The current state of the solar modelling problem

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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**:

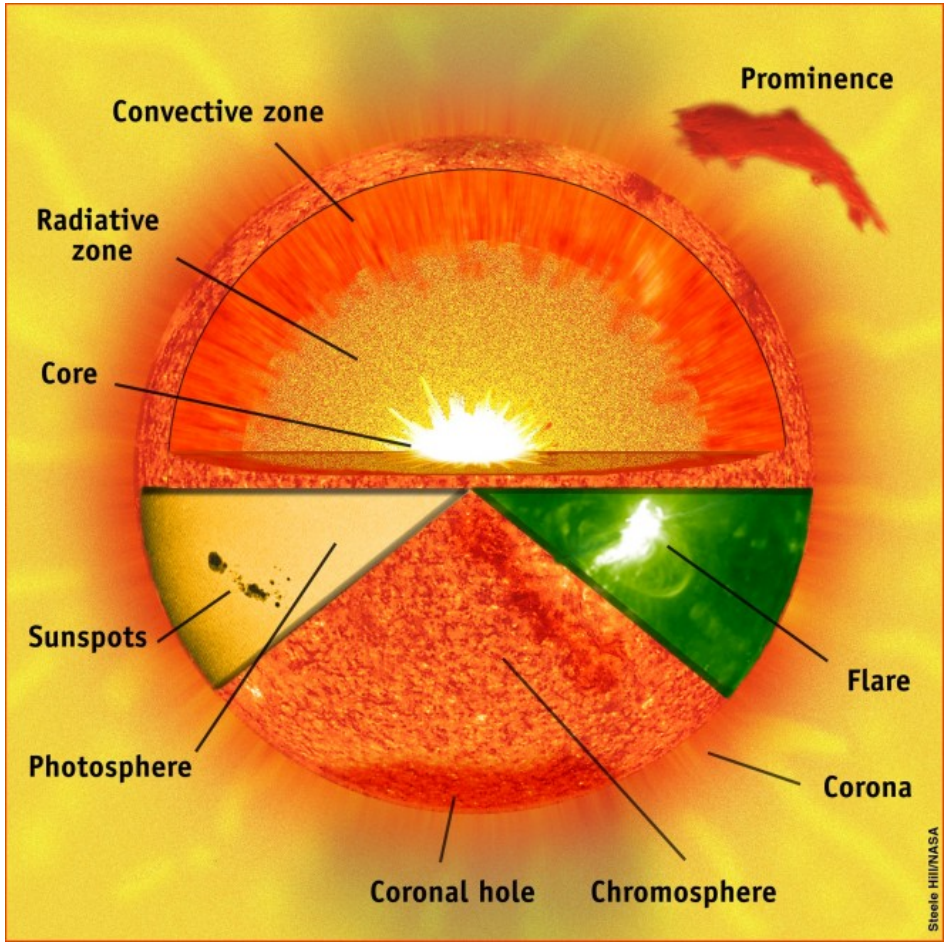
- Metallicity scale,
- Enrichment laws,
- SSM framework,
- Paved the way for asteroseismology using solar-like oscillations.

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.

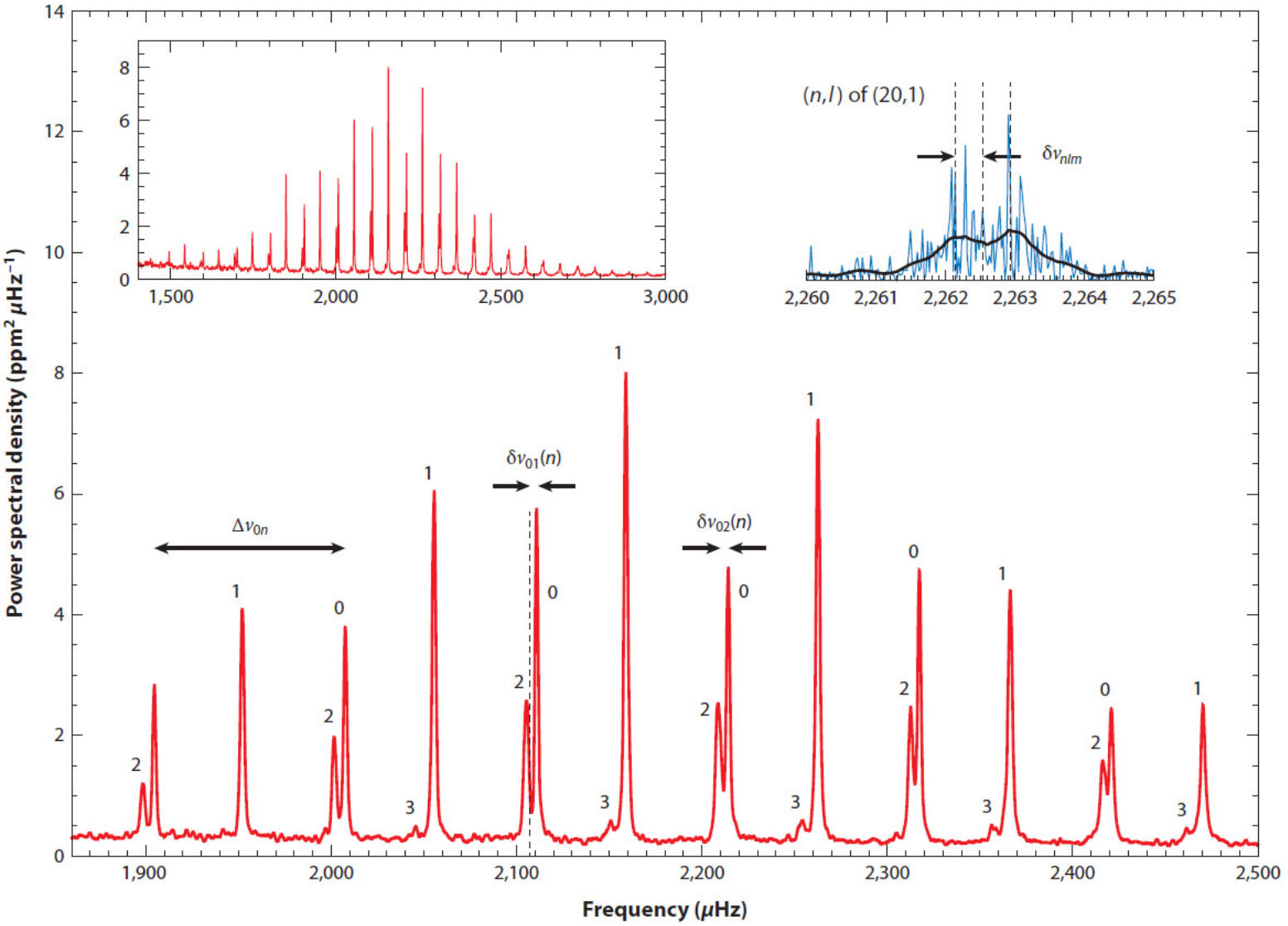
But how well do we know the Sun?

Stellar Structure (Low-mass main-sequence star, like the Sun)

- **Convective layers:** macroscopic motions of the fluid,
- **Radiative layers:** transport of energy by photons,
- **Core:** Thermonuclear reactions.



Observational Context - Solar-like oscillations



Chaplin & Miglio 2013

What is the problem with the Sun?

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 abundance in the CZ,
3. Sound Speed profile relative differences of up to 0.006.

(From Kosovichev & Fedorova 1991, 1993, Vorontsov et al. 1991)
But: slow degradatation as physical ingredients were updated.

From 2004, downward revision of the solar Z:

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

The controversy in "brief"

Spectroscopy

1. Asplund et al. 2005: **Low Z.**
2. Asplund et al. 2009: **Low Z.**
3. Caffau et al. 2011: **Higher Z.**
4. Scott et al. 2015a,b: **Low Z.**
5. Amarsi et al. 2017, 2019, 2020, 2021: **Low Z.**
6. Young 2018: **Higher Ne.**
7. Asplund et al. 2021: **Low Z, Ne Confirmed.**
8. Magg et al. 2022: **High Z.**

Some "disagreements" remain... (Nahar 2022)

Helioseismology & Neutrinos

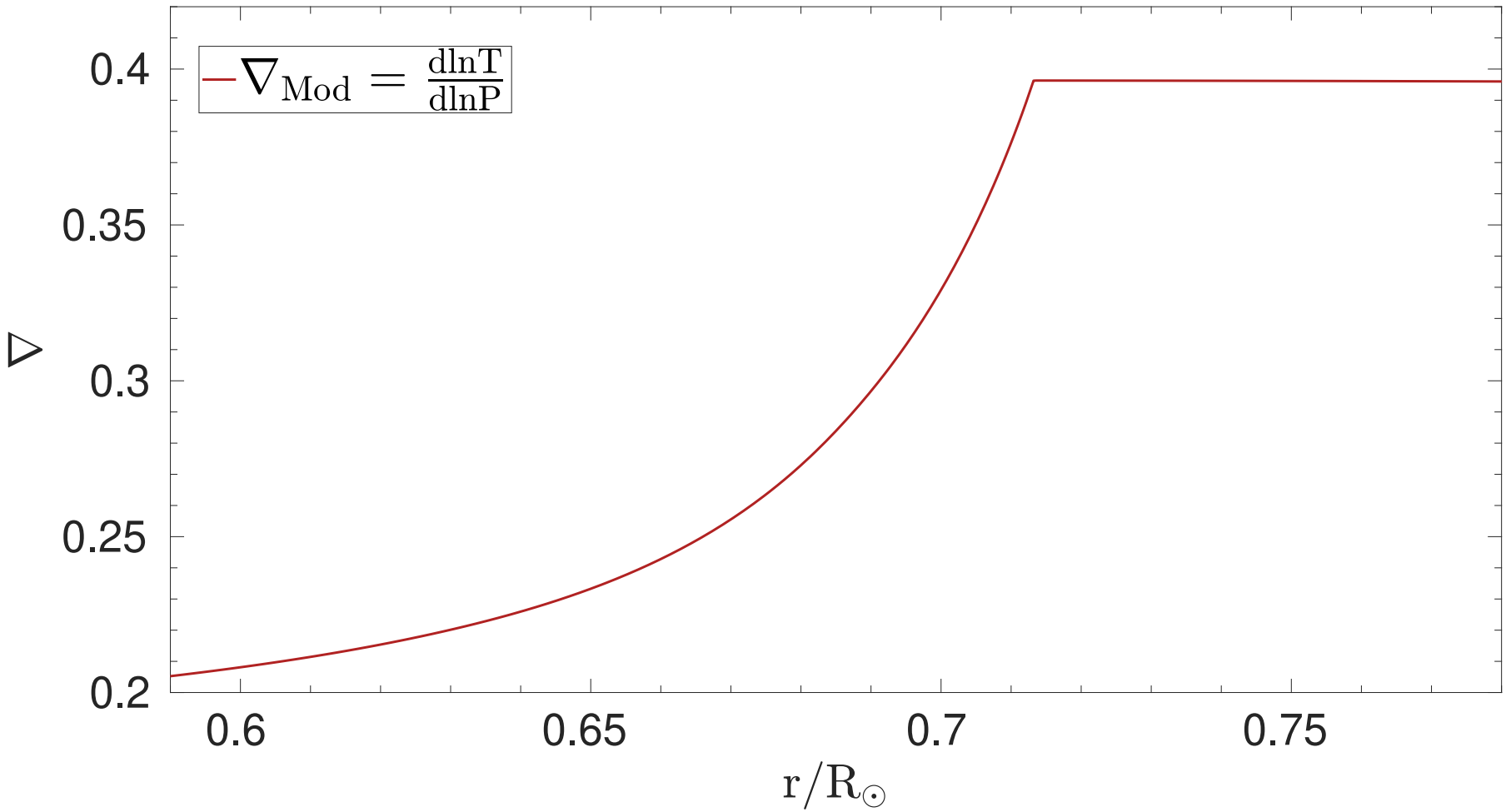
1. Sound speed is wrong!
2. Helium is wrong!
3. Neutrino fluxes are wrong!
4. BCZ is wrong!

$\Rightarrow$ Abundances **HAVE TO** change! They **ARE** higher! Helioseismology says so!

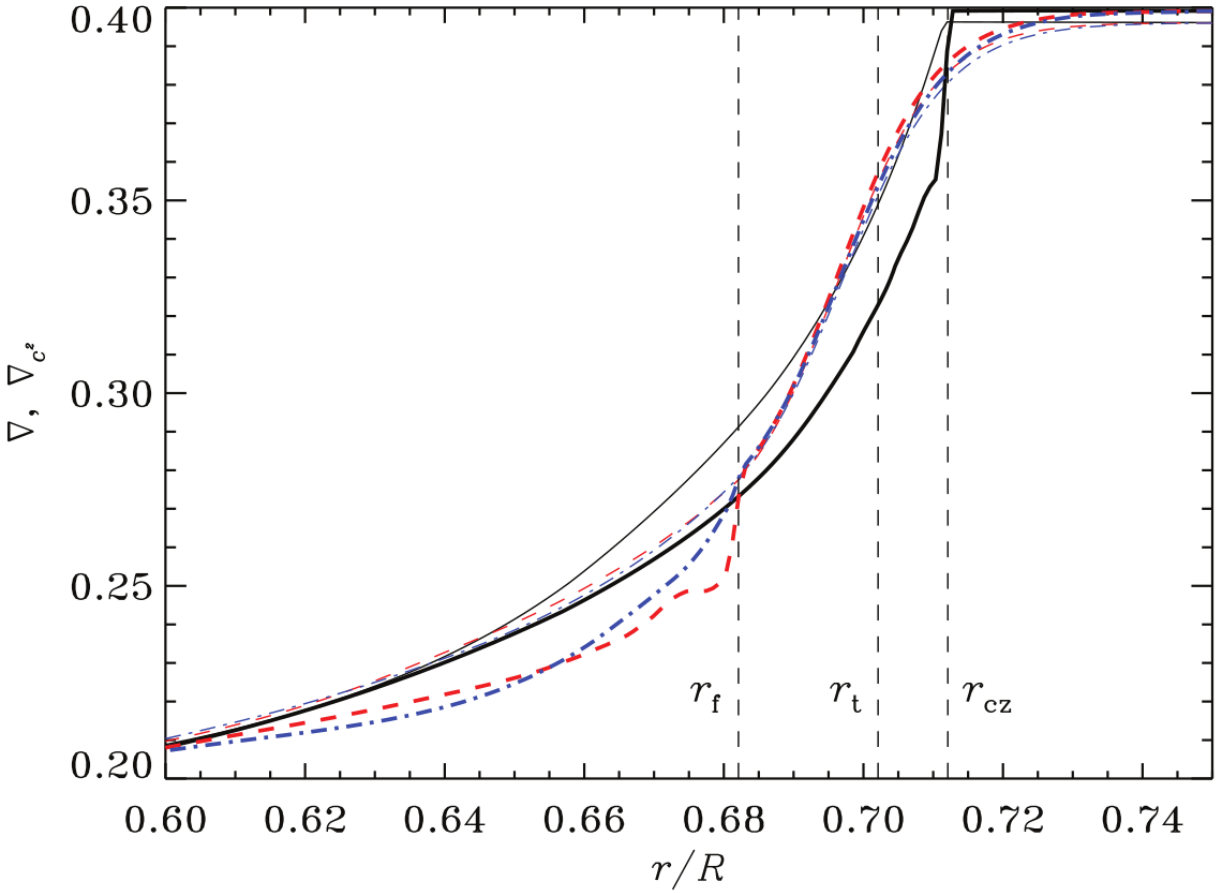
Or are they? What does helioseismology actually say?

The problem of the BCZ

$r_{CZ} = 0.713 \pm 0.001 R_\odot$ **(Basu & Antia 1997), SSM High Z:** $r_{CZ} \approx 0.713$**, SSM Low Z:** $r_{CZ} \approx 0.720 \Rightarrow$ **Low Z is wrong!**



What actually influences the BCZ position?



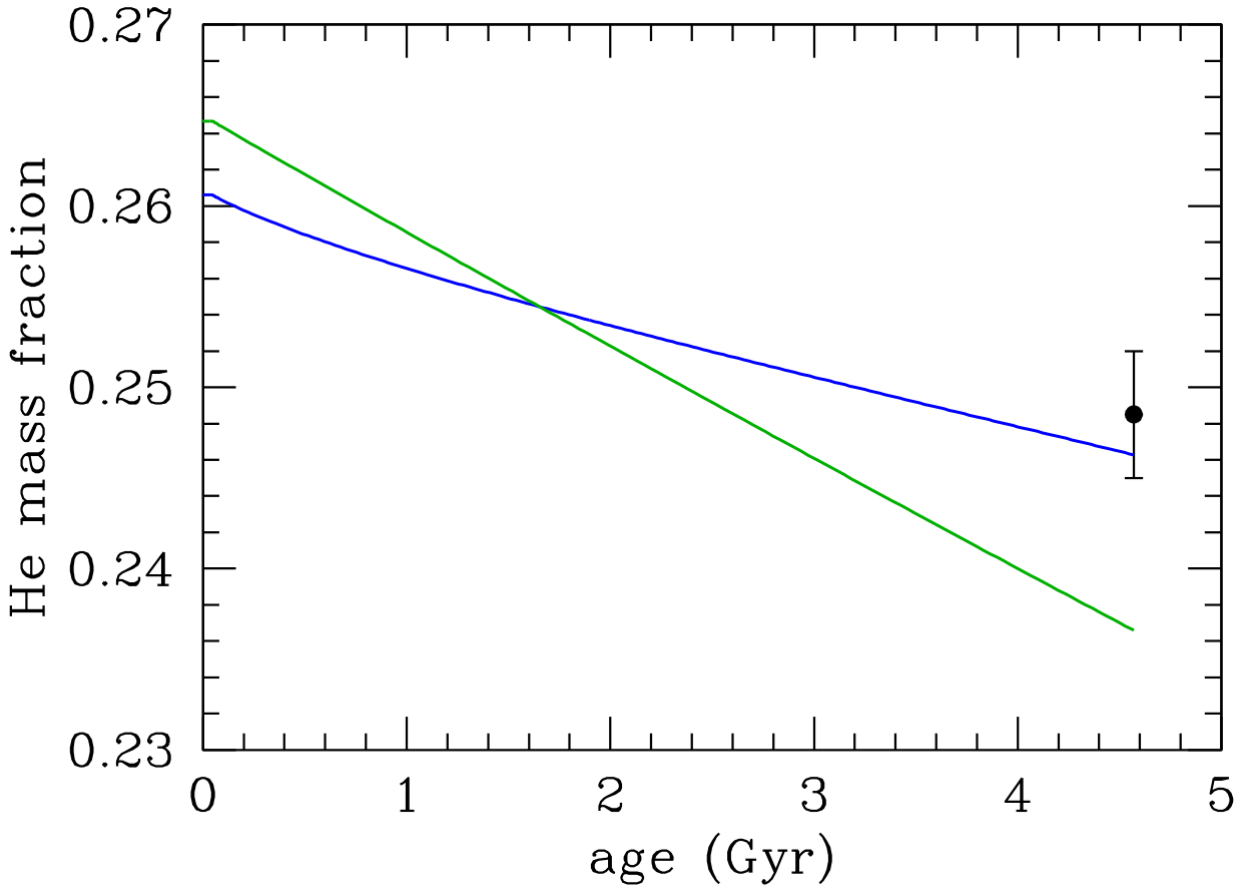
Christensen-Dalsgaard et al. 2011; see also Zhang et al. 2019 and Monteiro et al. 1994 for older references!

BCZ position is affected by:

- Overshooting;
- Opacities at the BCZ;
- Nuclear reaction rates;
- Transport of chemicals;
- ...;

The problem of Helium

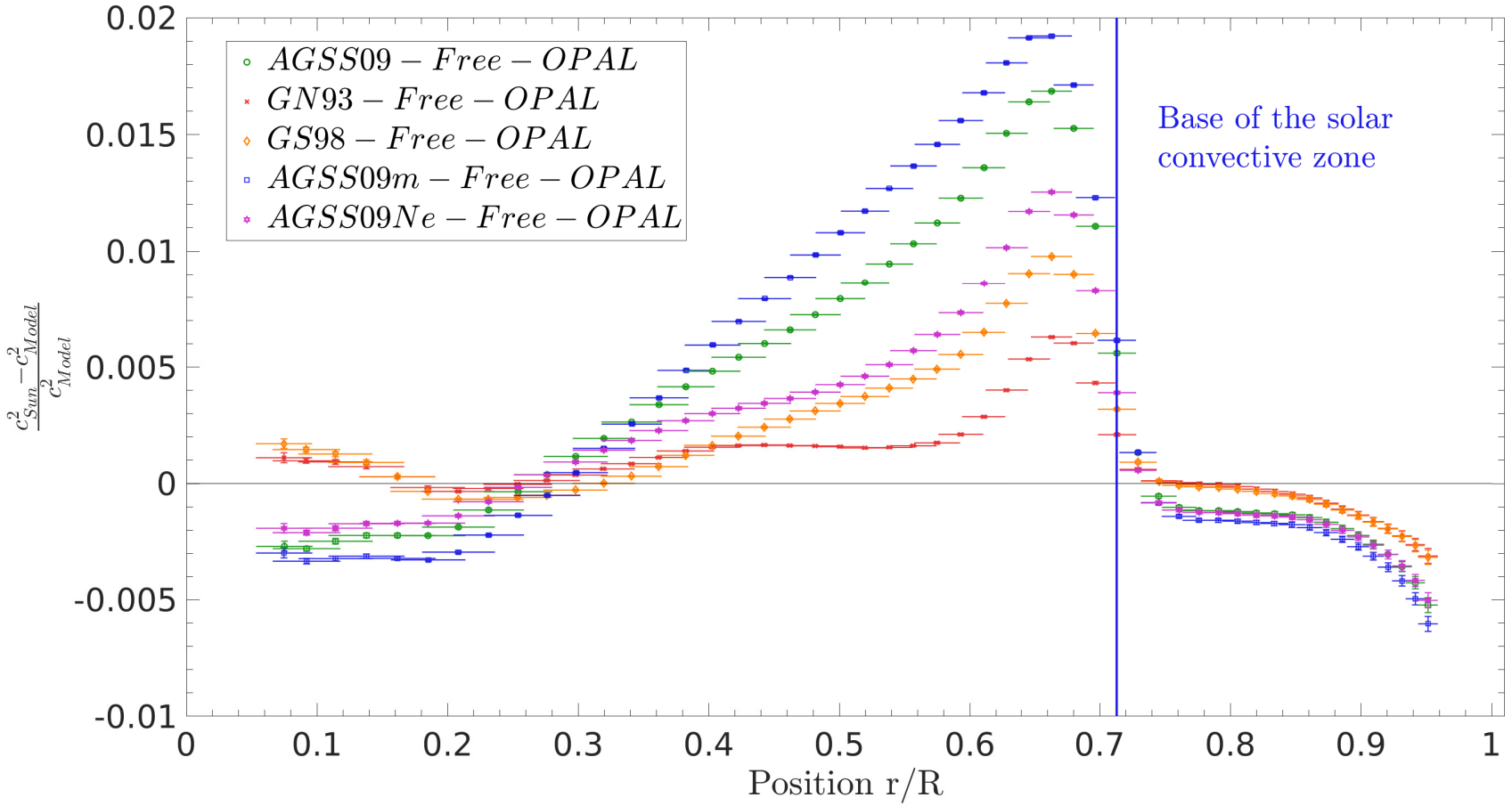
$Y_{CZ} = 0.2485 \pm 0.0035$ **(Basu et al. 1995), SSM High Z:** $Y_{CZ} \approx 0.245$, **SSM Low Z:** $Y_{CZ} \approx 0.235 \Rightarrow$ **Low Z is wrong!**



Helium is affected by:

- Abundances ($Z_\odot$ value);
- Opacities at high T;
- Nuclear reaction rates;
- Transport of chemicals;

The problem of Sound Speed



Sound speed is NOT a direct measurement of abundances.

What is a Standard Solar Model?

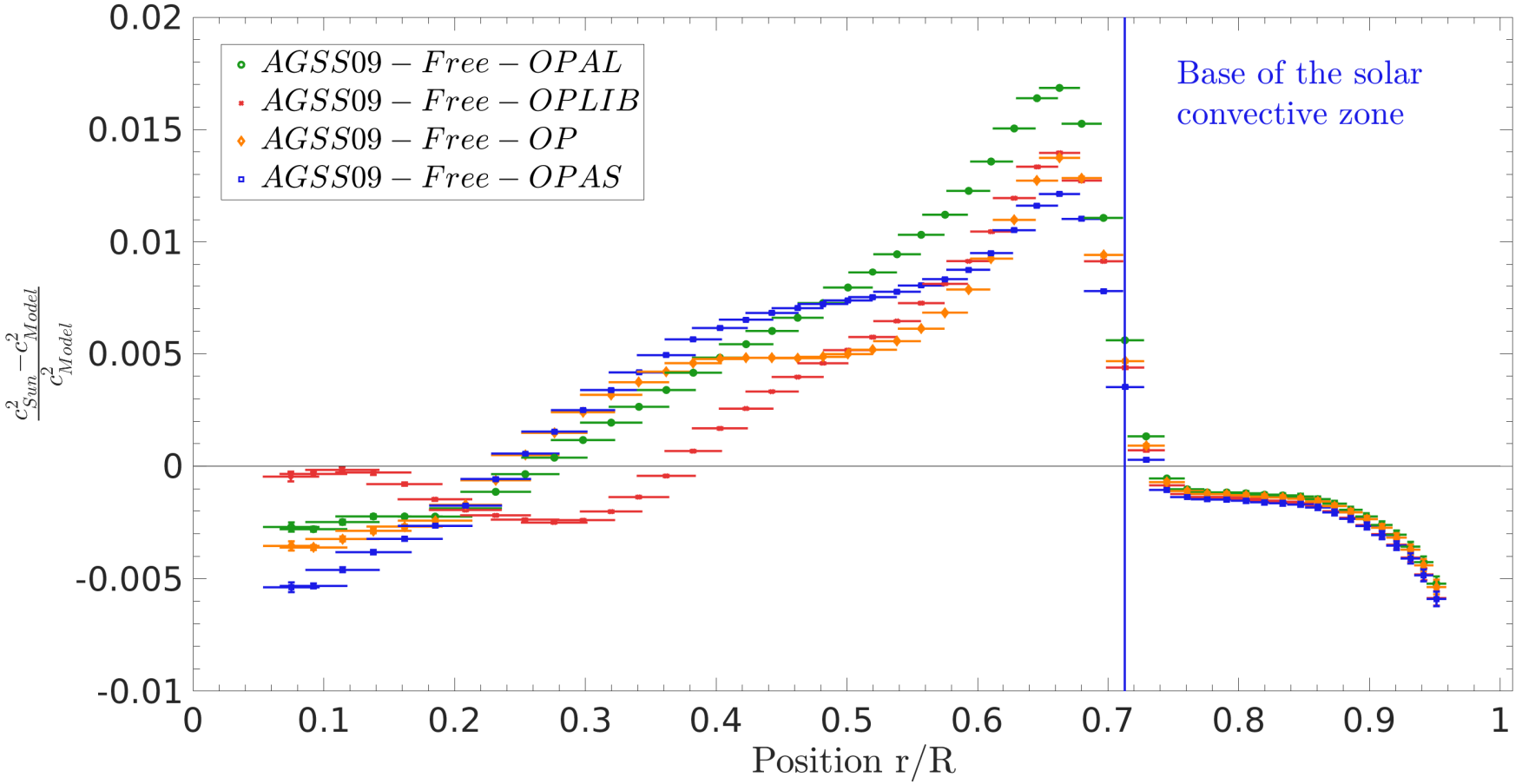
Definition of SSMs (Bahcall et al. 1982)

Recipe to compute solar models (Magg et al. 2022):

1. Standard opacities (OP, Badnell et al. 2005),
2. Standard EOS (FreeEOS, Irwin 2012),
3. Mixing length theory of convection (Böhm-Vitense 1958).
4. Effects of microscopic diffusion (Thoul et al. 1994).
5. Standard nuclear rates (Adelberger et al. 2011).

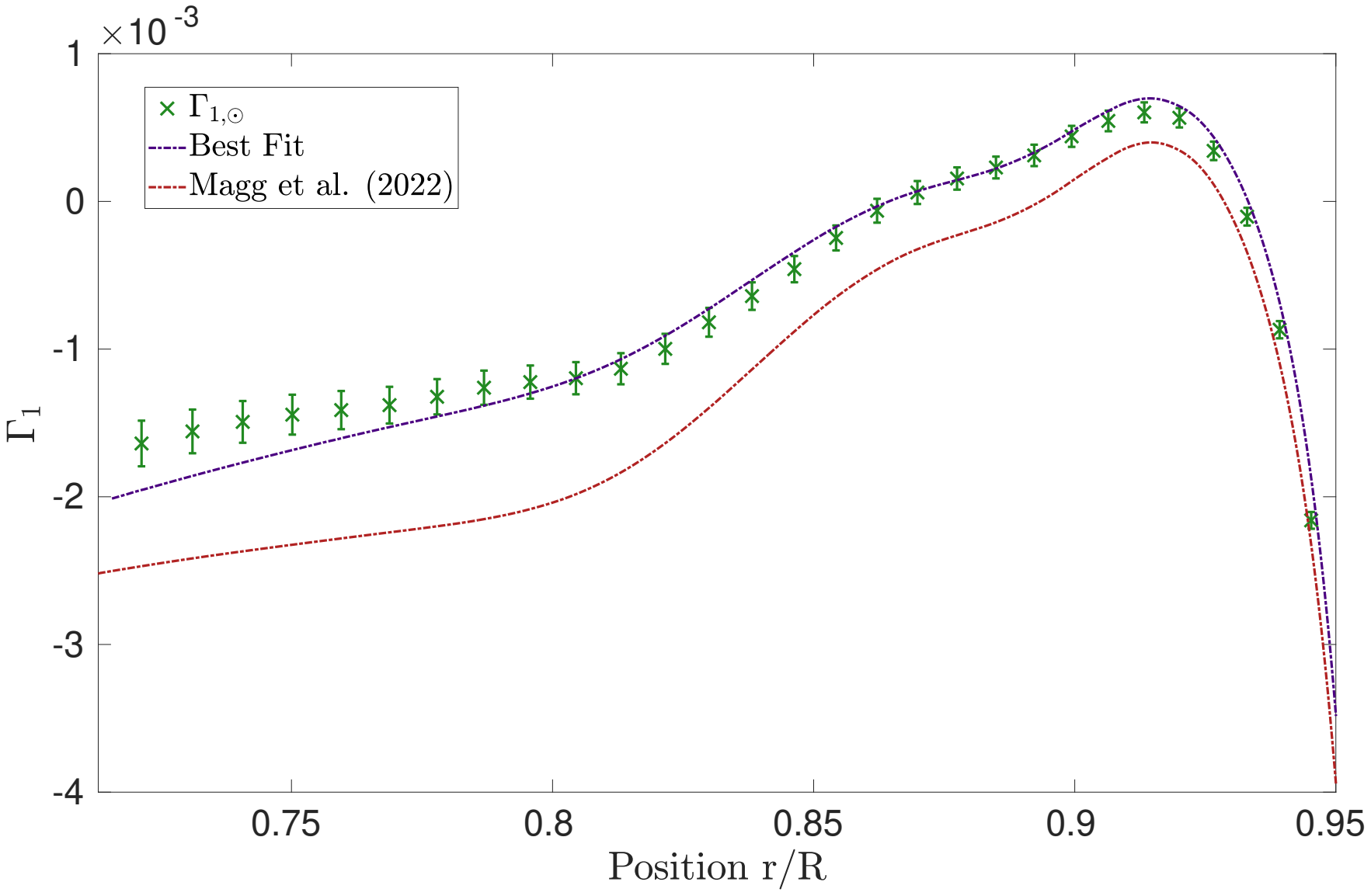
Other ingredients: OPLIB (Colgan et al. 2016), OPAS (Mondet et al. 2015), Saha-S (Baturin et al. 2013,2017,2019), ...
Simplified physics: Rotation, overshooting, radiative accelerations, convection ...

What does helioseismology actually say?

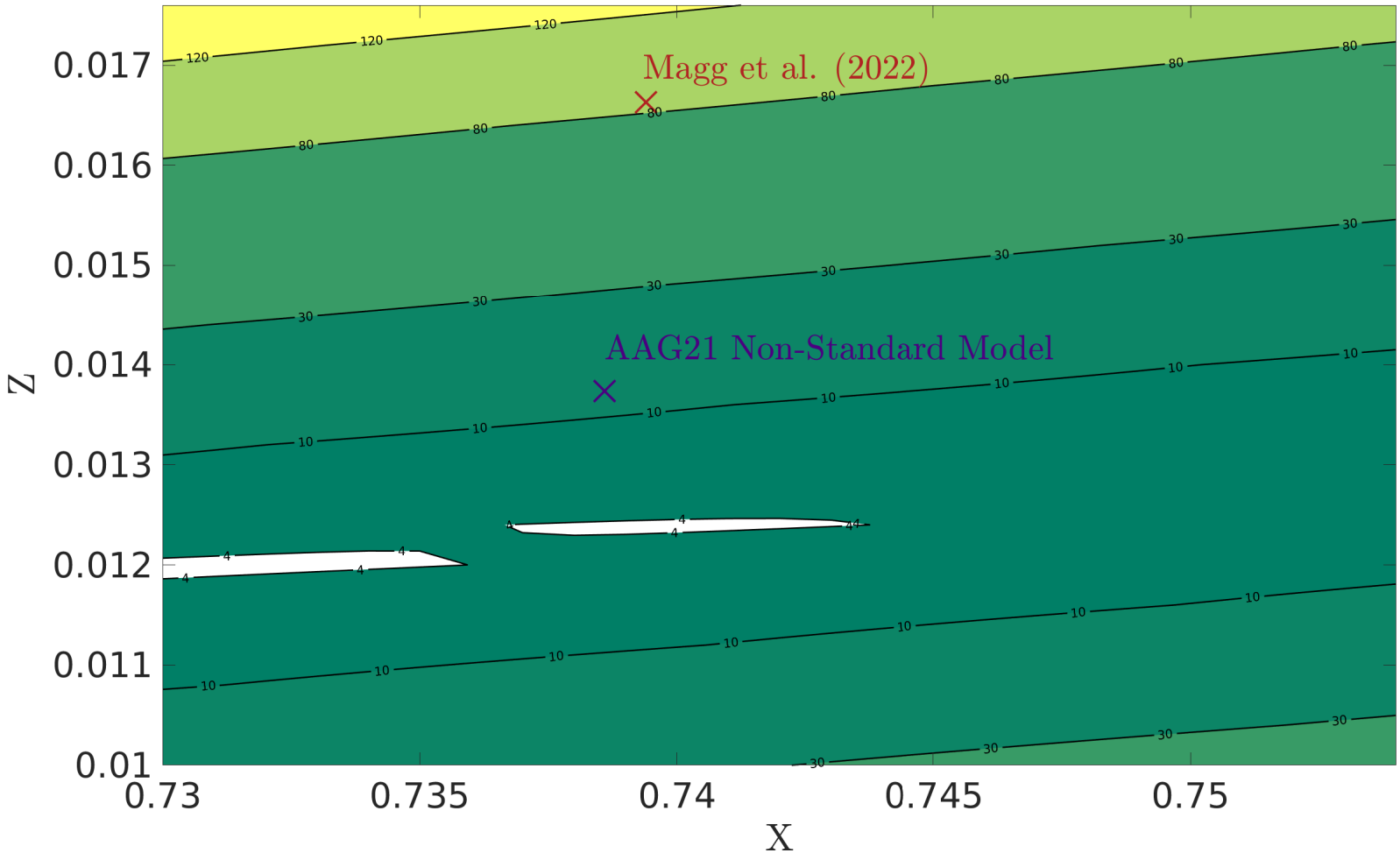


Opacity modifications have the same effect as abundance modifications. Sound speed provides degenerate information.

Helioseismology and abundances

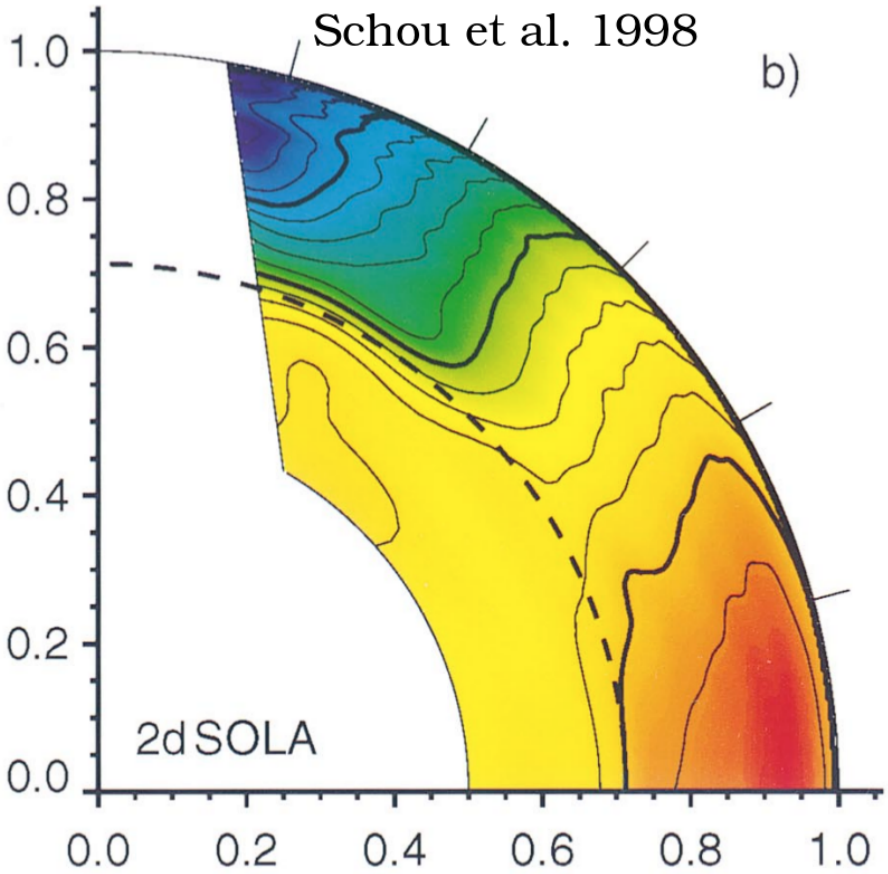


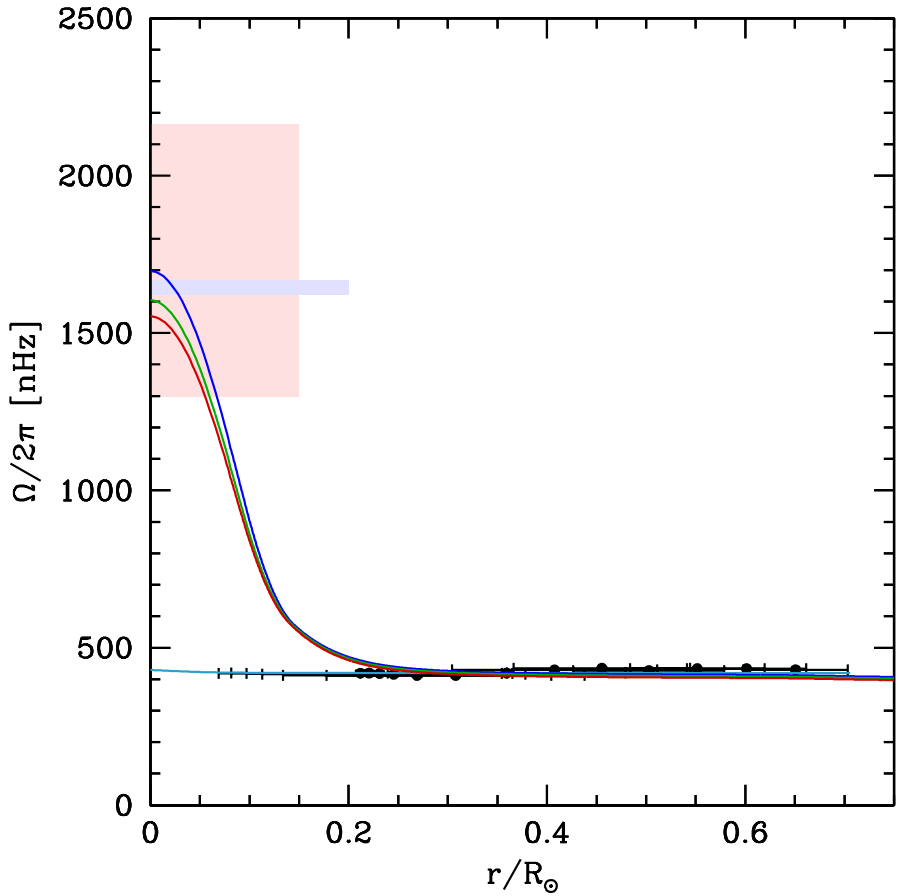
Helioseismology and abundances (Buldgen et al. (in prep)



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. (in prep).

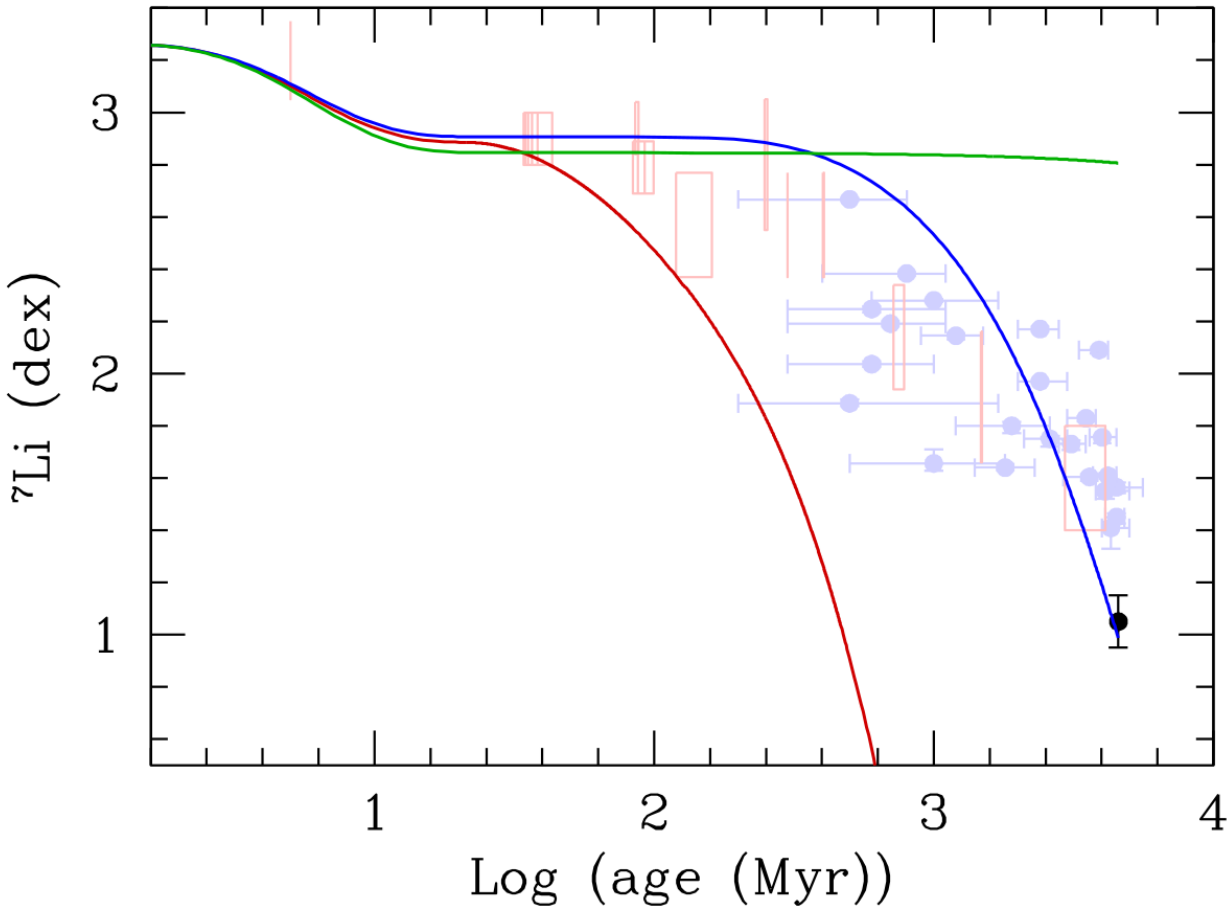
What does helioseismology actually say?





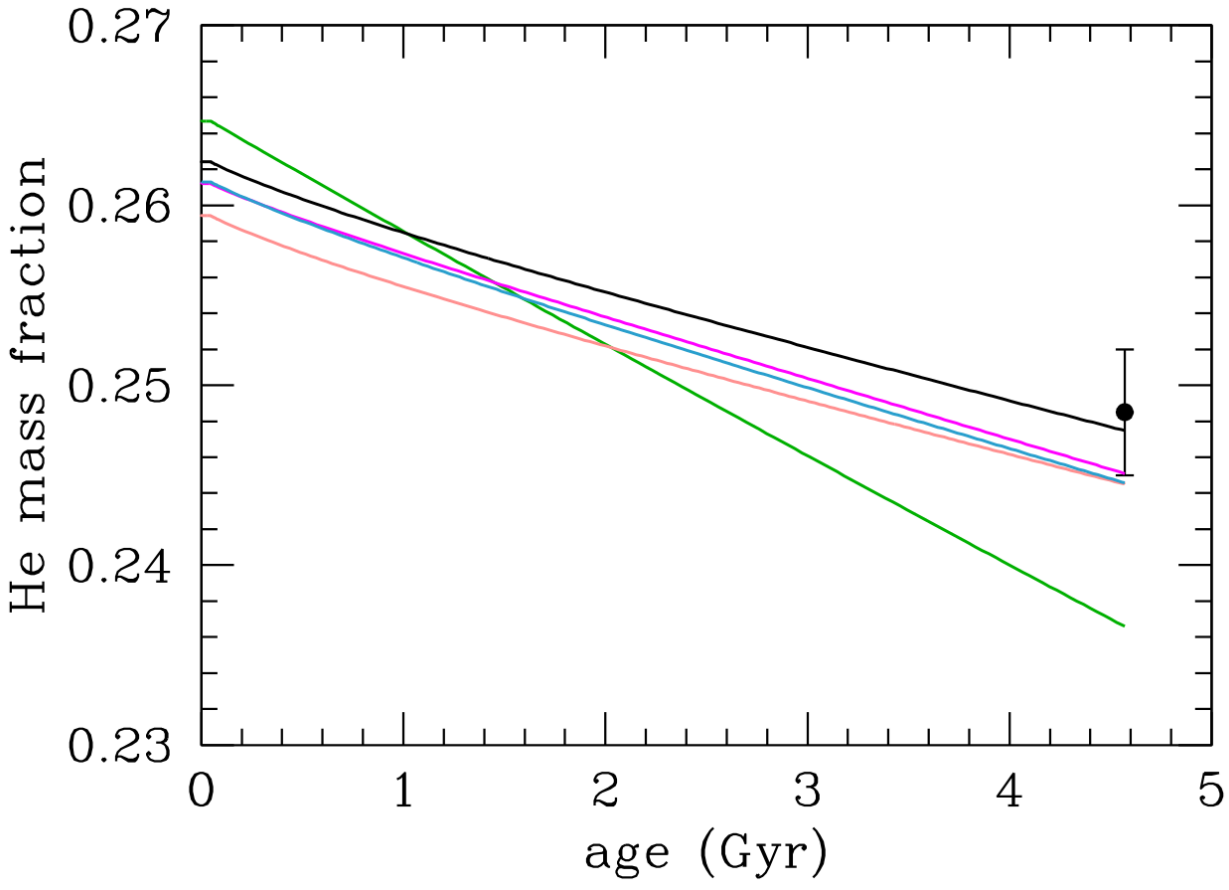
The internal rotation of Sun is known since 1988 (Kosovichev 1988), explained for a while (e.g. Eggenberger et al. 2005).

Depletion of light elements (Eggenberger et al. 2022)



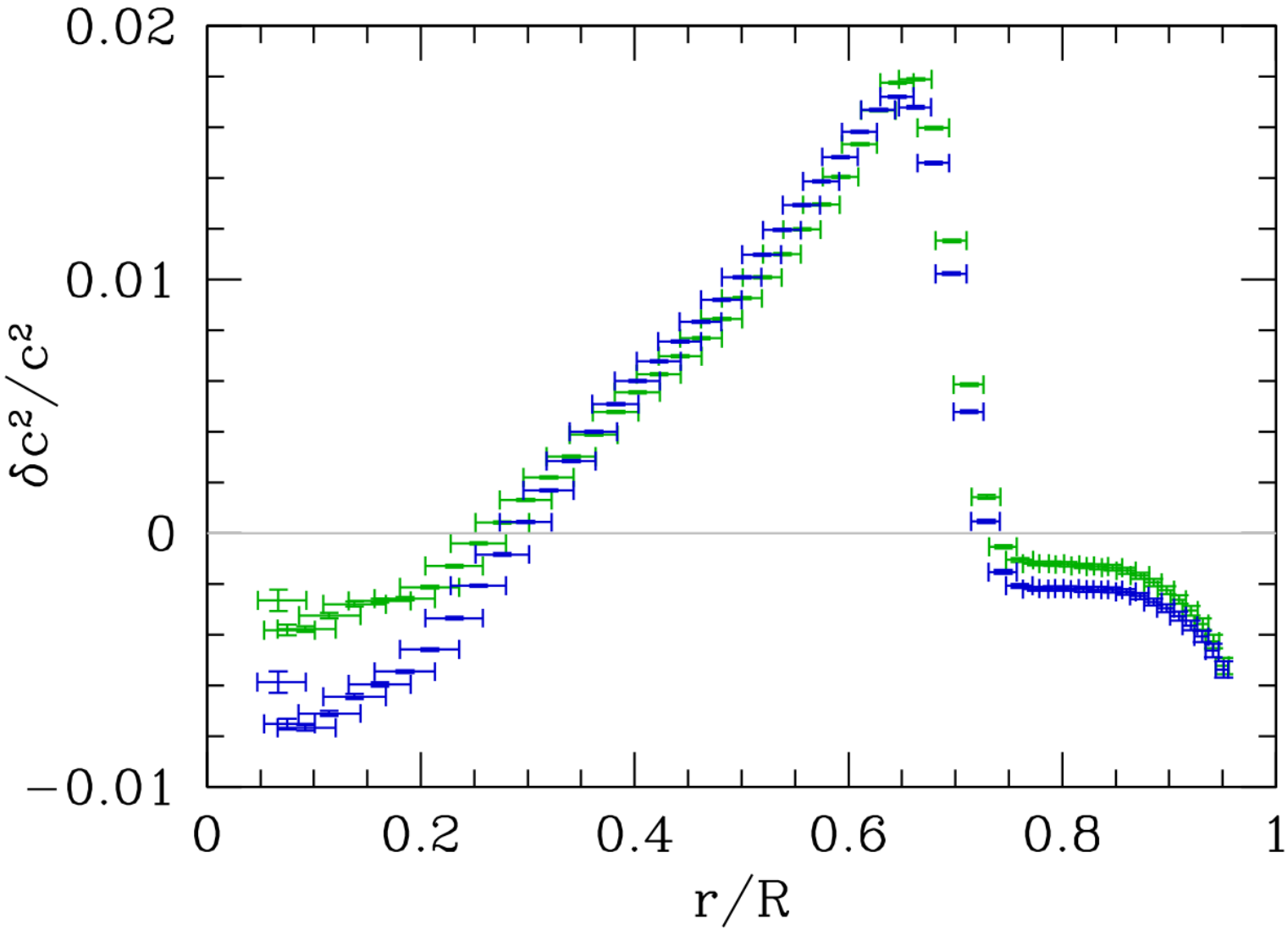
Lithium depletion is an issue since 1990s (Proffitt & Michaud 1991, Richard et al. 1996).

Non-standard models and helium



The helium-lithium correlation exists for multiple shapes of the transport coefficients!

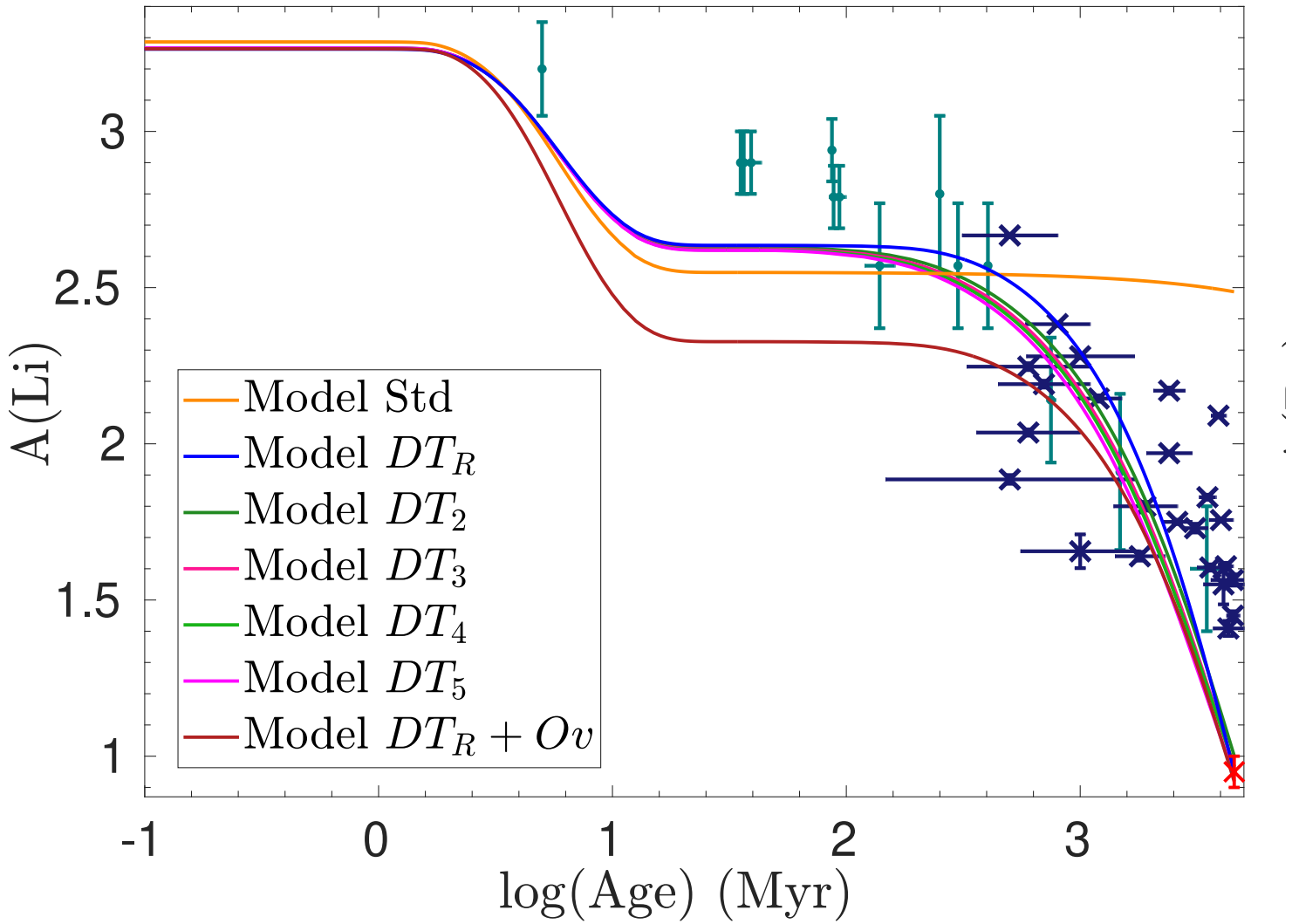
Non-standard models and the BCZ



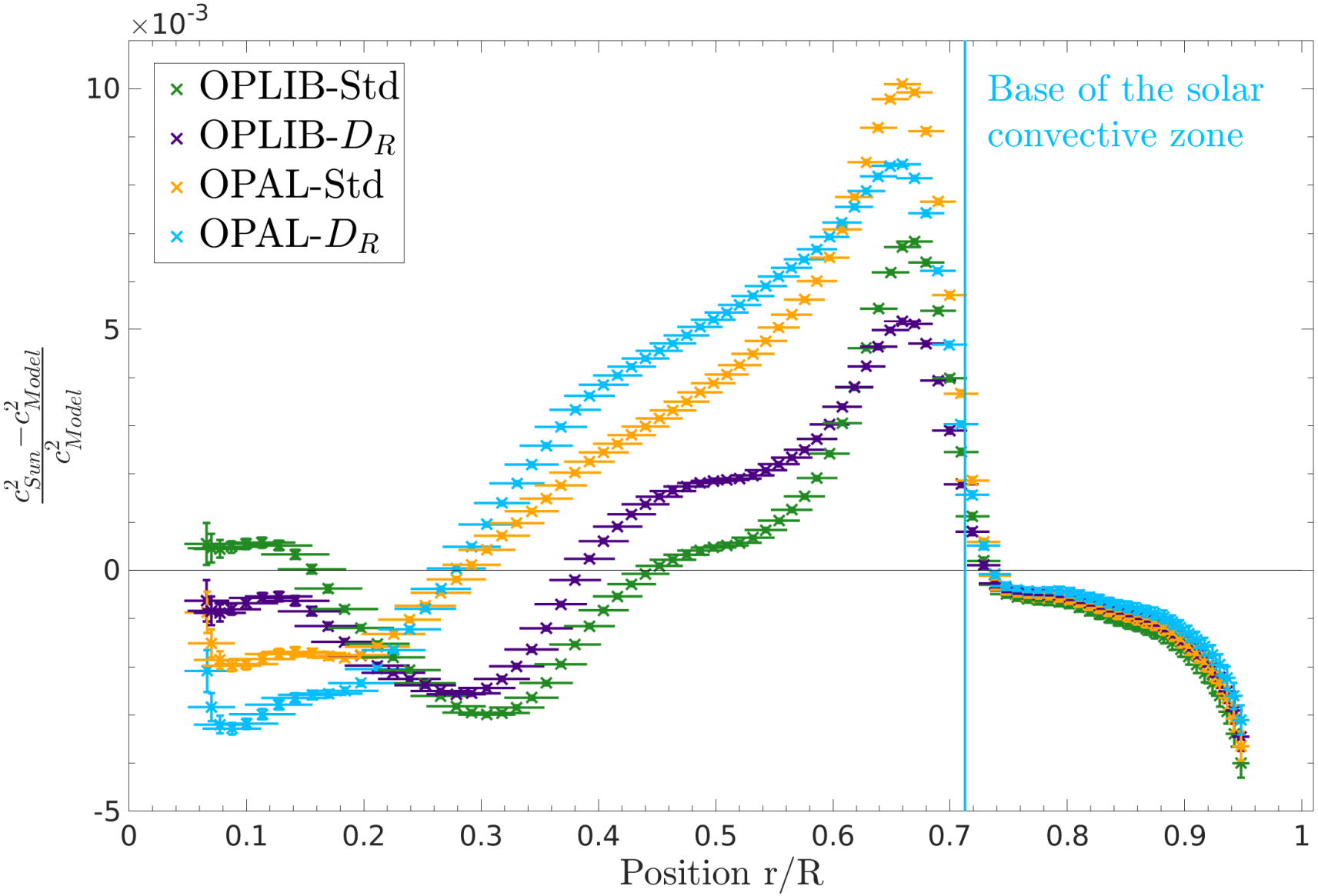
Sound speed at the BCZ not strongly affected by mixing.

Is the problem solved with higher abundances?

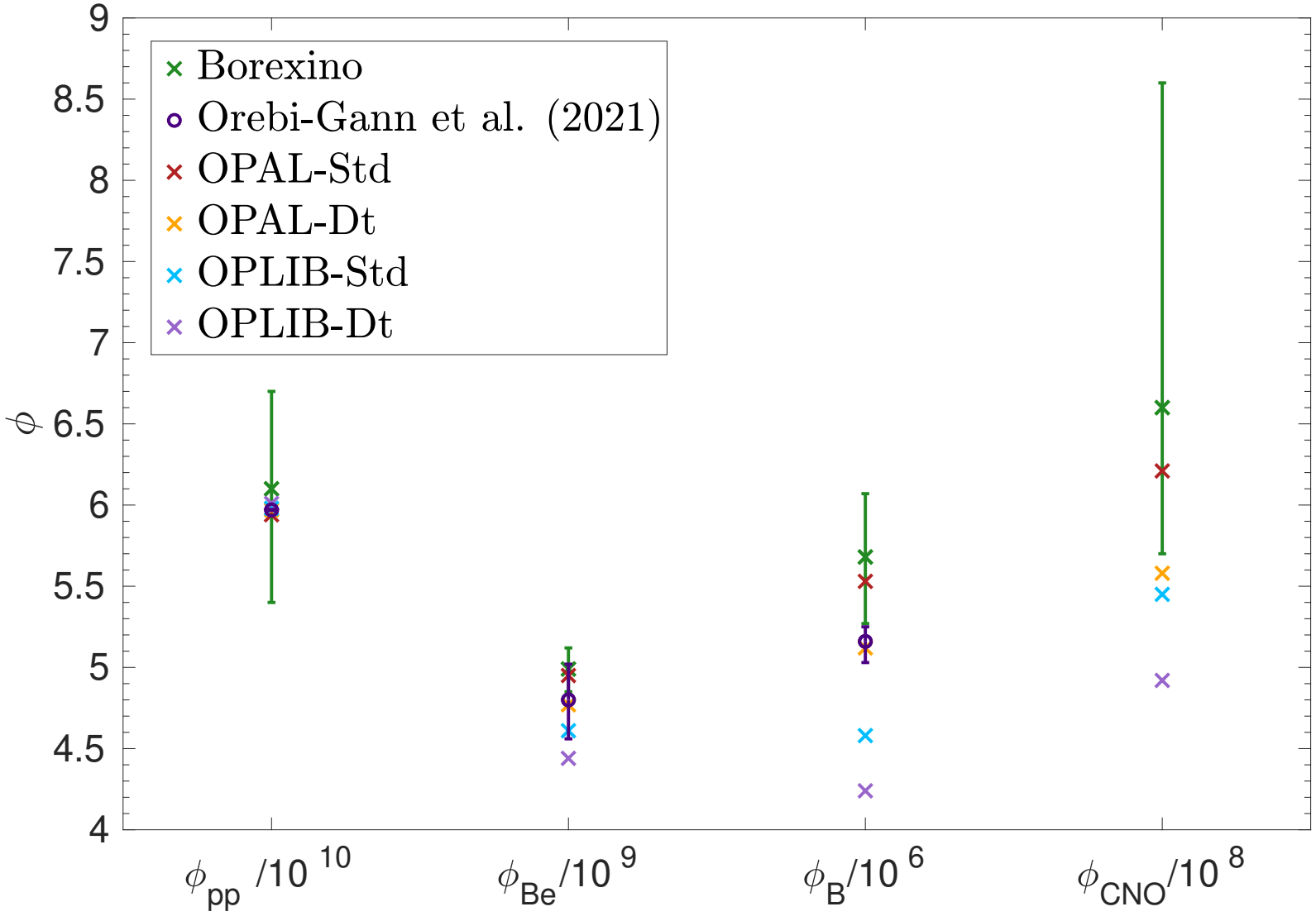
Magg et al. 2022 Models - Lithium (Buldgen et al. 2023)



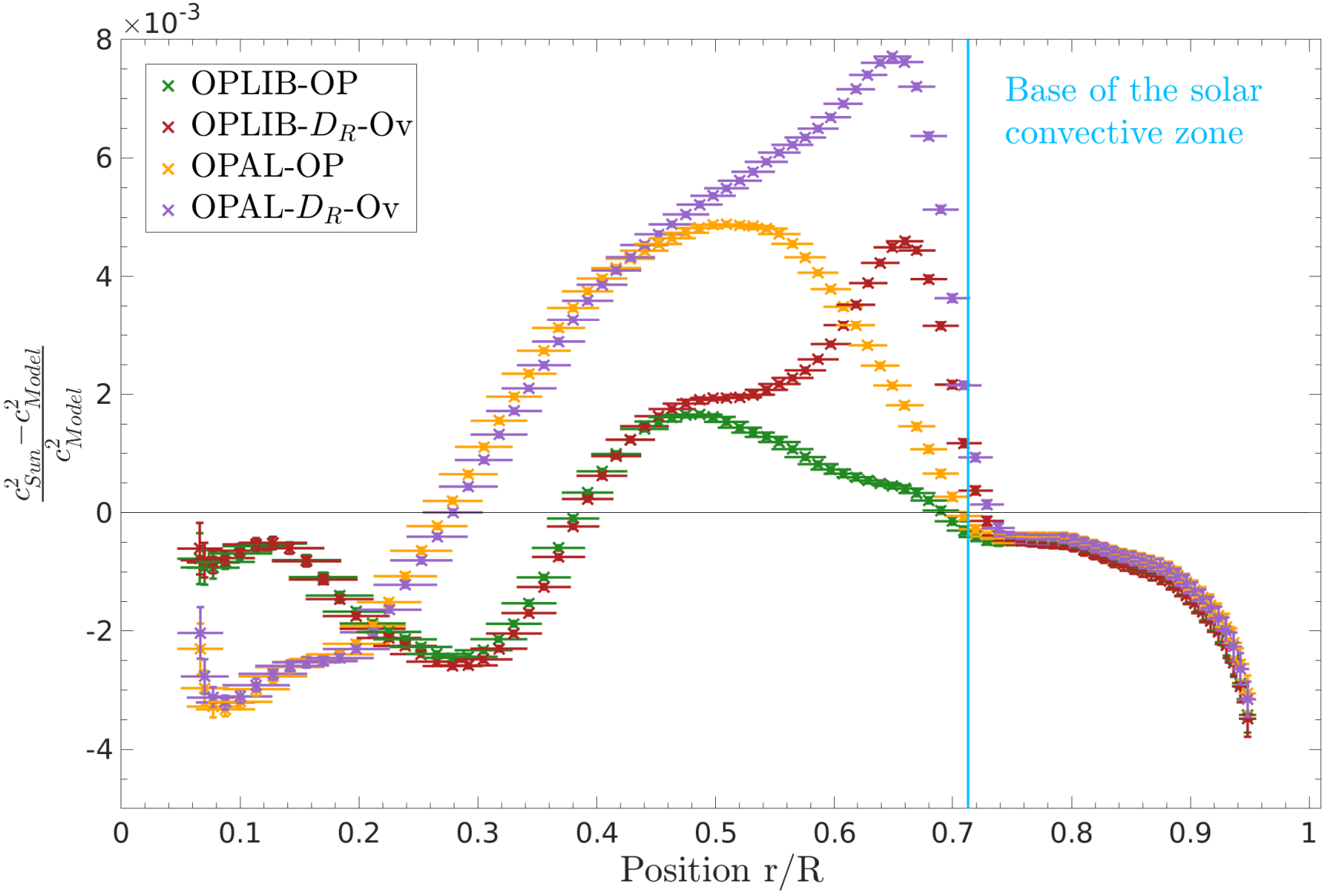
Magg et al. 2022 Models - Sound Speed (Buldgen et al. in prep)



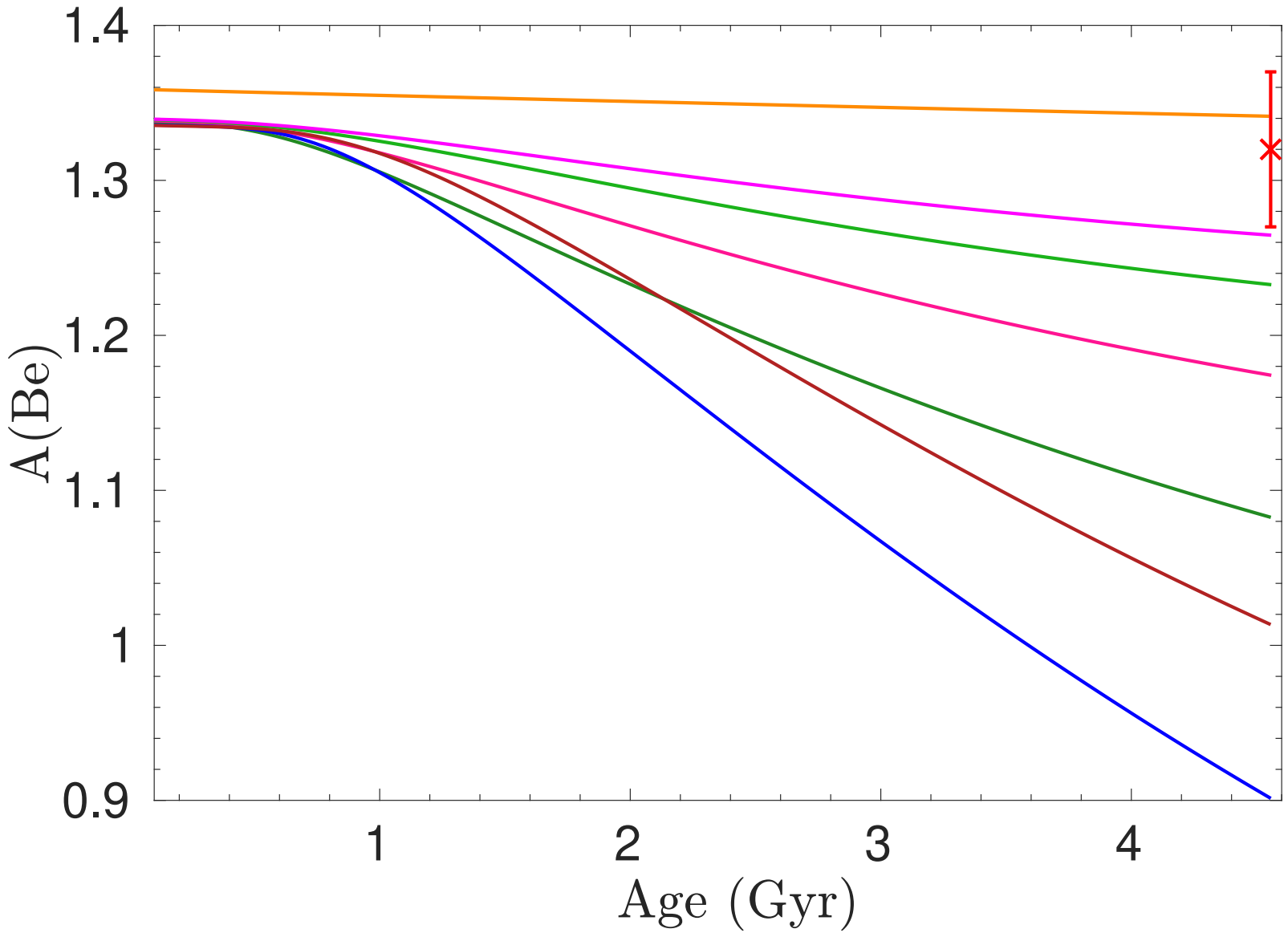
Magg et al. 2022 Models - Neutrino Fluxes



Magg et al. 2022 Models - Sound Speed

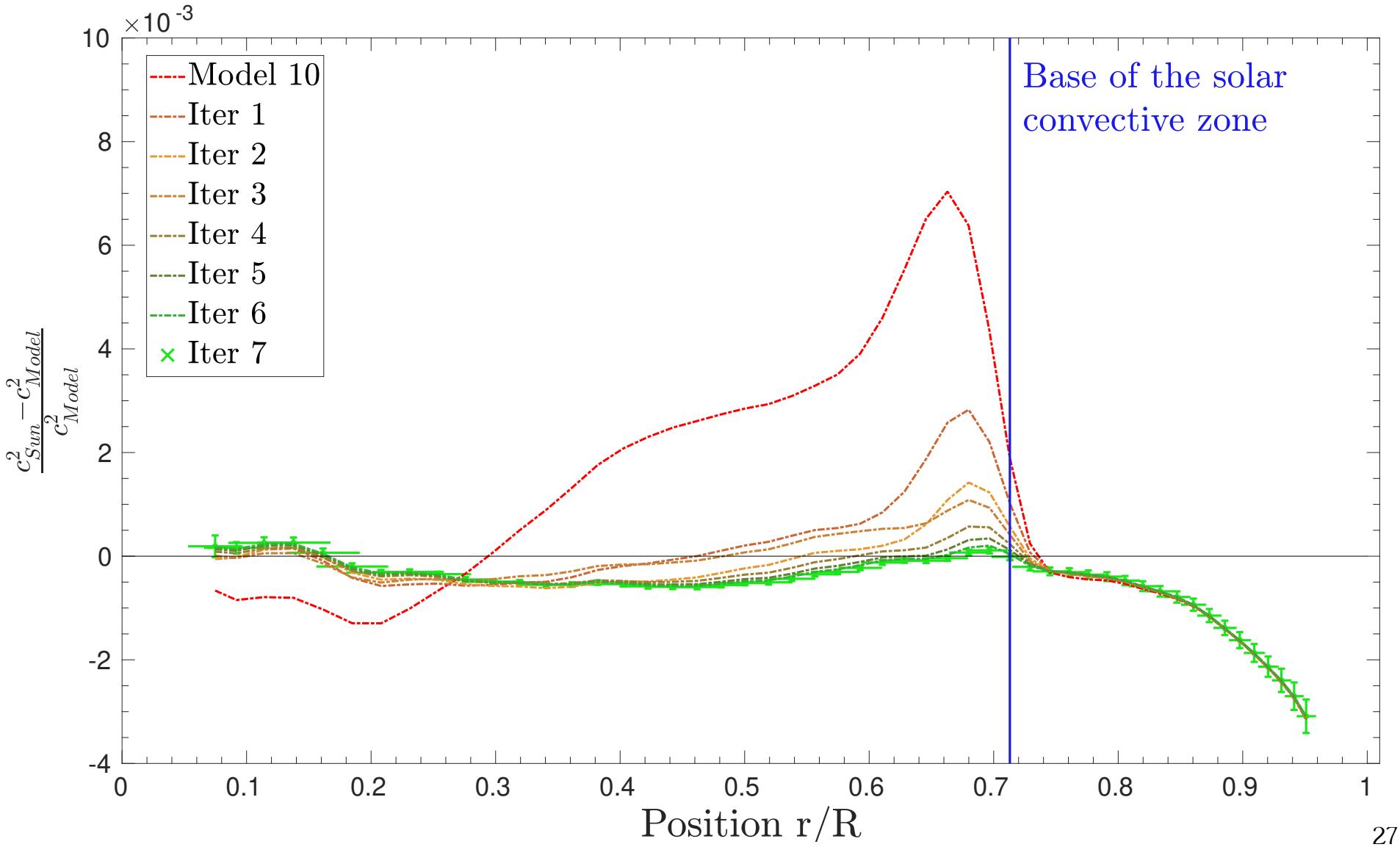


Magg et al. 2022 Models - Beryllium



Can you push models further?

Seismic models: providing a full structure (Buldgen et al. 2020)



Prospects

Wishes for coming years:

From modelling side:

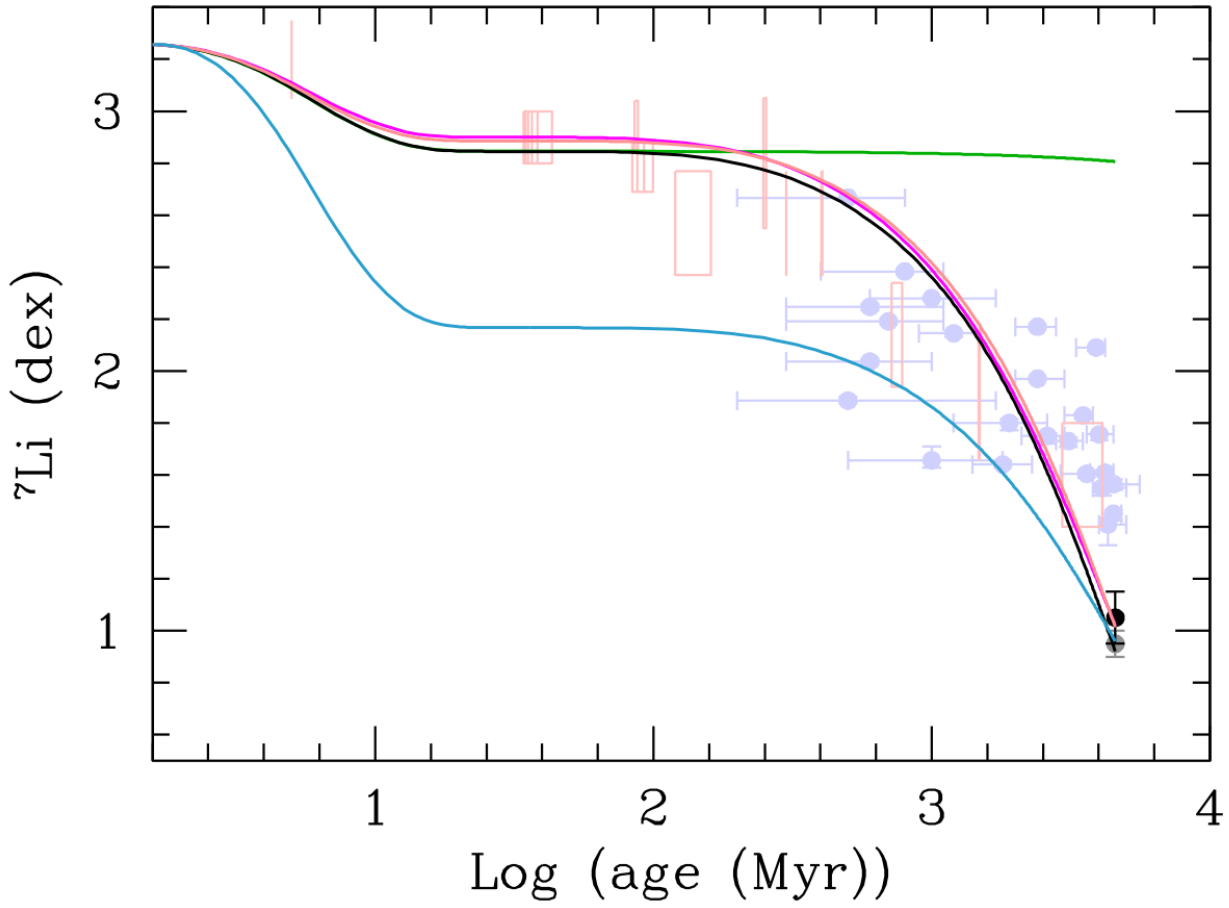
- Beryllium determination and transport calibration.
- Differentiation of overshooting and κ modification for entropy of the CZ.
- Determination of the metallicity in the envelope.
- Analysis of numerical robustness of solar models.

From physics side:

- New opacities (SCO-RCG tables, OP), comparisons on more TD paths.
- New EOS (MHD2020).

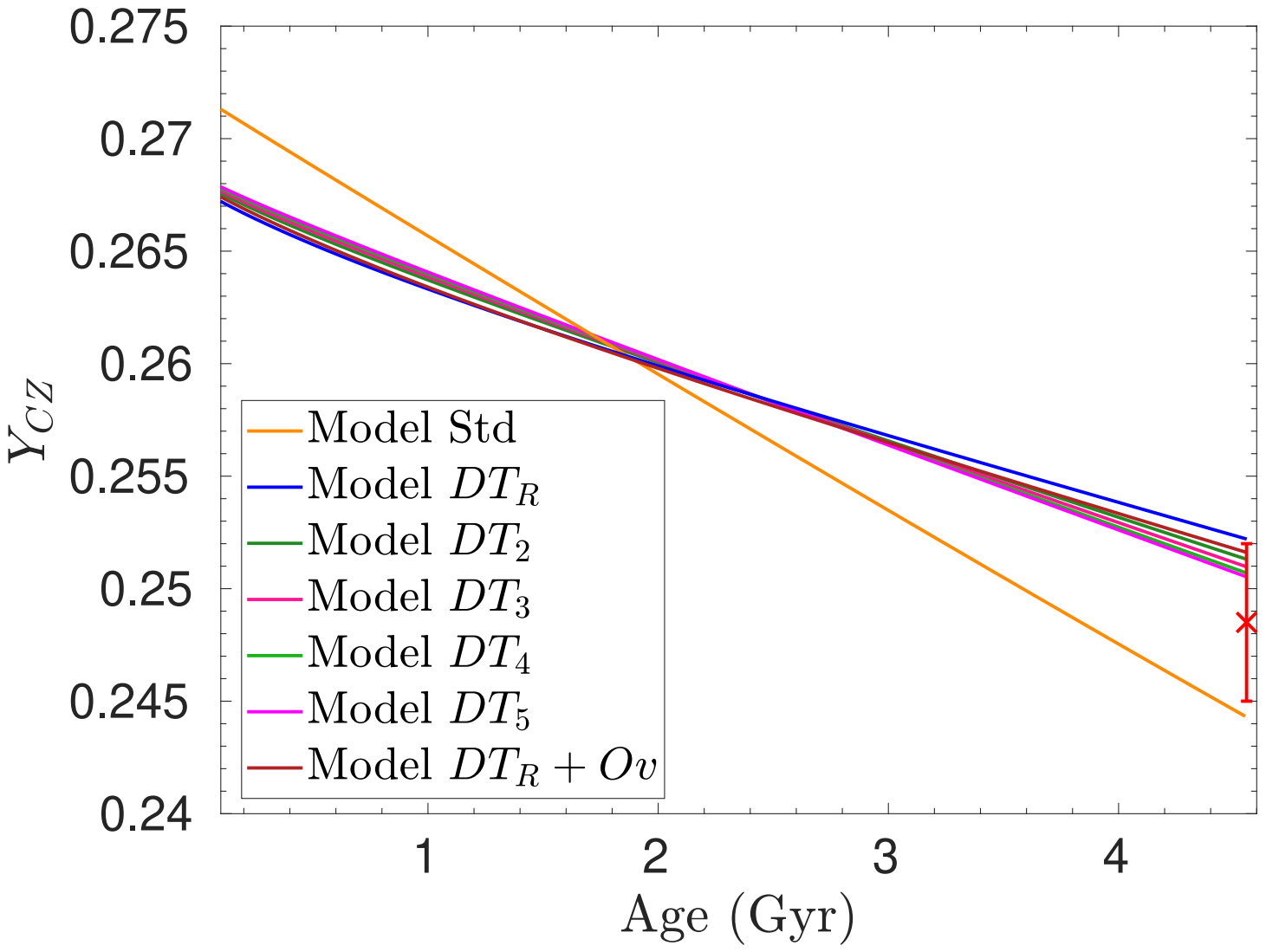
Thank you for your attention!

Non-standard models and overshooting

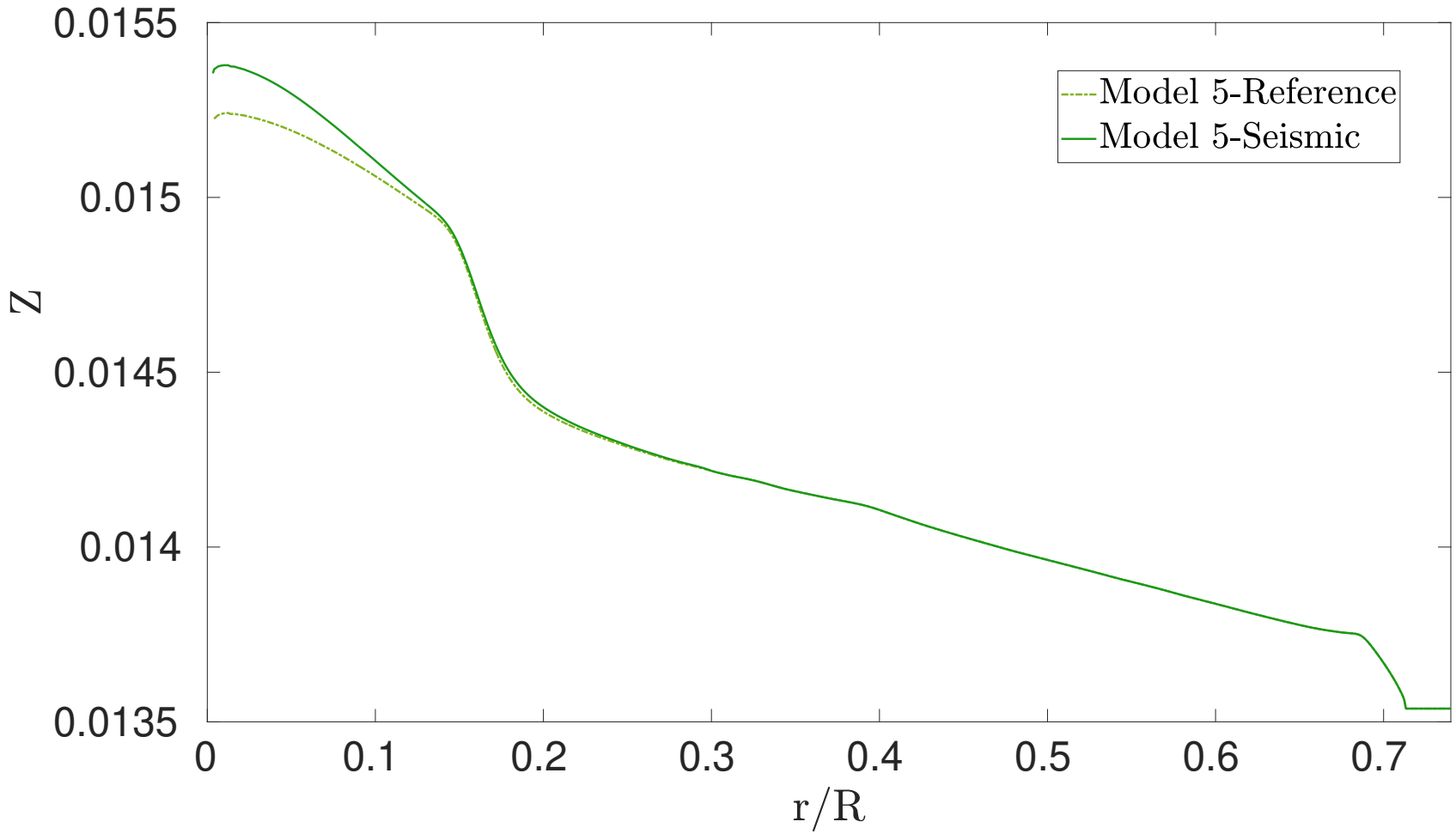


You also get constraints on overshooting at the BCZ!

Magg et al. 2022 Models - Helium

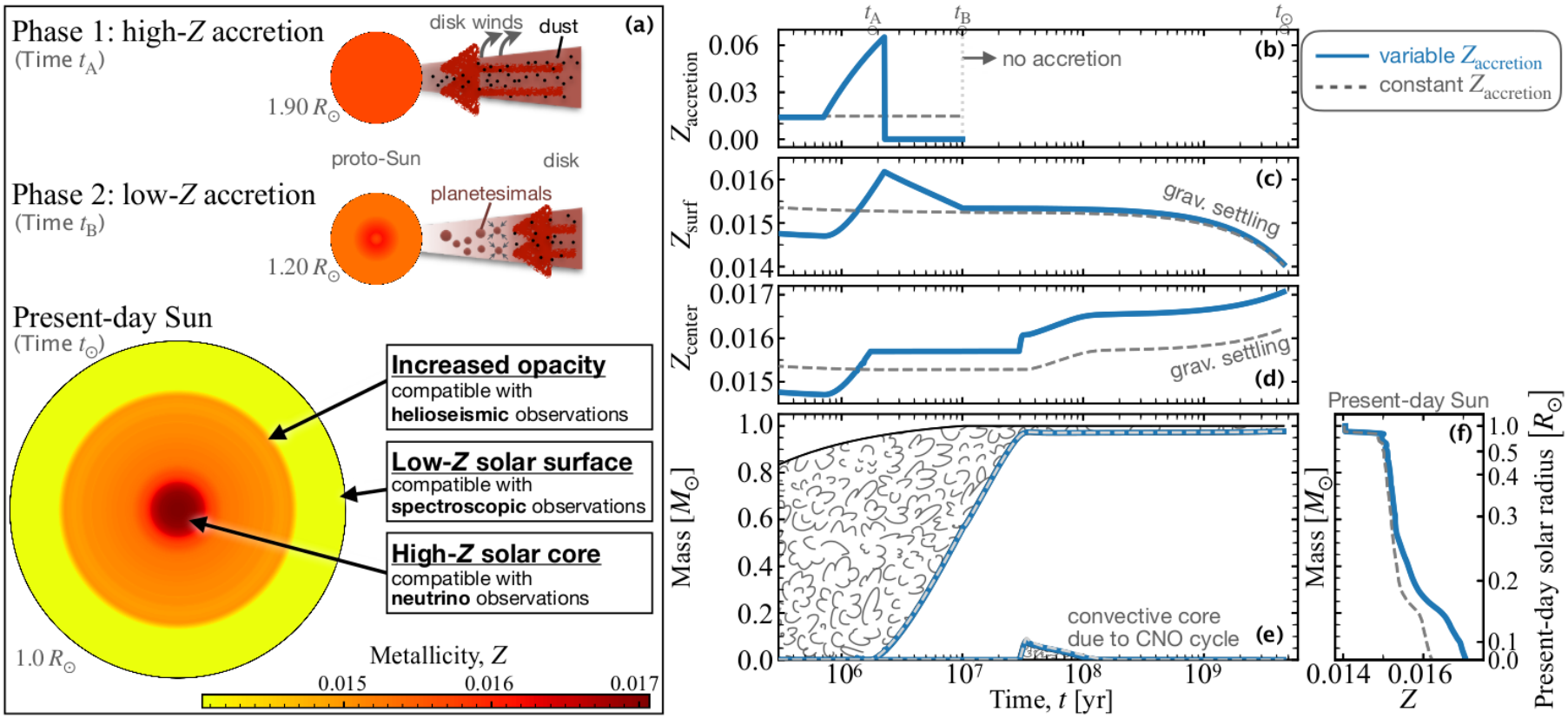


Seismic models: providing a full structure



Solution: from P and ρ for a given X and Z, determine from the EOS $T(\rho, P, X, Z)$. Then compute $\varepsilon(T, \rho, X, Z)$ so that $L = L_{\odot}$.

Non-standard models and planetary formation



Solar core influenced by planetary formation mechanisms!