Solar Neutrino Physics with Borexino

Chiara Ghiano
on behalf of the Borexino collaboration
ICNFP 2019 — 8th International Conference on New Frontiers in Physics
OAC, Kolympari, Crete

photo: BOREXINO calibration
The BOREXINO detector

2212 8” ETL 9351 PMTs mounted inside the SSS

Water Tank
(d=18 m, V = 2400 m$^3$)
Shielding from $\gamma$ and n.
Water Cerenkov detector (Muon Veto) 208 PMTs

Stainless Steel Sphere
(d= 13.7 m, Volume = 1340 m$^3$)

Two Nylon balloons 150 µm thick
Inner Vessel
(8.5 m, V = 340 m$^3$)
Filled with 278 tons of scintillator (PC @ 1.5 g/l of PPO)
Inner Buffer (11.5 m)
filled with PC + DMP
Solar fusion reactions

Fusion reactions in the Sun (and in H-burning stars) that convert H to He → produce $\nu$

$$4p \rightarrow {}^4\text{He} + 2e^+ + 2\nu_e + 26.7 \text{ MeV}$$

**pp-chain** (5 $\nu$ species)

- $p+p \rightarrow ^2\text{H}+e^++\nu_e$
- $^2\text{H}+p \rightarrow ^3\text{He}+\nu$
- $^3\text{He}+e\rightarrow ^3\text{He}+\nu$
- $^3\text{He}+^3\text{He} \rightarrow ^4\text{He}+2p$
- $^3\text{He}+p \rightarrow ^4\text{He}+e^++\nu_e$

- pp chain:
  - pp-$\nu$: 99.6%
  - pep-$\nu$: 0.4%
  - hep-$\nu$: 85%

- $^7\text{Be}-\nu$: 99.87%
- $^7\text{Be}+e^- \rightarrow ^7\text{Li}+\nu_e$
- $^7\text{Li}+p \rightarrow ^8\text{Be}$
- $^8\text{B}-\nu$: 0.13%
- $^8\text{B}+p \rightarrow ^9\text{Be}+\gamma$
- $^8\text{Be}^*+p \rightarrow ^2\text{H}+e^++\nu_e$

CNO-cycle (3 $\nu$ species) contribute <1% energy production

- heavy star dominant

- $^{12}\text{C}+p \rightarrow ^{13}\text{N}+\gamma$
- $^{13}\text{N} \rightarrow ^{13}\text{C}+e^++\nu_e$
- $^{13}\text{C}+p \rightarrow ^{14}\text{N}+\gamma$
- $^{14}\text{N}+p \rightarrow ^{15}\text{O}+\gamma$
- $^{15}\text{O} \rightarrow ^{15}\text{N}+e^++\nu_e$
- $^{17}\text{F} \rightarrow ^{17}\text{O}+e^++\nu_e$
- $^{15}\text{N}+p \rightarrow ^{16}\text{O}+\gamma$

- CNO-$\nu$

- $^{16}\text{O}+p \rightarrow ^{17}\text{F}+\gamma$
- $^{15}\text{N}+p \rightarrow ^{16}\text{O}+\gamma$

- Still undetected!!!
Study the Sun with neutrinos
Study neutrinos with the Sun

(1) To measure solar neutrino flux
→ test Standard Solar Model

→ Astrophysics interest: Solve solar metallicity
Problem: tension between High Metallicity
and Low Metallicity Solar Models
( abundance of heavy elements in the Sun)

→ Agreement between optical and neutrino
luminosity: solar stability at $10^5$ years scale

→ Testing energy production mechanisms

<table>
<thead>
<tr>
<th>FLUX</th>
<th>B16-GS98</th>
<th>B16-AGSsmet</th>
<th>DIFF (HZ-LZ)/HZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp ($10^{10}$ cm$^{-2}$s$^{-1}$)</td>
<td>5.98(1±0.006)</td>
<td>6.03(1±0.005)</td>
<td>-0.8%</td>
</tr>
<tr>
<td>pep ($10^{8}$ cm$^{-2}$s$^{-1}$)</td>
<td>1.44(1±0.01)</td>
<td>1.46(1±0.009)</td>
<td>-1.4%</td>
</tr>
<tr>
<td>$^7$Be ($10^{8}$ cm$^{-2}$s$^{-1}$)</td>
<td>4.94(1±0.06)</td>
<td>4.50(1±0.06)</td>
<td>8.9%</td>
</tr>
<tr>
<td>$^8$B ($10^{6}$ cm$^{-2}$s$^{-1}$)</td>
<td>5.46(1±0.12)</td>
<td>4.50(1±0.12)</td>
<td>17.6%</td>
</tr>
<tr>
<td>$^{13}$N ($10^{8}$ cm$^{-2}$s$^{-1}$)</td>
<td>2.78(1±0.15)</td>
<td>2.04(1±0.14)</td>
<td>26.6%</td>
</tr>
<tr>
<td>$^{15}$O ($10^{8}$ cm$^{-2}$s$^{-1}$)</td>
<td>2.05(1±0.17)</td>
<td>1.44(1±0.16)</td>
<td>29.7%</td>
</tr>
<tr>
<td>$^{17}$F ($10^{8}$ cm$^{-2}$s$^{-1}$)</td>
<td>5.29(1±0.20)</td>
<td>3.26(1±0.18)</td>
<td>38.3%</td>
</tr>
</tbody>
</table>

(2) Particle Physics interest
→ confirm LMA-MSW

Borexino can measure the $P_{ee}$ (electron neutrino
Survival probability) both in the matter-enhanced
oscillation region and in the vacuum region.

→ testing the LMA (Large Mixing Angle) -
MSW Oscillation (matter effects) analysis
solution to Neutrino oscillations (energy
dependent day/night effects)
Solar Neutrinos Flux on Earth

- pp flux $\sim 91\%$
- $^7\text{Be}$ flux $\sim 7.6\%$
- CNO flux $\sim 0.8\%$
- $^8\text{B}$ $\sim 0.009\%$
- pp energy $< 0.423$ MeV

B16 - SSM

- pp $[\pm 0.6\%]$
- $^7\text{Be} [\pm 6\%]$
- $^{13}\text{N} [\pm 15\%]$
- $^{15}\text{O} [\pm 17\%]$
- $^{17}\text{F} [\pm 20\%]$
- pep $[\pm 1\%]$
- $^8\text{B} [\pm 12\%]$
- hep $[\pm 30\%]$

Chiara Ghiano, LNGS
Solar Neutrinos Flux on Earth

- **pp** \( \pm 0.6\% \)
- \(^{13}\text{N} \) \( \pm 15\% \)
- \(^{13}\text{O} \) \( \pm 17\% \)
- \(^{17}\text{F} \) \( \pm 20\% \)
- \(^{7}\text{Be} \) \( \pm 6\% \)
- **pep** \( \pm 1\% \)
- \(^{8}\text{B} \) \( \pm 12\% \)

- Water Cherenkov
- Chlorine
- Scintillator
- Radiochemical

Neutrino energy [MeV]

Solar neutrino flux \( [\text{cm}^{-2} \cdot \text{s}^{-1}] \)
Borexino performance

The Borexino PMTs detect the scintillation light produced by electrons scattered by Neutrinos

For each scintillation event Borexino records:

★ **Number of collected photons** (Photoelectron yield 500 p.e./MeV)
  → Energy
    Good energy resolution ~ 5% @ 1MeV

★ **Time of arrival of photons** → **Position reconstruction** (by T.O.F.)
    Good position reconstruction ~10cm @ 1 MeV

→ For $\alpha$ and $\beta^+$ we can apply the pulse shape discrimination $\alpha/\beta, \beta^+\beta^-$

**Drawbacks** → **No directionality**

→ **Crucial point: Extreme low background required!!!**

★ **Very low energy threshold** (~<100 keV)
Signal and backgrounds

Expected ~50 events/day on 100ton of liquid scintillator from neutrinos ~ 6 \times 10^{-9} \text{Bq/kg}

But

• Natural water is ~10 \text{Bq/Kg} in \text{^{238}U}, \text{^{232}Th} and \text{^{40}K}

• Air is ~10 \text{Bq/m}^3 in \text{^{39}Ar}, \text{^{85}Kr} and \text{^{222}Rn}

• Typical rock is ~100-1000 \text{Bq/m}^3 in \text{^{238}U}, \text{^{232}Th} and \text{^{40}K}

→ Borexino’s scintillator must be 9/10 orders of magnitude less radioactive than anything on Earth!
Signal and backgrounds

Expected ~50 events/day on 100ton of liquid scintillator from neutrinos → ~ $6 \times 10^{-9}$ Bq/kg

But
• Natural water is ~10 Bq/Kg in $^{238}\text{U}$, $^{232}\text{Th}$ and $^{40}\text{K}$
• Air is ~10 Bq/m$^3$ in $^{39}\text{Ar}$, $^{85}\text{Kr}$ and $^{222}\text{Rn}$
• Typical rock is ~100-1000 Bq/m$^3$ in $^{238}\text{U}$, $^{232}\text{Th}$ and $^{40}\text{K}$

→ Borexino’s scintillator must be 9/10 orders of magnitude less radioactive than anything on Earth!

HOW??
→ Principle of graded shielding: materials get more pure towards the detector core
→ purification of target mass

15 years of work to reach the required Radio-purity

UNPRECEDENTELY RADIO PURE DETECTOR!!

$^{238}\text{U} < 9.4 \times 10^{-20}$ g/g
$^{232}\text{Th} < 5.7 \times 10^{-19}$ g/g
Solar Neutrino Detection: Elastic Scattering

(1) Theory: Solar neutrino spectrum

(2) Data: Electron recoil spectrum in Borexino → $\nu + \text{backgrounds}$
Solar Neutrino Detection: Elastic Scattering

(1) Theory: Solar neutrino spectrum

(2) Data: Electron recoil spectrum in Borexino → $\nu +$ backgrounds

(3) Fit → $\nu +$ backgrounds rates
Borexino Achievements so far

**Purification I**

- $\nu(7\text{Be})$ flux\(^{[1-3]}\)
- $\nu(8\text{B})$ flux\(^{[4]}\)
- $\nu(\text{pep})$ flux\(^{[5]}\)
- $\nu(\text{CNO})$ limit\(^{[5]}\)
- $\nu(7\text{Be})$ day-night asymmetry\(^{[6]}\)
- Limit on NMM\(^{[1]}\)
- First Geo-$\nu$ observation at $> 4\sigma$\(^{[7]}\)
- Detailed study of the cosmogenics in LS
- Limits on rare processes
- Muon seasonal mod.

**Purification II**

- Improved radiopurity: (6 cycles of scintillator purification)
  - $^{85}\text{Kr}$ reduced by $\sim 4.6$
  - $^{210}\text{Bi}$: reduced by $\sim 2.3$
  - Th and U negligible ($\sim 10^{-19} \text{g/g}$)

**External Tank Insulation**

- $\textbf{pp solar neutrinos}^{[8]}$
- New results on the solar fluxes
  1st global spectral fit
  @ $(0.186-2.97) \text{ MeV}$!
  - Simultaneous measurement of $\text{pp}$, $7\text{Be}$, $\text{pep}$ neutrinos\(^{[9]}\)
  - Seasonal modulation of $7\text{Be}$\(^{[10]}\)
  - New limit on neutrino magnetic moment\(^{[11]}\)
  - Improved $8\text{B}$ measurement\(^{[12]}\)
  - Geoneutrinos evidence at $5\sigma$\(^{[13]}\)

**Phase I (2007-2010)**

- 2010
- 2012

**Phase II (2012-2016)**

**Phase III**

- The detector has been stabilized in temperature;
  Attempt to search for CNO neutrinos in progress

---

Phase I vs Phase II

**Phase 1**
- analysis split into energy ranges.
- $^7$Be, pep, $^8$B → fitted separately

**Phase 2**
- lower radioactive background levels:
  - $^{85}$Kr (factor 4.6 reduction w.r. Phase I),
  - $^{210}$Bi (factor 2.3 reduction w.r. Phase I),
  - $^{210}$Po
- → all low-energy fluxes determined in combined fit
  - (pp, $^7$Be, pep, CNO)
Comprehensive measurement of pp-chain solar neutrinos

Analysis performed in two energy ranges:

- **LER** → **pp**, **pep**, **⁷Be**, **CNO**
  
  (0.19 - 2.93 MeV)
  
  Exposure: 1291.51 days × 71.3 t
  
  First simultaneous extraction of pp, pep and **⁷Be** rates

- **HER** → **⁸B**, **hep**
  
  (3.2 - 16 MeV)
  
  **HER-I** (3.2 – 5.7 MeV)
  
  **HER-II** (5.7 – 16 MeV)

  no natural long-lived radioactive background above 5 MeV

  Exposure **HER-I**: 2062.4 days × 227.8 t

  Exposure **HER-II**: 2062.4 days × 266.0 t

  Lowest energy threshold

  → HER and LER have different backgrounds
Comprehensive measurement of pp-chain solar neutrinos

Analysis performed in two energy ranges:

- **LER → pp, pep, $^7$Be, CNO**
  
  (0.19 - 2.93 MeV)
  
  Exposure: 1291.51 days $\times$ 71.3 t
  
  First simultaneous extraction of pp, pep and $^7$Be rates

- **HER → $^8$B, hep**
  
  (3.2 - 16 MeV)
  
  HER-I (3.2 – 5.7 MeV)
  
  HER-II (5.7 – 16 MeV)
  
  no natural long-lived radioactive background above 5 MeV
  
  Exposure HER-I: 2062.4 days $\times$ 227.8 t
  
  Exposure HER-II: 2062.4 days $\times$ 266.0 t
  
  Lowest energy threshold

$\rightarrow$ HER and LER have different backgrounds
**11C background rejection**

Three-fold Coincidence technique (TFC) for 11C tagging
suppression of cosmogenic 11C (e+) ($\tau = 29.4$ min)

- Space-time correlation between muon track, neutron capture, 11C decay

$\mu + ^{12}\text{C} \rightarrow n + ^{11}\text{C} + ^{\mu}$

$\mu^+$ can form ortho-positronium with 50% probability and ~3ns lifetime in Borexino’s scintillator

$\rightarrow$ formation of different pulse shapes for electrons and positrons
$\rightarrow$ distribution of scintillation time signal for $e^+$ delayed with respect to $e^-$
$\rightarrow$ different event topology (energy deposit is not point-like because of the two annihilation gammas)

$\rightarrow$ use such difference to discriminate $e^+/e^-$ events

(92±4)% $^{11}$C-tagging efficiency
(64.28±0.01)% of the total exposure in the TFC-subtracted spectrum

$^{11}$C rate:
27 $\rightarrow$ 2.5 cpd/100tons

**PULSE SHAPE technique to discriminate $\beta^-\beta^+$ events**

- $e^+$ can form ortho-positronium with 50% probability and -3ns lifetime in Borexino’s scintillator

$^{11}$C $\rightarrow^{11}$Be + $e^+ + \nu_e$
Main analysis variable is visible energy

→ **Spectral fit**: fit of known signal and background spectra to the data spectrum to extract neutrino rates
→ **Multivariate fit analysis** includes further variables in analysis fit, originally developed for pep-neutrino analysis (2012)

**Tecnique consists in including in the likelihood:**

★ **2 energy spectra**
  TFC-subtracted: 64% of exposure, 8% of $^{11}\text{C}$
  TFC-tagged: 46% of exposure, 92% of $^{11}\text{C}$

★ **pulse shape analysis for $\beta^+/\beta^-$ separation**
  Pulse-shape discriminator (PSD) of $e^+/e^-$:
  ($^{11}\text{C}$ decays emitting $\beta^+$) based on the difference of the scintillation time profile for $e^-$ and $e^+$

★ **Radial distribution**
  To better disentangle external background from internal contaminants
Multivariate analysis

Multivariate Likelihood Definition:

\[ \mathcal{L}_{MV}(\Theta) = \mathcal{L}_{tag}(\Theta) \cdot \mathcal{L}_{sub}(\Theta) \cdot \mathcal{L}_{PS}(\Theta) \cdot \mathcal{L}_{Rad}(\Theta) \]

- **2 energy spectra**
  - TFC tagged energy spectrum
  - Energy spectrum after TFC veto

- **Radial Distribution** → To better disentangle external background from internal contaminants

- **Pulse Shape Analysis**
Improved measurement of $^8$B solar neutrinos with 1.5 kt y of Borexino exposure

- **Fit** done on radial distribution in two energy ranges
  - HER-1 (3.2 - 5.7 MeV)
  - HER-2 (5.7 - 16 MeV)
  - No natural radioactivity expected above 5 MeV

- Data-set: January 2008 - December 2016
  - Total exposure: 1.5 kton years
    - (x 11.5 of the Phase I analysis)

- No FV cut

- Better understanding of backgrounds (external $\gamma$s, cosmogenic)

  Gamma due to n capture
  n produced through (a,n) reaction
  $^{208}$Tl from $^{232}$Th of the vessel
  and in the scintillator bulk
  PDF from MonteCarlo

- Lowest energy threshold among Real Time Detectors

$^8$B analysis performed in two energy ranges

Fit of the radial distribution of the events in the HER1

Lowest energy threshold among Real Time Detectors
**BX Phase II Results → Nature Paper**

- **pp neutrinos**: improved accuracy respect to previous Borexino results
- **$^7$Be neutrinos**: 2.7% precision, twice more accurate than SSM predictions
- **pep neutrinos**: significance $> 5\sigma$ for the first time (constraining CNO rate)
- **CNO neutrinos**: confirmed previous Borexino result, best upper limit available

First Simultaneous Precision Spectroscopy of pp, $^7$Be, and pep Solar Neutrinos with Borexino Phase-II

Improved measurement of $^8$B solar neutrinos with 1.5 kt y of Borexino exposure

$\nu(^8B)$ independent measurement

Comprehensive measurement of pp-chain solar neutrinos

*Nature volume 562, pages 505–510 (2018)*

**ARTICLE**

Comprehensive measurement of pp–chain solar neutrinos

The Borexino Collaboration

About 98 per cent of solar energy is produced through sequences of nuclear reactions that convert hydrogen into helium, starting from the fusion of two protons (the pp-chain). The neutrinos emitted by the two of these reactions represent a unique probe of the Sun’s internal working and, at the same time, offer an intense natural neutrino beam for fundamental physics. Here we report a complete study of the pp-chain. We measure the neutron–electron elastic-scattering rates for neutrinos in the $^8$B-solute region for the first time, constraining the CNO rate ($^{17}$O) for the first time with $\nu(8B)$ and the $^{12}$C($^{12}$C,${}^{12}$Be) reaction. We perform a comprehensive measurement of solar neutrinos from pp chain reactions and separately confirm, for the first time, direct solar $^{7}$Be neutrino measurements, improving the results of previous studies. Neutrino fluxes and energy spectra are measured with unprecedented accuracy, using a 1.5 kt y of Borexino exposure, with data collected from March 2012 to July 2018. This is the longest exposure of a solar neutrino detector under the Mediterranean Sea, near the bottom of the Martinengo Mar, which is the location of the CERN’s underground CNGS beam. We confirm the solar neutrino signal from $^{7}$Be and $^{8}$B, the latter being the proton–proton reaction (pp) that provides the highest intensity of the two primary termination of the pp-chain (pp– and $^{7}$Be) and an indication that the temperature profile in the Sun is more compatible with solar models that assume high surface metallicity. We also determine the survival probability of solar electrons neutrinos at different energies. This profiling simultaneously and with high precision the neutrino thermal–conversion paradigm, both in vacuum and in matter–dominated regimes.
### BX Phase II Results

All rates are fully compatible with and improve the uncertainty of the previously published Borexino results

<table>
<thead>
<tr>
<th></th>
<th>Phase I (cpd/100t)</th>
<th>Phase II (cpd/100t)</th>
<th>Uncertainty reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp</td>
<td>144±13±10</td>
<td>134±10±6</td>
<td>1.3</td>
</tr>
<tr>
<td>7Be</td>
<td>48.3±2.0±0.9</td>
<td>48.3±1.1</td>
<td>1.8</td>
</tr>
<tr>
<td>pep</td>
<td>3.1±0.6±0.3</td>
<td>(HZ) 2.43±0.36</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(LZ) 2.65±0.36</td>
<td></td>
</tr>
<tr>
<td>8B</td>
<td>0.217±0.038±0.008</td>
<td>0.223±0.015</td>
<td>2.4</td>
</tr>
<tr>
<td>CNO</td>
<td>&lt; 7.9 (95 % C.L.)</td>
<td>&lt; 8.1 (95 % C.L.)</td>
<td></td>
</tr>
</tbody>
</table>
Global analysis: electron neutrino survival probability

→ Only experiment to simultaneously test neutrino flavour conversion both in the vacuum and in the matter-dominated regimes

→ Most precise in the low-energy range (vacuum oscillations)

→ Excellent agreement with MSW-LMA solution

→ Rejection of vacuum LMA hypothesis at 98.2%

From the measured interaction rates and assuming HZ-SSM fluxes we get:

\[ P_{ee}(pp) = 0.57 \pm 0.10 \]
\[ P_{ee}(\^7\text{Be}, 862\text{KeV}) = 0.53 \pm 0.05 \]
\[ P_{ee}(\text{pep}) = 0.53 \pm 0.05 \]
\[ P_{ee}(\text{^8B}) = 0.36 \pm 0.8 \quad <E_{\nu}> = 8.7 \text{ MeV} \]
Global analysis: metallicity

The metallicity determines the opacity of solar plasma and, as a consequence, regulates the central T of the Sun and the Branching Ratios of the different pp-chain terminations.

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

Hints about HZ is weaker

Borexino only:
Hints in favor of HZ

LZ is disfavoured at 96.6%

note: only 1 σ theoretical uncertainty in the plot → important to reduce the theoretical uncertainty
Motivations:

⭐ **CNO neutrinos have never been detected**  
According to astrophysical models, CNO cycle is responsible of ~1% of the solar luminosity and it is the main mechanism of energy generation in massive stars

⭐ **CNO neutrinos measurement will allows to complete the SSM and stellar astrophysics**

⭐ help solar physicists to solve the solar metallicity problem

---

**Expected CNO rate (MSW-LMA):**

**High metallicity**

(B16)GS98  \( R_{\text{CNO}} = 4.91 \pm 0.55 \text{ cpd/100 t} \)

**Low Metallicity**

(B16)AGSS09  \( R_{\text{CNO}} = 3.52 \pm 0.37 \text{ cpd/100 t} \)

**Borexino:**  \( \Phi(\text{CNO}) < 7.9 \times 10^8 \text{ cm}^{-2} \text{ s}^{-1} \) (95% C.L.)  
\( R(\text{CNO}) < 8.1 \text{ cpd/100 t} \) (95% C.L.)
Key to the Solar metallicity: CNO flux

The detection of CNO neutrinos in Borexino is challenging:

- The low flux of CNO neutrinos (CNO cycle responsible of $\approx 1\%$ of the total Solar Power)
- The absence of prominent spectral features
- Anticorrelation with $^{210}\text{Bi}$ and pep $\nu$

Note also the low rate:

- $R(\text{CNO})$ expected $\sim 3-5$ cpd/100ton
- $R(\text{^{210}Bi})$ $\sim 20$ cpd/100ton
- $R(\text{pep})$ $\sim 2.7$ cpd/100ton

The spectral fit returns only the sum of the components, if both are left free!

Borexino data

CNO $\nu$ expected spectrum
$^{210}\text{Bi}$ spectrum
pep $\nu$ spectrum

$\rightarrow$ Strict anticorrelation between CNO $\nu$, pep $\nu$ and $^{210}\text{Bi}$
(1) Measure the $^{210}\text{Po}$ rate to costrain $^{210}\text{Bi}$ and remove degeneracy with CNO spectrum

$^{210}\text{Po}$ is “easier” to identify wrt $^{210}\text{Bi}$:
- Monoenergetic decay $\rightarrow$ “gaussian” peak
- $\alpha$ decay $\rightarrow$ pulse shape discrimination

If the $^{210}\text{Bi}$ is in radioactive equilibrium with $^{210}\text{Po}$, an independent measurement of the latter decay rate gives directly the $^{210}\text{Bi}$.

$^{210}\text{Bi}$ homogeneity is required $\rightarrow$ Thermal insulation for preventing convective motions and background mixing

(2) Temperature stabilization for preventing Background mixing

We observed $^{210}\text{Po}$ leaching out the nylon vessel and moving into the FV due to convection motions

$\rightarrow$ Thermal insulation & temperature control of the detector to reduce and control thermal gradients

(3) Purification

Further purification of the LS by water extraction to reduce $^{210}\text{Bi}$
**Temperature stabilization**

**Hardware**
- Insulation with rock wool (2015)
- Active T control system

**Monitoring**
- 54 temperature probes located both in the buffer and in the external tank and at different levels

**Results**
- The T profile has stabilized after insulation
- We are collecting data in these stable conditions to verify our capability to tag $^{210}$Bi from $^{210}$Po
Sensitivity to CNO $\nu$ detection

→ what level of precision on the background do we need?

Sensitivity studies with thousands of data-sets simulated with toy MC with different constraints on $^{210}$Bi and pep

→ Possibility to get a measurement of CNO flux between $2\sigma$ and $4\sigma$
Conclusions and Outlook

We are approaching 12 years of Borexino running with

- Unprecedented backgrounds
- A new wide range multivariate fit strategy
- Low-background techniques developed

Borexino alone has performed the full spectroscopy of pp-chain neutrinos

- Improved precision in all flux measurements
- $^7$Be (862+384) precision 2.7 % (stat+sys)
- 5σ evidence of pep Neutrinos for the first time
- Improved $^8$B measurement
- Borexino has slight preference to High Metallicity at 96.6 % C. L.
- Exclusion of Vacuum-LMA scenario at 98.2 % C. L.
- Simultaneous test of the $P_{ee}$ in the vacuum and matter dominated region;

- Test of Sun’s nuclear processes and its long term stability

CNO Sensitivity and Measurement under investigation

- Current Best Limit: $\Phi$ (CNO) < 7.9×10 cm$^{-2}$ s$^{-1}$ (95 % C.L.)
- Future: Continue data taking with stable conditions to attempt a CNO measurement
Evidence of pep $\nu$ signal

Applying more stringent cuts on FV and on the pulse-shape variable we can actually see the pep $\nu$ shoulder!

Break $^{210}\text{Bi} - \text{pep} - \text{CNO}$ correlation by fixing the CNO rate to:

$R_{\text{CNO}}$ (HZ) = 4.92 ± 0.55 cpd/100t
$R_{\text{CNO}}$ (LZ) = 3.52 ± 0.37 cpd/100t

→ 5$\sigma$ evidence of pep signal (including systematic errors)

Sensitivity studied from distribution of maximum likelihood estimators obtained from simulated datasets → Clear correlation between CNO, $^{210}\text{Bi}$ and pep
The Borexino signal

Mainly a solar neutrino experiment: 
\[ \nu_e + e^- \rightarrow \nu_e + e^- \]
in an organic liquid scintillator
But can detect also anti-neutrinos
(Geo, Reactors, SuperNova)

\* Neutrinos

Elastic scattering on electrons: 
\[ \nu + e^- \rightarrow \nu + e^- \]
Mono energetic \( \nu \) produce characteristic shoulder

\[ e^- \rightarrow e^- \]
\[ \nu_e, \nu_\mu, \nu_\tau \]
\[ e^- \rightarrow e^- \]
\[ \nu_e, \nu_\mu, \nu_\tau \]
\[ e^- \rightarrow e^- \]
\[ \nu_e \]
\[ Z^0 \]
\[ W \]

@1-2 MeV for electron flavour: \( \sigma \sim 10^{-44} \text{ cm}^2 \)
for \( \mu, \tau \) flavours: \( \sigma \) is ~6x smaller

\* Electron anti neutrinos

Inverse \( \beta \)-decay on p

\[ \bar{\nu}_e + p \rightarrow n + e^+ \]
\[ n \rightarrow p + d + \gamma (2.2 \text{ MeV}) \]
(250 \( \mu \text{sec} \))

Energy threshold
\[ = 1.8 \text{ MeV} \]

Electron flavour only
\( \sigma @ \text{few MeV} - 10^{-42} \text{ cm}^2 \)
(\(~100 \times \text{more than scattering}\))
**Sensitivity** studied from distribution of maximum likelihood estimators obtained from *simulated datasets*

Clear correlation between **CNO**, $^{210}\text{Bi}$ and *pep*
$^{210}\text{Po}$ rate evolution in time

**Decreasing trend:**
$^{210}\text{Po}$ out of equilibrium!
(1400 cpd/100ton at beginning of 2012)

**Irregular/“oscillating” trends:** possibly due to scintillator temperature variations (seasonally correlated)

$$R_{\text{Po}}(t) = (A - B)e^{-t/\tau_{\text{Po}}} + B$$

$\tau_{\text{Po}} \approx 200$ days

**A:** “unsupported term”, out of equilibrium
**B:** “supported term”, directly related to the $^{210}\text{Bi}$ parent

Core of the analysis: understand the validity and the features of this relation, quantifying this B-term.
### Background issues

<table>
<thead>
<tr>
<th>Source of contamination</th>
<th>Typical flux</th>
<th>Borexino requirements</th>
<th>Strategy (hardware)</th>
<th>Strategy (softw.)</th>
<th>Result phase 1</th>
<th>Result phase 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$</td>
<td>cosmic</td>
<td>$\sim 200$ s$^{-1}$m$^{-2}$ @ sea level</td>
<td>$&lt; 10^{-10}$s$^{-1}$m$^{-2}$</td>
<td>Underground, water detector</td>
<td>Cherenkov PS analysis</td>
<td>$&lt; 10^{-10}$ eff $&gt; 0.9992$</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>--</td>
<td>--</td>
<td>water</td>
<td>FV</td>
<td>negligible</td>
<td>negligible</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>PMT, SSS</td>
<td>--</td>
<td>buffer</td>
<td>FV</td>
<td>negligible</td>
<td>negligible</td>
</tr>
<tr>
<td>$^{14}$C</td>
<td>Intrinsic PC</td>
<td>$\sim 10^{-12}$ g/g</td>
<td>$\sim 10^{-18}$ g/g</td>
<td>selection</td>
<td>threshold</td>
<td>$\sim 2 \times 10^{18}$ g/g</td>
</tr>
<tr>
<td>$^{238}$U, $^{232}$Th</td>
<td>Dust, metallic</td>
<td>$10^{-5}$-$10^{-6}$ g/g</td>
<td>$&lt; 10^{-16}$ g/g</td>
<td>Distillation</td>
<td>Tagging $\alpha/\beta$</td>
<td>$1.6+0.1 \times 10^{-17}$ g/g</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>WE, filtration, mat. Selection, cleanliness</td>
<td></td>
<td>$5.1+1 \times 10^{-18}$ g/g</td>
</tr>
<tr>
<td>$^7$Be</td>
<td>cosmogenic</td>
<td>$\sim 3 \times 10^{-2}$ Bq/t</td>
<td>$&lt; 10^{-6}$ Bq/t</td>
<td>distillation</td>
<td>--</td>
<td>Not seen</td>
</tr>
<tr>
<td>$^{40}$K</td>
<td>Dust, PPO</td>
<td>$\sim 2 \times 10^{-6}$ g/g (dust)</td>
<td>$&lt; 10^{-18}$ g/g</td>
<td>Distillation, WE</td>
<td>--</td>
<td>Not seen</td>
</tr>
<tr>
<td>$^{210}$Po</td>
<td>Surface cont. from $^{222}$Rn</td>
<td></td>
<td>$&lt; 1 c/d/t$</td>
<td>Distillation, WE, filtration, cleanliness</td>
<td>fit</td>
<td>May '07 70 c/d/t</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>fit</td>
<td>Jan '10 $\sim 1$ c/d/t</td>
</tr>
<tr>
<td>$^{222}$Rn</td>
<td>Emanation from materials, rock</td>
<td>10 Bq/l air, water 100-1000 Bq rock</td>
<td>$&lt; 10$ cpd 100 t</td>
<td>$N_2$ stripping</td>
<td>cleanliness</td>
<td>$&lt; 1$ cpd 100t</td>
</tr>
<tr>
<td>$^{39}$Ar</td>
<td>Air, cosmogenic</td>
<td>17 mBq/m$^3$ (air)</td>
<td>$&lt; 1$ cpd 100 t</td>
<td>$N_2$ stripping</td>
<td>fit</td>
<td>$&lt; 85$Kr</td>
</tr>
<tr>
<td>$^{85}$Kr</td>
<td>Air, nuclear weapons</td>
<td>1 Bq/m$^3$ (air)</td>
<td>$&lt; 1$ cpd 100 t</td>
<td>$N_2$ stripping</td>
<td>fit</td>
<td>$30 \pm 5$ cpd/100t</td>
</tr>
<tr>
<td>$^{210}$Bi</td>
<td>Surface cont. from $^{220}$Rn</td>
<td></td>
<td></td>
<td>Water extraction</td>
<td>fit</td>
<td>$10-50$ cpd/100t</td>
</tr>
</tbody>
</table>
BX Phase II Results
arXiv : 1707.09279

<table>
<thead>
<tr>
<th>Solar ν</th>
<th>Borexino experimental results</th>
<th>B16(GS98)-HZ</th>
<th>B16(AGSS09)-LZ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rate [cpd/100 t]</td>
<td>Flux [cm$^{-2}$s$^{-1}$]</td>
<td>Rate [cpd/100 t]</td>
</tr>
<tr>
<td>$pp$</td>
<td>134 ± 10$^{+6}_{-10}$</td>
<td>(6.1 ± 0.5$^{+0.3}_{-0.5}$) × 10$^{10}$</td>
<td>131.1 ± 1.4</td>
</tr>
<tr>
<td>$^7$Be</td>
<td>48.3 ± 1.1$^{+0.4}_{-0.7}$</td>
<td>(4.99 ± 0.11$^{+0.06}_{-0.08}$) × 10$^{9}$</td>
<td>47.9 ± 2.8</td>
</tr>
<tr>
<td>pep (HZ)</td>
<td>2.43 ± 0.36$^{+0.15}_{-0.22}$</td>
<td>(1.27 ± 0.19$^{+0.08}_{-0.12}$) × 10$^{8}$</td>
<td>2.74 ± 0.04</td>
</tr>
<tr>
<td>pep (LZ)</td>
<td>2.65 ± 0.36$^{+0.15}_{-0.24}$</td>
<td>(1.39 ± 0.19$^{+0.08}_{-0.13}$) × 10$^{8}$</td>
<td>2.74 ± 0.04</td>
</tr>
<tr>
<td>CNO</td>
<td>&lt; 8.1 (95% C.L.)</td>
<td>&lt; 7.9 × 10$^{8}$ (95% C.L.)</td>
<td>4.92 ± 0.55</td>
</tr>
</tbody>
</table>

$^{85}$Kr: Factor 4.6 reduction with respect to Phase-I
$^{210}$Bi: Factor 2.3 reduction with respect to Phase-I

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>$pp$</th>
<th>$^7$Be</th>
<th>pep</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fit method (analytical/MC)</td>
<td>-1.2</td>
<td>0.2</td>
<td>-4.0</td>
</tr>
<tr>
<td>Choice of energy estimator</td>
<td>-2.5</td>
<td>0.1</td>
<td>-2.4</td>
</tr>
<tr>
<td>Pile-up modeling</td>
<td>-2.5</td>
<td>0.5</td>
<td>0</td>
</tr>
<tr>
<td>Fit range and binning</td>
<td>-3.0</td>
<td>0.1</td>
<td>1.0</td>
</tr>
<tr>
<td>Fit models (see text)</td>
<td>-4.5</td>
<td>0.2</td>
<td>-6.8</td>
</tr>
<tr>
<td>Inclusion of $^{85}$Kr constraint</td>
<td>-2.2</td>
<td>0</td>
<td>-3.2</td>
</tr>
<tr>
<td>Live Time</td>
<td>-0.05</td>
<td>0.4</td>
<td>-0.05</td>
</tr>
<tr>
<td>Scintillator density</td>
<td>-0.05</td>
<td>0.6</td>
<td>-0.05</td>
</tr>
<tr>
<td>Fiducial volume</td>
<td>-1.1</td>
<td>0.6</td>
<td>-1.1</td>
</tr>
<tr>
<td>Total systematics (%)</td>
<td>-7.1</td>
<td>-1.5</td>
<td>-9.0</td>
</tr>
</tbody>
</table>
Temperature stabilization

- Insulation started
- Water Loop turned off
- 5th ring insulation completed
- Organ Pipes and 6th ring insulation completed
- CR4 floor and Top Organ Pipes insulation completed
- Temperature Active Control System tests started
- Hall C active control started
**Fit results**

Zoom into low-energy part of the spectrum

\[ \text{Events / (day \times 100 t \times N_p^{3/4})} \]

- \( ^7\text{Be} \rightarrow \) precision improved beyond 3% level
- \( \text{pp} \rightarrow \) absolute precision improved by 10%
- \( \text{pep} \rightarrow >5\sigma \) evidence in LZ/HZ, including systematics
- \( \text{CNO} \rightarrow \) slightly worse limit because of less stringent assumptions on pep rate
Seasonal modulations of the $^7$Be solar neutrino rate
Astroparticle Physics 92 (2017)

Search for the *seasonal variations of the neutrino interaction rate* due to the varying distance $L(t)$ between Sun and Earth during the year
→ Confirms the solar origin of the observed signal
→ Measurement of the astronomic year with solar neutrinos
→ The absence of an annual modulation is rejected at 99.99% C.L.

Only the events in the energy range: 215keV-715 keV

Fit to the evolution of the rate in time (bin of 30 days)

$\epsilon = 1.74 \pm 0.45 \%$
$T = 367 \pm 10 \text{ days}$
$\Phi = -18 \pm 24 \text{ days}$

After $^{210}$Po subtraction by pulse-shape discrimination
Borexino visible energy spectrum and background rejection

1. Raw spectrum
2. External and internal muon veto (veto of 300 ms after a muon in OD)
3. Fiducial volume cut for removing external background
Borexino backgrounds

**internal radioactivity**
traces of radioisotopes in the scintillator (U, Th, $^{40}$K)

**external $\gamma$ rays**
from fluid buffer, steel sphere, PMT glass and light concentrators ($^{40}$K, $^{208}$Tl, $^{214}$Bi)

**radon emanation**
from the PMTs and steel sphere

**cosmic muons**
and their secondaries

**cosmogenics**
neutrons and radionuclides from $\mu$ spallation and hadronic showers

**fast neutrons**
from external muons
Improved measurement of $^8$B solar neutrinos with 1.5 kt y of Borexino exposure

what is improved in analysis:

★ **Fit done on radial distribution in two energy ranges**
- HER-1 (3.2 - 5.7 MeV)
- HER-2 (5.7 - 16 MeV)

No natural radioactivity expected above 5 MeV

★ **Data-set: January 2008 - December 2016**
(Purification period removed)

★ **No FV cut**

★ **Total exposure: 1.5 kton years**
($\times$ 11.5 of the Phase I analysis)

★ **Better understanding of backgrounds**
(external $\gamma$s, cosmogenic)

★ **Lowest energy threshold among Real Time Detectors**

$^8$B analysis performed in two energy ranges

![Graph showing energy distribution with two energy ranges](image)

Selection cuts (27.6% dead time)

- Removed muons
- Neutron cut: 2 ms after all muons
- Cosmogenics cut: 6.5 after all internal muons ($^{12}$B, $^8$He, $^9$C, $^9$Li, $^8$B, $^8$He, $^8$Li)
- $^{10}$C TFC cut: 120 s, 0.8 m radius sphere around neutrons
- Fast coincidence cut: no $^{214}$Bi-$^{214}$Po
- Coincidence cut: no events closer than 5 s
Improved measurement of $^8$B solar neutrinos with 1.5 kt y of Borexino exposure

arXiv:1709.00756

- Radial Fit not Energy Fit → Not to assume shape of survival probability $P_{ee}$
- Radial information used to discriminate signals from external backgrounds

- Deep study of backgrounds close to the vessel border:
  - U/Th chain elements on the vessel (only $^{208}$Tl ranges above 3.2 MeV)
  - Emanation of $^{220}$Rn from the vessel → additional $^{208}$Tl component
  - High-energy gamma-rays from neutron capture on Fe/C

HER II Fit: [2950, 8500] p.e.  
$> 5.7$ MeV

HER I Fit: [1650, 2950] p.e  
3.2 to 5.7 MeV

Rate = $0.223^{+0.015+0.006}_{-0.016-0.006}$ cpd/100t

Flux = $(5.68^{+0.39+0.03}_{-0.41-0.03}) \times 10^6$ cm$^{-2}$ s$^{-1}$

Theoretical predictions:
Flux$=$ $5.46(1.0\pm0.12) \times 10^6$ cm$^{-2}$ s$^{-1}$ (HZ)
Flux$=$ $4.50(1.0\pm0.12) \times 10^6$ cm$^{-2}$ s$^{-1}$ (LZ)