Solar neutrinos: overview and new Borexino results

G. Testera
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On behalf of the Borexino Collaboration

The Borexino nylon vessel filled with the scintillator (picture of few days ago)

Inside view of the Borexino sphere holding the Photomultipliers
Fusion reactions in the core of the Sun
- pp dominant in the SUN (99% of the energy and $\nu$ production))
- CNO important for larger mass stars

$$4H + 2e^- \rightarrow ^4He + 2e^+ + 2\nu_e + 26.7 \ MeV$$
### About 50 years of solar ν: from the solar ν problem to ν oscillation: LMA-MSW

<table>
<thead>
<tr>
<th>Source</th>
<th>ν detected</th>
<th>Signal</th>
<th>Signal/SSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homestake</td>
<td>⁷Be, pep, CNO, ⁸B</td>
<td>256 ± 0.23 SNU</td>
<td>0.32 ± 0.05</td>
</tr>
<tr>
<td>Gallex/GNO/SAGE</td>
<td>pp, ⁷Be, pep, CNO, ⁸B</td>
<td>66.2 ± 3.1 SNU</td>
<td>0.52 ± 0.03</td>
</tr>
<tr>
<td>SK I+II+III+IV</td>
<td>⁸B</td>
<td>⁵⁸.² ± ⁹.⁴ cpd/100t</td>
<td>⁰.⁶⁶ ± ⁰.¹⁵</td>
</tr>
<tr>
<td>SNO</td>
<td>⁸B</td>
<td>¹⁴⁴ ± ¹⁶ cpd/100t</td>
<td>⁰.⁷⁵ ± ⁰.⁰⁸</td>
</tr>
<tr>
<td>Kamland</td>
<td>⁷Be, ⁸B</td>
<td>⁴⁶.⁰ ± ².² cpd/100t</td>
<td>⁰.⁶³ ± ⁰.⁰⁵</td>
</tr>
<tr>
<td>Borexino Phase I (new Phase II not included here)</td>
<td>⁷Be, pep CNO ⁸B</td>
<td>¹⁰.² ± ².² cpd/100t</td>
<td>⁰.⁴³ ± ⁰.¹⁰</td>
</tr>
</tbody>
</table>

- **Evidence of ν oscillations**
- **Interaction of ν with matter MSW**

Kamland reactor results + solar (before Borexino & Kamland solar) : LMA-MSW (year 2002)

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Adapted from A. Ianni Prog. Part. Nucl. Phys. 94 257 (2017)
Why do we still measure solar $\nu$? 1) Precision meas. to confirm LMA-MSW prediction

- Pee should show a vacuum to matter transition
- Non Standard Interactions modify Pee
- Precise flux meas. of single spectral component
- Measure $^8$B with low threshold
- Have good accuracy for the lowest $^8$B energy bin

Super-K spectral data

SK spectrum is consistent within
1 $\sigma$ with the MSW upturn obtained
with Osc. Param from solar
2 $\sigma$ with MSW upturn obtained
with Osc Param. from solar+Kamland

Plot from Yasuo Takeuchi
(Kamland Coll, Quy Nhon 18-July 2017)
Preliminary

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Pee vs energy: the importance of the precision spectroscopy

\[ P_{\text{ee}} \]

LMA-MSW
- Matter effect in the Earth:
- Day-Night flux asymmetry
- Only at high energy

All $\nu$ oscillation
Solar $\nu$ only

\[ \sin^2 \theta_{13} = 0.022, \sin^2 \theta_{12} = 0.31 \]
\[ \Delta m^2_{21} = (4.7, 7.5) \times 10^{-5} \text{ eV}^2 \]

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Why do we still measure solar $n$? 1) Confirm LMA-MSW prediction

- Matter effect in $\nu$ oscillation
- Regeneration effect during night ($\nu$ traverse the Earth)
- LMA-MSW: no effect for $^7$Be, measurable effect for $^8$B

SuperKamiokande $^8$B $E>4.5$ MeV


Borexino Phase I: $^7$Be


$A_{DN}^{8B} = \frac{D - N}{(N + D)/2} = (-3.3 \pm 1.0 \pm 0.5)\%$

Non zero significance 3σ !!!

$A_{DN}^{7Be} = \frac{D - N}{(N + D)/2} = (-0.1 \pm 1.2 \pm 0.7)\%$
Why do we still measure solar $\nu$?  

2) Solar models

- Evolution of a star from beginning until now $4.57 \times 10^9$ y
- Homogeneous mixture of H, He and heavy elements $X_{\text{ini}}, Y_{\text{ini}}, Z_{\text{ini}}$
- $\alpha_{\text{MLT}}$: parameter entering in the description of the convection
- Cross sections for nuclear reactions (S factors)
- Opacity
- Equilibrium between gravitational force and outward force due to gradient of pressure $P(r)$

Initial parameters adjusted to reproduce present days status:

- Solar Luminosity $L$
- Solar Radius
- $Z/X$ (abundance of metals) on the surface

Observables: elioseismology, solar neutrinos

Since 2001: new analysis of spectroscopic data from photosphere, revision of surface solar metallicity, lower values (LZ).

But solar models reproducing these new LZ values disagree with elioseismology data (solar abundance problem)

The prediction of solar $\nu$ flux is sensitive to the Sun metallicity

| Flux   | B16-GS98 | HZ | B16-AGSS09met | LZ
<table>
<thead>
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<th></th>
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<tr>
<td>$\Phi(\text{pp})$</td>
<td>5.98(1 ± 0.006)</td>
<td>6.03(1 ± 0.005)</td>
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<tr>
<td>$\Phi(\text{pcp})$</td>
<td>1.44(1 ± 0.01)</td>
<td>1.46(1 ± 0.009)</td>
<td></td>
<td></td>
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<tr>
<td>$\Phi(\text{hep})$</td>
<td>7.98(1 ± 0.30)</td>
<td>8.25(1 ± 0.30)</td>
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<tr>
<td>$\Phi(^{7}\text{Be})$</td>
<td>4.93(1 ± 0.06)</td>
<td>4.50(1 ± 0.06)</td>
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<tr>
<td>$\Phi(^{8}\text{B})$</td>
<td>5.46(1 ± 0.12)</td>
<td>4.50(1 ± 0.12)</td>
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<tr>
<td>$\Phi(^{13}\text{N})$</td>
<td>2.78(1 ± 0.15)</td>
<td>2.04(1 ± 0.14)</td>
<td></td>
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<tr>
<td>$\Phi(^{15}\text{O})$</td>
<td>2.05(1 ± 0.17)</td>
<td>1.44(1 ± 0.16)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Phi(^{17}\text{F})$</td>
<td>5.29(1 ± 0.20)</td>
<td>3.26(1 ± 0.18)</td>
<td></td>
<td></td>
</tr>
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</table>

Units:
- pp: $10^{19}$ cm$^{-2}$ s$^{-1}$
- Be: $10^6$ cm$^{-2}$ s$^{-1}$
- pep, N, O: $10^{8}$ cm$^{-2}$ s$^{-1}$
- B, F: $10^9$ cm$^{-2}$ s$^{-1}$

$^7\text{Be}$: 8.7% diff
$^8\text{B}$: 17.6% diff
CNO: 40% diff


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Scintillator: 270 t PC+PPO (1.5 g/l) in a 150 μm thick inner nylon vessel (R = 4.25 m)

Stainless Steel Sphere: R = 6.75 m 2212 PMTs

Buffer region: PC+DMP quencher 4.25 m < R < 6.75 m

Water Tank: γ and n shield μ water Č detector 208 PMTs in water

Borexino detector@LNGS

- ν detection: $\nu_x + e^- \rightarrow \nu_x + e^-$
- Energy E: $N_p$ : Normalized number of hits PMTs $N_h$: including multiple hits $N_{pe}$: number of phe (charge)
- Position: PMT hit time

550 $N_p$ @1MeV $\sigma_E= 50$ KeV@1MeV $\sigma_{x,y,z}=10$ cm@1MeV

Phase I  Scint. purification  Phase II

2007 $^7$Be pep $^8$B,geo ν rare processes + calibration

2010 2012 geo ν, pp, $^7$Be seasonal modulation

2017 2018 SOX

New data belong to Phase II

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New Borexino results: first simultaneous precision spectroscopy of low energy solar ν with Phase II data

- Low energy
  - pp, ⁷Be, pep interaction rates and fluxes (CNO limit)

- Precision
  - We increase the accuracy of our previous results
  - Increased exposure
  - Lower background
  - Improved models of the detector response functions

- First simultaneous
  - We analyze simultaneously all the energy spectrum from 0.186 to 2.97 MeV
  - All ν obtained with a single analysis
  - Previous data were obtained analyzing selected regions of the spectrum
Signal and background

Data energy spectrum
before and after cuts

Simulated energy spectrum
including solar \( \nu \) and the main background components

Event selection
• removal \( \mu \) and cosmogenics (1.5% dead time)
• removal of Bi-Po214
• noise events
• Fiducial Volume (\( R<2.8 \) m, \(-1.8 < z < 2.2 \) m)
• 71.3 tons
• no \( \alpha \beta \) discrimination
• Fraction of good events removed by cuts <0.1%

Purification: reduction of \( ^{85}\text{Kr} \), \( ^{210}\text{Bi} \)

\( ^{232}\text{Th} \) (from \( ^{212}\text{Bi-Po} \))
- \(< 5.7 \times 10^{-19} \) g/g 95% C.L.
- PHASE 1: \(< 3 \times 10^{-18} \) g/g

\( ^{238}\text{U} \) (from \( ^{214}\text{Bi-Po} \))
- \(< 9.4 \times 10^{-20} \) g/g 95% C.L.
- PHASE 1: \(< 5 \times 10^{-18} \) g/g

Dec 14th 2011 to May 21th, 2016
1291.51 days \times 71.3 \) tons

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See S. Caprioli poster
11C: Three Fold Coincidence and $\beta^+/\beta^-$ discrimination

$^{11}C \rightarrow \beta^+, \tau = 29 \text{ min}$

- Identify $\mu$ and $\mu$ track
- Detect n ($\gamma$ signal due to capture after thermalization)
- Space time cuts around the $\mu$ track and n position: $^{11}C$ should be there
- Build a Likelihood function to evaluate if an event is a $^{11}C$

Divide the exposure in 2 samples: $^{11}C$ subtracted & $^{11}C$ tagged

Performances: 92.4 +- 4 % tagging efficiency
exposure: 64% in the $^{11}C$ subtracted spectrum

Novel $\beta^+/\beta^-$ pulse shape parameter:
Energy normalized likelihood of the position reconstruction

- Pdf of the position rec. assumes point like, prompt scintillation but:
  - $e^+$ slows down, form O-Ps with few ns lifetime
  - Multiple interaction of 511 $\gamma$ within about 20 cm
  - The max likelihood assumes lower values for true $\beta^-$ events than for $^{11}C$ decay
Maximize a binned likelihood through a multivariate approach

$$L(\mathcal{G}) = L_{\text{sub}}(\mathcal{G}) \cdot L_{\text{tag}}(\mathcal{G}) \cdot L_{\text{rad}}(\mathcal{G}) \cdot L_{\text{PS} - \text{pr}}(\mathcal{G})$$
• Build MC data set with the same exposure as in the data
• Fit with pdf used to fit the data
• Check bias, sensitivity, correlations

Analysis strategy:

1) pp $^7$Be pep flux measurement:
   set a constraint of the CNO rate to the HZ and LZ values
   \[
   \begin{align*}
   CNO \text{ HZ} & \quad 4.92 \pm 0.56 \quad \text{cpd/100t} \\
   CNO \text{ LZ} & \quad 3.52 \pm 0.37 \quad \text{cpd/100t}
   \end{align*}
   \]

2) Upper limit CNO $\nu$ flux:
   we set a constraint on the ratio pp/pep
   \[ R(pp/pep) \quad 47.5 \pm 1.2 \]
Results

Example of multivariate fit of the data:
Energy spectrum $^{11}$C tagged $N_h$
Monte Carlo fit

![Graph showing energy spectrum with peaks labeled pp, CNO, 7Be, and 8B, and residuals plot.]
Results

Example of multivariate fit of the data:
Energy spectrum $^{11}$C subtracted
$N_h$
Monte Carlo fit
Fit results: radial distribution of the events and pulse shape parameter

- Uniform component
- External background, exp decrease (pdf from MC)

fit of the radial distribution of the events

- fit of the β+/β- pulse shape parameter (pdf from data samples or from MC)
Fit Results: details of the low energy region

Example of multivariate fit of the data:

- Energy spectrum zoomed in the low energy region (200-830 KeV)
- $N_p dt^2$
- Analytical fit
### Fit results: background

<table>
<thead>
<tr>
<th>Background</th>
<th>Rate (cpd/100t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{14}$C (Bq/100t)</td>
<td>40.0 ± 2.0</td>
</tr>
<tr>
<td>$^{85}$Kr</td>
<td>6.8 ± 1.8</td>
</tr>
<tr>
<td>$^{210}$Bi</td>
<td>17.5 ± 1.9</td>
</tr>
<tr>
<td>$^{11}$C</td>
<td>26.8 ± 0.2</td>
</tr>
<tr>
<td>$^{210}$Po</td>
<td>260.0 ± 3.0</td>
</tr>
<tr>
<td>Ext $^{40}$K</td>
<td>1.1 ± 0.6</td>
</tr>
<tr>
<td>Ext $^{214}$Bi</td>
<td>1.9 ± 0.3</td>
</tr>
<tr>
<td>Ext $^{208}$Tl</td>
<td>3.3 ± 0.1</td>
</tr>
</tbody>
</table>

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**Purification of the scintillator**

6 cycles, closed loop

Reduction factors:

- 4.6 for $^{85}$Kr
- 2.3 for $^{210}$Bi
Fit results: systematics uncertainty

1) Systematic uncertainties

\[(N_p, N_p^{dt2}, N_h)\]

- Energy scale
- Not uniformity of the energy response
- \(^{210}\)Bi spectral shape

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>(pp)</th>
<th></th>
<th>(^{7})Be</th>
<th></th>
<th>(pep)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fit method (analytical/MC)</td>
<td>-1.2</td>
<td>1.2</td>
<td>-0.2</td>
<td>0.2</td>
<td>-4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Choice of energy estimator</td>
<td>-2.5</td>
<td>2.5</td>
<td>-0.1</td>
<td>0.1</td>
<td>-2.4</td>
<td>2.4</td>
</tr>
<tr>
<td>Pile-up modeling</td>
<td>-2.5</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Fit range and binning</td>
<td>-3.0</td>
<td>3.0</td>
<td>-0.1</td>
<td>0.1</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Fit models (see text)</td>
<td>-4.5</td>
<td>0.5</td>
<td>-1.0</td>
<td>0.2</td>
<td>-6.8</td>
<td>2.8</td>
</tr>
<tr>
<td>Inclusion of (^{85})Kr constraint</td>
<td>-2.2</td>
<td>2.2</td>
<td>0</td>
<td>0</td>
<td>-3.2</td>
<td>0</td>
</tr>
<tr>
<td>Live Time</td>
<td>-0.05</td>
<td>0.05</td>
<td>-0.05</td>
<td>0.05</td>
<td>-0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Scintillator density</td>
<td>-0.05</td>
<td>0.05</td>
<td>-0.05</td>
<td>0.05</td>
<td>-0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Fiducial volume</td>
<td>-1.1</td>
<td>0.6</td>
<td>-1.1</td>
<td>0.6</td>
<td>-1.1</td>
<td>0.6</td>
</tr>
<tr>
<td>Total systematics (%)</td>
<td>-7.1</td>
<td>4.7</td>
<td>-1.5</td>
<td>0.8</td>
<td>-9.0</td>
<td>5.6</td>
</tr>
</tbody>
</table>

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New pp, $^7$Be, pep results of the analysis of Phase II data

<table>
<thead>
<tr>
<th></th>
<th>Borexino results cpd/100t</th>
<th>expected HZ cpd/100t</th>
<th>expected LZ cpd/100t</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>pp</strong></td>
<td>$134 \pm 10^{+6}_{-10}$</td>
<td>$131.0 \pm 2.4$</td>
<td>$132.1 \pm 2.4$</td>
</tr>
<tr>
<td>$^7$Be(862+384 KeV)</td>
<td>$48.3 \pm 1.1^{+0.4}_{-0.7}$</td>
<td>$47.8 \pm 2.9$</td>
<td>$43.7 \pm 2.6$</td>
</tr>
<tr>
<td><strong>pep (HZ)</strong></td>
<td>$2.43 \pm 0.36^{+0.15}_{-0.22}$</td>
<td>$2.74 \pm 0.05$</td>
<td>$2.78 \pm 0.05$</td>
</tr>
<tr>
<td><strong>pep (LZ)</strong></td>
<td>$2.65 \pm 0.36^{+0.15}_{-0.24}$</td>
<td>$2.74 \pm 0.05$</td>
<td>$2.78 \pm 0.05$</td>
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<thead>
<tr>
<th></th>
<th>Borexino results Flux (cm$^{-2}$s$^{-1}$)</th>
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<tr>
<td><strong>pp</strong></td>
<td>$(6.1 \pm 0.5^{+0.3}_{-0.5}) 10^{10}$</td>
<td>$5.98 (1\pm 0.006) 10^{10}$</td>
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<td>$^7$Be(862+384 KeV)</td>
<td>$(4.99 \pm 0.13^{+0.07}_{-0.10}) 10^{9}$</td>
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<td>$(1.27 \pm 0.19^{+0.08}_{-0.12}) 10^{8}$</td>
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Comparison between Phase I and Phase II results

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<th>Phase I</th>
<th>Phase II</th>
<th>Uncertainty reduction</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>pp</td>
<td>144 $\pm$ 13$\pm$10</td>
<td>134 $\pm$ 10$^{+6}_{-10}$</td>
</tr>
<tr>
<td>7Be(862KeV)</td>
<td>46.0 $\pm$ 1.5$^{+1.6}_{-1.5}$</td>
<td>46.3 $\pm$ 1.1$^{+0.4}_{-0.7}$</td>
<td>0.57</td>
</tr>
<tr>
<td>pep</td>
<td>3.1 $\pm$ 0.6 $\pm$ 0.3</td>
<td>(HZ) 2.43 $\pm$ 0.36$^{+0.15}_{-0.22}$</td>
<td>(LZ) 2.65 $\pm$ 0.36$^{+0.15}_{-0.24}$</td>
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5 $\sigma$ evidence of pep solar $\nu$
(including systematics uncertainties)

Likelihood profile resulting from the multivariate fit

Select innermost $\beta$- like events
Radius<2.4   PS-LPR<4.8
Upper limit on the CNO flux

- Set a constrain to the ratio pp/pep
- Very well known in the solar model
- Include oscillations LMA-MSW
- Toy MC study of the sensitivity: the median 95% CL is 9 cpd/100t for LZ 10 cpd/100t for HZ

95% C.L. limit on the CNO n rate
8.1 cpd/100t
including systematics errors

Previous limit (set by Borexino Phase I):
7.9 cpd/100t

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<td>CNO $\nu$</td>
<td>$&lt; 8.1 95%$ C.L. cpd/100t</td>
<td>4.91 $\pm$ 0.56 cpd/100t</td>
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G. Testera (Borexino Collaboration) - TAUP2017 Sudbury
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<td>cpd/100t</td>
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<td>cpd/100t</td>
</tr>
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Implication of the results: probe solar fusion with $R$

$$R = \frac{\text{Rate}(^3\text{He} + ^3\text{He})}{\text{Rate}(^3\text{He} + ^4\text{He})}$$

$$R = \frac{2 \Phi(^7\text{Be})}{\Phi(pp) - \Phi(^7\text{Be})}$$

Expected values: (C. Pena Garay, private comm.)

$R = 0.180 \pm 0.011 \quad HZ$

$R = 0.161 \pm 0.010 \quad LZ$

Measured value:

$R = 0.18 \pm 0.02$
Neutrino survival probability $P_{ee}$ with the Borexino results

Neutrino survival probability with the new Phase II results and $^8B$ from Borexino (PRD 82 033006 (2010))
Implication of the results: towards probing HZ and LZ

Global fit of all solar, Kamland reactors with new Borexino results

\[ f_B = \frac{\Phi(8B)}{\Phi_{HZ}(8B)} \quad f_{Be} = \frac{\Phi(7Be)}{\Phi_{HZ}(7Be)} \]

\[ \Delta m^2_{12} \sin^2(\theta_{12}) \]

- hints towards High Metallicity???
- Note: only 1 \( \sigma \) theoretical uncertainty in the plot!
- Important to reduce the theoretical uncertainty

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Conclusions

- Solar ν experiments (SK, Borexino) are running into a precision spectroscopy phase
- Validation of the MS-LMA model
- Testing solar models and helping to solve the metallicity issue
- New results from Borexino about pp, $^7$Be, pep
- Simultaneous measurement of the 3 fluxes
- Improved accuracy compared to Phase I
- 5 σ evidence of pep ν
- $^7$Be measured with 2.5% uncertainty (stat+sys)

- Also new limit on the effective neutrino magnetic moment from Phase II Borexino data
  \[ \mu_{\text{eff}} < 2.8 \times 10^{-11} \mu_B \]
  (presented by L. Ludhova on Monday)
\[ \mu_{\text{eff}}^2 = P_{3\nu}^3 \mu_e^2 + (1 - P_{3\nu}^3) (\cos^2 \theta_{23} \mu_\mu^2 + \sin^2 \theta_{23} \mu_\tau^2) \]

- \( P_{ee} = P_{3\nu}^3 = \sin^4 \theta_{13} + \cos^4 \theta_{13} P_{2\nu}^2 \)
- \( P_{2\nu}^2 = \sin^2 \theta_{13} \sin^2(\Delta m_{12}^2 L/4E) \)

Assuming LMA-MSW

\( P_{2\nu}^2 \) for pp- and \(^7\)Be-\( \nu \) is the same

(Dec 2011 - May 2016)
1391 days
90\% C.L.

from \( \mu_{\text{eff}} < 2.8 \times 10^{-11} \mu_B \):
- \( \mu_e < 4.8 \times 10^{-11} \mu_B \)
- \( \mu_\mu < 6.4 \times 10^{-11} \mu_B \)
- \( \mu_\tau < 6.8 \times 10^{-11} \mu_B \)


$^{210}$Bi independent constraint

$^{210}$Pb \[ (\beta^-, \tau = 32y) \] $\rightarrow$ $^{210}$Bi \[ (\beta^-, \tau = 7d) \] $\rightarrow$ $^{210}$Po \[ (\alpha, \tau = 200d) \]

- Assuming the secular equilibrium the $^{210}$Bi rate can be determined by the $^{210}$Po rate [F. Villante et al. Phys.Lett. B701 (2011) 336-341]:
The **period**, **amplitude**, and **phase** of the observed time evolution of the signal are consistent with its solar origin, and the absence of an annual modulation is rejected at 99.99% C.L.

<table>
<thead>
<tr>
<th></th>
<th>Simulated Data</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>(T) [year]</td>
<td>0.95 ± 0.02</td>
<td>0.96 ± 0.05</td>
</tr>
<tr>
<td>(\varepsilon)</td>
<td>0.0155 ± 0.0025</td>
<td>0.0168 ± 0.0031</td>
</tr>
<tr>
<td>(\phi) [day]</td>
<td>(-12 ± 11)</td>
<td>14 ± 22</td>
</tr>
</tbody>
</table>