Solar Neutrinos

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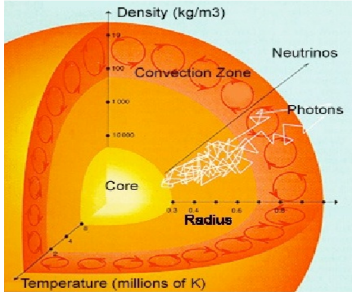
The Standard Solar Model(s): SSM

- Most recent Standard Solar Model (SSM) is named B16
  - N.Vinyoles et al., Astroph. Journ. 835 (2017) 202
  - previous version was SFII (2011)
- Model the evolution of the star from formation until now 4.57 10^9y
  - assume equilibrium between gravitation and pressure
- Input:
  - Solar Luminosity and Radius
  - 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
- Observables:
  - Helioseismology
  - Solar Neutrinos

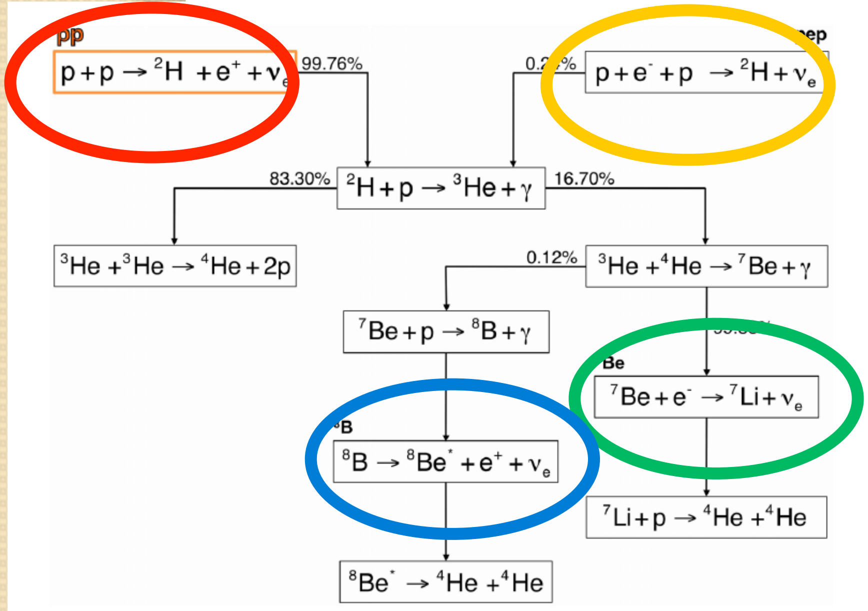


The pp chain

$$4H + 2e^{-} \rightarrow {}^{4}He + 2e^{+} + 2\nu_{e} + 26.7 \quad MeV$$

Each neutrino is labeled according to the reaction in which it is emitted:

- pp-neutrinos
- pep-neutrinos
- ^{7}Be-neutrinos
- ^{8}B-neutrinos
- hep-neutrinos



pp

$p + p \rightarrow {}^{2}H + e^{+} + \nu_{e}$ 99.76%

pep

0.24% $p + e^{-} + p \rightarrow {}^{2}H + \nu_{e}$

83.30% $^{2}H + p \rightarrow {}^{3}He + \gamma$ 16.70%

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

0.12% $^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$

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

^{7}Be

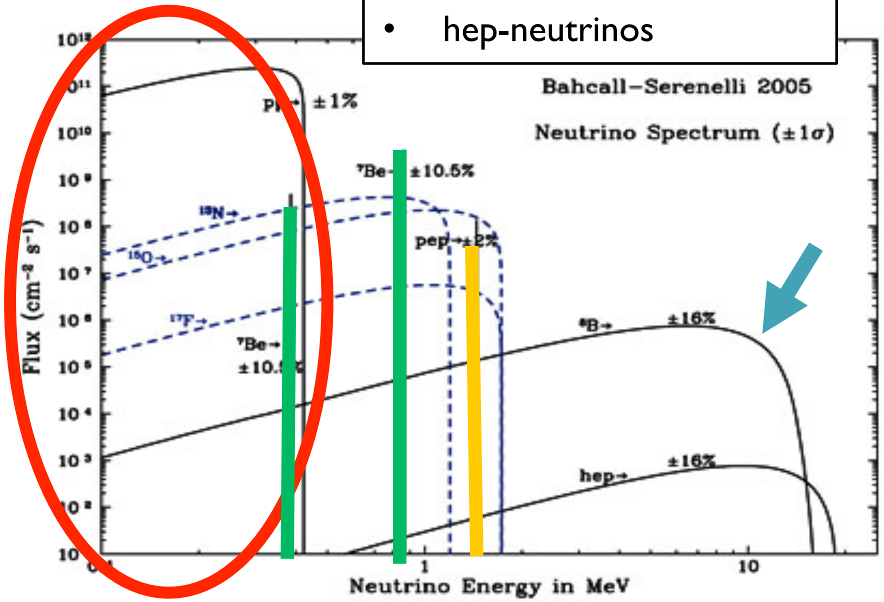
$^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu_{e}$

^{8}B

$^{8}B \rightarrow {}^{8}Be^{*} + e^{+} + \nu_{e}$

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

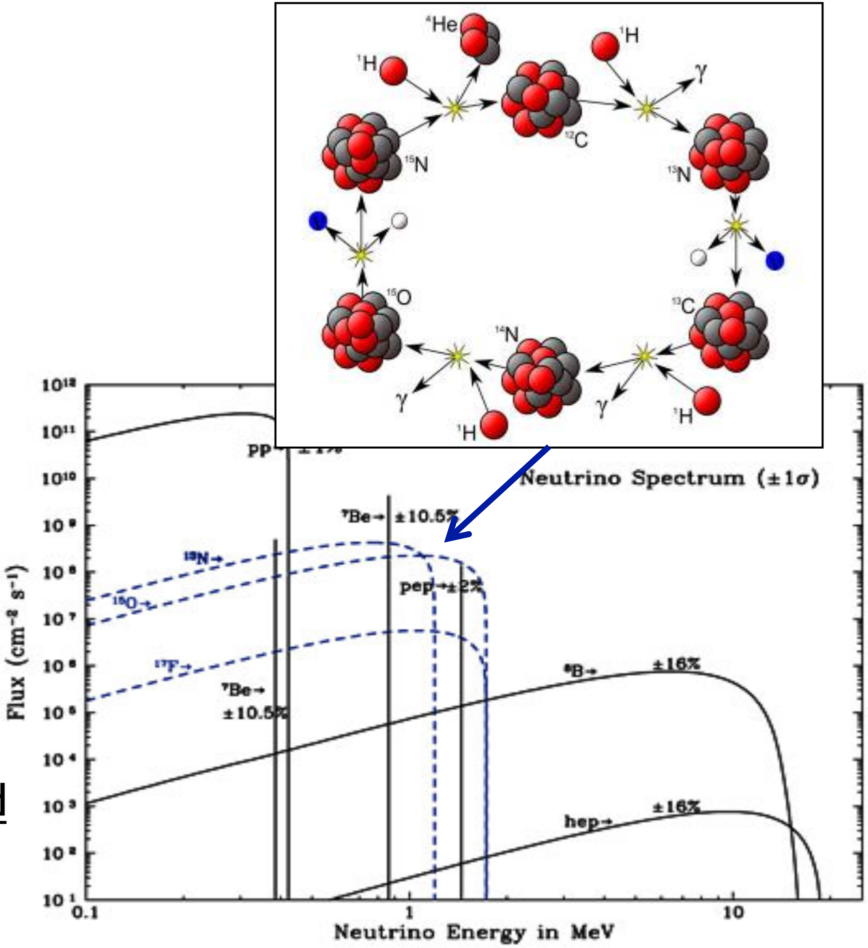
$^{8}Be^{*} \rightarrow {}^{4}He + {}^{4}He$



~99% of the Sun energy

The CNO cycle

- C, N, and O act as catalyzers of the same net reaction
- The CNO cycle has a strong temperature dependence
- It becomes dominant for stars heavier then the Sun
- In the Sun only about 1-2% of Energy is produced by CNO cycle
- The 3 neutrino species (^{13}N, ^{15}O, ^{17}F) emitted by the CNO cycle reactions have <u>never been observed so far.</u>



Why measure solar neutrinos?

Astrophysics

Original motivation of the first experiments on solar ν was to test Standard Solar Model (SSM)

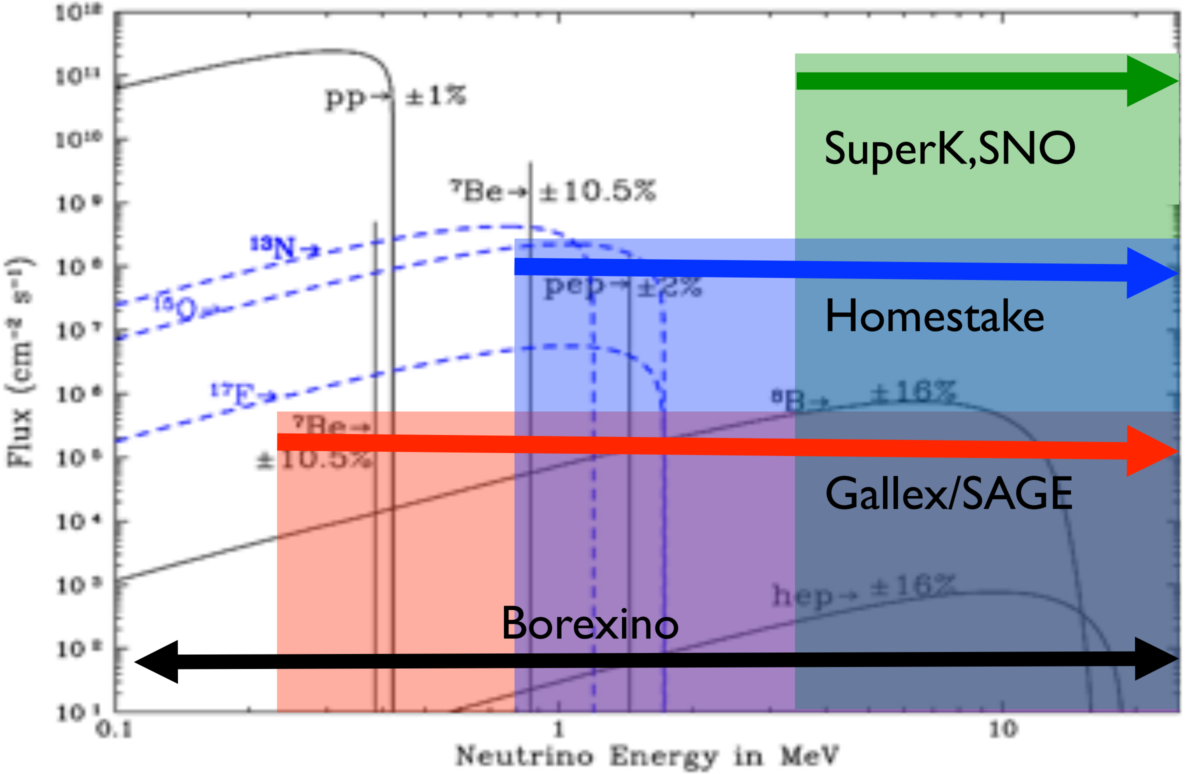
Study of the details of ν flux

Solar neutrino problem

Particle physics

Solar ν experiments played a major role in the discovery of oscillations

Solar neutrino detectors



50 years of solar neutrino detection

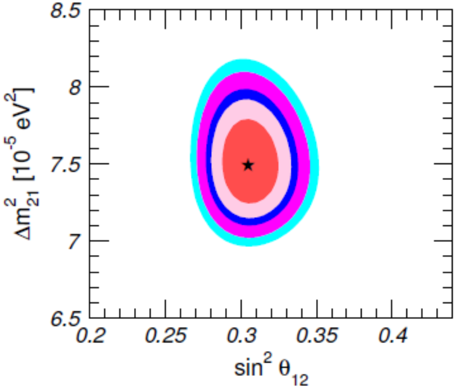
		ν detected	Signal	Signal/SSM
Radiochemical	Homestake	^{7}Be, pep, CNO, ^{8}B	256 ± 0.23 SNU	0.32 ± 0.05
	Gallex/GNO/ SAGE	pp,^{7}Be, pep,CNO,^{8}B	66.2 ± 3.1 SNU	0.52 ± 0.03
Water Cherenkov	SK I+II+III+IV	^{8}B	F_{8B}=2.345±0.039 10^6 cm^{-2} s^{-1}	0.42 ± 0.06
	SNO	^{8}B	F_{ES}=2.04±0.18 10^6 cm^{-2} s^{-1} F_{CC}=1.67±0.07 10^6 cm^{-2} s^{-1} F_{nc}=5.25±0.20 10^6 cm^{-2} s^{-1}	0.36 ± 0.06 0.30 ± 0.04 0.94 ± 0.14
Scintillator	Kamland	^{7}Be ^{8}B	58.2± 9.4 cpd/100t 0.15 ± 0.02 cpd/100t	0.66 ± 0.11 -
	Borexino Phase I (new Phase II not included here)	pp (Phase II) ^{7}Be pep CNO ^{8}B	144 ± 16 cpd/100t 46.0± 2.2 cpd/100t 3.1 ± 0.7 cpd/100t 0.22 ± 0.04 cpd/100t <7.9 95% CL cpd/100t	0.75 ± 0.08 0.63 ± 0.05 0.70 ± 0.15 0.43 ± 0.10 -

Adapted from A. Ianni Prog. Part. Nucl. Phys. 94 257 (2017)

We learned a lot…

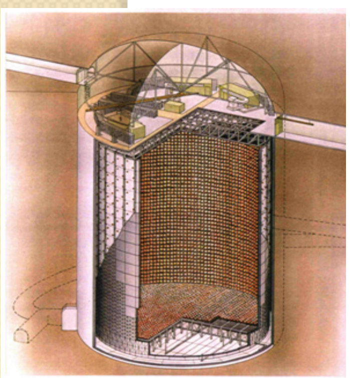
- Confirmation of the basic energy production mechanism in the Sun
- Solar Neutrino Problem was solved:
    - Evidence of ν oscillations
    - Interaction of ν with matter MSW

Global analysis of oscillation data



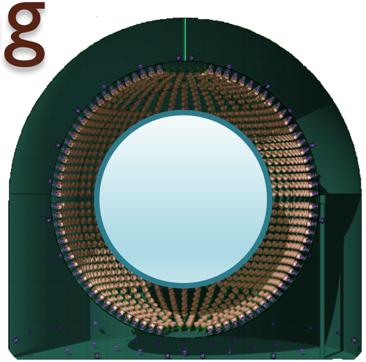
I. Esteban et al, JHEP 01 (2017).

…but we are still measuring



Water Chernkov:
Super-Kamiokande

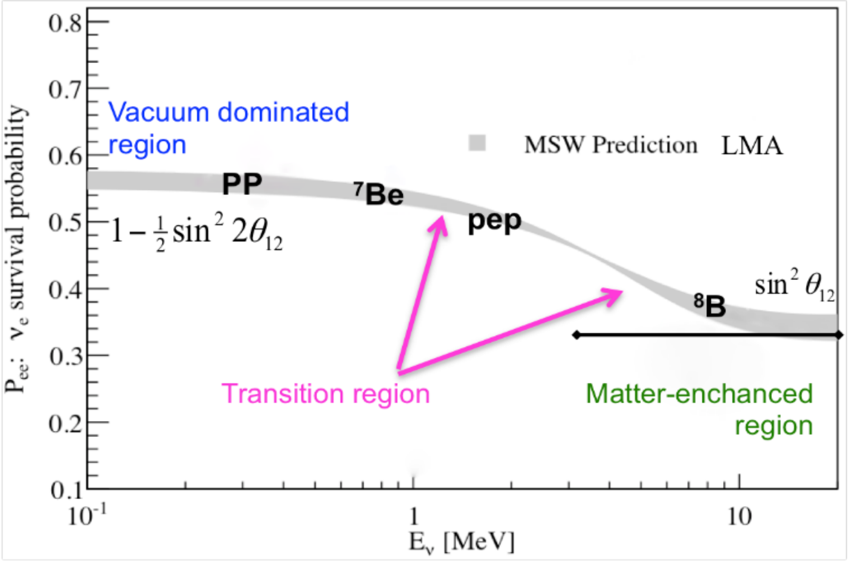
Liquid scintillator:
Borexino



Why still measure solar neutrinos? (1/2)

1. Particle Physics interest:
   Precision measurements to confirm LMA-MSW

- P_{ee} should show a Vacuum-to-Matter transition
- Non Standard Interactions could modify P_{ee} in the transition region
- Precise flux measurements of single spectral component
- Measure ^{8}B with low threshold
- Have good accuracy for the lowest ^{8}B energy bin

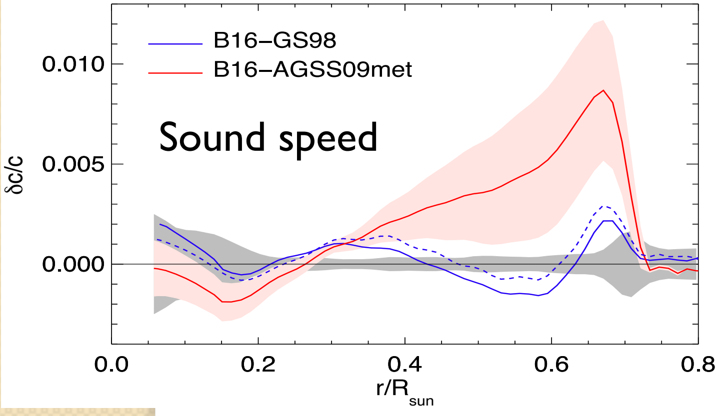


$$\boxed{i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}=\begin{pmatrix}-\frac{\Delta m^2}{4E}\cos 2\theta+\boxed{\sqrt{2}G_F N_e} & \frac{\Delta m^2}{4E}\sin 2\theta\\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}}$$

Why still measure solar neutrinos? (2/2)

2. Astrophysics interest: the metallicity puzzle

- Since 2001: a new 3D analysis of spectroscopic data from photosphere indicates lower values of surface solar metallicity (LZ)
- But solar models reproducing these new LZ values **disagree with helioseismology data**

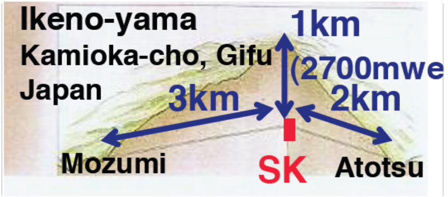


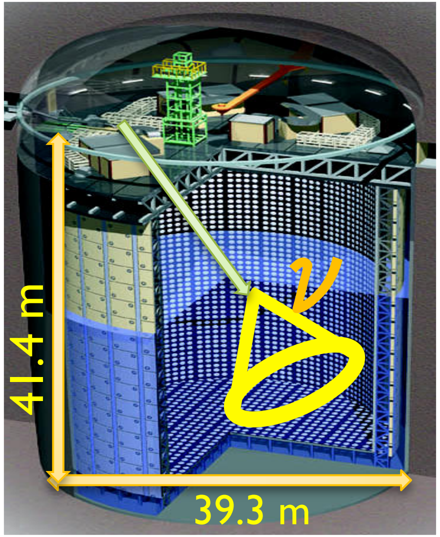
ν flux	GS98 (HZ)	AGSS09met (LZ)	cm^{-2} s^{-1}	Δ
pp	5.98 (1±0.006)	6.03 (1±0.005)	x 10^{10}	+0.8%
pep	1.44 (1±0.01)	1.46(1±0.009)	x 10^{8}	+1.4%
^{7}Be	4.93 (1±0.06)	4.50 (1±0.06)	x 10^{9}	-8.7%
^{8}B	5.46 (1±0.12)	4.50 (1±0.12)	x 10^{6}	-18%
^{13}N	2.78 (1±0.15)	2.04 (1±0.14)	x 10^{8}	-27%
^{15}O	2.05 (1±0.17)	1.44 (1±0.16)	x 10^{8}	-24%

Solar ν fluxes are potentially sensitive to the Sun metallicity

Super-Kamiokande

- Super-Kamiokande detector
  - Located at Kamioka, Japan
    - 1000 m under Ikenoyama mountain
    - 2700 m water equivalent
  - 50 kton ultra pure water tank
    - More than 11,000 20-inch PMTs for ID
    - 22.5 kton for the fiducial volume
  - Water Cherenkov technique
    - Energy, direction, particle ID
- Over 20 years of solar neutrino observation

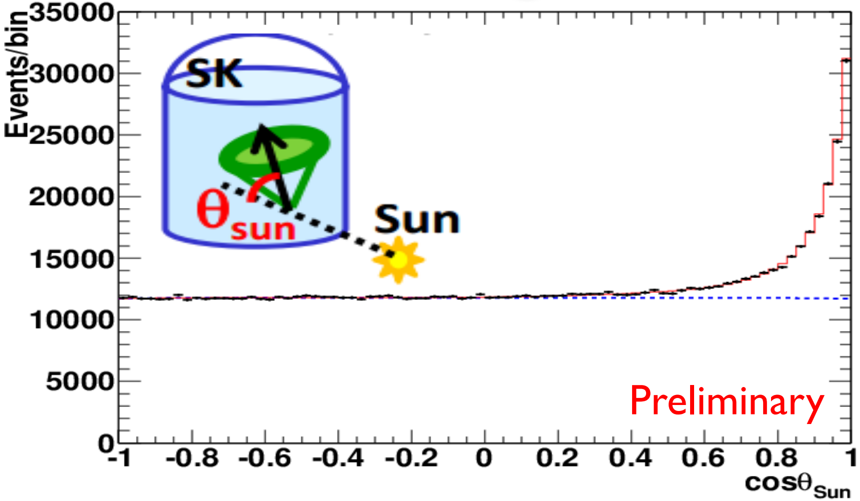




Observed ^{8}B solar neutrino signal

- 89k solar neutrino events observed (until March 2017)
- Measured ^{8}B fluxes are consistent within uncertainties

SK phase	Energy [MeV(kin)]	Live time [days]	^{8}B Flux [$\times 10^6$/cm^2/s]
SK I	4.5-19.5	1496	2.38±0.02±0.08
SK II	6.5-19.5	791	2.41±0.05±0.16
SK III	4.0-19.5	548	2.40±0.04±0.05
SK IV	3.5-19.5	2365 2645	2.32±0.02±0.04 under preparation
All SK		5200	2.355±0.033

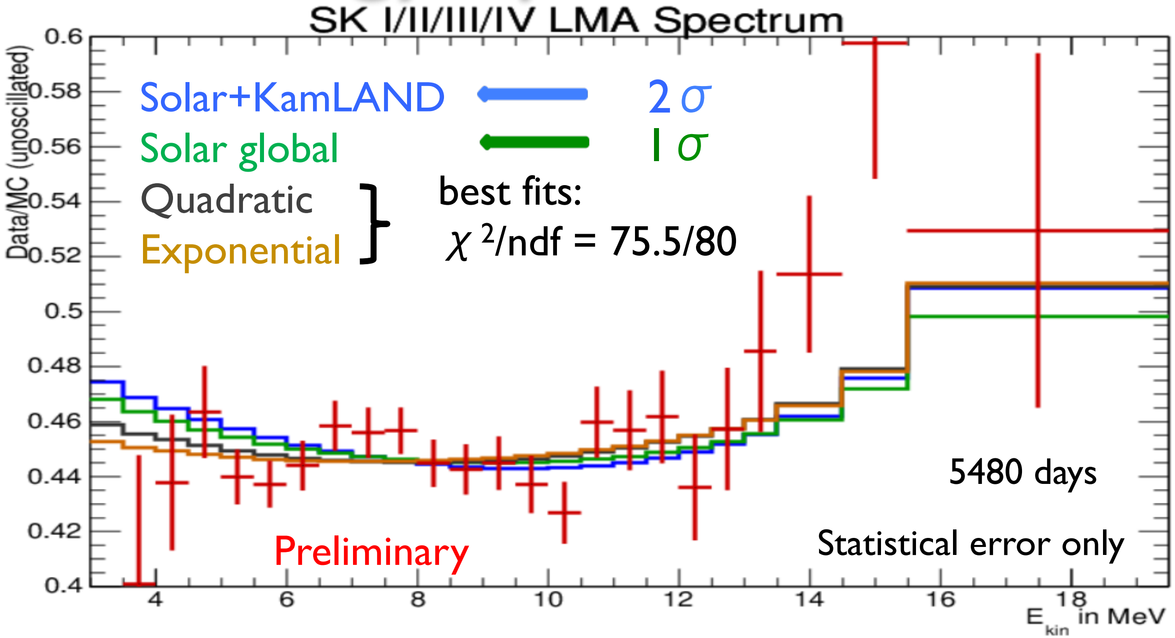


MC: 5.25×10^6/cm^2/s

DATA/MC = 0.4486±0.0062

(stat+syst)

SK energy spectrum



All SK phases are combined without regard to energy resolution or systematics in this figure.

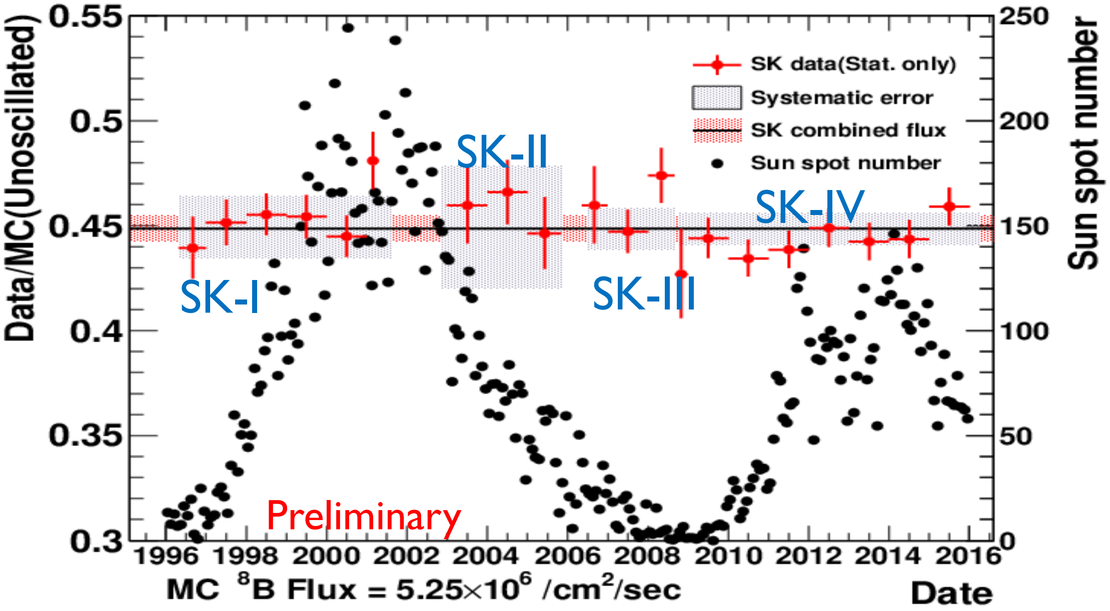
SK spectrum is consistent within

1 σ with the MSW upturn obtained with oscillation params from Solar Global Analysis

2 σ with the MSW upturn obtained with oscillation params from Solar+Kamland Analysis

^{8}B solar neutrino yearly flux

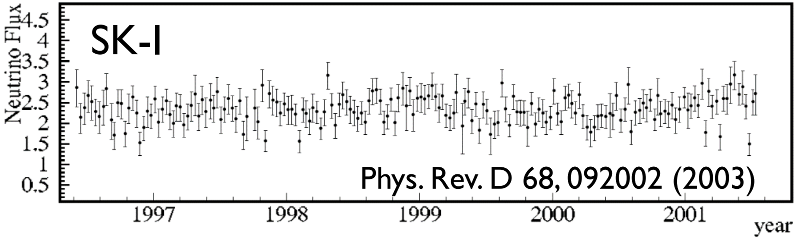
- Sun spot numbers are strongly correlated with the solar activity cycle (~11 years).
- SK has observed ^{8}B solar neutrinos for more than 1.5 cycles.
- Data taken until March 2016 is used.



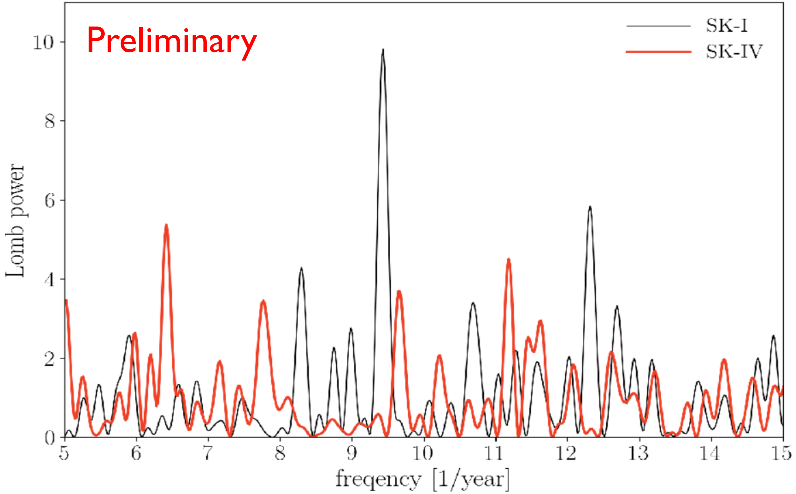
No correlation with the 11 years solar activity is observed: Super-K solar rate measurements are fully consistent with a <u>constant</u> solar neutrino flux: χ^2/ndf = 15.5/19 (Prob. = 68.9%)

SK Periodic modulation

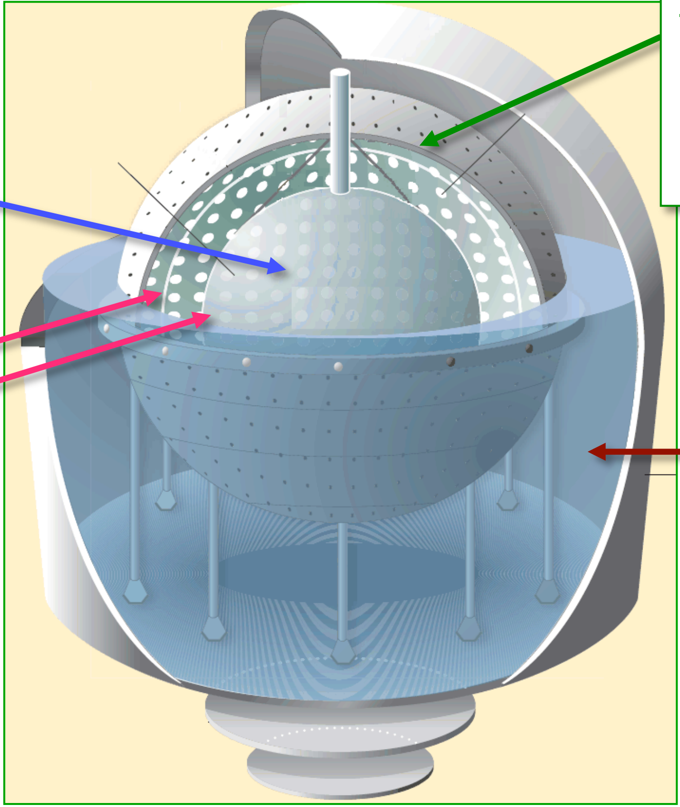
- In 2003, SK collaboration inspected time variations of SK-I ^{8}B ν flux (Phys. Rev. D 68, 092002 (2003)) using Lomb-Scargle (LS) method and found none.
- Others have observed a significant peak at 9.42 year^{-1}, e.g. Astropart. Phys. 82, 86-92 (2016), using Generalized Lomb-Scargle (GLS).
- SK has recently reanalyzed both SK-I and SK-IV using GLS:
  - 5-days binning
  - same energy range (4.5-19.5MeV$_{kin}$)
  - similar live time: SK-I: 1496d, SK-IV: 1664d
- Search region [5-15] year^{-1}
- Maximum peak at 9.42 year^{-1} found in SK-I but not in SK-IV



Phys. Rev. D 68, 092002 (2003)



The Borexino Detector



Stainless Steel Sphere:

- 2212 PMTs
- ~ 1000 m^3 buffer of pc+dmp (light queched)

Scintillator:

278 t PC+PPO (1.4 g/l)

Nylon vessels:

(125 μm thick)

Inner r: 4.25 m

Outer r: 5.50 m

(radon barrier)

Water Tank:

γ and n shield

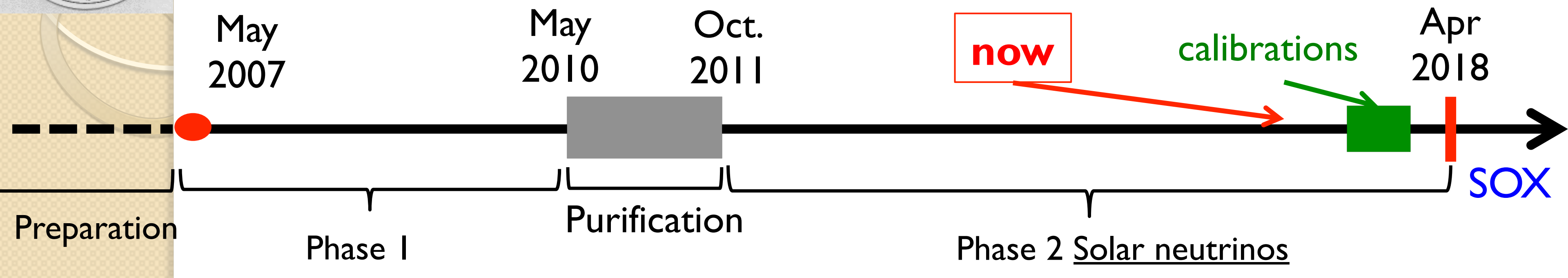
μ water Č detector

208 PMTs in water

2100 m^3

3800m w.e. of rock shielding

Borexino data taking campaign



May 2007

May 2010

Oct. 2011

now

calibrations

Apr 2018

SOX

Preparation

Phase 1

Purification

Phase 2 Solar neutrinos

Solar neutrinos

- ^{7}Be ν : 1st observation + precise measurement (5%); Day/Night asymmetry;
- pep ν : 1st observation;
- ^{8}B ν with low threshold;
- CNO ν : best limit;

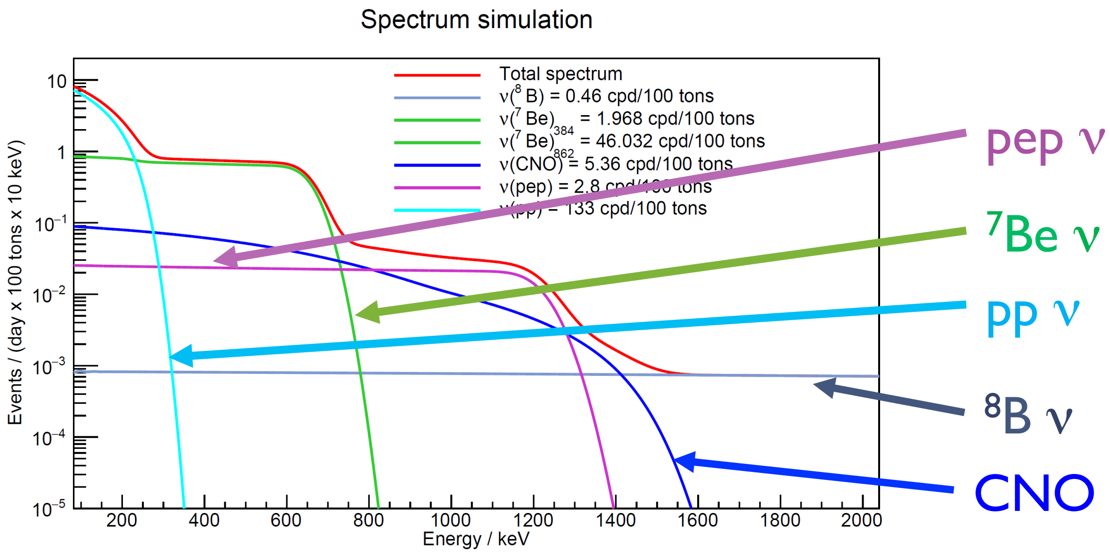
6 cycles of water extraction

- pp ν: 1st observation (Nature 2014)
- seasonal modulation of ^{7}Be ν (Astr.Phys. 92 (2017) 21) **NEW!**
- *First simultaneous precision spectroscopy of pp, ^{7}Be and pep solar ν* (arXiV:1707.09279) **NEW!**
- Update on ^{8}B neutrinos (arXiV:1709.00756) **NEW!**
- Update on ν eff. mag. moment (arXiv:1707.09355) **NEW!**

Borexino's solar neutrino signals

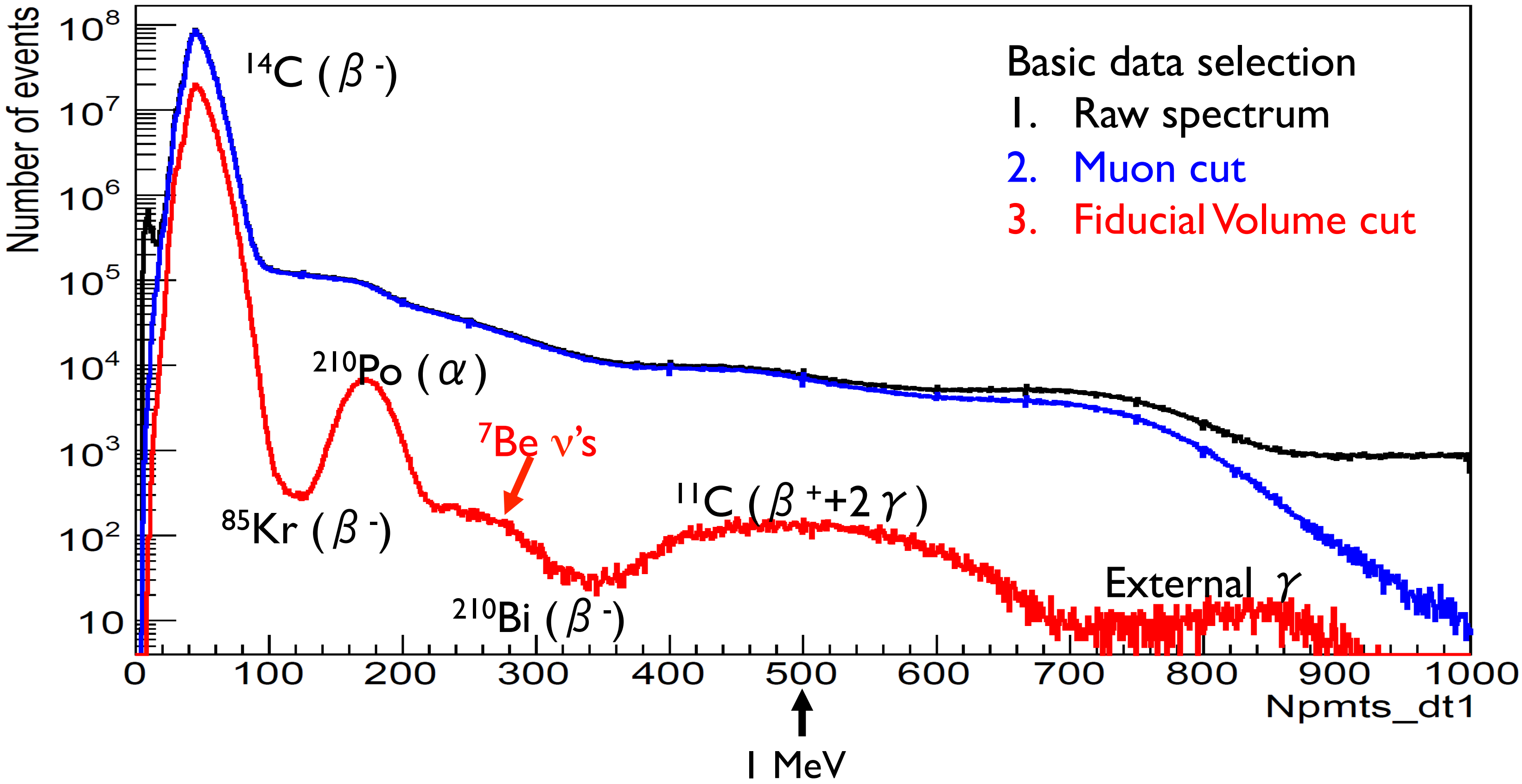
Elastic scattering on electrons

$$\nu_x + e^- \rightarrow \nu_x + e^-$$



So, what we see is only the energy carried away by the electron, NOT the total neutrino energy

The Borexino Energy spectrum



Borexino performance

For each scintillation event Borexino records

Number of collected photons [photoelectron yield ~ 500 p.e./MeV] → **Energy**

$$\frac{\sigma(E)}{E} \sim \frac{5\%}{\sqrt{E}}$$

Time of arrival each photons → **Position**

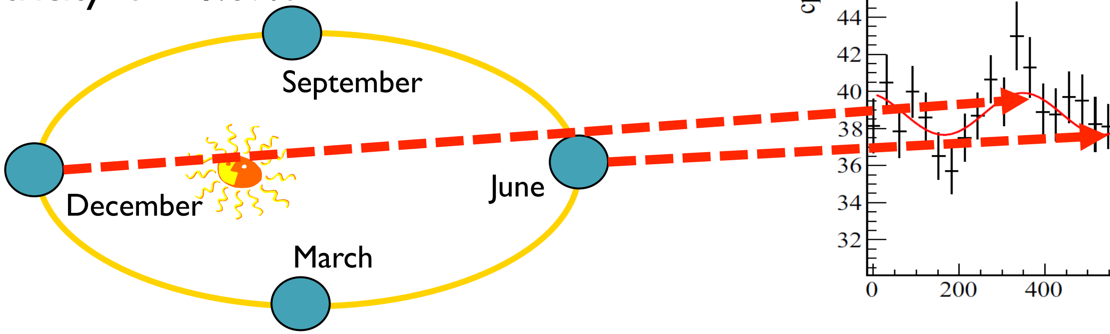
$$\frac{\sigma(x)}{x} \sim \frac{10\text{cm}}{\sqrt{E}}$$

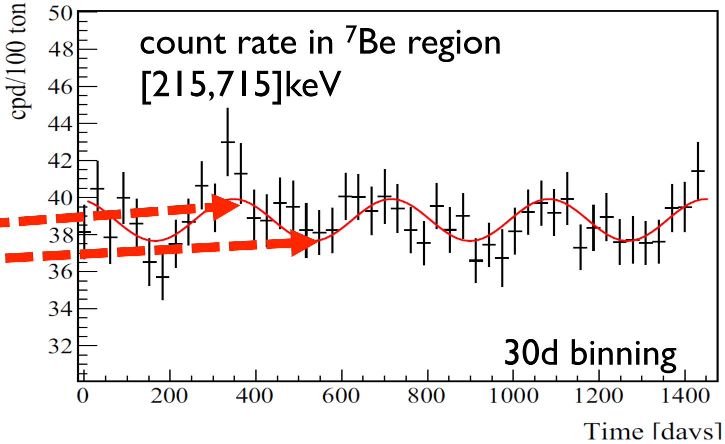
→ **Pulse-shape discrimination**

α, β^-, β^+

Seasonal Modulation

Expected yearly modulation due to Earth's orbit eccentricity ε = 1.67%





count rate in ^{7}Be region [215,715]keV

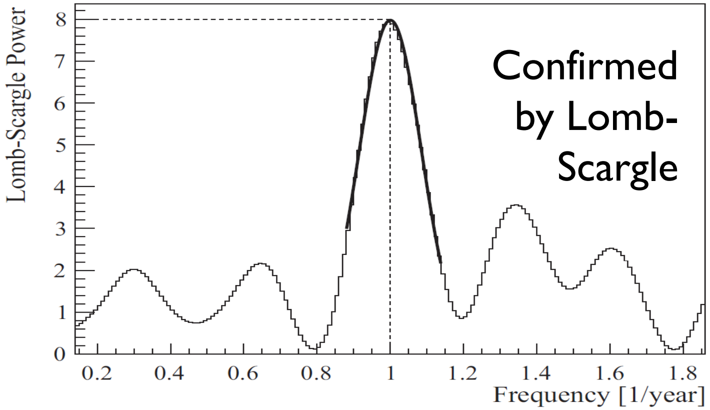
30d binning

$$R(t) = R_0 + \overline{R}\left[1 + \epsilon \cos \frac{2\pi}{T}(t - \phi)\right]^2$$

Eccentricity ε = (1.74 ± 0.45)%

Period T = (367 ± 10) days

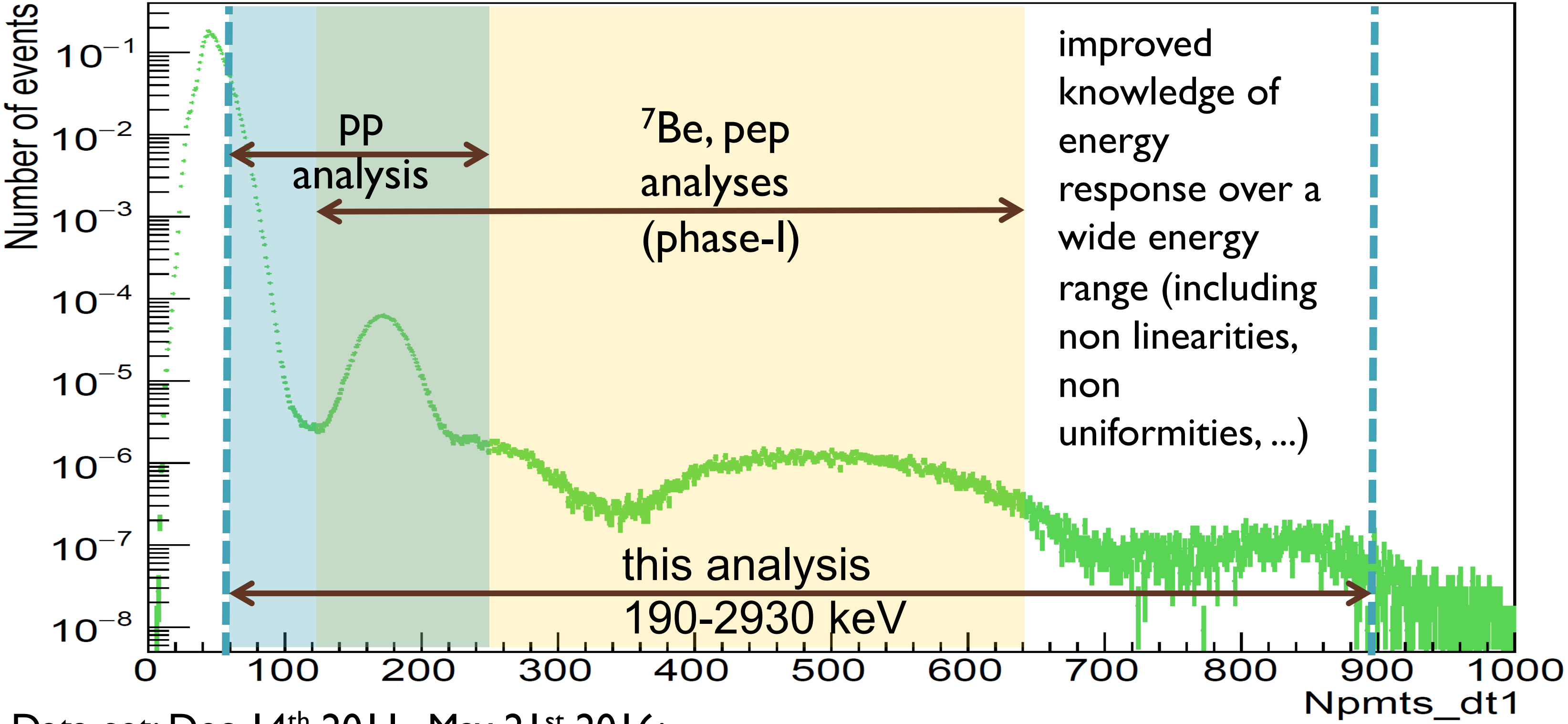
Phase Φ = (-18 ± 24) days



Confirmed by Lomb-Scargle

Borexino does indeed observe neutrinos from the Sun!

New wide energy range analysis



improved knowledge of energy response over a wide energy range (including non linearities, non uniformities, ...)

Data-set: Dec 14th 2011- May 21st 2016;

Total exposure: 1291.51 days x 71.3 tons;

Fit strategy

Radial distr.
(ext. gammas)

Pulse shape
(^{11}C)

Maximize a binned likelihood through a multivariate approach

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

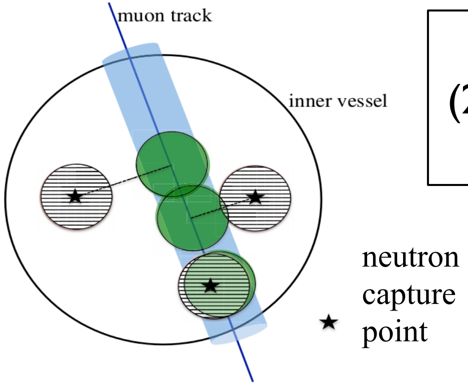
Monte Carlo

- Full simulation of energy loss, detector geometry, optical photons (scintill. & Cherenkov), PMTs & electronics response.
- Tuned with calibration data taken during Phase I ➔ sub% accuracy (arXiv:1704.02291)
- Included known time variations of the detector (vessel shape, PMT status)
- Only free parameters:
    - solar ν and background rate

Analytical

- Analytical model to link E to N_p, N_{pe} (including scintillation and Cherenkov light)
- Models the E resolution
- Free fit parameters:
    - solar ν and background rate
    - 6 model parameters: Light Yield, 2 resolution param., position & width of ^{210}Po peak, start of the ^{11}C spectrum
- Possibility to descrive unknown time variations

Fight ^{11}C: Three-Fold Coincidence (TFC)



^{11}C rate
(28.5 ± 0.5)
cpd/100t

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

~30min

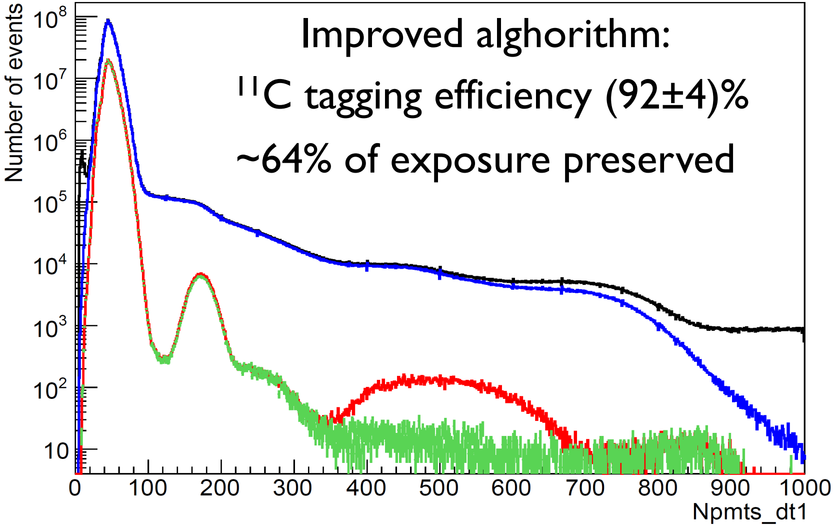
$$^{11}C \rightarrow {}^{11}B + e^{+} + \nu_e$$

~250μs

$$n + p \rightarrow d + \gamma_{2.2\,MeV}$$

The likelihood that an event is ^{11}C is computed from:

1. Space-time distance from the μ -track
2. Space-time distance from the neutron and from the n-projection on the track
3. neutron multiplicity
4. Muon dE/dx



Improved alghorithm:

^{11}C tagging efficiency (92±4)%

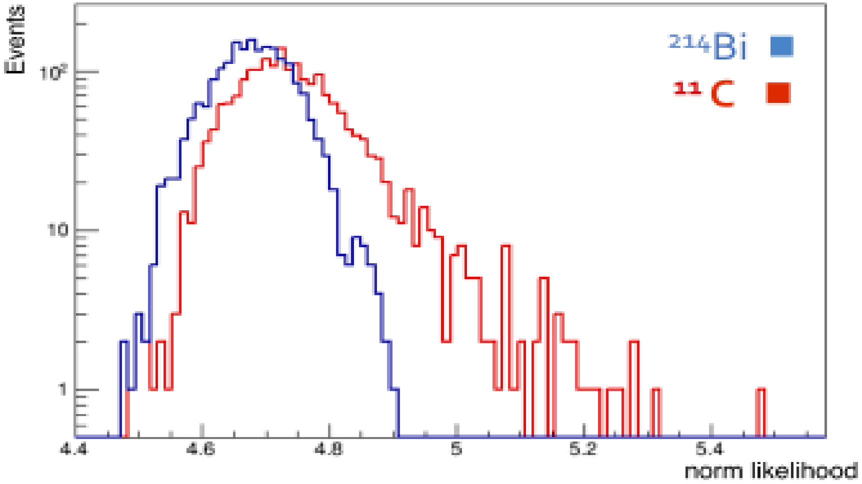
~64% of exposure preserved

Fight ^{11}C: Pulse Shape Discrimination

^{11}C decays β^{+} !

The scintillation time profile is different for e^- and e^+ for two reasons:

1. in 50% of the case e^+ annihilation is delayed by ortho-positronium formation (t~3ns)
2. e^+ energy deposit is not point-like because of the two annihilation gammas

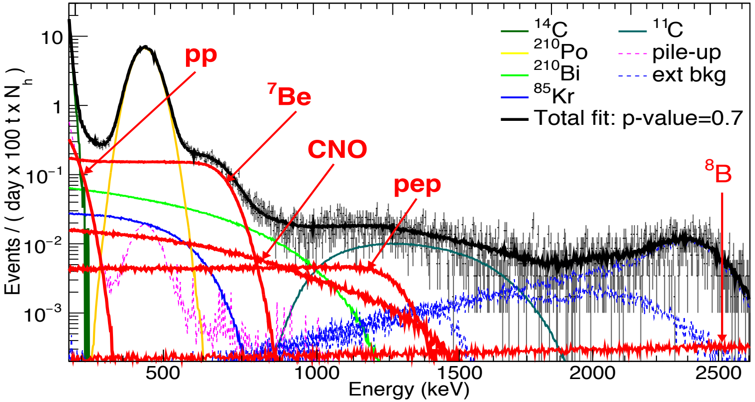


Identified a new pulse-shape variable: PS-L_{PR}

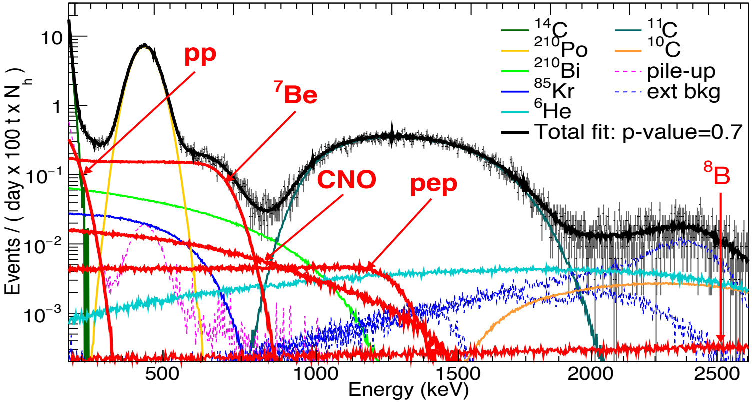
[the normalized output likelihood of the position reconstruction algorithm]

Multivariate fit example (MC)

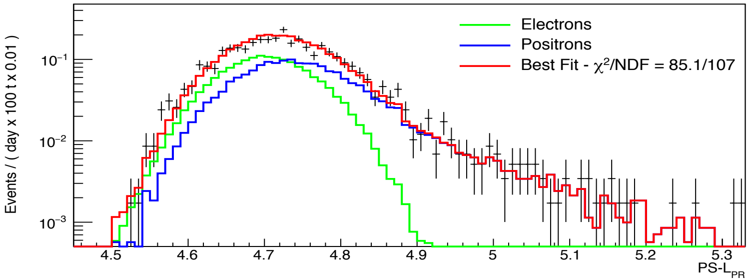
Energy spectrum (TFC subtracted)



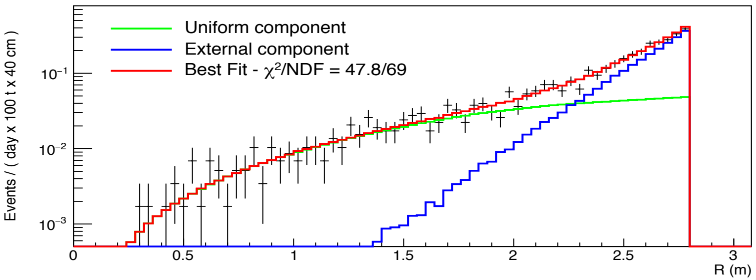
Energy spectrum (TFC tagged)



PS_L_{Pr} distribution



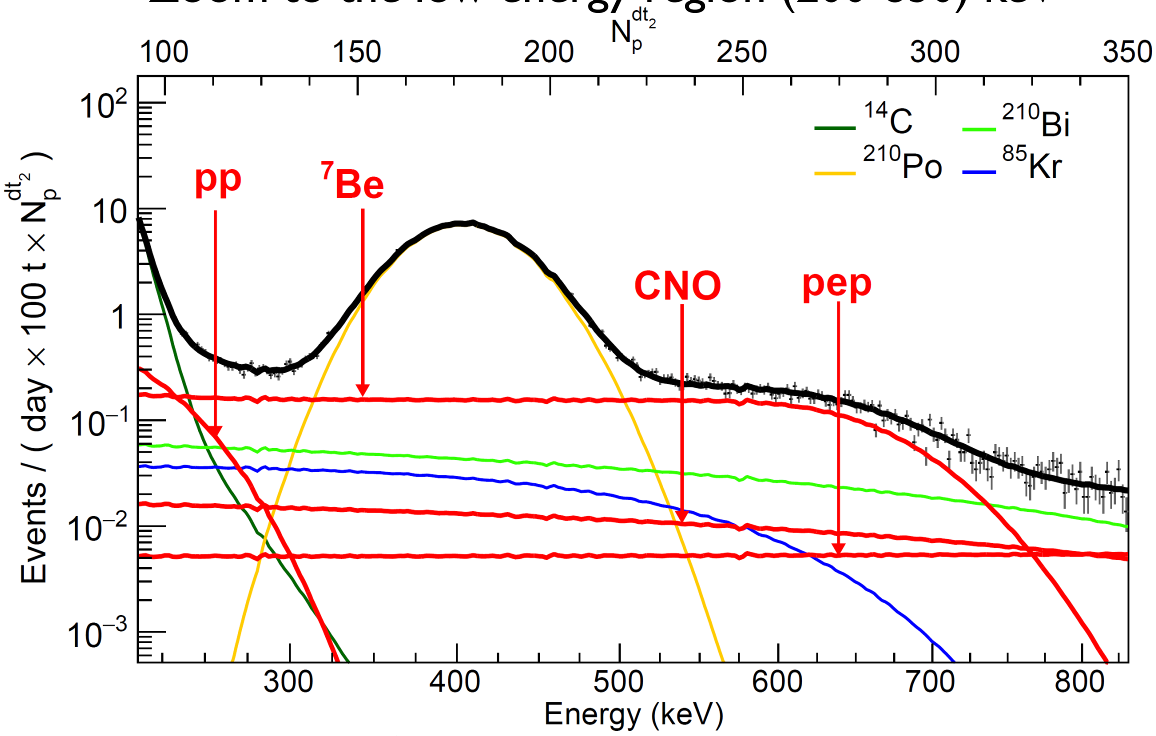
Radial distribution



Energy estimator: N_{hits}

Example using the analytical fit

Zoom to the low energy region (200-830) keV



Energy estimator: npmts_dt2

Whole energy range fit results

Rates	Borexino results (cpd/100t)	expected HZ cpd/100t	expected LZ cpd/100t
pp	$134 \pm 10^{+6}_{-10}$	131.0 ± 2.4	132.1 ± 2.4
^{7}Be(862+384 keV)	$48.3 \pm 1.1^{+0.4}_{-0.7}$	47.8 ± 2.9	43.7 ± 2.6
pep (HZ-CNO)	$2.43 \pm 0.36^{+0.15}_{-0.22}$	2.74 ± 0.05	2.78 ± 0.05
pep (LZ-CNO)	$2.65 \pm 0.36^{+0.15}_{-0.24}$	2.74 ± 0.05	2.78 ± 0.05

CNO rate fixed to HZ- or LZ-value

Fluxes	Borexino results ($cm^{-2}s^{-1}$)	expected HZ ($cm^{-2}s^{-1}$)	expected LZ ($cm^{-2}s^{-1}$)
pp	$(6.1 \pm 0.5^{+0.3}_{-0.5})\ 10^{10}$	$5.98\ (1 \pm 0.006)\ 10^{10}$	$6.03\ (1 \pm 0.005)\ 10^{10}$
^{7}Be(862+384 keV)	$(4.99 \pm 0.13^{+0.07}_{-0.10})\ 10^{9}$	$4.93\ (1 \pm 0.06)\ 10^{9}$	$4.50\ (1 \pm 0.06)\ 10^{9}$
pep (HZ-CNO)	$(1.27 \pm 0.19^{+0.08}_{-0.12})\ 10^{8}$	$1.44\ (1 \pm 0.009)\ 10^{8}$	$1.46\ (1 \pm 0.009)\ 10^{8}$
pep (LZ-CNO)	$(1.39 \pm 0.19^{+0.08}_{-0.13})\ 10^{8}$	$1.44\ (1 \pm 0.009)\ 10^{8}$	$1.46\ (1 \pm 0.009)\ 10^{8}$

The final numbers are the average values obtained in different fit conditions; differences are quoted as systematic error.

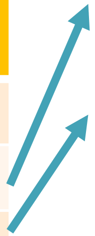
Improvement of the new analysis

	Phase I	Phase II	Uncertainty reduction $\frac{Phase\ II}{Phase\ I}$
pp	144 ± 13±10	$134 \pm 10^{+6}_{-10}$	0.78
^{7}Be(862keV)	$46.0 \pm 1.5^{+1.6}_{-1.5}$	$46.3 \pm 1.1^{+0.4}_{-0.7}$	0.57
pep	3.1 ± 0.6 ± 0.3	(HZ) $2.43 \pm 0.36^{+0.15}_{-0.22}$ (LZ) $2.65 \pm 0.36^{+0.15}_{-0.24}$	0.61

Borexino Phase-II backgrounds

Background species	**Rate (cpd/100t)**
^{14}C (Bq/100t)	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

^{39}Ar, ^{40}K below detection limit



factor 4.6 reduction with respect to Phase-I

factor 2.3 reduction with respect to Phase-I

^{238}U (from ^{214}Bi-Po) $< 9.4\ 10^{-20}$ g/g 95% C.L.

^{232}Th (from ^{212}Bi-Po) $< 5.7\ 10^{-19}$ g/g 95% C.L.

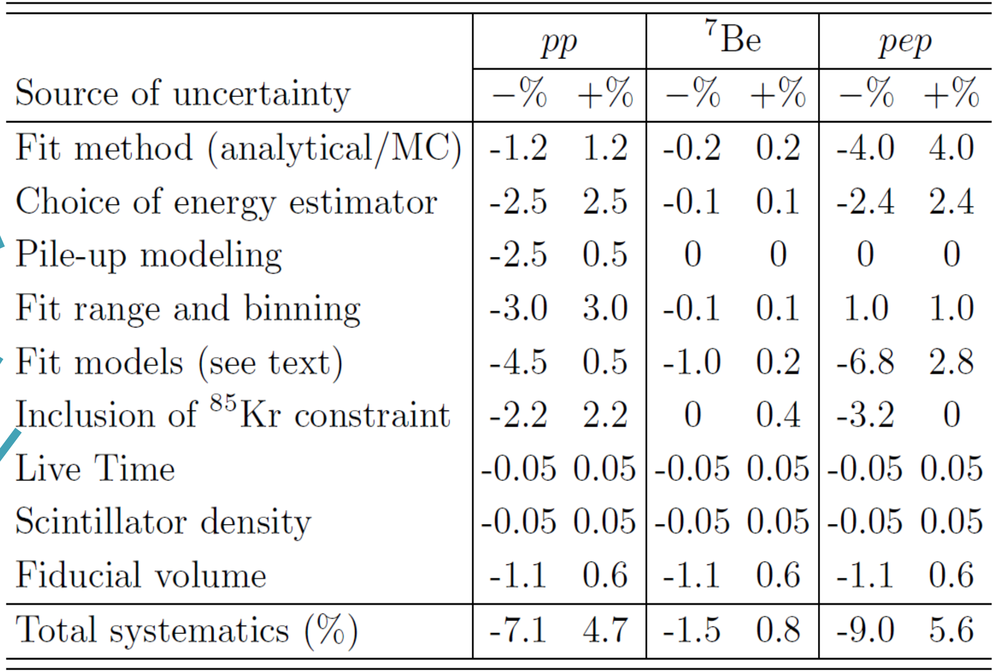
Borexino's core is the
radio-cleanest spot on Earth:
over 10 orders of magnitude
below typical radioactivity levels

Sources of systematic errors

Two methods to take into account pile-up:

- Effects of non perfect modelling of the detector response;
- Uncertainty on theoretical input spectra (^{210}Bi)

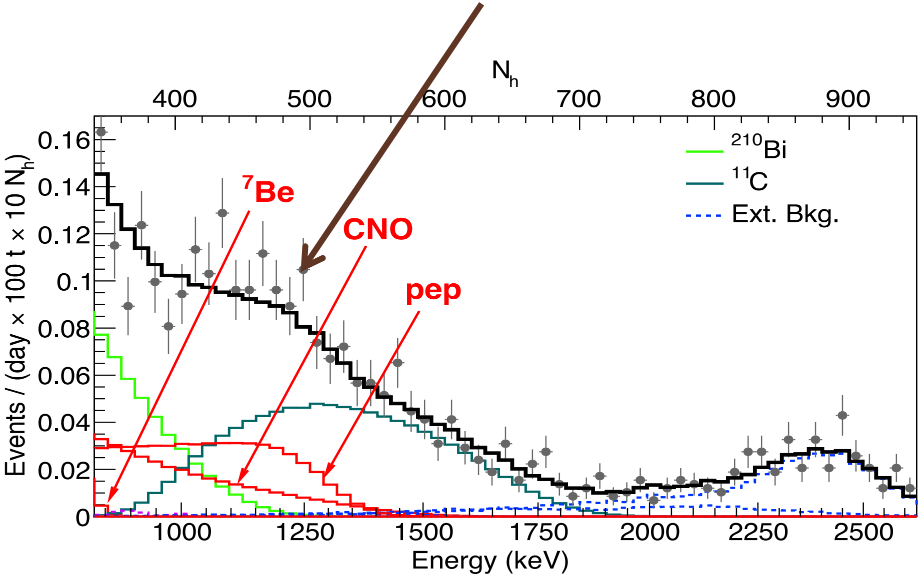
^{85}Kr constrained to be <7.5cpd/100t (95% C.L.) from Kr-Rb delayed coincidences

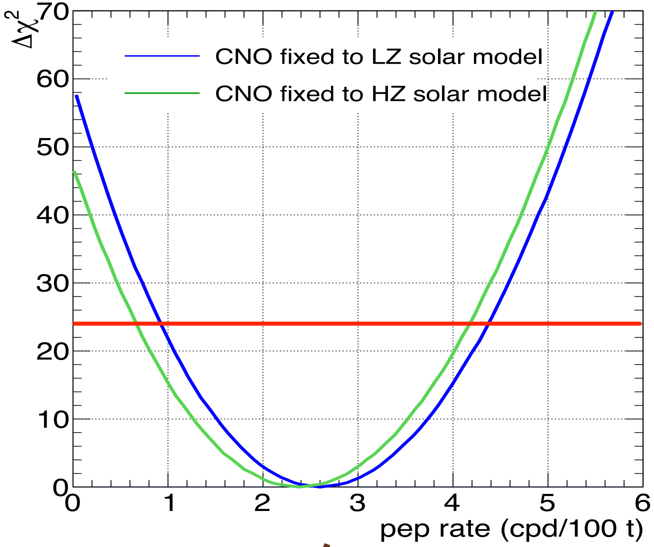


	pp		^{7}Be		*pep*	
Source of uncertainty	−%	+%	−%	+%	−%	+%
Fit method (analytical/MC)	-1.2	1.2	-0.2	0.2	-4.0	4.0
Choice of energy estimator	-2.5	2.5	-0.1	0.1	-2.4	2.4
Pile-up modeling	-2.5	0.5	0	0	0	0
Fit range and binning	-3.0	3.0	-0.1	0.1	1.0	1.0
Fit models (see text)	-4.5	0.5	-1.0	0.2	-6.8	2.8
Inclusion 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

Evidence of pep ν signal

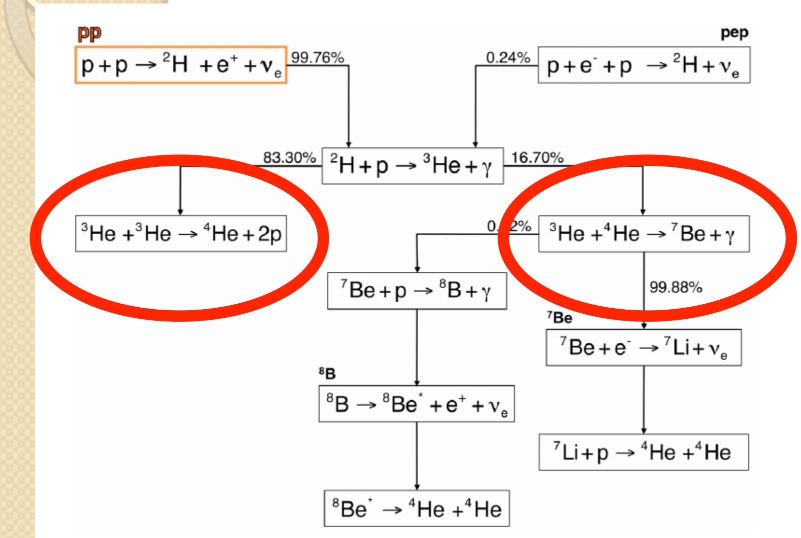
Applying more stringent cuts on FV and on the pulse-shape variable PS_L_{PR} we can actually see the pep n shoulder!





5σ evidence of pep signal (including systematic errors)

A probe of solar fusion



pp

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

99.76%

pep

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

0.24%

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

83.30%

16.70%

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

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

0.[illegible]2%

99.88%

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

^{7}Be

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

^{8}B

$^8B \rightarrow {}^8Be^* + e^+ + \nu_e$

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

$^8Be^* \rightarrow {}^4He + {}^4He$

From Borexino new flux measurements:

$$\boxed{R = 0.18 \pm 0.02}$$

- The competition between pp-I and pp-II branches of the pp chain is given by the ratio:

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

- From the pp and ^{7}Be fluxes it is possible to determine the ratio R
- An important experimental test of the solar fusion
- Theoretical predictions:

R(HZ)= 0.18 ± 0.01

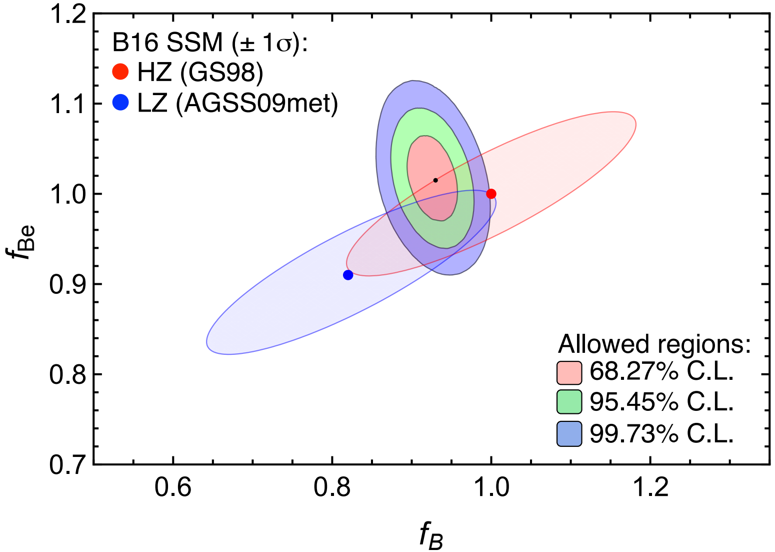
R(LZ)= 0.16 ± 0.01

Implications for solar metallicity

Global fit of all solar, Kamland reactors, and new Borexino results

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

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



"Hint" towards High Metallicity?

- p-value (HZ)= 0.87
- p-value (LZ)= 0.11

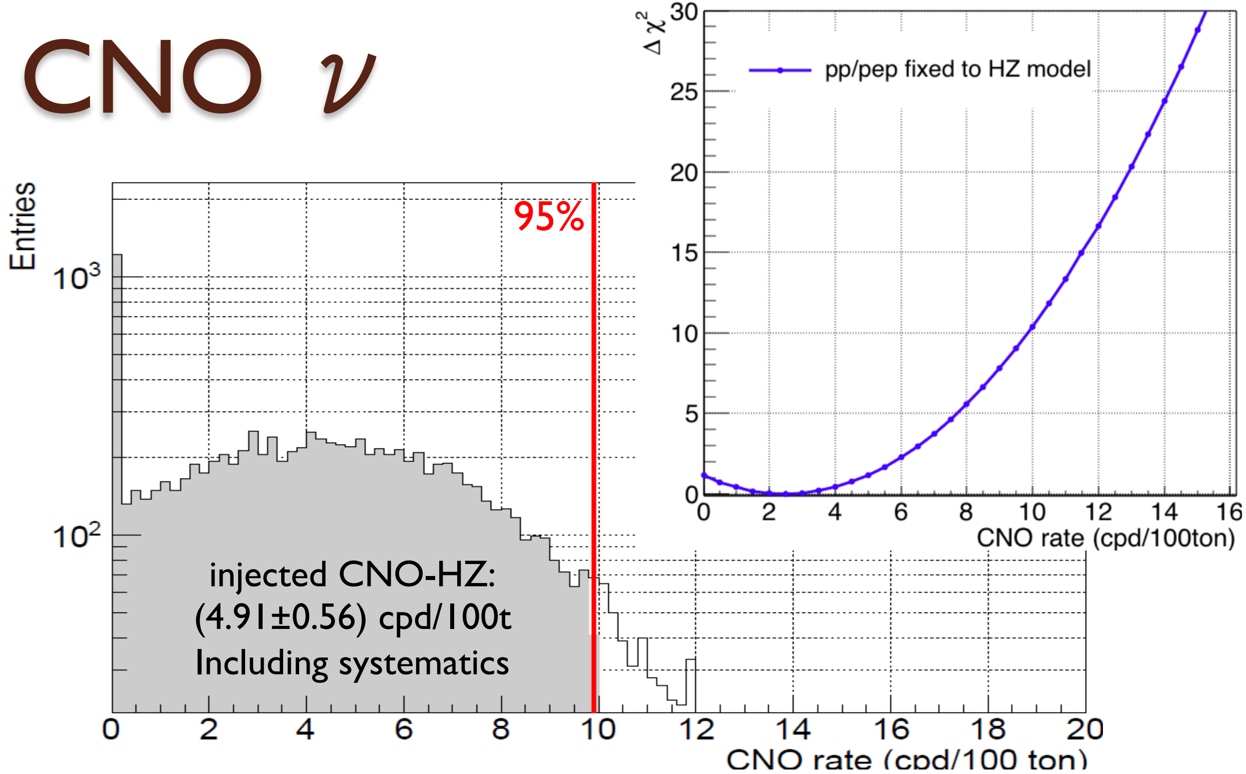
- Note: only 1 σ theorethical uncertainty in the plot
- Important to reduce the theorethical uncertainty

Limits on CNO ν

- Problem: CNO is highly correlated to pep and ^{210}Bi background
- Strategy: constrain the ratio pp/pep to 47.7±1.2
  - Include oscillations LMA-MSW
- Toy MC study of the sensitivity: 95% CL is

  9 cpd/100t for LZ

  10 cpd/100t for HZ
- Previous limit (Phase I): 7.9 cpd/100t (but with pep fixed!)



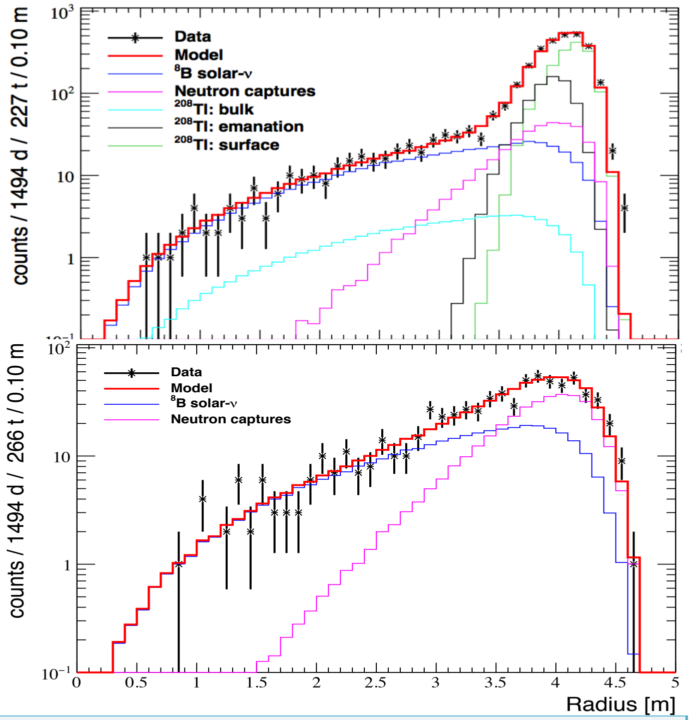
injected CNO-HZ:
(4.91±0.56) cpd/100t
Including systematics

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

Updated ^{8}B neutrino flux

- Enlarged FV (most of scintillator)
- Data of Phase I+II: 2008 ➔ 2016
- Exposure: 1.5 kt y
- Fit of radial distributions in two energy ranges:

LE: 3.2-6MeV$_{kin}$
Mean ν energy: 7.9 MeV
HE: 6-17MeV$_{kin}$
Mean ν energy: 9.9 MeV



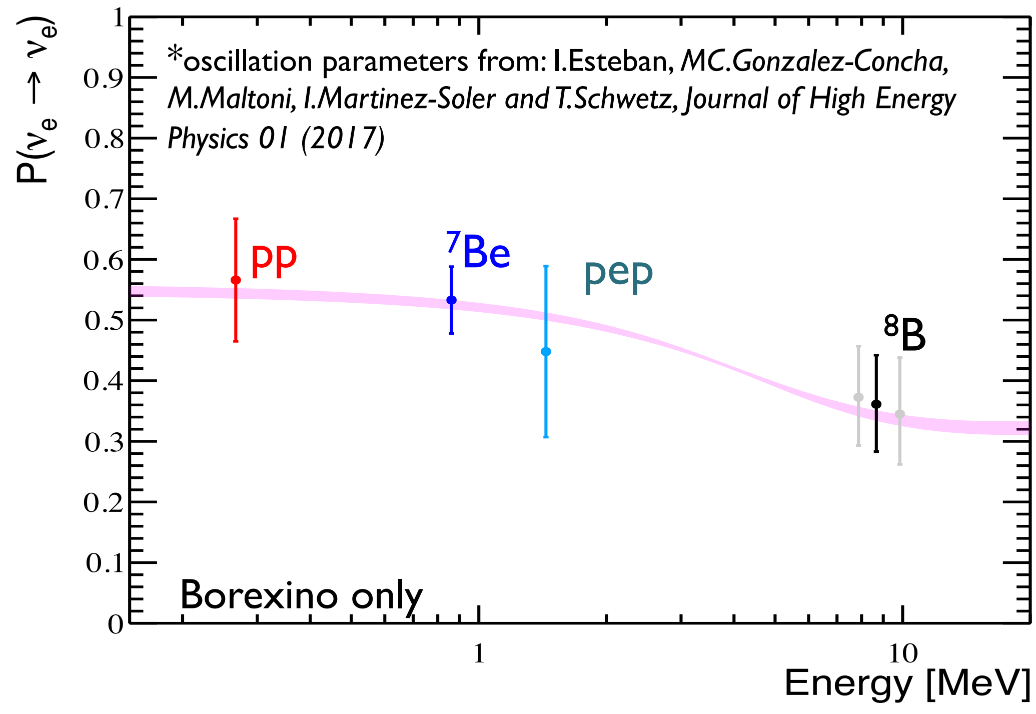
$$R_{LE} = 0.133^{+0.013}_{-0.013}\,(stat)\,^{+0.003}_{-0.003}\,(syst)\ \text{cpd}/100\,\text{t},$$

$$R_{HE} = 0.087^{+0.010}_{-0.008}\,(stat)\,^{+0.005}_{-0.005}\,(syst)\ \text{cpd}/100\,\text{t},$$

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

SuperKamiokande	2.345 ±0.014 ±0.036 x 10^6 cm^{-2} s^{-1}
Previous Bx	2.4 ±0.4 x10^6 cm^{-2} s^{-1}
This measurement	**2.55 ±0.18 ±0.07 x 10^6 cm^{-2} s^{-1}**

Survival probability meas. by Borexino



From the measured interacton rates and assuming HZ-SSM fluxes we get:

- $P_{ee}(pp)=0.57\pm0.10$
- $P_{ee}(^7Be,862keV)=0.53\pm0.05$
- $P_{ee}(pep)=0.43\pm0.11$
- $P_{ee}(^8B, 8.7MeV)=0.36\pm0.08$

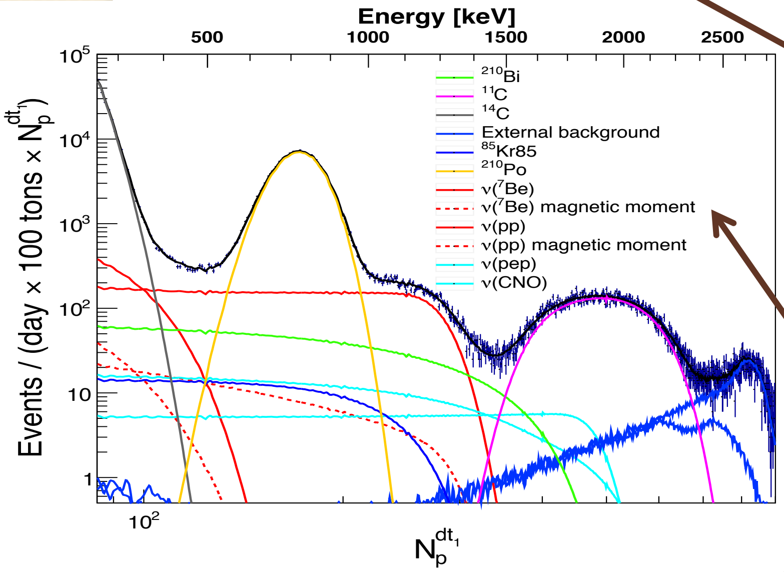
Limit on Neutrino Magnetic Moment

As neutrinos are massive, they can also have a MM
An EW term could show up in ν -e scattering

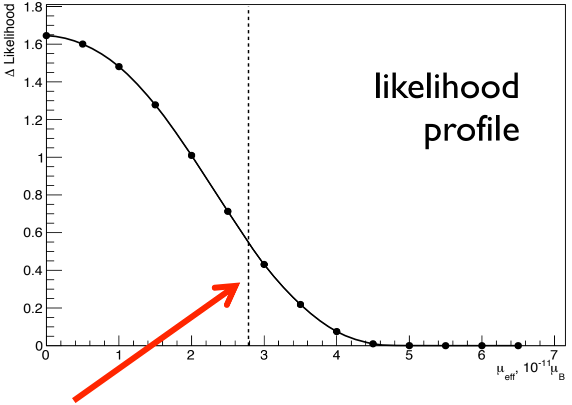
[effective as it refers to the admixture of mass eigenstates reaching Earth]

$$\frac{d\sigma_{\mathrm{EM}}}{dT_e}(T_e, E_\nu) = \pi\, r_0^2\, \mu_{eff}^2 \left(\boxed{\frac{1}{T_e}} - \frac{1}{E_\nu}\right)$$

low energy ν are sensitive (^{7}Be, pp)



Fit with different values of μ_{eff}



likelihood profile

$\mu_{eff} < 2.8\times10^{-11}\,\mu_B$ **at 90% C.L.**

about 2x lower than phase-I
best limit for μ_{eff}

Conclusions

- Two-fold interest in solar neutrino detection:
  1. *Particle physics:* test the LMA-MSW model vs. alternatives (e.g. NSI)
  2. *Astrophysics:* hunt for CNO neutrinos and try to solve the Solar metallicity puzzle
- Super-Kamiokande and Borexino have entered a precision spectroscopy phase:
  - SK is increasing precision on low energy ^{8}B
  - Borexino Phase-II whole-range analysis:
    - ^{7}Be flux at 2.5% uncertainty (stat+sys)
    - 5σ evidence of pep neutrinos
- Stay tuned for more results!

Thank you for your attention!

ADDITIONAL MATERIAL

Solar neutrinos on Earth

- Neutrino rate emitted by the Sun: **N_ν= $1.8 \cdot 10^{38}$ ν/s**
- only electron flavor neutrinos are produced in the Sun
- How many do reach the Earth?

$$4H + 2e^- \rightarrow {}^4He + 2e^+ + 2\upsilon_e + 26.7 \quad MeV$$

2 neutrinos produced per reaction

Luminosity of the Sun:
$3.846 \cdot 10^{26}$ Watt

$$\Phi_{\nu_e} \simeq \frac{1}{4\pi D_\odot^2}\frac{2L_\odot}{(Q-\langle E_\nu\rangle)} = 6\times 10^{10}\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

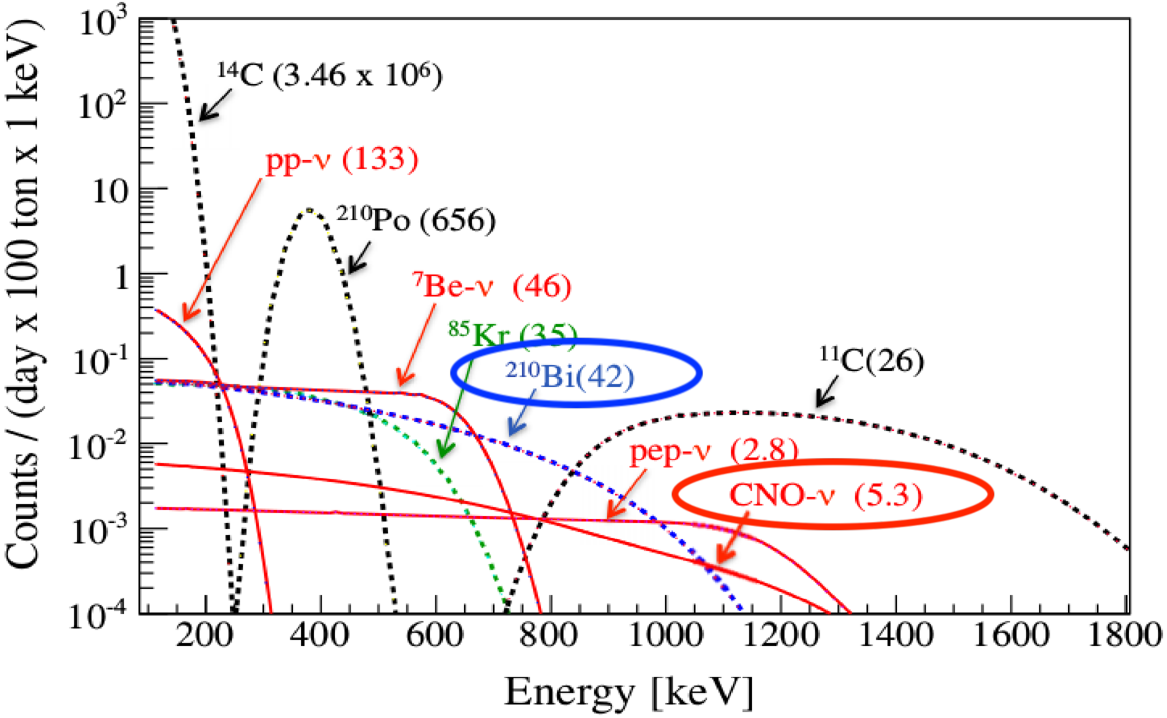
Distance Earth-Sun:
~$1.5 \cdot 10^{11}$ m

Energy released in the reaction:
~26.7 MeV

Energy carried away by ν:
~0.3MeV

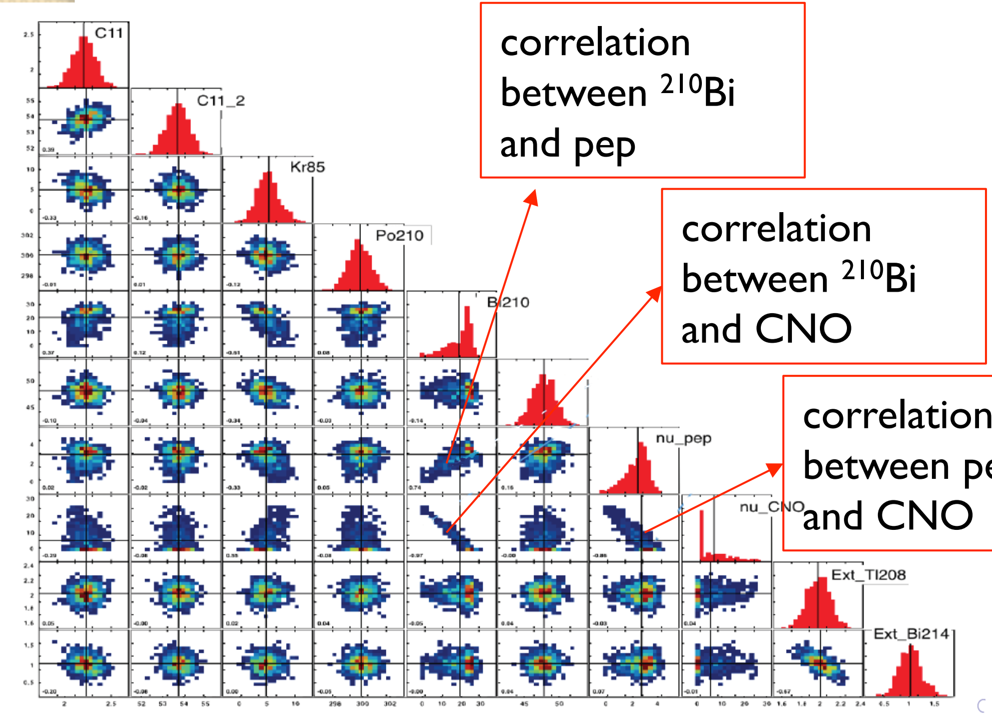
The ^{210}Bi issue

CNO and **^{210}Bi** spectra are *quasi-degenerate*



The ^{210}Bi background

An important issue: the similarity between pep, CNO and ^{210}Bi spectral shapes



correlation between ^{210}Bi and pep

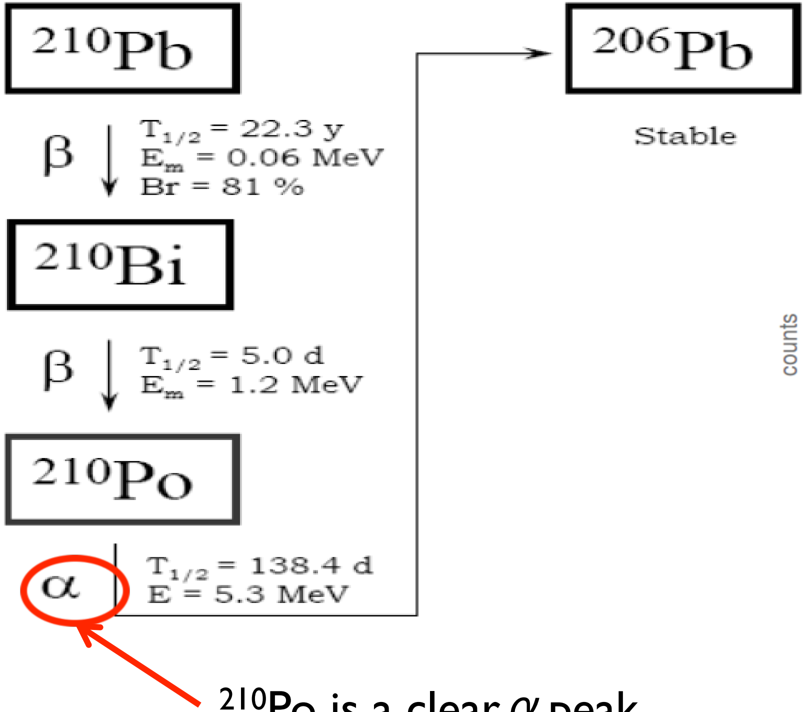
correlation between ^{210}Bi and CNO

correlation between pep and CNO

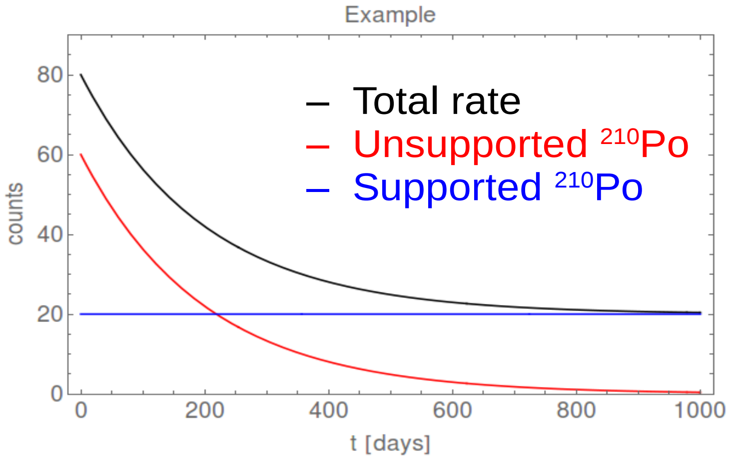
It critically affects our capability to measure the pep neutrino rate and to set a limit on the CNO neutrino rate, because it induces strong correlations in the fit.

Attempting ^{210}Bi constrain

<u>Assuming secular equilibrium</u>, we could constrain ^{210}Bi from its daughter: ^{210}Po



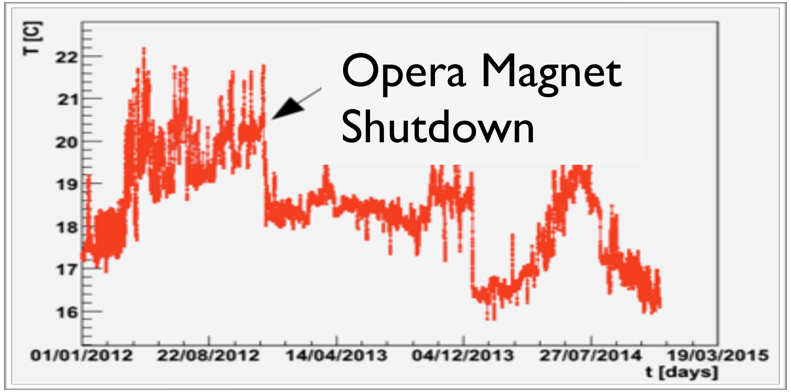
^{210}Po is a clear α peak



We need 10% precision or better
We need stability

The ^{210}Po instabilities

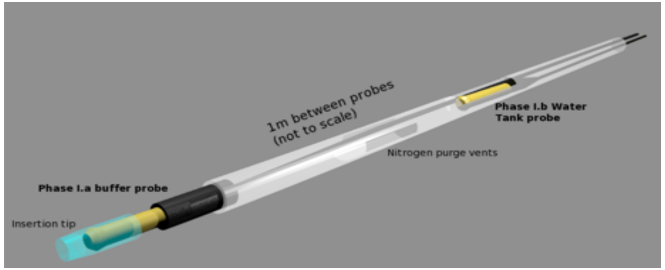
- However we have faced the equilibrium was broken so far.
- Temperature changes induced fluctuations in the ^{210}Po rate
  - Possibly due to convective currents

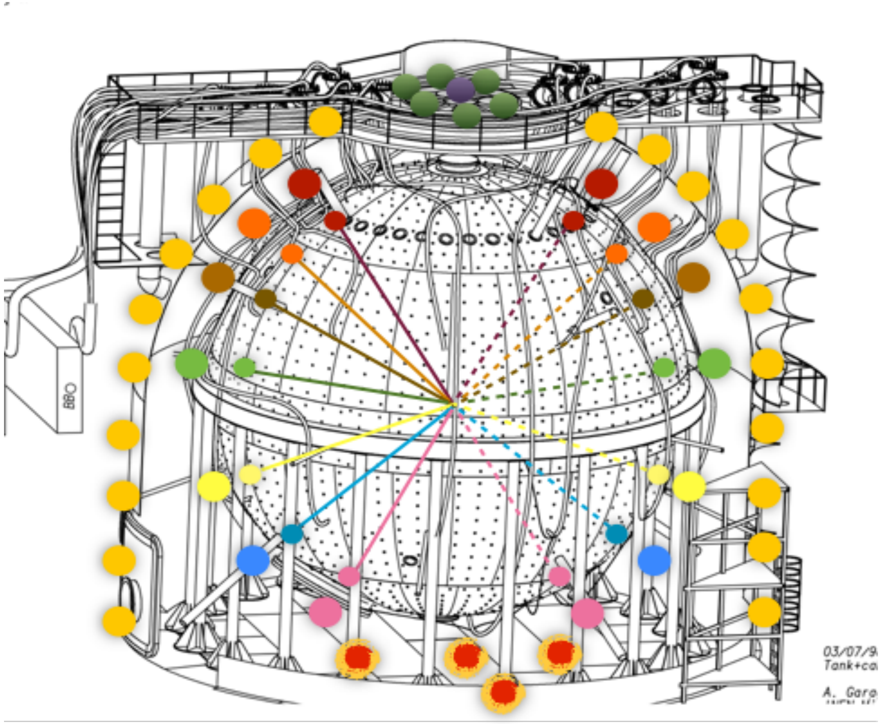


Opera Magnet Shutdown

Understanding the Temperature

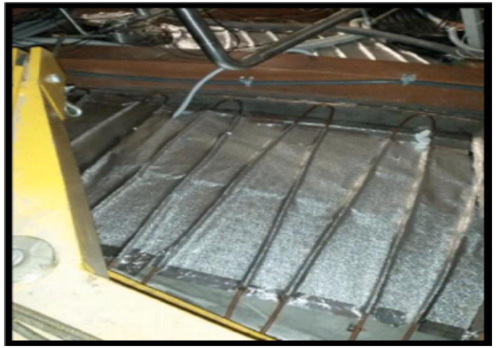
- 65 new calibrated T probes, internal and external.
- 0.1°C absolute accuracy.
- 0.01°C resolution stability.

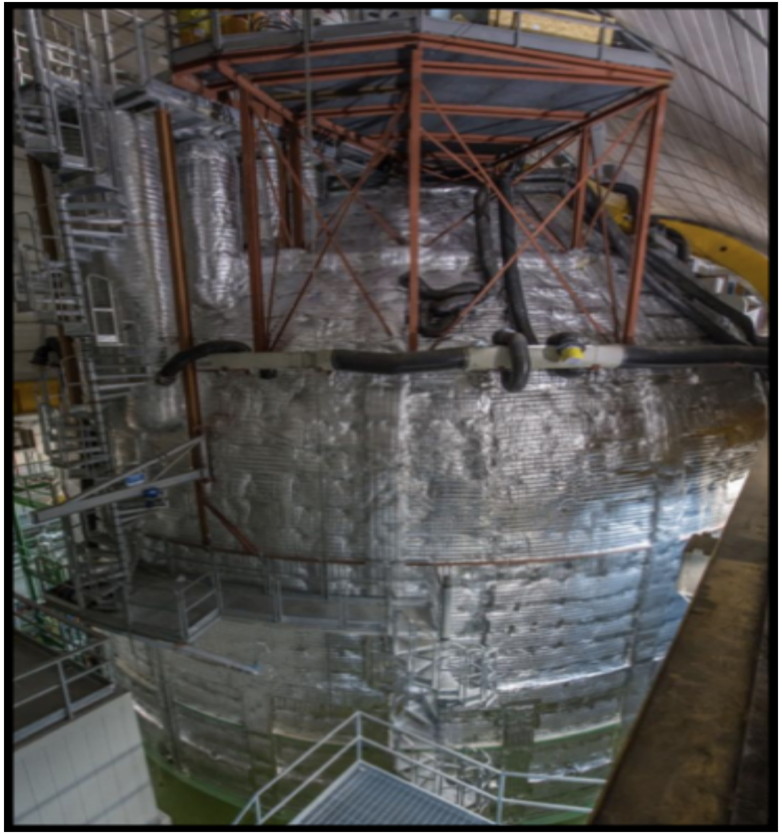




Insulation of the Water Tank

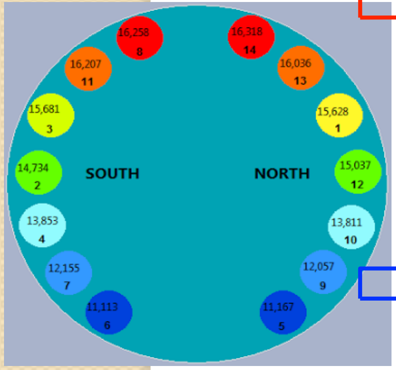
- Big effort: 20cm Mineral wool + reflective layer around the whole detector.
- May -> Dec 2015
- Active T control to be activated at need.



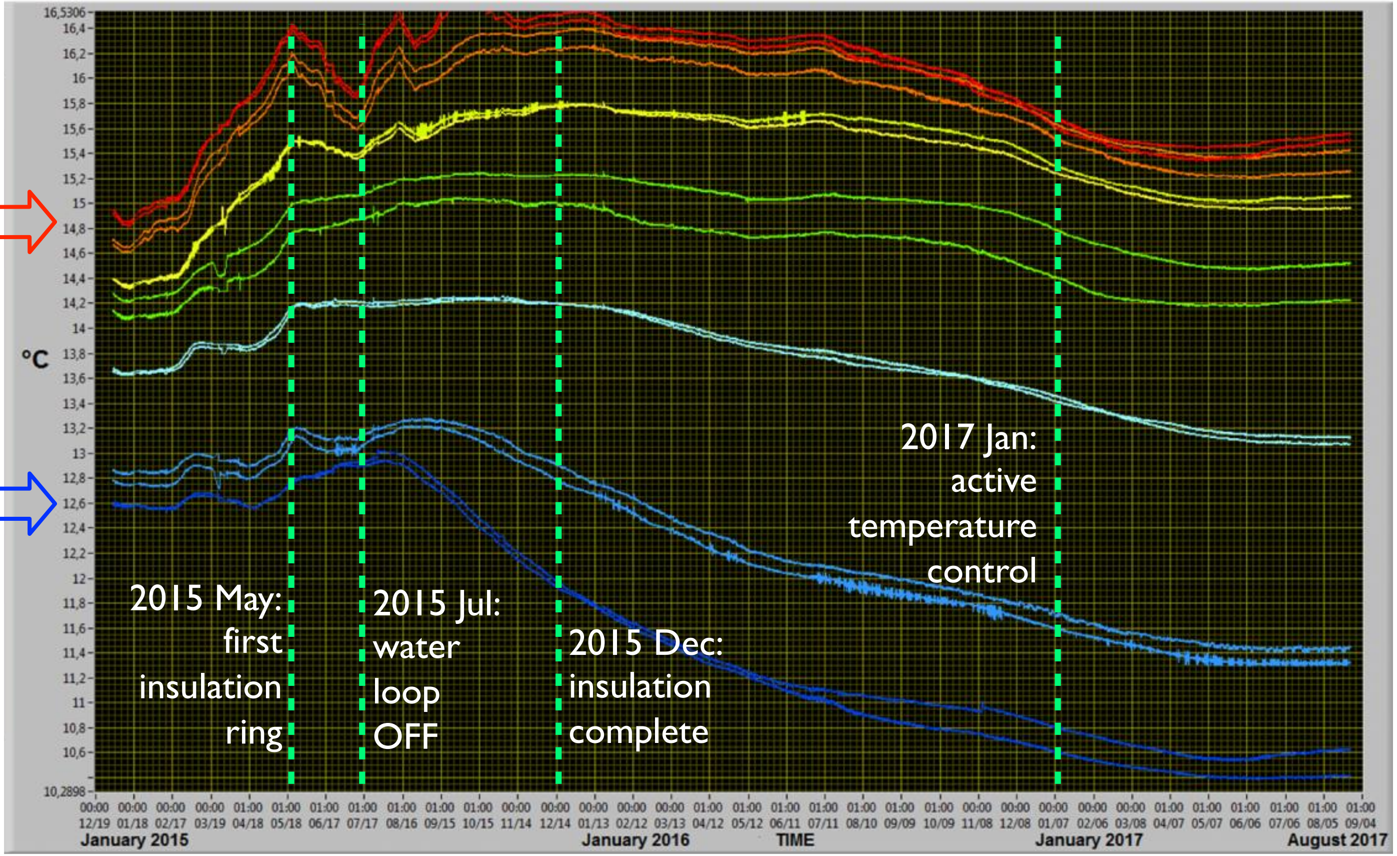


Temperature stabilization

Top



Bottom



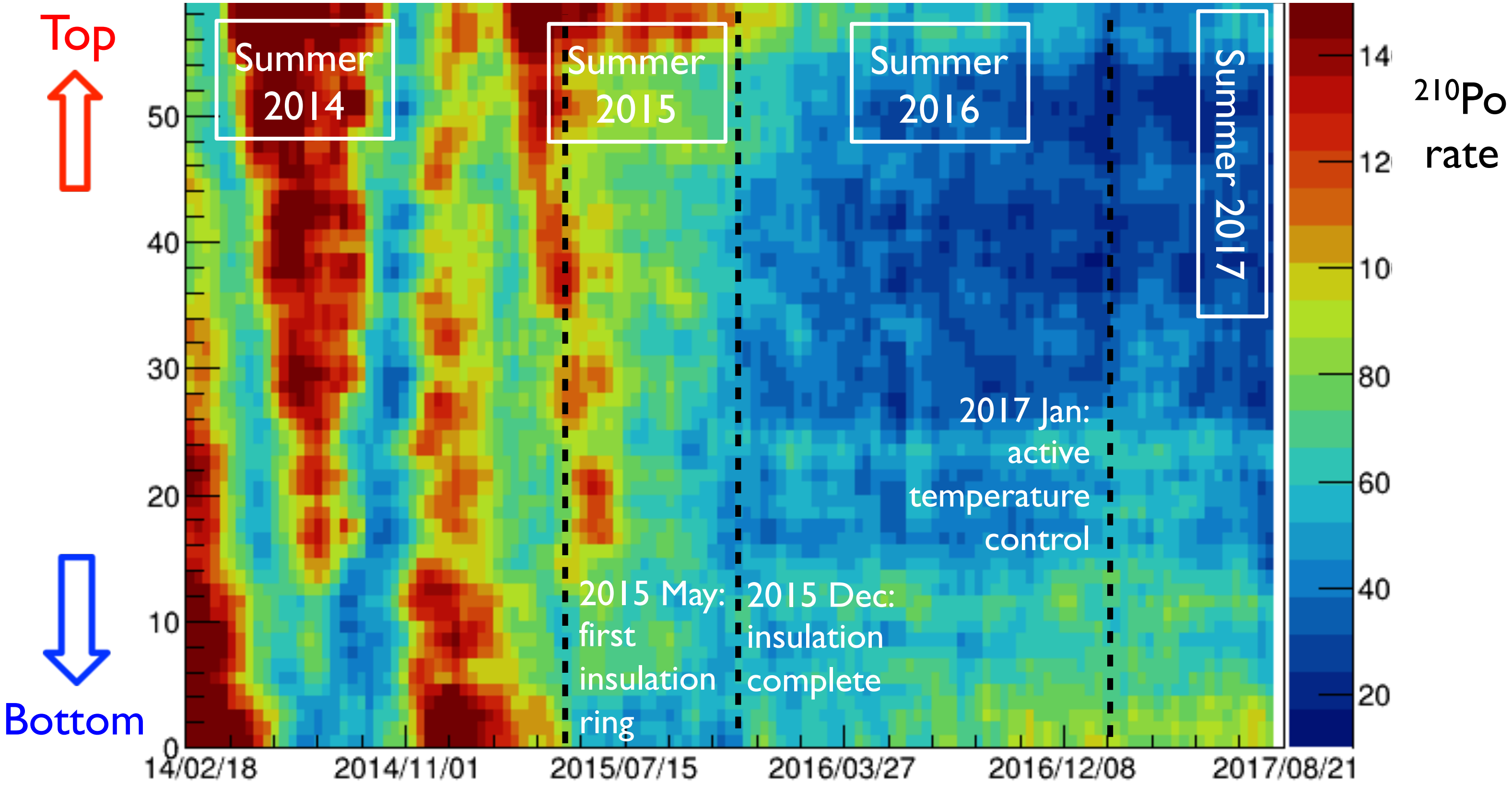
2015 May: first insulation ring

2015 Jul: water loop OFF

2015 Dec: insulation complete

2017 Jan: active temperature control

Effect of stabilization on ^{210}Po



Summer 2014

Summer 2015

Summer 2016

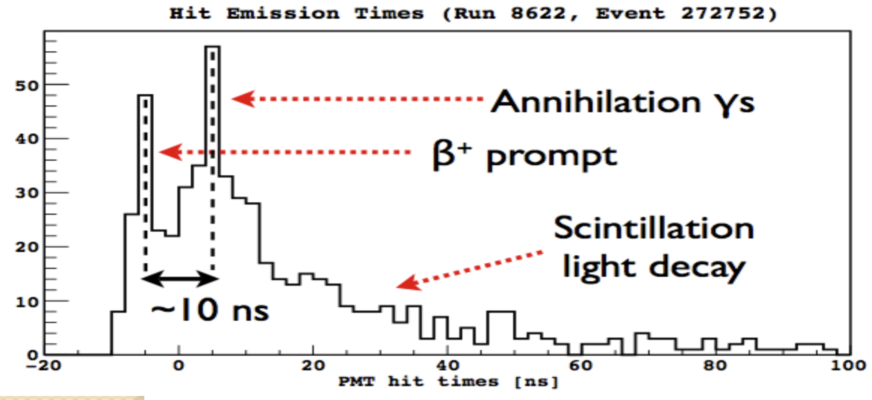
Summer 2017

2015 May: first insulation ring

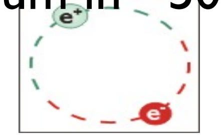
2015 Dec: insulation complete

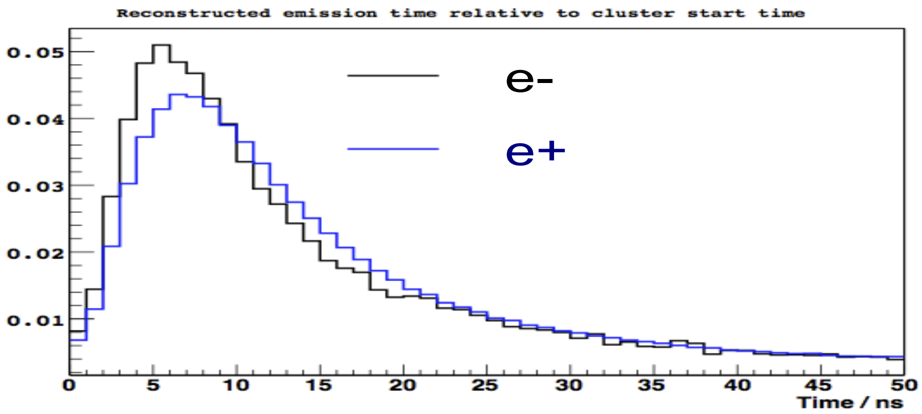
2017 Jan: active temperature control

PSD (e^+/e^-)



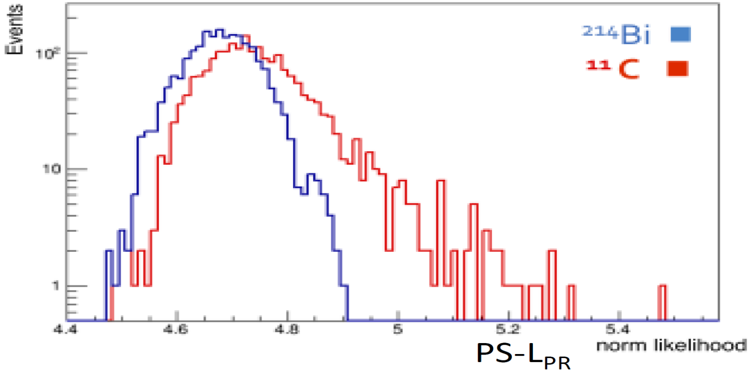
1. e^+ (such as ^{11}C) forms ortho-positronium in ~50% cases.



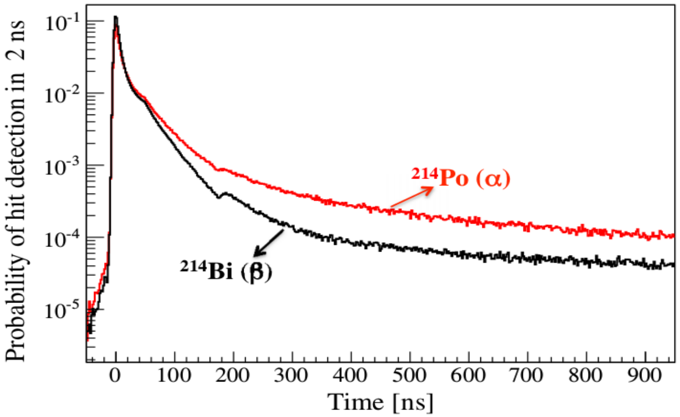


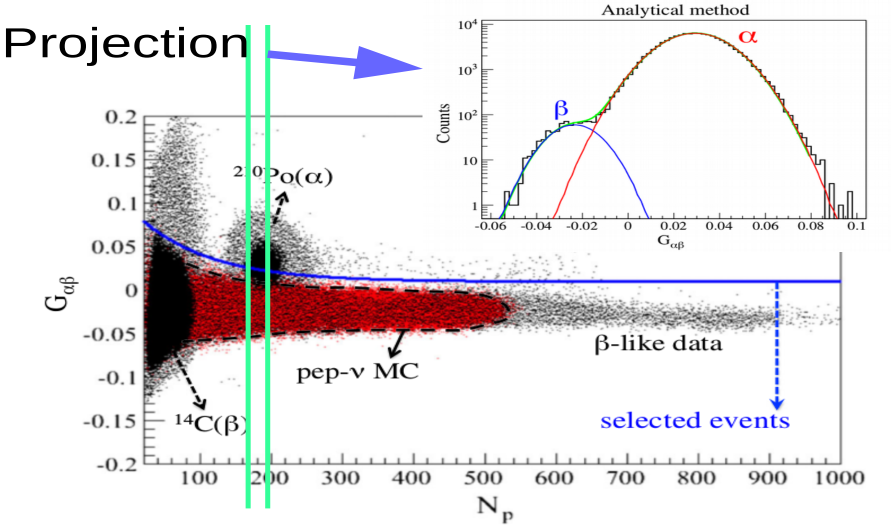
2. e^+ different pulse shape w. r. t. e^-

3. Boosted Decision Tree (BDT) parameter with discrimination capability

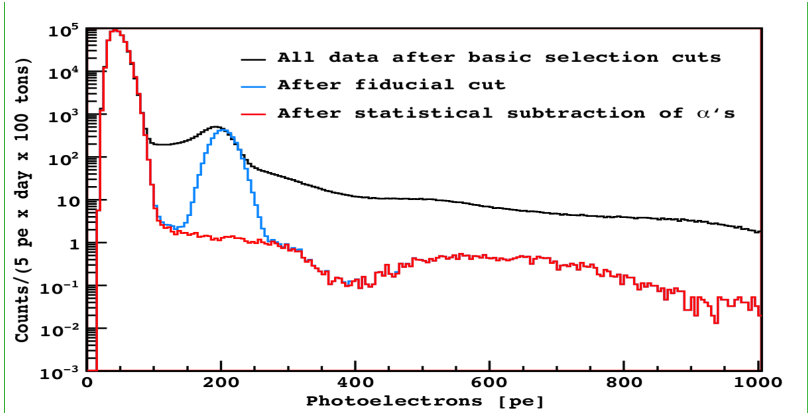


PSD (α / β)





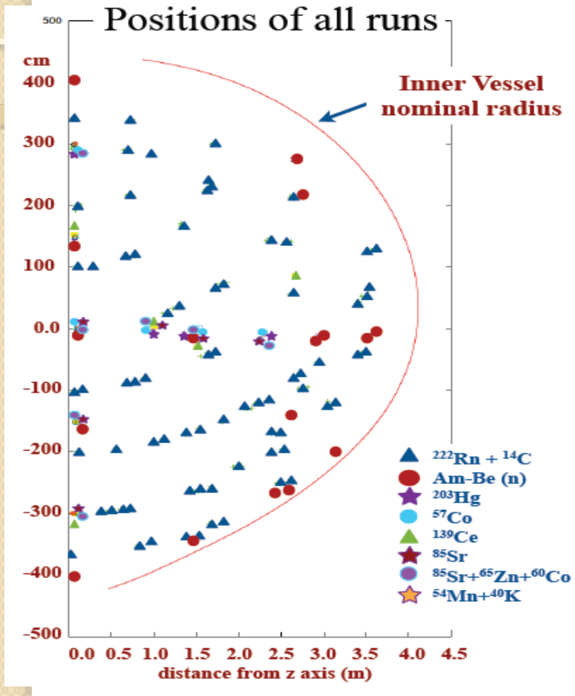
- Bin-by-bin statistical subtraction
- Formerly based on Gatti filter
- Now improving with Multi-Layer-Perceptron algorithm

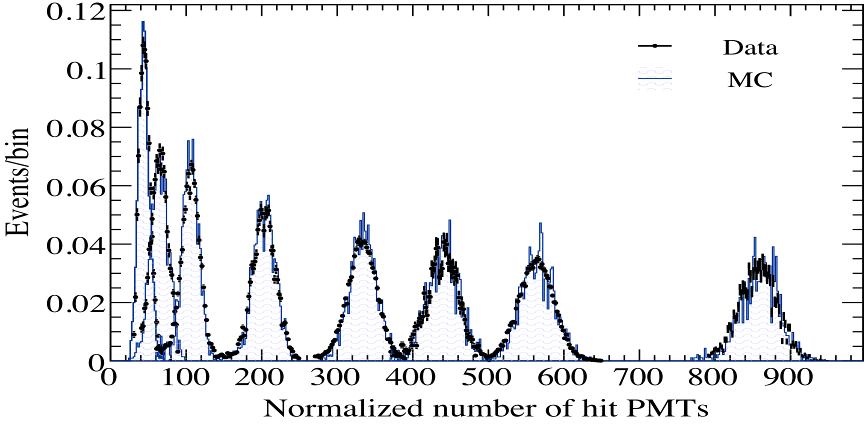


JINST 7(2012)P10018

Borexino calibration

2008-2011: 4 internal + 1 external calibration campaigns





1. MC tuned with several γ sources:
   Energy scale uncertainty in the range 0.2÷2 MeV down to **1.5%**
2. Rn source in 184 spots:
   Fiducial Volume uncertainty down to **-1.3% +0.5%**

Calibrations will be repeated before end of Phase-2 (2017)

Experimental site

Abruzzo, Italy

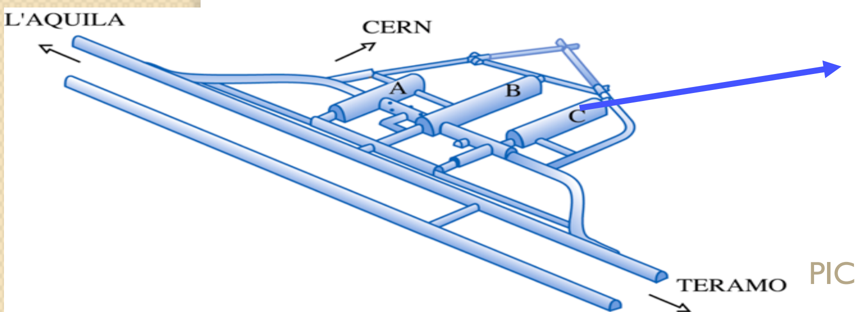
120 km from Rome

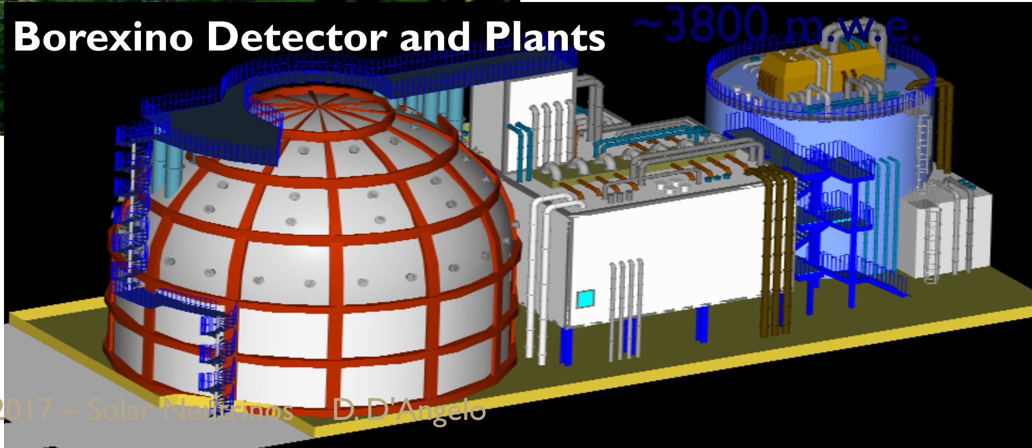
External Labs

Laboratori Nazionali del Gran Sasso

1400m of rock shielding

~3800 m.w.e.

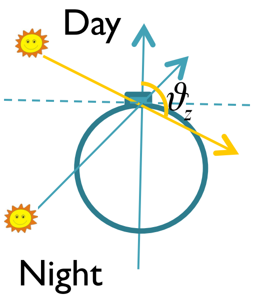




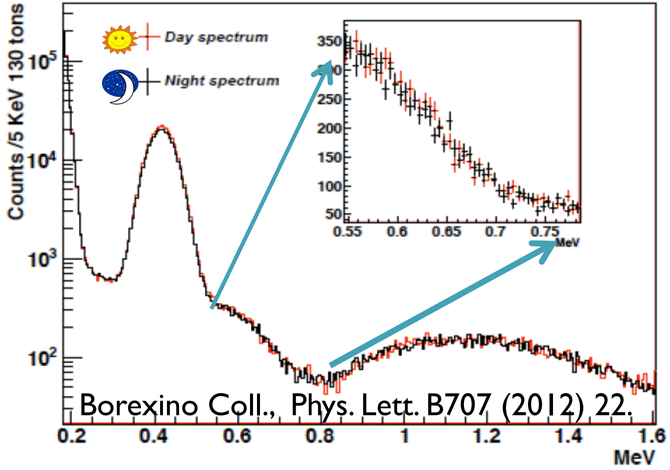
Borexino Detector and Plants

Day-Night Asymmetry

- Matter effect in ν oscillation
- Regeneration effect during night (ν traverse the Earth)
- LMA-MSW: no effect for ^{7}Be, measurable effect for ^{8}B



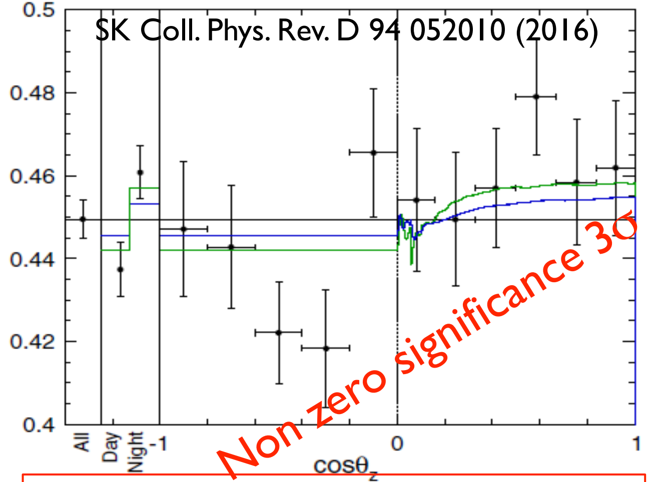
Borexino Phase I : ^{7}Be



Borexino Coll., Phys. Lett. B707 (2012) 22.

$$A^{^7Be}_{DN} = \frac{D-N}{(N+D)/2} = (-0.1 \pm 1.2 \pm 0.7)\%$$

SuperK ^{8}B E>4.5 MeV

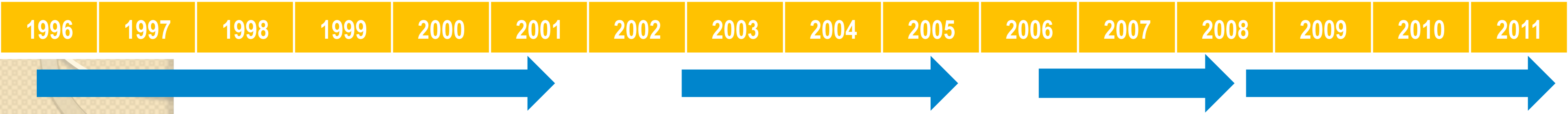


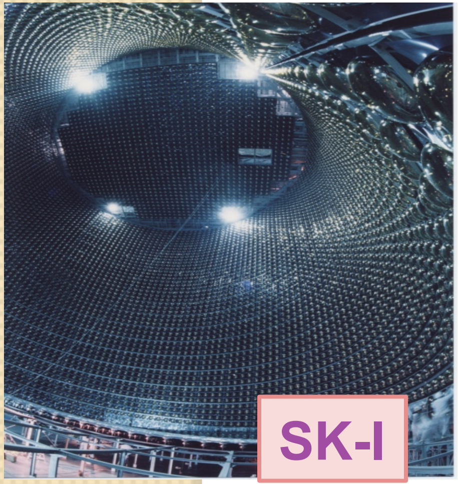
SK Coll. Phys. Rev. D 94 052010 (2016)

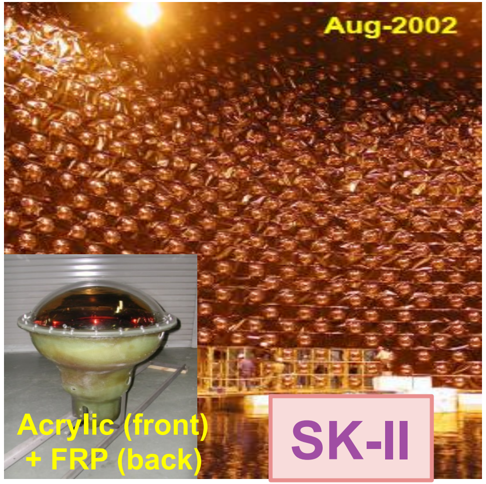
Non zero significance 3σ

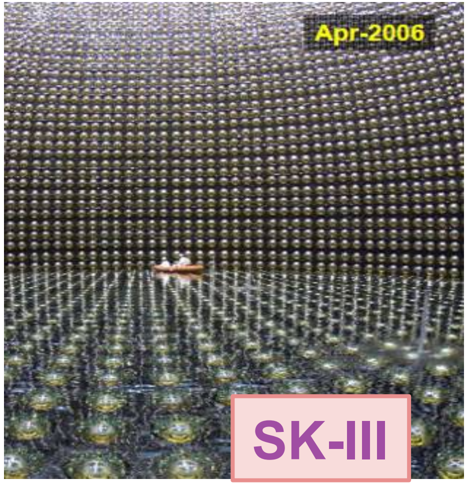
$$A^{8B}_{DN} = \frac{D-N}{(N+D)/2} = (-3.3 \pm 1.0 \pm 0.5)\%$$

Phases of Super-Kamiokande









	11146 ID PMTs (40% coverage)	**5182 ID PMTs (19% coverage)**	**11129 ID PMTs (40% coverage)**	**Electronics Upgrade**	
(Total E)	5.0 MeV	7.0 MeV	5.0 MeV	~4.5 MeV	< 4.0 MeV
(Kinetic E)	~4.5 MeV	~6.5 MeV	~4.5 MeV	~4.0 MeV	<~3.5 MeV
				Current	**Target**

Borexino Collaboration

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