Helioseismic determination of the metal mass fraction in the solar convective envelope

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The role of the Sun:

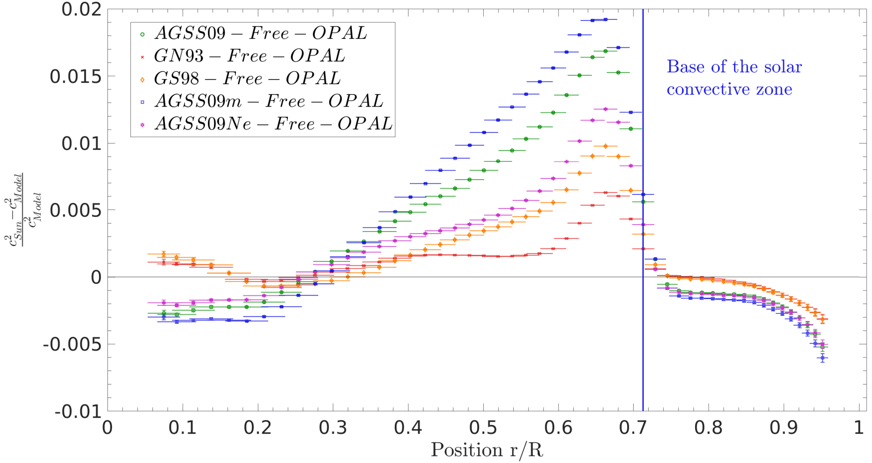
Well-studied, helioseismic constraints, neutrino fluxes, testbed for physical ingredients. The Sun is used as a **reference**:

- Metallicity scale,
- Enrichment laws,
- SSM framework,
- Paved the way for asteroseismology using solar-like oscillations.

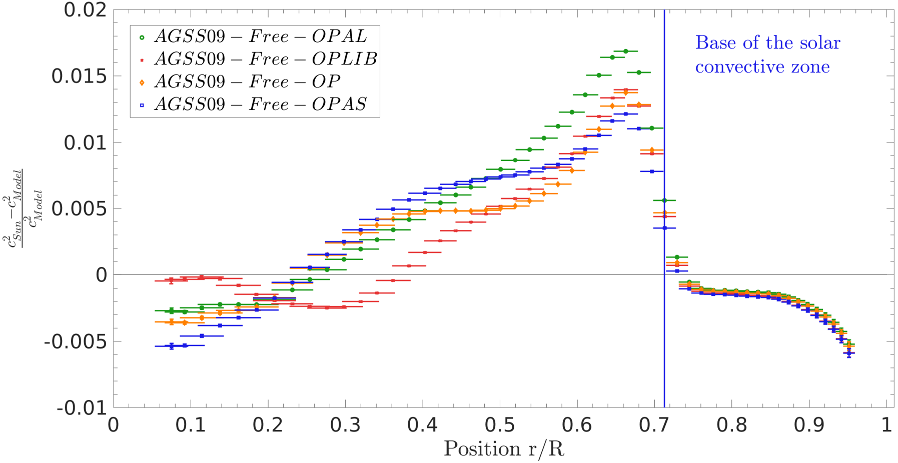
Most of our models will include some ingredients that have been calibrated on the Sun. Thus, if you change the way you model the Sun, you impact stellar physics as a whole.

But how well do we know the Sun?

The solar modelling problem



Effect of opacities



Constraints from seismic inversions:

Assuming an E.O.S, one can write:

$$\frac{\delta\Gamma_1}{\Gamma_1} = \left(\frac{\partial \ln \Gamma_1}{\partial \ln P}\right)_{\rho,Y,Z} \frac{\delta P}{P} + \left(\frac{\partial \ln \Gamma_1}{\partial \ln \rho}\right)_{P,Y,Z} \frac{\delta \rho}{\rho} + \left(\frac{\partial \ln \Gamma_1}{\partial Y}\right)_{P,\rho,Z} \delta Y + \left(\frac{\partial \ln \Gamma_1}{\partial Z}\right)_{P,\rho,Y} \delta Z, \tag{1}$$

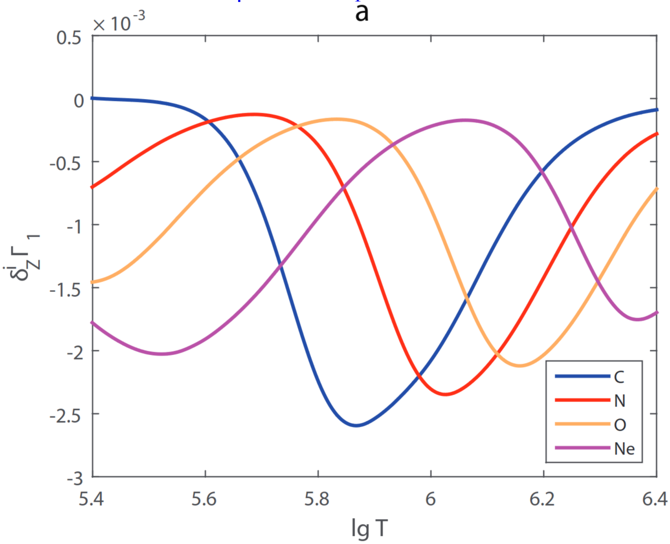
thus allowing to find Y and Z.

E.O.S., dataset, model dependencies. ⇒**Difficult inversion.**

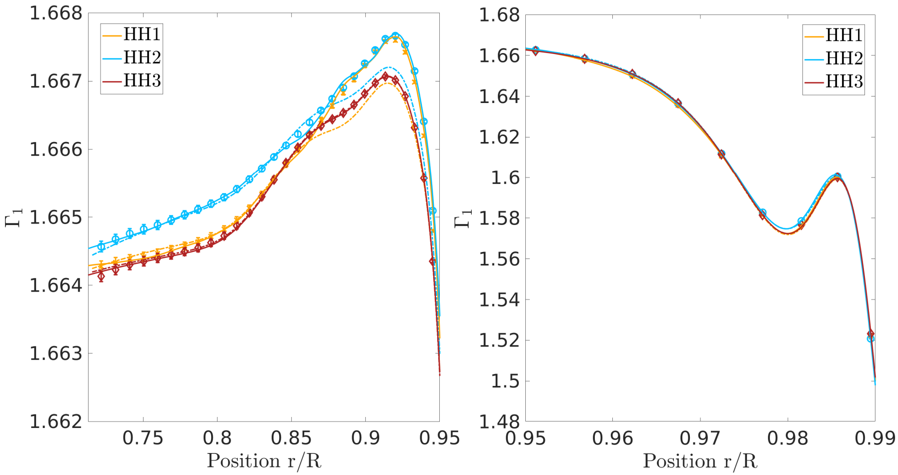
Studied since early 2000s: Takata & Shibahashi 2001; Lin & Däppen 2005; Lin et al. 2005; Antia & Basu 2005; Vorontsov et al. 2013, 2014; Buldgen et al. 2017; Baturin et al. 2022; Buldgen et al. 2024.

What do these contributions look like? (Baturin et al. 2022)

Each metal acts as a small dip in the Γ_1.

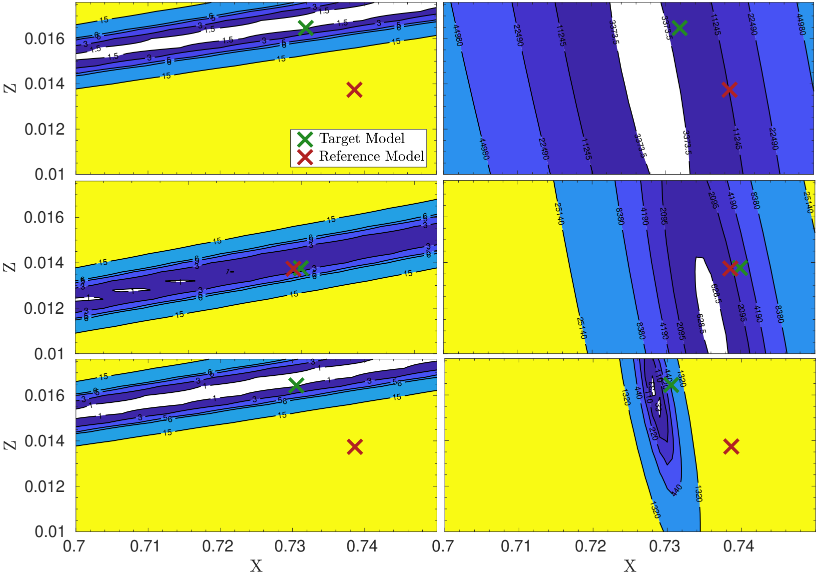


Testing the method: Γ_1 recovery

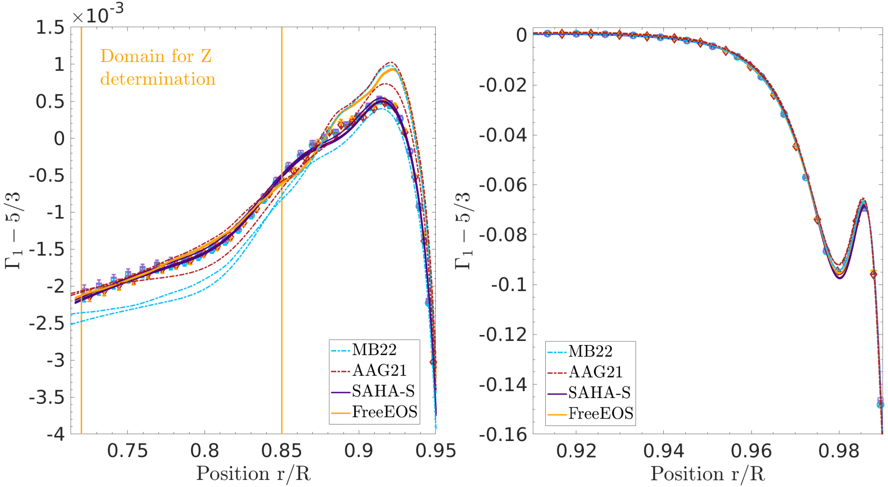


We get it in **each** case.

Testing the method: Y and Z recovery

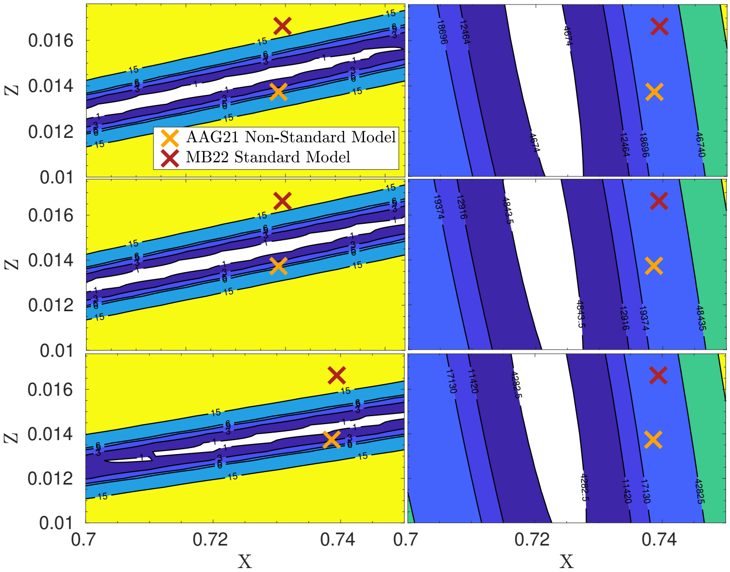


Solar case: Γ_1 recovery



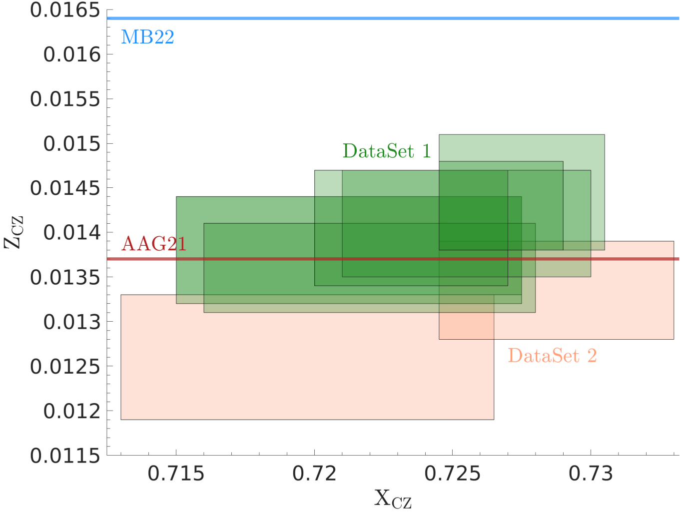
The solar profile is also recovered.

Solar case with SAHA-S equation of state

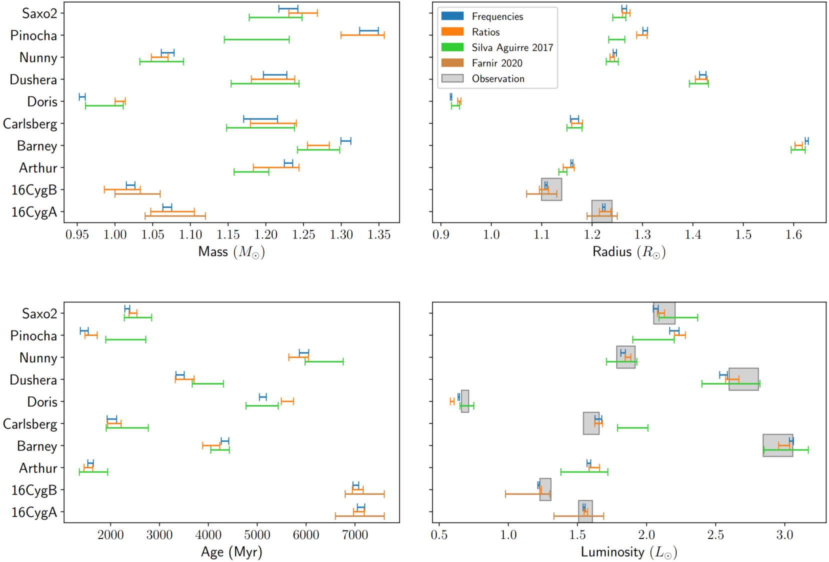


The overall picture

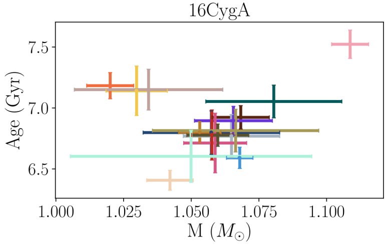
Combining all the results for two datasets and all EOS/models/opacities/abundances.

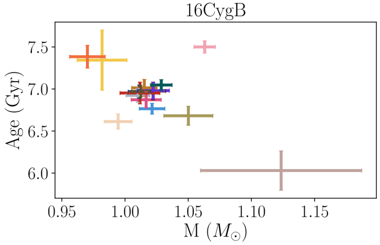


What happens for other stars? (Bétrisey et al. 2023)



What happens for other stars? (Farnir et al. 2019)





Summary

The impact of the solar metallicity is “compensated” in asteroseimic modelling.

But the physics of the solar models has to be revised.
⇒ Impact unknown!

Mostly tested on the MS, the impact on RGB models is not quantified.

Conclusion and perspectives

In conclusion

Low Z or High Z: Low Z, Magg et al. 2022 is invalidated.

What can we do? Improve the models and constrain physics.

Can the inversion still be improved?

New MDI+HMI data (around 6400 modes) ⇒ More constraints on fine structures in Γ_1.

Test with MHD EOS ⇒ Additional robustness and push for EOS comparisons

Test with patched models ⇒ Better control of surface effects! Effects of radius uncertainty ⇒ New formulation of equations (Takata & Gough 2024).

Thank you for your attention!