Chemical Abundances in Local Group Dwarf Galaxies and Their Implications for Formation Theories of the Galactic Halo

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Outline

- Motivation
- Observations of Sculptor and IC 1613
- The Problem
- Explaining The Problem
- Solving (?) The Problem

Hierarchical galaxy formation scenario:

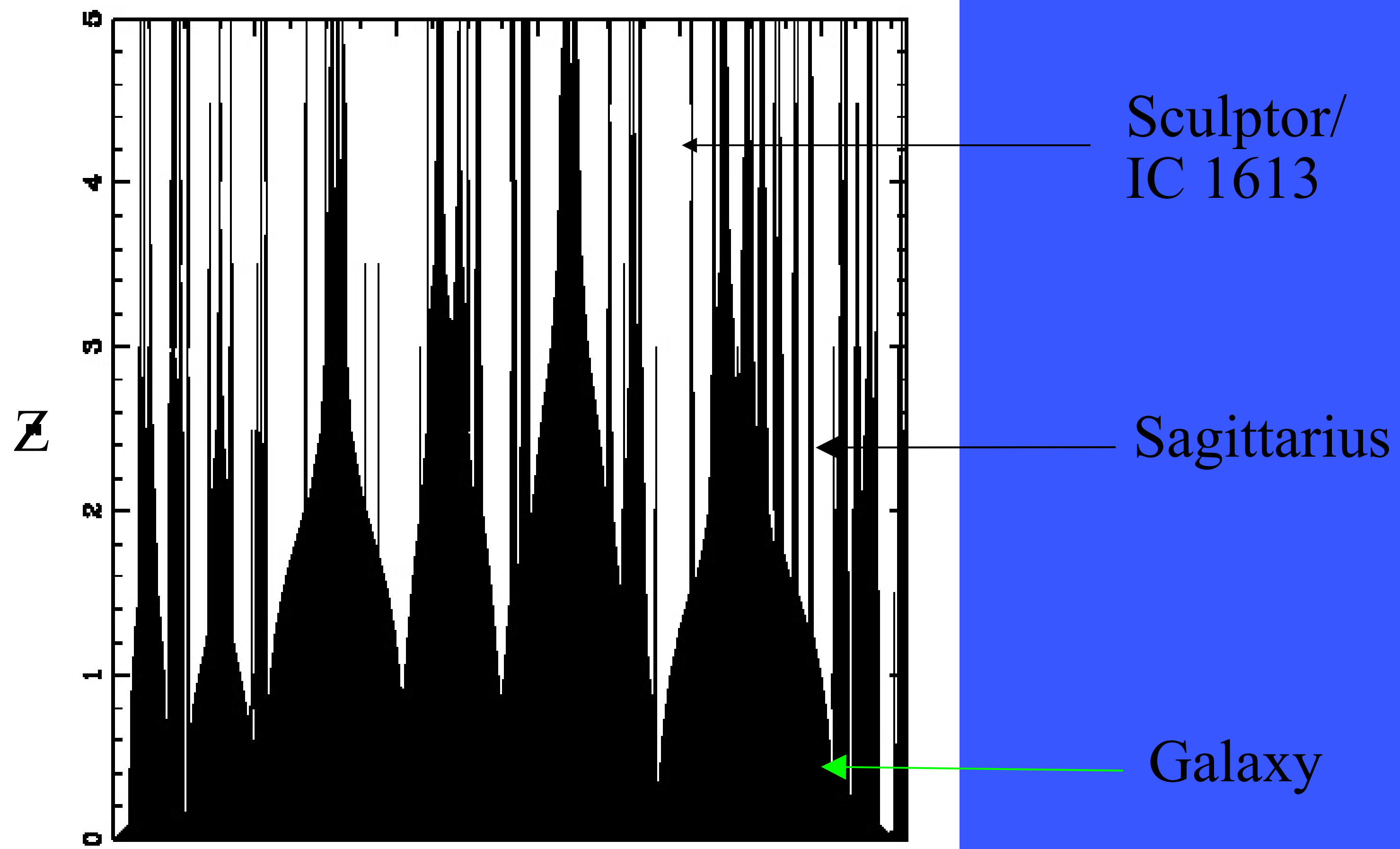
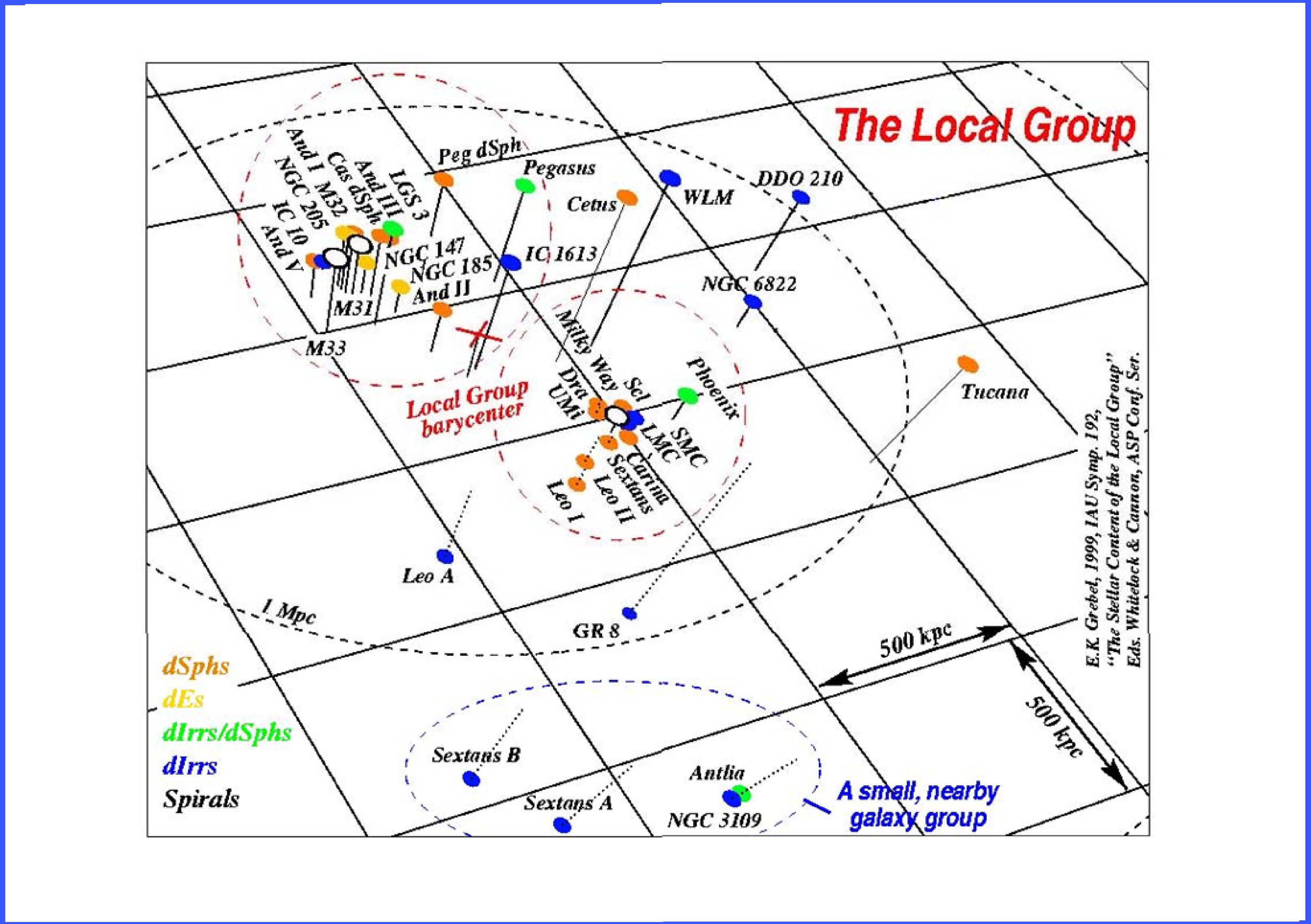


Figure 1. Merger tree for an elliptical galaxy of mass $\sim 2.3 \times 10^{11} M_{\odot}$, beginning at redshift 5, and proceeding up to the present day. The width of the 'branches' reflect mass at a given epoch. The merger tree has been normalized to possess unit width at $z = 0$.

Also Searle and Zinn (1978)



The Milky Way (and M31) are surrounded by 'Sculptors' and further out IC 1613's

Goals:

Why chemistry?

- Compare detailed chemistry of Scl/IC 1613 with Galactic Halo (chemical tagging)
- Reconstruct the chemical history of Sculptor and IC 1613
- Investigate relative contributions of SNeI, II, AGB stars
- Need abundances to constrain the Star Formation history

Why Sculptor (Scl)?

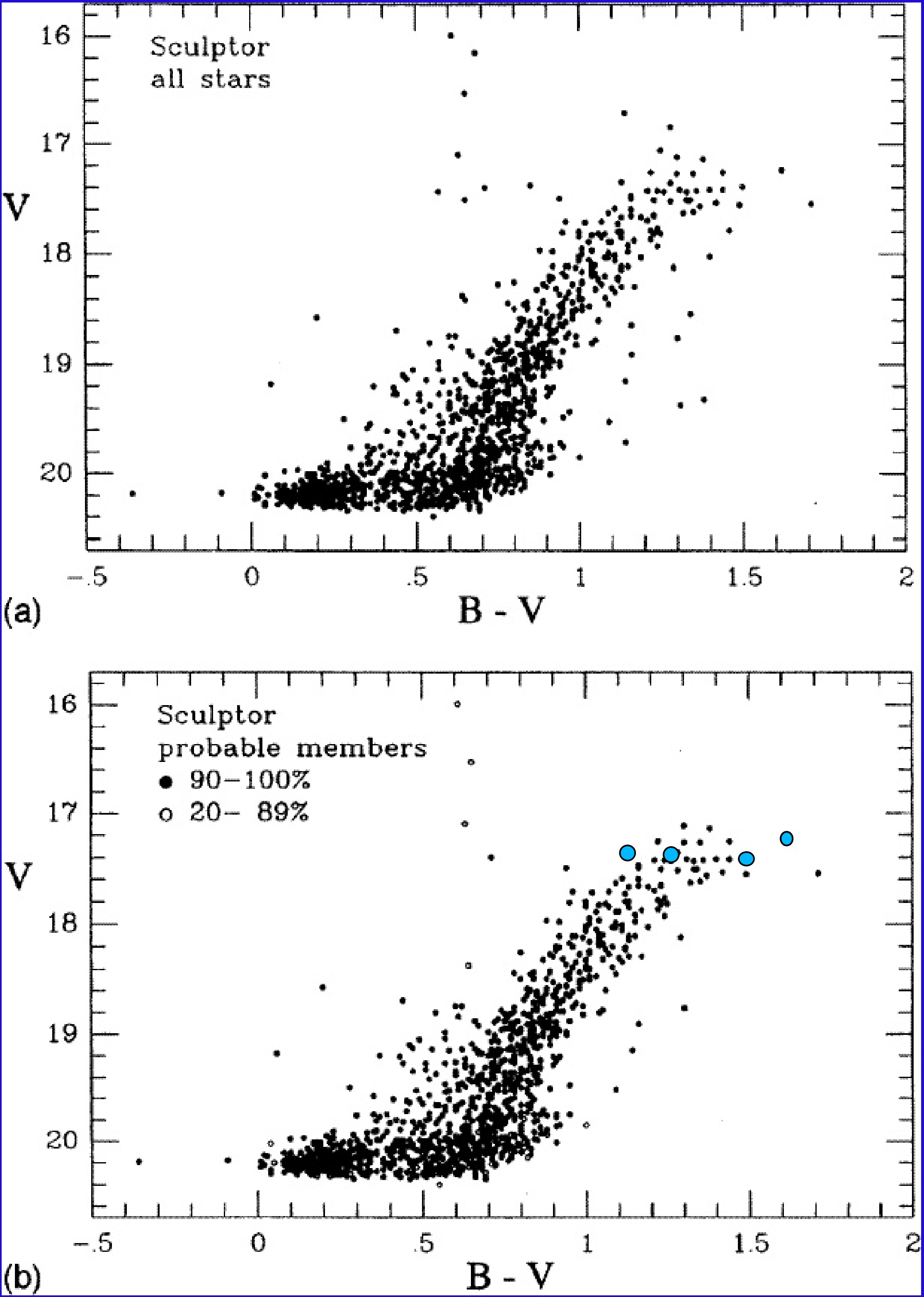
- One of the nearest dwarf spheroidal galaxies (dSphs)
- Not yet studied with high resolution spectra
- Representative of the most numerous type of galaxy
- Nearby analog to faint blue galaxies and/or damped Ly α gals.
- Like Halo - mostly very old (>10 Gyr) and metal-poor (~-1.5)

Why IC 1613?

- One of the nearest dwarf irregular (dIrr) galaxies
- Not yet studied with high resolution spectra
- Representative of a very numerous type of galaxy
- Very (?) metal-poor

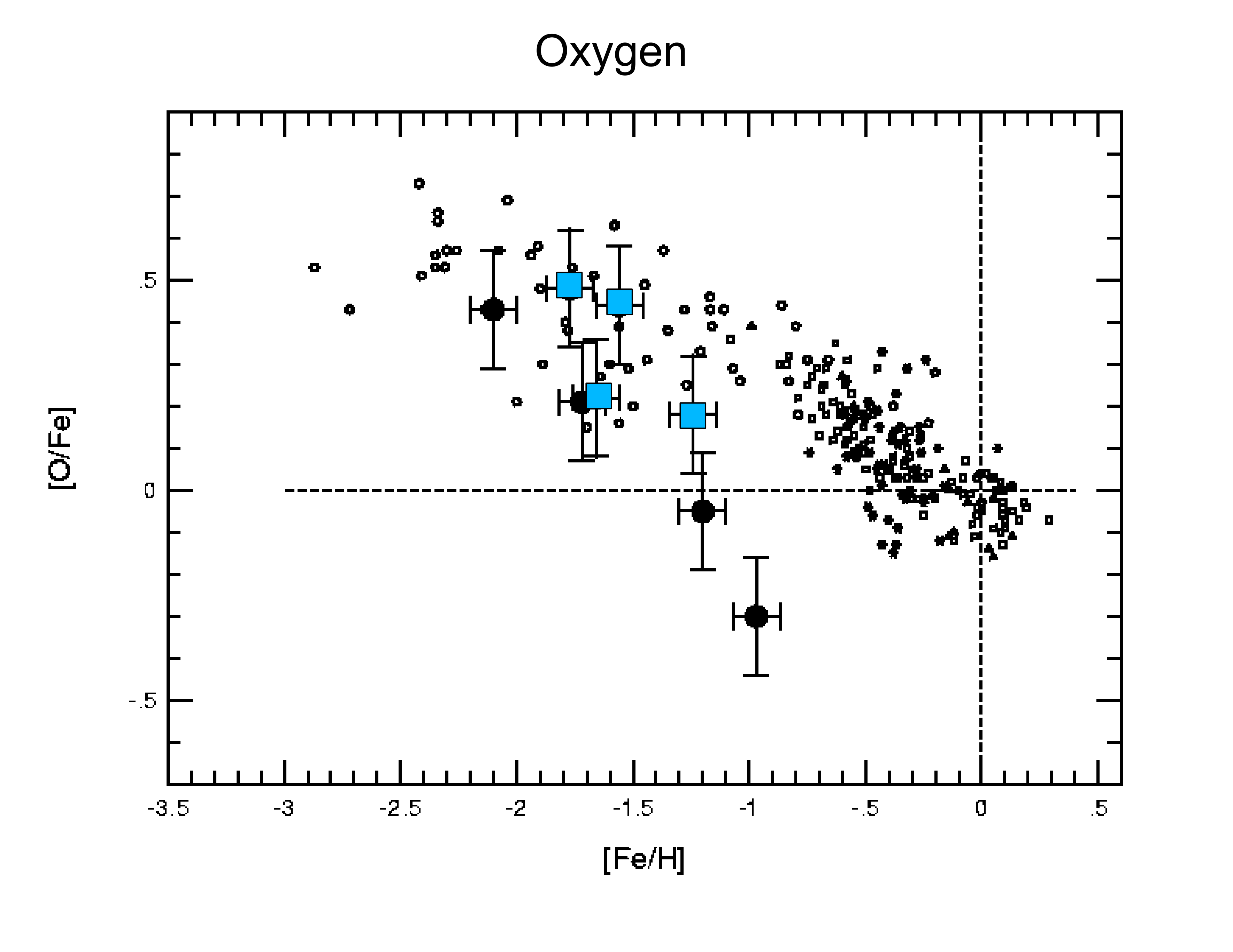
Time for a high resolution study!

- 4 nights on VLT/UT2 + UVES
- Complete coverage in blue from 3730-5000Å and in red from 5900-9800Å at R~40k (minus 1 order)
- Seeing 0.5-0.8"
- Scl: TRGB, V=17.3-17.5, 4x1h exp/star for 4 members;
- IC 1613: M Ia, V=17.0-17.8 (brightest stars in O/IR), 2x1h (2 stars) + 4x1h (1 star)
- S/N~120/px (in red) for Scl, ~30 for IC 1613
- Scl published (Geisler et al. 2005), IC 1613 coming…



V~17.3-17.5!
Wide color range

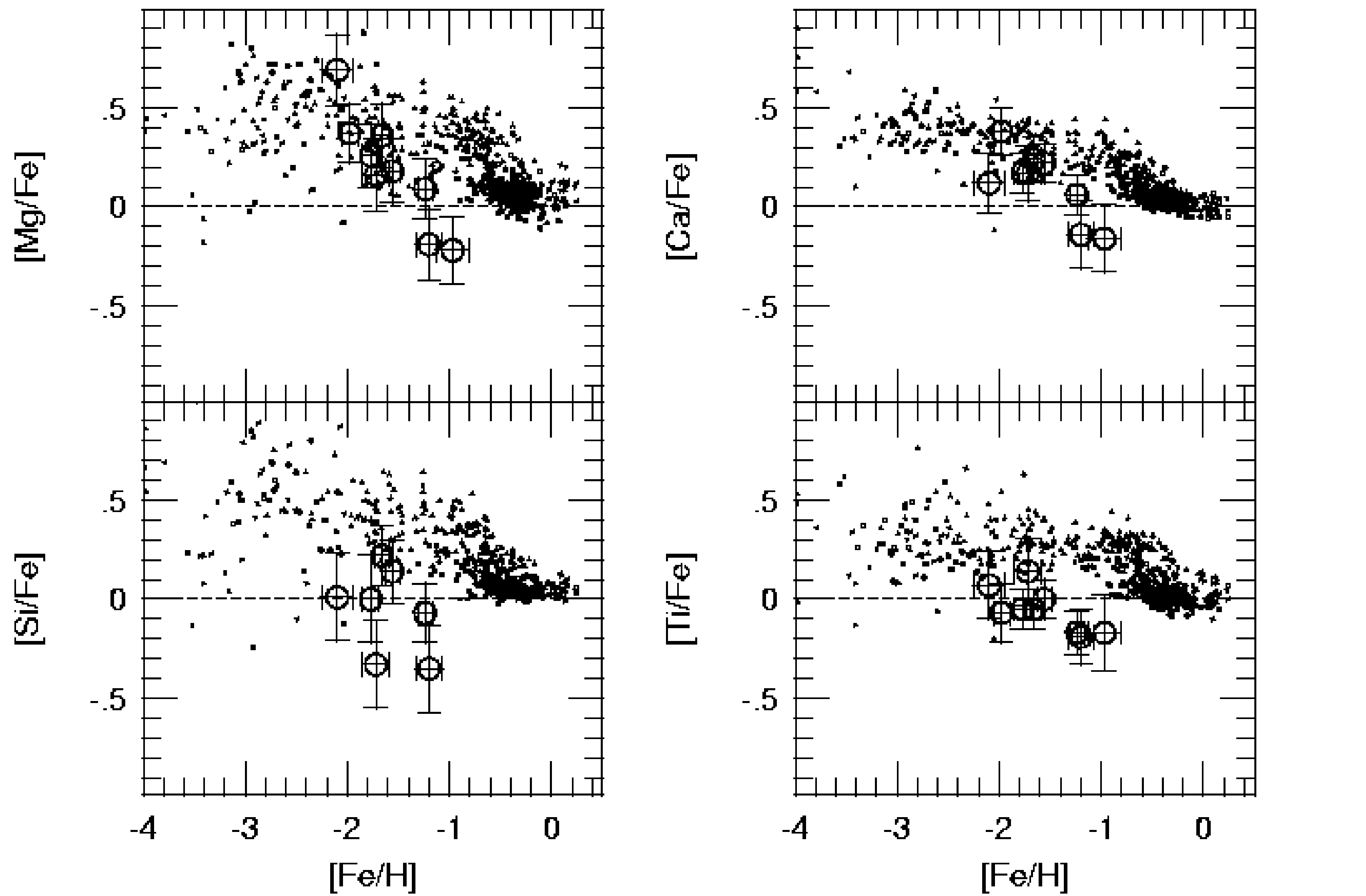
Schweitzer et al. (1995)



Combine our sample (●) with that of Shetrone et al. '03 (■) to better see any trends (note our wider metallicity range) and compare to Galactic halo stars.

O <~halo-like for most metal-poor stars but drops rapidly for [Fe/H]>~-1.5!

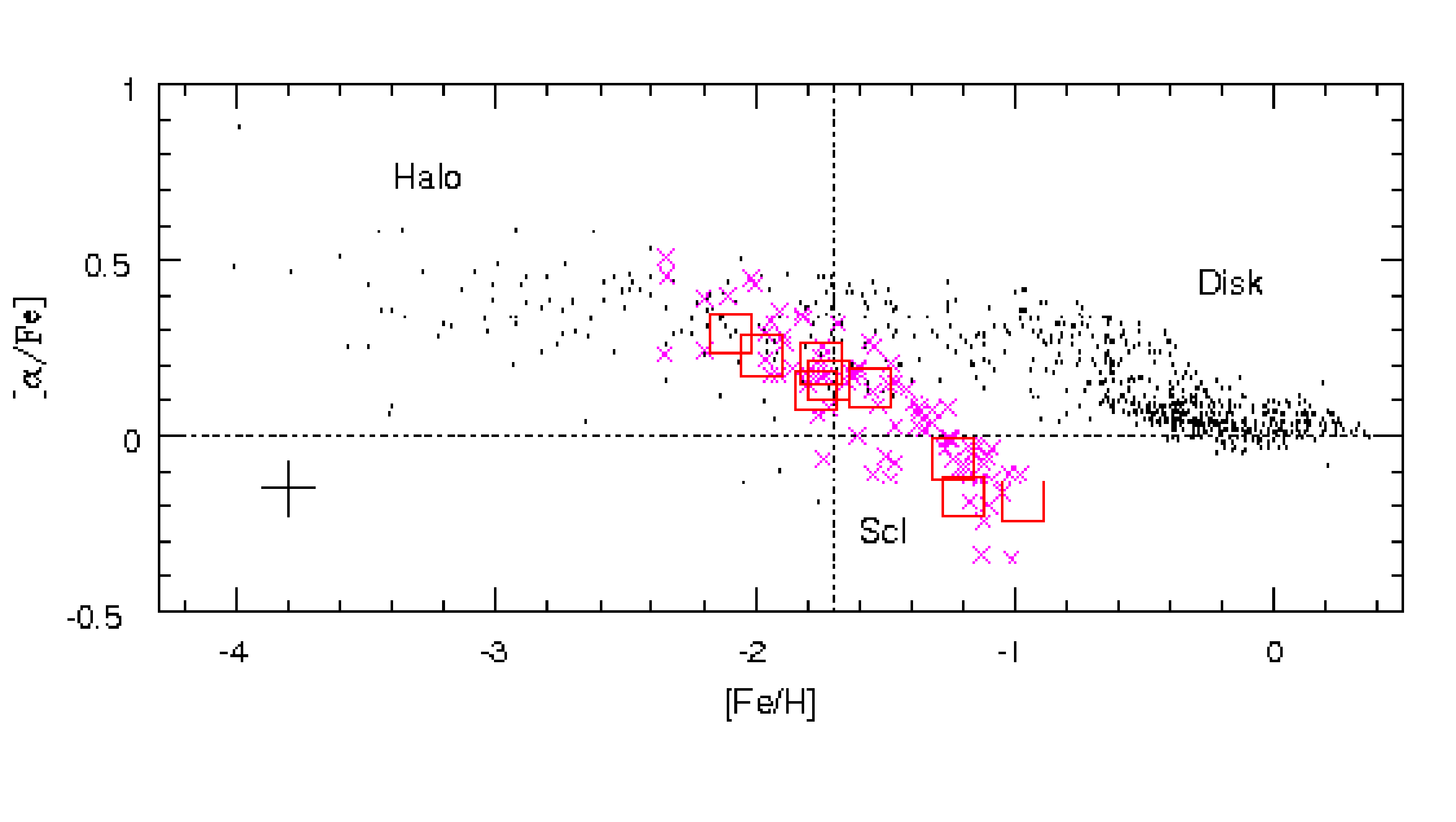
Other alpha elements



The other alpha elements show trends similar to that of O:≲halo-like for metal-poor stars but significantly depleted with respect to halo stars for [Fe/H]>-1.5.

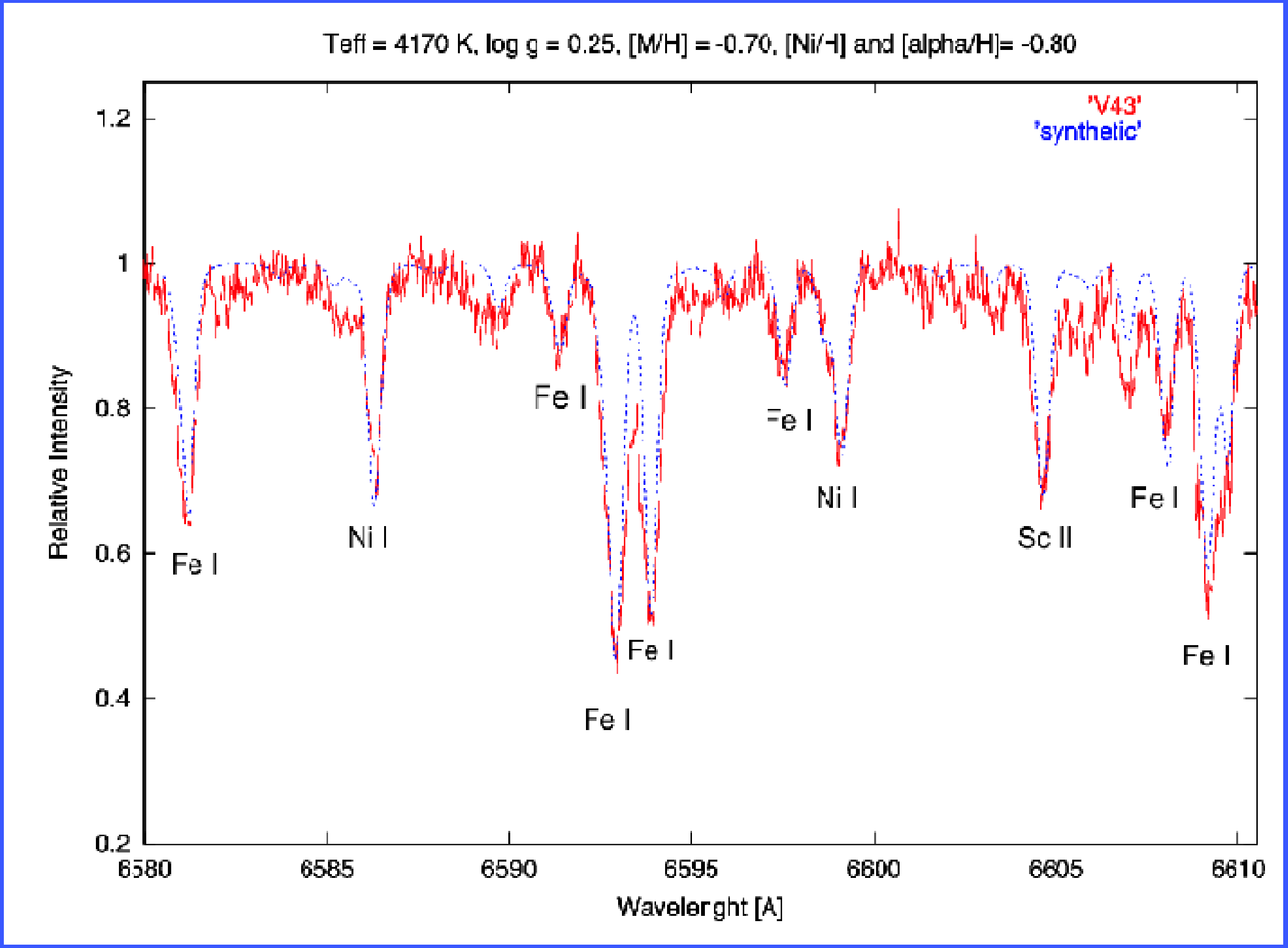
Combine α = <O,Mg,Si,Ca,Ti>

(similar nuc synth. sites, better stats)

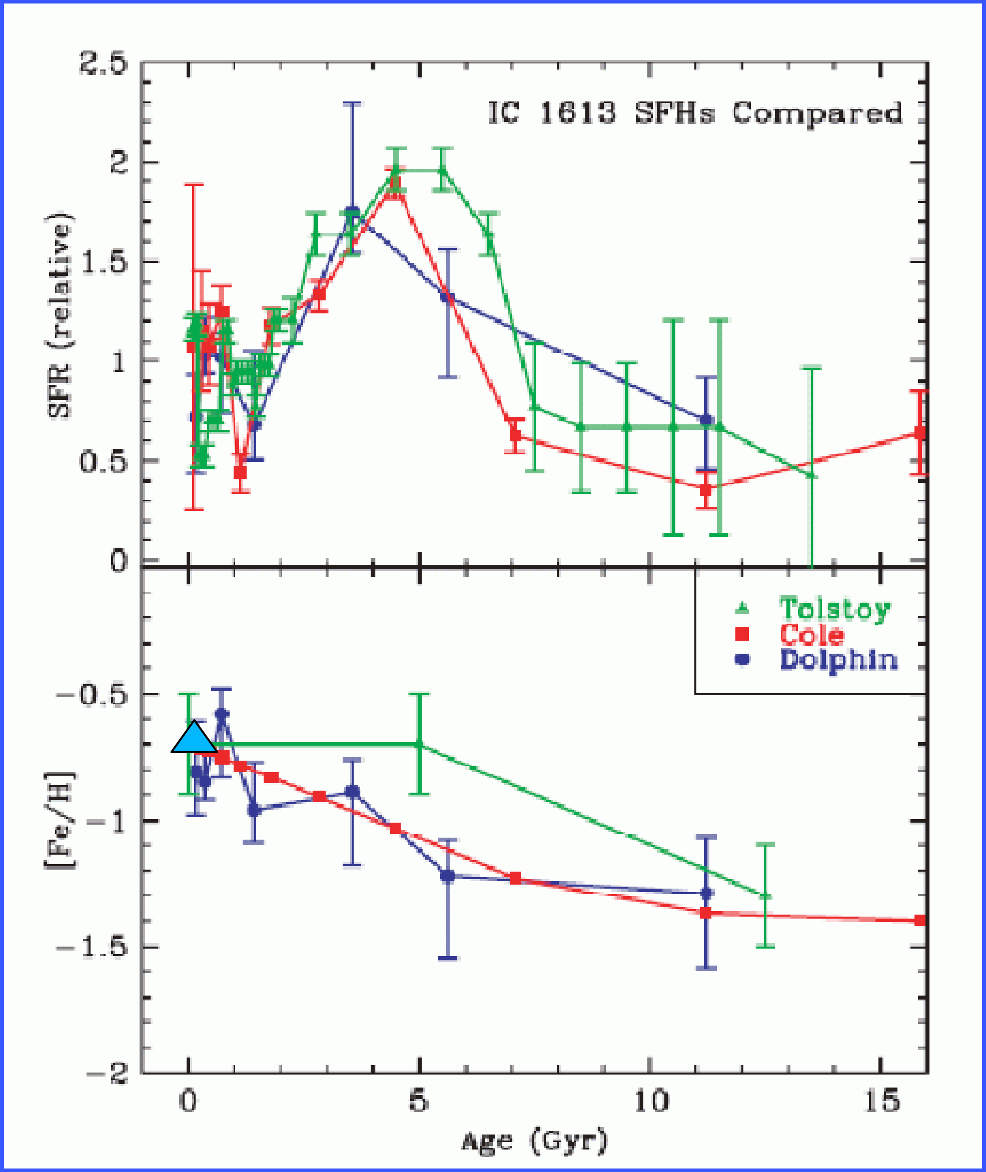


FLAMES will really heat this field up!
Tolstoy et al. (2004) have ~100 members with HRS.
At least we seem to have nailed the trend!
MP stars (<~-2) ~halo-like; ‘knee’~-1.7;
MR stars become increasingly different from halo

‘Recently’, we obtained similar data for 3 stars in IC1613 - LG dIrr without previous HRS. Met generally thought to be very low (-1.3, Lee et al. 1993).   Preliminary results:



SFR vs. time and Age - metallicity relation (AMR) from HST (Skillman et al. 2003)



Evan got it right for a change!

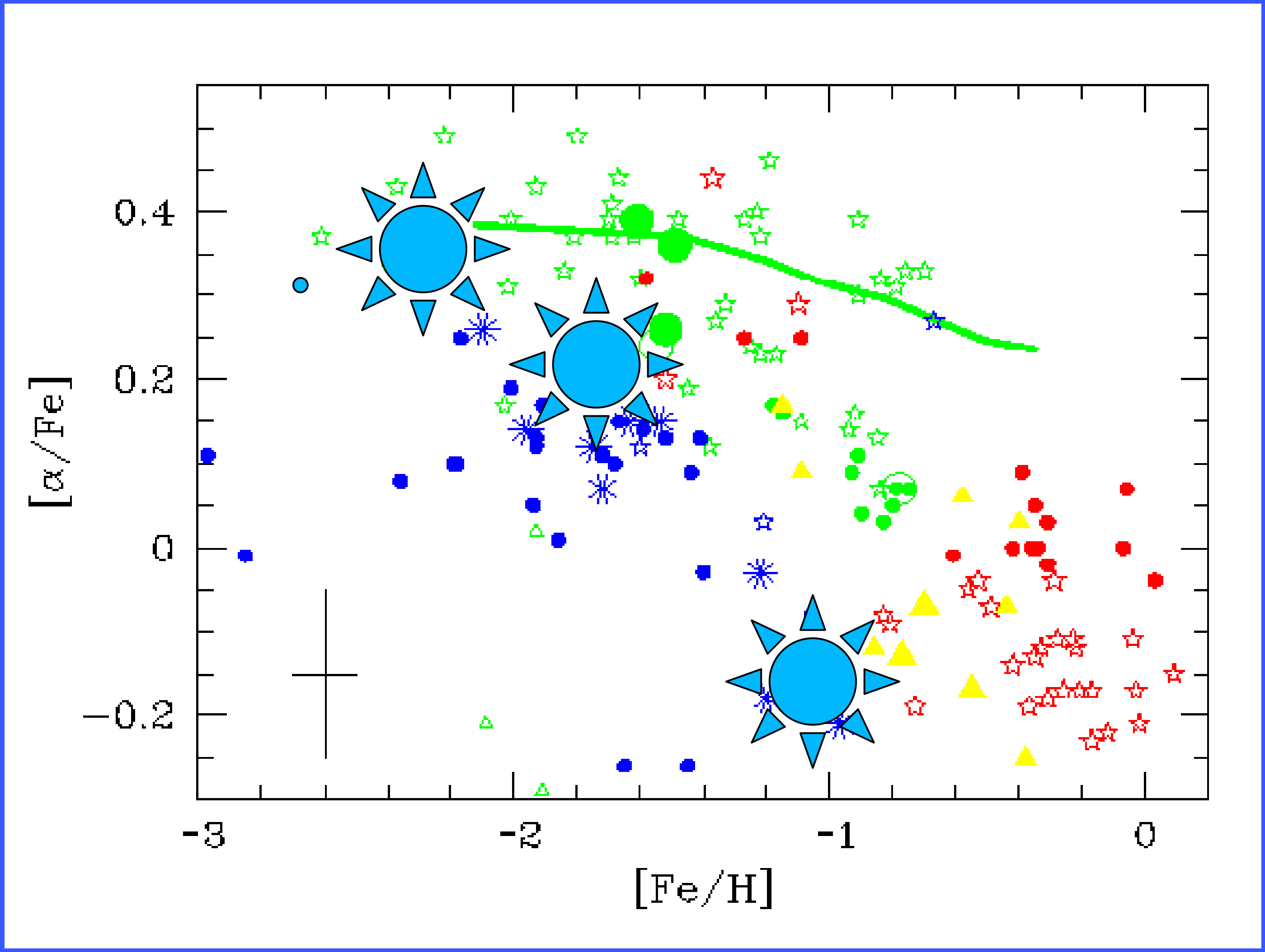
3 stars:

<[Fe/H]>=-0.67±0.1,

[α/Fe]~-0.1

Commonly listed met (-1.3 - Mateo 1998) is for OLD - INT. AGE stars

Dwarf galaxies (dSph and dIrr) vs. Halo:
(aka The Problem)

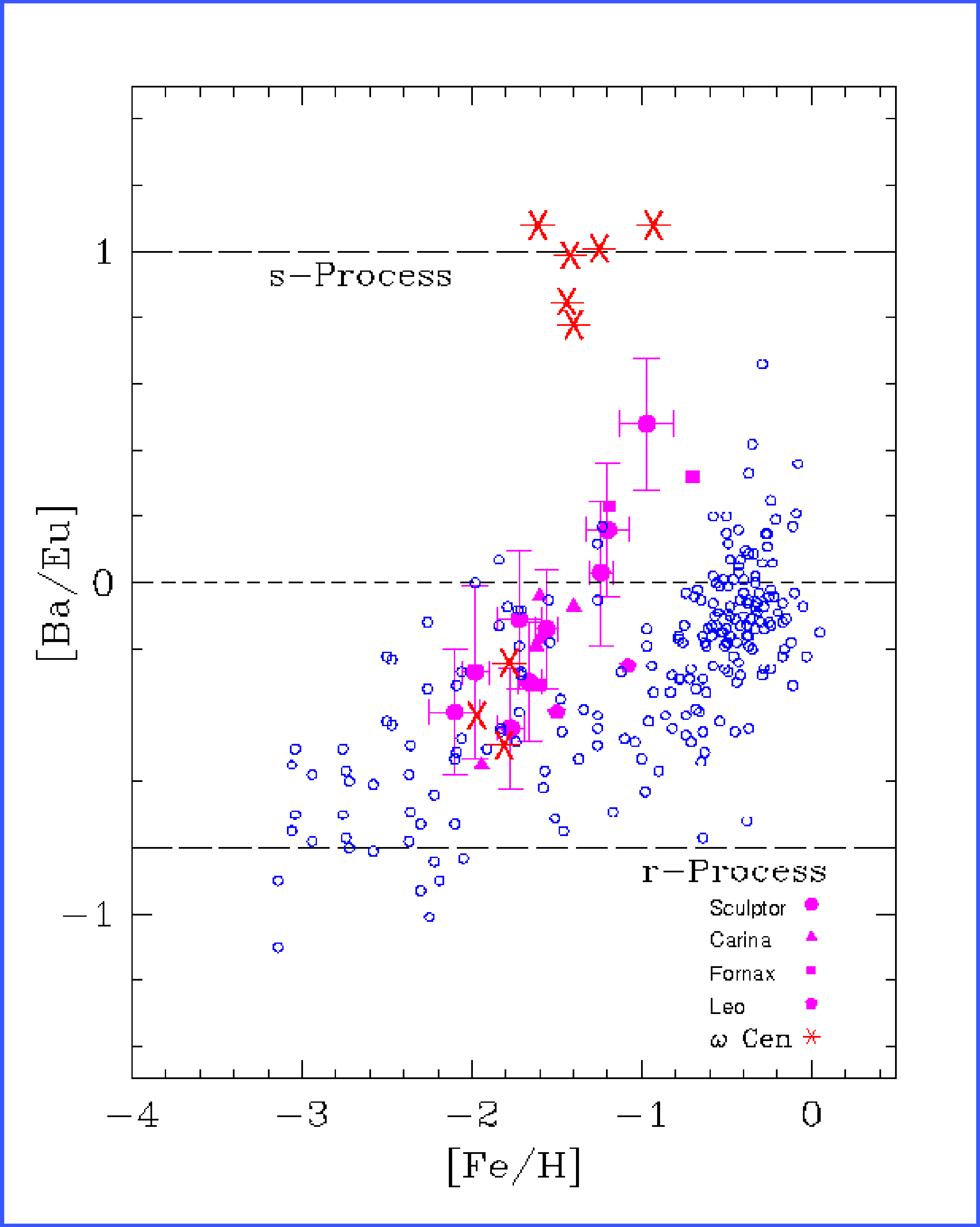


Comparing all dSph and dIrr stars with HRS with their closest Galactic counterparts:

Only the most massive dSphs have a few stars similar to the most extreme Galactic stars in alpha/Fe. For the other dSphs, the difference is largest for the most metal-rich stars.

Increasing evidence that the difference may not be very significant for [Fe/H]≤-2.

NB - most of extragalactic work due to Shetrone, Venn, Tolstoy and collabs.



The Problem is NOT restricted to α elements:

Ba/Eu similar: ~halo-like at lowest mets but increasingly divergent at higher mets!

The Problem

- Stars in present-day (PD) dSphs and dIrrs ARE CHEMICALLY DISTINCT from those in the Halo!
- You CAN'T form the Halo from such galaxies!

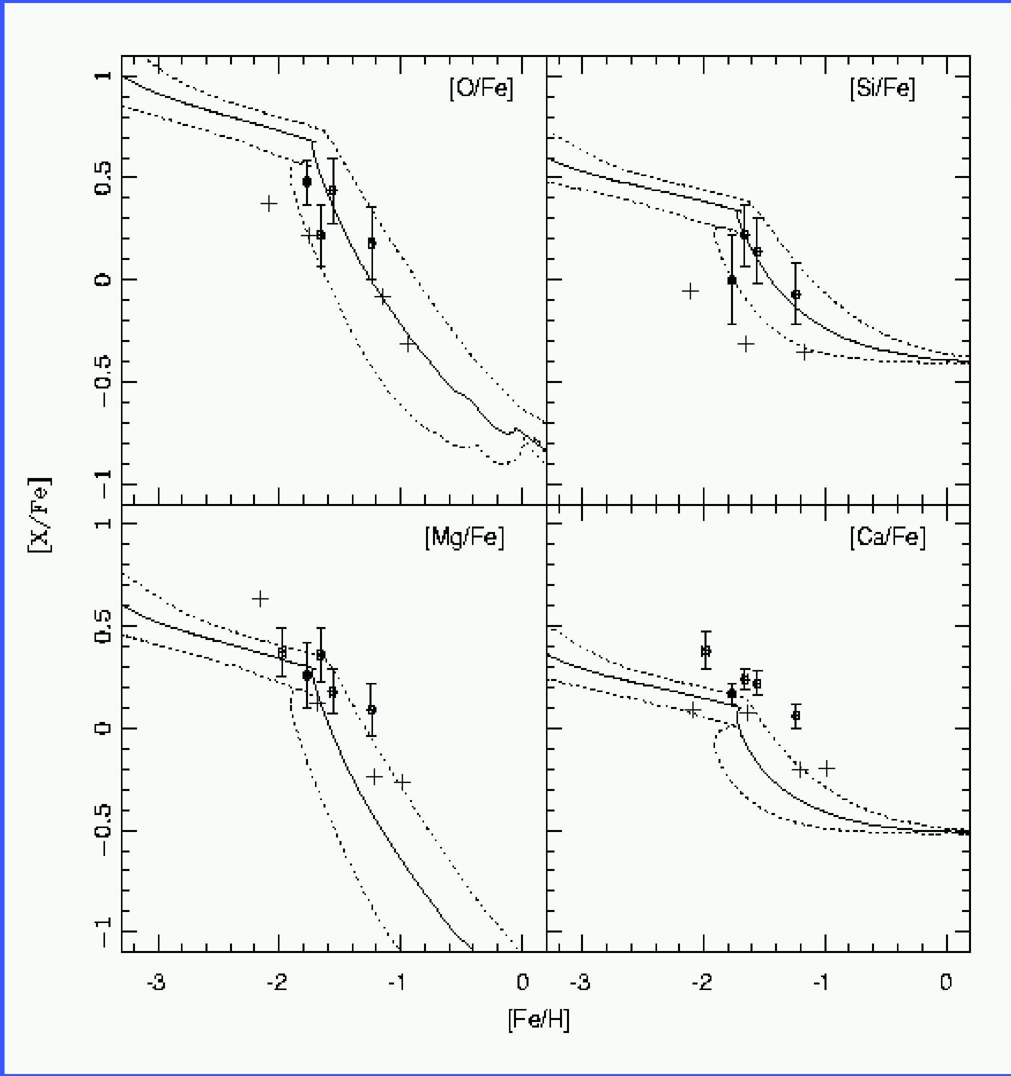
- Does this kill ΛCDM - hierarchical collapse/ Searle and Zinn Halo formation scenarios??
- Can we understand the origins of these differences?

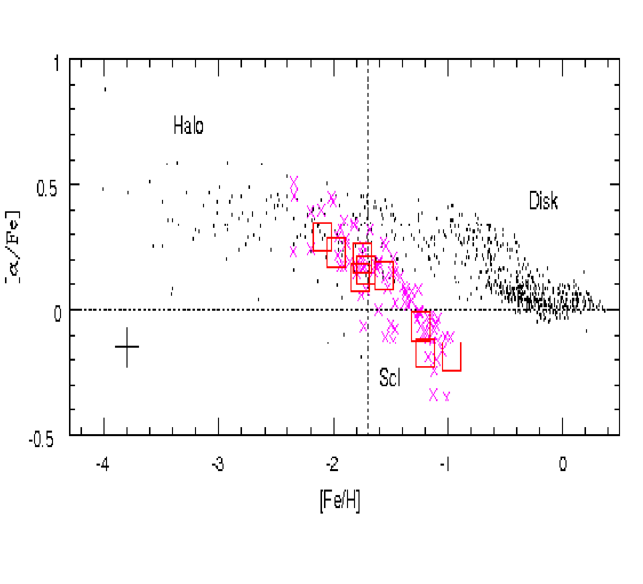
Until very recently, the answers to the above were Yes and No. But 'we' have made great progress in the last year and I think the answers are now No and Yes….

Let's look at the first question first….

Comparing observations to predictions of Chemical Evolution model of Lanfanchi & Matteucci 2004 (LM04):

Here I show the α elements for Scl but other dSphs similar:





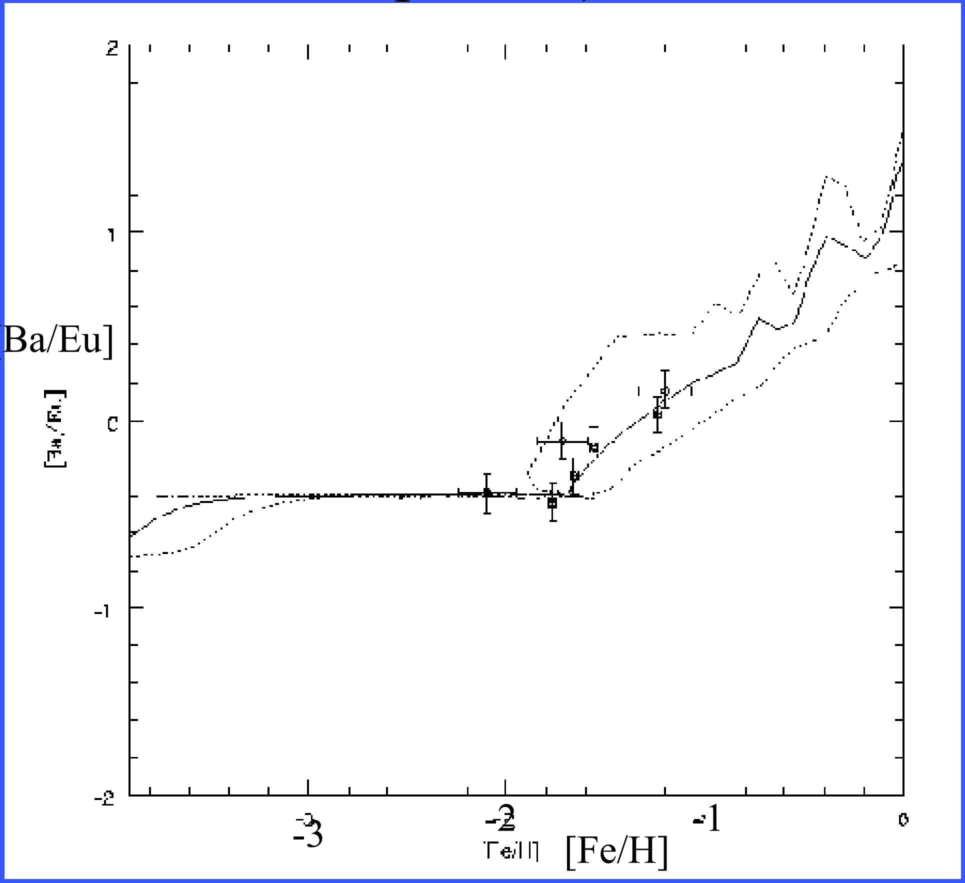
Can ~ explain low α abundances with LOW SFR and HIGH galactic wind (GW) efficiency.

Sudden decrease caused both by onset of SNIa and galactic wind.

'Knee' agrees well with latest (Tolstoy et al.) obs.

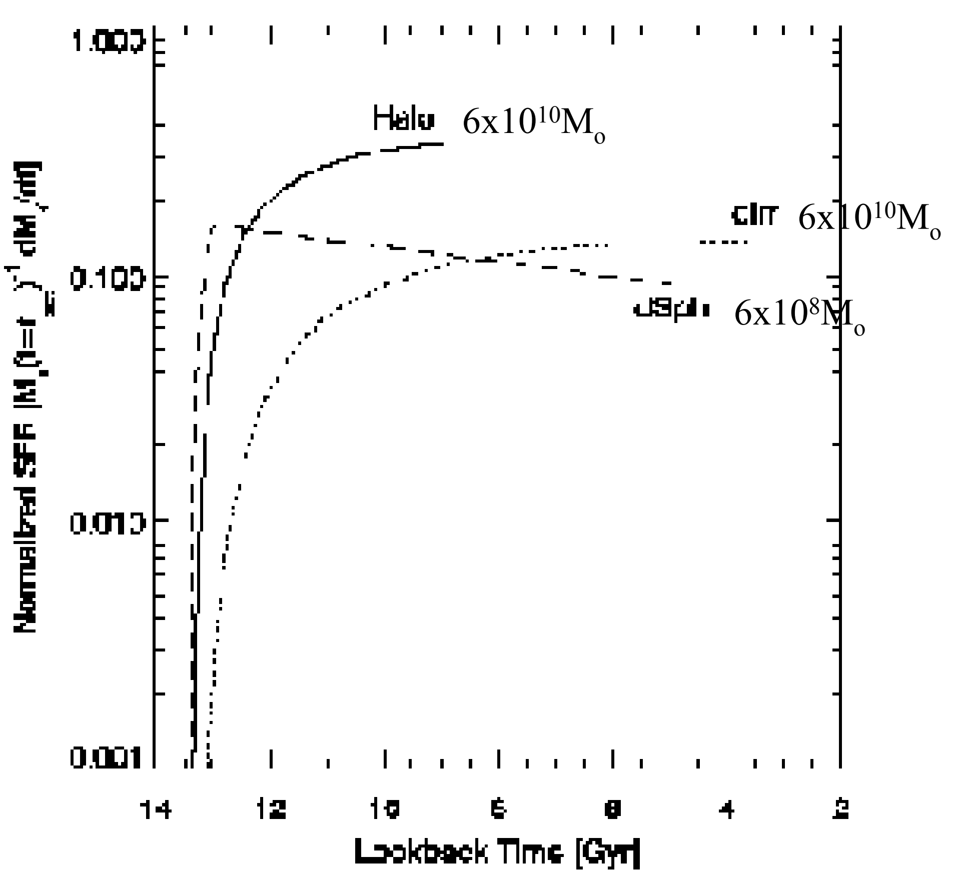
Lanfranchi et al. '05 using same models as LF04
can also explain heavy element abundances:

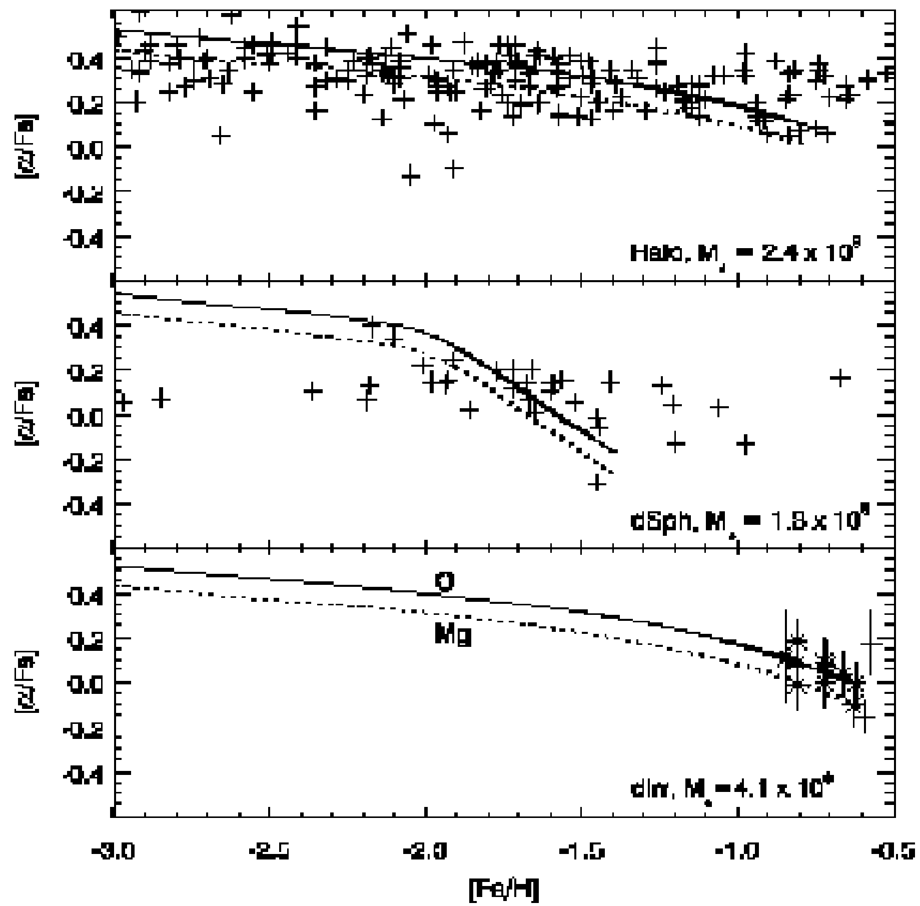
Again, let's look at Scl (good agreement for other dSphs too):



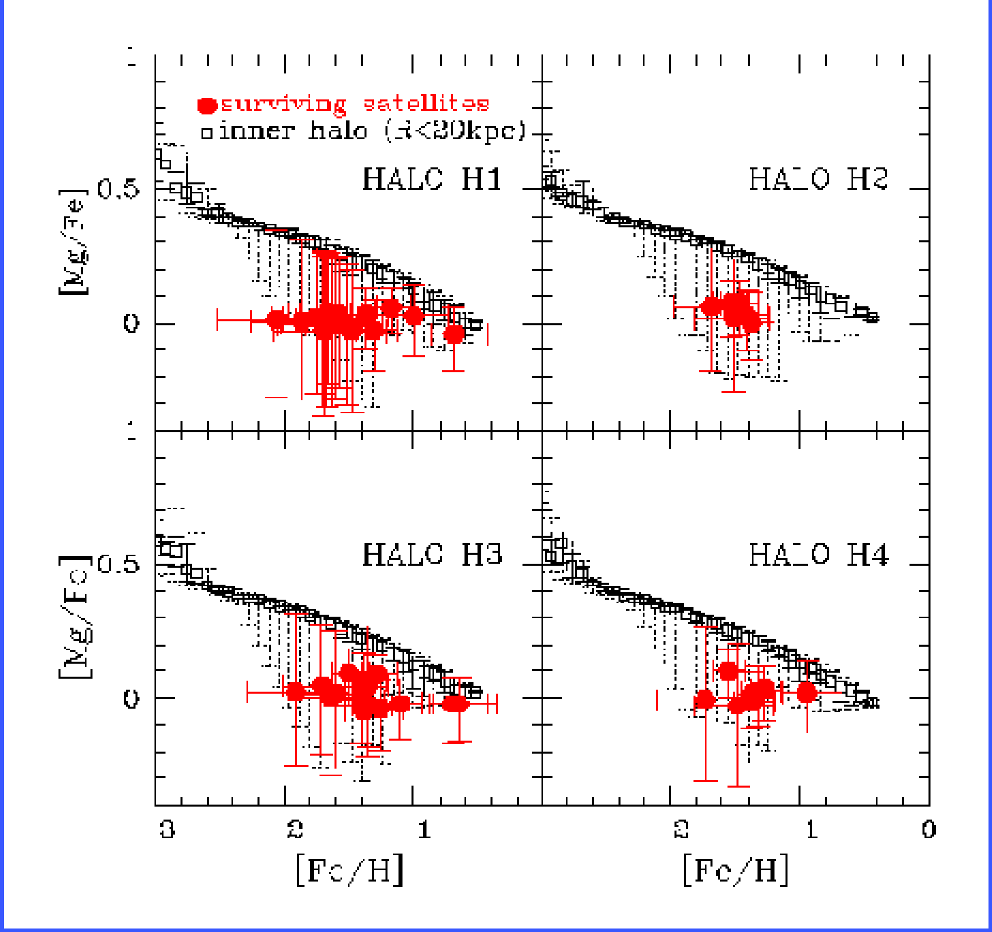
Kink at same met as for [α/Fe], for same reason - low SFR and high GW.
Ba both s- (AGB, t>10^9 yr) and r-process (SNII,t~10^{6-7}yr), while Eu only r.
Both produced early on in ~constant amounts by SNII until SNIa start (t>10^9 yr).
This generates GW which shuts off SF and further SNII. No more r prod.

So we seem to ~understand WHY the chemistry in surviving dSphs is different from that of the Halo. But can we still save hierarchical merging? YES!? Robertson et al. and Font et al. ‘05: from ΛCDM theories, most of MASS in Halo comes from only a few (~5!), very massive (~$5 \times 10^{10} M_o$) satellites accreted very early (~10 Gyr ago). These underwent rapid SF and thus show Halo abundances!



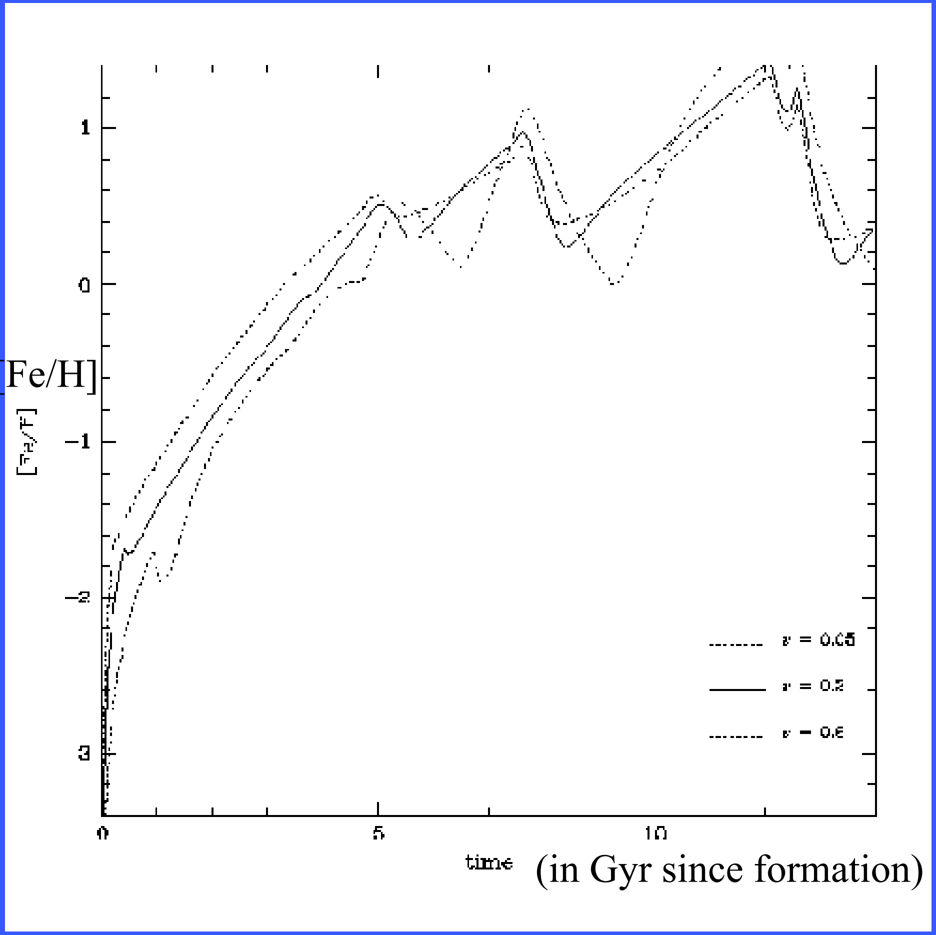


From same models, Font et al. (2005) make a Halo with Halo-like abundances from the accretion of hundreds of satellites. In addition, the still-surviving satellites have α abundances like the present-day dSphs!

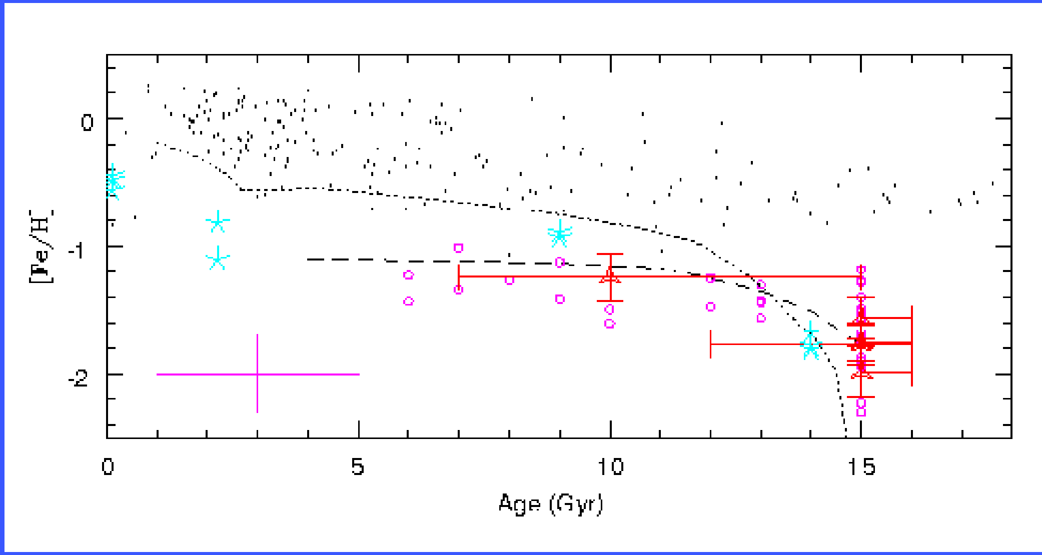


BUT…

Scl (theoretical) age-metallicity relation (AMR - from LM04):

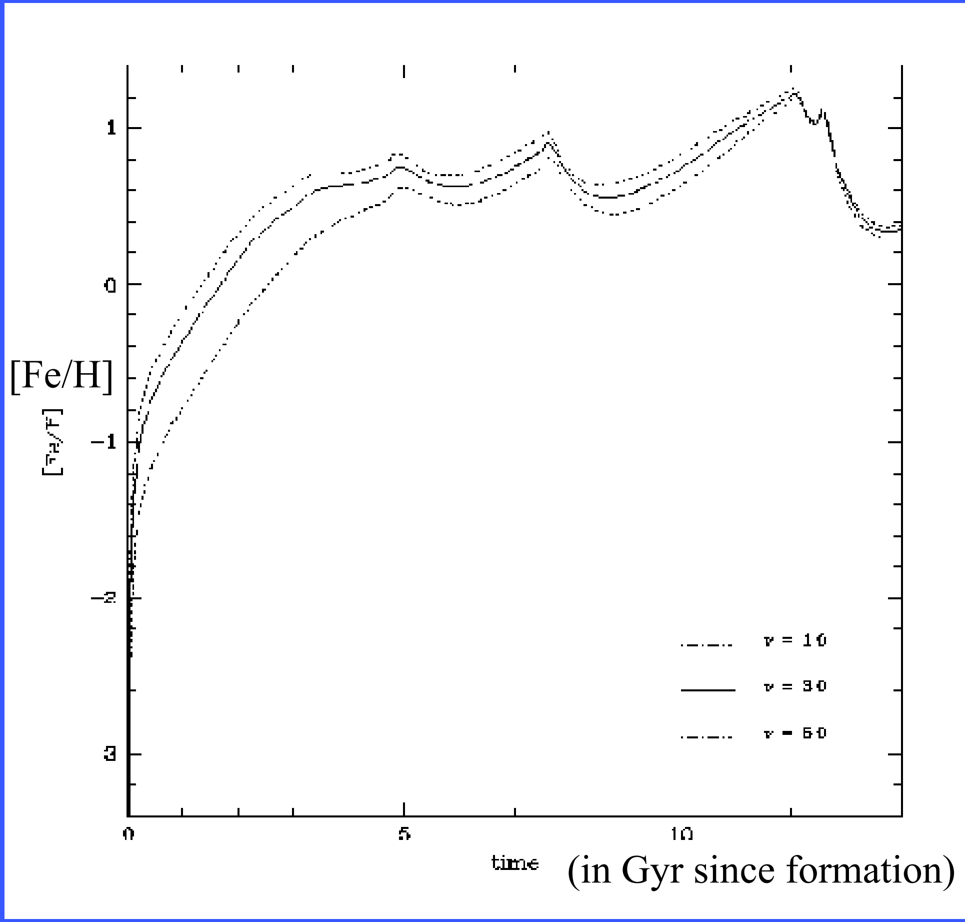


Scl observational AMR (from Tolstoy et al. 2003)



Scl reaches 'knee' (~-1.7) VERY quickly (<1Gyr) and VERY early!
If it is accreted after this - it will show The Problem…

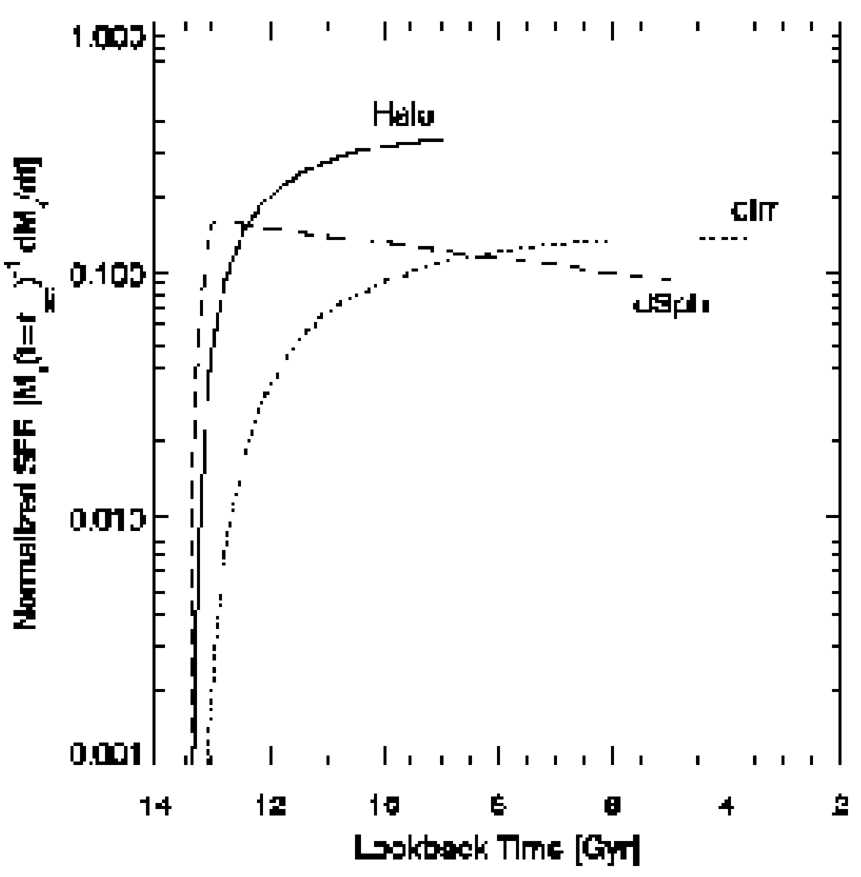
Sgr Theoretical AMR (LM04):

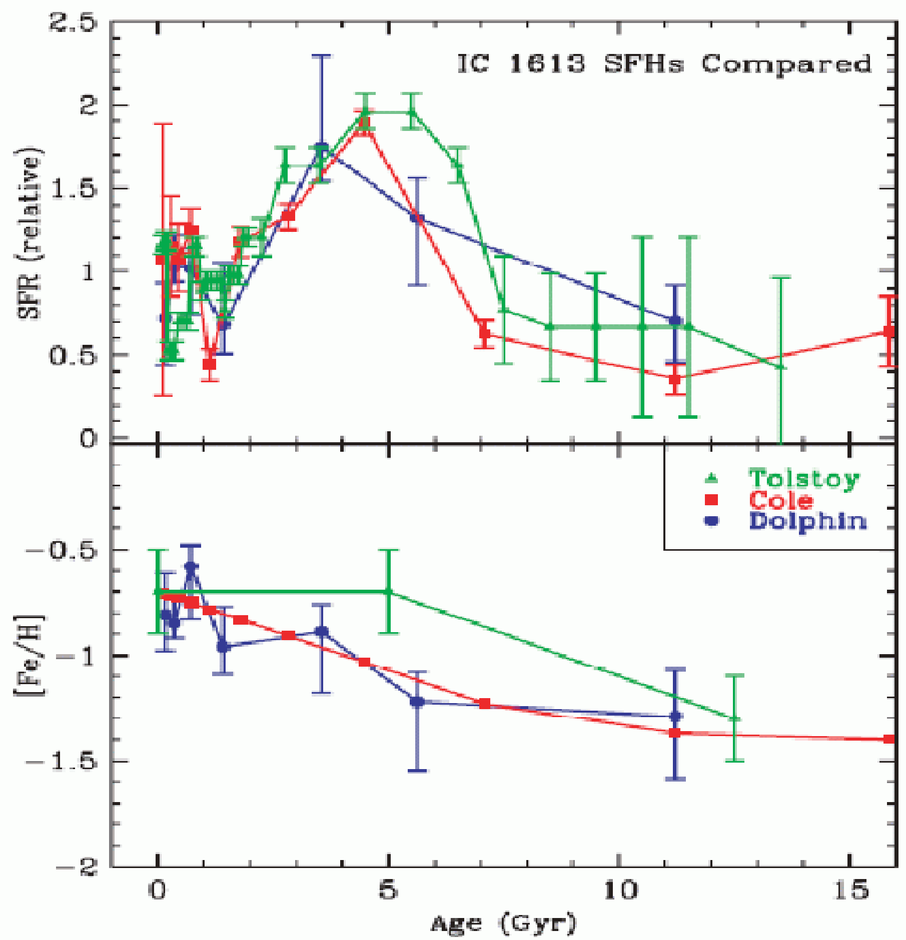


The more massive Sgr evolves more quickly and reaches the met (~-1) where it shows The Problem even more quickly…

If even massive sats. are allowed to evolve on their own, they will show The Problem very quickly!

Why did the Halo sat. gal. (with same M as dIrr) start SF so quickly? Triggered by close encounter? And if it formed so quickly, shouldn't we see The Problem? It had several Gyr to evolve before accreted…

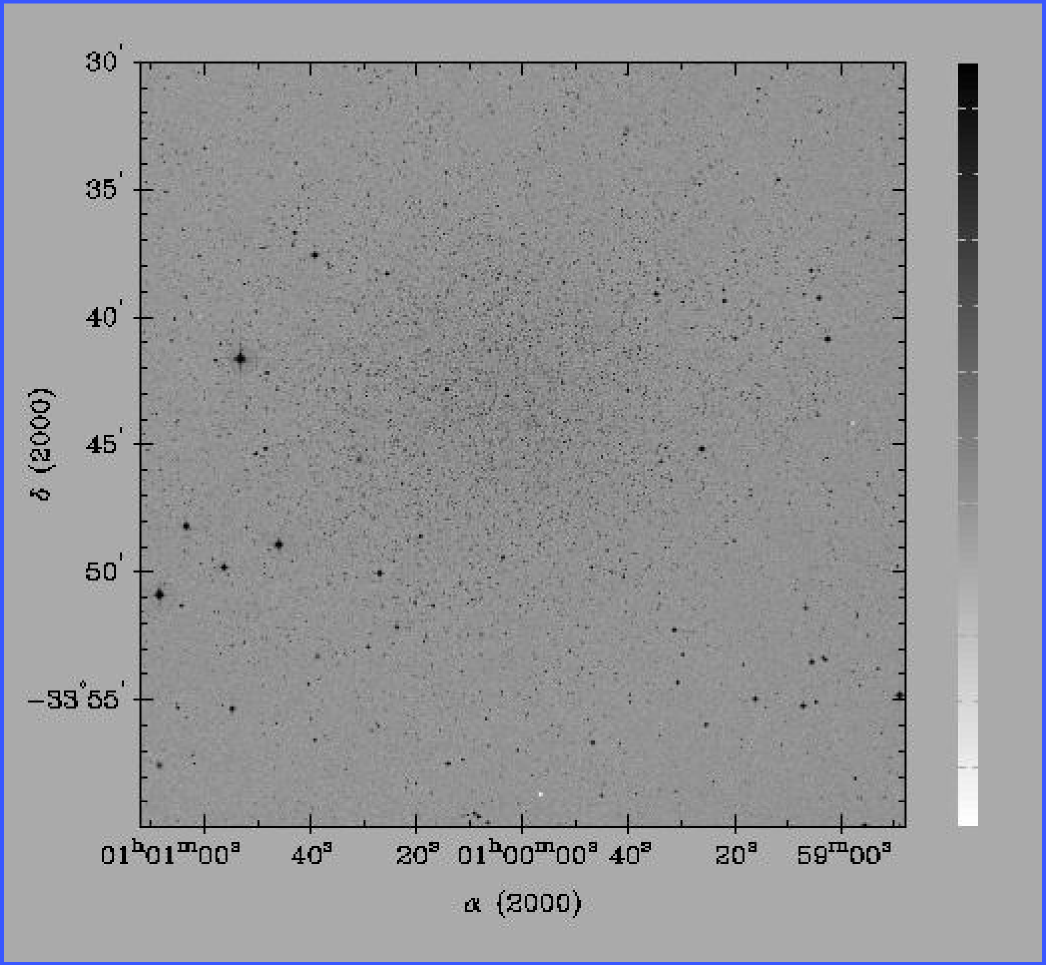




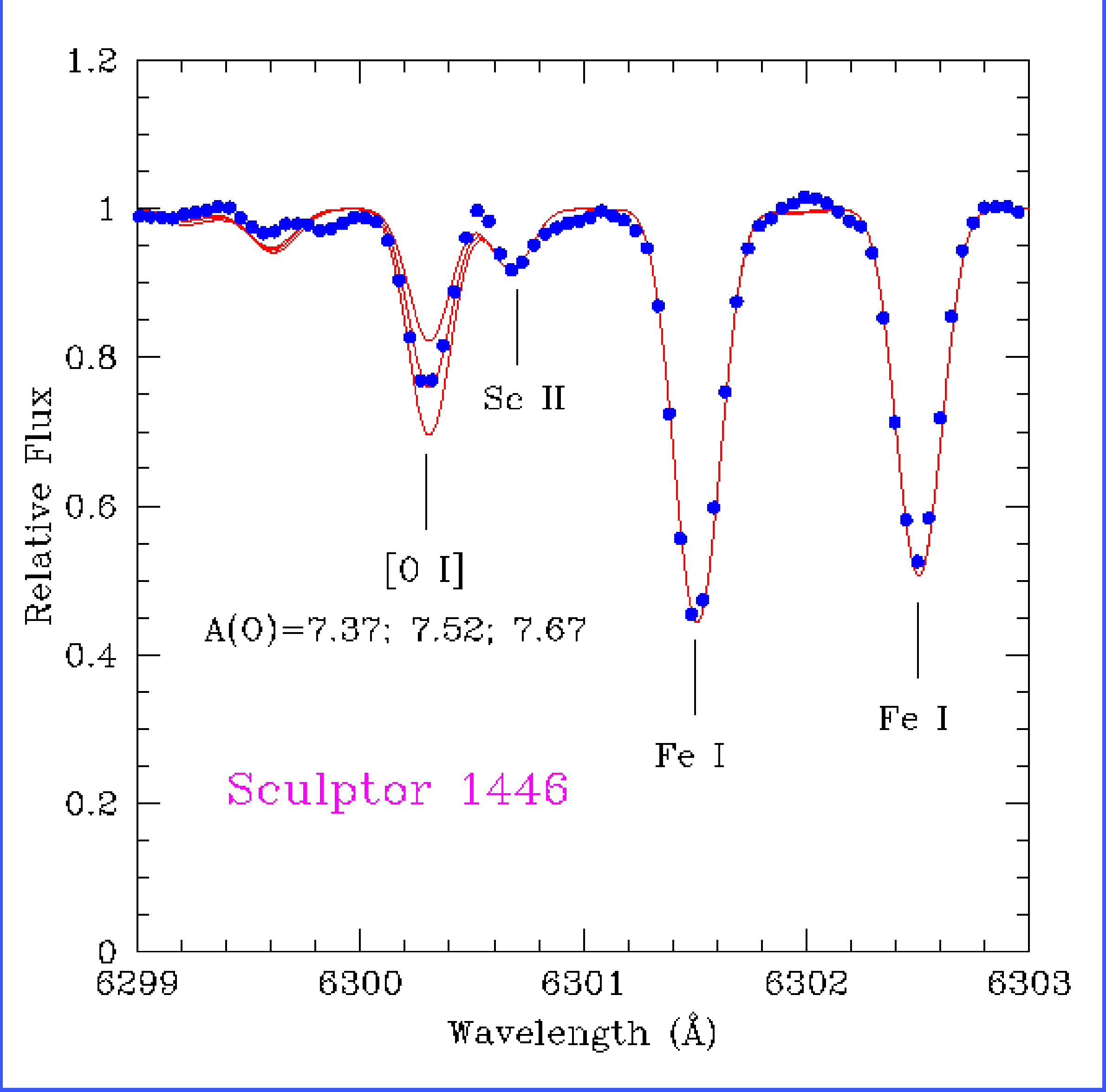
These halos must either be accreted MUCH earlier than thought (<1 Gyr after their formation), or NO SF occurred in them until after they were accreted. May have to fine tune to get a massive enough halo accreted early enough…

Conclusions

- Chemistry in Scl (and other dSphs) and IC 1613 (and other dIrrs) is DIFFERENT from that of the Halo, even for the most extreme Halo stars.
- The Halo could not have been formed by gals like PD dSphs or dIrrs
- The low α and high Ba/Eu abundances observed are due to low SFR and high galactic winds
- Hierarchical formation of the Halo can still be managed via accretion of very massive halos very early on but this may require some fine tuning to prevent The Problem from arising.



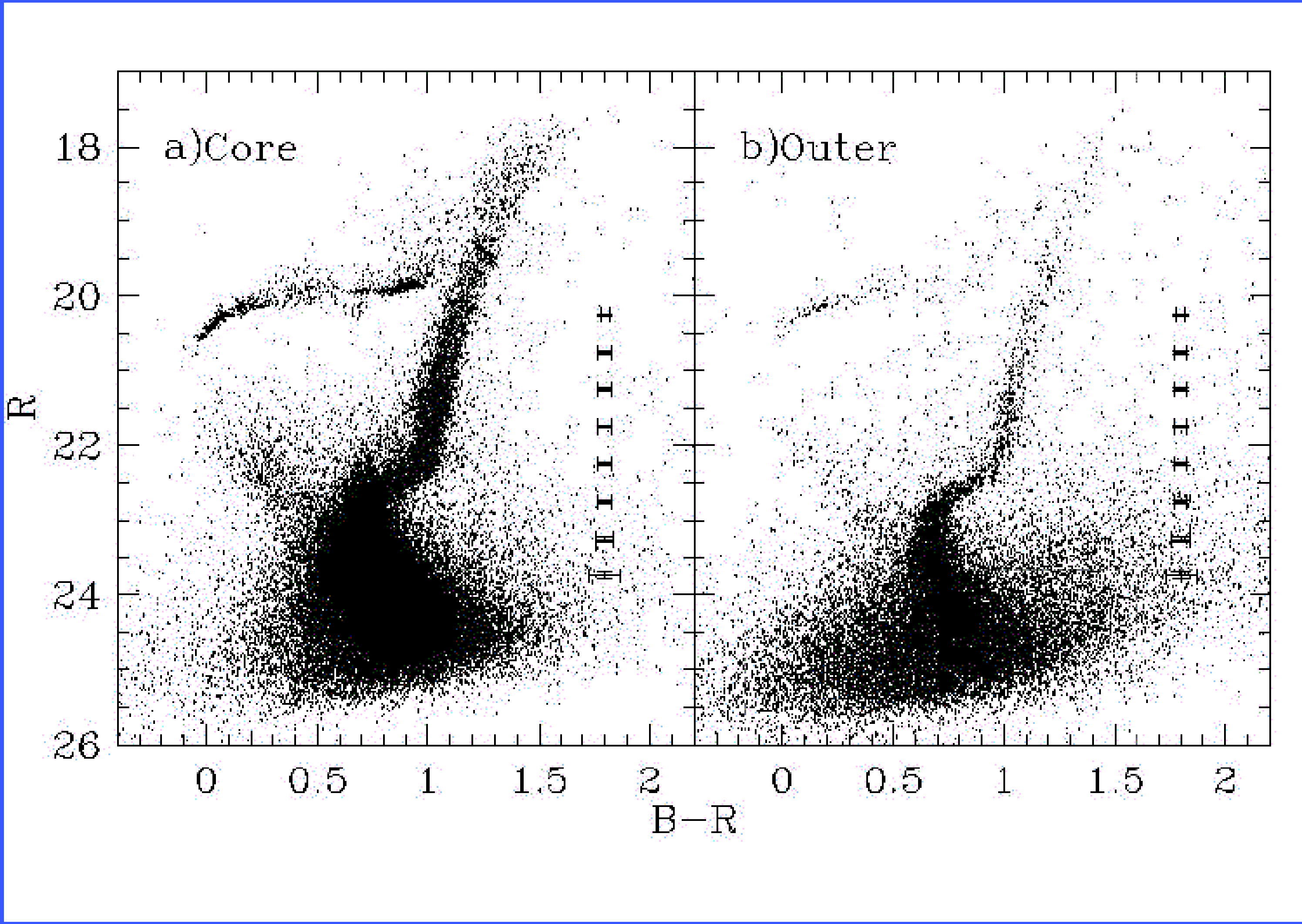
Would you want to make a real Galaxy out of these?
Are runts like Sculptor the Searle-Zinn “fragments”
which accreted to 'Sculptor' much/most/all of the outer
Galactic halo or even the Galaxy itself??



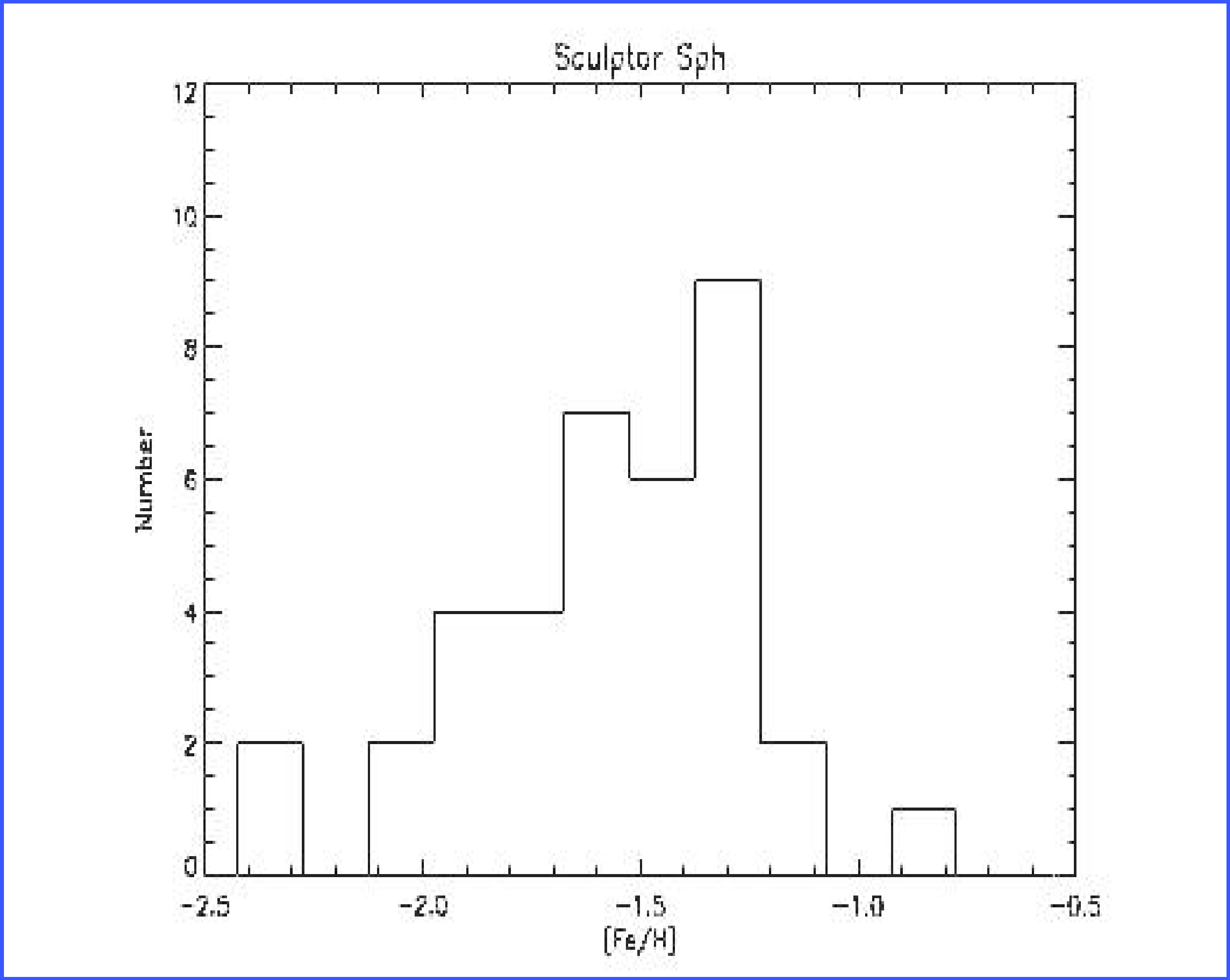
Good spectra! Abundances well determined.

Previous studies of Scl:

- First dSph discovered - Shapley 1938 (9 now known...)
- d=87kpc, M~10^7M(sun), l~200pc, M(V)~-11
- Early CMDs (Da Costa '84) indicated almost exclusively old, metal-poor stars, maybe 2-3 Gyr younger than M92. Thus, very similar to Galactic halo in basic age and metallicity.
- Wide RGB - metallicity spread from [Fe/H]~-2.1 - -1.6.
- Mostly red HB



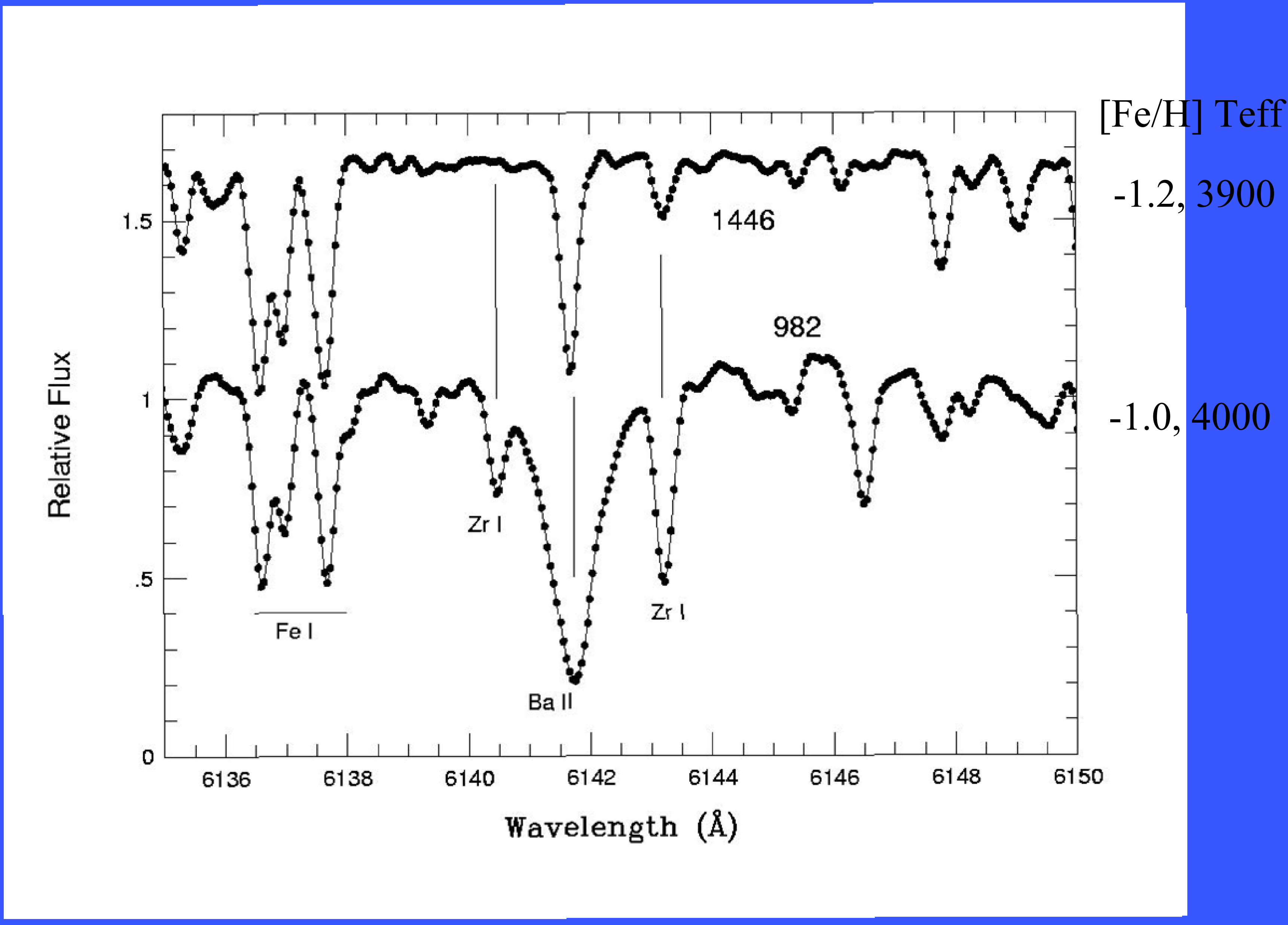
Hurley-Keller et al. ('99) - gradient in HB morphology but NO gradient in mean metallicity or age!?
□ Internal Second Parameter effect!



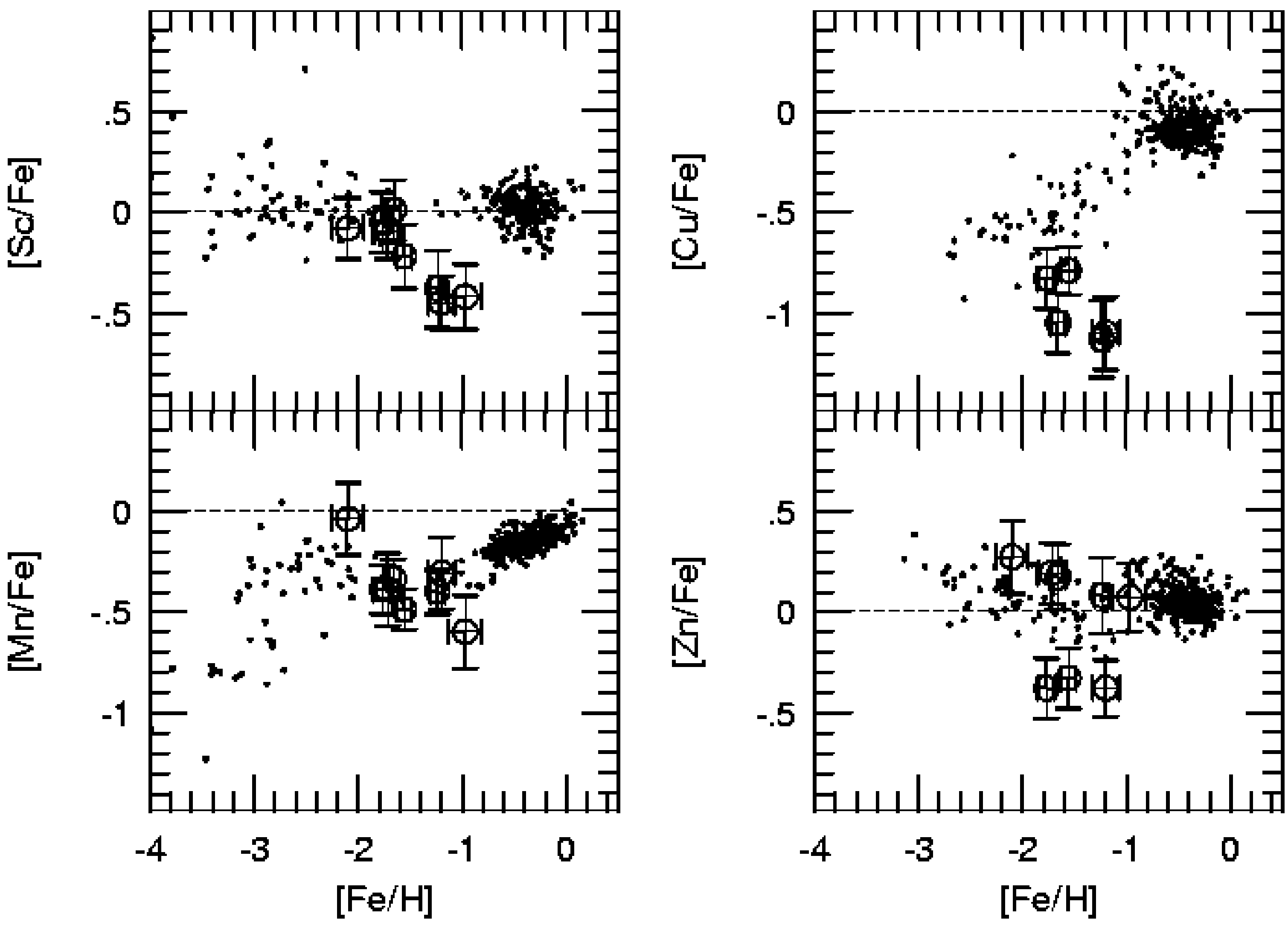
Tolstoy et al. (2001) derived metallicity from Ca triplet spectroscopy of 37 stars

- Significant metallicity spread from ~-1.3 - -2.1
- Mean metallicity =-1.5±0.3
- No bimodality in metallicity distribution
- No metallicity gradient

S-process star!

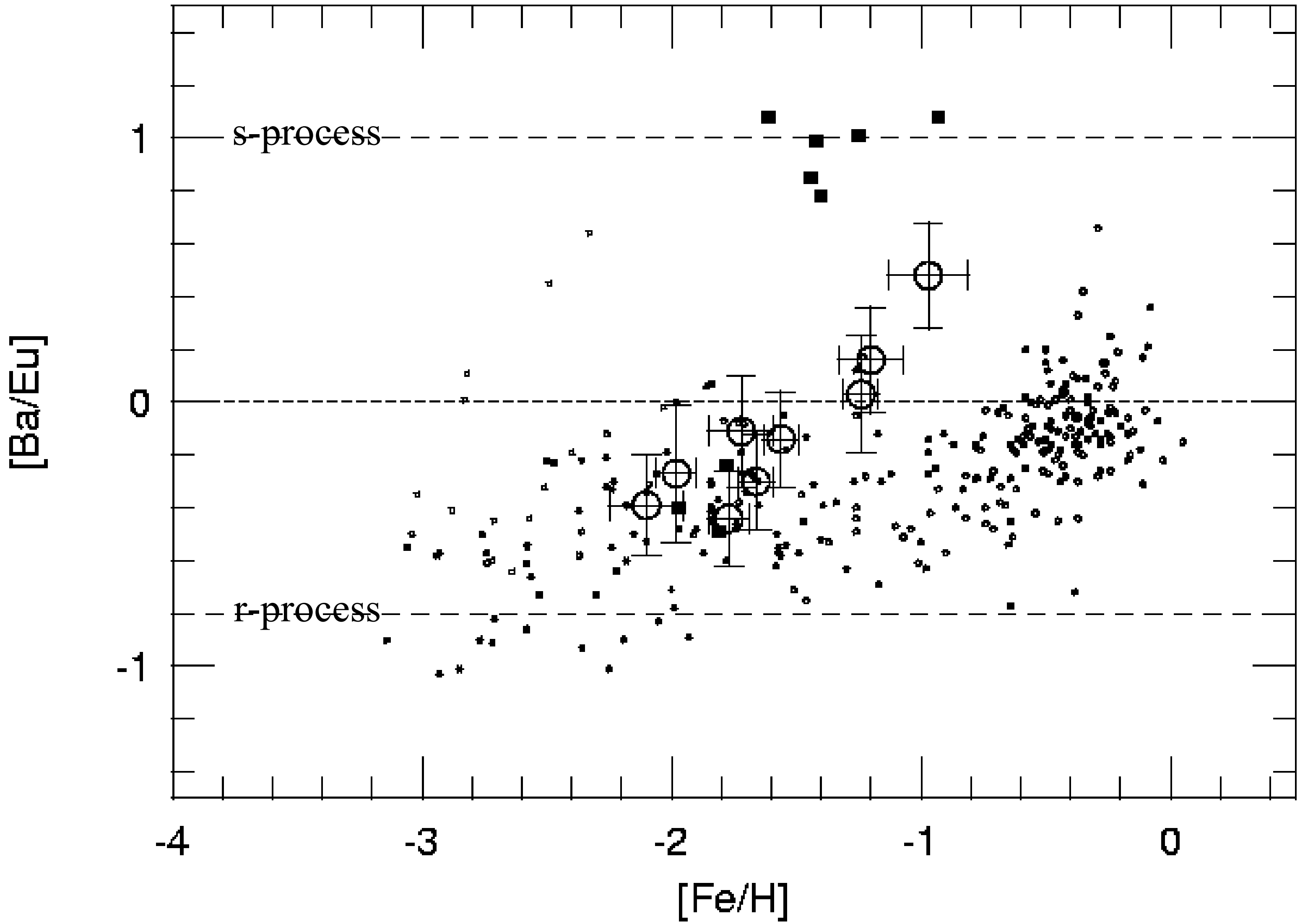


Fe -peak elements



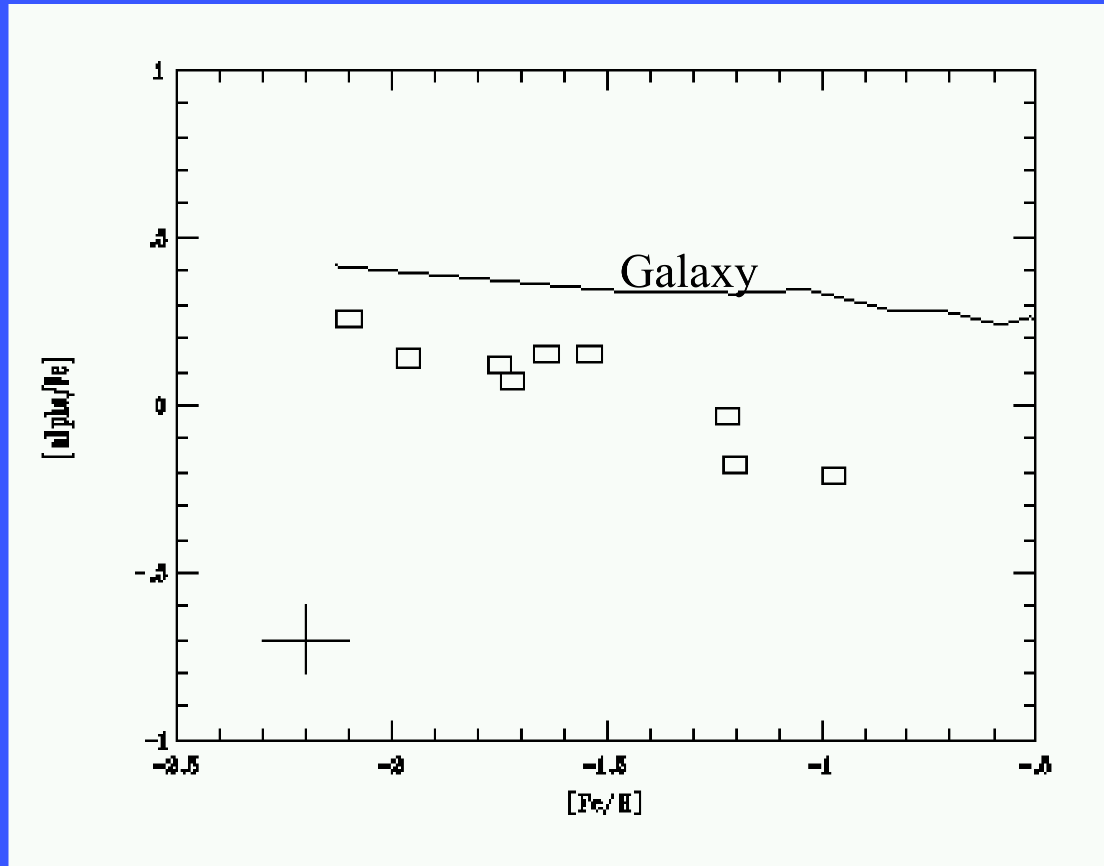
Sc is ~halo-like for the most metal-poor stars but drops significantly below that of the halo for [Fe/H]>-1.5, like □s. Cu depleted, especially for the metal-rich stars.

s/r process



Ba/Eu (~s-/r-process) ratio ~halo-like for the most metal-poor stars but is significantly enhanced with respect to the Galaxy for [Fe/H]>-1.5, just the opposite of the 's. AGB stars played a more important role in Scl than the Galaxy.

Alphas=<O,Mg,Si,Ca,Ti>

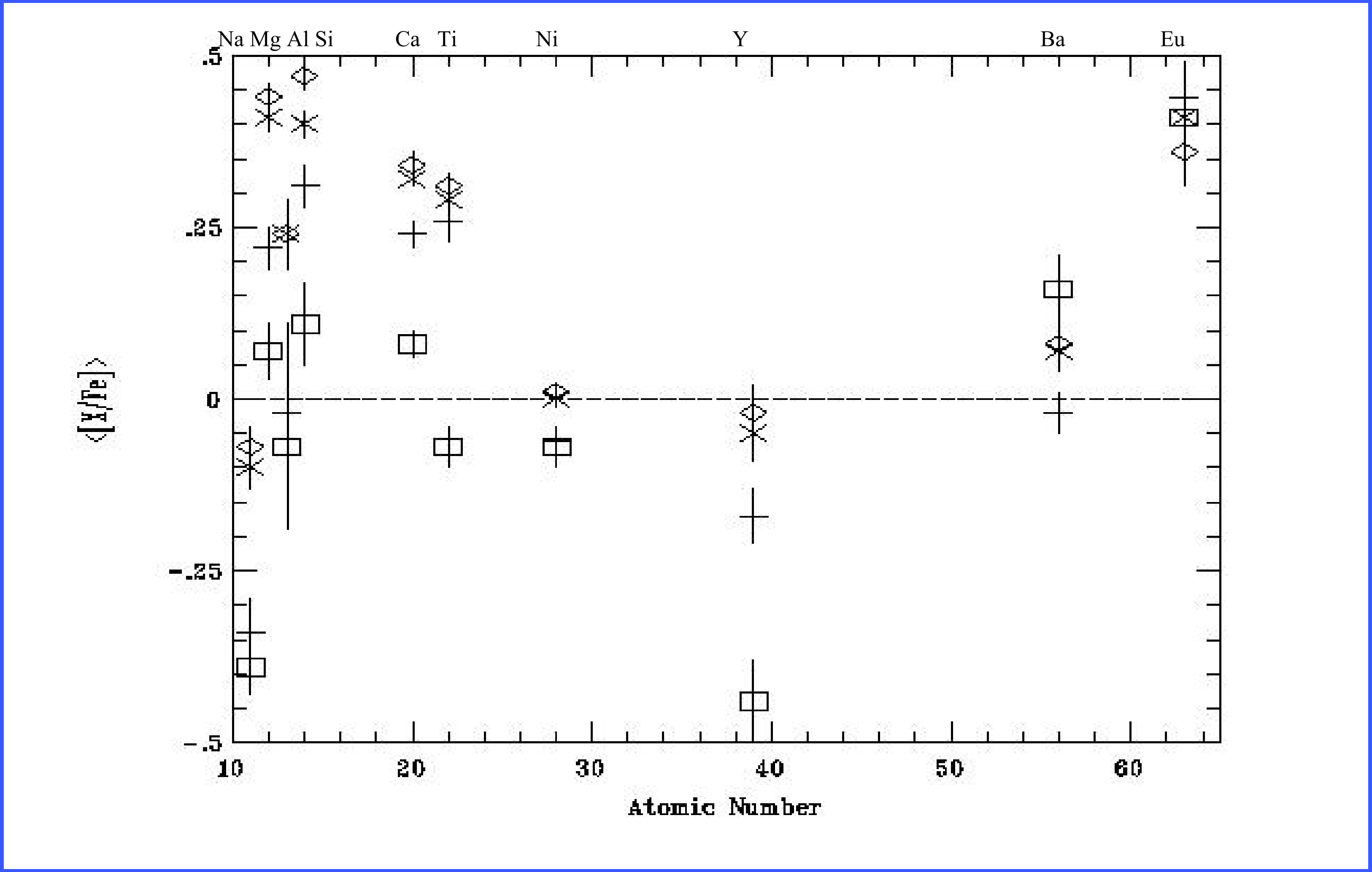


α/Fe is slightly less than that of the halo for the most metal-poor stars but is significantly less than that of the Galaxy for [Fe/H]>-1.5.

Depressed metal-poor plateau with 'knee' at -1.5 instead of -1. If knee caused by onset of SNeIa – depressed plateau must be caused by something else - lack of most massive stars (S03)? But SNeII models predict the most massive stars produce much more O than lower mass stars, while Ti production ~constant. So you expect O in the plateau to be the most affected (depleted) - Ti the least: observe the opposite!

Abundance difference between Scl and halo already in place BEFORE SNeIa exploded - only ~1 Gyr after initial star formation!

Comparing dSph stars with HRS with their closest Galactic counterparts:
In virtually all elements studied, the dSph stars are significantly underabundant wrt their extreme Galactic counterparts. Only Ba is high and Eu normal.



Fulbright '02 halo dwarfs (-2<[Fe/H]<-1)

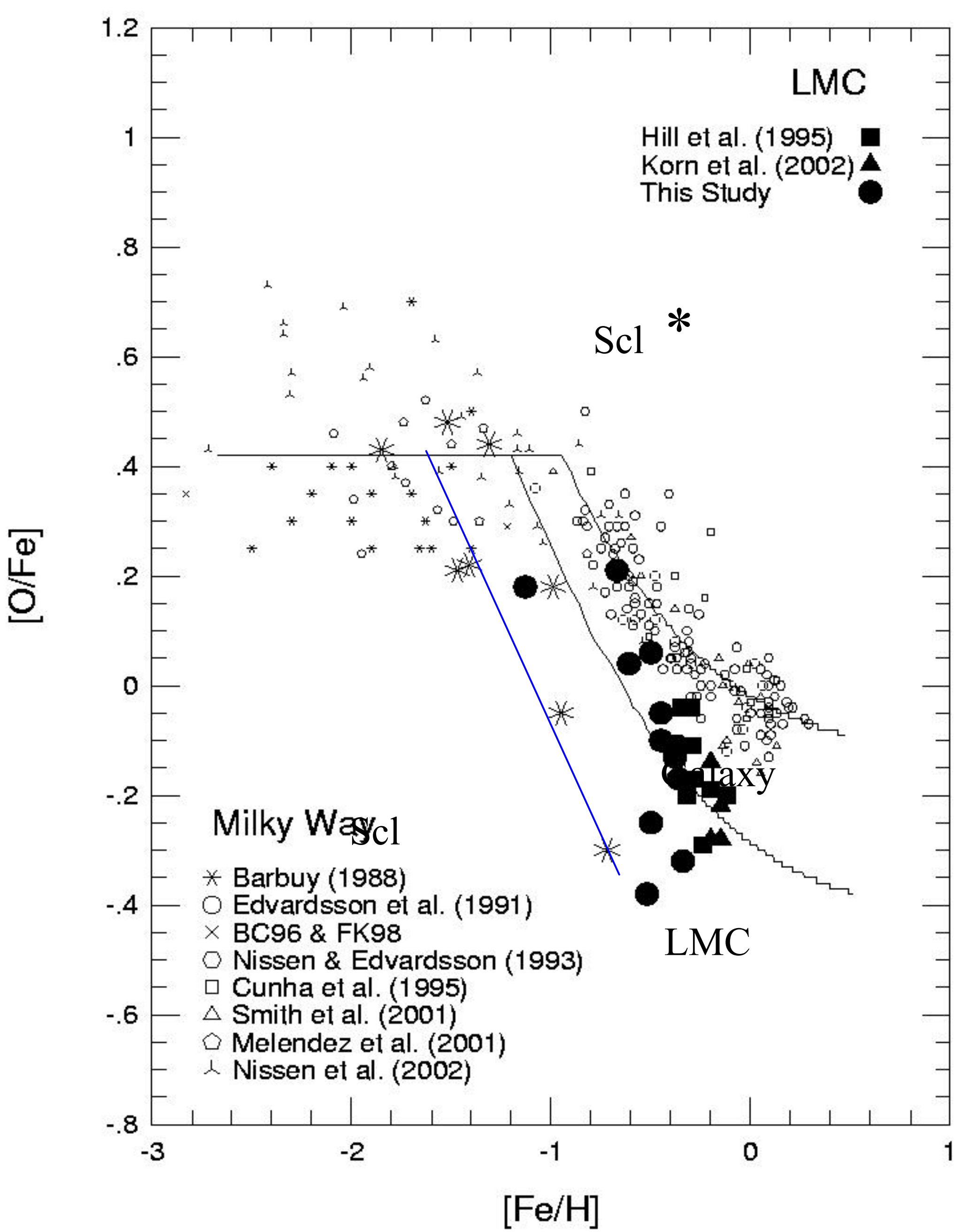
◇ = low velocity

X = medium velocity

+ = high velocity ("low alpha")

□ = dSph giants (29 stars)

Chemical evolution was significantly slower in Scl than in the Galaxy



Simple chem. Evol. Models

SFR (LMC)~1/3 SFR (Galaxy)

SFR (Scl) ~ 1/6 SFR (Galaxy)

Comparative Galactic Chemical Evolution

First stars form with range of masses. After ~10**6-8 yr most massive stars SNII and produce alpha's, Na, O, Eu and some Fe.
Second generation stars form from this enriched material. After ~Gyr, lower mass stars SNI and produce mainly Fe. Later generations form from Fe-enriched material.
This produces a “knee” in alpha/Fe graph at a [Fe/H] that depends on the chemical evolution rate - basically the Star Formation Rate (and yield) - how fast you can form stars and reastrate.

In the Milky Way, SFR was rapid and the Galaxy enriched itself to [Fe/H]~-1 within ~1 Gyr, when the first SNI started going off and produced the knee.
In Sculptor, SFR much slower (~6x) - only managed to enrich itself to [Fe/H]~-1.5 (factor of 3 lower metallicity) before SNI started.

But alphas in Scl lower at all metallicities: either lack of SNII (weird IMF) OR a small dSph in a “normal” star formation event simply does not make the most massive stars needed to manufacture the extra alphas. But expected effect on O/Ti is opposite to that observed...
Can be explained by lower SFR and high efficiency galactic wind.

Also Ba/Eu evolution was very different in Scl and the Galaxy, i.e. the relative importance of s- to r- process genesis. Ba comes mainly from AGB stars - there was a much stronger contribution of AGB stars in Scl. The timescale is also ~a Gyr.

Conclusions:

- Chemistry in Scl (and other dSphs) DIFFERENT from that of the Galaxy, even for the most extreme Galactic stars. The stars we see today in these 2 types of galaxies are different! This holds true for the metal-rich halo at least as much as it does for the metal-poor halo.

The Galaxy appears not to have been 'Sculptur'-ed

- Chemistry in dSphs is SIMILAR to that in damped Ly-α galaxies

- Maybe a small fraction of the Galaxy, the most extreme halo stars, came from the most massive dSphs like Sgr but NOT from Sculptors

- If 'Sculptur'-ed, merging must have happened BEFORE SNIa

- This could have serious implications for the Searle-Zinn scenario...

- Scl had a lower SF rate than the Galaxy, by ~ a factor of 5