

Revised turbulent transport in solar models and helioseismic determination of the solar opacity

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October 2025



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The Sun as a benchmark star

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

A brief history of Standard Solar Models

Before 2004, high metallicity solar models ($Z = 0.0182$):

- ① **Correct** position of the BCZ,
- ② **Correct** Helium mass fraction in the CZ,
- ③ Sound Speed profile relative differences of up to **0.006**.

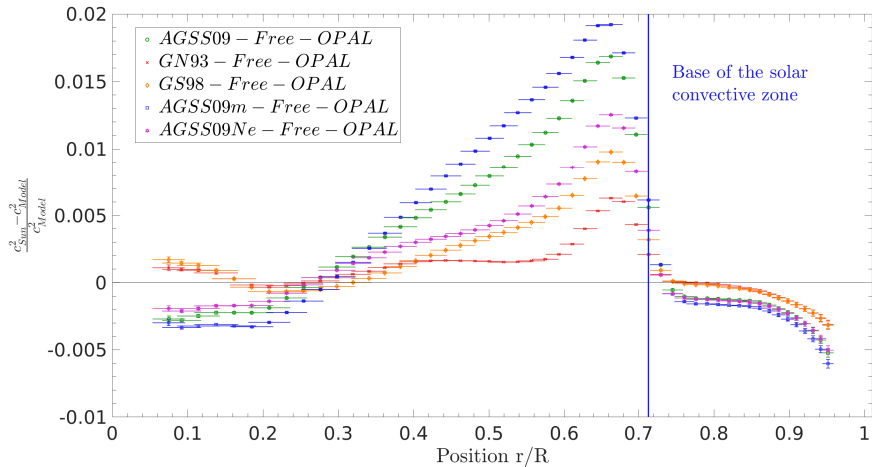
(Check Christensen-Dalsgaard 2021 and refs therein).

But: slow degradation as physical ingredients were updated.

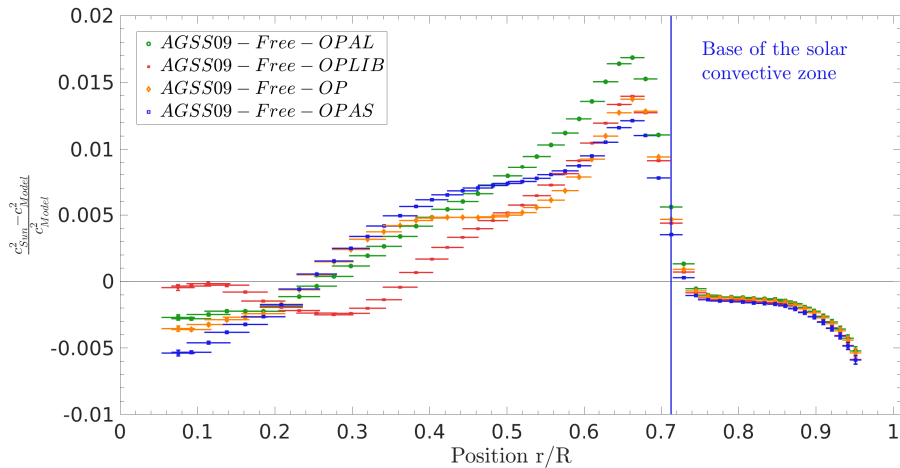
From 2004, downward revision of the solar Z :

- ① **Wrong** position of the BCZ,
- ② **Wrong** Helium mass fraction in the CZ,
- ③ Sound Speed profile relative differences of up to **0.02**.

Effect of abundances

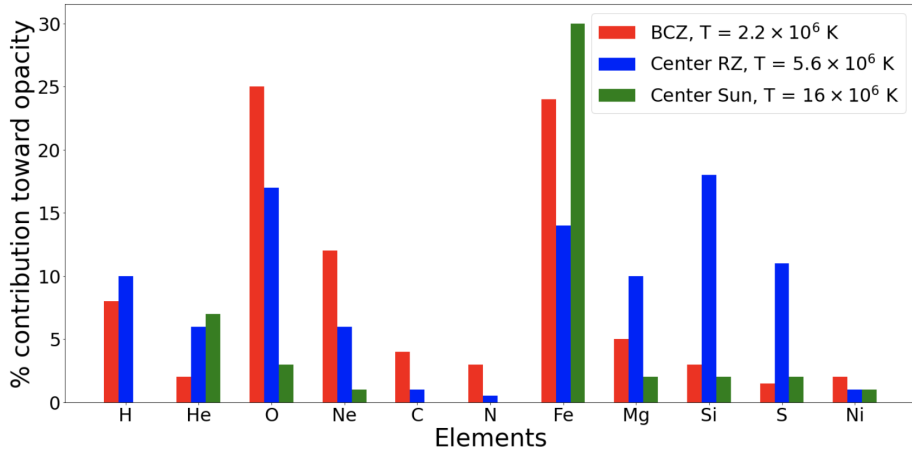


Effect of opacities



Elements contributing to opacity

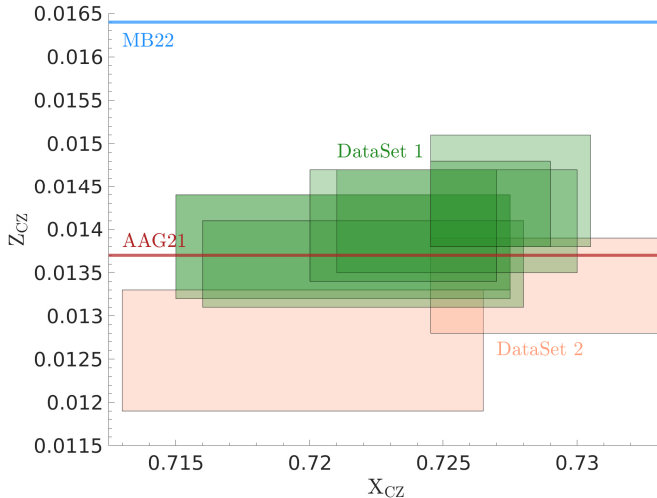
Trend originating from opacity contributions



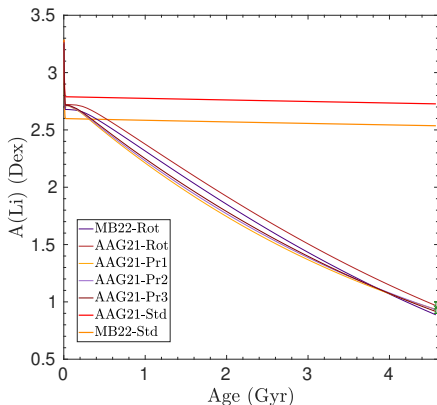
Courtesy of D. Chari & A. Pradhan

Helioseismic determination of Z

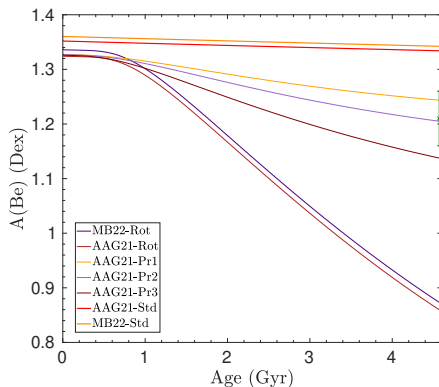
Results for various datasets/EOS/models/opacities/abundances.
(Vorontsov+2013, 2014, Buldgen+2017, 2024, Baturin+2025).



Light elements depletion and turbulence at the BCZ



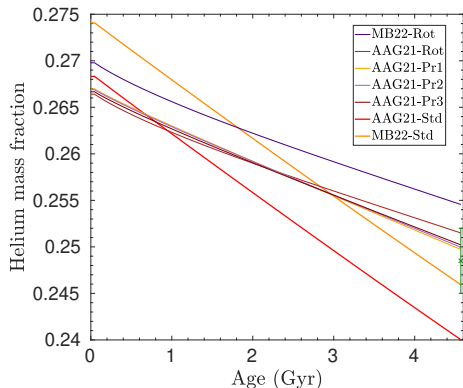
Lithium from Wang+(2021),
Efficient mixing required!



Beryllium from Amarsi+(2024),
favours steep transport efficiency.

e.g. Proffitt & Michaud 1991, Richard+1996, Brun+2002, Dumont+2021,
Eggenberger+2022, Buldgen+2025b.

Calibrating turbulence - Impact on helium



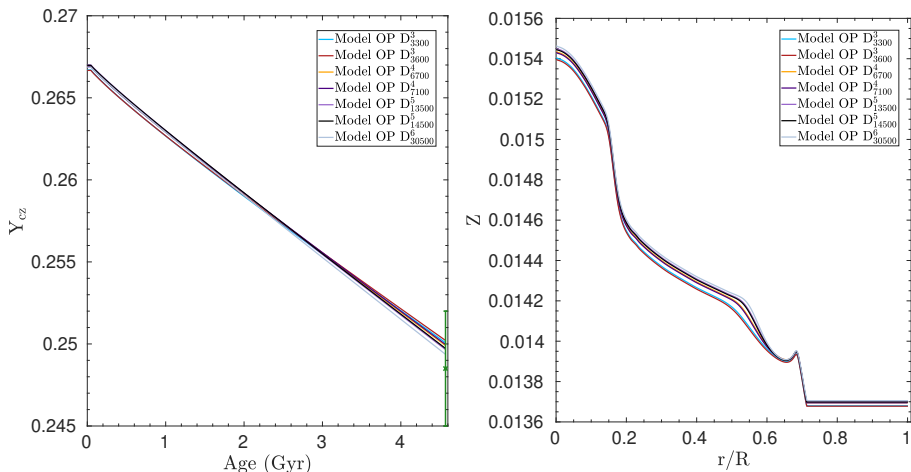
Looking at Y_{CZ} from Basu & Antia. (1995),
changes drastically the evolution.

Changing transport:

- Impact on initial conditions;
- Impact on conclusions based on Y_{CZ} ;
- Impact on stellar models of solar twins.

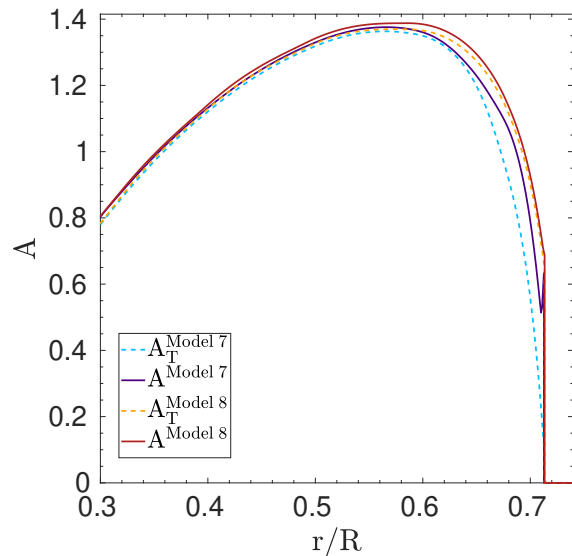
Macroscopic transport is paramount to understand the evolution of abundances.

Combined Li and Be constraints



Very similar helium depletion and metallicity profile.
(Buldgen+2025b)

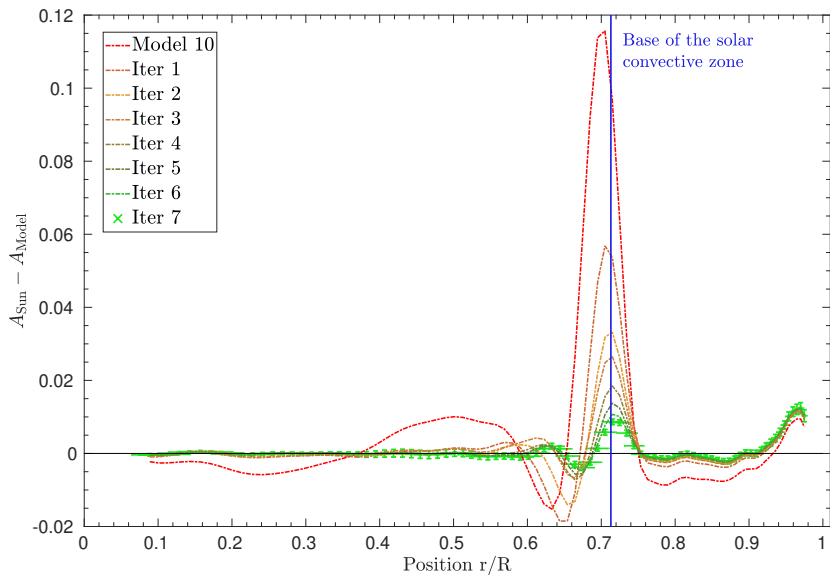
Probing temperature gradients



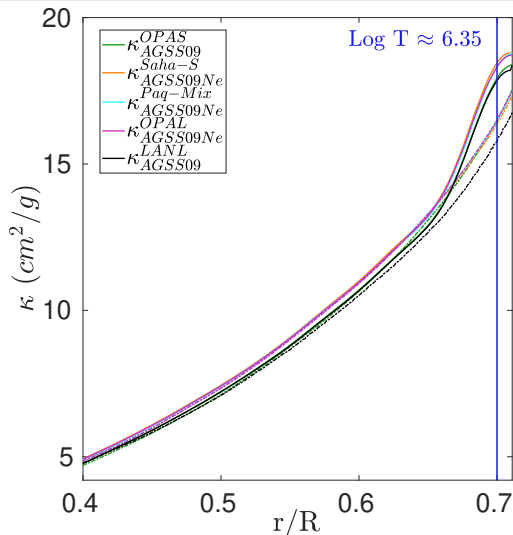
$$A = \frac{1}{\Gamma_1} \left(\frac{d \ln P}{d \ln r} \right) - \left(\frac{d \ln \rho}{d \ln r} \right) \\ = A_{\text{T}} + A_{\mu} \propto \nabla T$$

- 1 Determine $A_{\text{Sun}} - A_{\text{Mod}}$;
- 2 Integrate the structure satisfying equilibrium;
- 3 Compute oscillations;
- 4 Back to 1.

Level of agreement for seismic models



Opacity “Inversions” (Buldgen+2025a)

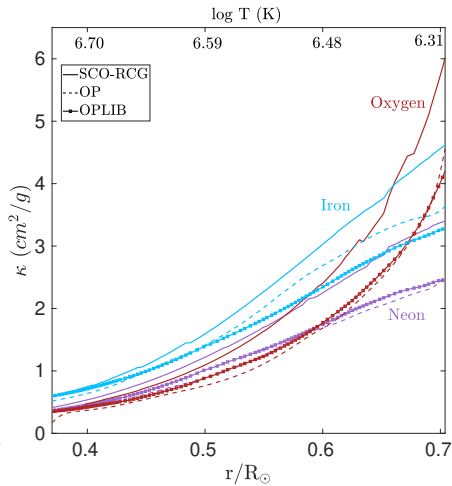
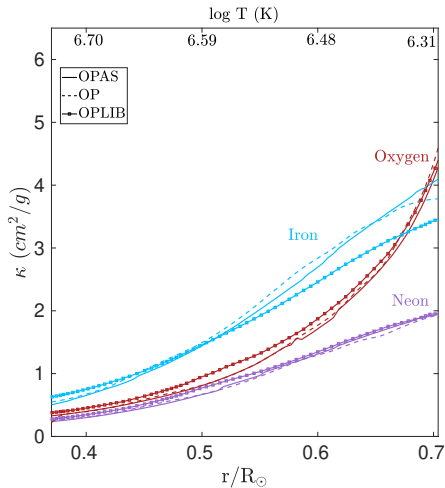


- Use seismic models (Buldgen+2020) and transport prescriptions (Buldgen+2025b).
- Integrate and iterate to reproduce $L_{\odot}$.
- Determination of amount of “missing” opacity.

**Consistent with
experiments
(Bailey+2015)**

Do codes agree with each other?

Major differences between codes at the same conditions.



Key points:

On the solar problem:

- We converge towards a low Z at the surface from independent techniques.
- Light elements should not be neglected $\Rightarrow$ Turbulence, helium, neutrinos.

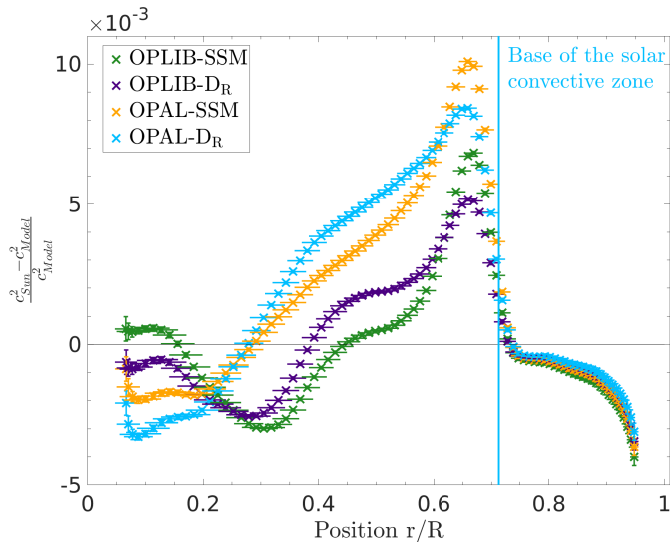
Abundances are one of many ingredients:

- Opacities, transport processes, early evolution,...

The Sun remains a complex system to study, with extremely precise constraints.

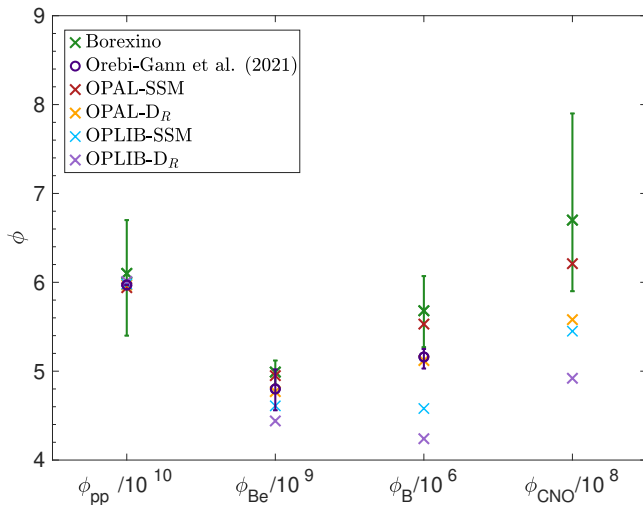
Thank you for your attention!

The Solar problem: Sound speed



- MB22 abundances;
- Mixing for Li;
- OPAL vs OPLIB.

The Solar problem: Neutrinos



The agreement for neutrinos worsen when Li and Be are considered.

Opacities - experiments and helioseismology

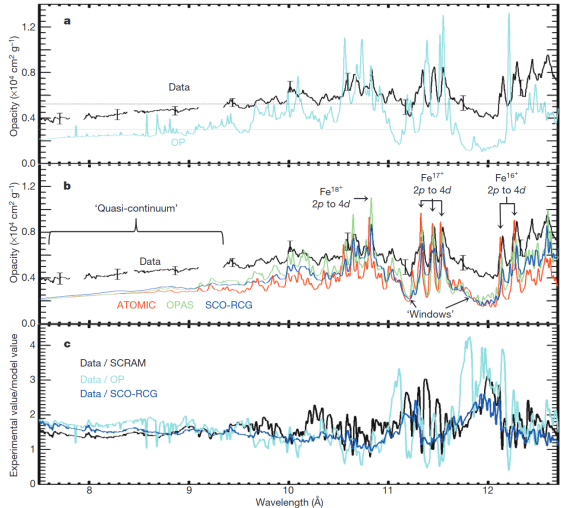
Experimental measures:

- Discrepancies for Iron.
- Increase with T and n_e .

Bailey+(2015),
Nagayama+(2019)

The physical origin is
still unknown.

The result has been
confirmed with other
setups over the last 10
years.



Bailey+2015

What do ab-initio computations say?

Codes give conflicting results for similar conditions.

