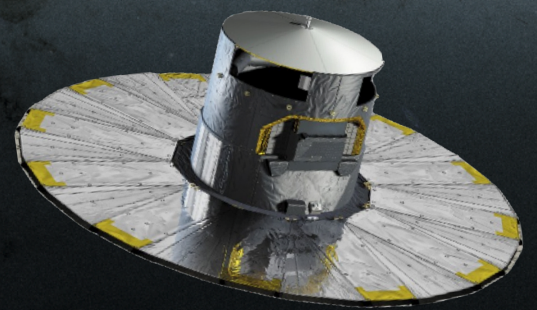
The evolution of galactic disk:

New insights with the Gaia-APOGEE-Kepler giant stars and the Besançon galaxy model

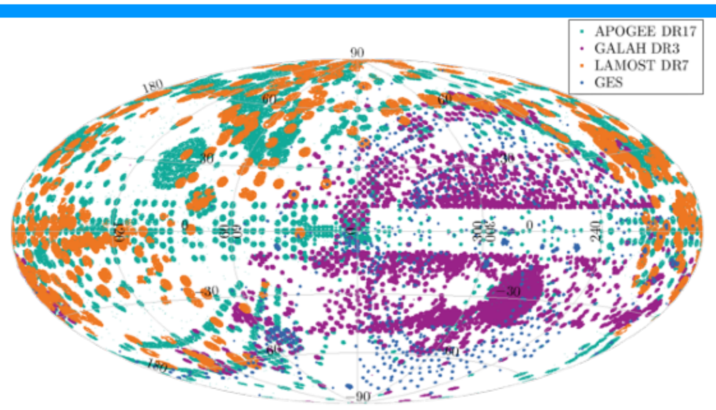


Nadège Lagarde

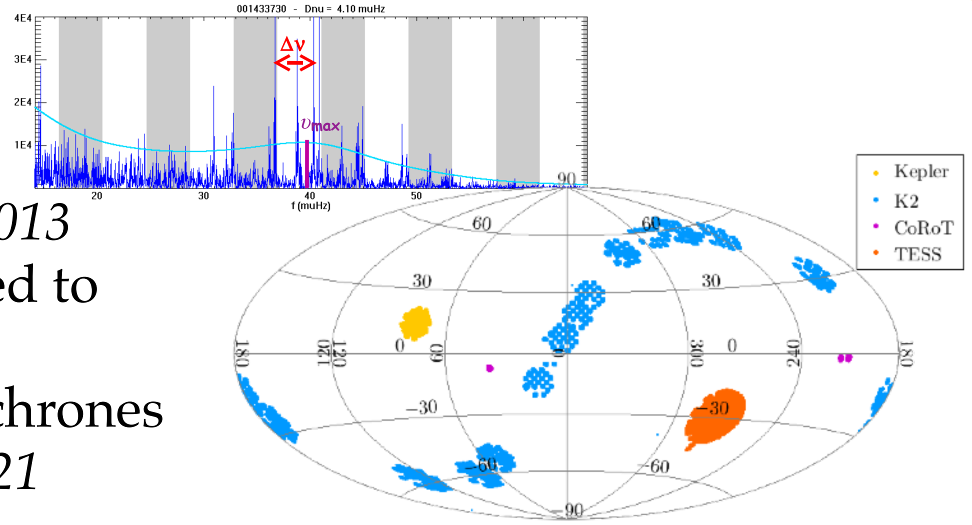
Laboratoire d'Astrophysique de Bordeaux

Spectroscopy

Surface properties of stars
chemical abundances ; T_{eff} ; gravity ;
[Fe/H]



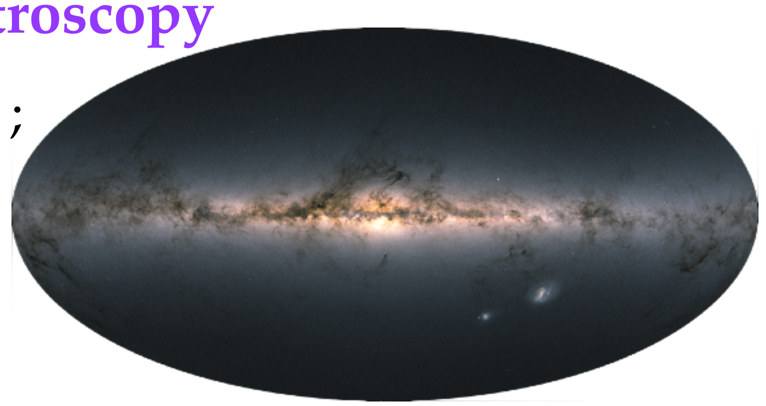
Asteroseismology



To probe stellar interiors *Chaplin & Miglio 2013*
- Stellar radius, masses without being limited to surface properties
- Stellar ages with higher accuracy than isochrones fitting *Lebreton et al 2014a,b ; Miglio et al 2021*

Gaia data Astrometry ; Photometry ; Spectroscopy

Distances ; proper motions ; Magnitude ; kinematic ;
[Fe/H] indicators
Some chemical abundances
GSPspec *Recio-Blanco et al (2023)*



A great diversity of chemical compositions, ages and masses to probe stellar and Galactic evolutions

Rich observational context

Spectroscopy

Surface properties of stars
chemical abundances ;
T_{eff} ; gravity ; [Fe/H]

Asteroseismology

Properties of stellar interiors
Mass ; Radius ; Age
Evolutionary stage ;
Core rotation Period

Gaia data

Astrometry
Photometry
Spectroscopy

Distances ; proper motions ; kinematics
Magnitude
[Fe/H] indicators
Some chemical abundances

Stellar Evolution

Complementary properties of stars at different ages

Stellar evolution

Transport processes and their impacts on :

✓ the stellar structure:
- => Effects on chemical profiles
- => Effects on asteroseismic quantities
- => **Stellar ages**, radius and mass of field stars

✓ the surface properties:
- => Surface chemical abundances
- => Position in the HRD diagram
- => **Age determination** of (open and globular) clusters

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chemical abundances ;
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Lagarde et al 2024 A&A 684A 70L

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chemical abundances ;
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Mass ; Radius ; Age
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Gaia data

Astrometry
Photometry
Spectroscopy

Distances ; proper motions ; kinematics
Magnitude
[Fe/H] indicators
Some chemical abundances

Stellar Evolution

Complementary properties of stars at different ages

All kind of observations probe **different stellar populations** in the Milky Way

Galactic Formation & Evolution

Stellar evolution

Transport processes and their impacts on :
✓ the stellar structure:
=> Effects on chemical profiles
=> Effects on asteroseismic quantities

Lagarde et al 2024 A&A 684A 70L

✓ the surface properties:
=> Surface chemical abundances
=> Position in the HRD diagram
=> **Age determination** of (open and globular) clusters

Formation and Evolution of stellar populations

✓ To investigate the properties of the stellar populations of the MW (e.g., thin/thick discs)
=> Relations between velocities and age, [Fe/H], [α/Fe],…
=> IMF ; SFR of stellar populations ?

✓ To provide clues to understand the chemical evolution of the MW
=> Relations [X/Fe] vs Age in different stellar populations

THIS TALK

Our sample

Spectroscopy

Spectroscopic parameters coming from the APOGEE DR14

Asteroseismology

Accurate ages and masses deduced from the asteroseismic measurements

Gaia data

StarHorse distances from *Queiroz et al. (2020)*

Galactic velocities are computed following the method developed by *Gaia collaboration et al (2018)*

~5000 giant stars :

[Fe/H], [α/Fe],

Mass, Age

dist., V_R, V_φ, V_Z

Lagarde et al. 2021

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Mass, Age

dist., V_R, V_φ, V_Z

APOKASC catalog
Pinsonneault et al. (2018)

Miglio et al (2021)

Selection criteria:

- APOKASC criteria
- the mass of clump stars, Mclump $\geq 1.2\, M_\odot$
- the radius of RGB stars, RGB $< 11 R_\odot$
- Used models including microscopic diffusion.

Lagarde et al. 2021

Age distributions

Spectroscopy

Spectroscopic parameters coming from the APOGEE DR14

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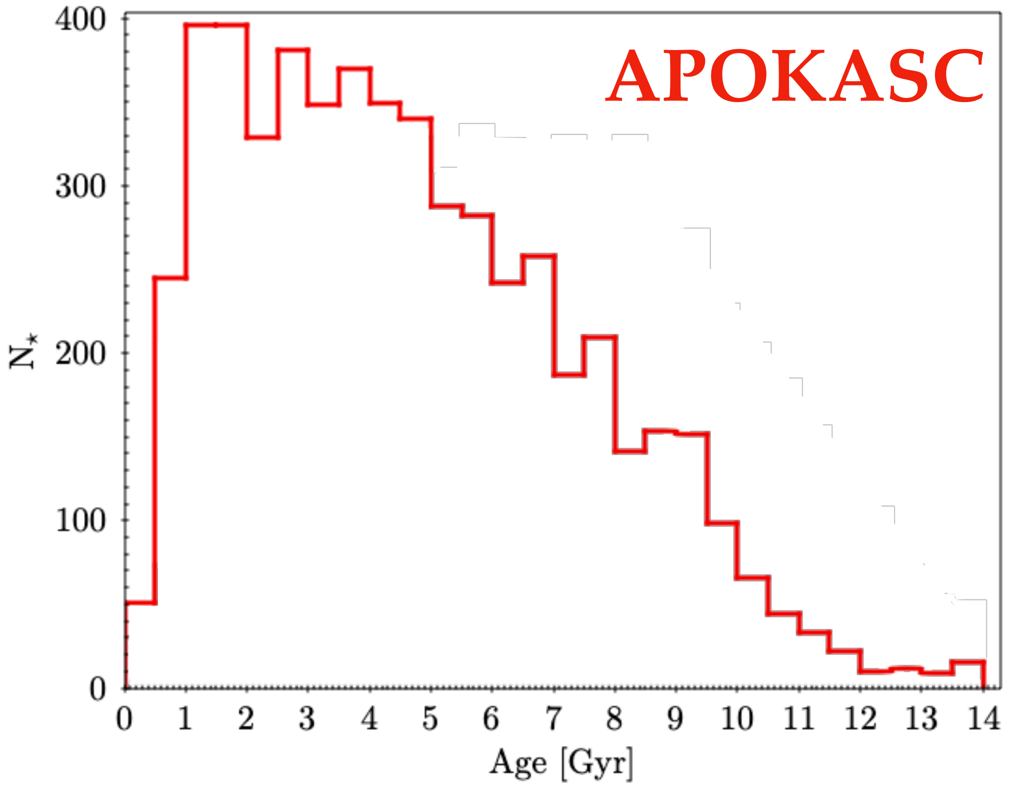

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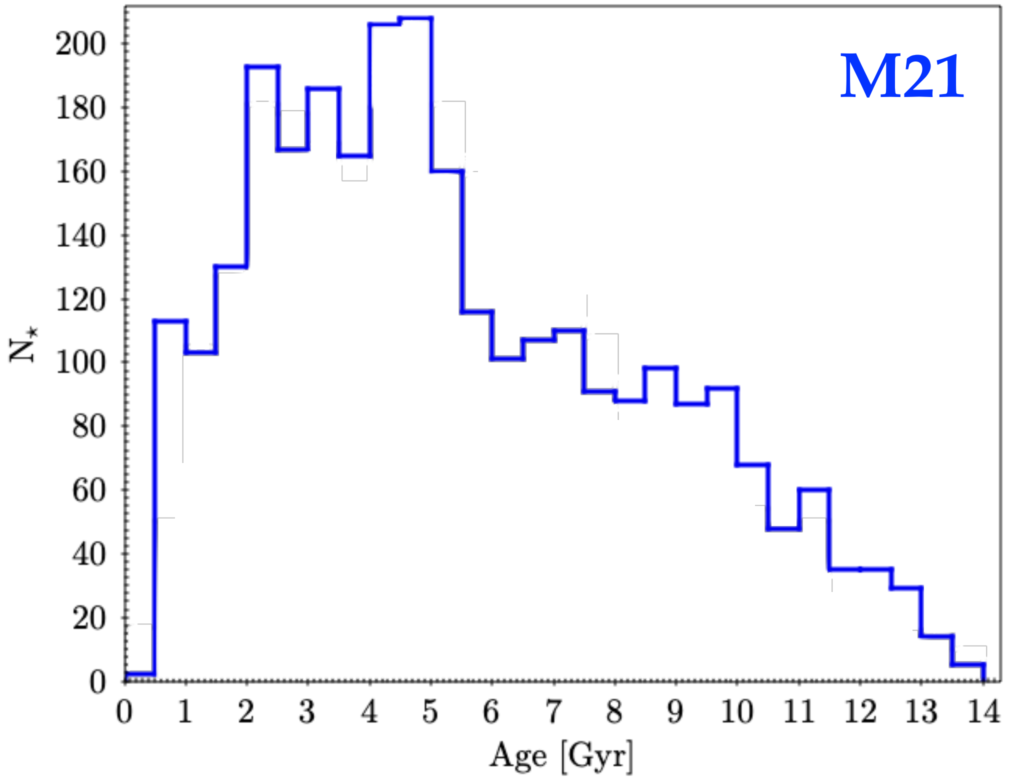

Lagarde et al. 2021

APOKASC catalog

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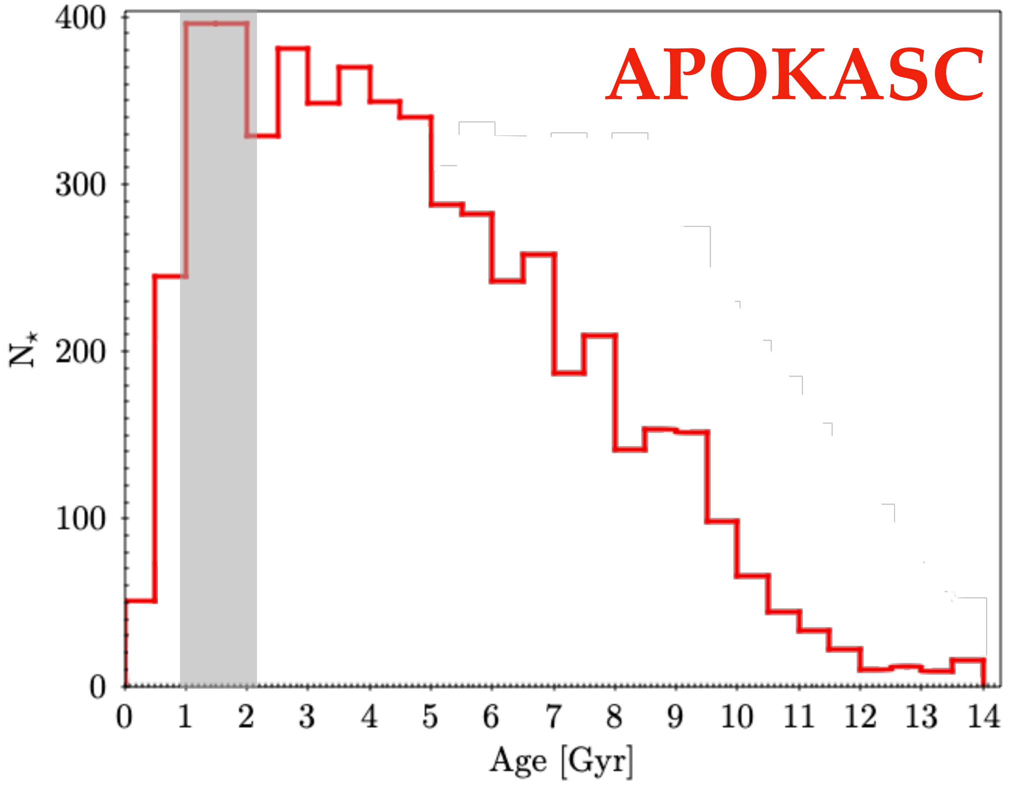
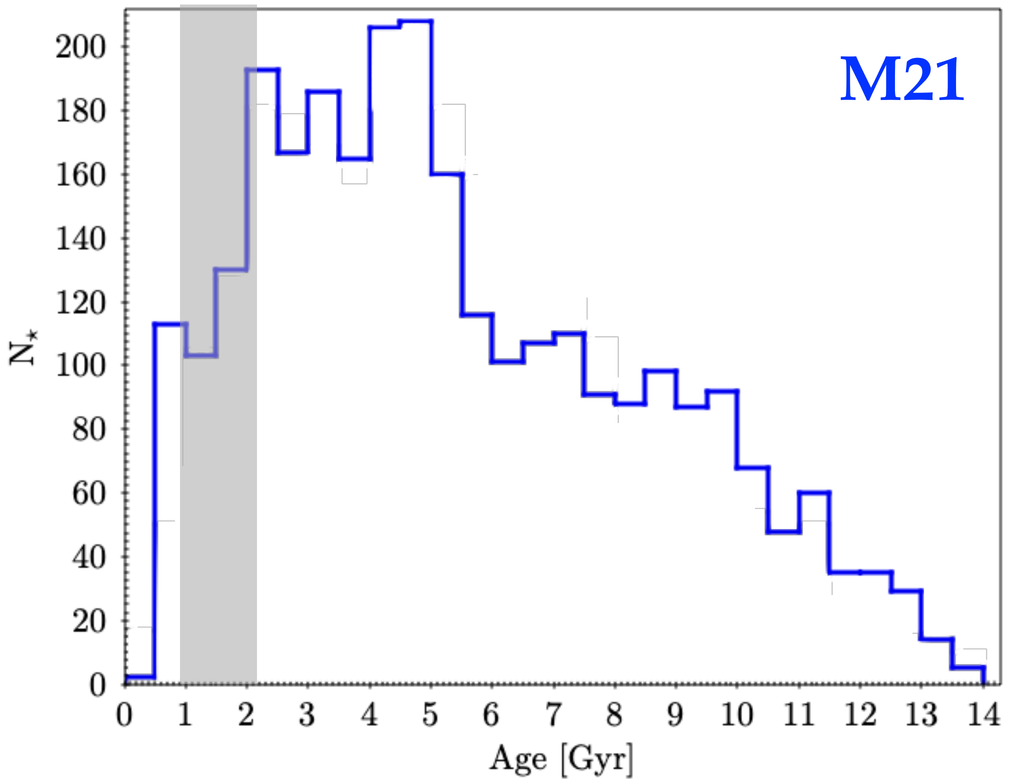


- **APOKASC** age distribution peaks around 1-2 Gyr
  => not seen in **M21 sample**

Miglio et al (2021)



Lagarde et al. 2021

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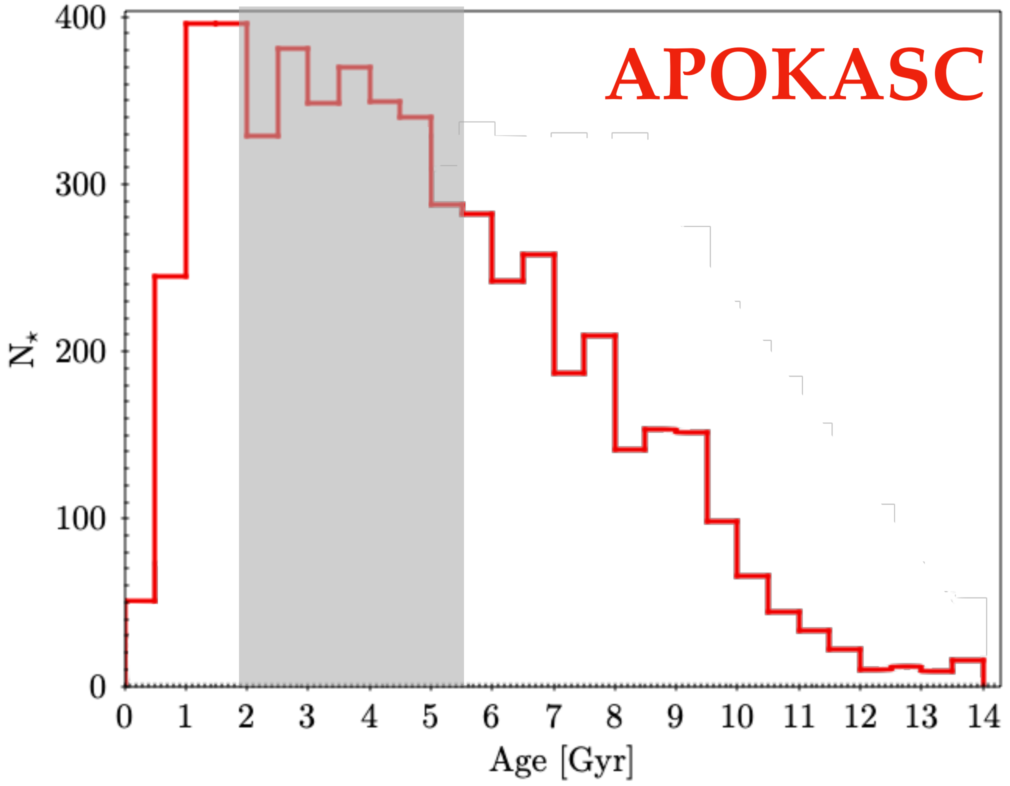


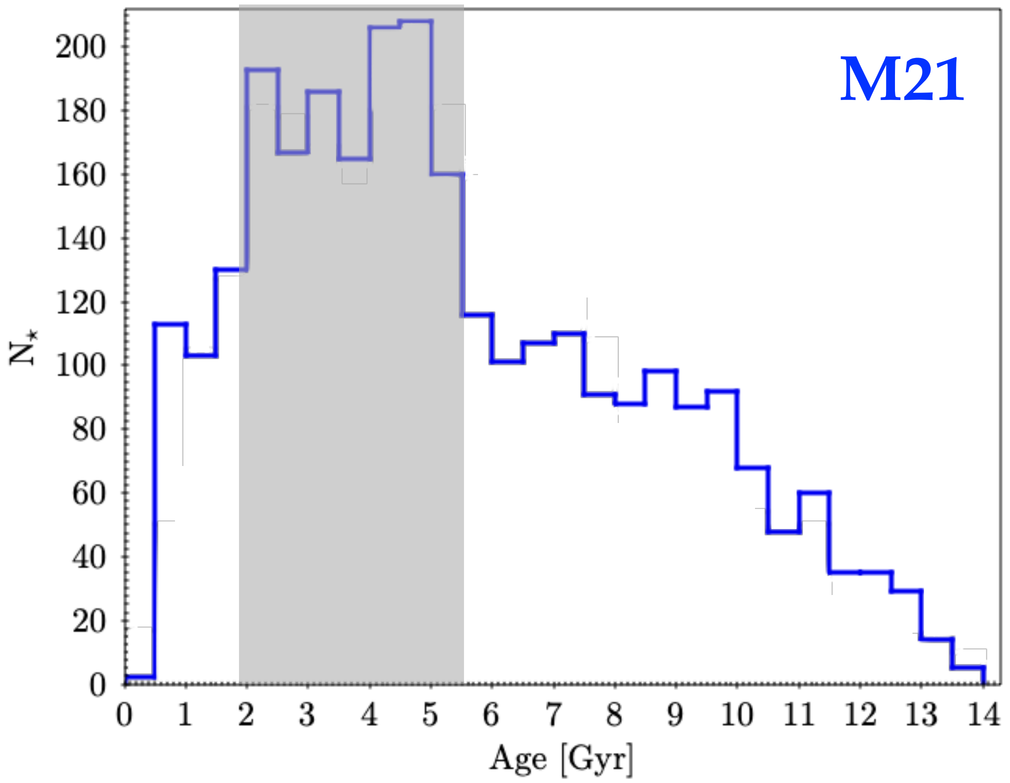
- **APOKASC** age distribution peaks around 1-2 Gyr
  => not seen in **M21 sample**

- **Both samples:**
  A small sign of SFR increase between 2 and 5.5 Gyr

  Between 2 and 3 Gyr = An increase in star formation
  (e.g., Cignoni et al 2006, Mor et al 2019, Donlon et al 2020)

  However low stellar ages are strongly dependent on hydrodynamical processes included in stellar evolution models.

Miglio et al (2021)



=> Need to be confirmed with larger seismic sample.

Lagarde et al. 2021

Spectroscopy

Spectroscopic parameters coming from the APOGEE DR14

Asteroseismology

Accurate ages and masses deduced from the asteroseismic measurements

- **APOKASC ages**
- ***M21 ages***

Gaia data

StarHorse distances from *Queiroz et al. (2020)*

Galactic velocities are computed following the method developed by *Gaia collaboration et al (2018)*

~5000
giant stars :

[Fe/H], [α/Fe],

2 determinations of Mass, Age

dist., V_R, V_φ, V_Z

Main goals

1) To discuss the main chrono-chemo-kinematics relations to highlight key constraints to MW evolution

Need to highlight selection bias

2) To highlight differences between observations and Galactic theory **using a stellar population synthesis model.**
Features not well reproduced by the mock catalog **can reveal missing physical processes** and improve our understanding of Galactic evolution..

Need to take into account selection function

Lagarde et al. 2021

Stellar populations synthesis model

Simulates the properties of stars in our Galaxy **by accurately reproducing the selection biases on observables (selection functions and observed errors)**.

Theories models predictions

Spectroscopy

Asteroseismology

Gaia data

Selection functions
(e.g., magnitude range, the region of the sky observed, the induced biaises…) should be take into account before drawing any conclusions.

Stellar Evolution

Galactic Formation & Evolution

Stellar populations synthesis model

Simulates the properties of stars in our Galaxy **by accurately reproducing the selection biases on observables (selection functions and observed errors)**.

Theories models predictions

Spectroscopy

Asteroseismology

Gaia data

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

Stellar Evolution

Galactic Formation & Evolution

OUTPUTS

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

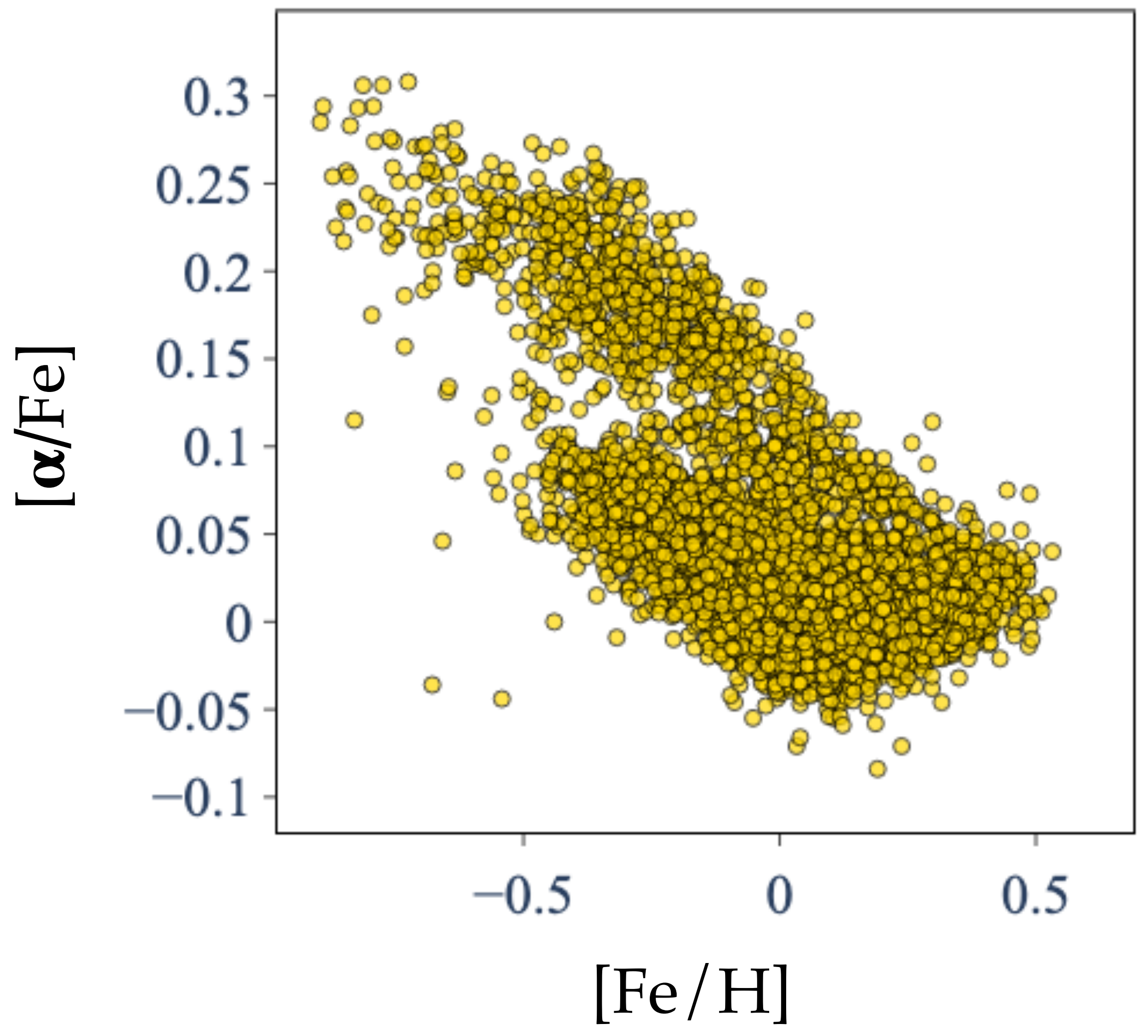
Seismic properties of stars: $\Delta\nu$, ν_{max}, $\Delta\Pi$(l=1)

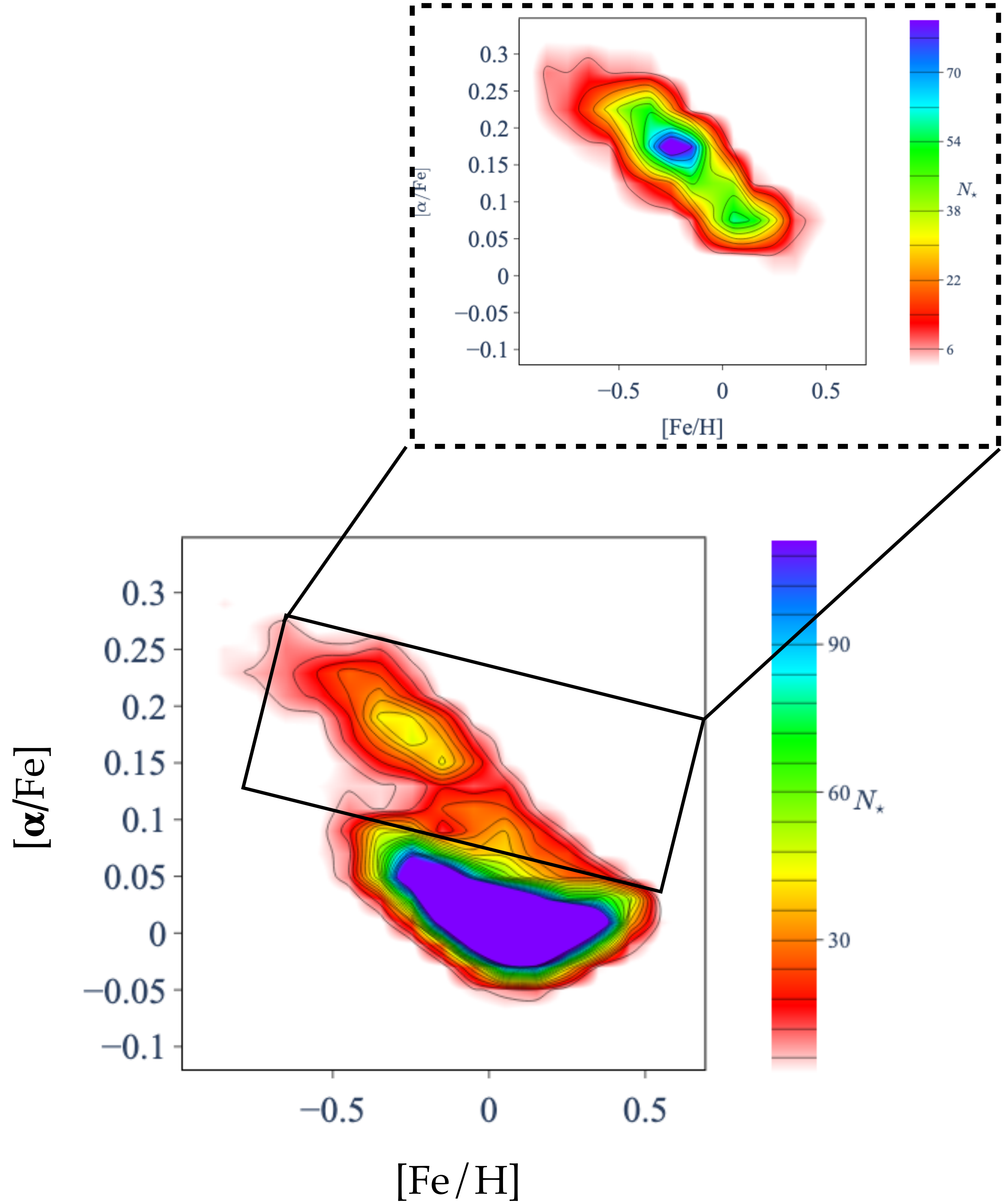
Stellar abundances of different chemical elements

Kinematics properties: Velocities

Lagarde et al. 2017, 2019

- Isolating « common » thick disc, two density peaks appears. Already mentioned by *Adibekyan et al (2013) and Anders et al (2018)*

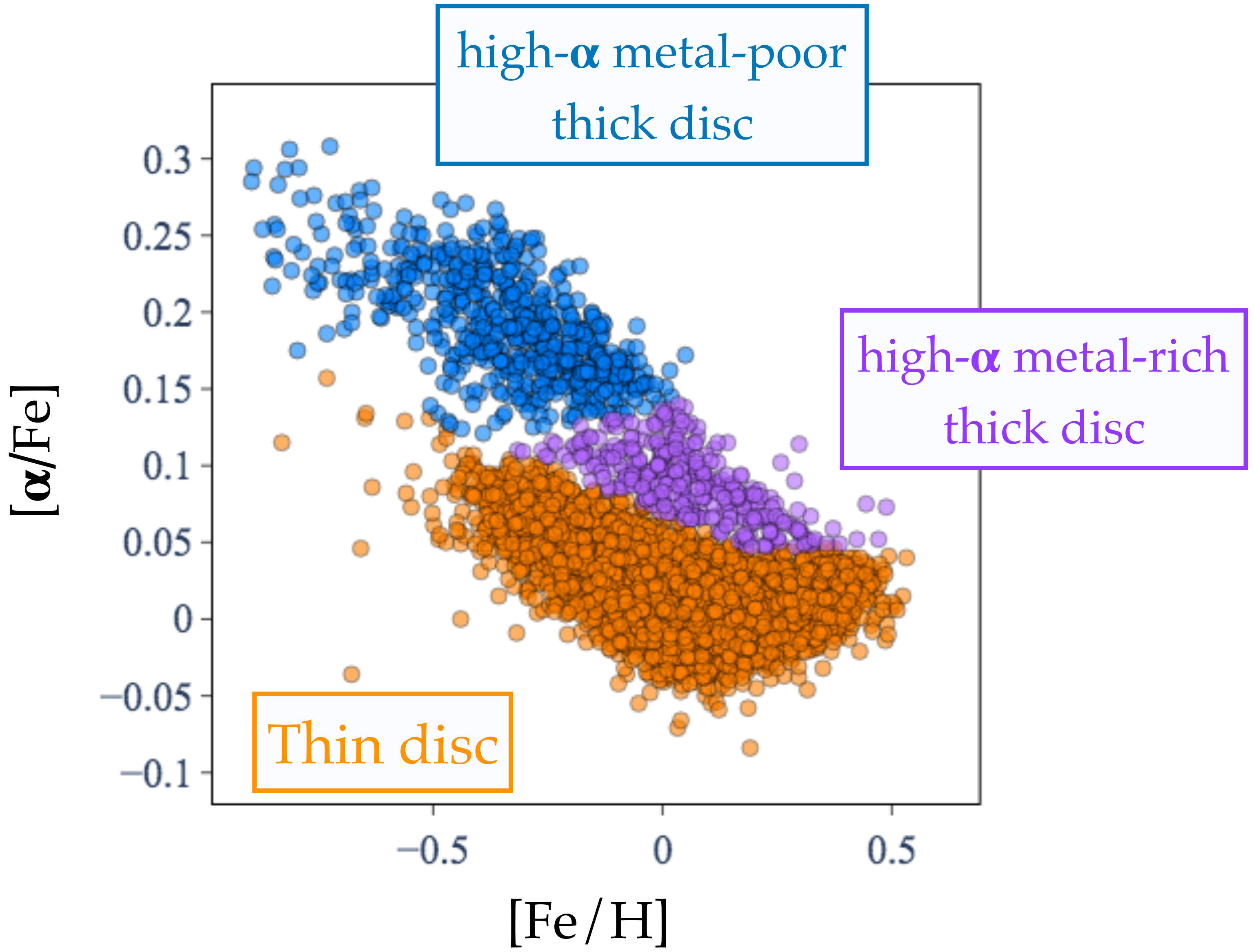


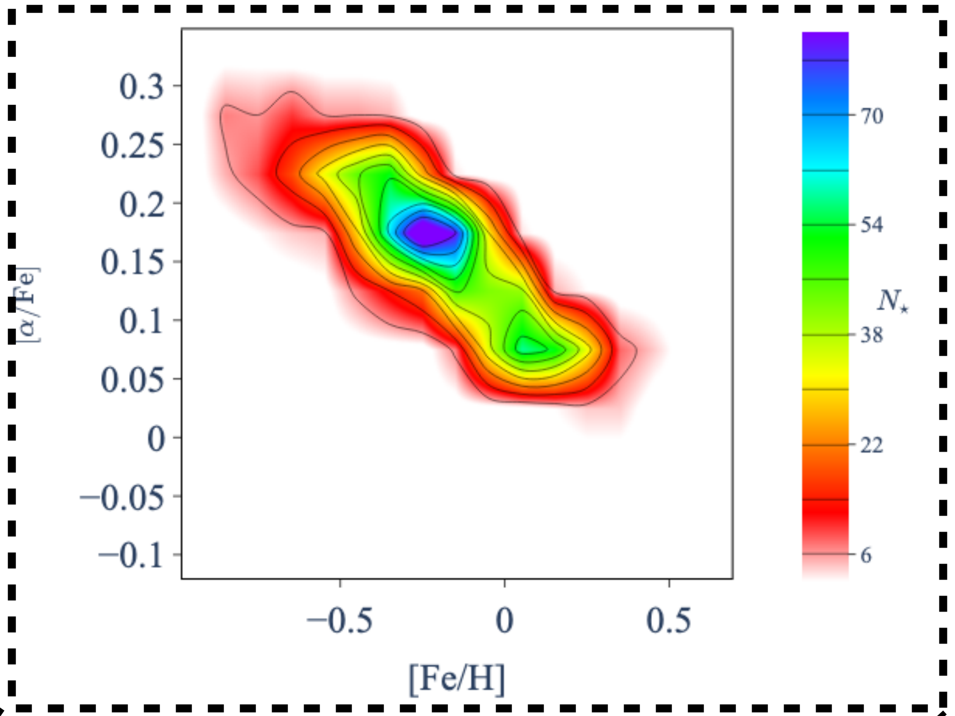


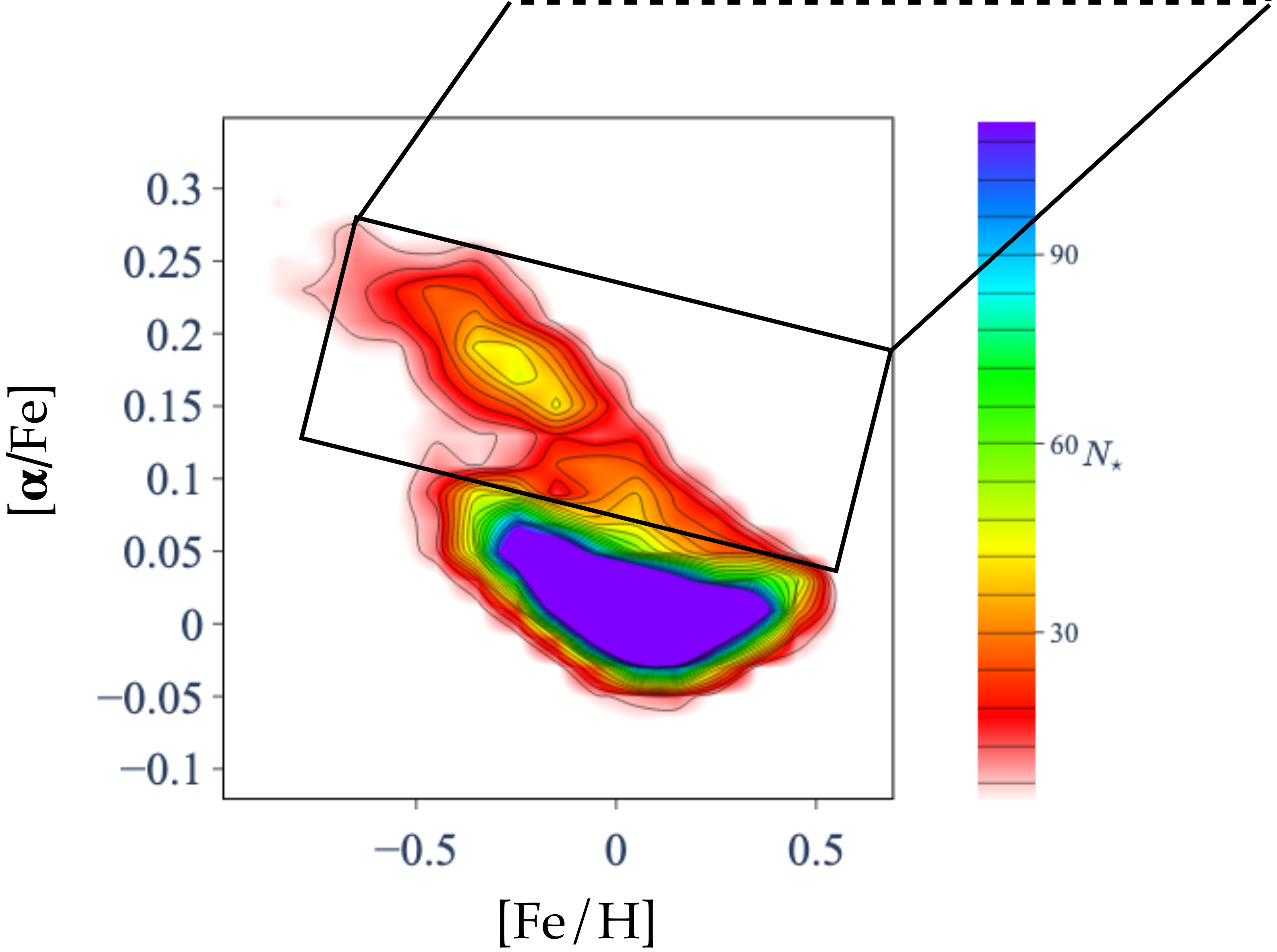
Lagarde et al. 2021

- Isolating « common » thick disc, two density peaks appears. Already mentioned by *Adibekyan et al (2013) and Anders et al (2018)*

For our study, we consider 3 stellar populations :
the thin disc ; the high-α metal-rich thick disc ; the high-α metal-poor thick disc

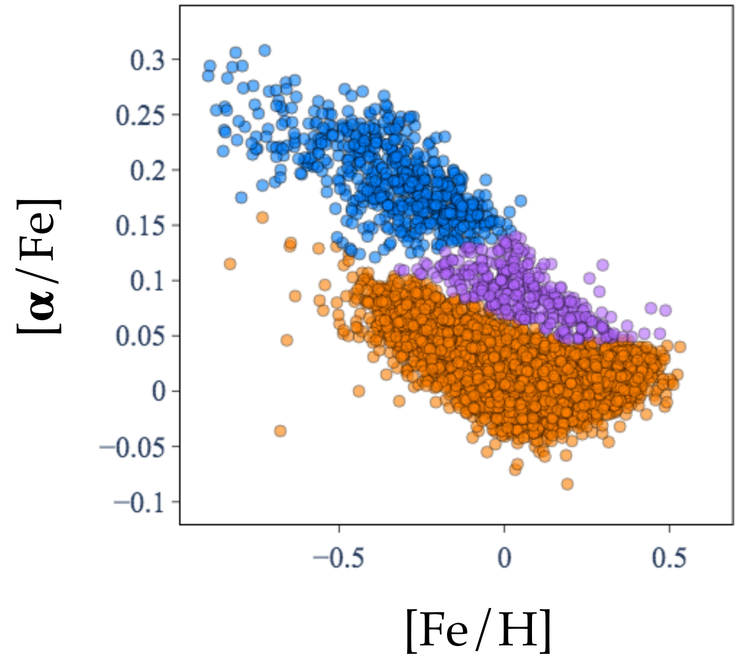


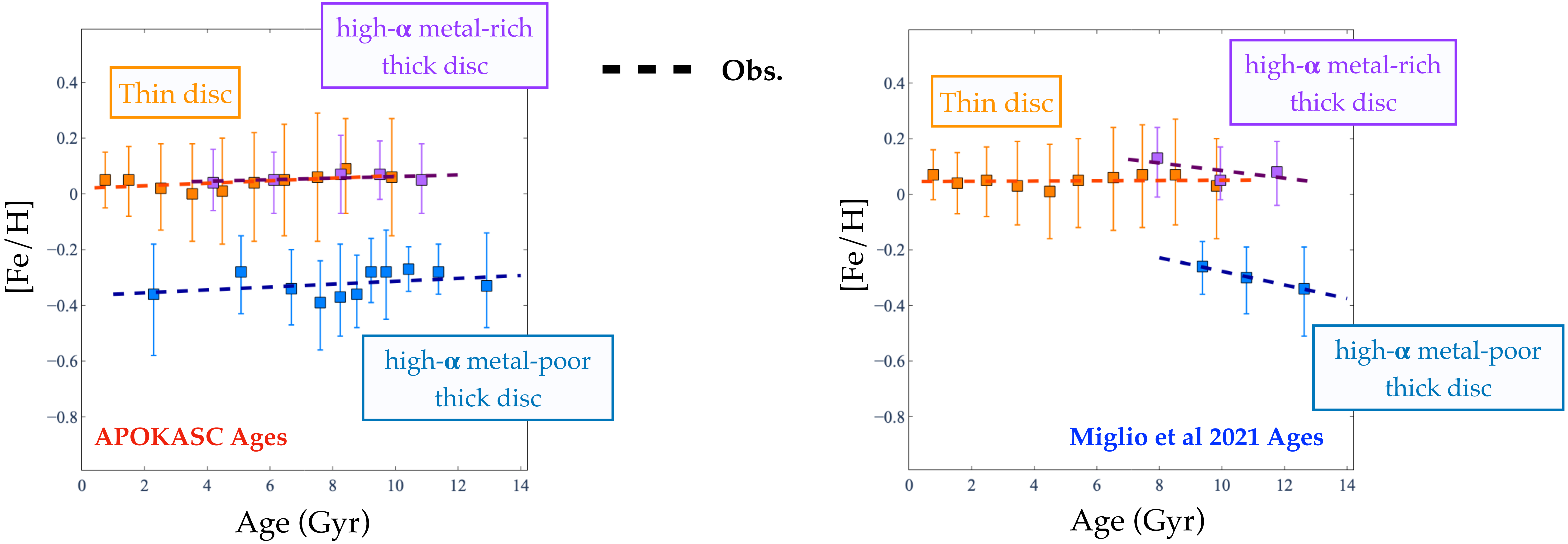




Lagarde et al. 2021

- **Thin disc** both samples show a flat age-metallicity relation
- **hαmr thick disc** No correlation between the stellar age and metallicity
- **hαmp thick disc** While for the age-metallicity relation is **flat for the APOKASC** sample, the M21 sample shows **a negative gradient.**





Lagarde et al. 2021

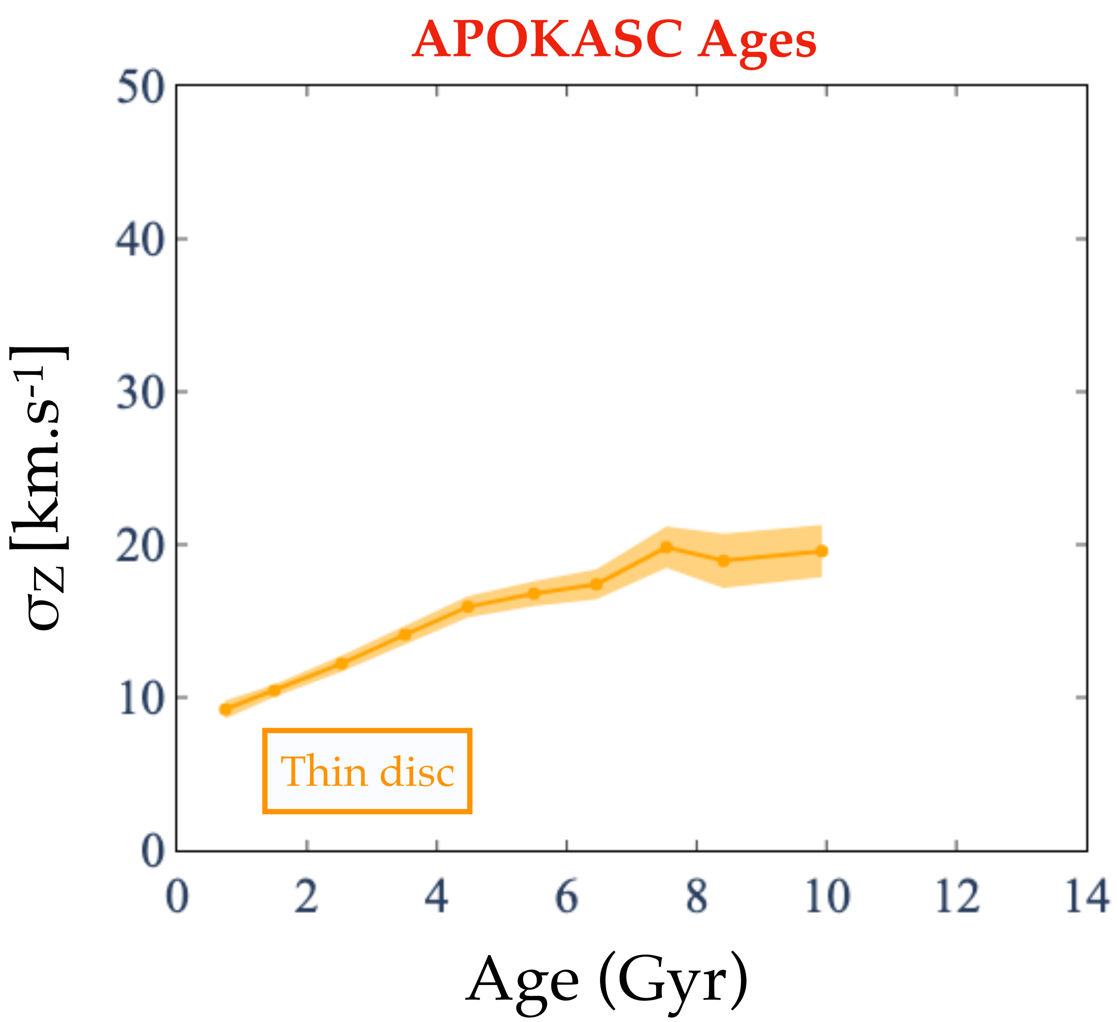
Thin disc : The older the thin disc population, the higher velocity dispersion
=> **Secular evolution in the disc** (*e.g., Spitzer & Schwarzschild 1951;Sellwood 2014)*

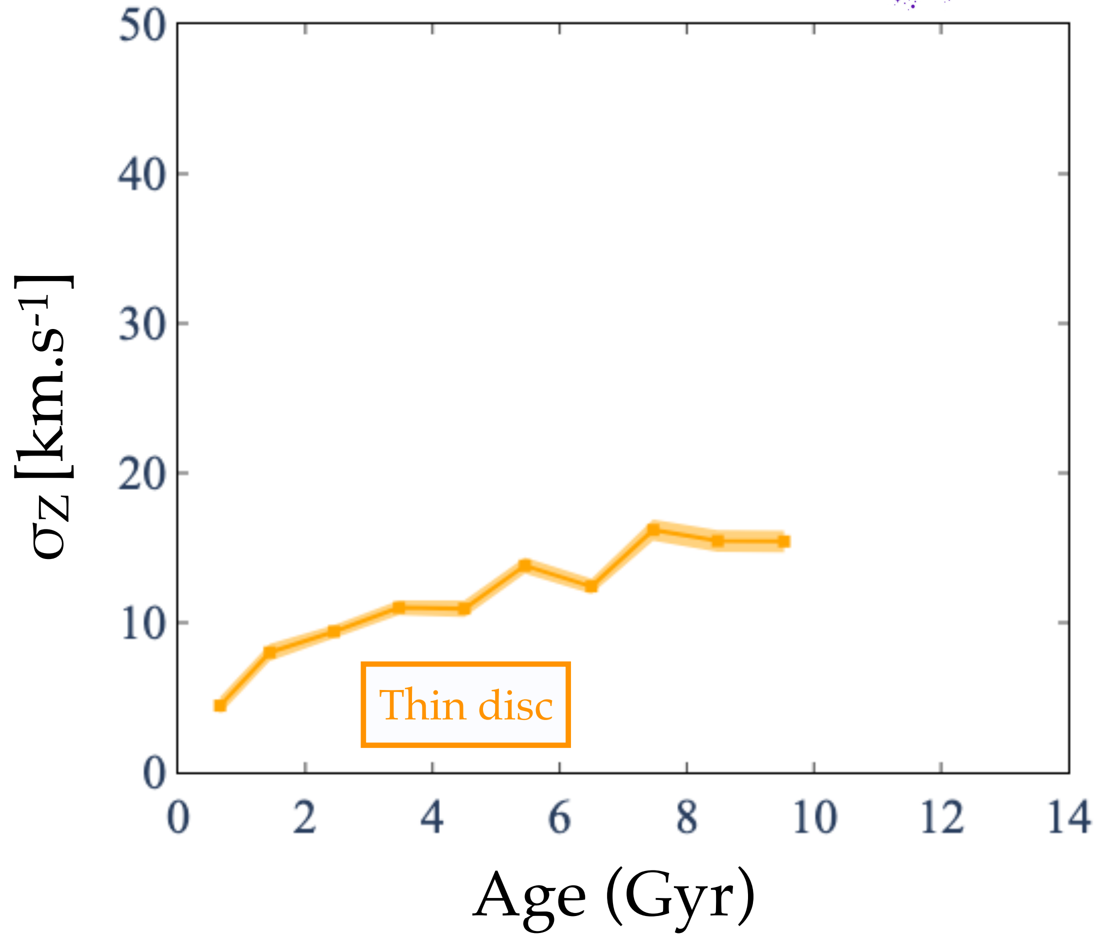
Inputs

σ_Z vs Age

constrained with RAVE survey *(Kordopatis et al 2013a)*
More details *Robin et al. 2017*

No merger and radial migration is included





Lagarde et al. 2021

At given age, σ_Z is **higher** in **hαmp thick disc** compared to **the thin disc** with the **hαmr thick disc** in between

- **thin disc** / **hαmp thick disc** => **a different history imprinted in their kinematics** *(e.g., Minchev et al 2013; Miglio et al 2021).*

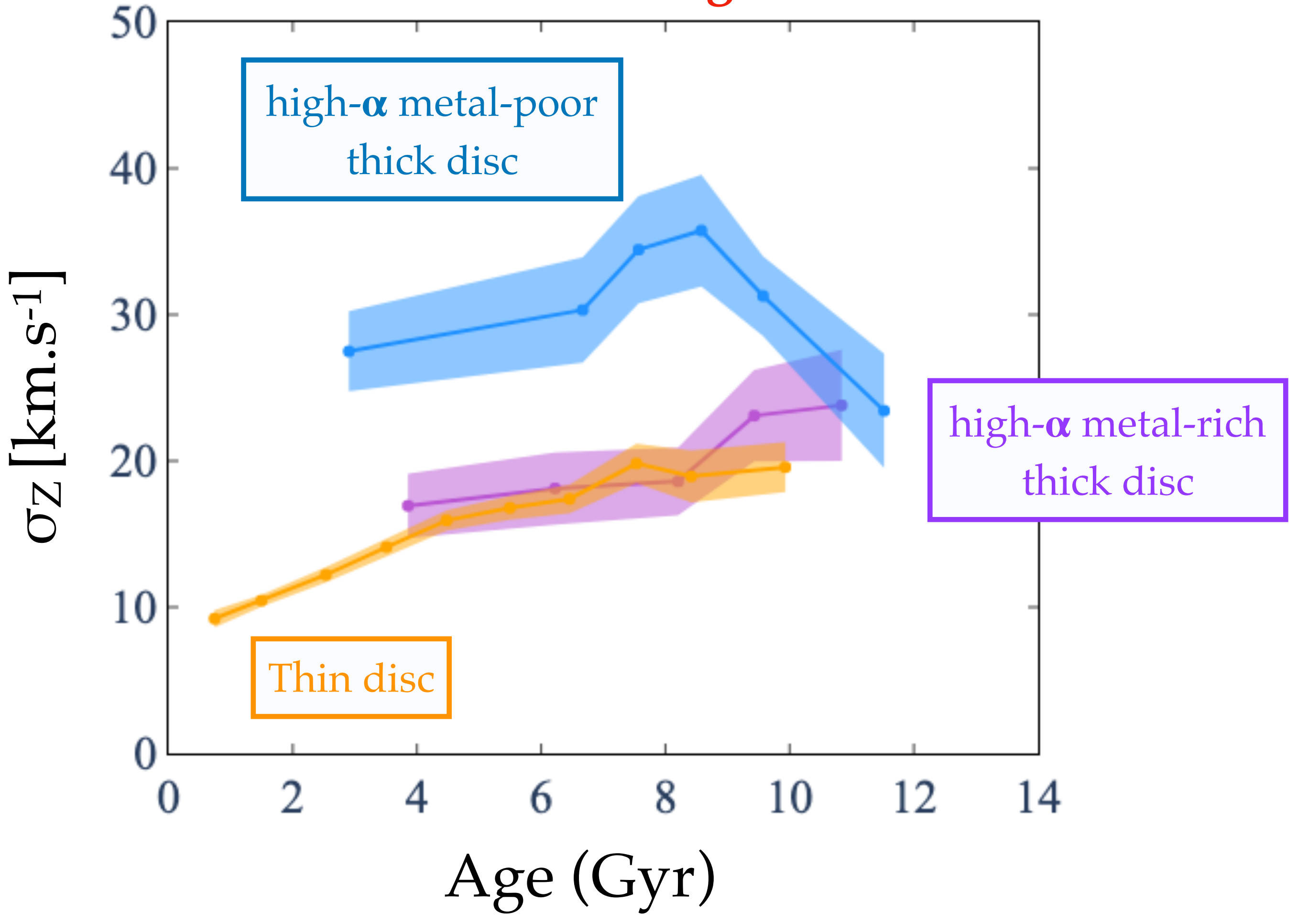
Inputs

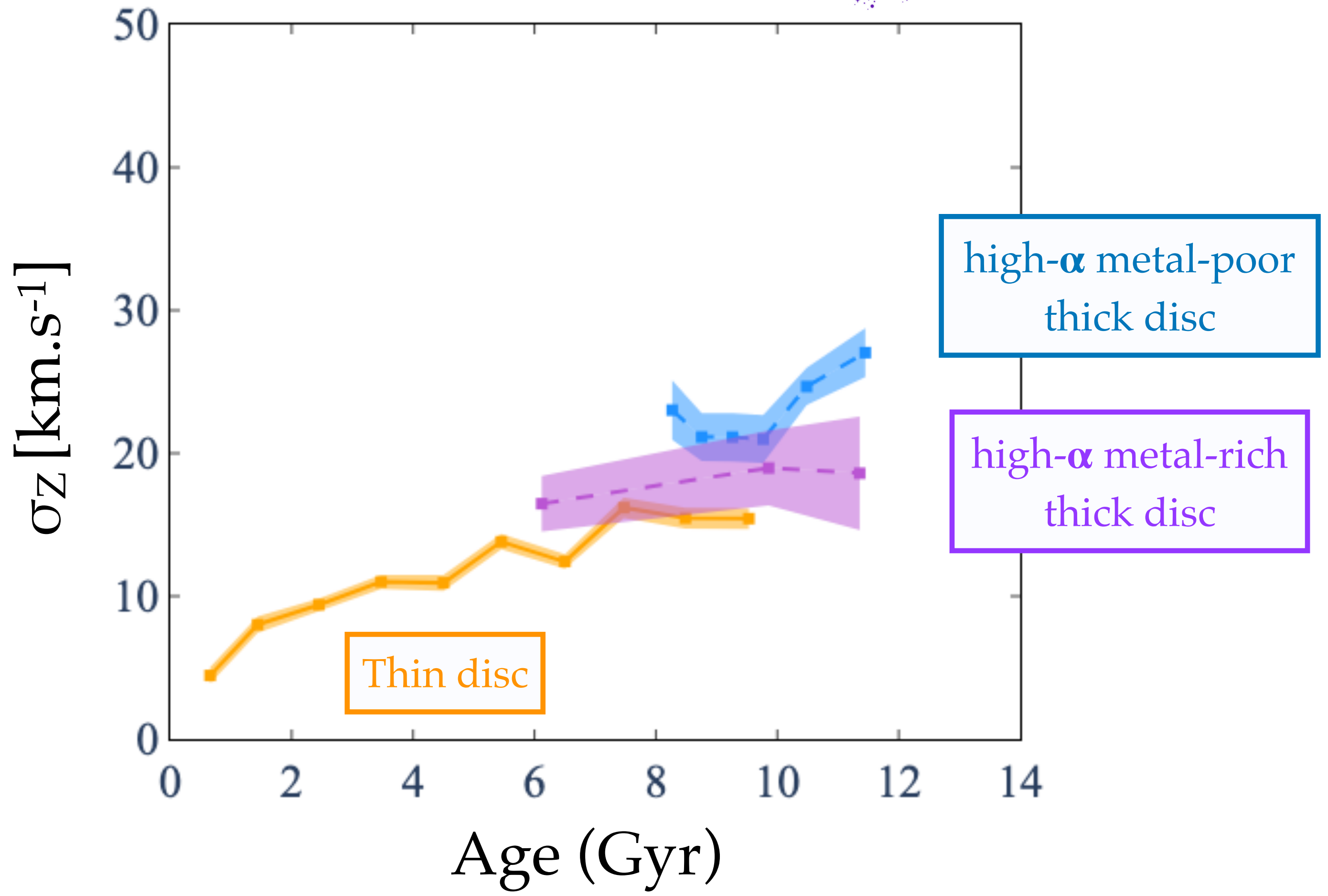
σ_Z vs Age

constrained with RAVE survey *(Kordopatis et al 2013a)*
More details *Robin et al. 2017*

No merger and radial migration is included

APOKASC Ages





Lagarde et al. 2021

hαmp thick disc : max in the σ_Z behavior at ~8 Gyrs not predicted by the BGM
=> not induced by sample selection

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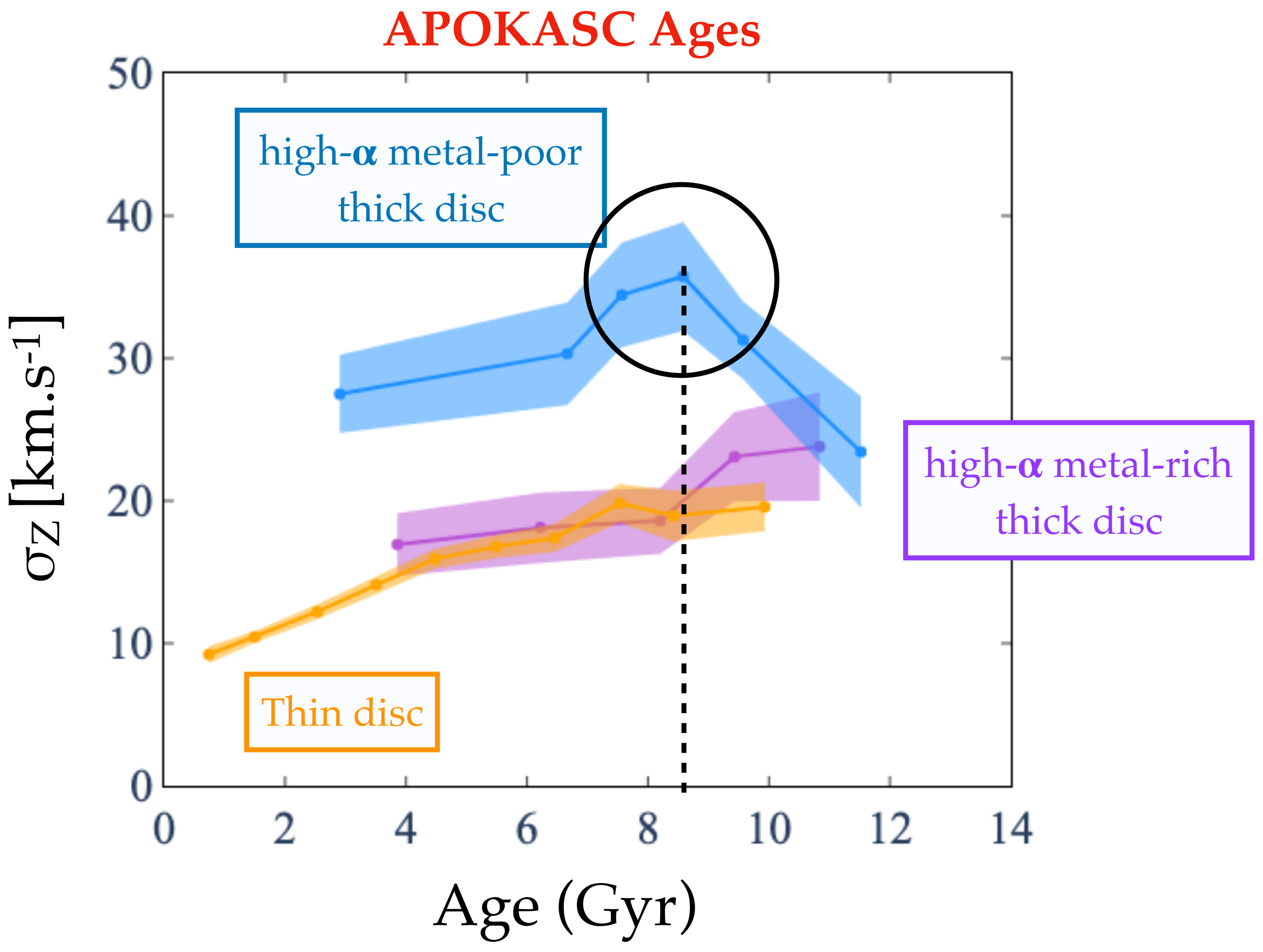

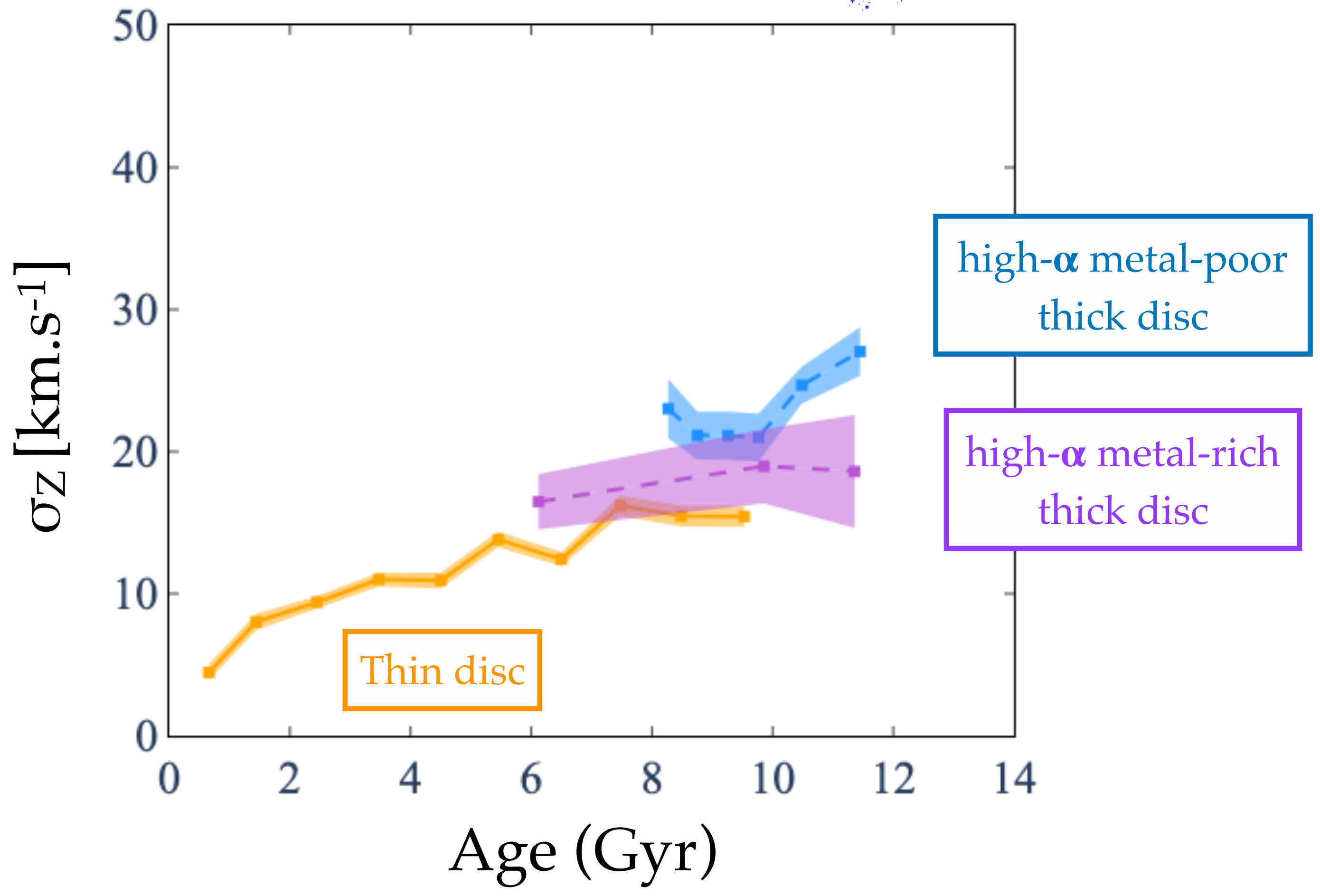

Lagarde et al. 2021

hαmp thick disc : max in the σ_Z behavior at ~8 Gyrs not predicted by the BGM

=> not induced by sample selection

=> could suggest a more complex chemo-dynamical scheme (mergers and radial migration effects, see *Minchev et al 2013, 2014a, b*)

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σ_Z vs Age

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More details *Robin et al. 2017*

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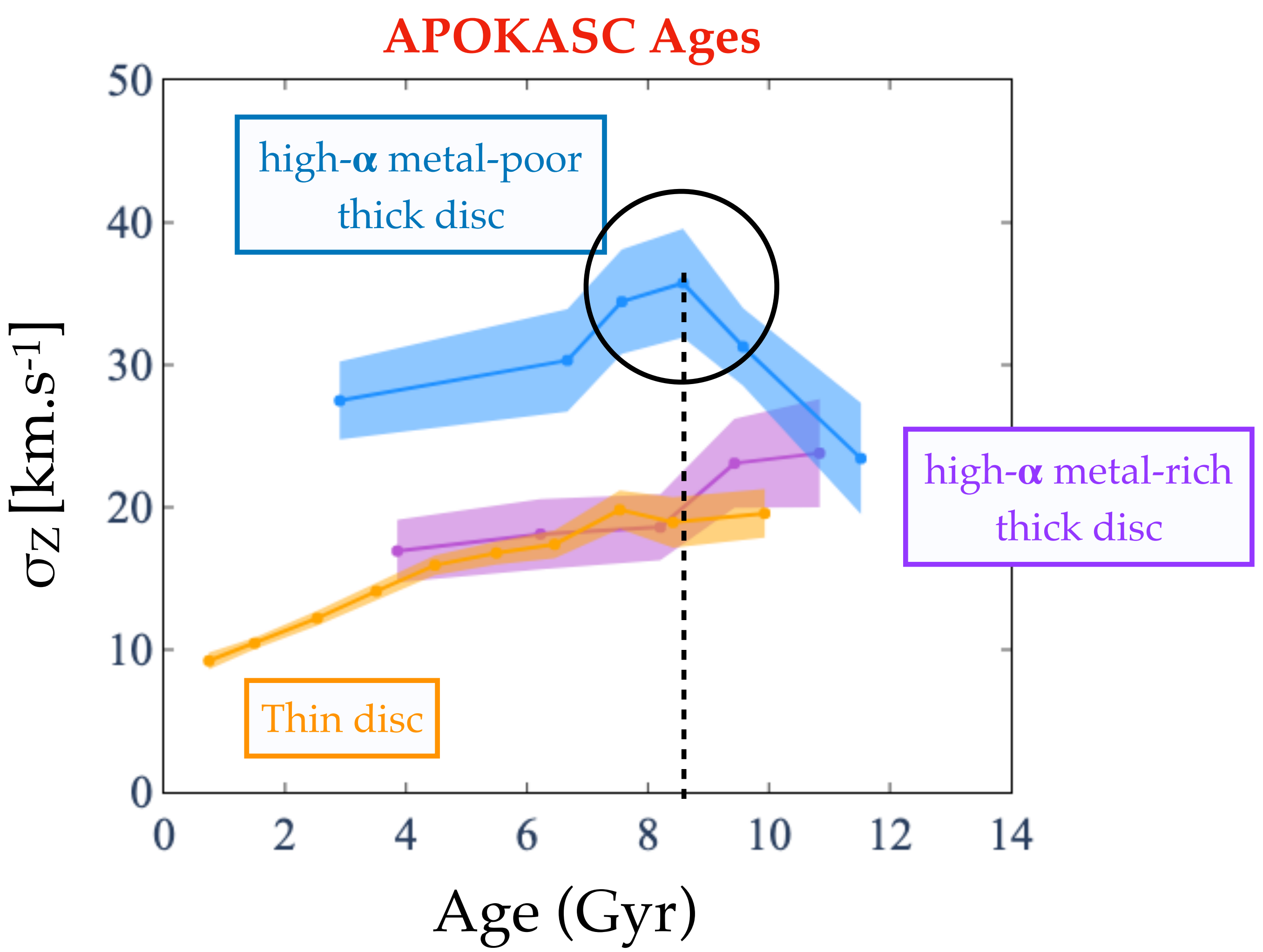

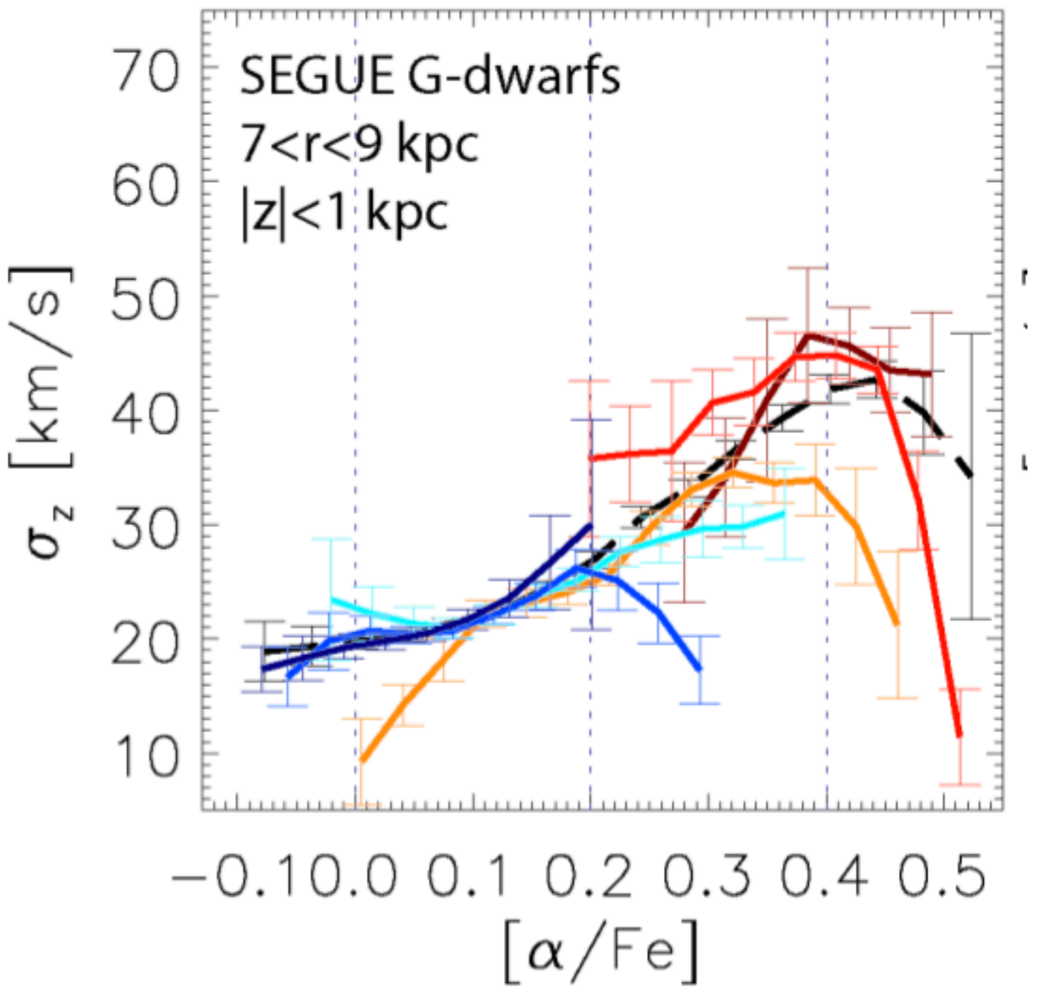

Lagarde et al. 2021

Lagarde et al. 2024

Spectroscopy

Spectroscopic atmospheric parameters

Abundances $^{12}C/^{13}C$

C, N, O

Asteroseismology

Accurate ages and masses deduced from the asteroseismic measurements

Evolutionary stages with $\Delta\Pi_{l=1}$

Gaia data

Luminosity, Spectroscopy, Kinematics

Lagarde et al. 2024

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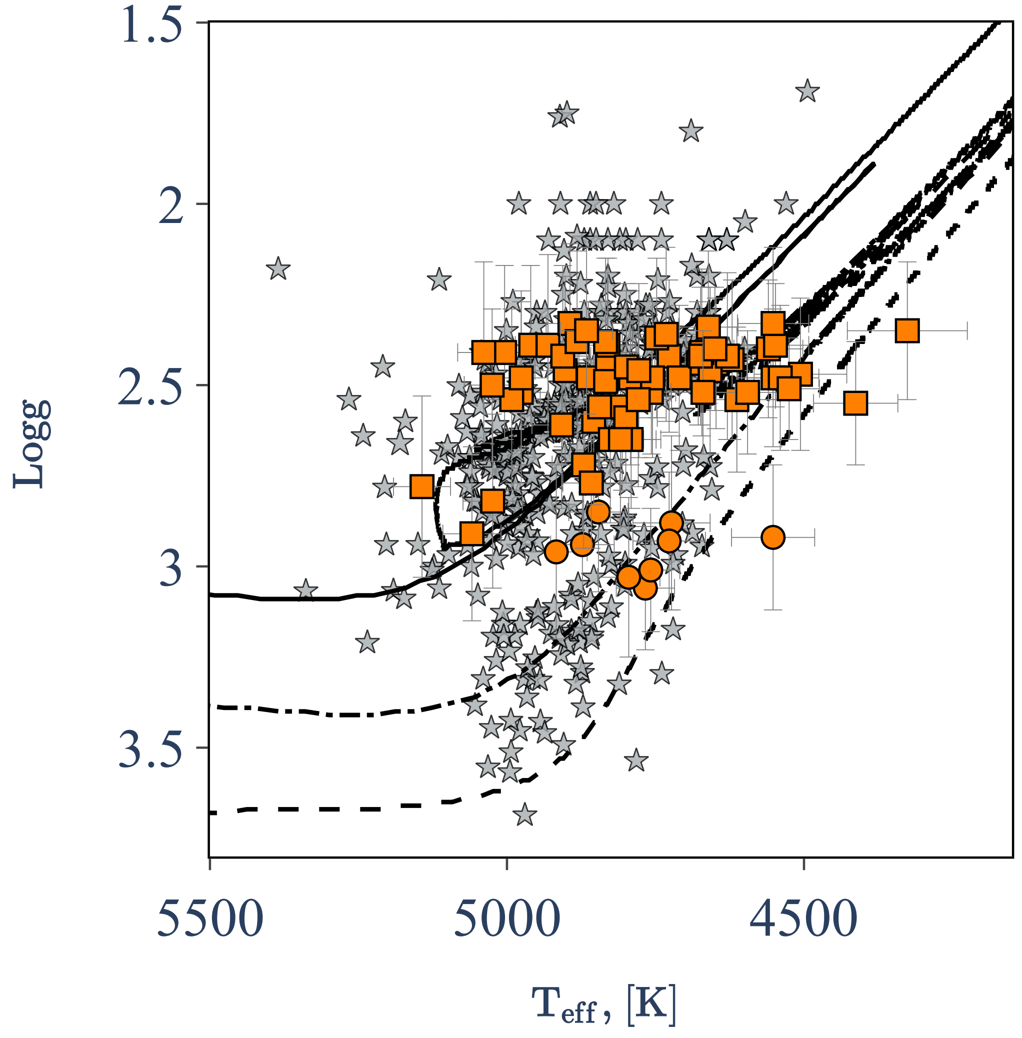
Gaia data

Luminosity, Spectroscopy, Kinematics

Golden sample

71 giant field stars

Sub-sample of giants with better observational constraints



First ascent RGB

Core He-burning stars

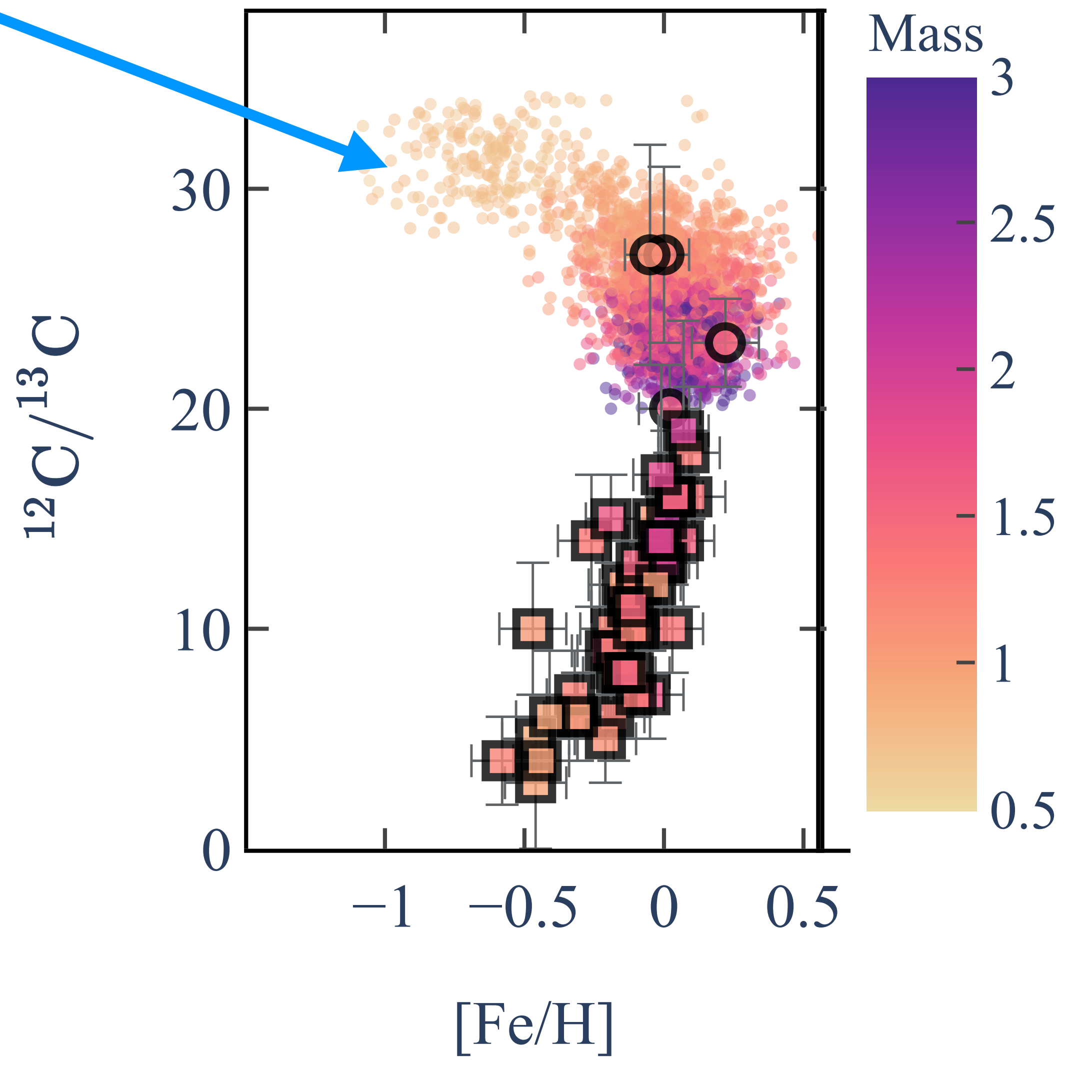
Other spectroscopic studies (*Tautvaisiene et al 2010,2013 ; Gratton 2000 ; Morel et al 2024 ; Takeda et al 2019 ; Aguilera-Gomez et al 2023)*

Lagarde et al. 2024

Stellar population synthesis model
(e.g., Lagarde et al. 2017, 2019)

Stellar evolution models computed with **STAREVOL**

w/o thermohaline mixing



Lagarde et al. 2024

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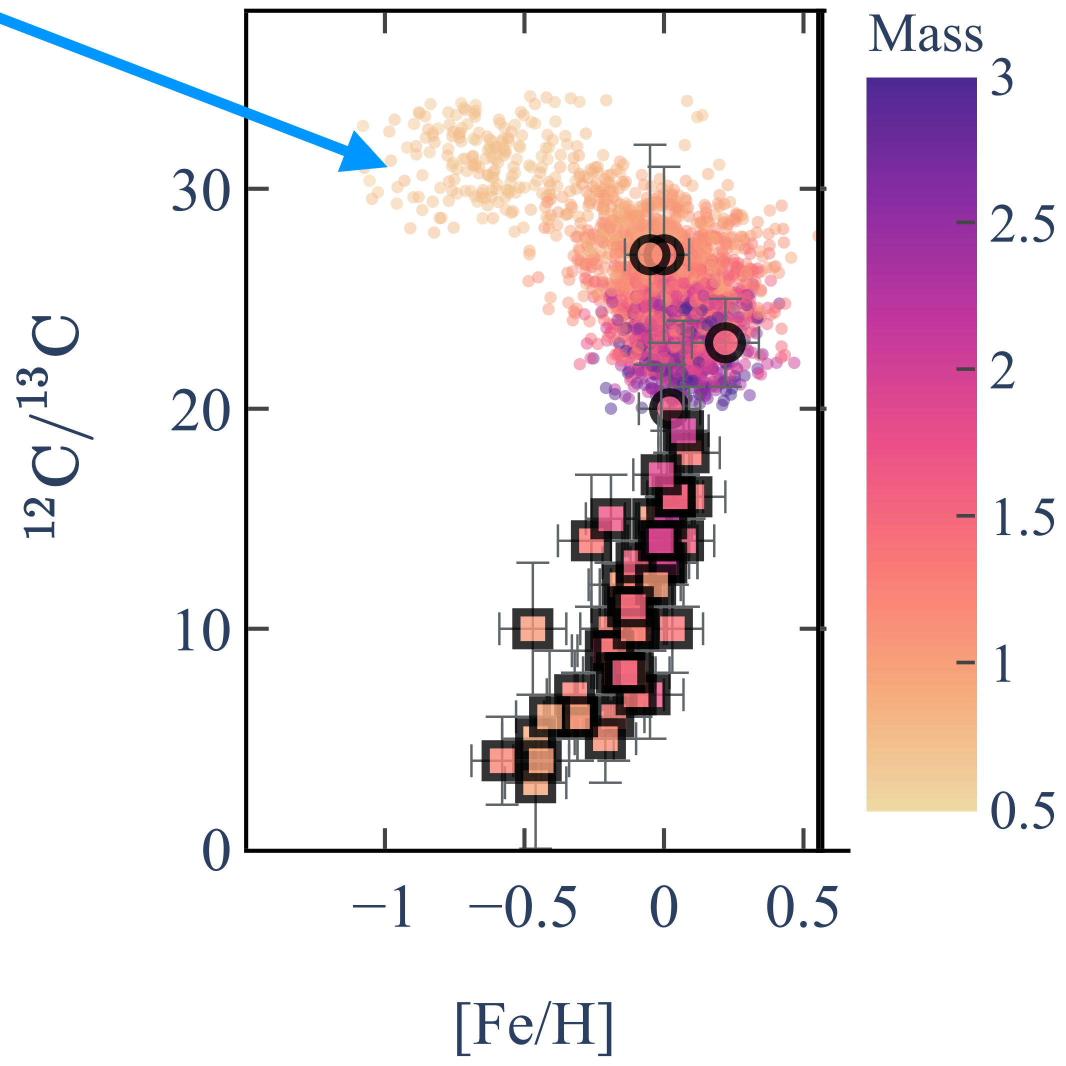
Stellar evolution models computed with **STAREVOL**

Thermohaline instability

Changes the surface abundances of chemical elements such as Li, **^{3}He**, **^{12}C, ^{13}C, ^{14}N but leaves the O values unchanged**

Thermohaline instability is more efficient for **lower-mass and metal-poor giants** (e.g., Lagarde et al 2019)

w/o thermohaline mixing



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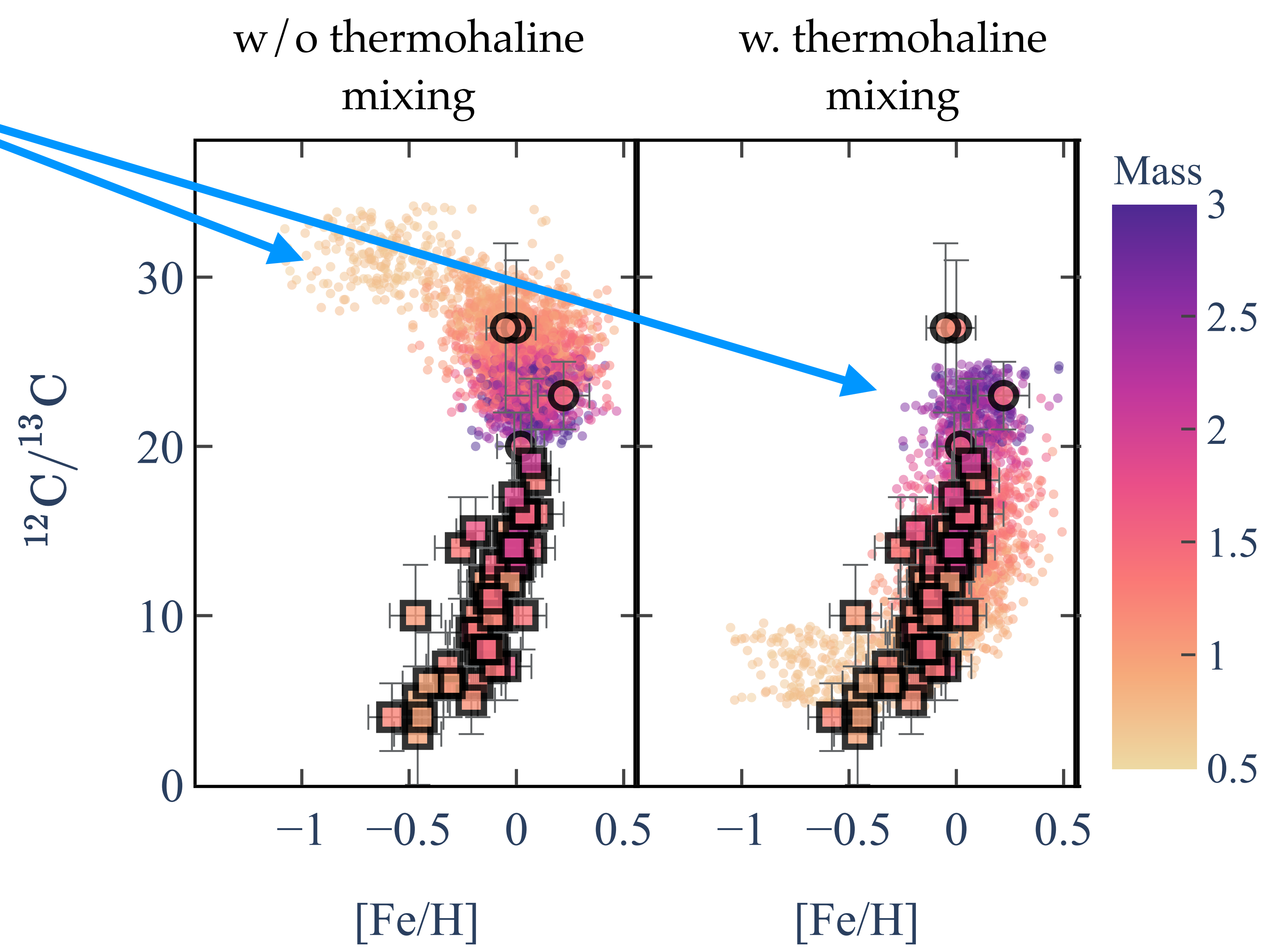
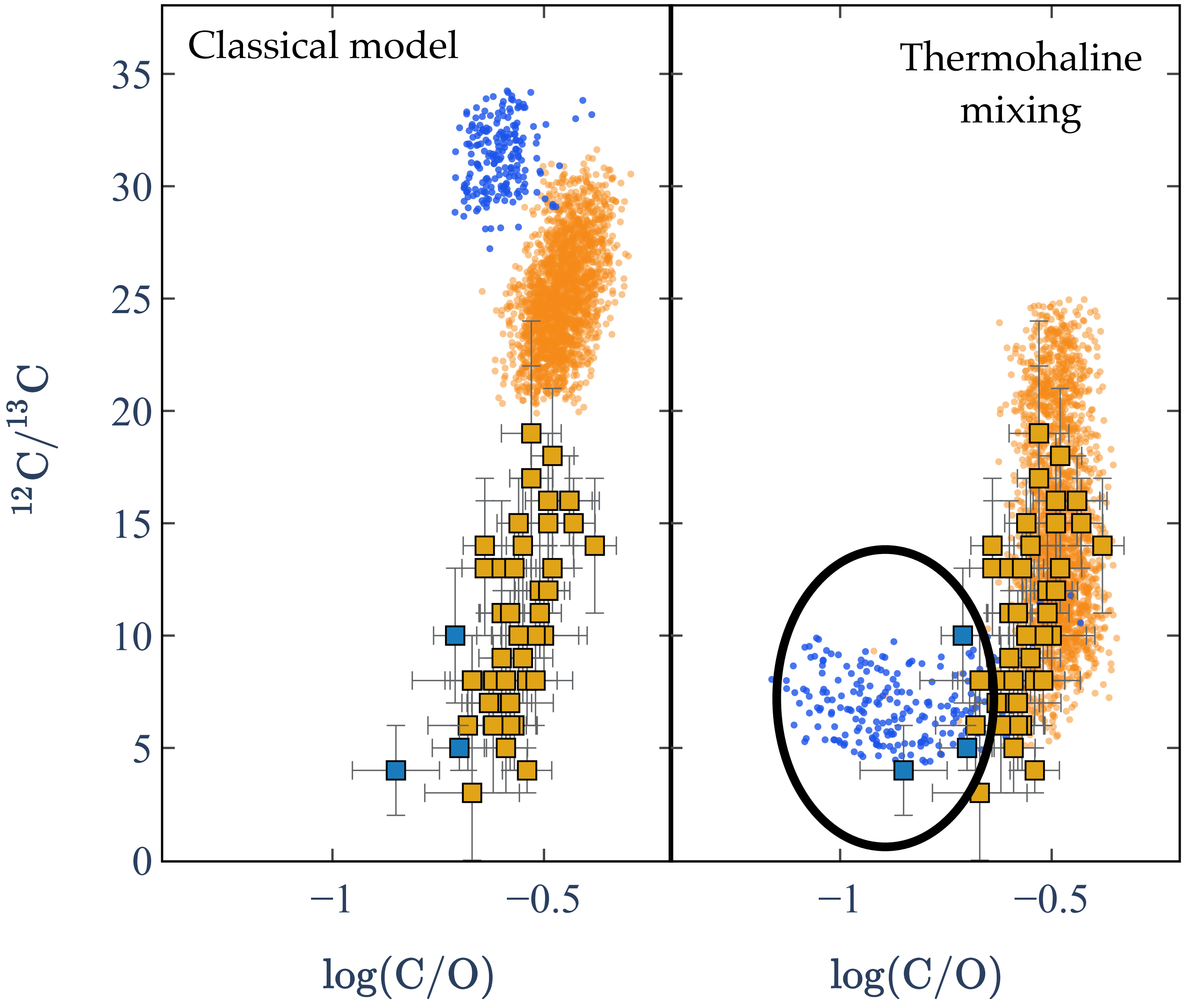


What about considering the different stellar populations?

Thin disc stars
Thick disc stars



Lagarde et al. 2024

What about considering the different stellar populations?

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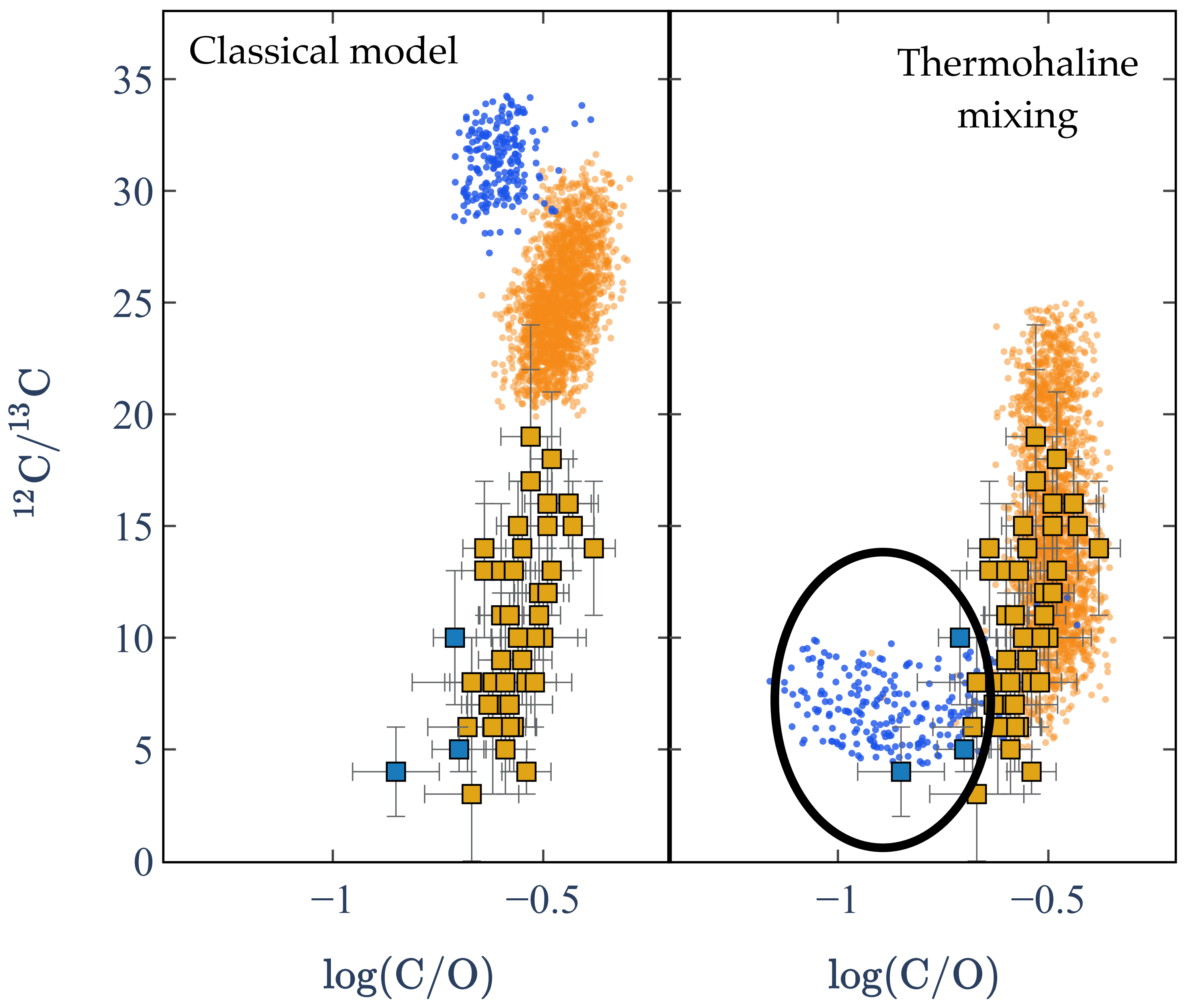

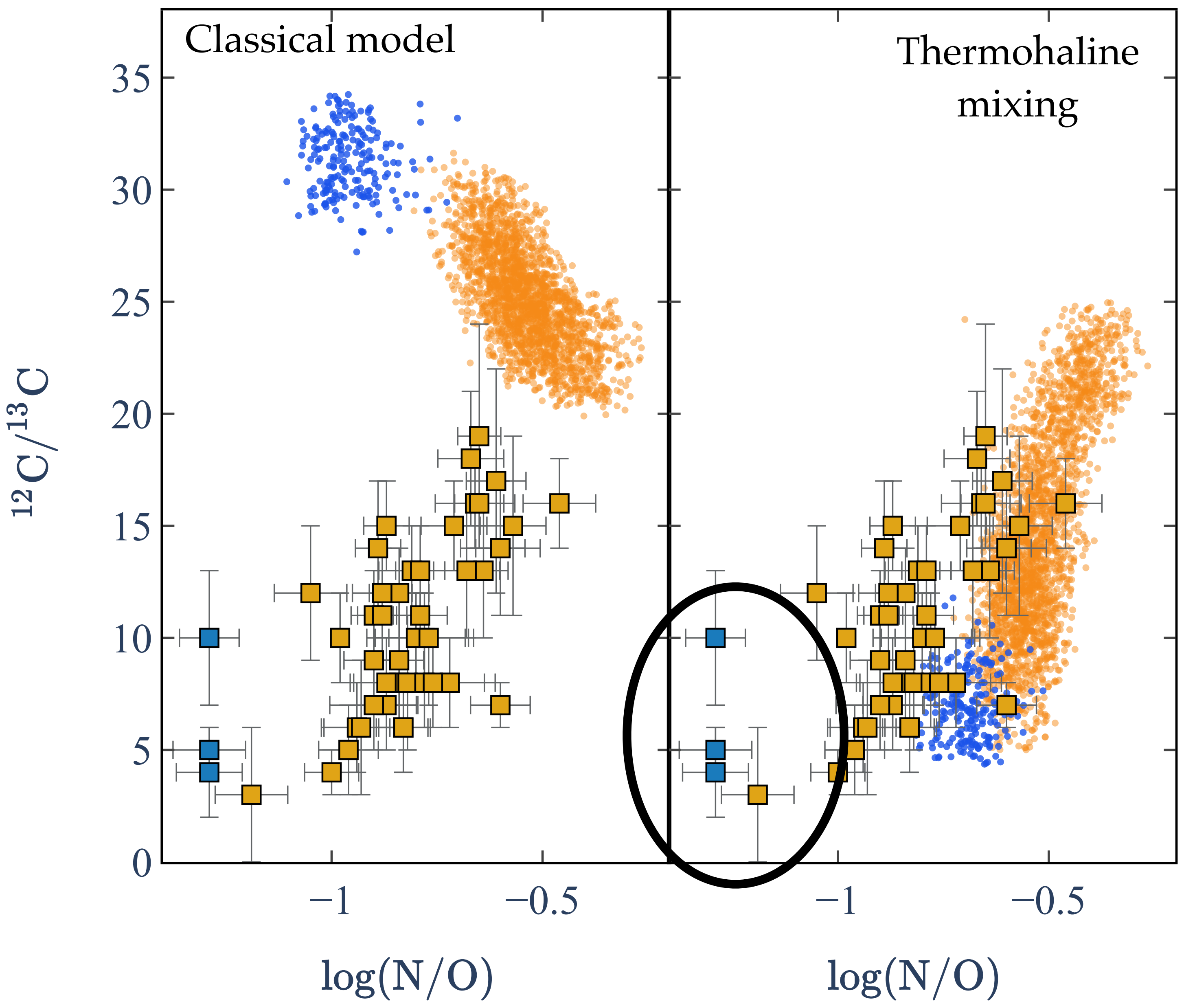

Lagarde et al. 2024

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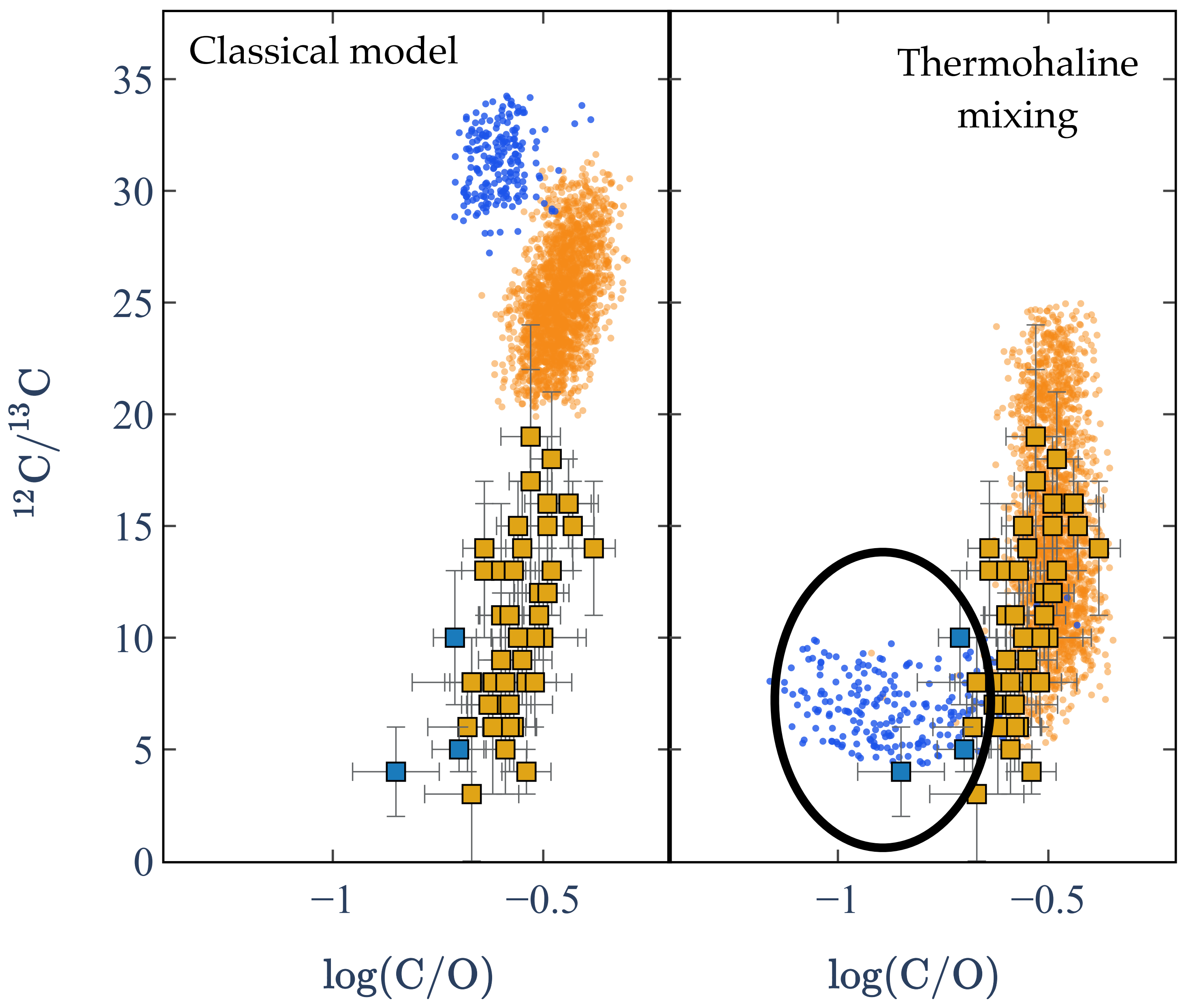
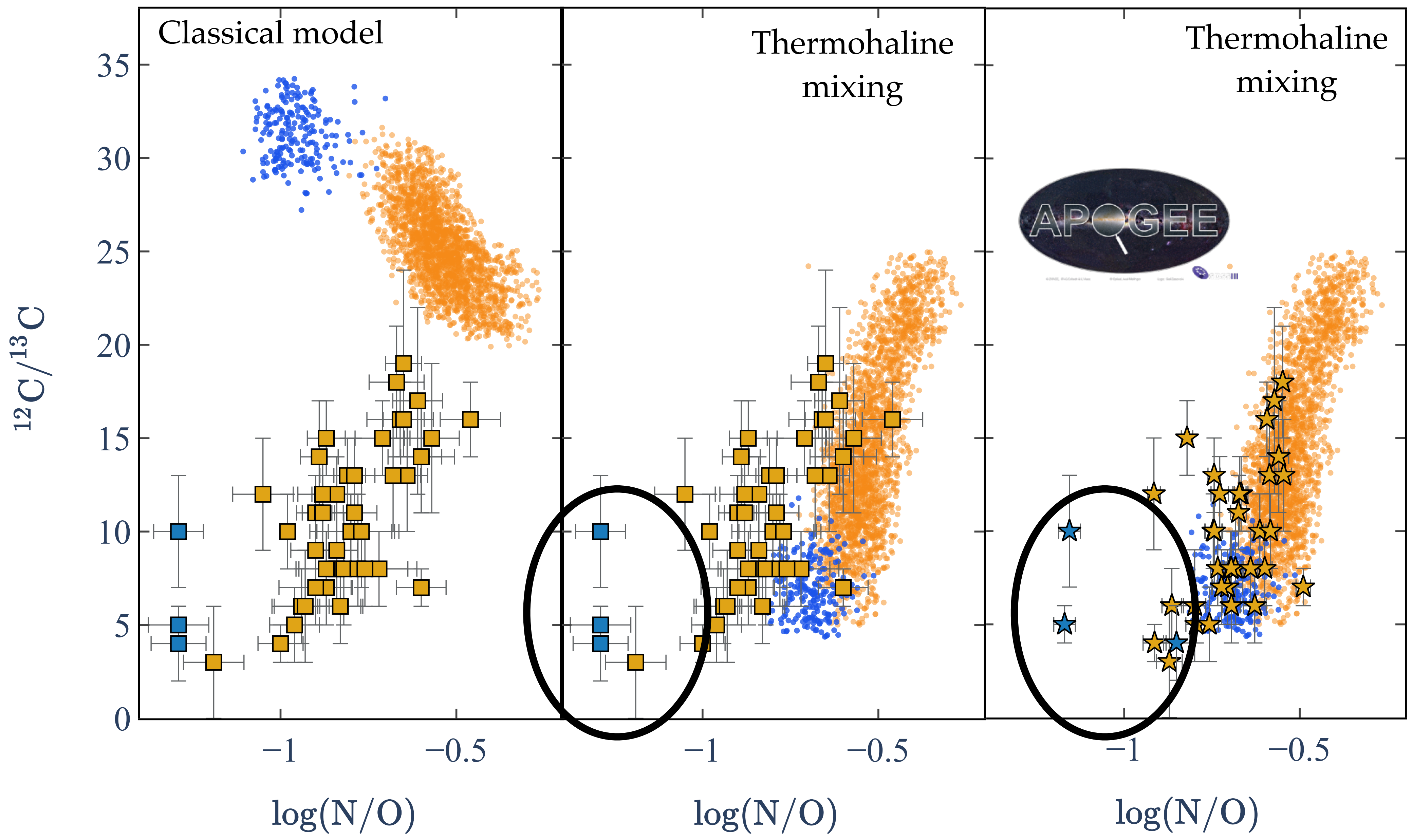




N abundances for thick disc stars not very explain
=> Need a larger sample of thick disc stars with strong chemical constraints

Lagarde et al. 2024

Lagarde et al. 2017

to highlight selection biases in the observed sample
and also mechanisms reveal by observations and not included in the model

Contact me !
nadege.lagarde@u-bordeaux.fr

Lagarde et al. 2021

(1) Probably, a small sign of SFR increase between 2 and 5.5 Gyr in both samples remains to be confirmed with larger seismic sample**.**

(2) a **flat age–metallicity relation for the thin disc**

(3) Different behaviours of σ_Z with age in the BGM simulations and in the observations, inducing a more complex chemo-dynamical scheme to explain the data (e.g., mergers and radial migration effects).

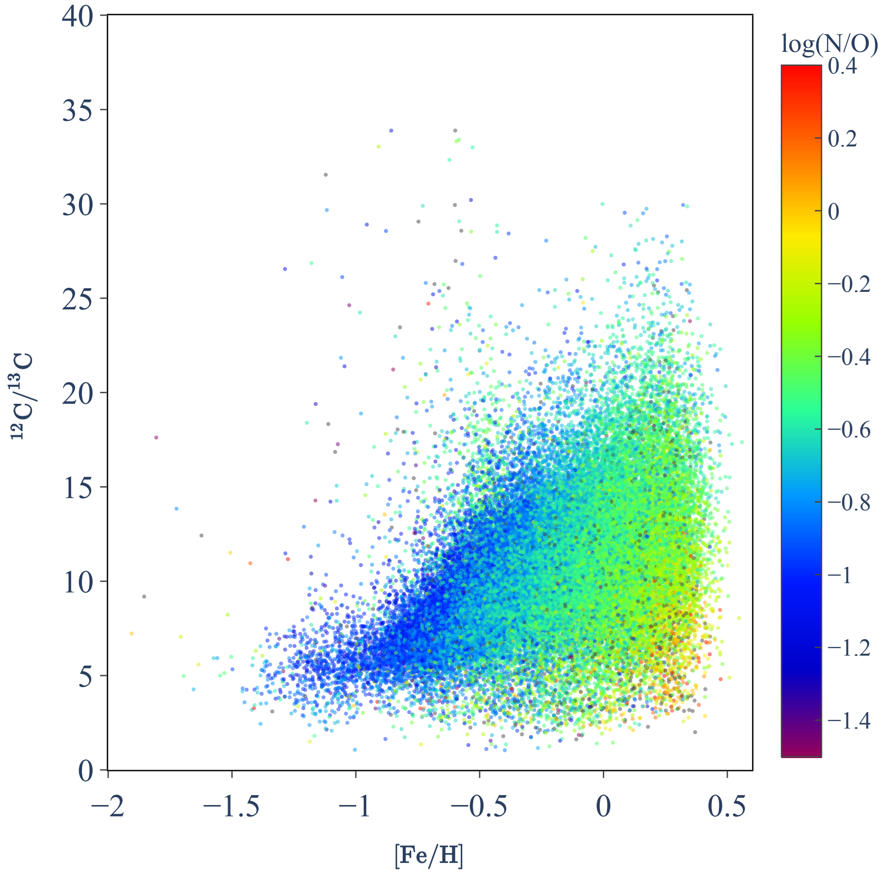
Lagarde et al. 2024

(1) ^{12}**C/**^{13}**C** at the surface of **core He-burning stars increases with [Fe/H] (and M)** while it decreases with stellar age. Simulations done with the BGM and including the effects of thermohaline mixing explain these trends in an exceptional way

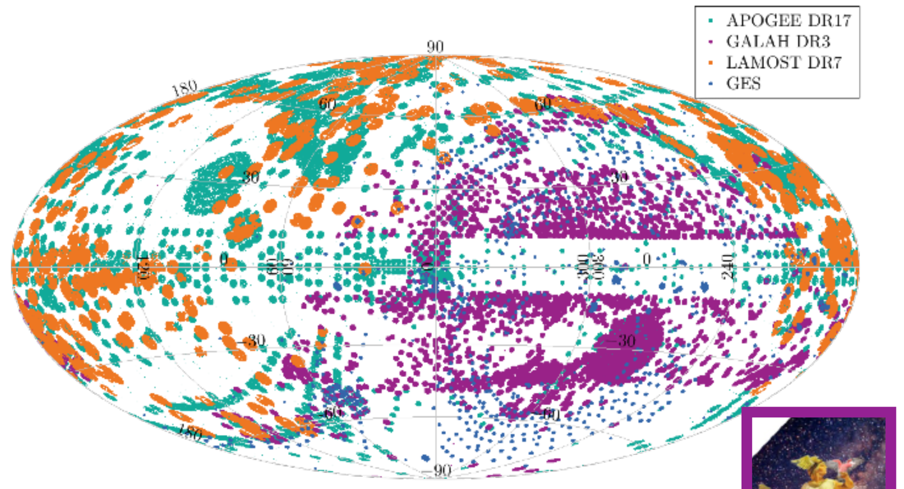
(2) Spectroscopic analysis shows that **low ^{12}C/^{13}C values are correlated with low C/O and N/O Pb : N abundances for stars belonging to the thick disc**
=> Need more thick disc stars with all observational constraints…

- **C,N,O in the thick disc** with larger samples of APOGEE survey (or GALAH DR4)

Lagarde, N et al. in prep.



- Studying stellar properties chrono-chemo-kinematics relations with different surveys in the Milky Way such as GALAH, LAMOST, APOGEE with Kepler, K2 and TESS survey



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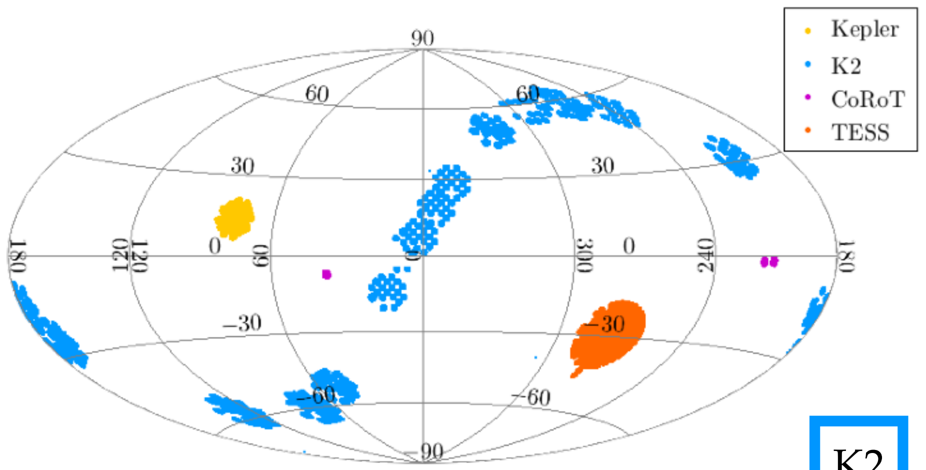

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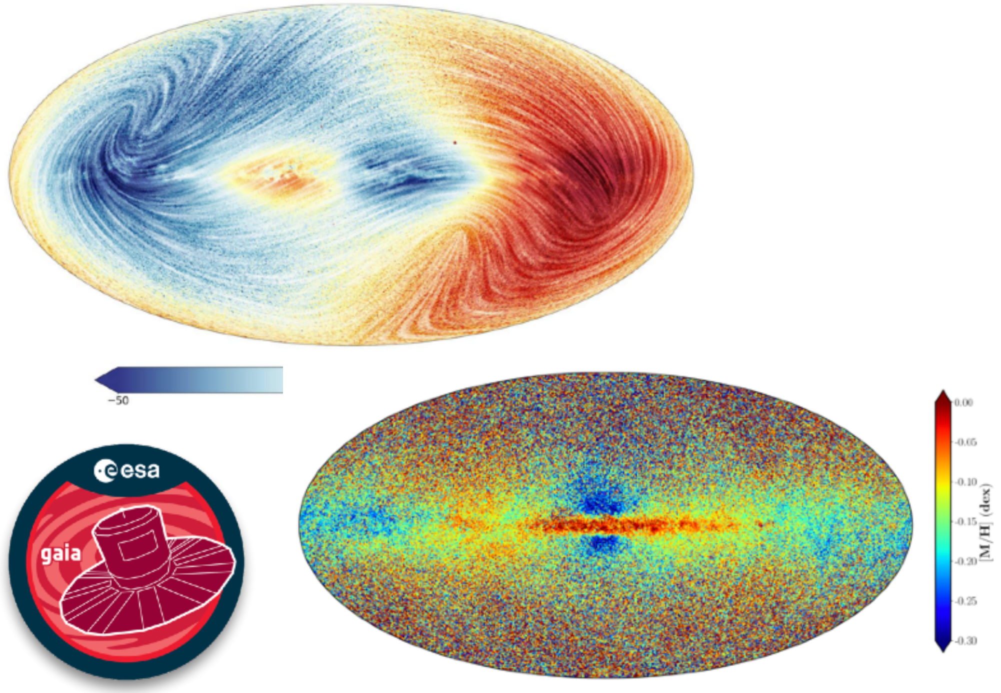

PRobing the orig**I**ns of the **M**ilky W**A**y's oldest stars

International Collaborative Research Project

2025-2028

anr agence nationale de la recherche

N. Lagarde
Laboratoire d'Astrophysique
de Bordeaux

1 Postdoc
~2yrs and 1/2
+
1 Computational Scientist
~2yrs and 1/2

Galactic stellar populations
Halo and thick disc
Observational bias
Mergers, accretions,
secular evolution

Stellar evolution
Asteroseismology
Age determinations
Internal transport processes

PRIMA

Swiss National Science Foundation

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1 Postdoc
~2-4 yrs