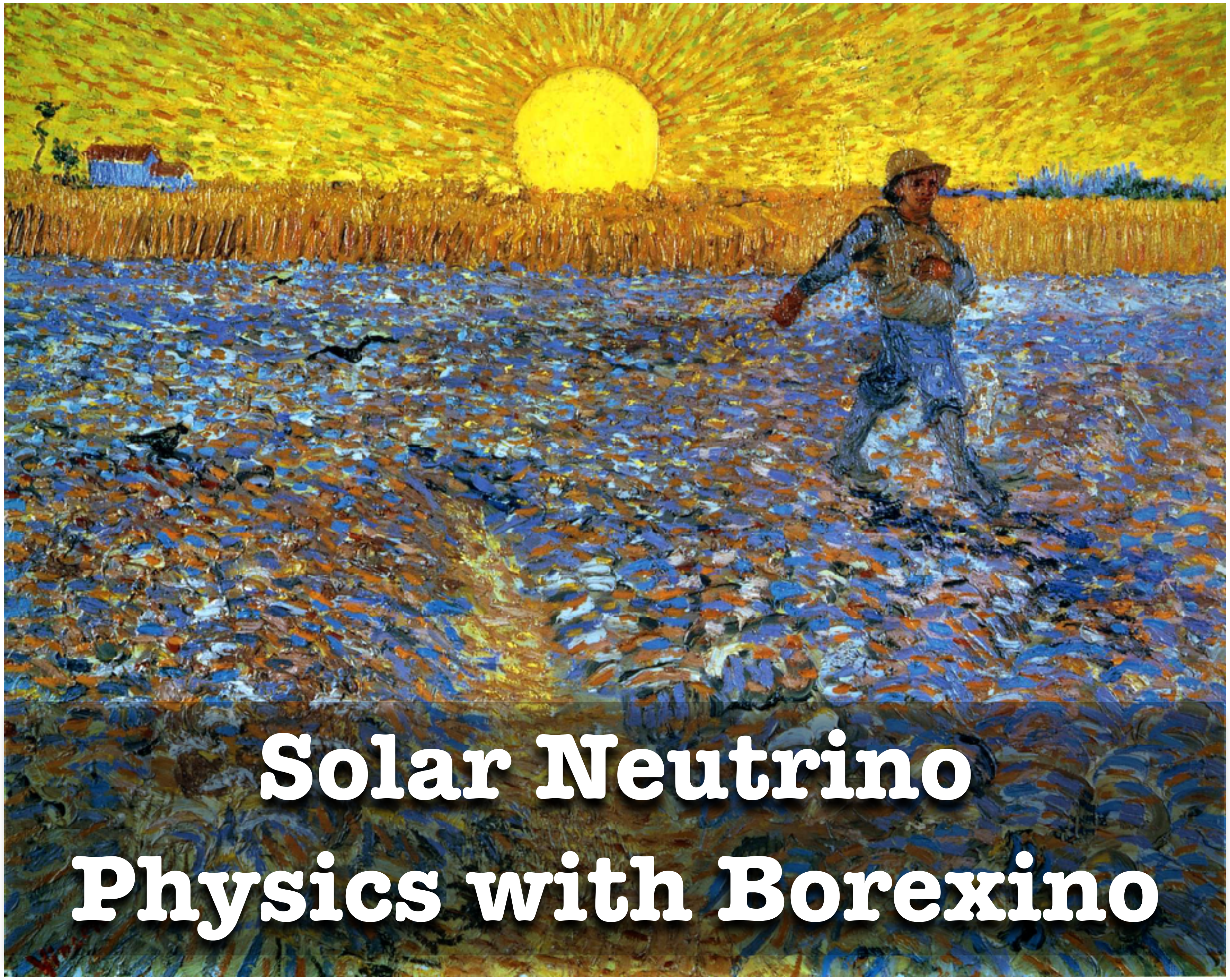

Solar Neutrino Physics with Borexino

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University of Massachusetts, Amherst

AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS
Physics at the interface: Energy, Intensity, and Cosmic frontiers
University of Massachusetts Amherst

Outline

Solar neutrinos

nuclear fusion in the Sun

Borexino

neutrino detection

Recent results

Outlook

CNO neutrinos
Solar metallicity

Solar fusion and neutrino emission: pp chain

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

2014
2017-18

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

2012
2017-18

99.76% | 0.24%

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

83.30% | 16.70%

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

ppI

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

99.88% | 0.12%

2007/2008
2011 (5%)
2012 (D/N)
2014 (seasonal)
2017

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

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

ppII

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

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

ppIII

2010, 2013
2017-18

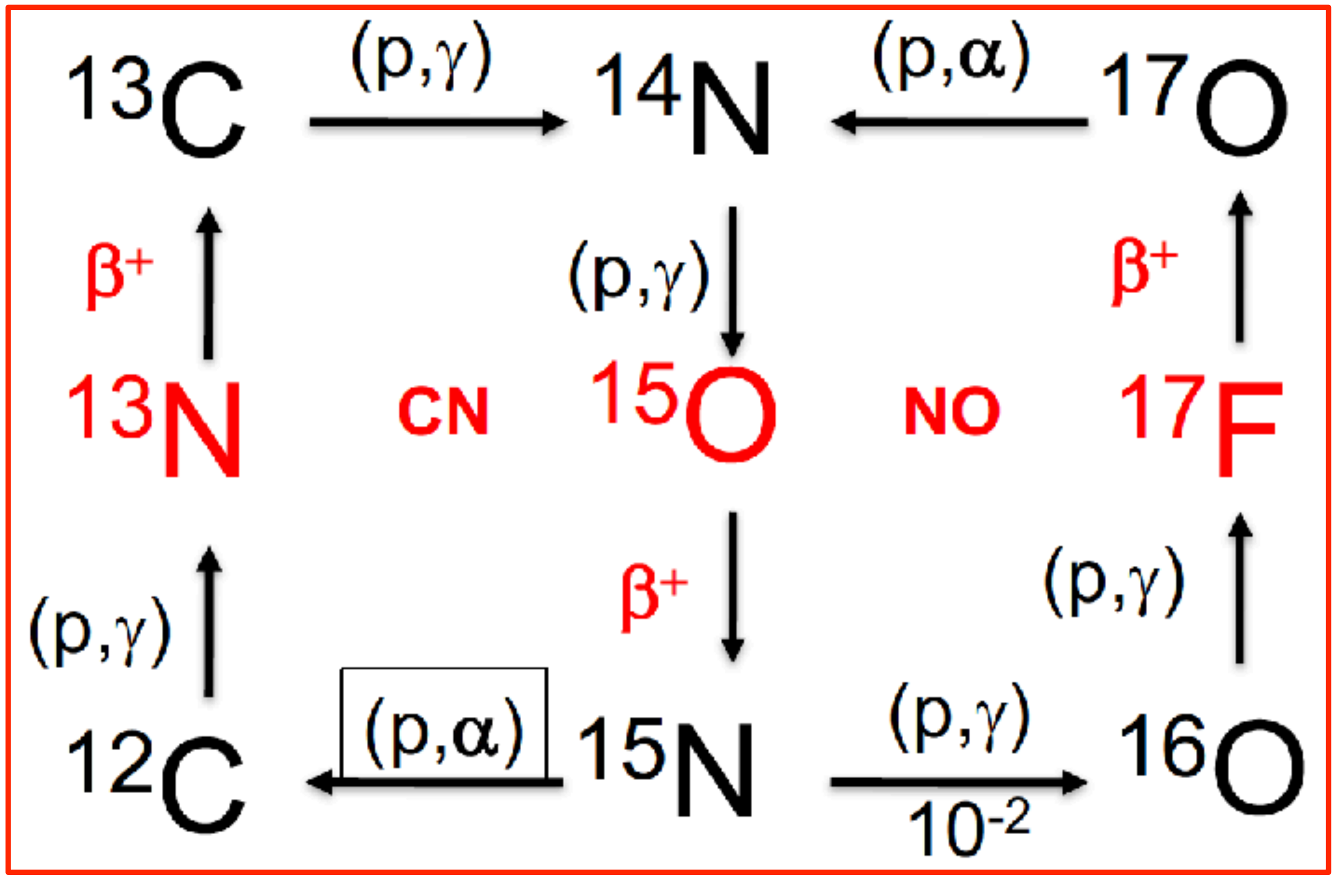
protons fused into He-4

$$4p \rightarrow {}^4He = 2e^+ + 2\nu_e + (24.7 + 2m_ec^2)\ \mathrm{MeV}$$

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

(~2% of the total energy)

Solar fusion and neutrino emission: CNO cycle



best limit on CNO solar neutrinos (2012, 2017-18)

Very sensitive probe of the **solar metallicity**, an open issue in solar/ stellar physics

protons fused into He-4

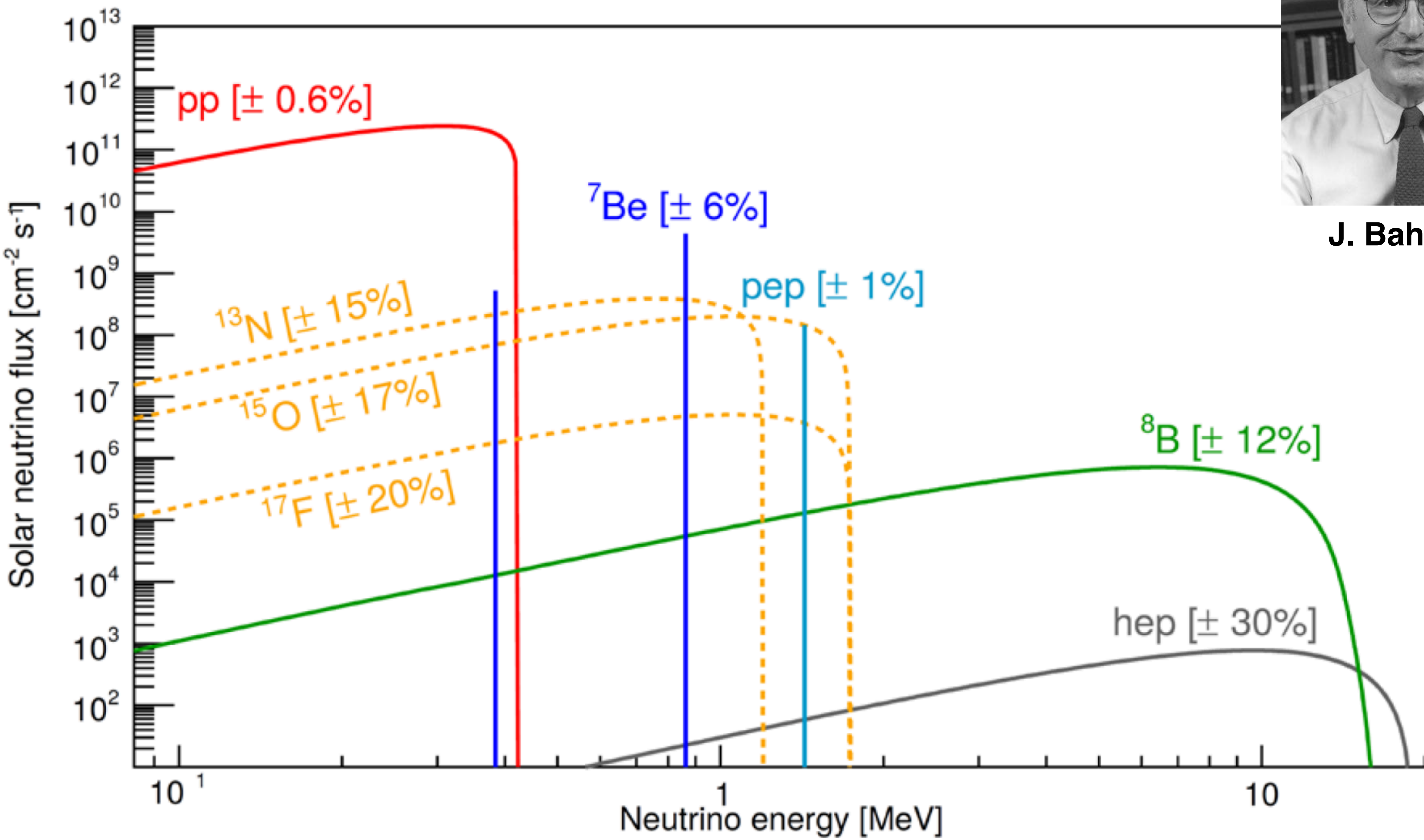
$$4p \rightarrow {}^4He = 2e^+ + 2\nu_e + (24.7 + 2m_ec^2)\ \mathrm{MeV}$$

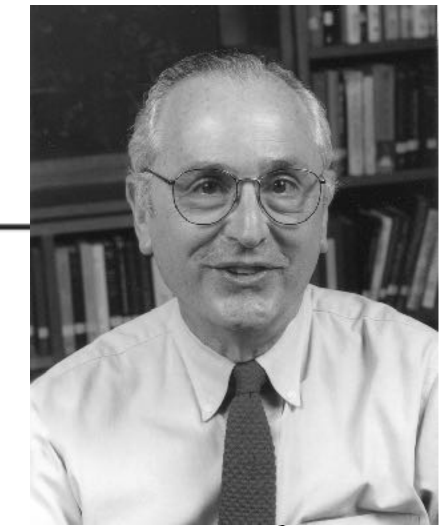
$$\langle E_\nu \rangle \sim 0.53\,\mathrm{MeV}$$

(~2% of the total energy)

Solar neutrino spectrum

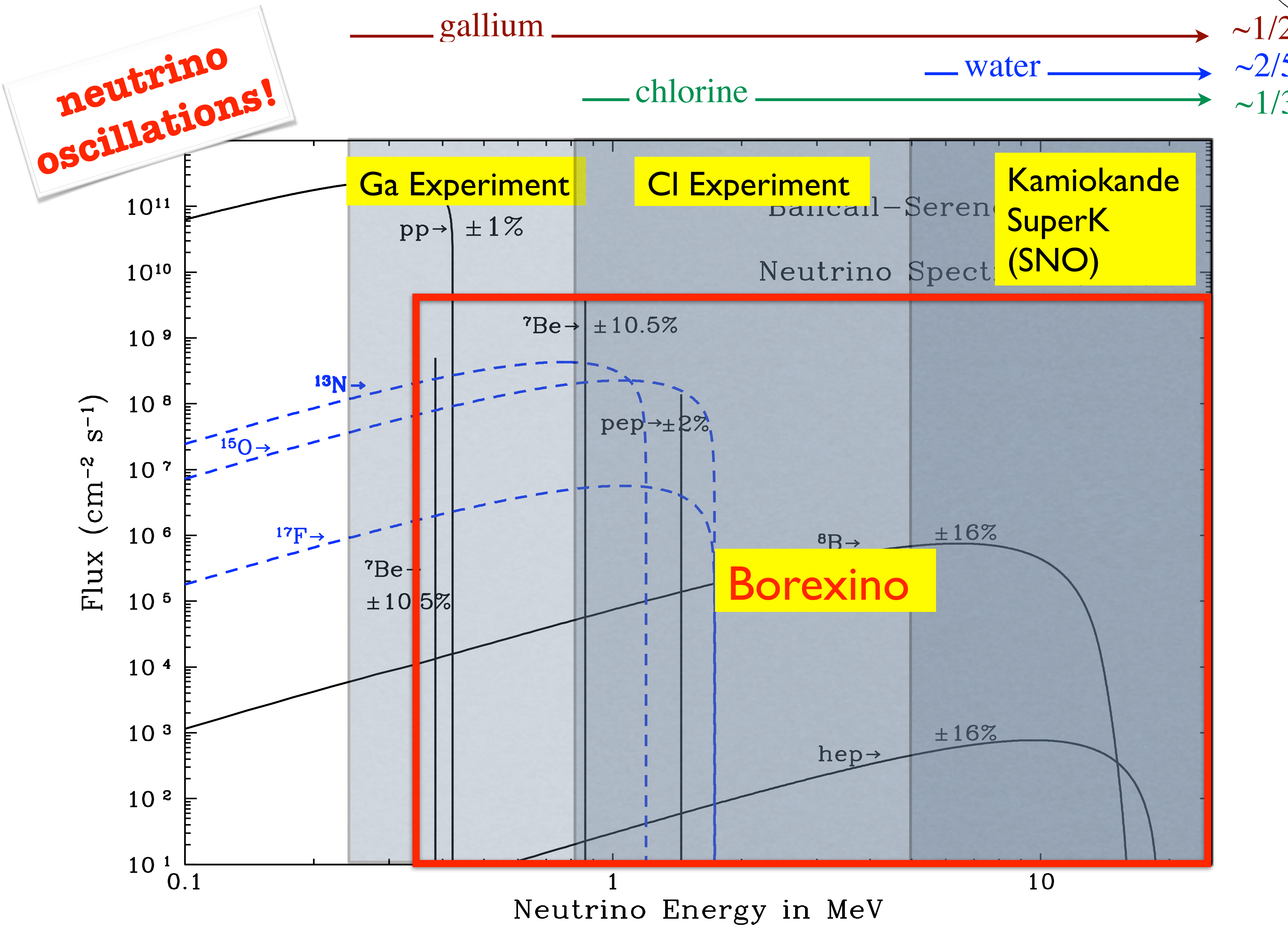
Aldo Serenelli et al, Astrophys. J. 835 (2017) no.2, 202





J. Bahcall

Borexino: low-threshold, real time



Borexino

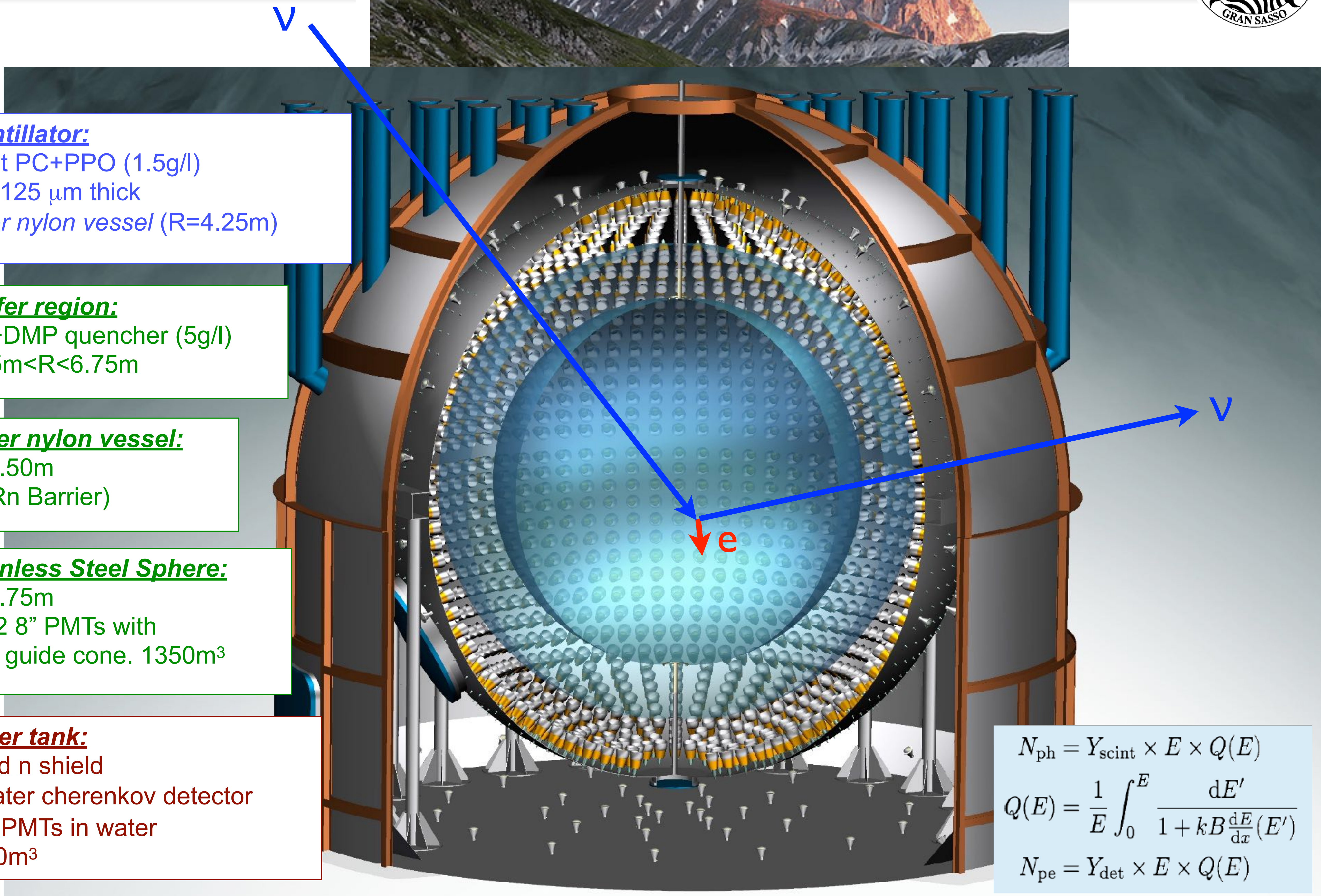
Scintillator:
270 t PC+PPO (1.5g/l)
in a 125 μm thick
Inner nylon vessel (R=4.25m)

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

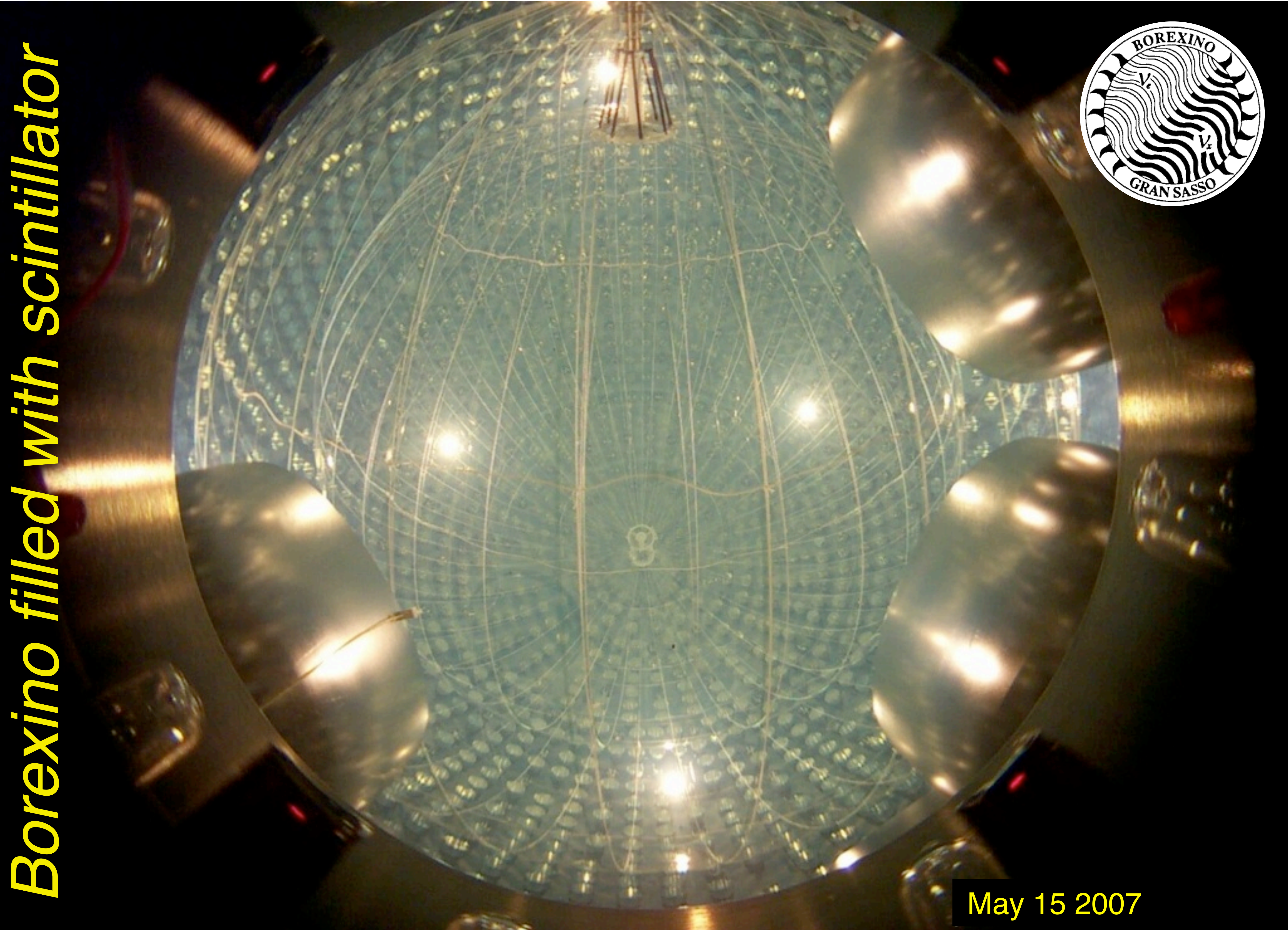


$$N_{\mathrm{ph}} = Y_{\mathrm{scint}} \times E \times Q(E)$$

$$Q(E) = \frac{1}{E} \int_0^E \frac{\mathrm{d}E'}{1 + kB \frac{\mathrm{d}E}{\mathrm{d}x}(E')}$$

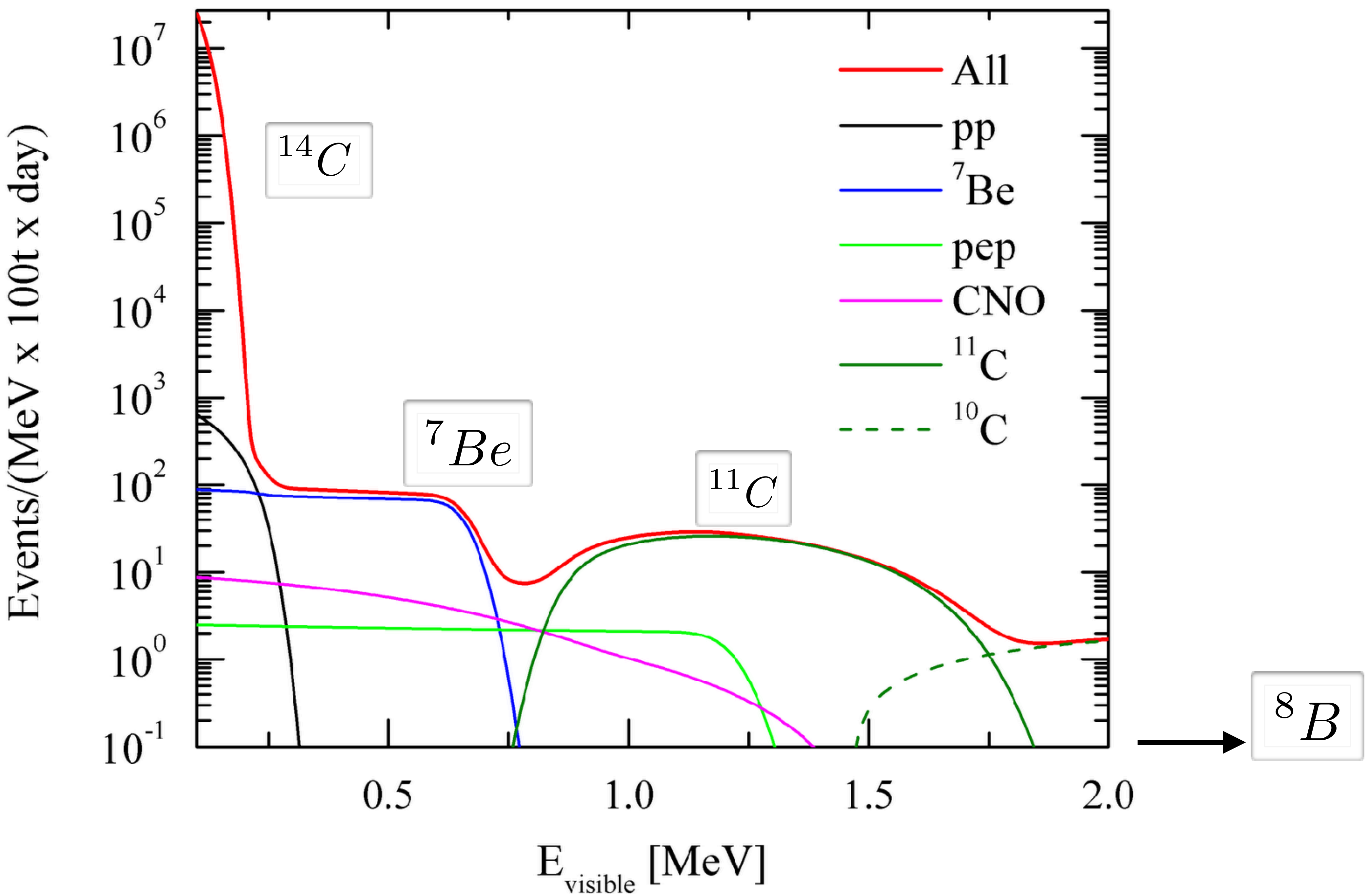
$$N_{\mathrm{pe}} = Y_{\mathrm{det}} \times E \times Q(E)$$

Borexino filled with scintillator

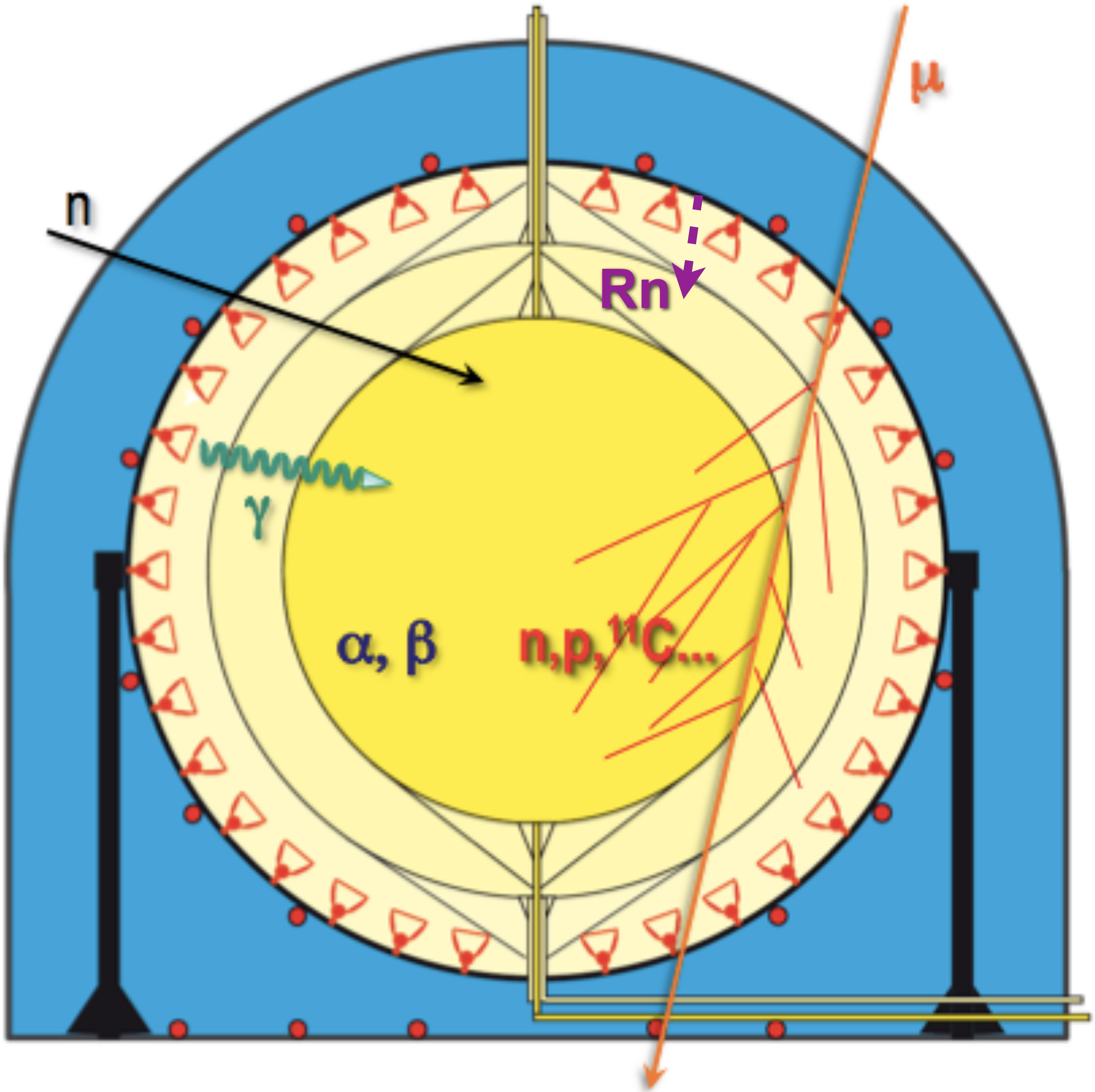


Borexino energy spectrum

with "irreducible" backgrounds



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)

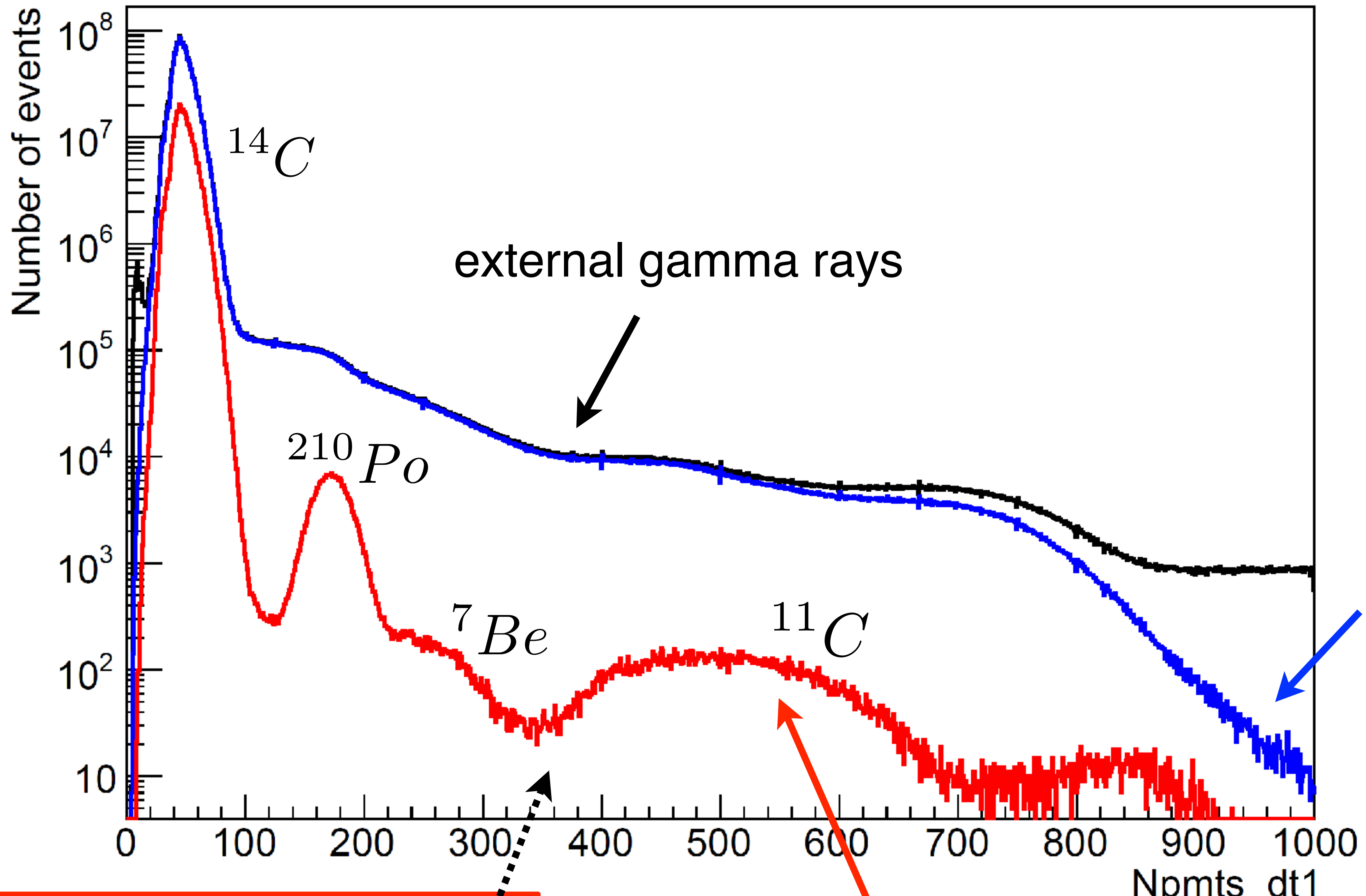
radon emanation
from the PMTs and steel sphere

cosmic muons
and their secondaries

cosmogenics
neutrons and radionuclides from μ spallation and hadronic showers

fast neutrons
from external muons

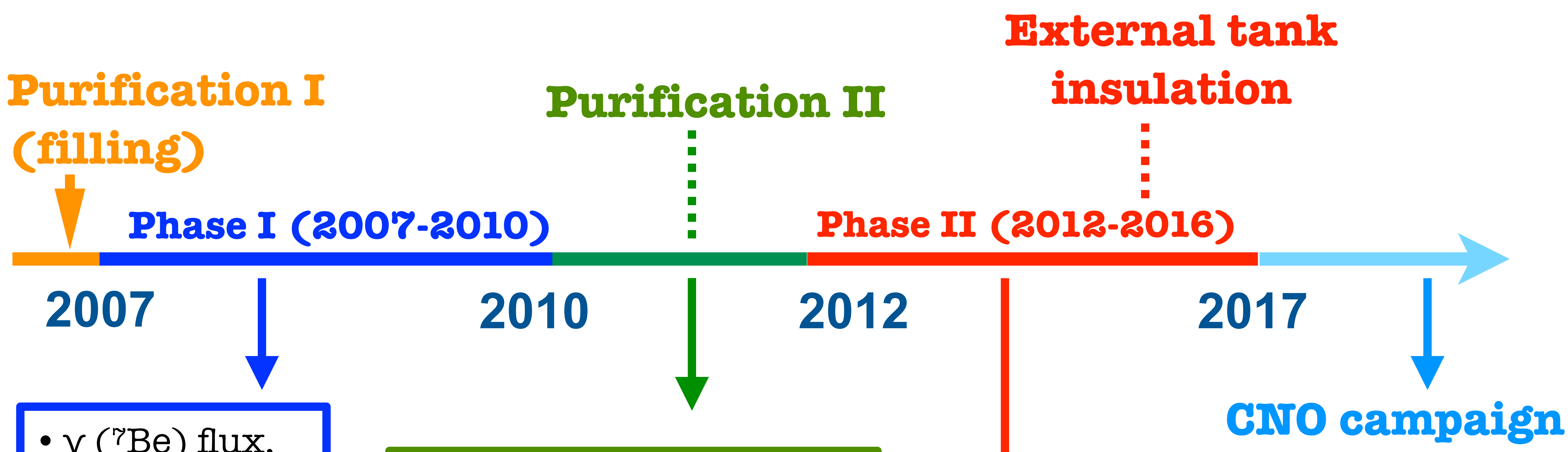
Borexino energy spectrum (data)



pep and CNO neutrinos buried under background

fiducial volume selection

Borexino timeline

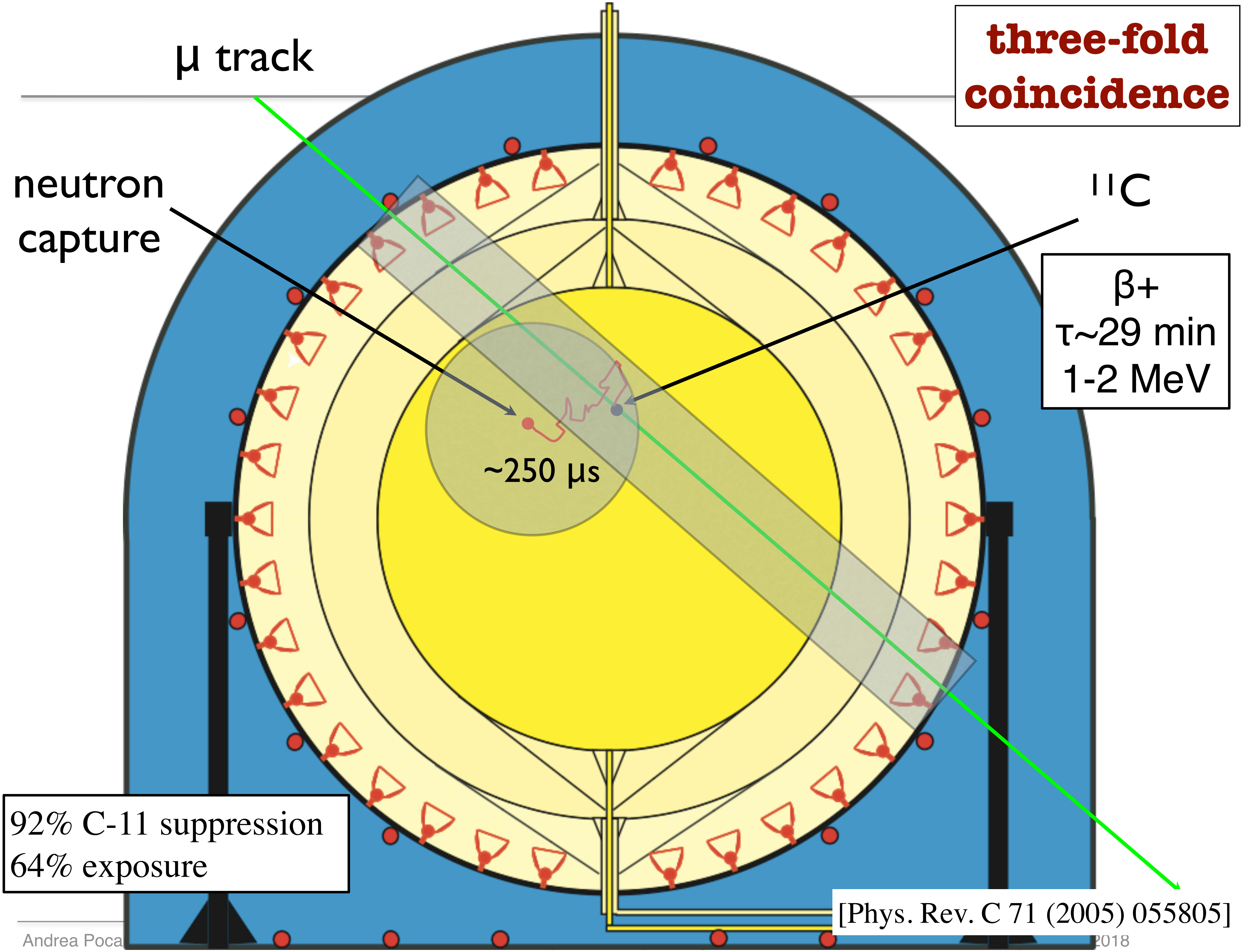


- ν (^{7}Be) flux, D/N
- ν (^{8}B) flux
- ν (pep) flux
- ν (CNO) limit
- geo-neutrinos

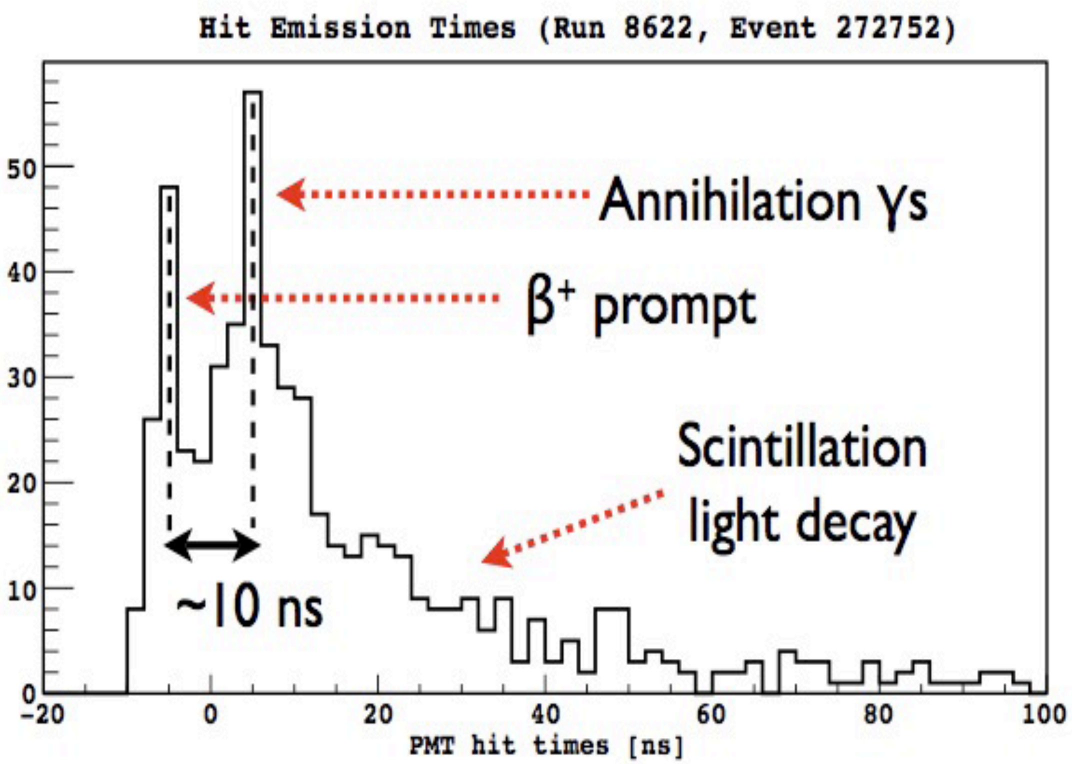
Improved radiopurity:
(6 cycles LS purification)

- ^{85}Kr: reduced by ~ 4.6
- ^{210}Bi: reduced by ~ 2.3
- Th and U negligible:
  - ^{238}U: < $9.4 * 10^{-20}$ g/g
  - ^{232}Th: < $5.7 * 10^{-19}$ g/g

- ν (pp) flux
- ν (^{7}Be) day-night
- geo-neutrinos
- ν magnetic moment
- Correlations with GWs and GRBs

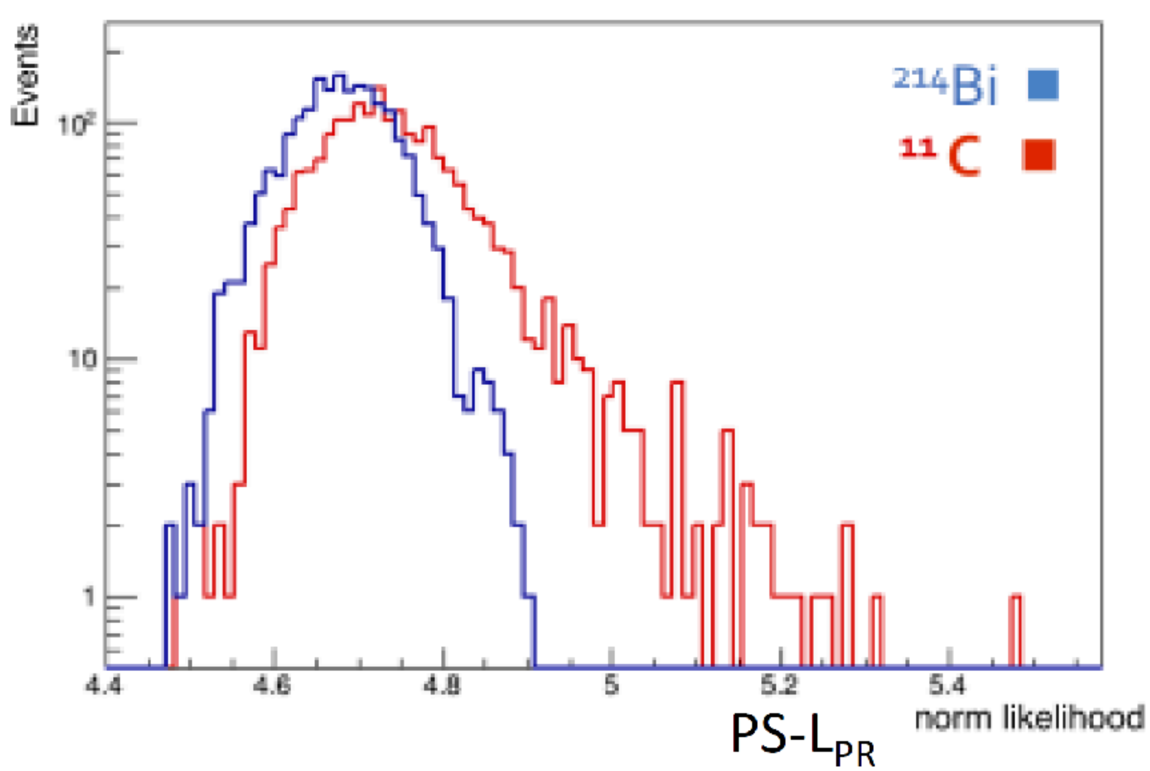

μ track
three-fold coincidence
neutron capture
^{11}C
β+
τ~29 min
1-2 MeV
~250 μs
92% C-11 suppression
64% exposure
[Phys. Rev. C 71 (2005) 055805]

Spectral fit: multivariate approach



50% of β^+ decays produce ortho-positronium ($t_{1/2}$ ~ 3 ns) —> pulse shape discriminator based on:

- time shift
- multi-site (gammas)
- ionization density profile

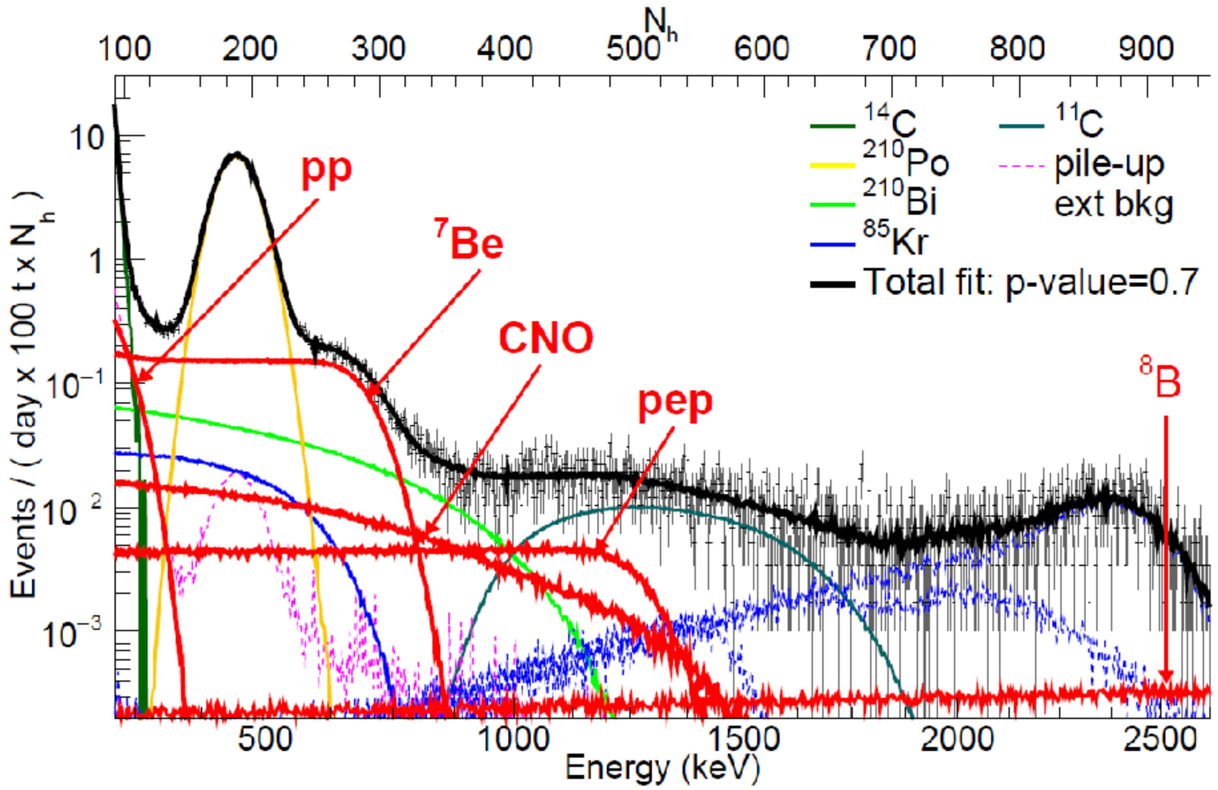


Likelihood built combining:

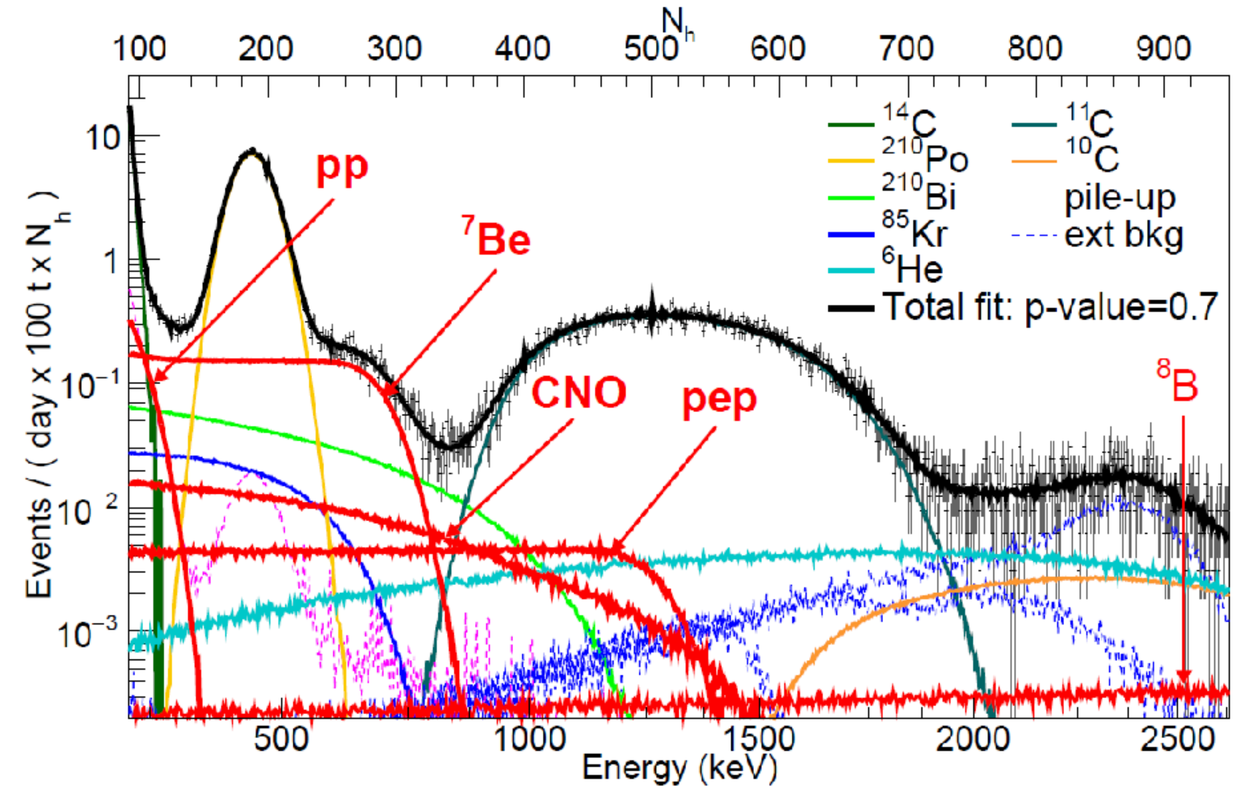
- simultaneous fit of TFC-tagged and TFC-subtracted energy spectra
- pulse-shape parameter
- radial distribution

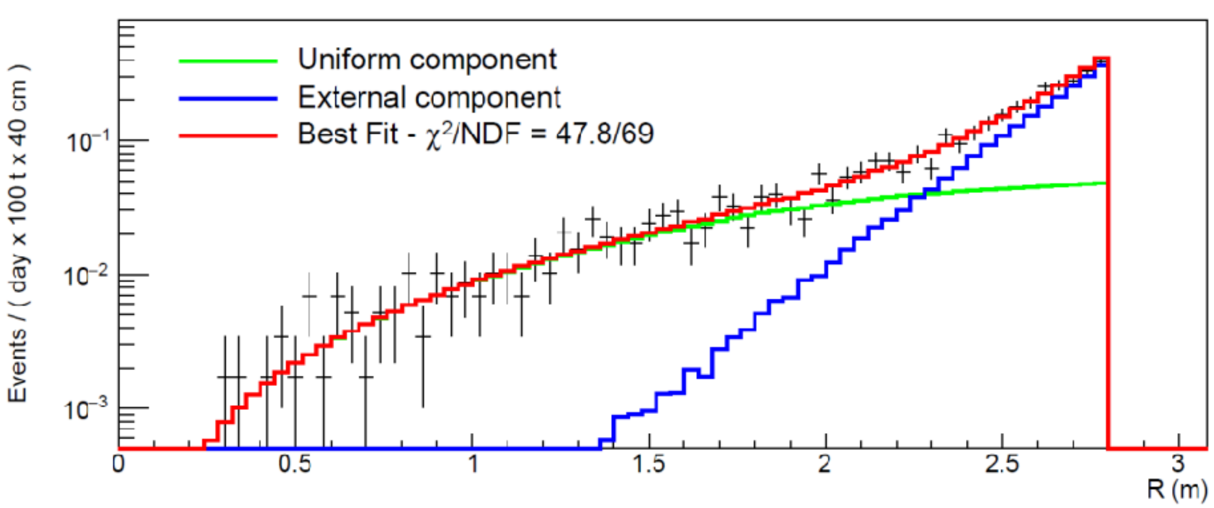
Multi-variate fits sampler

TFC subtracted energy spectrum

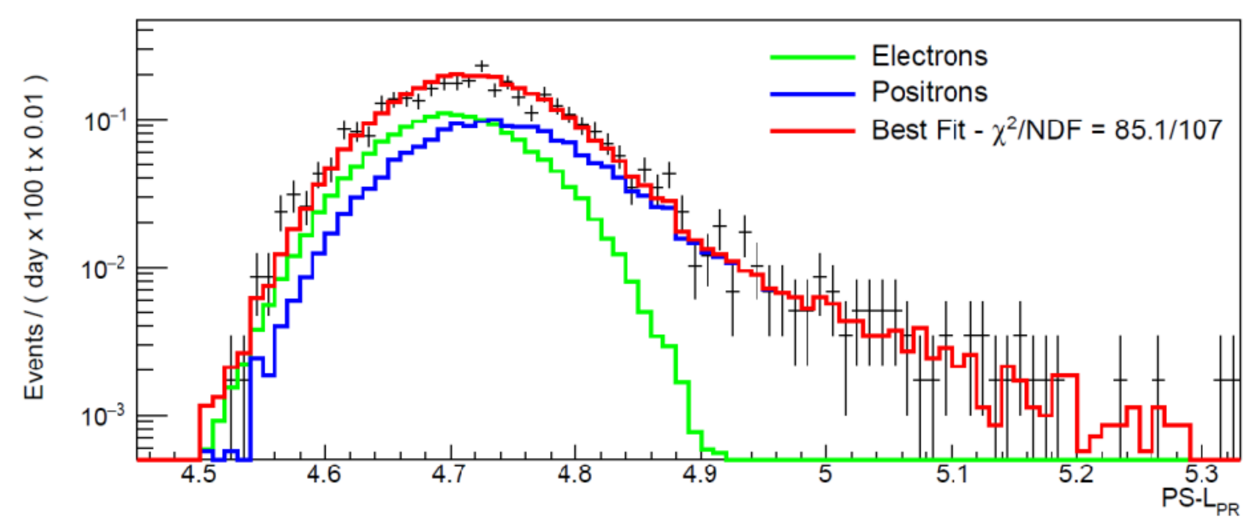


TFC tagged (C-11 rich) energy spectrum





L_{rad}

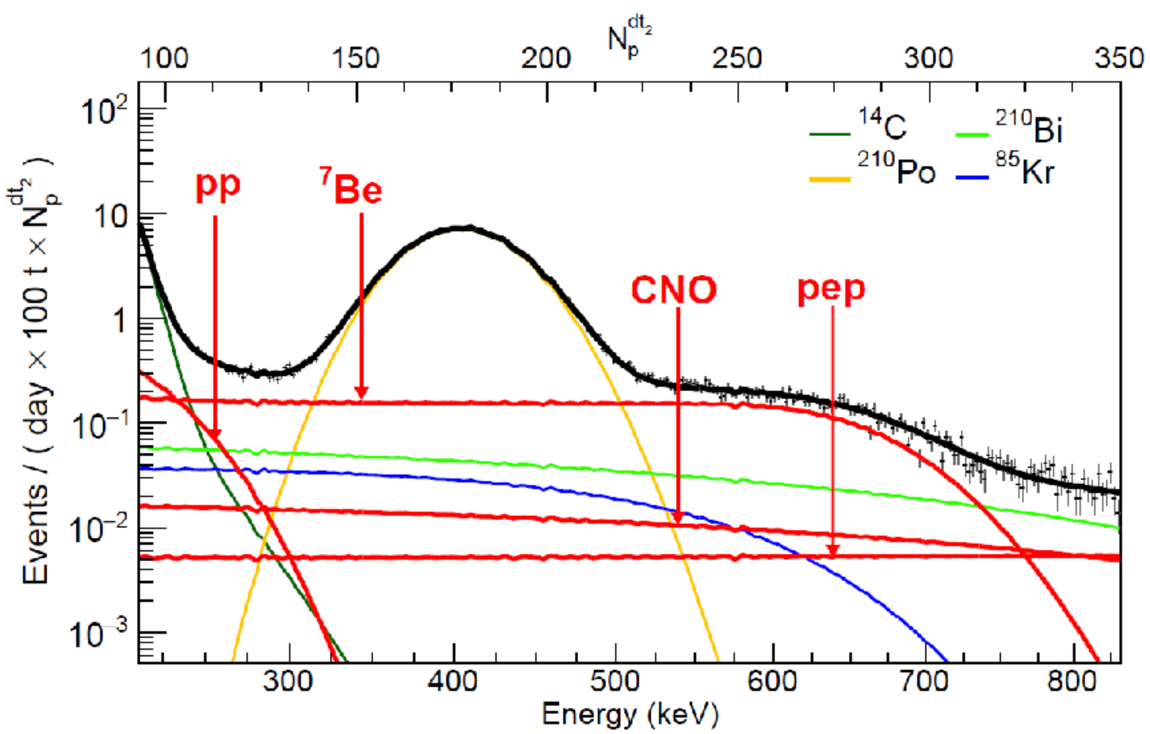


L_{PS}

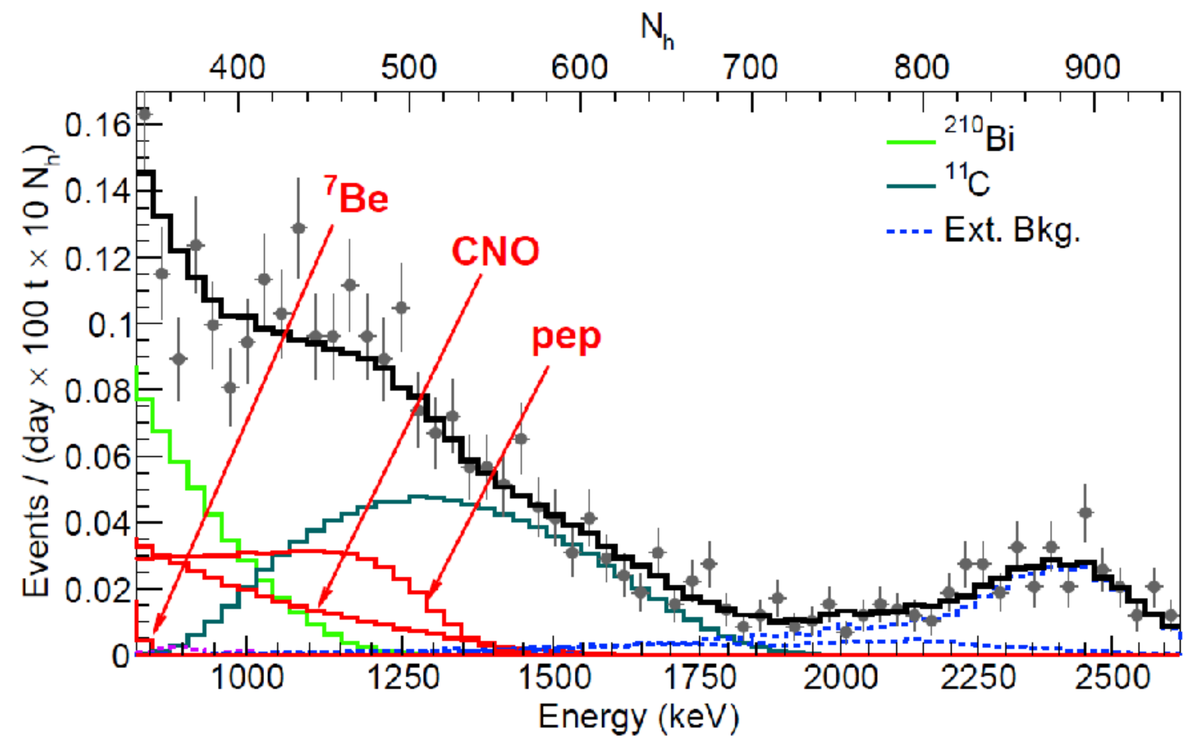
Simultaneous fit for all ν's

Astroparticle Physics 97 (2018) 136–15

Fits performed with analytical and Monte Carlo pdf's are consistent



lowest energy detail



R < 2.8 MeV and L_{PS} < 4.8
visible pep-shoulder

CNO ν's are included in the fit, but they are ~degenerate with Bi-210

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

>5σ evidence of pep neutrinos
R(CNO)<8.1 cpd/100 t (95% CL)

Results – arXiv:1707.09279

Dec 14 2011 — May 21 2016
Fit range: (0.19-2.93) MeV

Exposure:
1291.51 days x 71.3 tons

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	$3.51\,(1 \pm 0.10) \times 10^{8}$

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

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 (see text)	-4.5	0.5	-1.0	0.2	-6.8	2.8
Inclusion of ^{85}Kr constraint	-2.2	2.2	0	0.4	-3.2	0
Live Time	-0.05	0.05	-0.05	0.05	-0.05	0.05
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

210Bi, E-scale, response
R(85Kr)<7.5 @ 95%
LS mass

Improved measurement of B-8 neutrinos

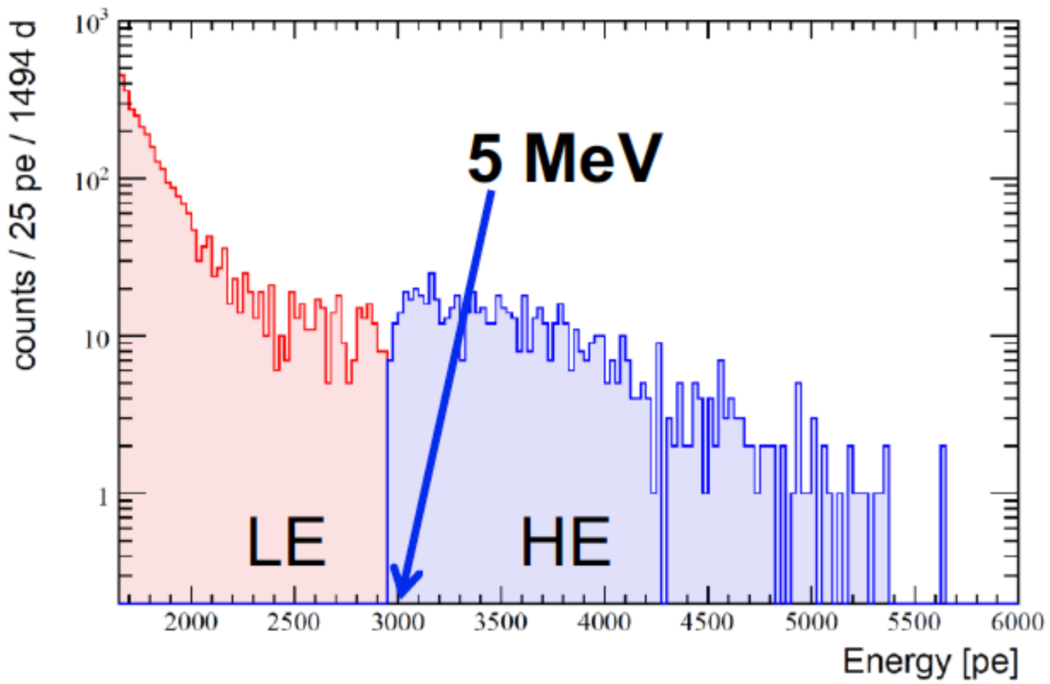
arXiv:1709.00756

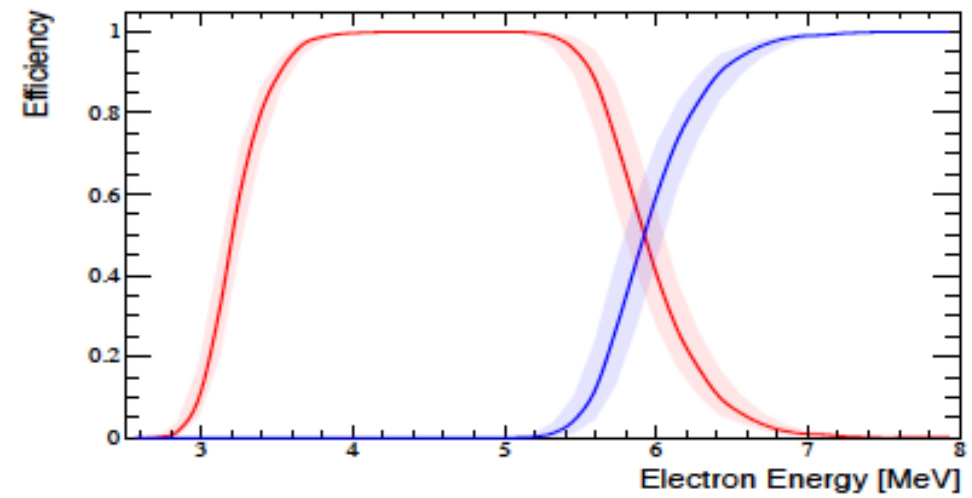
no FV cut, 3.2-17 MeV

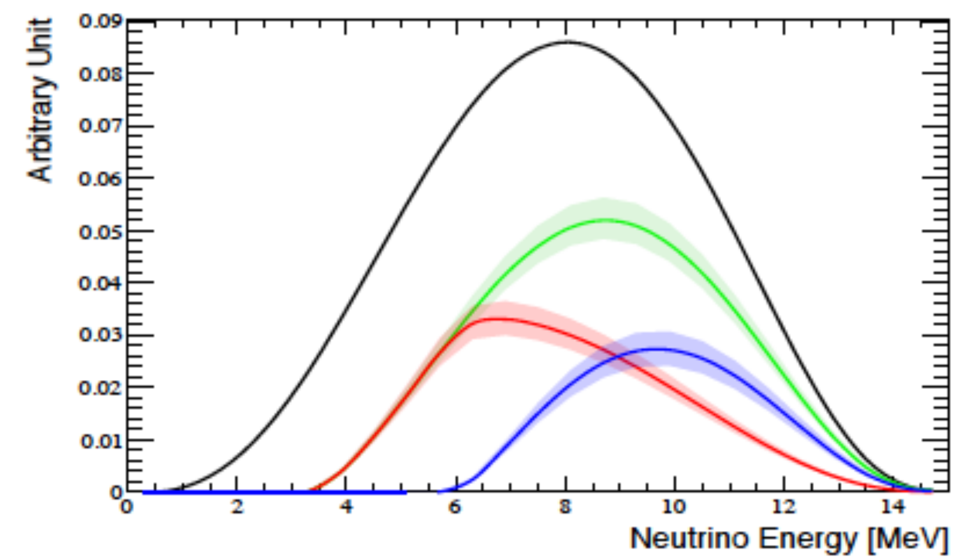
1.5 kton-yr exposure (x11 from phase-1)

better understanding of backgrounds
(cosmogenice Be-11, n-captures, surface)

> 3 MeV visible energy







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

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

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

Borexino Phase 2 (2010-2016): 1707.09279

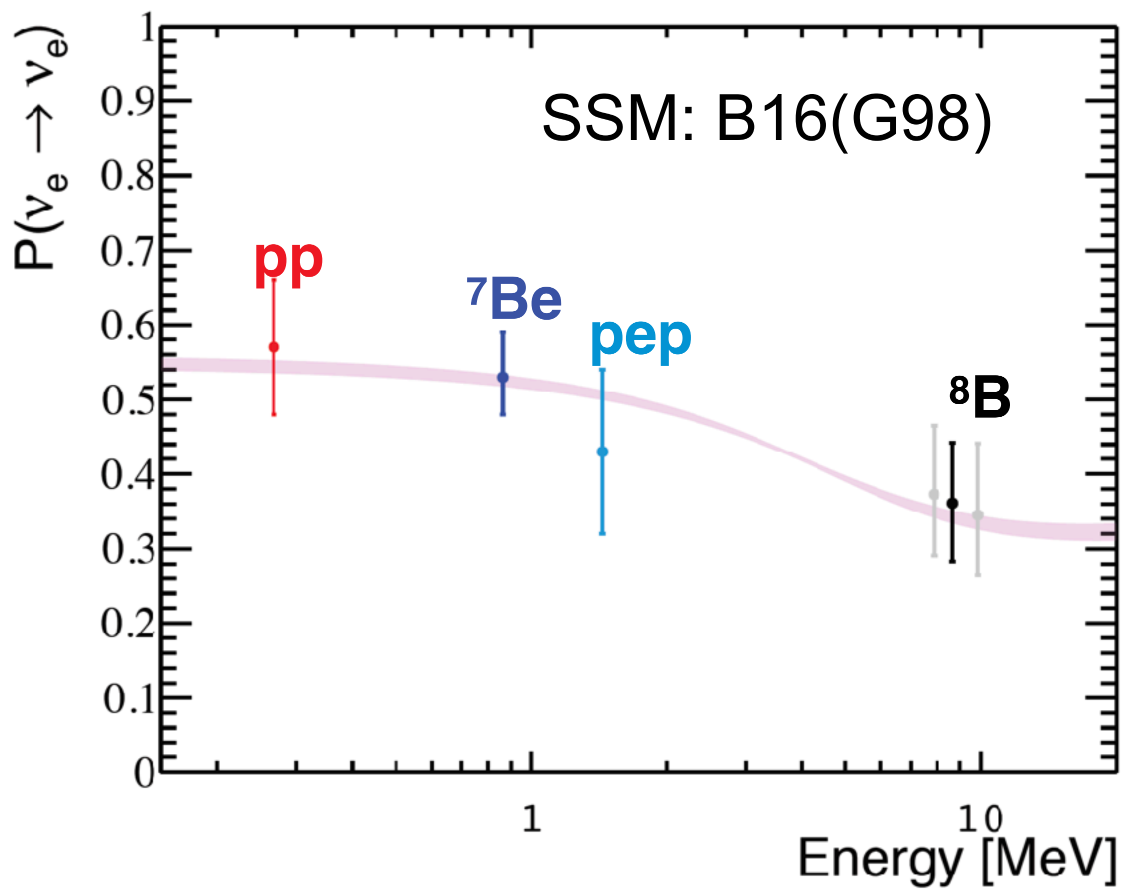
All rates are fully compatible with and improve the uncertainty of the previously published Borexino results

252 ton-yr exposure	Previous BX results (cpd/100t)	This work (cpd/100t)	Uncertainty reduction
pp	144 ± 13 ± 10	$134 \pm 10^{+6}_{-10}$	0.78
^{7}Be	48.3± 2.0 ± 0.9	$48.3 \pm 1.1^{+0.4}_{-0.7}$ 2.7% precision	0.57
pep	3.1 ± 0.6 ± 0.3	(HZ) $2.43 \pm 0.36^{+0.15}_{-0.22}$ (LZ) $2.65 \pm 0.36^{+0.15}_{-0.24}$ 5σ	0.61
^{8}B	0.217 ± 0.038 ± 0.008	$0.220^{+0.015}_{-0.016} \pm 0.006$	0.42
CNO	<12 (95% C.L.)	<8.1 (95% C.L.)	

also: improved measurement of ^{7}Be seasonal modulation

Survival probability, P_{ee}

High Metallicity

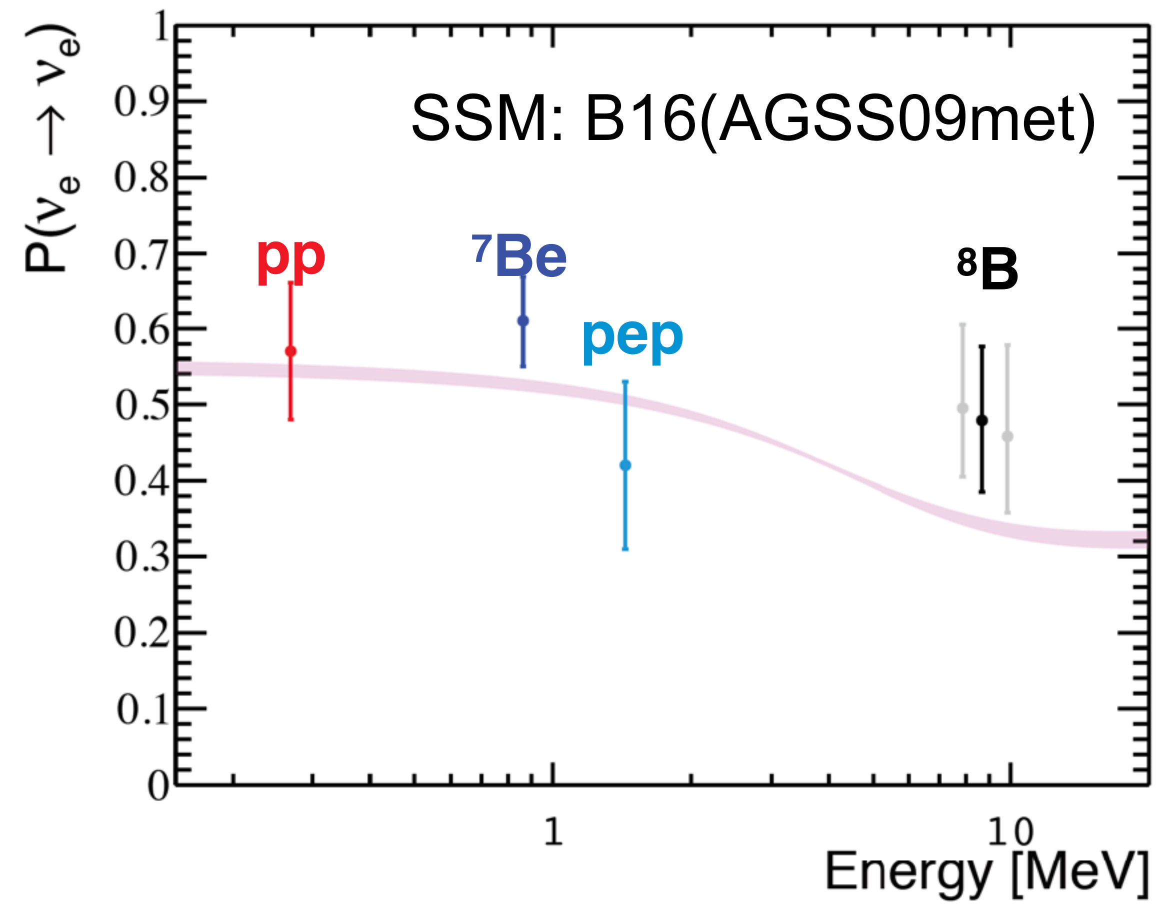


p-values:

Bx only: 0.998

All exp: 0.956

Low Metallicity



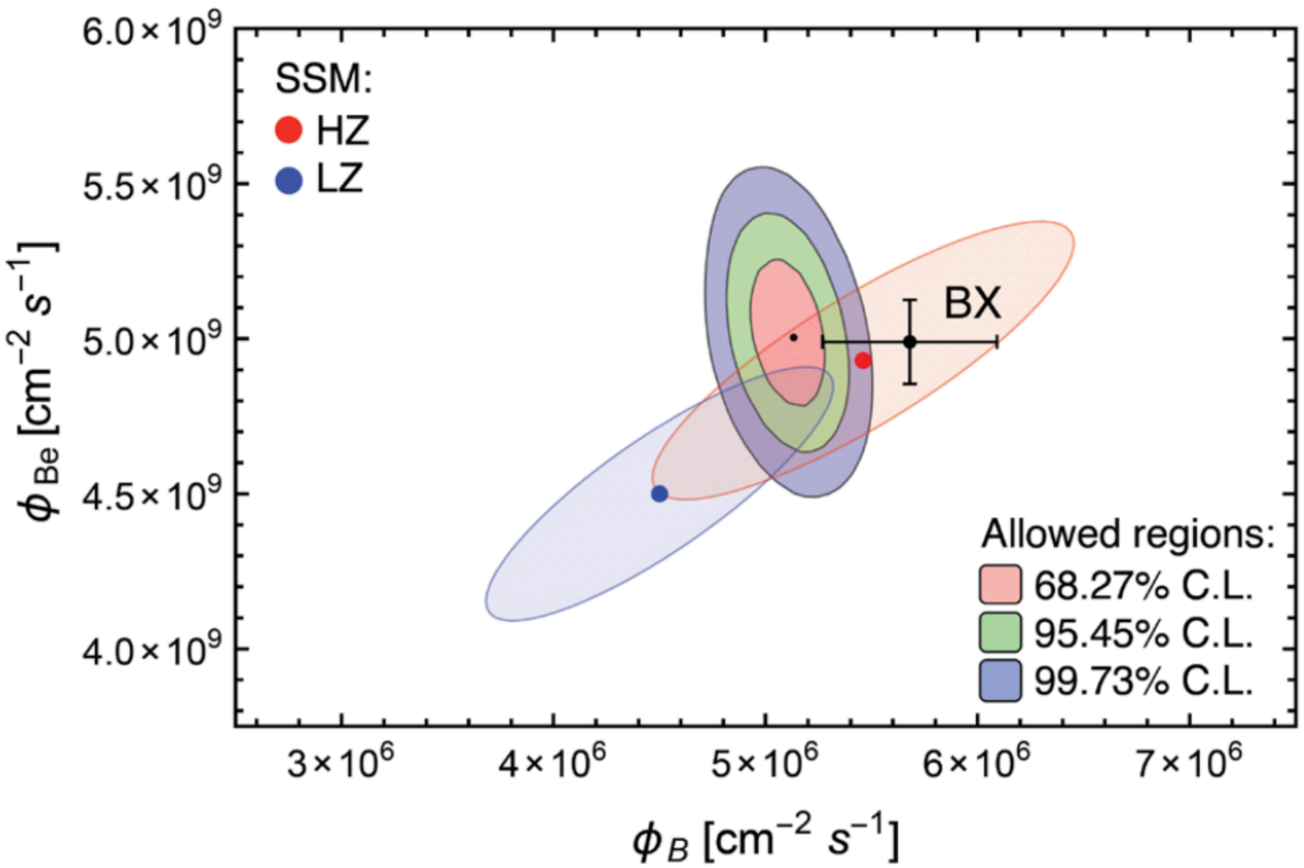
p-values:

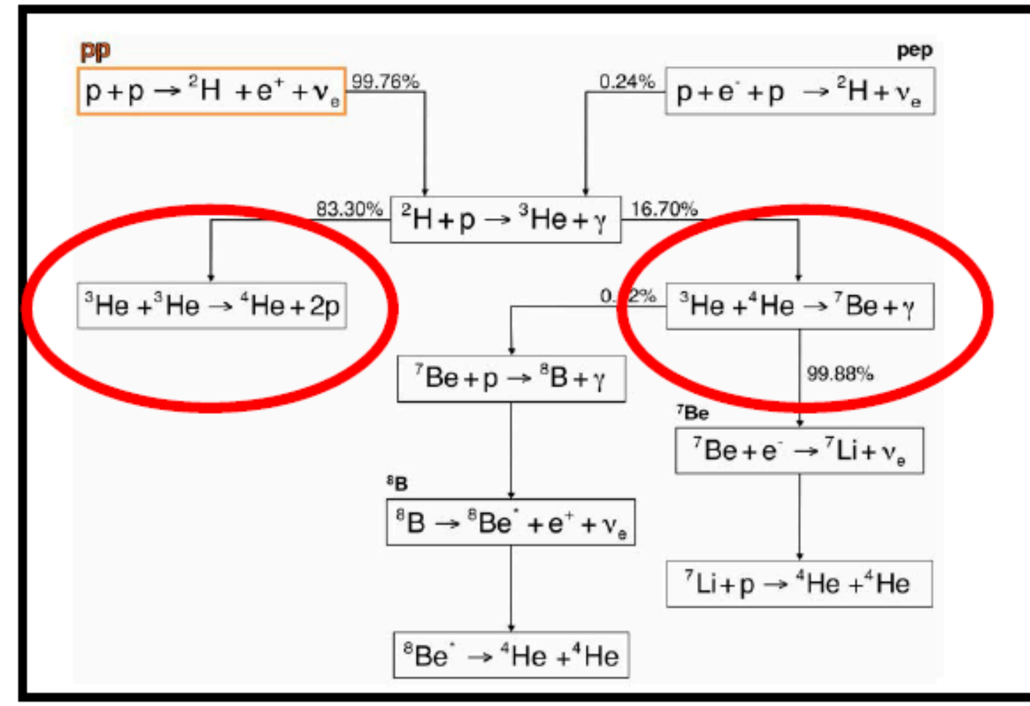
Bx only: 0.362

All exp: 0.465

20

Tests of the SSM





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

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

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

- **a hint towards the HM :**

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

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

R(HZ) = 0.180 ± 0.011
R(LZ) = 0.161 ± 0.010

from pp and Be-7 measurements:

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

Borexino outlook

- extract best CNO sensitivity from current data
  (*i.e.* complete the anatomy of the Sun)

- Other physics:
  - geo-neutrinos with full data set
  - neutrino magnetic moment
  - SuperNovae neutrinos

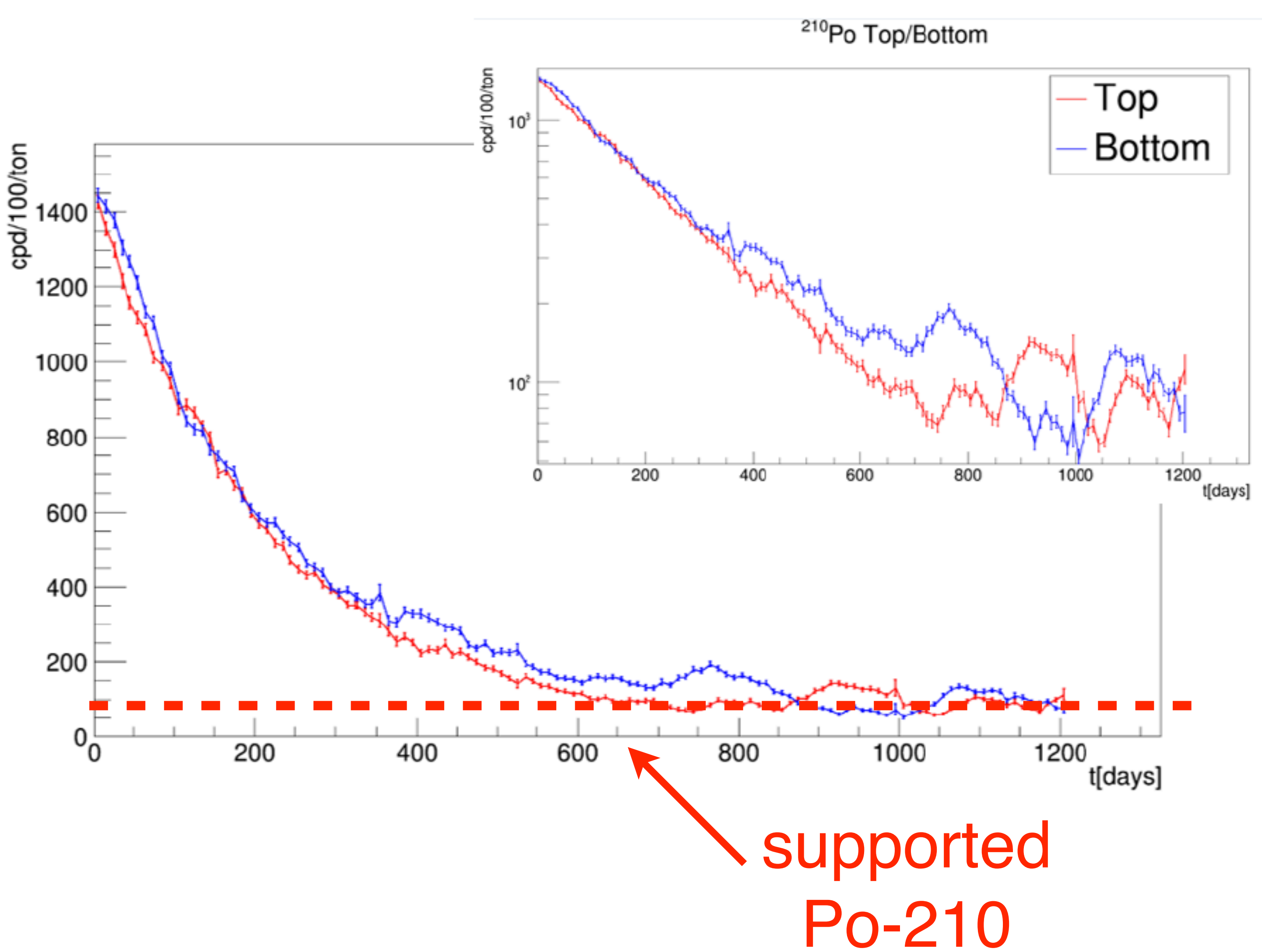
- Detector calibration
  - Improve all solar fluxes

- Scintillator purification
  - ultimate CNO measurement

Towards a CNO solar neutrino measurement

CNO solar neutrinos: the direct measurement of their rate could help solve the solar metallicity controversy surrounding the Standard Solar Model (^{7}Be (12% difference) and CNO (50-60% difference))

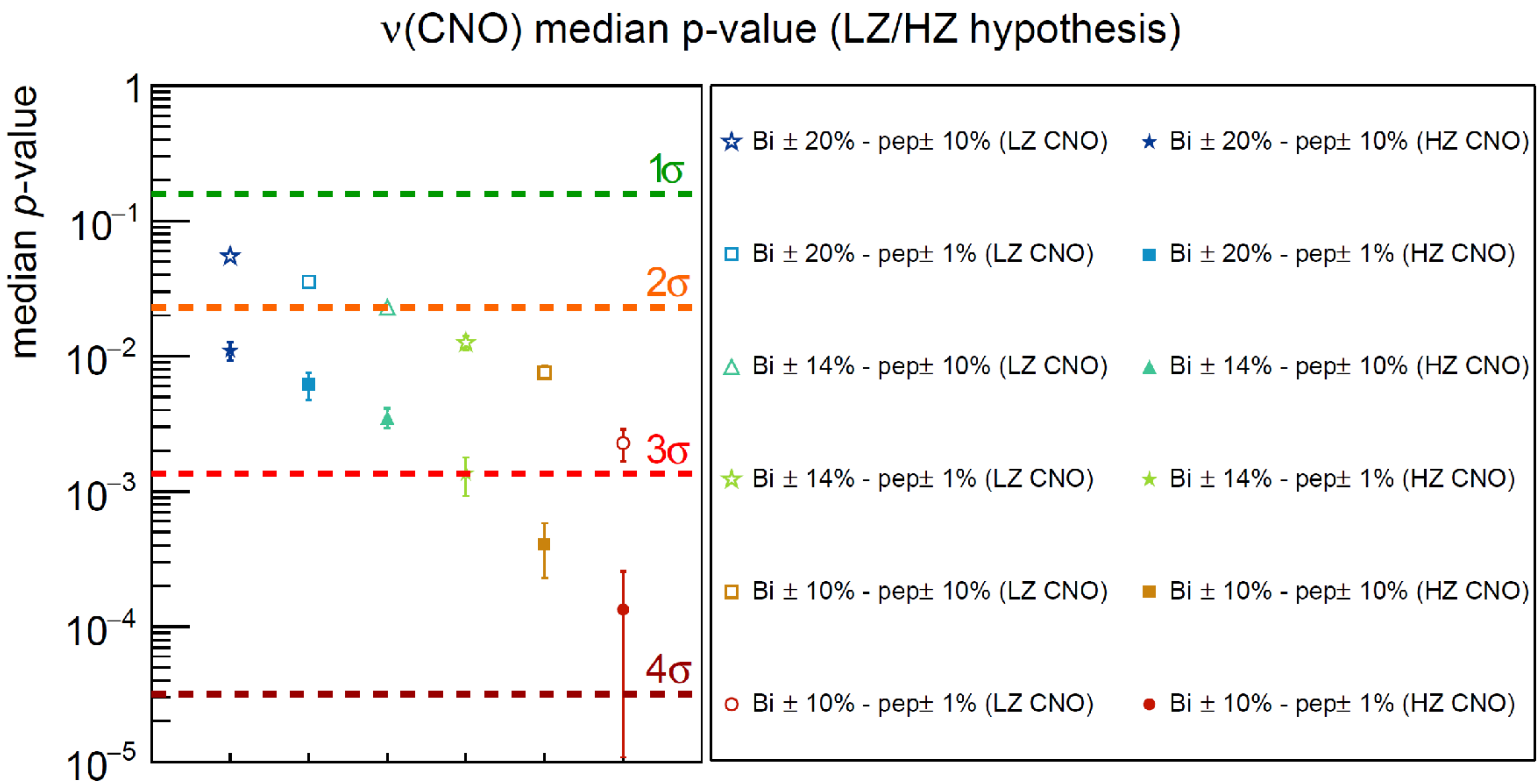
Bi-210 spectrum is quasi-degenerate



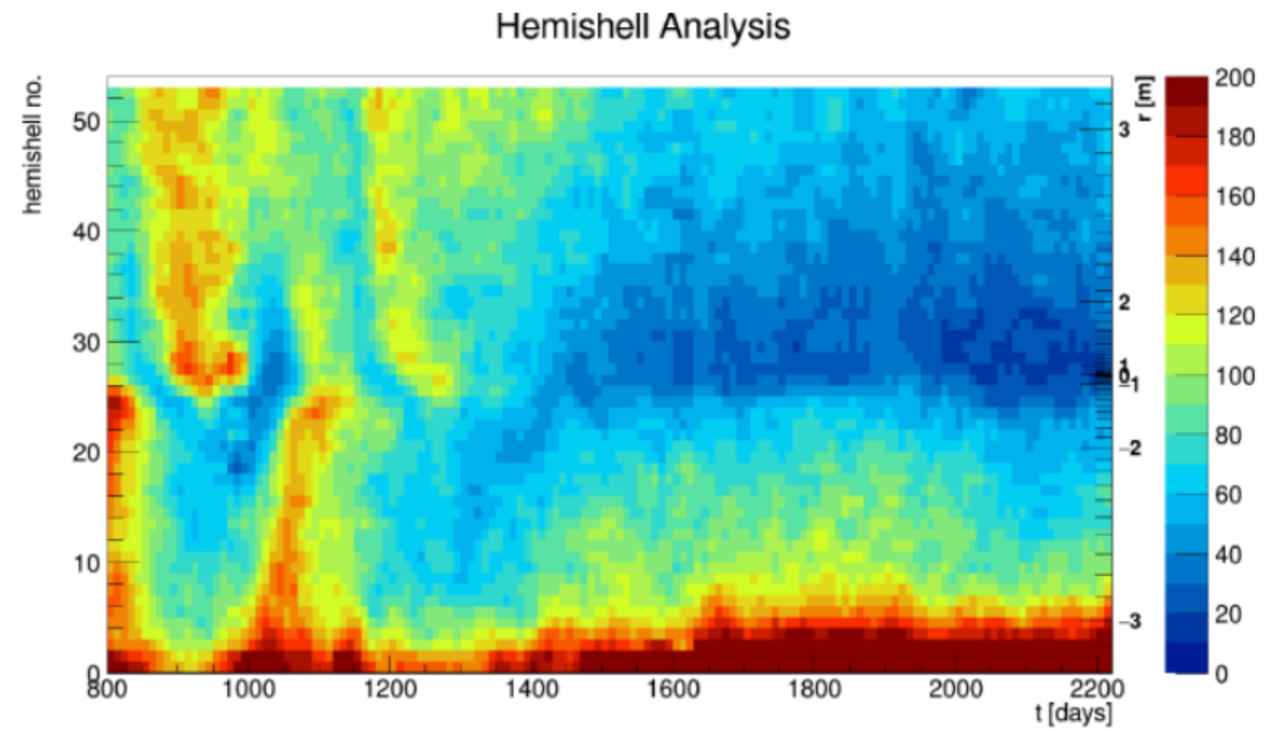
- supported Po-210 determines constrains residual Bi-210
- attempts plagued by fluid convection causing Po-210 mixing

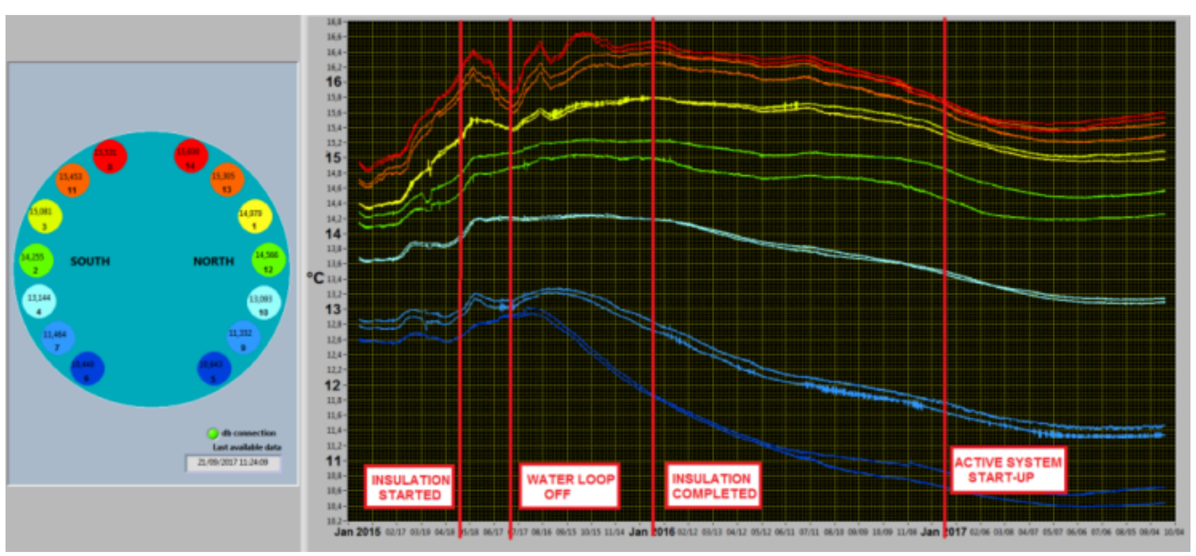
CNO sensitivity

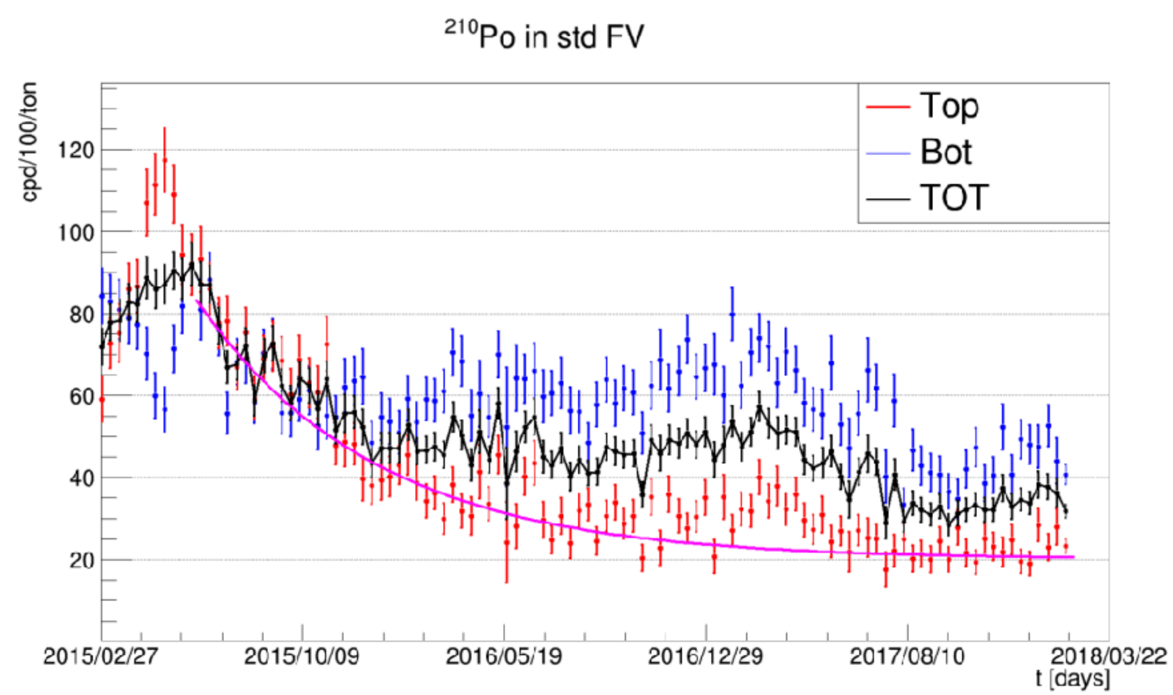
requires known and stable Bi-210, measured at 10-20%



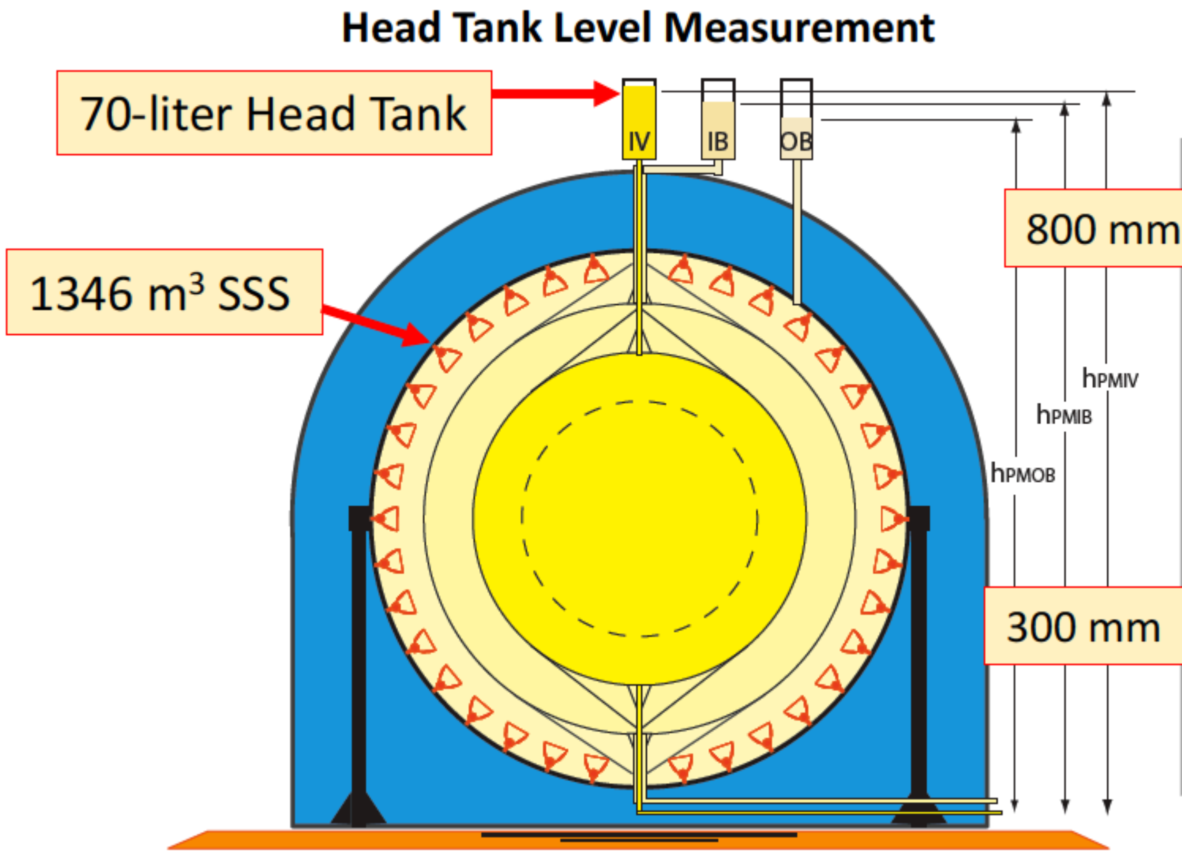
Detector thermal stabilization

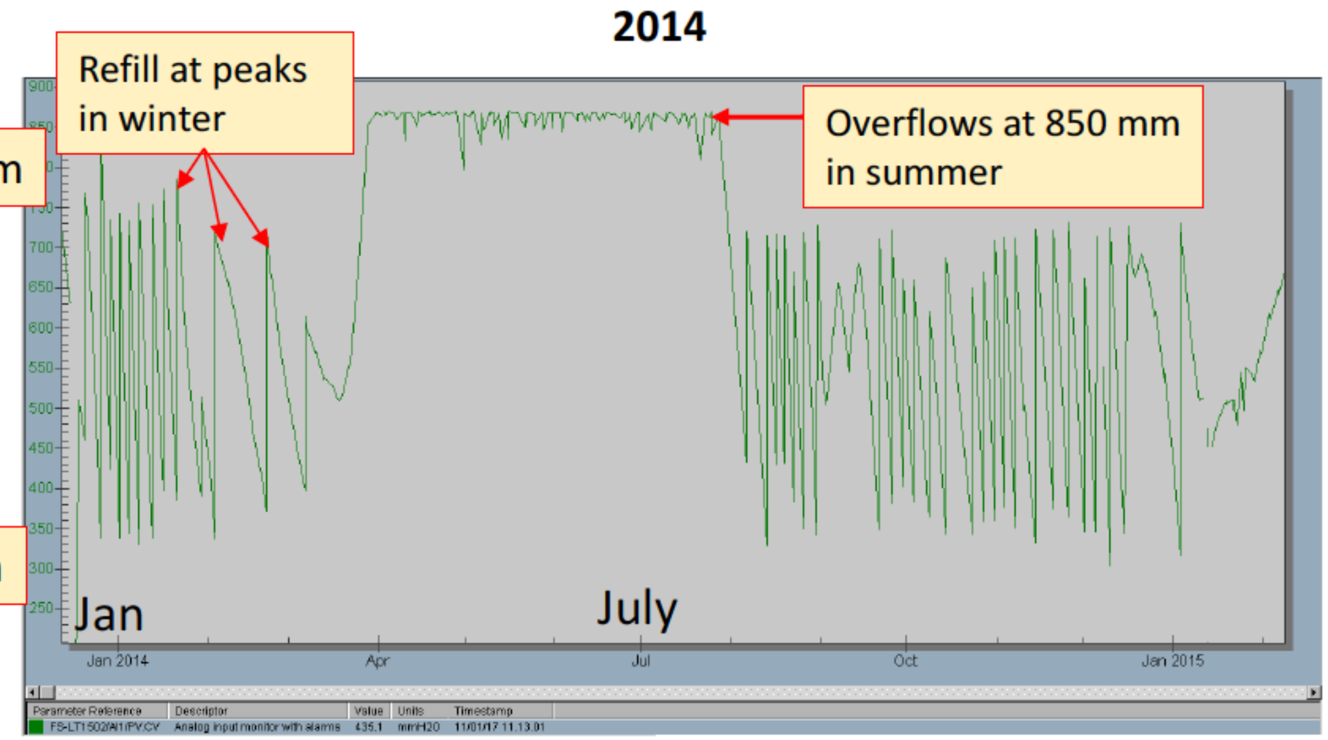


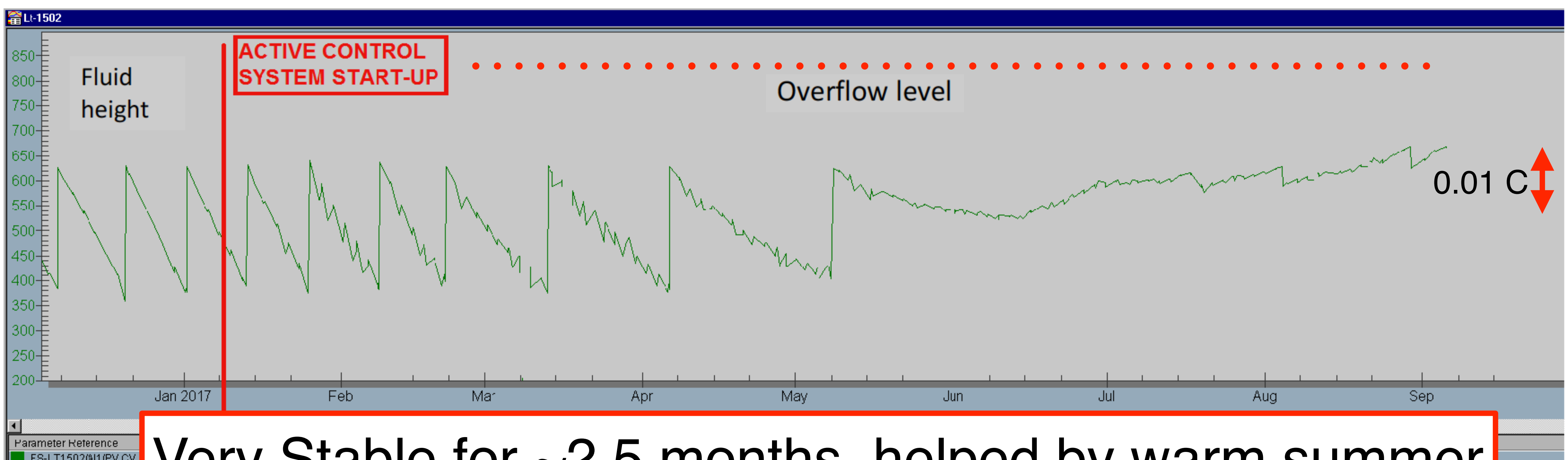




A very sensitive thermometer

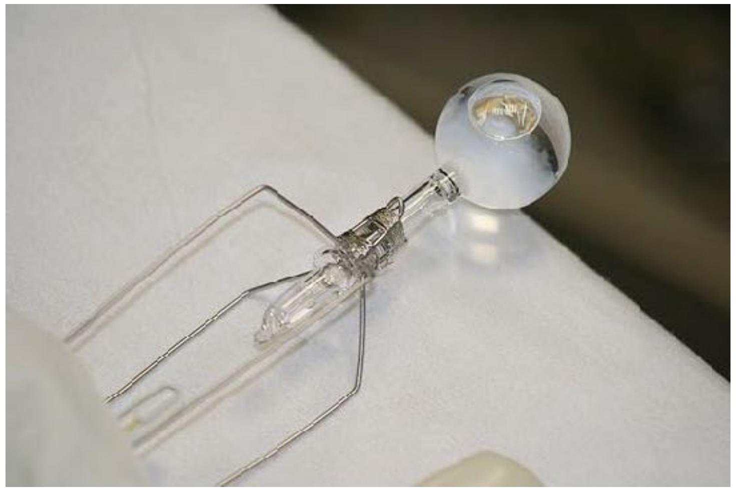




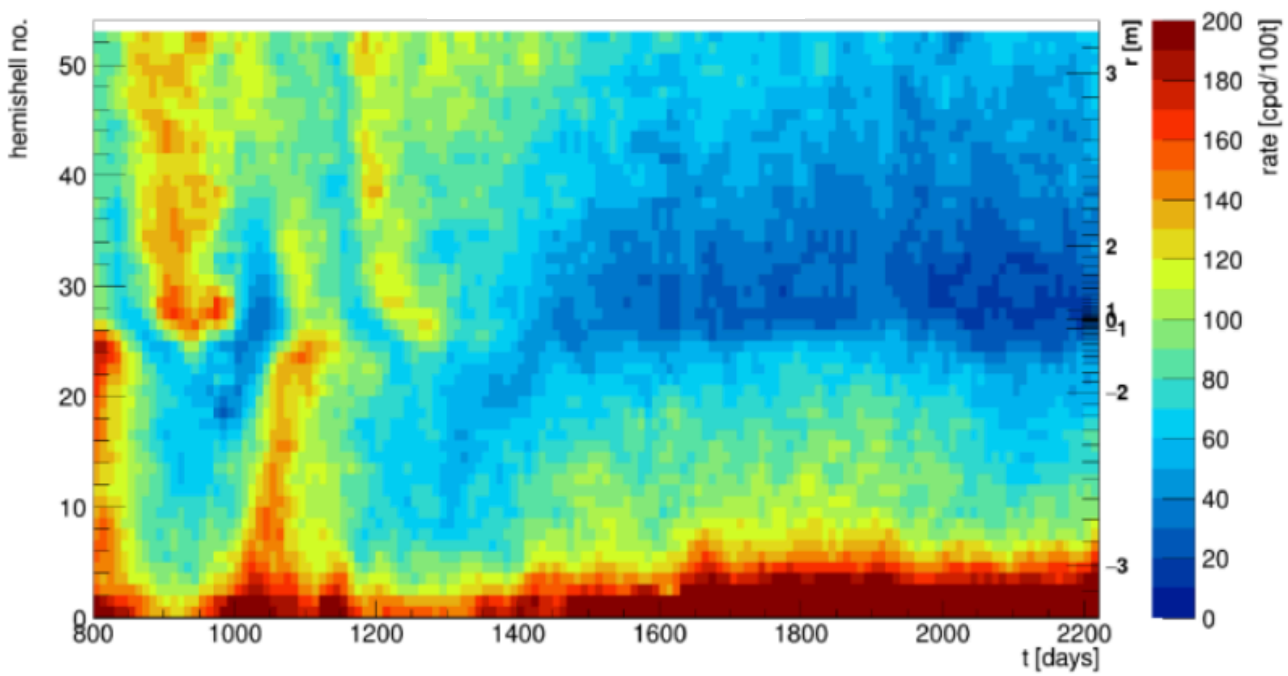


Very Stable for ~2.5 months, helped by warm summer

Summary



- Solar neutrinos essential in proving how the Sun burns and in discovering and studying the physics of neutrino oscillations
- Borexino has mapped out the entire pp solar fusion chain with high precision
- A measurement of CNO neutrinos would give us key knowledge of the Sun's metallicity
- Low-background techniques developed by Borexino have defined the standard for rare-event physics



the Borexino collaboration

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INFN Istituto Nazionale di Fisica Nucleare

LNGS

PRINCETON UNIVERSITY

UNIVERSITÀ DEGLI STUDI DI GENOVA

NATIONAL RESEARCH CENTER "KURCHATOV INSTITUTE"

St. Petersburg Nuclear Physics Inst.

TUM Technische Universität München

University of Houston

JAGIELLONIAN UNIVERSITY IN KRAKÓW

JÜLICH FORSCHUNGSZENTRUM

Virginia Tech

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UHH Universität Hamburg

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UNIVERSITY OF MASSACHUSETTS AMHERST 1863

Joint Institute for Nuclear Research

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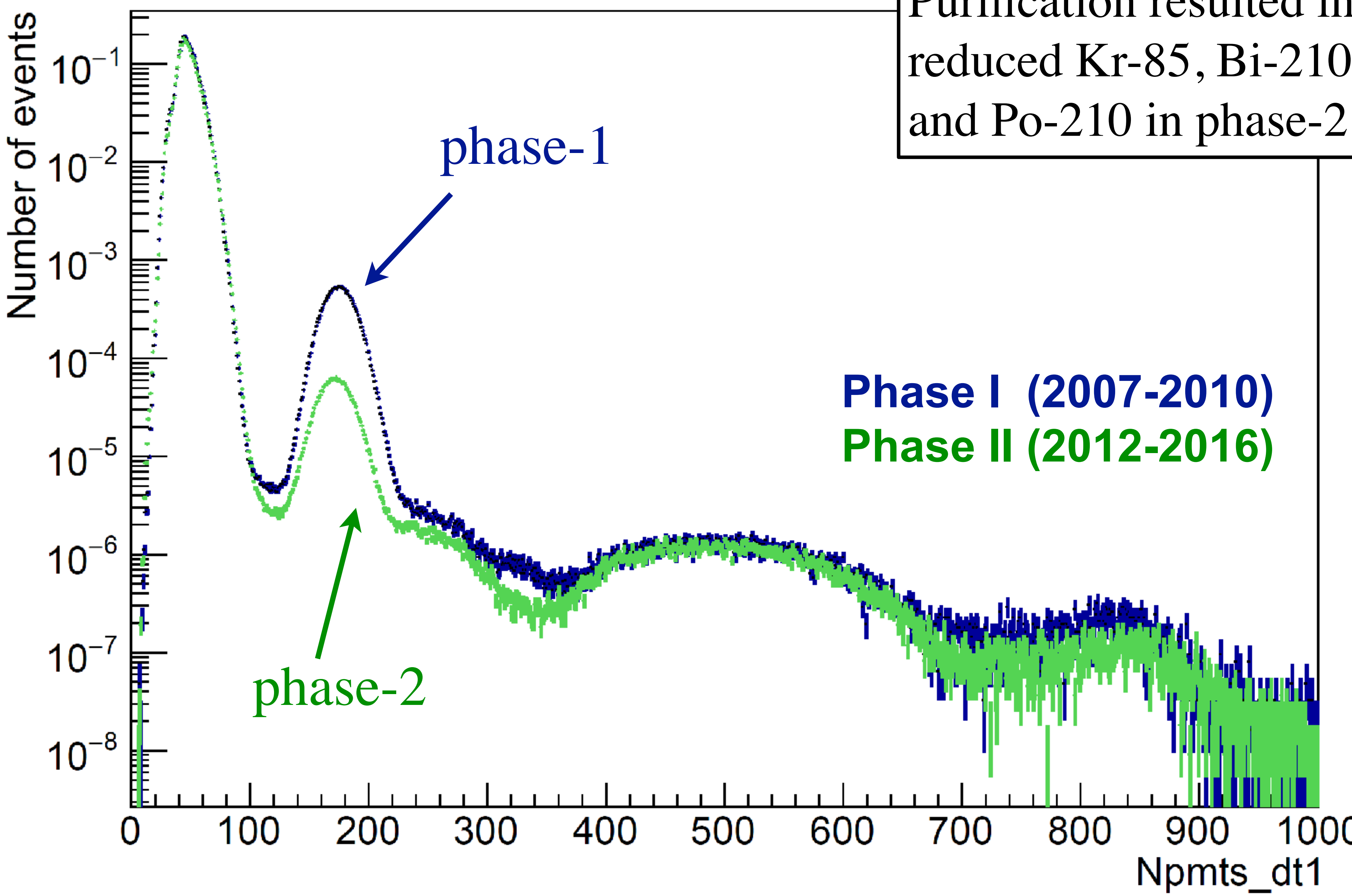
Stability between phase 1 and phase-2



Purification resulted in reduced Kr-85, Bi-210, and Po-210 in phase-2

two almost block diagonal 2-flavor ν mixings

solar, atmospheric, reactor, beam neutrinos build a picture of the oscillation of three active flavours

$$\delta m^2_{12} \sim 7.5 \times 10^{-5} \mathrm{eV}^2$$

$$\sin^2\theta_{12} \sim 0.3$$

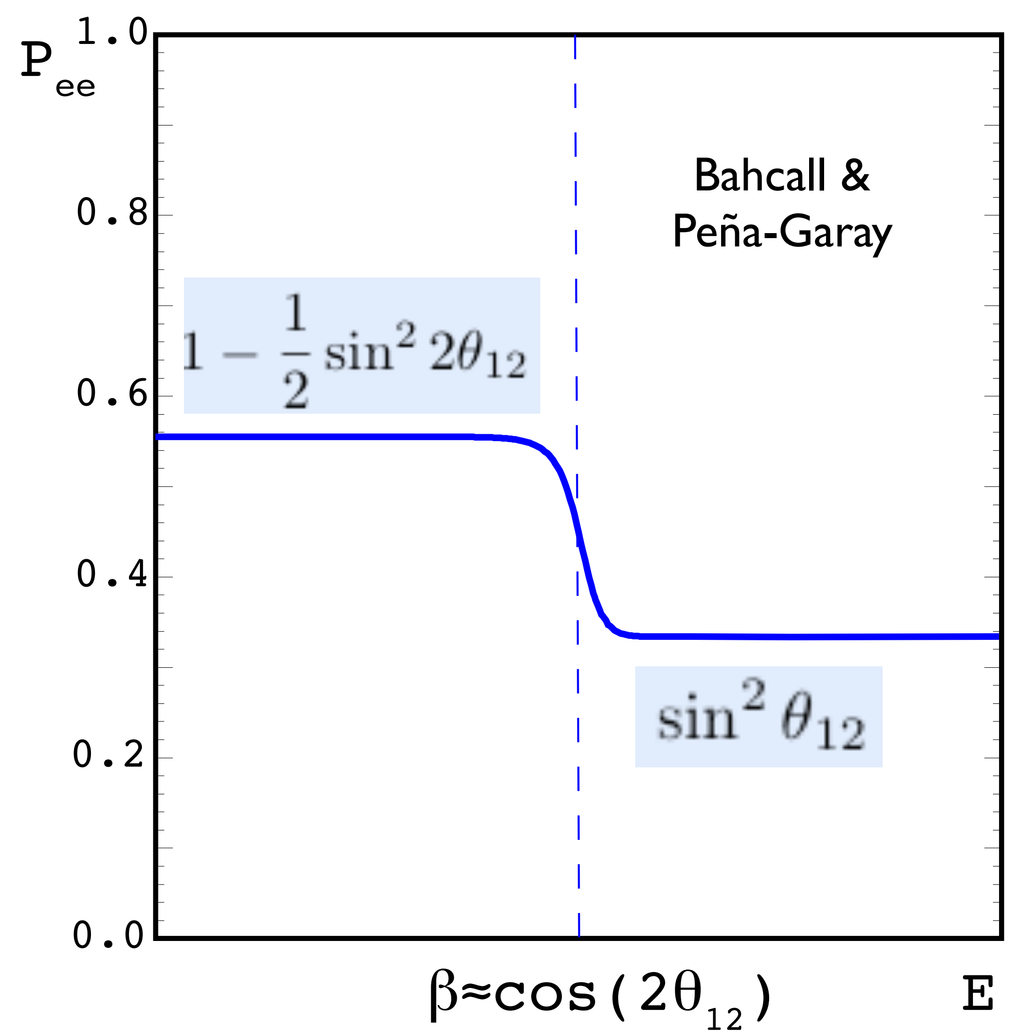
$$\delta m^2_{23} \sim 2.4 \times 10^{-3} \mathrm{eV}^2$$

$$\sin^2\theta_{23} \sim 0.4$$

$$\sin^2\theta_{13} \sim 0.02$$

neutrino oscillations firmly established

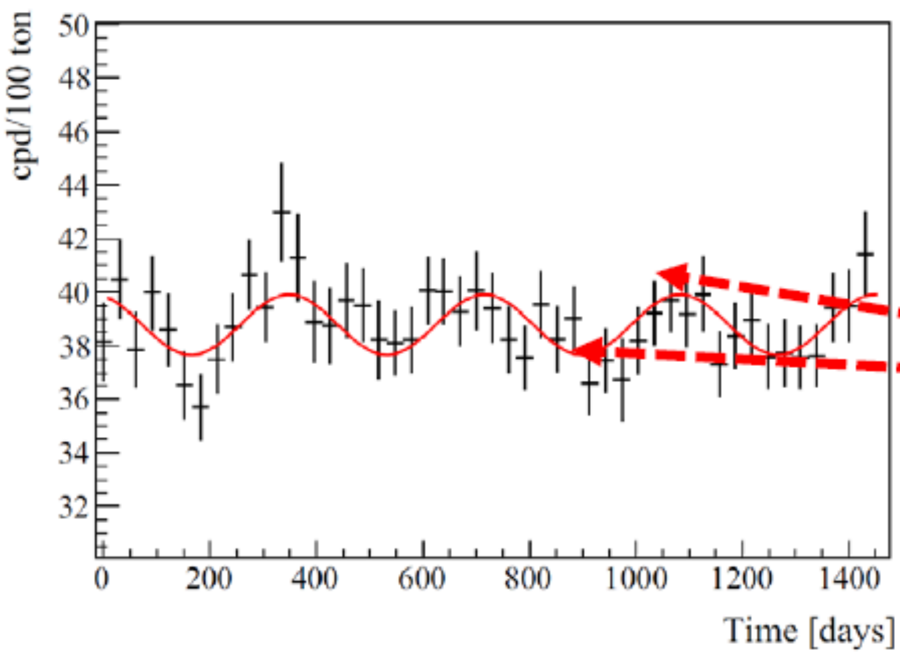
the MSW-LMA solution for solar neutrinos predicts an energy-dependent survival probability for electron neutrinos

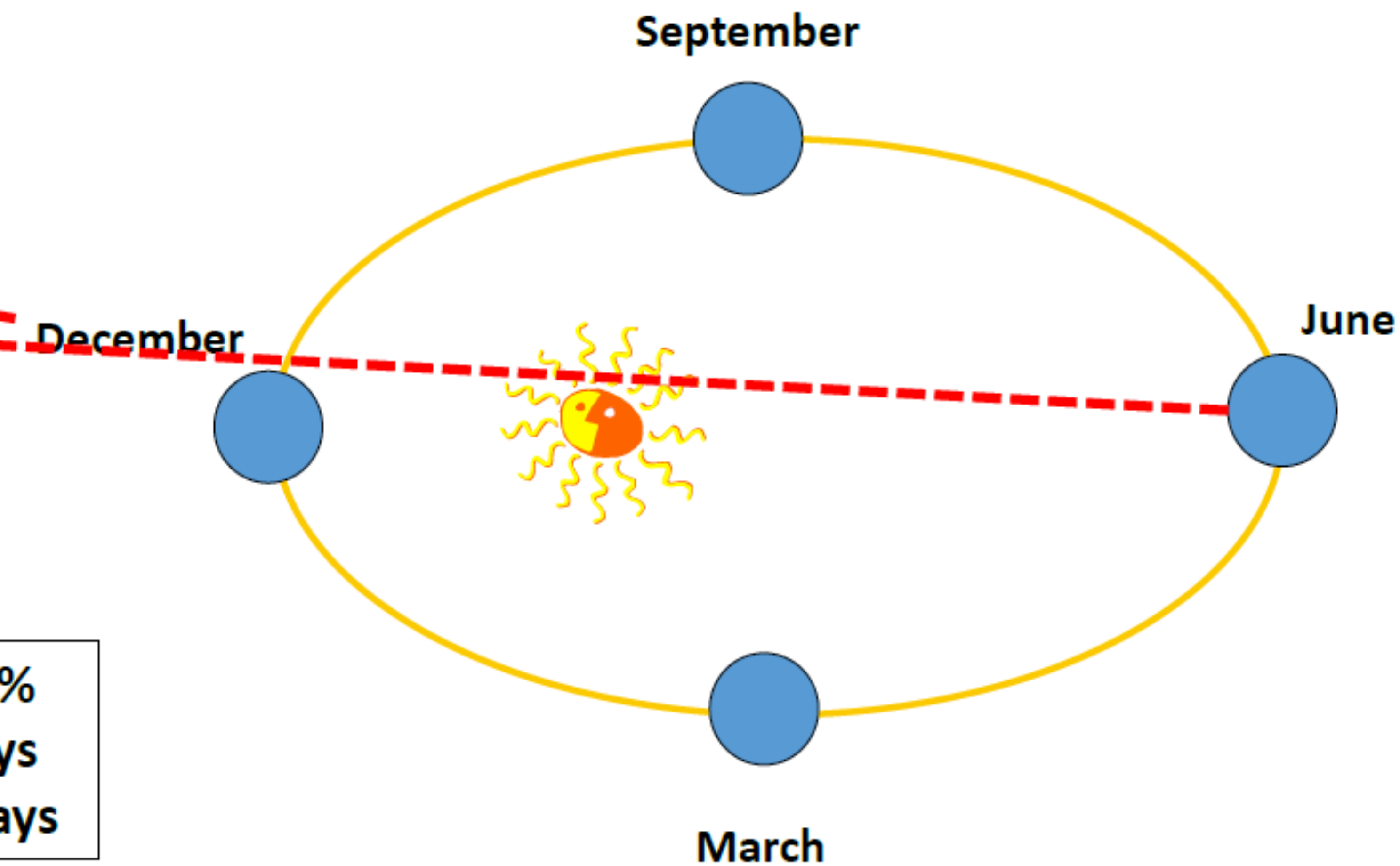


Solar metallicity

Be-7 seasonal modulation

M. Agostini et al., Astropart.Physics 92 (2017) 21–29



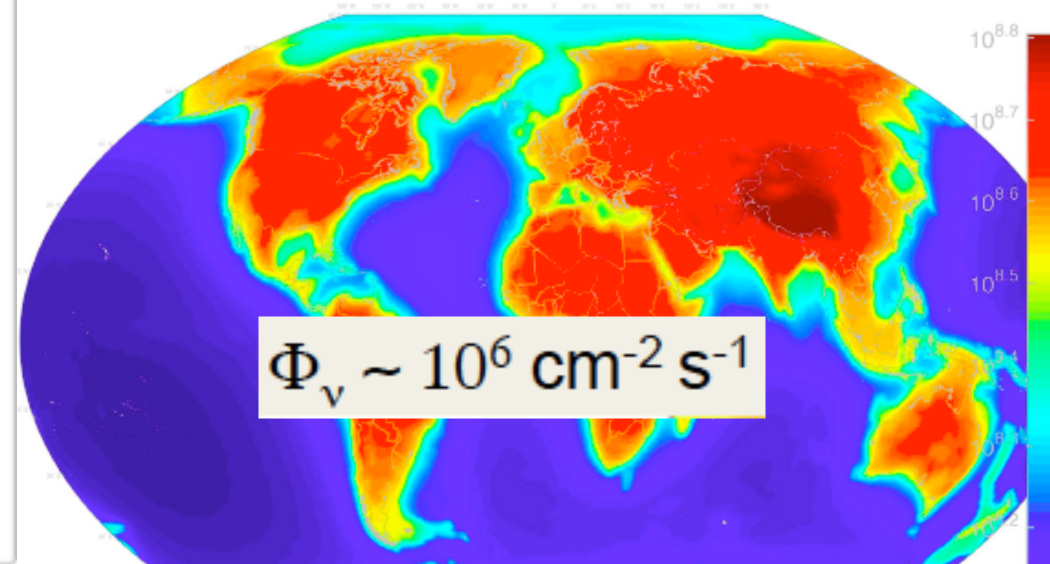


Fit to the evolution of the rate in time (bin of 30 days) ⇨

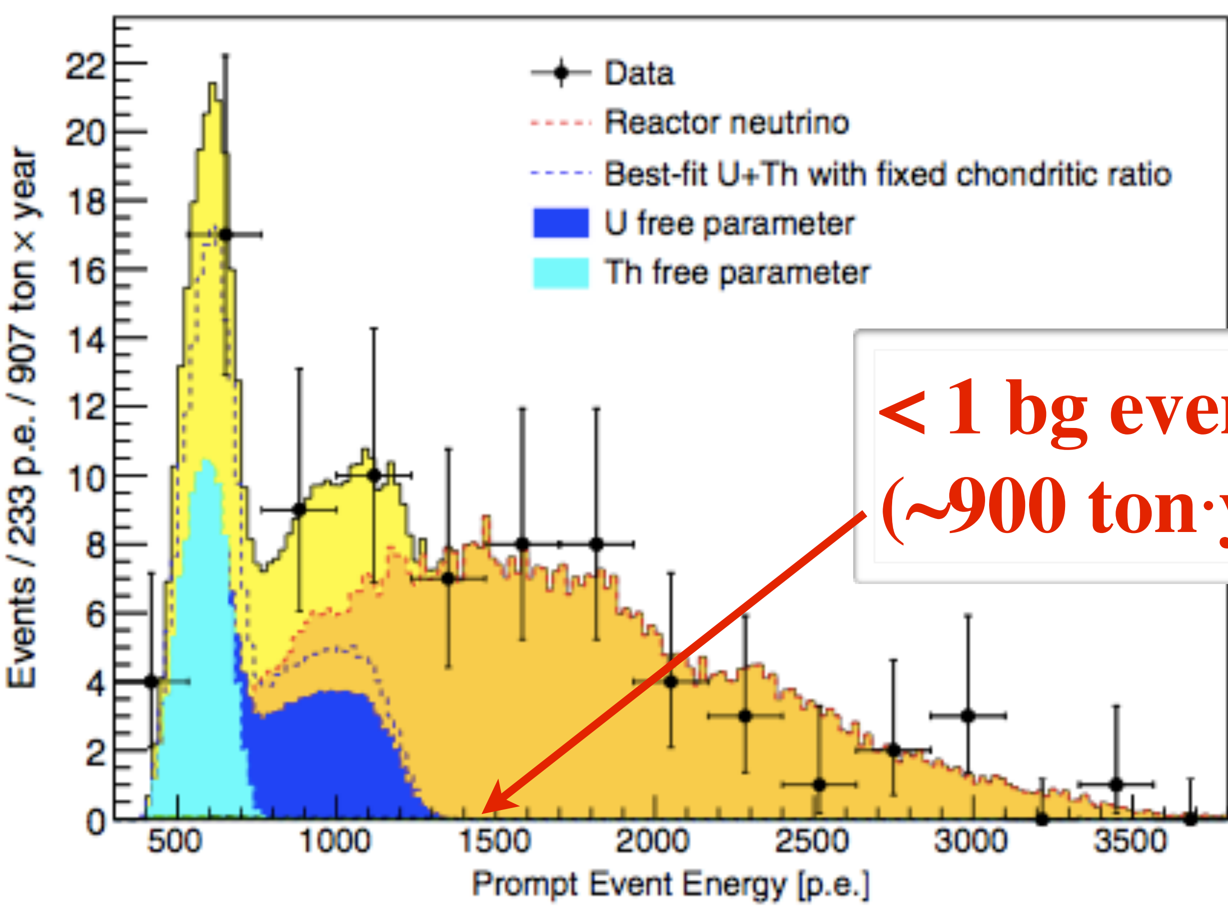
ε = (1.74 ± 0.45)%
T = (367 ± 10 days
Φ = (-18 ± 24) days

Geo-neutrinos (2056 days)

- Anti-neutrinos from beta decays in the Earth
- Detected via IBD, characteristic coincidence
    - ^{232}Th and ^{238}U chains
    - ^{40}K (below IBD threshold)
- Observed by two experiments:
    - First reported by KamLAND (’05), then ’11, ’13
    - Borexino published in ’10, ’13, ’15



Usman, Jocher, Dye, McDonough, Learned
Scientific Reports, Sept. 2015



< 1 bg event!
(~900 ton·yr)

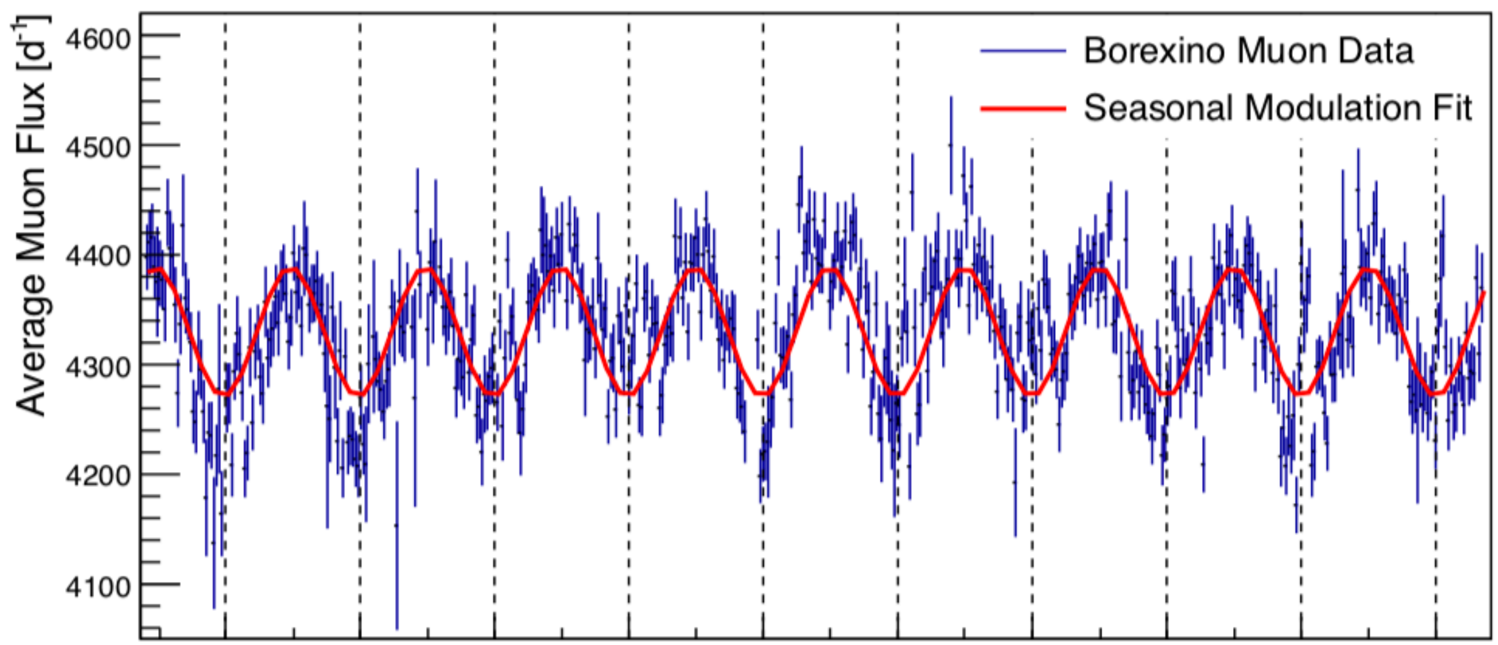
extremely low background allows for a measurement even with low statistics (null hypothesis excluded at 5.9σ)

[PRD 92 031101R (2015)]

$$\text{Sgeo} = 23.7^{+6.5}_{-5.7}(\text{stat})^{+0.9}_{-0.6}(\text{sys})$$

(assuming Th:U chondritic ratio = 3.9)

Cosmic ray flux



arXiv:1808.04207