Questions on the solar structure and evolution

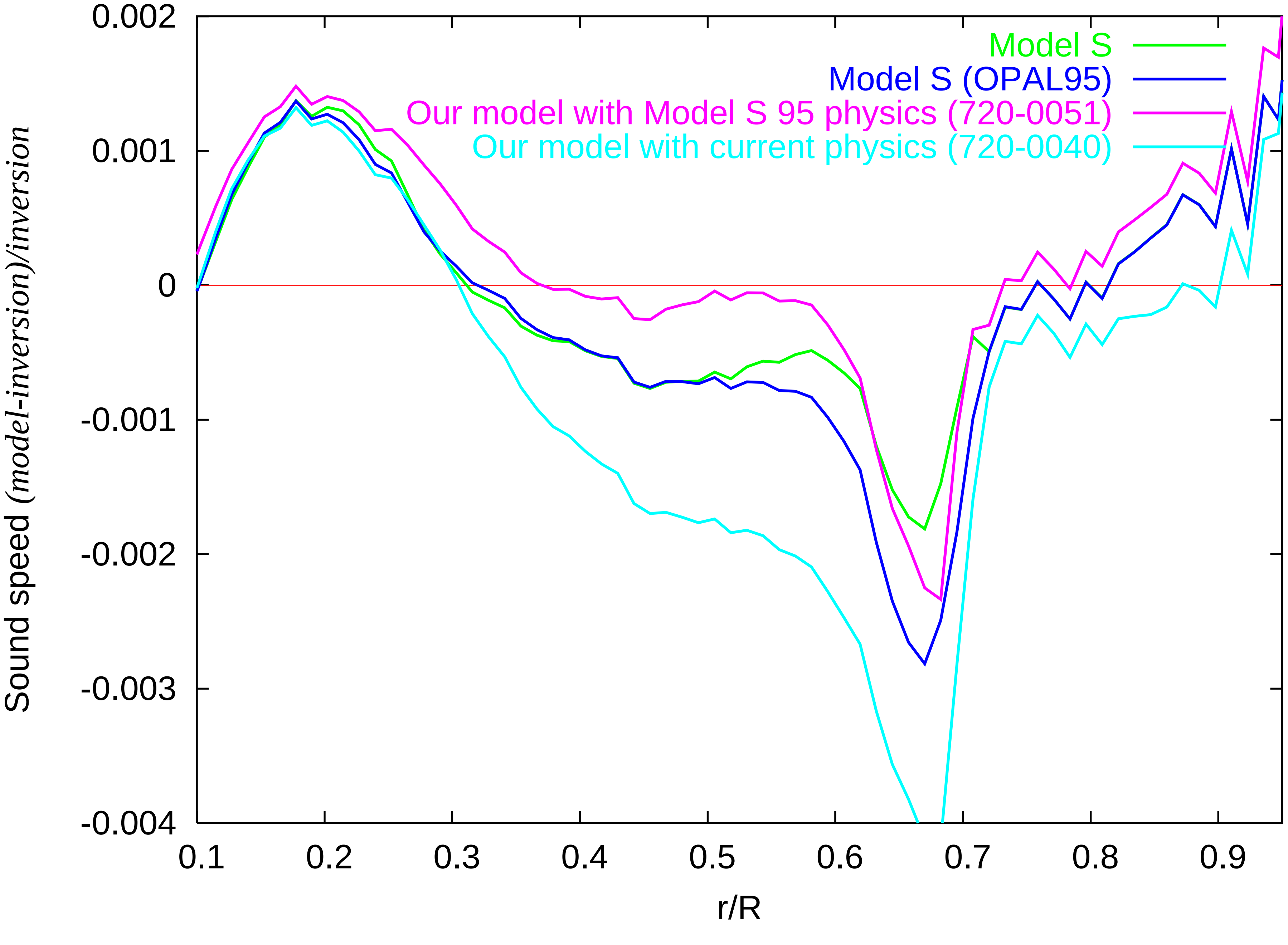
S. V. Ayukov, V. A. Baturin
Sternberg Astronomical Institute, Moscow, Russia

Solar Model =

Plasma physics		Structure Equations		Observational data
Equation of state Opacity Nuclear reactions Convection Overshooting Diffusion	+	Hydrostatic equilibr. Poisson equation Energy generation Energy transfer	+	Mass Radius Luminosity Age Abundances Helioseismic data and inversions*

*Inversions: Ycz, Rcz and sound speed profile from: S.Basu, H.M.Antia, Phys. Rep. **457** (2008), 217

13 years of modelling



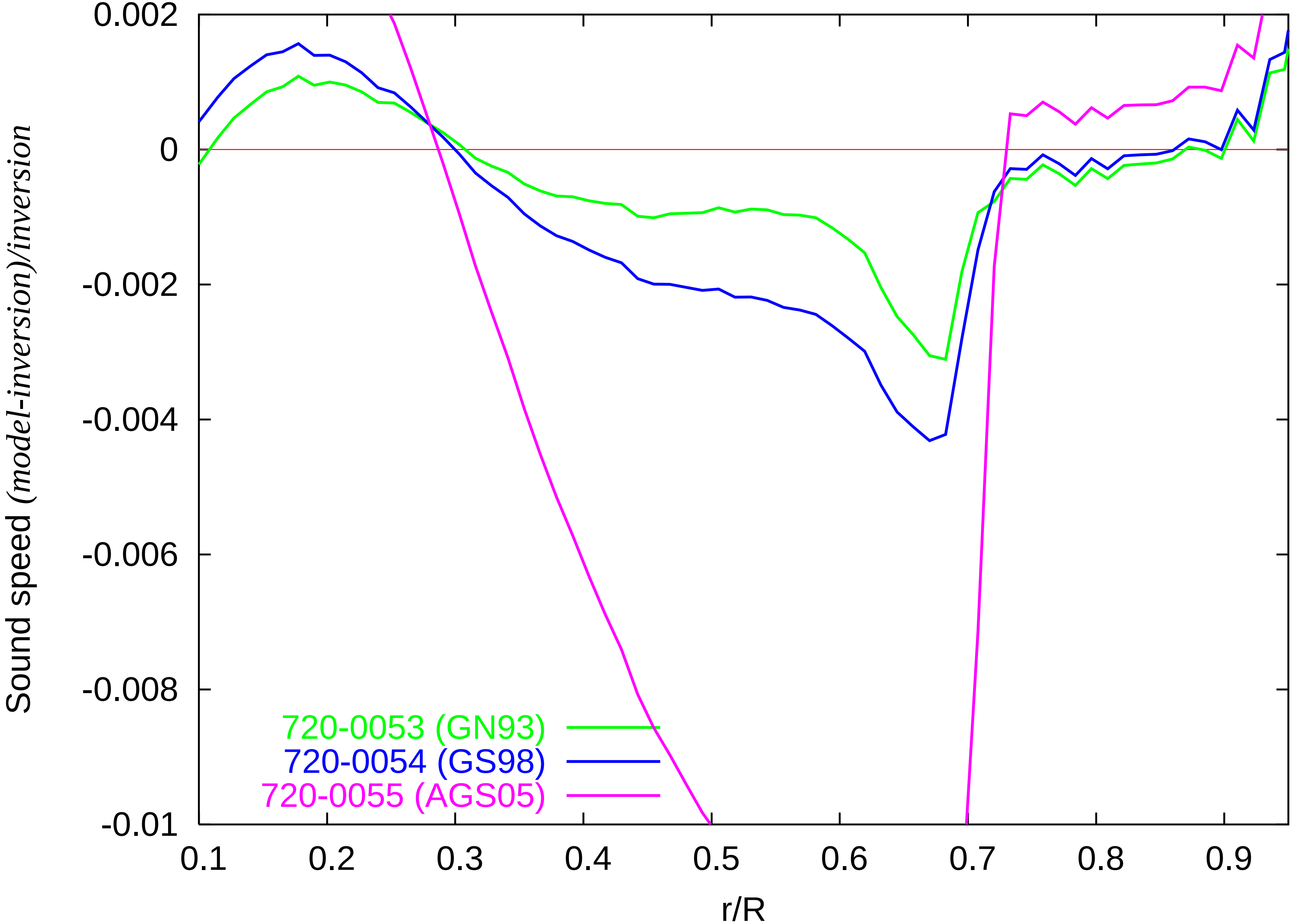
Heavy element abundances

Elements heavier than helium: ***heavy elements***
Relative concentrations of heavy elements: ***mixture***
Are obtained from spectral analysis and meteorites

AG89 Anders, E., Grevesse, N. 1989, Geochimica et Cosmochimica Acta 53, 197–214.
GN93 Grevesse, N., Noels, A. 1993, in Origin and Evolution of the Elements, eds., N. Prantzos, E. Vangioni-Flam, M. Casse, Cambridge Univ. Press, p. 14–25.
GS98 Grevesse, N., Sauval, A. J. 1998, Space Sci. Rev. 85, 161–174.
AGS05 Asplund, M., Grevesse, N., Sauval, A. J. 2005a, in Cosmic Abundances as Records of Stellar Evolution and Nucleosynthesis, eds., T. G. Barnes, F. N. Bash, ASP Conf. Ser. 336, p. 25–38.

	AG89	GN93	GS98	AGS05
Z/X	0.0274	0.0244	0.0231	0.0165

13 years of modelling and abundances: worse and worse...



Chemical composition (abundances) and model calibration: question

Calibration: get solar model with proper R, L at given age. Initial hydrogen content X_0 and convection parameter α are varied to obtain $L=L_{sun}$, $R=R_{sun}$.

Question:

What data we have before computing? What do we get when solar model is computed? Who do these data relate to each other?

Observational data:

Abundances (GN93, GS98, AGS05), assuming $\log_{10}(H) = 12$. These are either for outer layers of the Sun or for meteorites.

Solar model:

Abundances (usually mass fractions), **altered by diffusion**.

Cannot use observational data as direct input for evolutionary computing because at t=0 abundances were different!

Chemical composition (abundances) and model calibration: solution

Three calibration parameters instead of two:

Initial hydrogen abundance X_0
Initial heavy element abundance Z_0
Convection parameter α

Three calibrated values instead of two:

Radius R
Luminosity L
Heavy element to hydrogen ratio Z/X

Z/X for given mixture can be computed from abundances if $\log_{10}$ (H) = 12 is assumed.

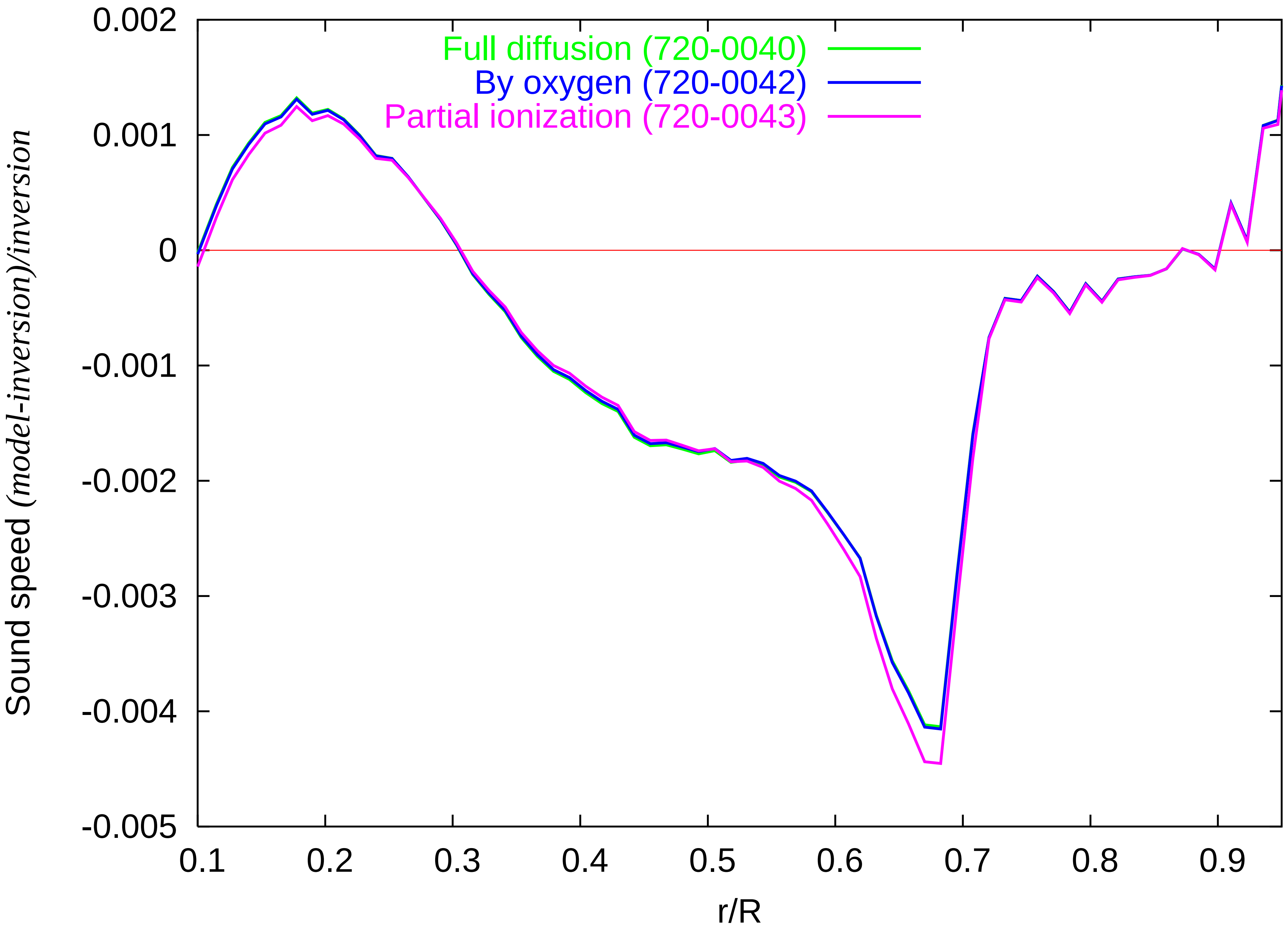
Problem: individual abundances are altered differently by diffusion!

Per-element treatment of diffusion

Diffusion rate depends on ion mass and charge. Different elements settle at different rates.

Modelling: 19 elements heavier than helium are included into calculations, the same elements included into OPAL opacity calculations

Three cases:
720-0040: full diffusion
720-0042: all diffusion rates by oxygen
720-0043: simulation of partial ionization (all ion charges of elements heavier than neon are halved)



Full diffusion (720-0040)
By oxygen (720-0042)
Partial ionization (720-0043)
Sound speed (model-inversion)/inversion
r/R
0.002
0.001
0
-0.001
-0.002
-0.003
-0.004
-0.005
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

Opacity

OPAL opacity, interpolated by: T, rho, X and **19 elements heavier than helium**

$\kappa = \kappa$ (T, rho, X, Zi[19])

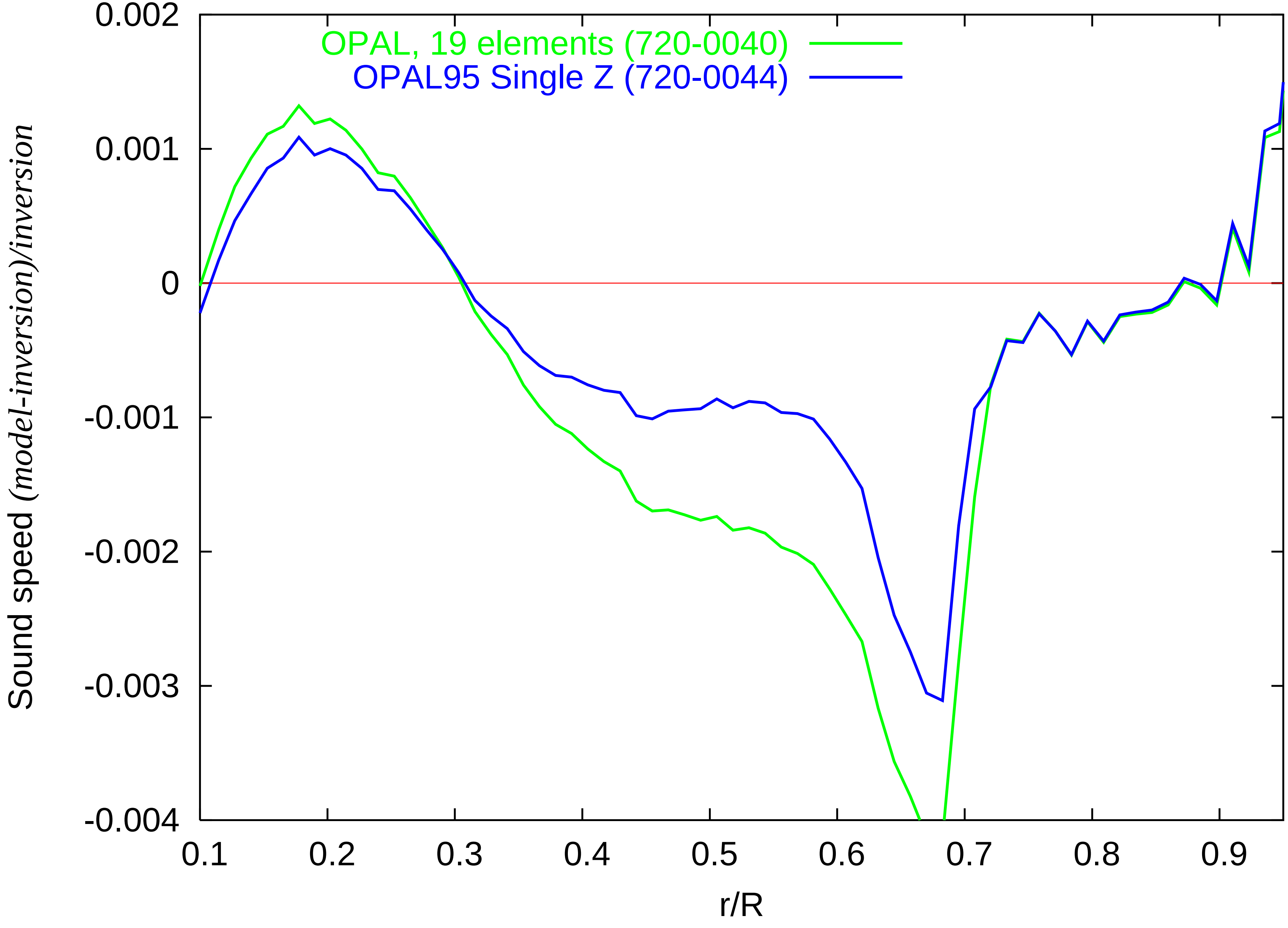
Tables for arbitrary composition are provided by Lawrence Livermore National Laboratory and can be generated at http://adg.llnl.gov/Research/OPAL/new.html

For every T, rho, X the following values are calculated and stored:
* opacity for Z=0.01
* 18 opacity derivatives by every element while keeping total Z=0.01
* opacity for Z=0.02
* 18 opacity derivatives by every element while keeping total Z=0.02

Opacity for any Z in any mixture (GN93, GS98, AGS05) can be obtained.

Supplemented by Ferguson, Alexander et al. 2005 low-temperature opacity, fixed mixture GN93.
Total memory used for tables: about 30MBytes

Opacity: switch to 19 elements, sound speed in models



Equation of state (EOS)

Two EOS are used in our calculations

1) OPAL96 (F.J.Rogers, F.J.Swenson, C.A.Iglesias, ApJ **456** (1996) 902), fixed mixture (C, N, O, Ne)

P = P (T, rho, X, Z)

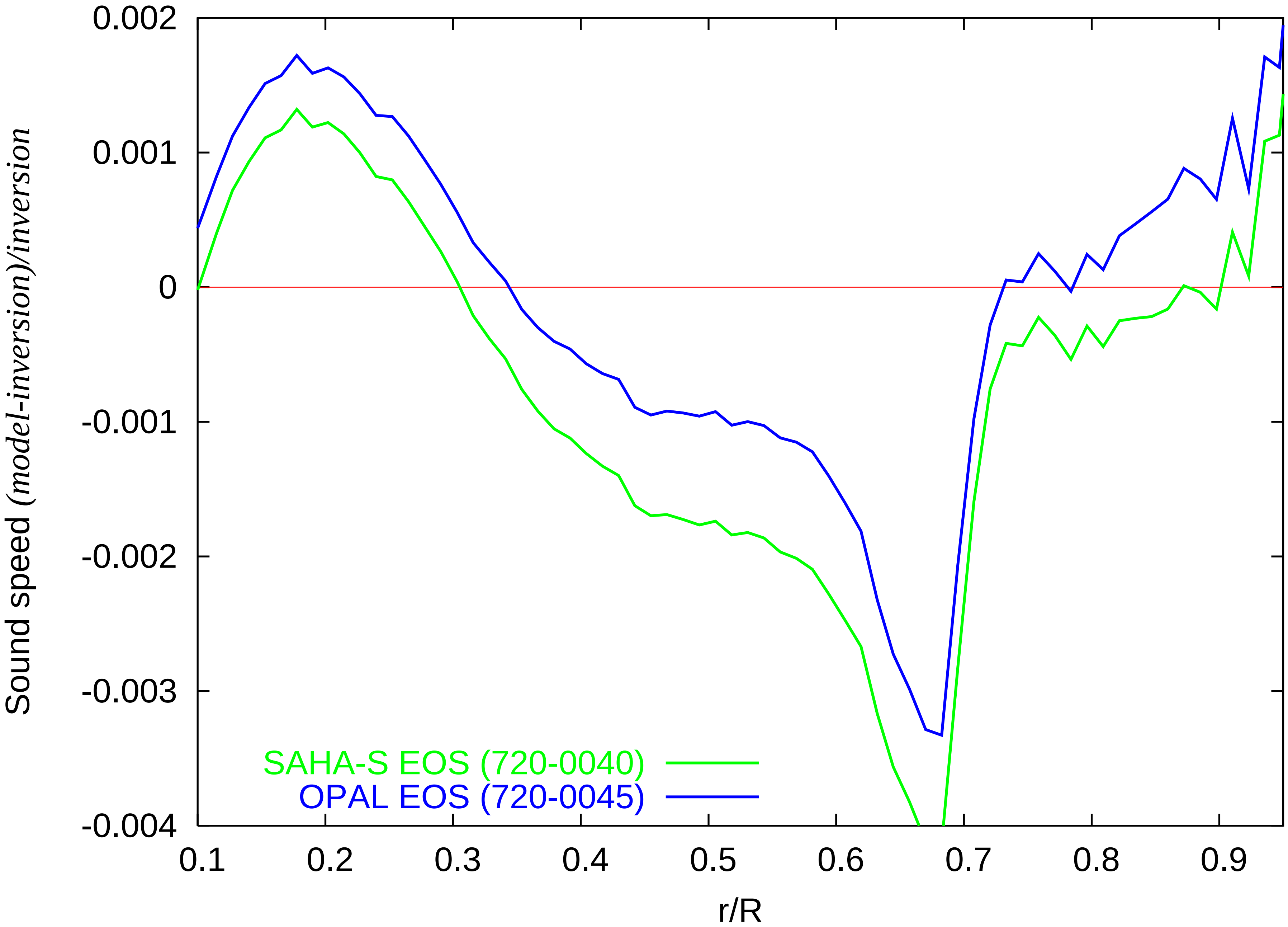
2) SAHA-S (V.K.Gryaznov et al., J. Phys. A: Math. Gen. **39** (2006) 4459), abundances from Allen «Astrophysical Quantities» 2000 (almost AG89), six elements included, three-variable mixture

P = P (T, rho, X, Z(CNO), Z(Ne), Z(FeSi))

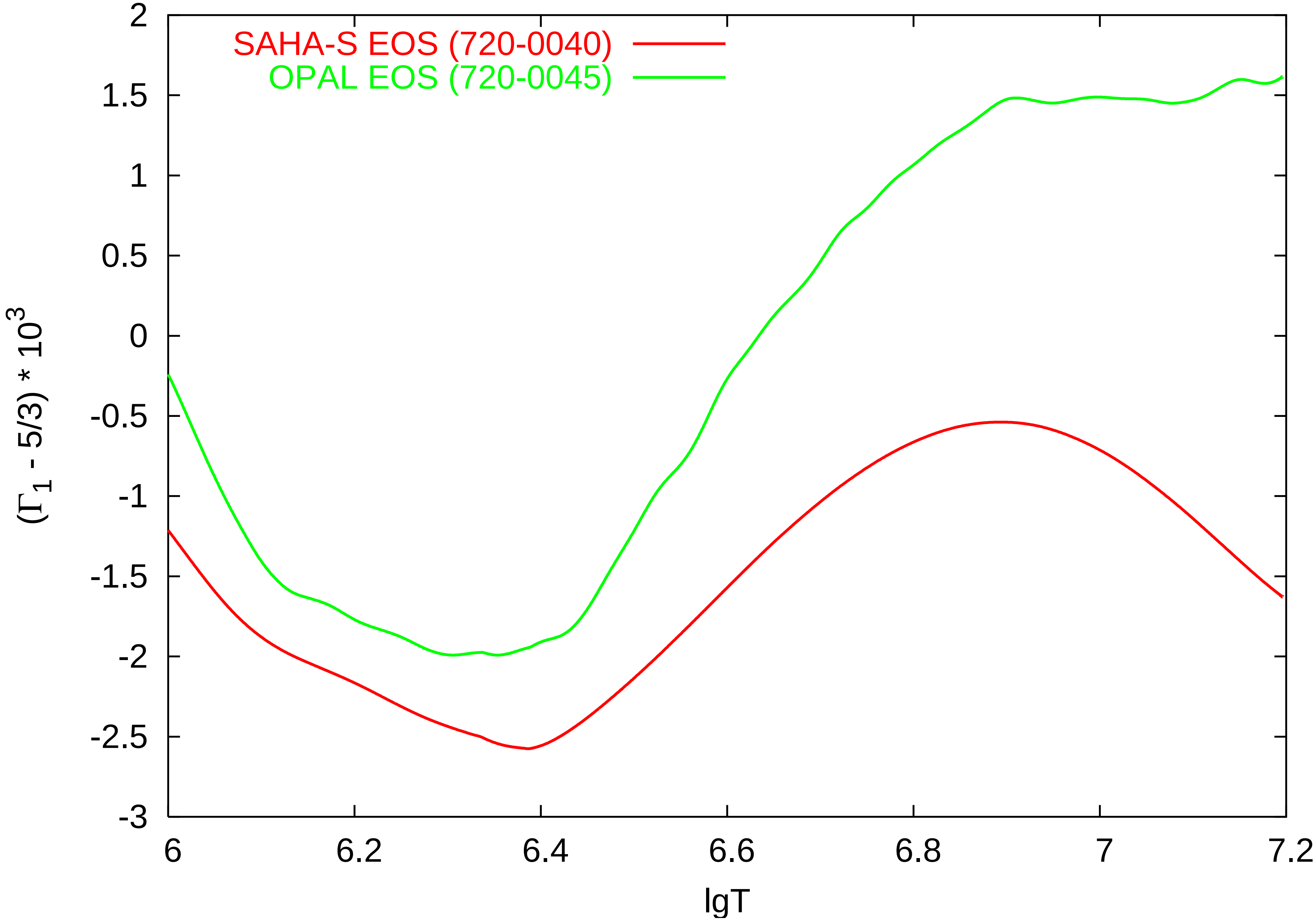
tables allow to interpolate for arbitrary X, Z(CNO), Z(Ne), Z(FeSi)

See detailed thermodynamic comparison between OPAL96 and SAHA-S in Leiden proceedings (S.V.Ayukov, V.A.Baturin et al., AIP Conference Proceedings v. 731, 2004, «Equation-of-State and Phase-Transition Issues in Models of Ordinary Astrophysical Matter», pp. 178-187).

Equation of state: OPAL and SAHA-S, sound speed in models



Equation of state: OPAL and SAHA-S, Γ_1 in models



Overshooting

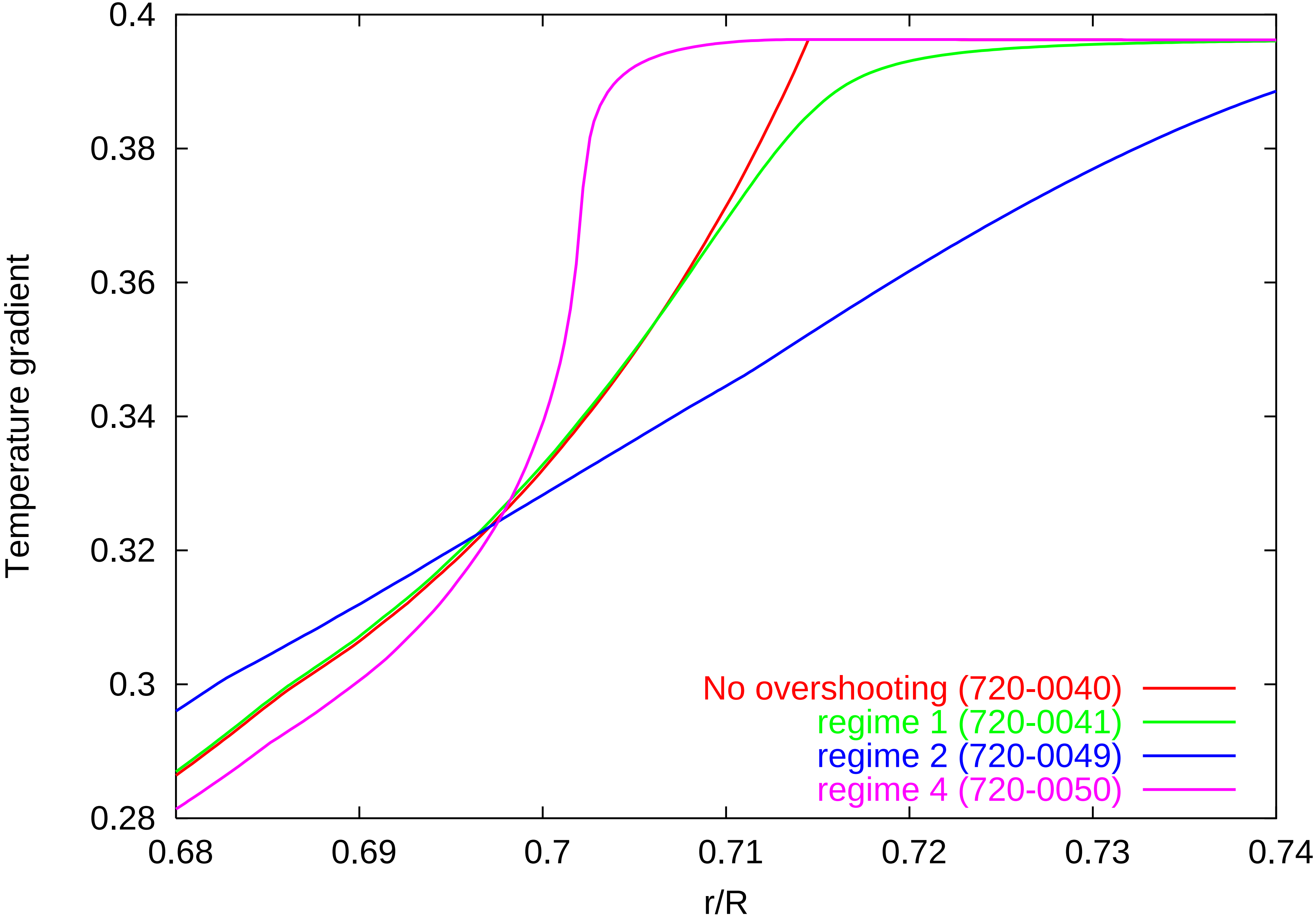
Convective overshooting: **temperature gradient** deviations and **element mixing**

Temperature gradient, four cases:
regime=0. Standard case (no overshooting)
regime=1. V. Baturin, I. Mironova (poster)
regime=2. V. Baturin, I. Mironova (poster)
regime=4. like Shaviv G., Salpeter E.E., ApJ, 1973, **184**, p.191

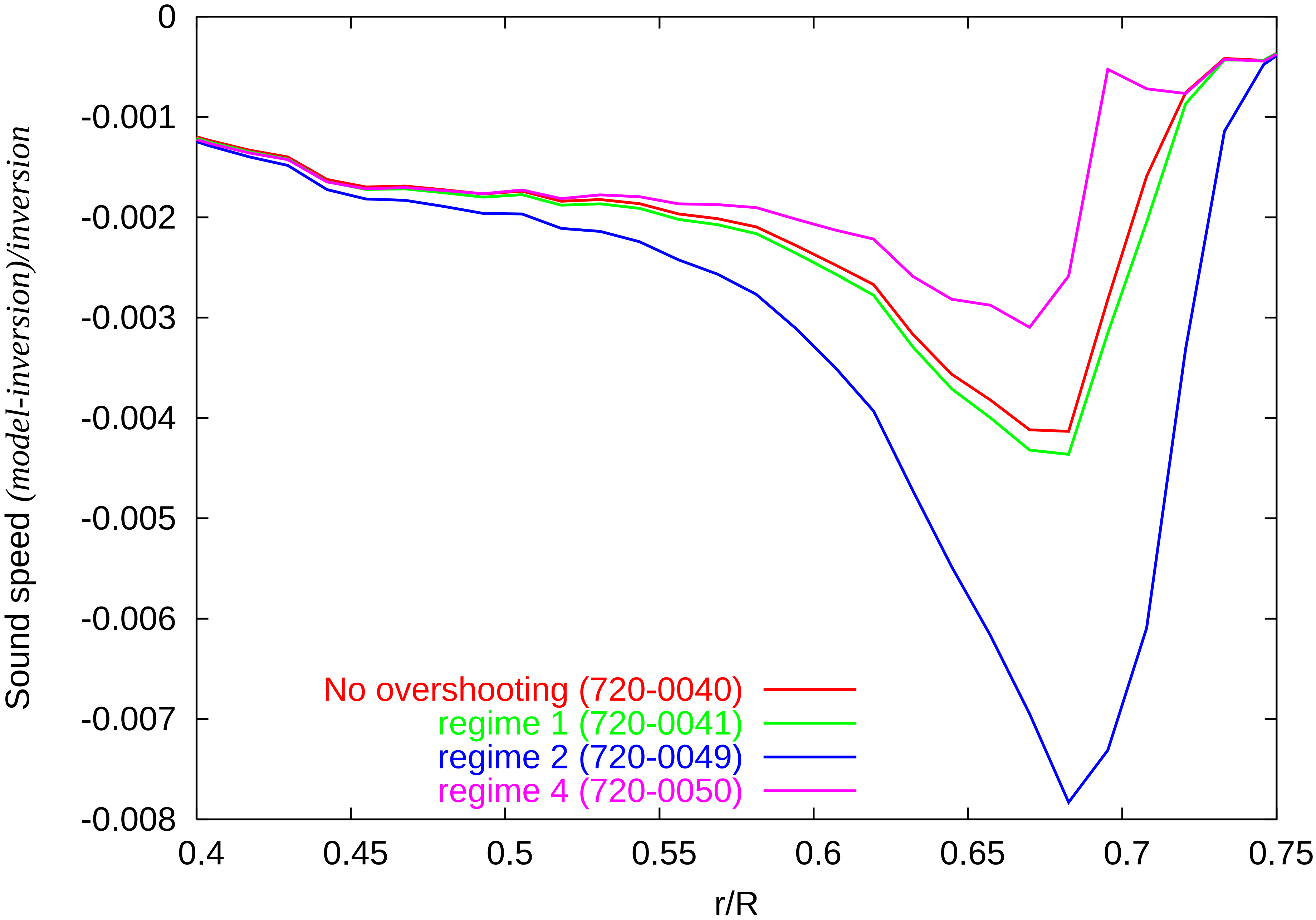
regimes 1-4 are simple numeric approximations, not exact theory

Also see poster by V. A. Baturin, I. V. Mironova.

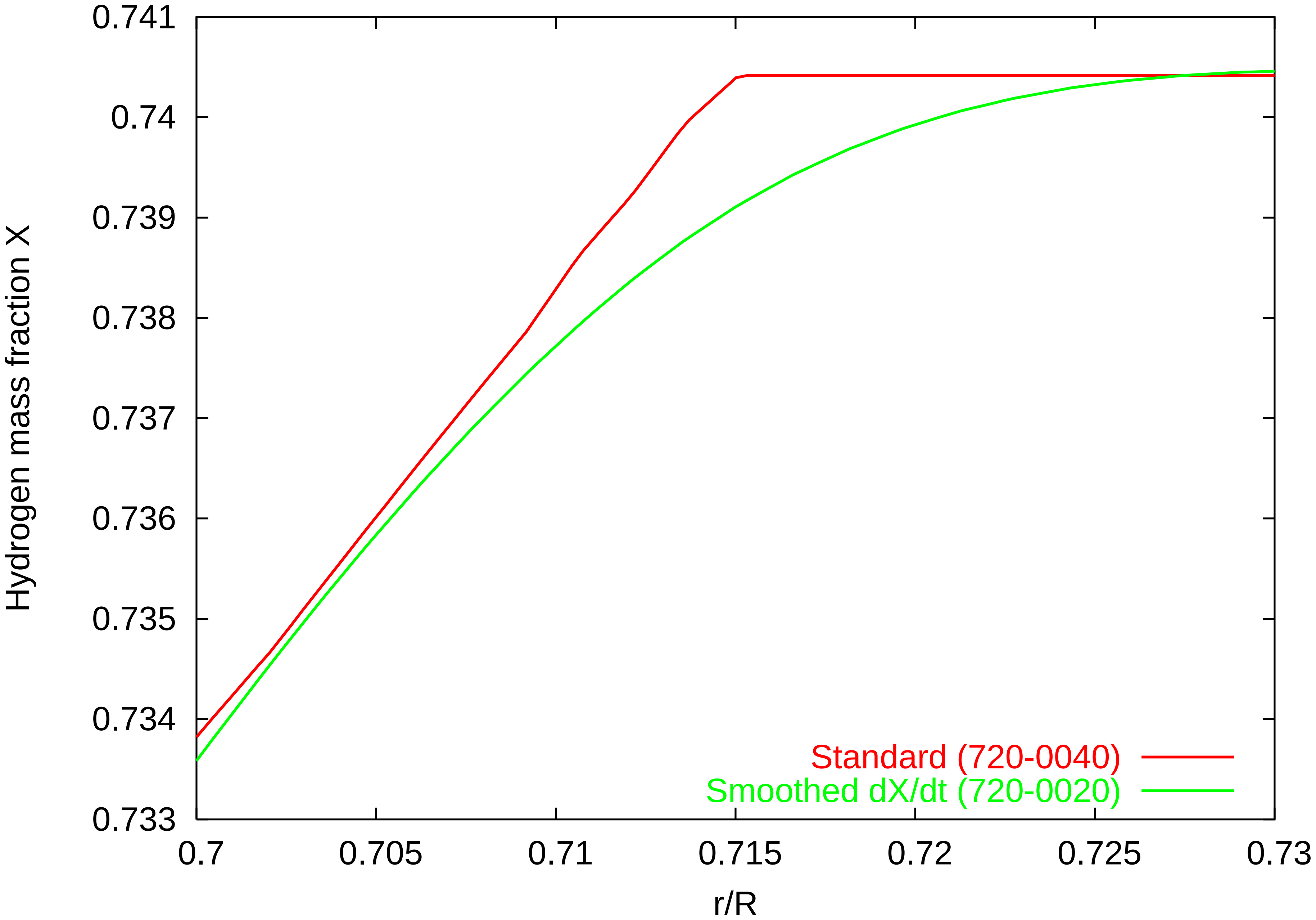
Various overshooting regimes, temperature gradient in models



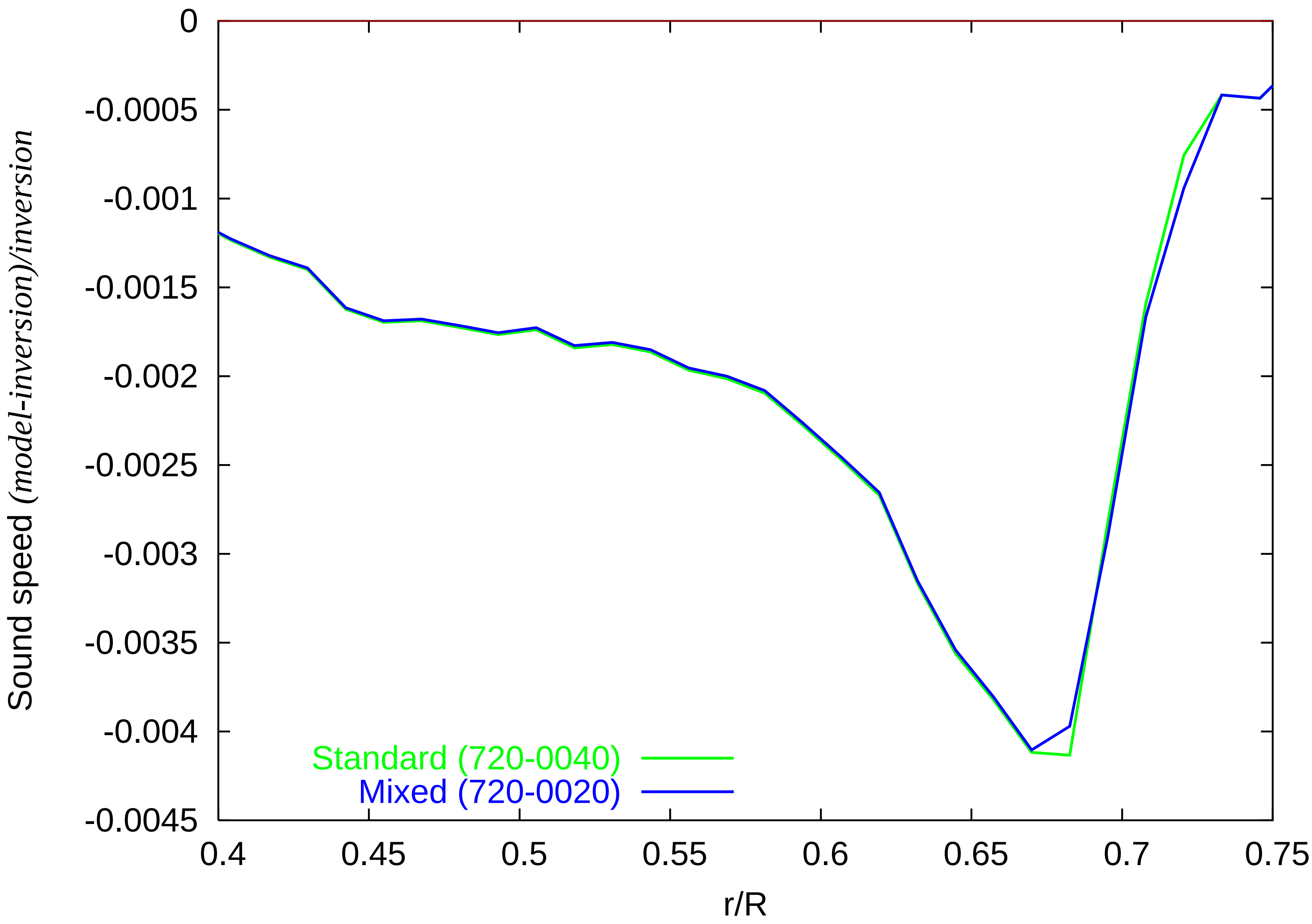
Various overshooting regimes, sound speed in models



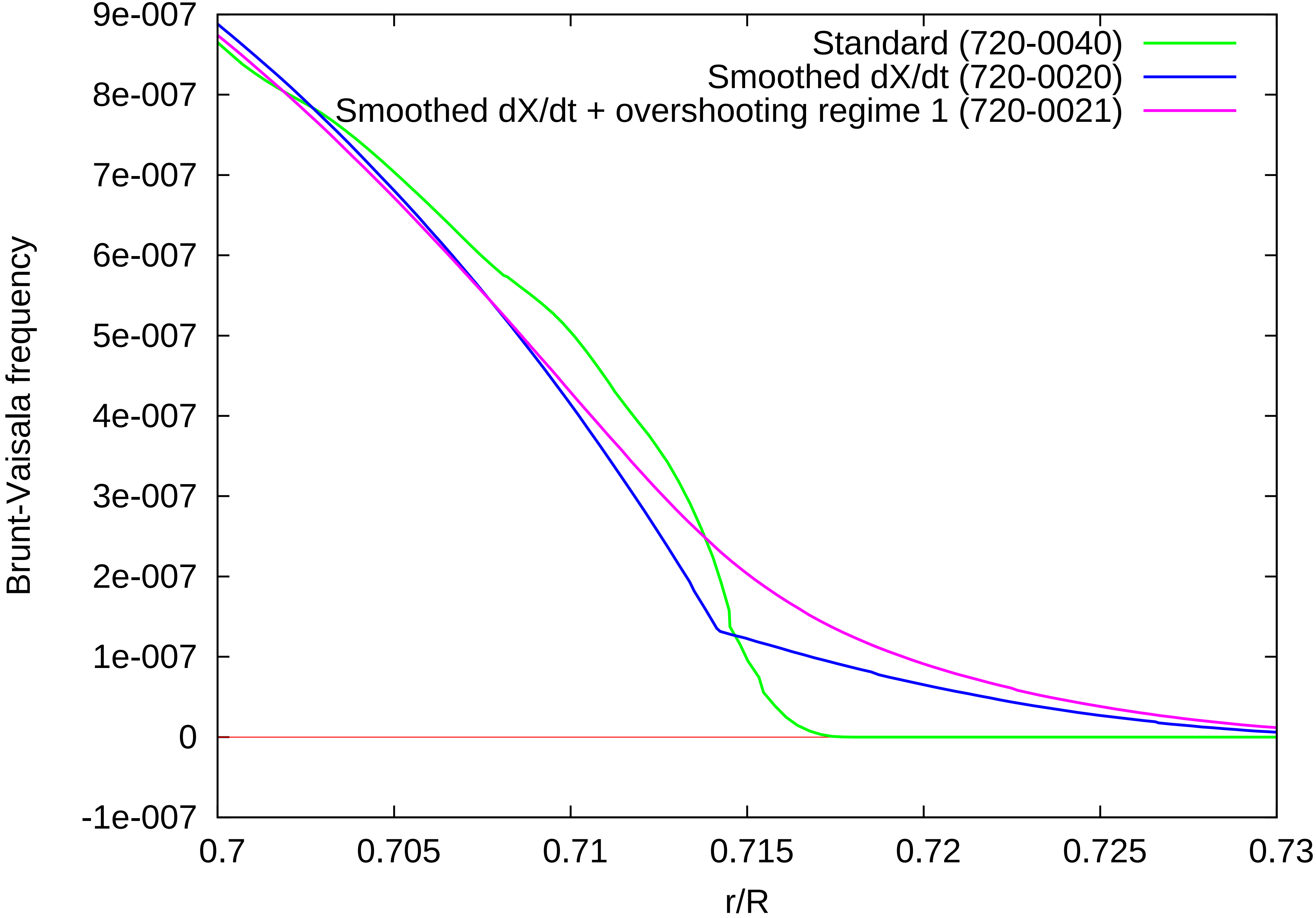
Element mixing approximation: smoothing dX/dt over CZ boundary



Element mixing approximation, sound speed in models



Element mixing approximation, N^2 in models



Neon riddle

Ne and Ar abundances are indirect determinations (=perhaps poorly known)

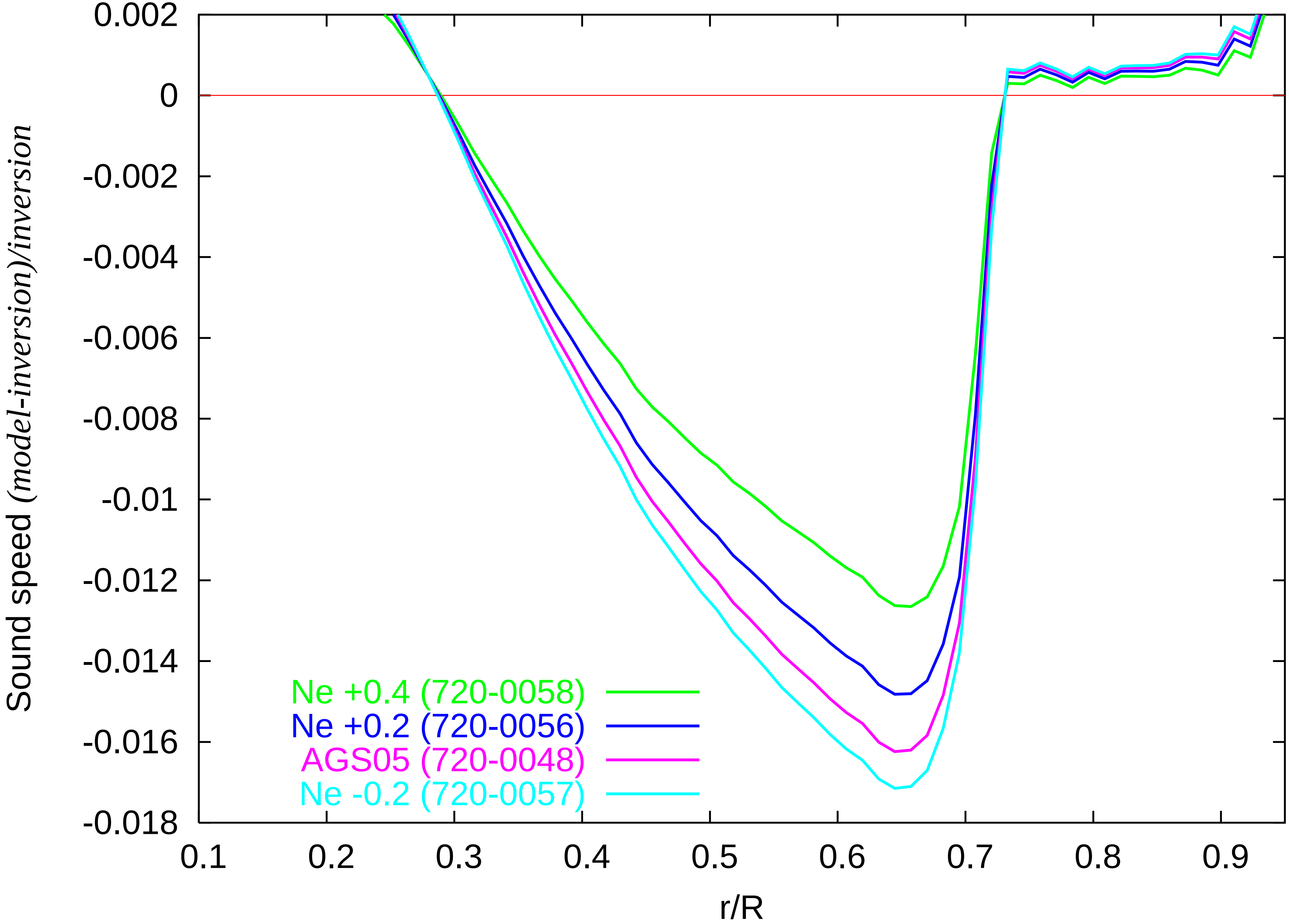
Ne abundance

AG89......................................8.09
GN93......................................8.07
GS98 ....8.08
AGS05 ....7.84

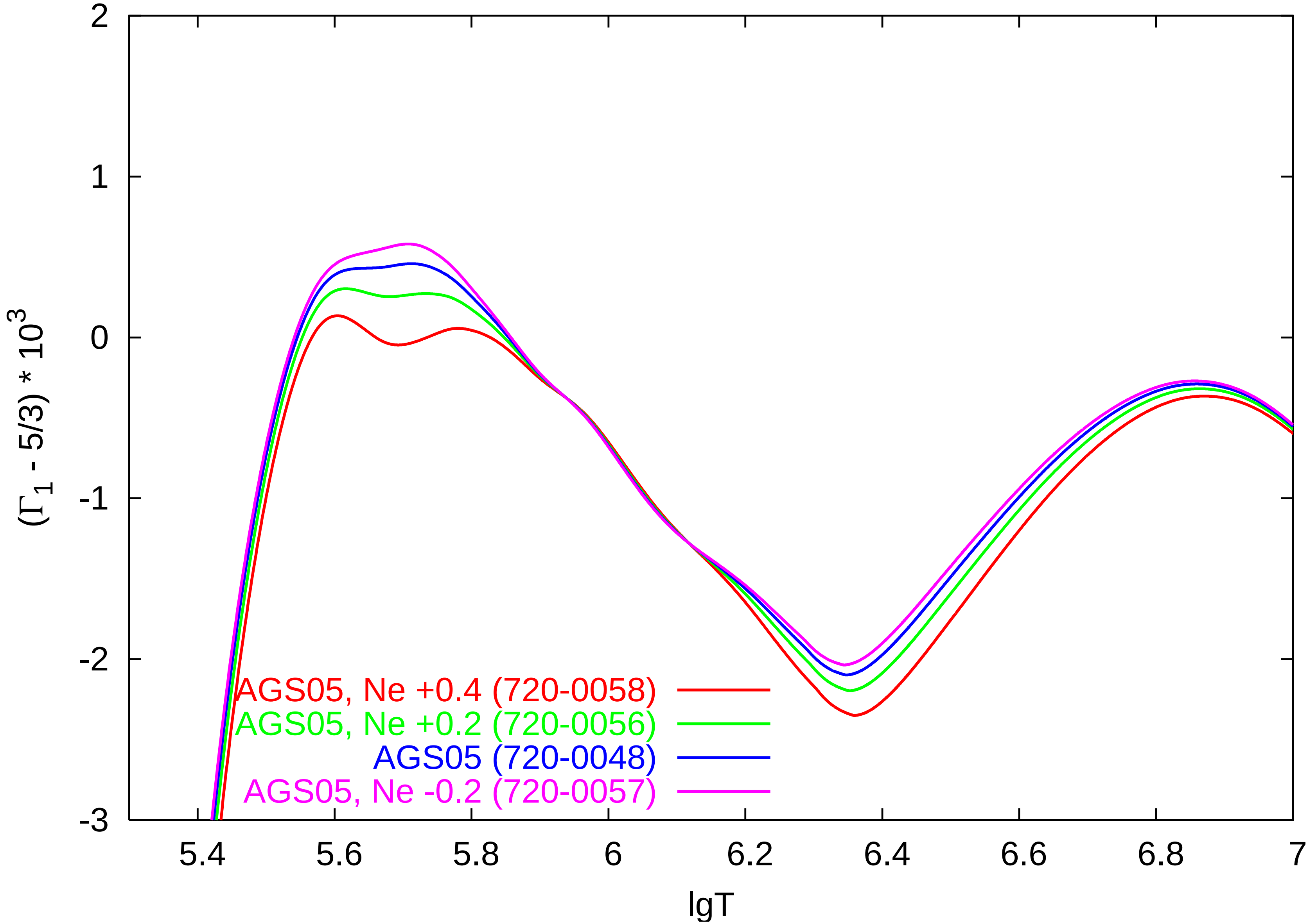
720-0057................................7.64
720-0048 (AGS05) 7.84
720-0056................................8.04
720-0058................................8.24

J.N.Bahcall, S.Basu, A.M.Serenelli (ApJ 2005, **631**, 1281) suggested 8.29 to solve low-Z problem

Ne abundance in AGS05: sound speed in models

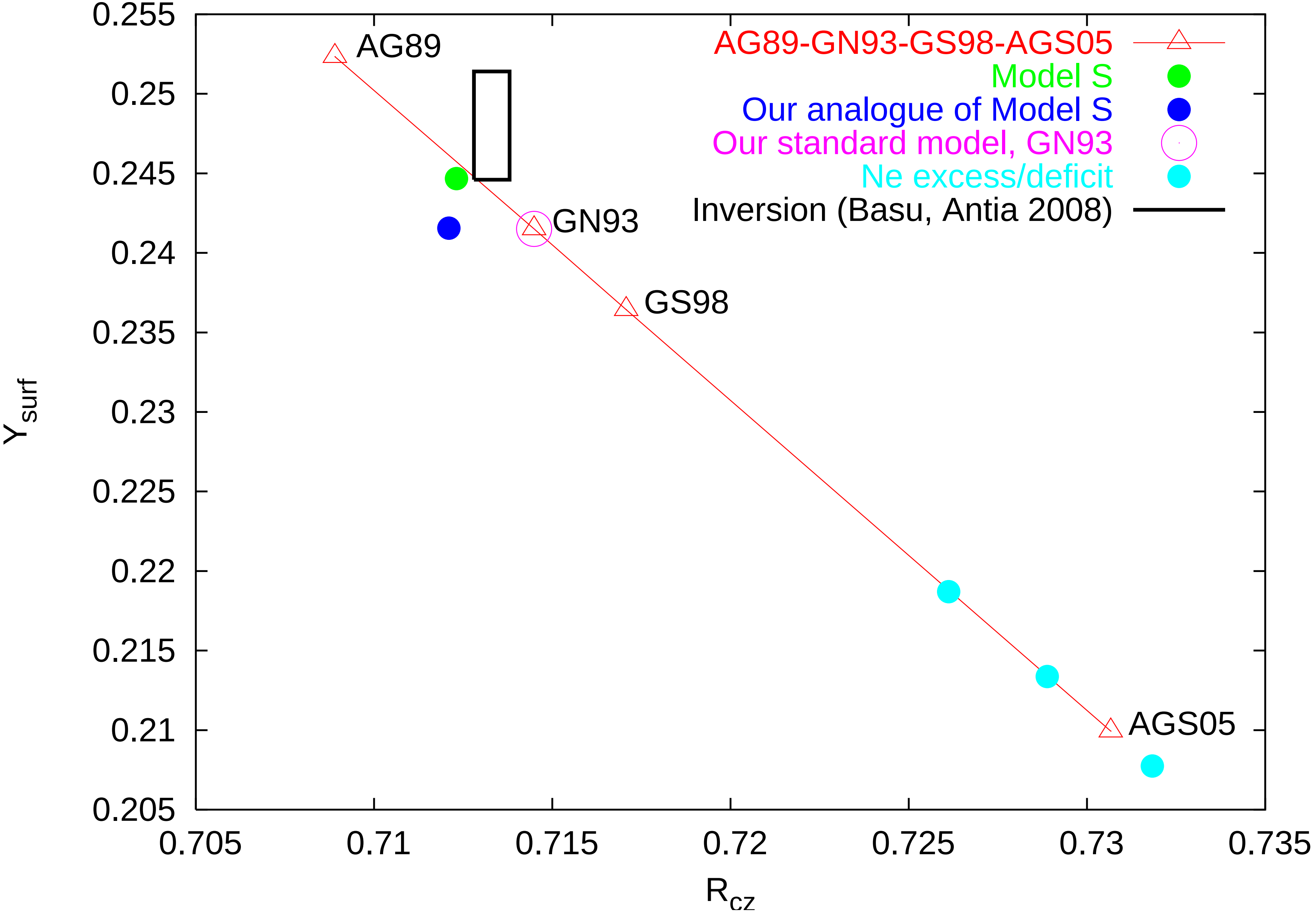


Ne abundance in AGS05: Γ_1 in models



Can neon abundance be calibrated with proper inversion data?

Helium-Convection zone depth roadmap (instead of conclusion)



The end