Solar neutrino and terrestrial antineutrino fluxes measured with Borexino at LNGS

Sandra Zavatarelli
INFN Genova (Italy)
(on behalf of the Borexino Collaboration)
A large volume ultrapure scintillation detector like Borexino can help to answer to key questions in multiple disciplines!!

• **Borexino:**
  • Experimental techniques and the detector

• **Neutrino astronomy results:**
  • What’s cool in the solar neutrino physics..
  • $^7\text{Be}$ $\nu$ and D/N asymmetry;
  • $^8\text{B}$ $\nu$ and the lowest threshold flux measurement (3 MeV);
  • $\nu_e$ survival probability in the transition region.

• **(Anti)-Neutrino geology:**
  • The first observation of geo-$\nu$ in Borexino (at 4.2 $\sigma$);
  • Limits on geo-reactor power in the Earth core;
  • The anti-$\nu$ survival probability on a baseline of 1000 km.

• **Particle physics:**
  • New limits on PEP forbidden transitions.

• **Summary and outlook**
How do we detect $\nu$ / anti-$\nu$ in BX??

Borexino is an ultrapure organic scintillator detector made by 278 tons of PC+PPO

$\nu_x$ are detected through their scattering off electrons:

$$\nu_x + e^- \rightarrow \nu_x + e^- \quad \sigma_{CC} = 9.2 \times 10^{-45} \, E_{\nu}(\text{MeV}) \, \text{cm}^2 \quad \sigma_{CC} \sim 6 \, \sigma_{NC}$$

anti-$\nu_e$ are detected through the inverse beta decay on protons:

$$\nu_e + p \rightarrow n + e^+ \quad \checkmark E_{\text{thr}} = 1.8 \, \text{MeV}$$
$$\checkmark E_{e^+} = E_{\nu} - 0.78 \, \text{MeV}$$
$$\checkmark \text{Delayed coincidence} : \tau_n \sim 256 \, \mu\text{s in PC}$$

Particle detection via the emitted scintillation light:

$\checkmark$ Very low energy threshold (40 keV);
$\checkmark$ Good energy and spatial resolution (L.Y.~500 p.e./MeV) ...but...
$\checkmark$ No directional information
$\checkmark$ Background rejection critical: the $\nu_x$ induced events can’t be distinguished from the other $\beta$ events due to natural radioactivity

A ultrapure detector is mandatory....
The BOREXINO detector

- PMT total collected charge -> light yield (p.e) -> event energy
- Photon arrival times on each PMT -> event position

**ENERGY RESOLUTION**
- 10% @ 200 keV
- 8% @ 400 keV
- 5% @ 1 MeV

**SPATIAL RESOLUTION**
- 35 cm @ 200 keV
- 16 cm @ 500 keV

Extreme radiopurity of scintillator = 15 years of work !!!

- **External backgrounds:** underground lab., principle of progressive shieldings
- **Internal backgrounds:** accurate material selections and clean manipulations, liquid handling plants in situ (WE, nitrogen stripping, distillation)

**Most important backgrounds:**
- $^{238}\text{U} \sim 2 \times 10^{17}$ g/g, $^{232}\text{Th} \sim 5 \times 10^{18}$ g/g, $^{210}\text{Po} \sim 10$ c/d/t, $^{210}\text{Bi} \sim 15$ c/d/100t, $^{85}\text{Kr} \sim 30$ c/d/100t

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ICHEP 2010, Paris
Neutrino astrophysics: probing our knowledge of the Sun

Importance of single solar-ν spectrum component precise flux measurements:

✓ Solve the high/Low metallicity solar model controversy
✓ Confirm MSW-LMA or exploit possible traces of non-standard neutrino-matter interaction / presence of mass varying ν’s
✓ Fix the amount of solar energy produced via CNO cycle
Neutrino astrophysics: probing our knowledge of the Sun

**Serenelli arXiv:0910.3690**

<table>
<thead>
<tr>
<th></th>
<th>GS98</th>
<th>AGS05</th>
</tr>
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<tbody>
<tr>
<td>pp</td>
<td>$5.97 \times 10^{10}$</td>
<td>$6.04 \times 10^{10}$</td>
</tr>
<tr>
<td>pep</td>
<td>$1.41 \times 10^{8}$</td>
<td>$1.44 \times 10^{8}$</td>
</tr>
<tr>
<td>hep</td>
<td>$7.91 \times 10^{3}$</td>
<td>$8.24 \times 10^{3}$</td>
</tr>
<tr>
<td>7Be</td>
<td>$5.08 \times 10^{9}$</td>
<td>$4.54 \times 10^{9}$</td>
</tr>
<tr>
<td>8B</td>
<td>$5.88 \times 10^{6}$</td>
<td>$4.66 \times 10^{6}$</td>
</tr>
<tr>
<td>13N</td>
<td>$2.82 \times 10^{8}$</td>
<td>$1.85 \times 10^{8}$</td>
</tr>
<tr>
<td>15O</td>
<td>$2.09 \times 10^{8}$</td>
<td>$1.29 \times 10^{8}$</td>
</tr>
<tr>
<td>17F</td>
<td>$5.65 \times 10^{6}$</td>
<td>$3.14 \times 10^{6}$</td>
</tr>
</tbody>
</table>

Flux: $cm^{-2}s^{-1}$ (BPS09)

- Solve the high/Low metallicity solar model controversy
- Confirm MSW-LMA or exploit possible traces of non-standard neutrino-matter interaction / presence of mass varying $\nu$’s
- Fix the amount of solar energy produced via CNO cycle
Neutrino astrophysics: probing our knowledge of the Sun

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Neutrino astrophysics: the measure of the $^7$Be solar neutrino flux

1\textsuperscript{st} result (30\% precision) - Phys.Lett.B (2007): $^7$Be Rate = $47\pm7_{\text{stat}}^{+12}_{\text{syst}}$ cpd/100t (47.4 days)

2\textsuperscript{nd} result (10\% precision) - PRL 101 (2008): $^7$Be Rate = $49\pm3_{\text{stat}}^{+4}_{\text{syst}}$ cpd/100 tons (192 days)

3\textsuperscript{rd} result: now a 5\% precision measurement and the seasonal variation study are possible!!!

- Detector calibrated
- Monte Carlo fitting procedure implemented
- $^{85}$Kr content known at 16\% level (delayed coincidence)
- 3 years of statistics!!!

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Neutrino astrophysics:

$^7$Be solar neutrino flux day/night asymmetry

- LMA solution to SNP -> no asymmetry
- MaVaN models -> possible asymmetry

$$ADN = \frac{N - D}{(N + D)/2}$$

Borexino result: $ADN = 0.007 \pm 0.073$ (stat)

Day spectrum: 387.5 d
Night spectrum: 401.57 d
Stat. Error: 2.3 cpd/100t

MaVaN model rejected at more than 3\sigma

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Neutrino astrophysics: the measure of the $^8$B solar neutrino flux


**First measurement of $^8$B-ν:**

- with liquid scintillator
- with the lowest energy threshold for a spectral measurement (3 MeV)

<table>
<thead>
<tr>
<th>Background</th>
<th>Rate [$10^{-4}$ cpd/100 t]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$&gt;3$ MeV</td>
</tr>
<tr>
<td><strong>Muons</strong></td>
<td>4.5±0.9</td>
</tr>
<tr>
<td><strong>Neutrons</strong></td>
<td>0.86±0.01</td>
</tr>
<tr>
<td><strong>External background</strong></td>
<td>64±2</td>
</tr>
<tr>
<td><strong>Fast cosmogenic</strong></td>
<td>17±2</td>
</tr>
<tr>
<td>$^{10}$C</td>
<td>22±2</td>
</tr>
<tr>
<td>$^{214}$Bi</td>
<td>1.1±0.4</td>
</tr>
<tr>
<td>$^{208}$Tl</td>
<td>840±20</td>
</tr>
<tr>
<td>$^{11}$Be</td>
<td>320±60</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>1270±63</td>
</tr>
</tbody>
</table>

Two analysis threshold: 3 MeV and 5 MeV

Expected signal rate ~ 0.25 cpd/100t

S/B ratio ~ 1/6000

The effect of analysis cuts

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Neutrino astrophysics: the $^8$B-$\nu$ final spectrum compared with models and other results

**Final spectrum (exp.: 97 tons y)**

**Comparison with solar models**

**$^8$B solar $\nu$ flux measurements via elastic scattering**

Threshold is defined @ 100% trigger efficiency

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Year</th>
<th>Energy [MeV]</th>
<th>$\Phi_{\text{exp}}$ ($10^6$ cm$^{-2}$s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BX</td>
<td>2010</td>
<td>3 MeV</td>
<td></td>
</tr>
<tr>
<td>BX</td>
<td>2010</td>
<td>5 MeV</td>
<td></td>
</tr>
<tr>
<td>SK-I</td>
<td>2003</td>
<td>5 MeV</td>
<td></td>
</tr>
<tr>
<td>SK-I</td>
<td>2008</td>
<td>7 MeV</td>
<td></td>
</tr>
<tr>
<td>SNO</td>
<td>2005</td>
<td>5.5 MeV</td>
<td></td>
</tr>
<tr>
<td>SNO</td>
<td>2007</td>
<td>7 MeV</td>
<td></td>
</tr>
<tr>
<td>SNO SaltP</td>
<td>2008</td>
<td>6 MeV</td>
<td></td>
</tr>
<tr>
<td>PropC</td>
<td>2008</td>
<td>6 MeV</td>
<td></td>
</tr>
</tbody>
</table>

**Borexino**

<table>
<thead>
<tr>
<th>Energy Range</th>
<th>Rate [cpd/100 t]</th>
<th>$\Phi_{\text{exp}}$ ($10^6$ cm$^{-2}$s$^{-1}$)</th>
<th>$\Phi_{\text{exp}}/\Phi_{\text{th}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0–16.3 MeV</td>
<td>0.22±0.04±0.01</td>
<td>2.4±0.4±0.1</td>
<td>0.88±0.19</td>
</tr>
<tr>
<td>5.0–16.3 MeV</td>
<td>0.13±0.02±0.01</td>
<td>2.7±0.4±0.2</td>
<td>1.08±0.23</td>
</tr>
</tbody>
</table>
Neutrino astrophysics: testing the LMA solution to the solar neutrino problem

- Borexino is the first experiment able to investigate simultaneously, in real time, the vacuum and matter regimes of oscillation

**Solar $\nu_e$ survival probability in vacuum-matter transition**

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**Before Borexino**

7Be $\nu$: $P_{ee} = (0.56 \pm 0.10)$

8B $\nu$: $\overline{P}_{ee} = (0.29 \pm 0.10)$

Distance = 1.9 $\sigma$

- CNO, pep and pp $\nu$-flux measurement: possible in case of positive result of running purifications

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Anti-Neutrino geology: Geo-ν a unique direct probe of the Earth interior

The Earth shines in anti-ν (Φ_ν ~ 10^6 cm^-2 s^-1)

\[
\begin{align*}
{}^{238}\text{U} & \rightarrow {}^{206}\text{Pb} + 8\ \alpha + 8\ \text{e}^- + 6\ \overline{\text{ν}_e} + 51.7\ \text{MeV} \\
{}^{232}\text{Th} & \rightarrow {}^{208}\text{Pb} + 6\ \alpha + 4\ \text{e}^- + 4\ \overline{\text{ν}_e} + 42.8\ \text{MeV} \\
{}^{40}\text{K} & \rightarrow {}^{40}\text{Ca} + \text{e}^- + 1\ \overline{\text{ν}_e} + 1.32\ \text{MeV}
\end{align*}
\]

✓ Now the existing large mass scintillation detectors (Borexino, Kamland) made their detection feasible!!!

✓ Released heat and anti-neutrinos flux in a well fixed ratio!

Open questions:
- What is radiogenic contribution to the Earth energy budget?
- What is the distribution of the radiogenic elements?
  • How much in the crust and how much in the mantle?
  • Core composition: energy source driving the geo-dynamo? ^{40}\text{K}? Geo-reactor (Herndon 2001)?
- Are the standard geochemical models (BSE) correct?
Models based on:
- Data on crustal thickness and composition
- Bulk Silicate Earth composition hypothesis (BSE)
- Chemical behavior of elements (U/Th/K = refractory-lithophile)

Flux not homogeneous!! Strong contribution from local geology.....

Need of multi-site measurements!!
- Continental sites (Borexino, Kamland, SNO+...)
- Oceanic site (Hanohano???)

Borexino:
✓ Low intrinsic radioactivity;
✓ Far from reactor power plants;
✓ Underground site: $\Phi_{\mu}$ reduced by $\sim 10^6$. 
Geo-ν: the signature in Borexino

Prompt:
ν + p → n + e⁺

$E_{\text{thr}} = 1.8$ MeV

Minimum det. energy: 2 x 511 keV

Expected rate:
2.5 cp/100 t

Delayed (τ~256 µs):
n + p → d + γ

Detected energy: 2.2 MeV

Energy window of observation:
NW: 1-2.6 MeV

Geo-ν energy spectrum

Expected positron energy spectrum in BX

Geo-ν window (GNW)

Reactor-ν window (RNW)

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Geo-ν: the background in BX

Geo-ν expected signal (BSE) = 2.5 cpd/100 t

Reactor antineutrinos
- Overall rate: 5.0 ± 0.3 cpd/100 t
- Rate in the GNW: 2.0 ±0.1 cpd/100 t

We are in contact with IAEA and EDF:
- Thermal powers for each European reactors are known on a monthly base;
- Expected signal @ LNGS evaluated with a dedicated code (sys. uncertainty: 5.4%)

Max. signal during winter

Cosmogenic/enviromental background
- Overall rate: 0.14 ± 0.02 cpd/100 t
- Rate in the GNW: 0.12 ±0.01 cpd/100 t

Muon correlated events
- Cosmogenic $^9$Li and $^8$He decay via $\beta$-n
  - $\tau \sim$ 150 ms
  - 2 s detector veto after scintillator muons
  - Residual background: 0.03±0.02 cpd/100 t

Radiogenic $^{13}$C($\alpha$,n)$^{16}$O
- $^{210}$Po a emitter: 12 cpd/100 t
- $^{13}$C low abundance: $^{13}$C/$^{12}$C~1.1%
- Background: 0.014±0.001 cpd/100 t

Random coincidences
- Searching for events in a window of 2 ms-2 s:
  - 0.080 ±0.001 cpd/100t
- Signal(BSE)/(non anti-ν Background) ~ 21

Signal (BSE)/(Reactor background) ~ 1.25
In the GNW

In the GNW: Signal(BSE)/(non anti-ν Background) ~ 21

Geo-ν: the background in BX

Geo-ν expected signal (BSE) = 2.5 cpd/100 t
Geo-ν: the selected events


21 selected antinu candidates in 252.6 tons y

Selection cuts – ε (with MC): 0.85 ± 0.01

- Light yield prompt event > 410 p.e.
- 700 p.e. < light yield delayed event < 1250 p.e.
- ΔR < 1m
- 20 µs < Δt < 1280 µs
- \( R_{IV} - R_{prompt} > 0.25 \) m

Event time distribution

Events radial distribution (prompt)

Light Yield of prompt event [p.e.]

Counts/bin

geo-ν window
reactor-ν window

Ichem 2010, Paris
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Geo-ν: the observation of the geo-ν signal


Unbinned maximal likelihood analysis

- Borexino data
- best-fit
- reactors ν_e
- contribution from geo-ν_e
- background

Our best estimates are:

\[ N_{geo} = 9.9^{+4.1+14.6}_{-3.4-8.2} \] @ 99.73% C.L

\[ N_{react} = 10.7^{+4.3+15.8}_{-3.4-8.0} \] @ 68.3% C.L

Background in the geo-ν energy window:

0.31 ± 0.05

- By studying the profile of the likelihood respect to \( N_{geo} \):

Null geo-ν hypothesis rejected at 4.2 \( \sigma \)

Geo-ν (U+Th) flux \([10^6 \text{ cm}^{-2} \text{ s}^{-1}]\)

<table>
<thead>
<tr>
<th>Source</th>
<th>Flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>Borexino</td>
<td>7.2 ±2.9</td>
</tr>
<tr>
<td>BSE (Mant.2004)</td>
<td>4.6 ±0.5</td>
</tr>
<tr>
<td>Max. rad. Earth</td>
<td>7.2</td>
</tr>
<tr>
<td>Min. rad. Earth</td>
<td>2.9</td>
</tr>
</tbody>
</table>

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Geo-ν: future BX results!

- Difficult to constrain with enough precision by a single exp. (if detector size ≤ kton)
- Better results through combined analysis:

\[ \frac{U}{Th} \] ratio free:

- 4 times present statistics
- Event rate as measured

Precision in the total flux:

- \( 6\sigma \)
- Max radiogenic
- BSE
- Min radiogenic

Precision \( (\%) \):

- Measure time (y)

- \( R(Th+U)/TNB \)
- \( Th/U \)

Fogli et al arXiv 1006.1113

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The detection of the European reactor anti-ν

\[ P_{ee}(E_\nu, L) \approx 1 - \sin^2(2\theta_{12}) \sin^2 \left( \frac{1.27\Delta m^2_{12}[eV^2]L[m]}{E_\nu} \right) \]

\[ \Delta m^2_{12} = 7.65 \cdot 10^{-5} eV^2 \]
\[ \sin^2 \theta_{12} = 0.304 \]

- 6 events observed in the RNW
- 16.3 ± 1.1 events expected (no osc.)

- The non oscillation hypothesis is excluded at 99.60 C.L.
- Geo-reactor power in the Earth core < 3TW @ 95% C.L.

ICHEP 2010, Paris

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Particle physics: test of the Pauli Exclusion Principle

- Search for $\gamma,n,p,\beta$ emitted in non-Paulian transitions on $^{12}\text{C}$ from $^{1}\text{P}_{3/2}$–shell nucleons to the already filled $^{1}\text{S}_{1/2}$ shell

<table>
<thead>
<tr>
<th>Channel</th>
<th>$Q$, MeV</th>
<th>$E$, MeV</th>
<th>E.M.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{12}\text{C}\rightarrow^{12}\text{C}^{\text{NP}} + \gamma$</td>
<td>16.4±19.4</td>
<td>16.4±19.4</td>
<td>E.M.</td>
</tr>
<tr>
<td>$^{12}\text{C}\rightarrow^{11}\text{B}^{\text{NP}} + p$</td>
<td>5.0±9.0</td>
<td>4.6±8.3</td>
<td>Strong</td>
</tr>
<tr>
<td>$^{12}\text{C}\rightarrow^{11}\text{C}^{\text{NP}} + n$</td>
<td>3.5±7.9</td>
<td>3.2±7.3</td>
<td></td>
</tr>
<tr>
<td>$^{12}\text{C}\rightarrow^{8}\text{Be}^{\text{NP}} + \alpha$</td>
<td>3.0±7.0</td>
<td>0.07±0.25</td>
<td></td>
</tr>
<tr>
<td>$^{12}\text{C}\rightarrow^{12}\text{N}^{\text{NP}} + e^+ + \nu$</td>
<td>18.9±2</td>
<td>0.0±18.9</td>
<td>Weak</td>
</tr>
<tr>
<td>$^{12}\text{C}\rightarrow^{12}\text{B}^{\text{NP}} + e^+ + \nu$</td>
<td>17.8±2</td>
<td>0.0±17.8</td>
<td></td>
</tr>
</tbody>
</table>

Examples of expected signals:

Measured spectrum

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The Borexino results are 3-4 orders of magnitude stronger than CTF ones.

Limits for NP transitions in $^{12}$C with $p$-, $n$-, $\beta^-$ emissions are the best to date.
What’s next?

✓ Neutrino astrophysics
  • Precise measurement of $^7$Be $\nu$ flux and its seasonal variation
    – 3 years of statistics;
    – Fiducial volume and energy response fixed by calibrations;
    – MC fitting procedure implemented;
    – $^{85}$Kr constrained by delayed coincidence measurement;
      Scintillator purification: $^{85}$Kr effectively removed by nitrogen stripping.
  • More precise measurement of the oscillation probability in the transition region:
    – Fiducial volume and energy response fixed by calibrations;
    – More statistics (measure time + increase of FV mass);
    – $^7$Be at 5% + 4 y of statistics $\rightarrow$ distance between $^7$Be and $^8$B $P_{ee}$ at more than 3σ.
  • CNO and pep-neutrino flux measurements:
    – Cosmogenic $^{11}$C tagging already improved;
    – $^{210}$Bi content could be reduced through PC purification.

✓ Anti-Neutrino geology
  • Error on fluxes decreased down to 15% in 6 y;
  • Test of various existing Earth models, evidence of contribution for the mantle;
  • Constrains to U/Th ratio (combined analysis).

✓ Neutrino properties and particle physics
  • Coming very soon limits on solar anti-$\nu$ fluxes, $\nu \rightarrow \bar{\nu}$ conversion in the Sun, $\mu_\nu$, $\mu_{\bar{\nu}}$. 

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THANK YOU!!!
Borexino has joined the SNEW community

**Neutrino Spectrum from a Standard SN @ 10kpc**

Detection channel | N events
--- | ---
ES ($E_\nu > 0.25\, \text{MeV}$) | 5
Electron anti-neutrinos ($E_\nu > 1.8\, \text{MeV}$) | 78
$\nu$-p ES ($E_\nu > 0.25\, \text{MeV}$) | 52
$^{12}\text{C}(\nu,\nu)^{12}\text{C}^*$ ($E_\gamma = 15.1\, \text{MeV}$) | 18
$^{12}\text{C}(\text{anti-}\nu,e^+)^{12}\text{B}$ ($E_{\text{anti-}\nu} > 14.3\, \text{MeV}$) | 3
$^{12}\text{C}(\nu,e^-)^{12}\text{N}$ ($E_\nu > 17.3\, \text{MeV}$) | 9
$\delta m^2 = 7.58 \times 10^{-5} \text{ eV}^2$

$\sin^2 2\theta_{12} = 0.87$

light yield = 500 p.e./MeV
$^{210}$Po background

May 13th, 2007 - End October 2008

- $^{210}$Po not in equilibrium
- Decay time: about 200 days
- $\alpha$ decay: visible energy in the scintillator 0.4 MeV electron equivalent
- Very useful to study the energy resolution and the light yield stability
Constraints on pp & CNO after the $^7$Be flux

• Combining the results obtained by Borexino on $^7$Be flux with those obtained by other experiments we can constrain the fluxes of pp and CNO $\nu_e$.

• The measured rate by Chlorine and Gallium experiments $R_k$:

\[ R_k = \sum_{i,k} f_i R_{i,k} P_{ee}^{i,k} \]

- $R_{i,k}$ and $P_{ee}^{i,k}$ are calculated in the hypothesis of high-Z SSM and MSW LMA, $f_{8B} = 0.87 \pm 0.07$, measured by SNO and SuperK.
- $f_{7Be} = 1.02 \pm 0.10$ is given by Borexino results.

$\chi^2$ based analysis with the additional luminosity constraint;
Constraints on pp & CNO after the $^7$Be flux

This is the best determination of pp flux (with luminosity constraint)

\[ f_{pp} = 1.005^{+0.008}_{-0.020} \ 1\sigma \]
\[ f_{CNO} < 3.80 \ (90\% \ C.L.) \]
The D/N asymmetry in the $^7\text{Be}$ flux

- MSW mechanism: $\nu$ interaction in the Earth could lead to a $\nu_e$ regeneration effect
- Solar $\nu$ flux higher in the night than in the day
- The amount of the effect depends
  - detector latitude
  - energy of the neutrinos $\theta \Delta m^2$

The absence of a day night effect for the $^7\text{Be}$ is a further confirmation of the LMA solution of the solar neutrino problem.
Geo-\(\nu\) signal at LNGS

Allowed region – consistent with geophysical & geochemical data

Slope – fixed by the reactions energetics

Intercept + width – site dependent, U+Th distribution

- Region allowed by the BSE geochemical model
- Minimum from known U+Th concentrations in the crust
- Maximum given by the total Earth heat flow

\[ S(U+Th) \text{ [TNU]} \]

Heat (U+Th) [TW]

for LNGS Mantovani et al., TAUP 2007

1 TNU (Terrestrial Neutrino Unit) = 1 event/10\(^{32}\) protons/year

Important local geology: cca. half of the signal comes from within 200 km range!!
<table>
<thead>
<tr>
<th>Background source</th>
<th>events/(100 ton-year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosmogenic $^9$Li and $^8$He</td>
<td>0.03 ± 0.02</td>
</tr>
<tr>
<td>Fast neutrons from $\mu$ in Water Tank (measured)</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Fast neutrons from $\mu$ in rock (MC)</td>
<td>&lt; 0.04</td>
</tr>
<tr>
<td>Non-identified muons</td>
<td>0.011 ± 0.001</td>
</tr>
<tr>
<td>Accidental coincidences</td>
<td>0.080 ± 0.001</td>
</tr>
<tr>
<td>Time correlated background</td>
<td>&lt; 0.026</td>
</tr>
<tr>
<td>$(\gamma,n)$ reactions</td>
<td>&lt; 0.003</td>
</tr>
<tr>
<td>Spontaneous fission in PMTs</td>
<td>0.003 ± 0.0003</td>
</tr>
<tr>
<td>$(\alpha,n)$ reactions in the scintillator $^{210}$Po</td>
<td>0.014 ± 0.001</td>
</tr>
<tr>
<td>$(\alpha,n)$ reactions in the buffer $^{210}$Po</td>
<td>&lt; 0.061</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>0.14 ± 0.02</strong></td>
</tr>
</tbody>
</table>

**Expected:** 2.5 geo-$\nu$/(100ton-year)  (assuming BSE)
### Anti-ν signal in BX: rate analysis

<table>
<thead>
<tr>
<th></th>
<th>Predicted from reactors</th>
<th>Background</th>
<th>Observed</th>
<th>Probability to get $N \geq N_{\text{obs}}$</th>
<th>Probability to get $N \leq N_{\text{obs}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geo-ν window</td>
<td>5.0±0.3</td>
<td>0.31±0.05</td>
<td>15</td>
<td>$5 \times 10^{-4}$ (3.5σ)</td>
<td></td>
</tr>
<tr>
<td>Reactor-ν window without oscillations</td>
<td>16.3±1.1</td>
<td>0.09±0.06</td>
<td>6</td>
<td></td>
<td>$5 \times 10^{-3}$ (2.9σ)</td>
</tr>
</tbody>
</table>
Geo-ν: new KamLand result

K. Inoue Neutrino 2010

Rate-shape-time analysis

Complementarity!!

KamLand: oceanic crust
Borexino: continental crust

Preliminary

Efficiency (%)
for geo-ν

Events / 0.2 MeV

Period: March 9, 2002 ~ November 4, 2009
Total exposure: 3.49 x 10^{32} target-proton-years

KamLAND data
best-fit Reactor \( \bar{\nu}_e \)
accidental

\( \nu_C(\alpha,p)\bar{\nu}_e \)
best-fit Geo \( \bar{\nu}_e \)
best-fit Reactor \( \bar{\nu}_e \) + BG
best-fit Geo \( \bar{\nu}_e \)

Kamioka  Gran Sasso  Hawaii

\( N_\nu \)

0 signal is rejected at 99.997% CL. (≈4σ)
(rate-shape-time \( \Delta \chi^2 \))

Borexino preliminary

mantle
crust

model standard

uniform mantle (44.2-7.0-3.5)TW

Fully radiogenic

Epsilon 147 (2007)
\( ^{238}\text{U},^{232}\text{Th} \)
7.0TW
\( ^{40}\text{K},^{238}\text{U} \)
3.5TW


Epsilon 147, 258 (2007)
\( ^{238}\text{U},^{232}\text{Th} \)
16TW
\( ^{40}\text{K},^{238}\text{U} \)
3.5TW

error bar is comparable with the mantle contribution
After SNO: D$_2$O replaced by 1000 tons of liquid scintillator


Placed on an old continental crust:
80% of the signal from the crust
(Fiorentini et al., 2005)

BSE: 28-38 events/per year

Mantovani et al., TAUP 2007
LENA at Pyhasalmi (Finland)

Project for a 50 kton underground liquid scintillator detector

80% of the signal from the continental crust (Fiorentini et al.)

BSE: 800-1200 events/per year

Scintillator loaded with 0.1% Gd:
- better neutron detection
- moderate **directionality** information
Project for a 10 kton liquid scintillator detector, movable and placed on a deep ocean floor

Since Hawaii placed on the U-Th depleted oceanic crust
70% of the signal from the mantle!
Would lead to very interesting results!
(Fiorentini et al.)

BSE: 60-100 events/per year