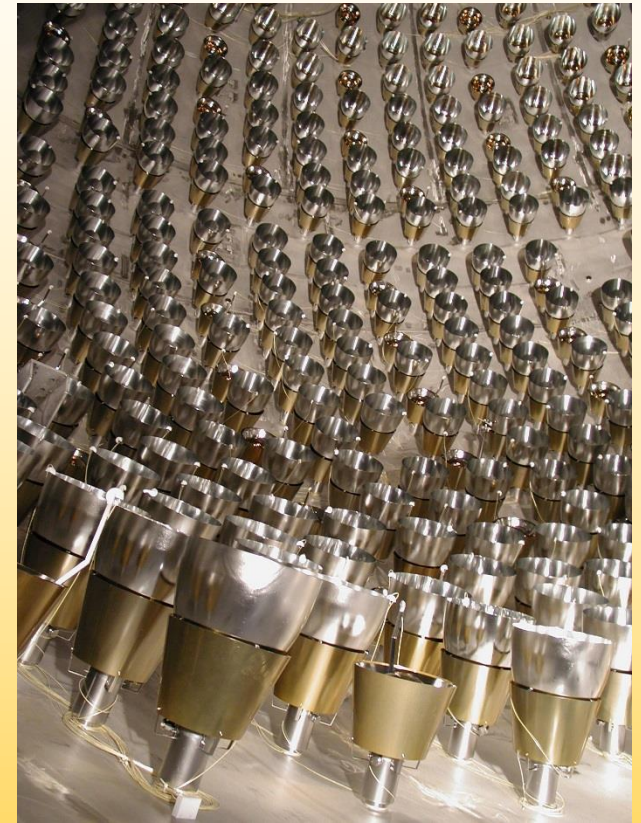
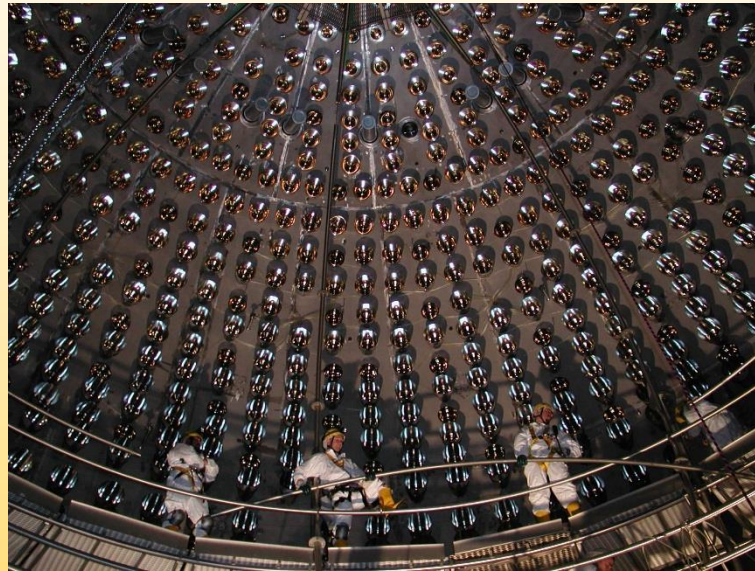
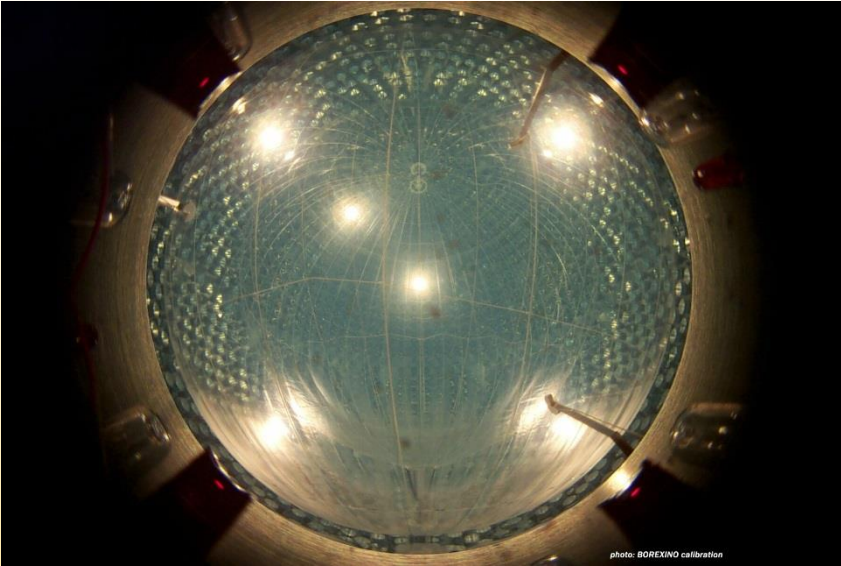


Results from Borexino on solar (and geo-neutrinos)

Gemma Testera

*Istituto Nazionale di Fisica Nucleare (Genova)
On behalf of the Borexino collaboration*

NOW 2018, September 2018



Scintillator:

270 t PC+PPO (1.5 g/l)
in a 150 μm thick
inner nylon vessel (R = 4.25 m)

Stainless Steel Sphere:

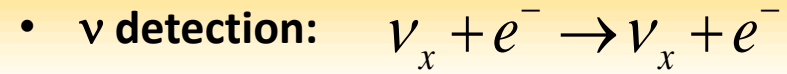
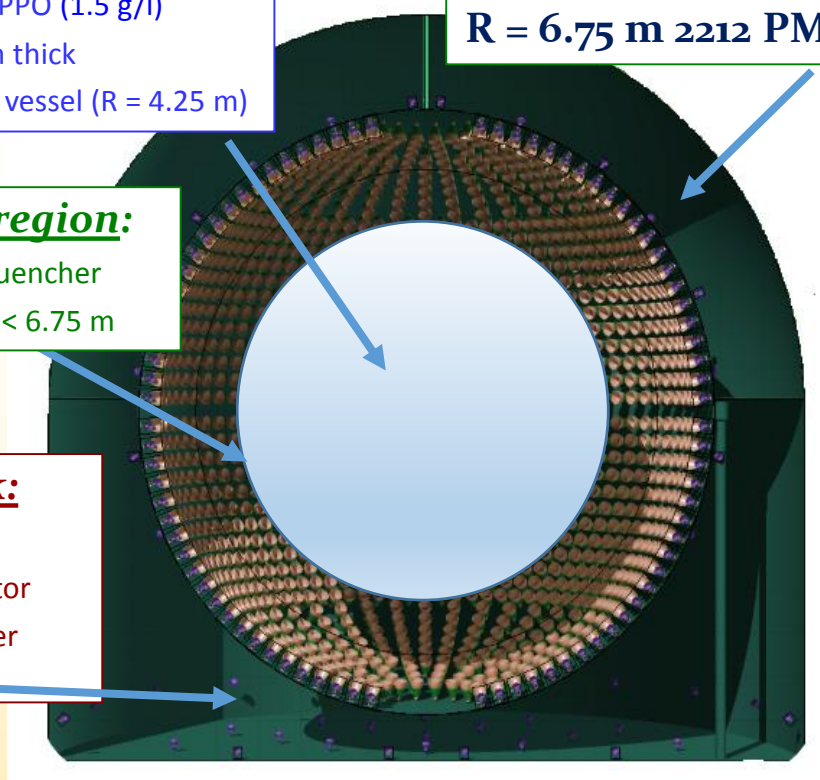
R = 6.75 m 2212 PMTs

Buffer region:

PC+DMP quencher
4.25 m < R < 6.75 m

Water Tank:

γ and n shield
μ water Č detector
208 PMTs in water



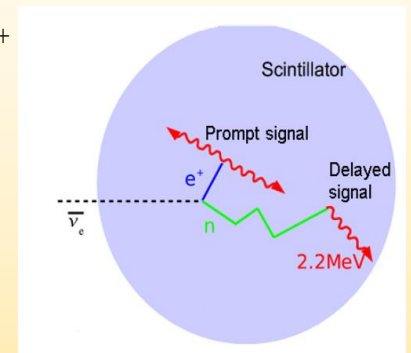
- **Energy E:** N_p : Normalized number of hits PMTs
 N_h : including multiple hits
 N_{pe} : number of phe (charge)

- **Position:** } PMT hit time
- **Pulse shape:** }

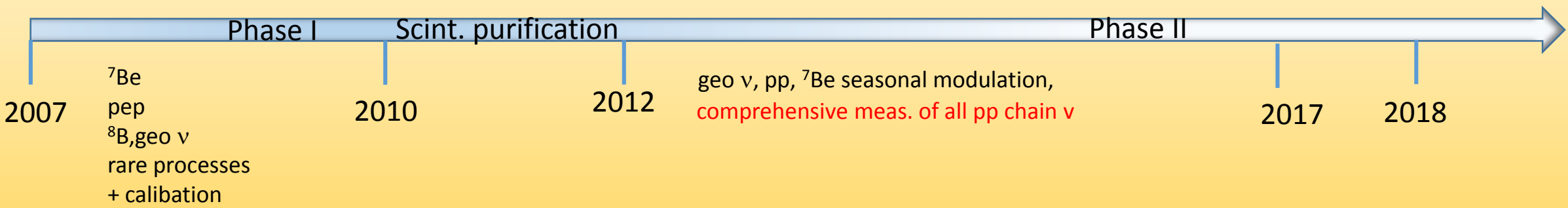
550 N_p @1MeV $\sigma_E = 50 \text{ KeV}@1\text{MeV}$
 $\sigma_{x,y,z} = 10 \text{ cm}@1\text{MeV}$



$E_{\text{prompt}} = E_{\text{antiv}} - 0.784 \text{ MeV}$

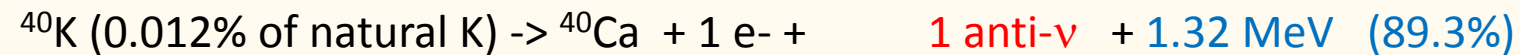
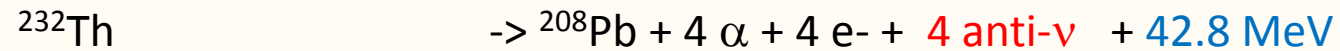
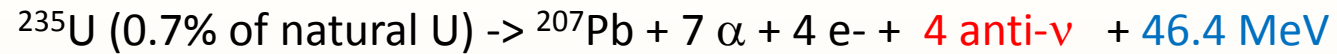
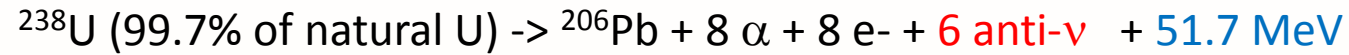


Extremely low levels of radiopurity



Geo Neutrinos

electron **antineutrinos** from the decays of long lived radioactive isotopes naturally present in the Earth

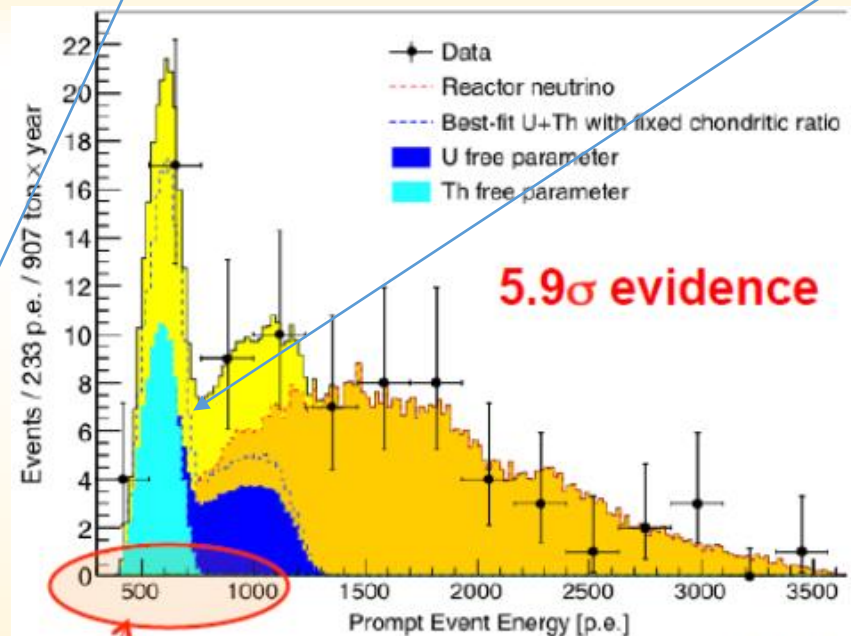
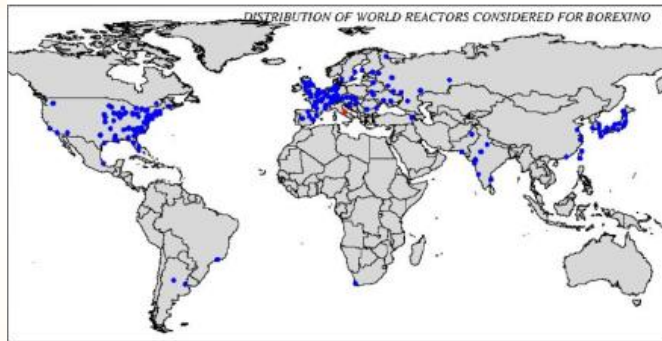


Flux: 10^6 anti- ν /($\text{cm}^2 \text{ s}$) 4 order of magnitude lower than solar neutrinos
but very clear signature (IBD)

- Probe of the interior of the Earth
- Understand source of radiogenic heat
- Determine U/Th ratio
- Discriminate among geological models
- Interdisciplinary interest

Background for geo-neutrinos and signal in Borexino

A) Reactor antineutrino background



✓ Non-antineutrino background almost invisible!

✓ 5.5×10^{31} target-proton year Dec2007-March2015

$23.7^{+6.5}_{-5.7} (stat)^{+0.9}_{-0.6} (sys)$ Geo-ν 26% precision

**New results coming soon: improved selection of events
< 20% precision**



B) Non-antineutrino background

1) Cosmogenic background

• ${}^9\text{Li}$ and ${}^8\text{He}$ ($T_{1/2} = 119/178$ ms) decay: β (prompt) +neutron (delayed);

• fast neutrons

scattered protons (prompt)

Estimated by studying coincidences detected AFTER muons

2) Accidental coincidences;

Estimated from OFF-time coincidences

3) Due to the internal radioactivity:

(α , n) reactions: ${}^{13}\text{C}(\alpha, n){}^{16}\text{O}$

Prompt: scattered proton, ${}^{12}\text{C}$ (4.4 MeV) and ${}^{16}\text{O}$ (6.1 MeV)

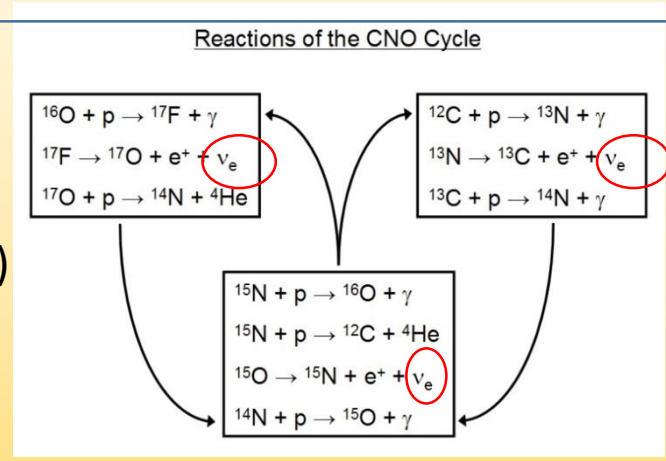
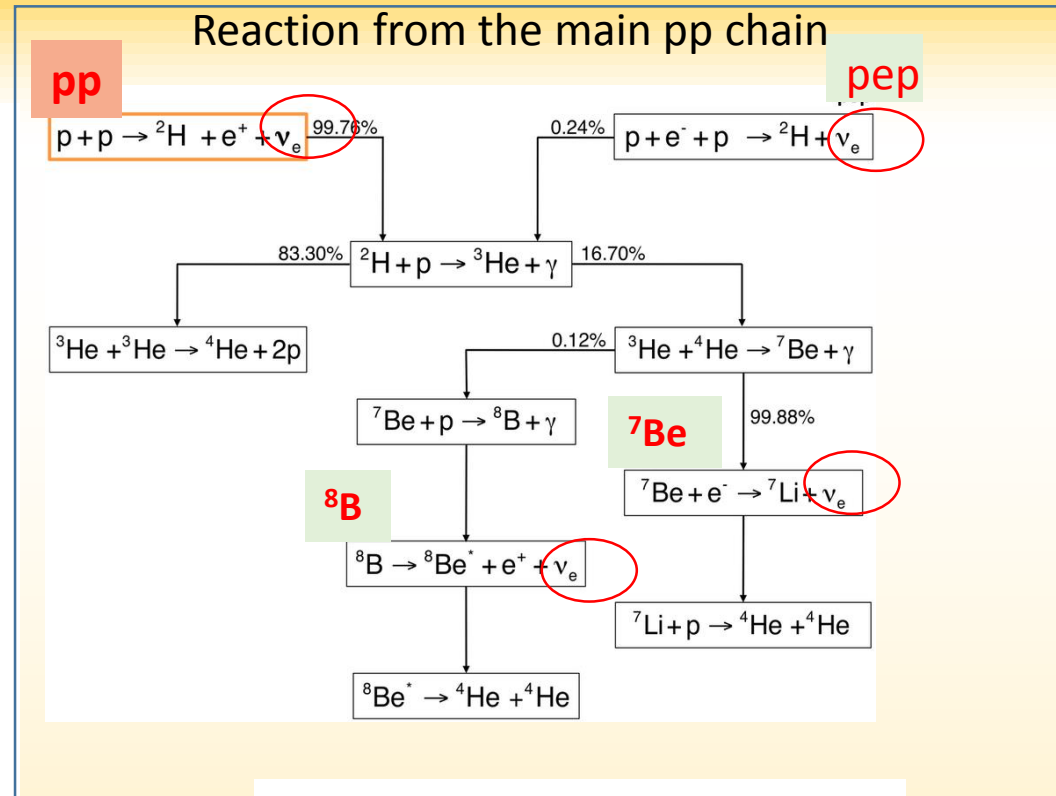
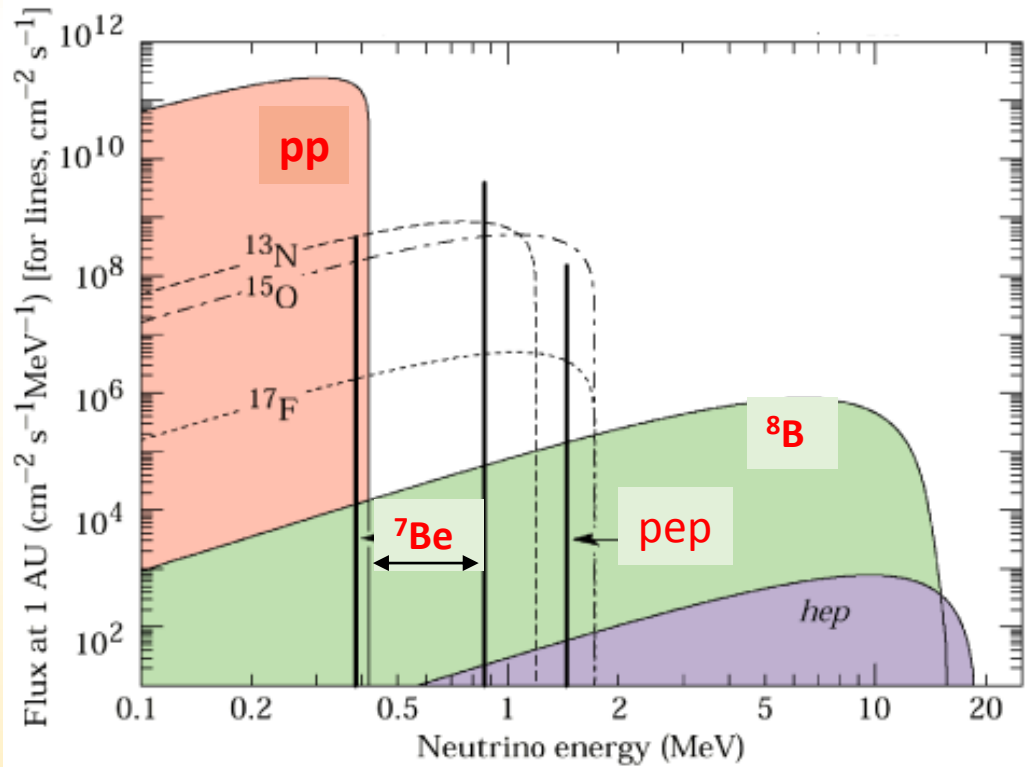
Estimated from ${}^{210}\text{Po}(\alpha)$ and ${}^{13}\text{C}$ contaminations, cross section

Radiogenic heat

$$U + Th + K = 33^{+28}_{-20} \text{ TW}$$

$$\text{Borexino} = 47 \pm 2 \text{ TW}$$

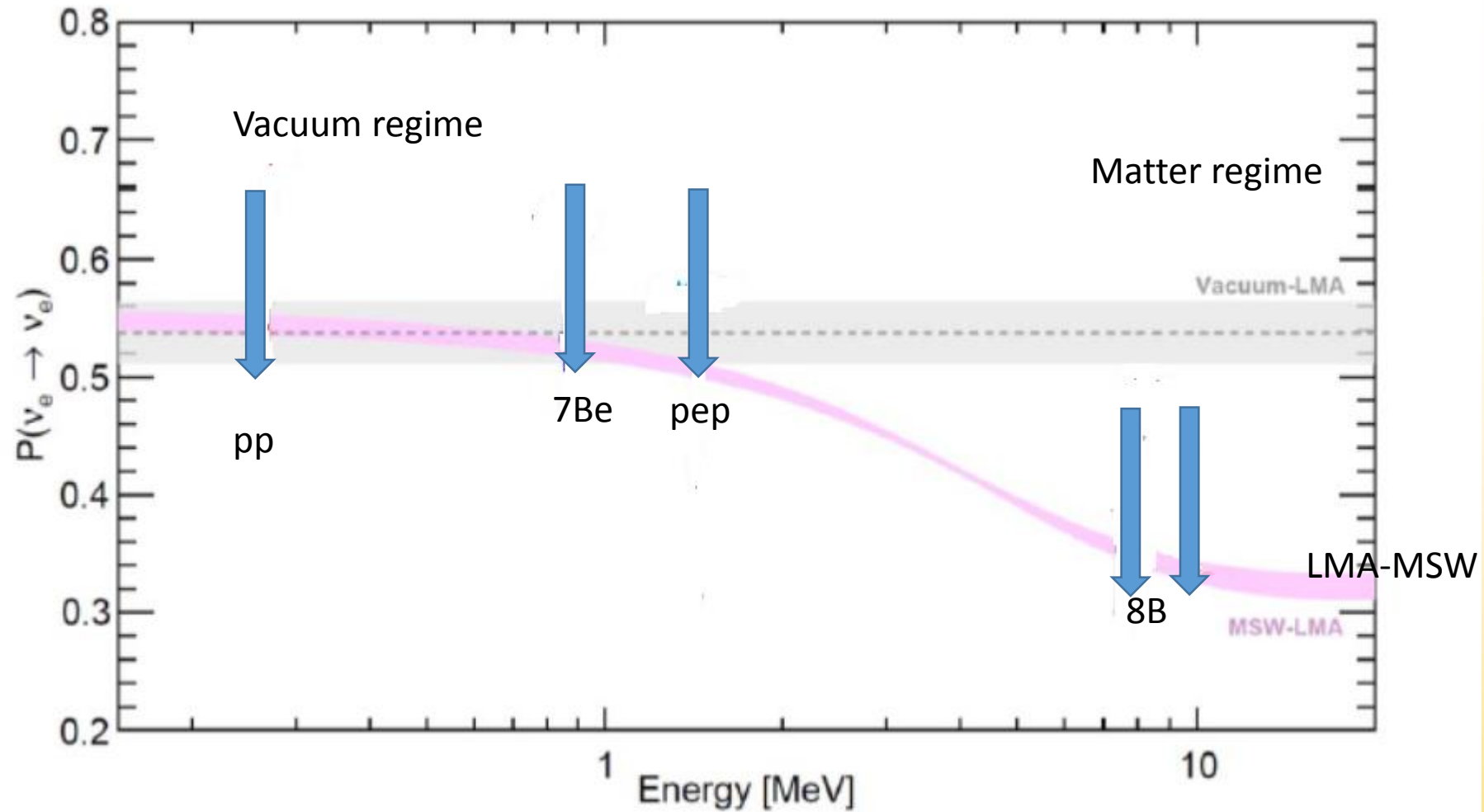
Solar Neutrinos



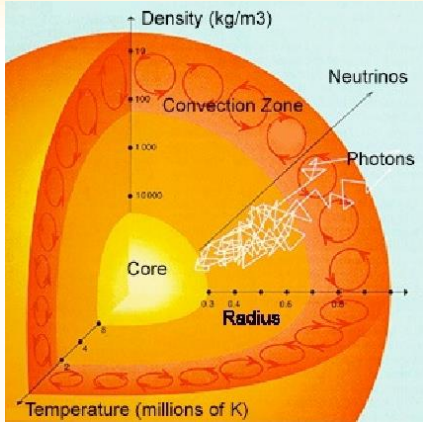
- Fusion reactions in the core of the Sun
- pp dominant in the SUN (99% of the energy and ν production))
- CNO important for larger mass stars

$$4H + 2e^- \rightarrow 4He + 2e^+ + 2\nu_e + 26.7 \text{ MeV}$$

LMA-MSW oscillations: P_{ee} , neutrino survival probability



Solar neutrinos and solar models



- Evolution of a star from beginning until now $4.57 \cdot 10^9$ y
- Homogeneous mixture of H, He and heavy elements $X_{ini}, Y_{ini}, Z_{ini}$
- α_{MLT} : parameter entering in the description of the convection
- Cross sections for nuclear reactions (S factors)
- Opacity
- Equilibrium between gravitational force and outward force due to gradient of pressure $P(r)$

Initial parameters adjusted to reproduce present days status:

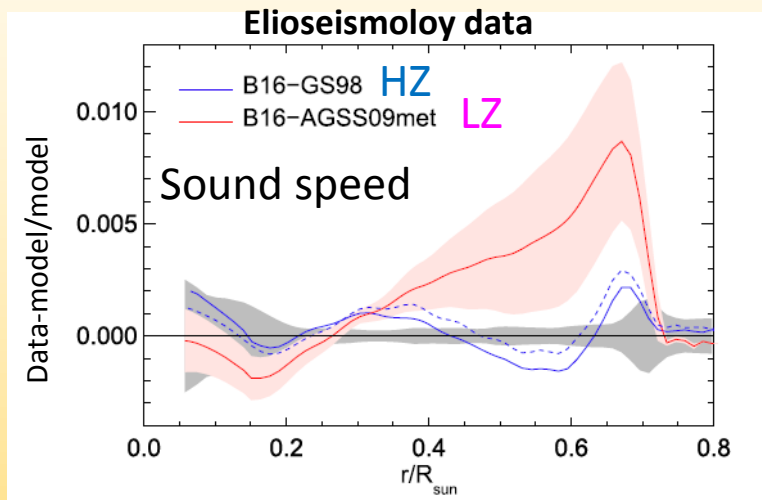
Solar Luminosity L
 Solar Radius
Z/X (abundance of metals) on the surface



Observables : elioseismology
 solar neutrinos

.....

Since 2001: **new analysis of spectroscopic data from photosphere**, revision of surface solar metallicity, **lower values (LZ)**
 But solar models reproducing these new LZ values **disagree with elioseismology data** (solar abundance problem)



N. Vinyoles et al. The Astrph. Journ. 835 1 (2017)
 Improved model

The prediction of solar ν flux is sensitive to the Sun metallicity

Flux	B16-GS98 HZ	B16-AGSS09met LZ
$\Phi(pp)$	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)

→
 →
 CNO {

Units:
 $pp: 10^{10} \text{ cm}^{-2} \text{ s}^{-1}$;
 $Be: 10^9 \text{ cm}^{-2} \text{ s}^{-1}$;
 $pep, N, O: 10^8 \text{ cm}^{-2} \text{ s}^{-1}$;
 $B, F: 10^6 \text{ cm}^{-2} \text{ s}^{-1}$;
 $hep: 10^3 \text{ cm}^{-2} \text{ s}^{-1}$

7Be : 8.7% diff
 8B : 17.6% diff
CNO: 40% diff

All the pp chain ν measured by Borexino with a unified analysis (Phase II)

Low Energy Region (LER)	0.19 – 2.93 MeV	pp, ^7Be , pep, (CNO)	
High energy region (HER)	3.2 – 16 MeV	^8B	HER1 (3.2-5.7) MeV + HER2 (5.7-16) MeV

Low energy threshold: limited by residual 2.6 γ rays from ^{208}Tl decays in the nylon vessel

The analysis strategy

- Scintillation light is not directional
- Apply cuts to remove known background on **event by event basis**
- ^{11}C tag and split the LER energy spectrum in ^{11}C tagged and ^{11}C subtracted
- Select a **proper fiducial volume**
- **Fit distribution of global quantities** built with the events surviving the cuts
- Use of an **accurate Monte Carlo** tuned with calibration sources covering all the range

Choice of the FV

- LER : 71.3 t ($r < 2.8$ m and $-1.8 < z < 2.8$ m)
- HER1 entire mass of the scintillator (266 t)
- HER2 $z < 2.5$ m (due to vessel leak events) (227.8 t)

- Maximize a binned likelihood through a multivariate approach in the LER region

$$L(\mathcal{G}) = L_{sub}(\mathcal{G}) \cdot L_{tag}(\mathcal{G}) \cdot L_{rad}(\mathcal{G}) \cdot L_{PS-L_{pr}}(\mathcal{G})$$

Energy spectrum ^{11}C subtracted

Energy spectrum ^{11}C tagged

Radial distribution of the events

Pulse shape parameter

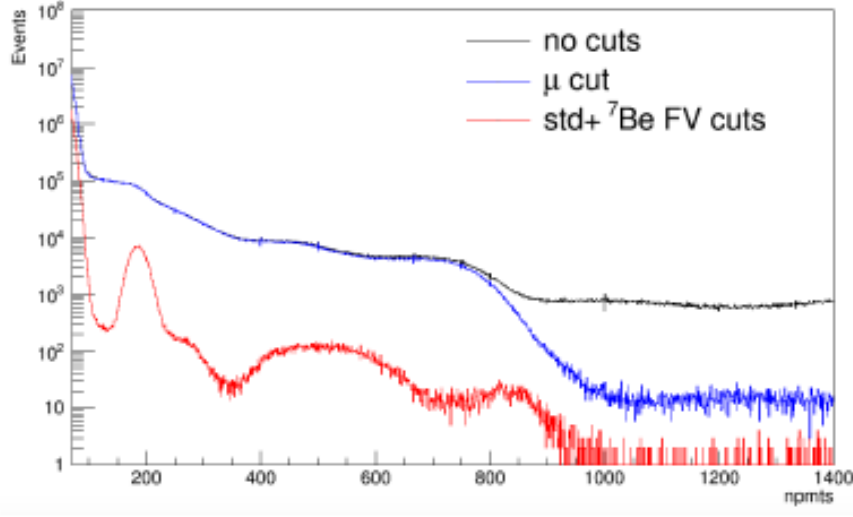
- Fit the radial distribution of the events in the ^8B energy region (HER1 and HER2)

<https://arxiv.org/abs/1707.09279>
<https://arxiv.org/abs/1709.00756>
 Astroparticle Physics, Vol. 97, 2018, Pages 136-159

Signal and background in the Low Energy Region

Data energy spectrum in the LER region (0.19-2.93 MeV) before and after cuts

present data set:
Dec 14th 2011 to May 21th, 2016
1291.51 days X 71.3 tons

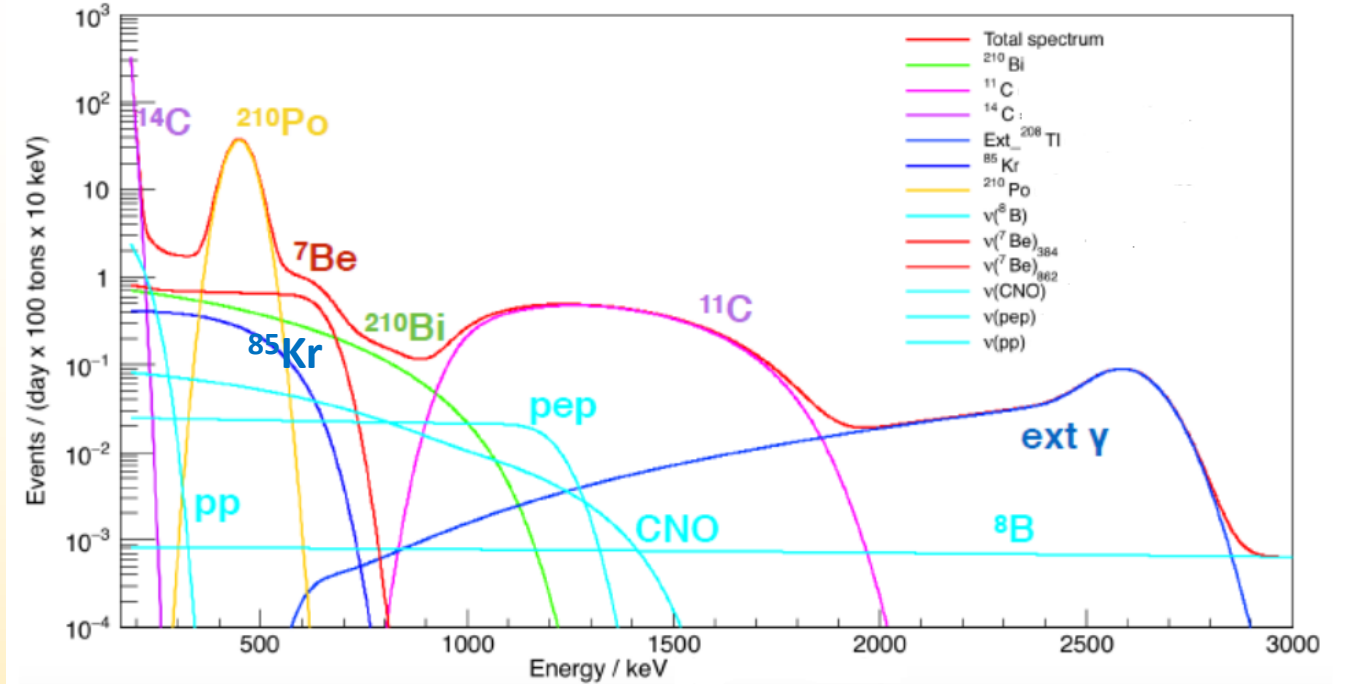


N_p

Event selection

- removal μ and cosmogenics (1.5% dead time)
- removal of Bi-Po214
- noise events
- Fiducial Volume ($R < 2.8$ m, $-1.8 < z < 2.2$ m)
- 71.3 tons
- no $\alpha\beta$ discrimination
- Fraction of good events removed by cuts $< 0.1\%$

Simulated energy spectrum in LER region including solar ν and the main background components



Purification: reduction of ^{85}Kr , ^{210}B

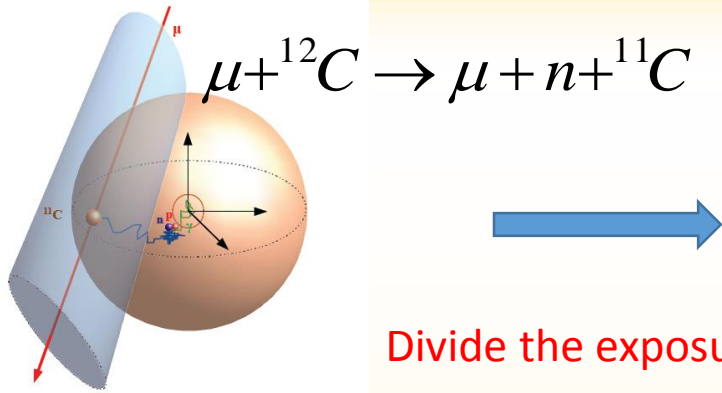
^{232}Th (from $^{212}\text{Bi-Po}$)

- $< 5.7 \cdot 10^{-19}$ g/g 95% C.L.
- PHASE 1: $3 \cdot 10^{-18}$ g/g

^{238}U (from $^{214}\text{Bi-Po}$)

- $< 9.4 \cdot 10^{-20}$ g/g 95% C.L.
- PHASE 1: $5 \cdot 10^{-18}$ g/g

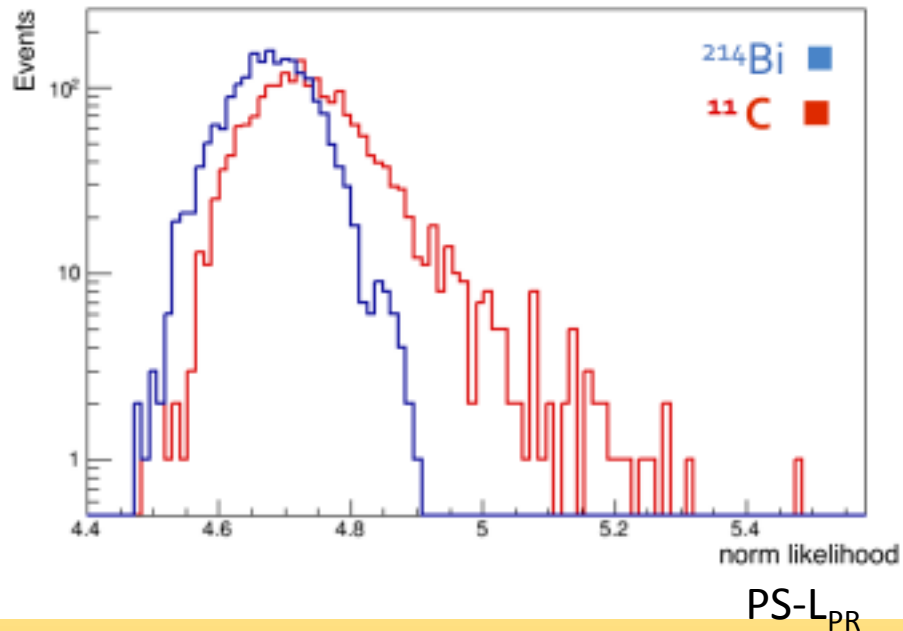
^{11}C : Three Fold Coincidence and β^+/β^- discrimination



- Identify μ and μ track
- Detect n (γ signal due to capture after thermalization)
- Space time cuts around the μ track and n position: ^{11}C should be there
- **Build a Likelihood function to evaluate if an event is a ^{11}C**

Divide the exposure in 2 samples: ^{11}C subtracted & ^{11}C tagged

Performances: 92.4 +/- 4 % tagging efficiency
exposure: 64% in the ^{11}C subtracted spectrum



Novel β^+/β^- pulse shape parameter:

Energy normalized likelihood of the position reconstruction

- Pdf of the position rec. assumes point like, prompt scintillation but:
 - e^+ slows down, form O-Ps with few ns lifetime
 - Multiple interaction of 511 γ within about 20 cm
 - The max likelihood assumes lower values for true β^- events than for ^{11}C decay

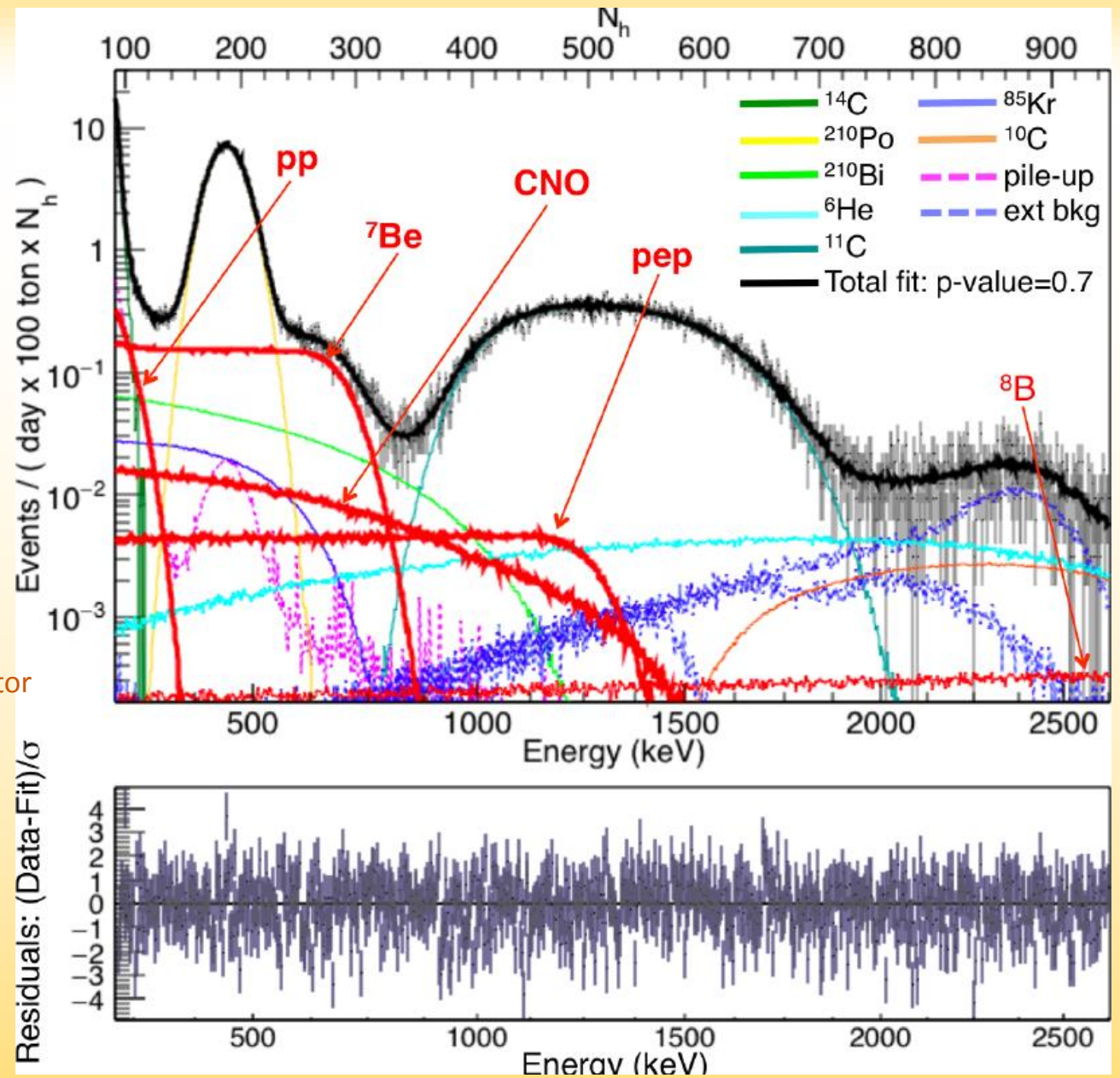
Example of results

Example of multivariate fit of the data:
Energy spectrum ^{11}C tagged

N_h

Monte Carlo fit

- Full simulation of energy loss & detector geometry
- Tracking of single scintill. & Cherenkov photons
- Absorption, re-emission, scattering..
- Detection on PMTs & electronics response simulation
- Tuned with calibration data taken during Phase 1
- Solar ν and back. simulated with known time variations of the detector
- Processed as real data
- Data analysis free fit parameters: solar ν and background rate
- If it works: MC well tuned & detector is stable



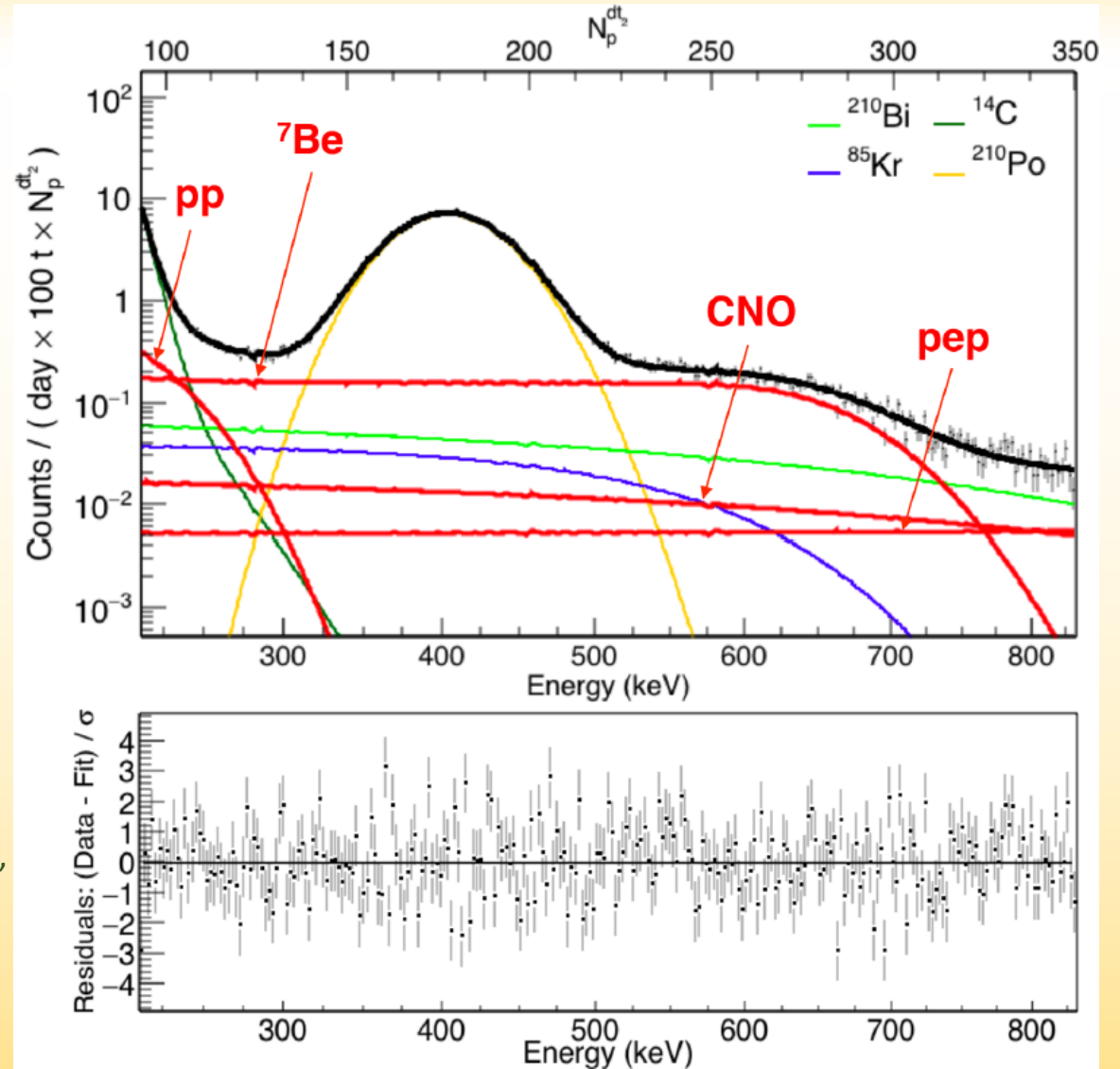
Zoom of the lowest energy region, below 800 KeV

Example of multivariate fit of the data:

- Energy spectrum zoomed in the low energy region (200-830 KeV)
- N_p^{dt2}
-

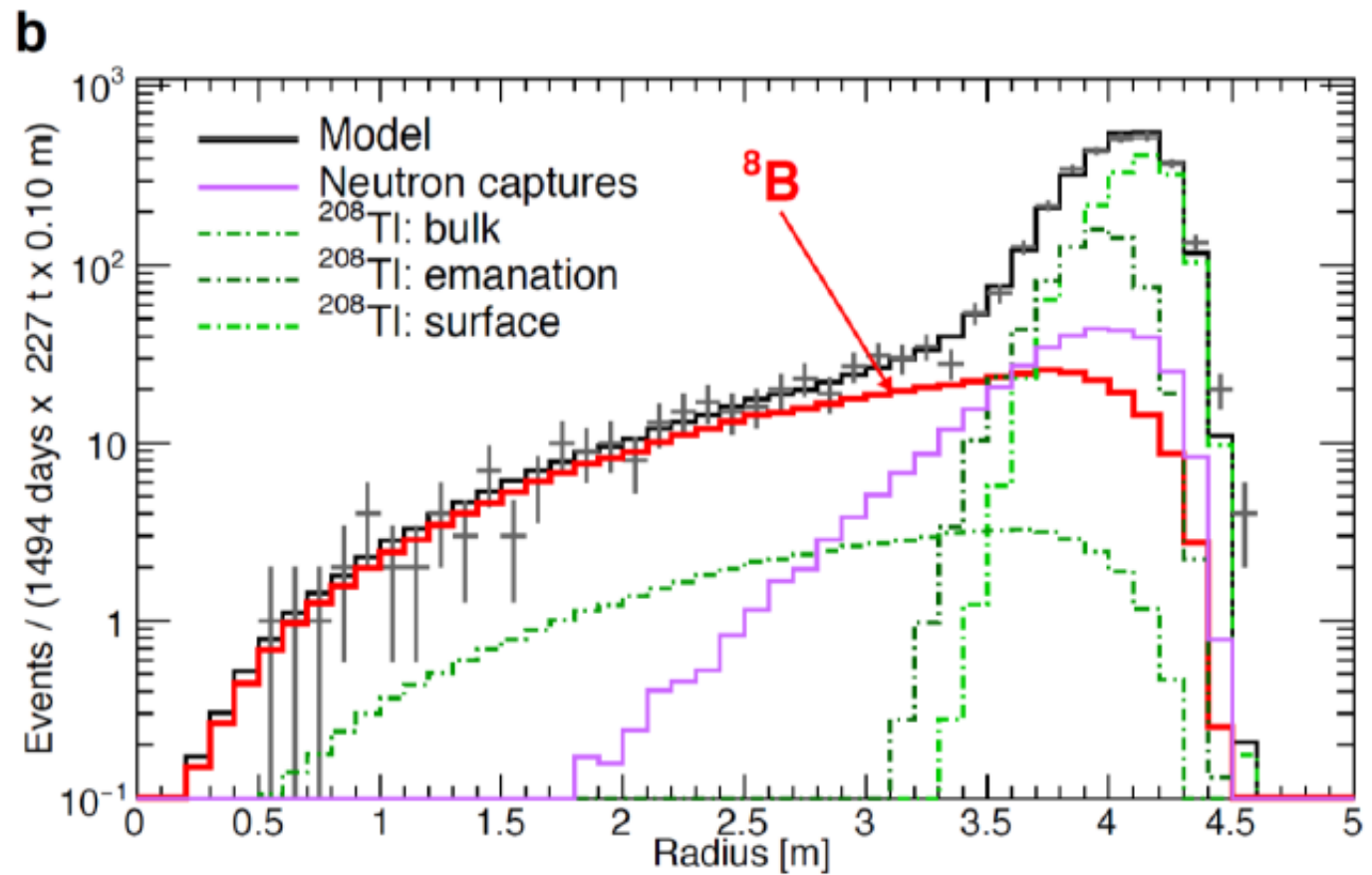
Analytical fit

- Analytical model to link E to N_p , N_{pe}
- Including scintillation and Cerenkov Light
- Model to describe the E resolution
- Some model parameters fixed (comparison with MC or calib, data)
- Describe the energy response and resolution averaged in the FV
- Data Analysis free fit parameters:
 - solar ν and background rate + 6 model parameters
(Light Yield, 2 resolution param., position & width of ^{210}Po peak, starting point of the ^{11}C spectrum)
- Possibility to describe unknown time variations
- Easy work at low energy (high rate ^{14}C)



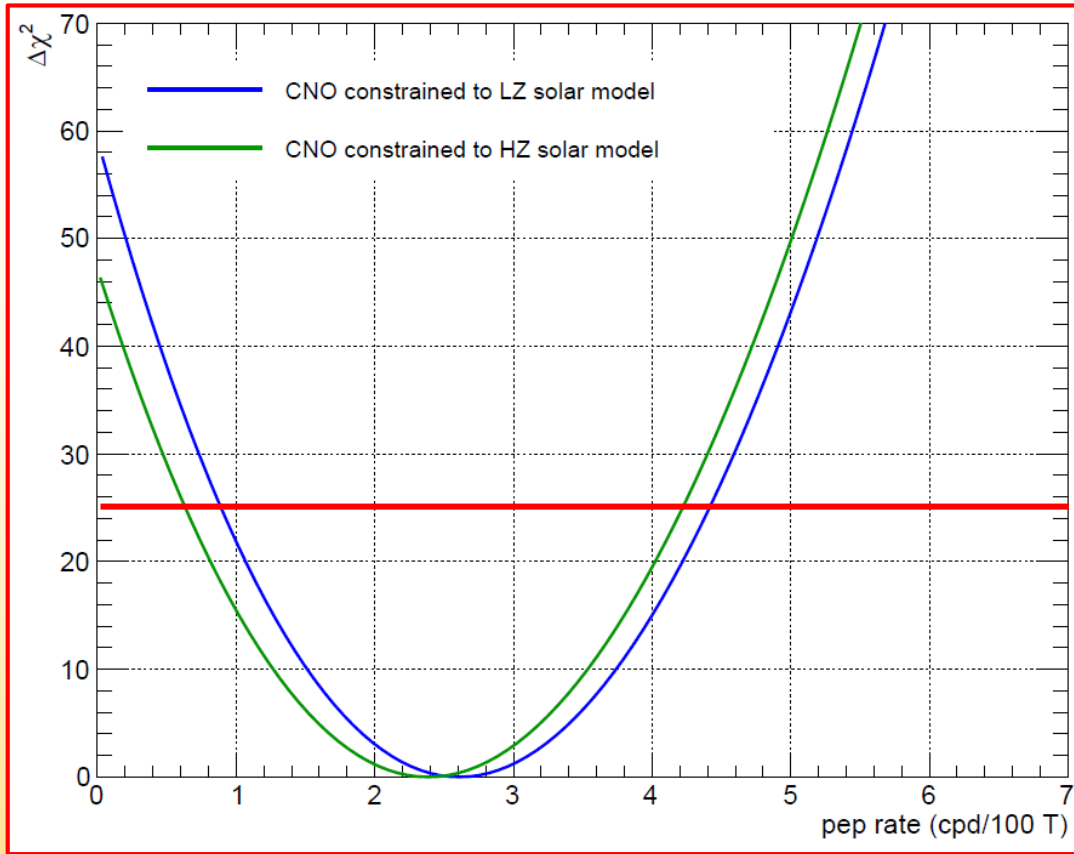
The ^8B signal: fit of the radial distribution of the events in the HER1 region (3.2-5.7 MeV)

- Gamma due to n capture
n produced through (α, n) reaction
- ^{208}Tl from ^{232}Th of the vessel
and in the scintillator bulk
- PDF from MonteCarlo



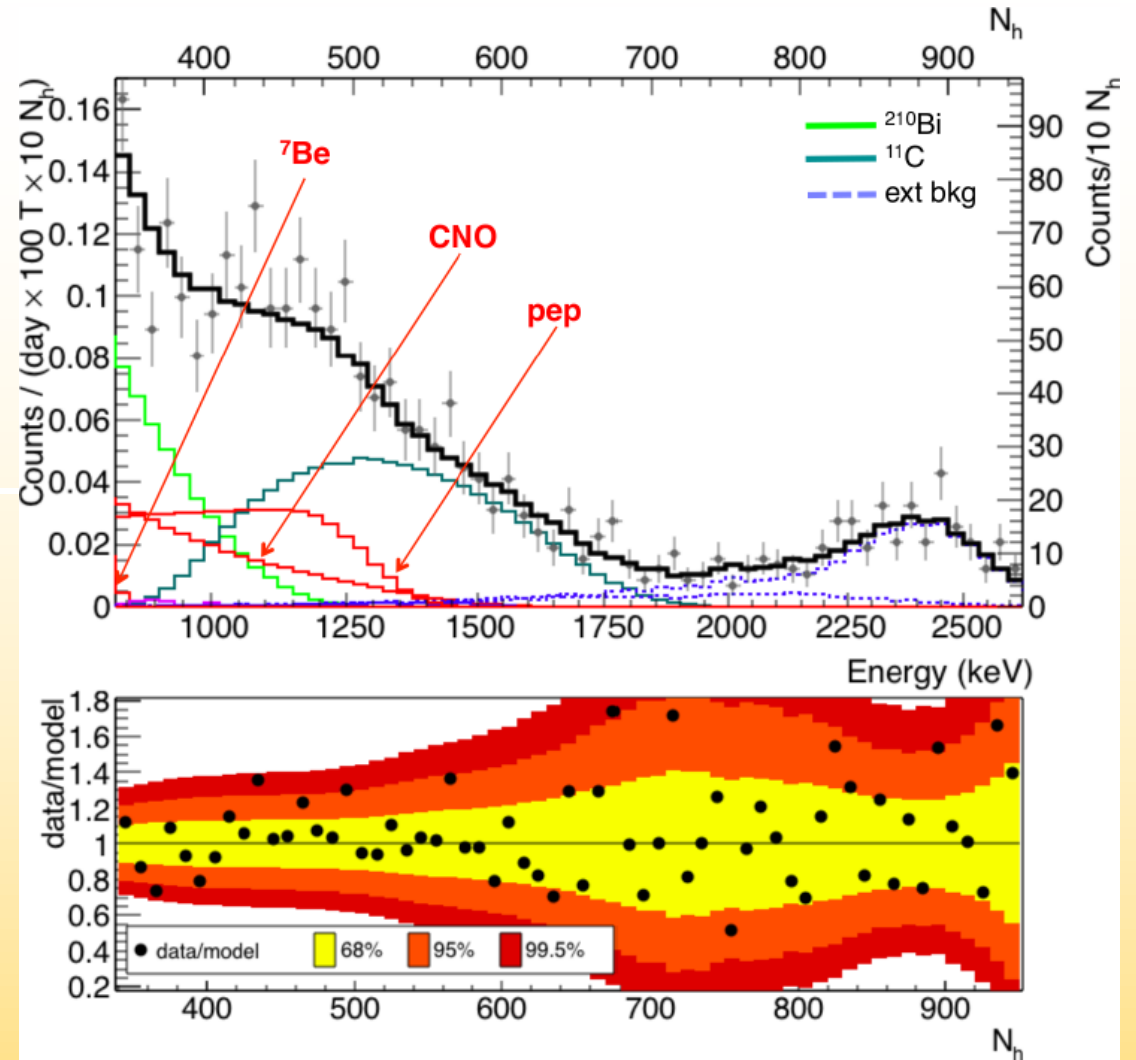
5 σ evidence of pep solar ν (including systematics uncertainties)

Likelihood profile resulting from the multivariate fit



Select innermost β - like events

Radius < 2.4 PS-LPR < 4.8

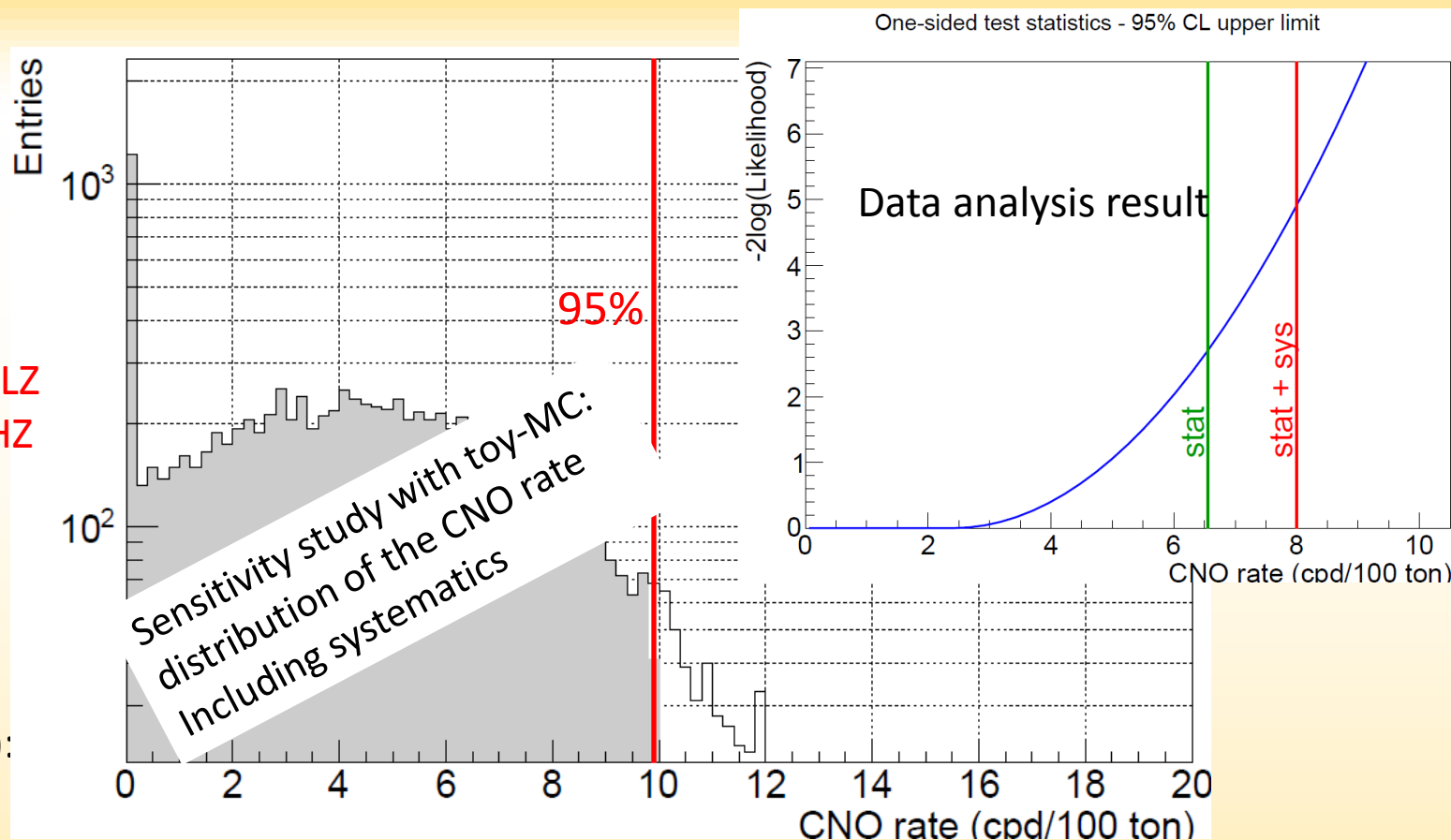


Upper limit on the CNO flux

- Set a constrain to the ratio pp/pep
- Very well know in the solar model
- Include oscillations LMA-MSW
- Toy MC study of the sensitivity :
the median 95% CL is **9 cpd/100t** for LZ
10 cpd/100t for HZ

95% C.L. limit on the CNO n rate
8.1 cpd/100t
including systematics errors

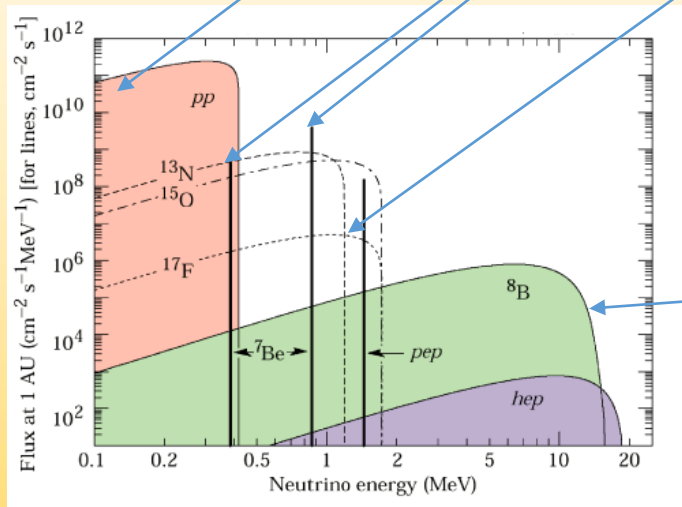
Previous limit (set by Borexino Phase I):
7.9 cpd/100t



	Borexino result	Expected HZ	Expected LZ
CNO ν	< 8.1 95%C.L cpd/100t	4.91 +-0.56 cpd/100t	3.62 +- 0.37 cpd/100t

The pp chain solar neutrino results of Borexino

2.5% accuracy



Borexino experimental results

Solar ν	Rate (cpd/100 t)	Flux ($\text{cm}^{-2} \text{s}^{-1}$)	Flux -SSM predictions ($\text{cm}^{-2} \text{s}^{-1}$)
<i>pp</i>	$134 \pm 10^{+6}_{-10}$	$(6.1 \pm 0.5^{+0.3}_{-0.5}) \times 10^{10}$	$5.98(1. \pm 0.006) \times 10^{10}$ (HZ) $6.03(1. \pm 0.005) \times 10^{10}$ (LZ)
${}^7\text{Be}$	$48.3 \pm 1.1^{+0.4}_{-0.7}$	$(4.99 \pm 0.11^{+0.06}_{-0.08}) \times 10^9$	$4.93(1. \pm 0.06) \times 10^9$ (HZ) $4.50(1. \pm 0.06) \times 10^9$ (LZ)
<i>pep</i> (HZ)	$2.43 \pm 0.36^{+0.15}_{-0.22}$	$(1.27 \pm 0.19^{+0.08}_{-0.12}) \times 10^8$	$1.44(1. \pm 0.009) \times 10^8$ (HZ) $1.46(1. \pm 0.009) \times 10^8$ (LZ)
<i>pep</i> (LZ)	$2.65 \pm 0.36^{+0.15}_{-0.24}$	$(1.39 \pm 0.19^{+0.08}_{-0.13}) \times 10^8$	$1.44(1. \pm 0.009) \times 10^8$ (HZ) $1.46(1. \pm 0.009) \times 10^8$ (LZ)
${}^8\text{B}_{\text{HER-I}}$	$0.136^{+0.013+0.003}_{-0.013-0.003}$	$(5.77^{+0.56+0.15}_{-0.56-0.15}) \times 10^6$	$5.46(1. \pm 0.12) \times 10^6$ (HZ) $4.50(1. \pm 0.12) \times 10^6$ (LZ)
${}^8\text{B}_{\text{HER-II}}$	$0.087^{+0.080+0.005}_{-0.010-0.005}$	$(5.56^{+0.52+0.33}_{-0.64-0.33}) \times 10^6$	$5.46(1. \pm 0.12) \times 10^6$ (HZ) $4.50(1. \pm 0.12) \times 10^6$ (LZ)
${}^8\text{B}_{\text{HE}}$	$0.223^{+0.015+0.006}_{-0.016-0.006}$	$(5.68^{+0.39+0.03}_{-0.41-0.03}) \times 10^6$	$5.46(1. \pm 0.12) \times 10^6$ (HZ) $4.50(1. \pm 0.12) \times 10^6$ (LZ)
CNO	< 8.1 (95 % C.L.)	$< 7.9 \times 10^8$ (95 % C.L.)	$4.88(1. \pm 0.11) \times 10^8$ (HZ) $3.51(1. \pm 0.10) \times 10^8$ (LZ)

Purification of the scintillator

6 cycles, closed loop

Reduction factors:

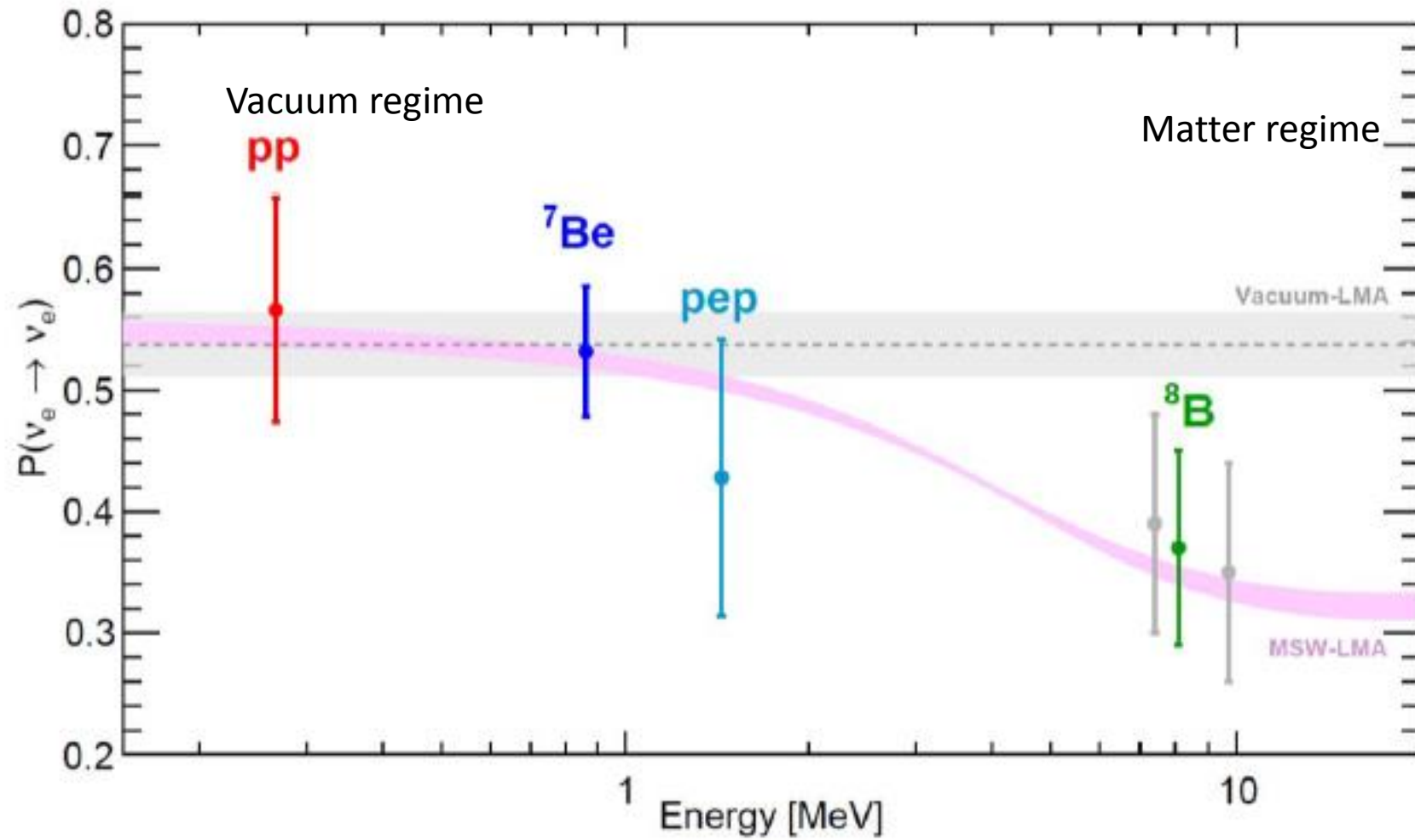
- 4.6 for ^{85}Kr
- 2.3 for ^{210}Bi

Background (<i>LER</i>)	rate (Bq/100 t)
^{14}C (0.156 MeV, β^-)	$[40.0 \pm 2.0]$
Background (<i>LER</i>)	rate (cpd/100 t)
^{85}Kr (0.687 MeV, β^-) (internal)	6.8 ± 1.8
^{210}Bi (1.16 MeV, β^-) (internal)	17.5 ± 1.9
^{11}C (1.02-1.98 MeV, β^+) (internal)	26.8 ± 0.2
^{210}Po (5.3 MeV, α) (internal)	260.0 ± 3.0
^{40}K (1.460 MeV, γ) (external)	1.0 ± 0.6
^{214}Bi (<1.764 MeV, γ) (external)	1.9 ± 0.3
^{208}Tl (2.614 MeV, γ) (external)	3.3 ± 0.1

Rate of relevant background

Background (<i>HER-I</i>)	rate (cpd/227.8 t)
μ , cosmogenics, ^{214}Bi (internal)	$[6.1_{-3.1}^{+8.7} 10^{-3}]$
(α , n) (external)	0.224 ± 0.078
^{208}Tl (5.0 MeV, β^- , γ) (internal)	$[0.042 \pm 0.008]$
^{208}Tl (5.0 MeV, β^- , γ) (emanated)	0.469 ± 0.063
^{208}Tl (5.0 MeV, β^- , γ) (surface)	1.090 ± 0.046
Background (<i>HER-II</i>)	rate (cpd/266.0 t)
μ , cosmogenics (internal)	$[3.8_{-0.1}^{+14.6} 10^{-3}]$
(α , n) (external)	0.239 ± 0.022

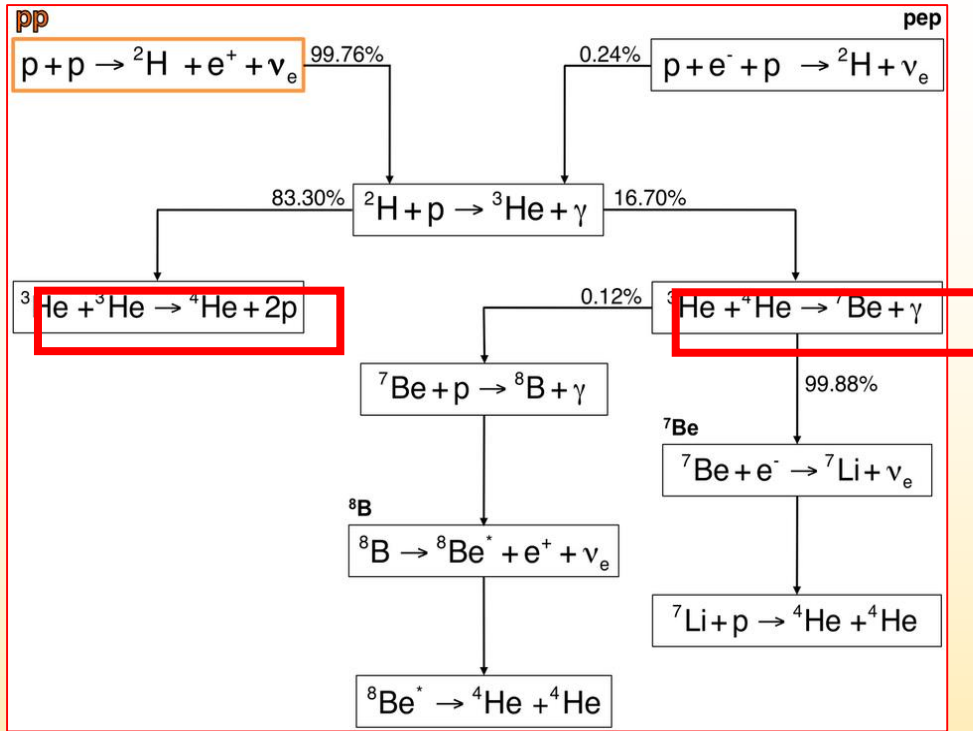
The neutrino survival probability



Implication of the results: probe solar fusion with R

$$R = \frac{Rate(^3He+^3He)}{Rate(^3He+^4He)}$$

Reaction from the main pp chain



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

Expected values: (C. Pena Garay, private comm,)

$$R = 0.180 \pm 0.011 \quad HZ$$

$$R = 0.161 \pm 0.010 \quad LZ$$

Measured value:

$$R(BRX) = 0.178^{+0.027}_{-0.023}$$

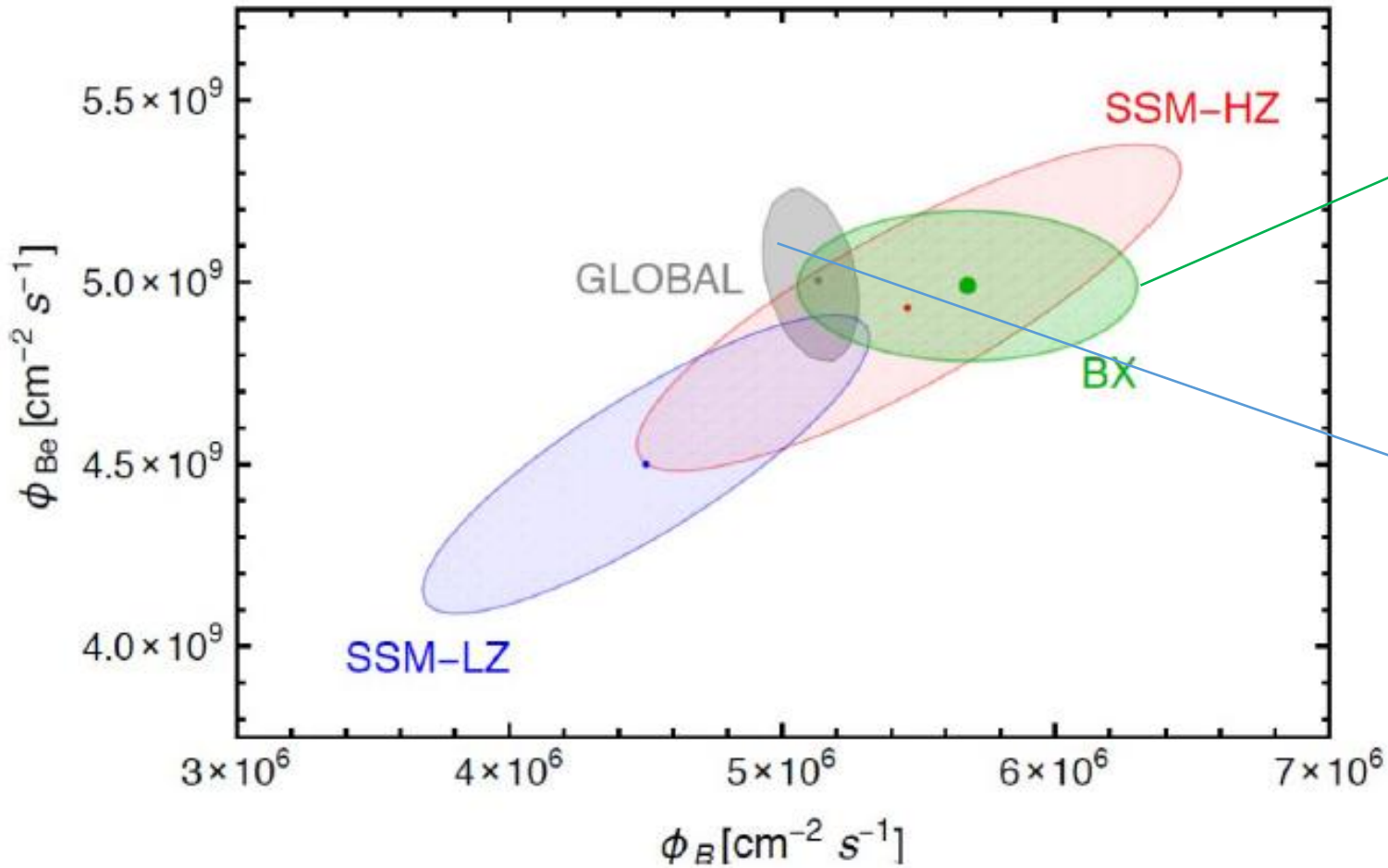
Also:

Sun luminosity calculated with Borexino data agrees with photon luminosity

$$L_{neutrinos} = 3.89^{+0.35}_{-0.42} \cdot 10^{33} \text{ erg / s}$$

$$L_{photon} = 3.846 \pm 0.015 \cdot 10^{33} \text{ erg / s}$$

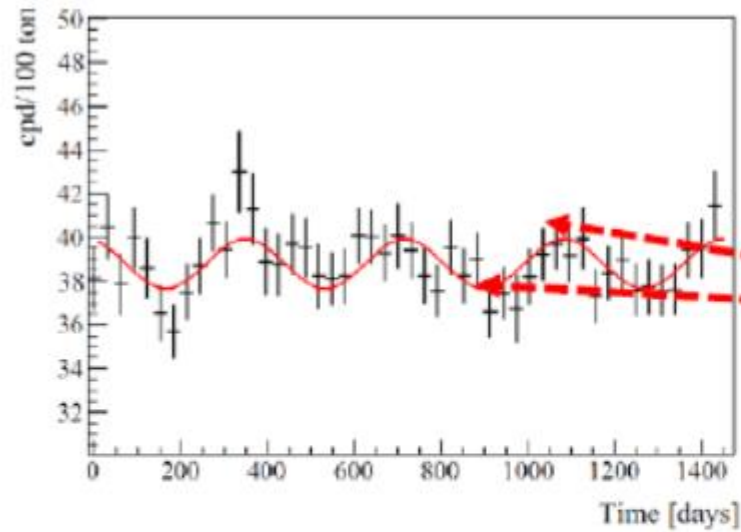
A step toward the understanding of the metallicity...?



Borexino only:
Hints in favor of HZ
Likelihood ratio test statistic
assuming HZ true
LZ is disfavoured at 96.6%

Borexino+other solars and Kamland
Global fit
Hints about HZ is weaker

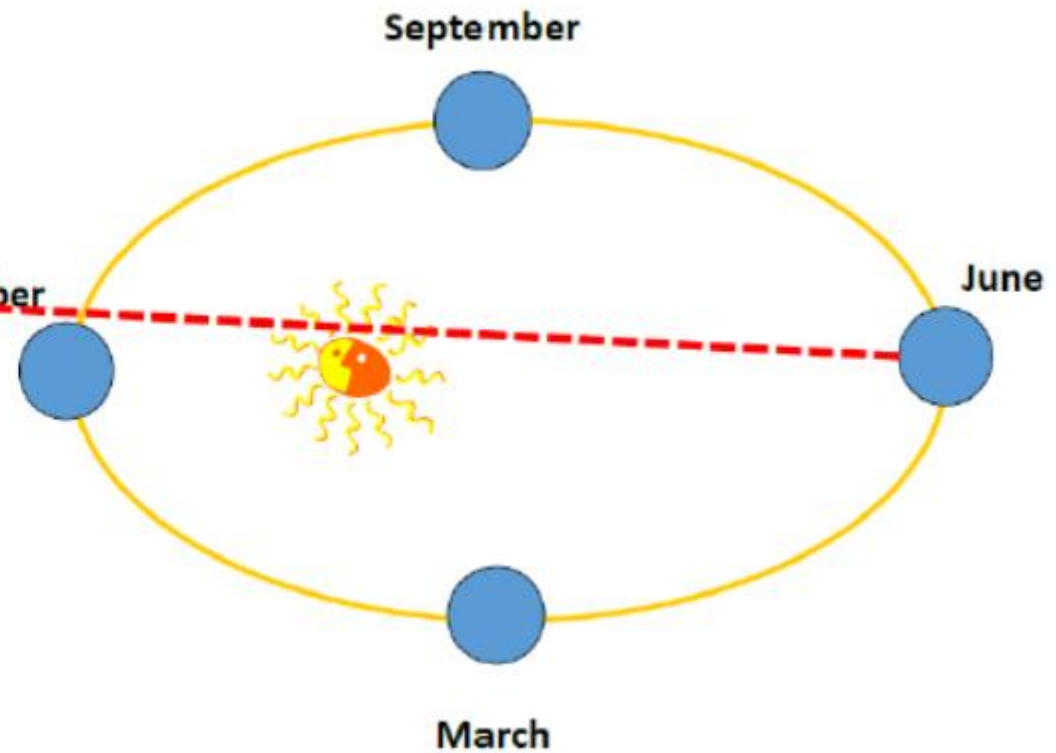
Annual modulation of the ^7Be solar ν in Borexino



Fit to the evolution
of the rate in time
(bin of 30 days)



$$\begin{aligned}\epsilon &= (1.74 \pm 0.45)\% \\ T &= (367 \pm 10)\text{days} \\ \Phi &= (-18 \pm 24)\text{ days}\end{aligned}$$



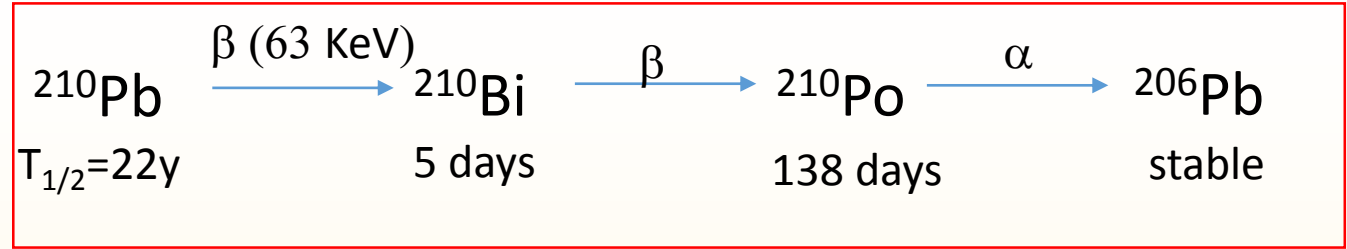
Effort toward the CNO solar ν measurement

1) Reduce ^{210}Bi by purification: partially achieved

2) Infer the ^{210}Bi activity from the ^{210}Po vs time

Assuming ^{210}Bi rate constant

$$n_{\text{Po}}(t) = [n_{\text{Po},0} - n_{\text{Bi}}] \exp(-t/\tau_{\text{Po}}) + n_{\text{Bi}}.$$



F. Villante et al., Phys. Lett. B 701 (2011)

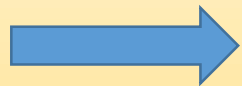
➤ Look at the ^{210}Po time decay: at regime we should have the same the amount of ^{210}Po and ^{210}Bi



^{210}Po is easy to count thanks to PSD in the scintillator

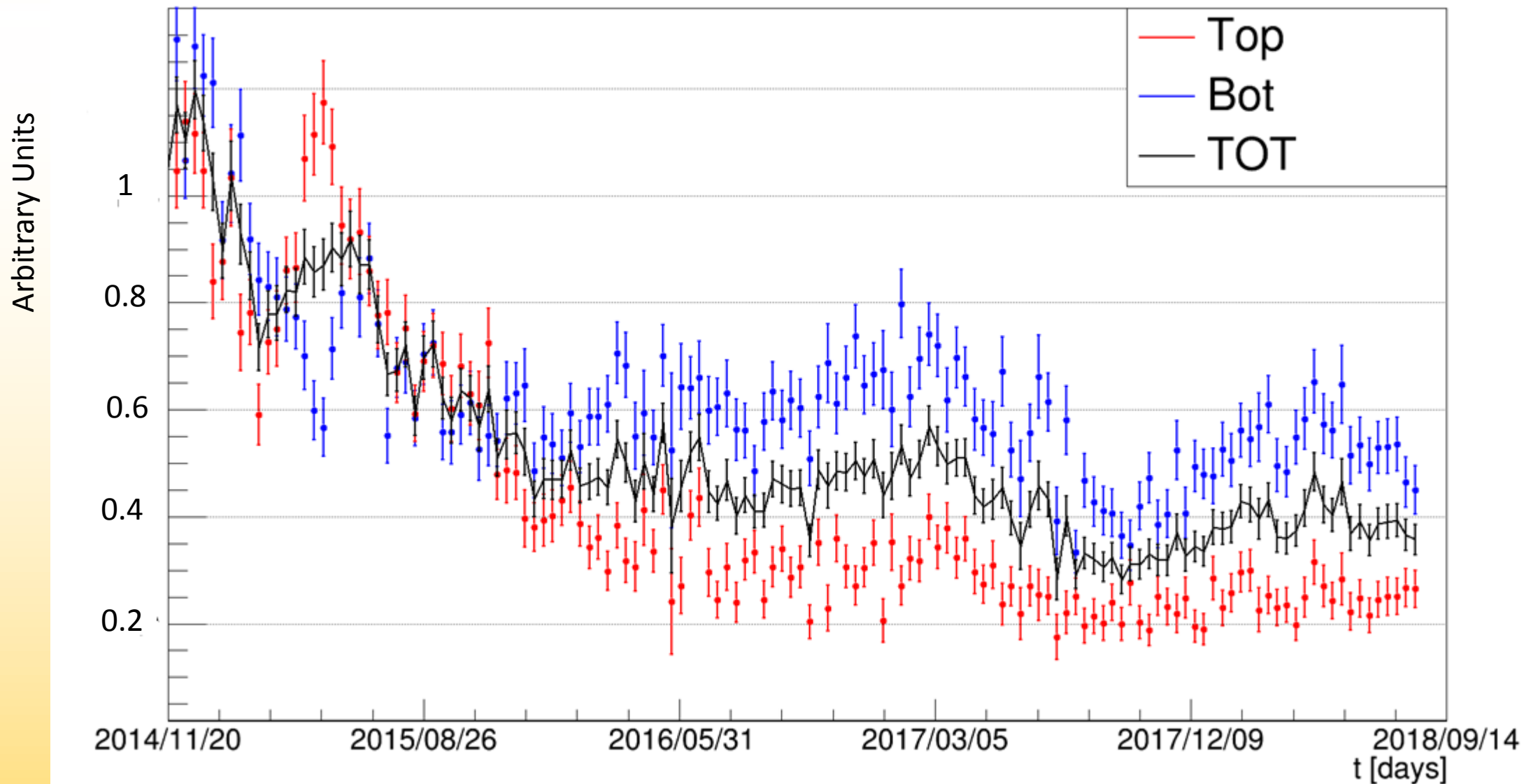
Needed:

- ^{210}Po activity not too high: actual values are OK
- stable conditions for long time (some years..)
- **no additional ^{210}Po sources**



We observed ^{210}Po leaching out the nylon vessel and moving into the FV due to convection motions
Thermal insulation of the detector to reduce and control thermal gradients

^{210}Po decay in the interior of the inner vessel ($r < 2.5\text{ m}$ and $\text{abs}(z) < 1.5\text{ m}$)





Before thermal insulation



After thermal insulation

Conclusions

- All pp chain neutrinos have been measured by Borexino
- We have reduced the uncertainties compared to Phase I

- 5 σ evidence of pep neutrinos
- Best limit on CNO
- Annual modulation of ^7Be
- New results about geoneutrinos coming soon

Solar n component	Uncertainty reduction (Phase II error / Phase I error)
pp	0.22
^7Be	0.57
pep	0.61
^8B	0.5

In progress:

- understanding the ^{210}Po evolution with detector thermally insulated
- new calibrations in a near future
- possible re-purification of the scintillator



Borexino Collaboration



UNIVERSITÀ
DEGLI STUDI
DI MILANO



PRINCETON
UNIVERSITY



UNIVERSITÀ DEGLI STUDI
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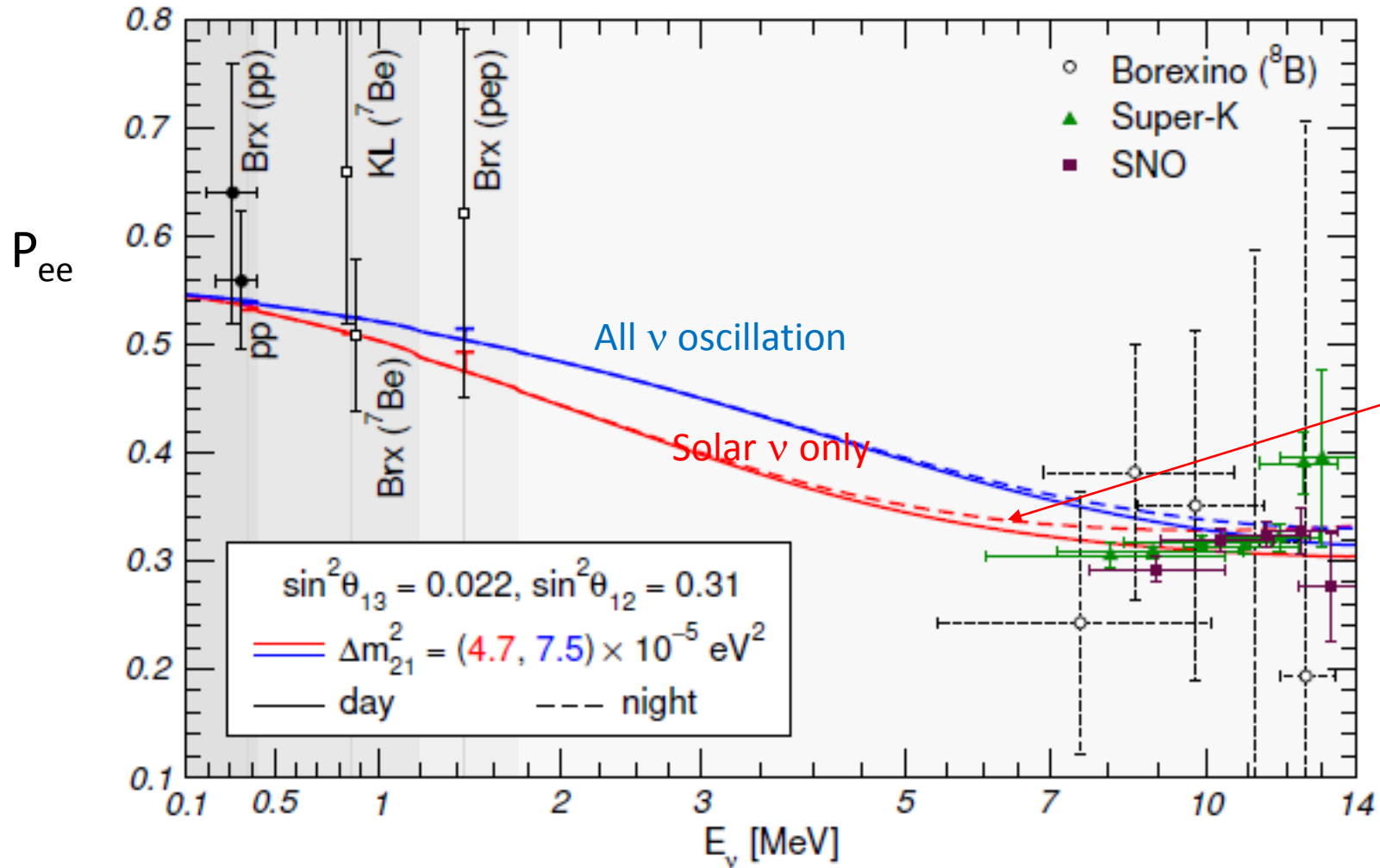
Thanks for the invitation
to this nice workshop!!!!

Geological implications of the new Borexino results

Mantle signal

- $S_{\text{Mantle}} = S_{\text{measured}} - S_{\text{crust}}$
- $S_{\text{measured}} = 43.5^{+11.8}_{-10.4}(\text{stat})^{+2.7}_{-2.4}(\text{sys}) \text{ TNU}$
- Crustal signal at LNGS “known”
ROC (Huang at al.) + LOC (Coltorti at al.)
 $S_{\text{Crust}} = (23.4 \pm 2.8) \text{ TNU}$
- Non-0 mantle signal at 98% CL
 $S_{\text{mantle(Borexino)}} = 20.1^{+15.1}_{-10.3} \text{ TNU}$

Pee vs energy: the importance of the precision spectroscopy of solar neutrinos



LMA-MSW

- Matter effect in the Earth:
- Day-Night flux asymmetry
- Only at high energy