On the origin of the Icarus stream (An accreted stream in the Milky Way disk)

Paola Re Fiorentin[1], Alessandro Spagna[1], Mario G. Lattanzi[1], and Michele Cignoni[2]

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ABSTRACT

The search for and the characterization of relics of the hierarchical formation have opened a new window for direct testing of cosmological models in the Milky Way.

Most notably, we reported the discovery of Icarus, the flattest among the fast-rotating stellar streams found in the Galactic disk (Re Fiorentin et al. 2021). With the latest releases from Gaia, APOGEE, GALAH, and GES, the presence of Icarus has been further corroborated.

In addition, in order to establish the actual origin of Icarus, remnant of a disrupted dwarf galaxy rather than a signature of the Milky Way's disk formation and evolution, we discuss the chemical distribution [Mg/Mn] vs. [Al/Fe] of its members through high-res spectroscopy and the comparison with tailored N-body high-resolution simulations.

STARS (Across the Universe)
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INTRODUCTION

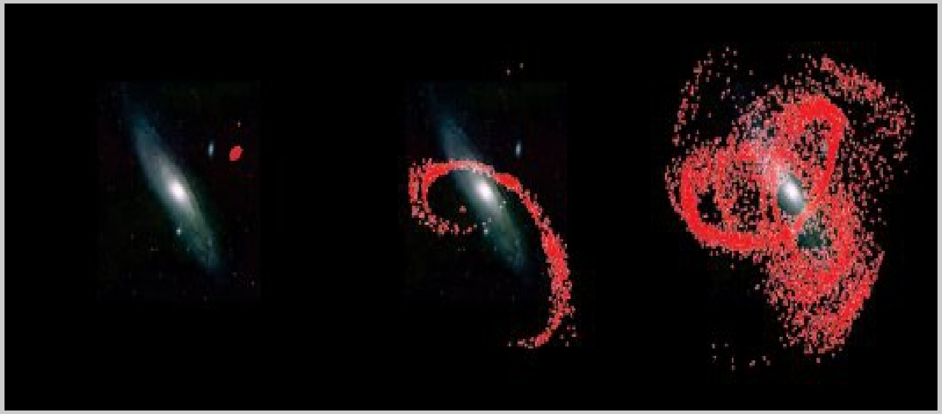

Fig. 1. Numerical simulation of the disruption of a small satellite/dwarf galaxy. Picture from Schoening & Harvey/REU program/NOAO/AURA/NSF.

In a ΛCDM Universe, structures grow by hierarchical merging, i.e. by progressive assembly of sub-units into larger ones, mainly driven by dynamical friction and tidal disruption, leaving substructures and streams as relict of this process (White & Frenk 1991). Simulations show that satellite galaxies are progressively destroyed by the gravitational pull of a large galaxy, giving rise to trails of stars which closely follow the orbit of their progenitor. Eventually the streams overlap spatially, and the stars become part of a roughly spherical halo around the main galaxy (see Fig.1).

The stellar halo of the Milky Way offers the best opportunity for testing theories, discriminating between alternative Galaxy formation scenarios and probing details of the accretions experienced over its lifetime (e.g., Bullock & Johnston 2005; Freeman & Bland-Hawthorn 2002; Helmi 2008). Relics of accretion events are more prominent in the outer region of the halo (Ibata+1994,2003; Belokurov+2006; Bell+2008; Malhan+2018; Naidu+2020), whereas the inner-halo region appears significantly smoother. Here, merger debris may be detectable as stellar groups with coherent kinematics despite being of very low spatial density (Helmi+1999; Klement+2010; Re Fiorentin+2015).

Thanks to the Gaia mission and synergies with large stellar spectroscopic surveys (e.g., SEGUE, RAVE, LAMOST, Gaia-ESO, APOGEE, GALAH) we have learnt that mergers have been important and built up the majority of the inner halo. Recent findings include retrograde debris of Gaia-Sausage-Enceladus (GSE, Belokurov+2018; Helmi+2018), Sequoia (Myeong+2019), Thamnos (Koppelman+2019) and Icarus, a flat and fast prograde stellar stream in the MW disk (Re Fiorentin+2021).

Large unbiased (non-kinematically selected) samples of stars with accurate 6D phase-space information and complete chemical properties for classification and following characterisation are needed. Here, we show the excellent synergy between Gaia (GaiaColl., Brown+2018), APOGEE (Majewski+2017), GALAH (De Silva+2015) and GES (Gilmore, Randich et al. 2012), and take advantage of high-quality data in order to study chemo-kinematic signatures in the local halo.

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DATA

This study starts with a new kinematic catalogue based on high quality astrometric and spectroscopic data, based on Gaia DR3, APOGEE DR17, GALAH DR3, and GES iDR6 (GaiaColl., Brown+2021; Ahumada+2019; Buder+2021; Gilmore, Randich et al. 2012).

Our sample includes 500191 stars down to G=18 mag, that we selected by applying the following quality cuts (Lindegren+2018; Queiroz+2020; Jönsson+2020; Buder+2021; private communications from C. Allende Prieto and G. Sacco):

- Gaia DR3:
```
SELECT g.*
FROM gaiadr3.gaia_source AS g
WHERE g.ruwe < 1.4 AND g.astrometric_params_solved = 31 AND g.parallax_over_error > 5
```
- APOGEE DR17: SNR > 50 AND ASPCAP_CHI2 < 15 AND 4000 < T_{eff} < 6000 AND 0 < log g < 6 with no *VERY BRIGHT NEIGHBOR* or any *BAD* flag
- GALAH DR3: SNR > 30 AND flag_sp = 0 AND flag_fe_h = 0 AND flag_X_fe = 0 (X=Mg, alpha)
- GES iDR6: GES_TYPE = *GE_MW* AND NN_MG1 >= 2

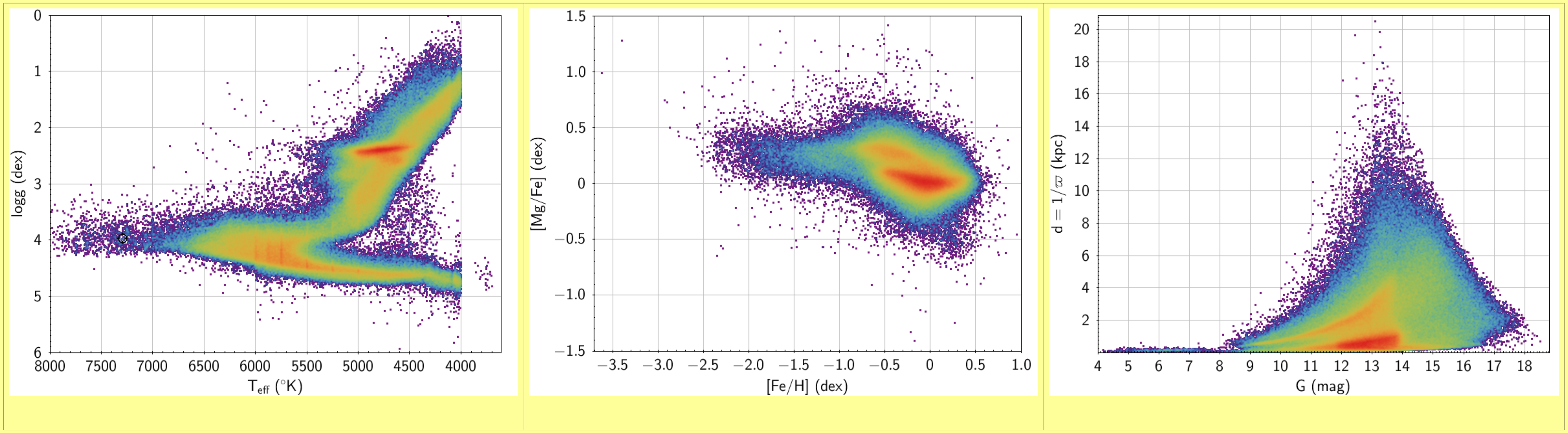

Fig. 2. Properties of the chemo-kinematic catalogue '**Gaia-APO.GAL.GES**': distribution of the 500191 stars in the atmospheric parameters plane log g -- T_{eff} (*left*), in the chemical plane [Mg/Fe] -- [Fe/H] (*middle*), and their distance as a function of Gaia magnitude (*right*). In the Gaia era, the 'Solar neighbourhood' extends up to 15 kpc.

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CHEMICAL HALO

We chemically select the tracers of the halo population according to Di Matteo+2019 and Mackereth+2019.

Halo stars:

- **[Fe/H] < −1 dex**
- **[Mg/Fe] < −0.2 − 0.5 · ([Fe/H] + 0.2)**

The full sample includes both main sequence and giant stars, while the chemically selected halo population is dominated by red giants.

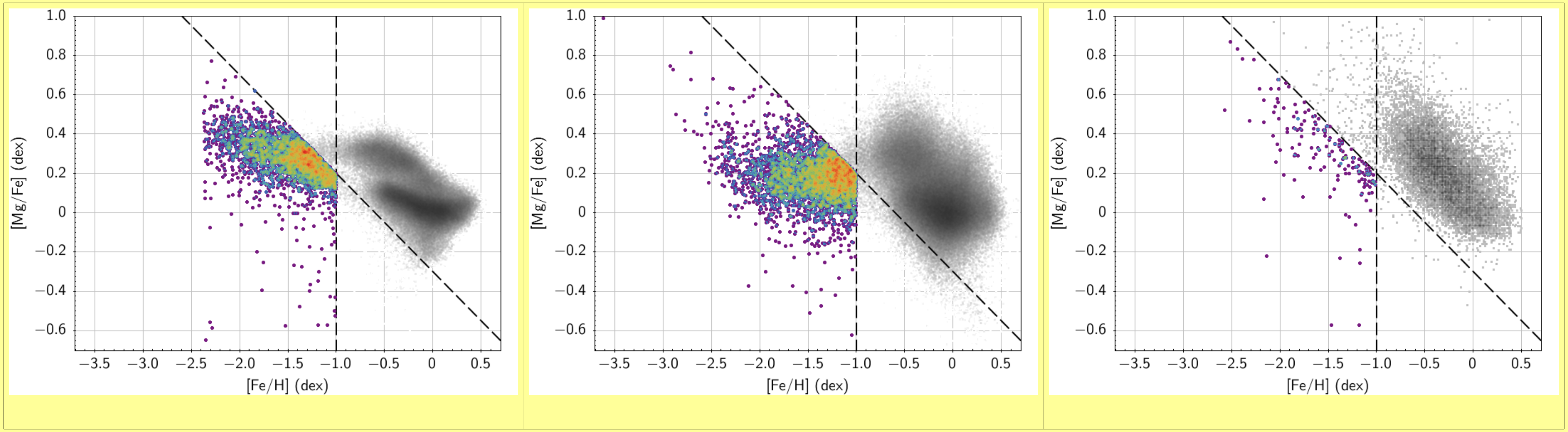

Fig. 3. *Left panel:* Chemical distribution, [Mg/Fe]--[Fe/H], for the 218940 Gaia-APOGEE stars. The dashed lines represent the adopted selection of 3061 halo stars (colour), separated from thick/thin disk stars (gray). *Middle panel*: Same distribution as left panel for the 3708 halo stars selected among the 267867 Gaia-GALAH stars. *Right panel*: As left and middle panels, the 166 halo stars (coulor) identified among the 13384 Gaia-GES stars (gray).

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DETECTION

We focus on the **local halo within 3 kpc** of the Sun, to limit the impact of the velocity gradients. After removing members of globular clusters (e.g. GaiaColl., Helmi+2018) and visual binaries, we explore the phase-space.

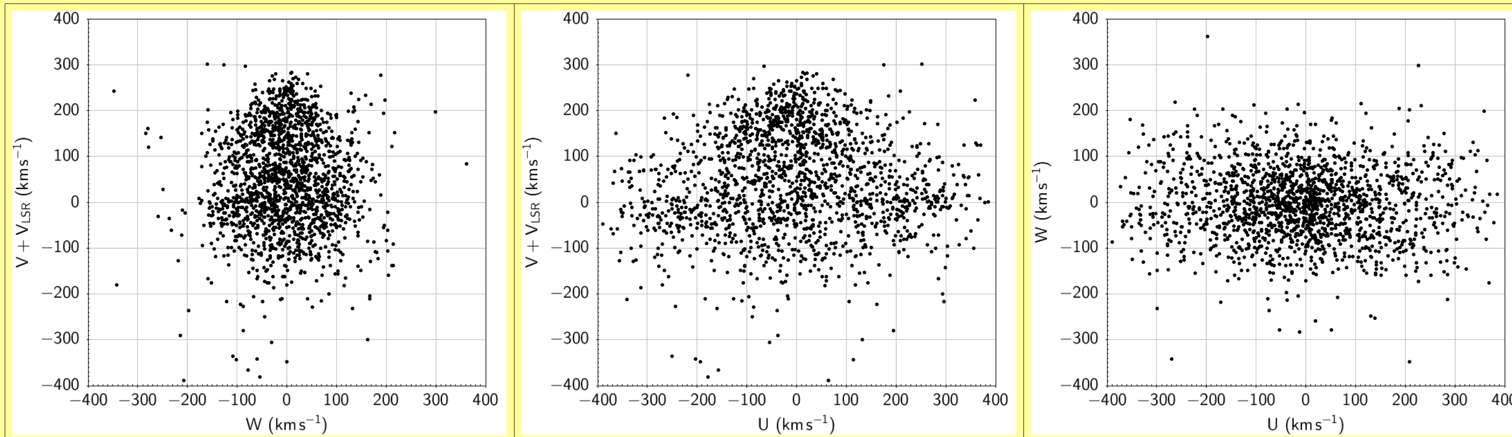
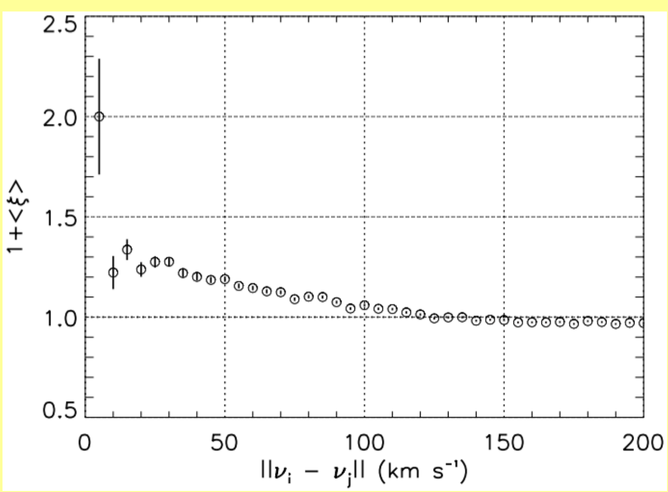


Fig. 4. 3D velocity distribution of the 1712 chemically selected nearby halo stars.



We quantify the presence of **kinematic substructures** with respect to a smooth random velocity distribution by means of the Two-Point Correlation function in velocity space:

$$\xi = \langle DD \rangle / \langle RR \rangle - 1$$

where:

‹DD›: # pairs of particles in our data with velocity difference less than a given value Δ;

‹RR›: # pairs of random particles with velocity difference less than *that* Δ given value.

Clumping due to kinematic substructures (i.e. groups of particles moving with similar velocities) is evident with values of ξ>1. Statistical evidence of substructures with small velocity separations is shown in Fig. 5.

Fig. 5. Differential velocity correlation function ξ for the full halo sample. The error bars are derived from Poisson's statistics of the counts.

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STREAMS

In order to classify into meaningful groups the objects detected by the two-point correlation funtion, we perform K-medoids clustering in 3D velocity space (Hastie+2001). We have assigned membership to the 685 sources with pairwise velocity differences less than 20 km/s (isolated pairs have been excluded). Figs. shows the kinematic groups with K=8.

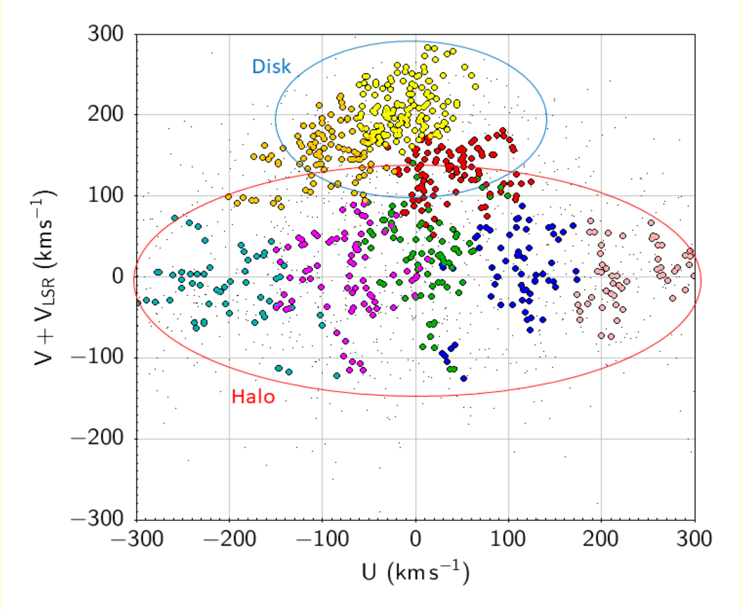

Fig. 6. V-U velocity distribution of the 1712 chemically selected nearby (d<3 kpc) halo stars. Circles show the 685 sources with pairwise velocity differences less than 20 km/s; the stars belonging to isolated pairs have been excluded. Different colours are used to indicate stars associated with the 8 clumps recovered by the clustering analysis

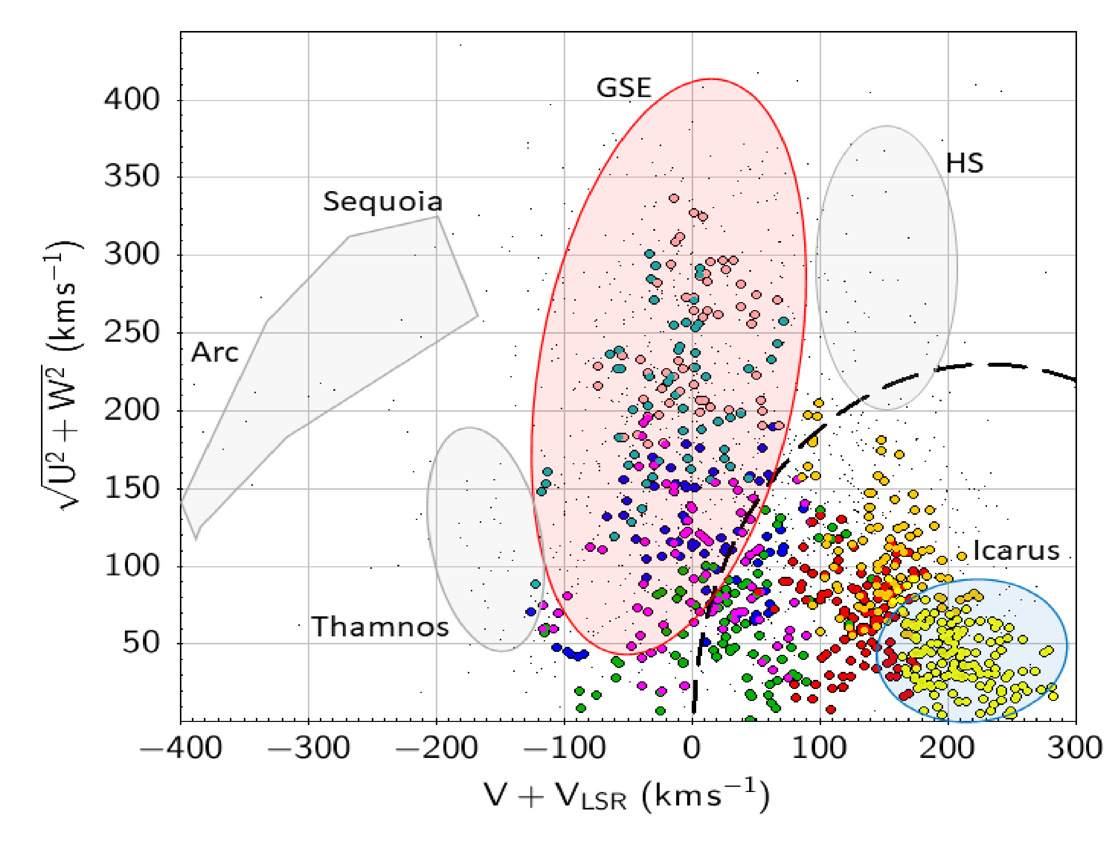

Fig. 7. Toomre diagram of the full local (d<3 kpc) chemically selected stellar halo. As in Figs. 6, different colours are used to indicate the 8 new kinematic streams recovered by the clustering analysis in velocity space.The approximate location of known substructures* (GSE, HS, Sequoia, the 'arc', Thamnos, and Icarus) is shown. The traditional kinematic selection for halo stars, $|\mathbf{v} - \mathbf{v}_{LSR}| > 230$ km/s, is represented by the dashed line.

*The Nyx stream is not included as detailed chemical analysis ruled out an extragalactic origin (Zucker+2021).

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DISCUSSION

We focus on the three prograde streams, with disk-like kinematics, that are shown as yellow, orange, and red circles in Figs. 6-7.

HINTS ON THE AGE

The stellar ages greater than 10 Gyr rule out the possibility that these kinematical groups are formed by in situ disk stars.

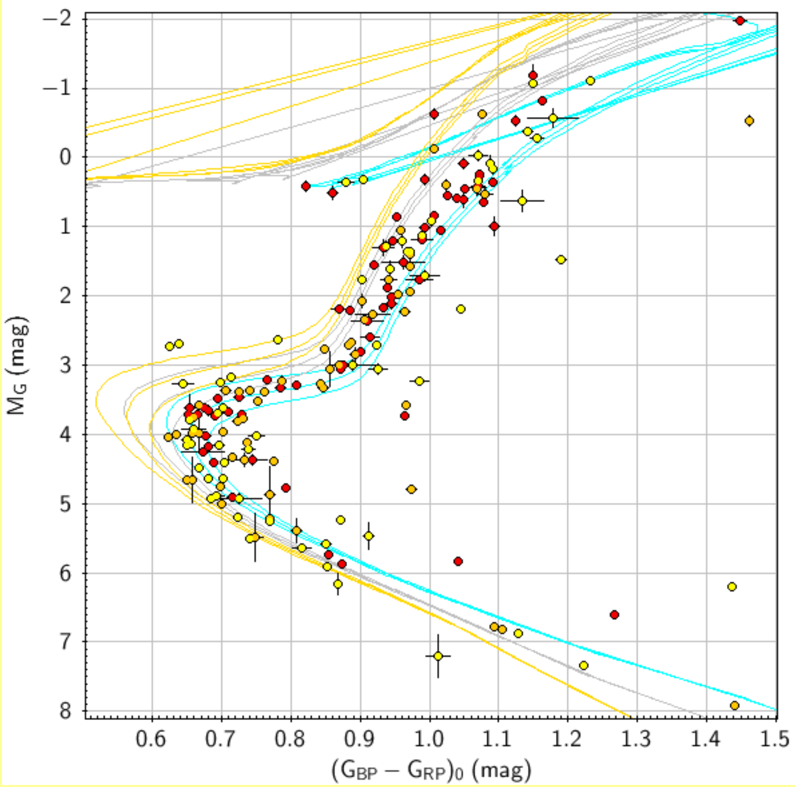

Fig. 8. CMD for the stars with |b|>30° associated with the 3 prograde streams (see Fig. 6). PARSEC-COLIBRI isochrones of ages 10, 12, and 14 Gyr for [M/H] = −1.0 (aqua), [M/H] = −1.5 (silver), and [M/H] = −2.0 (gold) are shown for reference (Bressan+2021, Marigo+2017, Maíz Apellániz & Weiler 2018).

CHEMICAL PROPERTIES

The low-metallicity and low-[Mg/Fe] indicate that these stars are most likely debris from an accreted satellite.

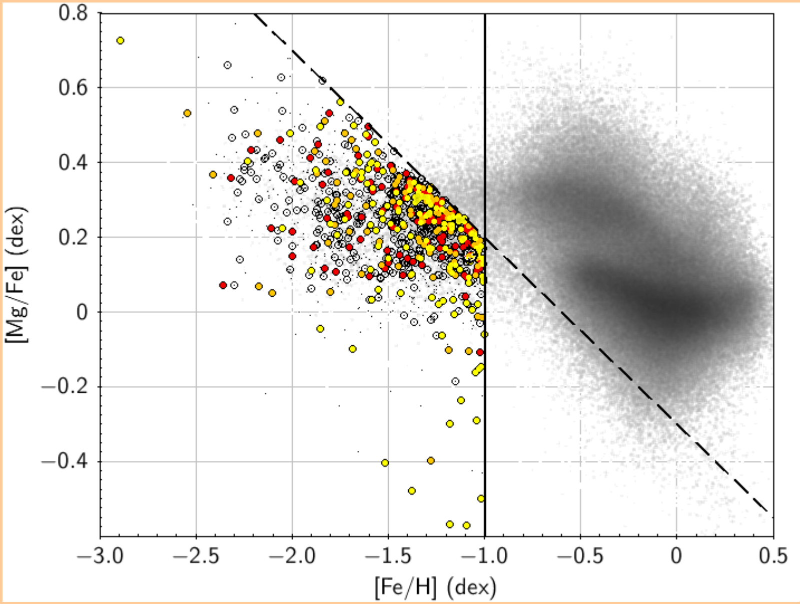

Fig. 9. Chemical distribution [Mg/Fe]-[Fe/H]. Among the 1712 chemically selected halo stars within 3 kpc, circles show objects of the 8 kinematic substructures detected (Figs. 6-7).

Different colours are used to indicate stars associated with the 3 prograde streams with disk-like kinematics. Open circles are members of the five halo streams associated with GSE.

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DISCUSSION: Comparison to SIMULATIONS

We compare our results to high-resolution *N*-body numerical simulations of LMC-like mergers published by Murante+2010 in the space of adiabatic invariants that allows better identification of merging events that might have given rise to the observed substructures. Clumping should be even stronger since all stars originating from the same progenitor should have very similar integrals of motion, resulting in a superposition of the corresponding stream; that is, the initial clumping of satellites are present even after the system has completely phase-mixed (e.g., Helmi & de Zeeuw 2000). Here, we focus on the plane defined by the components of angular momentum in and out the plane of the Galaxy's disk, i.e, L_{xy} and L_z, respectively (Fig. 10).

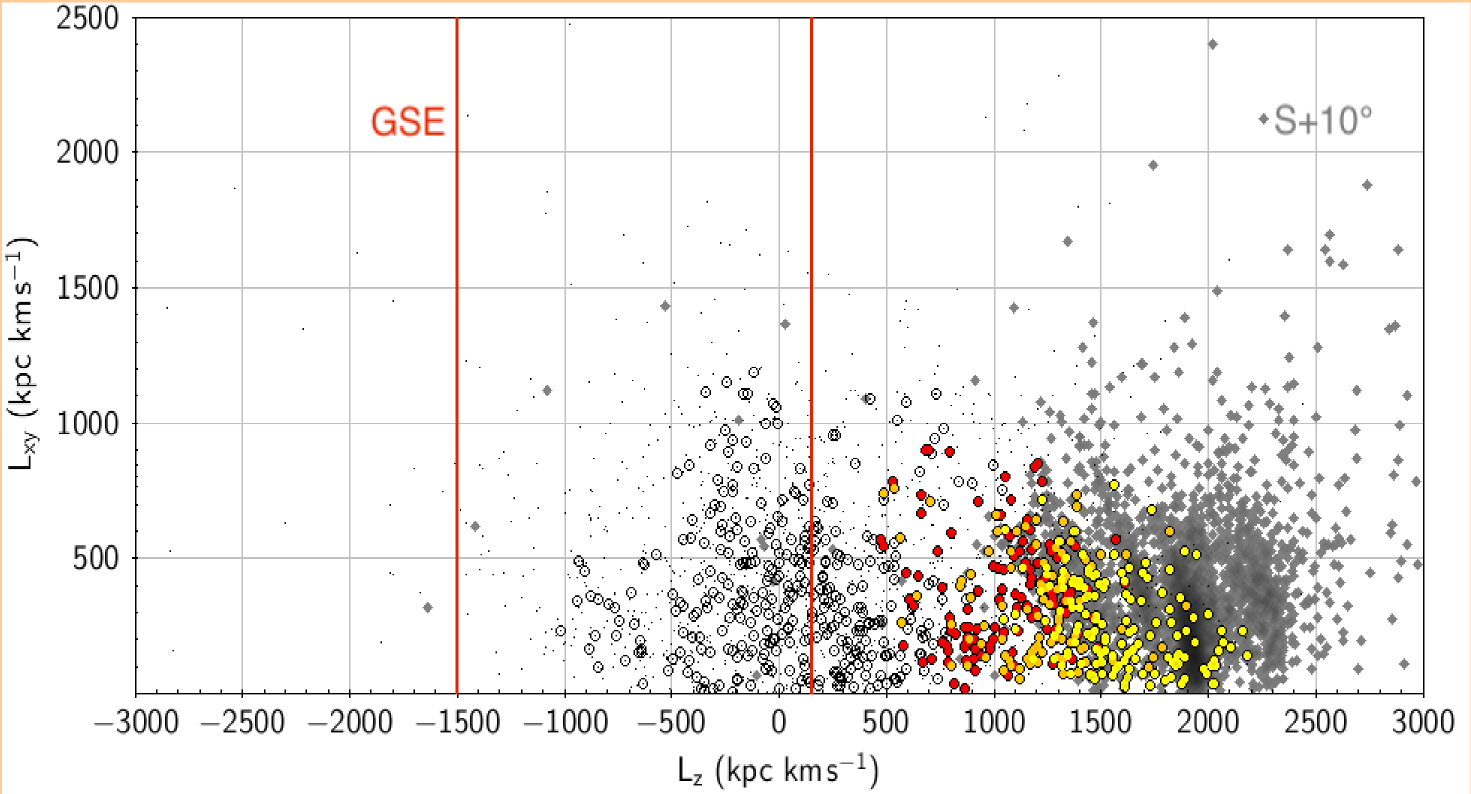

Fig. 10. Space of adiabatic invariants for all the halo objects shown in Fig. 9. As before, different colours are used to indicate stars associated with the 3 streams with disk-like kinematics. The red solid lines indicate the GSE locus (Helmi+2018). The debris of the simulated 10°-inclination prograde satellite analyzed in Re Fiorentin+2015 are overplotted for comparison (grey diamonds).

The peculiar chemical and dynamical properties of Icarus are consistent with the accretion of debris from a dwarf galaxy progenitor with a stellar mass of ~$10^9 M_{Sun}$ on an initial prograde low-inclination orbit, ~10°.

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We use the chemical plane [Mg/Mn] vs. [Al/Fe] to highlight an “extra-Galactic” origin (Hawkins+2015, Das+2020, Horta+2021).

CHEMICAL TAGGING TO UNCOVER AN ACCRETED ORIGIN

We validate the method on **GSE** stars (Belokurov+2018, Helmi+2018) and **Nyx** (Necib+2020, Zuker+2021)

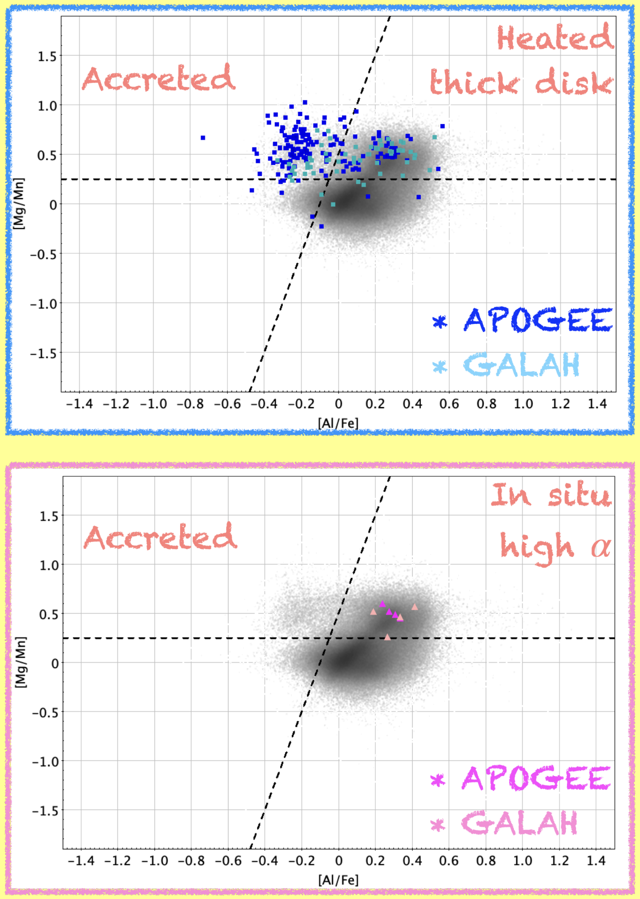

Fig. 11. Chemical distribution [Mg/Mn]-[Al/Fe] of the GSE (left) and Nyx (right) members included in our catalogue.

CHEMICAL PROPERTIES

The high-[Mg/Mn] and low-[Al/Fe] indicate that these **Icarus** stars are most likely debris from an accreted satellite.

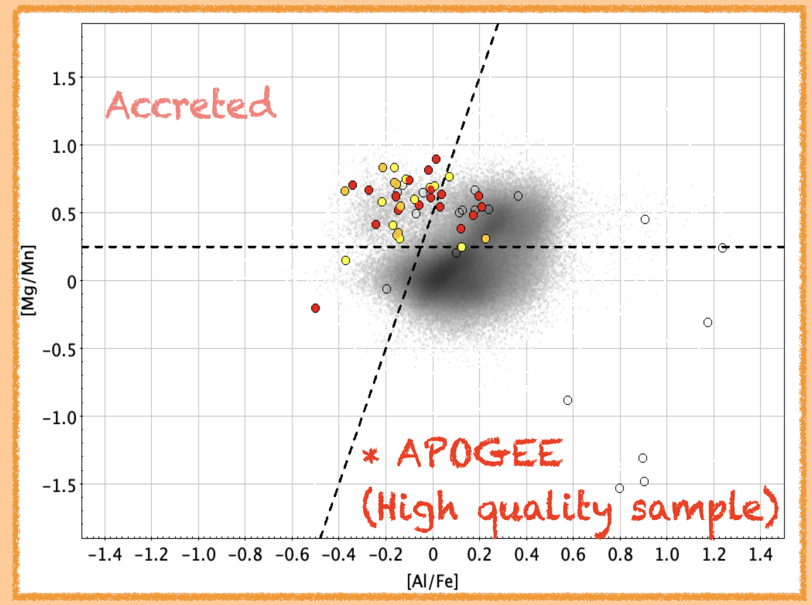

Fig. 12. As Fig. 11 for the Icarus members of the high-quality APOGEE sample. Different colours are used to indicate stars associated with the 3 prograde streams with disk-like kinematics.

Issues on chemical investigation:

- Include GALAH, GES data
- Check low quality abundances
- Spectroscopic follow up

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SUMMARY & FUTURE WORK

Detection and characterization of an accreted dwarf galaxy in the Galactic disk is a challenging task, to which Gaia in continuous synergy with ground-based wide field and high-resolution spectroscopic surveys play a crucial role.

We recently reported the **discovery of Icarus**, the flattest among the fast-rotating stellar stream found in the Galactic disk (Re Fiorentin et al. 2021). With the latest releases from Gaia, APOGEE, GALAH, GES the presence of Icarus has been **further corroborated**.

We gain more insight into the origin of Icarus as remnant of a disrupted dwarf galaxy rather than a signature of the Milky Way's disk formation and evolution, by means of more detailed chemical abundances of its members, also via dedicated spectroscopic follow up, a thorough analysis of tailored N-body high resolution numerical simulations.

As a prototype, the stars of Icarus are very important for chacterizing the debris of a prograde satellite galaxy in the disk of the Milky Way.

→ Coming soon / more by Re Fiorentin et al. (in preparation)

The fall of Icarus, fresco by Sebastiano Luciani known as del Piombo (1511), in the Loggia di Galatea of the Villa Farnesina in Rome. Credit: Lucco M., L'opera completa di Sebastiano del Piombo, Milano 1980, tav. XIX A

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