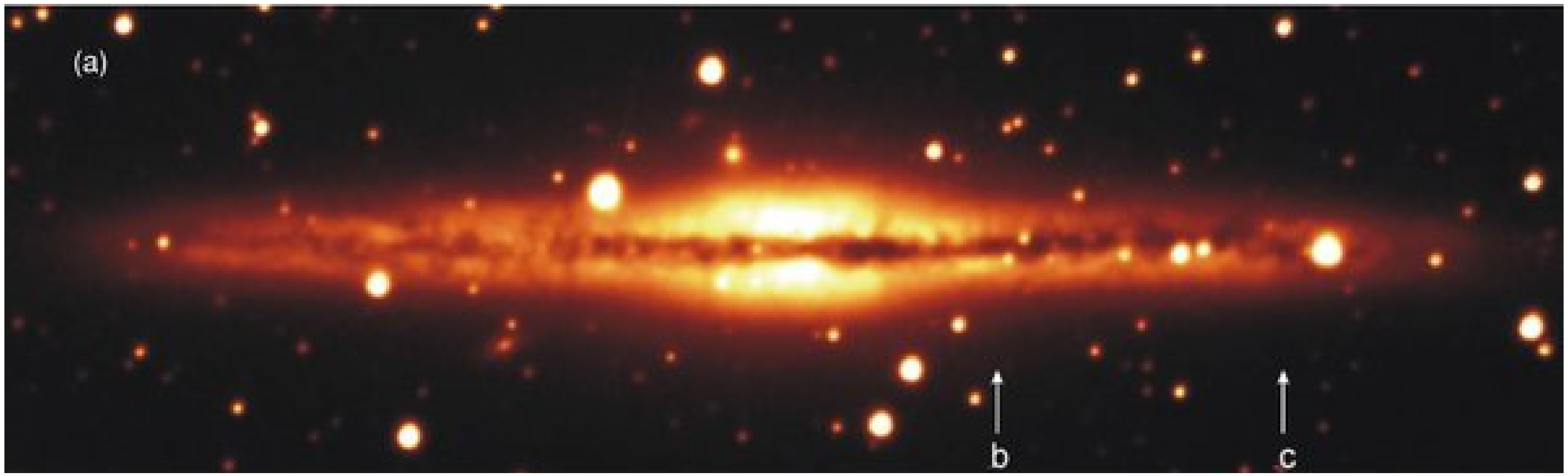
The Galactic Disk and Halo in the Gaia Era

Carlos Allende Prieto
Instituto de Astrofísica de Canarias

Introduction

- Hierarchical galaxy formation
- Galaxy disks
- Double disks seen in many disk galaxies observed edge-on (image credit: 2MASS, shown by Bournaud et al. 2009)
- Also present in the Milky Way



Star counts

- 2MASS (Cabrera-Lavers et al. 2

Thin/thick scaleheights 269 +/- 1

and 1062 +/- 52, respectively

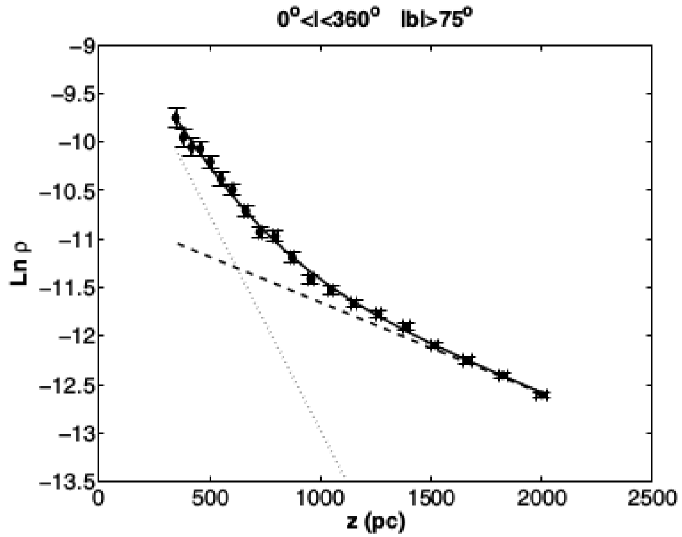
Scale-lengths of 2000 and 3100

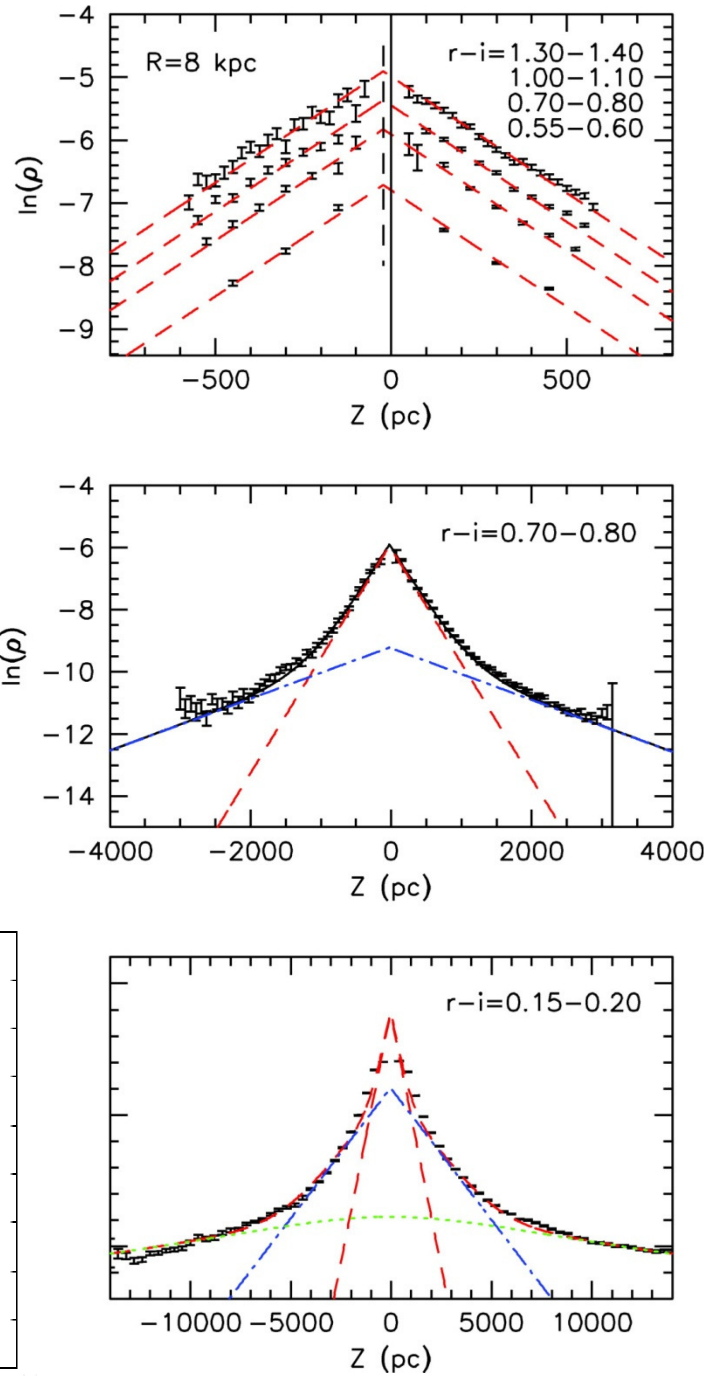
- SDSS (Juric et al. 2008)

Scale-height

Scale-length

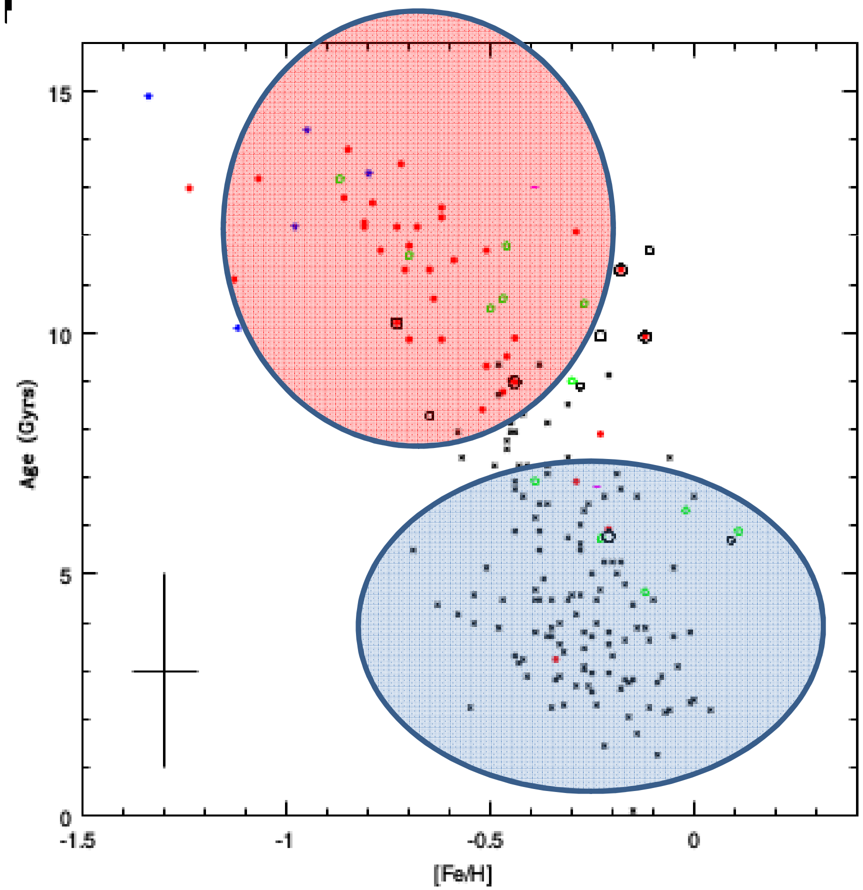
and 3600 pc





Ages and abundances

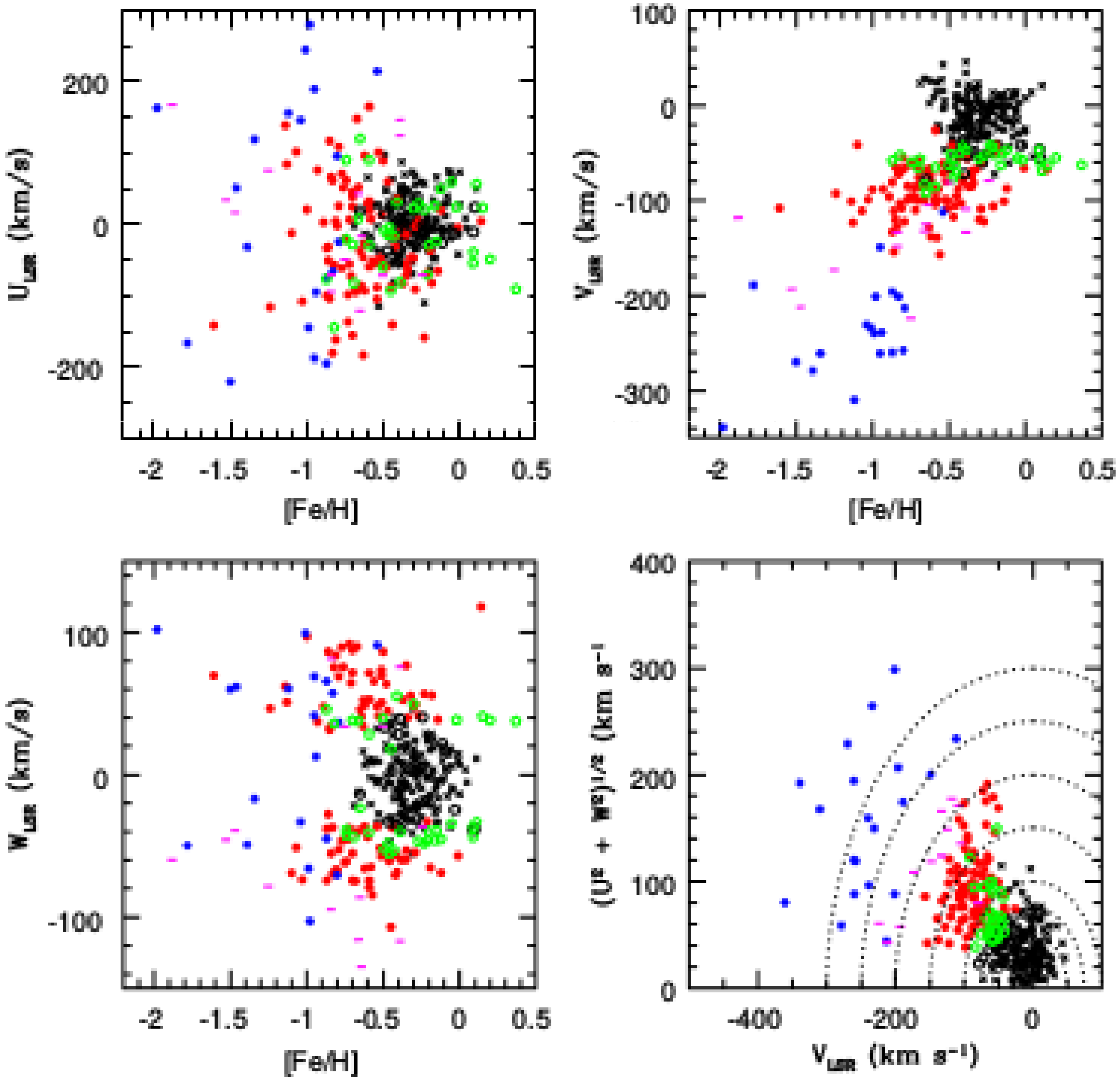
- Thick disk stars tend to be significantly older and more metal-poor than thin disk stars
- Seen in individual local turn-off stars
- Also seen in the turn-off colors of in-situ stars



Reddy et al. 2006

Kinematics and abundances

- The thick disks rotation speed



Fuhrmann 1998
Reddy et al. 2006

Vertical velocity dispersion

- A larger vertical
  to a larger scale-
- The thin disk sta
  between velocity

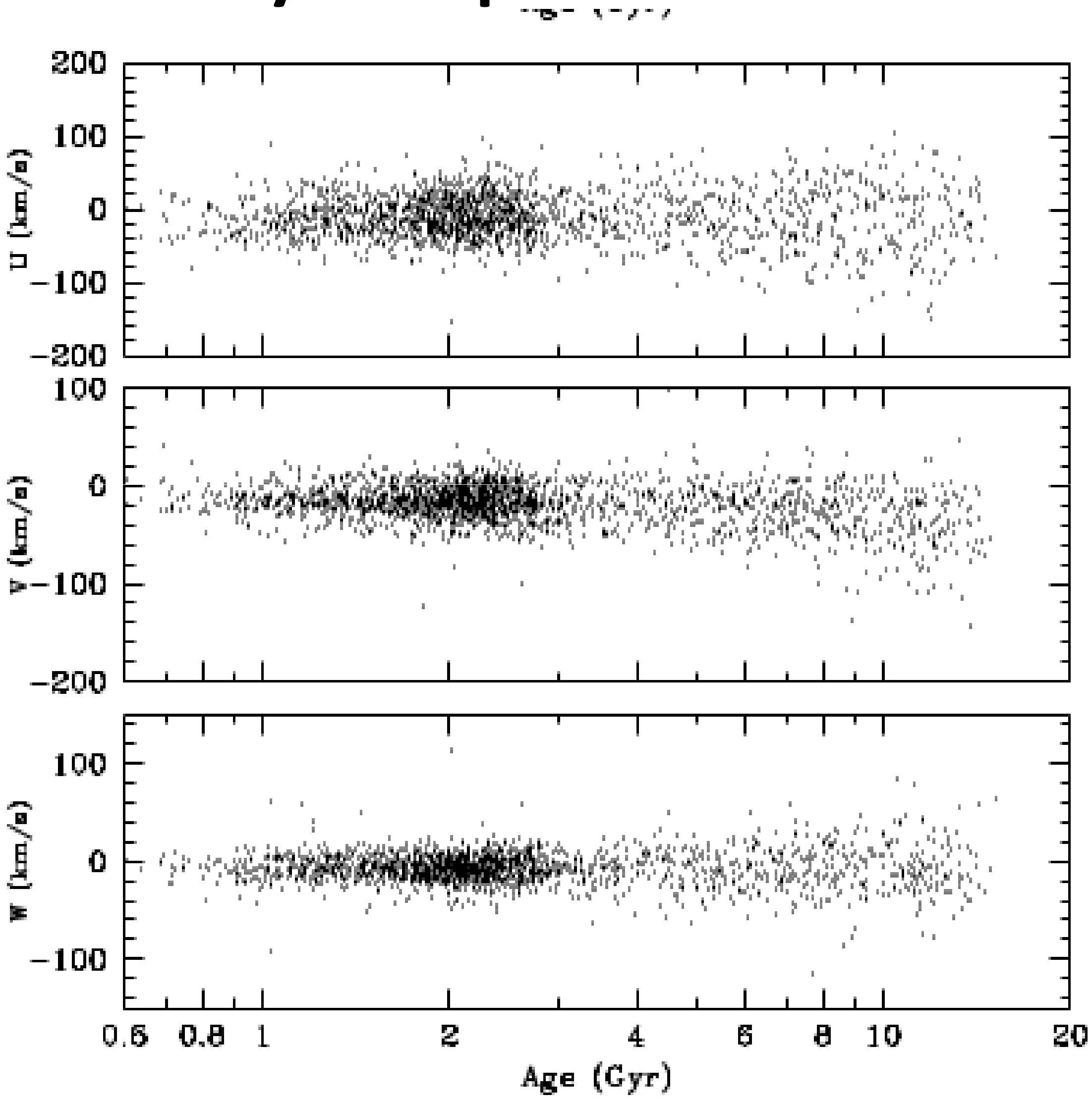
  with a smooth

  transition

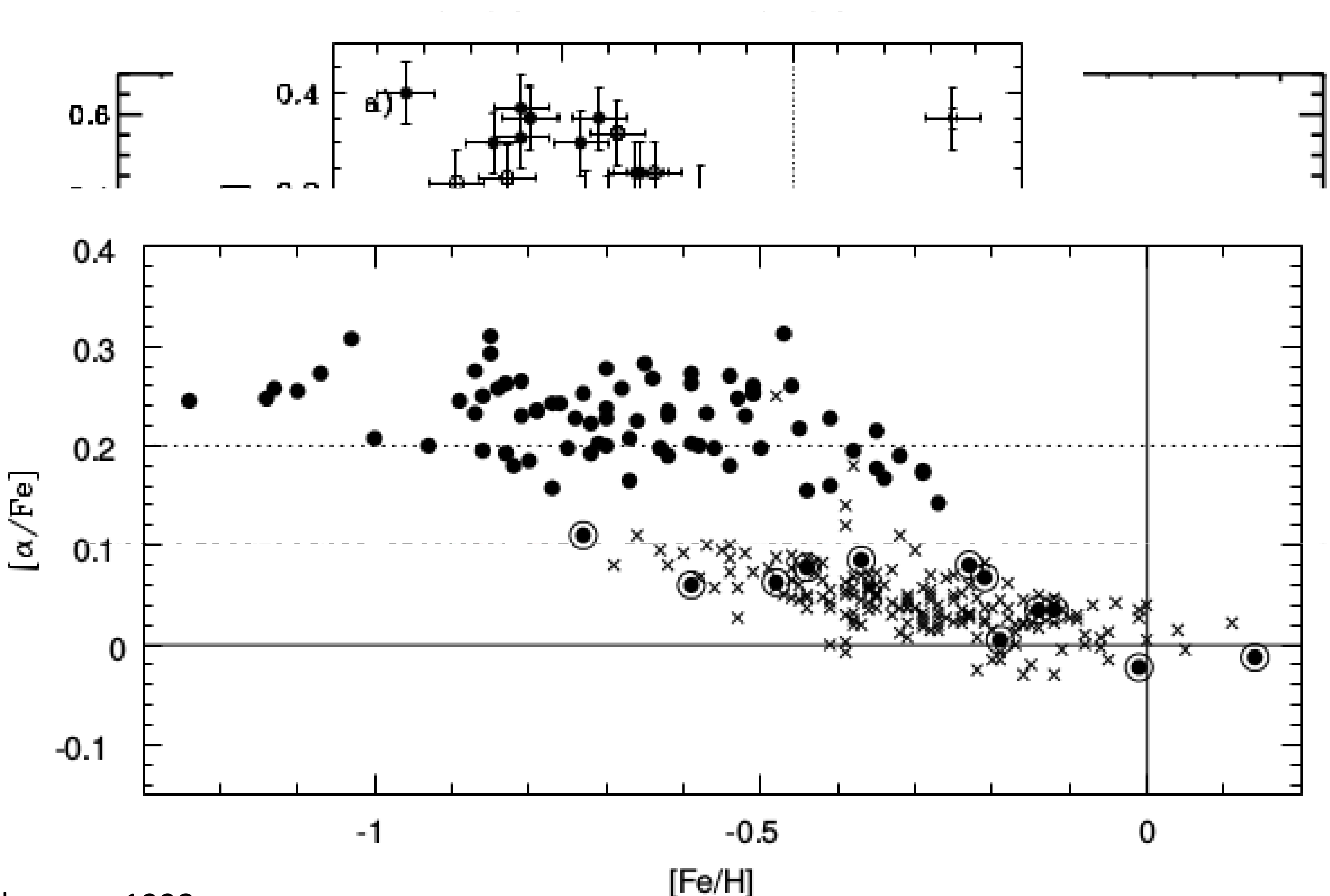
  suggesting the

  thick disk may

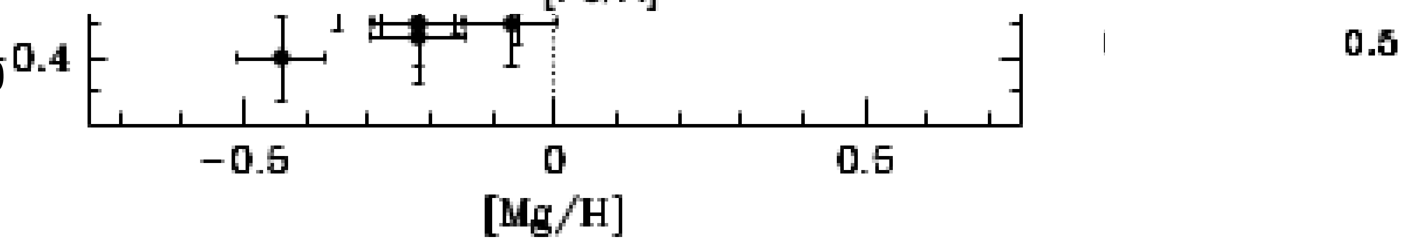
  have formed thi



Nordstrom et al. 2004

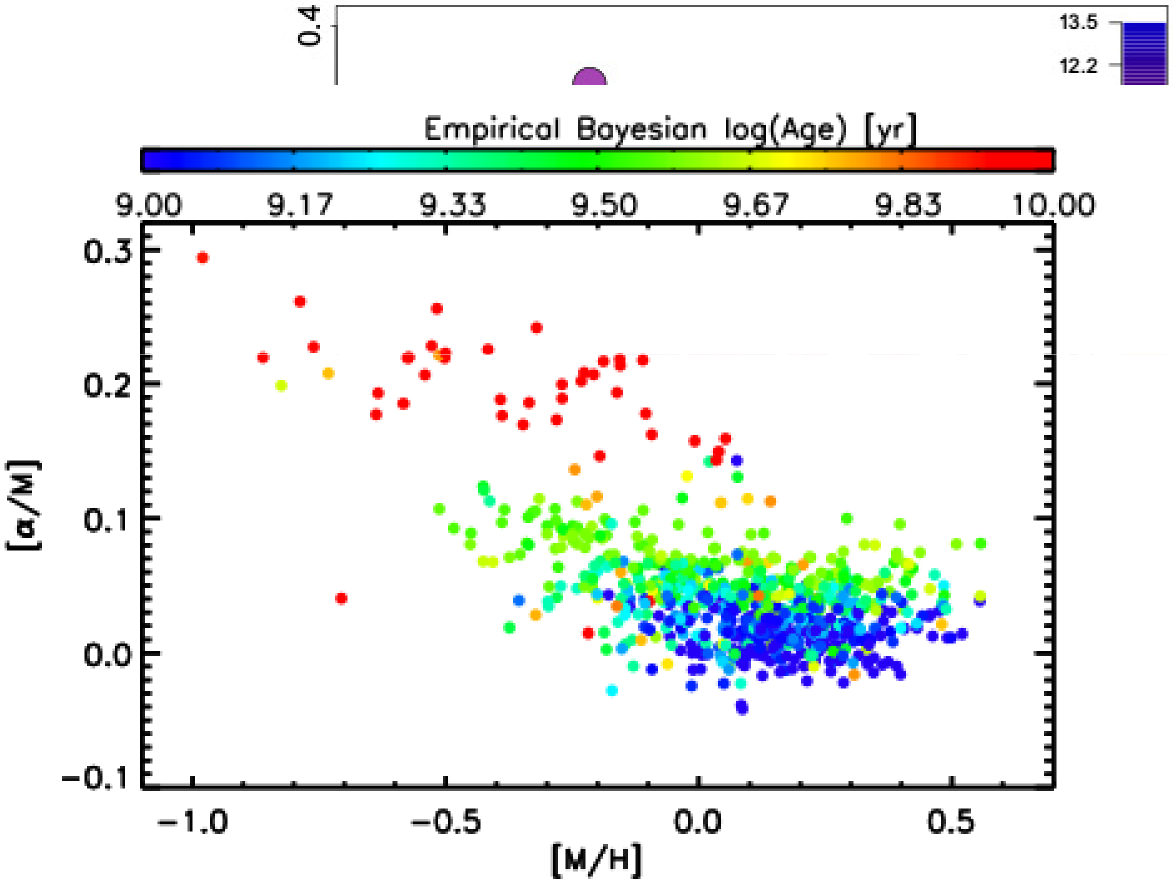


Fuhrmann 1998
Prochaska et al. 2000
Bensby et al. 2003
Reddy et al. 2006



Intermediate [α/Fe] stars

Haywoc



Feuillet et al. 2016

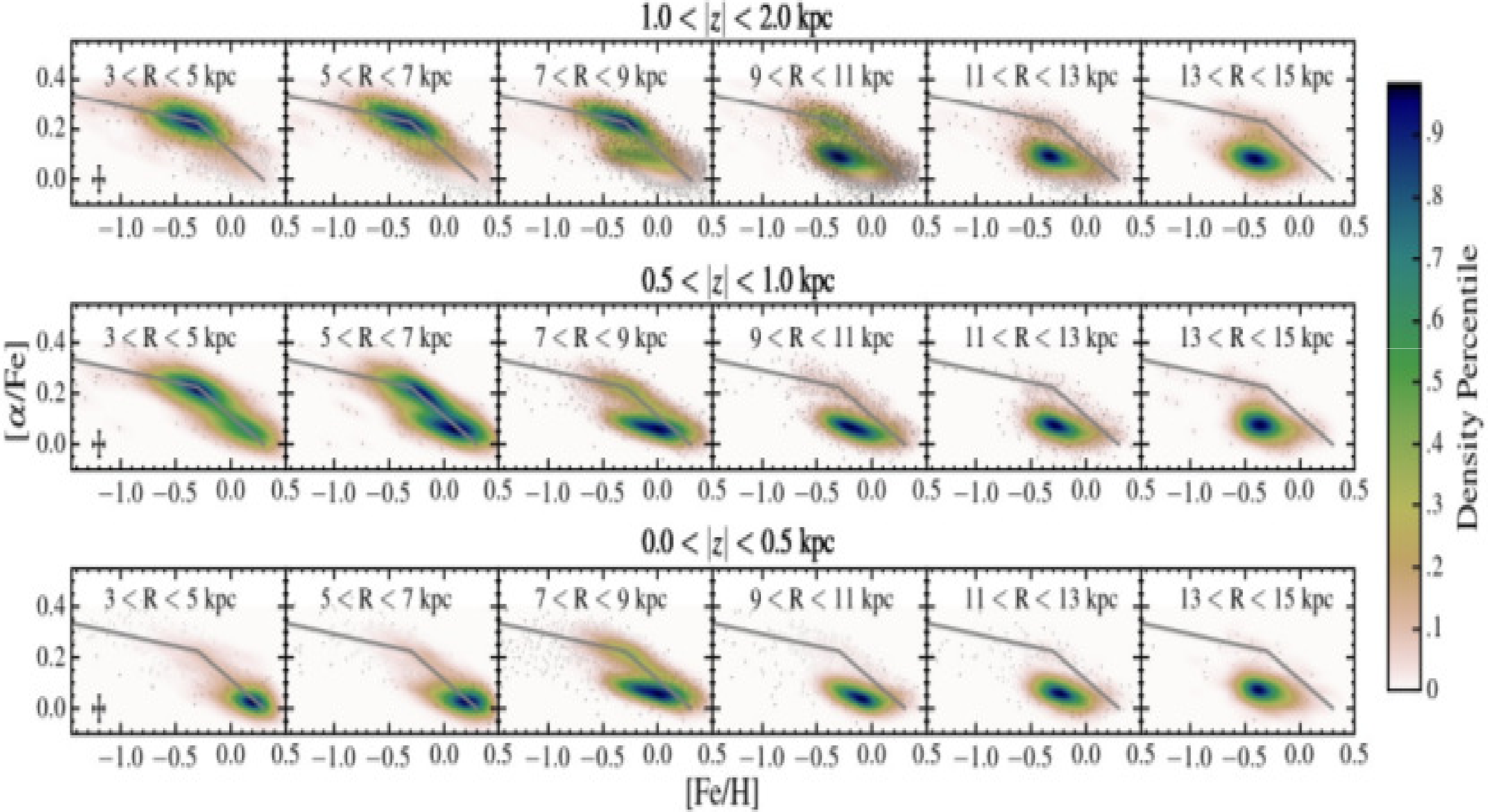
New more distant samples

- SDSS-SEGUE
- RAVE
- APOGEE
- Gaia-ESO
- LAMOST
- GALAH
- … 4MOST, WEAVE, DESI …

+ Gaia

- Revealing a larger scale-length for the thin disk than the thick disk (Bensby et al. 2011, Cheng et al. 2012, Bovy et al. 2012, Anders et al. 2014)
- This can be in contrast with star counts determinations due to flaring
- Radial abundance gradient clear in the thin disk (a tenth of a dex per kpc) not present in the thick disk stars (seen as a function of age in Nordstrom et al. 2004, in situ in Allende Prieto et al. 2006, now obvious in APOGEE and GES observations)

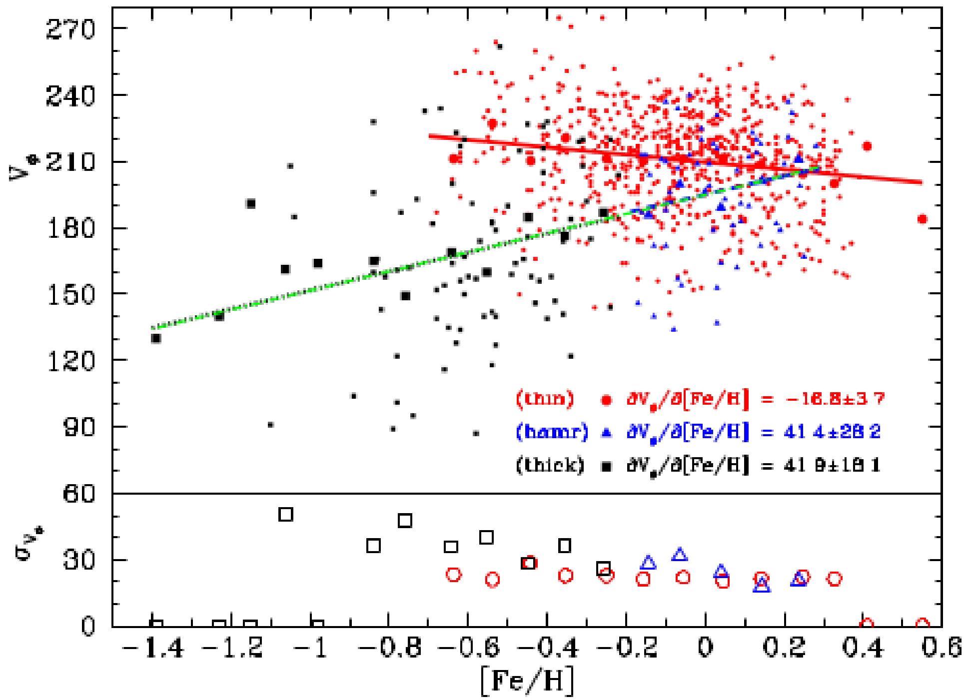
[α/Fe] as a function of R



Hayden et al. 2015

Correlation between V and [Fe/H]

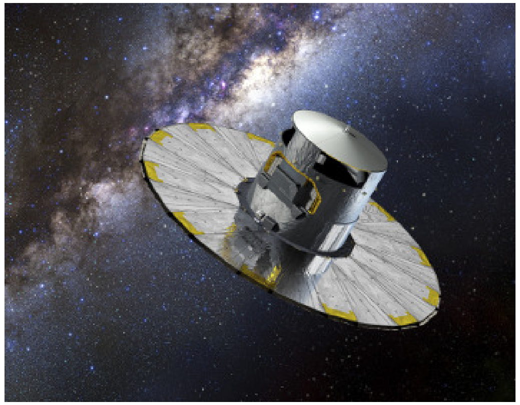
- Spagna et al. (2010)
- Lee et al. (2011)
- Adibekyan et al. (2013)
- Recio-Blanco et al. (2014)
- Kordopatis et al. (2016)



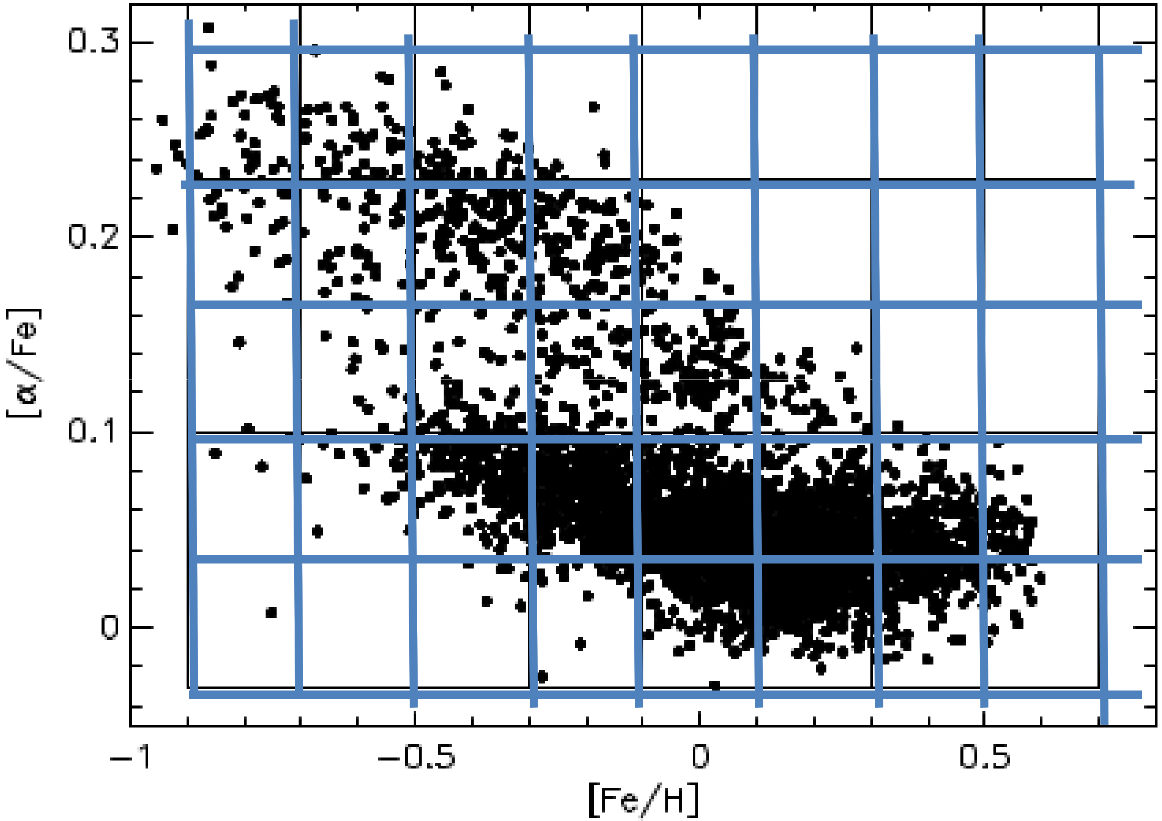
Adibekyan et al. 2013

Gaia DR1 TGAS

- Gaia provides global astrometry and spectrophotometry over the whole sky to 20th mag (1e12 sources), and radial velocities to 16th mag
- DR1 public last september, includes positions for the full sample, but parallaxes and proper motions only for the stars in Tycho-2 (TGAS, 2.5e6 sources)
- Combined with APOGEE,
  3D positions, motions and
  chemistry for thousands of stars

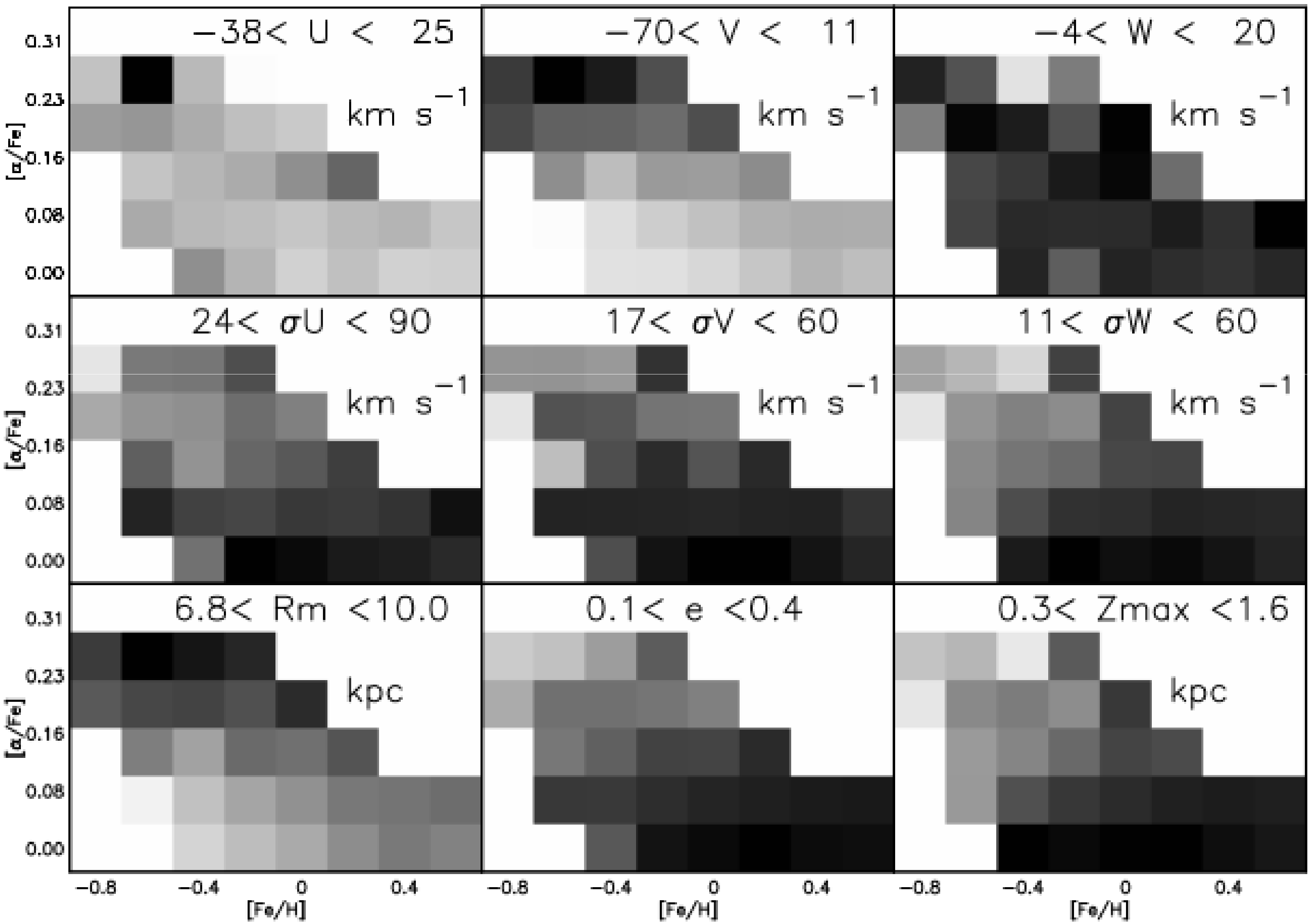


TGAS-APOGEE



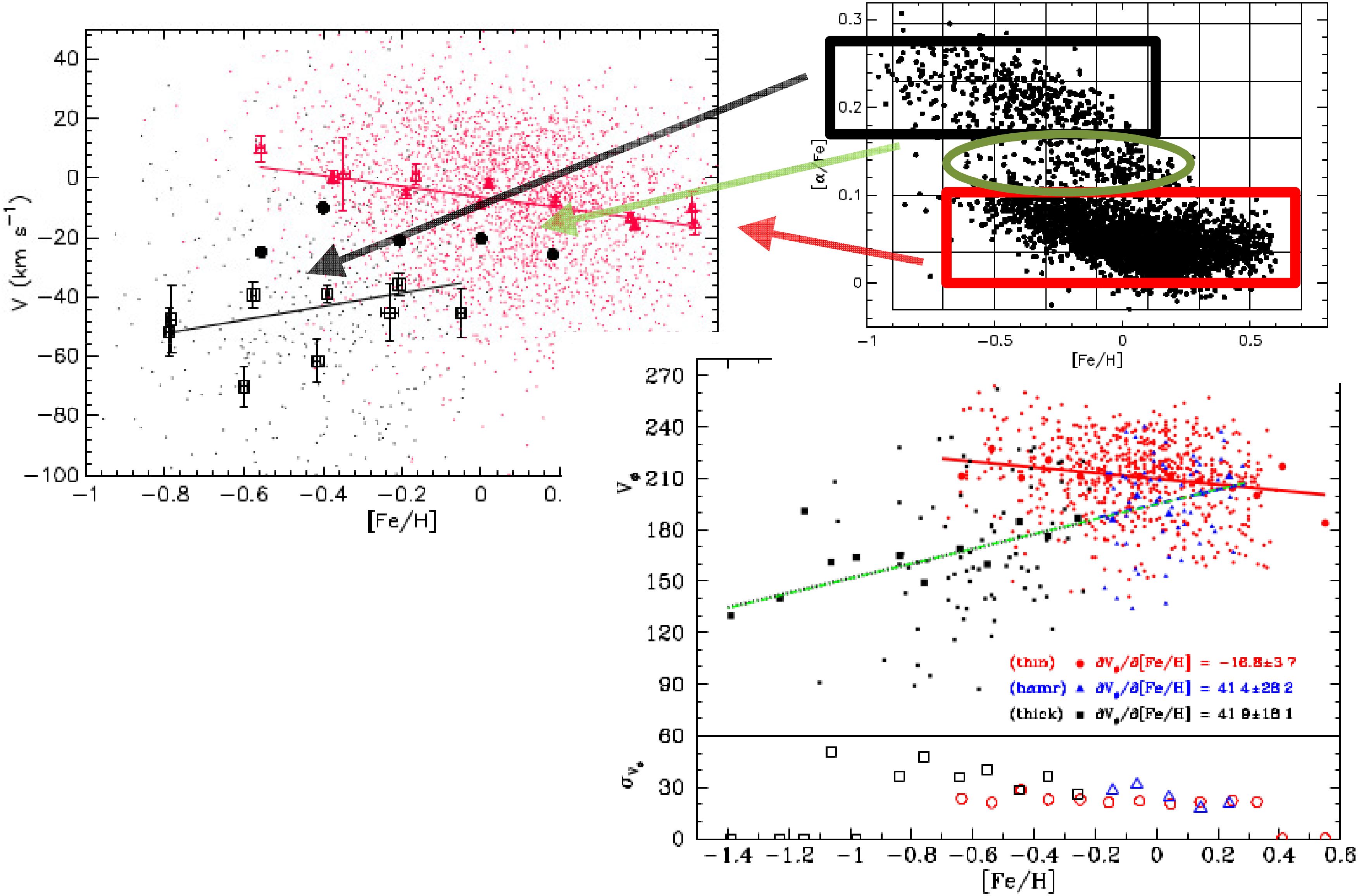
Allende Prieto, Kawata, Cropper 2016

TGAS-APOGEE

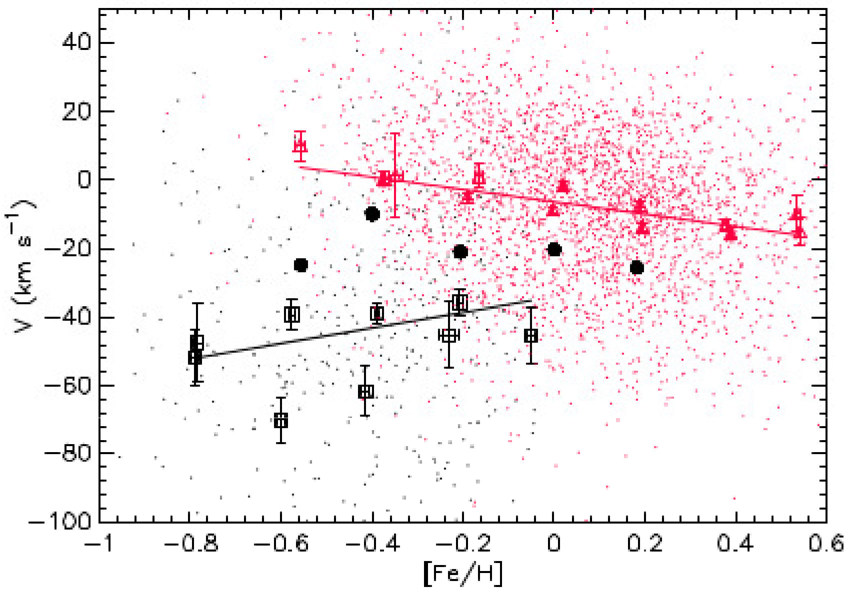


−38< U < 25
km s^{-1}
−70< V < 11
km s^{-1}
−4< W < 20
km s^{-1}
24< σU < 90
km s^{-1}
17< σV < 60
km s^{-1}
11< σW < 60
km s^{-1}
6.8< Rm <10.0
kpc
0.1< e <0.4
0.3< Zmax <1.6
kpc
[α/Fe]
0.31
0.23
0.16
0.08
0.00
[Fe/H]
−0.8
−0.4
0
0.4

Correlation between V and [Fe/H]

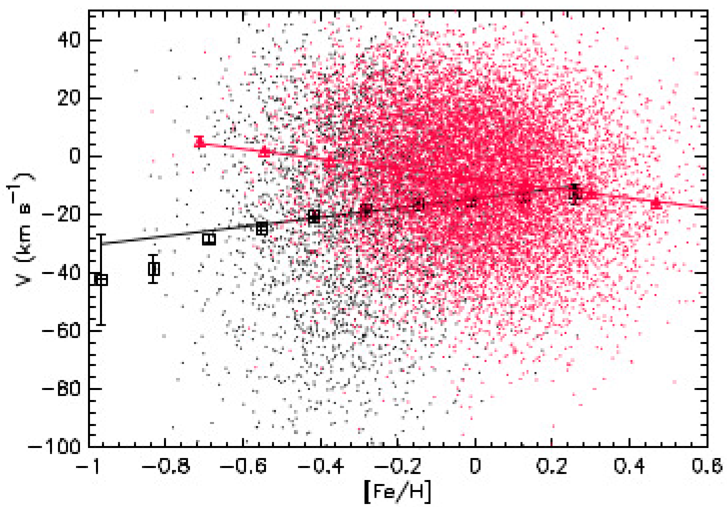


Correlation between V and [Fe/H]



data

Model (D. Kawata)

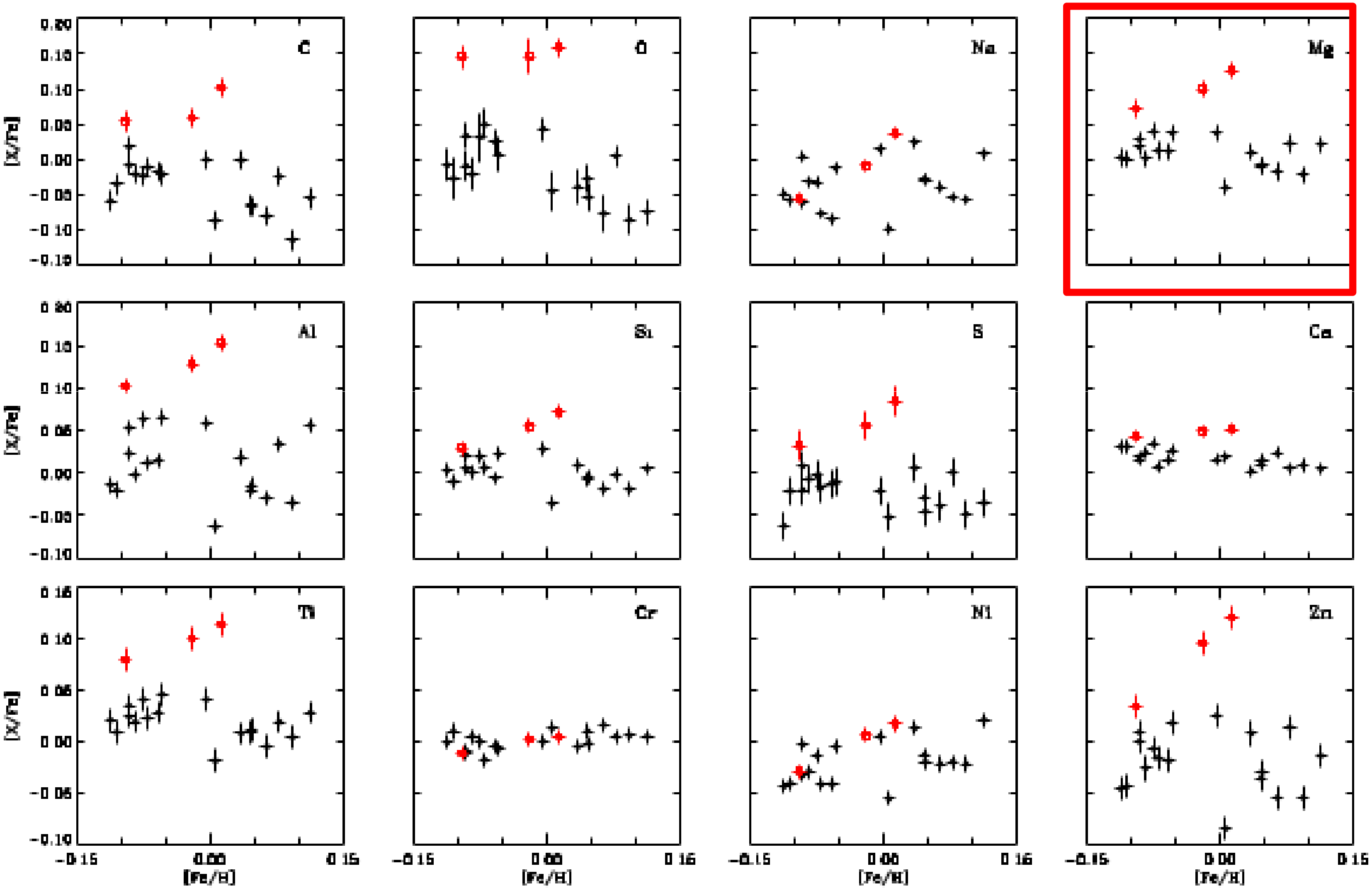


Allende Prieto, Kawata, Cropper 2016

Spread in abundance ratios

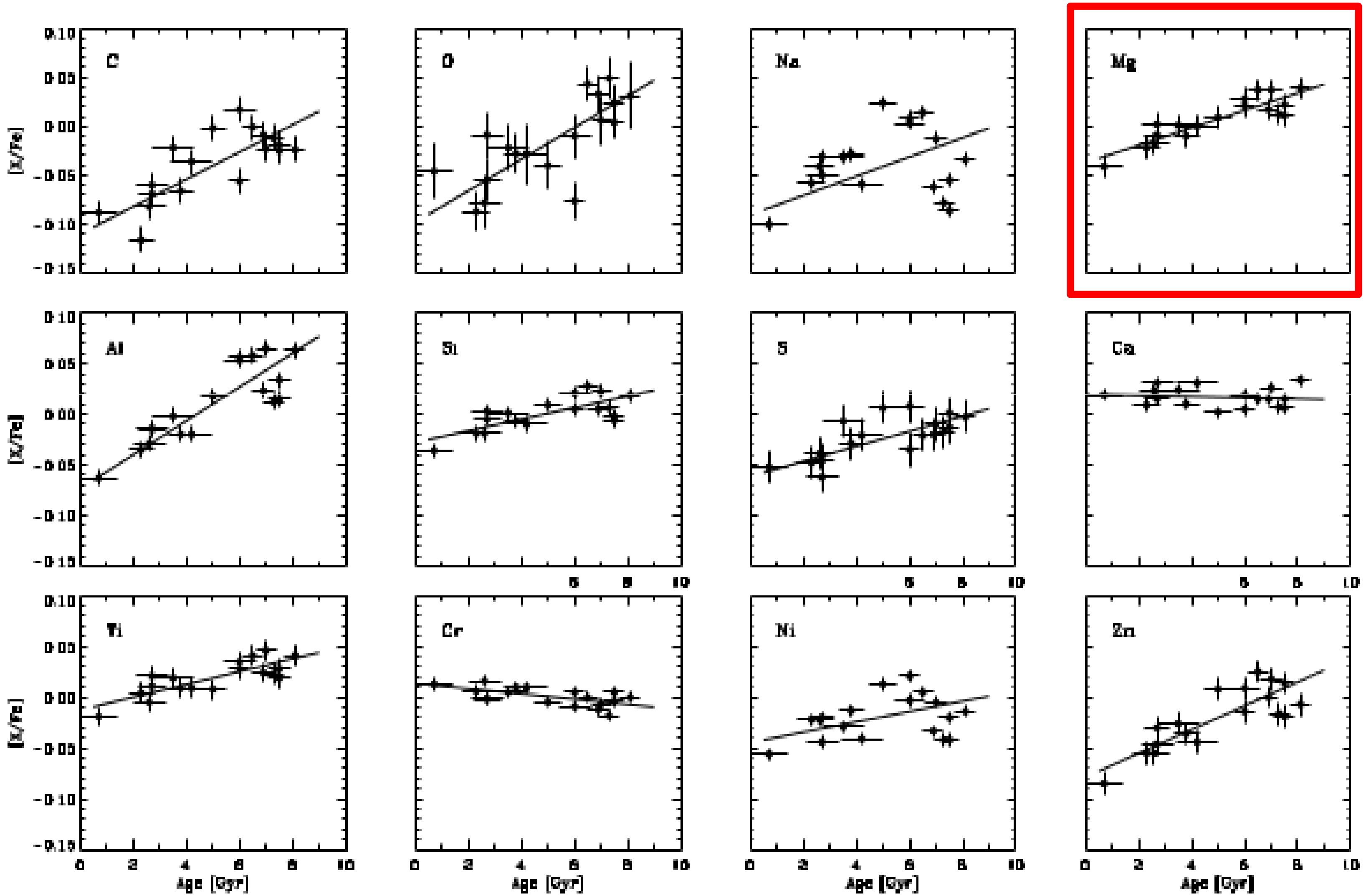
- Large abundance spread expected among the first stars formed after one or few supernovae
- Abundance spread reduces as the number of supernovae increases
- A measure of the spread in abundance ratios puts contraints on supernova rates and therefore star formation rates

Cosmic scatter in the disk



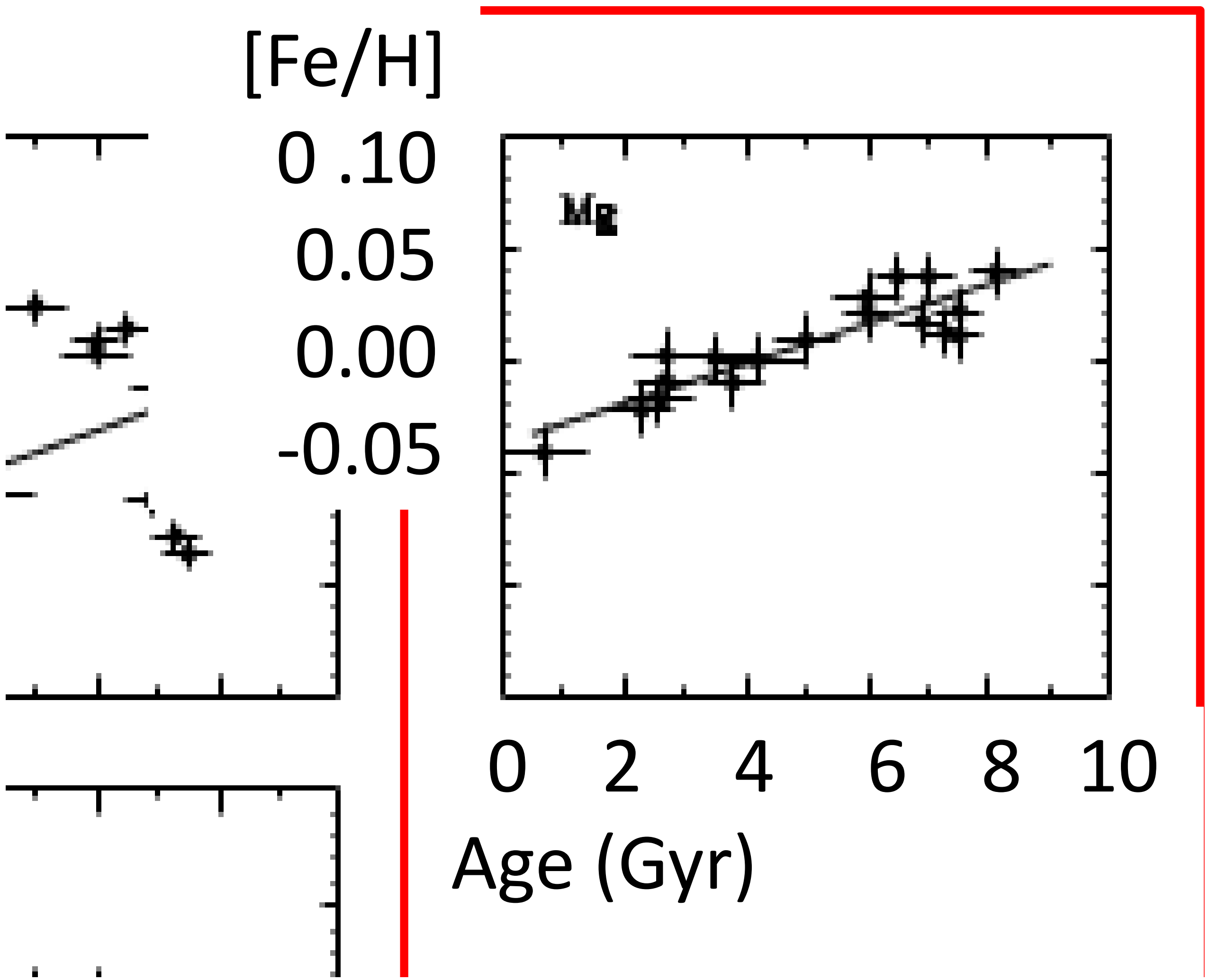
Nissen 2015

Cosmic scatter in the disk



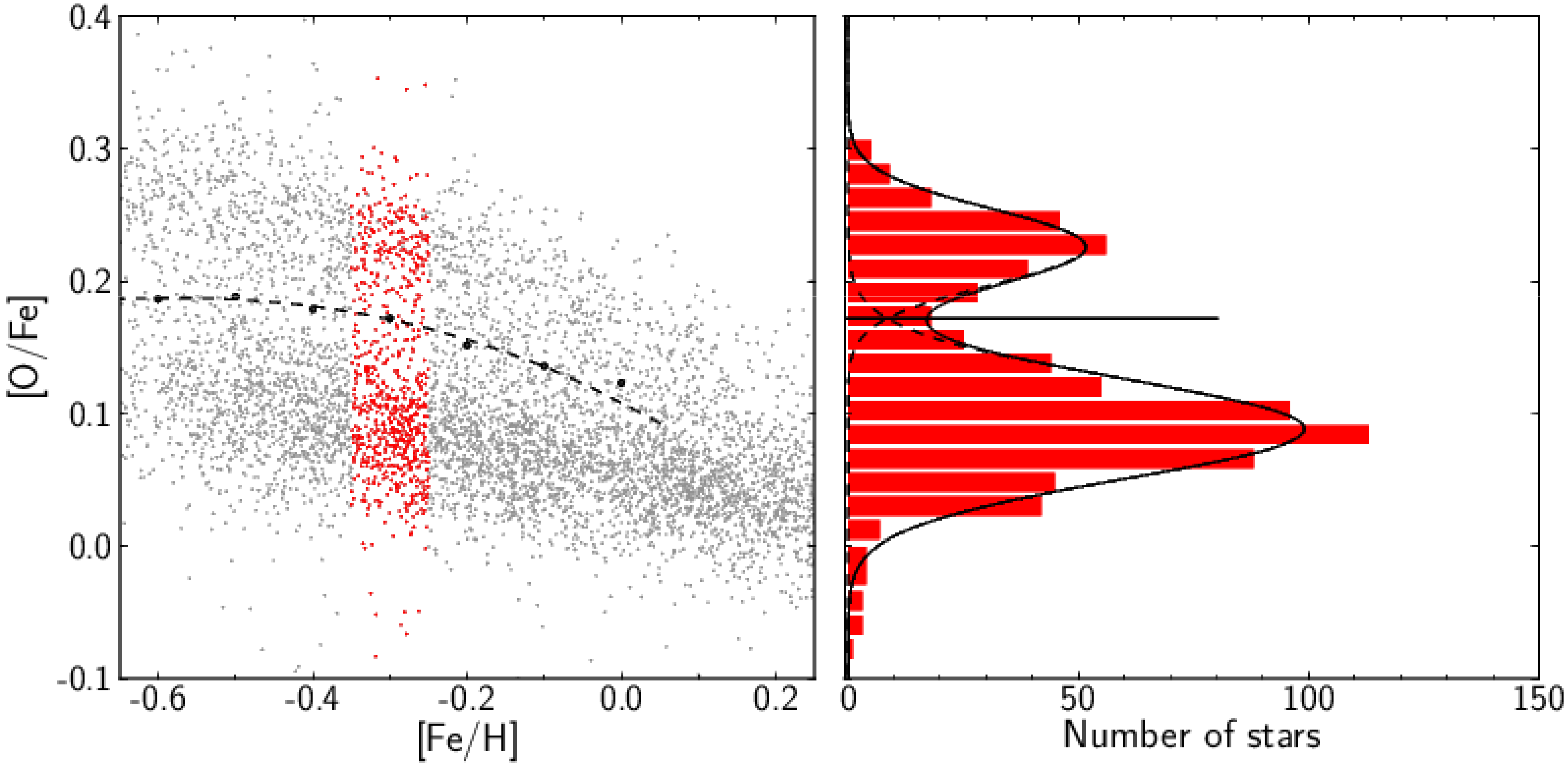
Nissen 2015

Cosmic scatter in the disk



Nissen 2015

Abundance ratio spread over larger scales



Bertran de Lis et al. 2016

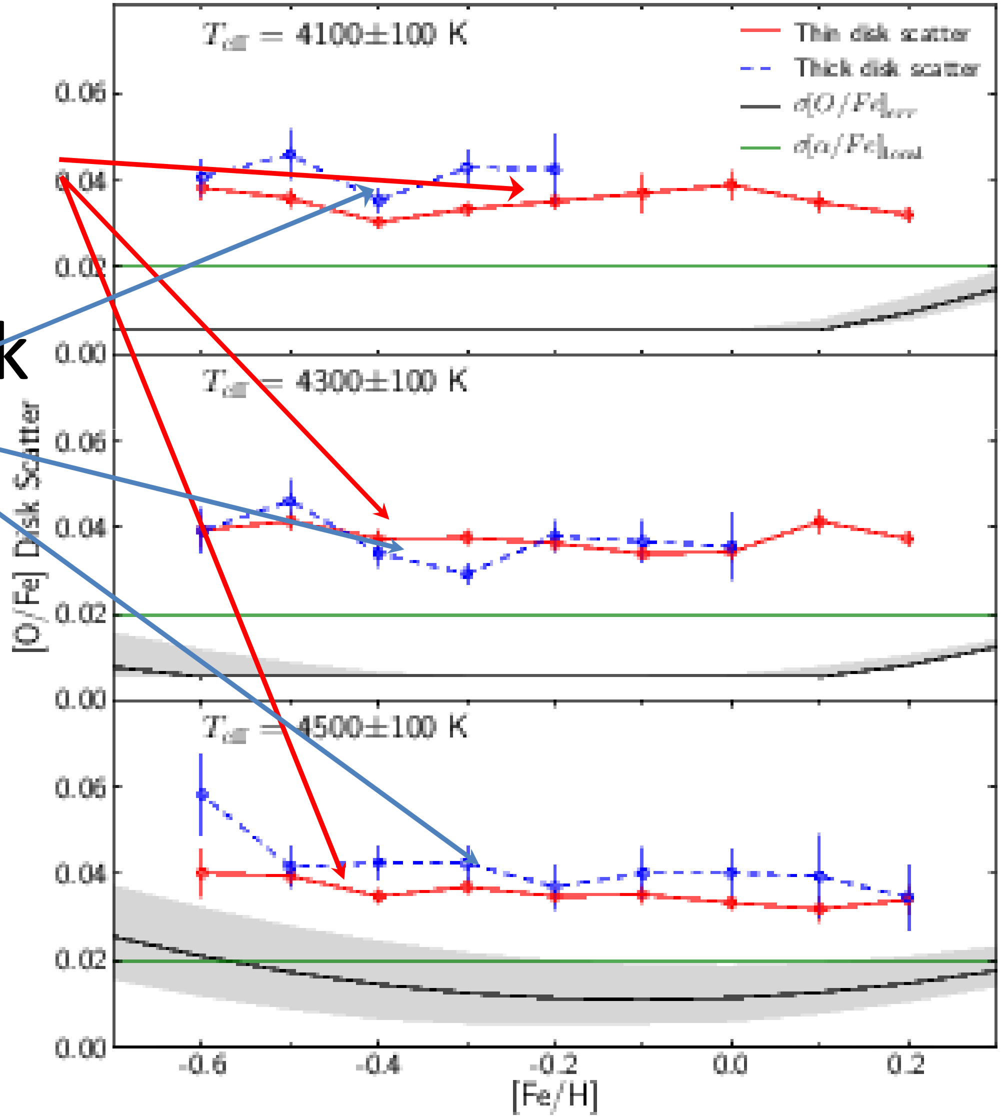
APOGEE data

Abundance ratio spread over larger

s

O/Fe spread in thin disk

O/Fe spread in thick disk



APOGEE data

Bertran de Lis et al. 2016

Models of formation for the thick disk

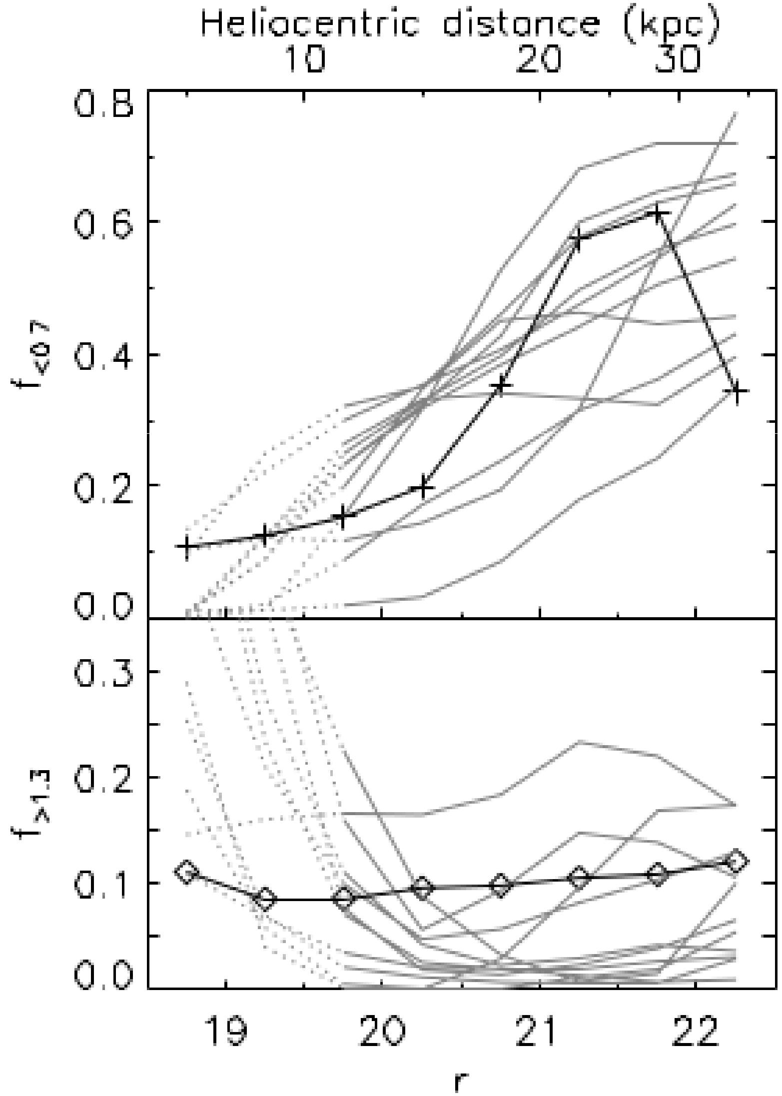
- Accretion/merger: stars (unlikely), gas
- Secular evolution: orbital migration (unlikely)
- Secular evolution: thick disk forms first (maybe as a thin disk that later fattens up), then thin disk forms after injection of fresh (metal-poor) gas

The formation of the Milky Way halo

- Monolithic collapse (Eggen, Linden-Bell, Sandage 1962) vs. accretion (Early and Zinn 1978)
- Streams and echoes (Yanny et al. 2009; Schlaufman et al. 2012; Grillmair 2017)
- Chemistry of extremely metal-poor stars (Cayrel et al. 2004)

The formation of the Milky Way halo

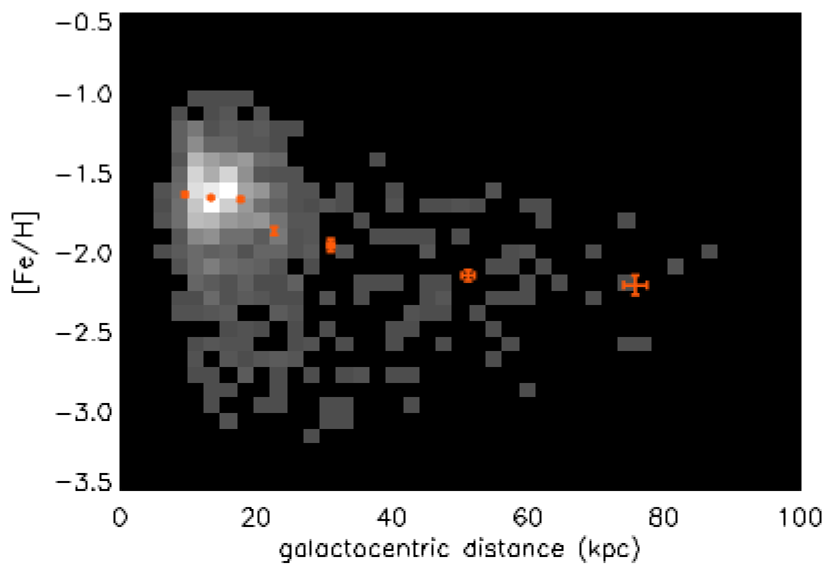
- Accretion seems to have left a clear signature in the outer halo

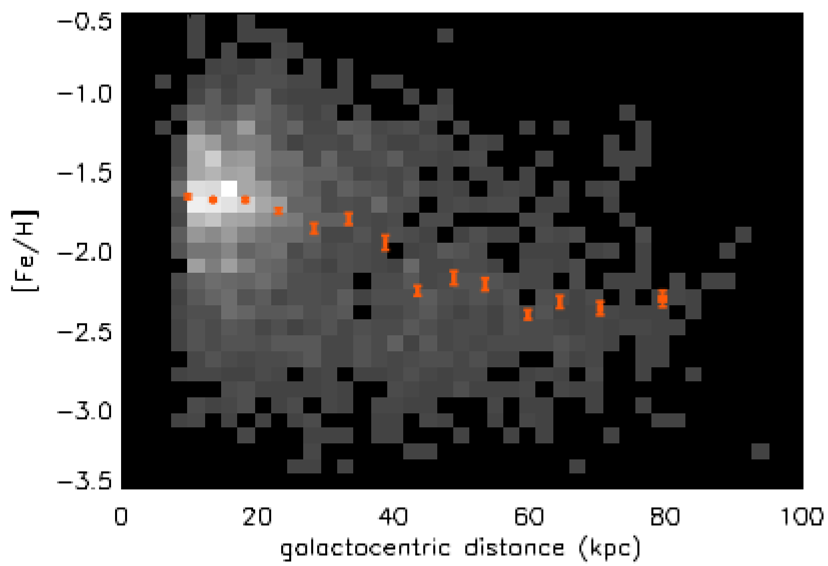


Bell et al. (2008)

The "double" halo

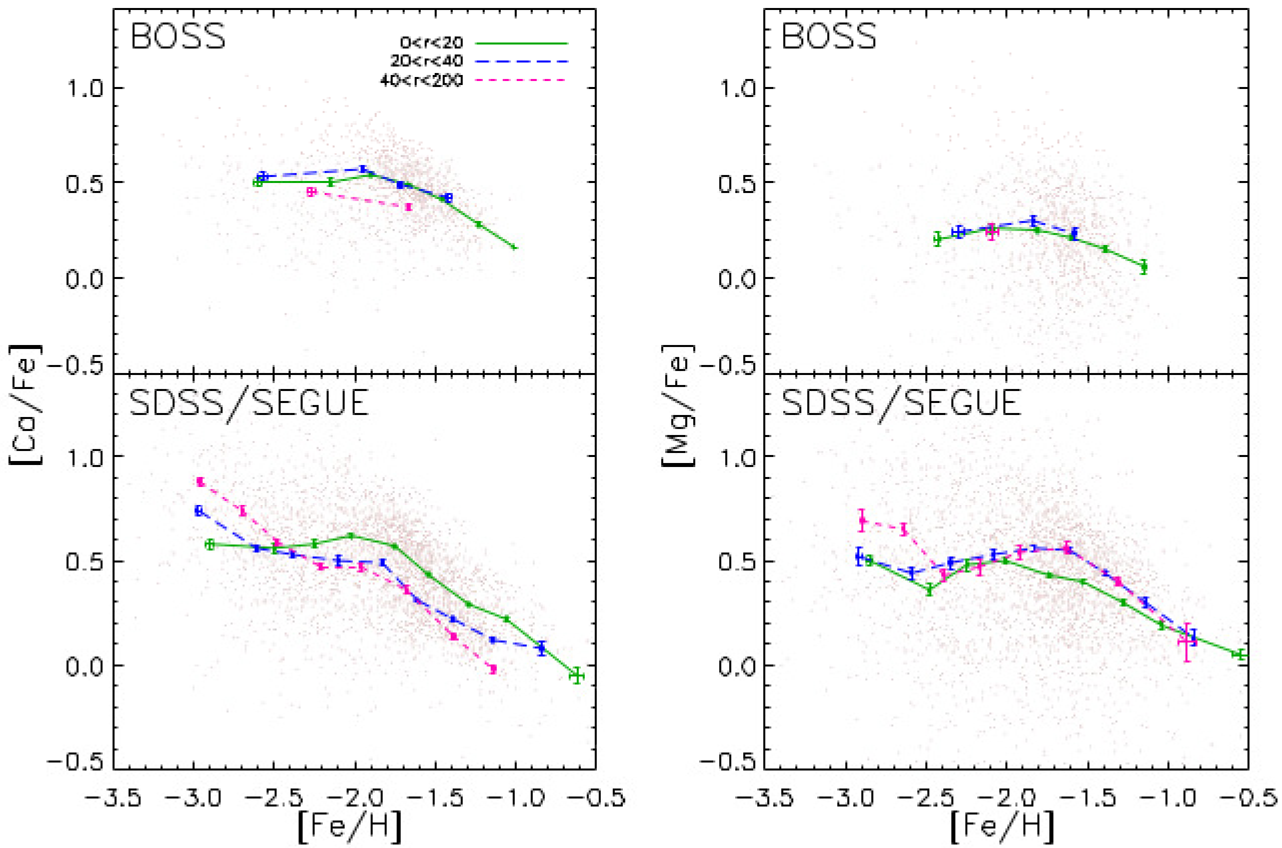
- SDSS/SEGUE (Carollo et al. 2008)
- Photometry (de Jong et al. 2012)
- Spectroscopy *in situ* (Fernandez-Alvar et al. 2015, 2016)





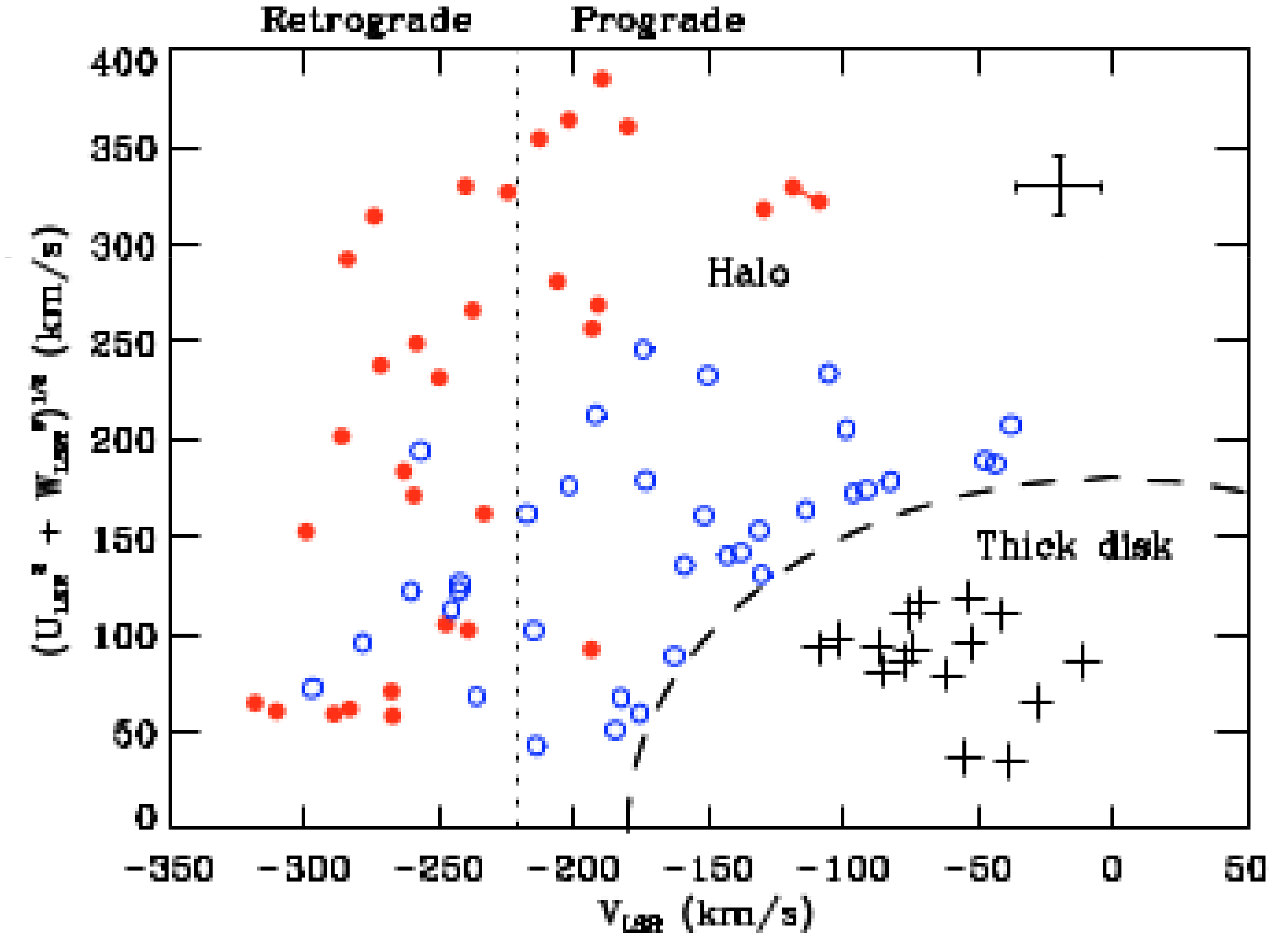
[α/Fe]

- Inner vs. outer parts (Fernandez-Alvar et al. 2015)



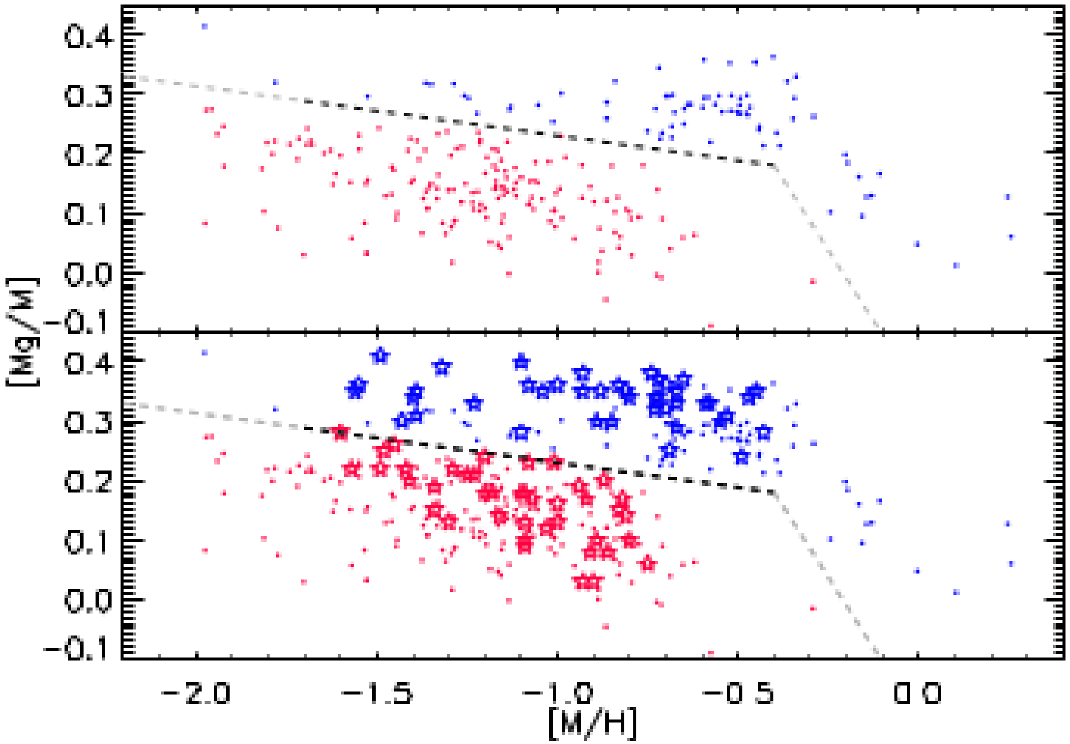
[α/Fe]

- Inner vs. outer parts (Fernandez-Alvar et al. 201
- Spli
  201



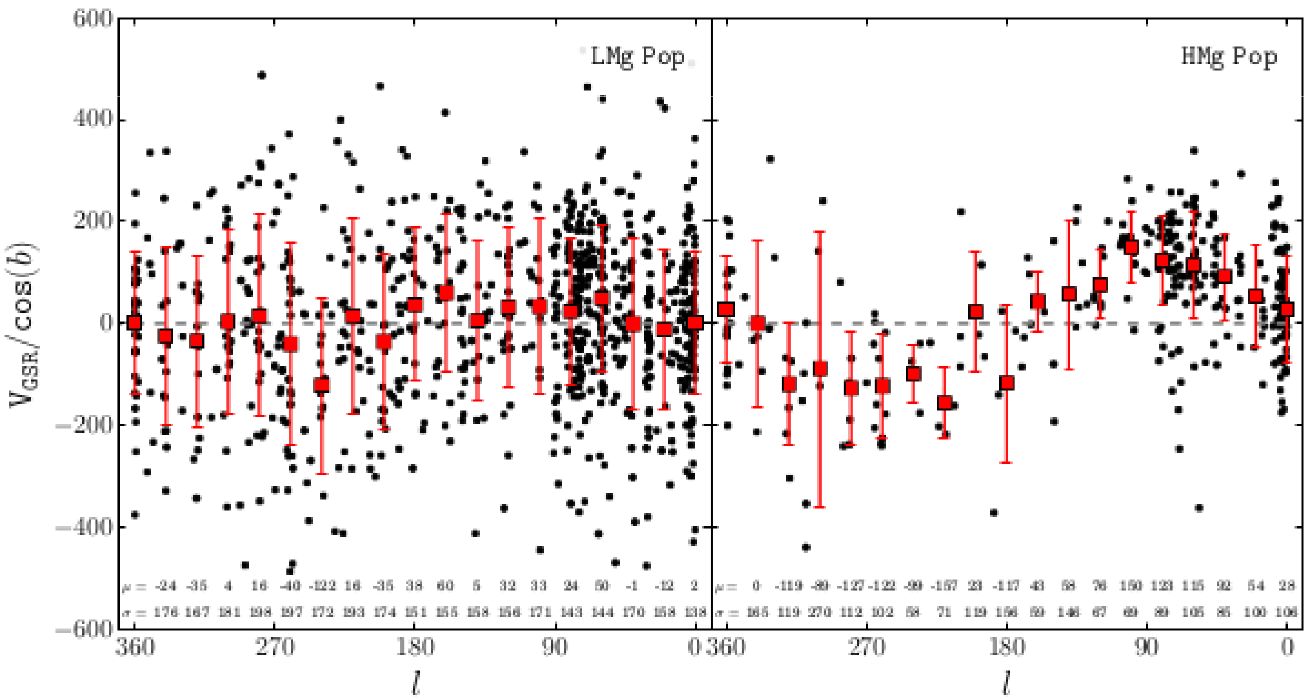
[α/Fe]

- APOGEE data (Hayes et al. 2017; Fernandez-Alvar et al. 2017)



[α/Fe]

- APOGEE data (Hayes et al. 2017; Fernandez-Alvar et al. 2017)



Summary

- The Milky Way has a double disk wich is distinct in kinematics, age, and chemistry from the thin disk
- There appears to be a connection between the two disks, stars in both that share properties, e.g. have the same age, yet they are clearly in one or other chemical group

Summary II

- We find evidence of both chemical evolution in the halo and accretion at early times
- There is chemical distinction between the inner and outermost parts of the halo at about 20-30 kpc
- The split in [α/Fe] found in the 'local' (inner) halo population is likely related to the metal-weak thick disk
- Gaia DR2 + ground-based spectroscopic surveys are a gigantic step for the study of the disk and the halo