

A Walk on the Retrograde Side (WRS) project

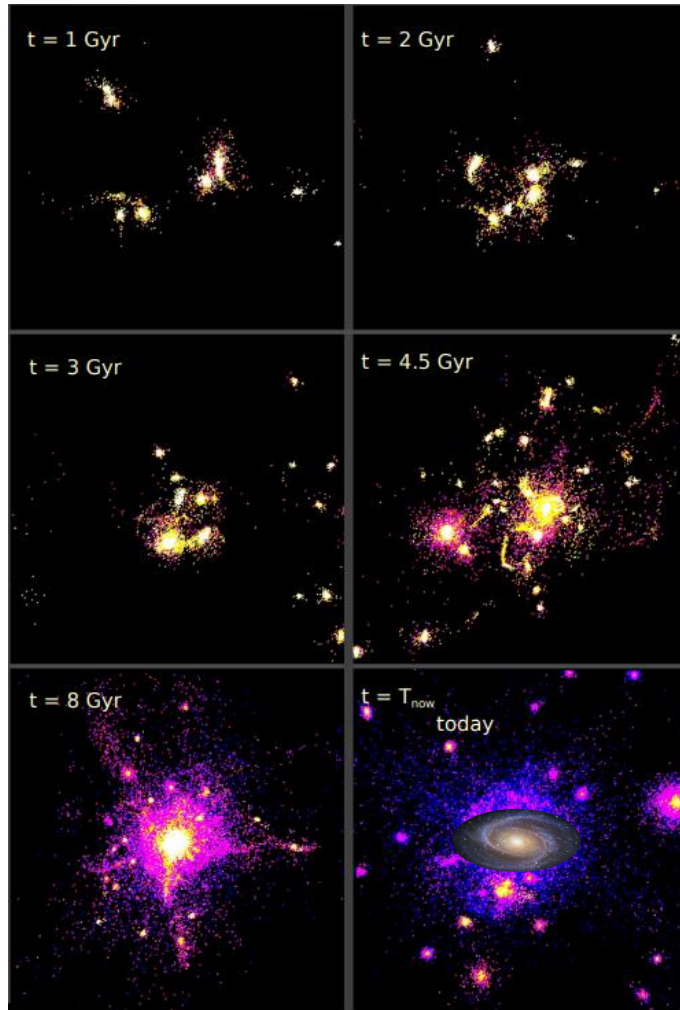
Edoardo Ceccarelli - PhD Student

INAF - OAS Bologna

Supervisors: D. Massari, A. Mucciarelli, M. Bellazzini, D. Romano

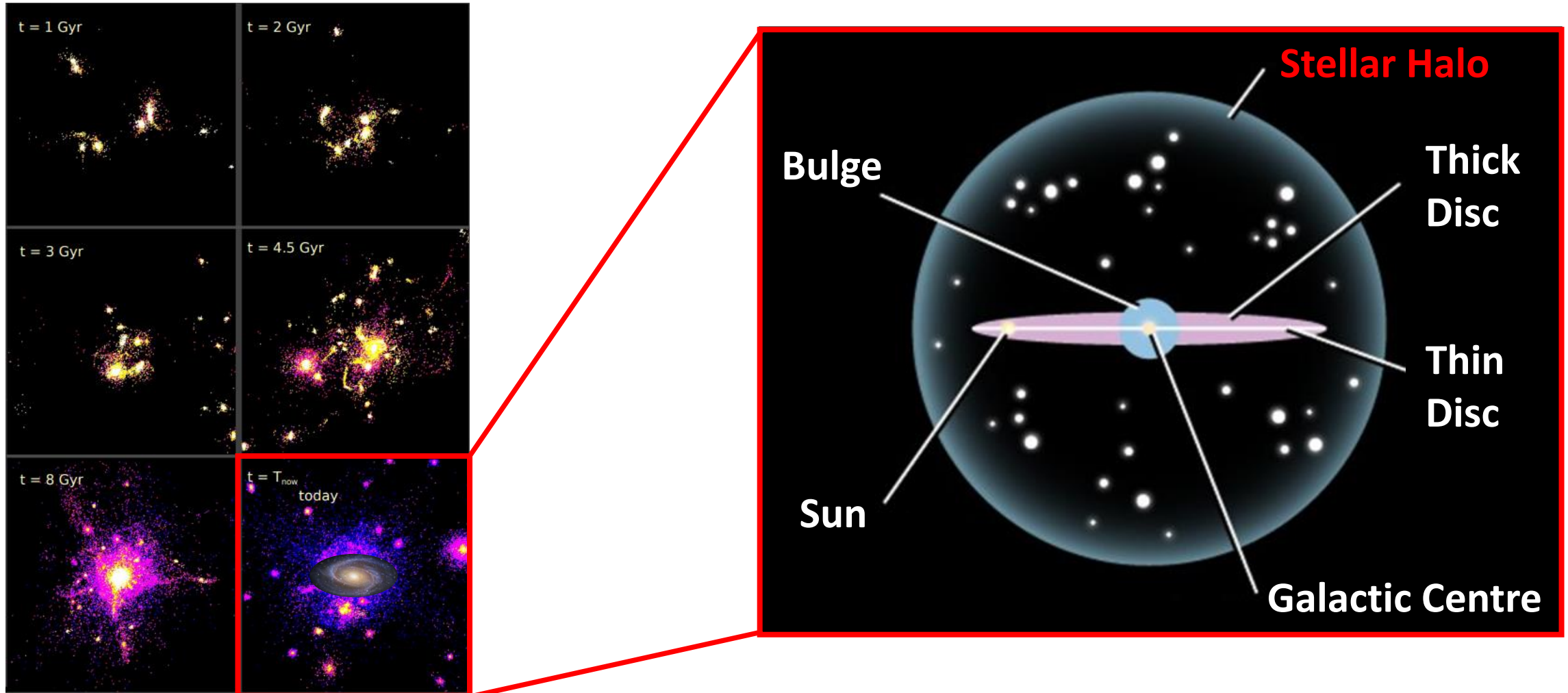
How did the MW reach its final shape?

J.Gardner



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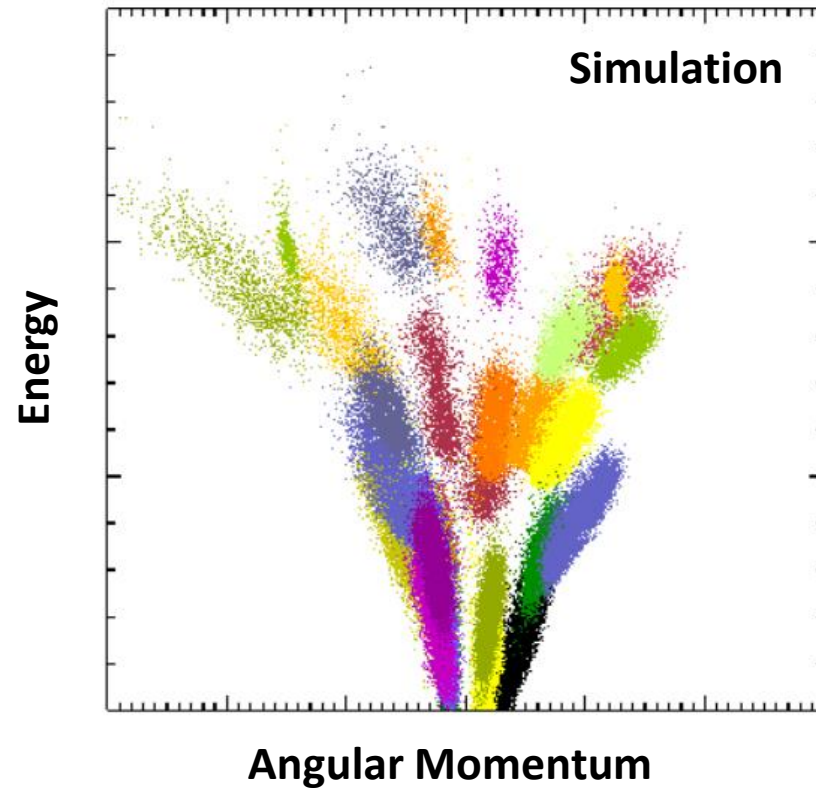
J.Gardner



DYNAMICS to trace past accretion events

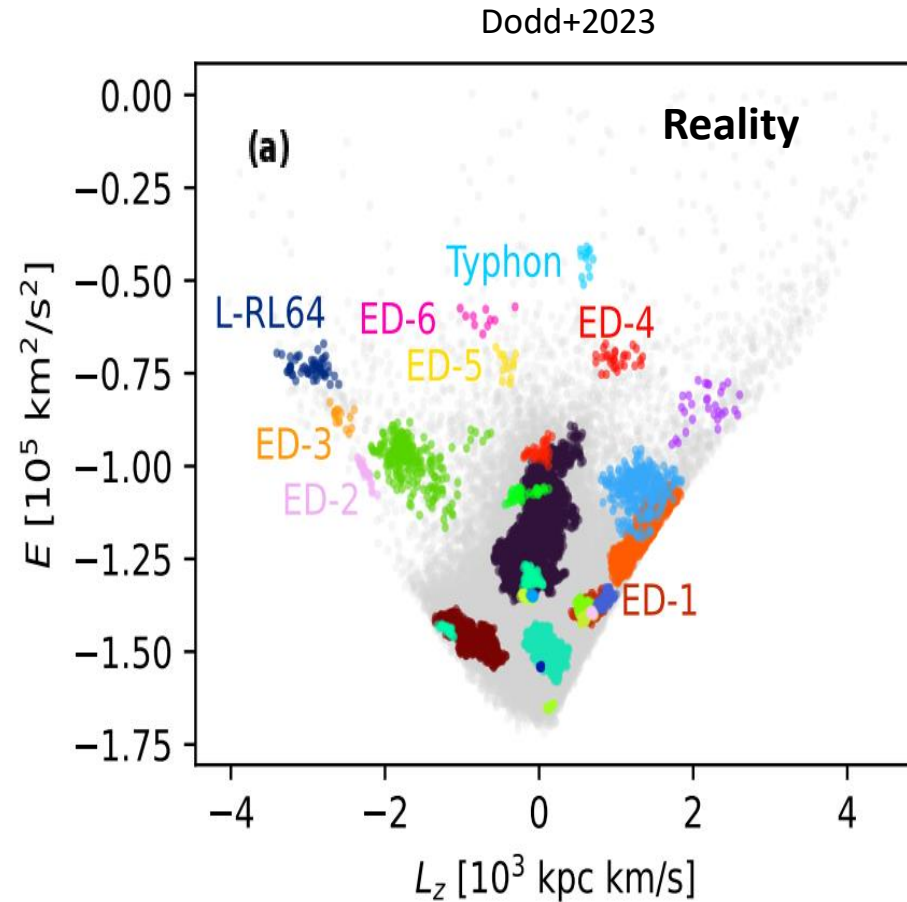
Clumps in the **loM** space

Helmi & de Zeeuw 2000



DYNAMICS to trace past accretion events

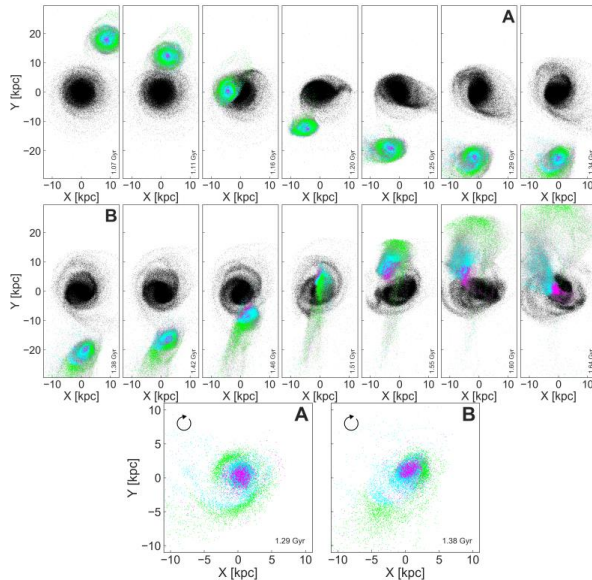
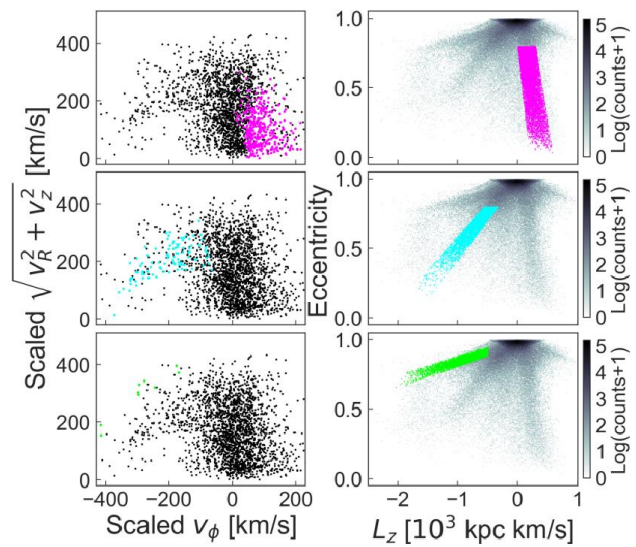
Clumps in the **IoM** space



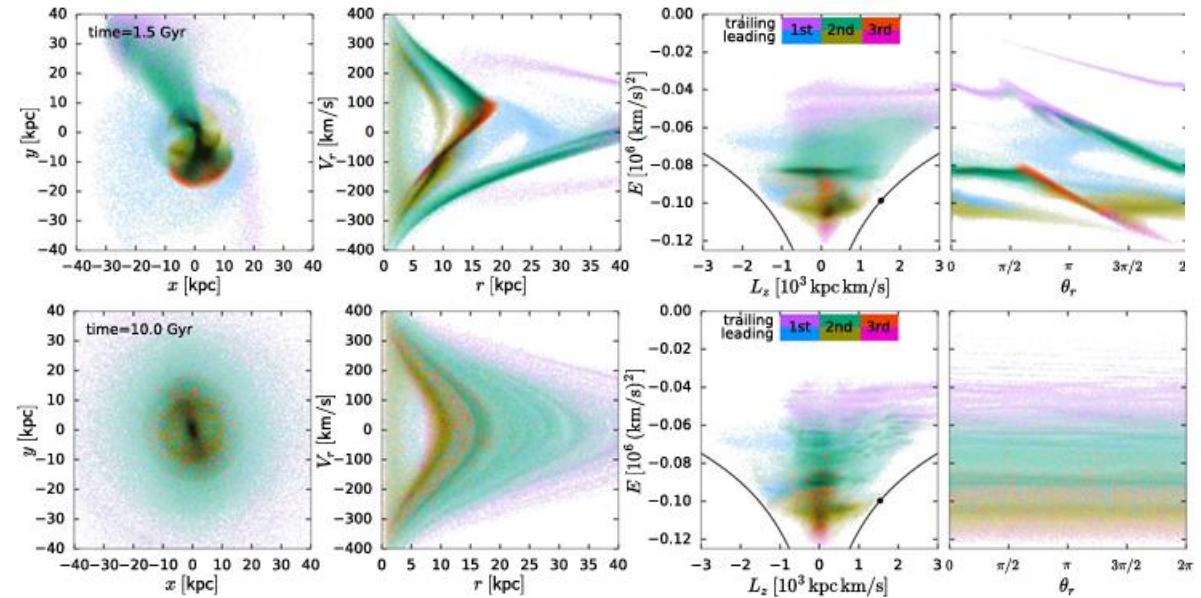
Dynamics alone is NOT enough

Clumps in the **loM** space: overlapping + contamination

Koppelman+2020

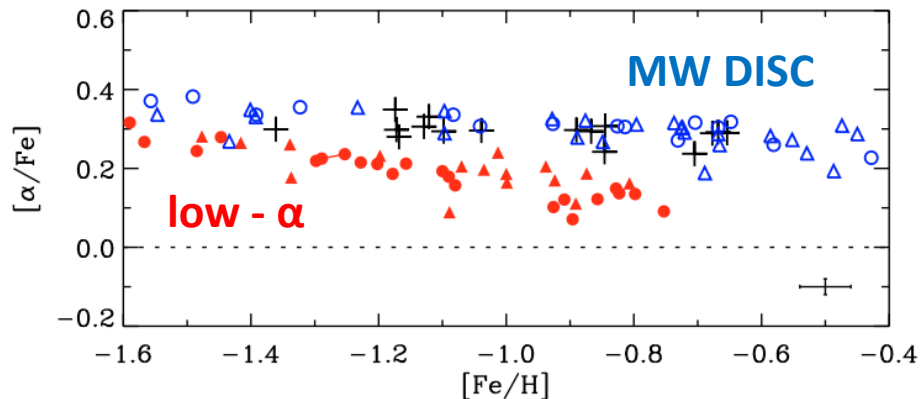


Belokurov+23

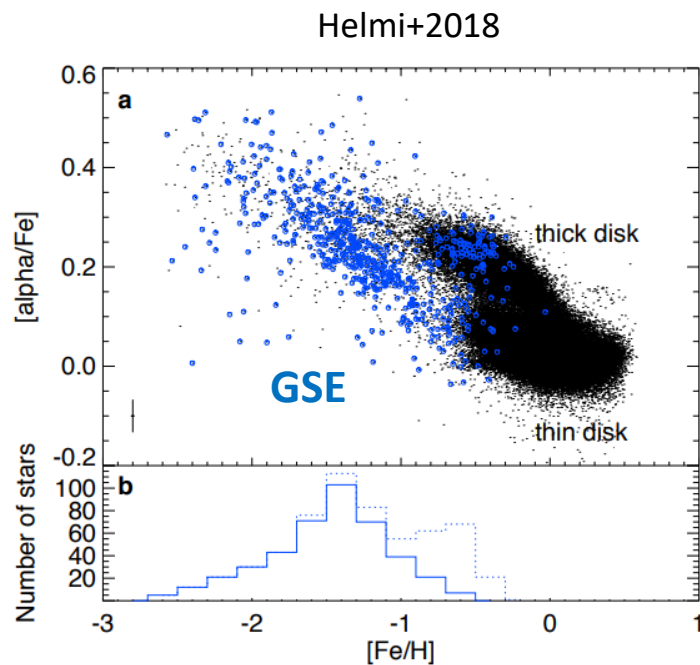


CHEMISTRY to resolve the dynamical degeneration

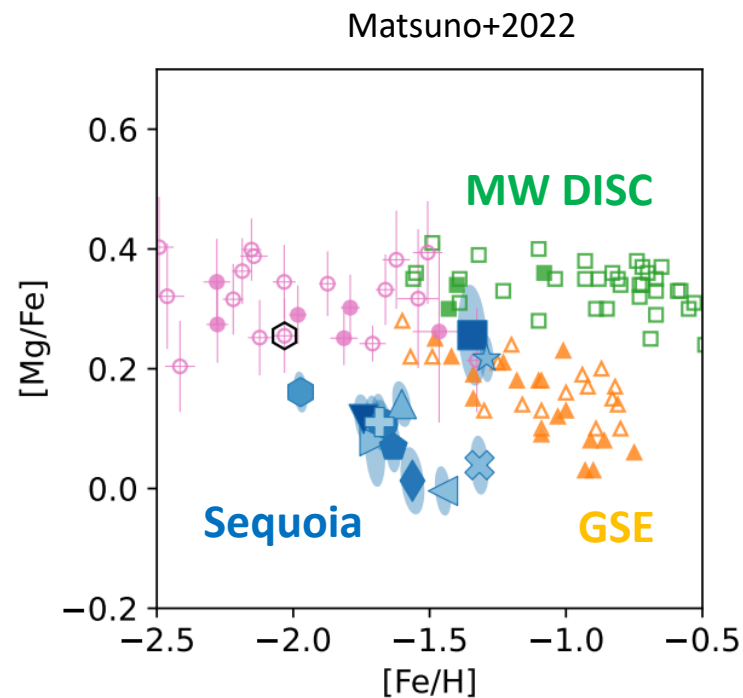
Abundance patterns reflect SF and CEH of the environment where they formed



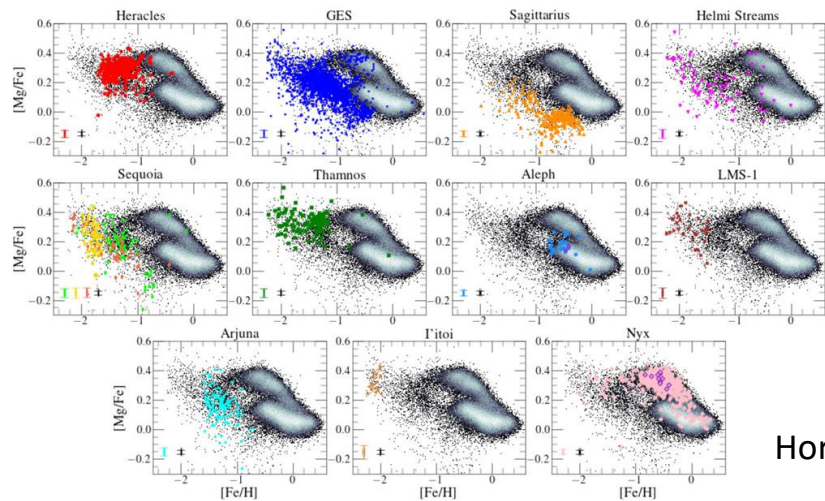
Nissen&Schuster 2010



Helmi+2018



Matsuno+2022



Horta+2023

Who are the best tracers of the assembly process?

STARS



GLOBULAR CLUSTERS



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A Walk on the Retrograde Side (WRS) project

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- **Extremely focused on the Solar Neighborhood ($D < 1.0$ kpc)**

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- HALO stars moving on **RETROGRADE** orbits (higher accreted fraction)
- Higher spectral resolution ($R = 40000$) than large spectroscopic surveys

WRS project - Selection criteria

- **Before Gaia DR3**

WRS project - Selection criteria

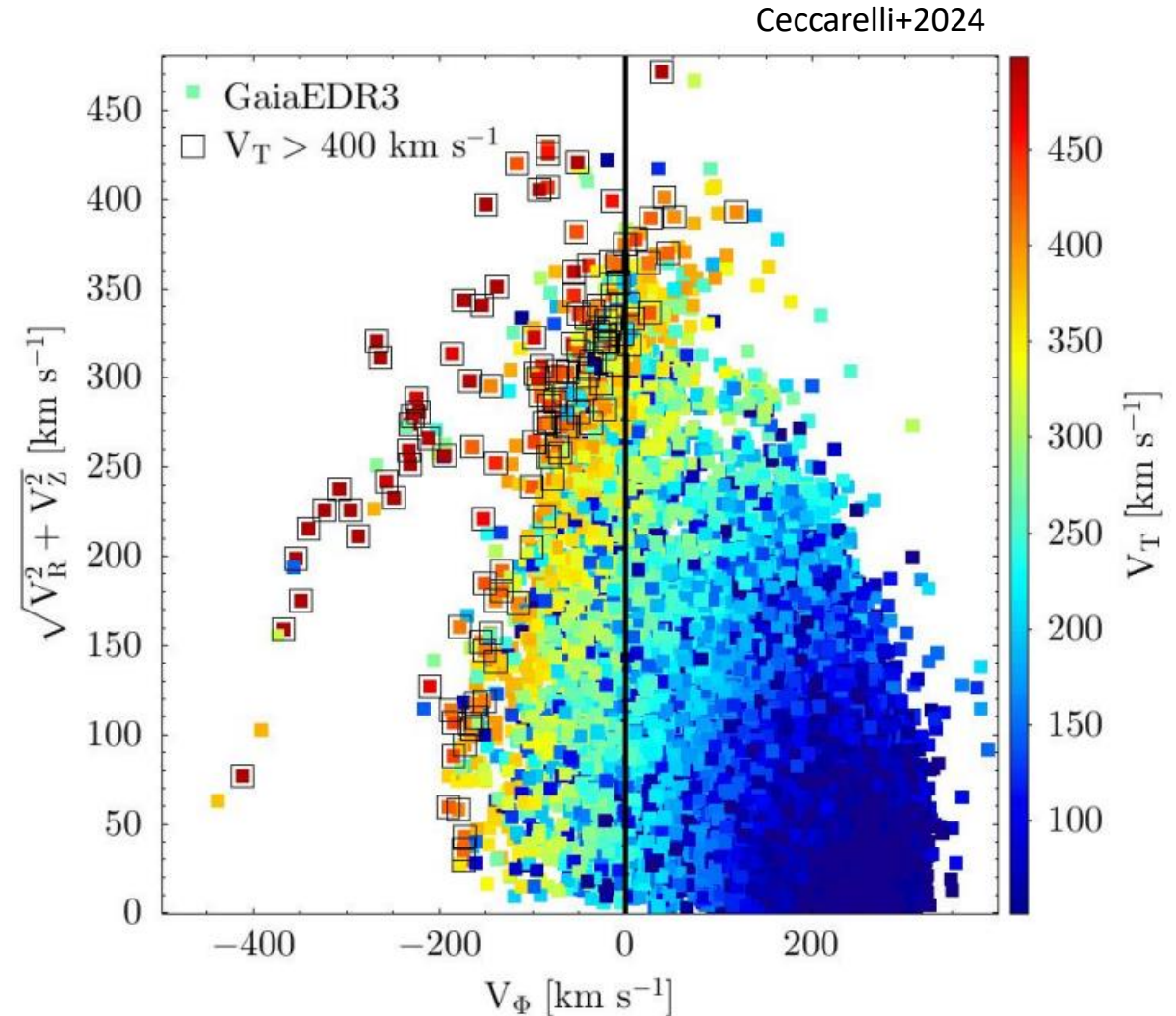
- **Before Gaia DR3**
- **$D < 1.0$ kpc + error in parallax $< 10\%$**
- **Stars with very accurate astrometry and photometry from Gaia**

WRS project - Selection criteria

- Before Gaia DR3
- $D < 1.0$ kpc + error in parallax $< 10\%$
- Stars with very accurate astrometry and photometry from Gaia + **Vlos**

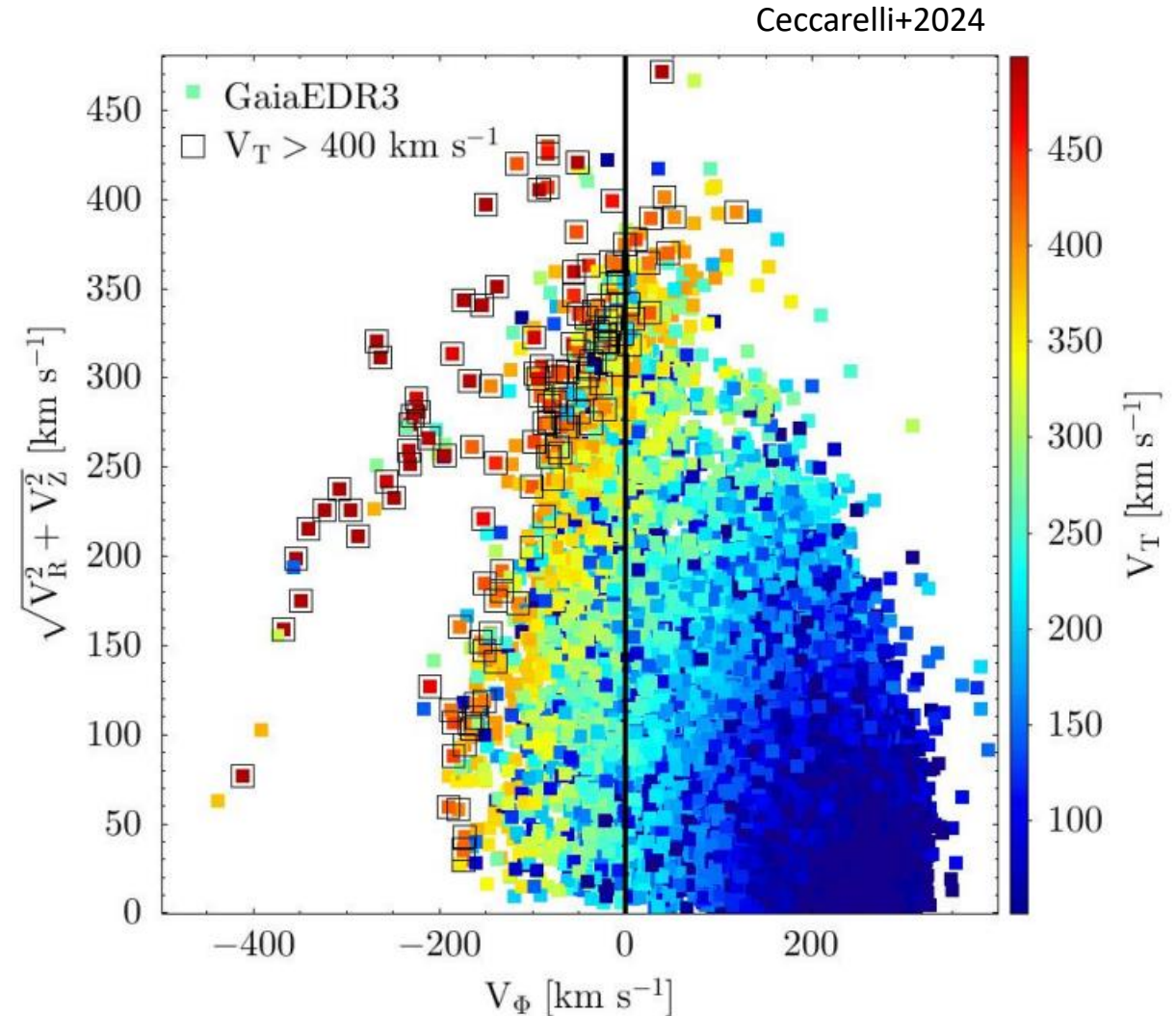
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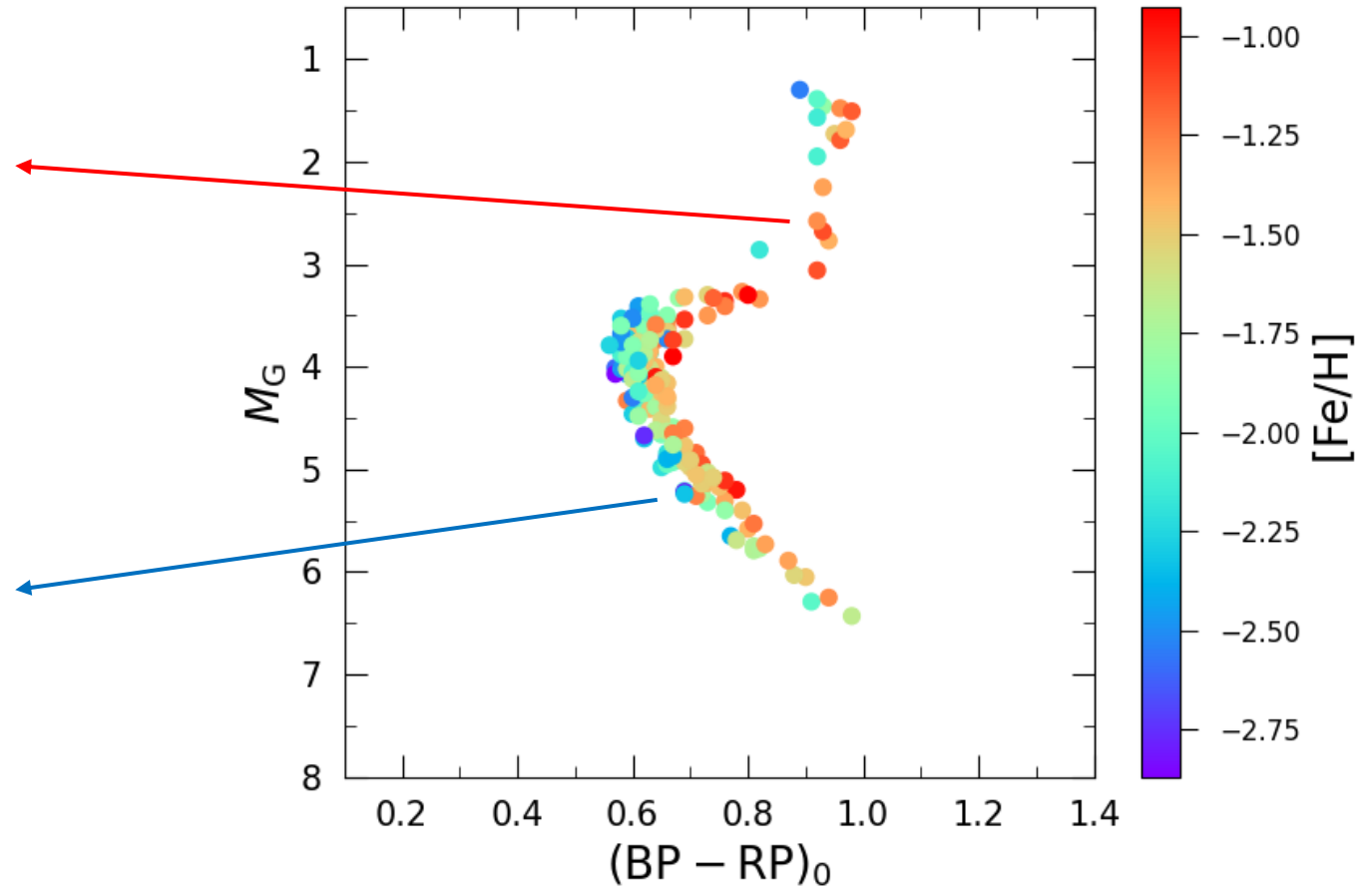
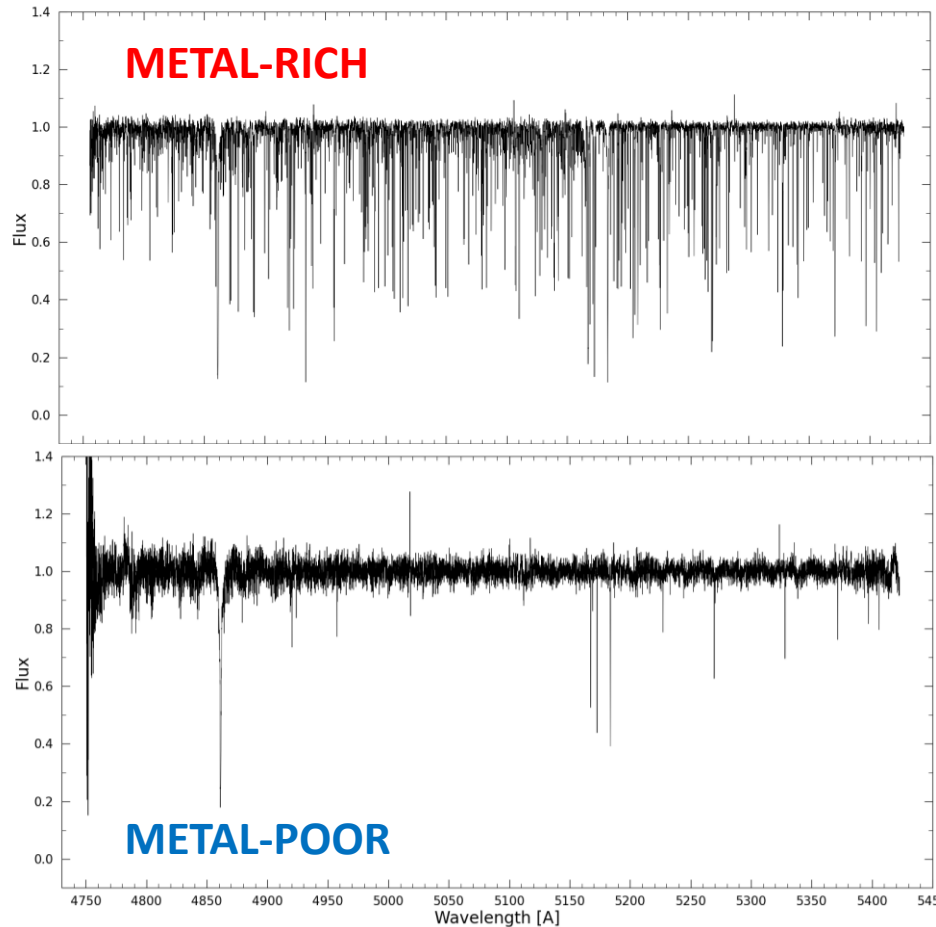
WRS project - Selection criteria

- Before Gaia DR3
- $D < 1.0$ kpc + error in parallax $< 10\%$
- Stars with very accurate astrometry and photometry from Gaia + V_{los}
- $V_T > 400$ km/s



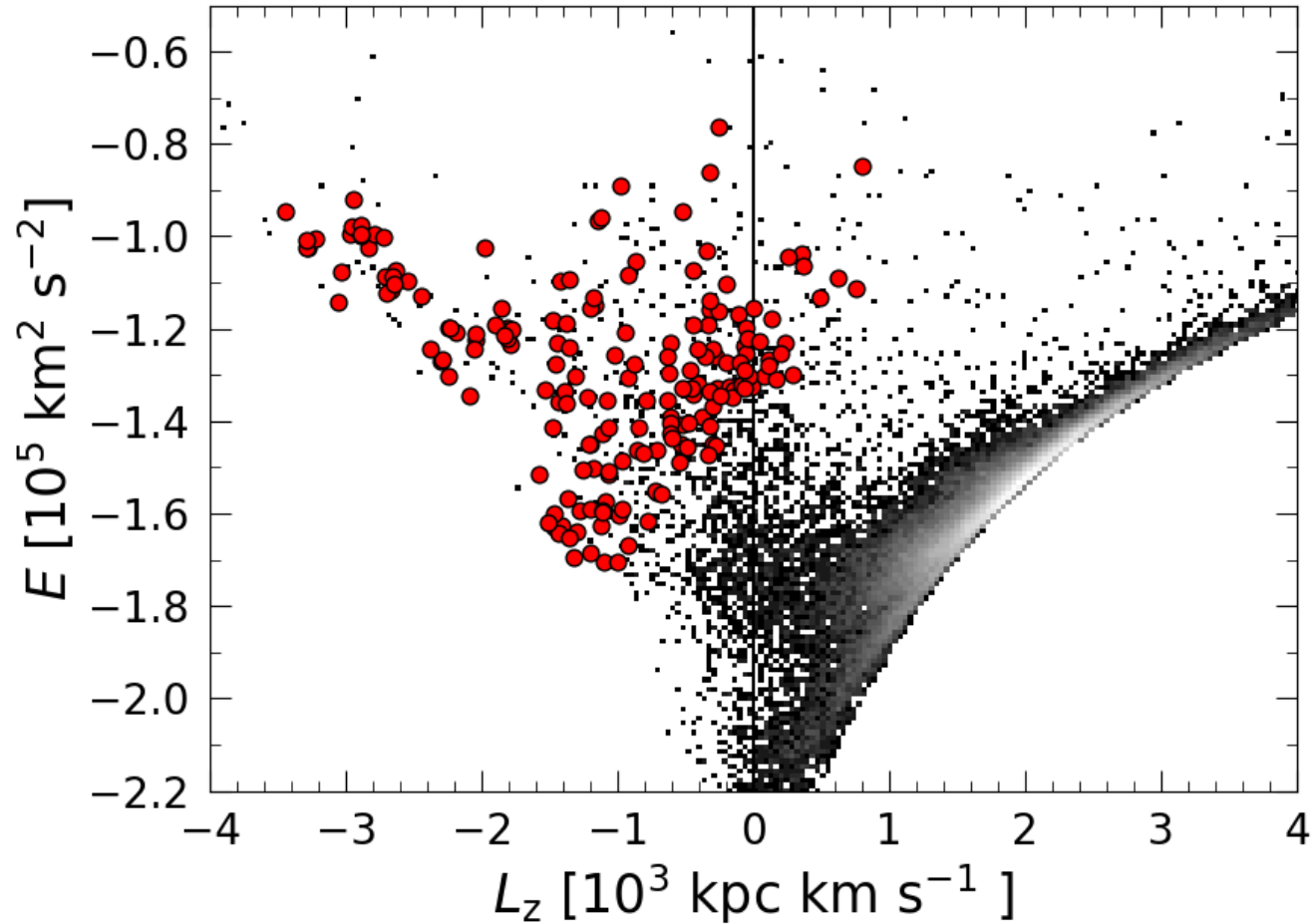
WRS project - HR spectra

86 stars with PEPSI@LBT + 100 stars with UVES@VLT ($R > 40000$ + $S/N > 40$)



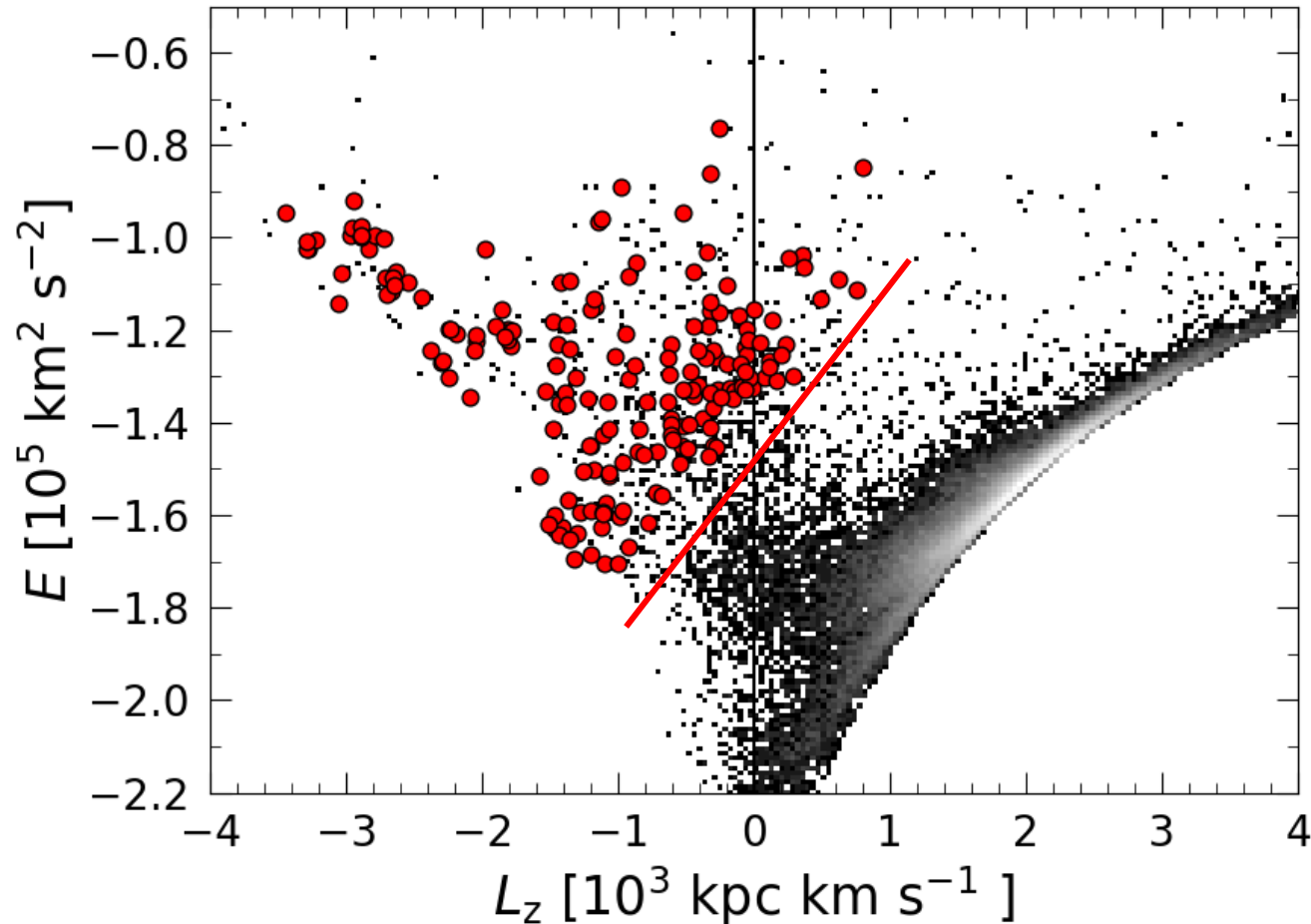
WRS project - RH substructures

Sampling a poorly explored region of the Solar Neighborhood



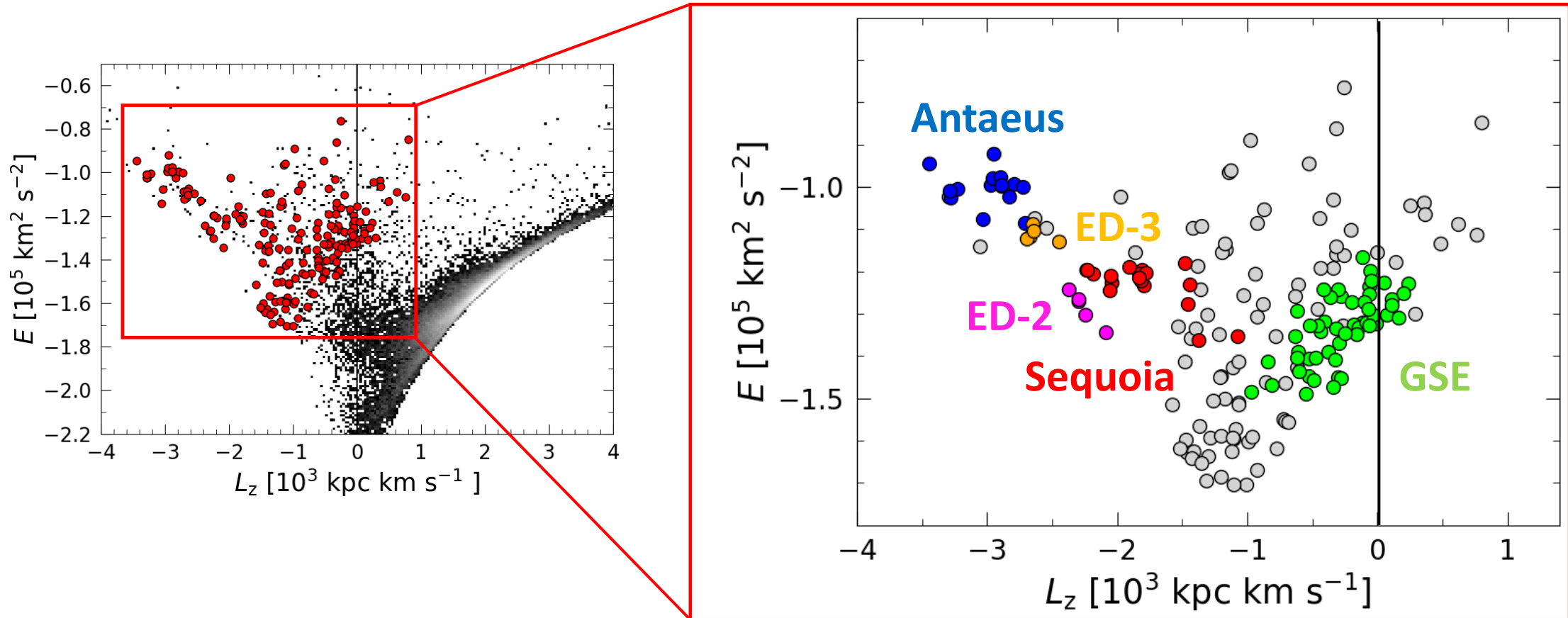
WRS project - RH substructures

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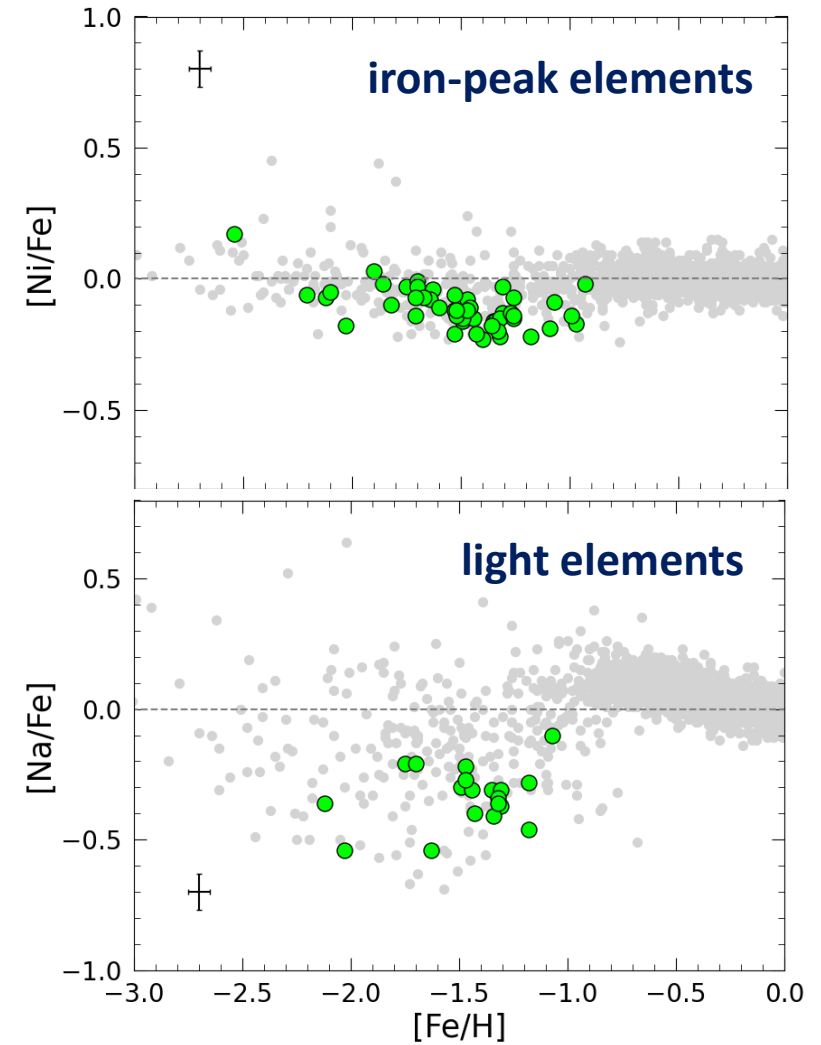
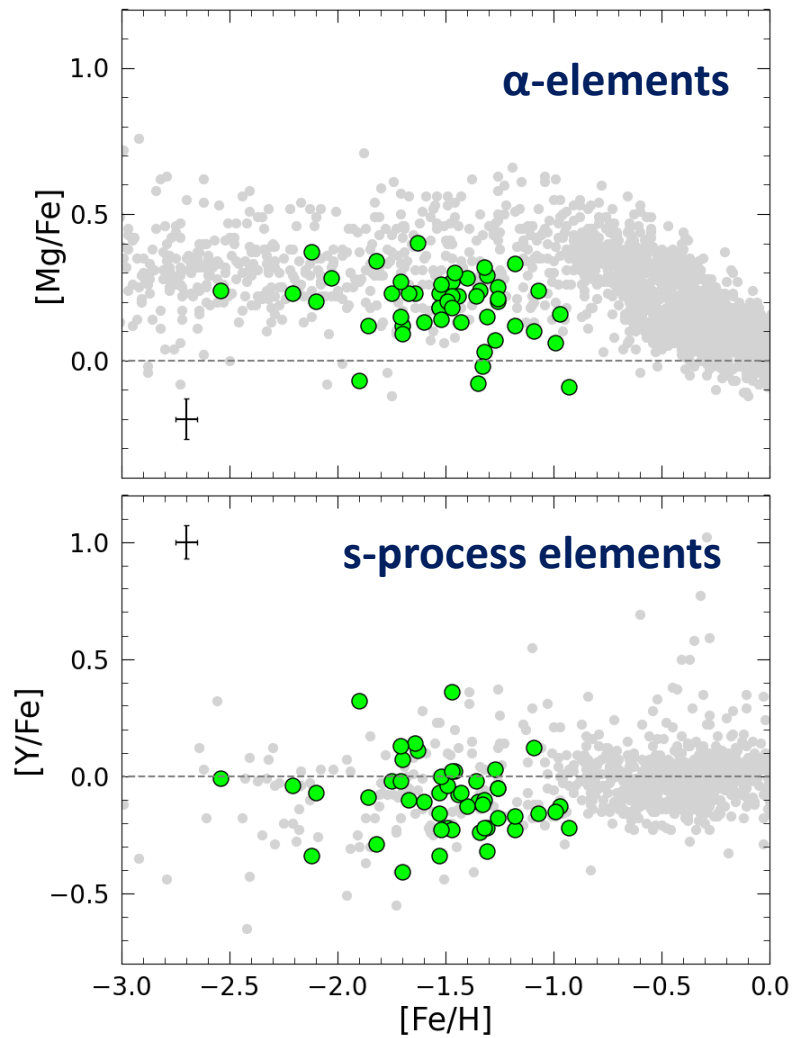


WRS project - RH substructures

First application: Dodd+2023 + clustering algorithm DBSCAN



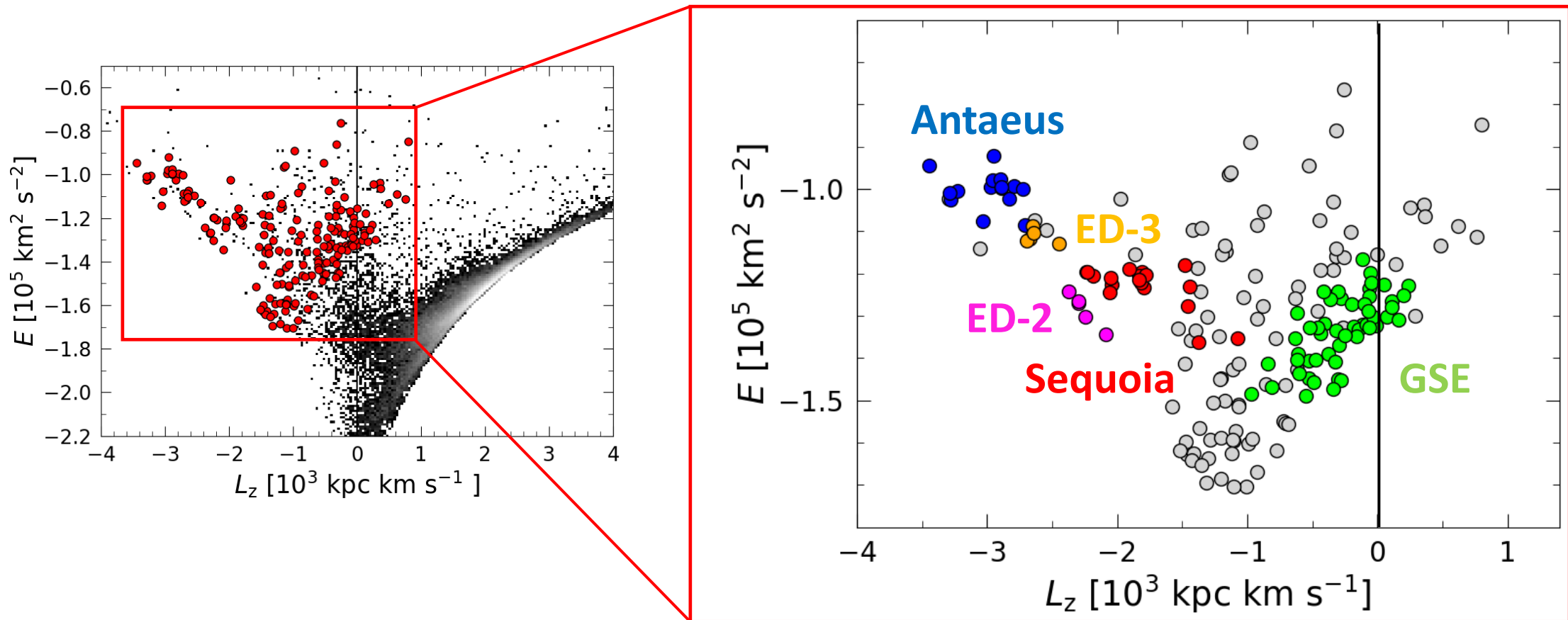
WRS project - GSE chemical composition



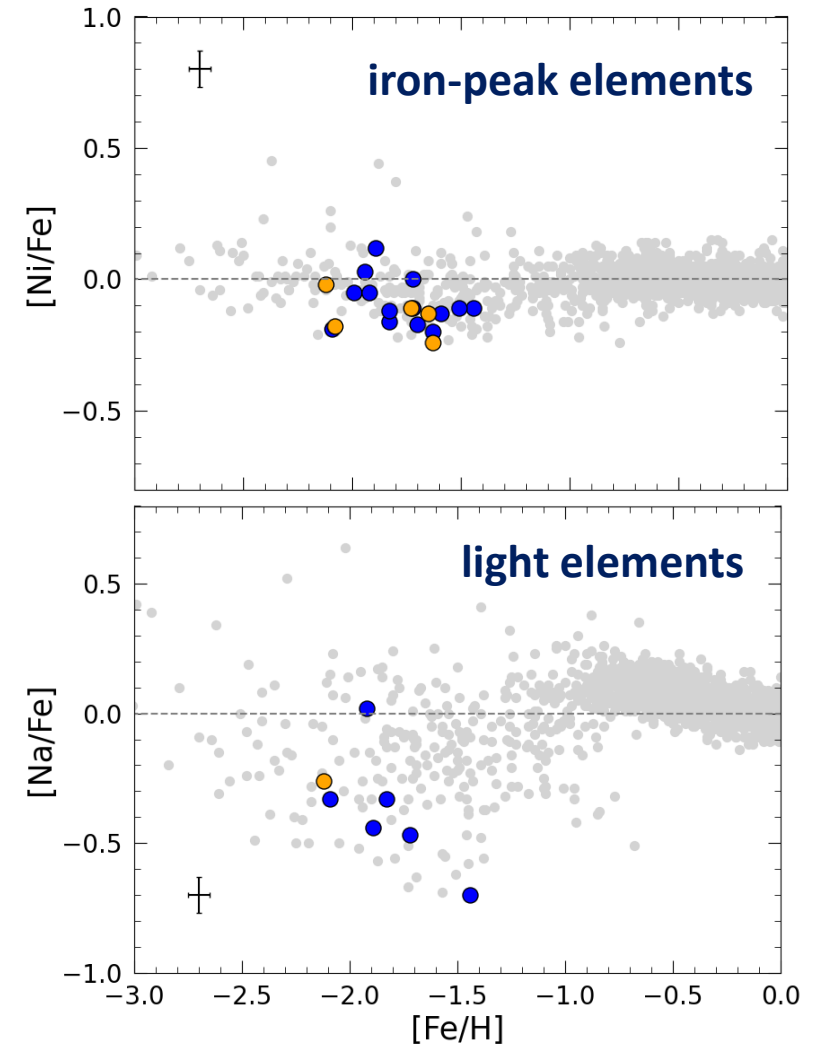
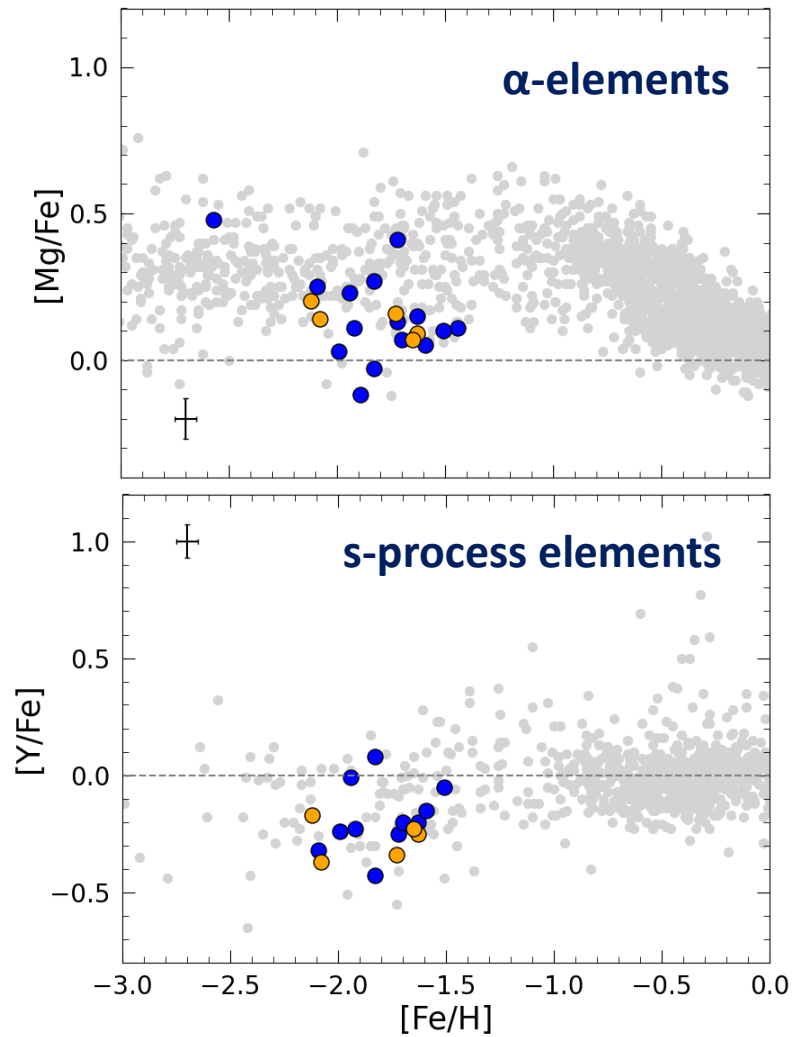
Ceccarelli+2024

WRS project - RH substructures

Antaeus and ED-3: the very retrograde halo

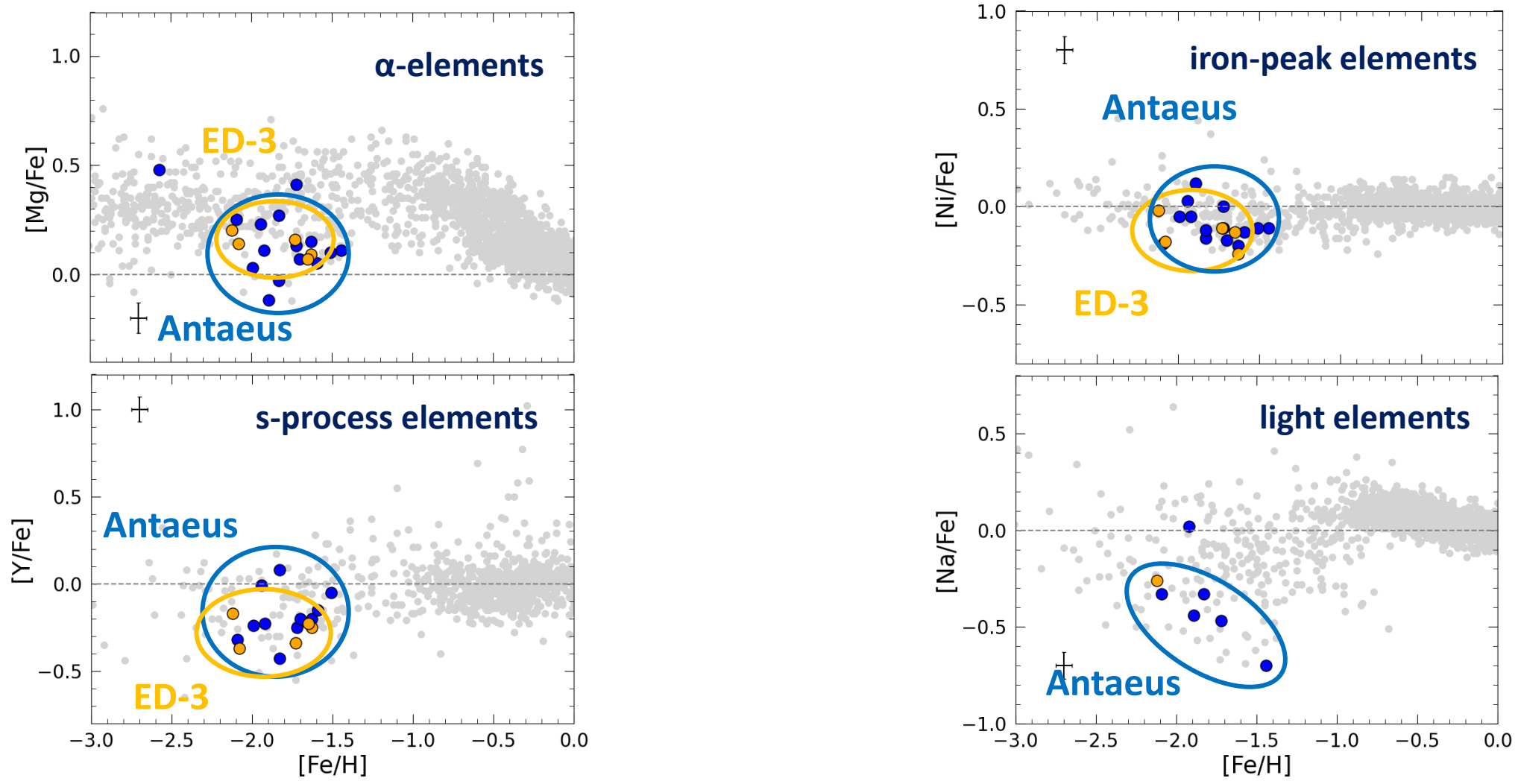


WRS project - Antaeus + ED3 chemical composition



Ceccarelli+2024

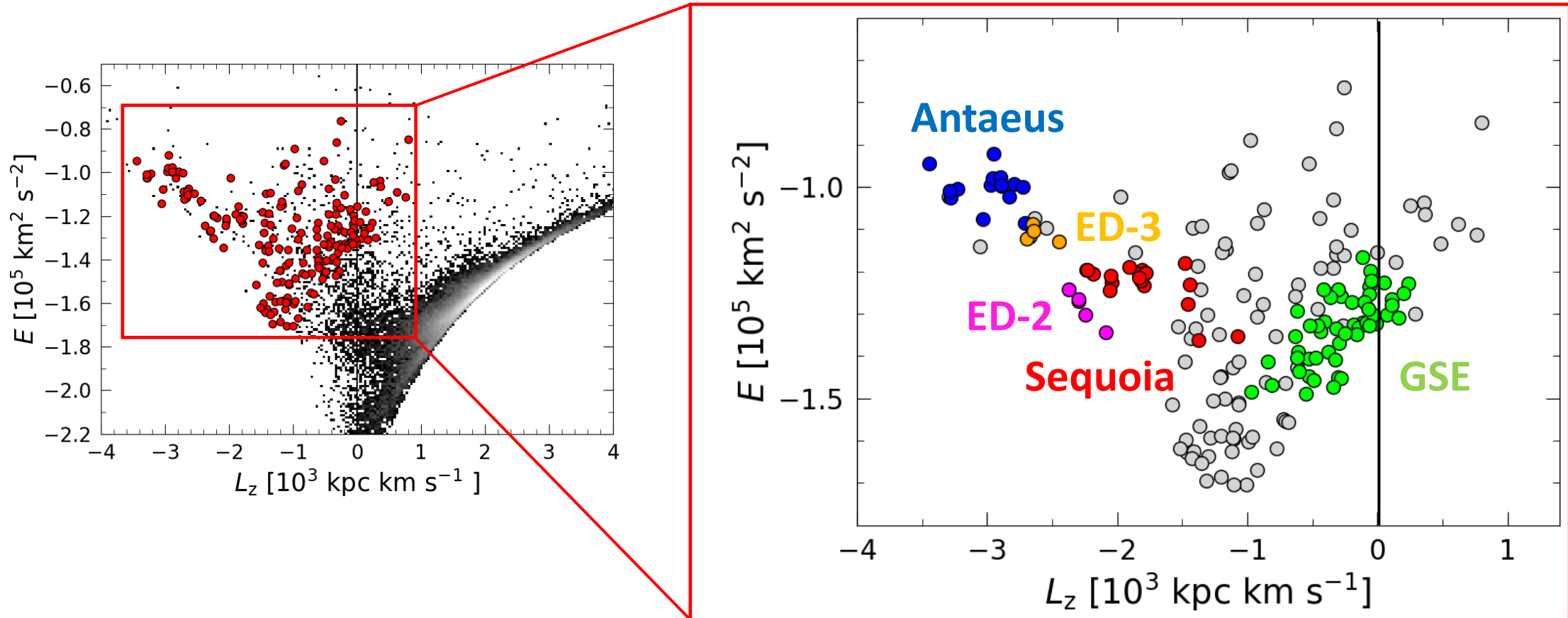
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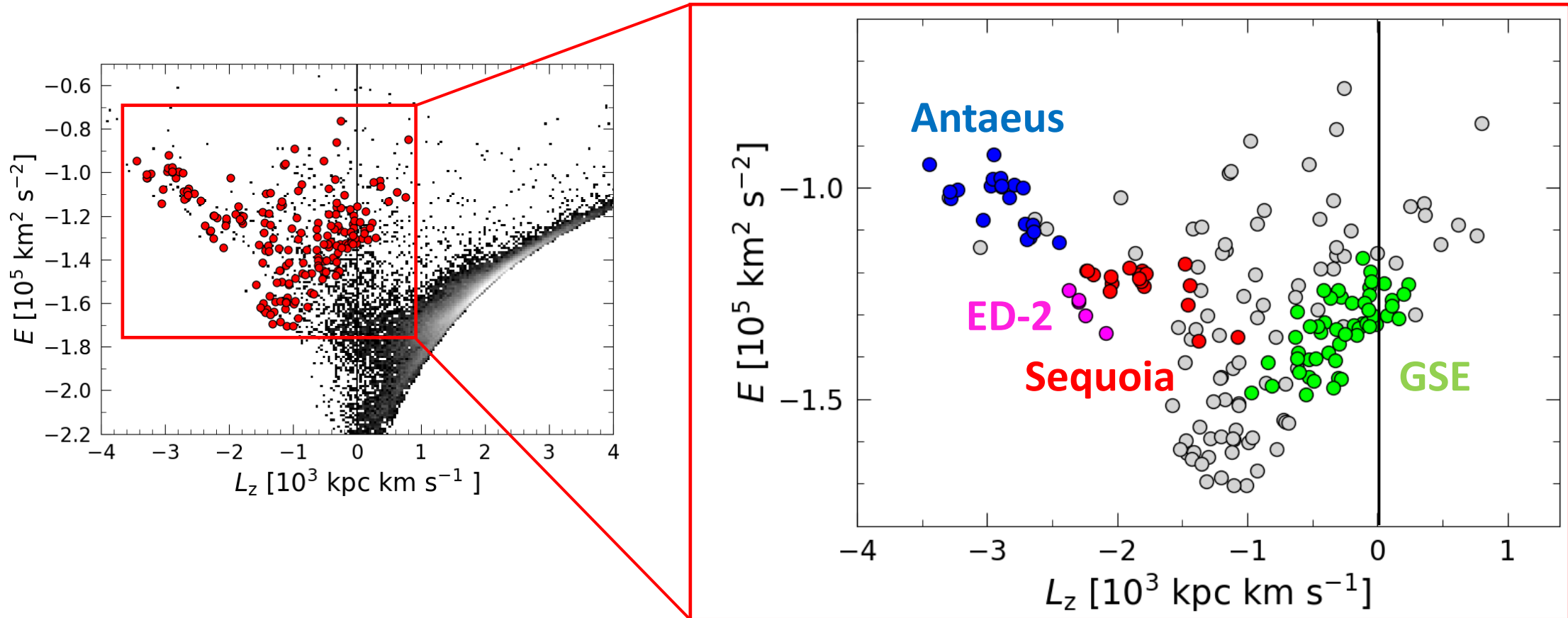
WRS project - RH substructures

Antaeus and ED-3 part of the same accretion event

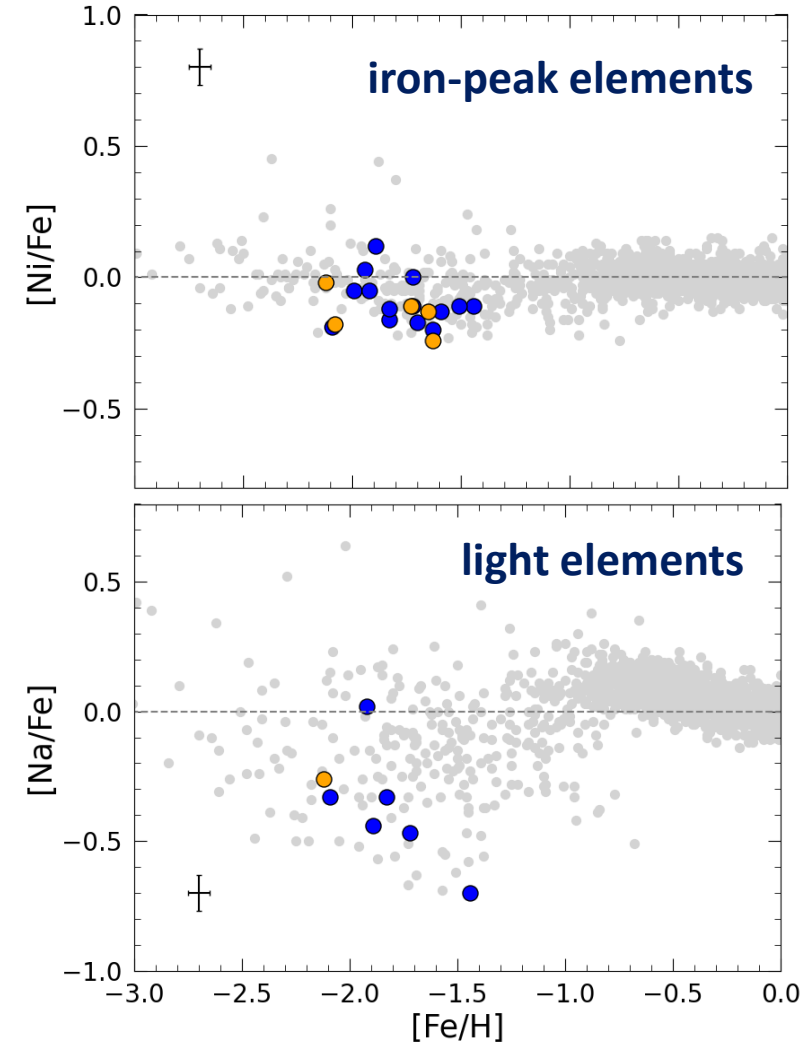
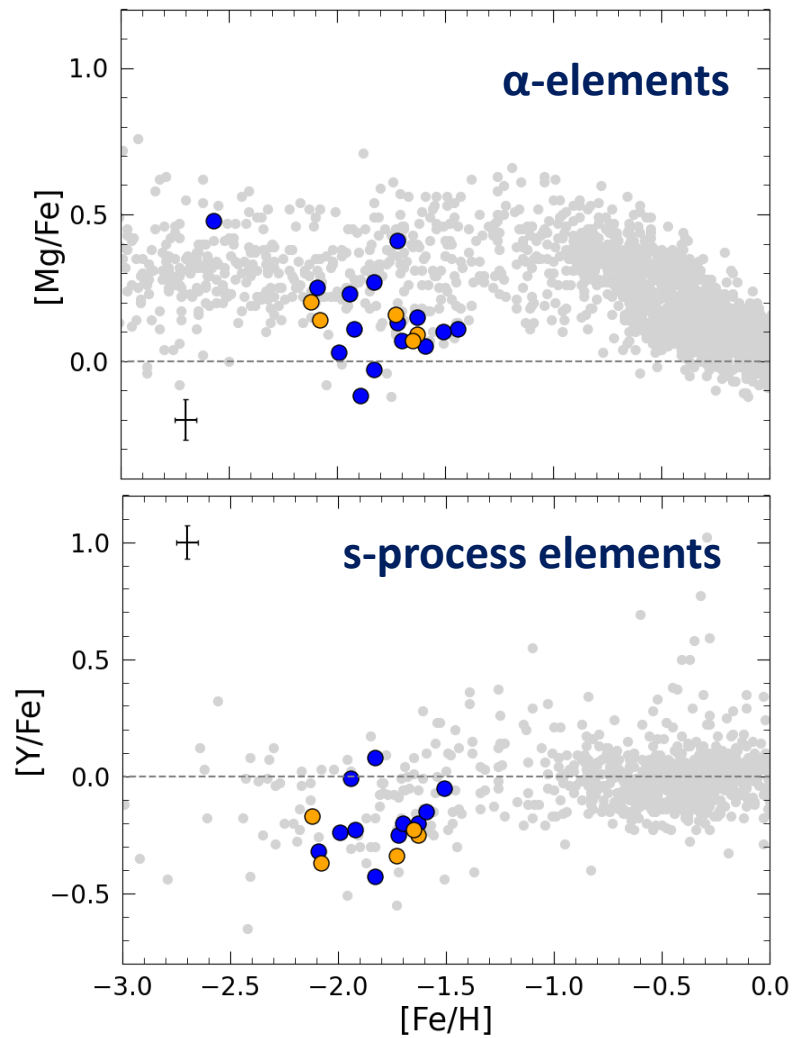


WRS project - RH substructures

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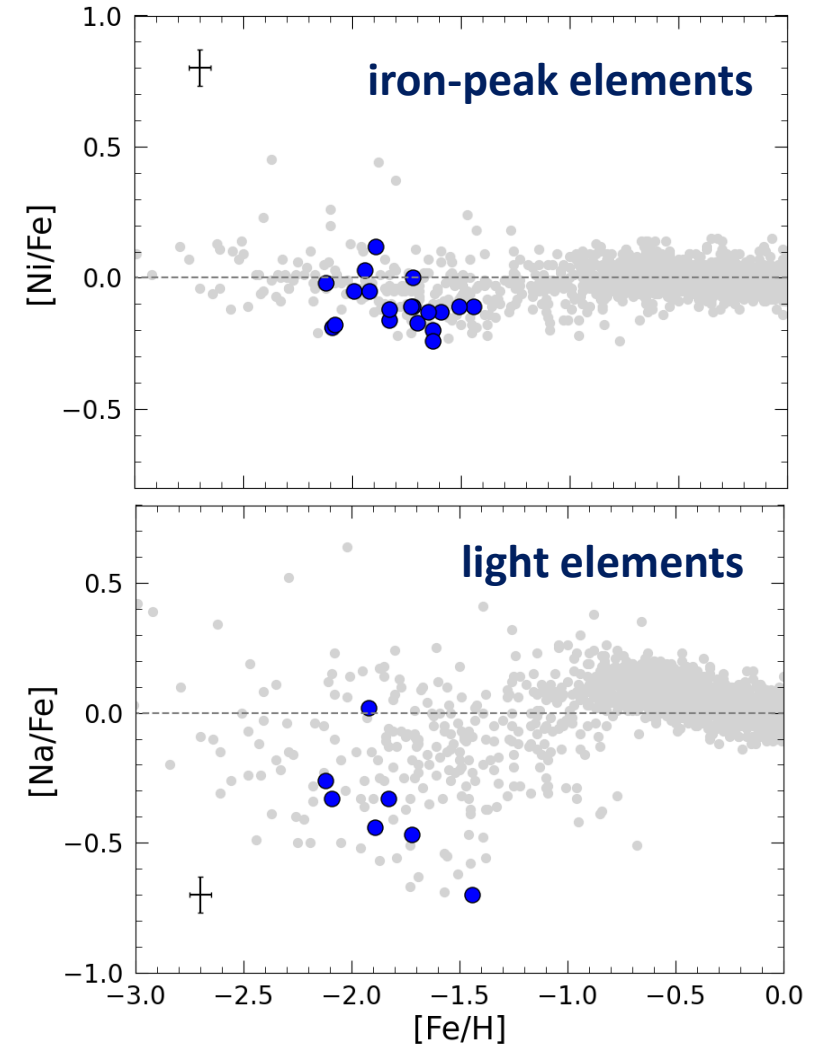
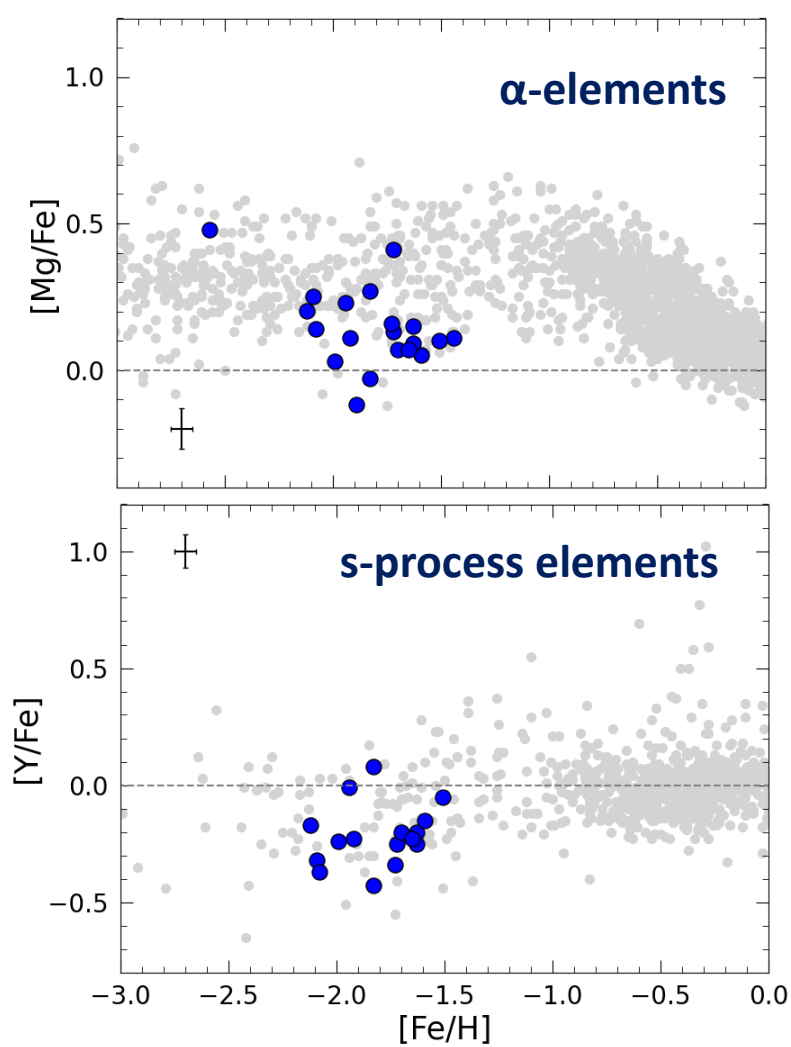


WRS project - Antaeus + ED3 chemical composition



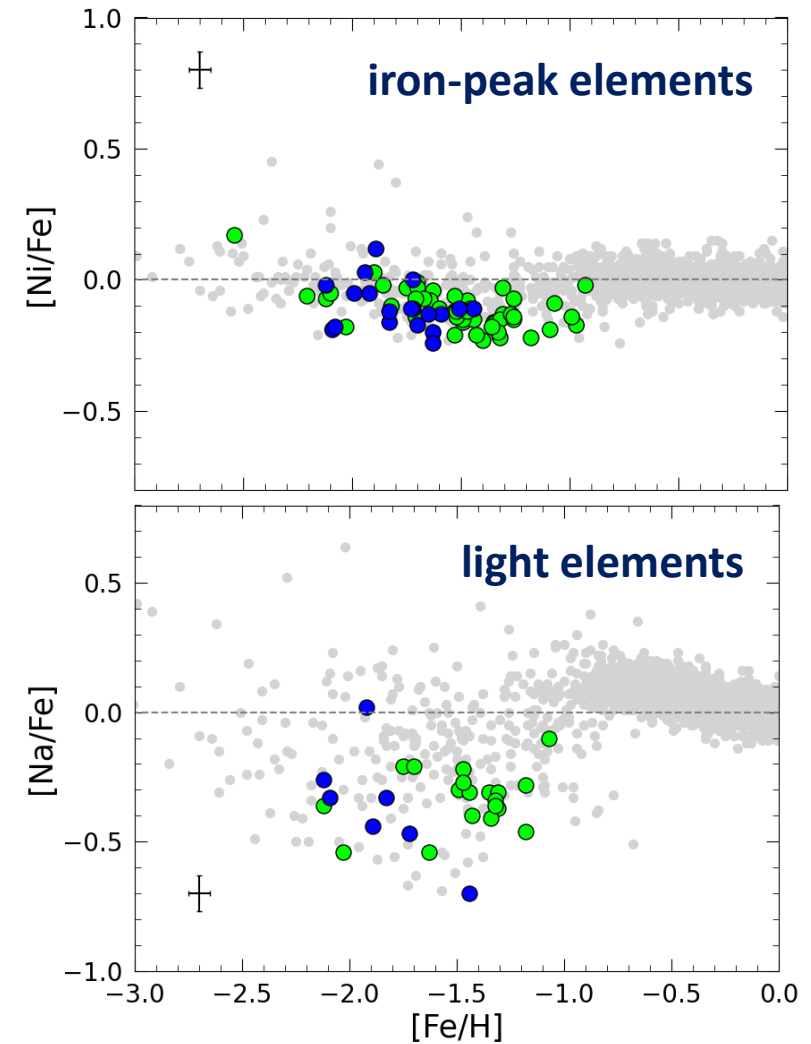
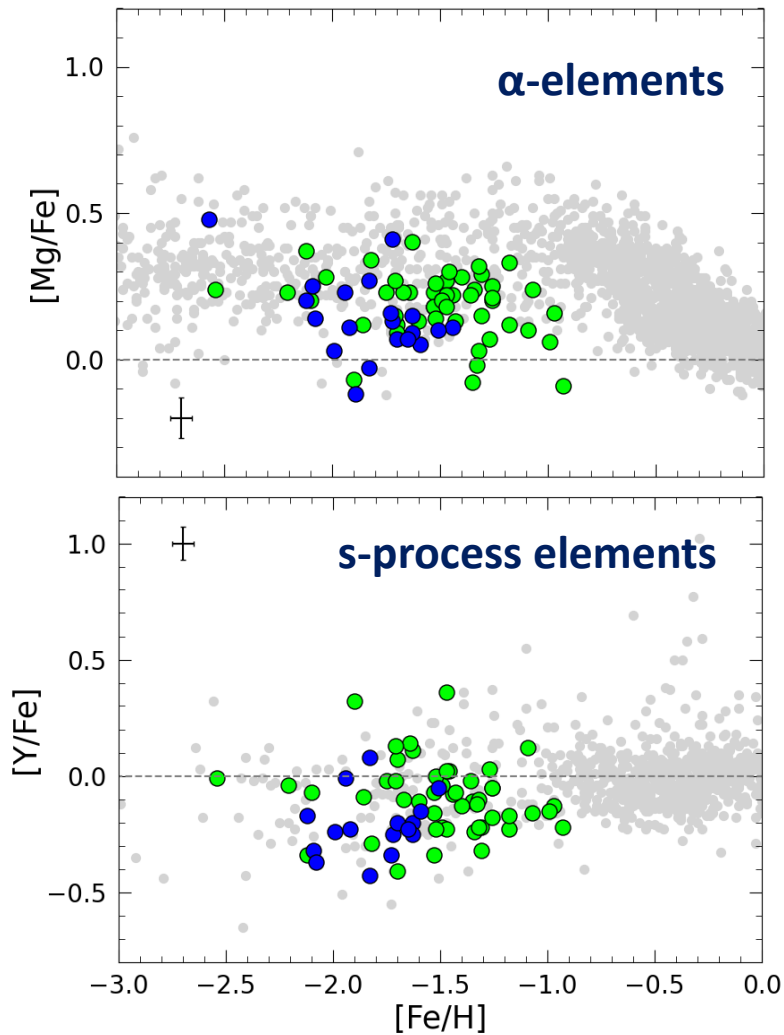
Ceccarelli+2024

WRS project - Antaeus chemical composition



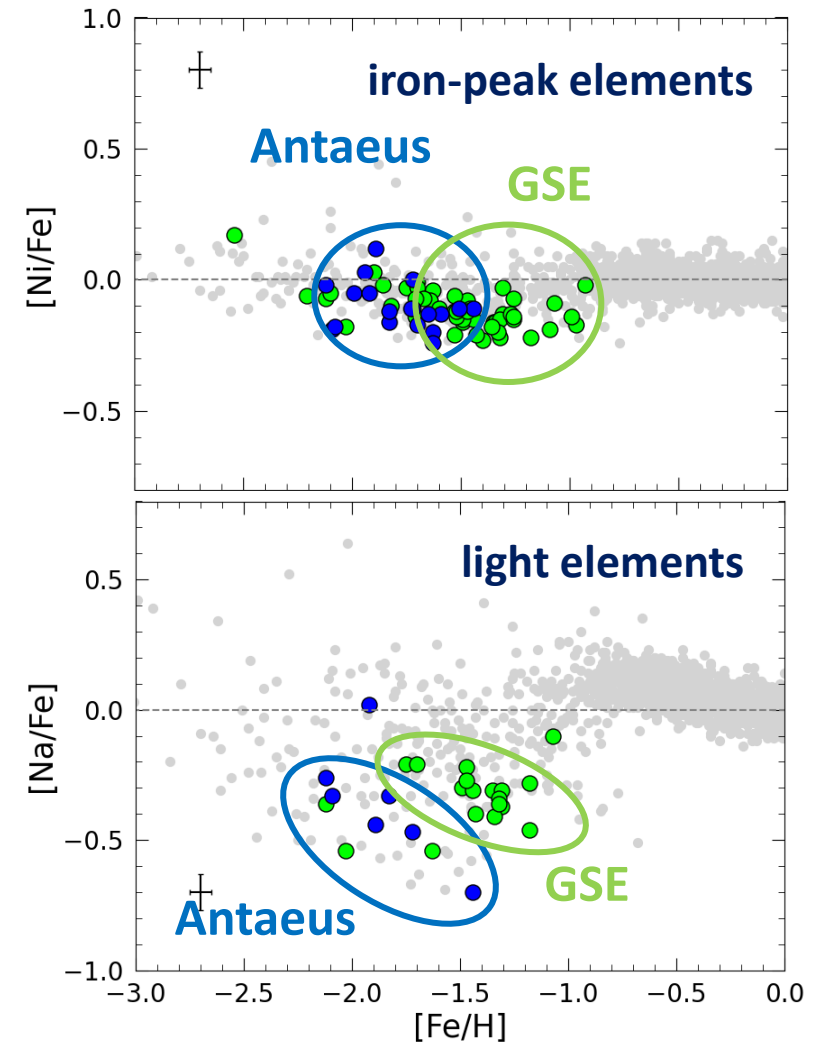
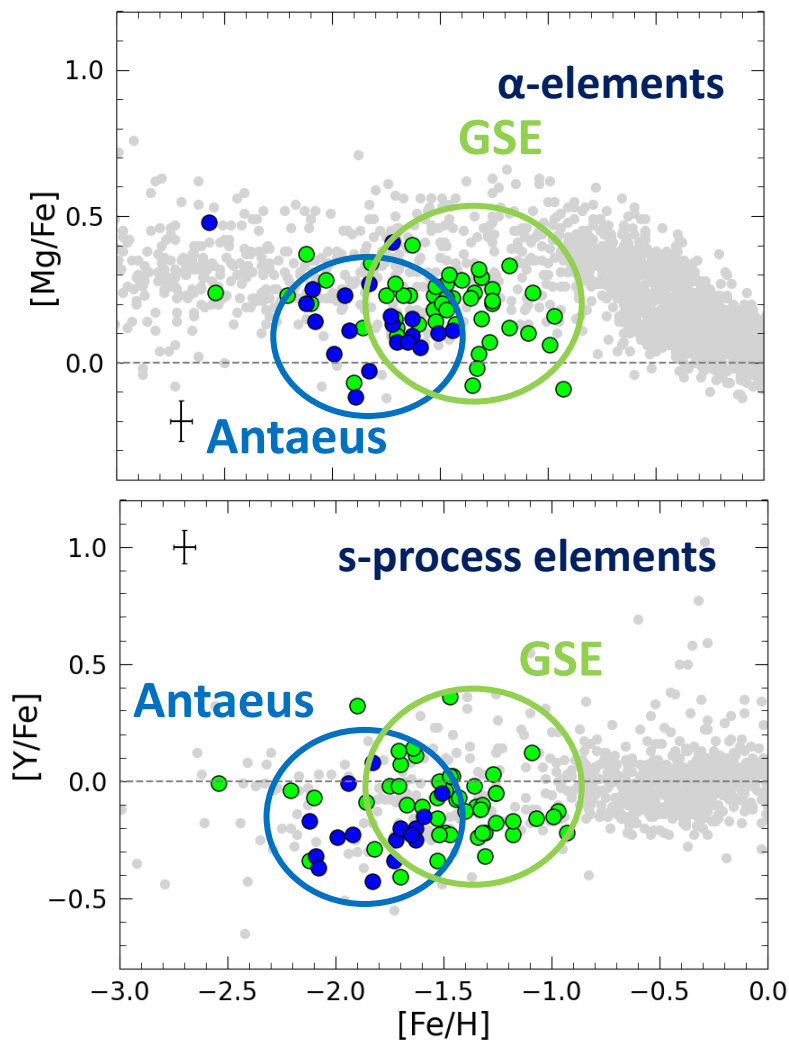
Ceccarelli+2024

WRS project - Antaeus chemical composition



Ceccarelli+2024

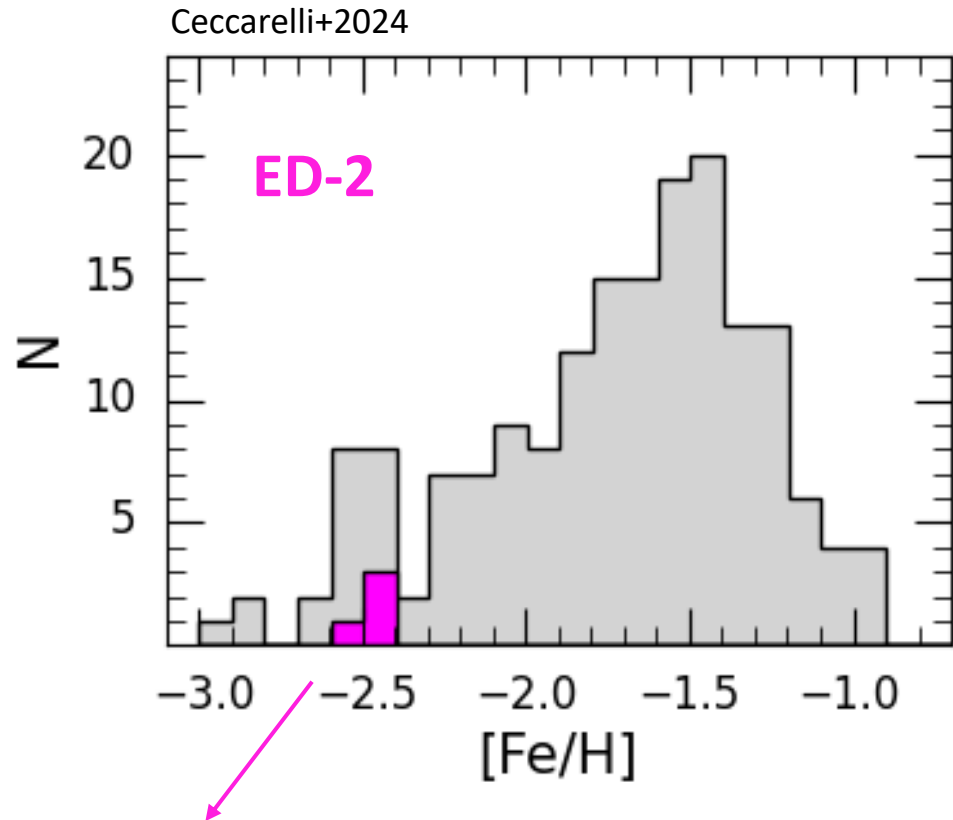
WRS project - Antaeus chemical composition



Ceccarelli+2024

WRS project - The peculiarity of ED-2

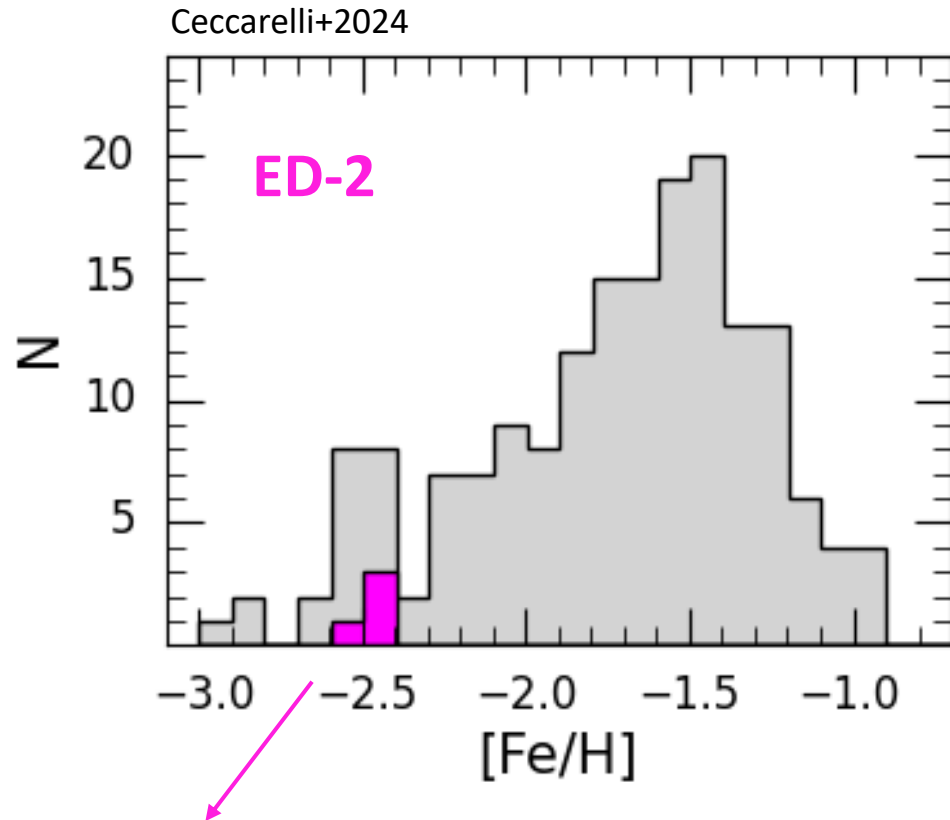
Negligible spread in [Fe/H]



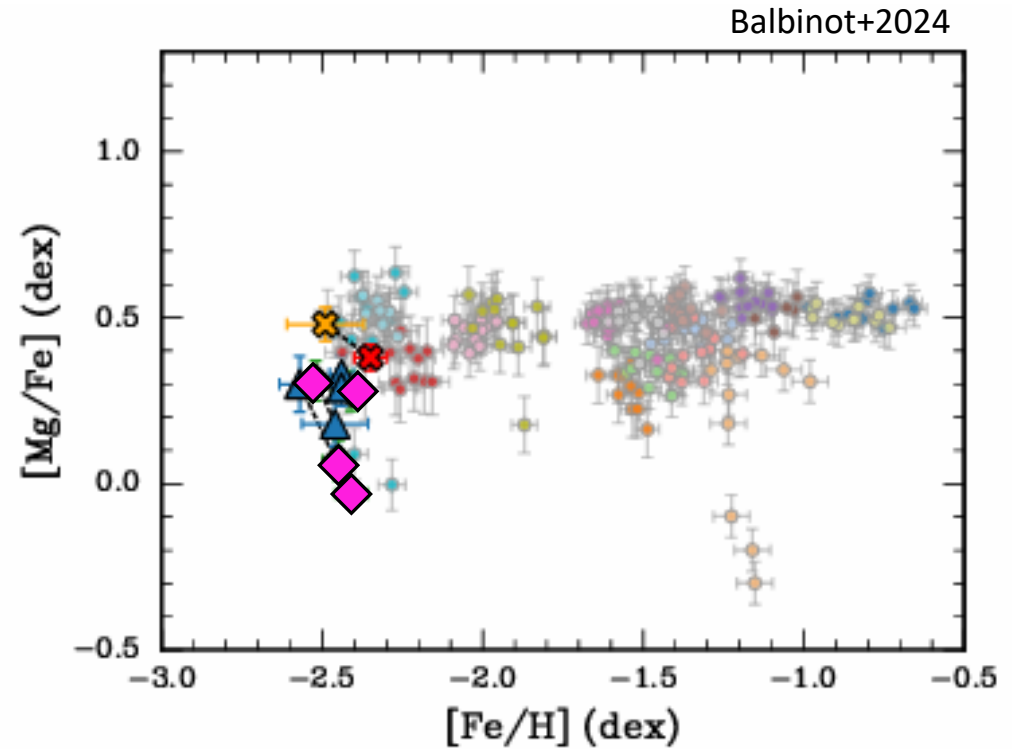
Consistent with Balbinot+2023, 2024

WRS project - The peculiarity of ED-2

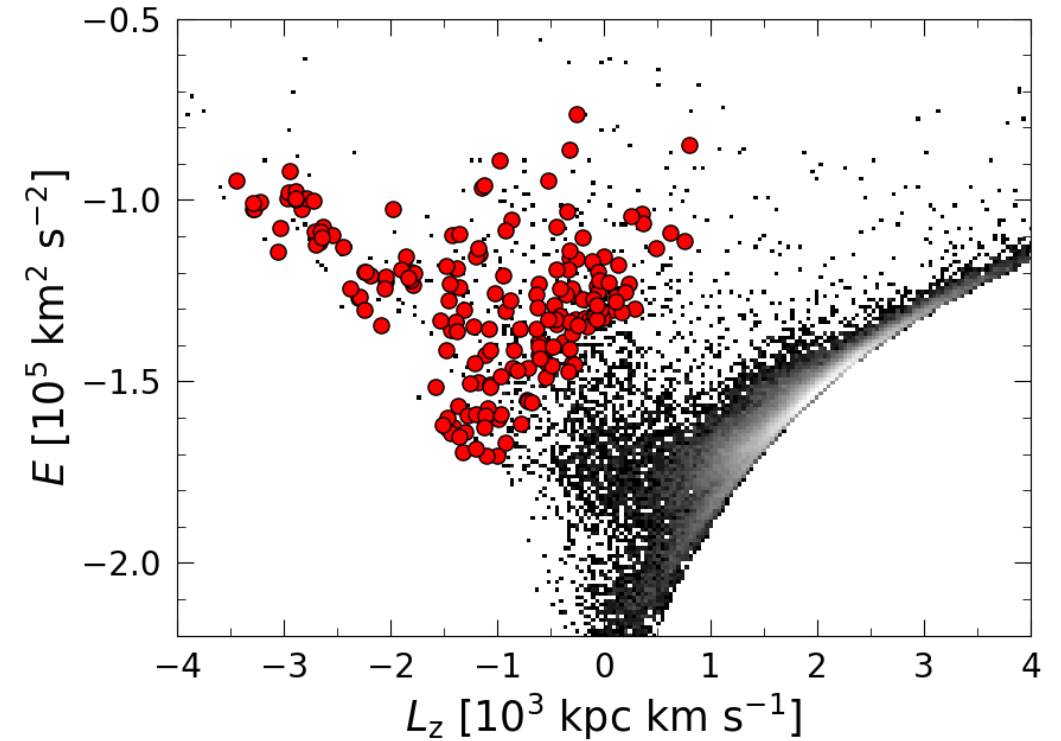
Remnant of a globular cluster?



Consistent with Balbinot+2023, 2024

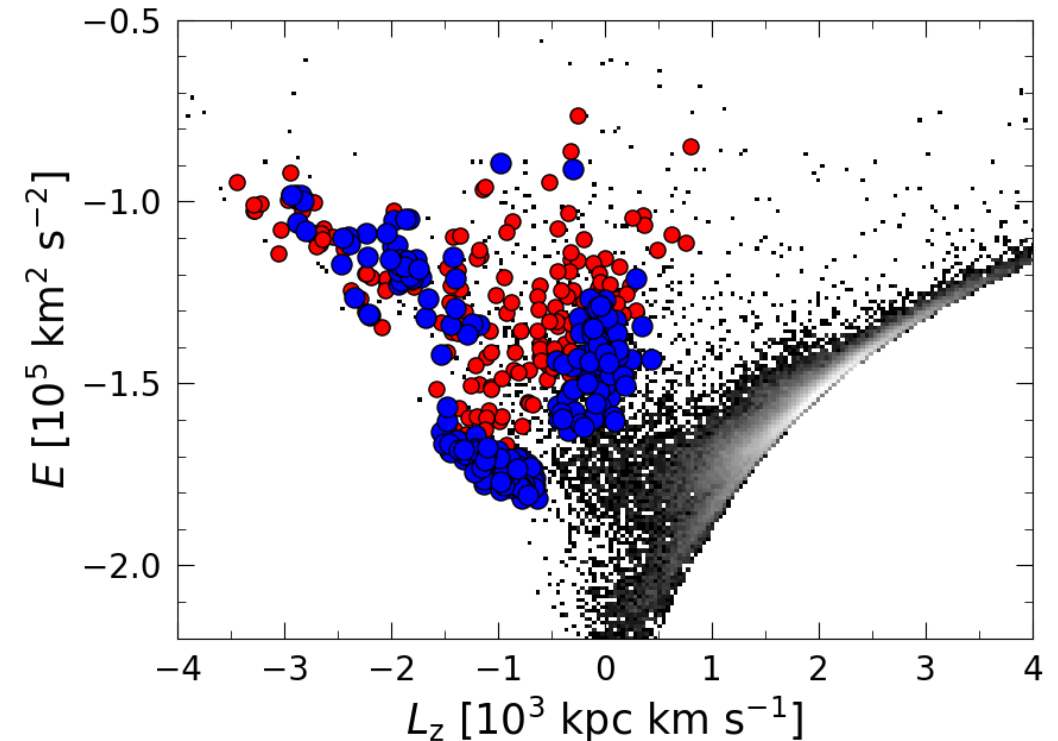


WRS project - Future perspectives



WRS project - Future perspectives

- **Two ESO-VLT P112 - P113 Proposals**
(PI: E.Ceccarelli, 140+ hours with UVES@VLT)
HR spectra of **280** new RH accreted stars
- **Strategic Program with LBT**
(PI: M.Bellazzini, 64+ hours with PEPSI@LBT)
HR spectra of **95** new RH stars



Who are the best tracers of the assembly process?

STARS



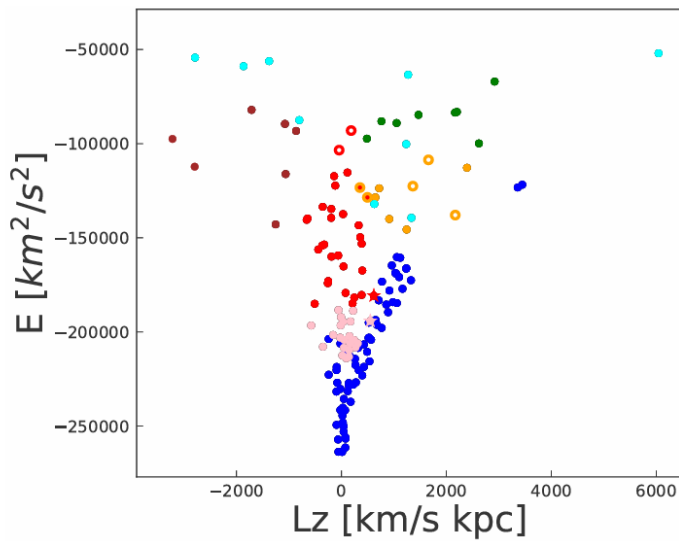
GLOBULAR CLUSTERS



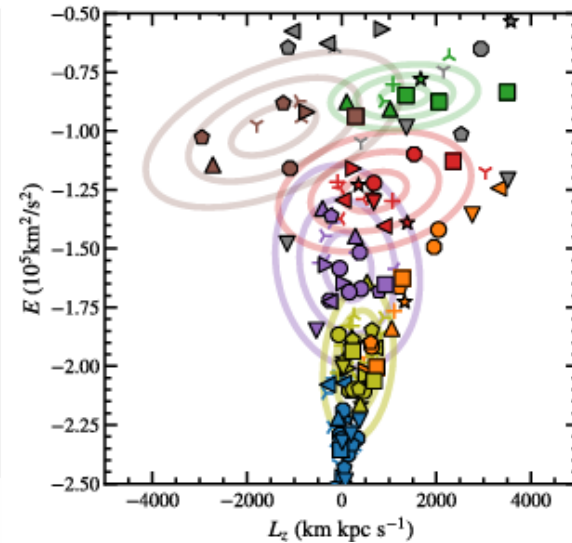
GCs as remnant of disrupted dwarf galaxies

IoM of GCs also trace several accretion events

Massari+2019



Callingham+2022

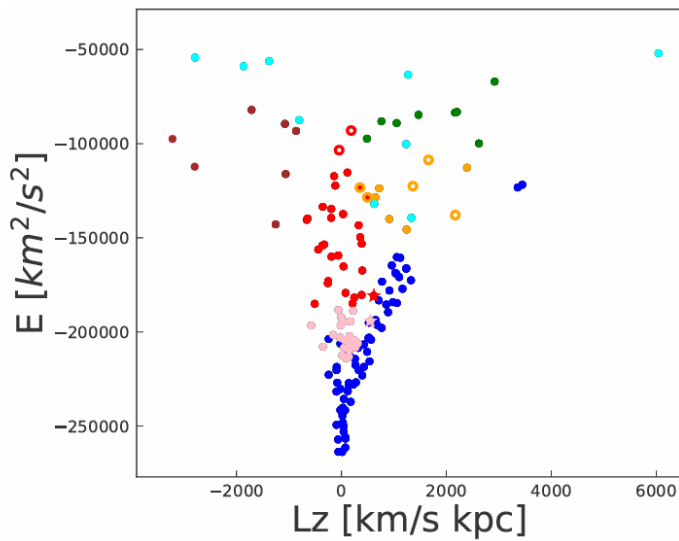


GCs as remnant of disrupted dwarf galaxies

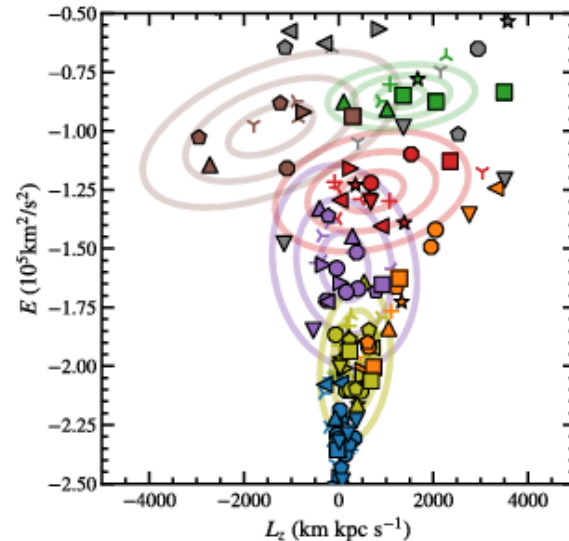
Different AMR for **accreted** and in situ GCs

Forbes&Bridges2010, Dotter+2011, VandenBerg+2013, Leaman+2013, Massari+2019, Mucciarelli+2023

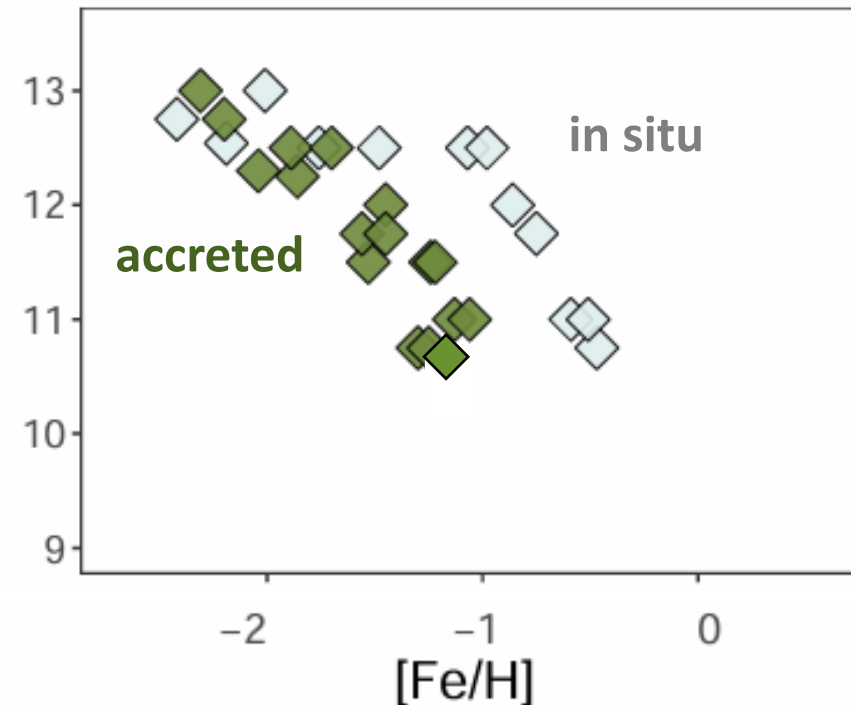
Massari+2019



Callingham+2022



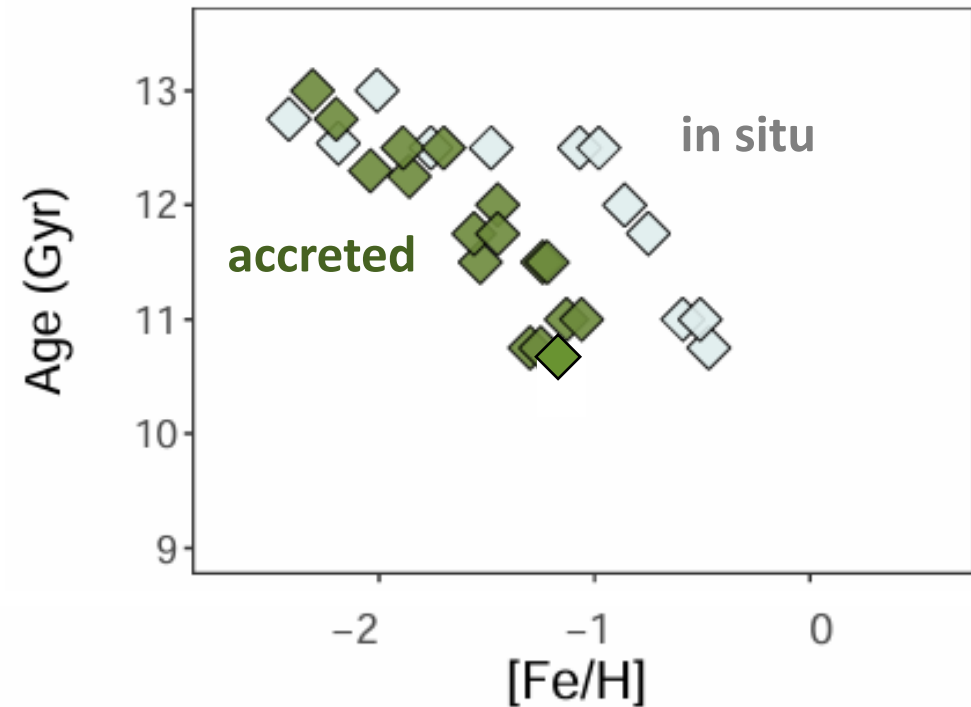
Age (Gyr)



Selection of the target GCs

4 GCs tagged to different DYNAMICAL groups (Massari+19, Callingham+22)

Forbes&Bridges2010, Dotter+2011, VandenBerg+2013,
Leaman+2013, Massari+2019, Mucciarelli+2023

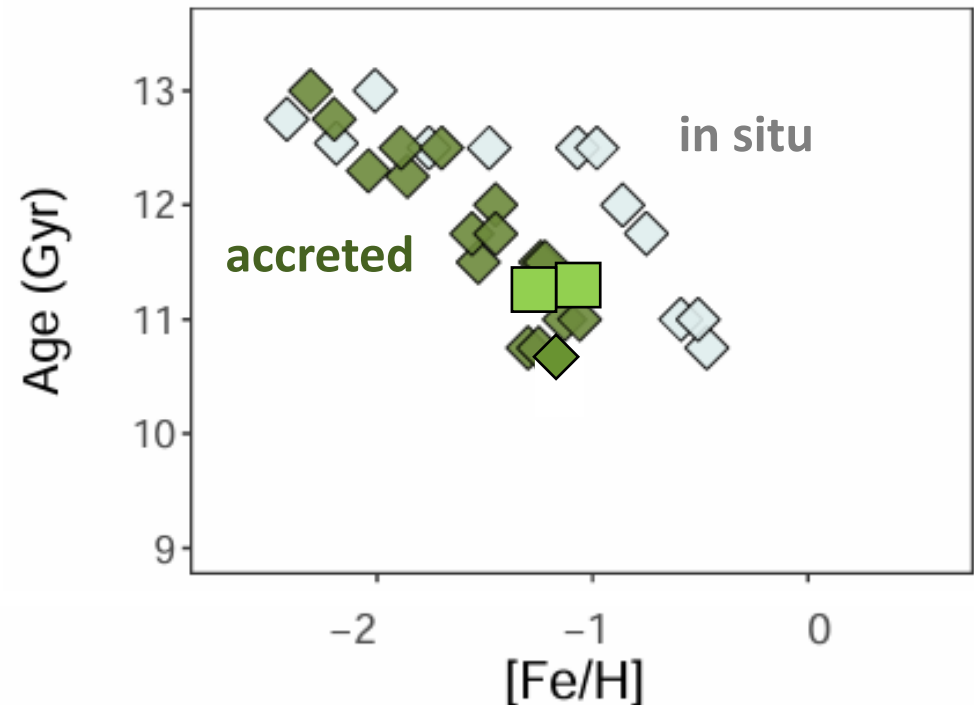


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- GSE: NGC 362 and NGC 1261

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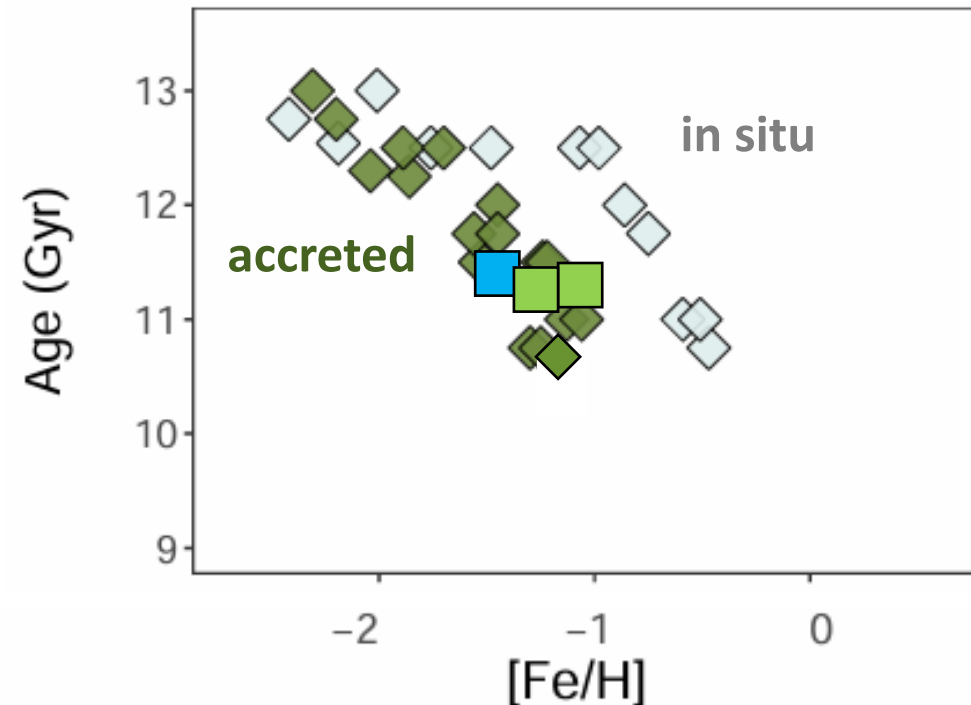


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- GSE: NGC 362 and NGC 1261
- Helmi Streams: Ruprecht 106

Forbes&Bridges2010, Dotter+2011, VandenBerg+2013,
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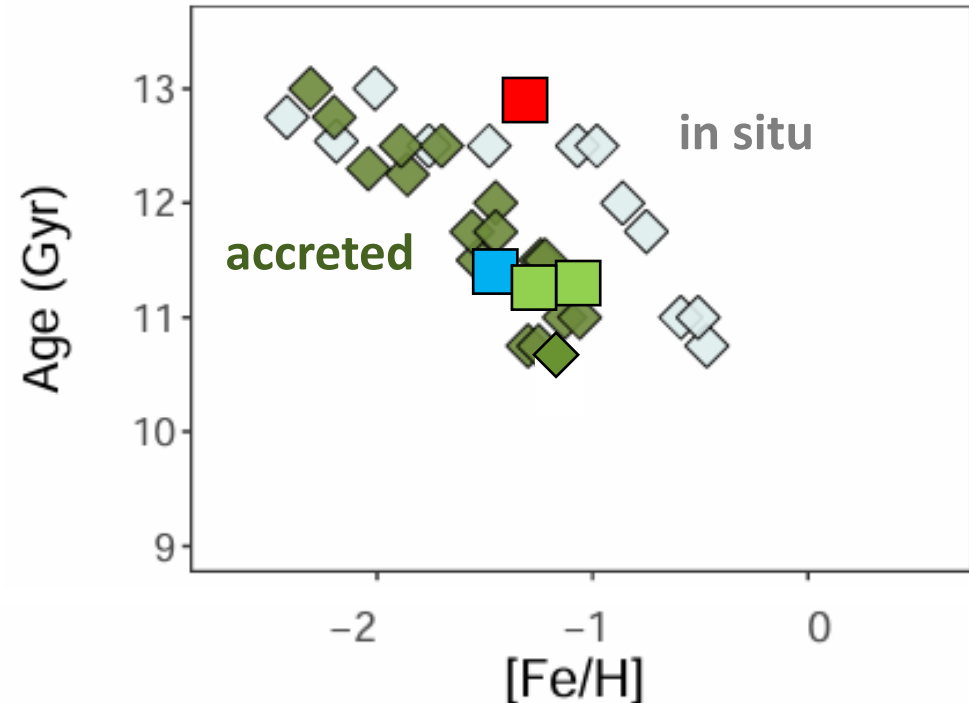


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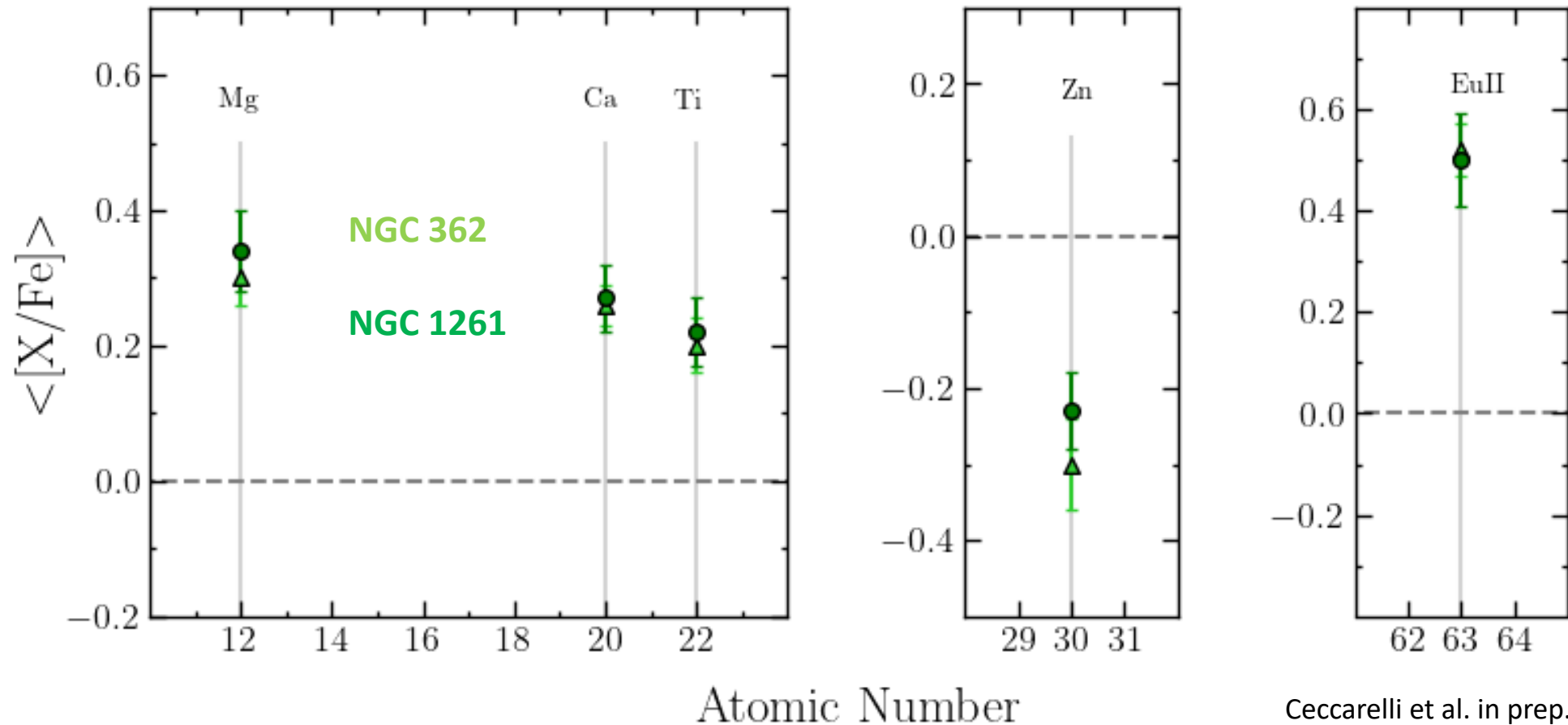
- GSE: NGC 362 and NGC 1261
- Helmi Streams: Ruprecht 106
- in situ: NGC 6218

Forbes&Bridges2010, Dotter+2011, VandenBerg+2013,
Leaman+2013, Massari+2019, Mucciarelli+2023



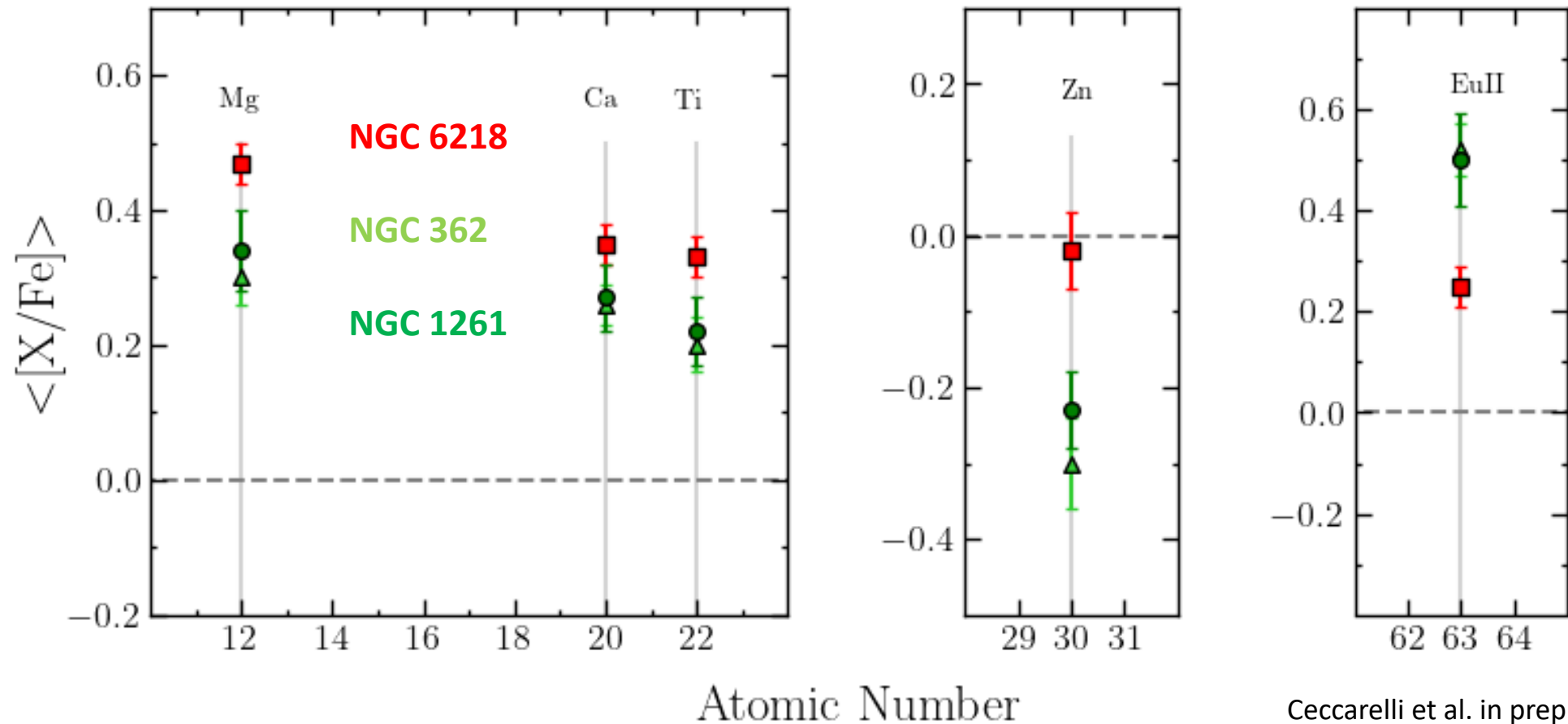
Does chemistry reflects the dynamical classification?

4 GCs tagged to different dynamical groups: **in situ** - **GSE** - **Helmi Streams**



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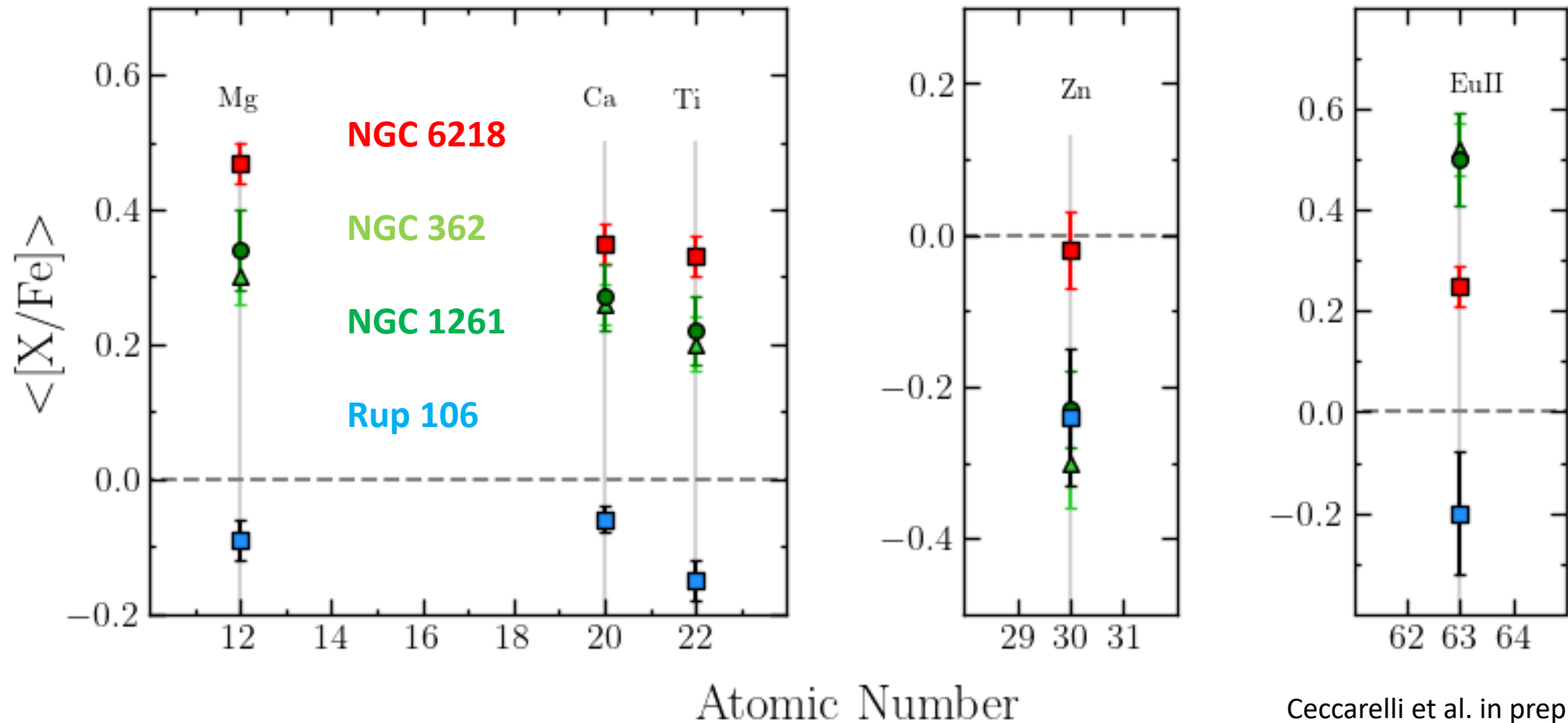
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Ceccarelli et al. in prep.

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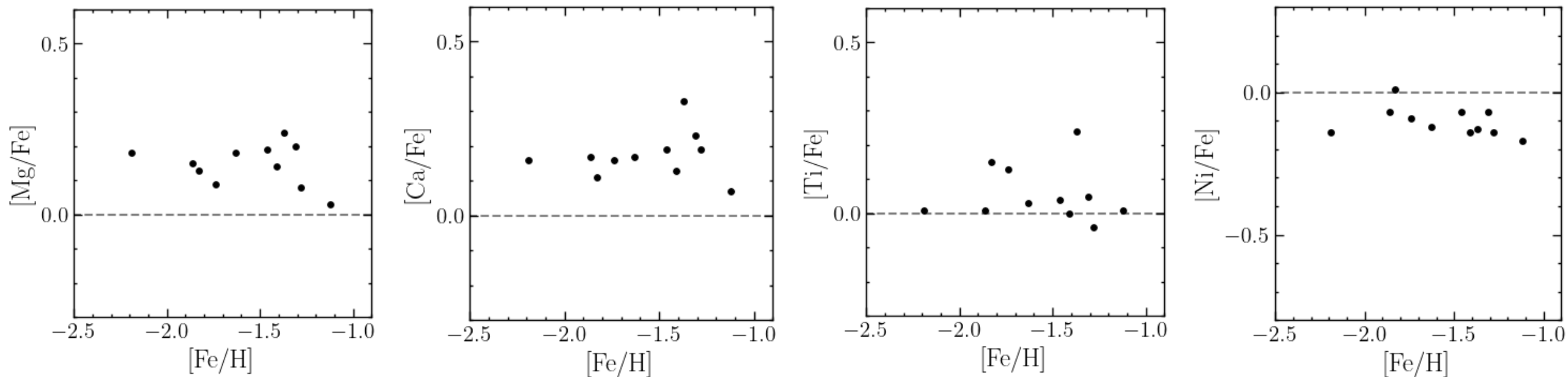


Ceccarelli et al. in prep.

Rup 106 as a relic of the progenitor of the Helmi Streams?

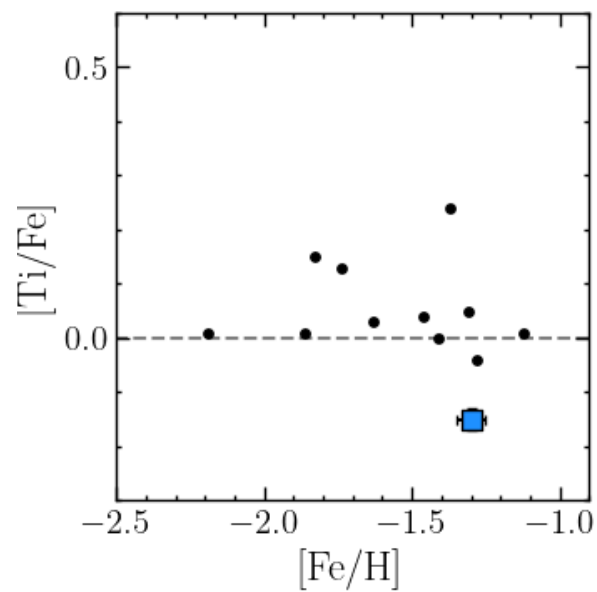
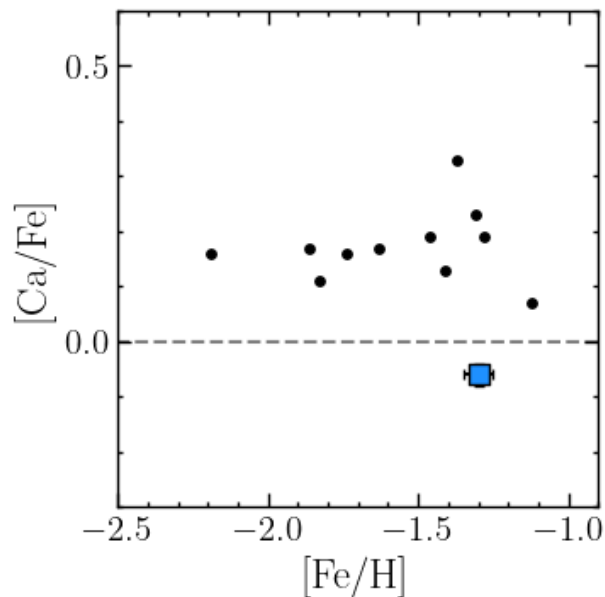
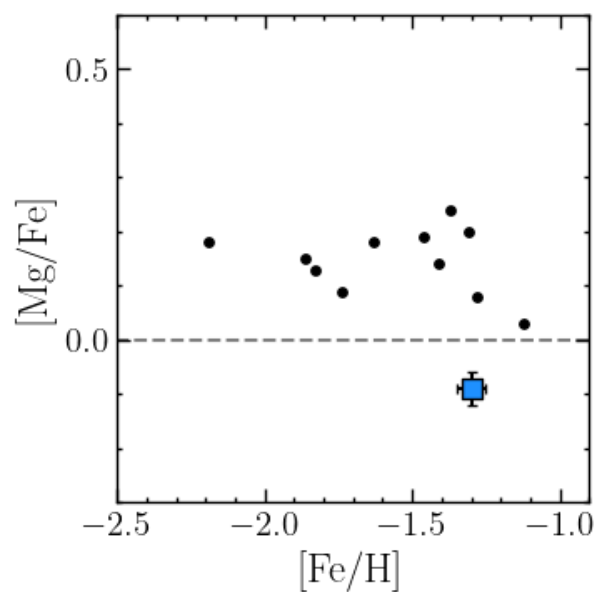
Comparison with Helmi Streams stars from Matsuno+22

Matsuno+22, Ceccarelli et al. in prep.

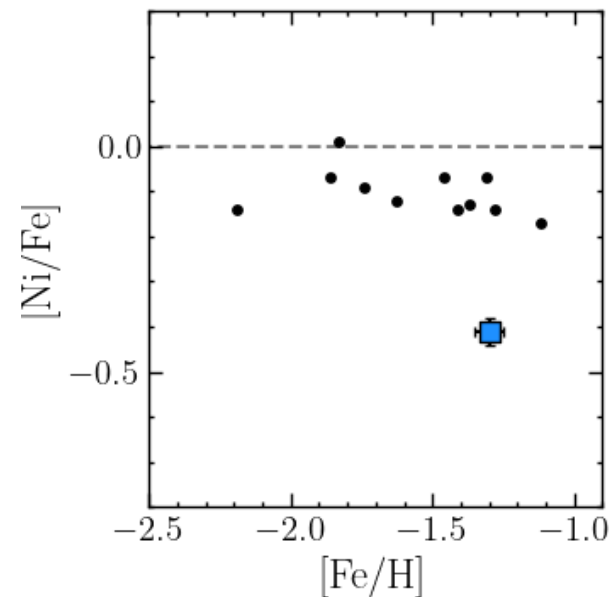


Rup 106 as a relic of the progenitor of the Helmi Streams?

Chemical composition NOT compatible

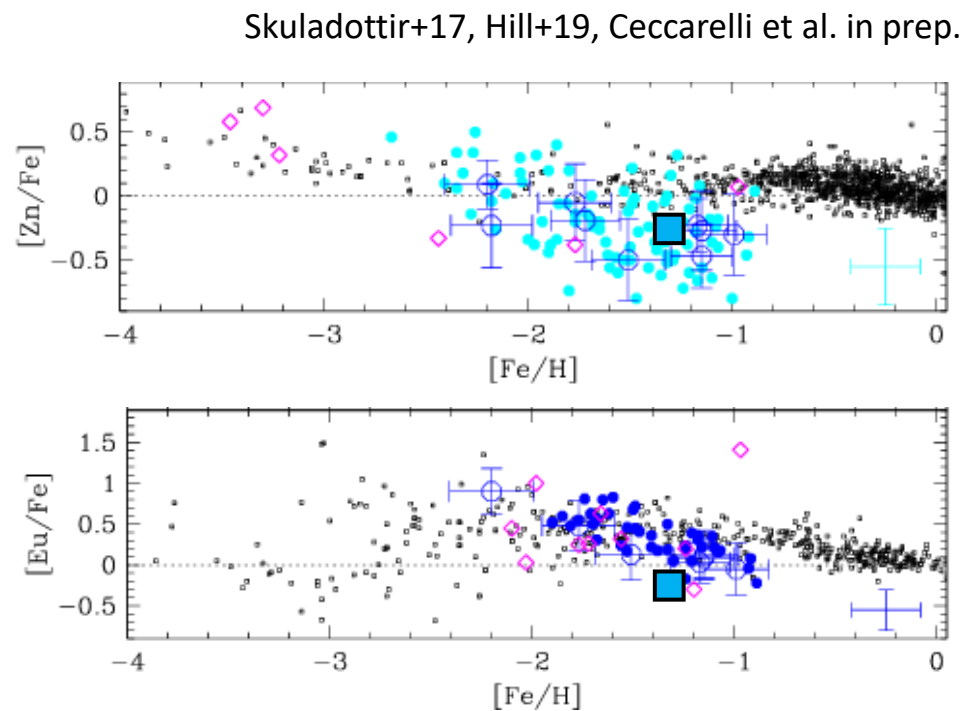
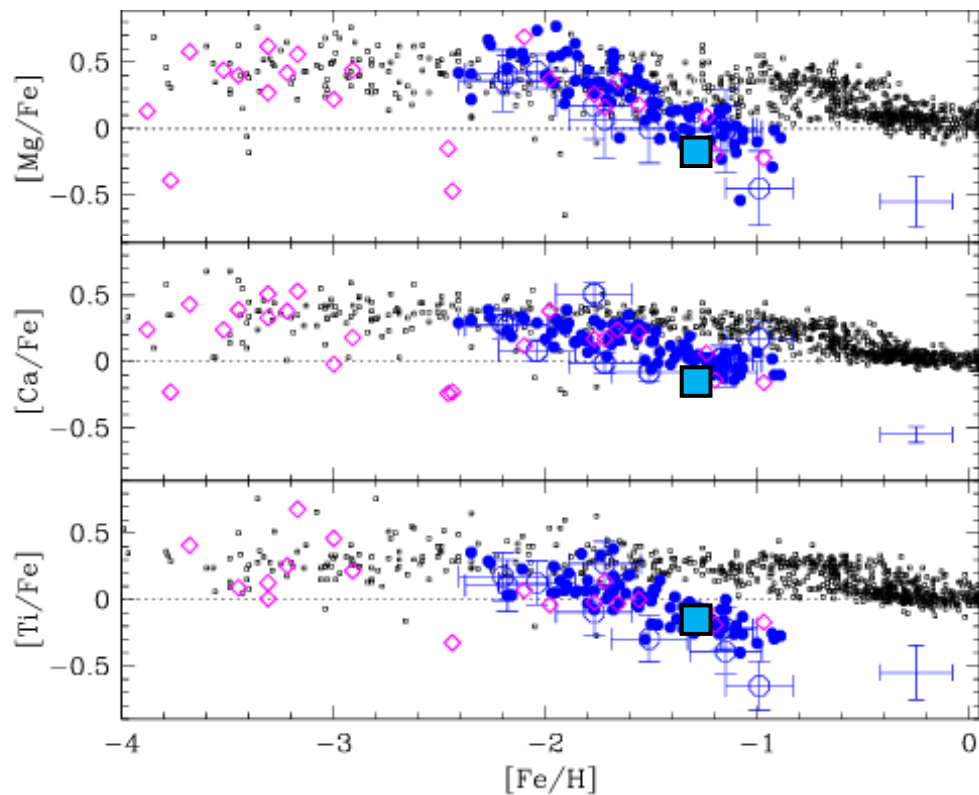


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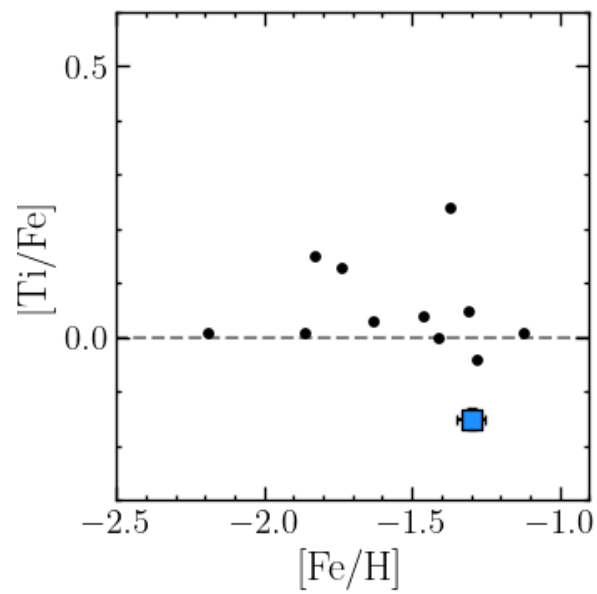
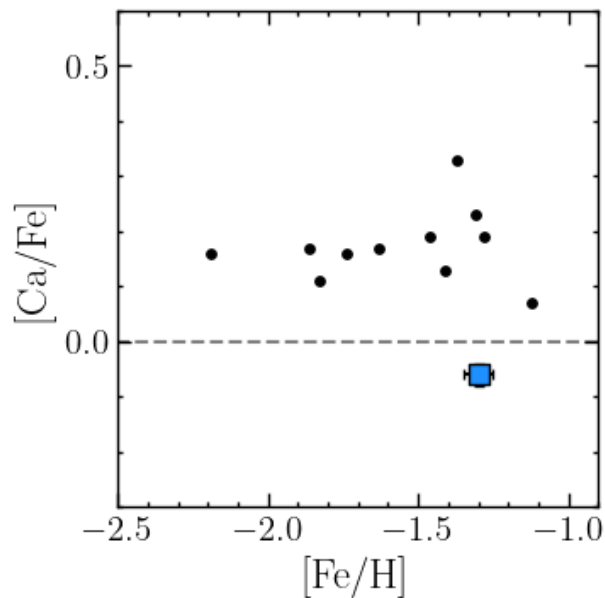
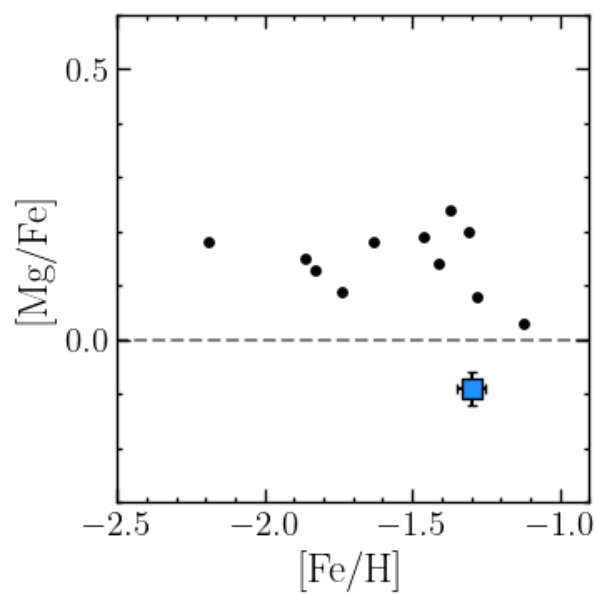


Rup 106 as a relic of the progenitor of the Helmi Streams?

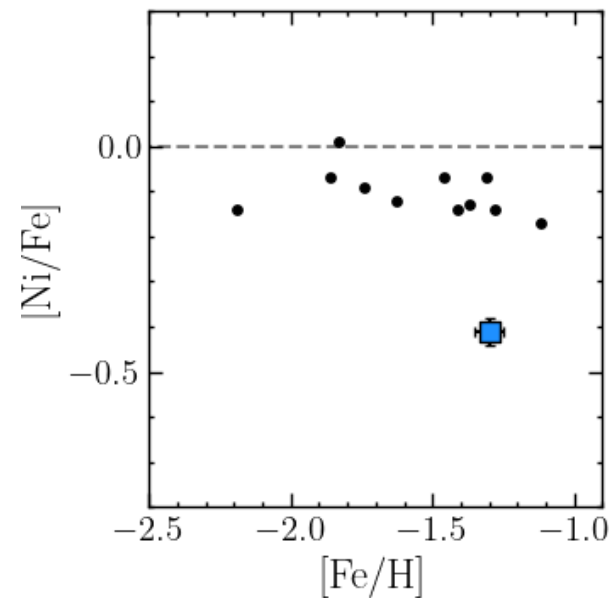
Similarities with surviving dwarf galaxies: Sculptor



Rup 106 as a relic of the progenitor of the Helmi Streams?

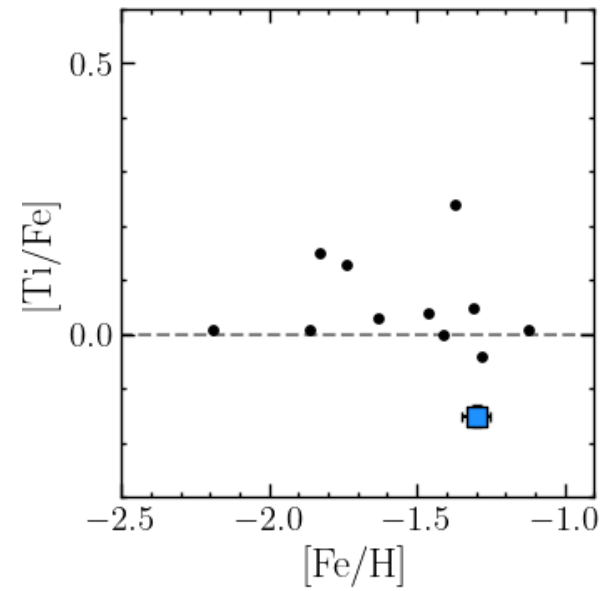
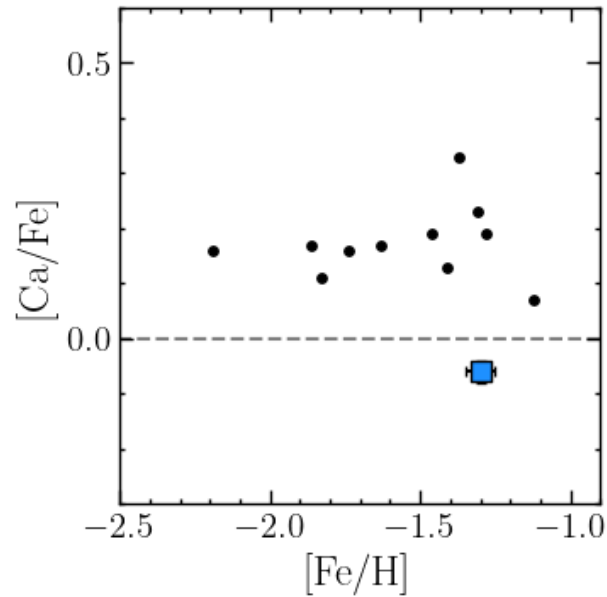
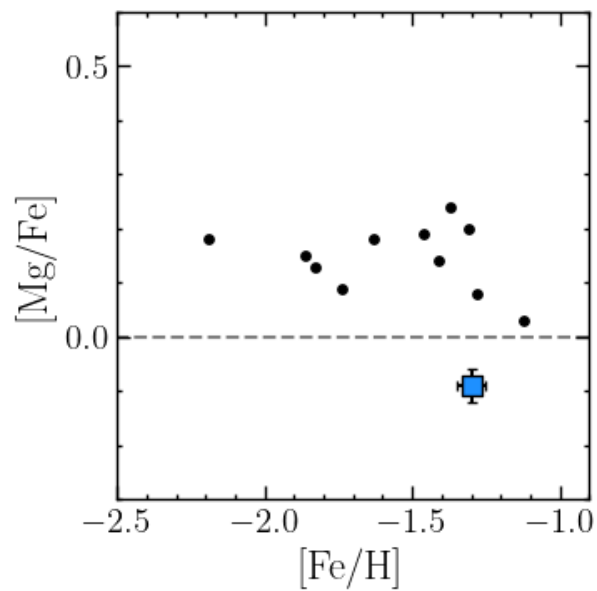


Matsuno+22, Ceccarelli et al. in prep.

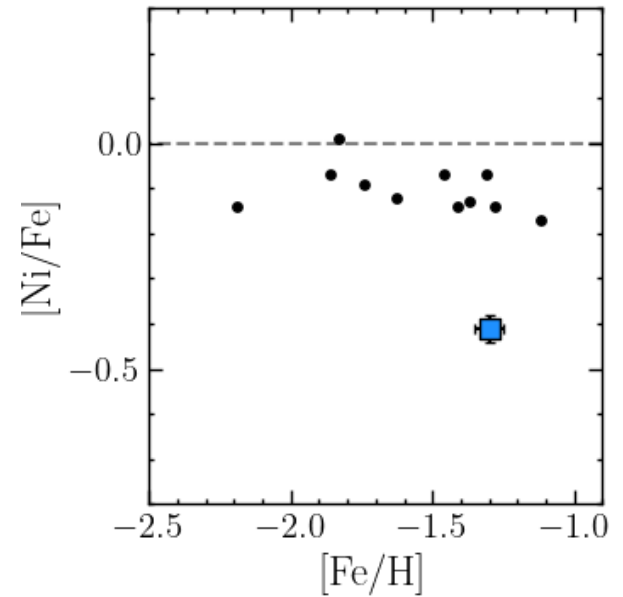


Rup 106 as a relic of the progenitor of the Helmi Streams?

- Progenitor of the Helmi Stream was chemical inhomogeneous

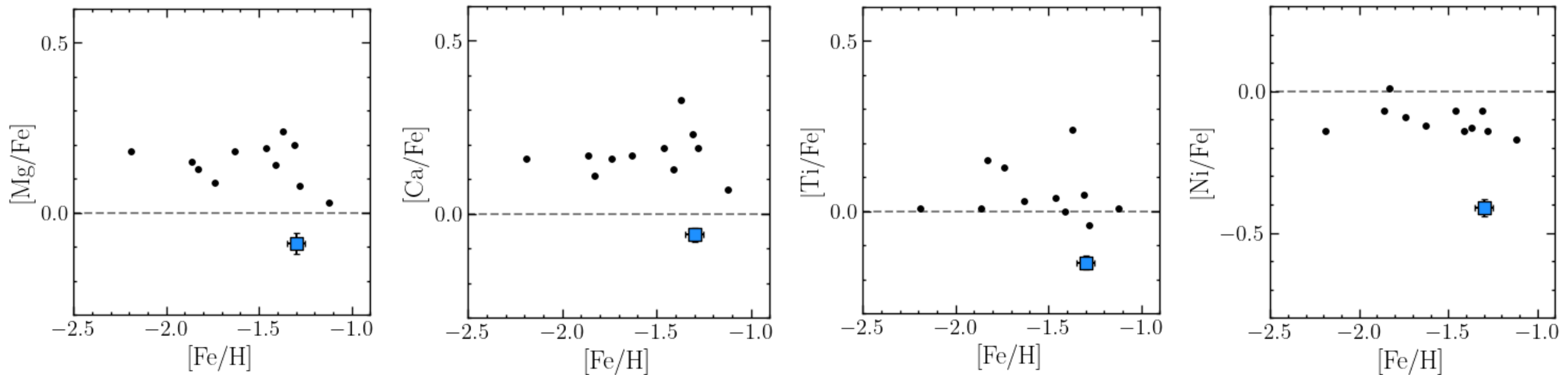


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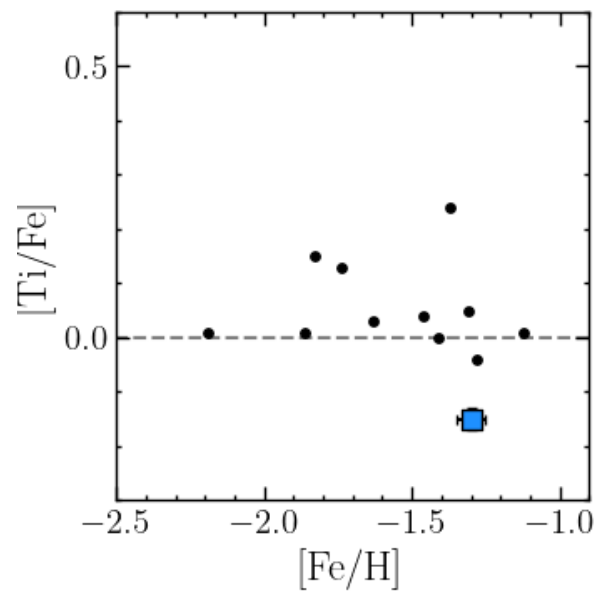
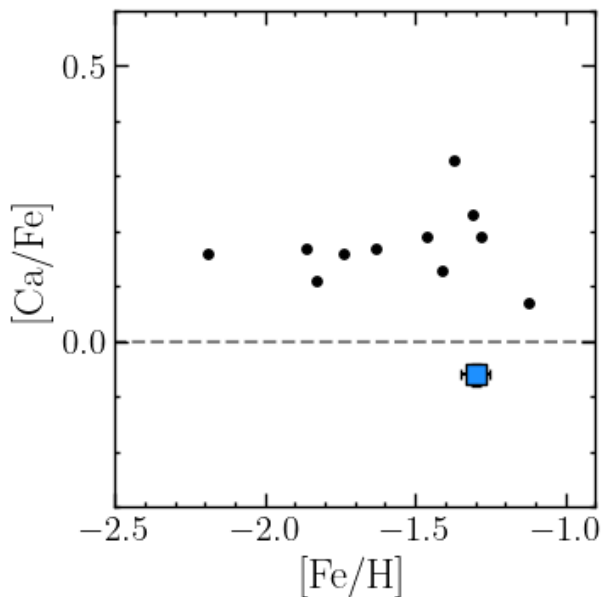
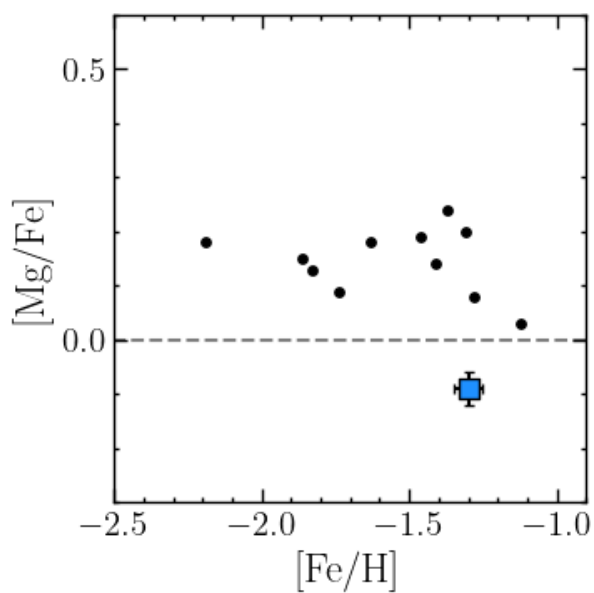
Rup 106 as a relic of the progenitor of the Helmi Streams?

- Progenitor of the Helmi Stream was chemical inhomogeneous
- Rup 106 formed in an environment with less efficient SF + different IMF

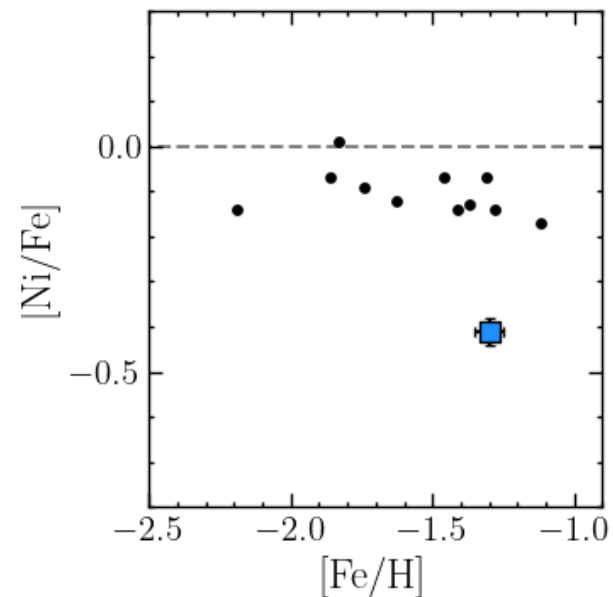


Rup 106 as a relic of the progenitor of the Helmi Streams?

- Progenitor of the Helmi Stream was chemical inhomogeneous
- Rup 106 formed in an environment with less efficient SF + different IMF: a satellite of the progenitor of the Helmi Streams?



Matsuno+22, Ceccarelli et al. in prep.



Summary

WRS:

- Antaeus and ED-3 share the same progenitor + independent merger from GSE
- ED-2 is the most metal-poor component with extremely tight [Fe/H]

Halo GCs (preliminary):

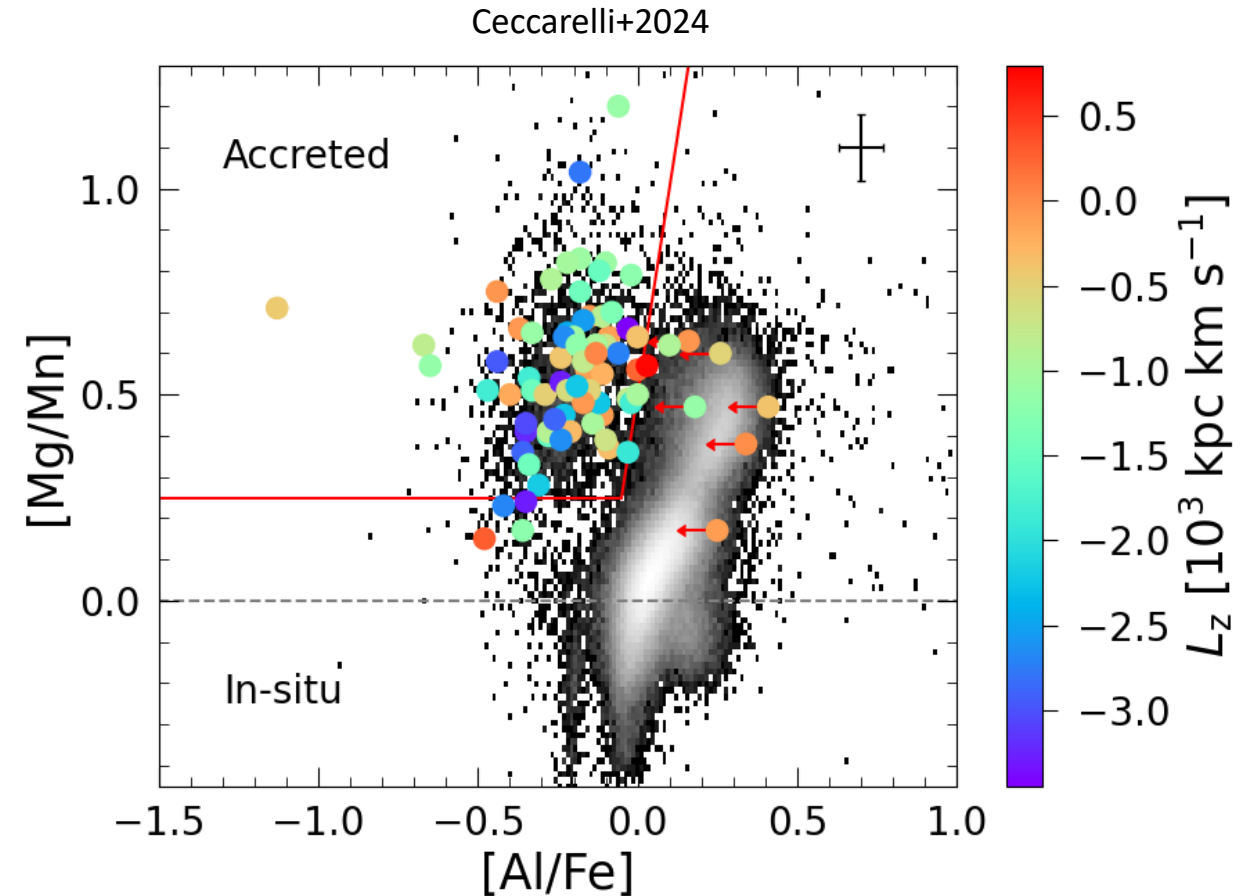
- Significant MW - GSE differences in [alpha/Fe], [Zn/Fe] and [Eu/Fe]
- Not all chemical elements are equally sensitive to the origin
- Ruprecht 106 chemistry NOT compatible with Helmi Streams: born in a satellite?

THANK YOU!

WRS project - [Mg/Mn] vs [Al/Fe] plane

Accreted or in-situ?

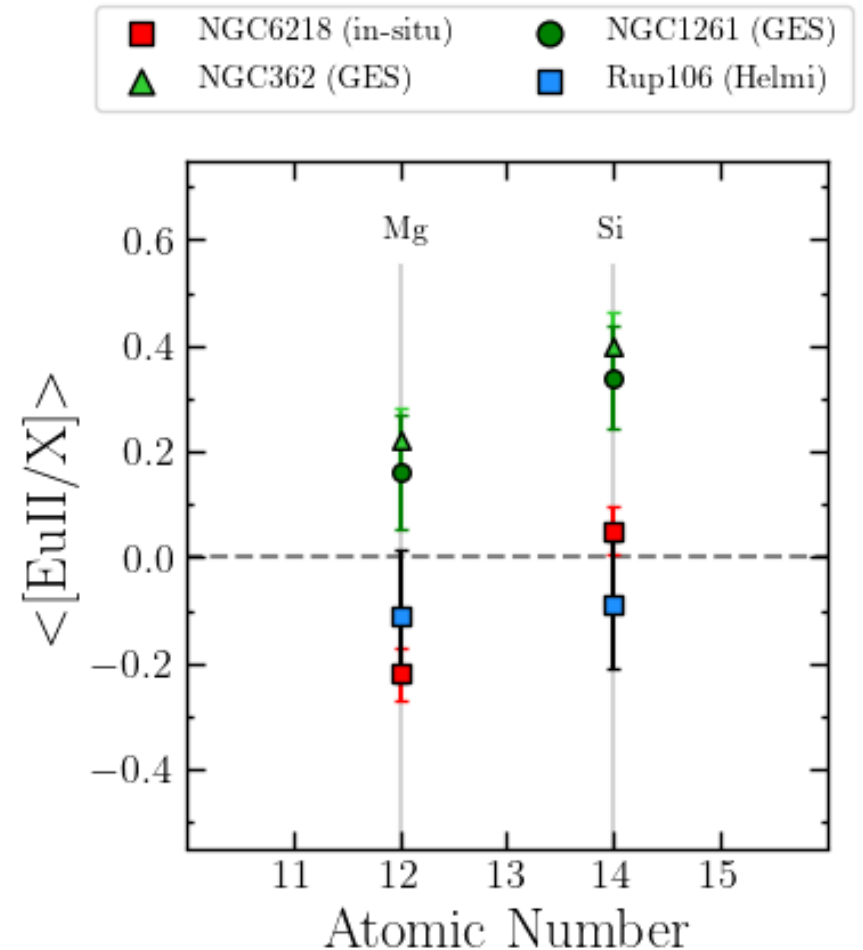
- Mg tracer of Sn II
- Mn pristine tracer of Sn Ia
- Al yield dependent on metallicity



[Eu/ α] as an indicator of the origin

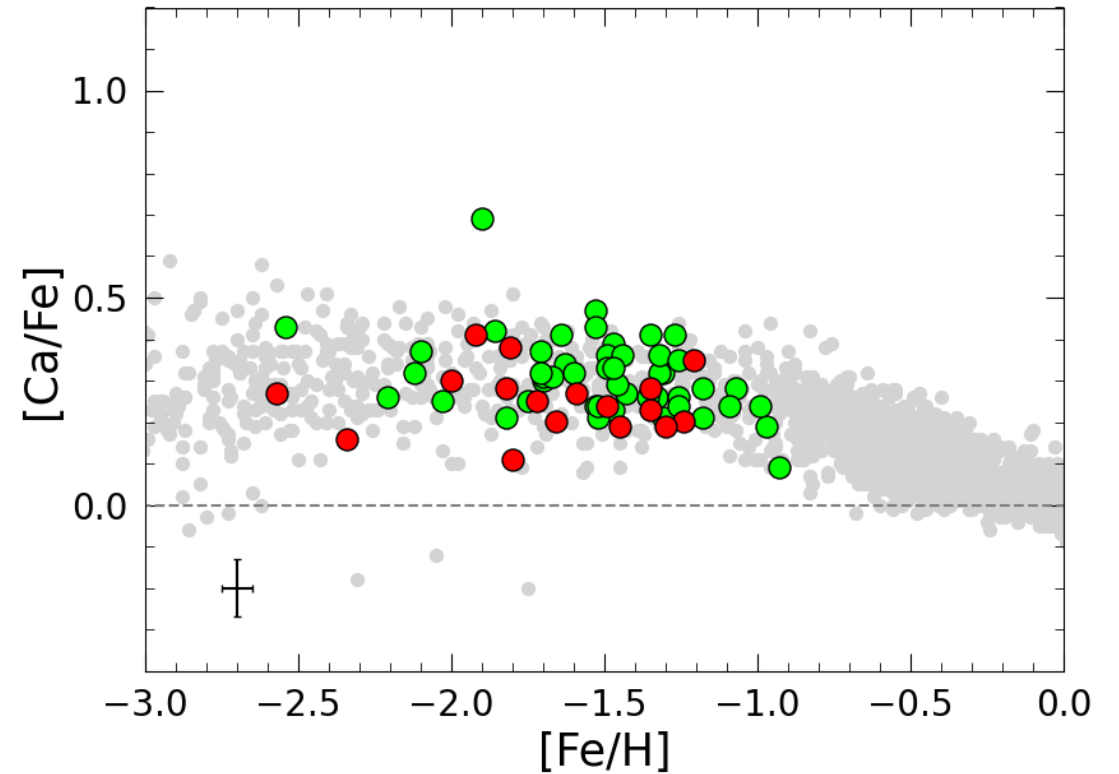
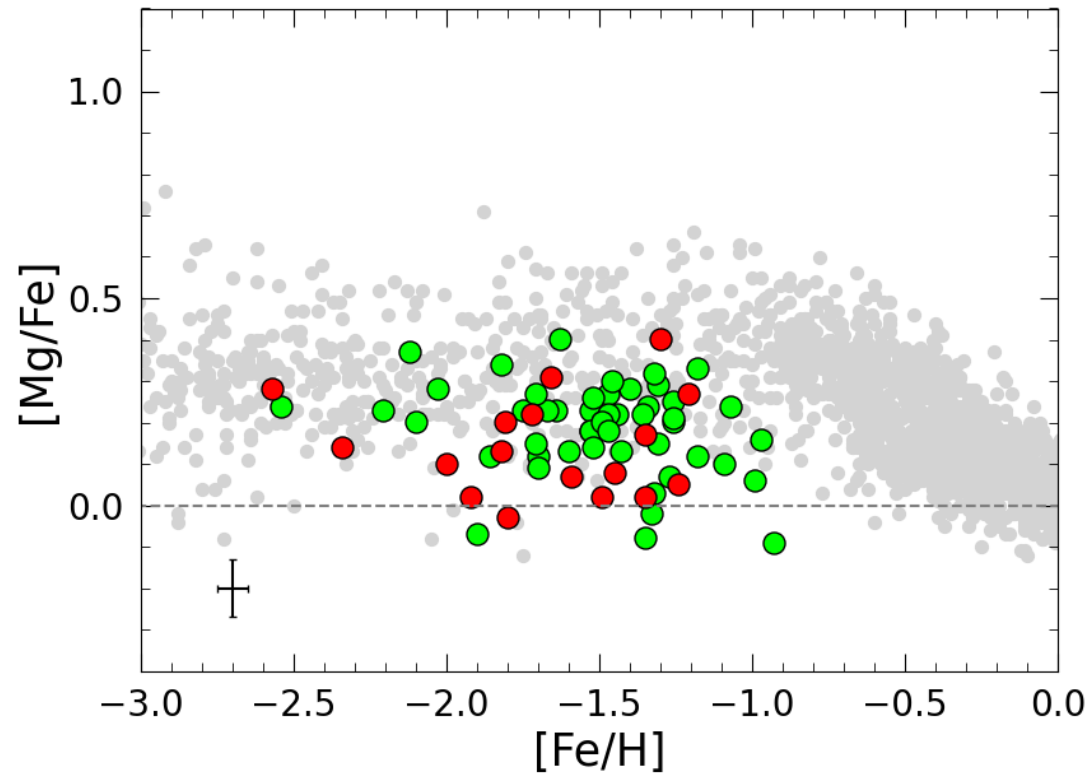
Accreted or in-situ?

- α -elements tracers of Sn II
- Eu formed by very massive stars (prompt) + NSM (delayed)
- Dependency on the SF efficiency



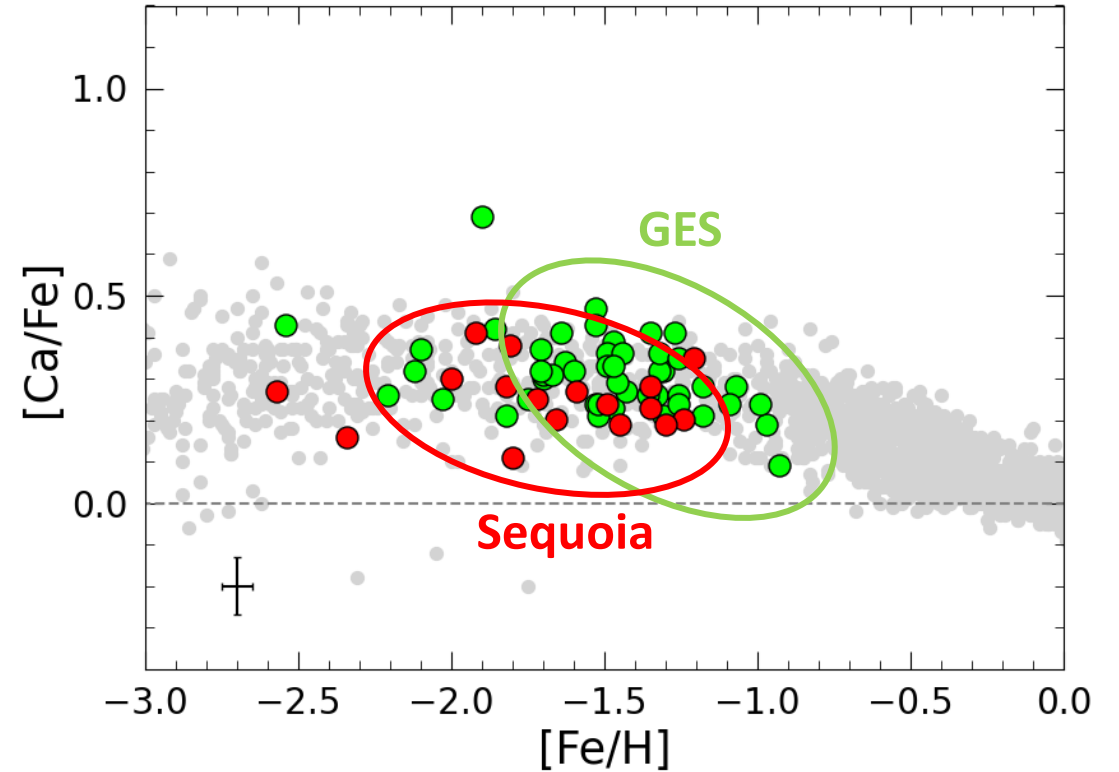
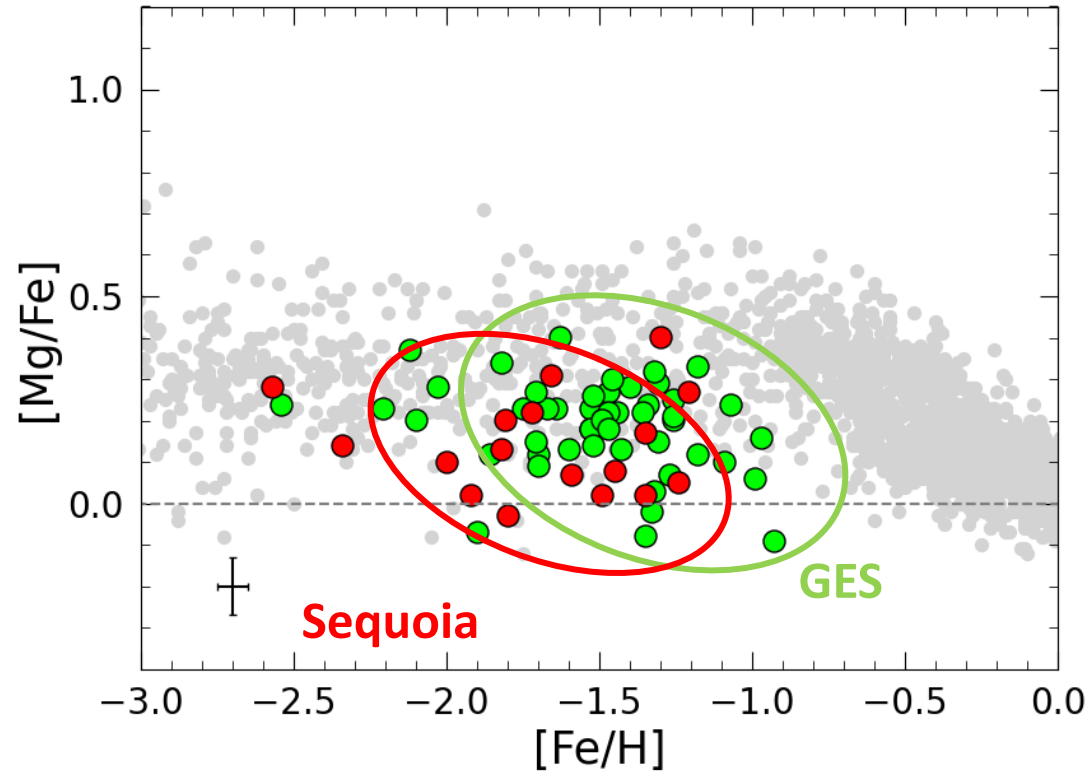
WRS project - Sequoia chemical composition

Ceccarelli+2024

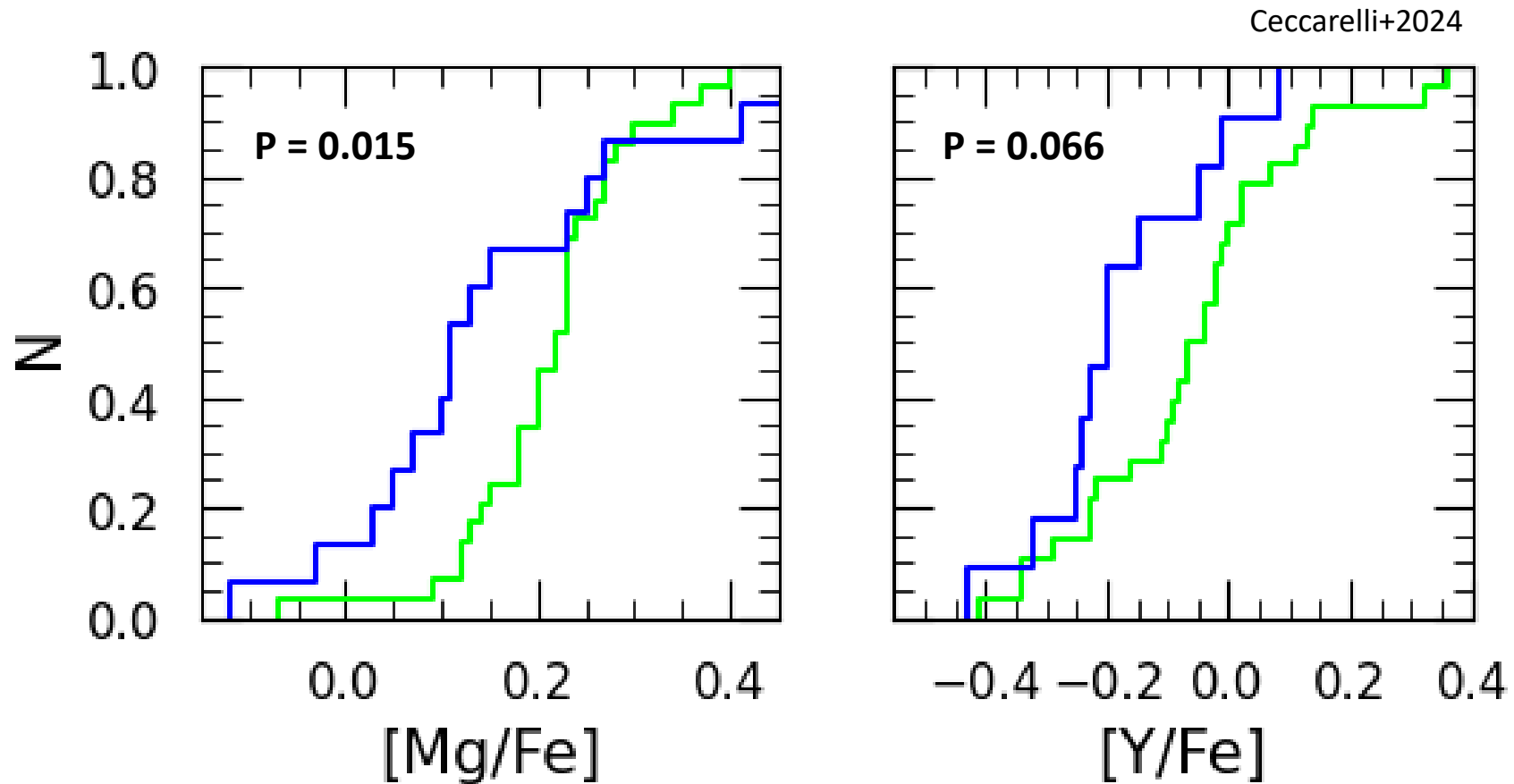


WRS project - Sequoia chemical composition

Ceccarelli+2024

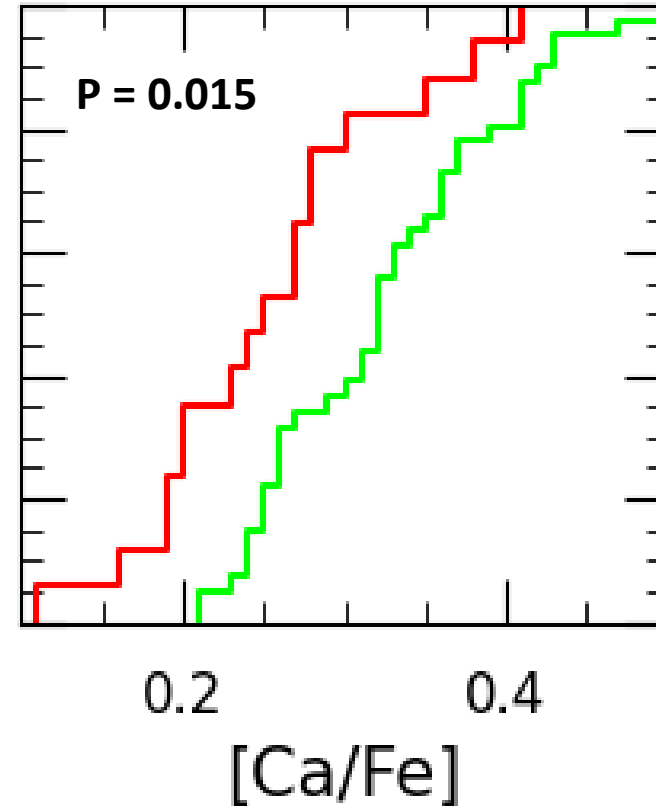
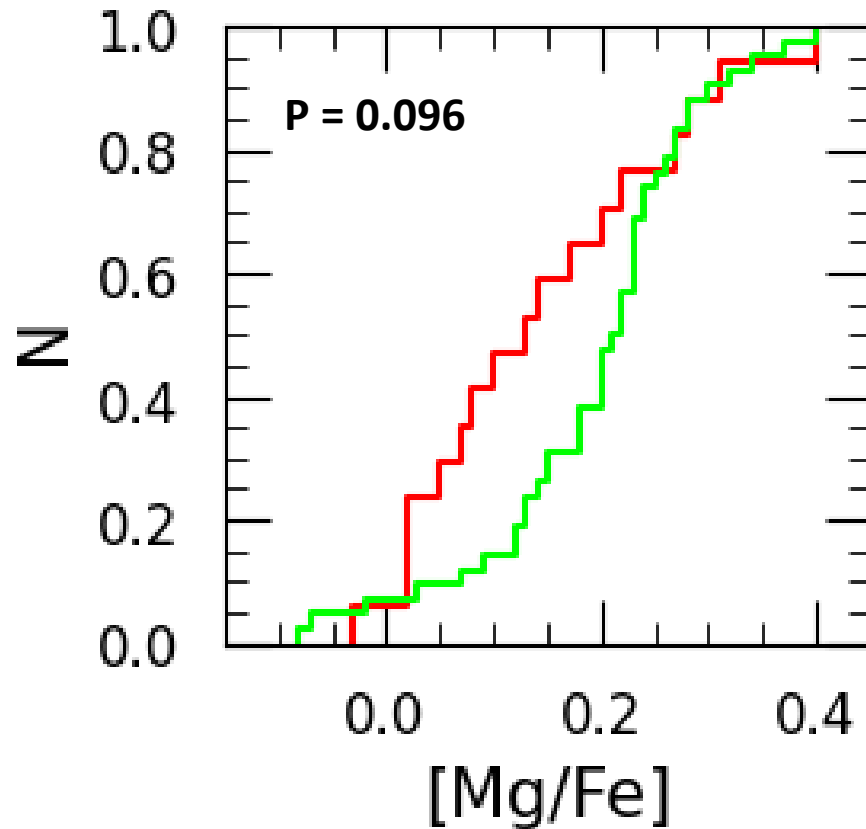


WRS project - Antaeus CDFs



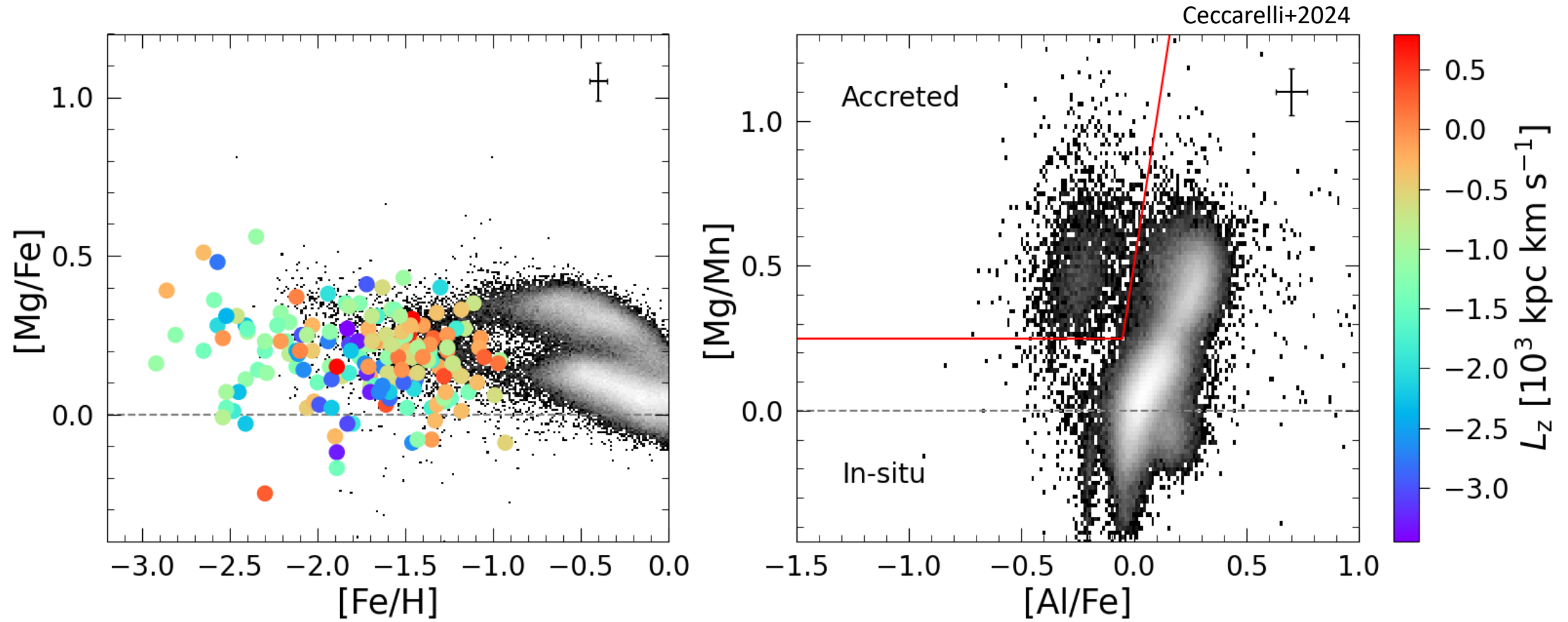
WRS project - Sequoia CDFs

Ceccarelli+2024



WRS project - Accreted or in-situ stars?

Chemical comparison with APOGEE DR17 confirms **accreted** nature of the targets



WRS project - Accreted or in-situ stars?

Chemical comparison with APOGEE DR17 confirms **accreted** nature of the targets

