Solar Models

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Numerical tools and physical ingredients

What we used in Liège:

- CLES stellar evolution code (Scuflaire et al. 2008a) and LOSC stellar oscillation code (Scuflaire et al. 2008b)
- EOS: FreeEOS, OPAL, CEFF, SAHA-S
- Opacities: OPAL, OP, OPLIB, OPAS
- Nuclear reaction rates: Adelberger 2011, Nacre, Nacre II, Caughlan & Fowler, (+Formicola's correction).
- Diffusion: Thoul et al. 1994, Paquette et al. 1986, Partial ionization, turbulent diffusion (ad-hoc approach)
- Convection: MLT, CM, CGM.
- Overshoot: instantaneous + radiative ∇T, adiabatic ∇T or ad-hoc ∇T (not used yet)

Possible sources of uncertainties

Major contributors:

- Opacities;
- Macroscopic mixing at the BCZ;
- Metallicity value itself.

Secondary contributors:

- Microscopic diffusion;
- Equation of state;

Unknown:

- Dynamical screening (Däppen & Mussack 2012);
- Early history.

Extensively discussed: Antia & Basu 2004, Bahcall et al. 2005a,b, 2006, Delahaye & Pinsonneault 2006, Montalban et al. 2006, Basu & Antia 2008, Serenelli et al. 2004, 2009, Guzik et al. 2004, 2005, 2008 ... ...

In-depth study of the contributors

Decomposing the issue

We start by looking at the major contributors:

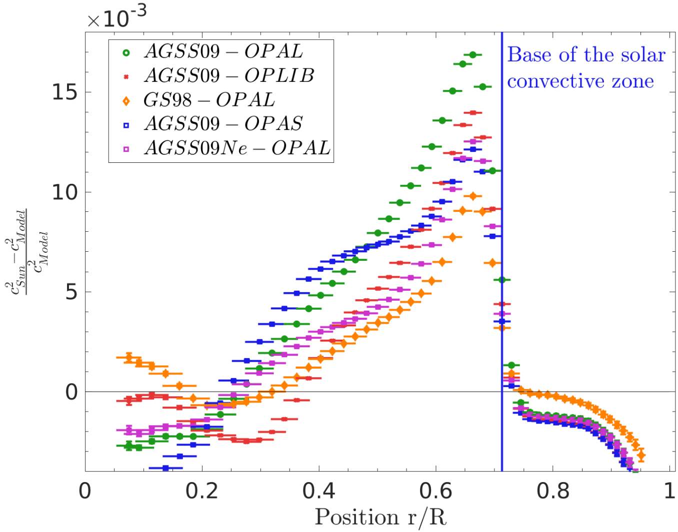
1. Test all standard ingredients;
2. Test various ad-hoc modifications.

Impact of secondary contributors:

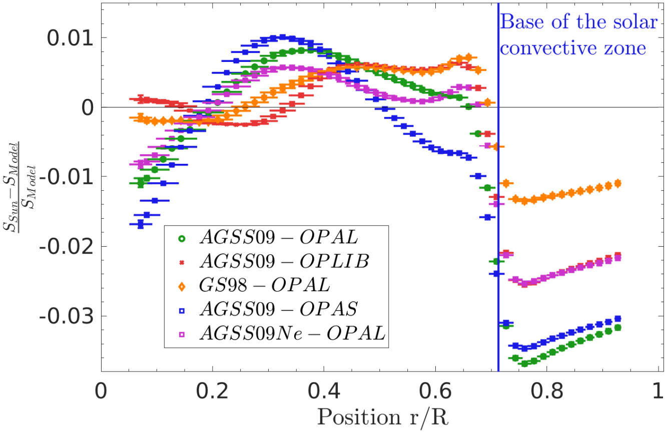
1. Vary the hypotheses of microscopic mixing + EOS.
2. Test ad-hoc modifications to mixing.

Analyse the global properties of models, their inverted profiles (c^2, A, $S_{5/3}$) and their frequency ratios.

Standard ingredients - opacity and abundances

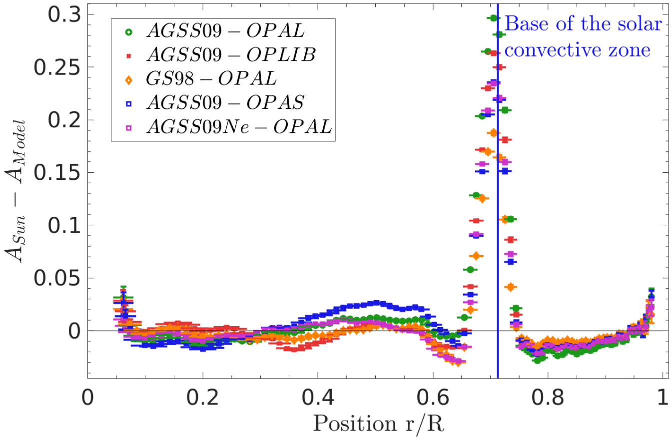


Standard ingredients - opacity and abundances



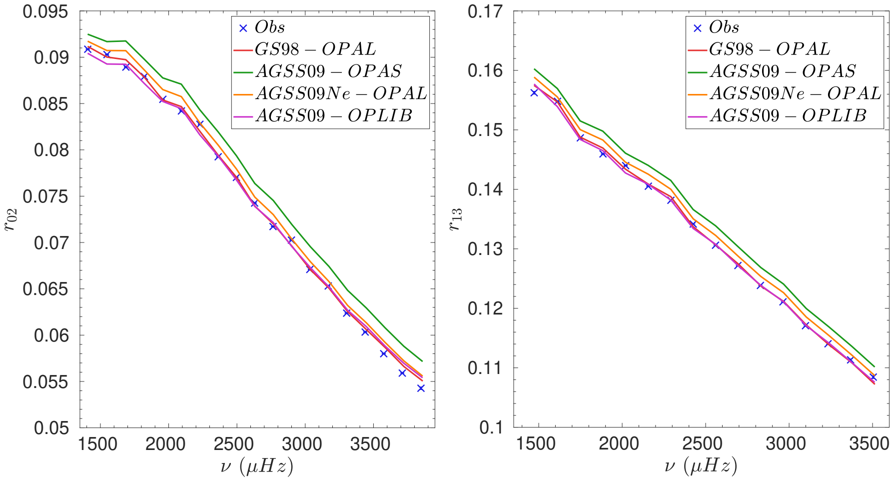
$S = P/\rho^{5/3}$, note the impact of the neon revision (Ne is the third contributor to opacity at the BCZ) (Landi & Testa 2015, Young 2018)

Standard ingredients - opacity and abundances



$A = \frac{1}{\Gamma_1}\frac{d\ln P}{d\ln r} - \frac{d\ln\rho}{d\ln r}$ is the Ledoux discriminant, note the disparity for the OPAS opacities in the deeper radiative layers).

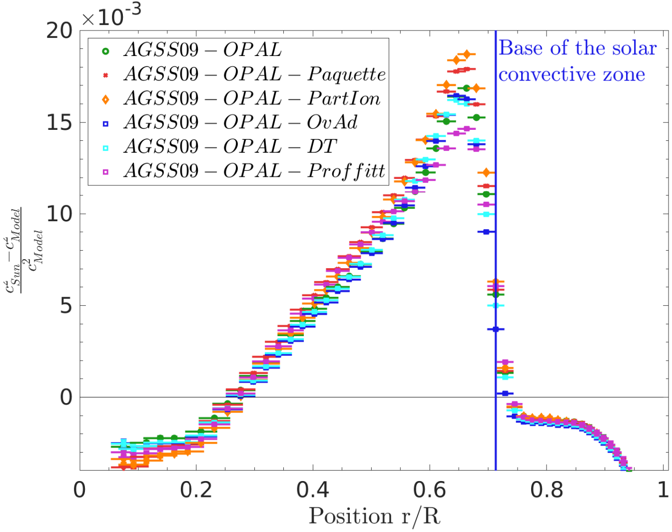
Frequency ratios



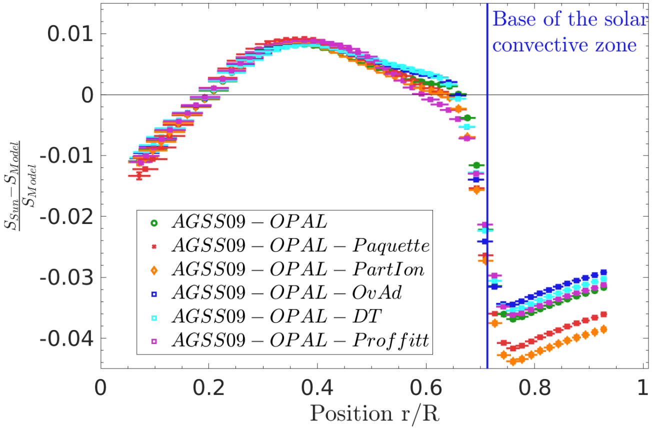
Global Properties

Name	$(r/R)_{BCZ}$	$(m/M)_{CZ}$	Y_{CZ}	Z_{CZ}
AGSS09-OPAL	0.7224	0.9785	0.2363	0.01361
AGSS09-OPLIB	0.7205	0.9777	0.2300	0.01372
AGSS09-OPAS	0.7196	0.9779	0.2322	0.01368
AGSS09-OPAL-Paquette	0.7235	0.9788	0.2373	0.01359
GS98-OPAL	0.7157	0.9764	0.2465	0.01706
AGSS09Ne-OPAL	0.7207	0.9780	0.2373	0.01393
AGSS09-OPAL-PartIon	0.7240	0.9790	0.2378	0.01355
AGSS09-OPAL-OvAd	0.7207	0.9780	0.2372	0.01356
AGSS09-OPAL-DT	0.7230	0.9786	0.2375	0.01355
AGSS09-OPAL-Proffitt	0.7244	0.9790	0.2411	0.01349

Standard ingredients - chemical mixing

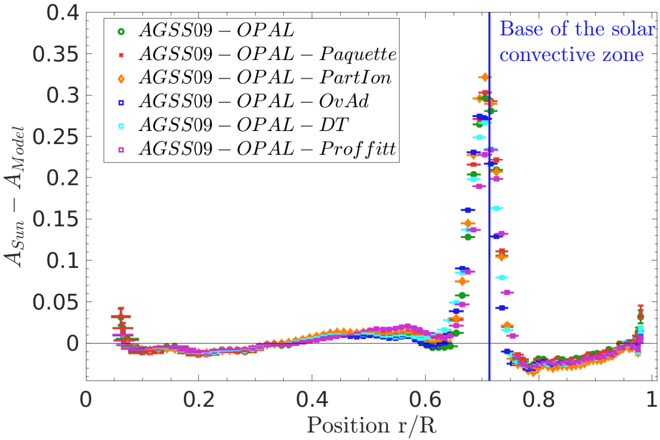


Standard ingredients - chemical mixing



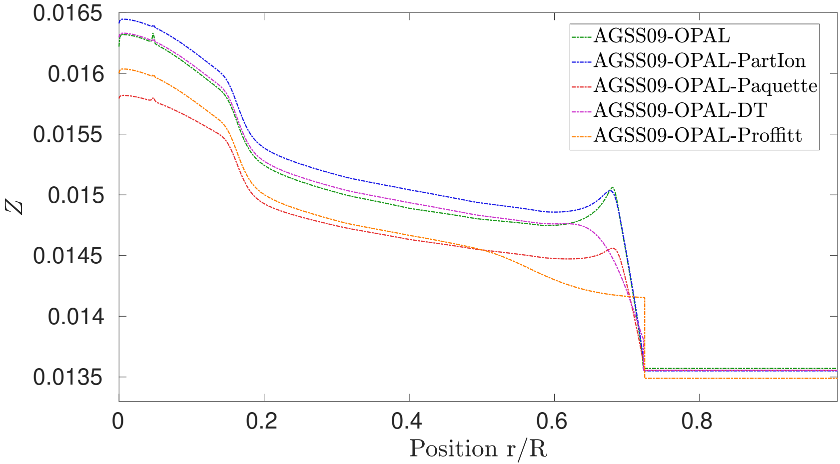
$S = P/\rho^{5/3}$, the impact is relatively low, note however the change due to partial ionization and the change in the collision integrals.

Standard ingredients - chemical mixing



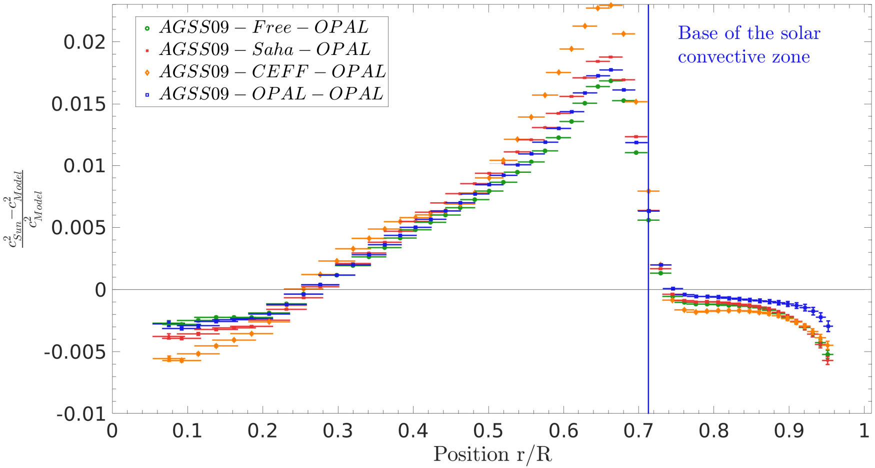
$A = \frac{1}{\Gamma_1}\frac{d\ln P}{d\ln r} - \frac{d\ln\rho}{d\ln r}$, is the Ledoux discriminant, note that the largest impact is found for a large amount diffusive mixing.

Standard ingredients - chemical mixing

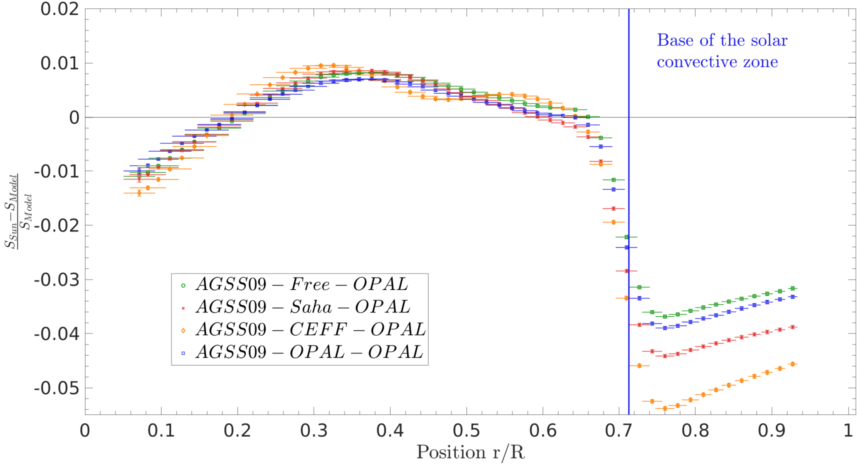


Modifications of chemical transport (Paquette et al. 1986, Proffitt & Michaud 1991) alters significantly the chemical composition profile.

Standard ingredients - equation of state



Standard ingredients - equation of state



Standard ingredients - conclusion

In conclusion

None of the current ingredients allow for a solution of the solar modelling problem. The revised neon certainly helps, but there is a clear issue with opacity and mixing (also lithium and beryllium constraints?).

Looking at the results of Bailey et al. 2015, can we test some modifications to the models?

Modified models - Philosophy:

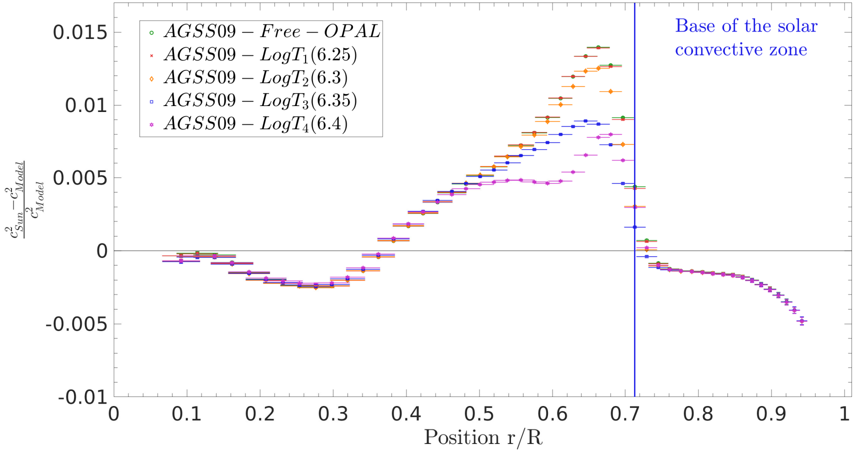
Completely ad-hoc and subjective:

- Modify opacity → compute calibration → check impact on the models

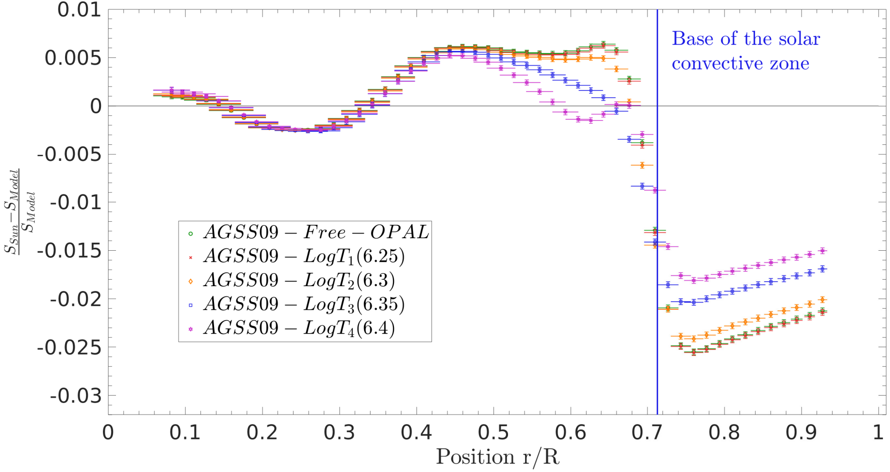
Attempt to infer the qualitative properties of the required modifications to the solar models.

Inversions with modified opacities:

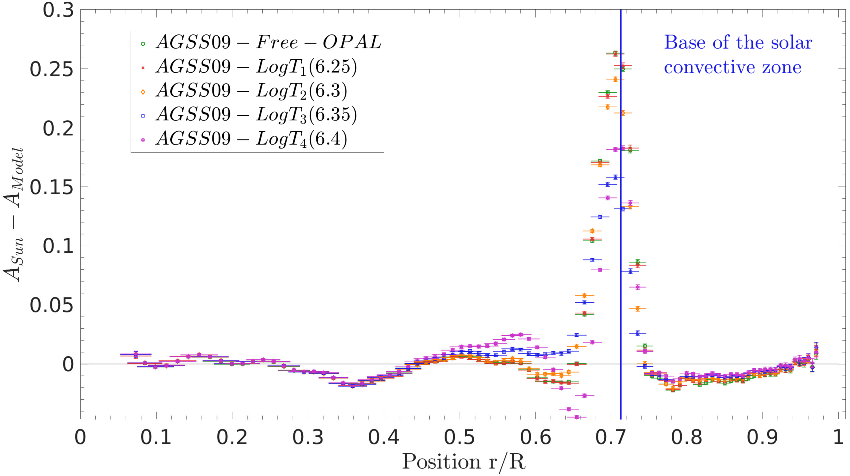
Impact of the position of a 13% Gaussian peak at various temperatures.



Inversions with modified opacities:



Inversions with modified opacities:

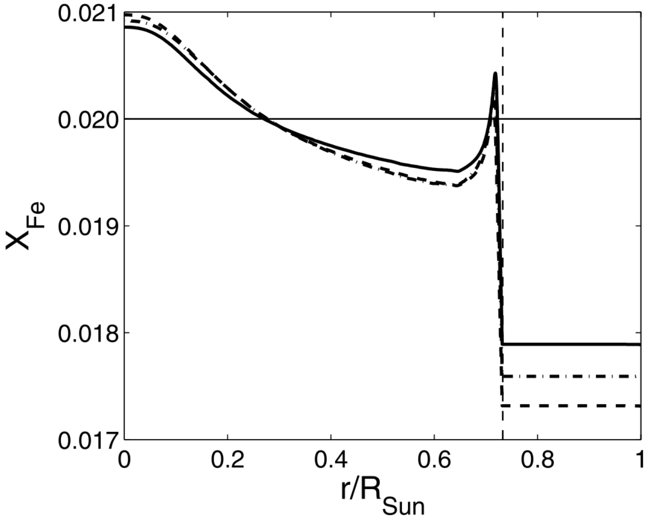


Inversions with modified opacities - Impact on global parameters

$(r/R)_{BCZ}$	$(m/M)_{CZ}$	Y_{CZ}	$\log T$
0.7200	0.9776	0.2300	$\log T_1$ (6.25)
0.7165	0.9769	0.2302	$\log T_2$ (6.30)
0.7155	0.9766	0.2304	$\log T_3$ (6.35)
0.7195	0.9773	0.2303	$\log T_4$ (6.40)

In brief: Improves the position of the BCZ, but unsufficient to solve the helium abundance issue $\Rightarrow$ requires an extended modification of opacity!

Inversions with modified opacities - A word of caution...

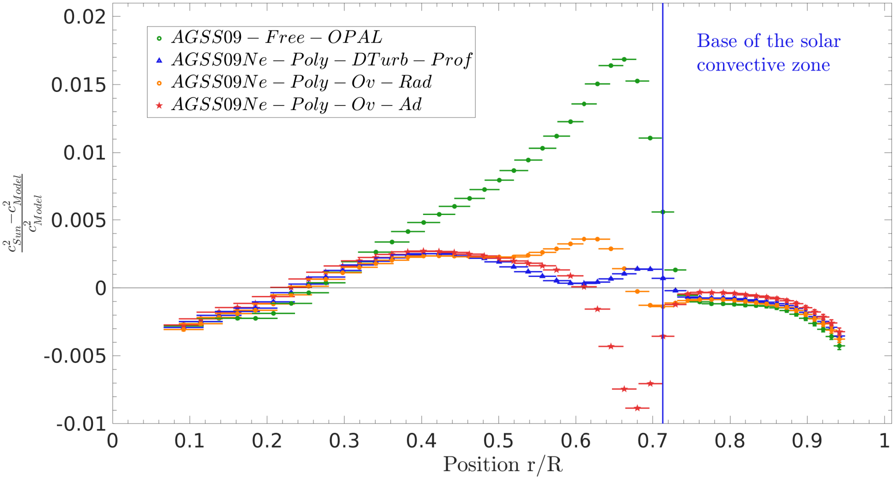


Opacity revision also impact radiative accelerations at a significant level (Gorshkov et al. 2010).

Currently: very small (Turcotte et al. 1998) but not for other stars (Deal et al. 2018).

Inversions with modified opacities - Polynomial Modifications + Mixing

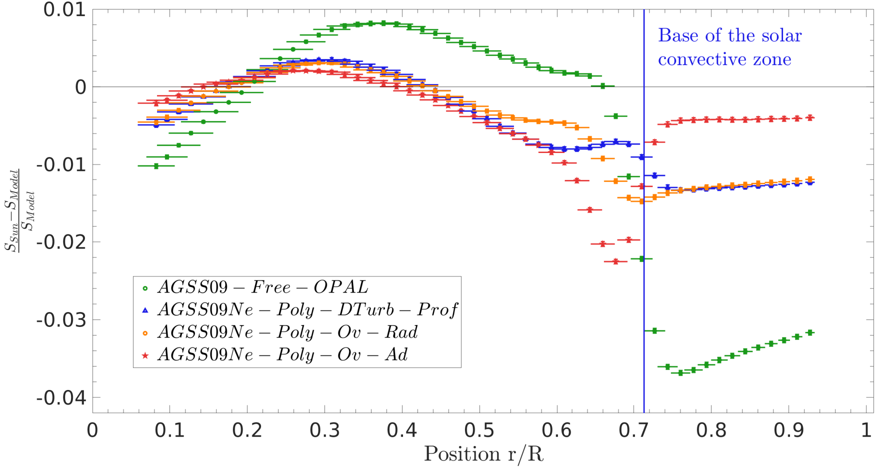
Combining: A, $S_{5/3}$, c^2, Y, position of BCZ, m_{CZ}...



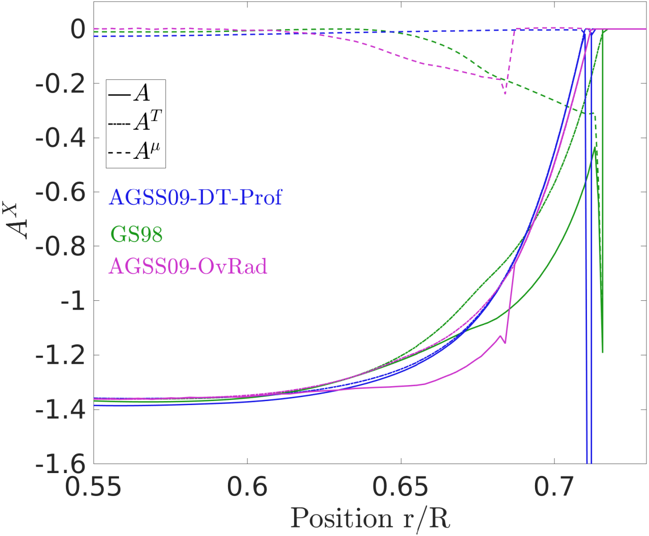
Similar to Christensen-Dalsgaard & Houdek (2010), Ayukov et al. (2011), Christensen-Dalsgaard et al. (2018).

Inversions with modified opacities - Polynomial Modifications + Mixing

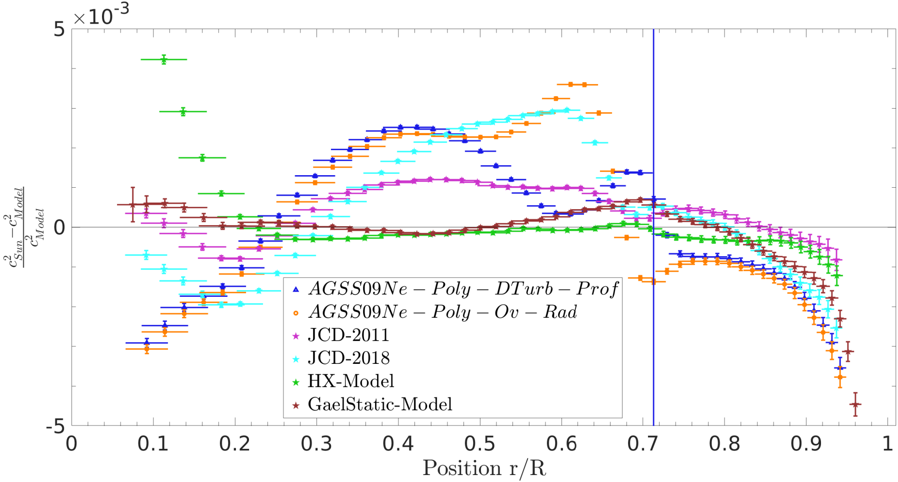
Combination of: Neon increase from Landi & Testa (2015) and Young et al. (2018), extra-mixing and opacity modification (from A. Pradhan)



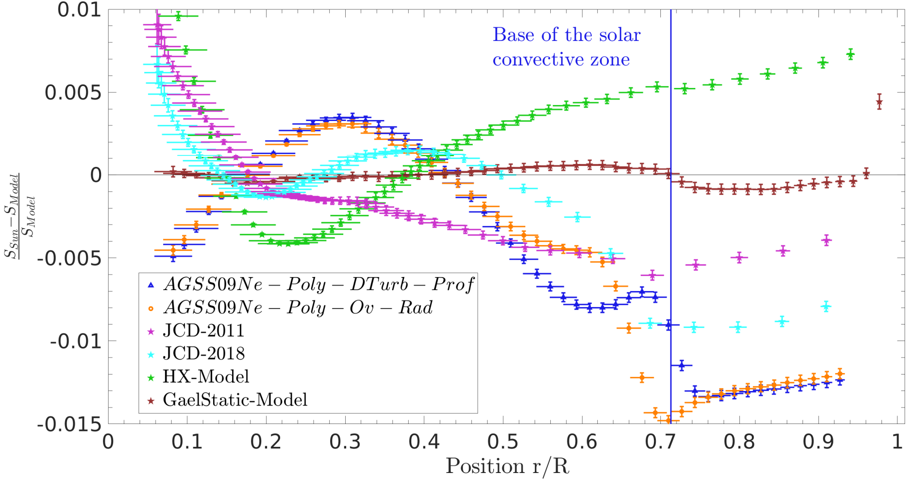
Inversions with modified opacities - Polynomial Modifications



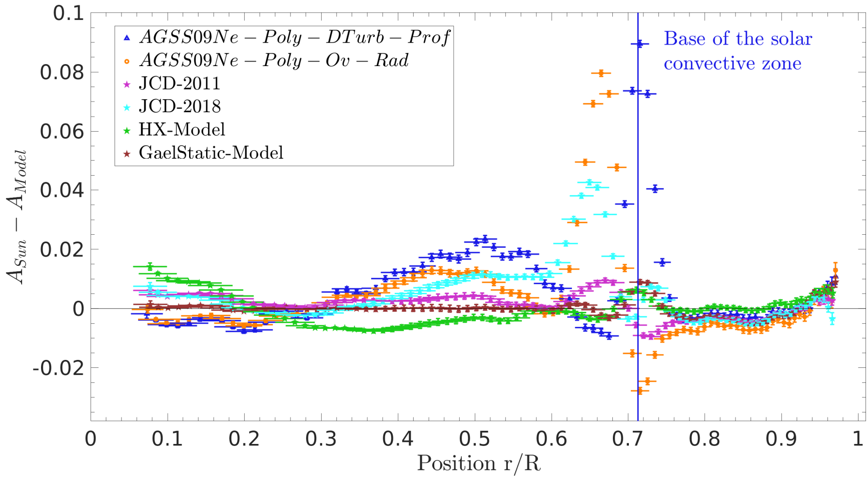
Comparison with seismic models



Comparison with seismic models



Comparison with seismic models



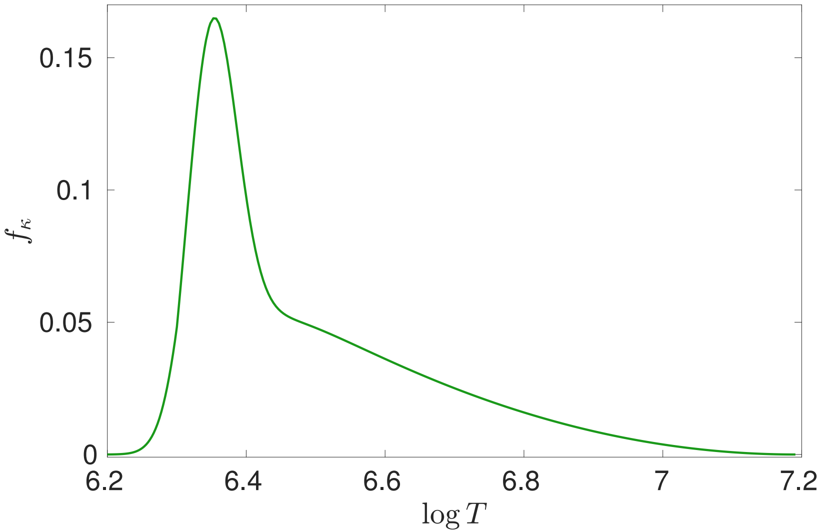
Conclusion and perspectives

In conclusion

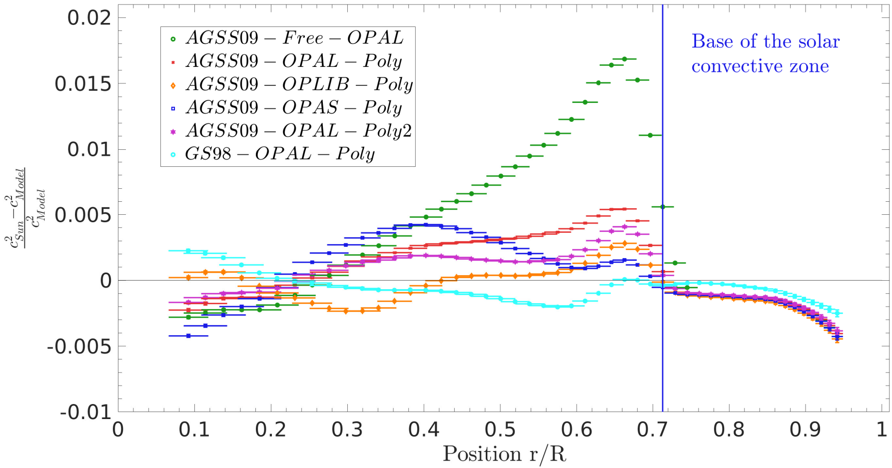
Still a problem: with OPLIB, OPAS, OPAL or OP. Will new opacity computations do it? Maybe. (Pradhan 2017, Zhao 2017, Pain et al. 2019).
What about the BCZ: Extensively studied (see e.g. Hughes 2007 and references therein and Christensen-Dalsgaard et al. (2011))
Is that it? No: Microscopic diffusion, EOS improvements (e.g. Baturin et al. 2013 for SAHA-S).
Is that really it? No: convection, instabilities, gravity waves, ... (e.g. Maeder 2009 and references therein)

Thank you for your attention!

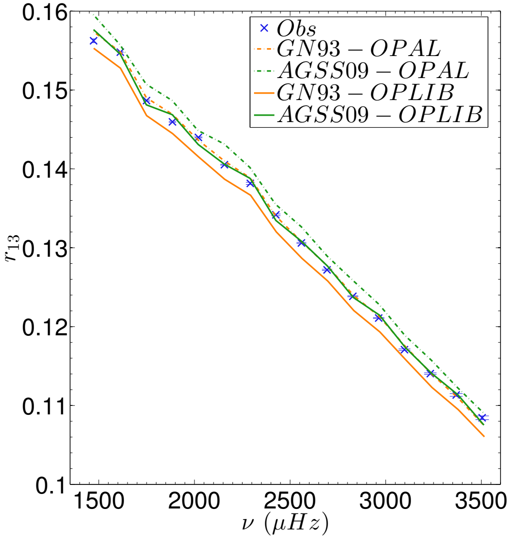
Considered opacity modification



Polynomial modifications for standard models



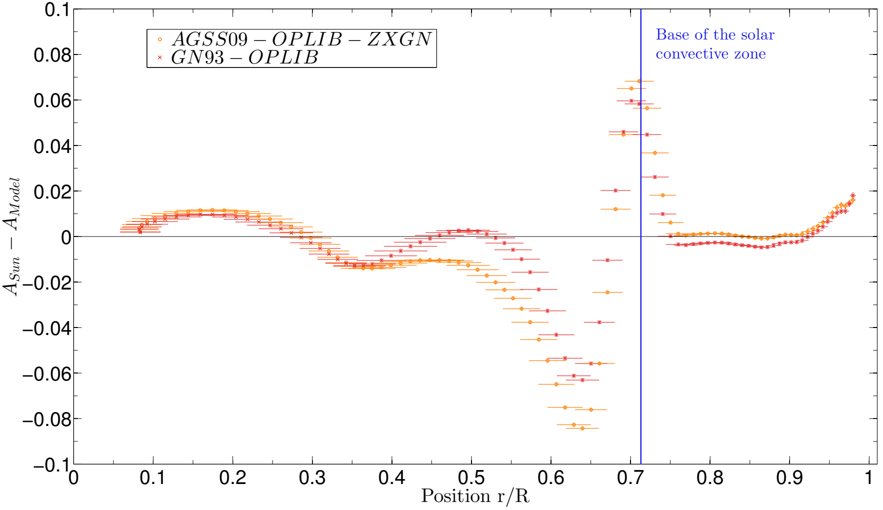
Standard Models with new opacities - Frequency ratios



- 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.

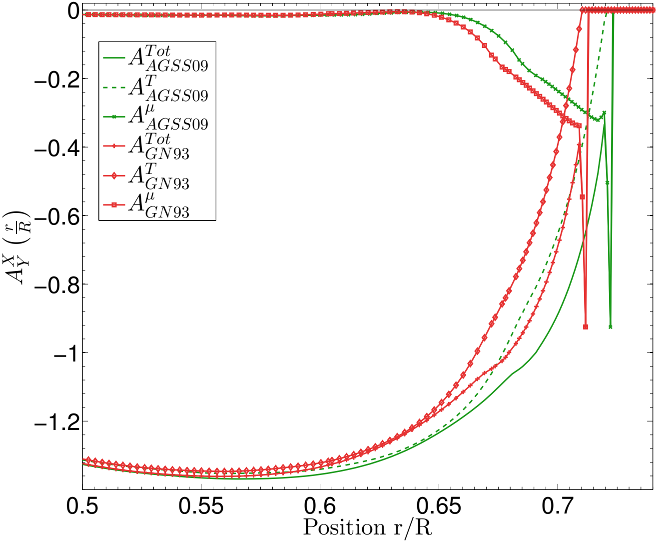
$\Rightarrow$ **Need new diagnostics.**

Inversions of the convective parameter for Standard Solar Models

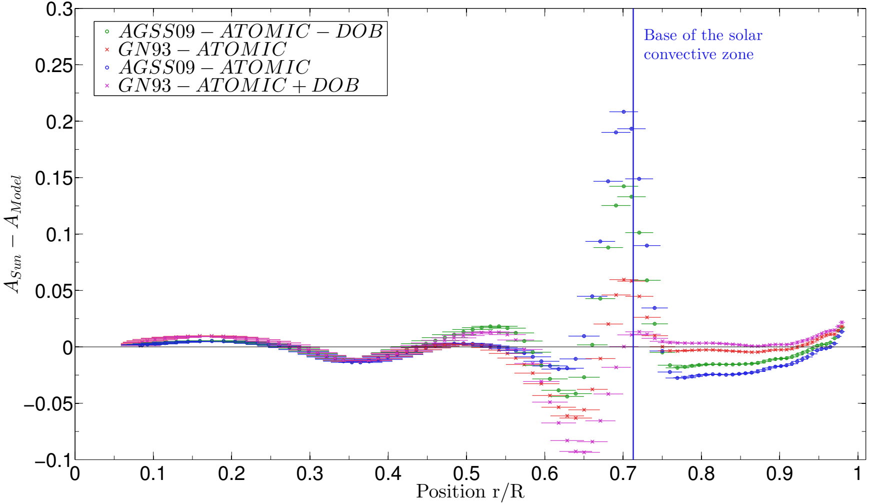


The compensation is related to the heavy-element mixture.

Inversions of the convective parameter for Standard Solar Models

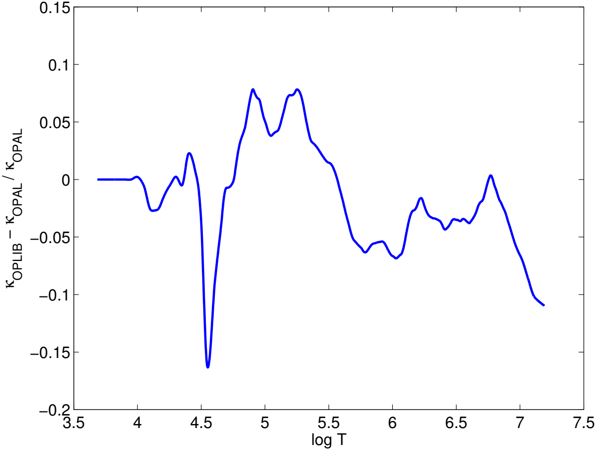


Inversions of the convective parameter for Standard Solar Models



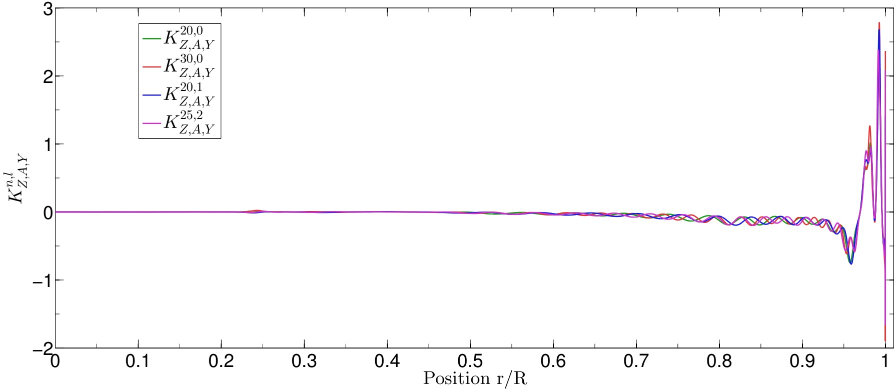
The compensation is also related to the temperature gradient.

Relative differences OPLIB-OPAL

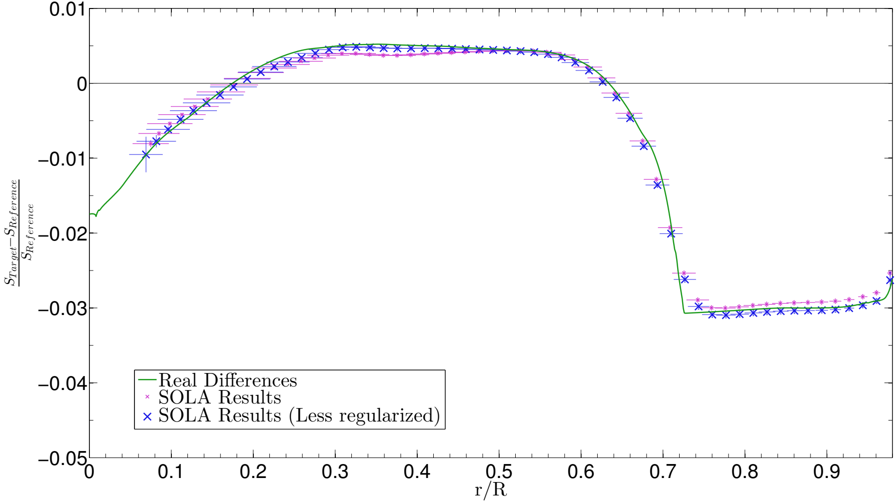


Metallicity Inversions for the Solar Envelope

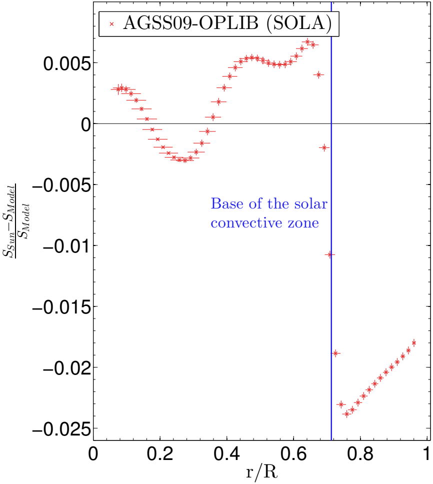
Metallicity kernels can thus be derived to estimate Z in the envelope.

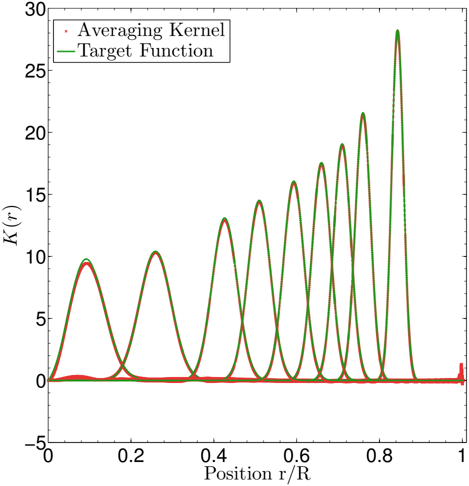


Appendices Helioseismology - Hare-and-Hounds exercises

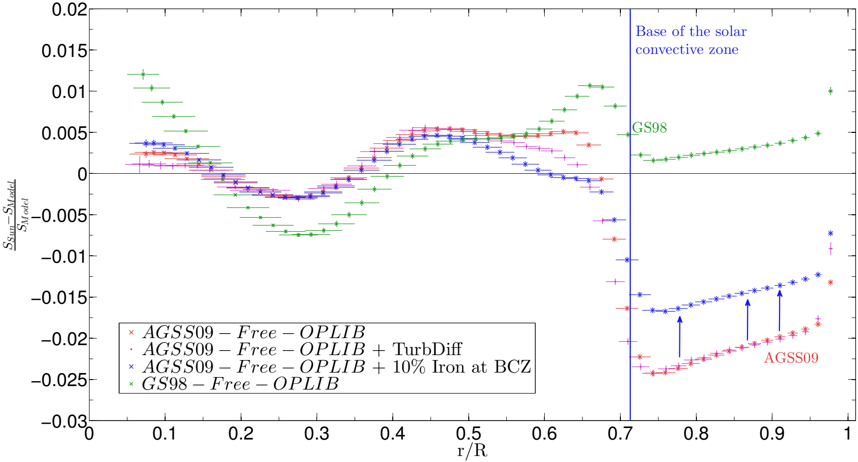


Appendices Helioseismology - Kernel fits





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