Solar models and solar neutrinos: a quantitative analysis of the solar composition problem

F. L. Villante – University of L’Aquila and LNGS-INFN
Outline

• The solar composition problem
• Metals vs. opacity
• CNO and ecCNO neutrinos
• Summary and conclusions
The solar composition problem

The **downward revision** of heavy elements photospheric abundances ...

<table>
<thead>
<tr>
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The solar composition problem

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The **downward revision** of heavy elements photospheric abundances ...

![Graph showing solar composition](image)

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... leads to SSMs which **do not correctly reproduce** helioseismic observables

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<th>GS98</th>
<th>Obs.</th>
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<tr>
<td>$Y_b$</td>
<td>0.2319 (1 ± 0.013)</td>
<td>0.2429 (1 ± 0.013)</td>
<td>0.2485 ± 0.0035</td>
</tr>
<tr>
<td>$R_b/R_\odot$</td>
<td>0.7231 (1 ± 0.0033)</td>
<td>0.7124 (1 ± 0.0033)</td>
<td>0.713 ± 0.001</td>
</tr>
<tr>
<td>$\Phi_{pp}$</td>
<td>6.03 (1 ± 0.005)</td>
<td>5.98 (1 ± 0.005)</td>
<td>6.05(1±0.003)</td>
</tr>
<tr>
<td>$\Phi_{Be}$</td>
<td>4.56 (1 ± 0.06)</td>
<td>5.00 (1 ± 0.06)</td>
<td>4.82(1±0.05)</td>
</tr>
<tr>
<td>$\Phi_B$</td>
<td>4.59 (1 ± 0.11)</td>
<td>5.58 (1 ± 0.11)</td>
<td>5.00(1 ± 0.03)</td>
</tr>
<tr>
<td>$\Phi_N$</td>
<td>2.17 (1 ± 0.08)</td>
<td>2.96 (1 ± 0.08)</td>
<td>$\leq 6.7$</td>
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<tr>
<td>$\Phi_O$</td>
<td>1.56 (1 ± 0.10)</td>
<td>2.23 (1 ± 0.10)</td>
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($\approx 4\sigma$ discrepancies)

**Units:**
- $pp$: $10^{10}$ cm$^2$ s$^{-1}$
- $Be$: $10^9$ cm$^2$ s$^{-1}$
- pep, N, O: $10^8$ cm$^2$ s$^{-1}$
- B, F: $10^6$ cm$^2$ s$^{-1}$
- hep: $10^3$ cm$^2$ s$^{-1}$
How severe is the solar composition problem?

To combine observational infos, we need an estimator that is non-biased and that can be used as a figure-of-merit for solar models with different composition:

$$\chi^2 = \min_{\{\xi_I\}} \left[ \sum_Q \left( \frac{\delta Q - \sum_I \xi_I C_{Q,I}}{U_Q} \right)^2 + \sum_I \xi_I^2 \right].$$

where:

$$\{\delta Q\} = \{\delta \Phi_B, \delta \Phi_{Be}, \delta Y_b, \delta R_b; \delta c_1, \delta c_2, \ldots, \delta c_{30}\}$$

\(^7\text{Be} \) and \(^8\text{B} \) neutrino fluxes  
Surface helium and convective radius  
Sound speed data points (from Basu et al, 2009)

and:

$$\begin{align*}
U_Q \\
C_{Q,I}
\end{align*}$$

Uncorrelated (observational) errors  
Correlated (systematical) uncertainties

We consider 18 input parameters:

$$\{I\} = \{\text{opa, age, diffu, lum, } S_{11}, S_{33}, S_{34}, S_{17}, S_e7, S_{1,14}, S_{\text{hep}}, C, N, O, Ne, Mg, Si, S, Fe\}$$

Enviromental  
Nuclear  
Composition
The status of the AGSS09 standard solar model

The SSM implementing the AGSS09 composition provides a poor fit of the observational data ($\chi^2 / \text{d.o.f.} = 72.5/34$; $\chi^2_{\text{obs}} = 42.9$; $\chi^2_{\text{syst}} = 29.6$)

$$\chi^2 \equiv \chi^2_{\text{obs}} + \chi^2_{\text{syst}} = \sum_Q \tilde{X}_Q^2 + \sum_I \tilde{\xi}_I^2$$

$$\tilde{X}_Q \equiv \frac{\Delta Q_{\text{obs}} - \sum_I \tilde{\xi}_I C_{Q,I}}{U_Q \tilde{\xi}_I}$$

Pulls of systematic
The status of the AGSS09 standard solar model

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$$\chi^2 \equiv \chi^2_{\text{obs}} + \chi^2_{\text{syst}} = \sum_Q \tilde{X}^2_Q + \sum_I \tilde{\xi}_I^2$$

$$\xi_I \equiv \text{Pulls of systematic}$$
$$\tilde{X}_Q \equiv \frac{\delta Q_{\text{obs}} - \sum_I \tilde{\xi}_I C_{Q,I}}{U_Q}$$

The distribution of the pulls of systematics highlight tensions in the model:

Obs. data requires an increase of the metal abundance of the sun, in particular for light elements (O, Ne).

For comparison:
GS98-SSM gives $\chi^2 / \text{d.o.f.} = 47.3/34$
Inferring composition from obs. constraints

- We take the **surface abundances** \( z_j \equiv Z_{j,b}/X_b \) (with respect to hydrogen) as free parameters.

- We infer the **best-fit composition** by minimizing the \( \chi^2 \)

- To avoid unphysical results, the number of free parameters has to be reduced. We group metals according to the method by which they are determined

\[
1 + \delta z_{\text{CNO}} \equiv \frac{\tilde{Z}_C}{Z_C} \equiv \frac{\tilde{Z}_N}{Z_N} \equiv \frac{\tilde{Z}_O}{Z_O} \quad \text{(photosphere)}
\]

\[
1 + \delta z_{\text{Ne}} \equiv \frac{\tilde{Z}_{\text{Ne}}}{Z_{\text{Ne}}} \quad \text{(chromosphere and corona)}
\]

\[
1 + \delta z_{\text{Heavy}} \equiv \frac{\tilde{Z}_{\text{Mg}}}{Z_{\text{Mg}}} \equiv \frac{\tilde{Z}_{\text{Si}}}{Z_{\text{Si}}} \equiv \frac{\tilde{Z}_{\text{S}}}{Z_{\text{S}}} \equiv \frac{\tilde{Z}_{\text{Fe}}}{Z_{\text{Fe}}} \quad \text{(meteorites)}
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\[
\begin{align*}
\text{volatiles} & : \quad 1 + \delta z_{\text{CNO}} \equiv \frac{Z_{\text{C}}}{Z_{\text{C}}} \equiv \frac{Z_{\text{N}}}{Z_{\text{N}}} \equiv \frac{Z_{\text{O}}}{Z_{\text{O}}} \\
\text{refractories} & : \quad 1 + \delta z_{\text{Ne}} \equiv \frac{Z_{\text{Ne}}}{Z_{\text{Ne}}} \\
\text{refractories} & : \quad 1 + \delta z_{\text{Heavy}} \equiv \frac{Z_{\text{Mg}}}{Z_{\text{Mg}}} \equiv \frac{Z_{\text{Si}}}{Z_{\text{Si}}} \equiv \frac{Z_{\text{S}}}{Z_{\text{S}}} \equiv \frac{Z_{\text{Fe}}}{Z_{\text{Fe}}} 
\end{align*}
\]

*(photosphere)*

*(chromosphere and corona)*

*(meteorites)*

Two parameter analysis ($\delta Z_{\text{CNO}} = \delta Z_{\text{Ne}} ; \delta Z_{\text{Heavy}}$)


Neutrinos + Helio

All obs. constraints
$\chi^2$/d.o.f. = 39.6/32

$\delta Z_{\text{CNO}} = \delta Z_{\text{Ne}} = 0.45 \pm 0.04$

$\delta Z_{\text{Heavy}} = 0.19 \pm 0.03$

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

\[
[\text{Fe/H}] = [\text{Fe/H}] + \log (1 + \delta z_{\text{Heavy}})
\]
However, data are **not so effective** in constraining composition in more realistic scenarios.

**Three parameter analysis** ($\delta Z_{\text{CNO}}$; $\delta Z_{\text{Ne}}$; $\delta Z_{\text{Heavy}}$)

**GS98** still favored by observational data but:

- errors in the inferred abundances larger than before;
- degeneracies appear among the various $\delta z_i$;
- No real constraints on the Ne/O ratio;
- **A prior for the Ne/O ratio** (forced at the AGSS09 value with 30% accuracy) was used to obtain realistic bounds.
The role of metals in the Sun

• Metals give a negligible contribution to EOS

• Metals give a **substantial** contribution to opacity:

  Energy producing region \((R < 0.3 \, R_\odot)\)

  \[ \kappa_Z \approx \frac{1}{2} \kappa_{tot} \]

  Fe gives the largest contribution.

Outer radiative region
\((0.3 < R < 0.73 \, R_\odot)\)

  \[ \kappa_Z \sim 0.8 \, \kappa_{tot} \]

  Relevant contributions from several diff. elements \((O, Fe, Si, Ne, ...\)

• \(Z_{CNO}\) control the efficiency of CNO cycle
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  Relevant contributions from several diff. elements \((O, Fe, Si, Ne, ...\)

- \(Z_{CNO}\) control the efficiency of CNO cycle

---

Solar composition problem?

What we know about the opacity profile of the present sun?
The opacity profile of the Sun

A change of the solar composition produces the same effects on the helioseismic observables and on $^8\text{B}$ and $^7\text{Be}$ neutrinos of a suitable change of the solar opacity profile $\delta\kappa(r)$.

$$\delta\kappa(r) = \frac{\partial \ln \kappa(r)}{\partial \ln Z_j} \delta z_j$$
The opacity profile of the Sun

A change of the solar composition produces the same effects on the helioseismic observables and on $^8$B and $^7$Be neutrinos of a suitable change of the solar opacity profile $\delta \kappa(r)$.

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

✓ Opacity (not composition) is directly constrained.

✓ Different admixtures $\{\delta z_i\}$ can reproduce (equally well) the required $\delta \kappa(r)$;

✓ The required variations $\delta \kappa(r)$ seems large wrt "nominal" uncertainties ($\approx$ few %).

✓ Non-standard effects (e.g. WIMPs accumulation in the solar core) alleviate the problem but do not provide the correct profile.

$\delta Z_{\text{CNO}} = 0.45$; $\delta Z_{\text{Ne}} = 0.80$; $\delta Z_{\text{Heavy}} = 0.13$

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%
CNO neutrinos

CNO neutrinos allows to determine directly the C+N abundance in the solar core:

\[ 1 + \delta \Phi_\nu = (1 + \delta X_{\text{CN}}) \left[ 1 + \int dr \ K_\nu(r) \delta \kappa(r) \right] \]

\[ X_{\text{CN}} \equiv X_C/12 + X_N/14 \]

Determines the central temperature

Total number of catalysts for CN-cycle

At present, we only have a loose upper limit on CNO neutrino fluxes:

<table>
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<td>( ^{13}\text{N} ) ( (10^8 \text{ cm}^{-2} \text{ s}^{-1}) )</td>
<td>2.96(1 ± 0.14)</td>
<td>2.17(1 ± 0.14)</td>
<td>≤ 6.7</td>
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<tr>
<td>( ^{15}\text{O} ) ( (10^8 \text{ cm}^{-2} \text{ s}^{-1}) )</td>
<td>2.23(1 ± 0.15)</td>
<td>1.65(1 ± 0.15)</td>
<td>≤ 3.3</td>
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<tr>
<td>( ^{17}\text{F} ) ( (10^6 \text{ cm}^{-2} \text{ s}^{-1}) )</td>
<td>5.52(1 ± 0.17)</td>
<td>3.04(1 ± 0.16)</td>
<td>≤ 59</td>
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Will it be possible to detect CNO neutrino?

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

How to improve?

Increase the detector depth → reduction of cosmogenic $^{11}\text{C}$ background
Consider larger detectors → Stat. uncertainties scales as $1/M^{1/2}$
SNO+ (1 kton), LENA (50 kton)

Event spectrum in ultrapure liquid scintillators (Borexino-like)

- GS98 – 5.1 cpd/100 ton
- AGSS09 – 3.6 cpd/100 ton
- $^{11}\text{C}$ will be a factor 100 lower in SNO+
- 20 cpd/100 ton
How to improve?

Increase the detector depth \(\rightarrow\) reduction of cosmogenic \(^{11}\text{C}\) background
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 \((^{210}\text{Bi})\)
Borexino: 20 cpd/100 ton \(\rightarrow\) 150 nuclei / 100 ton
ecCNO neutrinos

In the CN-NO cycle, besides the conventional CNO neutrinos (blue lines), monochromatic ecCNO neutrinos (red lines) are also produced by electron capture reactions:

\[ ^{13}\text{N} + e^- \rightarrow ^{13}\text{C} + \nu_e \quad E_\nu = 2.220 \text{ MeV} \]
\[ ^{15}\text{O} + e^- \rightarrow ^{15}\text{N} + \nu_e \quad E_\nu = 2.754 \text{ MeV} \]
\[ ^{17}\text{F} + e^- \rightarrow ^{17}\text{O} + \nu_e \quad E_\nu = 2.761 \text{ MeV} \]
ecCNO neutrinos

The ecCNO fluxes are extremely low: $\Phi_{\text{ecCNO}} \approx (1/20) \Phi_B$. Detection is extremely difficult but could be rewarding. Indeed:

- ecCNO neutrinos are sensitive to the **metallic content of the solar core** (same infos as CNO neutrinos);

- Being monochromatic, they probe the solar neutrino **survival probability** at specific energies ($E_\nu \approx 2.5$ MeV) exactly **in the transition region**.
Expected rates in Liquid Scintillators

- $\nu - e$ elastic scattering of ecCNO neutrinos produces Compton shoulders (smeared by energy resolution) at 2.0 and 2.5 MeV;

- ecCNO neutrino signal has to be extracted statistically from the (irreducible) $^8B$ neutrino background.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure.png}
\caption{Expected rates [1.5 MeV, 2.5 MeV]}
\end{figure}

$R_{\text{ecCNO}} \approx 100 \text{ counts/10 kton/year}$

$R_{\text{B}} \approx 2500 \text{ counts/10kton/year}$

$S/sqrt[B] \approx 2$ [for 10kton \times year exposure]
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 ≈20 kton in LENA);
- **Cosmogenic**: $^{11}$C overlap with the observation window.

Expected rates in Liquid Scintillators

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- **External**: reduced by self-shielding (Fid. mass reduced from 50 to ≈20 kton in LENA);
- **Cosmogenic**: $^{11}$C overlap with the observation window.

Signal comparable to stat. fluctuations for exposures $10\text{ kton} \times \text{year}$ or larger.

100 counts / year above 1.8 MeV in 20 kton detector $\rightarrow 3\sigma$ detection in 5 year in LENA

$^{11}$C background: rescaled proportionally to $\Phi_\mu$
Summary

The **solar composition problem** indicates that there is something **wrong** or **unaccounted** in solar models

- Are properties of the solar matter (e.g. **opacity**) correctly described?
- Are the new abundances (i.e. the atmospheric model) **wrong**?
- Is the **chemical evolution** not understood (extra mixing?) or peculiar (accretion?) with respect to other stars?

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 ...*

**CNO and ecCNO neutrinos**, besides testing CN-NO cycle, could provide clues for the solution of the puzzle.
Thank you
Additional Slides
The solar neutrino spectrum

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

First direct measurement of the solar pp-component
• Searching for the final confirmation of MSW transition (or looking for new physics):

The $\nu_e$ survival probability at $E_{\nu} = 1-3$ MeV probes transition between vacuum and matter dominated regimes

Sensitive to new physics effects (mass varying neutrinos, sterile neutrinos, NSI, etc.)

Combined analysis of SK I-IV PRL 112 (2014) 091805
Provide a 2.7$\sigma$ observation of day-night effect;

From Michael Smy talk @ WINP 15
Significance of CNO measurement in LENA

Assuming constraints of $^{210}\text{Bi}$ 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>
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Assuming no constraints of $^{210}\text{Bi}$ rate:

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<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>
The solar opacity profile

The “optimal” opacity profile (i.e. the temperature stratification) of the Sun is well determined by observational data.

Note that:

- The sound speed and the convective radius determine the tilt of $\delta k(r)$ (but not the scale).
- The surface helium and the neutrino fluxes determine the scale for $\delta k(r)$.

\[ \approx \text{few \%} \quad \approx 25 \% \]
The optimal detector is large (10 kton or more) has an energy resolution at the 10% level or better and is based on a detection reaction that does not wash-out the information on the incoming neutrino energy (e.g. CC-reaction on nuclei).


ecCNO neutrinos
The degeneracy between opacity and metals

- The derivative of the sound speed with respect to the (surface) composition

Solid lines → calculated from SSMs with different (surface) composition
Dotted lines → reconstructed performing ad-hoc opacity changes (in LSMs)
Standard Solar Models

Stellar structure equations are solved, starting from a ZAMS model to present solar age (we neglect rotation, magnetic fields, etc.):

\[
\begin{align*}
\frac{\partial m}{\partial r} &= 4\pi r^2 \rho \\
\frac{\partial P}{\partial r} &= -\frac{G_N m}{r^2} \rho \\
P &= P(\rho, T, X_i) \\
\frac{\partial l}{\partial r} &= 4\pi r^2 \rho \epsilon(\rho, T, X_i) \\
\frac{\partial T}{\partial r} &= -\frac{G_N m T \rho}{r^2 P} \nabla
\end{align*}
\]

\[
\nabla = \text{Min}(\nabla_{\text{rad}}, \nabla_{\text{ad}}) \rightarrow \begin{cases} \nabla_{\text{rad}} &= \frac{3}{16\pi ac G_N} \frac{\kappa(\rho, T, X_i) l P}{m T^4} \\ \nabla_{\text{ad}} &= (d \ln T/d \ln P)_s \approx 0.4 \end{cases}
\]

Chemical evolution driven by nuclear reaction, diffusion and gravitational settling, convection

Standard input physics for equation of states, nuclear reaction rates, opacity, etc.

Free-parameters (mixing length, \(Y_{\text{ini}}, Z_{\text{ini}}\)) adjusted to match the observed properties of the Sun (radius, luminosity, \(Z/X\)).

Note that equations are non-linear \(\rightarrow\) Iterative method to determine mixing length, \(Y_{\text{ini}}, Z_{\text{ini}}\)
Two parameter analysis ($\delta Z_{\text{CNO}} = \delta Z_{\text{Ne}}$; $\delta Z_{\text{Heavy}}$)

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

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