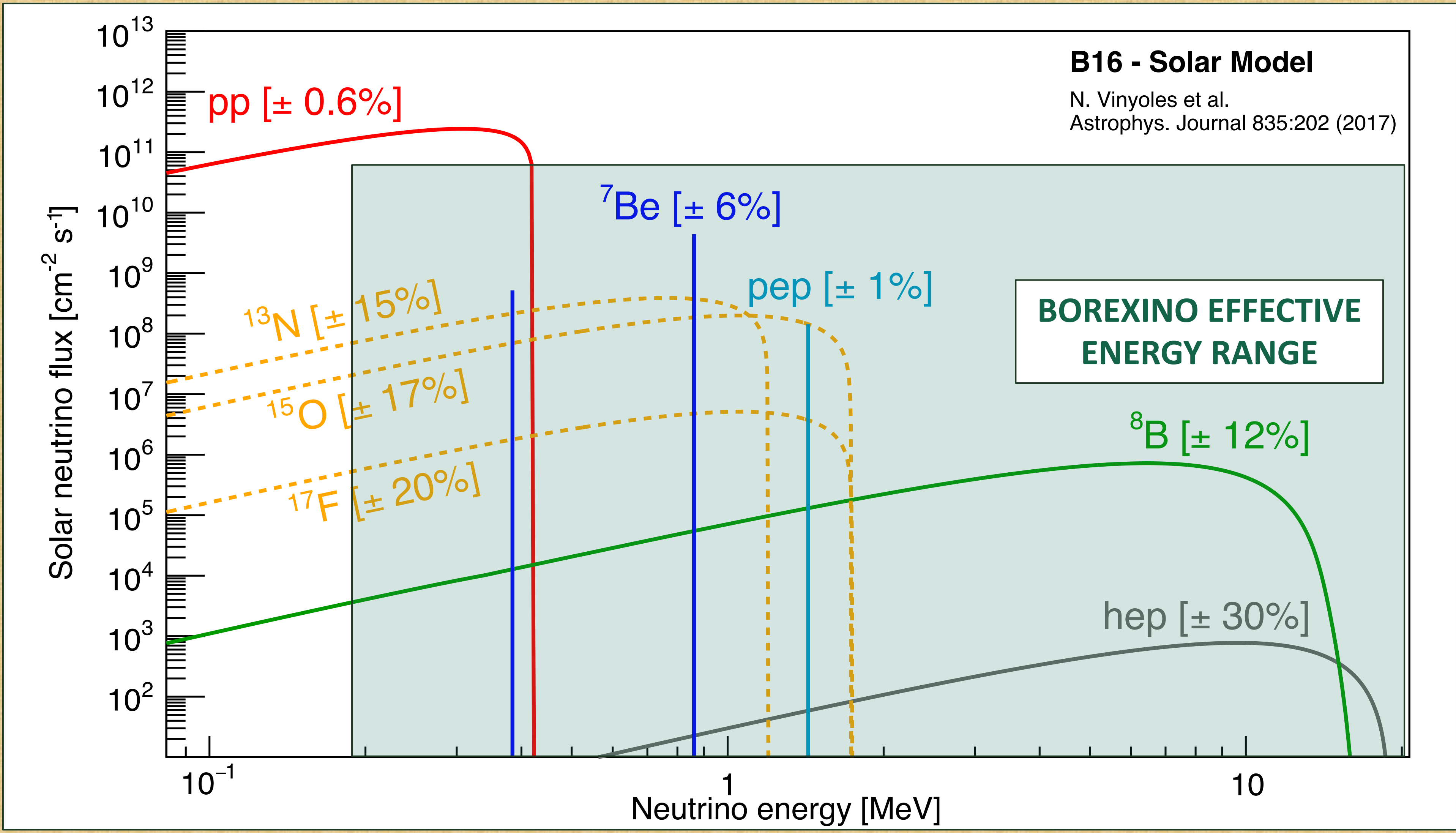
The Solar Neutrino Spectrum



THE SOLAR NEUTRINO SPECTRUM



THE SOLAR NEUTRINO SPECTRUM



SCINTILLATION LIGHT

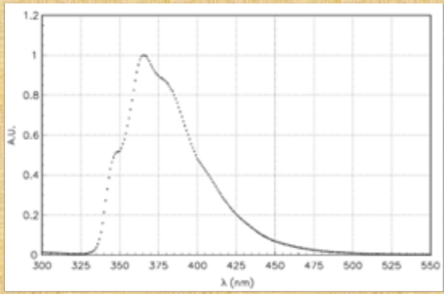
- Reconstruction of:
  - Event position
  - Energy
  - Particle kind (α, β+, β-)

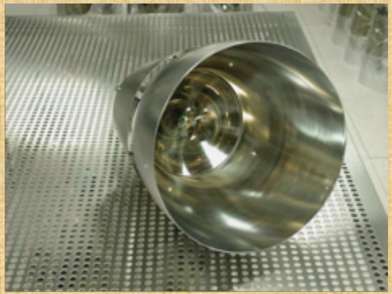
- Isotropic light:
  - No directionality (but Cherenkov)

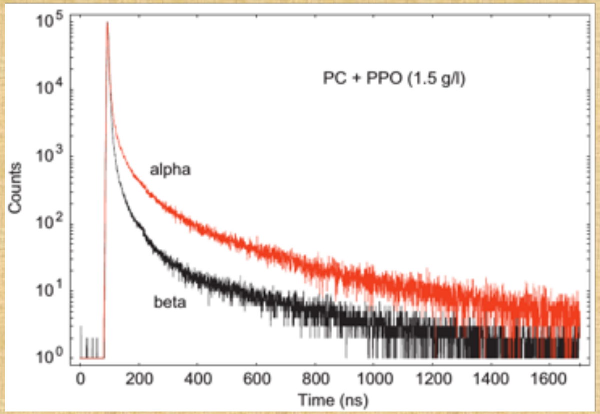
- σ(E) ~ 50 keV
- σ(r) ~10 cm

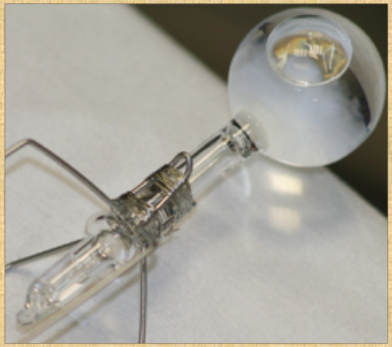
} @ 1 MeV

- Performances investigated using calibration sources









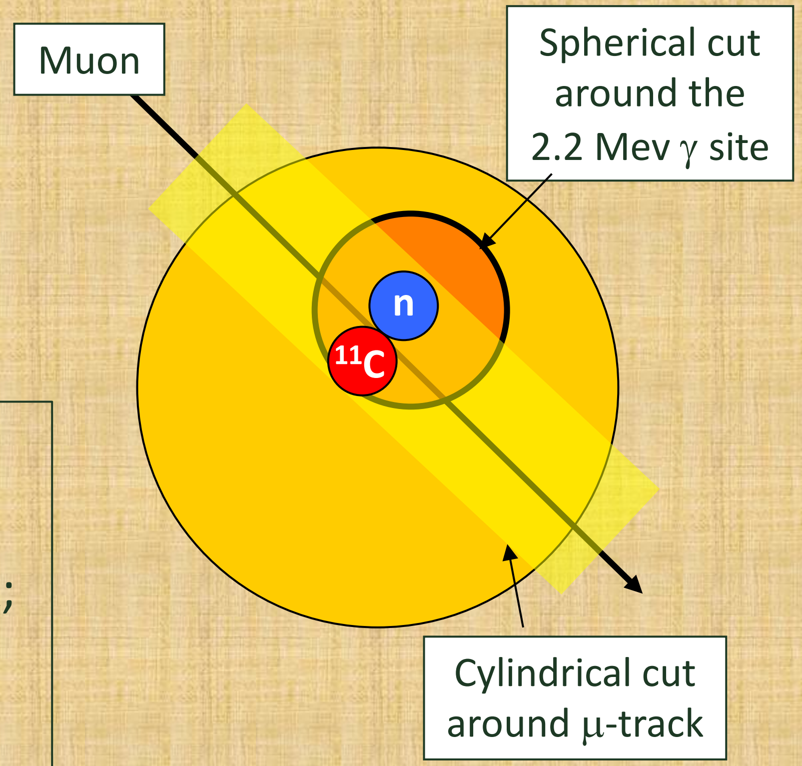
The Three-Fold Coincidence technique (TFC)

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

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

$${}^{11}\mathbf{C} \rightarrow {}^{11}\mathbf{B} + \mathbf{e}^{+} + \nu_{\mathbf{e}}$$
$\tau \sim 30$ min

$$\mathbf{n} + \mathbf{p} \rightarrow \mathbf{d} + \gamma$$
$\tau \sim 260$ μs

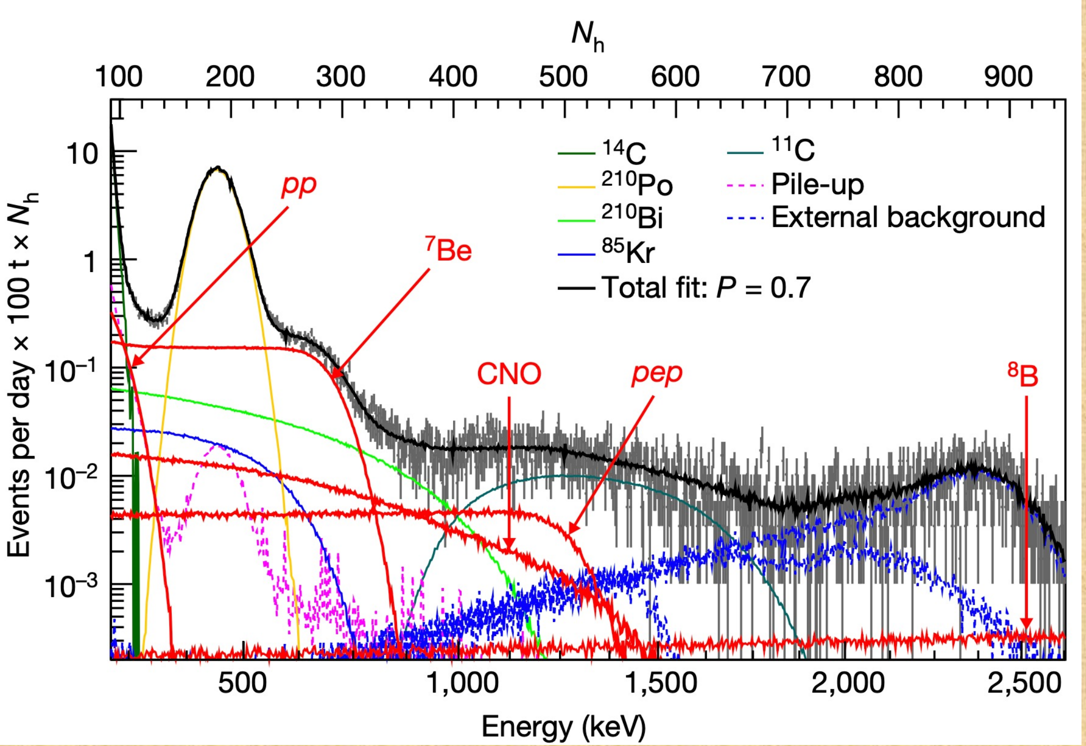


The likelihood that a certain event is ^{11}C is obtained using:

- 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 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).

COMPREHENSIVE SOLAR NEUTRINO SPECTROSCOPY

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

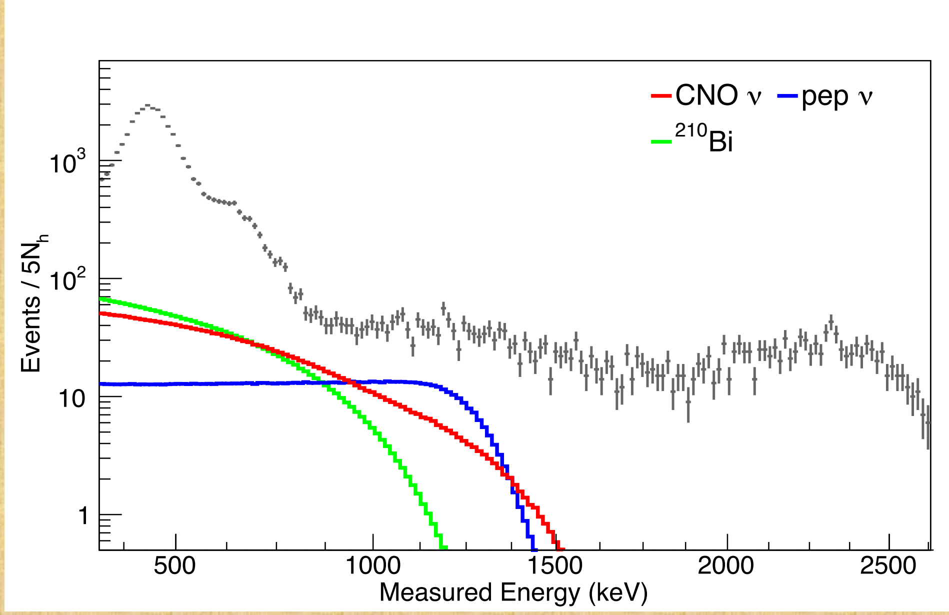
LER analysis *Physical Review D 100, 082004 (2019)*

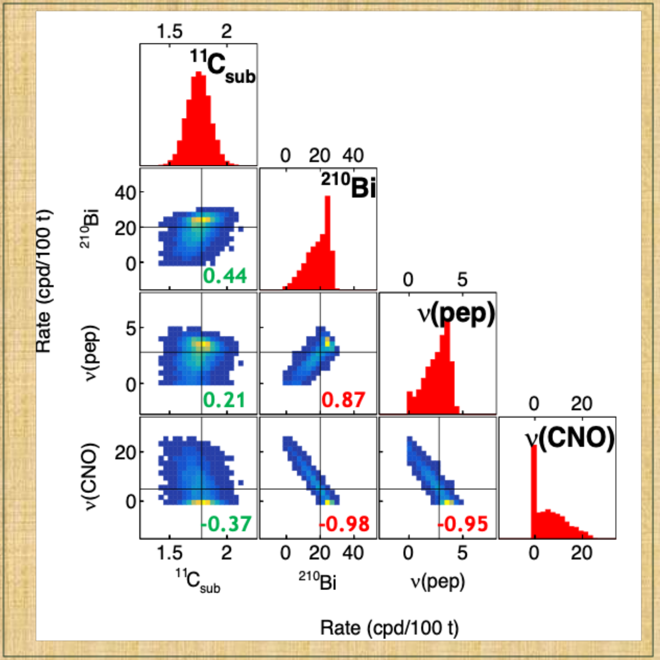
HER analysis *Physical Review D 101, 062001 (2020)*

Solar neutrino	Rate (counts per day per 100 t)	Flux ($cm^{-2}\,s^{-1}$)	Flux–SSM predictions ($cm^{-2}\,s^{-1}$)
pp	$134 \pm 10^{+6}_{-10}$	$(6.1 \pm 0.5^{+0.3}_{-0.5}) \times 10^{10}$	$5.98(1.0 \pm 0.006) \times 10^{10}$ (HZ) $6.03(1.0 \pm 0.005) \times 10^{10}$ (LZ)
^{7}Be	$48.3 \pm 1.1^{+0.4}_{-0.7}$	$(4.99 \pm 0.11^{+0.06}_{-0.08}) \times 10^{9}$	$4.93(1.0 \pm 0.06) \times 10^{9}$ (HZ) $4.50(1.0 \pm 0.06) \times 10^{9}$ (LZ)
pep (HZ)	$2.43 \pm 0.36^{+0.15}_{-0.22}$	$(1.27 \pm 0.19^{+0.08}_{-0.12}) \times 10^{8}$	$1.44(1.0 \pm 0.01) \times 10^{8}$ (HZ) $1.46(1.0 \pm 0.009) \times 10^{8}$ (LZ)
pep (LZ)	$2.65 \pm 0.36^{+0.15}_{-0.24}$	$(1.39 \pm 0.19^{+0.08}_{-0.13}) \times 10^{8}$	$1.44(1.0 \pm 0.01) \times 10^{8}$ (HZ) $1.46(1.0 \pm 0.009) \times 10^{8}$ (LZ)
$^{8}B_{HER}$	$0.223^{+0.015+0.006}_{-0.016-0.006}$	$(5.68^{+0.39+0.03}_{-0.41-0.03}) \times 10^{6}$	$5.46(1.0 \pm 0.12) \times 10^{6}$ (HZ) $4.50(1.0 \pm 0.12) \times 10^{6}$ (LZ)
CNO	<8.1 (95% C.L.)	$<7.9 \times 10^{8}$ (95% C.L.)	$4.88(1.0 \pm 0.11) \times 10^{8}$ (HZ) $3.51(1.0 \pm 0.10) \times 10^{8}$ (LZ)
hep	<0.002 (90% C.L.)	$<2.2 \times 10^{5}$ (90% C.L.)	$7.98(1.0 \pm 0.30) \times 10^{3}$ (HZ) $8.25(1.0 \pm 0.12) \times 10^{3}$ (LZ)

TOWARDS THE CNO-ν MEASUREMENT

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



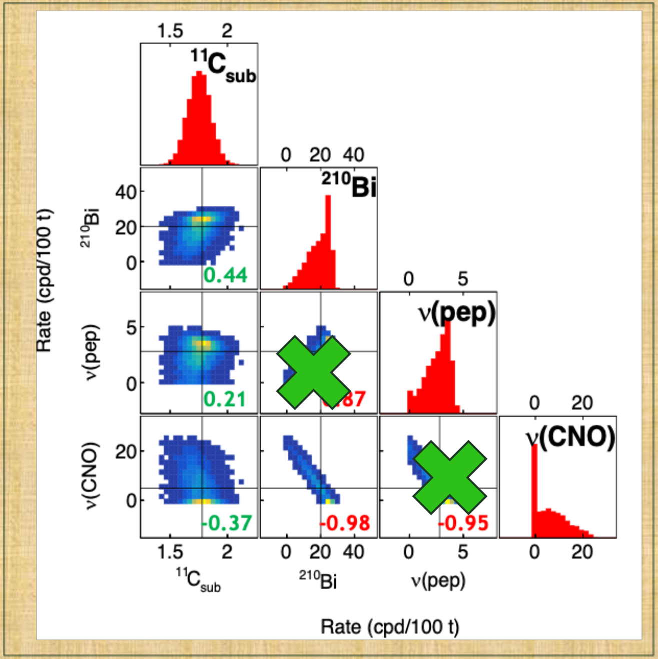


Expected rates:

- CNO ν ~ 4-5 cpd/100 ton
- pep ν ~ 3 cpd/100 ton
- ^{210}Bi ~ 15-20 cpd/100 ton

TOWARDS THE CNO-ν MEASUREMENT (2)

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.....

TOWARDS THE CNO-ν MEASUREMENT (2)

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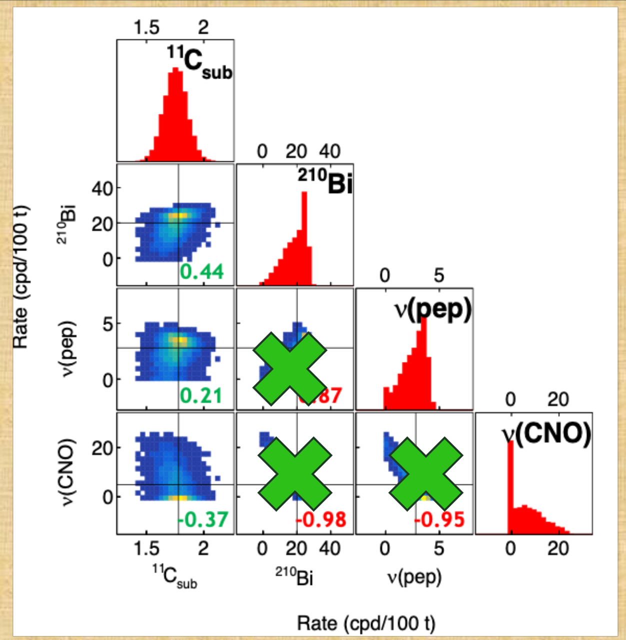
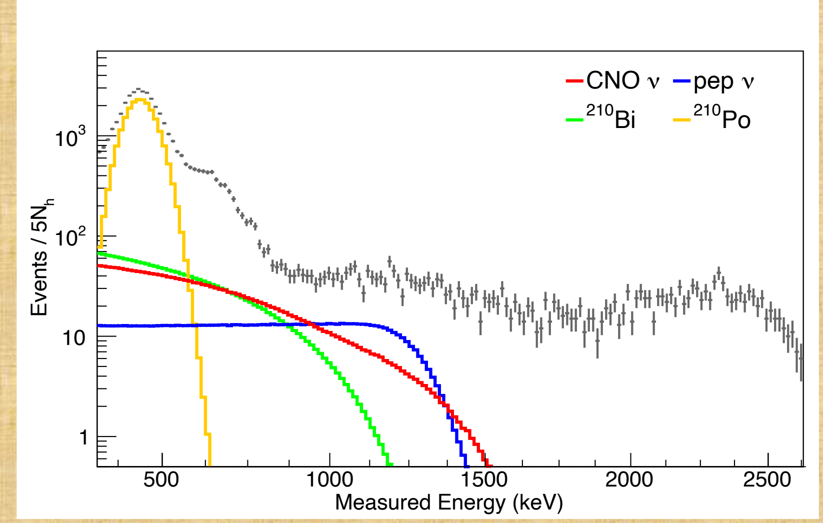


The ^{210}Bi spectrum is still quasi-degenerate with the CNO neutrino one…..
…. But the ^{210}Bi rate can be constrained by precisely (and independently) mapping the ^{210}Po rate!

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



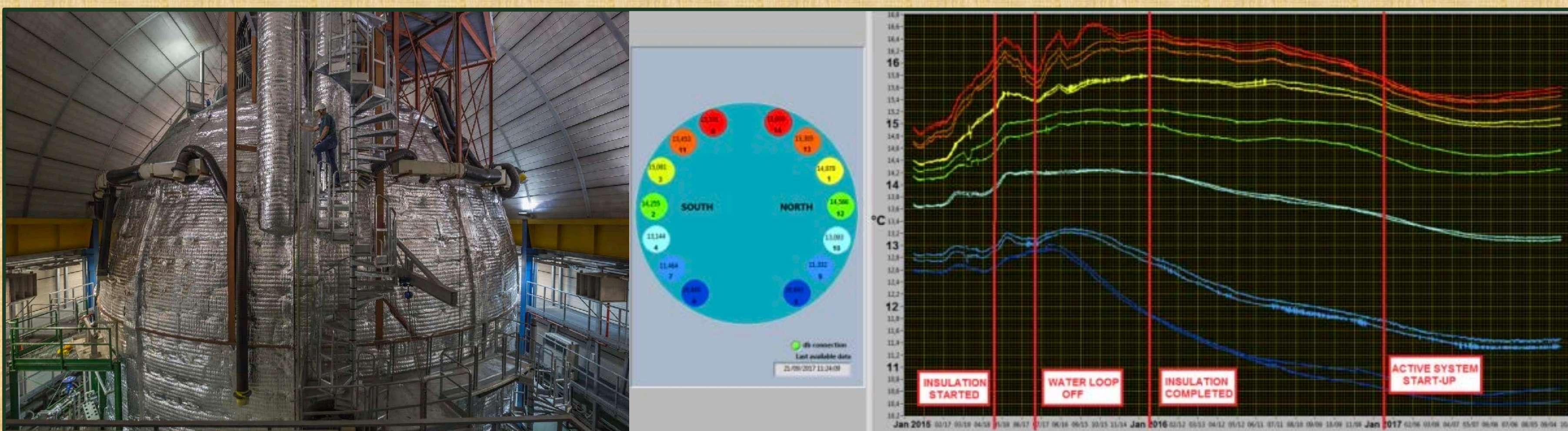
^{210}Po is "easier" to identify than ^{210}Bi:

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

TOWARDS THE CNO MEASUREMENT (3)

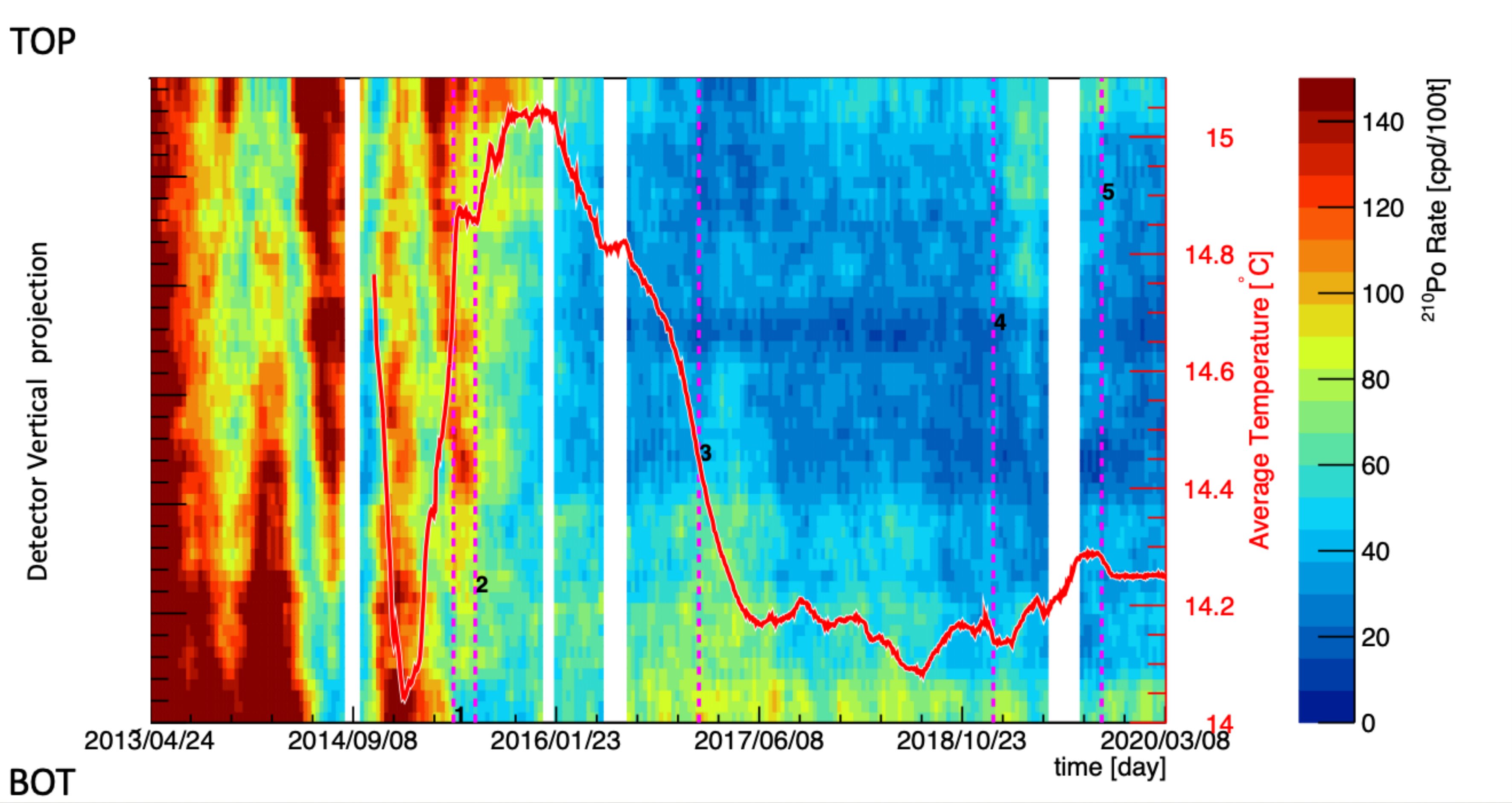
- Convective motions triggered by seasonal changes in temperature bring inside the scintillator an unknown amount of ^{210}Po which has been present on the nylon Inner Vessel.
- This breaks the secular equilibrium of the ^{210}Pb chain!

- **Before performing any counting analysis, we had to thermally insulate the detector to stop convective motions**! **DONE and COMPLETED in May 2016** ☺



TOWARDS THE CNO MEASUREMENT (4)

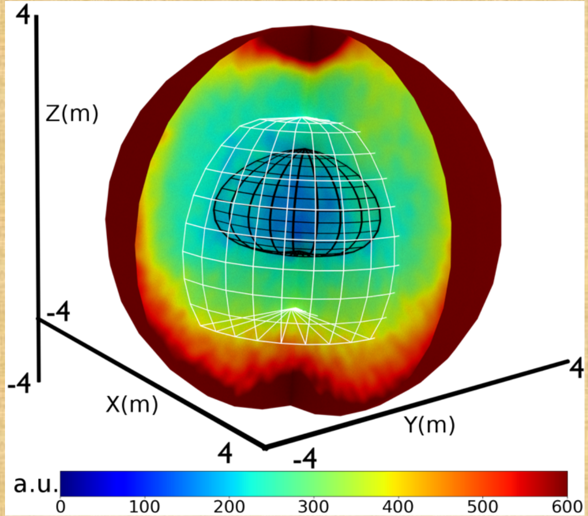
^{210}Po counting rate inside the Inner Vessel scintillator volume



TOWARDS THE CNO MEASUREMENT (5)

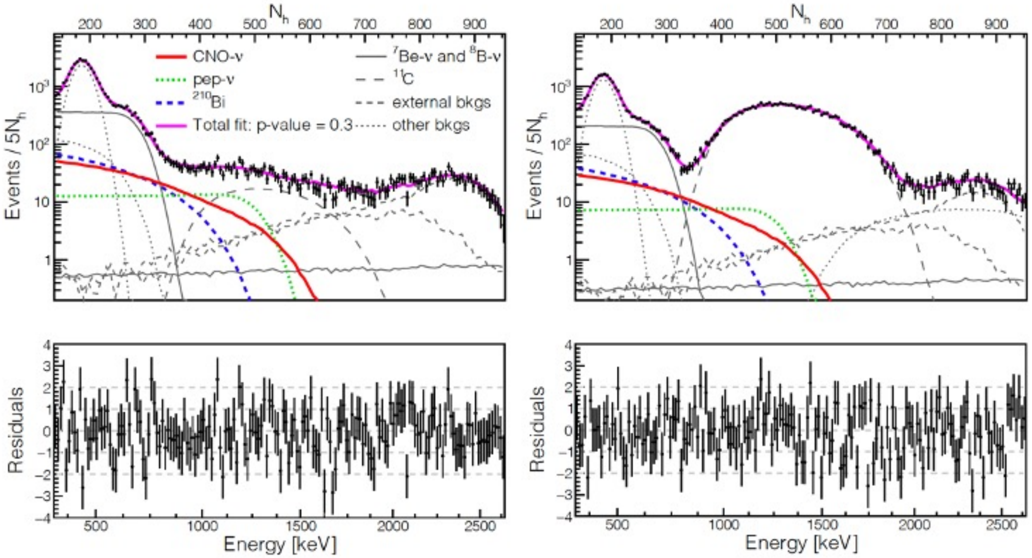
- There is an innermost region of the scintillator which is almost free of convective currents: the ^{210}Po rate can be there fitted assuming bulk+IV contributions.
- We get a minimum for the ^{210}Po rate and an upper limit for the ^{210}Bi rate!

This ^{210}Bi upper limit can be extended over the full FV **<u>if and only</u>** ^{210}Bi is found, within error, uniform both in the angular and radial distributions. And this is our case.
^{210}Bi stable in time → ^{210}Pb leaching from the nylon vessel is negligible.
R(^{210}Bi) < 11.5 ± 1.3 cpd/100t

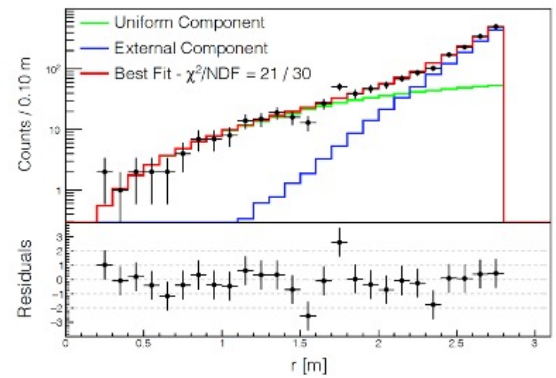


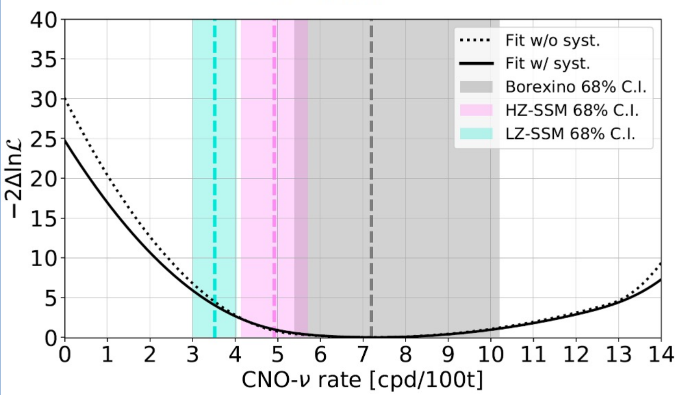
THE CNO MEASUREMENT

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



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





NO CNO hypothesis disfavored at 5 σ

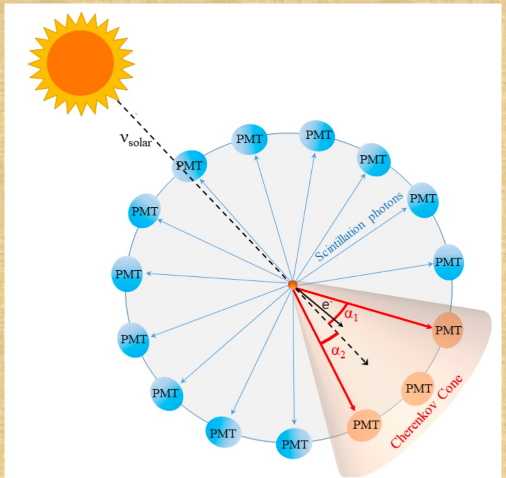
$$\mathcal{R}(\mathrm{CNO}) = \mathbf{7.2^{+3.0}_{-1.7}}\ \mathrm{cpd/100\,t\ (stat + sys)}$$

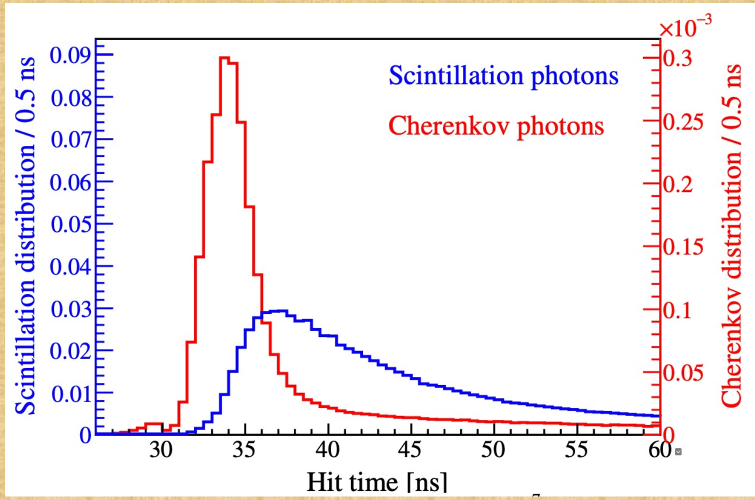
$$\Phi(\mathrm{CNO}) = \mathbf{7.0^{+3.0}_{-2.0}} \times \mathbf{10^8}\ \nu/\mathrm{cm^2/s\ (stat + sys)}$$

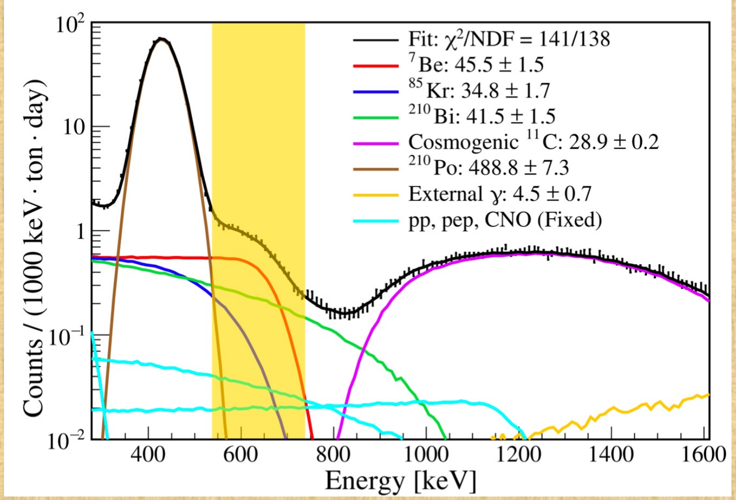
physicsworld TOP 10 BREAKTHROUGH 2020

Directionality

- Sub-MeV neutrino detection using Cherenkov light
- Correlated and Integrated Directionality (CID)
- Different time profile for Cherenkov and scintillation photons
- Analysis done on 1st and 2nd detected photoelectrons



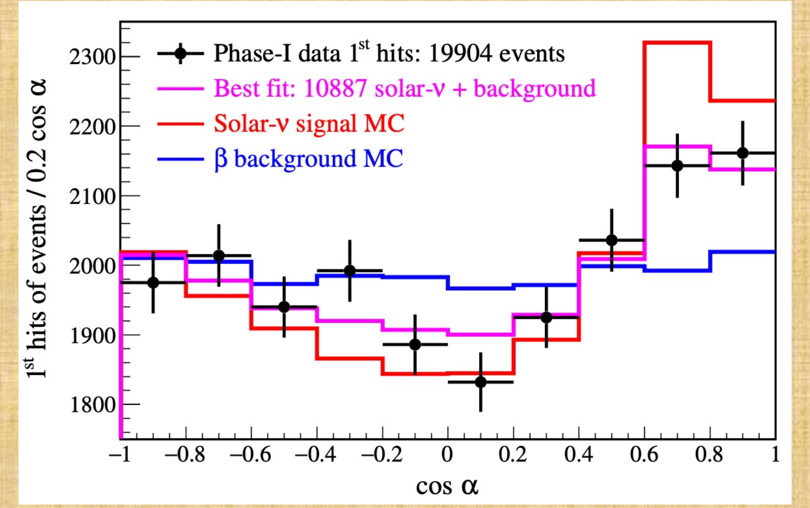


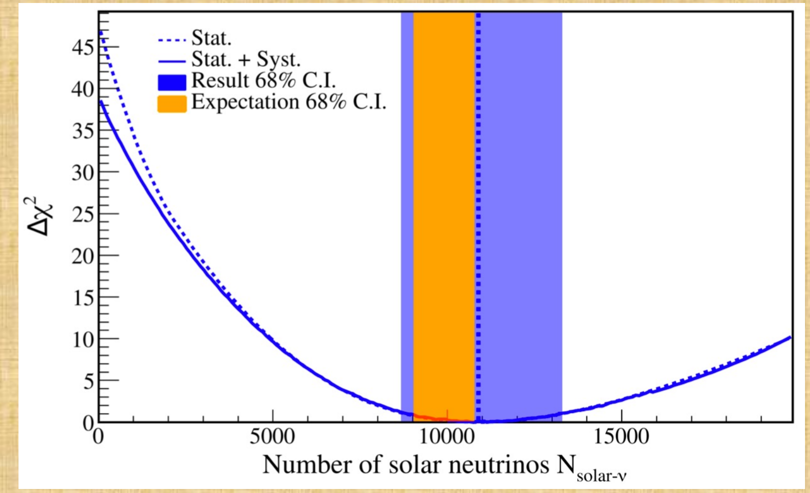


Directionality

"First Directional Measurement of sub-MeV Solar Neutrinos with Borexino" PhysRevLett.128.091803
"Correlated and integrated directionality for sub-MeV solar neutrinos in Borexino" PhysRevD.105.052002

- ROI: (0.54-0.74) MeV
- Dataset: 2007-2010
- CID: analysis statistical-based, no event by event analysis
- Ratio between Cherenkov and scintillation photons ~0.4%
- PDF obtained by MC simulations
- MC validated with calibration runs in 2009
- Background only hypothesis rejected > 5σ
- Measured rate compatible with theoretical expectations





CONCLUSIONS

- Borexino has mapped out the entire pp solar fusion chain with high precision and it has demonstrated the existence of CNO neutrinos for the first time (significance 5σ)
- Borexino provided the first directional measurement of sub-MeV solar neutrinos using Cherenkov light:
  - Exclusion of no neutrino signal hypothesis with >5σ
  - Other LS detectors can readily benefit from this analysis

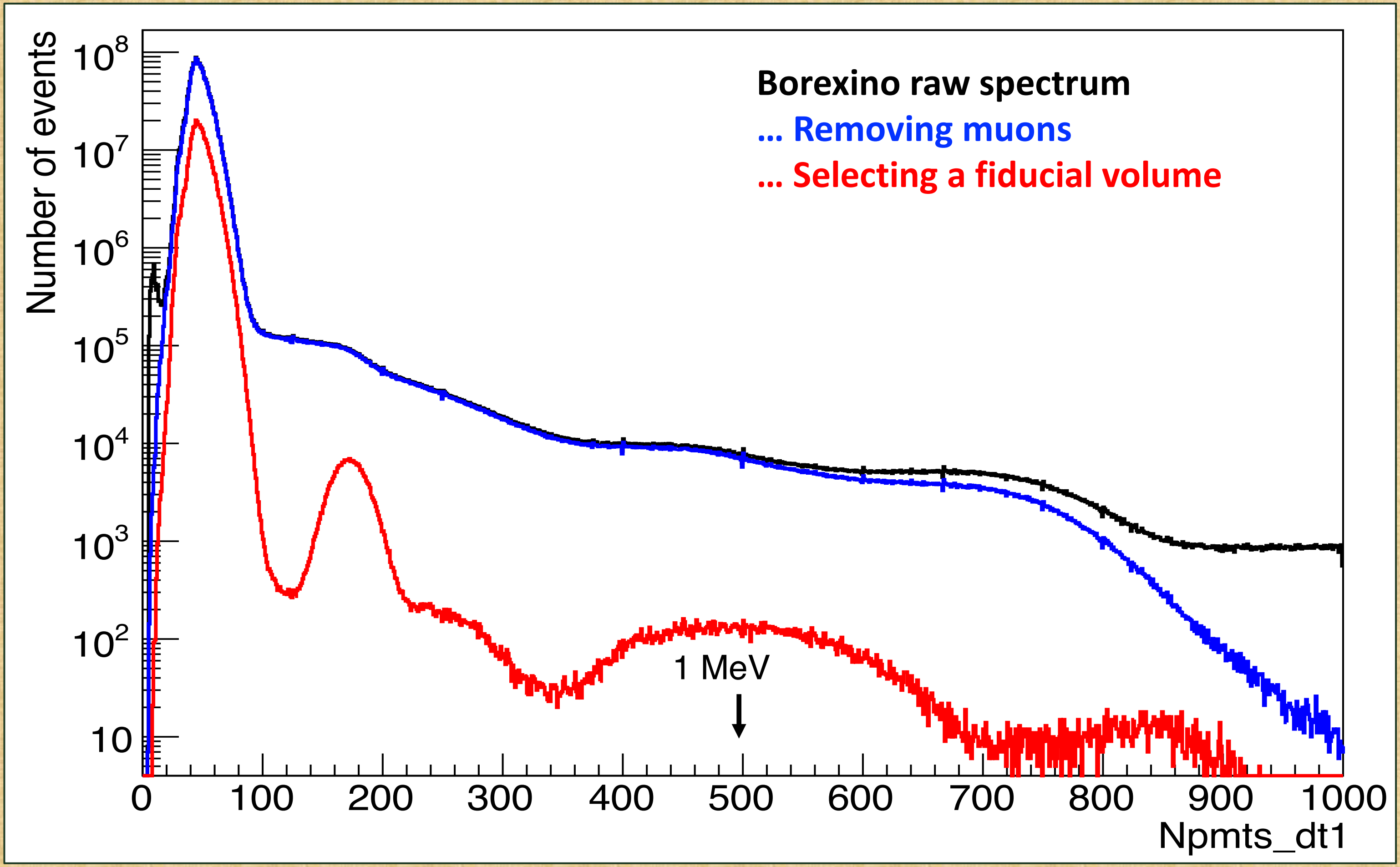
Farewell and thank-you Borexino!

- First Physics Run: 05/16/2007
- Last Physics Run: 10/07/2021

Thank you for your attention!

The Borexino Collaboration

HOW TO EXTRACT A NEUTRINO SIGNAL



We need to develop powerful tools to separate the signal from the residual background components

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, Metallicity….) are considered all together and result in expectations about the neutrino fluxes and helioseismology.

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

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

→ About 9 % difference (^{7}Be)

→ About 18 % difference (^{8}B)

} About 28 % difference (^{13}N, ^{15}O, ^{17}F)

B16 - Solar Model

N. Vinyoles et al.
Astrophys. Journal 835:202 (2017)

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 are 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 ^{7}Be ν)
- **HER** (High Energy Range) between (3.2 -16) MeV (^{8}B and hep ν)

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 ^{7}Be measurement @ 5%;
- 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.

The multivariate fit is performed including the likelihood of:

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

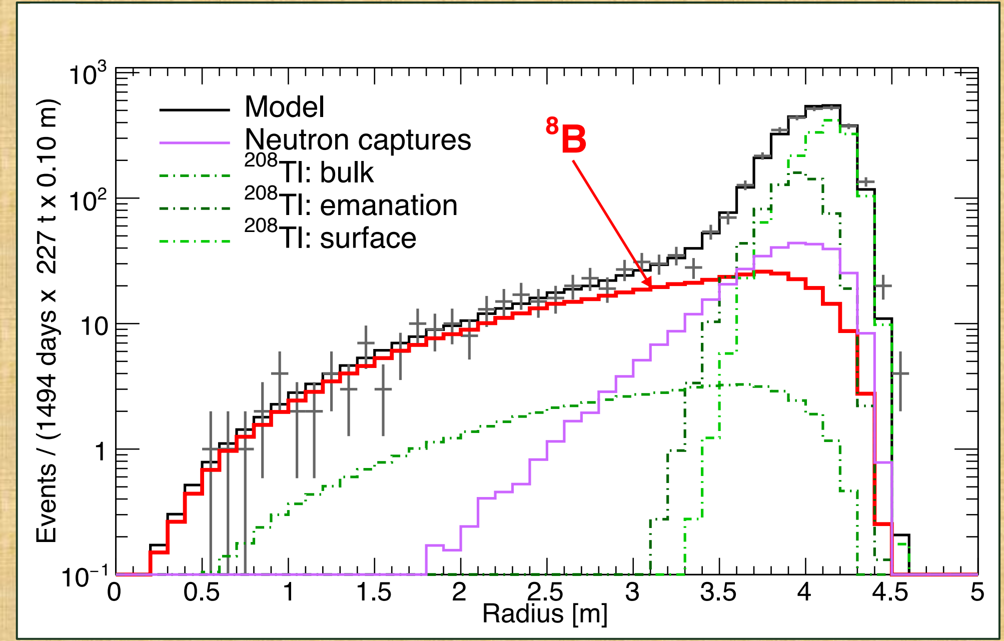
"Comprehensive measurement of pp-chain solar neutrinos", *Nature 562 (2018) 505*

HER analysis Phys. Rev. D 101, 062001 (2020)

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:

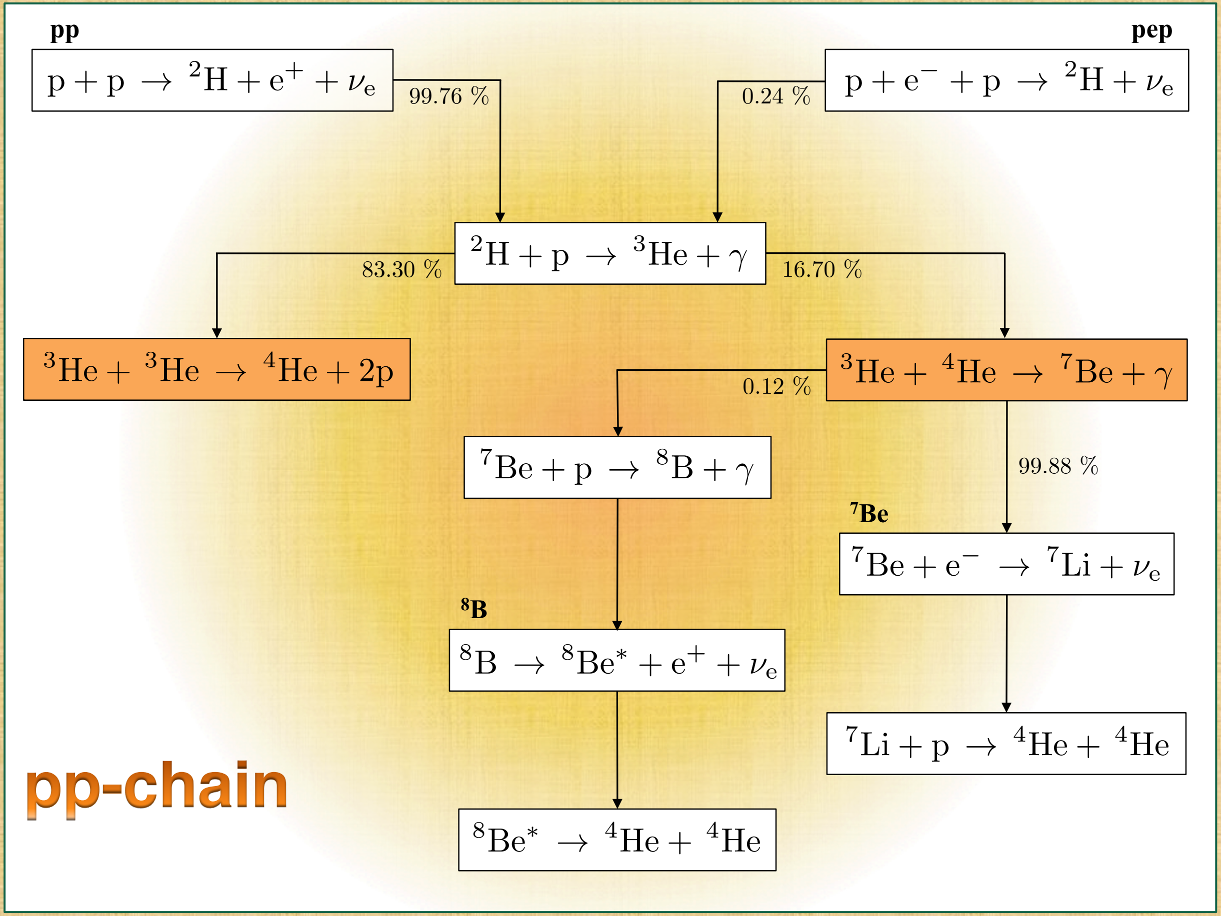
Residual backgrounds affecting the ^8B energy region are:

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

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.

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

B16-SSM expected values:

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

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

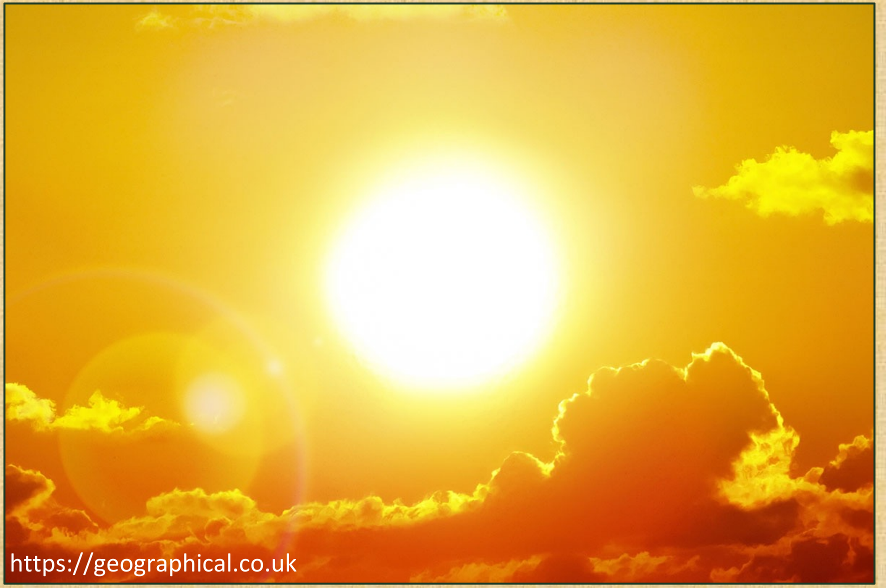
<u>**Borexino result**</u>:

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

COMPREHENSIVE SOLAR NEUTRINO SPECTROSCOPY

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

Astrophysical implications of the results: solar luminosity



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

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

which agrees with the well measured photon value:

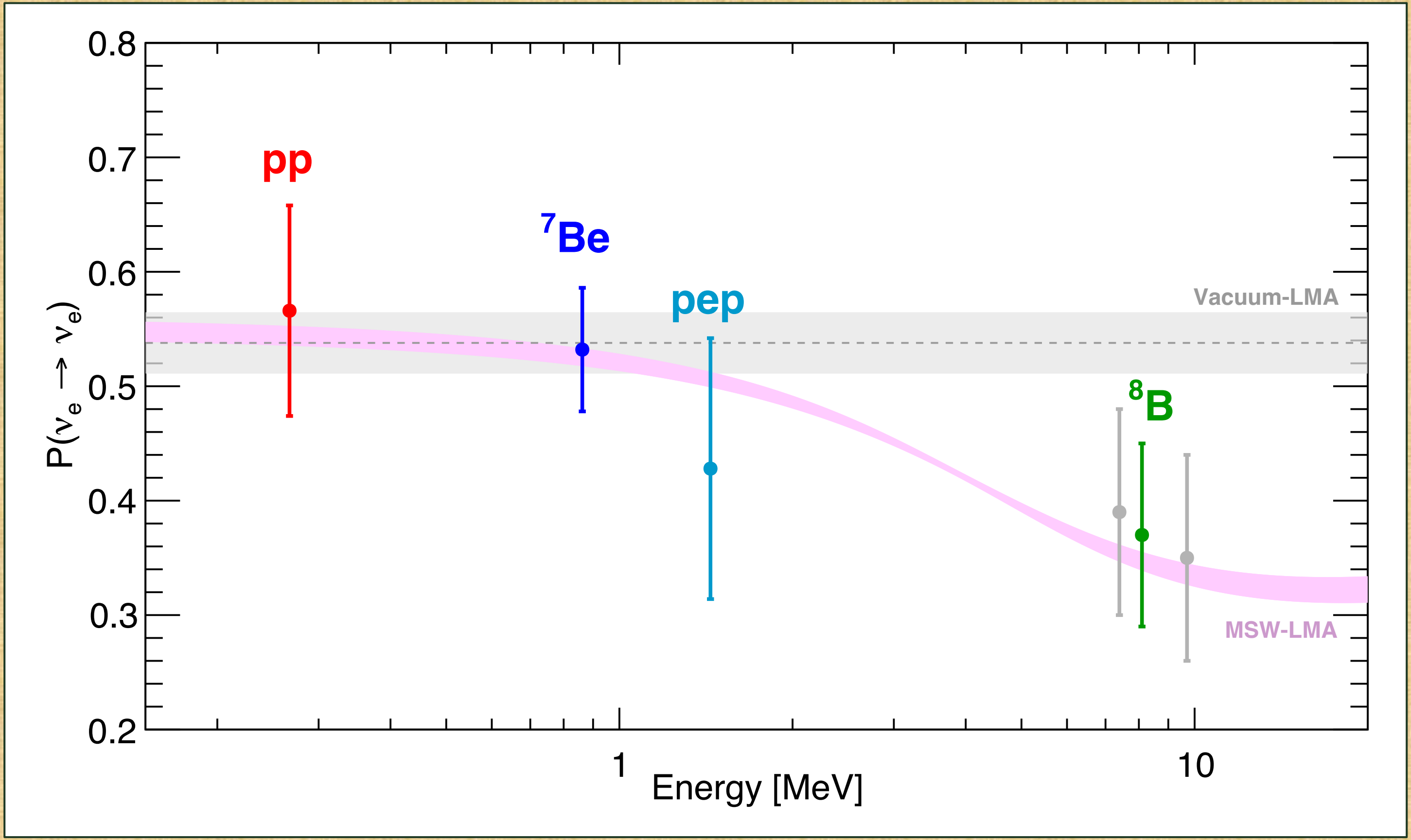
$$\mathbf{L_{ph}} = (\mathbf{3.846} \pm \mathbf{0.015}) \times \mathbf{10^{33}}\,\mathbf{erg\,s^{-1}}$$

→ 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

STUDYING THE SUN WITH NEUTRINOS…
…STUDYING NEUTRINOS WITH THE SUN

Neutrino physics implications of the results: testing MSW-LMA



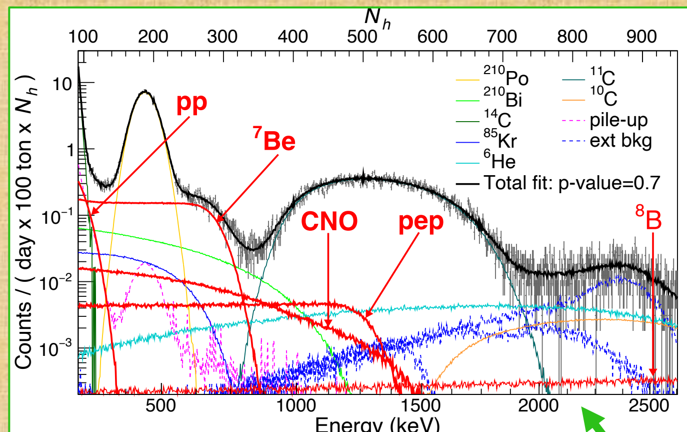
SSM-HZ solar-ν fluxes from *N. Vinyoles et al., Astrophys. Journal 835:202 (2017)*
Neutrino oscillation parameters from *I. Esteban et al., JHEP 01 (2017).*

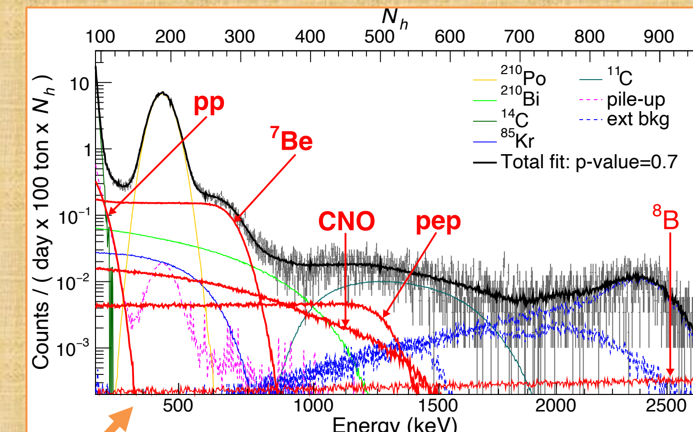
COMPREHENSIVE SOLAR NEUTRINO SPECTROSCOPY

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

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

Multivariate fit: neutrino interaction rates obtained by maximizing the binned likelihood function





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