What is the metallicity of our reference star, the Sun?

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The Sun as a benchmark star

The role of the Sun:

Well-studied, helioseismic constraints, neutrino fluxes, testbed for physical ingredients. The Sun is used as a **reference**:

- Metallicity scale,
- Enrichment laws,
- SSM framework,
- Paved the way for asteroseismology using solar-like oscillations.

Most of our models will include some ingredients that have been calibrated on the Sun. Thus, if you change the way you model the Sun, you impact stellar physics as a whole.

But how well do we know the Sun?

1D Models of the 20^{th} century

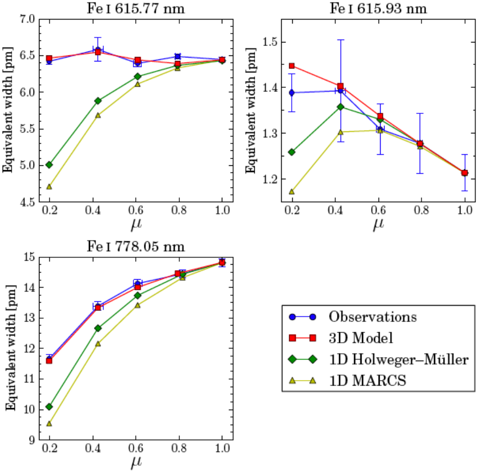
1D solar atmosphere models

Theoretical models: MARCS, Kurucz, ...

1. Hydrostatic,
2. MLT type convection,
3. LTE.

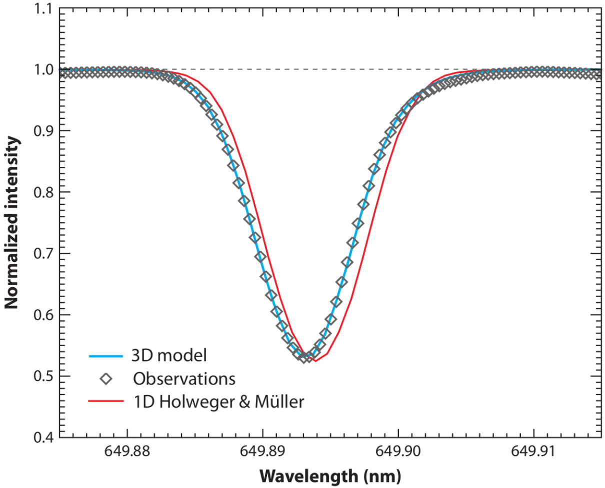
Usually, **semi-empirical models** were used e.g. Holweger-Müller model (1974).

Led to high abundances of C,N and O (AG89, GN93, GS98).



Pereira et al. (2009)

Advent of 3D Models and abundance revisions



Asplund et al. (2009)

Revision of the abundances:

- Hydrodynamical model,
- Non-LTE corrections,
- improved atomic data,
- Careful selection of lines,
- Use of all indicators.

$\Rightarrow$ 30% **reduction of $Z_\odot$!**

The solar modelling problem

A brief history of Standard Solar Models

Before 2004, high metallicity solar models ($Z = 0.0182$):

1. Correct position of the BCZ,
2. Correct Helium abundance in the CZ,
3. Sound Speed profile relative differences of up to 0.006.

(From Kosovichev & Fedorova 1991, 1993, Vorontsov et al. 1991)
But: slow degradatation as physical ingredients were updated.

From 2004, downward revision of the solar Z:

1. Wrong position of the BCZ,
2. Wrong Helium abundance in the CZ,
3. Sound Speed profile relative differences of up to 0.02.

Discussions of the revised abundances

Study by Caffau et al. 2011: Higher C,N,O abundances, closer to the "old values".
Subsequent analyses by Scott et al. 2015a, Scott et al. 2015b, Grevesse et al. 2015, Lind et al. 2017, Bergemann et al. 2017, Amarsi and Asplund 2017, Nordlander and Lind 2017, Amarsi et al. 2018, Amarsi et al. 2019: confirm low C,N,O abundances.

What causes the discrepancies?

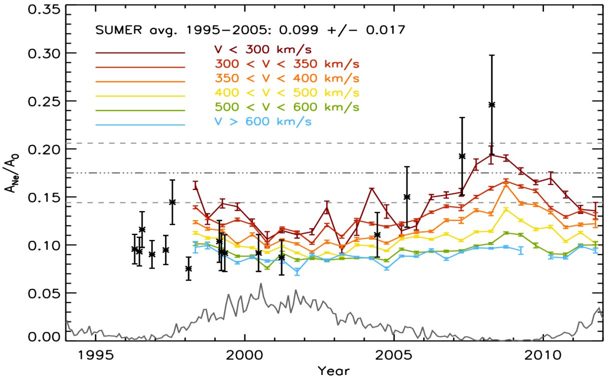
- 3D Models? No! Stagger and Co5bold agree (Beeck et al. 2012).
- Selection of lines, blends, molecular lines.

If the same inputs are used, the same results are obtained.

What about meteorites? Differentiation, they are not substitutes to photospheric abundances! (N.Grevesse, private communication)

Neon revision and latest changes

The problem of Neon: No photospheric lines.
⇒ Inferences from coronal lines, solar wind, ... Variations with activity!

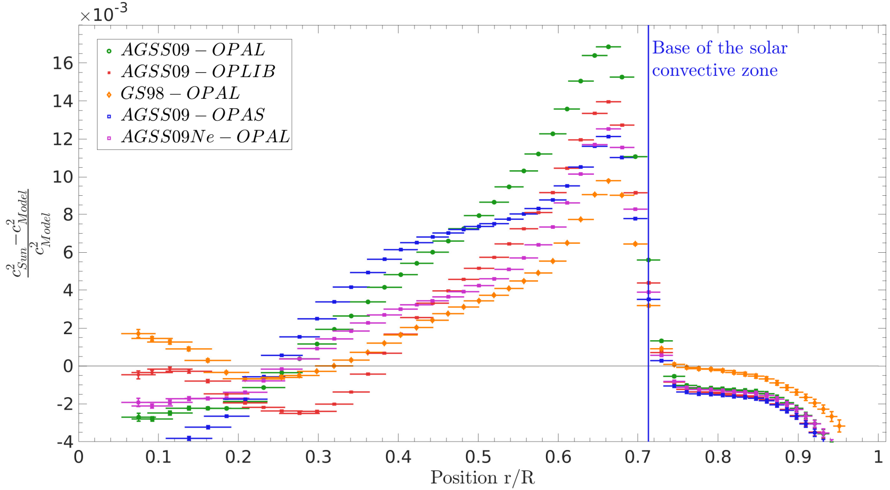


Landi & Testa (2015)

- Difficult measurements, Ne/H unacessible, Ne/O measured,
- Antia & Basu (2004): increase of 400% to solve the “solar problem”.
- **Landi & Testa 2015 + Young 2018**: increase of 40% of Ne/O.

The solar modelling problem as seen in seismology:

Current state of the issue, for various abundance and opacity tables...



Inferring Z from helioseismic data I

Constraints from seismic inversions:

Inversions can only constrain variables from the *acoustic structure* : ρ, c^2 or $\Gamma_1 = \left(\frac{\partial \ln P}{\partial \ln \rho}\right)_S$ for example.

However, assuming an E.O.S, one has:

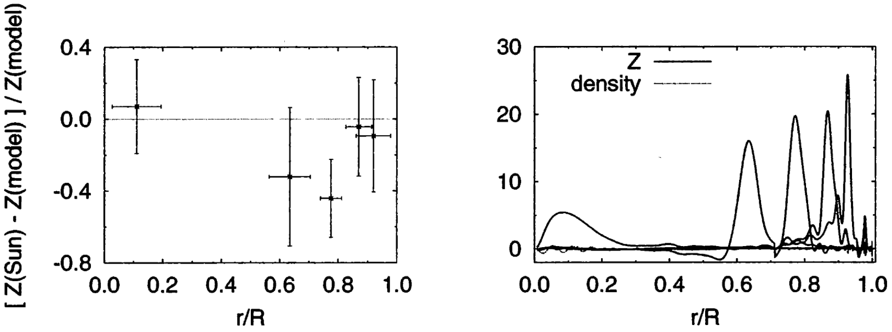
$$\frac{\delta \Gamma_1}{\Gamma_1} = \left(\frac{\partial \ln \Gamma_1}{\partial \ln P}\right)_{\rho,Y,Z} \frac{\delta P}{P} + \left(\frac{\partial \ln \Gamma_1}{\partial \ln \rho}\right)_{P,Y,Z} \frac{\delta \rho}{\rho} + \left(\frac{\partial \ln \Gamma_1}{\partial Y}\right)_{P,\rho,Z} \delta Y + \left(\frac{\partial \ln \Gamma_1}{\partial Z}\right)_{P,\rho,Y} \delta Z,$$

thus allowing for inversions of Y, the helium abundance, or Z, the metallicity.

Previous studies by Takata & Shibahashi (2001), Antia & Basu (2006) and Vorontsov et al. (2013).

Inferring Z from helioseismic data II

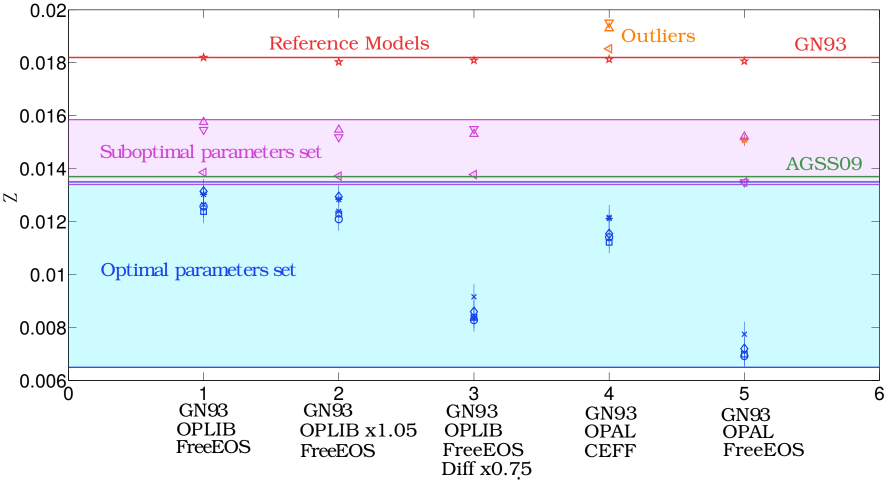
Initial attempts in Takata and Shibahashi (2001) using density and Γ_1 kernels.



Impossibility to conclude because of the errors bars.
However, the conclusion mentions that the three last point are consistent with a 30% reduction of the solar metallicity.

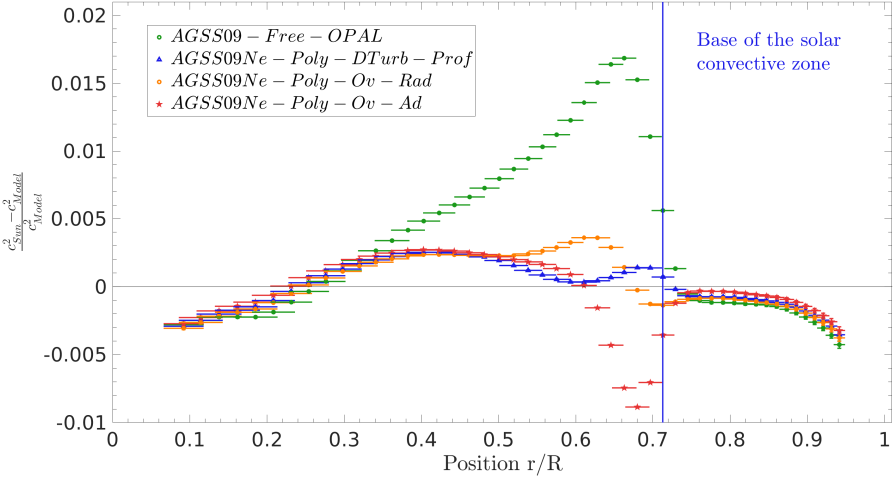
Inferring Z from helioseismic data III

This inversion (Buldgen et al. 2017c) favours a low metallicity (as in Vorontsov et al. 2013).



Potential solutions to the solar modelling problem I (Buldgen et al. 2019, in prep.)

Combination of: Neon increase from Landi & Testa (2015) and Young et al. (2018), extra-mixing and opacity modification (from A. Pradhan)



Impact on stellar physics

A few illustration of the potential impact of the solar problem

1. Solar reference for the chemical abundances,
2. Revision of key ingredients: opacity, EOS, screening factor (Mussack & Däppen 2011, Bailey et al. 2015),
3. Transport of chemicals (see talk by R. Hirschi),
4. Angular momentum transport processes (see talk by P. Eggenberger),
5. Impact on asteroseismic modelling and characterization of stellar populations in the Galaxy (see talk by C. Chiappini).

The role of calibrator of the Sun implies that changing its ingredients impacts a wide range of stellar models.

Conclusion and perspectives

In conclusion

Still a problem: Will new opacity computations do it? Maybe. (Pradhan 2017, Zhao 2017, Pain 2019).
What about the BCZ: Extensively studied (see e.g. Hughes 2007 and references therein)
Is that it? No: Microscopic diffusion, EOS improvements, convection, instabilities, early history (see also Zhang et al. 2019)...

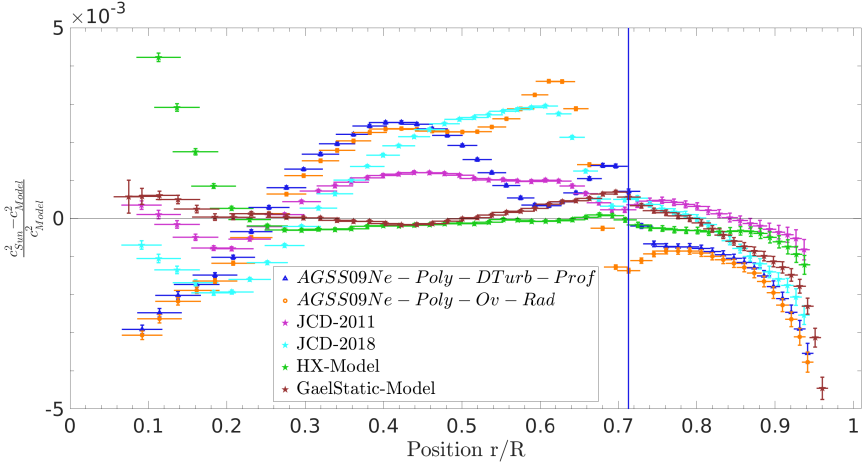
What is clear? **Stop using GN93 and GS98.** (listen to Nicolas Grevesse)

The solar problem is not purely an issue of abundances, rather an issue of other modelling ingredients. No significant variations found in 2015 by AGSS. Its impact reaches beyond the range of solar models.

Thank you for your attention!

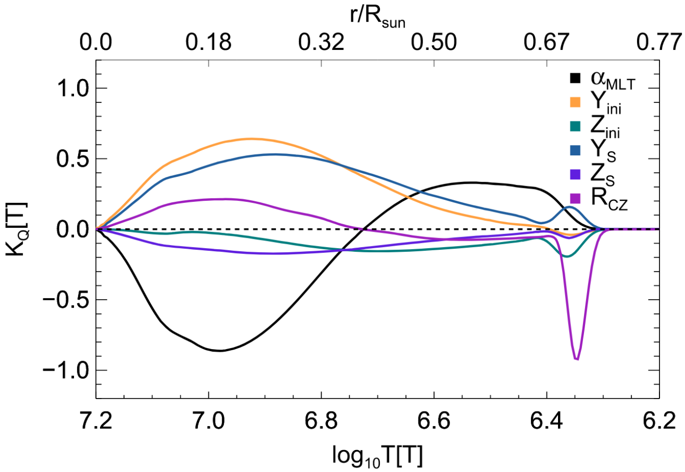
Potential solutions to the solar modelling problem II

Other approach: build a seismic model and try to see what its properties may be (Buldgen et al. In prep).



Help lift some degeneracies and drive revisions of physical ingredients.

Opacity kernels

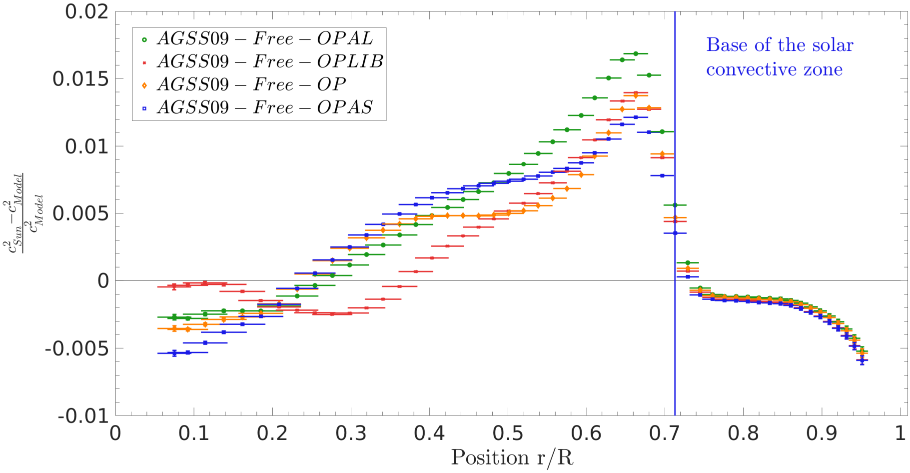


- Based on Tripathy & Christensen-Dalsgaard (1998).
- Assumes linear behaviour with respect to small κ perturbation.

Vinyoles et al. (2017)

Allow for a static analysis of the required changes in opacity to match helioseismic constraints.

The current state of the issue



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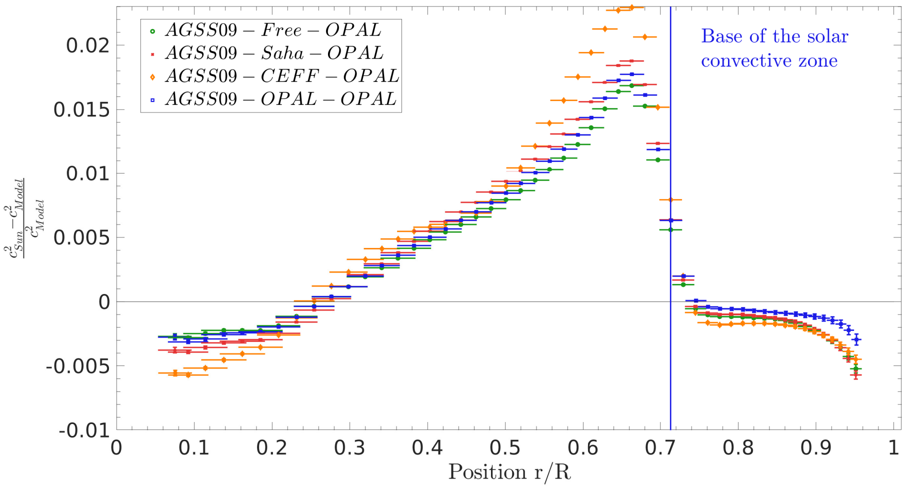

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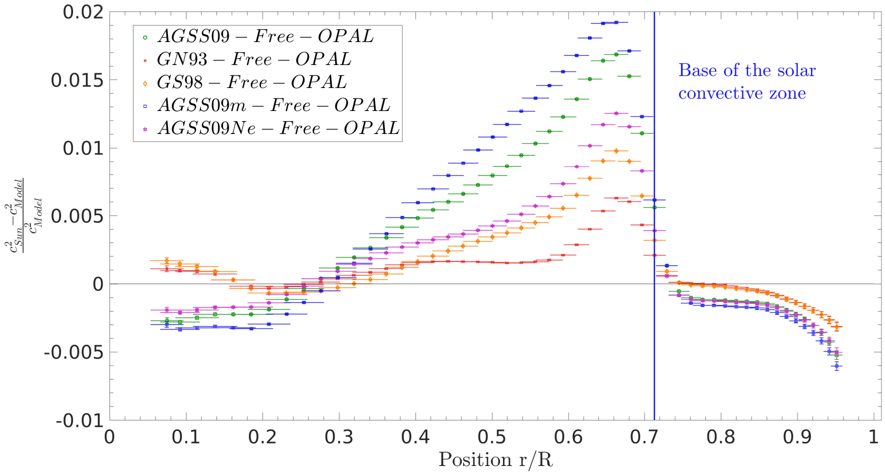
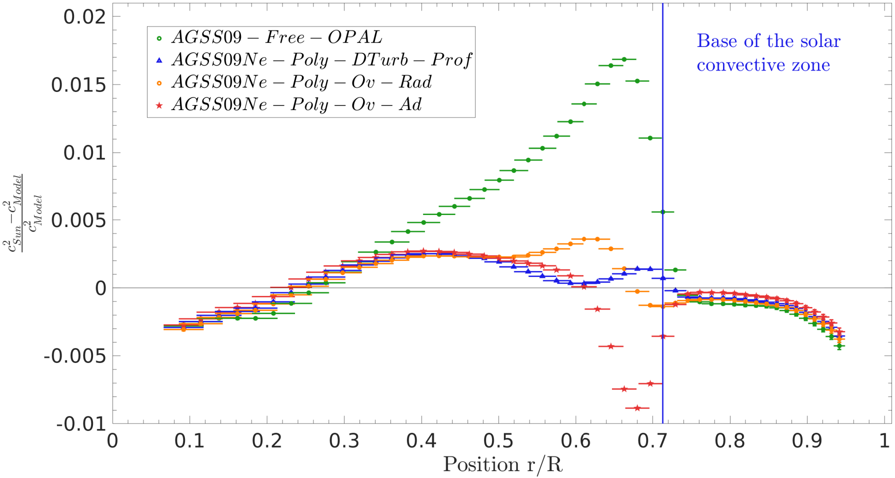


Combining seismic information I

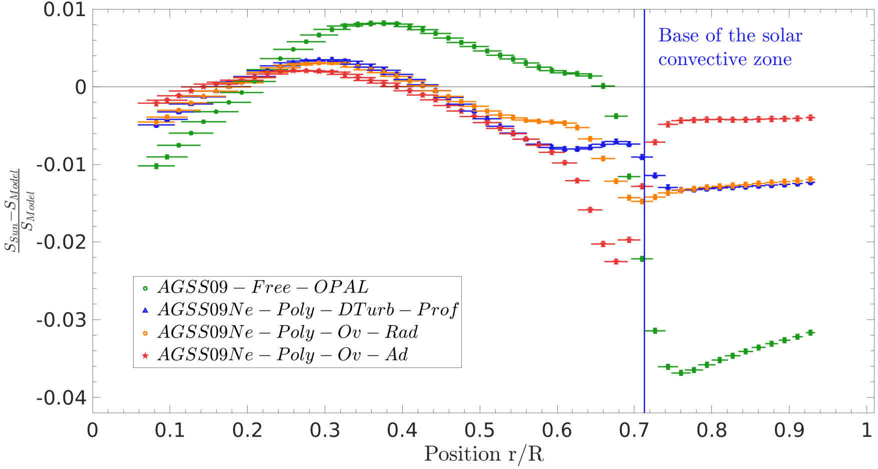
Combining: A, $S_{5/3}$, c^2, Y, position of BCZ, m_{CZ}... (Buldgen et al. submitted to A&A)



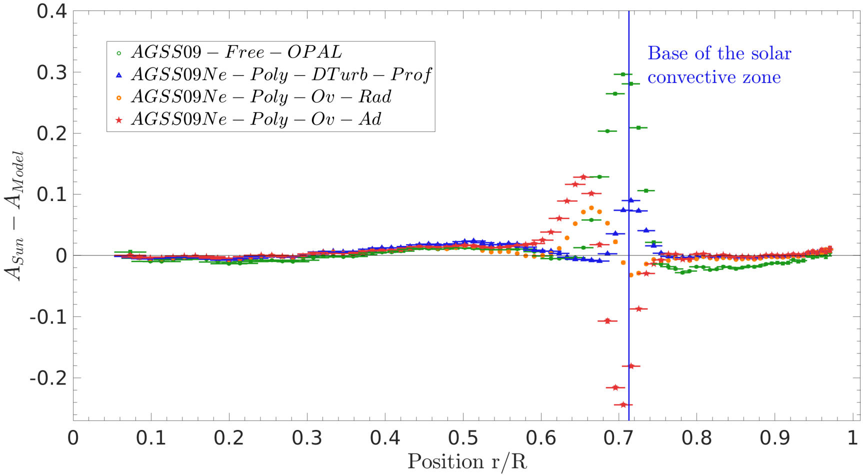
Similar to Christensen-Dalsgaard & Houdek (2010), Ayukov et al. (2011), Christensen-Dalsgaard et al. (2018).

Combining seismic information II

Combination of: Neon increase from Landi & Testa (2015) and Young et al. (2018), extra-mixing and opacity modification (from A. Pradhan)



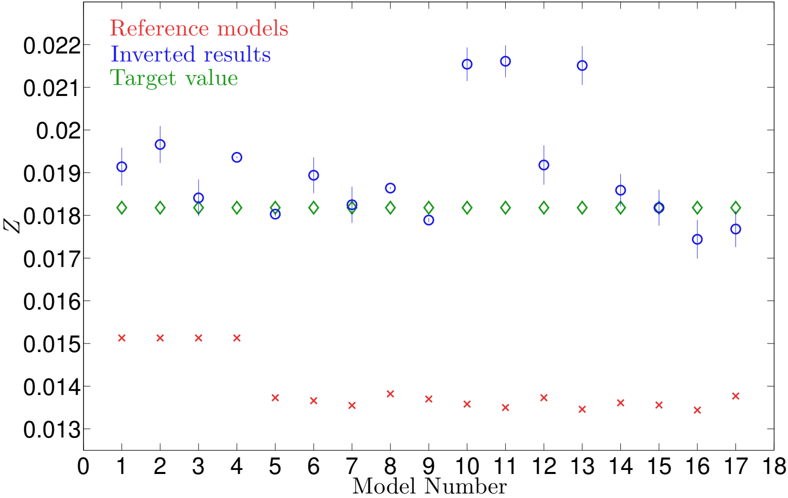
Combining seismic information III



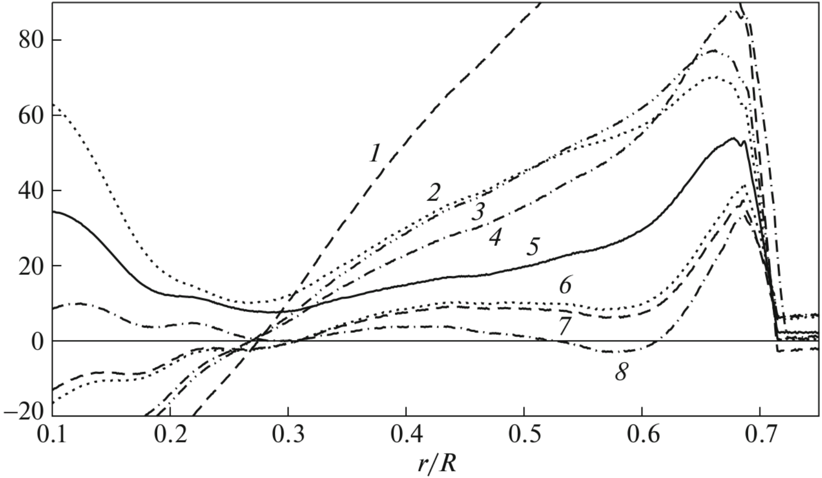
It seems: Opacity increase too high and perhaps too steep + wrong ∇T transition in overshooting region (improve on Christensen-Dalsgaard 2011)
(Work by Rempel et al. 2004, Zhang et al. 2012)

Inferring Z from helioseismic data - Tests

Tests on artificial data (same ν, same σ_ν) to ensure accuracy.

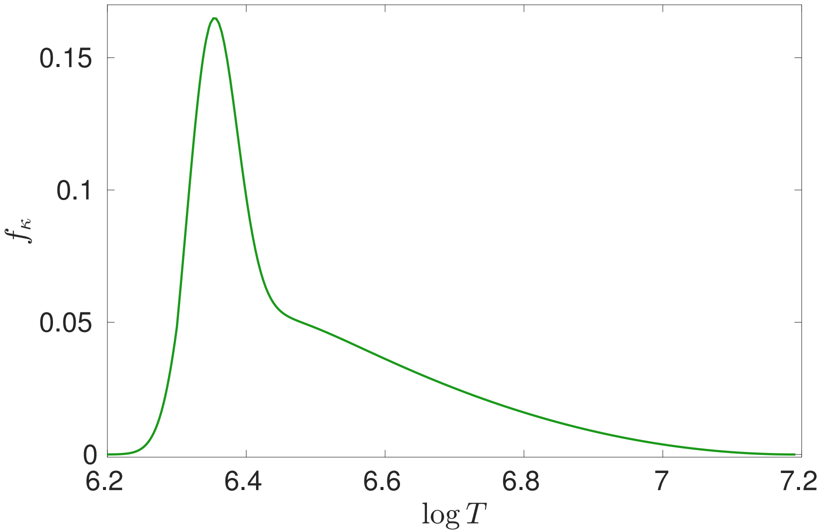


Extended solar calibration



Add additional free parameters and constraints to the solar models to expand the calibration procedure. (Ayukov & Baturin 2013, 2017)

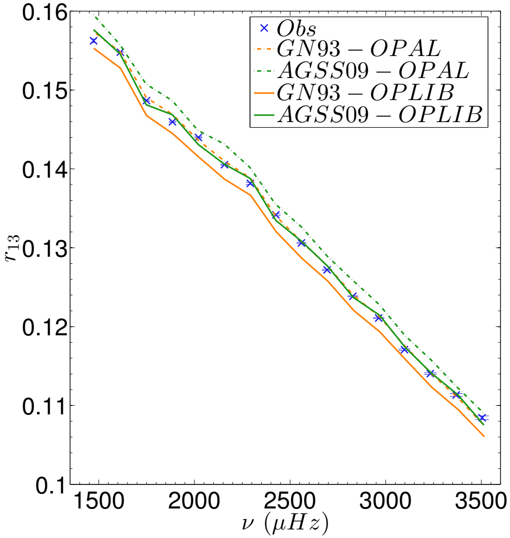
Considered opacity modification



Other classical diagnostics

	$r_{Conv}/R_{\odot}$	Y_{Conv}
Helioseismic measurements	0.713 ± 0.001	0.2485 ± 0.0035
SSM (AGSS09, Free, OPAL)	0.720	0.236
SSM (AGSS09, Free, OPLIB)	0.718	0.230
SSM (AGSS09, Free, OPAS)	0.717	0.232
SSM (GN93, Free, OPAL)	0.711	0.245
SSM (GN93, Free, OPLIB)	0.708	0.240

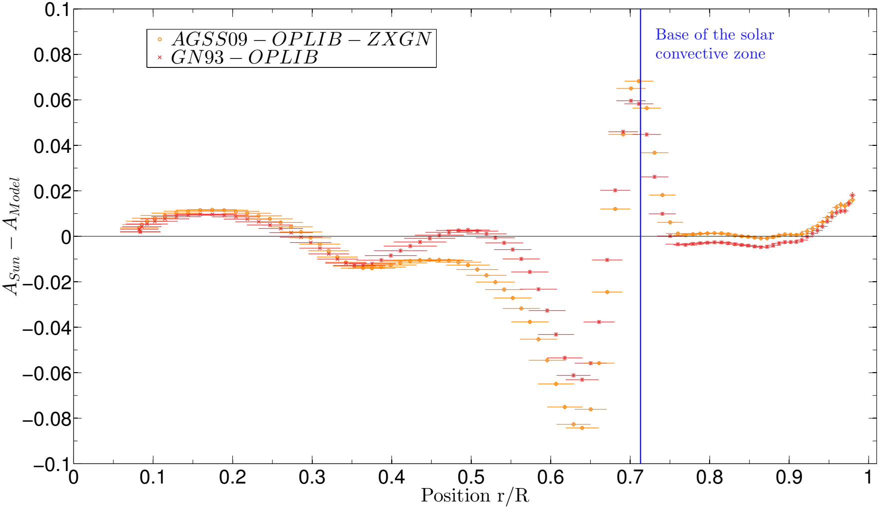
Standard Models with new opacities - Frequency ratios



- r_{02}, r_{13} $\Rightarrow$ AGSS09 favoured!
- c^2 inversions still favour GN93.
- BCZ wrong for both AGSS09 and GN93.
- Y_S very low for AGSS09.

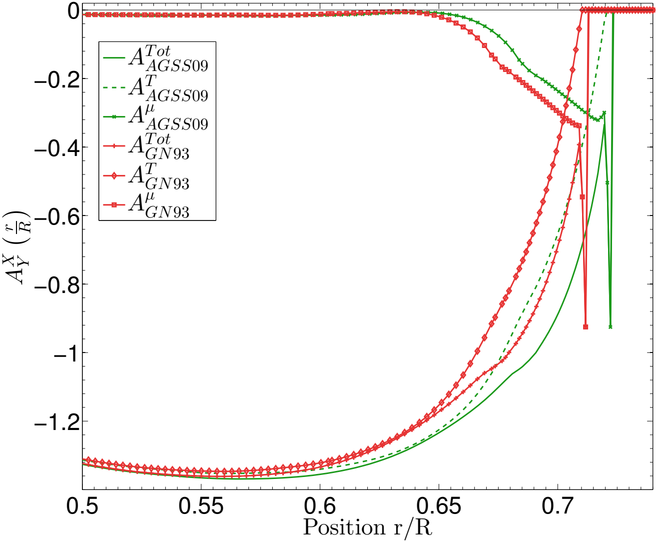
$\Rightarrow$ **Need new diagnostics.**

Inversions of the convective parameter for Standard Solar Models

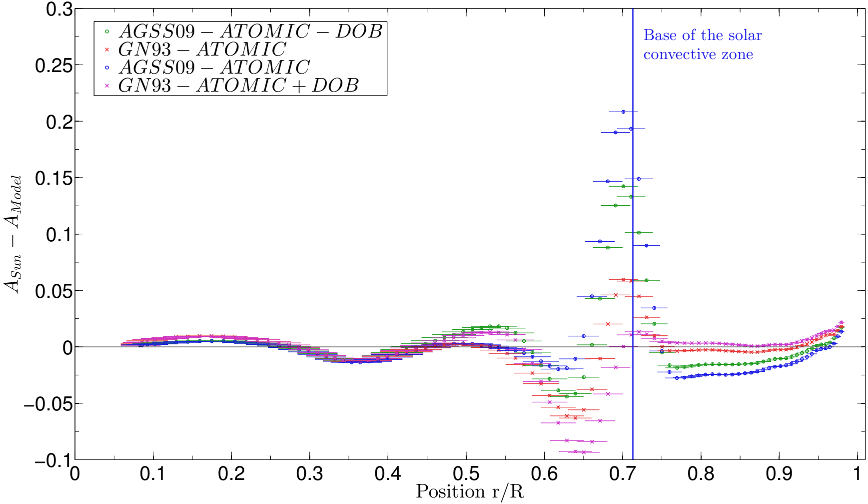


The compensation is related to the heavy-element mixture.

Inversions of the convective parameter for Standard Solar Models

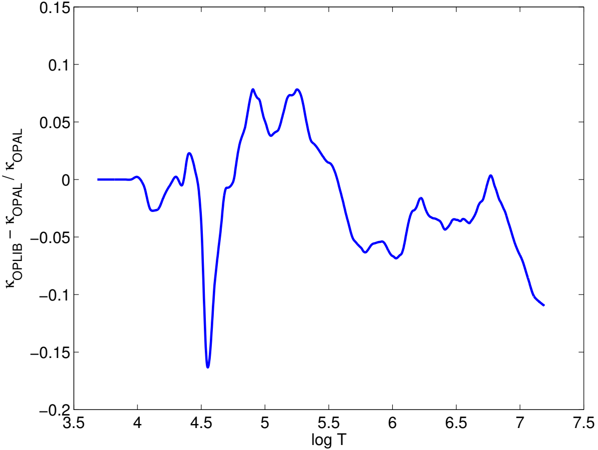


Inversions of the convective parameter for Standard Solar Models



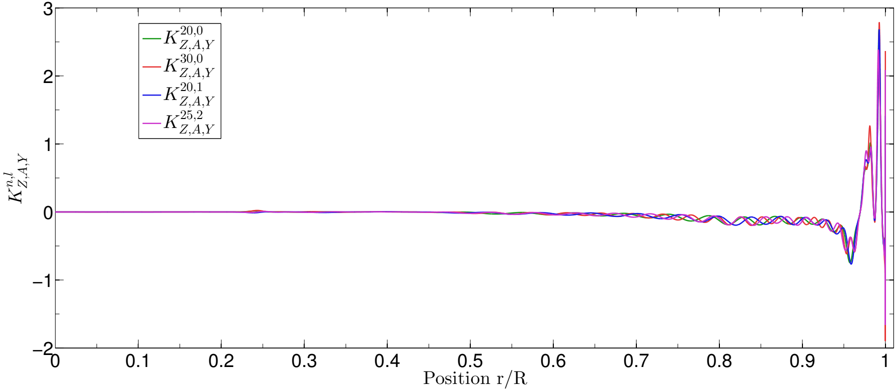
The compensation is also related to the temperature gradient.

Relative differences OPLIB-OPAL

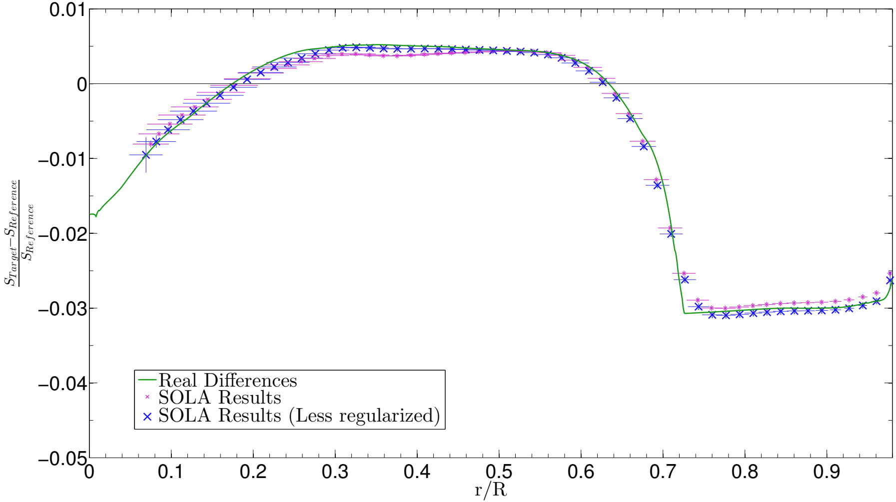


Metallicity Inversions for the Solar Envelope

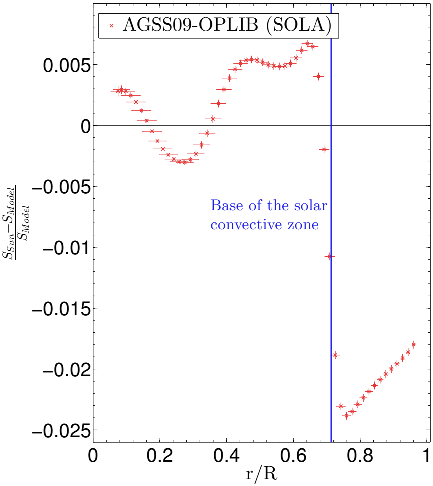
Metallicity kernels can thus be derived to estimate Z in the envelope.

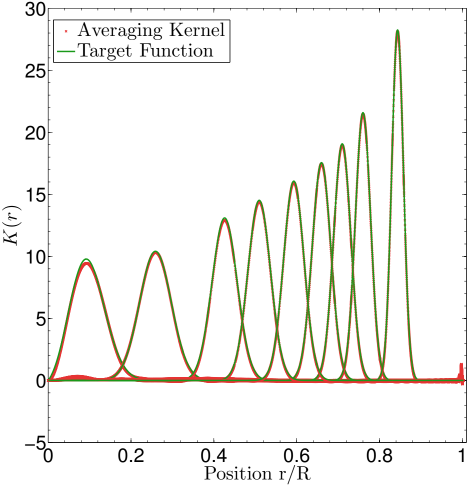


Appendices Helioseismology - Hare-and-Hounds exercises

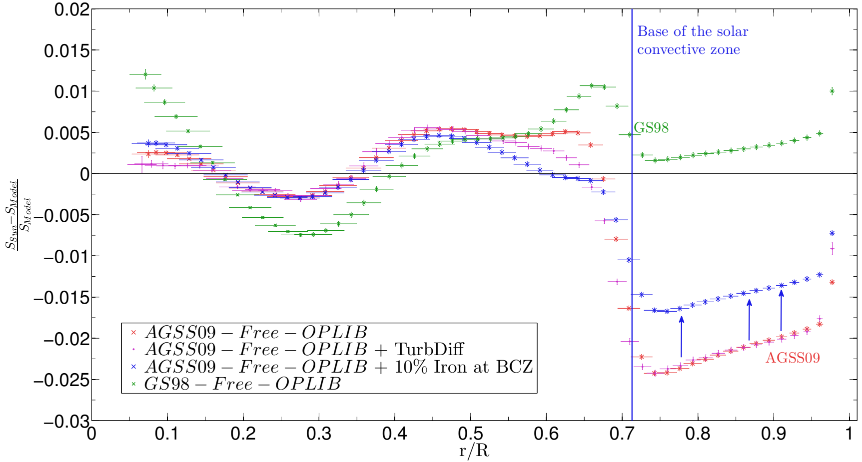


Appendices Helioseismology - Kernel fits





Links with opacity and chemical composition



Entropy inversions hint directly at inaccuracies in the radiative zone.

Parameters of the solar models with modified opacities and additional mixing used in this study

$(r/R)_{BCZ}$	$(m/M)_{CZ}$	Y_{CZ}	Z_{CZ}	Y_0	Z_0	**Opacity**	**Abundances**	**Diffusion**
0.7122	0.9757	0.2416	0.01385	0.2692	0.01494	OPAL+Poly	AGSS09Ne	Thoul
0.7129	0.9761	0.2427	0.01383	0.2678	0.01483	OPAL+Poly	AGSS09Ne	Paquette
0.7106	0.9762	0.2425	0.01383	0.2685	0.01466	OPAL+Poly	AGSS09Ne	Thoul+D_{Turb}
0.7106	0.9762	0.2374	0.01359	0.2645	0.01490	OPAS+Poly	AGSS09	Thoul+D_{Turb}
0.7121	0.9756	0.2460	0.01376	0.2696	0.01500	OPAL+Poly	AGSS09Ne	Thoul+D_{Turb} – Prof
0.7118	0.9757	0.2437	0.01381	0.2692	0.01495	OPAL+Poly	AGSS09Ne	Thoul+Ov – Rad
0.71056	0.9751	0.2438	0.01381	0.2700	0.01506	OPAL+Poly	AGSS09Ne	Thoul+Ov – Ad