The early and late evolution of our Galaxy through the lens of globular clusters

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In collaboration with: P. Di Matteo, M.Haywood, P. Bianchini, A.Mastrobuono-Battisti, F. Renaud, M. Mondelin, O. Agertz, L. Casamiquela, S. Khoperskov, and N. Ryde

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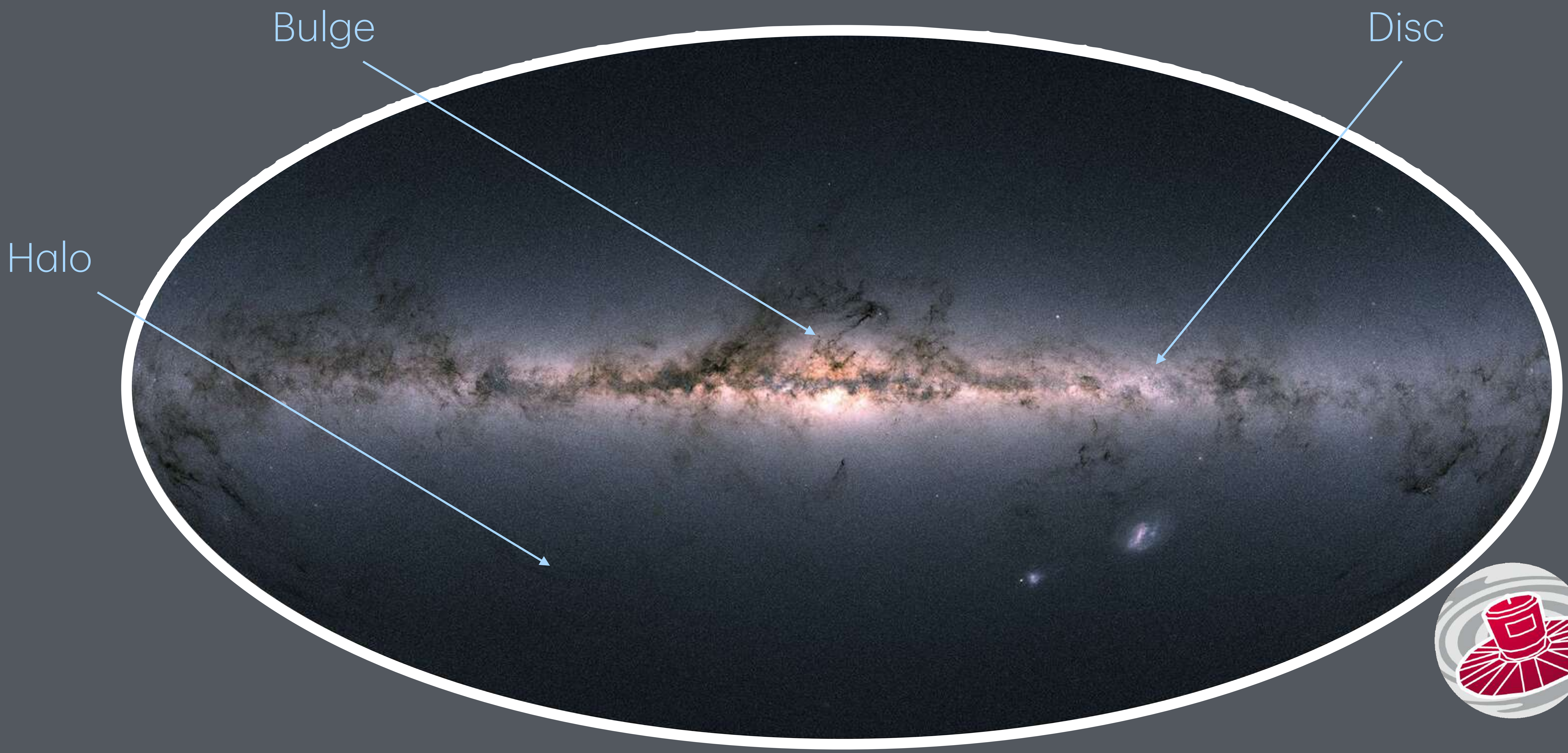
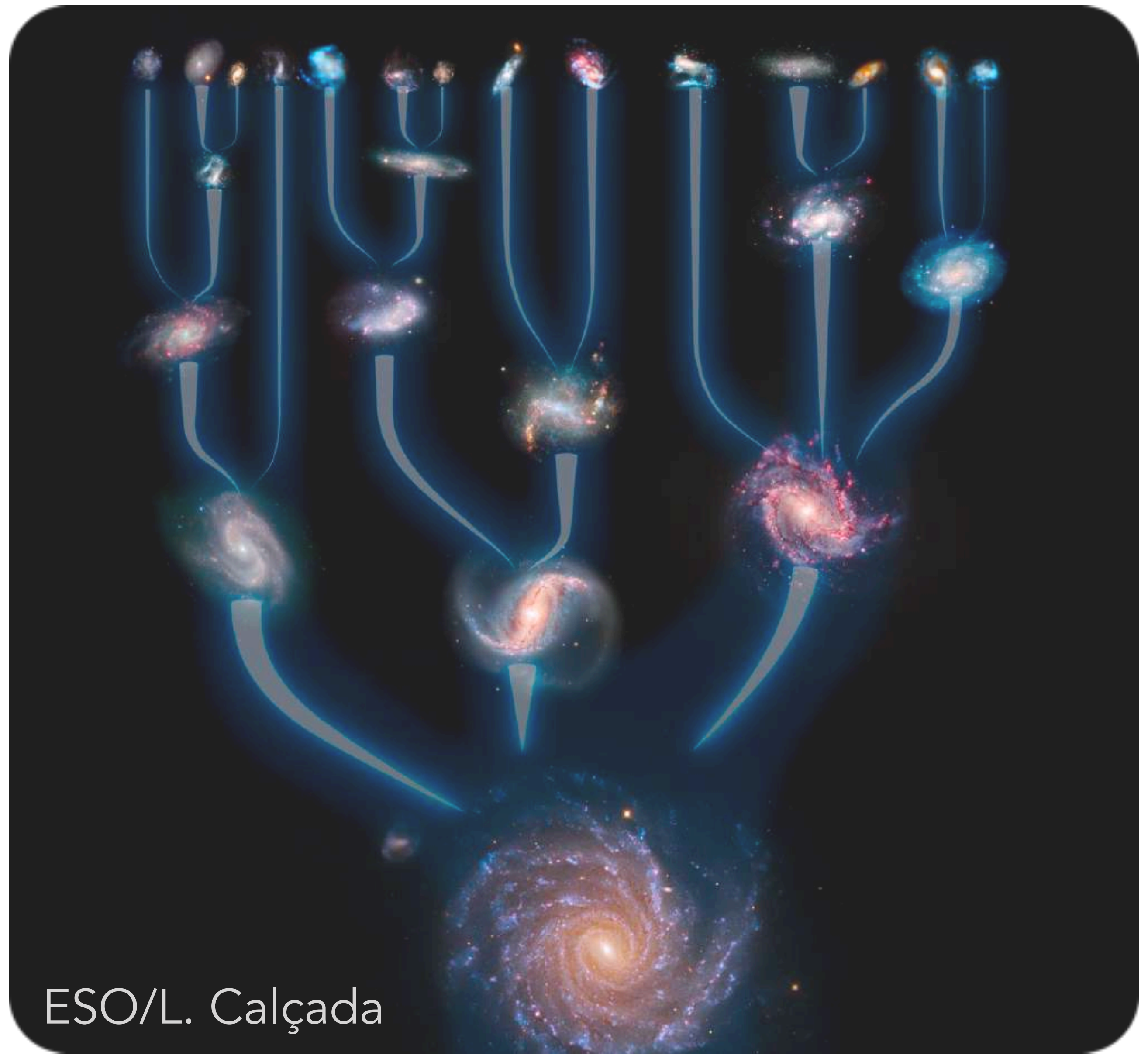
How did our Galaxy, the Milky Way, form?

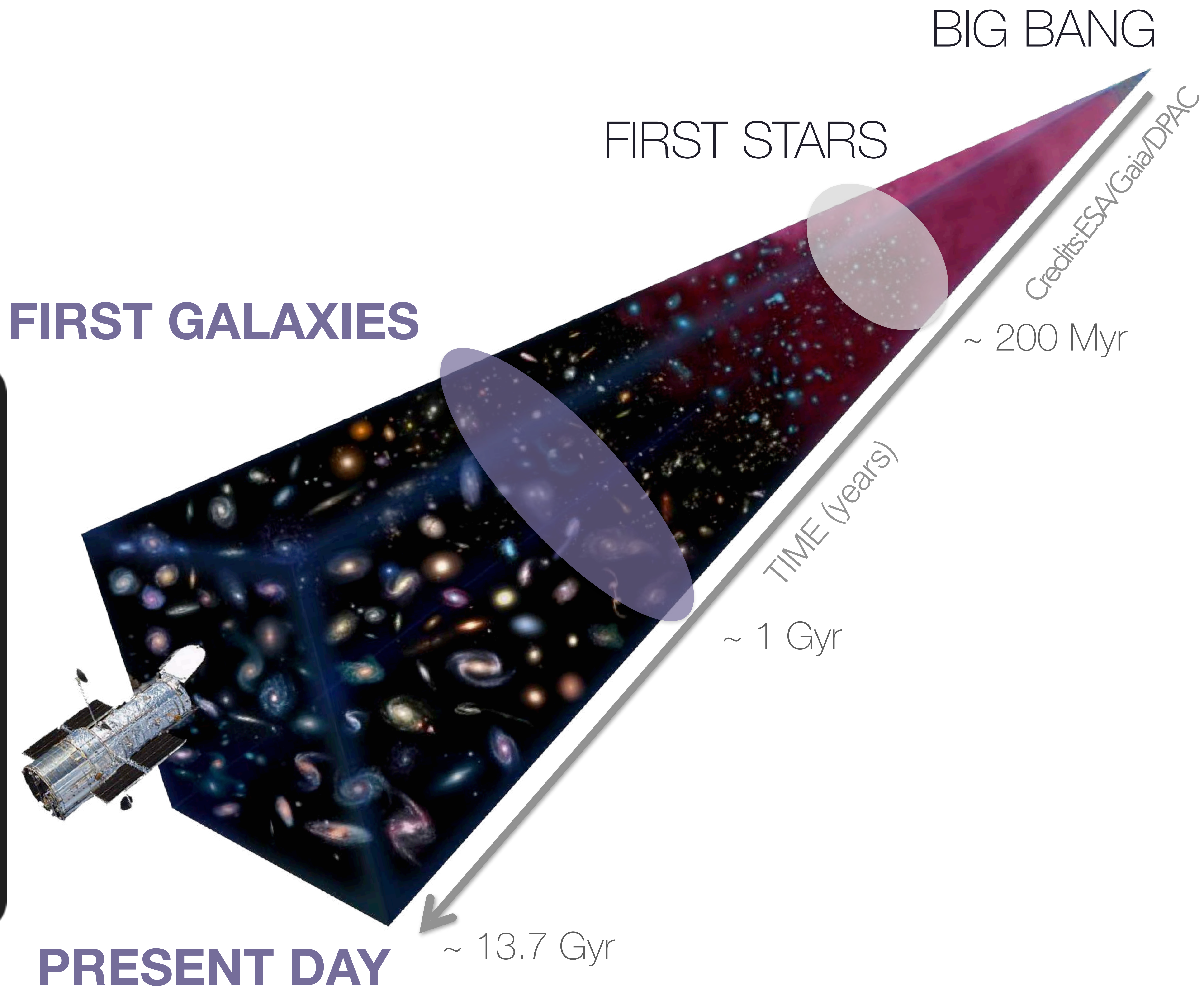


Context: Milky Way formation

According to the ΛCDM scenario **galaxy formation occurs in a hierarchical pattern**: smaller galaxies merge together to build up the larger galaxies that we observe today.

merger tree of the Milky Way?



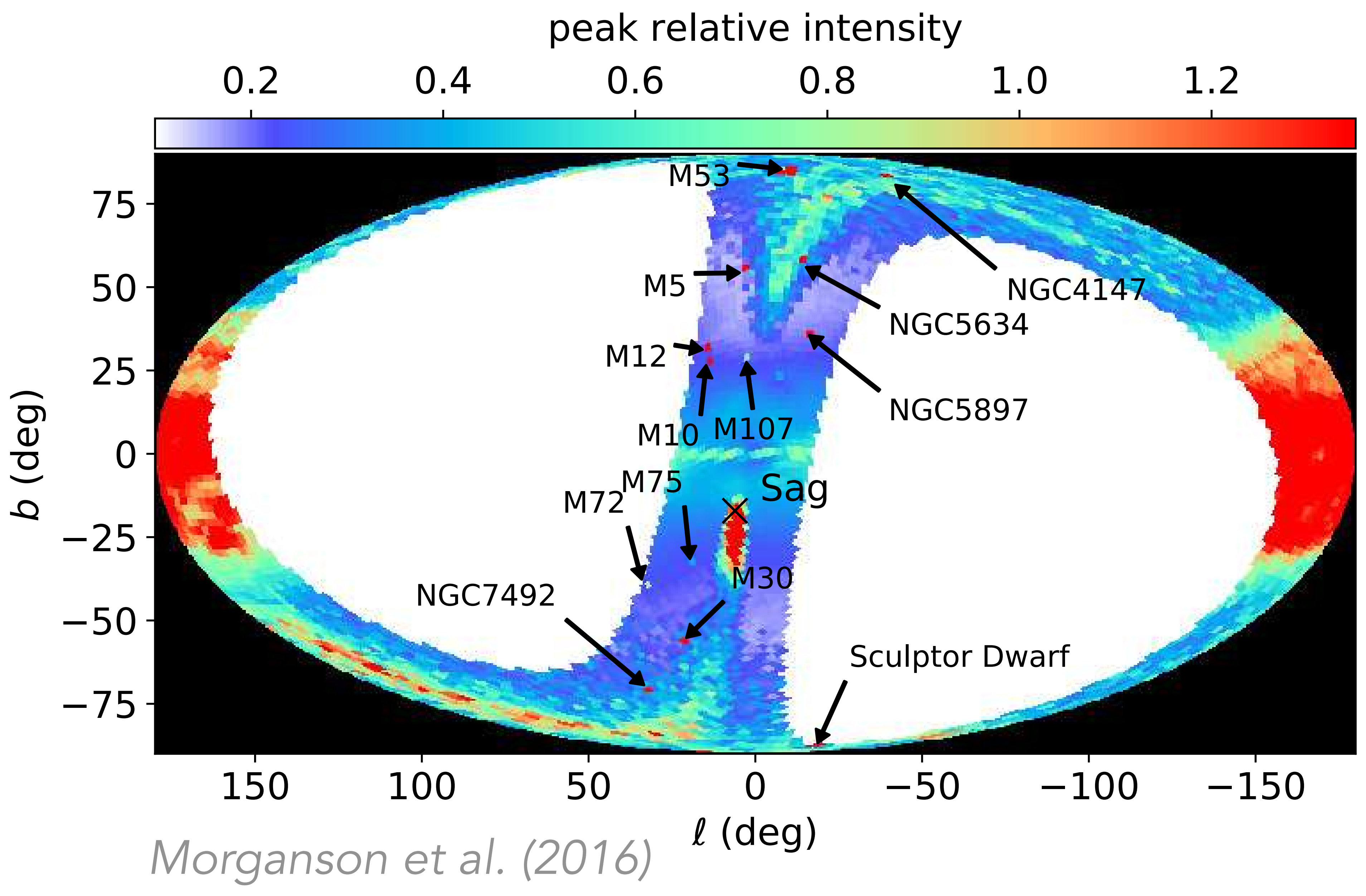


Context: Milky Way formation

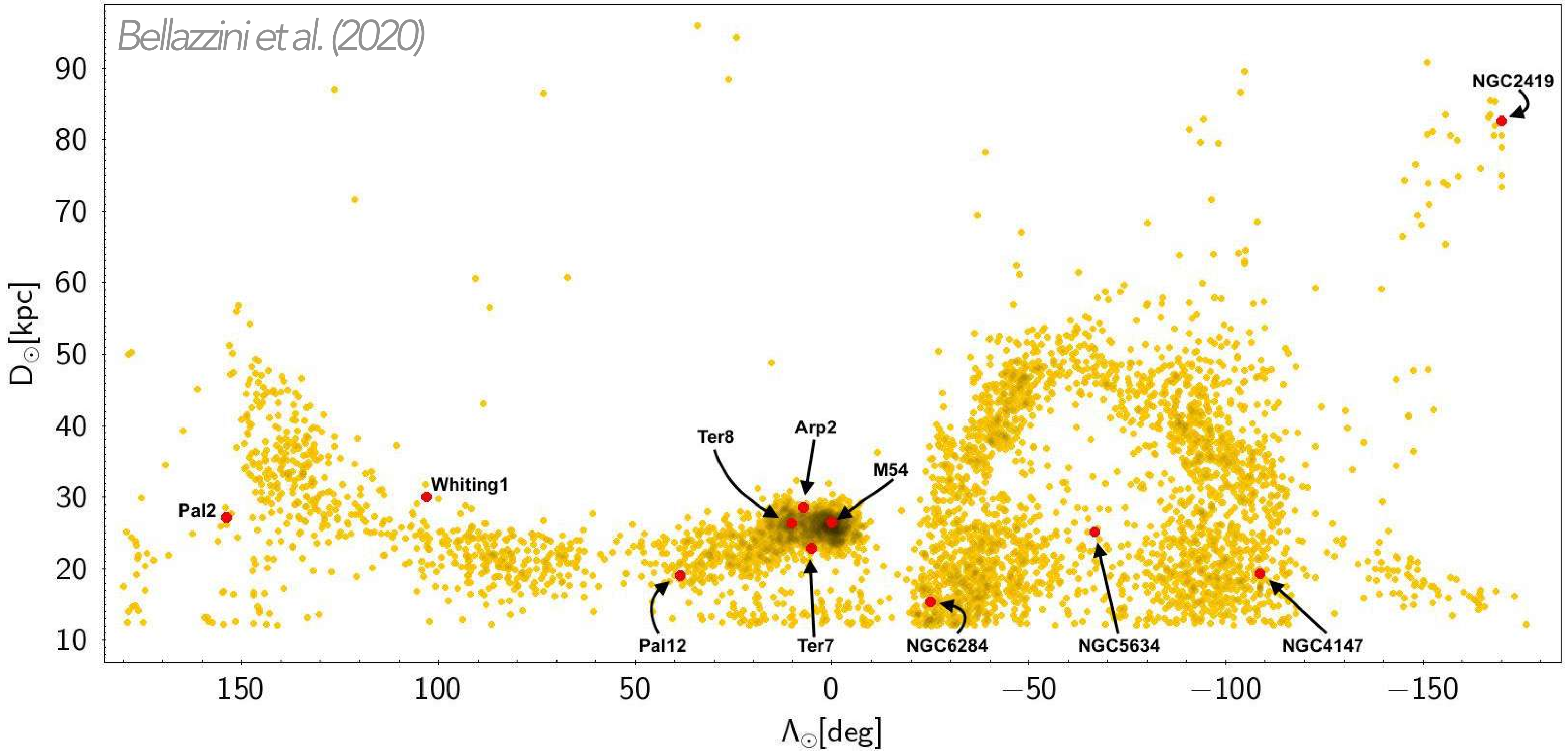
‣ Satellites of the Milky Way and ongoing accretions

Observational evidence of ongoing mergers can be recognised in the Milky Way (but also in other galaxies) as **stellar streams**.

Sagittarius



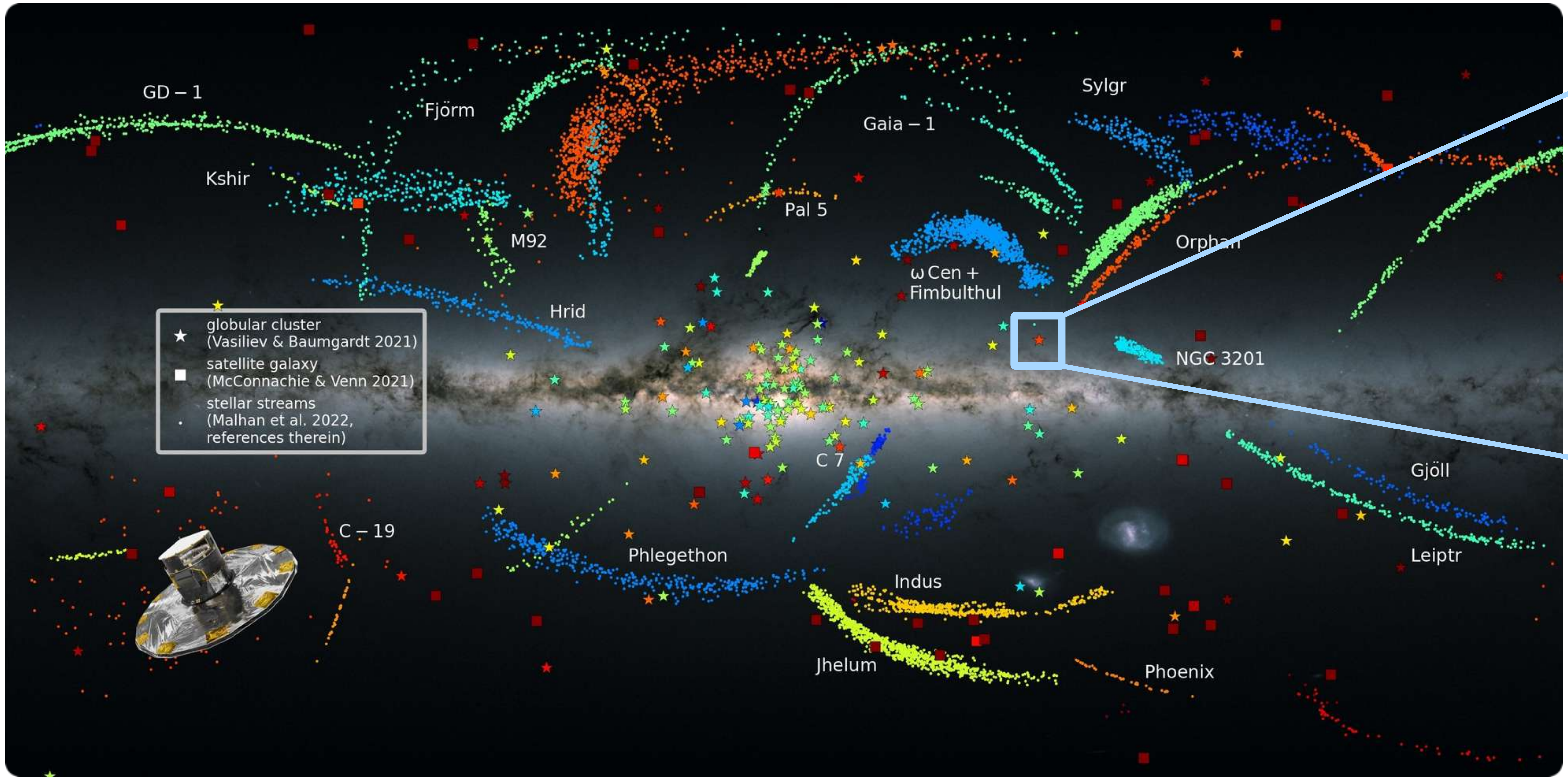
Morganson et al. (2016)



Satellite galaxies during their accretion process **bring with them** not only their field stellar populations but also **their globular cluster system**.

Context: Globular clusters (GCs)

- Tracers of the hierarchical formation of galaxies



Malhan et al. (2022)

Gravitationally bound
Massive: $\sim 10^5 M_\odot$
Compact: size ~ few pc
Old: age > 10 Gyr

Context: Milky Way formation

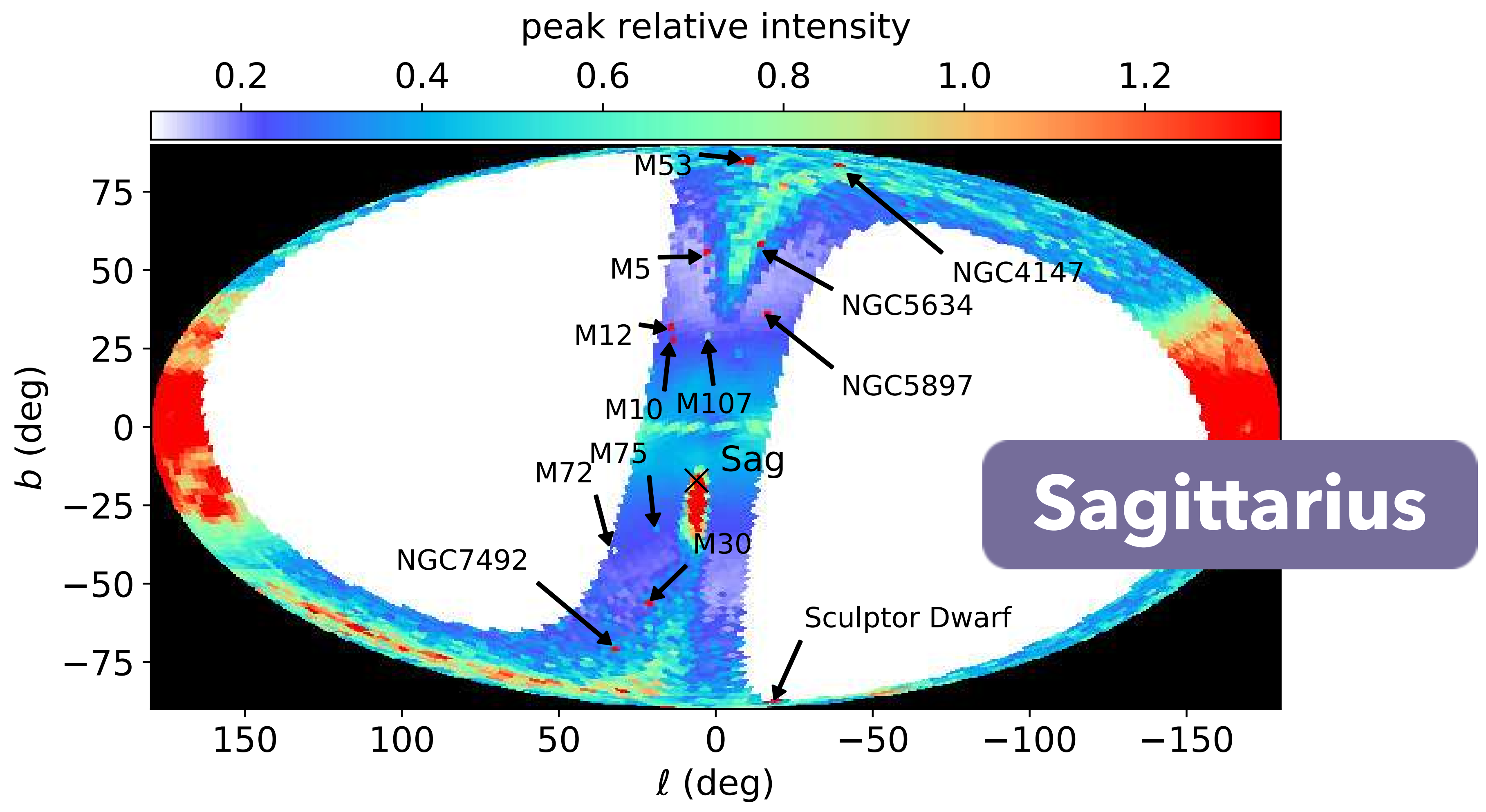
▸ Searching for past accretions: spatial mixing

1) **SPATIAL INFORMATION:**
positions on the sky + distances

2) DYNAMICAL INFORMATION:
proper motions + line-of-sight velocities

3) CHEMICAL ABUNDANCES & AGES

ONGOING MERGERS



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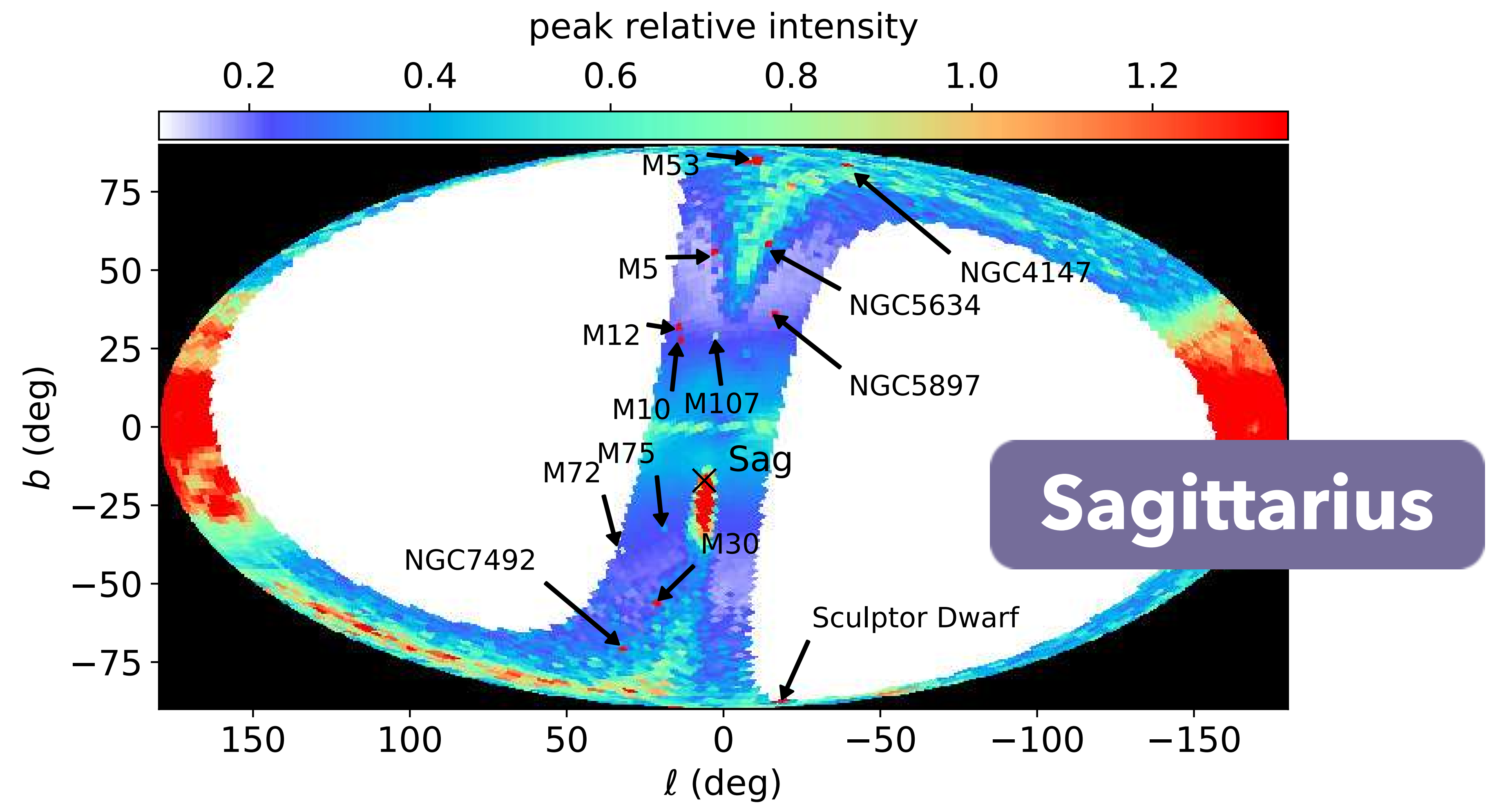
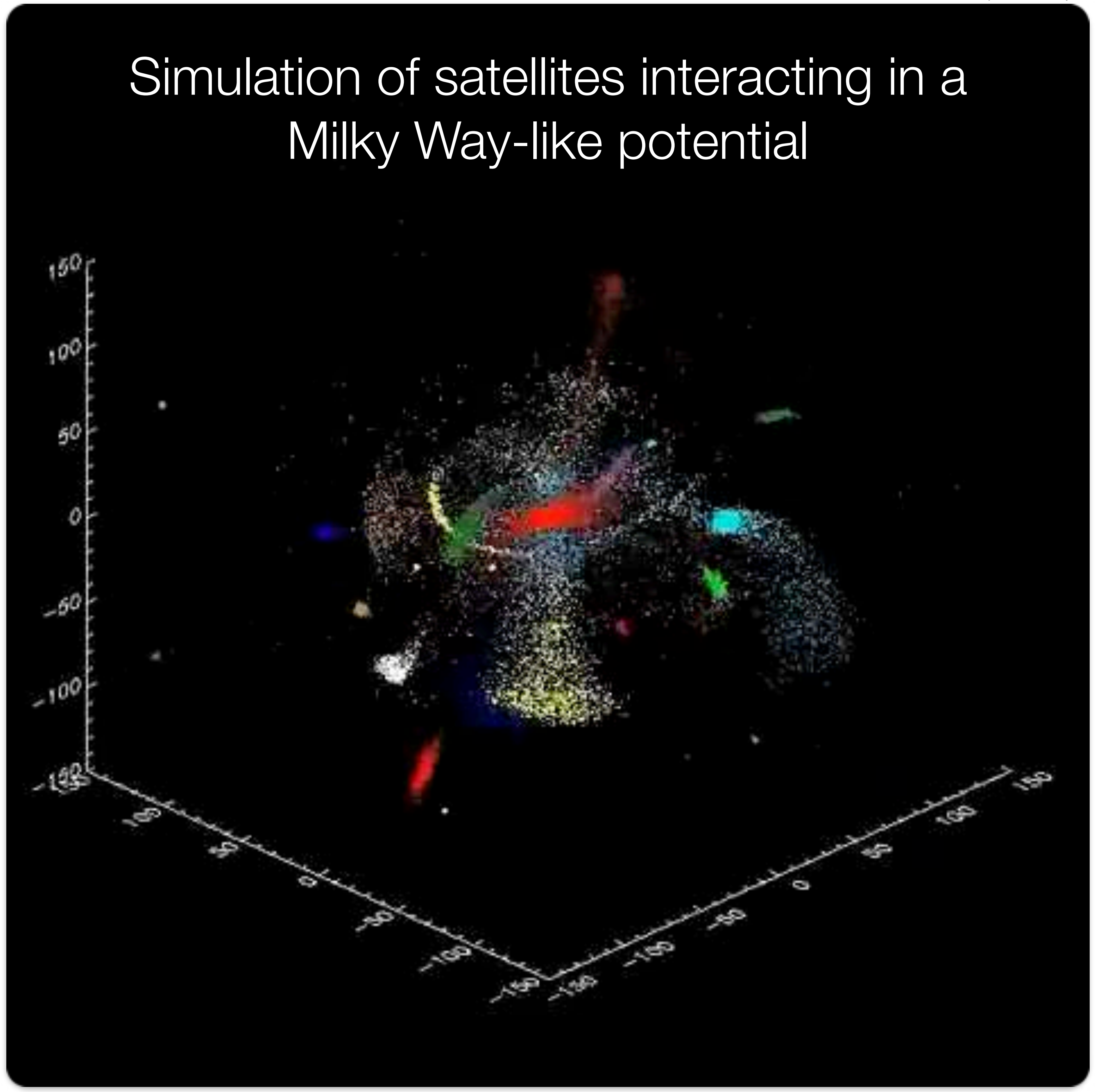


Bullock & Johnston (2005)



Disrupted satellites accreted in the past have lost their spatial coherence!

Context: Milky Way formation

‣ **Searching for past accretions: kinematic and "integral-of-motion" spaces**

1) ~~SPATIAL INFORMATION~~: only for ongoing mergers
~~positions on the sky + distances~~

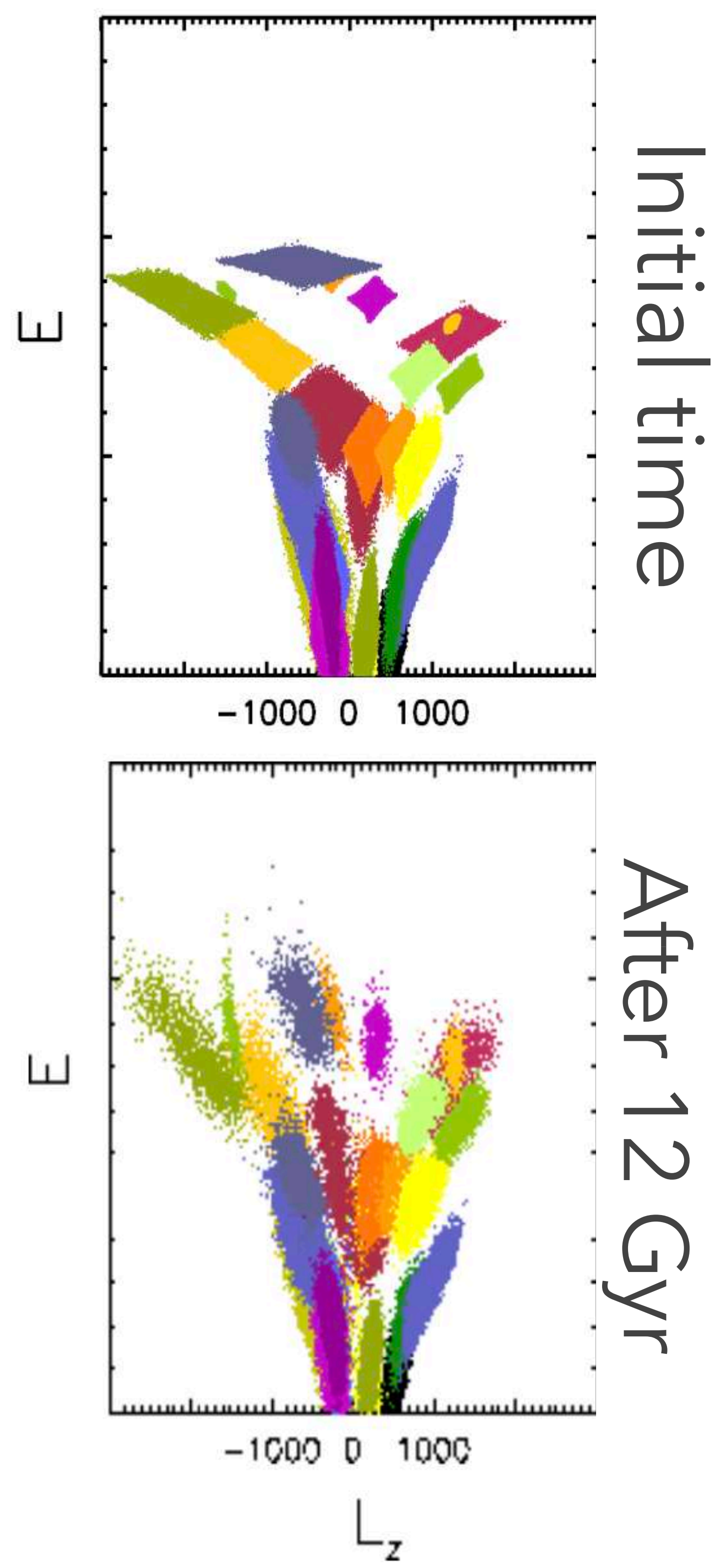
2) **DYNAMICAL INFORMATION**:
proper motions + line-of-sight velocities

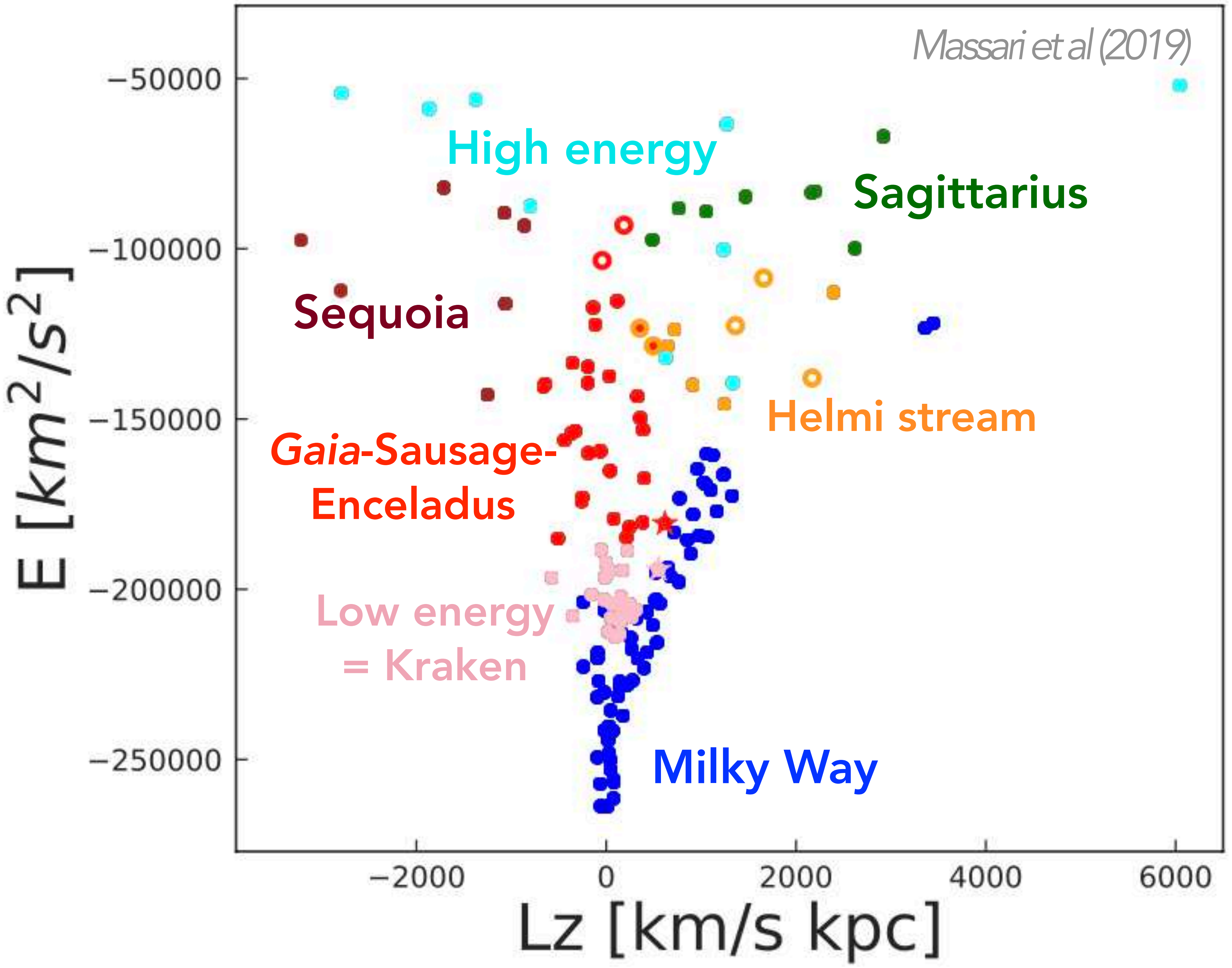
3) CHEMICAL ABUNDANCES & AGES

Searching similarities in the IoM spaces:
- orbital energy (E)
- total angular momentum (L)
- components of angular momentum (L_z, $L_\perp$)

Since these should be conserved during a merging process.

Helmi & de Zeeuw (2000)





Galactic globular clusters located in different regions of the E – L_z space are associated to different galactic progenitors

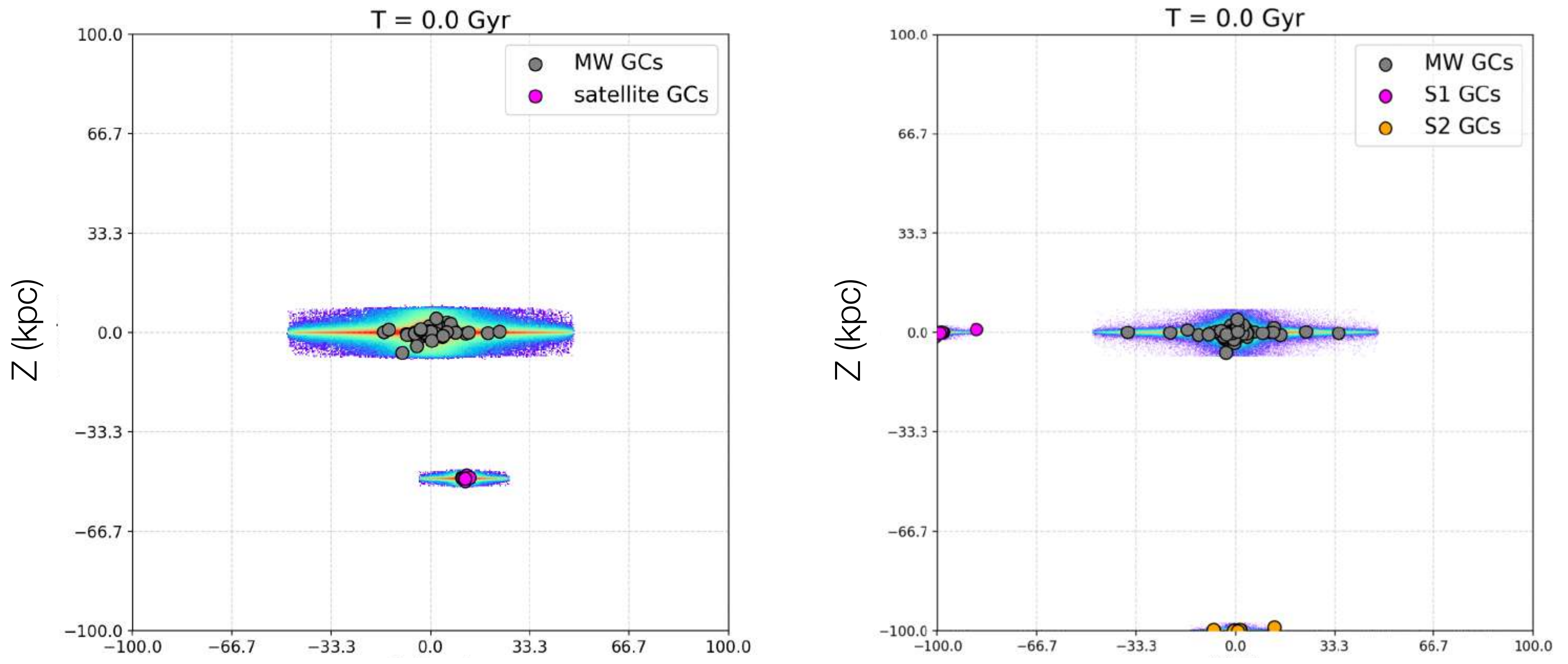
Testing the dynamical coherence of globular clusters

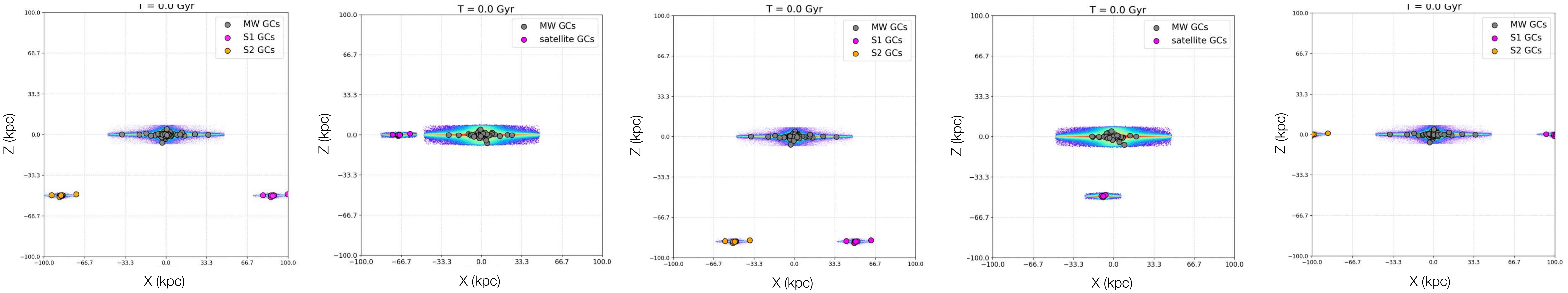
‣ **Method: *N*-body simulations**

Pagnini et al. 2023, A&A, 673, A86

***N*-body simulations of a Milky Way type galaxy accreting one or two satellites over a period of 5 Gyrs**

- MW-type galaxy and satellite(s) contain a population of **point-like globular clusters**
- **Satellite(s) mass is 1:10 (or 1:100) of the MW-type** galaxy mass
- 14 different initial inclinations of satellite(s) orbital planes





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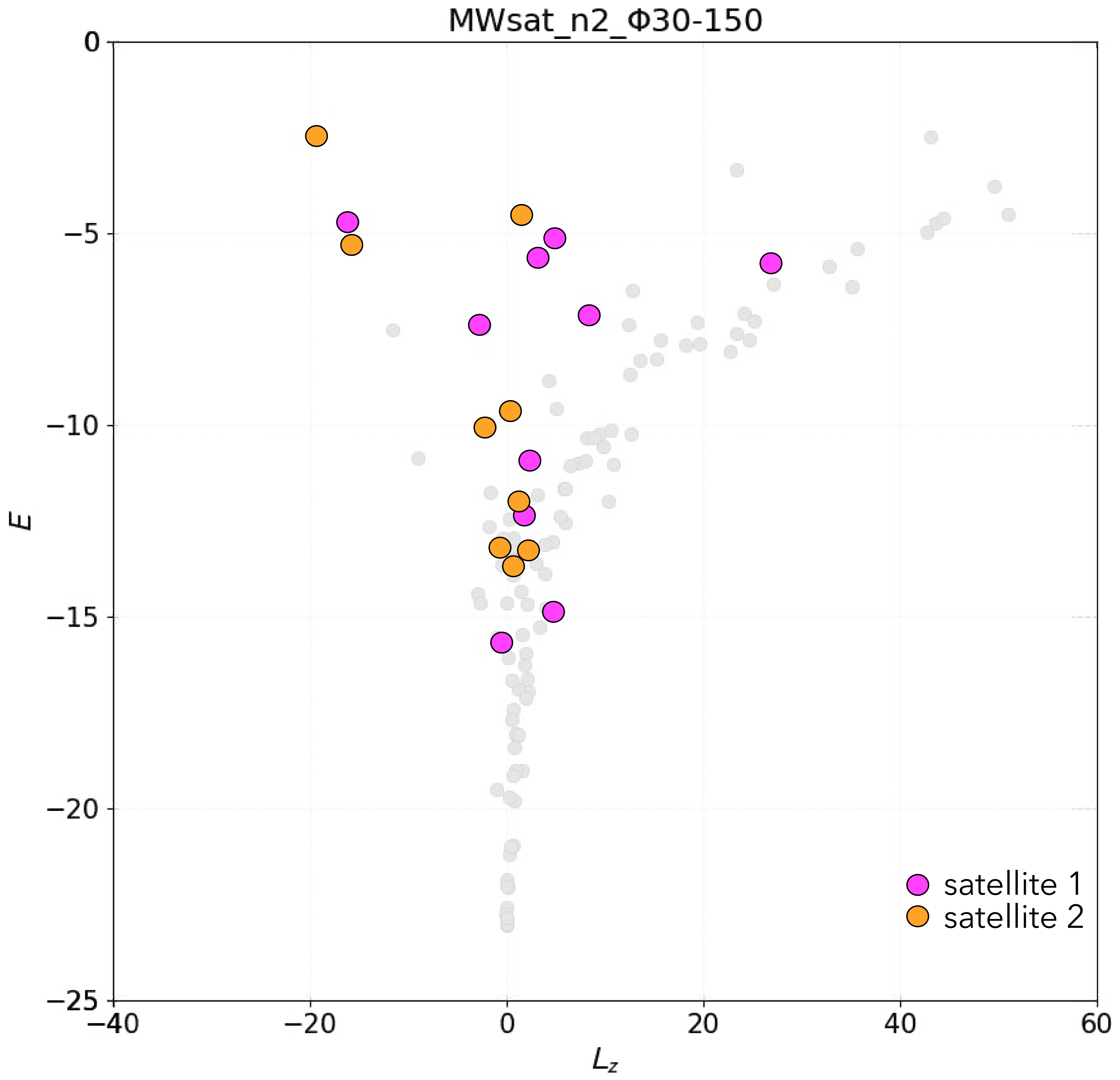
Results: GC mixing in E–L_z space

Pagnini et al. 2023, A&A, 673, A86



1. Globular clusters from the same progenitor do not group together

2. When multiple satellites are accreted, their cluster populations mix together

Results: GC mixing in E–L_z space

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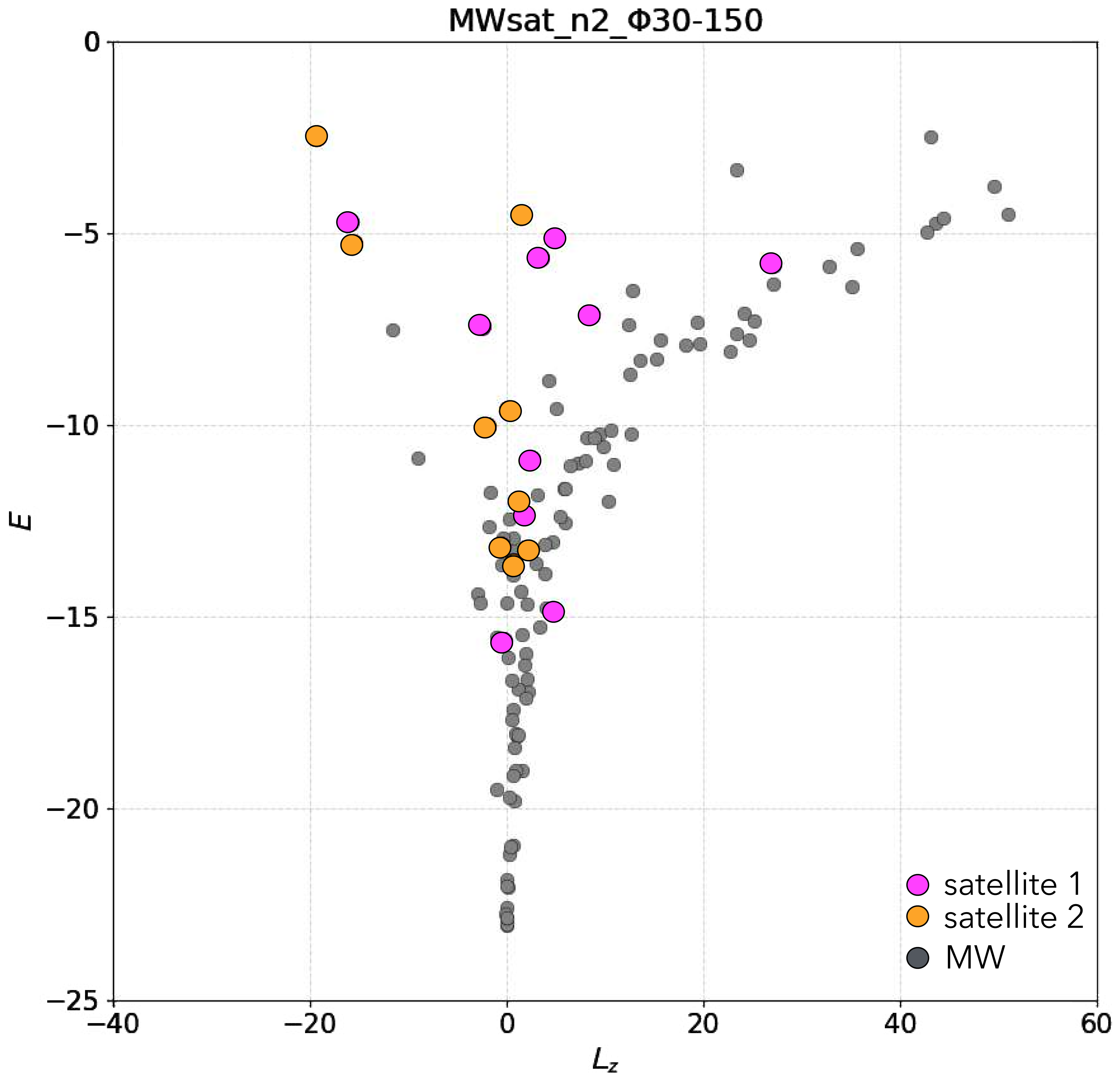


1. Globular clusters from the same progenitor do not group together
2. When multiple satellites are accreted, their cluster populations mix together
3. The population of clusters formed in-situ gets kinematically heated up

Clumps of globular clusters in kinematic spaces are not related to different galactic progenitors!

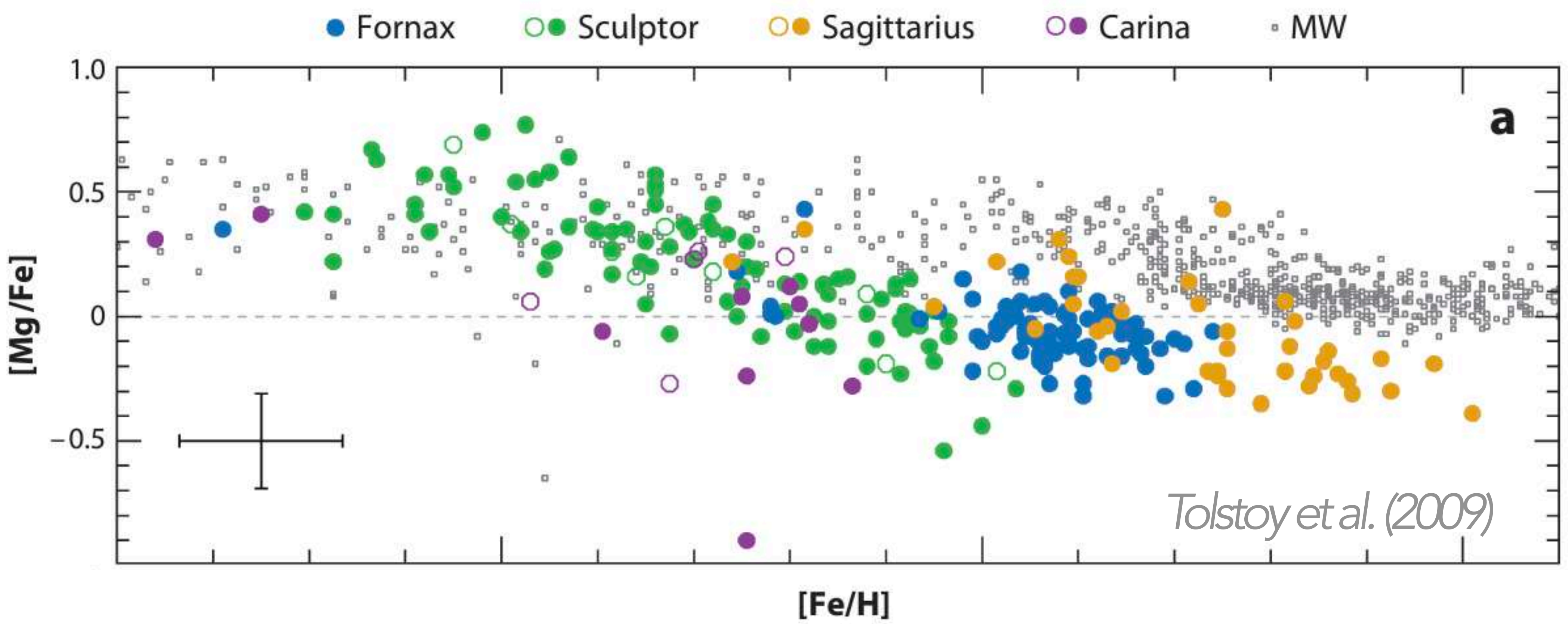
Context: Milky Way formation

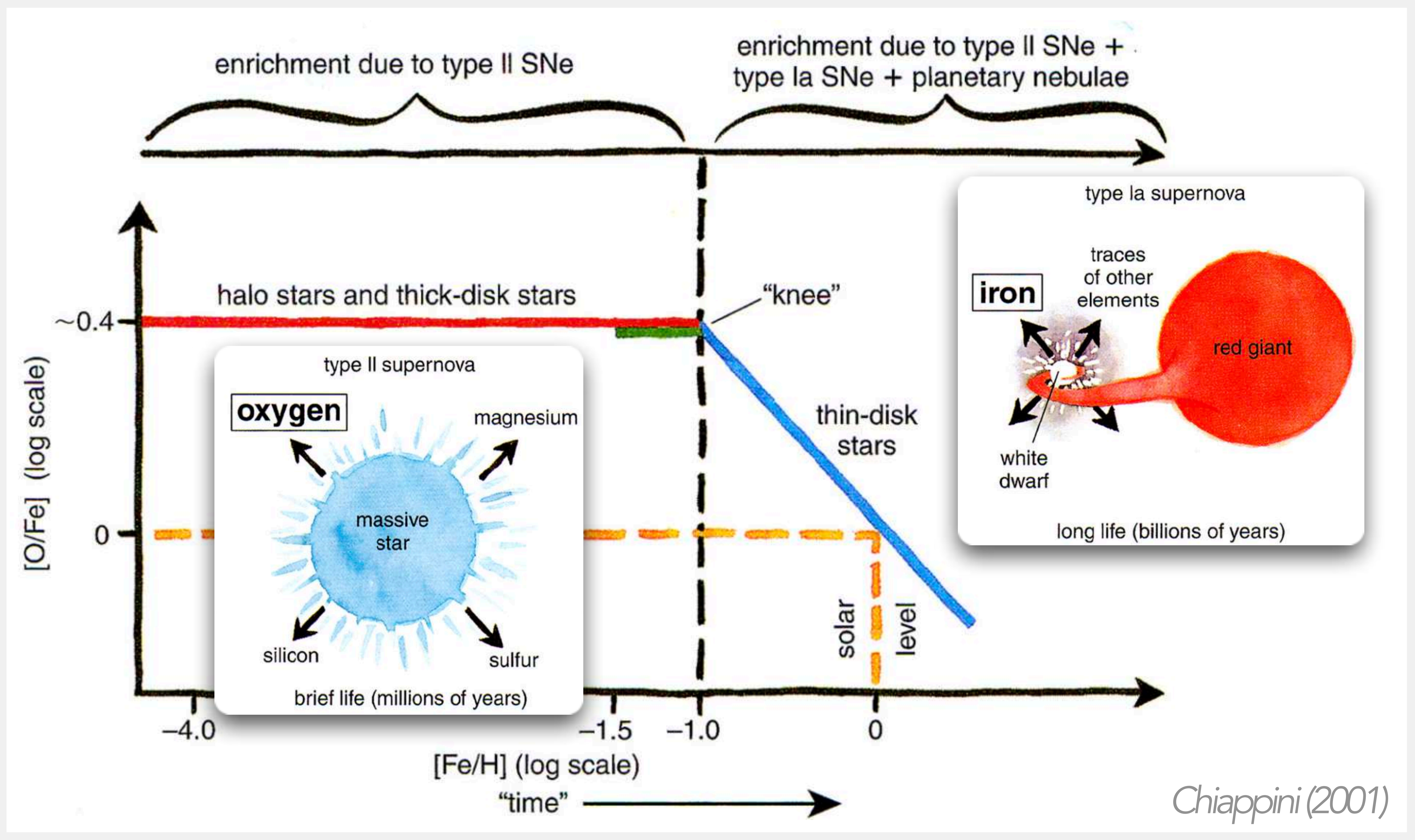
- Searching for past accretions: chemical abundance spaces

1) ~~SPATIAL INFORMATION~~: ~~positions on the sky + distances~~ only for ongoing mergers

2) ~~DYNAMICAL INFORMATION~~: ~~proper motions + line-of-sight velocities~~ alone is not reliable

3) **CHEMICAL ABUNDANCES**





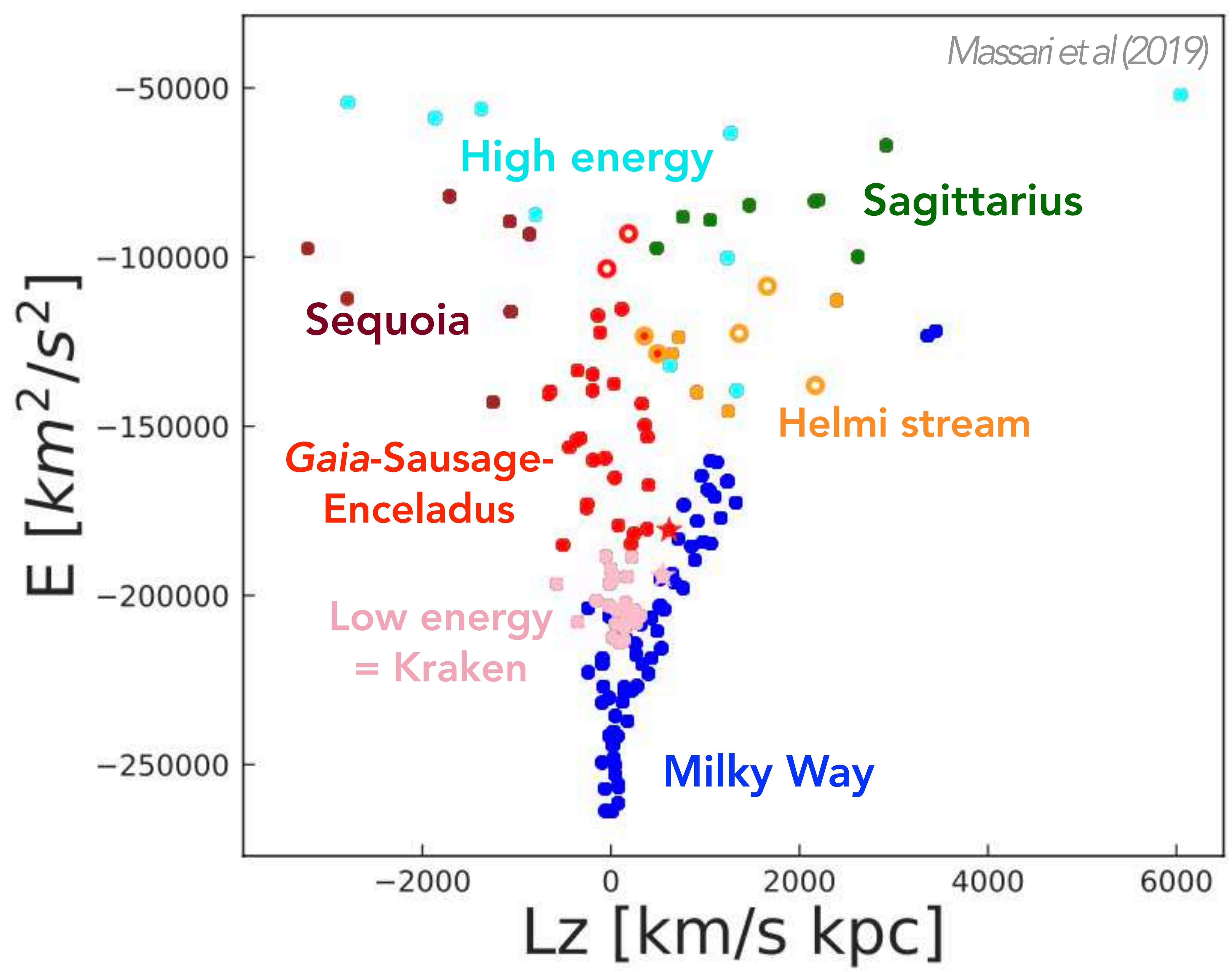
Stars belonging to satellite galaxies less massive than the MW have lower content of α elements

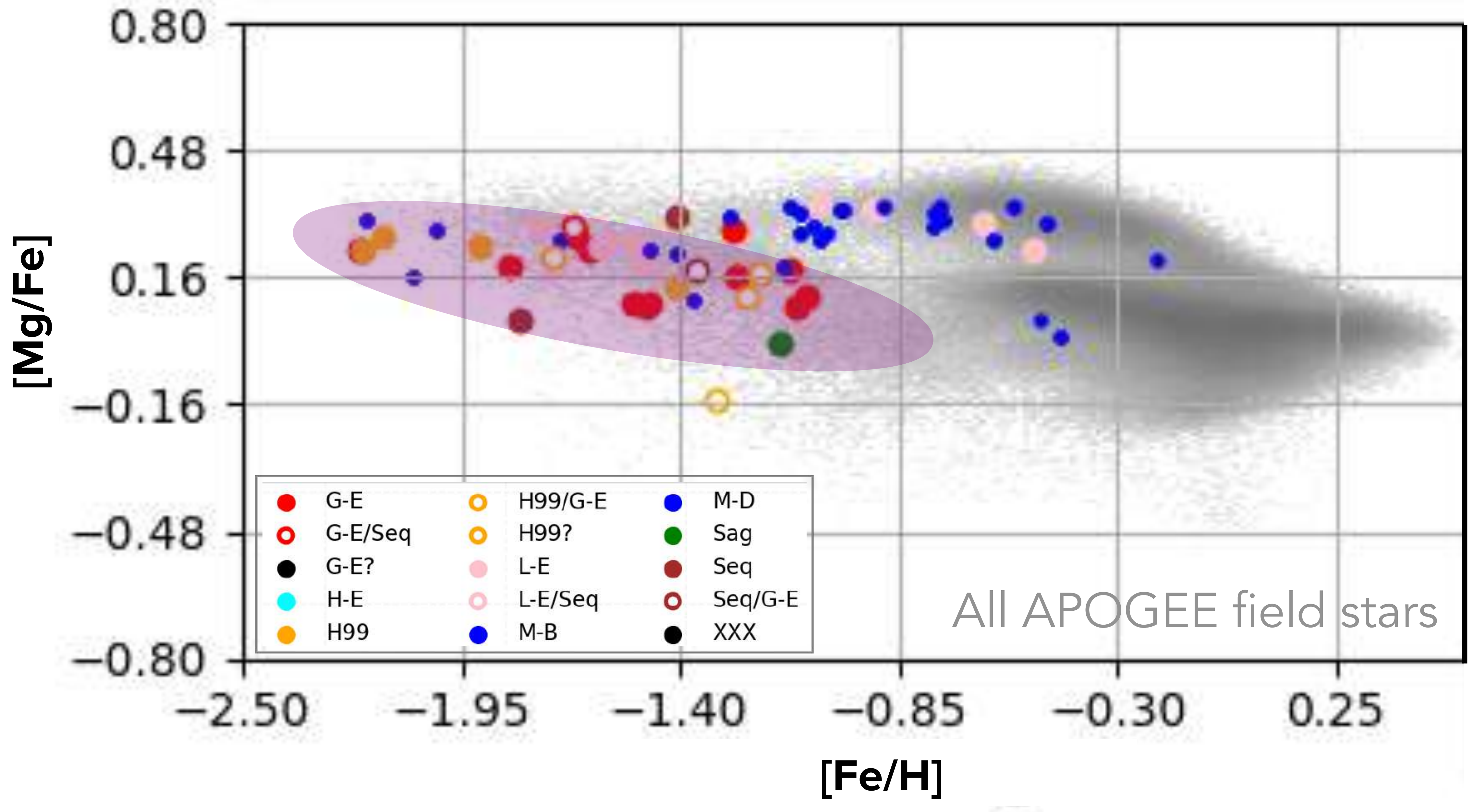
⇨ **Accreted stars and globular clusters = low α sequence**

Context: origin of Galactic globular clusters

- Chemical abundances could be the solutions

Can we disentangle the accreted sequence in chemical abundance spaces?



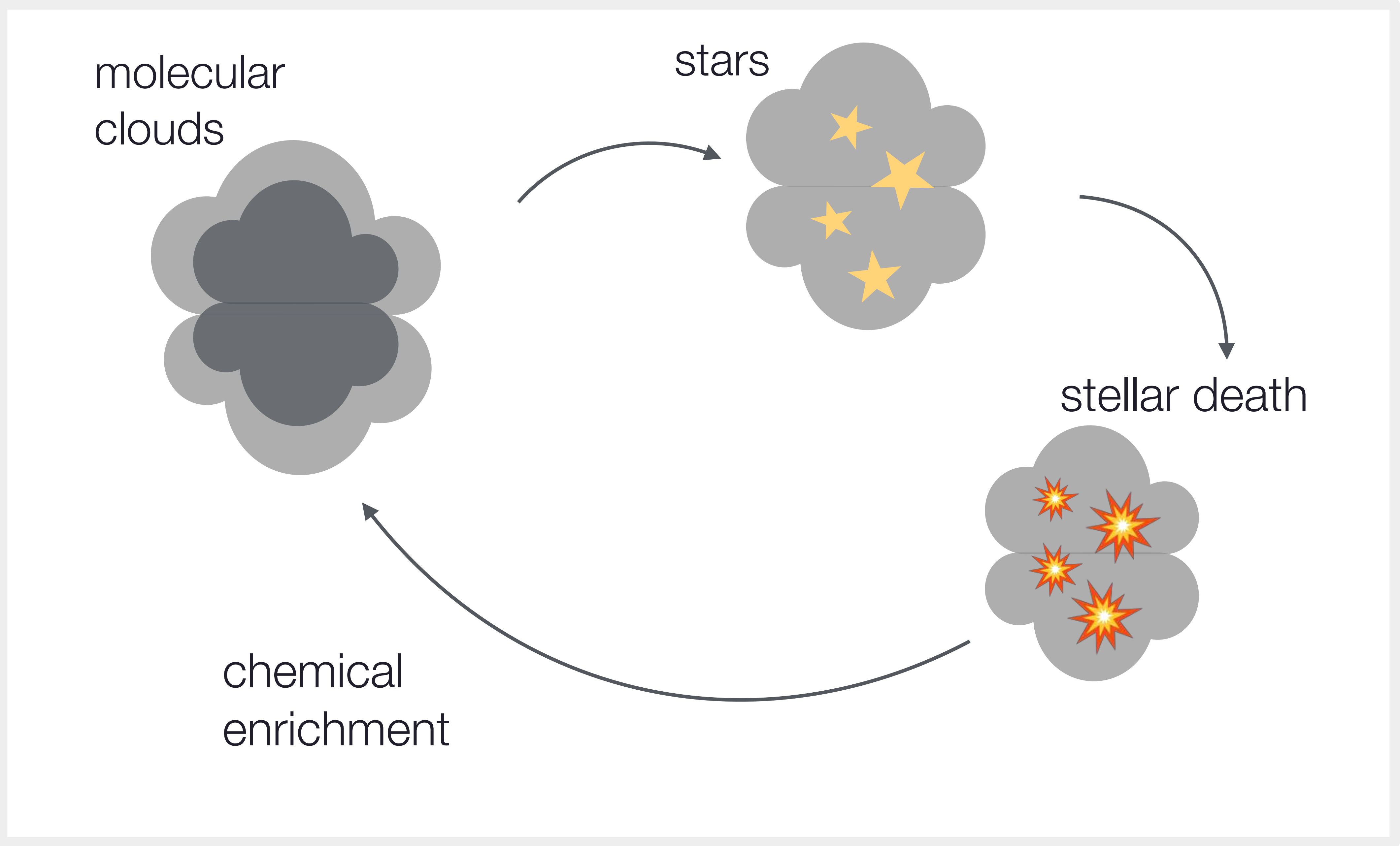


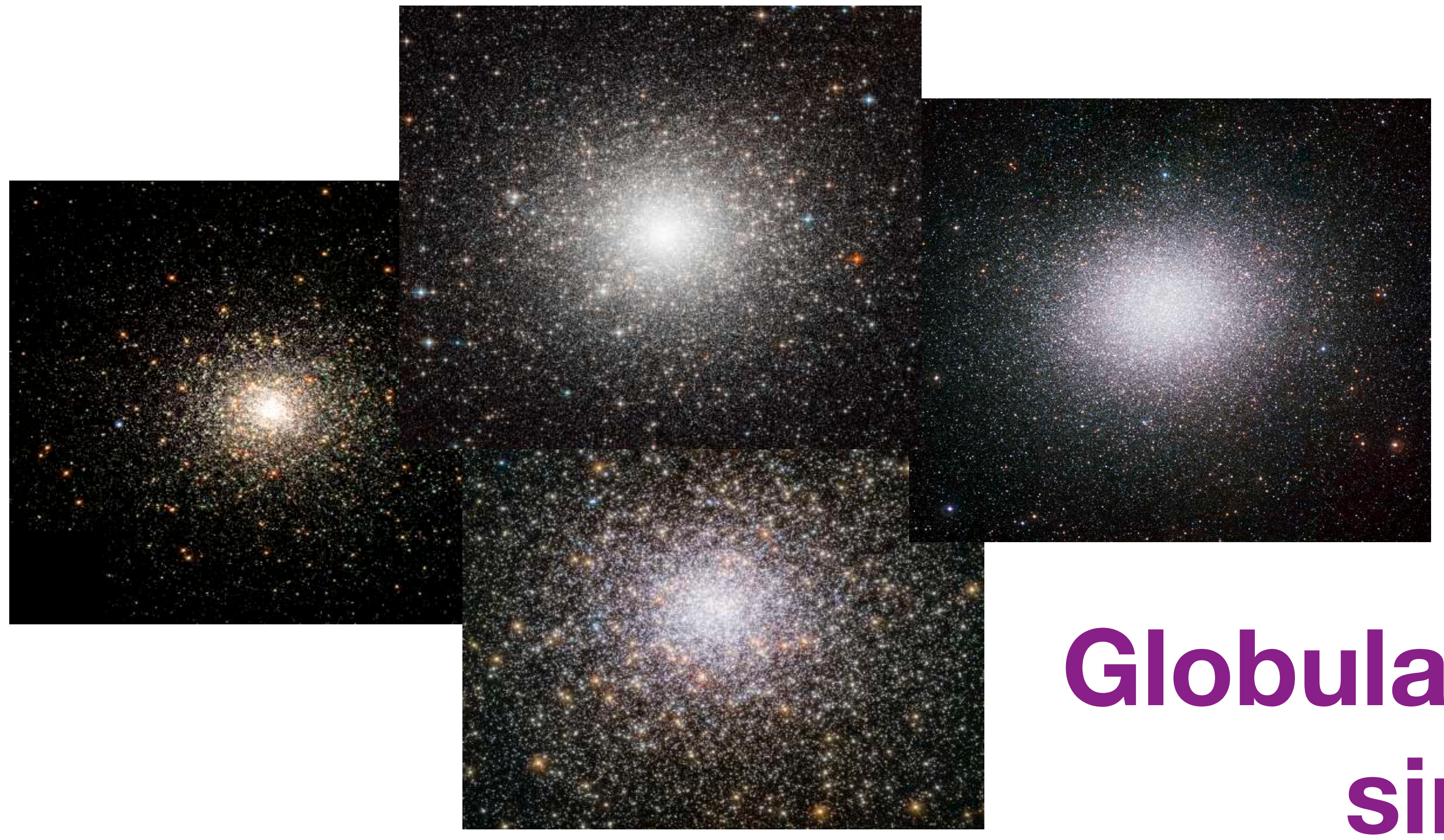
When considering **their mean abundance values**, there is still a **superposition of globular clusters with different progenitors.**

Context: origin of Galactic globular clusters

- Chemical abundances could be the solutions

A new approach: Instead of averaging chemical abundances, we compare the **full distribution of chemical abundances on a star-by-star basis** within each cluster.





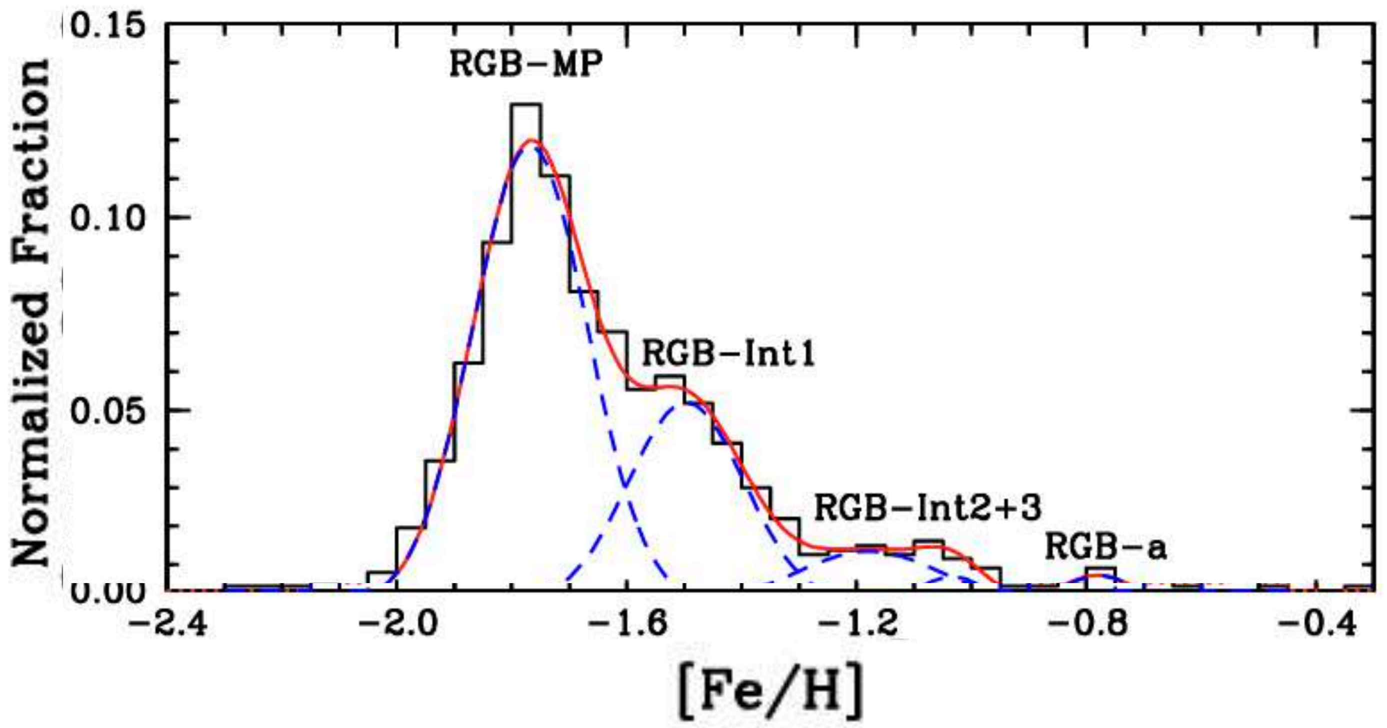
Globular clusters with similar chemical patterns likely share a common origin!

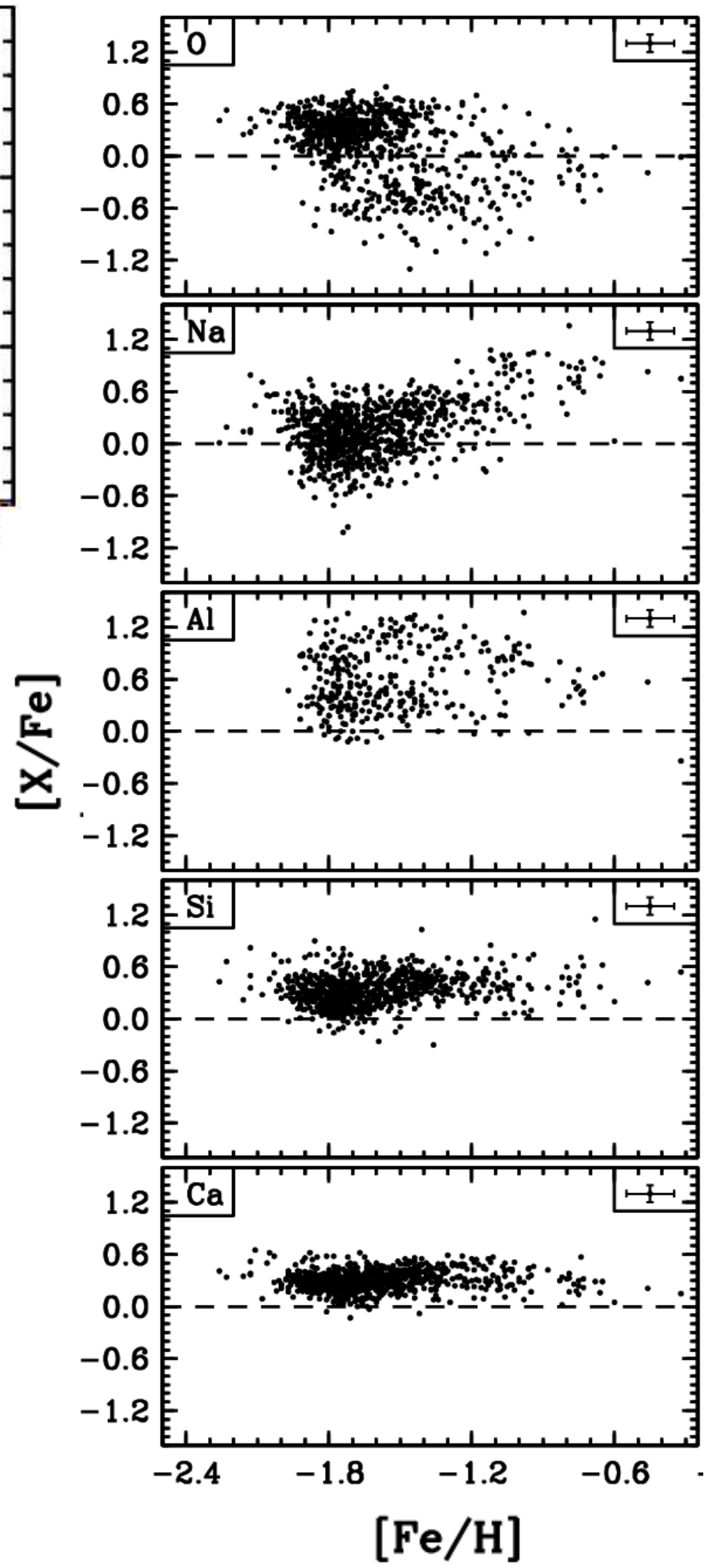
Context: ω Centauri

‣ **the most peculiar Galactic globular cluster**

- 3 x 10^6 $M_\odot$ ~ 10 times greater than the mean stellar mass of all Galactic GCs
- Stars with $-2.2 < [Fe/H] < -0.4$
- Spread in other abundances
- Extended age range of its stars

Johnson & Pilachowski (2010)





➜ Nuclear remnant of an accreted galaxy with an initial stellar mass of about 10^8 $M_\odot$

Bekki & Freeman (2003)

➜ ~12 globular clusters brought into the Milky Way

Eadie et al. (2022)

Can we find the other clusters brought by the progenitor of ω Centauri?

If ω Cen is representative of the inner regions of a galaxy, then its chemistry is representative at least in part of the chemistry of the progenitor

Pagnini et al. 2025, A&A, 693, A155

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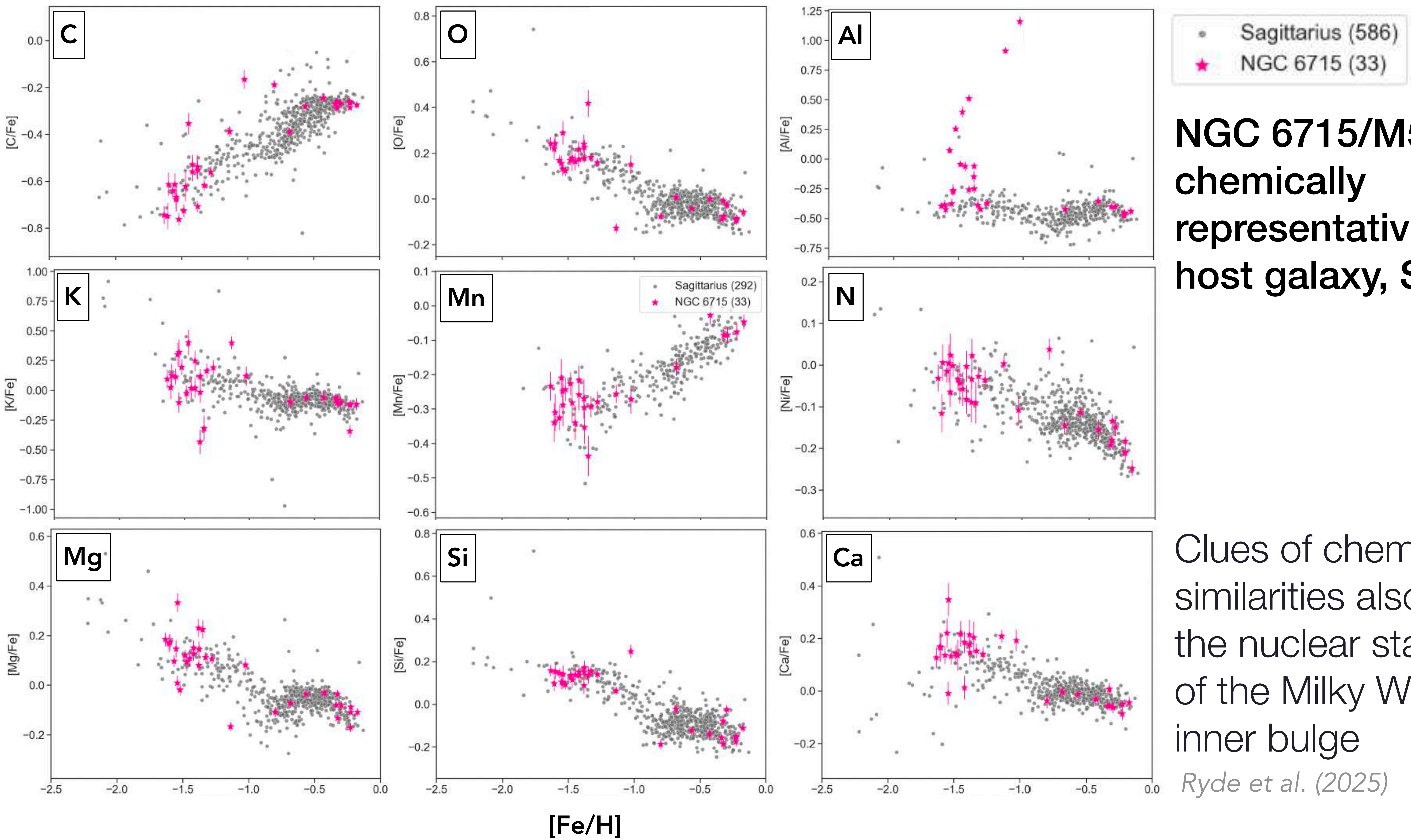
Context: nuclear star cluster and host galaxy

- The case of M54 and the Sagittarius



NGC 6715/M54 is chemically representative of its host galaxy, Sagittarius

Clues of chemical similarities also between the nuclear star cluster of the Milky Way and the inner bulge

Ryde et al. (2025)

Pagnini et al. 2025, A&A, 693, A155

NGC 6553
NGC 6522
NGC 6316
Terzan 5
M 15
NGC 3201
M 55
M 10
HP 1
APOGEE VAC catalog
Schiavon et al. (2024)
Terzan 10
M 68
M 80
M 22
NGC 6717
FSR 1758
NGC 6380
M 13
NGC 6723
NGC 6397
NGC 6760
NGC 6569
Terzan 9
NGC 6752
NGC 6229
M 54
M 92
47 Tuc
M 19
NGC 2808
NGC 6304
NGC 6642
NGC 362
M 107
M 12
M 5
M 79
Djorg 2
M 53
M 3
Terzan 4
NGC 288
M 71
NGC 6558
M 2
Ton 2
NGC 6544
NGC 6388
NGC 6293
NGC 2298
Terzan 2
Palomar 6
NGC 1851
M 4
ω Centauri

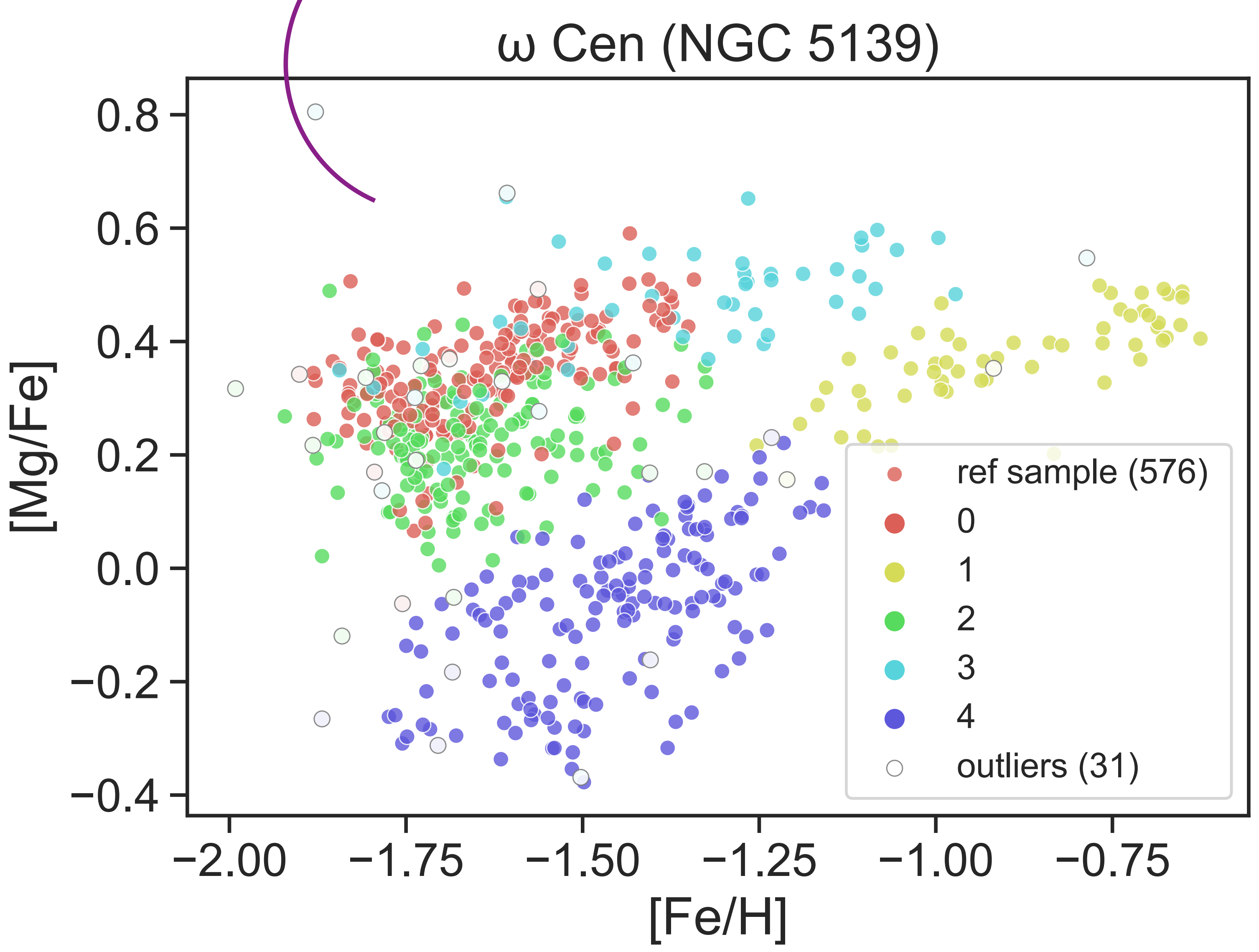
Method: clusters chemically compatible with ω Cen

▸ Multidimensional chemical link between Galactic globular clusters

GMMChem 8D	[Fe/H], [Mg/Fe], [Si/Fe], [Ca/Fe], [C/Fe], [Al/Fe], [K/Fe], [Mn/Fe]

1) **Distribution of ω Cen in 8-dimensional chemical space** fitted with increasing number of gaussian components
2) **Optimal number of components** determined by minimising the Bayesian information criterion

5 gaussian components



3) **For each cluster, the fraction of stars whose distribution falls in the GMM of ω Cen is estimated**
4) To estimate the uncertainties, this procedure is repeated each time bootstrapping ω Cen and each GC data

NGC 6752, NGC 6656, NGC 6809, NGC 6273, NGC 6205, and NGC 6254 with a high level of compatibility!

GC name	Fraction (%)	# stars
Ter10	98 ± 14	1
NGC2298	94 ± 22	2
NGC5139	**89 ± 3**	**607**
NGC6752	**84 ± 8**	**83**
NGC6656	**81 ± 8**	**68**
NGC6809	**79 ± 13**	**18**
NGC6273	**76 ± 9**	**40**
NGC6205	**69 ± 14**	**26**
NGC5024	64 ± 23	5
NGC6254	**64 ± 15**	**50**
NGC6544	56 ± 20	15
FSR1758	56 ± 26	7
NGC1904	52 ± 18	26
NGC6093	47 ± 50	1
NGC7089	44 ± 23	15
NGC6218	33 ± 19	40
NGC0288	31 ± 22	37
NGC6380	31 ± 28	9
Ter4	30 ± 46	1
NGC6121	29 ± 25	169
Djorg_2	24 ± 36	4
NGC6171	24 ± 21	23
NGC0104	20 ± 19	224
NGC6522	20 ± 34	2
NGC6715	16 ± 10	26
HP1	15 ± 20	10
NGC6838	14 ± 15	45
NGC6397	13 ± 15	10
NGC5272	11 ± 7	71
NGC6723	11 ± 18	7
NGC6558	11 ± 25	3
NGC6569	11 ± 19	6
Ter9	10 ± 15	9
NGC3201	8 ± 8	98

Pagnini et al. 2025, A&A, 693, A155

Results: the globular cluster family of ω Cen

- **Multidimensional chemical link between Galactic globular clusters**

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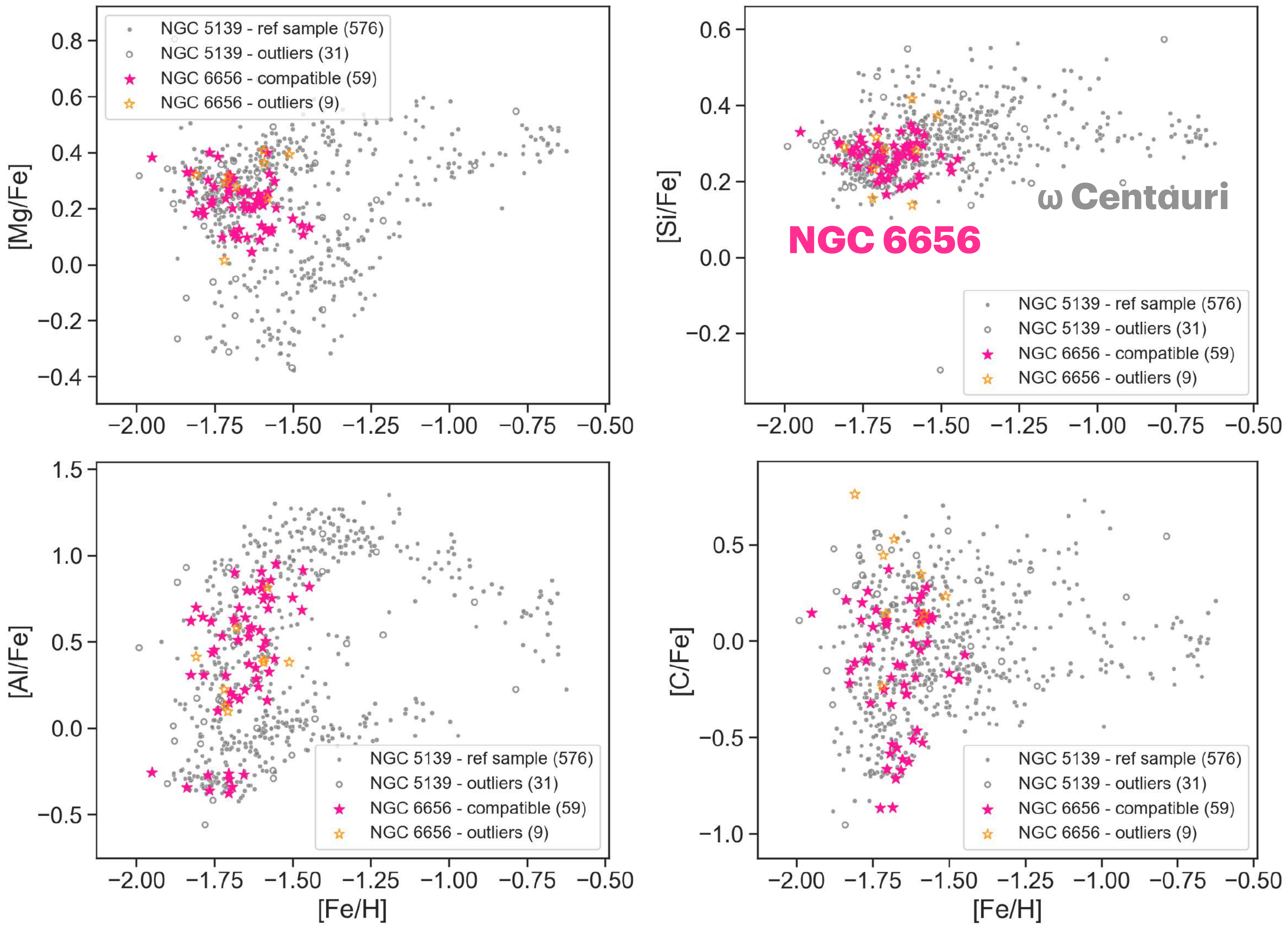
NGC7089	44 ± 23	15

ω Cen → NGC5139

"Metal-poor" → NGC6656, NGC6809, NGC6273

+ [Ca/Fe], [K/Fe], [Mn/Fe]



Pagnini et al. 2025, A&A, 693, A155

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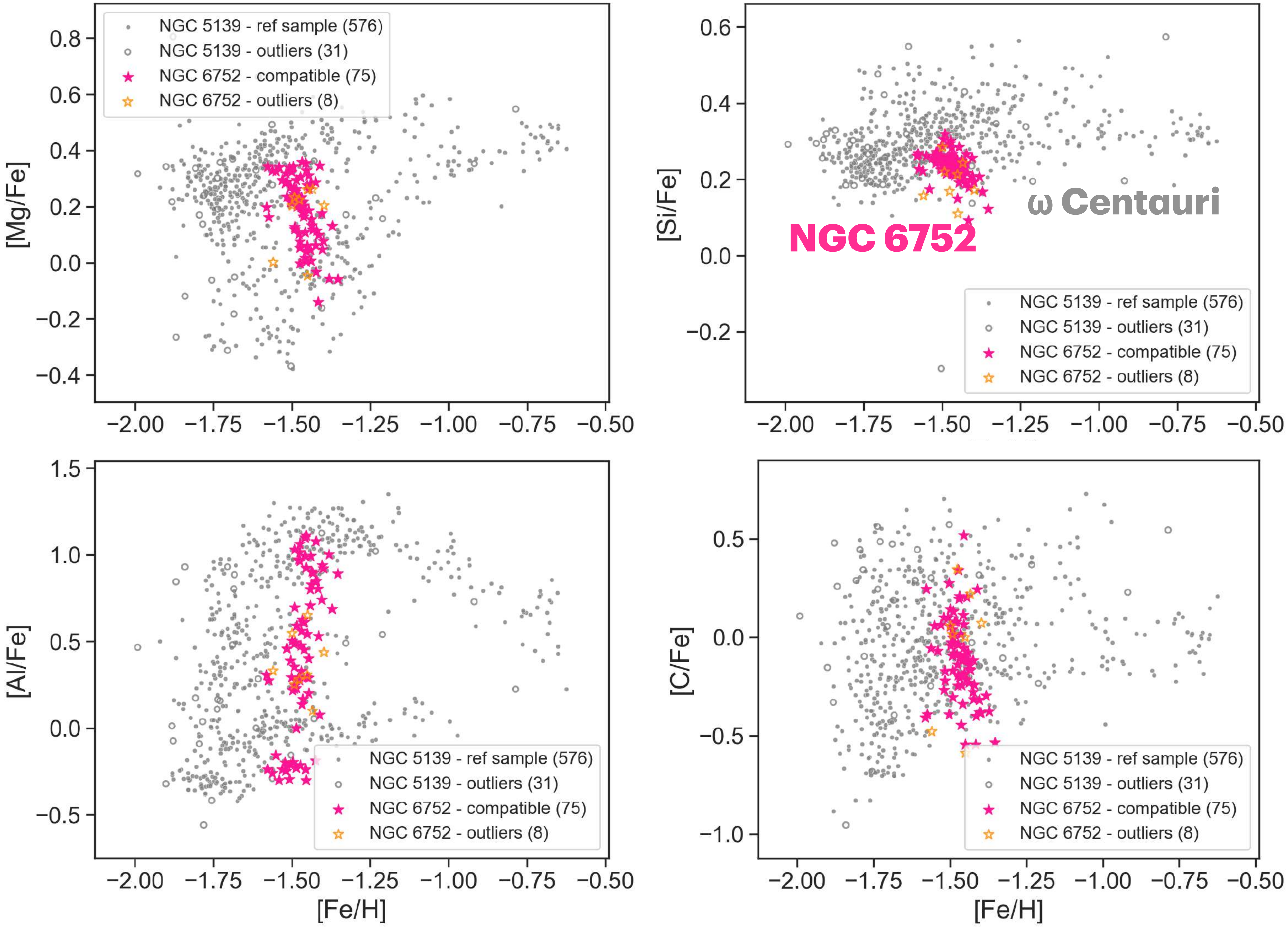


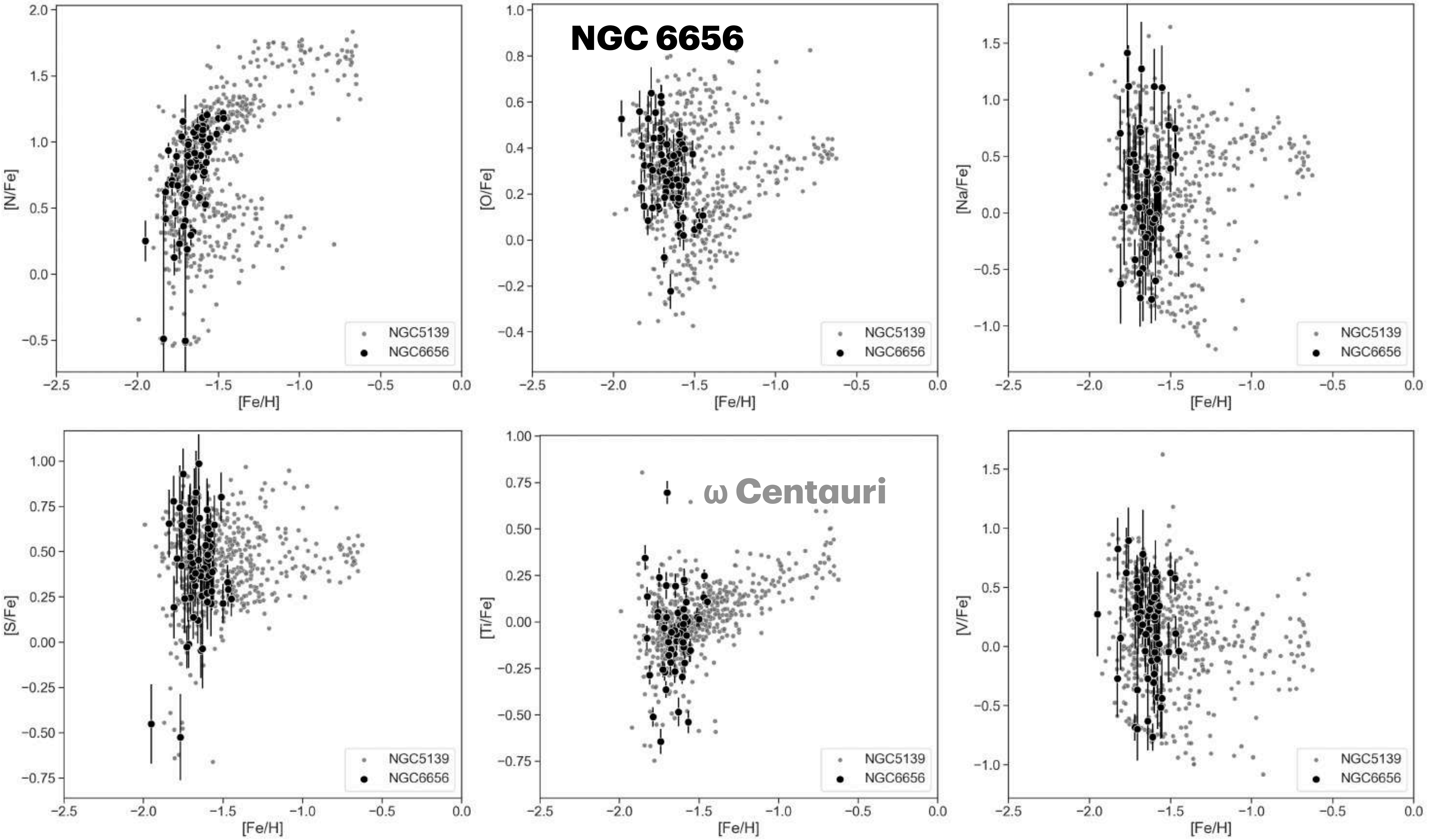
Pagnini et al. 2025, A&A, 693, A155

Results: the globular cluster family of ω Cen

- Clusters match ω Cen even beyond GMM dimensions

Pagnini et al. 2025, A&A, 693, A155

For all these clusters, the overlap with ω Cen qualitatively occurs also in the other chemical spaces not used in the GMM



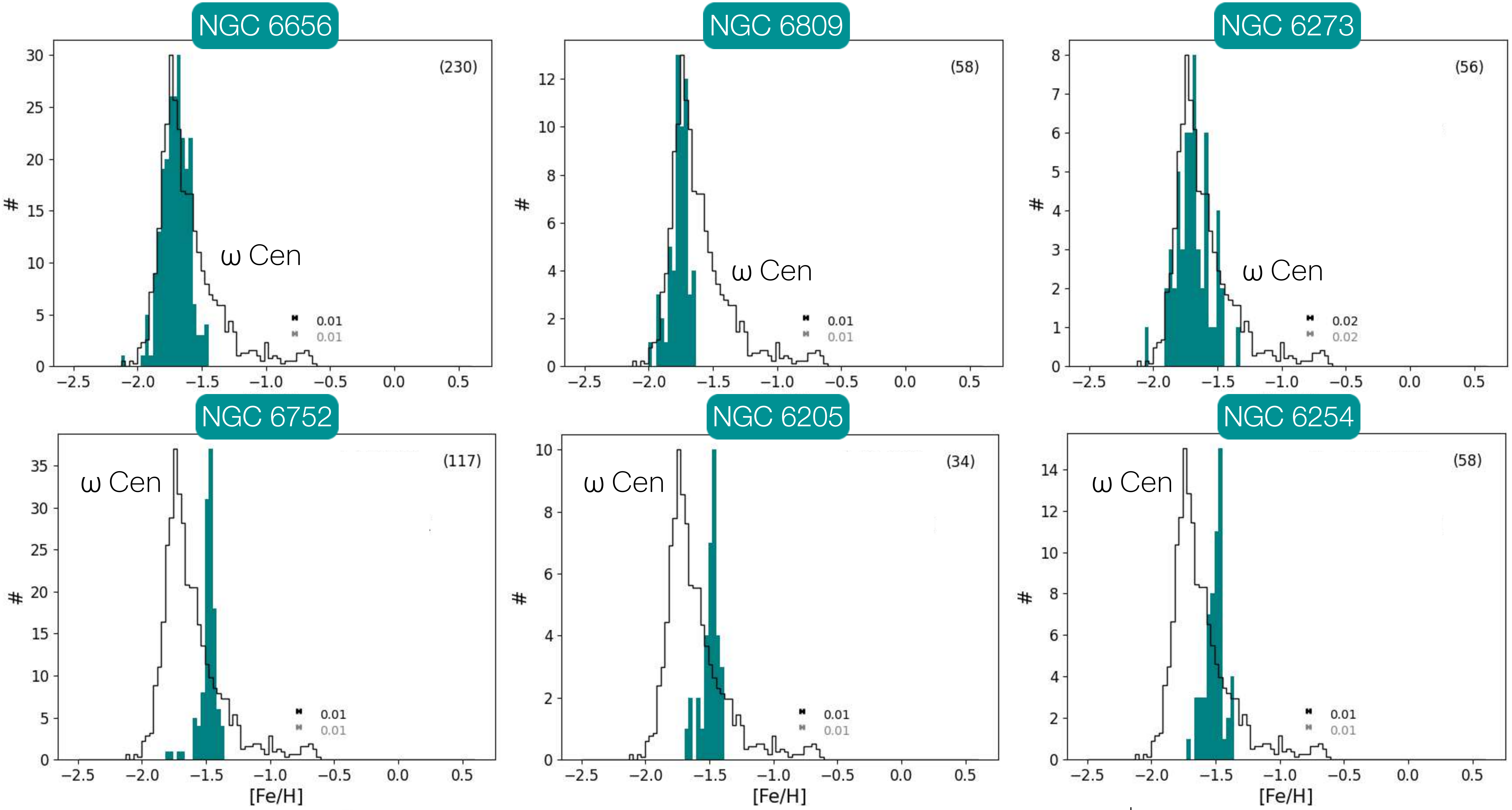
Results: the globular cluster family of ω Cen

- Similarities in the metallicity distribution functions (MDFs)

Pagnini et al. 2025, A&A, 693, A155

“Metal-poor” globular clusters

“Metal-rich” globular clusters



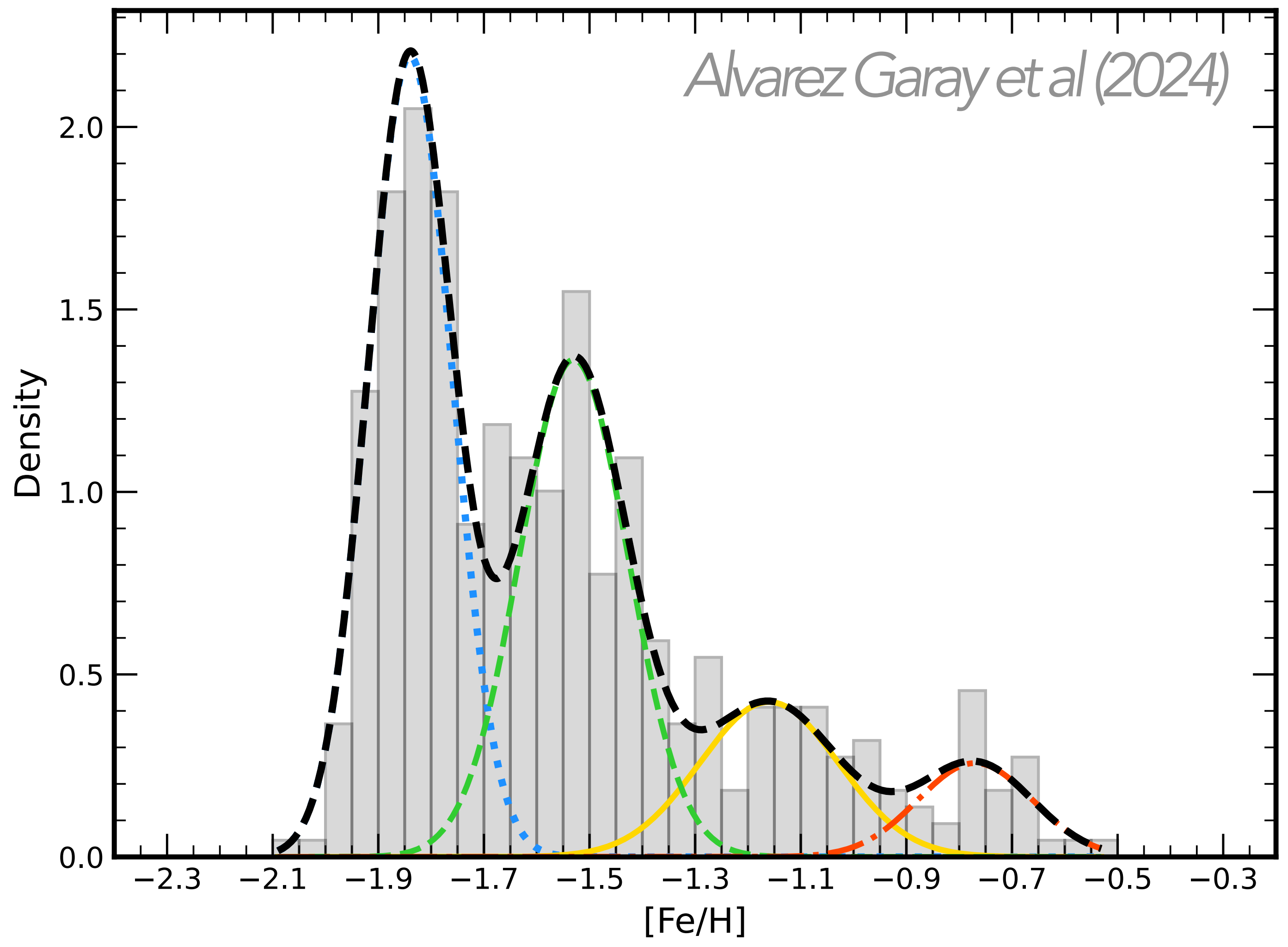
Results: the globular cluster family of ω Cen

- **Similarities in the metallicity distribution functions (MDFs)**

Pagnini et al. 2025, A&A, 693, A155

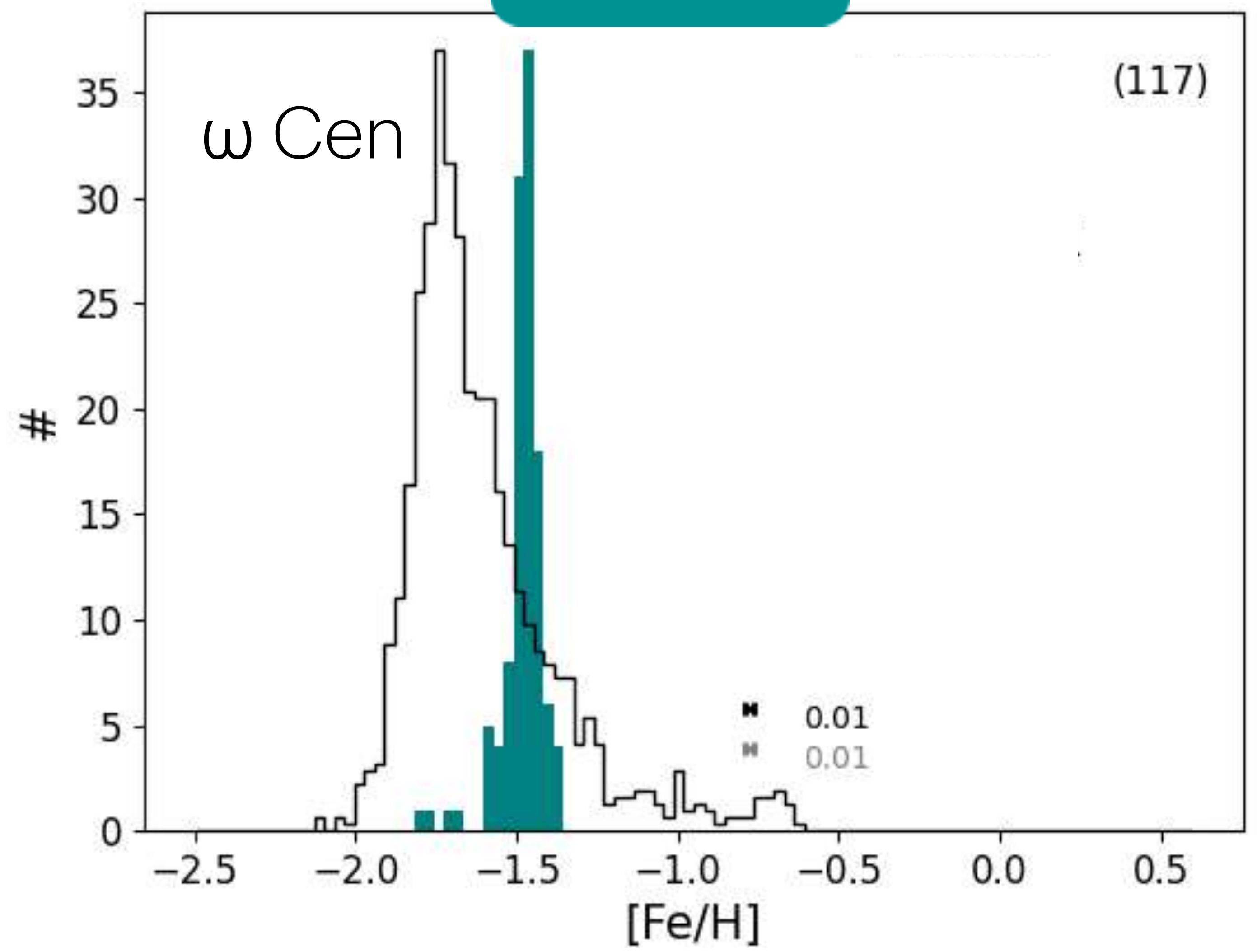
A **secondary peak in ω Cen's MDF** has been observed in literature

Not visibile in APOGEE, possibly due to the spatial coverage ω Cen, with a deficiency of stars in the central regions of the cluster

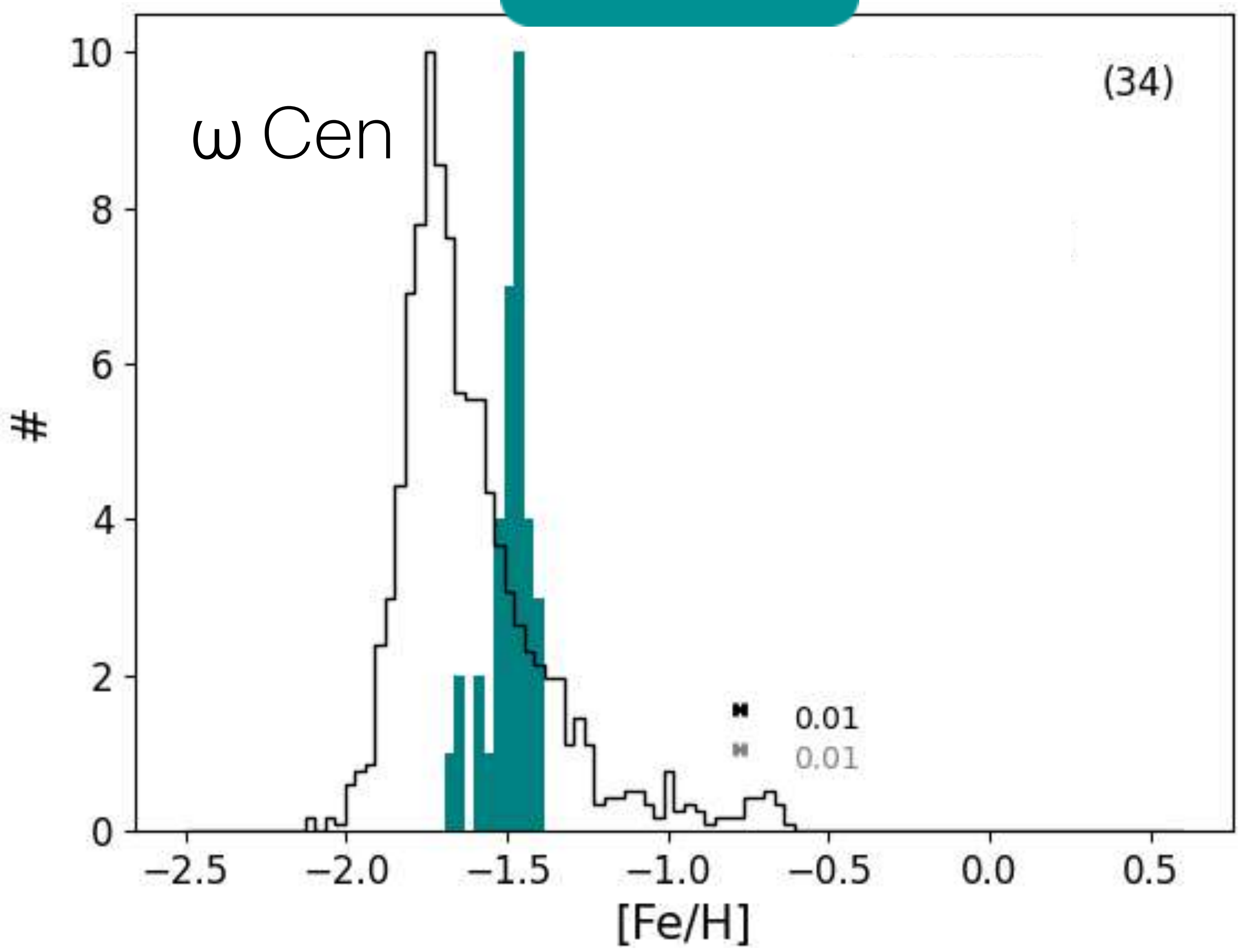


"Metal-rich" globular clusters

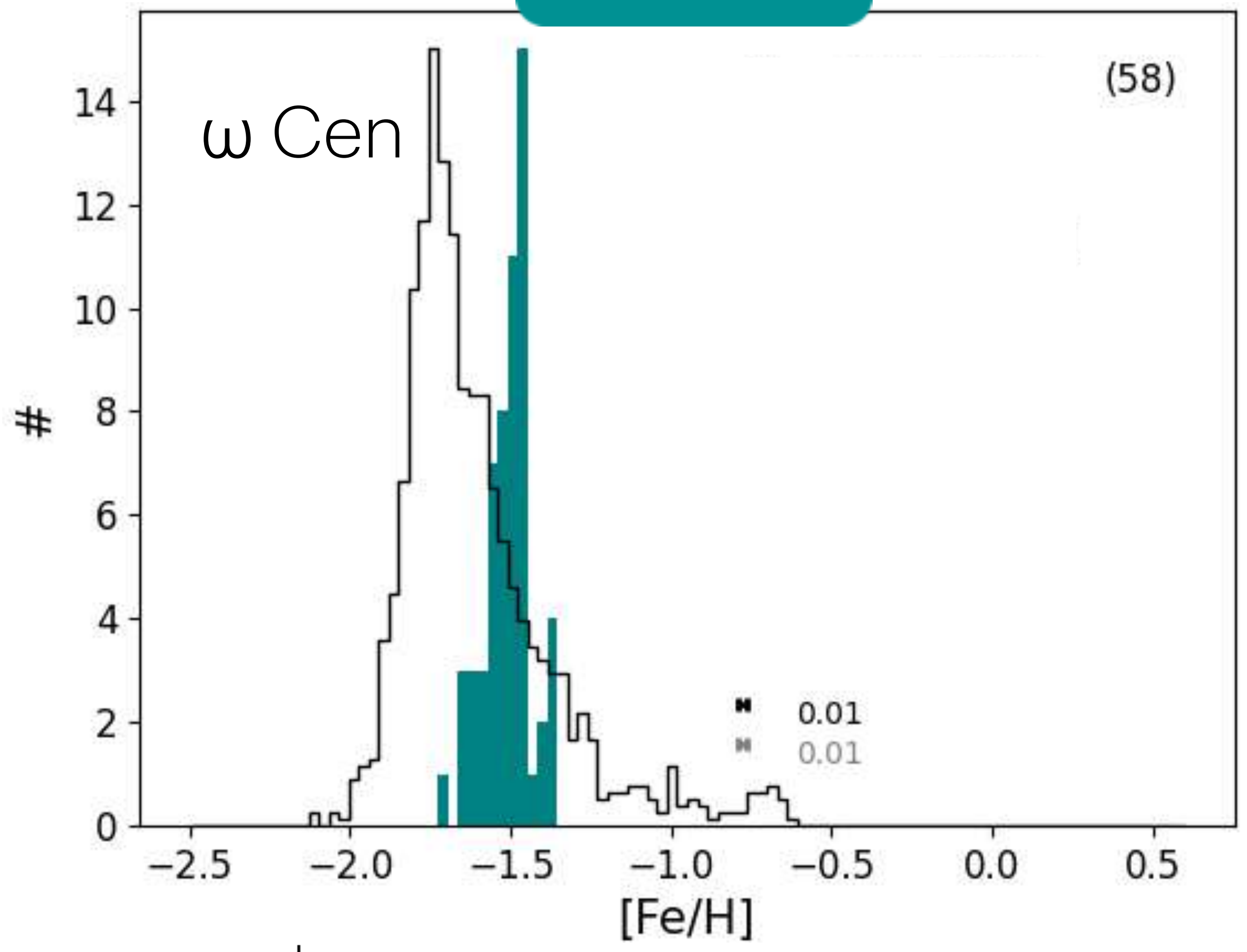
NGC 6752



NGC 6205



NGC 6254



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Pagnini et al. 2025, A&A, 693, A155

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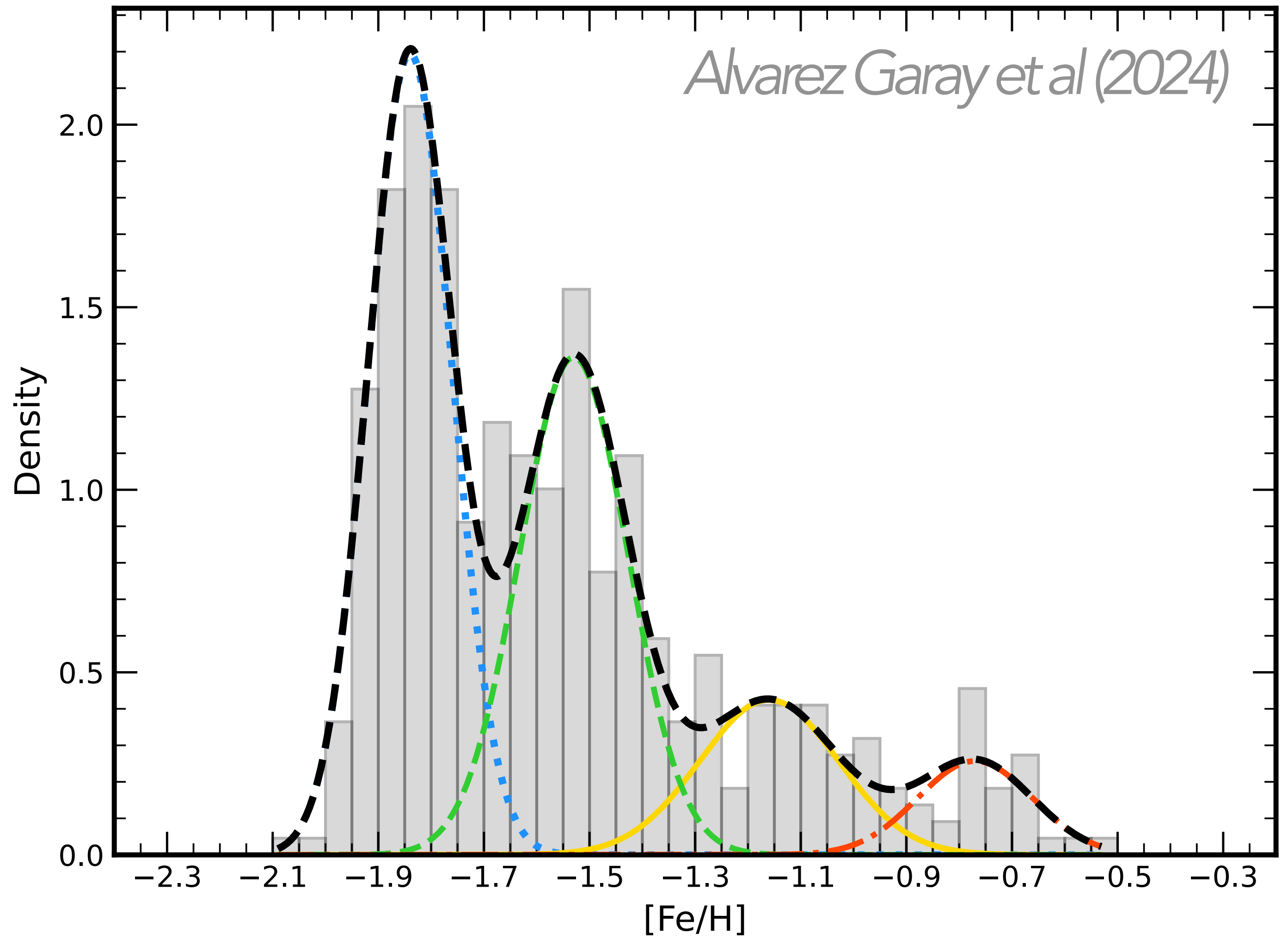
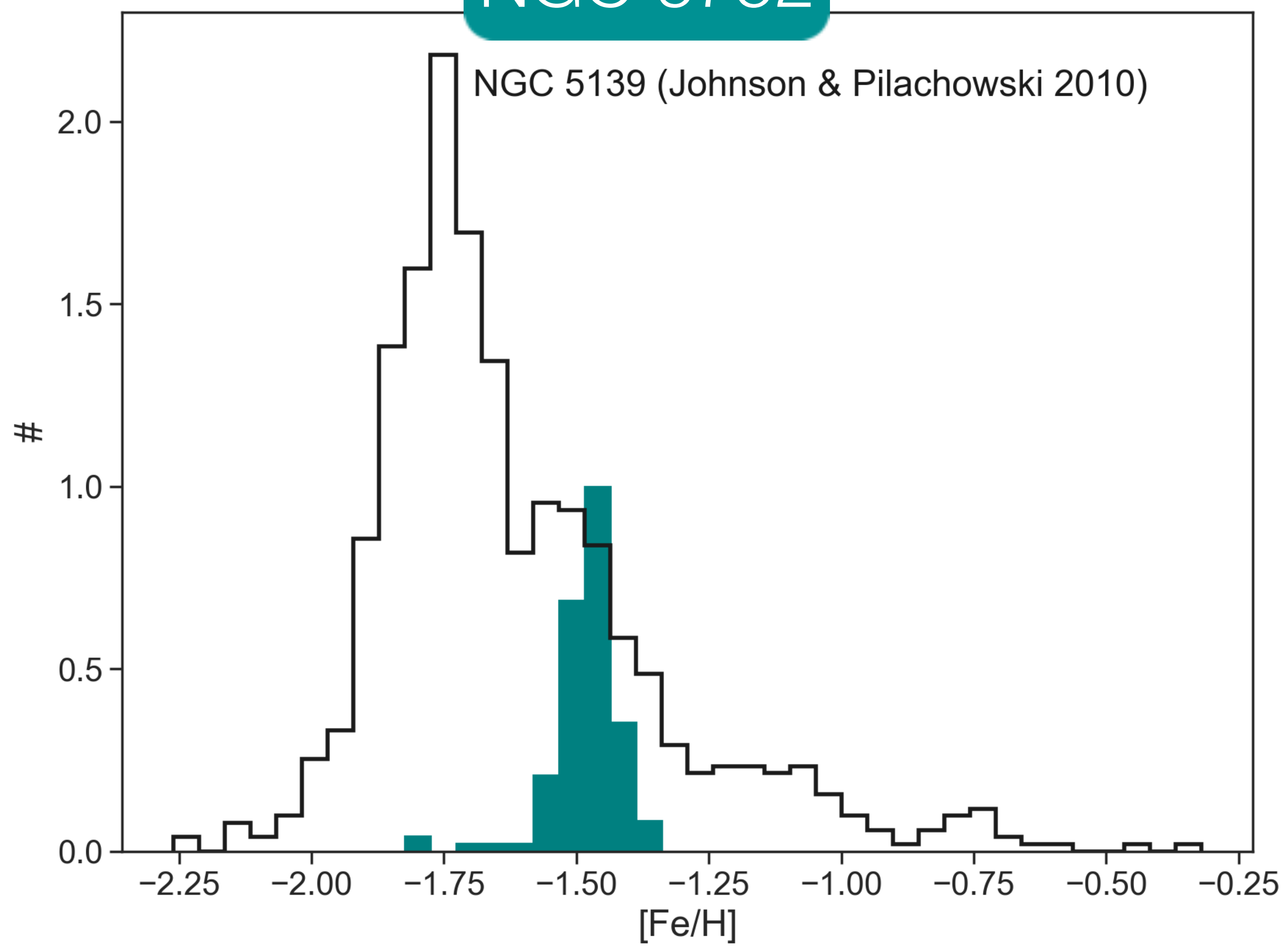


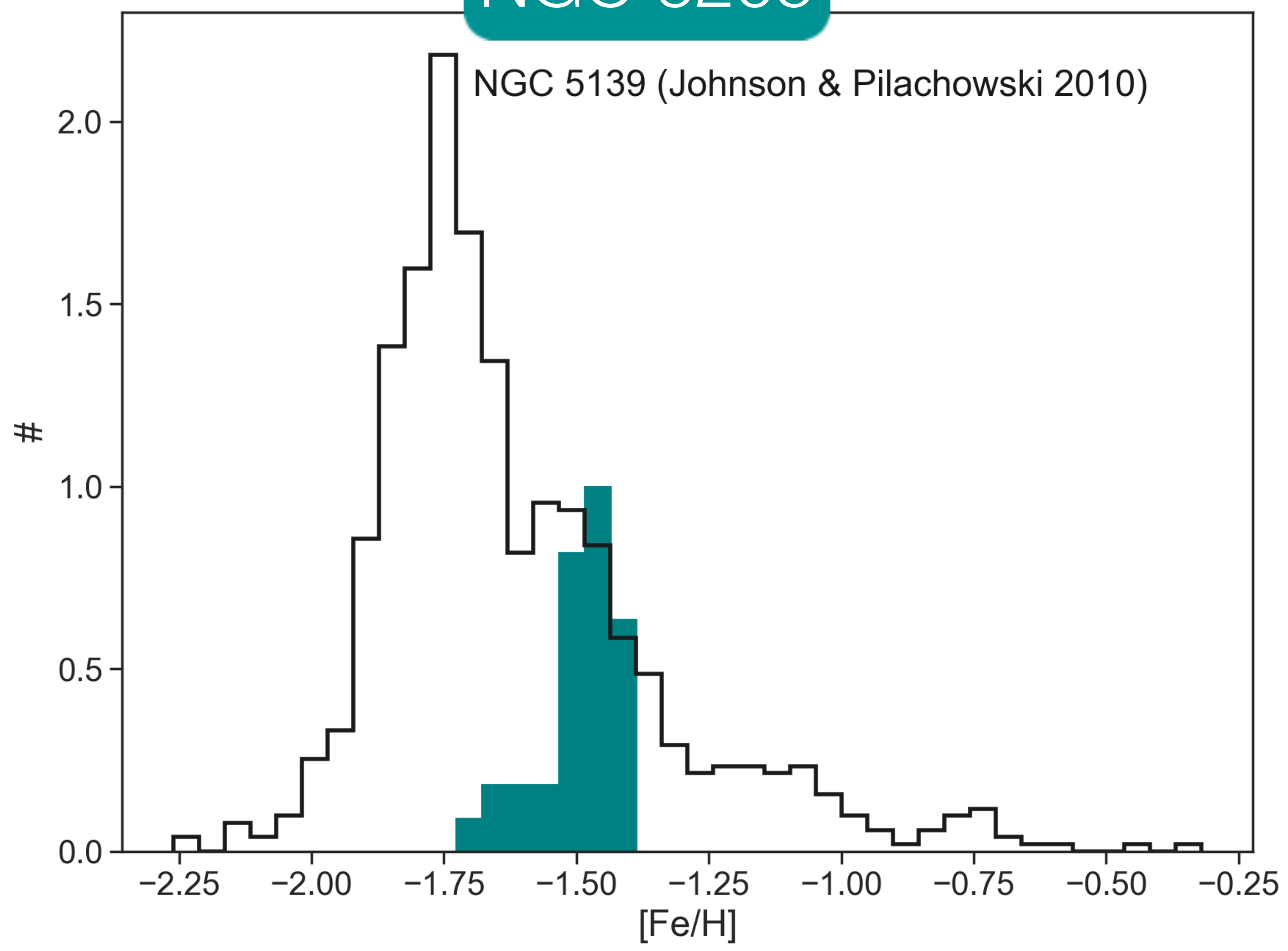
If these clusters formed in similar, but not same, systems, they must have formed in environments that experienced extremely similar star formation phases

"Metal-rich" globular clusters

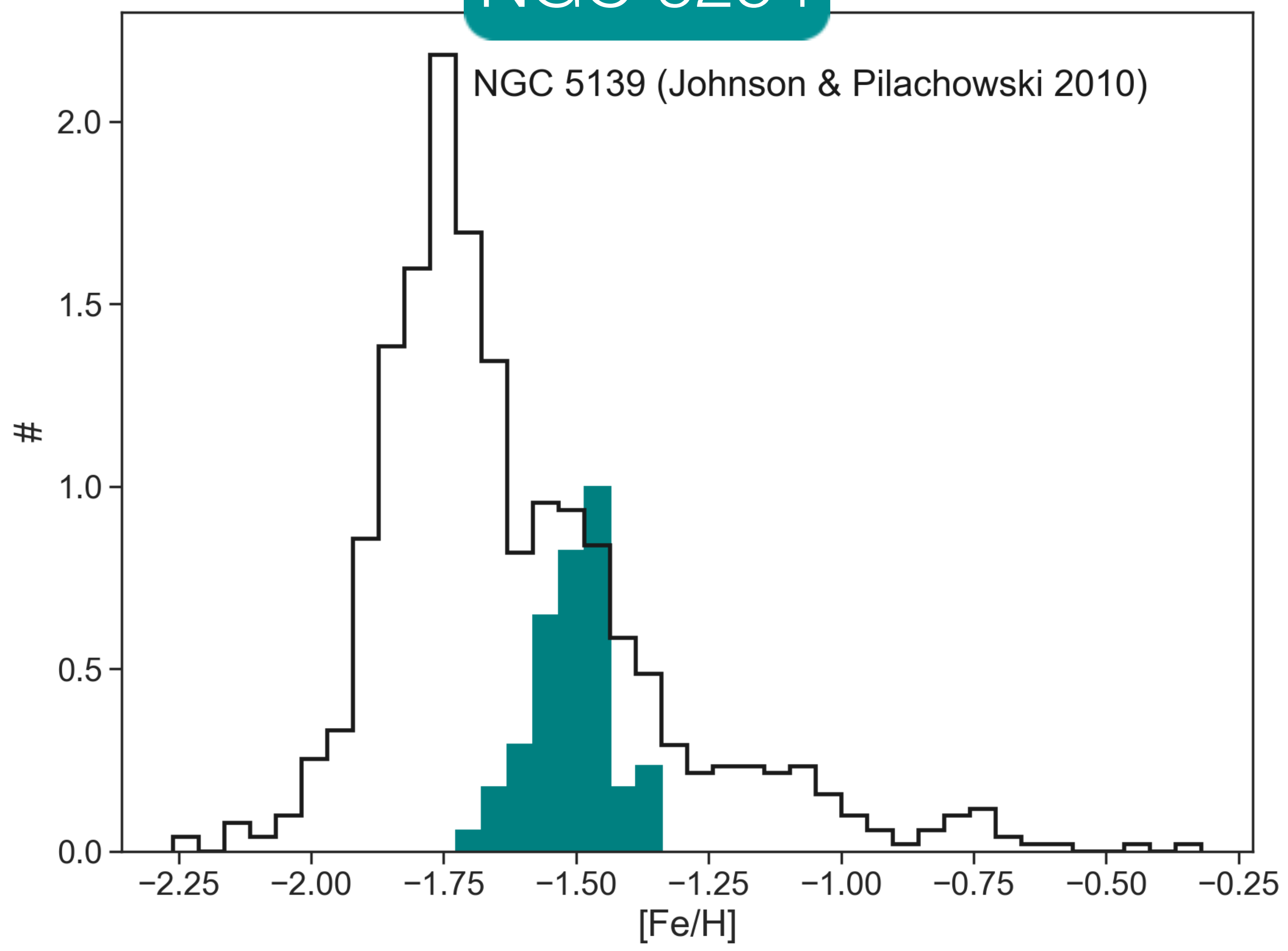
NGC 6752



NGC 6205



NGC 6254



Is this just a coincidence?
Do all systems at these metallicities look alike?

Pagnini et al. 2025, A&A, 693, A155

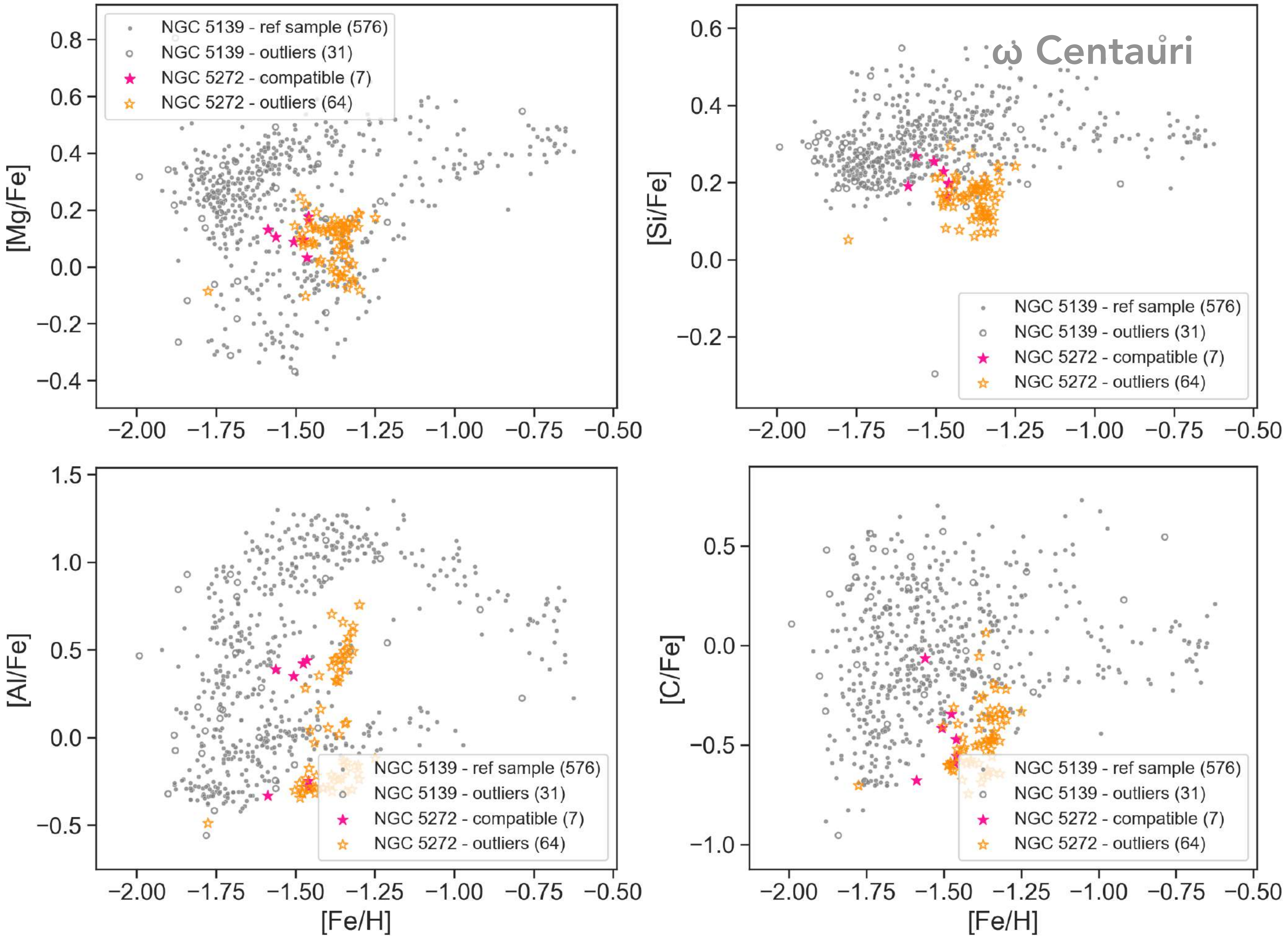
Results: the globular cluster family of ω Cen

▸ **Do all systems at low metallicities look alike?**

Pagnini et al. 2025, A&A, 693, A155

NGC6715, NGC5272, Ter9, NGC3201 have a **very low degree of compatibility** with ω Cen, **despite their MDF** modes and medians are **in the metallicity range of ω Cen** stars.

NGC 5272



Compatibility: 11 ± 7 %

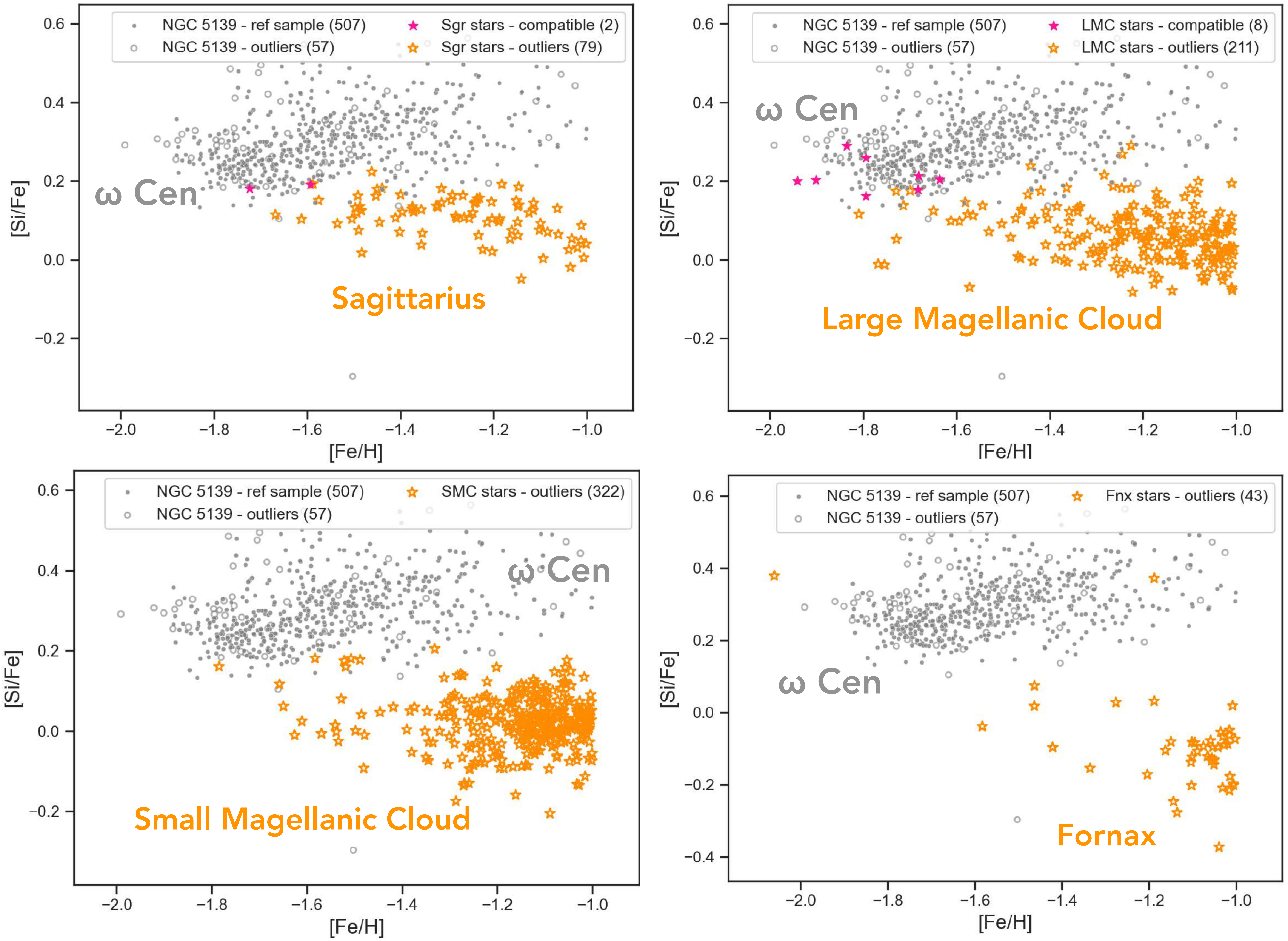
Results: the globular cluster family of ω Cen

- Do all systems at low metallicities look alike?

Pagnini et al. 2025, A&A, 693, A155

According to our GMM, the **chemical compatibility** of the Large and Small **Magellanic Clouds** (LMC, SMC), **Sagittarius** (Sgr), and **Fornax** (Fnx) **with ω Cen is very low**, even in the low metallicity regime.

⇨ **none of the clusters in the family of ω Cen have come from progenitors of these dwarf galaxies**



We suggest that NGC 6752, NGC 6656, NGC 6809, NGC 6273, NGC 6205, and NGC 6254 formed in the same satellite, the progenitor of ω Cen, that we name as *Nephele*

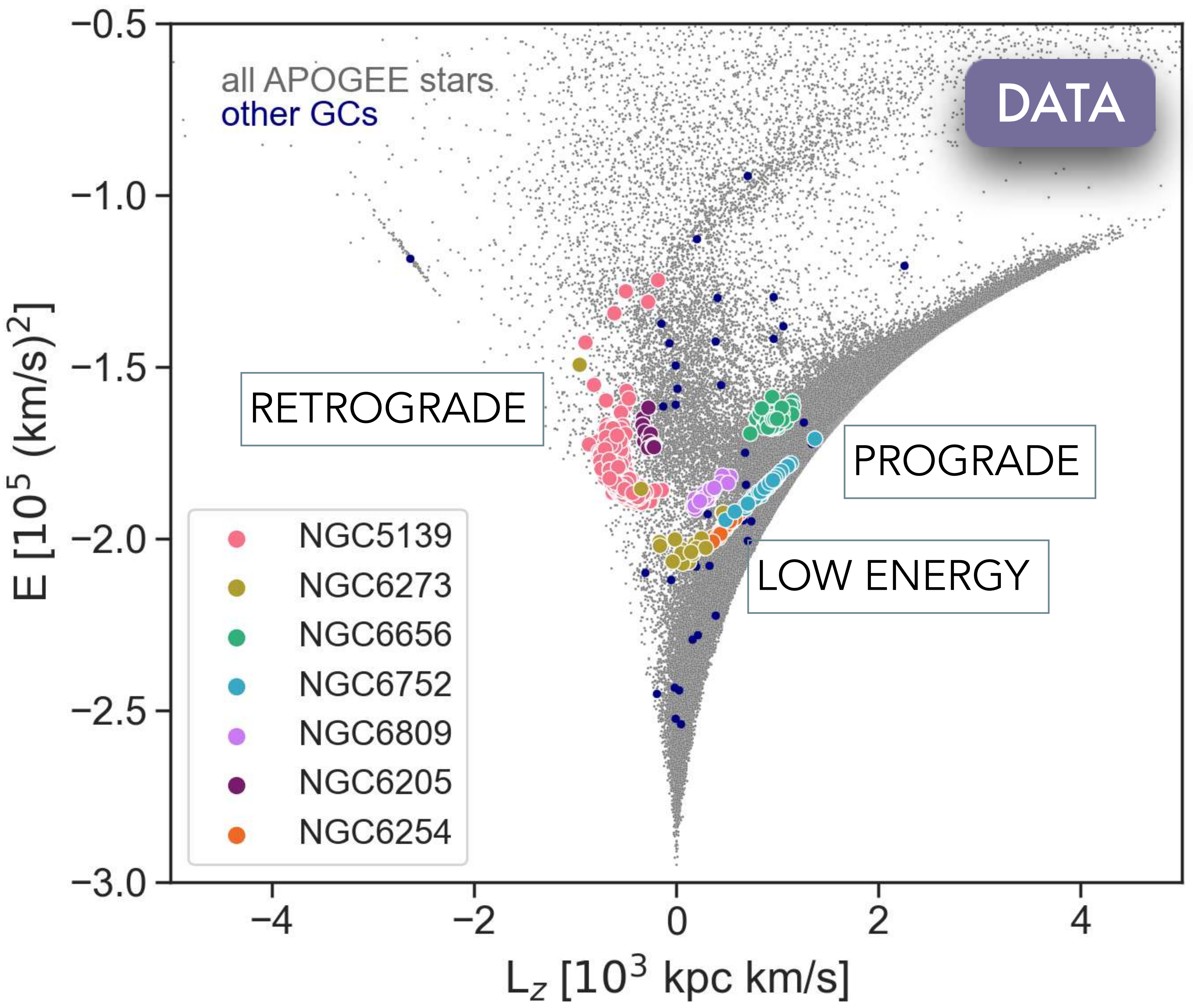
Pagnini et al. 2025, A&A, 693, A155

Results: the globular cluster family of ω Cen

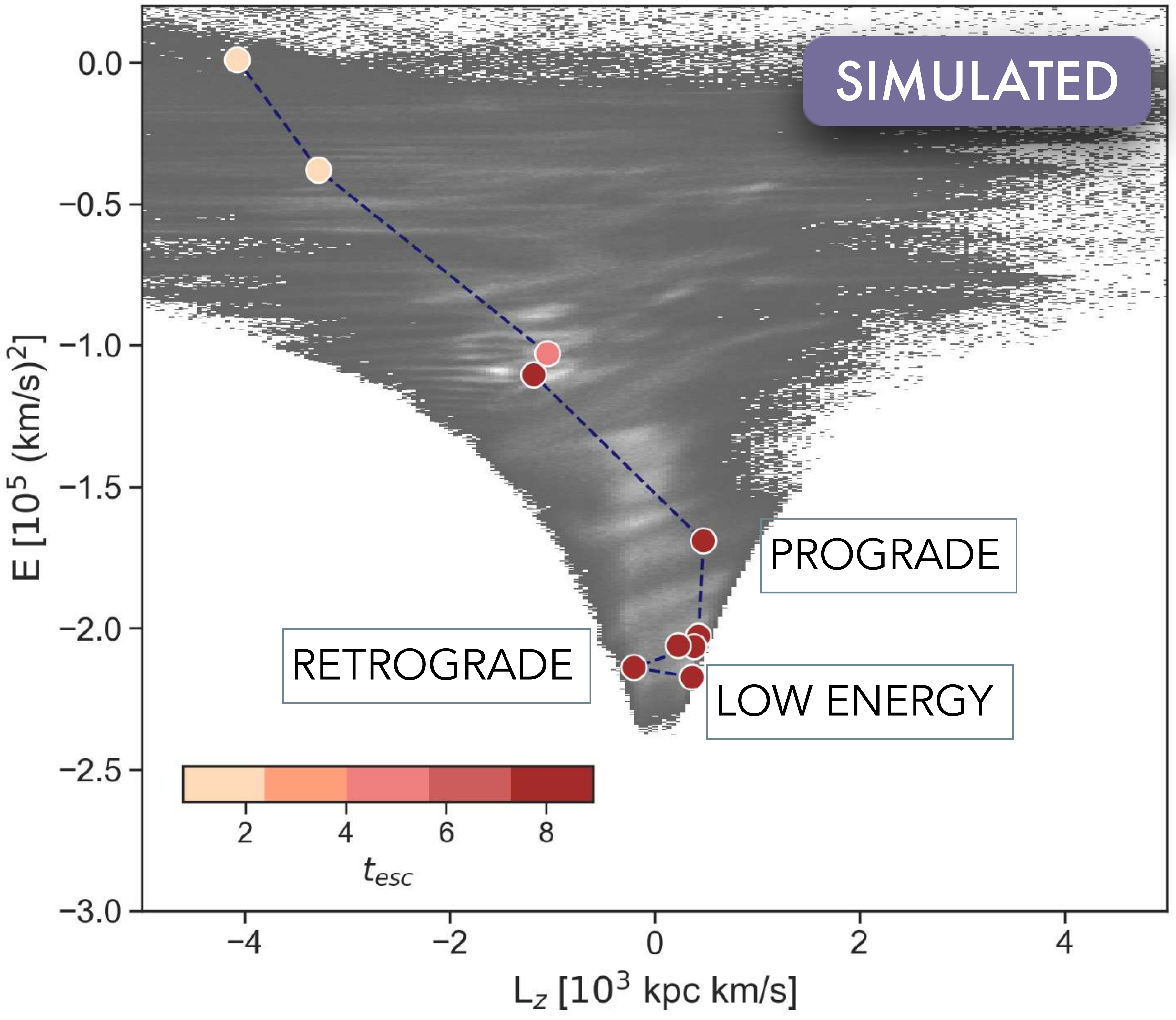
- **Coming back to the E - L_z space**

Pagnini et al. 2025, A&A, 693, A155

***Nephele*'s GCs result scattered across the E - L_z plane** as expected from the accretion of a massive satellite.



Simulated distribution in E - L_z of **10 clusters accreted together with their progenitor galaxy** having an **initially retrograde** orbit.



Can we "chemical tag" field stars in the Milky Way brought by *Nephele* or escaped from *Nephele*'s clusters ?

Pagnini et al. 2025, A&A, 693, A155

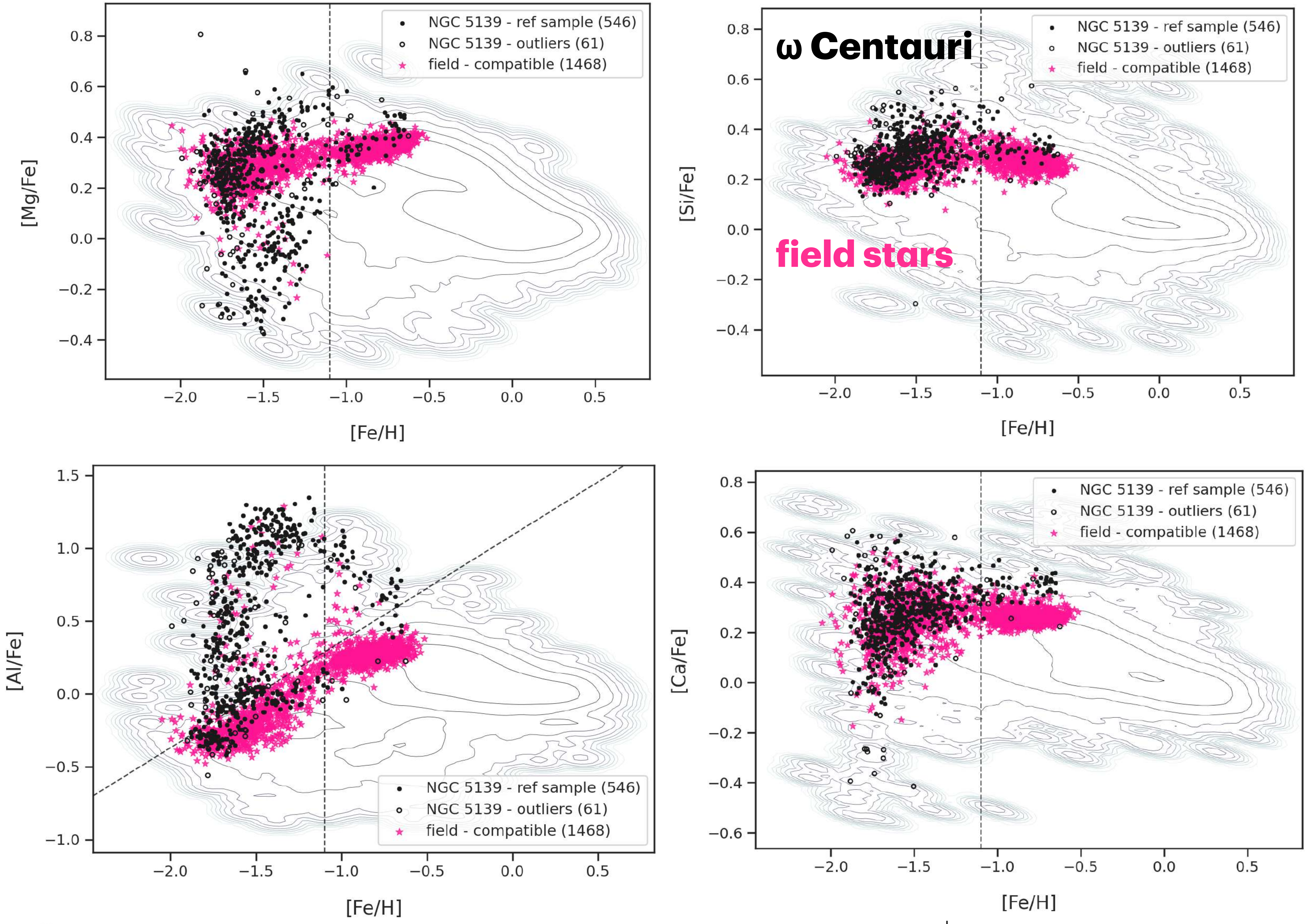
Chemically tagging stars to the *Nephele* accretion

Pagnini et al. to be submitted

+ [Ca/Fe], [K/Fe], and [Mn/Fe]

① Chemical filter

Using the same **multidimensional chemical approach on APOGEE** DR17 data tested on globular clusters, **we searched for stars in the field chemically compatible with ω Cen**.



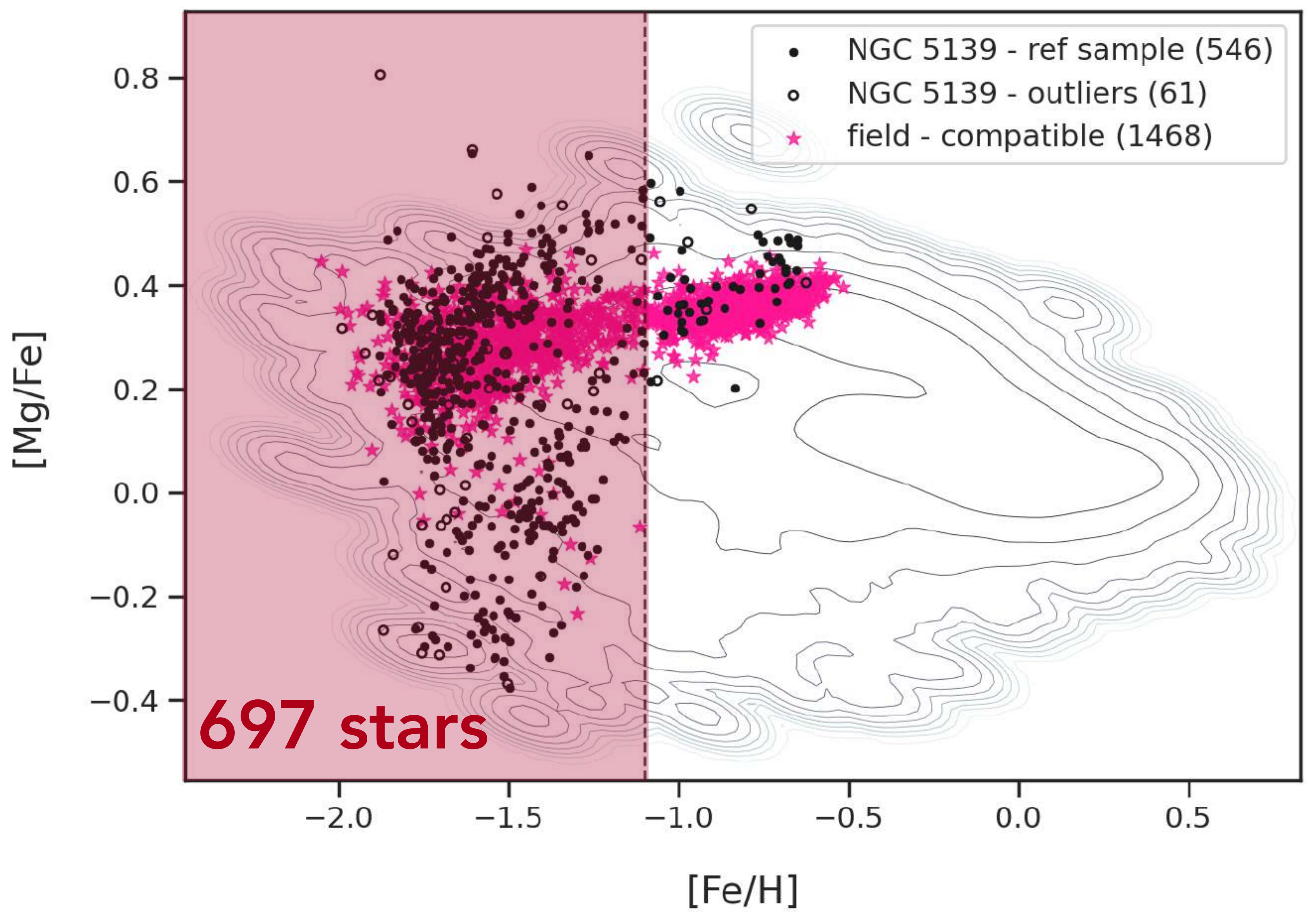
1468 field stars chemically compatible with ω Cen, 697 of which are metal-poor

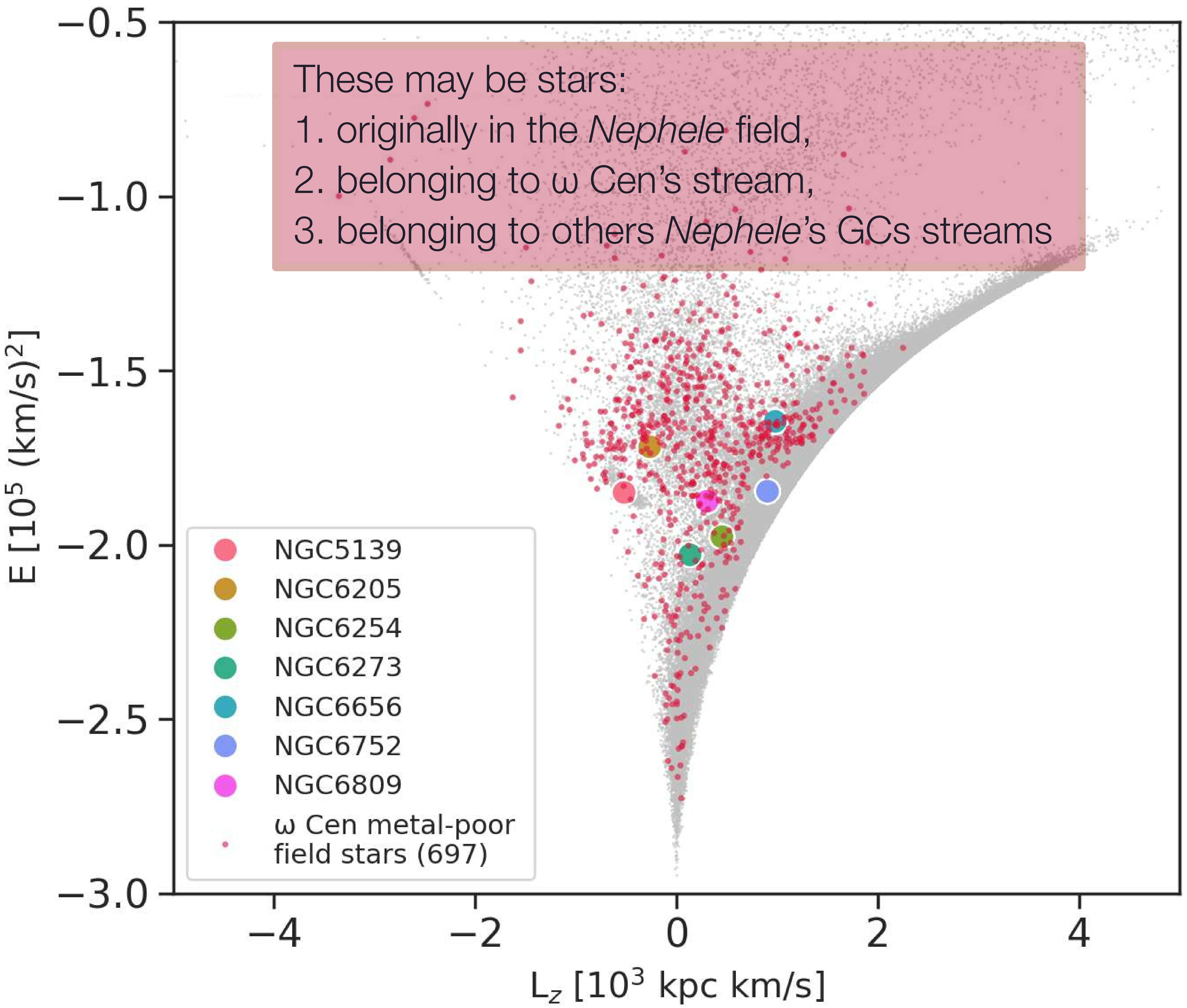
Giulia Pagnini - *pagnini@astro.unistra.fr*

Chemically tagging stars to the *Nephele* accretion

- **Metal-poor stars, chemically compatible with ω Cen in E - L_z**

Pagnini et al. to be submitted



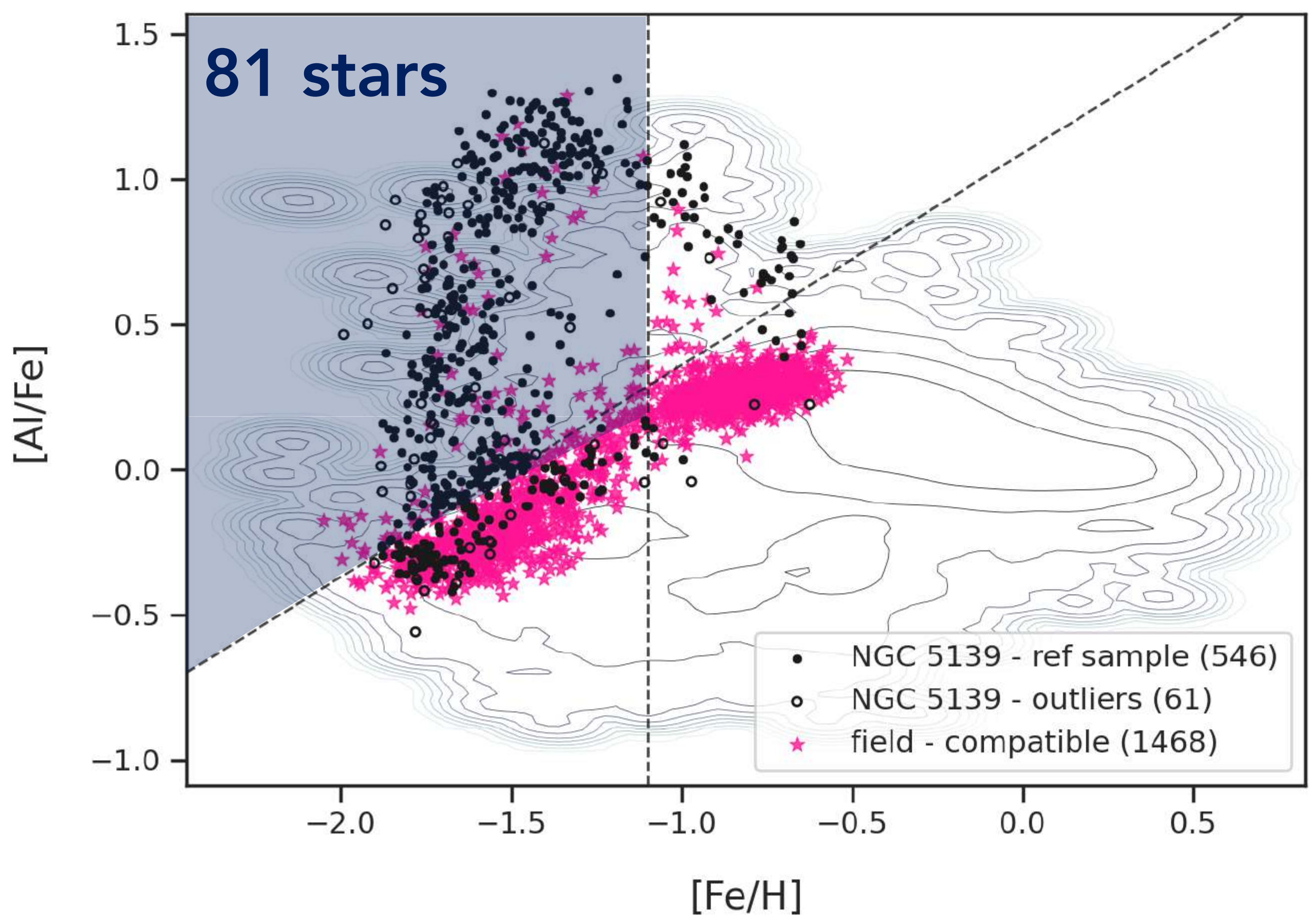


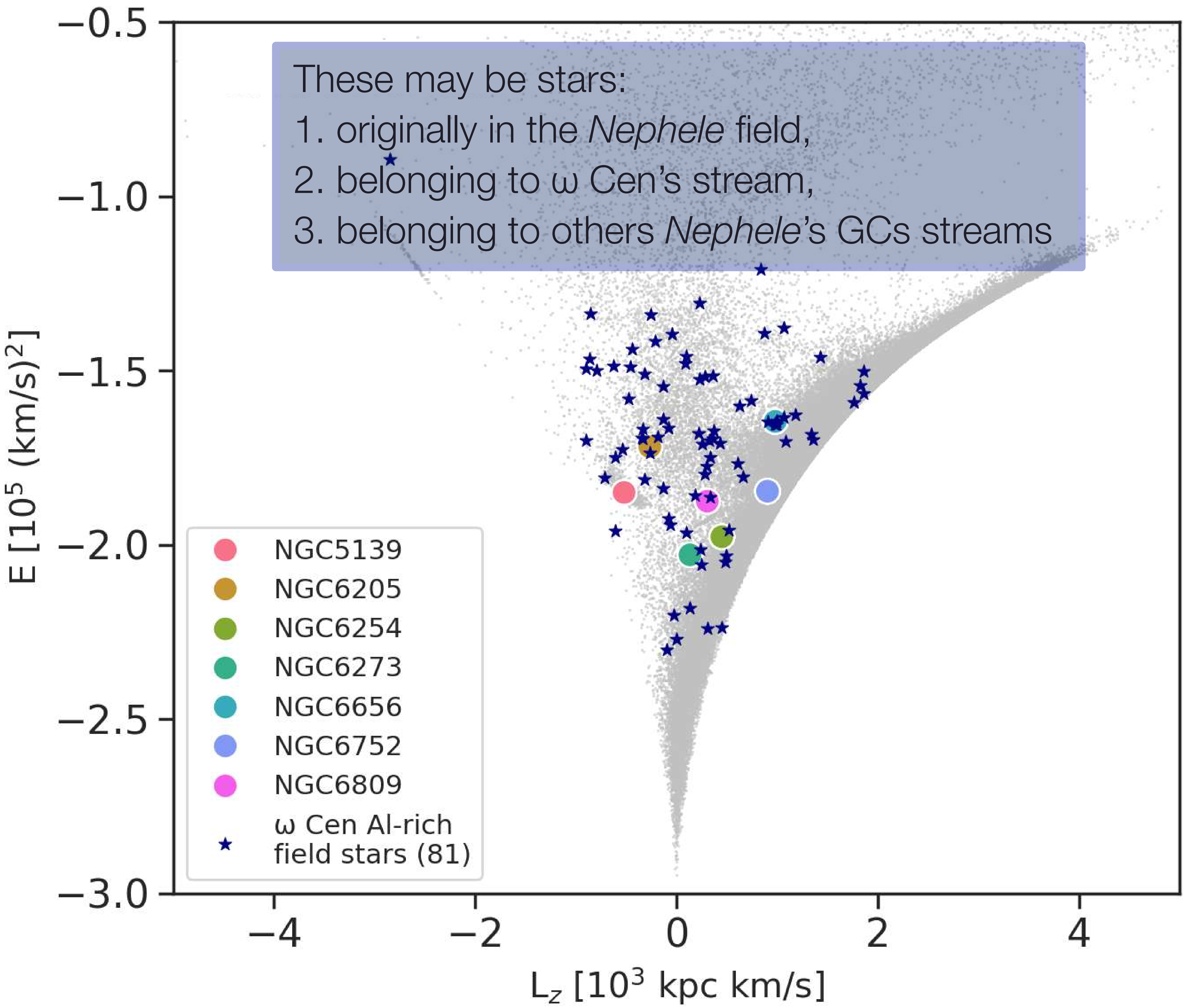
In E - L_z the distribution of *Nephele*'s field stars is broad as its GCs!

Chemically tagging stars to the *Nephele* accretion

‣ **Metal-poor + Al-rich stars, chemically compatible with ω Cen in E - L_z**

Pagnini et al. to be submitted





In E - L_z the distribution of *Nephele*'s field stars is broad as its GCs!

Comparing data with simulations

‣ Searching for stars chemically + kinematically compatible with *Nephele*'s GCs

Pagnini et al. to be submitted

② Kinematic filter

We searched which of these stars have **kinematic** properties **compatible** with **simulated disrupted *Nephele*'s GCs**.

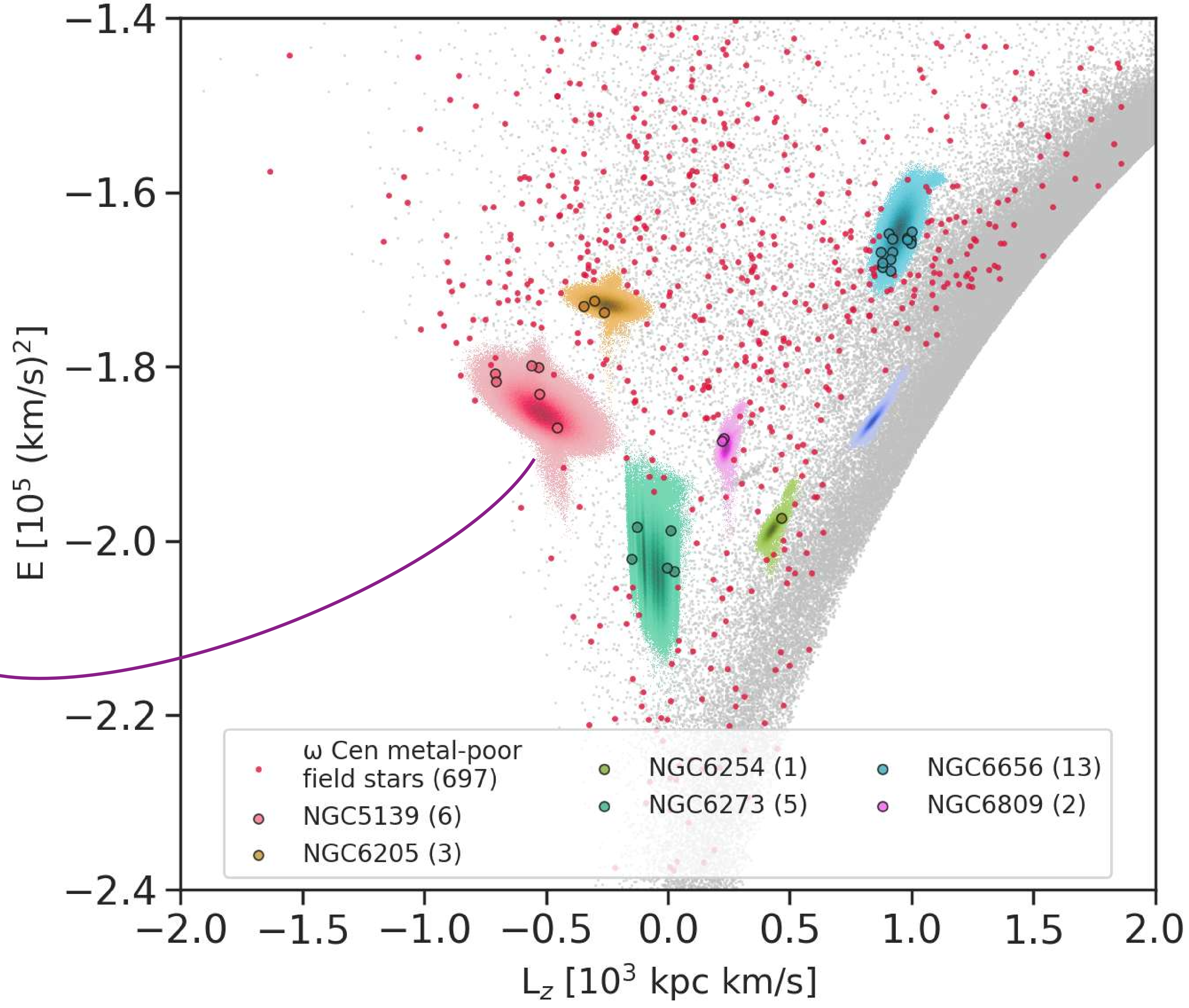
e-TidalGCs project : a library of simulations of Galactic globular clusters streams

https://etidal-project.obspm.fr/

Ferrone et al. (2023)

GMMKin 2D | E L_z

- **6 metal-poor stars consistent with ω Cen stream**
- **Additional stars linked to *Nephele* GC streams (excl. NGC6752)**



Comparing data with simulations

- Searching for stars chemically + kinematically compatible with *Nephele*'s GCs

Pagnini et al. to be submitted

② Kinematic filter

We searched which of these stars have **kinematic** properties **compatible** with **simulated disrupted** ***Nephele*'s GCs**.

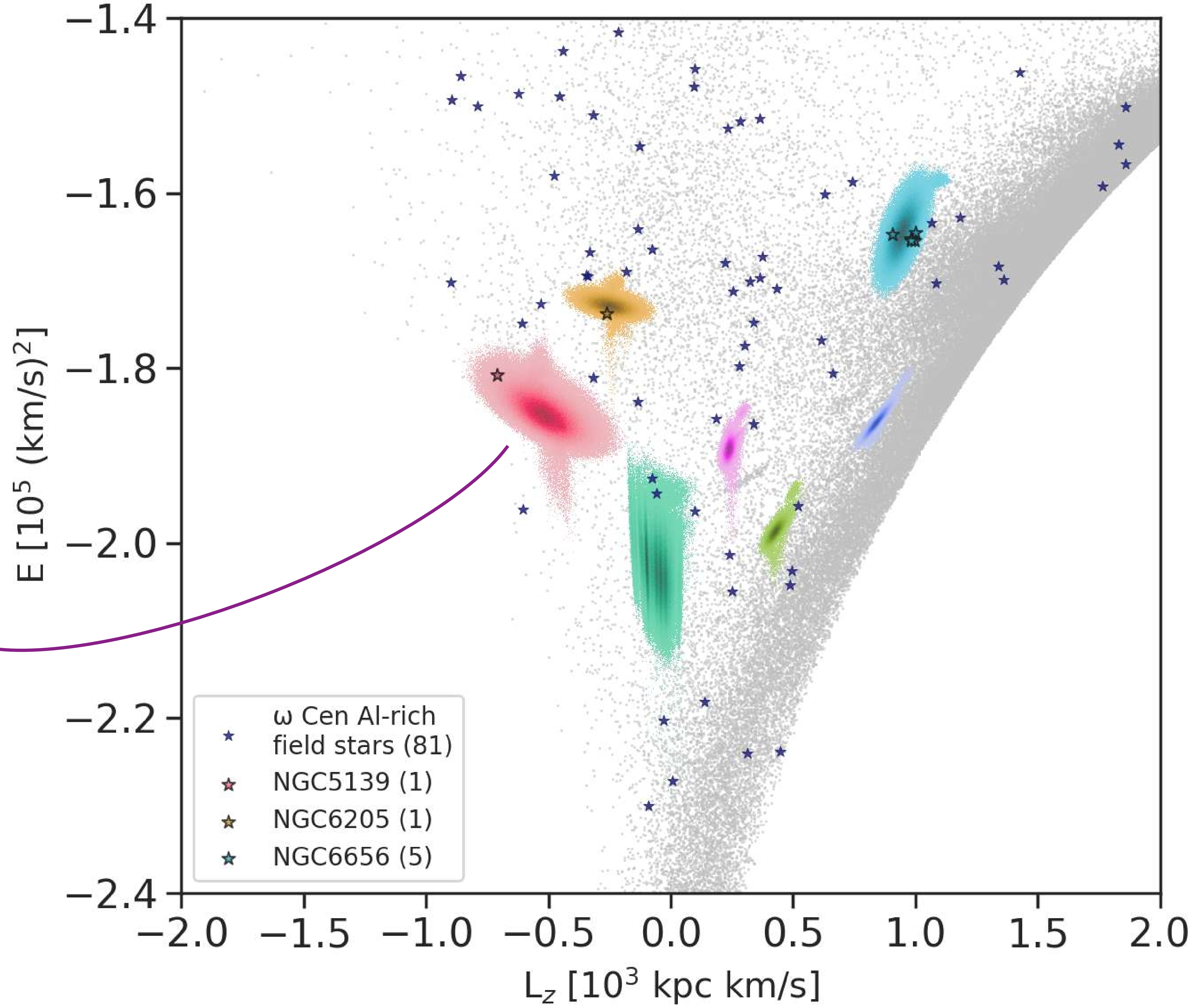
e-TidalGCs project : a library of simulations of Galactic globular clusters streams

https://etidal-project.obspm.fr/

Ferrone et al. (2023)

GMMKin 2D | E L_z

- **1 Al-rich star consistent with ω Cen stream**
- **Additional stars linked to NGC 6205 and NGC 6656**



Promising to find stellar streams candidates beyond their immediate surroundings!

The early and late evolution of our Galaxy through the lens of globular clusters

Pagnini et al. 2023, A&A, 673, A86

- **Dynamical coherence alone is insufficient for tracing the origins of globular clusters;**

Pagnini et al. 2025, A&A, 693, A155

- Using a **multidimensional chemical approach, we identify six GCs**— NGC 6752, NGC 6656, NGC 6809, NGC 6273, NGC 6205, and NGC 6254 — as likely **co-natal with ω Centauri**, suggesting a **shared origin in a now-destroyed satellite galaxy, *Nephele;***

Pagnini et al. to be submitted

- By applying the **same chemical tagging method to field stars**, we identify:
  - **1468 stars chemically compatible with ω Cen**
  - Including **697 metal-poor stars and 81 Al-rich stars**, possibly tracing *Nephele*'s stellar debris;
- A subset of these field stars **also shows kinematic compatibility with simulated tidal streams** from *Nephele*'s GCs.

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cnes