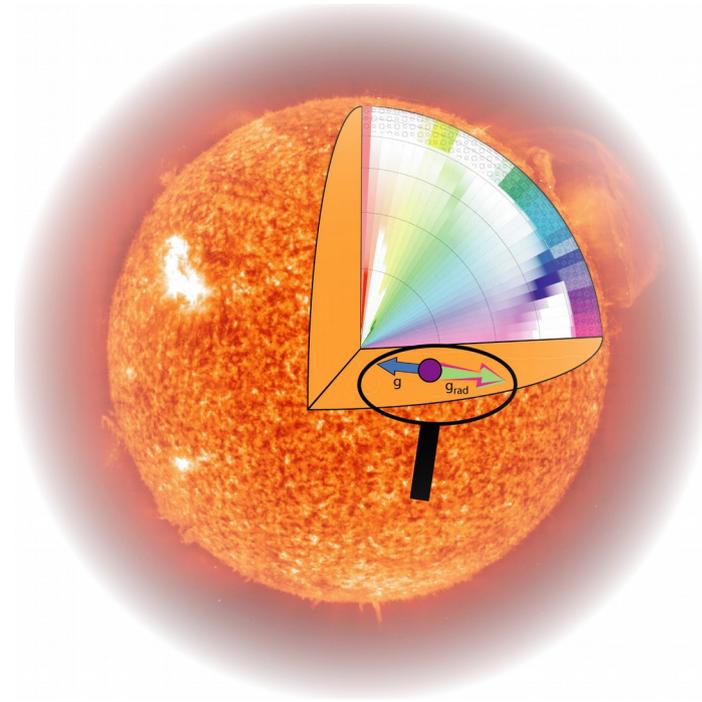# Impact of atomic diffusion on the structure and surface abundances of G and F type stars:
## stellar parameter determinations and effects of rotation

## Morgan Deal

Georges Alecian
Yveline Lebreton
Marie-Jo Goupil
Joao Pedro Marques

Francis LeBlanc

SteSci Workshop II – 24th may 2018

# Transport of elements inside stars

Diffusion velocity of element E (trace element case):

$$V_E = D_{E,p}\left[-\frac{\partial \ln c_E}{\partial r} + \frac{A_E m_p}{k_B T}\left(g_{rad,E} - g\right) + \frac{Z_E m_p g}{2 k_B T} + \kappa_T \frac{\partial \ln T}{\partial r}\right] + \sum D_{turb}\left[-\frac{\partial \ln c_E}{\partial r}\right]$$

Radiative acceleration term

Gravitational settling term
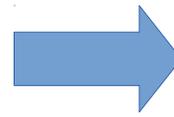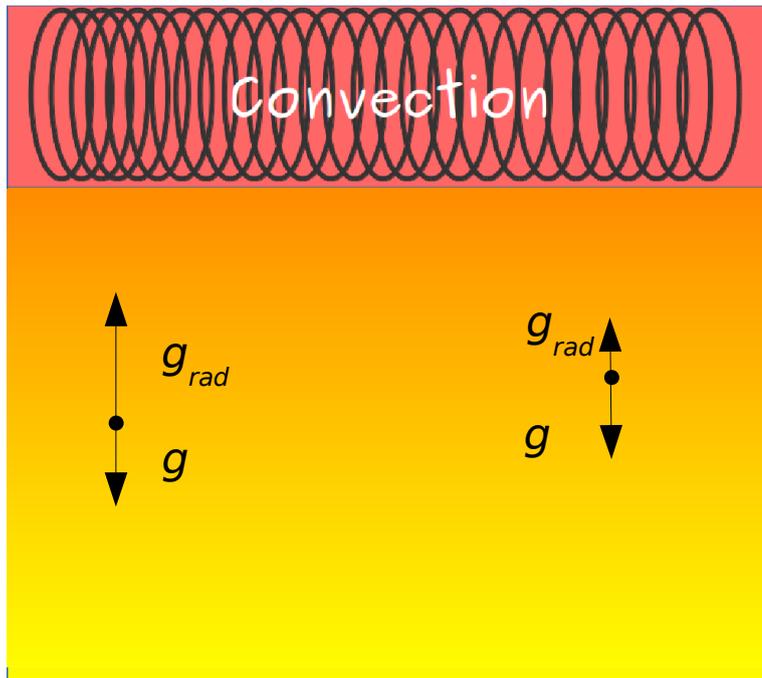
Macroscopic transport processes

Continuity equation :

$$\frac{\partial \rho c_E}{\partial t} = -\nabla \cdot \left(\rho V_E c_E\right)$$

The sign of the velocity mainly depends on the one of (if **D$_{turb}$ is negligible**)
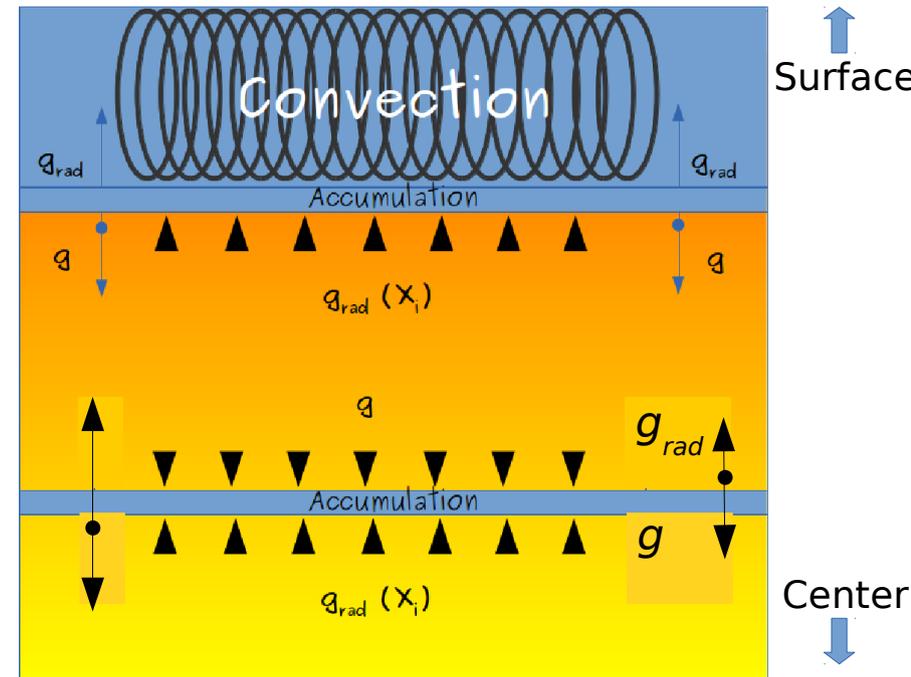
$$\left(g_{rad,E} - g\right)$$

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

# Atomic diffusion inside stars



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 : CESTAM

**CESTAM** (Marques +2013):

Based on the CESAM code (Morel & Lebreton 2008)

| | |
|---|---|
| **Atomic diffusion** | Michaud & Proffitt equations |
| **Radiative accelerations** | Single Valued Parameter approximation (LeBlanc & Alecian 2004) |
| **Opacities** | OP monochromatic opacities |

# Atomic diffusion inside stars : CESTAM

**CESTAM** (Marques +2013):

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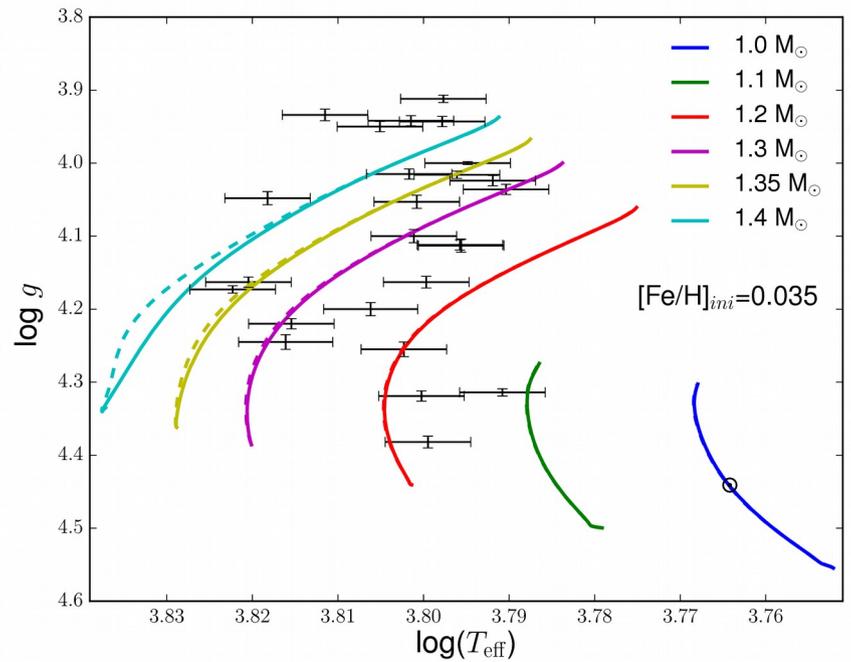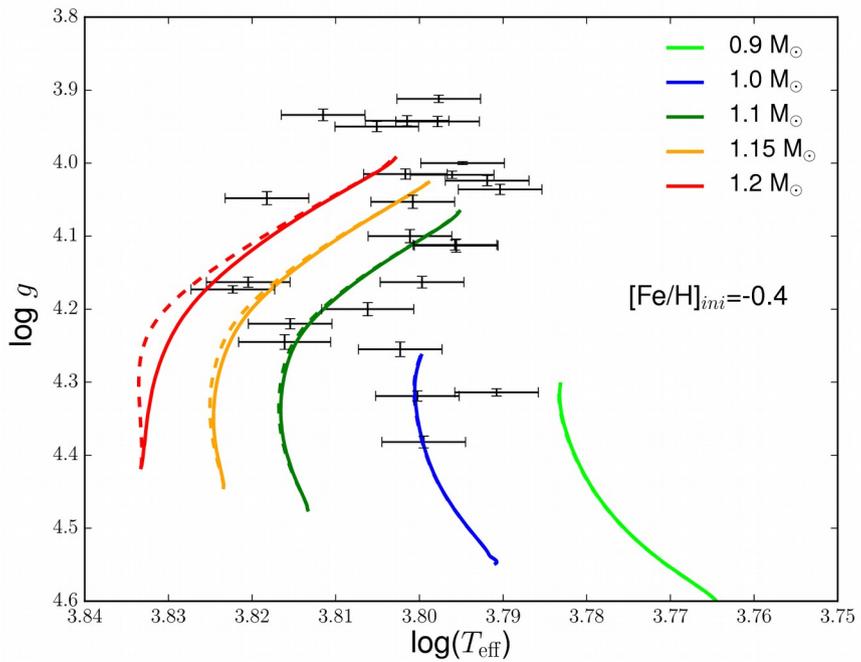| Atomic diffusion | Michaud & Proffitt equations |

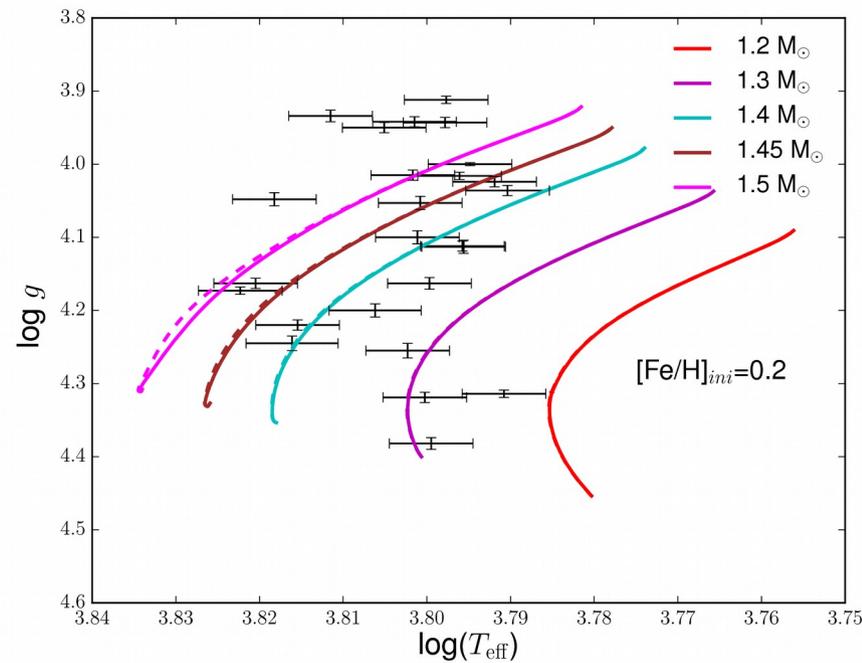| Radiative accelerations | Single Valued Parameter  approximation (LeBlanc & Alecian 2004) |

| Opacities | OP monochromatic opacities |

Diffusion of He, C, N, O, Ne, Na, Mg, Al,
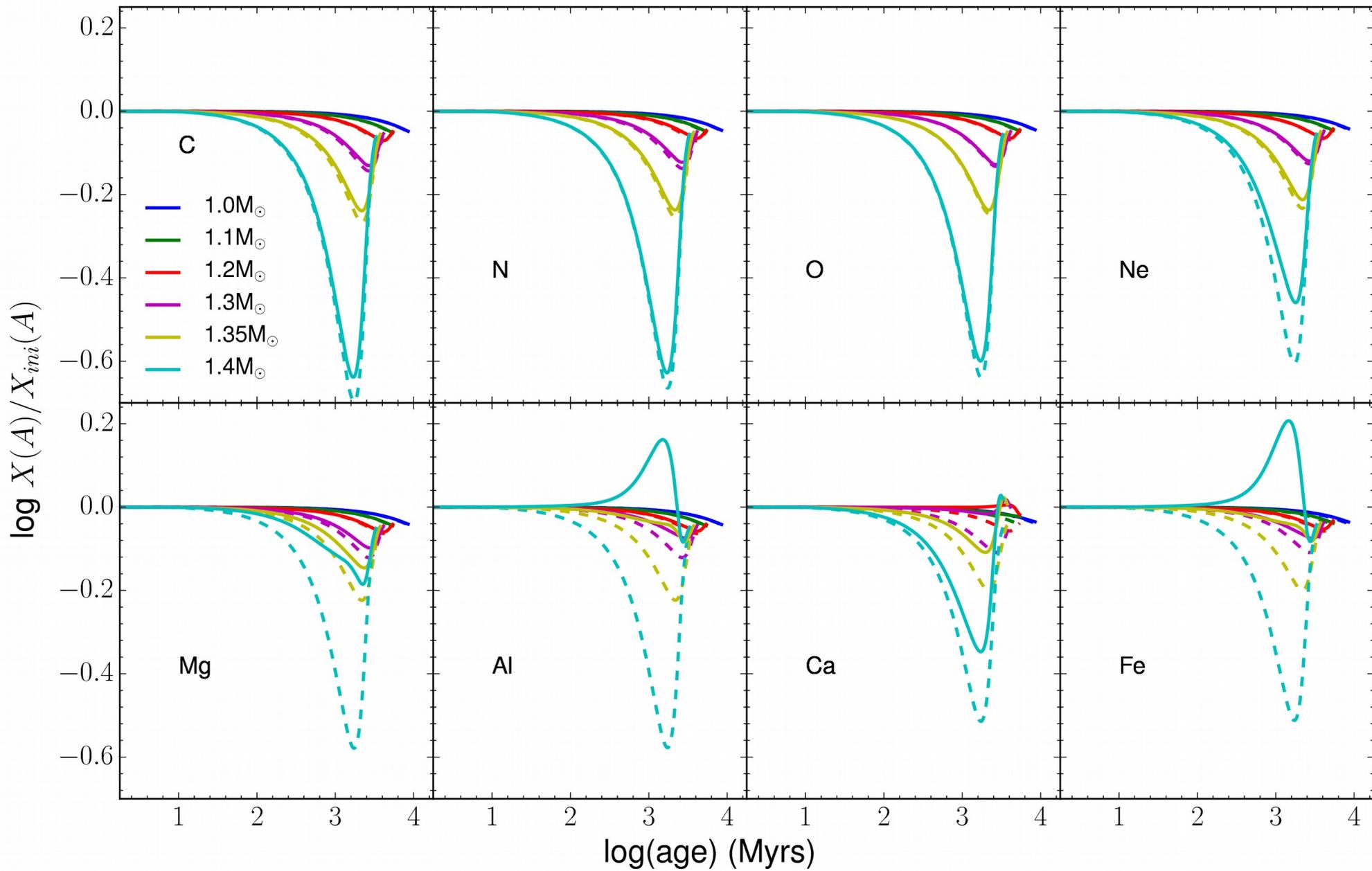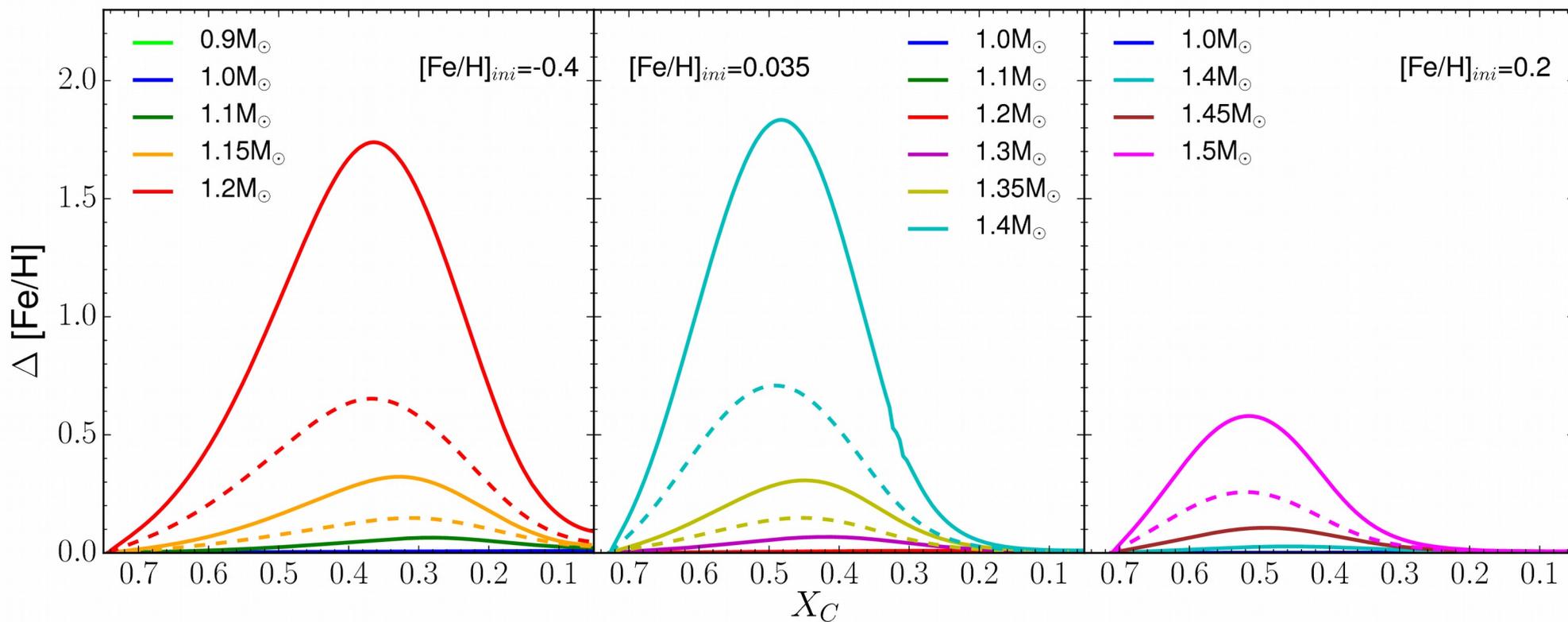Si, S, Ca and Fe (soon Ni!)

# Evolution



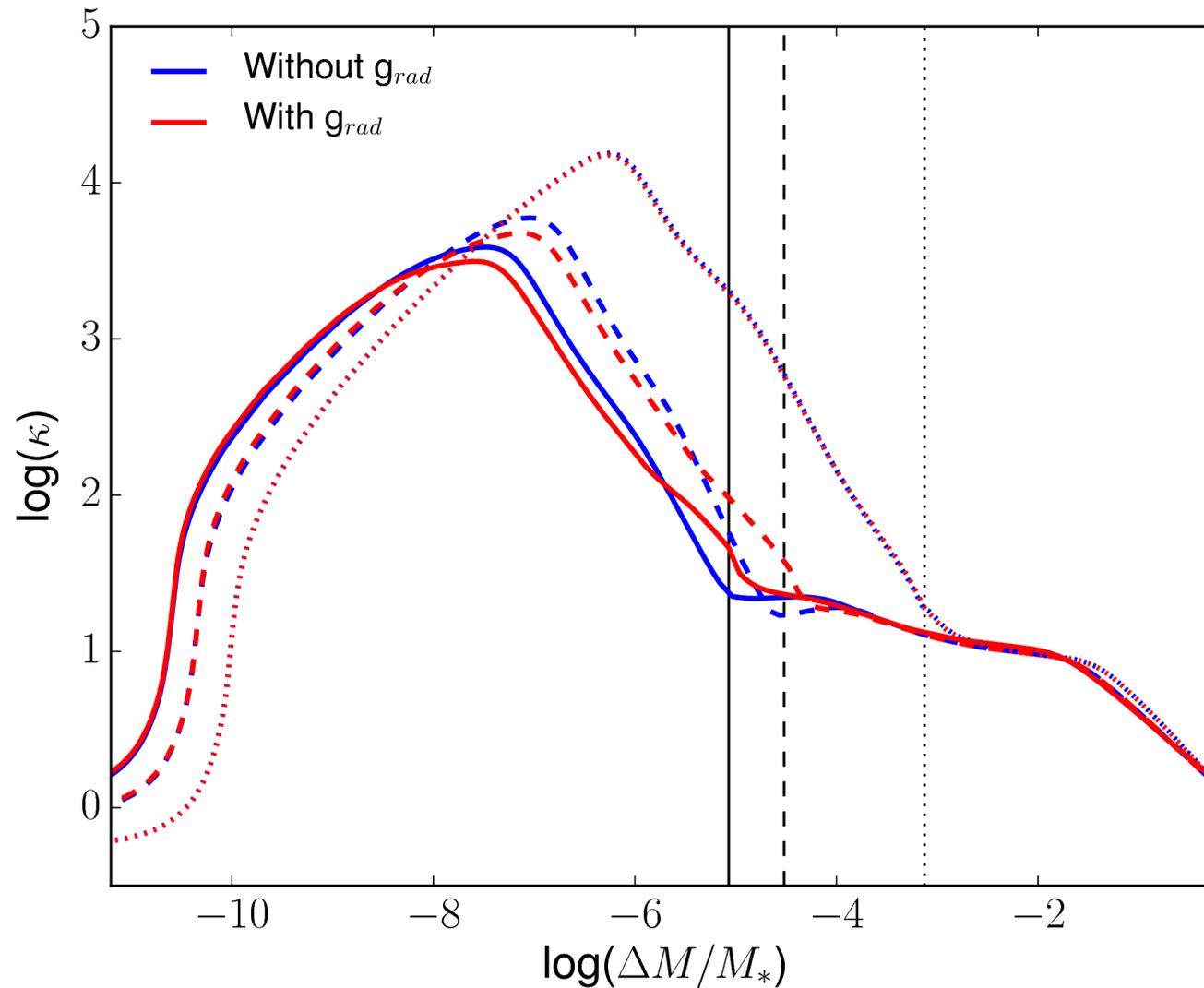Deal +2018 (subm.)

# Surface abundances

# Surface abundances

Difference of [Fe/H] between models with and without radiative accelerations



Deal +2018

# Surface convective zone

Local increase of the opacity due to iron accumulation

**1.4 $M_\odot$, [Fe/H]ini=0.035**

# Surface convective zone

Difference of $M_{cz}$ between models with and without radiative accelerations



Deal +2018

# Surface convective zone

Difference of $M_{cz}$ between models with and without radiative accelerations
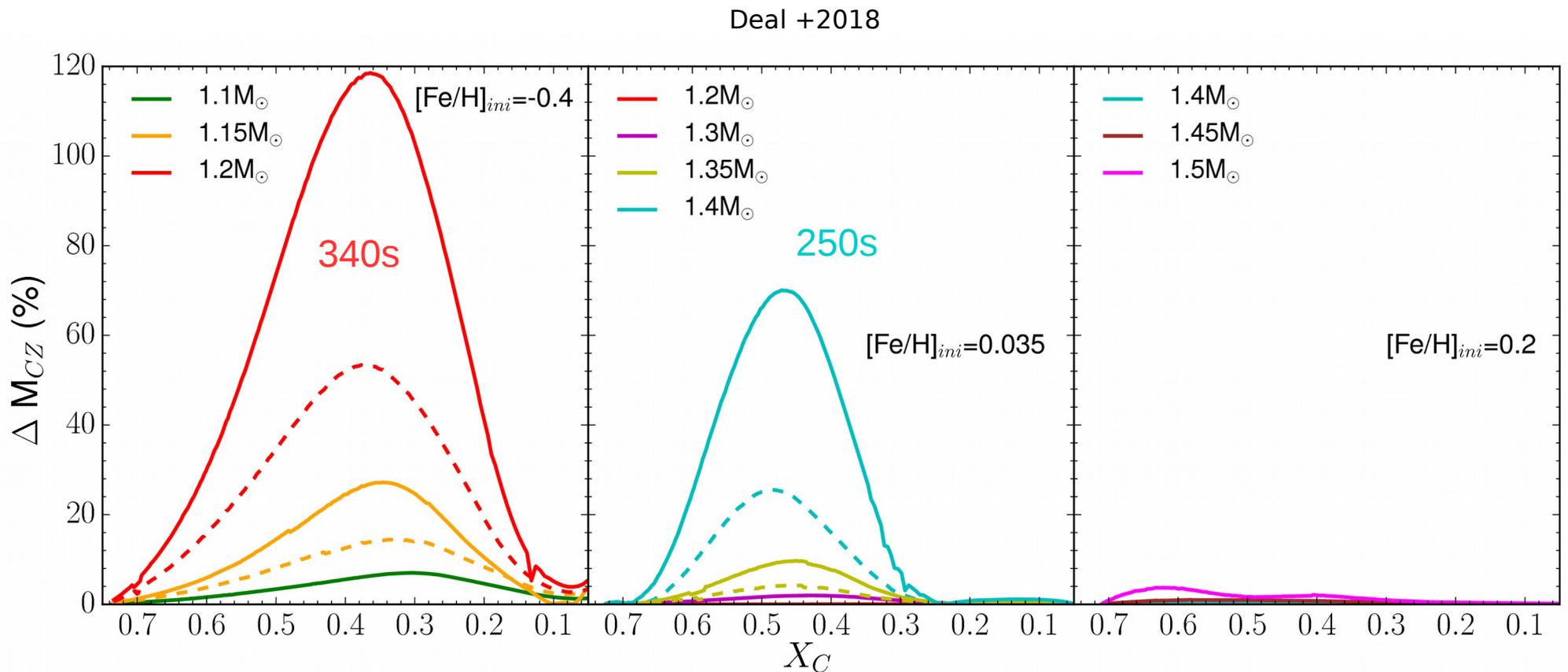
Deal +2018



**Larger than the uncertainty** on the **acoustic depth** of surface convective zone of some F type stars from ***Kepler*** (Verma+ 2017)

# Radius

Difference of radius between models with and without radiative accelerations



Deal +2018
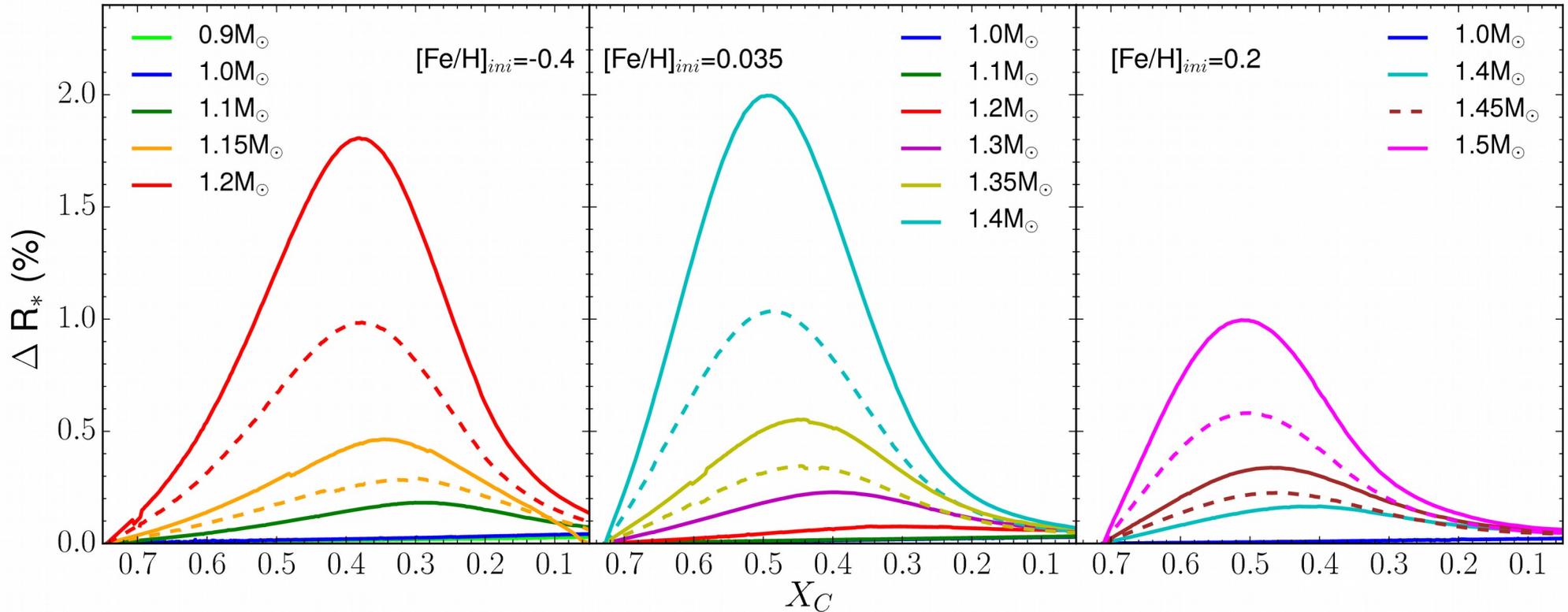
**2%** in radius at maximum

# Δv₀ and v_max



Deal +2018

# $\Delta v_0$ and $v_{max}$
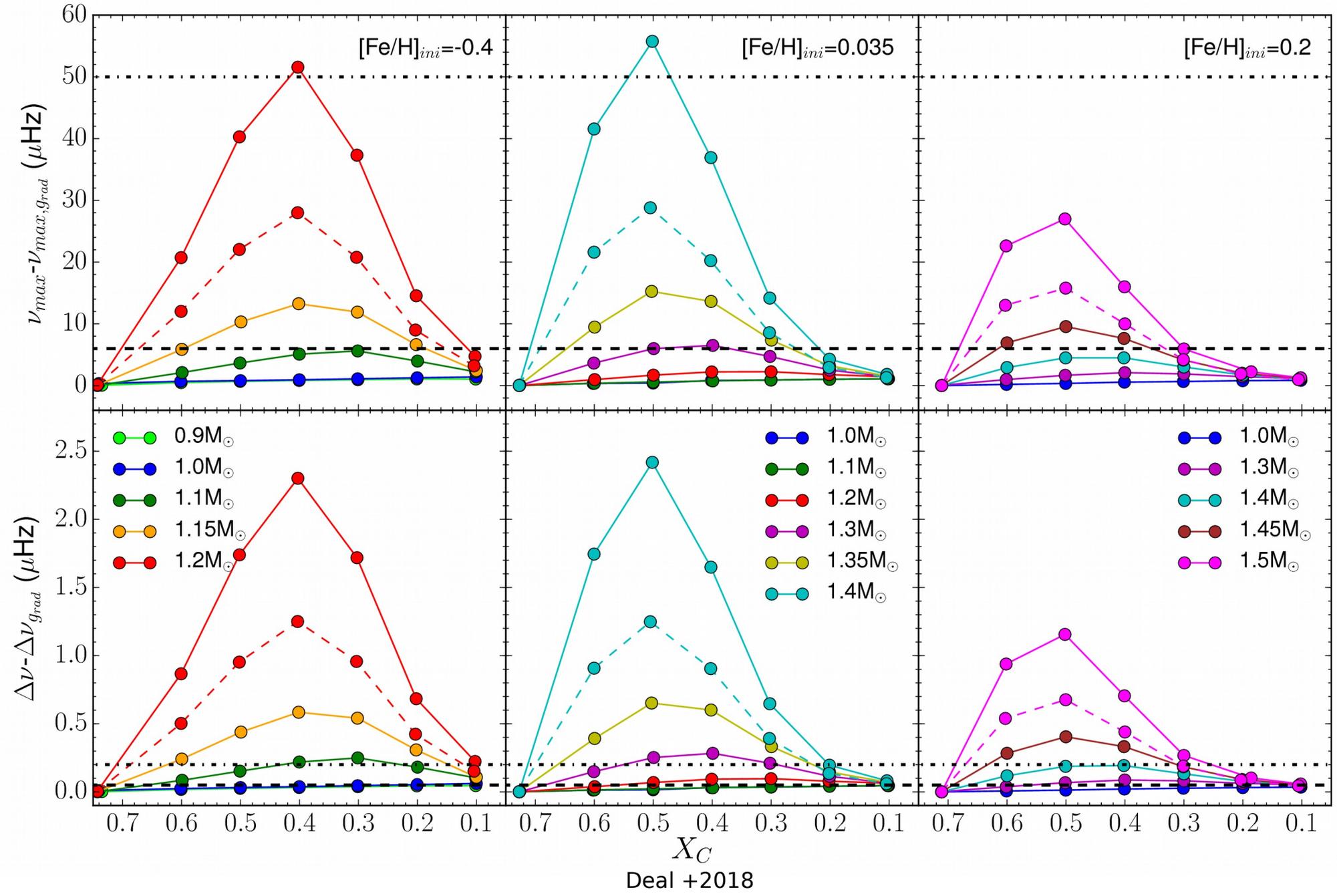
| Uncertainty sets (µHz) | $\delta v_{max}$ | $\delta \Delta v_0$ |
|---|---|---|
| A | 6 | 0.05 |
| B | 50 | 0.2 |

| | 1 | 2 | 3 |
|---|---|---|---|
| [Fe/H]$_{ini}$ | -0.4 | 0.035 | 0.2 |
| Limit Mass A ($M_\odot$) | 0.9 | 1.1 | 1.2 |
| Limit Mass B ($M_\odot$) | 1.05 | 1.25 | 1.4 |

# $\Delta v_0$ and $v_{max}$

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Deal +2018



*Simulation of stellar population from the Besançon code (A. Robin and T. Morel)*

*Kepler*

PLATO

# $\Delta \nu_0$ and $\nu_{max}$

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Deal +2018
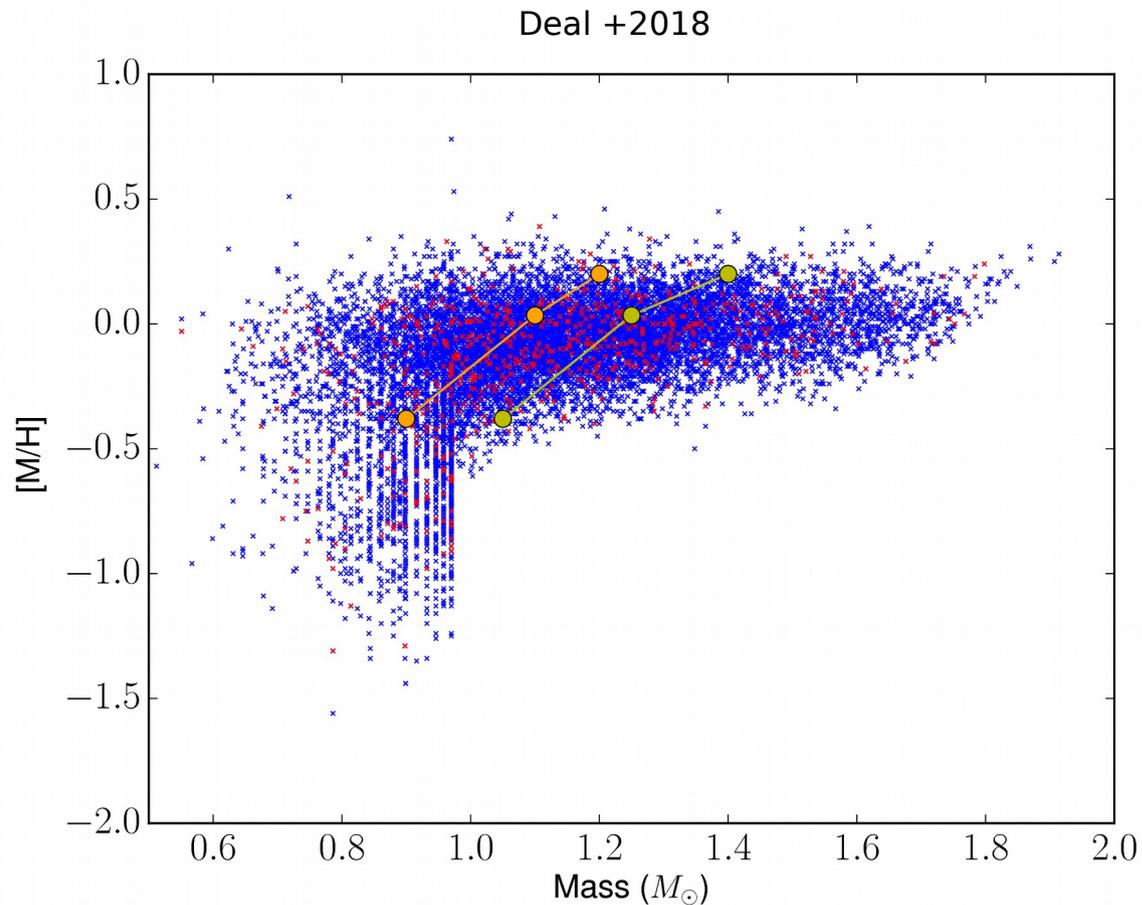
*Kepler*

PLATO
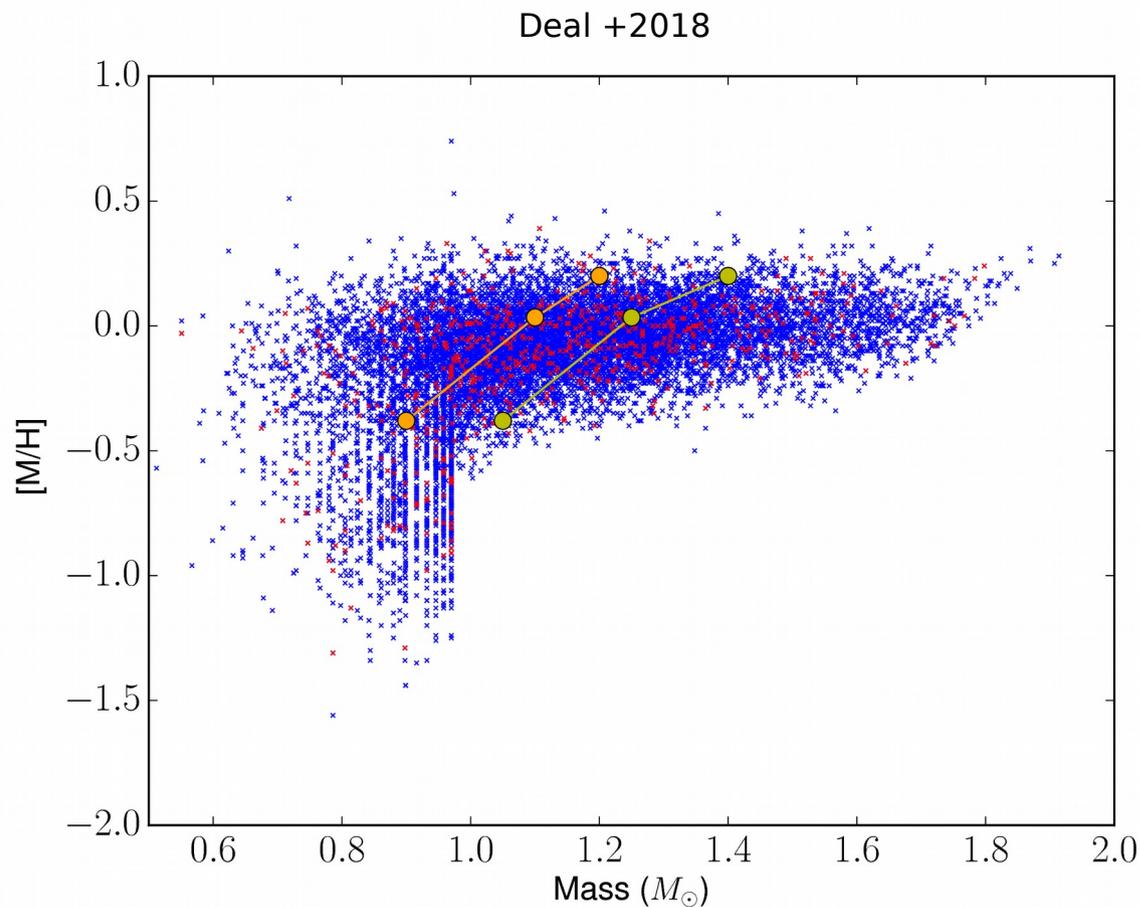
*Simulation of stellar population from the Besançon code (A. Robin and T. Morel)*

Between **33%** and **59%** of core program stars

# Parameter determinations

**94 Ceti A:** age difference of 4% (Deal et al. 2017)

**1.4 M$_\odot$ at solar metallicity:** age difference of 12%, mass difference 4% using AIMS (Deal et al. In prep.)

# Impact of rotation

Diffusion velocity of element E (trace element case):

$$V_E = D_{E,p}\left[-\frac{\partial \ln c_E}{\partial r} + \frac{A_E m_p}{k_B T}\left(g_{rad,E} - g\right) + \frac{Z_E m_p g}{2 k_B T} + \kappa_T \frac{\partial \ln T}{\partial r}\right] + \sum D_{turb}\left[-\frac{\partial \ln c_E}{\partial r}\right]$$

Radiative acceleration term

Gravitational settling term

Macroscopic transport processes

# Impact of rotation

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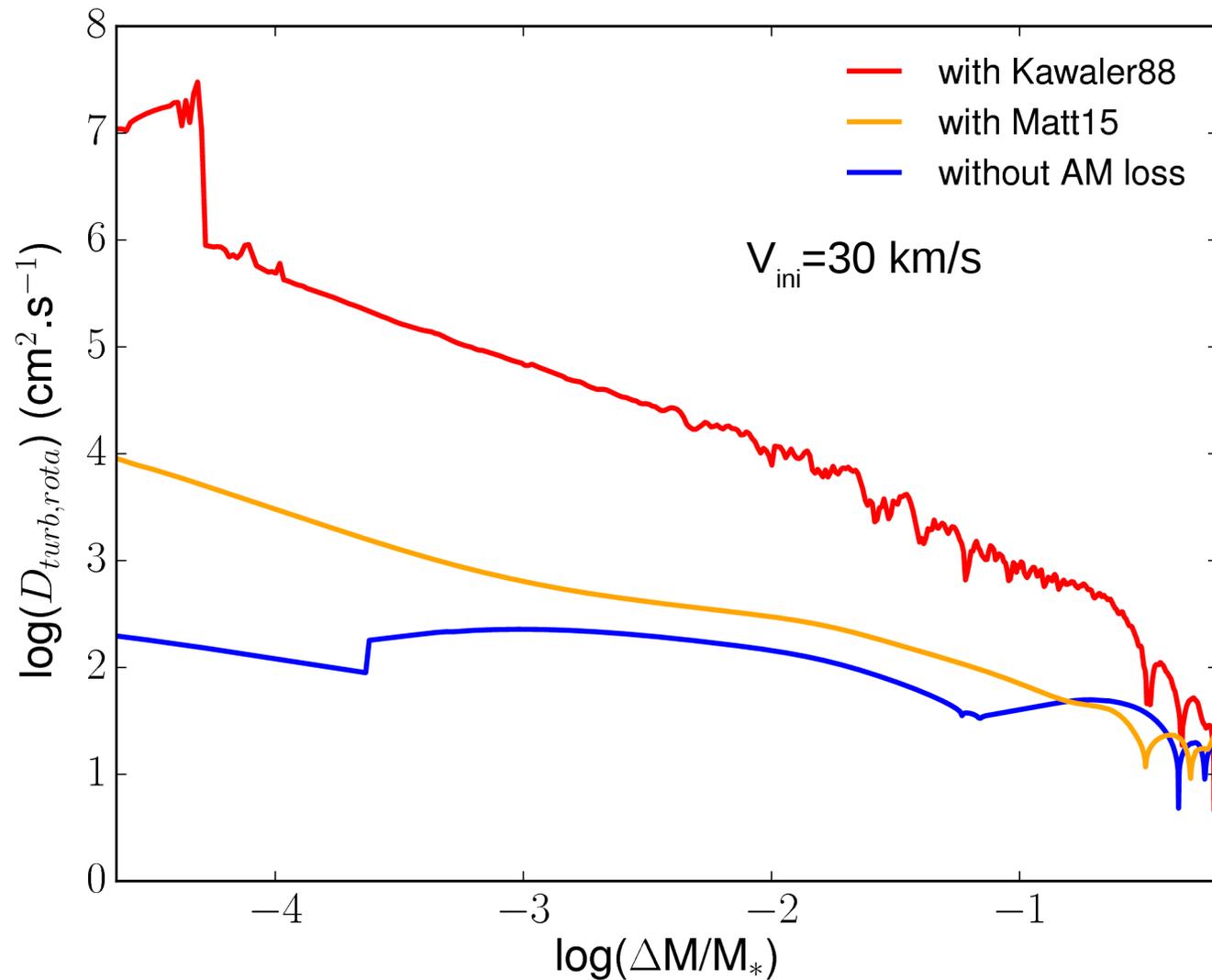
Macroscopic transport processes

Rotation-induced mixing turbulent diffusion coefficient:

$$D_{turb,rota} = D_v + \frac{\left(r U_2\right)^2}{30 D_h}$$

# Impact of rotation

## Angular momentum loss at the surface

$1.4\ M_\odot$, $[\text{Fe/H}]_{ini}=0.035$, age=1Gyr



with Kawaler88
with Matt15
without AM loss

$V_{ini}=30$ km/s

# Impact of rotation

## Angular momentum loss at the surface

$1.4\ M_{\odot}$, $[Fe/H]_{ini}=0.035$



Legend:
- $g_{rad}$ (solid)
- No $g_{rad}$ (dashed)
- with Kawaler88 (red)
- with Matt15 (orange)
- without AM loss (blue)
- no rotation (green)

Axes: [Fe/H] vs $X_C$
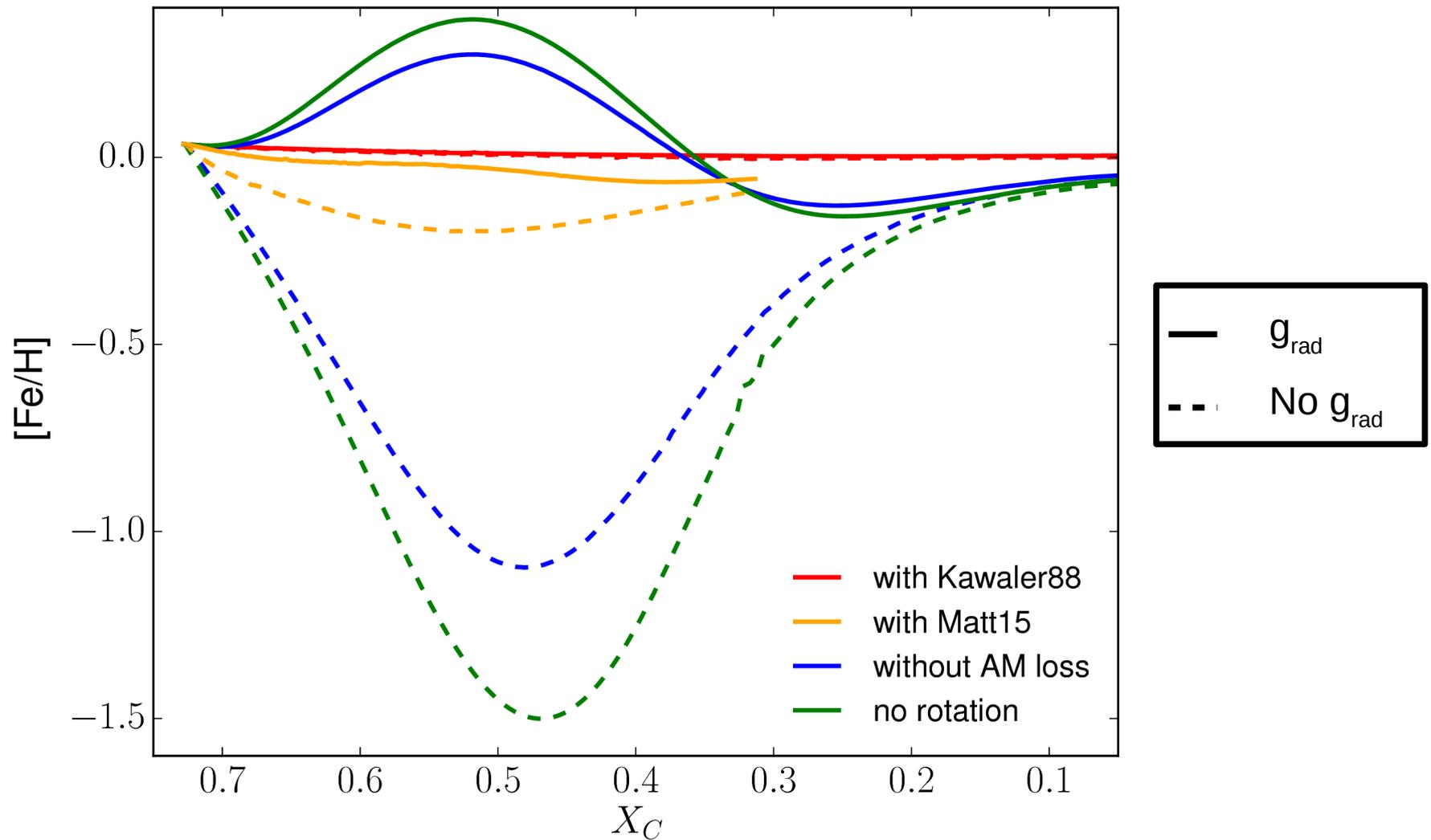
# Conclusion

**Atomic diffusion** leads to **structure and abundances** modifications and needs to be taken into account in stellar evolution codes

One of the most **important parameter** modified by radiative accelerations is **[Fe/H]**

$g_{rad}$ should lead to non negligible differences on the the **stellar parameter determinations** using oscillation frequencies in grid of models

# Conclusion

> **Rotation does not erase** the effect of atomic diffusion depending on the **angular momentum loss** prescription for stars showing solar-like oscillations

**What next?** :

- Impact of $g_{rad}$ in the case of the optimisation of stellar parameters

- Continue the study of the coupling between atomic diffusion and rotation

- Study the impact of atomic diffusion on glitches (size of surface convective zones)

- Study the ionisation zone of heavy elements (Brito+ 2017,2018)