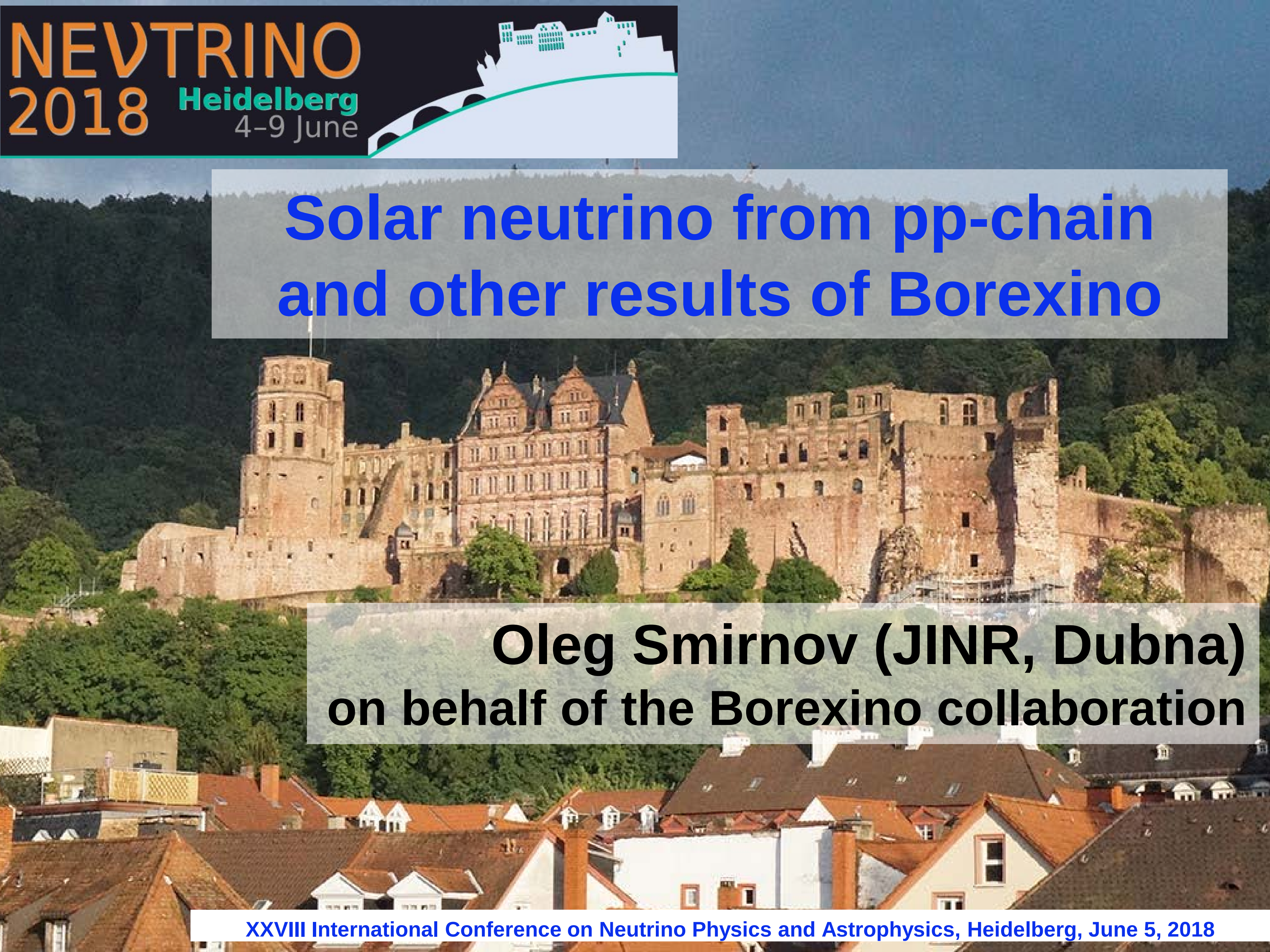

Solar neutrino from pp-chain and other results of Borexino

Oleg Smirnov (JINR, Dubna)
on behalf of the Borexino collaboration

XXVIII International Conference on Neutrino Physics and Astrophysics, Heidelberg, June 5, 2018

Borexino Collaboration

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JAGIELLONIAN UNIVERSITY IN KRAKÓW

JÜLICH FORSCHUNGSZENTRUM

Virginia Tech

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Universität Hamburg

SKOBELTSYN INSTITUTE OF NUCLEAR PHYSICS LOMONOSOV MOSCOW STATE UNIVERSITY

UNIVERSITY OF MASSACHUSETTS AMHERST 1863

Joint Institute for Nuclear Research

GRAN SASSO SCIENCE INSTITUTE — CENTER FOR ADVANCED STUDIES — Istituto Nazionale di Fisica Nucleare

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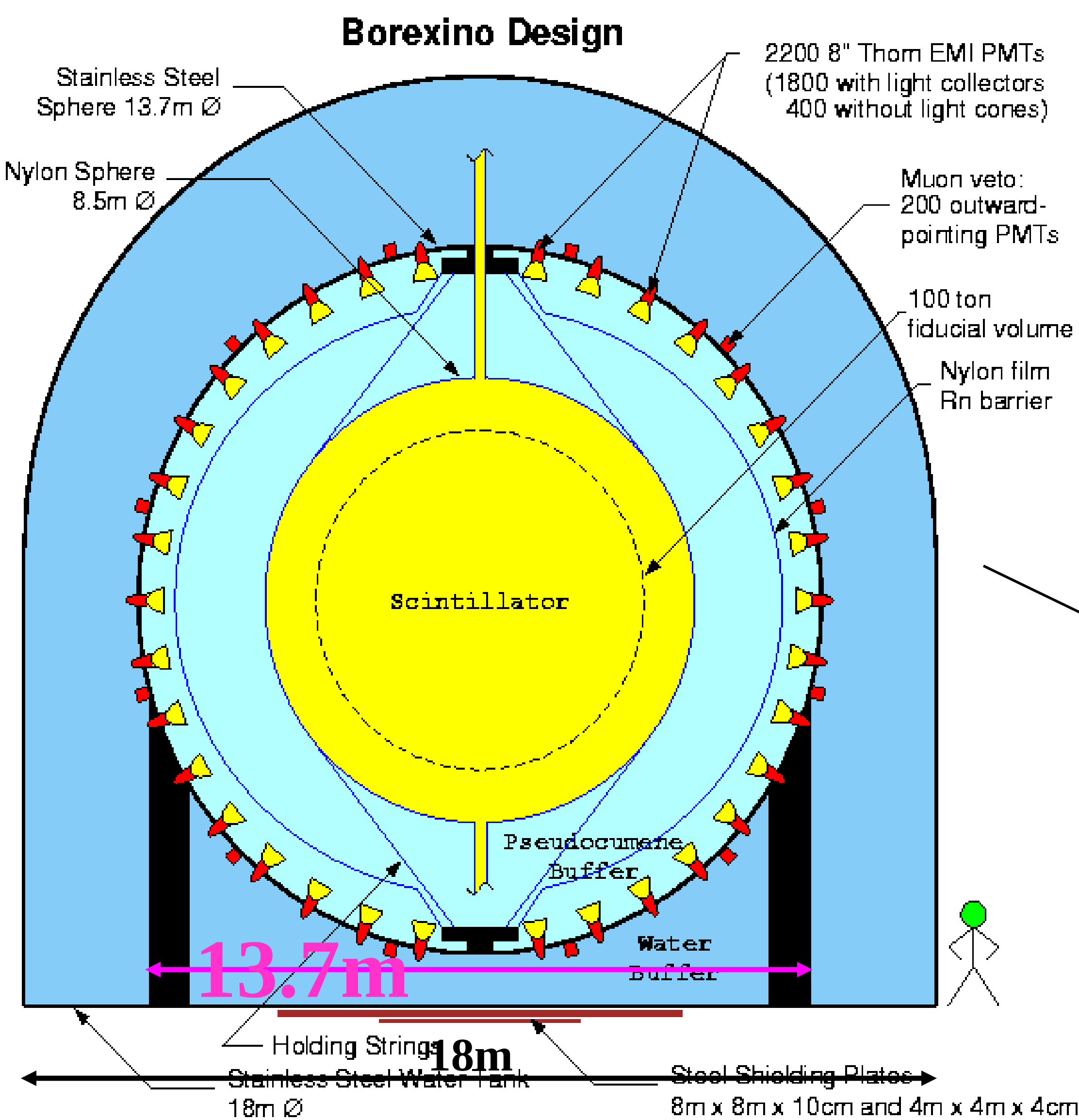
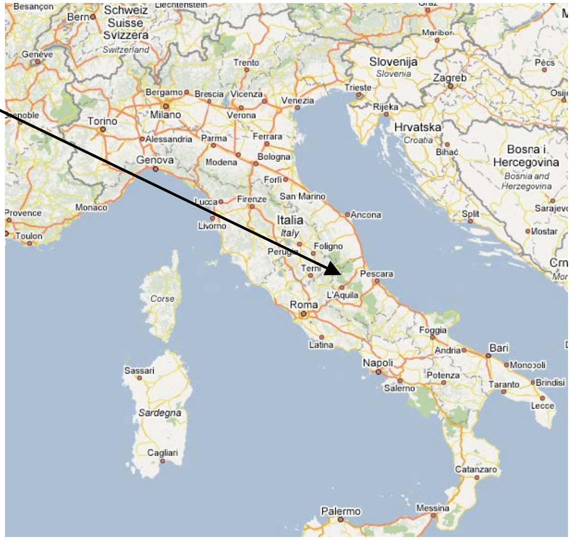
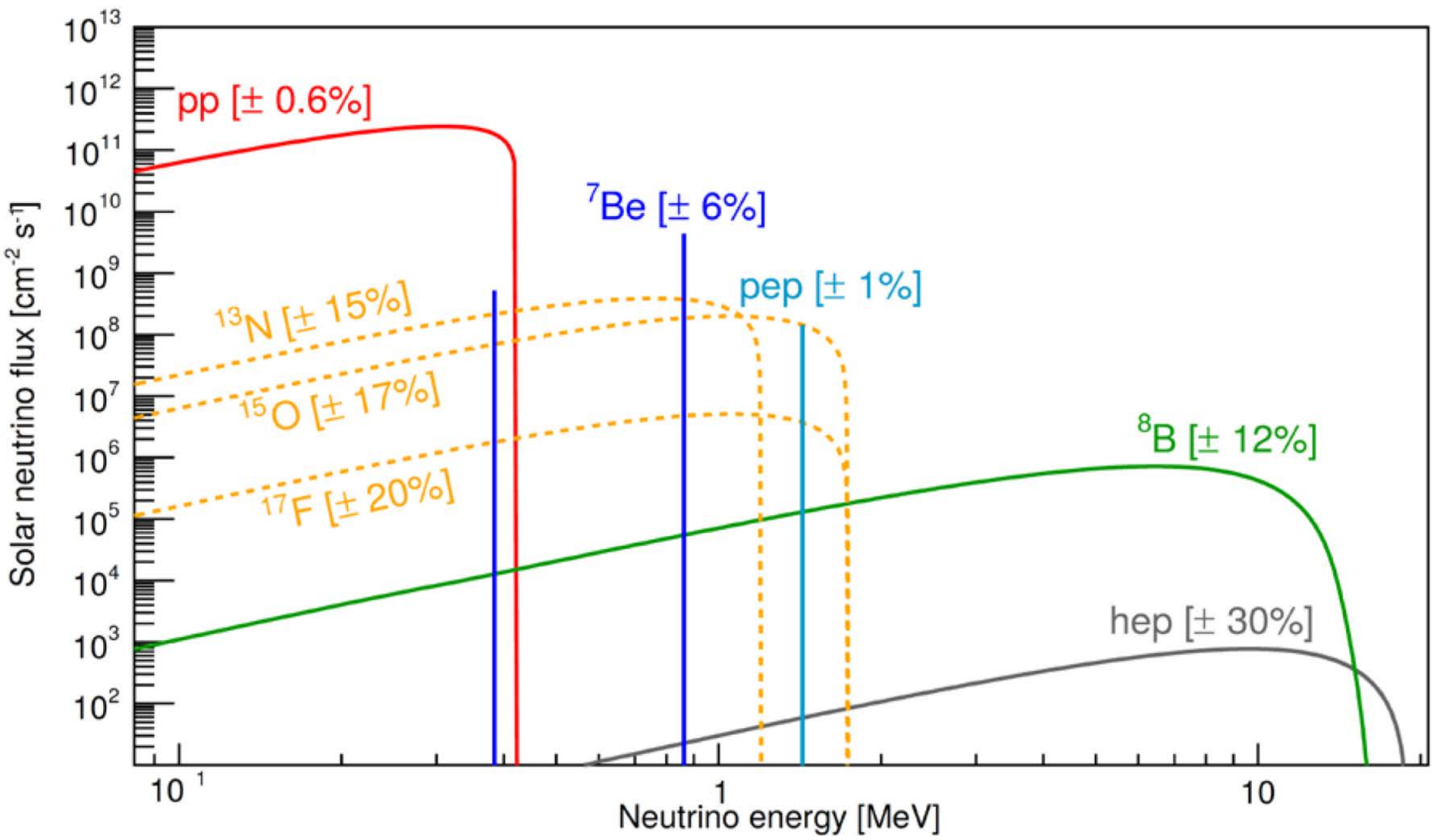
BOREXINO *(in operation from May,2007)*



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



Solar neutrino spectra

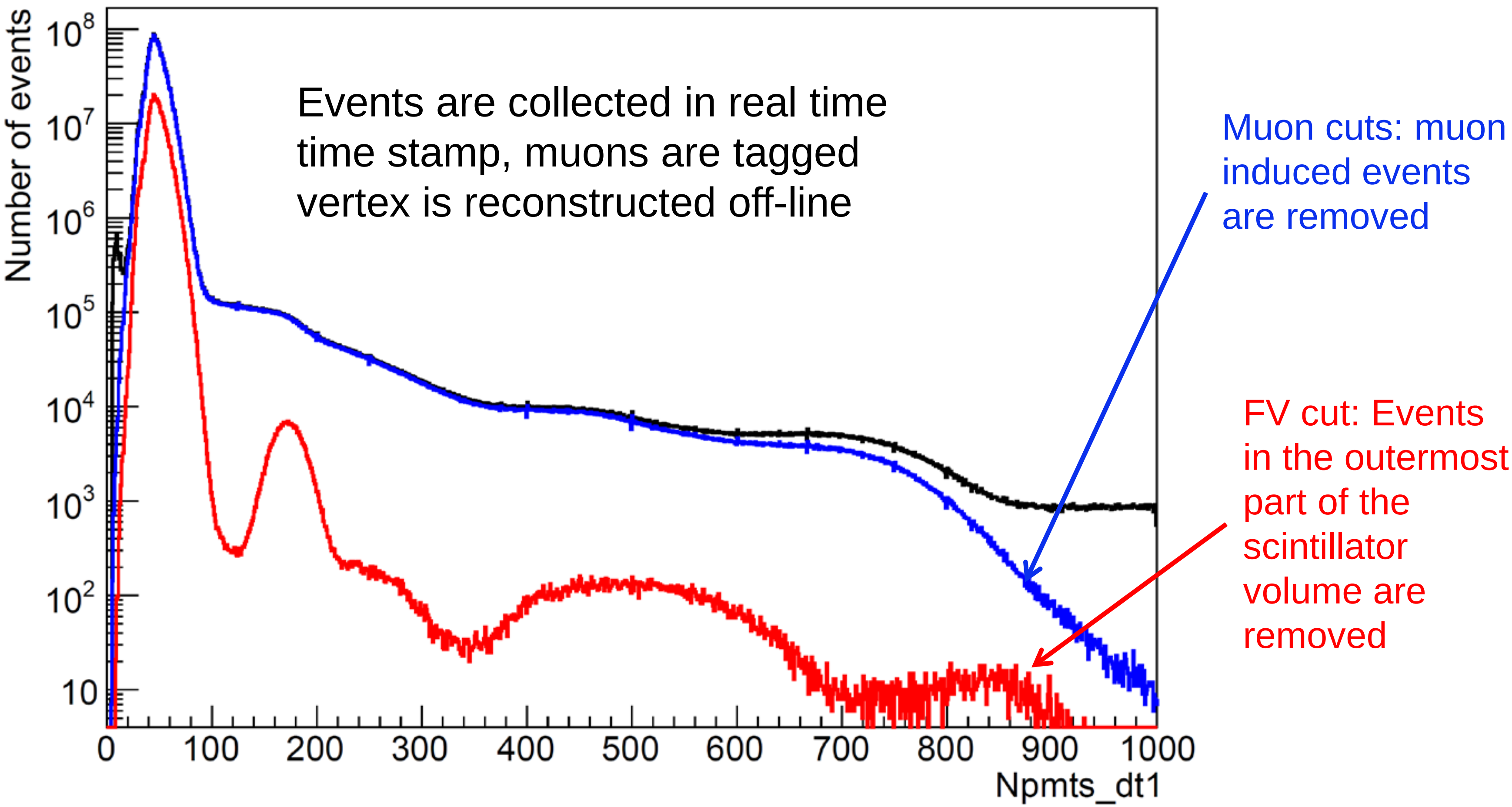


~1 Bq

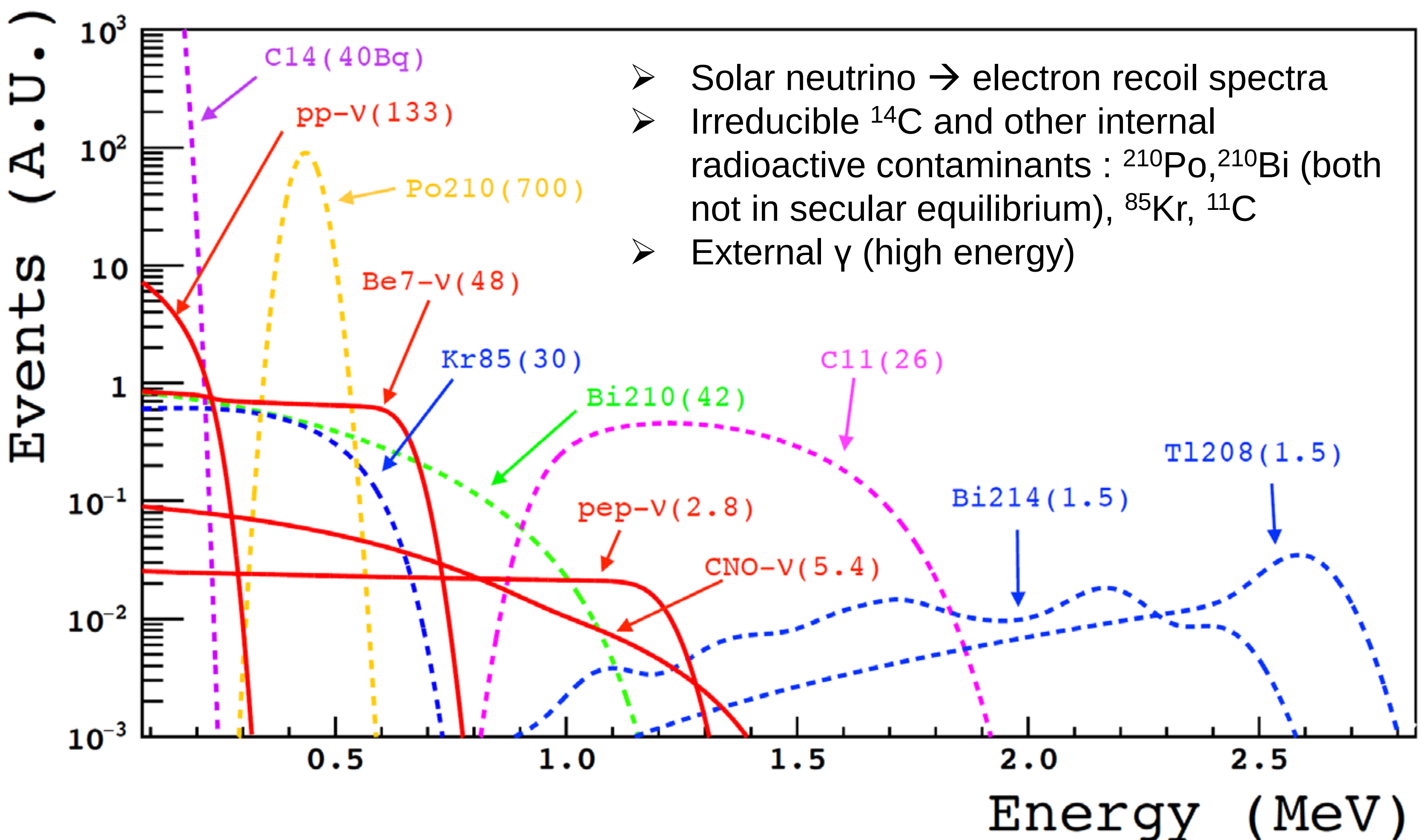
50 events/d/100t expected (ν_e and $\nu_{\mu,\tau}$ elastic scattering on e^-) or $5 \cdot 10^{-9}$ Bq/kg (typically: drinking water ~10 Bq/kg; human body in ^{40}K: 5 kBq)

Low energy->no Cherenkov light->No directionality,
no other tags-> extremely pure scintillator is needed

Data selection for solar neutrino analysis



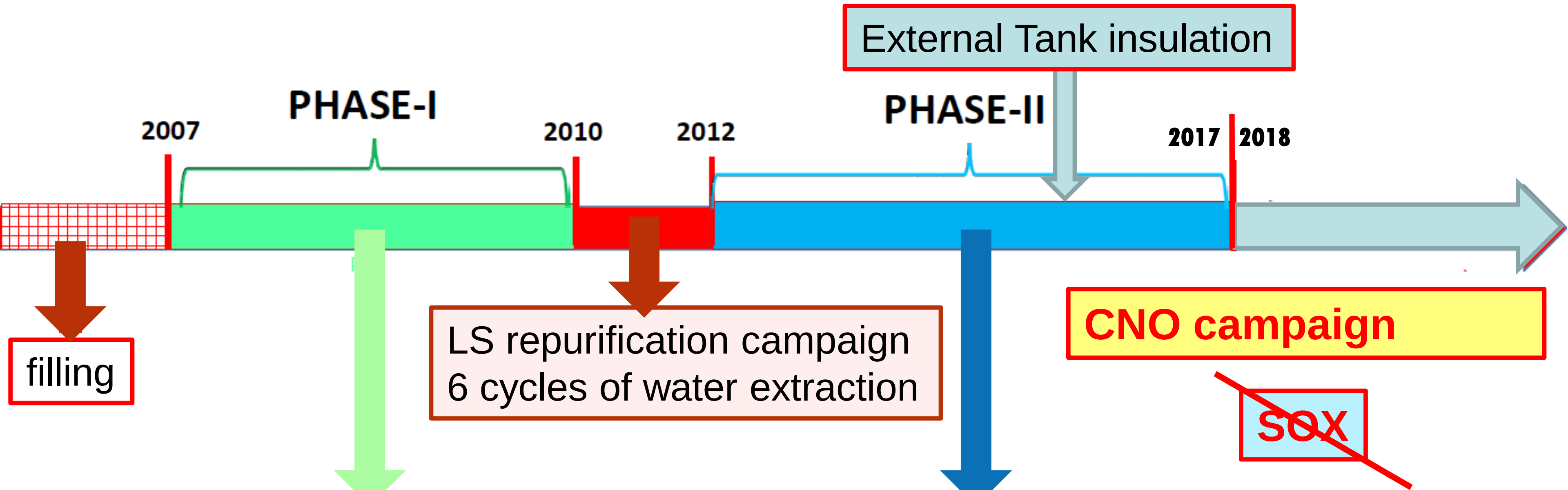
(Expected) contributions to the observed spectrum (MC)



- Solar neutrino → electron recoil spectra
- Irreducible ^{14}C and other internal radioactive contaminants : ^{210}Po,^{210}Bi (both not in secular equilibrium), ^{85}Kr, ^{11}C
- External γ (high energy)

MC input counting rates are quoted in cpd/100 t

Borexino since the start of the data taking

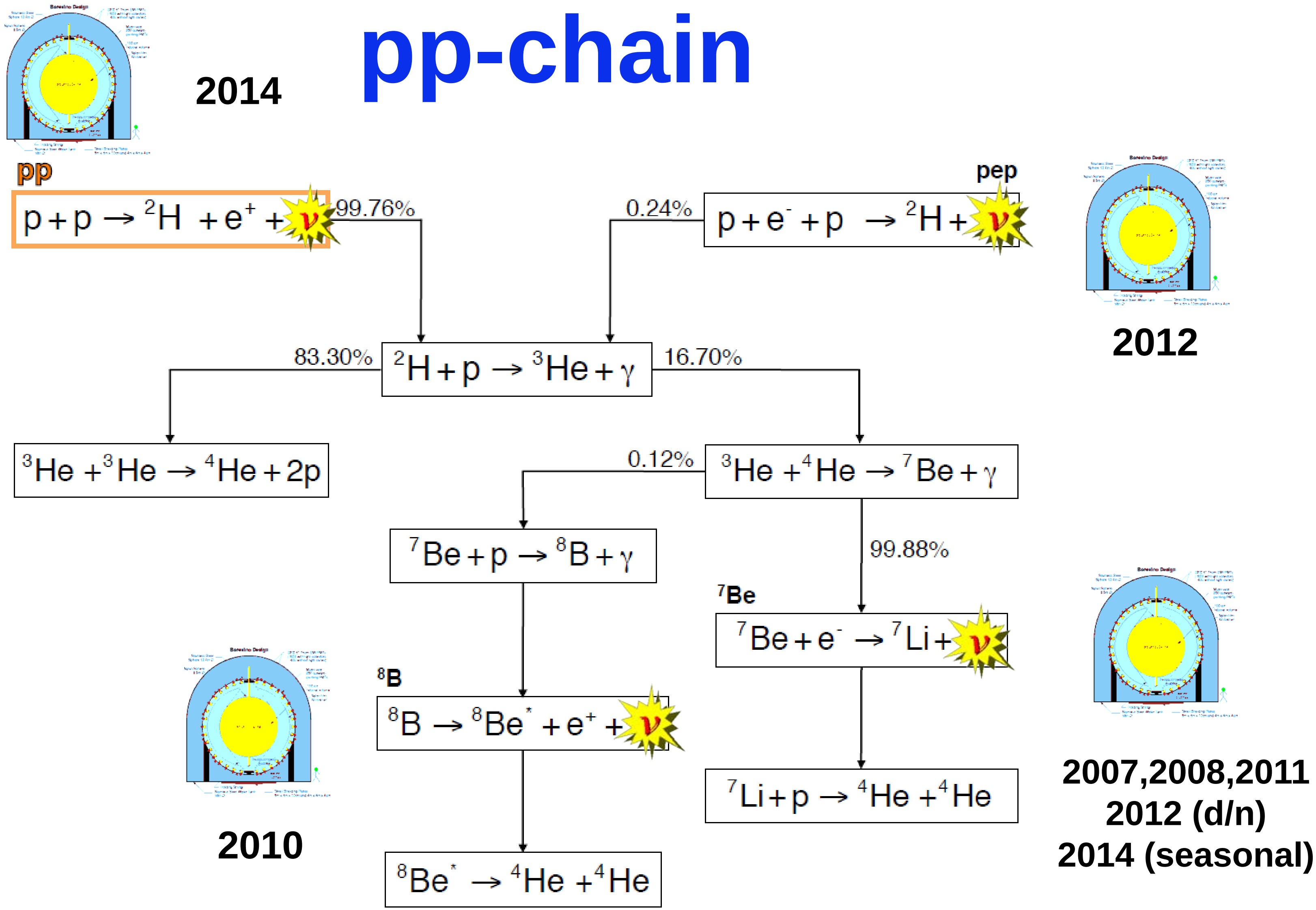


- R(^{7}Be) + D/N
- R(pep) – first observation
- R(^{8}B)– first with LS
- R(CNO) – limit

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

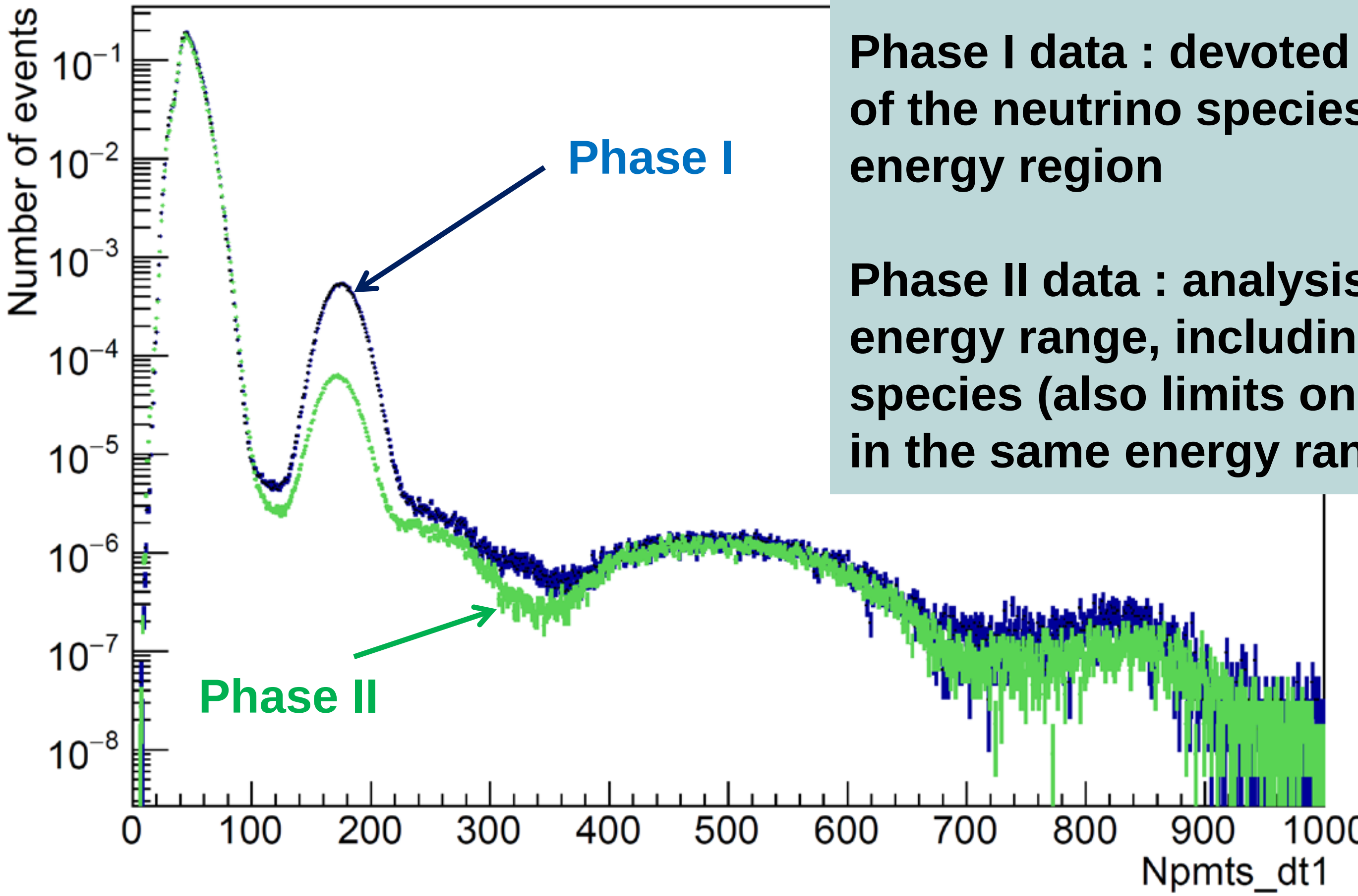
- R(pp)
- Seasonal variations of R(^{7}Be)
- Simultaneous spectroscopy of pp, ^{7}Be and pep ν
- R(^{8}B)–improved
- geo- ν
- ν magnetic moment
- NSI (under study)
- rare processes

pp-chain



2014+ → Phase II data used

Phase I/Phase II



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

Phase I data : devoted analysis for each of the neutrino species with restricted energy region

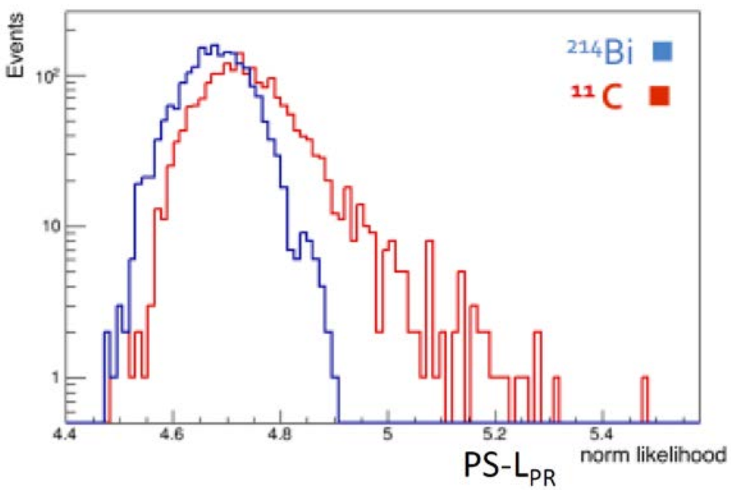
Phase II data : analysis in the extended energy range, including pp, ^{7}Be and pep species (also limits on CNO are obtained in the same energy range)

Multivariate approach

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

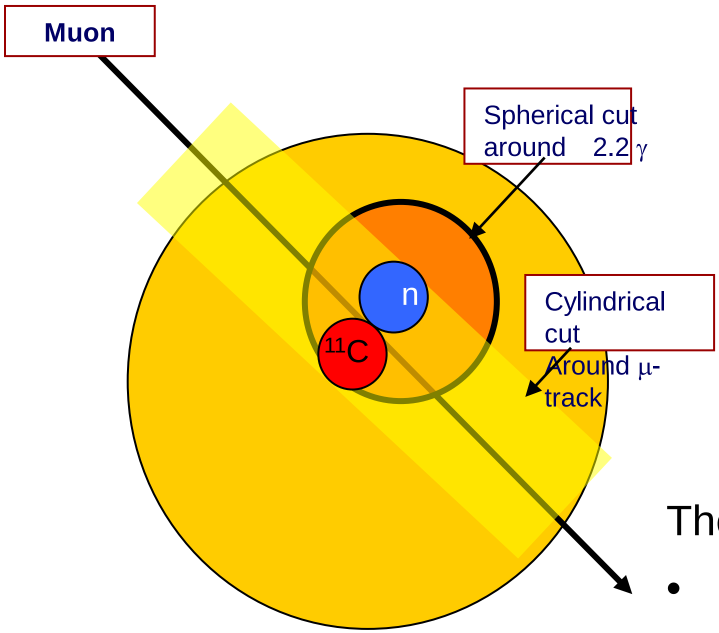
Technique consists in including in the likelihood:

- Energy spectrum split into complementary TFC-tagged (^{11}C enriched) and TFC-subtracted (^{11}C depleted) spectra →next slide for details.
- 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;



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

Three-fold Coincidence technique (TFC) for ^{11}C tagging



^{11}C production in muon interactions is accompanied by neutron:

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

~30 min: $^{11}B + e^{+} + \nu_e$

~250 us: $+p \rightarrow d + \gamma(2.2\ \text{MeV})$

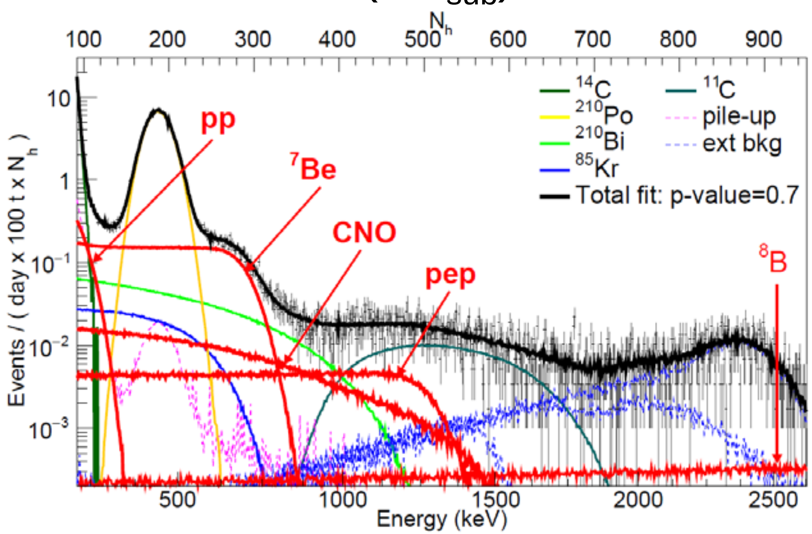
The likelihood for ^{11}C tagging is using:

- distance in space and time from the μ-track;
- distance from the neutron;
- neutron multiplicity;
- muon dE/dx and number of muon clusters in an event

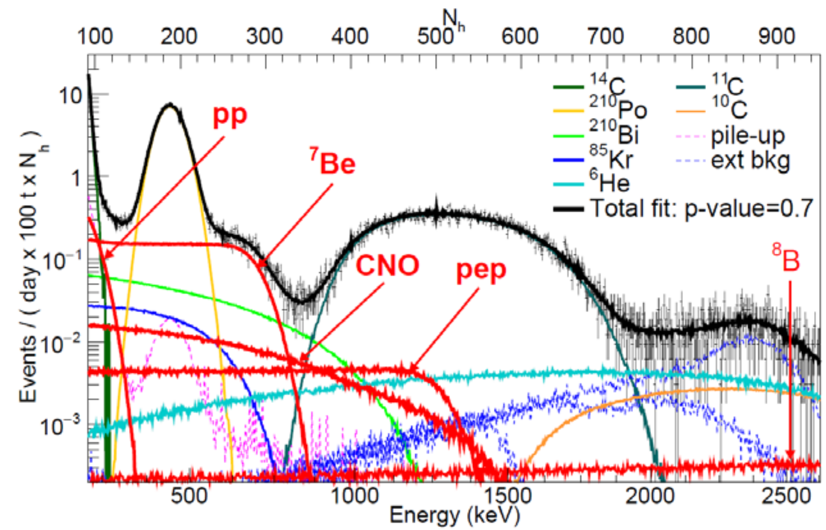
The TFC algorithm has (92±4)% ^{11}C-tagging eciency, while preserving (64.28±0.01)% of the total exposure in the TFC-subtracted spectrum.

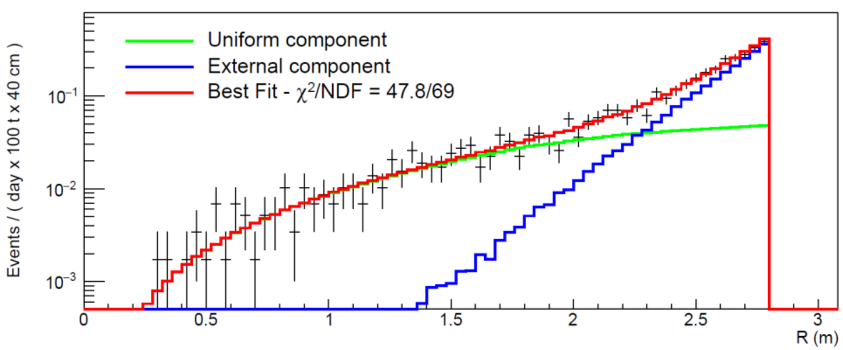
Multivariate fit example

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

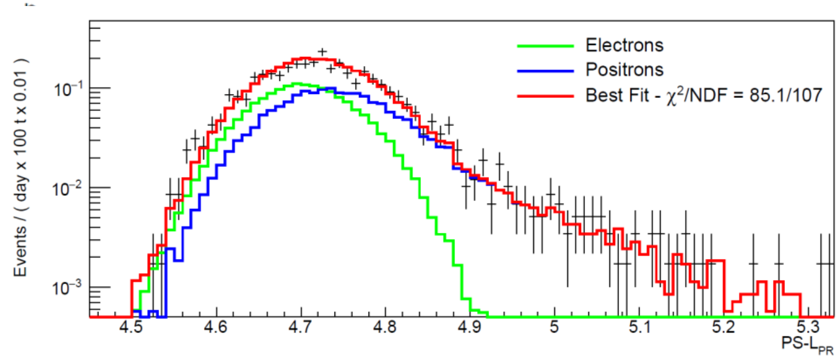


$L(^{11}C_{tag})$ x





L(Rad) x

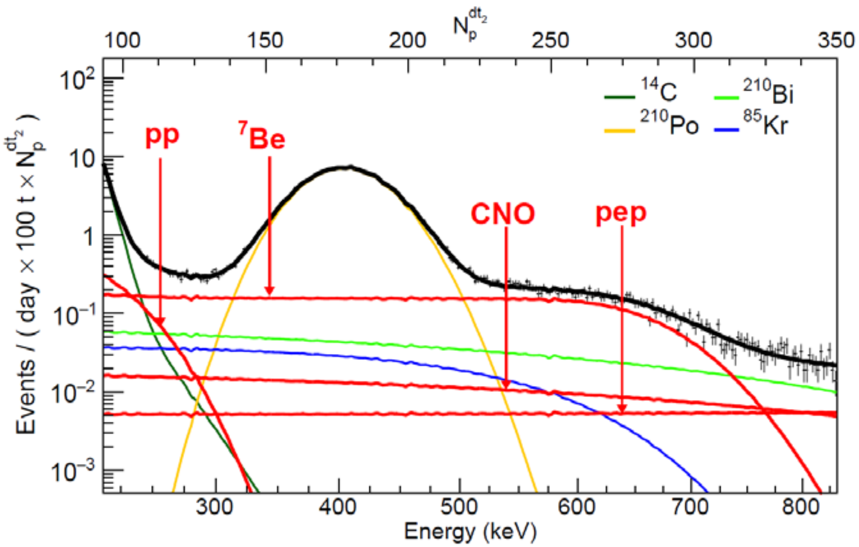


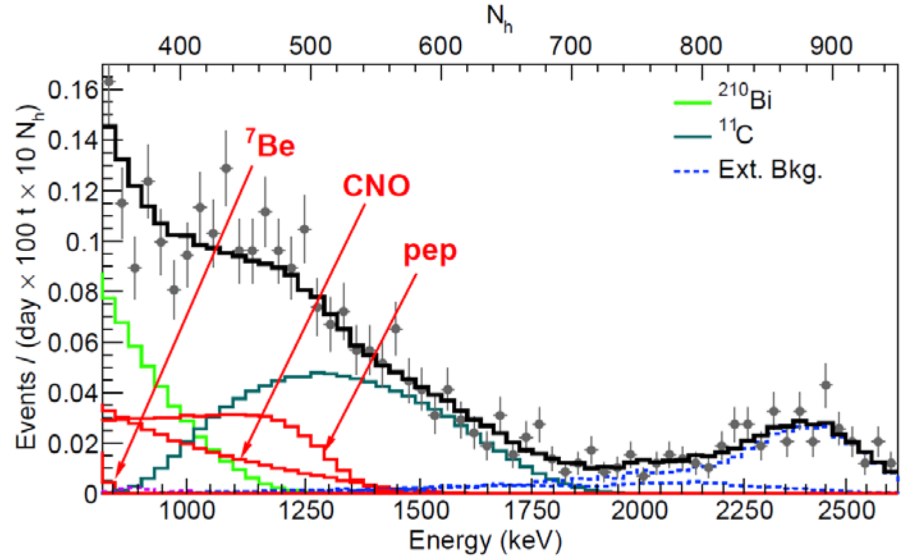
L(PS)

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

Note: CNO-neutrino energies are in the ROI and are included in the fit, but the sensitivity is limited because of the similarity to ^{210}Bi spectrum → pp/pep rates ratio constrained in the fit to the predictions of HZ/LZ models

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





Zoom into low-energy part of the spectrum

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

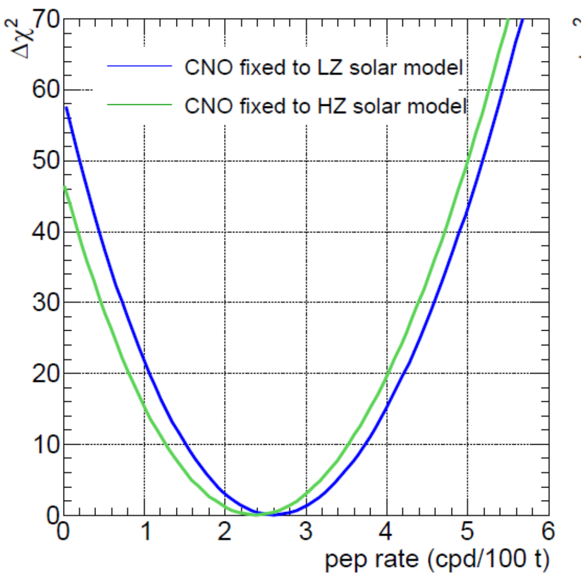
Background	Rate [cpd/100 t]
^{14}C [Bq/100 t]	40.0 ± 2.0
^{85}Kr	6.8 ± 1.8
^{210}Bi	17.5 ± 1.9
^{11}C	26.8 ± 0.2
^{210}Po	260.0 ± 3.0
Ext. ^{40}K	1.0 ± 0.6
Ext. ^{214}Bi	1.9 ± 0.3
Ext. ^{208}Tl	3.3 ± 0.1

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**
Scintillator density	-0.05	0.05	-0.05	0.05	-0.05	0.05	**LS mass**
Fiducial volume	-1.1	0.6	-1.1	0.6	-1.1	0.6	**LS mass**
Total systematics (%)	-7.1	4.7	-1.5	0.8	-9.0	5.6	

What is new

>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%
^{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**
Precision improved by 10,43, and 39% correspondingly in simultaneous fit of all 3 components

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

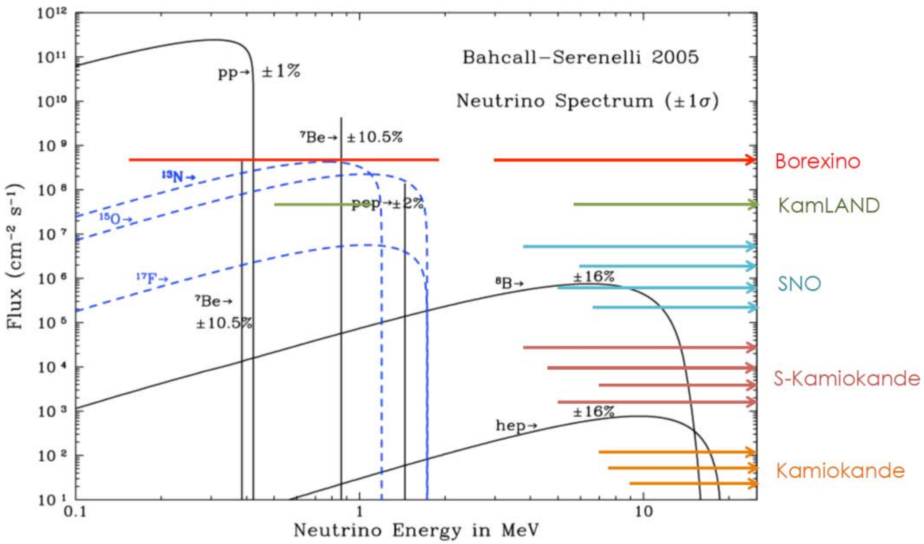
CNO: 95% C.L. limit on CNO rate : R(CNO)<8.1 cpd/100 t
flux : $\varphi(CNO) < 7.9 \cdot 10^{8}$ cm^{-2}s^{-1}

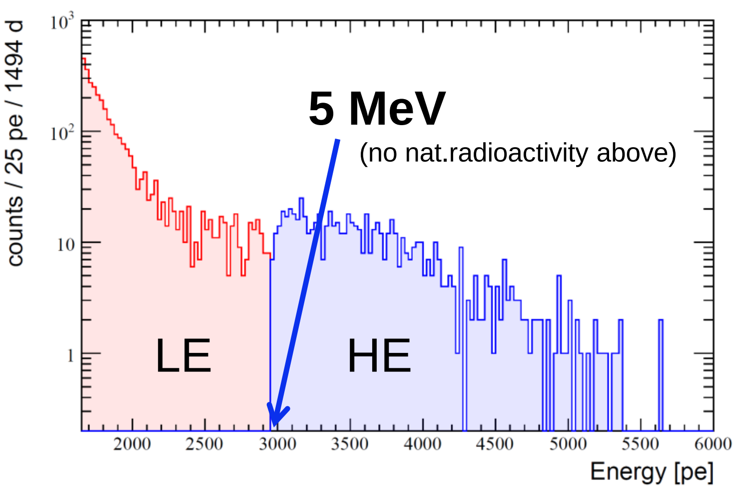
Less stringent constraints on pep in the CNO contribution analysis compared to Phase I

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

Improved measurement of ^{8}B solar neutrinos with 1.5 kt y of Borexino exposure

arXiv:1709.00756





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 RT detectors
- Identified new source of background due to n capture on C and Fe
- New estimate of the cosmodenic ^{11}Be

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

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

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

Expected rate in the LE+HE range:

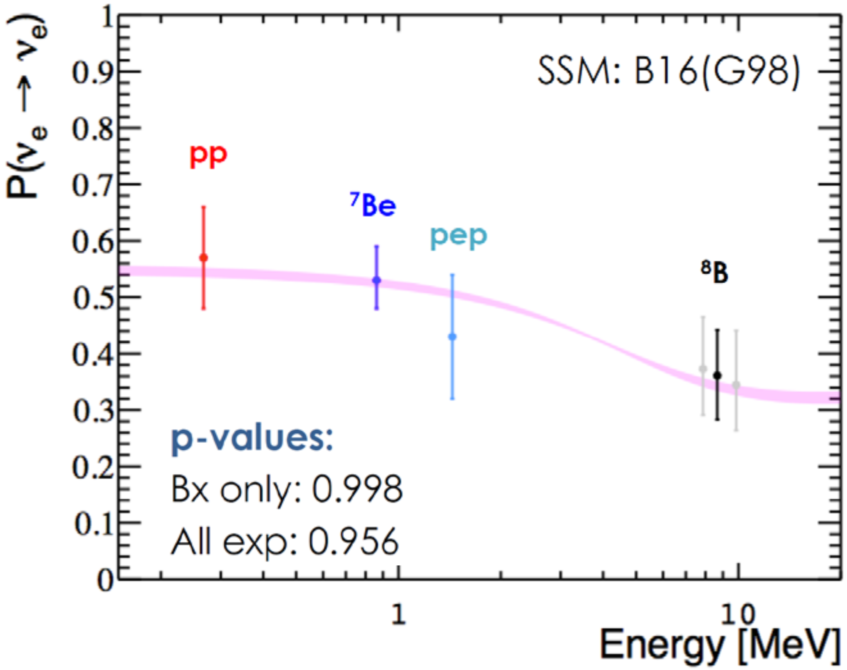
0.211± 0.025 cpd/100 t

Assuming B16(G98) SSM and MSW+LMA

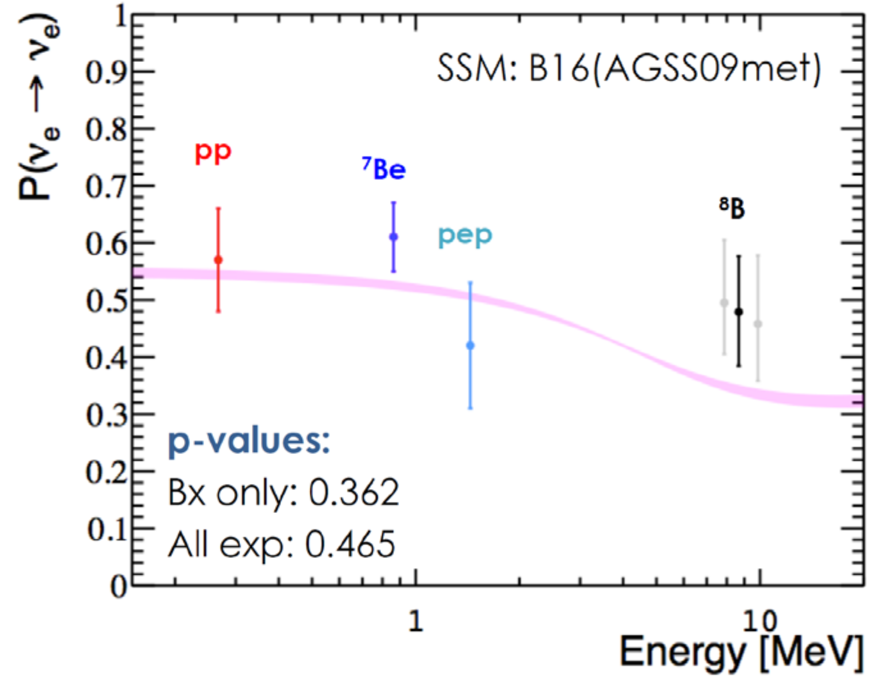
φ(hep)<2.2 × 10^{5} cm^{-2} s^{-1} (90% C.L.) vs 7.98/8.25 × 10^{3} in HZ/LZ SSM.

MSW/LMA : electron neutrino survival probabilities

High metallicity SSM



Low metallicity SSM

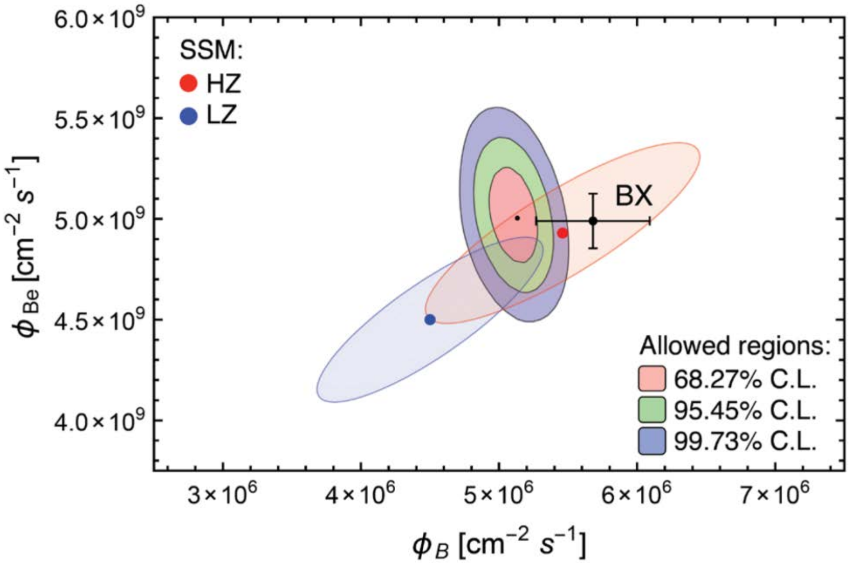


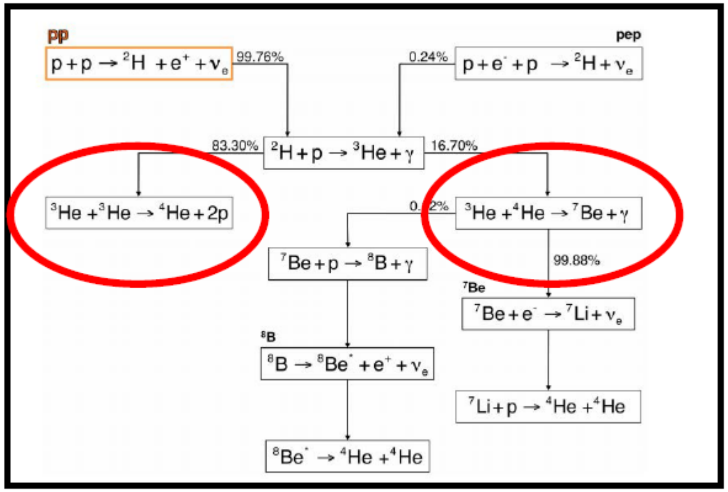
MSW errors (1σ) are shown by rose band

Total error on P_{ee}:

- **for pp and pep neutrinos, contribution of experimental errors dominates (easy to predict, difficult to measure)**
- **for ^{7}Be and ^{8}B theoretical predictions of the Solar model are worse than measurements**

Solar metallicity problem





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

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

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

- **a hint towards the HM :**

  LZ is excluded by BX data at 1.8σ level
- **theoretical errors are dominating**

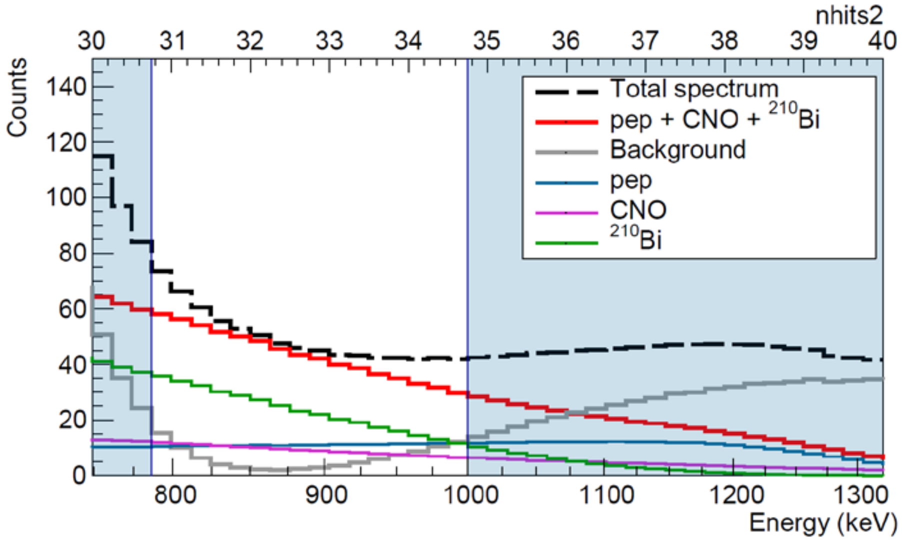
$$R \equiv \frac{<^3\,\text{He} +^4\,\text{He}>}{<^3\,\text{He} +^3\,\text{He}>} = \frac{2\phi(^7\text{Be})}{\phi(\text{pp}) - \phi(^7\text{Be})}$$

R(HZ)=0.180±0.011
R(LZ)=0.161±0.010

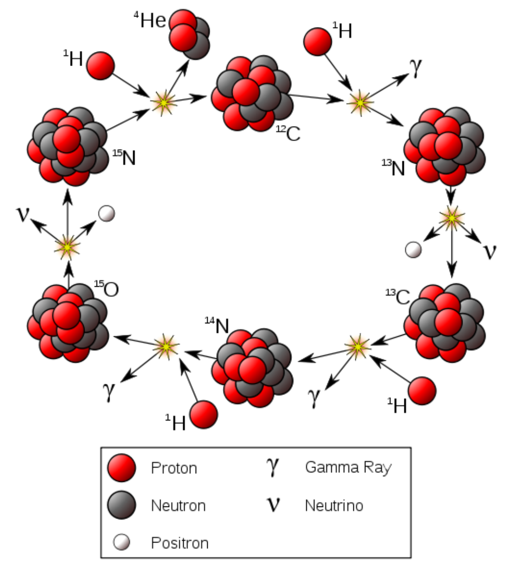
From the pp and ⁷Be fluxes measurement

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

Key to the Solar metallicity : CNO flux



Expected spectrum assuming ν(CNO) HZ flux and other rates from last solar analysis



Predictions: HZ ~5 cpd/100 t

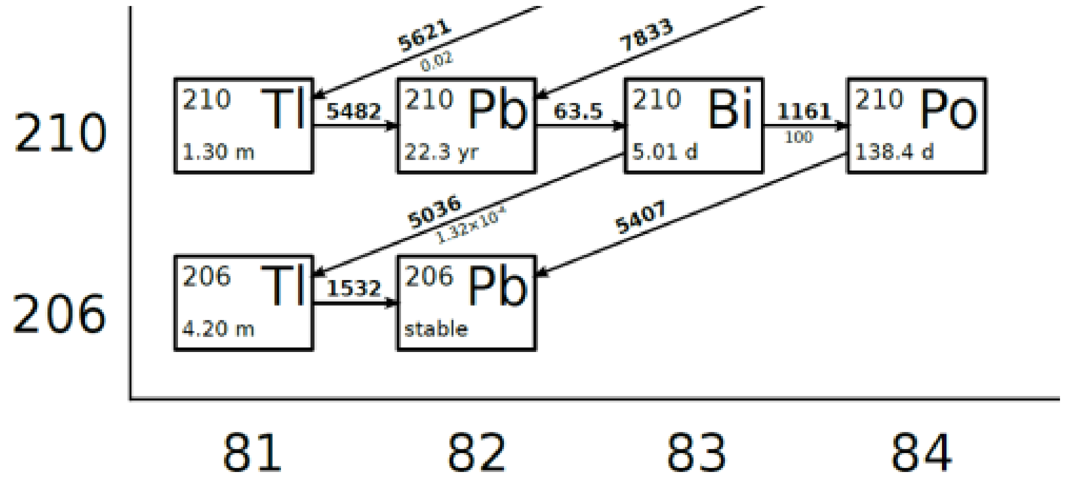
LZ ~3 cpd/100 t

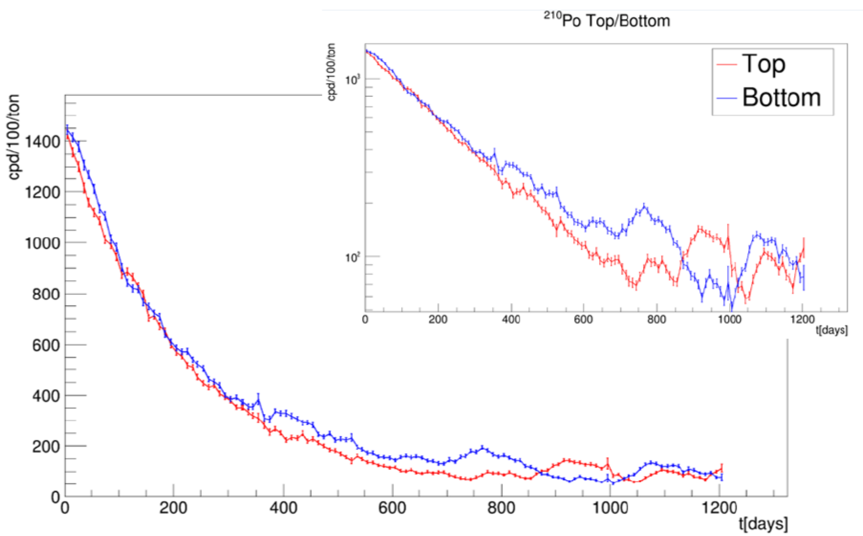
Main background from ^{210}Bi :
~20 cpd/100 t
If we will be able to extract ^{210}Bi with few counts precision, we will be able to constraint it in the spectral fit and extract the CNO flux.

Another background in the region of sensitivity is pep-neutrino flux. Can be constrained through pp/pep ratio, using theoretical prediction for pp (luminosity constraint) or pp measured value.

Strategy towards CNO measurement

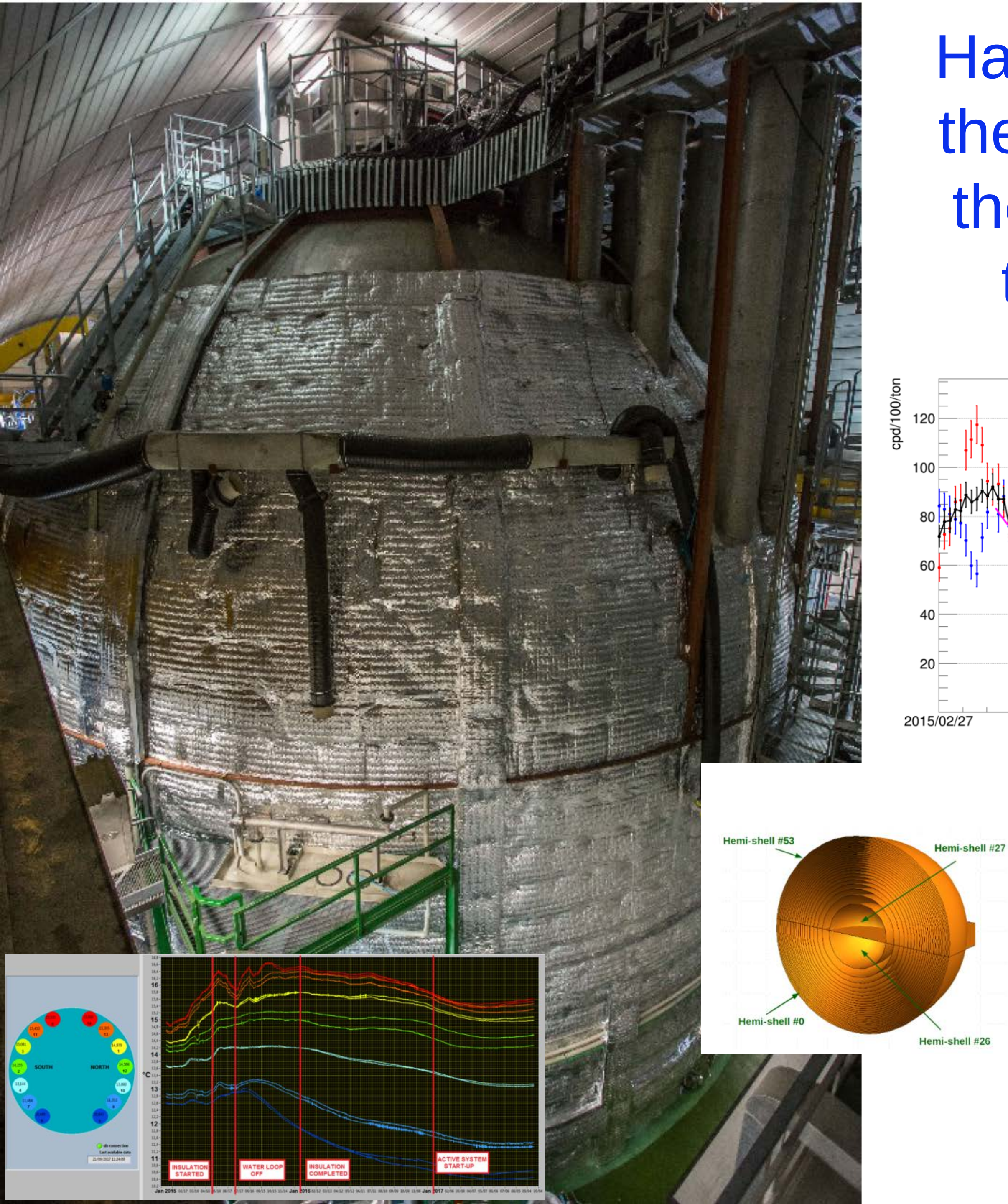
- Main route: using ^{210}Bi-^{210}Po temporal evolution to measure “support term” for ^{210}Po (secular equilibrium in ^{210}Pb sub-chain)
- Option: further purification of the LS by water extraction to reduce ^{210}Bi

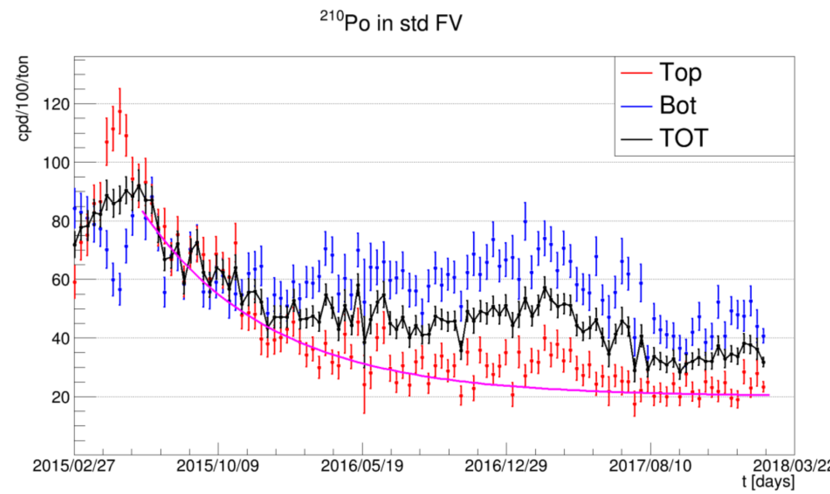


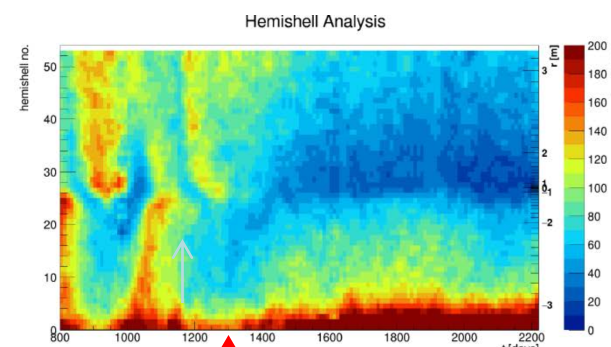


Instabilities observed in the temporal evolution of the ^{210}Po (making impossible precision evaluation of the ^{210}Bi) were found to be the result of the temperature instabilities of the surrounding

Hardware solution for thermal stabilization : thermal insulation of the external tank



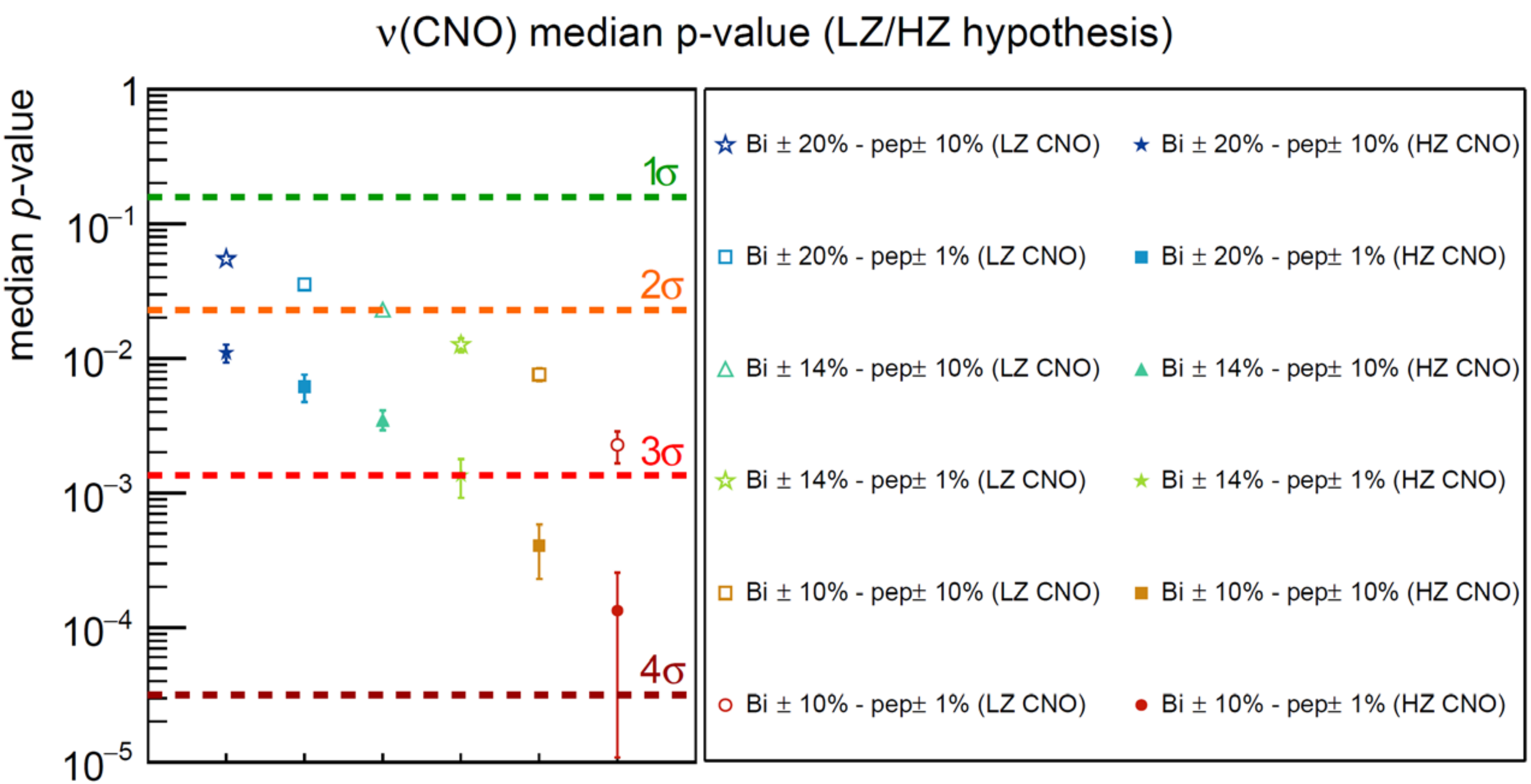




day 1300: insulation (summer 2015)

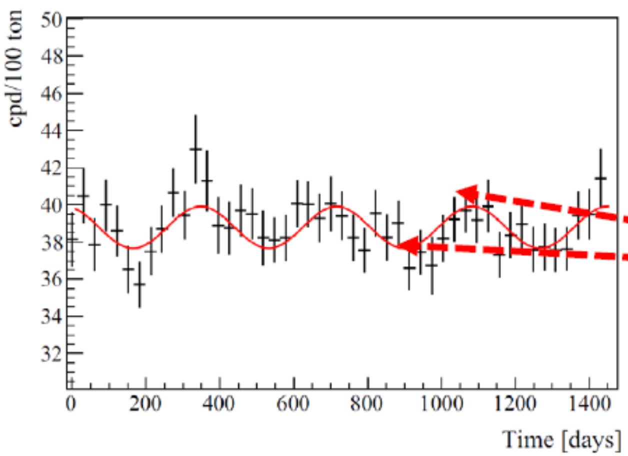
CNO sensitivity

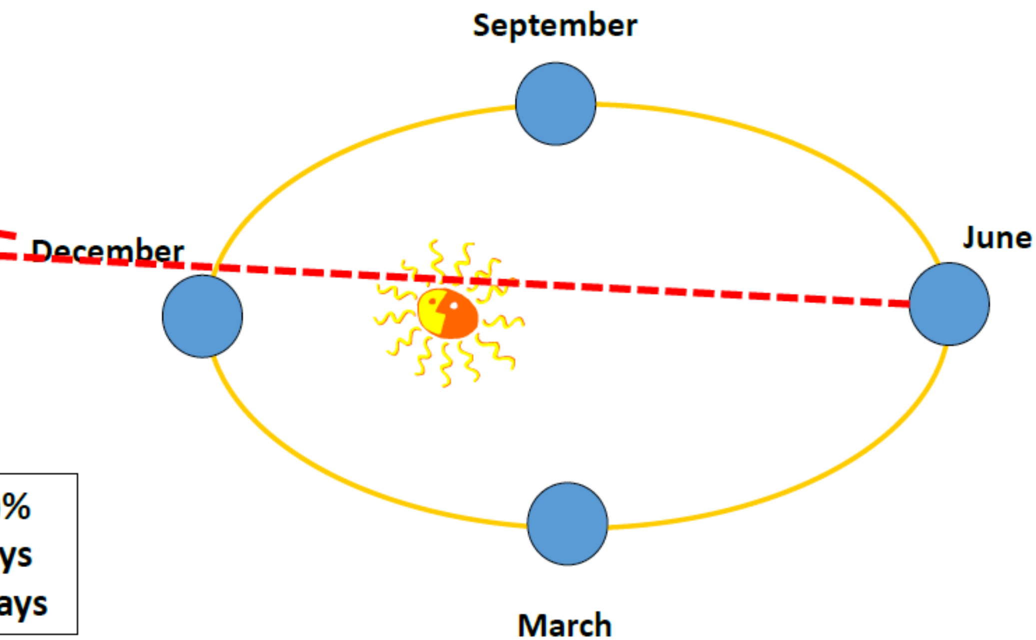
Depends on both ^{210}Bi and pep-neutrino rates. We assume that ^{210}Bi will be measured (10-20%) and pep-rate can be constrained by constraining pp/pep ratio in the fit.



Seasonal modulations of ^{7}Be neutrino flux

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





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

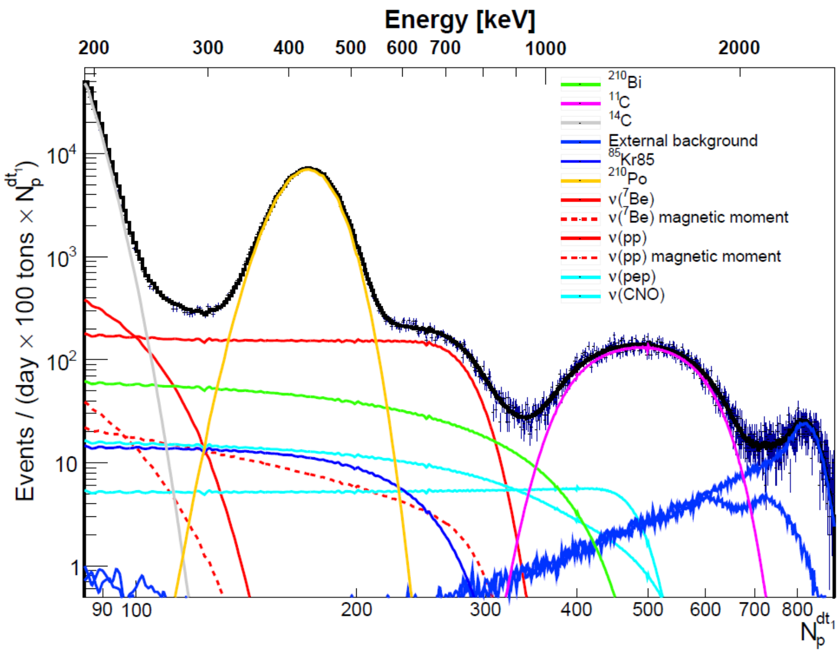
ε = (1.74 ± 0.45)%
T = (367 ± 10)days
Φ = (-18 ± 24) days

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

Effective magnetic moment of Solar neutrino

M.Agostini et al.," Limiting neutrino magnetic moments with Borexino Phase-II solar neutrino data", Phys. Rev D 96, 091103(R) (2017)

Borexino is spectroscopical detector.
Solar neutrino analysis (spectral fit) is performed assuming SM cross sections
The shapes can be adjusted to take into account any non-standard interactions (NSI), including neutrino EM interactions



$$\chi^2 = \sum_{i=1}^{N_{bin}} \left(\frac{O_R^i - N_R^i(\mu_R)}{\Delta_i} \right)^2$$

Radiochemical (Ga) constraints

$$\sum_i \frac{R_i{}^{Brx}}{R_i{}^{Expected}} R_i{}^{Ga} \frac{\langle \sigma^{\odot}{}_i \rangle_{new}}{\langle \sigma^{\odot}{}_i \rangle_{old}} = 66.1 \pm 3.1 \pm \delta_R \pm \delta_{FV}$$

Without Ga constraint: $\mu_\nu < 4.0 \cdot 10^{-11}\ \mu_B$, 90% C.L.

With Ga constraint: $\mu_\nu < 2.6 \cdot 10^{-11}\ \mu_B$, 90% C.L.

+ systematics: $\mathbf{\mu_\nu < 2.8 \cdot 10^{-11}\ \mu_B}$, 90% C.L.

Limits on mm of neutrino flavours and mass eigenstates

In Solar neutrino experiments we measure: $(\mu_\nu)_{eff}{}^2 = \sum_\alpha P_{e\alpha}(\mu_\nu)_\alpha{}^2$

In frames of the MSW/LMA solution:

$$\mu^2{}_{eff} = P^{3\nu}\mu^2{}_e + (1 - P^{3\nu})(\cos^2\theta_{23}\,\mu^2{}_\mu + \sin^2\theta_{23}\mu^2{}_\tau)$$

$\mu_{\nu_e} < 3.9$

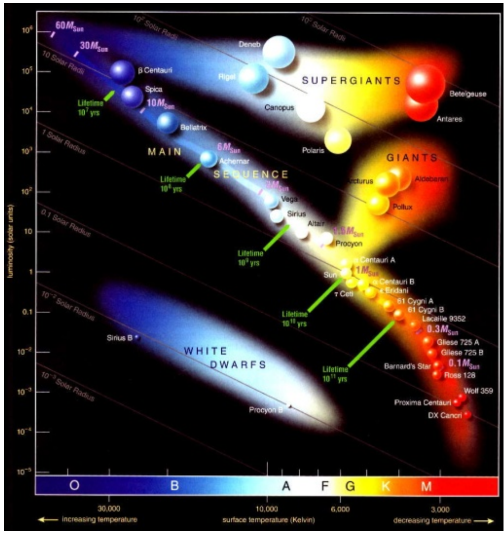
$\mu_{\nu_\mu} < 5.8$

$\mu_{\nu_\tau} < 5.8$

GEMMA:	$\mu_{\nu_e} < 2.9$
LSND:	$\mu_{\nu_\mu} < 68$
DONUT:	$\mu_{\nu_\tau} < 39000$

All @90% C.L.

units of $10^{-11}\mu_B$



Mass eigenstates basis:

- $|\mu_{11}| \le 3.4 \quad |\mu_{22}| \le 5.1 \quad |\mu_{33}| \le 18.7$

  $|\mu_{12}| \le 2.8 \quad |\mu_{13}| \le 3.4 \quad |\mu_{23}| \le 5.0$

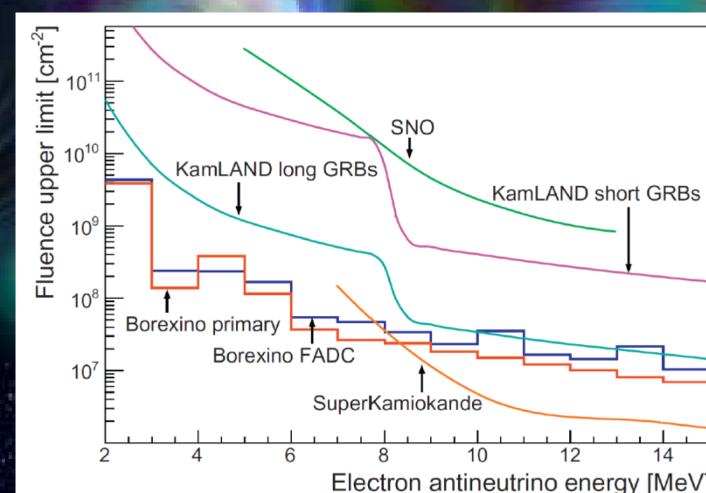
Astropysics: $\mu_\nu{}^2 = \sum_{\alpha,\beta}|\mu_\nu{}^{\alpha\beta}|^2 < 3\cdot 10^{-12}$

More information : poster by Alina Vishneva (JINR) “Limit on the effective magnetic moment of solar neutrinos from Borexino Phase-II data”

Search for neutrinos in coincidence with cosmic events

the four extrasolar messengers are electromagnetic radiation, gravitational waves, neutrinos, and cosmic rays. They are created by different astrophysical processes, and thus reveal different information about their sources.

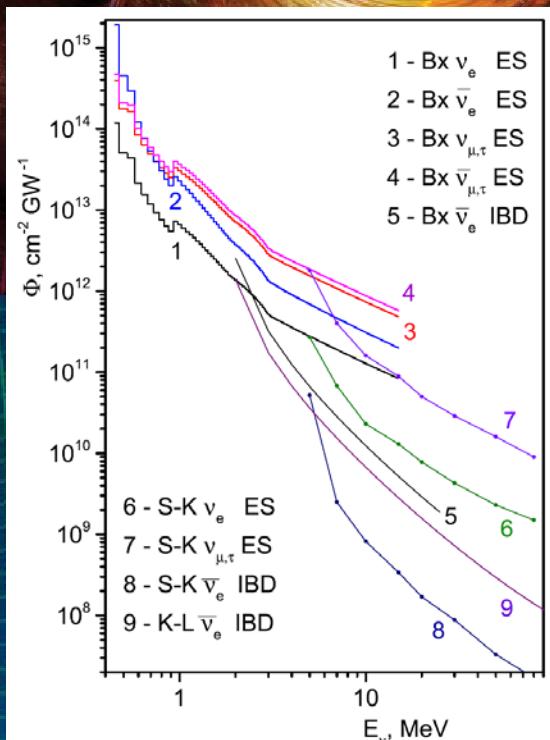
Multimessengers: GRBs



Search for neutrino/antineutrino in coincidence with 2350 GRB observed during 8 years of the Borexino data taking
Astropart. Phys. 86, p.11 (2017)

Multimessengers: GW

Search for neutrino/antineutrino in coincidence with GW events (GW150914, GW151226, GW170104) Astrophys. J., 850:21 (2017)



No statistically significant event count above expected background is observed

For more details see poster by Drachnev Ilia (PNPI NRC KI) "A search for low energy neutrinos in correlation with gravitational wave events GW150914, GW151226 and GW170104 with the Borexino detector"

Plans

- **CNO neutrino flux measurement (or reasonable constraints). The thermal stabilization of the detector and unprecedented low background of the LS are two milestones of the effort. Will need more data in (proved) stable conditions, calibrations, and (optional) additional cycle of water extraction**

- **Joint analysis of Phase I and Phase II data aiming to improve pp-neutrino flux measurement (till now only the Phase II data has been analyzed)**

- **Update of the geo-neutrino analysis with full statistics, improved selections and extended FV**

- **Neutrino non-standard interactions analysis**

- **Rare physics study (limits on unknown antineutrino fluxes, diffuse SN flux, some DM candidates etc.)**