Opacity profiles from helioseismic inversion techniques and the solar modelling problem

Gaël Buldgen

University of Geneva

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UNIVERSITÉ DE GENÈVE

FNSNF

The role of the Sun:

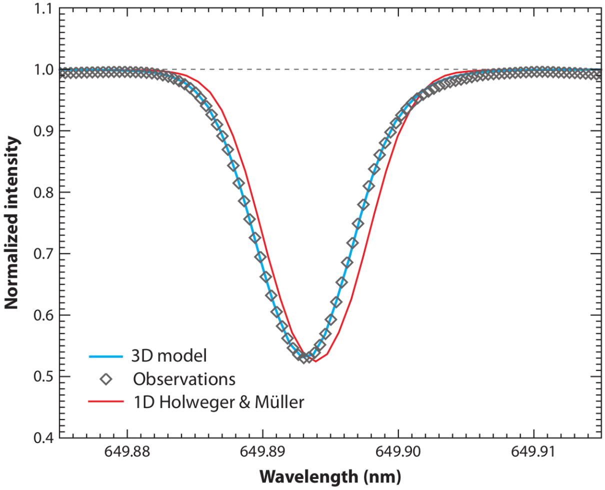
Well-studied, helioseismic constraints, neutrino fluxes, testbed for physical ingredients. The Sun is used as a **reference**:

- 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?

Advent of 3D Models and abundance revisions



Asplund et al. (2009)

Revision of the abundances:

- Hydrodynamical model,
- Non-LTE corrections,
- improved atomic data,
- Careful selection of lines,
- Use of all indicators.

⇒ 30% **reduction of $Z_\odot$!**

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:

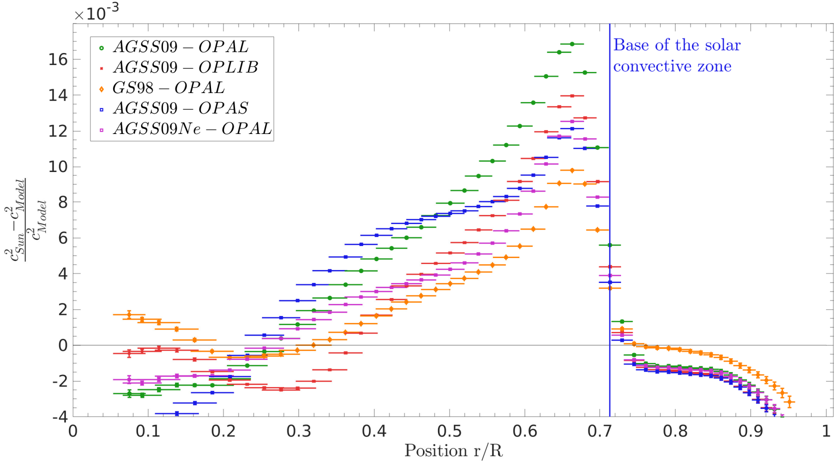
1. Wrong position of the BCZ,
2. Wrong Helium abundance in the CZ,
3. Sound Speed profile relative differences of up to 0.02.

Application of the variational principle of adiabatic stellar pulsations (Chandrasekhar 1964, Lynden-Bell & Ostriker 1967) led to linear integral relations between frequency and structure (Dziembowski et al. 1990):

$$\frac{\delta \nu^{n,l}}{\nu^{n,l}} = \int_0^R K^{n,l}_{\rho,c^2} \frac{\delta \rho}{\rho} dr + \int_0^R K^{n,l}_{c^2,\rho} \frac{\delta c^2}{c^2} dr + \mathscr{F}(\nu) \tag{1}$$

allowing for non-asymptotic structural inversions (e.g. Antia & Basu 1994, Marchenkov et al. 2000) with dedicated numerical techniques (RLS or Tikhonov method, MOLA method from Backus & Gilbert 1967 or SOLA method Pijpers & Thompson 1994).

Sound Speed profile of Standard Solar Models



With the new abundances, the solar models fail.

Where do we stand?

Current situation:

Still a problem: Opacity? Maybe. (e.g. Pradhan 2017, Zhao 2017, Pain 2019).
What about the BCZ? Extensively studied (see e.g. Hughes 2007 (+refs therein), JCD 2011, JCD 2018)
Is that it? No: Microscopic diffusion, EOS improvements, convection, instabilities, early history (see also Zhang et al. 2019)...

What is clear? **Stop using GN93 and GS98.** (listen to Nicolas Grevesse)

What do we do?

Changing the variables in the integral relations

Inversions are not limited to ρ, c^2, Γ_1. One can generalize:

$$\int_0^R K^{n,l}_{s_1,s_2}\frac{\delta s_1}{s_1}dr+\int_0^R K^{n,l}_{s_2,s_1}\frac{\delta s_2}{s_2}dr=\int_0^R K^{n,l}_{s_3,s_4}\frac{\delta s_3}{s_3}dr+\int_0^R K^{n,l}_{s_4,s_3}\frac{\delta s_4}{s_4}dr$$

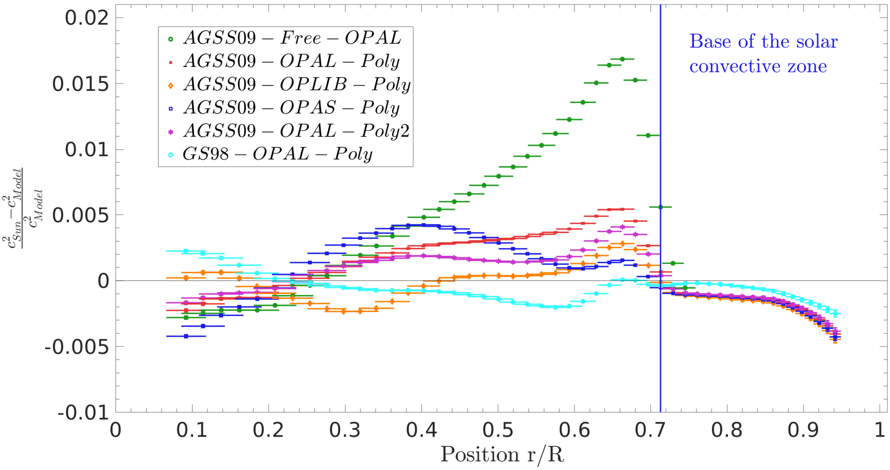
In practice, very general variables can be derived following two

approaches: conjugated functions (see e.g. Elliott 1996 or Kosovichev 1999 for a full description) or "direct method" (Buldgen et al. 2017a, following Masters et al. 1979).

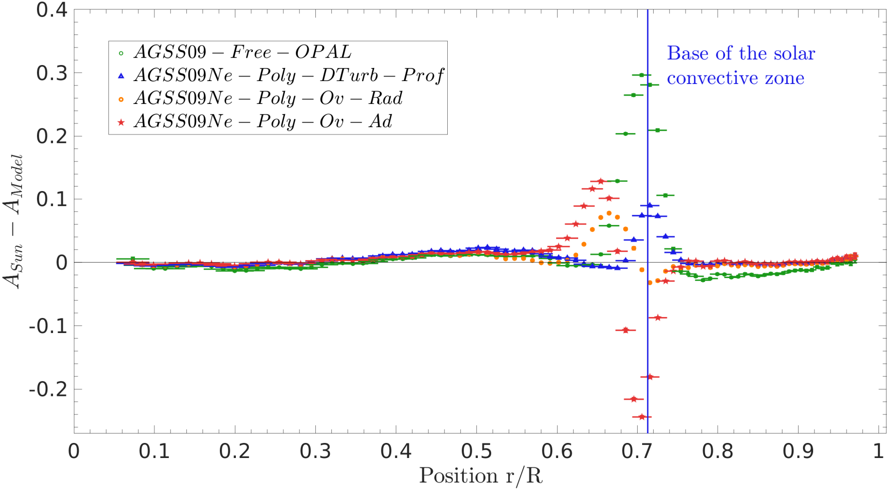
If E.O.S is assumed "secondary" variables (T,X,...) can be inverted (e.g. Gough & Kosovichev 1988).

Tweaking the models: Buldgen et al. 2019

Limitations of evolutionary models: many buttons to press.

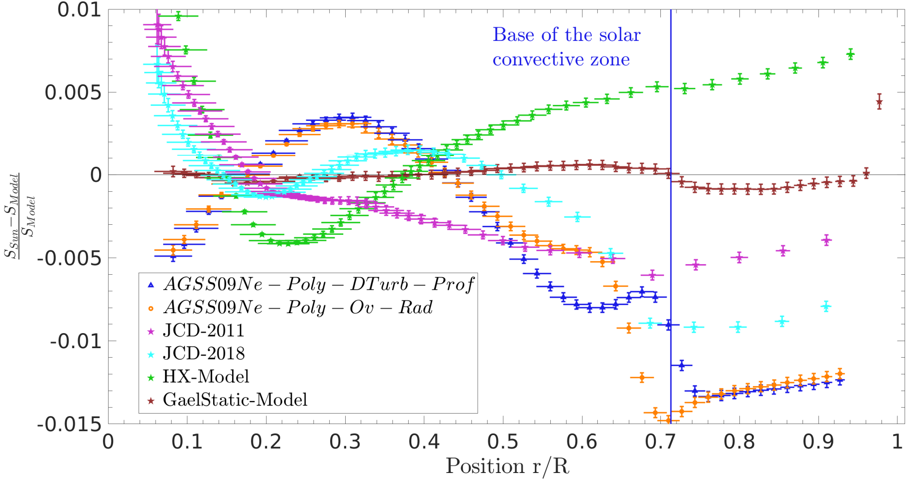


Limitations of evolutionary models: (too) many buttons to press.



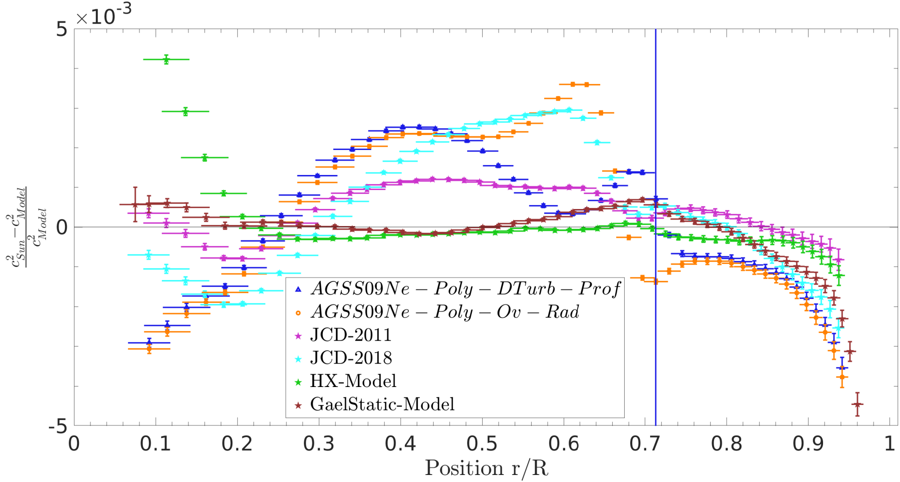
Inversions of entropy proxy

Different inversions allow to enhance some disagreements.

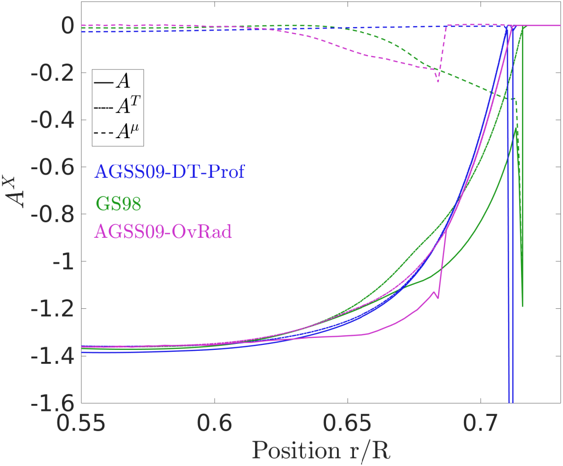


Back to sound speed: what can we learn by combining them?

No "combination" of ingredients seem to be working very well.



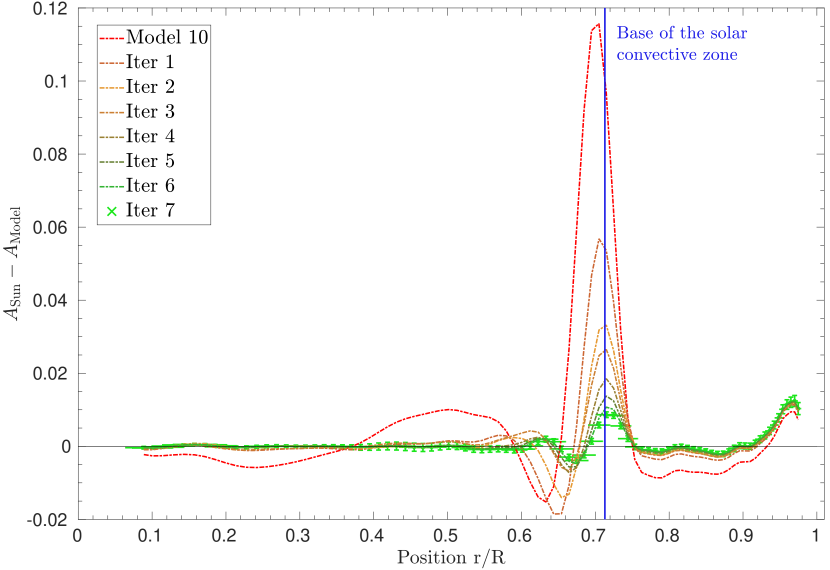
Determining seismic models from A inversions (Buldgen et al. 2020)



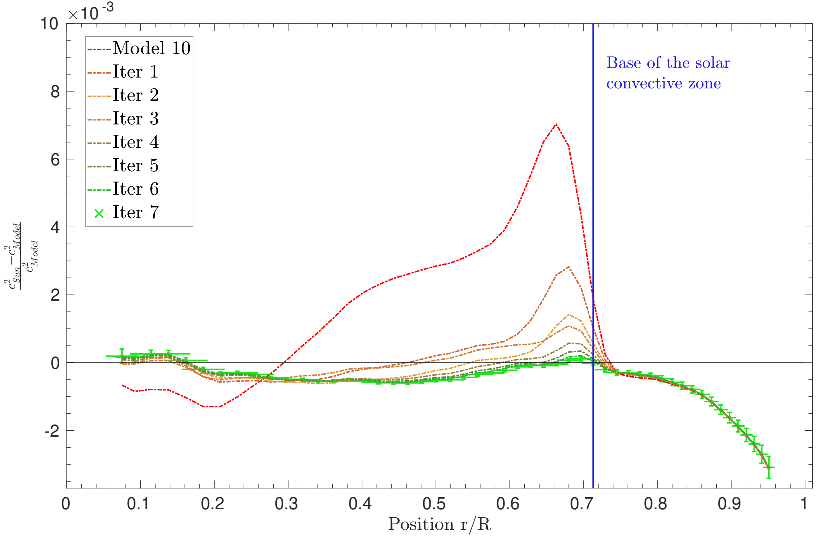
A is a direct trace of ∇T:

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

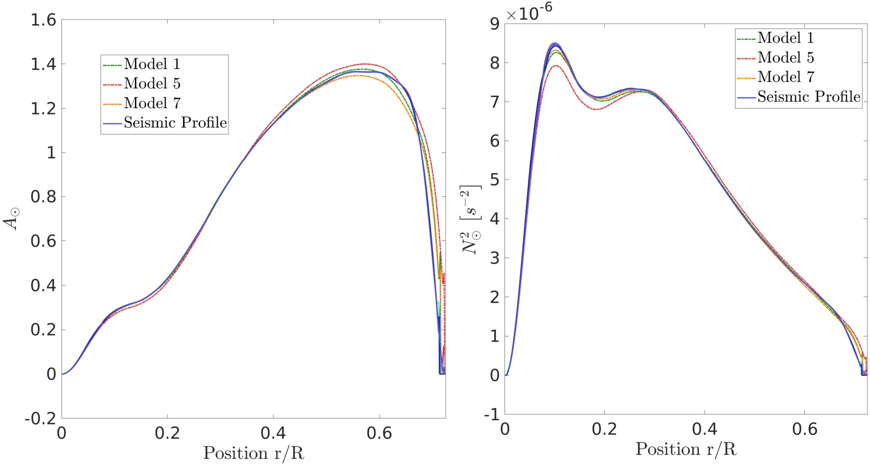
Level of agreement for seismic models



Level of agreement for seismic models



Level of agreement for seismic models



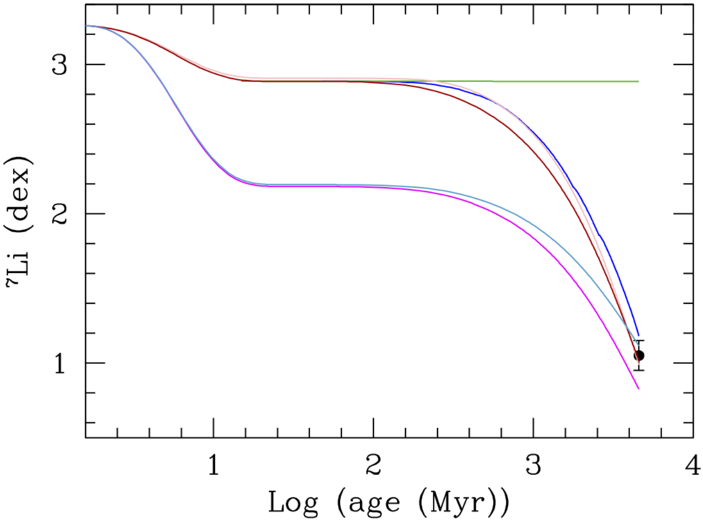
Same A and B-V profile ⇒ some control on P_0, values found around 2150s.

A few key issues:

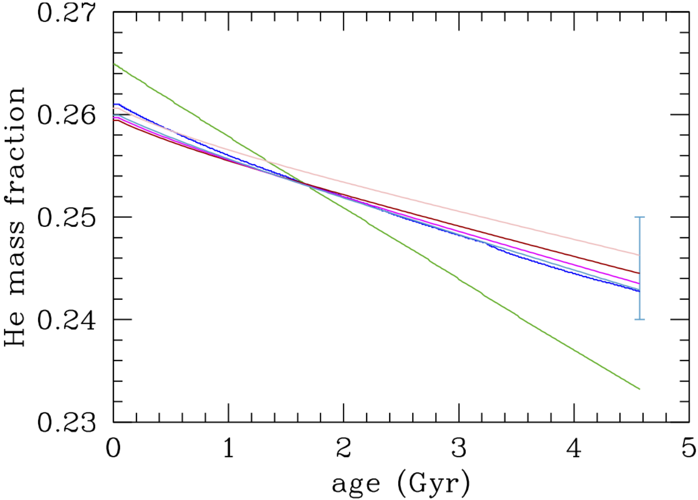
Envelope c^2: Not corrected by the procedure ⇒ patch an envelope model?
Degeneracy in chemical composition: we only have ρ, Γ_1.⇒ but wide choices of EOS, etc etc in CLES.
Deep core? Difficult to constrain, mostly influenced by reintegration. ⇒ Check after patching the envelope model.

Chemical evolution (Eggenberger et al. submitted)

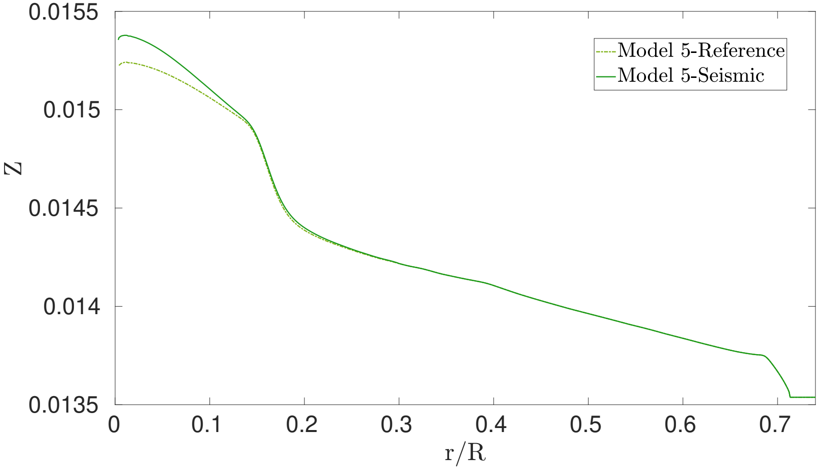
Standard models lack: rotation, lithium, helium (if AGSS09).



Formalism allowing to reproduce all three. Issue: is it really T-S acting? ⇒ Need g-modes for that...



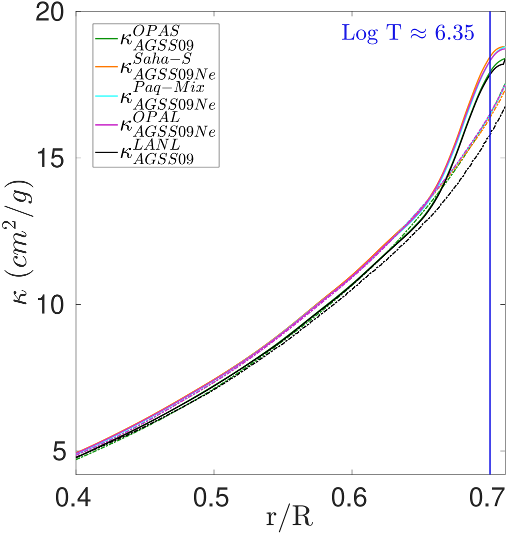
Seismic models: providing a full structure



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 $L = L_{\odot}$.

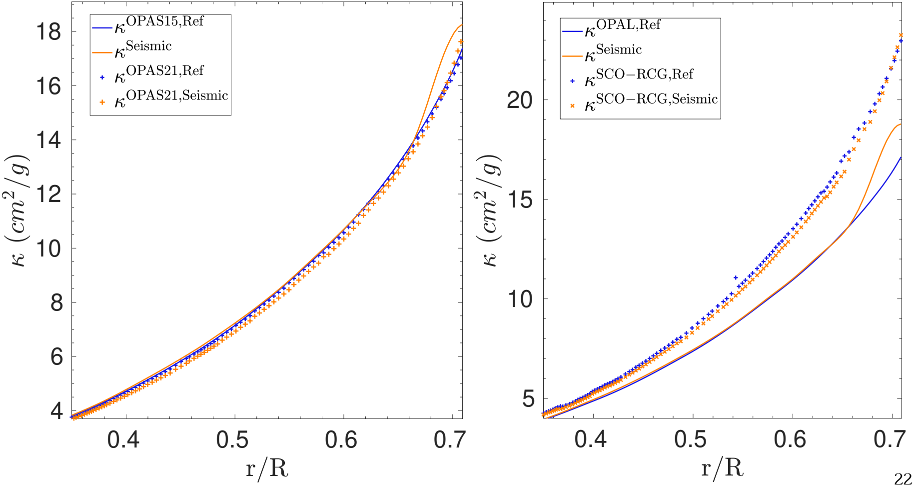
Opacity "Inversions" (Buldgen et al. in prep)

From the analysis of static models and non-standard models:

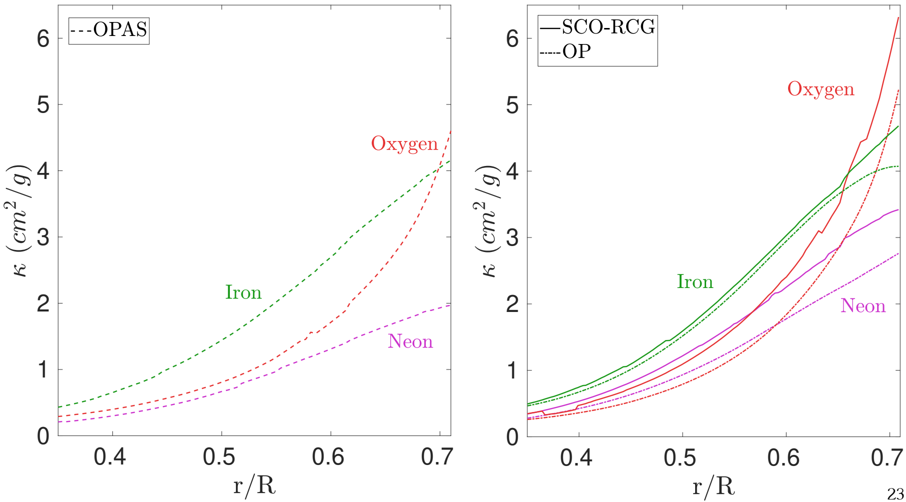


- Formalism to reproduce Lithium-Y_{CZ}-Rotation profile.
- Integrate and iterate to reproduce $L_{\odot}$.
- Determination of amount of "missing" opacity. (Robust for the upper radiative layers, for a given chemical composition profile)

Codes give conflicting results for similar conditions.



Oxygen, huge impact of neon revision. Stark effect?



What should we hope for?

In conclusion:

New opacity tables: Solar and stellar models, pulsations in massive stars.
Overshooting and mixing: better depiction of borders and seismic diagnostics.
Only changes? No: EOS, instabilities (T-S at least).

Solar gavity modes: direct view of MS ⇒ post-MS transition in transport + nuclear reactions.
Planetary formation: increase of 5% of Z_c, CNO neutrino fluxes?(Kunimoto et al. 2021)

Thank you for your attention!