Galactic Archaeology: elements in the disk

(fossil information preserved in stellar chemistry)

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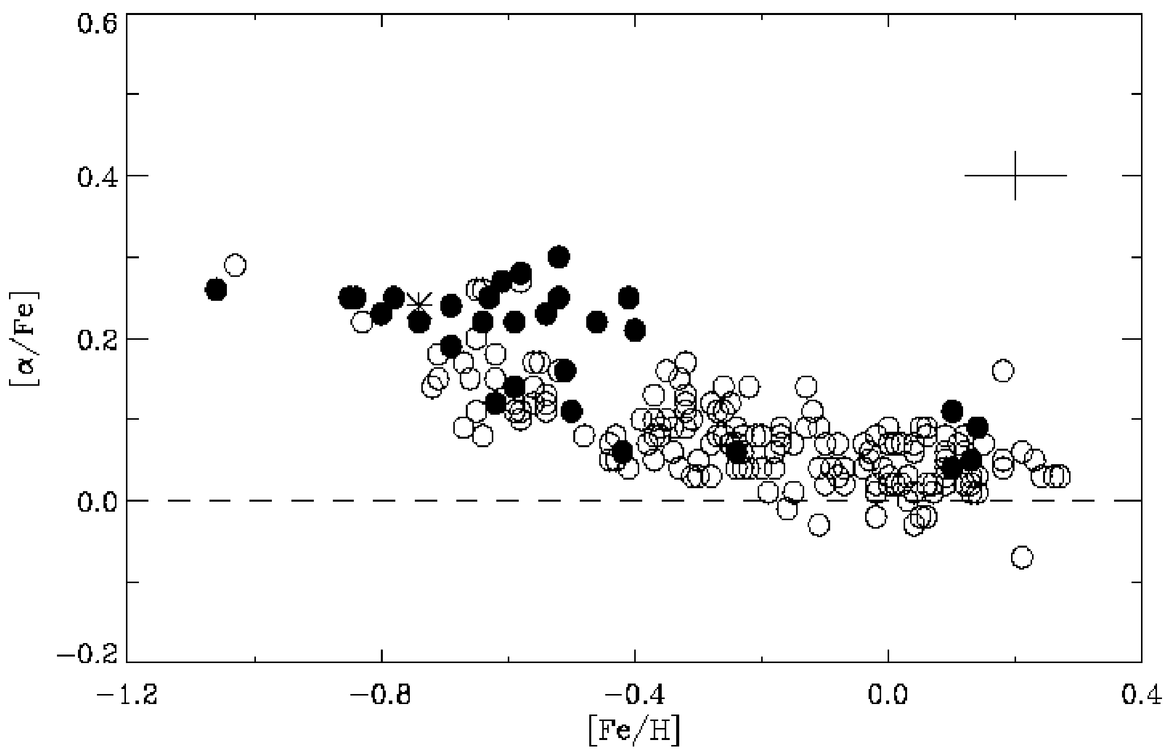


The goals of galactic archaeology

We seek signatures or fossils from the epoch of Galaxy formation, to give us insight about the processes that took place as the Galaxy formed.

Aim to reconstruct the star-forming aggregates that built up the disk, bulge and halo of the Galaxy

Some of these dispersed aggregates can be still recognised kinematically as stellar moving groups.

For others, the dynamical information was lost through disk heating processes, but they are still recognizable by their chemical signatures (chemical tagging).

A major goal is to identify
how important mergers and accretion events were
in building up the Galactic disk and the bulge.

CDM predicts a high level of merger activity which conflicts
with many observed properties of disk galaxies.

Start with the galactic stellar halo

(relatively easy but only ~ 1% of the stellar mass of the Galaxy)

Built up at least partly from accreted satellites

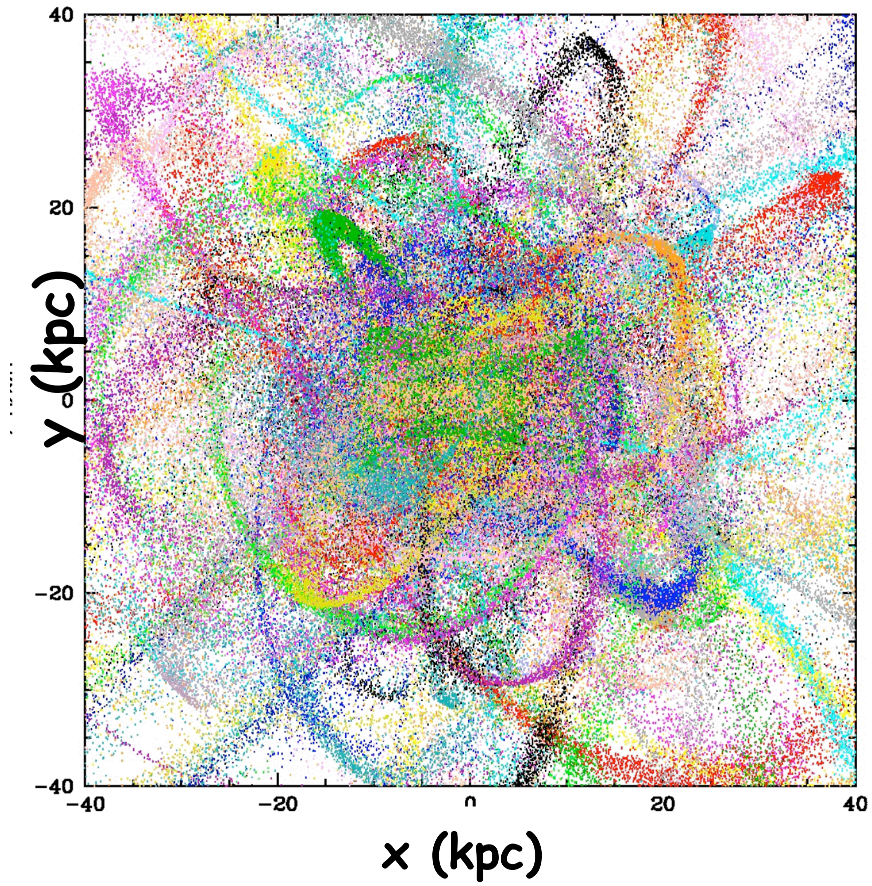
Most halo building events occurred long ago, but some are still ongoing and sometimes directly visible - eg Sgr dwarf

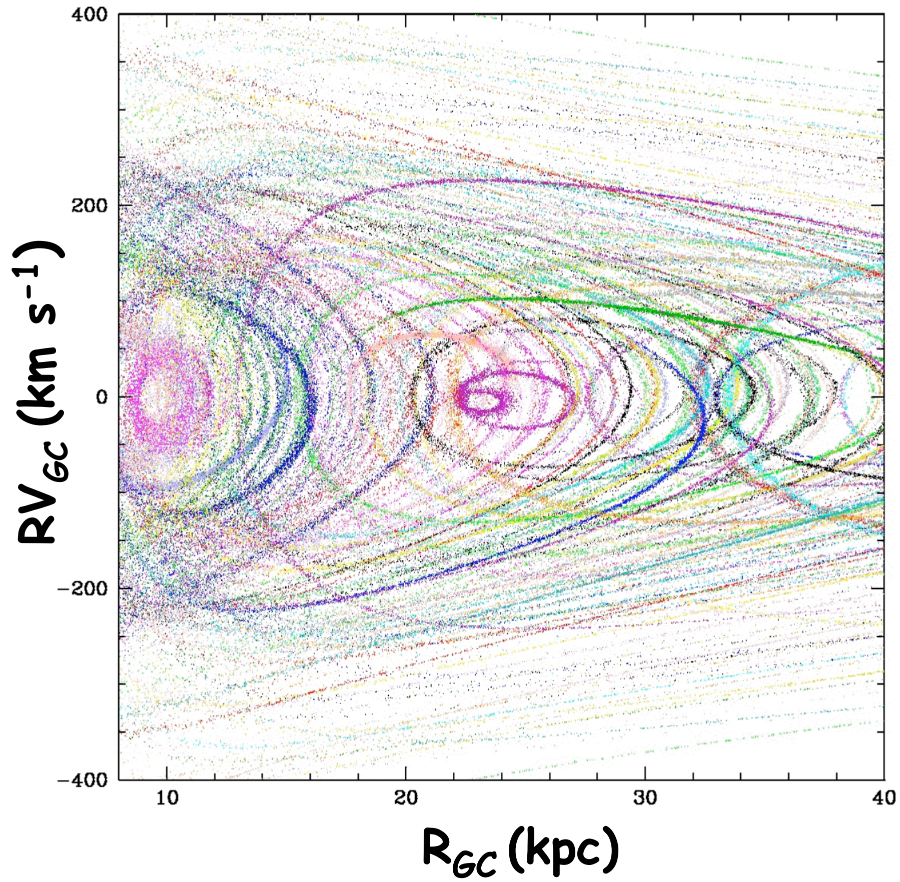
Halo events are easiest to reconstruct dynamically because they are minimally affected by dissipation:
long orbital periods
allow dynamical structures to survive

Accreted objects leave long-lived kinematic substructure
in the galactic halo ...
substructure too faint to see
in configuration space but visible in <u>phase</u> space
or <u>integral</u> space (eg E, L_z)

Tidal Streams in the Galactic Halo

(simulation of accretion of 100 satellite galaxies)

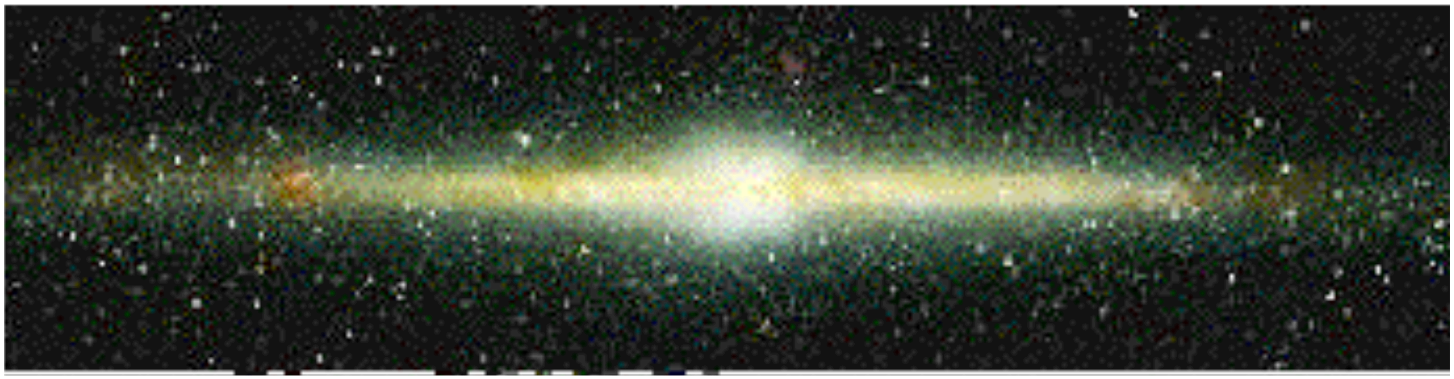




The Spaghetti Survey (Morrison et al)

Washington system; halo stars out to 100 kpc over 100 deg^2

We can extend this approach of reconstruction to other components of the Galaxy.

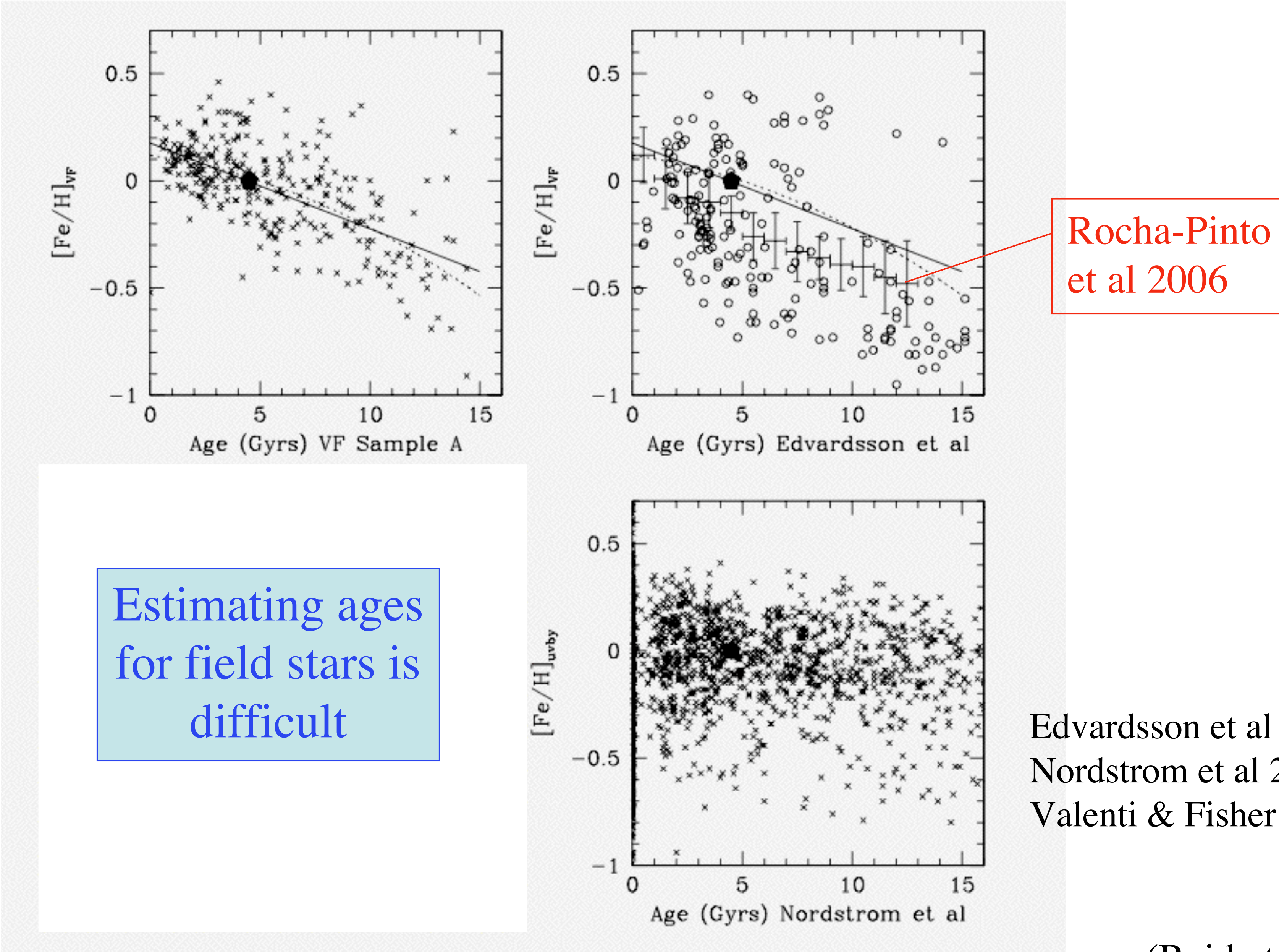


Understanding disk and bulge formation is more important than understanding the halo, because most of the galactic baryons are in the disk and bulge.

We would like to identify the remains of the star forming events and accretion events which built up the Galactic disk and bulge

Comments on the Chemical Evolution of the disk of the Milky Way

The age-metallicity relation in the solar neighborhood is still uncertain



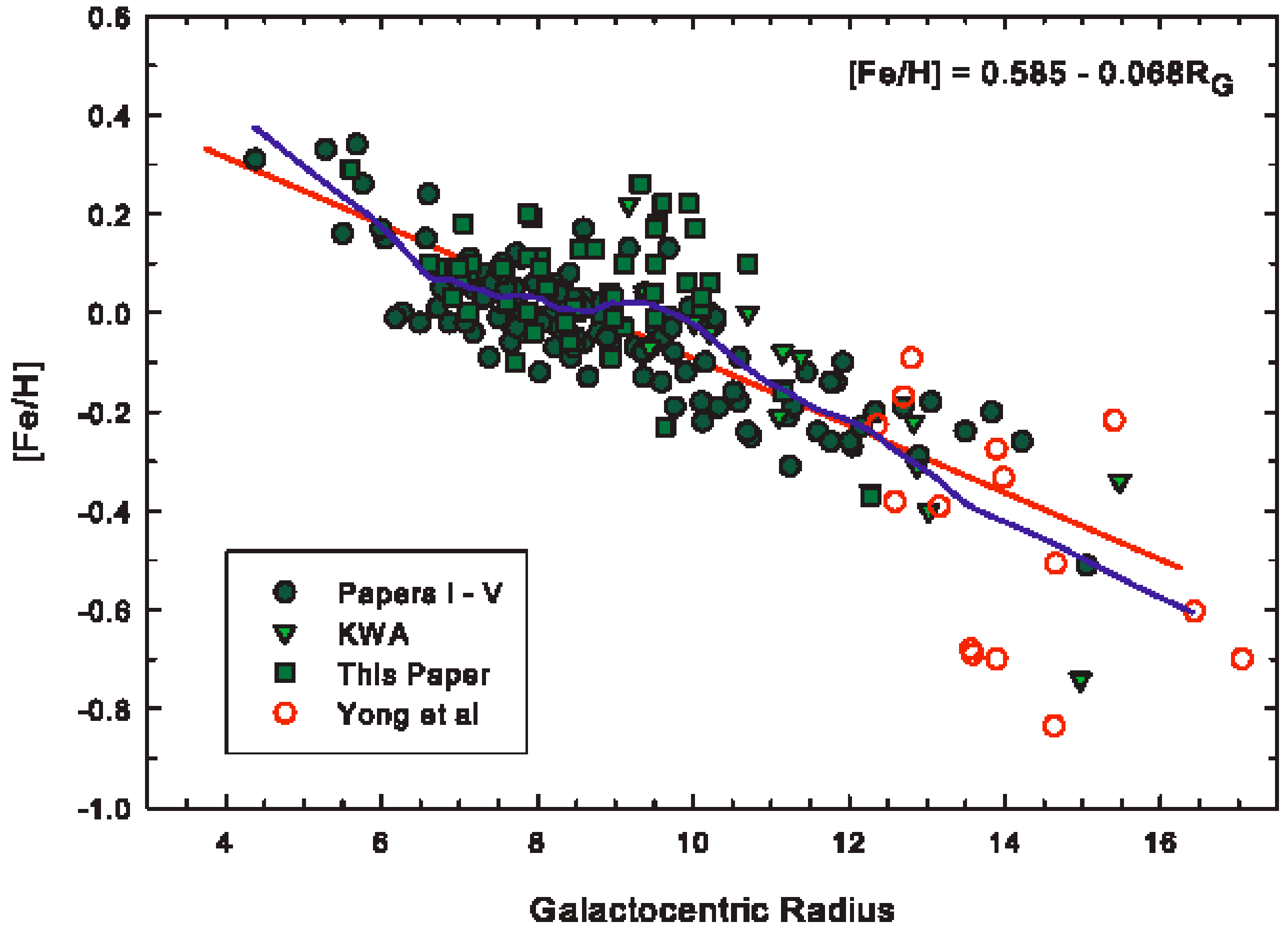
Estimating ages for field stars is difficult

Edvardsson et al 1993
Nordstrom et al 2004
Valenti & Fisher 2005

(Reid et al 07)

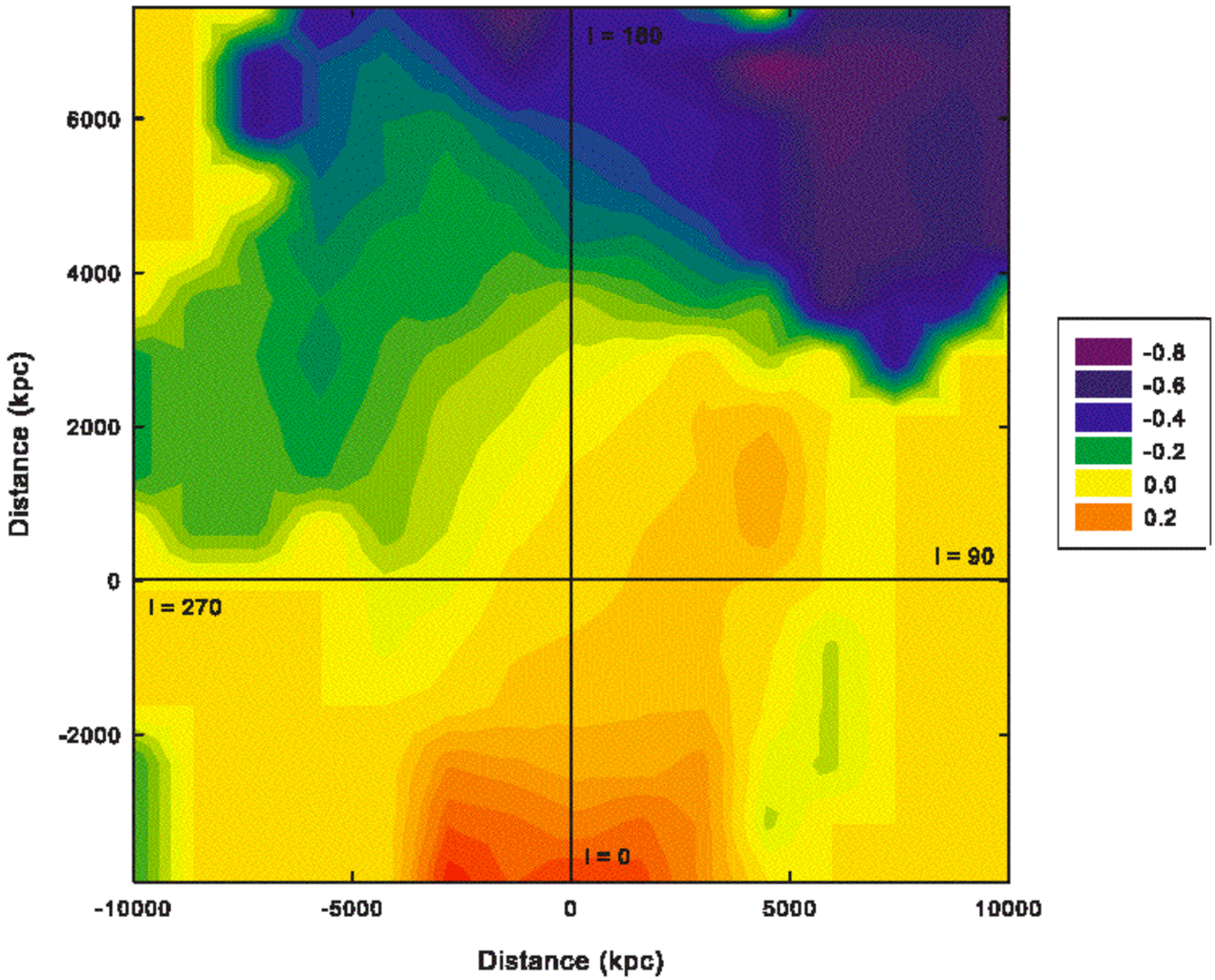
The galactic disk shows an abundance gradient

(eg galactic cepheids: Luck et al 2006) ....



but it is not a simple axisymmetric gradient

(Luck et al 2006: cepheids)

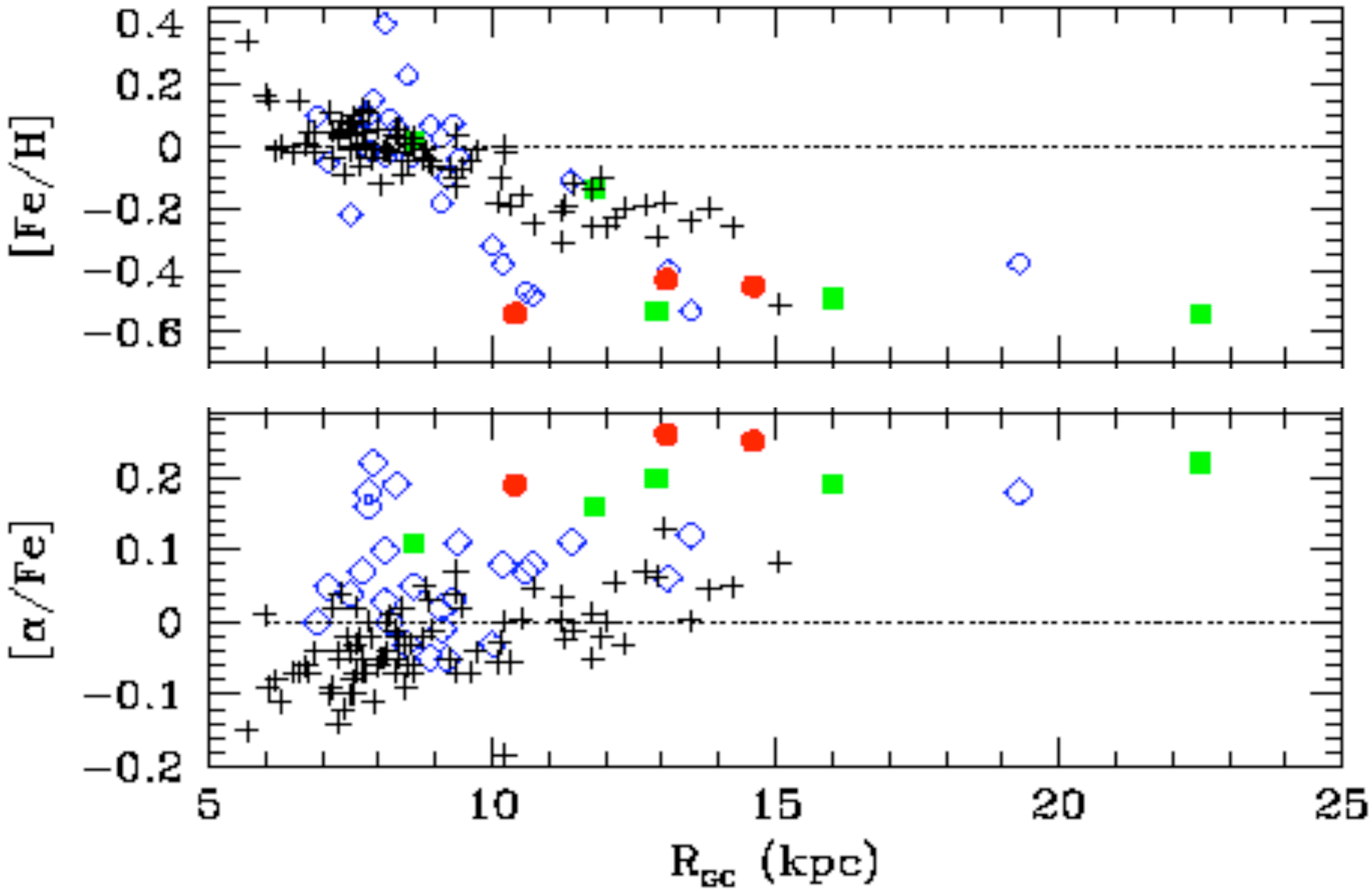


The abundance gradient is seen also for older star clusters
Yong & Carney 2005; Carney & Yong 2005

For the clusters (ages 1 to 5 Gyr) the abundance gradient bottoms out at $R_G = 12$ kpc ($R_G = 15$ kpc in M31), and at an abundance of [Fe/H] = -0.5 (as in M31).

Old stars in the outer disk are α-enhanced, with unusual α- abundance patterns : $[\alpha/Fe] = + 0.2$, indicating fairly rapid star formation history in the outer disk (unlike the solar neighborhood). Also s-process enhancements.

Star formation in the outer disk may have been merger-induced or come from accreted gas with chemical evolution history different from inner disk

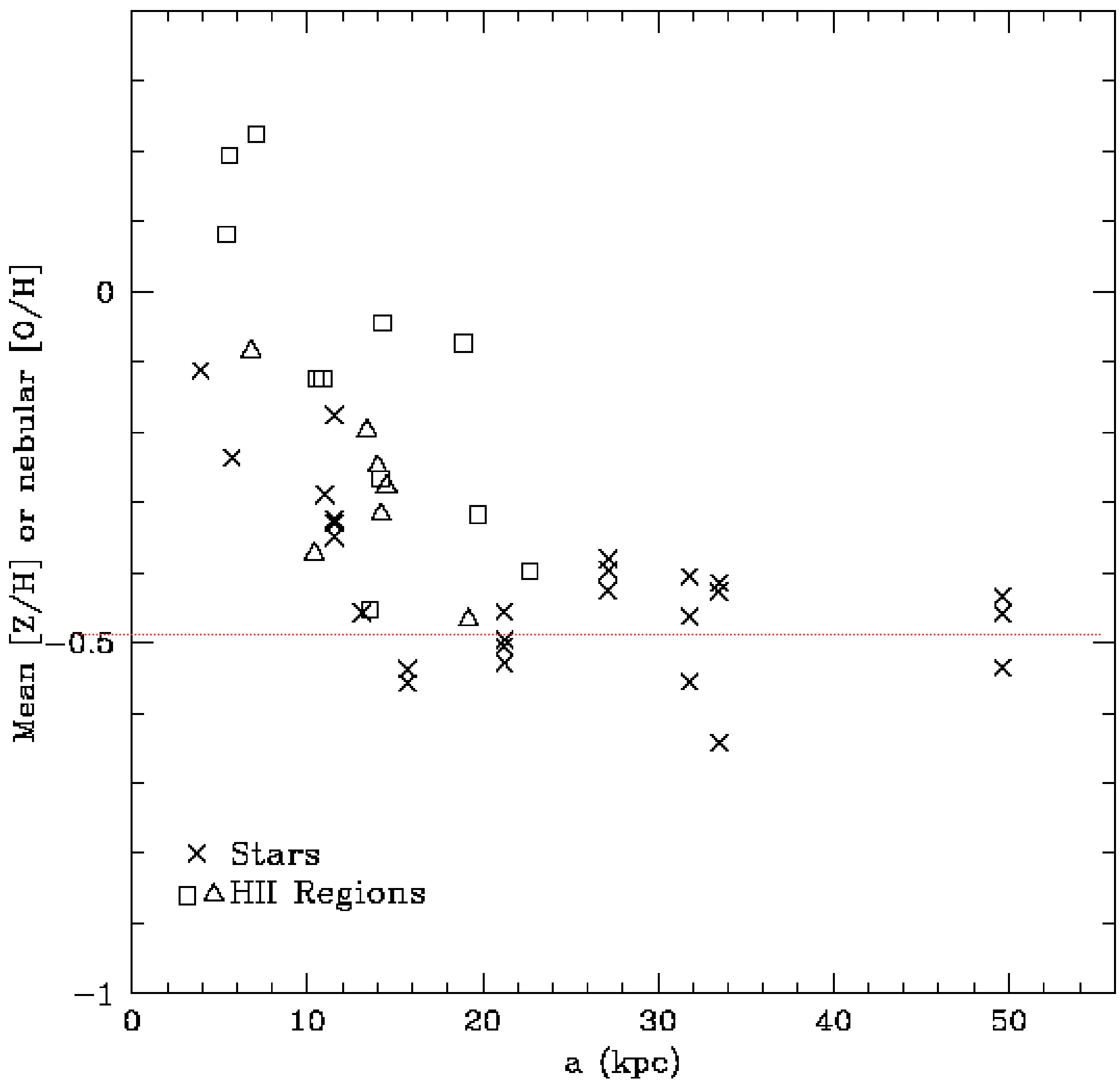


+ cepheids, other symbols are open clusters in the Galaxy.

Clusters have ages 1-5 Gyr, cepheids are younger

The abundance gradient and [α/Fe]-gradient in the disk has flattened with time, tending towards solar values.

Carney & Yong 2005



M31

Metallicity gradient in outer regions of M31 also bottoms out, as in the Milky Way

Worthey et al 2004

Kinematical substructure in the disk of the Milky Way

Galactic halo shows kinematical substructure - believed to be the remains of accreted objects that built up the halo

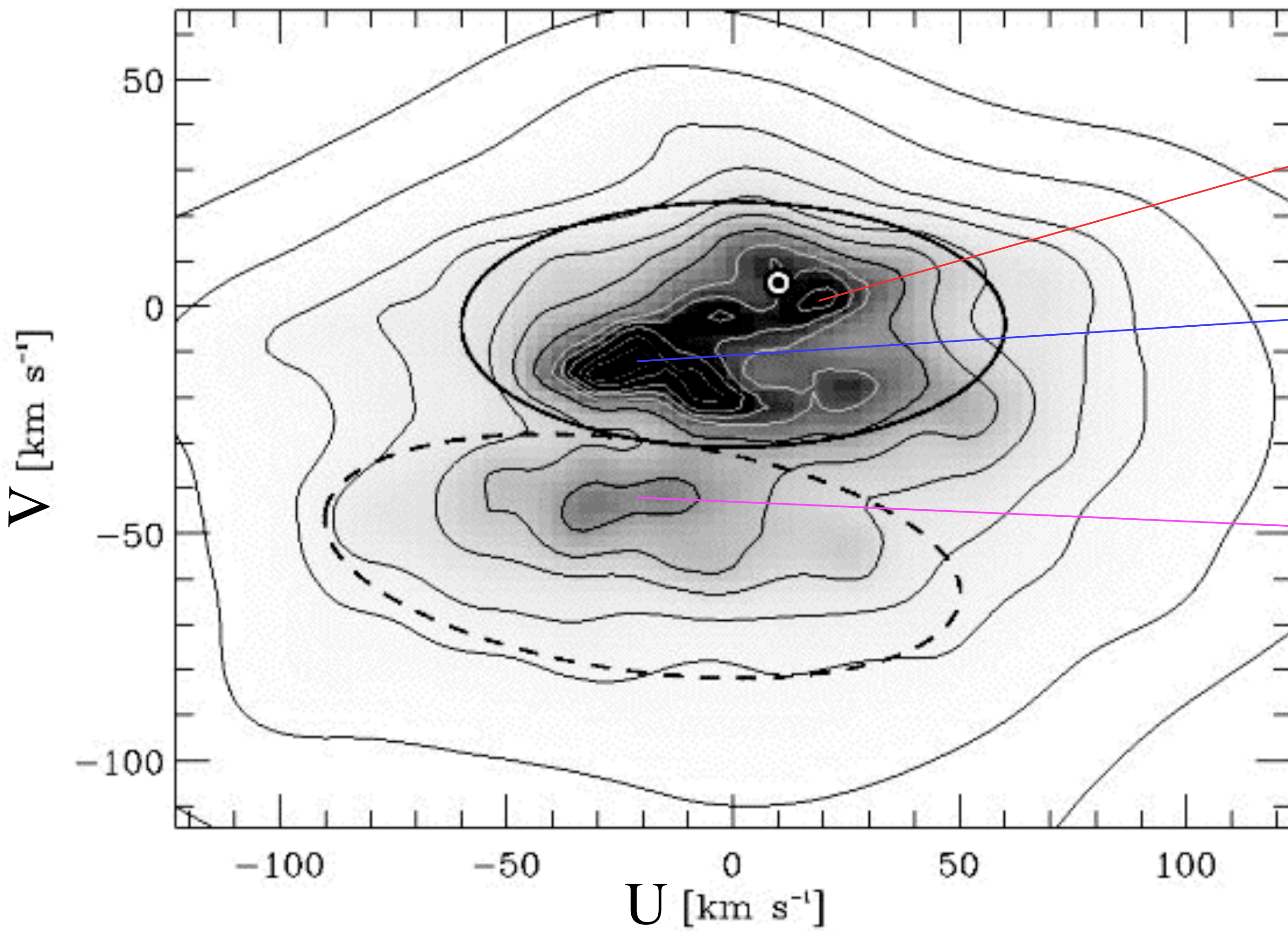
The galactic disk also shows kinematical substructure : usually called moving stellar groups. The stars of the moving groups are all around us

- Some are associated with dynamical resonances (bar) or spiral structure (eg Hercules moving group)

- Some are debris of star-forming aggregates in the disk (eg the HR1614 moving group), dispersed into extended regions of the Galaxy

- Others may be debris of infalling objects, as seen in ΛCDM simulations (eg Arcturus moving group)

The Hercules group is associated with local resonant kinematic disturbances by the inner bar : OLR is near solar radius (Hipparcos data) : Dehnen (1999), Fux (2001), Feast (2002)

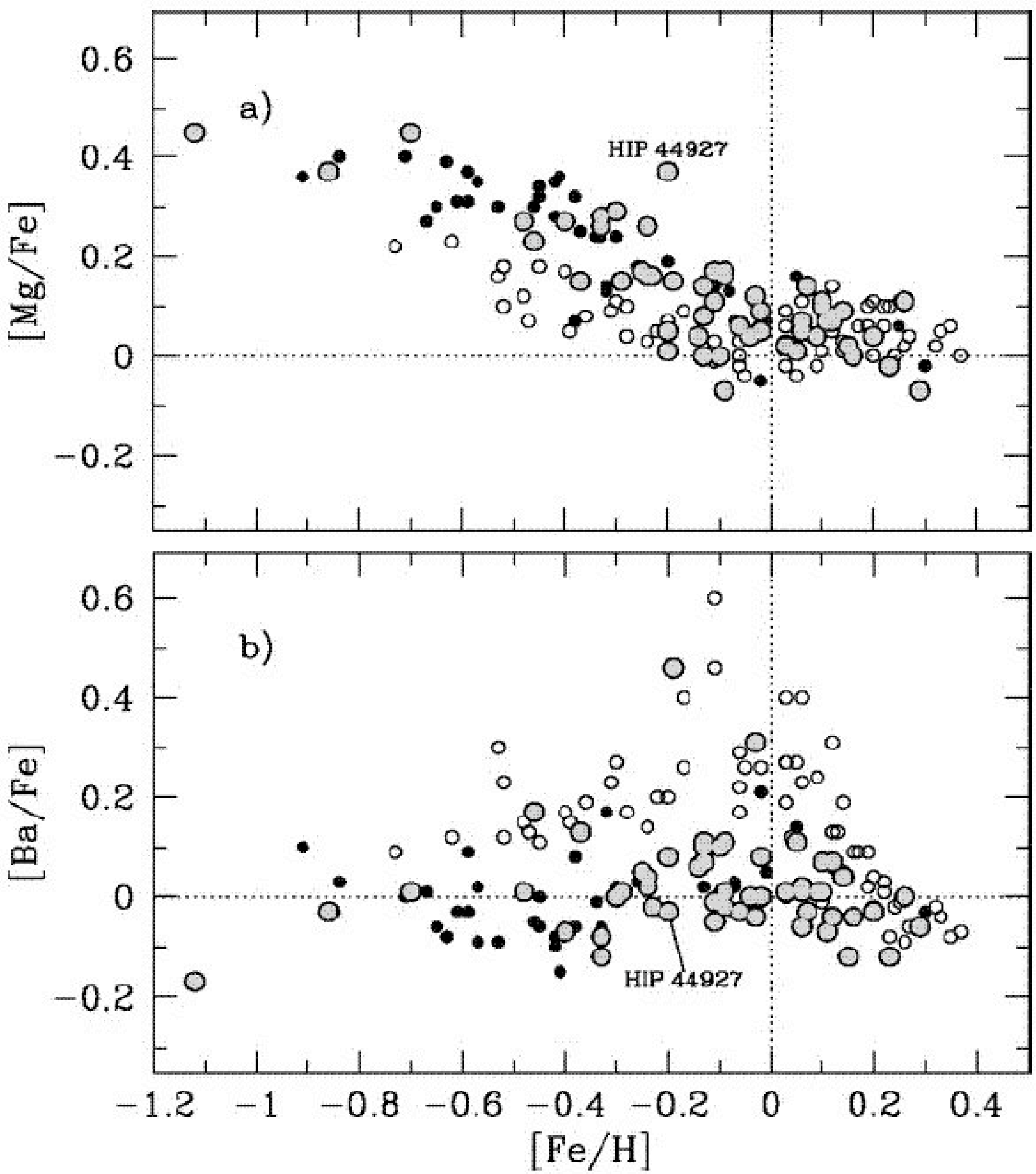


Sirius and Hyades streams - mainly earlier-type stars

Hercules disturbance from OLR -mainly later-type stars

(U,V are relative to the LSR)

Dehnen 1999



Hercules group

• o field stars

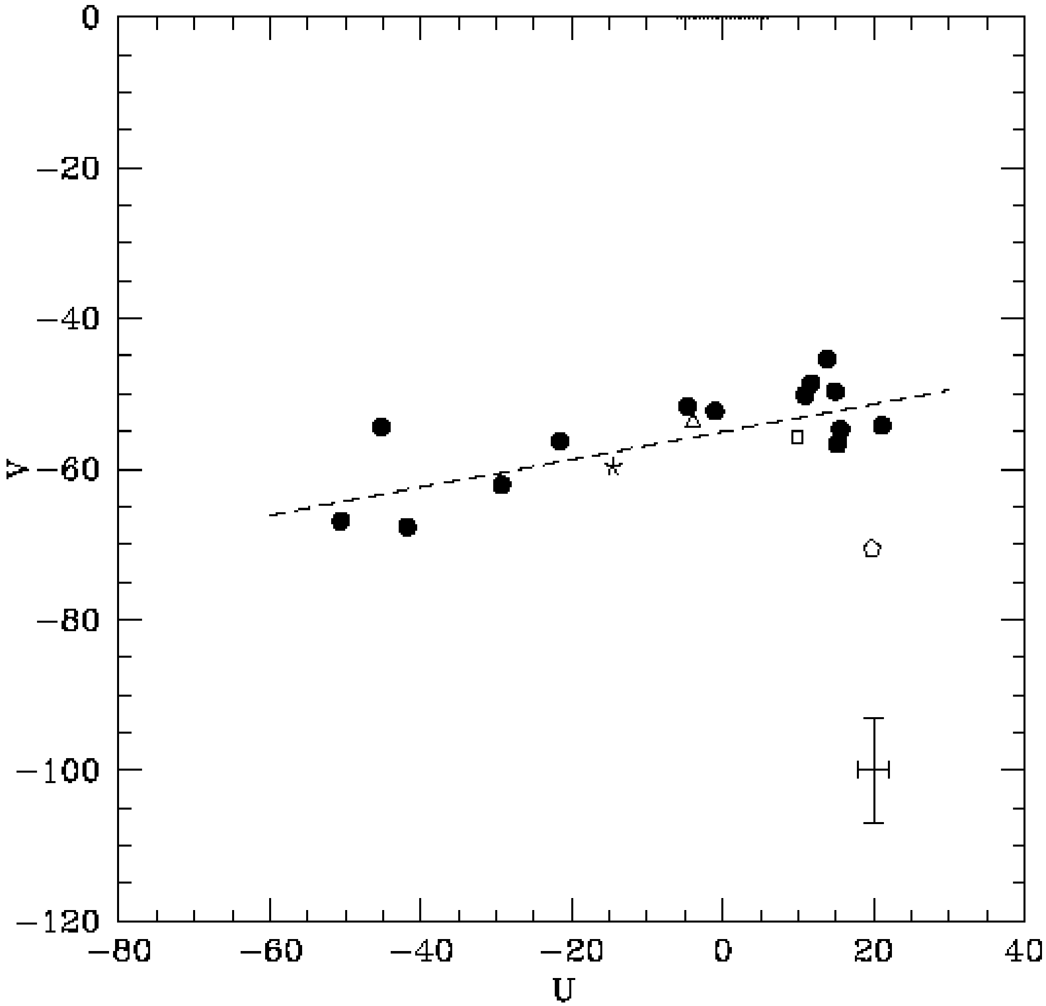
The abundances of Hercules Group stars cannot be distinguished from the field stars. This is a dynamical group, not the relic of a star forming event.

Bensby et al 2007

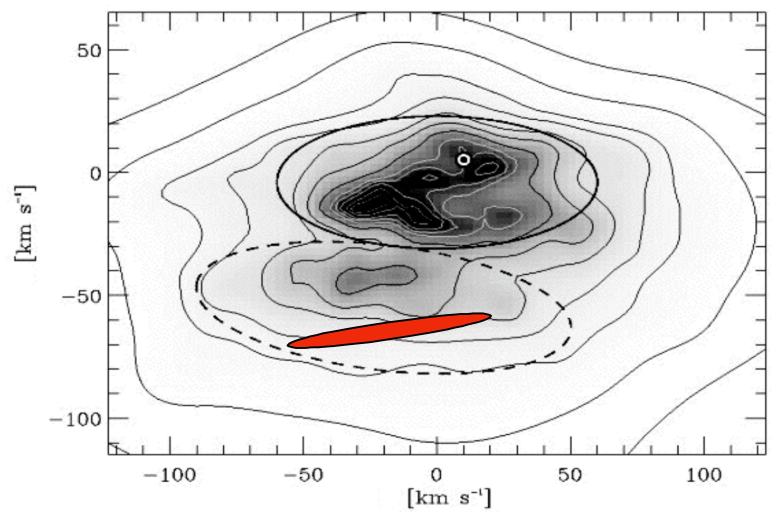
Now look at the HR1614 group (age ~ 2 Gyr, [Fe/H] = +0.2). Studied by Feltzing & Holmberg (2000) who argued for its reality as a relic group.

De Silva et al (2007) measured very precise chemical abundances for many elements in HR1614 stars, and finds a very small spread in abundances. (The stars of this group are all around us)

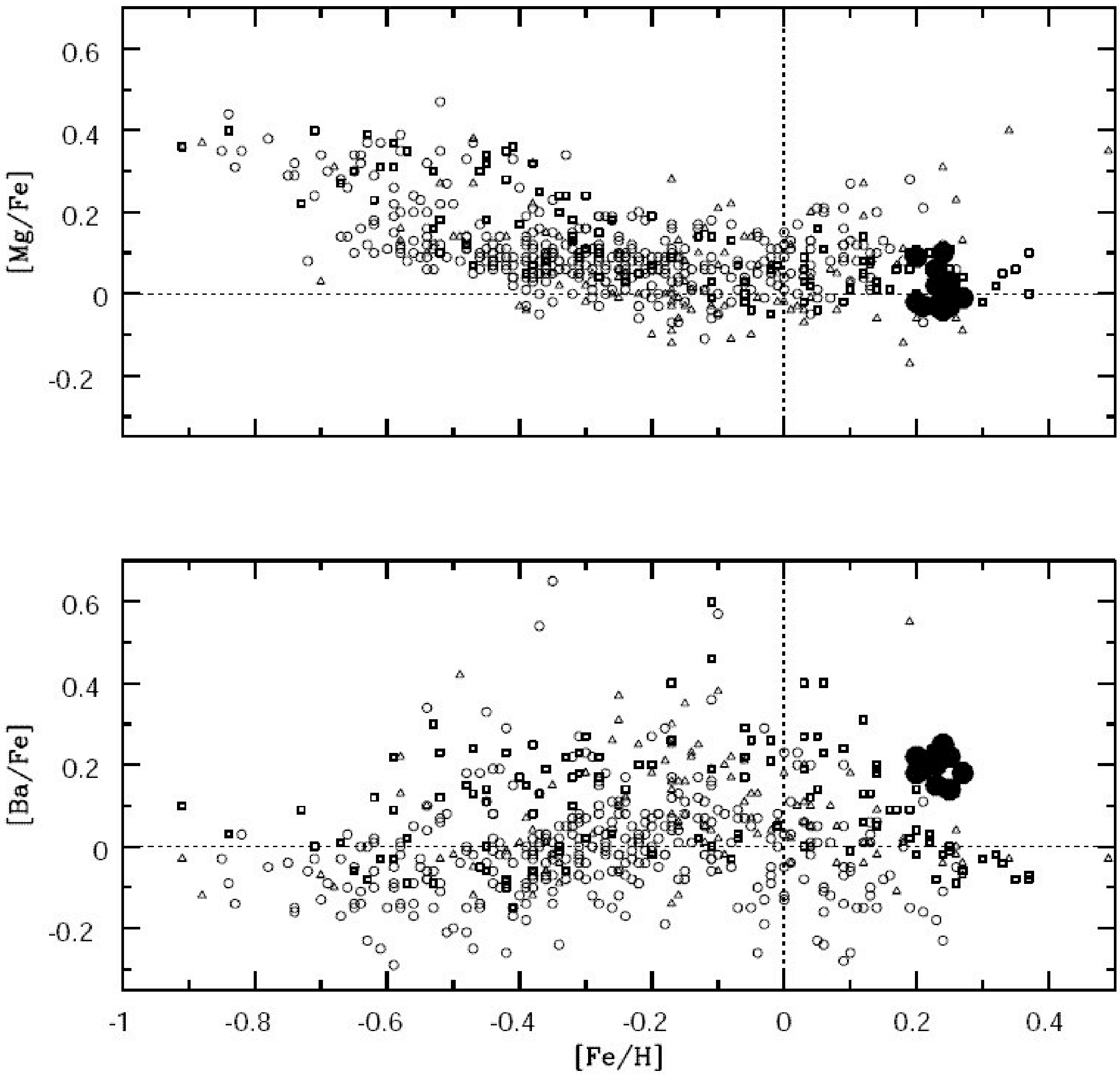
HR1614 moving group stars: the (U,V) plane



The small tilt is expected because epicyclic theory is not valid for these larger V-values.



De Silva et al 2007

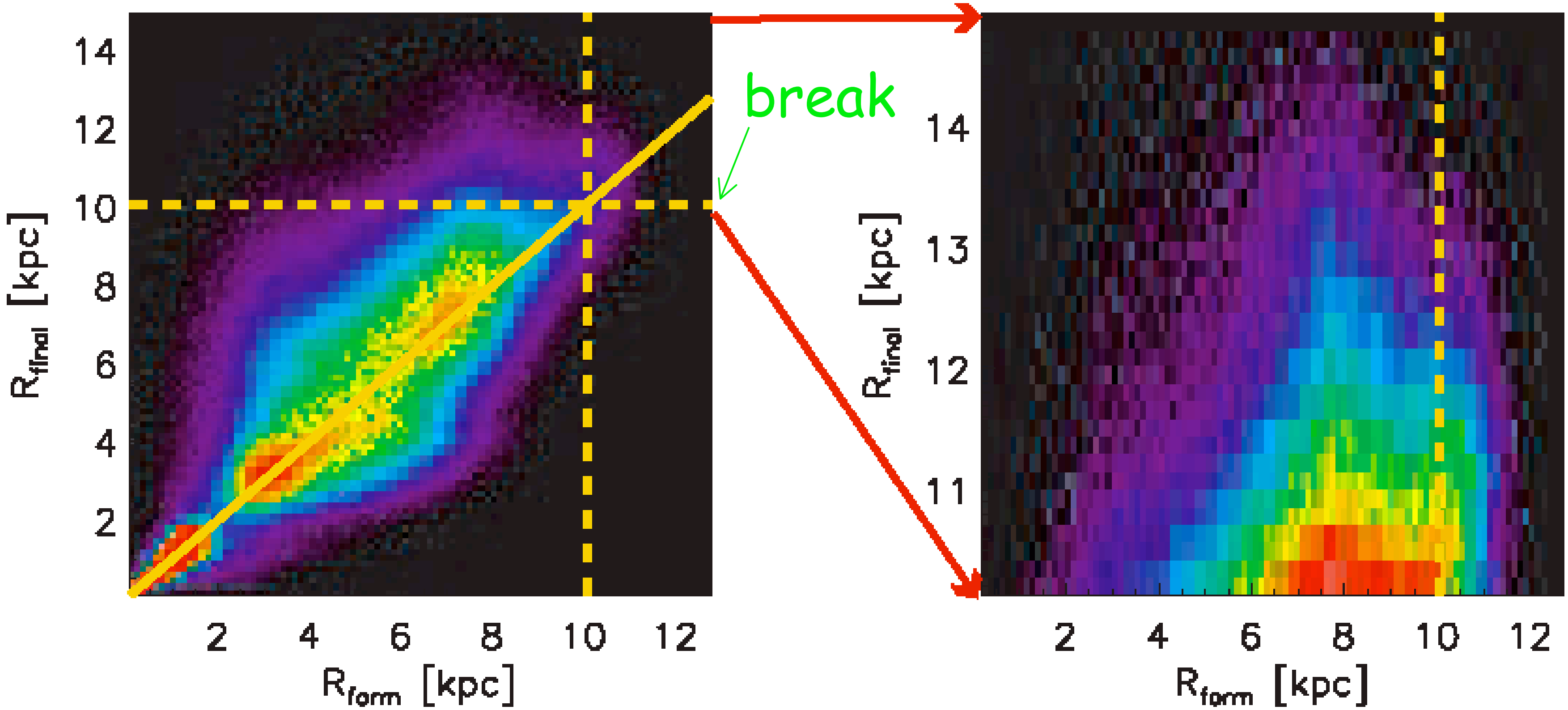


• HR 1614
o field stars

The HR 1614 stars (age 2 Gyr) are chemically homogeneous. They are probably the dispersed relic of an old star forming event.

De Silva et al 2007

Although the disk does show some surviving
kinematic substructure
in the form of moving stellar groups,
a lot of dynamical information was lost
in the dissipation that led to disk formation
and the subsequent heating and orbit swapping
by spiral arms and giant molecular clouds.



Secular radial distribution of stars via spiral arm interaction into outer (break) region of truncated disk. Stars move between near-circular orbits of different radii.

Roskar et al (2008)

Also, resonances generate kinematic substructures like Hercules and probably Arcturus (Mary Williams thesis) which are not associated with star-forming aggregates.

- **Many dispersed aggregates will not be recognizable dynamically**
- **Many dynamical structures are not dispersed aggregates**

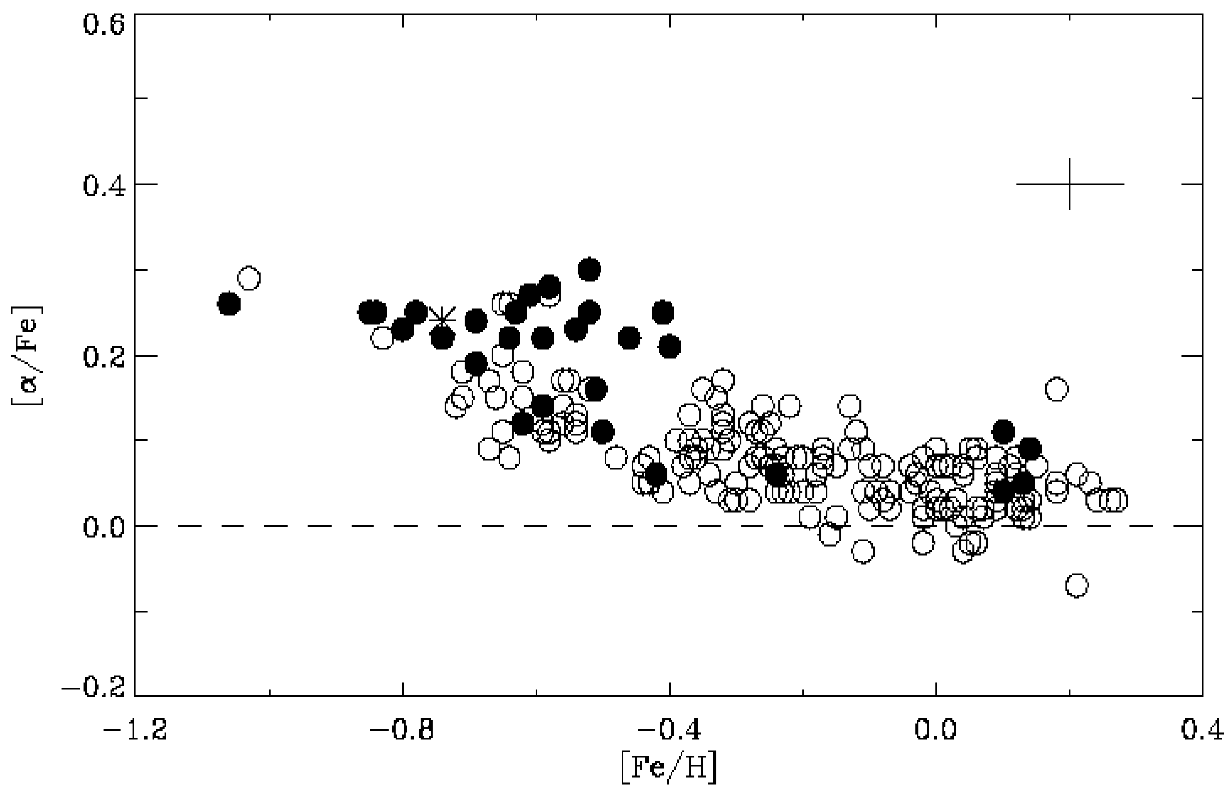
However ... we are not restricted to dynamical techniques. Much fossil information is locked up in the detailed distribution of chemical elements in stars.

The thick disk is particularly interesting ...

The galactic thick disk

- its mass is about 10% of the thin disk's
- it is significantly more metal poor than the thin disk:
  - 0.5 > [Fe/H] > - 2.2 and α-enhanced (formed rapidly)
- its stars are very old (> 10 Gyr)

P. E. Nissen



● thick disk
○ thin disk

higher [α/Fe] $\Rightarrow$
more rapid formation

The Galactic thick disk is believed to arise from
heating of the early stellar disk
by accretion events or minor mergers.

If this is correct, the thick disk presents a
'snap-frozen' relic of the (heated) early disk,
so it may be one of the most significant components
for studying signatures of galaxy formation

(Secular heating by spiral arms etc
does not affect its dynamics significantly,
because its stars spend most of their time
away from the galactic plane)

We would like to reconstruct the ancient star-forming aggregates of the thick disk: phase mixing has dispersed them azimuthally right around the Galaxy

Structurally invisible; may also be invisible in velocity space and integral space but, if they were initially homogeneous chemically, we can recognize them by <u>their chemical properties.</u>

For chemical tagging to work, need a few conditions:

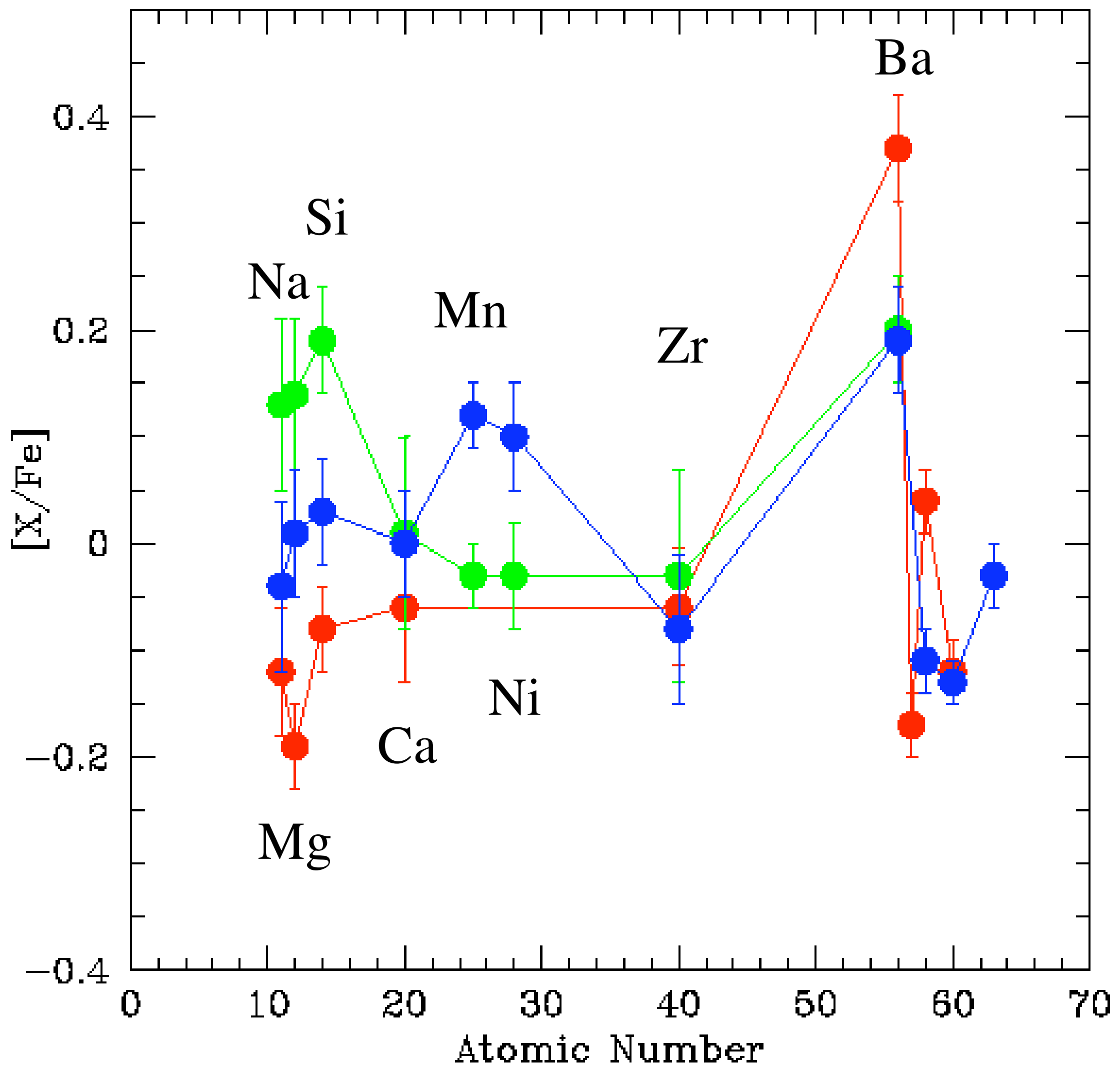
- stars form in large aggregates - believed to be true
- aggregates are chemically homogenous
- aggregates have unique chemical signatures defined by several elements which do not vary in lockstep from one aggregate to another. Need sufficient spread in abundances from aggregate to aggregate so that chemical signatures can be distinguished with accuracy achievable (~0.05 dex differentially)

Testing the last two conditions were the goals of Gayandhi de Silva's thesis on open clusters: they appear to be true

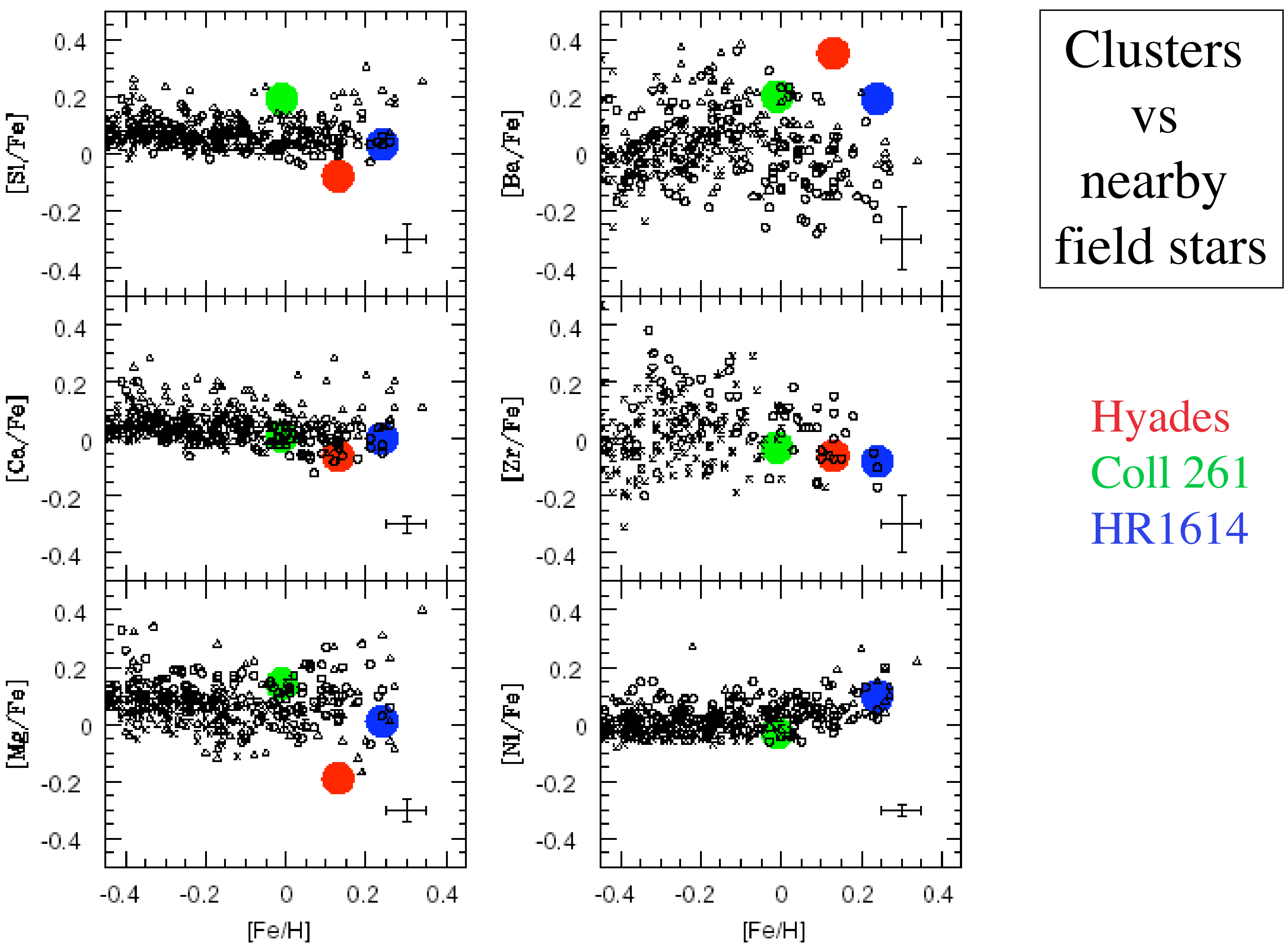
She found that the Hyades and Coll 261 were each chemically homogenous (but different) at the 0.05 dex level over a wide range of Fe-peak and n-capture elements (de Silva et al 2006, 2007)

She also studied the HR1614 moving stellar group. This is a moving group in the disk (age ~ 2 Gyr, [Fe/H] = +0.2). This group shows a very small spread in abundances (de Silva et al 2007) at the 0.05 dex level - encouraging for viability of chemical tagging

Cluster abundance patterns



Hyades
Coll 261
HR1614


[Si/Fe]
[Ba/Fe]
[Ca/Fe]
[Zr/Fe]
[Mg/Fe]
[Ni/Fe]
0.4
0.2
0
-0.2
-0.4
[Fe/H]
Clusters
vs
nearby
field stars
Hyades
Coll 261
HR1614

Chemical Tagging

Use the detailed chemical abundances of thick disk stars ([Fe/H], [α/Fe], r- and s- process elements) to tag them to common ancient star-forming aggregates with similar abundance patterns (eg Freeman & Bland-Hawthorn ARAA 2002)

The detailed abundance pattern reflects the chemical evolution of the gas from which the aggregate formed.

Different supernovae provide different yields (depending on mass, metallicity, detonation details, ejected mass ...) leading to scatter in detailed abundances, especially at lower metallicities (enrichment by only a few SN)

Reconstructing ancient stellar aggregates

Can we reconstruct ancient dispersed stellar aggregates from their chemical abundance patterns ?

Primary requirements:

- most stars are born in large aggregates √
- many elements must reflect progenitor cloud abundances, (i.e. unaffected by stellar evolution) √
- most stars within an aggregate must have similar abundance distributions for a set of elements (test on old open clusters) √
- all elements must **not** vary in lock-step √

How many distinct star formation sites might there have been for the thick disk (~ 2×10^9 $M_\odot$ within our observational horizon) ?

Stars form in large aggregates, say 10^5 $M_\odot$
Expect about 2×10^4 dispersed aggregates in the thick disk, each with their own chemical signature

- Can we detect ~ 2×10^4 different thick disk sites using chemical tagging techniques ?

Yes: we would need ~ 7 independent chemical elements each with 4 measurable abundance levels to get enough independent cells (4^7) in chemical abundance space.

- Are there 7 independent elements or element groups ?

Yes: from De Silva's cluster study ....

light elements (Na,Al)
Mg
other alpha-elements (O) Ca, Si, Ti
Fe and Fe-peak elements
light s-process elements (Sr, Zr)
heavy s-process elements (Ba)
r-process (Eu)

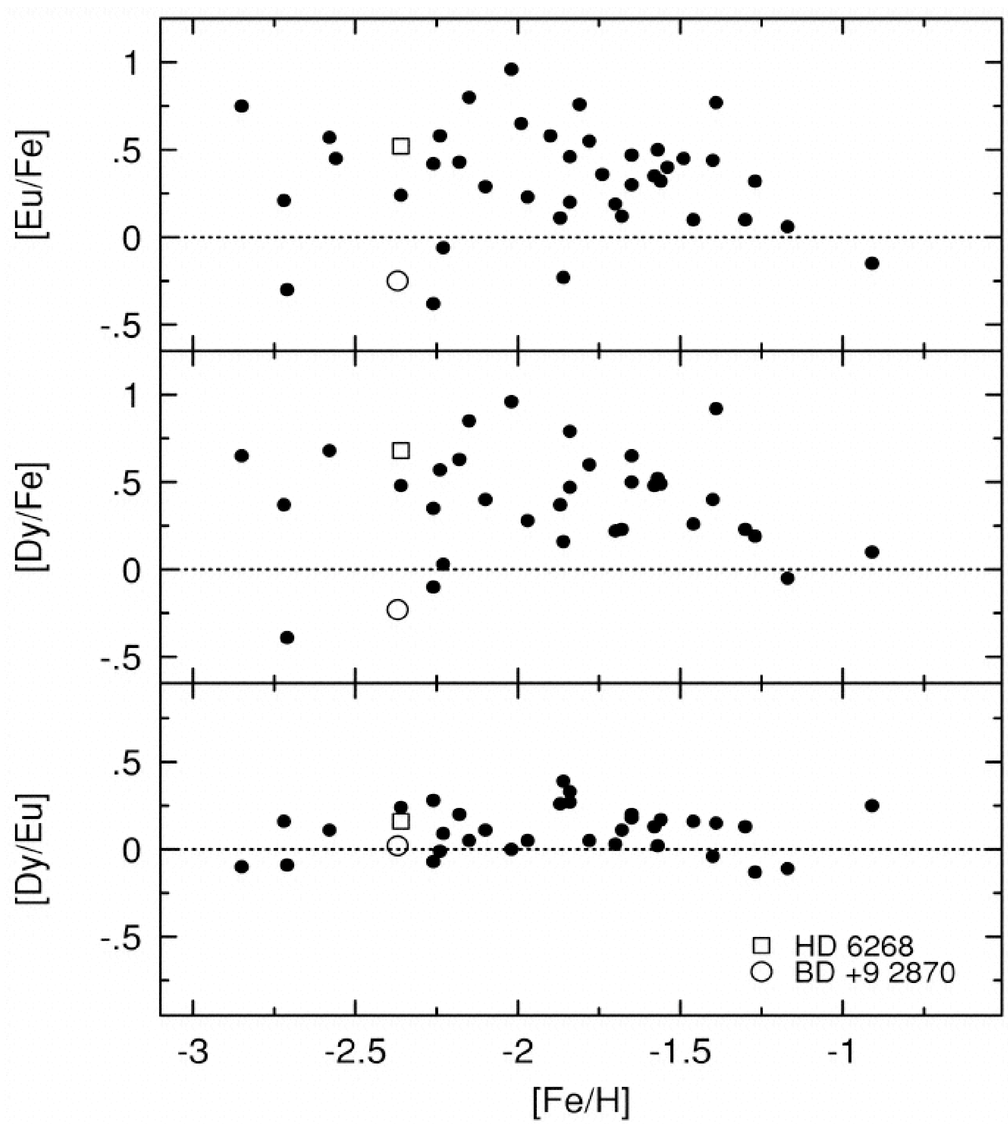
Potential show stopper

- heavy element production varies in lockstep from site to site

Already seen independent behaviour of different elements among the open clusters

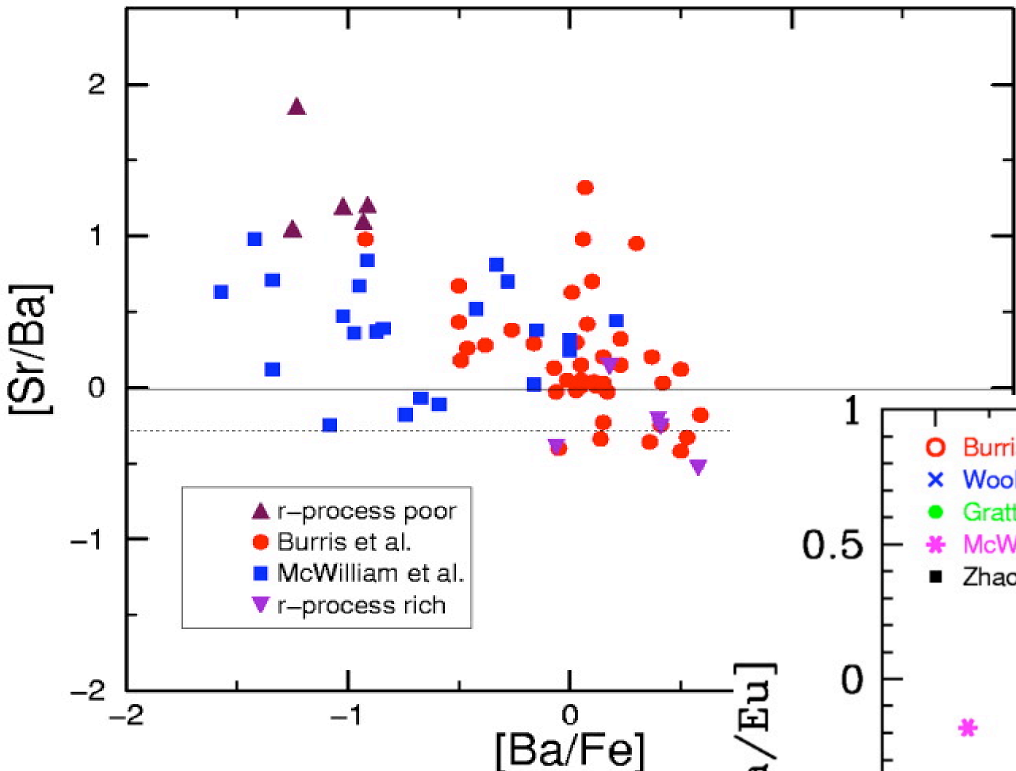
heavy element production varies in lockstep from site to site

some elements
do correlate ...
eg Eu,Dy -
both r-process

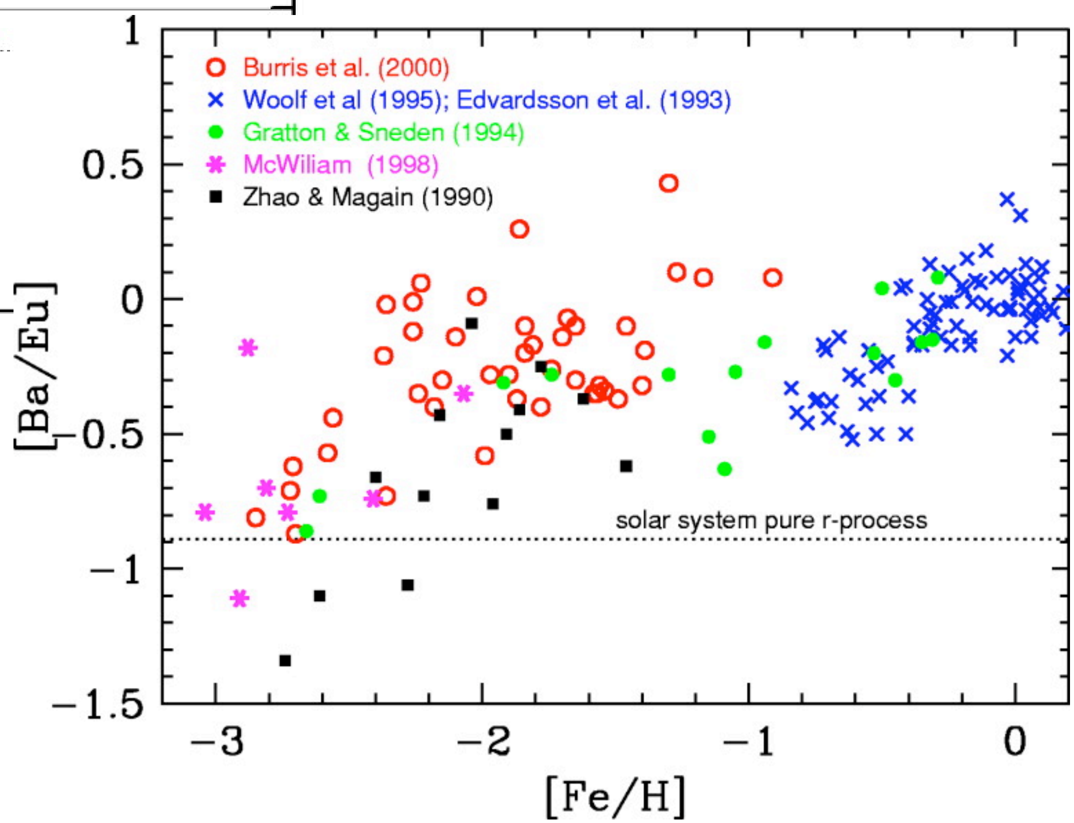


Burris et al (2000)

… but many heavy elements (e.g. Sr, Ba) do not correlate

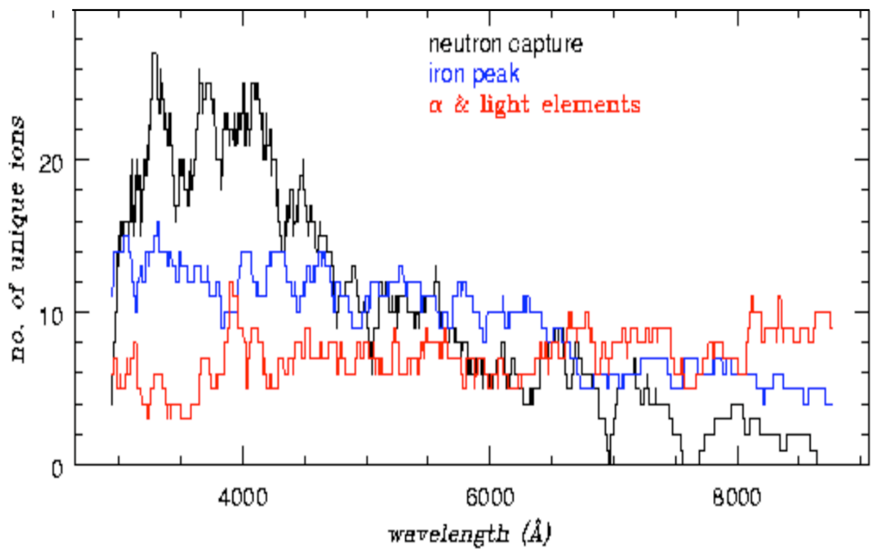


and Ba,Eu

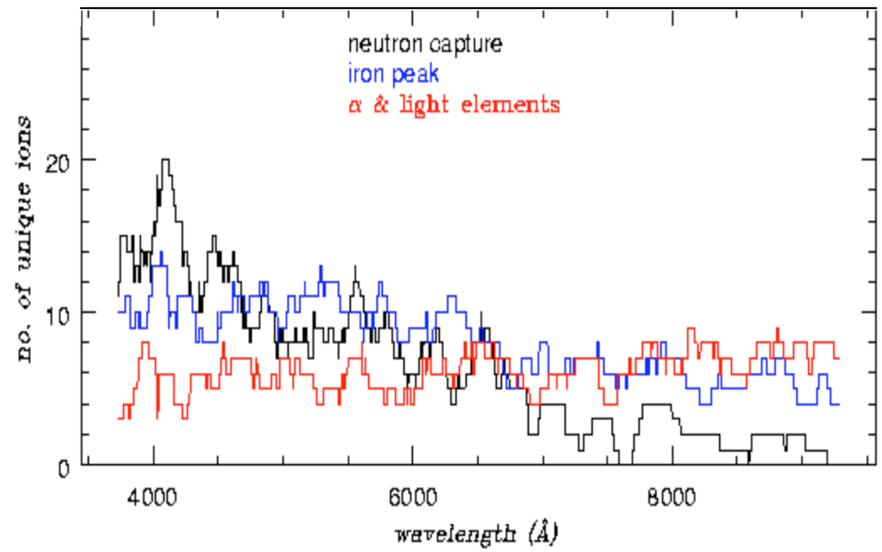


Where is most of the chemical information ?

Sun

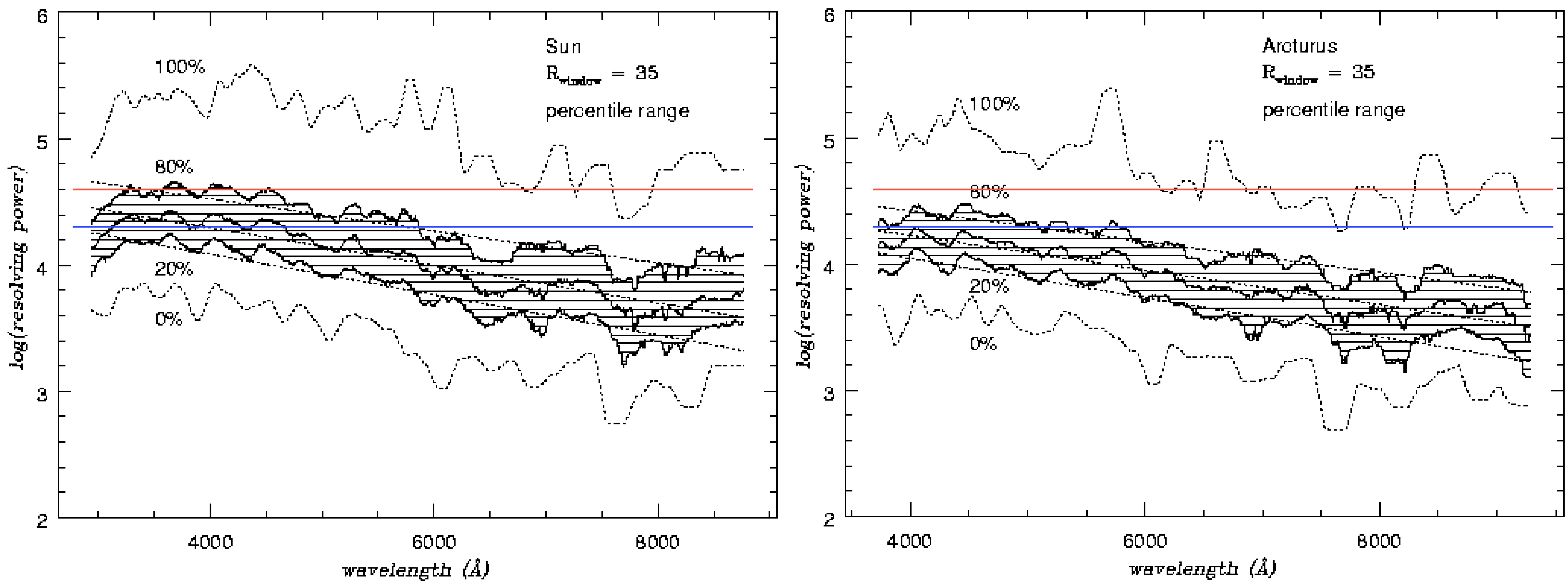


Arcturus (giant, [Fe/H] ~ -0.6)



Rolling window $\Delta\lambda = \lambda/35$ e.g single echelle order

Effect of resolving power on fraction of resolved lines



R = 40,000

R = 20,000

A model survey: assume 1500 high resolution fibers in a 1.5 deg field; V = 17, SNR = 100 per res, 4 hours

At V = 17, the typical stellar density at |b| ~ 30^o is about 1000 stars per square degree, matching the instrument

Fractional contribution from galactic components

	Dwarf	Giant
Thin disk	0.80	0.005
Thick disk	0.10	0.05
Halo	0.01	0.02

Disk dwarfs are seen out to distances of about	3 kpc
Disk giants	40
Halo giants	60

Searching for progenitor formation sites

How many stars are needed ?

Adopt 10^5 $M_\odot$ as the mass of the basic disk star-forming aggregate

About half of the thick disk stars pass through our 3 kpc dwarf horizon
Assume that all of their formation aggregates are azimuthally mixed right around the Galaxy, so all of these formation sites are represented within our horizon

For the halo, most of theWFMOS stars are giants (visible out to 60 kpc), so we sample most of the volume of the halo

Simulations (JBH&KF 2004) show that a random sample of 10^6 stars with $V < 17$ would allow detection of about

20 thick disk dwarfs from each of about 500 star formation sites
30 halo giants from each of about 100 star formation sites

* *A smaller survey means less stars from a similar number of sites*

Also get a large number of thin disk dwarfs to map the kinematical and chemical transition between thin and thick disk.

Chemical tagging *may* also be possible for the thin disk stars, using elements which show some scatter in their [X/Fe]-[Fe/H] correlations: eg K, S, Sc, Sr, Y , Ba, Ce, Nd, Eu (eg Reddy et al 2003).
May be able to detect about 20 stars in each of about 5000 sites

Possible high resolution program - chemical tagging

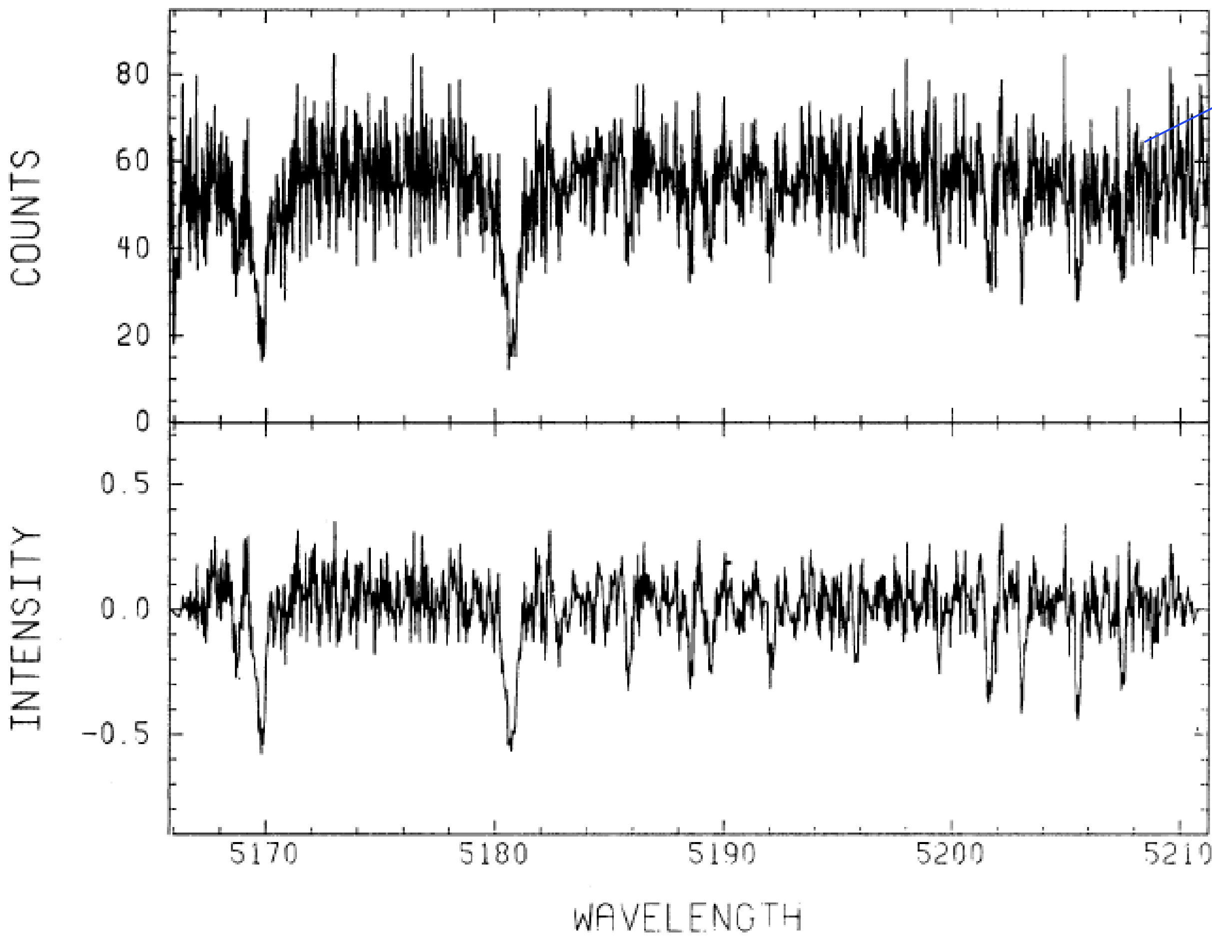
(1500 stars per field) x (1000 fields)
Integrations ~ 4 hours : two fields per night
500 clear nights using 1500 fibers: rest available for parallel programs

This is just an order of magnitude indication of the likely scope of a chemical tagging program to identify ancient galactic substructure

All aspects of such programs need proper modelling:

- numbers of stars
- region of the Galaxy
- magnitude and color range

So far, considered only high SNR (~ 100) science with WFMOS reaching to V = 17. Interesting opportunities for lower SNR (~ 10) observations which would go much fainter (V ~ 21 in 4^h)



V=21

Carney et al (1987) : R ~ 30,000 spectra with SNR ~ 10 per resolution element give [M/H] estimates with errors of 0.12. Radial velocity errors are < 1 km/s.

WFMOS and GAIA

GAIA (~ 2015) will provide precision astrometry for about 10^9 stars

For $V = 17$, $\sigma_\pi = 25$ μas, $\sigma_\mu = 20$ μas yr $^{-1}$

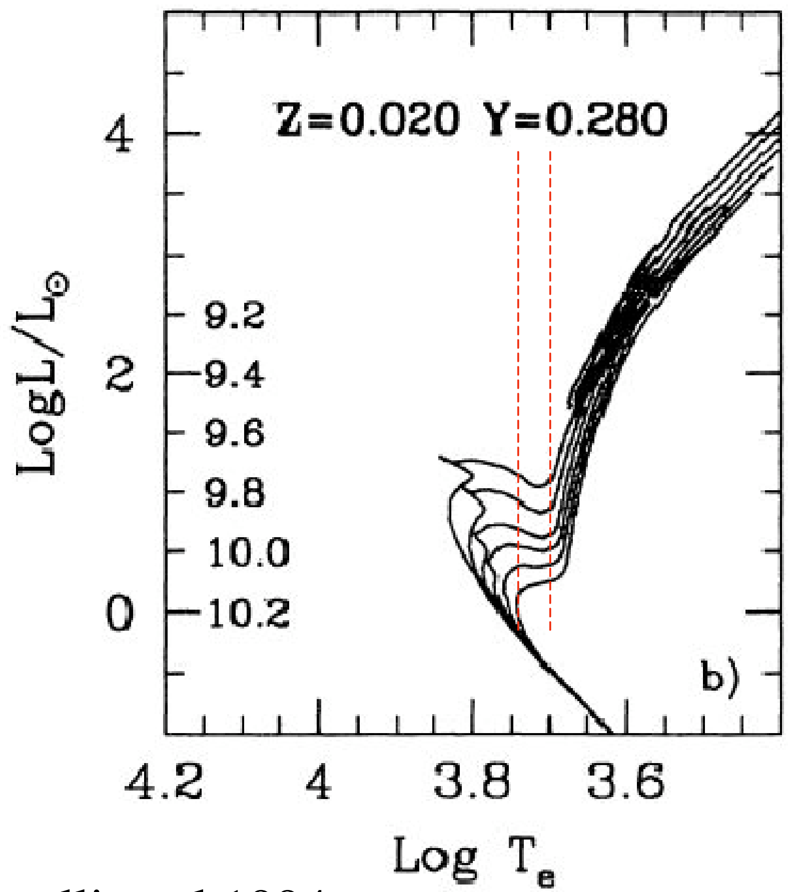
(10% distance errors at 4 kpc, 4 km s $^{-1}$ velocity errors at 40 kpc)

$\Rightarrow$ accurate transverse velocities for all stars in the WFMOS sample, and

$\Rightarrow$ accurate distances for all of the older main sequence stars and subgiants.

WFMOS+ GAIA will give accurate abundances and 3D motions.

- for subgiants in the thin disk, thick disk and halo, abundances and GAIA luminosities give their isochrone ages directly
- subgiants are numerous (about 10% of the sample) and are observable out to about 1 kpc



Bertelli et al 1994