# NEUTRINO, SOLAR AND STAR PHYSICS WITH BOREXINO

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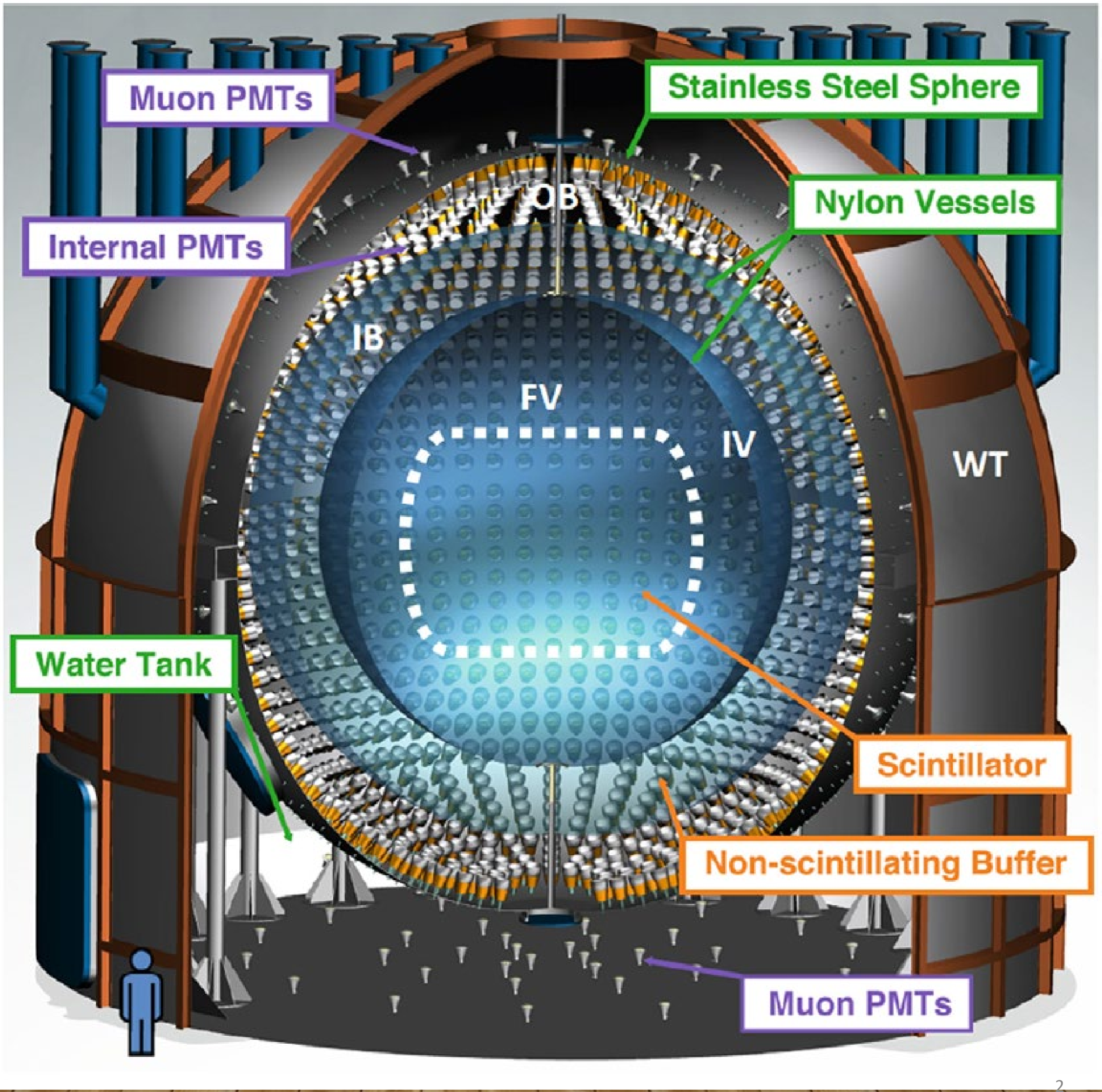
# The Borexino detector @ Gran Sasso

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)



# Borexino time table and phases

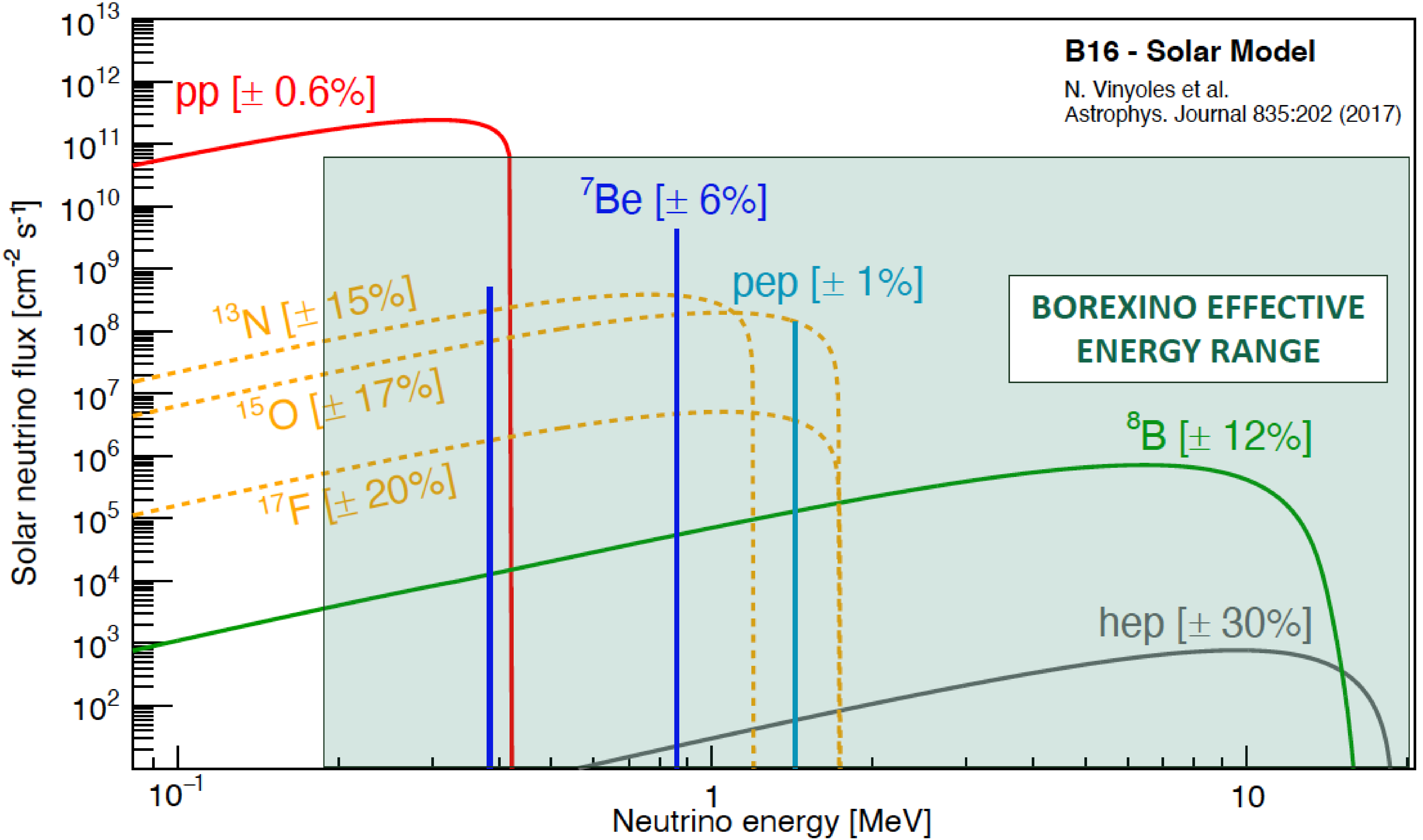
| 1990-1995 | 1996-2007 | 2007-2010 | 2011-2016 | 2016 → |
|---|---|---|---|---|
| R&D- radio-purification | Detector construction | Phase 1 | Phase 2 | Phase 3 |

1996-2007- The Borexino detector construction needed all this time because nothing is standard in it: everything was made either custom or developed on purpose or treated in a special way

pp solar cycle: phases 1+2

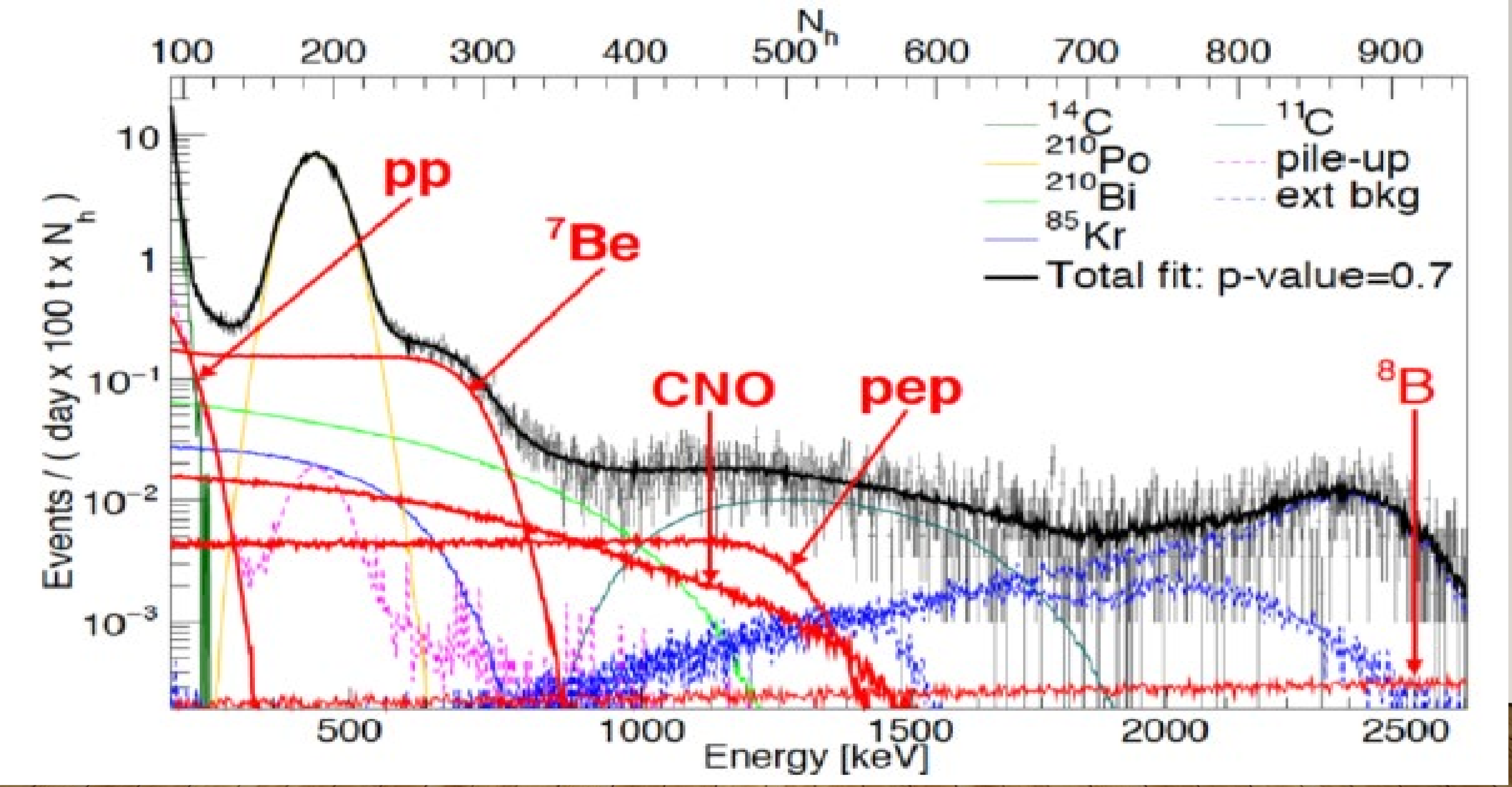
CNO cycle : phase 3

Geo-neutrinos: phases 1+2+3


B16 - Solar Model
N. Vinyoles et al.
Astrophys. Journal 835:202 (2017)
pp [± 0.6%]
$^{7}$Be [± 6%]
pep [± 1%]
$^{13}$N [± 15%]
$^{15}$O [± 17%]
$^{17}$F [± 20%]
$^{8}$B [± 12%]
hep [± 30%]
BOREXINO EFFECTIVE ENERGY RANGE
Solar neutrino flux [cm$^{-2}$ s$^{-1}$]
Neutrino energy [MeV]
$10^{-1}$
1
10
$10^{13}$
$10^{12}$
$10^{11}$
$10^{10}$
$10^{9}$
$10^{8}$
$10^{7}$
$10^{6}$
$10^{5}$
$10^{4}$
$10^{3}$
$10^{2}$

| Radio isotope | Source | Software reduction | Achieved Phase1 | Achieved Phase2 |
|---|---|---|---|---|
| $^{14}C$ | Intrinsic PC | Threshold<br>Fit on the shape | $\approx 2\ 10^{-18}\ {}^{14}C/{}^{12}C$ | |
| $^{238}U$<br>$^{235}Th$ | Dust, particulate all materials | α/β tagging fit | $1.67\pm0.06)\ 10^{-17}$<br>$(4.6\pm0.8)\ 10^{-18}$ g/g | $<9.5\ 10^{-20}$<br>$<7.2\ 10^{-19}$ g/g |
| $^{85}Kr$ | Air, weapons | | $30\pm5$ cpd/100t | $6.8\pm 0.8$ cpd/100t |
| $^{85}Ar$ | Air, cosmogenic | fit | << 1 cpd/100t | |
| $^{210}Po$ | Embedded on surfaces | fit | 500-100 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 cycle (1/4)



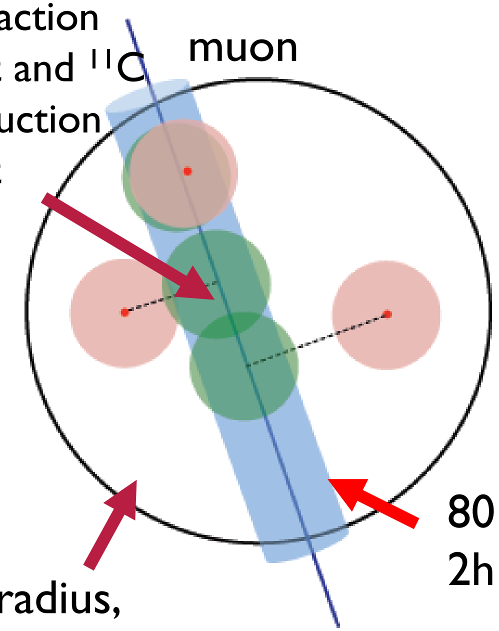
# $^{11}C$ reduction

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

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

Residual exposure 48.5%

**1.TFC- three fold concidence**



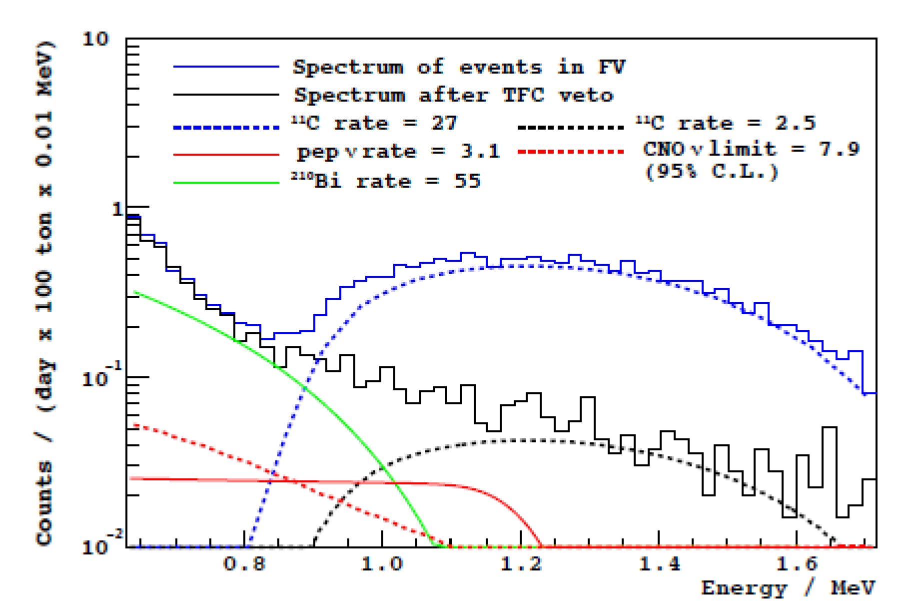

$\mu + {}^{12}C \rightarrow \mu + {}^{11}C + n$

${}^{11}C \rightarrow {}^{11}B + e^{+} + \nu_e$
t~30min

$n + p \rightarrow d + \gamma$
τ~260μs

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 cycle (3/4)

| 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 | $134 \pm 10^{+6}_{-10}$ | $(6.1 \pm 0.5^{+0.3}_{-0.5})$ x$10^{10}$ | 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 $\pm 1.1^{+0.4}_{-0.7}$ | $(4.99 \pm 0.11^{+0.06}_{-0.12})$ x$10^{9}$ | 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 $10^{8}$ | $1.448 \pm 0.08$ 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 | $0.220^{+0.015+}_{-0.016-}$ | $5.68^{+0.39+0.03}_{-0.41-0.03}$ | 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 ($1 \pm 0.30$) x$10^{3}$ | 8.25($1 \pm 0.12$) x $10^{3}$ | |

Z=metallicity

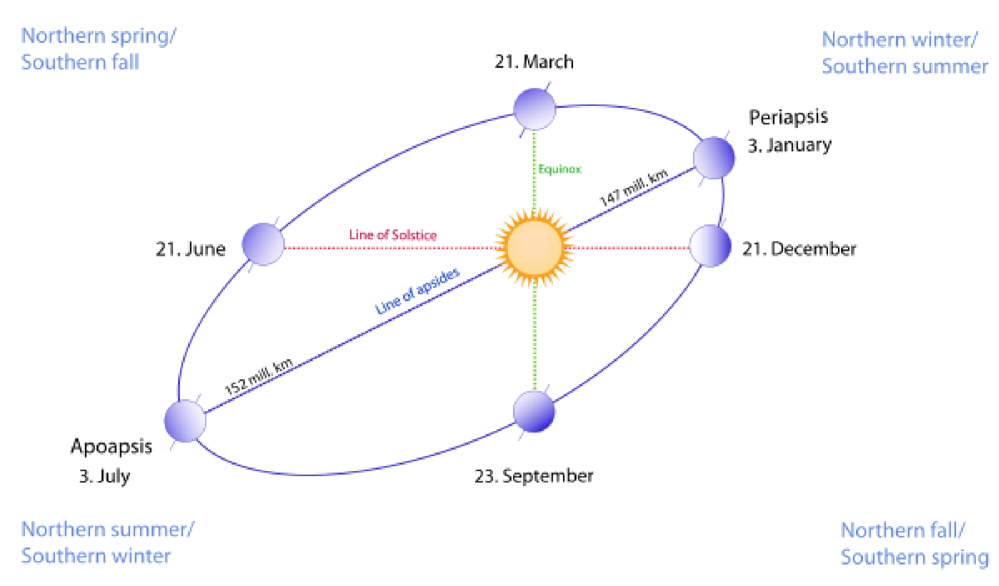
from A. Serenelli , F.Villante et al.

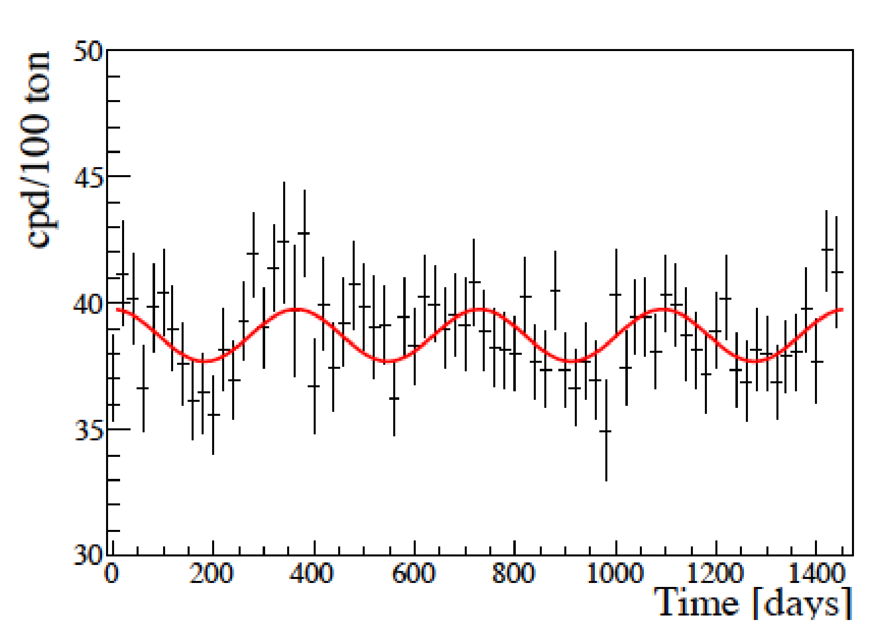
from J. Bergstroem et al.,

# Solar physics- pp cycle (4/4)

1. experimental evidence of the **individual nuclear reactions producing neutrinos in the pp solar cycle,** which is the source of **99% of the Sun's energy**.
2. a good **agreement between the experimental data and the model**, 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 give 0.180 $\pm$ 0.011 for the high metallicity and 0.161 $\pm$ 0.010 for the low metallicity

# Seasonal modulation




eccentricity of the Earth orbit: 6.7% of total rate difference

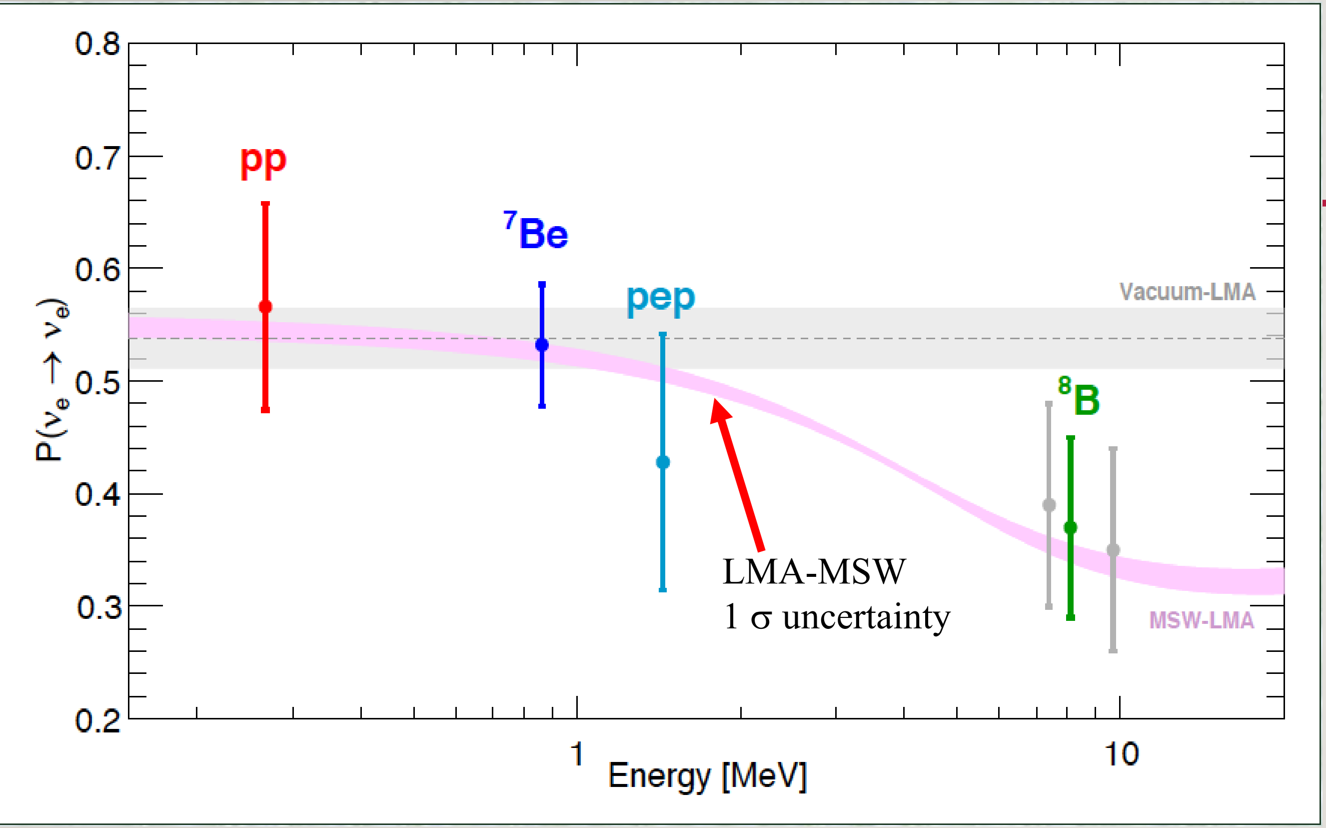
- 1456 astronomical days of data
- energy range: 215-715 keV ($^7$Be region)

**Modulation analysis**

- *sinusoidal fit*
- *Lomb-Scargle method*- an extension of the Fourier Transform approach- can treat data sets not evenly distributed in time

**- null hypothesis rejected at 3.9σ (99.99% C.L.)**
**- modulation amplitude (7.1±1.9)%**
**- best-t period** is **T = 367. 0 ±10 days**.

# 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 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 variois 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.

# Not Standard neutrino Interaction (NSI)

**exposure of 1271 days x 71.3 tons**

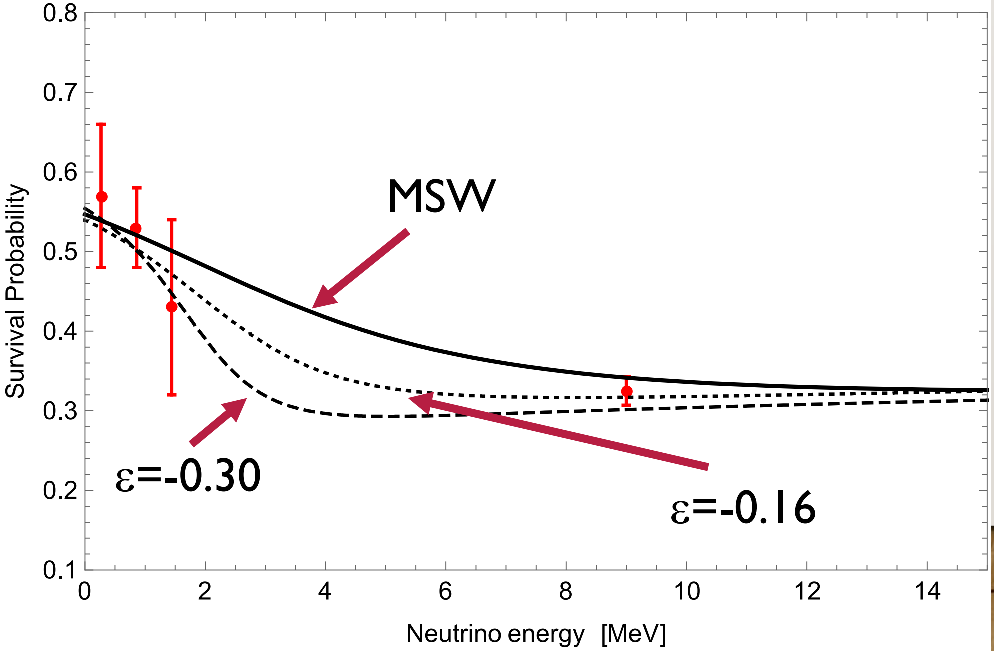
Theories beyond the Standard Model postulate the existence of Non-Standard Interactions (NSI), where flavor-changing NC is possible

The NSI Lagrangian : $-\mathcal{L}_{NC\text{-}NSI} = \sum_{\alpha,\beta} 2\sqrt{2} G_F \varepsilon_{\alpha\beta}^{ff'C} \left(\overline{\nu}_\alpha \gamma^\mu P_L \nu_\beta\right)\left(\overline{f}\gamma_\mu P_C f'\right)$, where $\epsilon_{\alpha\beta}^{ff'C}$ parametrizes the NSI strength

nomalized to $G_f$, f and f' are leptons or quarks, $\alpha,\beta$=e,$\mu,\tau$ and C is the chirality of ff' current (L or R). In this analysis only flavor-diagonal case f=f'=e and $\alpha=\beta$ is considered, with $\epsilon_\alpha^C = \epsilon_{\alpha\alpha}^{eeG}$.

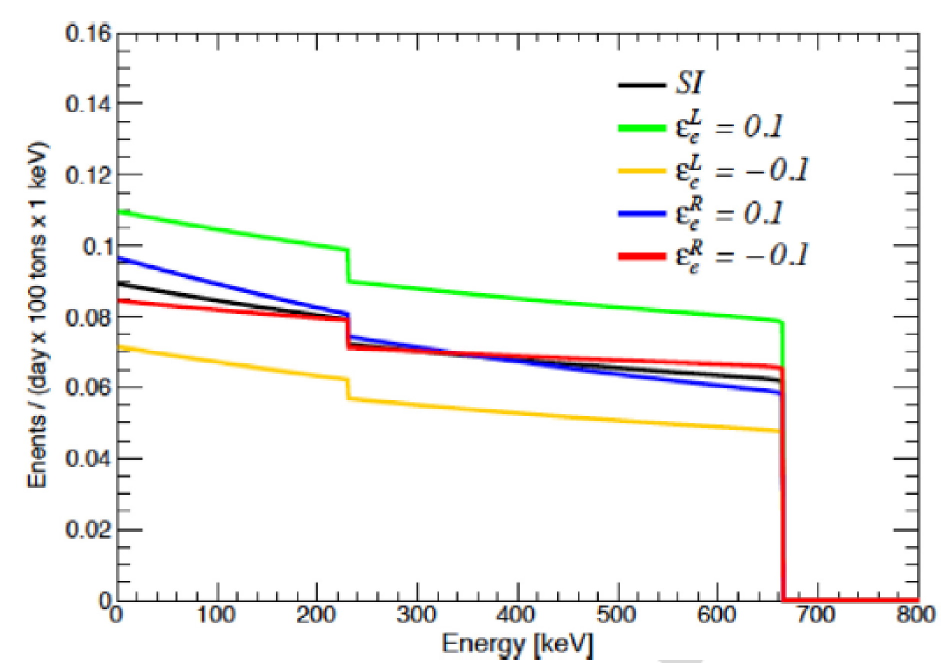
The NSI affects the neutrino propagation in matter and in particular **the vacuum-matter intermediate region**.

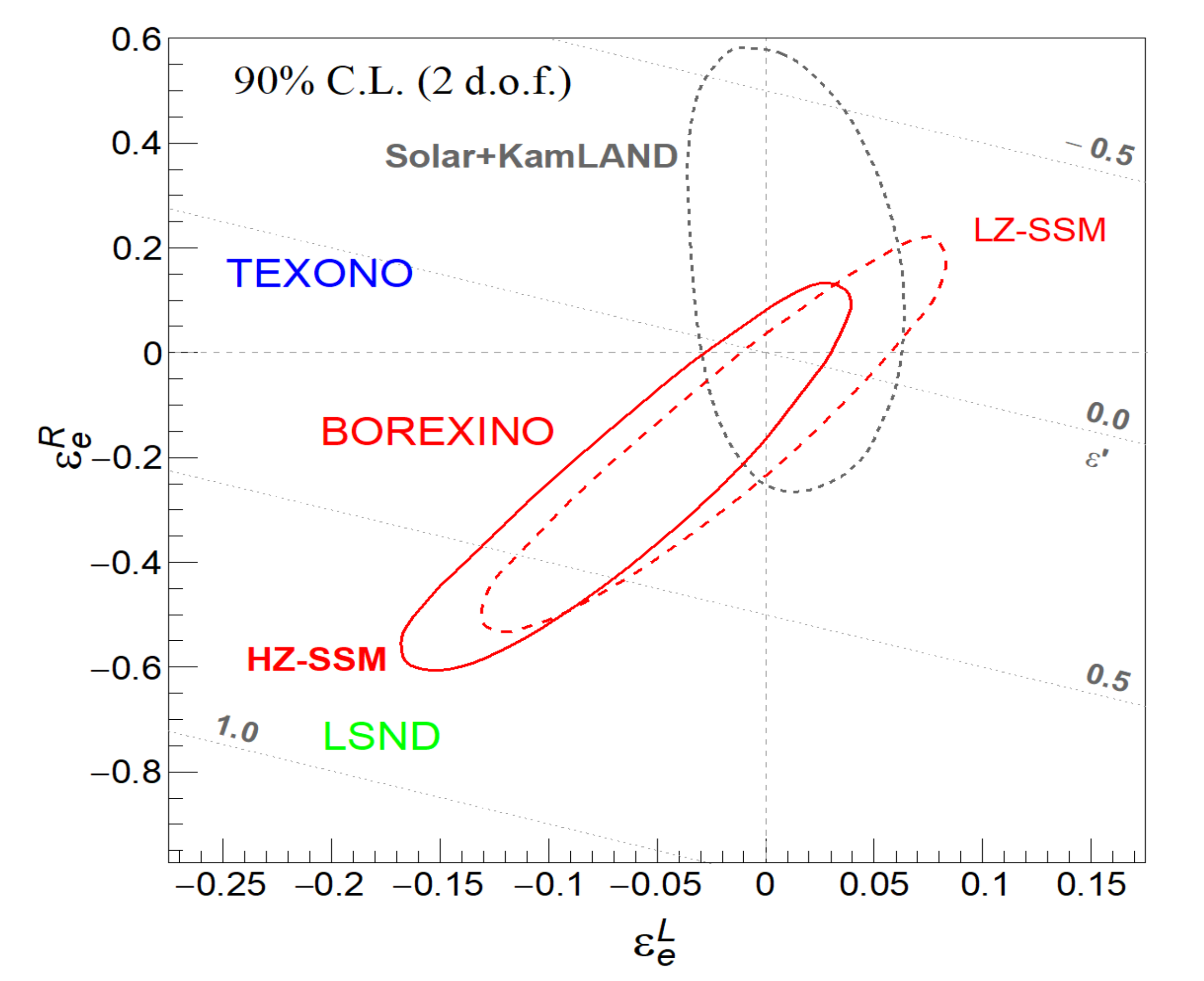
The analysis is carried out on the $\nu$-e elastic scattering which is very sensitive to NSI.




ν-e elastic scattering differential rate for $^7$Be solar neutrinos with and without NSI

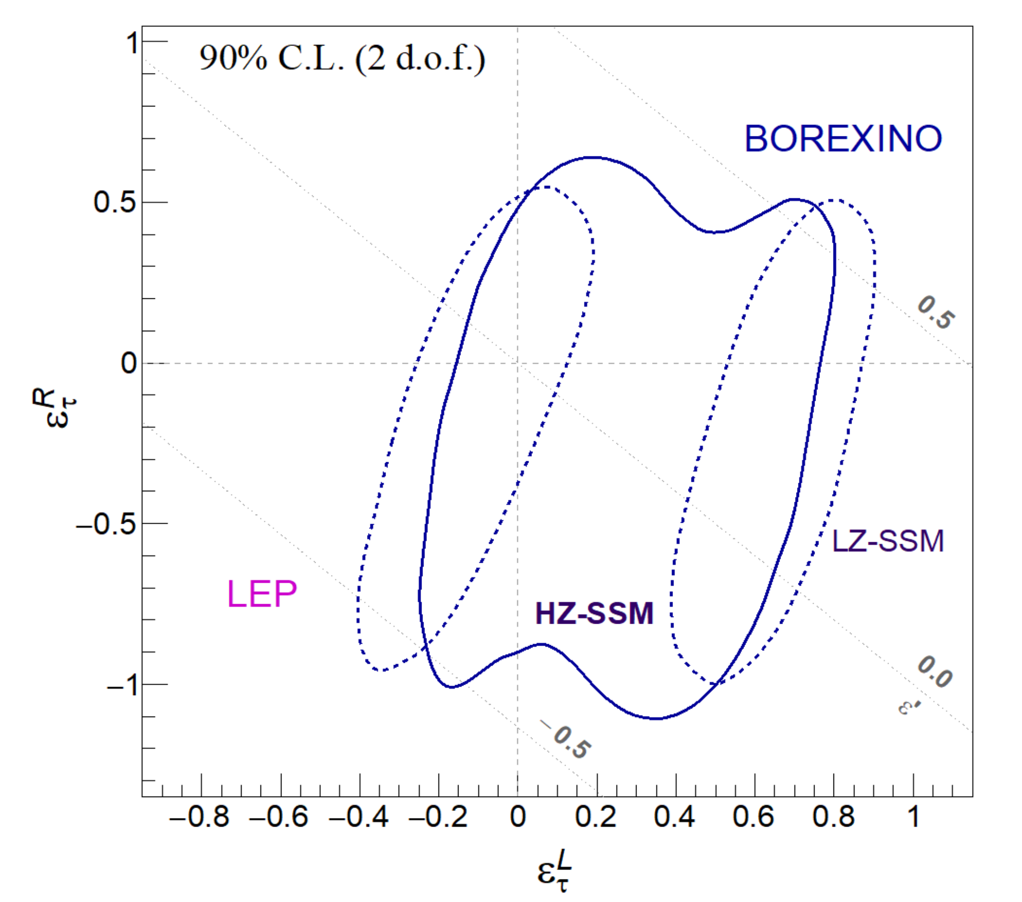
**pp, $^7$Be, pep data**






**allowed region for $\varepsilon_e^{R,L}$ with $\varepsilon_\tau^{R,L}$ fixed at zero**

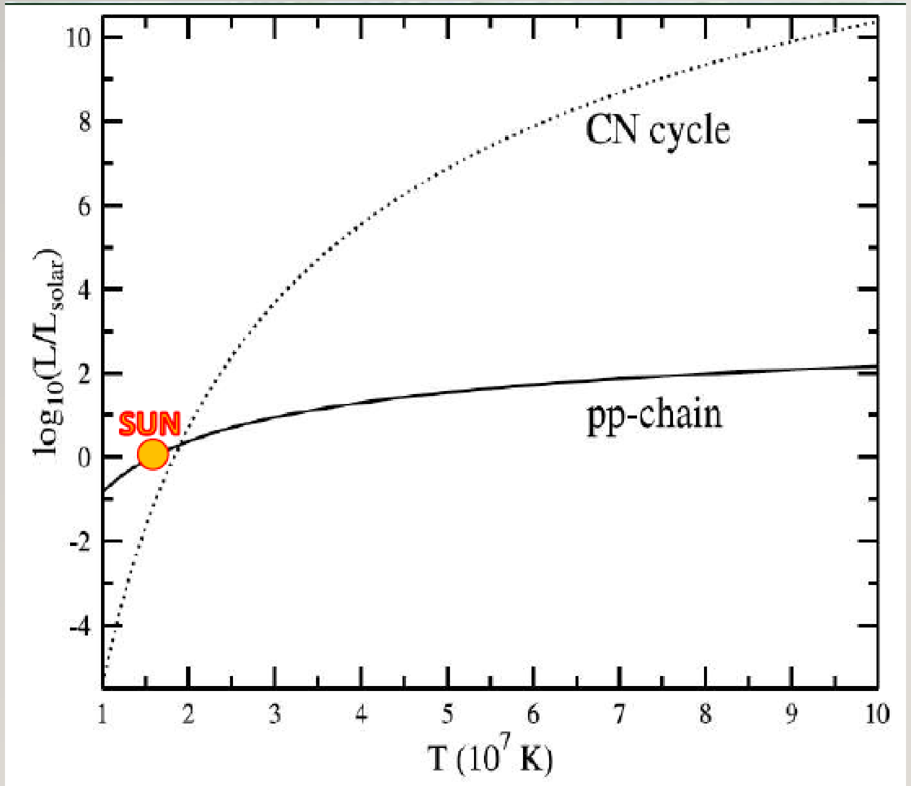
$\epsilon_{\alpha\beta}^{ff'C}$ parametrizes the strength of NSI



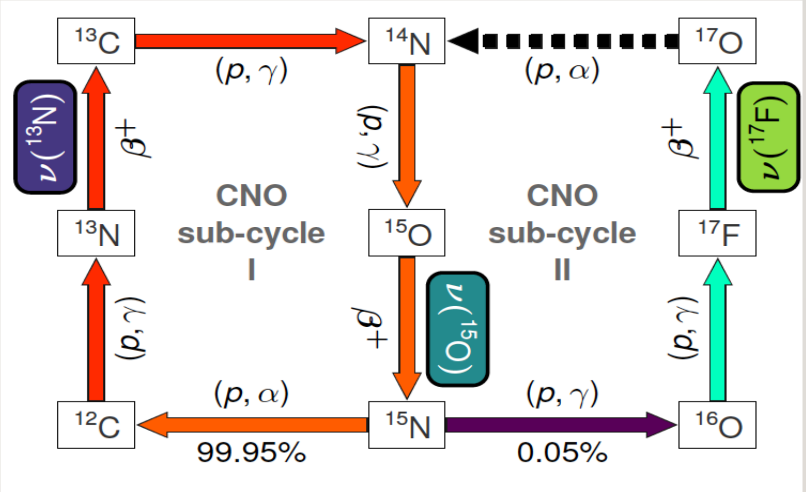

**allowed region for $\varepsilon_\tau^{R,L}$ with $\varepsilon_e^{R,L}$ fixed at zero.**

# CNO Cycle
# 1/9

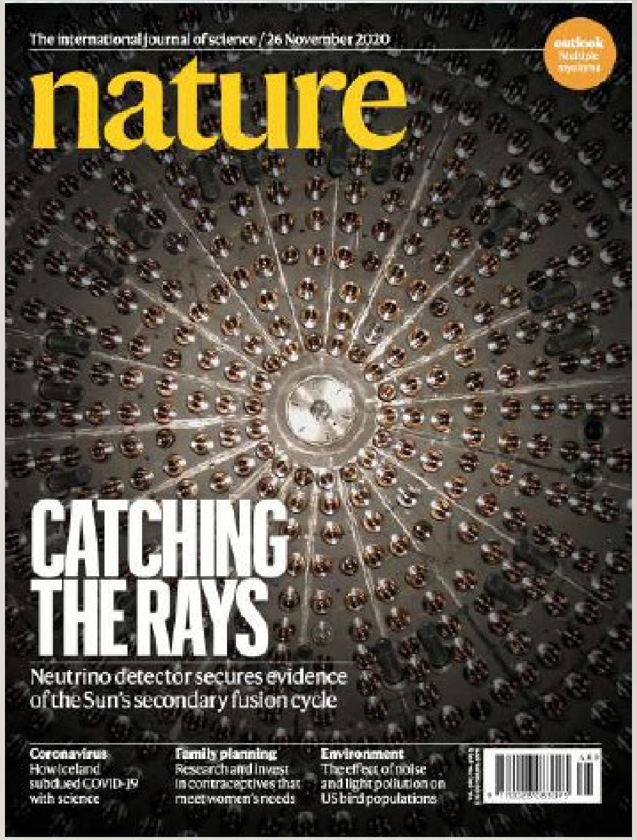
- In the Sun the CNO cycle **contributes only for 1%.**
- In the **massive stars is considered dominant** and reaches in their core a temperature of a few x $10^8$ K, needed to counterbalance the gravitational force thus preventing their implosion
- But this hypothesis, which dates back to the 1930 (Bethe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




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

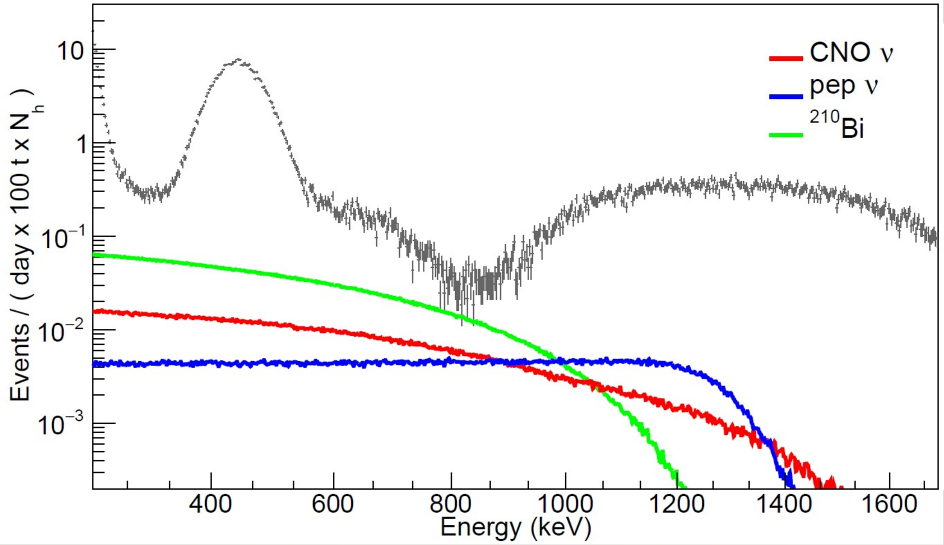



**The experimental demonstration of the existence of the CNO cycle has been the most recent achievement of Borexino**



# CNO Cycle
**2**/9

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
- pep ν spectrum

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

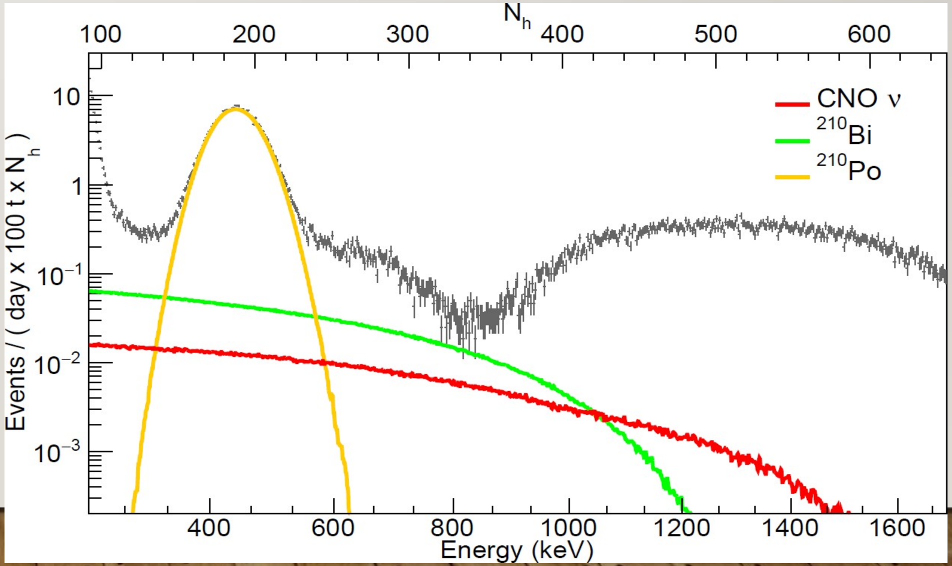
**BUT**

**The pep flux can be constrained at the 1.4 % level** through the solar luminosity constraint coupled to SSM predictions on the pp to pep rates ratio and the most recent oscillation parameters - J. Bergström et al., JHEP, 2016:132, 2016

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

secular equilibrium

$^{210}Pb \xrightarrow[23y]{\beta^-} {}^{210}Bi \xrightarrow[5d]{\beta^-} {}^{210}Po \xrightarrow[138\ d]{\alpha} {}^{208}Pb$ (stable)



# CNO Cycle
3/9

The goal is to extract the $^{210}$Bi rate from the $^{210}$Po, which decaying has to reach a constant plateau.
$^{210}$Po can be easily identified via the $\alpha/\beta$ pulse shape discrimination

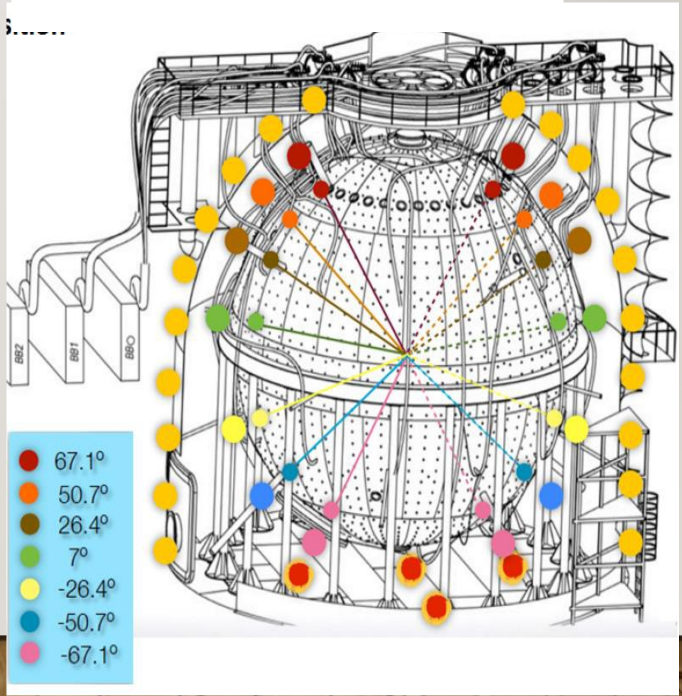
**Due to the secular equilibrium an independent measurement of the $^{210}$Po decay rate gives the $^{210}$Bi decay rate**

$^{210}$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.. Fluctuations are observed in this 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**

**a stabilization of the temperature is necessary**

**temperature probes-**



# CNO Cycle

4/9

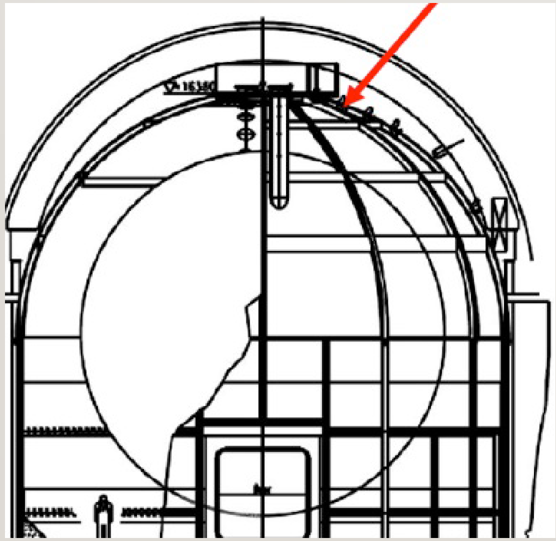
## Stabilization system-2014-2016

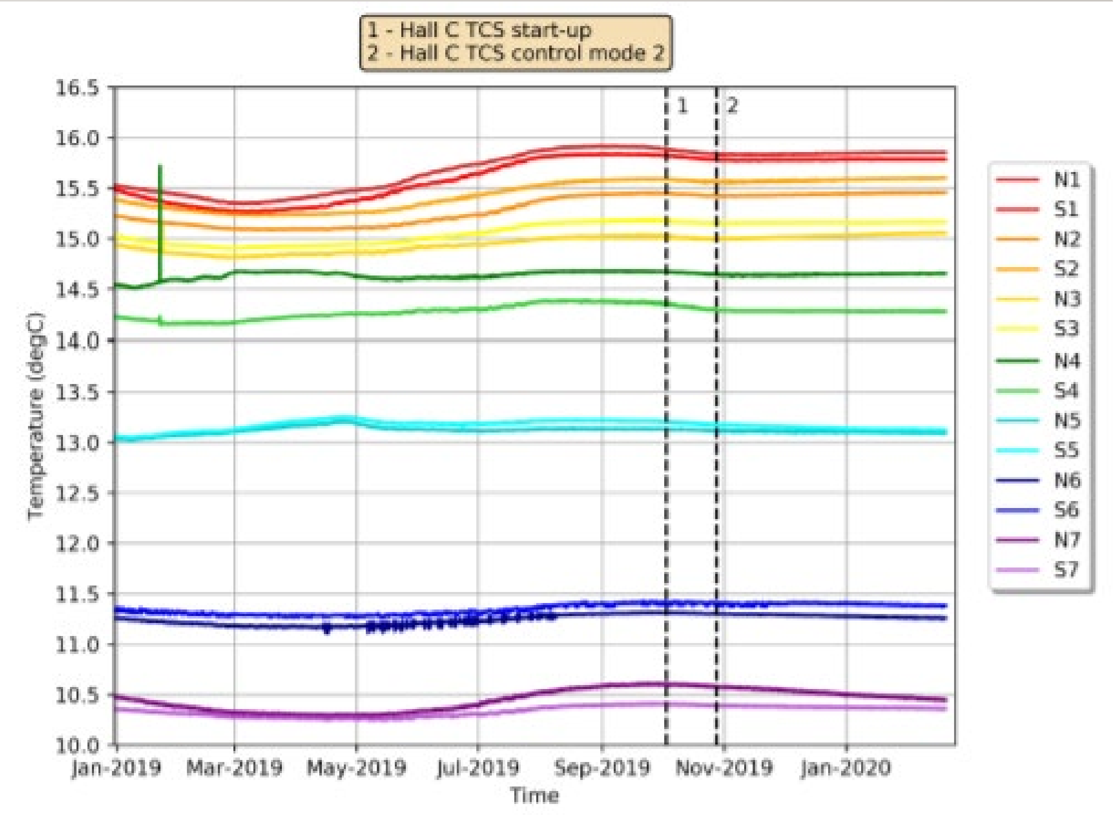
**I$^{st}$ step: thermal insulation**

- Double layer of mineral wool (thermal conductivity down to 0.03 W/m/K)

**2$^{nd}$ step: copper coils under insulation-** water in the serpentines controls the top temperature at about 15,5 K -the bottom temperature (rock ) is ~ 7. K

**Top-bottom gradient stabilized**

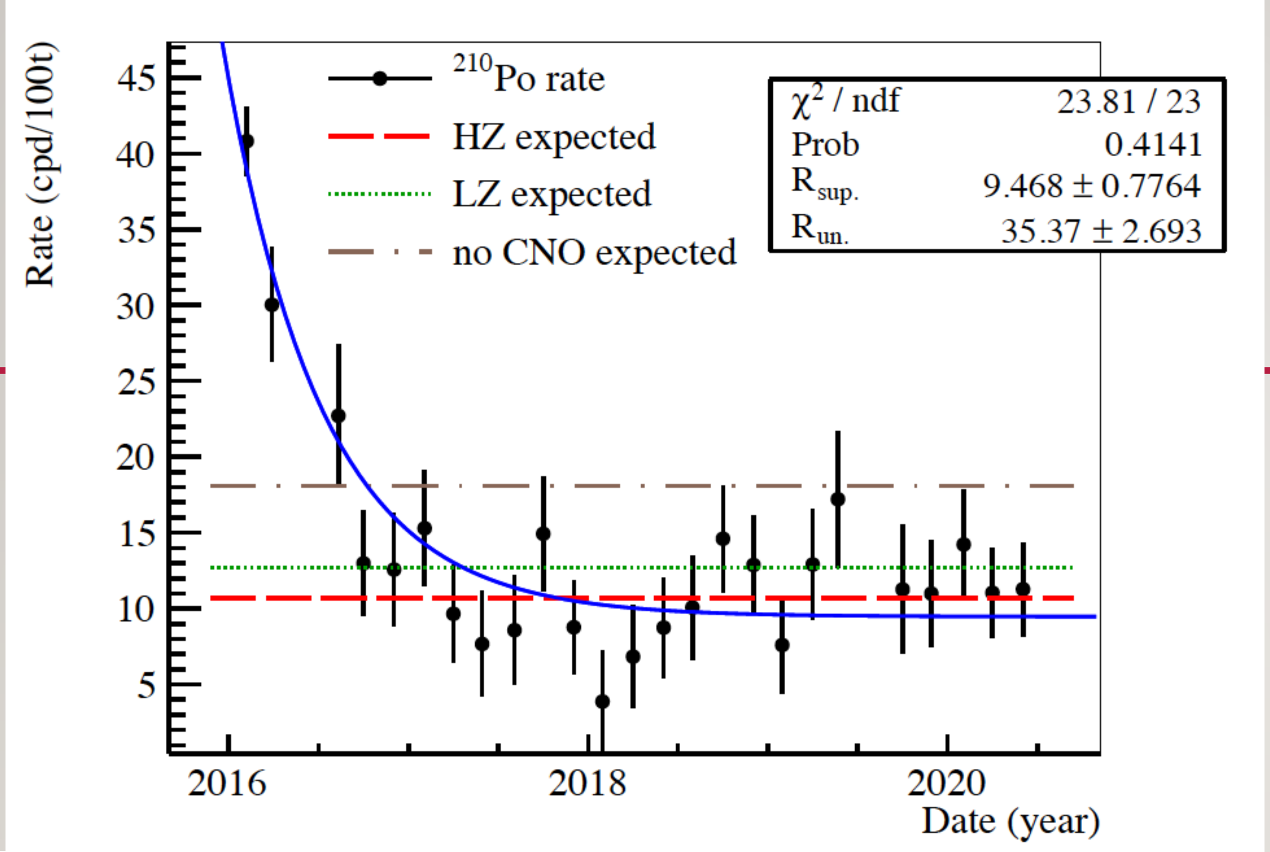




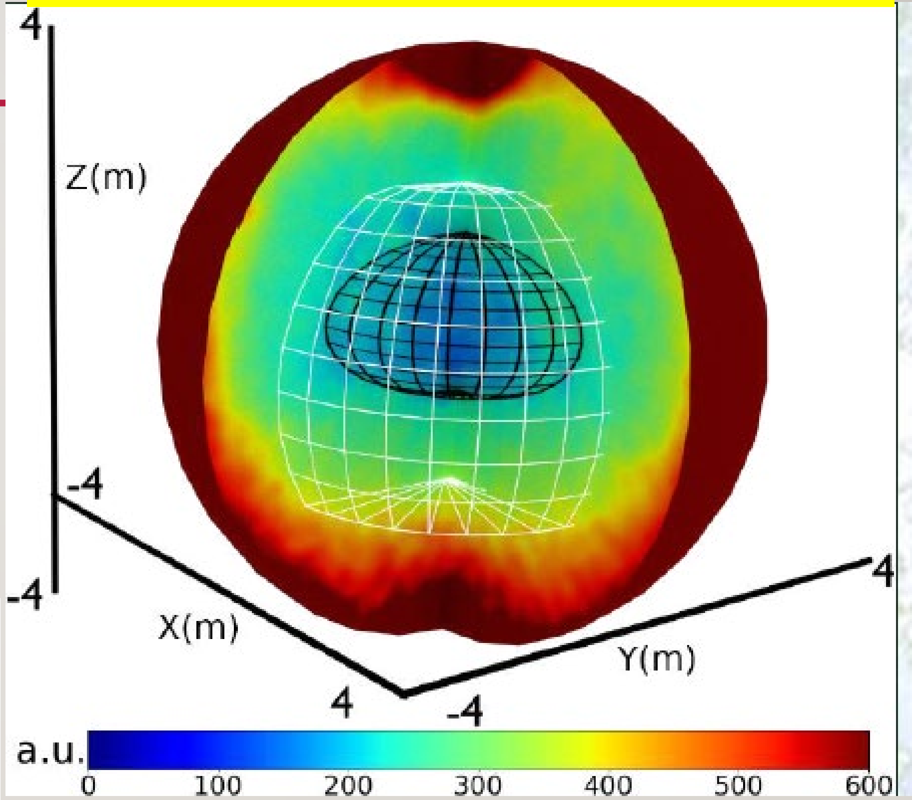

**Excellent temperature stability achieved**

Probes resolution 0.07 °C

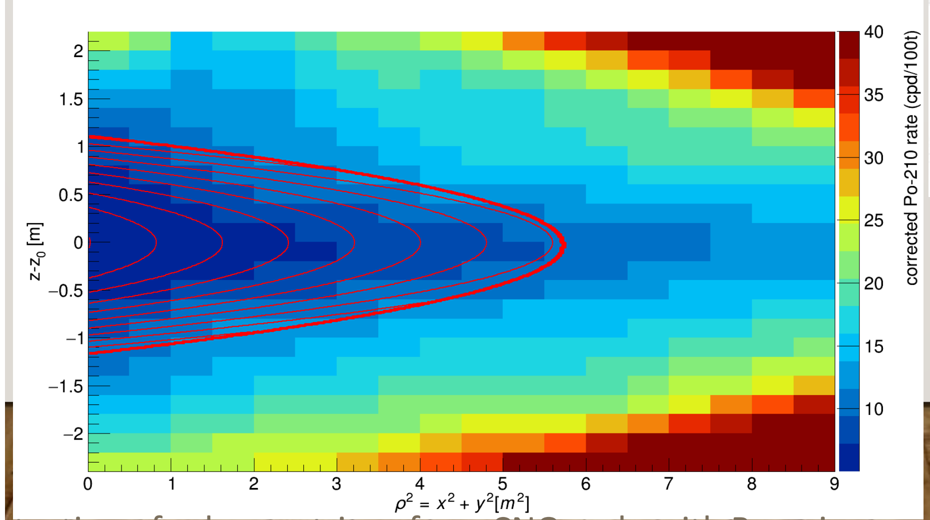
**CNO Cycle**
**5/9**




Three-dimensional view of the $^{210}$Po activity inside the entire Inner Vessel - the innermost **blueish region contains the LPoF (black grid) - the white grid is the software-defined Fiducial Volume**




1. $^{210}$Po (alpha) events are fitted to **find the minimum $^{210}$Po rate in the sub-region**
2. Low Polonium Field (LPoF) at around 80cm above equator, but it moves over time very slowly
3. Fit paraboloid over monthly data




The LPoF blueish region corresponds to **about 20 tons** to be compared to about 78 tons of the Fiducial adopted in this analysis

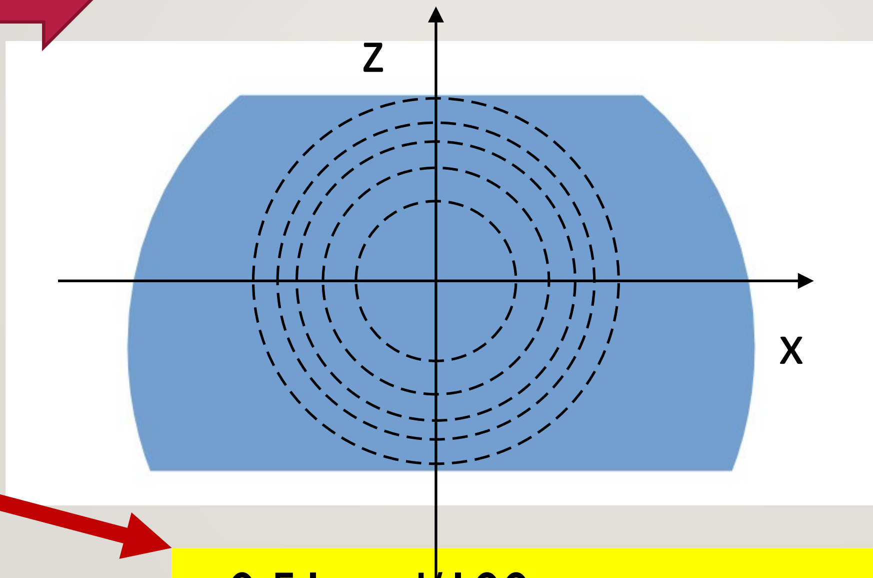
# $^{210}$Bi spatial uniformity systematics

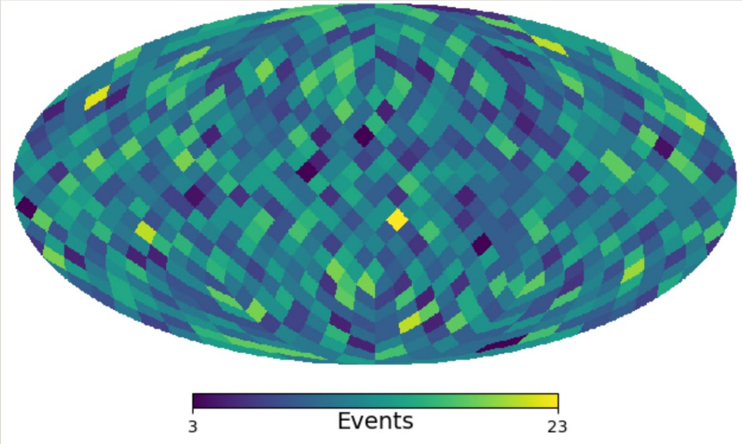
$^{210}$Bi constraint based on 20t region analysis

→ CNO analysis: implicitly extrapolating the $^{210}$Bi constraint from the LPoF **to the larger FV mass (78t)**

**Precision level for $^{210}$Bi uniformity in the FV**

| Radial β analysis | + | Angular β analysis |
|---|---|---|
| Radial shells | | Spherical harmonics decomposition |




0.51 cpd/100t

0.59 cpd/100t

**Overall $^{210}$Bi spatial uniformity systematics: 0.78 cpd/100t**

# CNO Cycle
**7/9**

## $^{210}$Po rate from the Low Polonium Field with all errors

| $R_{min}(cpd/100t)$ | $\sigma_{fit}$ | $\sigma_{mass}$ | $\sigma_{binning}$ | $\sigma_{^{218}Bi\ homog.}$ | $\sigma_{\beta\ leak}$ | $\sigma_{Total}$ |
|---|---|---|---|---|---|---|
| 11.5 | 0.88 | 0.36 | 0.31 | 0.78 | 0.30 | 1.3 |

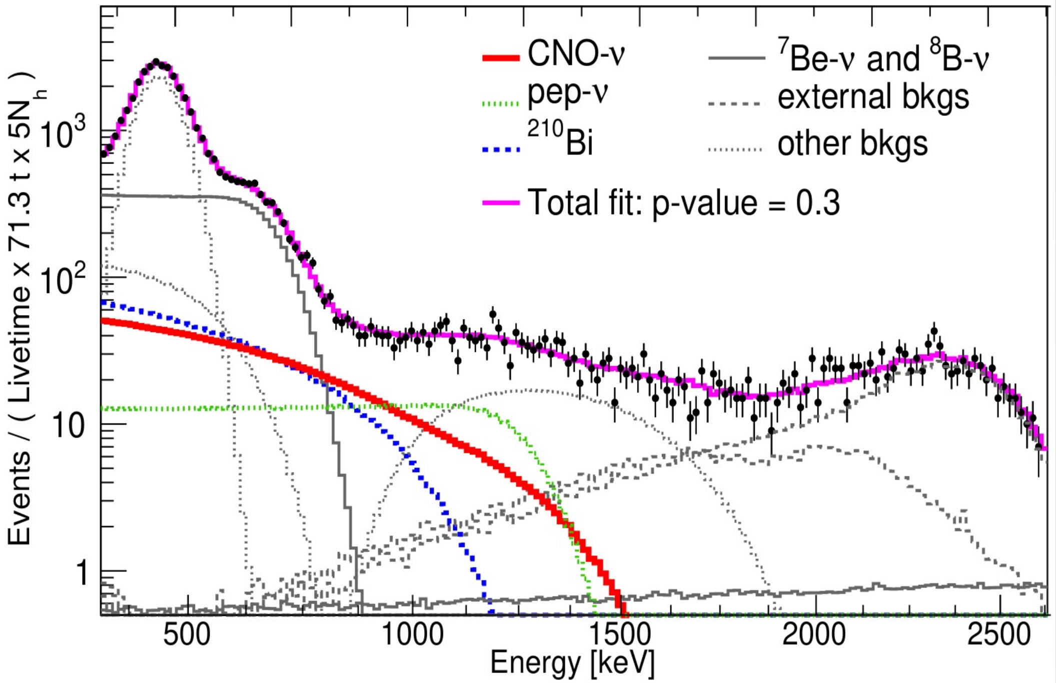
**The lowest $^{210}$Po rate has been conservatively assumed as a upper limit for $^{210}$Bi, because we cannot exclude in principle that residual $^{210}$Po from the vessel surface would be present**

**R($^{210}$Bi) ≤ 11.5 ± 1.3 cpd/100t**

**Multivariate fit (0.32-2.64 MeV)**
**July '16 – February '20**

**Maximization of a binned likelihood: 3 distributions simultaneously:**

- **Reconstructed energy for TFC-tagged and TFC-subtracted datasets ($^{11}$C identification)**
- **Radial position**




**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**

## From the multivariate fit

Further systematic: energy response function -from detector calibration

1. energy scale .~0.23%
2. non linearity ~ 0.4%

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

**corresponding to a flux of neutrinos on Earth;**
**$7.0\ (-1.9\ \ +2.9)\times10^{8}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$**

## Likelhood significance

**13.8 millions pseudo-datasets with no CNO**

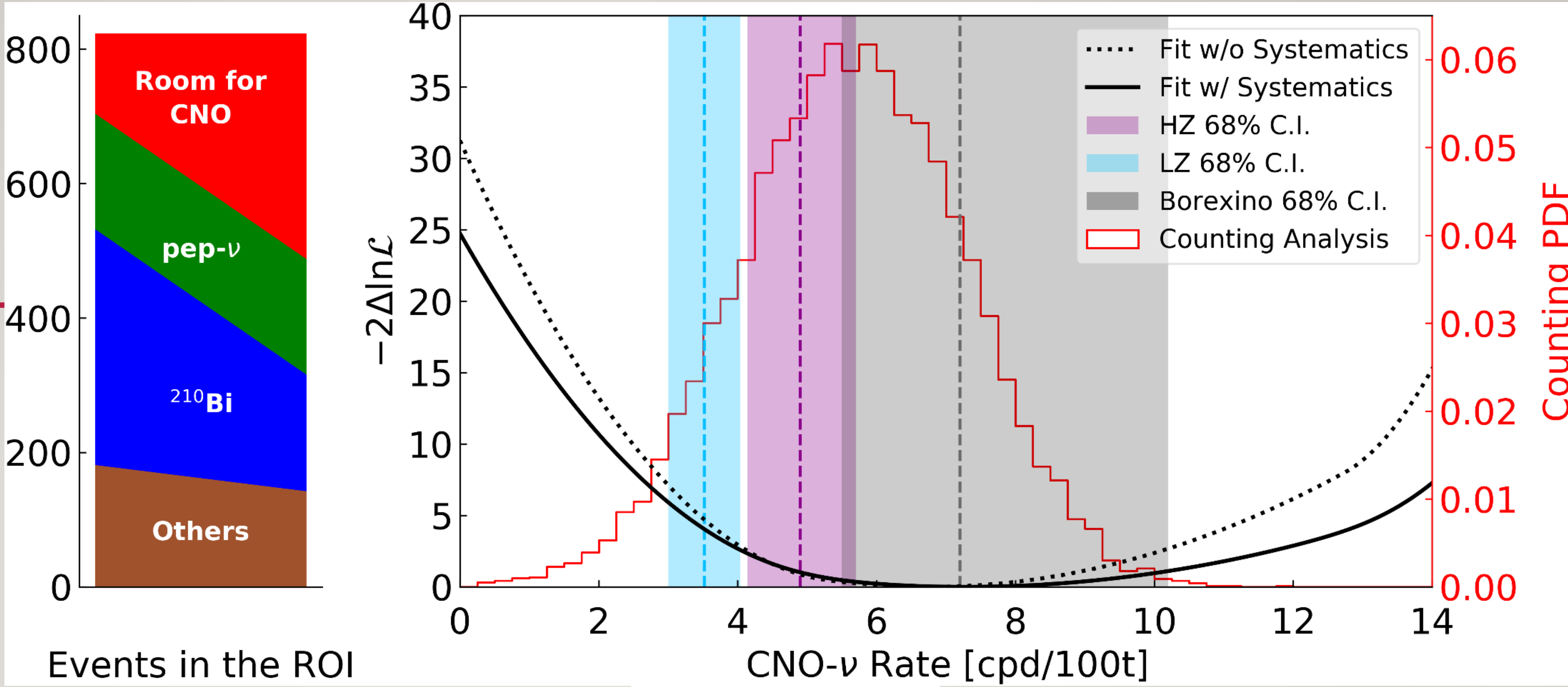
Real dataset

**M.L. significance** greater than **5 $\sigma$** at 99% CL

**No CNO hypothesis disfavored at 5 $\sigma$**

For the CNO analysis in Borexino see also the talks in the parallel sessions:

43, *Davide* Basilico
61. Omer Penek
60. Alexandre Göttel
63. Alessandra Carlotta Re




M.L. significance

the observed CNO rate is compatible with both SSM-HZ and SSM-LZ predictions.

When all solar neutrino fluxes measured by Borexino, including CNO, are combined, the LZ hypothesis is **disfavored at a level of 2.1σ.**

# 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.
3. These results paved the way to actual breakthroughs not only on Solar physics, but also on neutrino physics. **The $\nu_e$ 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, a number of non-standard neutrino interactions has been studied by Borexino with world leading limits.
4. The detection of the CNO cycle closes a long history, which began in the 90s 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. The pp and CNO cycles measurements give an hint in favor of the high metallicity inside the Sun.
6. Again thanks to the low intrinsic background, Borexino has **observed geo-neutrinos** with 5$\sigma$ statistical significance and studied them to obtain Earth geo-physical and geo-chemical information.

The Borexino collaboration

Thank you !!!!