Borexino: recent solar and terrestrial neutrino results

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Borexino physics

Data-taking since May 2007: many relevant results on solar/geo ν physics and rare processes detection achieved thanks to the unprecedented scintillator radio-purity.

Backgrounds now: $^{238}\text{U} < 8 \times 10^{-20} \text{g/g at 95\% C.L.}$, $^{232}\text{Th} < 9 \times 10^{-19} \text{g/g at 95\% C.L.}$, 3 order of magnitude better than proposal specifications.

- **Solar neutrinos**
- **Cosmogenics**
- **Geo-neutrinos**
- **Heavy neutrinos**

**Phase 1**
- May 2007
- Purifications

**Phase 2**
- May 2010
- Oct 2011

**Phase 3**
- 2015

**Rare processes**

**Δchi² profile for fixed pep and CNO**

**CNO rate cad/100 t**
Talk outline

- The Borexino detector, calibrations, main backgrounds & purifications
- Review of main phase 1 results ($^7$Be solar $\nu$ flux and day/night effect, pep and $^8$B solar $\nu$ fluxes, limits on CNO-$\nu$)
- The first phase 2 results: preliminary new plots on $^7$Be-$\nu$ seasonal flux modulations, updated geo-neutrinos fluxes and comogenics nuclides production in BX, limits on heavy sterile $\nu$;
- Future perspectives
The Borexino detector

**Stainless Steel Sphere:**
- $R = 6.75$ m, $1350$ m$^3$ of water
- Support for 2212 PMTs

**Buffer region:**
- PC+DMP quencher (5 g/l)
- $4.25$ m $< R < 6.75$ m

**Scintillator:**
- 270 t PC+PPO (1.5 g/l)
- $(R = 4.25$ m$)$

**Water Tank:**
- 2100 m$^3$ of water
- 208 PMTs Cherenkoc

- Scintillation light detected by PMT’s
  - # of photons $\Rightarrow$ energy
  - time of flight $\Rightarrow$ position
  - pulse shape $\Rightarrow$ $\alpha/\beta$ $\beta^+/-\beta^-$

- Light yield: $\sim 500$ phe/MeV
- Energy resolution: 5% @ 1MeV
- Space resolution: 10cm @ 1 MeV
- Pulse shape capability

**Principle of graded shielding:** “pure and pure material toward the center of the detector”…
Calibrations & purifications

2008-2011 calibration campaigns: 4 internal + 1 external

- **Energy scale** uncertainty in the range 0.2÷2 MeV better than 1.5%
- Using 184 points of Rn calibration data the FV uncertainty was reduced to -1.3% + 0.5%
Borexino backgrounds (phase 2)

6 purification campaigns in 2010-2011 (WE + nitrogen stripping)

Excellent on $^{238}\text{U}$, $^{232}\text{Th}$ and $^{85}\text{Kr}$, good on $^{210}\text{Bi}$

$^{238}\text{U}$
- $< 8 \times 10^{-20} \text{g/g}$ 95% C.L.
- 2007-2010: $5 \times 10^{-18} \text{g/g}$

$^{232}\text{Th}$
- $< 9 \times 10^{-19} \text{g/g}$ 95% C.L.
- 2007-2010: $3 \times 10^{-18} \text{g/g}$

$^{85}\text{Kr}$
- $< 7.1 \text{cpd/100t}$ 95% C.L.
- 2007-2010: $30.4 \pm 5.3 \pm 1.5$

$^{210}\text{Bi}$
- $25 \pm 2\text{(stat)} \text{cpd/100t}$
- 2007-2010: $41.8 \pm 2.8$

$^{210}\text{Po}$
- $97 \pm 3 \text{cpd/100t}$
- 2007: $10^4 \text{cpd/100t}$
The solar neutrino physics

Solar $\nu$ fluxes at Earth

Solar $\nu_e$ survival probability

Importance of single solar-$\nu$ spectrum component precise flux measurements:

- Help to understand the high/Low metallicity solar model controversy
- Confirm MSW-LMA or exploit possible traces of non-standard neutrino-matter interaction, sub-leading effects, mixing with light sterile $\nu$'s
High/low metallicity controversy

Solar ν fluxes: cm⁻²s⁻¹

<table>
<thead>
<tr>
<th>Diff.</th>
<th>GS98</th>
<th>AGS09</th>
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<tbody>
<tr>
<td>1%</td>
<td>5.98x10¹⁰</td>
<td>6.03x10¹⁰</td>
</tr>
<tr>
<td>2%</td>
<td>1.44x10⁸</td>
<td>1.47x10⁸</td>
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<tr>
<td>3%</td>
<td>8.04x10³</td>
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<tr>
<td>9%</td>
<td>5.00x10⁹</td>
<td>4.56x10⁹</td>
</tr>
<tr>
<td>18%</td>
<td>5.58x10⁶</td>
<td>4.59x10⁶</td>
</tr>
<tr>
<td>27%</td>
<td>2.96x10⁸</td>
<td>2.17x10⁸</td>
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<td>30%</td>
<td>2.23x10⁸</td>
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<tr>
<td>38%</td>
<td>5.52x10⁶</td>
<td>3.40x10⁶</td>
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</table>

Data from Heliosismology and metallicity

Thought to be wrong!!

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

- Help to understand the high/Low metallicity solar model controversy
- Confirm MSW-LMA or exploit possible traces of non-standard neutrino-matter interaction, sub-leading effects, mixing with light sterile ν's
The solar neutrino physics

Importance of single solar-$\nu$ spectrum component precise flux measurements:

✓ Help to understand the high/Low metalliclicity solar model controversy
✓ Confirm MSW-LMA or exploit possible traces of non-standard neutrino-matter interaction, sub-leading effects, mixing with light sterile $\nu$'s
Main BX phase 1 results
$^7$Be-$\nu$ flux at 5% and D/N asymmetry

$R_{^7Be} = 46.0 \pm 1.5^{(stat)} +1.5^{(syst)} \text{ cpd} / 100t$

$R_{\text{no oscillation}} = 74.0 \pm 5.2 \text{ cpd} / 100t$

$\nu_e$ survival probability: $0.51 \pm 0.07$ at 862 KeV

Monte Carlo fit to the spectrum without $\alpha/\beta$ subtraction of $^{210}$Po

Analytical fit to the spectrum after $\alpha/\beta$ subtraction of $^{210}$Po

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

Phase 2: $^{88}$Kr strongly reduced (compatible with zero) => door opened to further improvements.
\( ^7 \text{Be}-\nu \) flux at 5\% and D/N asymmetry

Absence of modulation => MSW-LMA

LOW region excluded at >8.5 \( \sigma \) with solar \( \nu_e \) only (no assumption of CPT symmetry)

LOW: \( \Delta m^2 = 1 \times 10^{-7} \text{eV}^2 \), \( \tan^2 \theta = 0.955 \)

Day--night spectra

\[
A_{dn} = 2 \frac{R_N - R_D}{R_N + R_D} = 0.001 \pm 0.012 \pm 0.007
\]

**pep-ν flux and limits on CNO**

First measurement of pep-ν flux and best limits on CNO! And now $^{210}$Bi reduced..

- **pep ν Rate:** $R = (3.1 \pm 0.6 \pm 0.3)$ cpd/100 t
- **$P_{pe} = 0.62 \pm 0.17$ at 1.44 MeV** High.Met. (GS98)
- **Strongest limit on CNO:** $\Phi_{CNO} < 7.7 \cdot 10^8$ cm$^{-1}$s$^{-1}$

**Main background:** $^{11}$C ($\beta^+$emitt.)
Space & time veto is applied

$^{11}$C tagged with triple coincidence $\mu, n, ^{11}$C decay

- Further reduced exploiting Ps formation:
  - $\beta^+ \rightarrow O$-Ps (50% in PC) \(\Rightarrow\) signal delayed by 3 ns\(\Rightarrow\)
  - Boosted decision tree analysis
- **Global multivariate fit**
First measurement of $^8$B-$\nu$ with liquid scintillator & with a very low energy threshold (3 MeV)

Threshold is defined @ 100% trigger efficiency

More statistics is needed => Phase 2
Phase 1 impact

Before Borexino

Borexino now

Vacuum regime

Combined analysis
Borexino & Radiochemical expts

LMA prediction

Matter regime

Borexino validate the MSW-LMA paradigm

Test of Not-Standard-Interaction or oscillation to sterile $\nu$?

- Reduce error on pep and $^7\text{Be}-\nu$ and on $^8\text{B}-\nu$
- Reduce threshold on $^8\text{B}-\nu$

pp and CNO-$\nu$ spectroscopy still missing

$P_{ee}$ curve (grey band) as expected from MSW-LMA

excluded by DN asymmetry
Phase 1 impact
High/low metallicity controversial

\[ \frac{^{7}\text{Be flux}}{^{7}\text{Be (SSM high met.)}} \]

\[ \frac{^{7}\text{Be} / ^{8}\text{B} - \nu}{^{8}\text{B flux}/^{8}\text{B (SSM high met.)}} \]

BX data are compatible with both high metallicity and low metallicity models

CNO-\( \nu \) are more sensitive...

First phase 2 results

- preliminary new plots on $^7$Be-$\nu$ seasonal flux modulations;
- limits on heavy sterile $\nu$;
- cosmogenics nuclides production rates;
- updated geo-neutrinos fluxes.

Smaller background

Increased statistics
$^7$Be seasonal variation due to the Earth’s orbit eccentricity

*Phys. Rev. D 25 (2014) 112007*

**Phase 1 data**

Progressive increase of backgrounds (60 d bin)

**Inferred period and eccentricity**

- $T = 1.01 \pm 0.07$ y
- $\varepsilon = 0.0398 \pm 0.0102$

Independently measured

No seasonal excluded at $> 3\sigma$
$^7$Be seasonal variation due to the Earth’s orbit eccentricity

The reduced and more stable backgrounds of phase 2 data give agreement with the expected modulation parameters $T$ and $\varepsilon$.
Limits on heavy neutrinos

G. Bellini et al. PRD 88 (2013) 072010

Mixing parameter $\nu_e^-\nu_H$

If heavy neutrinos with $m_{\nu_H} \geq 2m_e$ do exist they could be produced in the Sun via the decay $^8\text{B} \rightarrow ^8\text{Be} + e^+ + \nu_H$

Possible investigated decay: $\nu_H \rightarrow \nu_e + e^+ + e^-$

Events selection:
- FV cut (R=3m)
- 2 ms veto after ext. $\mu$, 2 s after internal $\mu$
- Lifetime after cuts: 446 days
- Fitting procedure:
  - Expected signal vs $m_{\nu_H}$ computed according to R. Shrock et al., Phys Rev D 24 1232 (1981)
  - Energy spectra maximum likelihood fit including elastic scatt. from $^8\text{B}$ solar neutrinos and cosmogenic $^{11}\text{Be}$ besides the sought signal:

$$S_{\text{int}}(m_{\nu_H}, |U_{eH}|) \sim m_{\nu_H}^6 |U_{eH}|^4 \exp(-\text{const} \times m_{\nu_H}^6 |U_{eH}|^2)$$

Red curve: Reactors data
C. Hagner, PRD 52 1343 (1995)

$\pi \rightarrow \nu + e$ decay
D. Britton et al., PRD 46 R885 (1992)
Cosmogenics nuclides production & Simulation codes

Borexino and surrounded area simulated with Fluka and 4 Geant4 physics list

Muon energy and angular distributions from MACRO

$\mu^+/\mu^- = 1.38$ from OPERA

<table>
<thead>
<tr>
<th>Isotopes</th>
<th>GEANT4 (Model III)</th>
<th>GEANT4 (Model IV)</th>
<th>FLUKA</th>
<th>Borexino</th>
<th>KamLAND</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Yield</td>
<td>$[10^{-7} (\mu g/cm^2)^{-1}]$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{12}$N</td>
<td>1.11 ± 0.13</td>
<td>3.0 ± 0.2</td>
<td>0.5 ± 0.2</td>
<td>&lt; 1.1</td>
<td>1.8 ± 0.4</td>
</tr>
<tr>
<td>$^{12}$B</td>
<td>30.1 ± 0.7</td>
<td>29.7 ± 0.7</td>
<td>28.8 ± 1.9</td>
<td>56 ± 3</td>
<td>42.9 ± 3.3</td>
</tr>
<tr>
<td>$^8$He</td>
<td>&lt; 0.04</td>
<td>0.18 ± 0.05</td>
<td>0.30 ± 0.15</td>
<td>&lt; 1.5</td>
<td>0.7 ± 0.4</td>
</tr>
<tr>
<td>$^9$Li</td>
<td>0.6 ± 0.1</td>
<td>1.68 ± 0.16</td>
<td>3.1 ± 0.4</td>
<td>2.9 ± 0.3</td>
<td>2.2 ± 0.2</td>
</tr>
<tr>
<td>$^8$B</td>
<td>0.52 ± 0.09</td>
<td>1.44 ± 0.15</td>
<td>6.6 ± 0.6</td>
<td>14 ± 6</td>
<td>8.4 ± 2.4</td>
</tr>
<tr>
<td>$^6$He</td>
<td>18.5 ± 0.5</td>
<td>8.9 ± 0.4</td>
<td>17.3 ± 1.1</td>
<td>38 ± 15</td>
<td>not reported</td>
</tr>
<tr>
<td>$^8$Li</td>
<td>27.7 ± 0.7</td>
<td>7.8 ± 0.4</td>
<td>28.8 ± 1.0</td>
<td>7 ± 7</td>
<td>12.2 ± 2.6</td>
</tr>
<tr>
<td>$^9$C</td>
<td>0.16 ± 0.05</td>
<td>0.99 ± 0.13</td>
<td>0.91 ± 0.10</td>
<td>&lt; 16</td>
<td>3.0 ± 1.2</td>
</tr>
<tr>
<td>$^{11}$Be</td>
<td>0.24 ± 0.06</td>
<td>0.45 ± 0.09</td>
<td>0.59 ± 0.12</td>
<td>&lt; 7.0</td>
<td>1.1 ± 0.2</td>
</tr>
<tr>
<td>$^{10}$C</td>
<td>15.0 ± 0.5</td>
<td>41.1 ± 0.8</td>
<td>14.1 ± 0.7</td>
<td>18 ± 5</td>
<td>16.5 ± 1.9</td>
</tr>
<tr>
<td>$^{11}$C</td>
<td>315 ± 2</td>
<td>415 ± 3</td>
<td>467 ± 23</td>
<td>886 ± 115</td>
<td>866 ± 153</td>
</tr>
<tr>
<td>Neutrons</td>
<td>Yield</td>
<td>$[10^{-4} (\mu g/cm^2)^{-1}]$</td>
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<td></td>
<td>3.01 ± 0.05</td>
<td>2.99 ± 0.03</td>
<td>2.46 ± 0.12</td>
<td>3.10 ± 0.11</td>
<td>2.79 ± 0.31</td>
</tr>
</tbody>
</table>

Fluka ad Geant4 reproduce the results satisfactory

Noticeable exceptions : $^{11}$C and $^{12}$B
Updated results on Geo-ν

The Earth shines in anti-ν ($\Phi_\nu \sim 10^6$ cm$^{-2}$ s$^{-1}$)

- $^{232}$Th $\rightarrow$ $^{208}$Pb + 6 $\alpha$ + 4 $e^-$ + 4 $\overline{\nu}_e$ + 42.8 MeV
- $^{238}$U $\rightarrow$ $^{206}$Pb + 8 $\alpha$ + 8 $e^-$ + 6 $\overline{\nu}_e$ + 51.7 MeV
- $^{235}$U $\rightarrow$ $^{207}$Pb + 7 $\alpha$ + 4 $e^-$ + 4 $\overline{\nu}_e$ + 46.4 MeV
- $^{40}$K $\rightarrow$ $^{40}$Ca + $e^-$ + 1 $\overline{\nu}_e$ + 1.32 MeV (89.3%)
- $^{40}$K + e $\rightarrow$ $^{40}$Ar + $e^+$ + 1 $\nu_e$ + 1.505 MeV (10.7%)

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

Geo-ν fluxes $\Rightarrow$ HPE’s abundances $\Rightarrow$ Earth energetics

Heat flux: 47 $\pm$ 2 TW , Radiogenic heat: 10-35 TW according to geological BSE models

Fluxes not homogeneous $\Rightarrow$ needs for multi-site measurements!!
Geo-ν as probes for deep Earth

IBD: $\nu_e + p \rightarrow e^+ + n$  \hspace{1cm} ($\tau \sim 250 \mu$s, $d \sim 70$ cm)

Threshold: 1.8 MeV, no $^{40}$K, $^{235}$U

$E_{\text{prompt}} = E_\nu - 0.78$ MeV

Event selecting cuts:
- $Q_{\text{prompt}} > 480$ p.e.
- $Q_{\text{delayed}} [860, 1300]$ p.e.
- $\Delta R$ (prompt-delayed) < 1 m
- $\Delta t$ (prompt-delayed) [20-1280] µs
- Gatti$_{\text{delayed}} < 0.015$ (must be “ß-like”)

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

Unbinned max. likelihood with unconstrained geo and reactor components

$U/Th$ ratio fixed to chondritic value = 3.9

Evidence for geo-ν signal at $4.5 \sigma$ C.L.

$N_{\text{geo}} = 14.3 \pm 4.4$ events

$N_{\text{react}} = 31.7 ^{+7}_{-6.1}$ events

The Mantle signal

\[ S_{\text{Measured}} = S_{\text{LOCal}} + S_{\text{Rest Of Crust}} + S_{\text{Mantle}} \]

1 TNU = 1 ev/year/10\(^{32}\) target protons

<table>
<thead>
<tr>
<th></th>
<th>LOC (TNU)</th>
<th>ROC (TNU)</th>
<th>DATA (TNU)</th>
<th>MANTLE (TNU)</th>
<th>U+Th total (TW)</th>
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<td>38.8±12.0</td>
<td>15.4±12.3</td>
<td>23±14</td>
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<td>KamLand</td>
<td>17.7±1.4</td>
<td>7.3±1.4</td>
<td>30±7</td>
<td>5.0±7.3</td>
<td>11.2 ±7.9 -5.1</td>
</tr>
</tbody>
</table>

\[ S_{\text{BX+KL}}(\text{Mantle}) = (7.7 \pm 6.2) \text{ TNU} \]

Geo-dynamical models slightly disfavoured (and perhaps explained by water recirculation);
- Needs to increase the measurements precision;
- Successful demonstration that geo-\(\nu\) can be a powerful probe of deep Earth!

Comparison with Earth models

- Homogeneous Mantle
- DM + EL 1
- DM + EL 2
- DM + EL 3

Uniform distribution

Band for the mantle signal (comb. analysis)

Enriched layer
Conclusions and perspectives

Unprecedented purity – further improved in phase II

Next steps (phase 2):

✔ To Increase the precision on $^7$Be (3%), $^8$B (10%), and pep-ν fluxes (=>Metallicity controversy, more stringent test of the profile of the Pee survival probability => sub-leading effect in  addition to MSW-LMA, new physics, NSI?)

✔ The first real time measure of pp-ν flux: currently in progress with Phase-II data.
Stay tuned!!!

The hunt for CNO-ν flux will continue....

.... towards an almost complete solar neutrino spectroscopy in one experiment!!!

✔ The increased statistics will help to reduce the uncertainty on geo-ν signal and to possibly select geological models and improve the knowledge of Earth energetics, also the limits on rare processes will be improved..

✔ Among the next exciting goals: measurements with artificial neutrino sources
⇒ Search for sterile neutrinos, ν magnetic moment

⇒ Talk on BX-SOX project by Dr. David Bravo
Thanks!!!
**Cosmogenics nuclides**

<table>
<thead>
<tr>
<th>Cosmogenic Isotope</th>
<th>Lifetime</th>
<th>Q-Value [MeV]</th>
<th>Decay Type</th>
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<th>Lifetime</th>
<th>Q-Value [MeV]</th>
<th>Decay Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{12})N</td>
<td>15.9 ms</td>
<td>17.3</td>
<td>(\beta^-)</td>
<td>(^{6})He</td>
<td>1.16 s</td>
<td>3.51</td>
<td>(\beta^-)</td>
</tr>
<tr>
<td>(^{12})B</td>
<td>29.1 ms</td>
<td>13.4</td>
<td>(\beta^+)</td>
<td>(^{8})Li</td>
<td>1.21 s</td>
<td>16.0</td>
<td>(\beta^-)</td>
</tr>
<tr>
<td>(^{8})He</td>
<td>171.7 ms</td>
<td>10.7</td>
<td>(\beta^-)</td>
<td>(^{11})Be</td>
<td>19.9 s</td>
<td>11.5</td>
<td>(\beta^-)</td>
</tr>
<tr>
<td>(^{9})C</td>
<td>182.5 ms</td>
<td>16.5</td>
<td>(\beta^+)</td>
<td>(^{10})C</td>
<td>27.8 s</td>
<td>3.65</td>
<td>(\beta^+)</td>
</tr>
<tr>
<td>(^{9})Li</td>
<td>257.2 ms</td>
<td>13.6</td>
<td>(\beta^-)</td>
<td>(^{11})C</td>
<td>29.4 min</td>
<td>1.98</td>
<td>(\beta^+)</td>
</tr>
<tr>
<td>(^{8})B</td>
<td>1.11 s</td>
<td>18.0</td>
<td>(\beta^+)</td>
<td></td>
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</tbody>
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Table 1. List of cosmogenic isotopes expected to be produced by muons in organic scintillators in measurable rates.

<table>
<thead>
<tr>
<th>Model III</th>
<th>HP</th>
<th>Binary</th>
<th>LEP</th>
<th>QGS</th>
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<tbody>
<tr>
<td>Protons</td>
<td></td>
<td>0 (\rightarrow) 9.9 GeV</td>
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<tr>
<td>(\pi, K)</td>
<td>0 (\rightarrow) 9.9 GeV</td>
<td>9.5 (\rightarrow) 25 GeV</td>
<td>12 GeV (\rightarrow) 100 TeV</td>
<td></td>
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<table>
<thead>
<tr>
<th>Model IV</th>
<th>HP</th>
<th>Bertini</th>
<th>LEP</th>
<th>QGS</th>
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<tr>
<td>Protons</td>
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Table 3. Summary of the Hadronic Models used in GEANT4.
Earth radiogenic power

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

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<td>11.2±7.9±5.1</td>
</tr>
</tbody>
</table>

The U/Th radiogenic power is still poorly constrained=> need to improve measurements precision => more statistics..
Fit with unconstrained U/Th

**Borexino**

- $N_U = 9.8 \pm 7.2$ events
- $N_{Th} = 3.9 \pm 4.7$
- $N_{react} = 31.7^{+7.2}_{-6.3}$

Large uncertainty but close to the chondritic ratio

**KamLAND**

Null U signal rejected at 90% C.L. (2.6 $\sigma$)