HOW THE SUN AND THE STARS SHINE

SOLAR AND NEUTRINO PHYSICS

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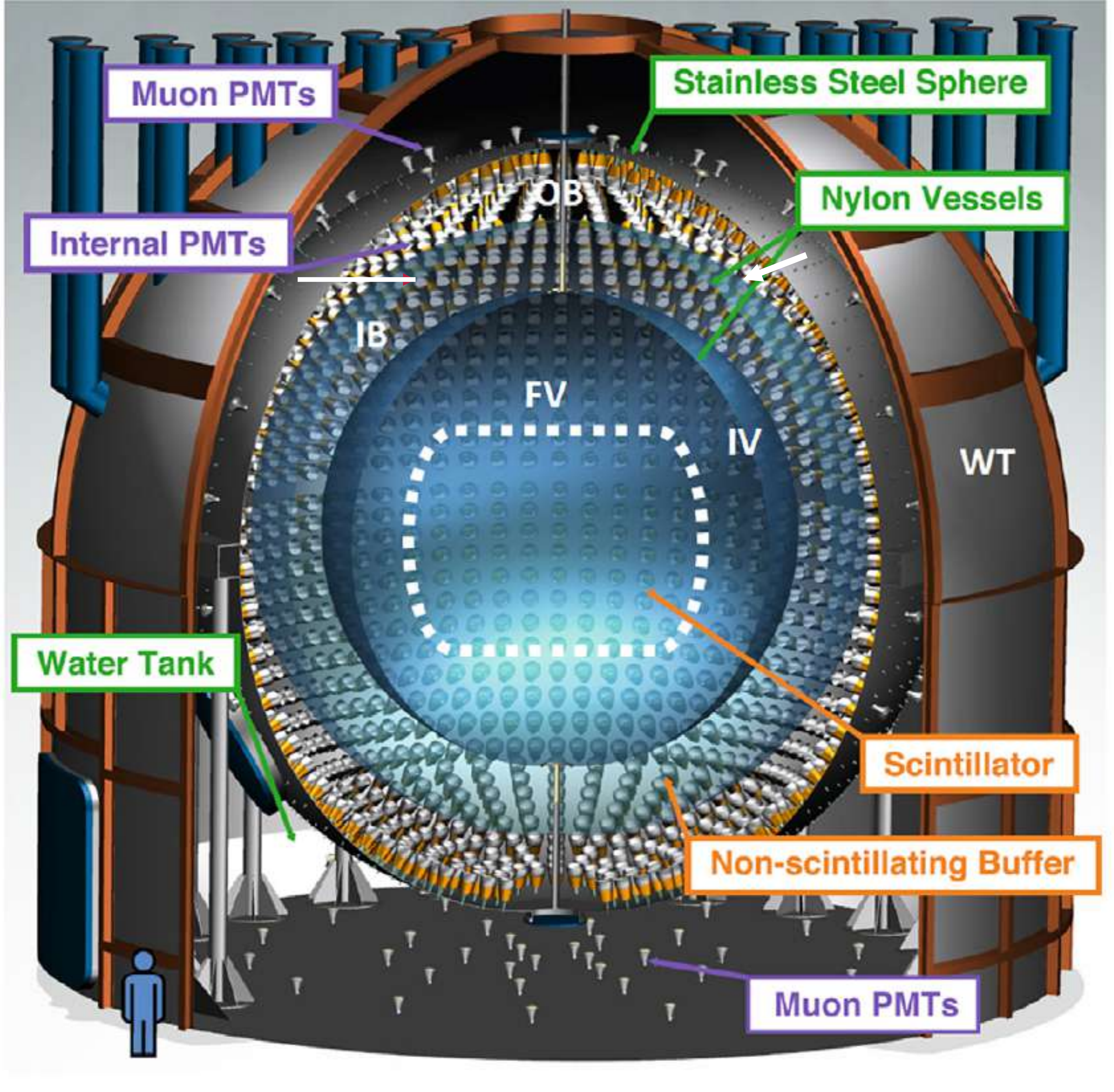
The Borexino detector @ Gran Sasso

Active volume 280 tons of liquid scintillator

Detection principle

$$\nu_x + e \rightarrow \nu_x + e$$

Elastic scattering off the electrons of the scintillator threshold at ~ 60 keV (electron energy)

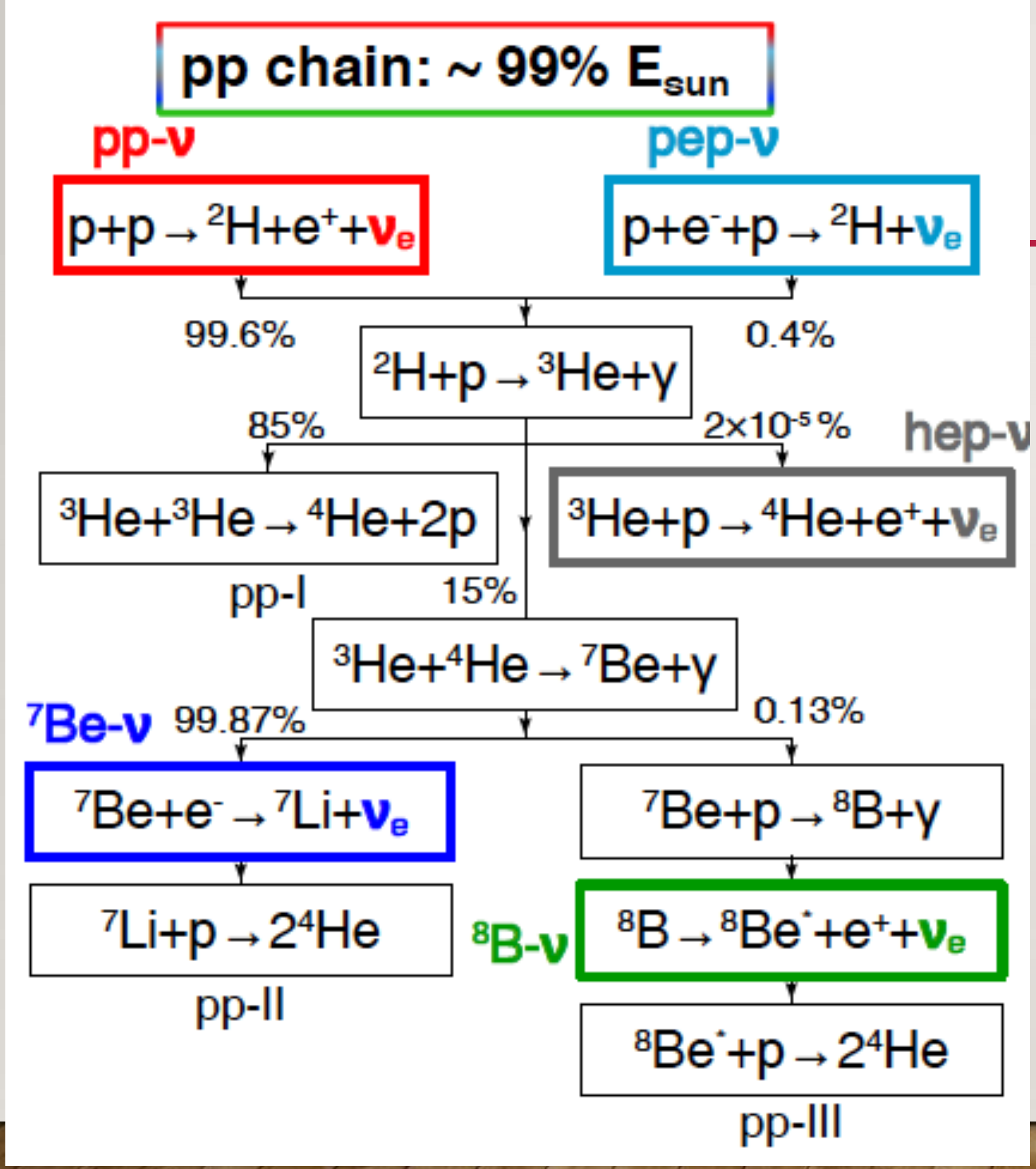


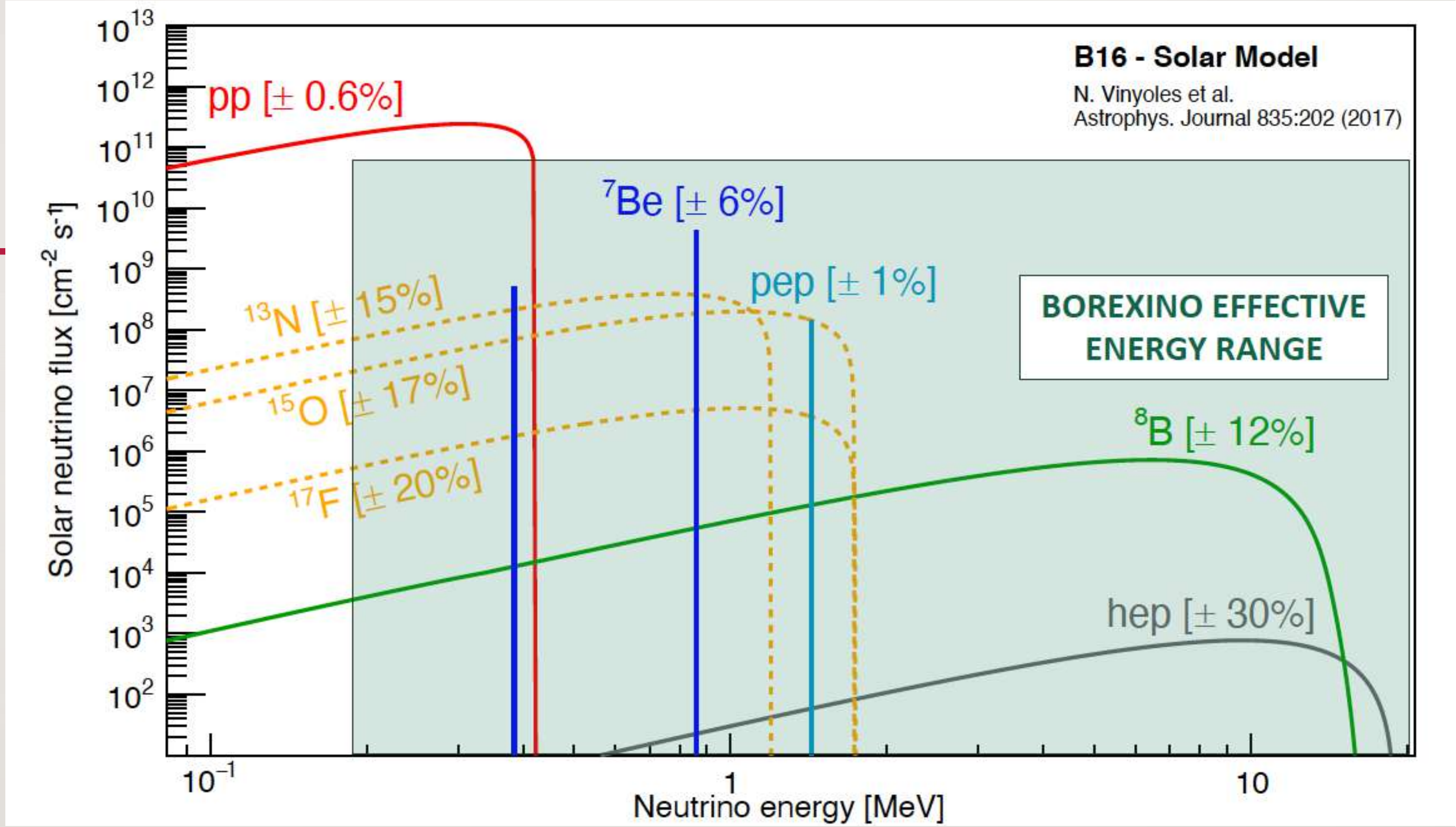
TIME TABLE:

- 1990-1995 R&D
- 1995-2007 detector set up*
- 2007-2010 phase I
- 2011-2016 phase 2
- 2016- 2021 phase 3

*nothing is standard in it: everything was made either custom or developed on purpose or treated in a special way with the purpose to reach unprecedented cleanliness and the related radiopurity

pp chain

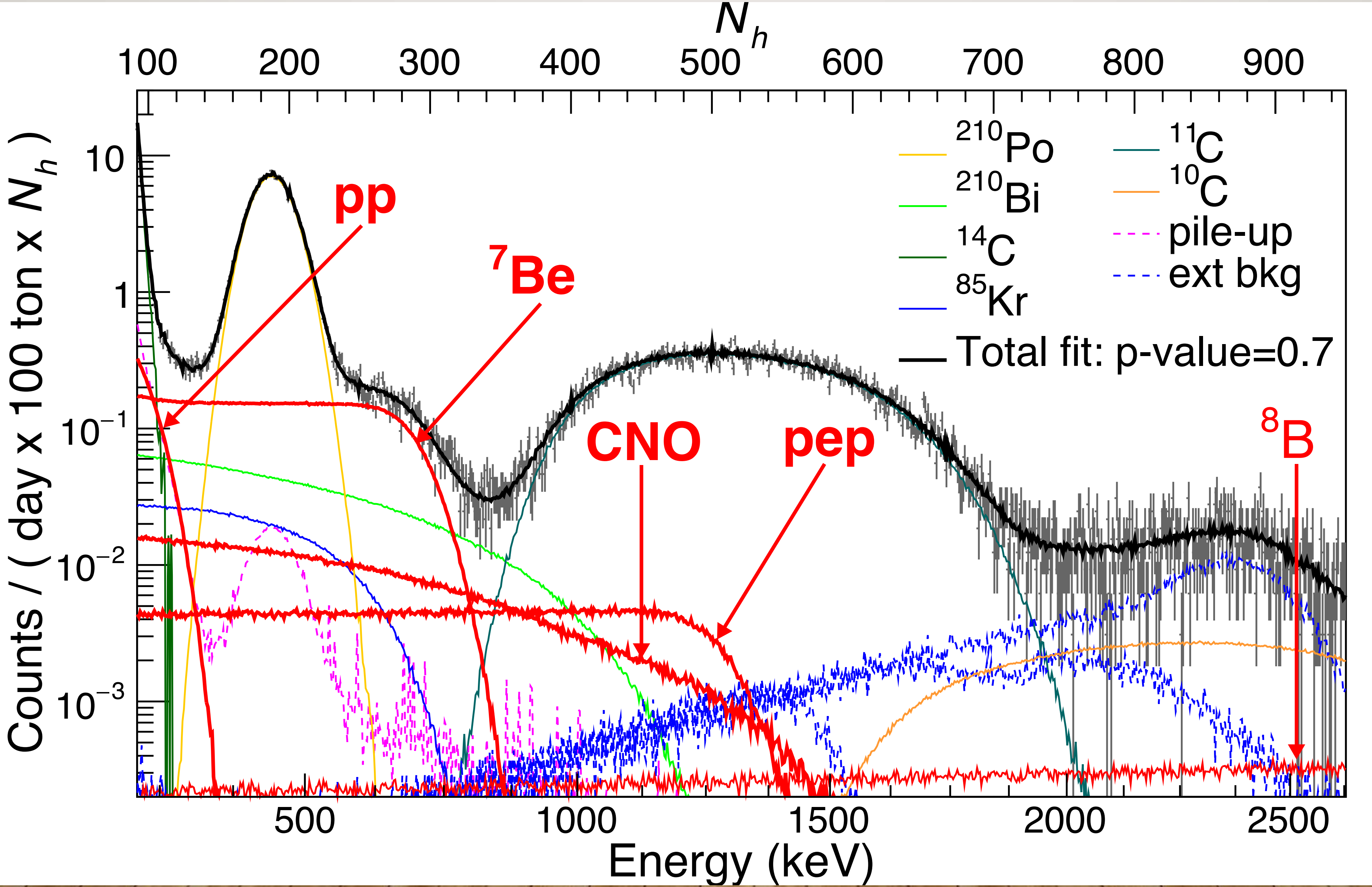




- 26.2 MeV effective thermal energy
- Dominant in the SUN
- Dominant in 1st generation Stars

Radio isotope	Source	Software reduction	Achieved Phase1	Achieved Phase2
^{14}C	Intrinsic PC	Threshold Fit on the shape	$\approx 2\ 10^{-18}\ ^{14}C/^{12}C$	
^{238}U ^{232}Th (secular eq.)	Dust, particulate all materials	α/β tagging fit	$1.67\pm0.06)\ 10^{-17}$ $(4.6\pm0.8)\ 10^{-18}$ g/g	$<9.5\ 10^{-20}$ $<7.2\ 10^{-19}$ g/g
^{85}Kr	Air, weapons		30 ± 5 cpd/100t	6.8 ± 0.8 cpd/100t
^{39}Ar	Air, cosmogenic	fit	<< 1 cpd/100t	
^{210}Po	Out of secular equilibrium	α/β tagging fit	500-100 cpd/100t	<<100 cpd/100t Natural decay
^{222}Rn and its progeny	In the underground air and water	α/β tagging, delayed coincidences	< 1 cpd/100t	

Solar physics- pp chain



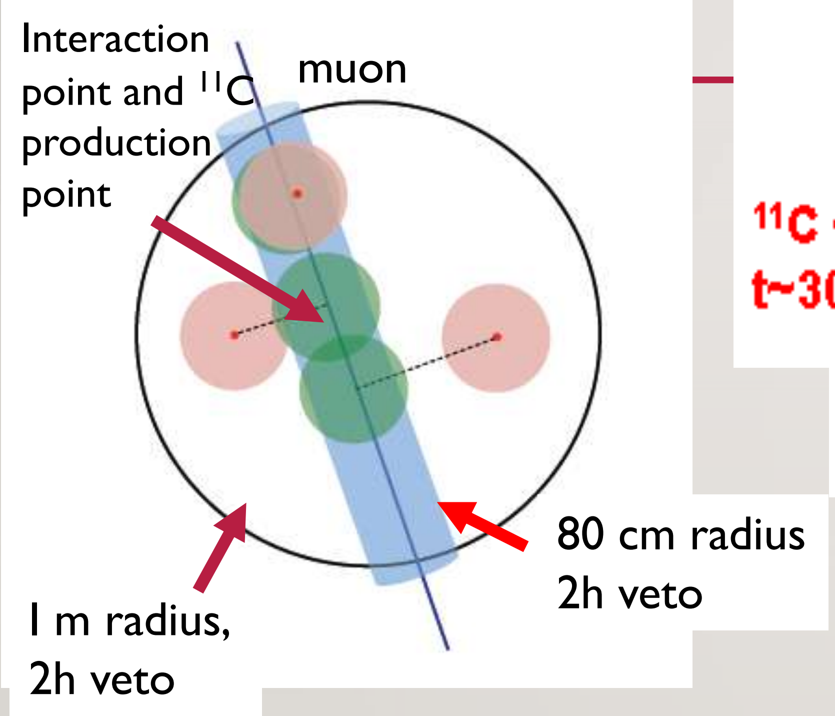
^{11}C reduction

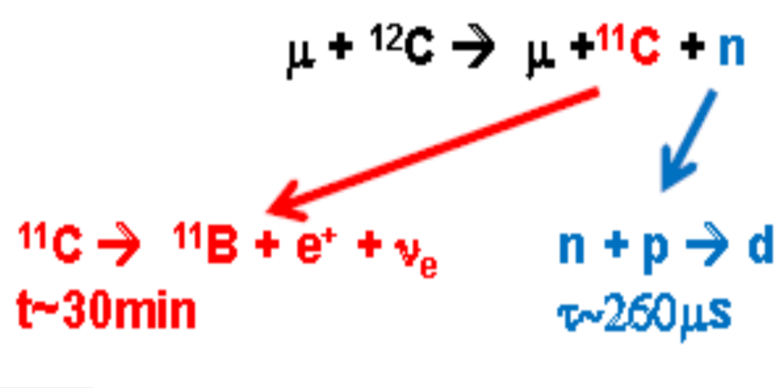
1. TFC prompt and delayed signal. Reduction to 10%
2. Pulse shape discrimination. Reduction to 5%

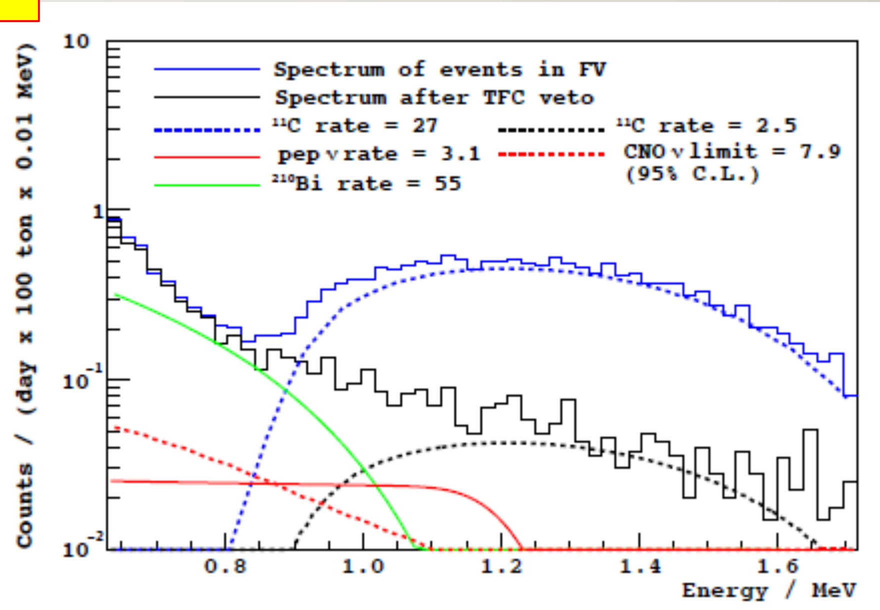
Residual exposure 48.5%

Cosmogenic muons (1.2 μ m^{-2} h^{-1})
Constant rate

1.TFC- three fold concidence







n capture on H: γ 2.2 MeV
Space and time Veto

- Annihilation of the positron
- n thermalization

2. Pulse shape discrimination

-ortho-positronium with 140 ns lifetime, reduced to about 3 ns in the l.s.
-2 γs produced in the positron annihilation ➔ distributed topology

Solar physics- pp chain

reaction	Borexino rates (cpd/100t)	Borexino fluxes ($cm^{-2}s^{-1}$)	SSM HZ Fluxes ($cm^{-2}s^{-1}$)	SSM LZ Fluxes ($cm^{-2}s^{1}$)	Global fit Fluxes (*) ($cm^{-2}s^{1}$)
pp	$134 \pm 10^{+6}_{-10}$	$(6.1 \pm 0.5^{+0.3}_{-0.5})$ x10^{10}	$5.98(1 \pm 0.006)$ x 10^{10}	$6.03(1 \pm 0.005)$ x 10^{10}	$5.97^{+0.037}_{-0.033}$ x 10^{10}
^{7}Be	48.3 $\pm 1.1^{+0.4}_{-0.7}$	$(4.99 \pm 0.11^{+0.06}_{-0.12})$ x10^{9}	$4.93\ (1 \pm 0.06)$ x 10^{9}	$4.50(1 \pm 0.06)$ x 10^{9}	$4.80^{+0.24}_{-0.22}$ x 10^{9}
pep§ (HZ)	2.43 $\pm 0.36^{+0.15}_{-0.22}$	$(1.27 \pm 0.19^{+0.08}_{-0.12})$ x 10^{8}	$1.44\ (1 \pm 0.009)$ x 10^{8}	$1.46\ (1 \pm 0.009)$ x 10^{8}	1.448 ± 0.08 x 10^{8}
pep§ (LZ)	2.65 $\pm 0.36^{+0.15}_{-0.24}$	$(1.39 \pm 0.19^{+0.08}_{-0.13})$ x 10^{8}	$1.44\ (1 \pm 0.009)$ x 10^{8}	$1.46\ (1 \pm 0.009)$ x 10^{8}	
^{8}B	$0.220^{+0.015+}_{-0.016-}$	$5.68^{+0.39+0.03}_{-0.41-0.03}$ x 10^{6}	$5.46\ (1 \pm 0.12)$ x 10^{6}	$4.50(1 \pm 0.12)$ x 10^{6}	$5.16^{+0.13}_{-0.09}$ x 10^{6}
hep	<0.002 (90% C.L.)	< 1.6 x 10^{5} (90% C.L.)	$7.98\ (1 \pm 0.30)$ x10^{3}	$8.25(1 \pm 0.12)$ x 10^{3}	

Z=metallicity

from A. Serenelli , F. .Villante et al.

from J. Bergstroem et al.,

Solar physics- pp chain

1. experimental evidence of the **individual nuclear reactions producing neutrinos in the pp solar chain,** which is the source of **99% of the Sun's energy**.

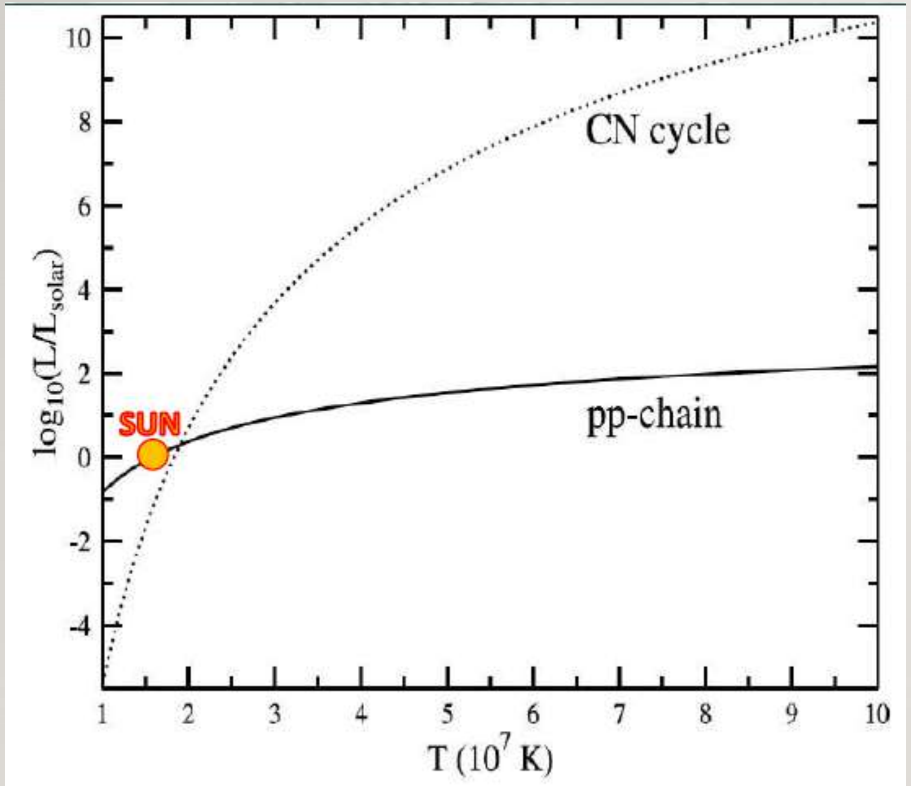
2. a good **agreement between the experimental data and SSM**, obviously within the experimental errors and the uncertainties of the model predictions

3. good agreement between the solar luminosities measured through photons and through neutrinos : L = ($3.89^{+0.35}_{-0.42}$) x 10^{33} erg s^{-1} for neutrinos and L = (3.846 $\pm$ 0.015) x 10^{33} erg s^{-1}) for photons ➡ the Sun is in **thermodynamic equilibrium over 10^5 years time scale**

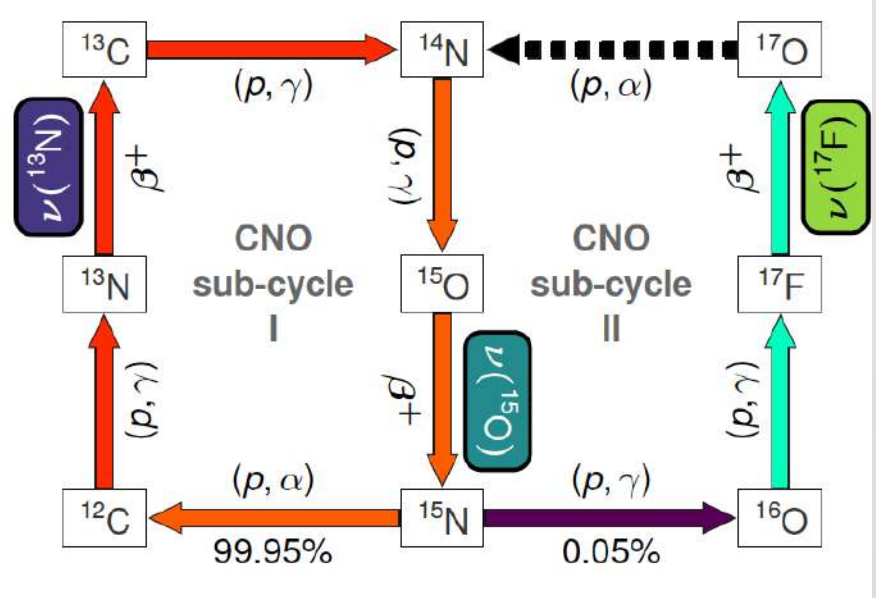
4. ratio between the **two pp chain branches**,: **RI/II** = 2Φ (^{7}Be) / [Φ (pp) - Φ (·Be)] = $0.178^{+0.027}_{-0.023}$, in **accordance with the expectations of the solar model** that gives 0.180 $\pm$ 0.011 for the high metallicity and 0.161 $\pm$ 0.010 for the low metallicity

CNO Cycle

- In the Sun the CNO cycle **contributes only for 1%.**
- In the **massive stars is considered dominant** and reaches in their core a temperature of a few x 10^8 K, needed to counterbalance the gravitational force, thus preventing their implosion
- But this hypothesis, which dates back to the 1930 (Bethe and Von Weizsäcker), has never been experimentally verified.



W.C. Haxton, A:M Serenelli (2008)



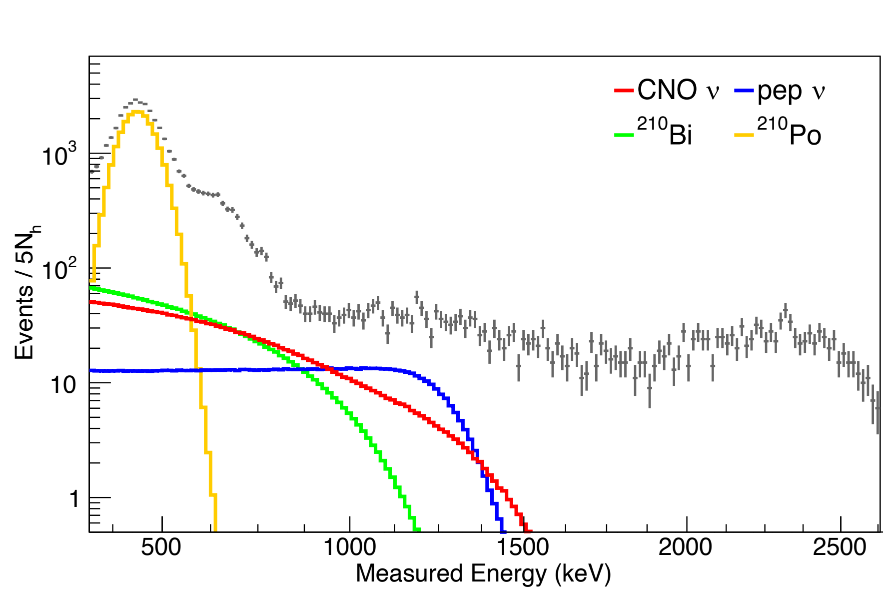
The experimental demonstration of the existence of the CNO cycle has been the most recent achievement of Borexino

Important for nucleosynthesis of ^{16}O and ^{17}O

- $\epsilon_{pp} \propto T^4$
- $\epsilon_{CNO} \propto T^{18}$

CNO Cycle

difficulties in measuring the CNO because ^{210}Bi, CNO, pep fall in the same energy window and the energy spectrum of CNO has no particular tagging



- Borexino data
- CNO ν expected spectrum
- ^{210}Bi spectrum-residue
- pep ν spectrum
- 210 Po- residue

The **spectral fit** returns only the sum of **CNO** and **^{210}Bi**, if both are left free

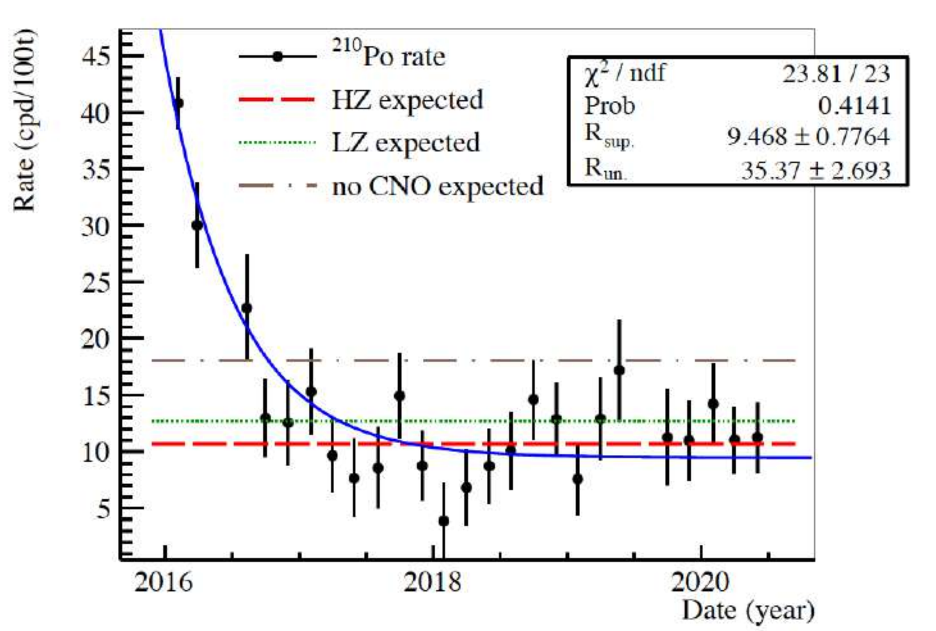
what is needed is **a reliable determination** of ^{210}Bi; a **constraint** on it can be obtained from ^{210}Po

secular equilibrium

$^{210}Pb \xrightarrow{\beta^-} {}^{210}Bi \xrightarrow{\beta^-} {}^{210}Po \xrightarrow{\alpha} {}^{208}Pb$

23y 5d 138 d

BUT



^{210}Po consists of two components, one **out of equilibrium** which increases during operations as purification or scintillator refilling and a second one **in secular equilibrium.** The component O. of S.E. decays and the rate reaches a constant plateau corresponding to the component in S.E with ^{210}Pb and then with ^{210}Bi

^{210}Po can be easily identified via the α/β pulse shape discrimination

CNO Cycle

a stabilization of the temperature is necessary

Fluctuations are observed in the plateau due to convective motions which bring in the F.V. ^{210}Po present on the I.V. walls, produced by the ^{210}Pb

Then we have to avoid the convective motions

Thermal insulation **: copper coils on the top-** warm water in serpentines at ~ 15.5 °C to create a **gradient top -bottom-** bottom rocks **at** ~ 7 °C

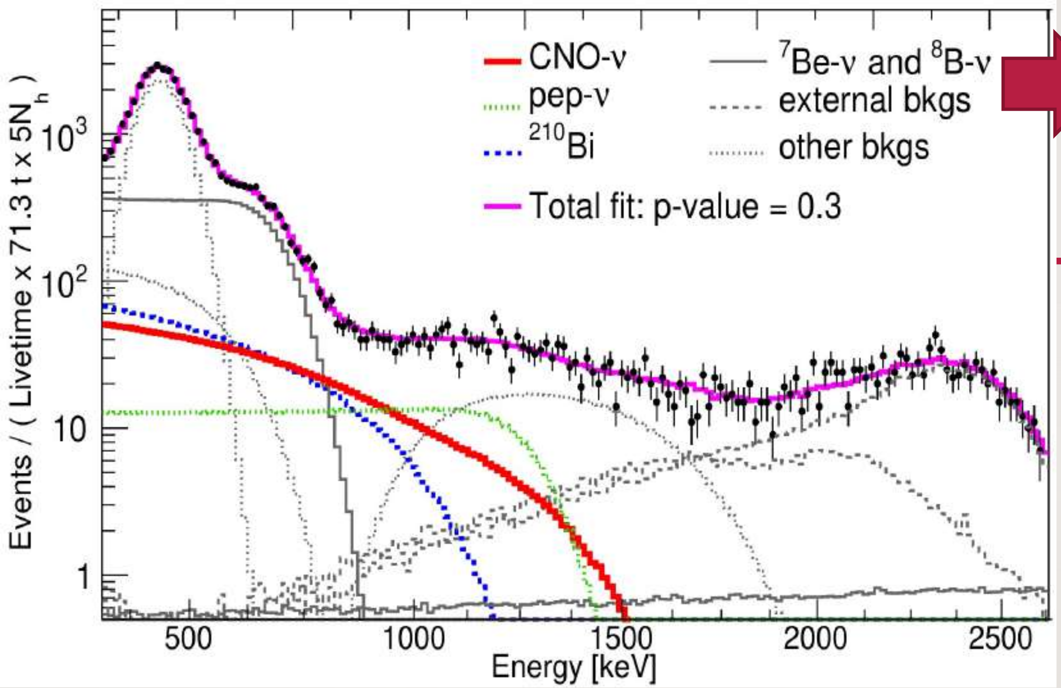
Excellent temperature stability achieved 0.1 °C

^{210}Po rate from the plateau with all errors: R_{min} =11.5 $\pm 1.3\ \frac{cpd}{100\ t}$

The lowest ^{210}Po rate has been conservatively assumed as a upper limit for ^{210} Bi, because we cannot exclude in principle that residual ^{210}Po from the vessel surface would be present

R(^{210}Bi) ≤ 11.5 ± 1.3 cpd/100t

CNO Cycle



CNO result 7.2 (-1.7 +3.0) cpd/100t stat + sys

corresponding to a flux of neutrinos on Earth;
7.0 (−1.9 +2.9)×10^{8} cm^{-2} s^{-1}

pep-ν rate constrained – solar luminosity
^{210}Bi rate constrained -- ^{210}Bi-^{210}Po tagging
CNO rate -- left free
Other ν and bkg rates-- left free

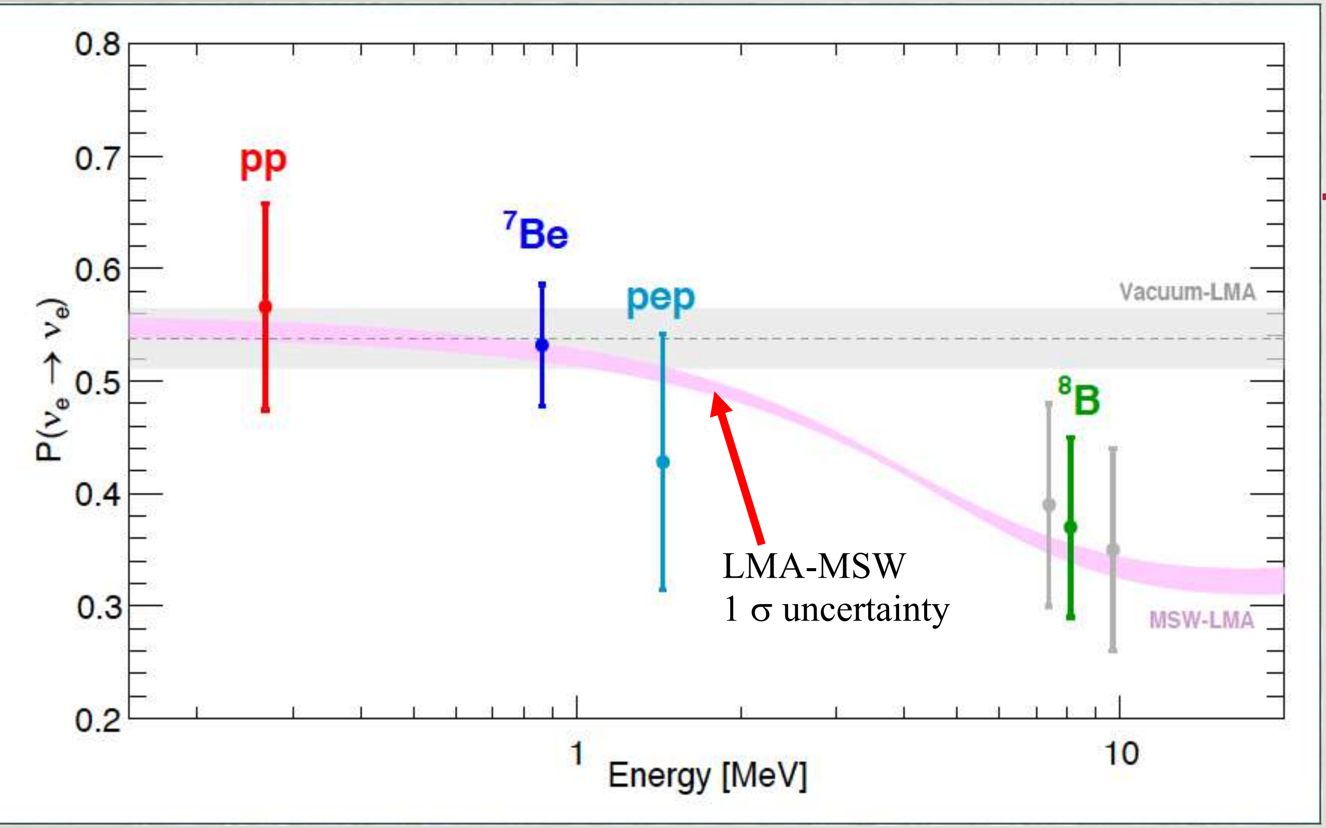
M.L. significance greater than
5 σ at 99% CL

13.8 millions pseudo-datasets with no CNO ↔ Real dataset

No CNO evidence disfavored at 5 σ

Therefore Borexino has demonstrated the existence of the CNO cycle

Neutrino Physics



electron neutrino survival probability: from 60 keV to >10 MeV.

1. Borexino has measured the electron neutrino Pee in the *vacuum regime*, where, according to the MSW-LMA model, the vacuum dominates
2. The Borexino data allowed to probe the vacuum–matter transition from a single experiment.
3. Despite the uncertainty of the various points, that incorporate both the experimental errors and the SSM uncertainties, the experimental results seem in agreement with the predictions of the MSW-LMA model.

day/night effect: the electron-neutrino, oscillated to other flavor during the journey Sun-Earth, can regenerate itself, interacting with the electrons during the night-Earth crossing.. Not expected if LMA region is valid, but important in the LOW region ($\Delta m^2_{21} \approx 10^{-7}\, eV^2$). For ^{7}Be we have found $A_{DN} = \frac{N-D}{(N+D)/2}$ = 0.0001± 0.012 (stat.) ± 0.07 (sys) .This means that the **LOW region is ruled out at more than 8.5 σ** from the solar data only, without tthe Kamland's anti-neutrinos data

Conclusions

1. Borexino has been the first experiment probing **sub-MeV neutrinos in real-time,** and is still now **the unique experiment** able to proceed with these studies.
2. Borexino has measured for **the first time all pp chain nuclear reactions producing neutrinos**, measuring, in particular, simultaneously the pp, ^{7}Be, and pep neutrino flux, ^{8}B neutrinos with a low threshold and probing hep neutrinos. From the neutrino energy distribution **it was possible to identify the nuclear reactions they come from**.
3. These results paved the way to actual breakthroughs not only on Solar physics, but also on neutrino physics. **The ν_e survival probability in the vacuum regime is measured** for the first time by Borexino and the **vacuum–matter transition** has been probed by a single experiment. In addition, the non-standard neutrino interactions has been studied by Borexino reaching world leading limits.
4. The detection of the CNO cycle closes a long history, which began in the 30s of the last century, when Hans Bethe and Carl Friedrich von Weizsacker, independently, proposed that the fusion of hydrogen in stars could also be catalyzed by nuclei heavier than He. Then the theory of energy generation hypothesizes that the CNO would be the primary channel for hydrogen burning in stars more massive than the Sun , and it is in fact the primary channel for hydrogen burning in the Universe. This hypothesis never received an observational confirmation until now, when Borexino **has observed CNO neutrinos** proving also that its contribution in the Sun is of the order of 1%.
5. When all solar neutrino fluxes measured by Borexino, including CNO, are combined, the LZ hypothesis is **disfavored at a level of 2.1σ.**
6. Again thanks to the low intrinsic background, Borexino has **observed geo-neutrinos** with 5σ statistical significance and studied them to obtain Earth geo-physical and geo-chemical information.

The Borexino collaboration

Thank you !!!!