Helioseismic determination of the Solar metallicity

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Abstract

The solar chemical composition is a key element entering **both solar and stellar models**. Therefore, knowing the chemical composition of the Sun is relevant for the choice of physical elements entering stellar model grids. Following the revision in the early 2000s of the solar heavy element content (Asplund et al. 2009), an ongoing debate has agitated the solar modelling community as keeping the Grevesse & Sauval (1998) value would provide a much better agreement with some helioseismic constraints (sound speed, base of the convective envelope position, ...). **The recent spectroscopic determinations of solar abundances provided by Asplund et al. 2021 (AAG21) has been challenged by Magg et al. 2022 (MB22), revising the solar metallicity back to the 1998 value.**

The solar metallicity can also be inferred from helioseismic inversions, without any need for spectroscopic measurements. We present a new determination of the solar metallicity from helioseismic inversions. For all modern equations of state, we find **a metallicity in agreement with the Asplund et al. (2021) abundances, strongly rejecting the Magg et al. (2022) value.** Our low Z inference is in agreement with earlier studies (Vorontsov et al. 2013,2014; Buldgen et al. 2017), but with higher precision.

Context: Solar Abundance Problem

Solar abundances play a key role in stellar structure and evolution:

- Reference for the metallicity scale,
- Anchoring point of the $Y-Z$ enrichment law,
- Validation of solar models paves the way for large-scale asteroseismic modelling of solar-like oscillators (PLATO).

However: revision of abundances by Asplund et al. 2009 caused problems with helioseismic constraints.

How degenerate are the classical seismic constraints?

Sound speed, neutrino fluxes, BCZ position and Y_{CZ} are not direct constraints on solar abundances (Buldgen et al. 2023). They are influenced by other ingredients: Equation of state, opacities, mixing prescription for chemicals.

⇒ Avoid issues by looking directly at Γ_1 in the solar envelope (only dependency on EOS) and provide an independent measurement of $Z_{\odot}$.

Inversion strategy

Analysis: we start from extended calibration procedures (as in Buldgen et al. 2023) to reproduce $R_{\odot}$, $L_{\odot}$, $[Z/X]_{\odot}$ and r_{bcz} using X_0, Z_0, α_{MLT} and α_{Ov} (instantaneous mixing, ∇_{Ad}).

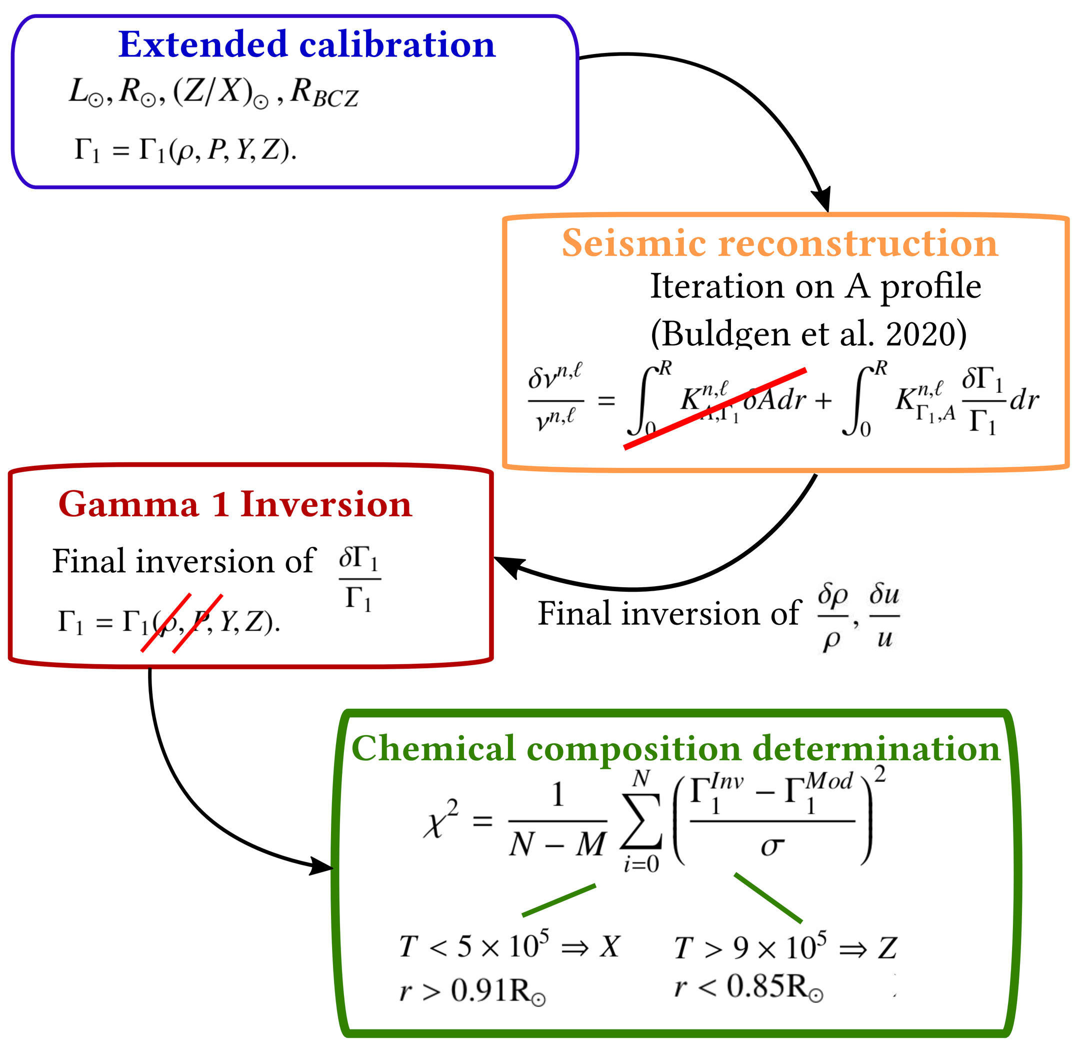

Fig. 1: Inversion strategy to determine the solar metallicity from helioseismic data.

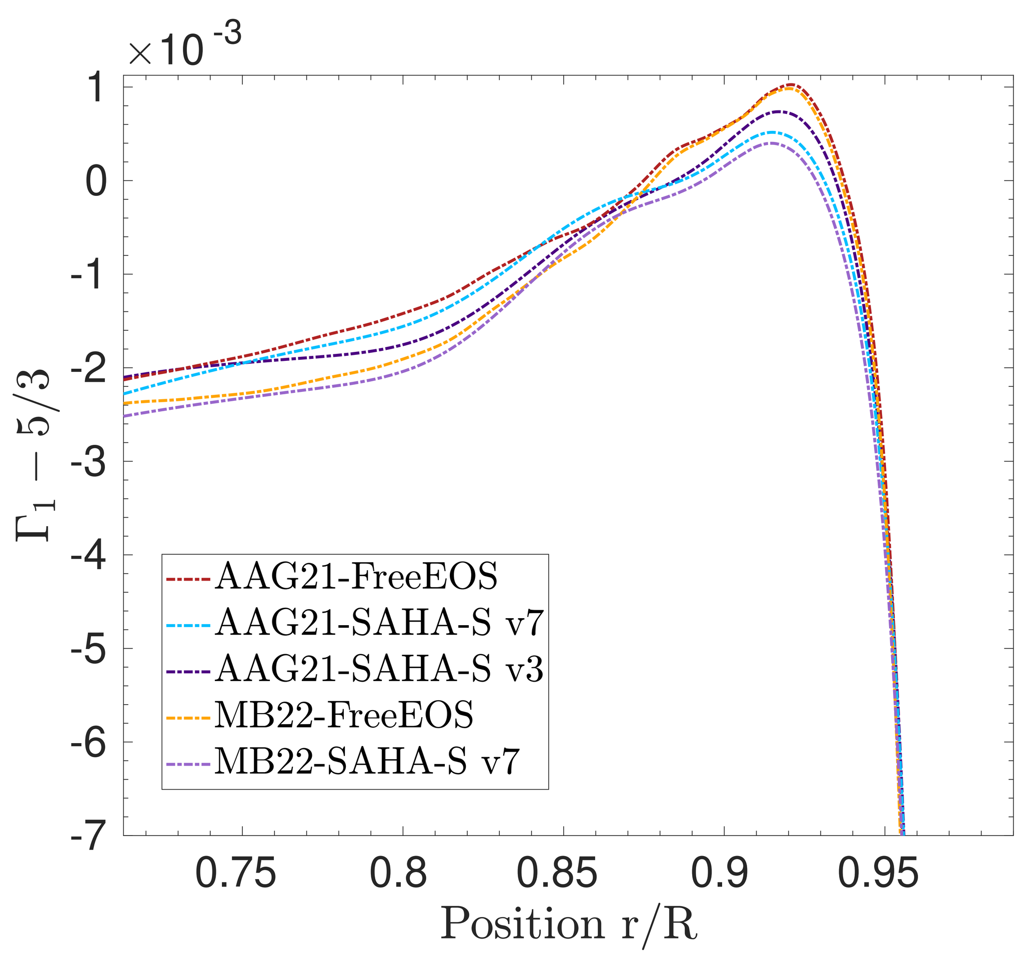

Fig. 2: Γ_1 profile of solar models with various EOS and abundances.

Hare-and-hounds exercises

Setup: same set of modes and errors as actual solar values. Calibrated trade-off parameters for each inversion. Three test cases are used:

- **HH1:** Differing EOS and abundances, both Z and EOS effects are present.
- **HH2:** Differing EOS but same abundances, only EOS effects are present.
- **HH3:** Same EOS but differing abundances, only Z effects are present.

Results: In all cases, the correct Z and X are recovered by the inversion. **A high-Z model cannot be mistaken for a low-Z model (and vice versa).**

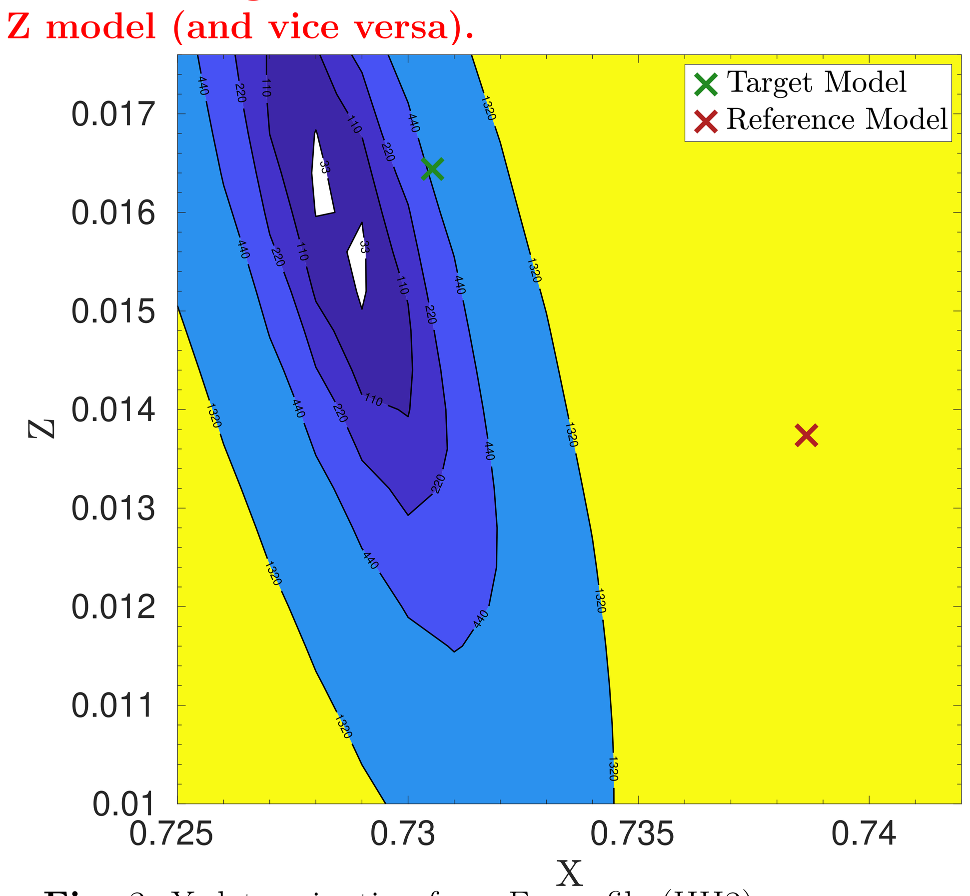

Fig. 3: X determination from Γ_1 profile (HH3).

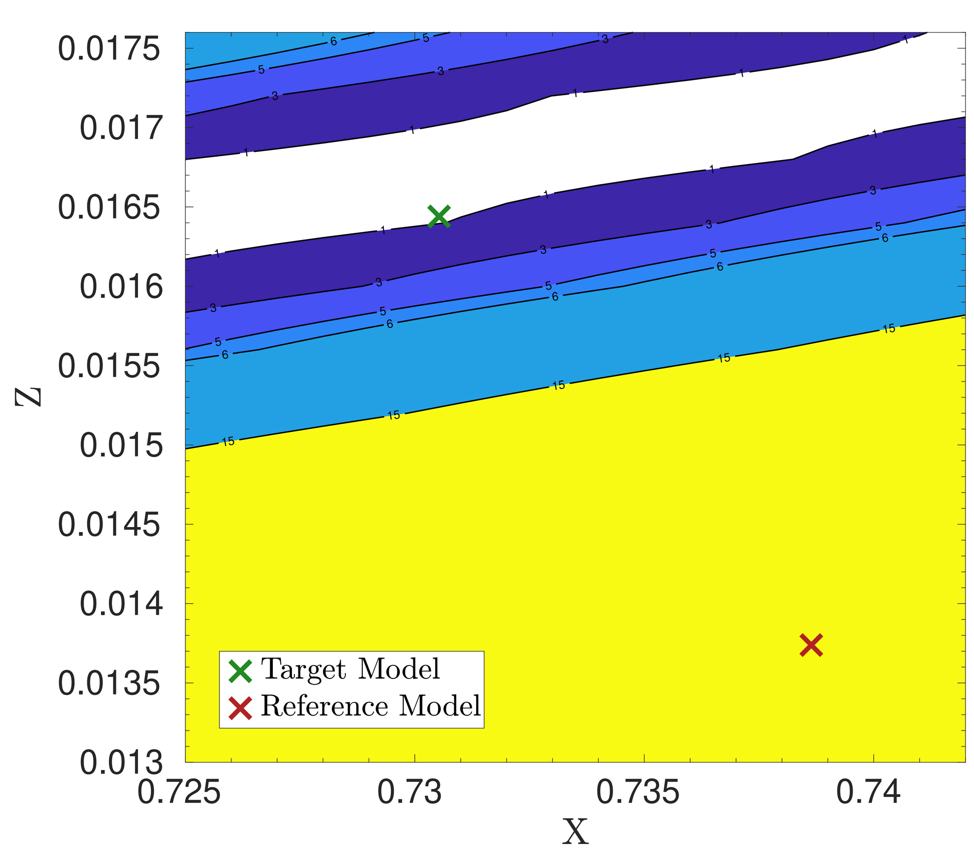

Fig. 4: Z determination from Γ_1 profile (HH3).

Inversion of Solar data

Setup: 2 helioseismic datasets, 2 different equations of states, 5 different models.

Method: each Γ_1 profile is reconstructed individually from detailed non-linear inversions.

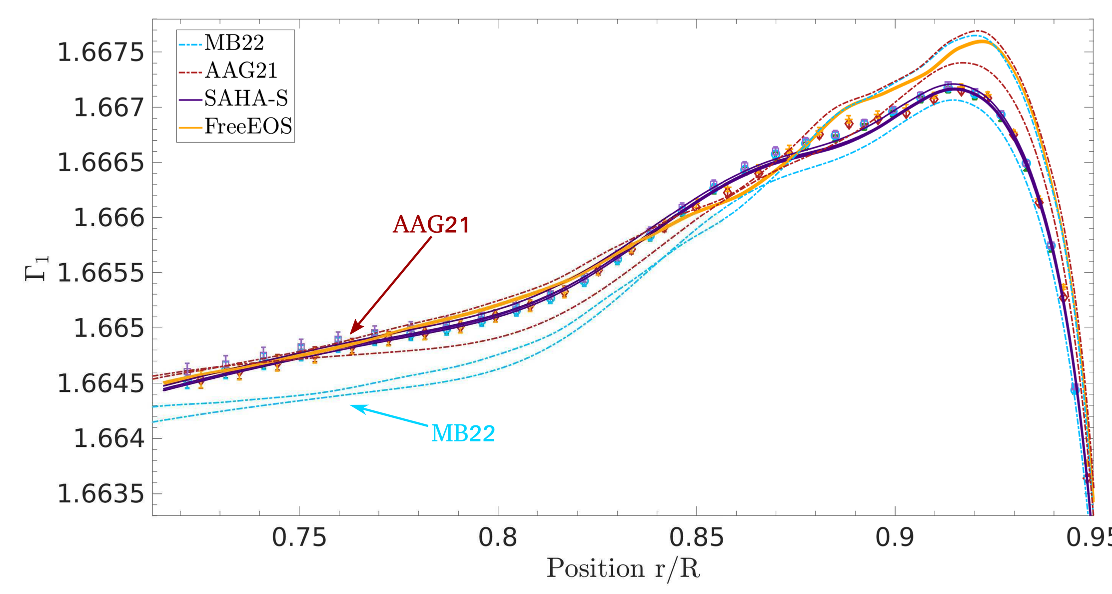

Fig. 5: Γ_1 fitting at high T for various EOS.

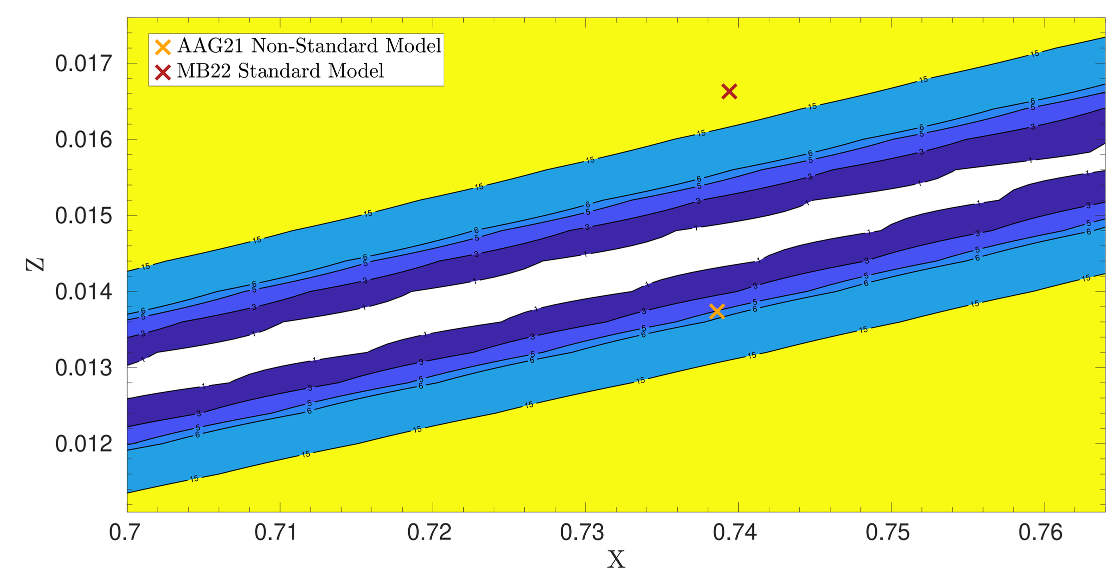

Fig. 6: χ^2 map of the high T domain for solar data, the red and orange crosses show the values from calibrated solar models.

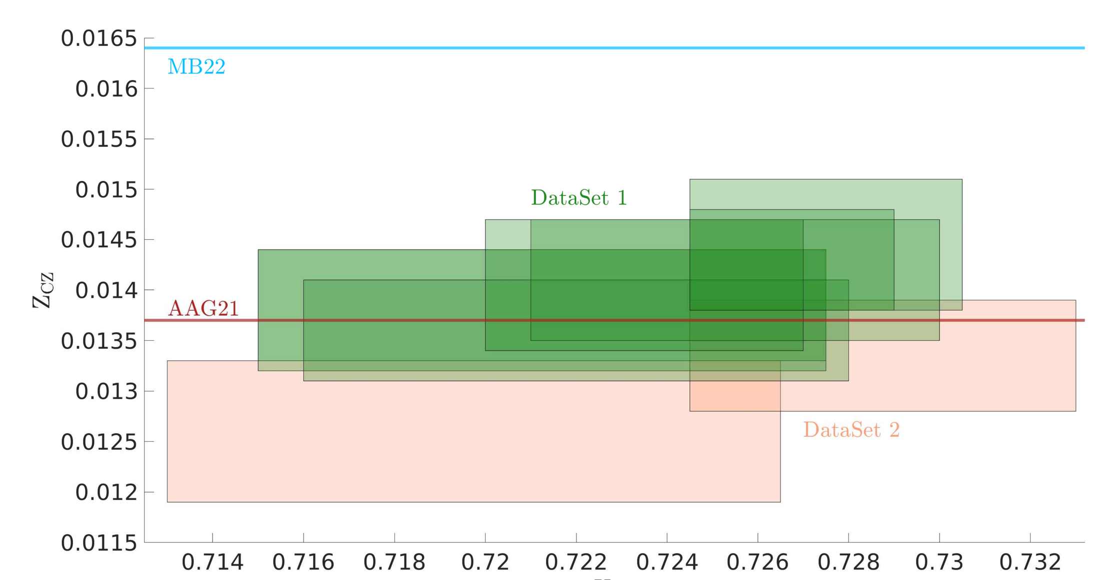

Fig. 7: X-Z range inferred for all models, EOS and datasets.

Differences in reduced χ_2 values between high-Z and low-Z models range from a factor 6 to 10. The highest degree of rejection is found for high-Z, high-Y models (around 0.245-0.25), which is the output of high-Z calibrated evolutionary models.

Future works are needed to explain the origins of the differences between FreeEOS and SAHA-S. MHD2020 could play the role of third party in this analysis.

Conclusion

Helioseismic inversions of the solar metallicity allow to distinguish between high and low metallicity models. Further modifications can be expected from improvements of the equation of state of the solar material. A detailed procedure is required to extract precise and accurate results:

1. Use combined inversions to minimize cross-term contributions;
2. Analyse systematics from various equations of state (FreeEOS, SAHA-S);
3. Analyse systematics from various datasets;

We conclude that helioseismic data does not favour a high solar metallicity of the convective envelope (as shown by Vorontsov et al. (2013, 2014) and Buldgen et al. (2017)).

We determine a precise interval of inferred metallicity of [0.0120 , 0.0151] and hydrogen [0.715 , 0.732]. In all our cases using two different datasets and equations of state, the solar metallicity of Magg et al. 2022 is strongly rejected. The SAHA-S equation of state is also favoured over FreeEOS.

References

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