Dynamical processes in the Sun and non-standard solar models.

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The limitations of Standard Solar Models:

Simplifying hypotheses:

- Convection $\Rightarrow$ MLT (or a variant of it), no Overshooting.
- Rotation and magnetism $\Rightarrow$ not included.

Changes outcomes and initial conditions of solar calibrations.

Already noted in Christensen-Dalsgaard et al. 1996:

> Given the microphysics, the preceding description provides a well-defined procedure for computing standard models in accordance with the known overall properties of the Sun. On the other hand it involves several significant simplifications, which might compromise the resulting models. It neglects possible macroscopic motion in the solar interior, which would change the composition profile; such motion might result from instabilities associated with the slow-down of rotation or convective overshoot into the stable region beyond the base of the convection zone (*18*).

How to model them and include them in the calibration?

What to expect:

Focus on solar evolution models.

1. Observational signatures of dynamical processes.
2. Rotation: issues in the radiative zone, constraints and implementation.
3. Convection and overshooting: modelling and seismic probing.
4. The Sun as a star in asteroseismology.
5. A non-standard model calibration?

For reviews: Howe et al. 2009, Thompson et al. 2013, Kupka & Muthsam 2017, Thompson et al. 2017, Christensen-Dalsgaard 2021, Kosovichev et al. 2025

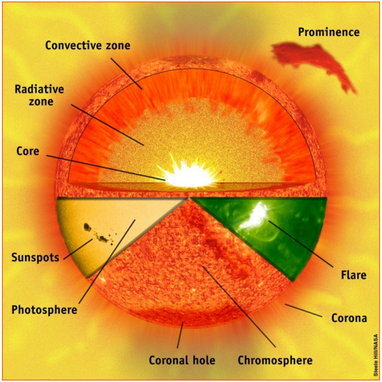
Internal rotation of low-mass stars:

Key feature: Outer convective envelope during hydrogen burning.

- Magnetic braking of the surface.
- Contraction of the core as the star evolves.

Angular momentum: Hydro + magnetic.

Evolutionary timescales: Core Hydrogen burning ≈ few Gy, Shell Hydrogen burning ≈ 1Gy, Core Helium burning ≈ 100My, final stages ≈ 10ky.

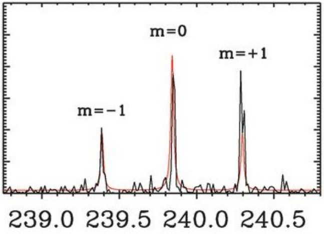


Internal rotation measurements

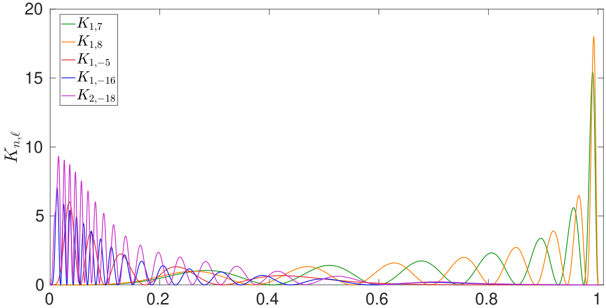
For a slow rotator, a perturbative approach (Ledoux 1951) is applicable

$$\delta\nu_{n,\ell,m} = \int_0^R \int_0^\pi K_{n,\ell,m}(r,\theta)\Omega(r,\theta)drd\theta$$

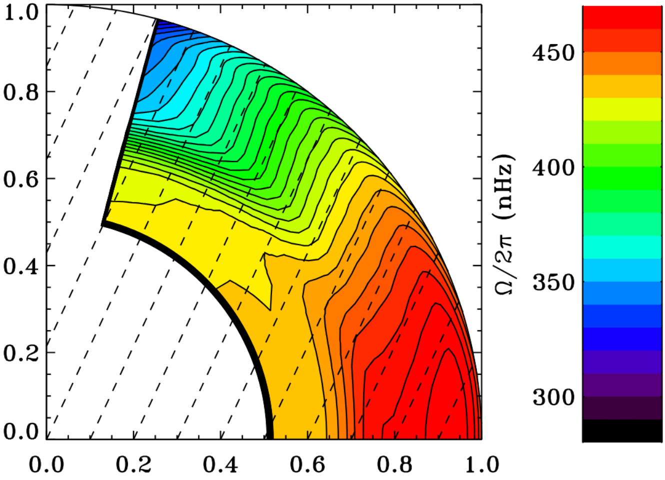
In most cases, directly from the observations ⇒ Inversion of the solar internal rotation. (Kosovichev & Fedorova 1989, Thompson et al. 1996, Schou et al. 1997, Corbard et al. 1999, Thompson et al. 2013,...)



(Huber et al. 2013)



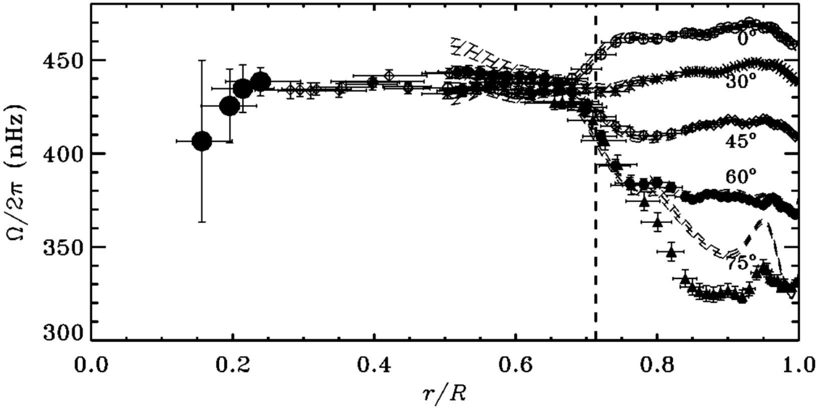
The rotational profile of the Sun



- Inferences on rotation: Brown et al. (1987) Kosovichev et al. (1988), see Howe (2009) and Thompson (2013).

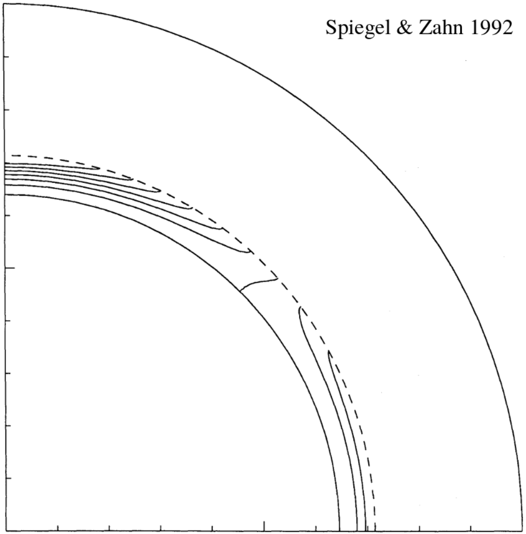
Two main properties:

1. differential rotation in the envelope,
2. solid-body rotation in the deep layers.



(Thompson et al. 2013)

The solar tachocline



Noted Properties

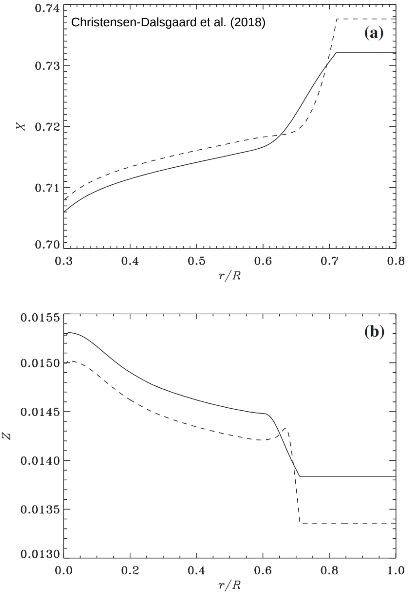
- Seat of intense mixing;
- Important for Lithium depletion;
- Link with activity;

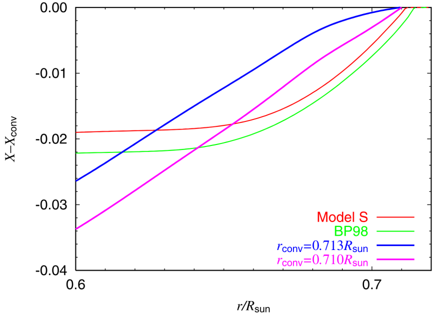
Some focus on the modelling: e.g. Gabriel (1997), Brun et al. (2002), Takata & Shibahashi (2003), Brun et al. (2011), Christensen-Dalsgaard (2018), Garaud et al. (2025).

Others on its observed properties: e.g. Corbard et al. 1999, Antia & Basu 2011, Basu et al. (2024)

See the book by Hughes et al. (2007)

Mixing of chemicals in the tachocline





(Takata & Shibahashi 2003)

Smooth profile of X and Z, increase of Z_{CZ} and Y_{CZ}

Solving additional equations when computing the models (simplest form, see Maeder 2009 for a reference textbook)

$$\rho \frac{d}{dt}\left(r^2\Omega\right)_m = \frac{1}{5r^2}\frac{\partial}{\partial r}\left(\rho r^4 \Omega U(r)\right) + \frac{1}{r^2}\frac{\partial}{\partial r}\left(\rho\left(D_{shear}+\nu_T\right) r^4 \frac{\partial \Omega}{\partial r}\right)$$

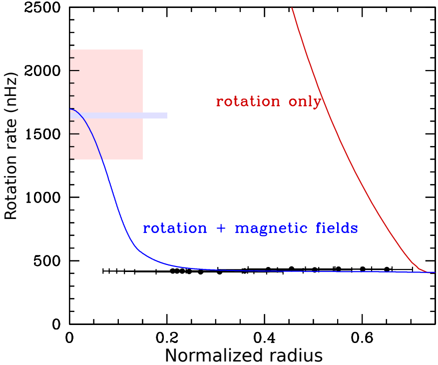
$$\rho r^2 \frac{\partial X_i}{\partial t}\Big|_m = \frac{\partial}{\partial r}\left(D_{Mix}\rho r^2 \frac{\partial X_i}{\partial r}\right) - \frac{\partial}{\partial r}\left(w_i \rho r^2 X_i\right)$$

Additional parameters: $U(r)$, D_{Shear}, ν_T, D_{Mix}.
Prescriptions exist: Zahn 1992, Maeder 1997, Talon & Zahn 1997, Maeder 2003, Mathis et al. 2004, Mathis et al. 2018, Prat et al. 2021. See Nandal et al. 2024.
And implementations differ... (Endal & Sofia 1976)

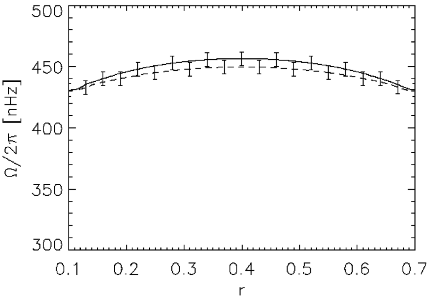
ν_T and D_{Mix} hide unknown physics: Spruit et al. 2002, Charbonnel & Talon 2005, Fuller et al. 2019, Eggenberger et al. 2022, ... See also Turk-Chièze et al. 2010 for a test on solar models.

See also Canuto 2011 a,b,c,d,e.

Candidates: fossil field (Gough & McIntyre 1998), magnetic instabilities (Spruit 2002), IGWs (Charbonnel & Talon 2005).

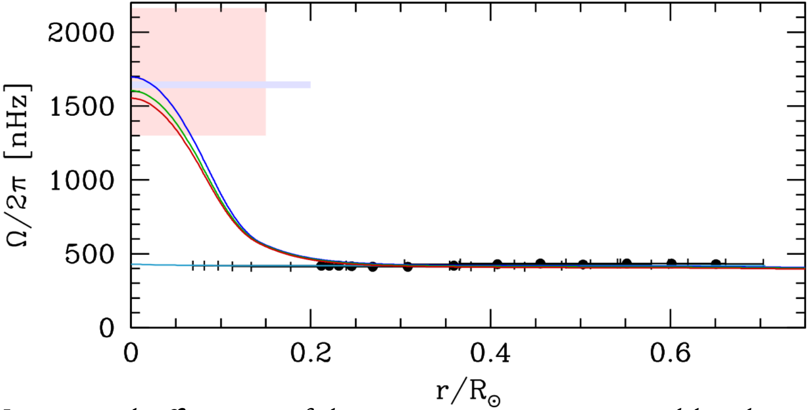


(Eggenberger et al. 2019b)



(Spada et al. 2010)

Towards the g-modes and the core rotation

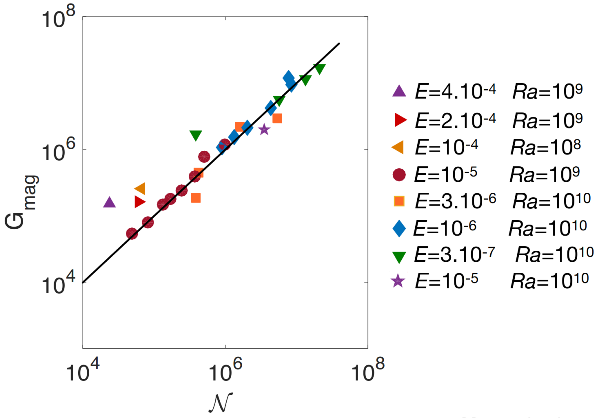


Nature and **efficiency** of the mecanism is constrained by the core rotation.

We need the solar g-modes.

(Garcia et al. 2007, Fossat et al. 2017, Schunker et al. 2017, Appourchaux et al. 2019, Scherrer et al. 2019)

What do simulations say?



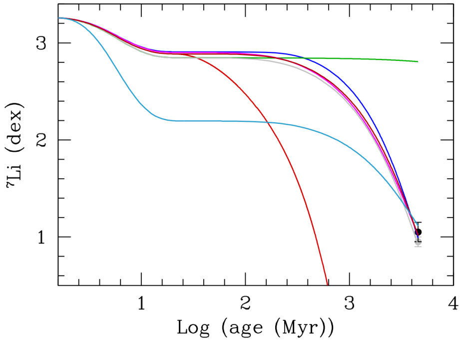
Zahn et al. 2007, Braithwaite & Spruit 2017, Petitdemange et al. 2023, 2024

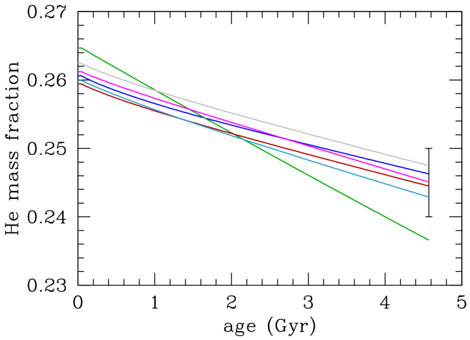
T-S dynamo appears in simulations

- A-M extraction in line with Spruit 2002.
- bifurcation towards Fuller et al. 2019 solution.

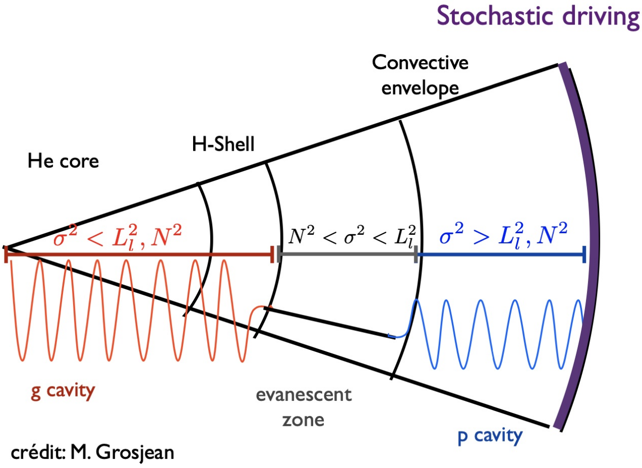
Implementation in stellar evolution codes? Is T-S the only instability? (AMRI, MRI, GSF, ...)

Rotation might not be the only indicator of AM transport.





Link with the depletion of light elements and the inhibition of settling. (Eggenberger et al. 2022)



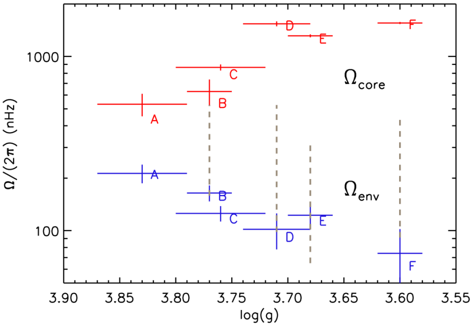
During evolution:

- $R \nearrow$ so $\nu_{Ac} \searrow$
- $N \nearrow$ so $\nu_{Grav} \nearrow$

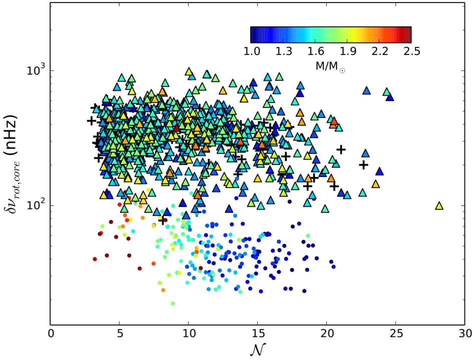
The g and p cavities are coupled.

References: Beck et al. 2011, 2012, Bedding et al. 2011, Mosser et al. 2012, Deheuvels et al. 2014, 2015, 2020, Spada et al. 2016, Takata 2016ab, Di Mauro et al. 2016, 2018, Noll et al. 2021, ...

Internal rotation subgiants, red giants and clump stars from CoRoT and *Kepler* (+TESS and Plato).



Deheuvels et al. (2014)



Gehan et al. (2018)

Measurement orders of magnitude from theoretical models.

(Ceillier et al. 2013, Marques et al. 2013)

Potential solutions for evolved stages?

A resurgence of the AM transport issue:

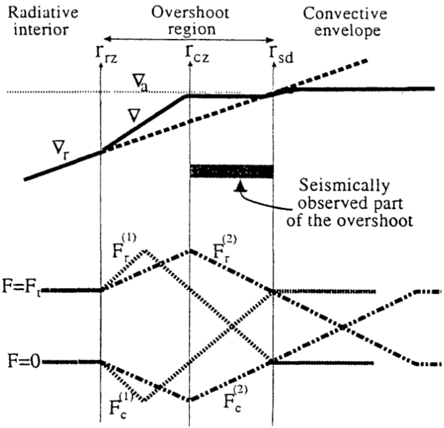
Can we test the previous candidates?

- Magnetic instabilities (known formalism). ⇒ No. (Cantiello et al. 2014)
- Internal gravity waves by turbulence.⇒ No. (Fuller et al. 2014)
- Fossil fields? ⇒ No. (Fellay et al. 2021, Buldgen et al. 2024b)

Revised prescriptions and new processes: IGWs by plumes (Pincon et al. 2016, 2017), modification of magnetic instabilities (Fuller et al. 2019) , transport by mixed modes (Belkacem et al. 2015).

See Aerts et al. 2019 for a review on asteroseismology and angular momentum transport.

Overshooting at the BCZ - The problem



The "simple" 1D problem

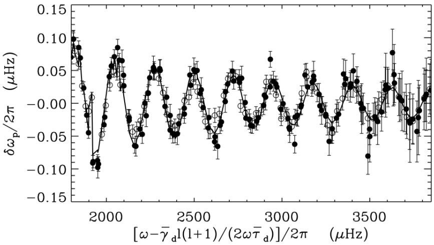
- MLT is inaccurate;
- Schwarzschild criterion is dynamical;
- Properties likely depend from case to case!

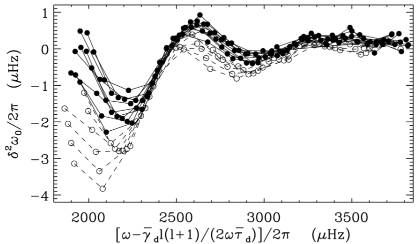
See also (amongst many others): Arnett et al. (2010), Viallet et al. (2015), Käpylä et al. (2017)

Zahn (1991), Corbard et al. (2001)

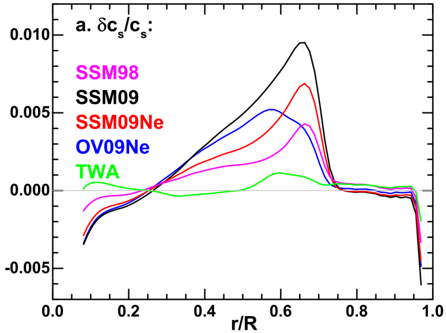
Observations: Overshooting at the BCZ - Seismology

"Seismic glitches"



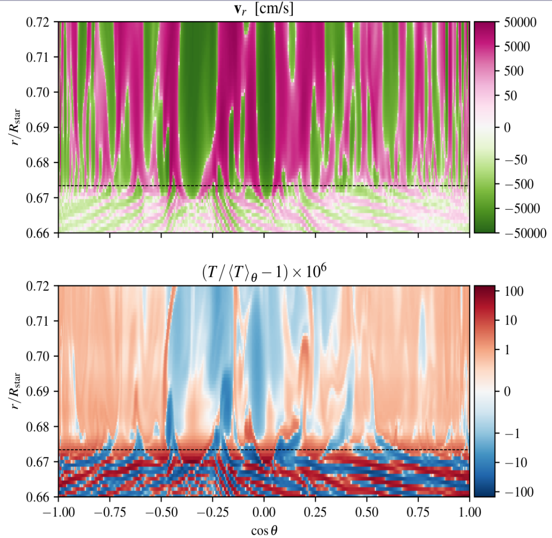


Sound speed "bump"



See e.g. Monteiro et al. 1994, Roxburgh & Vorontsov 1994, Christensen-Dalsgaard 1995, Christensen-Dalsgaard et al. 2011, Zhang et al. 2012, Zhang et al. 2019

Observations: Overshooting at the BCZ - Simulations



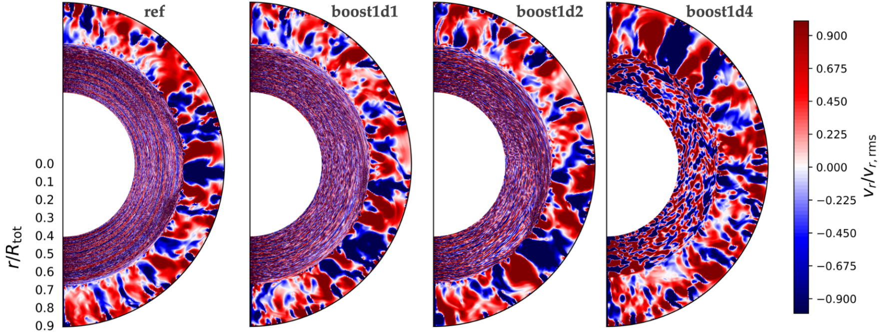
Baraffe et al. 2021

Modelling of convection

- Relaxation?
- Dimensions?
- Additional physics?
- Conditions of the simulations?

See Kupka & Muthsam 2017 and refs therein.

Generation of internal gravity waves in the solar radiative zone: transport of angular momentum and chemicals?

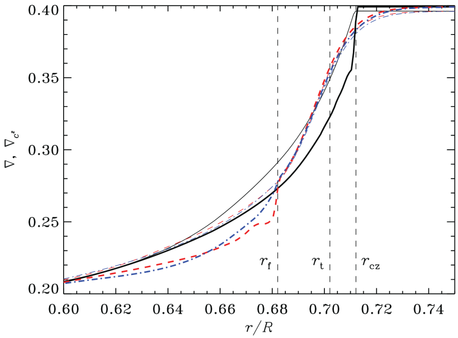


Le Saux et al. 2022

See also e.g. Talon et al. 1998, 2002, Rogers et al. 2006 a,b 2008, Pinçon et al. 2016.

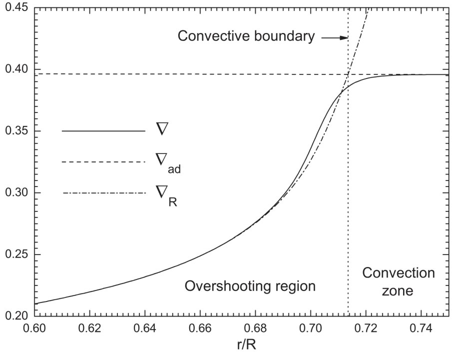
Including overshooting - Examples

Based on Seismology



Christensen-Dalsgaard et al. (2011)

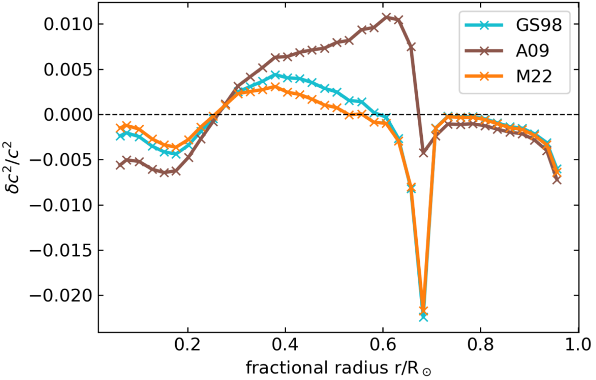
Based on Convection models



Zhang et al. (2012)

Including overshooting - New models

Theoretical developments e.g.: Xiong et al. (2001), Rempel (2004), Zhang et al. (2012), Augustson & Mathis (2019)



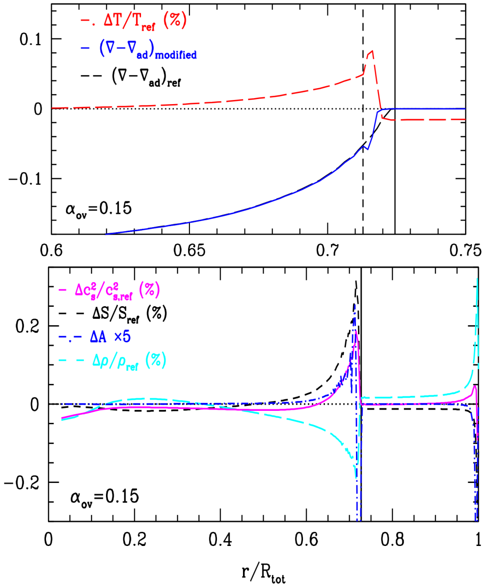
Kupka et al. (2021), Ahlborn et al. (2022), Braun et al. (2024)

Similar to rotation:

- additional free parameters.
- depends on closure model.

Also improving convection:
Spada et al. (2018), Joergensen et al. (2019, 2021), Manchon et al. (2024)

Including overshooting - What do simulations say?



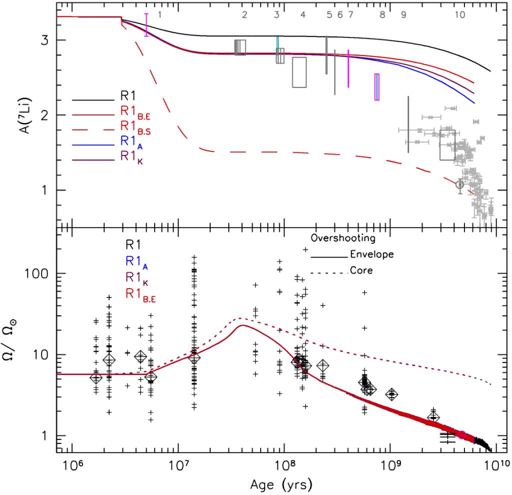
Main results

- Shallow penetration;
- Small temperature gradient changes;
- Negligible impact on sound speed and transport.

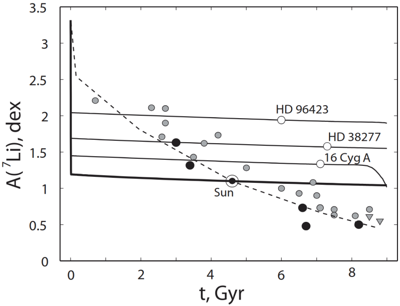
Overshooting is not a solution to the solar problem.

Baraffe et al. (2022)

Including overshooting - What about light element depletion?



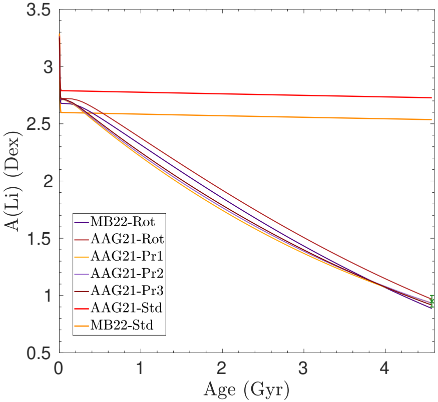
Dumont et al. (2021)



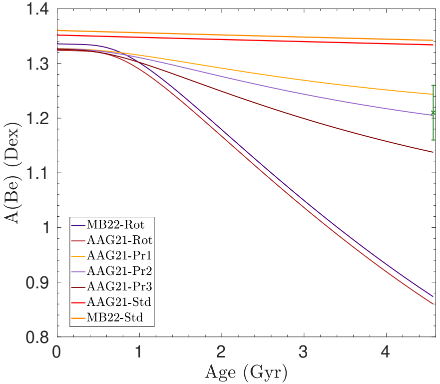
Thévenin et al. (2017)

Depletion is quick, followed by a plateau.

Observations: Lithium and Beryllium depletion



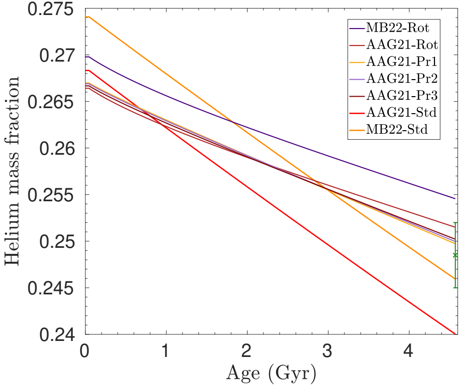
Lithium from Wang et al. (2021),
Efficient mixing required!



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

e.g. Proffitt & Michaud 1991, Richard et al. 1996, Brun et al. 2002, Thévenin et al. 2017, Dumont et al. 2021, Buldgen et al. 2025b, Deal et al. Sol.Phys.

Calibrating turbulence - Impact on helium



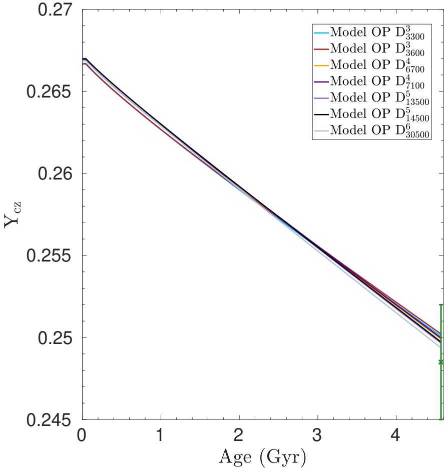
Looking at Y_{CZ} from Basu & Antia. (1995), **changes drastically the evolution.**

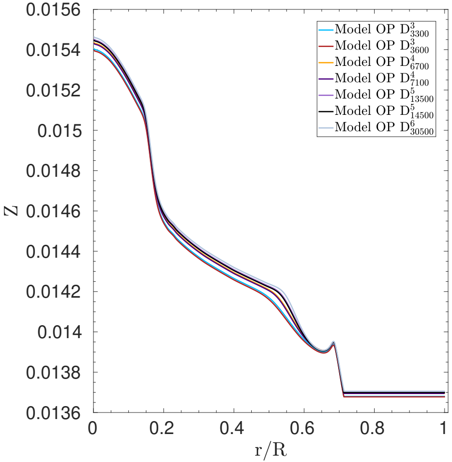
Changing transport:

- 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.

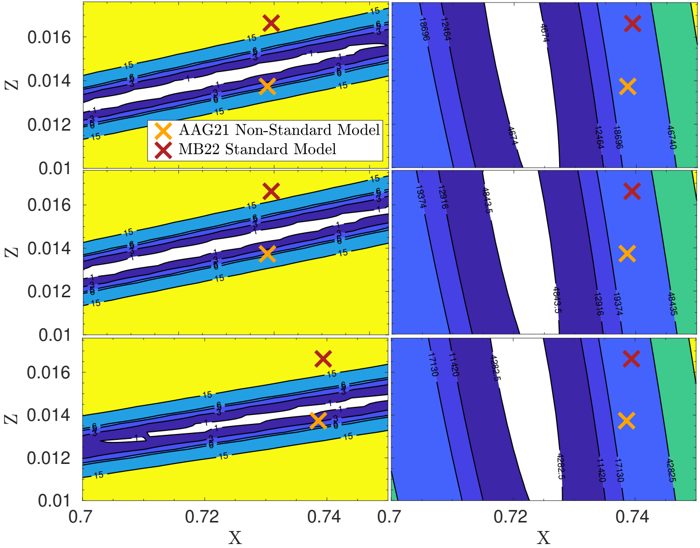
Simply calibrating transport?





Very similar helium depletion and metallicity profile.

But what chemical composition? - Γ_1 inversions



Vorontsov et al. 2013, 2014, Buldgen et al. 2017, 2024a, Baturin et al. 2024

Standard solar models - quick - simple - efficient:

3 Parameters - 3 Constraints

- Mixing length parameter ($\alpha_{\rm MLT}$), initial hydrogen (X_0), initial metallicity (Z_0).
- Solar radius ($R_\odot$), solar luminosity ($L_\odot$), surface metallicity $(Z/X)_\odot$.
- The rest is fixed as standard. (which ones?)

Transport of chemicals in radiative zones: microscopic diffusion, no dynamical effects.

Modelling of convection: no additional penetration/mixing at the BCZ.

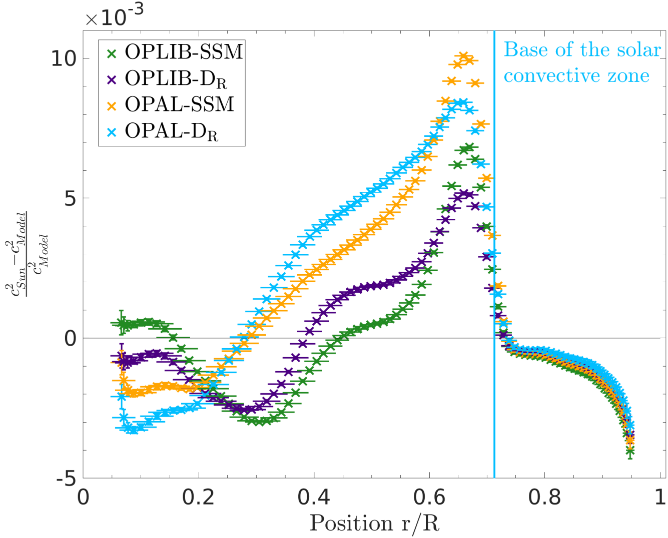
Both processes will require **at least one** additional free parameter.

But which constraints should we use and how?

One needs to define an extended calibration scheme.

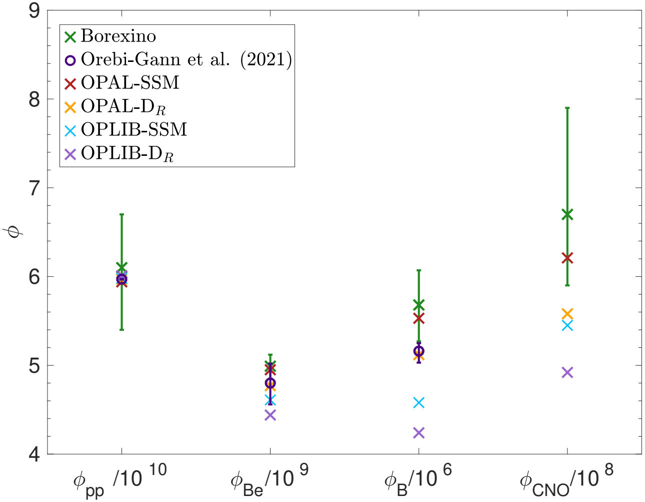
(Ayukov et al. 2017, Kunitomo et al. 2021, Basinger et al. 2024, Yang, W. et al. 2025)

What do things look like? Sound speed



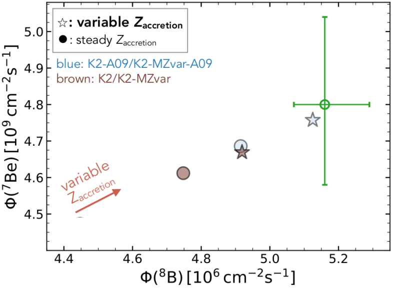
- MB22 abundances;
- Mixing for Li;
- OPAL vs OPLIB;

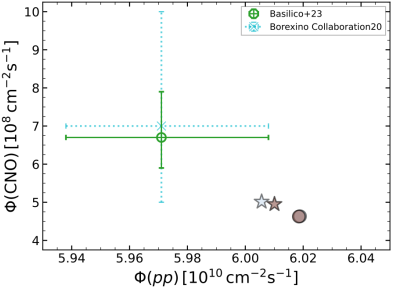
What do things look like? Neutrinos



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

What do things look like? Planetary formation





Extended calibration scheme of Kunitomo & Guillot:

- Opacity increase (Gaussian, from Mondet et al. 2015),
- X_0, Z_0, α_{MLT},
- Accretion with variable Z,

Minimize: sound speed (rms of profile), $(Z/X)_S$, Y_{CZ}, L, R,

As soon as mixing is included: Z_0 decreases, $\phi_{\rm CNO}$ too?

Free and fixed parameters:

X_0 and Z_0: Free, but changing from OPAL to OPLIB $\Rightarrow$ change Y_{CZ} by $\approx 2\sigma$, x_{CZ} by about $\approx 3\sigma$.
α_{MLT}: Free, but varies with opacity, outer boundary conditions, abundances, EOS, ...

Conclusions are only valid within a given scheme of fixed physics and evolutionary history.

Name	$(r/R)_{\rm BCZ}$	$(m/M)_{\rm CZ}$	$Y_{\rm CZ}$	A(Li) [dex]
Model OPAL SSM	0.7173	0.9770	0.2460	2.536
Model OPAL $D_{\rm R}$	0.7210	0.9779	0.2545	0.954
Model OPAL $D_{\rm R}$ + Ov	0.7133	0.9777	0.2535	0.915
Model OPAL $D_{\rm R}$ + OPAC	0.7136	0.9762	0.2546	0.918
Model OPLIB SSM	0.7142	0.9761	0.2404	2.611
Model OPLIB $D_{\rm R}$	0.7185	0.9769	0.2484	0.991
Model OPLIB $D_{\rm R}$ + Ov	0.7133	0.9768	0.2479	0.991
Model OPLIB $D_{\rm R}$ + OPAC	0.7132	0.9757	0.2485	0.982

Key points regarding dynamics:

The negatives:

- Neglected in Standard Solar Models despite a strong impact.
- Main difficulty: Implementation in stellar models? Reliability?
- What constraints? How to robustly include them in calibration procedures?

The positives:

- More targets: Asteroseismology provides new "laboratories".
- More simulations: Renewed interest in transport processes in radiative zones.
- Improved inferences: Definitions of extended calibration schemes.

There is a crucial need to work on improved solar models and calibration schemes.

Thank you for your attention!