Recent Borexino results and prospects for near future

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the Borexino Collaboration
Energy production in the sun

PP-chain
>99% energy production
5 $\nu$ species

CNO-cycle
<1% energy production
3 $\nu$ species
Why Borexino?
Why Borexino?

Borexino design goal: $^7$Be

Borexino design threshold $\sim 250$keV
The Borexino Detector

Neutrino electron scattering
\( \nu_e \rightarrow \nu_e \)

**Scintillator:**
270 + PC+PPO (1.4 g/l)

**Nylon vessels:**
(125 \( \mu \)m thick)
Inner: 4.25 m
Outer: 5.50 m (radon barrier)

**Stainless Steel Sphere:**
- 2212 PMTs
- \( \sim 1000 \) m\(^3\) buffer of pc +dmp (light quenched)

**Water Tank:**
\( \gamma \) and \( n \) shield
\( \mu \) water Č detector
208 PMTs in water
2100 m\(^3\)

**Carbon steel plates**

20 legs
Experimental site

120 Km from Rome

External Labs

Laboratori Nazionali del Gran Sasso

Assergi (AQ)
Italy
1400m of rock shielding
~3800 m.w.e.
Borexino data taking campaign

- May 2007
- May 2010

Preparation

Phase I

- (First) solar $^7$Be-$\nu$ measurement
- $^7$Be-$\nu$ day-night asymmetry
- Low-threshold $^8$B-$\nu$
- First pep-$\nu$ detection
- Best upper limit on CNO-$\nu$
- First geo-$\nu$ observation at $> 4\sigma$
- Muon seasonal variations
- Limits on rare processes

Purification

Phase II

- Measurement of pp-$\nu$ flux
- Measurement of CNO-$\nu$ flux
- Short-base $\nu$ oscillations: SOX

Neutrons and other cosmogenics
- $^7$Be-$\nu$ seasonal modulation
- Updated geo-$\nu$ flux
# Borexino backgrounds

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Typical</th>
<th>Required</th>
<th>Before purification</th>
<th>After purification</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{238}\text{U}$</td>
<td>$2 \cdot 10^{-5}$ (dust)</td>
<td>$\leq 10^{-16}$ g/g</td>
<td>$(5.3 \pm 0.5) \cdot 10^{-18}$ g/g</td>
<td>$&lt; 0.8 \cdot 10^{-19}$ g/g</td>
</tr>
<tr>
<td>$^{232}\text{Th}$</td>
<td>$2 \cdot 10^{-5}$ (dust)</td>
<td>$\leq 10^{-16}$ g/g</td>
<td>$(3.8 \pm 0.8) \cdot 10^{-18}$ g/g</td>
<td>$&lt; 1.0 \cdot 10^{-18}$ g/g</td>
</tr>
<tr>
<td>$^{14}\text{C}/^{12}\text{C}$</td>
<td>$10^{-12}$ (cosmogenic)</td>
<td>$\leq 10^{-18}$</td>
<td>$(2.69 \pm 0.06) \cdot 10^{-18}$ g/g</td>
<td>unchanged</td>
</tr>
<tr>
<td>$^{222}\text{Rn}$</td>
<td>100 atoms/cm$^3$ (air)</td>
<td>$\leq 10$ cpd/100t</td>
<td>$\sim 1$ cpd/100t</td>
<td>unchanged</td>
</tr>
<tr>
<td>$^{40}\text{K}$</td>
<td>$2 \cdot 10^{-6}$ (dust)</td>
<td>$\leq 10^{-18}$ g/g</td>
<td>$\leq 0.4 \cdot 10^{-18}$ g/g</td>
<td>unchanged</td>
</tr>
<tr>
<td>$^{85}\text{Kr}$</td>
<td>1 Bq/m$^3$ (air)</td>
<td>$\leq 1$ cpd/100 t</td>
<td>$(30 \pm 5)$ cpd/100 t</td>
<td>$\leq 5$ cpd/100 t</td>
</tr>
<tr>
<td>$^{39}\text{Ar}$</td>
<td>17 mBq/m$^3$ (air)</td>
<td>$\leq 1$ cpd/100 t</td>
<td>$&lt;&lt; ^{85}\text{Kr}$</td>
<td>$&lt;&lt; ^{85}\text{Kr}$</td>
</tr>
<tr>
<td>$^{210}\text{Po}$</td>
<td>not specified</td>
<td></td>
<td>$(\sim 80) \sim 20$ cpd/100 t</td>
<td>unchanged</td>
</tr>
<tr>
<td>$^{210}\text{Bi}$</td>
<td>not specified</td>
<td></td>
<td>$(\sim 20) \sim 70$ cpd/100 t</td>
<td>$(20 \pm 5)$ cpd/100 t</td>
</tr>
</tbody>
</table>
Borexino calibration

2008-2011: 4 internal + 1 external calibration campaigns

Energy scale uncertainty in the range $0.2 \div 2$ MeV is better than $1.5\%$

Using 184 points of Rn calibration data, the Fiducial Volume uncertainty was taken to $-1.3\% \pm 0.5\%$
$^7$Be neutrino flux and $A_{DN}$

$46.0 \pm 1.5 \text{(stat)}^{+1.5}_{-1.6} \text{(syst)} / d / 100t$

for the first time the experimental error (4.8%) is smaller than theoretical error (7%)

$\phi_{Be} = (3.10 \pm 0.15) \times 10^9 \text{ cm}^{-2}\text{s}^{-1}$

$P_{ee} = 0.51 \pm 0.07$ at 0.862 MeV

$A_{DN} = \frac{N - D}{(N + D)/2} = 0.001 \pm 0.012 \text{(stat)} \pm 0.007 \text{(sys)}$

Then solar neutrino results with Borexino can isolate the LMA region without the Kamland antineutrino data


$^8$B flux at 3MeV

<table>
<thead>
<tr>
<th>Energy [MeV]</th>
<th>Rate $[c/d/100 \text{ t}]$</th>
<th>$\Phi_{\text{exp}}^{\text{ES}} [10^6 \text{ cm}^{-2}\text{s}^{-1}]$</th>
<th>$\Phi_{\text{exp}}^{\text{ES}} / \Phi_{\text{th}}^{\text{ES}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0–16.3</td>
<td>$0.22 \pm 0.04 \pm 0.01$</td>
<td>$2.4 \pm 0.4 \pm 0.1$</td>
<td>$0.88 \pm 0.19$</td>
</tr>
<tr>
<td>5.0–16.3</td>
<td>$0.13 \pm 0.02 \pm 0.01$</td>
<td>$2.7 \pm 0.4 \pm 0.2$</td>
<td>$1.08 \pm 0.23$</td>
</tr>
</tbody>
</table>
pep flux and CNO limits

\[ R = (3.1 \pm 0.6_{\text{stat}} \pm 0.3_{\text{sys}}) \text{ cpd/100 t} \]

\[ \Phi^{\text{LMA}}_{\text{pep}} = (1.6 \pm 0.3) \times 10^8 \text{ cm}^{-2} \text{ s}^{-1} \]

\[ P_{ee} = 0.62 \pm 0.17 \text{ at 1.44 MeV} \]

\[ R < 7.1 \text{ cpd/100 t (95 \% C.L.)} \]

\[ \Phi^{\text{LMA}}_{\text{CNO}} < 7.7 \times 10^8 \text{ cm}^{-2} \text{ s}^{-1} \text{ (95 \% C.L.)} \]
pp neutrino analysis

Neutrino energy: < 420keV
Electron recoil energy: < 264keV
This analysis threshold: 165keV
(cmp. design thresh. 250KeV, radiochem. exp. 233keV)
14C background issues

Pure 14C β spectrum

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

- Solution for 14C close to \( E_{th} \): Trigger with two random events: 2. event (14C) unaffected by \( E_{th} \)
  → Spectral shape threshold: 100 keV → 50 keV
  → 14C rate: \( (40\pm1) \text{ c/s/100ton} \)

14C pile-ups

- Pile-up problem:
  - 14C overlap with PMT dark rate, 14C, 210Po
  → 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
  → 14C pile-up rate: \( (154\pm10) \text{ c/d/100ton} \)
pp neutrino results

Rate = $144 \pm 13\,(\text{stat}) \pm 10\,(\text{sys})$ c/d/100ton

Null hypothesis rejection: $10\sigma$

Expected: $131 \pm 2$ c/d/100ton

Interpretations:
1. If you believe SSM:
   - confirms MSW-LMA
2. If you believe MSW-LMA:
   - confirms SSM
3. If you believe both:
   - the sun is stable over $10^5$ time span

\begin{tabular}{|l|l|}
\hline
Parameter & Systematics: \\
\hline
energy estimator & $\pm 7\%$ \\
fit energy range & \\
data selection & \\
pile-up evaluation & \\
\hline
fiducial mass & $\pm 2\%$ \\
\hline
\end{tabular}
$P_{\text{ee}}$ after Borexino

In the transition region:
Is there room for new physics?

Still missing: CNO neutrinos

Two approaches to transition region:
1. Reduce error on pep (and $^7\text{Be}$) flux
2. Lower threshold on $^8\text{B}$
   (upturn not yet observed by SNO-LETA)

Borexino will work on both sides
Geo-neutrinos

\[ \Phi_{\bar{\nu}} \sim 10^6 \text{cm}^{-2}\text{s}^{-1} \]

<table>
<thead>
<tr>
<th>Decay</th>
<th>(T_{1/2}) [10^9 yr]</th>
<th>(E_{\text{max}}) [MeV]</th>
<th>(Q) [MeV]</th>
<th>(\varepsilon_{\bar{\nu}}) [kg^{-1}s^{-1}]</th>
<th>(\varepsilon_H) [W/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{238}\text{U} \rightarrow ^{206}\text{Pb} + 8, ^{4}\text{He} + 6, e + 6, \bar{\nu})</td>
<td>4.47</td>
<td>3.26</td>
<td>51.7</td>
<td>(7.46 \times 10^7)</td>
<td>(0.95 \times 10^{-4})</td>
</tr>
<tr>
<td>(^{232}\text{Th} \rightarrow ^{208}\text{Pb} + 6, ^{4}\text{He} + 4, e + 4, \bar{\nu})</td>
<td>14.0</td>
<td>2.25</td>
<td>42.7</td>
<td>(1.62 \times 10^7)</td>
<td>(0.27 \times 10^{-4})</td>
</tr>
<tr>
<td>(^{40}\text{K} \rightarrow ^{40}\text{Ca} + e + \bar{\nu} \text{ (89%)})</td>
<td>1.28</td>
<td>1.311</td>
<td>1.311</td>
<td>(2.32 \times 10^8)</td>
<td>(0.22 \times 10^{-4})</td>
</tr>
</tbody>
</table>

Neutron inverse beta decay threshold

E > 1.8MeV

"delayed" ~250 \(\mu\) s, ~70 cm

\(\gamma\) (2.2 MeV)

\(\gamma\) (511 keV)

K is not visible in liquid scintillator
Th/U ratio is "fixed" to 3.9 by analysis of chondrites
Geo-neutrinos: event selection

- $Q_{\text{prompt}} > 480 \text{ p.e.}$
- $Q_{\text{delayed}} [860,1300] \text{ p.e.}$
- $\Delta R \ (\text{prompt-delayed}) < 1 \text{ m}$
- $\Delta t \ (\text{prompt-delayed}) [20-1280] \mu s$
- $G_{\text{delayed}} < 0.015 \ (\text{must be "$\beta$-like"})$

Large Fiducial Volume:
- distance from the vessel > 25 cm

77 golden coincidences
907$\pm$44 ton x year

$S_{\text{react}} = 96.6 \pm 15.9 \text{ TNU}$

Expected = $87 \pm 4 \text{ TNU} \ (\text{after oscillations})$

$N_{\text{geo}} = 23.7 \pm 6.1 \text{ events}$

$S_{\text{geo}} = 43.5 \pm 11.1 \text{ TNU}$

1 TNU = 1 event / $10^{32}$ protons / year
**Geo-neutrinos: implications**

\[ S_{\text{Expected}} = S_{\text{Local}} + S_{\text{Rest Of Crust}} + S_{\text{Mantle}} \]

- **43.5 ± 11.1** (data)
- **9.7 ± 1.3** (geological survey)
- **13.7 ± 2.5** (model)

**20.9 ± 15.1**

No mantle contribution excluded at 98% C.L.

Compatible with different BSE flavors and mantle elemental distributions.

**Neutrino flux [TNU]** vs. **Heat [TW]**
SOX concept

If reactor anomaly is interpreted in terms of oscillations into light sterile neutrinos it points to $L/E \sim 1\text{m/MeV}$

in Borexino with $\sim 1\text{MeV}$ source: resolution $\sim 15\text{cm} < L < \text{detector size} \sim 10\text{m}$

Uninvasive deployment: no work on the detector no risk of contamination does not terminate the solar run.
$^{144}$Ce-Pr antineutrino generator up to 3MeV
Inverse Beta Decay detection tuned by geo-neutrino analysis
“long” half life: 285d
Activity: $\sim 100$kCi, $> 10^{13}$ anti-nu /s
Must be determined at 1% precision: two calorimeters
SOX $^{144}\text{Ce}-^{144}\text{Pr}$ run

- Source can be produced out of spent nuclear fuel in Mayak (Ru).
- Larger anti-nu cross section.
- Problem with 2.1 MeV gamma: needs tungsten shielding.

$\Delta m^2_{41} = 2 \text{eV}^2 \Rightarrow$ oscillations within detector

$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2(2\theta_{ee}) \sin^2 \frac{\Delta m^2_{41} L}{4E}$

[Cribier et al., PRL 107, 201801 (2011)]

tentative schedule:
late 2016
run for 1.5 year
SOX: sensitivity

- shape-only
- rate-only
- rate + shape

$144\text{Ce} - 100\text{kCi} - 1.5\text{y} - 4.25\text{m}, 95\% \text{ CL}$

- rate only, $\sigma_h = 1\%$
- shape only, $\sigma_h = \text{inf.}$
- rate + shape, $\sigma_h = 1\%$

- anomalies, 95\% CL

- anomalies, 99\% CL

- Best Fit, PRD 88 073008 (2013)
Conclusions and outlook

✔ Borexino is taking data regularly since 2007:

✔ The *background levels are unprecedented* and still improving.

✔ Phase-I brought fundamental results over a broad range of solar neutrinos (*⁷Be, ⁸B, pep, CNO limits*) and geo-nu.

✔ We are now in Phase-II since 2012:

✔ **pp-neutrino flux** accomplished

  ✔ First direct observation of neutrinos from the primary proton-proton fusion reaction taking place in the Sun's core.

✔ upcoming: **CNO flux measurement** (or stronger limits): 2016

  ✔ first confirmation of fusion process that powers most stars.

  ✔ it could resolve the solar “metallicity problem”.

✔ Also pep, ⁷Be, ⁸B and geo-neutrino more stringent measurements.

✔ **SOX** project will test indications for **sterile neutrinos** with a ¹⁴⁴Ce-Pr source 2017
# Geo-nu systematics

<table>
<thead>
<tr>
<th>Source</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^9\text{Li}-^8\text{He}$</td>
<td>$0.194^{+0.125}_{-0.089}$</td>
</tr>
<tr>
<td>Accidental coincidences</td>
<td>$0.221\pm0.004$</td>
</tr>
<tr>
<td>Time correlated</td>
<td>$0.035^{+0.029}_{-0.028}$</td>
</tr>
<tr>
<td>$(\alpha,n)$ in scintillator</td>
<td>$0.165\pm0.010$</td>
</tr>
<tr>
<td>$(\alpha,n)$ in buffer</td>
<td>$&lt;0.51$</td>
</tr>
<tr>
<td>Fast n’s ($\mu$ in WT)</td>
<td>$&lt;0.01$</td>
</tr>
<tr>
<td>Fast n’s ($\mu$ in rock)</td>
<td>$&lt;0.43$</td>
</tr>
<tr>
<td>Untagged muons</td>
<td>$0.12\pm0.01$</td>
</tr>
<tr>
<td>Fission in PMTs</td>
<td>$0.032\pm0.003$</td>
</tr>
<tr>
<td>$^{214}\text{Bi}-^{214}\text{Po}$</td>
<td>$0.009\pm0.013$</td>
</tr>
<tr>
<td>Total</td>
<td>$0.78^{+0.13}_{-0.10}$</td>
</tr>
<tr>
<td></td>
<td>$&lt;0.65$ (combined)</td>
</tr>
</tbody>
</table>