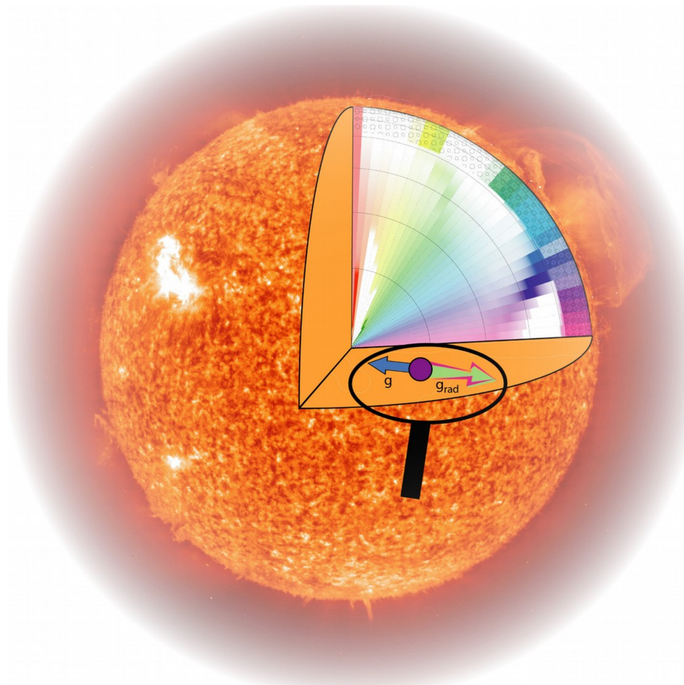
Impact of atomic diffusion in main sequence stars



M. Deal

5th forum of Action Fédératrice Etoiles, 13/11/2017

Atomic diffusion inside stars

Diffusion velocity of element i (trace element case):

$$V_i = D_{i,p}\left[-\frac{\partial \ln c_i}{\partial r} + \frac{A_i m_p}{k_B T}\left(g_{rad,i} - g\right) + \frac{Z_i m_p g}{2 k_B T} + \kappa_T \frac{\partial \ln T}{\partial r}\right]$$

Radiative acceleration term

Gravitational settling term

Continuity equation :

$$\frac{\partial \rho c_i}{\partial t} = -\nabla . \left(\rho V_i c_i\right)$$

The sign of the velocity mainly depends on the one of

$$\left(g_{rad,i} - g\right)$$

Two main computational methods in stellar evolution codes: **Burgers method** and **Chapman & Cowling method**

Atomic diffusion inside stars : Evolution codes

Montreal/Montpellier code :		Toulouse Geneva Evolution Code (TGEC) :
Burger's equations	**Atomic diffusion**	Chapman & Cowling equations
Opacity sampling	**Radiative accelerations**	Single Valued Parameter approximation (LeBlanc & Alecian +04)
OPAL monochromatic opacities	**Opacities**	OP monochromatic opacities(Seaton +05)

↓

Comparisons between codes including different physics and methods

↓

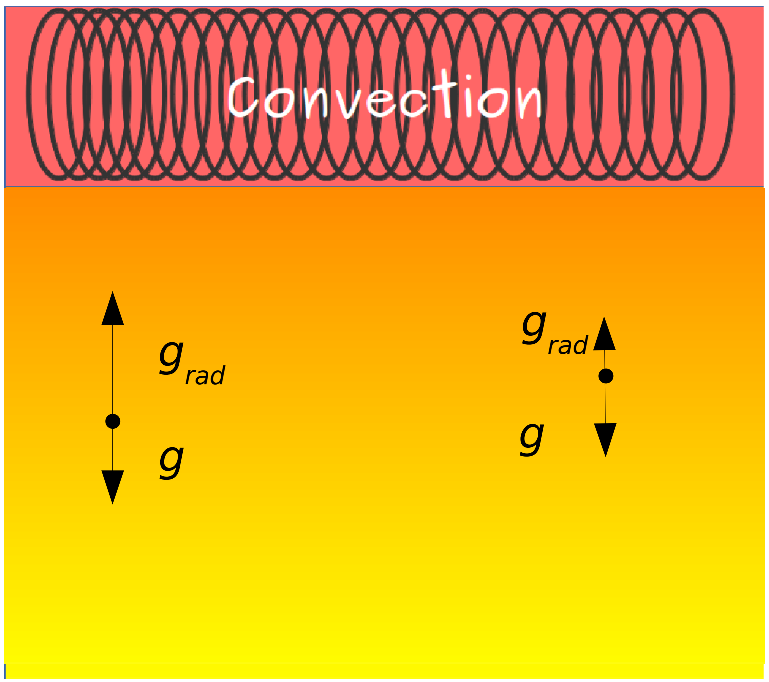
Robustness of results

Atomic diffusion inside stars : Evolution codes

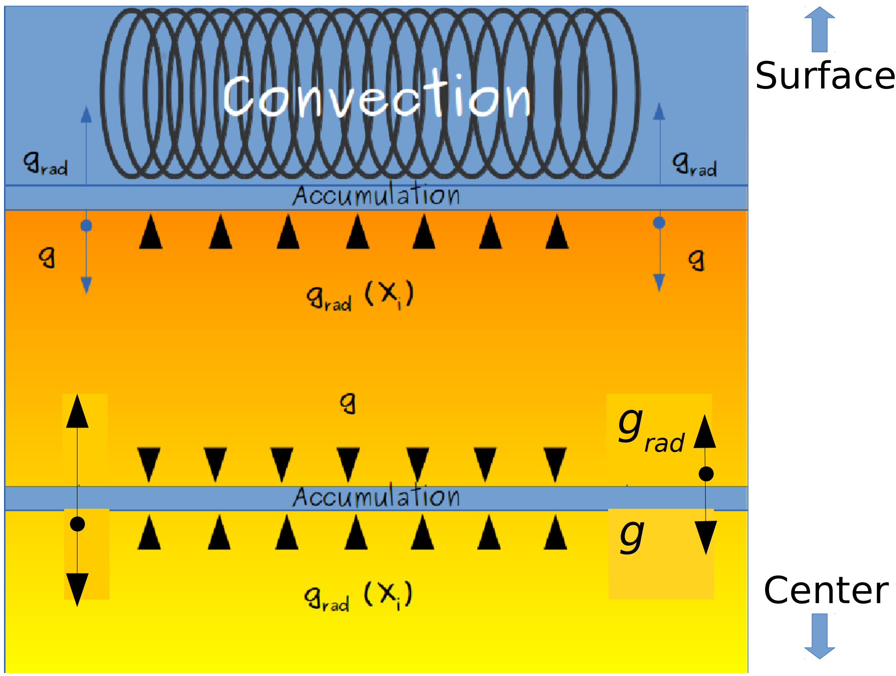
CESTAM evolution code:

Atomic diffusion	Burger's and Proffit & Michaud equations
Radiative accelerations	Single Valued Parameter approximation (LeBlanc & Alecian +04)
Opacities	OP monochromatic opacities (Seaton +05)

Atomic diffusion inside stars



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**

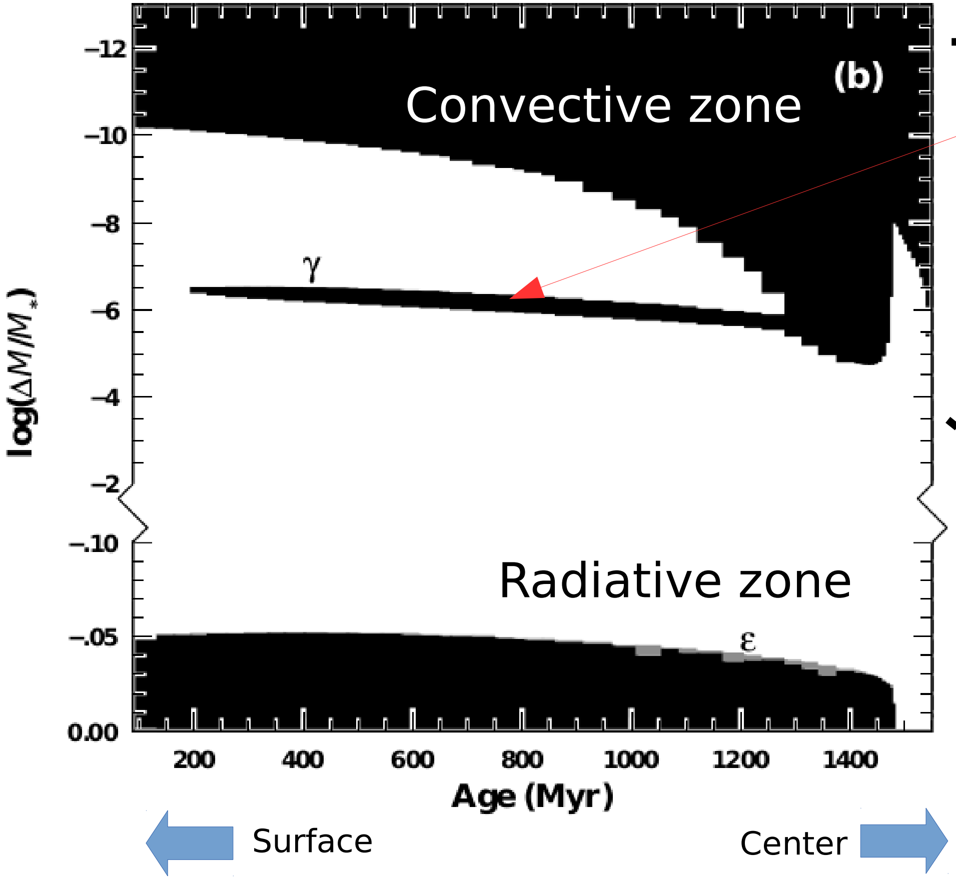
➡ **Direct influence** on stellar **structure** and **hydrodynamics**

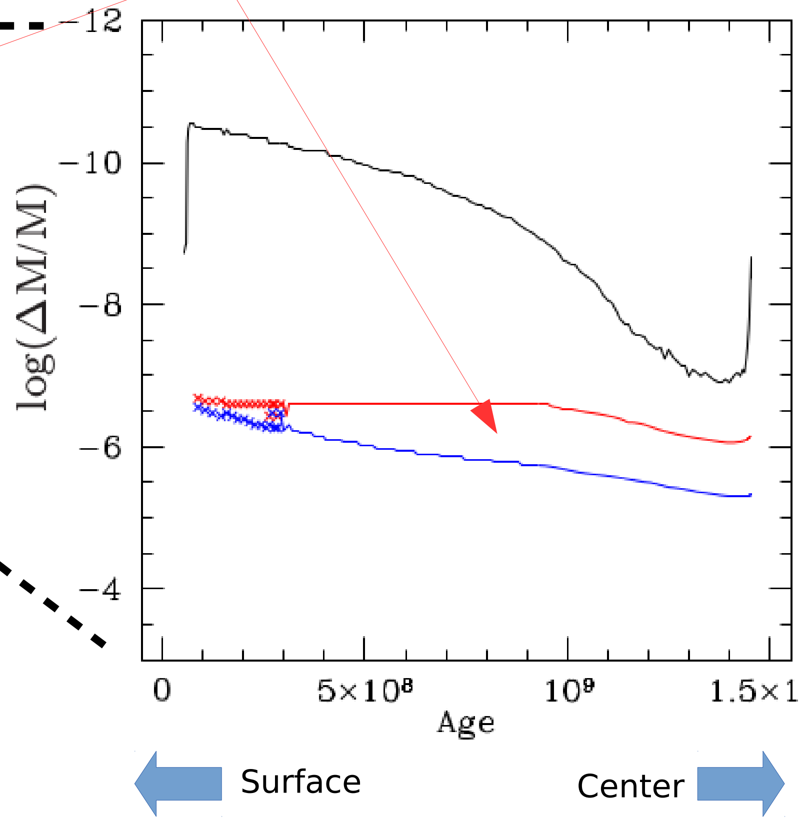
Atomic diffusion inside stars

Microscopic processes have a direct impact on stellar structure

1.7 $M_\odot$ at solar metallicity

Iron opacity induced convective zone





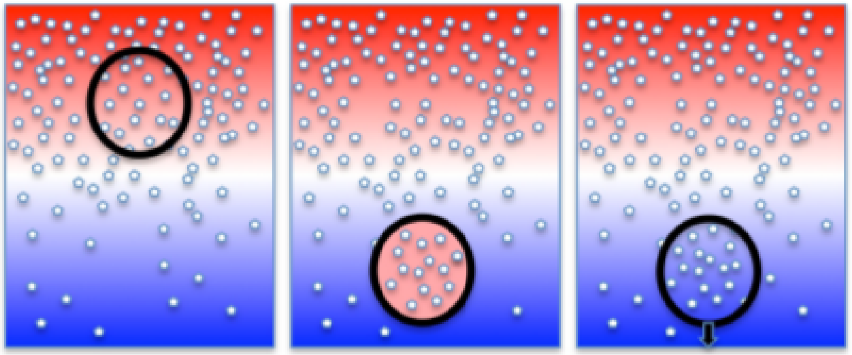
Richard + 2001

Montréal/Montpellier Evolution Code

Théado + 2009

Toulouse Geneva Evolution Code

Fingering (thermohaline) convection



Garaud + 2014

unstable mean molecular weight gradient

stable temperature gradient

1D prescriptions (from 2D and 3D simulations):

Denissenkov +2010, Traxler +2011, Brown +2013 tested by Zemskova, Garaud, Deal, Vauclair 2014

The term $-D_{fing}\frac{\partial c_i}{\partial r}$ is added to the diffusion velocity

Apply on stellar cases : Planetary matter accretion, elements accumulation due to radiative accelerations, ...

F-A stars

Stars with masses larger than ~**1.3** $\boldsymbol{M_\odot}$ undergo efficient radiative accelerations

Some elements are main contributors to the opacity in some regions of the star

Due to their **ionisation state**

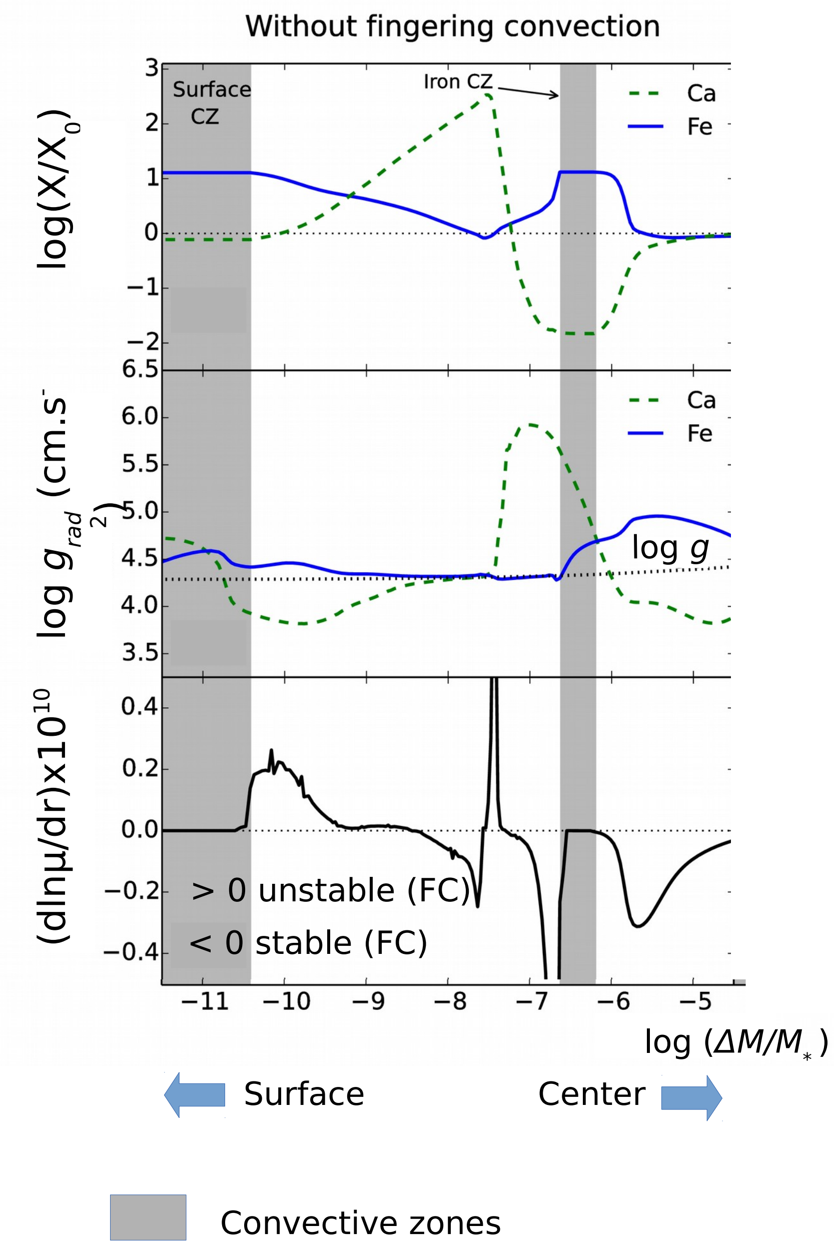
This leads to an **accumulation of the element** and an **increase of the opacity** in this region

Modification of the structure

A stars : Fingering convection

1.7 $M_\odot$

100 Myrs

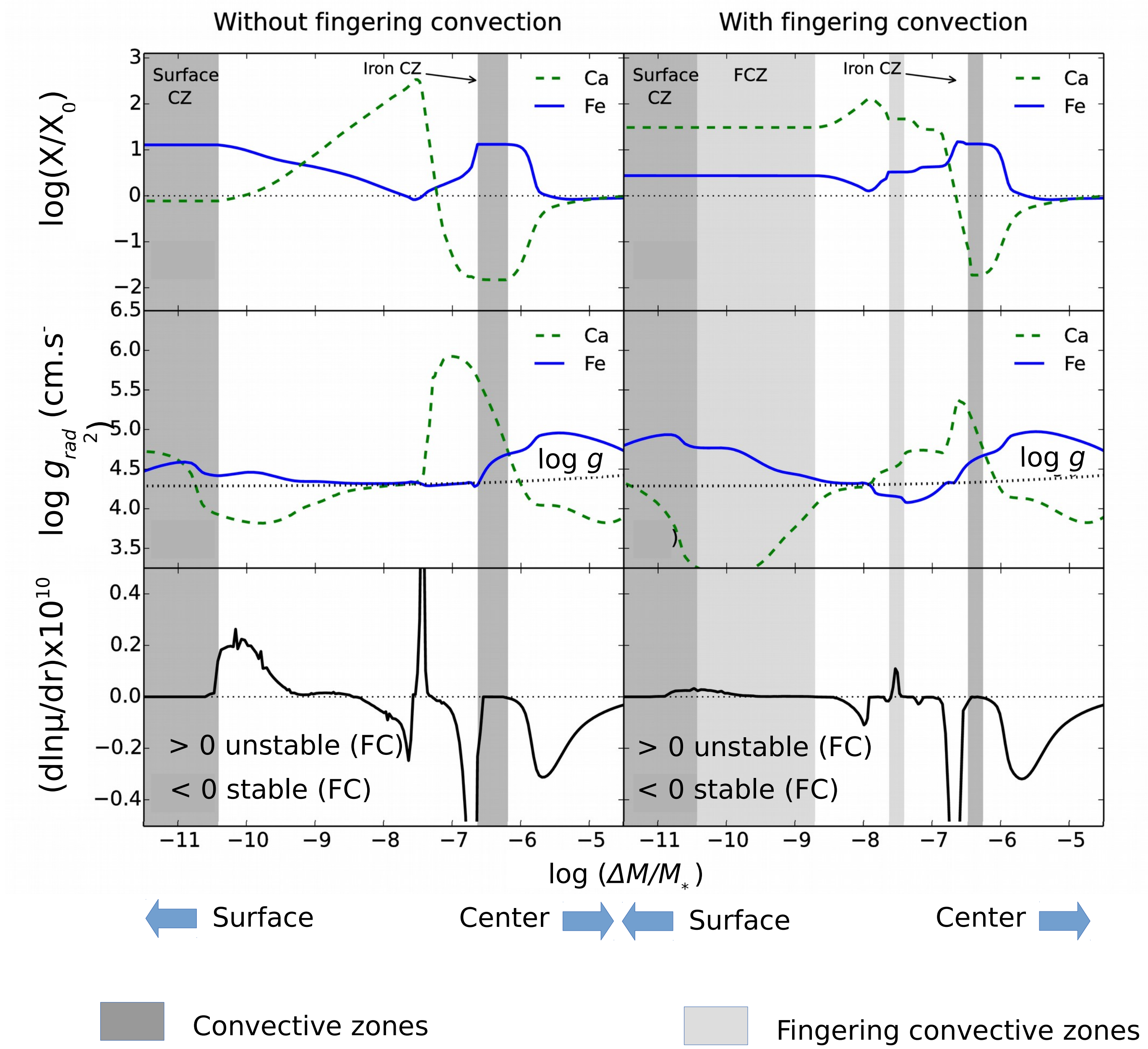


Deal +2016

A stars : Fingering convection

1.7 $M_\odot$

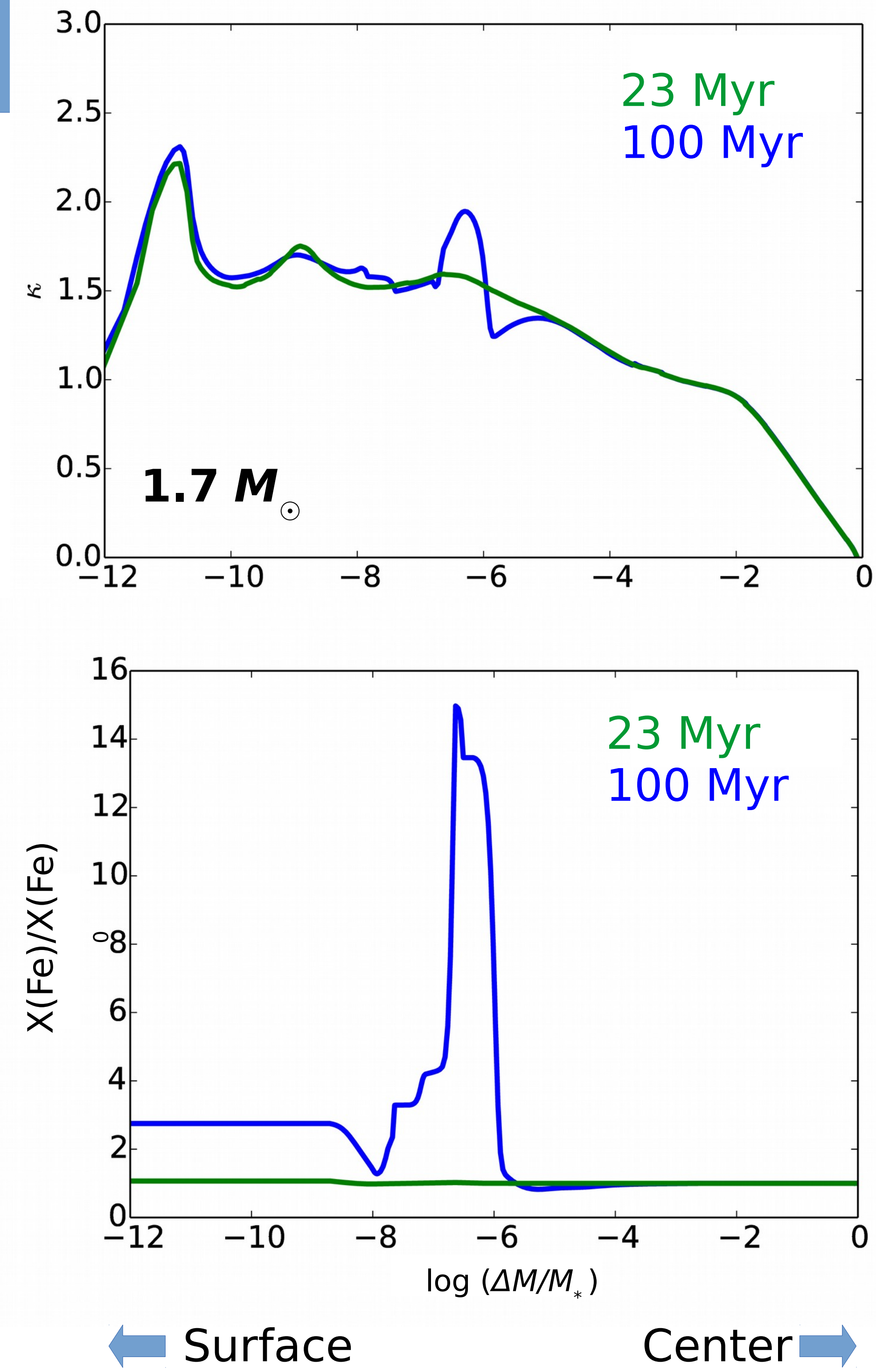
100 Myrs



Deal +2016

A stars : Opacity

The accumulation occurs where the element is **the main contributor to the global opacity**



About the Plato space mission

Planetary **T**ransit and **O**scillation of stars

ESA mission, adopted in June 2017, launch in 2026

Main goal: Find Earth-like planets around solar-like stars

Precisions on stellar: - age 10%

- mass 15%

- radius 2%

94 Ceti A (TGEC): seismic comparison

94 Ceti A is a **F-type** star (1.44 $M_{\odot}$, [Fe/H]=0.17)

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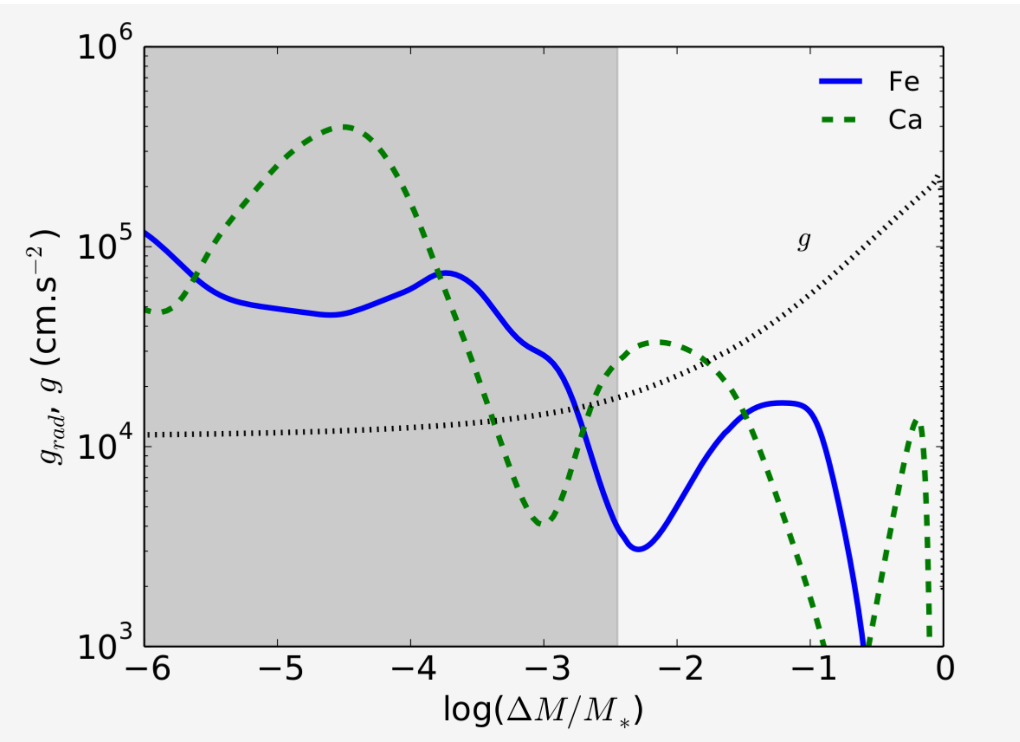

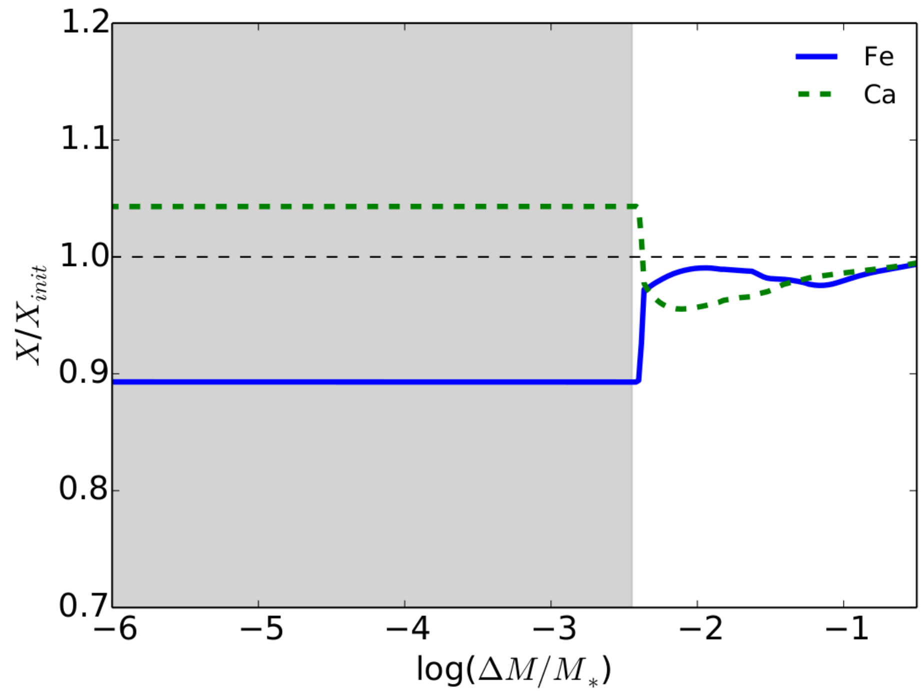

Deal +2017

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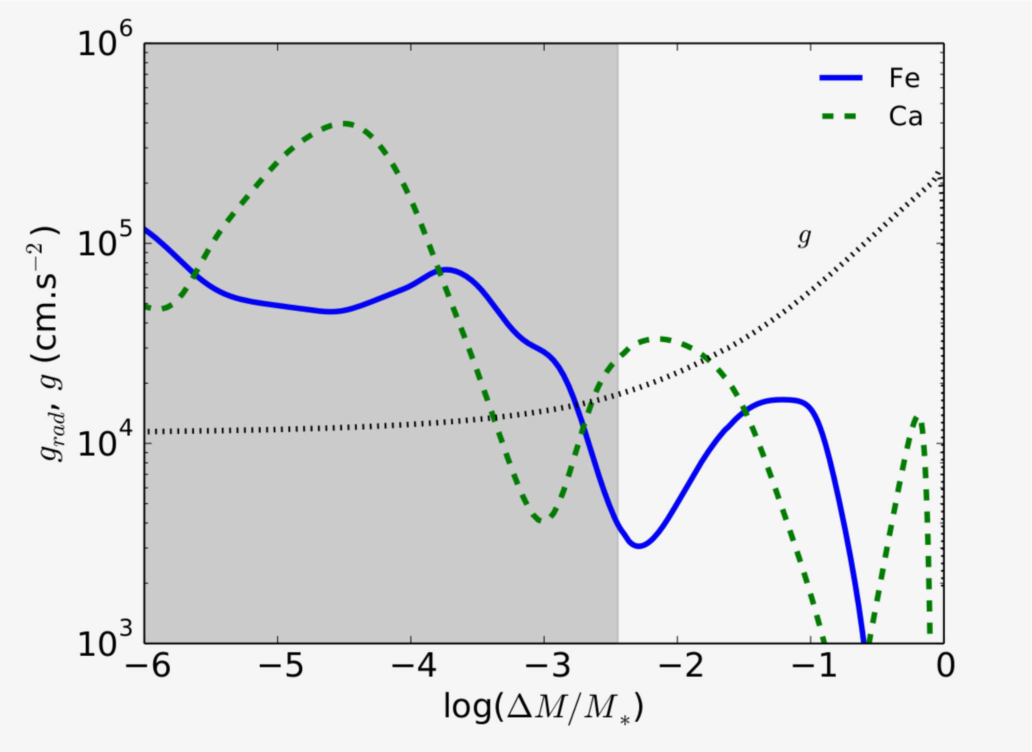

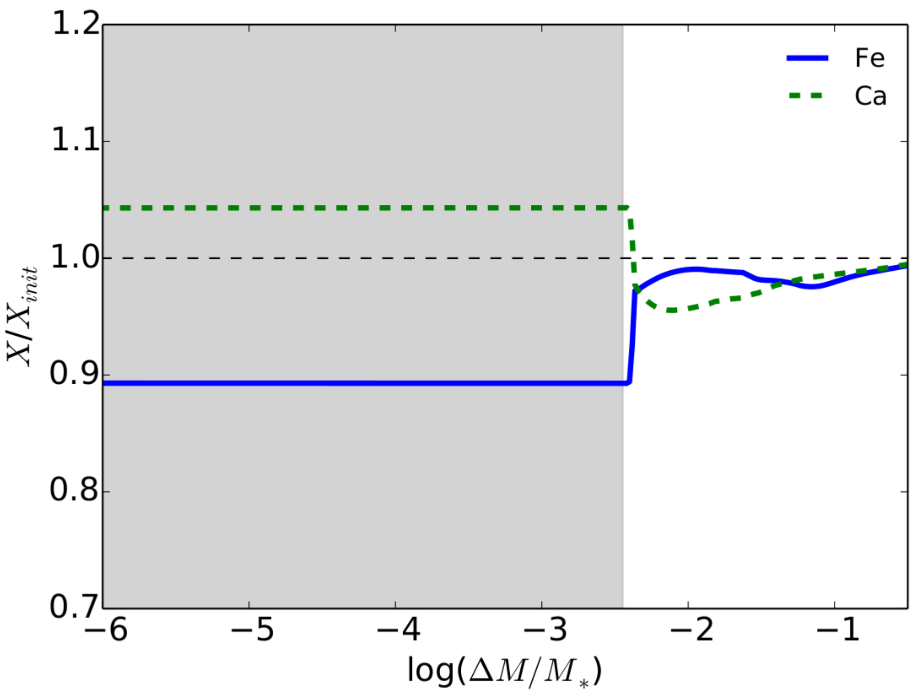

Deal +2017

Increase of the mass of the surface convective zone (~**20%** in this case)

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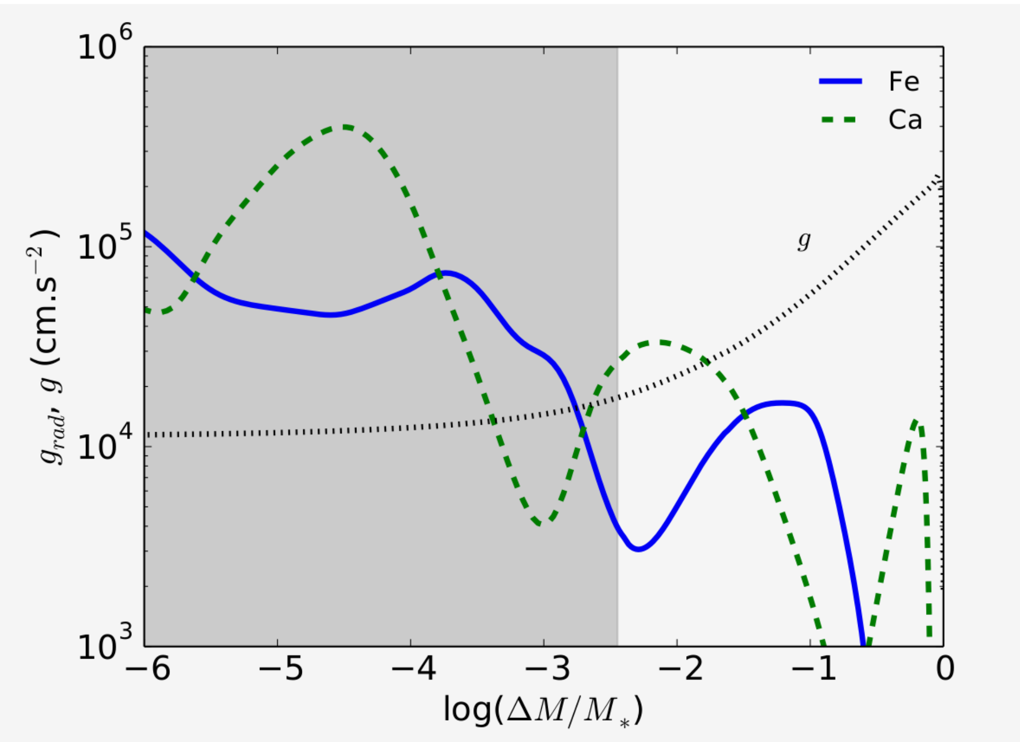
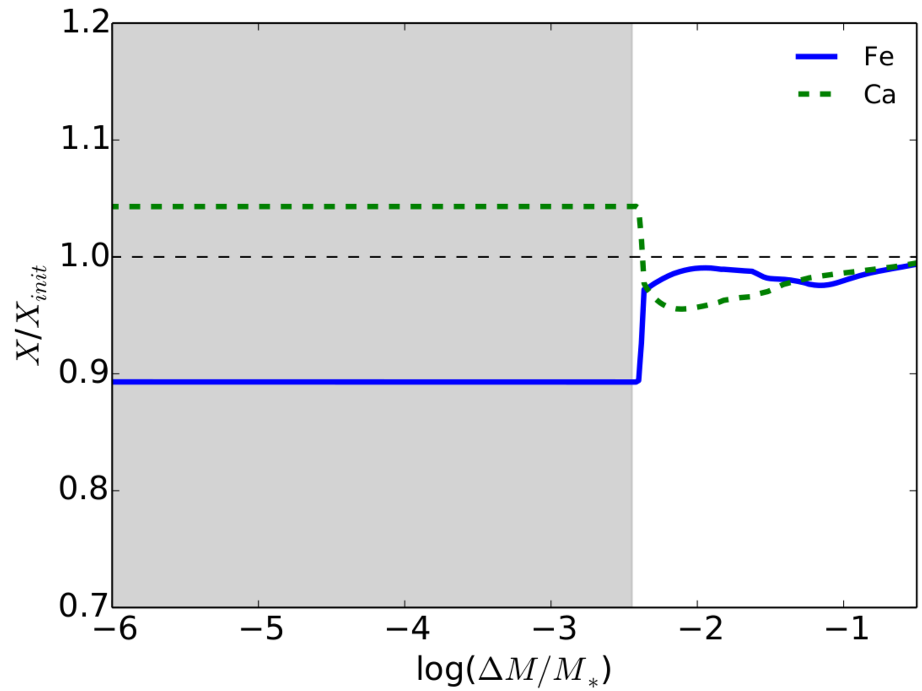




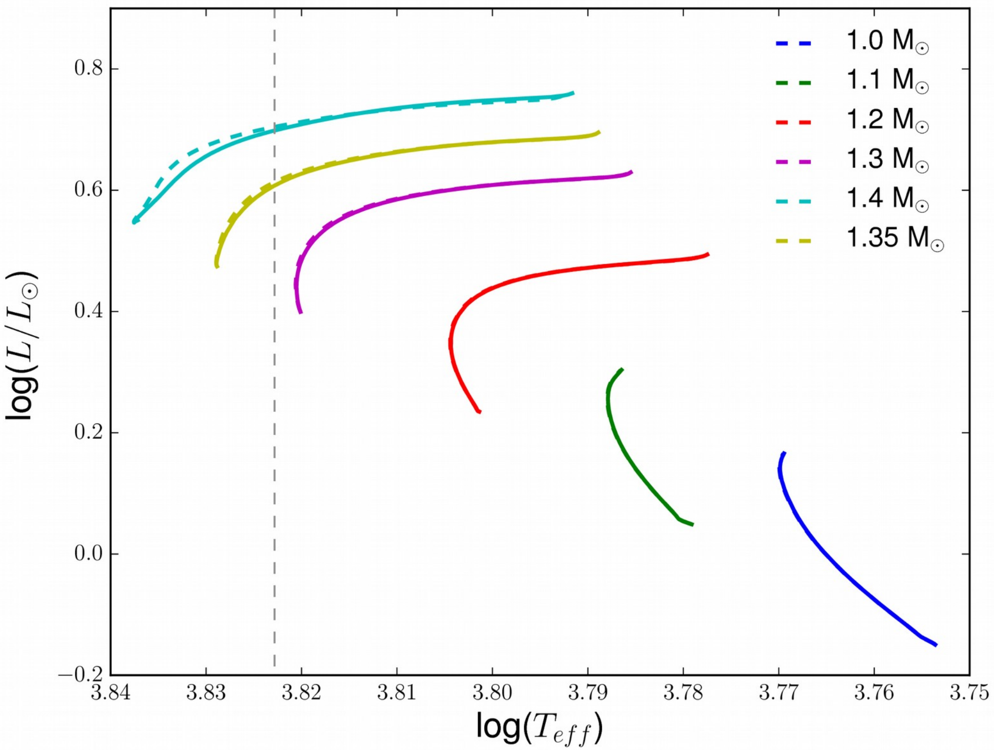
Deal +2017

Increase of the mass of the surface convective zone (~**20%** in this case)

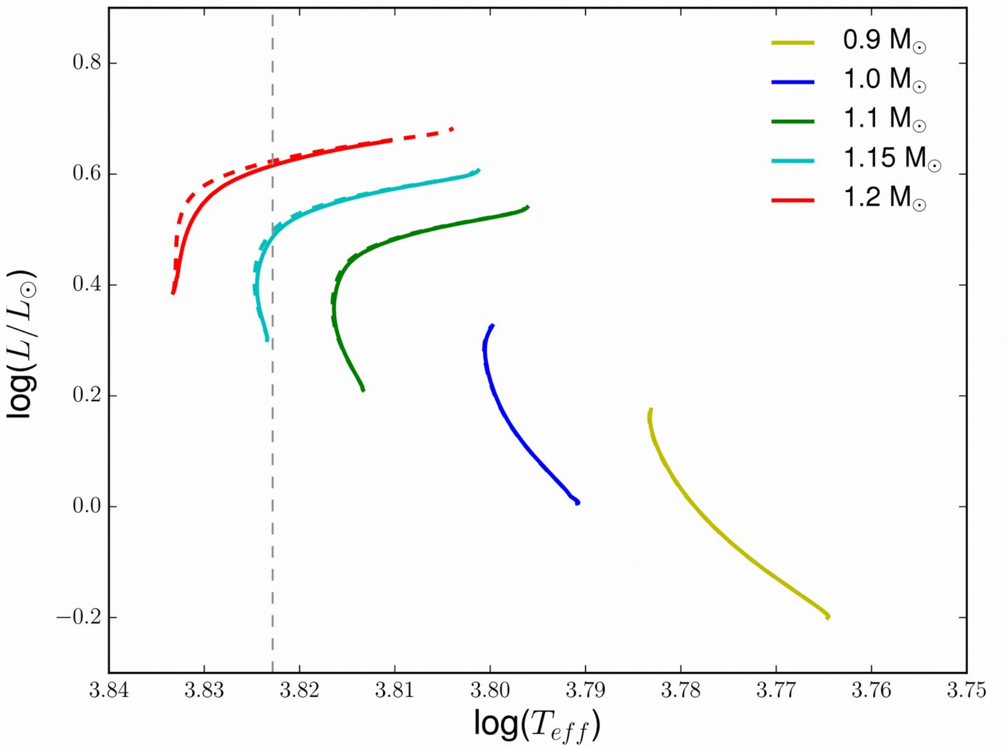
Age difference of 4%, radius difference of 1%

Cestam: Impact on seismic parameters

$[Fe/H]_0=0$



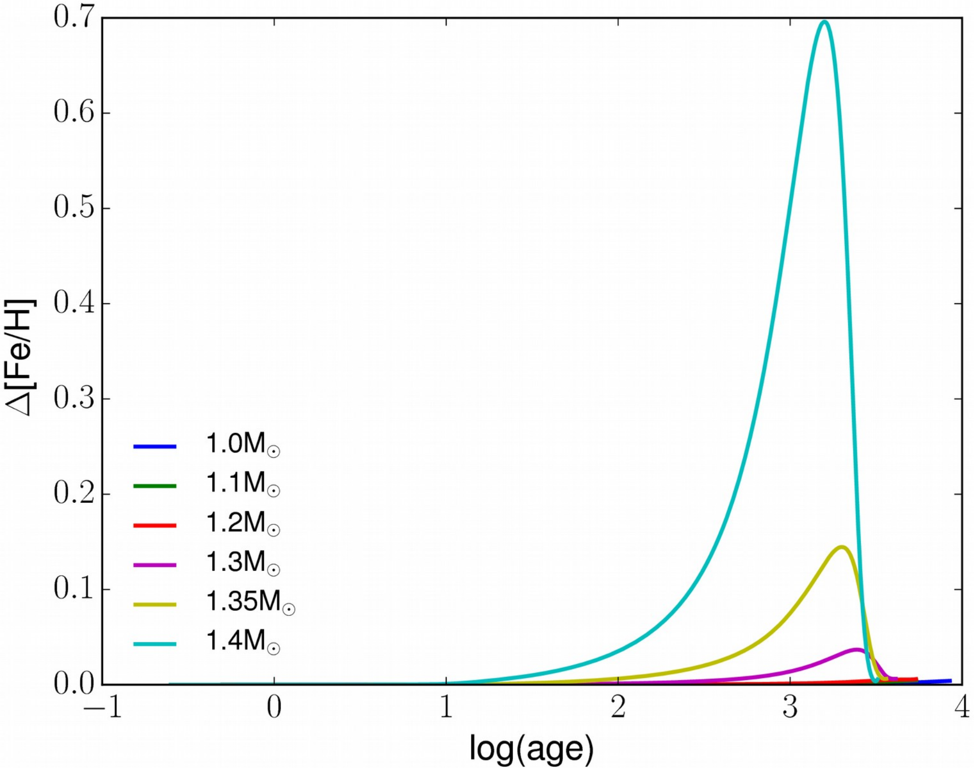
$[Fe/H]_0=-0.4$



Models computed with the **new version of CESTAM** including the **selective diffusion** (gravitational settling + radiative accelerations) of H, He, C, N, O, Ne, Na, Mg, Al, Si, P, S, Ca, Fe and some isotopes

Cestam: Impact on seismic parameters

$[Fe/H]_0=0$



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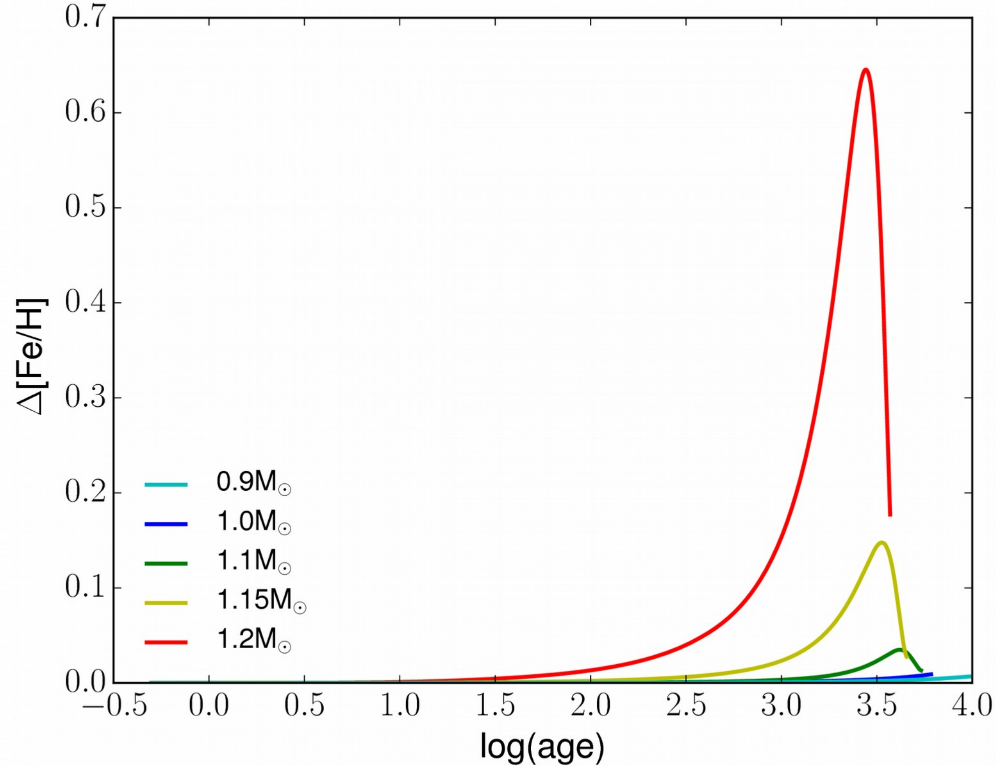
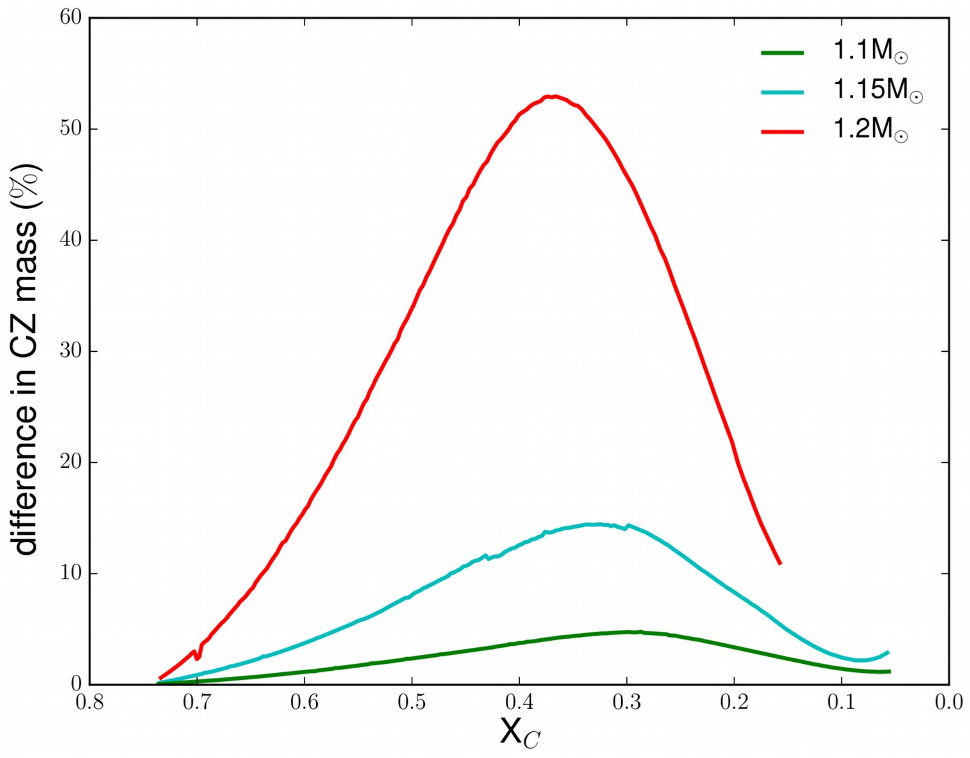


Δ[Fe/H]

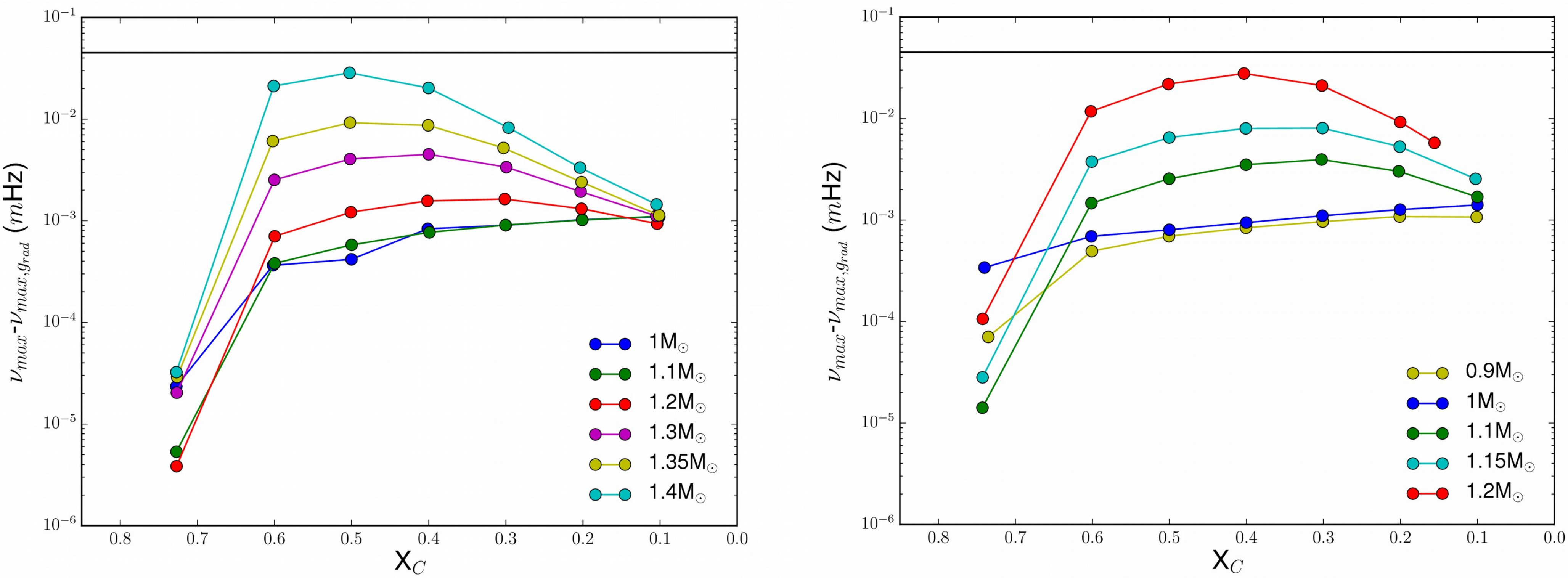
Cestam: Impact on seismic parameters

$[Fe/H]_0$=-0.4



Cestam: Impact on seismic parameters

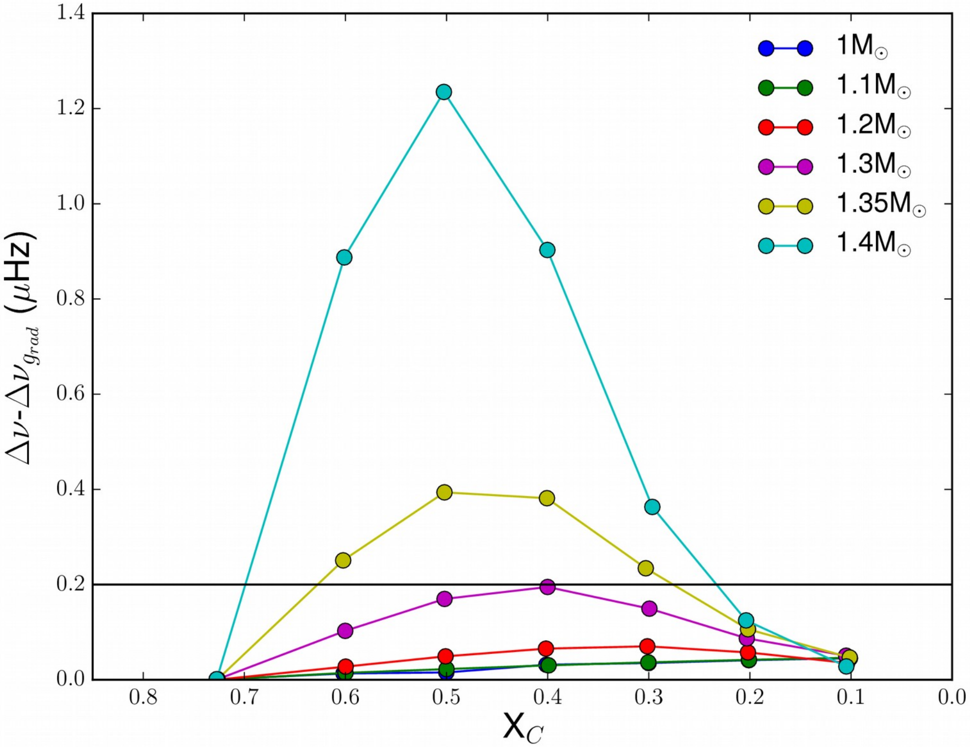
$[Fe/H]_0=0$ $\quad$ $[Fe/H]_0=-0.4$



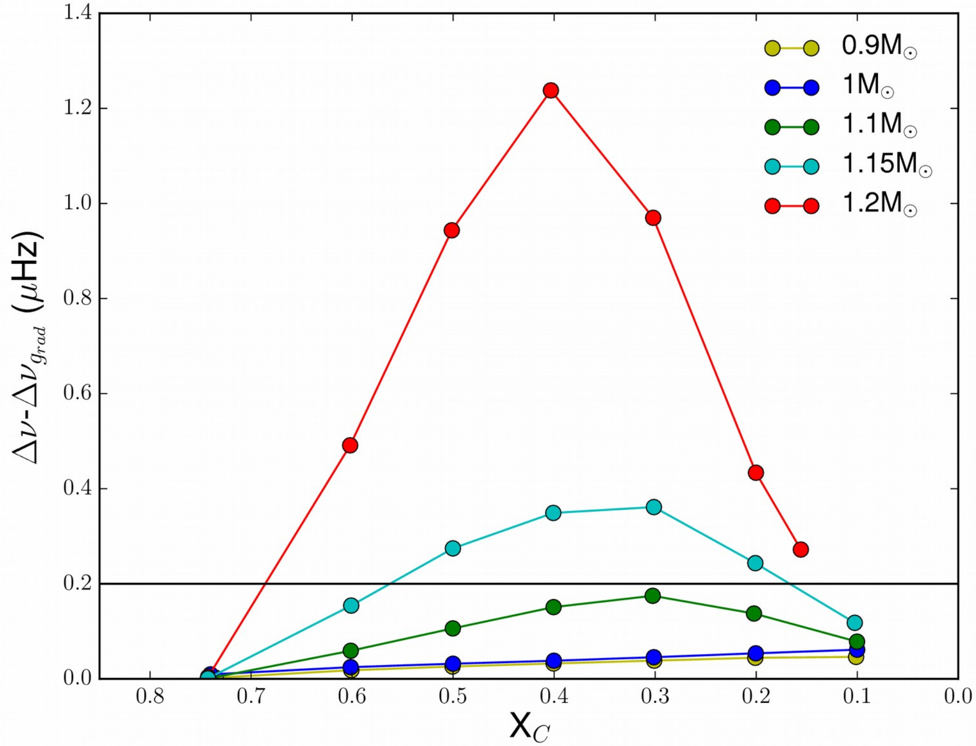
ν_{max}

Cestam: Impact on seismic parameters

$[Fe/H]_0=0$



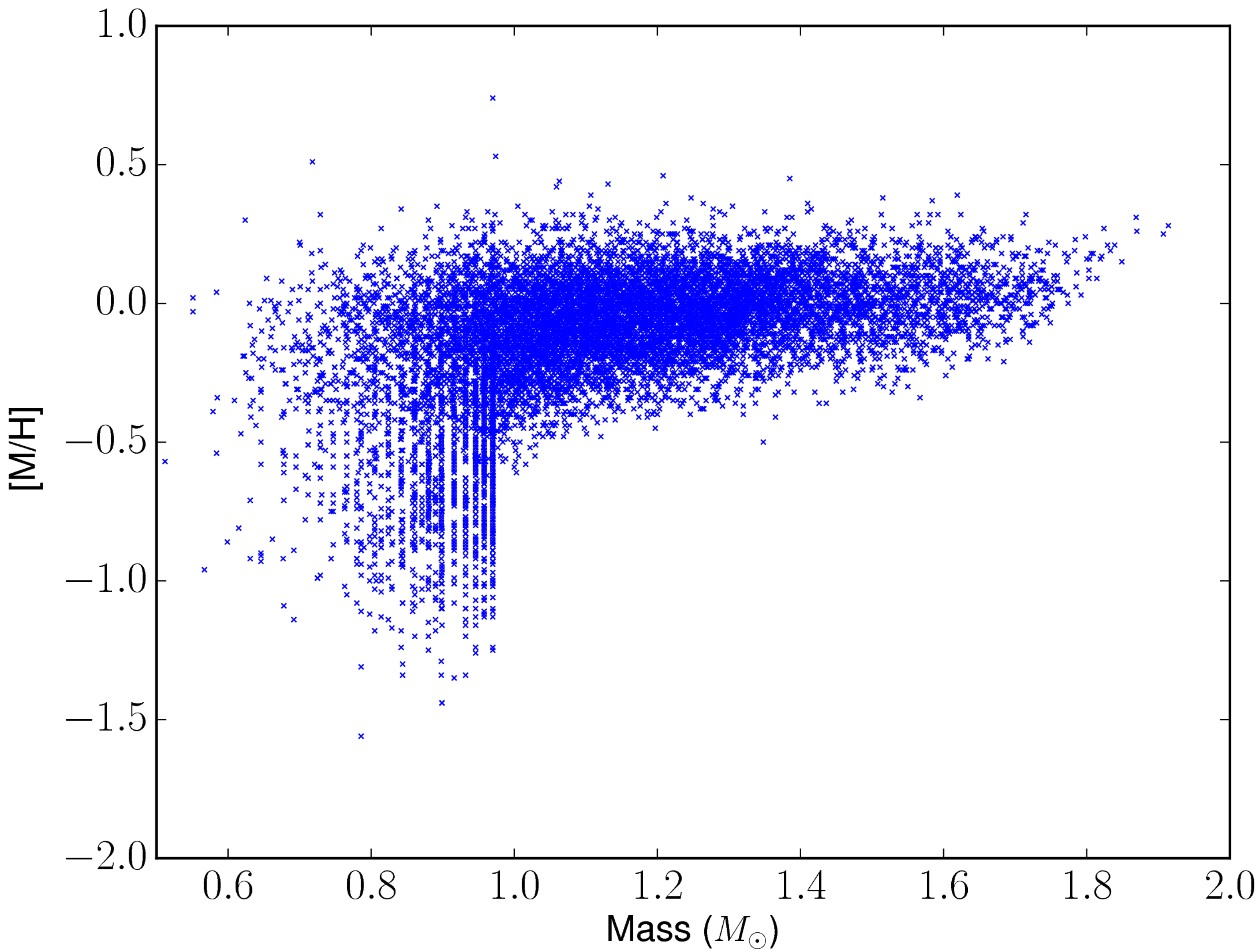
$[Fe/H]_0=-0.4$



$\Delta\nu$

About the Plato space mission

Core program stars (simulation from T. Morel and A. Robin)



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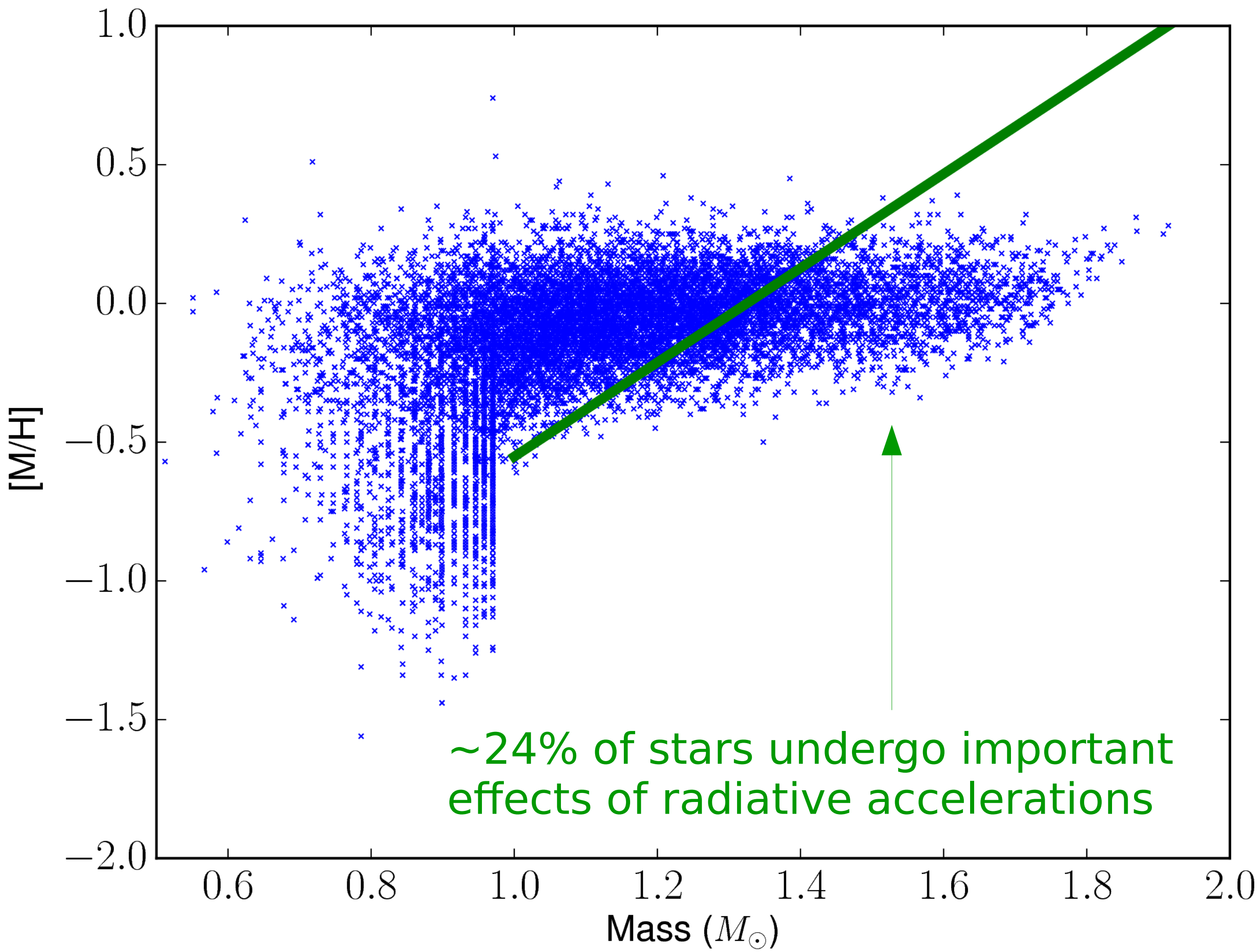

(~51% of the total field)

Conclusion

Atomic diffusion leads to **macroscopic instabilities** (opacity induced convection, fingering convection) that need to be taken into account in stellar evolution codes

Radiative accelerations can modify the **age determination** from asteroseismology by 4% (94 Ceti A)

These processes will impact up to **24%** of the core program stars of the **Plato** space mission (can't be neglected but other transport processes may reduce the effect)