Understanding the first stages of Galaxy formation with dynamically informative very metal-poor stars

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Near Field Cosmology with Very Metal-Poor stars

VMP stars: [Fe/H] < -2.0
→ We can understand the Galaxy assembly processes and the chemical enrichment of the early Galaxy

Two basic pieces of information

Their motion has an imprint of the dynamical history of the Galaxy

The time required for stars to exchange energy and angular momentum is longer than the age of the Galaxy.

Their chemical composition encode information about the environment in which they formed during the early history of the Galaxy

Where are VMP stars in the Galaxy?

The *coarse-grained* phase-space distribution of the MW's halo system

Carollo & Chiba, 2021, ApJ 908, 191

"Coarse-grained" phase-space distribution of halo stars, where the properties of the halo system averaged over the phase space are close to a dynamically steady state (Binney & Tremaine 2008).
→ Differs from the "fine-grained"one, which still contains non relaxed, small-scale substructures.

- **Data: SDSS-SEGUE DR7 + APOGEE DR16 cross-matched with Gaia DR2.**
- **Phase-space: three Integrals of Motion (Lz,E,I_3) – Stackel type potential (de Zeeuw, 1985)**

Coarse-grained phase-space distribution

In the prograde motion:
Halo stars can be separated from disk stars on an orbit based selection → cuts in I_3 and Lz.

- **Large values of I_3: (2*I3)^1/2 > 1000 kpc kms-1 (θorb > 15°– 20°)**
- **0 < Lz < 1500 kpc kmsec-1 &**
  E < -1.5 km^2/sec^2
- **Lz < 0 kpc kmsec-1 → we don't need to perform cuts in the retrograde motion**

Disk stars:

- **Lz > 1500 kpc kmsec-1 & (2*I_3)^1/2 < 1000 kpc kms-1 (θorb < 15°–20°)**

Coarse-grained phase-space distribution

Inner halo includes (Carollo et al. 2007, 2010):

- Gaia-Enceladus → dominates this component at [Fe/H] ∼−1.5
- Low-energy stars (E < −1.5 × 105 km2 s−2) at [Fe/H] < −1
- A significant number of metal-poor prograde stars

Outer halo:

- Dominated by VMP stars with [Fe/H] ~ -2.2 with predominantly retrograde motion
- Likely made of superposition of "fine-grained" elements such as Sequoia, Arjuna, DTGs etc.

The fraction of VMP stars with [Fe/H] < −2.2, composing the outer halo, relative to more metal-rich halo stars (−2 < [Fe/H] < −1.4), starts to dominate at (2I_3)^1/2 ∼ 2000 kpc km s−1, corresponding to θorb ∼ 50° (Zmax ~ 10 kpc), at the solar radius (see Figure 11 in Carollo & Chiba 2021).

Where are VMP stars in the Galaxy?

In the halo primarily at large orbital angles on a prograde or retrograde motion → mainly outer halo.

Not many in GES: It was shown that the GES structure exhibits a metallicity distribution function (MDF) with a metal-weak tail **much steeper than the average MW Halo MDF** (see discussion in Bonifacio et al. 2021, and their Figure 21).

Where are VMP stars in the Galaxy?

Surprisingly, they were found in phase-space dominated by the MW's disks (Sestito+ 2021, Di Matteo et al. 2020; Venn et al. 2020, Carollo et al. 2023).

Hamburg ESO Survey (HES) : the fainter part of the sample.

- HES is an objective-prism survey that was carried out with the 1m ESO Schmidt telescope.

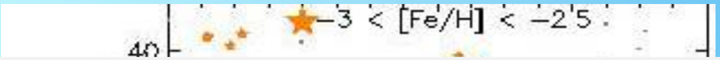
- Spectral resolution of $\Delta\lambda \approx 10$Å at the Ca II K line made it possible to also select stellar objects efficiently

- In this analysis: 4519 stars with spectroscopic follow-up (R ~ 2000 A)

- Cross-matched with Gaia EDR3 (Gaia collaboration 2021)

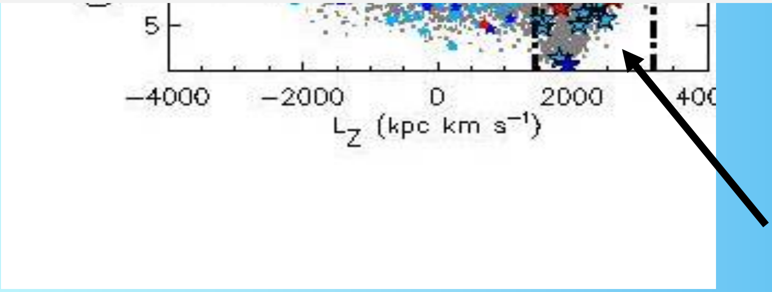
VMP ([Fe/H] < −2) : N = 1826
EMP ([Fe/H] < −3): N = 228
UMP ([Fe/H] . −4): N = 10

Dinamically Informative Stars: VMP stars with disk(s) dynamics



We found 33, 13, 9, 2 and 2 VMP with disks dynamic in the metallicity intervals −3.0 < [Fe/H] <−2.5, 3.5 < [Fe/H] <−3.0, −4 < [Fe/H] < −3.5 and [Fe/H] <−4.0

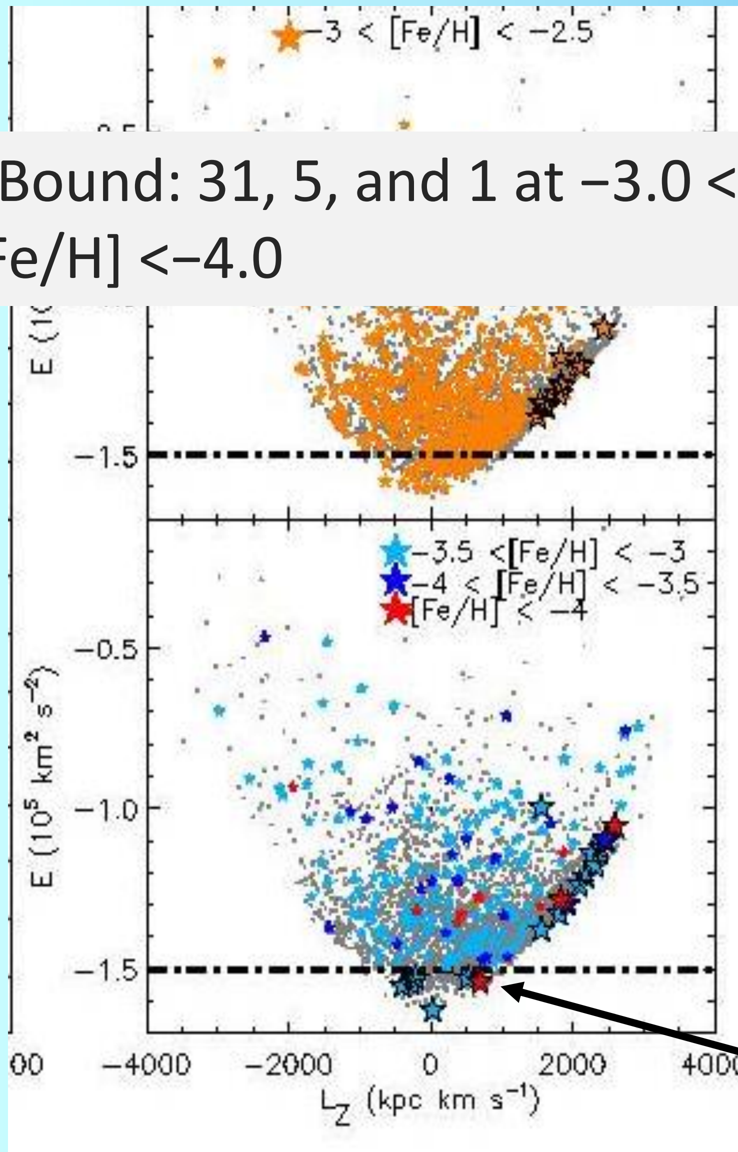
Number of stars with [Fe/H] ~ −2.5 and disk kinematics is more than three times its retrograde counterpart Lz < -1500 kpc kms-1 ($N_{Prograde}$ = 26, $N_{Retrograde}$ = 8), in agreement with Sestito et al. (2020).



Disks phase-space

Dinamically Informative Stars: Most Bound Halo Stars

Most Bound: 31, 5, and 1 at −3.0 < [Fe/H] <−2.5, 3.5 < [Fe/H] <−3.0 and [Fe/H] <−4.0



Lz distribution around 0 km^2 sec^-2

The most bound stars

VMP stars with disks dynamic: Candidate In-situ stars

Early infalling, pristine gas would have been settled into an equatorial plane of a progenitor dark halo in the presence of an initial angular momentum (Katz & Gunn 1991). From this gas, a fraction of very metal-poor stars, with low I_3 and relatively high L_z, may have been formed and left there (see Carollo & Chiba and references therein).

In-situ and accreted stars

Theoretical predictions suggest that in situ stars formed inside a parent halo within the virial radius (Zolotov et al. 2010; Tissera et al. 2012, 2013).

→ Stellar components in dark halos originate from multiple sources:

- Star formation within cooled gas originally present in parent halos
- Gas stripped from merging satellites and subsequently cooled,
- Stars supplied by merging/accreting halos that disappear after tidal interaction or survive as luminous satellites

Each dark halo grows through merging and accretion with other dark halos, and stellar populations within the product of this merging are then composed of preexisting stars formed inside the main progenitor halo (in-situ) and merged/accreted stars in other halos (accreted).

Most Bound Halo Stars: Candidate In-situ stars

A finite fraction of stars, formed from cooled gas in the bottom of a main progenitor halo are most tightly bound to the gravitational potential of that progenitor halo after dissipative cooling.

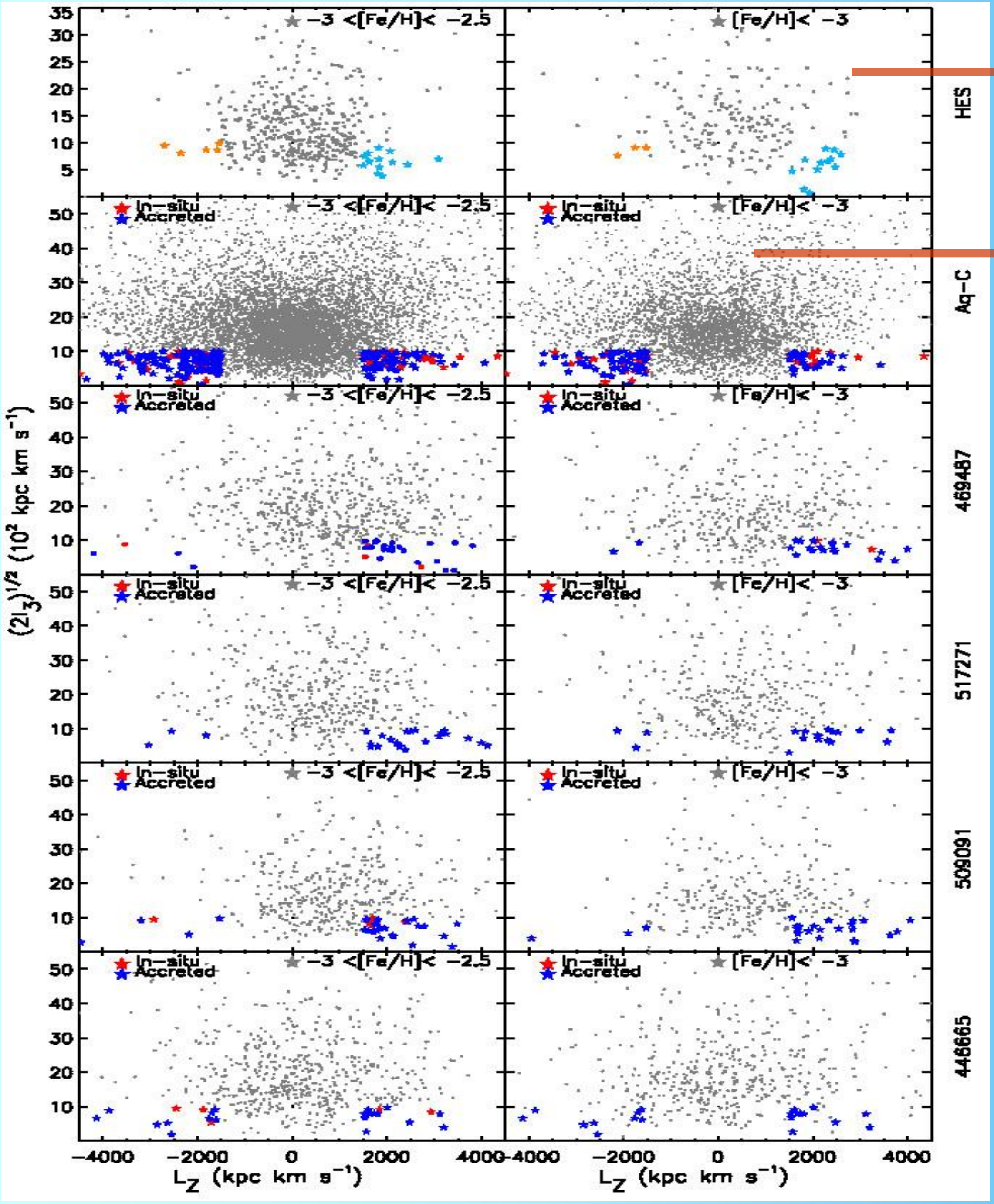
In comparison, accreted stars supplied by merging/accretion events from outside, are less bound, due to their larger binding energies.

Then, **candidate in situ halo stars can be defined as those being most tightly bound to the Milky Way gravitational potential, or, in other words, those having the lowest binding energy, E.**

Comparison with high resolution hydrodynamical simulations in ΛCDM scenario with different subgrid physics and codes: Aquarius Project (Springel et al. 2008) and IllustrisTNG (Nelson et al. 2018).

In both simulations we follow all star particles back to their site of formation → system where they formed

→ time of formation



HES

Aq-C (Tissera et al. 2013, 2017)

TNG50 MW Analogs (Nelson et al. 2019b Pillepich et al. 2019)

Comparison with galaxy formation simulations: VMP disk

Table 3

Stellar Mass Fractions of In Situ and Accreted VMP Halo Components with Disk Kinematics and Their Retrograde Counterparts for the Analyzed Simulated Halos

Metallicity	Rotation	Origin	Aq-C M_F (%)	Age (Gyr)	469487 M_F (%)	Age (Gyr)	517271 M_F (%)	Age (Gyr)	509091 M_F (%)	Age (Gyr)	446665 M_F (%)	Age (Gyr)
	Disk kinematics	In situ	0.4	12.2	0.9	12.9	…	…	0.8	12.7	**0.3**	12.5
$-3 < [Fe/H] \leqslant -2.5$	Disk kinematics	Accreted	0.8	12.7	2.6	12.9	4.3	12.8	5.3	12.8	1.6	12.5
	Retrograde Counterpart	In situ	0.5	13.5	**0.3**	12.5	…	…	0.3	12.3	0.4	12.9
	Retrograde Counterpart	Accreted	1.3	13.5	**0.2**	12.3	0.6	12.5	0.6	12.5	1.3	12.4
	Disk kinematics	In situ	0.3	12.6	1.0	12.9	…	…	…	…	…	…
$[Fe/H] \leqslant -3$	Disk kinematics	Accreted	0.7	13.5	3.3	13.3	4.0	13.3	7.3	13.2	1.8	13.0
	Retrograde Counterpart	In situ	0.6	13.6	…	…	…	…	…	…	…	…
	Retrograde Counterpart	Accreted	1.5	13.5	0.2	13.0	**1.0**	12.8	0.9	13.2	2.7	13.2

Note. The corresponding median ages are also shown. Boldface numbers denote mass fractions within three bootstrap σ.

- Both Aq-C and TNG50 MW analogs exhibit a systematic larger contribution of accreted stars.
- Interestingly, in some of them there is also a contribution from VMP stars formed in situ.

Comparison with galaxy formation simulations

- In situ and accreted components **are very old, with median ages larger than 12.5 Gyr,** corresponding to redshift $z > 5$. This is consistent with the claim that they have been formed during the very first stages of galaxy assembly.

These results reflect the diversity of halo properties that originated by the particular assembly history of each galaxy, they also suggest a clear trend of a more significant contribution of accreted stars with disk rotation in the VMP regime, as well as the presence of stars that originated in situ.

Comparison with galaxy formation simulations: most bound halo stars

Table 5

The Most Bound Stellar Populations in the Halo: Mass Fractions of In Situ and Accreted Stars (Given in Percentages), and Their Median Age (in Gyr) for the Analyzed Simulated Halos

Metallicity	Origin	Aq-C M_F (%)	Age (Gyr)	469487 M_F (%)	Age (Gyr)	517271 M_F (%)	Age (Gyr)	509091 M_F (%)	Age (Gyr)	446665 M_F (%)	Age (Gyr)
$-3 < [Fe/H] \leqslant -2.5$	In situ	1.2	13.7	**1.0**	13.4	0.1	13.1	0.5	13.0	0.4	13.2
	Accreted	6.4	13.5	**1.3**	13.2	1.9	13.3	1.9	13.4	1.8	13.3
$[Fe/H] \leqslant -3$	In situ	1.4	13.7	0.5	13.6	...	...	...	...	0.5	13.7
	Accreted	5.3	13.6	1.9	13.6	0.9	13.3	2.7	13.3	1.7	13.5

Note. Boldface numbers denote mass fractions within three bootstrap σ.

- **Both mechanisms of formation: in-situ and accreted**
- **These stars are the oldest detected, with a median age ~13.3 Gyr.**

Key Points

- **Disk VMP and Most Bound halo stars: Both channels of formation in-situ and accreted are valid**

- **Most of the star particles are accreted**

- **A fraction of them formed in situ**

- VMP stars with disk kinematics **In Situ channel**: likely formed by early infalling, *pristine gas* settled into in equatorial plane of a progenitor dark halo in the presence of an initial angular momentum

- Recent works in the extragalactic domain show the existence of gaseous disks in star-forming galaxies at high redshift, z ~ 4–5 (12 Gyr ago), (Neeleman et al. 2019, 2020)

Spectroscopic follow-up

- High resolution spectroscopy with VLT-UVES and Subaru-HDS successful outcome (6 nights)

- Explore possible chemical signatures of the two channels of formation, in-situ and accreted.

- It is important to remark that it is not known yet which chemical abundances or patterns are best suited to distinguish in-situ from accreted stars at ”such low metallicities”

- Possible chemical patterns in VMP stars with disk rotation may be linked to stars born in a pristine gas of an early gaseous disk $\sim$ 12 Gyr ago, or stars accreted from primordial satellite galaxies → Signatures of Pop. III stars? CEMP-no, for example.
- N-capture elements

- Any other possible trend, suggestions are welcome!