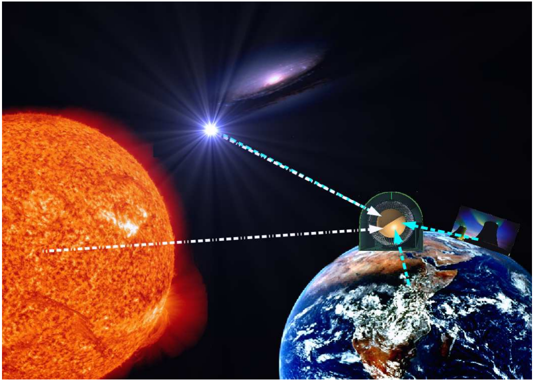
Highlights and future prospects of the neutrino experiment BOREXINO



Werner Maneschg

The Borexino experiment

Main purpose, location and collaboration:

- Detection and spectroscopy of low-energy (anti)-neutrinos
- Location: Laboratori Nazionali del Gran Sasso (Assergi, Italy)
- Operated by the Borexino collaboration: 21 universities/institutes from 6 countries (Status: October 2014)

Borexino experiment: overview

Borexino detector: main properties

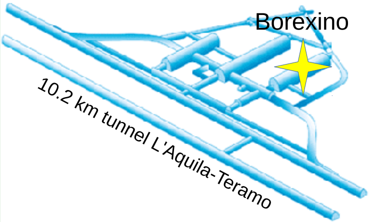
- large-volume organic liquid scintillator detector
- ultra low background detector (cleanest environment ever measured)
- in real-time (time stemp and pulse shape available for every event)
- at low energies, typically between 0.1-10 MeV

Borexino's rich physics program (performed or planned in near future)

- Solar neutrinos: ^{7}Be (main goal), ^{8}B (above 2.8 MeV) *pep*, CNO, *pp* (all branches except for *hep* neutrinos since they are too faint)
- Geo- and reactor-antineutrinos
- SN-(anti)neutrinos
- Sterile neutrino search
- Other exotic particles and processes (solar axions, Pauli-forbidden transitions,..)
- Neutrino properties (oscillation parameters, magnetic moment...)

Borexino: detector design

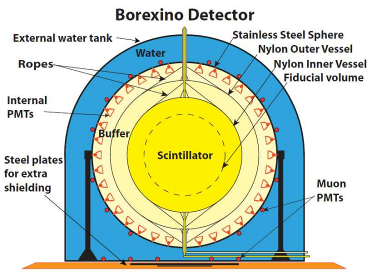
Cosmic ray attenuation:



- Overburden: 1.4 km of dolomite rock, corr. 3800 m w.e.
  $\rightarrow$ μ-flux red. by $\sim 10^6$ to $1\ \mu/\mathrm{h}/\mathrm{m}^2$

Nut shell profile:

1. Water tank (2100 m^3):
   - Absorption of environmental γ's and neutrons
   - μ Cherenkov detector (208 PMTs)
2. Stainless Steel Sphere:
   - 2212 PMTs, 1350 m^3, R=6.85 m
3. 2 buffer layers: PC+DMP
   - Outer R_2=5.50 m, Inner R_1=4.25 m
   - Shielding from external γ's
4. Scintillator: 270 tons of PC+PPO



Borexino: background specifications

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

- 40-50 neutrino signals/d/100 tons $\rightarrow$ 6×10^{-9} Bq/kg
- Background requirements to the scintillator (less than 10 c/d/100 tons):
  - U: 10^{-9} Bq/kg $\rightarrow$ $<0.8\times10^{-16}$ g/g (sec. eq.)
  - Th: 10^{-9} Bq/kg $\rightarrow$ $<2.4\times10^{-16}$ g/g (sec. eq.)
  - ^{14}C: 10^{-18} 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
μ	cosmic	200/s/m^2 (at sea level)	$\sim10^{-10}$
^{11}C	in-situ μ-ind.	$\sim$15 c/d/100	
Ext. γ (U,Th)	SSS		$\sim10^{-10}$ g/g
Ext. γ (U,Th)	PMTs		$\sim10^{-8}$ g/g
Ext. γ (U,Th)	PC buffer	$\sim10^{-16}$-10^{-15} g/g	$\sim10^{-15}$ g/g
^{14}C	Scintillator	$\sim10^{-12}$ g/g	10^{-18} g/g
^{238}U	Dust	$\sim10^{-16}$-10^{-15} g/g	$<10^{-16}$ g/g
^{232}Th	Dust	$\sim10^{-16}$-10^{-15} g/g	$<10^{-16}$ g/g
^{222}Rn	Emanation (air)	100 atoms/cm^3 (air)	$<10^{-16}$ g/g
^{210}Po	Surface cont. (from ^{222}Rn)		100 c/d/100t
^{210}Pb	Surface cont. (from ^{222}Rn)		
^{39}Ar	air/nitrogen	$\sim$17 mBq/m^3 (air)	<1 c/d/100t
^{85}Kr	air/nitrogen	$\sim$1 Bq/m^3 (air)	<1 c/d/100t

Selection & cleanliness of detector components

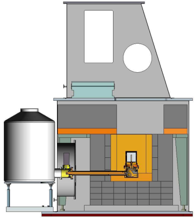
From MPI-K: B. Freudiger, W. Hampel, G. Heusser, T. Kirsten, W. Rau, H. Simgen, G. Zuzel

Selection of construction materials

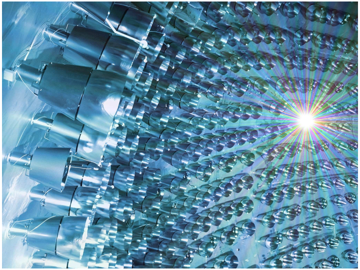
- Low level Ge spectrometry:
  (GeMPI: U/Th: $\sim$10 μBq/kg)
  $\rightarrow$ steel, teflon, wires, PMTs...
- ^{222}Rn diffusion/emanation detectors:
  (counted with proportional counters):
  $\rightarrow$ nylon and steel foils, gaskets...

Clean gases for scintillator purification

- Search for N_2 low in Kr and Ar:
  (counted with mass spectrometers:
  $\sim$1.4 nBq/m^3 ^{39}Ar, $\sim$0.1 μBq/m^3 ^{85}Kr)
  Found: Ar<0.4 ppm; Kr<0.2 ppt
  (**LAKN**)
- Low level nitrogen supply plant:
  - Production rate: 100 m^3/h, ^{222}Rn <0.5 μBq/m^3
  - Refurbished in 2014



Particle interactions with the scintillator

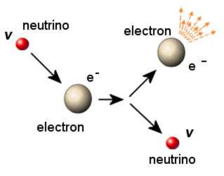


Scintillation process and collected information

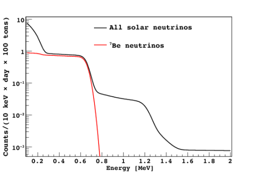
1. Particle interacting with scintillator transfers energy to organic molecules
2. Isotropic emission of scintillation light
3. Isotropic distributed PMTs measure:
   - a) number of hit PMTs and collected charge signal → energy
     high light yield+transparency, 30% PMT coverage → energy resolution
   - b) time of arrival of photons → T.o.F. → position of baricenter
     → fiducial volume cut
     → risetime of pulse → particle differentiation
   - c) combine information from a)+b) → coincident signals

Neutrino and antineutrino detection in the Borexino scintillator

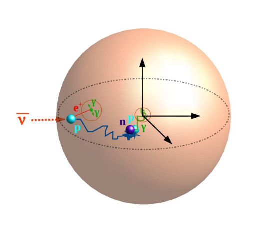
Neutrinos: elastic neutrino-electron scattering



- Mainly ν_e, but also ν_μ and ν_τ
- Compton-like formalism
  → Mono-energetic neutrino source has a Compton-like edge

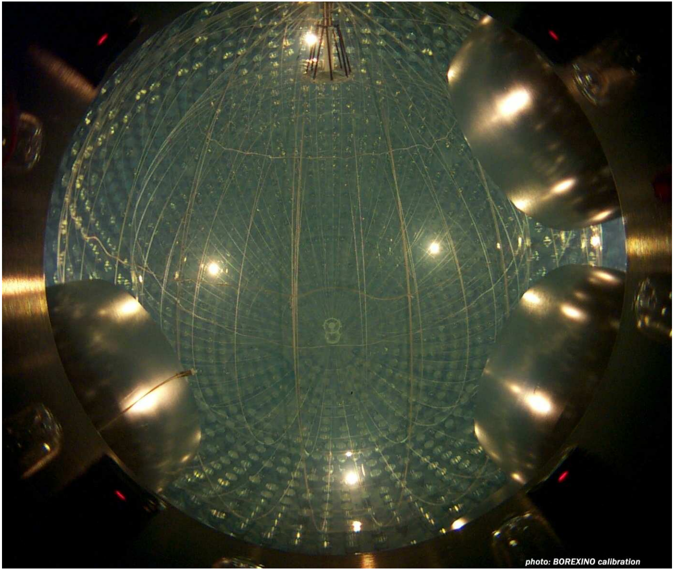


Antineutrinos: inverse beta decay



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

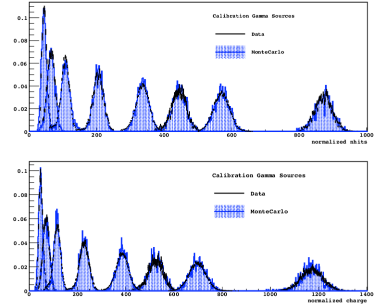
Borexino: Data collection start on May 17, 2007



Reached performance: energy reconstruction

Borexino calibration data

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



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

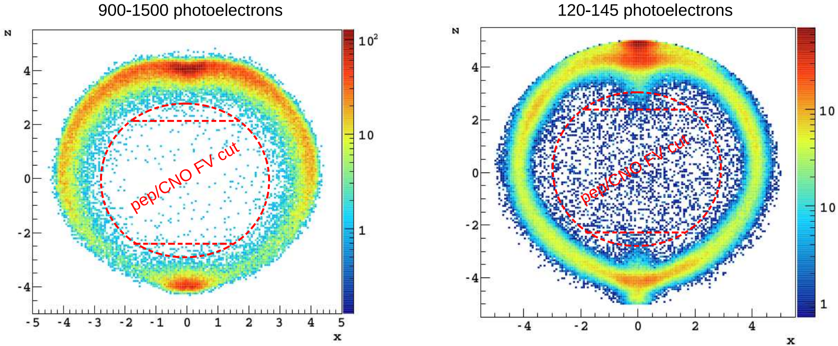
Main results:

- **Resolution** ($1\,\sigma$): $5\%/\sqrt{(}E(MeV))$ ($\leftrightarrow$ KamLAND: $6.5\%/\sqrt{(}E(MeV))$)
- **Light yield**: 10000 photons/MeV, → 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

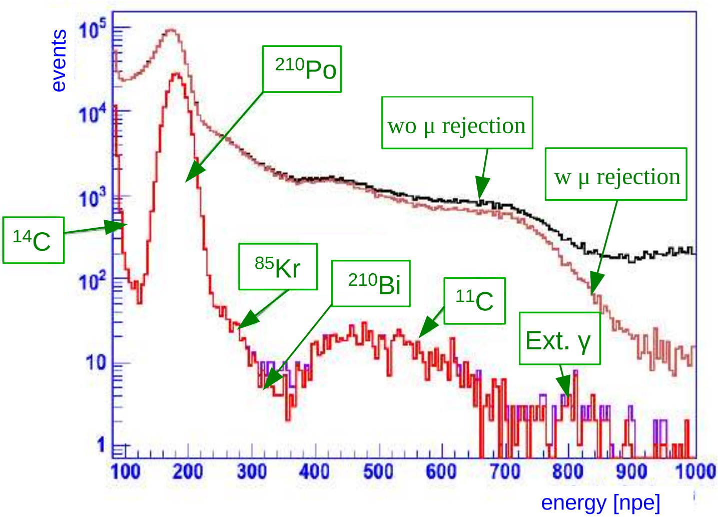
Reached performance: position reconstruction

Main results:

- **Resolution** ($1\,\sigma$):
  - 2.2 MeV (^{214}Bi, γ): (13±2) cm in x,y; (14±2) cm in x,y
  - 0.25 MeV (^{14}C, endpoint): (42±6) cm
- **Fiducial Volume cuts**: analysis-dependent:
  - Solar ^{7}Be: R<3.067 m, z< |1.67| m
  - Solar pep/CNO: R<2.8 m, -2.4 m<z<2.2 m (similar to FV for solar pp)
  - Geo-/reactor-antineutrinos: R<4 m



Borexino: background data (2007)

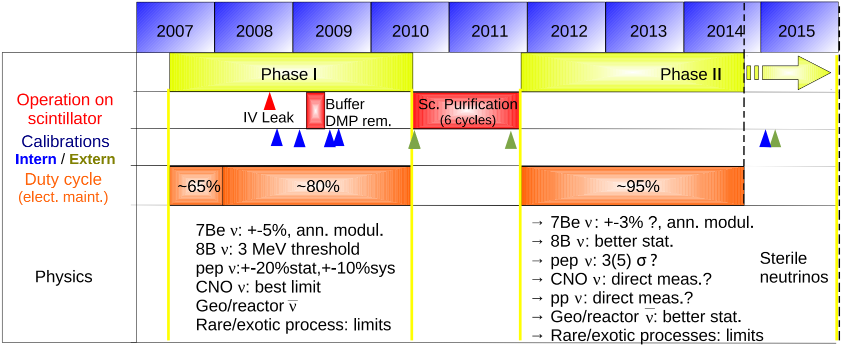


Borexino background decomposition (2007-2009 data)

Contaminant	Source	Normal/Expected conc./flux/rate	Required	Achieved
μ	cosmic	$200/s/m^2$ (at sea level)	$\sim 10^{-10}$	$\sim 10^{-10}$
^{11}C	in-situ μ-ind.	$\sim$15 c/d/100		$\sim$27 c/d/ton
Ext. γ (U,Th)	SSS		$\sim 10^{-10}$ g/g	$\sim 10^{-10}$-10^{-9} g/g
Ext. γ (U,Th)	PMTs		$\sim 10^{-8}$ g/g	$\sim 10^{-10}$-10^{-7} g/g
Ext. γ (U,Th)	PC buffer	$\sim 10^{-16}$-10^{-15} g/g	$\sim 10^{-15}$ g/g	
^{14}C	Scintillator	$\sim 10^{-12}$	$\sim 10^{-18}$	$(2.7\pm0.1)\times10^{-18}$
^{238}U	Dust	$\sim 10^{-16}$-10^{-15} g/g	$< 10^{-16}$ g/g	$(1.6\pm0.1)\times10^{-17}$ g/g
^{232}Th	Dust	$\sim 10^{-16}$-10^{-15} g/g	$< 10^{-16}$ g/g	$(6.8\pm1.5)\times10^{-18}$ g/g
^{nat}K	Dust	$\sim 10^{-14}$ g/g	$\sim 10^{-14}$ g/g	Spectral fit: $\leq 3\times10^{-16}$ g/g
^{222}Rn	Emanation	100 atoms/cm^3 (air)	$< 10^{-16}$ g/g	$\sim 10^{-17}$ g/g
^{210}Po	Surface cont. (from ^{222}Rn)		$\sim$100 c/d/100t	$\sim$6000 c/d/t (May 2007) $\sim$1 c/d/100t
^{210}Pb	Surface cont. (from ^{222}Rn)		^{210}Bi: $\sim$1 c/d/100t	^{210}Bi: $\sim$70 c/d/100t (not in equil. with ^{210}Po)
^{39}Ar	air/nitrogen	$\sim$17 mBq/m^3 (air)	$<$1 c/d/100t	not measurable
^{85}Kr	air/nitrogen	$\sim$1 Bq/m^3 (air)	$<$1 c/d/100t	Spectral fit: (25 ± 5) c/d/100t Fast coinc.: (30 ± 5) c/d/100t

In terms of natural radioactivity: radiopurest environment ever measured!

Borexino operations: 2007-2014



Description of the solar structure

Standard Solar Model (SSM)

Frame: equations of state
- mass conservation
- hydrostatic eq.
- energy transport
- energy production
- change of elem. abundances Xi (t)

Inputs:
- Starting conditions: p, T, radius, ρ
- cross section factors, opacities
- chemical adundance of Xi
  (based on photospheric & meteoritic meas.

Predictions / test of observables:
- Radial density profile
- Sound speed profile
- Convection zone radius
- At any time: p, T, radius, ρ, photosphere luminosity
- **Neutrino fluxes** → neutrino luminosity

Helioseismology

Frame: Sun as resonator
- linear perturbation of hydrodynamic syst.
  (approx. linear adiabatic approximation)

Inputs:
High-accuracy measurement of acoustic modes of pulsation of entire Sun (high/low degree modes)

Predictions / test of observables:
- Radial density profile
- Sound speed profile
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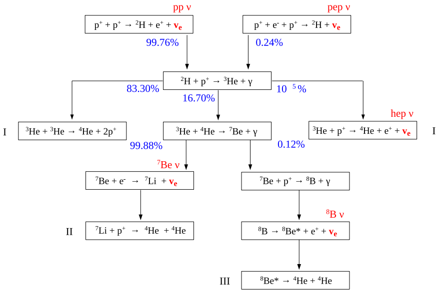
Fusion reactions in the Sun

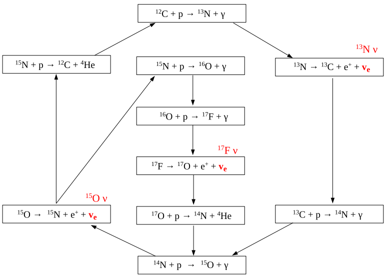
Overall reaction: $4p \rightarrow {}^4He + 2e^+ + 2\nu_e + 26.73$ MeV

pp chain



≈99% of electromagn. energy release

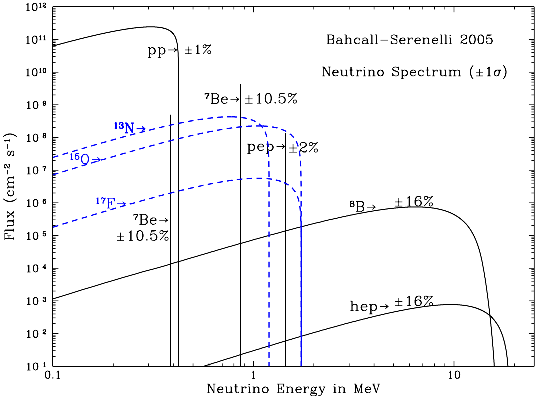
CNO cycle



≈1% of electromagn. energy release

SSM prediction: solar neutrino fluxes

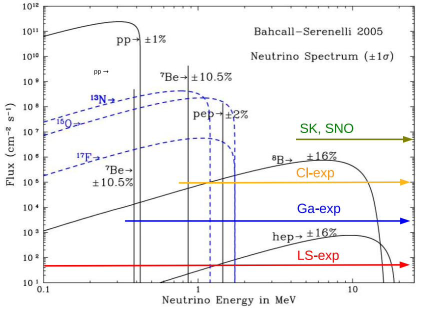
Neutrino fluxes at 1 AU, according to BS05(GS98,OP)



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

Solar neutrino detection

Experiments and their E-thresholds

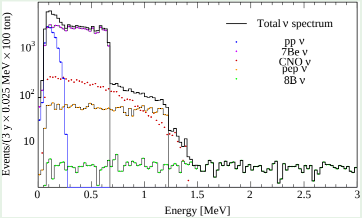


Borexino

- lowest energy threshold at 0.05 MeV
- real-time detection

Solar neutrinos in Borexino

MC simulation:



- mono-energetic neutrino sources: Compton-like edge
- pp and ^{7}Be neutrinos: major contribution
- hep neutrinos: too faint

Tensions in the solar model predictions

Standard Solar Model (SSM)

Frame: equations of state
-mass conservation
-hydrostatic eq.
-energy transport
-energy production
-change of elem. abundances Xi (t)

Inputs:
-Starting conditions: p, T, radius, ρ
-cross section factors,
-chemical adundance of heavier elem. Xi
(based on photospheric studies GS98)

Helioseismology

Frame: Sun as resonator
- linear perturbation of hydrodynamic syst.
(approx. linear adiabatic approximation)

Inputs:
High-accuracy measurement of acoustic modes of pulsation of entire Sun
(high/low degree modes)

Todays outer solar param's:

- p, T, radius, ρ, photosphere luminosity

⟺

Predictions / test of observables:
- Radial density profile
- Sound speed profile
- Convection zone radius
- At any time: p, T, radius, ρ, photosphere luminosity
- **Neutrino fluxes** → neutrino luminosity

→ 1/3 – 2/3 of expected neutrinos missed
→ Solved: neutrino oscillations in vac/matter

⟺

Predictions / test of observables:
- Radial density profile
- Sound speed profile
- Convection zone radius

" Solar Neutrino Puzzle"

Solving tensions in the solar neutrino flux prediction

Neutrino oscillation formalism

Neutrino flavor α=e,μ,τ:

$$|\nu_\alpha\rangle = \sum_i \mathrm{U}_{\alpha i}|\nu_i\rangle.$$

Maki-Nakagawa-Sakata-Pontecorvo matrix (MNSP matrix):

$$U_{MNSP} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha} & 0 \\ 0 & 0 & e^{-i\beta} \end{pmatrix}$$

Electron neutrino survival probability for a simple '2-flavor' World::

In vacuum:

$$P(\bar{\nu}_e \to \bar{\nu}_e, L, E) = 1 - \sin^2 2\theta \sin^2 \frac{1.27\Delta m^2[\mathrm{eV}^2]\mathrm{L}[\mathrm{m}]}{E[\mathrm{MeV}]}.$$

In matter: Mikheyev-Smirnov-Wolfenstein effect (MSW):

$$\sin^2(2\vartheta_m) = \frac{\Delta m^2 \sin(2\vartheta)}{\sqrt{(2\sqrt{2}G_F n_e E - \Delta m^2\cos(2\vartheta))^2 + (\Delta m^2\sin(2\vartheta))^2}}.$$

Tensions in the solar model predictions

Standard Solar Model (SSM)

Frame: equations of state
-mass conservation
-hydrostatic eq.
-energy transport
-energy production
-change of elem. abundances Xi (t)

Inputs:
-Starting conditions: p, T, radius, ρ
-cross section factors,
-chemical adundance of heavier elem. Xi
(based on photospheric studies GS98)

GS98: Z/X =0.0229 (high metallicity)
AGS09: Z/X = 0.0178 (low metallicity)

Helioseismology

Frame: Sun as resonator
- linear perturbation of hydrodynamic syst.
(approx. linear adiabatic approximation)

Inputs:
High-accuracy measurement of acoustic modes of pulsation of entire Sun (high/low degree modes)

Todays outer solar param's:

- p, T, radius, ρ, photosphere luminosity

Predictions / test of observables:
- Radial density profile
- Sound speed profile
- Convection zone radius
- At any time: p, T, radius, ρ, photosphere luminosity
- **Neutrino fluxes** → neutrino luminosity
→ neutrino oscillations

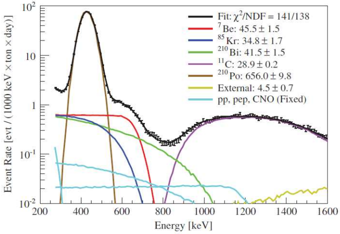
→ pp; pep: + 1%; +2%
→ 8B; 7Be: - (21-11)%; (10-5)%
→ CNO: - (44-21)%

Predictions / test of observables:
- Radial density profile
- Sound speed profile
- Convection zone radius

" Solar Metallicity Puzzle"

Measurement of the ^{7}Be neutrino rate and day-night asymmetry

MC-fitted spectrum



Averaged ^{7}Be-ν rate:

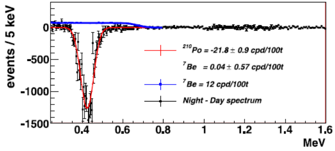
- Calibrations drastically reduced the syst. uncertainy:

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	$^{+3.4}_{-3.6}$

- Two independent fit approaches: analytical vs. MC
- Combined result: R=(46±1.5(stat)$^{+1.5}_{-1.6}$(sys)) cpd/100 ton
- Comparison to SSM predictions:
  - Without osc.: (74±5.2) cpd/100 tons (5σ exclusion)
  - With osc.: 44 (High-met.) and 48 (Low-met.) cpd/100 ton

Day-Night asymmetry in ^{7}Be-ν rate:

1. LOW solution: MSW effect might regenerate ν_e's through Earth, i.e. during night
2. Large-Mixing-angle solution: no enhancement expected
3. Results: (N-D)/((N+D)/2) = 0.001±0.012(stat)±0.007(sys) (exclusion by 8.5 σ)



Annual modulation of ^{7}Be neutrino rate

Expectation:

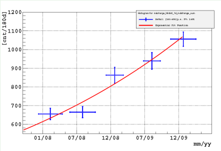
Earth eccentricity ϵ=0.0167 (maximum on January 3):

→ Perihelion-Aphelion flux difference of ±7%

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

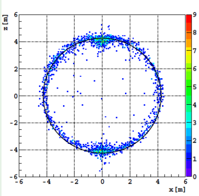
Question: Possible to measure? i.e. Proving origin of detected neutrinos?

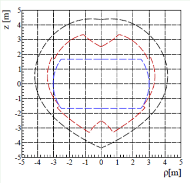
Challanging 1: Stability of detector response and backgrounds



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

Challanging 2: Statistics

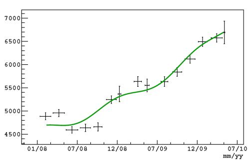


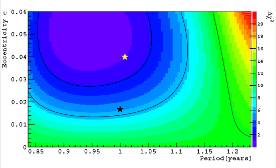


- Fit of subperiods have too large stat. errors;
  → for a given energy interval group data in time bins of 1-2 months and look for periodicity (3 methods applied; 2 are presented on next slide)
- Increase the fiducial volume from 75.5 to 141.8 tons and follow time-dependent change of nylon vessel

Annual modulation of ^{7}Be neutrino flux

1. Method: Rate vs. time

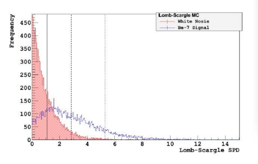


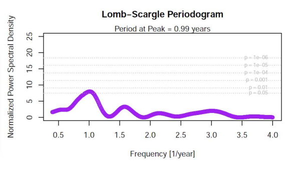


Used fit function: $R = R_0 + e^{\Lambda_{Bi} t} + \bar{R}\,\{1 + 2\epsilon cos(2\pi/T - \phi)\}$

Results: T=1.01±0.07; ϵ=0.0398±0.0102 → Expected values are within 2 σ)

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





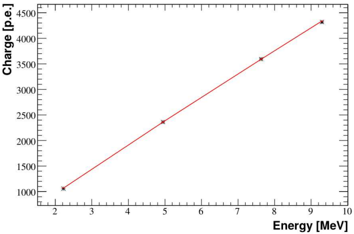
Results: Peak at period T=0.979; Spectral power density: 7.96

→ Non-existence of annual modulation excluded at ~3 σ

Solar ^{8}B neutrino measurement

Challenging:

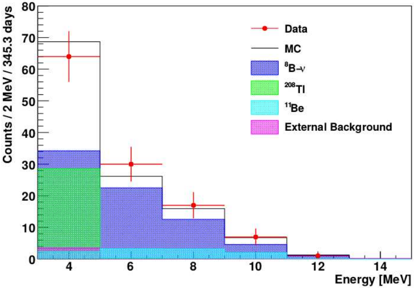
- ^{8}B neutrinos: energy up to ∼15 MeV, but low rate
- Detector response: dependency from quenching, geometrical effects, saturation and electronics effects
  → energy scale at higher energies
  → position vertex reconstruction for high energy events
- Background: consider many small background components:
  → muons and cosmogenic radionuclides (short- and longer-lived)
  → internal U, Th; external ^{228}Th (limit **2.8 MeV**)



Isotopes	τ	Q [MeV]	Decay
^{12}B	0.03 s	13.4	β^-
^{8}He	0.17 s	10.6	β^-
^{9}C	0.19 s	16.5	β^+
^{9}Li	0.26 s	13.6	β^-
^{8}B	1.11 s	18.0	β^+
^{6}He	1.17 s	3.5	β^-
^{8}Li	1.21 s	16.0	β^-
^{10}C	27.8 s	3.6	β^+
^{11}Be	19.9 s	11.5	β^-

Solar ^{8}B neutrino measurement: results

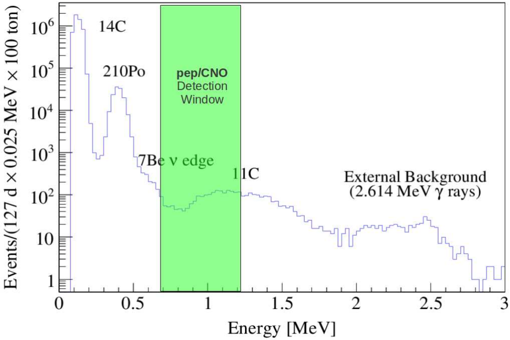
Data vs. MC of ^{8}B recoil energy spectrum



Results and remarks:

- Rate above 3 MeV: 0.217±0.038(stat)±0.008(syst) c/d/100ton
- Flux at 1 AU: $(2.7\pm0.4\pm0.1)\times10^{6}$ cm^{-2} s^{-1}
  → good agreement with SuperKamiokaNDE and SNO
  → confirmation of MSW-LMA solution for oscillation in vacuum/matter
- No disentaglement of SSM metallicity scenarios possible
- Data set: used 488 d; → can be ∼3× higher

Search for the solar pep / CNO neutrinos

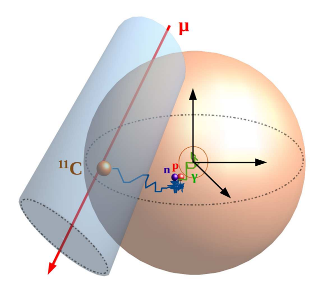


Relevant backgrounds

- Main background is the cosmogenic ^{11}C:
  - $^{12}C + \mu \rightarrow ^{11}C + n + \mu$
  - ν signal-to-^{11}C background ratio: ∼1:10
- Scintillator-intrinsic contaminants (^{210}Bi, ^{40}K,..)
- External γ-rays (2.6 MeV from ^{208}Tl,..)

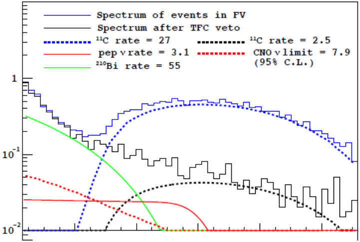
pep/CNO neutrinos: The ^{11}C background analysis I

Tagging ^{11}C via a threefold coincidence (TFC)



- Prompt muon signal (where ^{11}C is generated)
- Delayed neutron capture ($\tau \sim$255 μs) on H (or C): $n + p \rightarrow D + 2.2 MeV \gamma$
- Delayed ^{11}C β^{+}decay ($\tau \sim$29.4 min): $^{11}C \rightarrow ^{11}B + e^{+} + \nu_e$
  $\rightarrow$ Energy intervals, space-and-time correlations $\rightarrow$ TFC-cuts

TFC subtracted spectrum



Removed ^{11}C fraction: $\sim$90%;

Exposure loss: $\sim$50%

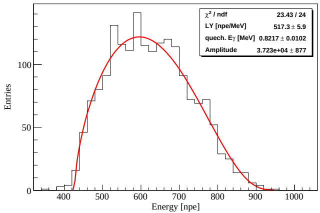
pep/CNO neutrinos: The ^{11}C background analysis II

Pulse-Shape discrimination of residual ^{11}C

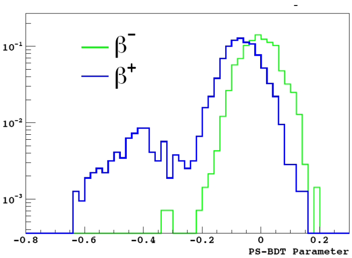
- ^{11}C β^+ emitter, while ^{210}Bi, ext.γ's induce β^- emission
- Positron forms in 50% positronium (lifetime of few ns in scintillator) before annihilation
- Training of Boosted Decision Tree with pure β^+/β^-samples to quantify discrimination parameter

98% pure ^{11}C sample tagged via sharp TFC-cuts

and used for BDT training



BDT-PS parameter



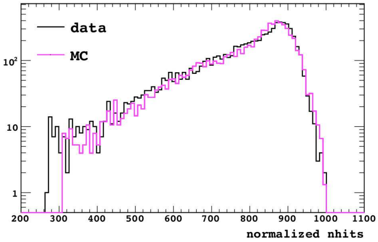
pep/CNO neutrinos: external background analysis

Procedure: based on calibration data and simulated spectra

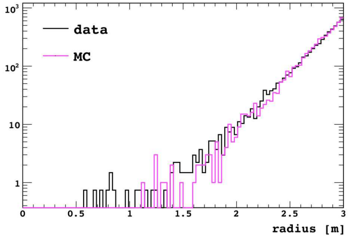
- External high-energetic γ's (mainly 2.6 MeV from ^{208}Tl) from PMTs, light concentrators, SS-Sphere
- Use 5 MBq ^{228}Th (^{208}Tl) source at different external positions
- Use data to test MC (energy/radial dist.); $\rightarrow$ simulate ext. background

MC code validation with calibration data

Energy spec. of ext. γ-source



Radial distr. of ext. γ-source

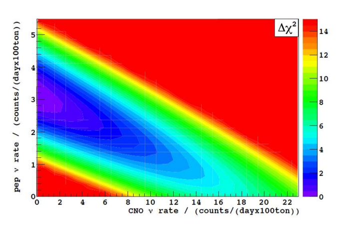


Measurement of the pep neutrino rate (+CNO limit)

Final strategy:

- Tag ^{11}C candidates via the TFC method and subtract them from spectrum
- Multivariate simultaneous fit of residual spectrum considering:
  - energy spectrum (including MC-simulated external components)
  - radial distribution spectrum
  - BDT Pulse shape parameter for β^+/β^- separation

Results:



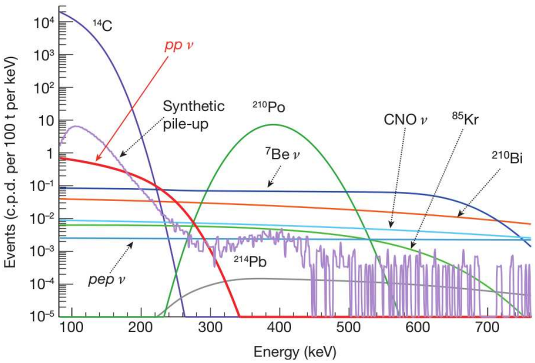
Component	[counts/(day·100 ton)]
pep	$3.1 \pm 0.6_{\text{stat}} \pm 0.3_{\text{syst}}$
CNO	< 7.9 ($< 7.1_{\text{stat only}}$)
^{85}Kr	19^{+5}_{-3}
^{210}Bi	55^{+3}_{-5}
^{11}C	27.4 ± 0.3
^{10}C	0.6 ± 0.2
^{6}He	< 2
^{40}K	< 0.4
^{234m}Pa	< 0.5
Ext. γ	2.5 ± 0.2

- pep: first evidence!; Including the MSW effect and LMA solution: DATA/SSM(AG98)= 1.1±0.2
- CNO: best upper limit to date!; DATA/SSM(AG98)<1.5
- Solar Metallicity problematics not yet solved

Solar pp neutrinos: background in Borexino

Expected recoil energy spectrum

(all components analytical/simulated, only pile-up from data)



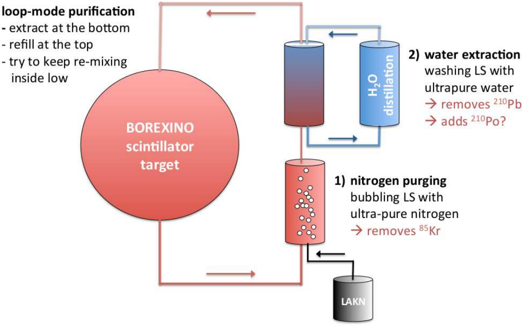
pp neutrinos: Spectrum:

0<E<420 keV
→ E_{rec} <264 keV
Expected rate:
(131±2) c/d/100ton
Energy threshold E_{th}:
Borexino: ∼50 keV
Radiochem. exp: 233 keV

Main obstacles:

- Above ∼240 keV: decays of ^{85}Kr, ^{210}Bi (^{210}Pb)
- Below ∼240 keV: decays of ^{14}C, ^{14}C pile-ups

Scintillator purification campaigns (2010/06 - 2011/08)



Background rates before/after purification* (6 full cycles):

Nuclide	Phase I c/d/100t (or mass fr.)	Phase II c/d/100t (or mass fr.)
^{210}Po	$\sim$6000*	$\sim$200*
^{85}Kr	31$\pm$5	<7 (95% C.L.)
^{210}Po	$\sim$70	$\sim$25
^{238}U	$(1.6\pm0.1)\times10^{-17}$ g/g	$<9.7\times10^{-19}$ g/g (95% C.L.)
^{232}Th	$(6.8\pm1.5)\times10^{-18}$ g/g	$<1.2\times10^{-18}$ g/g (95% C.L.)

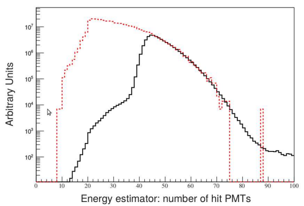
* For ^{210}Po: Phase I: 2007/05, Phase II: 2013/05 (end of pp data set period)

^{14}C background: identification strategies

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

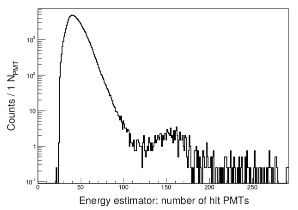
Pure ^{14}C β spectrum

- Trigger problem:
  - Rate: ∼30 Hz for E_{th} ∼50 keV
  → Expected rate: (10-100) Bq/100ton
  - Aquisition window: 16μs;
  - Events with E close to E_{th}: often problematic
- Solution for ^{14}C close to E_{th}: - Trigger with two random events: 2. event (^{14}C) unaffected by E_{th}
  → Spectral shape threshold: 100 keV → 50 keV
  → Rate: (40±1) Bq/100ton



^{14}C pile-ups

- Pile-up problem:
  - ^{14}C overlap with PMT dark rate, ^{14}C, ^{210}Po
  → Spectral shape hardly known
  → Position reco. largely fails
  (expected rate: (6-600) c/d/100ton)
- Solution: Generate 'synthetic' pile-ups:
  - Overlap artificially uncorrelated data with regular events
  → ^{14}C-^{14}C rate: (154±10) c/d/100ton

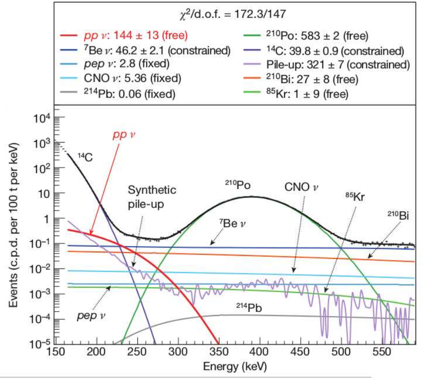


Measurement of the pp neutrino rate

Measured recoil energy spectrum

Fit in (165-590 keV)

Nature, Vol. 512, August 28, 2014



Rates in [c/d/100ton], except for ^{14}C [Bq/100ton]

Results:

R_{pp} = 144±13(stat)±10(sys) c/d/100ton

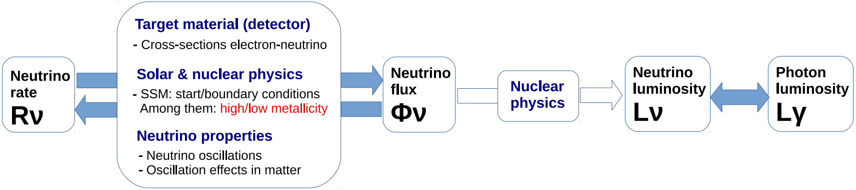
(absence of pp excluded at 10σ)

- Robustness of analysis:

Parameter	Syst.:
energy estimator	±7%
fit energy range	
data selection	
pile-up evaluation	
fiducial mass	±2%

- Check of residual background

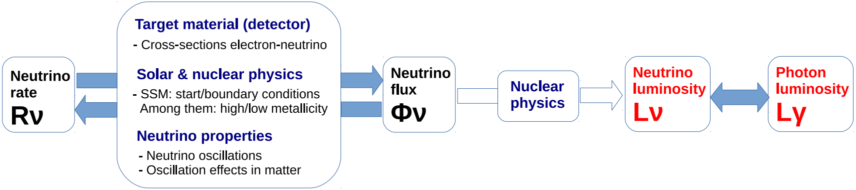
Interpretation I: convertion of pp rate into a flux

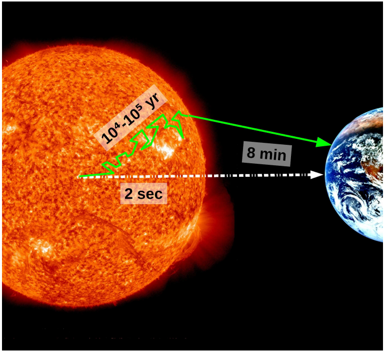


SSM predictions and Borexino measurement (at Earth):

- High metallicity (GS98): $5.98\times(1\pm0.006)\times10^{10}$ cm^2 s^{-1}
- Low metallicity (AGS09): $6.03\times(1\pm0.006)\times10^{10}$ cm^2 s^{-1}
  $\rightarrow$ mean values differ by 0.8% only
- Measured: $(6.6\pm0.7)\times10^{10}$ cm^2 s^{-1}
  $\rightarrow$ agreement with both models, but no disentaglement of metallicity

Interpretation II: test the luminosity constraint





Luminosity variability:

- O(10 yr): 22 yr solar cycle → 0.1%
- O(10^4-10^5 yr): ? → BX measurement
- O(4.6×10^9 yr): SSM → young faint Sun:
  -25% less bright than today

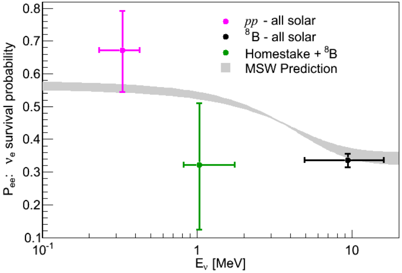
SSM/Borexino vs. solar photosphere prediction:

- $L_\nu = 3.84\times10^{33}$ erg s^{-1} ($\pm10\%$)
- $L_\gamma = 3.846\times10^{33}$ erg s^{-1}
  - → No hint for variability;
  - → pp meas. 1% precision

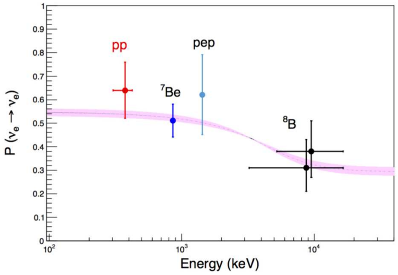
Interpretation III: Neutrino oscillations in vacuum/matter

Electron neutrino survival probability:

Before Borexino:



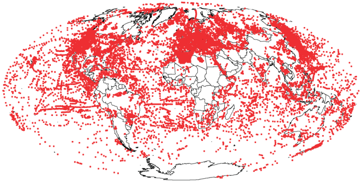
Borexino alone (2014):



Borexino results:

- Data points well-consistent with the MSW - Large-Mixing-Angle solution
- Improvements expected from:
  - data sets with more statistics/lower systematics (pp, pep, 8B)
  - direct CNO neutrino rate measurement (?)

Description of Earth's interior



Geophysics

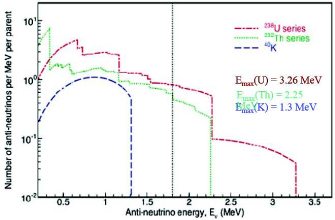
- Earth heat: (47±2) TW, estimated from 40,000 deep bore-holes integrating over entire surface: ∼0.09 Wm^2 (compare: solar constant 0.34 kW/m^2)
  → Possibilities: radiogenic heat, primordial planetary accrection/contraction
- Seismology: insight about structure/density, but not about composition
  → Possibilities: Petrologic and meteoritic samples (Chrondrite Th/U=3.9), geo-antineutrinos

Bulk Silicate Earth model (BSE)

- Description of the 'Primitive Mantel's chemical composition before crust differentiation, but after the metal core separation
- Prediction of radiogenic heat (local-dependent variations):
  - Crust: ∼7 TW
  - Mantle: 1-19 TW (differing for BSE-submodels)
  - Core: 0 TW

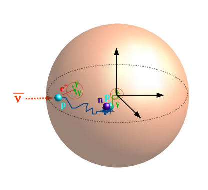
  → Probe with geo-$\bar{\nu}$s:

  Expected rate in Borexino: ∼10 c/yr/278 ton



Geo-neutrino detection in Borexino

Inverse beta decay in scintillator

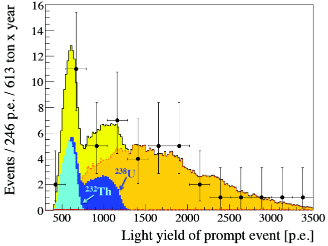


- Reaction: $\bar{\nu} + p \rightarrow n + e^{+}$
- Prompt signal of positron annihilation $e^{-} + e^{+} \rightarrow 2\gamma$
  Herein, threshold is $E_t = 1.806$ MeV
- Delayed neutron capture ($\tau \sim 255\,\mu$s) on H (or C):
  $n + p \rightarrow D + 2.2\,MeV\,\gamma$
  $\rightarrow$ Energy intervals, space and-time correlations
  $\rightarrow$ Inverse beta decay is very efficient rejection method

Main backgrounds

- Reactor-antineutrinos: Calculated expectation considers:
  - 446 cores worldwide (196 European)
  - Weighted mean baseline: 1170 km $\rightarrow$ ν oscillation
  - Exact duty cycles and fuel composition provided by IAEA and EDF
  $\rightarrow$ Only spectral disentaglement possible
- Muons, short-lived cosmogenics (e.g. ^{9}Li, ^{8}He), fast neutrons
  $\rightarrow$ Apply time-space cuts
- Intrinsic contaminants in the scintillator (mainly ^{210}Po) and spontaneus fission in PMTs
  $\rightarrow$ Reject data periods after purification campaigns (e.g. ^{214}Bi-^{214}Po from ^{222}Rn)

Latest geo-neutrino result from Borexino



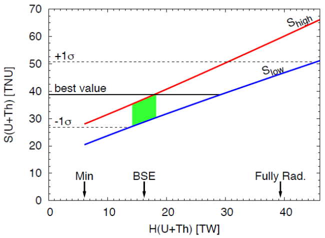
New statistics (March 2013)

- Exposure: 1352.6 d live time; after all cuts: (613±26) ton×year, $(3.69\pm0.16)\cdot10^{31}$ protons×year
- 46 golden candidates found:
  - Geo-$\bar{\nu}$: (14.3±4.4) ev, (38.8±12.0) TNU*
  - Reactor-$\bar{\nu}$: $(31.2^{+7.0}_{-6.1})$ ev, $(84.5^{+19.3}_{-16.9})$ TNU
  (Expected: w osc. (33.3±2.4) ev; wo osc. (60.4±4.1) ev)
  - Included background: (0.70±0.18) ev

  *TNU: Terrestial Neutrino Unit=1 ev/yr/10^{32} protons

Main results and conclusions:

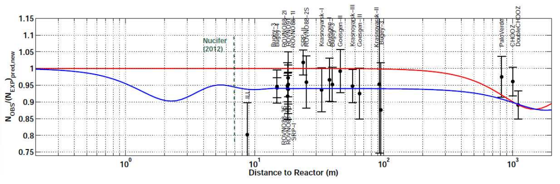
- Null-hypothesis of geo-$\bar{\nu}$ rejected at 4.5 σ
- Subtract calculated local/residual crust contribution from measured geo-$\bar{\nu}$ signal to obtain mantle geo-$\bar{\nu}$ signal: (15.4±12.3) TNU
  → in agreement with pred. of many BSE-submodels
- Generated heat - within the possible BSE models - explainable by the observed geo-$\bar{\nu}$
- For the first time U and Th contribution fitted separtely (26.6 TNU vs. 10.6 TNU)
- Reactor-$\bar{\nu}$: full agreement with neutrino osc.



Near-future plan: Short-distance $\bar{\nu}/\nu$ oscillation experiment

Motivations for using a $\bar{\nu}/\nu$ source:

- **Evidence for a fourth neutrino flavor ?**
  - LNSD: clear excess (3.8 σ); partially confirmed by MiniBooNE
  - W-MAP 9 years: N_{eff}=3.84±0.40; Planck + H_0 const. meas.: N_{eff}=3.63±0.27
  - Gallium (2.7 σ) and reactor anomalies: deficit on short-distances



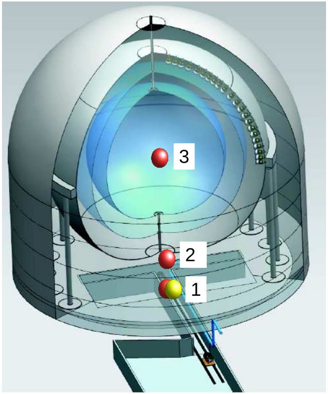
→ Hints for sterile neutrino(s): in (3+1) scenario L/E∼1 m/MeV, Δm^2_{14} ∼1-2 eV^2, $\sin^2(\theta_{14})$ ∼0.1

- Measurement of **Weinberg angle** θ_W at low energy (∼1 MeV)
- Measurement of **neutrino magnetic moment** μ_ν
- Check of **coupling constants** g_V and g_A at low energies

$\bar{\nu}/\nu$ source candidates:

Source	Neutrinos	Decay mode	τ	E [MeV]	Mass [kg/MCi]	Heat [W/kCi]
^{51}Cr	ν	e-capt., 320 keV γ 10%	40 d	0.781 (81%)	0.011	0.19
^{90}Sr-^{90}Y	$\bar{\nu}$	Fission prod. β^-	15160 d	<2.28 (100%)	7.25	6.7
^{144}Ce-^{144}Pr	$\bar{\nu}$	Fission prod. β^-	411 d	<2.9975 (97.9%)	0.314	7.6

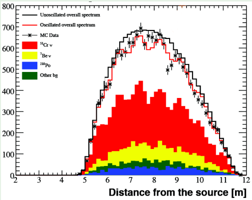
Short-distance Oscillation in BoreXino (SOX)



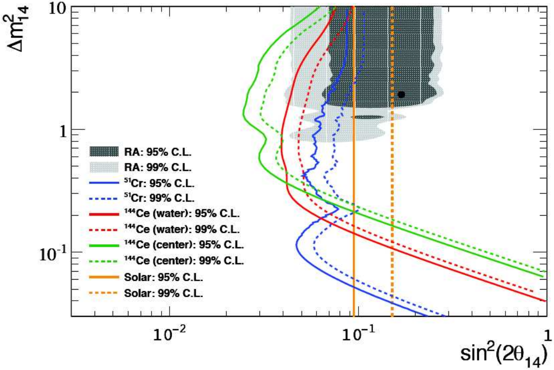
Deployment of $\bar{\nu}/\nu$ sources in Borexino:

- Phases:
  - SOX-A External source deployment in pos. 1, 8.25 m from center:
    end 2015?: 5 PBq ^{144}Ce
    begin 2017?: 200-400 PBq ^{51}Cr
  - SOX-B External source deployment in pos. 2, 7.15 m from center:
    (mid 2017?): 2-4 PBq ^{144}Ce
  - SOX-C External source deployment in pos. 3, at center:
    (>2018?): 2-4 PBq ^{144}Ce

Simulated outcome of ^{51}Cr test:



Borexino: Challanges and sensitivity for sterile neutrinos



Challenging:

- construction/enrichment of active elements
- radiation: heat generation and shielding construction
- fast delivery of ^{51}Cr source to experimental site
- activity measurement: requirement of 1% precision; 2 calorimeters under construction
- safety and permissions: highly complicated
- detector response: very good knowledge about energy reco. for large fiducial volumes

Summary and outlook

Achieved main results:

- Solar neutrino rates:
  ^{7}Be (high precision), ^{8}B (lowest E-threshold), *pep* (first direct observation),
  CNO (best upper limit), *pp* (first direct observation)
- Annual modulation of solar neutrino flux
- Geo-$\bar{\nu}$ signal observed, separation of crust/mantle component, separation of U/Th content
- Calibration campaigns (perservation of cleanliness of scintillator)

Next goals and beyond:

- Improve precision of present results due to lower background (^{7}Be rate,..)
- Improve precision of present results due to higher statistics (geo-$\bar{\nu}$,..)
- Improve limit on CNO or try to quote a rate (^{210}Bi most problematic)
  $\rightarrow$ solve solar metallicity problem
- External ^{144}Cr $\bar{\nu}$ and ^{51}Cr ν source test (SOX)
- Supernova detection: BX member of SNEWS, low E-threshold and 95% duty cycle

Further reading

- **Solar neutrinos**
  - 7Be rate @ 17%: C. Arpesella at al., First real time detection of 7Be solar neutrinos by Borexino, Phys. Lett. B 658 (2008) 101-108
  - 7Be rate @ 10%: C. Arpesella at al., Direct measurement of the 7Be solar neutrino flux with 192 days of Borexino data, Phys. Rev. Lett. 101 (2008) 091302
  - 7Be rate @ 5%: G. Bellini et al., Precision measurement of the 0.862 MeV 7Be solar neutrino interaction rate in Borexino, Phys. Rev. Lett. 107 (2011) 141302
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  - 7Be annual mod.: G. Bellini at al., Final results of Borexino Phase-I on low-energy solar-neutrino spectroscopy, Phys. Rev. D 89 (2014) 112007
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