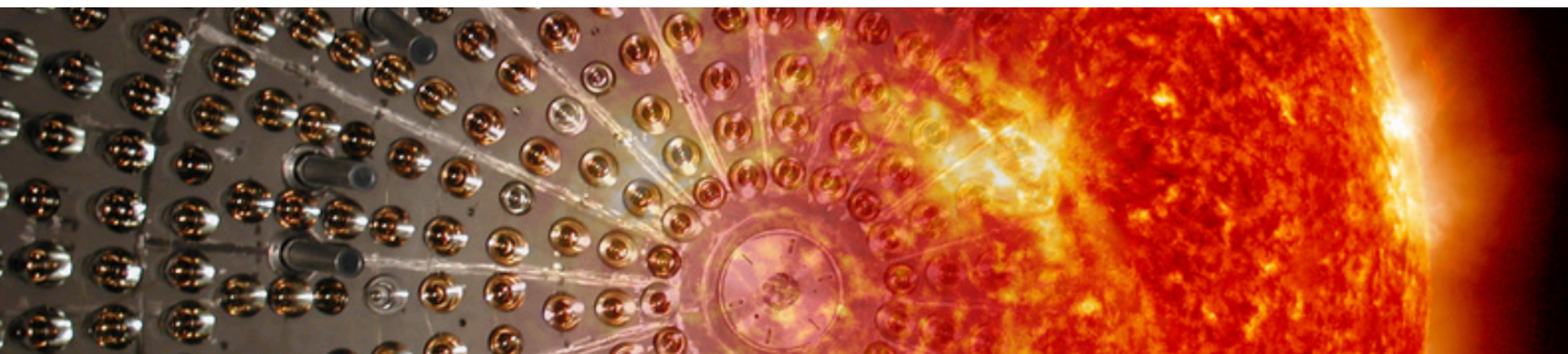
7th International Conference on New Frontiers in Physics (ICNFP2018)

Conference Center of the Orthodox Academy of Creta 4-12 July 2018

Solar Neutrinos Spectroscopy with Borexino Phase-II

Lino Miramonti *on behalf of Borexino Collaboration*

Dipartimento di Fisica, Università degli Studi di Milano & INFN-Sezione di Milano

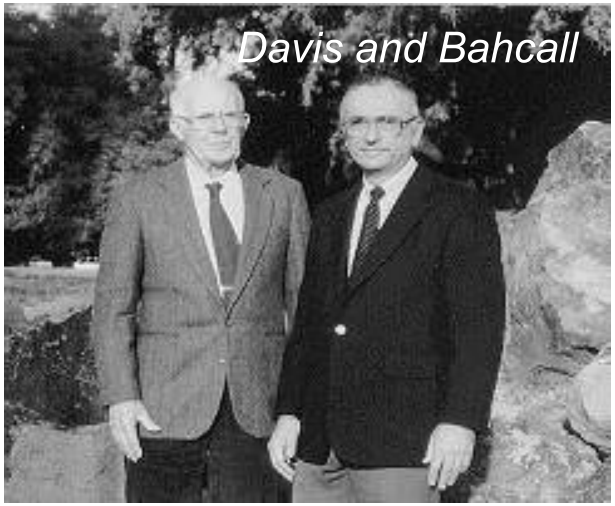


Abstract:: Solar neutrinos have played a central role in the discovery of the neutrino oscillation mechanism. They still are proving to be a unique tool to help investigate the fusion reactions that power stars and further probe basic neutrino properties. The Borexino neutrino observatory has been operationally acquiring data at Laboratori Nazionali del Gran Sasso in Italy since 2007. Its main goal is the real-time study of low energy neutrinos (solar or originated elsewhere, such as geo-neutrinos). The latest analysis of experimental data, taken during the so-called Borexino Phase-II (2011-present), will be showcased in this talk - yielding new high-precision, simultaneous wideband flux measurements of the four main solar neutrino components belonging to the "pp" fusion chain (pp, pep, 7Be, 8B), as well as upper limits on the remaining two solar neutrino fluxes (CNO and hep).

Neutrinos production in stars

ν_e are copiously produced by thermonuclear processes that power the **Sun** and the others **stars**

The original motivation of the first experiments on solar ν was to test the Standard Solar Model (SSM)



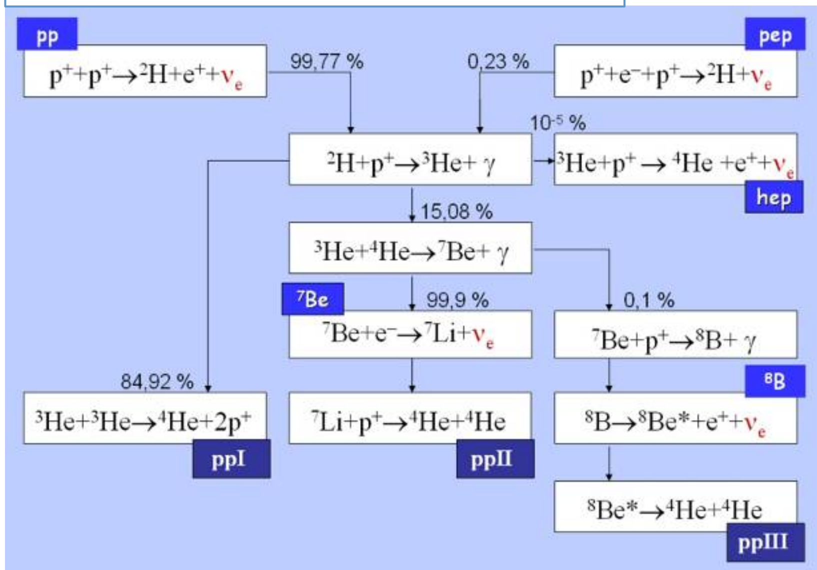
"…..to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars."

Phys. Rev. Lett. 12, 300–302 (1964)
Solar Neutrinos. I. Theoretical
John N. Bahcall Caltech

Phys. Rev. Lett. 12, 303–305 (1964)
Solar Neutrinos. II. Experimental
Raymond Davis, Jr. BNL

Solar neutrinos fluxes

pp chain 99 % of Sun Energy



ν from:

pp

pep

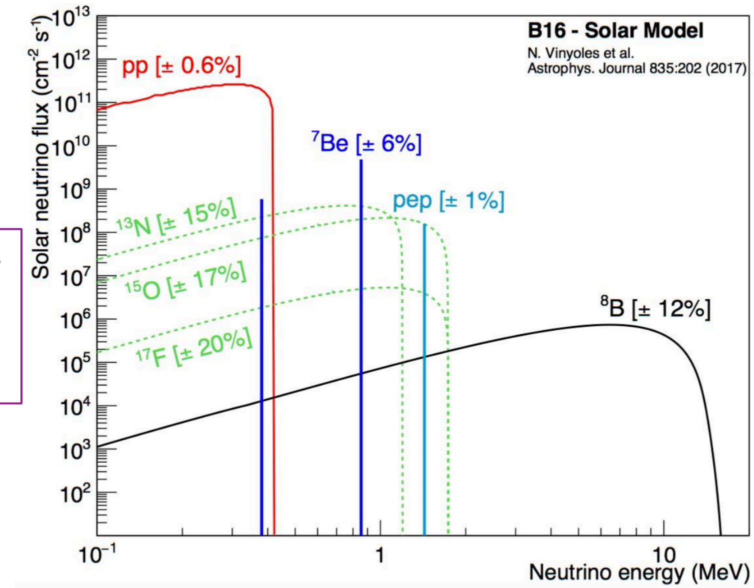
^{7}Be

^{8}B

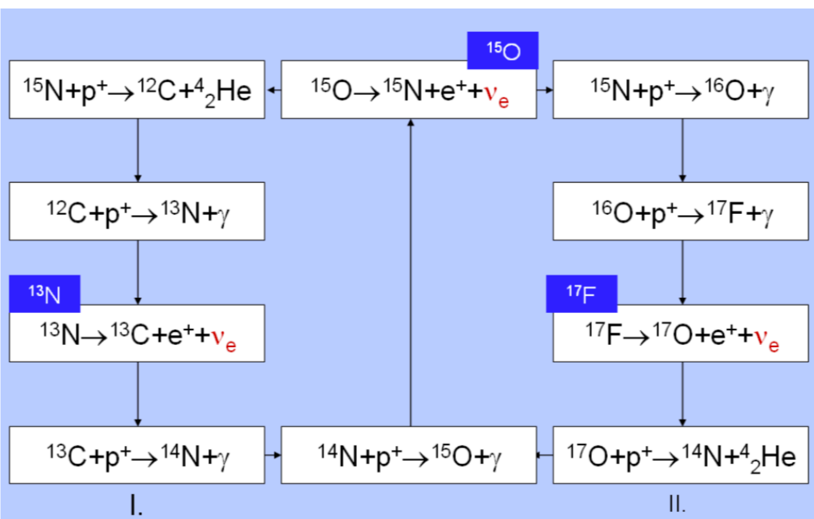
~~hep~~

flux to low to be detected in current experiments

expected ν fluxes from the **SSM**



CNO cycle <1 % of Sun Energy



ν from:

^{13}N

^{15}O

^{17}F

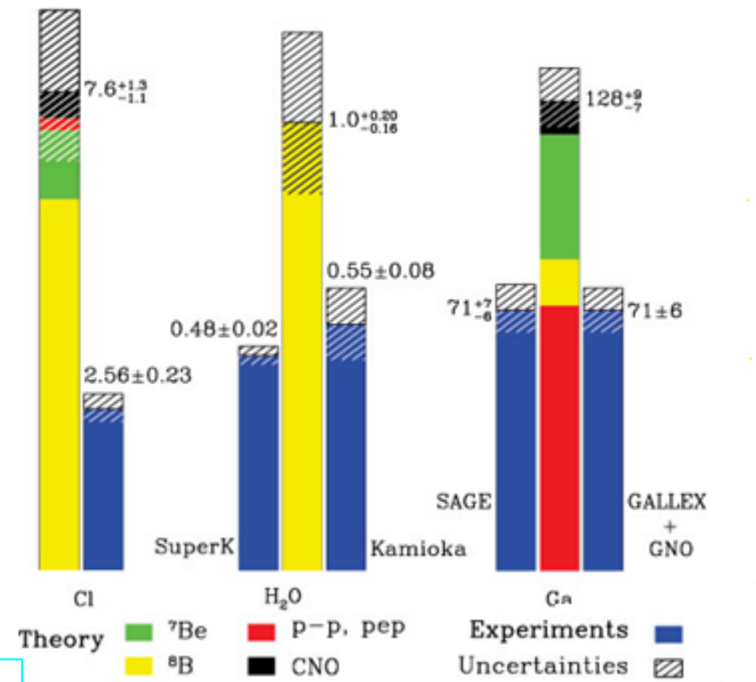
CNO

Solar Neutrino Problem

The **rise** of the **Solar Neutrino Problem - SNP** (from 1970 to 2000):

- Homestake (Cl)
- Kamiokande-SuperKamiokande (H_2O)
- Gallex-Sage (Ga)

Neutrino fluxes 1/2 or 1/3 of expectations!

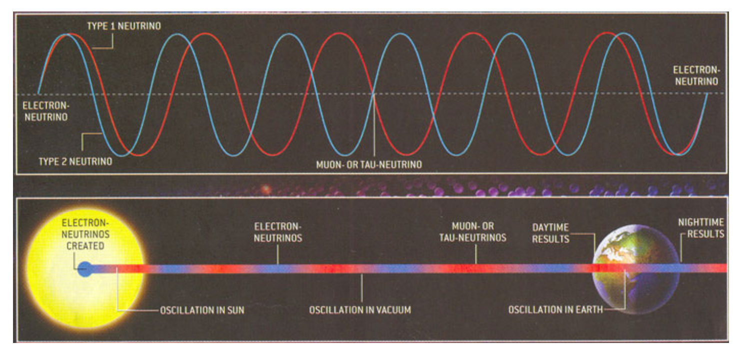


Possible explanation for the SNP:

– **Experiments inefficiencies?**
Calibration with artificial neutrino sources

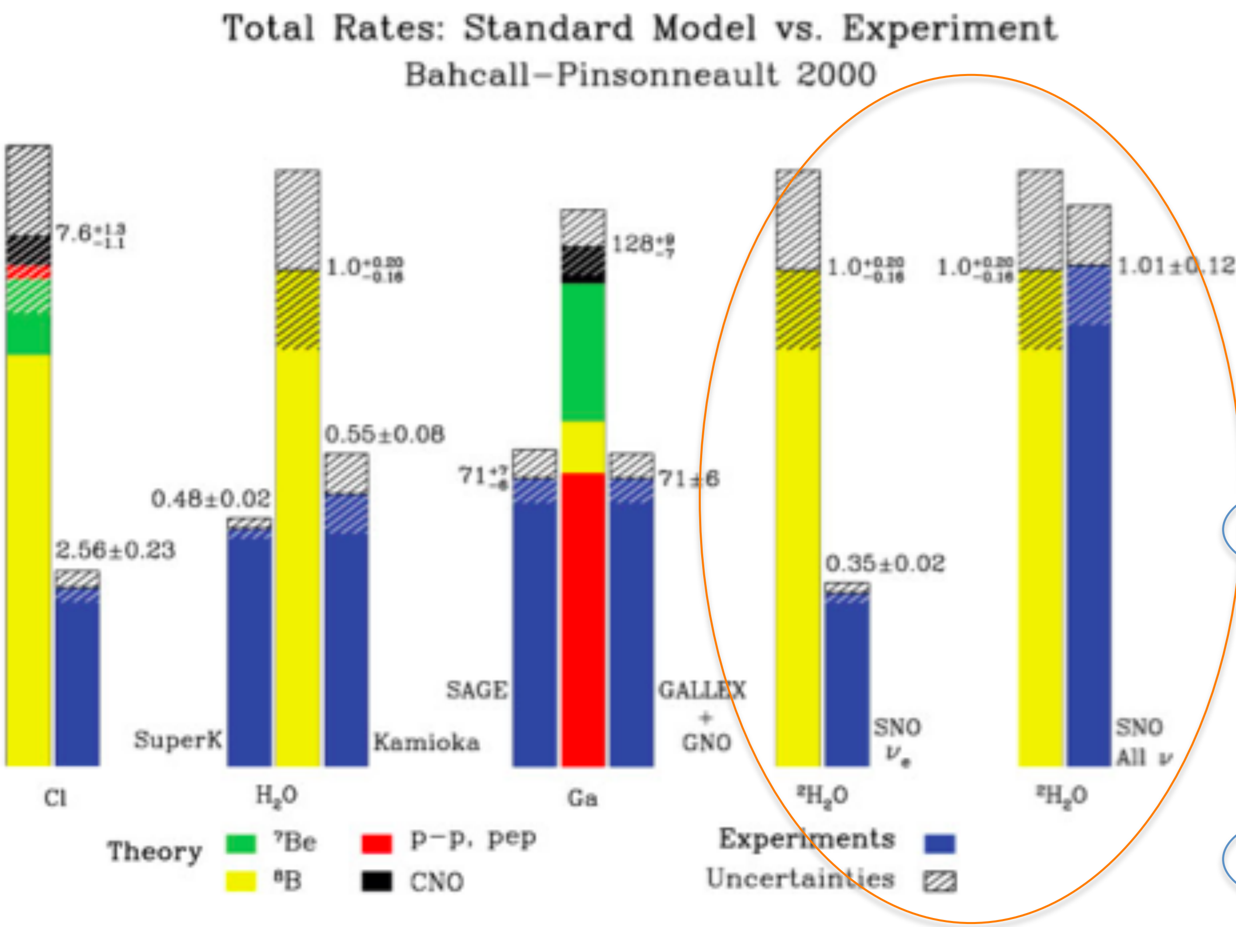
– **Problem with the SSM?**
Good agreement with helioseismology

– **If neutrinos are massive: flavor oscillations?**

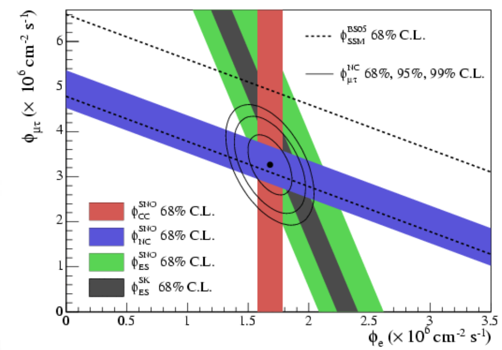


The **solution** of the **solar neutrino problem** (2000):

- SN (D_2O)



The signal depends on the detection reaction and on the neutrino flavor composition at the detector



$$\varphi_{CC} = 1.68 \ {}^{+0.06}_{-0.06}(\text{stat.})^{+0.08}_{-0.09}(\text{syst.})$$

$$\varphi_{NC} = 4.94 \ {}^{+0.21}_{-0.21}(\text{stat.})^{+0.38}_{-0.34}(\text{syst.})$$

$$\varphi_{ES} = 2.35 \ {}^{+0.22}_{-0.22}(\text{stat.})^{+0.15}_{-0.15}(\text{syst.})$$

(In units of $10^6 \text{cm}^{-2}\text{s}^{-1}$)

$$\phi_{SSM} = 5.46\,(1 \pm 0.12) \cdot 10^6 \ cm^{-2} s^{-1}$$

The Solar Neutrino Problem can be considered solved!

The MSW-LMA solution

- Low Energy electron neutrinos oscillate in vacuum;

- For High Energy electron neutrinos (multi-MeV) there is an enhanced conversion in the Sun because of ν_e forward scattering process with electrons (MSW effect) Mikheyev-Smirnov-Wolfenstein.

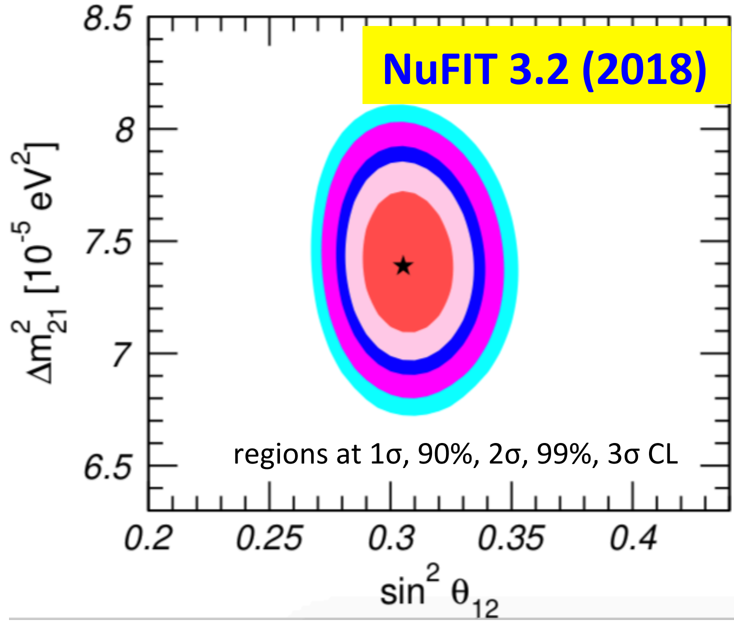
The solution to the SNP is the (Large Mixing Angle) **LMA solution**

$$P_{ee}^{3\nu} = \frac{1}{2}\cos^4\theta_{13}\left(1+\cos 2\theta_{12}^M \cos 2\theta_{12}\right)$$

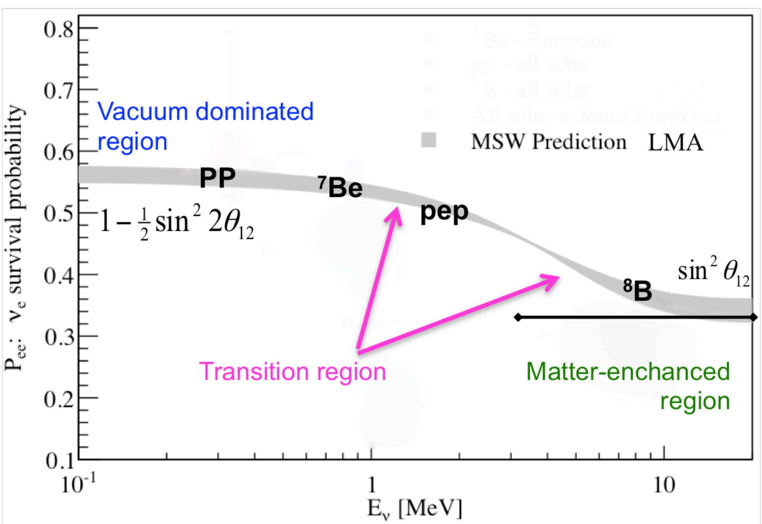
$$\cos 2\theta_{12}^M = \frac{\cos 2\theta_{12} - \beta}{\sqrt{\left(\cos 2\theta_{12} - \beta\right)^2 + \sin^2 2\theta_{12}}}$$

where $$\beta = \frac{2\sqrt{2}G_F \cos^2\theta_{13} n_e E_\nu}{\Delta m_{12}^2}$$

Global 3ν oscillation analysis



http://www.nu-fit.org/?q=node/8



Why it is still interesting to study Solar Neutrinos?

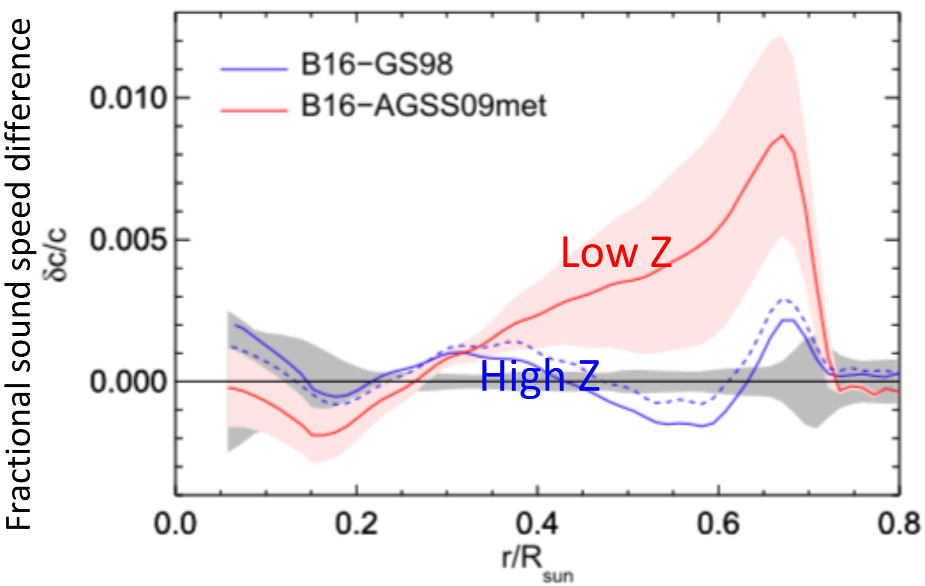
Studying the **Sun** with Neutrinos

- **Metallicity** problem
- Testing **stability** of the Sun
- Energy production/loss mechanisms
- Fusion rates (pp, CNO)

Recent measurements suggest that the solar metallicity might be **lower** than previously assumed. With this assumption SSMs are **less** in agreement with helioseismic data:

***Solar Metallicity* Problem**

Solar neutrino measurements could provide a solution of this puzzle.



New Generation of Standard Solar Models.
N.Vinyoles et al.
The Astrophysical Journal, 835:202, 2017

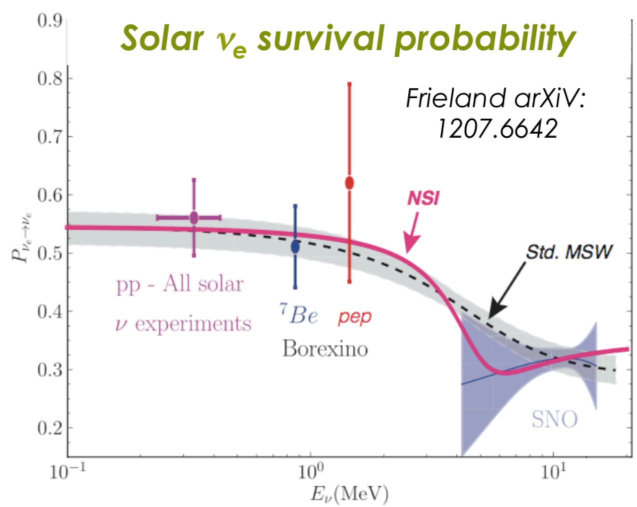
High Z   Low Z

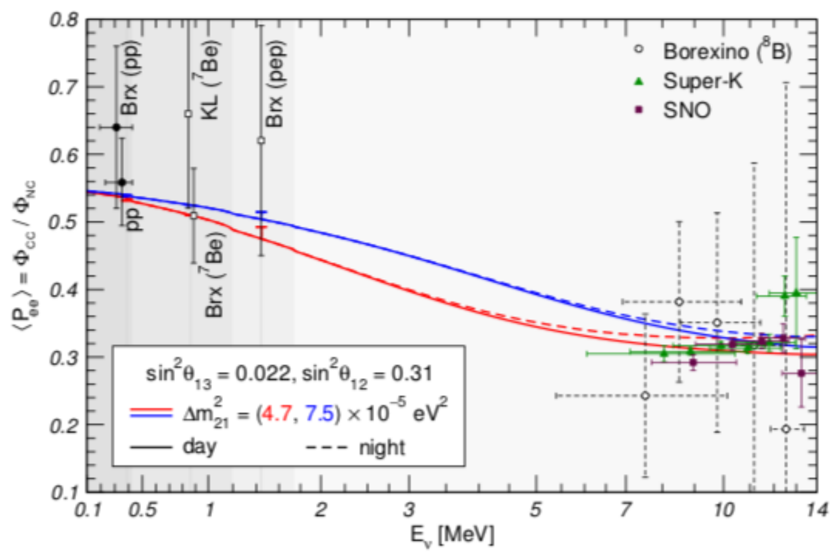
FLUX	B16-GS98	B16-AGSs09met	DIFF. (HZ-LZ)/HZ
pp (10^{10} cm^{-2} s^{-1})	5.98(1±0.006)	6.03(1±0.005)	-0.8%
pep (10^{8} cm^{-2} s^{-1})	1.44(1±0.01)	1.46(1±0.009)	-1.4%
^{7}Be (10^{9} cm^{-2} s^{-1})	4.94(1±0.06)	4.50(1±0.06)	8.9%
^{8}B (10^{6} cm^{-2} s^{-1})	5.46(1±0.12)	4.50(1±0.12)	17.6%
^{13}N (10^{8} cm^{-2} s^{-1})	2.78(1±0.15)	2.04(1±0.14)	26.6%
^{15}O (10^{8} cm^{-2} s^{-1})	2.05(1±0.17)	1.44(1±0.16)	29.7%
^{17}F(10^{6} cm^{-2} s^{-1})	5.29(1±0.20)	3.26(1±0.18)	38.3%

Why it is still interesting to study Solar Neutrinos?

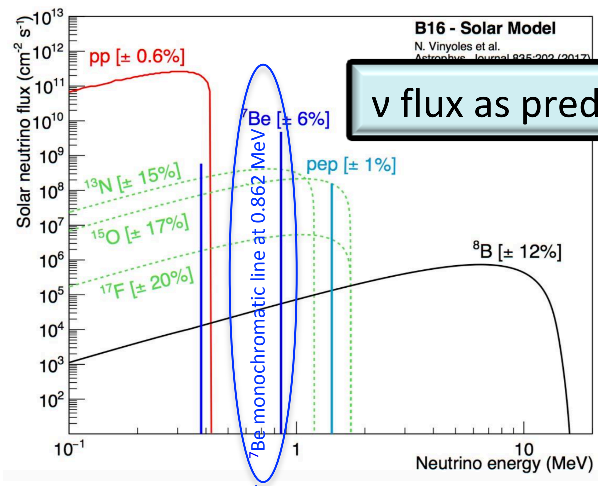
Studying **Neutrinos proprieties** with the Sun

- Improve the **precision** of the neutrino oscillation parameters (**θ_{12}** and **Δm_{12}^2**)
- Searching for **deviations** from **MSW-LMA** (e.g. **NSI** - non-standard neutrino interactions models, sub-leading effects, mixing with light sterile neutrinos)
- Anomalous **magnetic moment** neutrinos





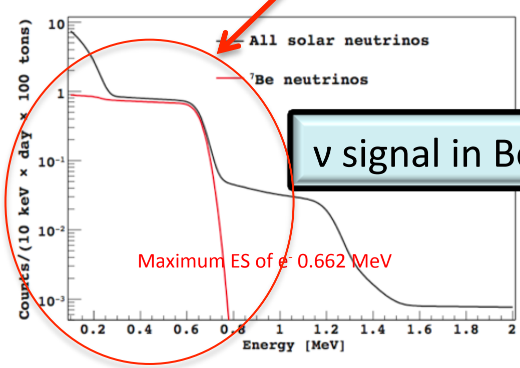
Solar Spectroscopy with Borexino



ν flux as predicted by SSM

<u>Detection principle</u>: elastic scattering (ES) on electrons

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



ν signal in Borexino

It is impossible to disentangle electron from beta decay from scattered electron from neutrino.

Radiochemical experiments (*Homestake, Gallex, SAGE*) integrate in <u>time</u> and <u>energy</u>.

H_2O & D_2O Real time experiments (*Kamiokande, SuperK, SNO*) can detect solar neutrinos starting from about <u>3-4 MeV</u>.

Liquid Scintillator Detector able to measures solar neutrinos in real time with a low energy threshold.

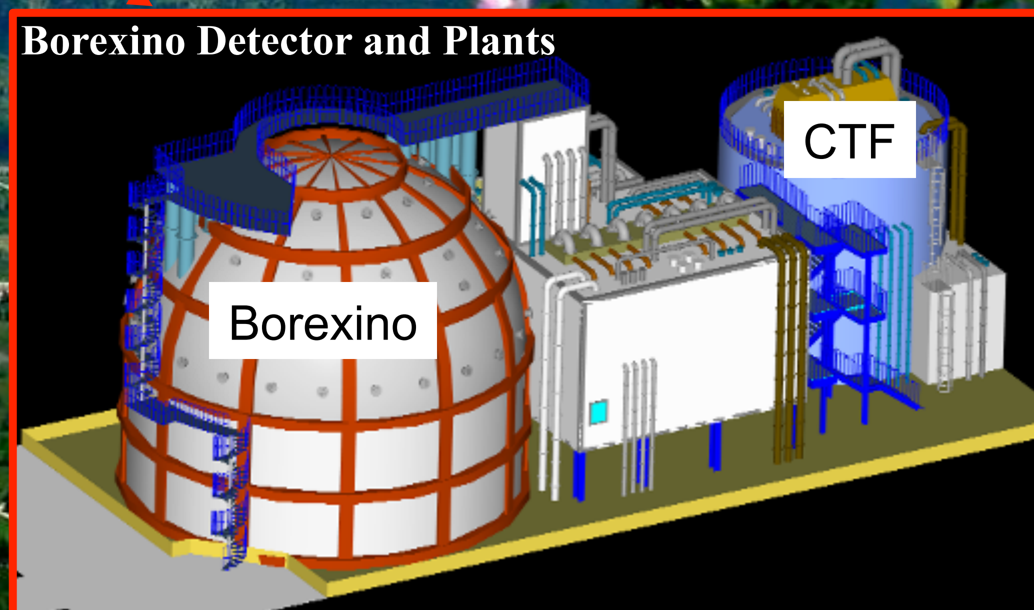
<u>Neutrino signal</u>:
is on the order of ≈ 50 events/day/100 tons above threshold. This means **10^{-9} events/(kg s)**

$$\frac{\text{Signal}(\nu)}{\text{Noise}(\text{BKG})} \approx 1$$

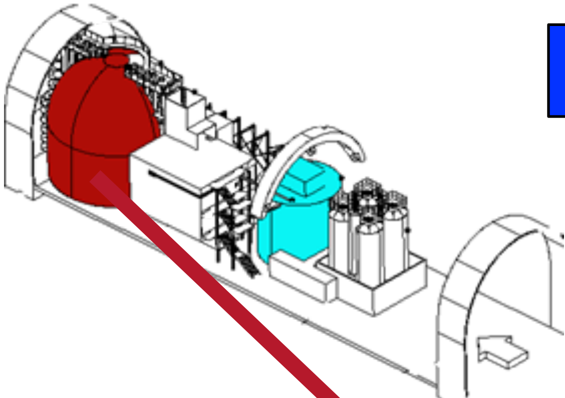
10 orders of magnitude!

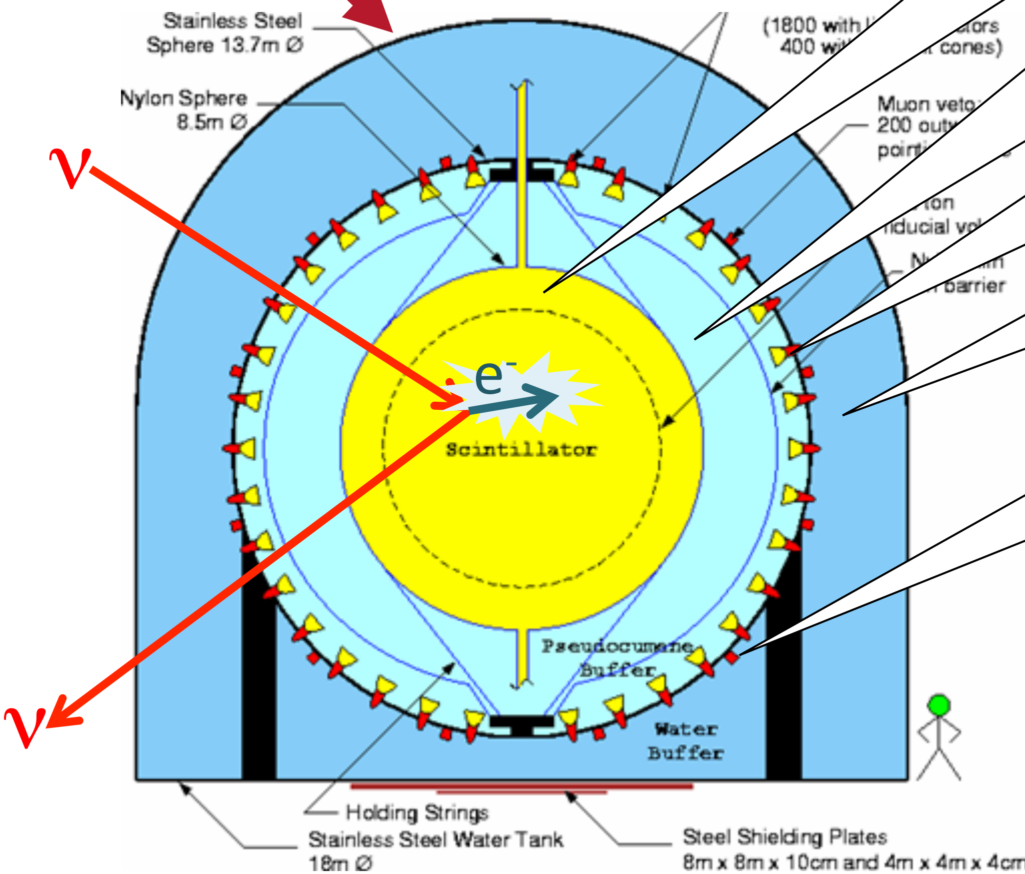
<u>Radioactive background (ex: ^{238}U)</u>:
The typical concentration of ^{238}U in standard material is of the order of ppm (10^{-6} g/g). 1 g of ^{238}U corresponds to about 12500 Bq
This means that in 1 kg of material we have about 10 Bq of radioactivity. This means **10 events/(kg s)**

Laboratori Nazionali del Gran Sasso (LNGS)



Borexino design





Core of the detector: 300 tons of liquid scintillator (PC+PPO) contained in a nylon vessel of 8.5 m diameter. The thickness of nylon is 125 μm.

1st shield: 1000 tons of ultra-pure buffer liquid (PC+DMP) contained in a stainless steel sphere of 13.7 m diameter (SSS).

2200 photomultiplier tubes pointing towards the center to view the light emitted by the scintillator.

2nd shield: 2400 tons of ultra-pure water contained in a cylindrical dome.

200 photomultiplier tubes mounted on the SSS pointing outwards to detect Cerenkov light emitted in the water by muons.

Scintillation light detected by PMT's
- \# of photons → **energy**
- time of flight → **position**
- pulse shape → **α/β β⁺/β⁻ discrim.**

Light yield: ~500 phe/MeV

Energy resolution: 5% @ 1MeV

Space resolution: 10 cm @ 1MeV

Borexino Phase II

^{7}Be, pep, ^{8}B,
geo ν,
Rare process.

Improved radiopurity:

^{85}Kr: reduced by ~4.6

^{210}Bi: reduced by ~2.3

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

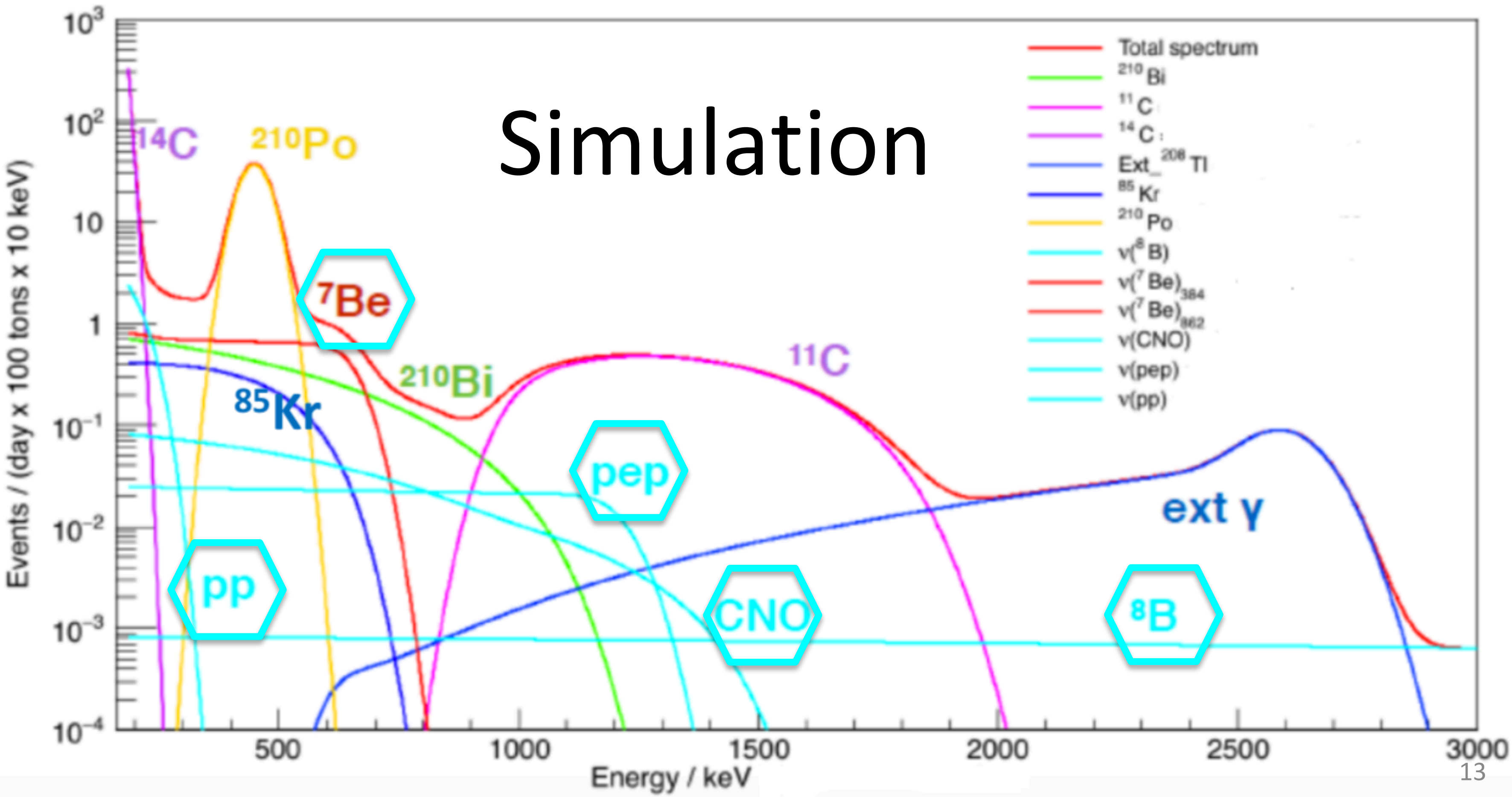
^{232}Th: < $5.7 \cdot 10^{-19}$ g/g (95% C.L.)

The ***New phase II data*** consists in a:
- Background reduction;
- Larger exposure;
- More accurate description of detector response

- **Spectral measurement of the pp rate** (*Nature, Vol. 512 2014*)
- **Seasonal modulations of the ^{7}Be solar neutrino signal** *(Astr.Phys. 92 (2017) 21)*
- **First Simultaneous Precision Spectroscopy of *pp*, *^{7}Be* and *pep* Solar Neutrinos** *(arXiV:1707.09279)*
- **Improved measurement of ^{8}B solar neutrinos with 1.5 kt·y of Borexino exposure** *(arXiV: 1709.0075)*
- **New upper limit on neutrino magnetic moment** *(arXiV:1707.09355)*

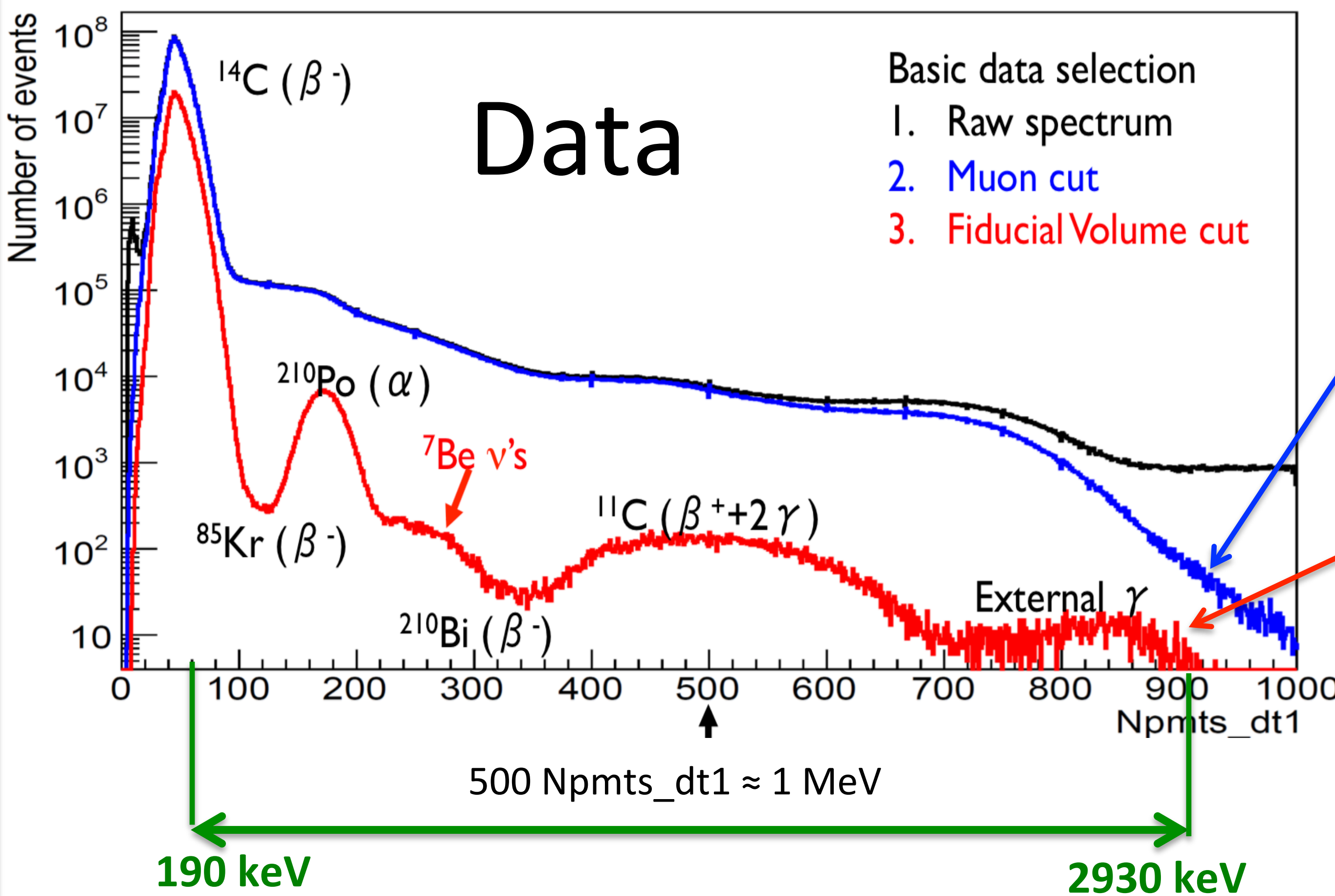
First simultaneous spectroscopy of pp, ^{7}Be and pep-ν

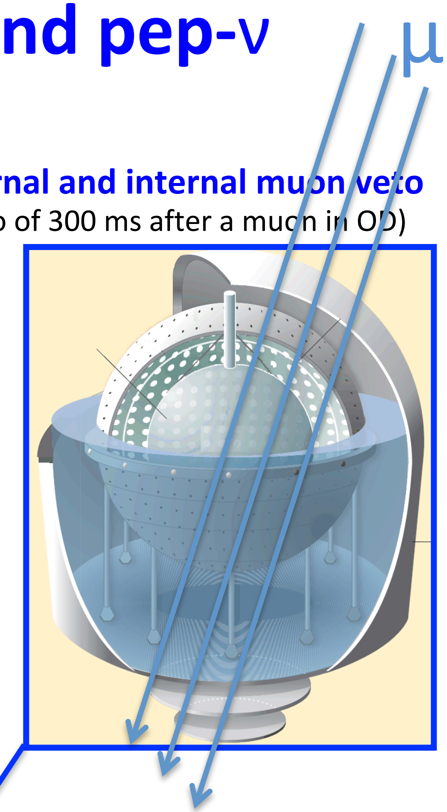
Simulated energy spectrum - solar neutrino signals and main background component in Borexino



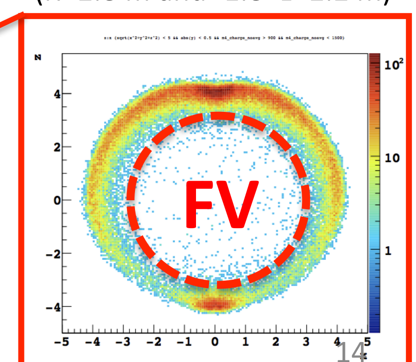
First simultaneous spectroscopy of pp, ^{7}Be and pep-ν

- **Data-set:** Dec 14th 2011- May 21st 2016
- **Total exposure**: 1291.5 days x 71.3 tons= 252.3 ton·year
- **Fit range**: (0.19-2.93) MeV



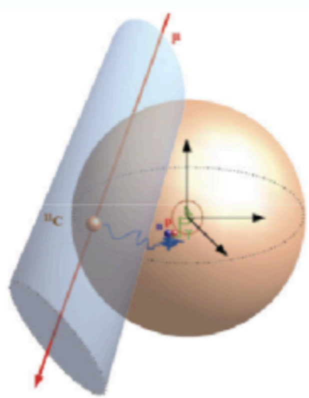


Fiducial volume cut for removing external background
(R<2.8 m and -1.8<z<2.2 m)



First simultaneous spectroscopy of pp, ^{7}Be and pep-ν

^{11}C Tag: Three Fold Coincidence and β^+/β^- discrimination



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

$$n + p \rightarrow \mathrm{D} + \gamma_{2.2\,\mathrm{MeV}} \qquad (250\ \mu\mathrm{s})$$

$$^{11}\mathrm{C} \rightarrow {}^{11}\mathrm{B} + e^+ + \nu_e \qquad (\sim 30\ \mathrm{min})$$

1) the three fold coincidence (TFC)

^{11}C are always produced with neutrons thus their signals are correlated in space and time with a muon and a neutron

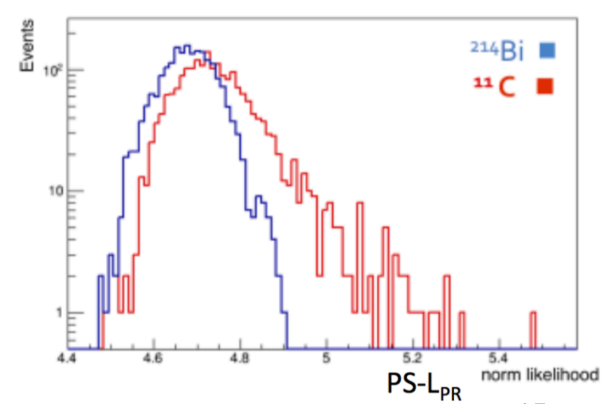
- ^{11}C rejection efficiency: 92 + 4 %
- Residual life time: 64%

The data set is divided in **two spectra**: one depleted in ^{11}C (**TFC - subtracted**) and one enriched in ^{11}C (**TFC-tagged**) which are then simultaneously fit

2) The β^+/β^- pulse-shape variable PS-LPR

^{11}C decays β^+ : the probability density function (PDF) of the scintillation time profile is different for e^- and e^+ for two reasons:

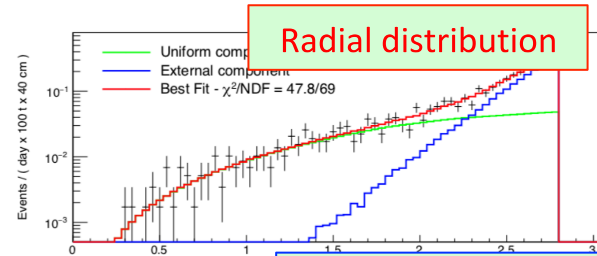
- in 50% of the case e^+ annihilation is delayed by ortho-positronium formation (τ≈3ns);
- e^+ energy deposit is not point-like because of the two annihilation gammas;

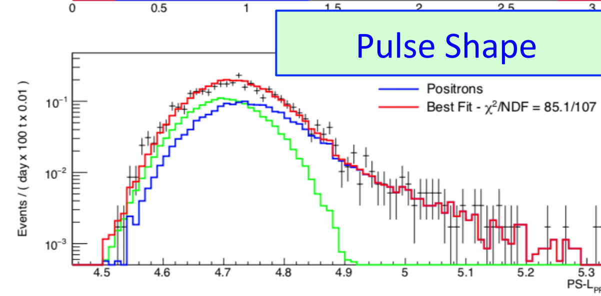


First simultaneous spectroscopy of pp, ^{7}Be and pep-ν
Fit strategy

In order to extract the neutrino signal from data we adopted a strategy that consists in **maximize a binned likelihood** through a multivariate approach

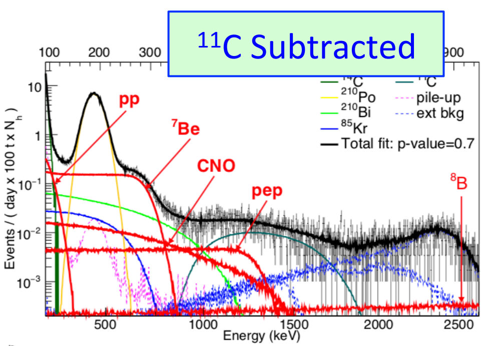
$$L(\vartheta)=\underbrace{L_{11C-sub}(\vartheta)\cdot L_{11C-tag}(\vartheta)\cdot L_{PS}(\vartheta)}_{\text{to disentangle } ^{11}\text{C}}\cdot\underbrace{L_{radial}(\vartheta)}_{\text{to disentangle external BKG}}$$

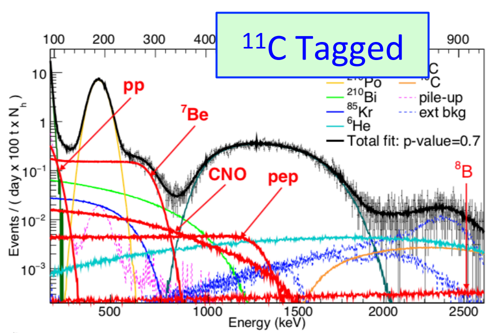




In the likelihood is included:

- Energy spectrum (^{11}C-tagged and ^{11}C-subtracted)
- Pulse-shape distribution PS-*L*PR
- Radial distribution



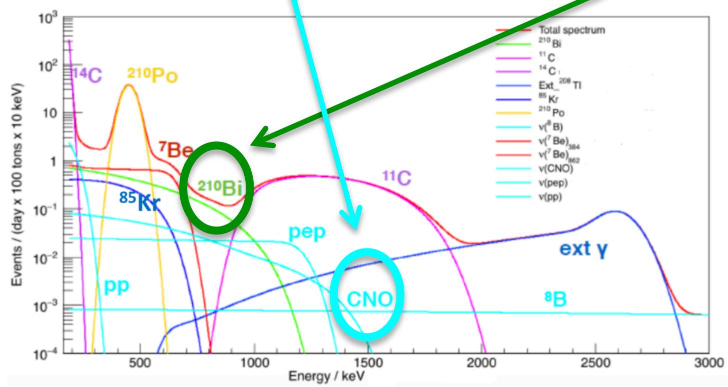


Checks for systematical effects:

- Fit performed in different conditions (energy range, energy variable, binning..);
- Developed a Toy-MC to:
  - Build MC data set with the same exposure as in the data
  - Fit with pdf used to fit the data
  - Check bias, sensitivity, correlations
- Energy fit performed both with the MonteCarlo and the Analytical methods.

First simultaneous spectroscopy of pp, ^{7}Be and pep-ν

Problem: the CNO ν recoil and ^{210}**Bi** have a very similar energy spectrum



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}

Flux	B16-GS98	B16-AGSS09met	Solar[a]	Chg.
Φ(pp)	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.005)$	$5.97^{(1+0.006)}_{(1-0.005)}$	0.0
Φ(pep)	$1.44(1 \pm 0.01)$	$1.46(1 \pm 0.009)$	$1.45^{(1+0.009)}_{(1-0.009)}$	0.0
Φ(hep)	$7.98(1 \pm 0.30)$	$8.25(1 \pm 0.30)$	$19^{(1+0.63)}_{(1-0.47)}$	-0.7
$\Phi(^7$Be)	$4.93(1 \pm 0.06)$	$4.50(1 \pm 0.06)$	$4.80^{(1+0.050)}_{(1-0.046)}$	-1.4
$\Phi(^8$B)	$5.46(1 \pm 0.12)$	$4.50(1 \pm 0.12)$	$5.16^{(1+0.025)}_{(1-0.017)}$	-2.2
$\Phi(^{13}$N)	$2.78(1 \pm 0.15)$	$2.04(1 \pm 0.14)$	$\leqslant 13.7$	-6.1
$\Phi(^{15}$O)	$2.05(1 \pm 0.17)$	$1.44(1 \pm 0.16)$	$\leqslant 2.8$	-8.1
$\Phi(^{17}$F)	$5.29(1 \pm 0.20)$	$3.26(1 \pm 0.18)$	$\leqslant 85$	-4.2

$$\phi_{HZ}(CNO) = 4.88\,(1 \pm 0.11) \cdot 10^8\ cm^{-2} s^{-1}$$
$$\Downarrow$$
$$\text{rate CNO HZ} = 4.92 \pm 0.55\ cpd/100t$$

$$\phi_{LZ}(CNO) = 3.51\,(1 \pm 0.10) \cdot 10^8\ cm^{-2} s^{-1}$$
$$\Downarrow$$
$$\text{rate CNO LZ} = 3.52 \pm 0.37\ cpd/100t$$

Analysis strategy

- **pp ^{7}Be pep** ν flux measurement.

  We set a **constraint of the CNO rate** to the HZ and LZ values
  - *CNO HZ = (4.92 ± 0.55) cpd /100t*
  - *CNO LZ = (3.52 ± 0.37) cpd /100t*

First simultaneous spectroscopy of pp, ^{7}Be and pep-ν (Comparison between Phase I and Phase II results)

Neutrinos	Phase I (cpd/100 t)	Phase II (cpd/100 t)	Uncertainty reduction
pp	144 ± 13 ± 10	**$134 \pm 10\ ^{+6}_{-10}$**	0.78
^{7}Be	48.3 ± 2.0 ± 0.9	**$48.3 \pm 1.1\ ^{+0.4}_{-0.7}$**	0.57

All rates are fully compatible with the ones obtained in Phase I and **improve the uncertainty** of the previously published Borexino results.

The total uncertainty of the pp is ≈10%

The total uncertainty of the ^{7}Be is 2.7%

Solar ν	Borexino experimental results: Rate [cpd/100 t]	Borexino experimental results: Flux [cm^{-2}s^{-1}]
pp	$134 \pm 10\ ^{+6}_{-10}$	$(6.1 \pm 0.5\ ^{+0.3}_{-0.5}) \times 10^{10}$
^{7}Be	$48.3 \pm 1.1\ ^{+0.4}_{-0.7}$	$(4.99 \pm 0.11\ ^{+0.06}_{-0.08}) \times 10^{9}$

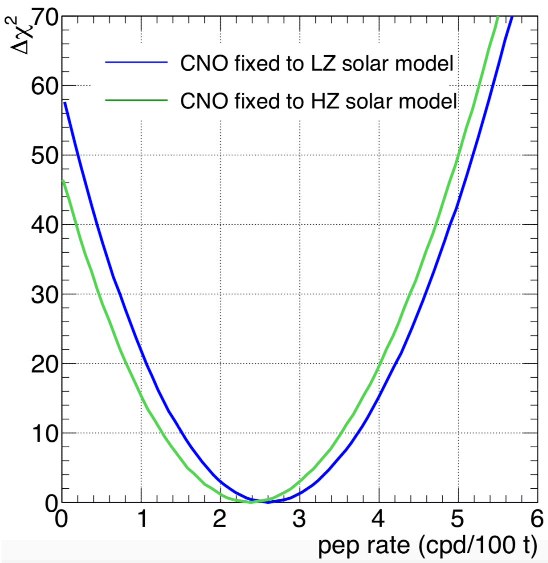
First simultaneous spectroscopy of pp, ^{7}Be and pep-ν

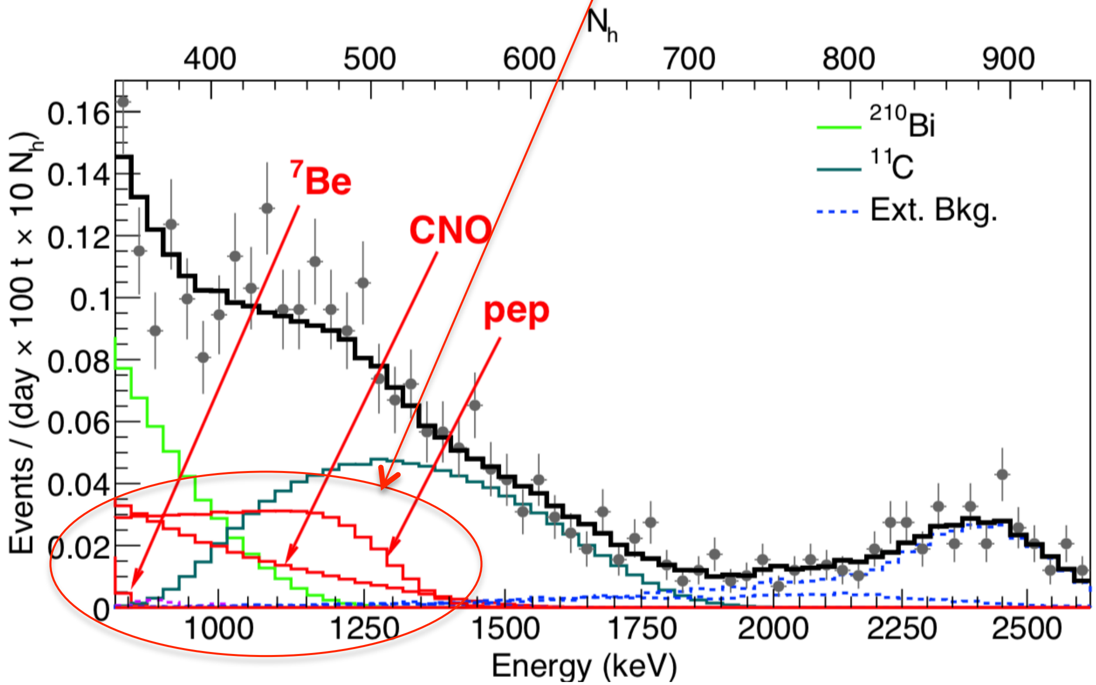
evidence of **pep ν at 5σ**

The characteristic Compton-like shoulder in the electron-recoil spectrum visible in the plot is due to pep ν interactions.

Likelihood profile resulting from the multivariate fit for pep ν rates

(*systematical uncertainties included*)





TFC-subtracted energy spectrum zoomed between 800 keV and 2700 keV after applying stringent selection cuts on the radial distribution (R<2.4m) and on the pulse- shape variable distribution (PS-L_{PR} <4.8).

First simultaneous spectroscopy of pp, ^{7}Be and pep-ν upper limit on the CNO flux

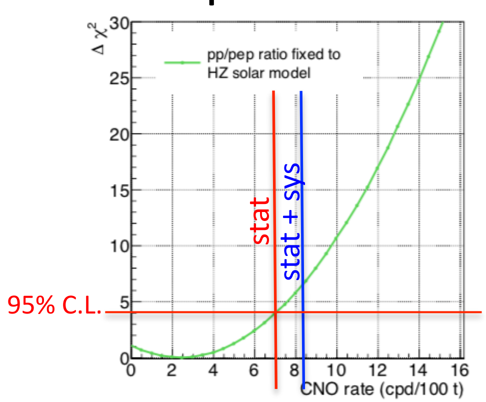
In the current analysis, where pp ν's are included in the extended energy range, we place an **indirect constraint on pep ν's** by exploiting the theoretically well known pp and pep flux ratio.

$$R\left(\frac{pp}{pep}\right) = 47.8 \pm 0.8 \;\; (HZ)^{(*)}$$

(*) Constraining R(pp/pep) to the LZ hypothesis value 47.5 ± 0.8 gives identical results.

Solar ν	Borexino experimental results		B16(GS98)-HZ		B16(AGSS09)-LZ	
	Rate [cpd/100 t]	Flux [cm^{-2}s^{-1}]	Rate [cpd/100 t]	Flux [cm^{-2}s^{-1}]	Rate [cpd/100 t]	Flux [cm^{-2}s^{-1}]
pp	$134 \pm 10\,^{+6}_{-10}$	$(6.1 \pm 0.5\,^{+0.3}_{-0.5}) \times 10^{10}$	131.1 ± 1.4	$5.98\,(1 \pm 0.006) \times 10^{10}$	132.2 ± 1.4	$6.03\,(1 \pm 0.005) \times 10^{10}$
^{7}Be	$48.3 \pm 1.1\,^{+0.4}_{-0.7}$	$(4.99 \pm 0.11\,^{+0.06}_{-0.08}) \times 10^{9}$	47.9 ± 2.8	$4.93\,(1 \pm 0.06) \times 10^{9}$	43.7 ± 2.5	$4.50\,(1 \pm 0.06) \times 10^{9}$
pep (HZ)	$2.43 \pm 0.36\,^{+0.15}_{-0.22}$	$(1.27 \pm 0.19\,^{+0.08}_{-0.12}) \times 10^{8}$	2.74 ± 0.04	$1.44\,(1 \pm 0.009) \times 10^{8}$	2.78 ± 0.04	$1.46\,(1 \pm 0.009) \times 10^{8}$
pep (LZ)	$2.65 \pm 0.36\,^{+0.15}_{-0.24}$	$(1.39 \pm 0.19\,^{+0.08}_{-0.13}) \times 10^{8}$	2.74 ± 0.04	$1.44\,(1 \pm 0.009) \times 10^{8}$	2.78 ± 0.04	$1.46\,(1 \pm 0.009) \times 10^{8}$
CNO	< 8.1 (95% C.L.)	$< 7.9 \times 10^{8}$ (95% C.L.)	4.92 ± 0.55	$4.88\,(1 \pm 0.11) \times 10^{8}$	3.52 ± 0.37	$3.51\,(1 \pm 0.10) \times 10^{8}$

Likelihood profile for CNO ν rates



95% C.L. limit on the CNO-ν rate:

Rate < 8.1 cpd/100t

Flux < 7.9 10^8 cm^{-2} s^{-1}

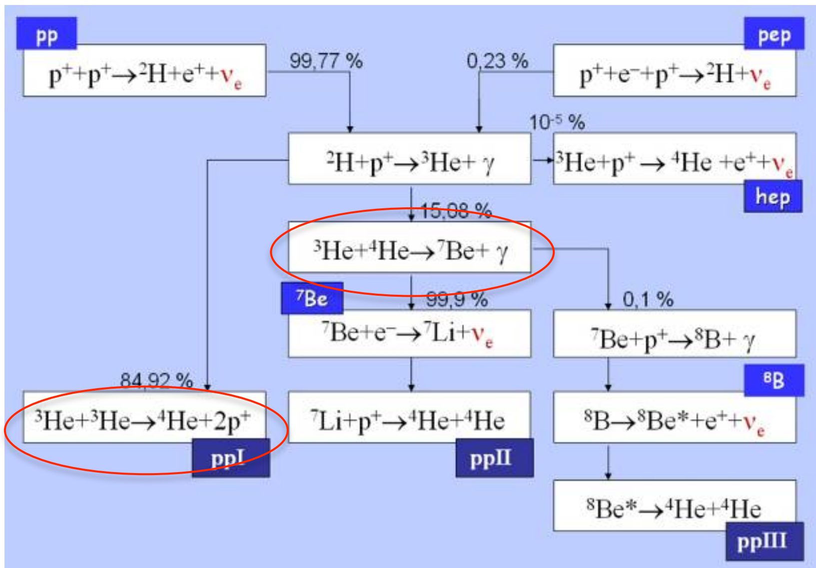
(including systematical uncertainties)

First simultaneous spectroscopy of pp, ^{7}Be and pep-ν
(Comparison between Phase I and Phase II results)

Neutrinos	Phase I (cpd/100 t)	Phase II (cpd/100 t)	Uncertainty reduction
pp	$144 \pm 13 \pm 10$	**$134 \pm 10\ ^{+6}_{-10}$**	0.78
^{7}Be	$48.3 \pm 2.0 \pm 0.9$	**$48.3 \pm 1.1\ ^{+0.4}_{-0.7}$**	0.57
pep	$3.1 \pm 0.6 \pm 0.3$	**(HZ) $2.43 \pm 0.36\ ^{+0.15}_{-0.22}$** **(LZ) $2.65 \pm 0.36\ ^{+0.15}_{-0.24}$**	0.61
CNO	(Phase I + Phase II)	**< 8.1 (95% C.L.)**	

Solar ν	Borexino experimental results	
	Rate [cpd/100 t]	Flux [cm^{-2}s^{-1}]
pp	$134 \pm 10\ ^{+6}_{-10}$	$(6.1 \pm 0.5\ ^{+0.3}_{-0.5}) \times 10^{10}$
^{7}Be	$48.3 \pm 1.1\ ^{+0.4}_{-0.7}$	$(4.99 \pm 0.11\ ^{+0.06}_{-0.08}) \times 10^{9}$
pep (HZ)	$2.43 \pm 0.36\ ^{+0.15}_{-0.22}$	$(1.27 \pm 0.19\ ^{+0.08}_{-0.12}) \times 10^{8}$
pep (LZ)	$2.65 \pm 0.36\ ^{+0.15}_{-0.24}$	$(1.39 \pm 0.19\ ^{+0.08}_{-0.13}) \times 10^{8}$
CNO	< 8.1 (95% C.L.)	$< 7.9 \times 10^{8}$ (95% C.L.)

First simultaneous spectroscopy of pp, ^{7}Be and pep-ν probe solar fusion with ν-flux rates



The competition between pp-I and pp-II branches of the pp chain is given by the ratio:

$$R \equiv \frac{{}^3He + {}^4He}{{}^3He + {}^3He} = \frac{2\Phi({}^7Be)}{\Phi(pp) - \Phi({}^7Be)}$$

J. Bahcall 2003

From the pp and ^{7}Be fluxes it is possible to determine the ratio R. This is an important experimental test of the solar fusion

Theoretical predictions

$(G.Pena\text{–}Garay)$

$$R = 0.180 \pm 0.011 \quad (High\,Z)$$

$$R = 0.161 \pm 0.010 \quad (Low\,Z)$$

Measured value

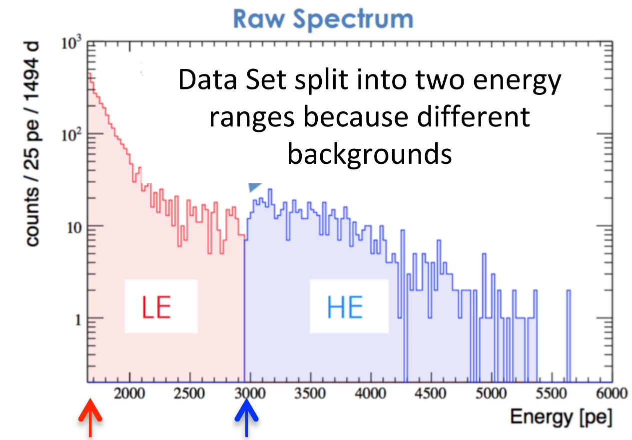
$(Borexino)$

$$R = 0.18 \pm 0.03$$

A hint toward the high metallicity!?

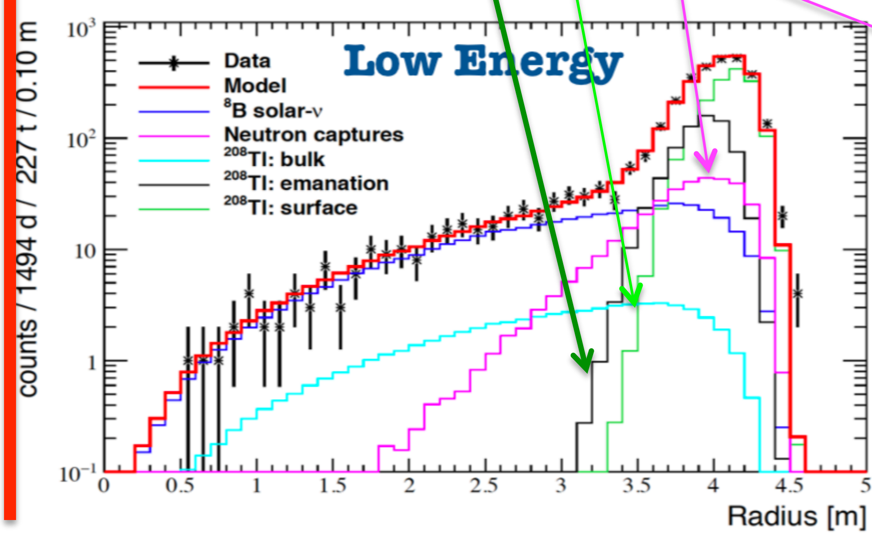
Improved measurement of ^{8}B solar neutrinos with 1.5 kt·y

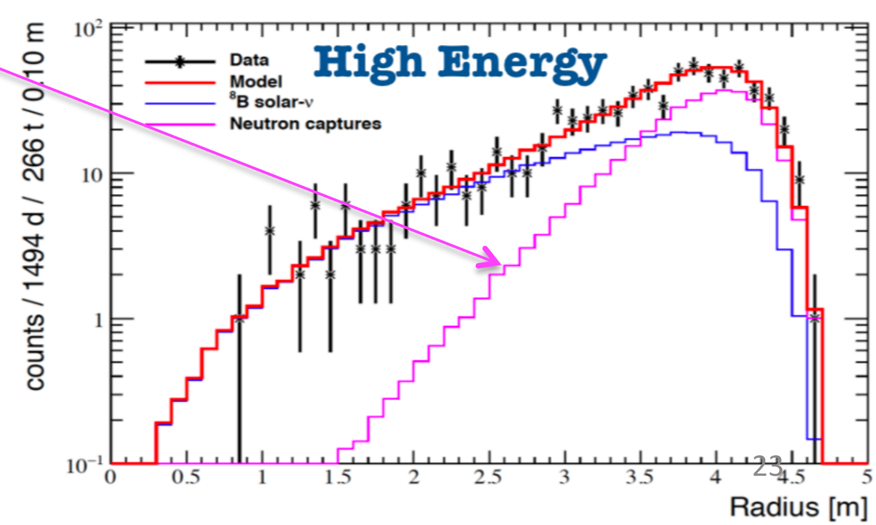
- **Data-set:** January 2008 - December 2016 (Purification period removed)
- **Total exposure**: 1.5 kton x years (11.5-fold increase from Phase I)
- **Extending the fiducial mass** (~100 t) to the entire active mass (~300 t)
- **Fit range**: 3.2 -17 MeV
- **Fit of radial distribution** performed with the MonteCarlo, split into **Low Energy ([1650, 2950] p.e.** and **High Energy ([2950, 8500] p.e.**



no natural radioactivity in the HE event sample!

- U/Th chain elements on the vessel (only ^{208}Tl ranges above 3.2 MeV)
- Emanation of ^{220}Rn from the vessel (additional ^{208}Tl component)
- High-energy gamma-rays (from neutron capture on Fe/C)





Improved measurement of ^{8}B solar neutrinos with 1.5 kt·y

$$R_{LE} = 0.133^{+0.013}_{-0.013}\,(stat)\,^{+0.003}_{-0.003}\,(syst)\ \mathrm{cpd}/100\,\mathrm{t},$$

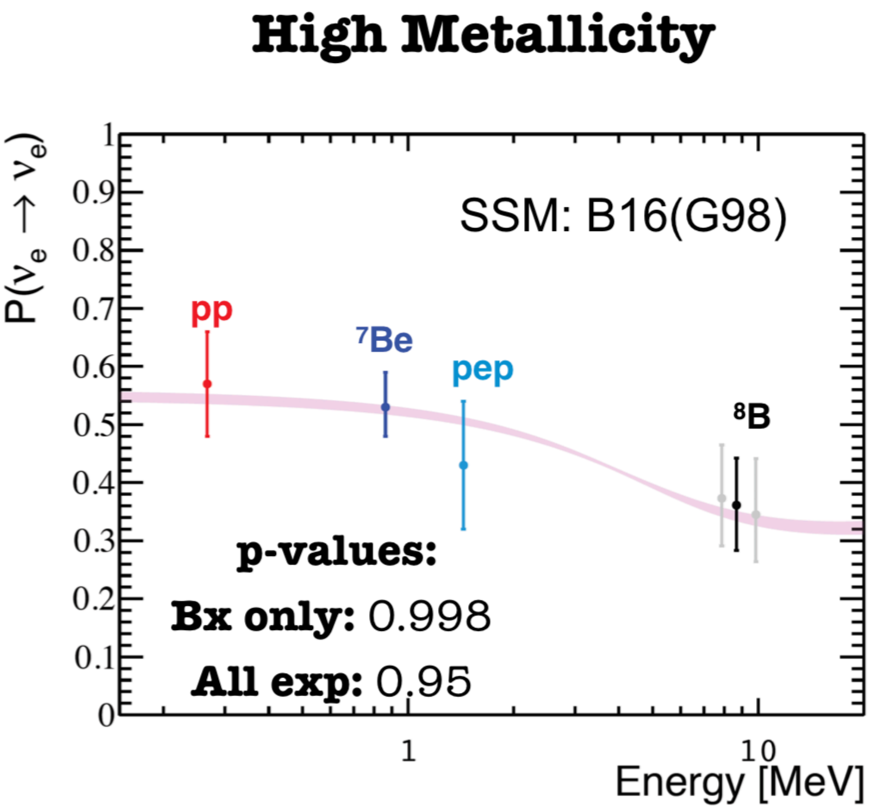
$$R_{HE} = 0.087^{+0.08}_{-0.010}\,(stat)\,^{+0.005}_{-0.005}\,(syst)\ \mathrm{cpd}/100\,\mathrm{t},$$

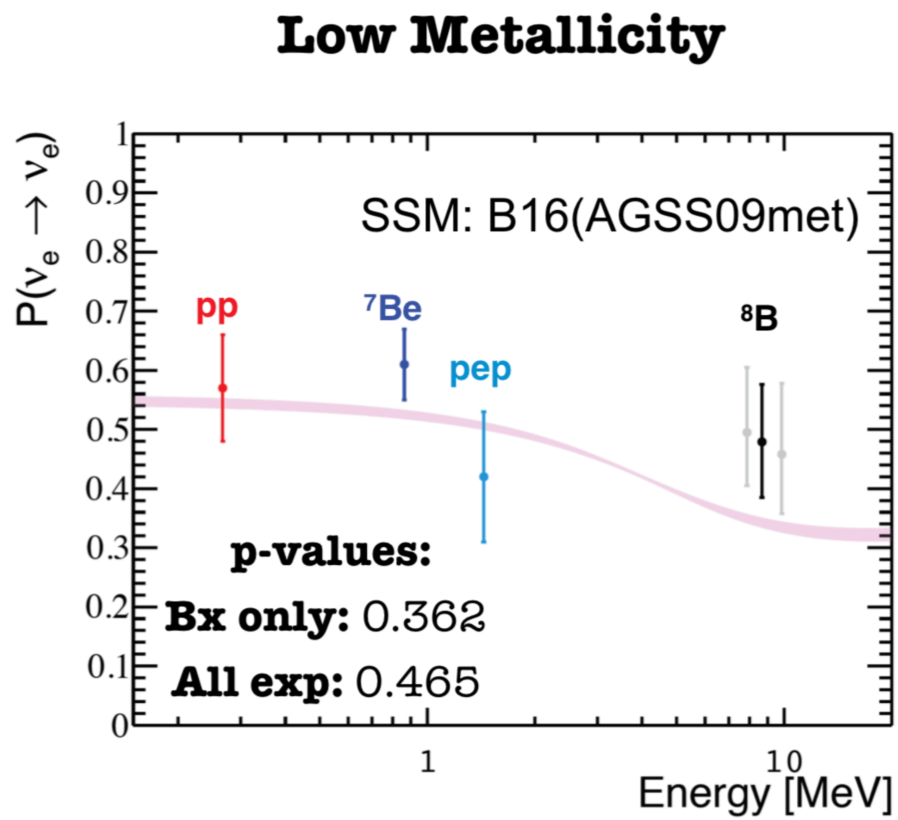
$$R_{LE+HE} = 0.220^{+0.015}_{-0.016}\,(stat)\,^{+0.006}_{-0.006}\,(syst)\ \mathrm{cpd}/100\,\mathrm{t}.$$

Neutrinos	Phase I (cpd/100 t)	Phase II (cpd/100 t)	Uncertainty reduction
pp	144 ± 13 ± 10	**$134 \pm 10\ ^{+6}_{-10}$**	0.78
^{7}Be	48.3 ± 2.0 ± 0.9	**$48.3 \pm 1.1\ ^{+0.4}_{-0.7}$**	0.57
pep	3.1 ± 0.6 ± 0.3	**(HZ) $2.43 \pm 0.36\ ^{+0.15}_{-0.22}$** **(LZ) $2.65 \pm 0.36\ ^{+0.15}_{-0.24}$**	0.61
CNO	(Phase I + Phase II)	**< 8.1 (95% C.L.)**	
^{8}B	0.217 ± 0.038 ± 0.008	**$0.220\ ^{+0.015}_{-0.016} \pm 0.006$**	0.42

The precision on the LE+HE ^{8}B rate measurement is ~8%, improved by more than a factor 2 with respect to our previous result

Neutrino survival probability P_{ee}



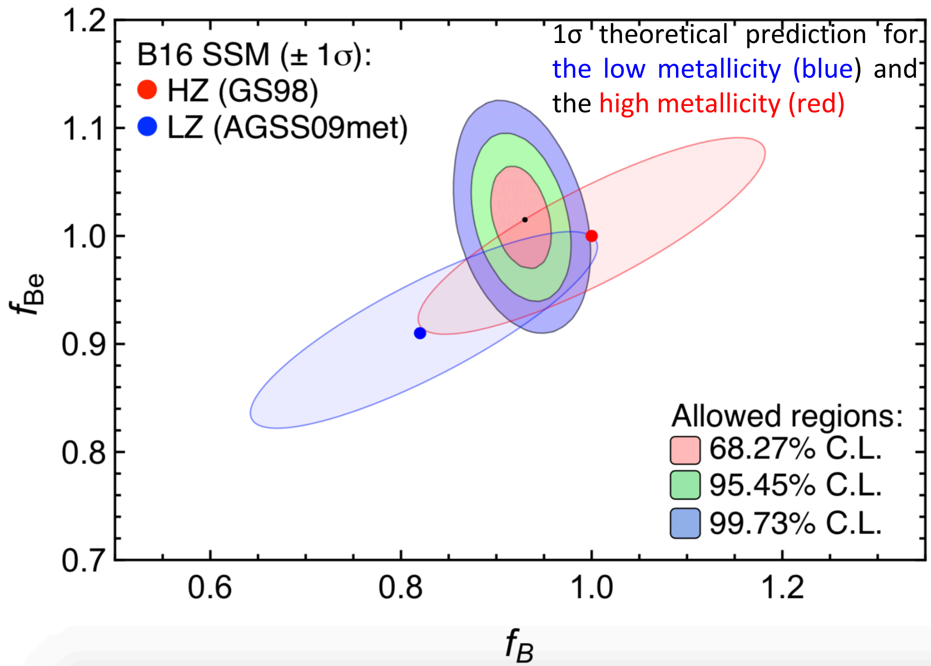


Electron neutrino survival probability as function of the neutrino energy, assuming the high-Z B16(GS98) SSM or low-Z B16(AGSS09met) SSM and the flavor conversion parameters from the MSW-LMA solution (Δm^2_{12} =7.50×10^{-5} eV^2 , tan^2 θ_{12} =0.441, and tan^2 θ_{13} =0.022).

Dots represent the Borexino results from **pp (red)**, **^{7}Be (blue)**, **pep (azure)**, and **^{8}B** neutrino measurements (black for the LE+HE range, and grey for the separate sub-ranges).

Implications for solar metallicity

Currently, **$\phi(^8B)$** and **$\phi(^7Be)$** are the fluxes most precisely determined experimentally, and can be used to perform a simple test of the models.
Furthermore, these are also the two fluxes from the pp-chains that are most sensitive to temperature, i.e., to the conditions in the solar core and the inputs in solar models.



$$p-value\,(HZ) = 0.87$$

$$p-value\,(LZ) = 0.11$$

A hint toward the high metallicity!?

Allowed contours in the **reduced fluxes f_{Be}-f_B** parameter space obtained by combining the new Borexino result on ^{7}Be ν's with solar and KamLAND data.

$$f_{Be} = \frac{\phi(^7Be)}{\phi(^7Be)_{HZ}} = 1.01 \pm 0.03$$

$$f_B = \frac{\phi(^8B)}{\phi(^8B)_{HZ}} = 0.93 \pm 0.02$$

- Note: only 1σ theoretical uncertainty in the plot

- Important to reduce the theoretical uncertainty!

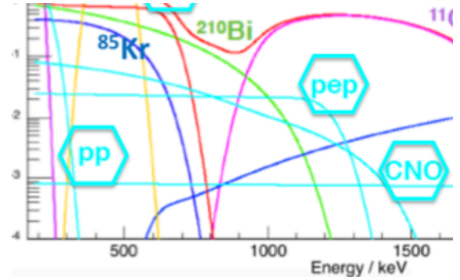
Sensitivity to CNO

Motivations:

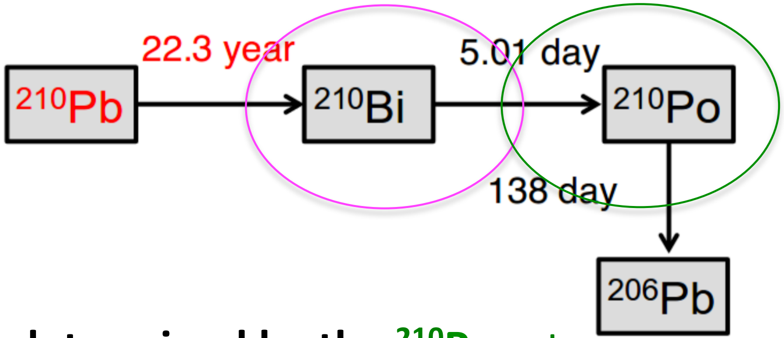
- CNO neutrinos have never been detected
  According to astrophisical models, CNO cycle is responsible of ~1% of the solar luminosity and it is the main mechanism of energy generation in massive stars.
- CNO neutrinos measurement will allows to complete the SSM and stellar astrophysics.
- A solution for the solar metallicity problem.
  Relative species predicted by nuclear physics, absolute abundance still unknown.

Experimental challenges:

- Low rate expected in Borexino: ~5 cpd/100t (HZ) or ~3 cpd/100t (LZ)
- Almost degenerate with ^{210}**Bi** beta spectrum
- Same region as **pep** (but correlation pp-pep can help!)

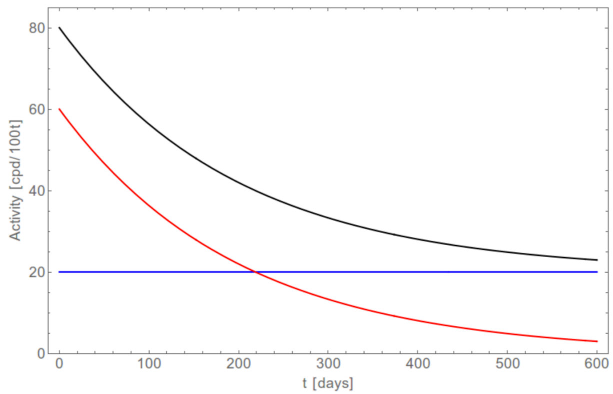


Sensitivity to CNO
^{210}Bi independent constraint



Assuming the **secular equilibrium** the ^{210}Bi rate **can be determined by the** ^{210}**Po** rate
[F. Villante et al. Phys.Lett. B701 (2011) 336-341]

CNO



Example:
– Total rate A(t)
– Unsupported ^{210}Po term A
– ^{210}Bi-supported ^{210}Po term B

$$A(t) = (A_0 - B_0)\, e^{-\frac{t}{\tau_{Po}}} + B_0$$

But, in order to determine the ^{210}**Po** rate:

The **contaminants** must be **homogeneous** and we have to have **no motions** of the contaminants in the FV (due to convention motions) -> **stable temperature**

Sensitivity to CNO

The thermal insulation and temperature active control system

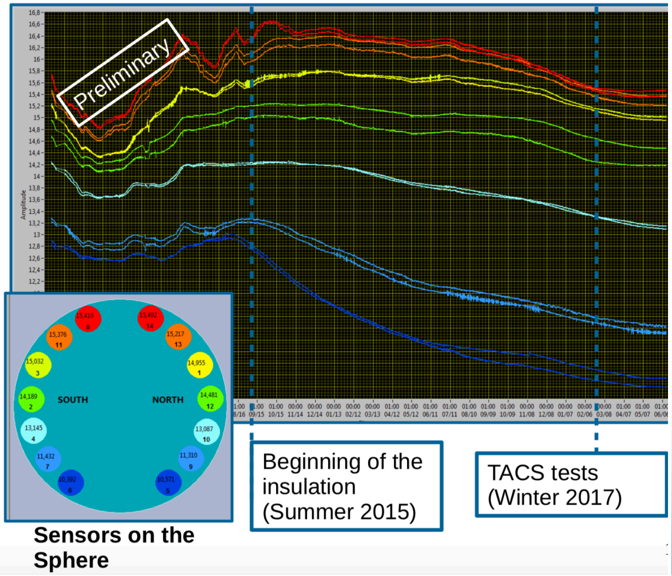
CNO

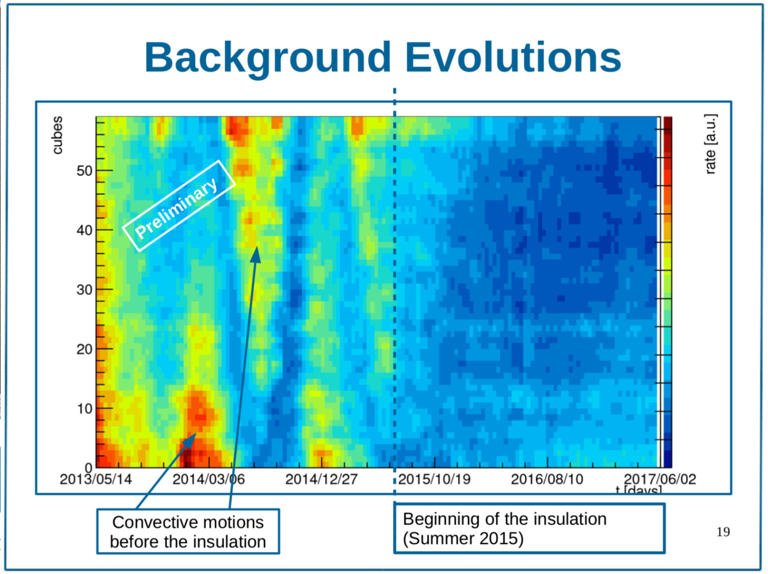
Since the end of 2015 the detector is surrounded by a thick layer of **rock wool**.

Before thermal insulation

After thermal insulation

The dome of Borexino is equipped with a **water coil** able to provide heat for compensating the heat sink from the bottom (rock at ~6°C)





Conclusion and Outlook

- Borexino Phase II result are based on a cleaner data set; the analysis contain many methodical improvements: Improved precision on pp, ^{7}Be, pep and ^{8}B neutrinos.

- Still missing: combined analysis of Phase I + Phase II data set.

- Attempt to measure the CNO neutrinos.

- Others non solar neutrino measurement:
  - Geo-neutrinos,
  - Supernova neutrino,
  - unknown anti-neutrinos fluxes,
  - non-standard searches (neutrino magnetic moment, Non Standard Interaction, ecc…)

Thank you

Borexino Collaboration

UNIVERSITÀ DEGLI STUDI DI MILANO

INFN

LNGS

PRINCETON UNIVERSITY

UNIVERSITÀ DEGLI STUDI DI GENOVA

NATIONAL RESEARCH CENTER "KURCHATOV INSTITUTE"

St. Petersburg Nuclear Physics Inst.

TUM Technische Universität München

UH University of Houston

JAGIELLONIAN UNIVERSITY IN KRAKÓW

JÜLICH FORSCHUNGSZENTRUM

Virginia Tech

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

UHH Universität Hamburg

НИИЯФ МГУ SKOBELTSYN INSTITUTE OF NUCLEAR PHYSICS LOMONOSOV MOSCOW STATE UNIVERSITY

UNIVERSITY OF MASSACHUSETTS AMHERST 1863

Joint Institute for Nuclear Research

GSSI GRAN SASSO SCIENCE INSTITUTE CENTER FOR ADVANCED STUDIES Istituto Nazionale di Fisica Nucleare

UNIVERSITÀ DEGLI STUDI DI FERRARA

THE UNIVERSITY OF CALIFORNIA UCLA

TECHNISCHE UNIVERSITÄT DRESDEN

APC

STUDIUM GENERALE CIVITATIS PERUSII A.D. MCCCVIII

POLITECNICO MILANO 1863