Understanding the Sun with neutrinos: results from the Borexino experiment

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Russbach, 13.03.2013

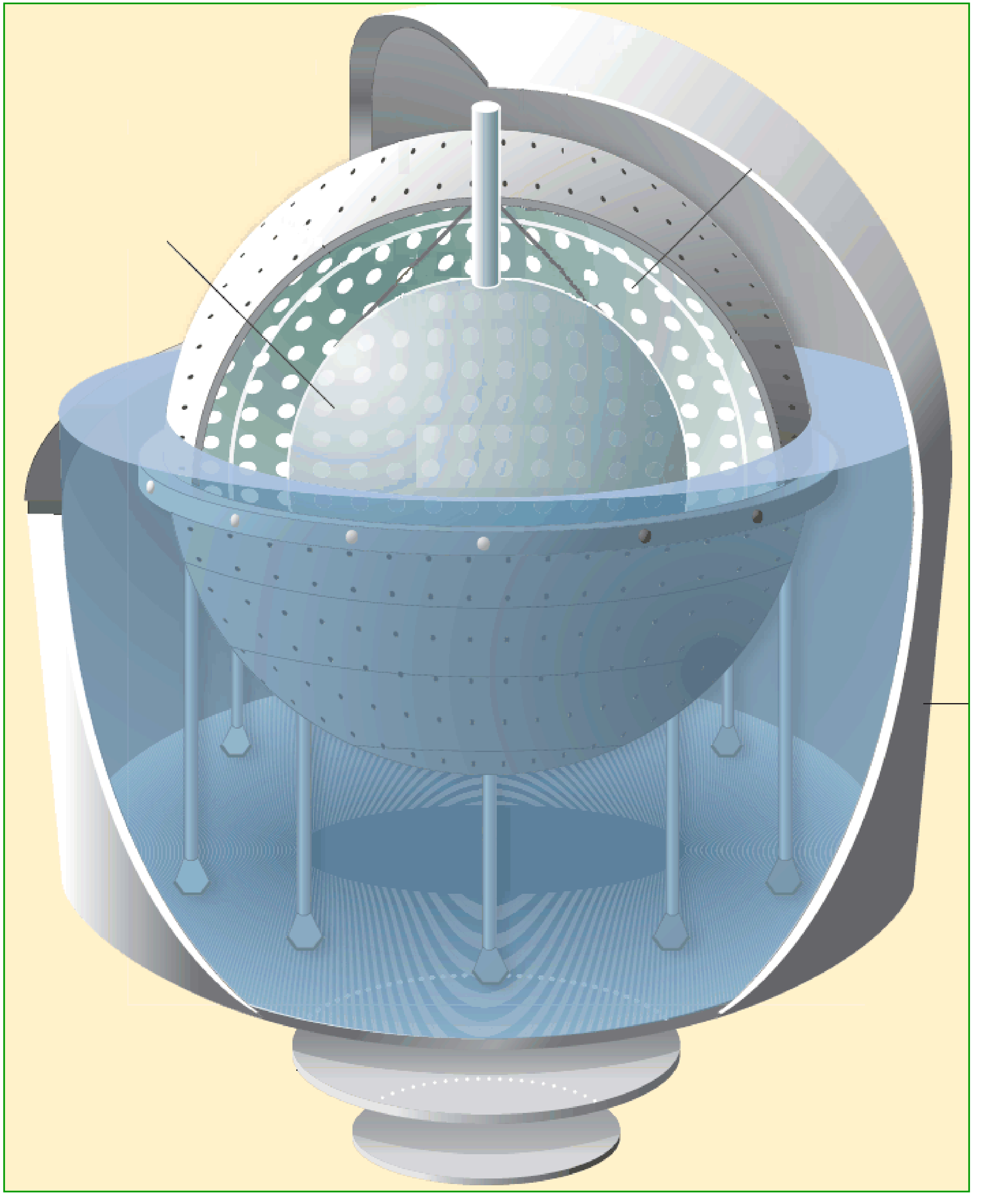
Outline

Motivation:
solar neutrinos
neutrino oscillations

Borexino:
the detector
signal and background

Solar neutrino results:
7Be
8B
pep and CNO
Future plans

Conclusion



The Sun

energy production by nuclear fusion

(hydrogen burning)

$$4p \rightarrow {}^{4}He + 2e^{+} + 2\,\nu_e + 26.7\ MeV$$

predict solar neutrino flux from solar luminosity:

1370 W/m^2 (at earth) => 6.5 x $10^{10}\nu/cm^2\,s$

light (photons) takes 10^5- 10^6 years from core to surface

↕

neutrinos escape from the core

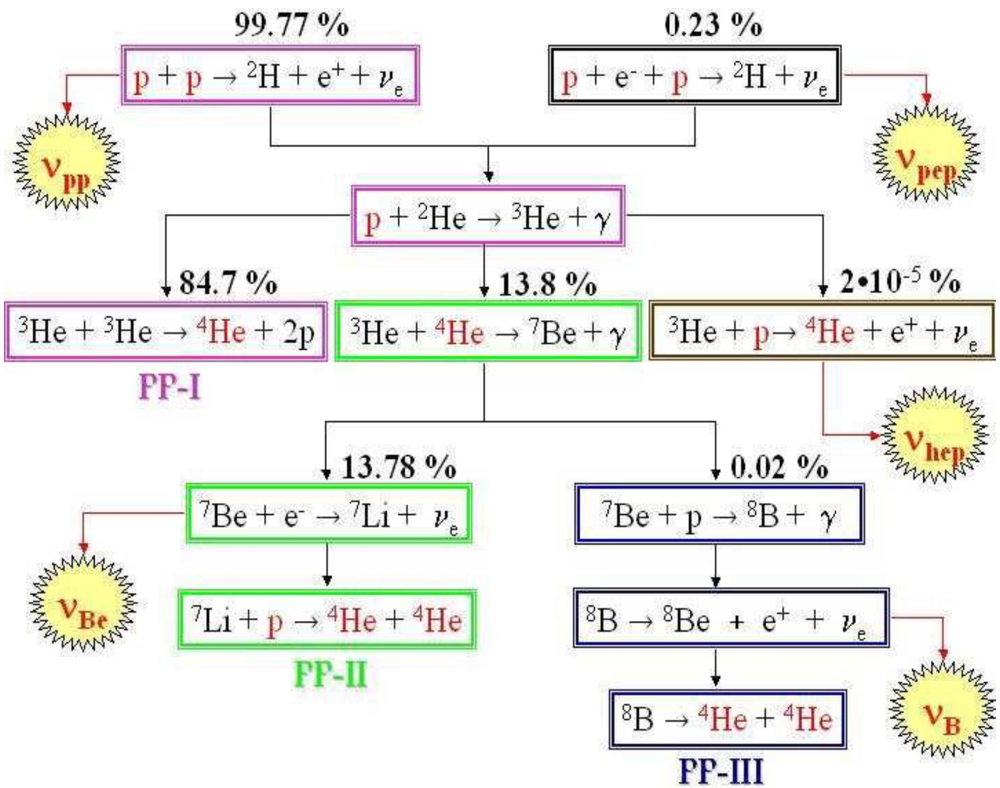
real-time information from the solar core

(~ 8 minutes delay)

Nuclear reactions in the solar core

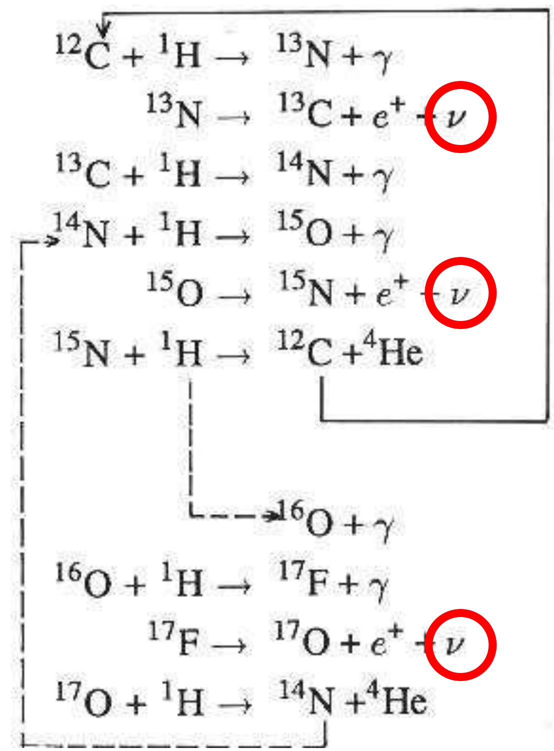
pp cycle

~ 99% of energy



CNO cycle

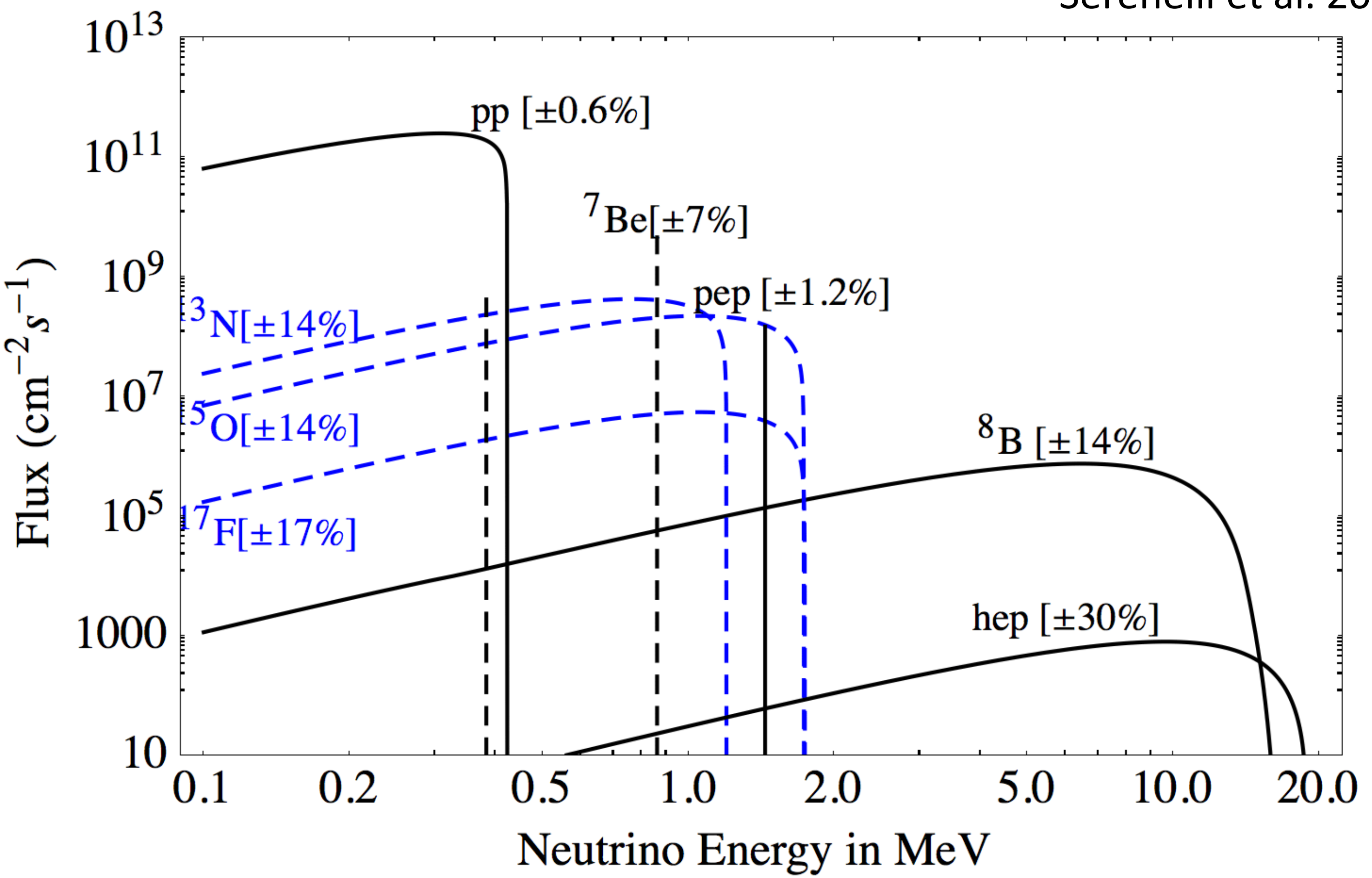
<1% of energy
poorly known
not directly measured yet



The Standard Solar Model

The SSM is the theoretical framework which is used to make predictions on the solar neutrino fluxes.

Serenelli et al. 2011



The Standard Solar Model

The SSM is the theoretical framework which is used to make predictions on the solar neutrino fluxes.

Recent improvements in the SSM (>2004):

- new determination of $^{14}N(p,\gamma)^{15}O$ cross section reduced CNO fluxes by a factor ~2
- a factor of 2 better accuracy for $^{3}He(^{4}He,\gamma)^{7}Be$ cross section
- new opacities calculations
- more accurate solar surface abundancies
- improved 3D models

$\Rightarrow$ suggest lower metallicity Z

Prediction of Solar Neutrino Fluxes

Source	Neutrino Flux [$cm^{-2}s^{-1}$] SSM-GS98 (high Z)	Neutrino Flux [$cm^{-2}s^{-1}$] SSM-AGS09 (low Z)	Difference [%]
pp	$5.98(1\pm0.006)\times10^{10}$	$6.03(1\pm0.006)\times10^{10}$	0.8
pep	$1.44(1\pm0.012)\times10^{8}$	$1.47(1\pm0.012)\times10^{8}$	2.1
^{7}Be	$5.00(1\pm0.07)\times10^{9}$	$4.56(1\pm0.07)\times10^{9}$	8.8
^{8}B	$5.58(1\pm0.13)\times10^{6}$	$4.59(1\pm0.13)\times10^{6}$	17.7
^{13}N	$2.96(1\pm0.15)\times10^{8}$	$2.17(1\pm0.15)\times10^{8}$	26.7
^{15}O	$2.23(1\pm0.16)\times10^{8}$	$1.56(1\pm0.16)\times10^{8}$	30.0
^{17}F	$5.52(1\pm0.18)\times10^{6}$	$3.40(1\pm0.16)\times10^{6}$	38.4
CNO total	5.24×10^{8}	3.76×10^{8}	28.3

But: low Z models are in conflict with helioseismology (R_{CZ}, Y_{surf})

Can solar neutrino measurements decide?

The Solar neutrino problem

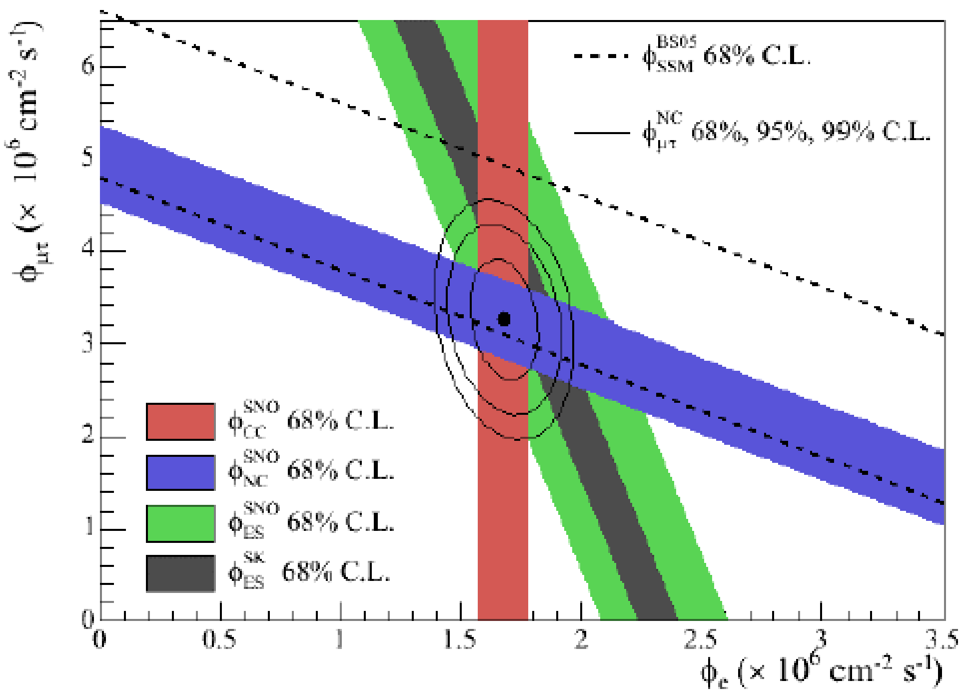
Objective of the first solar neutrino experiment:
"…to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars."
(Bahcall, PRL 12, 300, 1964)

Experiment	Data/ SSM
Homestake ($\nu_e + {}^{37}Cl \to {}^{37}Ar + e$)	0.34 ± 0.03
Sage + Gallex ($\nu_e + {}^{71}Ga \to {}^{71}Ge + e$)	0.56 ± 0.04
Superkamiokande ($\nu_x + e \to \nu_x + e$)	0.46 ± 0.02

finally solved by the SNO experiment:

CC: $\nu_e + d \to p + p + e^-$
NC: $\nu_x + d \to p + n + \nu_x$

$$\frac{\phi^{NC}_{SNO}}{\phi_{SSM}} = 1.01 \pm 0.12$$



solar neutrino flux is compatible with SSM

neutrinos undergo flavor conversion: neutrino oscillations

Solar Neutrino Oscillations in Vacuum

- Solar neutrino oscillations are well approximated by 2-flavor mixing:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

- Only ν_e are produced in solar fusion and detected by (most) experiments. In vacuum, the survival probability is

$$P_{ee} = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

- Due to the large distance and loss of coherence, P_{ee} takes an average of

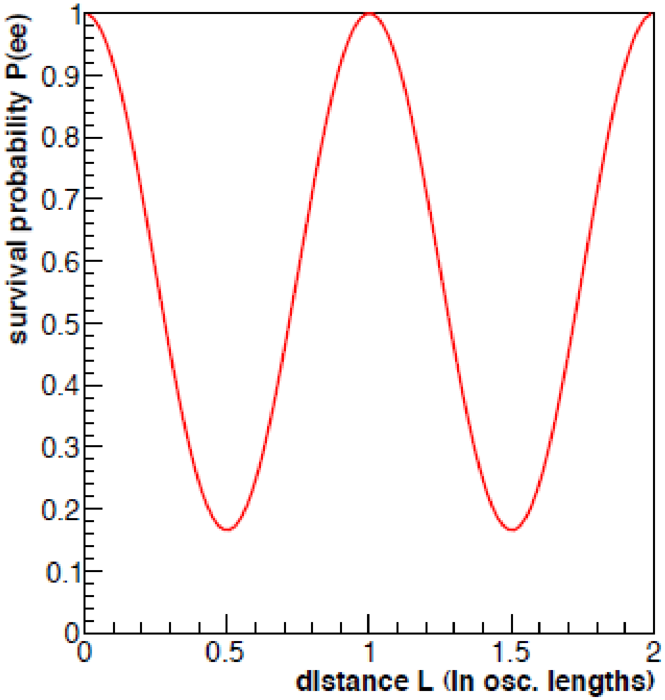
$$P_{ee} = 1 - \frac{1}{2}\sin^2 2\theta \approx 0.6$$

ν_e, ν_μ : flavor eigenstates

ν_1, ν_2 : mass eigenstates

θ_{12} : mixing angle

Δm^2_{12} : mass squared difference

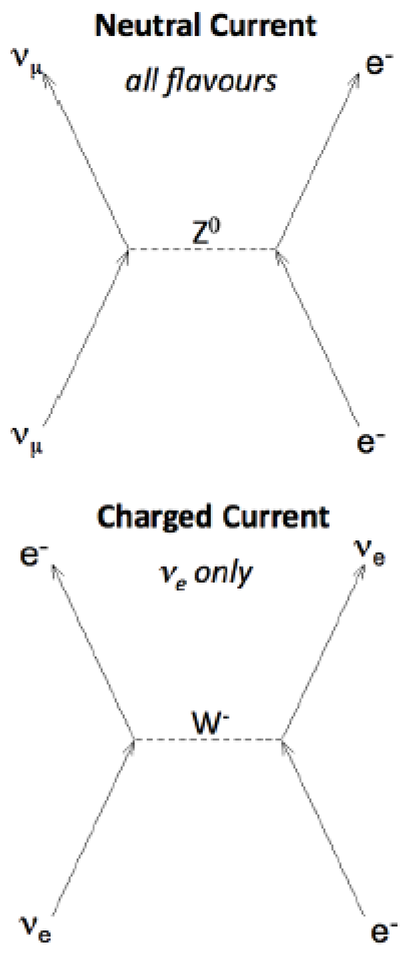


Solar Neutrino Oscillations in Matter

Matter is made of e^- (no μ, τ)

- coherent ν-e^- scattering affects oscillations
- $\boldsymbol{\nu_e}$ interactions different from $\nu_{\mu,\tau}$
- *"effective potential"* for ν_e different from $\nu_{\mu,\tau}$

(**W**olfenstein, '78)



Resonance effect (**M**ikheyev & **S**mirnov, 1985)

- adiabatic conversion in matter with slowly varying density

MSW Effect in the Sun:

- Low energy neutrinos (pp ν) → oscillations as in **vacuum**

  $\mathbf{P_{ee} \approx 1 - ½ \sin^2 2\theta \approx 0.6}$

- High energy neutrinos (^{8}B ν) → **matter enhanced** oscillations

  $\mathbf{P_{ee} \approx \sin^2\theta \approx 0.3}$

- **Transition region** between 1-4MeV

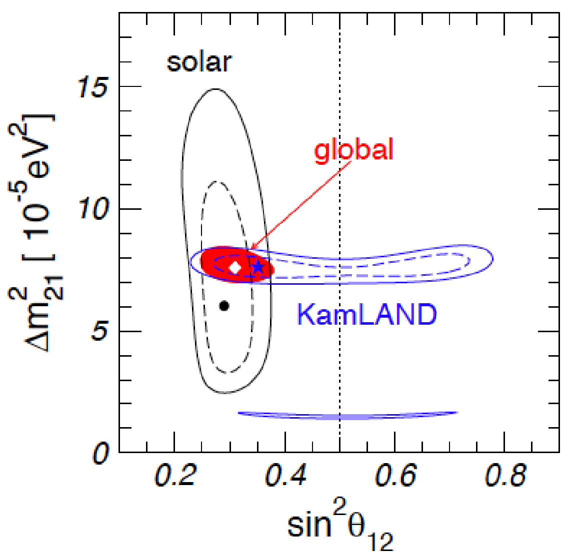
The MSW – LMA oscillation scenario

Large Mixing Angle

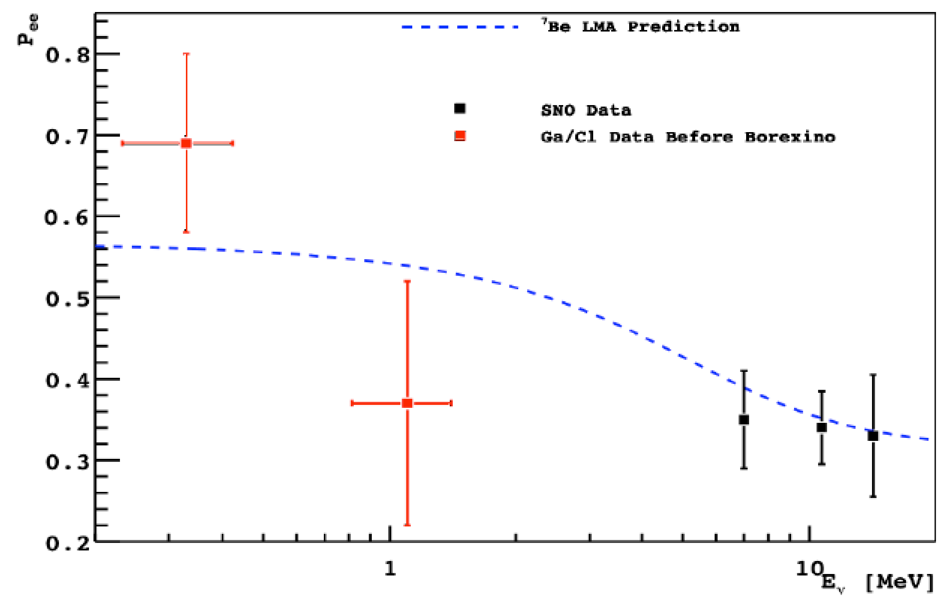
Global analysis of
solar neutrino data
+ KamLAND:

$\Delta m^2_{21} = 7.6 \cdot 10^{-5}\ eV^2$

$\theta_{12} = (34 \pm 3)°$



Schwetz et al. 1103.0734



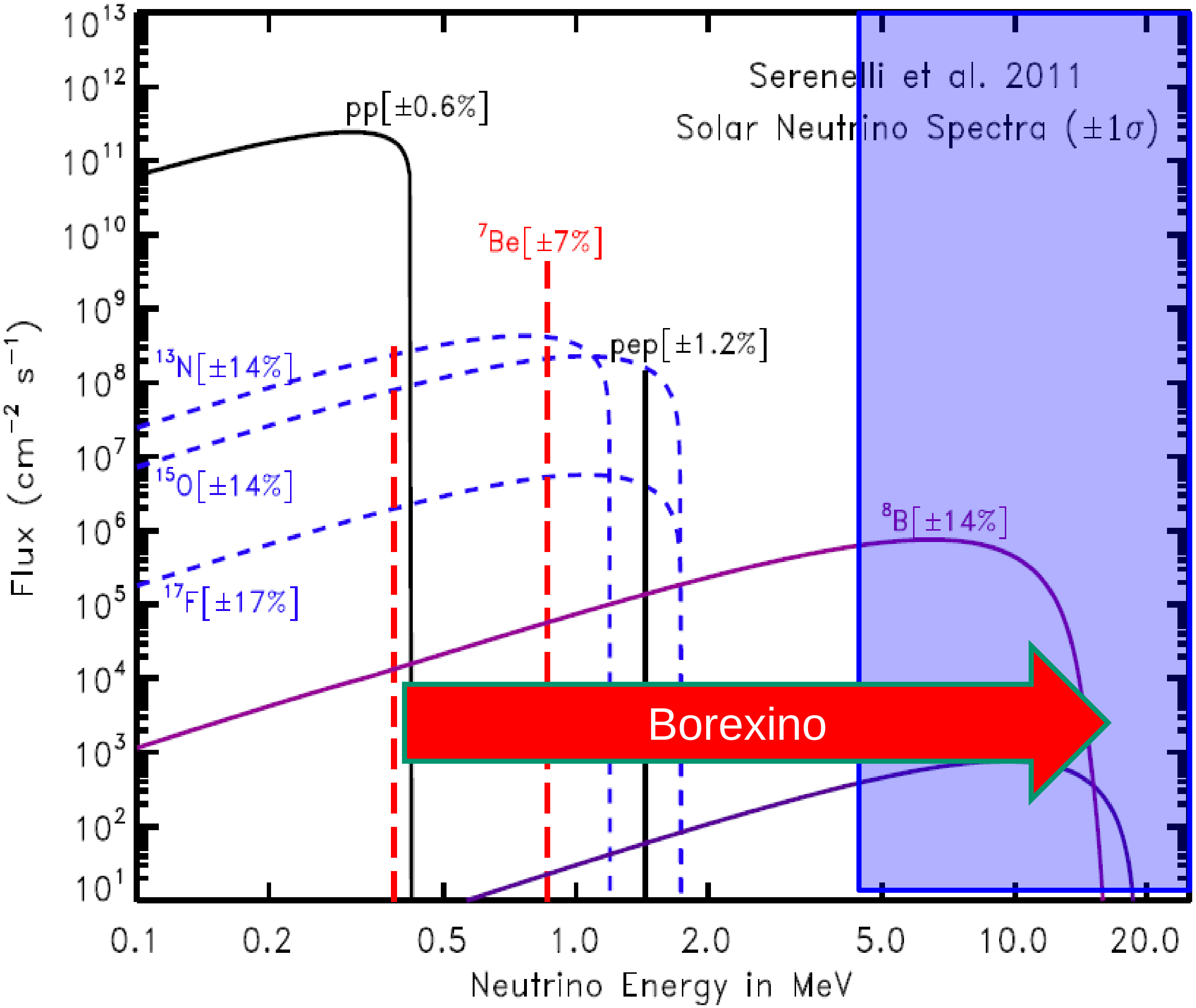
Oscillations in vacuum
probability averages
over long distances, **$P_{ee} \approx 0.6$**

⇔

Matter-enhanced oscillations
interaction with solar matter
increases osc. probability, **$P_{ee} \approx 0.3$**

Solar Neutrinos: what next?

- real-time spectroscopy of low energy neutrinos: ^{7}Be, pep, CNO, pp
  (99% of solar neutrino flux is < 1 MeV)



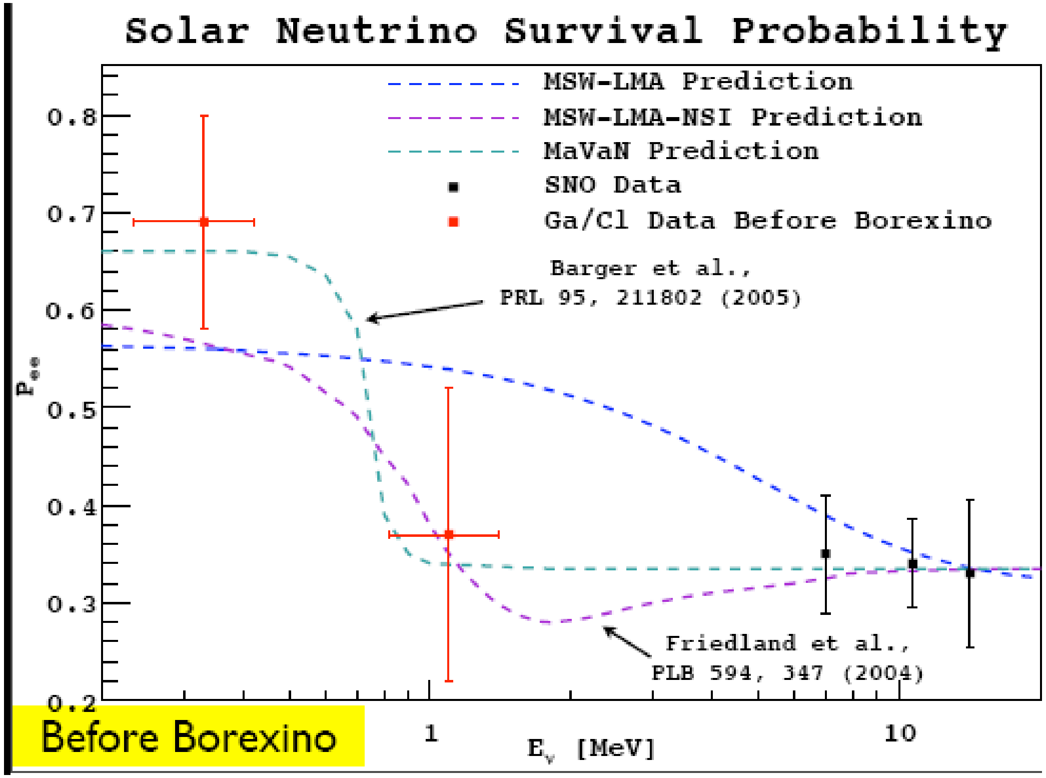
Cerenkov-experiments
(SNO, SuperK)
< 10^{-4} of the total
solar neutrino flux

Solar Neutrinos: what next?

- real-time spectroscopy of low energy neutrinos: ^{7}Be, pep, CNO, pp
  (99% of solar neutrino flux is < 1 MeV)

- neutrino physics:
  test transition region MSW to vacuum oscillations (1 – 4 MeV)
  - precision measurement θ_{12}, Δm_{21}^2
  - Non-Standard Interactions

- solar physics:
  - high Z/ low Z SSM
  - test luminosity constraint
    $L_\nu = L_\odot$
  - determination of CNO:
    important for heavy stars



Borexino Collaboration

INFN

Genova

Perugia

Milano

APC Paris

Princeton University

Virginia Tech. University

LNGS Laboratori Nazionali del Gran Sasso

Istituto Nazionale di Fisica Nucleare INFN

Dubna JINR (Russia)

Kurchatov Institute (Russia)

Jagiellonian U. Cracow (Poland)

Max-Planck-Institut für Kernphysik

Heidelberg (Germany)

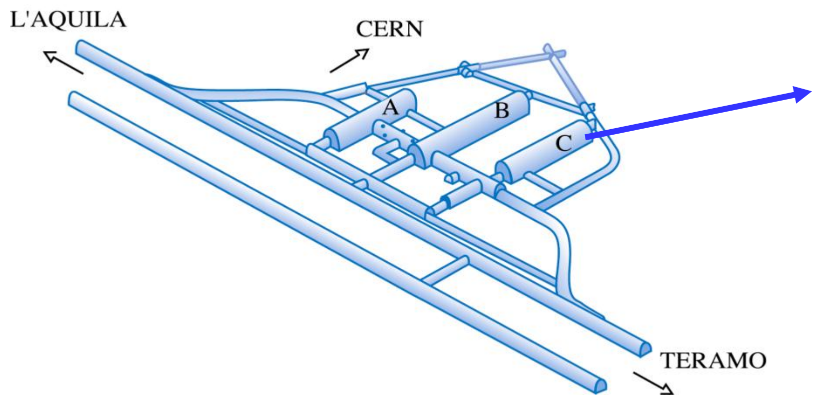
TUM Technische Universität München

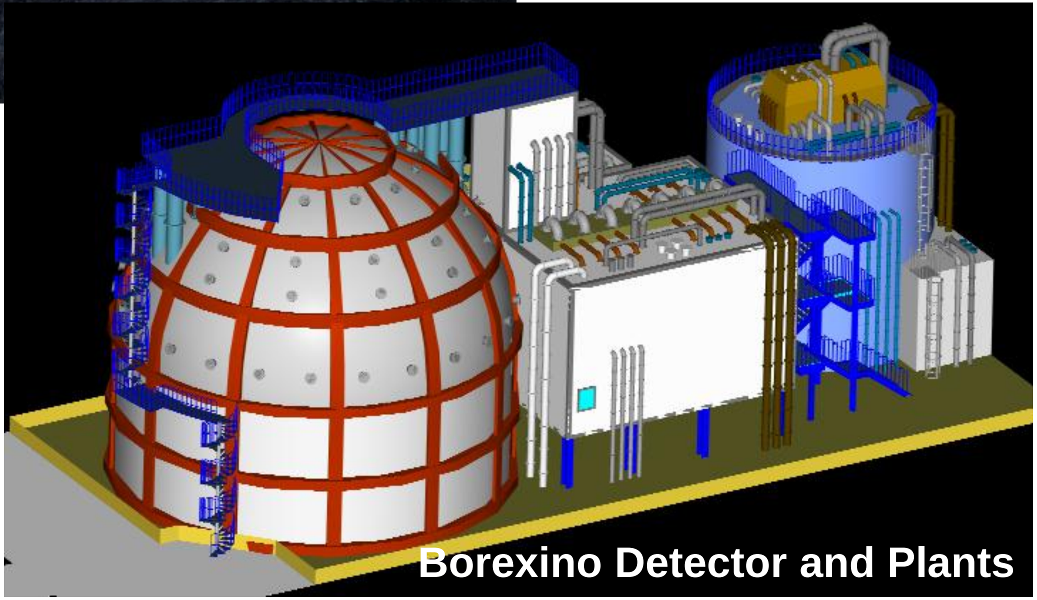
Munich (Germany)

Borexino: Detector Location

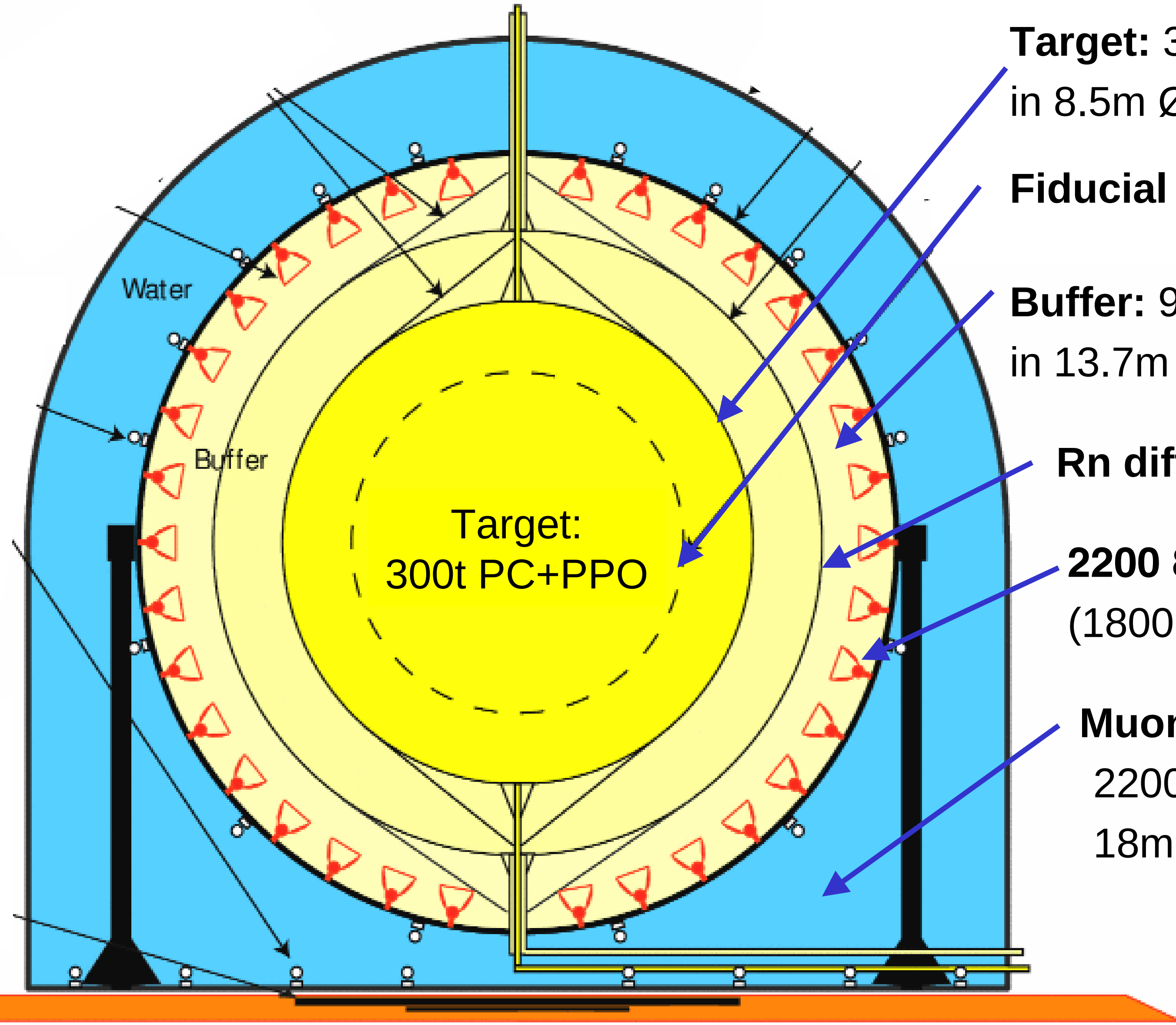
INFN: Laboratori Nazionali del Gran Sasso, Assergi (AQ), Italy

~3500 m.w.e





The Borexino Detector



Target: 300t PC + PPO (1.5 g/l) in 8.5m Ø nylon vessel (0.1 mm)

Fiducial volume: 100t (6 m Ø)

Buffer: 900t PC + DMP (5g/l) in 13.7m Ø stainless steel sphere

Rn diffusion barrier (11m Ø)

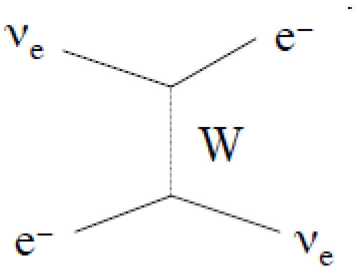
2200 8'' PMTs
(1800 with concentrators)

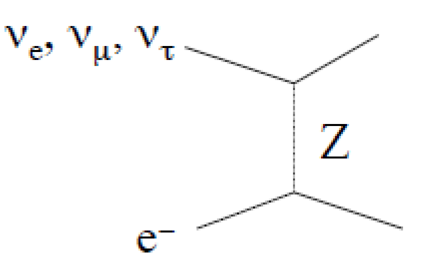
Muon veto: 208 8'' PMTs
2200 t H_2O in steel tank
18m Ø


taking data since May 2007

Borexino: detection principle

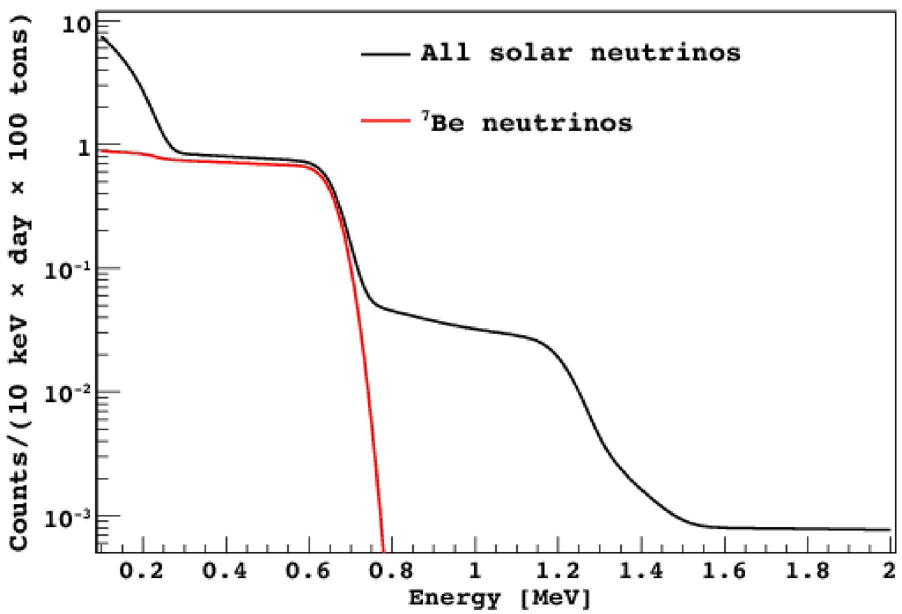
- **elastic scattering on electrons in organic liquid scintillator**





- **detection via scintillation light:**
  + low energy threshold
  + good energy & position resolution

  but:
  – no direction measurement
  – no distinction of ν induced events from other β events



⇒ **extreme radiopurity of the scintillator required**

shielding, material selection, purification

Radiopurity constraints

No specific signature of neutrino events except recoil energy of scattered e^-

=> Background suppression is crucial

Intrinsic contamination of the **liquid scintillator** :

Background	Typical abundance (source)	Goal	Measured
$^{14}C/^{12}C$	10^{-12} (cosmogenic) g/g	~ 10^{-18} g/g	~ 2 x 10^{-18} g/g
^{238}U (by ^{214}Bi-^{214}Po)	2 x10^{-5} (dust) g/g	10^{-16} g/g	(1.6 $\pm$ 0.1) x 10^{-17} g/g < 9.7 x 10 $^{-19}$g/g (2012)
^{232}Th (by ^{212}Bi-^{212}Po)	2 x 10^{-5} (dust) g/g	10^{-16} g/g	(5 $\pm$ 1) x 10^{-18} g/g < 2 x 10 $^{-18}$g/g (2012)
^{210}Po	Surface contamination	~1 c/day/t	2007: 70 c/d/t 2012: 4 c/d/t
^{40}K	2 x 10^{-6} (dust) g/g	~10^{-18} g/g	< 3 x 10^{-18} (90%) g/g
^{85}Kr	1 Bq/m^3 (air)	~1 c/d/100t	(28 $\pm$ 7) c/d/100t < 6 c/d/100t (2012)
^{39}Ar	17 mBq/m^3 (air)	~1 c/d/100t	<< ^{85}Kr

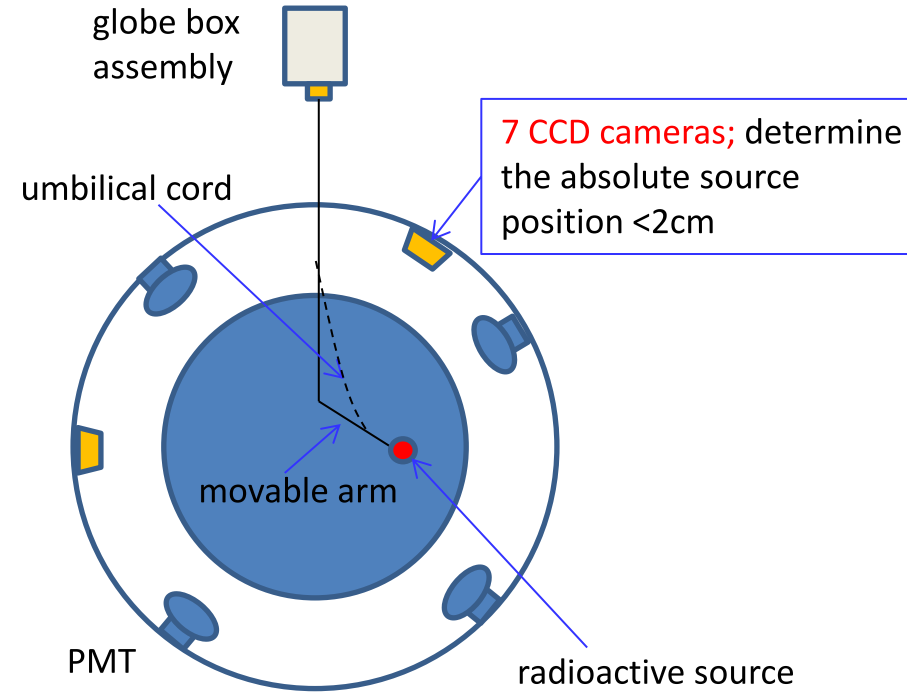
Detector Calibration (2009)

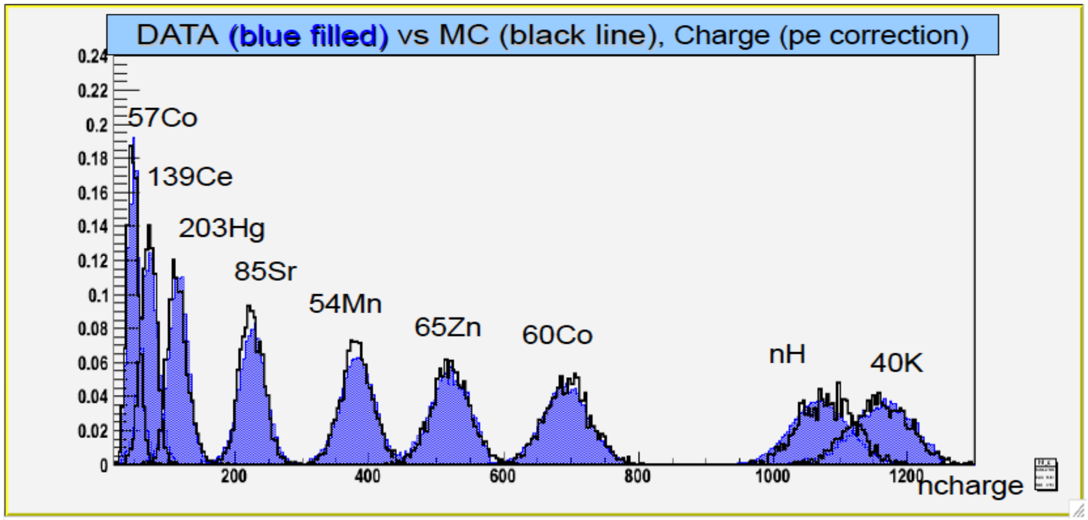
Detector response vs position:

– 100 Hz ^{14}C+^{222}Rn in scintillator in ~ 200 positions

Quenching and energy scale:

– Beta: ^{14}C, ^{222}Rn in scintillator
– Alpha: ^{222}Rn in scintillator
– Gamma: ^{139}Ce, ^{57}Co, ^{60}Co, ^{203}Hg, ^{65}Zn, ^{40}K, ^{85}Sr, ^{54}Mn
– Neutron: AmBe





Light Yield ~ 500 p.e./MeV

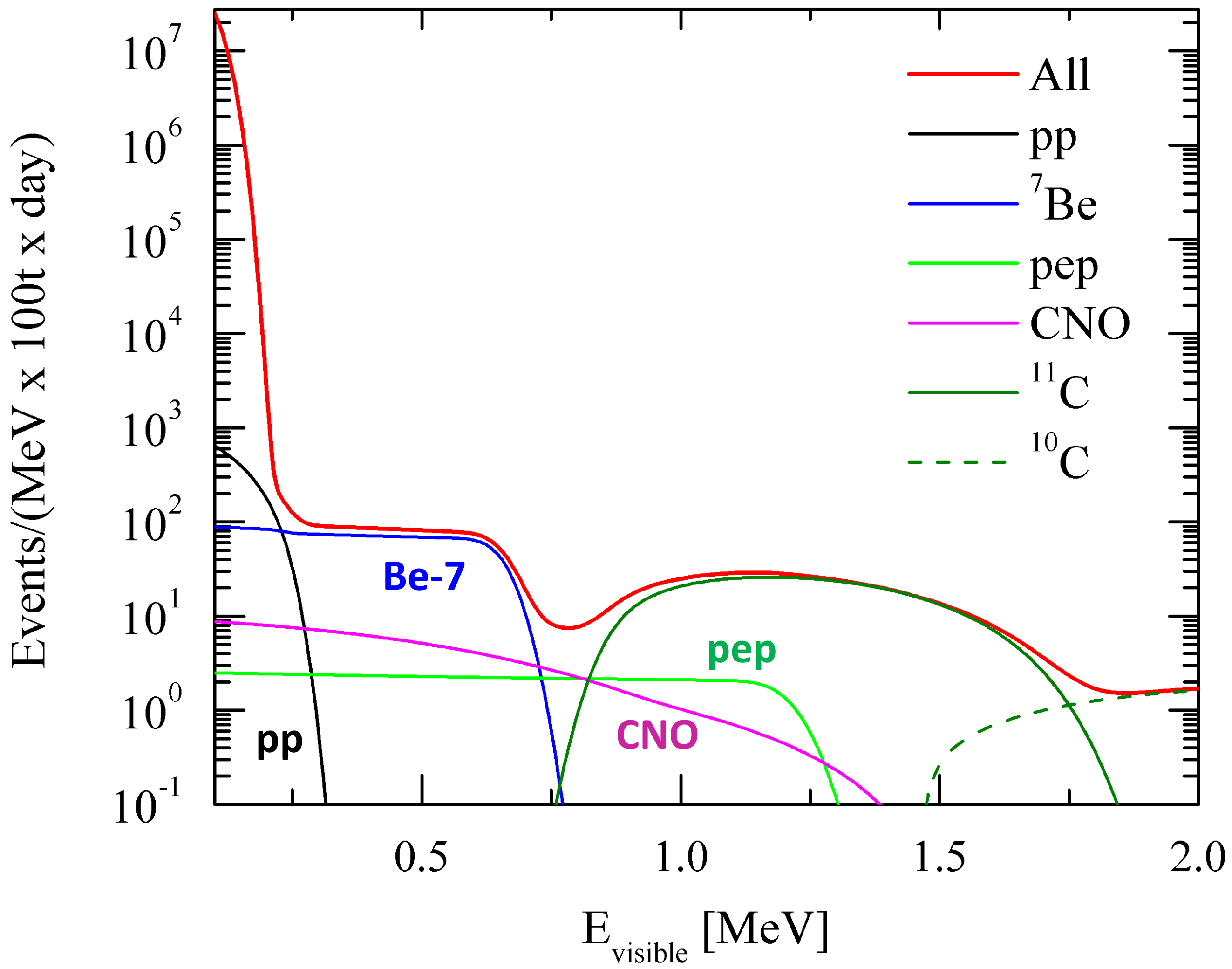
$\sigma(E)/E \approx 4.5\%/\sqrt{E}$

fiducial volume uncertainty: 1.3%

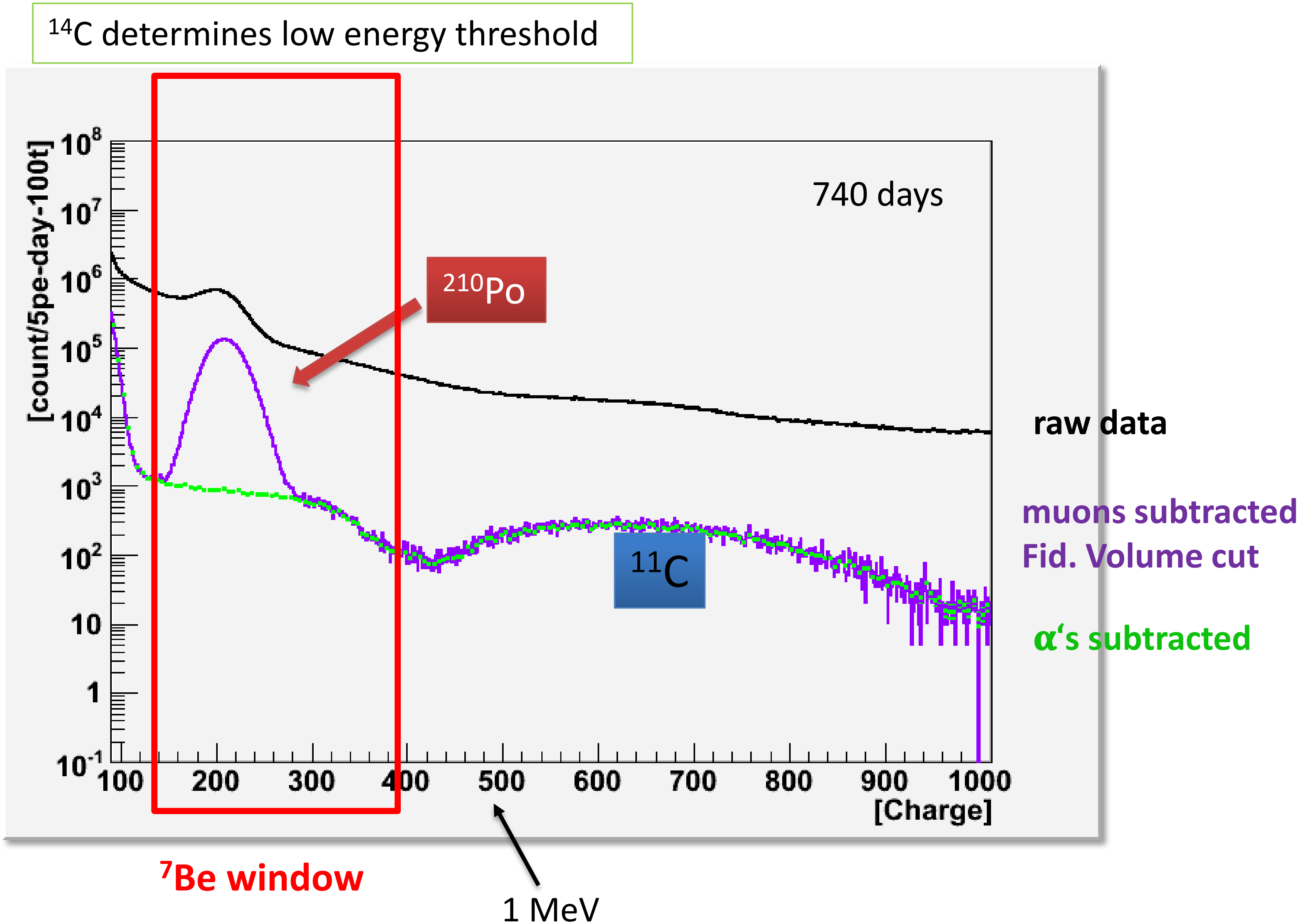
energy scale uncertainty (0-2 MeV): < 1.5 %

Borexino Expected Solar ν Spectrum

Spectrum with irreducible backgrounds:

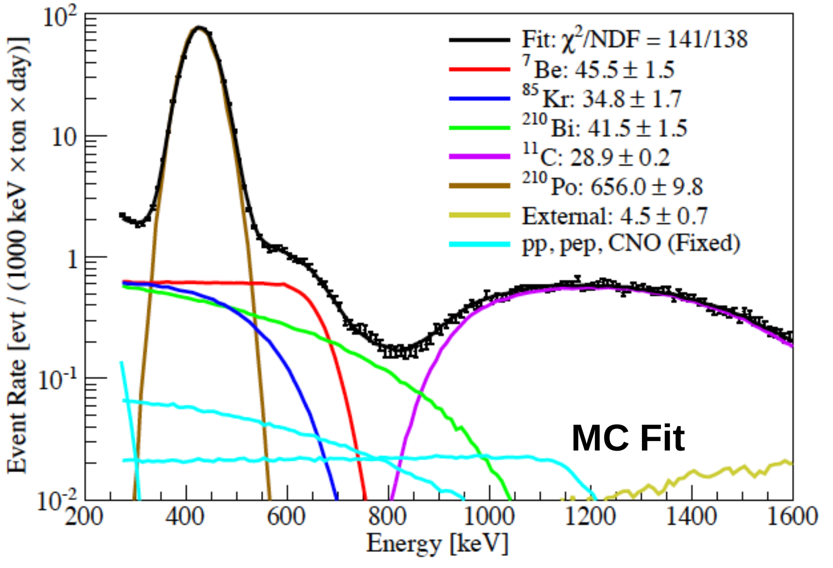


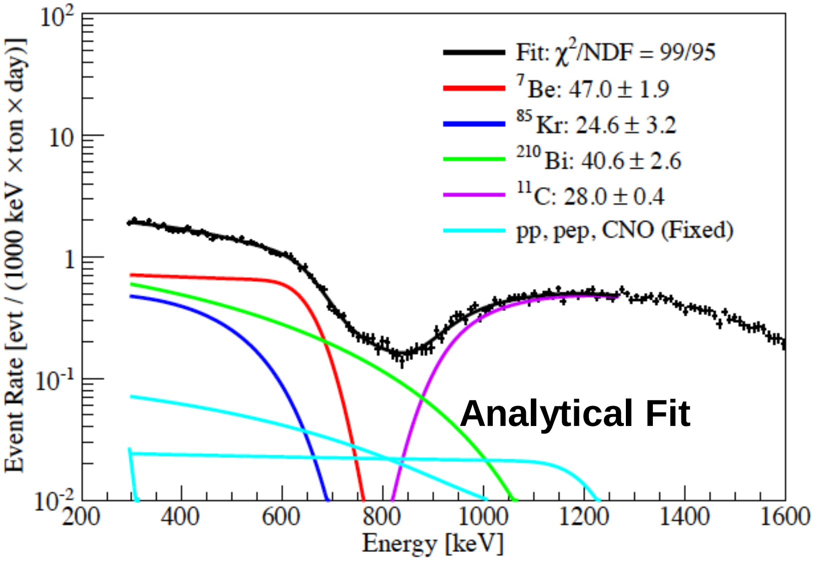
Data reduction



Precision measurement of ^{7}Be neutrino rate

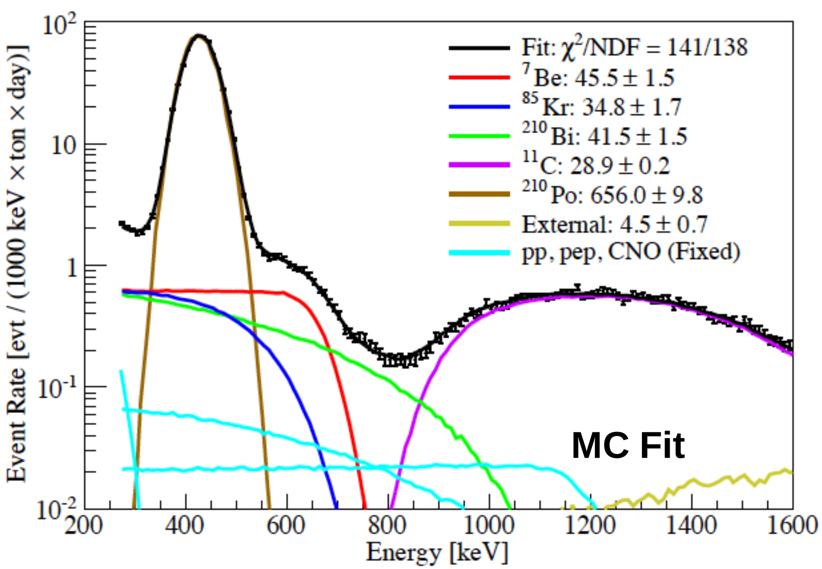
740 live days

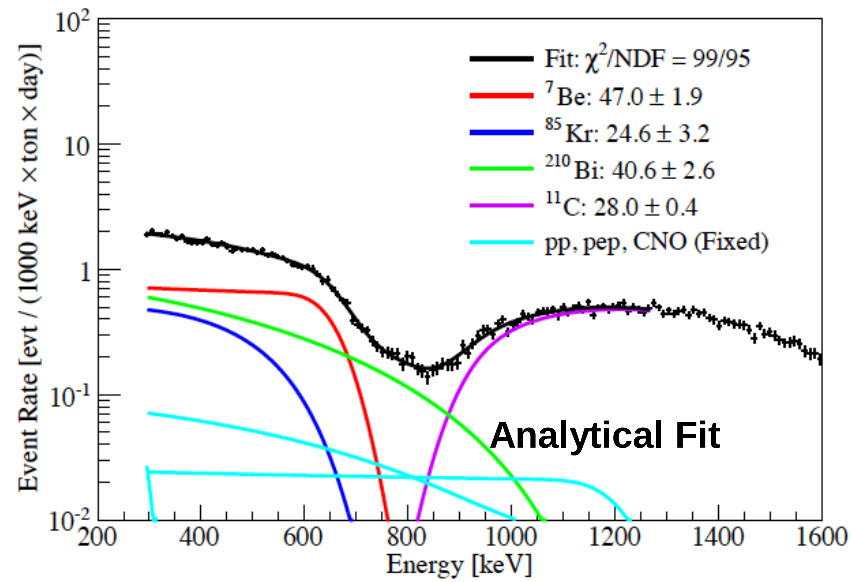




- A spectral fit is applied including the following signal + all intrinsic back ground components.
  - ^{7}Be, ^{85}Kr, ^{14}C, ^{11}C
  - ^{210}Bi (very similar to CNO in this limited energy region)
  - pp, pep, ^{8}B, and CNO neutrinos fixed at SSM-LMA value
- Fit with and without statistical subtraction of ^{210}Po events, based on α/β pulse shape discrimination.
- Two independent ways (MC based and analytical) were applied.

Precision measurement of ^{7}Be neutrino rate





Systematics

740 live days

Source	[%]
Trigger efficiency and stability	<0.1
Live time	0.04
Scintillator density	0.05
Sacrifice of cuts	0.1
Fiducial volume	$^{+0.5}_{-1.3}$
Fit methods	2.0
Energy response	2.7
Total Systematic Error	$^{+3.4}_{-3.6}$

^{7}Be	$46.0\pm1.5(\mathrm{stat})^{+1.5}_{-1.6}(\mathrm{syst})$
^{85}Kr	$31.2\pm1.7(\mathrm{stat})\pm4.7(\mathrm{syst})$
^{210}Bi	$41.0\pm1.5(\mathrm{stat})\pm2.3(\mathrm{syst})$
^{11}C	$28.5\pm0.2(\mathrm{stat})\pm0.7(\mathrm{syst})$

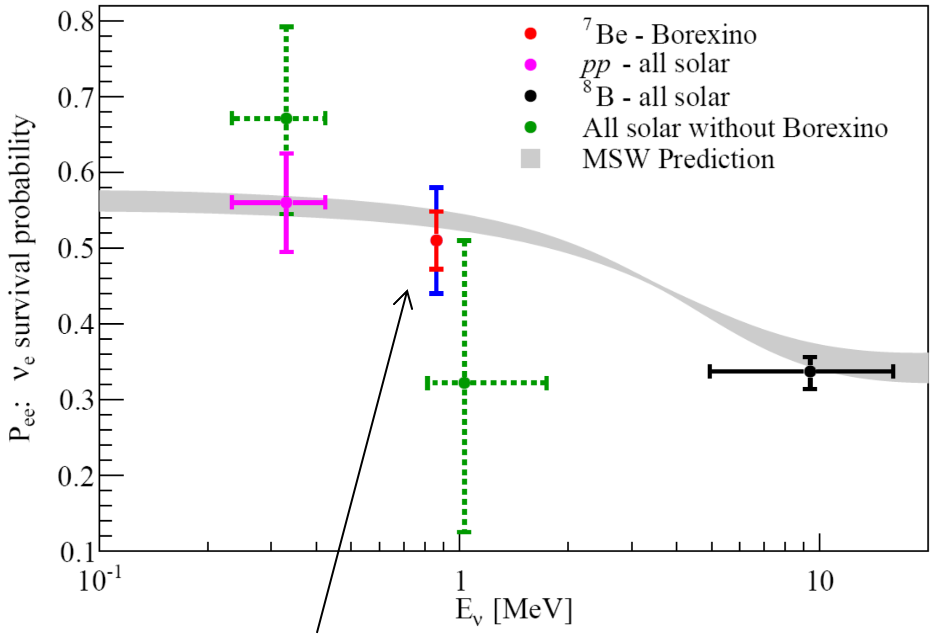
combined error: 4.5%

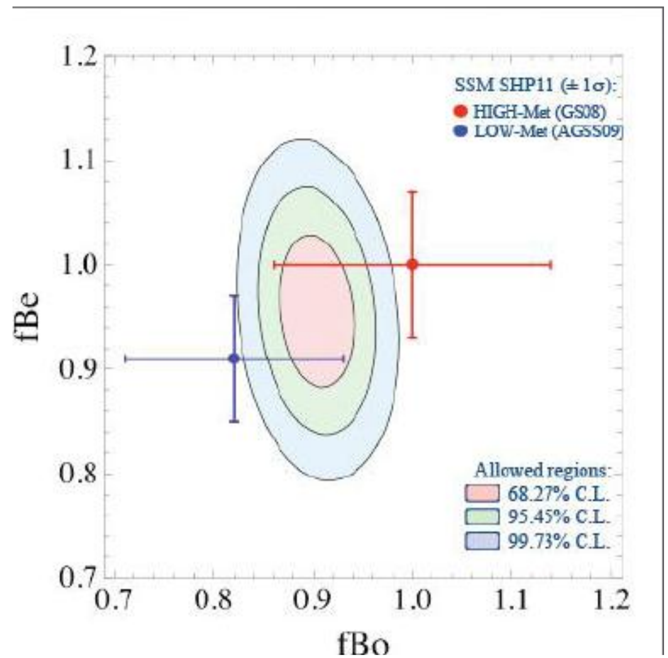
Phys. Rev. Lett. 107, (2011) 141302

Implications of the ^7Be measurement

- electron equivalent flux (862 keV line): $(2.78 \pm 0.13) \times 10^9\ cm^{-2}\ s^{-1}$
  no oscillation excluded @ **5.0 σ**

- assuming MSW-LMA: $f_{7Be} = \boldsymbol{\phi/\phi_{SSM}} = 0.97 \pm 0.09$
- including all solar experiments + luminosity constraint:
  $f_{pp} = 1.013\ ^{+0.003}_{-0.010}$ $f_{CNO} < 1.7\%$ (95 % C.L.)





$P_{ee} = 0.51 \pm 0.07$ @ 862 keV

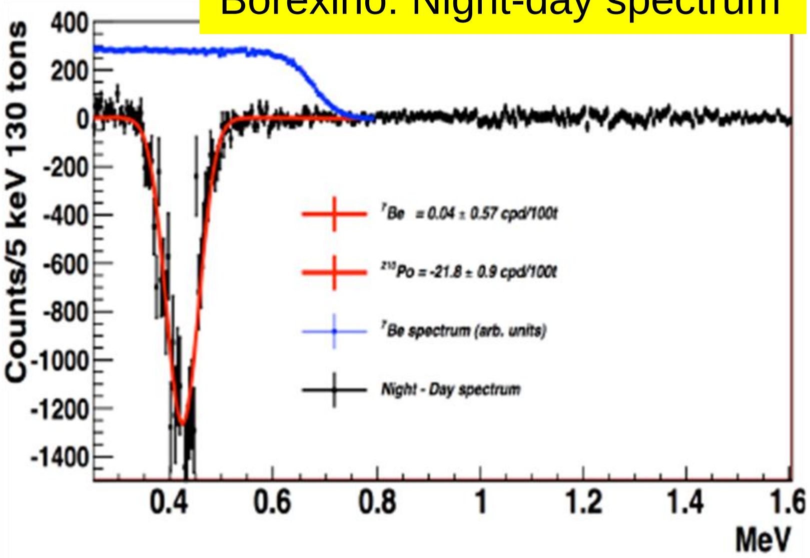
no power to resolve low/high metallicity problem

Absence of day-night asymmetry for ^{7}Be ν

Phys. Lett. B 707, 22-26, 2012

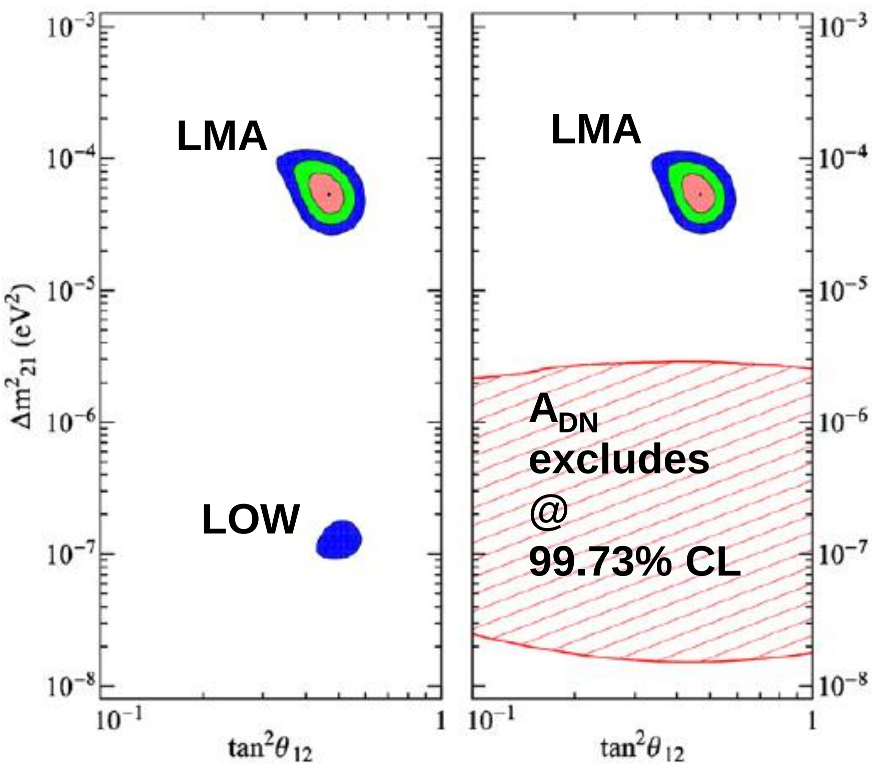
MSW: a possible regeneration of electron neutrinos in the matter (within the Earth during night): effect depends on the oscillation parameters and on energy

Borexino: Night-day spectrum



$$A_{dn} = 2\frac{R_N - R_D}{R_N + R_D} = \frac{R_{\text{diff}}}{\langle R \rangle}$$

solar neutrino data WITHOUT Borexino | **solar neutrino data WITH Borexino**

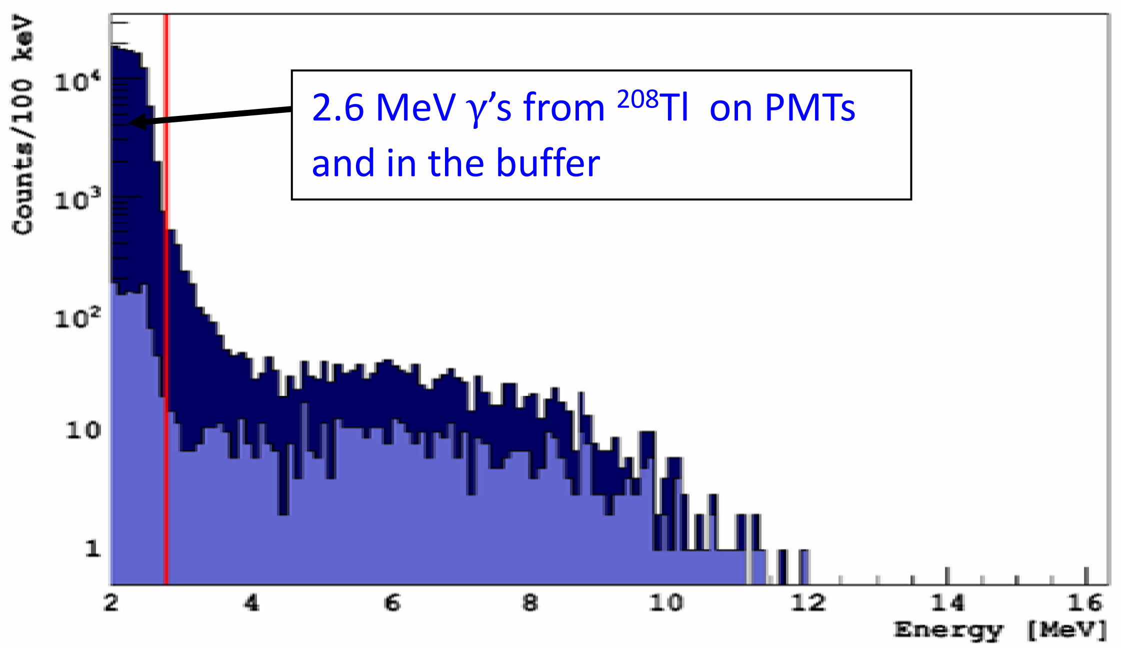


A_{DN}= 0.001 ± 0.012(stat) ± 0.007(syst)

- in agreement with MSW-LMA;
- LOW region excluded at > 8.5 σ with solar neutrinos only: for the first time without the use of reactor antineutrinos (KamLAND) and the assumption of CPT symmetry

Low threshold measurement of the ^{8}B solar ν

Borexino energy spectrum after muon subtraction:
246 live days



Borexino threshold: 2.8 MeV

Expected (MSW-LMA) count rate due to ^{8}B neutrinos above 2.8 MeV:

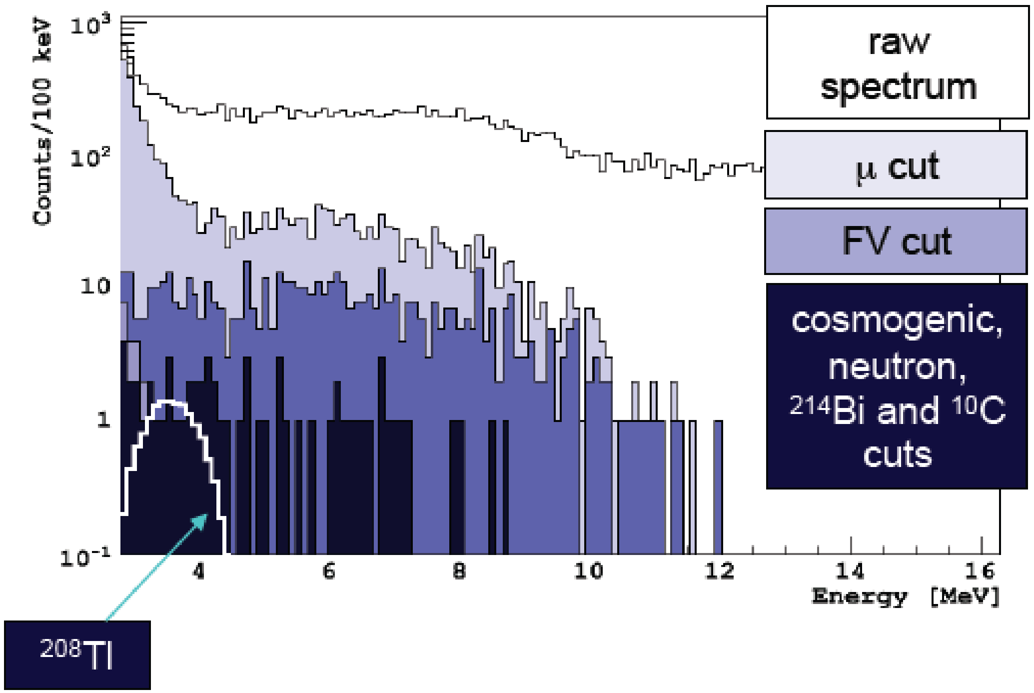
0.26±0.03 c/d/100 tons

Major background sources:

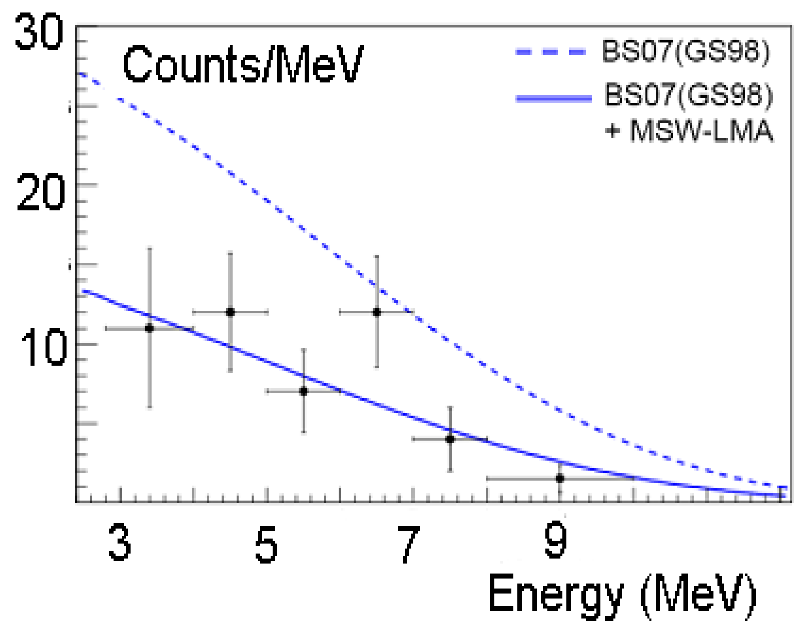
- Muons
- Gammas from neutron capture
- Radon emanation from the nylon vessel
- Short lived (t < 2 s) cosmogenic isotopes
- Long lived (t > 2 s) cosmogenic isotopes (^{10}C)
- Bulk ^{232}Th contamination (^{208}Tl)

Signal/Background (>2.8 MeV):
~ 1/6000

Low threshold measurement of the 8B solar ν



Phys. Rev. D82 (2010) 033006



	3.0-16.3 MeV	5.0-16.3 MeV
Rate [c/d/100 t]	0.22±0.04±0.01	0.13±0.02±0.01
Φ^{ES}_{exp} [10^6 $cm^{-2}s^{-1}$]	2.4±0.4 ±0.1	2.7±0.4 ±0.2
$\Phi^{ES}_{exp}/\Phi^{ES}_{th}$	0.88±0.19	1.08±0.23

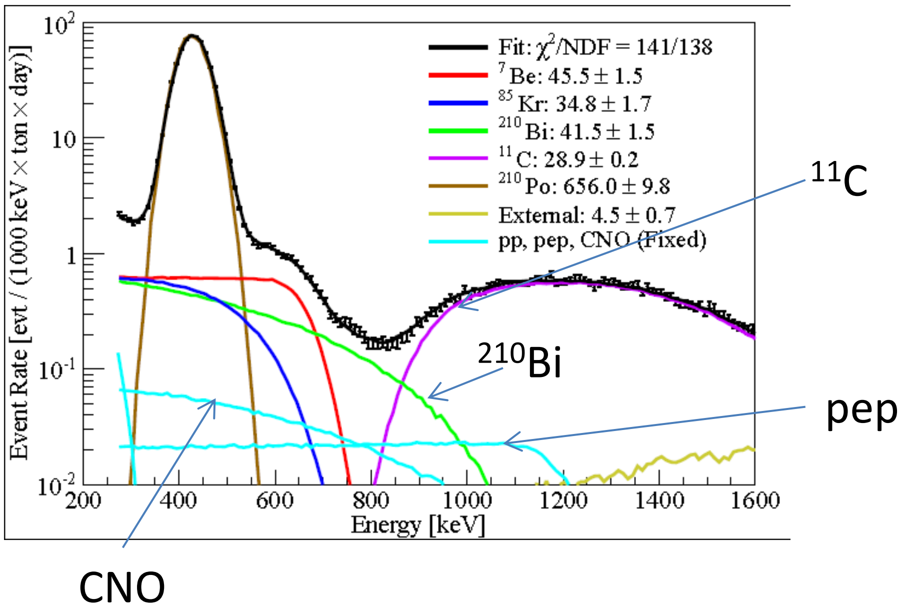
^{7}Be and ^{8}B flux measured with the same detector

Borexino ^{8}B flux above 5 MeV agrees with existing data (SNO, SuperK)

Neutrino oscillation is confirmed at 4.2 σ

The first pep ν measurement

Phys. Rev. Lett. 108 (2012) 051302



Expected pep interaction rate:

2-3 cpd/100t

Main background:

^{11}C , ^{210}Bi, external γ

^{210}Bi and CNO:

very similar spectral shape

^{11}C reduction:

- Three Fold Coincidence (muon + neutron + C11)
- Novel pulse shape discrimination: e^+ /e^- discrimination (D. Franco et al., Phys. Rev. C 015522 (2011))

Multivariate analysis:

- fit of the energy spectra
- fit the radial distribution of the events (external γ background is not uniform)
- fit the pulse shape parameter

^{11}C reduction: Threefold coincidence (TFC)

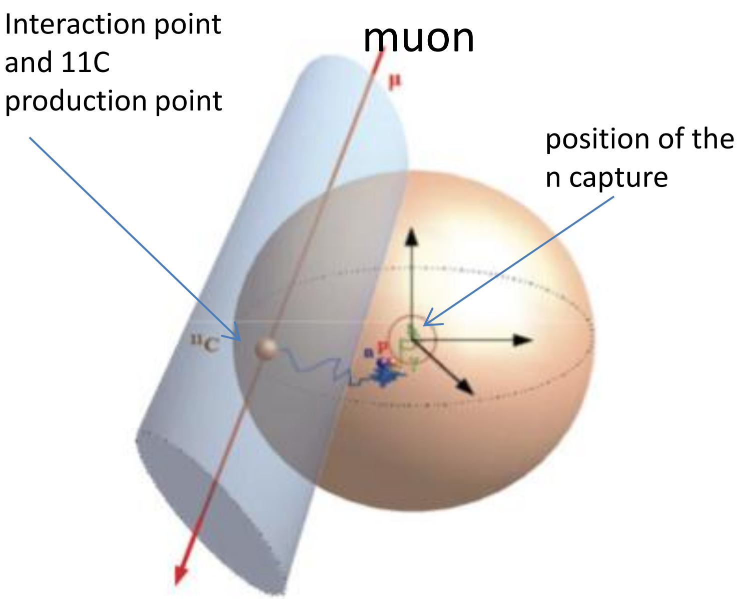
$$\mu + {}^{12}C \rightarrow \mu + {}^{11}C + n$$

$$n + p \rightarrow d + \gamma$$

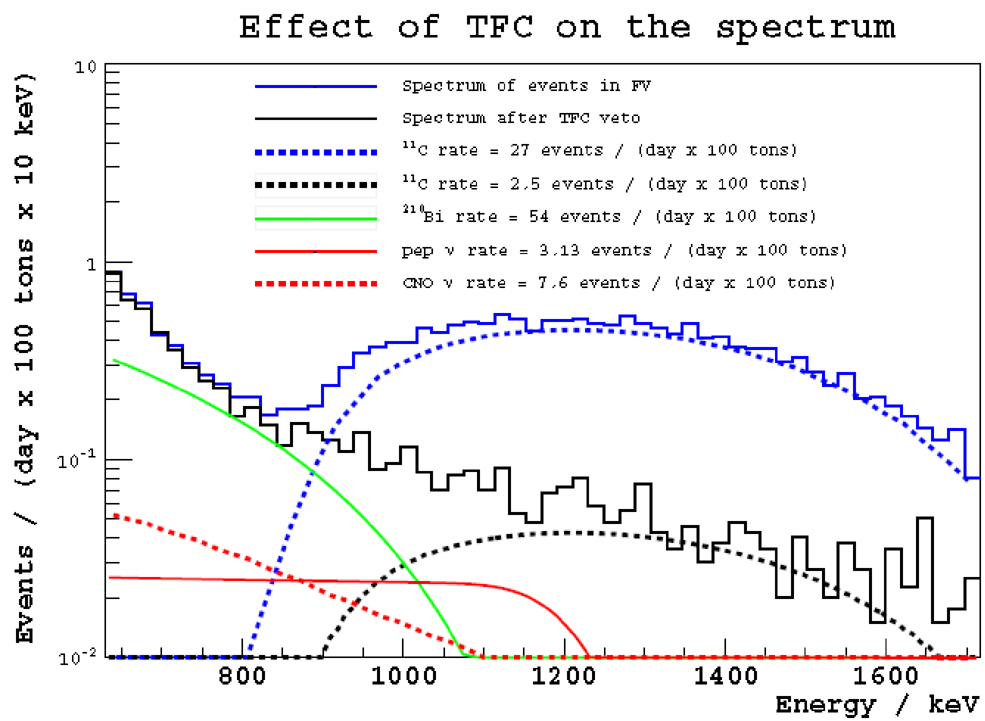
$$^{11}C \rightarrow {}^{11}B + e^{+} + \nu_e$$

^{11}C $\tau \sim 30$ min

in Borexino:
~ 4300 muons/day
> 250 neutrons /day
~ 25 ^{11}C /day



cylindrical cut around muon
+ spherical cut around γ
removes 90% of C11
residual exposure 48.5%

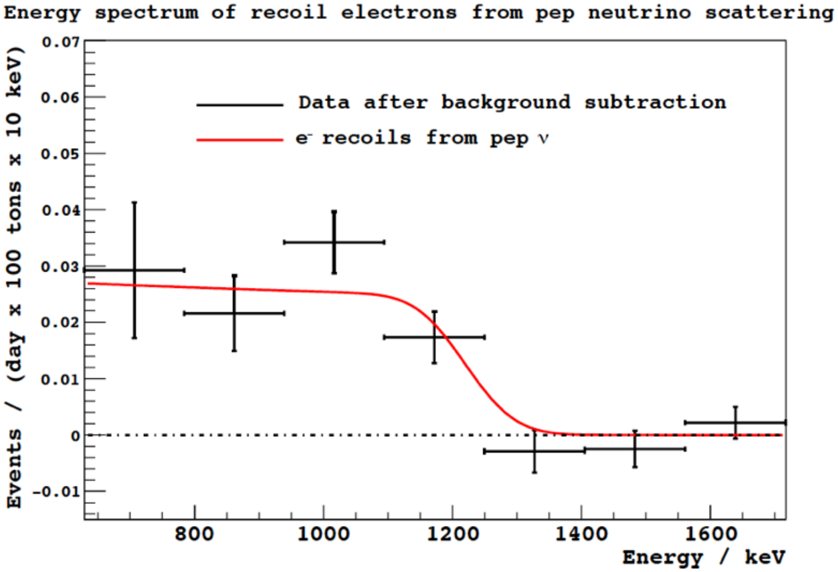


pep and CNO neutrinos: results

Phys. Rev. Lett. 108 (2012) 051302

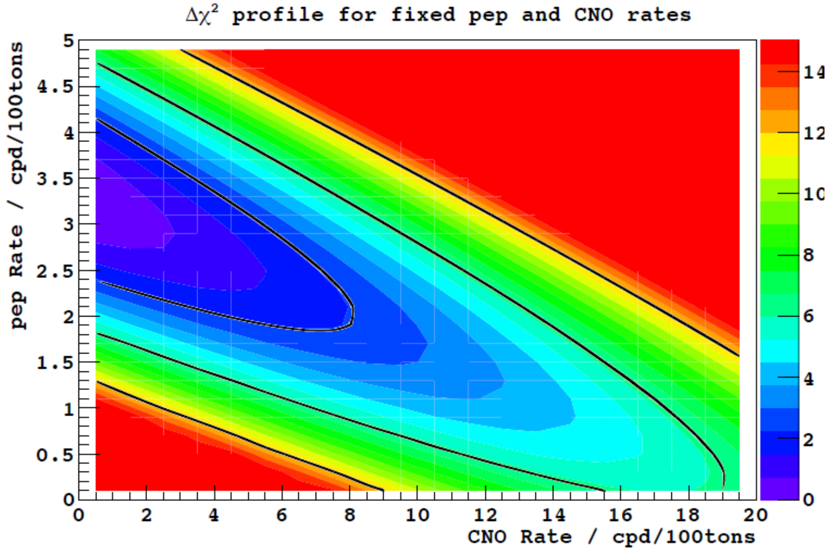
pep neutrinos:

- **Rate: 3.1 ± 0.6$_{(stat)}$ ± 0.3$_{(sys)}$ cpd/100 t**
- **Φ_{pep} = (1.6 ± 0.3) x 10^8 cm^{-2} s^{-1}**
- No oscillations excluded at **97% C.L.**
- Absence of pep solar ν excluded at 98%



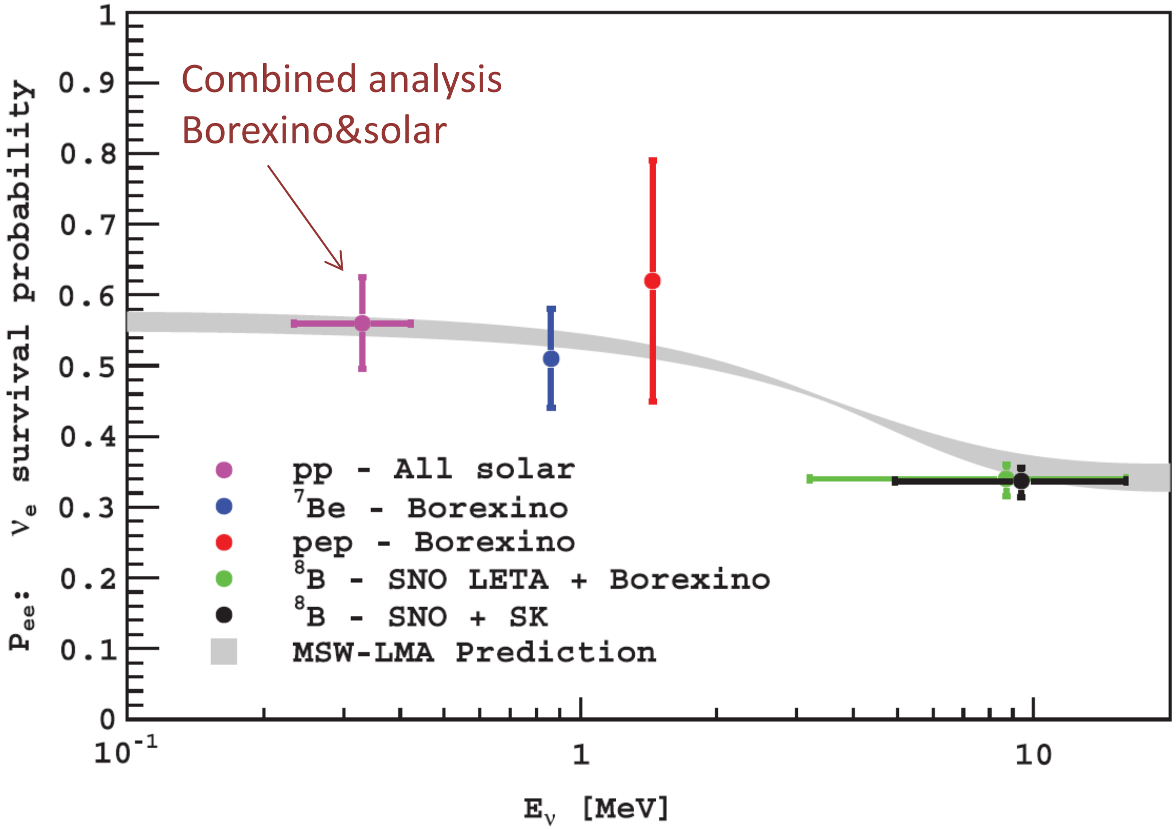
CNO neutrinos:

- only limits, strong correlation with ^{210}Bi
- CNO limit obtained assuming pep @ SSM
  CNO rate < 7.1 cpd/100 t (95% c.l.)
- **Φ_{CNO} < 7.7 10^8 cm^{-2} s^{-1} (95% C.L.)**
- **the strongest limit to date**
- **not sufficient to resolve metallicity problem**

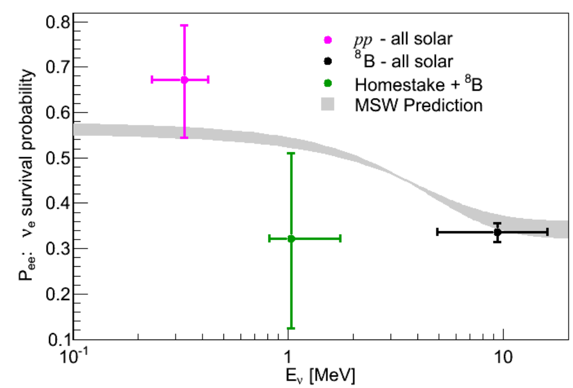


Physics implication of the Borexino results

MSW-LMA confirmed (7Be,pep and 8B measurement)



Before the Borexino results



LOW excluded (solar only) by day-night-asymmetry

Predicted vs. measured solar neutrino fluxes

Source	Flux [$cm^{-2}s^{-1}$] SSM-GS98	Flux [$cm^{-2}s^{-1}$] SSM-AGSS09	Measured Flux [$cm^{-2}s^{-1}$] global analysis
pp	$5.98(1\pm0.006)\times10^{10}$	$6.03(1\pm0.006)\times10^{10}$	**$6.05(1\pm0.01)\times10^{10}$**
pep	$1.44(1\pm0.012)\times10^{8}$	$1.47(1\pm0.012)\times10^{8}$	**$1.46(1\pm0.014)\times10^{8}$**
^{7}Be	$5.00(1\pm0.07)\times10^{9}$	$4.56(1\pm0.07)\times10^{9}$	**$4.82(1\pm0.05)\times10^{9}$**
^{8}B	$5.58(1\pm0.13)\times10^{6}$	$4.59(1\pm0.13)\times10^{6}$	**$5.00(1\pm0.03)\times10^{6}$**
^{13}N	$2.96(1\pm0.15)\times10^{8}$	$2.17(1\pm0.15)\times10^{8}$	
^{15}O	$2.23(1\pm0.16)\times10^{8}$	$1.56(1\pm0.16)\times10^{8}$	
^{17}F	$5.52(1\pm0.18)\times10^{6}$	$3.40(1\pm0.16)\times10^{6}$	
CNO total	5.24×10^{8}	3.76×10^{8}	**$< 7.7 \times 10^{8}$**

high metallicity   low metallicity

metallicity problem can not be resolved with present data

Borexino: phase 2 (2012 – 2015)

Goals (solar neutrinos):

- reach 3σ significance of pep signal (reduce ^{210}Bi background)
- measure ^{7}Be neutrinos to 3% (reduce ^{85}Kr and ^{210}Bi backgrounds)
- improve ^{8}B measurement with low energy threshold (statistics)

  => **test MSW**

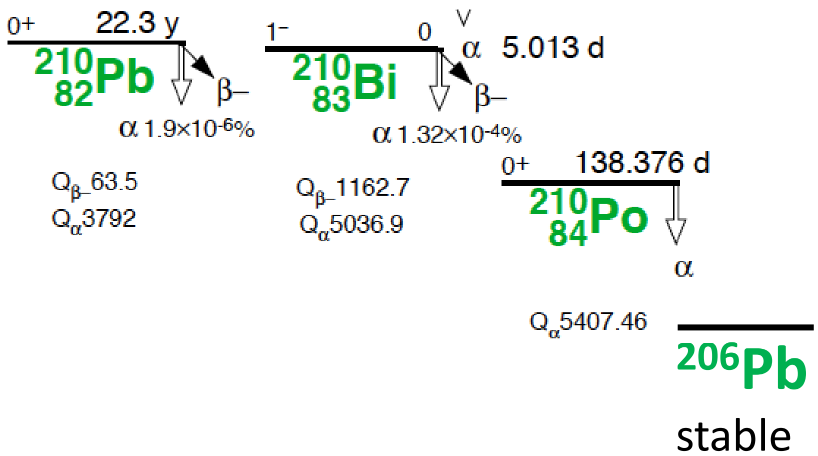
- improve limit on CNO neutrinos (reduce ^{210}Bi background!)

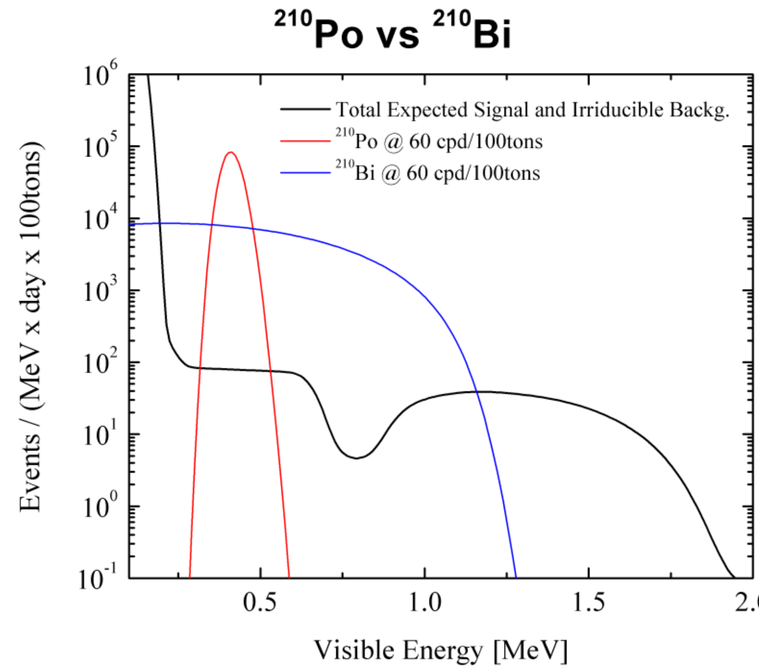
  => **probe metallicity**

- direct detection of pp neutrinos (very challenging, need to improve knowledge on ^{14}C spectrum and pile-up effects)

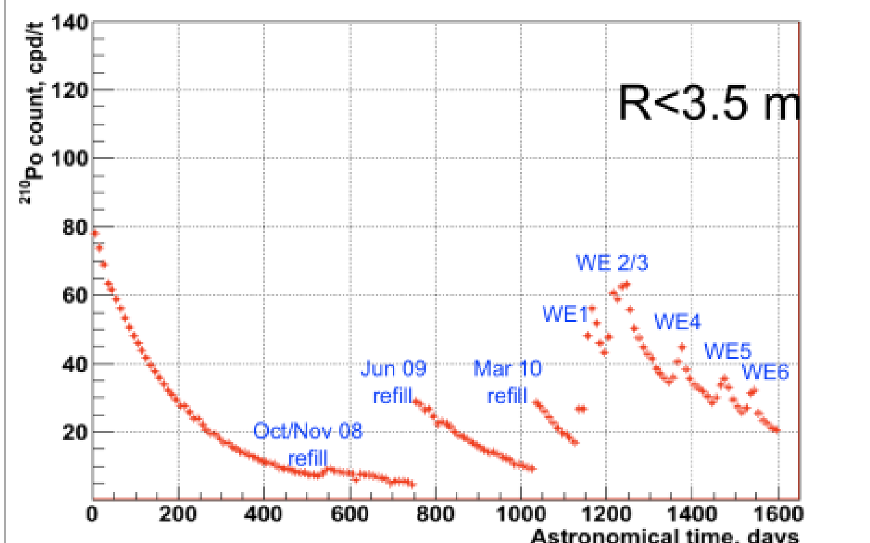
^{210}Bi and ^{210}Po in Borexino

- last part of the ^{238}U chain:



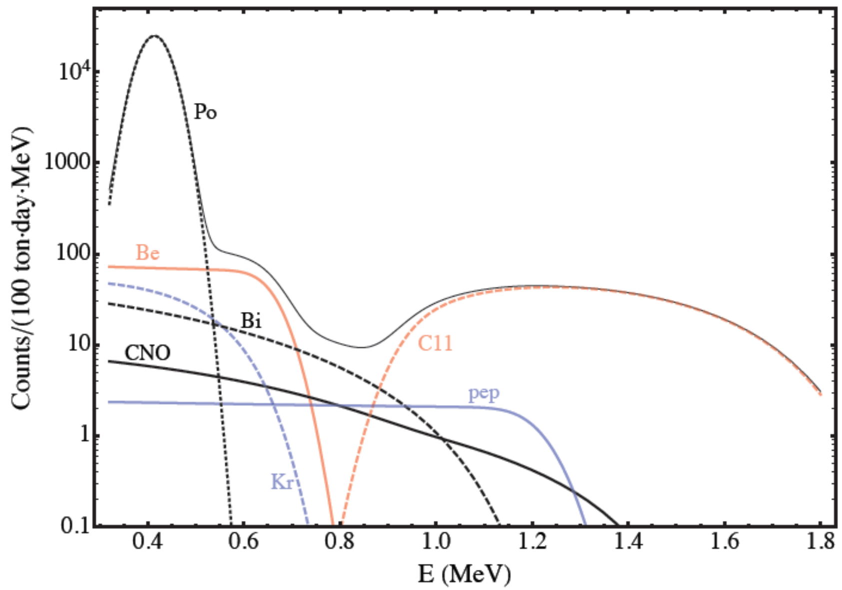


- ^{210}Po not in equilibrium
- not a surprise: seen in the CTF (prototype)
- origin not clear (surface contamination of filling tubes ?)
- introduced Po210 with every operation
- now at ~ 3.5 c/d/t



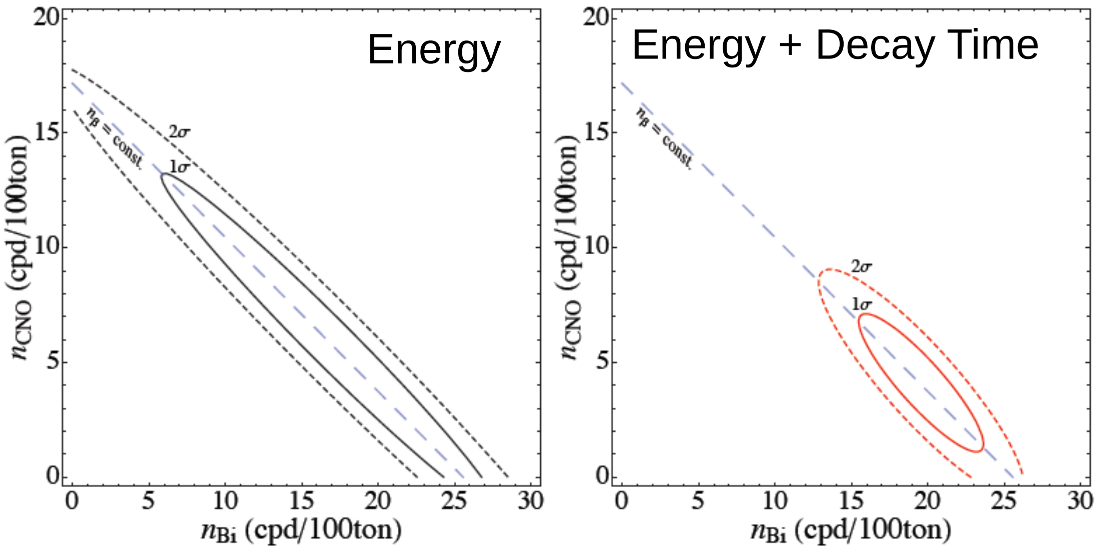
CNO Neutrino Measurement

Main background: ^{210}Bi, β-decay
similar spectral shapes



Strategy suggested by Villante et al. (Phys.Lett.B701:336-341,2011):

Constraining ^{210}Bi rate looking at time evolution of ^{210}Po decay rate:



^{210}Po R(t=0) = 2000 cpd/100 t
M = 100 ton
Δt = 1 year

Conclusions

- **Phase 1** of the Borexino experiment **successfully concluded**
  - First detection and 5% measurement of solar ^{7}Be neutrinos
  - ^{8}B-ν at low energy (>3 MeV), ^{7}Be-ν day-night
  - First detection of pep solar neutrinos

- Scintillator purification was successful, and **Phase 2 is starting**
  - rich program on solar neutrino physics:
    - probe MSW through ^{8}B at low energy, pep and more precise ^{7}Be
    - attempt to detect pp in real time
    - possible interesting upper limit on CNO, probe solar metallicity

  - on our wish list: a galactic Supernova

Borexino References

- **Solar neutrino results**
  - ^{7}Be evidence: PhysLett B658 101-108 (2008)
  - ^{7}Be at 10% + f_{pp}/f_{CNO}: PhysRevLett 101, 091302 (2008)
  - Measurement of the solar 8B neutrino rate with a liquid scintillator target and 3MeV energy threshold in the Borexino detector, PRD 82 (2010) 033006
  - Precision measurement of the 7Be solar neutrino interaction rate in Borexino,
    Phys. Rev. Lett. 107, 141302, 2012
  - Absence of day-night asymmetry of 862 keB 7Be solar neutrinos in Borexino and MSW oscillation parameters, **Phys. Lett. B 707, 22-26, 2012**
  - First evidence of pep solar neutrinos by direct detection in Borexino,
    Phys. Rev. Lett. 108, 051302, 2012

- **Other physics:**
  - Observation of Geo-Neutrinos, Phys. Lett. B687, 299-304, 2012
  - Cosmic muon flux and annual modulation in Borexino, JINST 1205 ,015, 2012
  - Measurement of CNGS muon neutrino speed with Borexino, Phys Lett B716, 401, 2012

- **Search of rare processes**
  - Anti-neutrinos from unknown sources, PLB 696 (2011) 191-196
  - Limits on Pauli forbidden transitions on 12C, PRC 81 (2010) 034317
  - Search for solar axions from p(d,3He)a, PRD 85 (2012) 092003

more interesting results to come


Thank you for the attention!