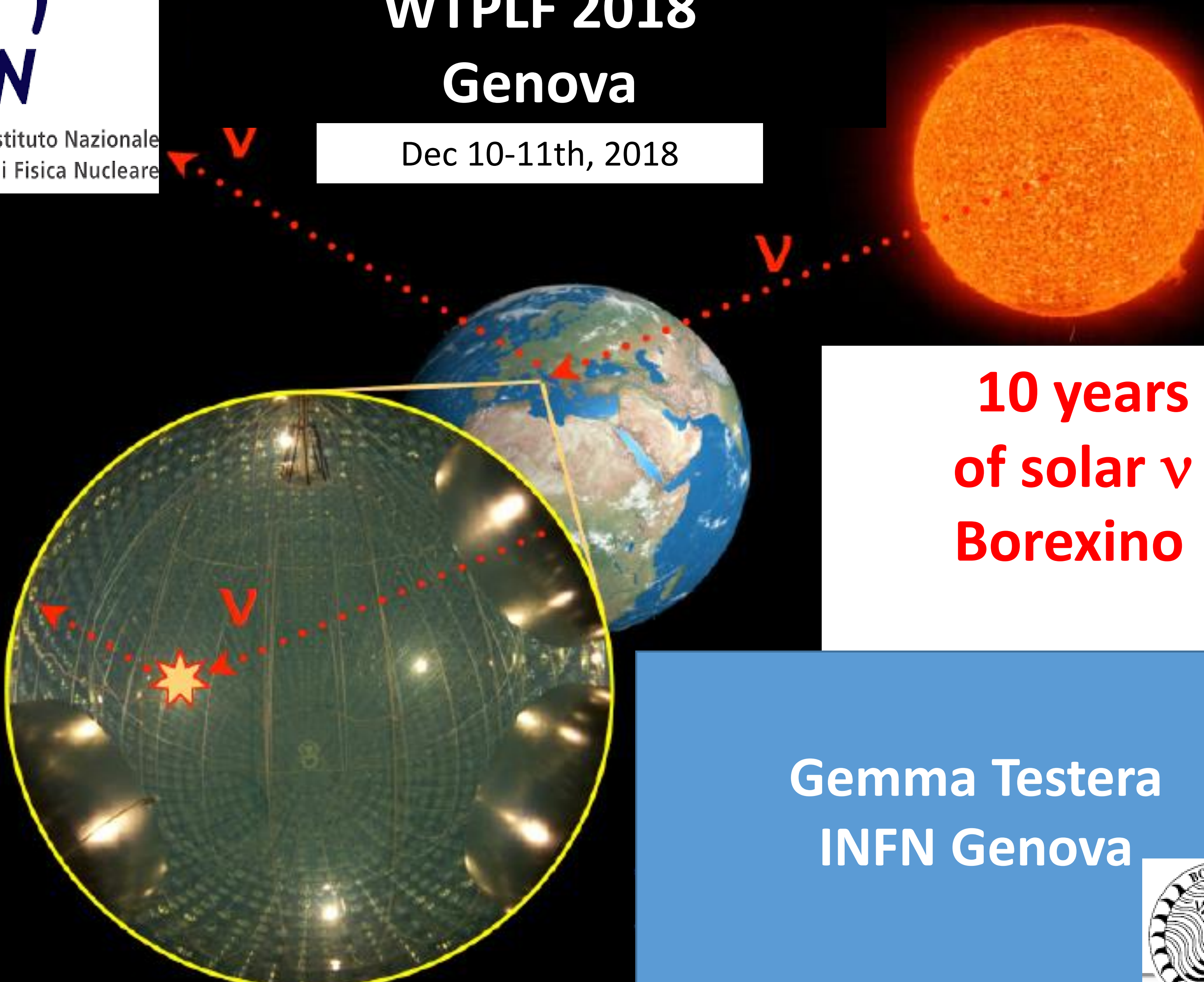
WTPLF 2018
Genova

Dec 10-11th, 2018

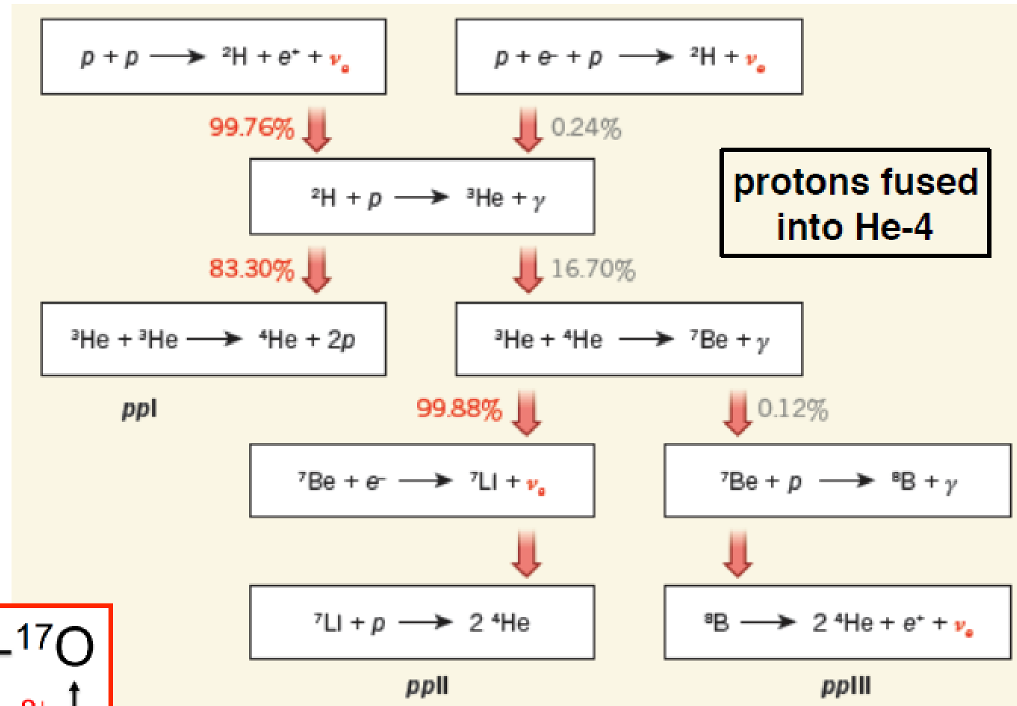


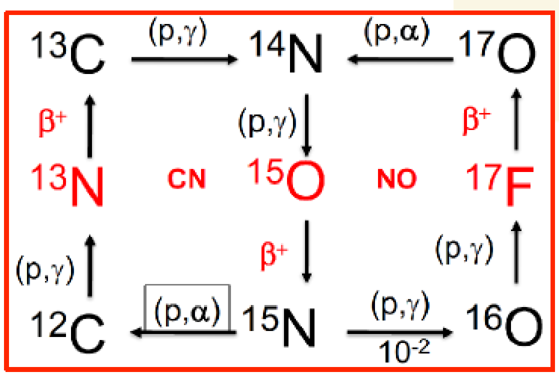
10 years of solar ν in Borexino

Gemma Testera
INFN Genova

Solar fusion in the Sun and neutrino emission

- 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



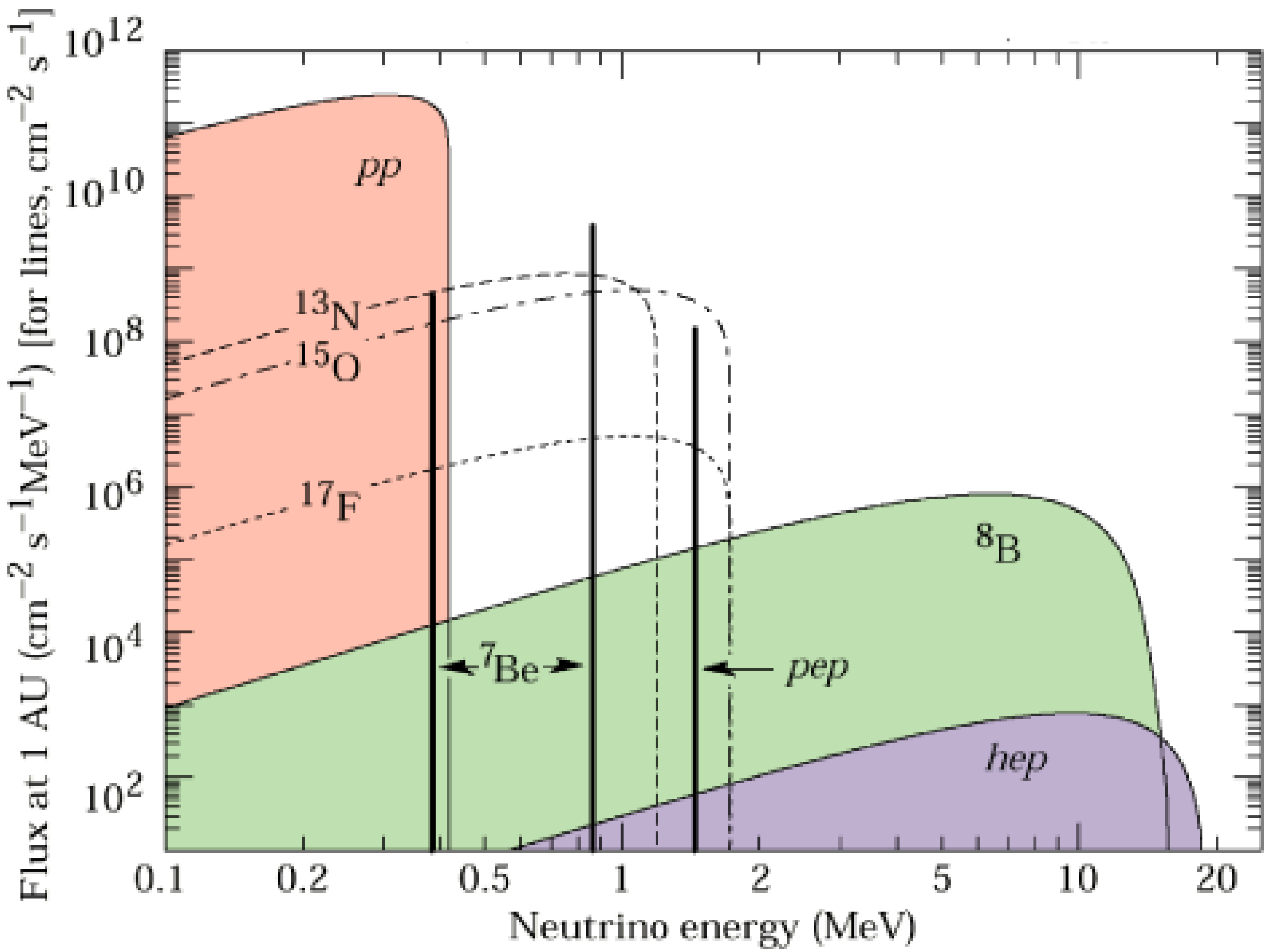


$$4p \to {}^4\mathrm{He} + 2e^+ + (24.69 + 2m_e c^2)\,\mathrm{MeV}$$

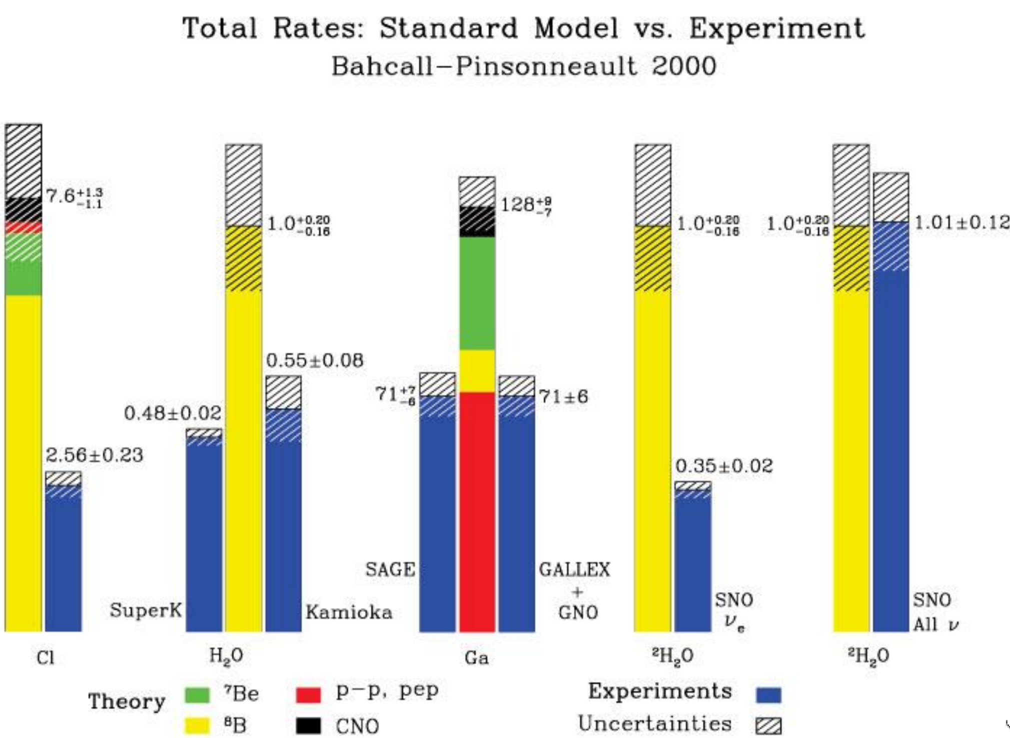
$$\langle E_\nu \rangle \sim 0.53\,\mathrm{MeV}$$

(~2% of the total energy)

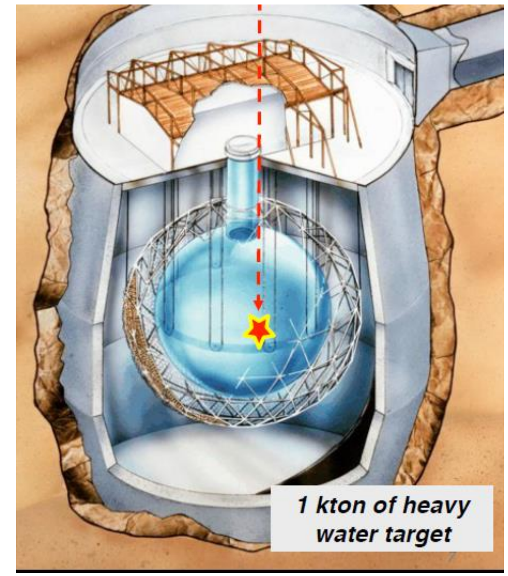
Solar neutrinos spectrum



Many years long scientific debate: solar fusion and ν oscillation

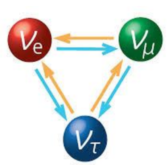


SNO detector

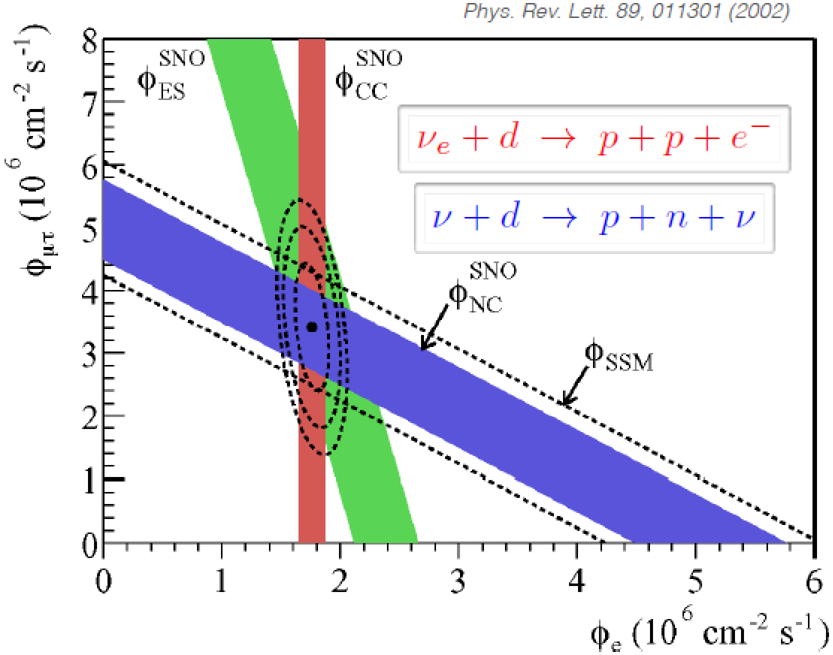


SNO in 2002

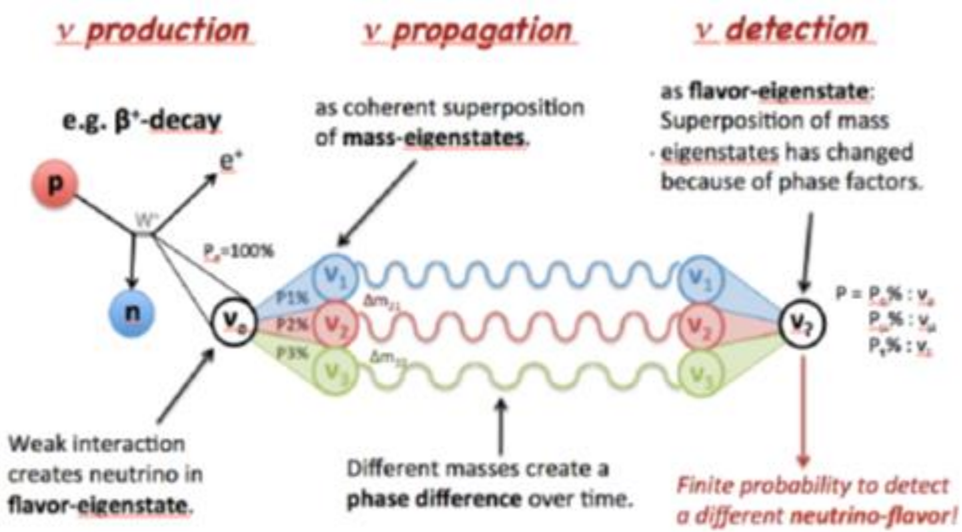
- 2 different reactions in heavy water
- Detect ν_e and ν_μ,ν_t
- Neutrino oscillations



Phys. Rev. Lett. 89, 011301 (2002)



ν oscillation



Flavor eigenstate

PMNS matrix

Mass eigenstate

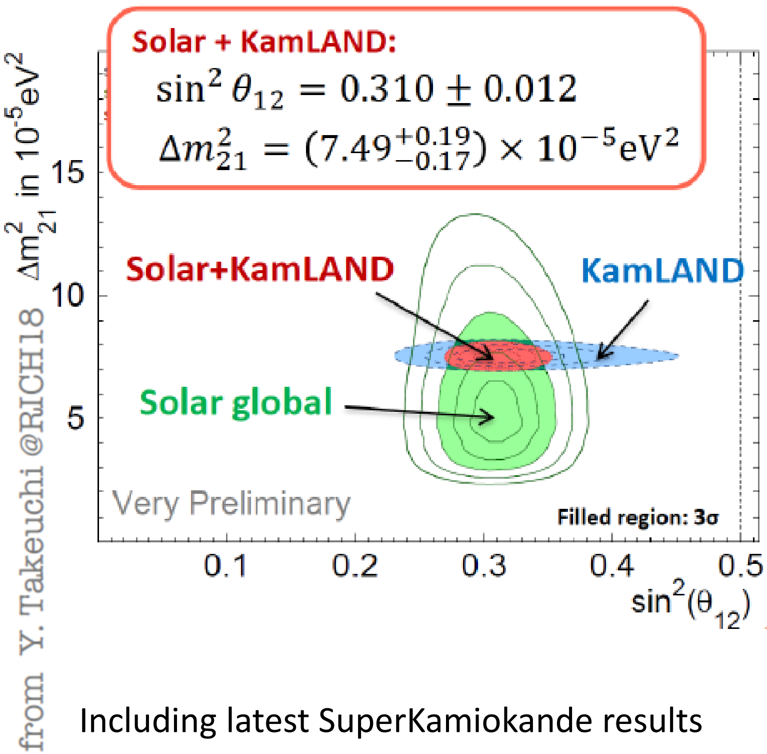
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\boxed{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}}_{\text{Atmospheric term}} \underbrace{\boxed{\begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix}}}_{\text{Reactor term}} \underbrace{\boxed{\begin{pmatrix} \cos\theta_{12} & \cos\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}}_{\text{Solar term}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Oscillation parameters:

- Mixing angles: $\theta_{12}, \theta_{13}, \theta_{23}$
- Mass squared differences: $\Delta m^2_{21}, \Delta m^2_{32}$ and the sign of Δm^2_{32}
- Complex phase: $\delta \equiv \delta_{CP}$

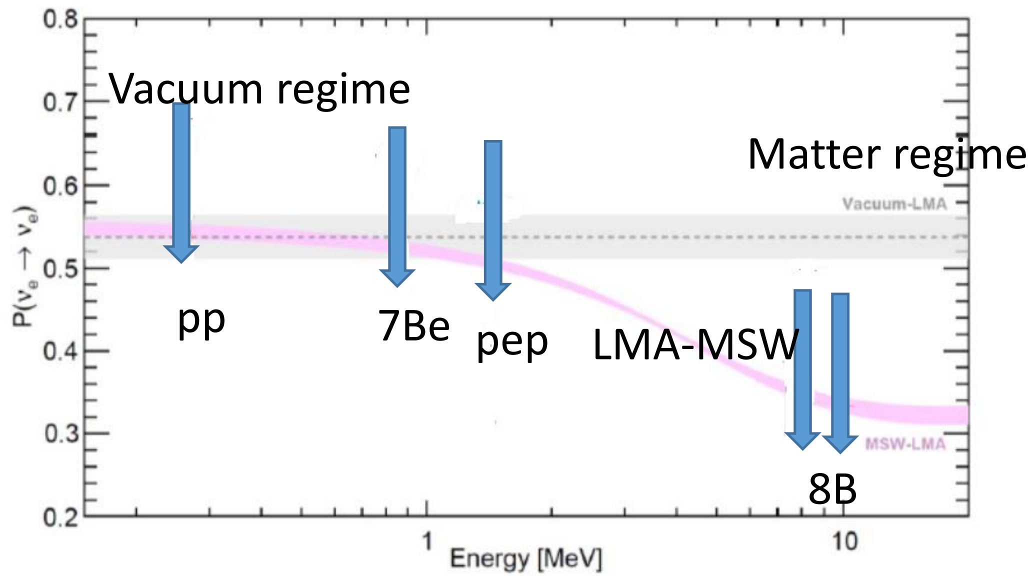
- **3 mixing angles θ_{ij}:**
  - $\theta_{23} \approx 45°$ (which quadrant?)
  - $\theta_{13} \approx 9°$ (non-0 value confirmed in 2012)
  - $\theta_{12} \approx 33°$
- **Majorana phases $\alpha1$, $\alpha2$** and **CP-violating phase δ** unknown

ν oscillation: LMA-MSW parameters



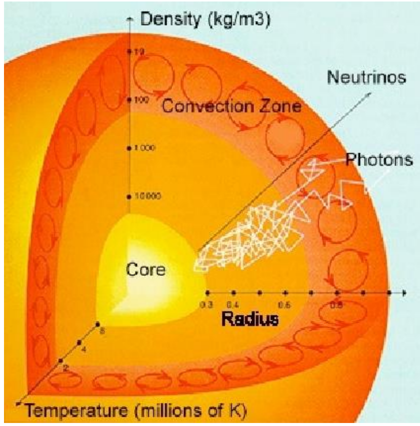
Including latest SuperKamiokande results

ν oscillation:
Solar electron ν survival probability after traversing the SUN (LMA-MSW)



ν_e conversion probability influenced by matter interaction depending on electron density

Solar metallicity and solar neutrinos



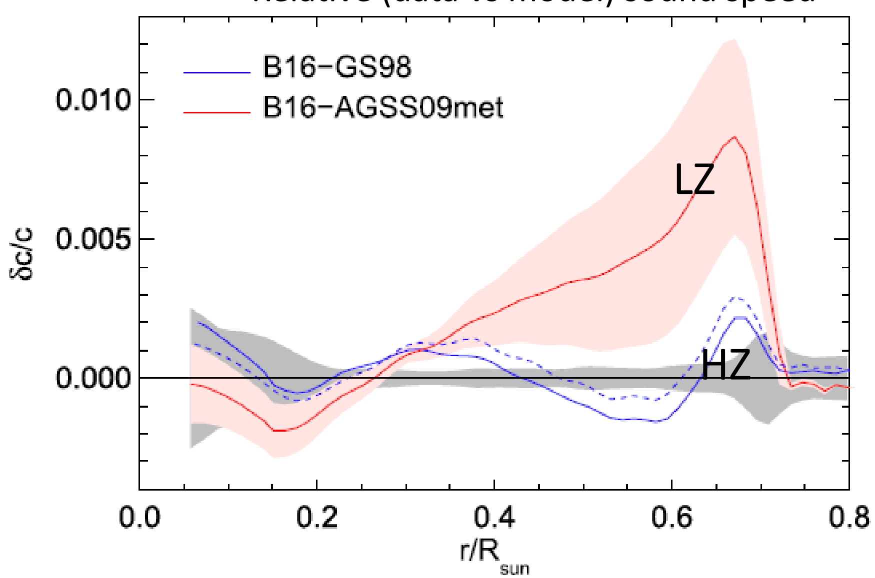
- Evolution of a star from beginning until now 4.57 10^9y
- Homogeneous mixture of H,He and heavy elements X_{ini}, Y_{ini}, Z_{ini}
- α_{MLT} : parameter entering in the description of the convection
- Cross sections for nuclear reactions (S factors)
- Opacity
- Equilibrium between gravitational force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

Relative (data vs model) sound speed



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

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

Flux	B16-GS98 HZ	B16-AGSS09met LZ
$\Phi(pp)$	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.005)$
$\Phi(pep)$	$1.44(1 \pm 0.01)$	$1.46(1 \pm 0.009)$
$\Phi(hep)$	$7.98(1 \pm 0.30)$	$8.25(1 \pm 0.30)$
$\Phi(^7Be)$	$4.93(1 \pm 0.06)$	$4.50(1 \pm 0.06)$
$\Phi(^8B)$	$5.46(1 \pm 0.12)$	$4.50(1 \pm 0.12)$
$\Phi(^{13}N)$	$2.78(1 \pm 0.15)$	$2.04(1 \pm 0.14)$
$\Phi(^{15}O)$	$2.05(1 \pm 0.17)$	$1.44(1 \pm 0.16)$
$\Phi(^{17}F)$	$5.29(1 \pm 0.20)$	$3.26(1 \pm 0.18)$

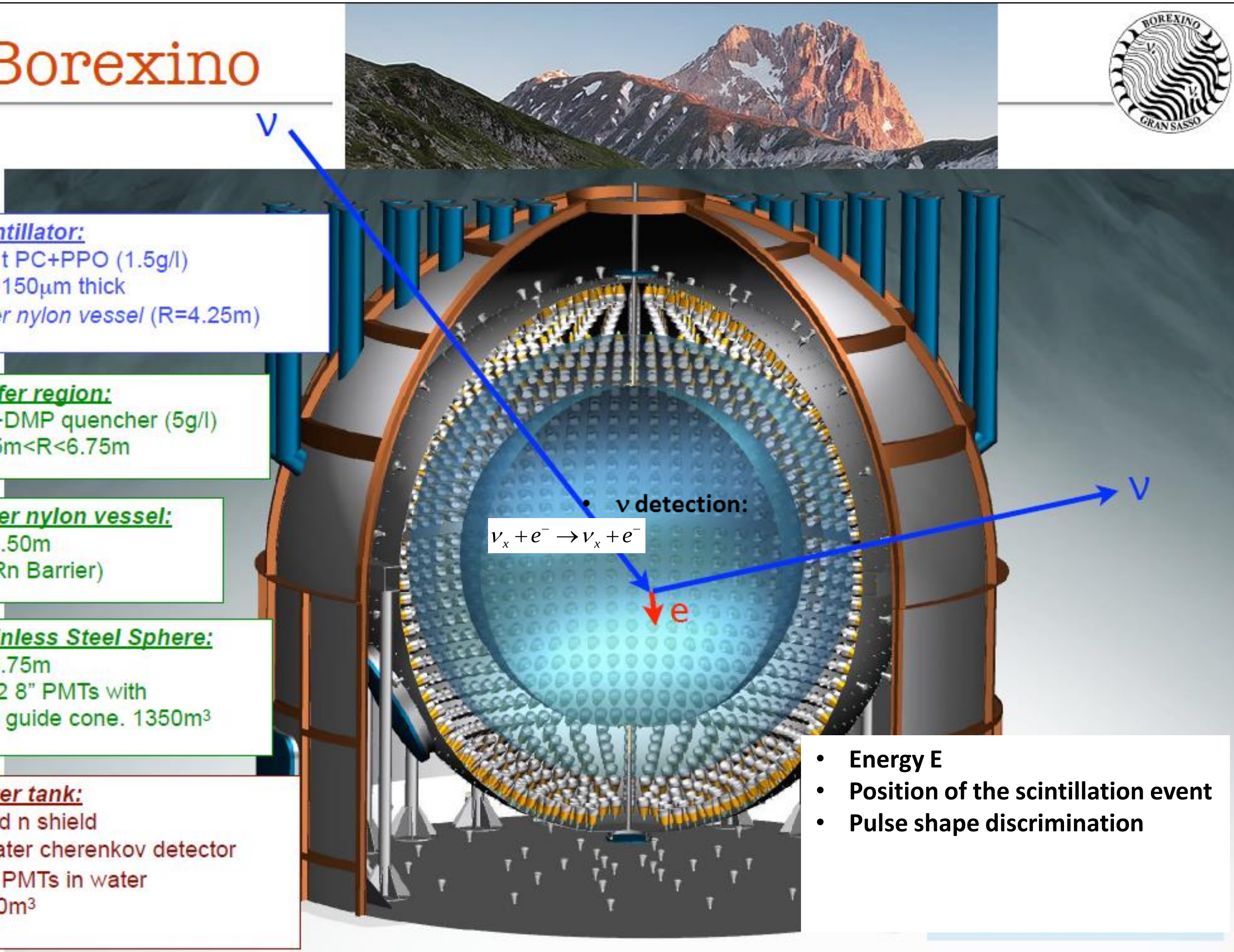
CNO

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

^{7}Be: 8.7% diff
^{8}B: 17.6% diff
CNO: 40% diff

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

Borexino



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

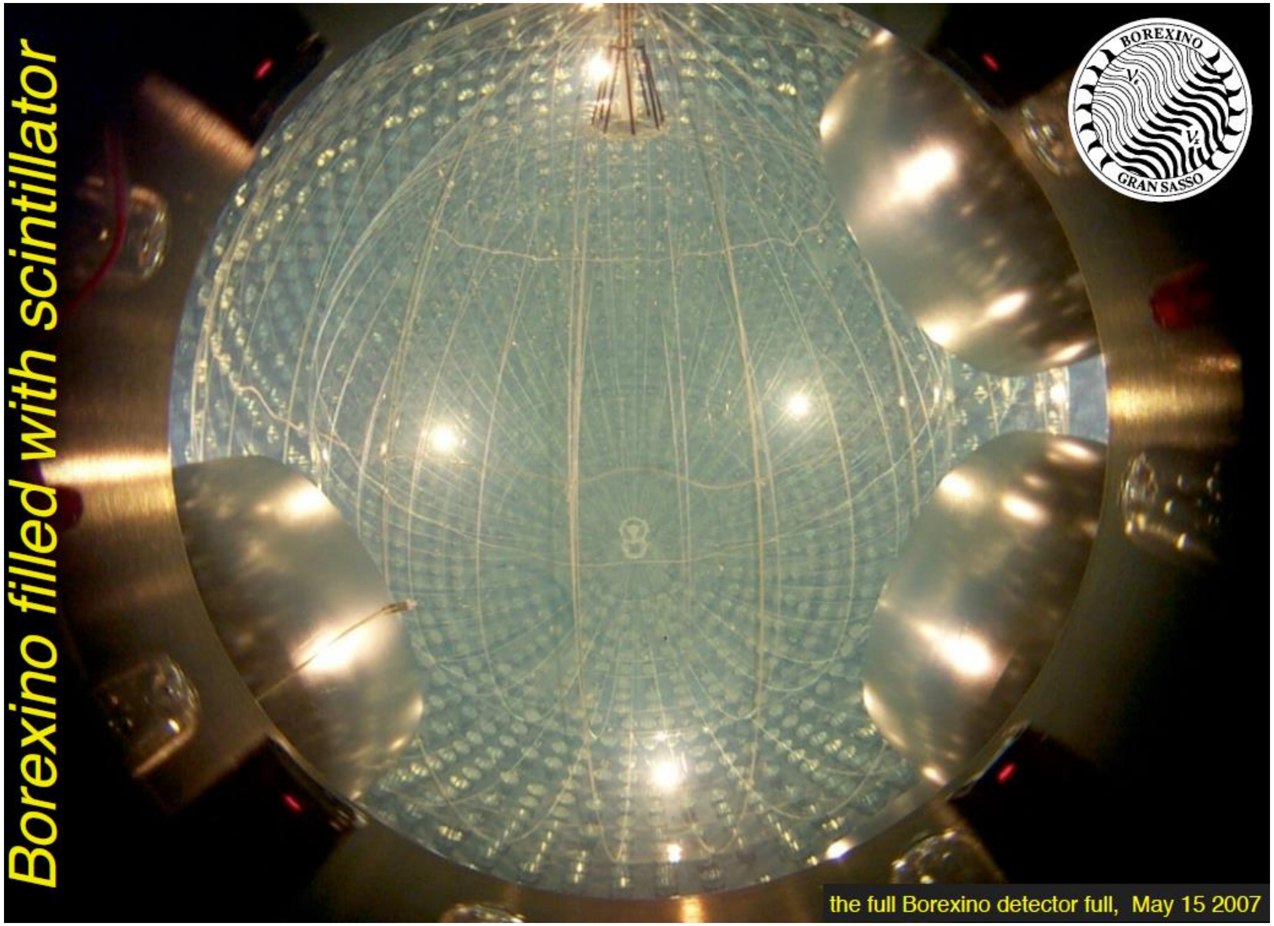
Buffer region:
PC+DMP quencher (5g/l)
4.25m<R<6.75m

Outer nylon vessel:
R=5.50m
(^{222}Rn Barrier)

Stainless Steel Sphere:
R=6.75m
2212 8" PMTs with
light guide cone. 1350m^3

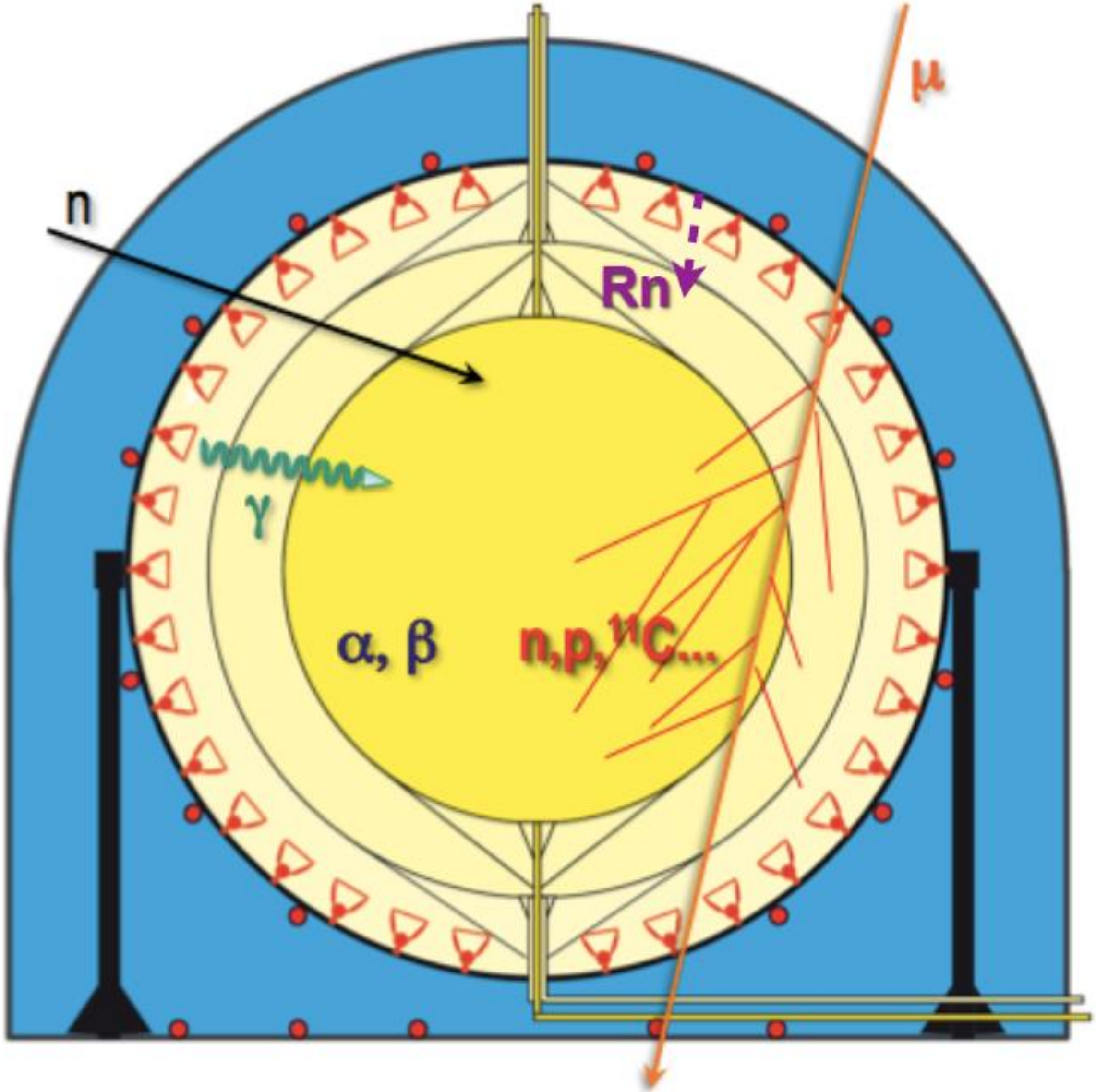
Water tank:
γ and n shield
μ water cherenkov detector
208 PMTs in water
2100m^3

- **Energy E**
- **Position of the scintillation event**
- **Pulse shape discrimination**



- Designed to detect solar ^{7}Be ν
- We measure the entire pp spectrum
- Has become a standard against which compare low background experiments

Extreme radio-purity



internal radioactivity
traces of radioisotopes in the scintillator (U,Th,^{40}K)

external γ rays
from fluid buffer, steel sphere, PMT glass and light concentrators (^{40}K,^{208}Tl,^{214}Bi)

radon emanation
from the PMTs and steel sphere

cosmic muons
and their secondaries

cosmogenics
neutrons and radionuclides from μ spallation and hadronic showers

fast neutrons
from external muons

The need of low radioactive background in Borexino

Detection of MeV-subMeV ν

No event by event signature in liquid scintillator

- shape of energy spectrum,
- radial distribution of the events,
- some pulse shape discrmination

Lack of directionality

~50 events/day 100 t expected for ^{7}Be ν

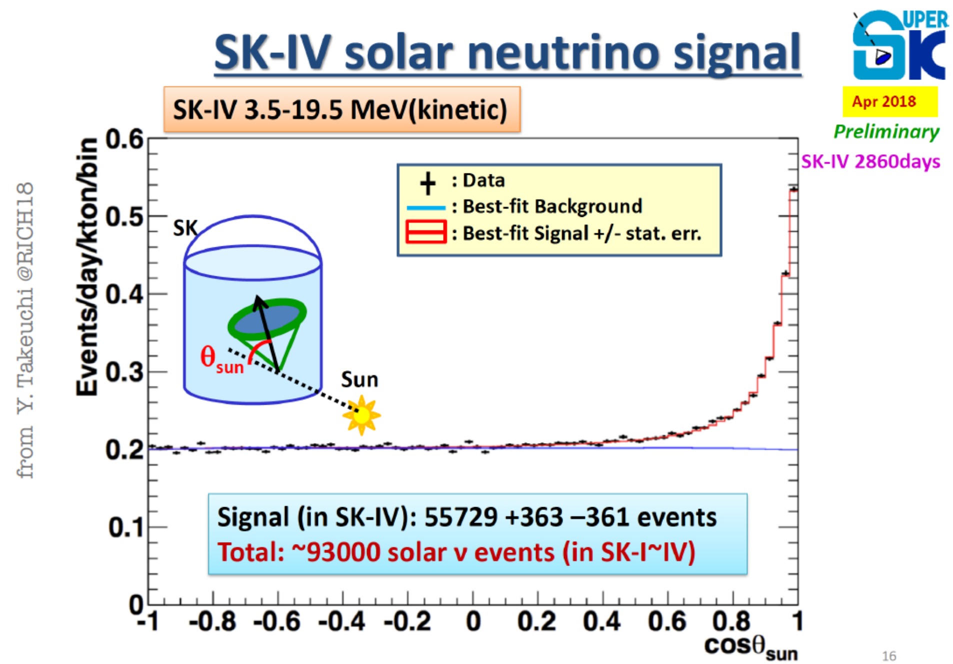
$5\ 10^{-9}$ Bq/Kq

Drinking water: 10 Bq/Kg

Human body is: 5 KBq (^{40}K)

~1 Bq

Water Cerenkov detectors can see the ν direction

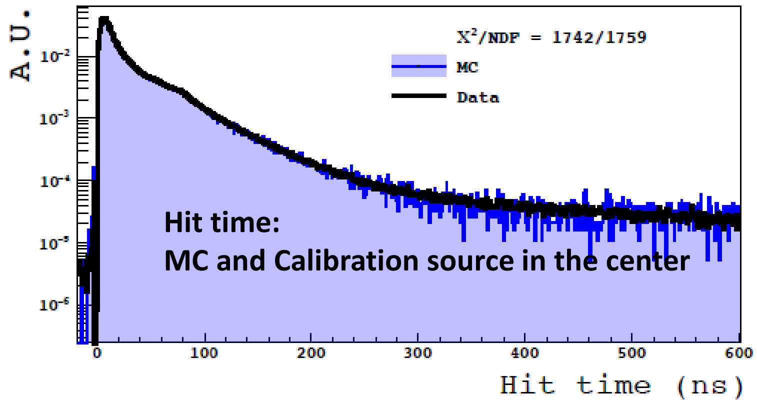


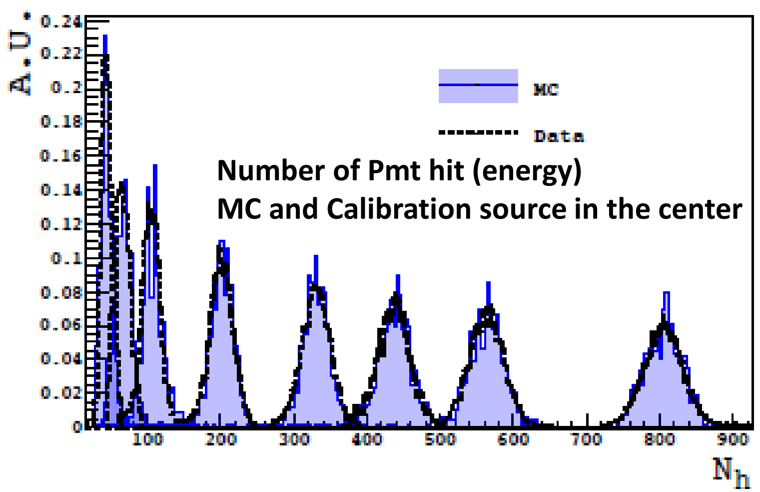
Accurate modelling of the detector response

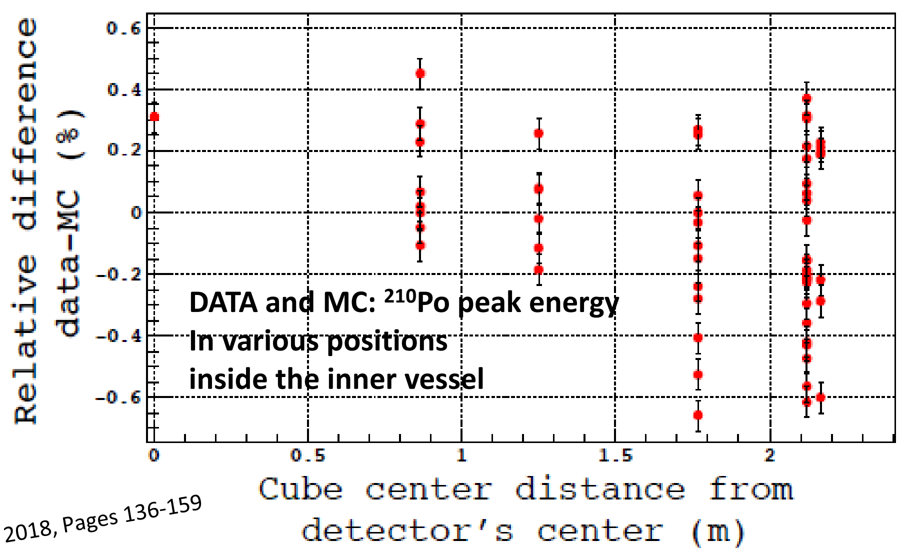
Event energy : from the number of PMT hits (or charge)
550 Np@1 MeV
σ_E= 50 KeV@1MeV

Position reconstruction: use events in the inner part of the vessel
$\sigma_{x,y,z}$ =10 cm@1MeV

Pulse shape discrimination: from the scintillation time profile
β α
β+ β–

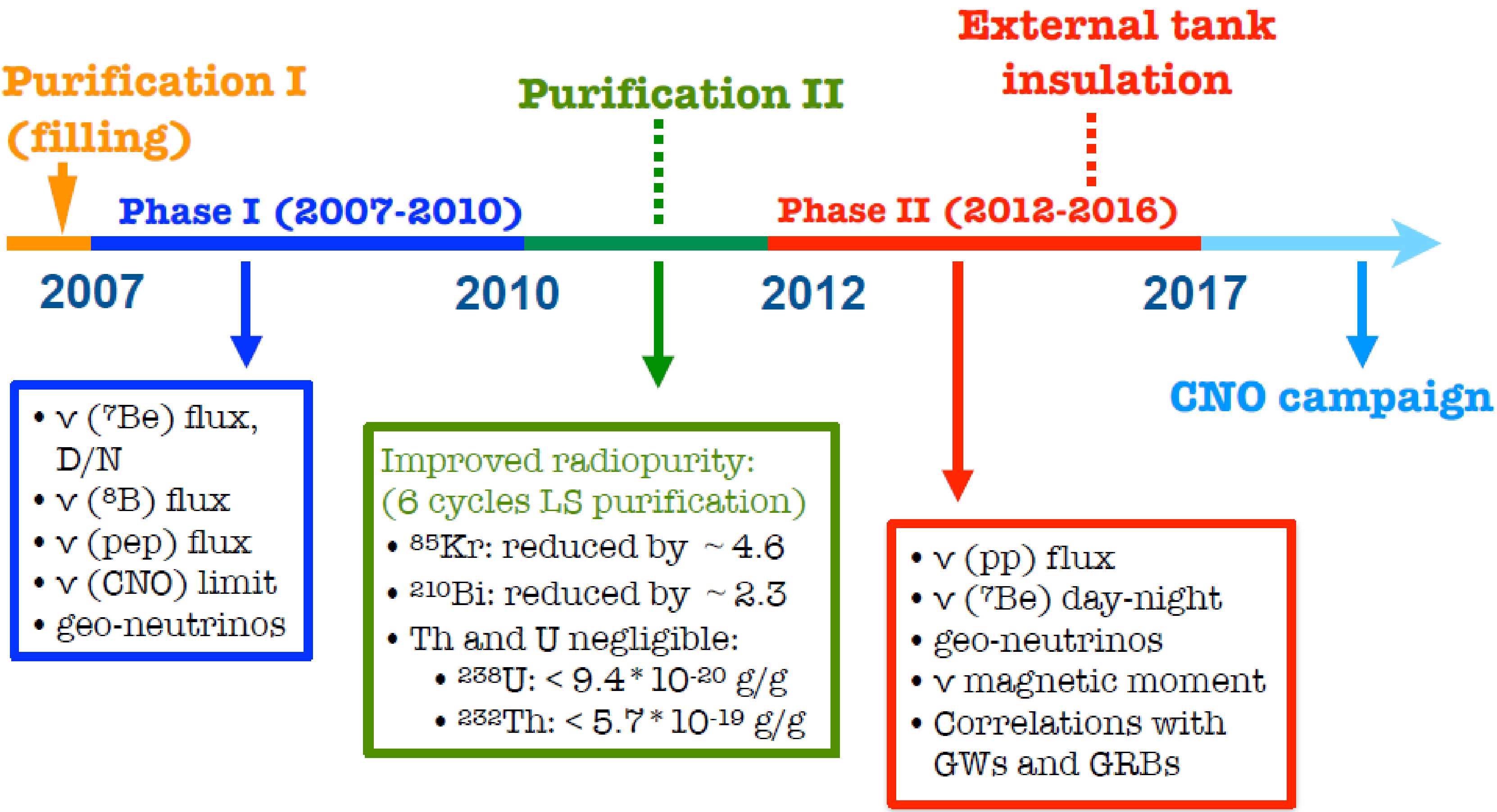






Astroparticle Physics, Vol. 97, 2018, Pages 136-159

Borexino data taking history



.. not only solar neutrinos!!!

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

Low Energy Region (LER) 0.19 – 2.93 MeV pp, ^{7}Be, pep, (CNO)

High energy region (HER) 3.2 – 16 MeV ^{8}B 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 stratetgy

- Apply cuts to remove some 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 surving 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)

https://arxiv.org/abs/1707.09279

https://arxiv.org/abs/1709.00756

Astroparticle Physics, Vol. 97, 2018, Pages 136-159

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

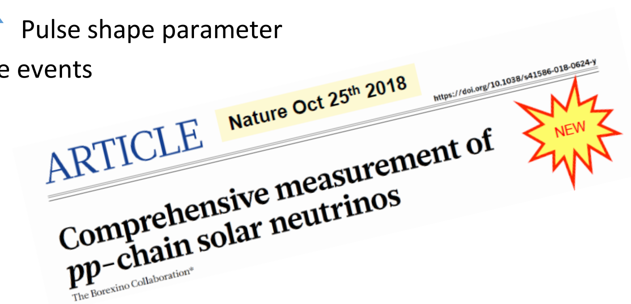
$$L(\vartheta) = L_{sub}(\vartheta)\cdot L_{tag}(\vartheta)\cdot L_{rad}(\vartheta)\cdot L_{PS-L_{pr}}(\vartheta)$$

Pulse shape parameter

Radial distribution of the events

Energy spectrum ^{11}C tagged

Energy spectrum ^{11}C subtracted


ARTICLE

Nature Oct 25th 2018

https://doi.org/10.1038/s41586-018-0624-y

NEW

Comprehensive measurement of pp-chain solar neutrinos

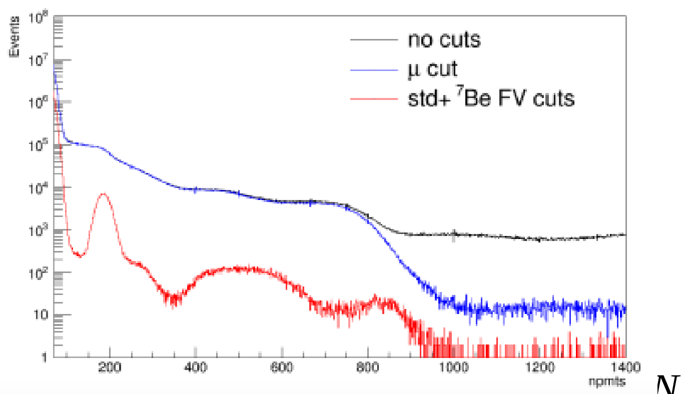
The Borexino Collaboration*

- Fit the radial distribution of the events in the ^{8}B energy region

Signal and background in the Low Energy Region

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

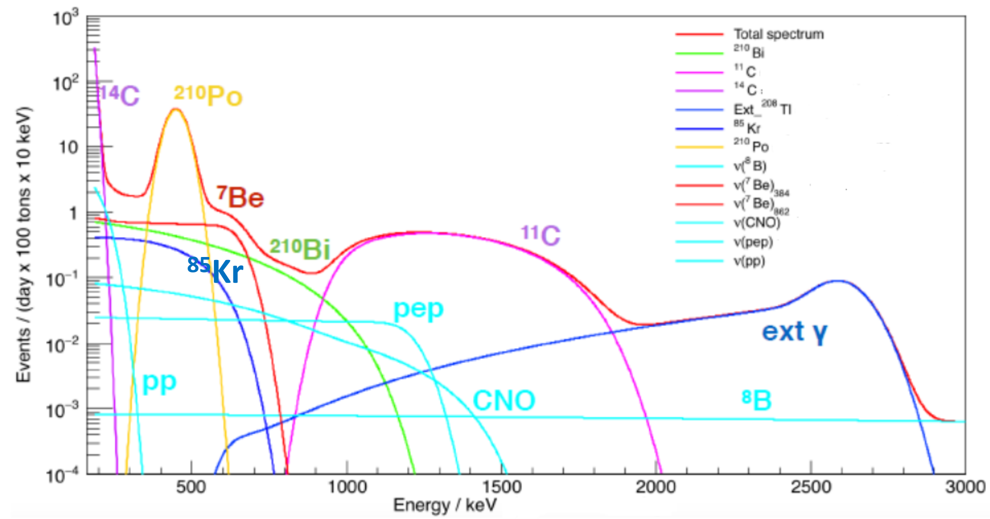
present data set:
Dec 14th 2011 to May 21th, 2016
1291.51 days X 71.3 tons



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 < 2.2m)
- 71.3 tons
- no αβ 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

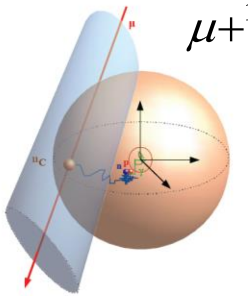
^{232}Th (from ^{212}Bi-Po)

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

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

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

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



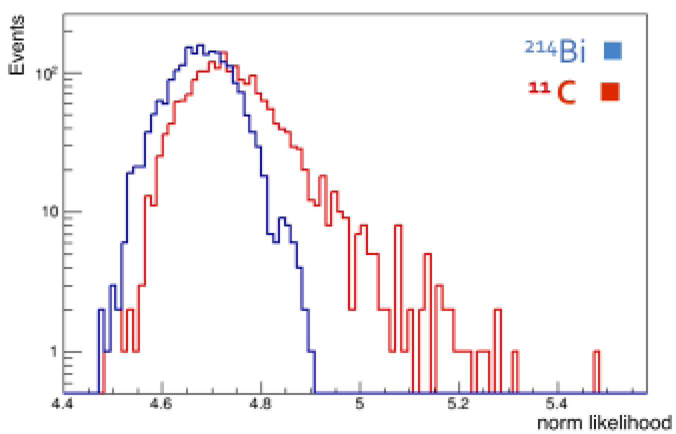
$$\mu + {}^{12}C \rightarrow \mu + n + {}^{11}C$$

- Identify μ and μ track
- Detect n (γ signal due to n capture after themalization)
- 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



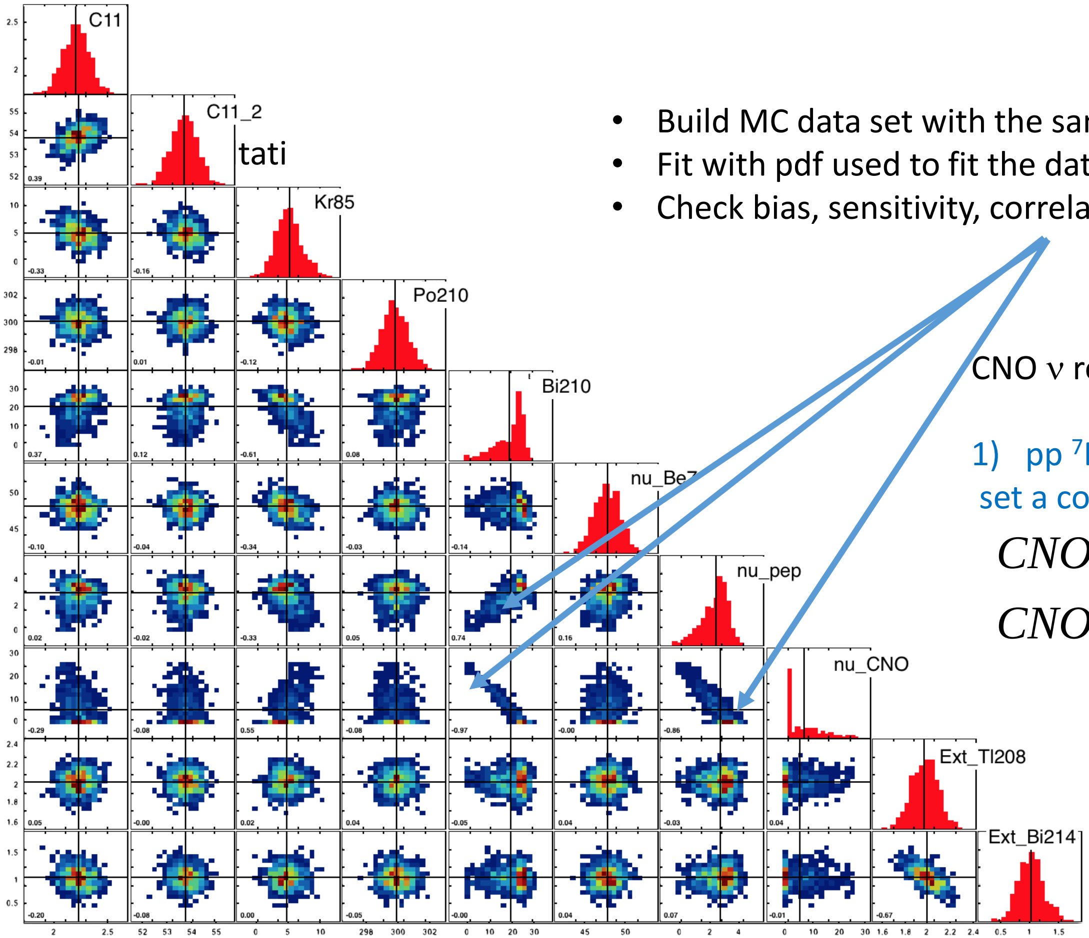
PS-L_{PR}

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 likelihhood assumes lower values for true β- events than for ^{11}C decay

Toy-MC and sensitivity studies



- Build MC data set with the same exposure as in the data
- Fit with pdf used to fit the data
- Check bias, sensitivity, correlations

Analysis strategy:

CNO ν recoil and ^{210}Bi: very similar energy spectrum

1) pp ^{7}Be pep flux measurement:
set a constraint of the CNO rate to the HZ and LZ values

$$CNO\ HZ \quad 4.92 \pm 0.56 \quad cpd/100t$$

$$CNO\ LZ \quad 3.52 \pm 0.37 \quad cpd/100t$$

2) Upper limit CNO ν flux:
we set a constraint on the ratio pp/pep

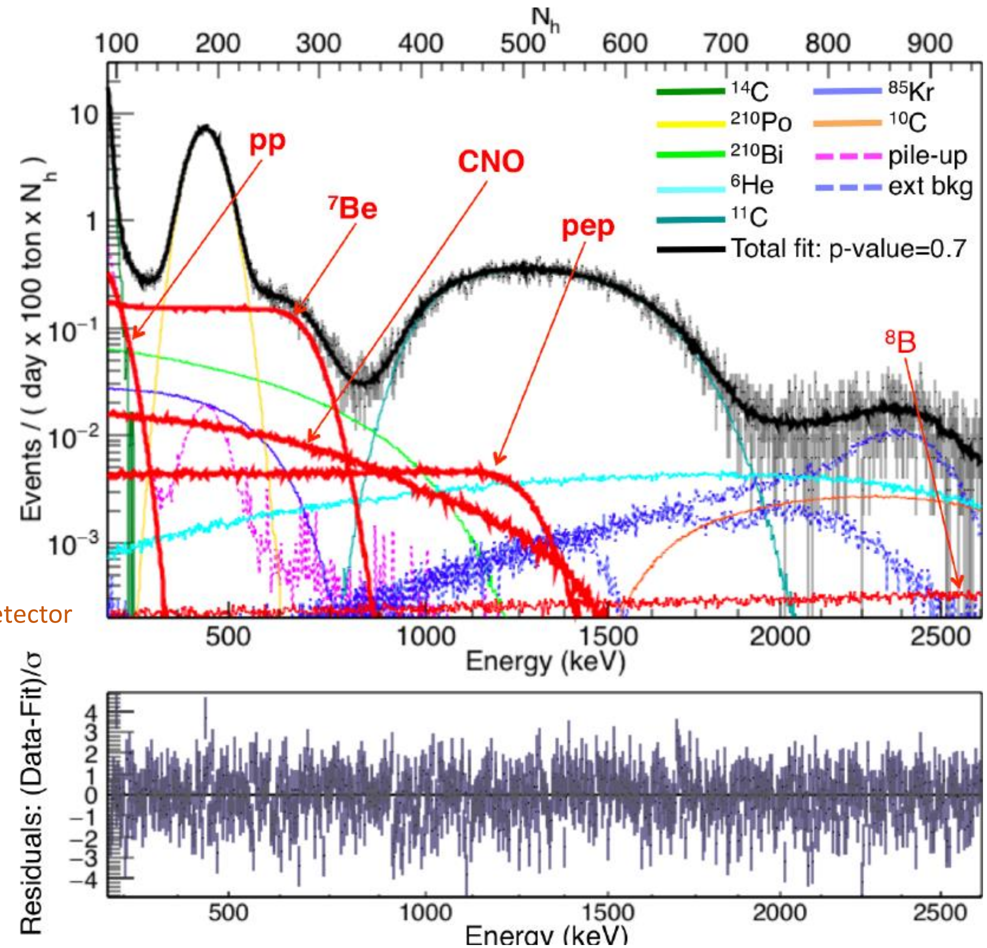
$$R(pp/pep) \quad 47.5 \pm 1.2$$

Example of multivariate fit: energy spectrum

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



CNO fixed to HZ and LZ values

Example of multivariate fit: energy spectrum

Energy spectrum ^{11}C subtracted
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
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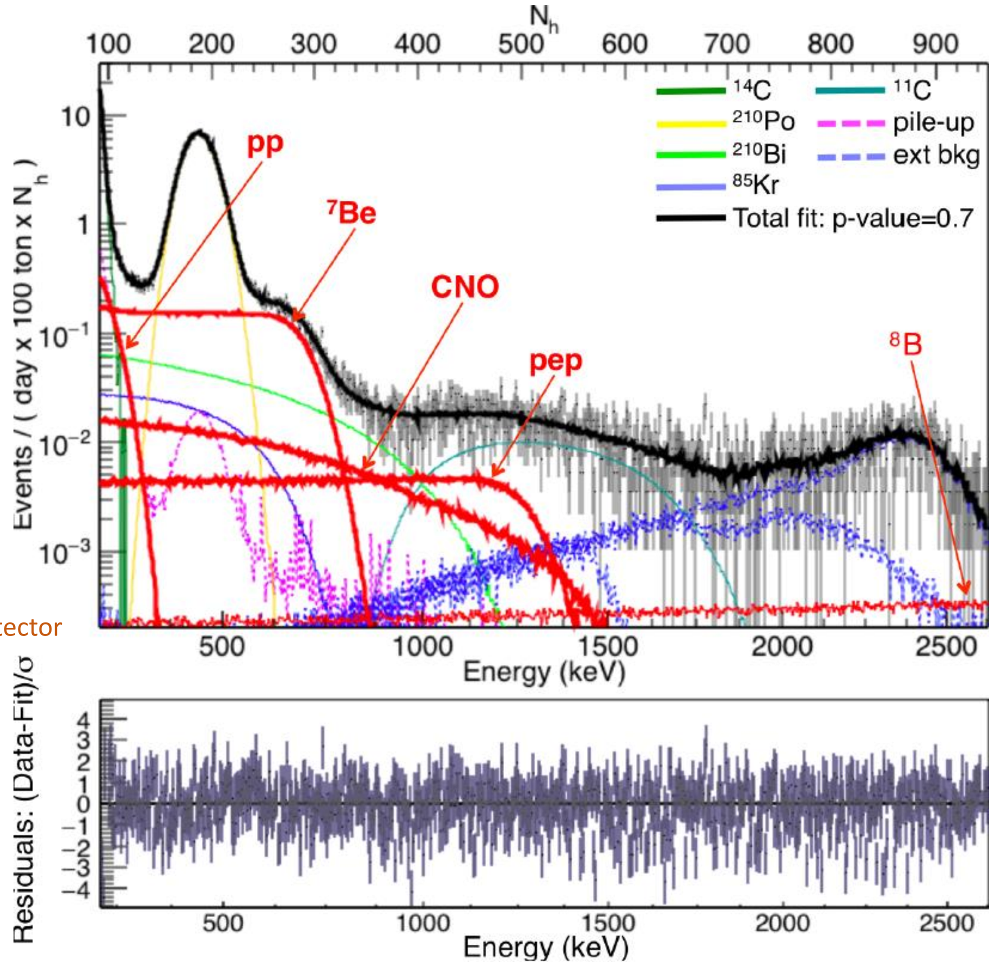


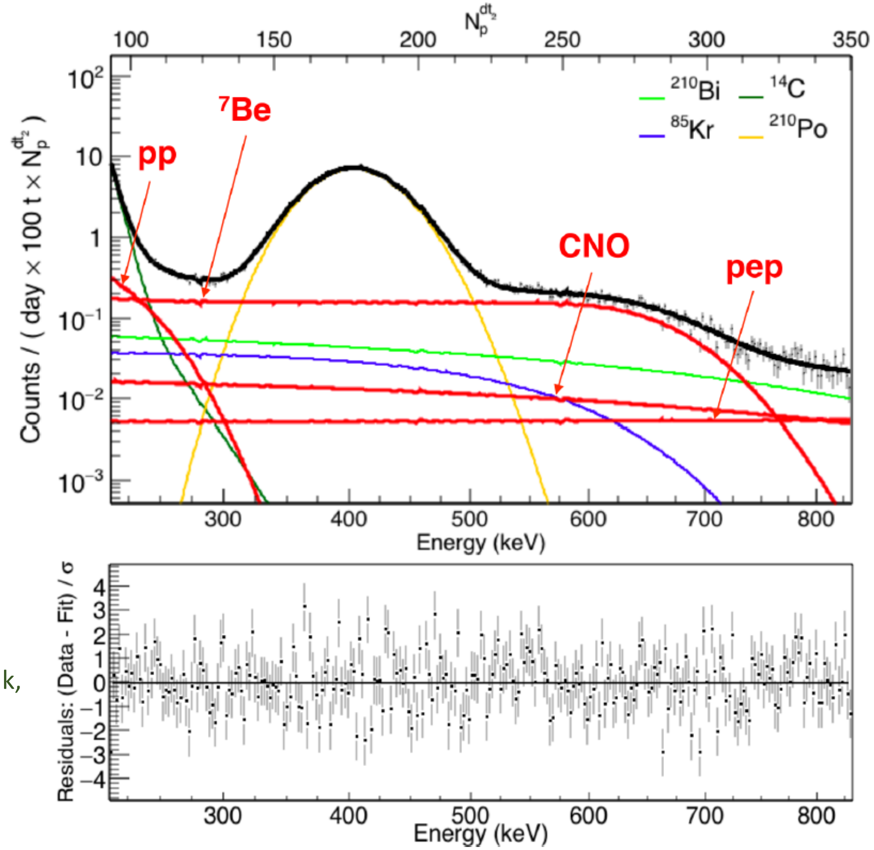
CNO fixed to HZ and LZ values

Zoom of the lowest energy region, below 800 KeV

Fit with analytical models

Example of multivariate fit of the data:

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



- Analytical model to link E to Np, Npe
- 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:

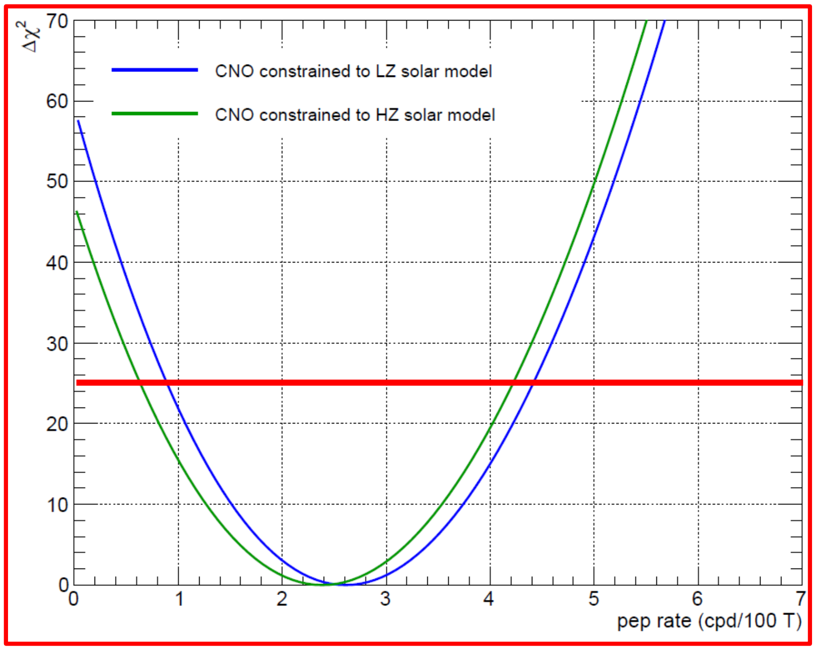
  solar ν and background rate + 6 model parameters
  (Light Yield, 2 resolution param., position & width of 210Po peak, starting point of the 11C spectrum)

- Possibility to descrive unknown time variations
- Easy work at low energy (high rate 14C)

CNO fixed to HZ and LZ values

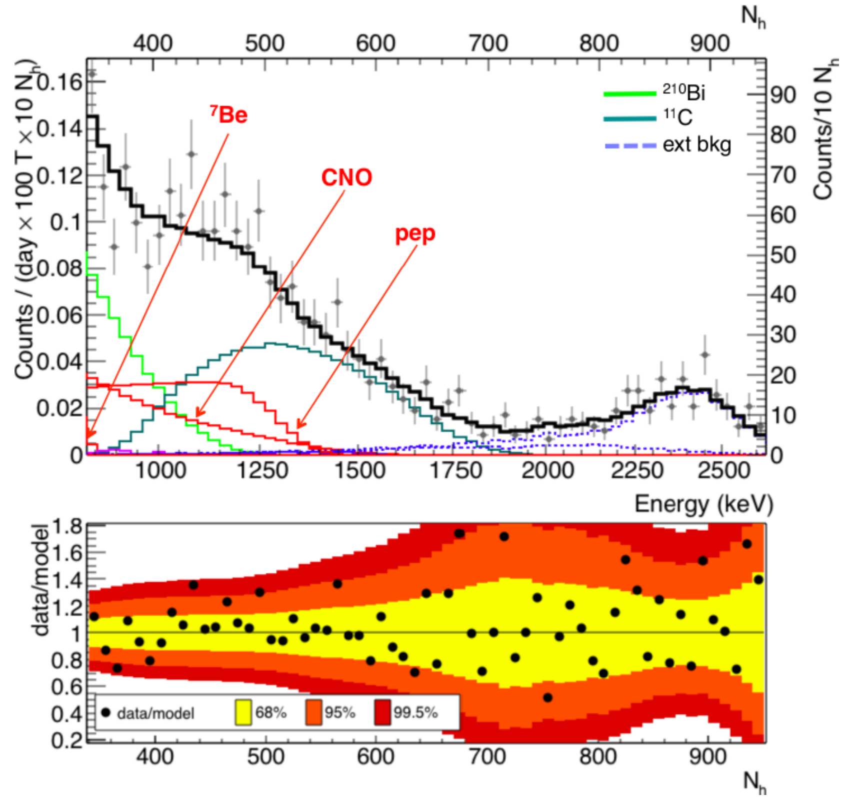
5 σ evidence of pep solar ν
(including systematics uncertainties)

Likelihood profile resulting from the multivariate fit



Select innermost β- like events

Radius<2.4 PS-LPR<4.8



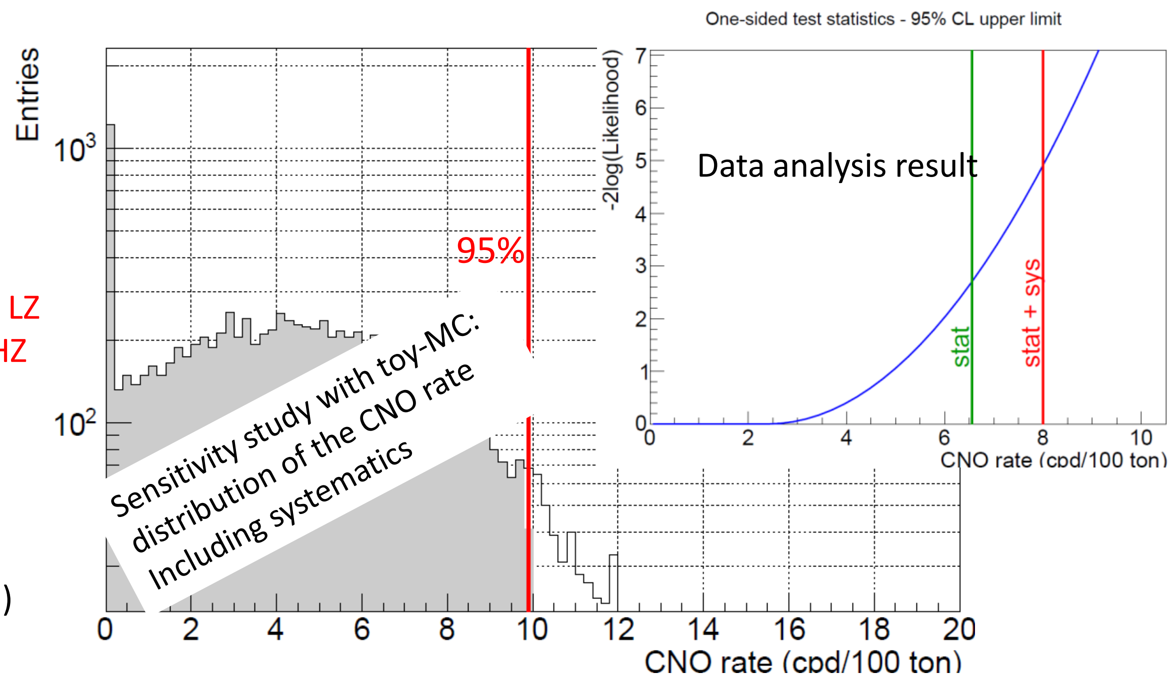
Upper limit on the CNO flux

- 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



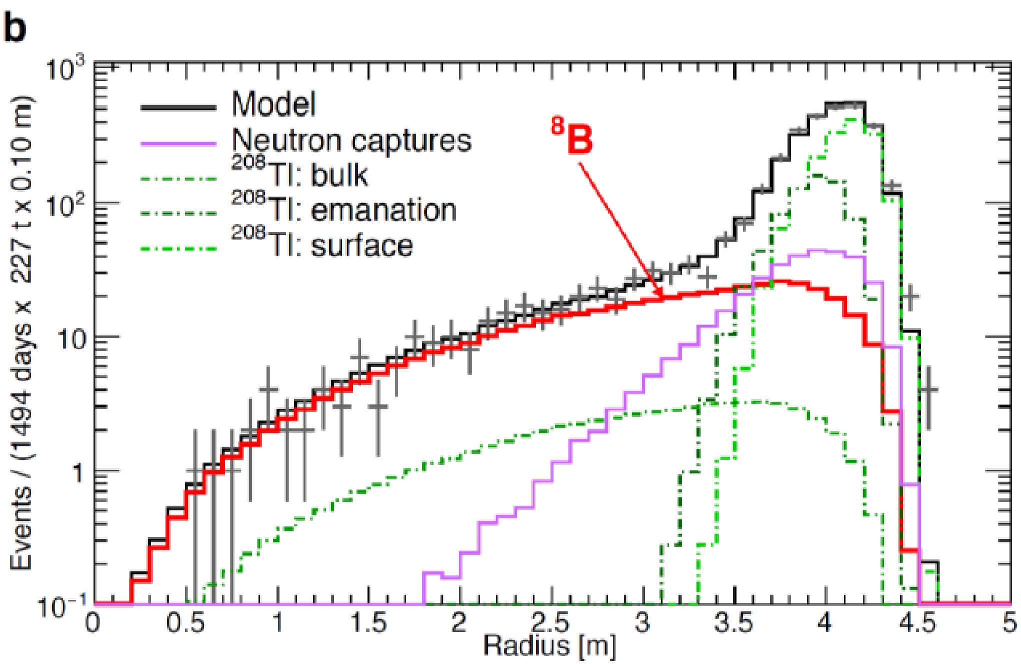
	Borexino result	Expected HZ	Expected LZ
CNO ν	**< 8.1 95%C.L cpd/100t**	**4.91 +-0.56 cpd/100t**	**3.62 +- 0.37 cpd/100t**

The ^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

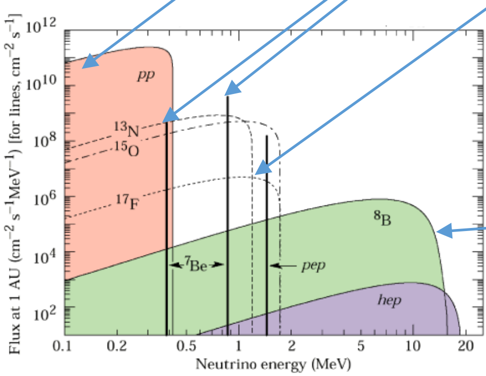
- ^{208}Tl from ^{232}Th of the vessel
- and in the scintillator bulk

- PDF from MonteCarlo



The pp chain solar neutrino results of Borexino

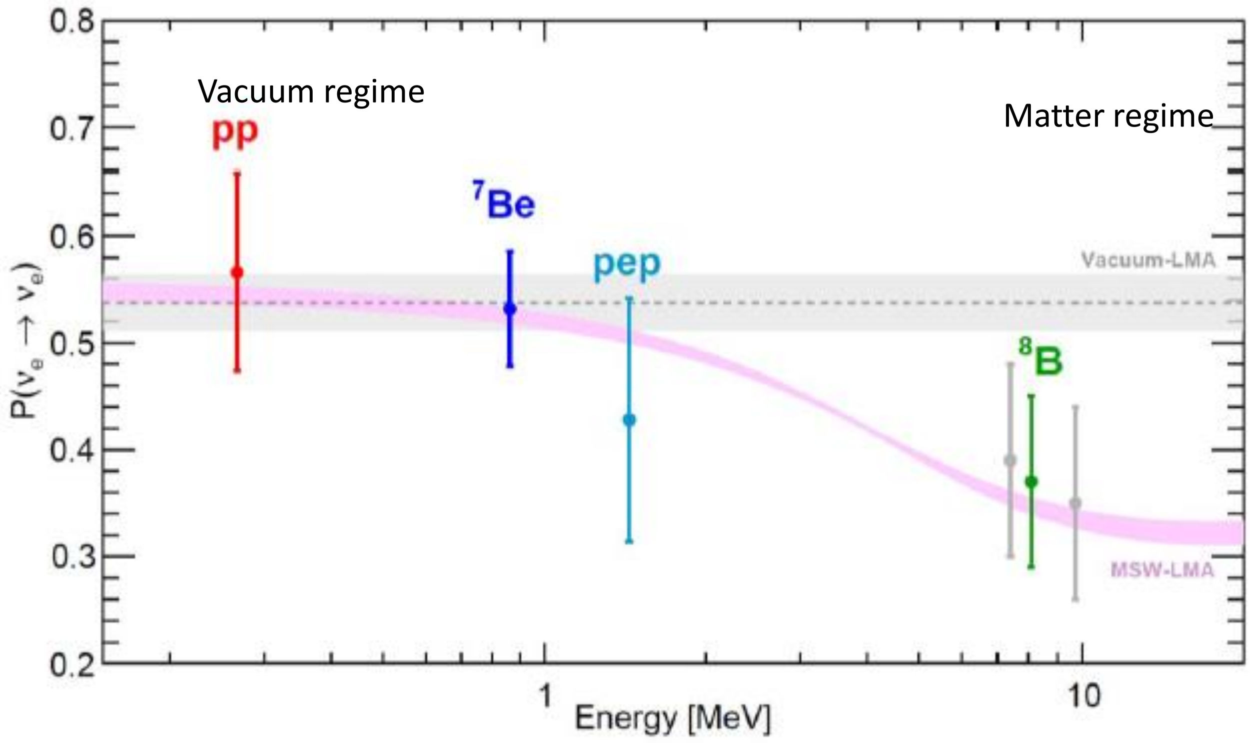
2.5% accuracy



Borexino experimental results

Solar ν	Rate (cpd/100 t)	Flux (cm^{-2} s^{-1})	Flux –SSM predictions (cm^{-2} s^{-1})
pp	$134 \pm 10^{+6}_{-10}$	$(6.1 \pm 0.5^{+0.3}_{-0.5}) \times 10^{10}$	$5.98(1. \pm 0.006) \times 10^{10}$ (HZ) $6.03(1. \pm 0.005) \times 10^{10}$ (LZ)
^{7}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)
pep (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)
pep (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}B$_{HER\text{-}I}$	$0.136^{+0.013+0.003}_{-0.013-0.003}$	$(5.77^{+0.56+0.15}_{-0.56-0.15}) \times 10^{6}$	$5.46(1. \pm 0.12) \times 10^{6}$ (HZ) $4.50(1. \pm 0.12) \times 10^{6}$ (LZ)
^{8}B$_{HER\text{-}II}$	$0.087^{+0.080+0.005}_{-0.010-0.005}$	$(5.56^{+0.52+0.33}_{-0.64-0.33}) \times 10^{6}$	$5.46(1. \pm 0.12) \times 10^{6}$ (HZ) $4.50(1. \pm 0.12) \times 10^{6}$ (LZ)
^{8}B$_{HE}$	$0.223^{+0.015+0.006}_{-0.016-0.006}$	$(5.68^{+0.39+0.03}_{-0.41-0.03}) \times 10^{6}$	$5.46(1. \pm 0.12) \times 10^{6}$ (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)

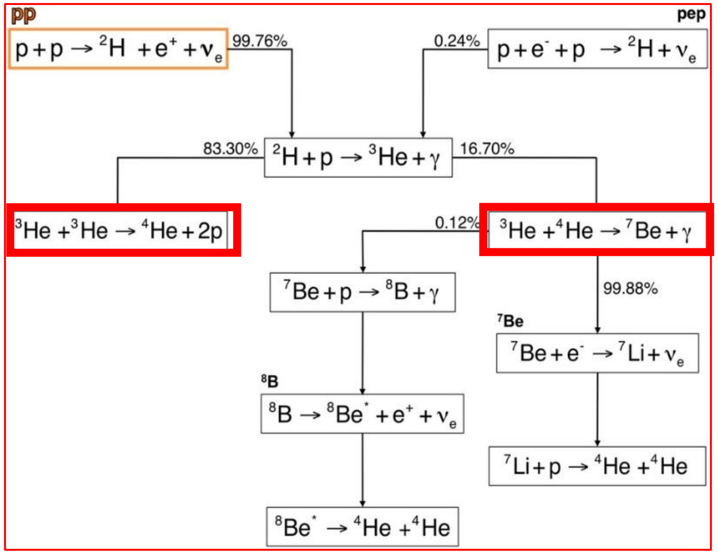
The neutrino survival probability



Not Standard ν Interactions modify the survival probability…

Implication of the results: probe solar fusion with R

Reaction from the main pp chain



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

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

$$R = 0.180 \pm 0.011 \quad HZ$$
$$R = 0.161 \pm 0.010 \quad LZ$$

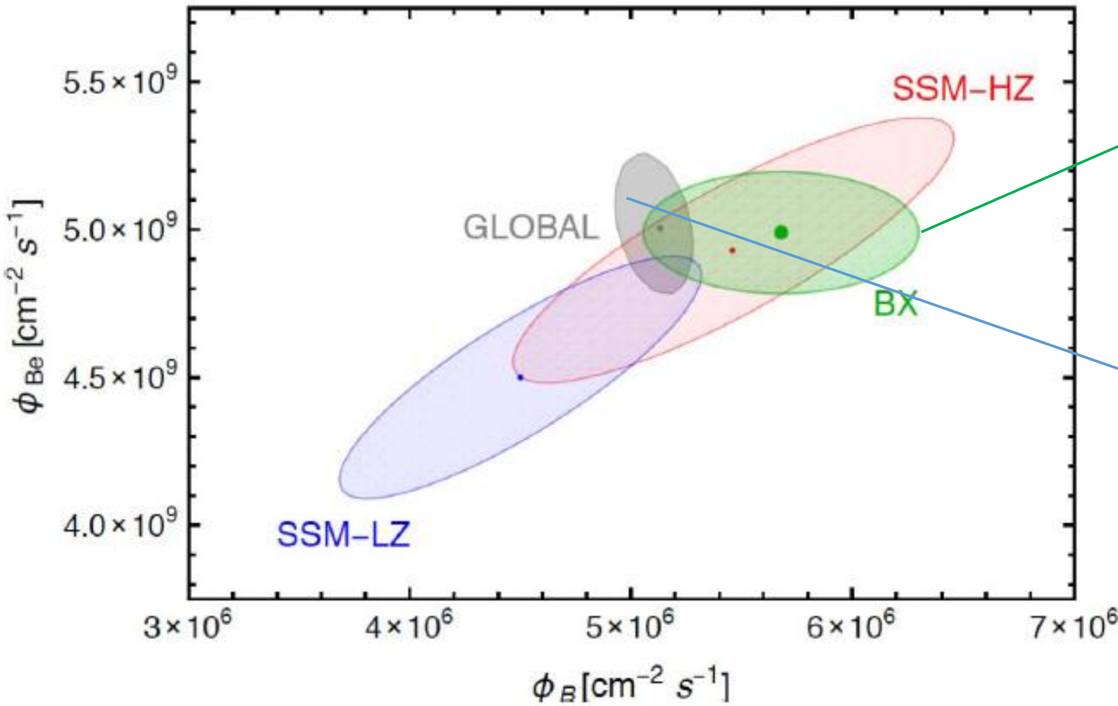
Measured value: $R(BRX) = 0.178^{+0.027}_{-0.023}$

Implication of the results: check solar Luminosity with ν and with photons

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

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

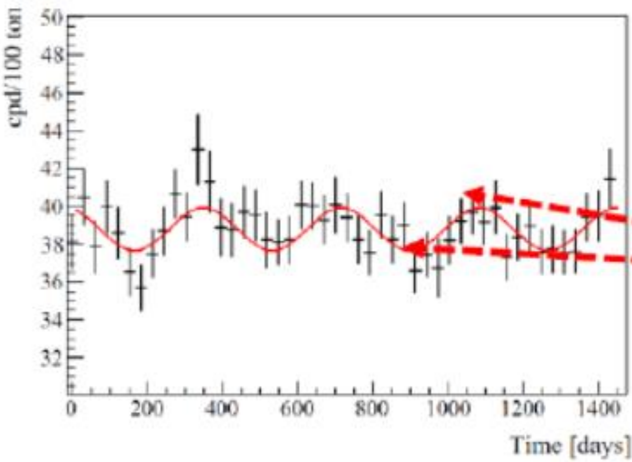
A step toward the understanding of the metallicity…?



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

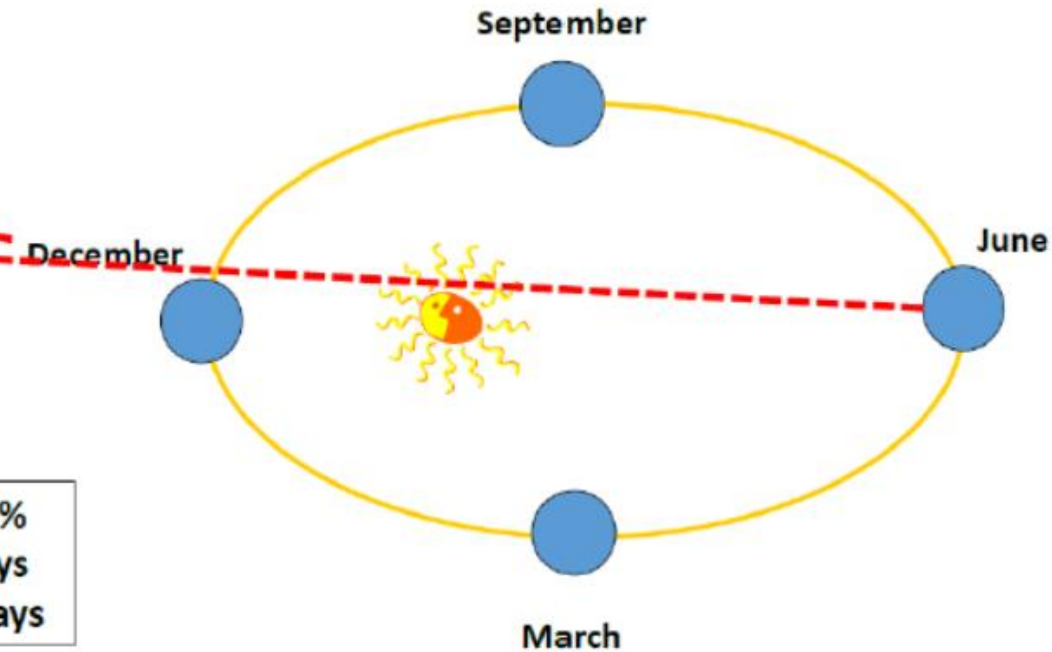
Borexino+other solars and Kamland
Global fit
Hints about HZ is weaker

Annual modulation of the ^{7}Be solar ν in Borexino



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

ε = (1.74 ± 0.45)%
T = (367 ± 10)days
Φ = (-18 ± 24) days



M. Agostini et al. / Astroparticle Physics 92 (2017) 21–29

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

$$^{210}\mathrm{Pb} \xrightarrow{\beta\ (63\ \mathrm{KeV})} {}^{210}\mathrm{Bi} \xrightarrow{\beta} {}^{210}\mathrm{Po} \xrightarrow{\alpha} {}^{206}\mathrm{Pb}$$

^{210}Pb	^{210}Bi	^{210}Po	^{206}Pb
$T_{1/2}$=22y	5 days	138 days	stable

Assuming ^{210}Bi rate constant

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

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

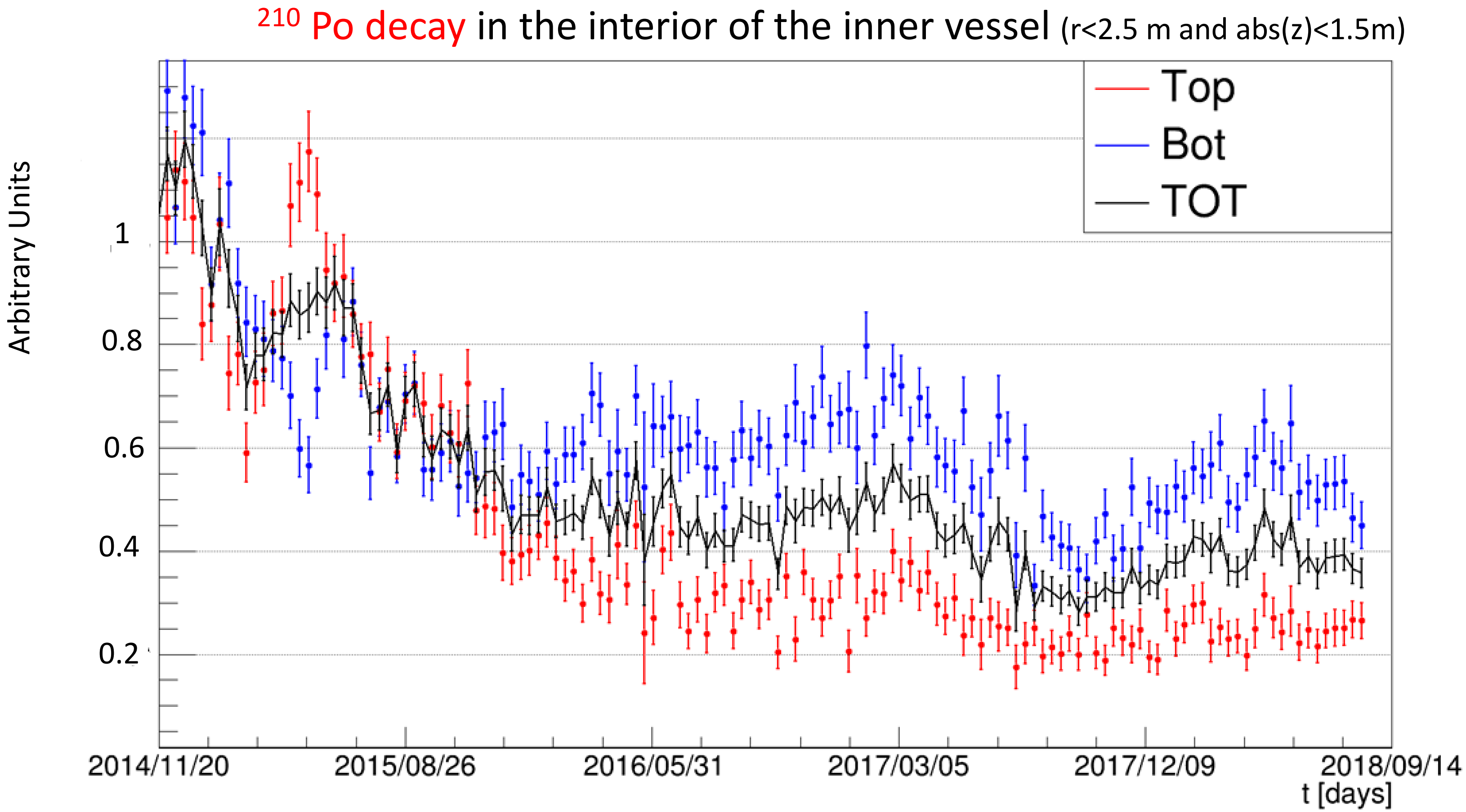
Needed:

- ^{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 &temperature control of the detector to reduce and control thermal gradients

Before thermal insulation

After thermal insulation



210 Po decay in the interior of the inner vessel (r<2.5 m and abs(z)<1.5m)
Top
Bot
TOT
Arbitrary Units
1
0.8
0.6
0.4
0.2
2014/11/20
2015/08/26
2016/05/31
2017/03/05
2017/12/09
2018/09/14
t [days]

Conclusions

- Borexino running since May 2007
- We measured all ν from pp chain
- Annual modulation of 7Be ν detected
- Additional results on rare processes
- Geoneutrinos detected with 5.9 s (using data from the year 2007 to 2015) and new results coming soon
- Effort in progress to measure CNO ν

Borexino Collaboration

Purification of the scintillator
6 cycles, closed loop
Reduction factors:

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

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^-) (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 (*HER-I*)	rate (cpd/227.8 t)
μ, cosmogenics, ^{214}Bi (internal)	$[6.1^{+8.7}_{-3.1} 10^{-3}]$
(α , n) (external)	0.224 ± 0.078
^{208}Tl(5.0 MeV, β^-, γ) (internal)	[0.042 ± 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 (*HER-II*)	rate (cpd/266.0 t)
μ, cosmogenics (internal)	$[3.8^{+14.6}_{-0.1} 10^{-3}]$
(α , n) (external)	0.239 ± 0.022