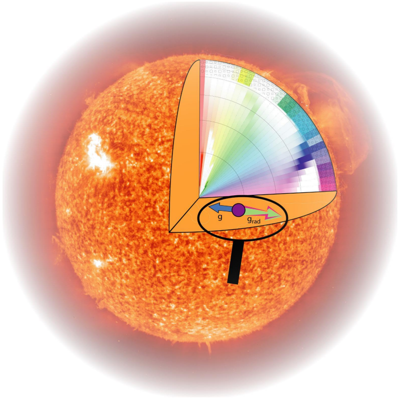
Atomic diffusion



Morgan Deal
LUPM, University of Montpellier

What can affect chemical elements in the Sun?

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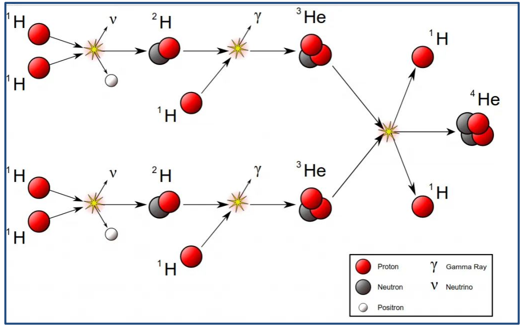
Nuclear reactions



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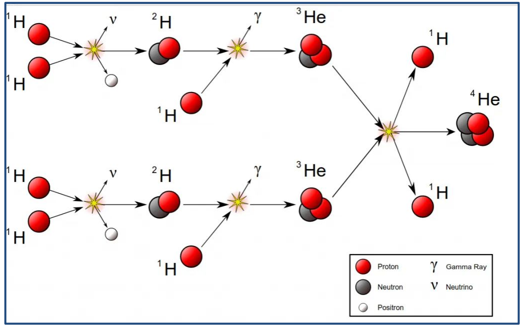

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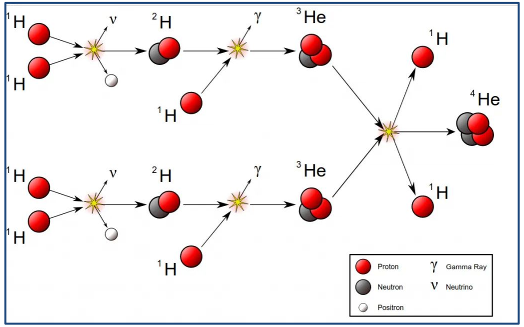

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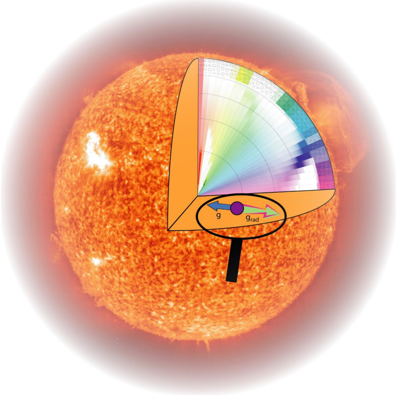

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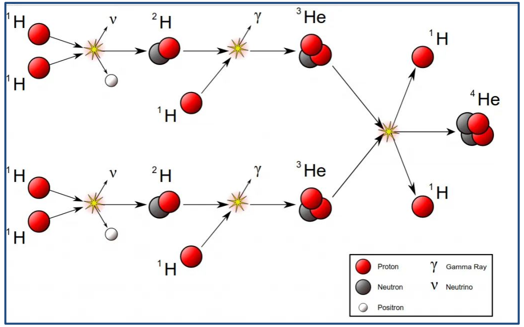

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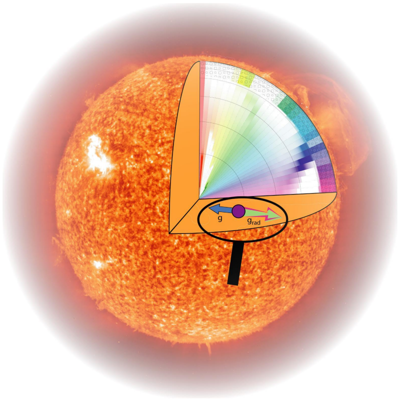

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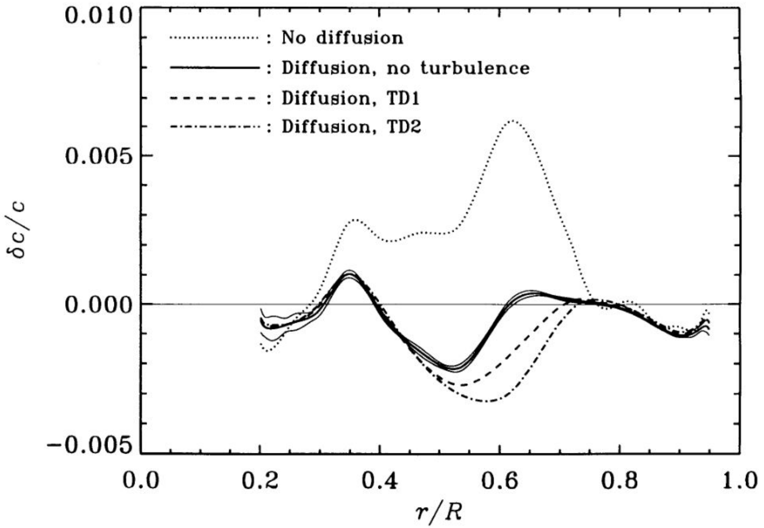
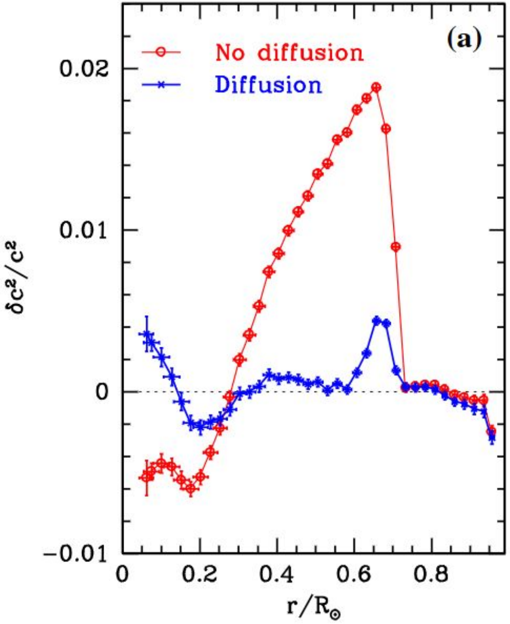


Christensen Dalsgaard+ 1993



Basu 2016

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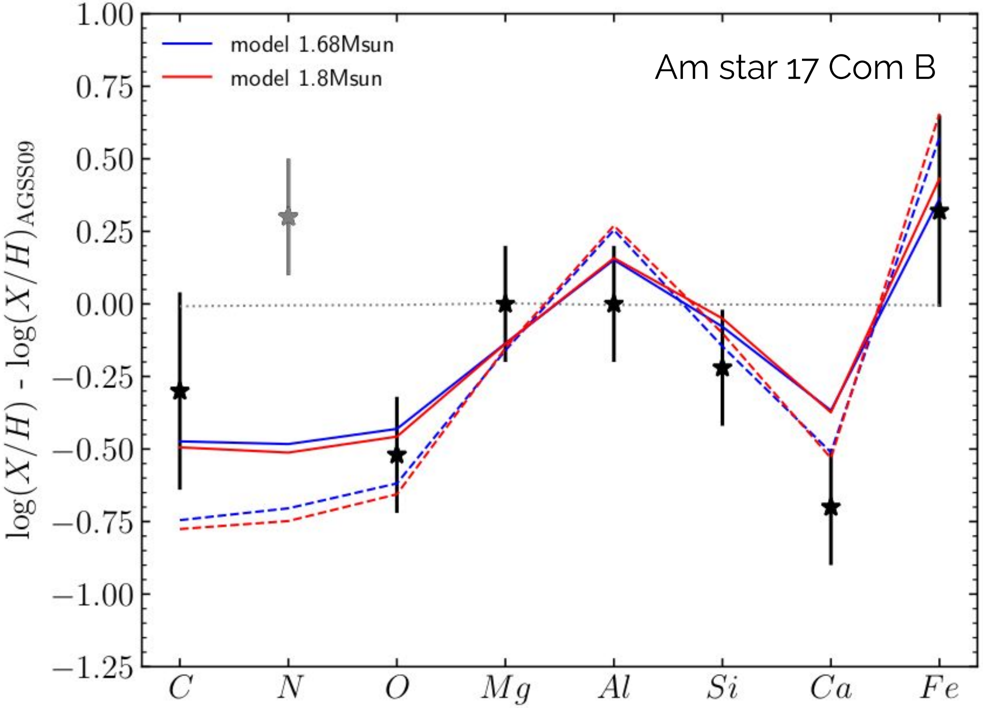

Deal & Monier 2020

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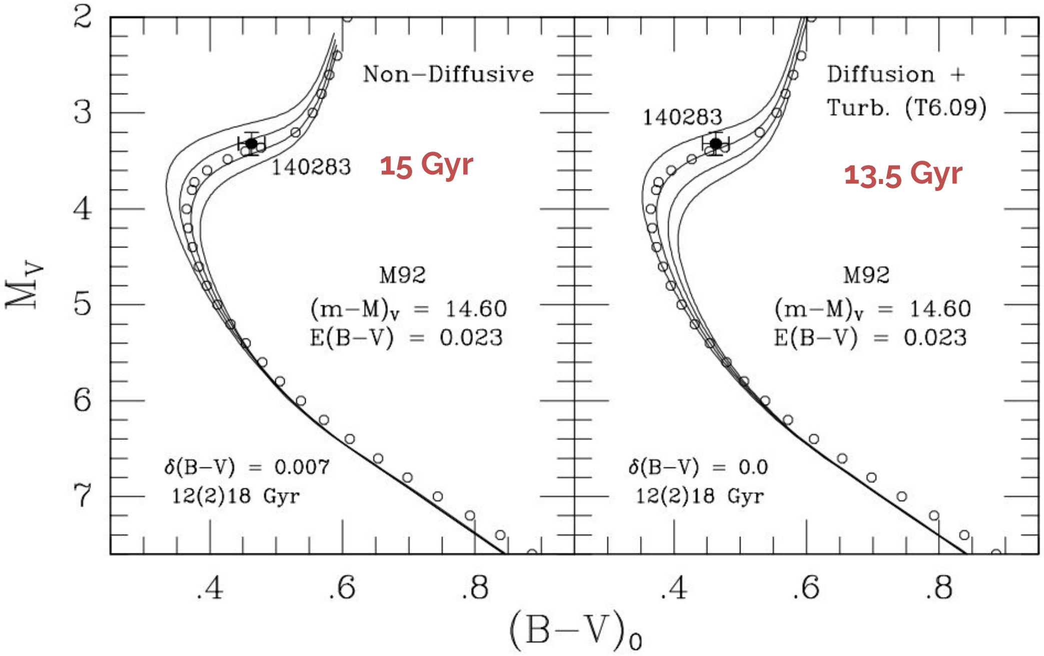

VandenBerg+2002

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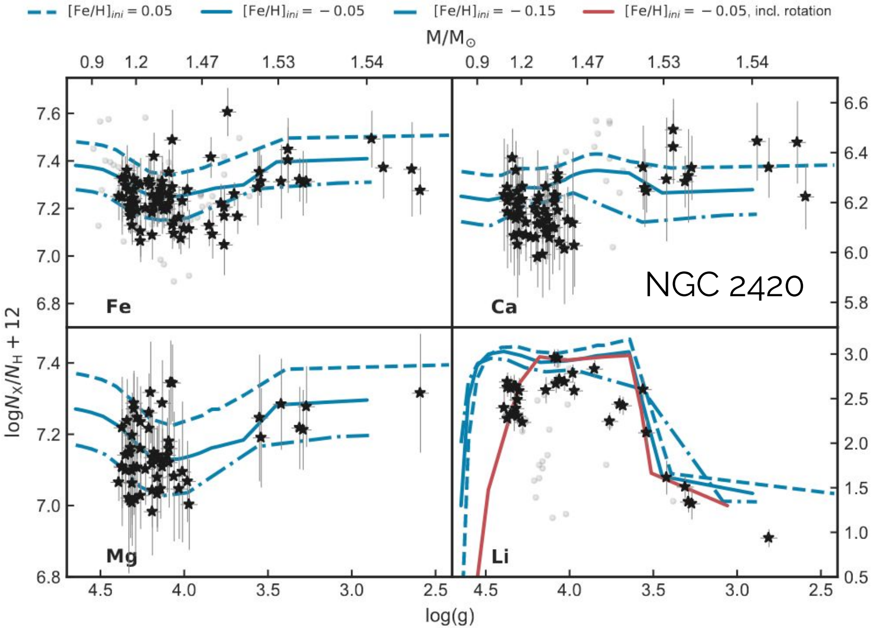


- Abundance trends (Korn+2007; Norlander+2012; Gruyters+2013,+2016; Bertelli Motta+2015; Dotter+2017; Souto+2018; Semenova+2020; ...)

Semenova+2020

Diffusion equation

$$\rho \frac{\partial X_i}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2 \rho \boxed{D_{\mathrm{turb}}} \frac{\partial X_i}{\partial r}\right] - \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2 \rho \boxed{v_i}\right] + \boxed{A_i m_p \left[\sum_j (r_{ji} - r_{ij})\right]}$$

Turbulent processes

Atomic diffusion

Nuclear reactions

Diffusion velocities (trace element)

$$v_i = D_{ip}\left[-\frac{\partial \ln X_i}{\partial r} + \frac{A_i m_p}{kT}\left(\boxed{g_{rad,i}} - \boxed{g}\right) + \frac{(\bar{Z}_i + 1) m_p g}{2kT} + \kappa_T \frac{\partial \ln T}{\partial r}\right]$$

Radiative acceleration

Gravitational settling

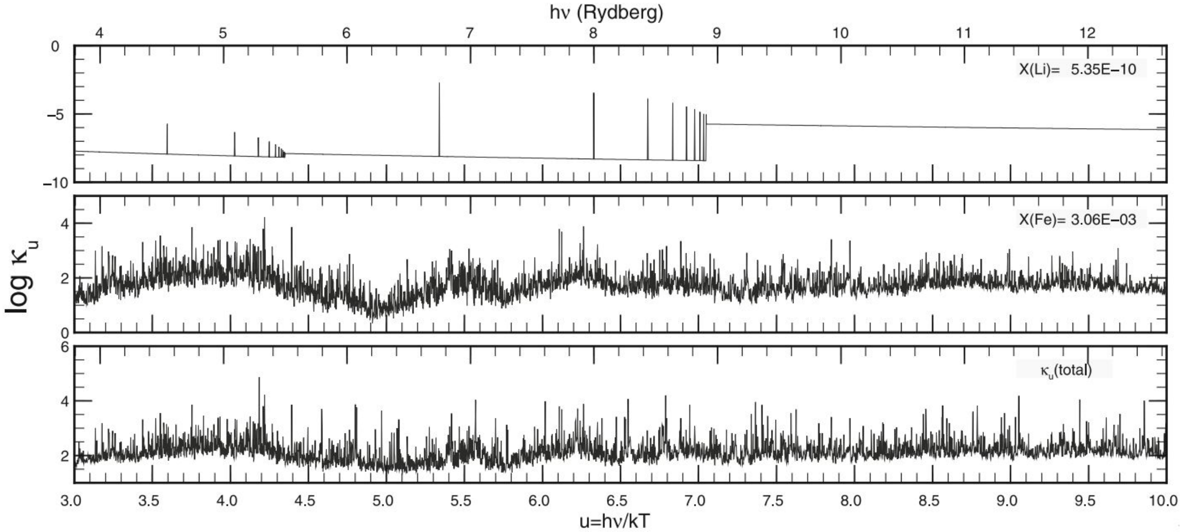
$$D_{ip} \propto \frac{1}{Z_i^2}$$

Partial ionisation is crucial for atomic diffusion computations !

Radiative acceleration

$$g_{rad,i} = \frac{1}{4\pi r^2}\frac{L\kappa_R}{cX_i}\int_0^\infty \boxed{\frac{\kappa_{u,i}}{\kappa_{u,tot}}}\mathcal{P}(u)\mathrm{d}u$$

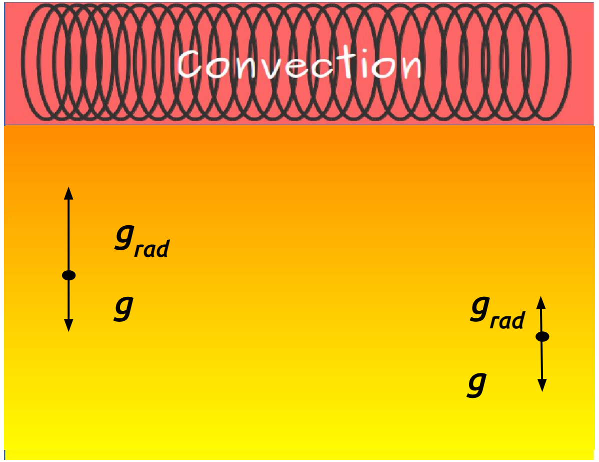
Monochromatic opacities



Richer & Michaud 2005

Atomic diffusion is efficient in radiative zones

$$D_{\mathrm{conv}} \approx 10^{13}\ \mathrm{cm}^2.\mathrm{s}^{-1}$$
$$D_{\mathrm{He}} \approx 3.6\ \mathrm{cm}^2.\mathrm{s}^{-1}$$



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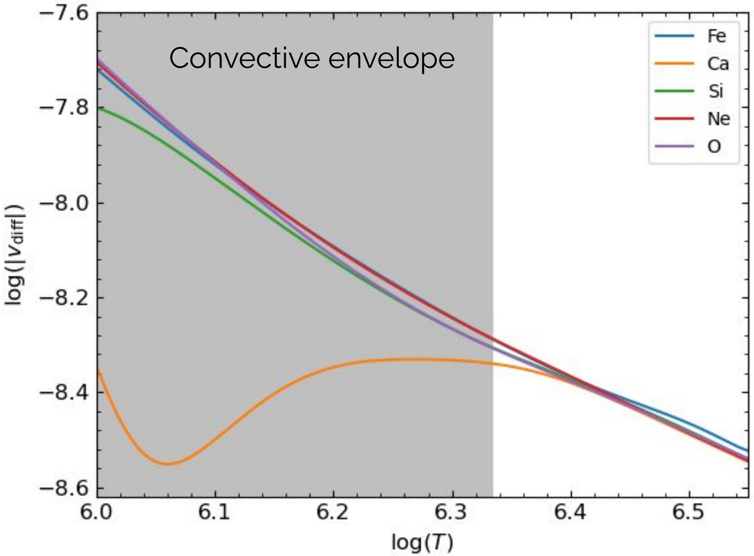
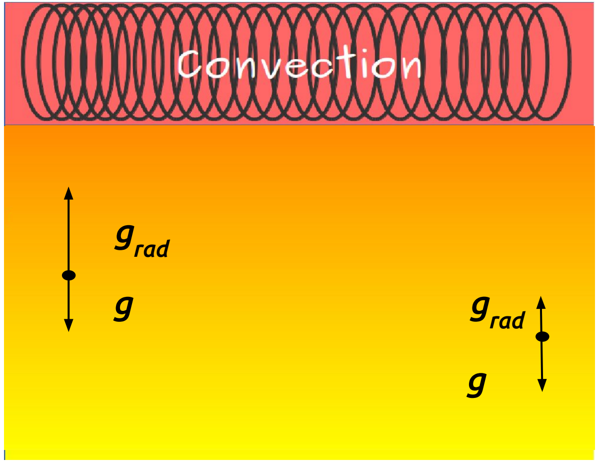
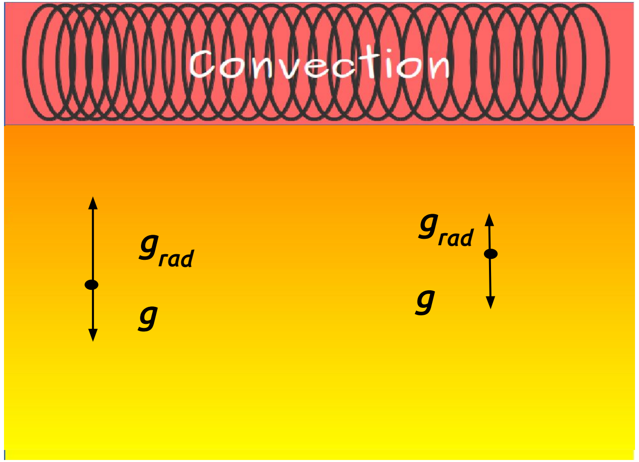
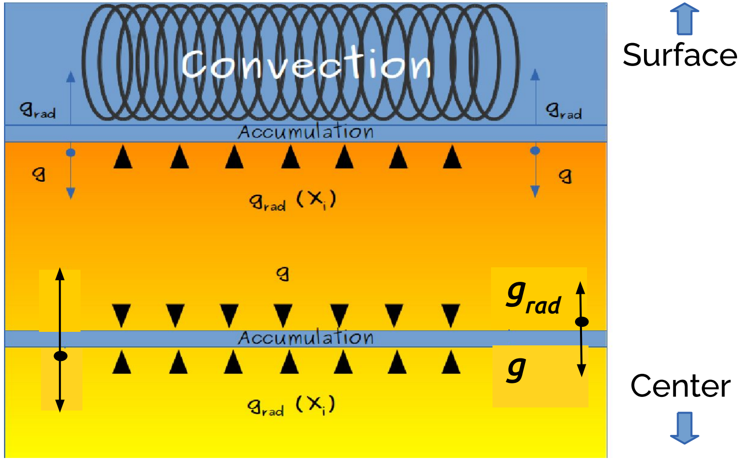
It is more efficient close to the surface







Leads to accumulation of some elements



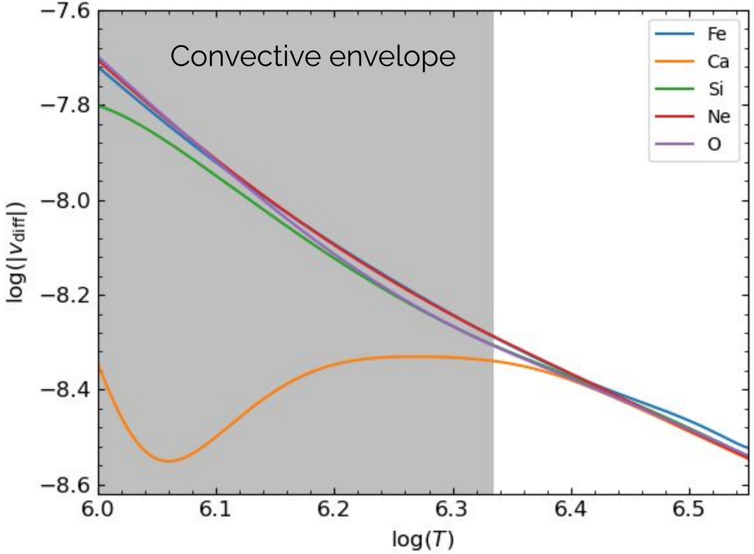
These effects are different **for each element** and depend on :

- the **abundance** of the element
- the **ionisation state**
- the **photon flux**

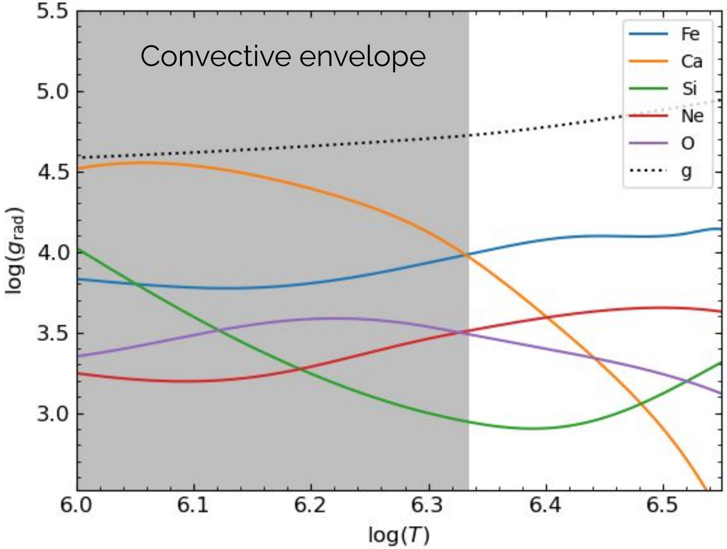
→ **Direct influence** on stellar **structure** and **surface abundances**

Radiative accelerations in the Sun

Velocities



radiative accelerations



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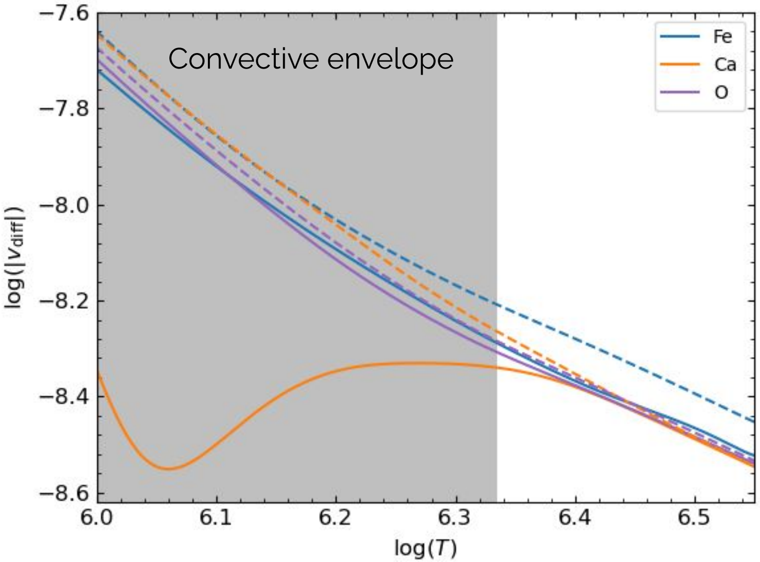

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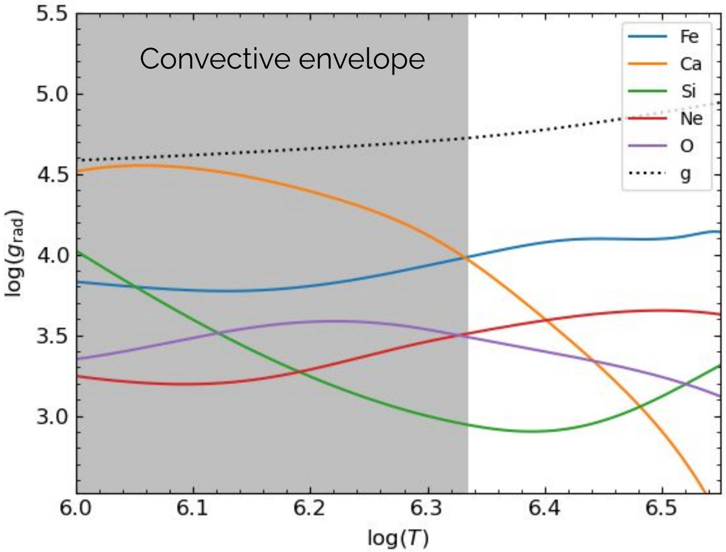
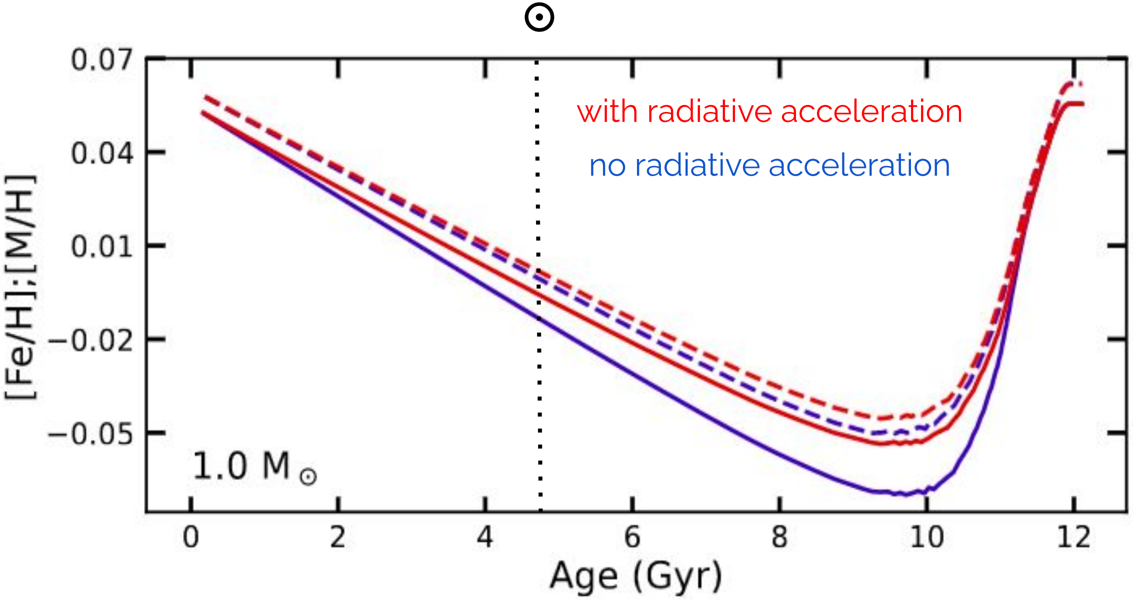


Evolution of the surface abundances of solar models



Moedas+2022

Even if **g > g**$_{\mathbf{rad}}$, radiative accelerations have an impact on solar models

Possible impact of iron opacity increase on iron g_{rad}

(toy model)

Iron opacity underestimated by 30-400% at the bottom of the CE of the Sun (`Bailey+2015`)

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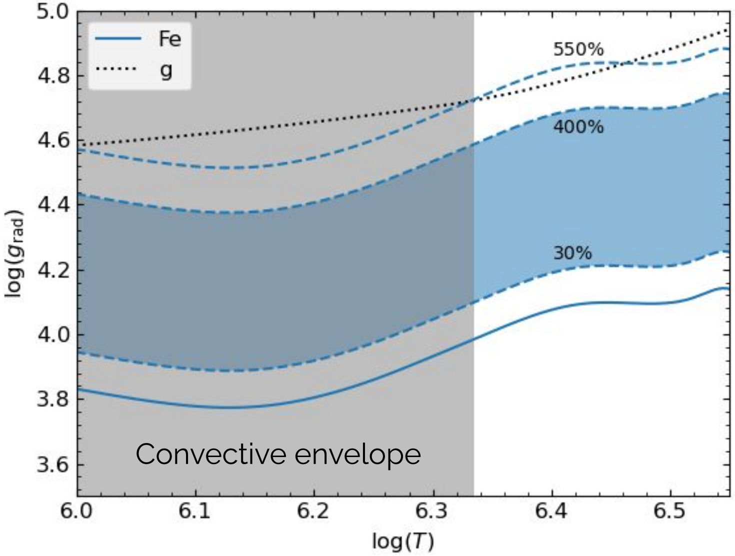
If we assume that the whole spectra is affected in the same way (**which is not the case!**)



Implementation in stellar evolution codes

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(for mixture of metals)

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Implementation in stellar evolution codes

CESTAM
Montpellier/Montréal code
TGEC
MESA

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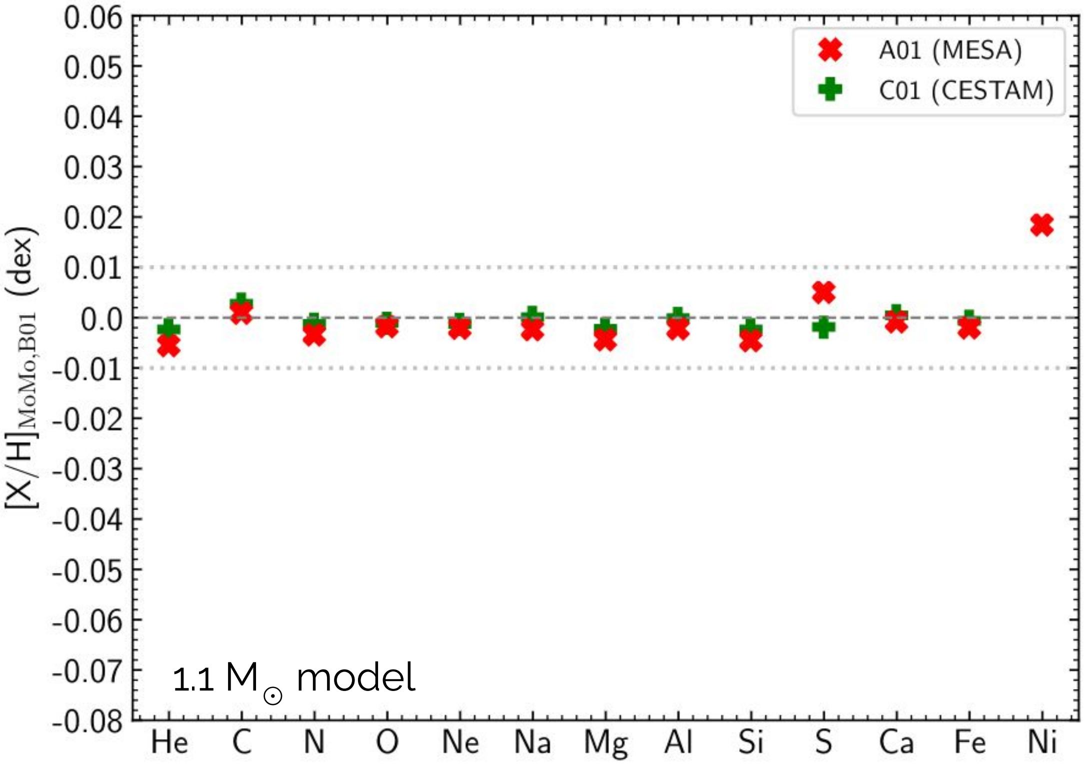

Campilho+2022

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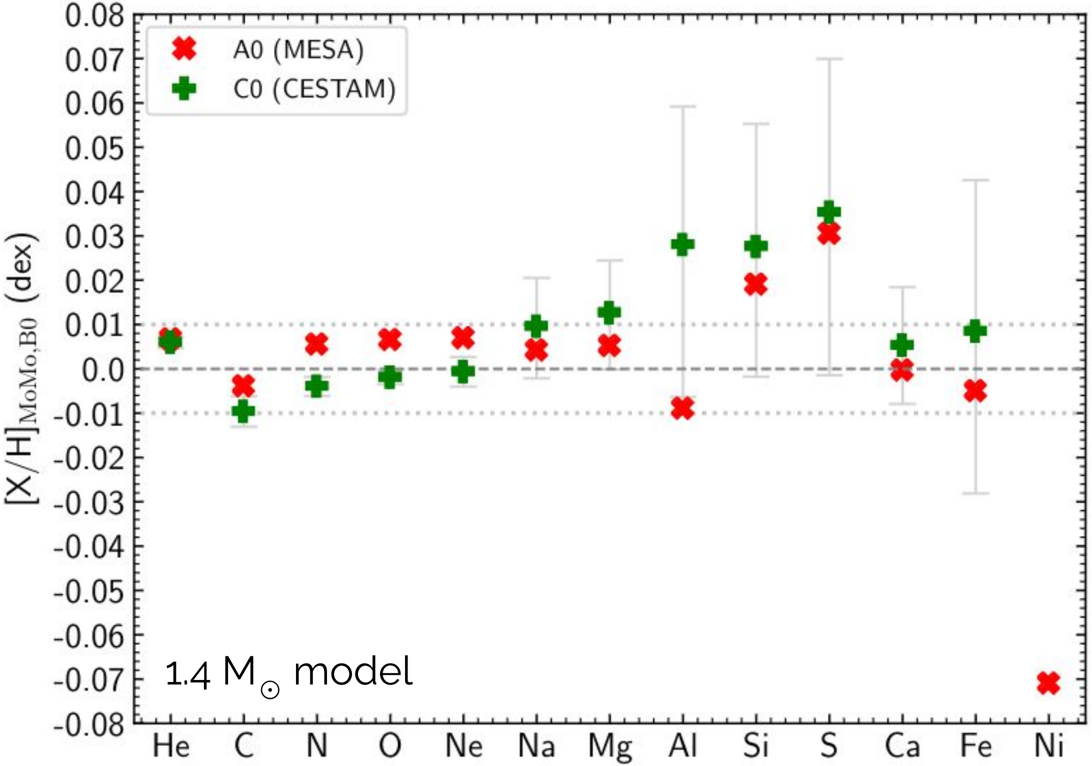

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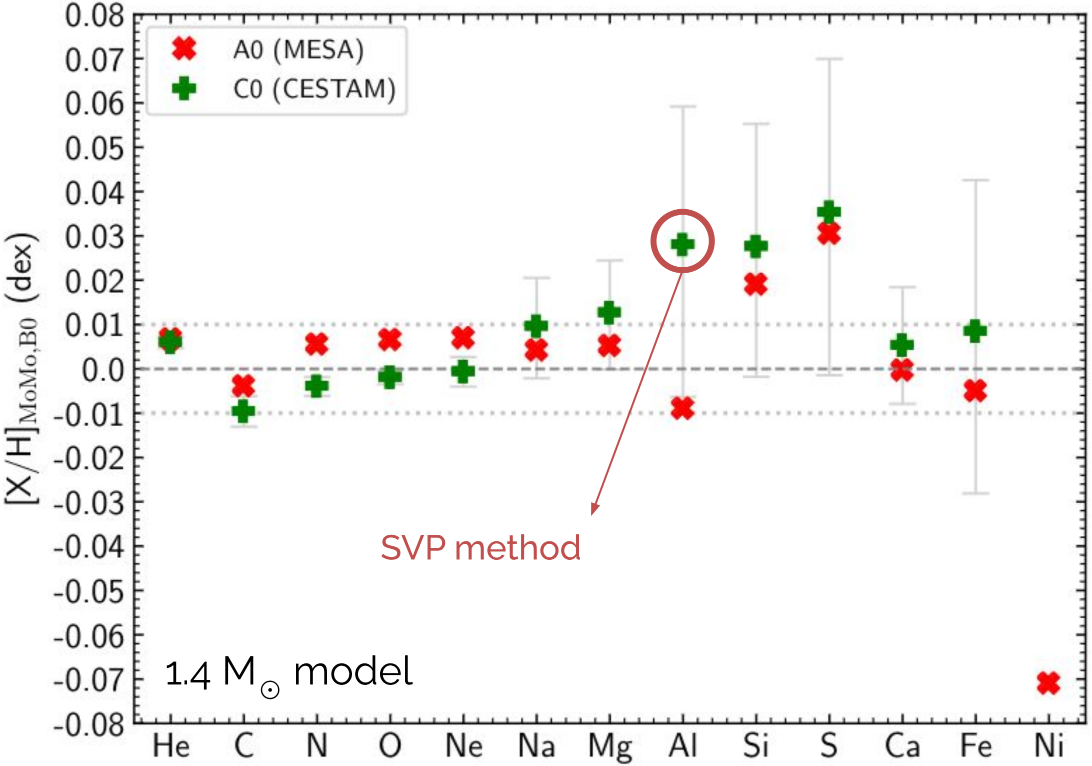

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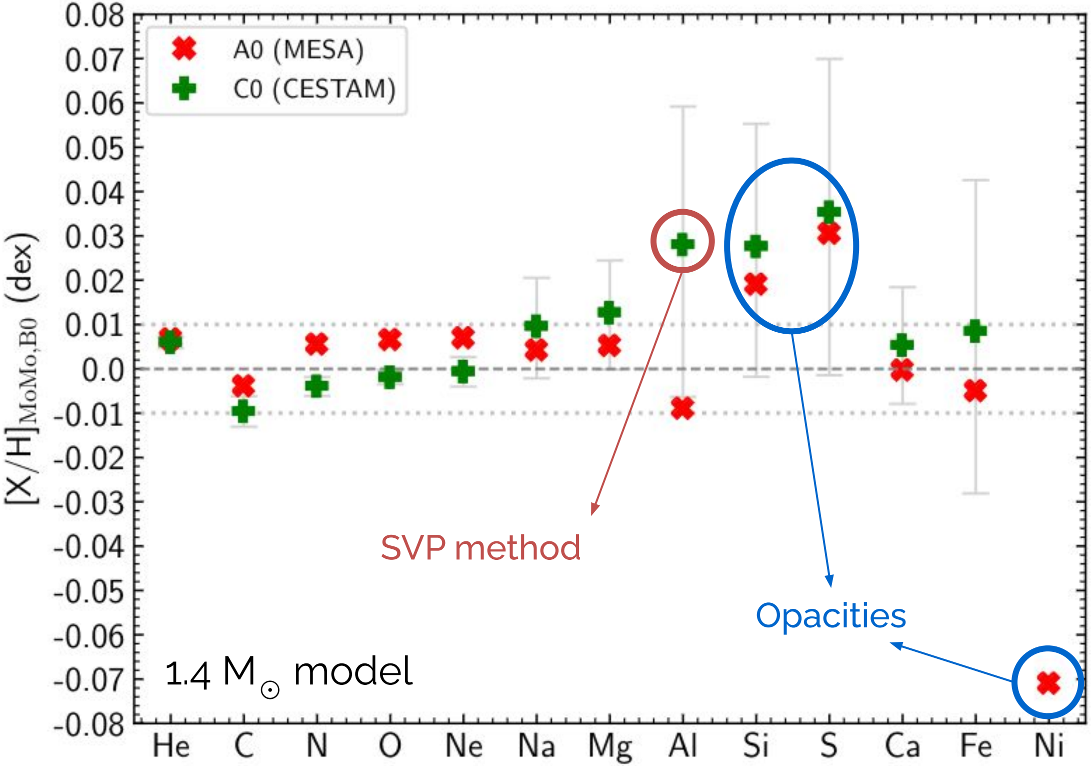


$1.4\ M_\odot$ model

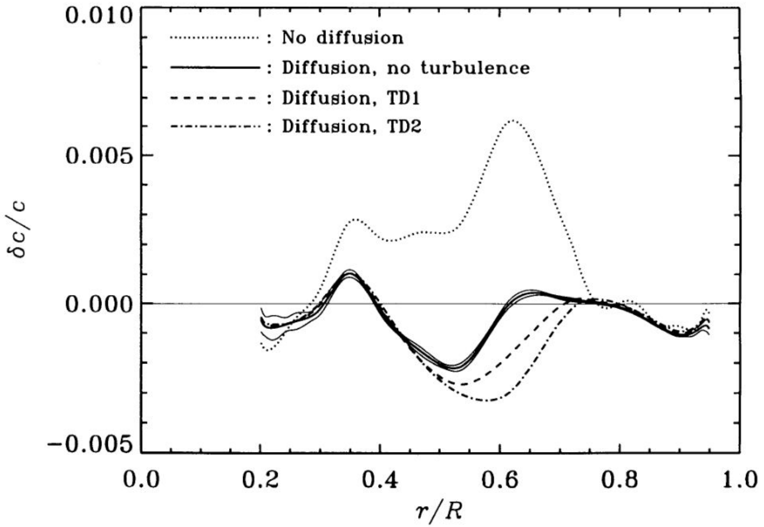
SVP method

Opacities

Campilho+2022

Additional transport processes

Solar models including **atomic diffusion** show a **better agreement** with helioseismology



Christensen Dalsgaard+ 1993

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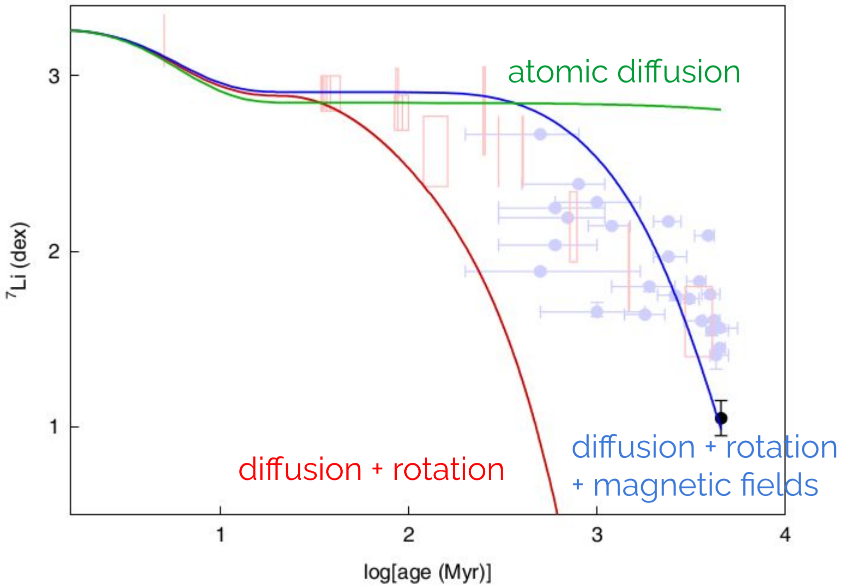
Sun



Eggenberger+2022

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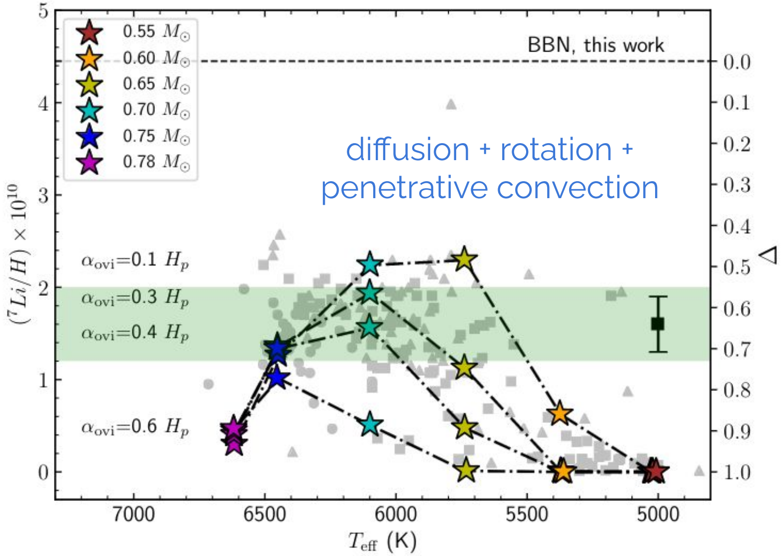

Deal+2021

What should we use for solar models?

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Radiative accelerations	- direct use of atomic data (for atmospheres) - use of opacity tables with fixed frequency grids (Montréal/Montpellier code, Turcotte+1998; OPCD, Seaton 2005) - Single-Valued Parameter approximation (LeBlanc & Alecian 2004,2020)
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Conclusions

- ➔ Atomic diffusion is an **important ingredient of solar models**
- ➔ **Radiative accelerations play a role**, but small compare to gravitational settling
- ➔ **Opacity revisions** may have a significant impact on radiative accelerations …
- ➔ … which may help to **reconcile models and observations**
- ➔ Atomic diffusion is only **one of the transport processes** acting in the Sun

Thank you for your attention !