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 m³):**
   - Absorption of environmental γ rays and neutrons
   - μ Cherenkov detector (208 PMTs)
2. **Stainless Steel Sphere:**
   - 2212 PMTs, 1350 m³, R=6.85 m
3. **2 buffer layers**: PC+DMP
   - Outer R₂=5.50 m, Inner R₁=4.25 m
   - Shielding from external γ 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: $E_{\nu} = 1.806$ MeV)
- Prompt signal of positron annihilation: $e^- + e^+ \rightarrow 2\gamma$
- Delayed neutron capture ($\tau \sim 255$ $\mu$s) on H:
  $n + p \rightarrow D + 2.2$ 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.

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

**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:** cm$^{-2}$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
**Results and remarks:**

- **Averaged rate:** $R = (46 \pm 1.5 \text{(stat)})^{+1.5}_{-1.6} \text{(sys)}$ c/d/100 ton (uncertainty $\pm 5\%$)

  Comparison to SSM predictions:
  - Without osc.: $(74 \pm 5)$ 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: $T = (1.01 \pm 0.07)$ yr; $\epsilon = 0.0398 \pm 0.0102 \rightarrow$ expected value within $2\sigma$
Solar $^8$B neutrino rate measurement

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

Results and remarks:

- **Challenging:** low neutrino rate, many small background components
- **Rate above 3 MeV:** $0.217\pm0.038$(stat)$\pm0.008$(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
- **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 $^{11}$C: S/B~1:10
  → Apply a threefold coincidence method (90% $^{11}$C red., 50% exposure loss)
  → Apply pulse shape BDT algorithm for $\beta^+/\beta^-$ separation
- **Other background**: $^{210}$Bi, $^{40}$K, external γ-rays (2.6 MeV from $^{208}$Tl),...
- **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; new analysis ongoing
- **Solar Metallicity** problematics not yet solved (needs $^{210}$Bi understanding)
Towards the detection of solar pp neutrinos

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

pp neutrinos:

- **Endpoint energy $E_{mx}$**: 
  \[ 0 < E_{mx} < 420 \text{ keV} \]
  \[ \rightarrow E_{\text{rec}} < 264 \text{ keV} \]

- **Energy threshold $E_{th}$**: 
  - Borexino: $E_{th} \sim 50$ keV
  - Radiochem. experiments: $E_{th} \sim 233$ keV

Main obstacles:

- **Above $\sim 240$ keV**: decays of $^{85}$Kr, $^{210}$Bi ($^{210}$Pb daughter)
- **Below $\sim 240$ keV**: decays of $^{14}$C, $^{14}$C pile-ups
Reduction of the $^{85}$Kr and $^{210}$Bi background in Borexino

Scintillator purification campaigns:
Period: 2010/06-2011/08
6 full cycles

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Phase I</th>
<th>Phase II</th>
<th>Spec’s (analysis dep.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>rate or mass fr.</td>
<td>rate or mass fr.</td>
<td>rate or mass fr.</td>
</tr>
<tr>
<td>$^{85}$Kr</td>
<td>$(31\pm5)$ c/d/100 t</td>
<td>$&lt;7$ c/d/100 t (95% C.L.)</td>
<td>few $10$ c/d/100 t ($^7$Be,pp)</td>
</tr>
<tr>
<td>$^{210}$Bi</td>
<td>$\sim70$ c/d/100 t</td>
<td>$\sim25$ c/d/100 t</td>
<td>few $10$ ($^7$Be,pp) / few c/d/100 t (CNO)</td>
</tr>
<tr>
<td>$^{210}$Po</td>
<td>$\sim6000$ c/d/100 t *</td>
<td>$\sim200$ c/d/100 t *</td>
<td>100 c/d/100 t (pp)</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>$(1.6\pm0.1)\times10^{-17}$ g/g</td>
<td>$&lt;9.7\times10^{-19}$ g/g (95% C.L.)</td>
<td>$&lt;10^{-16}$ g/g (7Be)</td>
</tr>
<tr>
<td>$^{232}$Th</td>
<td>$(6.8\pm1.5)\times10^{-18}$ g/g</td>
<td>$&lt;1.2\times10^{-18}$ g/g (95% C.L.)</td>
<td>$&lt;10^{-16}$ g/g (7Be)</td>
</tr>
</tbody>
</table>

* $^{210}$Po ($\tau=138$ d): Phase I: 2007.05, Phase II: 2013.05 (end of pp data set period)
Rate and spectral shape of the $^{14}$C background in Borexino

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

**Pure $^{14}$C $\beta$ spectrum**

- **Trigger problem:**
  - Total rate: $\sim$30 Hz for $E_{th} \sim$50 keV
  - $^{14}$C expected rate: (10-100) c/s/100ton
  - Acquisition window: 16 $\mu$s;
  - 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 $E_{th}$
  $\rightarrow$ Spectral shape threshold: 100 keV $\rightarrow$ 50 keV
  $\rightarrow$ $^{14}$C rate: $(40 \pm 1)$ c/s/100ton

**$^{14}$C pile-ups**

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

- **Solution:** Generate ‘synthetic’ pile-ups:
  - Overlap artificially uncorrelated data with regular events
  $\rightarrow$ $^{14}$C pile-up rate: $(154 \pm 10)$ c/d/100ton
Solar pp neutrino rate measurement (August 2014)

Results and remarks:

- **Rate:**
  144 ± 13 (stat) ± 10 (sys) c/d/100 ton
  *(10σ exclusion of pp ν absence)*

- **Robustness of analysis:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Systematics:</th>
</tr>
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<tbody>
<tr>
<td>energy estimator</td>
<td>±7%</td>
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<tr>
<td>fit energy range</td>
<td></td>
</tr>
<tr>
<td>data selection</td>
<td></td>
</tr>
<tr>
<td>pile-up evaluation</td>
<td></td>
</tr>
<tr>
<td>fiducial mass</td>
<td>±2%</td>
</tr>
</tbody>
</table>

- **Check** of residual background

Measured recoil energy spectrum

Fit in (165-590) keV

Rates in [c/d/100 ton], except for $^{14}$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, $^8$B)
  - 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: \( \sim 7 \) TW
  - Mantle: 1-19 TW
    (differing for BSE-submodels)
  - Core: 0 TW
  → Probe with geo-\( \bar{\nu} \)’s:
    Expected rate in Borexino:
    \( \sim 10 \) c/yr/270 ton

Geophysics

- Earth heat: \( (47 \pm 2) \) TW,
  from 40000 deep bore-holes integrated over surface:
  \( \sim 0.09 \) W/m\(^2\)
  (\( \leftrightarrow \) Solar constant: 342 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-\( \bar{\nu} \)’)

W. Maneschg (MPIK Heidelberg)
Borexino: Solar And Geo neutrinos
HEP 2015, July 24, 2015
Main background components (after 2 s muon rejection cut)

- **Accidental coincidences**
- **Short-lived cosmogenic isotopes**: e.g. $\beta+n$ decay of $^9$Li-$^8$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**: $(907\pm44)$ ton year
- **77 $\bar{\nu}$ candidates** found:
  - Unbinned likelihood fit with fixed chondritic ratio Th/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~100)

* TNU = Terrestrial Neutrino Unit = 1 ev/yr/10$^{32}$ protons
Implications for terrestrial radiogenic heat production

**U/Th identification and local distribution:**

- **Geo-ν 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:
  \[ \frac{S(\text{Th})}{S(\text{U})} \approx 0.6, \] within \(1\sigma\) in agreement with chondritic model pred.
  \[ \frac{S(\text{Th})}{S(\text{U})} = 0.3 \]
- **Localisation of U/Th in crust/mantle:**
  1. Geological survey to deduce local crust contribution: \((9.7\pm1.3)\) TNU
  2. BSE models to deduce total crust contribution: \((23.4\pm2.8)\) TNU
  3. BSE models to deduce mantle contribution = total-crust: \((20.9^{+15.1}_{-10.3})\) TNU
    \[ \rightarrow \text{Null-hypothesis of mantle contribution rejected at 98\% C.L.} \]
- **Total radiogenic heat (Th+U+K):** \((33^{+28}_{-20})\) TW (BSE model dependent)
  \[ \rightarrow \text{In well agreement with terrestrial power output of (47±2) TW} \]
**Summary: Physics highlights and future goals**

**Plans for next years:**

- **Improved precision** of present results of solar pp, pep, $^7$Be and $^8$B $\nu$'s, as well as geo- and reactor-$\bar{\nu}$; ...

- **CNO $\nu$'s**: Last undetected of the 'Big Five': improve limit or try to quote a rate ('solar metallicity puzzle')

- **Sterile neutrino** search with $^{144}$Ce $\bar{\nu}$ and $^{51}$Cr $\nu$ sources (SOX)

- **Supernova $\nu/\bar{\nu}$'s**: BX member of SNEWS, keep high duty cycle of 95% (low E-threshold)
Further reading

**Solar neutrinos**
- **7Be rate @ ±17% precision**: C. Arpesella at al., First real time detection of 7Be solar neutrinos by Borexino, Phys. Lett. B 658 (2008) 101-108
- **7Be rate @ ±10% precision**: 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% 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 at 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 at al., Final results of Borexino Phase-I on low-energy solar-neutrino spectroscopy, Phys. Rev. D 89 (2014) 112007
- **pp rate**: G. Bellini at al., Neutrinos from the primary proton-proton fusion process in the Sun, Nature 512, August 28, 2014

**Geo-Antineutrinos**:
- **rate @ ±32% precision**: G. Bellini et al., Measurement of geo-neutrinos from 1353 days of Borexino, Phys. Lett. B 722 (2013) 295-300
- **rate @ ±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

![Graph showing the evolution of various solar properties over time. The graph plots the ratio of various solar properties (L/L_sun, T_eff/T_eff_sun, R/R_sun) against the age of the Sun (in Gyr). The x-axis represents the age of the Sun, ranging from 0 to 12 Gyr, and the y-axis represents the ratio of these properties relative to today's Sun. The lines show an increase in all parameters with age.]
Tensions in the SSM predictions

**Standard Solar Model (SSM)**

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

Inputs:
- Starting conditions: $p$, $T$, radius, $\rho$
- cross section factors,
- chemical abundance of heavier elem. $X_i$
  (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)

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

$\rightarrow 1/3 - 2/3$ of expected neutrinos missed
$\rightarrow$ Solved: neutrino oscillations in vac/matter

"Solar Neutrino Puzzle"
Tensions in the SSM 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: \( p, T, \text{radius}, \rho \)
- cross section factors,
- chemical abundance 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)

**Predictions / test of observables:**
- Radial density profile
- Sound speed profile
- Convection zone radius
- At any time: \( p, T, \text{radius}, \rho, \) photosphere luminosity
- Neutrino fluxes → neutrino luminosity
  → neutrino oscillations
  → \( pp; pep: \) +1%; +2%
  → \( 8B; 7Be: \) - (21-11)%; (10-5)%
  → CNO: - (44-21)%

"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): $6.03 \times (1 \pm 0.006) \times 10^{10} \text{ cm}^2 \text{ s}^{-1}$
  \[\rightarrow \text{mean values differ by 0.8% only}\]
- Measured: $(6.6 \pm 0.7) \times 10^{10} \text{ cm}^2 \text{ s}^{-1}$
  \[\rightarrow \text{agreement with both models, but no disentaglement of metallicity}\]
Interpretation II: test the luminosity constraint

**Target material (detector)**
- Cross-sections electron-neutrino

**Solar & nuclear physics**
- SSM: start/boundary conditions
  Among them: high/low metallicity

**Neutrino properties**
- Neutrino oscillations
- Oscillation effects in matter

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**Neutrino rate** $R_v$

**Neutrino flux** $\Phi_\nu$

**Nuclear physics**

**Neutrino luminosity** $L_\nu$

**Photon luminosity** $L_y$

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**Luminosity variability:**
- $O(10 \text{ yr})$: 22 yr solar cycle $\rightarrow$ 0.1%
- $O(10^4$-$10^5 \text{ yr})$: ? $\rightarrow$ BX measurement
- $O(4.6 \times 10^9 \text{ yr})$: SSM $\rightarrow$ young faint Sun:
  -25% less bright than today

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**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 $^7$Be neutrino rate

**Expectation:**
Earth eccentricity $\epsilon = 0.0167$ (maximum on January 3):
→ Perihelion-Aphelion flux difference of $\pm 7\%$
→ $^7$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:**
  
  $$ R = R_0 + e^{B_i t} + \bar{R} \left\{ 1 + 2\epsilon \cos \left( \frac{2\pi}{T} - \phi \right) \right\} $$

- **Results:**
  
  $$ T = 1.01 \pm 0.07; \quad \epsilon = 0.0398 \pm 0.0102 \rightarrow \text{Expected values are within } 2\sigma $$

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

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

  $\rightarrow$ Non-existence of annual modulation excluded at $\sim 3\sigma$
Main results:

- **Resolution** ($1\sigma$):
  - 2.2 MeV ($^{214}$Bi, $\gamma$): $(13\pm2)$ cm in x, y; $(14\pm2)$ cm in x, y
  - 0.25 MeV ($^{14}$C, endpoint): $(42\pm6)$ cm

- **Fiducial Volume cuts**: analysis-dependent:
  - Solar $^7$Be: $R<3.067$ m, $z<|1.67|$ m
  - Solar pep/CNO: $R<2.8$ m, $-2.4<m<2.2$ 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)

![Graphs showing calibration gamma sources data and Monte Carlo predictions.]

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

**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 $^7$Be neutrinos in sub-MeV region

- 40-50 neutrino signals/d/100 tons $\rightarrow 6 \times 10^{-9}$ Bq/kg
- Background requirements to the scintillator (less than 10 c/d/100 tons):
  - U: $10^{-9}$ Bq/kg $\rightarrow <0.8 \times 10^{-16}$ g/g (sec. eq.)
  - Th: $10^{-9}$ Bq/kg $\rightarrow <2.4 \times 10^{-16}$ 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)

<table>
<thead>
<tr>
<th>Contaminant</th>
<th>Source</th>
<th>Normal/Expected mass frac./flux/rate</th>
<th>Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{11}$C</td>
<td>cosmic in-situ $\mu$-ind.</td>
<td>$200/s/m^2$ (at sea level) $\sim 15$ c/d/100</td>
<td>$\sim 10^{-10}$ g/g</td>
</tr>
<tr>
<td>Ext. $\gamma$ (U,Th)</td>
<td>SSS</td>
<td>$\sim 10^{-16}$-10^{-15} g/g</td>
<td>$\sim 10^{-10}$ g/g</td>
</tr>
<tr>
<td>Ext. $\gamma$ (U,Th)</td>
<td>PMTs</td>
<td>$\sim 10^{-16}$-10^{-15} g/g</td>
<td>$\sim 10^{-8}$ g/g</td>
</tr>
<tr>
<td>Ext. $\gamma$ (U,Th)</td>
<td>PC buffer</td>
<td>$\sim 10^{-16}$-10^{-15} g/g</td>
<td>$\sim 10^{-15}$ g/g</td>
</tr>
<tr>
<td>$^{14}$C</td>
<td>Scintillator</td>
<td>$\sim 10^{-12}$ g/g</td>
<td>$10^{-18}$ g/g</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>Dust</td>
<td>$\sim 10^{-16}$-10^{-15} g/g</td>
<td>$&lt;10^{-16}$ g/g</td>
</tr>
<tr>
<td>$^{232}$Th</td>
<td>Dust</td>
<td>$\sim 10^{-16}$-10^{-15} g/g</td>
<td>$&lt;10^{-16}$ g/g</td>
</tr>
<tr>
<td>$^{222}$Rn</td>
<td>Emanation (air)</td>
<td>100 atoms/cm$^3$ (air)</td>
<td>$&lt;10^{-16}$ g/g</td>
</tr>
<tr>
<td>$^{210}$Po</td>
<td>Surface cont. (from $^{222}$Rn)</td>
<td>100 c/d/100t</td>
<td></td>
</tr>
<tr>
<td>$^{210}$Pb</td>
<td>Surface cont. (from $^{222}$Rn)</td>
<td>100 c/d/100t</td>
<td></td>
</tr>
<tr>
<td>$^{39}$Ar</td>
<td>air/nitrogen</td>
<td>$\sim 17$ mBq/m$^3$ (air)</td>
<td>$&lt;1$ c/d/100t</td>
</tr>
<tr>
<td>$^{85}$Kr</td>
<td>air/nitrogen</td>
<td>$\sim 1$ Bq/m$^3$ (air)</td>
<td>$&lt;1$ c/d/100t</td>
</tr>
</tbody>
</table>
Borexino background decomposition (2007-2009 data)

<table>
<thead>
<tr>
<th>Contaminant</th>
<th>Source</th>
<th>Normal/Expected conc./flux/rate</th>
<th>Required</th>
<th>Achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{11}\mu$ C</td>
<td>cosmic in-situ $\mu$-ind.</td>
<td>200/s/m$^2$ (at sea level) $\sim$15 c/d/100</td>
<td>$\sim10^{-10}$</td>
<td>$\sim10^{-10}$</td>
</tr>
<tr>
<td>Ext. $\gamma$ (U,Th)</td>
<td>SSS</td>
<td></td>
<td>$\sim10^{-10}$ g/g</td>
<td>$\sim10^{-10}$-10$^{-9}$ g/g</td>
</tr>
<tr>
<td>Ext. $\gamma$ (U,Th)</td>
<td>PMTs</td>
<td></td>
<td>$\sim10^{-8}$ g/g</td>
<td>$\sim10^{-10}$-10$^{-7}$ g/g</td>
</tr>
<tr>
<td>Ext. $\gamma$ (U,Th)</td>
<td>PC buffer</td>
<td>$\sim10^{-16}$-$10^{-15}$ g/g</td>
<td>$\sim10^{-15}$ g/g</td>
<td>$\sim27$ c/d/ton</td>
</tr>
<tr>
<td>$^{14}$C</td>
<td>Scintillator</td>
<td>$\sim10^{-12}$</td>
<td>$\sim10^{-18}$</td>
<td>$(2.7\pm0.1)\times10^{-18}$ g/g</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>Dust</td>
<td>$\sim10^{-16}$-$10^{-15}$ g/g</td>
<td>$&lt;10^{-16}$ g/g</td>
<td>$(1.6\pm0.1)\times10^{-17}$ g/g</td>
</tr>
<tr>
<td>$^{232}$Th</td>
<td>Dust</td>
<td>$\sim10^{-16}$-$10^{-15}$ g/g</td>
<td>$&lt;10^{-16}$ g/g</td>
<td>$(6.8\pm1.5)\times10^{-18}$ g/g</td>
</tr>
<tr>
<td>natK</td>
<td>Dust</td>
<td>$\sim10^{-14}$ g/g</td>
<td>$\sim10^{-14}$ g/g</td>
<td>Spectral fit: $\leq3\times10^{-16}$ g/g</td>
</tr>
<tr>
<td>$^{222}$Rn</td>
<td>Emanation</td>
<td>100 atoms/cm$^3$ (air)</td>
<td>$&lt;10^{-16}$ g/g</td>
<td>$\sim10^{-17}$ g/g</td>
</tr>
<tr>
<td>$^{210}$Po</td>
<td>Surface cont. (from $^{222}$Rn)</td>
<td></td>
<td>$\sim100$ c/d/100t</td>
<td>$\sim6000$ c/d/t (May 2007)</td>
</tr>
<tr>
<td>$^{210}$Pb</td>
<td>Surface cont. (from $^{222}$Rn)</td>
<td>$^{210}$Bi: $\sim1$ c/d/100t</td>
<td></td>
<td>$\sim1$ c/d/100t</td>
</tr>
<tr>
<td>$^{39}$Ar</td>
<td>air/nitrogen</td>
<td>$\sim17$ mBq/m$^3$ (air)</td>
<td>$&lt;1$ c/d/100t</td>
<td>(not in equil. with $^{210}$Po)</td>
</tr>
<tr>
<td>$^{85}$Kr</td>
<td>air/nitrogen</td>
<td>$\sim1$ Bq/m$^3$ (air)</td>
<td>$&lt;1$ c/d/100t</td>
<td>Spectral fit: $(25\pm5)$ c/d/100t</td>
</tr>
</tbody>
</table>

In terms of natural radioactivity: radiopurest environment ever measured!
Borexino purification plants

Full Infrastructure:


Water extraction plant: