Vulcano Workshop 2018 - Frontier Objects in Astrophysics and Particle Physics

LOW ENERGY SOLAR NEUTRINOS WITH BOREXINO

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on behalf of the Borexino collaboration

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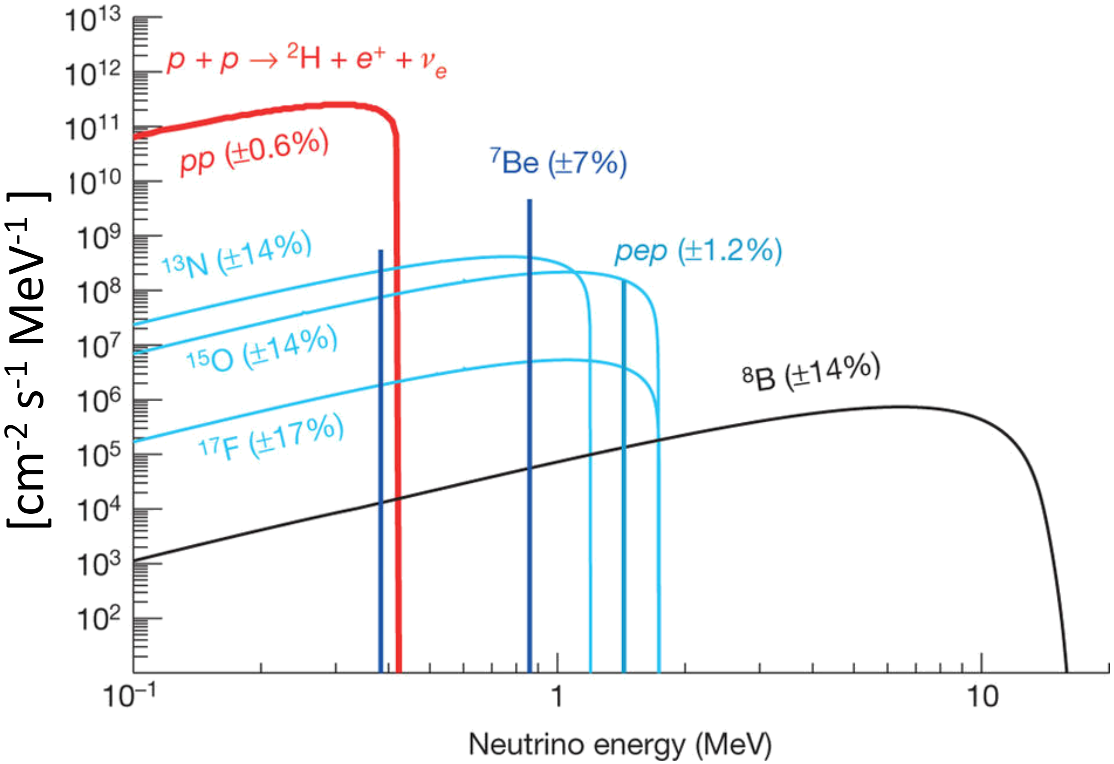
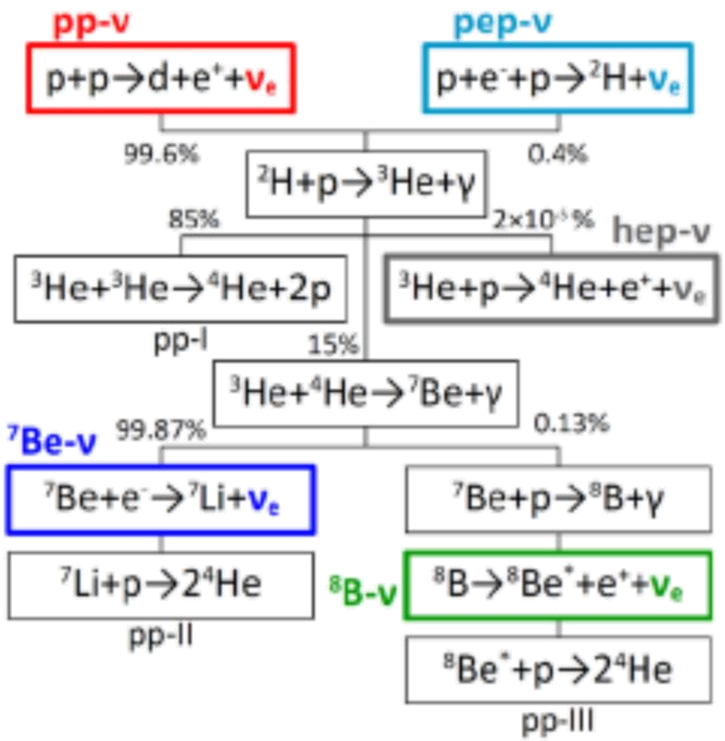
SOLAR NEUTRINOS

Electrons neutrinos are produced by the nuclear fusion in the star:

- pp chain ≈ 99 % of Sun energy
- CNO chain



pp chain



THE IMPORTANCE OF SOLAR NEUTRINOS

- **IN THE PAST:**
  Deficit on observed flux
  → Discovery of flavor oscillation
  The deficit depends on energy
  → MSW effect

EXPERIMENTS:
- Radiochemical experiment,
- Cherenkov detector:
  Kamiokande
  SuperKamiokande
  SNO

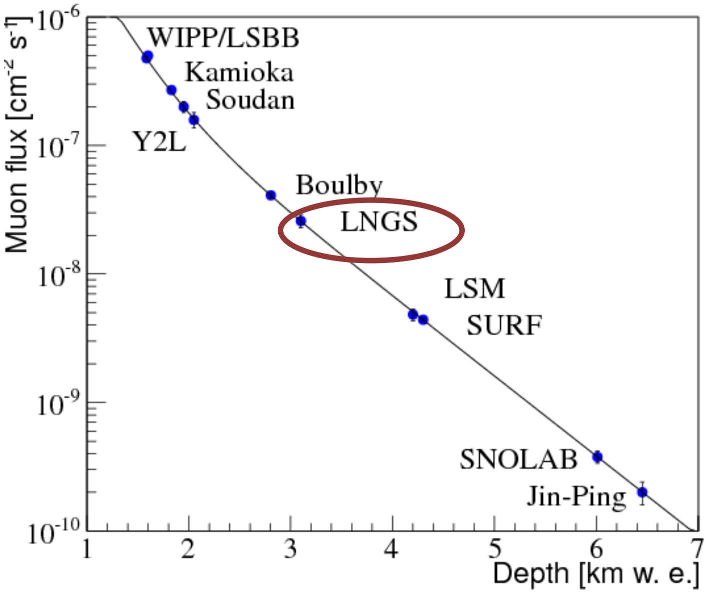
- **NOW and FUTURE**: the precision era
  - for testing solar model
    (high or low metallicity model)
  - for a deep comprehension of stars and neutrino physics

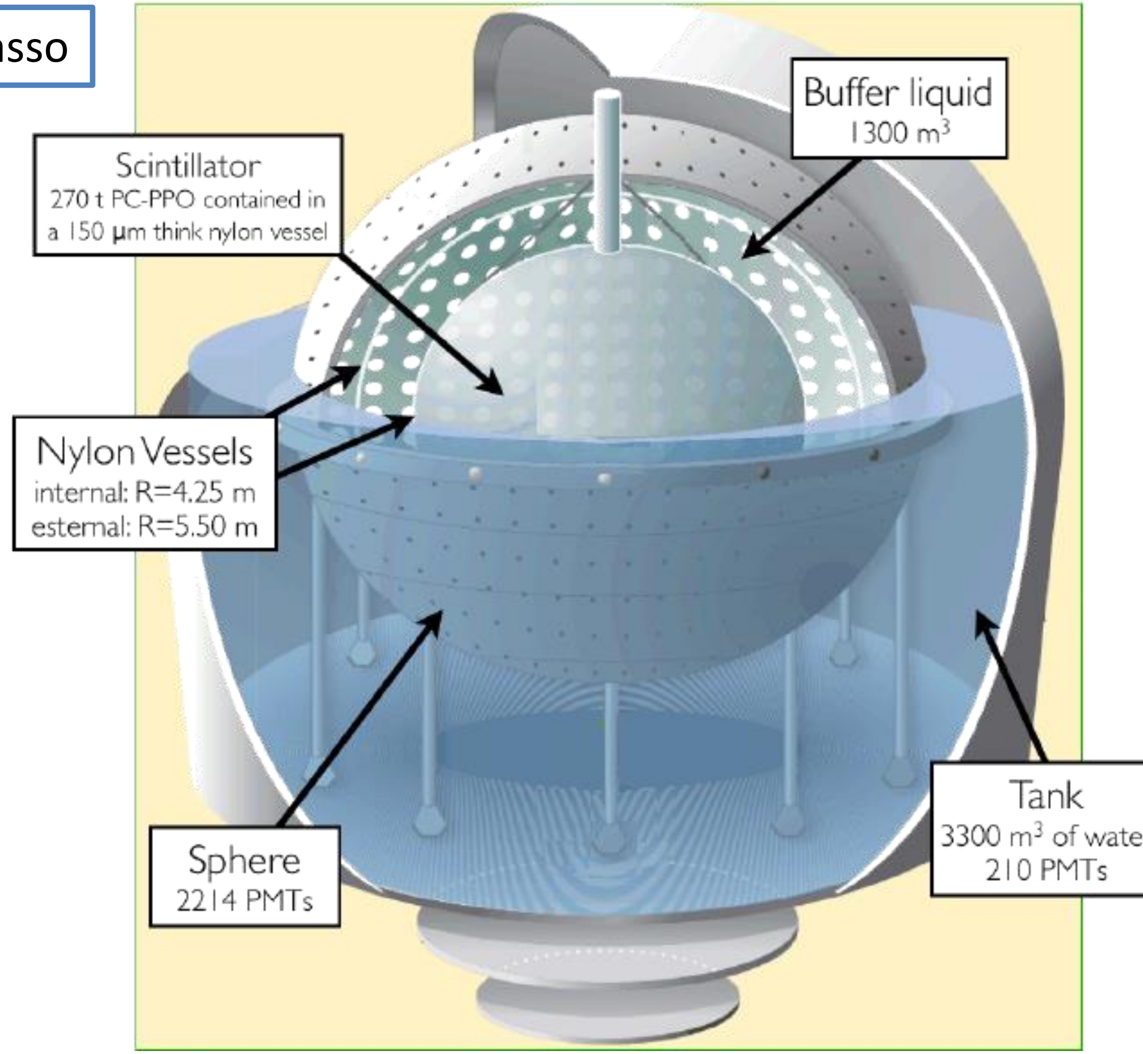
EXPERIMENTS:
(Kamland)
SuperKamiokande
Borexino

the only one in the **sub-MeV** region!

THE BOREXINO DETECTOR

At the Laboratori Nazionali del Gran Sasso





Borexino history:

Construction: up to 2007

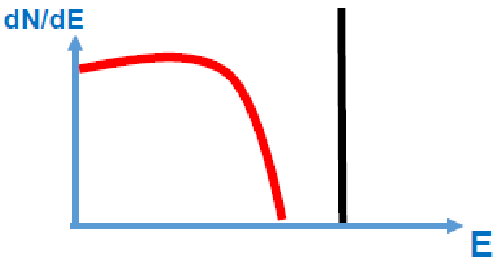
Phase I: 2007-2014

Phase II: 2014-2016

the data taking is continuing

THE BOREXINO DETECTOR

$$\nu + e^{-} \rightarrow \nu + e^{-}$$



Borexino detects **the electron recoil energy** seen by 2200 PMTS **in single p.e. regime**

From the signal of all PMTS:

- the **energy** is related to the sum of the charge of each pmt signal → **500 p.e /MeV**

$$\frac{\sigma(E)}{E} = \frac{5\%}{\sqrt{E}}$$

- the **position** of the neutrino interaction is achieved by the different time of arrival of gamma to the PMT (laser calibration for timing)

$$\frac{\sigma(x)}{x} = \frac{10\ cm}{\sqrt{E}}$$

Energy range: from **190 KeV** to **10 MeV**

Also **antineutrinos** from Earth can be observed by a coincidence measurement

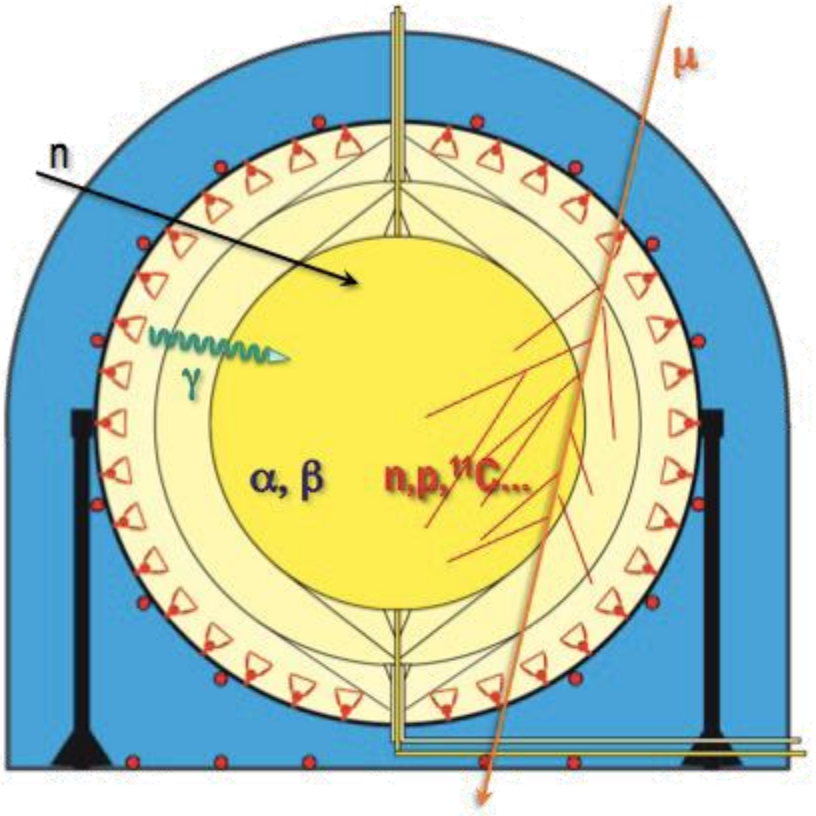
BACKGROUND IN BX SPECTRUM

Expected neutrino events: 50 counts/day 100 ton
signal is 5 10^{-9} Bq/kg   water is 10 Bq/kg!!

BACKGROUND COMPONENTS:

- **External background:**
  - -cosmogenic ^{11}C and neutron
  - -gamma rays from ^{208}Tl, ^{214}Bi from PMT

- **Internal background:**
  - ^{14}C in scintillator
  - ^{85}Kr in air
  - ^{238}U in rock → (^{210}Bi and ^{210}Po)
  - ^{232}Th in rock
  - ^{40}K
  - ^{49}Ar
  - ^{222}Rn



BACKGROUND IN BX SPECTRUM

Thanks to a big work of purification during the construction and between Phase I and Phase II

BACKGROUND COMPONENTS:

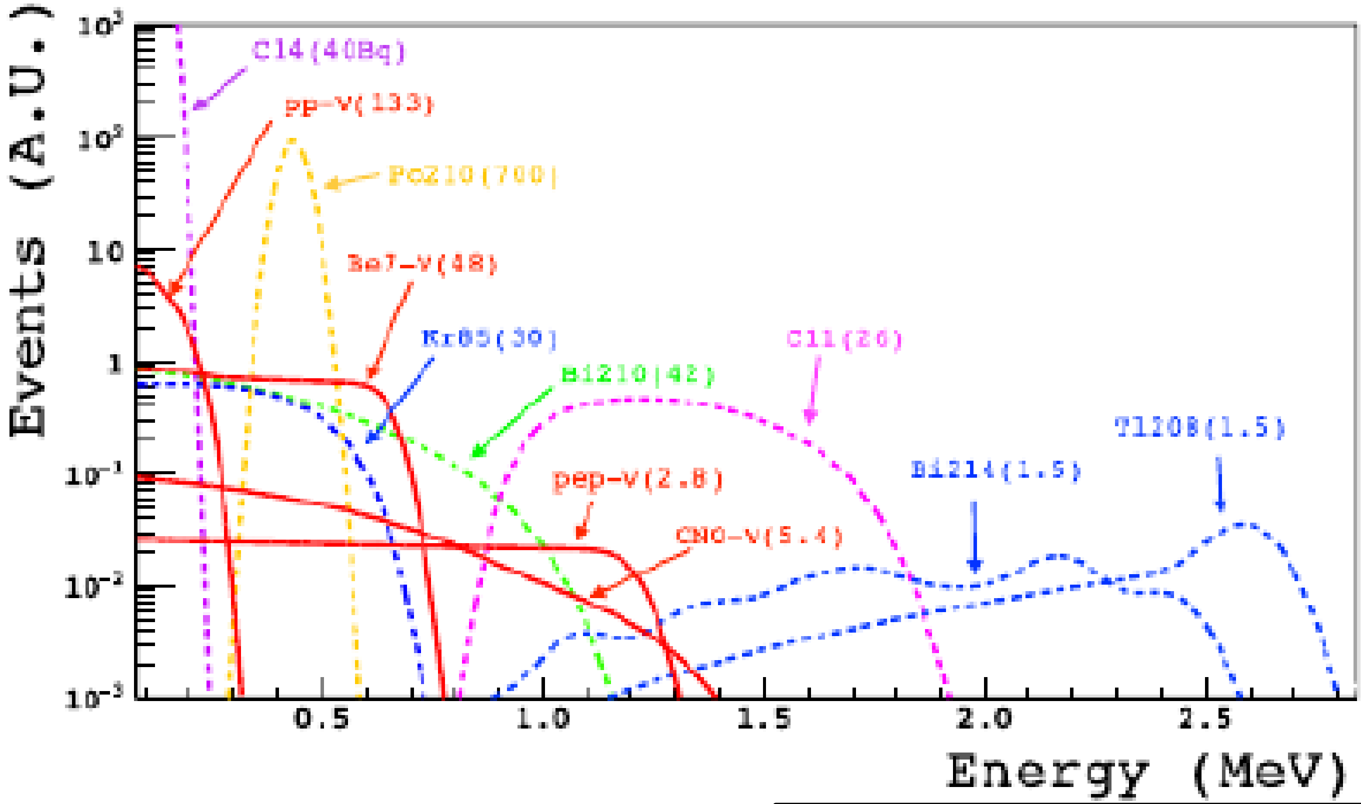
- **External background:**
  - -cosmogenic ^{11}C and neutron
  - -gamma rays from ^{208}Tl, ^{214}Bi from PMT
- **Internal background:**
  - ^{14}C in scintillator $^{14}C/^{12}C$ 10^{-18} g/g!
  - ^{85}Kr in air reduced of a factor 4 in Phase II
  - ^{238}U 9.4 10^{-20} g/g !
  - ^{232}Th 5.7 10^{-19} g/g !
  - ^{40}K few counts /day
  - ^{49}Ar few counts /day

Background (LER)	rate (Bq/100 t)
^{14}C(0.156 MeV, β^-)	[40.0 ± 2.0]

Background (LER)	rate (cpd/100 t)
^{85}Kr (0.687 MeV, β^-)	6.8 ± 1.8
^{210}Bi (1.16 MeV, β^-)	17.5 ± 1.9
^{11}C (1.02-1.98 MeV, β^+)	26.8 ± 0.2
^{210}Po (5.3 MeV, α)	260.0 ± 3.0
Ext. ^{40}K (1.460 MeV, γ)	1.0 ± 0.6
Ext. ^{214}Bi (<1.764 MeV, γ)	1.9 ± 0.3
Ext. ^{208}Tl (2.614 MeV, γ)	3.3 ± 0.1

Borexino is the less radioactive detector on the Earth!!

THE BOREXINO SPECTRUM



Low energy
NEUTRINO: pp – Be - CNO
BACKGROUND: ^{14}C, ^{210}Po, pile-up

Higher energy:
NEUTRINO: pep signal
BACKGROUND: ^{11}C, ^{214}Bi, ^{208}Tl,

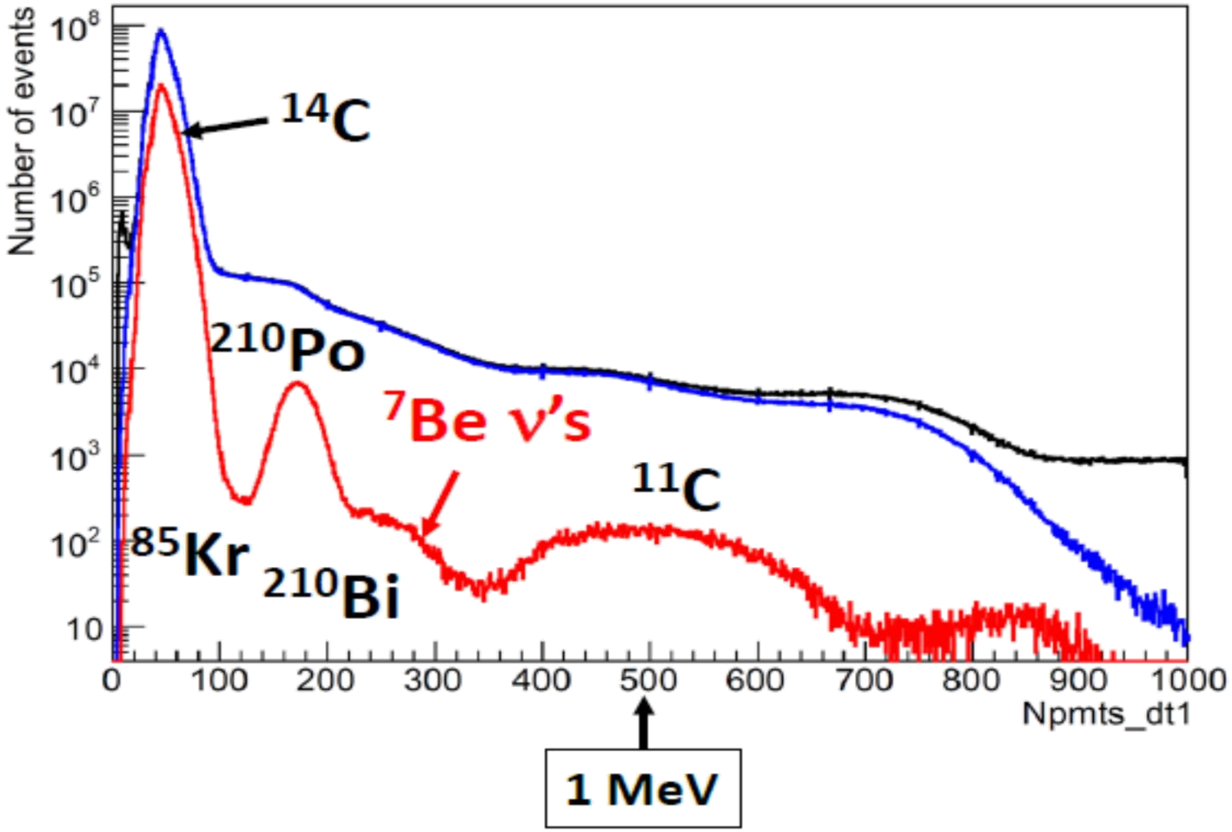
In addition: ^{210}Bi, pep, CNO signals are in the same energy range

THE BACKGROUND REJECTION

GENERAL TECHNIQUES:

- **External and internal muon veto**
  (veto of 300 ms after a muon in OD)

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



THE ^{11}C BACKGROUND REJECTION

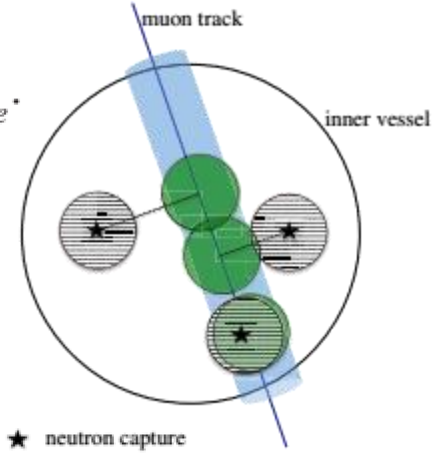
THREE FOLD COINCIDENCE technique

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

$$^{11}\mathrm{C} \rightarrow {}^{11}\mathrm{B} + e^{+} + \nu_{e}.$$

Lifetime 30 min

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



2 different data set for the final fit! (TFC subtracted and TFC tagged)

Tagging efficiency= 92±4%

PULSE SHAPE technique

$$^{11}\mathrm{C} \rightarrow {}^{11}\mathrm{B} + e^{+} + \nu_{e}.$$

The PDF of scintillation **time profile** is significantly different for *e*+ and *e*- events because:

- in 50% of the cases, *e*+ annihilation is **delayed** by ortho-positronium formation, ($\tau \sim 3$ ns)
- the energy deposit is **not point-like**

CALIBRATIONS

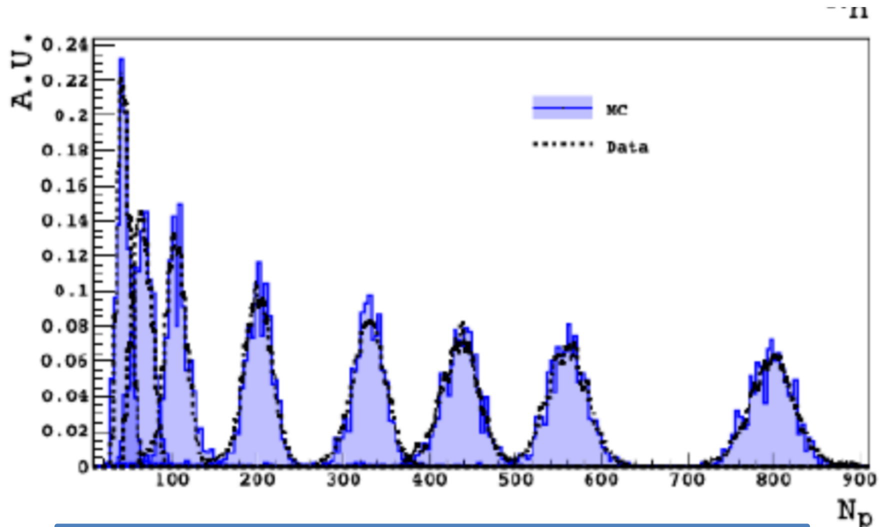
With different gamma and neutron sources in many points

- for **energy resolution** response
- for tuning **position reconstruction** algorithm

as a function of the position in the sphere

Isotope	Type	Energy(keV)
^{57}Co	γ	122
^{139}Ce	γ	165
^{203}Hg	γ	279
^{85}Sr	γ	514
^{54}Mn	γ	834
^{65}Zn	γ	1115
^{60}Co	γ	1173–1332
^{40}K	γ	1460
^{222}Rn	$\alpha\beta$	$0 \div 3200$
^{14}C	β	$0 \div 156$
$^{241}Am\ ^{9}Be$	n	$\sim 0 \div 10{,}000$
Ext. ^{228}Th	γ	2615

- for tuning many parameters in the **Monte Carlo simulation**:



a full simulation of all physical process, from the neutrino interaction to the light production and propagation, up to the electronics and to data acquisition chain

for a precise knowledge of the detector response

Astroparticle Physics 97, 136-159 (2018)

THE FIT PROCEDURE

Data set: 14th Dec 2011- 21st May 2016
Exposure 1291.51 days x 71.3 tons
Energy range 0.19 MeV → 2.93 MeV

a **multi-variate** approach: A simultaneous **fit** of

- the **TFC**-*subtracted* and the TFC-*tagged* energy spectra,
- the **spatial** distribution, (for residual external bk)
- the distribution of the **pulse-shape** discrimination variable

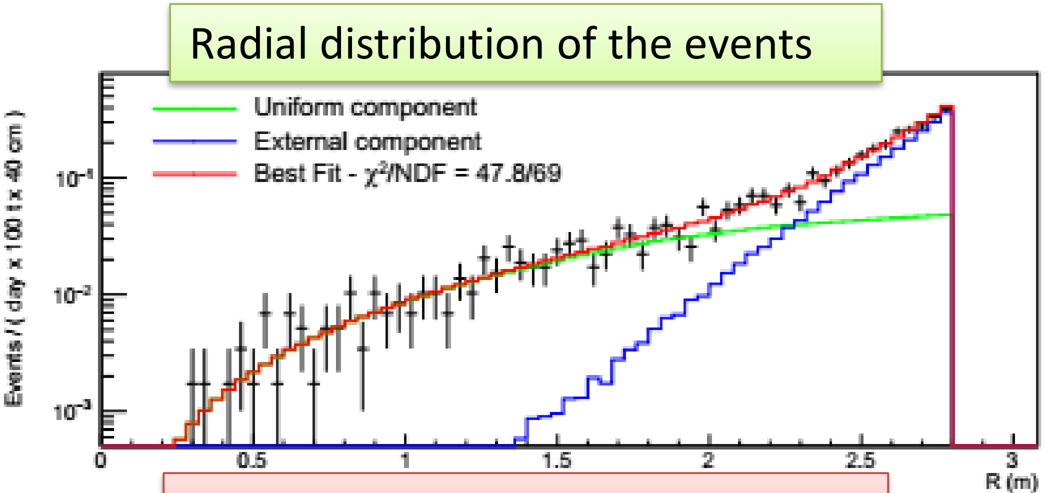
2 complementary methods

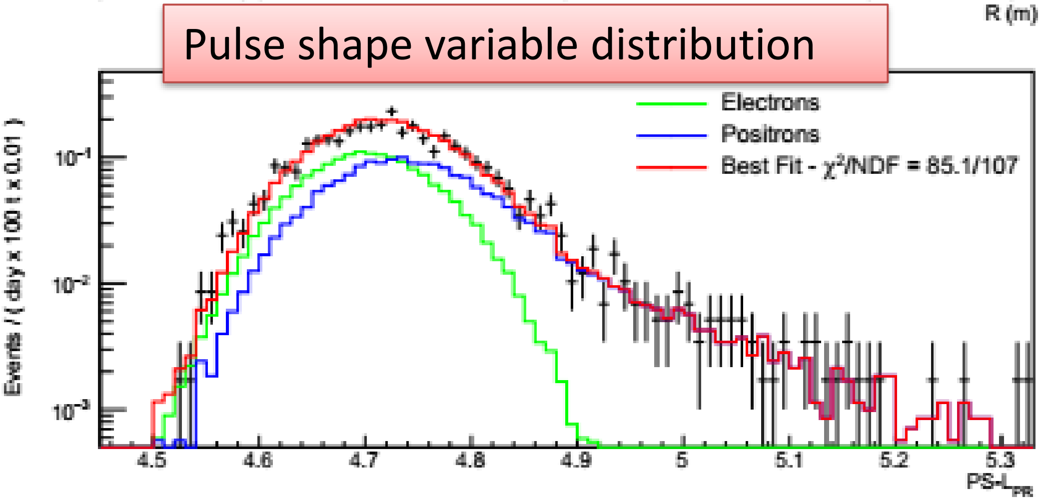
MC fit:
only the rate of **solar neutrino** components and of the **background** components are free parameters

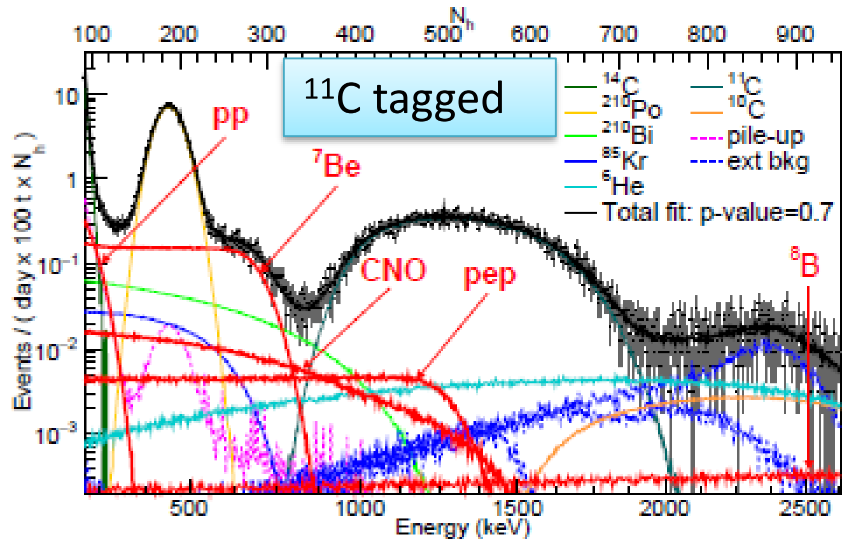
Analytical fit:
energy response function described analytically: 6 parameters of the response function are free in the fit

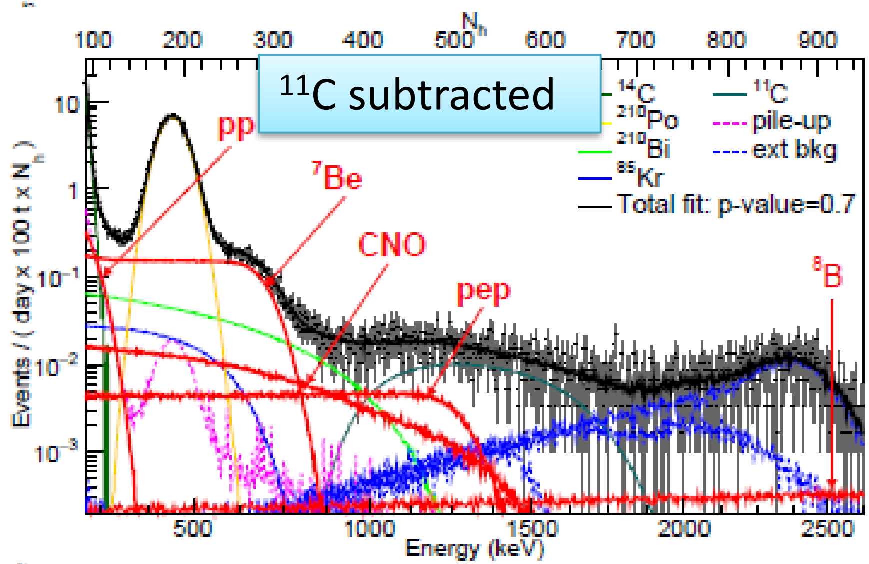
Since the degeneracy of CNO and pep, we fix CNO to HZ-SSM (with LMA oscillation)

THE MULTIVARIATE FIT









PHASE II RESULTS

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.)

arXiv: 1707.09279v2 (2017)

The robustness of the results was checked by performing the fit in several configurations (energy variable, binning)

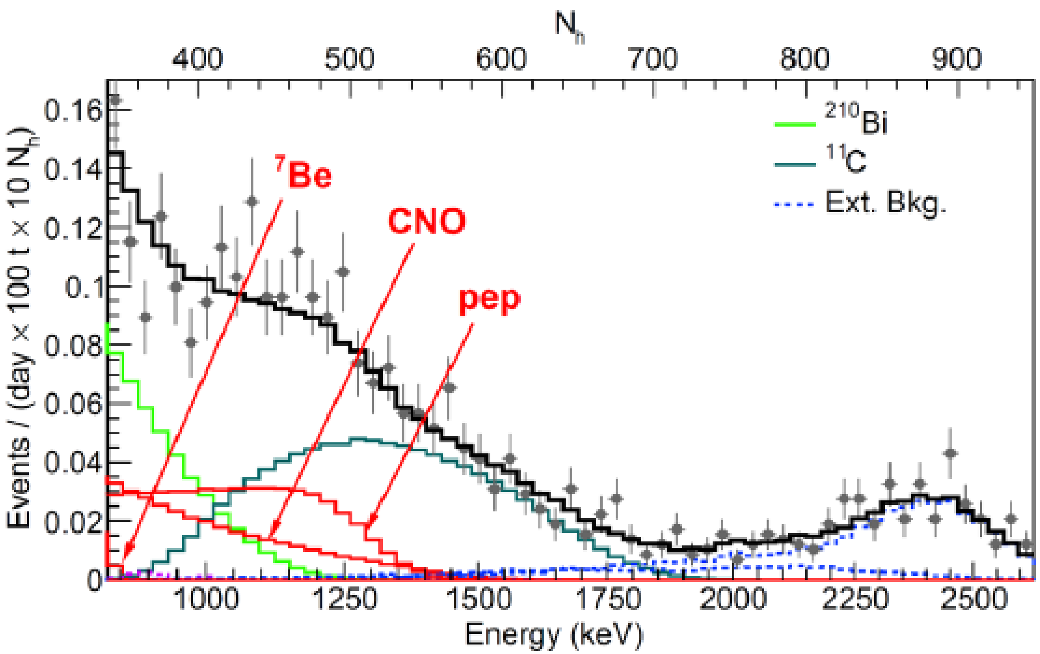
The differences between the results were quoted as systematic errors

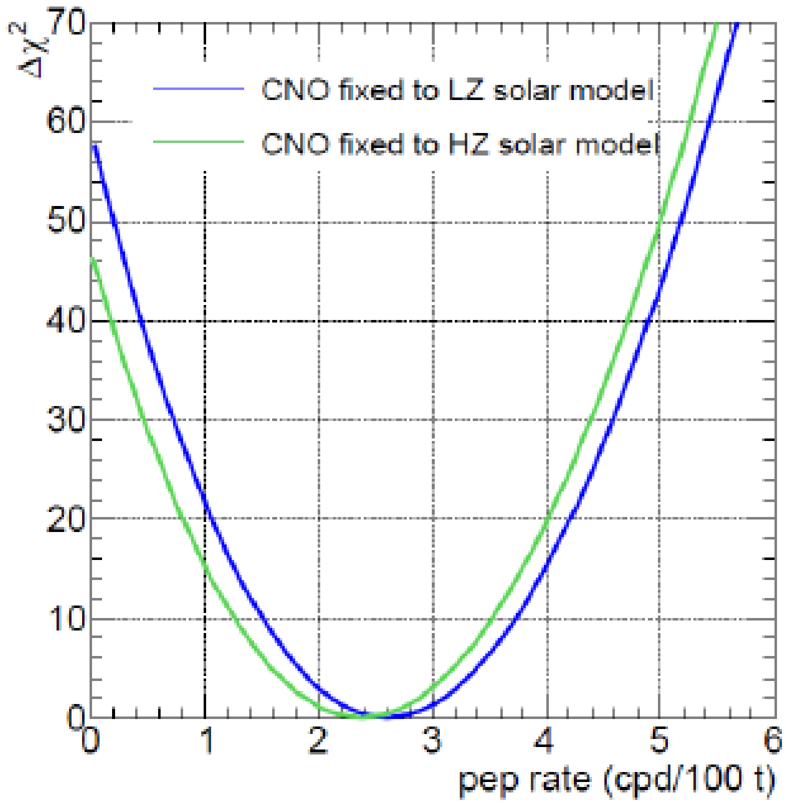
	pp		^{7}Be		*pep*	
Source of uncertainty	−%	+%	−%	+%	−%	+%
Fit method (analytical/MC)	-1.2	1.2	-0.2	0.2	-4.0	4.0
Choice of energy estimator	-2.5	2.5	-0.1	0.1	-2.4	2.4
Pile-up modeling	-2.5	0.5	0	0	0	0
Fit range and binning	-3.0	3.0	-0.1	0.1	1.0	1.0
Fit models (see text)	-4.5	0.5	-1.0	0.2	-6.8	2.8
Inclusion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

5σ EVIDENCE OF PEP

Likelihood profile from the multivariate fit

Zooming in the pep energy region



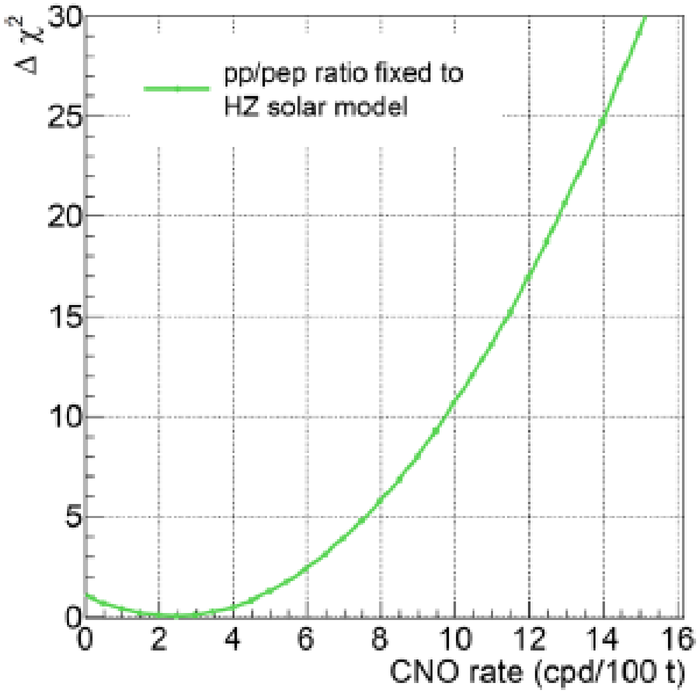


We see the pep shoulder!

A NEW UPPER LIMIT ON CNO

Fixing the ratio between pp/pep:
47.7 ± 1.2

Likelihood profile from the multivariate fit



Bx: $\Phi < 8.1$ cpd/100ton (95%) C.L

HZ : 4.91 ± 0.56 cpd/100 ton

LZ: 3.62 ± 0.37 cpd/100 ton

THE ^{8}B NEW RESULTS

Different type of analysis:

- events in the entire scintillator (only z<2.5 m cut)
- energy threshold 3.2 MeV to cut gammas from ^{208}Tl from PMT

The neutrino signal is extracted from the radial distribution of the events

High energy range:
Neutrinos+neutrons captures

Low energy range:
Neutrinos+neutrons+ 3 components of ^{208}Tl (inner, surface, diffused)

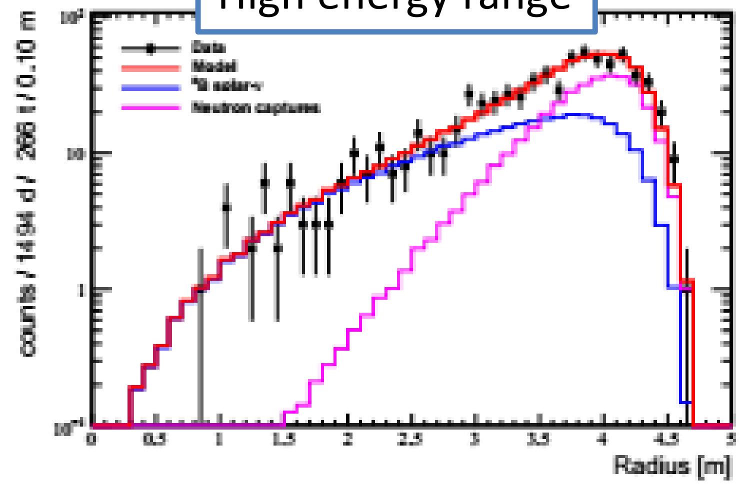
$$R_{LE} = 0.133^{+0.013}_{-0.013}\,(stat)\,^{+0.003}_{-0.003}\,(syst)\ \text{cpd/100 t},$$

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

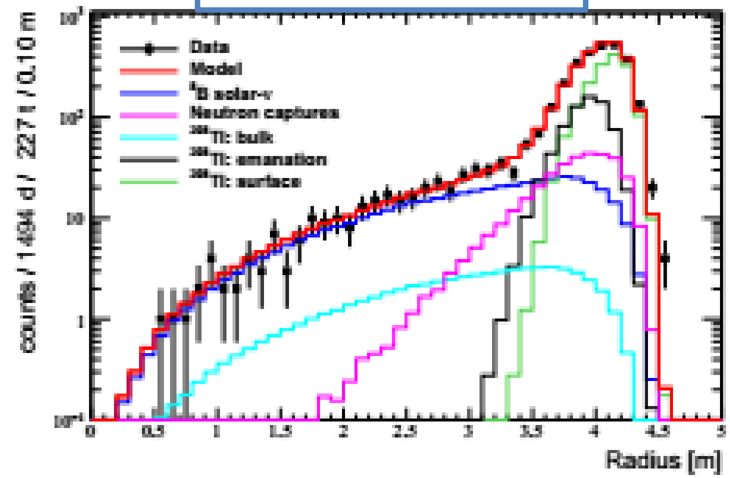
$$R_{LE+HE} = 0.220^{+0.015}_{-0.016}\,(stat)\,^{+0.006}_{-0.006}\,(syst)\ \text{cpd/100 t}.$$

arXiv:1709.00756 (2017)

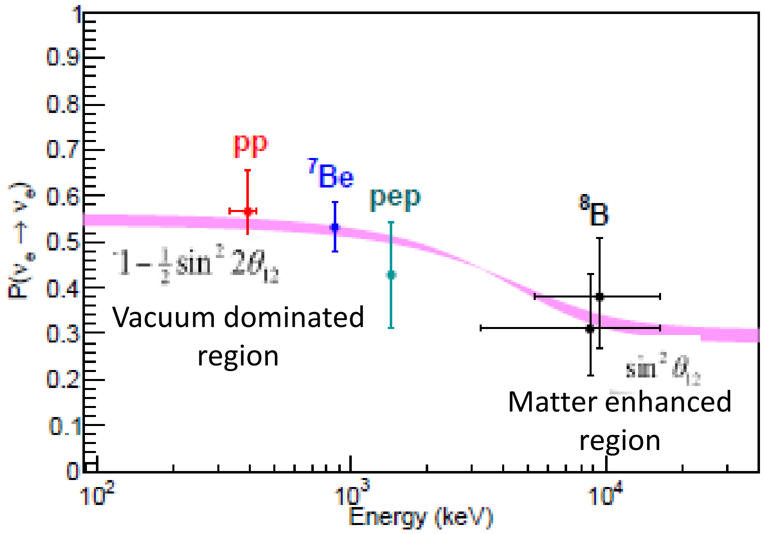
High energy range



Low energy range



THE GLOBAL ANALYSIS



Solar neutrino survival probability

- P_{ee}(pp)=0.57±0.10
- P_{ee}(^{7}Be,862keV)=0.53±0.05
- P_{ee}(pep)=0.43±0.11

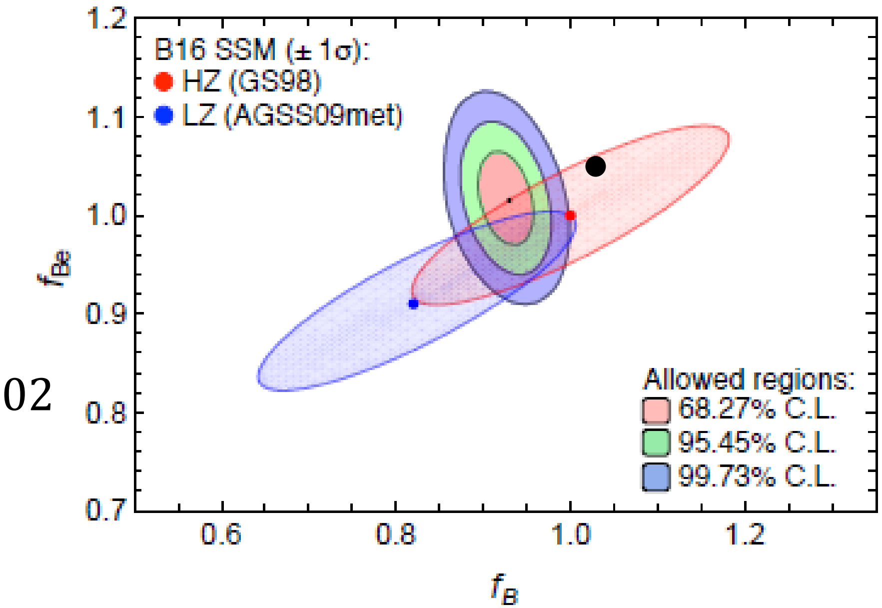
in the HZ-SSM hypothesis

Results consistent with the **MSW-LMA solution**!

Solar metallicity

R(HZ)=0.18 ± 0.01
R(LZ)= 0.16 ± 0.01

$$R \equiv \frac{<^3\text{He} + ^4\text{He}>}{<^3\text{He} + ^3\text{He}>} = \frac{2\phi(^7\text{Be})}{\phi(\text{pp}) - \phi(^7\text{Be})} = 0.18 \pm 0.02$$



An hint to the high metallicity

CONCLUSIONS

- **Borexino detector:**

  → ultra low radioactive background
  → well tuned MC
  → refined analysis for background subtraction

- Phase II **results**:

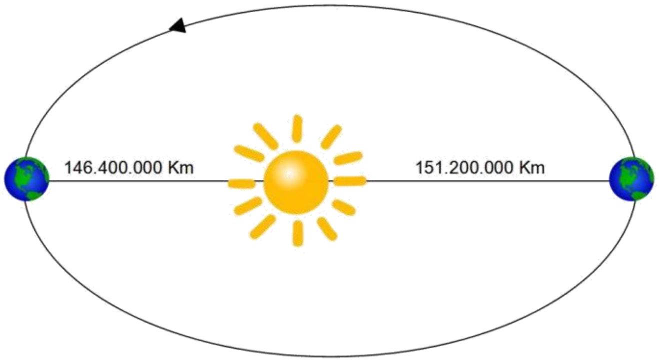
  → More precise measurement of pep, ^{7}Be, pp solar components
  → More precise measurement of ^{8}B flux

- Borexino **future:**

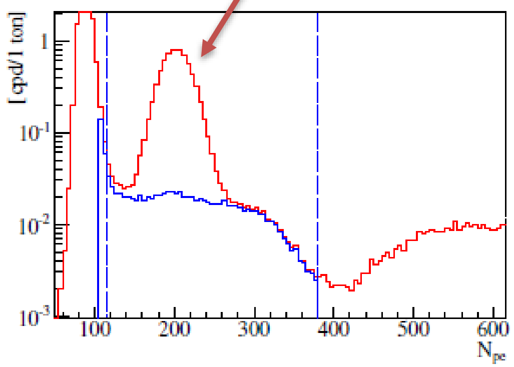
  → CNO measurement (?)

THANKS!

The SEASONAL MODULATION

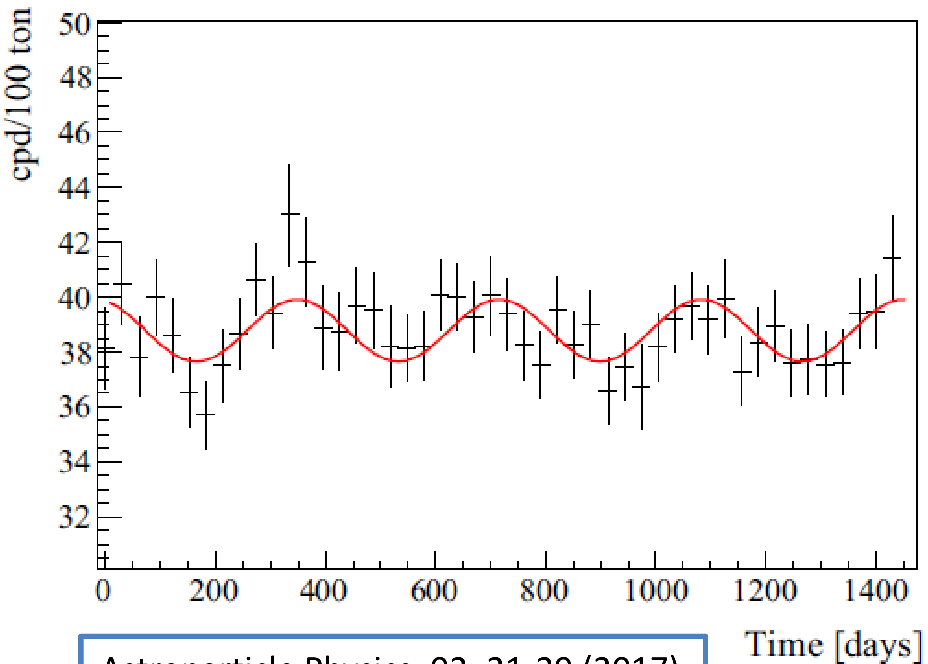


Only the events in the energy range:
215 keV-715 keV
After ^{210}Po subtraction by pulse-shape discrimination



$$R(t) = R_0 + \overline{R}\left[1 + \epsilon \cos\frac{2\pi}{T}(t-\phi)\right]^2$$

$\varepsilon = 1.74 \pm 0.45$ %
T= 367 ± 10 days
$\Phi = -18 \pm 24$ days



Astroparticle Physics, 92, 21-29 (2017)