# Metal-poor stars observed by the Gaia-ESO Survey (and other large surveys)

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(image credit: ESA/ESO)

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# Metal-poor stars

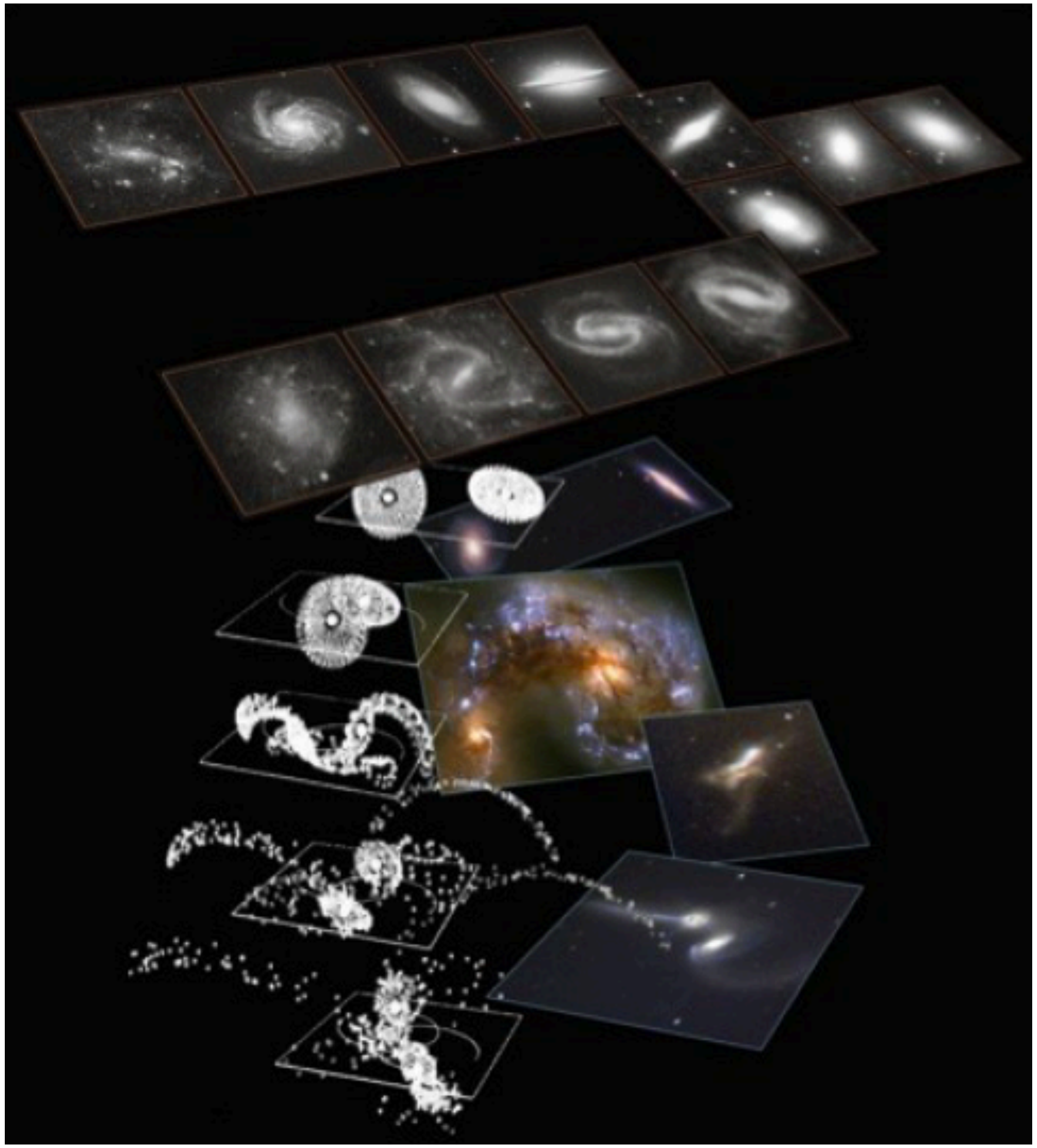
- The main interest is to use large surveys to extract a (large) sample of halo stars

- The halo: an unique window to study the early stages of Galactic formation (Helmi 2008)

- Trace the hierarchical assembly of the Galaxy (e.g., Zolotov et al. 2009; Tissera et al. 2014)

- Understand the history of early chemical enrichment (e.g., Brusadin et al. 2013) - but we need good ages!

- Use large surveys to understand the halo substructure: inner x outer halo; accreted x in situ stars (e.g., Carollo et al. 2010; Smiljanic et al. 2009)



# The Gaia-ESO Survey

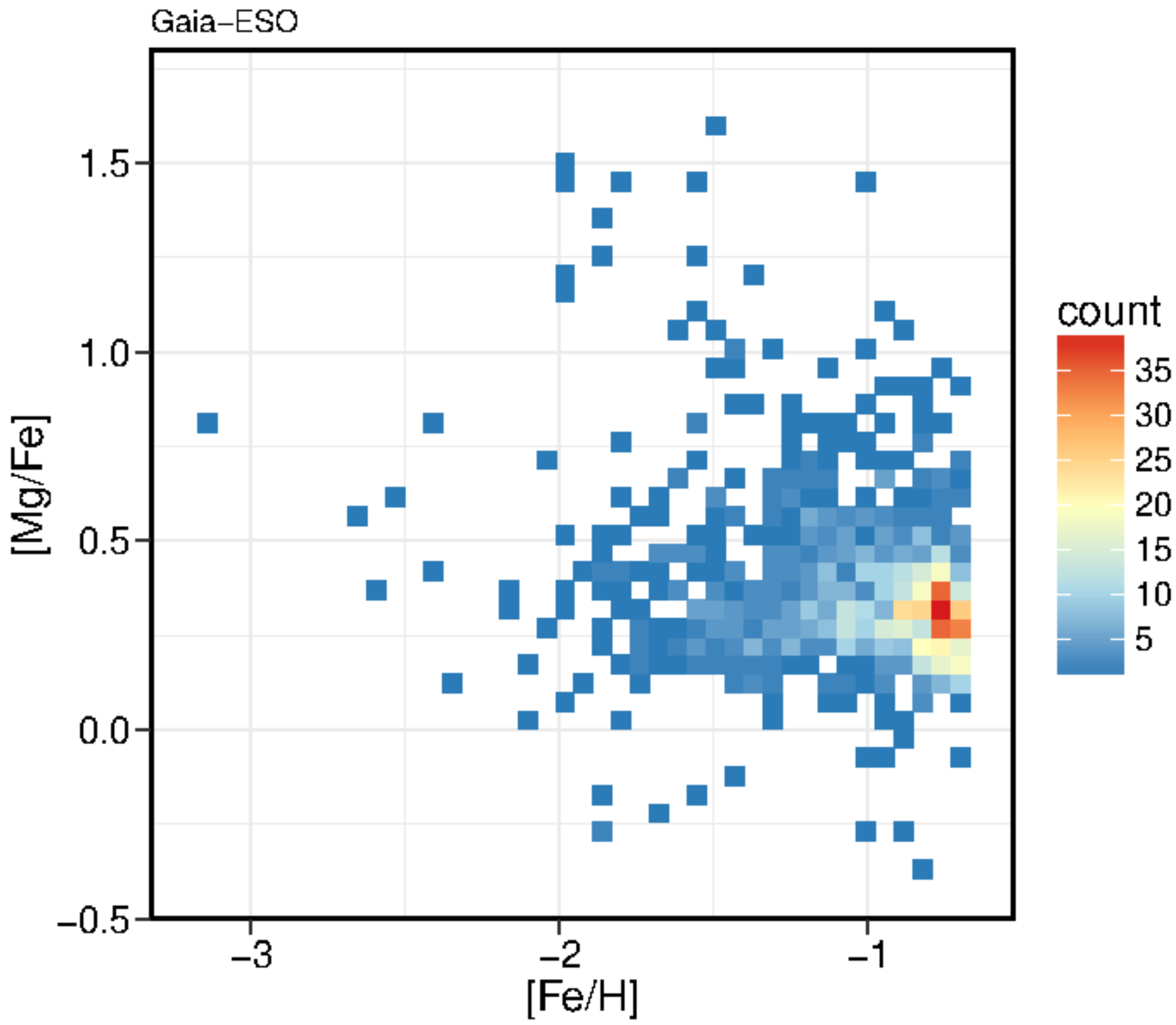
http://www.gaia-eso.eu

- Public stellar spectroscopic survey (Gilmore et al. 2012, Randich & Gilmore 2013)
- FLAMES @ VLT (Giraffe & UVES)
- > $10^5$ Galactic stars
- Observations completed: 300 nights + compensation (from Dec. 2011 to January 2018)
- All Galactic components: halo, thick disk, thin disk, bulge, globular and open clusters
- > 400 Co-Is
- Last analysis cycle ongoing: will take into account Gaia DR2 data

(source: ESO)

# Goals & Sample

- From the Gaia-ESO results: 1171 stars ([Fe/H] ≤ -0.70; no GC stars; and a series of quality constraints)
- 1161 stars with Gaia DR2 parallaxes (but 1054 stars with positive π values; and only 531 stars with $\sigma_\pi/\pi \leq 0.3$)
- How to extract the halo stars out of this sample?
- There's at least the thick disk (plus the metal-weak tail of the thick disk and, maybe, the most metal-poor thin disk stars)
- Selection in metallicity? kinematics?
- Why not let the data tell how the stars are organised?



# Goals & Sample

- Can also study how the populations transition into one another

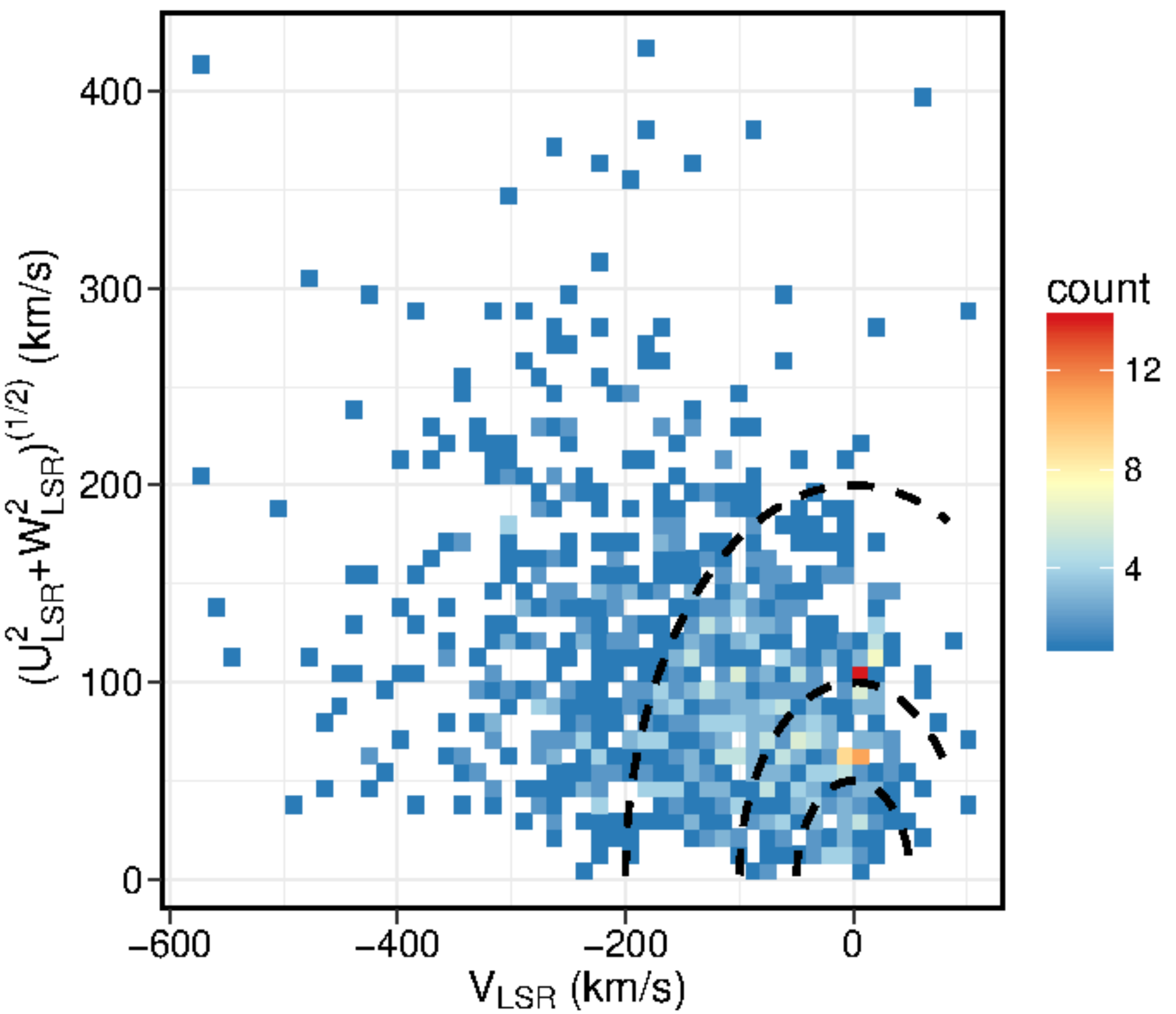
- Quantities available include:

  ➡ Chemistry: Fe, Mg, Al, and Si (see Mikolaitis et al. 2014)

  ➡ Velocities: U, V and W (Gaia DR2 proper motions, Lindegren et al. 2018, and distances from Bailer-Jones et al. 2018)

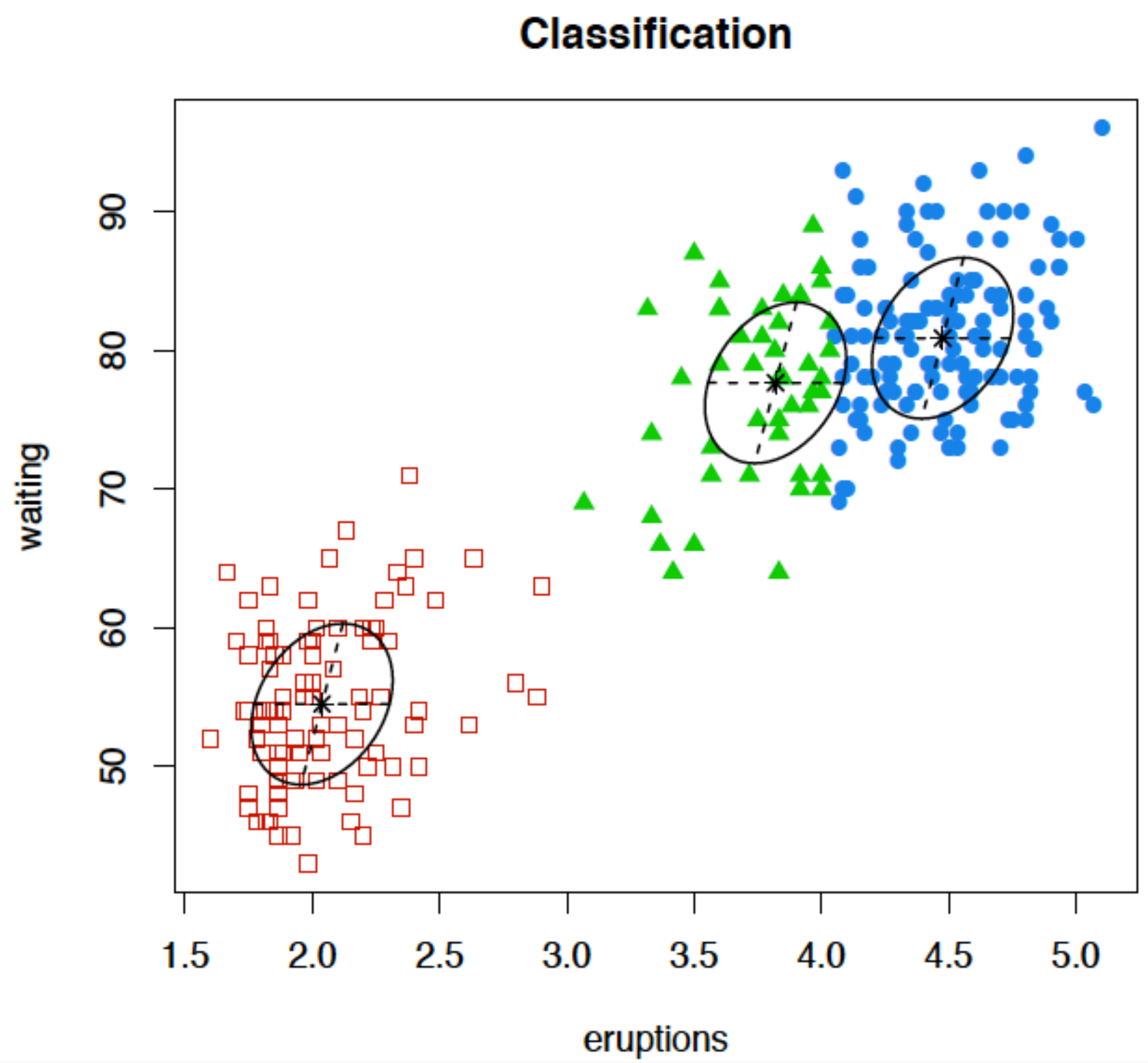
  ➡ Orbits: Rmin, Rmax, Zmax, ecc, Energy, Ang. Mom. (using GalPot - McMillan 2017)

  ➡ Ages (using UniDAM - Mints & Hekker 2017)



# Method

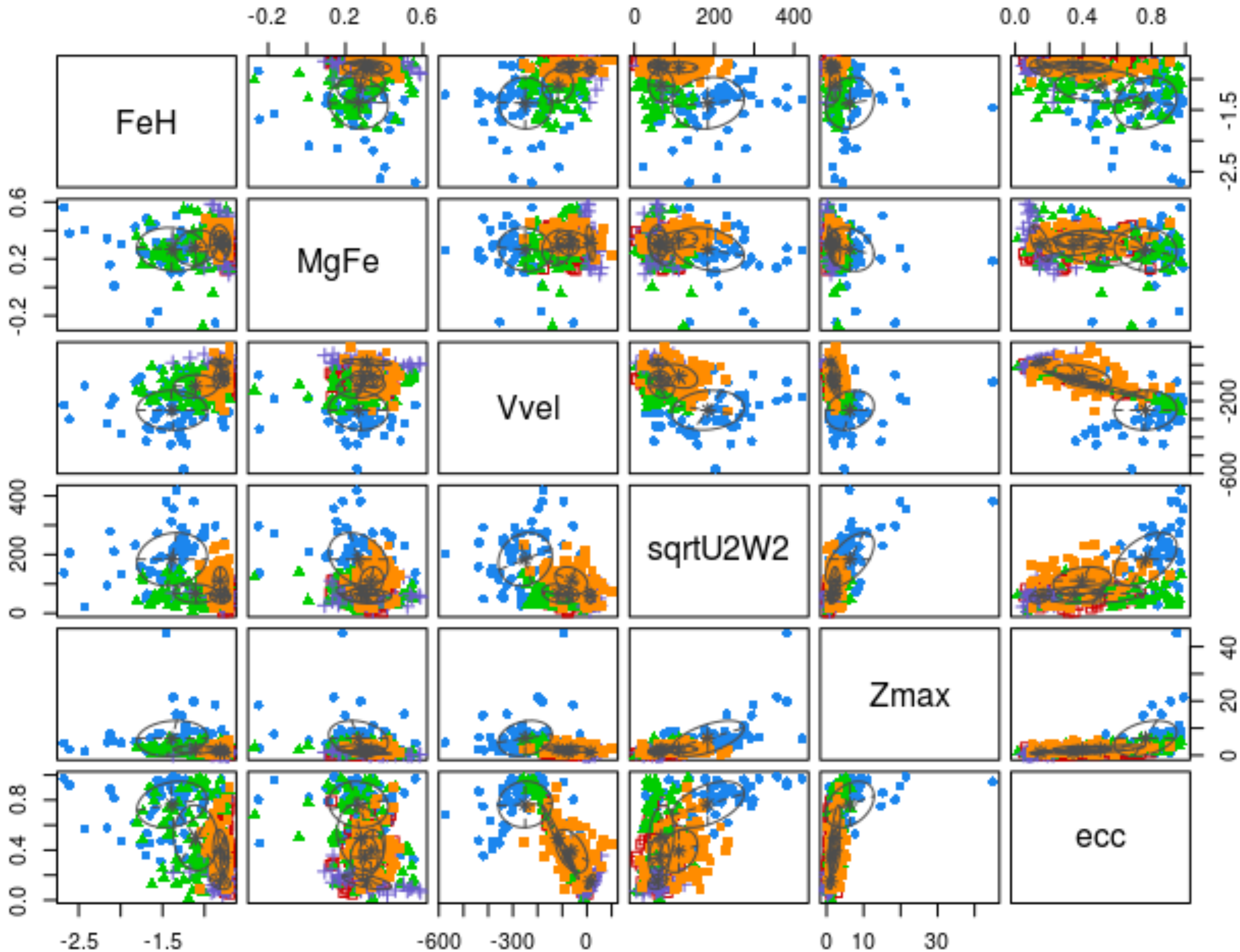
- Analysis in a multi-dimensional space to identify the stars of similar properties
- After a principal component analysis - work with 6 variables: [Fe/H], [Mg/Fe], V, sqrt(U^2 + W^2), Zmax, and eccentricity
- Model-based clustering based on Gaussian mixture modelling (*Mclust* in R; Fraley et al. 2012, Fraley & Raftery 2002)
- Divide the stars in “clusters” (i.e., groups) that can be fit by 6D Gaussians of variable shapes, volumes and orientations
- The algorithm decides how many groups
- But the groups that are found do not need to correspond to real and distinct stellar populations



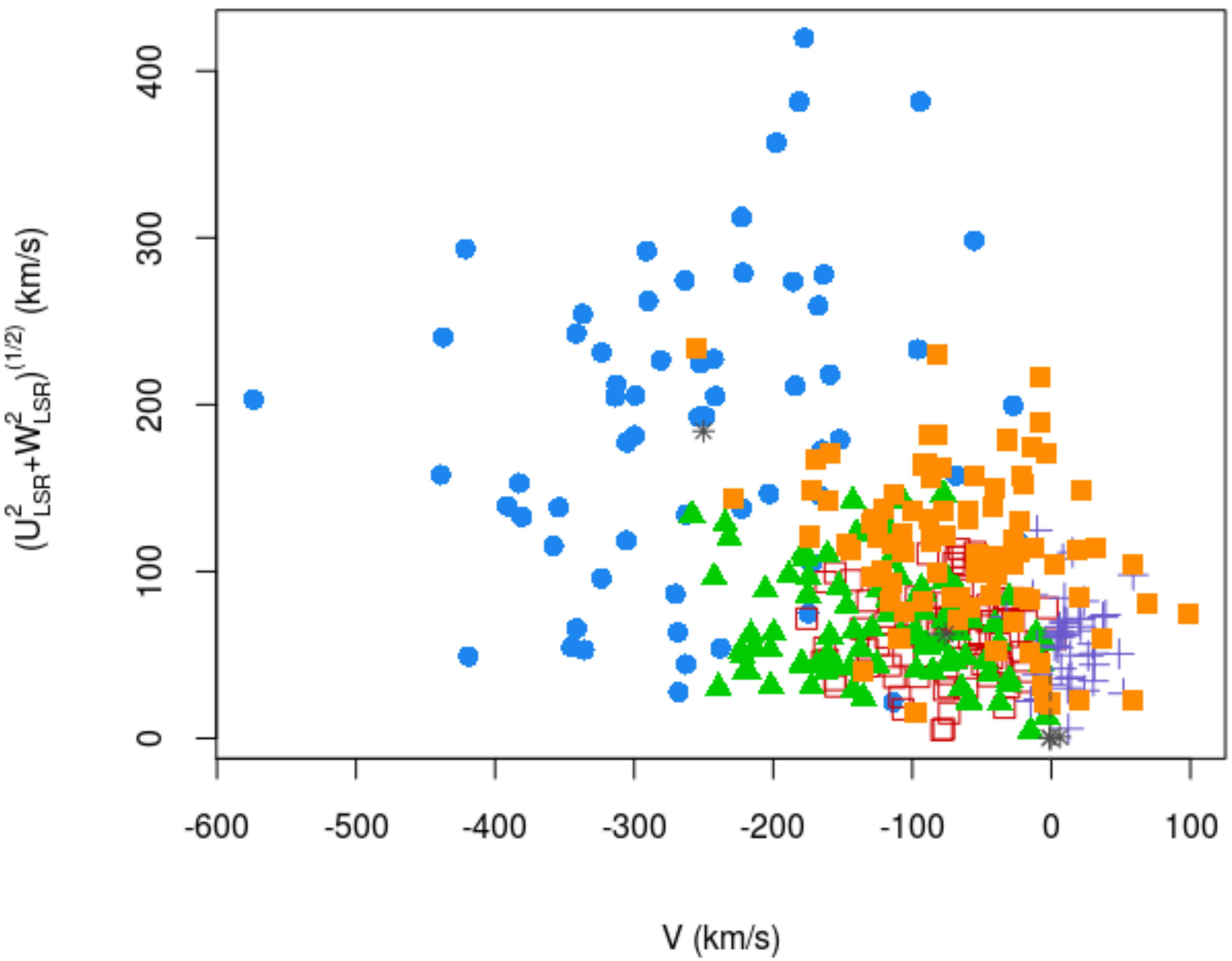

(From Mclust manual; Fraley et al. 2012)

# Found five clusters

In a reduced sample of 375 stars (best parallaxes and PMs)



# Galactic velocities




Looks remarkably close to the division we would propose anyway

- Blue circles (63): my halo stars??

  ➡ Mean V = -250 ± 109 km/s

- Green triangles + orange squares + red open squares(88+90+88): the thick disk??

  ➡ Mean V = -118 ± 64 km/s

  ➡ Mean V = -63 ± 65 km/s

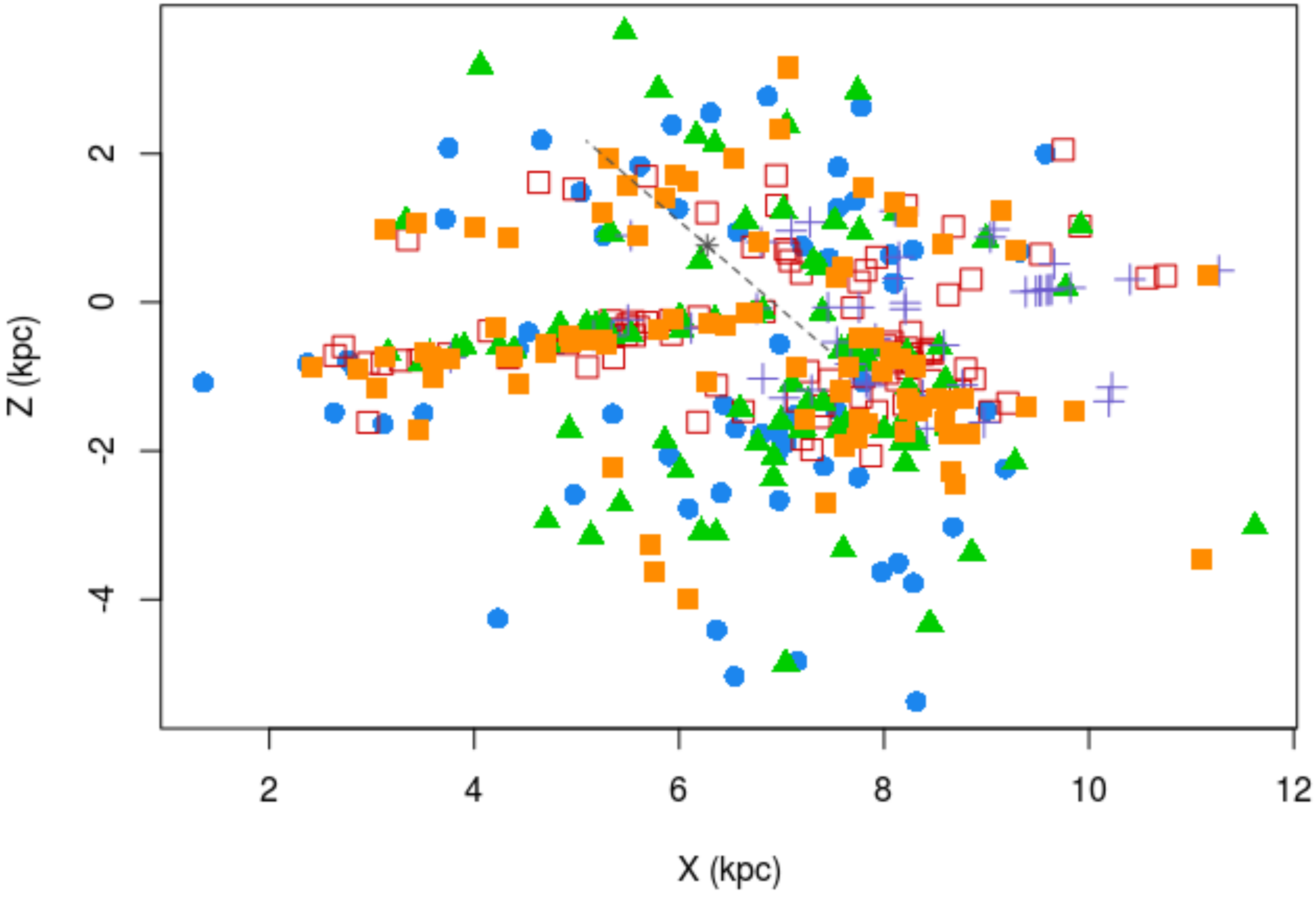
  ➡ Mean V = -76 ± 43 km/s

- Purple crosses(46): the (metal-poor) thin disk??

  ➡ Mean V = +13 ± 17 km/s

# Spatial distribution

Cartesian distances
Quantities not used in the clustering




- Blue circles: my halo stars?

  ➡ Mean Z distance = 1.88 ± 1.22 kpc

- Green triangles + orange squares: a thicker disk?

  ➡ Mean Z dist = 1.40 ± 1.06 kpc

  ➡ Mean Z dist = 1.23 ± 0.79 kpc

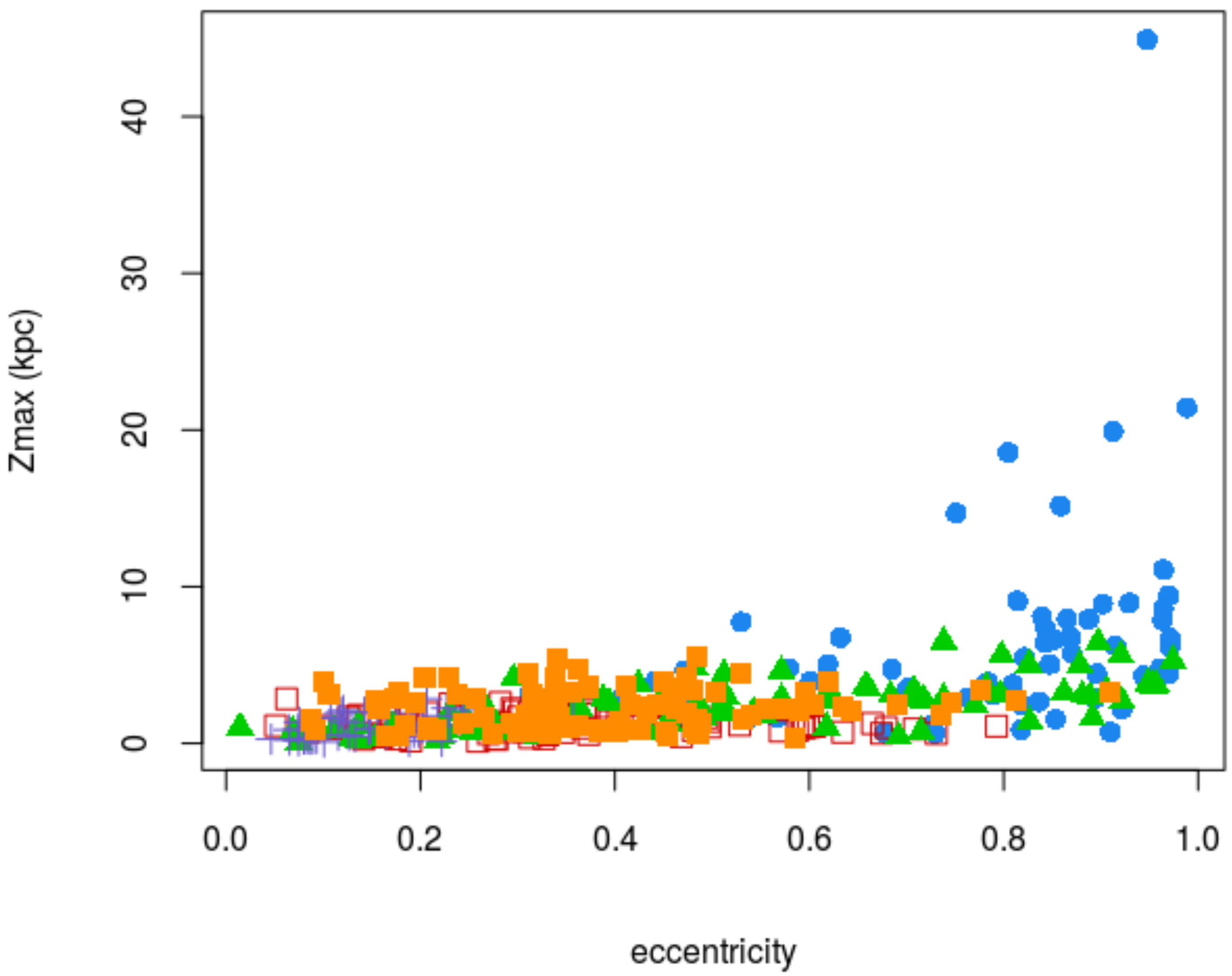
- Purple crosses and red squares: a less thick disk?

  ➡ Mean Z dist = 0.65 ± 0.47 kpc

  ➡ Mean Z dist = 0.86 ± 0.49 kpc

# Zmax and eccentricity

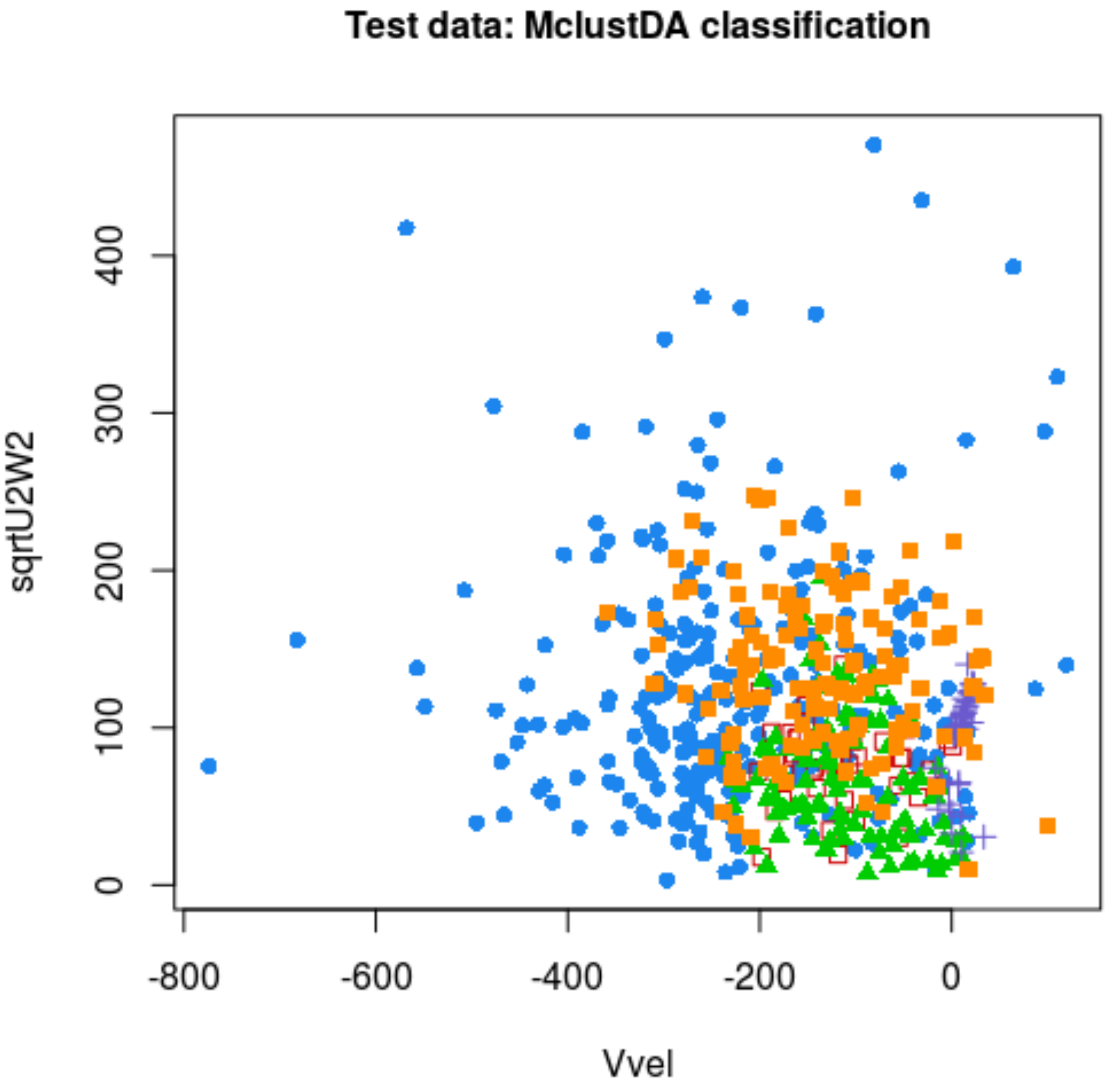
Perhaps 3 groups only

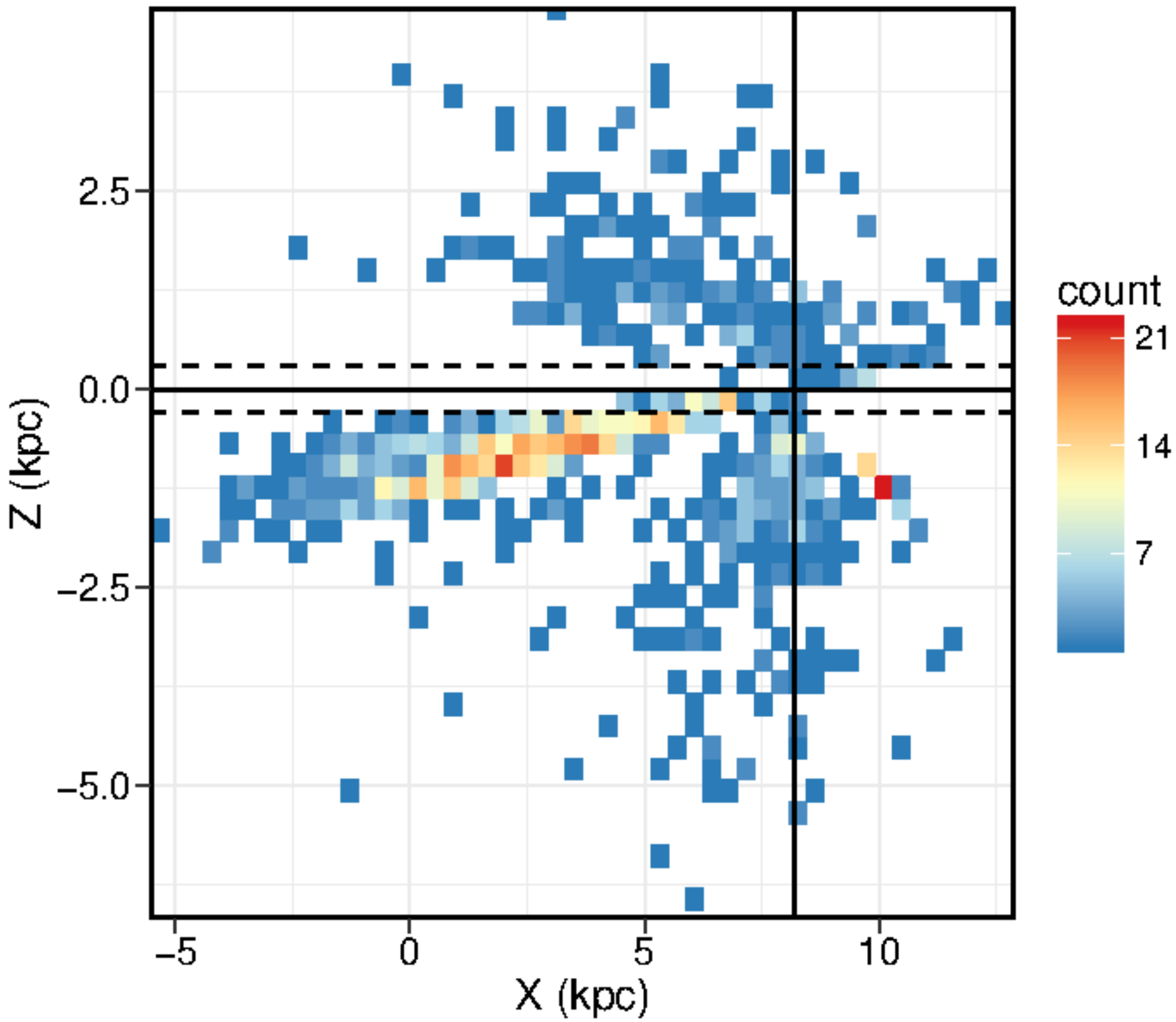



- Blue circles: halo stars
  - ➡ Mean Zmax = 6.27 ± 6.55 kpc
  - ➡ Mean ecc. = 0.77 ± 0.18
- Green triangles + orange squares: a thicker disk?
  - ➡ Mean Zmax = 2.27 ± 1.50 kpc
  - ➡ Mean ecc. = 0.50 ± 0.26
  - ➡ Mean Zmax = 2.21 ± 1.25 kpc
  - ➡ Mean ecc. = 0.39 ± 0.17
- Purple crosses and red squares: a less-thick disk? or the metal-poor part of the thin disk?
  - ➡ Mean Zmax = 1.16 ± 0.59 kpc
  - ➡ Mean ecc. = 0.34 ± 0.17
  - ➡ Mean Zmax = 1.09 ± 0.74 kpc
  - ➡ Mean ecc. = 0.15 ± 0.06

# Discriminant analysis

Use the previous 5 clusters to classify
the larger sample (that has more uncertain parameters)




+250 halo stars? - Maybe not; the sample also has metal-poor Bulge stars

# Other large surveys

- Preliminary similar analysis finds 11 or 10 clusters in GALAH, RAVE and APOGEE

- Let’s compare the halo from Gaia-ESO, GALAH and RAVE:

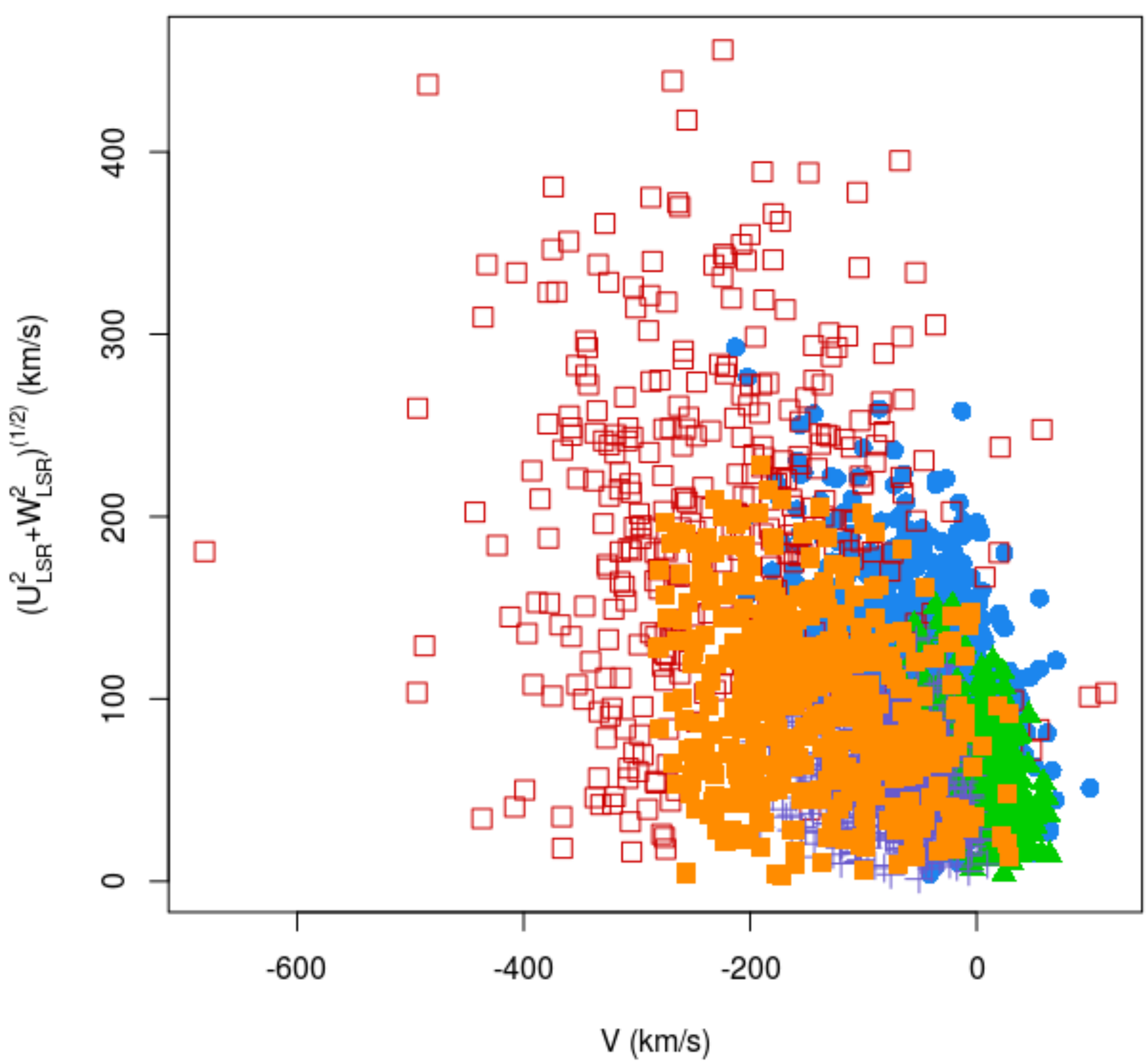
➡ Gaia-ESO: <V> = -232 ± 108 km/s; <Zmax> = 6.88 ± 6.54 kpc; <ecc.> = 0.80 ± 0.18

➡ GALAH: <V> = -250 ± 109 km/s; <Zmax> = 6.27 ± 6.16 kpc; <ecc.> = 0.77 ± 0.16

➡ RAVE: <V> = -214 ± 85 km/s; <Zmax> = 4.87 ± 3.12 kpc; <ecc.> = 0.80 ± 0.16

But forcing a division in 5 clusters can give similar results:

See for GALAH below



# Summary

- A model based clustering analysis on a 6D space ([Fe/H], [Mg/Fe], V, sqrt($U^2$+$W^2$), $Z_{max}$, eccentricity
- It can retrieve, from Gaia-ESO data, at least one population of (63) metal-poor stars that can be associated to the halo (metal-poor, large total velocity, high eccentricity, large $Z_{max}$)
- At least two other components are present, including a thick disk (178 stars) down to [Fe/H] ~ 1.6 dex (with the metal-weak part having more eccentric orbits)
- Data from other large surveys are best divided in more components (10/11) - but whose reality remains to be determined
- A group of halo stars of similar properties is found in two other surveys (RAVE, GALAH) but the division in APOGEE is somewhat different (but it focus on the inner disk)
- This seems a promising way to separate stellar populations without hard a priori selection cuts

# REFERENCES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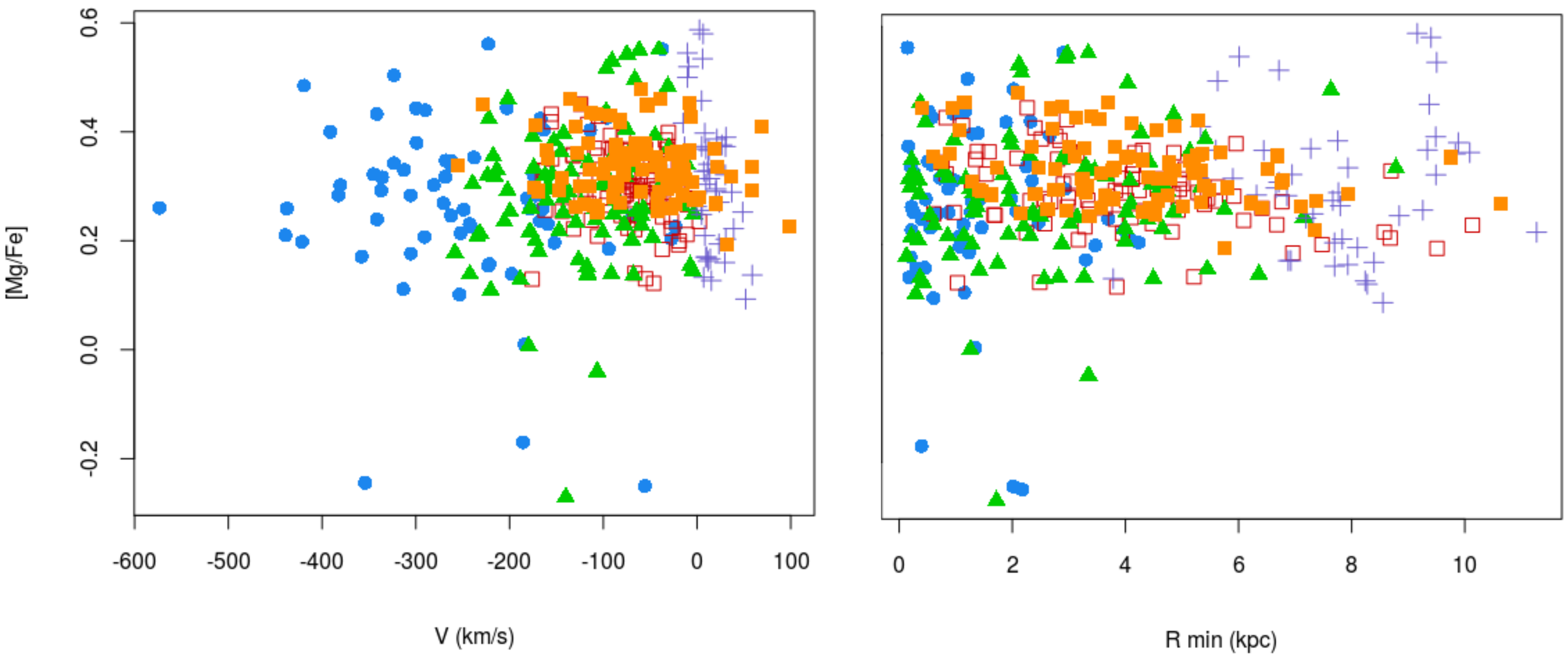
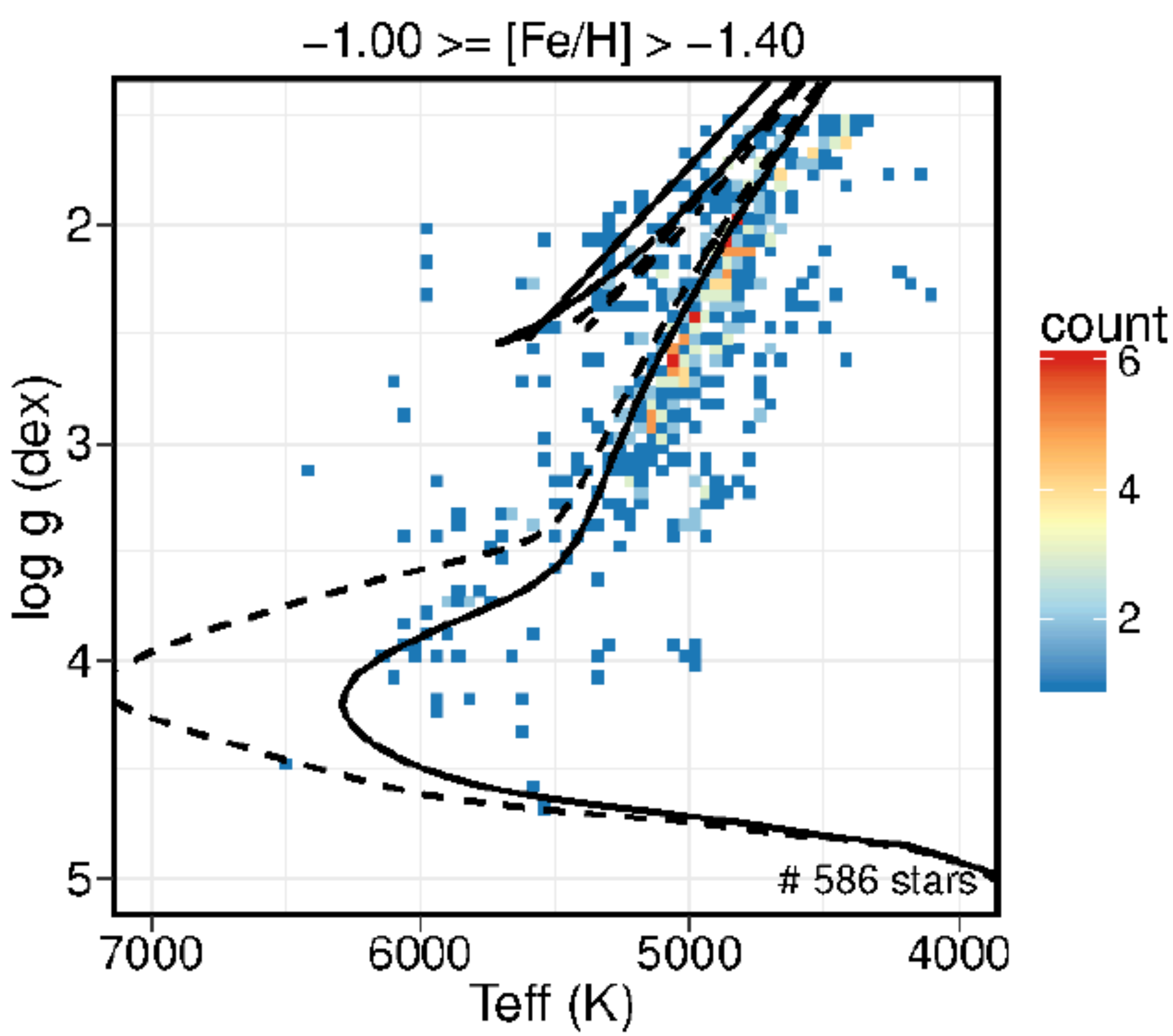
# Signs of the accreted halo?



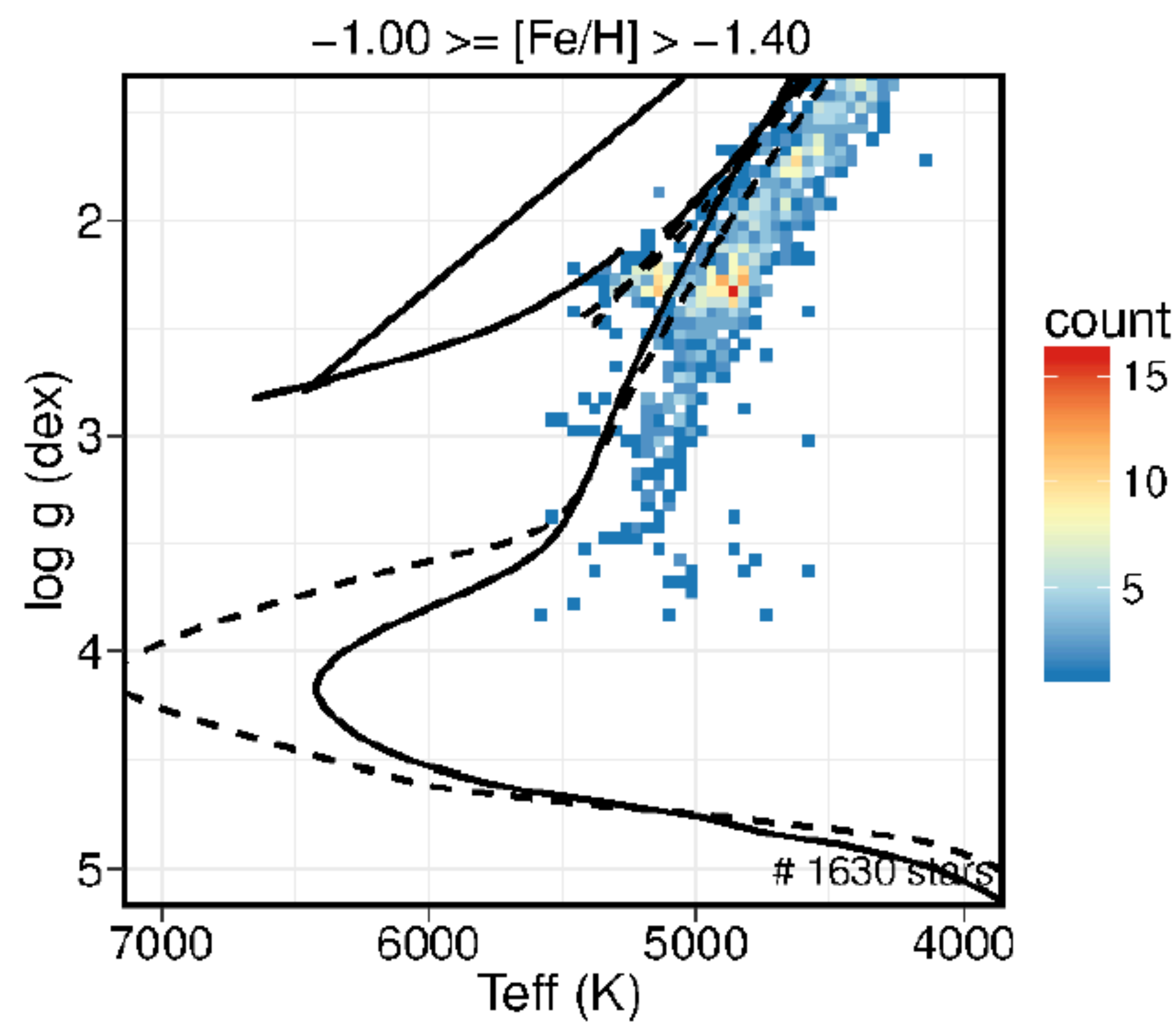

A handful of low [Mg/Fe] stars going rather close to the Galactic centre
But not enough for the algorithm to identify as a different component
And apart from [Mg/Fe], not necessarily very different from the rest

# We need good ages but…

The metal-poor stars are not really in the right place in the HR diagram

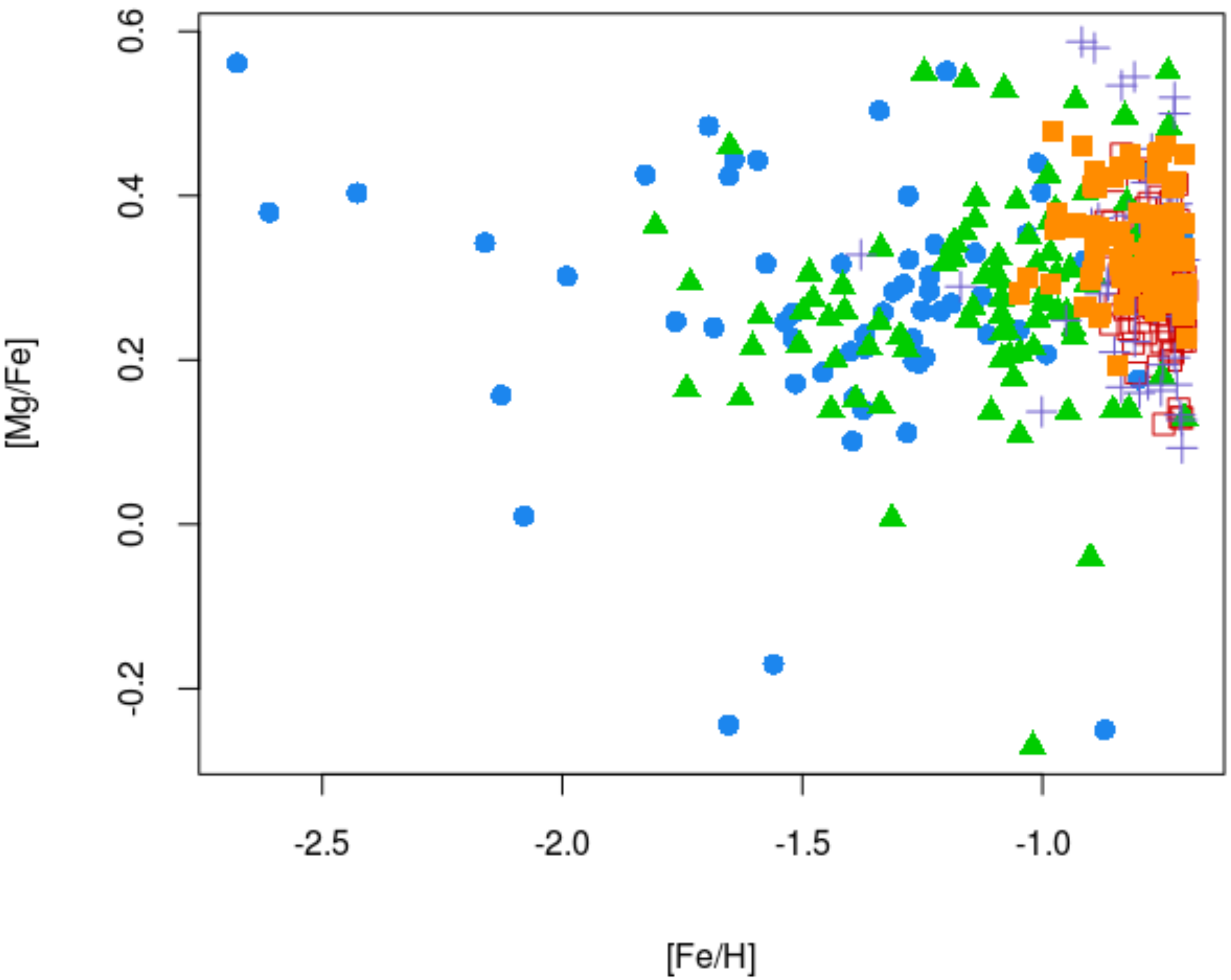



(Gaia-ESO)




(APOGEE)

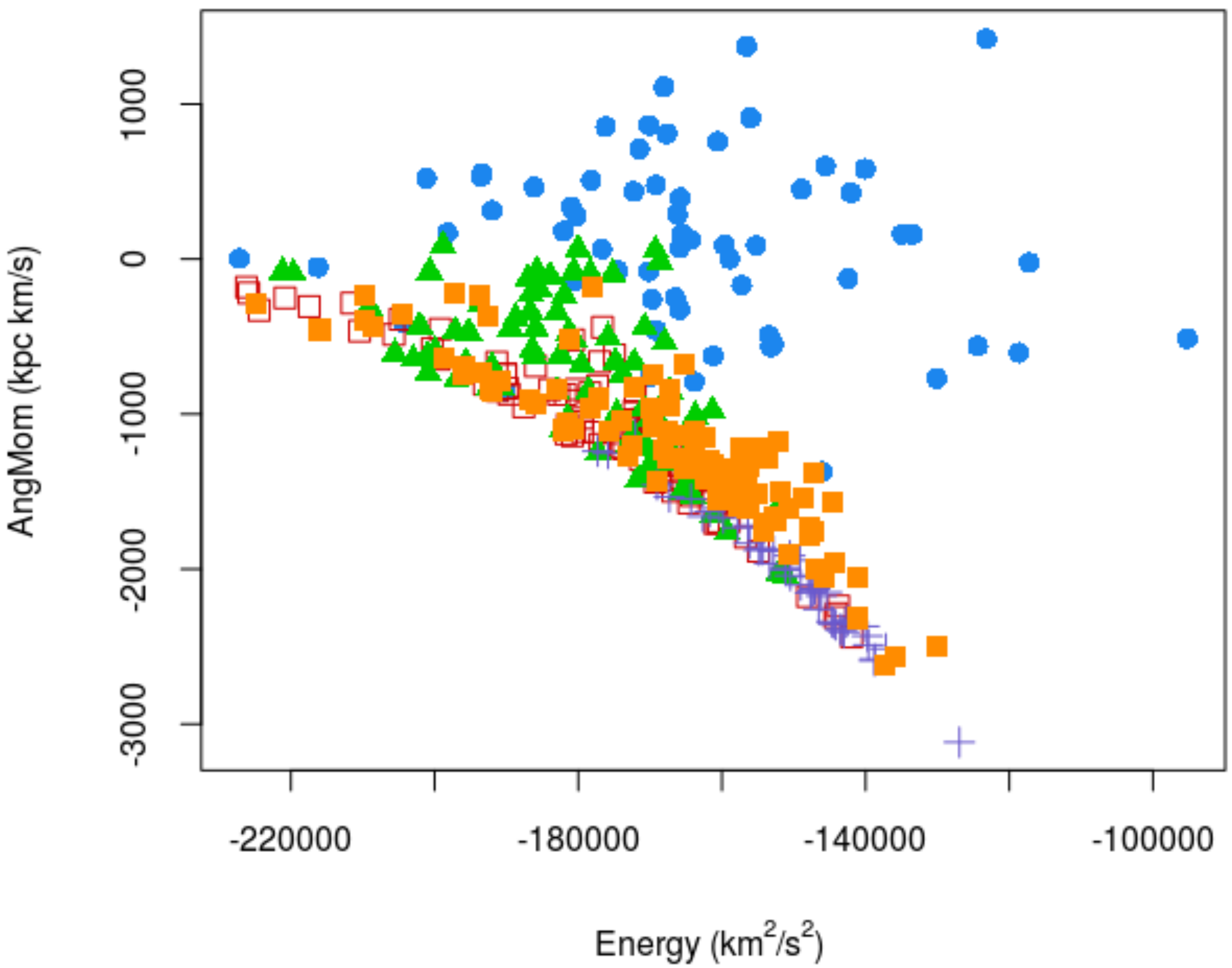
# Chemistry




- Blue circles: my halo stars
- Green triangles + orange squares: the thick disk, including the metal-weak thick disk (green triangles)
- Purple crosses + red open squares: a less-thick disk or the (metal-poor) thin disk with [Fe/H] down to ~ -0.80 dex

Green triangles seem to be the metal-poor extension of the orange squares

# Energy vs. Ang.Mom.




Blue circles: my halo stars (binding energy not as low as the retrograde halo component seen in Helmi et al. 2017)

Green triangles + orange squares: the thick disk, including the metal-weak thick disk (green triangles)

Purple crosses + red open squares: a less-thick disk or the (metal-poor) thin disk with [Fe/H] down to ~ -0.80 dex

# Other large surveys

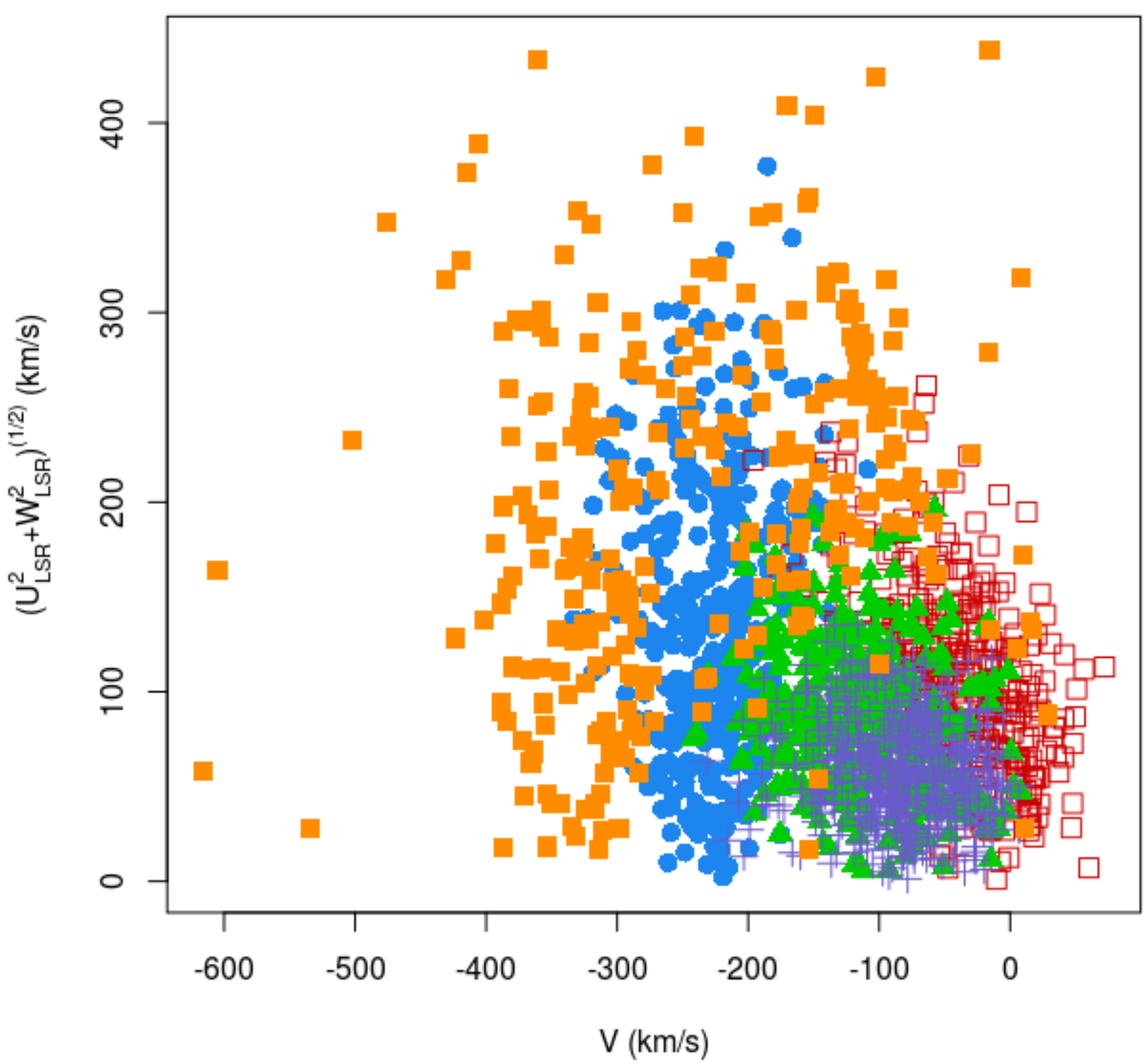
But even forcing 5 clusters; they are not necessarily similar:
See APOGEE below

- Preliminary similar analysis finds 11 or 10 clusters in:

➡ GALAH DR2 (Buder et al. 2018): total of 2324 stars

➡ RAVE DR5 (Kunder et al. 2017): total of 3742 stars

➡ APOGEE DR14 (Majewski et al. 2017): total of 1850 stars



# Other large surveys

But forcing a division in 5 clusters can give similar results:
See for RAVE below

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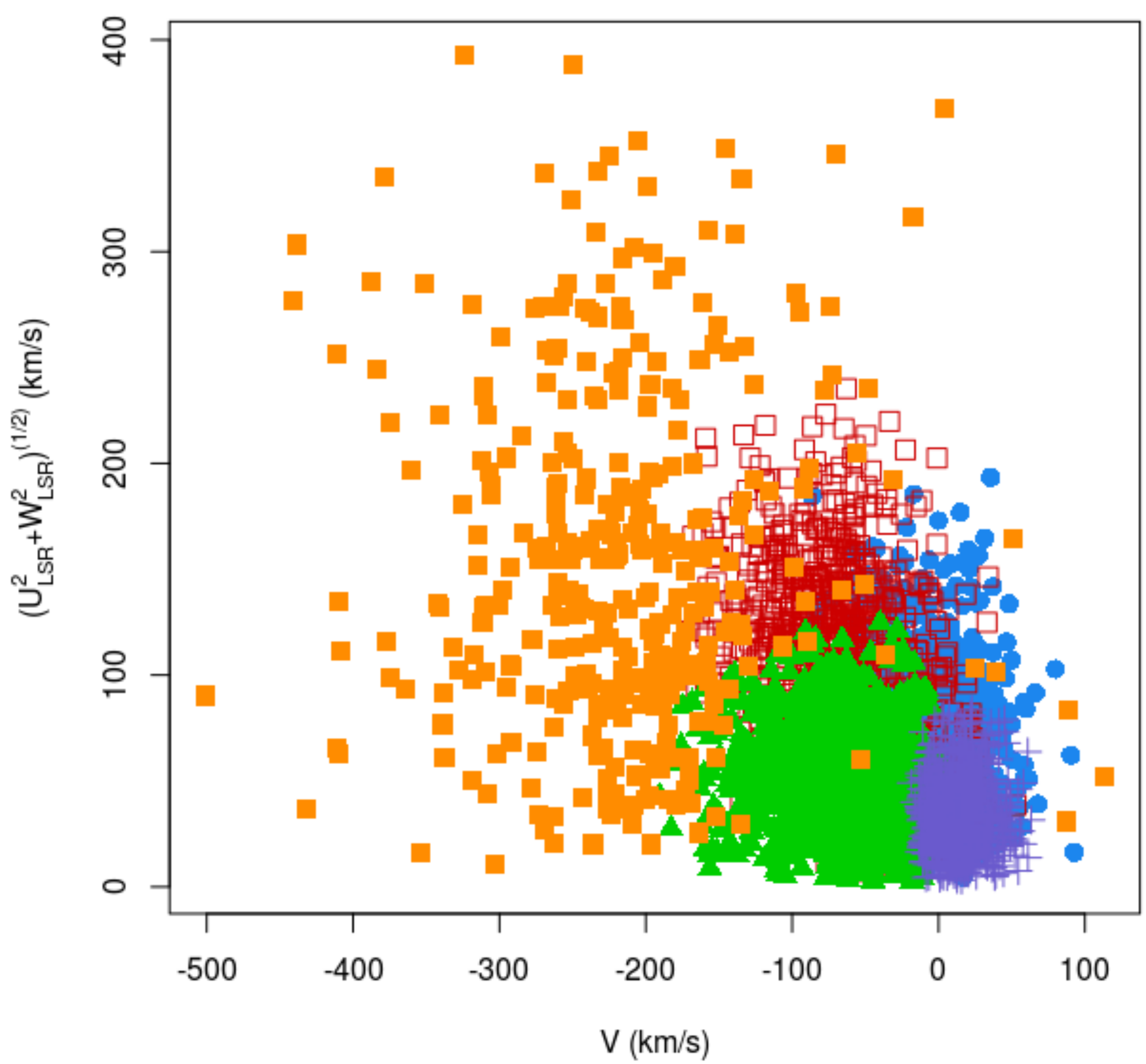
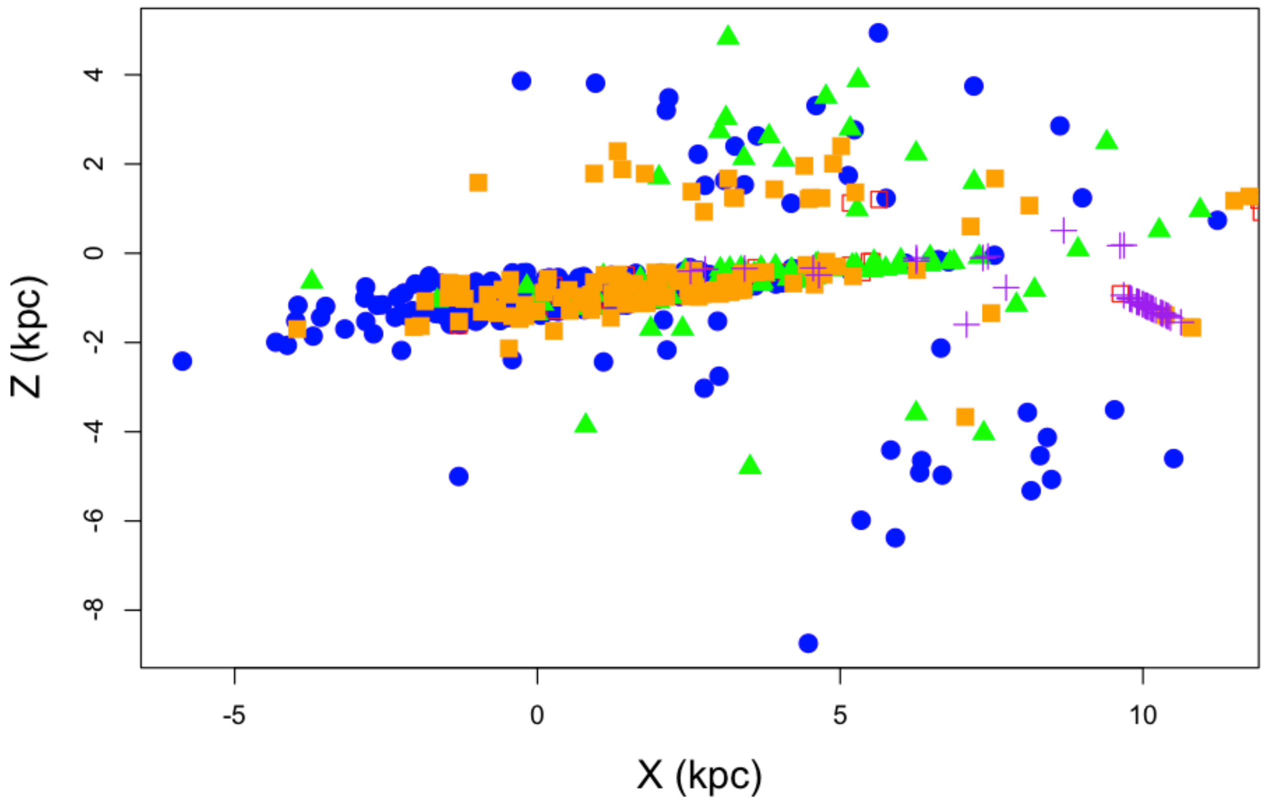
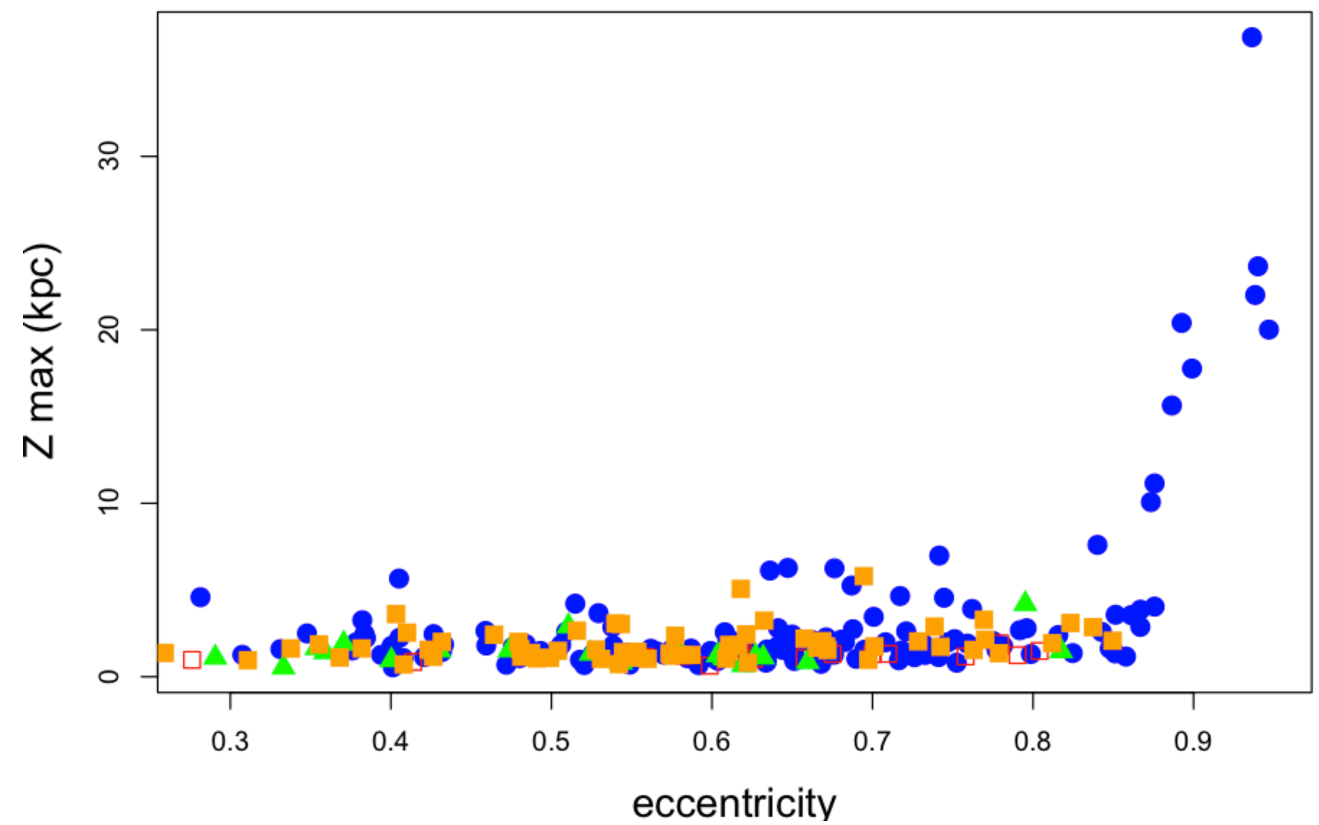


# The metal-poor Bulge




255 stars with X < 2