Recent inferences of element abundance from helioseismology

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Aim

The aim is estimation of the content of heavy elements in the convection zone of the Sun.

For this purpose, we use adiabatic exponent

$$\Gamma_1 = \left.\frac{\partial \ln P}{\partial \ln \rho}\right|_S .$$

Profile $\Gamma_1(r)$ is obtained from the helioseismic inversion. We use the results of inversion by Buldgen et al. (2023).

Method

The method is based on the effect of Γ_1 decrease in the regions of ionization of the chemical elements. If plasma is fully ionized and ideal, Γ_1 is 5/3. If some element is being ionized at some temperature, then Γ_1 decreases in this region.

The decrease of the adiabatic exponent is proportional to the mass fraction of the element.

We adjust the abundances of each elements to find a mixture that best approximates the inverted profile $\Gamma_1(r)$.

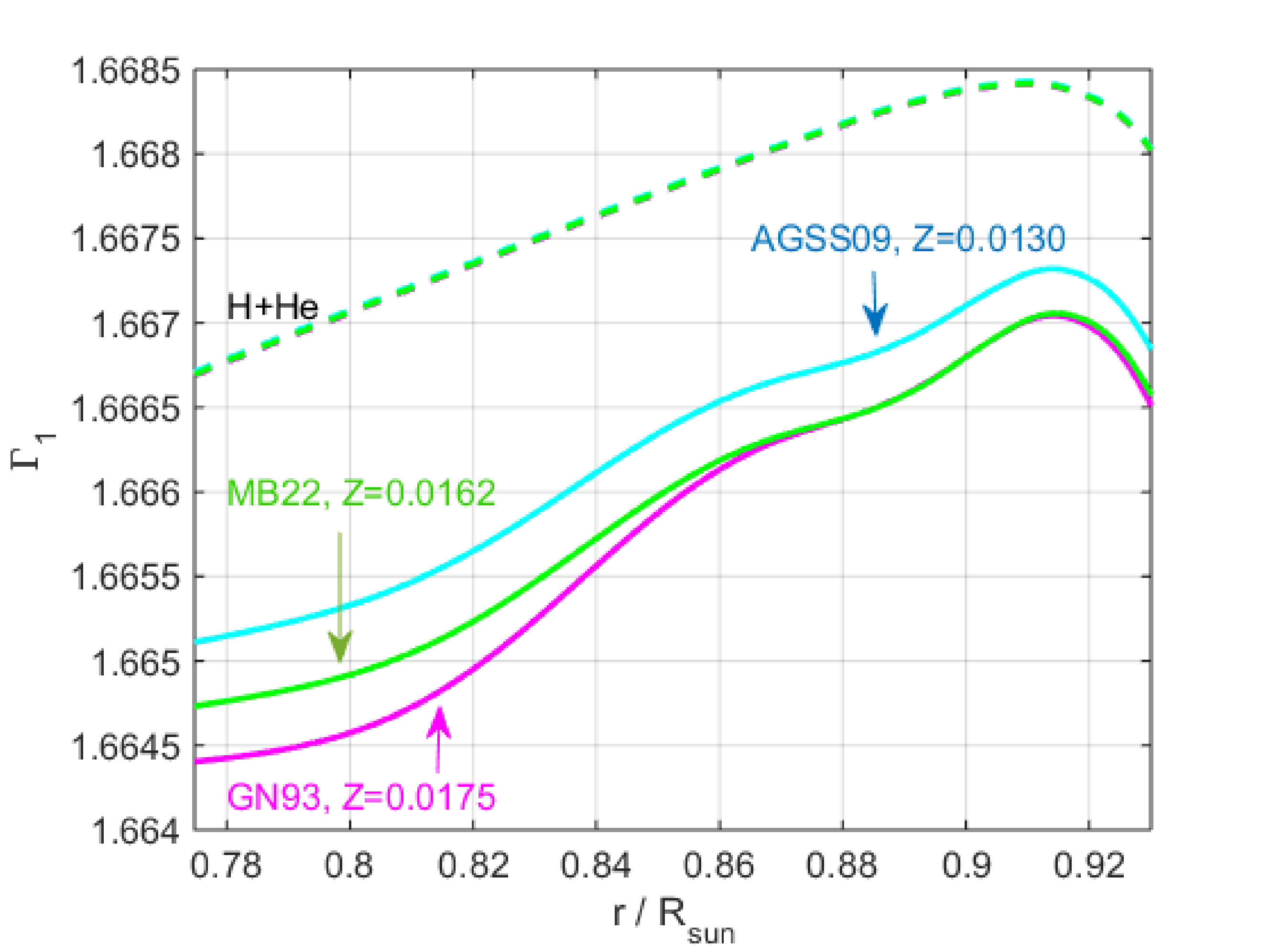
Examples of adiabatic exponent as a function of radius in the convection zone in the solar models

The models are computed for various mixtures of heavy elements. Ratios of these elements correspond to those obtained in the cited papers:

GN93 (Grevesse & Noels 1993), AGSS09 (Asplund et al. 2009), MB22 (Magg et al. 2022).

Dashed curve is for the hydrogen-helium plasma.

Distance between dashed and solid lines corresponds to Γ_1 decrease due to ionization of heavy elements.

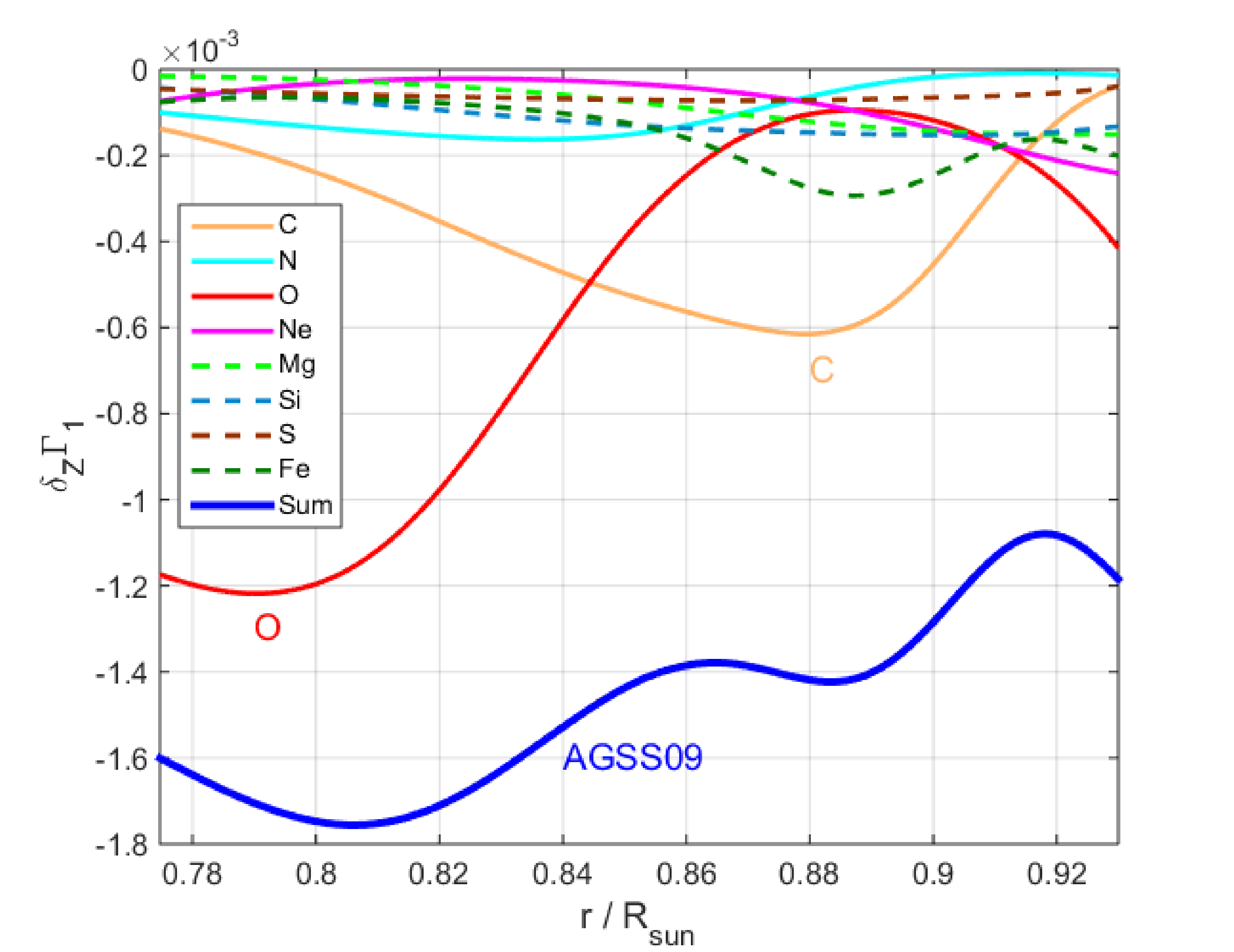


Γ_1 decreases with increasing mass fraction Z of heavy elements. Its profile depends on mixture.

Z-contribution in Γ_1

Distance between H-He Γ_1 and total Γ_1 is called Z-contribution:

$$\delta_Z \Gamma_1 = \Gamma_1 - \Gamma_1^{HHe}$$



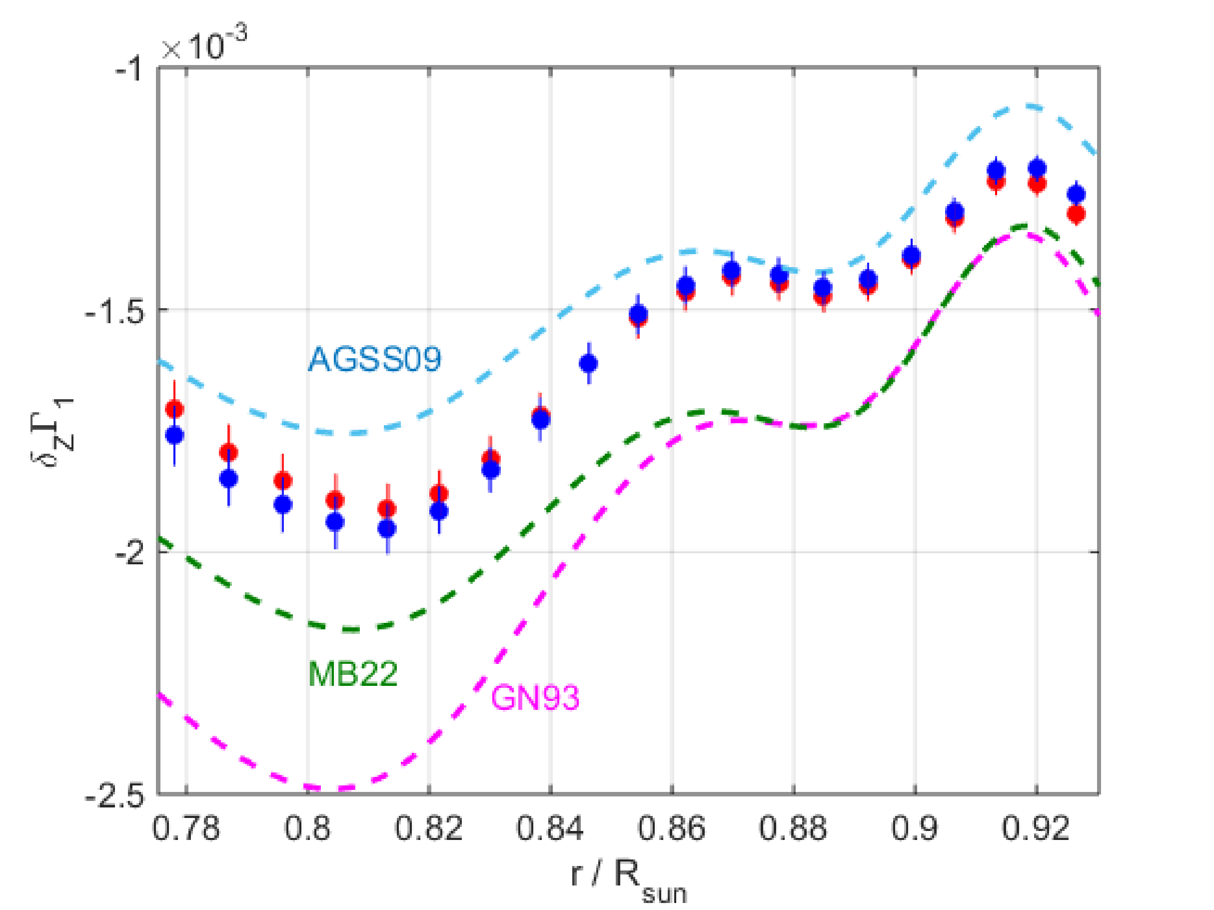
The Z-contribution can be decomposed into Z-contributions of individual elements:

$$\delta_Z \Gamma_1 = \sum_i \delta_Z^i \Gamma_1$$

Each chemical element makes a contribution mainly in the region where its ionization occurs. For example, oxygen ionization takes place at about r=0.8Rsun, carbon – at r=0.88Rsun. Amplitude of the decrease is proportional to the mass fraction of the element. We computed the individual contributions using SAHA-S EOS.

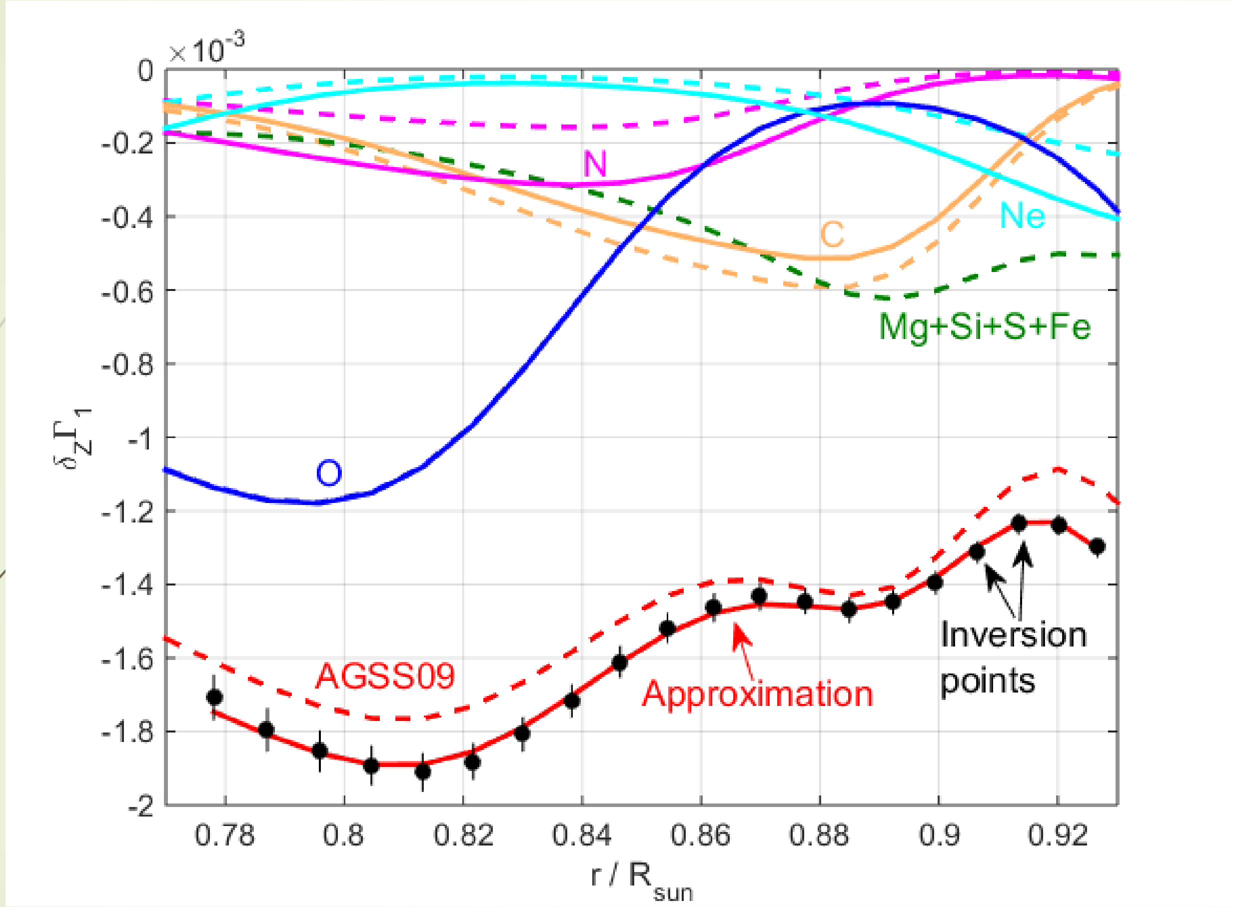
Z-contributions in inversions and in models

The inversion results are plotted by points. They lie between theoretical curves for AGSS09 and MB22 mixtures.



Inversions are described by Buldgen et al. (2023). The inversions use different solar models as a start point. Red points correspond to basic model computed with AGSS09 mixture and increased Ne (from Young 2018). Blue points are for the model with MB22 mixture.
Dataset: BiSON+MDI (Davies et al, 2014; Basu et al. 2009), degrees 0-250.

Results of approximation of inversion 1

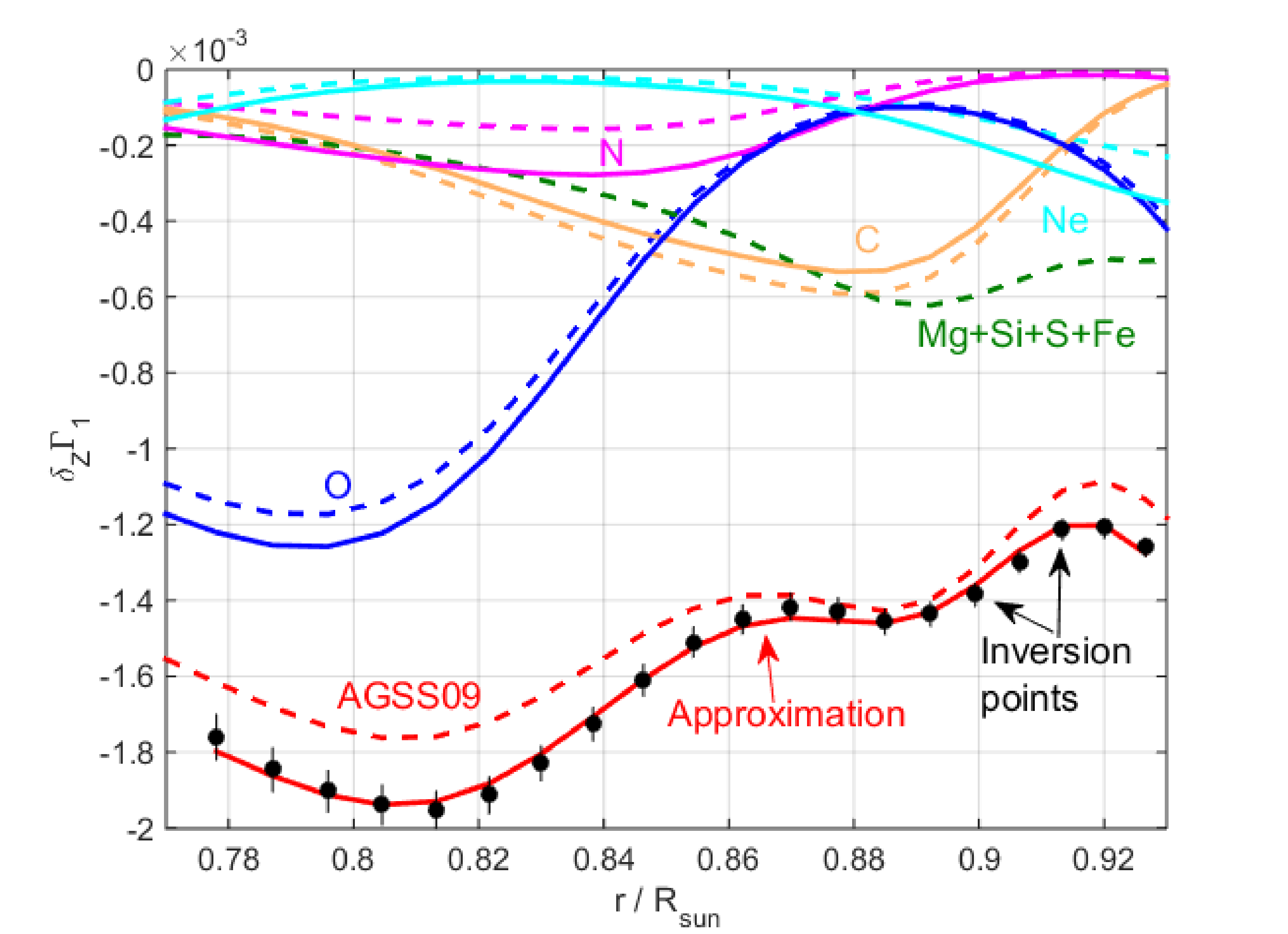


Mass fractions in the best approximation

Element	Zi
C	0.0020
N	0.0013
O	0.0057
Ne	0.0022
Z_8	0.0144

We approximate total decrease as a sum of individual contributions. Mass fractions of C, N, O, Ne are adjusted to fit the inverted Γ_1 points. Mass fractions of Mg, Si, S, Fe are fixed as in AGSS09 mixture (it does not differ significantly in other mixtures such as GN93 or MB22).
Solid curves are results of our approximation for inversion, dashed ones – standard AGSS09 mixture.

Results of approximation of inversion 2

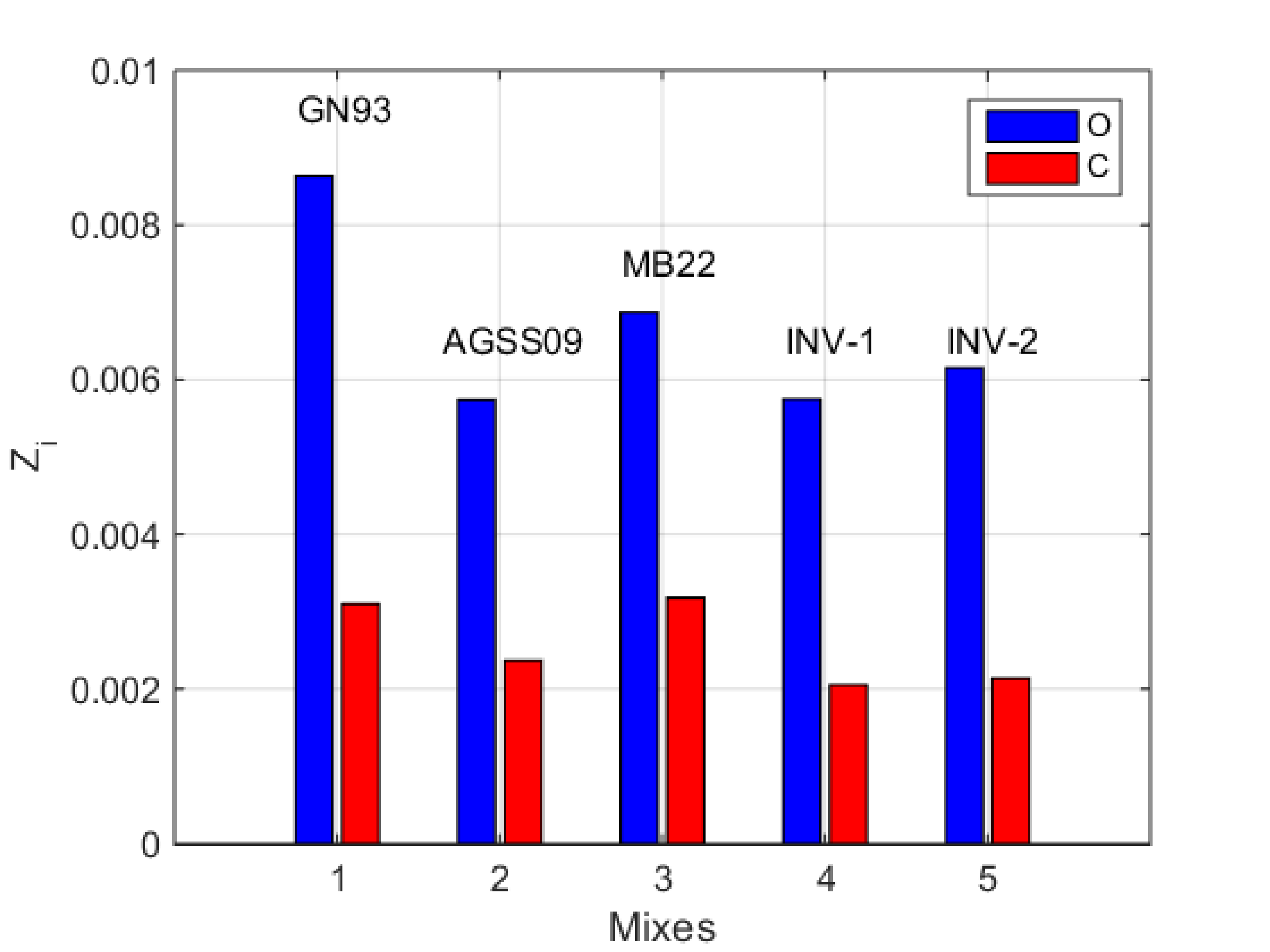


Mass fractions in the best approximation

Element	Inversion 1	Inversion 2
C	0.0020	0.0021
N	0.0014	0.0012
O	0.0057	0.0061
Ne	0.0022	0.0019
Z_8	0.0144	0.0144

The approximation of the inversion can be significantly improved compared to standard mixtures by adjusting the content of the elements.

Mass fractions of oxygen and carbon



Inversions are closer to AGSS09 mixture, than to MB22 or GN93. The total mass fraction of heavy elements in inversions is Z=0.014 whereas it is Z=0.013 in AGSS09. It is because approximations lead to more N and Ne than in AGSS09.

Mass fractions of heavy elements in inversions and standard mixtures

Element	Inversion 1	Inversion 2	GN93*	AGSS09*	MB22*
C	0.0020	0.0021	0.0031	0.0024	0.0032
N	0.0014	0.0012	0.0009	0.0007	0.0010
O	**0.0057**	**0.0061**	**0.0086**	**0.0057**	**0.0069**
Ne	0.0022	0.0019	0.0017	0.0013	0.0021
Mg			0.0007	0.0008	0.0006
Si			0.0007	0.0007	0.0008
S			0.0004	0.0003	0.0003
Fe			0.0013	0.0013	0.0013
Z_8	0.0144	0.0144	0.0175	0.0130	0.0162

Conclusion

- We approximate inverted Γ_1 profiles adjusting mass fractions of the heavy elements (C, N, O, Ne).
- Mass fraction of eight heavy elements (C, N, O, Ne, Mg, Si, S, Fe) in our approximations is Z=0.014.
- Mass fraction of oxygen Z_0=0.0057-0.0061, logarithmic abundance is

$$\lg \varepsilon(O) = \log_{10}\left[N_O / N_H\right] + 12 = 8.68 - 8.71.$$

- Carbon mass fraction is lower than in AGSS09.

Thank you for your attention!

Merci pour votre attention!