Solving the puzzle of mixing in giant stars with the Besançon galaxy model.

Nadège Lagarde

Laboratoire d'Astrophysique de Bordeaux

In collaboration with G. Tautvaisiene, A. Drazdauskas, R. Minkevičiūtė, C. Charbonnel, A. Miglio, C. Reylé, C. Soubiran

Stellar evolution along the HR diagram with Gaia - Naples - Sept 2022

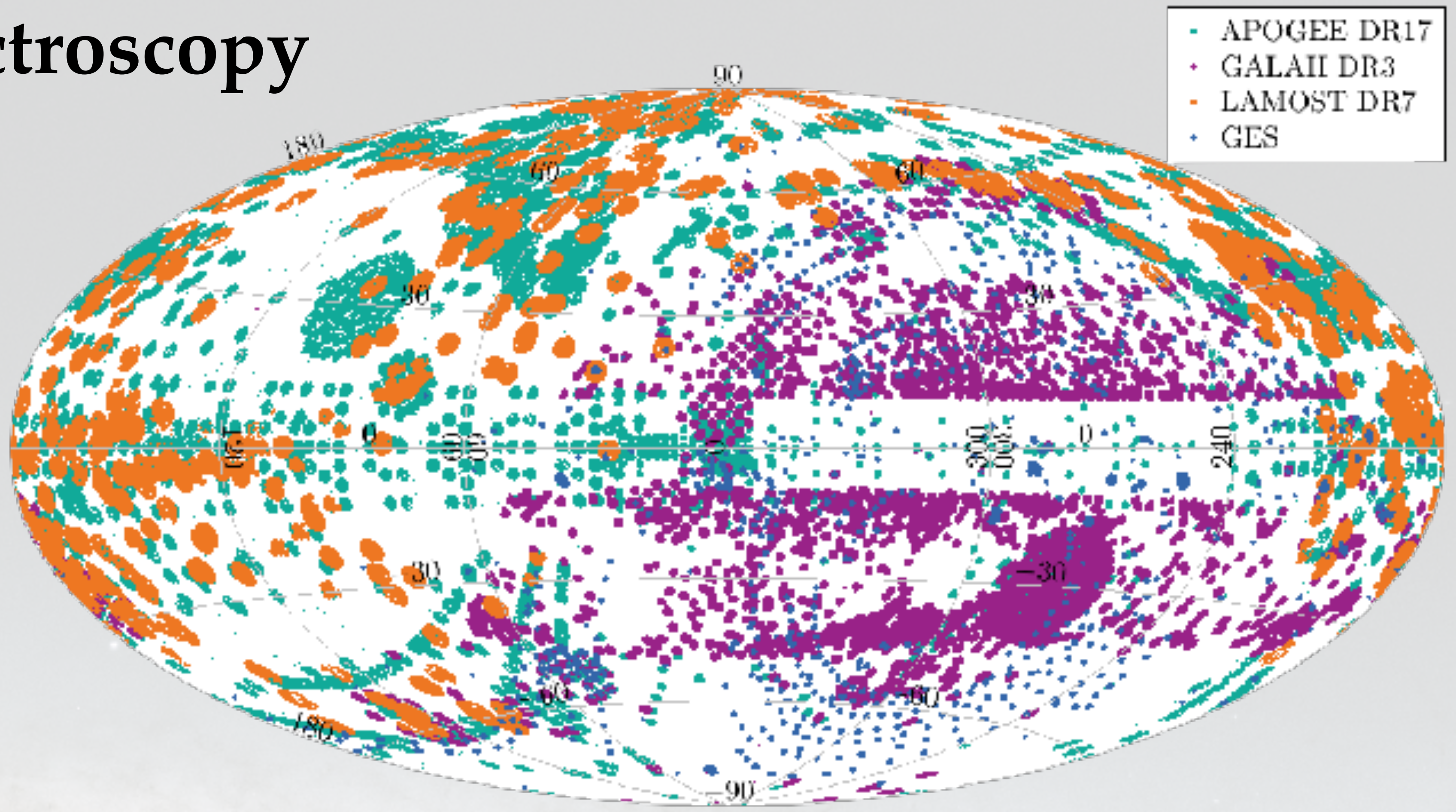
Very rich observational context

- Thanks to the current surveys we have access to the chemical, seismic and photometric properties of a very large number of stars in the Milky Way.

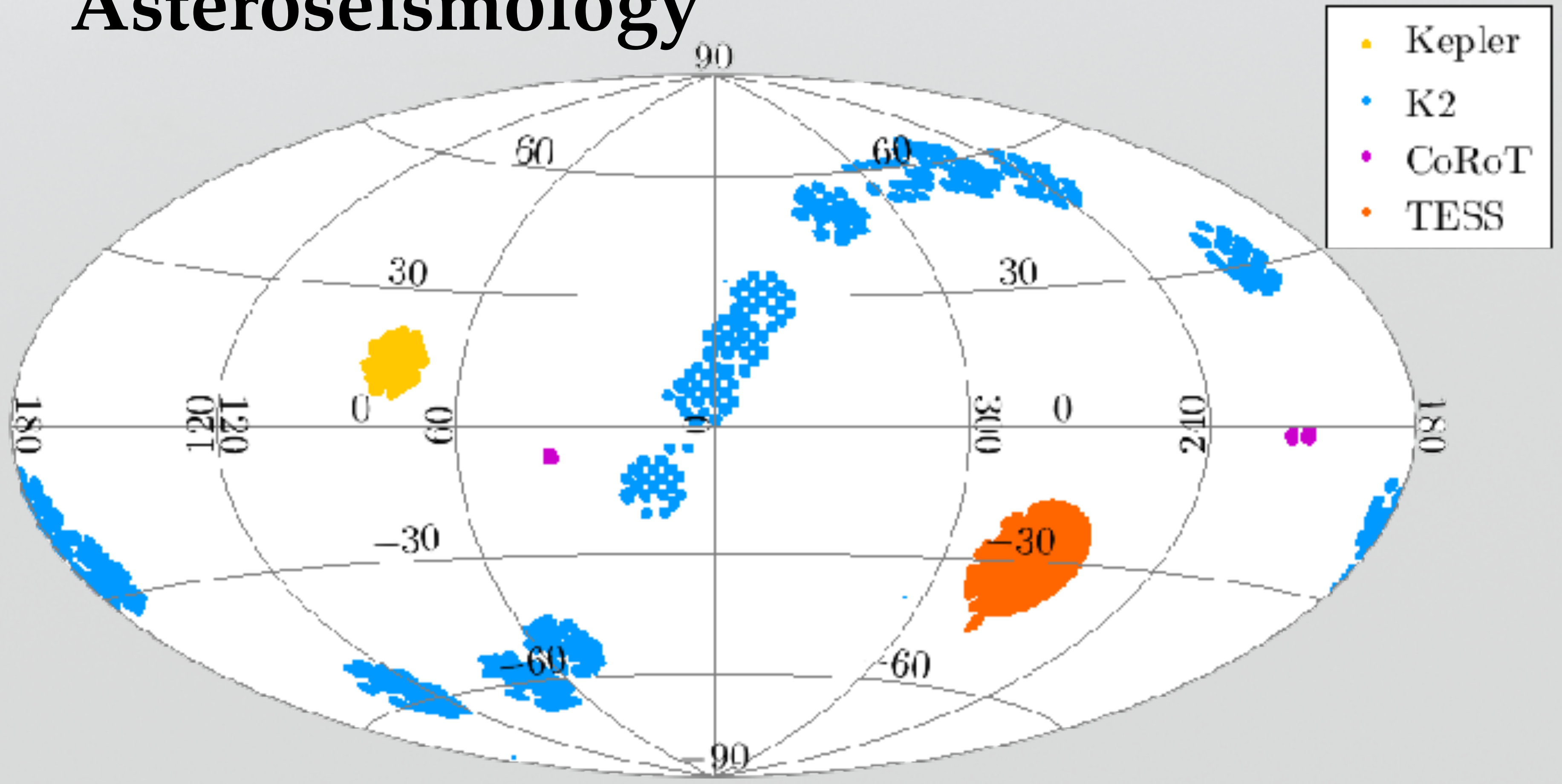
- All of these large surveys also allow us to probe different regions of the Milky Way and to obtain the properties of stars belonging to stellar populations with different formation and evolution histories.

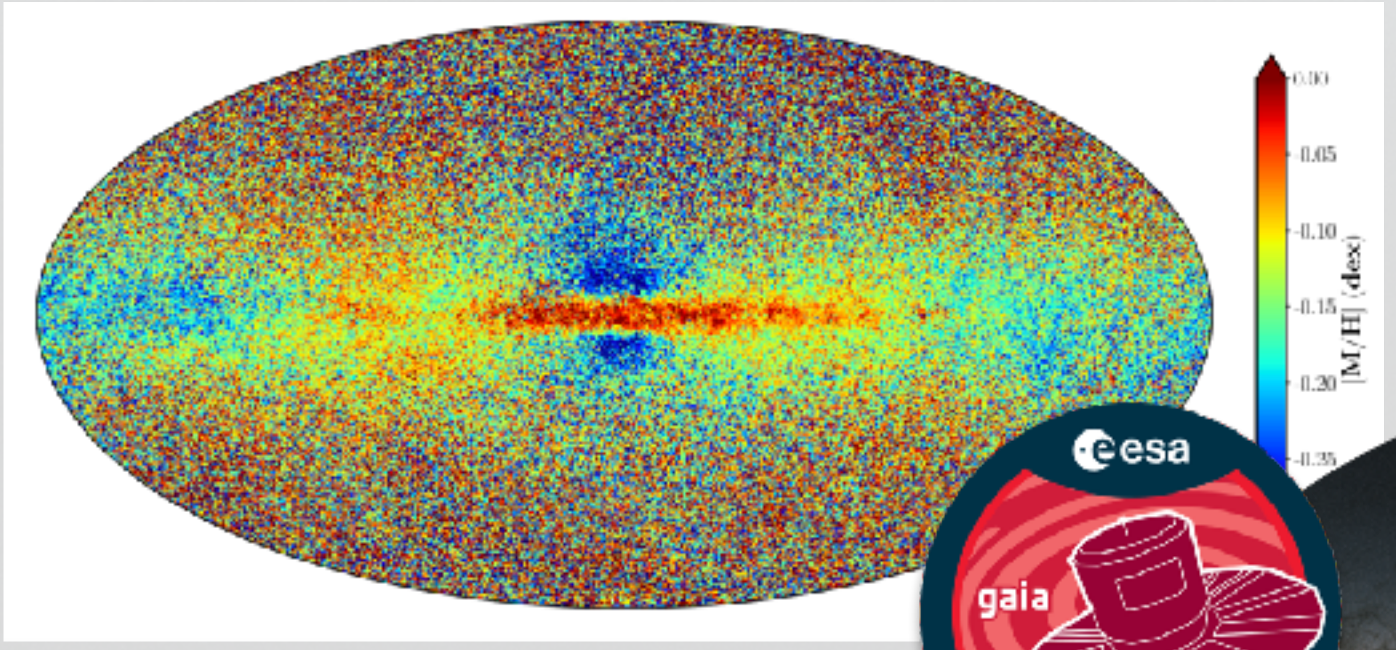
=> a great diversity of chemical compositions, ages and masses.

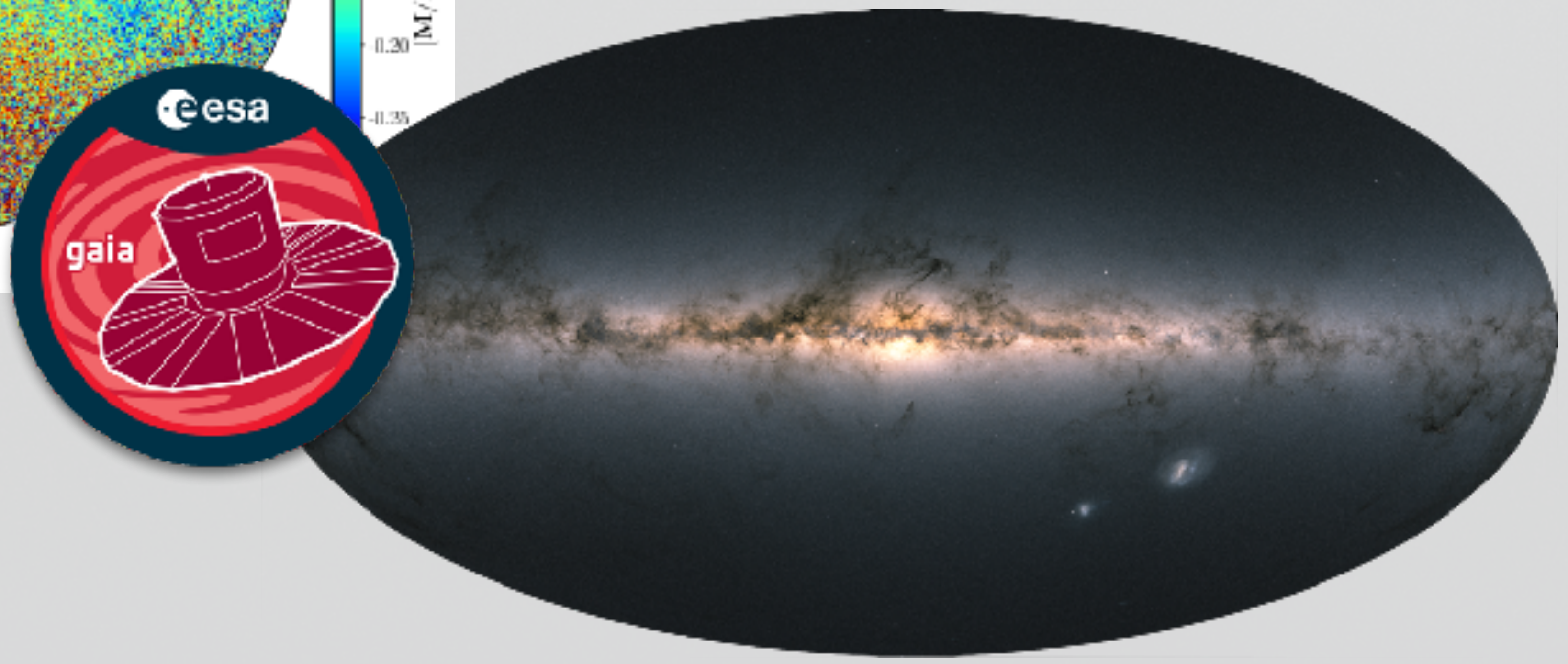
Spectroscopy



Asteroseismology







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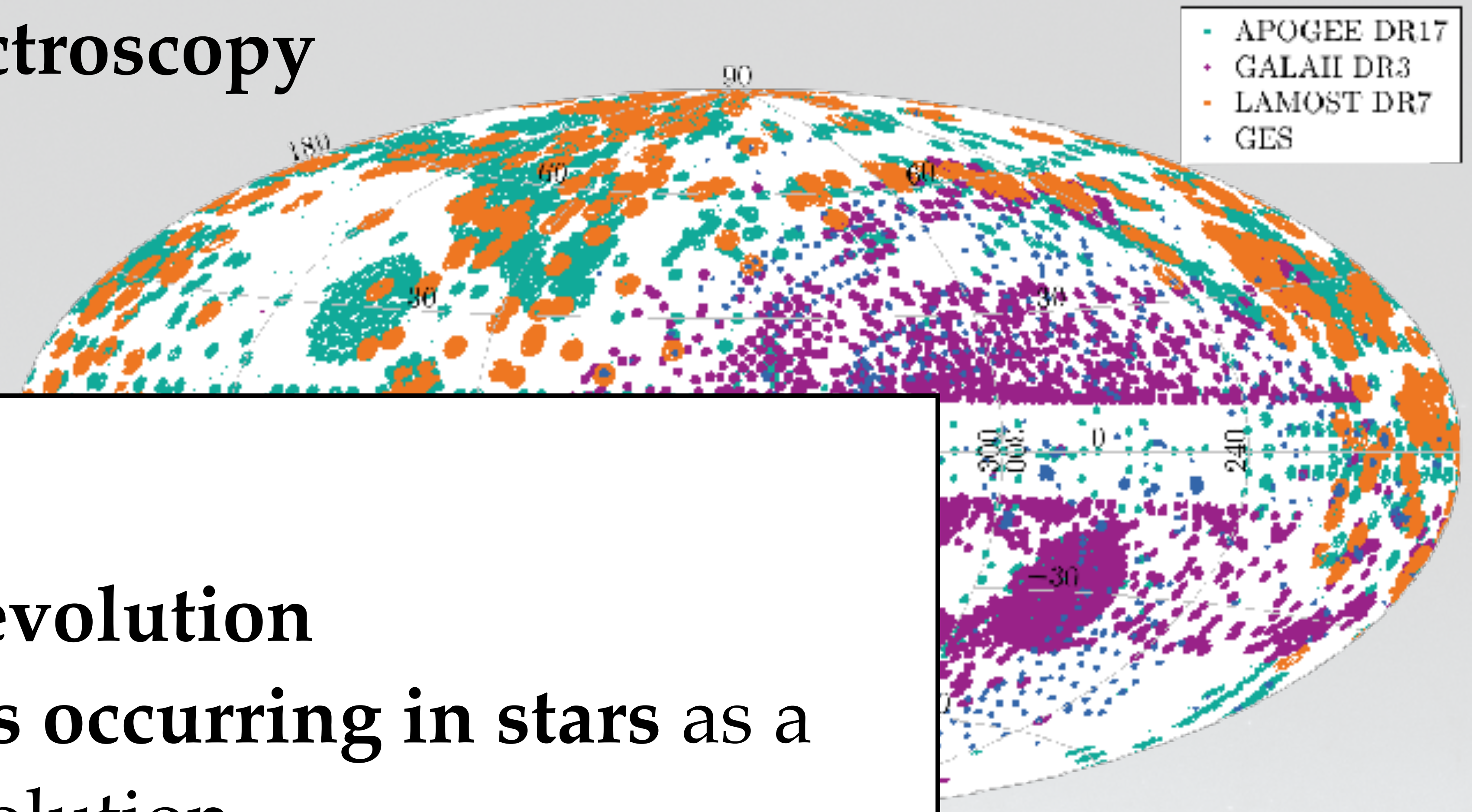
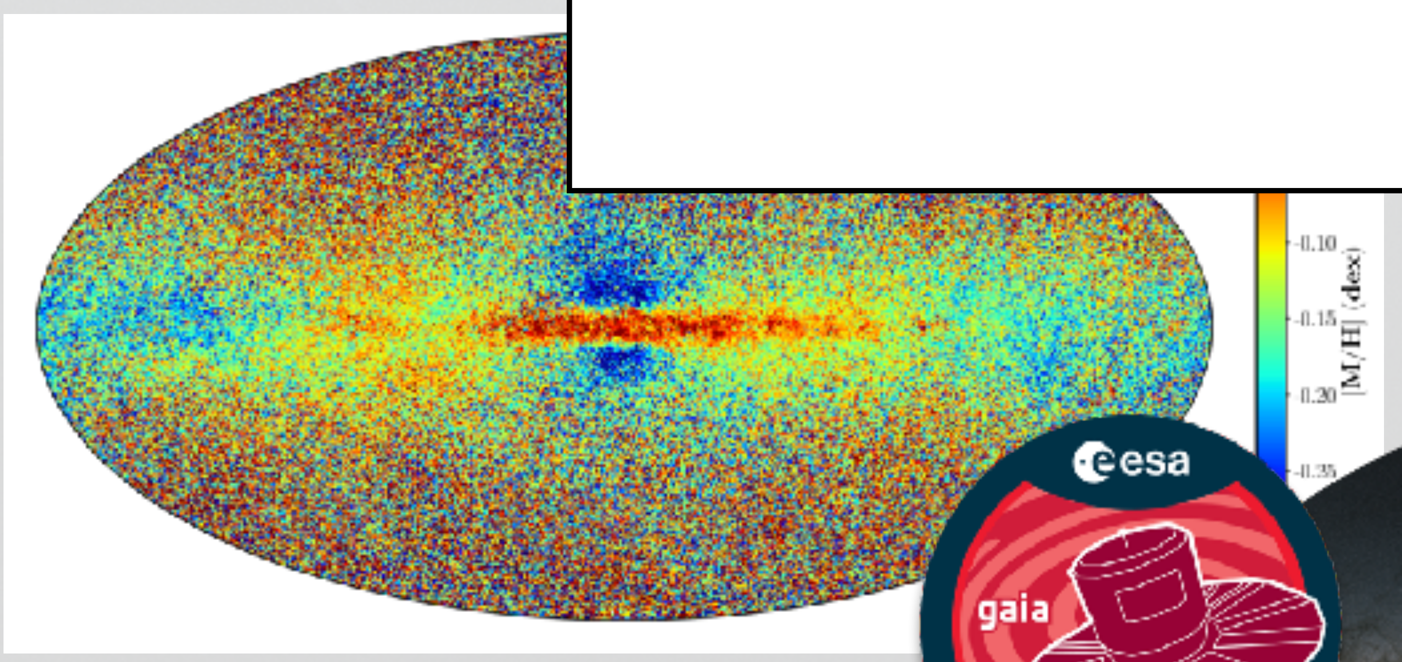
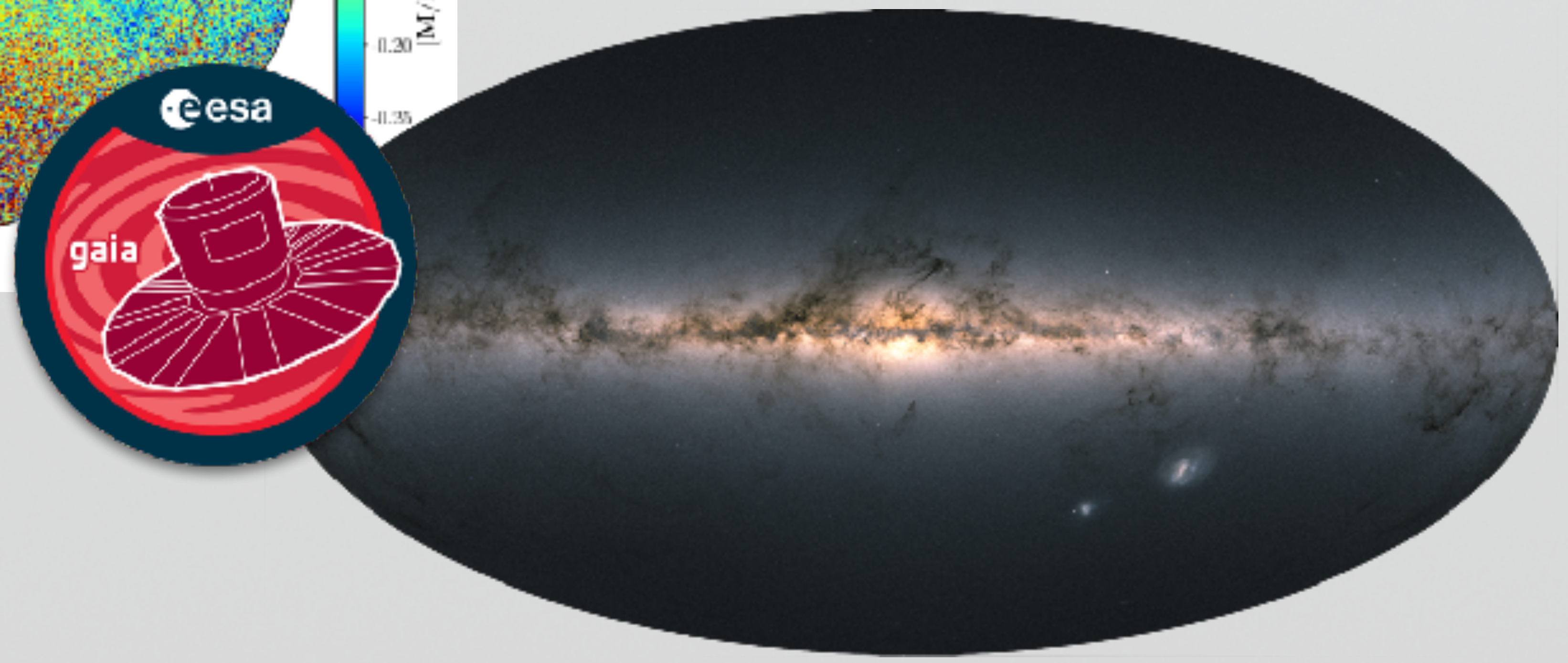
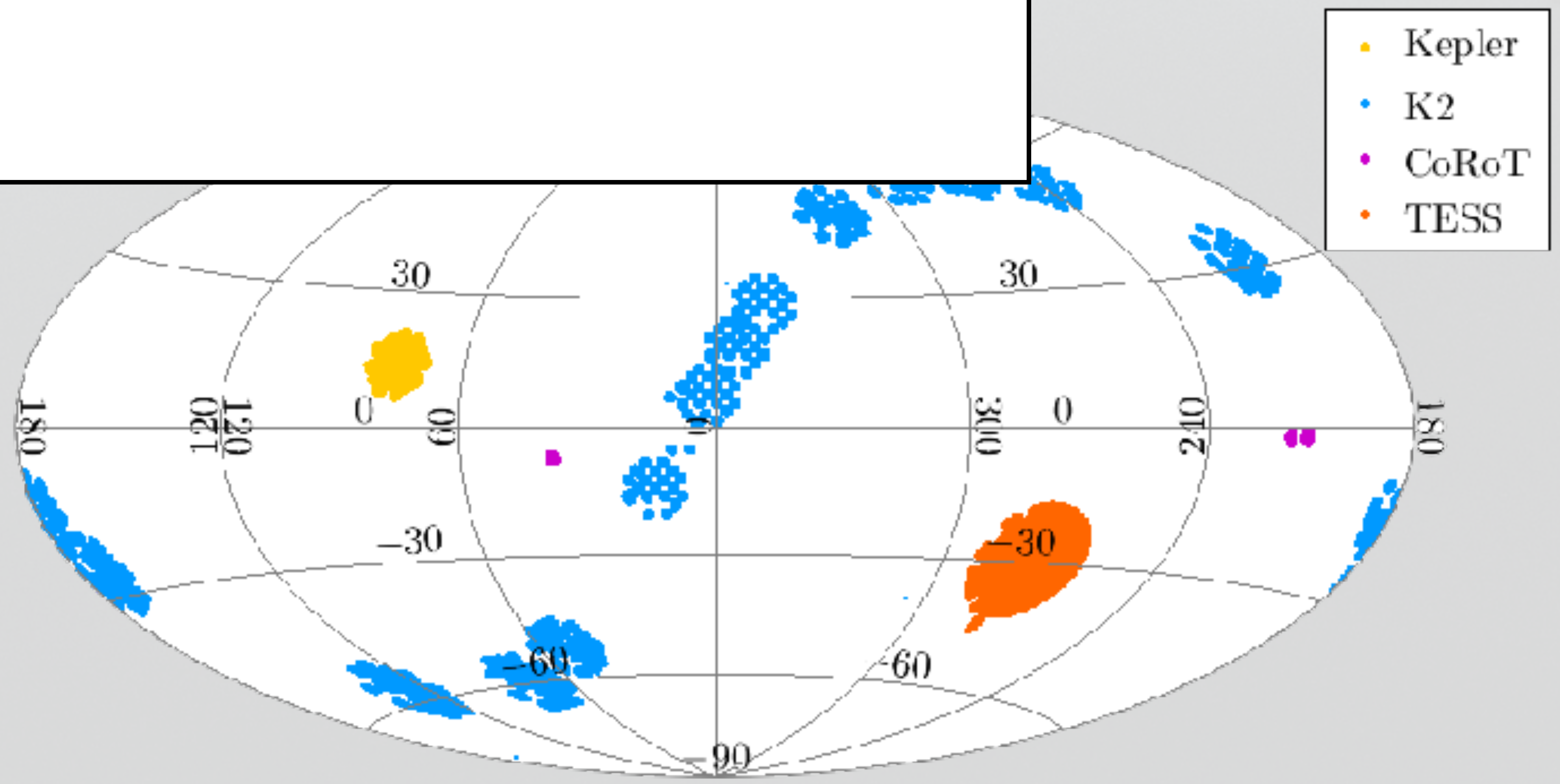


These data are **an incredible source to constrain the stellar evolution** and more specifically **the impact of hydrodynamic processes occurring in stars** as a function of their properties and at different times on their evolution.

To handle this huge statistic for stellar evolution, Galactic stellar populations synthesis codes are essential tools.







Forward modeling using BGM

Observations

Observables
Selection function of the survey
Limits and biases of the instrument

Forward modeling using BGM

Galactic formation and evolution

Stellar evolution

Interstellar medium

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(e.g., *Lagarde et al. 2017, 2019*)

BGM

Stellar population synthesis model of the Milky Way

BGM acts as a filter between observations and theories, allowing **a direct comparison of large surveys data with theoretical patterns.**

Observations

Observables

Selection function of the survey

Limits and biases of the instrument

OUTPUTS

Global properties of stars: Teff, logg, age, colors, magnitudes,…

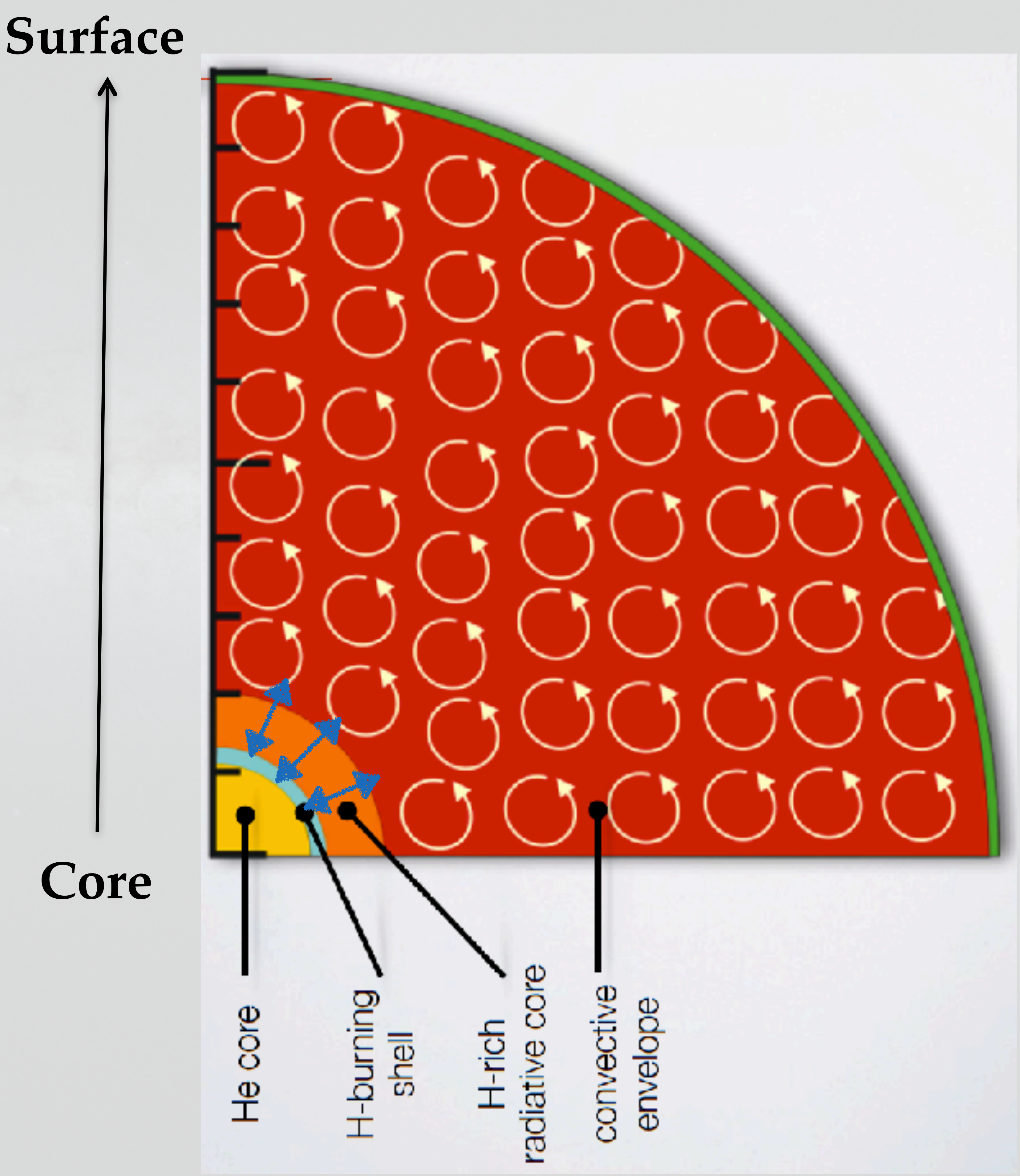
Seismic properties of stars: $\Delta\nu$, ν_{max}, $\Delta\Pi$(l=1)

Surface chemical properties: from ^{1}H to ^{37}Cl

Kinematics properties: Velocities

Testing the efficiency of extra-mixing along the Red giant branch

- Thermohaline mixing *(Charbonnel & Zahn 2007a, Charbonnel & Lagarde 2010)*



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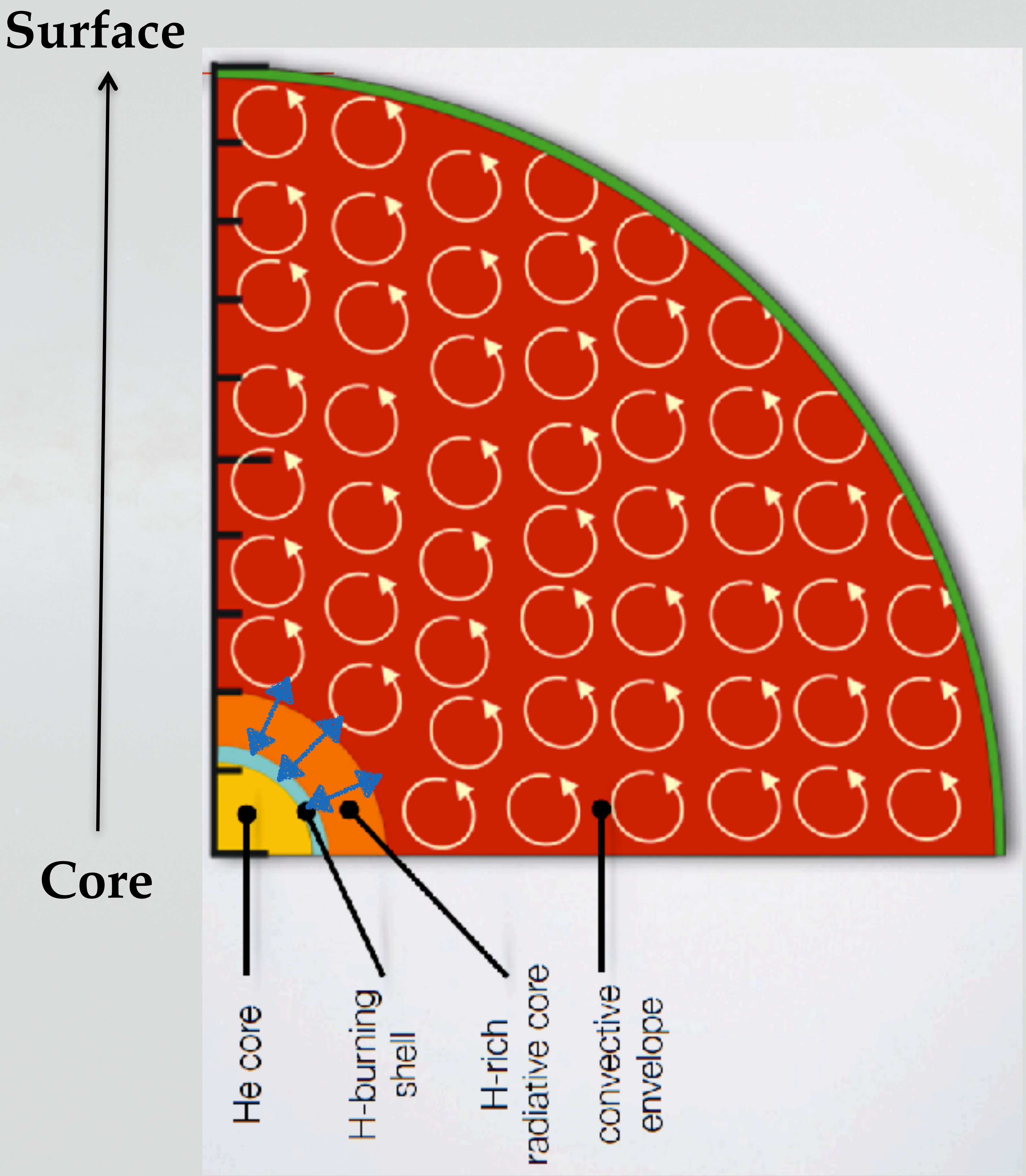

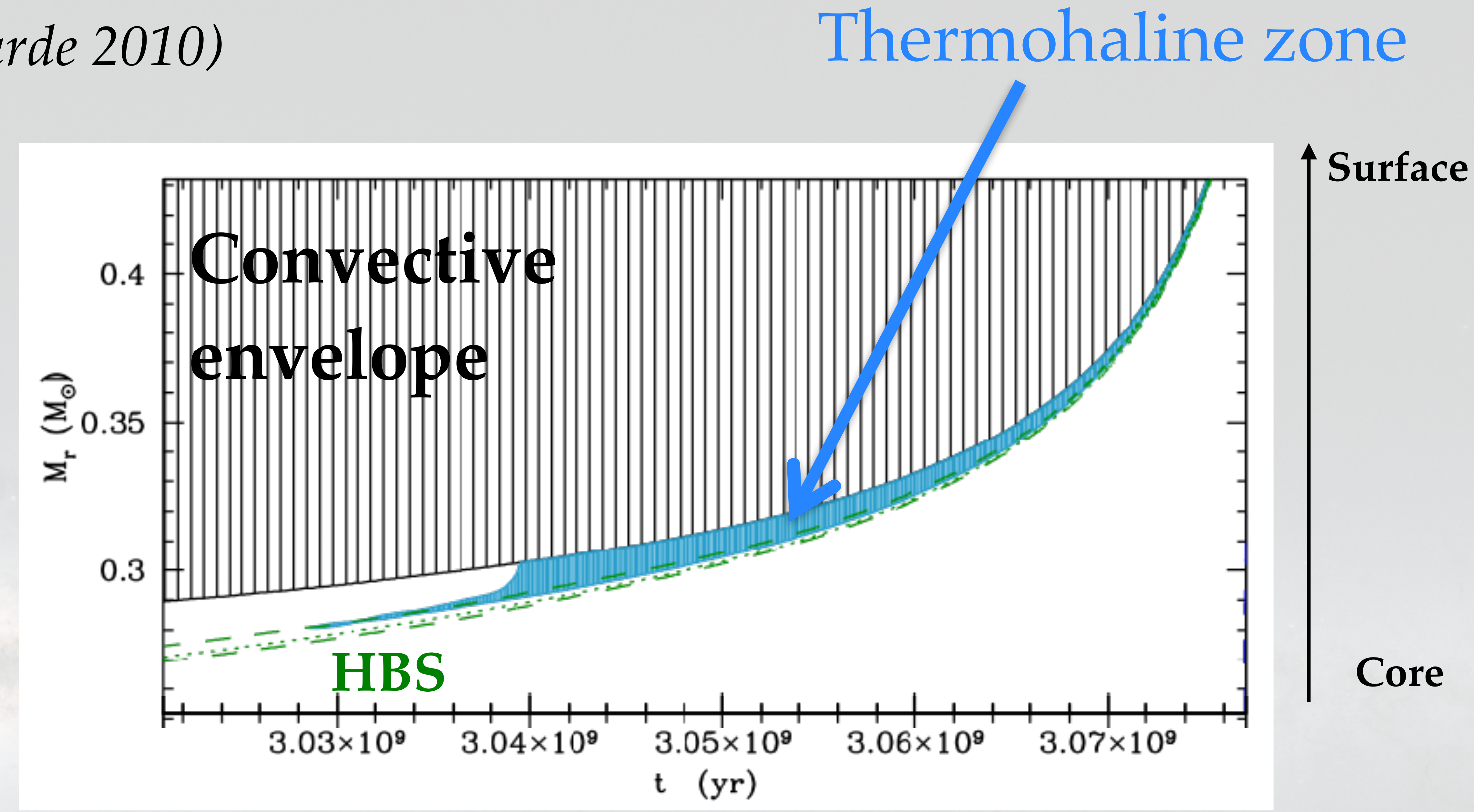

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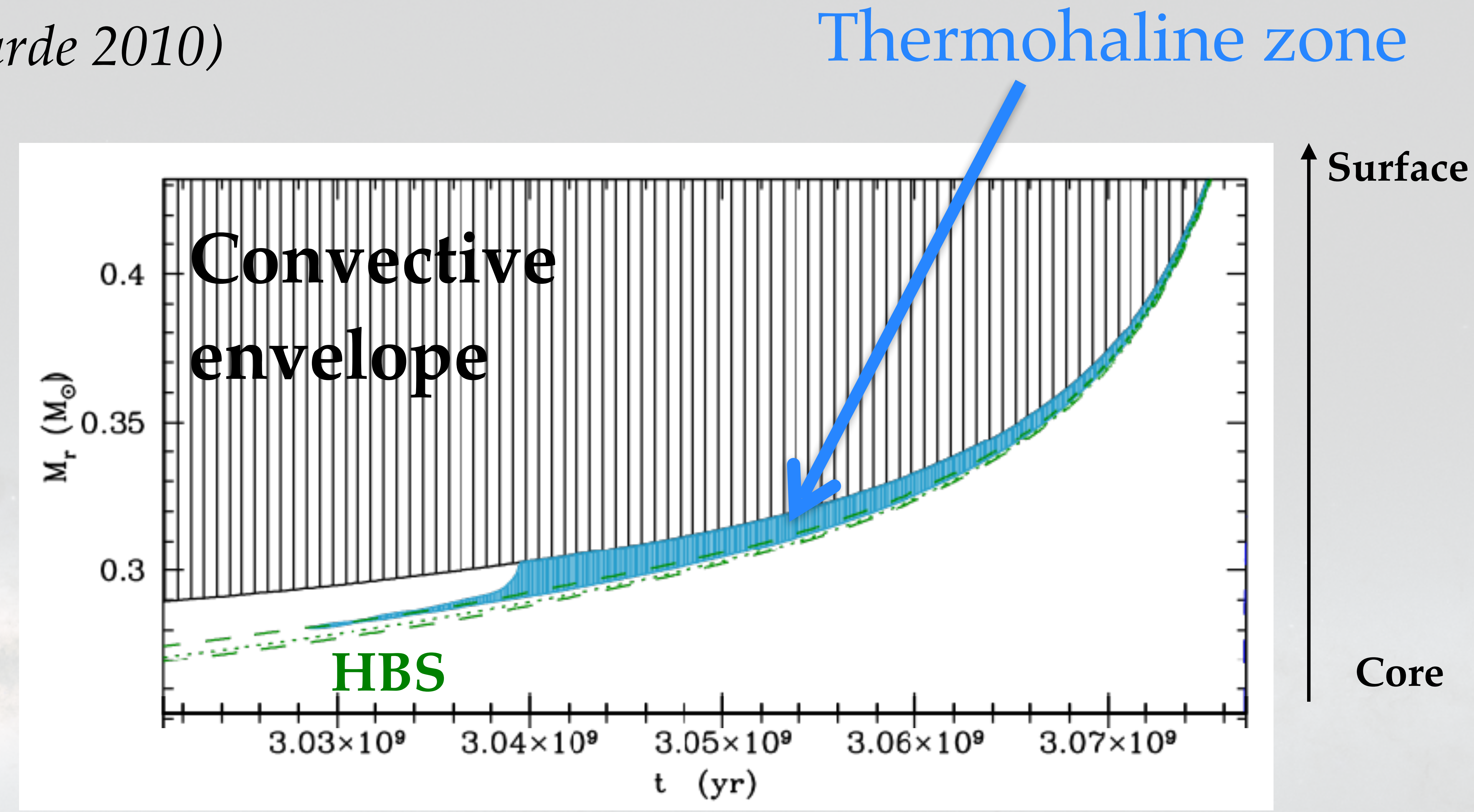
  - At the top of the HBS by an inversion of mean molecular weight

$$^3He + ^3He \longrightarrow ^4He + 2p$$

  - After the star has reached the luminosity bump on the RGB



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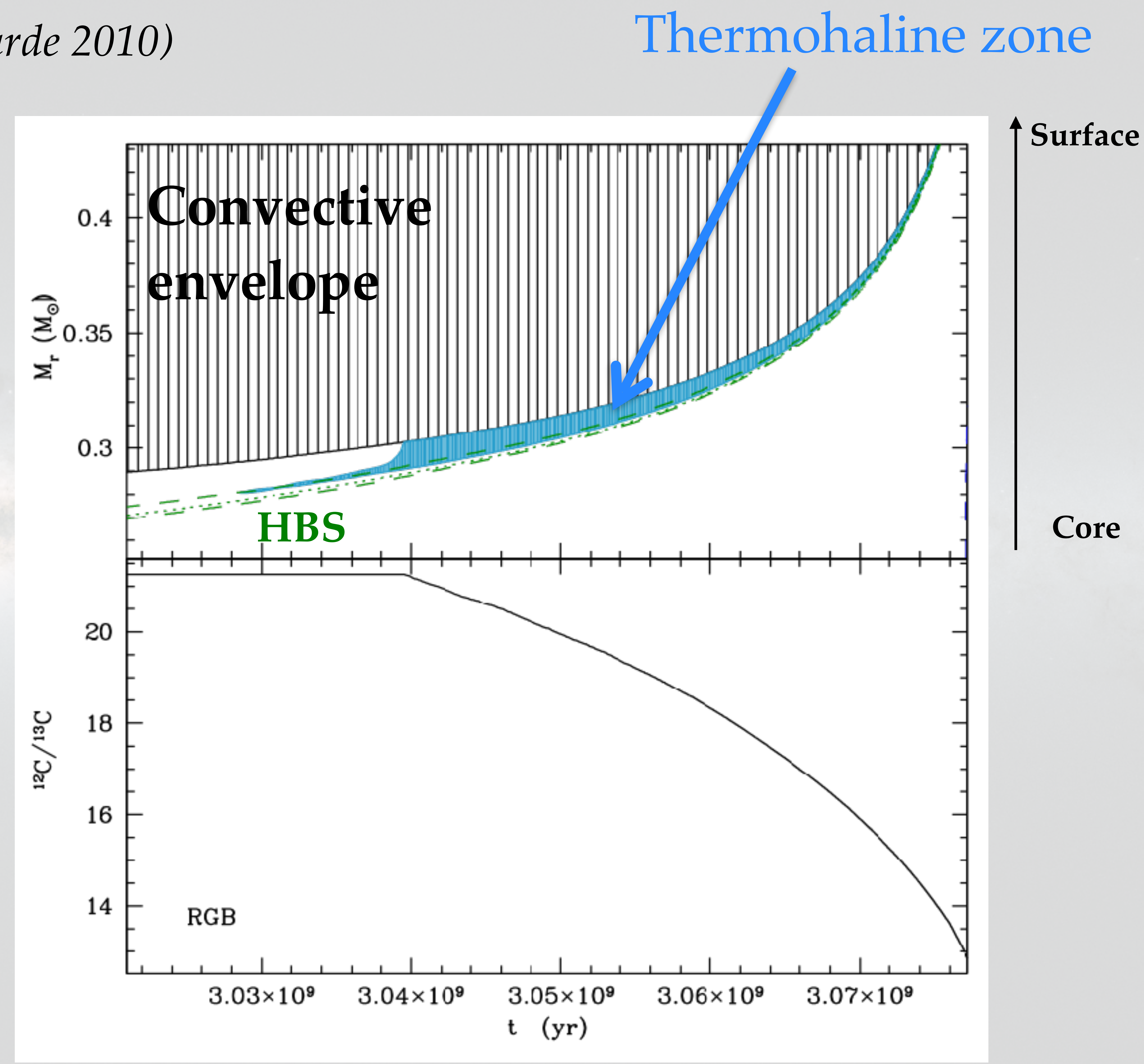
- Changes the surface abundances of chemical elements such as Li, ^{3}**He**, ^{12}**C**, ^{13}**C**, ^{14}**N**



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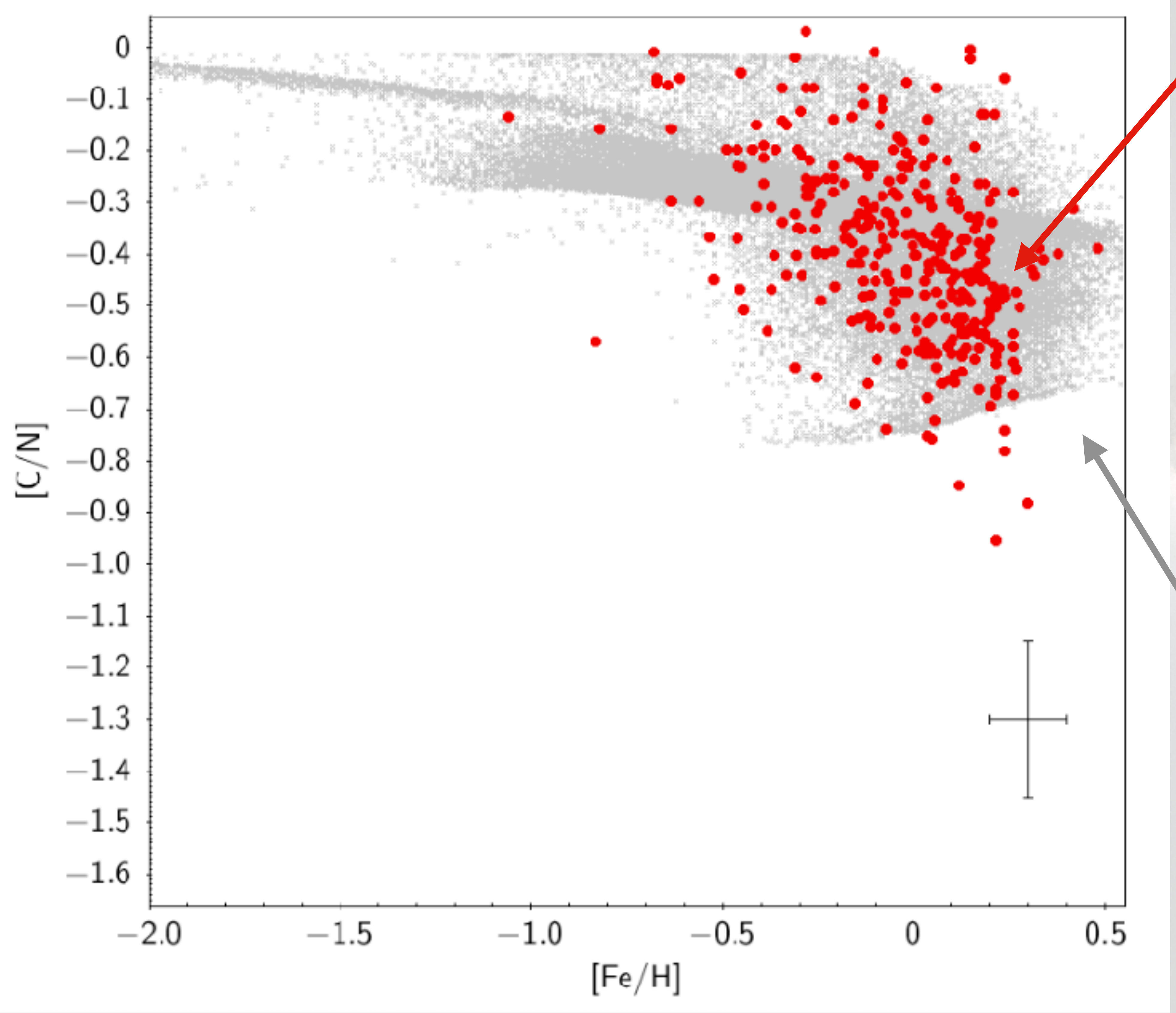
Giant stars in Gaia-ESO survey

Lagarde et al. (2019)

Fields stars (374 giants with C, N abundances)



Simulation for the GES survey including standard stellar evolution models

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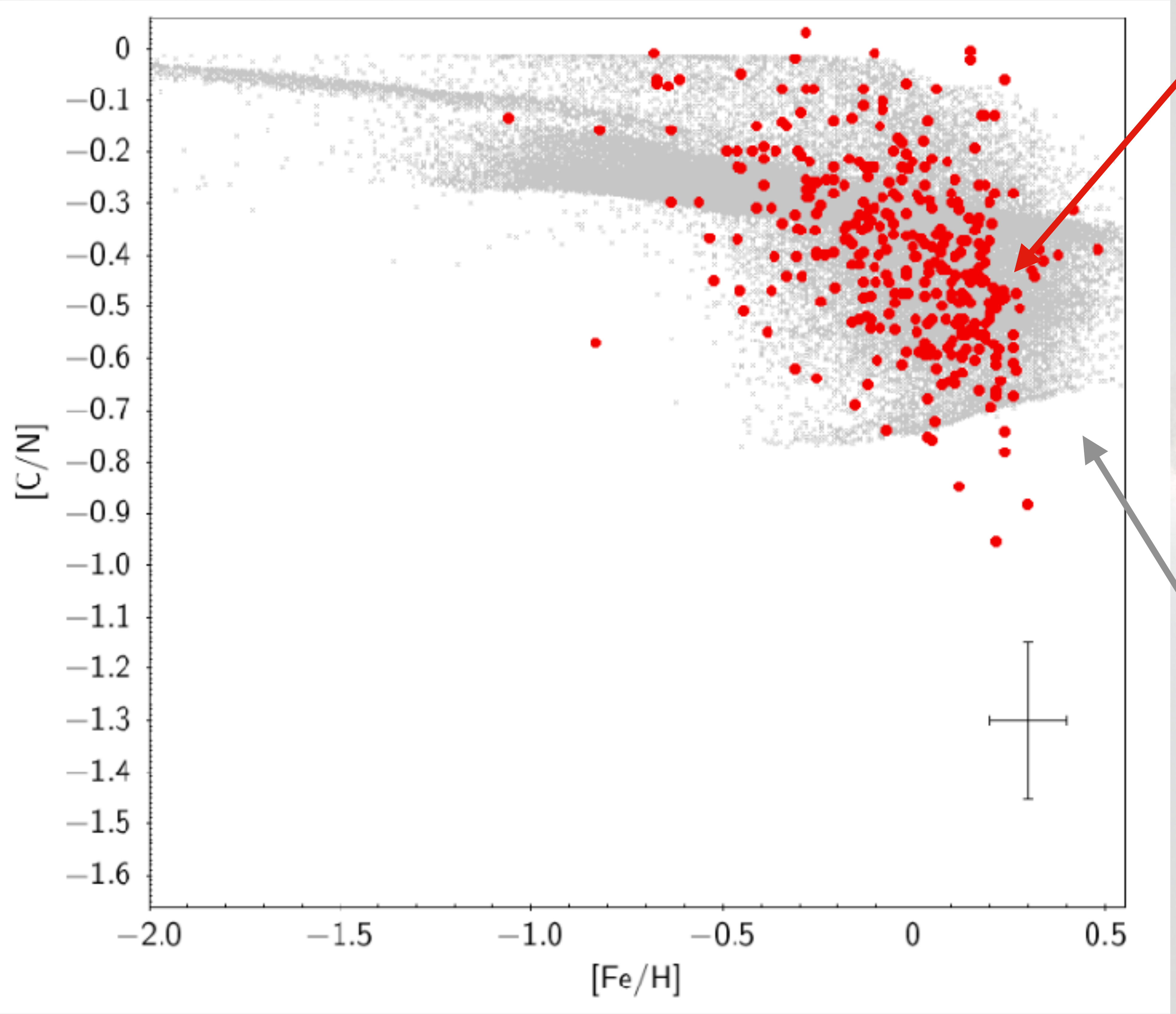

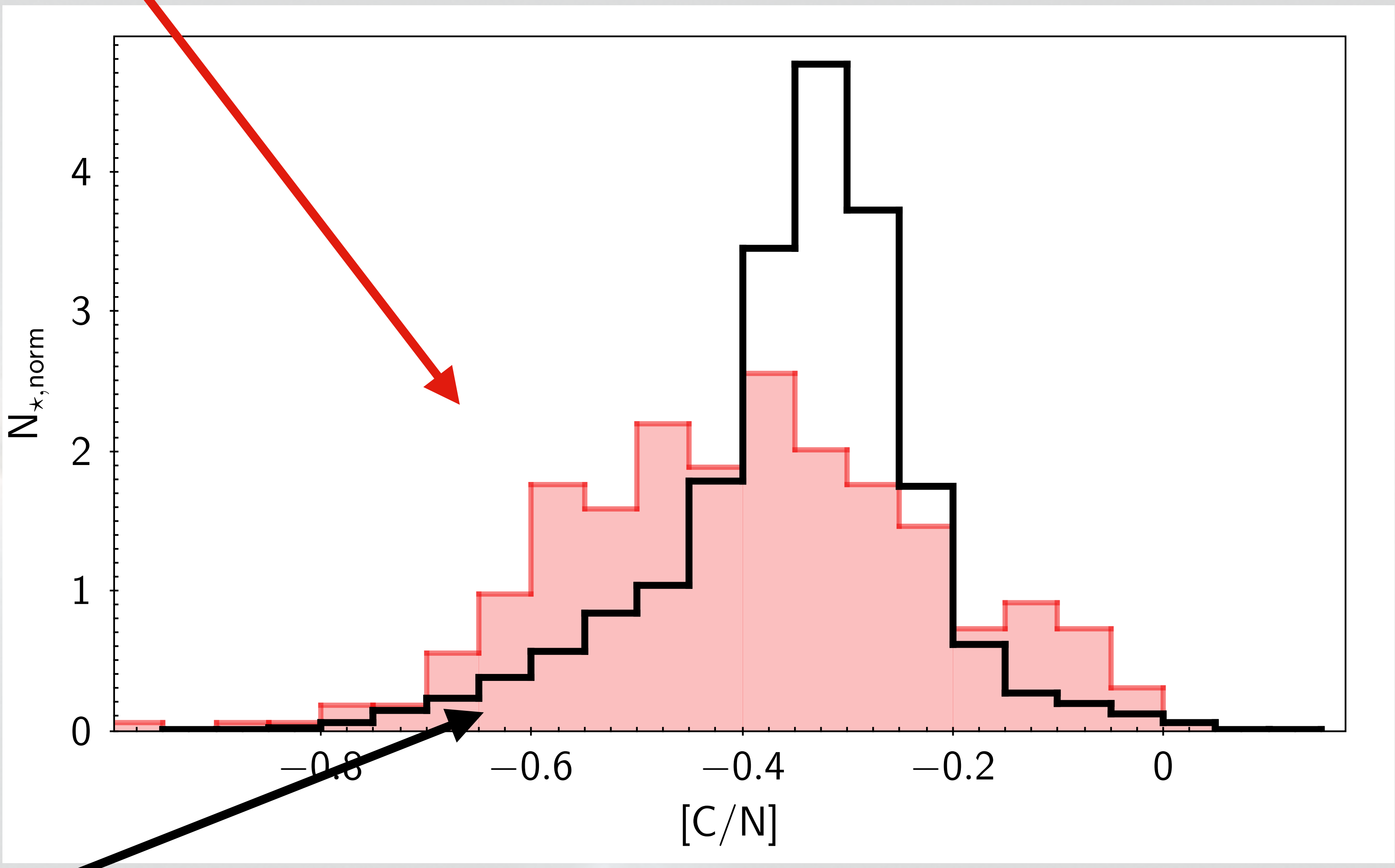

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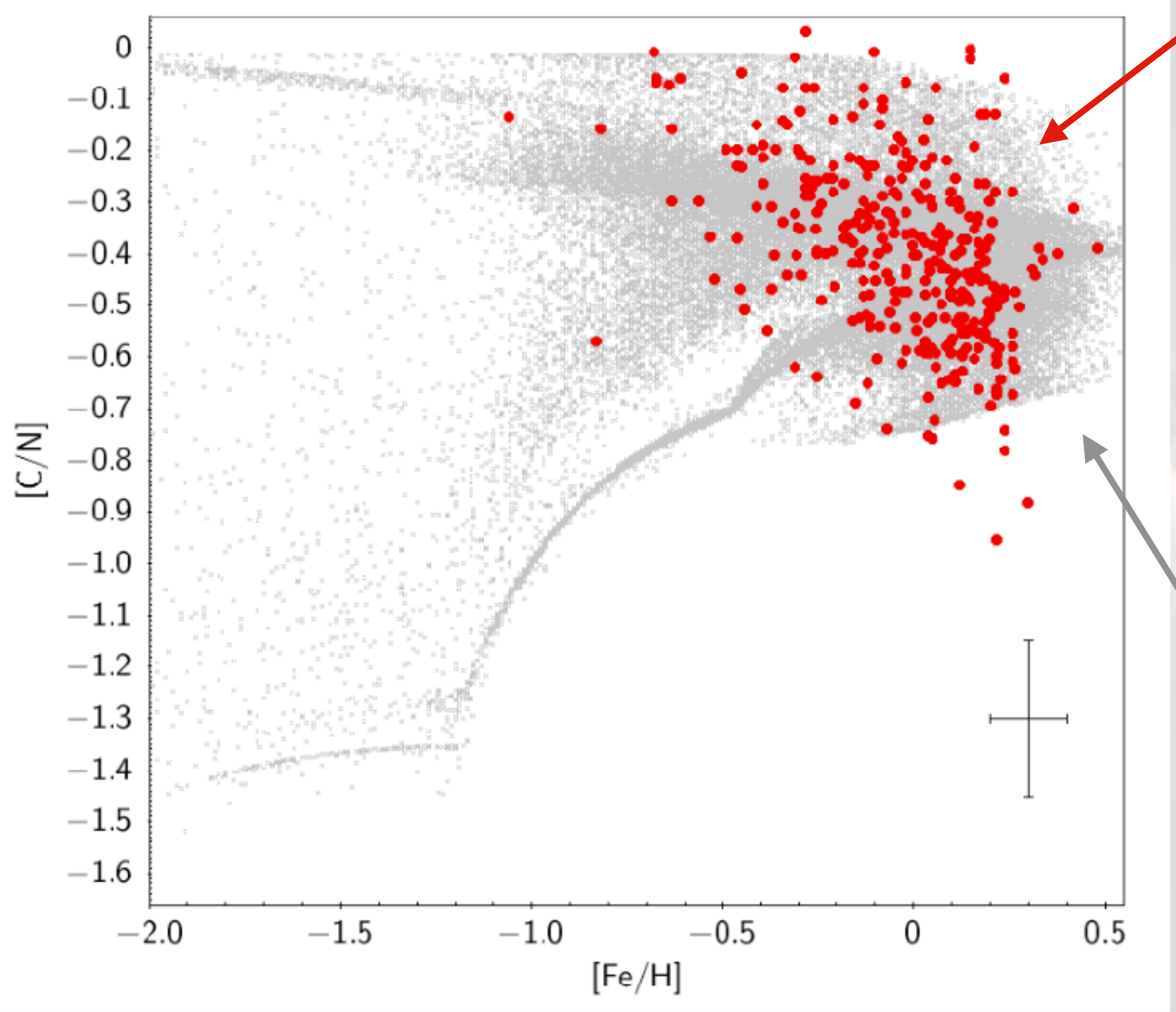

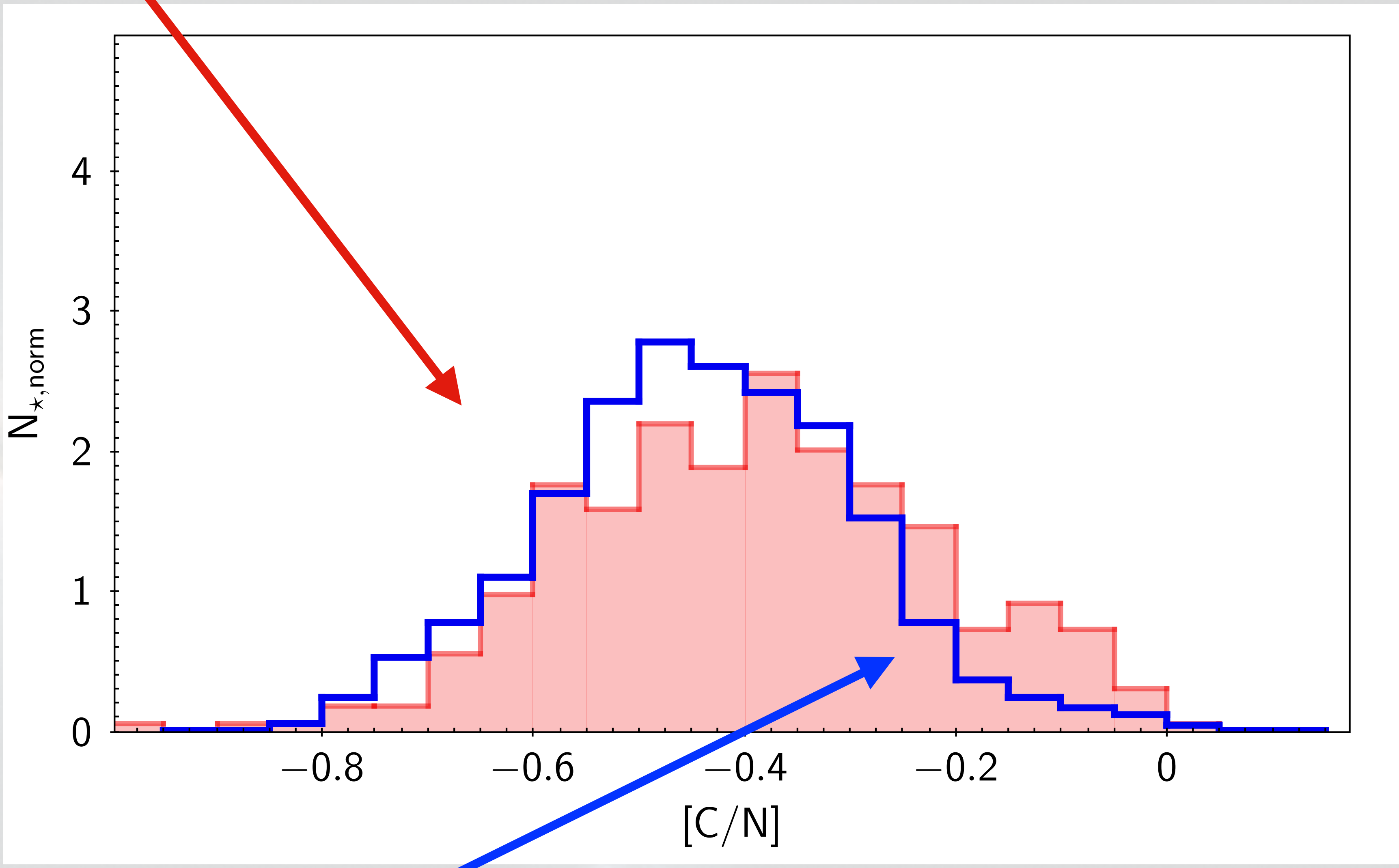

Simulation for the GES survey including the effects of thermohaline mixing

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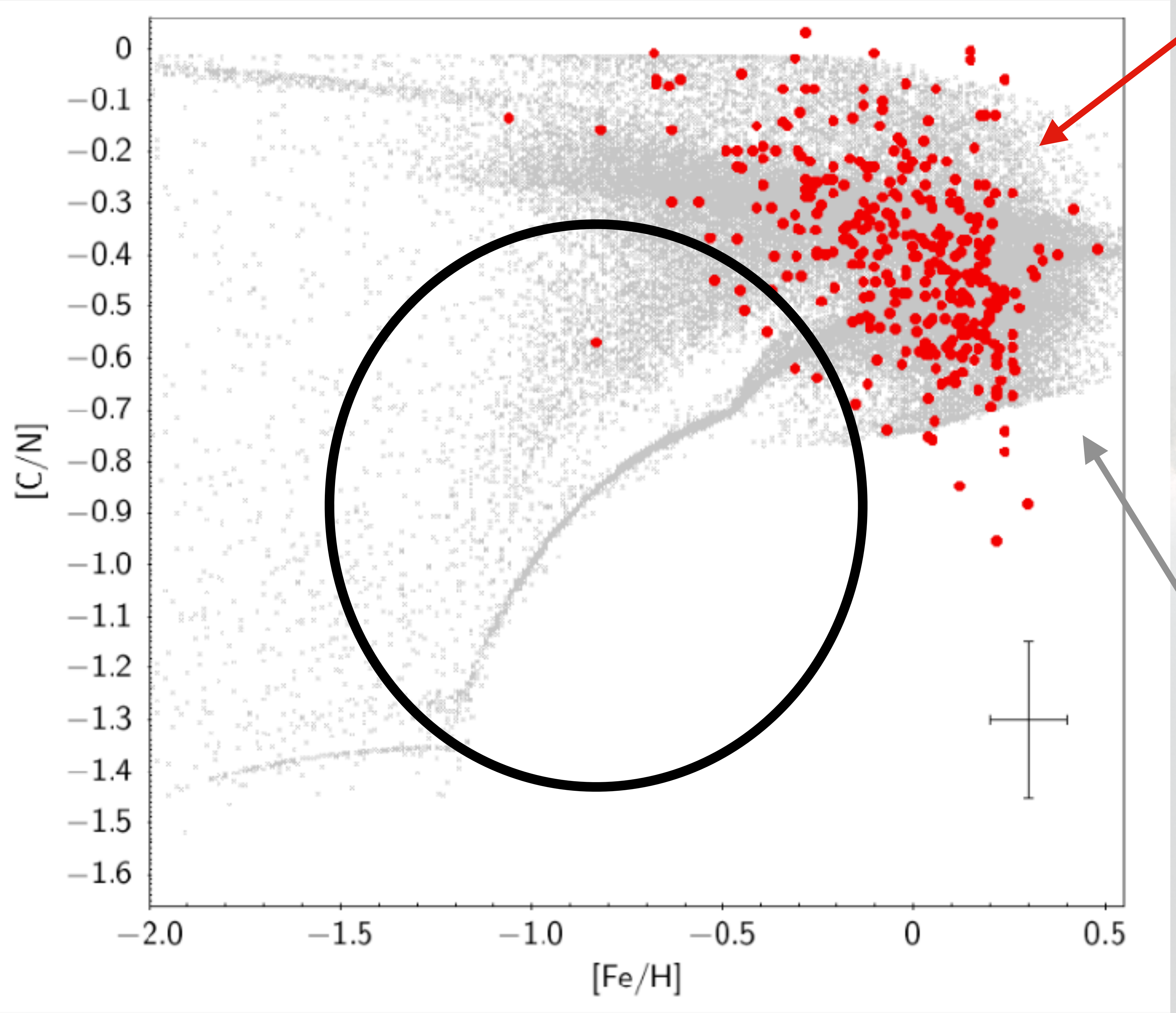

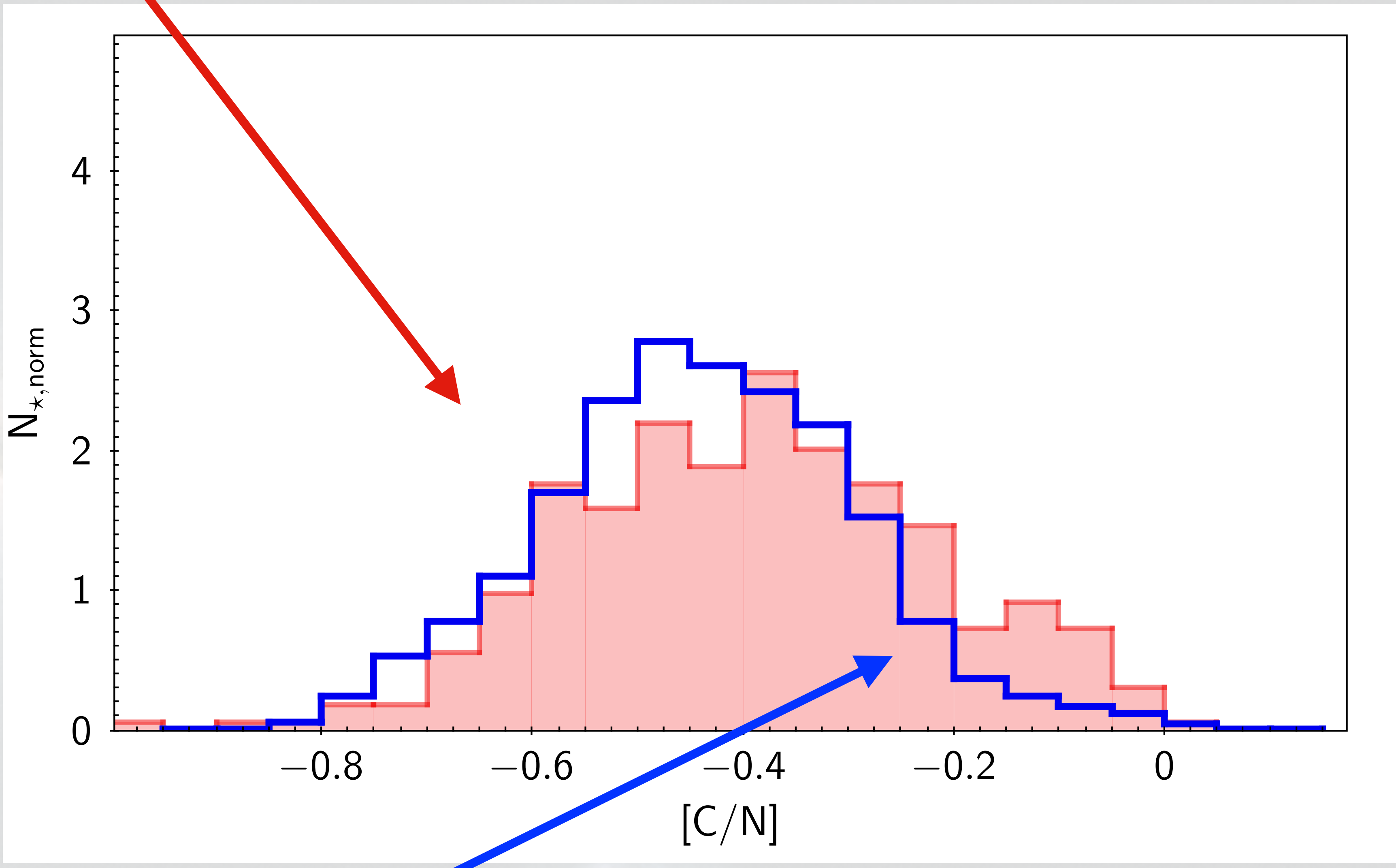

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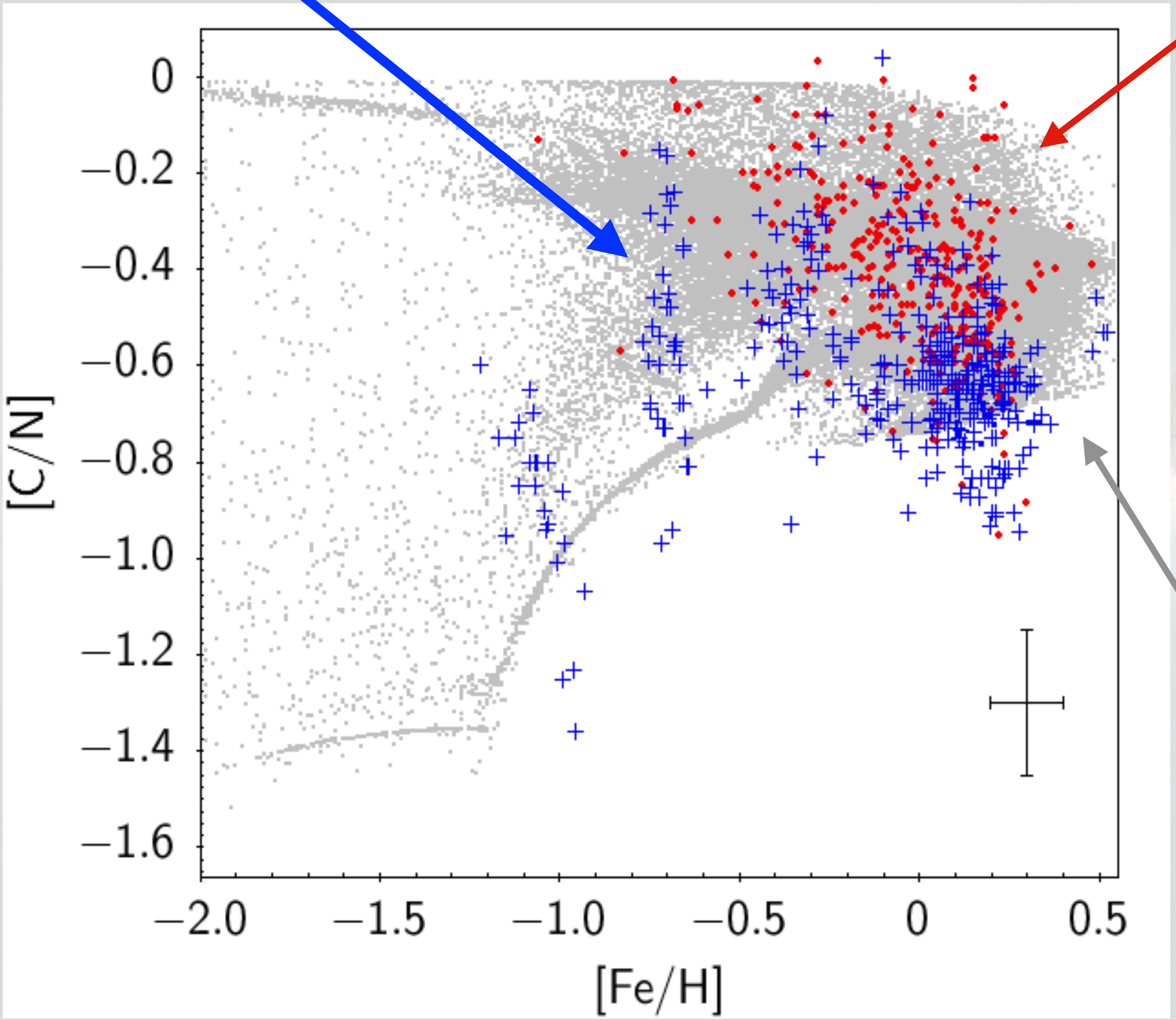
Fields stars (374 giants with C, N abundances)

open and globular clusters



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Giant stars in Gaia-ESO survey *Lagarde et al. (2019)*

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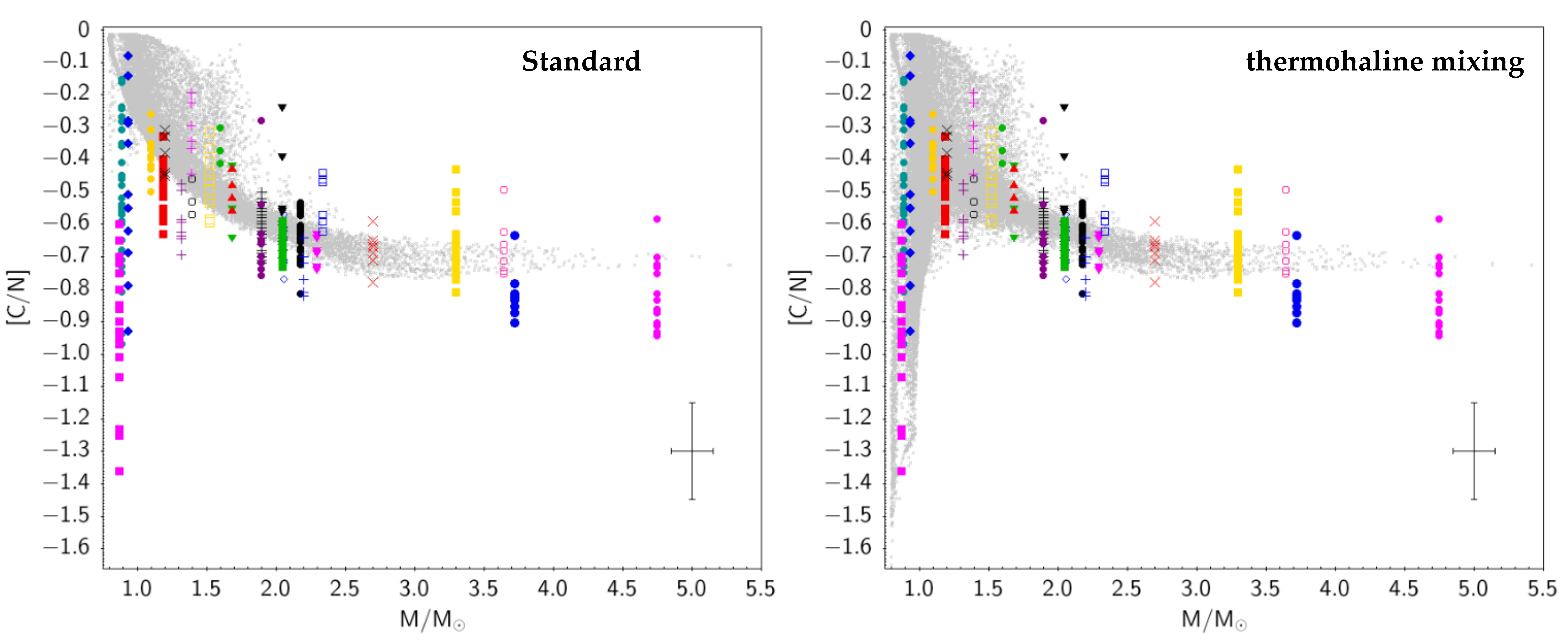

Giant stars in Gaia-ESO survey
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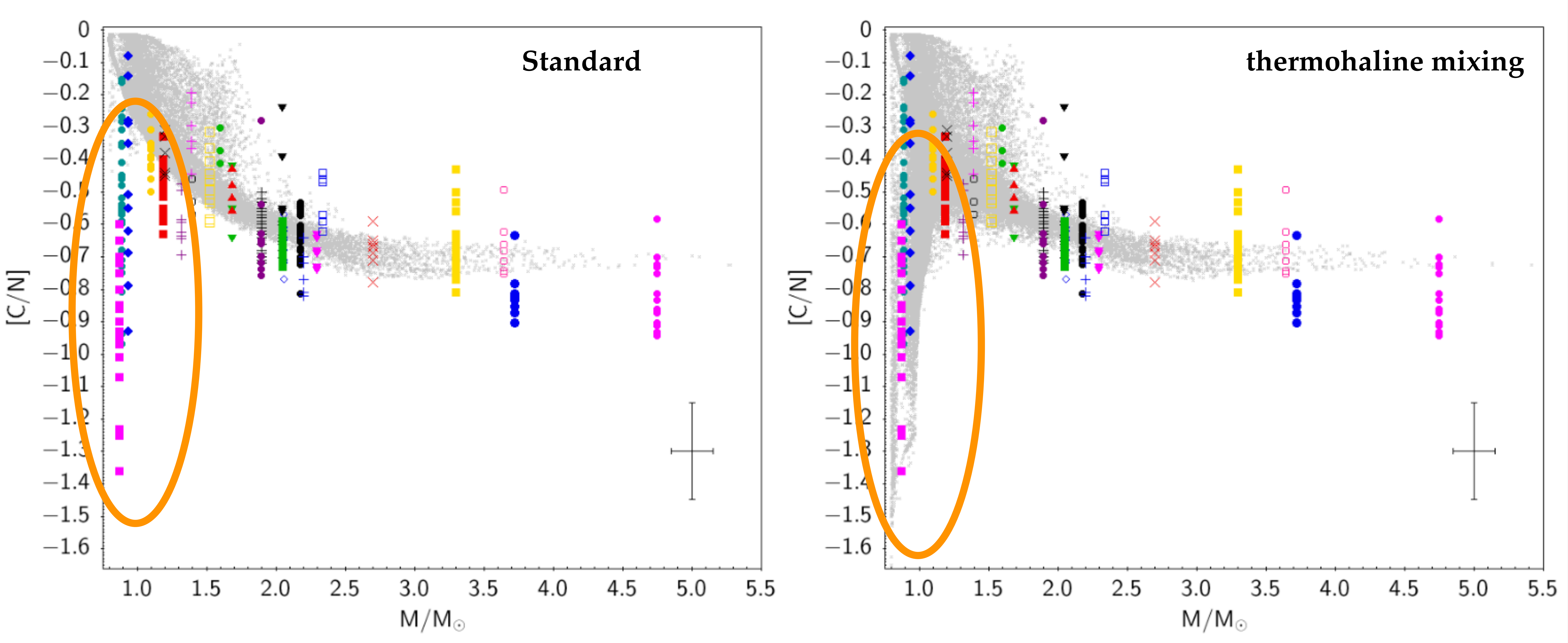

-> explain the [C/N] ratio observed as a function of stellar mass

Giant stars in Gaia-ESO survey

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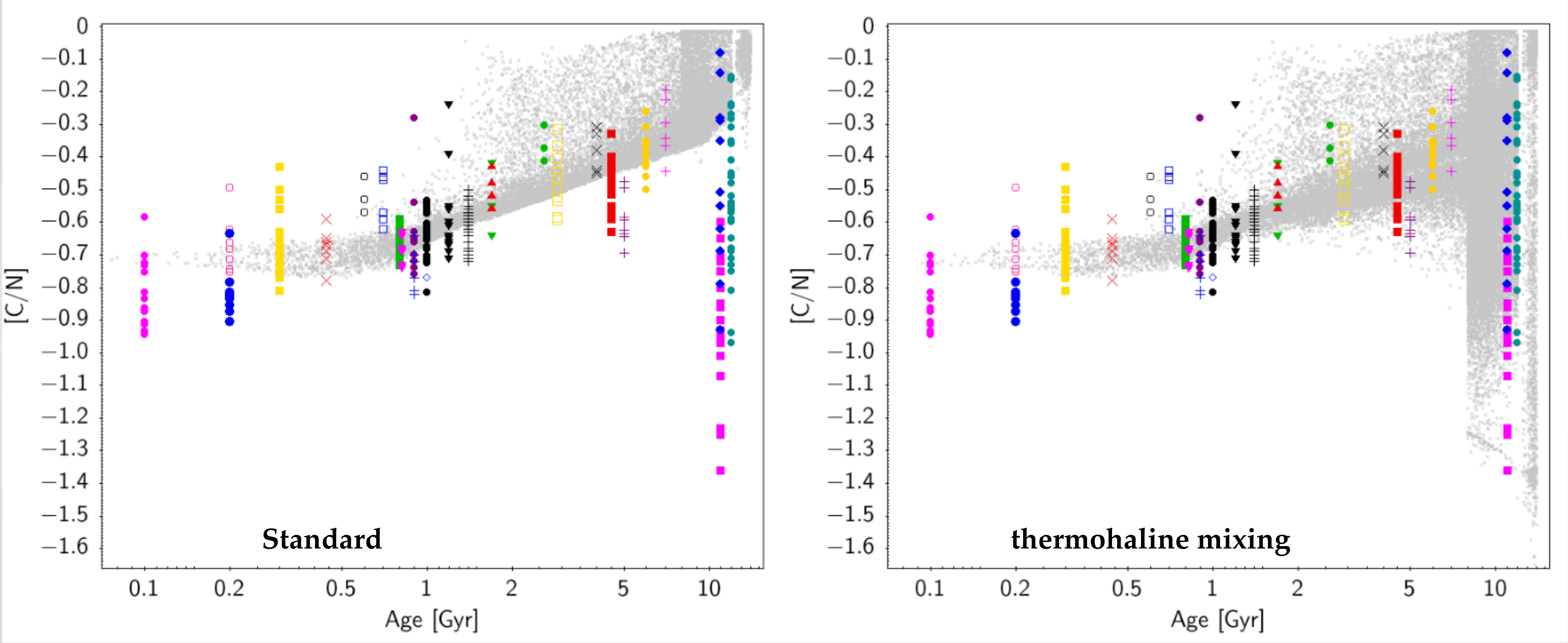

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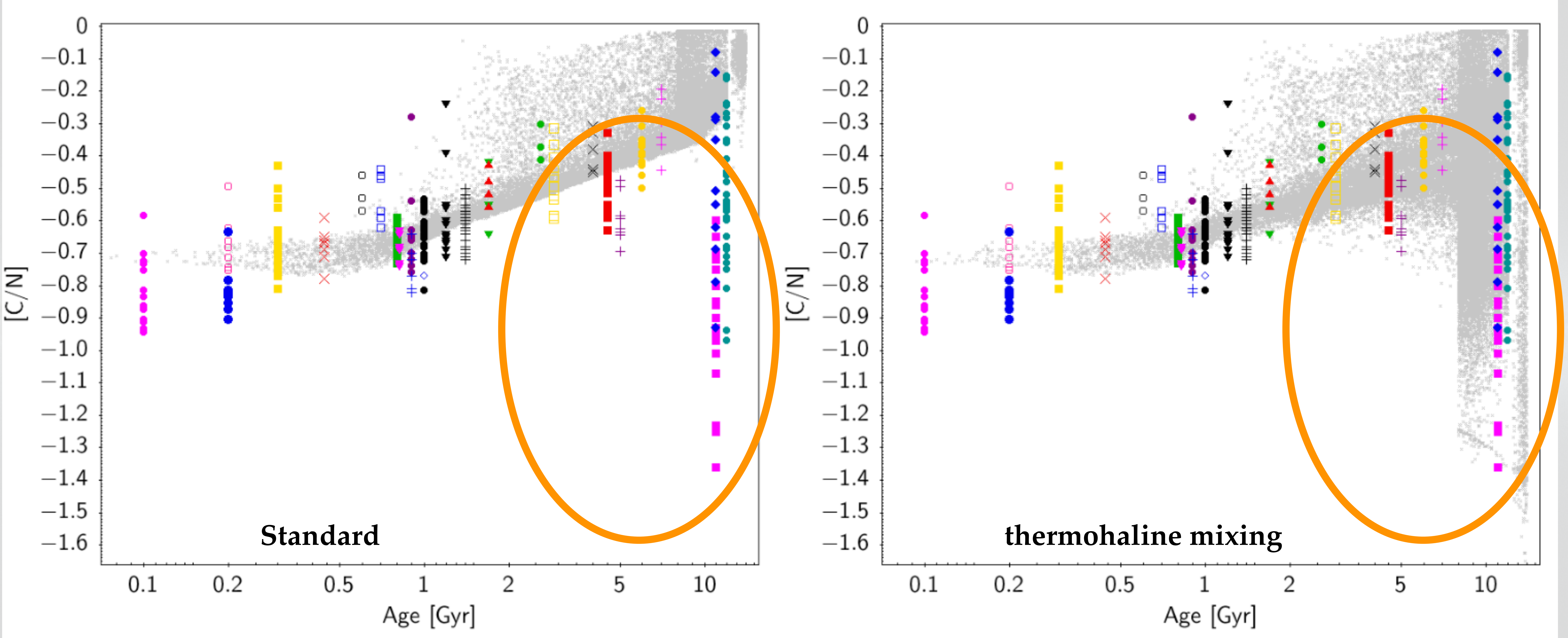


-> explain the [C/N] ratio observed as a function of stellar age

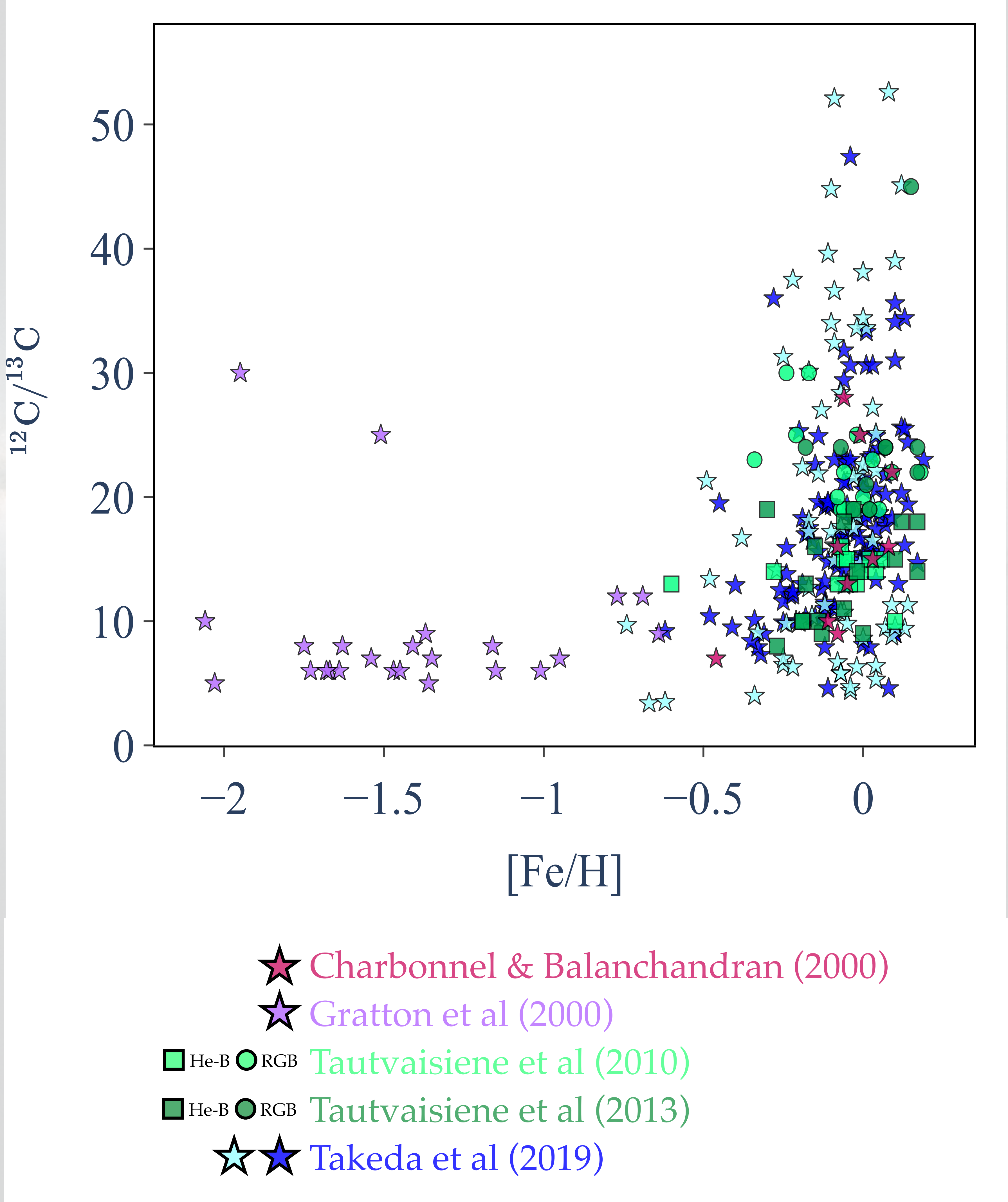
$^{12}C/^{13}C$ one of the best tracer of extra-mixing

- $^{12}C/^{13}C$ have been derived for few field giant stars (~90 stars in literature until 2019 + 190 published by Takeda et al 2019)

- *Morel et al (2014)* derived $^{12}C/^{13}C$ for only **4 CoRoT field stars**

=> Need to derive carbon isotopic ratio for asteroseismic targets

Field stars



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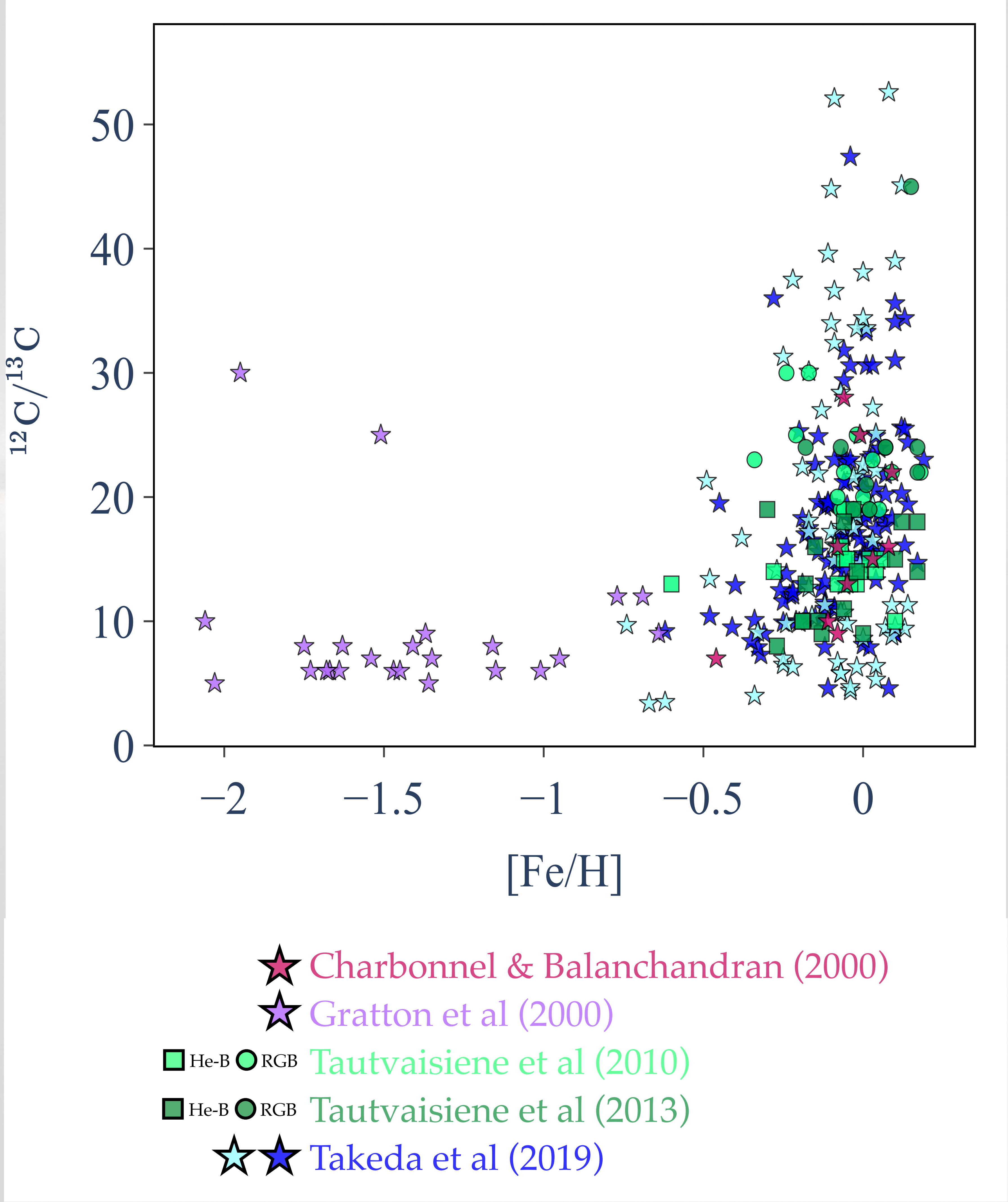
Lagarde et al. (in prep.) :
spectroscopic study of Kepler field giants using FIES spectrograph

+

Field stars



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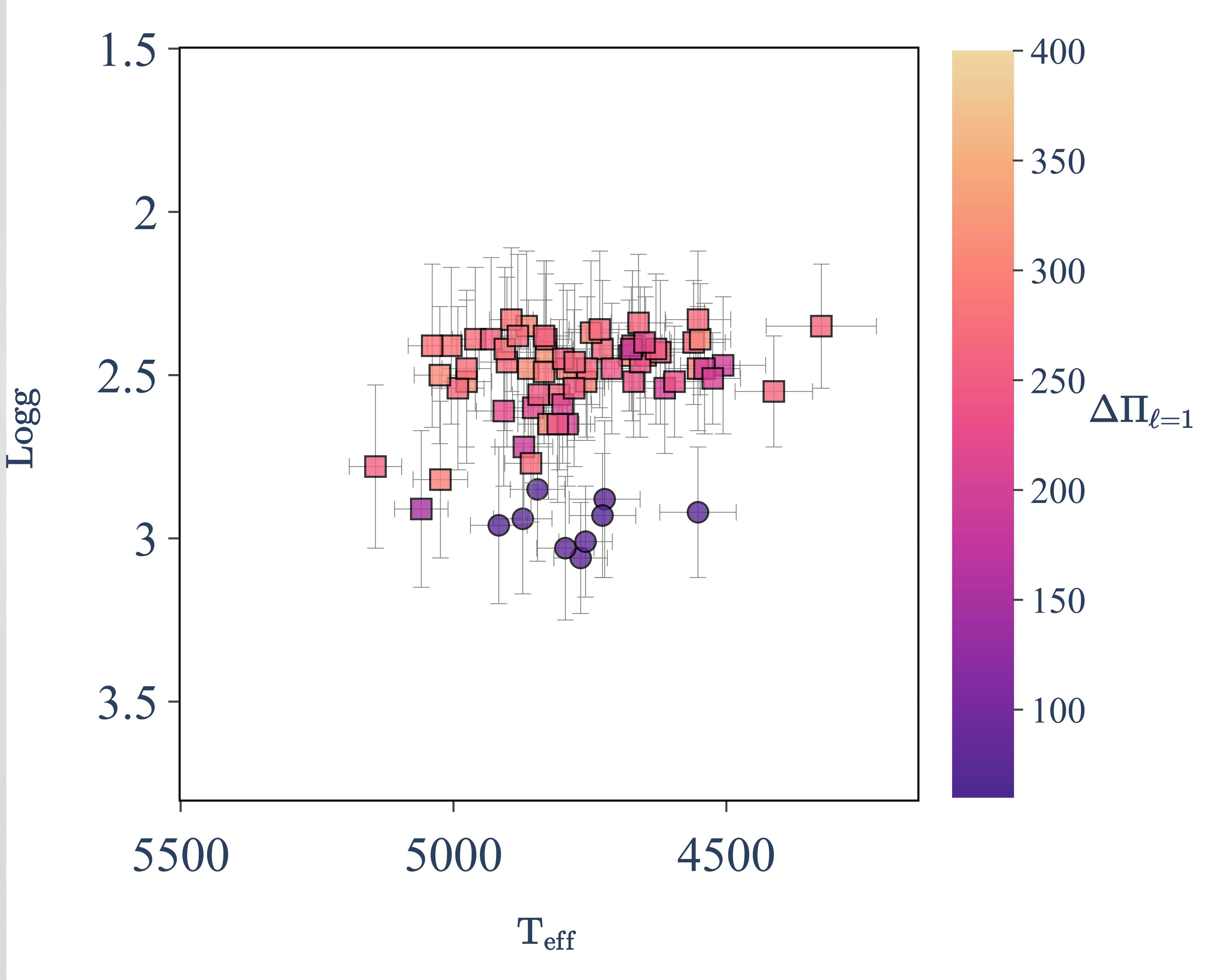

Lagarde et al. (in prep.)

Our sample

- 71 Kepler giant stars with a maximum of asteroseismic constraints

9 RGB stars (with $\mathbf{\Delta\Pi}_{l=1} < 100$ s)

62 He-burning stars (with $\mathbf{\Delta\Pi}_{l=1} > 100$ s)

$$\Delta\Pi(\ell = 1) \propto \frac{1}{\text{size of the radiative zone}}$$

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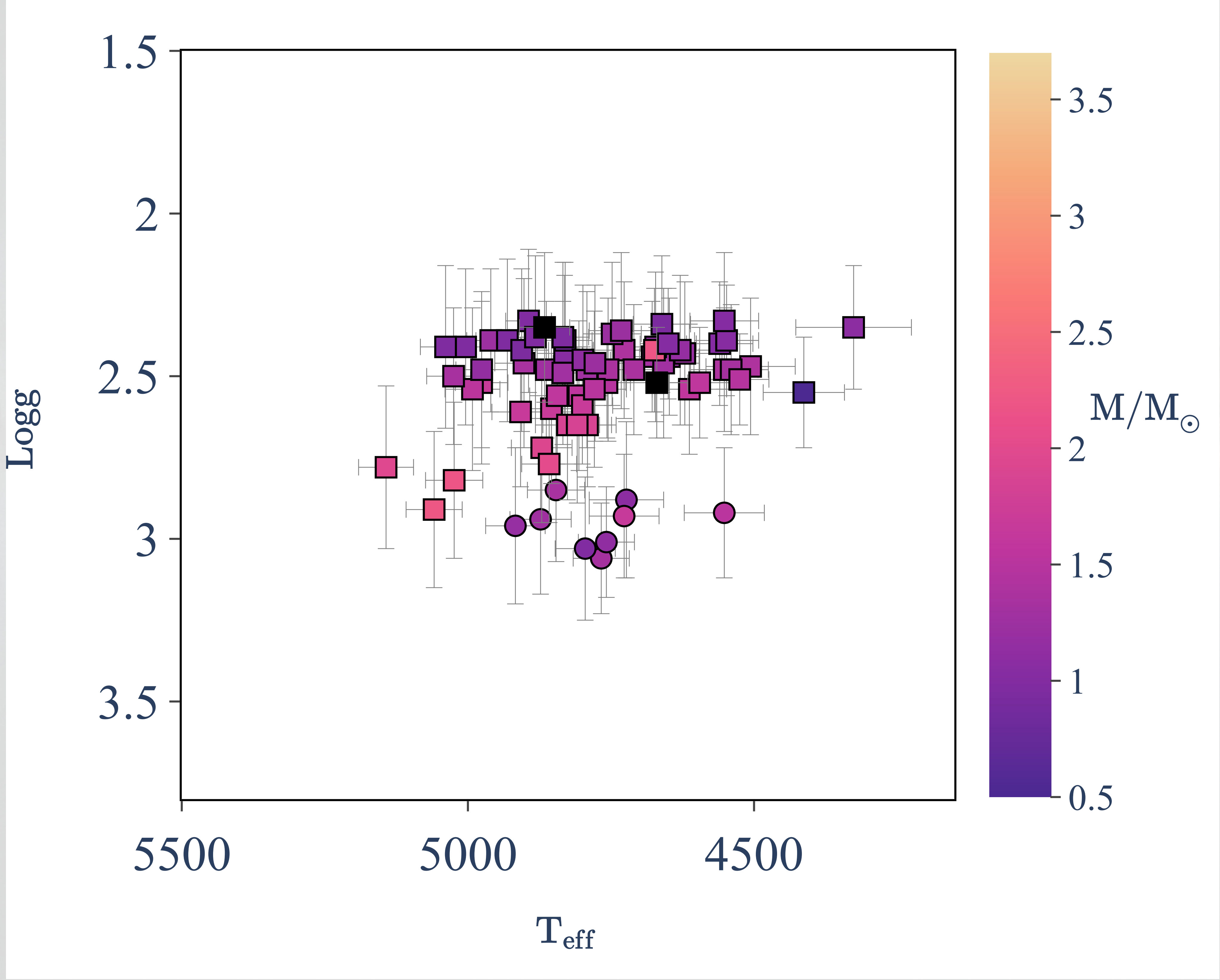
- Mass range between 0.8 $M_{\odot}$ and 2.3 $M_{\odot}$
  the mass range where thermohaline mixing should be more efficient



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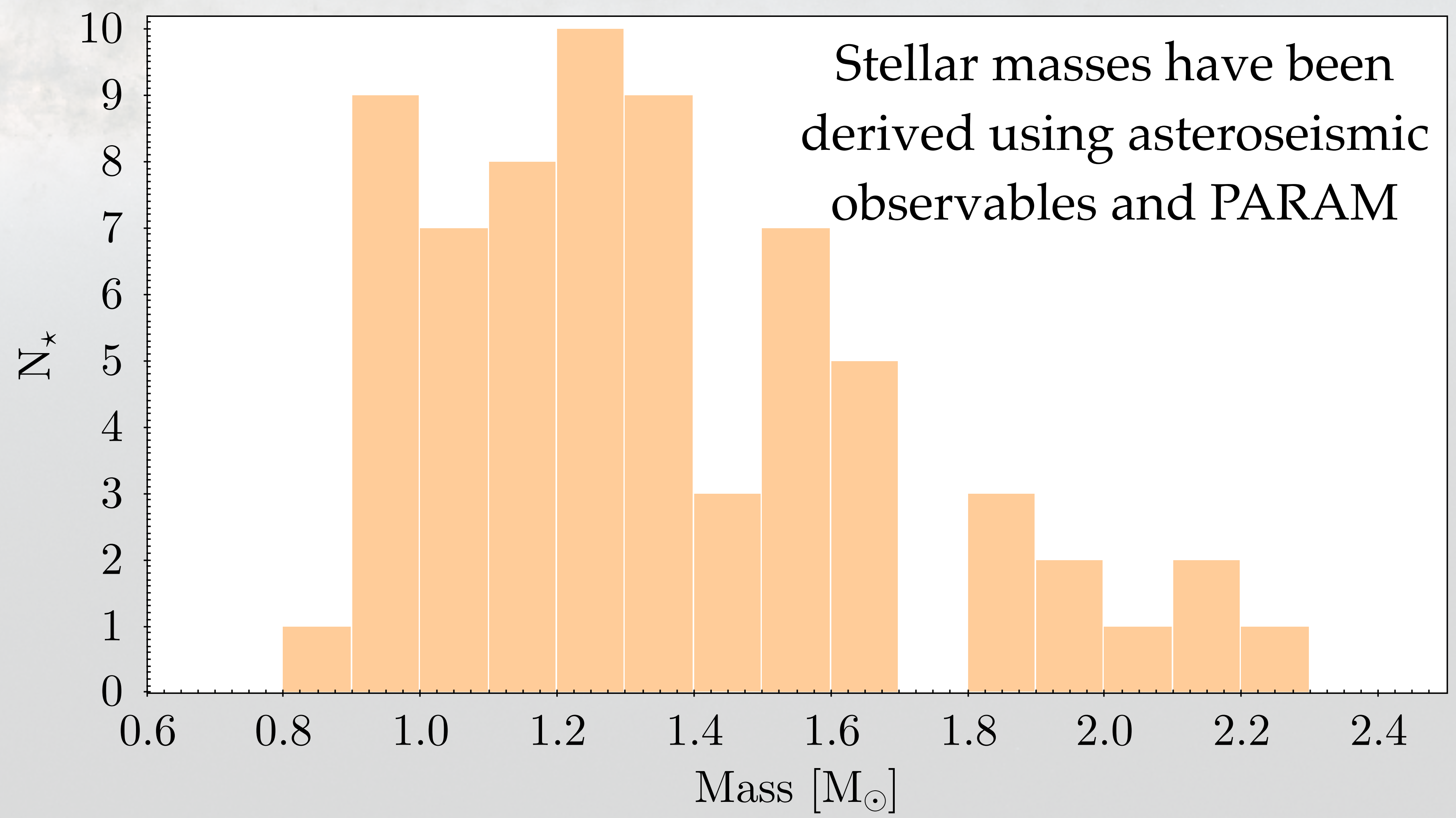

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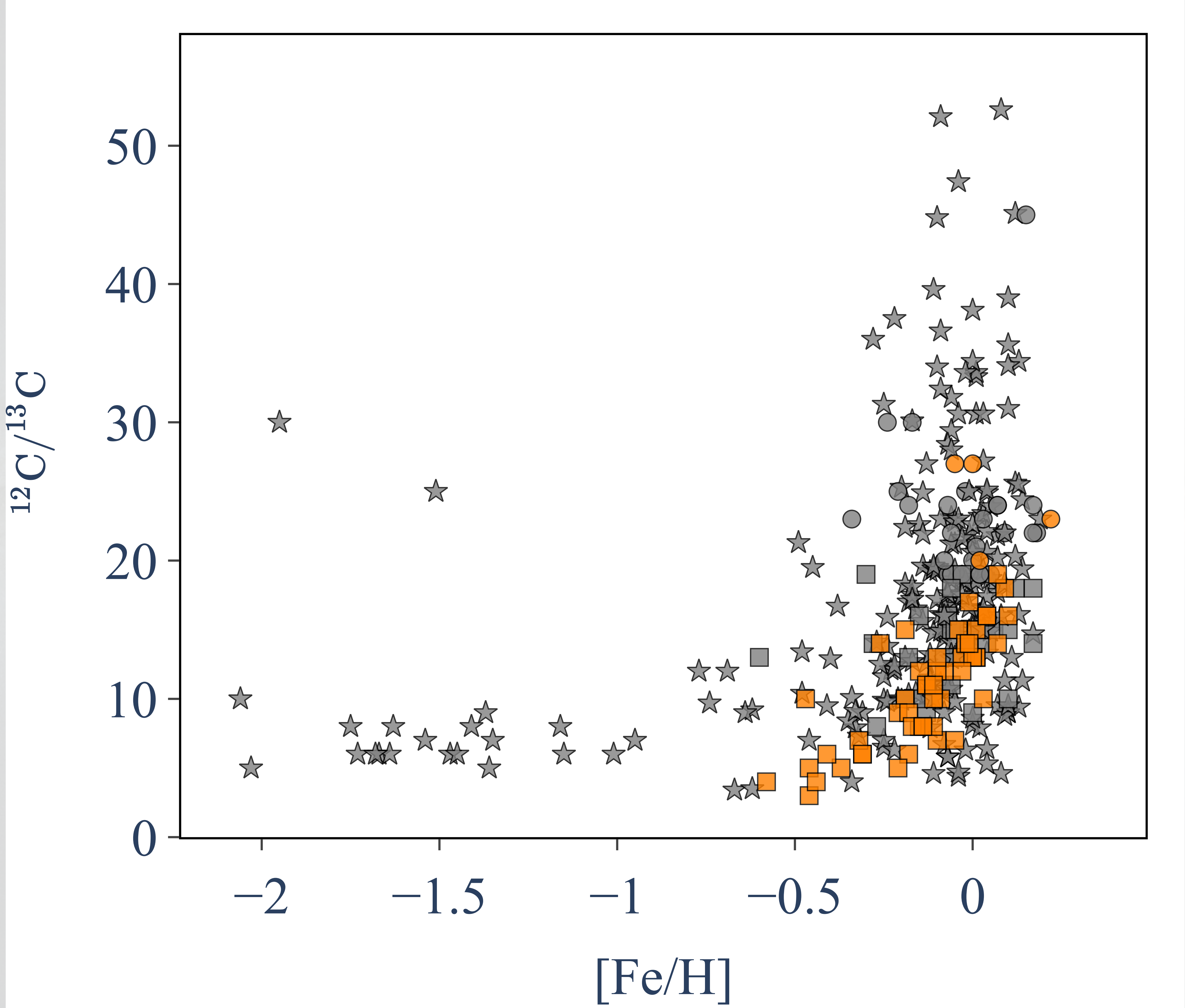

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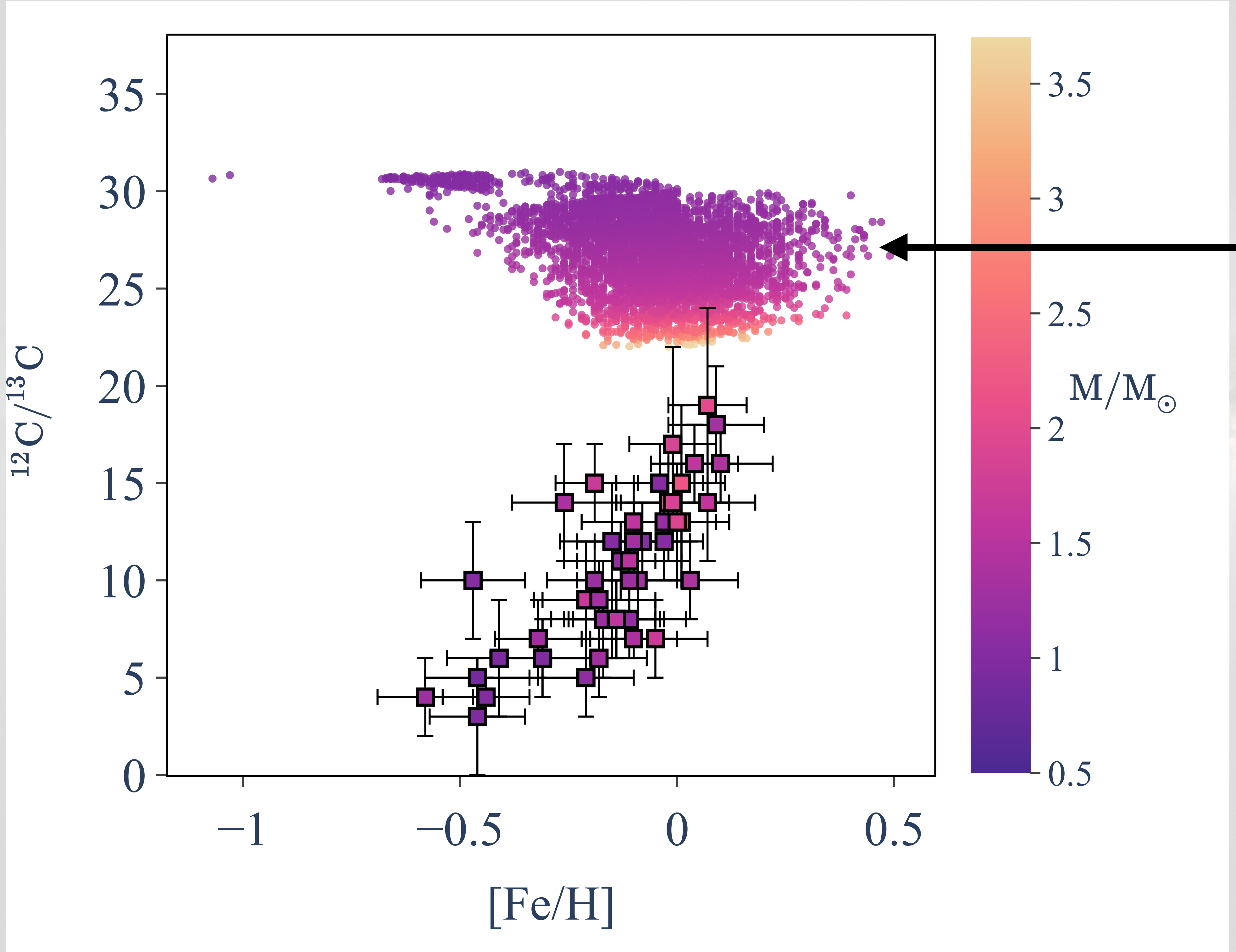
- We performed two observing runs using the high-resolution FIbre-fed Echelle Spectrograph at the Nordic Optical Telescope

- We derived the CNO abundances as well as $^{12}C/^{13}C$ and $^{12}C/^{14}N$ ratios

First results for He-burning stars

Lagarde et al. (in prep.)



Without mixing

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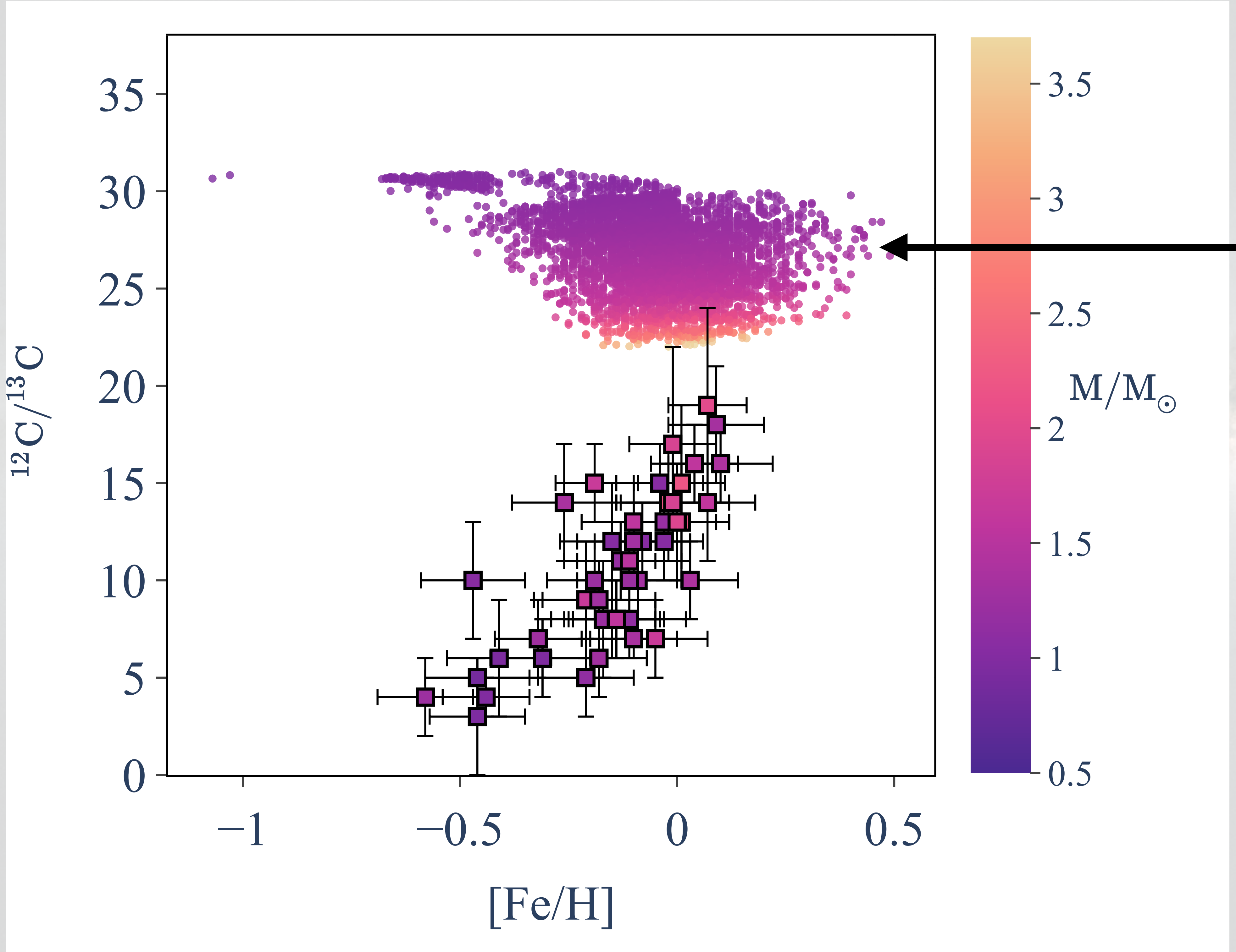
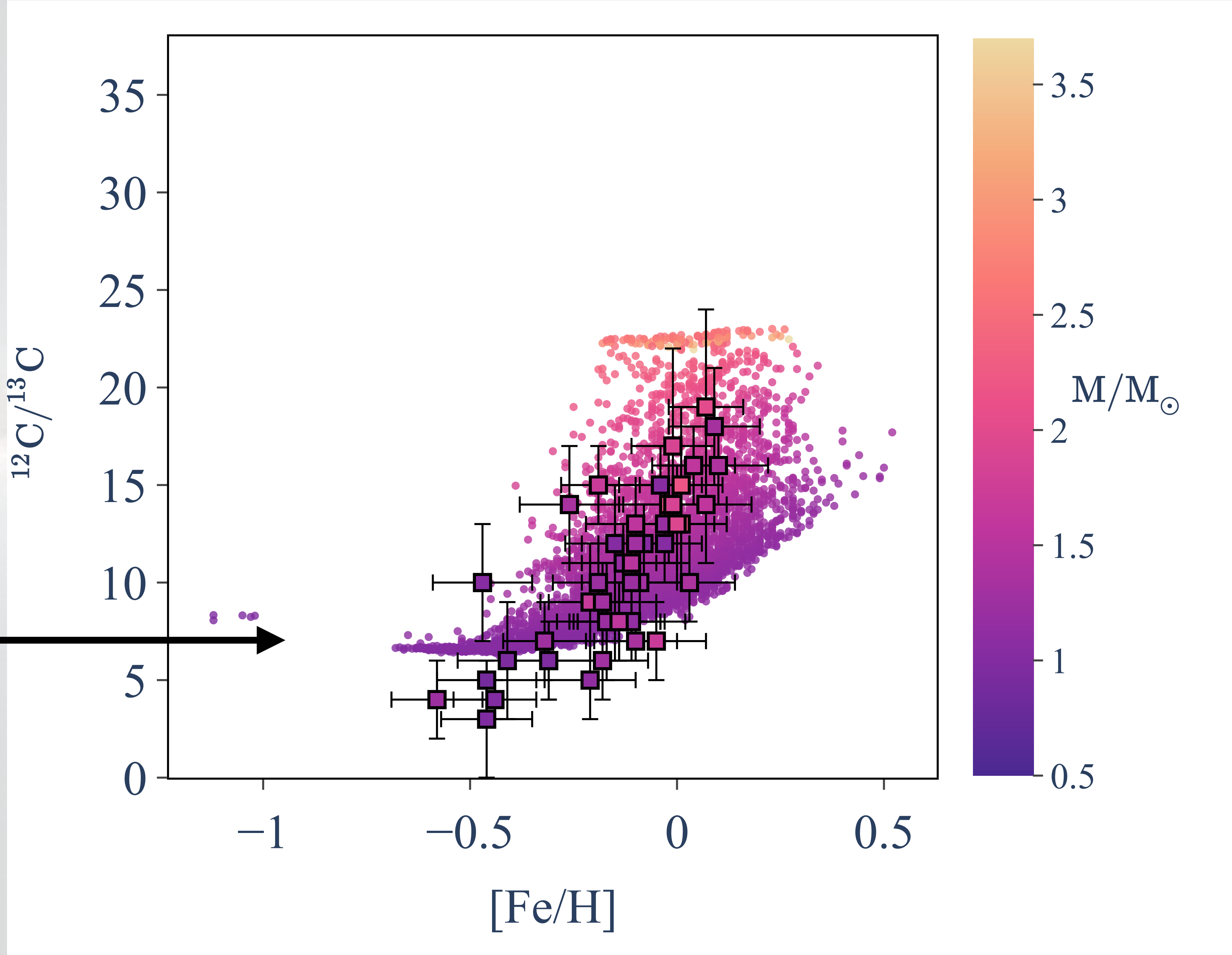


Without mixing

With thermohaline mixing



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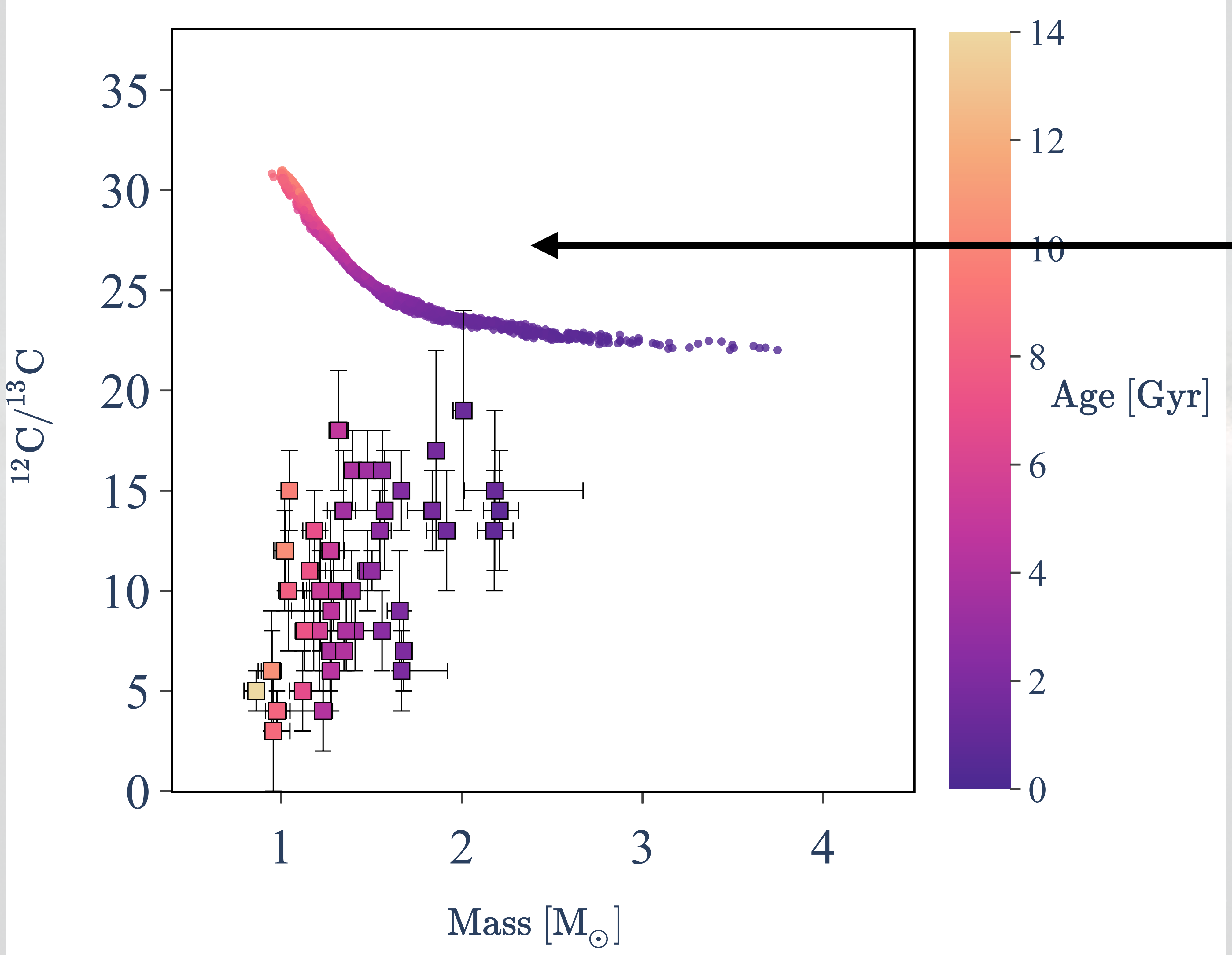

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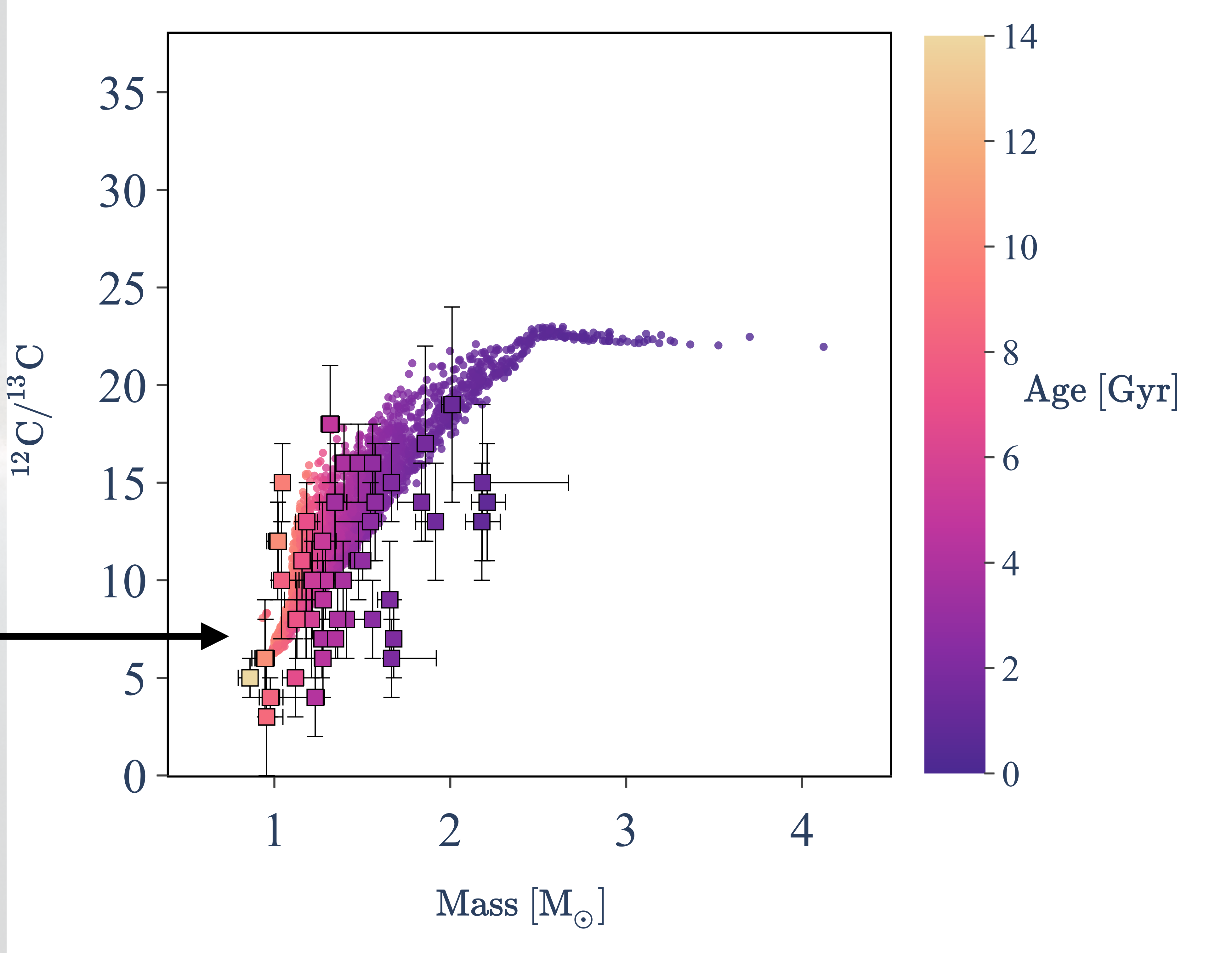

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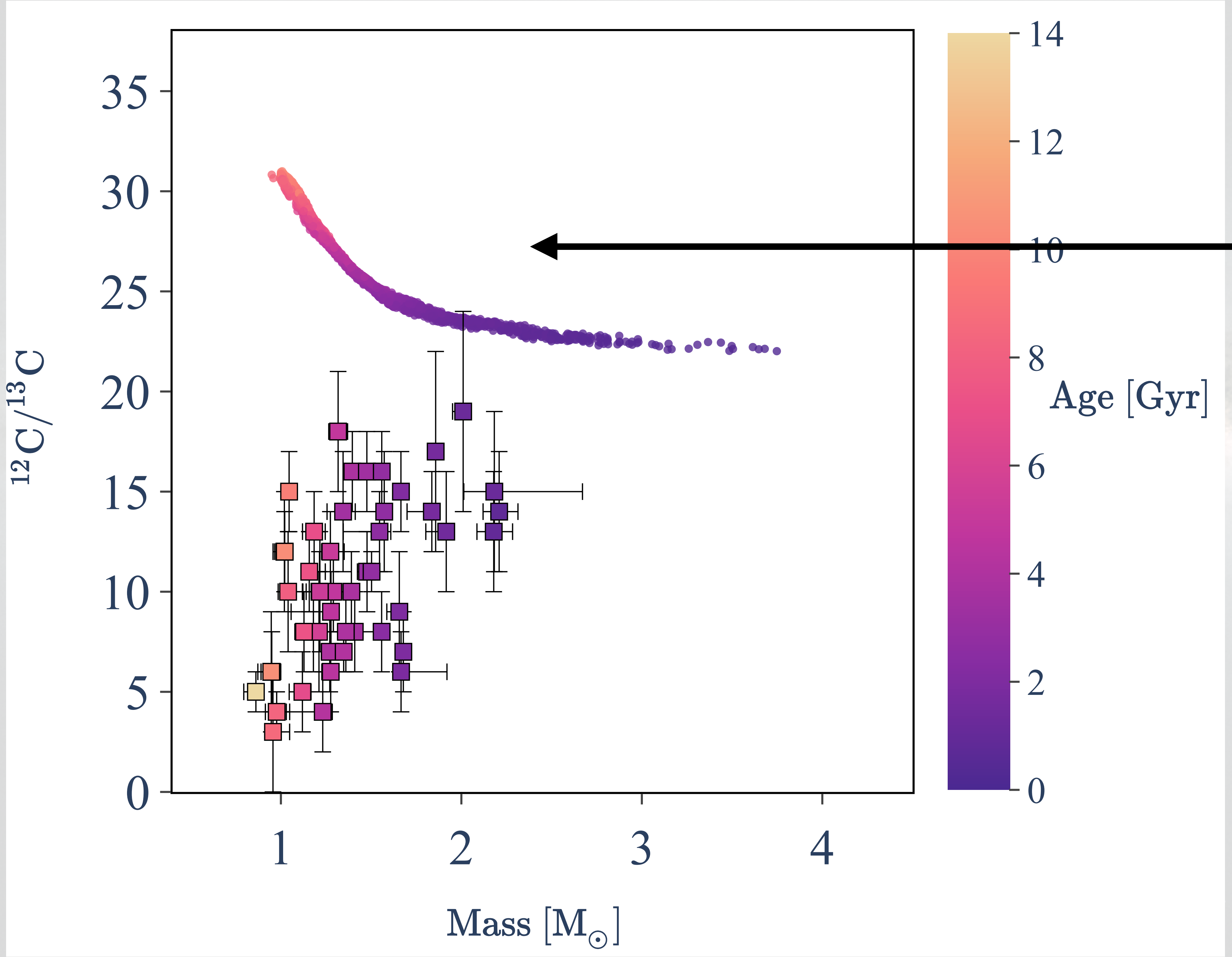

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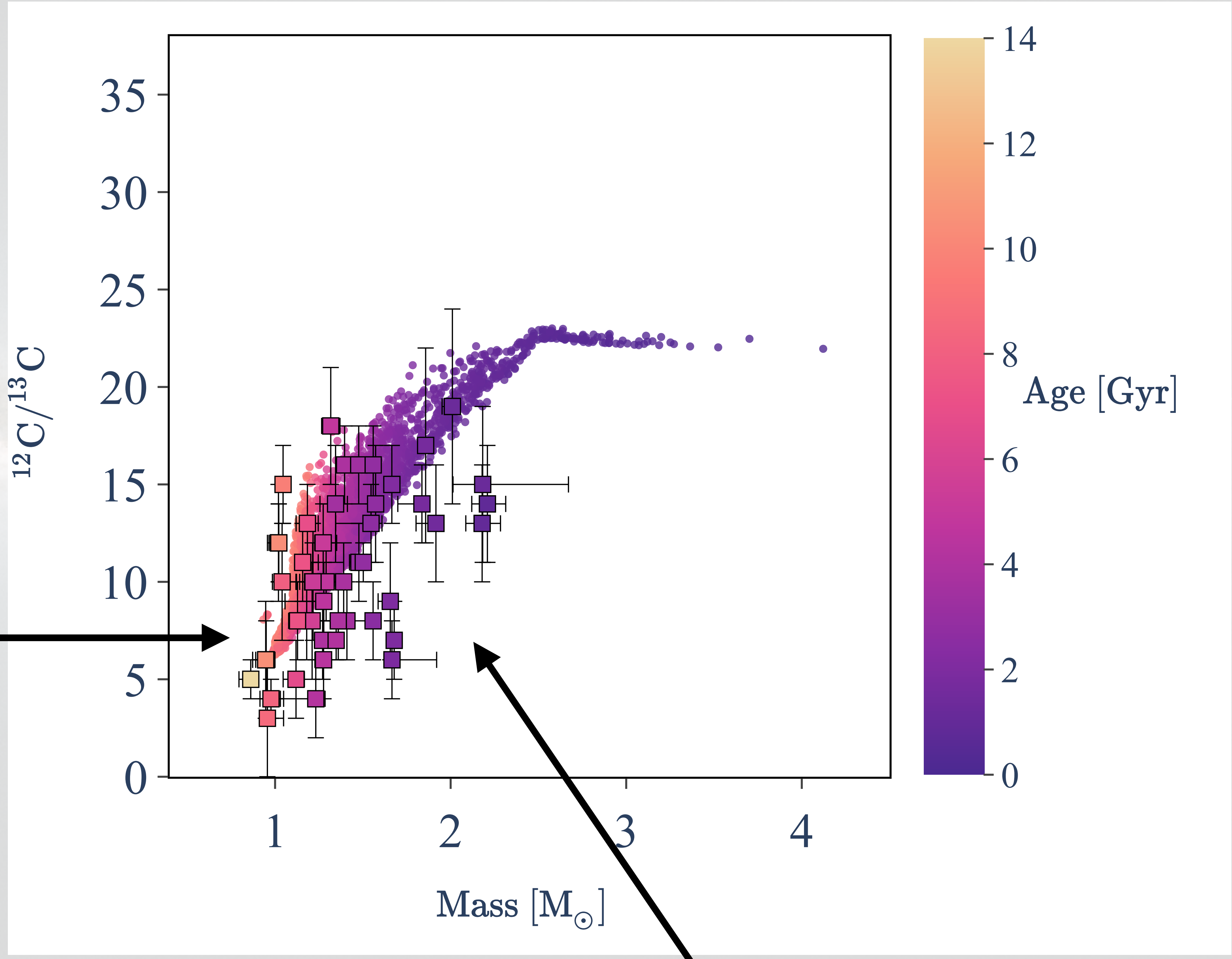


$^{12}C/^{13}C$ at the surface of more massive stars should be explain with rotation-induced mixing and thermohaline mixing (see *Charbonnel &Lagarde 2010*)

Conclusions

Could simulate global, chemical and seismic properties of stars in the Milky Way
Lagarde et al (2017)

should be used to handle the huge statistic providing by recent survey ; and should be also used to constrain the efficiency of transport processes occurring stellar interiors.

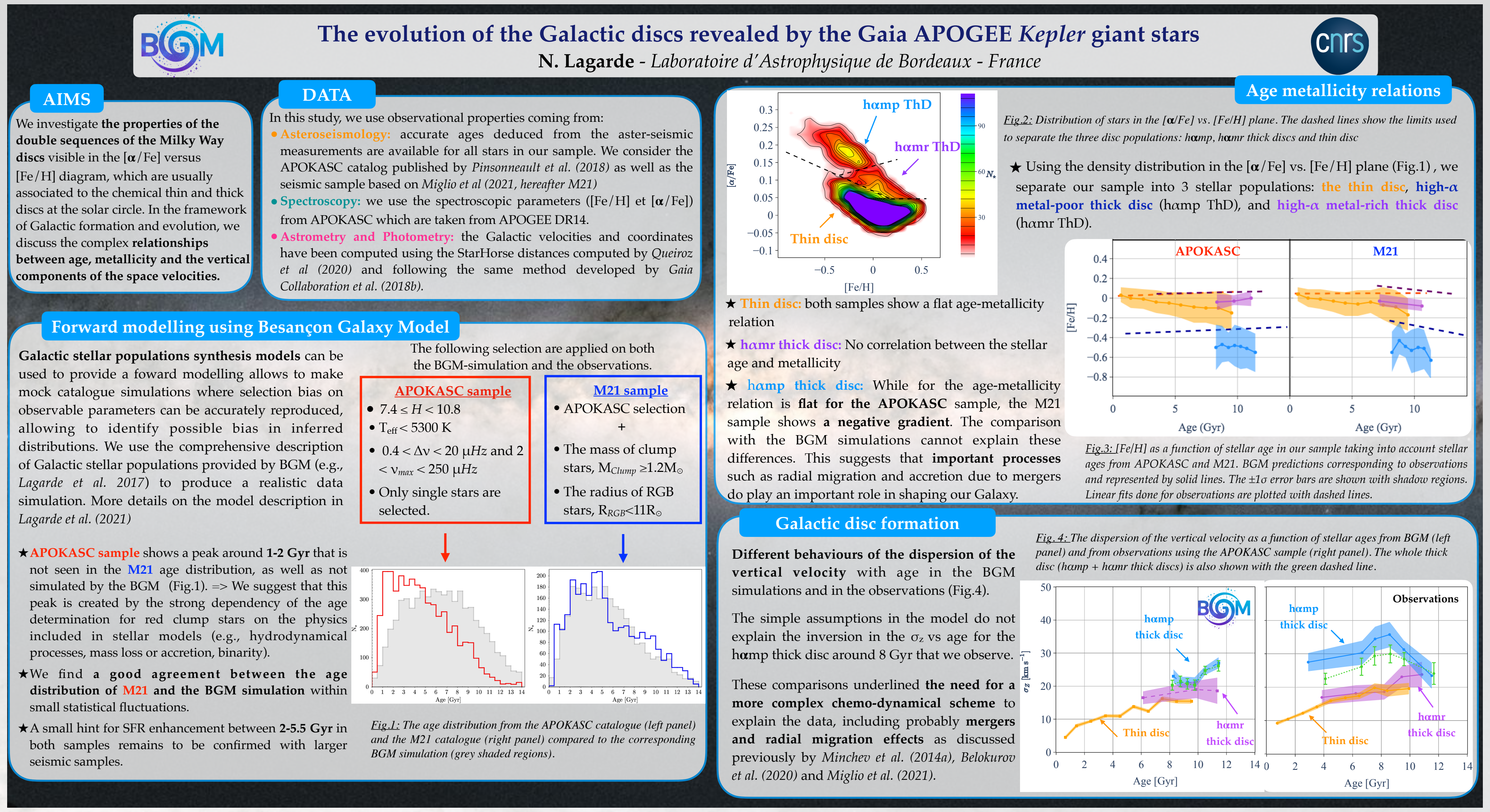
- Using the GES survey, we showed that stellar evolution models including extra-mixing could reproduce the decrease of [C/N] at the surface of giant field stars and clusters members with [Fe/H], mass, and age - ***Lagarde et al (2019)***

- New study reporting the $^{12}C/^{13}C$ for 71 Kepler giants stars. ***Lagarde et al (in prep.)***
With this study, the number of stars with a determination of $^{12}C/^{13}C$ and seismic constraints is considerably increased (4 to 75 field stars).

the $^{12}C/^{13}C$ at the surface of low-mass, low-metallicity and oldest giant stars are quite well reproduce with models including thermohaline mixing.

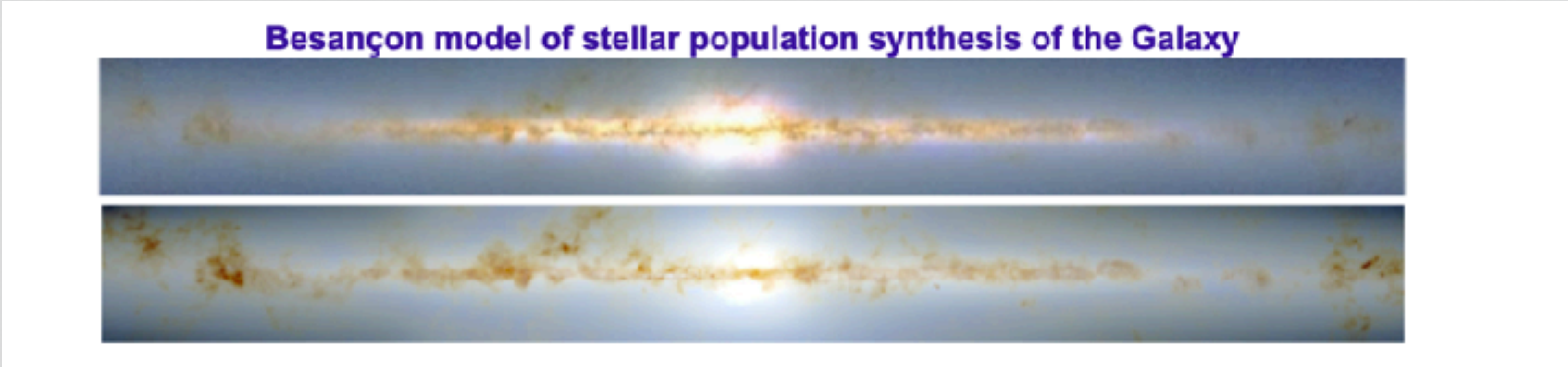
- Galactic formation and evolution using the BGM

→ My poster « The evolution of the Galactic discs revealed by the Gaia APOGEE *Kepler* giant stars »
Lagarde et al (2021)



- You and BGM simulations

https://model.obs-besancon.fr/



or send me an email

=> **nadege.lagarde@u-bordeaux.fr**