Neutrino astrophysics with Borexino: comprehensive study of solar neutrinos

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Why study solar neutrinos: from solar physics to astrophysics and cosmology

- Solar surface spectroscopic observations demonstrated lower metal abundances. Do they indeed contradict to helioseismology?
  - Metallicity puzzle: do we correctly measure elemental abundances of stars?
    - Age, luminosity, temperature of stars do depend on metallicity
  - Do we correctly understand the opacity of stars?
    - Opacity defines star’s brightness, size, temperature
  - Consequences for the whole astrophysics
    - If we’re not perfectly aware of our own star, we’re probably wrong about the others…

- CNO cycle is believed to be dominant in most stars in the Universe
  - Experimental confirmation of the CNO cycle is highly required
Why study solar neutrinos: not only astrophysics... Neutrino itself!

- Solar neutrinos survival probability $P_{ee}(E_\nu)$ is sensitive to the physics beyond Standard Model.
- After establishing LMA MSW solution a set of sub-leading effects affecting neutrino propagation in the Sun is still possible:
  - Probe for the non-standard neutrino interaction (NSI)?
  - Mixing with sterile neutrino state?
    - Effect on $P_{ee}$ largely depends on relation between $\Delta m^2_{12}$ and $\Delta m^2_{\alpha\beta}$.
  - Large neutrino magnetic moments?
  - Neutrino decay?

Vacuum oscillations | Transition region | Matter-enhanced

Precision measurements of $P_{ee}(E_\nu)$, especially in transition zone between vacuum and matter-enhanced MSW-LMA regimes, would be a very powerful probe for the new physics.

Solar engine: neutrinos from pp-chain and CNO cycle

Solar neutrinos energy spectrum and fluxes in various solar models (SM)

<table>
<thead>
<tr>
<th>Flux</th>
<th>High-Z SM</th>
<th>Low-Z SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp</td>
<td>5.98±0.6%</td>
<td>6.03±0.5%</td>
</tr>
<tr>
<td>pep</td>
<td>1.44±1.0%</td>
<td>1.46±0.9%</td>
</tr>
<tr>
<td>hep</td>
<td>7.98±30%</td>
<td>8.25±30%</td>
</tr>
<tr>
<td>7Be</td>
<td>4.93±6%</td>
<td>4.50±6%</td>
</tr>
<tr>
<td>8B</td>
<td>5.46±12%</td>
<td>4.50±12%</td>
</tr>
<tr>
<td>13N</td>
<td>2.78±15%</td>
<td>2.04±14%</td>
</tr>
<tr>
<td>15O</td>
<td>2.05±17%</td>
<td>1.44±16%</td>
</tr>
<tr>
<td>17F</td>
<td>5.29±20%</td>
<td>3.26±18%</td>
</tr>
</tbody>
</table>

Overall flux $\approx 6 \times 10^{10}$ cm$^{-2}$s$^{-1}$

$^{7}$Be, $^{8}$B and CNO neutrino fluxes are most sensitive to solar metallicity

Units: $10^{10}$ (pp), $10^{9}$ ($^{7}$Be), $10^{8}$ (pep, $^{13}$N, $^{15}$O), $10^{6}$ ($^{8}$B, $^{17}$F), $10^{3}$ (hep) cm$^{-2}$s$^{-1}$.

The instrument: BOREXINO

- Detector takes data since 2007 in Gran Sasso national laboratories (LNGS, Italy), 3500 m.w.e.
- Primary detection channel: neutrino-electron elastic scattering
- 280 tons of PC-based liquid scintillator
  - $\sigma/E @ 1 \text{ MeV} = 5\%$
  - $\sigma_{x,y,z} @ 1 \text{ MeV} = 10 \text{ cm}$
- 2212 8” PMTs
- Active muon shielding
  - 2100 m$^3$ ultra-pure water Cherenkov detector
- $E_{th} \approx 100 \text{ keV}$
Key ingredients of the Borexino success

- Extreme radiopurity achieved:
  - $^{238}\text{U} < 9.4 \times 10^{-20}$ g/g (95% C.L.)
  - $^{232}\text{Th} < 5.7 \times 10^{-19}$ g/g (95% C.L.)

- Brand new data analysis techniques, including:
  - Three-fold coincidence (TFC) technique to tag cosmogenic $^{11}\text{C}$
  - $e^+/e^-$ pulse-shape discrimination to further reduce cosmogenic $^{11}\text{C}$
  - $\alpha/\beta$ discrimination based on neural network approach
Hunting for \textit{pp}-chain solar neutrinos
Data analysis strategy

- Latest results were obtained with the phase-II data taken in 2011-2016
- Event selection: a set of cuts is applied in order to maximize signal-to-background ratio
  - Remove cosmic muons and cosmogenics within 300 ms after muon, delayed coincidences $^{214}\text{Bi} - ^{214}\text{Po}$
- In order to suppress external background, events are required to be reconstructed within the fiducial volume:
  - $r < 2.8$ m and $-1.8 < z < 2.2$ m
- Two energy regions:
  - 0.19-2.93 MeV (pp, pep, $^7\text{Be}$)
  - 3.2-16 MeV ($^8\text{B}$)
- Interaction rates are obtained by maximizing a binned likelihood function
Multivariate fit in 0.19÷2.93 MeV range

Method: binned likelihood fit through a multivariate approach:

\[
L(\vec{\theta}) = L_{E}^{TFC_{\text{sub}}}(\vec{\theta}) \cdot L_{E}^{TFC_{\text{tagged}}}(\vec{\theta}) \cdot L_{PS}(\vec{\theta}) \cdot L_{Rad}(\vec{\theta})
\]

Unknown parameters: pp rate, \(^{7}\text{Be} \) rate etc…

Energy spectrum \(^{11}\text{C} \) subtracted  
Energy spectrum \(^{11}\text{C} \) tagged  
Pulse shape parameter  
Radial distribution
Multivariate fit in $0.19 \div 2.93$ MeV range

<table>
<thead>
<tr>
<th></th>
<th>Borexino rate [cpd/100 t]</th>
<th>High-Z predicted [cpd/100 t]</th>
<th>Low-Z predicted [cpd/100 t]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pp$</td>
<td>$134 \pm 10^{+6}_{-10}$</td>
<td>$131.1 \pm 1.4$</td>
<td>$132.2 \pm 1.4$</td>
</tr>
<tr>
<td>$^7$Be</td>
<td>$48.3 \pm 1.1^{+0.4}_{-0.7}$</td>
<td>$47.9 \pm 2.8$</td>
<td>$43.7 \pm 2.5$</td>
</tr>
<tr>
<td>$pep$</td>
<td>$2.43 \pm 0.36^{+0.15}_{-0.22}$ (high-Z)</td>
<td>$2.74 \pm 0.04$</td>
<td>$2.78 \pm 0.04$</td>
</tr>
<tr>
<td></td>
<td>$2.65 \pm 0.36^{+0.15}_{-0.24}$ (low-Z)</td>
<td>$2.74 \pm 0.04$</td>
<td>$2.78 \pm 0.04$</td>
</tr>
<tr>
<td>$^8$B</td>
<td>$0.217 \pm 0.038 \pm 0.008$</td>
<td>$0.211 \pm 0.025$</td>
<td>$0.174 \pm 0.022$</td>
</tr>
</tbody>
</table>
High vs. low metallicity SSM after Borexino measurements

\[ f_{Be} = \frac{\Phi(7Be)}{\Phi(7Be)_{\text{high-Z}}} \quad f_B = \frac{\Phi(8B)}{\Phi(8B)_{\text{high-Z}}} \]

Combined results. We take:
- precision Borexino measurements for $^7$Be neutrinos,
- more accurate Super-Kamiokande and SNO results for $^8$B neutrinos

Global fit performed with $\theta_{12}$ and $\Delta m^2_{12}$ left free, $\sin^2 \theta_{13} = 0.02$ (fixed).

The discrimination between the high and low metallicity solar models is now largely dominated by theoretical uncertainties.
What about survival probability $P_{ee}$?

Borexino examines the MSW-LMA neutrino oscillation paradigm both in the vacuum ($pp$, $^7$Be-neutrino) and the matter dominated ($^8$B-neutrino) regimes.

High-Z SSM B16(G98)  
Low-Z SSM B16(AGSS09met)
Hunting for CNO cycle solar neutrinos
Spectral shapes of betas from CNO $\nu$, pep $\nu$ and $^{210}$Bi are similar.

Hence, Borexino sensitivity to CNO neutrinos is low unless the $^{210}$Bi and pep $\nu$ rates are sufficiently constrained in the fit.

**Strategy:**
- constrain pep $\nu$ rate based on solar luminosity constraint coupled to SSM predictions on the pp to pep rate ratio plus the most recent oscillation parameters (1.4% accuracy) – J. Bergstrom et al., JHEP, 2016:132, 2016
- constrain $^{210}$Bi through its link to daughter $^{210}$Po ($\alpha$). However:
  - The intrinsic value of $^{210}$Po rate is perturbed by the convective motions within the IV, caused the seasonal and man-made temperature change in the Hall C
  - Need thermal insulation in order to stop convective motions
Effort in reducing $^{210}$Po motion

- Double layer of mineral wool and active gradient stabilization system (2014-2016)
- 54 temperature monitoring probes (2014-2015)
- Fluid dynamical simulations showed very good agreement with measured temperatures
- Hall C temperature stabilization (2019)
Low Polonium field (LPoF)

Low Po field 20 m$^3$ size from which we can infer the intrinsic $^{210}\text{Po}$ and hence $^{210}\text{Bi}$ – in agreement with fluid dynamical simulation

Reconstructed central position of LPoF over time for different methods

$R(^{210}\text{Bi}) \leq 11.5 \pm 1.3$ cpd/100 tons
Data analysis strategy

- Results were obtained with the phase-III data taken in 2016-2020
- Event selection: a set of cuts is applied in order to maximize signal-to-background ratio
  - Remove cosmic muons and cosmogenics within 300 ms after muon, delayed coincidences $^{214}\text{Bi}-^{214}\text{Po}$
- In order to suppress external background, events are required to be reconstructed within the fiducial volume:
  - $r < 2.8 \text{ m and } -1.8 < z < 2.2 \text{ m}$
- Data are analyzed in the energy region:
  - $0.32\div2.64 \text{ MeV}$
- Interaction rates are obtained by maximizing a binned likelihood function
Multivariate fit in $0.32 \div 2.64$ MeV range

$^{210}$Bi and pep $\nu$ rates are constrained in the fit
CNO and other $\nu$ rates & backgrounds are free to vary

Final CNO result: Rate(CNO) = 7.2 (-1.8 +2.9) cpd/100 t.
Flux at Earth: = 7.0 (-1.9 +2.9) $\cdot$ $10^8$ cm$^{-2}$c$^{-1}$

No CNO hypothesis disfavored at 5$\sigma$. 
Result corroborated by a simplified counting analysis

ROI corresponds to energy window which maximizes CNO signal to bkgd: 780 ÷ 885 keV

Rate(CNO) = 5.6 ± 1.6 cpd/100 t. (~3.5σ) – in agreement with the result, obtained through the multivariate fit approach

CNO neutrino rate negative log-likelihood profile directly from multivariate fit (dashed black line) and after accounting for systematic uncertainties (solid black line)
Publications

- Comprehensive study of $^7$Be neutrinos:
Summary

Borexino has completely unraveled the two processes powering the Sun: proton-proton chain and CNO cycle

- Several years long effort to thermally stabilize the detector has finally led to the first detection of CNO neutrinos with $5\sigma$ significance.

First hint to the solar metallicity puzzle delivered

- Combined Borexino plus other solar data indicate $2\sigma$ preference of high-Z solar models.

By measuring neutrinos produced in different reactions of pp-chain Borexino examines the MSW-LMA neutrino oscillation paradigm both in the vacuum and the matter dominated regimes.