The Dichotomy of the Galactic Halo of the Milky Way

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SDSS

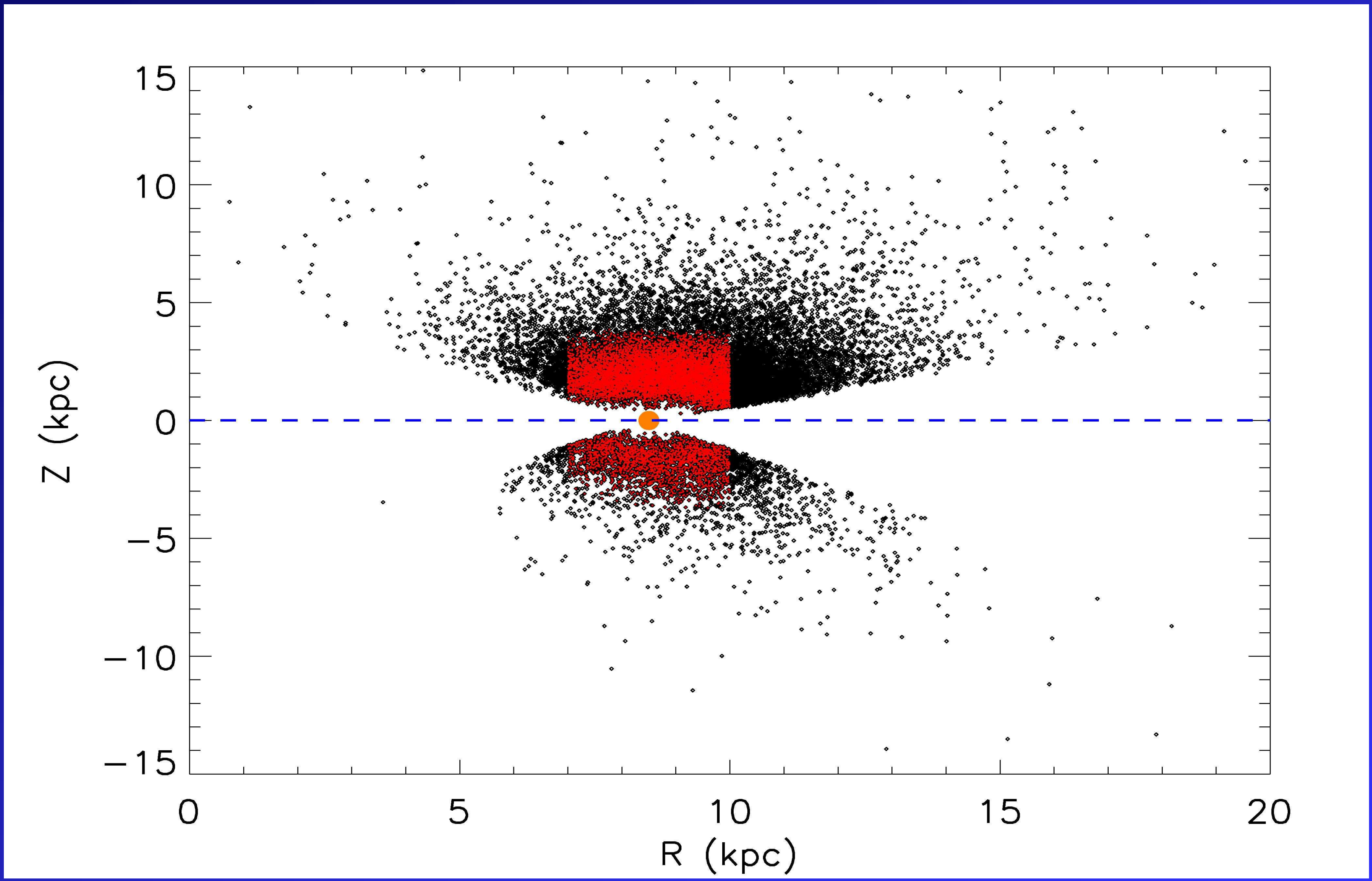
The structural components of the stellar populations in the Galaxy have been known for several decades:

- **Bulge / Thin Disk / Thick Disk (MWTD) / Halo**

- **New results from SDSS have now revised this list (Carollo D. et al. Nature, 2007):**

- **Halo → Halos**

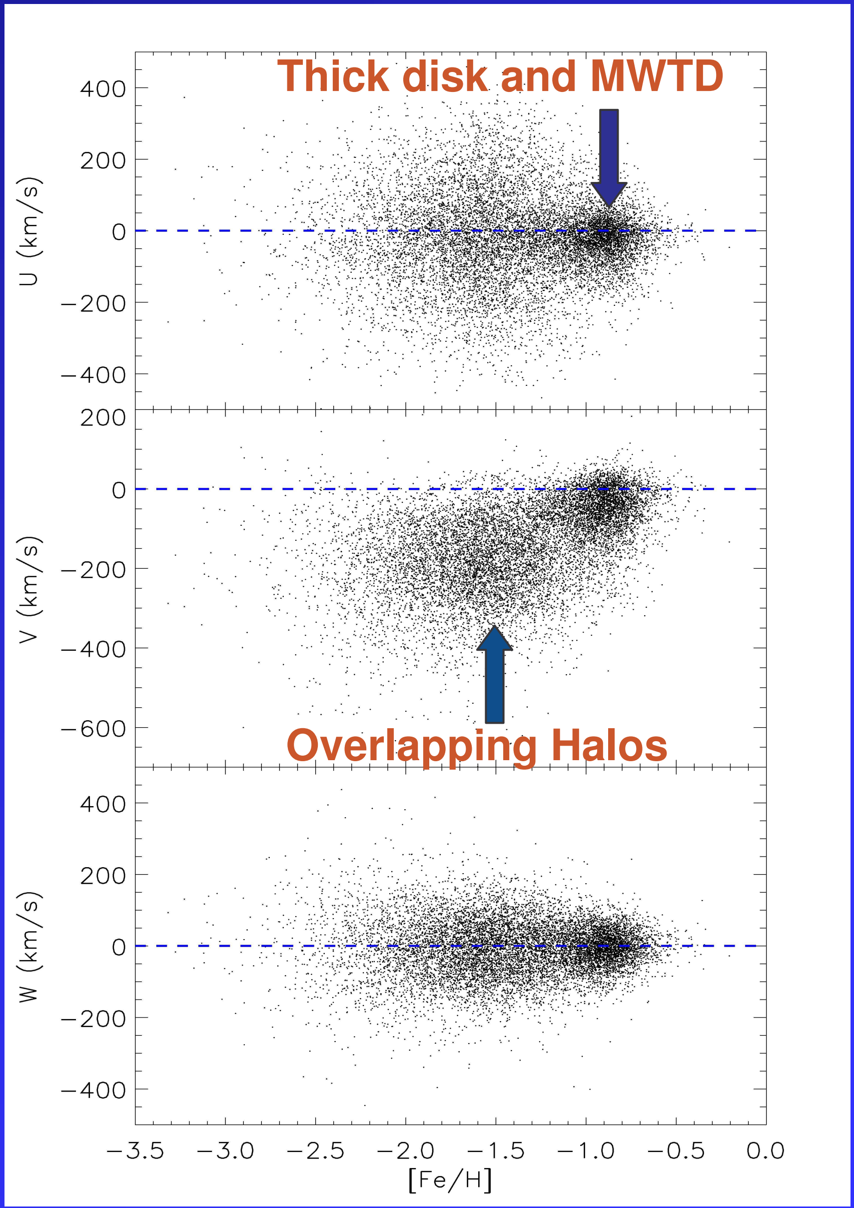
- **Inner Halo:** Dominant at R < 10-15 kpc
  Highly eccentric (slightly prograde) orbits
  Metallicity peak at [Fe/H] = -1.6
  Likely associated with major/major collision
  of massive components early in galactic history
- **Outer Halo:** Dominant at R > 15-20 kpc
  More uniform distribution of eccentricity,
  including highly retrograde orbits
  Metallicity peak around [Fe/H] = -2.2
  Likely associated with accretion of low-mass,
  dwarf-like galaxies over an extended period, up to present



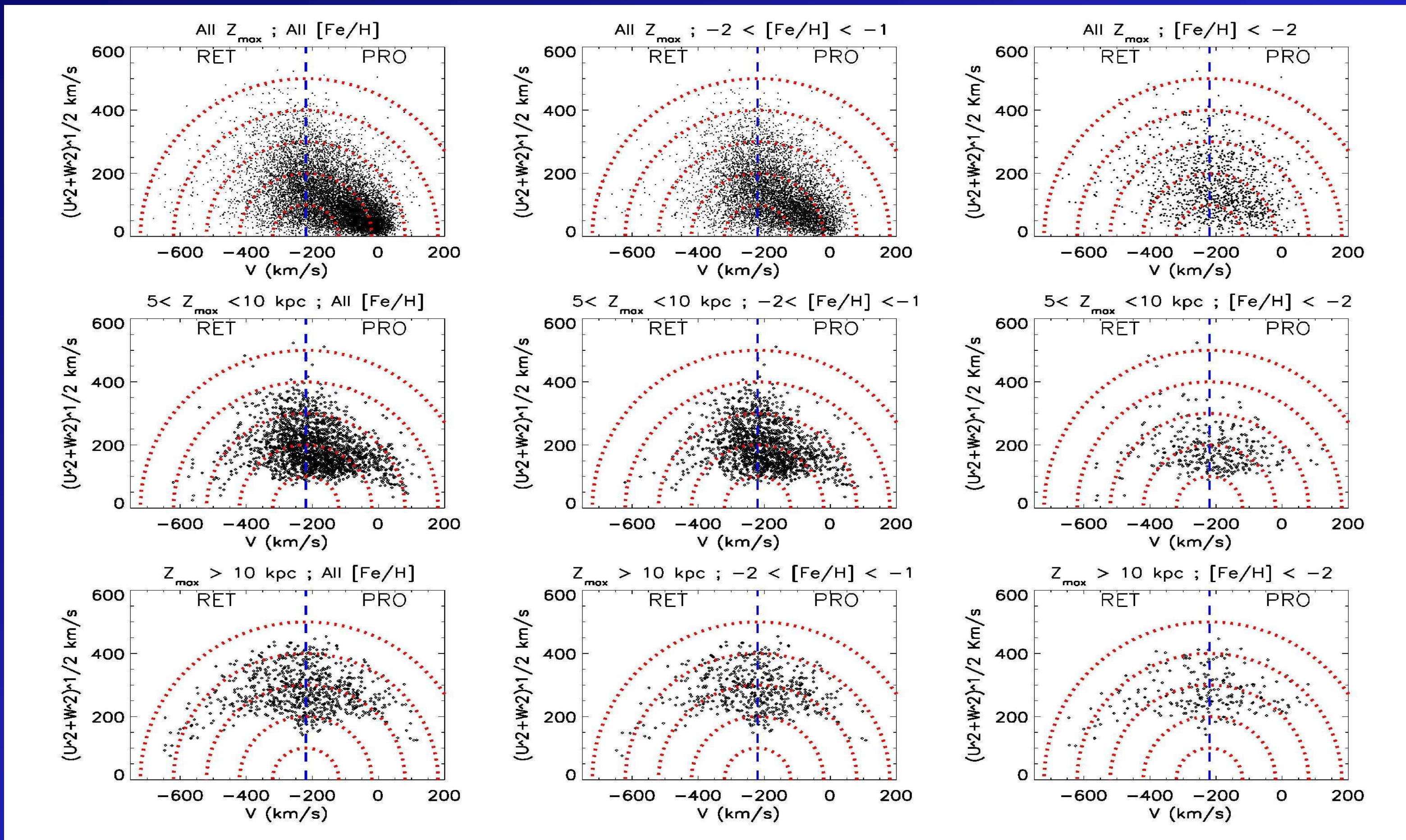
Distribution of the full sample of 20,366 unique SDSS in the Z-R plane. The red points indicate the 11,458 stars that satisfy our criteria of a 'local sample'.

Galactic velocity components

- Proper motion are obtained from the re-calibrated USNOB-2 catalogue, typical accuracy 3-4 mas/yr (Munn et al. 2004).
- These are used in combination with the measured radial velocities and estimated distances provide the information required to calculate the full space motions (U,V,W) of the stars relative to the Local Standard of Rest.
- We have obtained also the rotational component of the star motion about the Galactic center V_{ϕ}.
- Orbital parameters, such as, peri-Galactic and apo-Galactic distance, eccentricity and Z_{max} were derived adopting an analytic Stackel-type potential.



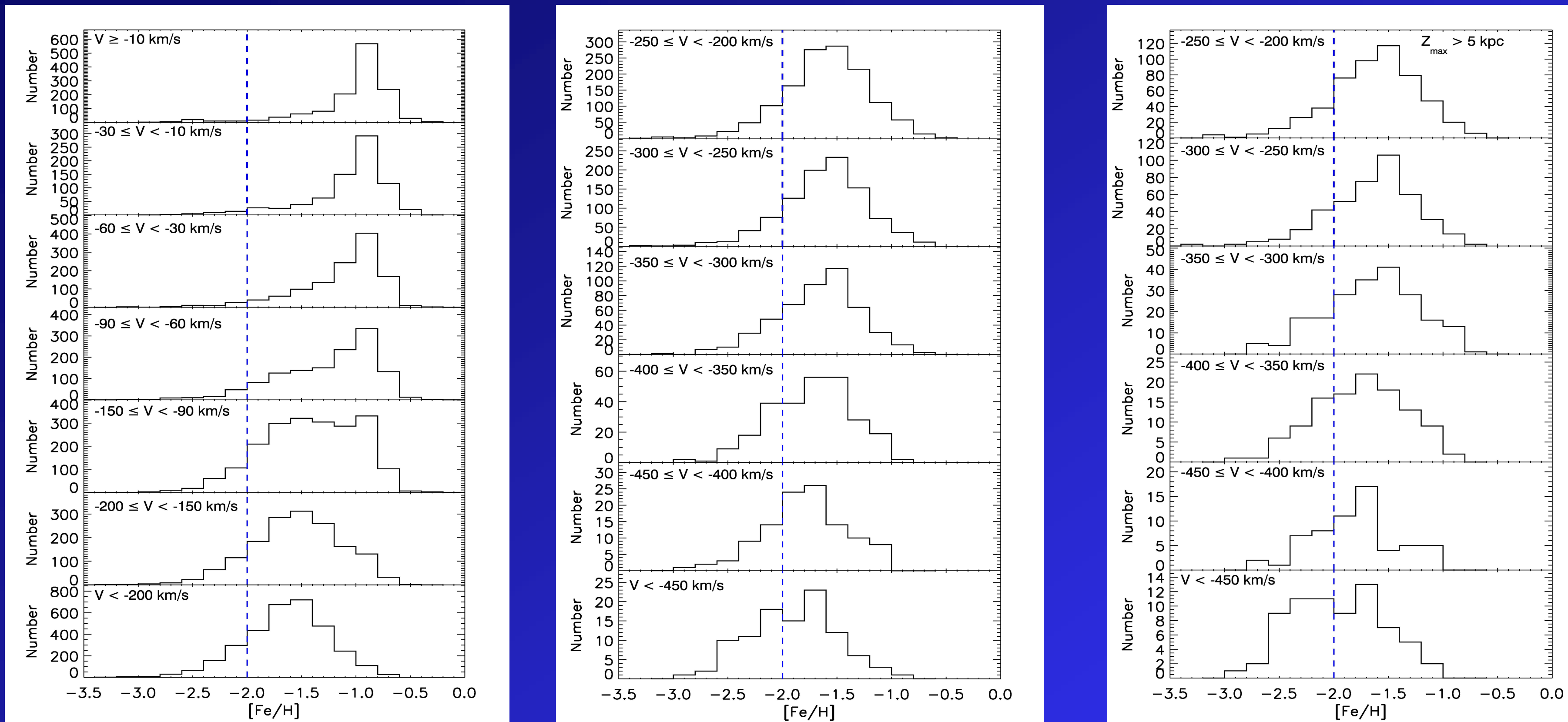
Toomre energy diagrams for various cuts in [Fe/H] and Z_{max}



Red dotted lines: Total space velocities of the orbits. **Upper row**: Stars exploring all ranges of Z_{max} and various cuts in [Fe/H]; note the decreasing importance of stars on disk-like orbits with declining [Fe/H] and how the retrograde orbits explore much larger energies than the prograde stars.

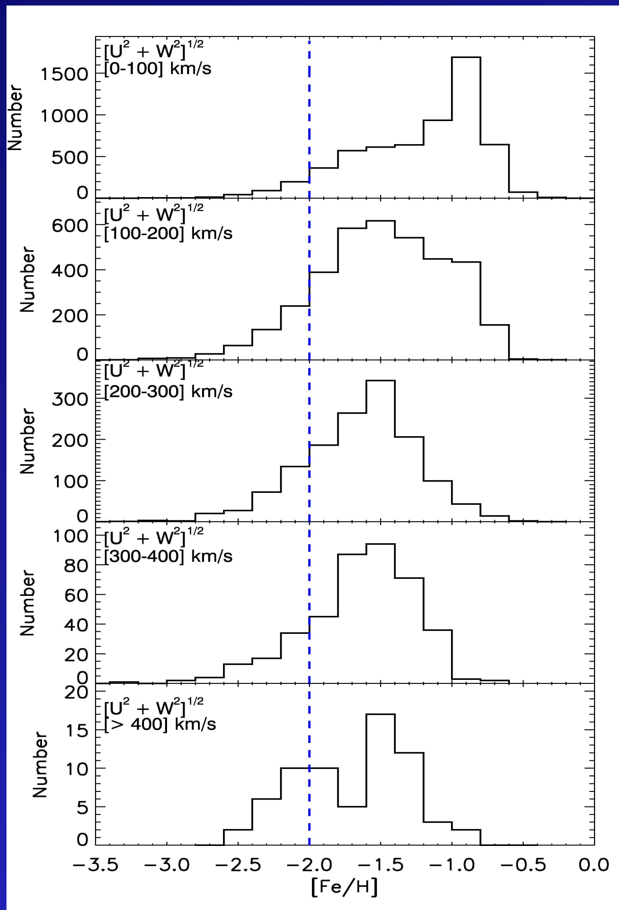
Middle panels: 5 < Z_{max} < 10 kpc, same cuts on [Fe/H]. Still clear the contrast between the high orbital energies of the retrograde stars and the lower energy orbits of the prograde stars. **Lower panel**: Z_{max} > 10 kpc; energy much more evenly distributed between retrograde and prograde orbits, but the V velocities explore lower values than the prograde orbit explore at higher V.

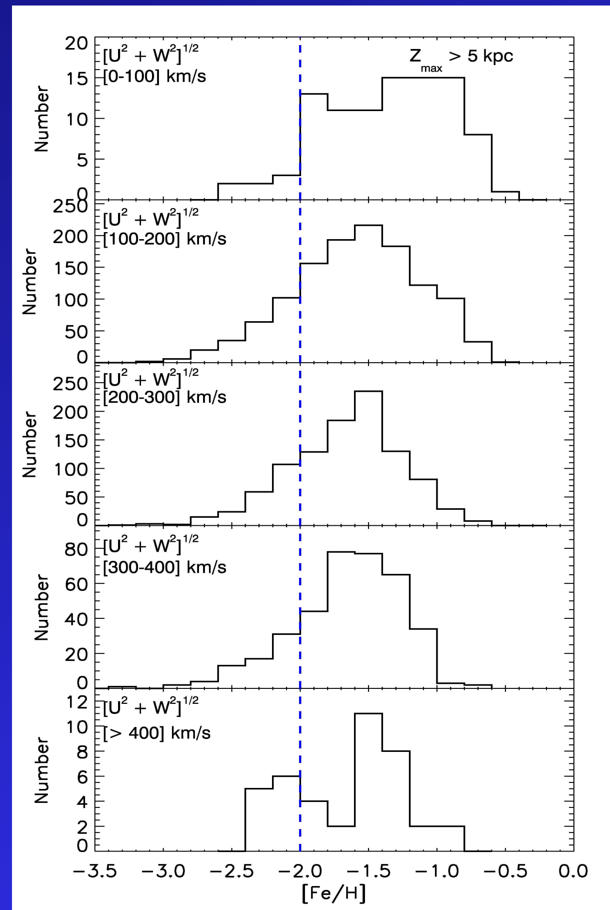
Distribution of [Fe/H] for various cuts in V velocity



Left column: Full data set. Note that the upper three panels are dominated by the thick disk and MWTD population (peak in [Fe/H] ~ -0.9). For V < -90 km/s become evident the transition to dominance by inner-halo and outer halo population. In the bottom panel the distribution appears similar to what in the past was considered the “Halo”. Middle column: Just stars with V < -200 km/s and different cuts. Note that as V becomes increansingly retrograde, the [Fe/H] distribution shift to include larger number of stars with [Fe/H] < -2 and fewer stars with [Fe/H] ~ -1.5. Right column: same velocity cuts as in the middle panel but for stars with Zmax > 5 kpc. Here the increasing dominance of stars with [Fe/H] < -2 is more apparent. In both middle and right end columns of plots, the distribution of [Fe/H] becomes bi-modal.

Distribution of [Fe/H] for various cuts on the parameter $(U^2 + W^2)^{1/2}$

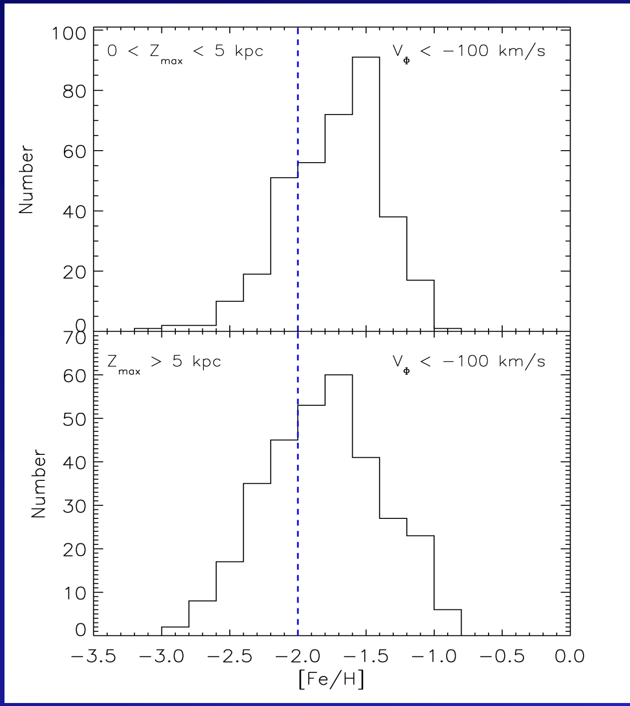


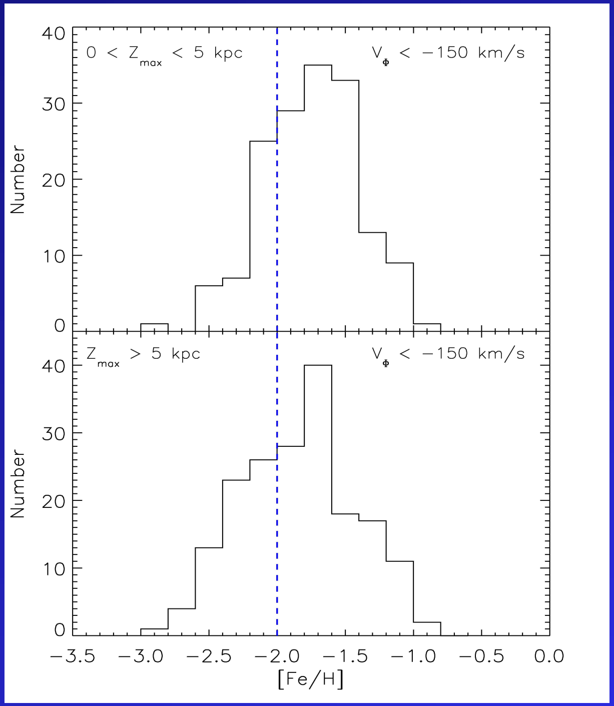


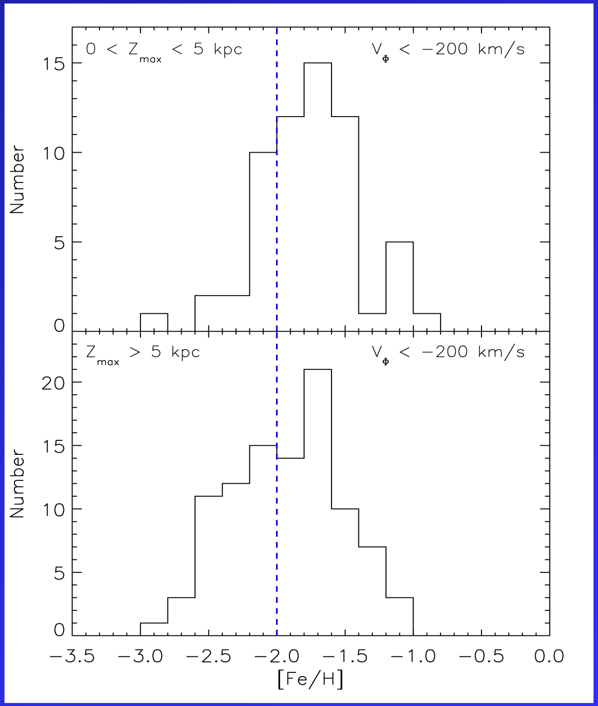
Left column: Full data set. In the upper panel a clear peak at [Fe/H] ~ -0.9→ low-energy orbits for stars in the TD and MWTD populations. Middle panels: Increasing contribution from the inner halo stars with peak at [Fe/H] ~ -1.5. Last panels: Shift of the distribution to lower values as energy increases. Bi-modal distribution at highest energy!

Right column: Z_{max} > 5 kpc, no stars with disk like orbits. Tails of stars with [Fe/H] < -2 becomes stronger and bi-modal in the last panel.

Distribution of [Fe/H] for stars on higly retrograde orbits with various cuts in V_ϕ







Upper panels: 0 < Z_{max} < 5 kpc. Lower panels: Zmax > 5 kpc

Left column: V_ϕ < -100 km/s. Note as the increased contribution from lower metallicity stars as one progresses from the low (Z_{max} < 5 kpc) to the high (Z_{max} > 5 kpc) sub-samples. Note how the predominance of stars from the inner halo population, with [Fe/H] < -1.5, decrease and shift to lower [Fe/H].

Middle and right columns: Cuts on V_ϕ < -150 km/s and V_ϕ < -200 km/s respectively, show similar behaviours. In the lower panel of the right-end side, the stars with [Fe/H] < -2 constitute over 40% of the total sample.

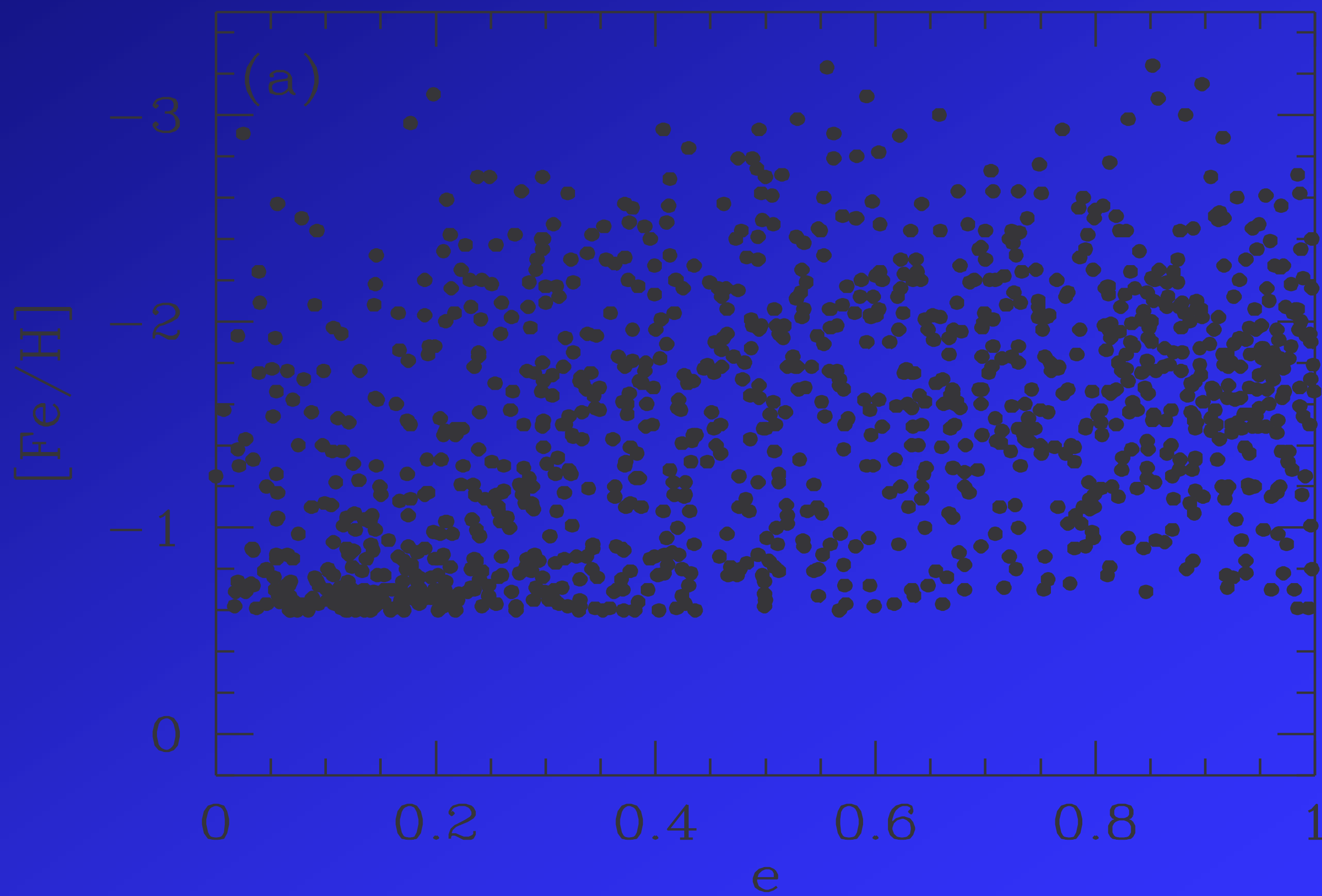
From the analysis of the kinematic parameters and metallicity we can conclude:

1. **The change in the distribution of [Fe/H] with V (or V_{ϕ}), $(U^2+W^2)^{1/2}$ and Z_{max} WOULD NOT BE expected if the "Halo" were a SINGLE ENTITY**

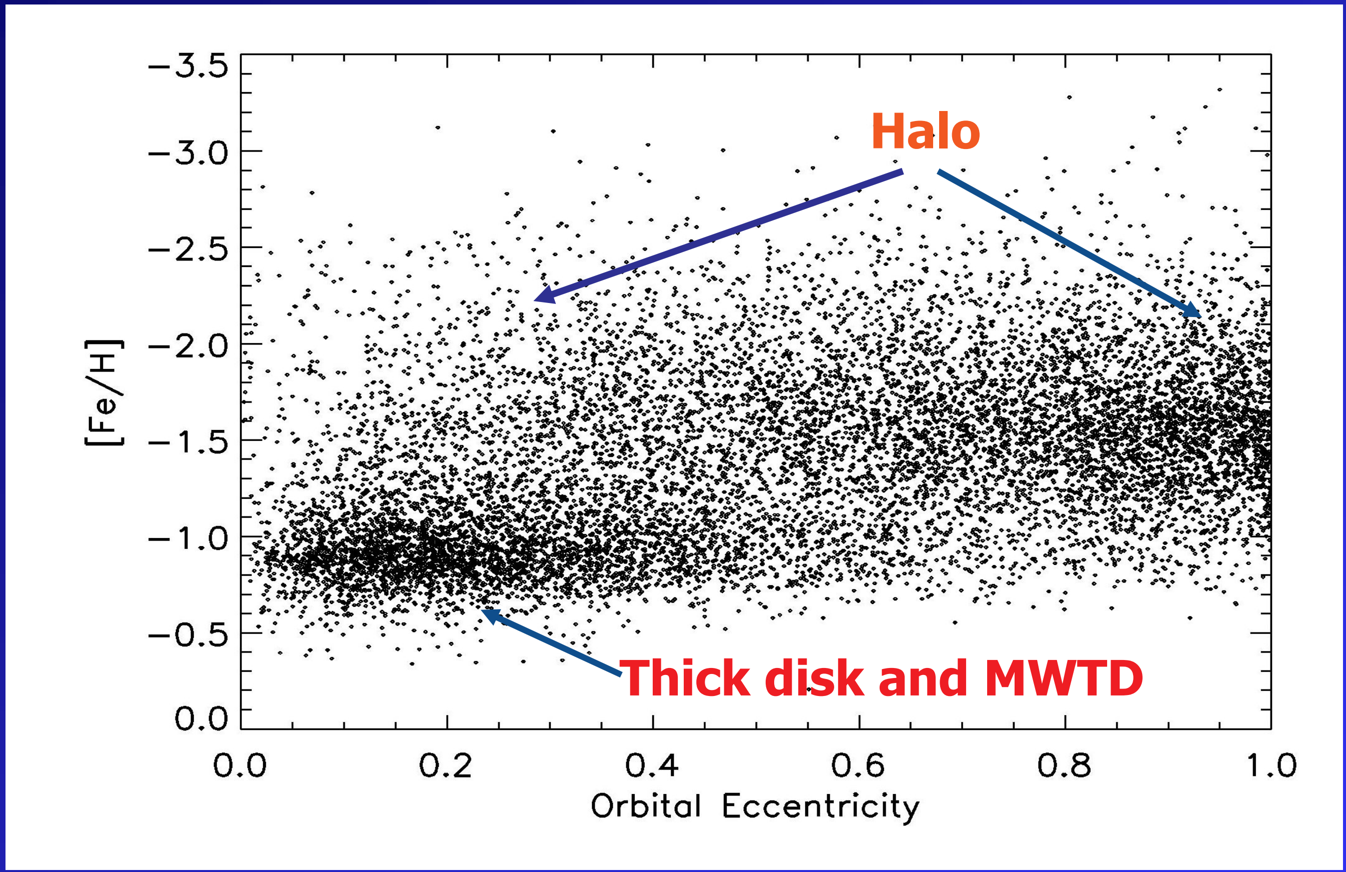
2. **"The Halo" of the Galaxy comprises stars with INTRINSICALLY DIFFERENT DISTRIBUTION of [Fe/H], which we associate with the inner-and –outer halo populations**

[Fe/H] vs. Eccentricity
Chiba & Beers (2000)

Based on a sample of ~ 1200 Non-Kinematically Selected Stars



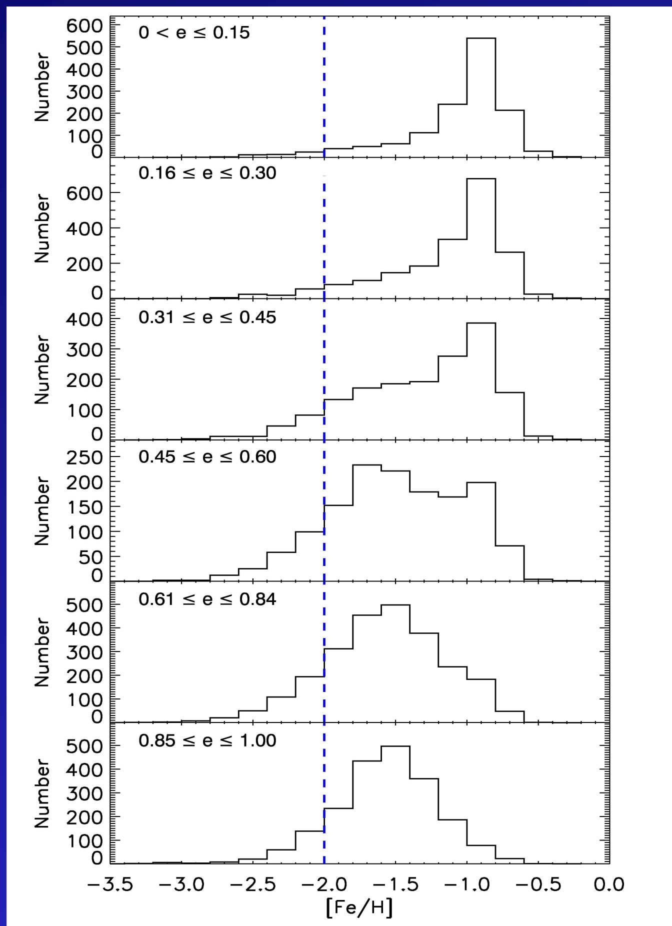
[Fe/H] vs. orbital eccentricity – SDSS – 11458 stars

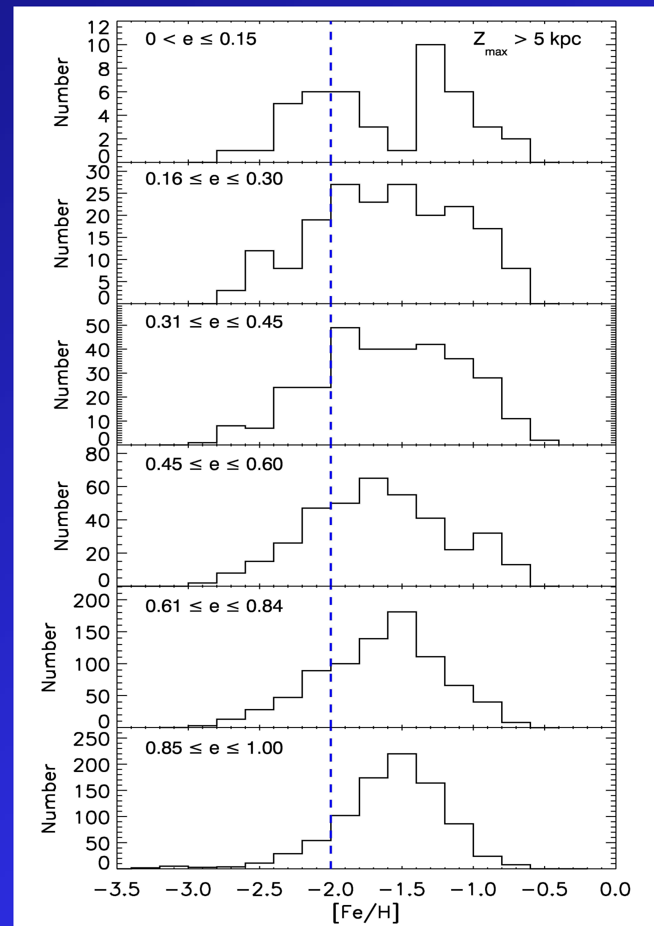


Bottom left: we can distinguish the thick disk and MWTD population with moderate metallicity (-1.3 < [Fe/H] < -0.3) and low eccentricity stars (0.0-0.4).

Middle right: clearly visible the presence of low metallicity (-2.0 < [Fe/H] < -1.0) and high eccentricity (0.6-1.0) stars which we associate to the inner-halo population. The outer halo population exhibits a relatively uniform distribution of eccentricity over the full range from 0.0 to 1.0 and is dominated by lower metallicity stars (-1.5 to -3.5) and mode [Fe/H]~ -2.0. Not easily separated from other populations.

Distribution of [Fe/H] for various cuts on the orbital eccentricity



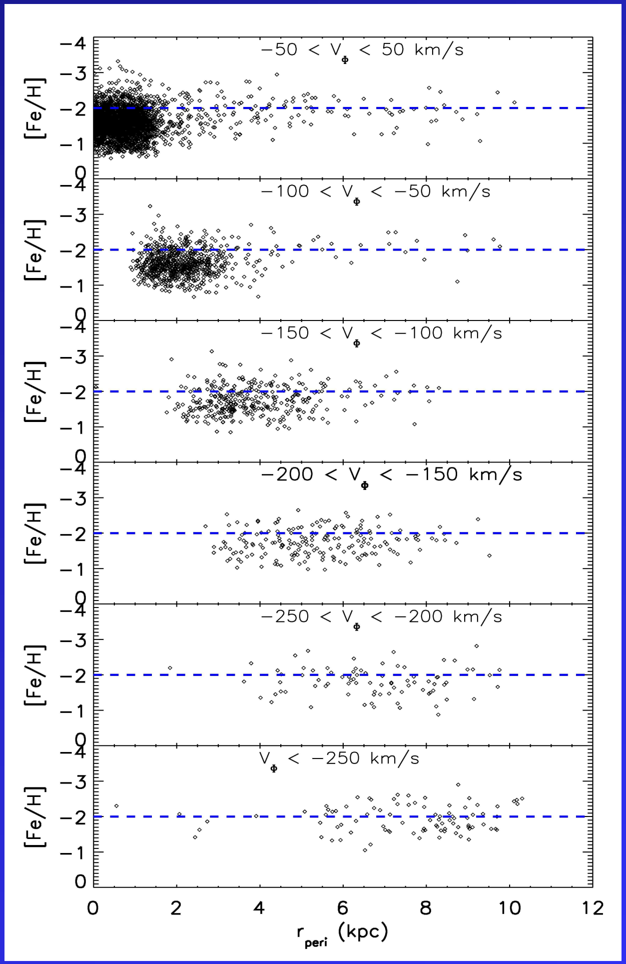


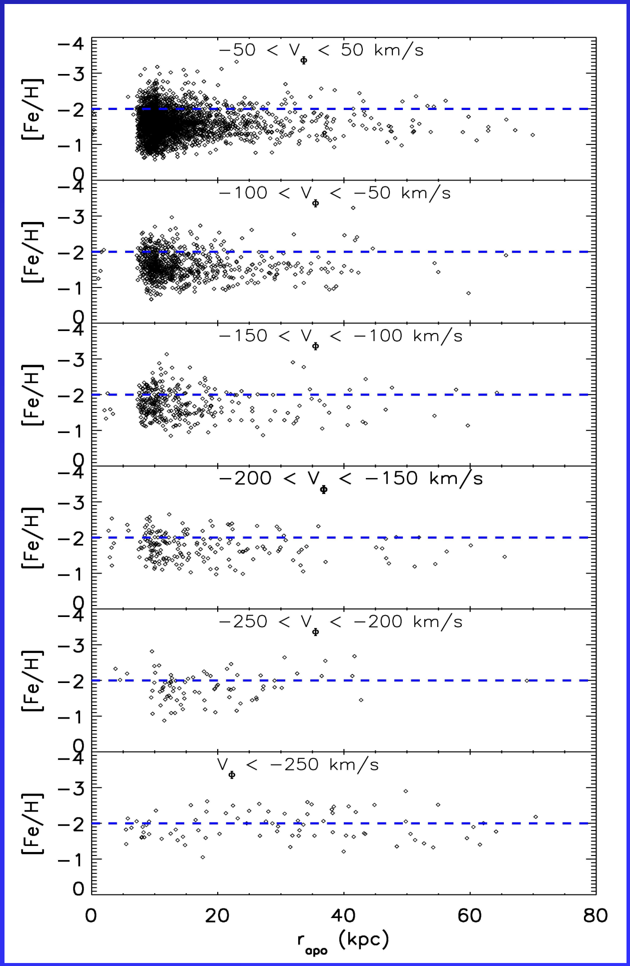
Left column: Full data set. At low eccentricity clearly visible the TD and MWTD stars. At higher eccentricity the influence of disk-like stars decreases and we recognize the a distribution similar to the "canonical halo". **Right column:** Stars with Zmax > 5 kpc. No stars from the disk-like population BUT at low eccentricity we see a **bi-modal distribution** (upper panel) transitioning to a distribution with peak [Fe/H] ~ -1.5 at high eccentricity.

Nature of the Orbits

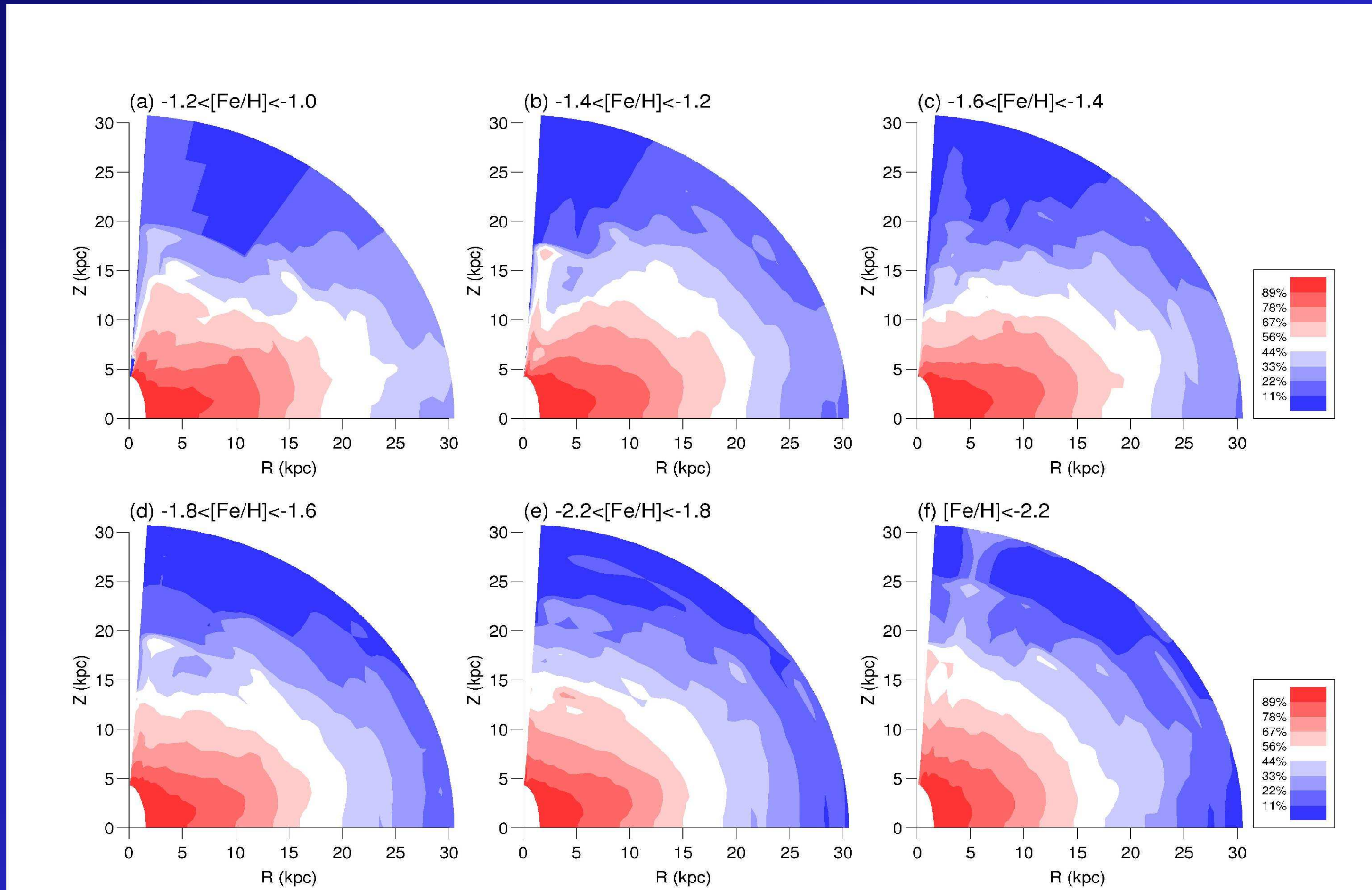
Left column: Pericentric distance vs [Fe/H] and different cuts in V_ϕ. The upper panel is dominated by inner halo stars which penetrate the region near the Galactic center. At more retrograde orbits the fraction of stars that penetrate to the Gal. center decreases. The most highly retrograde stars, which are dominated by the outer halo, exhibit $r_{peri} > 6$ kpc.

Right column: Apocentric distance. The first panel shows that the inner halo stars do not posses orbits that take them beyond ~ 15-20 kpc. This trend become more evident at higher retrograde orbits.



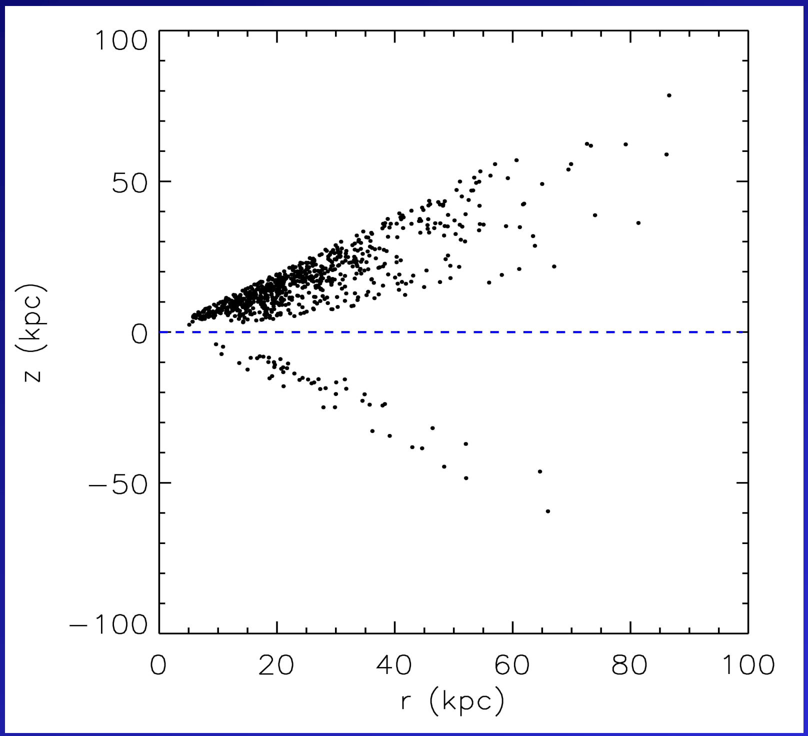


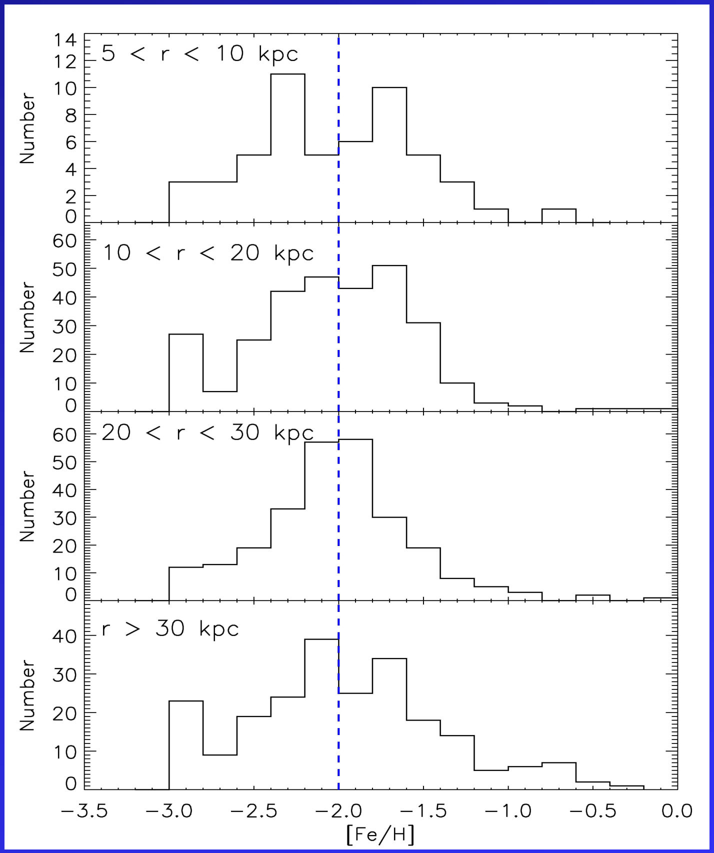
Equidensity contours of the reconstructed global density distribution in the Z-R plane for various cuts in metallicity



The halo is more flattened for halo stars in the metal rich range (axis ratio ~ 0.6-0.7) whereas the most metal poor range of the halo is nearly spherical (axis ratio ~ 0.9). The inner-halo population is characterized as a flattened density distribution that dominates for stars with [Fe/H] > -2. The outer-halo population is spherical, dominates at larger distances and for stars with [Fe/H] < -2.

Further confirmation of the existence of the outer halo: An in-situ sample of FHB stars from SDSS





Distribution in the Z-r plane of an in-situ sample of blue horizontal-branch stars selected from SDSS DR-5

- **Metallicity distribution for different cuts in the distance from the Galactic center. Note: Bi-modal distribution (upper panel) for stars within 10 kpc.**
- **Overlapping distribution of [Fe/H] at intermediate distances 10 < r < 20 kpc**
- **MDF almost unimodal at 20 < r < 30 kpc**
- **Bi-modal again at r > 30 kpc due to the presence of inner-halo stars with highly eccentric orbit.**

From the analysis of the orbital parameters and [Fe/H] we can conclude:

1. **Inner and Outer Halo populations exhibit different orbital characteristics**
2. **The Inner Halo dominates locally for stars with [Fe/H] > -2 and shows a flattened distribution, whereas the Outer-Halo population dominates for all [Fe/H] at distances r ~ 15-20 kpc and also locally for stars with [Fe/H] < -2**

Note that: only the very large sample of stars form SDSS has demonstrated the change of the global density distribution with such SMALL step in [Fe/H]

Net rotation of the outer halo
Frenk & White analysis

Stars at Z_{max} > 5 kpc

[Fe/H] range	N_{stars}	V_{rot} (km/s)	Error
-1.00 to -2.00	2041	-43.	7.
-2.00 to -5.00	549	-46.	14.

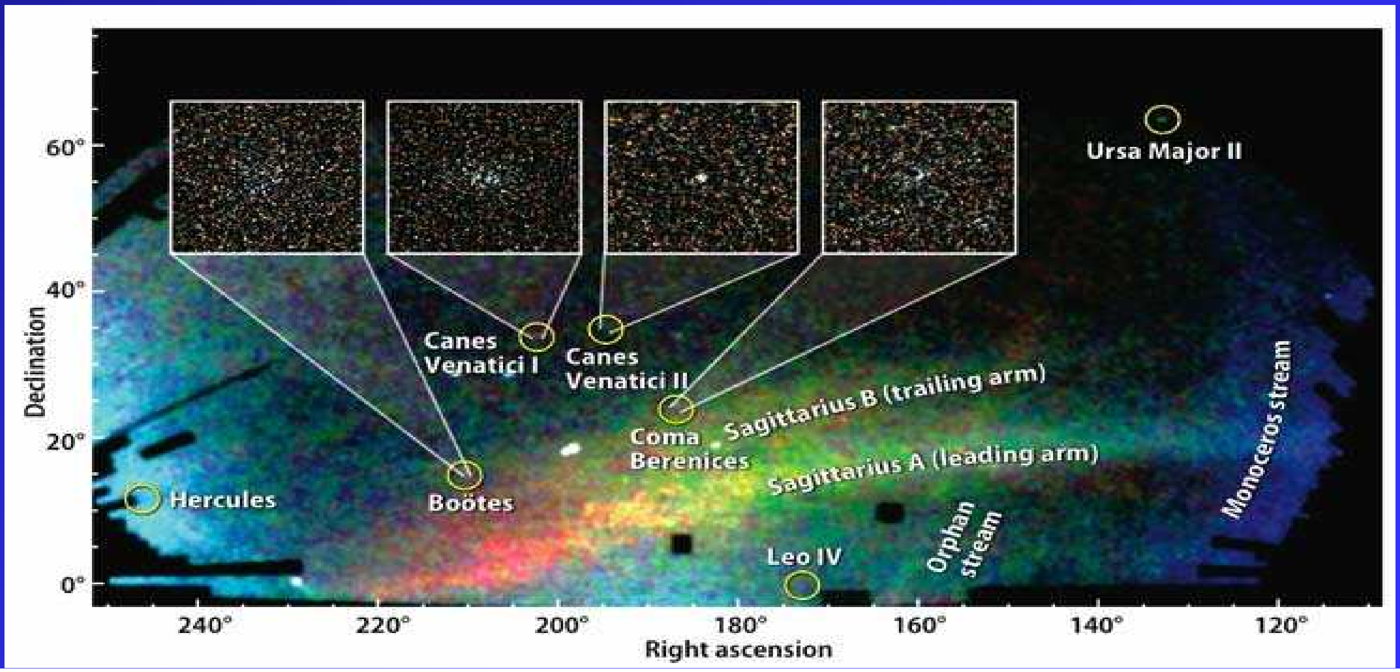
Stars at Z_{max} > 10 kpc

[Fe/H] range	N_{stars}	V_{rot} (km/s)	Error
-1.00 to -2.00	554	-75.	16.
-2.00 to -5.00	231	-61.	27.

Note that our determination of the net rotation of the Outer Halo is probably influenced by the unavoidable overlap with stars from the Inner Halo population

Possible scenario for the formation of the Outer Halo

- **The outer halo exhibits a net retrograde rotation, different distribution of orbital properties, different spatial distribution, and different metallicity distribution. This suggests that *the formation of the outer halo is distinct from that of both the inner-halo and disk components.***
- **The outer halo component has been formed through a (dissipationless) *chaotic merging of smaller sub-systems with a pre-existing dark halo.***
- **These sub-systems have lower mass and are subject to strong tidal disruption in the outer part of a dark halo**
- **The surviving counterpart for such sub-systems could be the *currently observed low luminosity dwarf spheroidal galaxies surrounding the Galaxy.***



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