Insights into the Galactic Stellar Halo with APOGEE

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The Stellar Halo: An Introduction

First Formation Model: Monolithic Collapse (Eggen et al. 1962)

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Λ Cold Dark Matter model predictions:
Hierarchical formation

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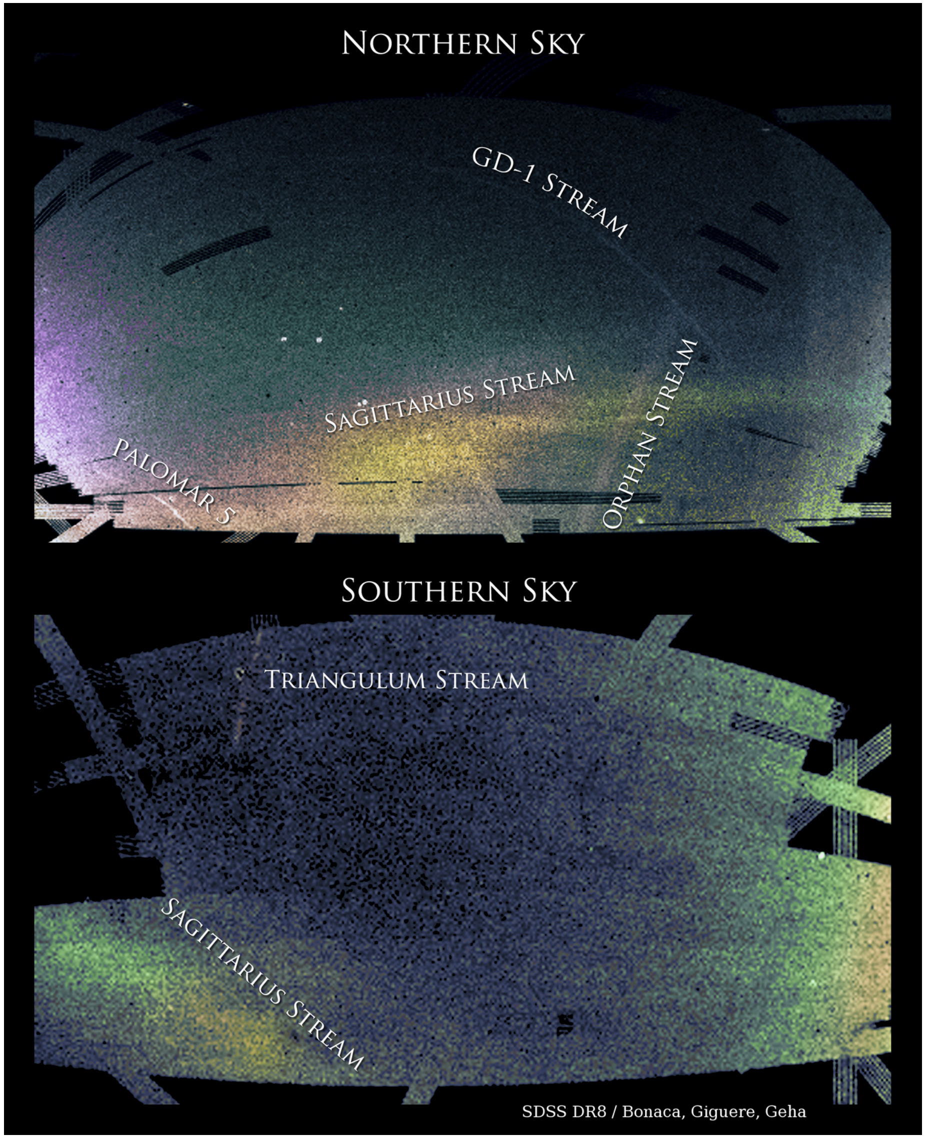
Λ Cold Dark Matter model predictions:
Hierarchical formation

Observational support: substructure detected



Bonaca et al. (2012)

The Stellar Halo: An Introduction

Dual scenario?

Different chemical, kinematical and spatial structure between INNER and OUTER halo regions.

The Stellar Halo: An Introduction

Dual scenario?

Different chemical, kinematical and spatial structure between INNER and OUTER halo regions.

Carollo et al. (2007, 2010)

(although critized by Schönrich et al. 2014)

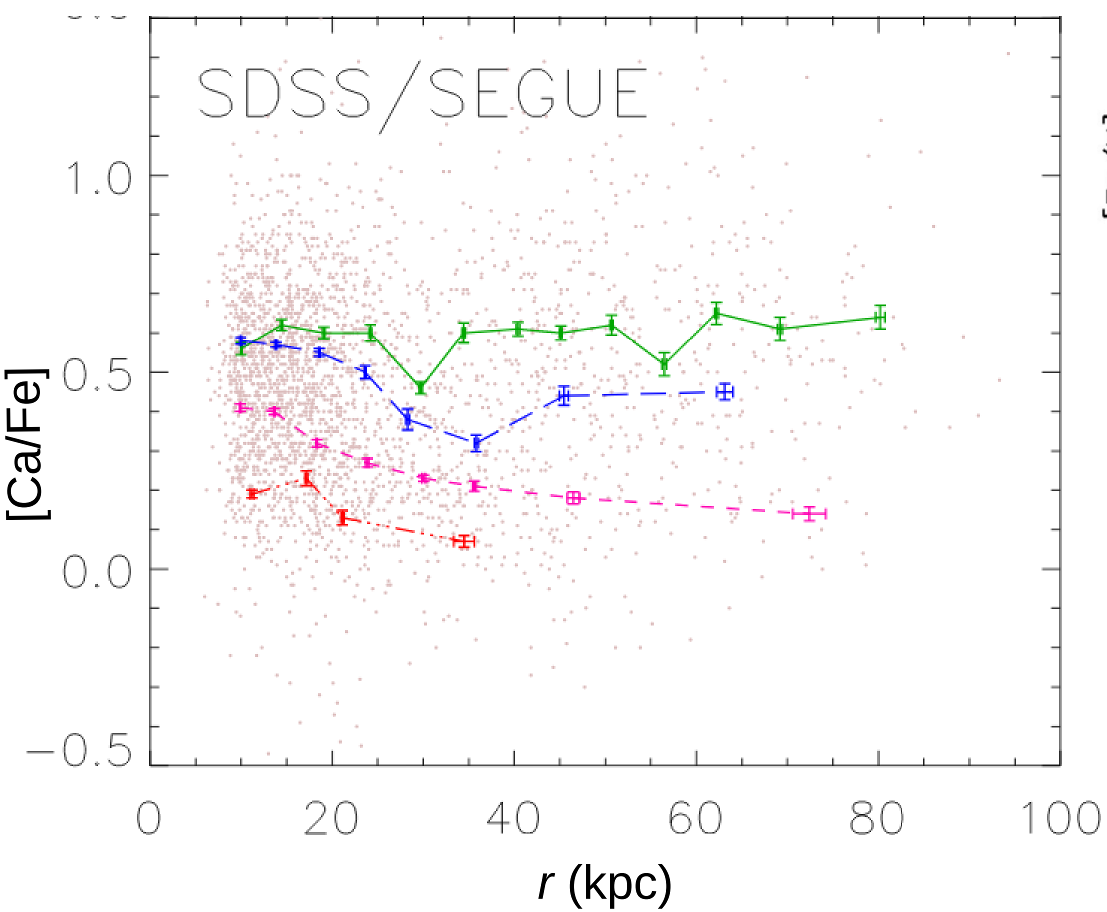
de Jong et al. 2010

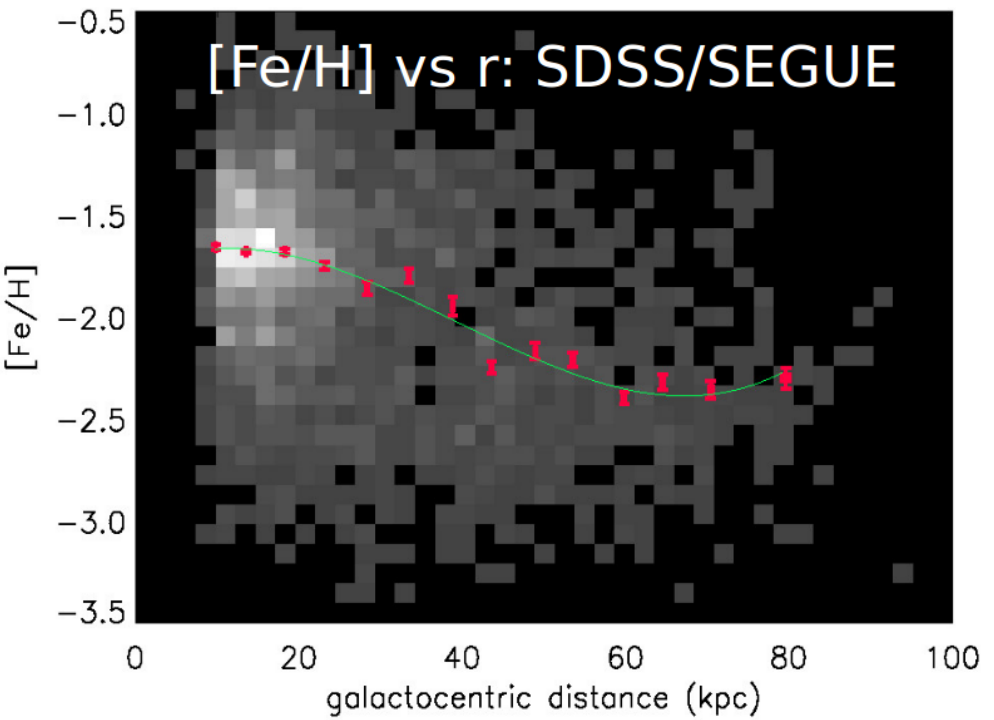
Xue et al. 2015

The Stellar Halo: An Introduction

Chemical gradient with distance

Fernández-Alvar et al. (2015)

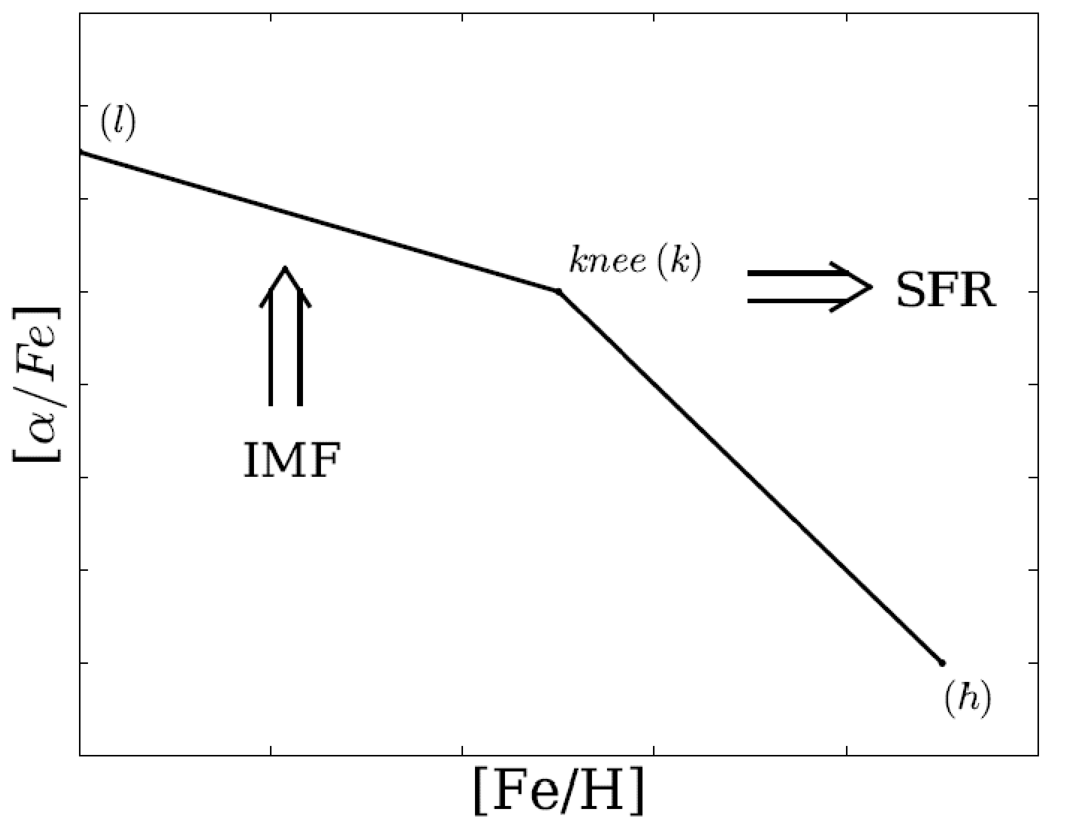




The Stellar Halo: An Introduction

The chemistry as a tool:

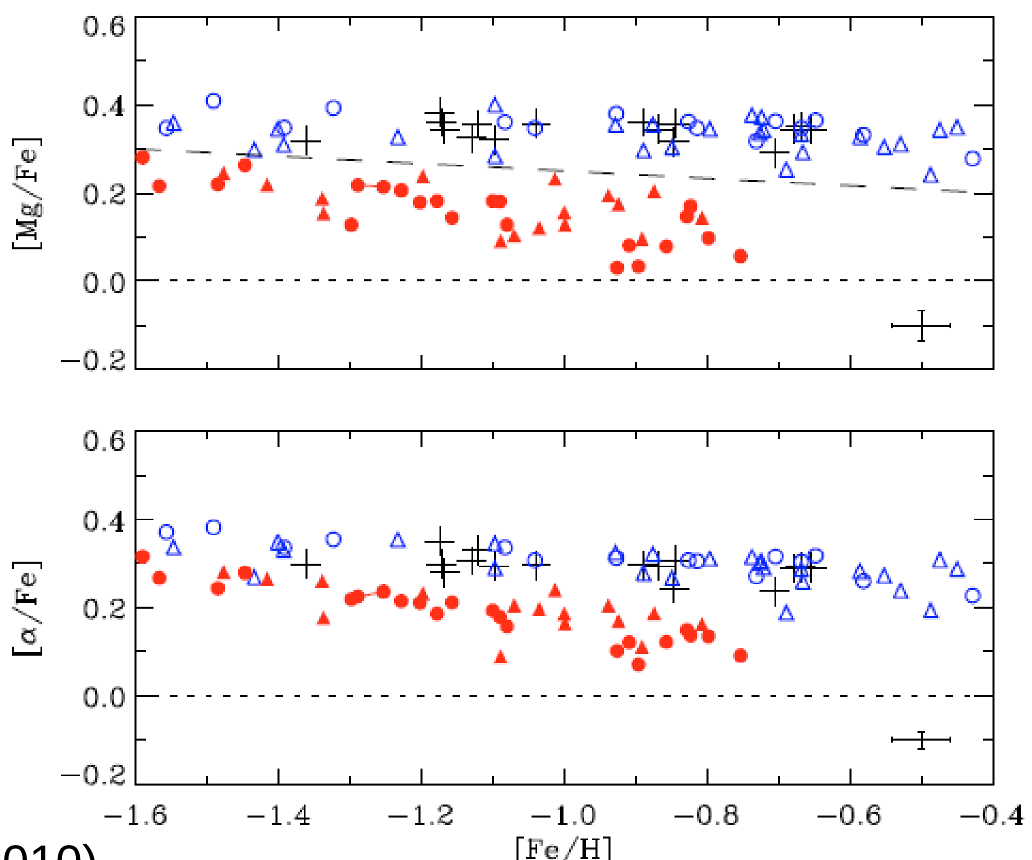
- Processes underwent during the halo formation affect the star formation
- Current chemical composition in stars are the result of such star formation
- [α/Fe] vs. [Fe/H]



The Stellar Halo: An Introduction

Dual scenario?

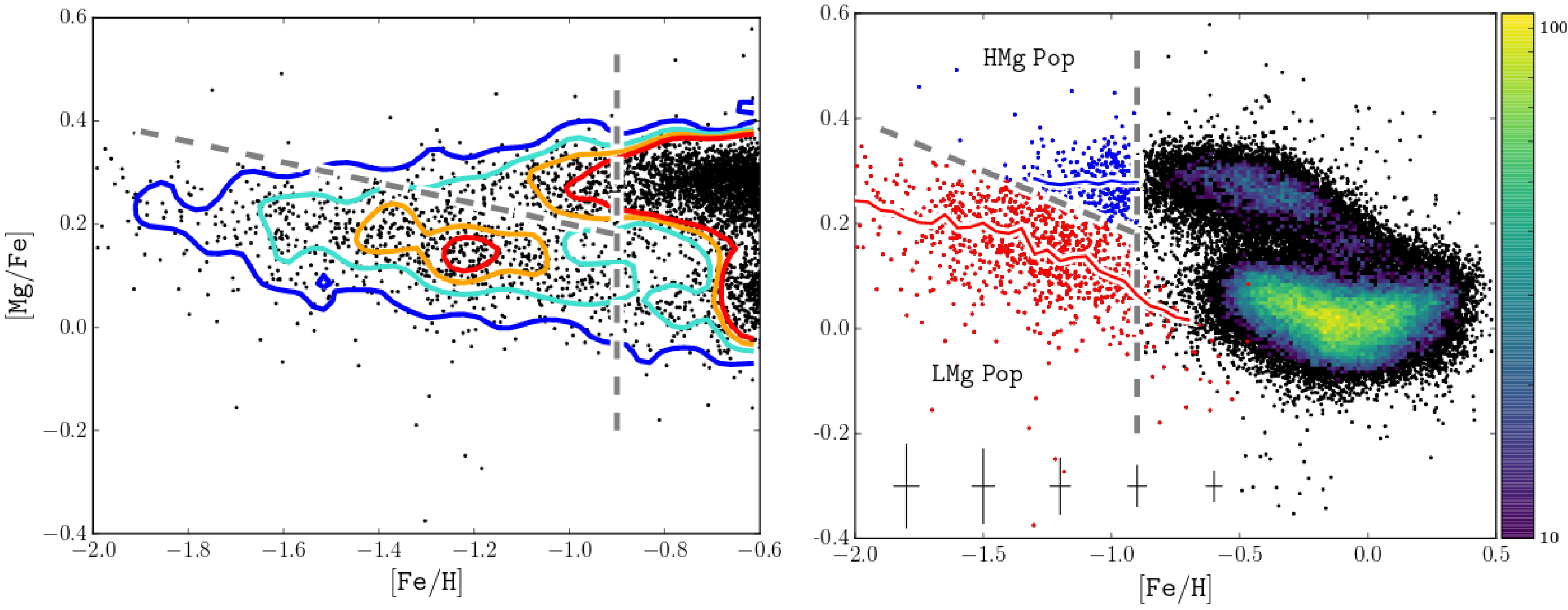
Two chemically distinct halo populations in the solar neighbourhood



Nissen & Schuster (2010)

The Stellar Halo: An Introduction

Metal-poor populations: Nissen & Schuster pop trends

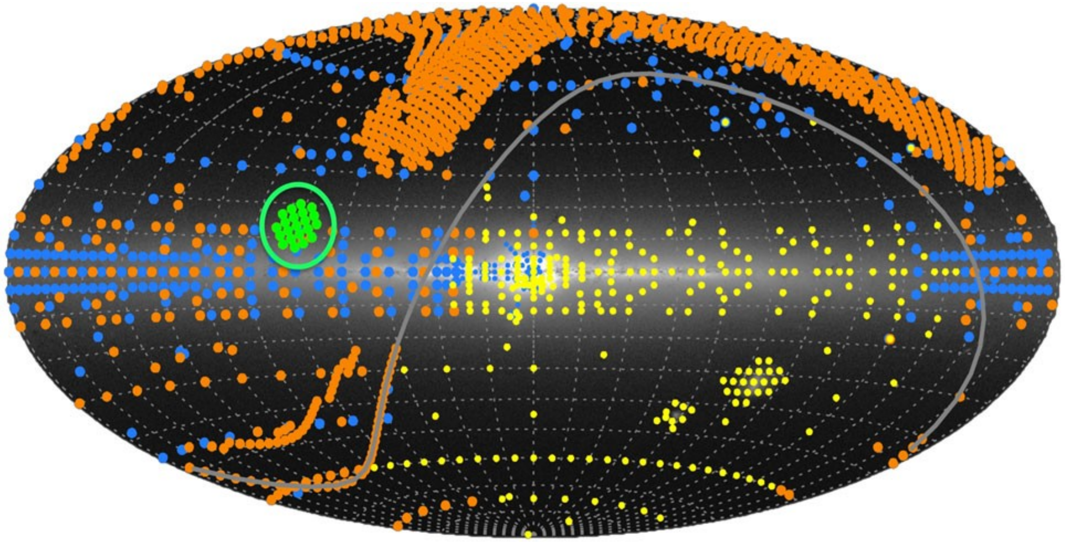


Hayes et al. (2018)

The Data: APOGEE

Observations in APO and LCO

- *2014 - 2020*
- *300 fiber plates, 7 deg^2 (APO), 3.5 deg^2 (LCO)*
- *1.51-1.70 µm*



- ***R** ~ 22,500*
- ***300,000** stars, **S/N > 100***
- ***Radial velocities:** accuracy ~200m/s*
- ***Chemical abundances:** 19 species, accuracy ~ 0.1 dex*

The Analysis

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- Chemical trends with distance with the Galactic center (*r*)

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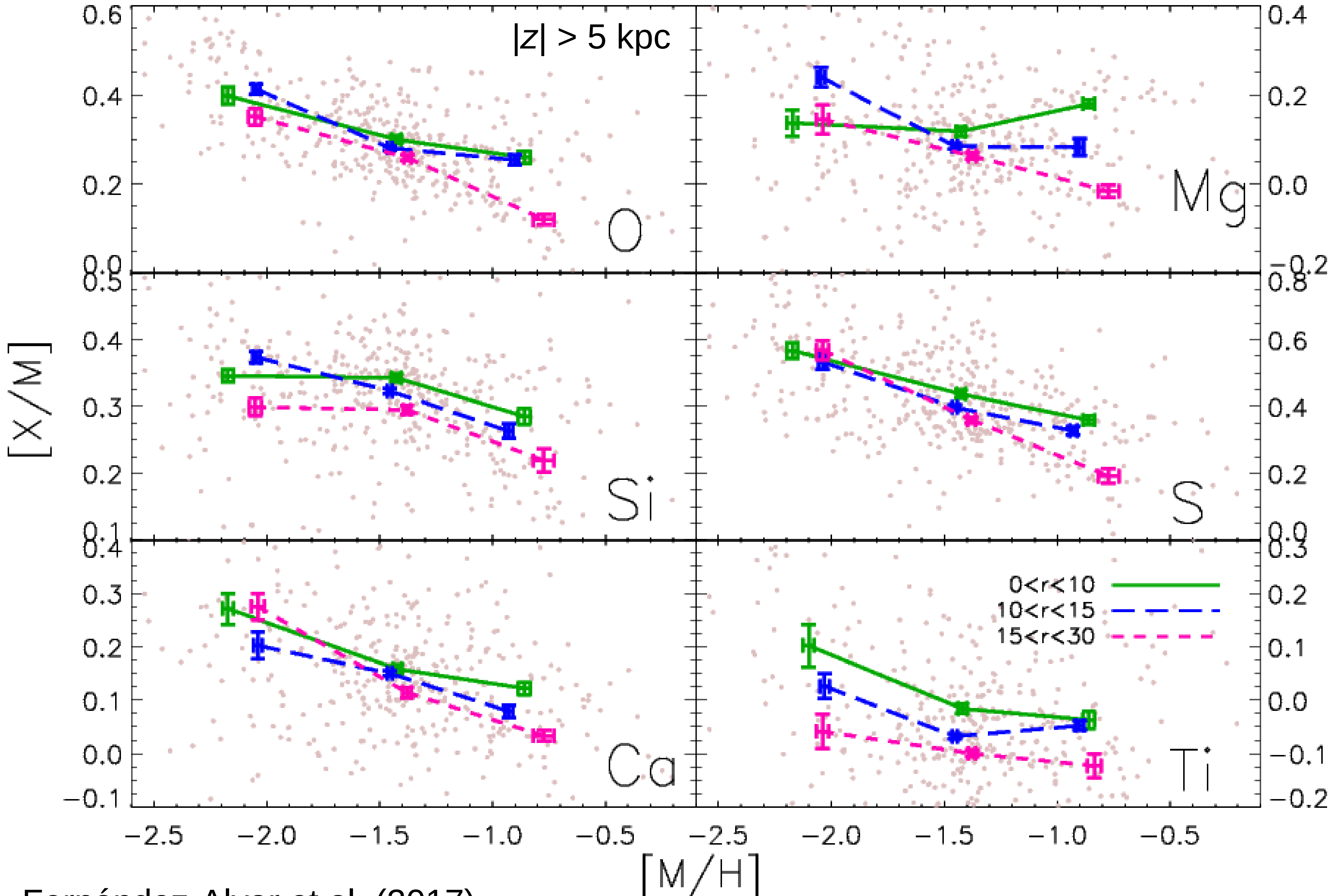
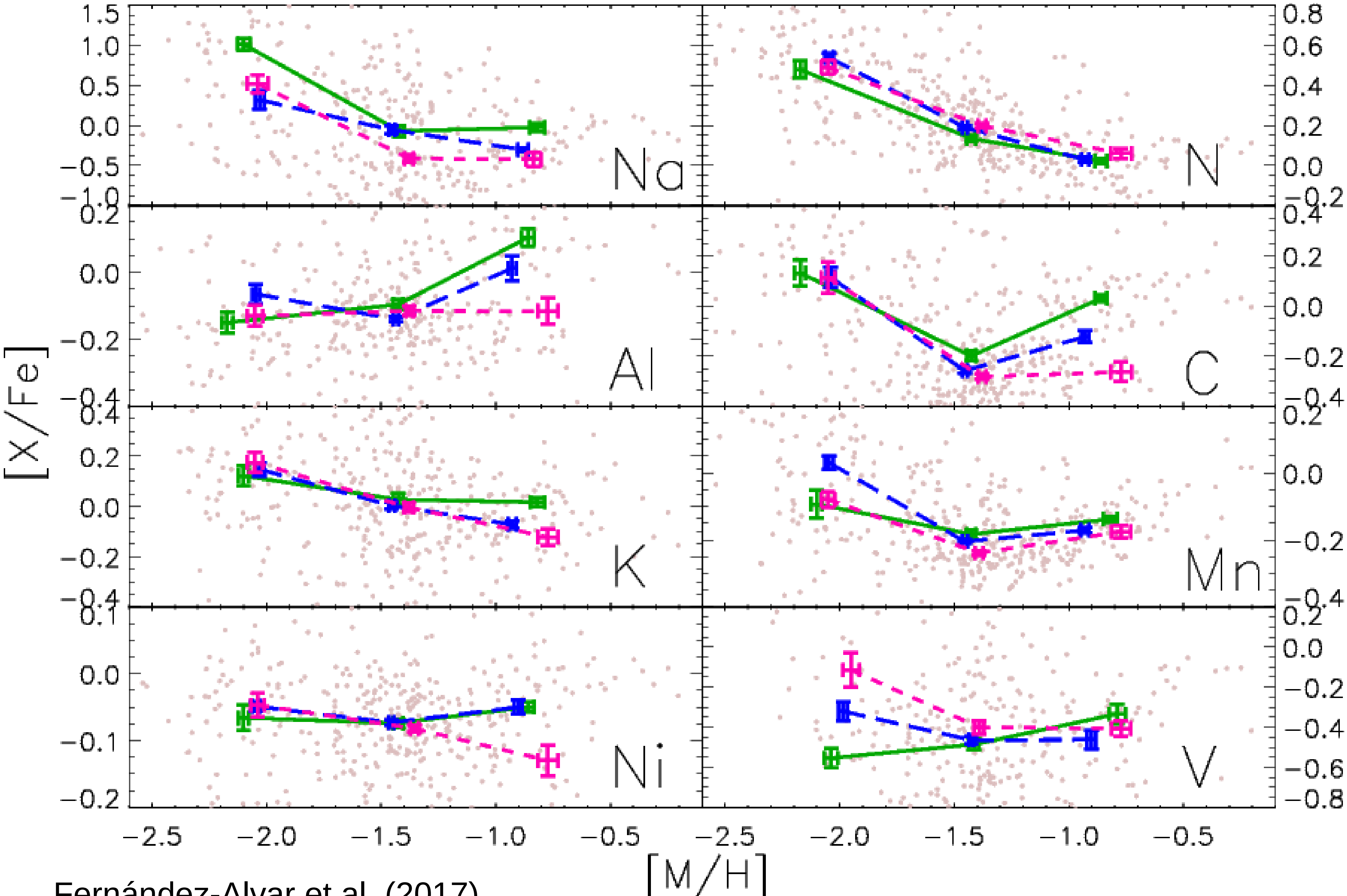
- The orbits

Chemical trends with *r*

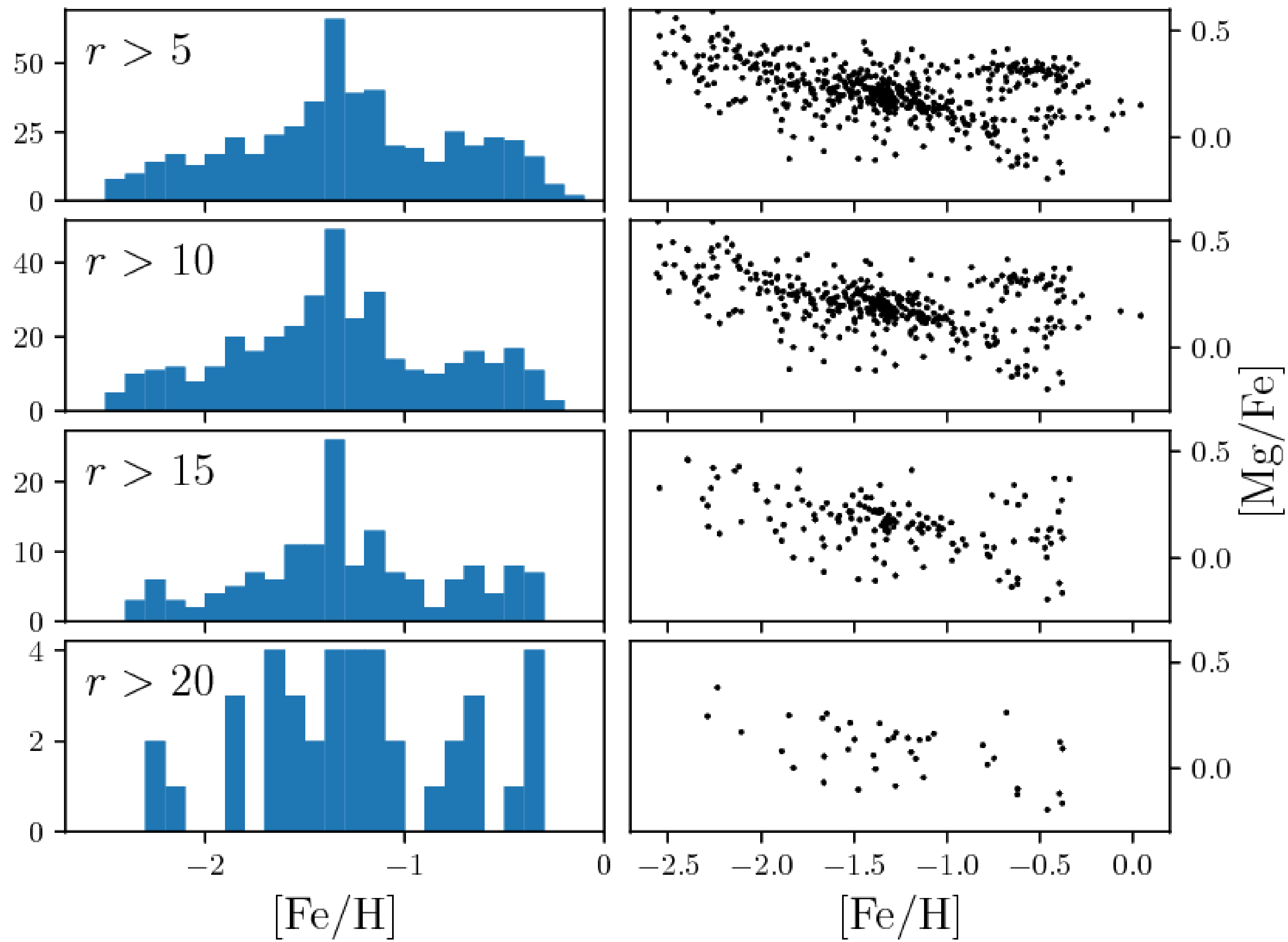


Fernández-Alvar et al. (2017)



Fernández-Alvar et al. (2017)

MDF as a function of *r*



Δ[α/Fe] ≥ 0.1 and steeper slope at r > 15 kpc with [Fe/H]

Distant stars show different chemical enrichment

The chemical trend for the low-α population in Nissen & Schuster 2010 dominates at r > 15 kpc.

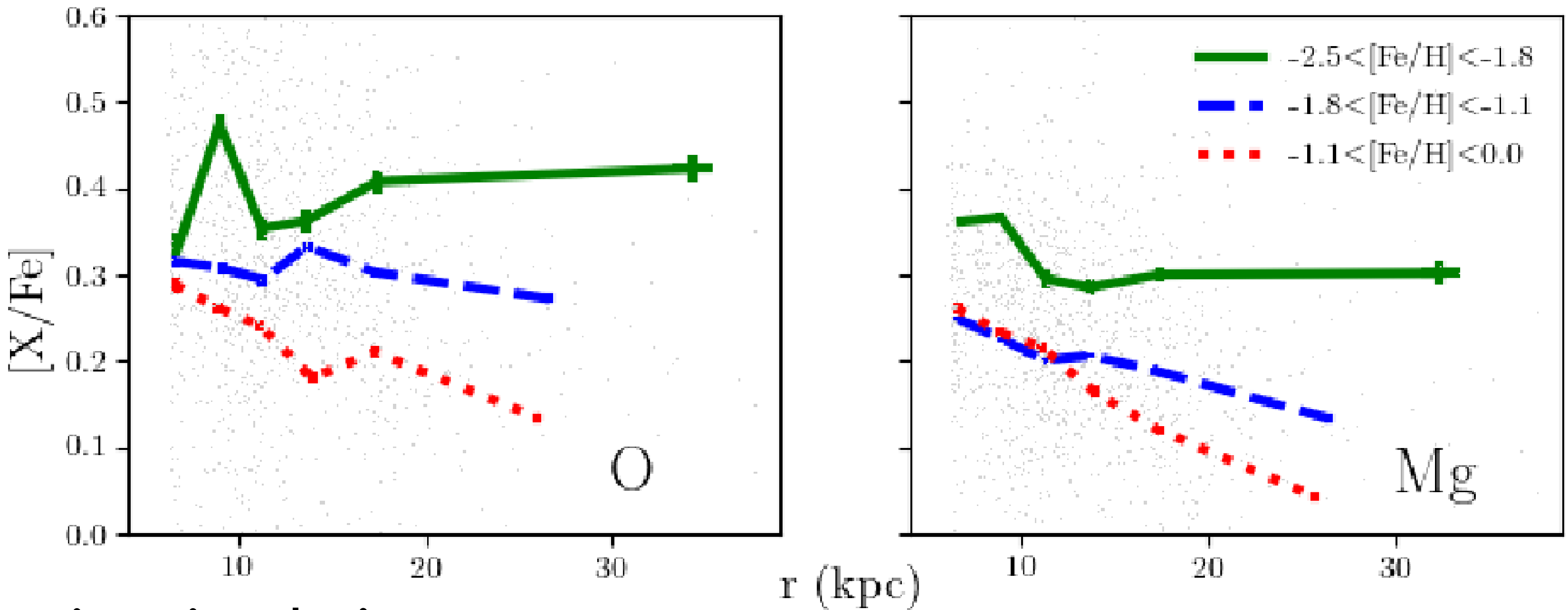
Comparison with Cosmological Simulations

Fernández-Alvar et al. (in prep)

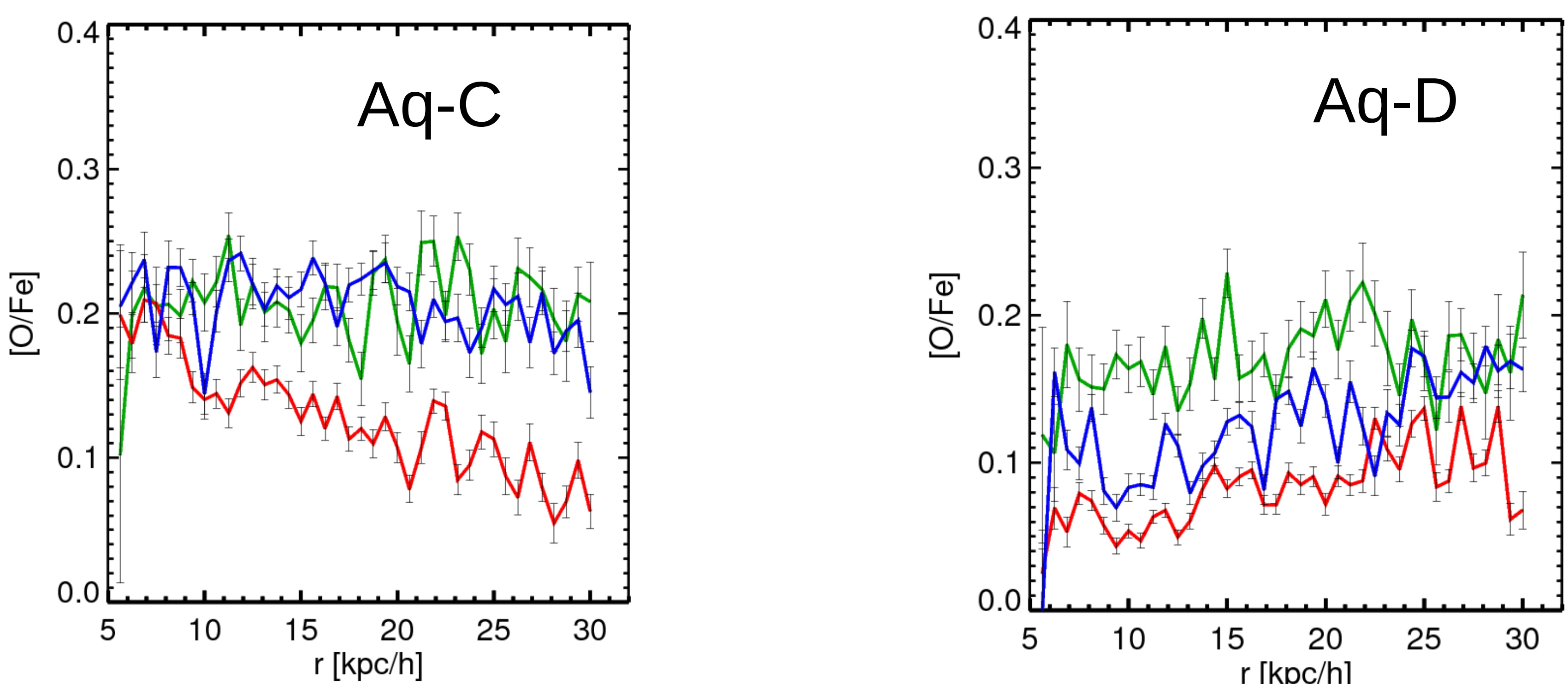
- Aquarius Simulations (Scannapieco et al. 2009)
- Six Milky-Way mass-sized halos (Tissera et al. 2012, 2013, 2014)

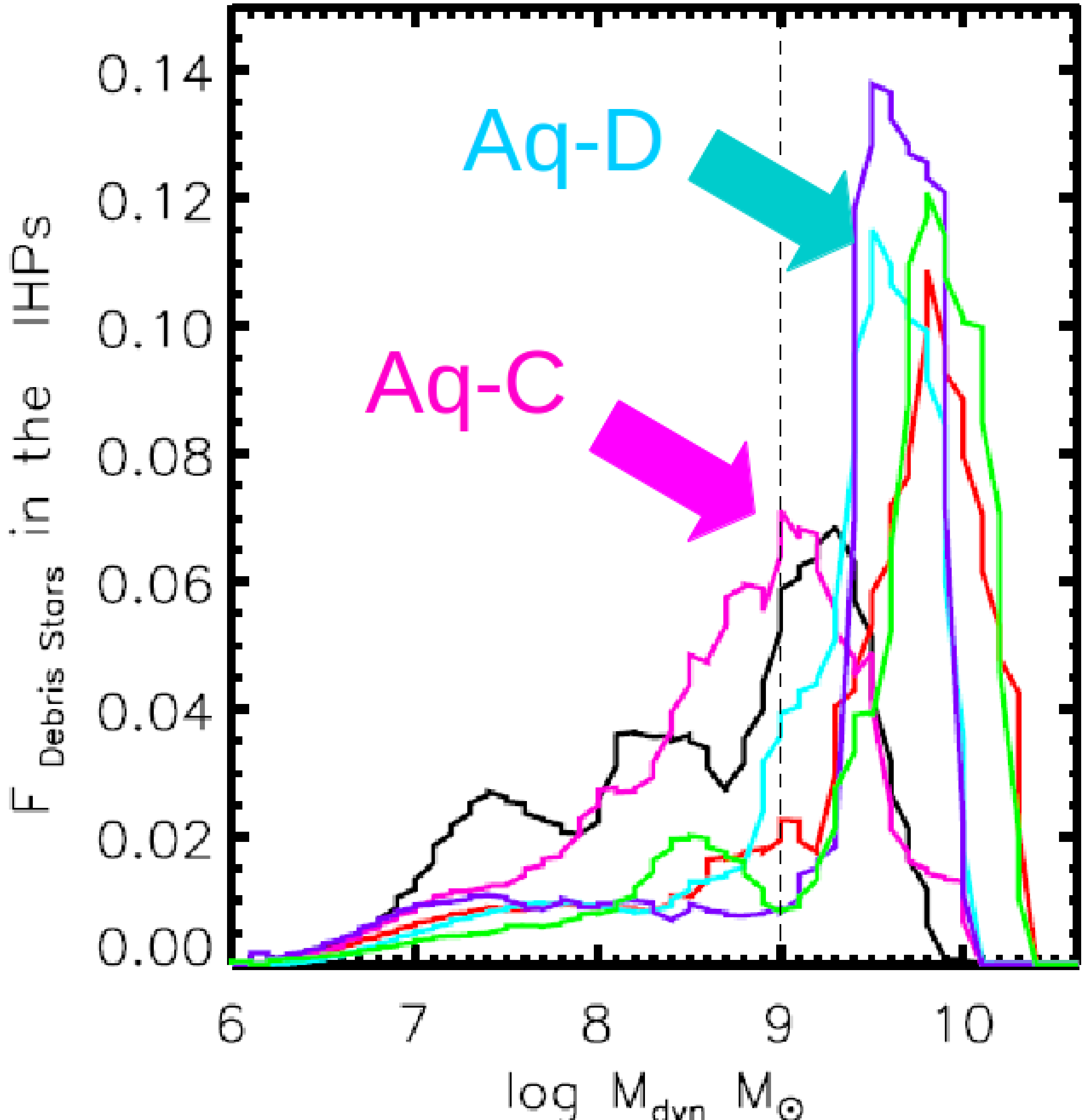
APOGEE DR14 chemical abundances

Fernández-Alvar et al. (in prep)

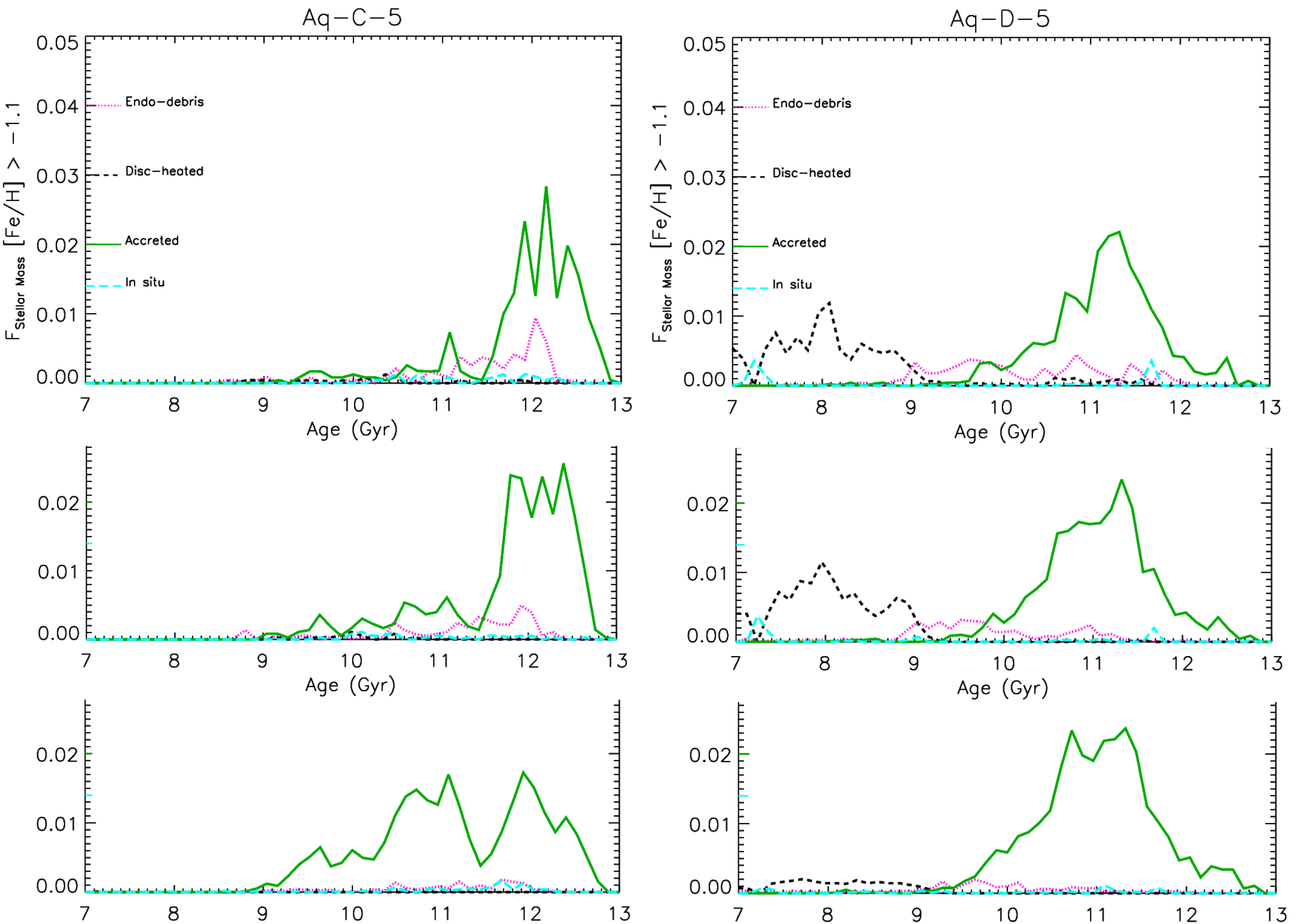


Aquarius simulations





Tissera et al. (2014)



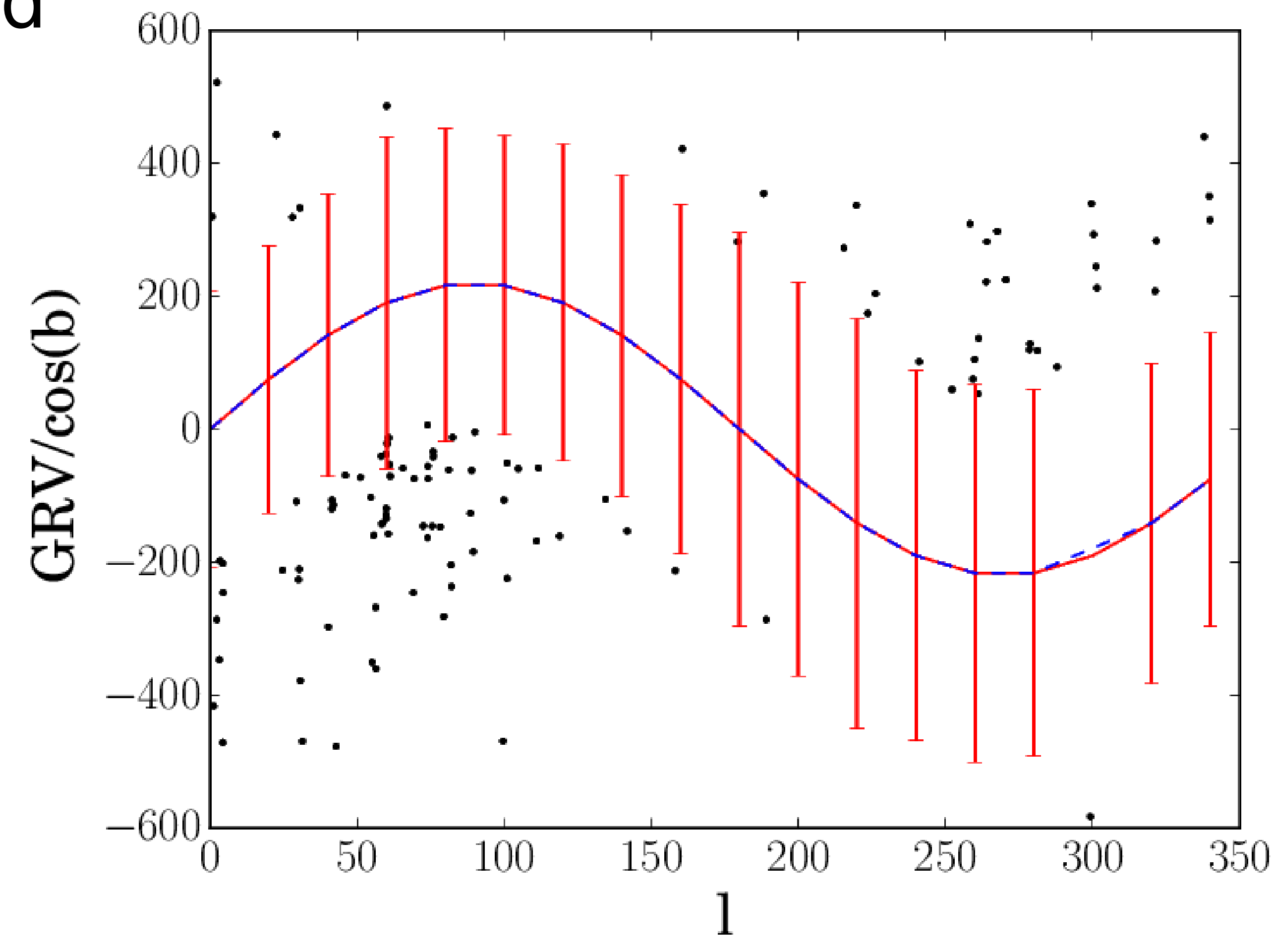
Fernández-Alvar et al. (in prep)

Comparison with Chemical Evolution Models

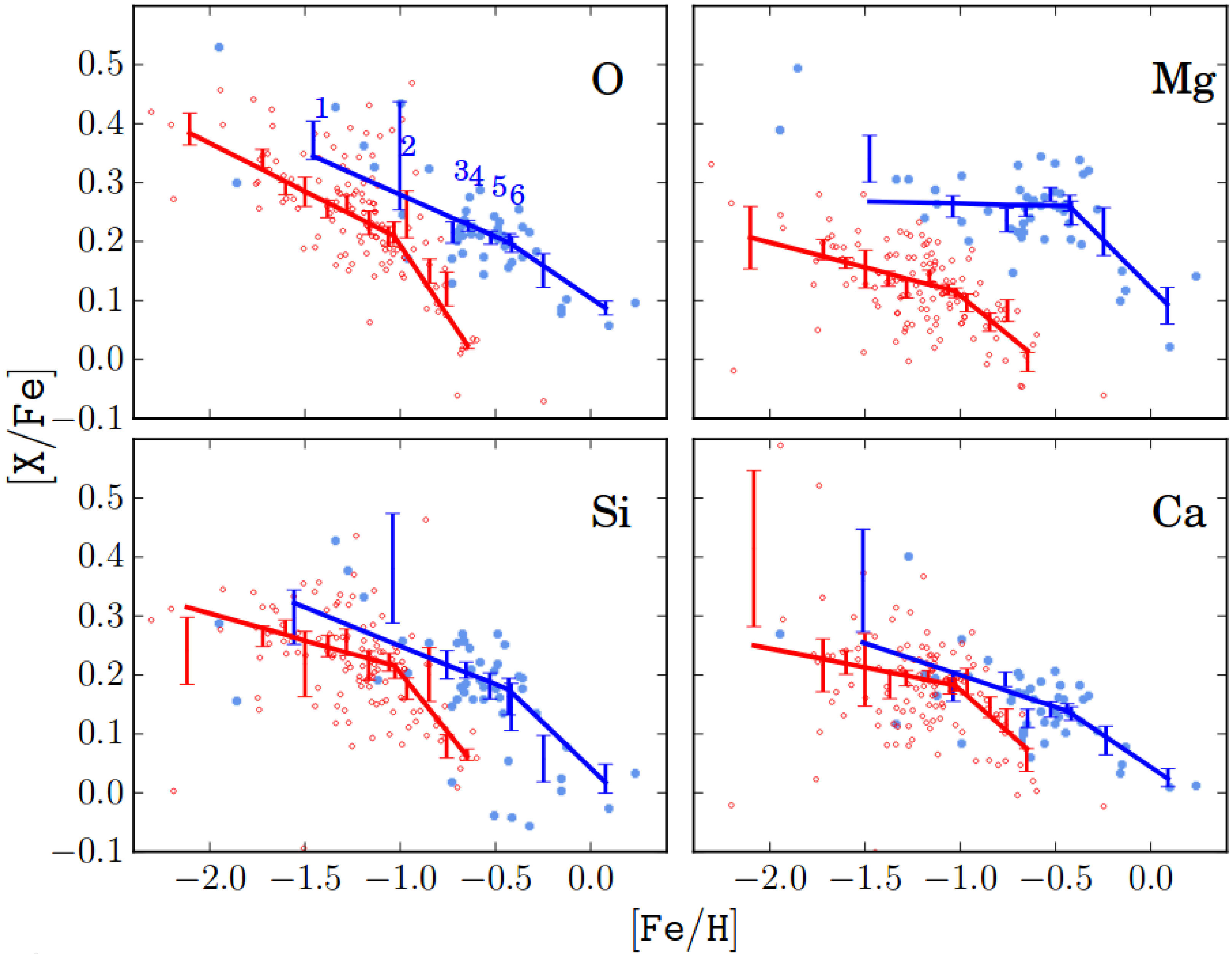
Fernández-Alvar et al. (2018)

- V_{rad} > 180 km/s (halo like motion)
- GRV/cos(b) vs l:

  >3σ disk sinusoid



Fernández-Alvar et al. (2018)



Fernández-Alvar et al. (2018)

Chemical model

- HMg and LMg are two independent populations

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- **Semi-instantaneous recycling approximation**

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Chemical model

- HMg and LMg are two independent populations

- **Semi-instantaneous recycling approximation**

- A **closed-box model**

- Each [X/Fe] vs. [Fe/H] range represents a different evolutionary stage

  -Before the ‘knee’, only SNII contribute

  -After the ‘knee’, both SNII and SNIa pollute the ISM.

Upper mass limit IMF

$\Delta X = X(t2) - X(t1) = - < Y/X >_{2-1} \log(\mu(t2)/\mu(t1))$

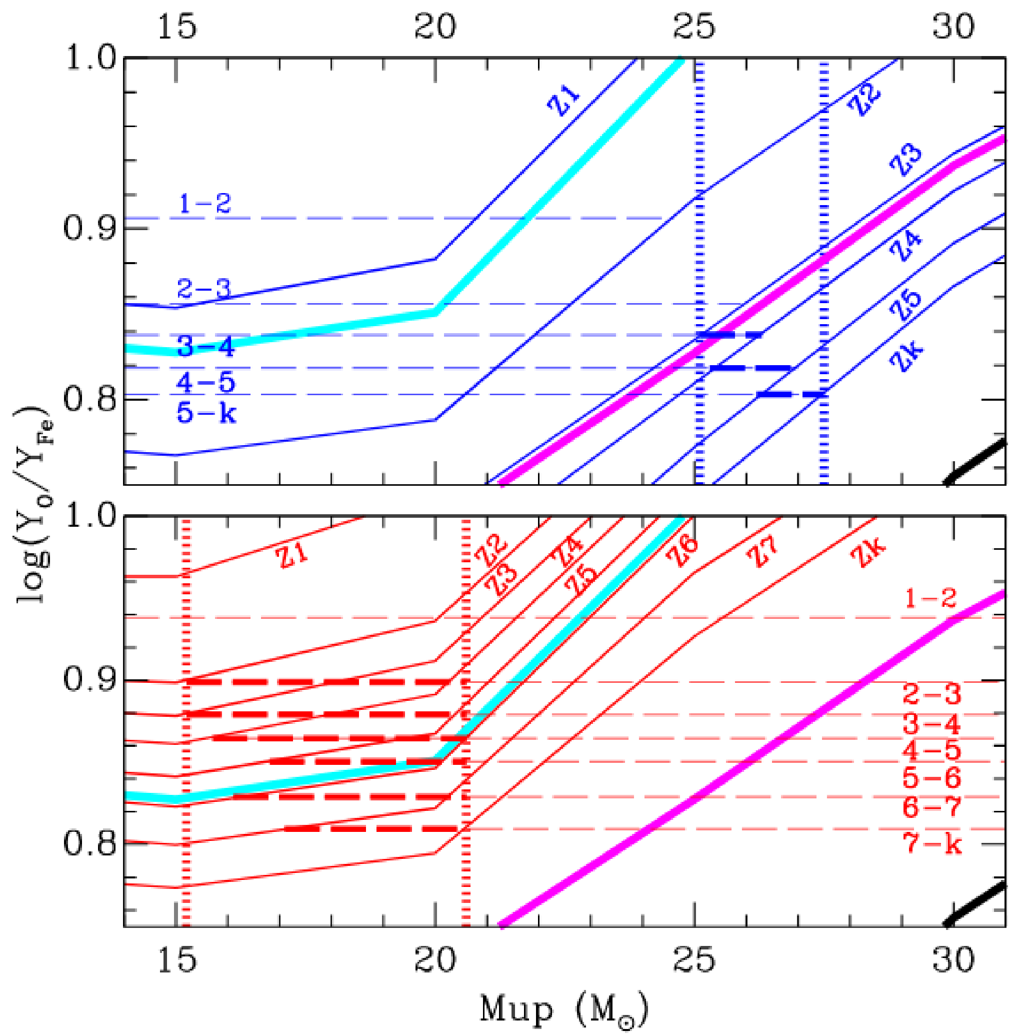
$\Delta(X/H)/\Delta(Fe/H) = < Y/X >_{2-1} / < Y/Fe >_{2-1}$

SNII:
 Kobayashi et al.(2006)

Pre-SN:
 Robles-Valdés et al.(2013)
(Geneva group)

SNIa:
 Iwamoto et al. (1999)

Kroupa-Tout-Gilmore IMF



Fernández-Alvar et al. (2018)

- SFR proportional to the mass of the gas at t:

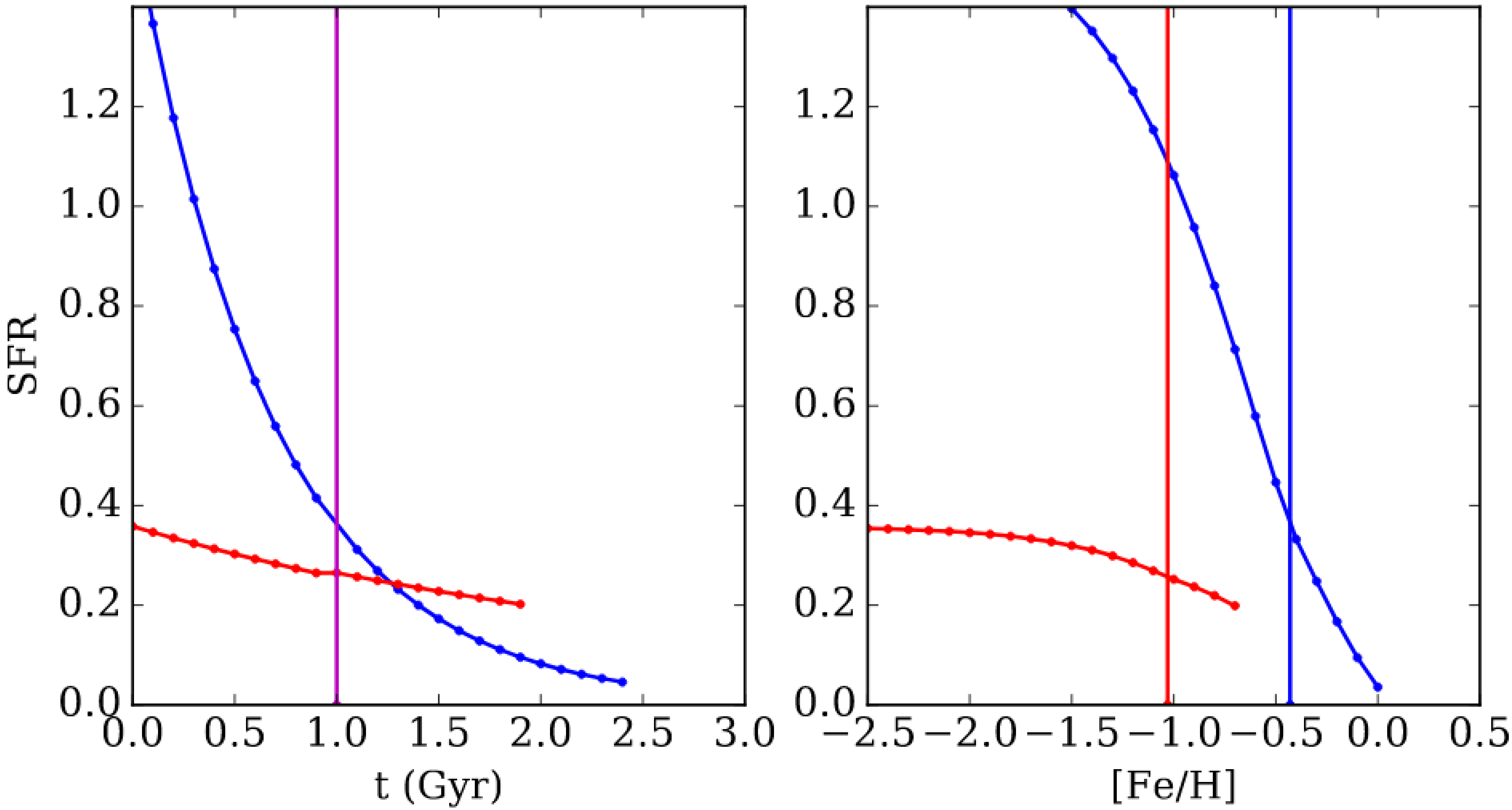
$$SFR(t) = \nu M_{gas}(t)$$

- Efficiency, ν, constant with time

$$M_{gas}(t) = M_{gas}(0)\, e^{-\nu(1-R)t}$$

$$X(t_k) = \langle Y/X \rangle\, \nu(1-R)\, t_k$$

$$SFR(t) = M_{gas}(0)\, e^{-\nu(1-R)t}$$



Fernández-Alvar et al. (2018)

According to our closed-box model, more massive stars contribute to the ISM where the **HMg** formed with respect to the LMg population, which implies an **IMF weighted to a higher upper mass limi**t.

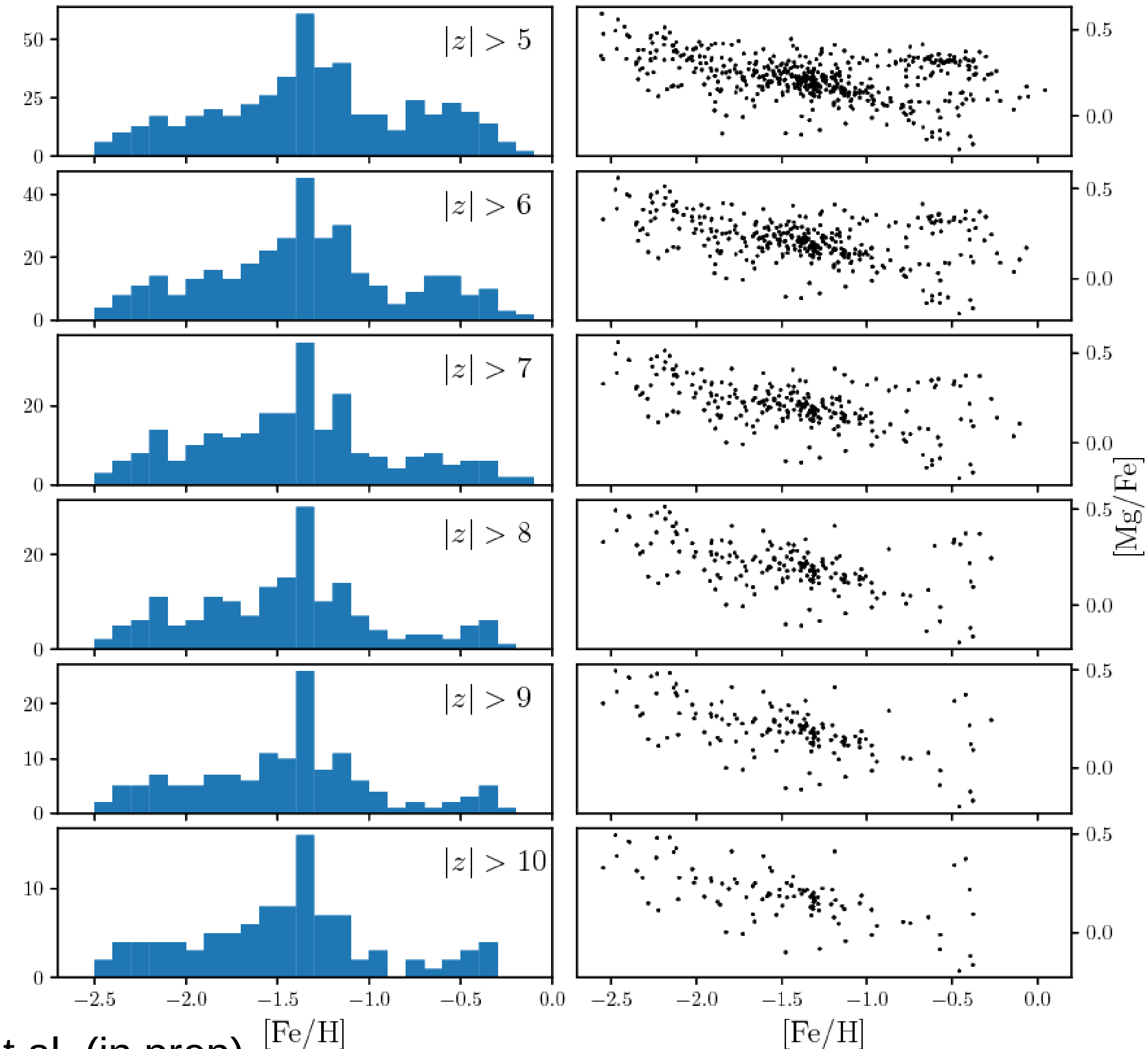
There is **no significant difference between the two populations** regarding the **contribution of SNIa** to enrich the ISM from which the populations formed.

The **star-formation rate** was **higher in the HMg** population during most of the evolution, **decreases more steeply** with time, and was **longer** than the SFR(t) inferred for the LMg population. The latter was lower, more constant, and shorter.

The orbits

Fernández-Alvar et al. (in prep)

Metal-rich halo: extended in z



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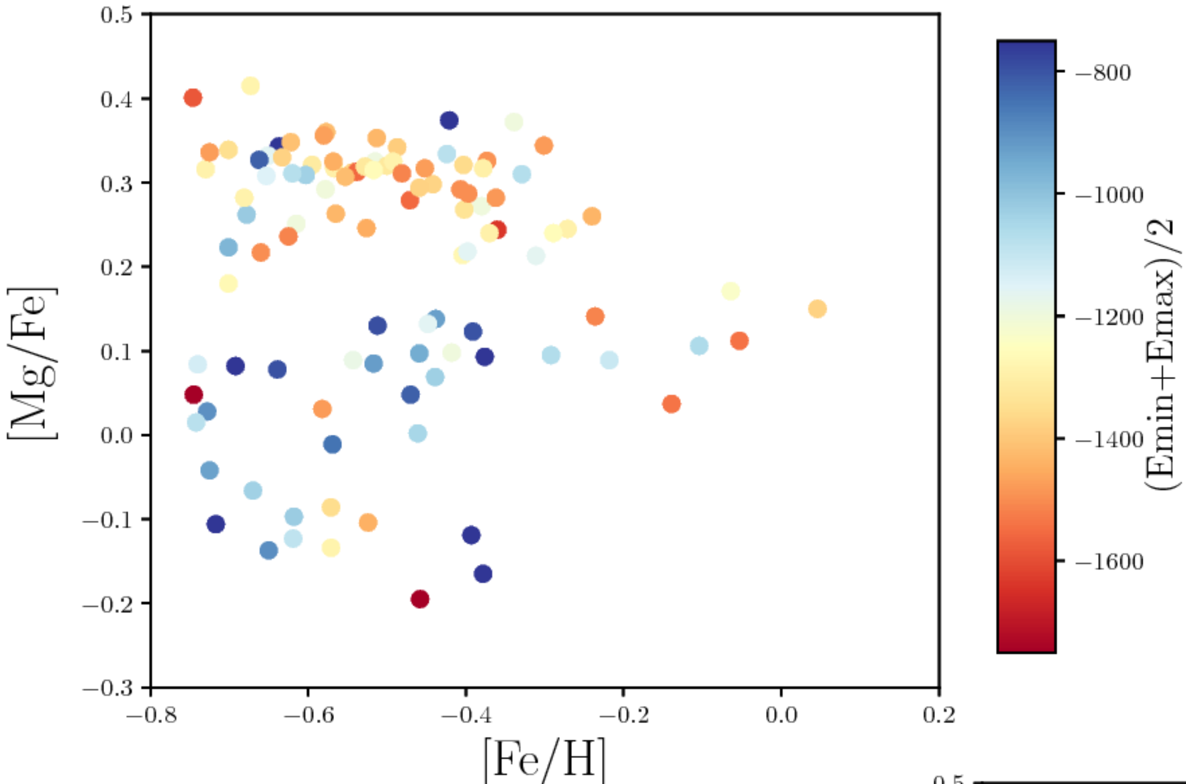

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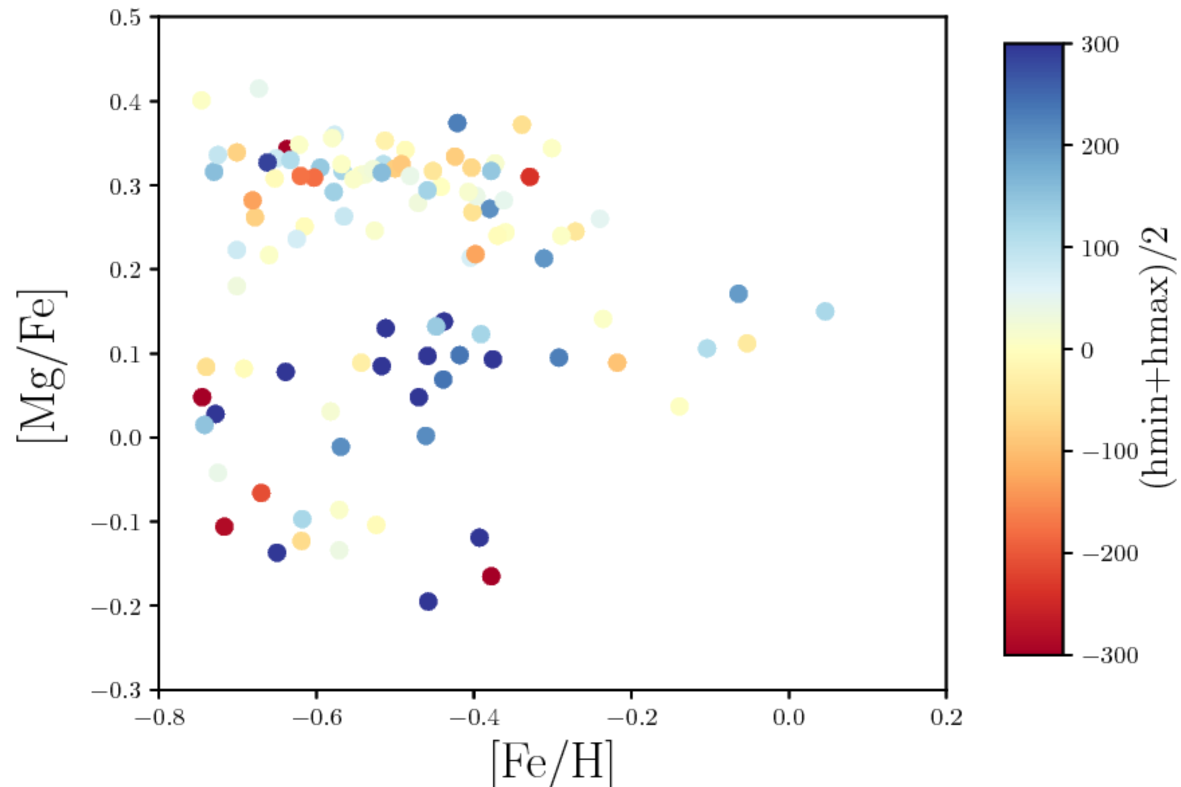

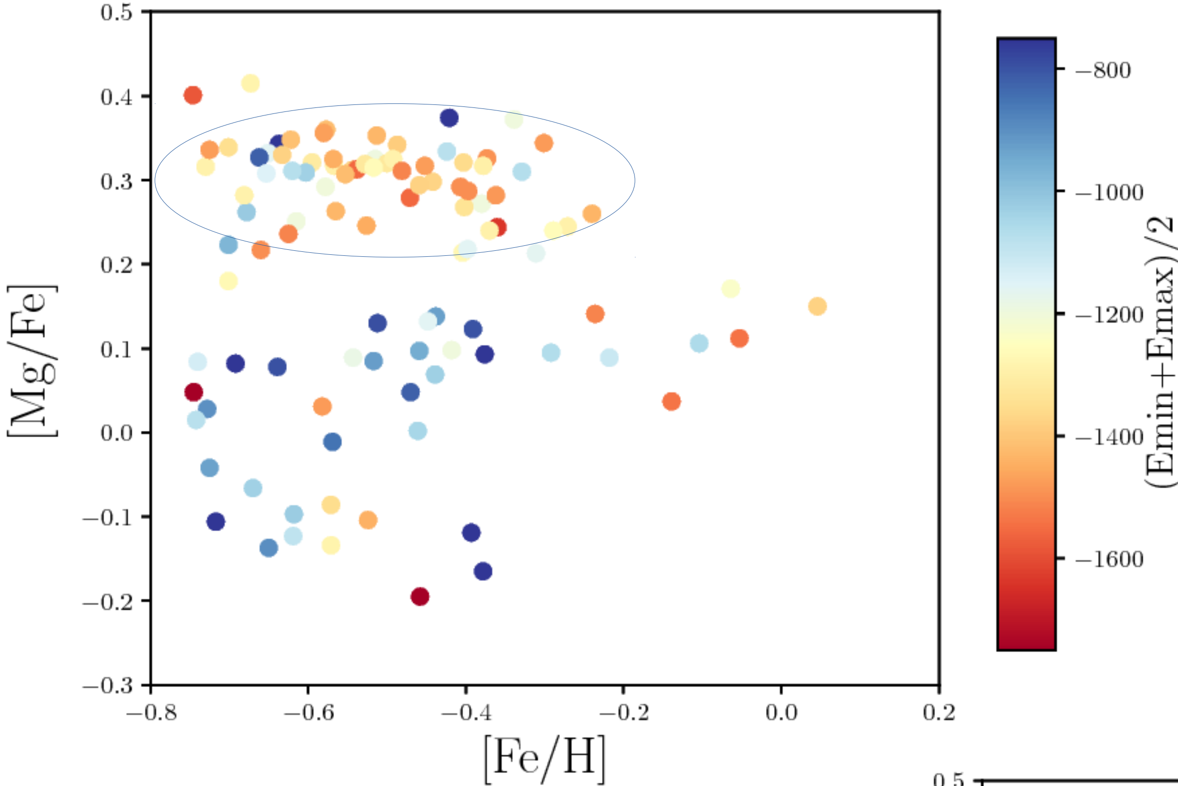

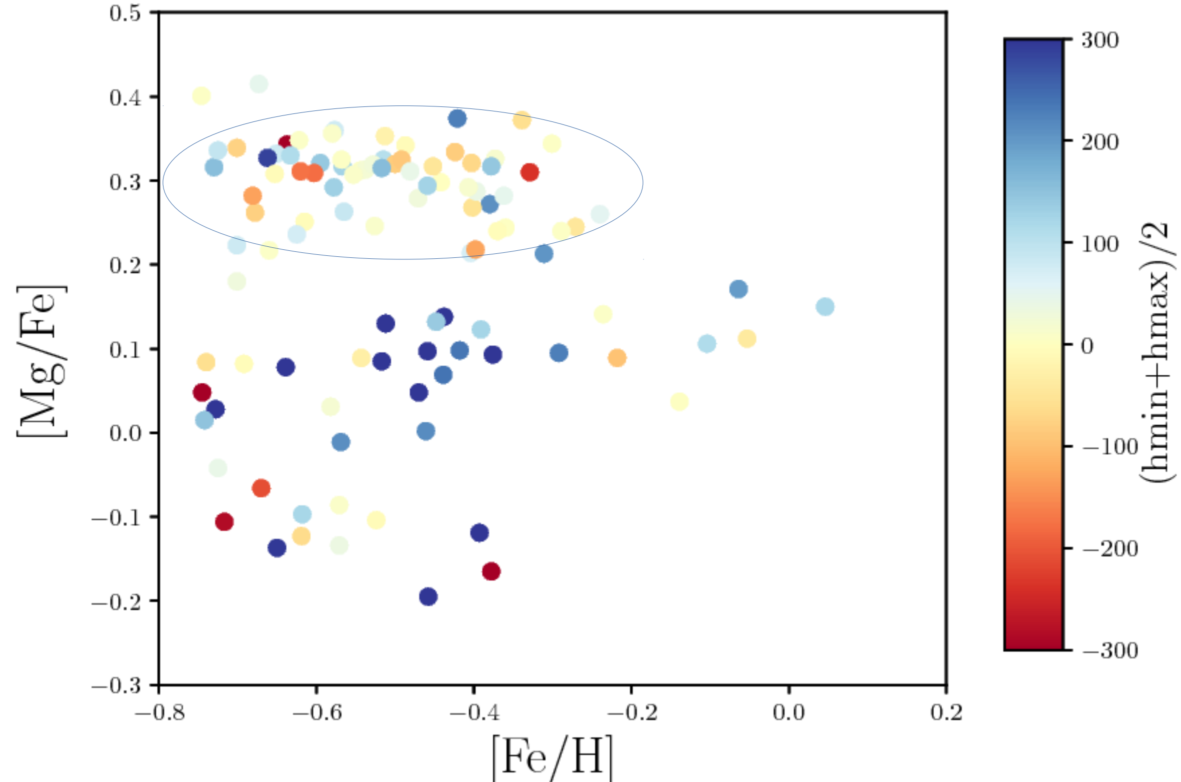

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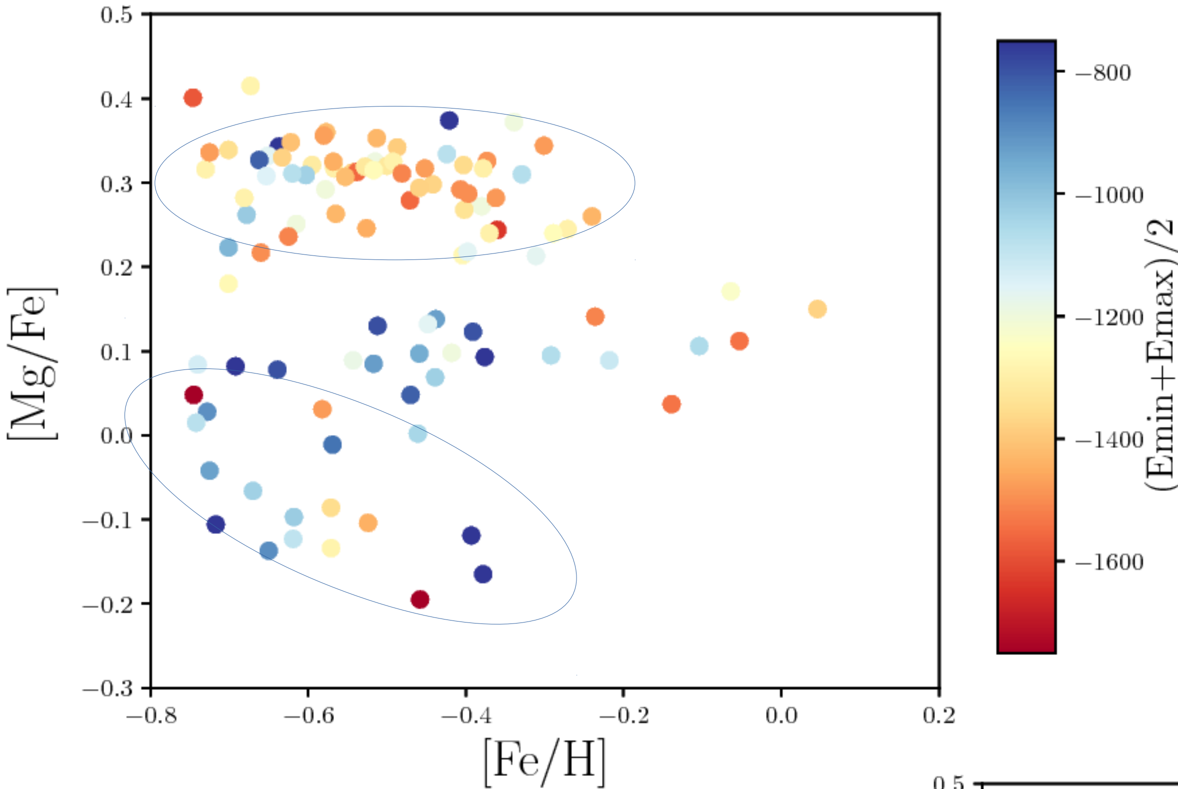

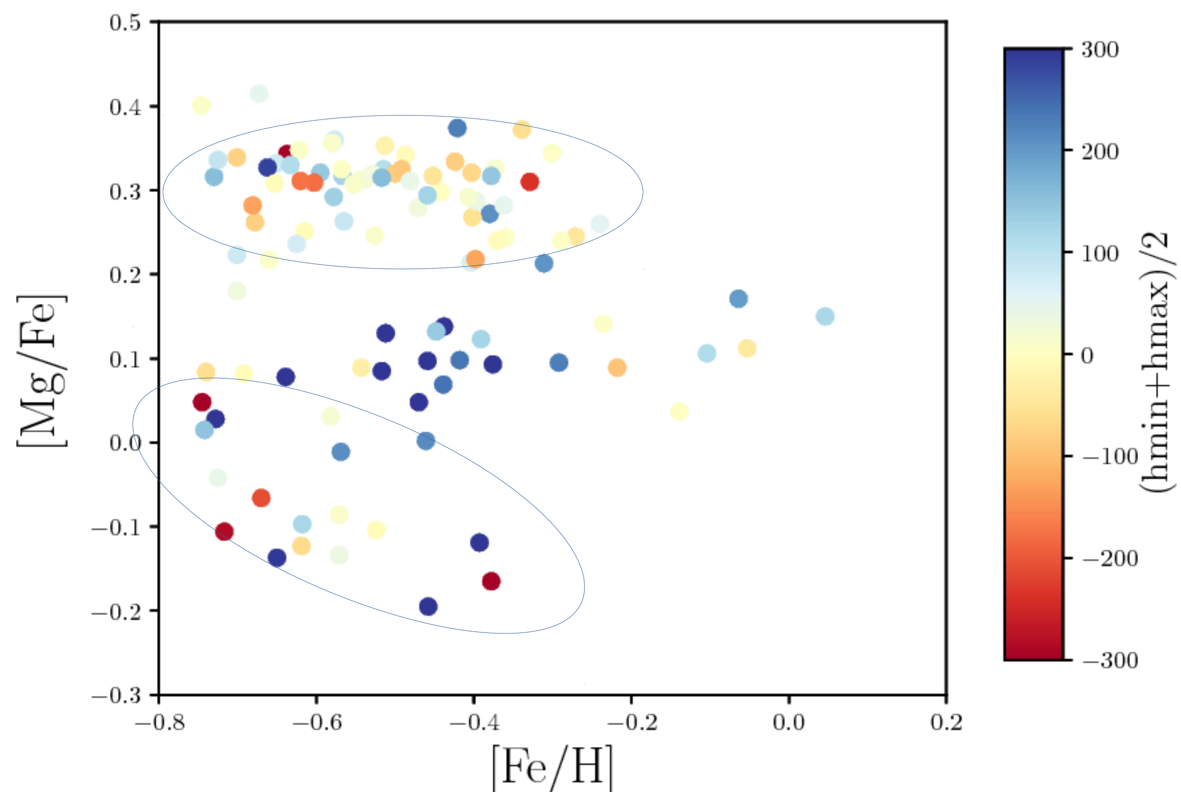

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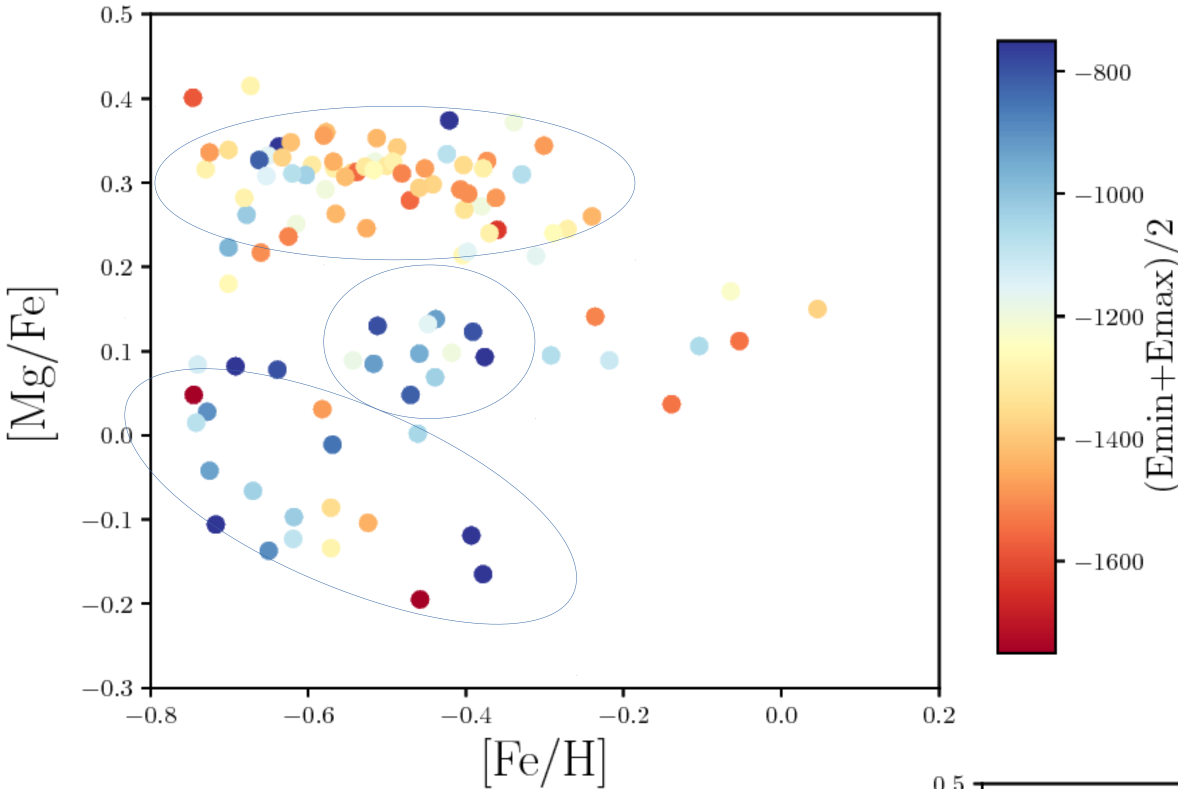

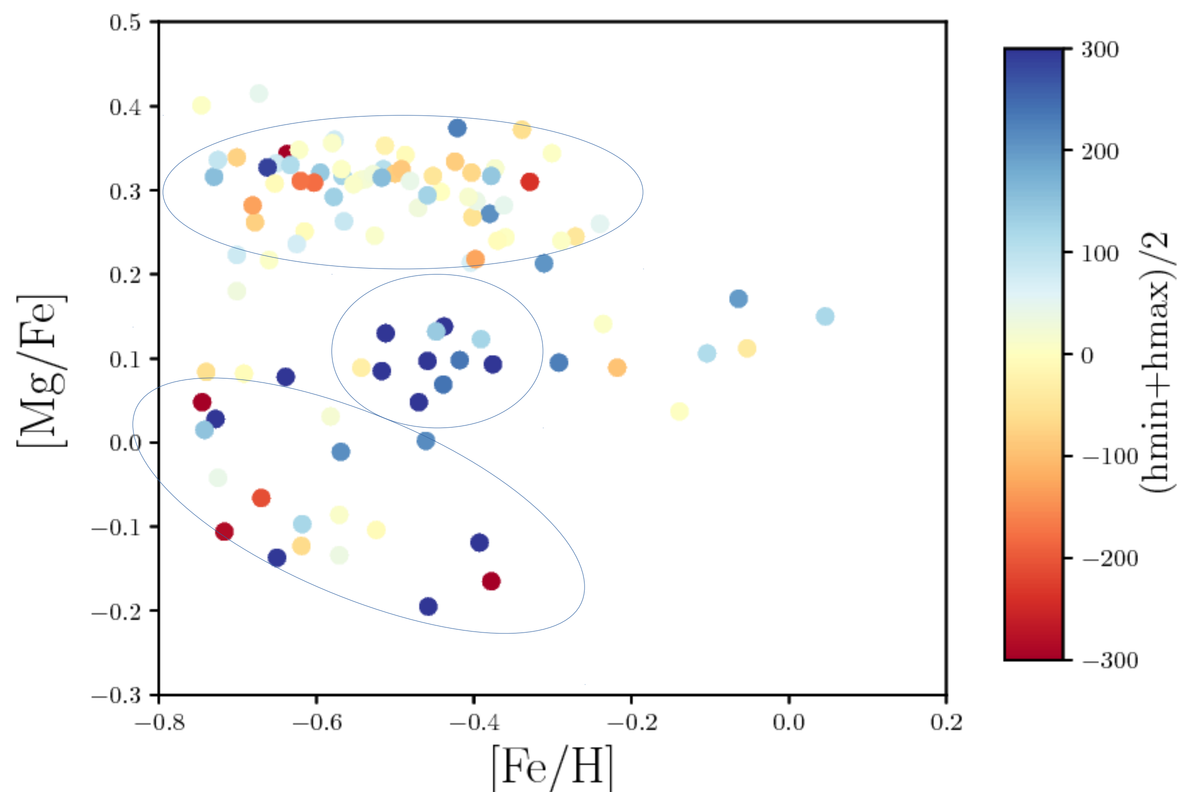

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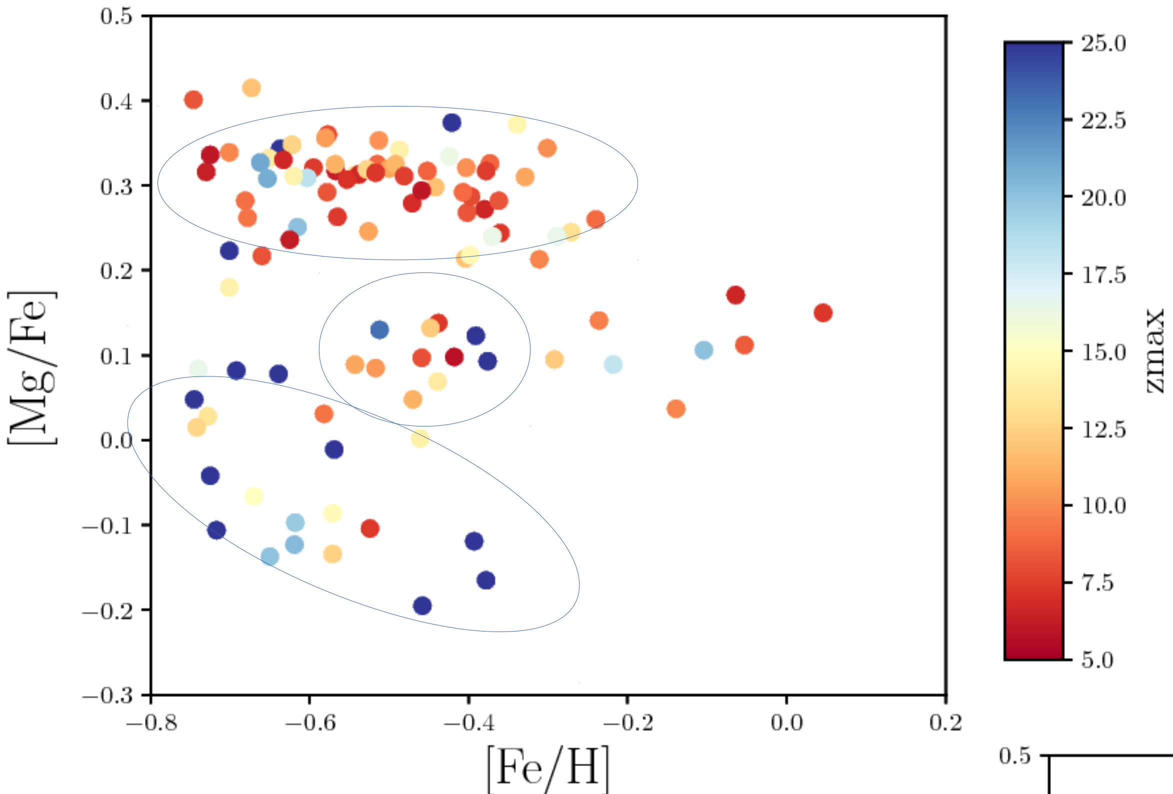

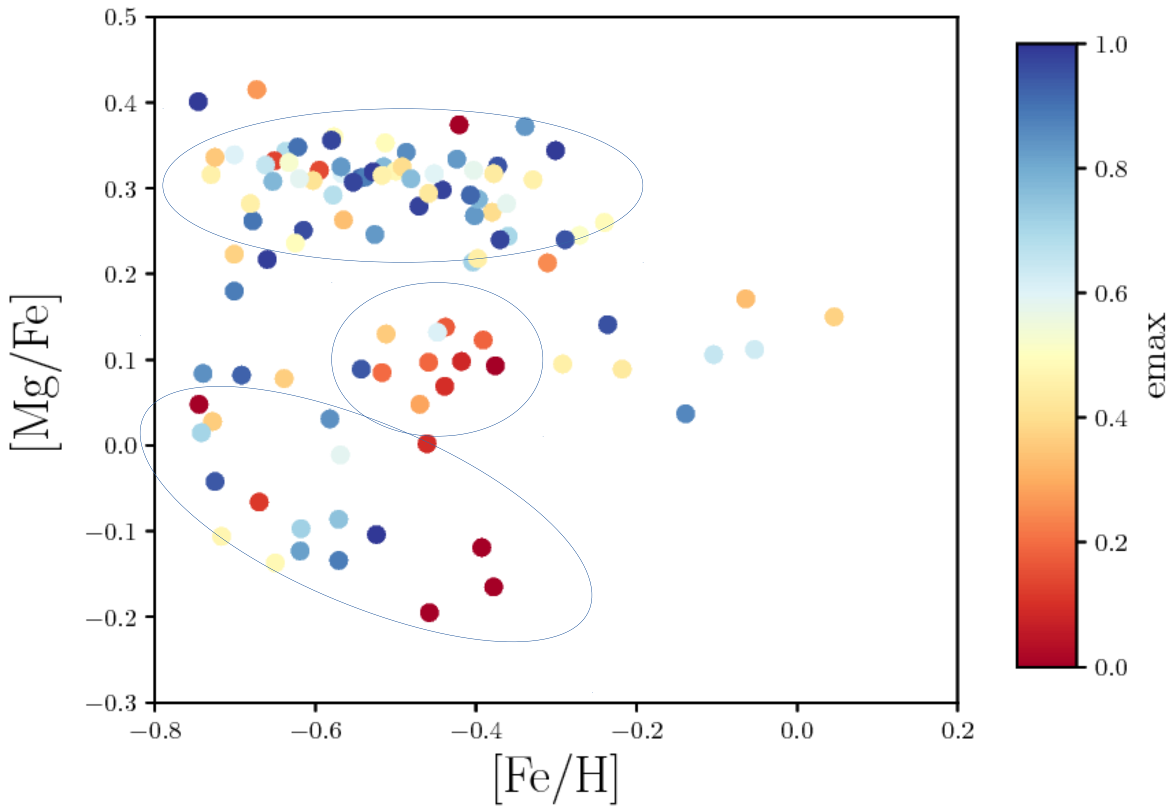

Fernández-Alvar et al. (in prep)

Metal-rich halo: at |z| up to 10 kpc

Three [alpha/Fe] populations with different orbital properties

High-alpha population: h ~ 0   ORIGIN?

Summary

- Different chemical enrichment beyond *r* > 15 kpc
- Low-alpha population dominates at *r* > 15 kpc
- Observational chemical trends with *r* in the inner halo (*r* < 30 kpc) compatible with an accretion history of satellites with masses ~ 10^9 solar masses.
- Chemical enrichment histories between high-alpha and low-alpha populations (IMF towards more massive stars and a higher and more extended SFR for the high-alpha population).
- Different dynamical properties:

  High-alpha: h~0, z_{max} < 10 kpc

  Low-alpha: larger dispersion in h, larger z_{max}

Future work

Future work

- AMBRE

  Confirm results

Future work

- AMBRE

  Confirm results

- Gaia

  Ages