Low-Z solar model: sound speed profile under the convection zone

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Low-Z problem in solar physics

5-minute oscillation frequencies -> helioseismic inversion:
– convection zone depth;
– sound speed profile below convection zone;
– helium abundance in the convection zone
Inversion data in this work: Basu, Antia 2008 review

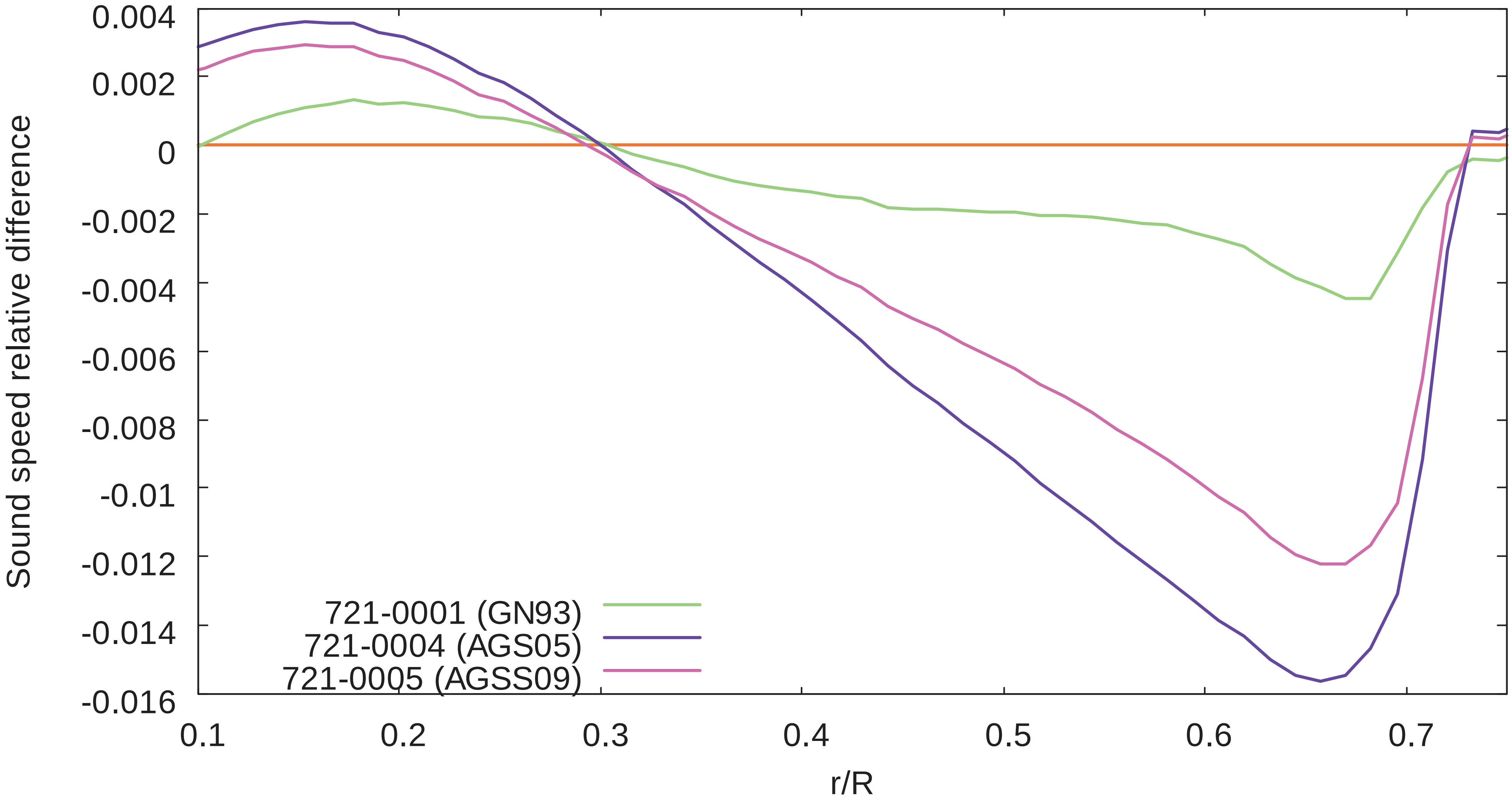
2004-2005: new solar atmosphere abundances, significantly lower; **disagreement with inversion results!**

Recent results **AGSS09**
Asplund, M., Grevesse, N., Sauval, A. J., Scott, P., 2009, Ann. Rev. of Astron. and Astrophys., vol. 47, Issue 1, 481

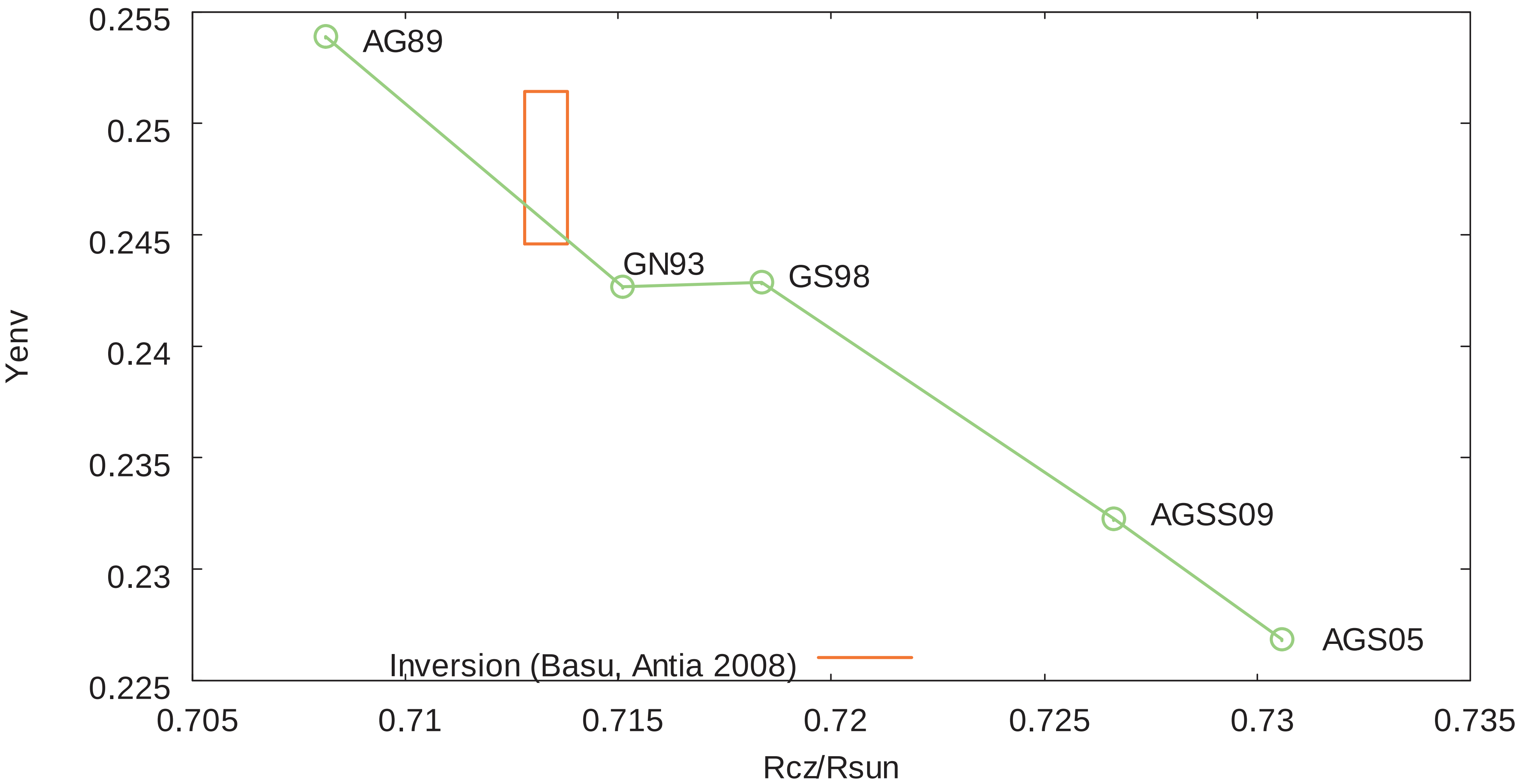
AGSS09: Z/X = **0.0181** vs **0.0244** for GN93

Low-Z abundances: sound speed

Relative difference between models and helioseismic inversion



Low-Z abundances: helium and convection zone depth



Solutions to low-Z problem?

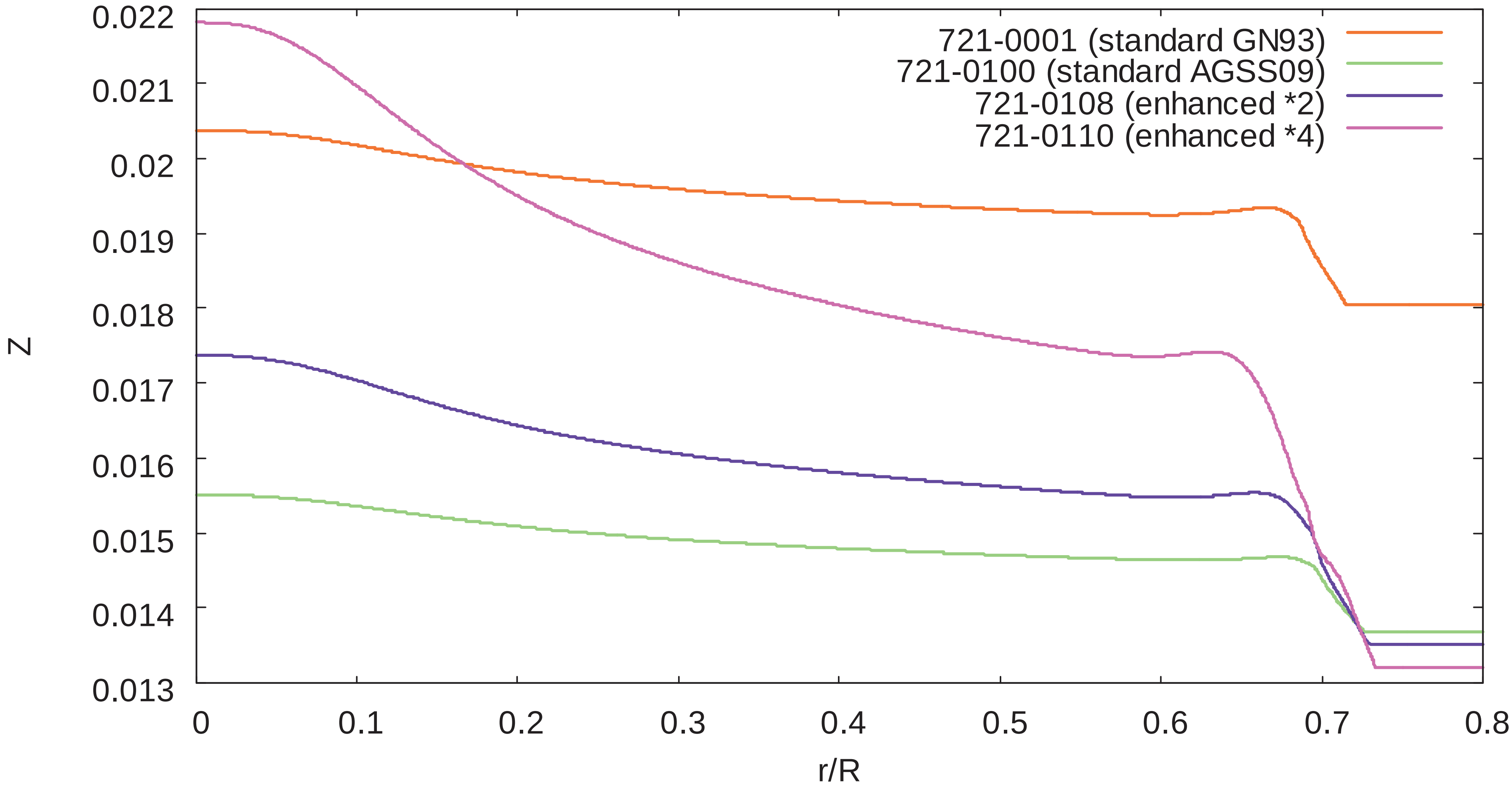
— enhanced Z diffusion
— overshooting
— opacity errors?

Some important input physics

— equation of state: SAHA-S
(e.g. J. Phys. A: Math. Gen. **39** (2006) 4459–4464)
— opacity: OPAL, 19 metals + hydrogen
— 19 element diffusion according Michaud, Proffitt (1993)
— calibration to exact value of Z/X (= 0.0181 for low-Z)

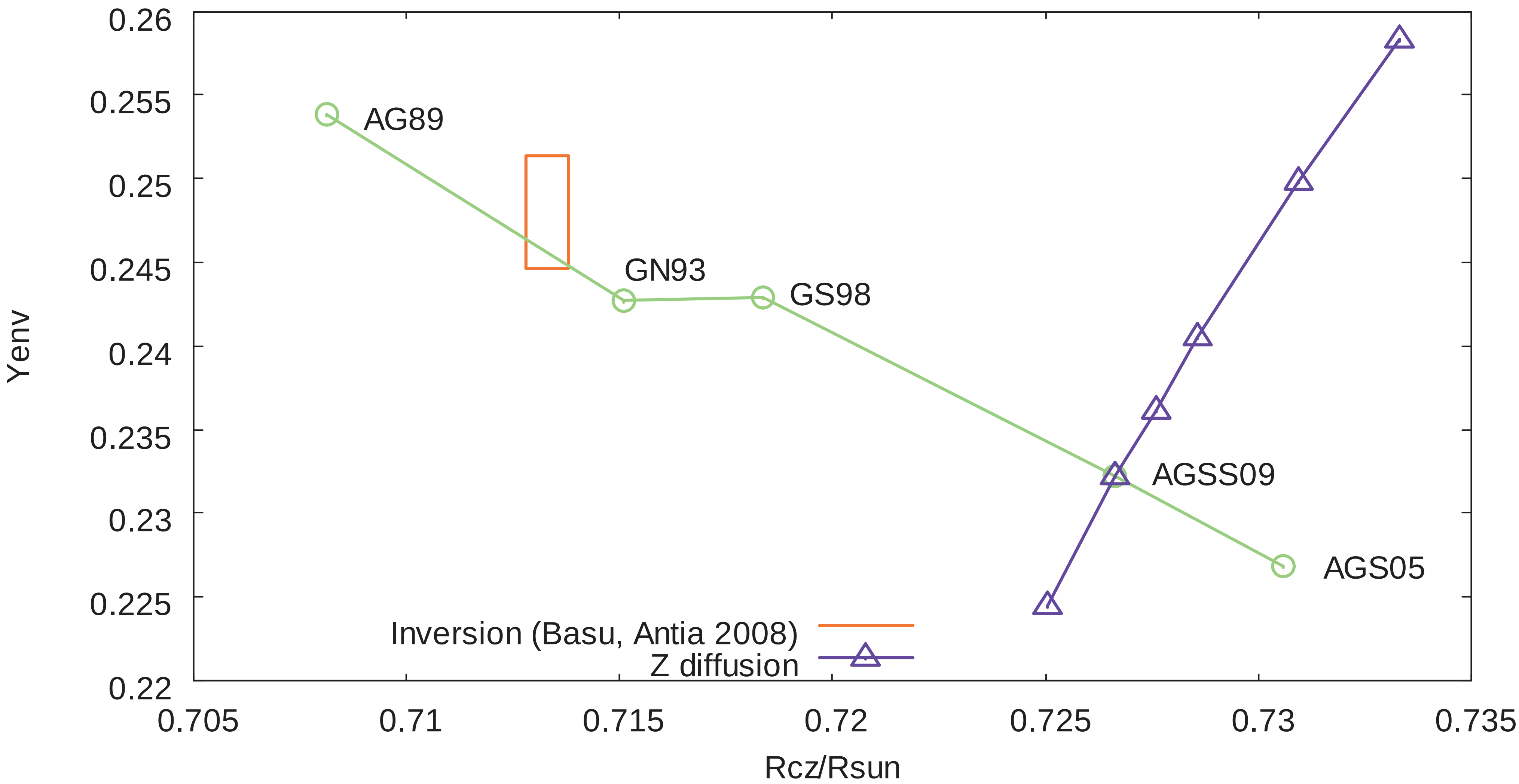
Heavy element diffusion, enhanced

Z shape is different in the core for high-Z and enhanced diffusion models



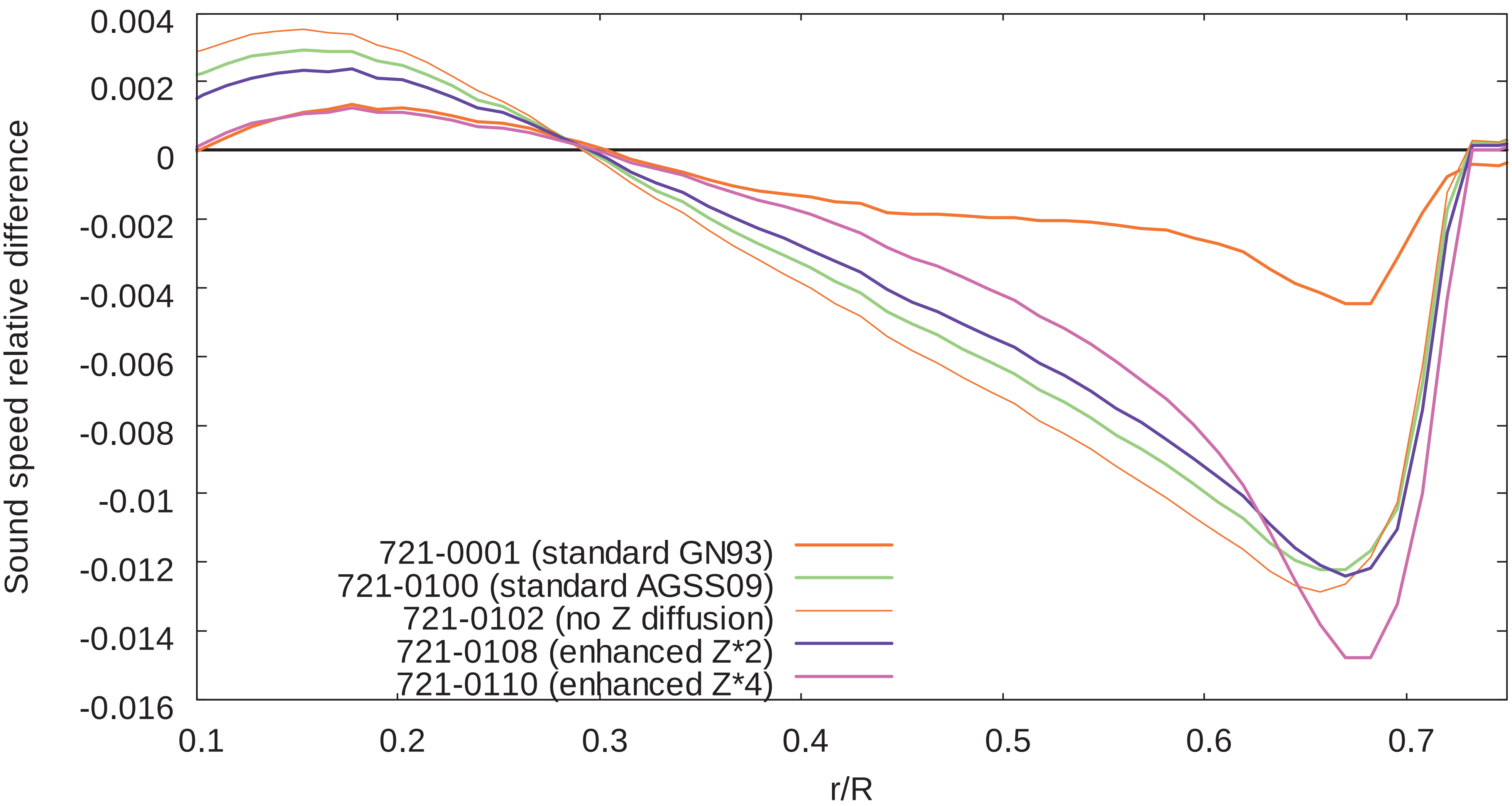
Heavy element diffusion, enhanced

Enhanced Z diffusion helps with Yenv, worsens Rcz
Why CZ is shallower? Opacity in the core.



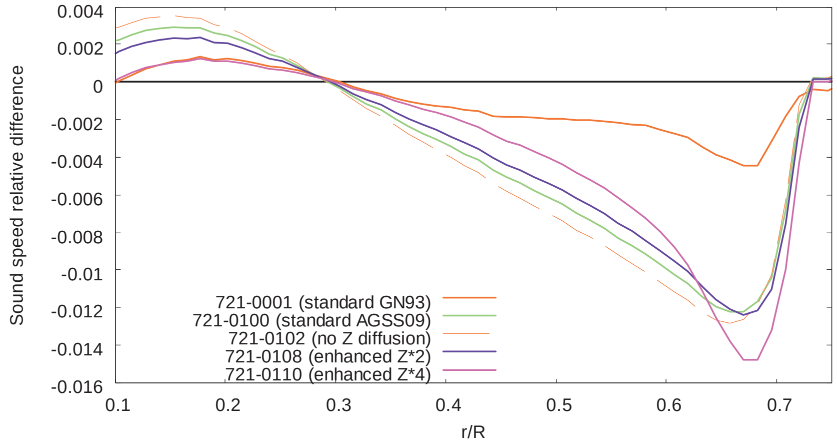
Heavy element diffusion, enhanced

Effect on sound speed profile is minor

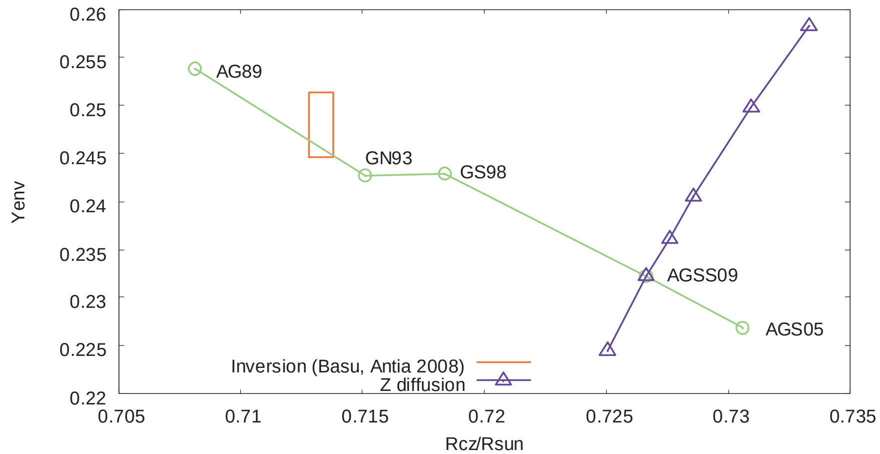


Conclusion on enhanced heavy element diffusion

1. Moderate and undesired effect on CZ depth, small effect on sound speed profile.



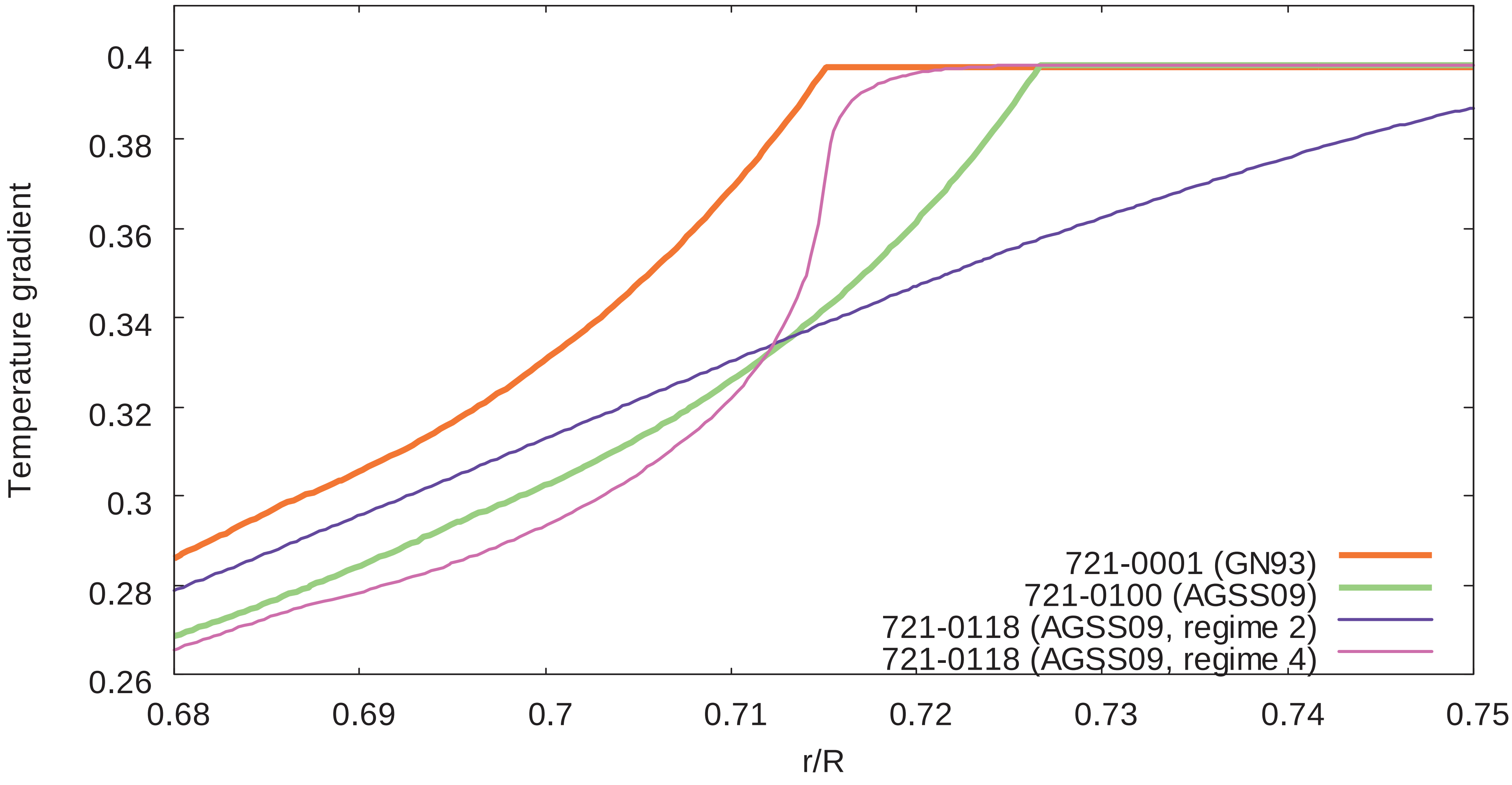
2. Affects Y in the envelope: Can help with low helium abundance in the envelope, but price is high (3x diffusion rate)



Overshooting (penetrating convection)

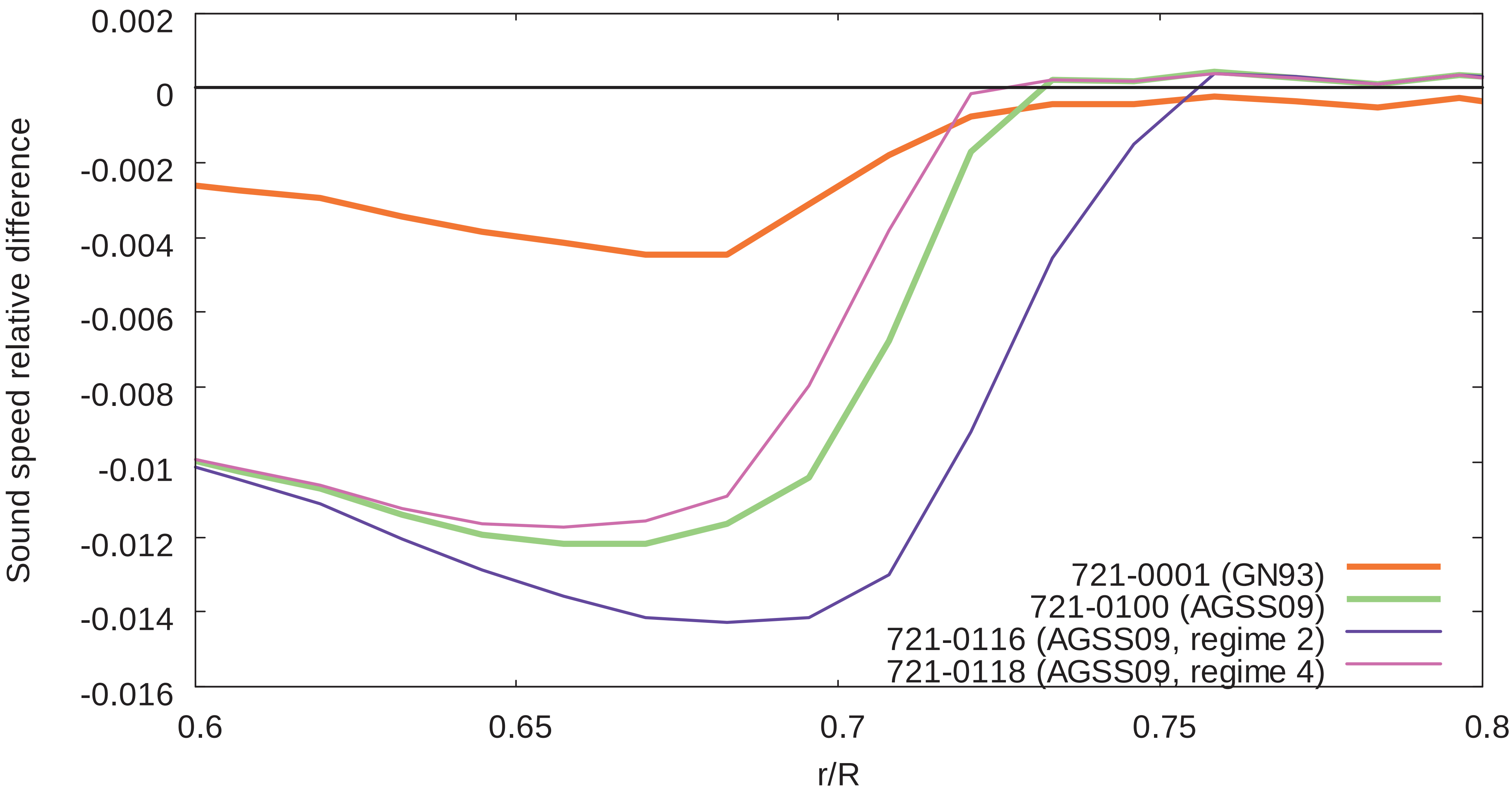
Description of overshooting regimes see in:

S.Ayukov, V.Baturin: ApSS, 2010, DOI 10.1007/s10509-010-0298-x



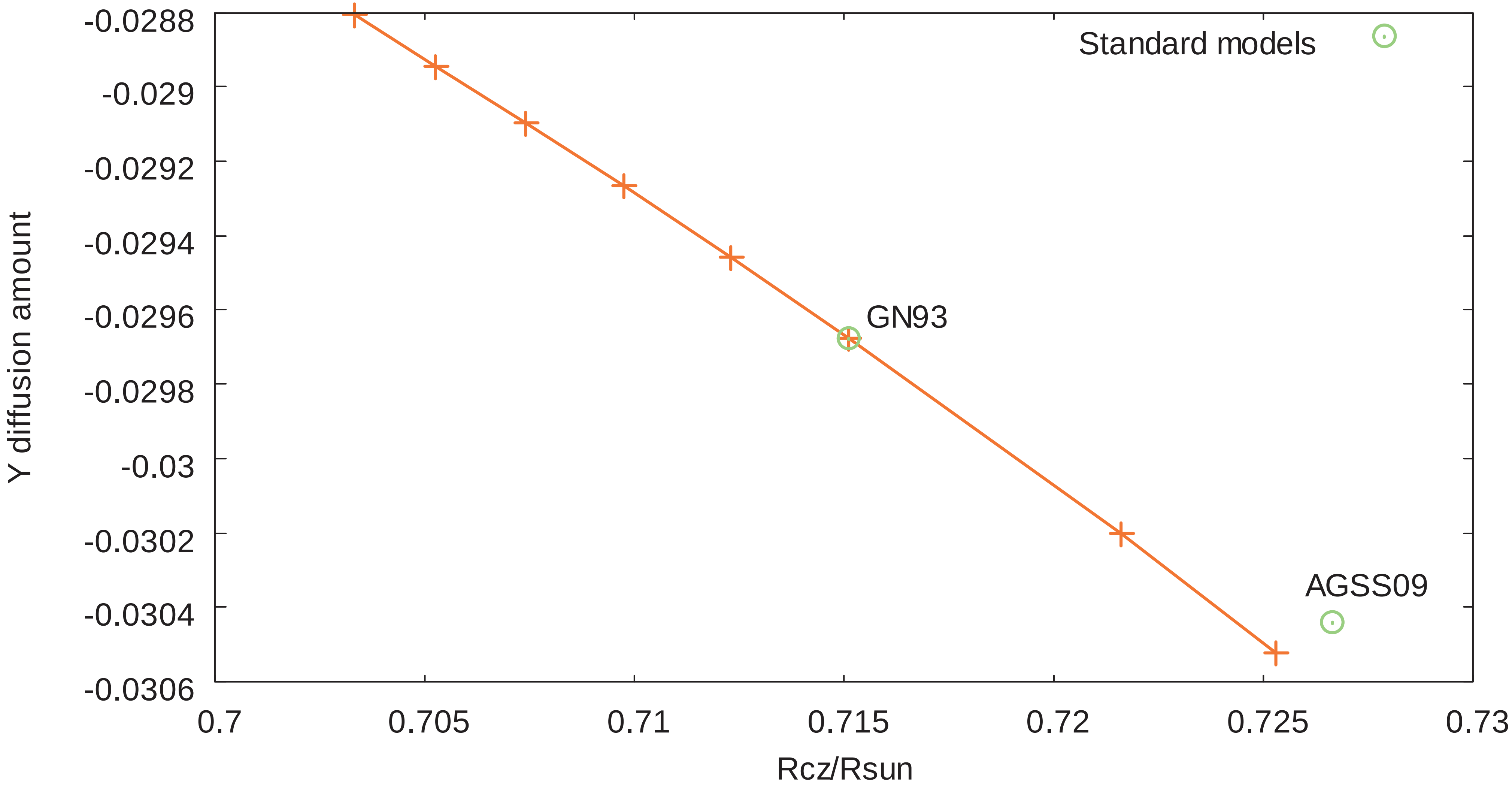
Overshooting, effect on sound speed profile

Mostly reflects CZ depth change



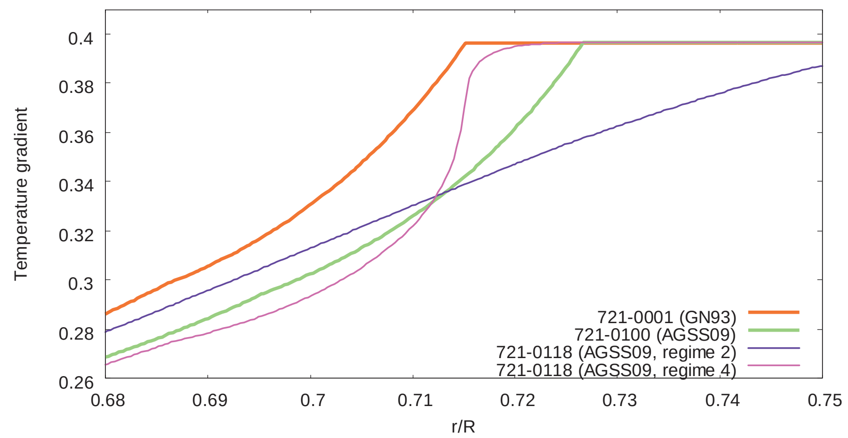
Overshooting, CZ depth and Y depletion

Change in mixing position **0.01** Rsun (GN93-AGSS09) due to overshooting produces change in Y **0.001**

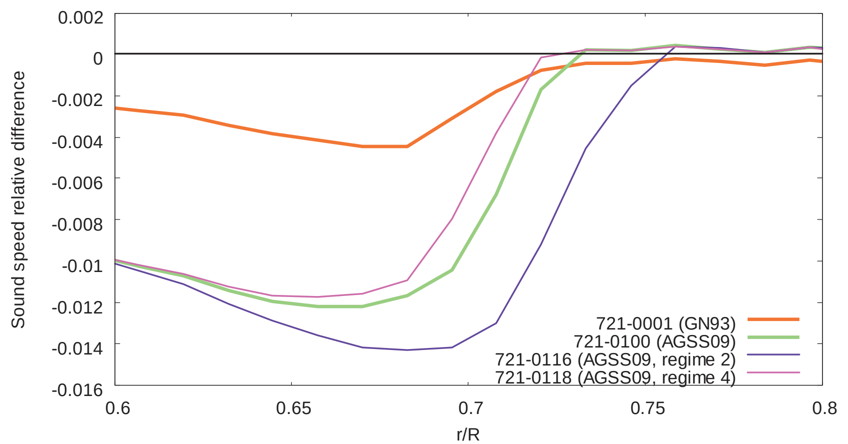


Conclusion on overshooting

1. Can increase effective CZ depth, but sound speed profile under CZ is not improved.



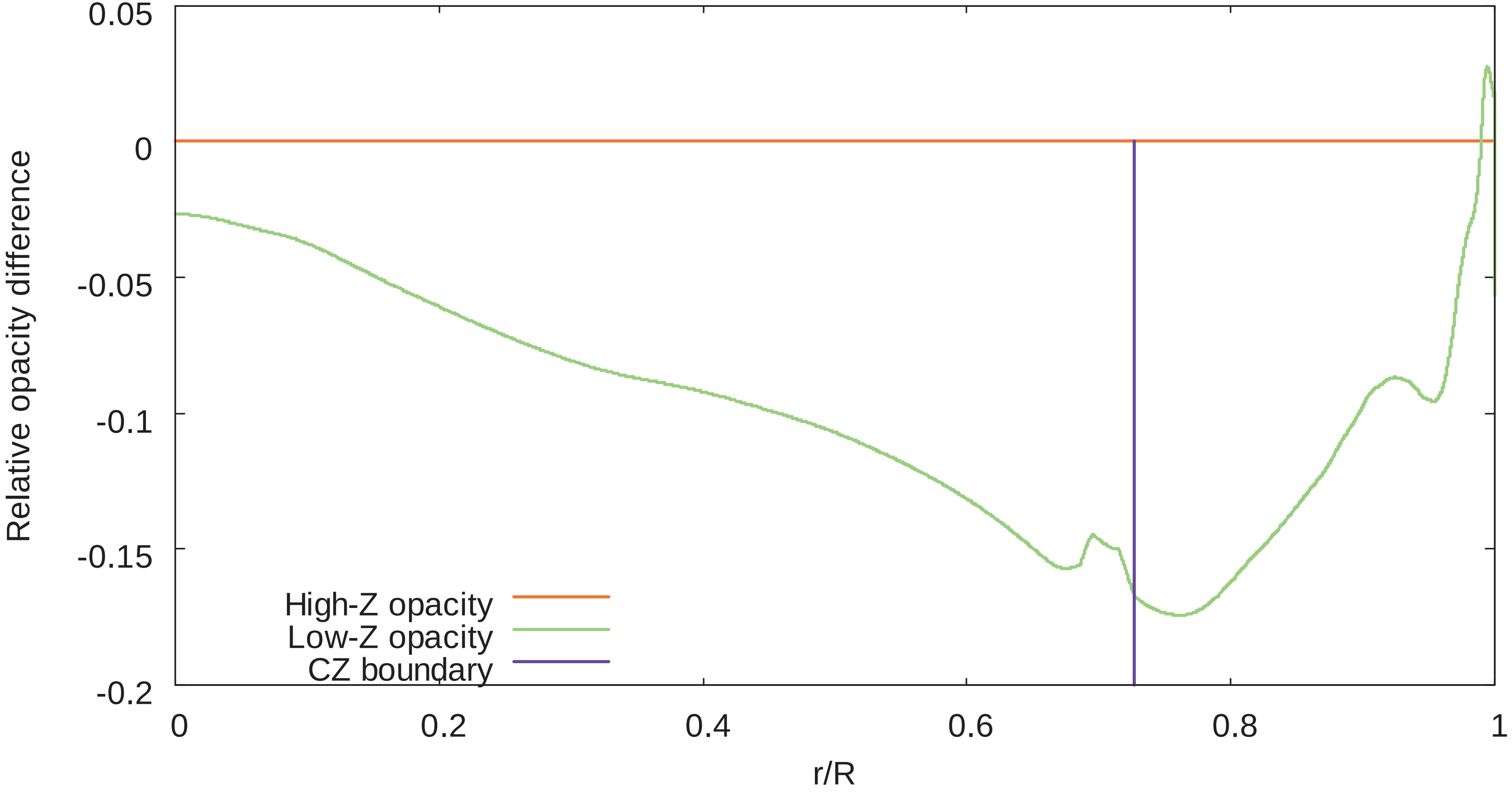
2. Can give smooth sound speed transition between convection and radiative zones, at the cost of decreasing convection zone depth.



3. Effect on He depletion amount is is not significant.

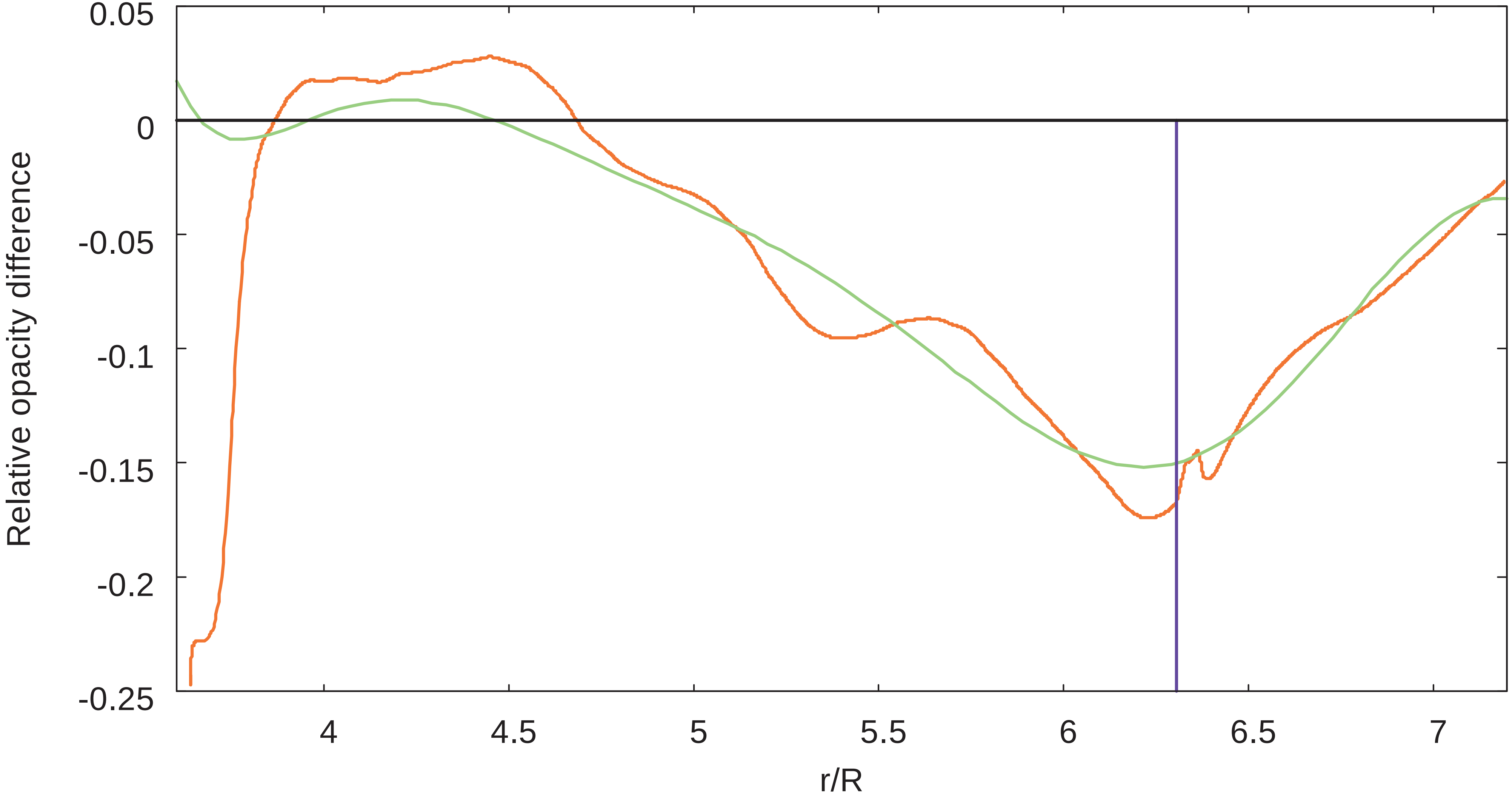
Effect of low Z abundance on opacity

Only opacity below CZ bottom affects the model.
–3% in the center, –17% near CZ bottom



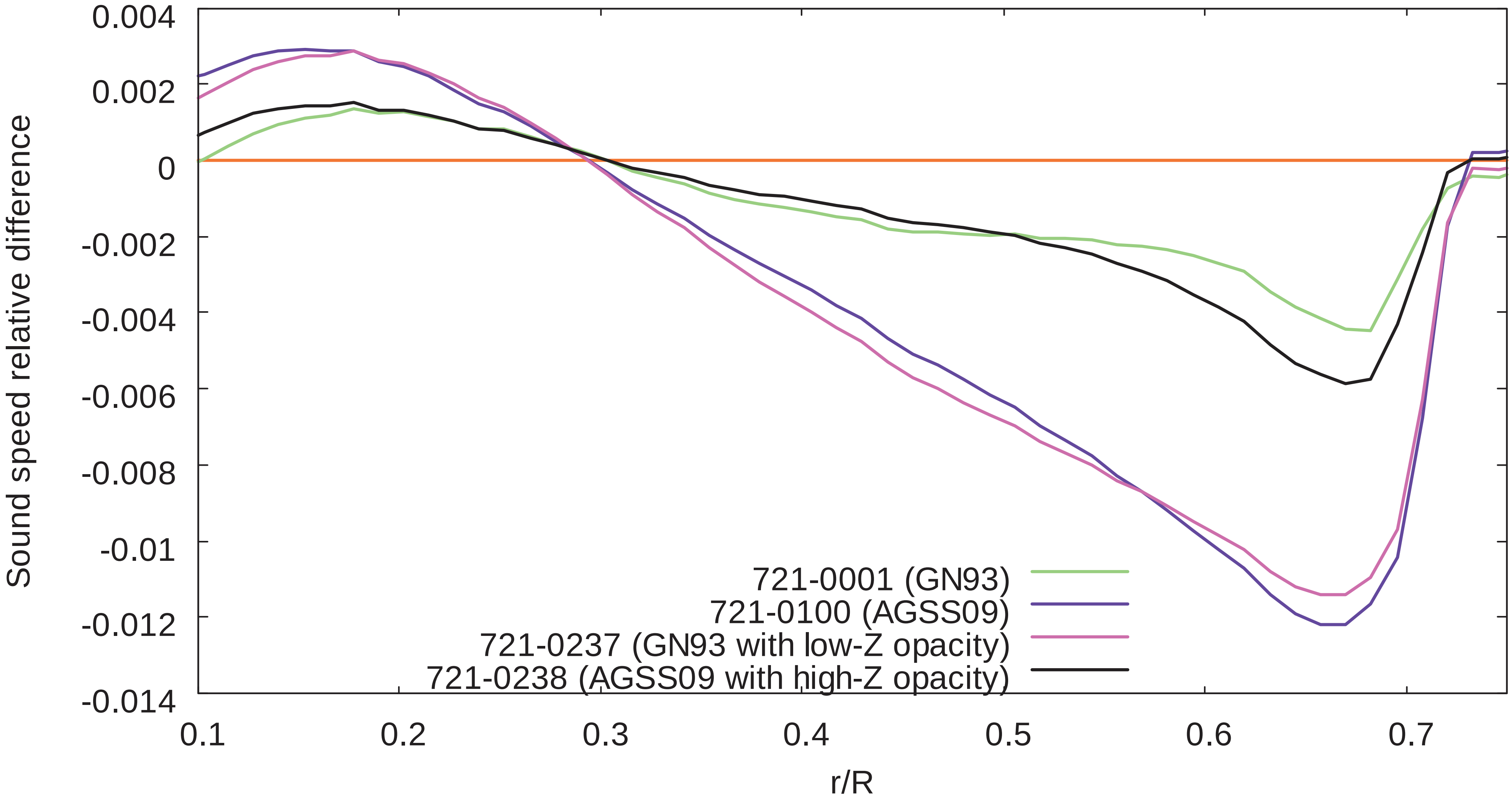
Approximation of low-Z effect on opacity

Approximation is simple polynomial temperature-dependent function



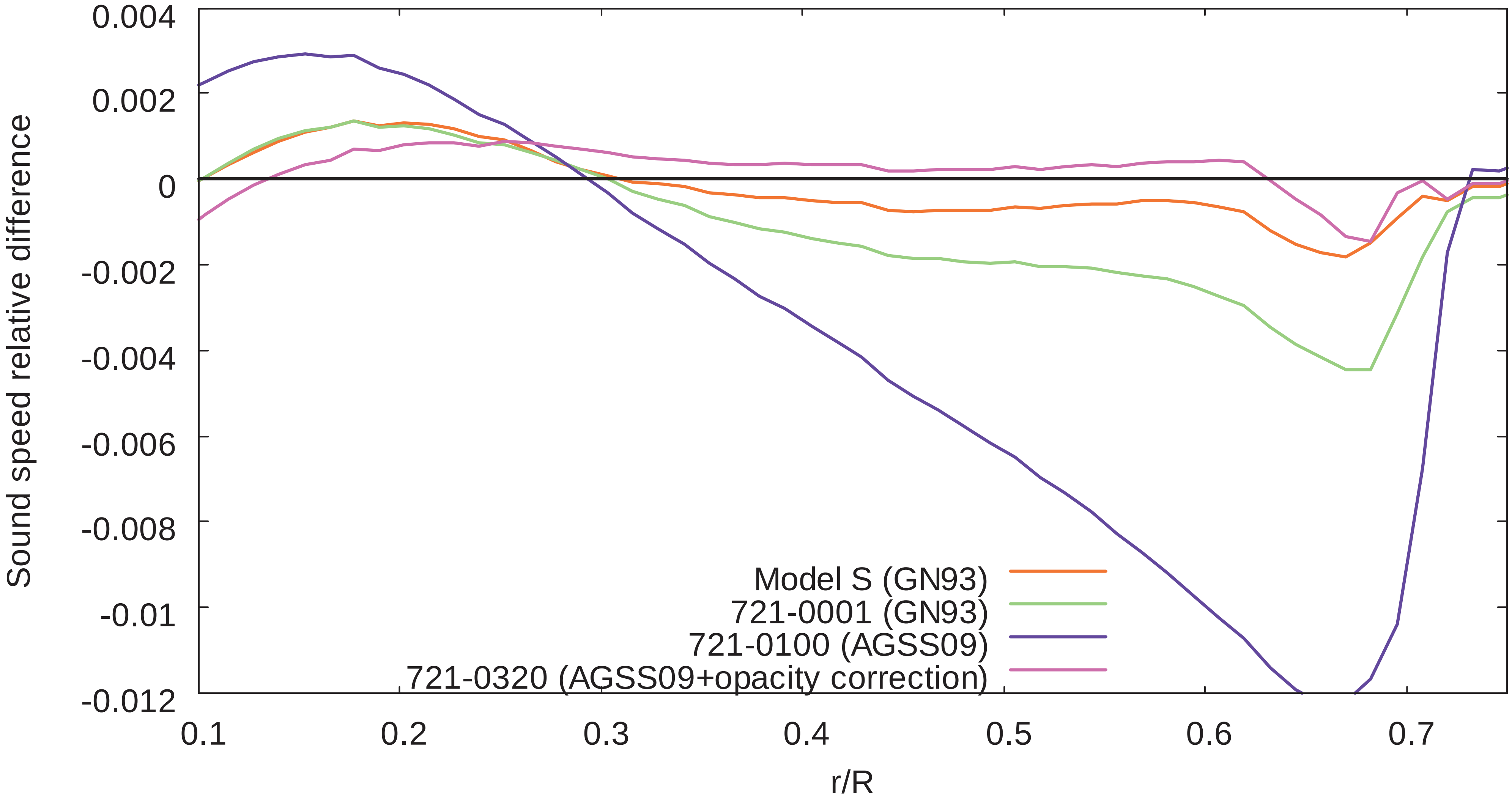
Low-Z model with high-Z opacity

He abundance and Rcz in the simulated models are also restored:
Ys (721-0238) = 0.2436, Rcz (721-0238) = 0.7177



Further improvements?

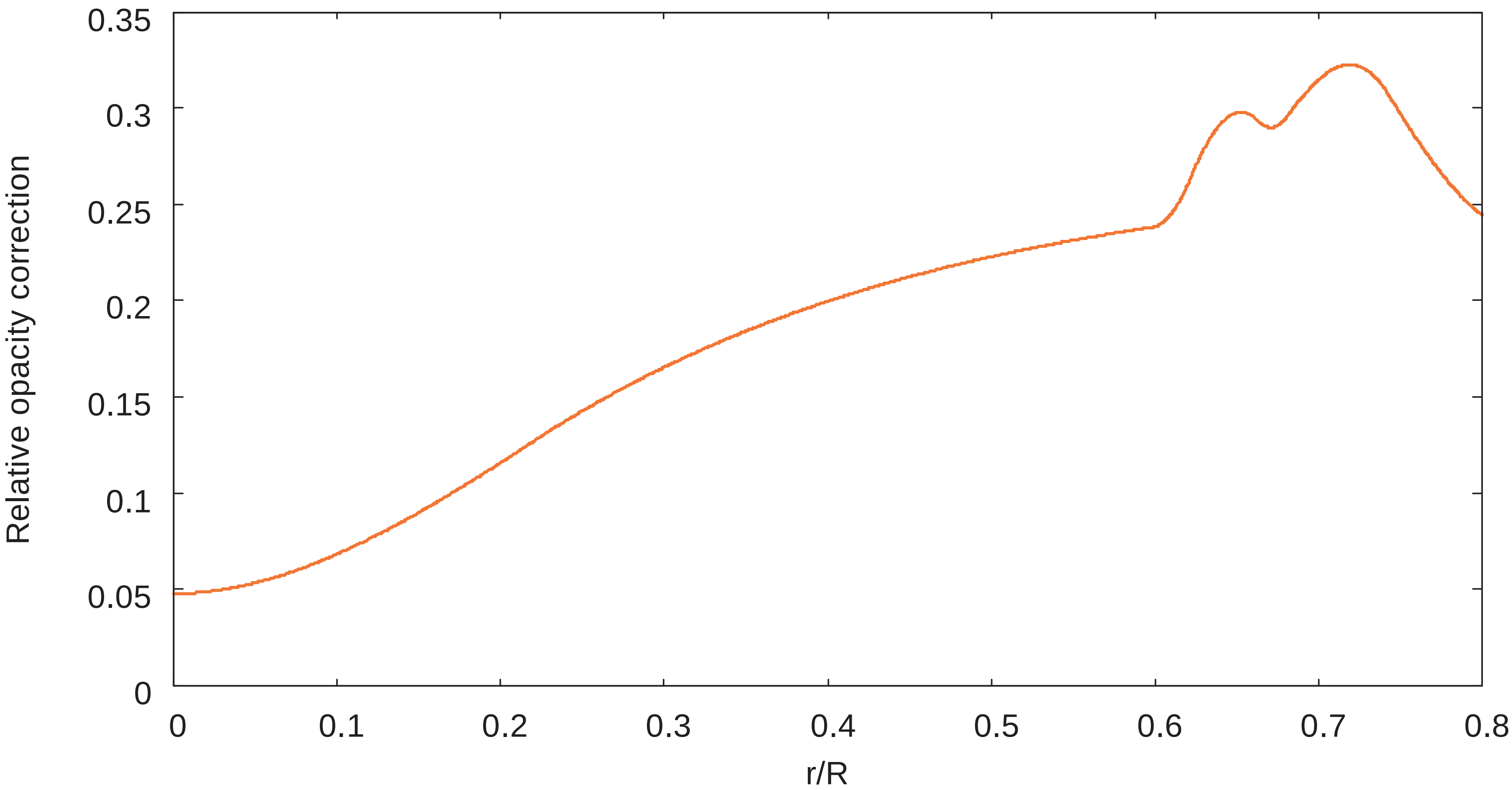
Change amplitude and add more opacity corrections!



Opacity correction in the best model with low-Z

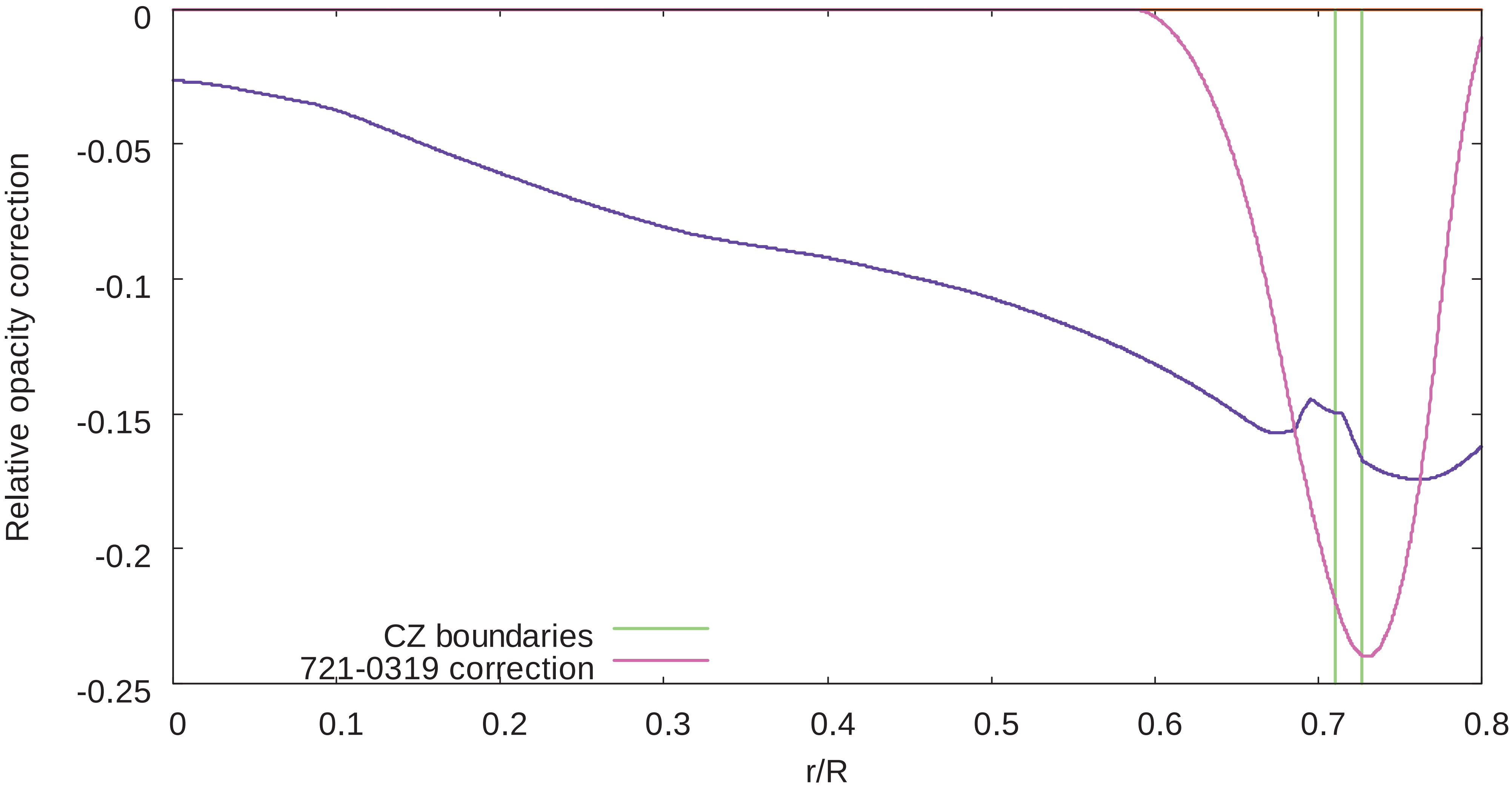
+5% in the center, +25-30% near CZ bottom!

Ys = 0.254, Rcz = 0.710



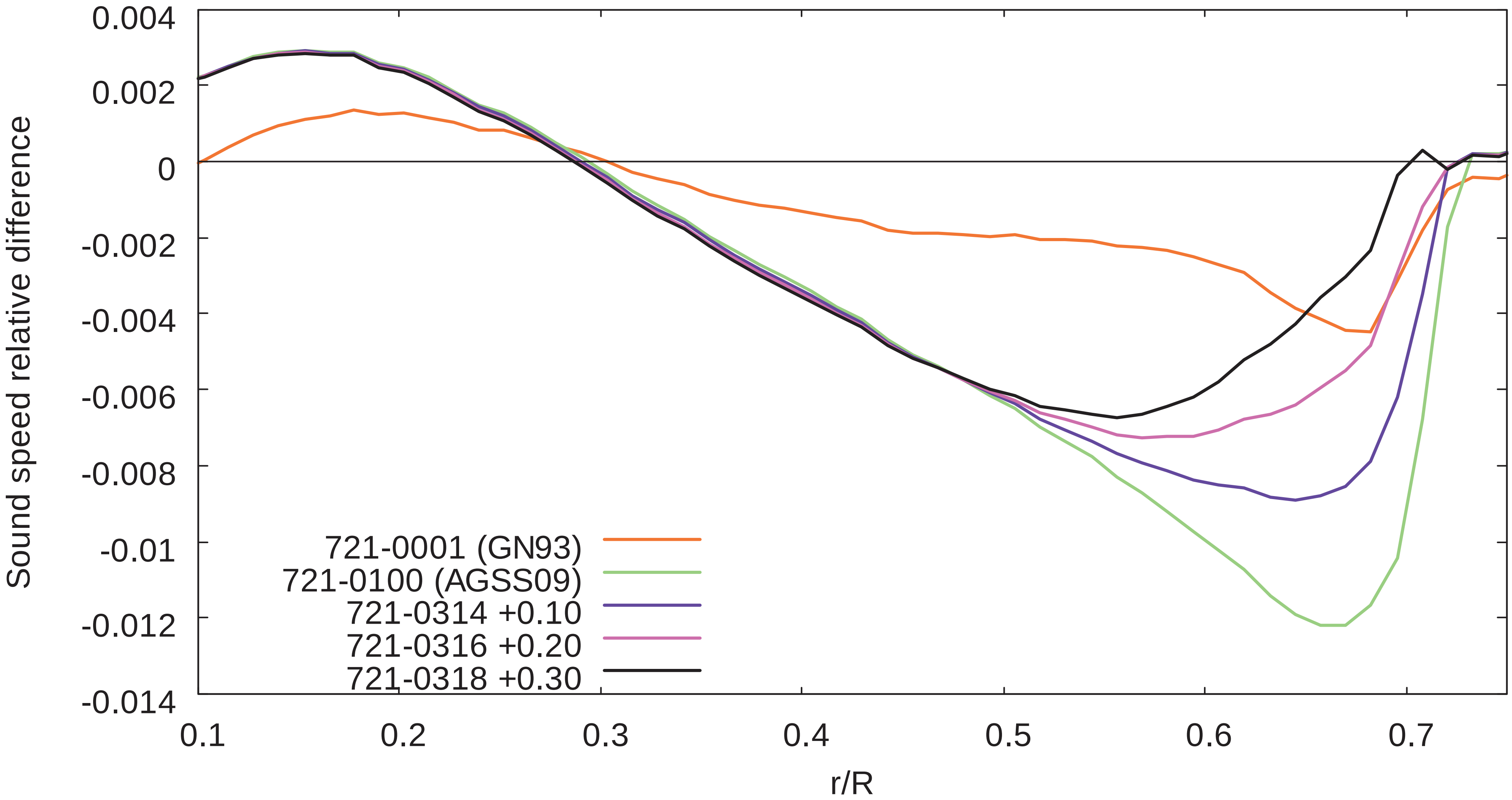
Opacity correction near CZ bottom

CZ depth difference in low-Z and high-Z: 0.011 Rsun
correction range in lgT: 6.1 -- 6.5
Can give proper CZ depth (721-0319), +24% correction



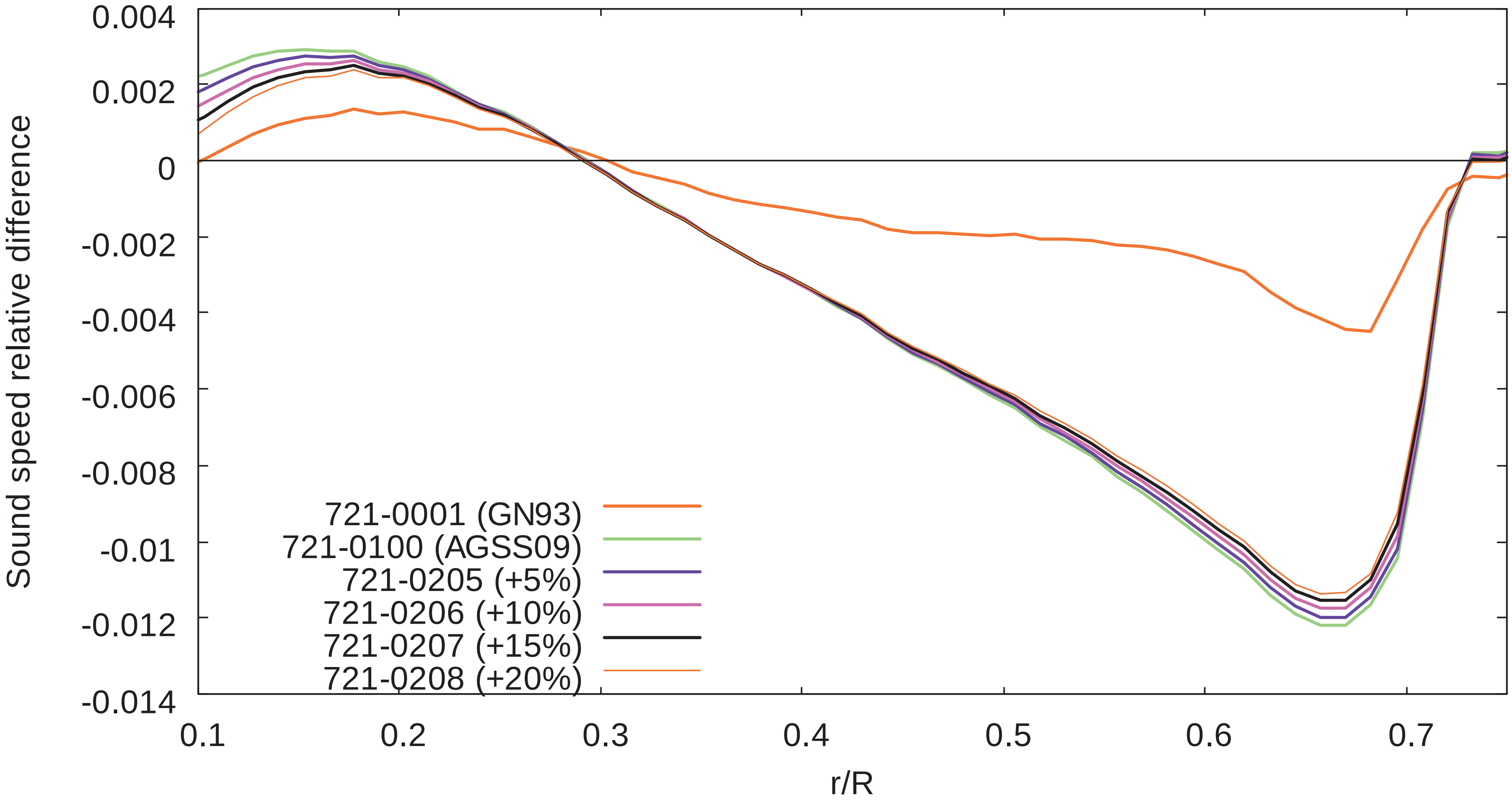
Opacity correction near CZ bottom: sound speed

Only affects region below CZ boundary, deeper layers are unaffected



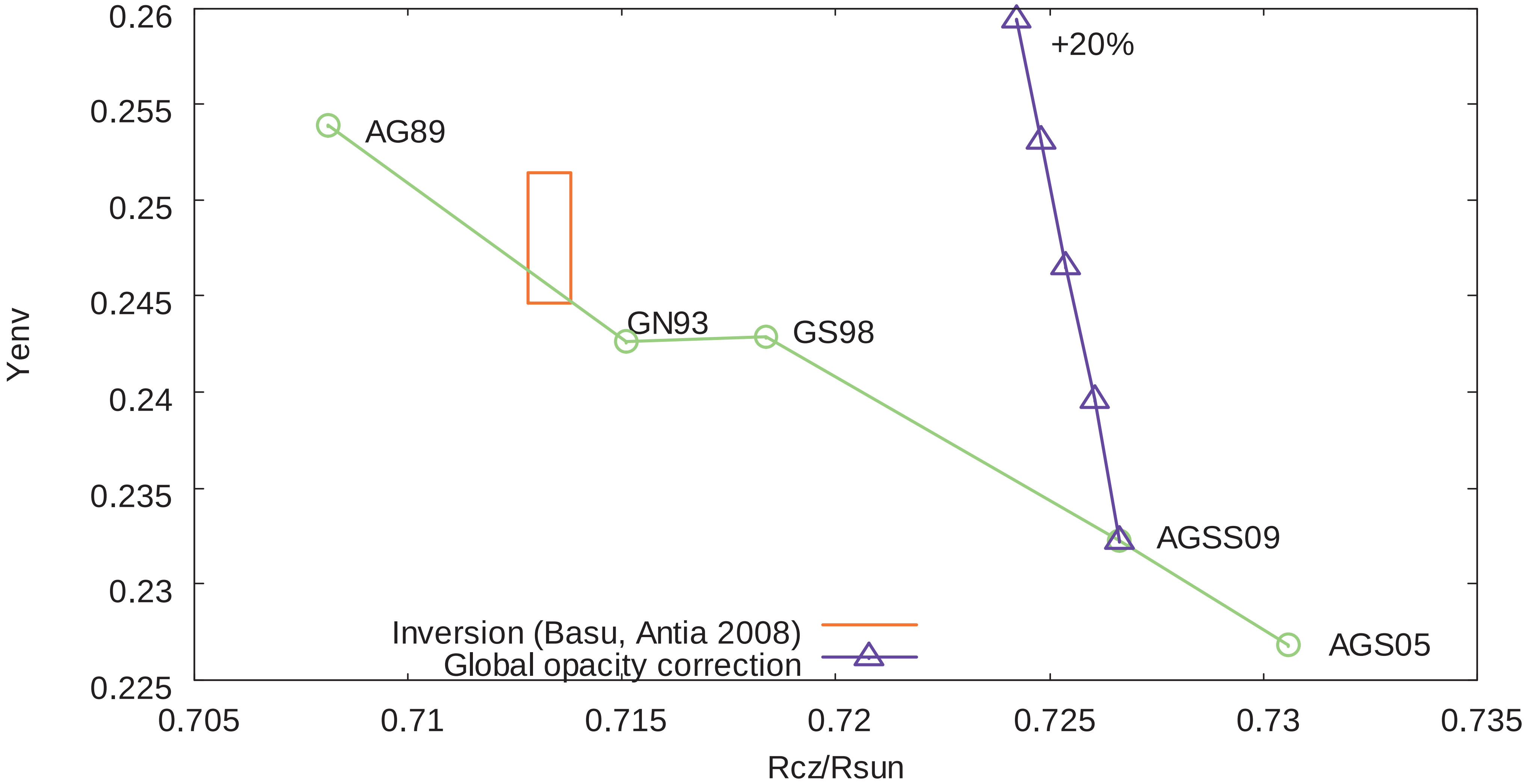
Global opacity correction: sound speed

Uniform opacity correction (applied everywhere): very small effect on sound speed profile, mostly near the center



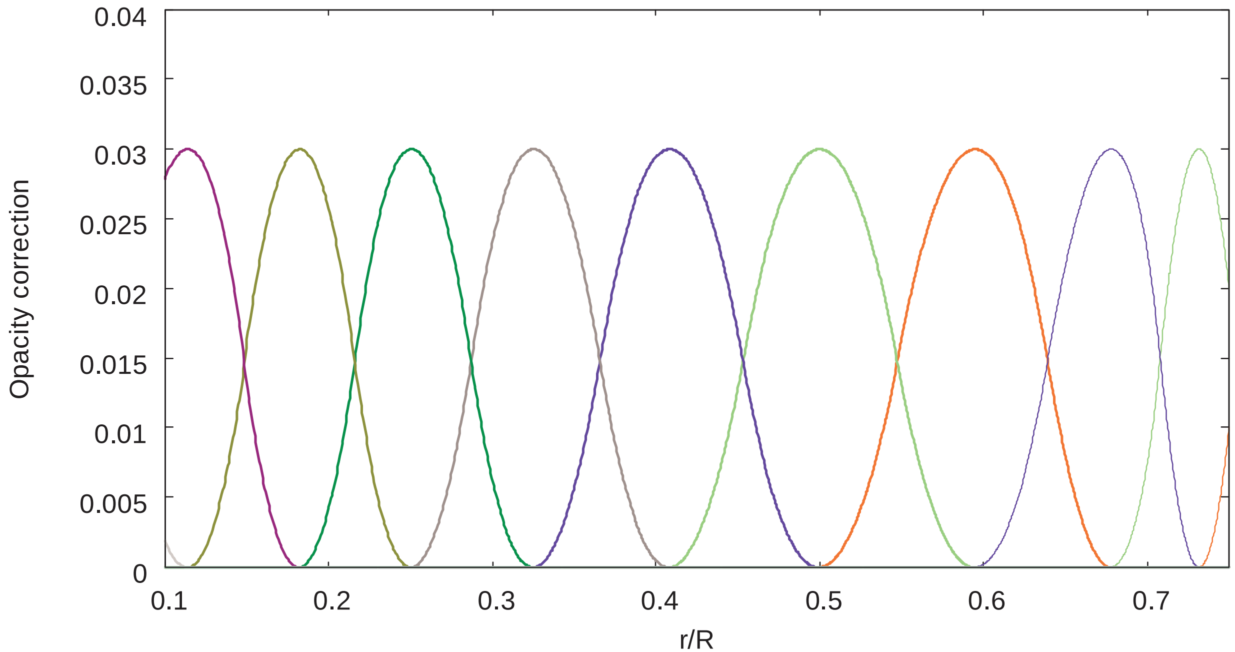
Global opacity correction: model parameters

Helium abundance!

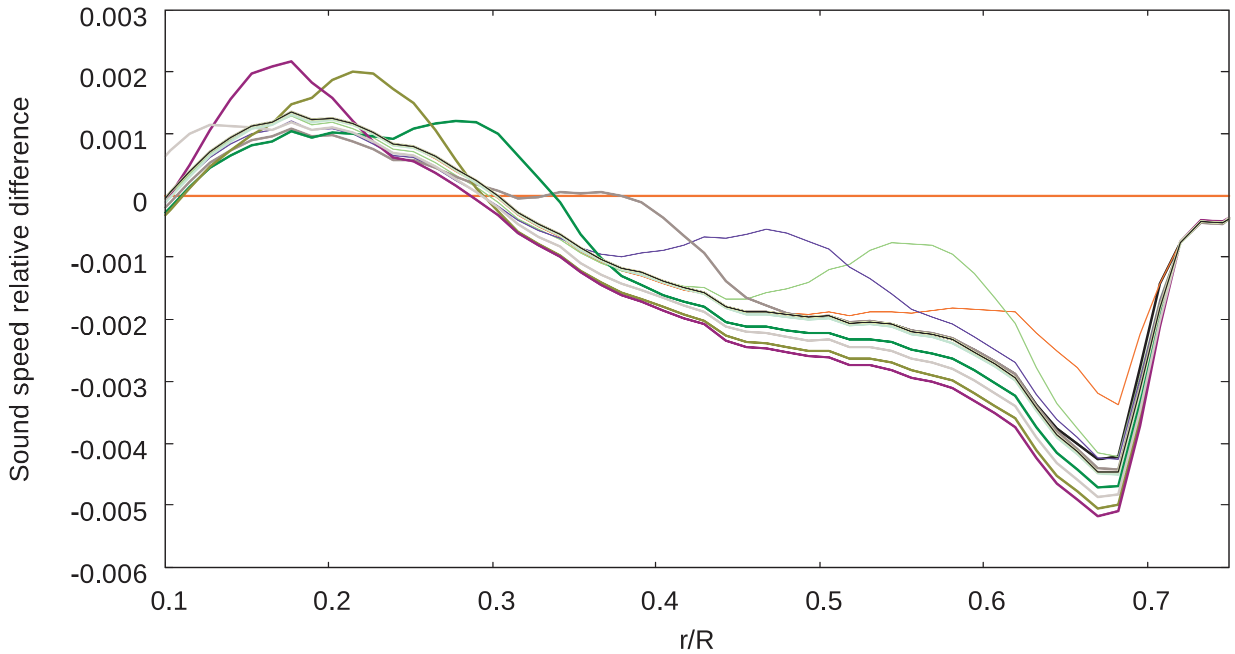


Localized opacity corrections

Signal — localized opacity correction

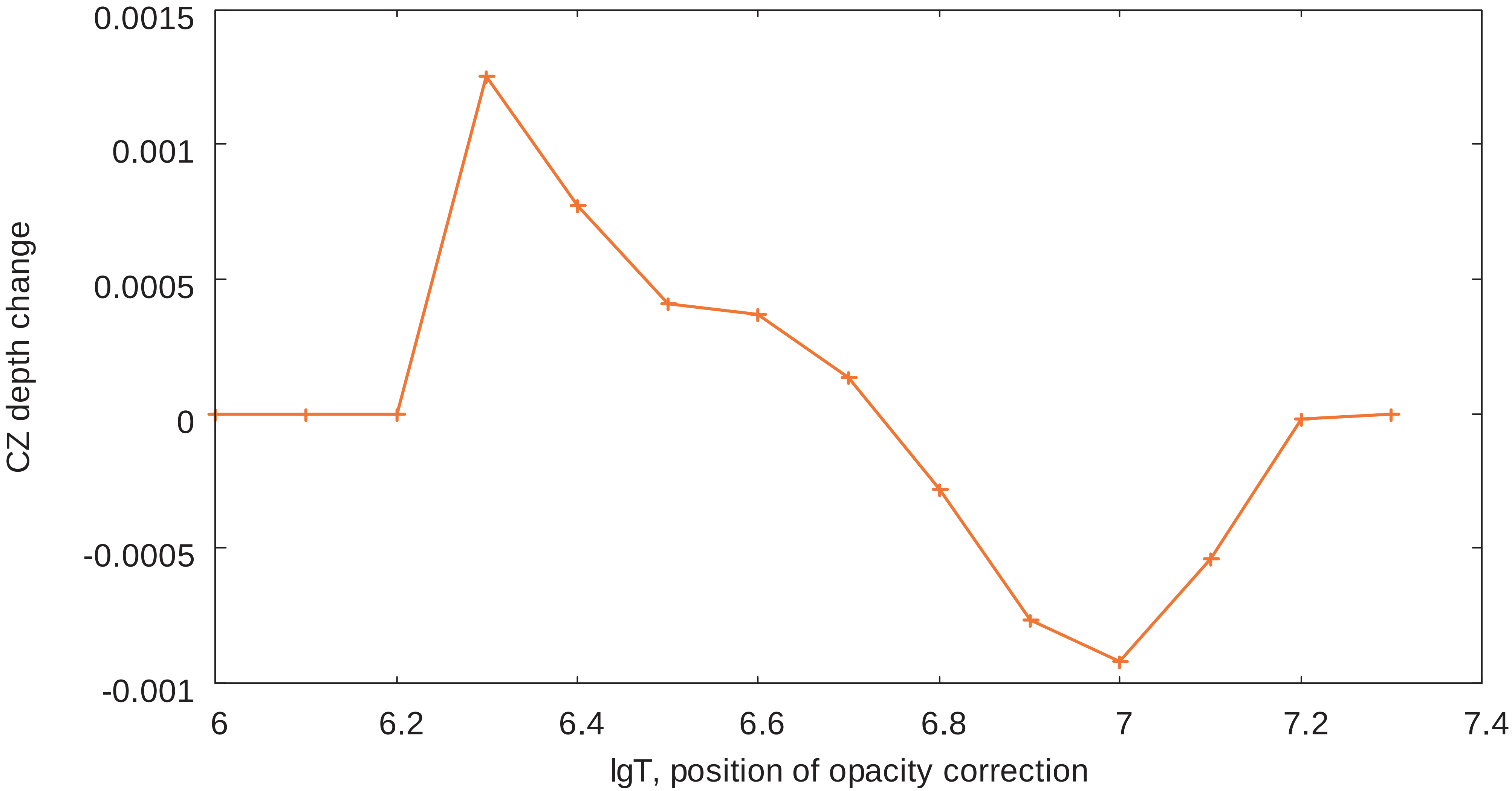


Response — sound speed change



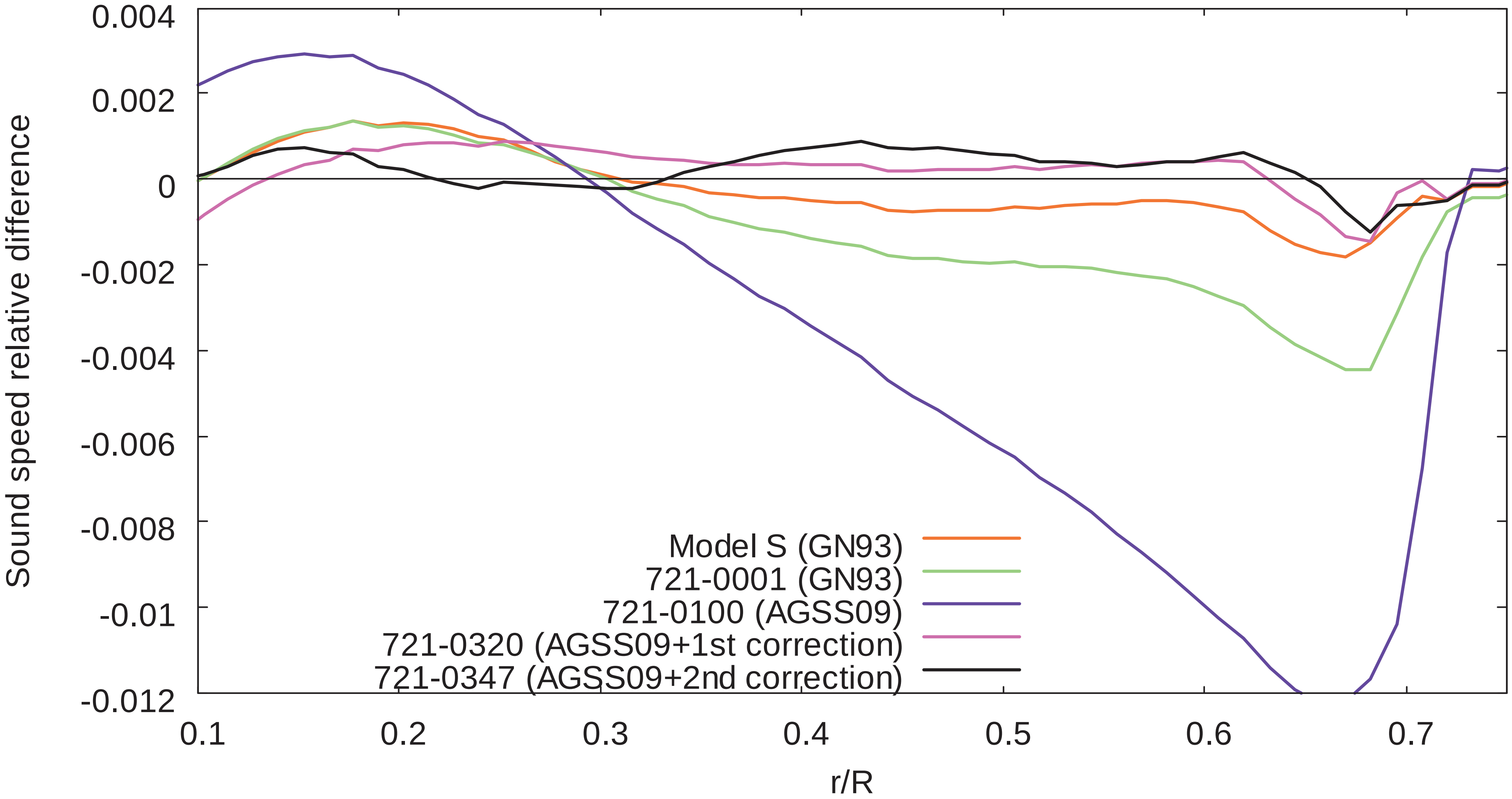
Localized opacity correction: effect on CZ depth

Increasing opacity in the center leads to shallower CZ



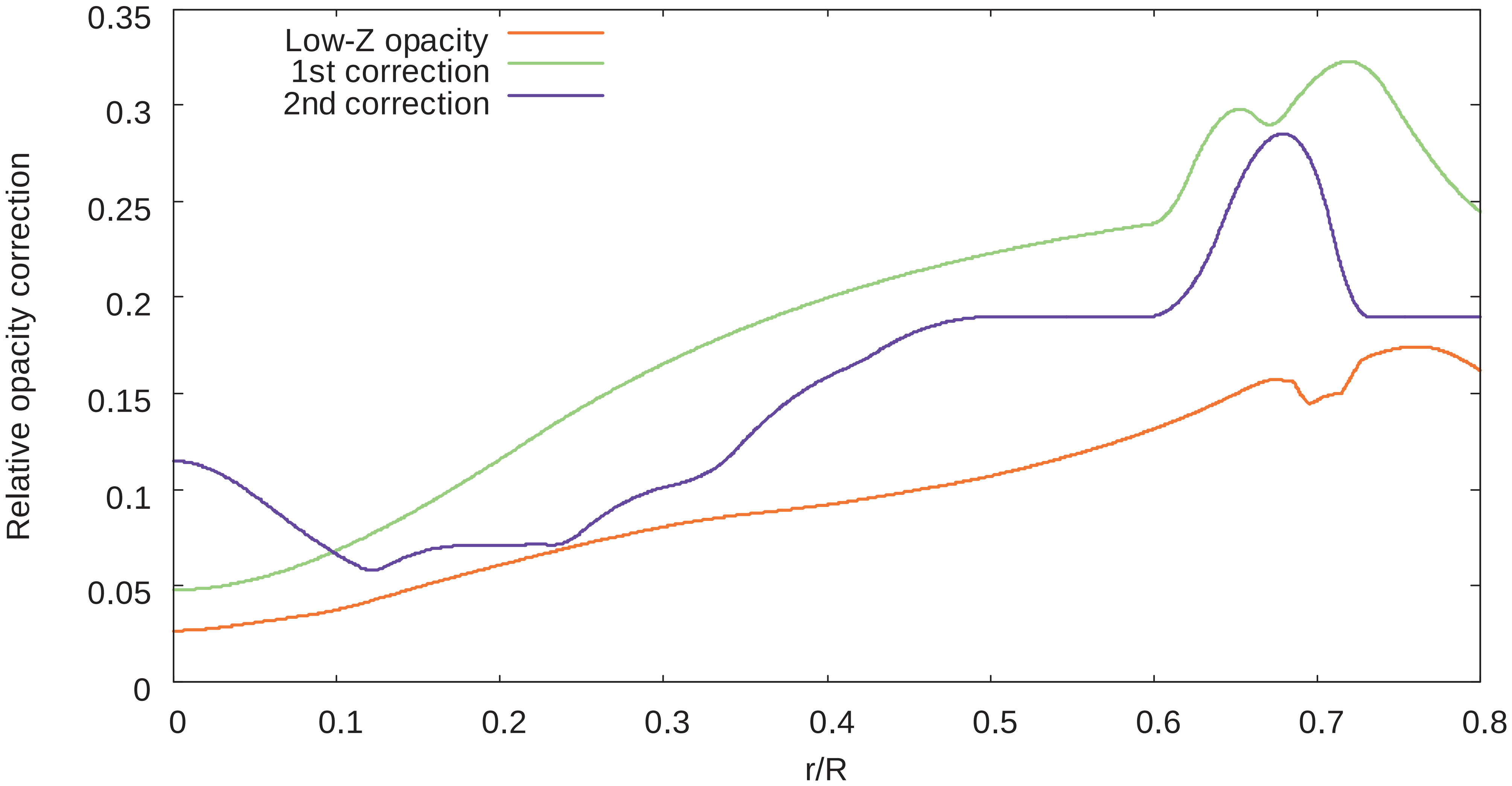
Set of localized corrections

Set of local opacity corrections + global correction:
helioseismically consistent model with low Z and modified opacities



Resulting opacity correction

Amplitudes are comparable!



Conclusions

– No natural solution for low-Z problem was found in this work

– If we compensate opacity for low-Z, we get low-Z model with high-Z sound speed profile

– Helioseismically consistent low-Z model requires opacity corrections of +5% (center) to +25% (below convection zone)

– Low-Z effect in opacity is of the same order of magnitude as remaining sound speed errors in high-Z model