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On the possibility of constructing solar model with helioseismic convection zone

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Standard Solar Model (SSM)

- **Basic observational data (input for SSM)**

  mass $M_\odot$, luminosity $L_\odot$, radius $R_\odot$, age $t_\odot$
  Z/X in the atmosphere (new 0.0181 or old 0.0245??)

- **Helioseismic data: (NOT an input for SSM)**

  position of the convection zone base
  $R_{cz} = 0.7133 \pm 0.0005$ (Basu, Antia 2004)

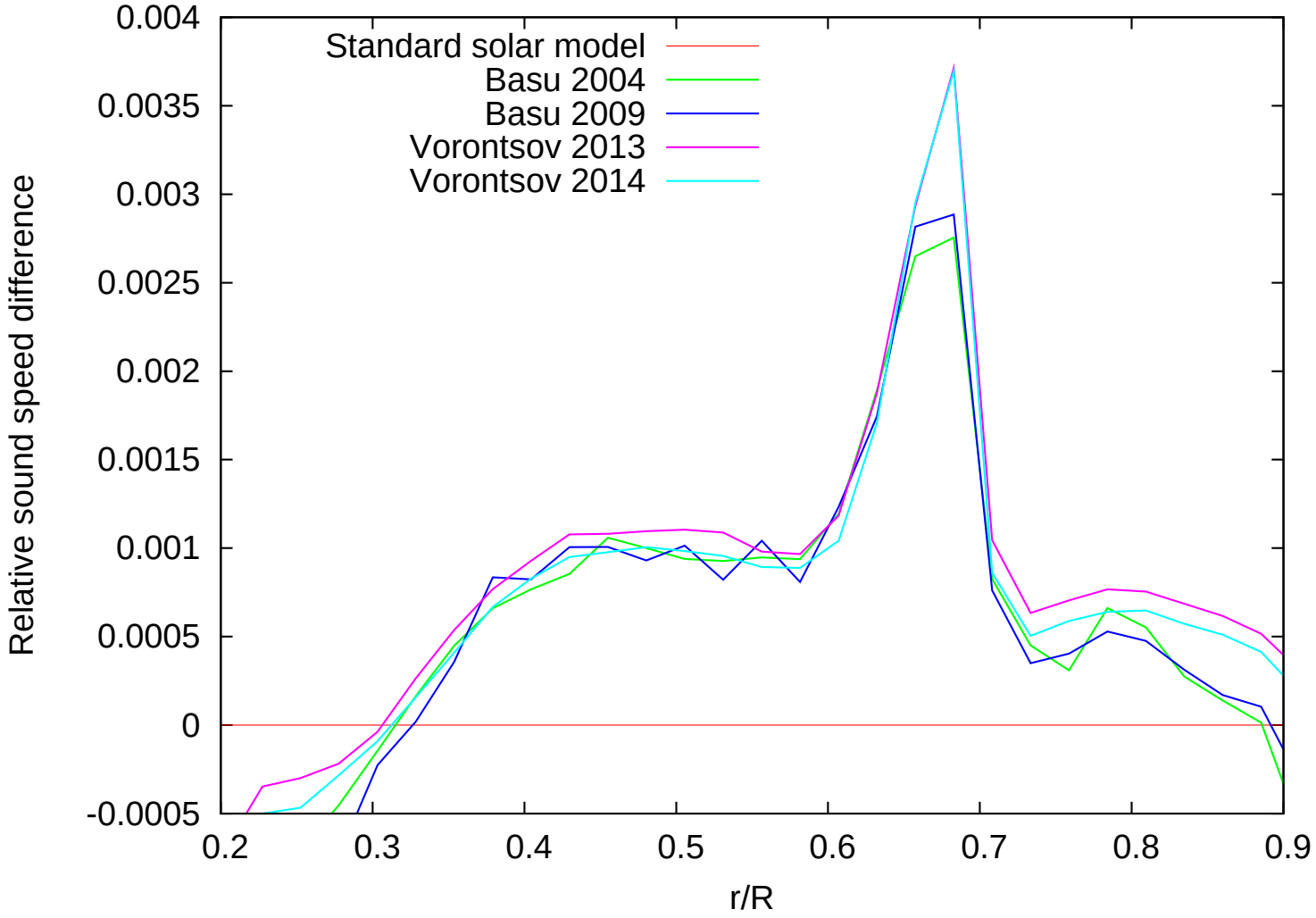
  helium abundance in the convection zone
  $Y_{cz} = 0.2485 \pm 0.0034$ (Basu, Antia 2004)

  heavy element abundance in the convection zone
  $Z_{cz} = 0.010 \pm 0.002$ (previous talk)

  mass inside $0.75 R_\odot$ ($M_{75} = m(r/R_\odot = 0.75)/M_\odot$)
  $M_{75} = 0.9822 \pm 0.0002$ (Vorontsov et al. MNRAS 2013, v.403, p.1636)

  sound speed, density, $\Gamma_1 \equiv (\partial \log P / \partial \log \rho)_{ad}$ profiles

About the sound speed inversions



Uncertainty in lower part of CZ and in radiative zone: about 0.0005

Determination of envelope mass parameter M_{75}

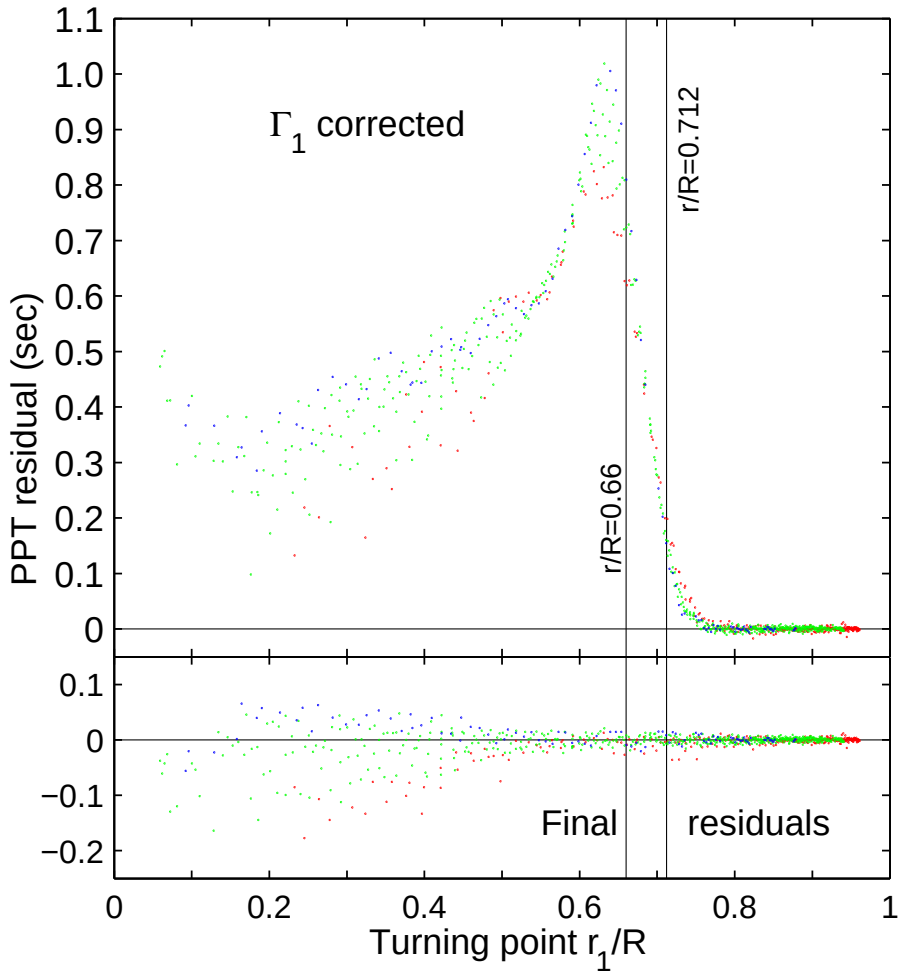
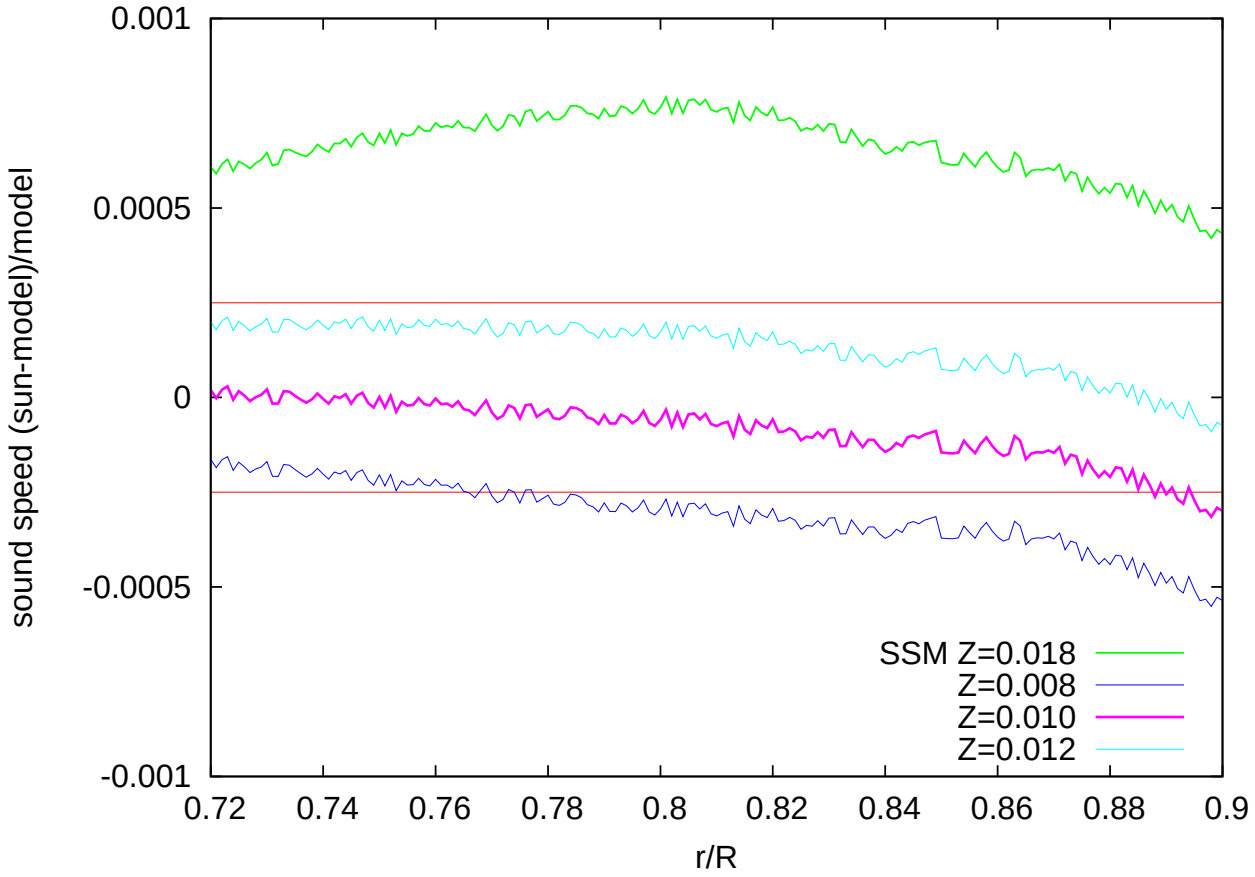


Figure 1: Figure from: *Vorontsov S.V., Proc. SOHO 11 Symposium, Davos, Switzerland, 11–15 March 2002, ESA SP-508.* Scattering of the initial residuals of the structural inversion after the adiabatic exponent profile has been corrected (top panel), and the final residuals of the inversion (bottom panel) for Model S ($M_{75} = 0.9824$).

Can we compose 'fully seismic' convection zone?

Model of the convection zone (CZ) with $M_{75} = 0.9822$, $Y_{cz} = 0.25$, $Z_{cz} = 0.010$: sound speed inside convection zone



Convection zone depth: $0.257 \div 0.272$ instead of 0.287 ($0.2 \div 0.4$ H_P).
Convective overshooting? Opacities?

Can we compute evolved model with seismic CZ?

Convection zone parameters:

helium abundance in the convection zone
$Y_{cz} = 0.2485 \pm 0.0034$
heavy element abundance in the convection zone
$Z_{cz} = 0.010 \pm 0.002$
mass inside $0.75 R_\odot$ $(m(r/R_\odot = 0.75)/M_\odot)$
$M_{75} = 0.9822 \pm 0.0002$

Full (evolved) solar model?

Have to give up on low Z abundances! Assume $Z = 0.010$ in convection zone, high-Z (Grevesse, Noels 1993) in the radiative zone and core

Extended model calibration

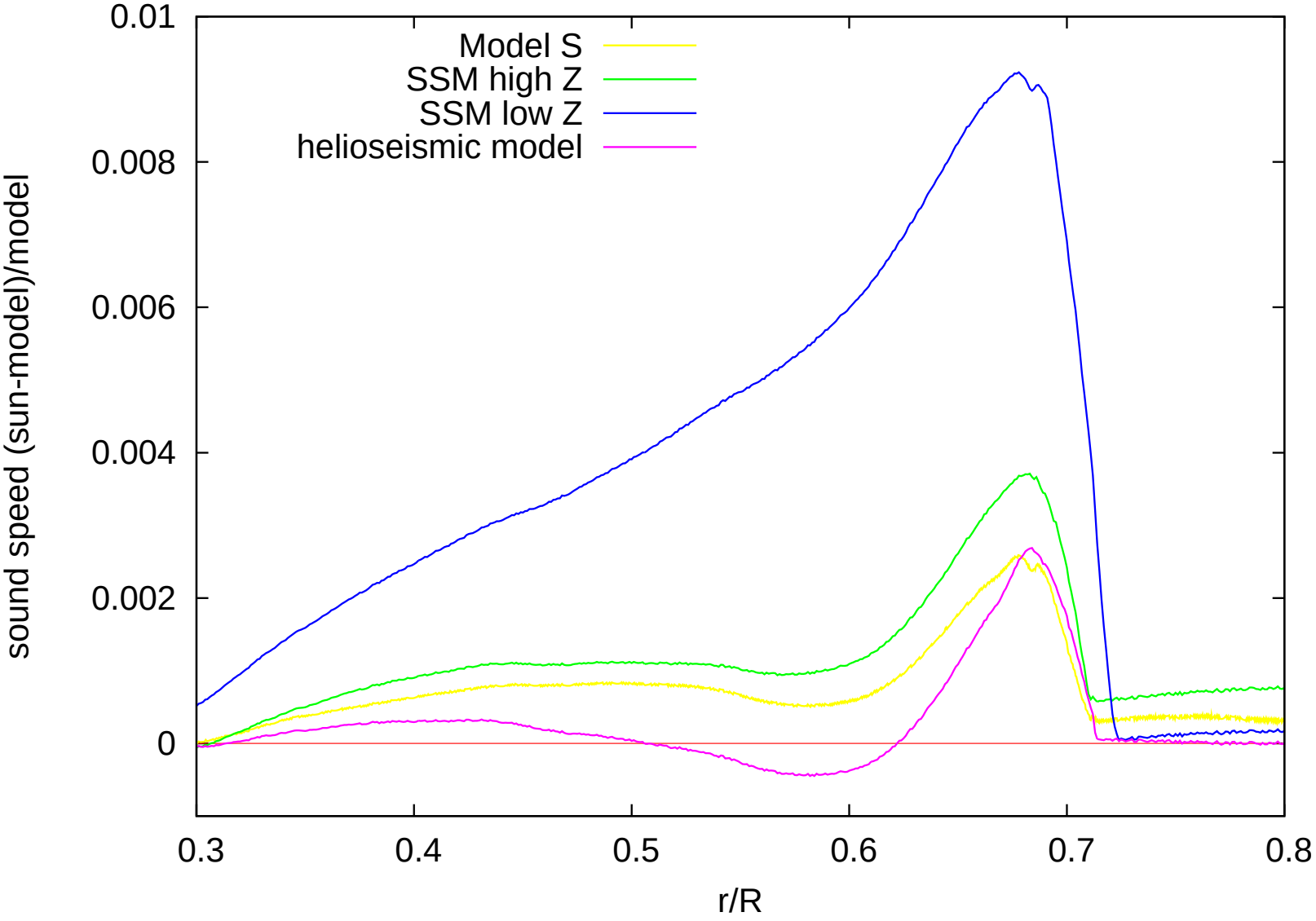
Extended calibration:
adjust physics to obtain required values of model parameters such as M_{75}, R_{cz}, Y_{cz} etc.

Free parameters to adjust:
K global opacity correction
K_b local opacity correction near CZ lower boundary
pp reaction cross section

See also: *Ayukov S., Baturin V. A new approach to the solar evolutionary model with helioseismic constraints // Astronomical Society of the Pacific Conference Series, Vol. 479, 2013, p. 3*

Target: construct evolved models with proper $M_{75} = 0.9822$, $R_{cz} = 0.7133$, $Y_{cz} = 0.25$, $Z_{cz} = 0.010$.
Required modification of physics: Global opacity correction: almost absent (0.04%), local opacity correction near CZ bottom: -5%, pp rate correction: $+5\%$

Model with seismic envelope parameters



Changing hydrogen profile to improve sound speed

1) $\Delta c^2 \to N^2$ $(\Delta c^2 = c^2_\odot - c^2_{model})$

$$c^2 = \Gamma_1 \frac{P}{\rho}, \qquad \frac{N^2}{g} = \frac{1}{\Gamma_1}\frac{d\log P}{dr} - \frac{d\log\rho}{dr}$$

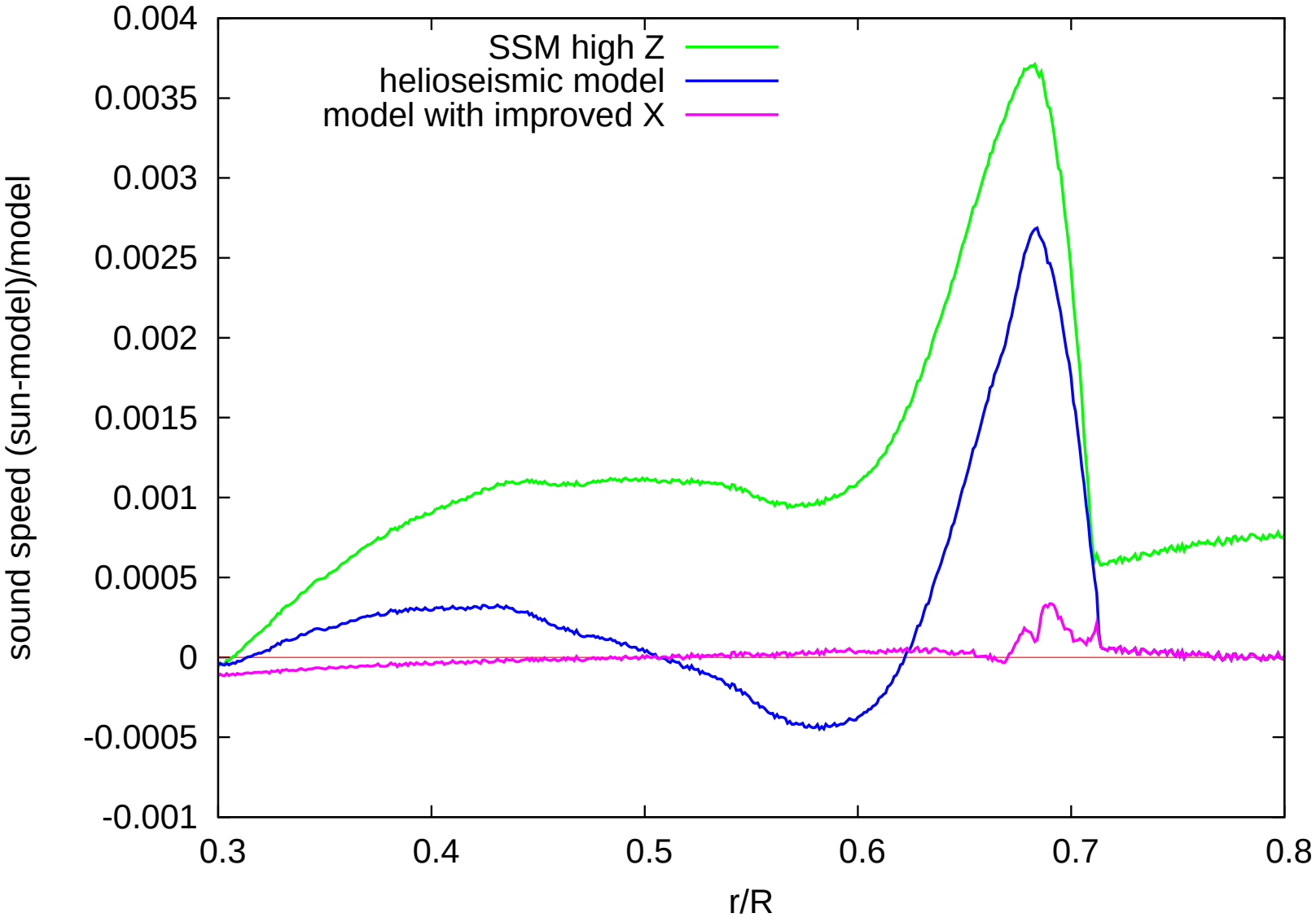
$$\frac{d(\log c^2)}{dr} = \frac{d\ln\Gamma_1}{dr} + \frac{N^2}{g} + \frac{\Gamma_1 - 1}{\Gamma_1}\cdot\frac{d\ln P}{dr}$$

2) $N^2 \to dX/dr$

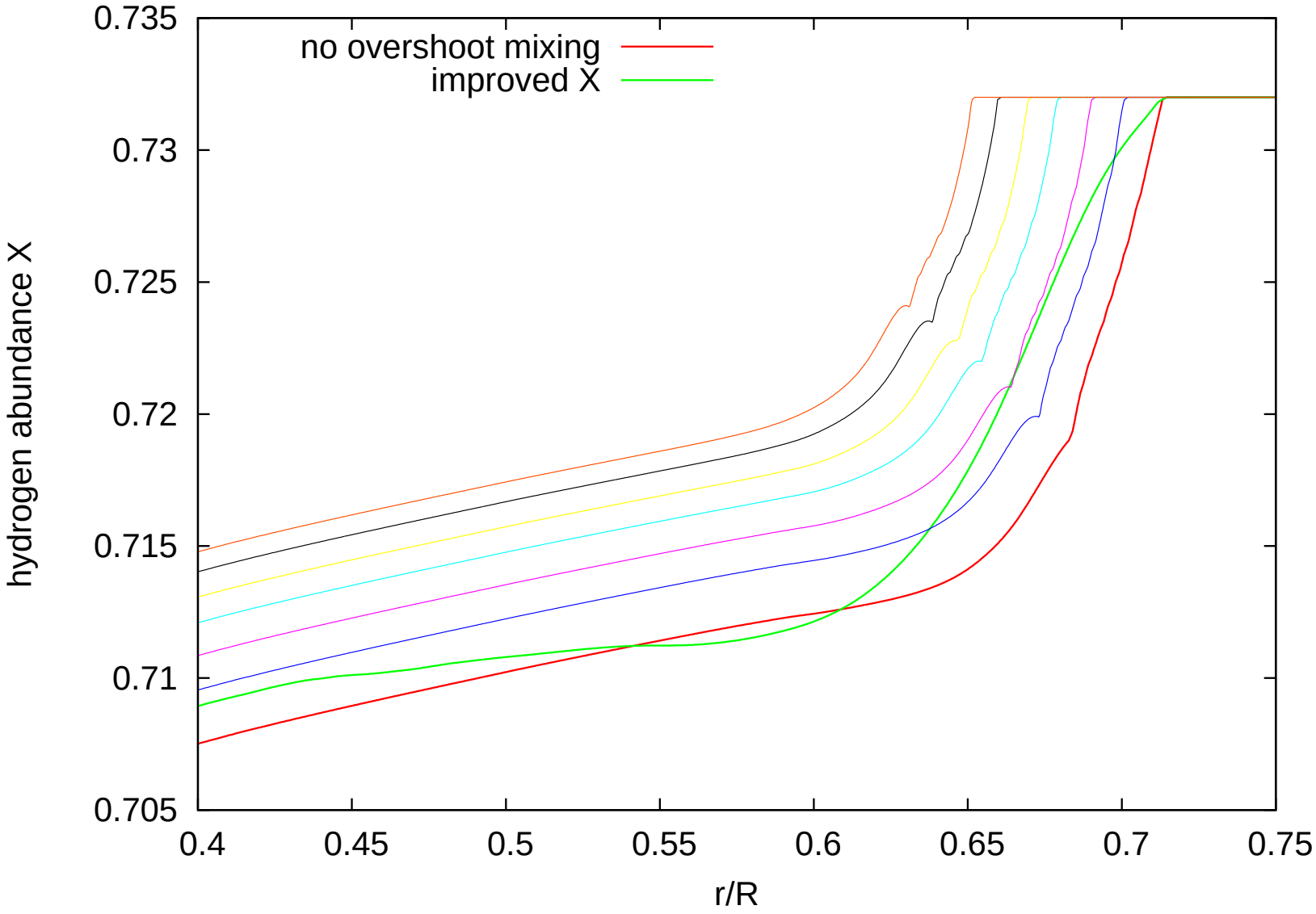
$$N^2 = -g^2\frac{\rho}{P}\frac{\chi_T}{\chi_\rho}(\nabla - \nabla_{ad}) + \frac{g}{X}\frac{\chi_X}{\chi_\rho}\cdot\frac{dX}{dr}$$

here $\chi_\rho \equiv (\partial\log P/\partial\log\rho)_T$ etc.

Changing hydrogen profile to improve sound speed



Changing hydrogen profile to improve sound speed



Conclusions

- high-Z models with current equations of state have too high sound speed inside convection zone. If one attributes sound speed difference to Z then $Z_{cz} \approx 0.010 \pm 0.002$ which is even lower than AGSS09 data
- neither high-Z nor low-Z solar models reproduce convection zone mass parameter ($M_{75} = 0.9822 \pm 0.0002$). While standard high-Z model is fairly close (0.9826), low-Z model (0.9833) drastically deviates from helioseismic value. In this work change in pp reaction cross section was used to obtain models with proper M_{75} (4.7% for high Z model)
- our analysis suggests low heavy element abundances in convection zone but "conventional" Z below convection zone
- sound speed difference under convection zone can be attributed to tachocline mixing. No physical model of mixing is considered in this work; the size of the partially mixed area is about 10% by radius