How can CNO neutrinos unravel the solar metallicity problem?

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on behalf of the Borexino collaboration

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University of Milan, INFN Milan
1) Solar-ν and SSMs
**Solar neutrinos**

- Sun is powered by nuclear fusion reactions → neutrino emission
- "Photography" of the Sun core
- Two sequences: pp-chain (primary in the Sun, ~99% lum.) and the secondary CNO cycle

**Net reaction:**

\[
4p \rightarrow ^{4}\text{He} + 2e^{+} + (2\nu_{e}) + Q
\]

26.731 MeV
Solar neutrinos

strict interplay between astrophysics and particle physics

Solar neutrinos as messengers

Solar metallicity problem

CNO neutrinos

Sun as neutrino source

Flavor oscillations: matter effects, Non-Standard interactions...
Standard Solar Model

Describing the Sun evolution: from a protostar to the current star

Nuclear physics  Gravitation
Radiative opacity  Plasma physics

an interdisciplinary physics laboratory
Describing the Sun evolution: from a protostar to the current star

Input parameters:
- mass; H, He, metal fractions (X,Y,Z);
- nuclear astrophysical factors

Boundary conditions:
- $L_\odot$, $\tau_\odot$, surface metal to H abundance ($Z/X)_\odot$

Building equations:
- Mass conservation
- Nuclear reactions
- Hydrostatic equilibrium
- Energy transport

Standard Solar Model

Nuclear physics  Gravitation
Radiative opacity  Plasma physics
Standard Solar Model

Describing the Sun evolution: from a protostar to the current star

- Nuclear physics
- Gravitation
- Radiative opacity
- Plasma physics

Building equations:
- Mass conservation
- Nuclear reactions
- Hydrostatic equilibrium
- Energy transport

Predictions:
- Physical description of the global properties of the Sun
  including solar neutrino fluxes and sound speed profiles
Why are CNO-ν interesting?

1) Missing tile of the solar fusion puzzle
2) Primary mechanism in massive and older stars
3) Solar metallicity puzzle
   - re-evaluation of photospheric chemical composition → 20% reduction of solar metallicity (from HZ to LZ)
   - new sound speed profile inconsistent with helioseismology
   - Solar ν fluxes depend on metallicity (see later)

~1% discrepancy for LZ-SSM
Borexino detector

• **Low-energy spectroscopy of solar $\nu$, located at LNGS**

• Data-taking since 2007

• **Active mass**: 300t of ultrapure liquid scintillator

• Detection via **elastic scattering**

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

$x = e, \mu, \tau$

Graded shielding: buffer liquid and Gran Sasso

• **Low radioactivity**: $10^{-19}$ g/g $^{238}$U, $5 \cdot 10^{-18}$ g/g $^{232}$Th
  - Radiopure materials
Borexino timeline

**Phase-I** 2007-10

- Purifications
- 7Be-ν: 4.5% (original design goal)
- ν day-night asymmetry

**Phase-II** 2012-16

- Simultaneous spectroscopy of the ν pp-chain

**Phase-III** 2016-Feb 2020

- CNO-ν detection

**NeuTel talks**
- G. Bellini: Neutrino, Solar and star physics with Borexino
- A. C. Re: A successful strategy for the CNO measurement with Borexino: the multivariate Fit
- A. Göttel: Data analysis for a low Po field for the discovery of CNO neutrinos in Borexino
- Ö. Penek: Sensitivity to CNO cycle solar neutrinos in Borexino
Borexino CNO-ν detection

“Experimental evidence of neutrinos produced in the CNO fusion cycle in the Sun”

Borexino Collaboration, Nature 587 (2020) 577-582

CNO-ν flux: $\phi_{CNO} = 7.0 \left(1^{+0.43}_{-0.29}\right) \times 10^8 \text{ cm}^{-2}\text{s}^{-1}$

No CNO-ν hypothesis excluded at $5.0\sigma$ significance level
Solar physics implications

- HZ/LZ discrimination
- C+N abundance in solar core
Borexino $\nu$ results

<table>
<thead>
<tr>
<th>$\nu$ source</th>
<th>$\Phi$(BX) [cm$^{-2}$s$^{-1}$]</th>
<th>$\Phi$(SSM) [cm$^{-2}$s$^{-1}$]</th>
<th>$\Delta\Phi/\Phi$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNO</td>
<td>$7.0(1^{+0.43}_{-0.29}) \cdot 10^8$</td>
<td>$4.88(1 \pm 0.16) \cdot 10^8$ (HZ)</td>
<td>28%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$3.51(1 \pm 0.14) \cdot 10^8$ (LZ)</td>
<td></td>
</tr>
<tr>
<td>$^7$Be</td>
<td>$5.0(1 \pm 0.027) \cdot 10^9$</td>
<td>$4.93(1 \pm 0.06) \cdot 10^9$ (HZ)</td>
<td>17%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$4.50(1 \pm 0.06) \cdot 10^9$ (LZ)</td>
<td></td>
</tr>
<tr>
<td>$^8$B</td>
<td>$5.68(1 \pm 0.076) \cdot 10^6$</td>
<td>$5.46(1 \pm 0.12) \cdot 10^6$ (HZ)</td>
<td>8%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$4.50(1 \pm 0.12) \cdot 10^6$ (LZ)</td>
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</table>

CNO reactions are catalyzed by metals
$\rightarrow$ CNO flux is strongly dependent on metallicity ($\sim 28\%$ difference)
Simulations of pseudo-datasets: triplets of $^7$Be, $^8$B, CNO fluxes according to LZ-SSM and HZ-SSM

1. 3D gaussian distributions
2. $\chi^2$ and test statistics $t$

\[
\Phi_{\text{data}} = \left( \Phi_{\text{Be}}^{\text{data}}, \Phi_{\text{B}}^{\text{data}}, \Phi_{\text{CNO}}^{\text{data}} \right) \quad \text{(Pseudo-)data results}
\]

\[
\Phi_{\text{SSM}} = \left( \Phi_{\text{Be}}^{\text{SSM}}, \Phi_{\text{B}}^{\text{SSM}}, \Phi_{\text{CNO}}^{\text{SSM}} \right) \quad \text{SSM predictions}
\]

\[
\sum^{\text{tot}} = \sum^{\text{BX}} + \sum^{\text{SSM}} \quad \text{Th+Exp error matrix}
\]

\[
\chi^2 = \left( \Phi_{\text{data}} - \Phi_{\text{SSM}} \right)^T \left( \sum^{\text{tot}} \right)^{-1} \left( \Phi_{\text{data}} - \Phi_{\text{SSM}} \right)
\]
HZ vs LZ: hypothesis testing

<table>
<thead>
<tr>
<th>Borexino results</th>
<th>LZ disfavoring</th>
</tr>
</thead>
<tbody>
<tr>
<td>7Be-ν + 8B-ν (Phase-II)</td>
<td>1.8σ</td>
</tr>
<tr>
<td><strong>CNO-ν + 7Be-ν + 8B-ν (Phase-III and Phase-II)</strong></td>
<td>2.1σ</td>
</tr>
</tbody>
</table>

- Borexino CNO rate = $7.2 _{-1.7}^{+2.9}$ cpd/100t,
  ○ compatible with both HZ-SSM and LZ-SSM (0.5σ and 1.3σ)

- Limiting factors:
  1) Experimental error (~23%) should be lowered to ~10% to impact on HZ/LZ testing.
  2) The precision of the solar model predictions astrophysical S-factors $S_{114}$ (CNO, 7.4%), $S_{34}$ ($^7$Be, 3.4%), $S_{17}$ ($^8$B) → reduction of nuclear cross section uncertainties is crucial.
Determination of C+N core abundance

- CNO fluxes directly (and indirectly) depend on Carbon and Nitrogen content in solar core
- pp chain fluxes depend indirectly on metallicity, via T of solar core

Solar-$\nu$ fluxes estimations $\rightarrow$ degeneracy of metallicity + $T_c$ + opacity

How to disentangle them to extract C and N content?
Determination of C+N core abundance

$^8\text{B-}\nu$ as a thermometer of solar core:
- CNO-\$\nu$ and $^8\text{B-}\nu$ fluxes depends on $T_c$ by power-laws; $\Phi_i \sim T_c^{\gamma_i}$
- Taking a ratio, dependence on $T_c$ is nearly cancelled out
- Only the dependence on the C+N content holds

Projected uncertainty for C+N abundance from a CNO-\$\nu$ measurement (HZ or LZ).
- Borexino CNO-\$\nu$ rate: $7.2^{+2.9}_{-1.7}$ cpd/100t
- Error dominated by experimental uncertainty
- Future measurement $\sigma_{\text{CNO}} = 0.5$ cpd/100t (~10%)
  $\rightarrow$ C+N constrained at 15% level (as photospheric techniques)
Conclusions

● Borexino provided the first direct experimental evidence of CNO-\(\nu\)
● Combining Borexino CNO-\(\nu\) + \(^7\)Be-\(\nu\) + \(^8\)B-\(\nu\) measurements, LZ scenario is mildly disfavoured (2.1\(\sigma\))
  ○ Limiting factor: CNO-\(\nu\) experimental error

Future perspectives

● If next-future experiments lower CNO error to 10%:
  ○ Statistically significant distinction between LZ/HZ
  ○ Determination of C and N abundance in the sun, combining \(\phi(\text{CNO})\) and \(\phi(\text{8B})\)
Thank you!
Thank you!

Borexino NeuTel 2021 talks

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- A. C. Re: A successful strategy for the CNO measurement with Borexino: the Multivariate Fit
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Backup
Why a CNO-ν measurement is challenging?

Spectral degeneracy between CNO-ν, pep-ν, ⁴⁰⁰Bi background

Borexino Phase-III energy spectrum

pep-ν neutrinos signal is constrained according to Standard Solar Model predictions (1.4% precision level)

Low CNO-ν signal/background ratio (~3-6 cpd/100t)
Why a CNO-ν measurement is challenging?

Spectral degeneracy between CNO-ν, pep-ν, ²¹⁰Bi background

The annoying ²¹⁰Bi background is constrained independently on the spectral fit → secular equilibrium with its daughter ²¹⁰Po

See A. Göttel flash talk “Low Po field”
Borexino CNO-ν measurement

**Multivariate fit (below, the energy fit)**
See A. C. Re talk

**-2LnL CNO rate profile**

CNO rate: $7.2^{+2.9}_{-1.7}$ cpd/100t $\rightarrow$ CNO flux: $\phi_{\text{CNO}} = 7.0 \left(1^{+0.43}_{-0.29}\right) \times 10^8 \text{ cm}^{-2}\text{s}^{-1}$

First CNO neutrino detection, $5.0\sigma$ significance level

See G. Bellini talk on 23/2
**HZ vs LZ: test statistics**

\[
\chi^2(\text{SSM}) = (\Phi^{\text{SSM}} - \Phi^{\text{Exp}})^T (\Sigma^{\text{SSM}} + \Sigma^{\text{Exp}})^{-1} (\Phi^{\text{SSM}} - \Phi^{\text{Exp}})
\]

Distributions of the test statistics \( t \):

\[
t = -2 \log \left[ \mathcal{L}(\text{HZ}) / \mathcal{L}(\text{LZ}) \right] = \chi^2(\text{HZ}) - \chi^2(\text{LZ})
\]

Median discovery power:

- \( \sigma_{\text{CNO}} = 1.5 \text{ cpd/100t (~30-40%)}: \) 1.7\( \sigma \)
- \( \sigma_{\text{CNO}} = 0.5 \text{ cpd/100t (~10-14%)}: \) 2.1\( \sigma \)
Power law fluxes-temperature

$$\Phi_i \sim T_c^{\gamma_i}$$

<table>
<thead>
<tr>
<th></th>
<th>$pp$</th>
<th>$^7$Be</th>
<th>$^8$B</th>
<th>$^{15}$O</th>
<th>$^{13}$N</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma_i$</td>
<td>0.8</td>
<td>10.5</td>
<td>23</td>
<td>19.6</td>
<td>14.7</td>
</tr>
</tbody>
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D. Fuschini & F. Villante, private communication