The Sun and solar neutrinos

F. L. Villante
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Hydrogen Burning: PP chain and CNO cycle

The Sun is powered by nuclear reactions that transform H into \(^4\)He:

\[
4H + 2e^- \rightarrow \ ^4\text{He} + 2\nu_e + \text{energy}
\]

\[Q = 26.7 \text{ MeV (globally)}\]

Free stream – 8 minutes to reach the earth
Direct information on the energy producing region.

The PP-chain

The CN-NO cycle

The pp chain is responsible for about 99% of the total energy (and neutrino) production.

C, N and O nuclei are used as catalysts for hydrogen fusion.

CNO cycle is responsible for about 1% of the total neutrino (and energy) budget. Important for more advanced evolutionary stages.
The solar neutrino spectrum
The solar neutrino spectrum

\[ \Phi_{\text{pp}} = (6.6 \pm 0.7) \times 10^{10} \text{ cm}^{-2} \text{ s}^{-1} \]

Borexino, Nature 2014
First direct measurement of the solar pp-component
The solar neutrino spectrum

**Bergstrom et al, 2016**

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<th>Neutrino Type</th>
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**Units:**
- $pp: 10^{10} \text{ cm}^{-2} \text{ s}^{-1}$;
- $Be: 10^{9} \text{ cm}^{-2} \text{ s}^{-1}$;
- $\text{pep, N, O}: 10^{8} \text{ cm}^{-2} \text{ s}^{-1}$;
- $\text{B, F}: 10^{6} \text{ cm}^{-2} \text{ s}^{-1}$;
- $\text{hep}: 10^{3} \text{ cm}^{-2} \text{ s}^{-1}$

**First direct measurement of the solar pp-component**

\[\Phi_{pp} = (6.6 \pm 0.7) \times 10^{10} \text{ cm}^{-2} \text{ s}^{-1}\]
The solar neutrino survival probability

$$P_{ee} \approx 1 - \frac{1}{2} \sin^2(2\theta_{12})$$

Matter enhanced

$$P_{ee} \approx \sin^2(\theta_{12})$$
The solar neutrino survival probability

"Transition" at:  

\[ E^* = \frac{\Delta m^2_{21} \cos(2\theta_{12})}{2\sqrt{2} G_F n_{e,\odot}} \]

Vacuum averaged  

\[ P_{ee} \approx 1 - \frac{1}{2} \sin^2(2\theta_{12}) \]

Matter enhanced  

\[ P_{ee} \approx \sin^2(\theta_{12}) \]
The solar neutrino survival probability

Combined analysis of SK I-IV (PRL 2014) also provided 2.7 σ evidence for D/N effect (see Shigetaka Moriyama talk at this conference).

The transition region:

• Final confirmation of LMA-MSW paradigm
• Constraints on new physics beyond the standard 3ν paradigm: see e.g. Maltoni & Smirnov, Eur. Phys. J. 2016
“Advertising” electron-capture CNO neutrinos...

“Transition” at: 

$$E^* = \frac{\Delta m_{21}^2 \cos(2\theta_{12})}{2\sqrt{2} G_F n_{e,\odot}}$$

- ecCNO neutrinos:
  - produced by e.c. reactions within the CNO cycle \( \Phi_{ecCNO} \approx 1/20 \Phi_B \)
  - monochromatic (and located in the transition region)

J.N. Bahcall, PRD 1990
L.C. Stonehill et al., PRC 2004
F.L. Villante, PLB 2015
The Standard Solar Model (SSM)

Our comprehension of the Sun is based on the **Standard Solar Model (SSM)**. This implies:

- Stellar structure equations; 
  \(\alpha = \) mixing length

- Chemical evolution paradigm: 
  ZAMS homogenous model \((Y_{\text{ini}}, Z_{\text{ini}})\) 
  Nuclear reactions + elemental diffusion

- Knowledge of the properties of solar plasma 
  (i.e. opacity, equation of state, nuc. cross sections);

**Note that:**

*The Sun provide the benchmark for stellar evolution. If there is something wrong in solar models, then this is wrong for all the stars ...*
Latest (improved) SSM calculations
N.Vinyoles et al., 2016 – in preparation

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- Improved EOS;
- Updated astrophysical factors (\( S_{11}, S_{34}, S_{17}, S_{114} \));
- Different treatment of opacity uncertainties.

Heavy elements photospheric abundances \( \rightarrow \) inputs for SSM calculations

Grevesse et al. 98 (GS98): 1D atm. model (old) – High metallicity
Asplund et al. 09 (AGSS09): 3D + NLT model (new) – Low metallicity
(20% for C,N; 40% for O,Ne; 12% Fe,Si, S,Mg)

Note: GS98 and AGSS09 abundances are used as references but do not exhaust the list of possible values. See e.g.:
CO\textsuperscript{5}BOLD (Caffau et al, 2011)
Solar wind abundances (von Steiger & Zurbuchen, 2016) and criticisms (Serenelli et al., 2016).
- $^8B$ and $^7Be$ neutrino fluxes are decreased by about 5%
SSM and Neutrinos
N.Vinyoles et al., 2016 – in preparation

- $^8$B and $^7$Be neutrino fluxes are decreased by about 5%
- The recent updates brought GS98 (AGSS09) in better (worse) agreement with expt. data

Note that:
- Solar $\nu$–data did not differentiate among High-Z and Low-Z up to now;
- Significance is still marginal ($\approx 1\sigma$).
- Experimental errors are : 4.5% for $^7$Be; 2.5% for $^8$B.
- Theoretical (correlated) errors are: 6% for $^7$Be; 12% for $^8$B.
High-Z models are clearly preferred by helioseismology.

\[
\delta c \equiv \frac{c_{\text{obs}} - c_{\text{mod}}}{c_{\text{mod}}}
\]
The solar composition problem

There is something **wrong** or **unaccounted** in solar models

- Are the new abundances (i.e. the atmospheric model) **wrong**?

- Are properties of the solar matter (e.g. **opacity**) correctly described?
  
  see e.g. Villante, ApJ 2011  
  Bailey et al, Nature 2015  
  Krief et al, arXiv:1603.01153

- Non standard effects (e.g. DM accumulation in the solar core)?
  
  see e.g. Vincent et al. – arxiv:1411.6626 / 1504.04378 / 1605.06502

- Is the **chemical evolution** not understood (extra mixing?) or peculiar (accretion?) with respect to other stars?
  
  see e.g. Serenelli et al. – ApJ 2011

**Note that:**

It is not just the problem of deciding between AGSS09 (new) and GS98 (old and presumably wrong) abundances
CNO neutrinos

- Probe the dominant H-burning mechanism in massive and/or evolved stars
CNO neutrinos

- Probe the dominant H-burning mechanism in massive and/or evolved stars
- Provide a direct determination of the C+N abundance in the solar core:

\[
\frac{\Phi(^{15}O)}{\Phi(^{15}O)_{SSM}} \left/ \left[ \frac{\Phi(^{8}B)}{\Phi(^{8}B)_{SSM}} \right]^{0.785} \right. = \left[ \frac{C + N}{C_{SSM} + N_{SSM}} \right] (1 \pm 0.4\% (env) \pm 2.6\% (diff) \pm 10\% (nucl))
\]

Serenelli et al., PRD 2013

- $^{8}B$ neutrinos are used as a solar thermometer;
- $^{15}O/^{8}B \rightarrow$ breaks the (otherwise complete) degeneracy between temperature stratification (i.e. opacity, DM accumulation, etc.) and chemical composition effects (accretion, diffusion, atmospheric models, etc.)

High-Z vs. Low-Z:

\[
\frac{\Phi_{GS98}(^{15}O)}{\Phi_{AGSS09}(^{15}O)} - 1 \simeq 40\%
\]
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High-Z vs. Low-Z:

\[
\frac{\Phi_{GS98}(^{15}O)}{\Phi_{AGSS09}(^{15}O)} - 1 \approx 40\%
\]

Beyond solar composition problem (10%):
CNO neutrinos allow us to test for mixing processes in the Sun (and other stars)

\[
Y(r) = Y_{ini} \left[ 1 + D_Y(r) \right] + Y_{nuc}(r)
\]

\[
Z(r) = Z_{ini} \left[ 1 + D_Z(r) \right]
\]
Is it possible to observe CNO neutrinos in LS?

The detection of CNO neutrinos is very difficult:
- Low energy neutrinos $\rightarrow$ endpoint at about 1.5 MeV
- Continuous spectra $\rightarrow$ do not produce recognizable features in the data.
- Limited by the background produced by beta decay of $^{210}$Bi.

Event spectrum in ultrapure liquid scintillators (Borexino-like)

GS98 – 5.1 cpd/100 ton
AGSS09 – 3.6 cpd/100 ton

20 cpd/100 ton
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Determining \(^{210}\text{Bi}\) from \(^{210}\text{Po}\) time evolution?

*Not impossible, in principle. Very difficult, in practice* …..

Villante et al., PLB 2011
How to improve?

Increase the detector depth  \[ \rightarrow \] reduction of cosmogenic $^{11}$C background

SNO+: factor 100 lower than BX

Consider larger detectors  \[ \rightarrow \] Stat. uncertainties scales as $1/M^{1/2}$

SNO+ (1 kton), LENA (50 kton)

The final accuracy depends, however, on the internal background ($^{210}$Bi)

Borexino: 20cpd/100 ton  \[ \rightarrow \] 150 nuclei / 100 ton
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Future Proposals

\begin{itemize}
  \item Water based Liquid Scintillators (WbLS)
  \item “Salty” WbLS \(\rightarrow\) doped (1% by mass) with \(^7\text{Li}\) (CC detection of \(\nu_\text{e}\) on \(^7\text{Li}\))
  \item \textbf{Advanced Scintillator Detector Concept} discussed in \textit{arXiv:1409.5864} (assuming 30-100 kton detector)
\end{itemize}

\textbf{See also G. Orebi-Gann talk@Neutrino2014}
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- G2 DD dark matter experiments will probe solar neutrinos, see e.g.
  Cerdeno et al., arXiv:1604.01025;
  Franco et al. arXiV:1510.04196 (300 ton Lar-detector@LNGS for solar-$\nu$).
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• ecCNO neutrinos: A challenge for gigantic ultra-pure LS detectors (Villante, PLB 2015)
Expt. requirements: as clean (and deep) as Borexino;
as big as JUNO;
Summary and conclusions

✓ Helioseismology (and neutrinos) shows that a solar composition problem exists.
   This could potentially indicate inadequacies in the standard solar model paradigm.

✓ Borexino opened the way to pp-neutrino detection and tested the dominant hydrogen burning mechanism in the Sun.

✓ CNO neutrinos would allow us to see the dominant hydrogen burning mechanism in more massive and/or evolved stars and to test for mixing processes in the Sun.

✓ CNO neutrino detection requires careful bkgd evaluation in existing or next future LS detectors and/or new experimental approaches.
Thank you
Additional slides
Latest (improved) SSM calculations
N.Vinyoles et al., 2016 – in preparation

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$^8B @ 2.5\% \ (SNO & SK)$ and now $^7Be @ 4.5\% \ (Borexino)$
theoretical uncertainties are dominant (6\% for $^7Be$ and 12\% for $^8B$)

CNO neutrinos essentially not constrained

$pp$ and $pep$ are strongly bound by the “luminosity constraint”
Otherwise directly measured by Borexino @ 10\% (see N. Rossi talk at this conference)
Observational constraints on n fluxes – Bergstrom et al, JHEP 2016
Helioseismology

The Sun is a non radial oscillator. The observed oscillation frequencies can be used to determine the properties of the Sun. Linearizing around a known solar model:

\[
\frac{\delta \nu_{nl}}{\nu_{nl}} = \int_0^R \, dr \, K_{u,Y}^{nl}(r) \frac{\delta u}{u}(r) + \int_0^R \, dr \, K_{Y,u}^{nl}(r) \delta Y + \frac{F(\nu_{nl})}{\nu_{nl}}
\]

- **squared isothermal sound speed**
- **surface helium abundance**

Related to temperature stratification in the sun

See Basu & Antia 07 for a review
Re-determination of the photospheric abundances of nearly all available elements (inputs for SSM calculations)

Improvements with respect to previous analysis(*):

- 3D model instead of the classical 1D model of the lower solar atmosphere

- Careful and very demanding selection of the spectral lines... AVOID blends!!! NOT TRIVIAL!!!

- Careful choice of the atomic and molecular data NOT TRIVIAL!!!!

- NLTE instead of the classical LTE hypothesis... WHEN POSSIBLE !!!

- Use of ALL indicators (atoms as well as molecules, CNO)

- Downward revision of heavy elements photospheric abundances ...

\[ [I/H] \equiv \log (N_I/N_H) + 12 \]

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<td>0.23</td>
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<td>N</td>
<td>7.92 ± 0.06</td>
<td>7.83 ± 0.05</td>
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</tr>
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<td>O</td>
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<td>0.38</td>
</tr>
<tr>
<td>Ne</td>
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</tr>
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<td>Mg</td>
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<td>0.12</td>
</tr>
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<td>Si</td>
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</tr>
<tr>
<td>Fe</td>
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</tr>
<tr>
<td>Z/X</td>
<td>0.0229</td>
<td>0.0178</td>
<td>0.29</td>
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(*)N. Grevesse talk at PHYSUN10
The role of metals

A change of the solar composition produces the same effects on the helioseismic observables and on neutrino fluxes (except CNO neutrinos) of a suitable change of the solar opacity profile $\delta \kappa(r)$.

$$\delta \kappa(r) = \sum_j \frac{\partial \ln \kappa(r)}{\partial \ln Z_j} \delta Z_j$$

- Opacity (not composition) is directly constrained by present obs. data.
- The required variations are too large wrt uncertainties ($\approx$ few %)
- Different admixtures $\{\delta z_j\}$ can reproduce (equally well) the required $\delta \kappa(r)$;

$\delta Z_{\text{CNO}} = \delta Z_{\text{Ne}} = 0.45; \delta Z_{\text{Heavy}} = 0.19$

$\delta Z_{\text{CNO}} = 0.37; \delta Z_{\text{Ne}} = 0.80; \delta Z_{\text{Heavy}} = 0.13$

Wrong surface composition?

We can use helioseismology + neutrinos ($R_b, Y_b; \Phi_B, \Phi_{Be}; c_1, ..., c_{30}$) to determine the optimal composition (Villante et al. – ApJ 2014):

- The best-fit abundances are **consistent** at 1σ with GS98. The **errors** on the inferred abundances are **smaller** than what is obtained by observational determinations.

- Substantial agreement between the infos provided by the various obs. constraints. The quality of the fit is quite good being $\chi^2/\text{d.o.f.} = 39.6/32$.

![Two parameter analysis](chart)

\[ [\text{O/H}] = [\text{O/H}] + \log (1 + \delta z_{\text{CNO}}) \]
\[ [\text{Fe/H}] = [\text{Fe/H}] + \log (1 + \delta z_{\text{Heavy}}) \]

However, data are not effective in constraining composition **in more realistic scenarios**: - different admixtures $\{\delta z_i\}$ can reproduce (equally well) the required $\delta k(r)$; - no real constraints on the Ne/O ratio
Wrong opacity?

(Very) recent progress:

- Opacity is being measured at stellar interiors conditions (see Bailey et al., Nature 2015);
- Monochromatic opacity is higher than expected for iron (up to a factor 2);
- Total opacity of solar plasma (integrated over the wavelength and summed over the composition), is increased by about 7%
Wrong chemical evolution?

Helioseismic observables and neutrino fluxes are sensitive to the metallicity of the radiative core of the Sun.

The observations determine the chemical composition of the convective envelope (2-3% of the solar mass).

Difference between AGSS09 and GS98 correspond to \( \approx 40M_\odot \) of metal, when integrated over the Sun’s convective zone.

Could this difference be accounted in non standard chemical evolution scenarios (e.g. by accretion of material with non standard composition)?


This is a well posed and extremely important question but ...

... no satisfactory solutions have been proposed up to now, in my opinion
Asymmetric DM

DM accumulation in the solar core:

- Additional energy transport;
- **Reduction** of the “effective opacity”;
- Modification of temperature profile;

Agreement with helioseismic data can be improved. However:

- DM accumulation do not provide the optimal opacity profile;
- Potential tension with neutrino fluxes and surface helium;
- **Caveat**: DM evaporation not accounted for (relevant for few GeV masses)

\[
\sigma = \sigma_0 \left( \frac{q}{q_0} \right)^2
\]

\[
\begin{align*}
m_\chi & = 3 \text{ GeV} \\
\sigma_0 & = 10^{-37} \text{ cm}^2 \\
q_0 & = 40 \text{ MeV}
\end{align*}
\]
Determining $^{210}\text{Bi}$ with the help of $^{210}\text{Po}$?

$$^{210}\text{Bi} \rightarrow ^{210}\text{Po} + e^- + \bar{\nu}_e$$
$$^{210}\text{Po} \rightarrow ^{206}\text{Pb} + \alpha$$

$\tau_{\text{Bi}} = 7.232 \text{ d}$
$\tau_{\text{Po}} = 199.634 \text{ d}$

Event spectrum in ultrapure liquid scintillators

- Deviations from the exponential decay law of $^{210}\text{Po}$ can be used to determine $^{210}\text{Bi}$
- Borexino already have the potential to probe the CNO neutrino flux ... but the detector should be stable (no convective motions) over long time scales.
ecCNO - Expected rates in Liquid Scintillators

Additional background sources:
- **Intrinsic:** negligible/tagged (with Borexino Phase-I radio-purity levels);
- **External:** reduced by self-shielding (Fid. mass reduced from 50 to \( \approx 20 \) kton in LENA);
- **Cosmogenic:** \(^{11}\)C overlap with the observation window.

\[R_{\text{ecCNO}} \approx 53 \text{ counts/10 kton/year}\]
\[R_{8B} \approx 1760 \text{ counts/10 kton/year}\]
\[R_{11C} \approx 1000 \text{ counts/10 kton/year}\]

\(S/\sqrt{B} \approx 1\) [for 10kton \( \times \) year exposure]

Signal comparable to stat. fluctuations for exposures 10 kton \( \times \) year or larger.

100 counts / year above 1.8 MeV in 20 kton detector \( \rightarrow 3\sigma\) detection in 5 year in LENA
## Significance of CNO measurement in LENA

### Assuming constraints of $^{210}$Bi rate at the 1% level:

<table>
<thead>
<tr>
<th>Time</th>
<th>CNO prec (stat.)</th>
<th>PEP prec. (stat.)</th>
<th>CNO significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 y</td>
<td>10.7%</td>
<td>2.5%</td>
<td>4.2 $\sigma$ (avg)</td>
</tr>
<tr>
<td>2 y</td>
<td>9.2%</td>
<td>1.9%</td>
<td>5.5 $\sigma$ (avg)</td>
</tr>
<tr>
<td>3 y</td>
<td>8.2%</td>
<td>1.7%</td>
<td>6.5 $\sigma$ (avg)</td>
</tr>
<tr>
<td>4 y</td>
<td>7.5%</td>
<td>1.6%</td>
<td>$&gt; 5\sigma$ (99% prob.)</td>
</tr>
<tr>
<td>5 y</td>
<td>7.0%</td>
<td>1.4%</td>
<td>$&gt; 5\sigma$ (99% prob.)</td>
</tr>
<tr>
<td>10 y</td>
<td>5.6%</td>
<td>1.1%</td>
<td>$&gt; 5\sigma$ (99% prob.)</td>
</tr>
</tbody>
</table>

### Assuming no constraints of $^{210}$Bi rate:

<table>
<thead>
<tr>
<th>Time</th>
<th>CNO prec (stat.)</th>
<th>PEP prec. (stat.)</th>
<th>CNO significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 y</td>
<td>22.7%</td>
<td>4.3%</td>
<td>0.7 $\sigma$ (avg)</td>
</tr>
<tr>
<td>2 y</td>
<td>16.0%</td>
<td>3.0%</td>
<td>1.8 $\sigma$ (avg)</td>
</tr>
<tr>
<td>3 y</td>
<td>13.1%</td>
<td>2.5%</td>
<td>2.8 $\sigma$ (avg)</td>
</tr>
<tr>
<td>4 y</td>
<td>11.3%</td>
<td>2.2%</td>
<td>3.7 $\sigma$ (avg)</td>
</tr>
<tr>
<td>5 y</td>
<td>10.1%</td>
<td>1.9%</td>
<td>4.5 $\sigma$ (avg)</td>
</tr>
<tr>
<td>10 y</td>
<td>7.2%</td>
<td>1.4%</td>
<td>8.1 $\sigma$ (avg)</td>
</tr>
</tbody>
</table>
In the future … Advanced Scintillator Detector Concept (ASDC)

It combines:
- Water based Liquid Scintillators (WbLS)
- High efficiency and ultra fast photosensor
- Deep underground location

“Salty” WbLS → doped (1% by mass) with $^7$Li
CC detection of $\nu_e$ on $^7$Li enhances spectral separation

30-100 kton scale detector
Cherenkov + Scintillation
100pe/MeV

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