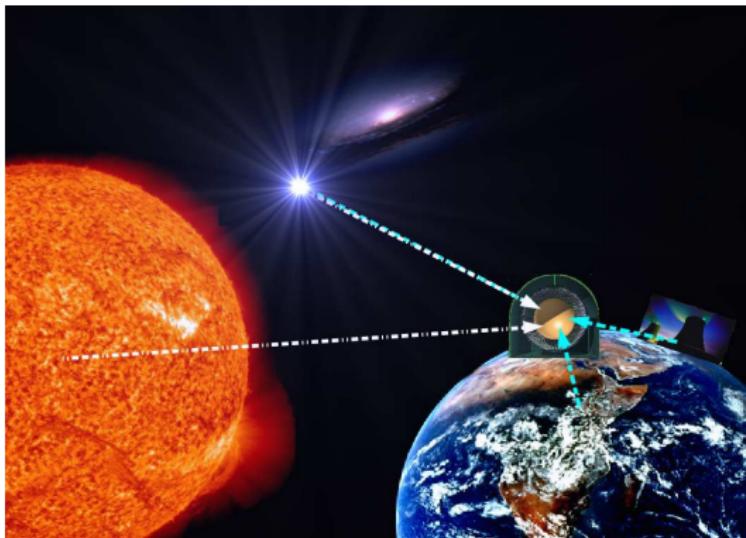


# BOREXINO

## Recent Solar And Terrestrial Neutrino Results



Werner Maneschg  
on behalf of the Borexino Collaboration

# Borexino: detector properties & design, and physics goals

## Main properties:

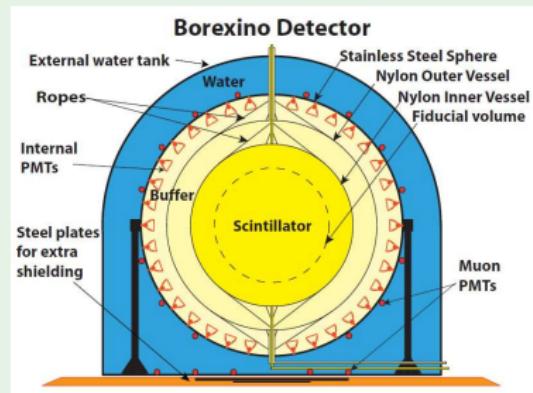
- Large volume organic liquid scintillator detector:
  - at LNGS (1.4 km overburden)
  - operational since May 2007
- Ultra low background (radiopurest environment ever measured)
- Real-time detection (time stamp and pulse shape for every event)
- Spectroscopy at low energies, typically between 0.1-15 MeV
- 3D position reconstruction

## Main physics goals:

- Neutrinos from Sun
- Antineutrinos from Earth & reactors
- Sterile neutrinos (TH 23-07-15:13.5)
- SN-(anti)neutrinos & other exotic particles and processes

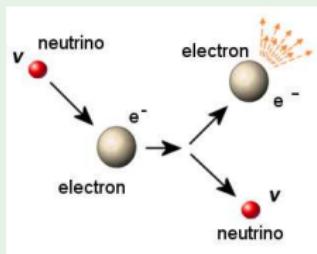
## Nut shell profile:

- 1 Water tank ( $2100 \text{ m}^3$ ):
  - Absorption of environmental  $\gamma$  rays and neutrons
  - $\mu$  Cherenkov detector (208 PMTs)
- 2 Stainless Steel Sphere:
  - 2212 PMTs,  $1350 \text{ m}^3$ ,  $R=6.85 \text{ m}$
- 3 2 buffer layers: PC+DMP
  - Outer  $R_2=5.50 \text{ m}$ , Inner  $R_1=4.25 \text{ m}$
  - Shielding from external  $\gamma$  rays
- 4 Scintillator: 270 tons of PC+PPO

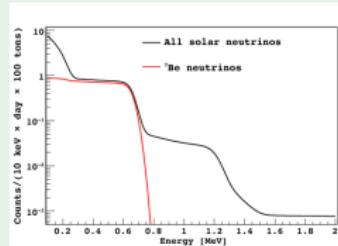


# Neutrino and antineutrino detection with Borexino

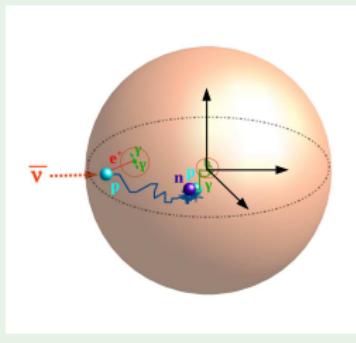
## Neutrinos: elastic neutrino-electron scattering



- >Mainly  $\nu_e$ , but also  $\nu_\mu$  and  $\nu_\tau$
- Compton-like formalism  
→ Mono-energetic neutrino source has a Compton-like edge



## Antineutrinos: inverse beta decay

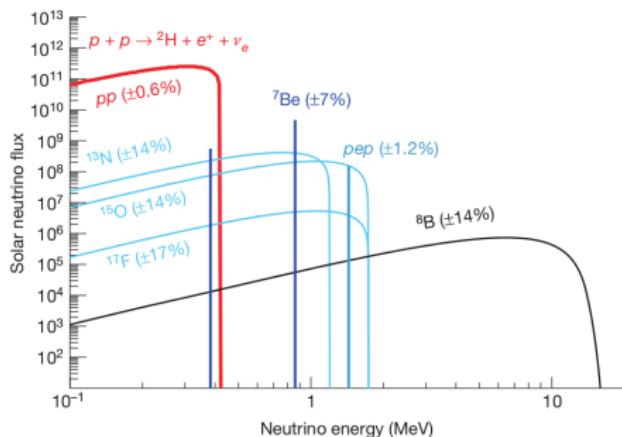


- Reaction:  $\bar{\nu} + p \rightarrow n + e^+$   
(Threshold:  $E_\nu = 1.806 \text{ MeV}$ )
- Prompt signal of positron annih.:  $e^- + e^+ \rightarrow 2\gamma$
- Delayed neutron capture ( $\tau \sim 255 \mu\text{s}$ ) on H:  
 $n + p \rightarrow D + 2.2 \text{ MeV}\gamma$   
→ Energy intervals, space and time correlations  
→ very efficient rejection method

# Solar neutrino fluxes (according to Standard Solar Model predictions)

## Neutrino fluxes at 1 AU:

from simulations by A. Serenelli et al., *Astrophys. J.* 743, 24 (2011)



Units:  $[\text{cm}^{-2}\text{s}^{-1}\text{MeV}^{-1}]$  for continuum neutrino sources,  $[\text{cm}^{-2}\text{s}^{-1}]$  for mono-energetic neutrino sources.

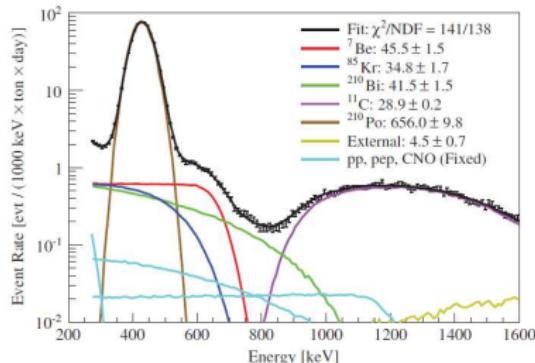
$\nu$ flux	GS98	AGSS09
$pp$	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.006)$
$^{7}\text{Be}$	$5.00(1 \pm 0.07)$	$4.56(1 \pm 0.07)$
$pep$	$1.44(1 \pm 0.012)$	$1.47(1 \pm 0.012)$
$^{13}\text{N}$	$2.96(1 \pm 0.14)$	$2.17(1 \pm 0.14)$
$^{15}\text{O}$	$2.23(1 \pm 0.15)$	$1.56(1 \pm 0.15)$
$^{17}\text{F}$	$5.52(1 \pm 0.17)$	$3.40(1 \pm 0.16)$
$^{8}\text{B}$	$5.58(1 \pm 0.14)$	$4.59(1 \pm 0.14)$

Factors:  $10^{10}$  ( $pp$ ),  $10^9$  ( $^{7}\text{Be}$ ),  
 $10^8$  ( $pep$ ,  $^{13}\text{N}$ ,  $^{15}\text{O}$ ),  $10^6$  ( $^{8}\text{B}$ ,  $^{17}\text{F}$ );  
Units:  $\text{cm}^{-2}\text{s}^{-1}$ .

Solar neutrino measurements:  
different obstacles: diff. background, detector response, energy threshold  
sensitivity for different phenomena:  
neutrino osc. (incl. matter effects (MSW)), SSM metallicity scenarios

# Solar $^7\text{Be}$ neutrino rate measurement

Averaged  $^7\text{Be}-\nu$  rate fitted with MC (ROI: 0.2-0.7 MeV)



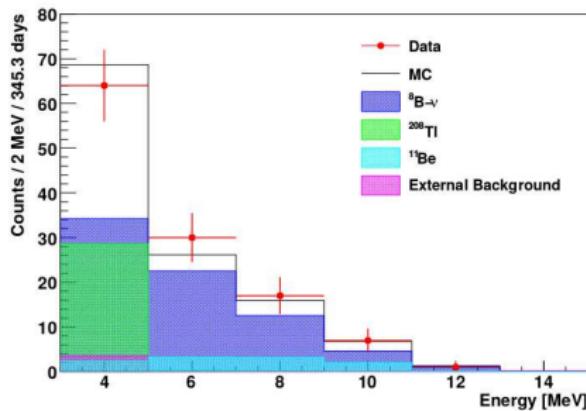
## Results and remarks:

- **Averaged rate:**  $R = (46 \pm 1.5(\text{stat})^{+1.5}_{-1.6}(\text{sys})) \text{ c/d/100 ton}$  (**uncertainty  $\pm 5\%$** )  
Comparison to SSM predictions:
  - Without osc.:  $(74 \pm 5) \text{ c/d/100 ton}$  ( **$5\sigma$  exclusion**)
  - With osc.: 44 (High-met.) and 48 (Low-met.) c/d/100 ton
- **Day-Night asymmetry:**  $(N-D)/((N+D)/2) = 0.001 \pm 0.012(\text{stat}) \pm 0.007(\text{sys})$   
( **$8.5\sigma$  exclusion of LOW osc. solution**)
- **7% Annual modulation:** according to rate-vs-time analysis:  $T = (1.01 \pm 0.07) \text{ yr}$ ;  
 $\epsilon = 0.0398 \pm 0.0102 \rightarrow$  **expected value within  $2\sigma$**



# Solar $^8\text{B}$ neutrino rate measurement

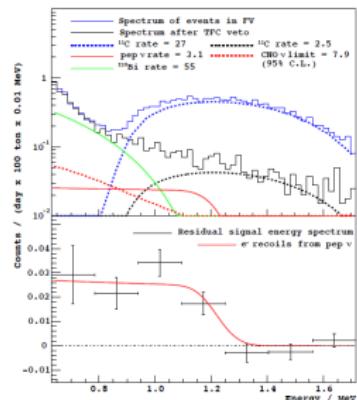
Data vs. MC of  $^8\text{B}$  recoil energy spectrum (ROI: 3-15 MeV)



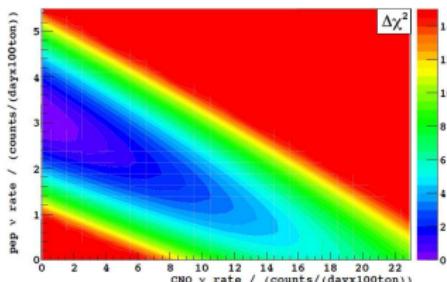
## Results and remarks:

- Challenging: low neutrino rate, many small background components
- Rate above 3 MeV:  $0.217 \pm 0.038(\text{stat}) \pm 0.008(\text{syst}) \text{ c/d/100ton}$
- Flux at 1 AU:  $(2.7 \pm 0.4 \pm 0.1) \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$ 
  - good agreement with SuperKamiokaNDE and SNO
  - confirmation of MSW-LMA solution for oscillation in vacuum/matter
- Data set: used 488 d; new analysis with multiple statistics ongoing

# Solar pep and CNO neutrino rate measurement



← pep/CNO recoil energy spectrum (ROI: 0.7-1.7 MeV)  
↓ pep vs. CNO rate

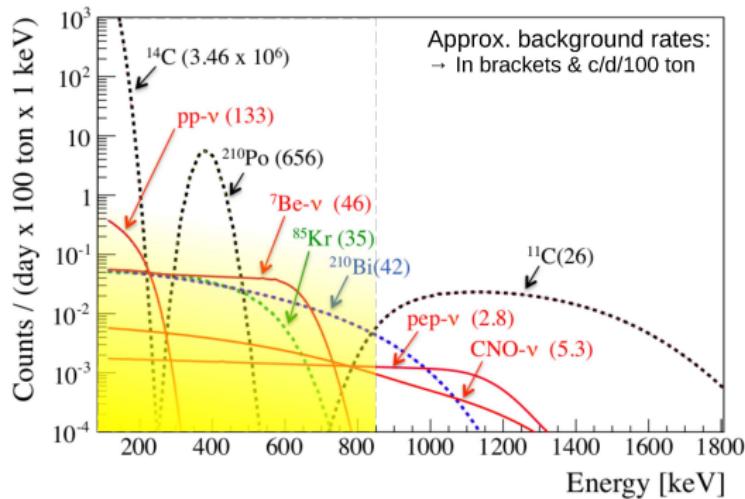


## Results and remarks:

- Main background cosmogenic  $^{11}\text{C}$ : S/B~1:10
  - Apply a threefold coincidence method (90%  $^{11}\text{C}$  red., 50% exposure loss)
  - Apply pulse shape BDT algorithm for  $\beta^+/\beta^-$  separation
- Other background:  $^{210}\text{Bi}$ ,  $^{40}\text{K}$ , external  $\gamma$ -rays (2.6 MeV from  $^{208}\text{Tl}$ ),...
- pep: first evidence; Including the MSW effect and LMA solution:  
DATA/SSM(AG98)=  $1.1 \pm 0.2$
- CNO: best upper limit to date; DATA/SSM(AG98)<1.5; new analysis ongoing
- Solar Metallicity problematics not yet solved (needs  $^{210}\text{Bi}$  understanding)

# Towards the detection of solar pp neutrinos

pp recoil energy spectrum (ROI: 0.05-0.27 MeV)



pp neutrinos:

Endpoint energy  $E_{mx}$ :

$0 < E_{mx} < 420 \text{ keV}$

$\rightarrow E_{rec} < 264 \text{ keV}$

Energy threshold  $E_{th}$ :

Borexino:  $E_{th} \sim 50 \text{ keV}$

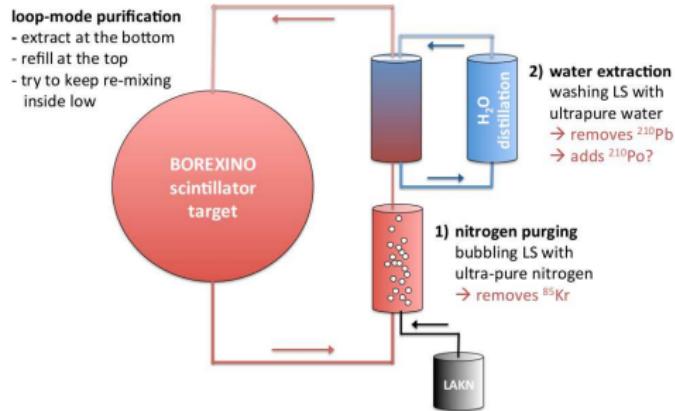
Radiochem. experiments:

$E_{th} \sim 233 \text{ keV}$

## Main obstacles:

- Above  $\sim 240 \text{ keV}$ : decays of  $^{85}\text{Kr}$ ,  $^{210}\text{Bi}$  ( $^{210}\text{Pb}$  daughter)
- Below  $\sim 240 \text{ keV}$ : decays of  $^{14}\text{C}$ ,  $^{14}\text{C}$  pile-ups

# Reduction of the $^{85}\text{Kr}$ and $^{210}\text{Bi}$ background in Borexino



## Scintillator purification campaigns:

Period: 2010/06-2011/08  
6 full cycles

### Background rates before / after purification:

Nuclide	Phase I rate or mass fr.	Phase II rate or mass fr.	Spec's (analysis dep.) rate or mass fr.
$^{85}\text{Kr}$	(31±5) c/d/100 t	<7 c/d/100 t (95% C.L.)	few 10 c/d/100 t ( $^7\text{Be},\text{pp}$ )
$^{210}\text{Bi}$	~70 c/d/100 t	~25 c/d/100 t	few 10 ( $^7\text{Be},\text{pp}$ ) / few c/d/100 t (CNO)
$^{210}\text{Po}$	~6000 c/d/100 t *	~200 c/d/100 t *	100 c/d/100 t (pp)
$^{238}\text{U}$	$(1.6 \pm 0.1) \times 10^{-17} \text{ g/g}$	$< 9.7 \times 10^{-19} \text{ g/g}$ (95% C.L.)	$< 10^{-16} \text{ g/g}$ ( $^7\text{Be}$ )
$^{232}\text{Th}$	$(6.8 \pm 1.5) \times 10^{-18} \text{ g/g}$	$< 1.2 \times 10^{-18} \text{ g/g}$ (95% C.L.)	$< 10^{-16} \text{ g/g}$ ( $^7\text{Be}$ )

\*  $^{210}\text{Po}$  ( $\tau=138$  d): Phase I: 2007.05, Phase II: 2013.05 (end of pp data set period)

# Rate and spectral shape of the $^{14}\text{C}$ background in Borexino

$$^{14}\text{C}/^{12}\text{C}: 10^{-18} \text{ g/g}$$

## Pure $^{14}\text{C}$ $\beta$ spectrum

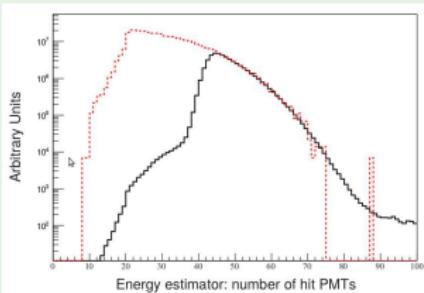


### Trigger problem:

- Total rate:  $\sim 30$  Hz for  $E_{th} \sim 50$  keV
- $^{14}\text{C}$  expected rate:  $(10\text{-}100)$  c/s/100ton
- Acquisition window:  $16\mu\text{s}$ ;
- Events with  $E$  close to  $E_{th}$ : often problematic

### Solution for $^{14}\text{C}$ close to $E_{th}$ :

Trigger with two random events: 2. event ( $^{14}\text{C}$ ) unaffected by  $E_{th}$   
→ Spectral shape threshold: 100 keV → 50 keV  
→  $^{14}\text{C}$  rate:  $(40\pm 10)$  c/s/100ton



## $^{14}\text{C}$ pile-ups



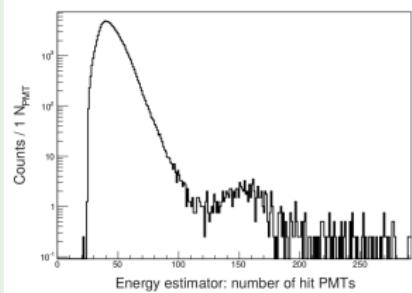
### Pile-up problem:

- $^{14}\text{C}$  overlap with PMT dark rate,  $^{14}\text{C}$ ,  $^{210}\text{Po}$
  - Spectral shape hardly known
  - Position reco. largely fails
- Expected rate:  $(6\text{-}600)$  c/d/100ton

### Solution:

Generate 'synthetic' pile-ups:

- Overlap artificially uncorrelated data with regular events
- $^{14}\text{C}$  pile-up rate:  $(154\pm 10)$  c/d/100ton



# Solar pp neutrino rate measurement (August 2014)

## ARTICLE

### Neutrinos from the primary proton-proton fusion process in the Sun

Borexino Collaboration\*

Nature, Vol. 512, August 28, 2014

#### Results and remarks:

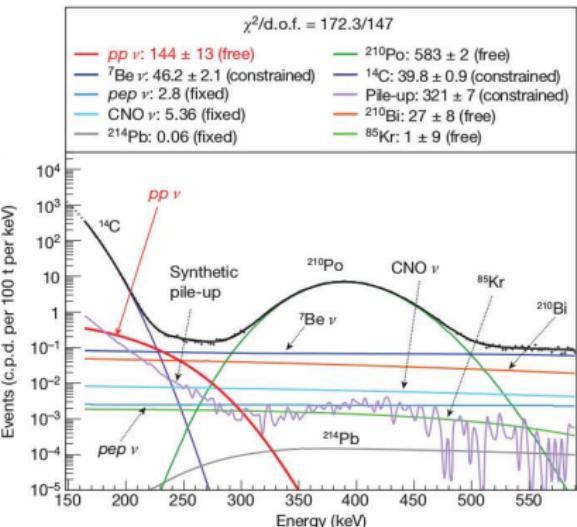
- Rate:  
 $144 \pm 13(\text{stat}) \pm 10(\text{sys}) \text{ c/d/100 ton}$   
( $10\sigma$  exclusion of pp  $\nu$  absence)
- Robustness of analysis:

Parameter	Systematics:
energy estimator	$\pm 7\%$
fit energy range	
data selection	
pile-up evaluation	
fiducial mass	$\pm 2\%$

- Check of residual background

#### Measured recoil energy spectrum

#### Fit in (165-590) keV

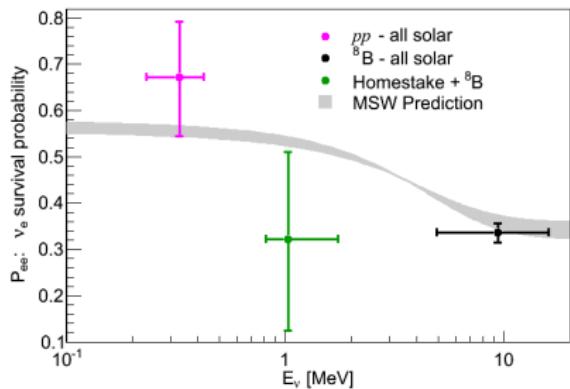


Rates in [c/d/100 ton], except for  $^{14}\text{C}$  [c/s/100 ton]

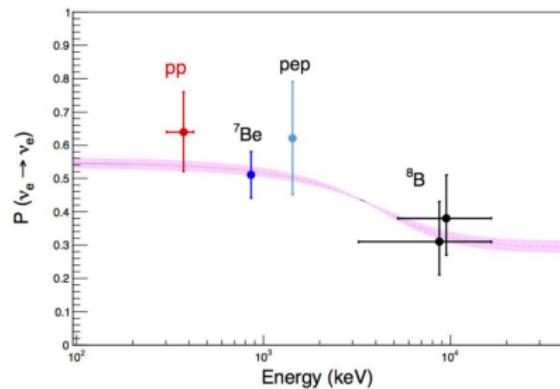
# Solar neutrino oscillations in vacuum/matter

Electron neutrino survival probability:

Before Borexino:



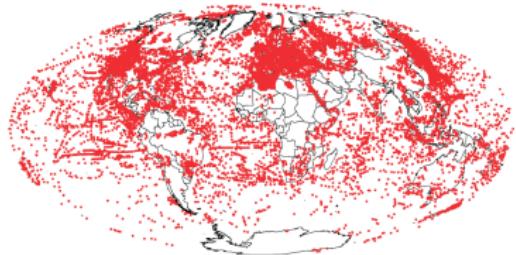
Borexino alone (2014/08):



Borexino results:

- Borexino data standalone confirm **MSW - Large-Mixing-Angle** solution
- Further improvements expected from:
  - Data sets with more statistics/lower systematics ( $pp$ ,  $pep$ ,  $^8B$ )
  - Potentially first direct detection of the CNO neutrino rate

# Description of Earth's interior

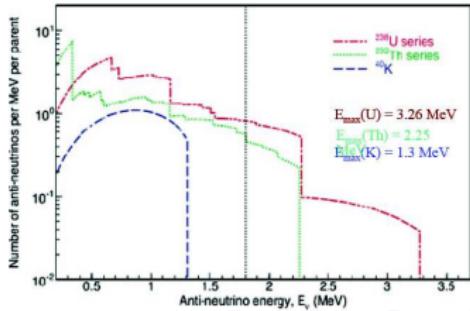


## Bulk Silicate Earth model (BSE)

- Describes the 'Primitive Mantel's chem. comp. before crust differentiation, but after metal core separation
- Prediction of radiogenic heat (with local-dependent variations):
  - Crust: ~7 TW
  - Mantle: 1-19 TW  
(differing for BSE-submodels)
  - Core: 0 TW
- Probe with geo- $\bar{\nu}$ 's:  
Expected rate in Borexino:  
**~10 c/yr/270 ton**

## Geophysics

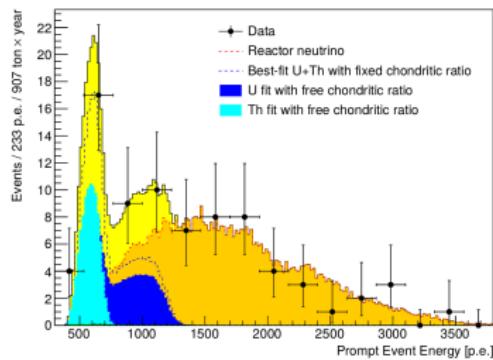
- **Earth heat:**  $(47 \pm 2)$  TW, from 40000 deep bore-holes integrated over surface:  
 $\sim 0.09 \text{ W/m}^2$   
(↔ Solar constant:  $342 \text{ W/m}^2$ )  
→ Potential origin: **radiogenic heat**, primordial planetary contraction
- **Seismology:** insight of structure/density, but not chem. composition  
→ Further messengers:  
Petrologic/meteoritic samples and  $\bar{\nu}$ 's from U & Th decays ('geo- $\bar{\nu}$ ')



# Geo-neutrino rate measurement with Borexino (June 2015)

## Main background components (after 2s muon rejection cut)

- Accidental coincidences
- Short-lived cosmogenic isotopes: e.g.  $\beta + n$  decay of  $^9\text{Li}-^8\text{He}$
- $(\alpha, n)$  reactions: in scintillator and in buffer
- Untagged muons, fast neutrons, spontaneous fission decays in PMTs
- Reactor-antineutrinos:
  - Same signature as geo- $\bar{\nu}$ 's; only **spectral disentanglement** possible
  - Calculation of reactor- $\bar{\nu}$  signal: 446 cores worldwide (196 European), weighted mean baseline 1170 km, exact duty cycles and fuel composition (<IAEA and EDF)



## Results from 5.63 yr dataset

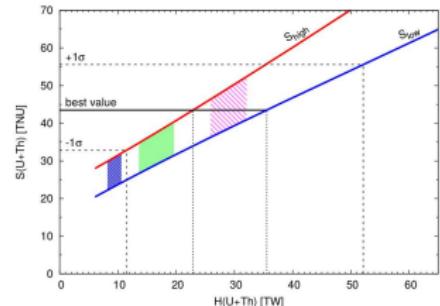
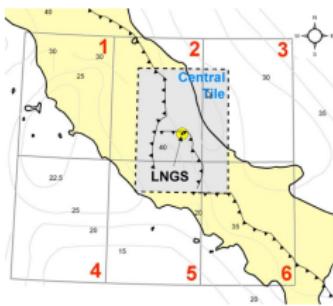
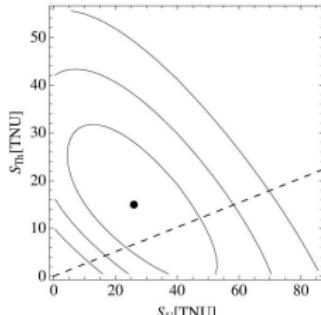
- **Exposure:**  $(907 \pm 44)$  ton  $\times$  year
- **77  $\bar{\nu}$  candidates found:**  
Unbinned likelihood fit with fixed chondritic ratio  $\text{Th}/\text{U}=3.9$ :
  - **Geo- $\bar{\nu}$ :**  $(23.7^{+5.7}_{-6.6})$  ev,  $(43.5^{+12.1}_{-10.7})$  TNU\*
  - **Reactor- $\bar{\nu}$ :**  $(52.7^{+7.8}_{-8.5})$  ev,  $(96.6^{+16.4}_{-15.1})$  TNU\*
    - Agrees well with expect. incl. osc.
  - 3 main background components (**S/B** $\sim$ 100)

\*TNU = Terrestrial Neutrino Unit = 1 ev/yr/ $10^{32}$  protons

# Implications for terrestrial radiogenic heat production

## U/Th identification and local distribution:

- Geo- $\bar{\nu}$  signal of  $(43.5^{+12.1}_{-10.7})$  TNU: rejects null-hypothesis with  $5.9\sigma$
- Separation of Th/U: If Th/U ratio is kept free in the fit:  
→  $S(\text{Th})/S(\text{U}) \approx 0.6$ , within  $1\sigma$  in agreement with chondritic model pred.  
 $S(\text{Th})/S(\text{U}) = 0.3$
- Localisation of U/Th in crust/mantle:
  - Geological survey to deduce local crust contribution:  $(9.7 \pm 1.3)$  TNU
  - BSE models to deduce total crust contribution:  $(23.4 \pm 2.8)$  TNU
  - BSE models to deduce mantle contribution = total-crust:  $(20.9^{+15.1}_{-10.3})$  TNU  
→ Null-hypothesis of mantle contribution rejected at **98% C.L.**
- Total radiogenic heat (Th+U+K):  $(33^{+28}_{-20})$  TW (BSE model dependent)  
→ In well agreement with terrestrial power output of  $(47 \pm 2)$  TW



# Summary: Physics highlights and future goals

	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Calibrations Intern / Extern		Phase I		Sc. Purification (6 cycles)		Phase II				
Physics		▲ ▲ ▲			▲				▲	
	7Be ν: +-5%, ann. modul. 8B ν: 3 MeV threshold pep ν: +-20%stat, +-10%sys CNO ν: best limit Geo/reactor ν Rare/exotic process: limits									→ 7Be ν: +-3% ?, ann. modul. → 8B ν: better stat. → pep ν: 3(5) σ ? → CNO ν: direct meas.? → pp ν: +-11%; <? % → Geo ν: +-28%; <20%? → Rare/exotic processes: limits → SN ν: high duty cycle of 95%
										Sterile neutrinos

## Plans for next years:

- Improved precision of present results of solar pp, pep,  $^7\text{Be}$  and  $^8\text{B}$  ν's, as well as geo- and reactor- $\bar{\nu}$ ; ...
- CNO ν's: Last undetected of the 'Big Five': improve limit or try to quote a rate ('solar metallicity puzzle')
- Sterile neutrino search with  $^{144}\text{Ce}$   $\bar{\nu}$  and  $^{51}\text{Cr}$  ν sources (**SOX**)
- Supernova ν/ $\bar{\nu}$ 's: BX member of **SNEWS**, keep high duty cycle of 95% (low E-threshold)



'Big Five'

# Further reading

## ● Solar neutrinos

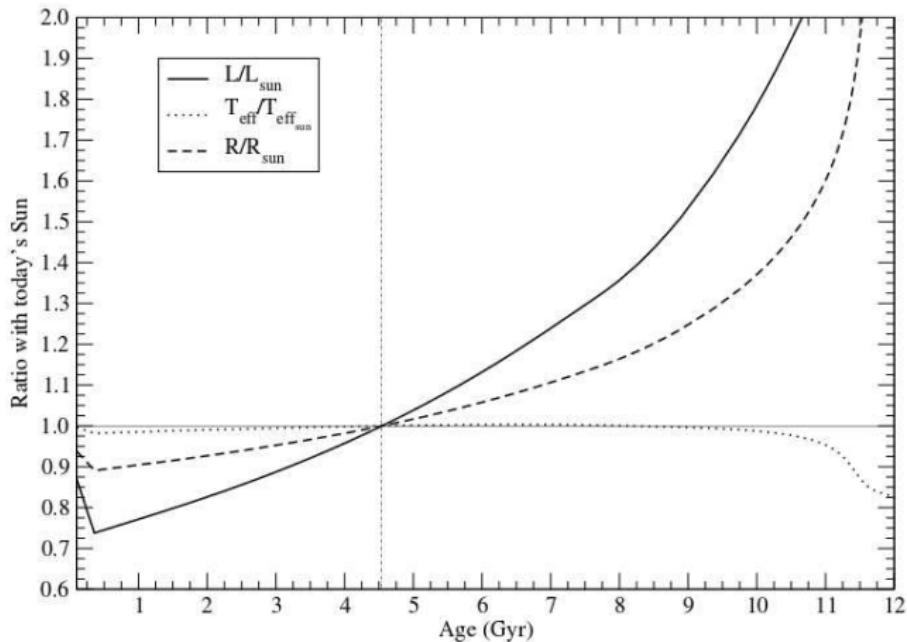
- **7Be rate @  $\pm 17\%$  precision:** C. Arpesella et al., First real time detection of 7Be solar neutrinos by Borexino, Phys. Lett. B 658 (2008) 101-108
- **7Be rate @  $\pm 10\%$  precision:** C. Arpesella et al., Direct measurement of the 7Be solar neutrino flux with 192 days of Borexino data, Phys. Rev. Lett. 101 (2008) 091302
- **7Be rate @  $\pm 5\%$  precision:** G. Bellini et al., Precision measurement of the 0.862 MeV 7Be solar neutrino interaction rate in Borexino, Phys. Rev. Lett. 107 (2011) 141302
- **7Be day-night asym.:** G. Bellini et al., Absence of day-night asymmetry of 862 keV 7Be solar neutrino rate in Borexino and MSW oscillation parameters, Phys. Lett. B 707 (2012) 22-26
- **7Be annual mod.:** G. Bellini et al., Final results of Borexino Phase-I on low-energy solar-neutrino spectroscopy, Phys. Rev. D 89 (2014) 112007
- **pep rate & CNO limit:** G. Bellini et al., First Evidence of pep Solar Neutrinos by Direct Detection in Borexino, Phys. Rev. Lett. 108 (2012) 051302
- **8B rate:** G. Bellini et al., Measurement of the solar 8B neutrino rate with a liquid scintillator target and 3 MeV energy threshold in the Borexino detector, Phys. Rev. D 82 (2010) 033006
- **pp rate:** G. Bellini et al., Neutrinos from the primary proton-proton fusion process in the Sun, Nature 512, August 28, 2014

## ● Geo-Antineutrinos:

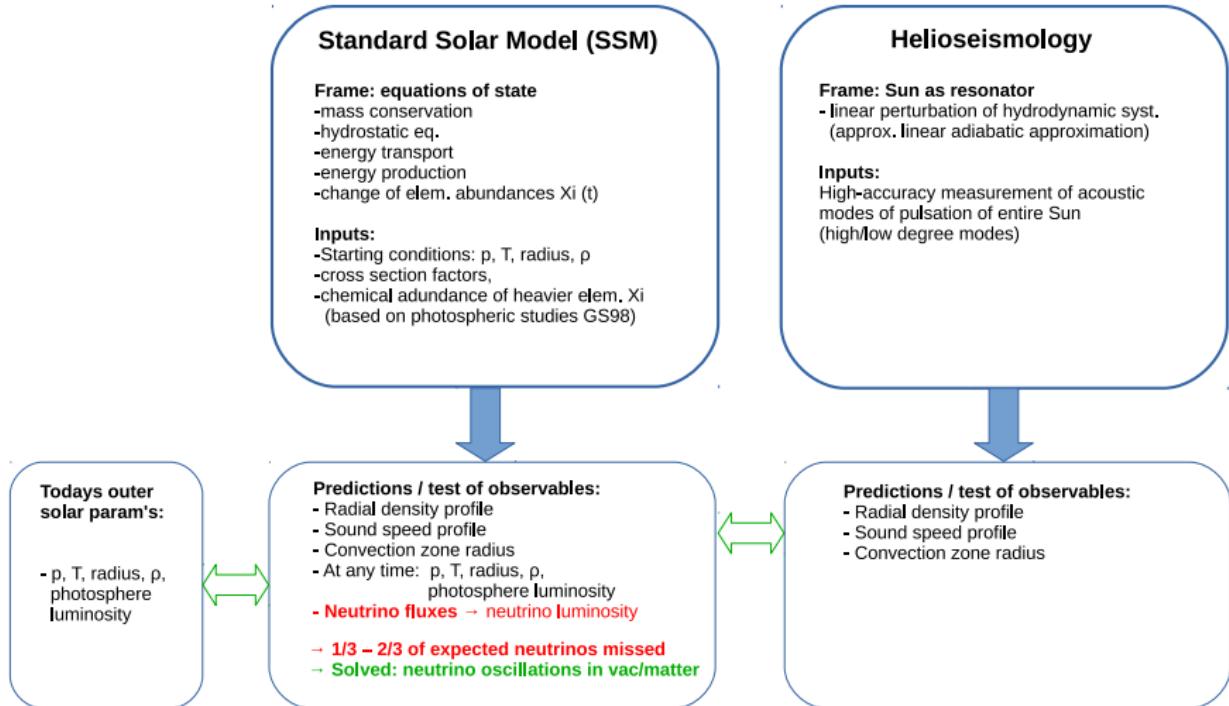
- **rate @  $\pm 40\%$  precision:** G. Bellini et al., Observation of Geo-Neutrinos: Phys. Lett. B 687 (2010) 299-304
- **rate @  $\pm 32\%$  precision:** G. Bellini et al., Measurement of geo-neutrinos from 1353 days of Borexino, Phys. Lett. B 722 (2013) 295-300
- **rate @  $\pm 28\%$  precision:** M. Agostini et al., Spectroscopy of geo-neutrinos from 2056 days of Borexino data, arXiv: 1506.04610v2 (hep-ex) June 2015, accepted for publication in Phys. Rev. D

# BACK UP

# Solar evolution according to the SSM

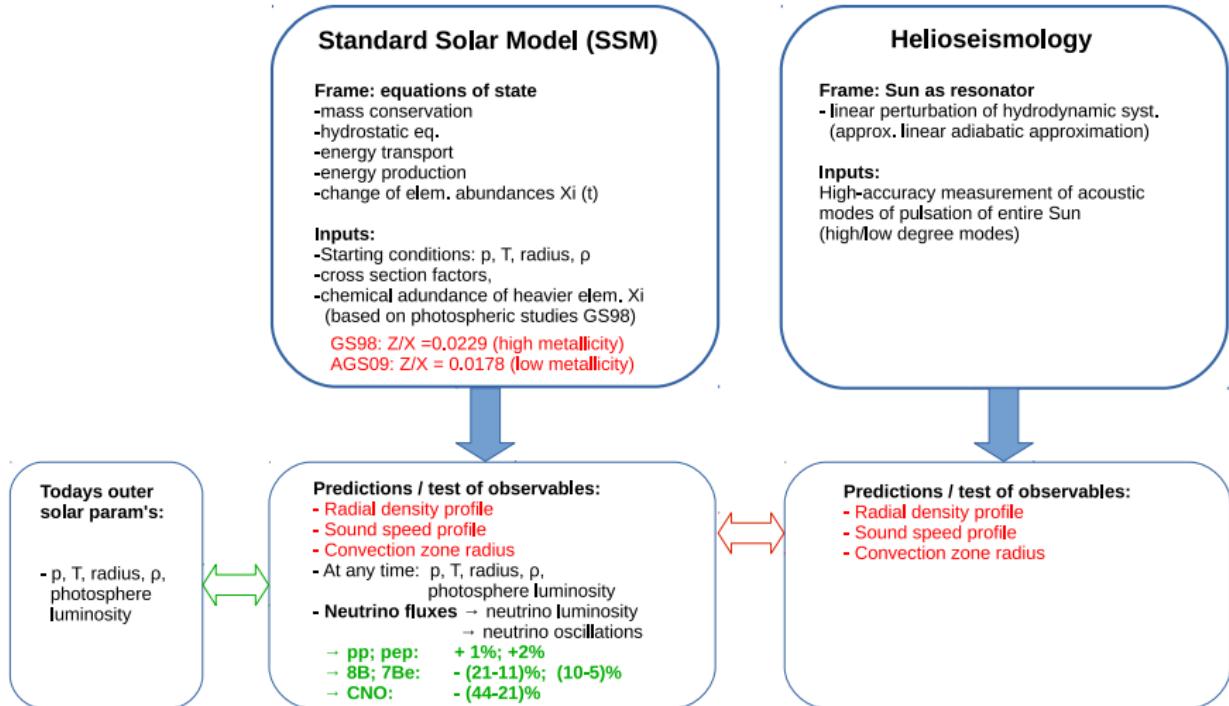


# Tensions in the SSM predictions



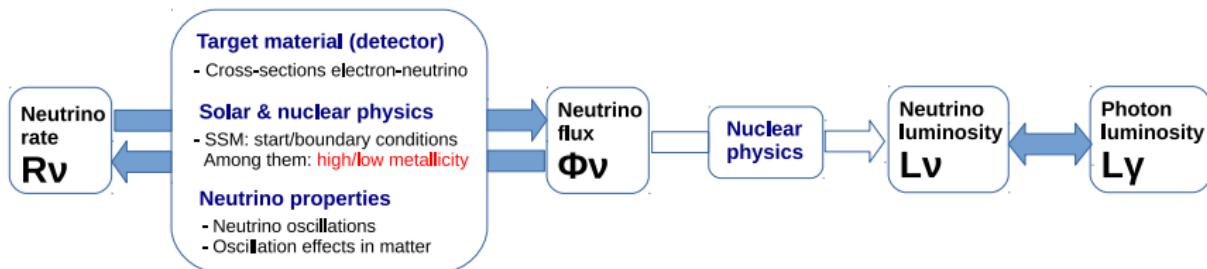
## " Solar Neutrino Puzzle"

# Tensions in the SSM predictions



" Solar Metallicity Puzzle"

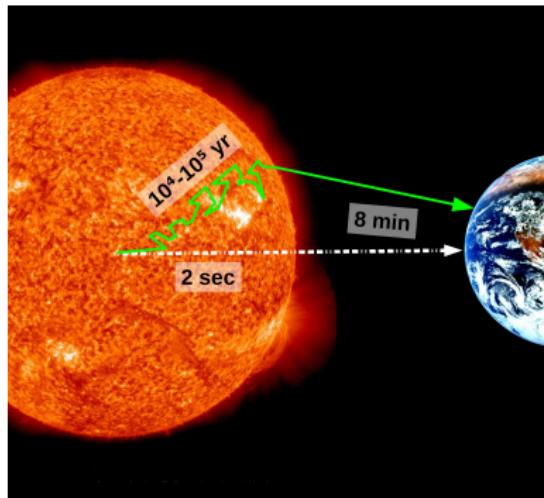
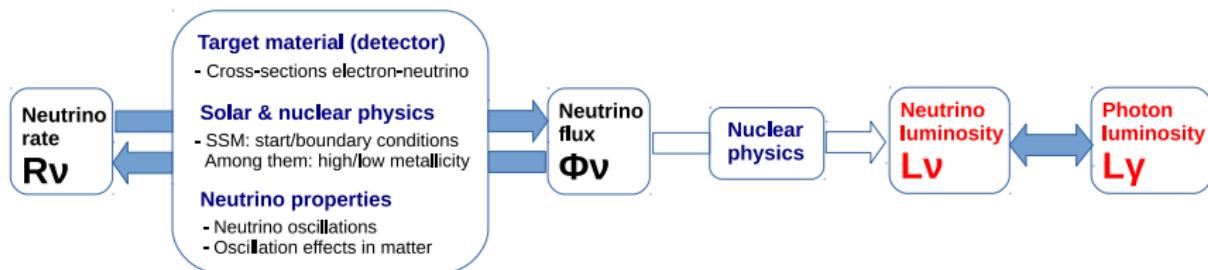
# Interpretation I: conversion of pp rate into a flux



## SSM predictions and Borexino measurement (at Earth):

- High metallicity (GS98):  $5.98 \times (1 \pm 0.006) \times 10^{10} \text{ cm}^2 \text{ s}^{-1}$
- Low metallicity (AGS09):  $6.03 \times (1 \pm 0.006) \times 10^{10} \text{ cm}^2 \text{ s}^{-1}$ 
  - mean values differ by 0.8% only
- Measured:  $(6.6 \pm 0.7) \times 10^{10} \text{ cm}^2 \text{ s}^{-1}$ 
  - agreement with both models, but no disentanglement of metallicity

## Interpretation II: test the luminosity constraint



### Luminosity variability:

- O(10 yr): 22 yr solar cycle  $\rightarrow$  0.1%
- O(10<sup>4</sup>-10<sup>5</sup> yr): ?  $\rightarrow$  BX measurement
- O(4.6×10<sup>9</sup> yr): SSM  $\rightarrow$  young faint Sun:  
-25% less bright than today

### SSM/Borexino vs. solar photosphere prediction:

- $L_\nu = 3.84 \times 10^{33} \text{ erg s}^{-1}$  ( $\pm 10\%$ )
- $L_\gamma = 3.846 \times 10^{33} \text{ erg s}^{-1}$ 
  - $\rightarrow$  No hint for variability;
  - $\rightarrow$  pp meas. 1% precision

# Annual modulation of $^{7}\text{Be}$ neutrino rate

## Expectation:

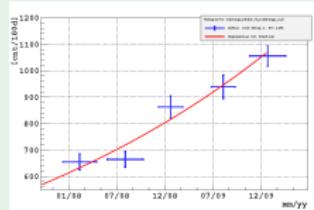
Earth eccentricity  $\epsilon=0.0167$  (maximum on January 3):

→ Perihelion-Aphelion flux difference of  $\pm 7\%$

→  $^{7}\text{Be}$  neutrino rate variation:  $47.5$  and  $44.5 \text{ c/d/100 ton}$

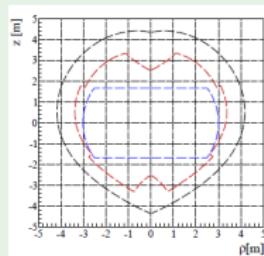
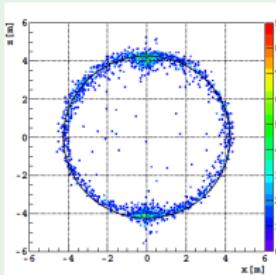
Question: Possible to measure? i.e. Proving origin of detected neutrinos?

## Challenging 1: Stability of detector response and backgrounds



- Detector response very stable in time
- Energy scale, pulse shape discrimination and position reconstruction stable
- However Untaggable background  $^{210}\text{Bi}$  in the valley  $^{7}\text{Be}-^{11}\text{C}$  is not stable in time: rms/peak 0.8%

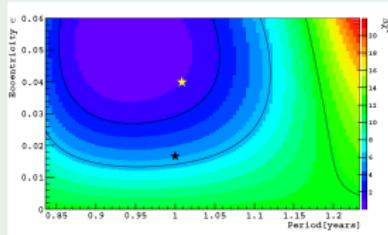
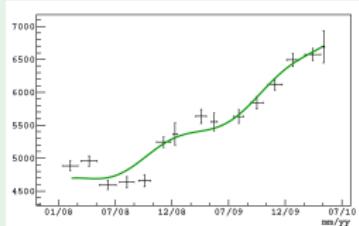
## Challenging 2: Statistics



- Fit of subperiods have too large stat. errors;  
→ for a given energy interval group data in time bins of 1-2 months and look for periodicity (3 methods applied; 2 are presented on next slide)
- Increase the fiducial volume from 75.5 to 141.8 tons and follow time-dependent change of nylon vessel

# Annual modulation of $^{7}\text{Be}$ neutrino flux

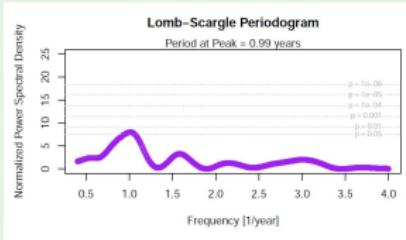
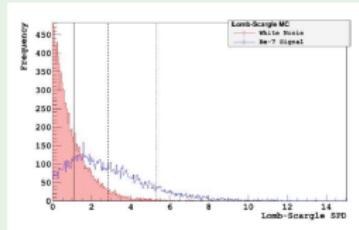
## 1. Method: Rate vs. time



Used fit function:  $R = R_0 + e^{A Bi t} + \bar{R} \{1 + 2\epsilon \cos(2\pi/T - \phi)\}$

Results:  $T=1.01 \pm 0.07$ ;  $\epsilon=0.0398 \pm 0.0102$  → Expected values are within  $2\sigma$

## 2. Method: Lomb-Scargle (extension of Fourier transformation)



Results: Peak at period  $T=0.979$ ; Spectral power density: 7.96  
→ Non-existence of annual modulation excluded at  $\sim 3\sigma$

# Reached performance: position reconstruction

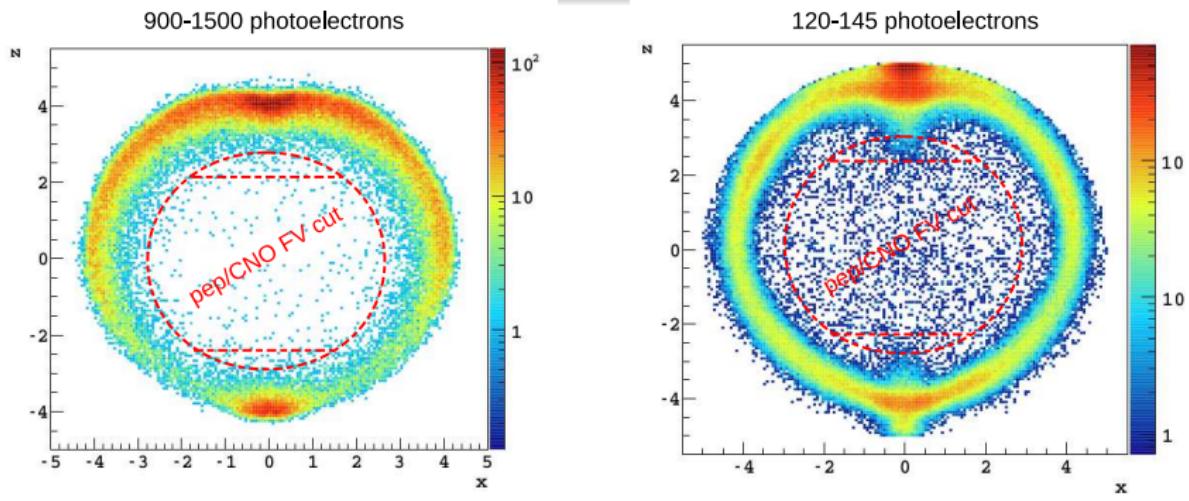
## Main results:

- **Resolution ( $1\sigma$ ):**

- 2.2 MeV ( $^{214}\text{Bi}, \gamma$ ):  $(13 \pm 2)$  cm in x,y;  $(14 \pm 2)$  cm in x,y
- 0.25 MeV ( $^{14}\text{C}$ , endpoint):  $(42 \pm 6)$  cm

- **Fiducial Volume cuts:** analysis-dependent:

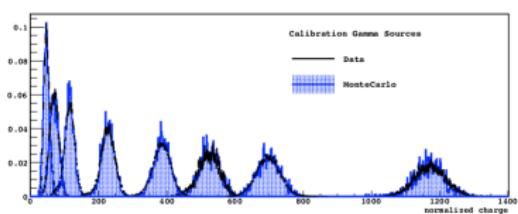
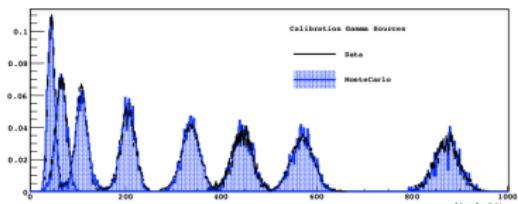
- Solar  $^7\text{Be}$ :  $R < 3.067$  m,  $z < |1.67|$  m
- Solar pep/CNO:  $R < 2.8$  m,  $-2.4 \text{ m} < z < 2.2 \text{ m}$  (similar to FV for solar pp)
- Geo-/reactor-antineutrinos:  $R < 4$  m



# Reached performance: energy reconstruction

## Borexino calibration data

(several 100 positions, different source types; several campaigns)



Isotope	Type	Energy [keV]
$^{57}\text{Co}$	$\gamma$	122
$^{139}\text{Ce}$	$\gamma$	165
$^{203}\text{Hg}$	$\gamma$	279
$^{85}\text{Sr}$	$\gamma$	514
$^{54}\text{Mn}$	$\gamma$	834
$^{65}\text{Zn}$	$\gamma$	1115
$^{40}\text{K}$	$\gamma$	1173-1332
$^{60}\text{Co}$	$\gamma$	1460
$^{222}\text{Rn}$	$\alpha, \beta$	1460
$^{14}\text{C}$	$\gamma$	1460
$^{241}\text{Am}^9\text{Be}$	neutron	2223 - $\sim$ 9500

### Main results:

- Resolution ( $1\sigma$ ):  $5\%/\sqrt{E(\text{MeV})}$  ( $\leftrightarrow$  KamLAND:  $6.5\%/\sqrt{E(\text{MeV})}$ ))
- Light yield: 10000 photons/MeV,  $\rightarrow$  500 photoelectrons/MeV
- Stability: no scintillator deterioration observed, light yield constant
- Monte Carlo code: 1% accuracy in 0.1-2 MeV, few % 0.2-2.6 MeV



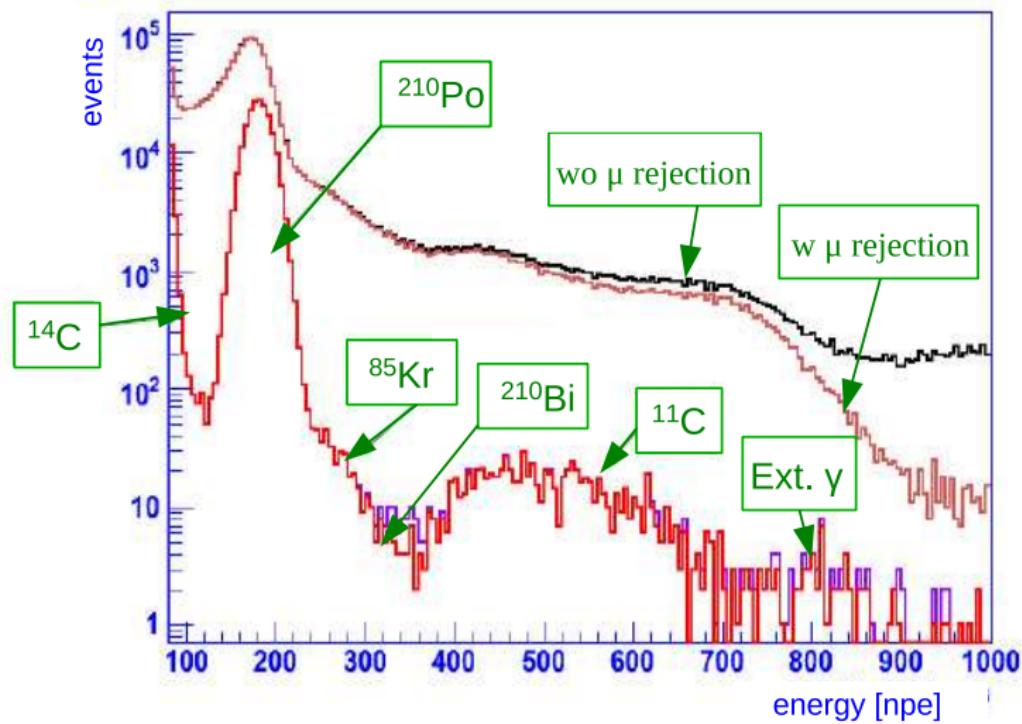
# Borexino: background specifications

Expected magnitude: solar  $^7\text{Be}$  neutrinos in sub-MeV region

- 40-50 neutrino signals/d/100 tons →  $6 \times 10^{-9} \text{ Bq/kg}$
- **Background requirements** to the scintillator (less than 10 c/d/100 tons):
  - U:  $10^{-9} \text{ Bq/kg} \rightarrow < 0.8 \times 10^{-16} \text{ g/g}$  (sec. eq.)
  - Th:  $10^{-9} \text{ Bq/kg} \rightarrow < 2.4 \times 10^{-16} \text{ g/g}$  (sec. eq.)
  - $^{14}\text{C}$ :  $10^{-18} \text{ g/g}$
- *For comparison:* U in water: O(10-100 Bq/kg), U/Th in rock: O(1000 Bq/kg)

Contaminant	Source	Normal/Expected mass frac./flux/rate	Required
$\mu$ $^{11}\text{C}$	cosmic in-situ $\mu$ -ind.	$200/\text{s/m}^2$ (at sea level) $\sim 15 \text{ c/d/100}$	$\sim 10^{-10}$
Ext. $\gamma$ (U,Th)	SSS		$\sim 10^{-10} \text{ g/g}$
Ext. $\gamma$ (U,Th)	PMTs		$\sim 10^{-8} \text{ g/g}$
Ext. $\gamma$ (U,Th)	PC buffer	$\sim 10^{-16}$ - $10^{-15} \text{ g/g}$	$\sim 10^{-15} \text{ g/g}$
$^{14}\text{C}$	Scintillator	$\sim 10^{-12} \text{ g/g}$	$10^{-18} \text{ g/g}$
$^{238}\text{U}$	Dust	$\sim 10^{-16}$ - $10^{-15} \text{ g/g}$	$< 10^{-16} \text{ g/g}$
$^{232}\text{Th}$	Dust	$\sim 10^{-16}$ - $10^{-15} \text{ g/g}$	$< 10^{-16} \text{ g/g}$
$^{222}\text{Rn}$	Emanation (air)	$100 \text{ atoms/cm}^3$ (air)	$< 10^{-16} \text{ g/g}$
$^{210}\text{Po}$	Surface cont. (from $^{222}\text{Rn}$ )		$100 \text{ c/d/100t}$
$^{210}\text{Pb}$	Surface cont. (from $^{222}\text{Rn}$ )		
$^{39}\text{Ar}$	air/nitrogen	$\sim 17 \text{ mBq/m}^3$ (air)	$< 1 \text{ c/d/100t}$
$^{85}\text{Kr}$	air/nitrogen	$\sim 1 \text{ Bq/m}^3$ (air)	$< 1 \text{ c/d/100t}$

## Borexino: background data (2007)



# Borexino background decomposition (2007-2009 data)

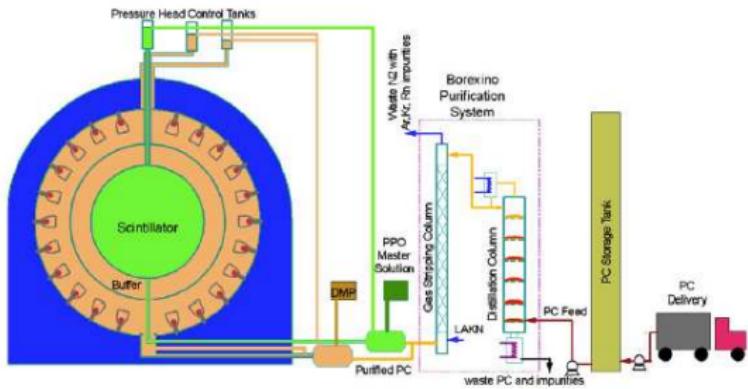
Contaminant	Source	Normal/Expected conc./flux/rate	Required	Achieved
$\mu$ $^{11}\text{C}$	cosmic	200/s/m <sup>2</sup> (at sea level)	$\sim 10^{-10}$	$\sim 10^{-10}$
	in-situ $\mu$ -ind.	$\sim 15 \text{ c/d/100}$		$\sim 27 \text{ c/d/ton}$
Ext. $\gamma$ (U,Th)	SSS		$\sim 10^{-10} \text{ g/g}$	$\sim 10^{-10}\text{--}10^{-9} \text{ g/g}$
Ext. $\gamma$ (U,Th)	PMTs		$\sim 10^{-8} \text{ g/g}$	$\sim 10^{-10}\text{--}10^{-7} \text{ g/g}$
Ext. $\gamma$ (U,Th)	PC buffer	$\sim 10^{-16}\text{--}10^{-15} \text{ g/g}$	$\sim 10^{-15} \text{ g/g}$	
$^{14}\text{C}$	Scintillator	$\sim 10^{-12}$	$\sim 10^{-18}$	$(2.7\pm 0.1) \times 10^{-18}$
$^{238}\text{U}$	Dust	$\sim 10^{-16}\text{--}10^{-15} \text{ g/g}$	$< 10^{-16} \text{ g/g}$	$(1.6\pm 0.1) \times 10^{-17} \text{ g/g}$
$^{232}\text{Th}$	Dust	$\sim 10^{-16}\text{--}10^{-15} \text{ g/g}$	$< 10^{-16} \text{ g/g}$	$(6.8\pm 1.5) \times 10^{-18} \text{ g/g}$
<i>nat</i> K	Dust	$\sim 10^{-14} \text{ g/g}$	$\sim 10^{-14} \text{ g/g}$	Spectral fit: $\leq 3 \times 10^{-16} \text{ g/g}$
$^{222}\text{Rn}$	Emanation	100 atoms/cm <sup>3</sup> (air)	$< 10^{-16} \text{ g/g}$	$\sim 10^{-17} \text{ g/g}$
$^{210}\text{Po}$	Surface cont. (from $^{222}\text{Rn}$ )		$\sim 100 \text{ c/d/100t}$	$\sim 6000 \text{ c/d/t}$ (May 2007) $\sim 1 \text{ c/d/100t}$
$^{210}\text{Pb}$	Surface cont. (from $^{222}\text{Rn}$ )		$^{210}\text{Bi}: \sim 1 \text{ c/d/100t}$	$^{210}\text{Bi}: \sim 70 \text{ c/d/100t}$ (not in equil. with $^{210}\text{Po}$ )
$^{39}\text{Ar}$	air/nitrogen	$\sim 17 \text{ mBq/m}^3$ (air)	$< 1 \text{ c/d/100t}$	not measurable
$^{85}\text{Kr}$	air/nitrogen	$\sim 1 \text{ Bq/m}^3$ (air)	$< 1 \text{ c/d/100t}$	Spectral fit: $(25\pm 5) \text{ c/d/100t}$ Fast coinc.: $(30\pm 5) \text{ c/d/100t}$

In terms of natural radioactivity: **radiopurest environment** ever measured!

# Borexino purification plants

Full Infrastructure:

J. Benziger et al. / Nuclear Instruments and Methods in Physics Research A 587 (2008) 277–291



Water extraction plant:

