Investigating the formation of the Milky Way stellar halo

with chemical abundances of in-situ outer halo stars

Giuseppina Battaglia

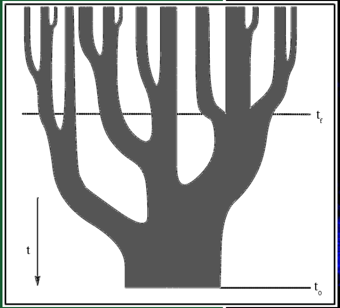
Ramon y Cajal fellow at the IAC, Tenerife

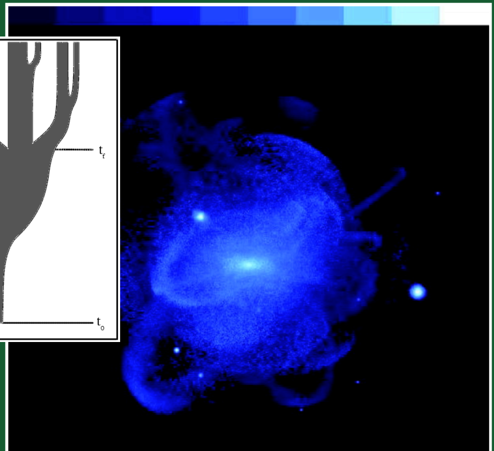
In collaboration with

M.Shetrone, P. Jablonka, D. Minniti,
M.Diaz, P. North, E.Starkenburg

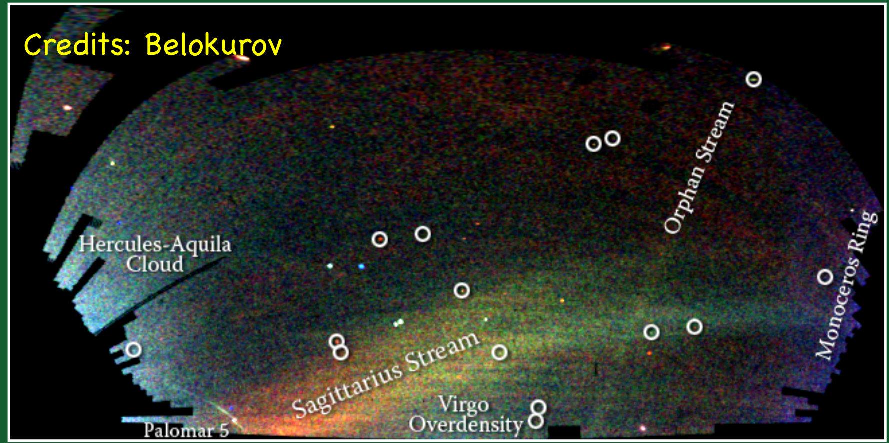
Stellar haloes and the hierarchical build-up of structures

Credits: Lacey & Cole 1993

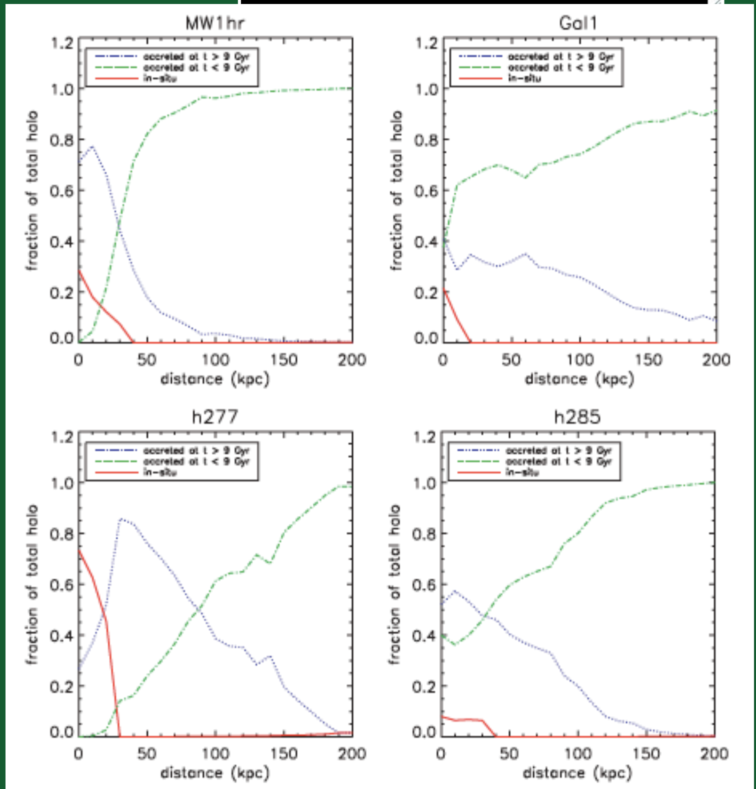


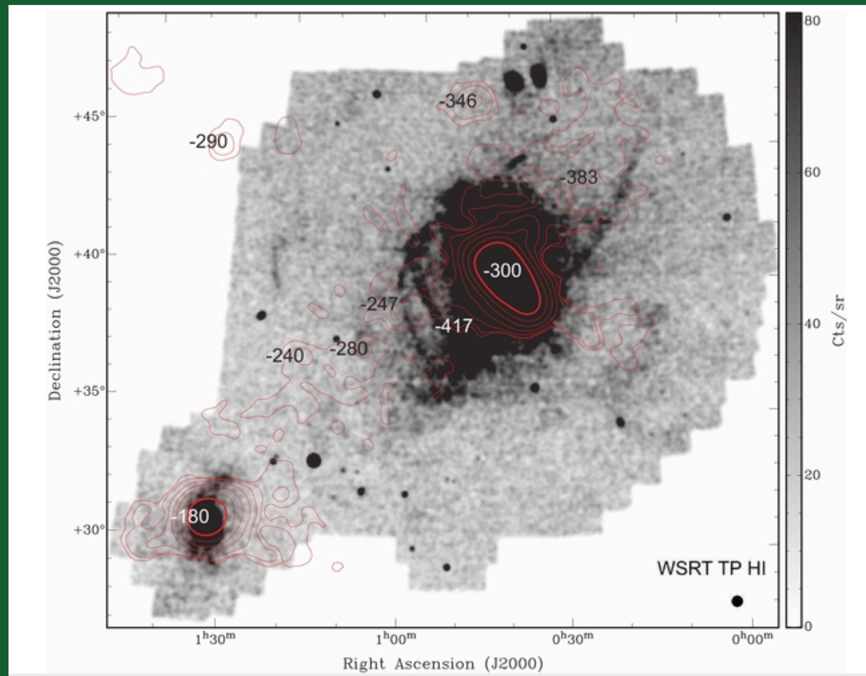


Bullock & Johnston (2005)



Zolotov et al. 2009 (see also Purcell et al. 2010, Tissera et al. 2012 etc.)





M31: e.g. McConnachie et al. (2009); Lewis et al. (2013)

Dual nature of the Milky Way halo (e.g. Searle & Zinn 1979 from globular clusters,Carollo et al. 2007, 2012; de Jong et al. 2010; Beers et al. 2012; etc.)

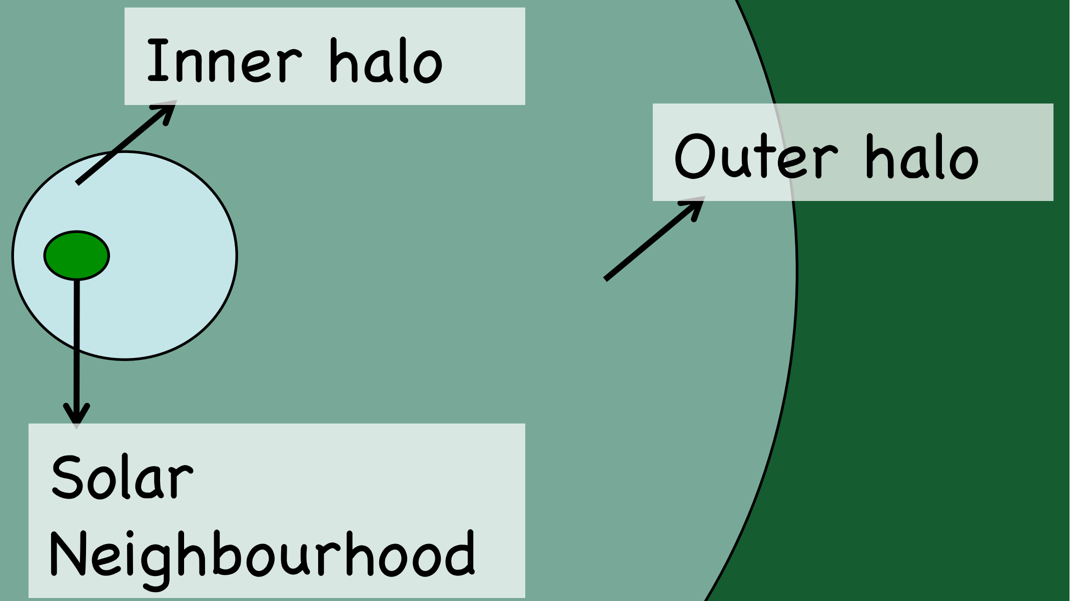
- Inner halo: rather flattened & prograde rotation; peaks at [Fe/H]=-1.6

- Outer halo: more spherical & no (or some retrograde) rotation; peaks at [Fe/H]=-2.2

- Transition at R ~ 15-20 kpc

=> DIFFERENT FORMATION MECHANISM?

- At [Fe/H] > -2, Solar Neighbourhood samples are dominated by inner halo stars



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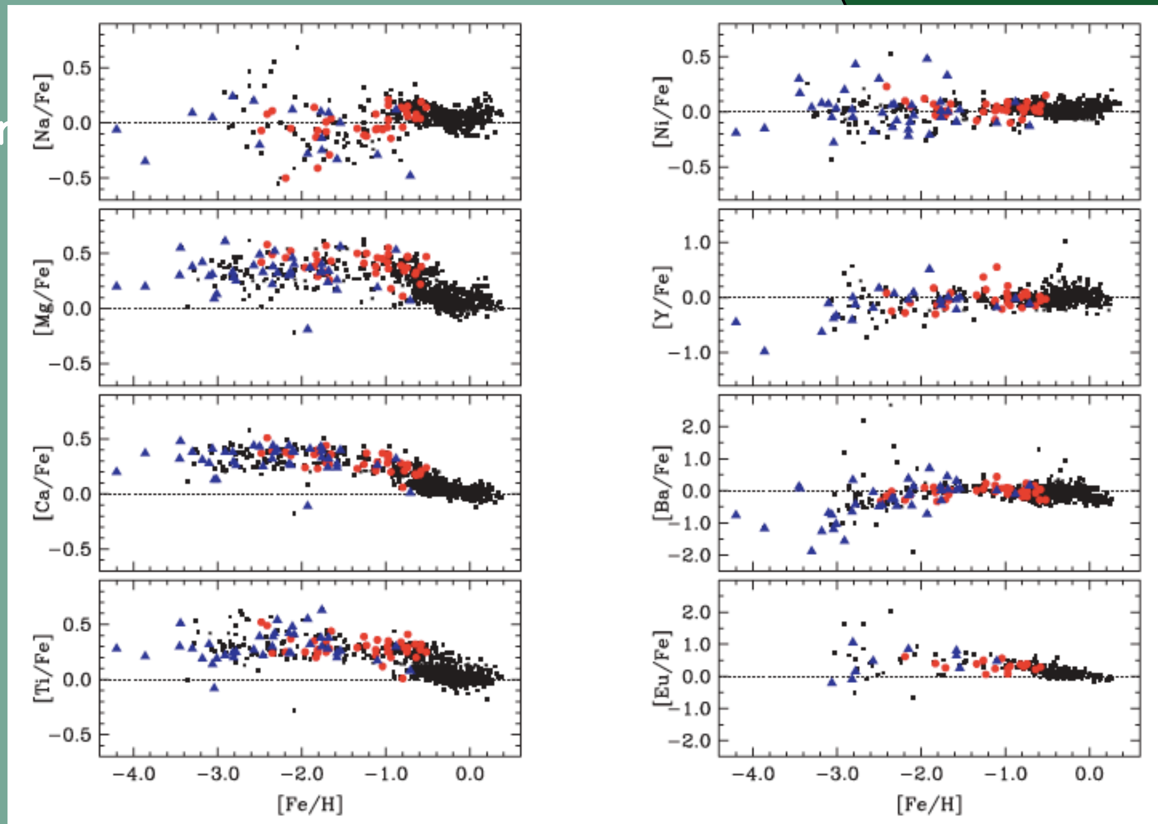
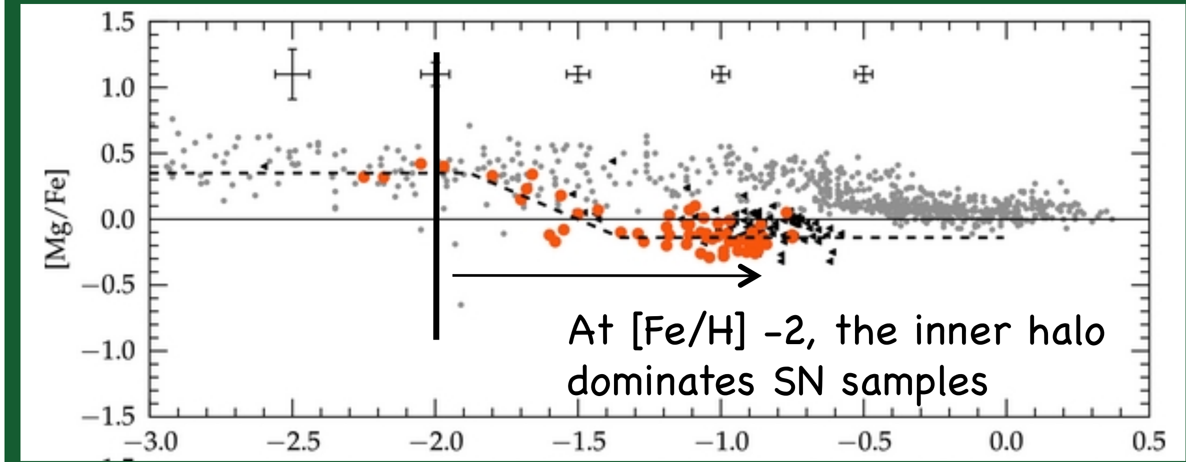


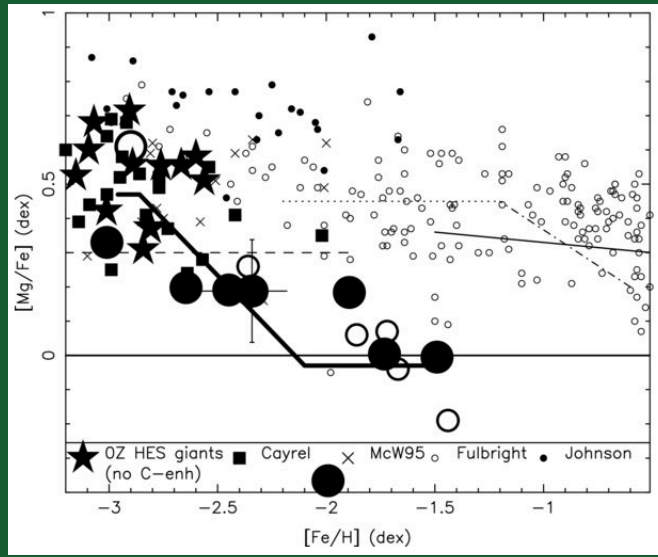
Roederer (2009)

Comparison with the Milky Way halo: the bright dSphs

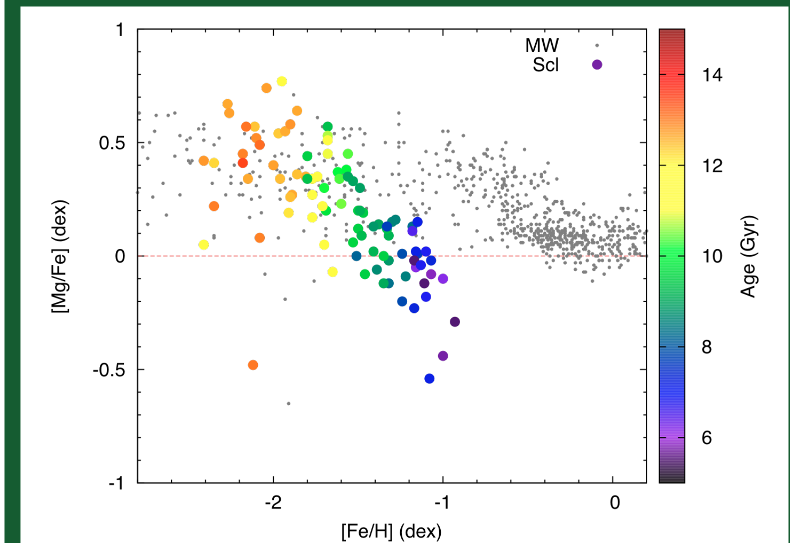
Fornax: Hendricks et al. 2014 (black points from Letarte et al. 2010); Lemasle et al. submitted



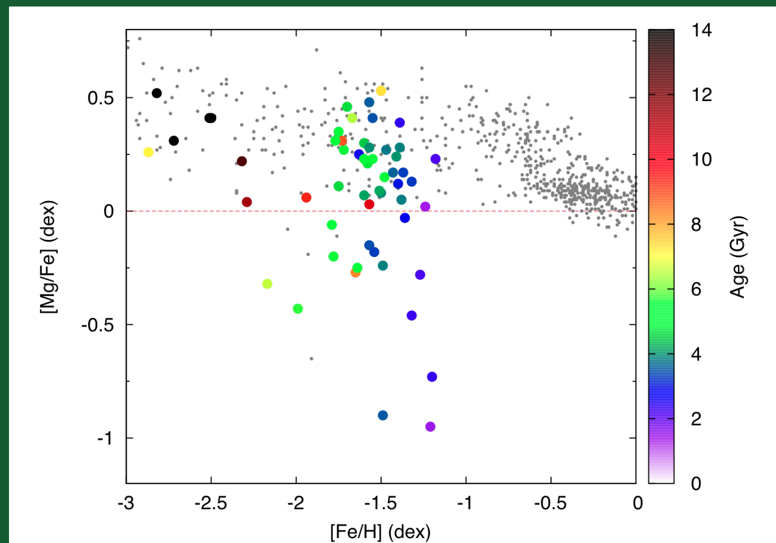
Draco: Cohen & Huang 2009



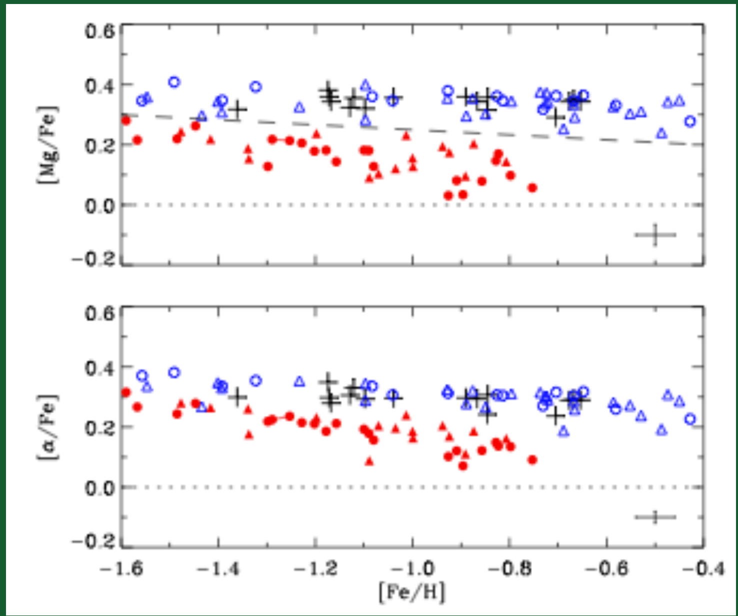
Sculptor: de Boer et al. 2012 (see Tolstoy, Hill & Tosi 2009 and references therein; see also **Geisler et al. 2005, Shetrone et al. 2003**)



Carina: de Boer et al. in prep; Lemasle et al. submitted (see also Koch et al. 2008, Lemasle et al. 2012, Venn et al. 2012)

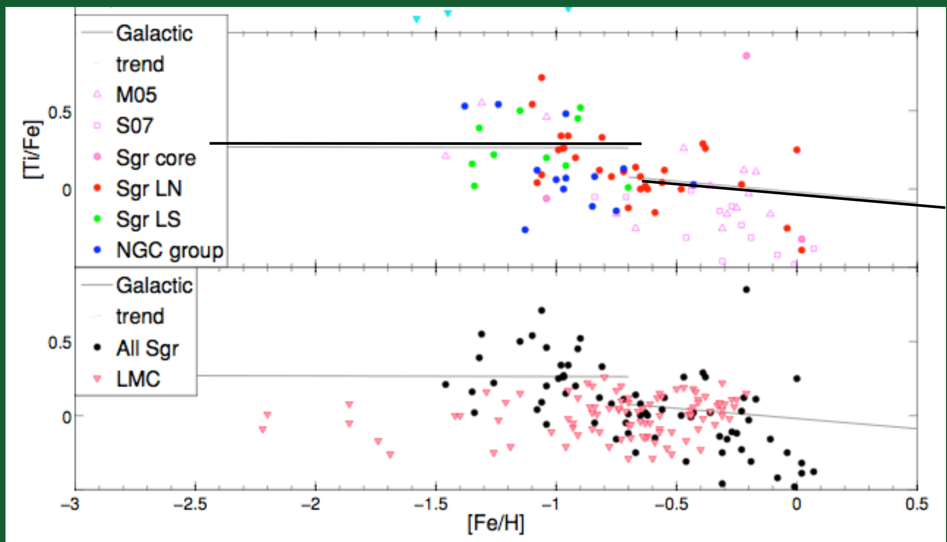


Systems with high initial SFR needed: like Sagittarius?

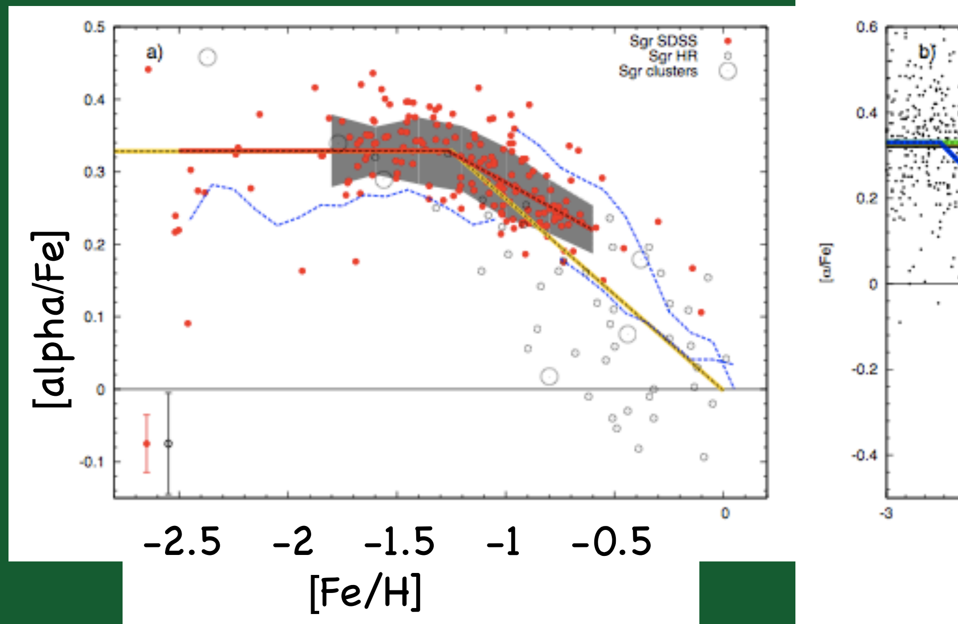


Nissen & Schuster 2010

Chou et al. 2011: high res of 59 candidate Sgr M-giants (data also from Monaco et al. 2005, Sbordone et al. 2007)



De Boer et al. 2014 using SEGUE data



Our program: Chemical abundances of in-situ outer halo stars

- Questions: how do the chemical abundances of in-situ outer halo stars compare to those of inner halo stars? And to those of classical dSphs?

- In-situ outer halo: with a present Galactocentric distance > 15 kpc (present distance < = apocenter)

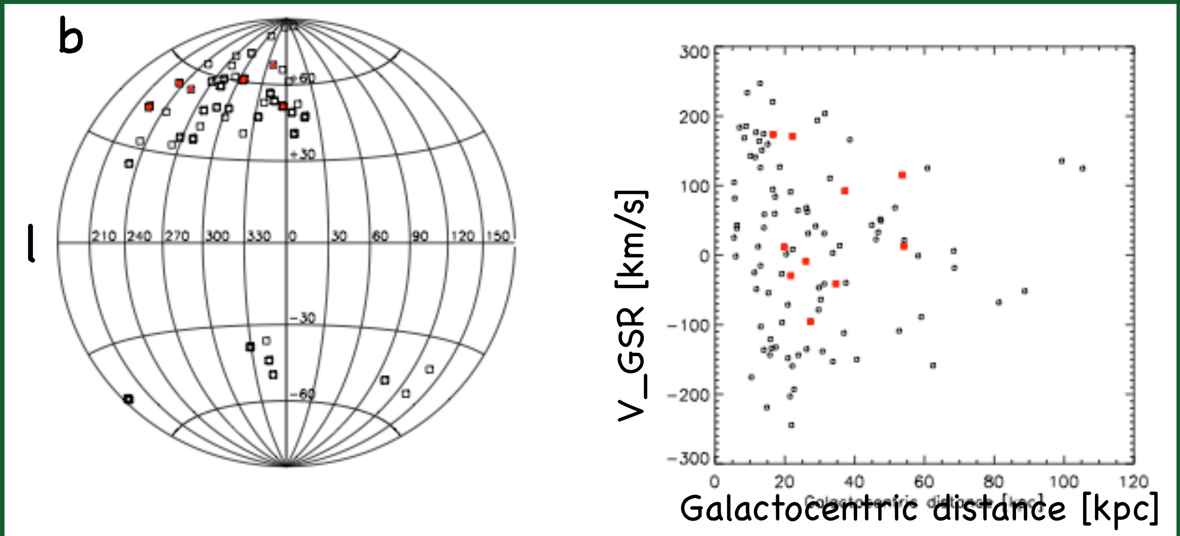
- Facilities:
  - high res. Spectrograph at the Hobby Eberly Telescope, 34h -> 10 stars (R ≈ 18000), data acquired in 2013 (Battaglia, Shetrone & Jablonka in prep)
  - VLT/UVES, 45h priority A -> 10stars (R ≈ 40000), data are being acquired
  - Magellan/MIKE, 2 nights -> 11stars (R ≈ 25000), data just acquired

The HET sample

- Distant targets -> need to be giant stars -> selected from the Spaghetti survey (Morrison et al. 2000, 2003; Starkenburg 2010, PhD thesis) using their coordinates, distances, l.o.s. velocities, [Fe/H]. Note that Xue et al. 2014 catalogue has very recently become available.

  ugriz photometry from SDSS, JHK from 2MASS

- Wavelength range 4800Å-6800Å; 45 < S/N/pixel < 95 (except for 1 star that has a S/N/pixel = 20)



$-2.7 < [Fe/H] < -1.2$

$V < 17.5$

Generalities on data reduction and analysis

- Data reduction performed with IRAF
- Stellar atmospheric parameters (derived iteratively):
  - Teff from average of T_VI, T_VJ, T_VH, T_VK – color – [Fe/H] relations from Ramirez & Melendez (2005); errors: 40-65K (except for one star)
  - First guess [Fe/H] from purely spectroscopic analysis; assumed error=0.2dex
  - Logg from Dartmouth isochrones of appropriate Teff, [Fe/H] (age= 4,8,12 Gyr; [alpha/Fe] =0.0, +0.2, +0.4; -2.4 < [Fe/H] < -0.6 spaced of 0.2dex)
  - Microturbolent velocity = value that minimizes the slope in Ews
  - The above values are refined with the spectroscopic analysis
- EWs measured from ROBOSPECT (Hollek et al. 2013)
- Analysis using MOOG2013 and Kurucz alpha-enhanced opacity distribution function models
- Elements that we derive: Fe, Mg, Ca, Ti, Si, Ba using line-list from Letarte et al. 2010, Tafelmayer et al. 2010, Venn et al. 2012

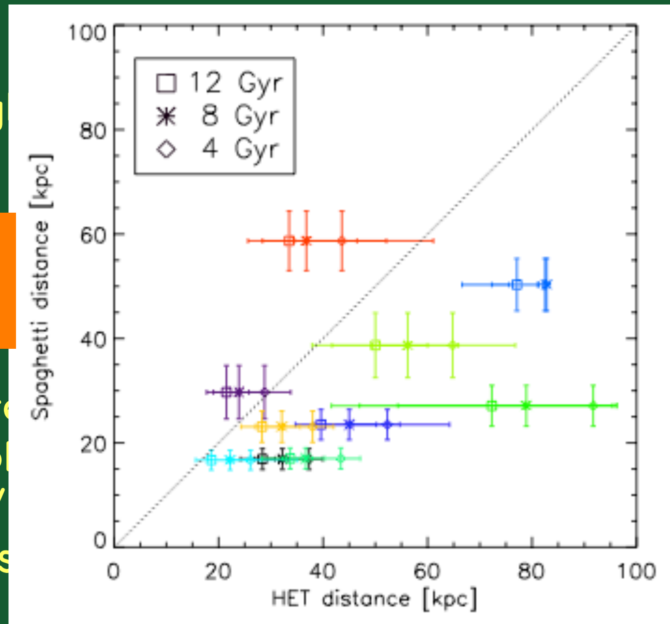
Comparison of [Fe/H], hel. Vel and distances Spaghetti vs HET

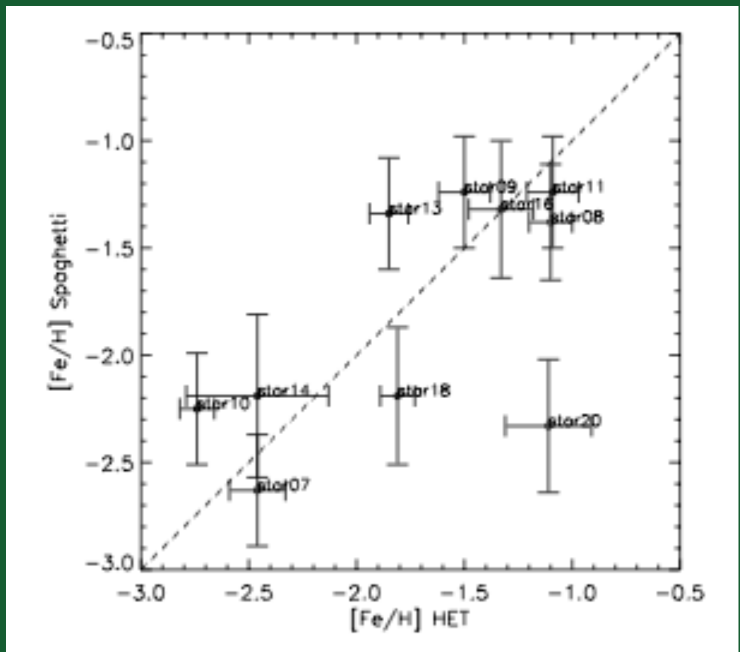
- Resolution = 2.5-3.5 Å
- [Fe/H] from the CaIIK and Mgb features (typical error = ±0.3dex)
- Distances using the globular clusters RGB from Da Costa & Armandroff (1990) using the observed M-T2 color and [Fe/H]

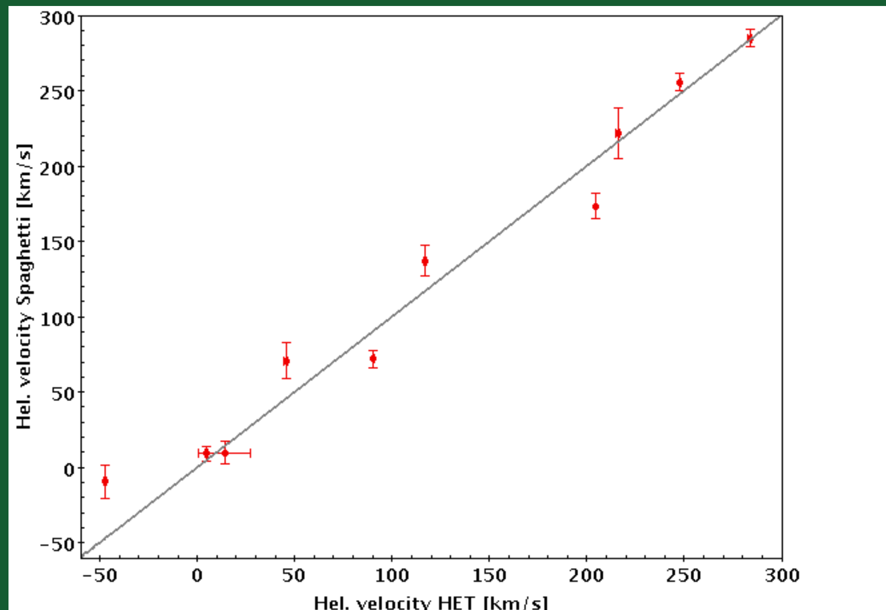
- 10x hig

Still in the outer-halo!

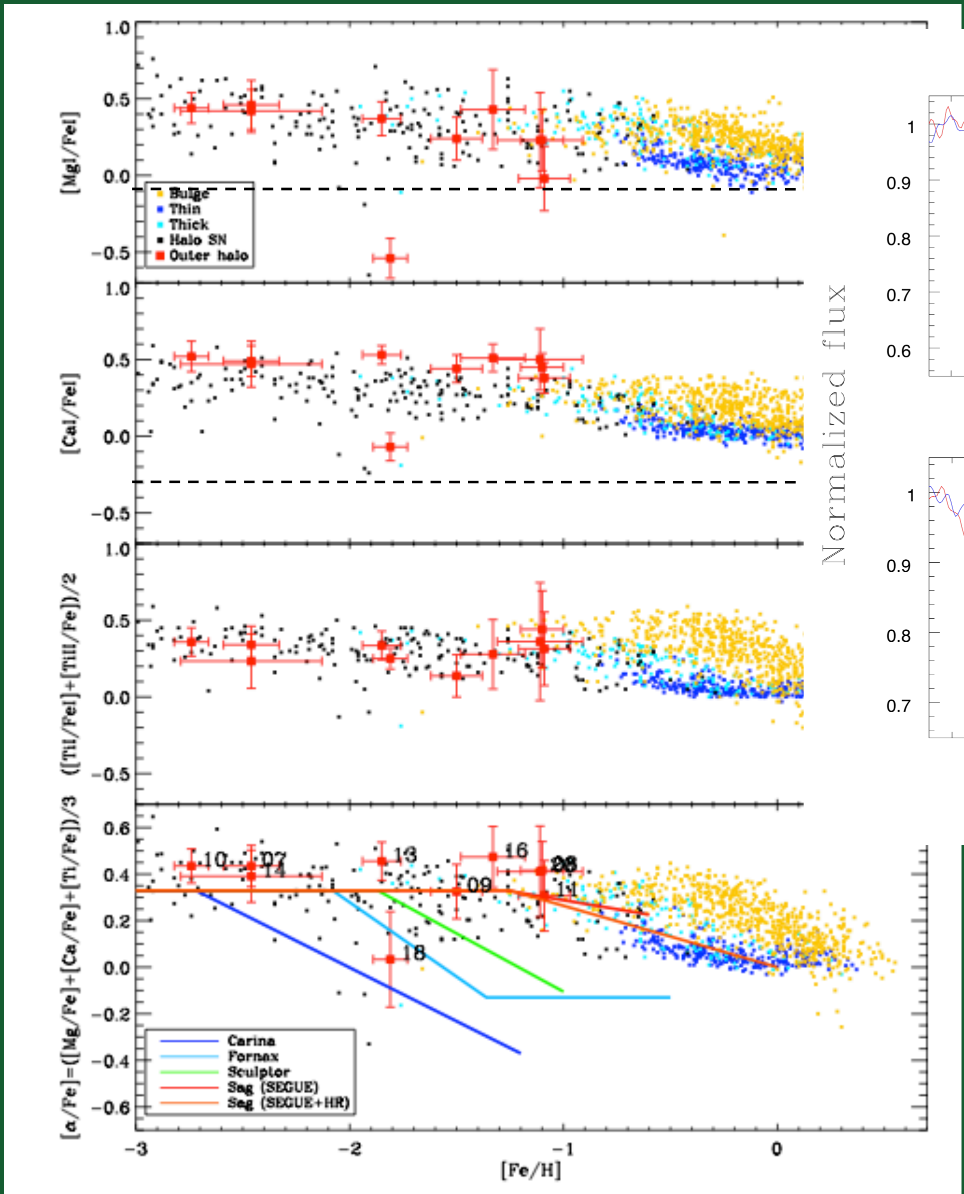
- Distanc using p [alpha/ to inves

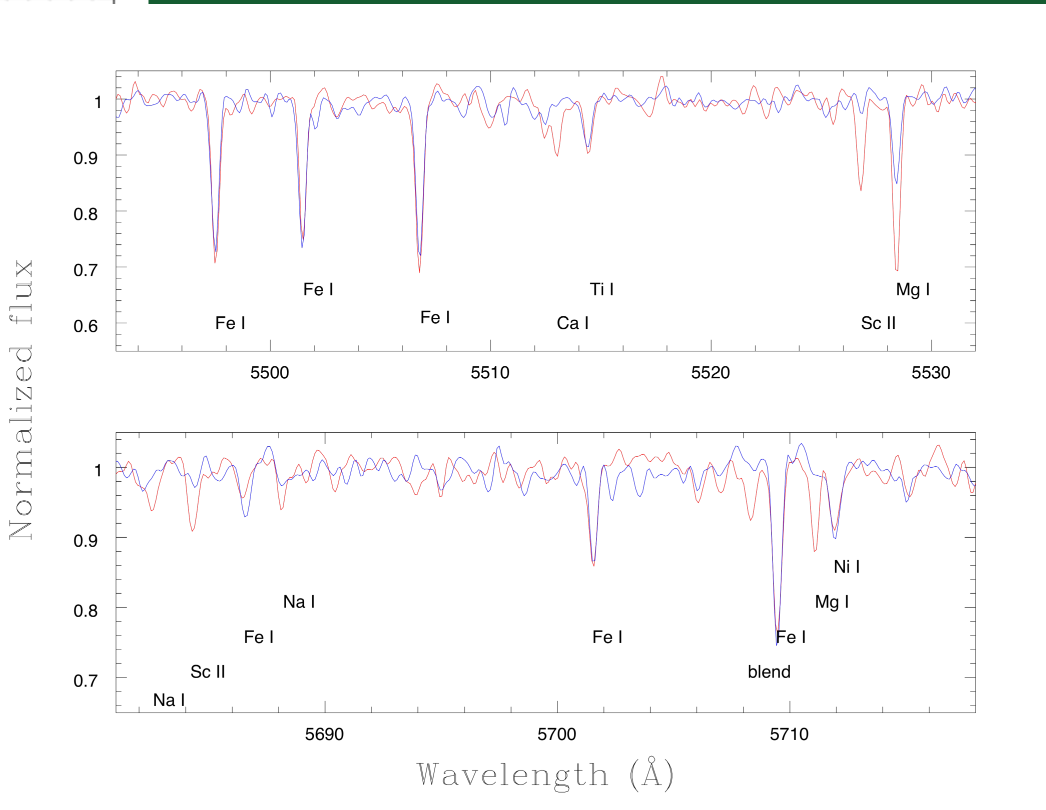






The alpha-elements Mg, Ca, Ti





from de Boer et al. (2014)

Star18 ([Mg/Fe] = -0.5, [Ca/Fe]=-0.06;[Ti/Fe] & [TiII/Fe] = 0.25)
Star13: similar [Fe/H] = -1.8; [Mg/Fe] = 0.4; [Ca/Fe] = 0.5; [TiI/Fe]=0.4; [TiII/Fe]= 0.25)

Battaglia, Shetrone & Jablonka in prep

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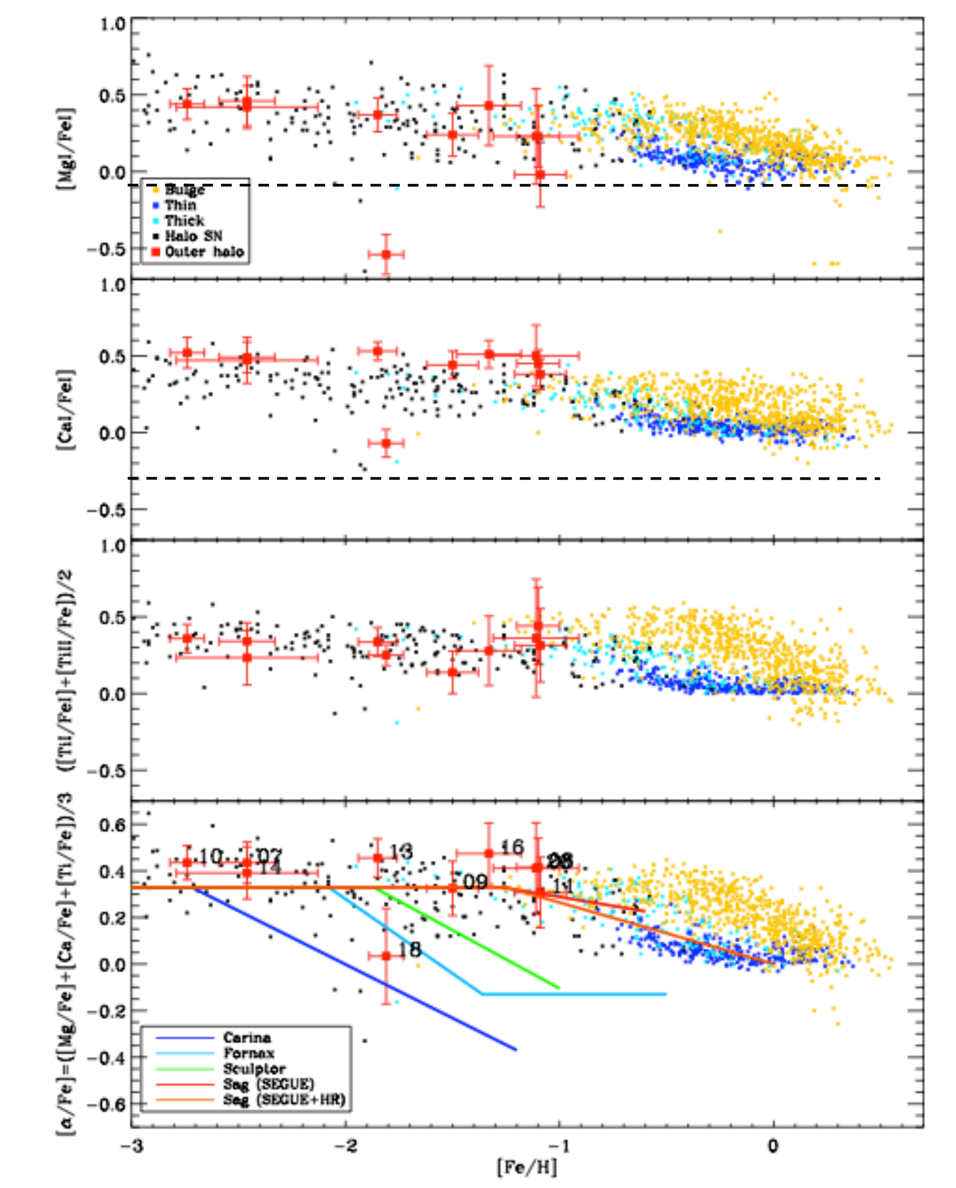


Battaglia, Shetrone & Jablonka in prep

Hill et al. 2012, in prep., Geisler et al. 2005, Shetrone et al. 2003 AJ, Letarte et al. 2010 A&A, Koch et al. 2008, Venn et al. 2012 ApJ, Lemasle et al. 2012 A&A , Sbordone et al. 2007,Venn et al. 2004

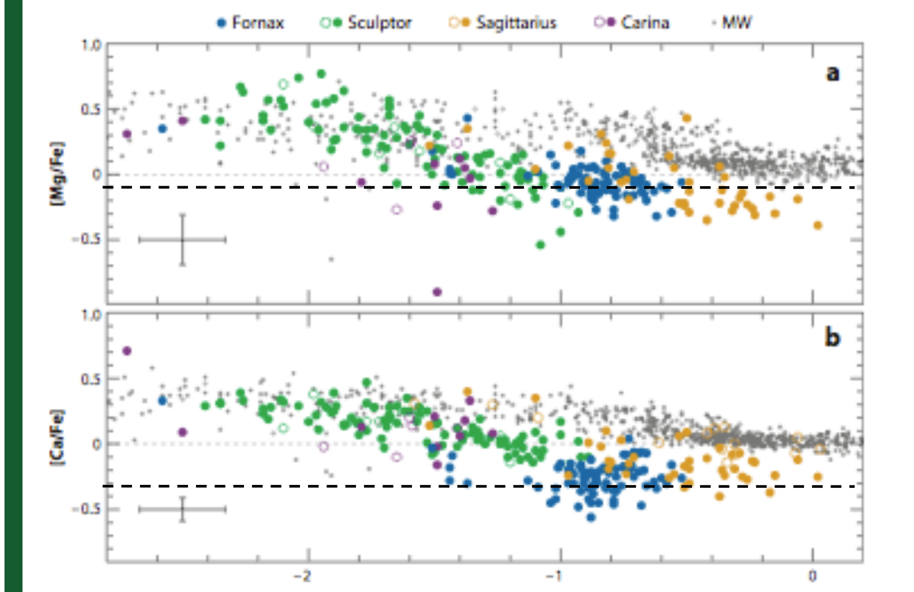


Figure from Tolstoy, Hill & Tosi (2009), ARA&A

Bulge: Gonzalez et al. (2009); thin/thick disc and halo: compilation by Venn et al. 2004; lines from de Boer et al. (2014)

Chemical similarity of inner and in-situ outer halo stars

The alpha-elements of in-situ outer halo stars differ from those of classical dSphs at [Fe/H] > -1.6

Members to substructures?

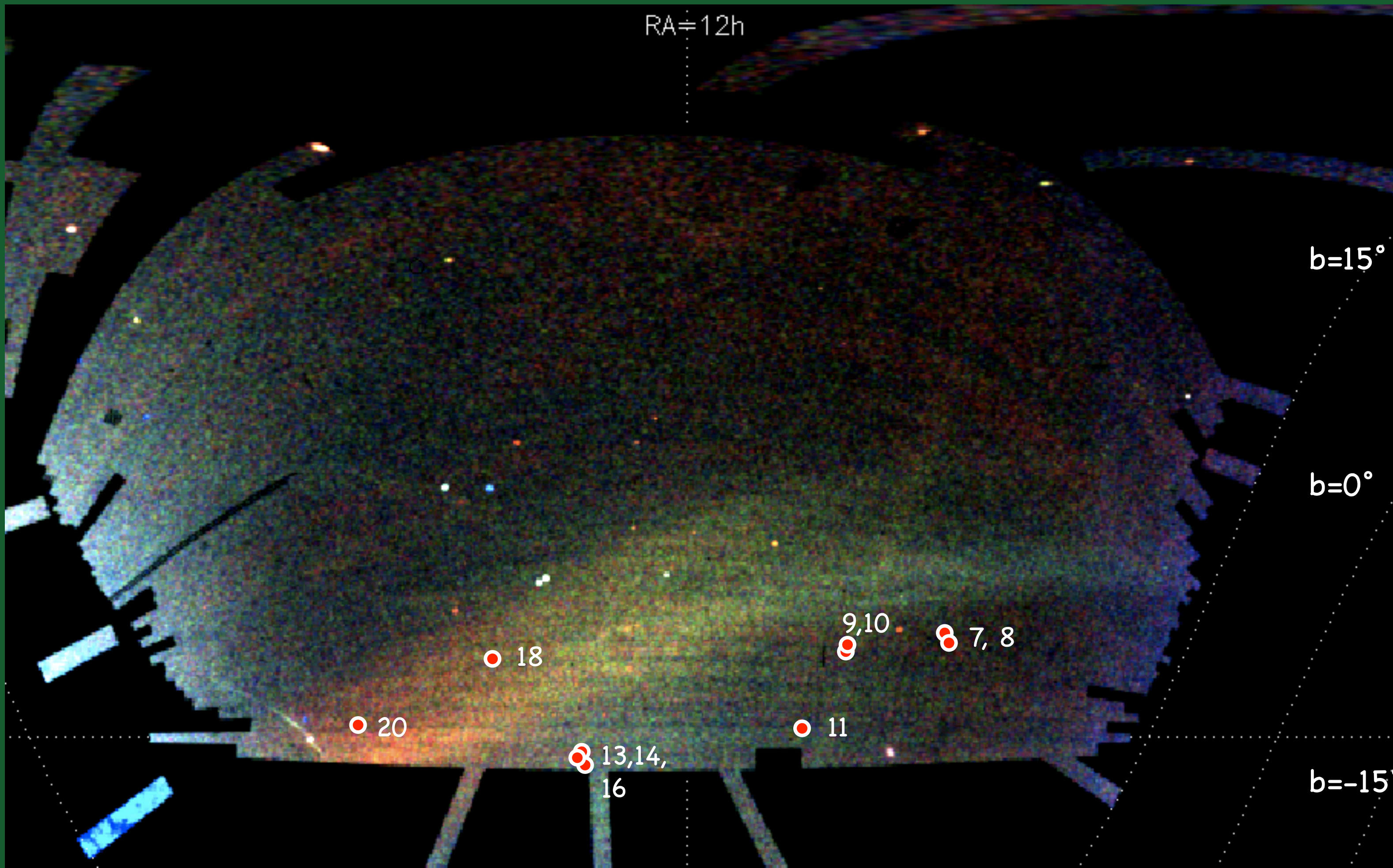
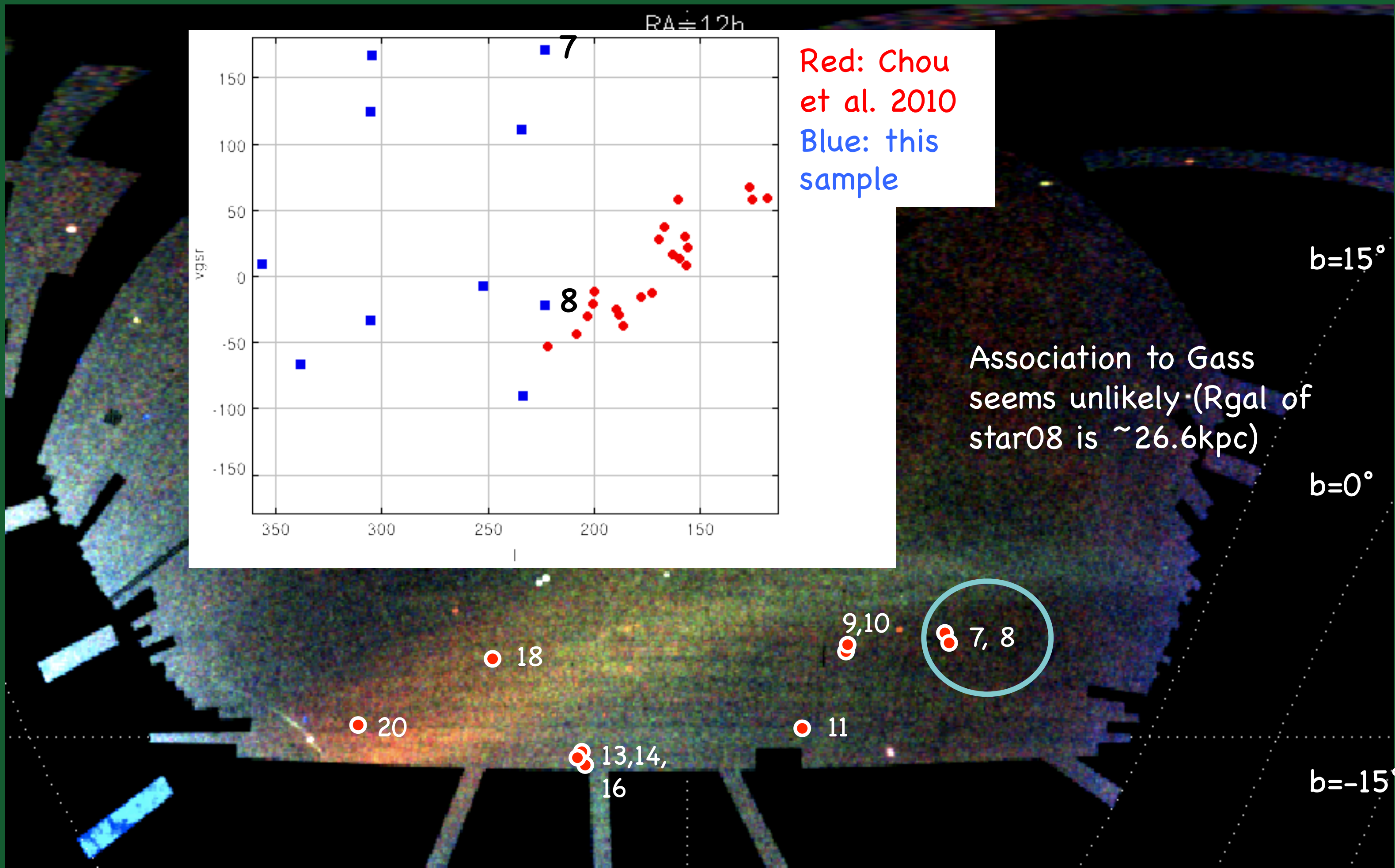
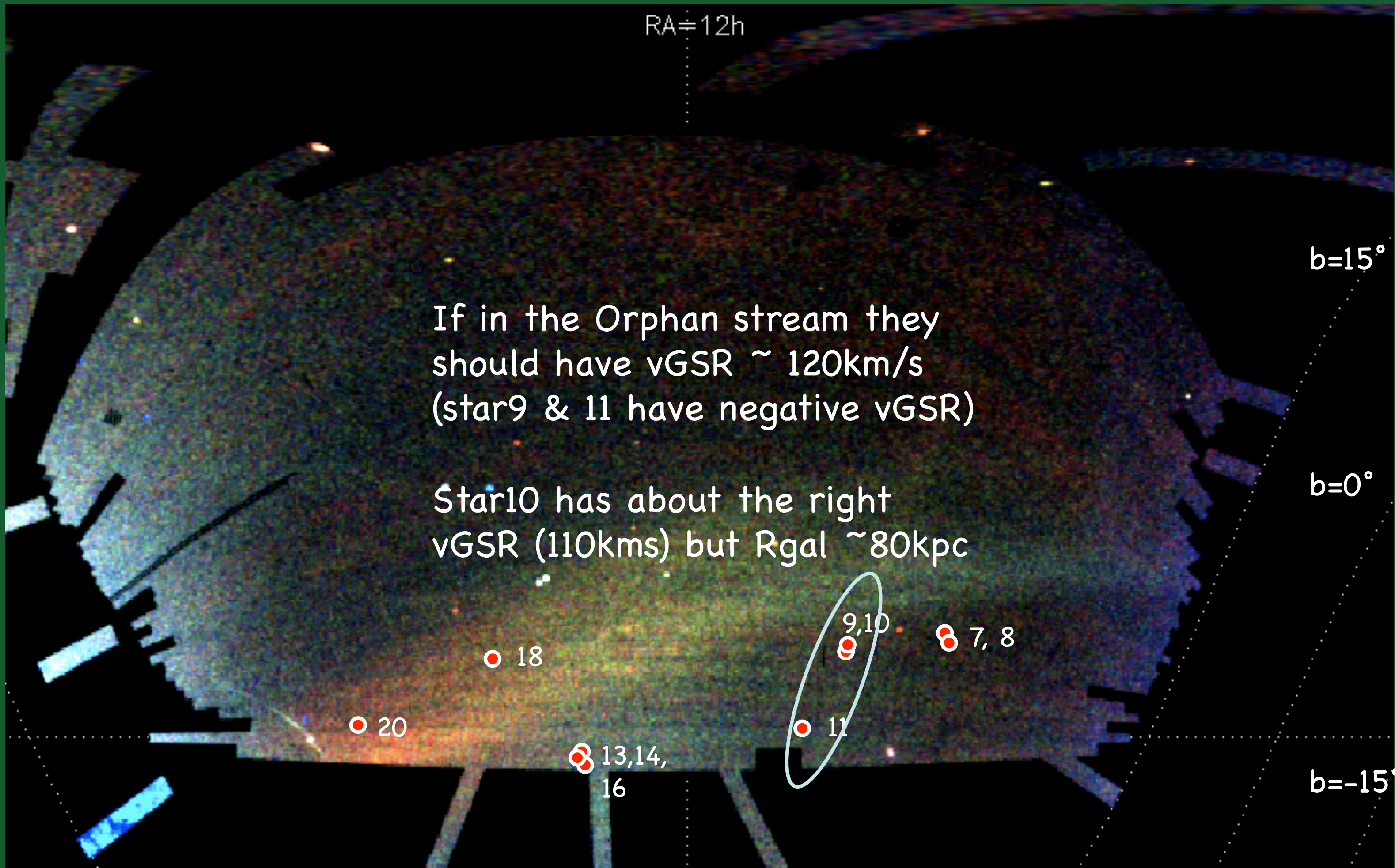


Fig. courtesy of V.Belokurov

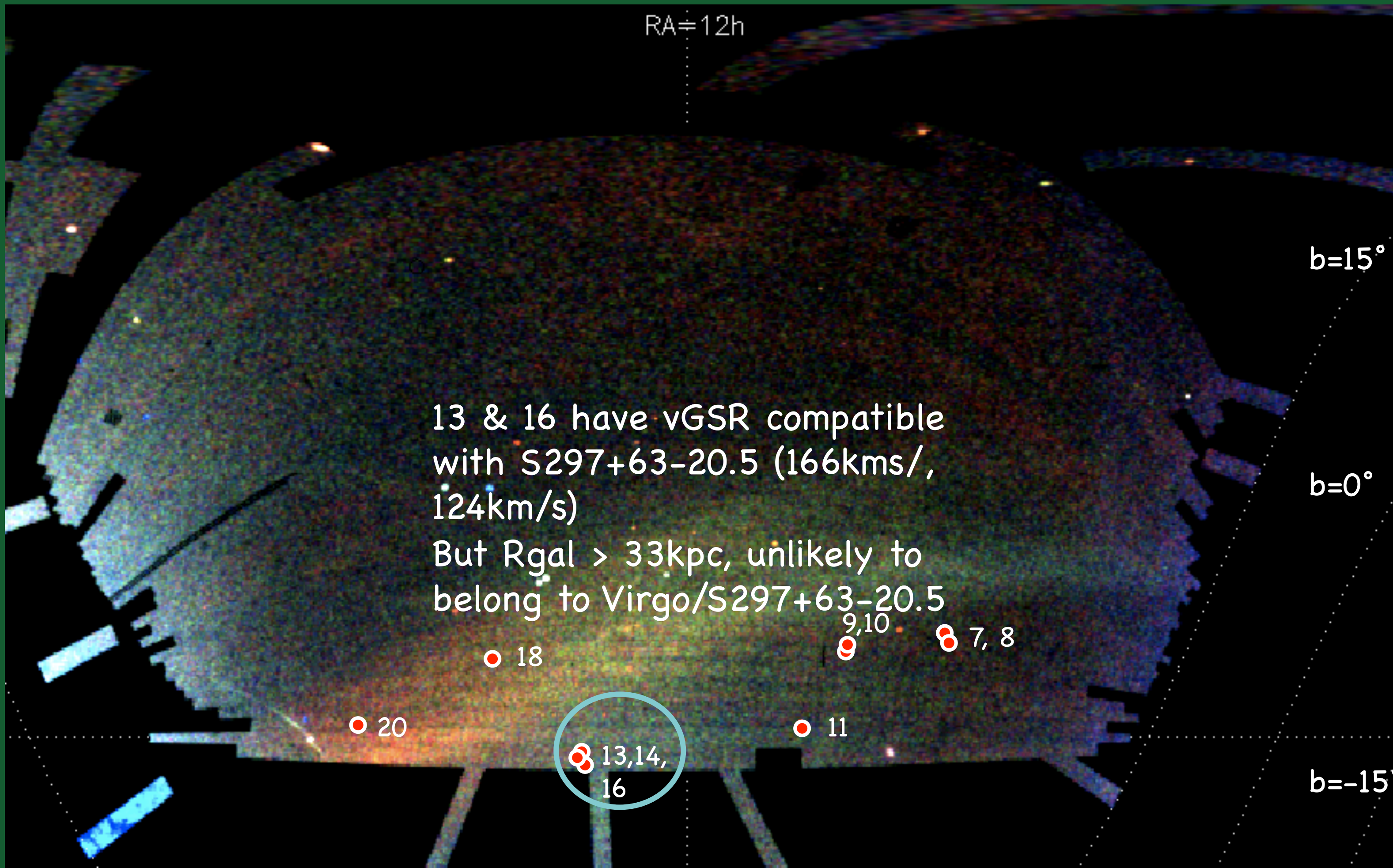
Members to substructures? GASS



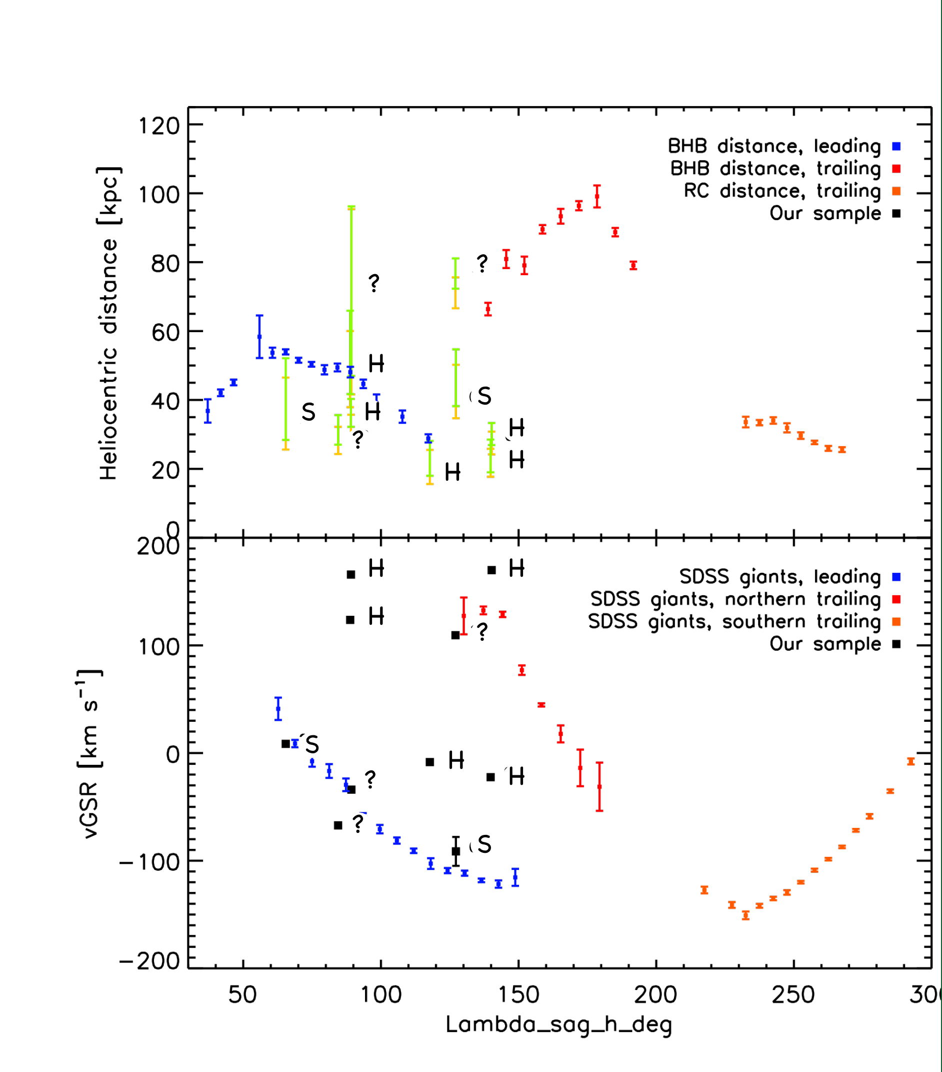
Members to substructures? Orphan stream

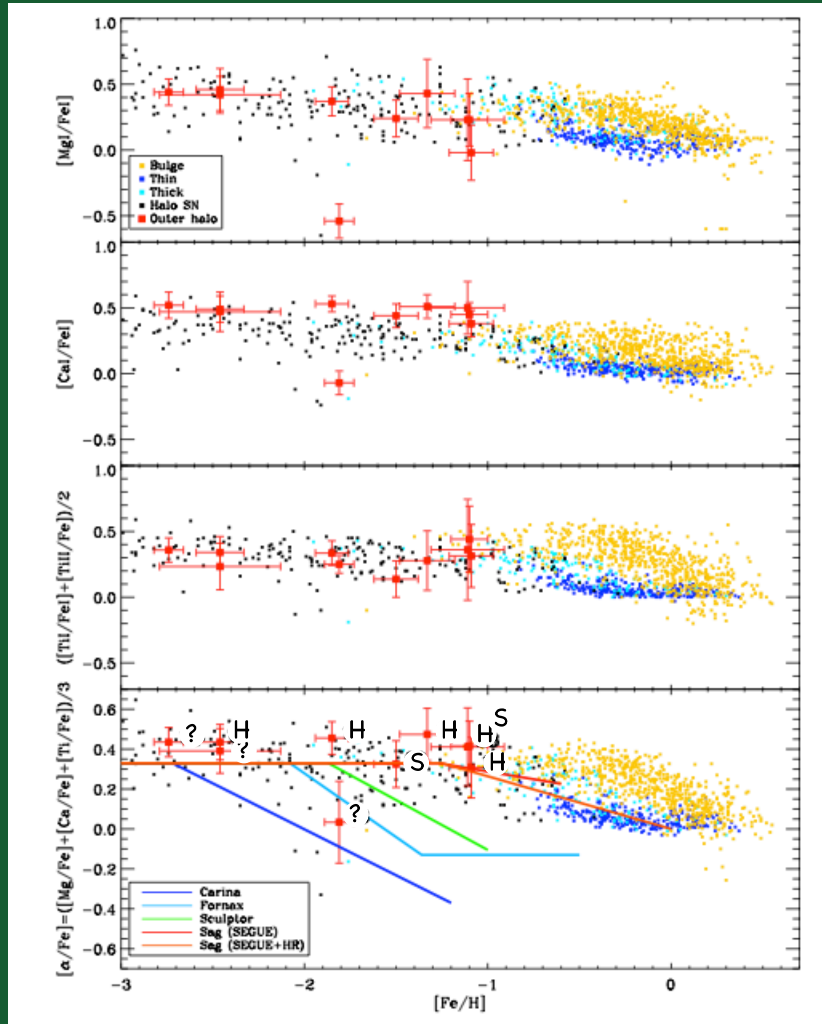


Members to substructures? Virgo/ S297+63-20.5



Can the stars belong to Sagittarius





Distances and velocity measurements of Sagittarius tidal streams from Koposov et al. (2012) & Belokurov et al. (2014)

Summary

- First analysis of the chemical abundances of a sample of in-situ outer halo stars, from HET high resolution spectroscopic data for 10 stars

- The trend in [α/Fe] vs [Fe/H] appears very similar to inner-halo stars
  - -> fast chemical enrichment (environment with initial high SFR)
  - -> The comparison to classical dSphs remains unchanged, as when using Solar neighbourhood samples

- 2 stars may be part of Sagittarius and have [α/Fe] in agreement with those measured by other studies of Sag over a similar [Fe/H] range

- With the Magellan/MIKE data acquired and VLT/UVES soon to be acquired, sample size will triple