The Galactic Halo As Seen By The Hamburg/ESO Survey

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on behalf of Norbert Christlieb, Tim Beers, Andy McWilliam, Ian Thompson, Steve Shectman, John Norris, and many others

Back to the Galaxy II – KITP – Santa Barbara – Sep 2008

Outline

Introduction to the HES (Major goal: find bright QSOs)

Abundances for C-normal EMP stars

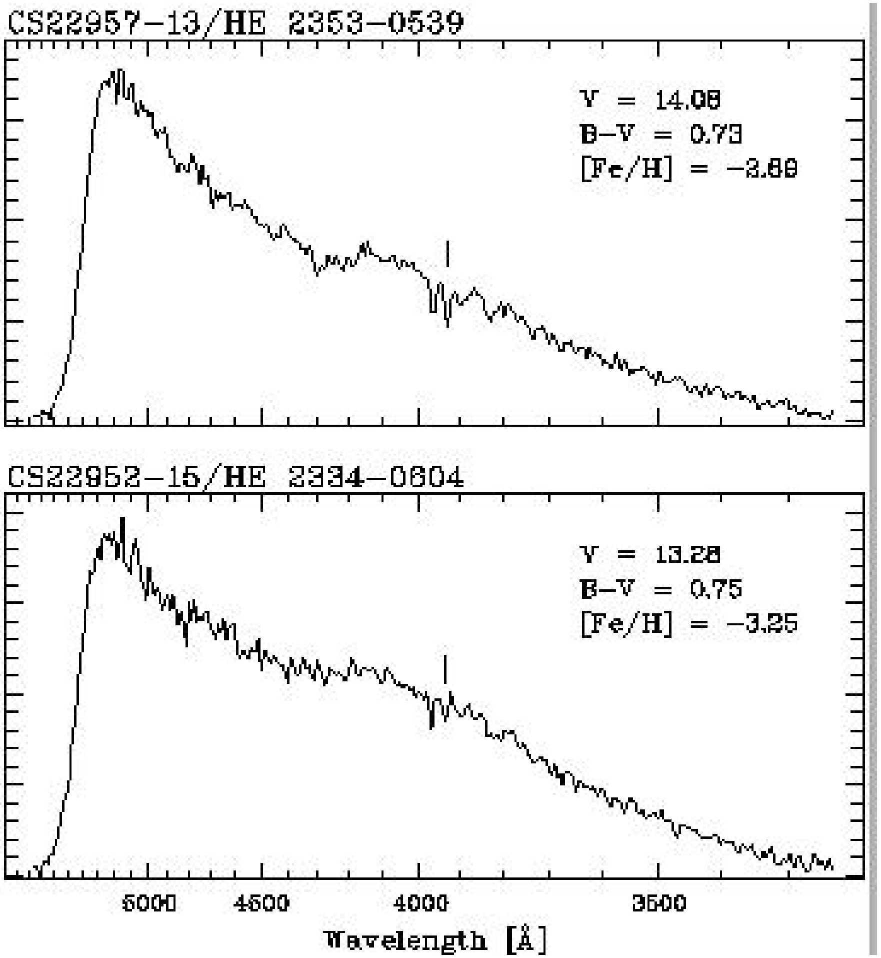
Abundances for C-rich EMP stars

The Neutron Capture Elements

Outliers and stars with [Fe/H] < -4.5 dex

The MDF of the Galactic Halo from the HES (NEW)

An example of the low res objective prism spectra from the HES (these are bright EMP stars found by the HK Survey)



HES: Objective Prism Survey for Bright QSOs

HES gives rough grade for EMP only. [Fe/H](HES) is obtained from follow up spectra applying updated algorithm used by the HK project developed by Shectman, Preston and Beers.

Relies on KP index (strength of 3933 CaII line) versus Teff as indicated by B-V, Hδ, or (after 2MASS available) J-K to derive [Fe/H](HES), calibrated with high-dispersion spectra [Fe/H]

Also an index measuring the G band of CH (GP)

Crude Taxonomy of EMP Stars

C-normal stars
  outliers (very few in number), including low (and high)-alpha stars

C-rich stars
  with (~80%) and without (~20%) s-proces enhancement
  small fraction – enhanced Na, Mg, Al, Si

r-process enhanced stars
  r+s enhanced stars

[Fe/H] ~ -5 dex stars

Key Themes Emerging from the Much Bigger HES Sample of EMP stars

Discovery of -5 stars, better data on C-rich EMP stars

Further tightening of small dispersions in [X/Fe] among C-normal stars for Ca to Ni

Evidence for internal mixing (C down, N up) among luminous giants (first reported by Cayrel et al)

Trends in [X/Fe] much more clearly defined than from earlier work.

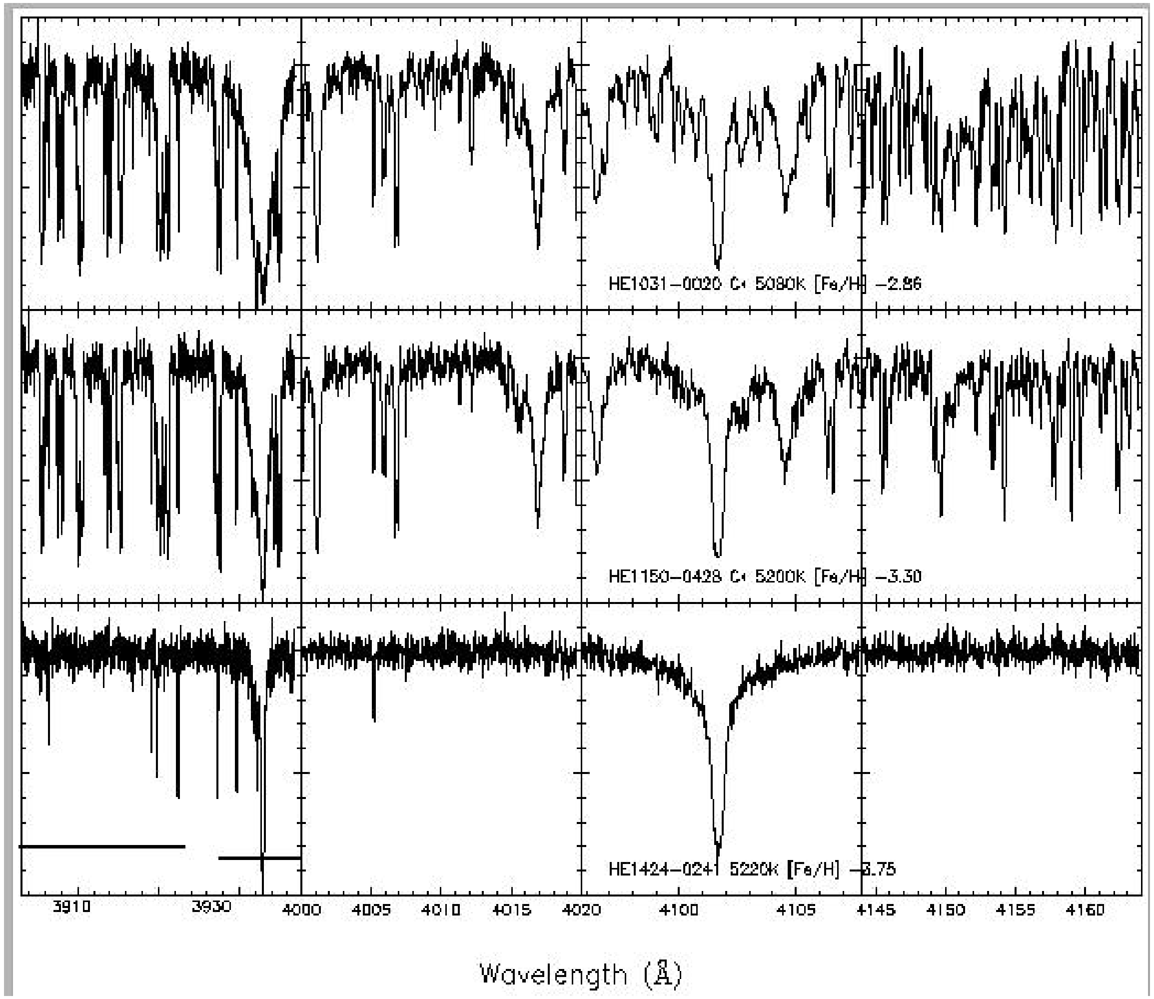
NEW: MDF – sharp drop below [Fe/H] ~ -3.6 dex

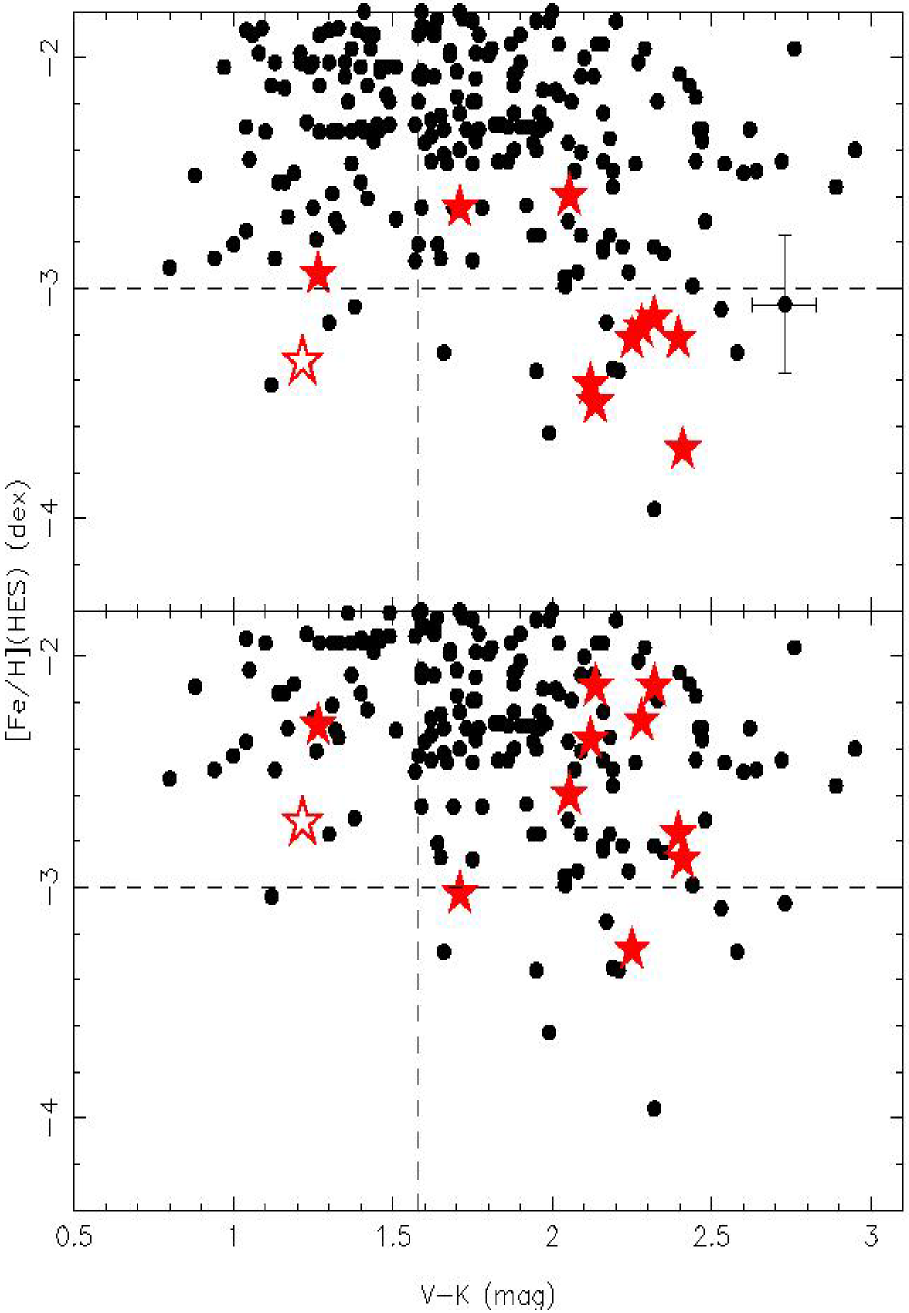
Lessons Learned re Validity of [Fe/H](HES)

- Do not use standard HES metallicity algorithms for highly C-enhanced cool stars, they are biased low by ~1 dex

- HES algorithms do work OK for stars which are not highly C-enhanced. Algorithms can be tested/tuned against set of stars with detailed abund. analyses

CH Absorption in the Continuum Bandpasses of the Beers et al [Fe/H] Estimation Algorithm as of 2005 (since corrected or C-rich stars omitted from samples)



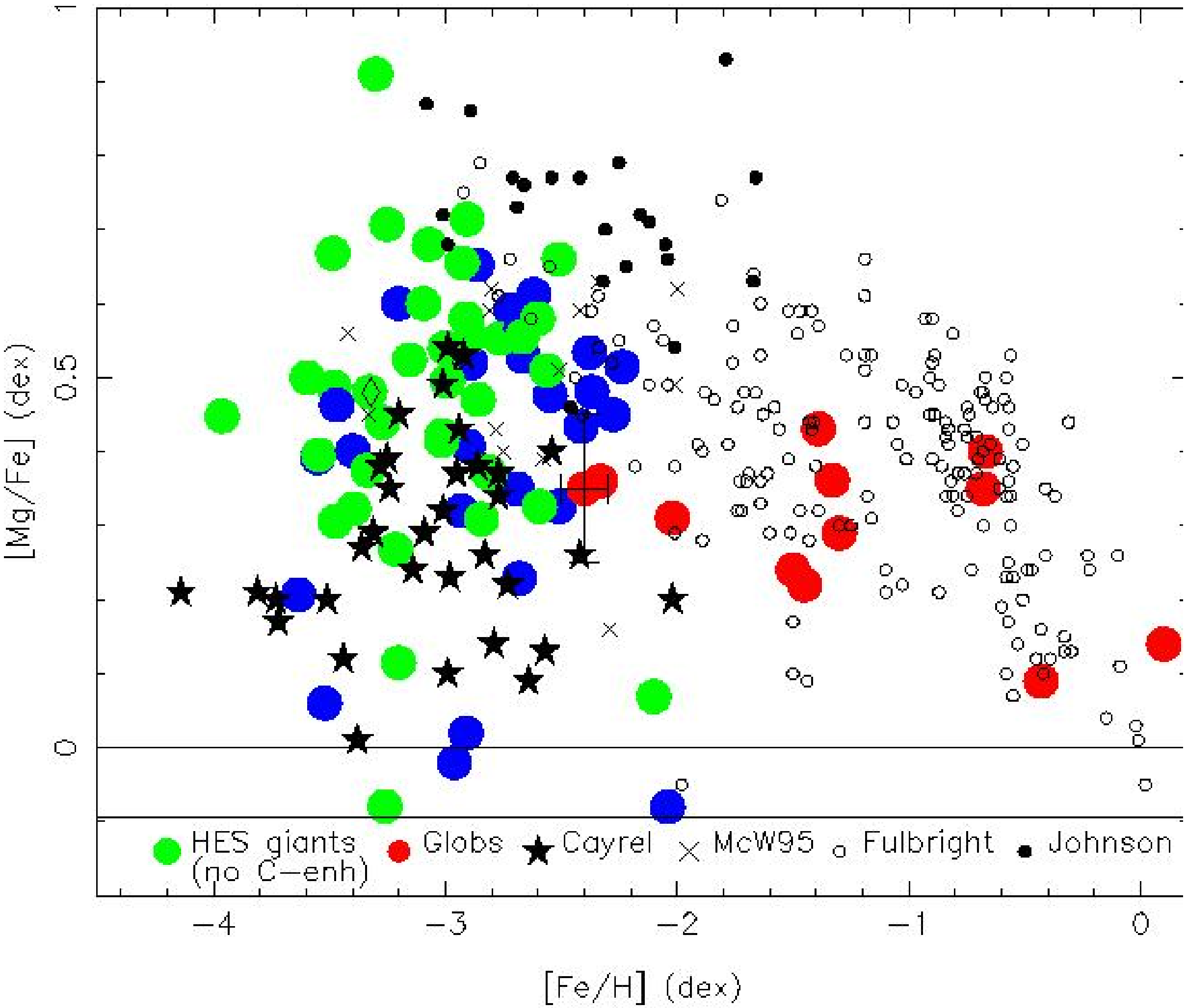


Distribution of [Fe/H] from the HES as a function of V-K (top)

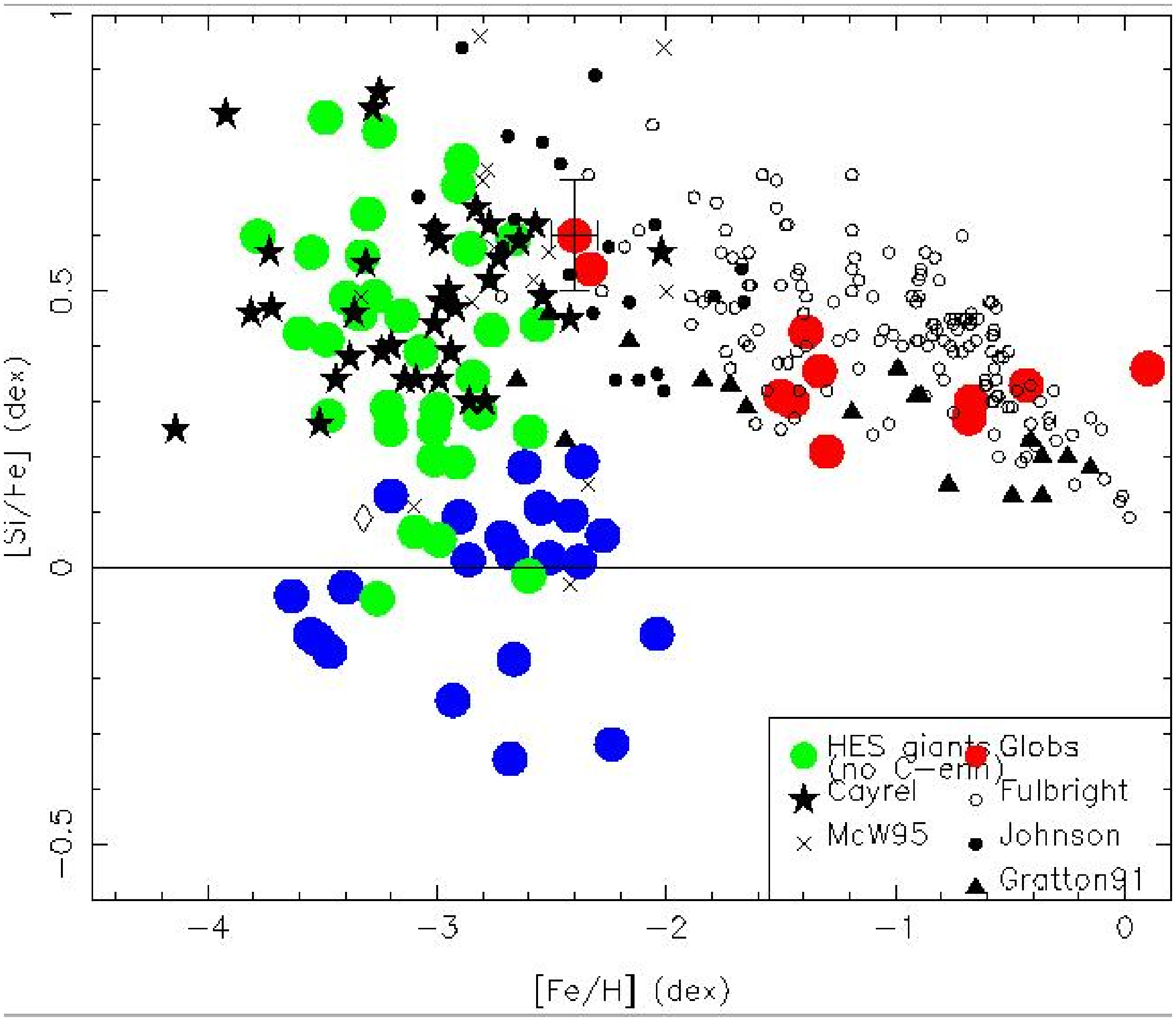
Bottom: [Fe/H]HIRES used when available.

Cohen et al, 2005, ApJL

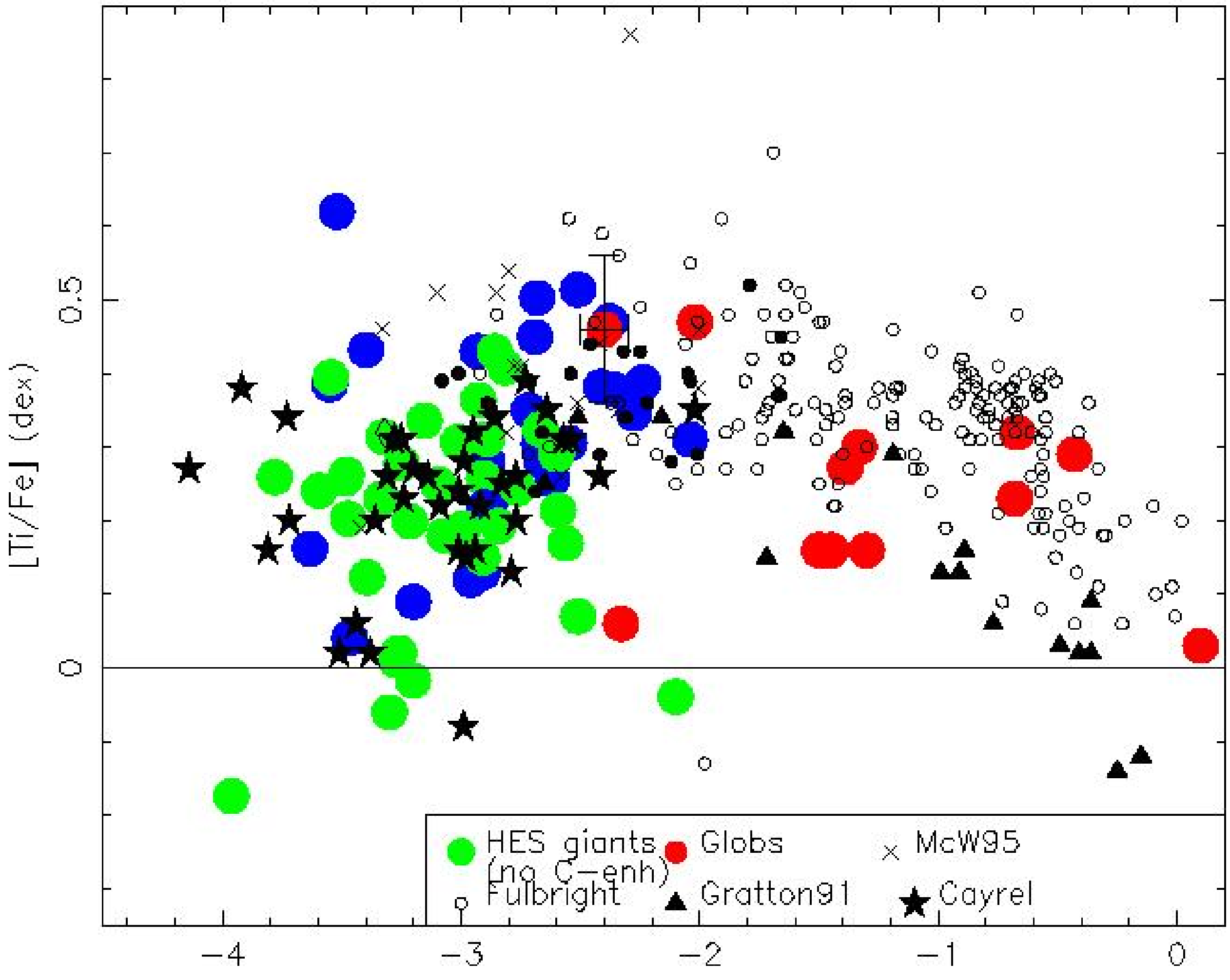
[Mg/Fe] for C-normal stars only, part of large range is from mixing in the most luminous giants, part is real range in initial chemical inventory, J.Cohen's unpublished set of homogenous abund analyses



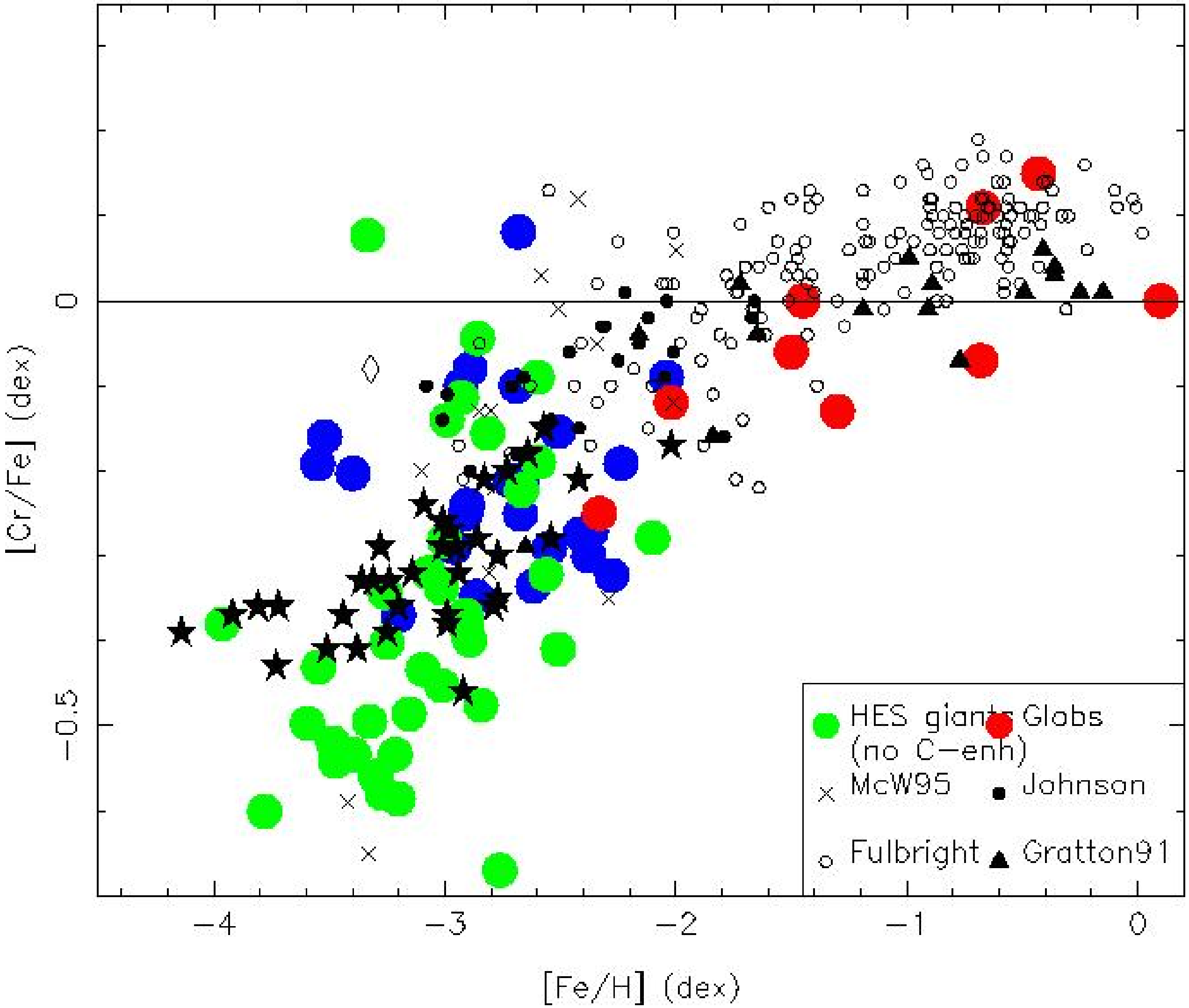
[Si/Fe] for halo stars, note problem EMP giants vs dwarfs



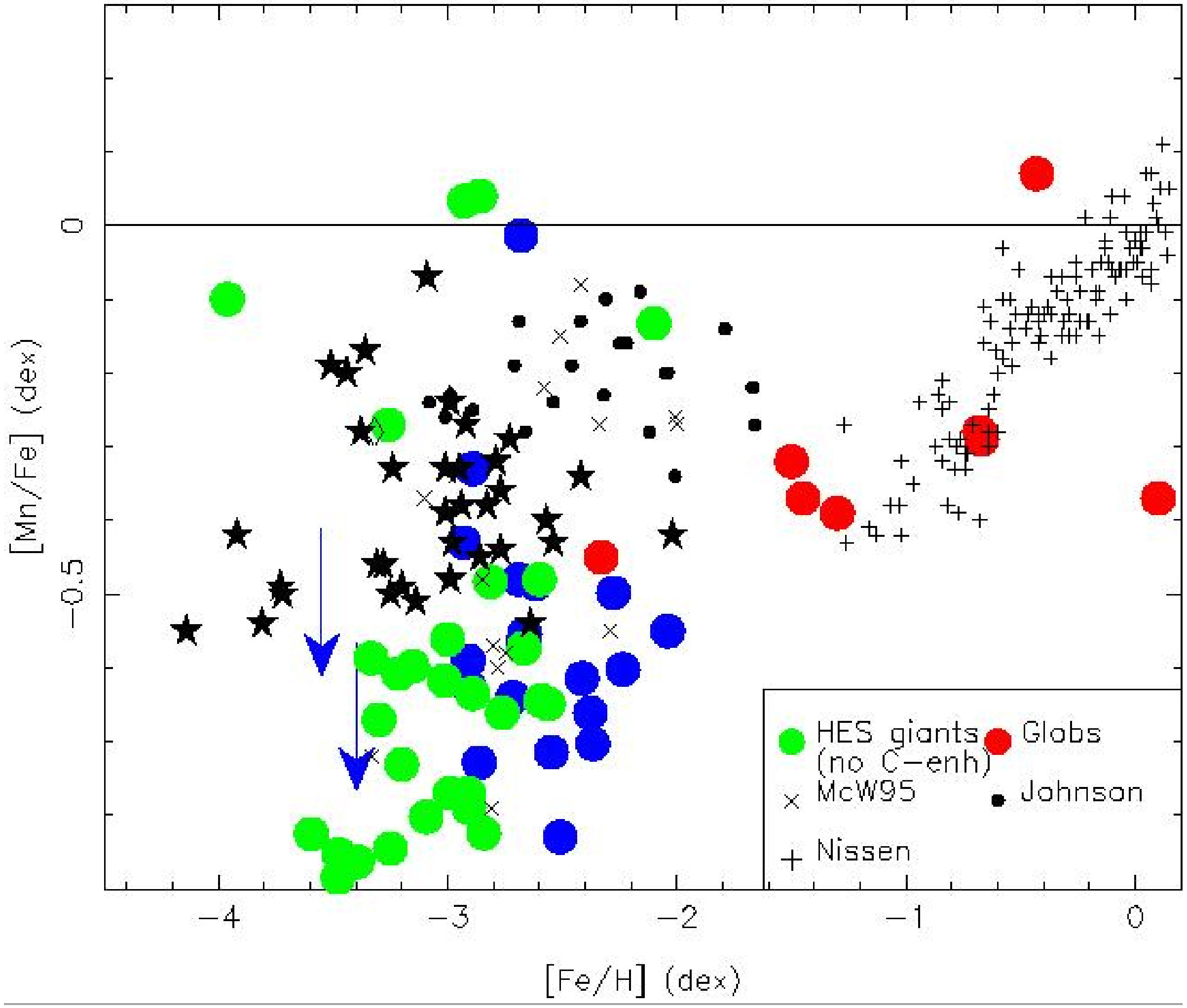
[Ti/Fe] (α element) showing gradual rise, then maybe a plateau



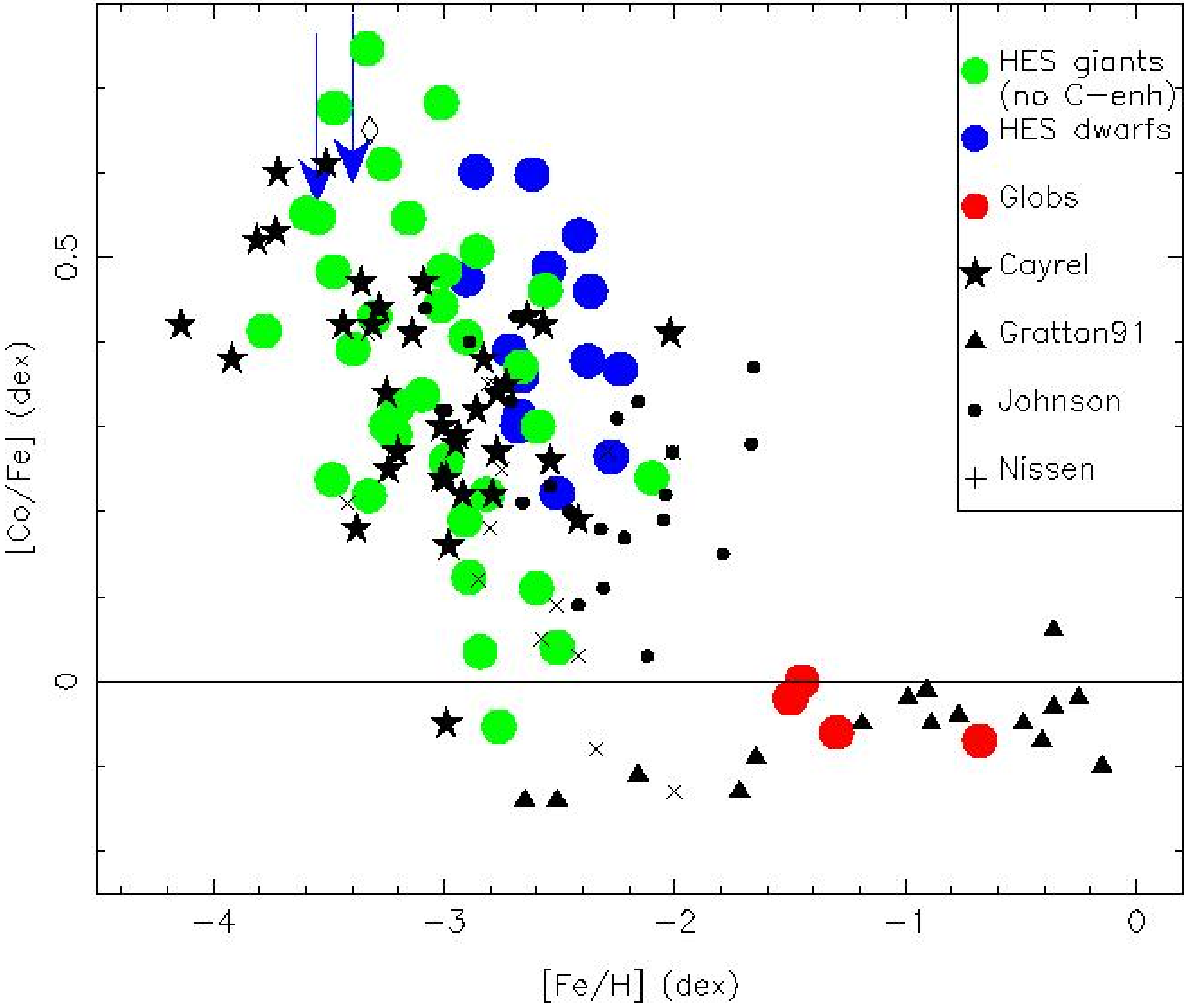
[Cr/Fe] vs [Fe/H], a trend which is almost certainly real, Cr has a reasonable number of non-resonance detected lines



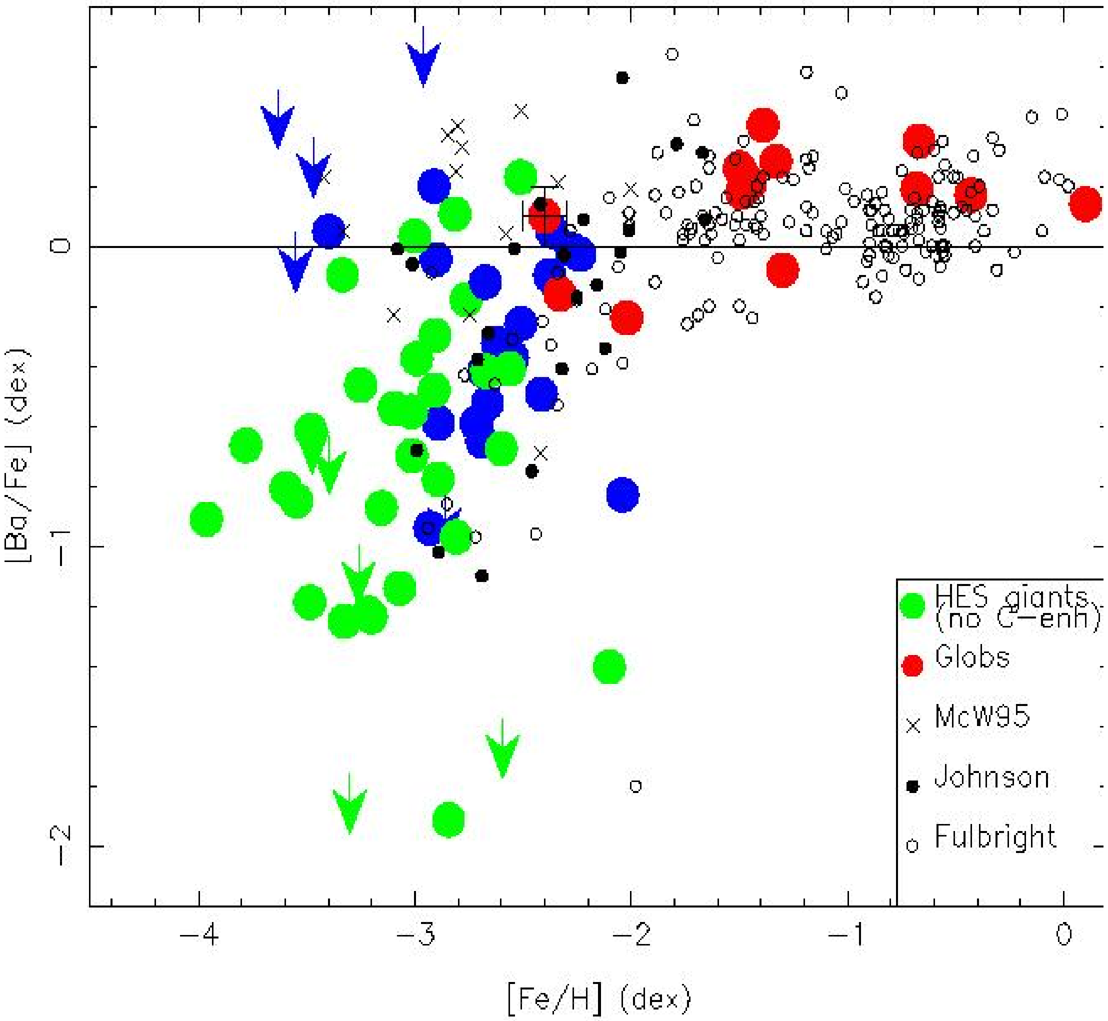
[Mn/Fe], offset Cayrel vs J.Cohen due to correction for use of strong resonance MnI lines, only ones that are seen in EMP stars



[Co/Fe] trend with [Fe/H], but only a very small number of Co lines detected in EMP stars



[Ba/Fe] for C-normal stars only, trend plus very large scatter



Impressions of Abund. Ratios Among EMP Stars

- Many separate processes contribute to chemical inventory: LiBeB, CNO, hydrostatic α (Mg), explosive α (Si, Ca, Ti), Fe-peak (SN), heavy elements via neutron capture s process (AGB stars) and r-process (SN ?)

- These appear decoupled among EMP stars, they operate independently of each other to first order.

- This leads to α-rich and α-poor stars with same Fe-peak abundances, n-capture rich stars vs n-normal with same Fe-peak abundances, etc.

Derived Constraints on Early IMF and SN

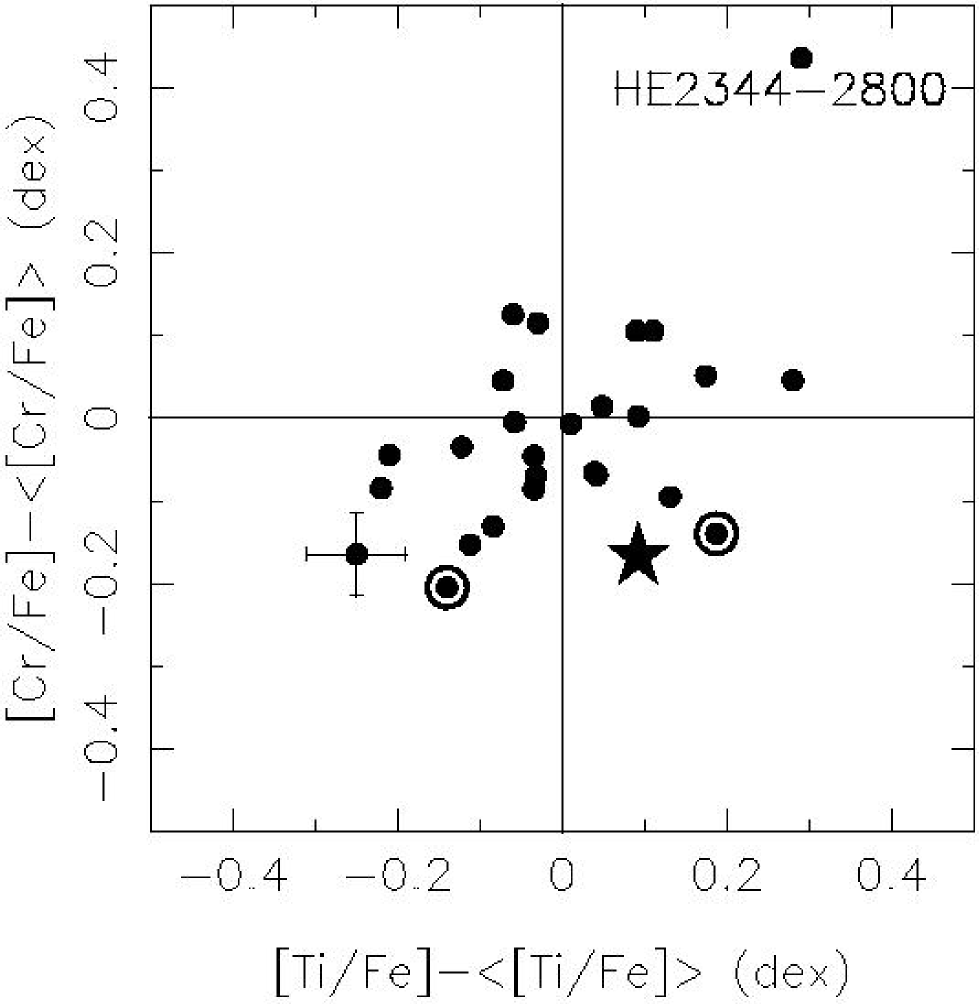
- Grids of SN models (explosion, nuclear reaction networks, fallback, ejection) by Nomoto, Umeda, Kobayashi, Woosley & Heger can reproduce most X/Fe trends up to Zn, trouble K, Sc, Mn, Co (all odd atomic numbers)

- No sign of PISN (low Z, no remnant, initial mass range ~140 to 260 Msun), big constraint on IMF

- Hypernovae (E > 10**52 ergs) probably important

- Low σ suggests a well mixed proto-galaxy or small range in chemical inventory of SN ejecta

Finding outliers among the EMP dwarfs, from J. Cohen’s internally consistent abundance analyses (outlier in both Cr and Mn/Fe)



The Very Peculiar [Fe/H] -4 star HE1424-0241

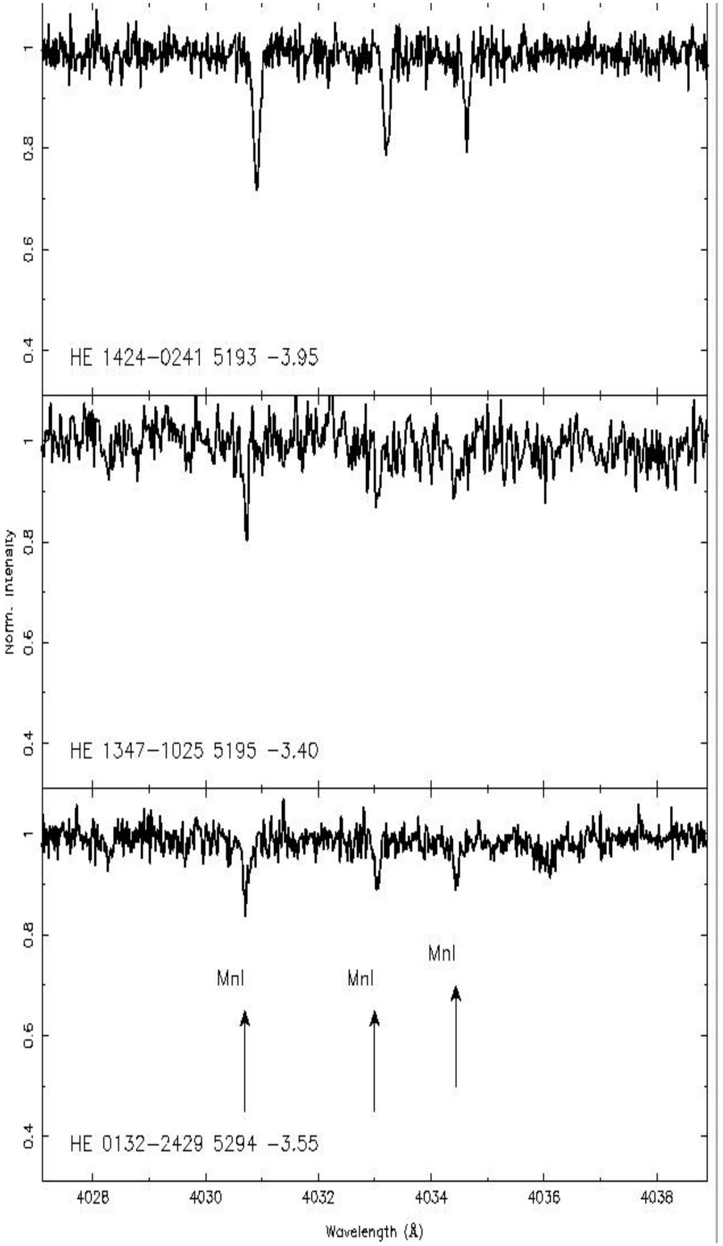
Normal Carbon

Highly depleted Si (i.e. low [Si/Fe]), strongly depleted Ca, Ti

Apparent separation of hydrostatic (Mg) and explosive α elements (also seen in dSph satelites)

Enhanced Mn and Co

None of the recent SN models can reproduce this star



A comparison of the MnI triplet in three EMP stars of similar Teff, HE1424-021 on the top has highly enhanced [Mn/Fe]

Origin of C-rich stars

Much easier to make C-rich (or anything rich) stars among EMP stars because X/H is so low initially. 15 to 25% of EMP stars are C-rich between -4 < [Fe/H] < -2.5 dex.

See this in increasing C/M ratios luminous giants in Galaxy, LMC, SMC

Approx constant C/H of most extreme C-rich stars at [C/H] ~ ¼ Solar at all [Fe/H] (even extending to -5 stars)

This suggests a source producing C primordially (just from H) with a fixed maximum efficiency, supporting binary mass transfer

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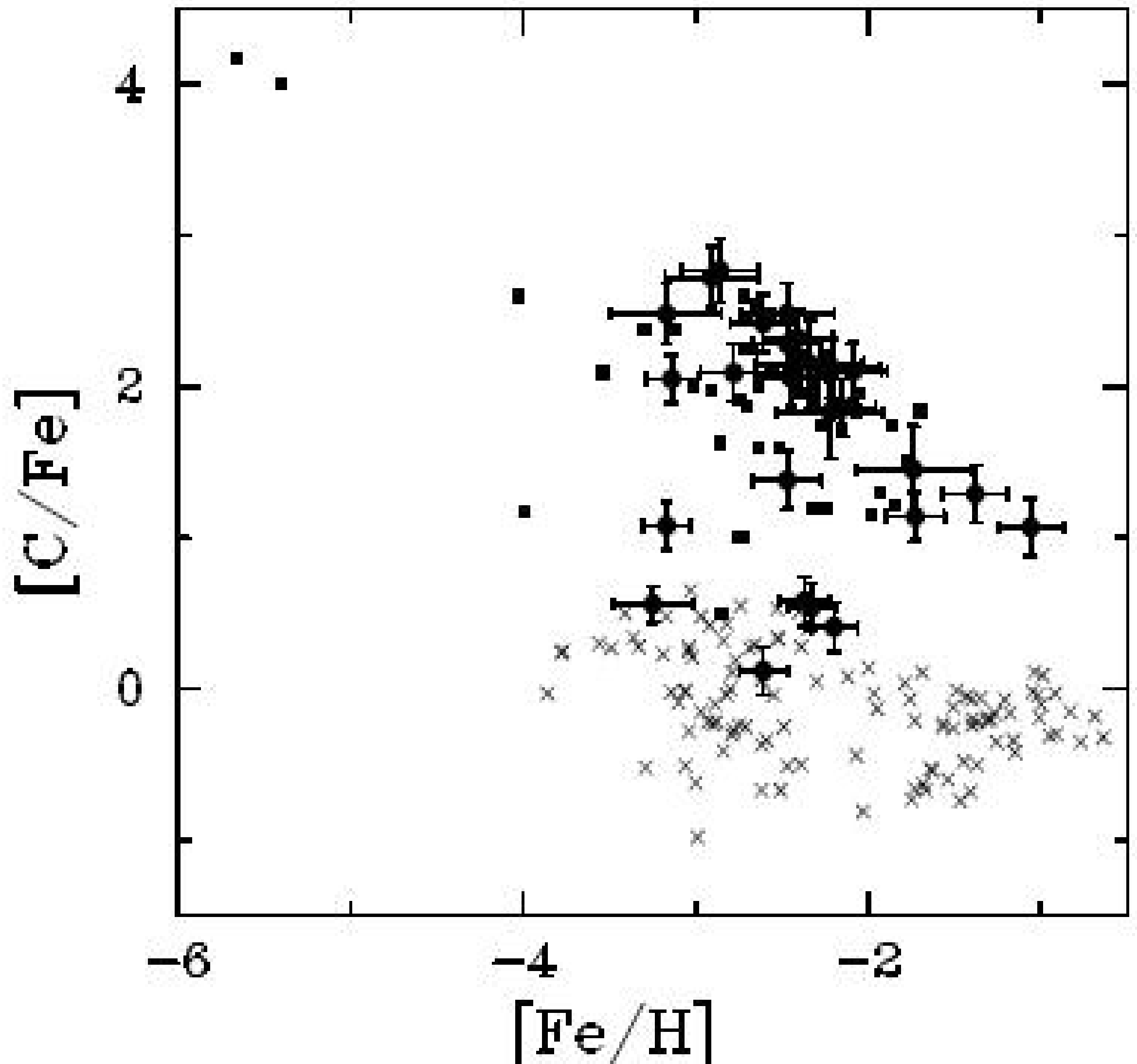
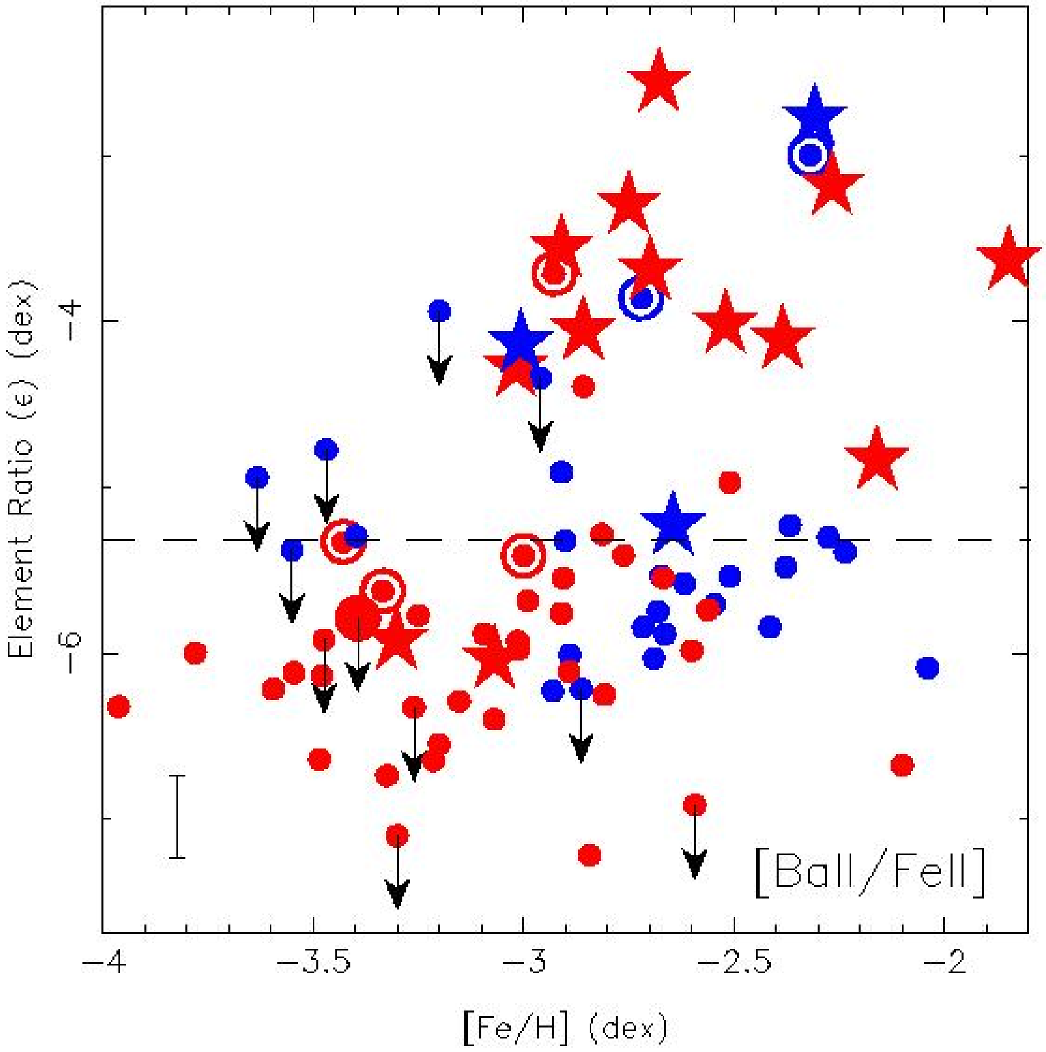
Judy Cohen, 9/4/2008

[C/Fe] vs [Fe/H] including -5 stars, from Aoki et al (2007)



[Ba/Fe] vs [Fe/H]. C-stars often have very high Ba. From J. Cohen's abund anal of 87 HES EMP candidates



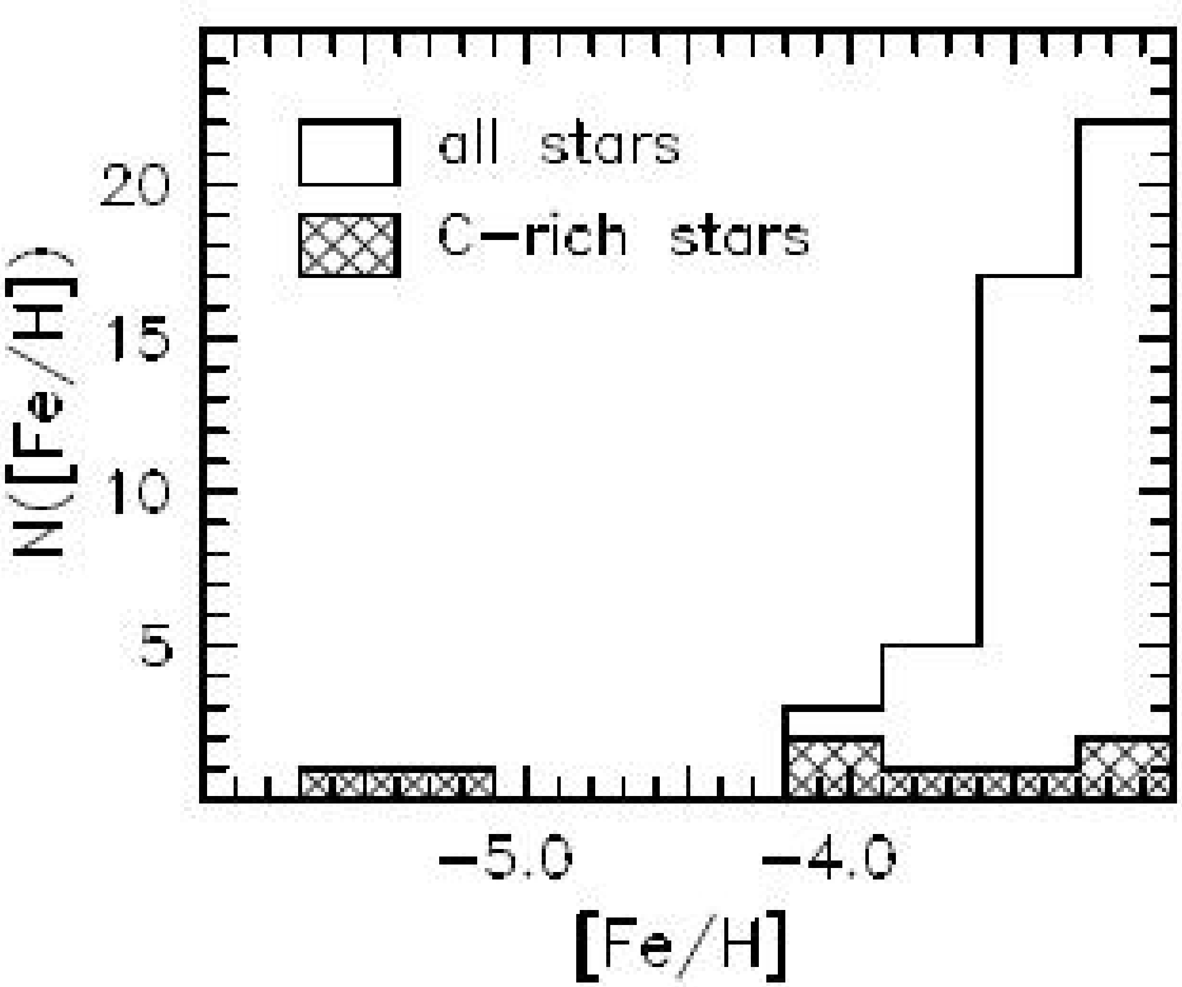
[Fe/H] ~ -5 Stars (only 2 known, of ~7000 candidates with spectra)

- No stars below -4 dex found in HK Survey
- Two found in HES at ~-5.3 dex, plus one more at -4.75 dex (Christlieb, Frebel, Norris…) 1st one, HE0107-520 found in 2002)
- All 3 have very high C/Fe, [C/Fe] ~ 4 for -5.3 stars, 1.6 for -4.8 star, so these stars are anomalously Fe-poor, not anomalously low Z
- N also highly enhanced, O as well, when abund known
- Remaining elements more or less like stars at -4.0 dex

Formation Mechanisms for -5 stars

- At what Z can low Z clouds cool and low mass stars form
- Mass transfer from AGB * in binary (can’t rule out yet)
- Single star with ejecta from rotating massive stars (Meynet) ~50 Msun
- Ejecta from SN with specific unusual mass cut and fall-back (Umeda, Nomoto, Iwamoto)
- Ejecta from a 2 different SN (Heger & Woosley)
- Many other hypotheses and many published speculative papers
- We need to find more such stars, but finding many more is going to be hard.

Increase in fraction of C-rich stars at very low Fe/H, from Norris et al, 2008 (star at -4.8 also C rich)

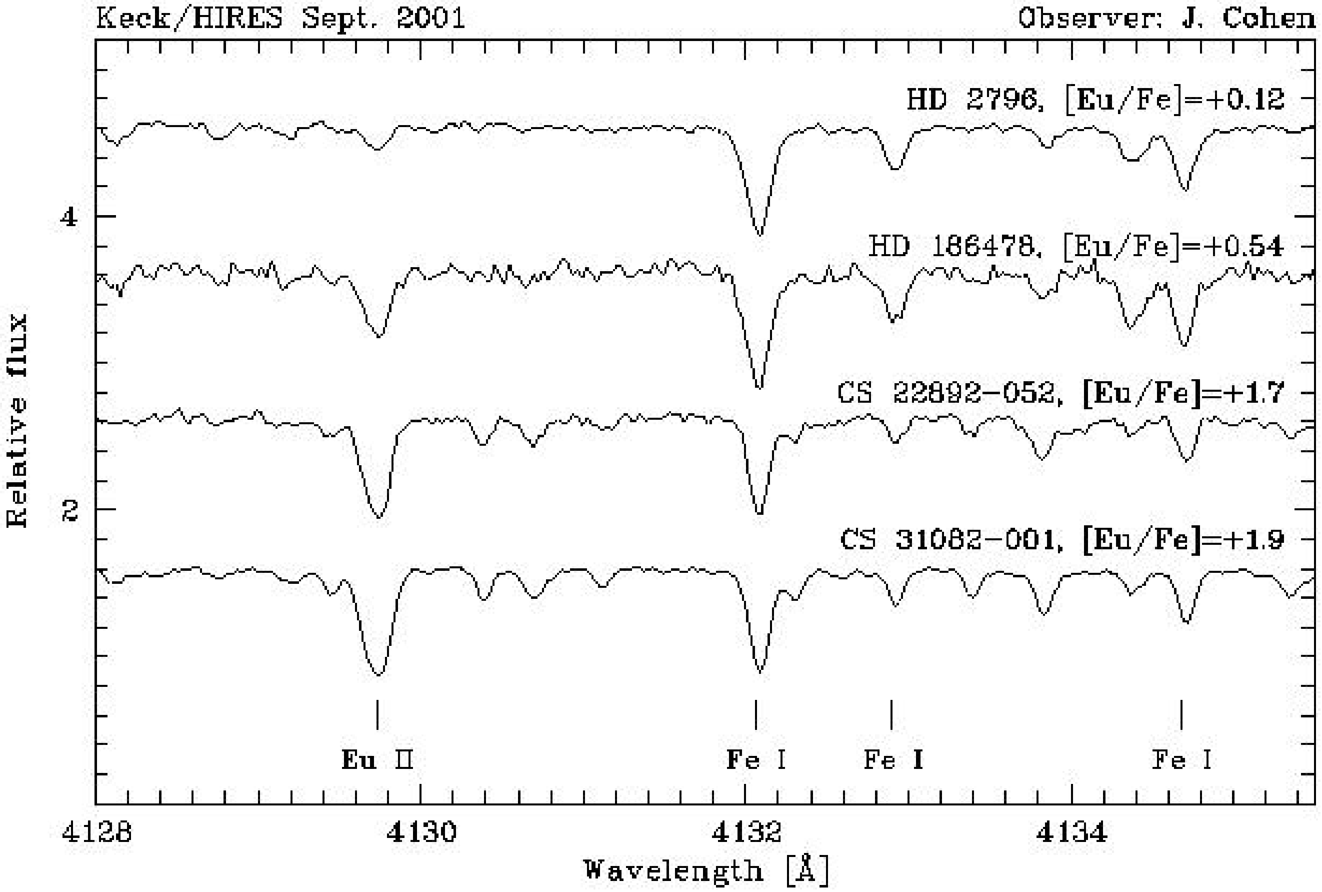


Highly r-process enhanced stars [Eu/Fe] > 1 dex

- Wide range of X(heavy neutron capture)/Fe at low [Fe/H]. Production mechanisms are decoupled
- rII stars rare (~3% of stars at [Fe/H] -2.8) (HERES, Barklem 2006)
- Useful for cosmochronology, if can detect uranium (and Th)
- Closely follow Solar r-proces abundance ratios beyond Fe-peak
- Most have [Fe/H] ~ -2.8 dex

Suggest hypothesis: add a fixed maximum amount of Eu (i.e. Eu/H), this fixed increment too diluted to detect in higher Fe stars, lower Fe stars do not show this, perhaps because either timescale too short or not enough seeds to produce the Eu.

Eu is easiest (by far !) r-process element to detect



CS22892-052, prototype r-star, [Eu/Fe] ~ 1.6 dex (40 x Solar), compared to Solar r and s-process distributions from Burris (fig from Sneden et al 2003)

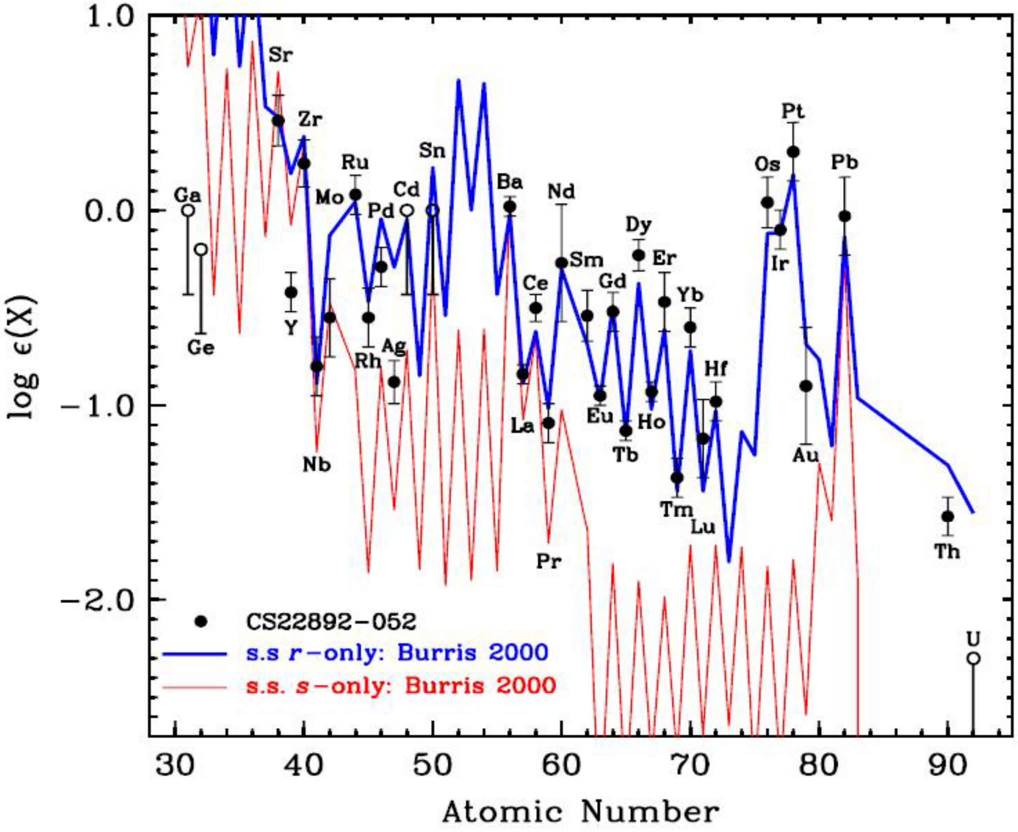
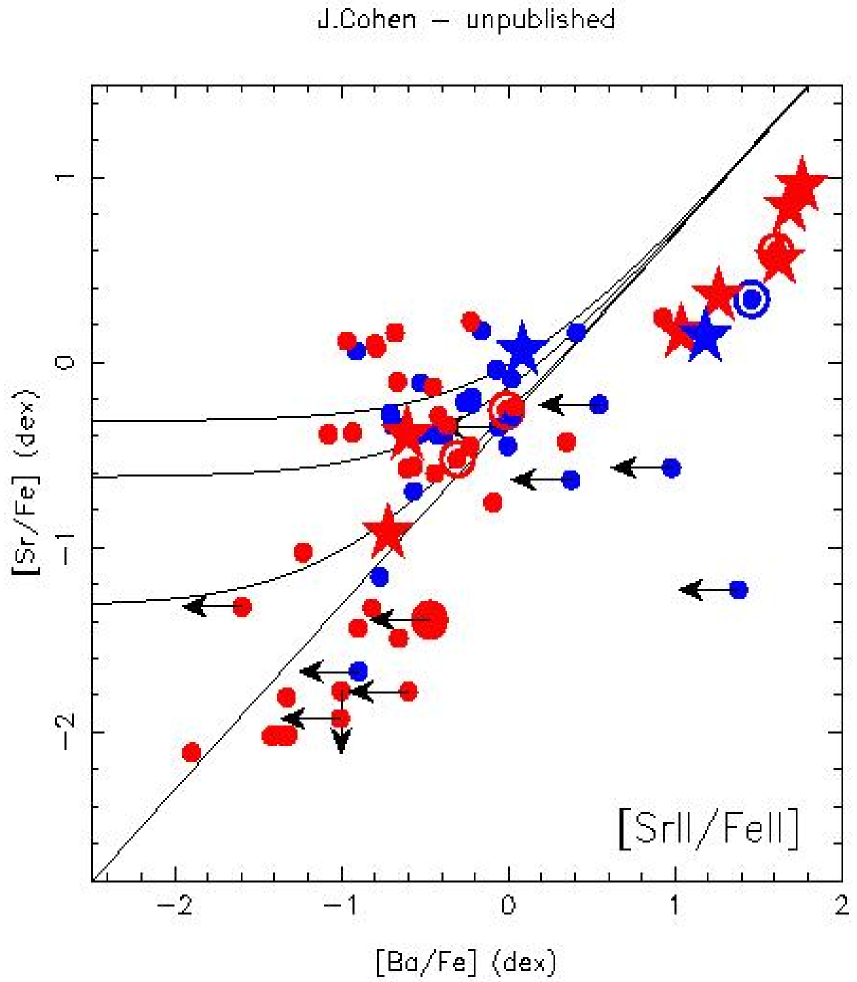


Fig. 6.— Observed n-capture abundances in CS 22892-052 and two scaled solar-system abundance distributions (Burris et al. 2000). Detected elements are shown as solid circles with complete error bars, and upper limits are denoted with open circles with only the lower half of an arbitrary-length error bar. The solar-system r-process abundance set (solid line) is vertically scaled by a single additive constant to match the observed Eu abundance, while the s-process set (dashed line) is scaled to match the observed Ba abundance.

New (ApJ 2008) model of Qian & Wasserburg including low-mass & normal SNII and hypernovae in EMP stars, f(Fe,L*) 1 to 0



The MDF for the Galactic Halo Field Stars from the HES

- The HES was designed to find EMP stars with [Fe/H] < -3 dex.
- Since higher Fe-metallicity stars are much more common, the HES strongly rejects them
- The metallicity distribution of the Galactic halo field thus cannot be derived directly from HES star counts.
- A selection efficiency correction must be derived and applied to obtain the true MDF for the Galactic halo field.

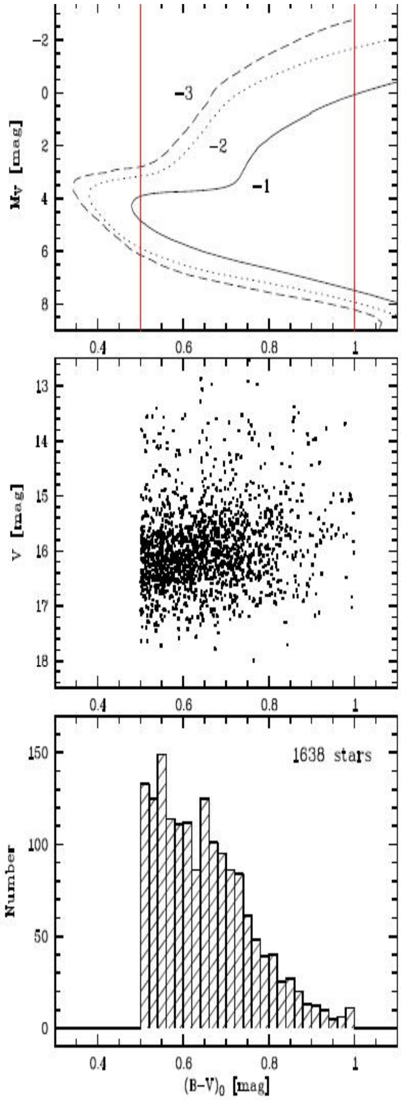
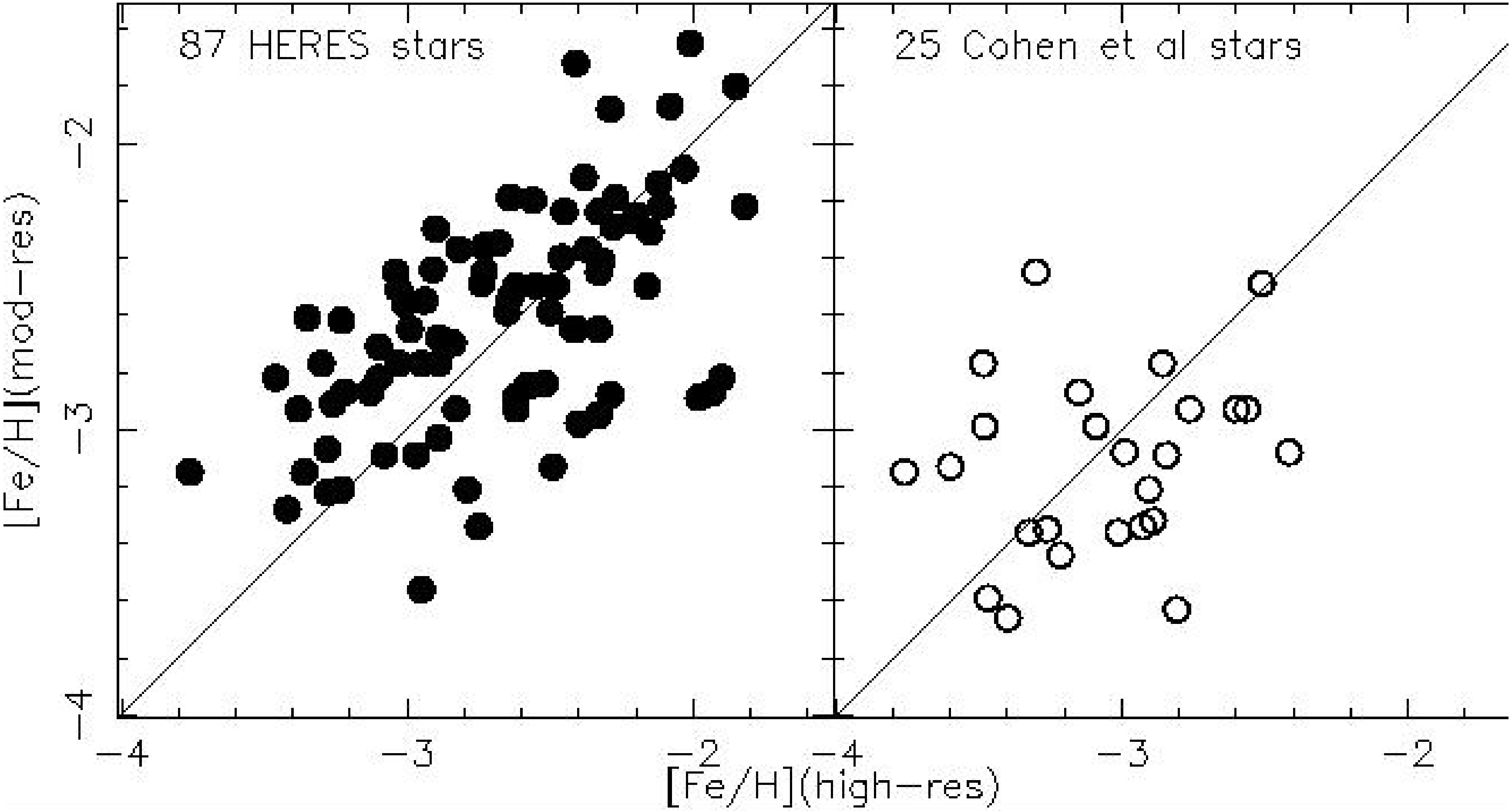


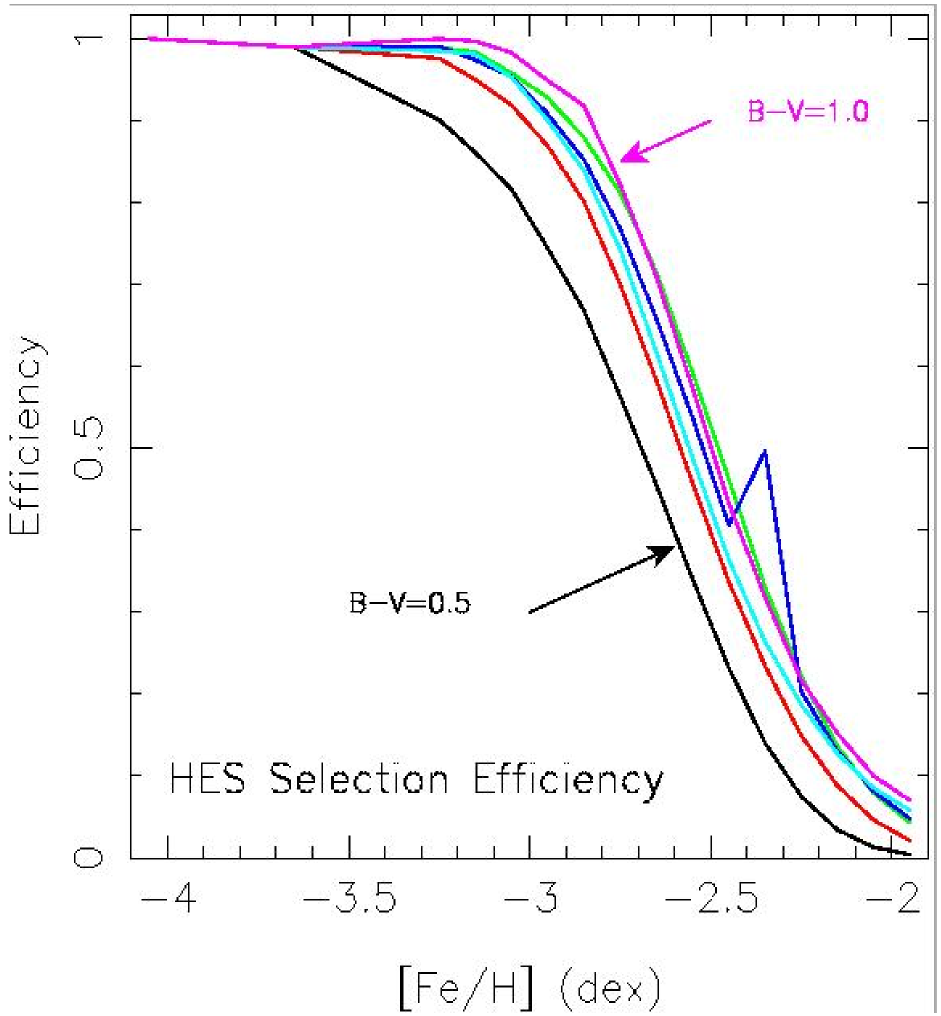
Fig. 1. Upper panel: Isochrones for an age of 12 Gyr and metallicities of [Fe/H] = −1, −2, and −3 (Kim et al. 2002); middle panel: *V* magnitude distribution of the HES sample from which we construct the halo MDF; lower panel: $(B-V)_0$ distribution. Taking into account that the peak of the MDF our sample is approximately at [Fe/H] = −2.2 (see e.g. Fig. 6), one can read from this figure that the bulk of our stars are located at distances of ~ 6 kpc from the Sun, and that a few cool giants are more than 50 kpc away.

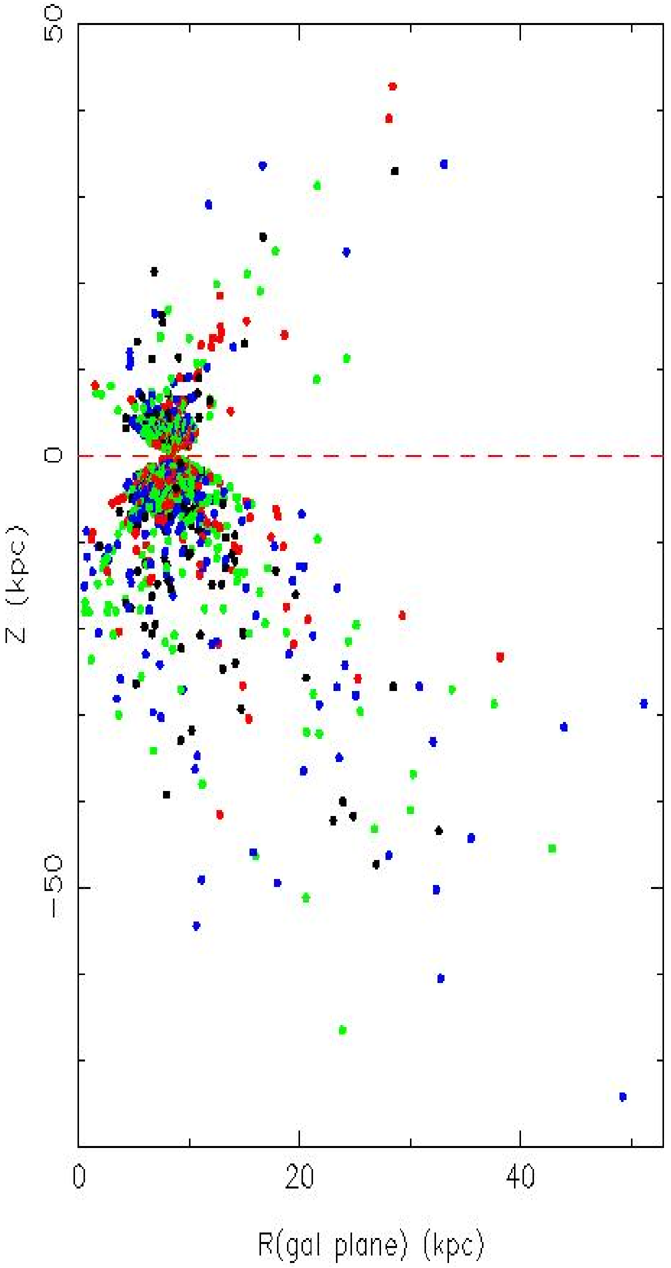
HES statistically complete sample, 1638 stars within
0.6 < (B-V)o < 1.0 mag

Comparison of [Fe/H](HES) from follow-up mod-res spectra based on 3933 KP index and Hδ with that from high dispersion abundance analyses



Selection efficiency of the HES as a function of [Fe/H] for B-V 0.6, 0.7,..,1.0 mag. HES design: [Fe/H] < -2.5 dex





Z above gal. plane
versus R (proj onto
Gal plane) for HES
statistical sample.

Red: [Fe/H >-1.2
Green: -2.2 < [Fe/H]
> -1.2
Blue: -2.8 < [Fe/H]
< -2.2
Black: [Fe/H] < -2.8

Heavy suppression
of high [Fe/H] stars
via selection eff.
Large range at all Z.

Comparison of the HES Halo MDF with various models, big dropoff at [Fe/H] < -3.6 dex

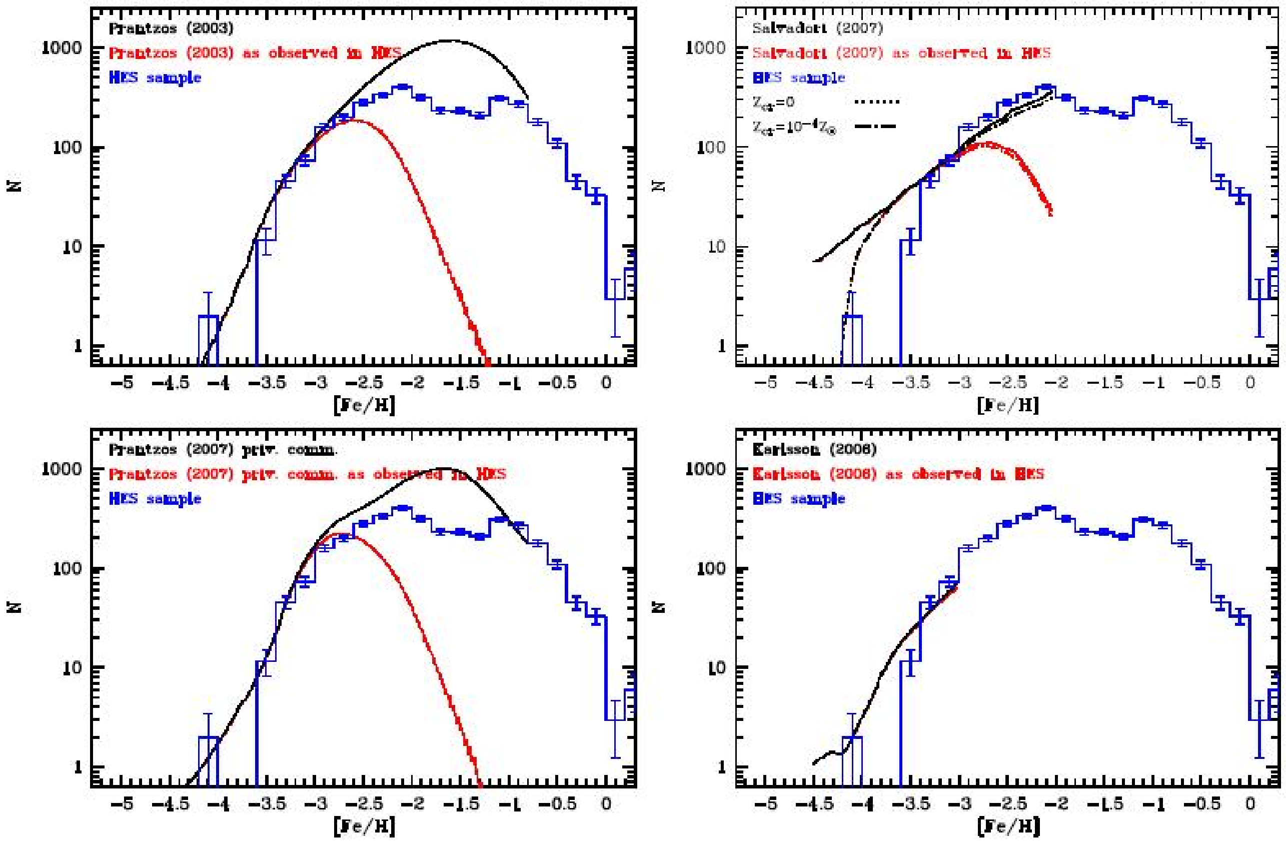
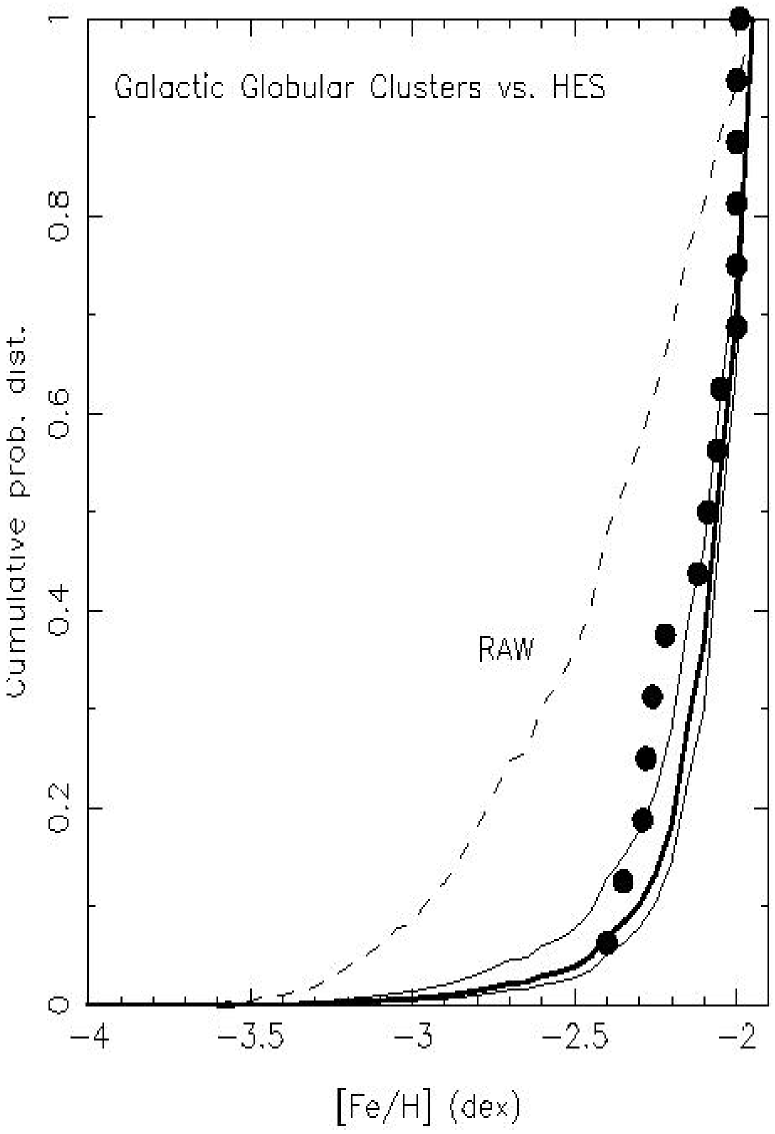


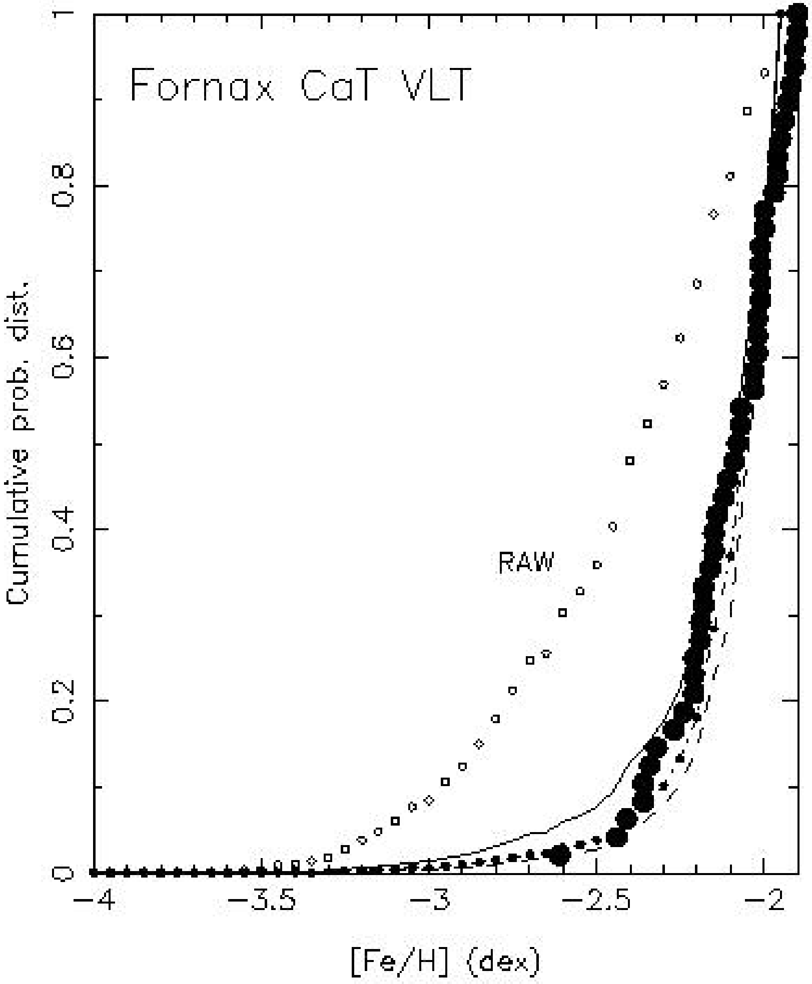
Fig. 10. Comparison of the MDF observed in the HES with theoretical predictions. Upper left panel: Prantzos (2003); upper right panel: Salvadori et al. (2007); lower left panel: Prantzos (2007); lower right panel:Karlsson (2006).



Comparison of HES halo field cumulative MDF with that of Gal GCs for [Fe/H] < -1.95 dex
(16 GCs)

Note importance of HES sel. eff and good agreement once they are used.

Same for Fornax dSph, data Battaglia et al (VLT survey), 48 giants [Fe/H] < -1.9 dex. Same result ! Same Draco and UMi dSph



Conclusions re GC/dSph and Gal halo field MDF

ONCE SELECTION EFFICIENCY CORRECTIONS ARE APPLIED TO THE GALACTIC FIELD STAR MDF DEDUCED FROM THE HES,

1. The GC MDF is, to within the uncertainties, identical to the halo field star MDF at [Fe/H] < -2 dex. (Both share the same [Ca/Fe] trend, so details of what index or features are used is not important.)

2. The same holds true for the Fornax, Draco, and Umi dSph galaxies modulo some issues regarding transforming Ca triplet line strengths to [Fe/H] .

3. The HES selection efficiency is small (<20%) for stars with [Fe/H] ~ -2 dex, that is why the apparent raw halo MDF contains a much higher fraction of EMP stars than do the GCs or dSph samples.

The Promise of SEGUE (SDSSII)

- Uniform mod. high res spectra, can skip the vetting required for HES samples, go directly to 8-10m
- Good multi-color photometry, uniform over sky
- Very large and deep samples

- Expect to find many stars at -3 to -3.5.
- Will better characterize the halo MDF below -4 dex
- Will explore outer halo better with its fainter mag limit

- 8-10m – will be hard to get spectra of fainter SEGUE stars, 30 m needed !