Full pp-chain solar neutrino spectroscopy with Borexino

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on behalf of the Borexino collaboration

Borexino Collaboration

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St. Petersburg Nuclear Physics Inst.

Technische Universität München

University of Houston

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Solar Neutrinos

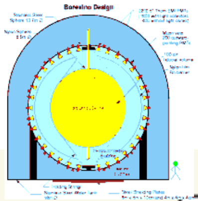
Fundamental paradigm:
The source of energy in the sun (and in H-burning stars) makes neutrinos:

$$4p \rightarrow {}^4He + 2e^+ + 2\nu_e + (24.69 + 2 \cdot 1.022)\,MeV$$

$\langle E_\nu \rangle \sim 0.53$ MeV, 2% of total energy produced

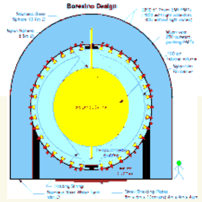
Hydrogen burning works through:
- pp-chain reactions
- CNO bi-cycle

pp chain



2014

$p + p \longrightarrow {}^2H + e^+ + \nu_e$



2012

$p + e^- + p \longrightarrow {}^2H + \nu_e$

99.76% ↓ ↓ 0.24%

${}^2H + p \longrightarrow {}^3He + \gamma$

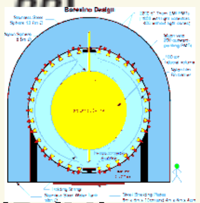
83.30% ↓ ↓ 16.70%

${}^3He + {}^3He \longrightarrow {}^4He + 2p$

ppI

${}^3He + {}^4He \longrightarrow {}^7Be + \gamma$

99.88% ↓ ↓ 0.12%



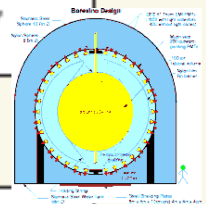
2007, 2012(D/N),
2014 (seasonal)

${}^7Be + e^- \longrightarrow {}^7Li + \nu_e$

${}^7Li + p \longrightarrow 2\,{}^4He$

ppII

${}^7Be + p \longrightarrow {}^8B + \gamma$

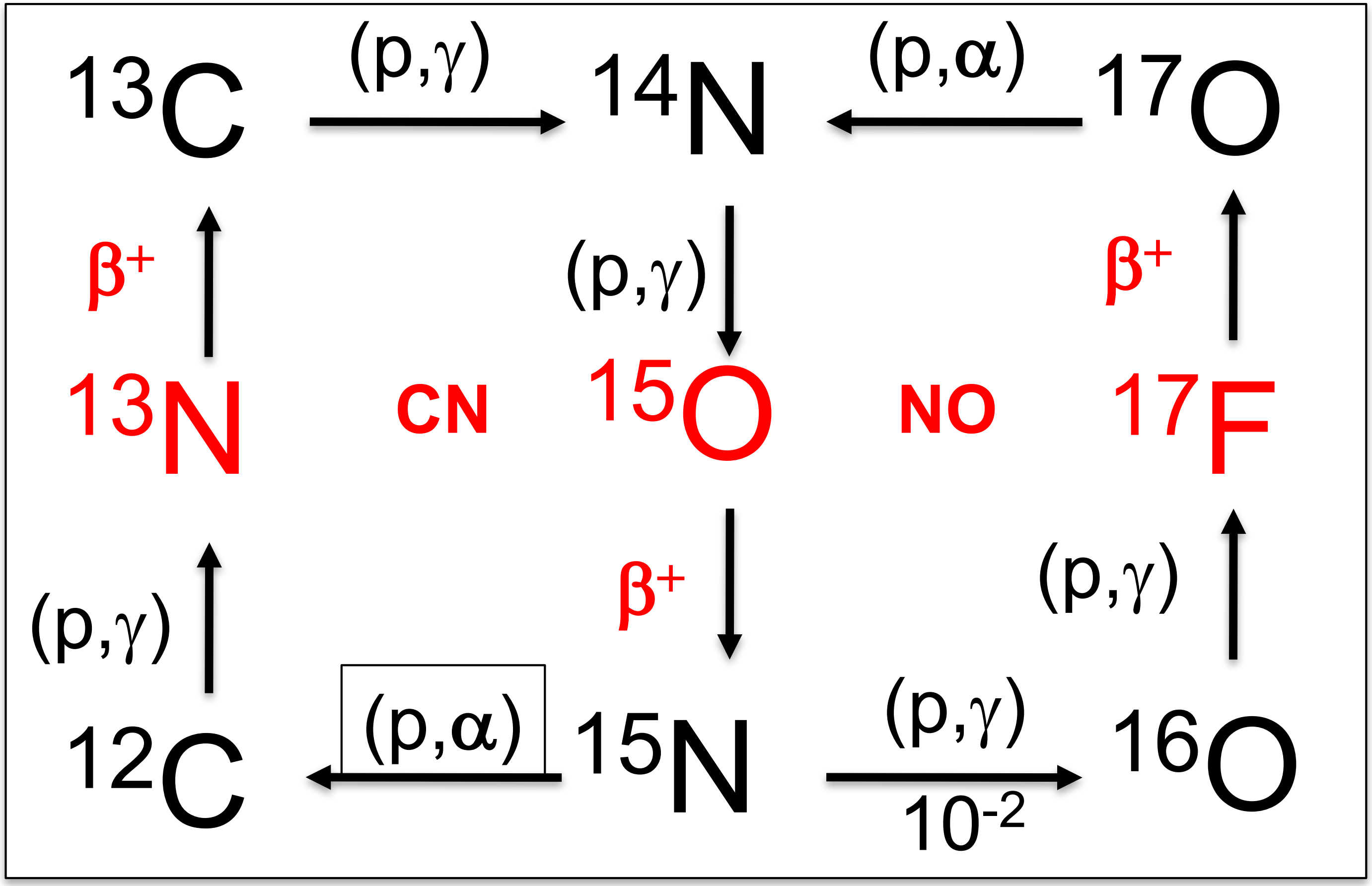


2010

${}^8B \longrightarrow 2\,{}^4He + e^+ + \nu_e$

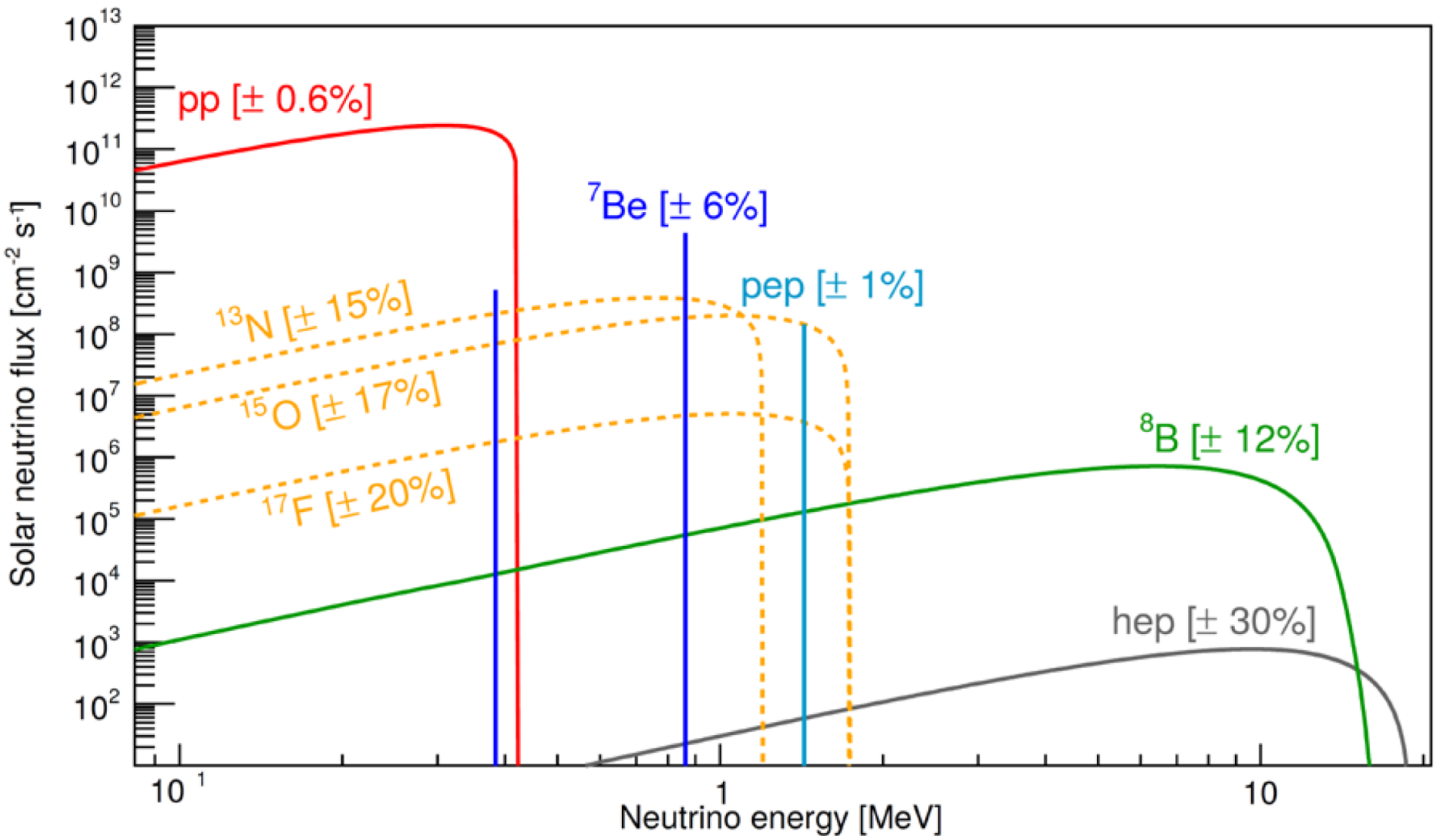
ppIII

CNO bi-cycle H burning

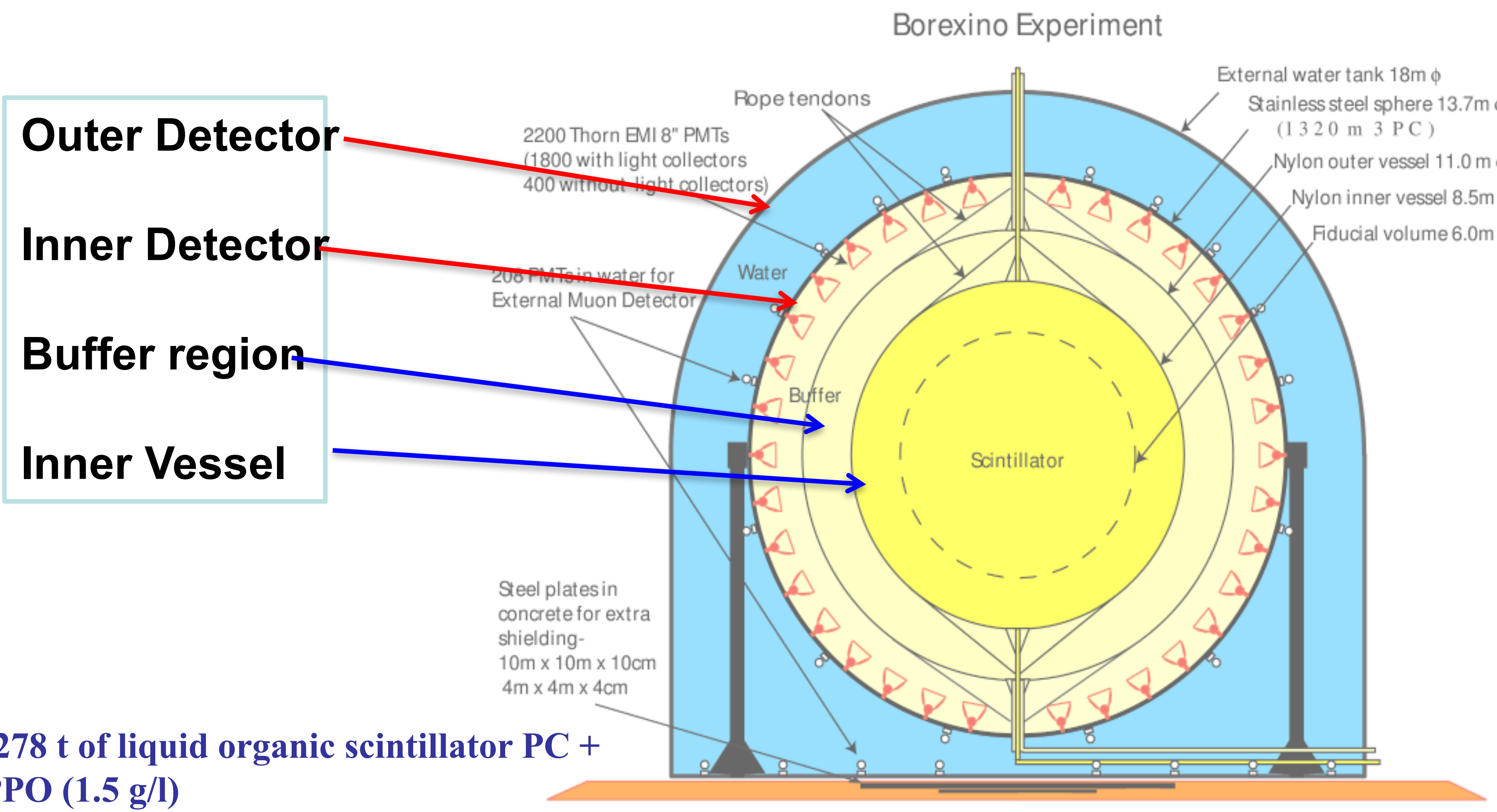


Solar neutrino spectra

A. Serenelli et al, **Astrophys.J. 835 (2017) no.2, 202**



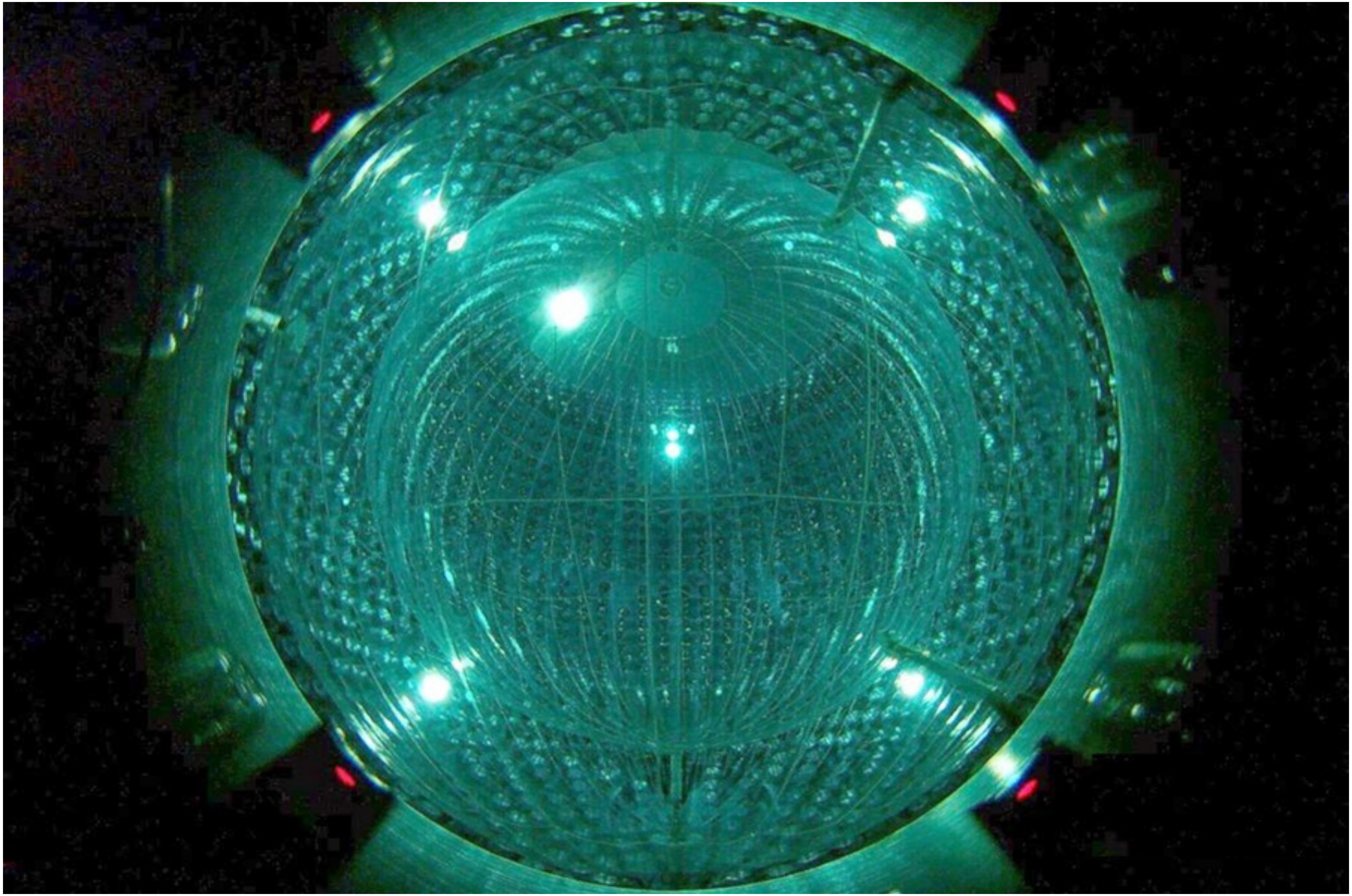
The Borexino detector



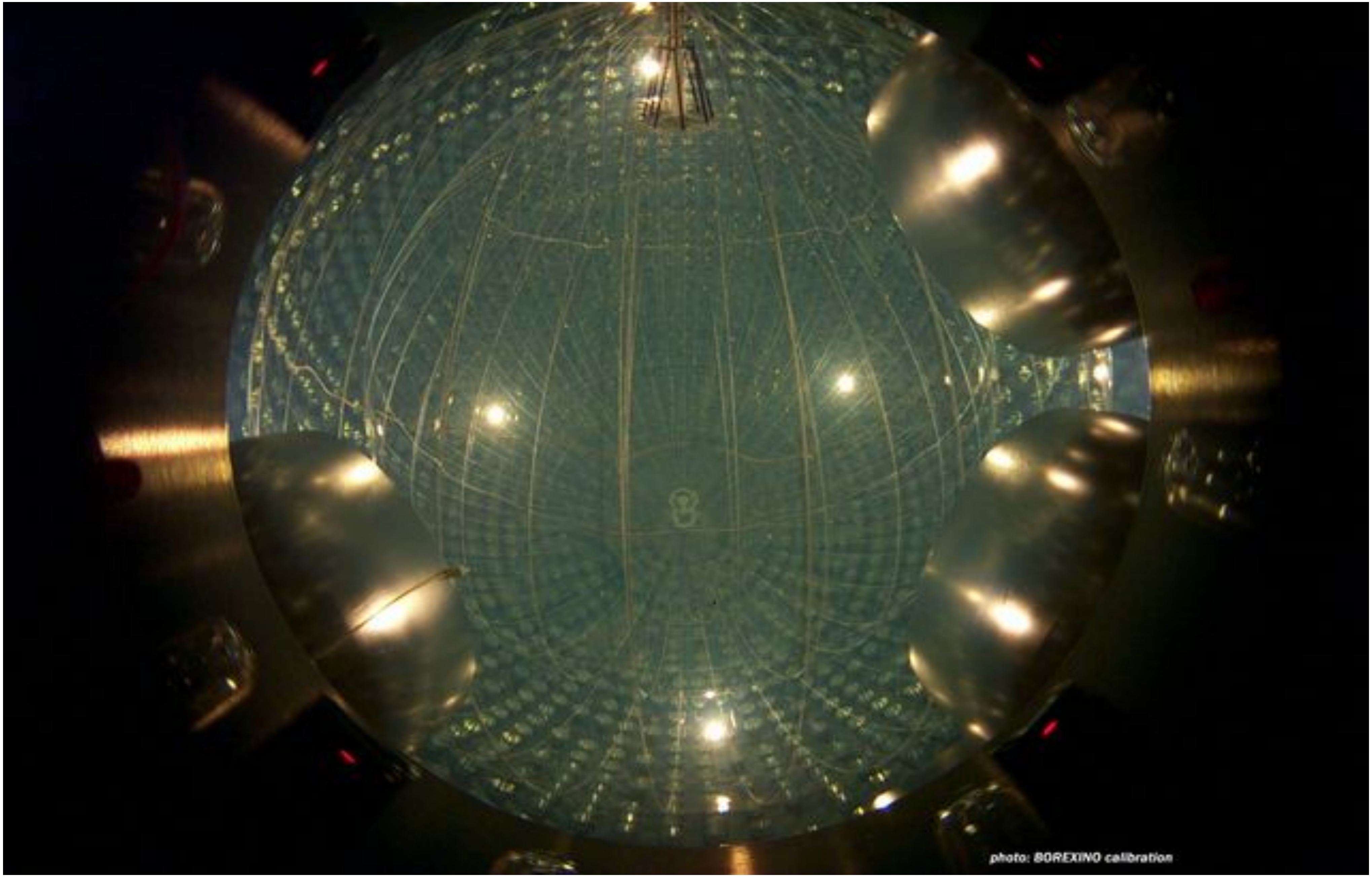
- 278 t of liquid organic scintillator PC + PPO (1.5 g/l)
- (ν,e)-scattering with low threshold (~200 keV)

In data taking at LNGS since 2007

Borexino: water filling

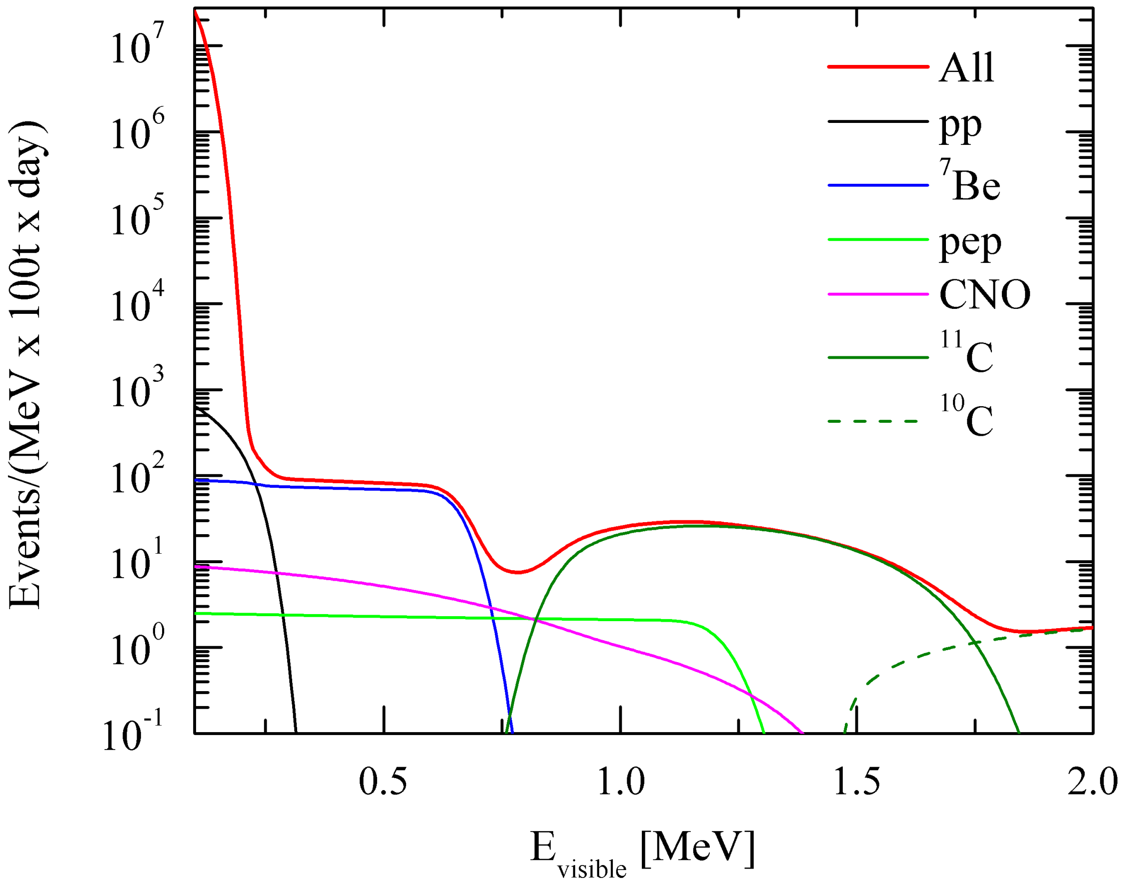


Borexino: liquid scintillator filling May 2007

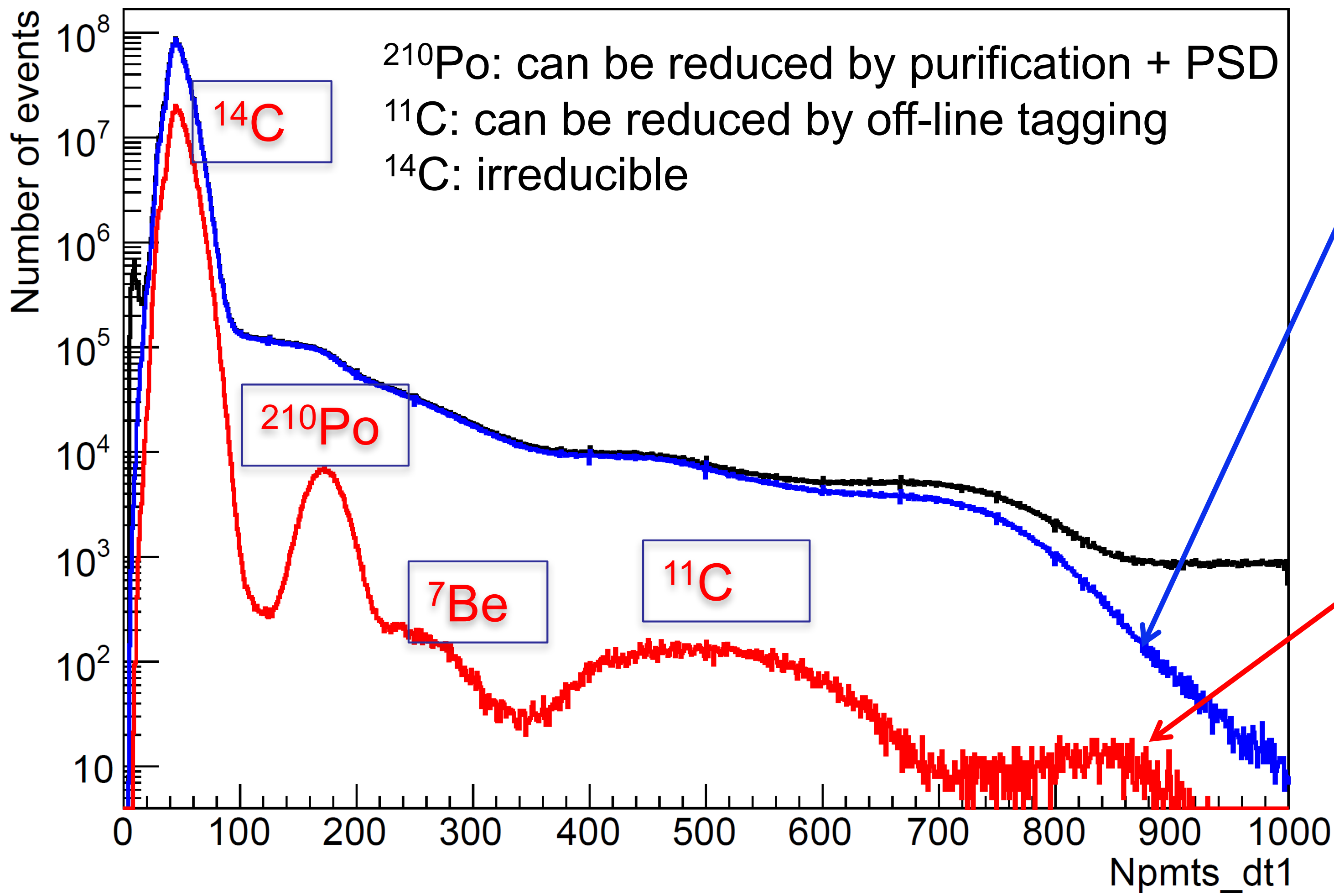


Borexino Expected Solar ν Spectrum

Spectrum with irreducible backgrounds



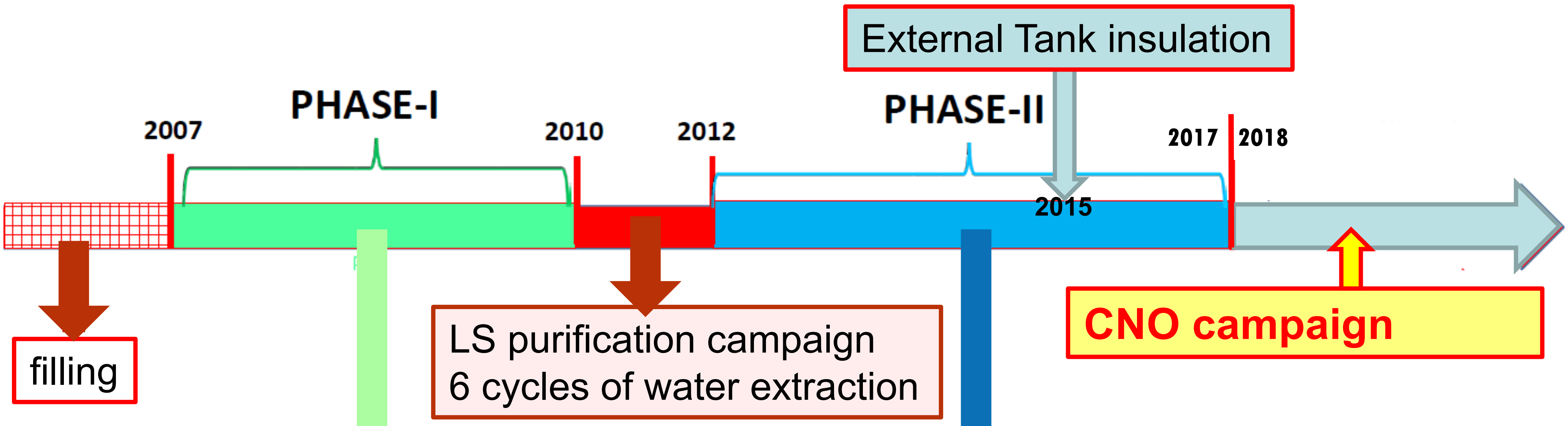
Data selection for solar neutrino analysis



Muon cuts: muon induced events are removed

FV cut: Events in the outermost part of the scintillator volume are removed

Borexino: timeline of activities



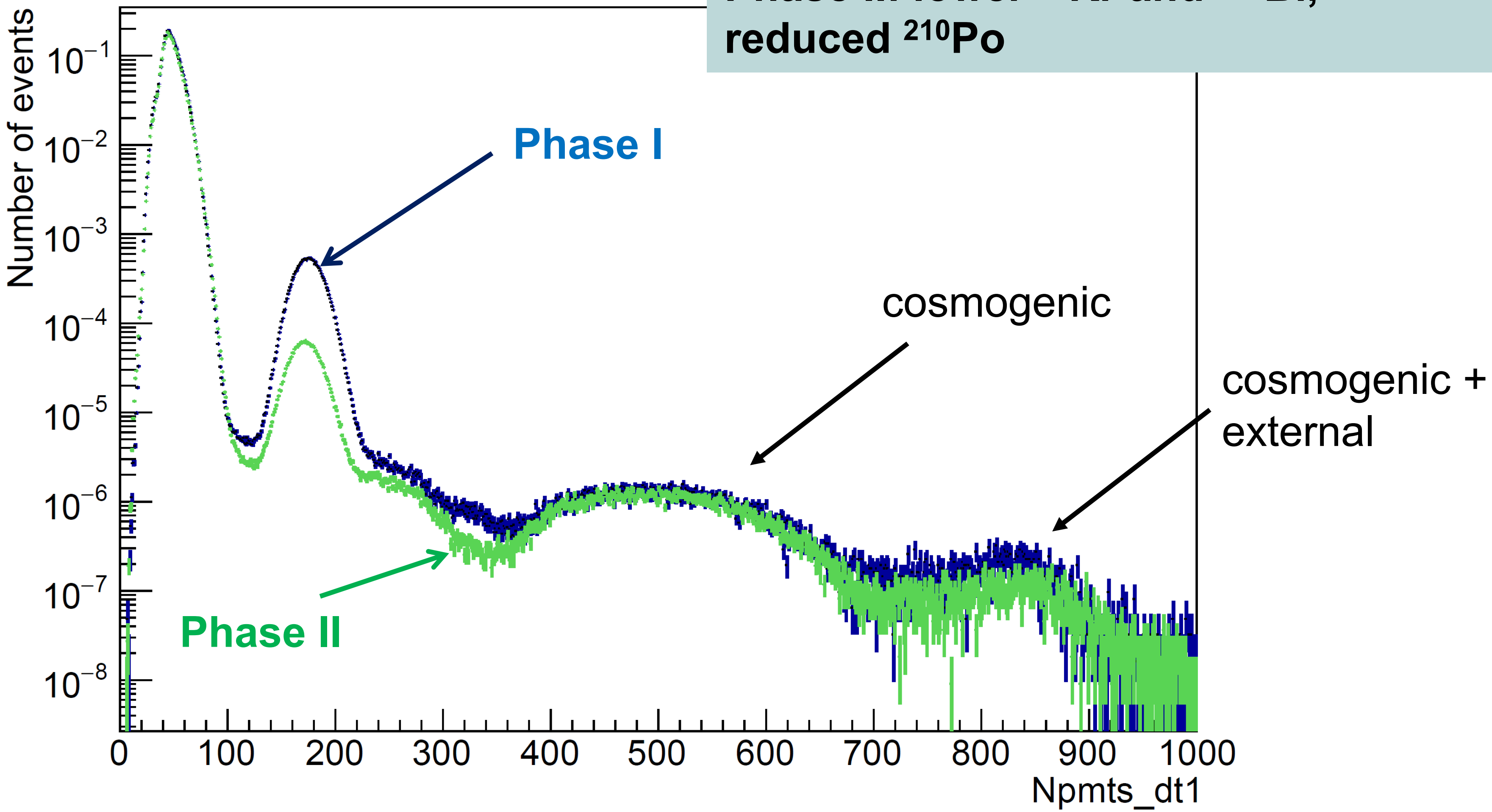
- R(^{7}Be) + D/N
- R(pep) – first observation
- R(^{8}B)– first with LS
- R(CNO) – limit

geo- ν – first robust observation
cosmic muons flux studies
rare processes

- R(pp) *first in real time*
- Seasonal variations of R(^{7}Be)
- Simultaneous spectroscopy of pp, ^{7}Be and pep ν
- R(^{8}B)–improved
- geo- ν
- ν magnetic moment
- NSI (under study)
- rare processes

Phase I/Phase II

Phase II: lower ^{85}Kr and ^{210}Bi, reduced ^{210}Po

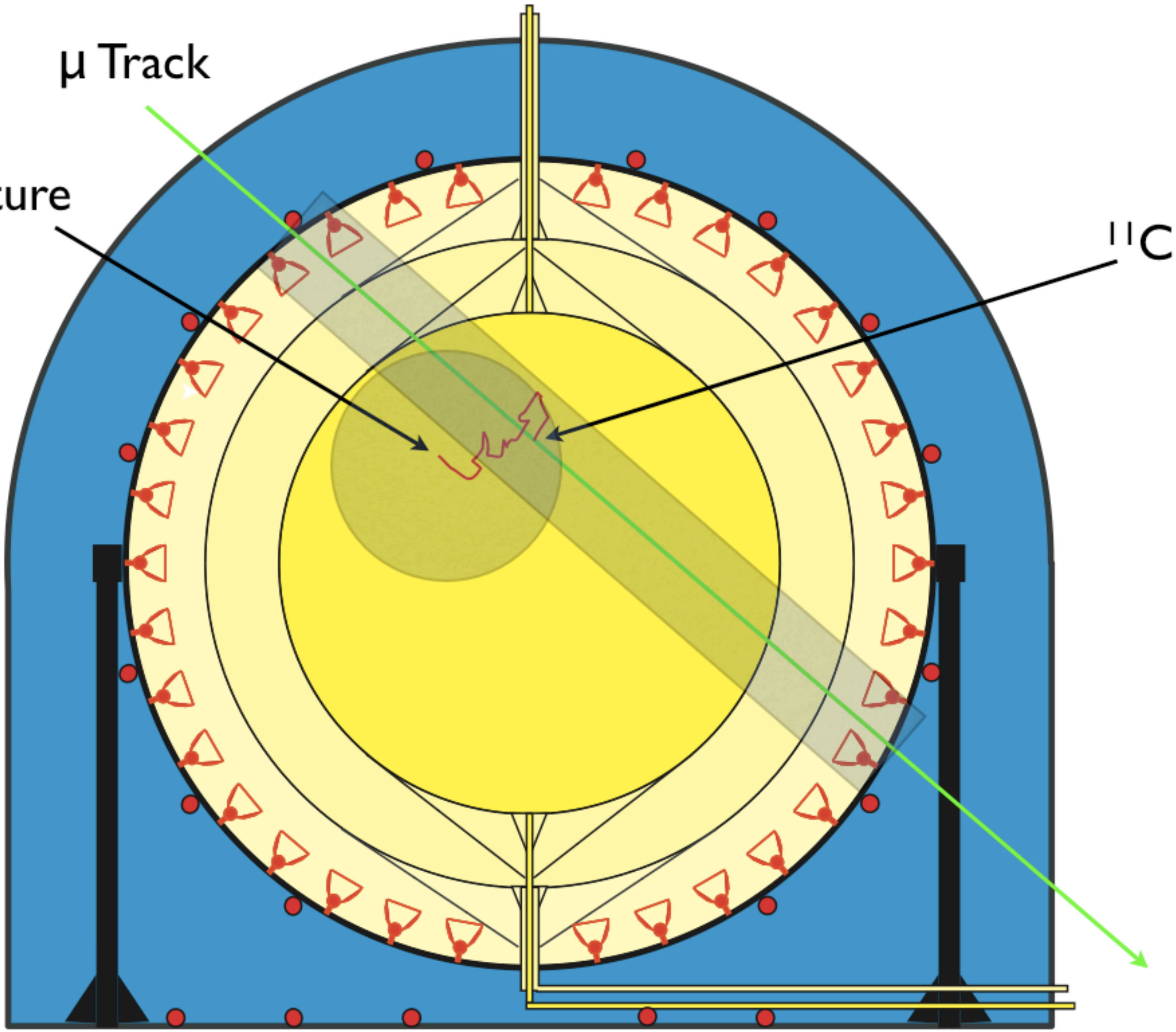


Removing ^{11}C background: Three-Fold Coincidence

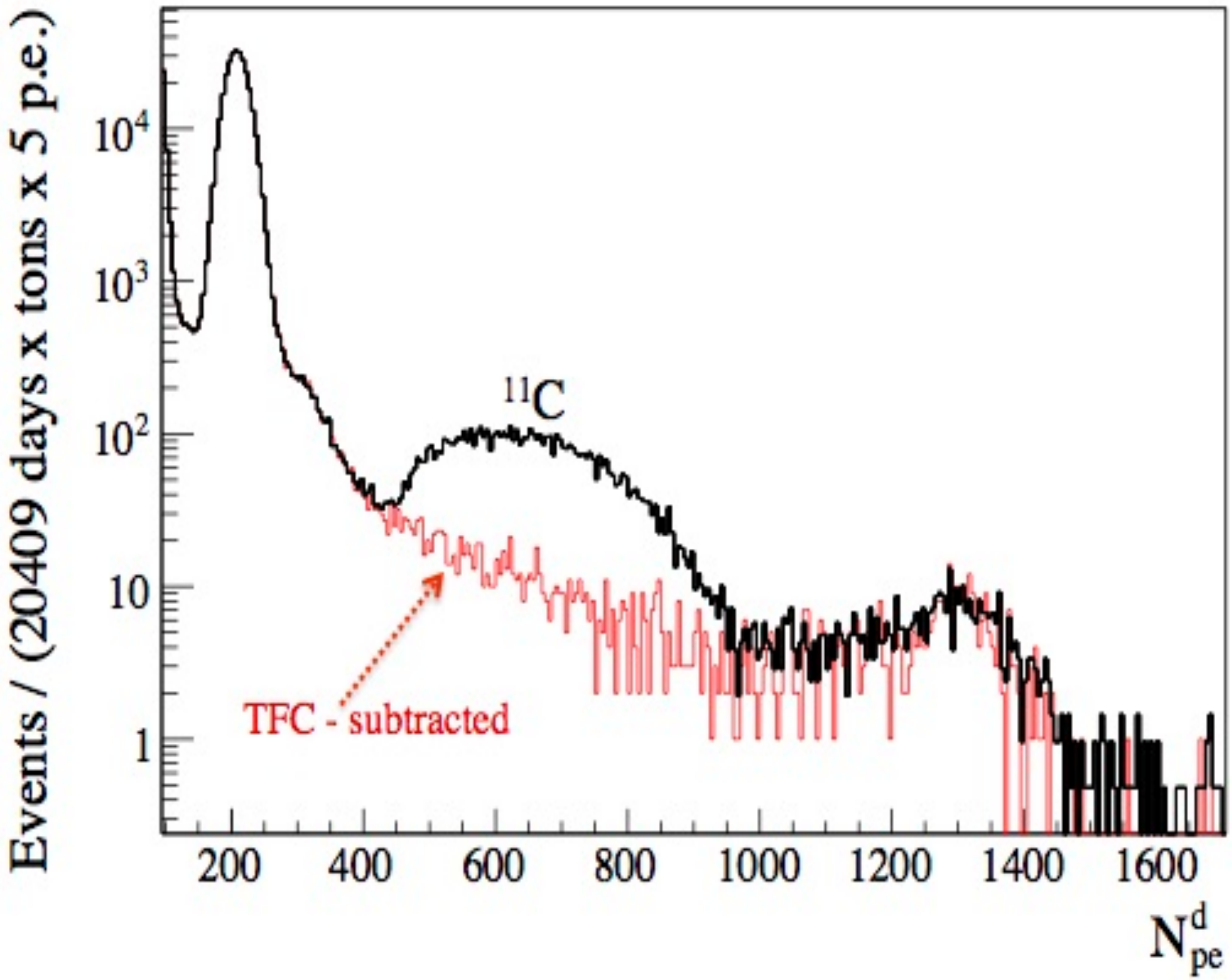
$\mu + ^{12}C \rightarrow \mu + ^{11}C + n$
$^{11}C \rightarrow ^{11}B + e^{+} + \nu_e$
$\tau = 29.4$min
$E_{vis} = 1 - 2$ MeV

n diffuses before capture on H in ~ 250 μs

The TFC eff. is **92±4%** ^{11}C preserving **64%** of the total exposure



Three-fold Coincidence at work



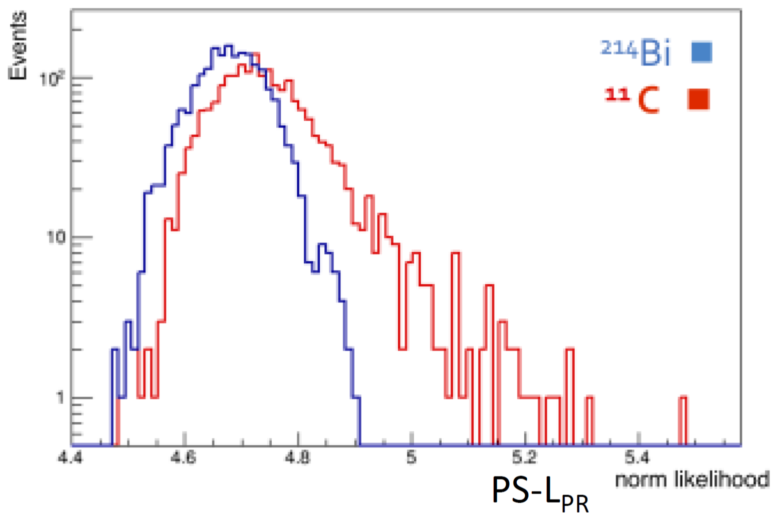
Multivariate approach to spectral fit

Originally developed for pep-neutrino analysis (2012) to separate electron spectra from overhelming contribution of ^{11}C

The technique consists in combining the likelihoods:

- (1) Energy spectrum with and without the TFC tagging

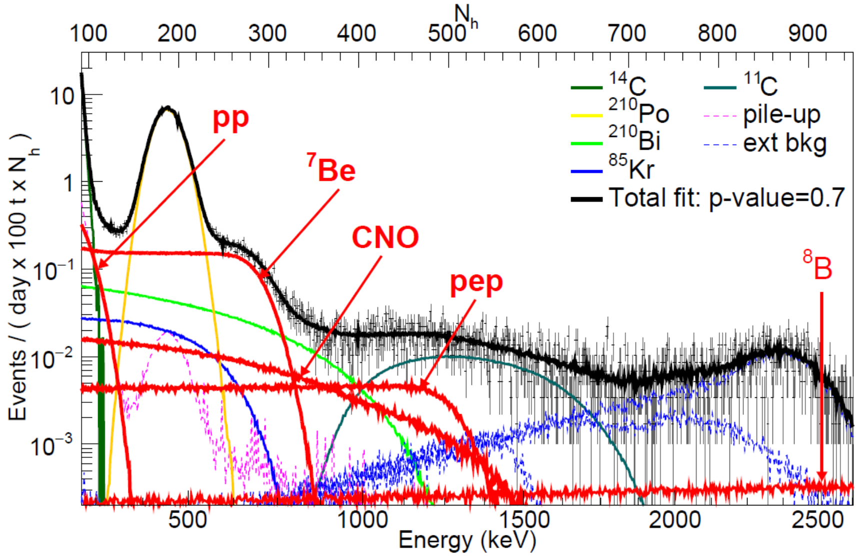
- (2) Pulse-shape discriminator (PS-L_{PR}) of e^+/e^- (^{11}C decays emiting β^+) based on the difference of the scintillation time profile for e^- and e^+ due to:
  - 50% of e^+ annihilation is delayed by ortho-positronium formation (τ~3 ns);
  - e^+ energy deposit is not point-like because of the two annihilation gammas;



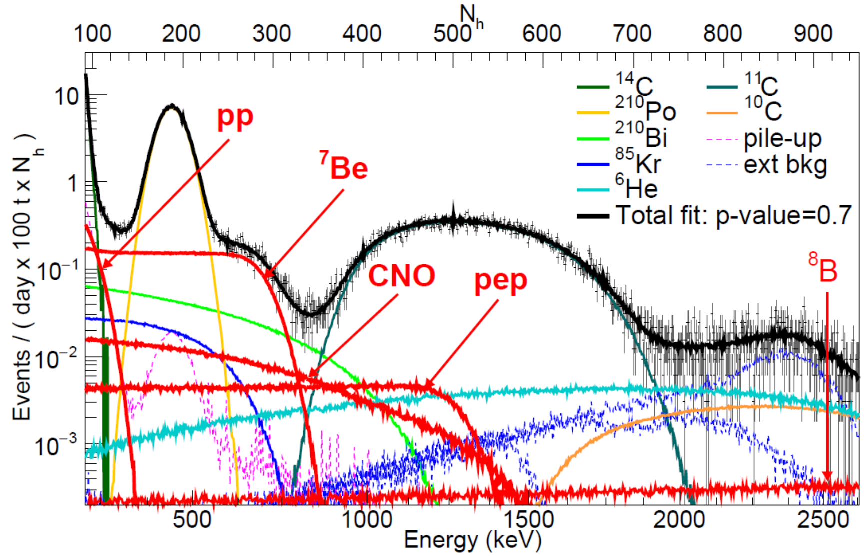
- (3) Radial distribution (allows to separate external backgrounds from uniformly distributed signals);

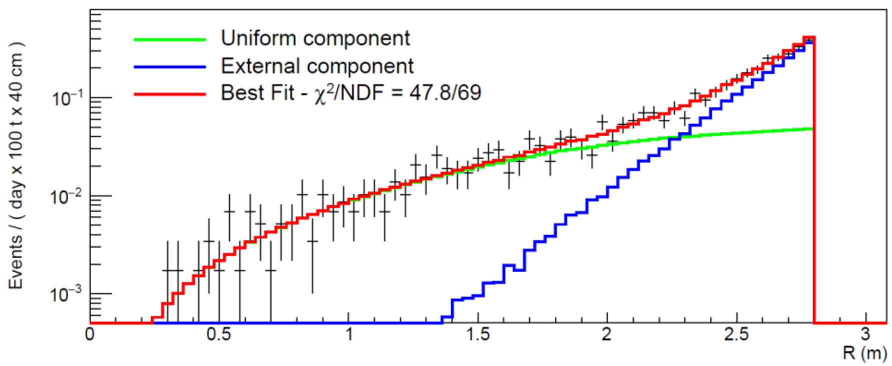
Multivariate fit example

$L(^{11}C_{sub})$

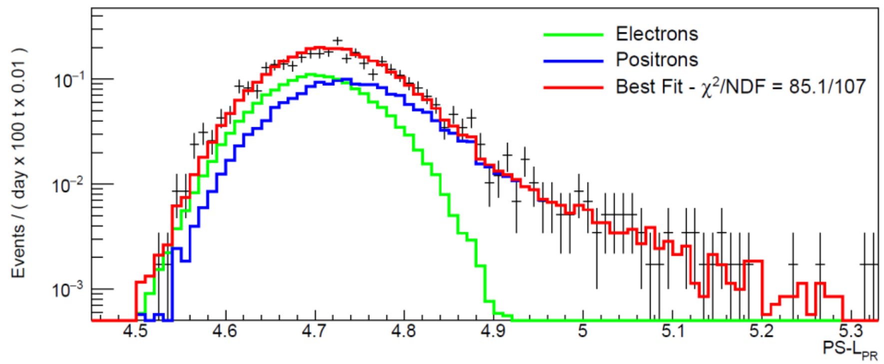


$L(^{11}C_{tag})$





L(Rad)

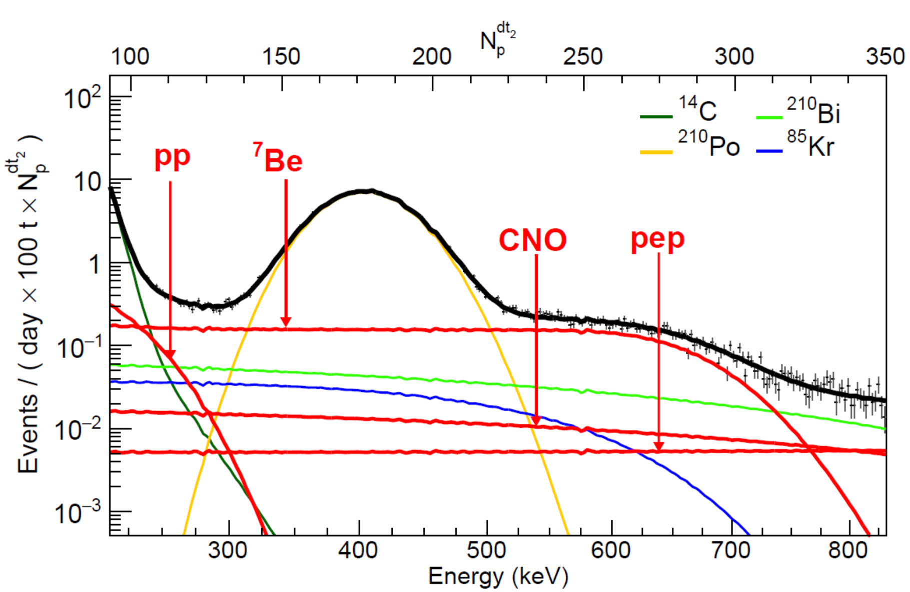


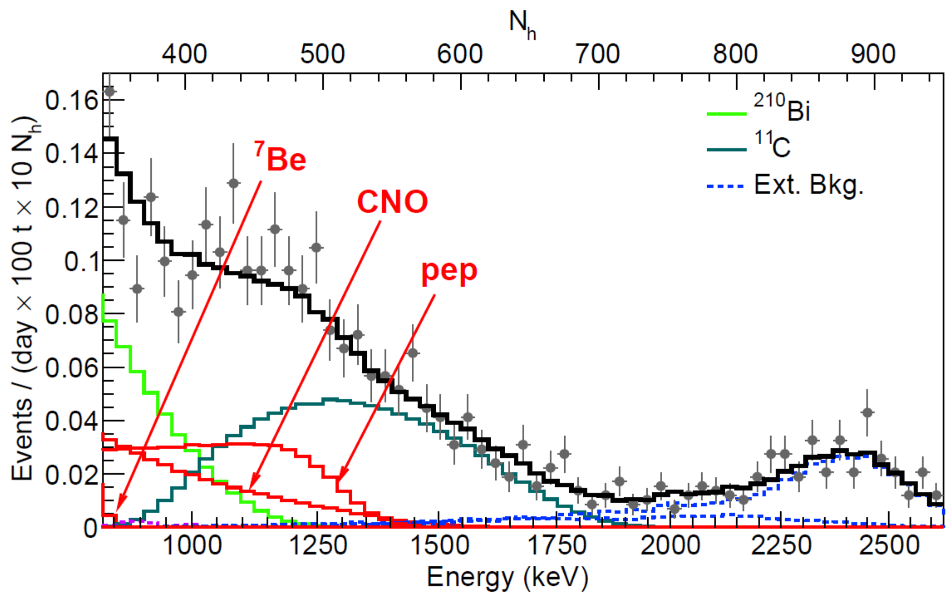
L(PS)

Multivariate fit is sensitive to pp, ^{7}Be and pep contributions

CNO neutrinos are included in the fit, but the sensitivity is limited because of energy spectrum degeneracy with similarity to ^{210}Bi

CNO (MSW/LMA):
HZ: (4.92±0.55) cpd/100t
LZ: (3.52±0.37) cpd/100t





In this plot pep-neutrino characteristic shoulder is made visible by applying more stringent cuts (R<2.8 m and L_{PS}<4.8)

Results

arXiv : 1707.09279

- **Data-set:** Dec 14th 2011- May 21st 2016
- **Total exposure**: 1291.51 days x 71.3 tons
- **Fit range**: (0.19-2.93) MeV

Solar ν	Borexino experimental results		B16(GS98)-HZ		B16(AGSS09)-LZ	
	Rate [cpd/100 t]	Flux [$cm^{-2}s^{-1}$]	Rate [cpd/100 t]	Flux [$cm^{-2}s^{-1}$]	Rate [cpd/100 t]	Flux [$cm^{-2}s^{-1}$]
pp	$134 \pm 10\, ^{+6}_{-10}$	$(6.1 \pm 0.5\, ^{+0.3}_{-0.5}) \times 10^{10}$	131.0 ± 2.4	$5.98\,(1 \pm 0.006) \times 10^{10}$	132.1 ± 2.3	$6.03\,(1 \pm 0.005) \times 10^{10}$
^{7}Be	$48.3 \pm 1.1\, ^{+0.4}_{-0.7}$	$(4.99 \pm 0.13\, ^{+0.07}_{-0.10}) \times 10^9$	47.8 ± 2.9	$4.93\,(1 \pm 0.06) \times 10^9$	43.7 ± 2.6	$4.50\,(1 \pm 0.06) \times 10^9$
pep (HZ)	$2.43 \pm 0.36\, ^{+0.15}_{-0.22}$	$(1.27 \pm 0.19\, ^{+0.08}_{-0.12}) \times 10^8$	2.74 ± 0.05	$1.44\,(1 \pm 0.009) \times 10^8$	2.78 ± 0.05	$1.46\,(1 \pm 0.009) \times 10^8$
pep (LZ)	$2.65 \pm 0.36\, ^{+0.15}_{-0.24}$	$(1.39 \pm 0.19\, ^{+0.08}_{-0.13}) \times 10^8$	2.74 ± 0.05	$1.44\,(1 \pm 0.009) \times 10^8$	2.78 ± 0.05	$1.46\,(1 \pm 0.009) \times 10^8$
CNO	< 8.1 (95% C.L.)	$< 7.9 \times 10^8$ (95% C.L.)	4.91 ± 0.56	$4.88\,(1 \pm 0.11) \times 10^8$	3.52 ± 0.37	$3.51\,(1 \pm 0.10) \times 10^8$

Backgrounds

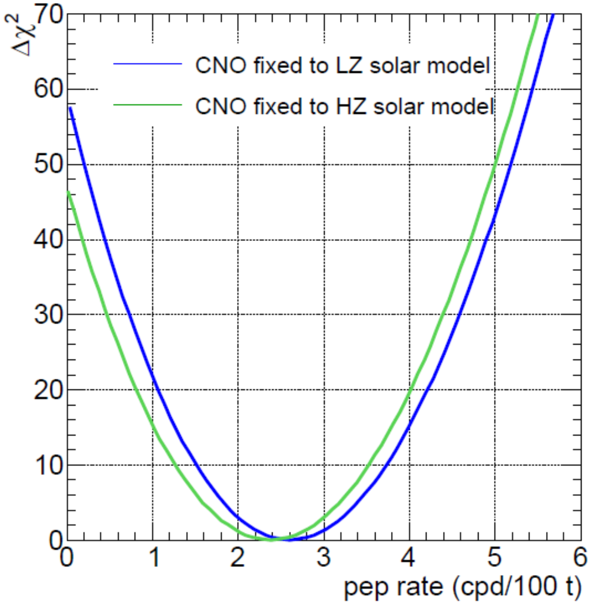
Background	Rate [cpd/100 t]
^{14}C [Bq/100 t]	40.0 ± 2.0
^{85}Kr	6.8 ± 1.8
^{210}Bi	17.5 ± 1.9
^{11}C	26.8 ± 0.2
^{210}Po	260.0 ± 3.0
Ext. ^{40}K	1.0 ± 0.6
Ext. ^{214}Bi	1.9 ± 0.3
Ext. ^{208}Tl	3.3 ± 0.1

Systematics

Source of uncertainty	*pp* −%	*pp* +%	^{7}Be −%	^{7}Be +%	*pep* −%	*pep* +%	
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	-4.5	0.5	-1.0	0.2	-6.8	2.8	^{210}Bi, E-scale, response
Inclusion of ^{85}Kr constraint	-2.2	2.2	0	0.4	-3.2	0	**R(^{85}Kr)<7.5 @ 95%**
Live Time	-0.05	0.05	-0.05	0.05	-0.05	0.05	**LS mass** (Live Time, Scintillator density, Fiducial volume)
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	

Results highlights

>5σ evidence of pep signal (including systematics)



	Earlier result (cpd/100t)	Actual result (cpd/100t)	Precision
pp	144±13±10	$134 \pm 10^{+6}_{-10}$	11→10%
^{7}Be(*)	$46.0 \pm 1.5^{+1.6}_{-1.5}$	$46.3 \pm 1.1^{+0.4}_{-0.7}$	4.7→2.7%
pep	3.1±0.6±0.3	(HZ) $2.43 \pm 0.36^{+0.15}_{-0.22}$ (LZ) $2.65 \pm 0.36^{+0.15}_{-0.24}$	22→16%

*Result for ^{7}Be 862 keV line is quoted

Solar luminosity: $L_\nu^{Borexino} = (3.9 \pm 0.4) \times 10^{33}$ erg/s, is in agreement with measured photon luminosity $L_\gamma = (3.846 \pm 0.015) \times 10^{33}$ erg/s

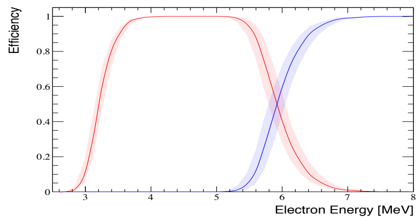
CNO: 95% C.L. limit on CNO rate : R(CNO)<8.1 cpd/100 t
flux : $\varphi(CNO) < 7.9 \cdot 10^8$ cm^{-2}s^{-1}

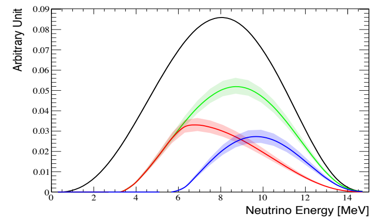
Expected (HZ) 4.92±0.55 (LZ) 3.52±0.37 cpd/100 t (2σ apart)

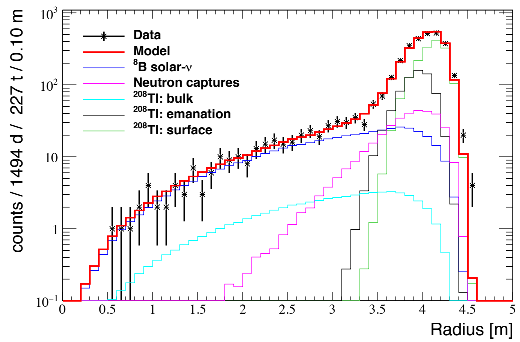
Improved measurement of ^{8}B

What is improved in analysis:

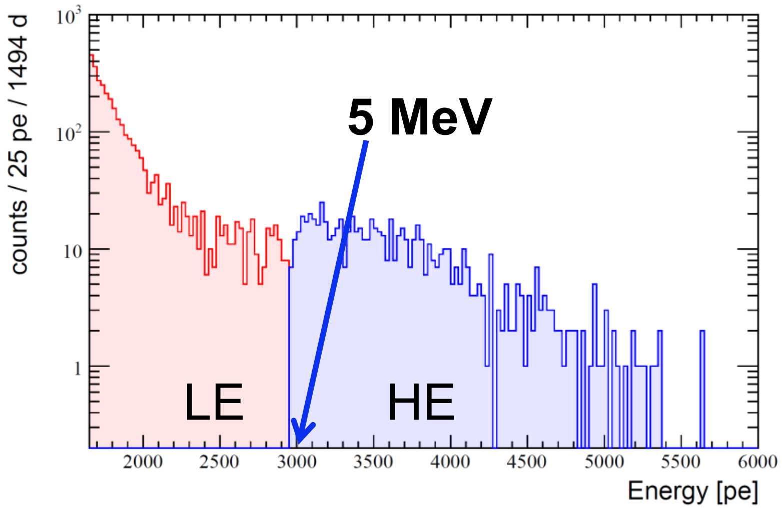
- better understanding of backgrounds (external γs, cosmogenic)
- No FV cut: 1.5 ktons·yr exposure between 2008 and 2016 (x11.5 of the Phase I analysis)
- Lowest energy threshold among real time detectors
- Identified new source of background due to n capture on C and Fe
- New estimate of the cosmogenic ^{11}Be







> 3 MeV visible energy



arXiv:1709.00756

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

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

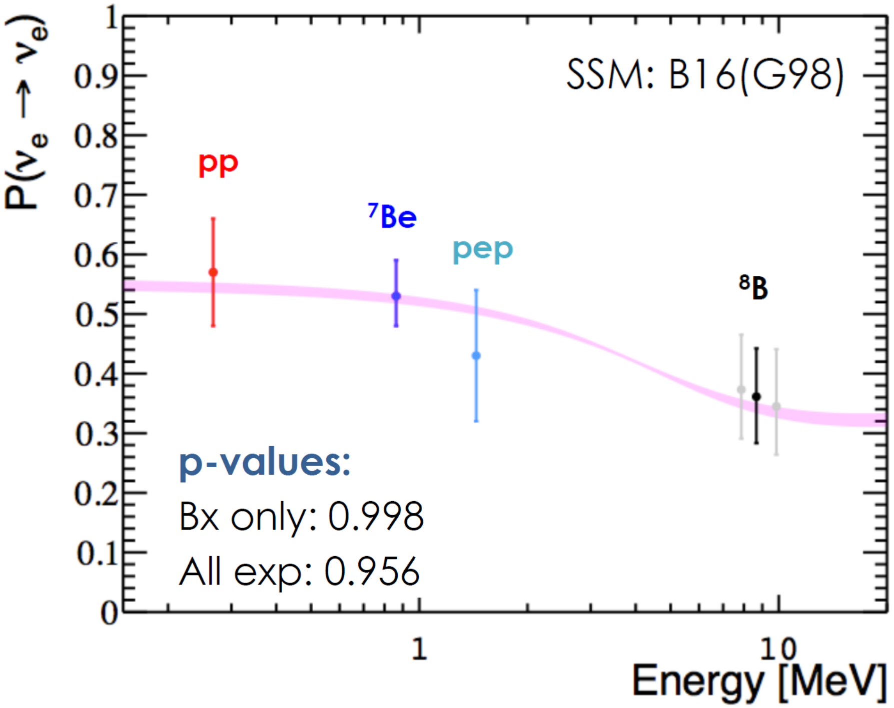
$$R_{LE+HE} = 0.220^{+0.015}_{-0.016}\,(stat)\,^{+0.006}_{-0.006}\,(syst)\ \mathrm{cpd}/100\,\mathrm{t}.$$

Expected rate in the LE+HE range:
0.211± 0.025 cpd/100 t
Assuming B16(G98) SSM and MSW+LMA

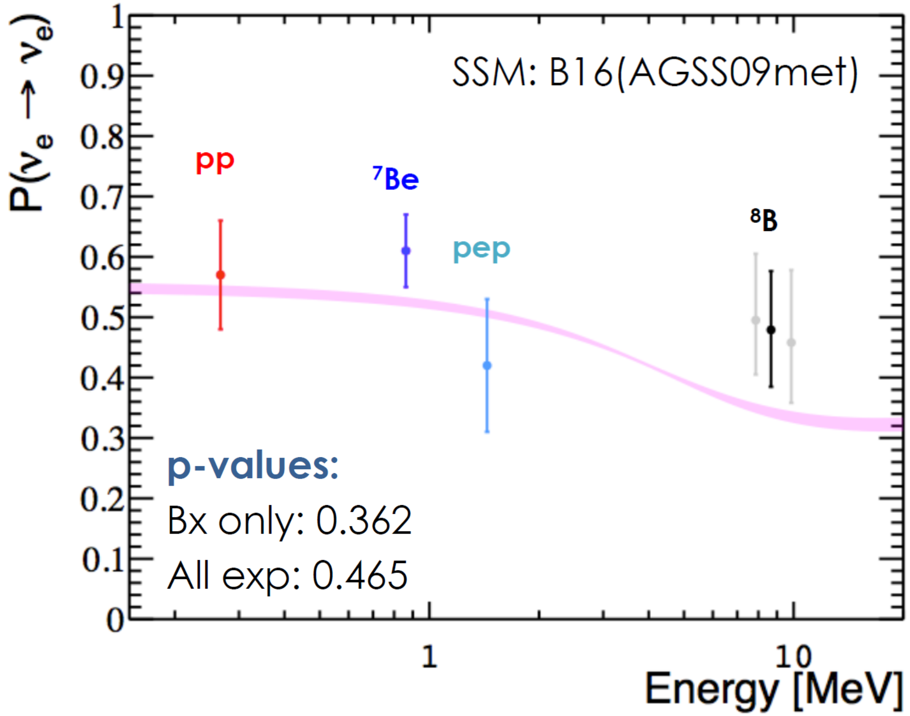
φ(hep)<2.2 × 10^{5} cm^{-2} s^{-1} (90% C.L.)
vs 7.98/8.25 × 10^{3} in HZ/LZ SSM.

MSW-LMA : electron neutrino survival probability

High metallicity SSM



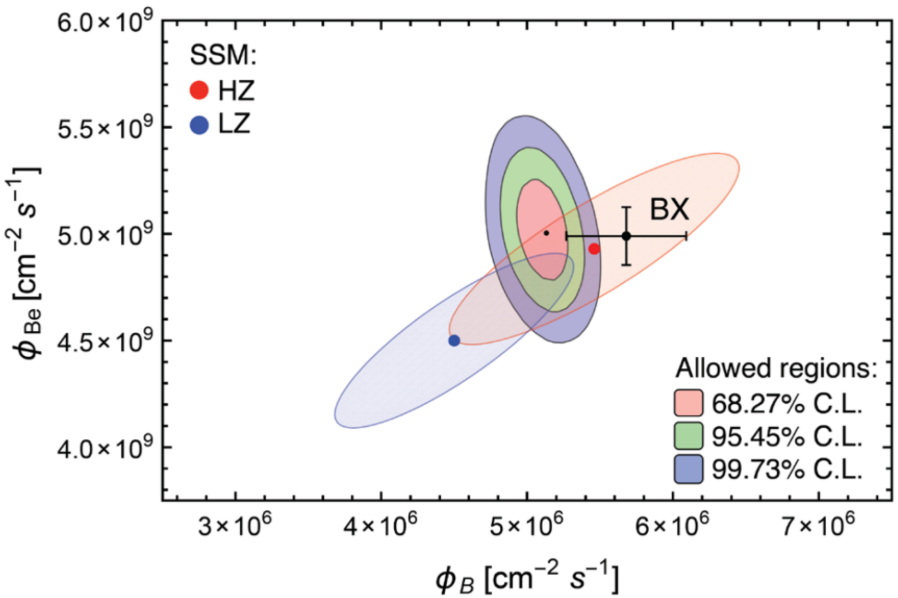
Low metallicity SSM

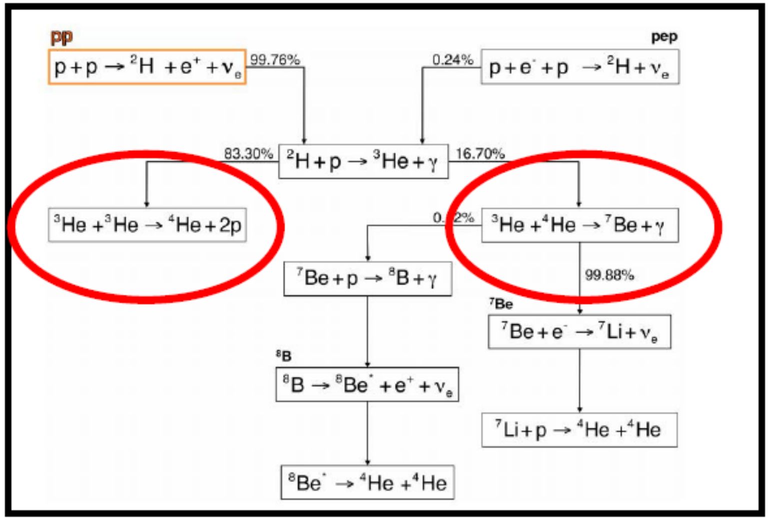


MSW error band is 1σ

Borexino vs SSM

See also A. Serenelli this meeting





- **Global fit to all solar + Kamland data (including the new ^{7}Be result from BX)**

$$f_{Be} = \frac{\Phi(\mathrm{Be})}{\Phi(\mathrm{Be})_{HZ}} = 1.01 \pm 0.03$$

$$f_B = \frac{\Phi(\mathrm{B})}{\Phi(\mathrm{B})_{HZ}} = 0.93 \pm 0.02$$

- **a hint towards the HM :**

LZ is excluded by BX only data at 93% CL

- **theoretical errors are dominating**

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

R(HZ)=0.180±0.011
R(LZ)=0.161±0.010

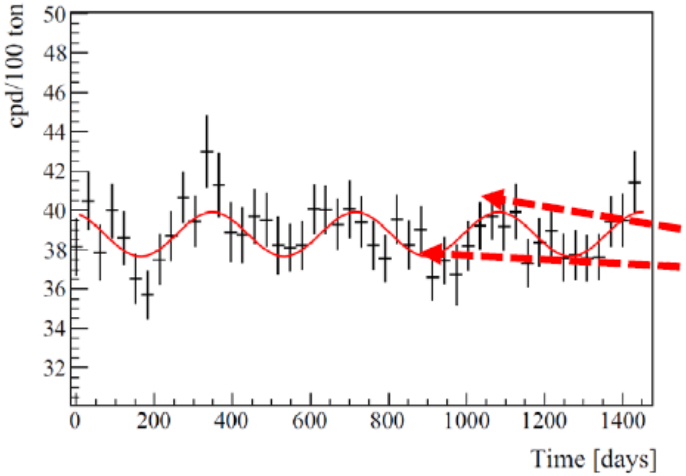
From the pp and ^{7}Be fluxes measurement

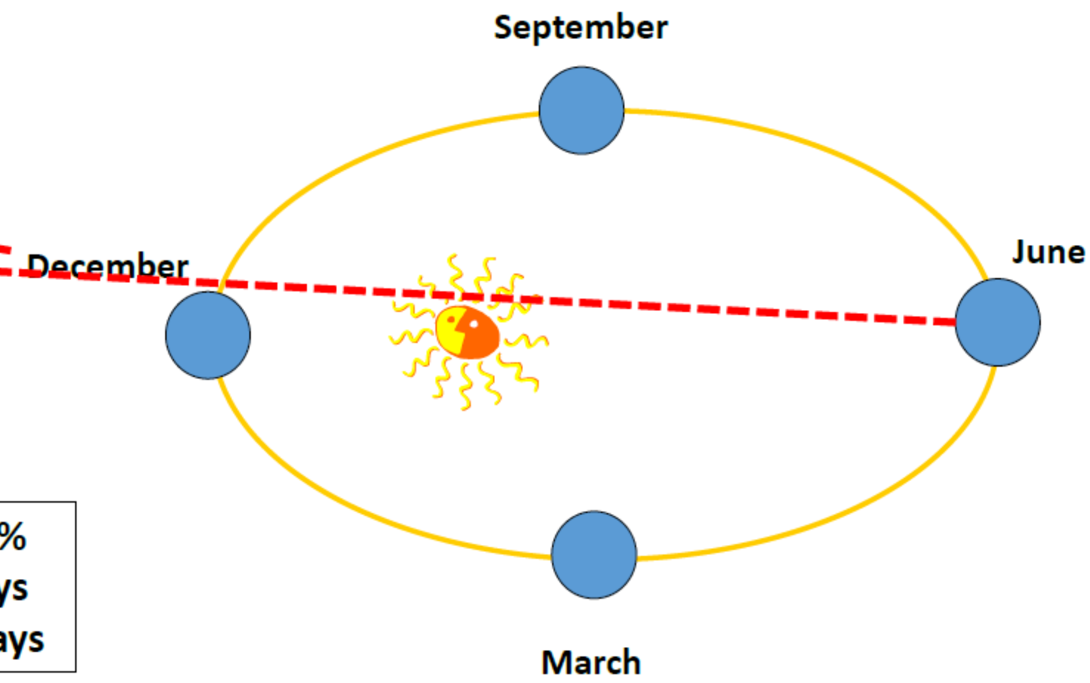
R(BRX)=$0.178^{+0.027}_{-0.023}$

Seasonal modulations of ^{7}Be neutrino flux

Astroparticle Physics 92 (2017) 21–29

ROI is around ^{7}Be shoulder





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

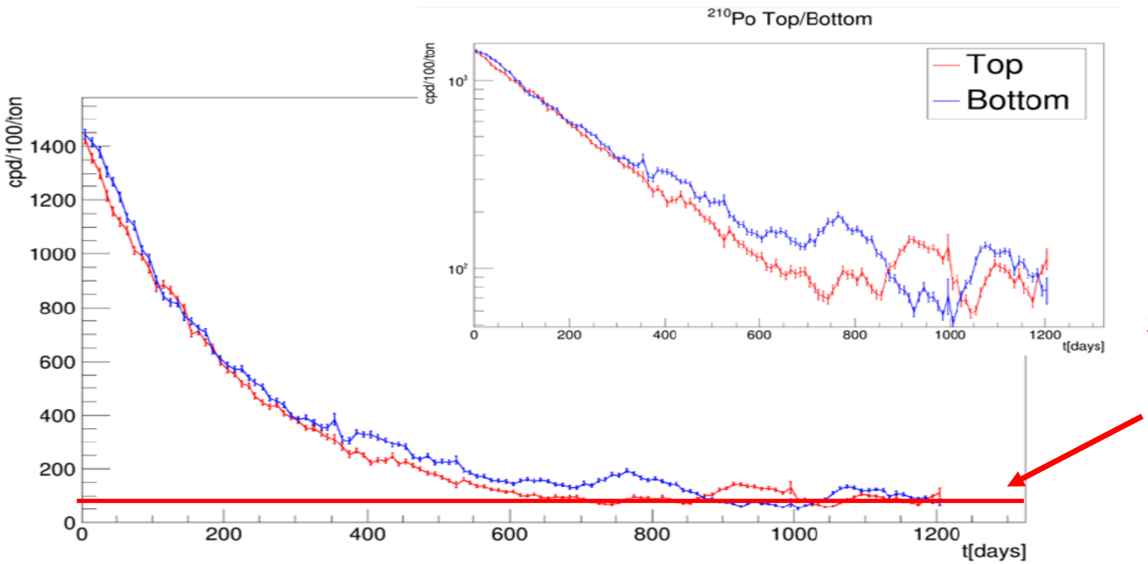
The duration of the astronomical year is measured from underground using neutrino!

Borexino: next goals

- **Goals**:
  - Main: attempt to measure CNO neutrinos with present data
  - Geo-neutrinos: update previous results
  - Rare processes: supernova (watch), neutrino magnetic moment, …
  - Calibration
  - Preparation for a Water Extraction purification with an upgraded plant
    - See F. Calaprice at TAUP 2017
  - measure CNO neutrinos

Strategy for a CNO measurement

- Main background is ^{210}Bi
- With present data: attempt to measure ^{210}Bi supported component from internal ^{210}Pb
  - We have observed ^{210}Po leaching out the nylon vessel and moving into the FV due to convection motions
  - Reduce convection into FV and let ^{210}Po decay to determine supported contribution from ^{210}Pb
  - Supported ^{210}Po activity determines/constraints ^{210}Bi



α/β PSD determines ^{210}Po activity

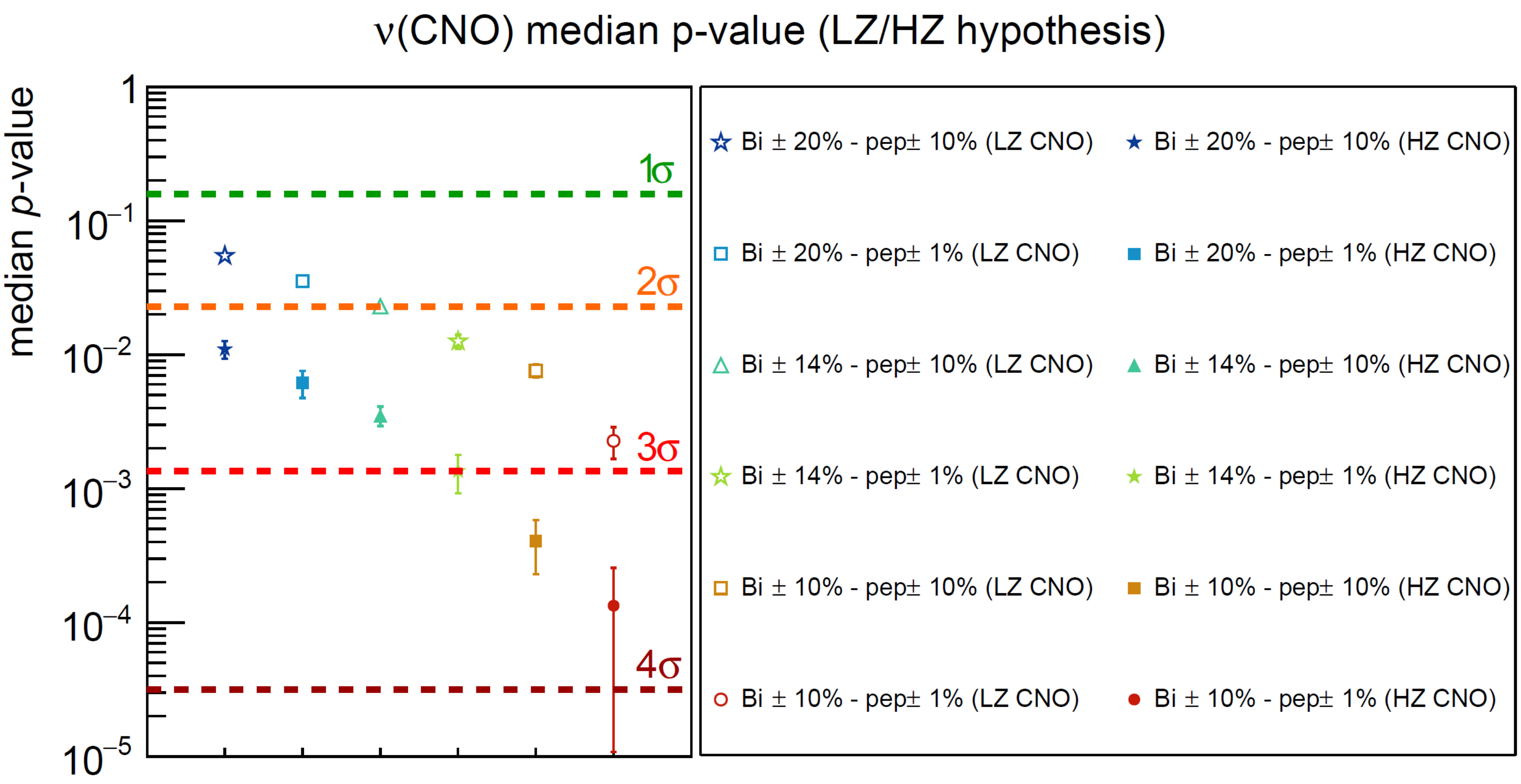
supported component + residual surface convection

$$R_{po} = (A-B)e^{-t/\tau} + B$$

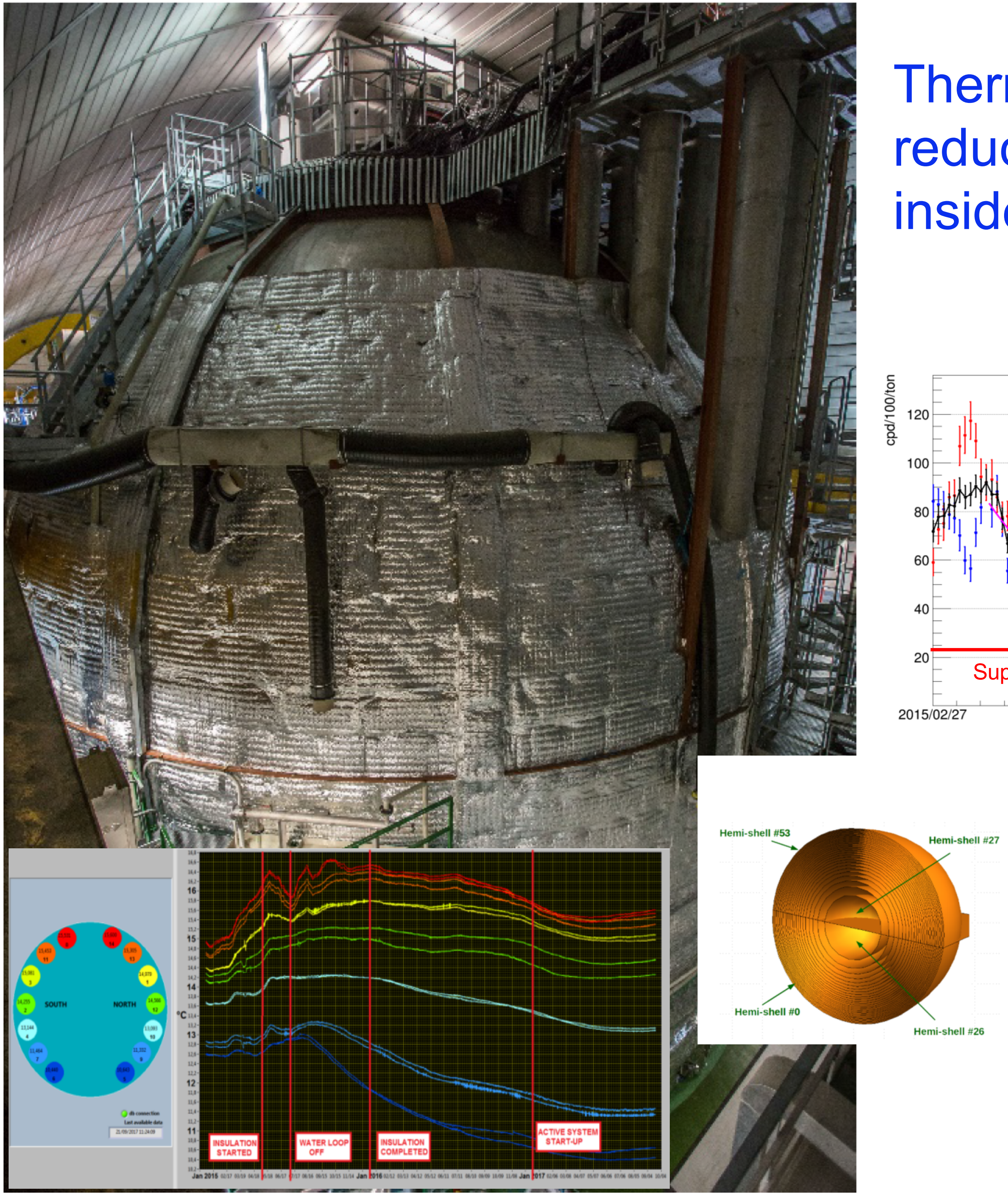
CNO neutrino sensitivity

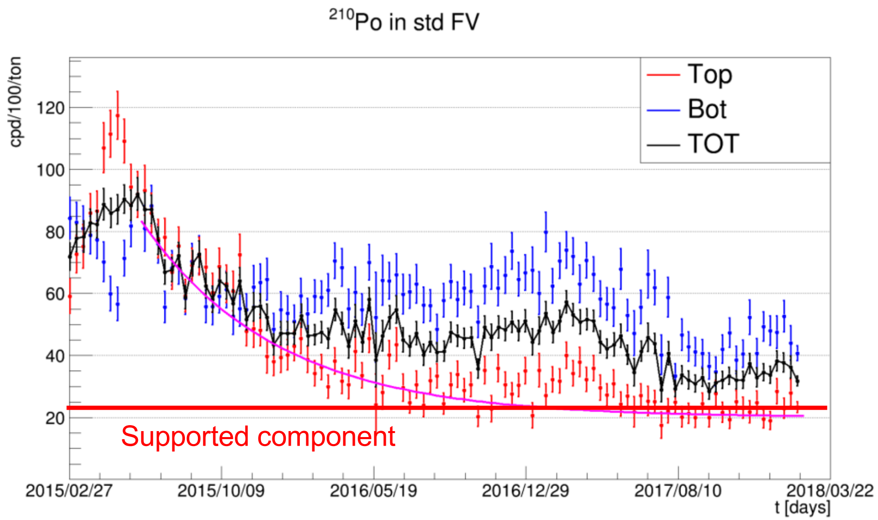
Depends on ^{210}Bi background.

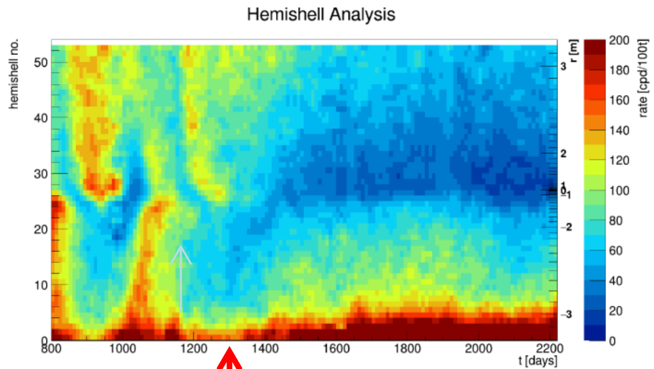
We assume that ^{210}Bi will be measured with 10-20% accuracy



Thermal insulation to reduce convection motion inside the FV







Thermal insulation (summer 2015)

Borexino: next future prospect

- Borexino has measured all neutrinos from the pp-chain

NEXT:

- Exploit thermal insulation to determine/constraint ^{210}Bi
- Improve present thermal insulation
- Set-up underground plants to make water extraction with new purification system
- Plan calibration campaing
- Plan new results on geo-neutrinos and rare processes