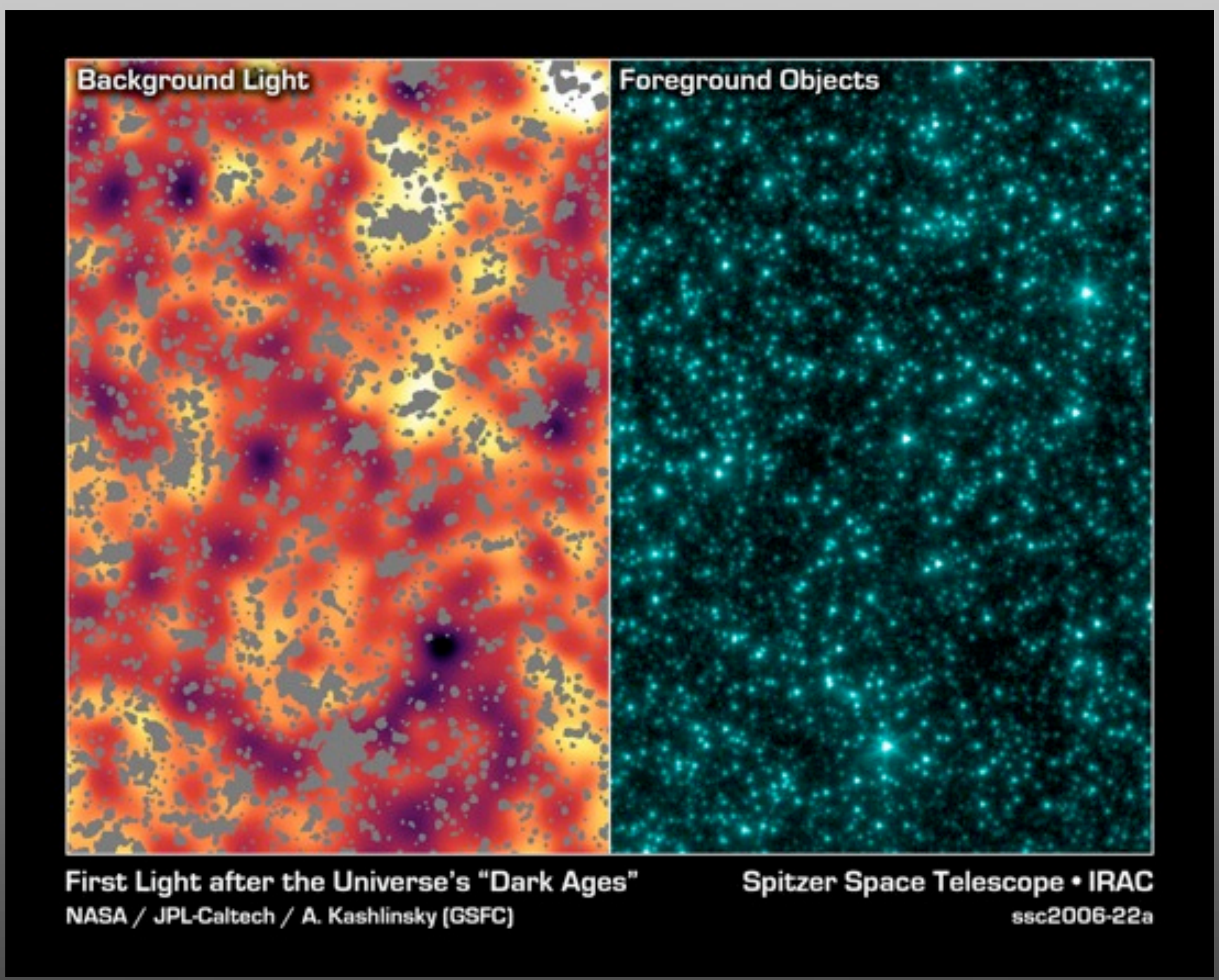
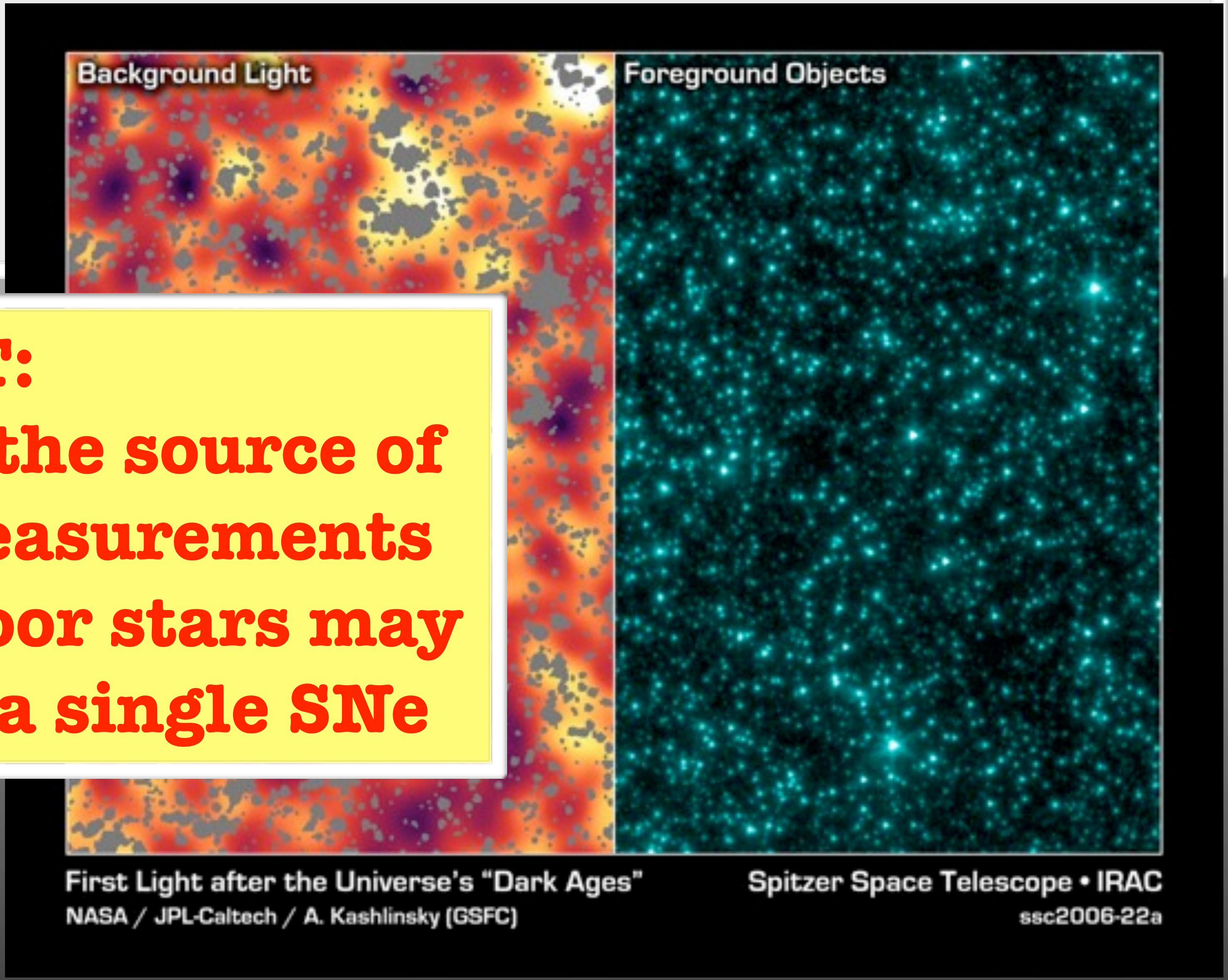
Chemical Abundances in the Most Metal-Poor Stars



Outline

- **Introduction**
- Target selection and observations
- Analysis
- Results
- Future directions



CONTEXT:
Metal-poor stars are the source of r-process element measurements and the most metal-poor stars may contain the ejecta of a single SNe

Japanese Contributions

Japanese astronomers have made significant contributions and provided international leadership in the study of nucleosynthesis, chemical abundances and metal-poor stars.

Ando	Ito	Takada-Hidai
Aoki	Iwamoto	Takeda
Arimoto	Kajino	Tominaga
Chiba	Kobayashi	Tsujimoto
Fujimoto	Maeda	Umeda
Honda	Nomoto	Wanajo
Ishigaki	Shigeyama	Yoshii
Ishimaru	Suda	and many others!

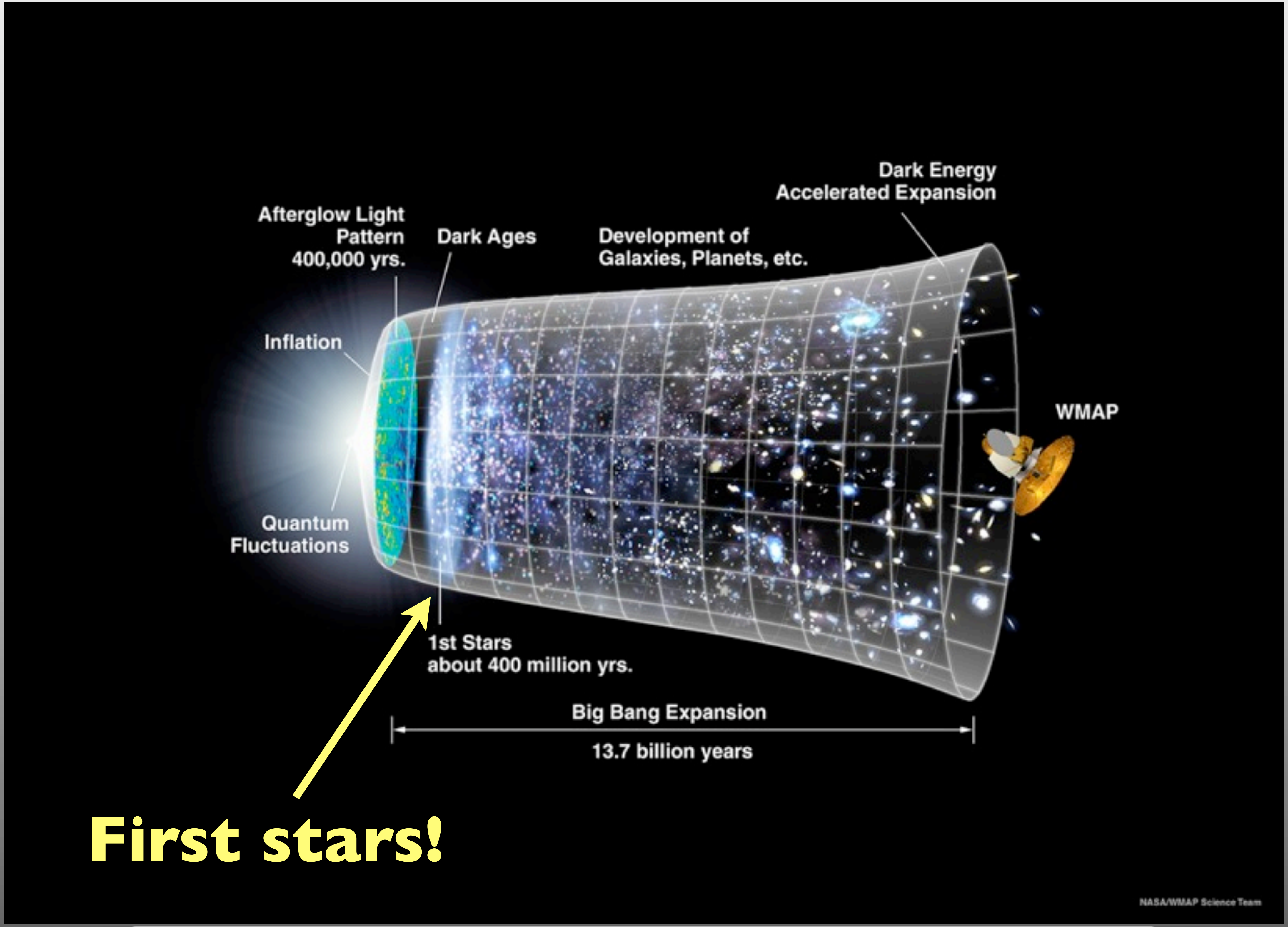
Collaborators

John Norris (ANU)
Mike Bessell (ANU)
Norbert Christlieb (Heidelberg)
Martin Asplund (ANU)
Timothy Beers (NOAO, MSU)
Paul Barklem (Uppsala)
Anna Frebel (MIT)
Sean Ryan (Hertfordshire)

Reasons to Care About the Most Metal-poor Stars

They provide insights into

- the nature of the first generation of stars
- the origin of the elements
- the early epochs of the Universe



They are the local equivalent of the high redshift Universe

Definitions

Name	Metallicity	Metallicity	#
Metal-poor	[Fe/H] < -1	1/10	150,000+
Very Metal-Poor	[Fe/H] < -2	1/100	30,000+
Extremely Metal-Poor	[Fe/H] < -3	1/1,000	1000+
Ultra Metal-Poor	[Fe/H] < -4	1/10,000	5
Hyper Metal-Poor	[Fe/H] < -5	1/100,000	2
Mega Metal-Poor	[Fe/H] < -6	1/1,000,000	0

Beers & Christlieb (2005)

Beers (2010)

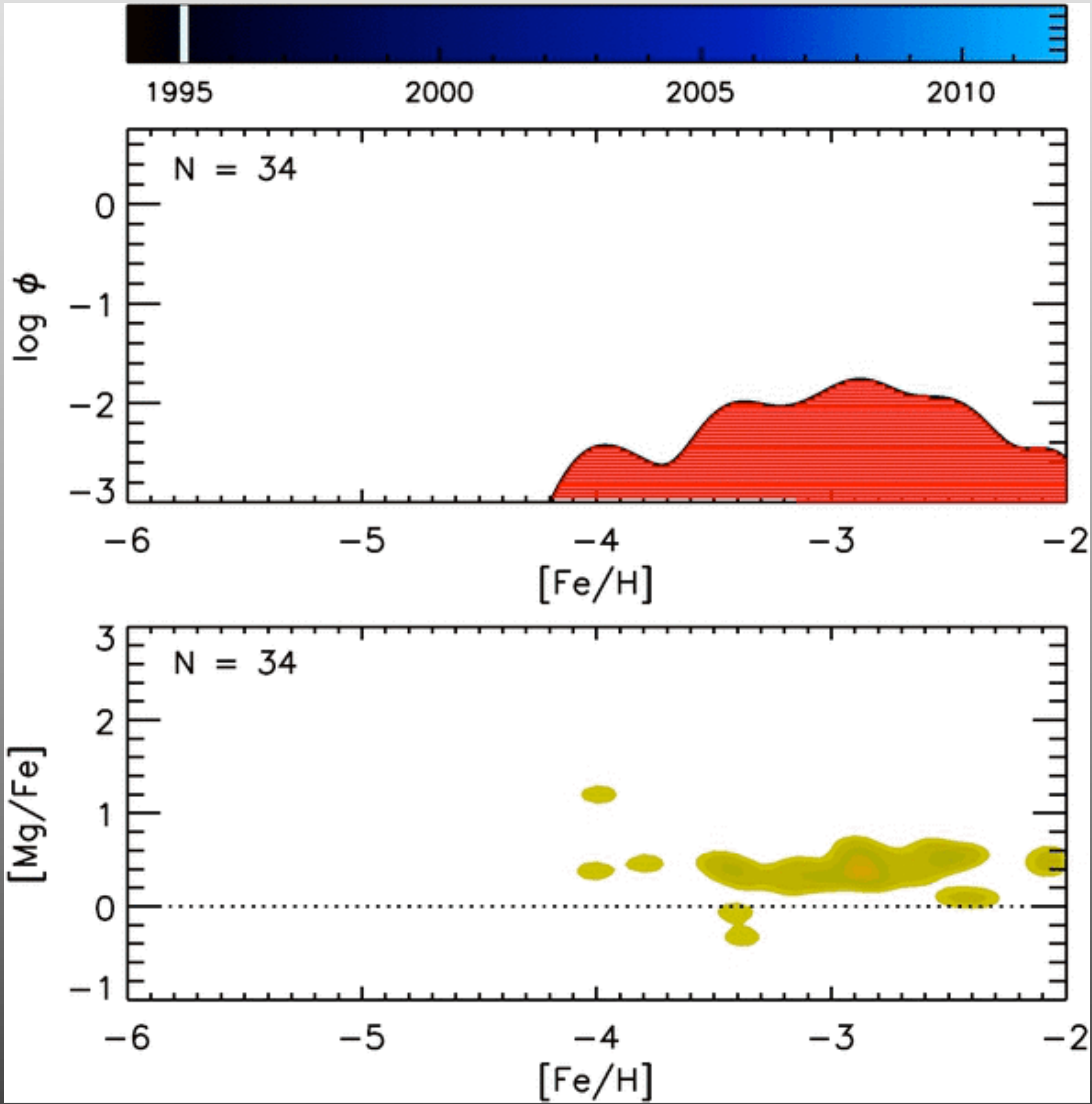
$$[Fe/H] = \log_{10}(Fe/H)_{\star} - \log_{10}(Fe/H)_{\odot}$$

The Need for More Data

Circa 2005, **only 14 stars with [Fe/H] ≤ –3.5** with published accurate elemental abundance ratios (~40 such objects now published)

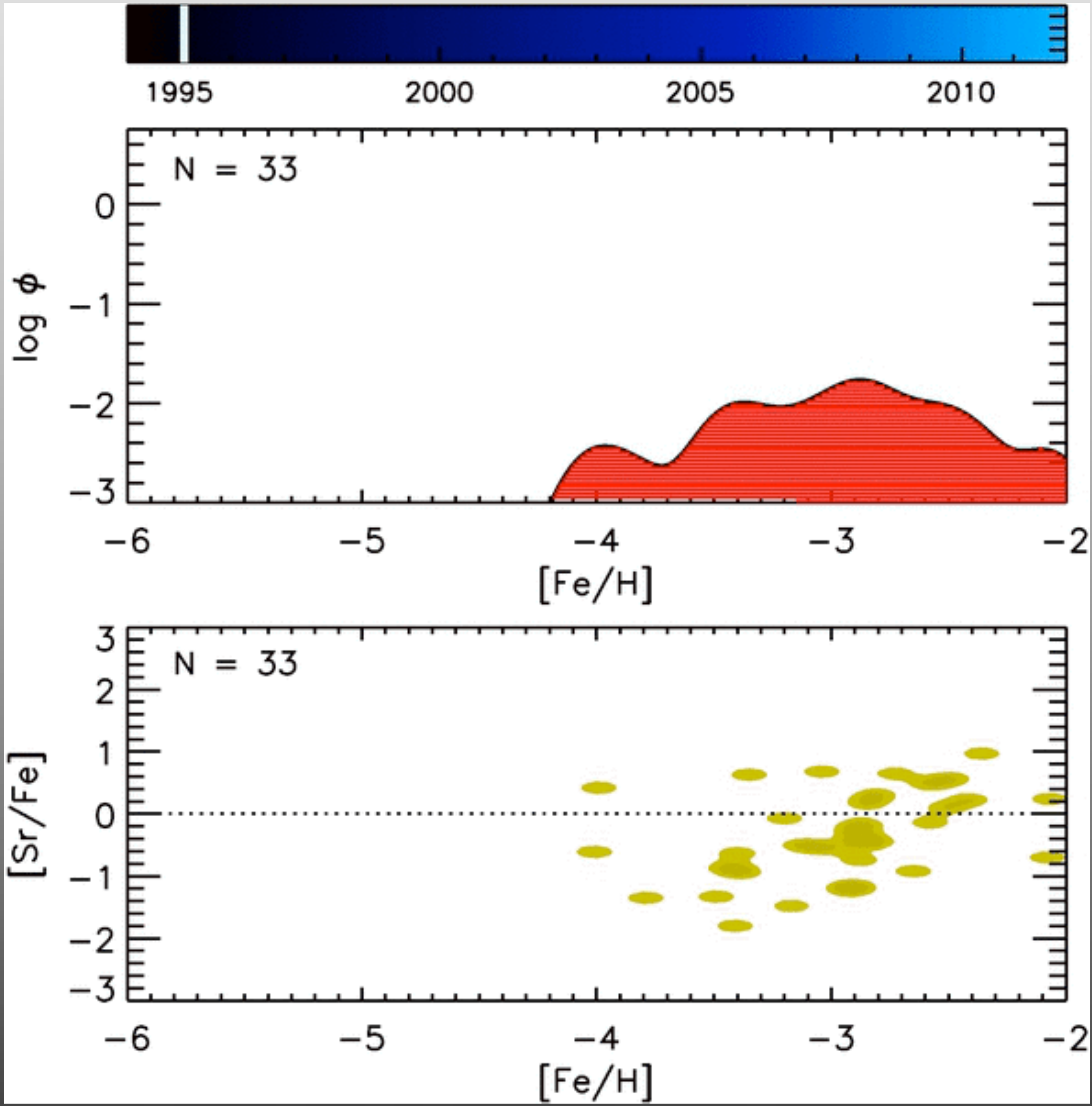
Only four stars with [Fe/H] ≤ –4.5, three of which were discovered within the Hamburg ESO Survey (HES) by our group (Bessell, Christlieb, Frebel, Norris etc.)

The Need for More Data



Animation generated using stars with [Fe/H] < -2.0 from the SAGA database (Suda 2008,2011)

The Need for More Data



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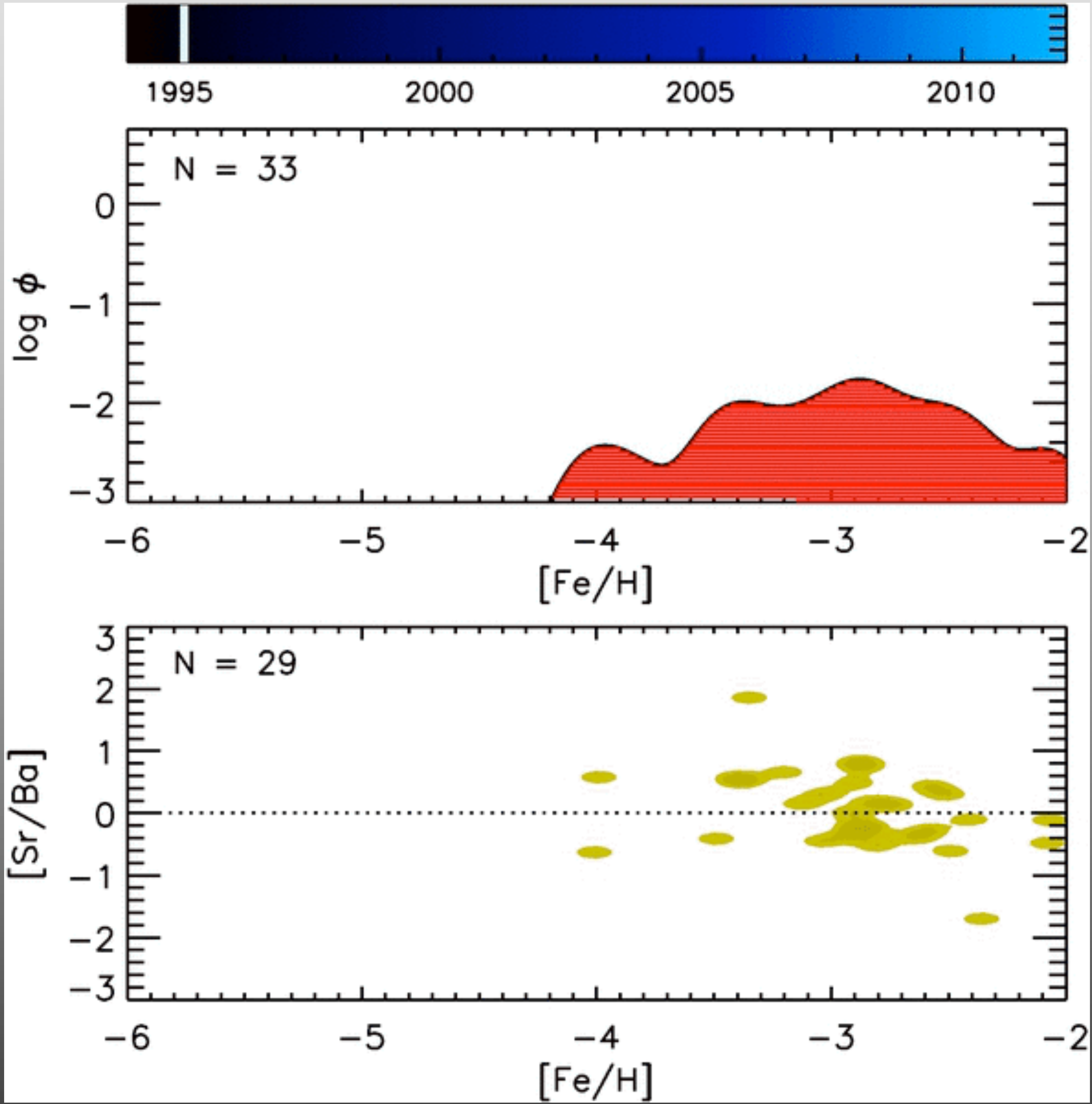
The Need for More Data



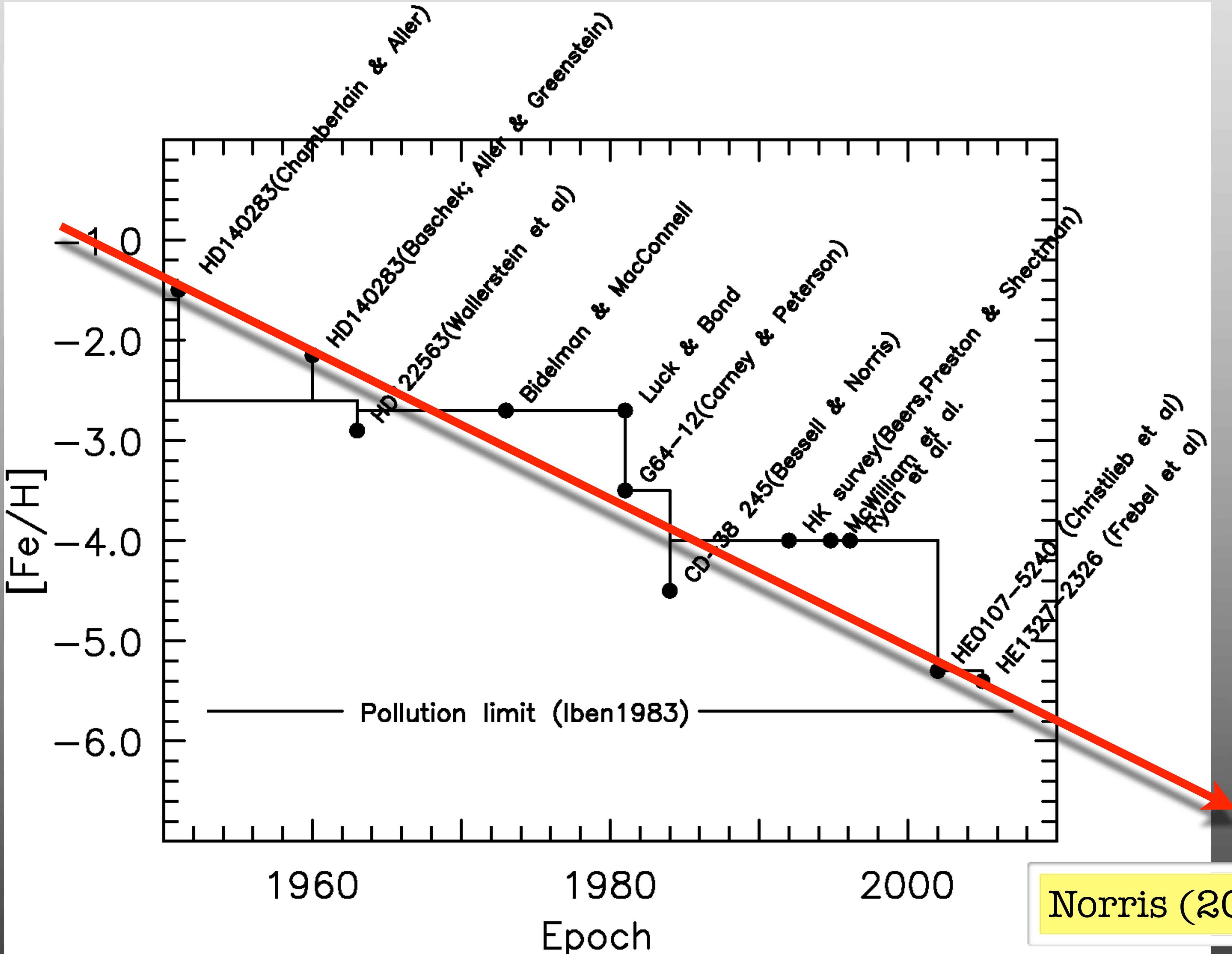
Animation generated using stars with [Fe/H] < -2.0 from the SAGA database (Suda 2008,2011)

The Need for More Data

With more stars we can ...

- Discover the elusive Pop III star (no metals)
- Better constrain the nature of the first stars by studying more objects with [Fe/H] < –4.0
- Quantify the fraction of stars at low metallicity with anomalously large abundances of C, N, O and/or Mg
- Discover r-process enhanced stars to measure ages (Th, U)
- Measure Li to test the cosmological lithium problem

Record Holders



Norris (2006)

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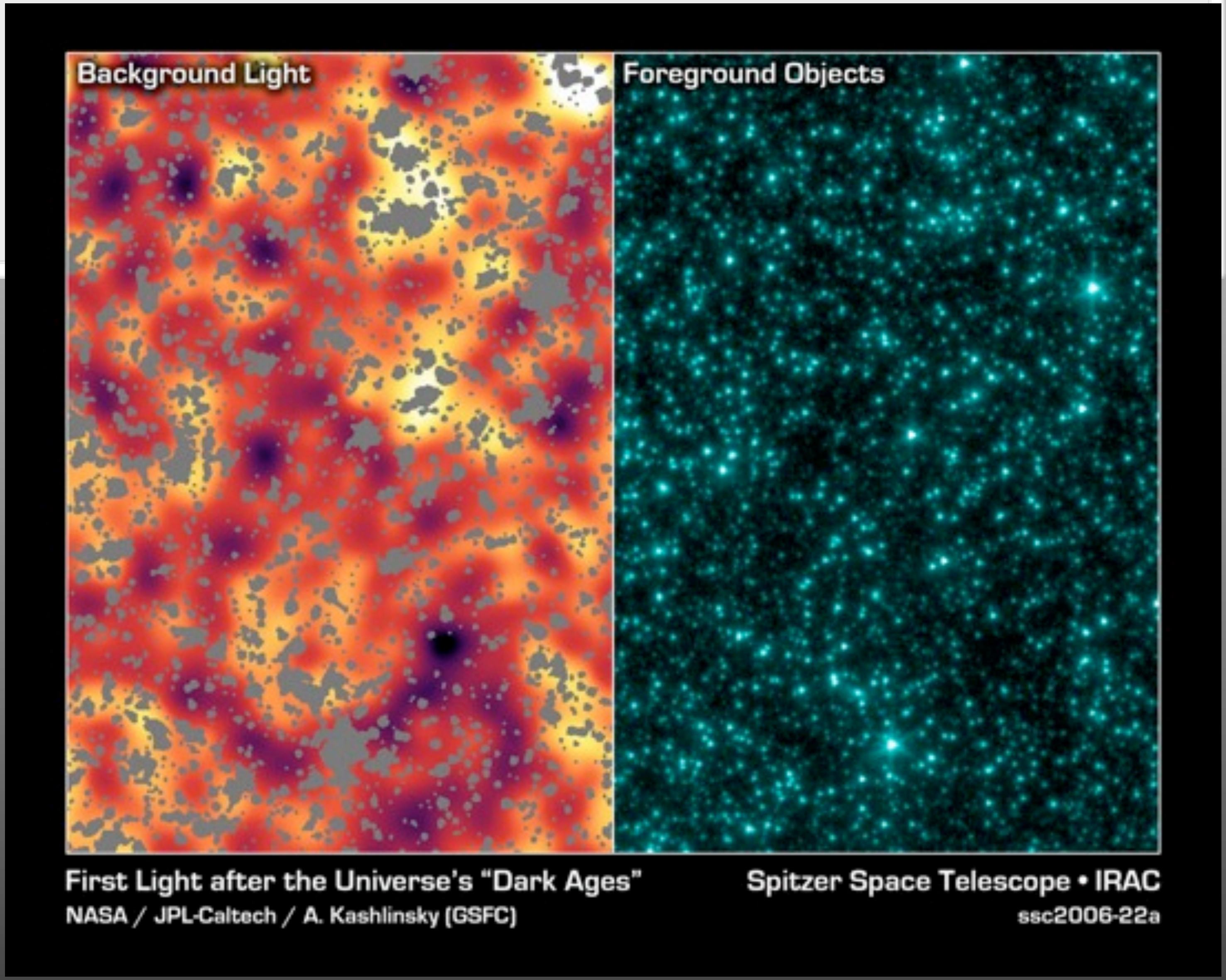
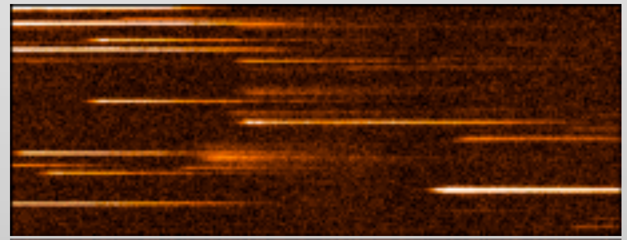
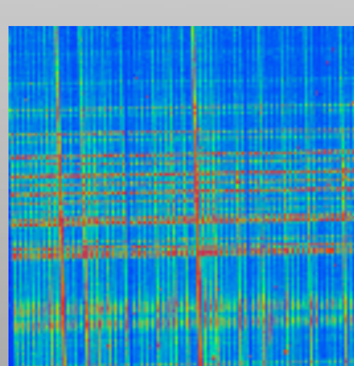


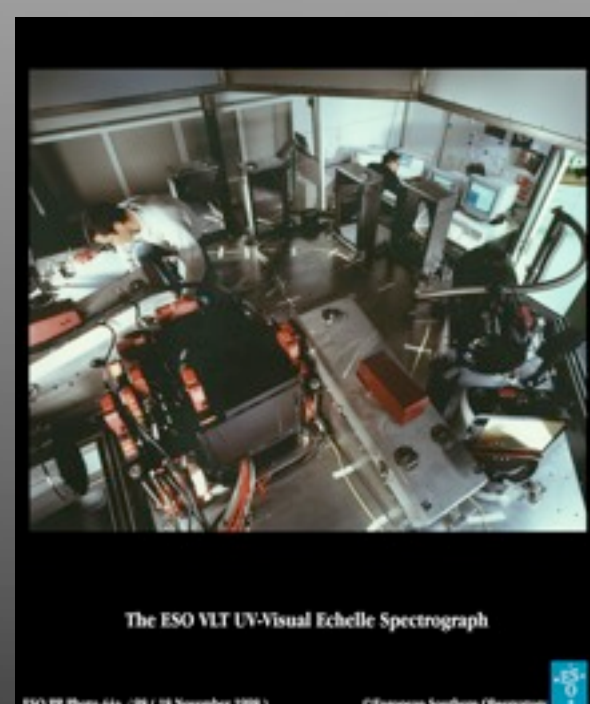
Finding the First Stars

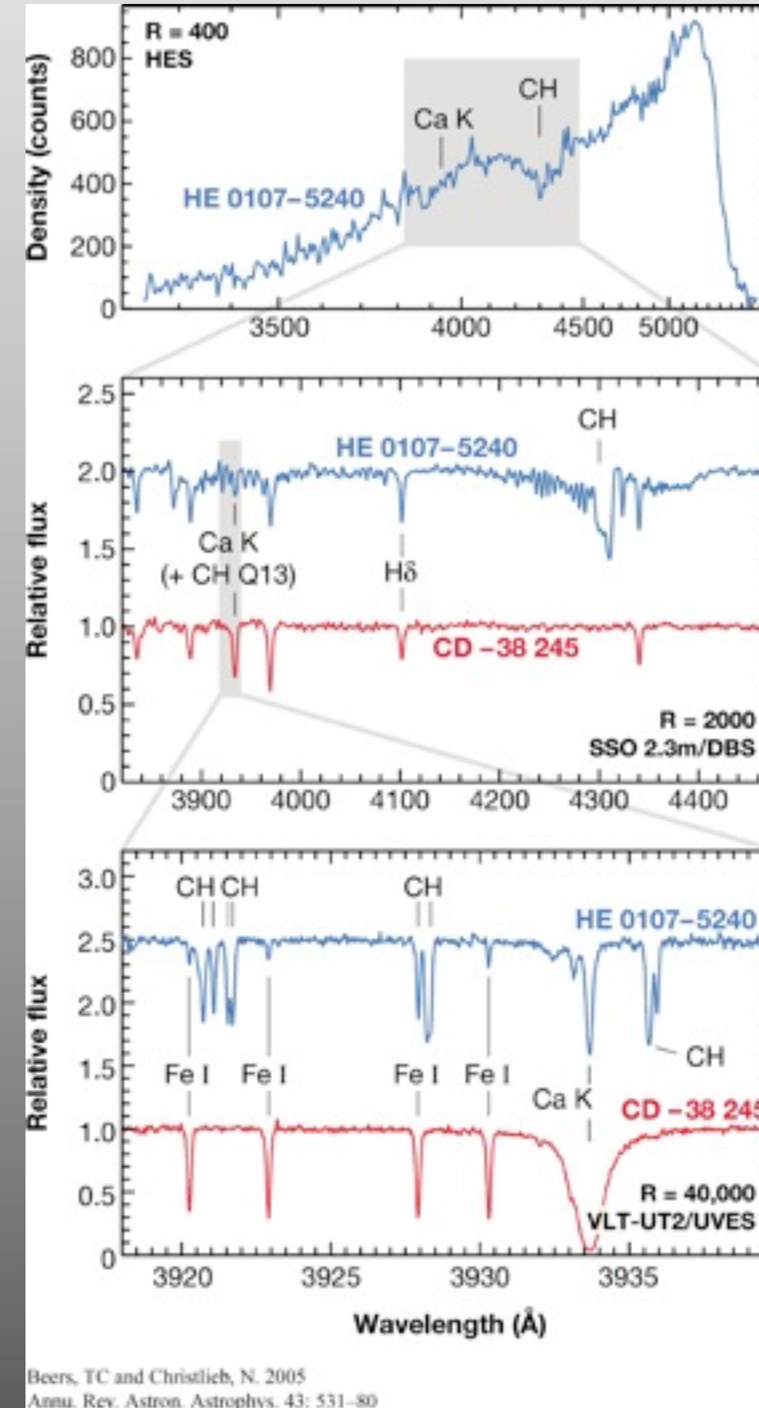
Hamburg ESO Survey plate





SDSS





Beers & Christlieb (2005)

Selecting Candidates

Hamburg ESO objective prism survey ==>

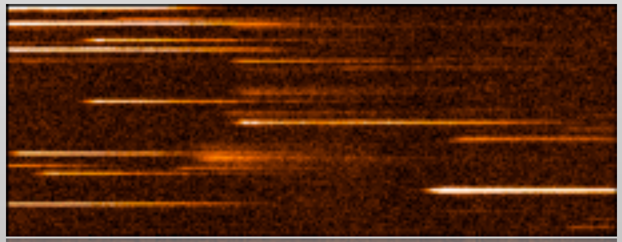
ANU's 2.3m telescope at Siding Spring Observatory

(Bessell, Norris, + others

500 nights, ~10 years)

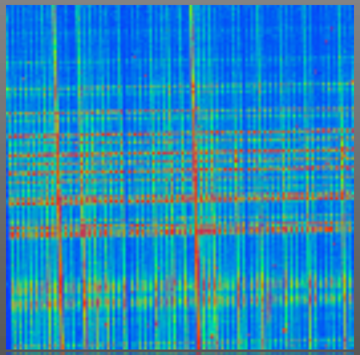
Sloan Digital Sky Survey (SDSS) spectra

Hamburg ESO Survey plate



ANU 2.3m

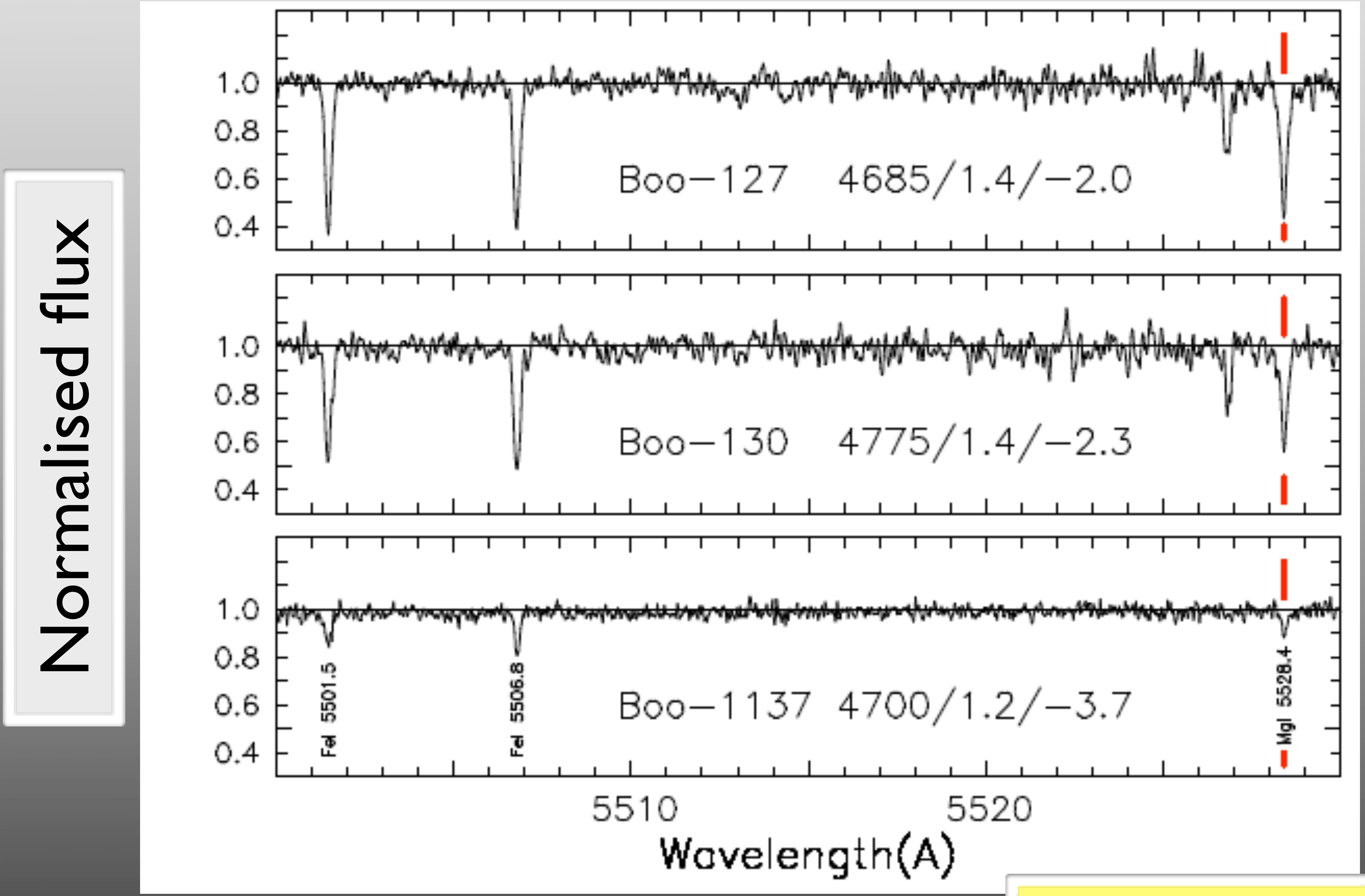
SDSS



Observations

- Magellan (7 nights) and Keck (4 nights) between Jun 2007 and Sep 2008
- Observed the 38 most promising candidates
- Resolution ~40,000
- S/N ~30 to 150
- Measured **20,000+ EWs**

Example spectra



Gilmore et al. (submitted)

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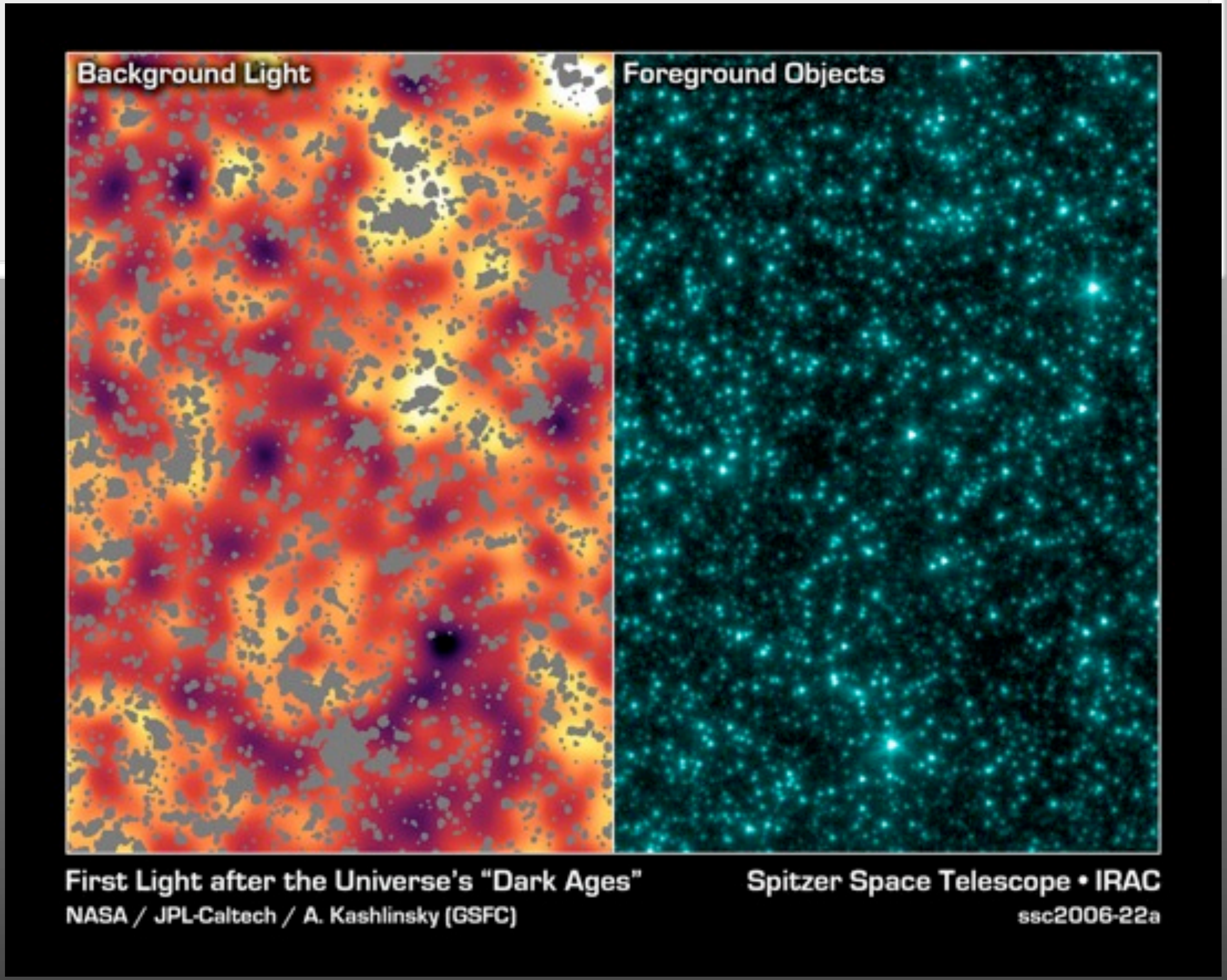
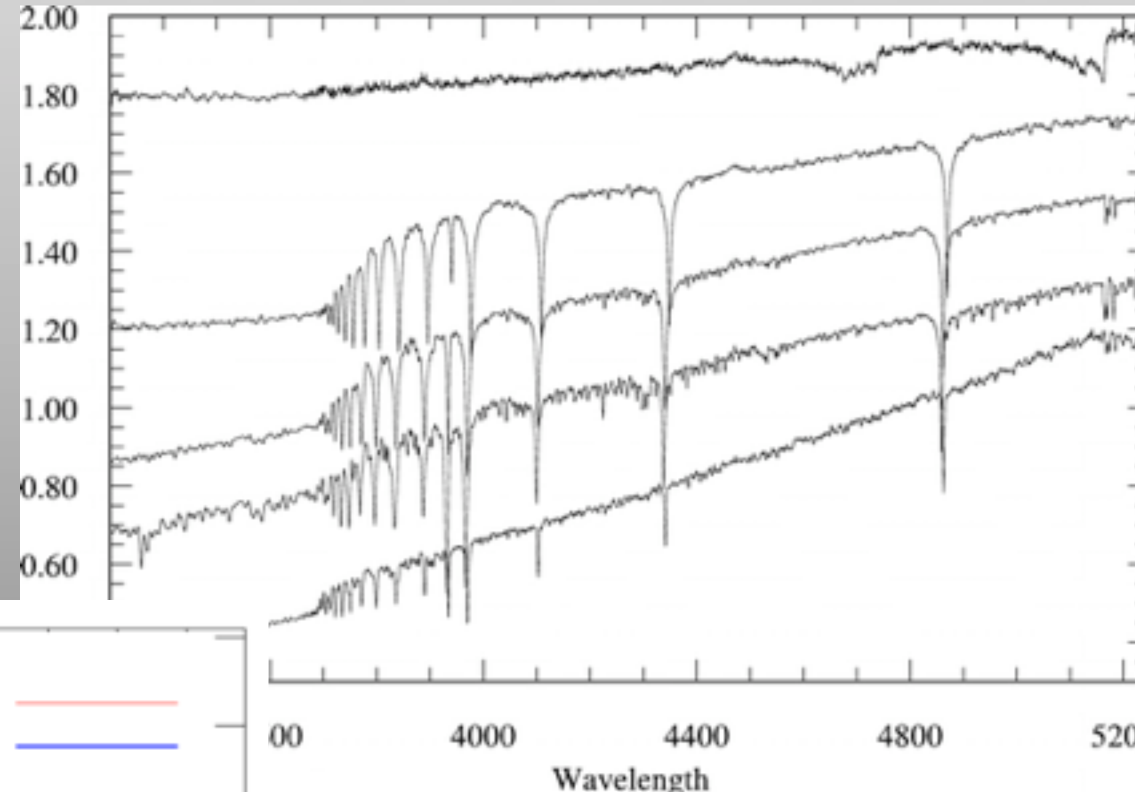
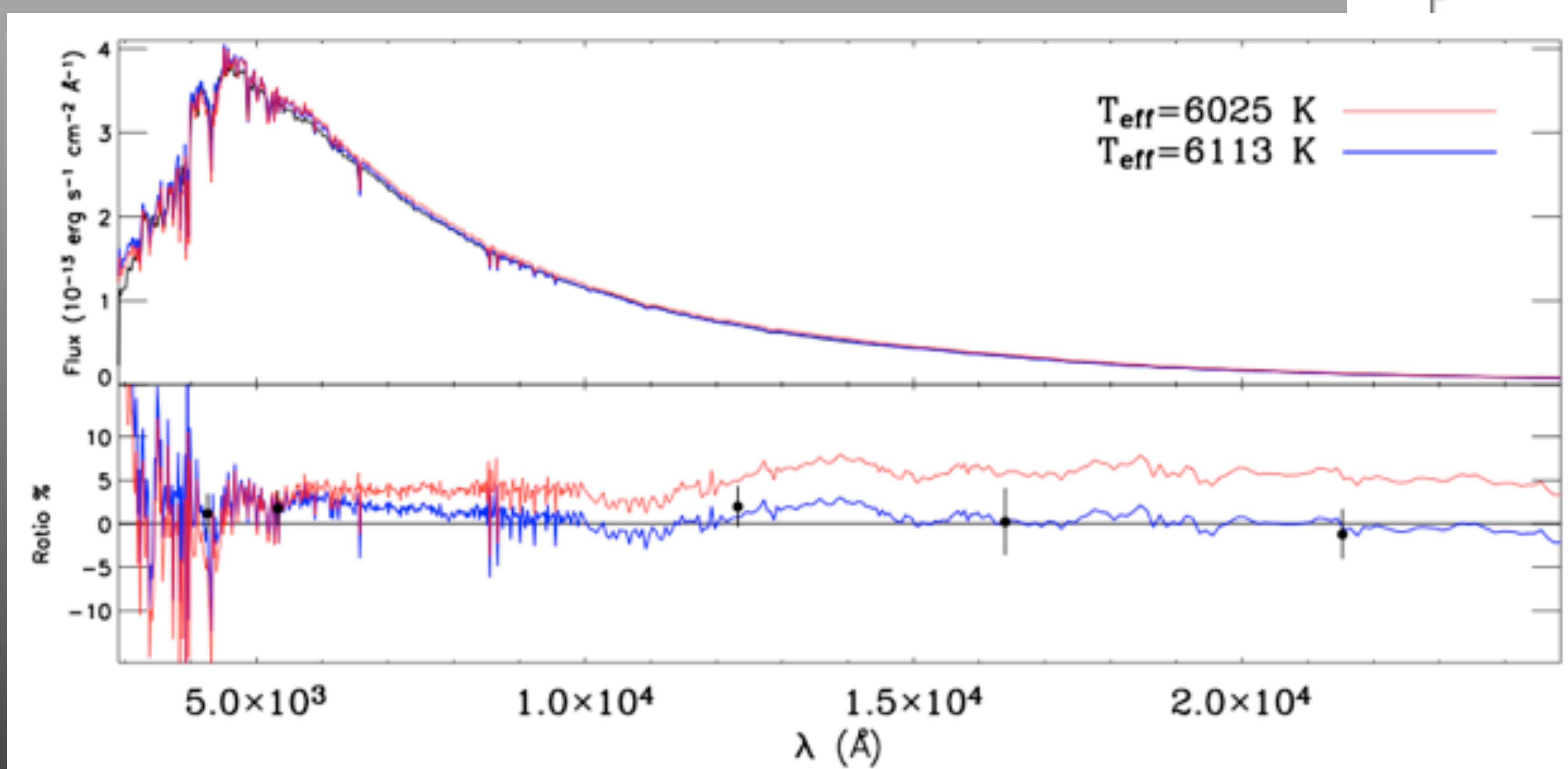


Stellar Parameters: Standard Analysis

Bessell (2007)



Casagrande et al. (2010)

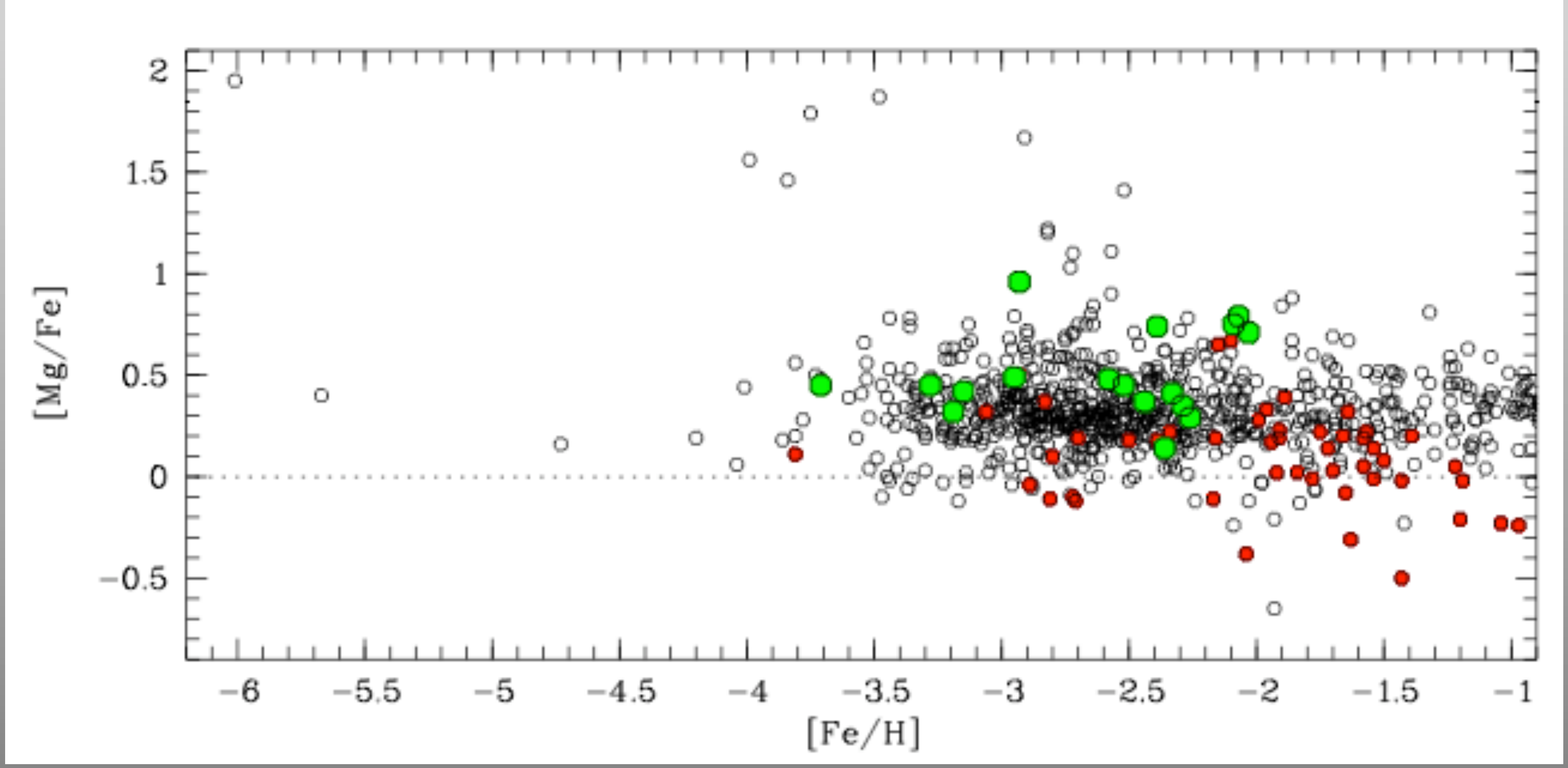


Re-analysis of Literature Stars with [Fe/H] < -3.0

"Why don't we re-analyse every star in the literature with [Fe/H] < -3.0"

Norbert Christlieb (Feb 2010)

Inhomogeneous Comparisons



Seek to study the dispersions and trends

Real or artificial?

Literature Re-analysis

Query **SAGA** (Suda+ 2008) database for all stars with [Fe/H] < −2.9 {... 196 stars}

Select 16 references with reliable EWs (i.e., high resolution, high S/N spectra) {204 stars, some with [Fe/H] > −3.0}

Teff from IRFM colour:Teff:[Fe/H] relations -- Casagrande+ (2010: dwarfs) and Ramírez & Meléndez (2005: giants) --apply-- small offsets onto our scale

Standard 1D LTE chemical abundance analysis

HOMOGENEOUS TEFF, LOGG, MICRO, LOG GF, SOLAR ABUNDANCES FOR 190 STARS

References. — 1 = Aoki et al. (2002); 2 = Aoki et al. (2006); 3 = Aoki et al. (2007); 4 = Aoki et al. (2008); 5 = Bonifacio et al. (2007, 2009); 6 = Carretta et al. (2002); Cohen et al. (2002); 7 = Cayrel et al. (2004); 8 = Christlieb et al. (2004); 9 = Cohen et al. (2004); 10 = Cohen et al. (2006); 11 = Cohen et al. (2008); 12 = Frebel et al. (2007); 13 = Honda et al. (2004); 14 = Lai et al. (2008); 15 = Norris et al. (2001); 16 = Norris et al. (2007);

Query **SAGA** (Suda+ 2008) database for all stars with [Fe/H] < –2.9 {... 196 stars}

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Standard 1D LTE chemical abundance analysis

HOMOGENEOUS TEFF, LOGG, MICRO, LOG GF, SOLAR ABUNDANCES FOR 190 STARS

CAUTION

- Our large sample represents an important step, but this is **NOT** the final word
- Usual caveats about NLTE and 3-D effects
- New major efforts (100+ star samples) underway by Aoki et al., Cohen et al., Roederer et al.

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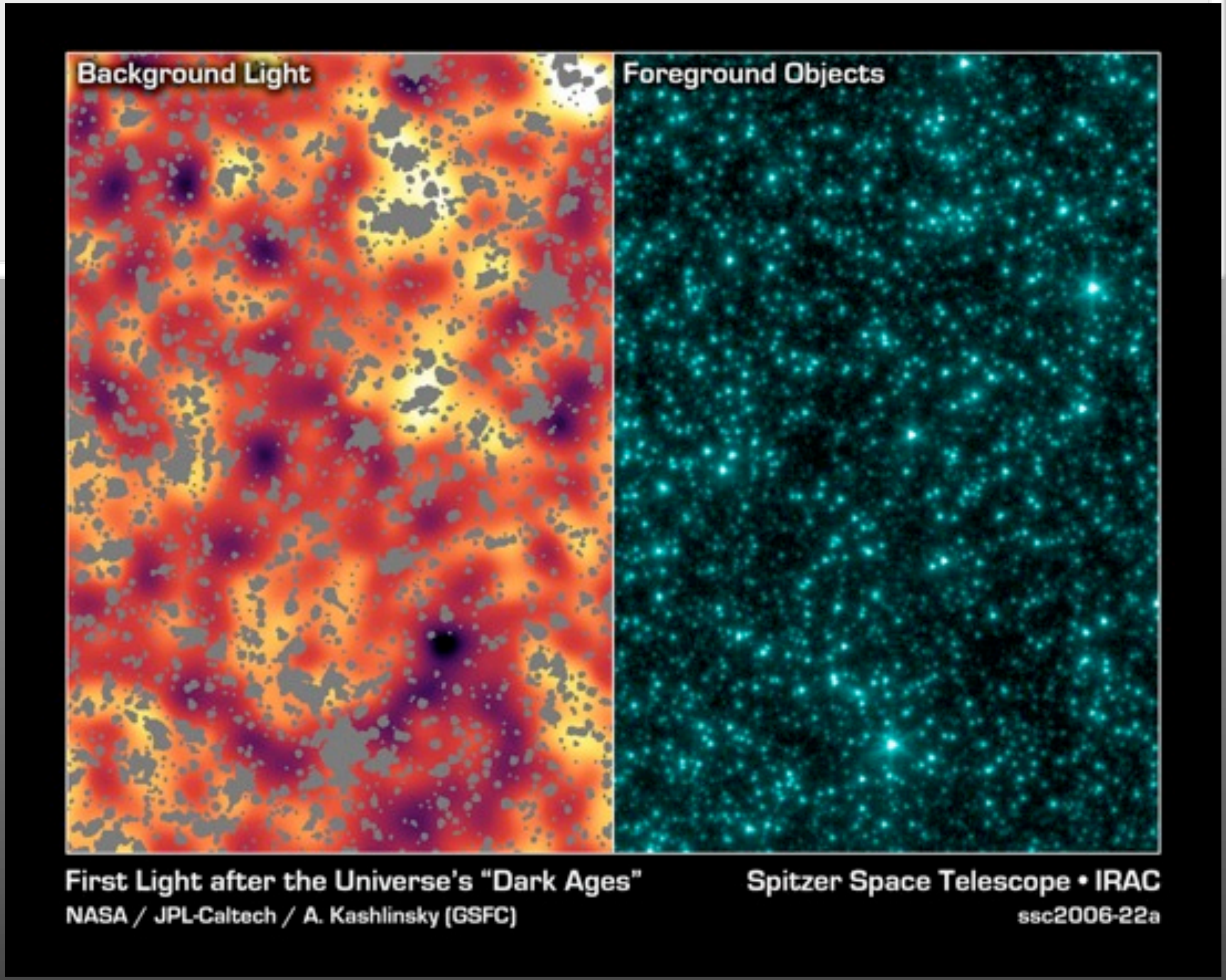
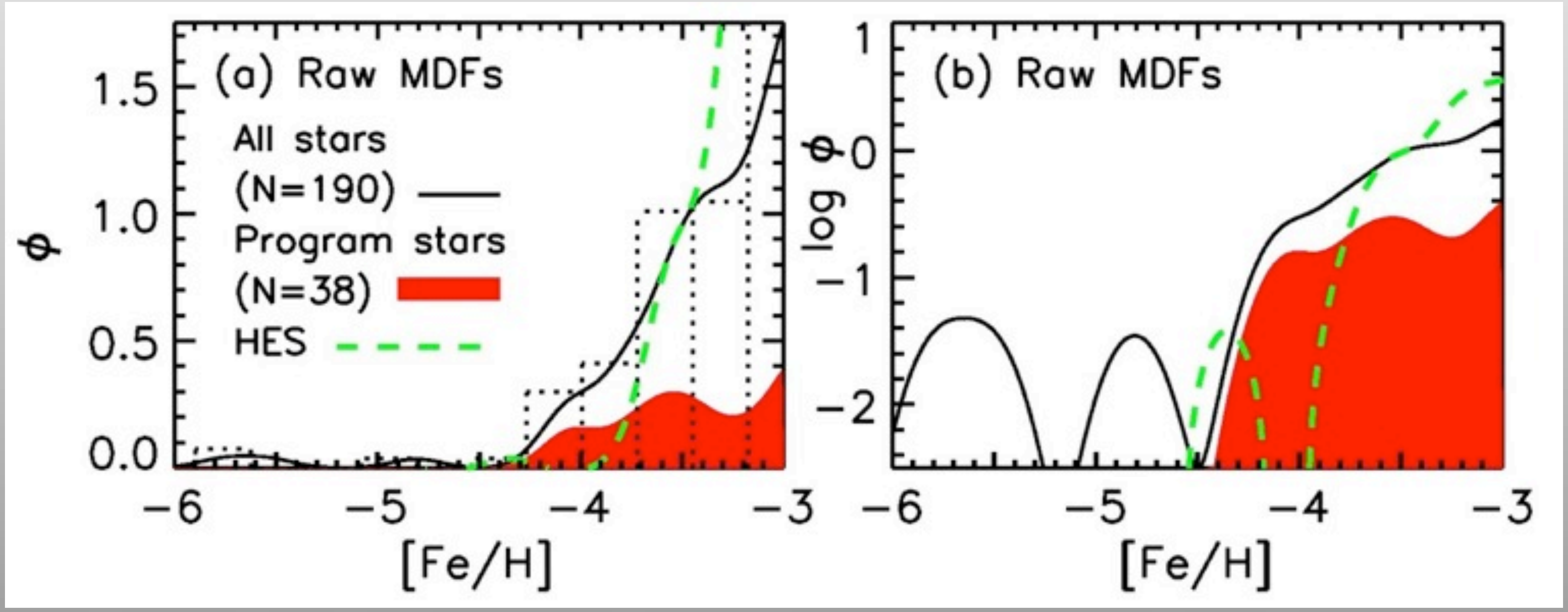


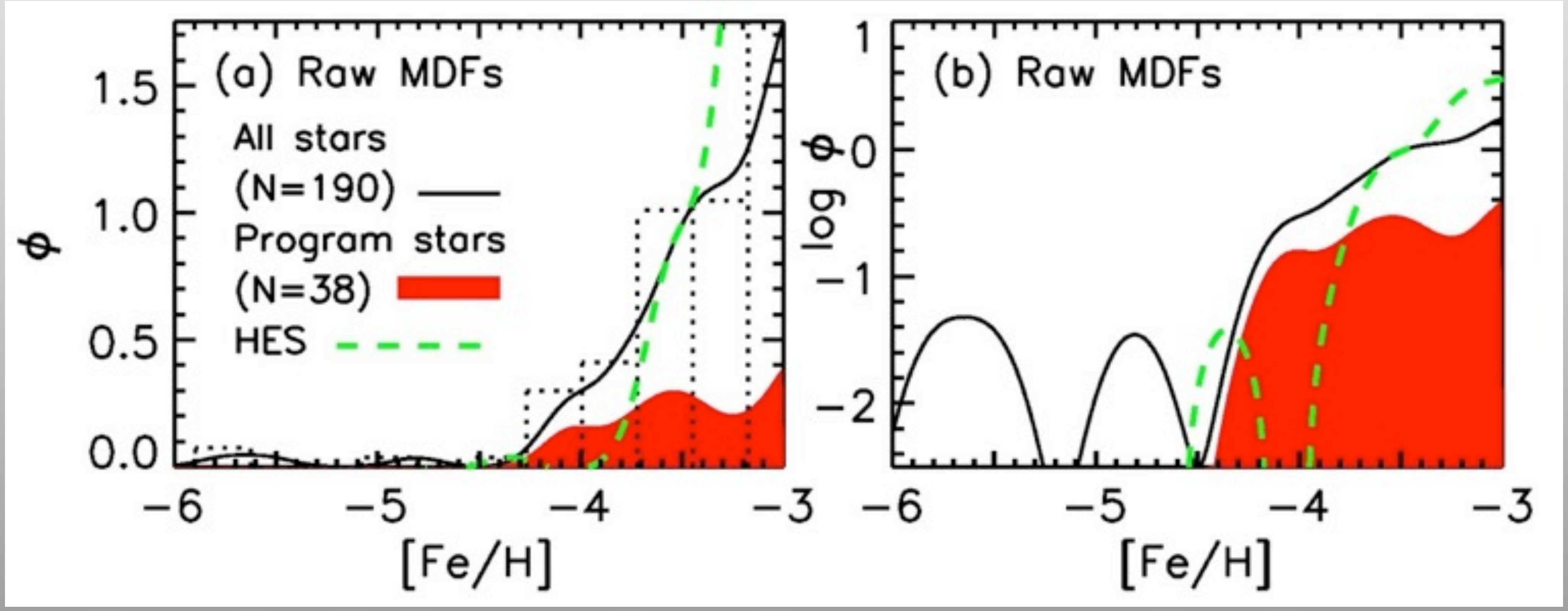
Raw MDF



HES MDF shifted by Δ[Fe/H] = –0.26 relative to Schörck+2009 and Li+2010

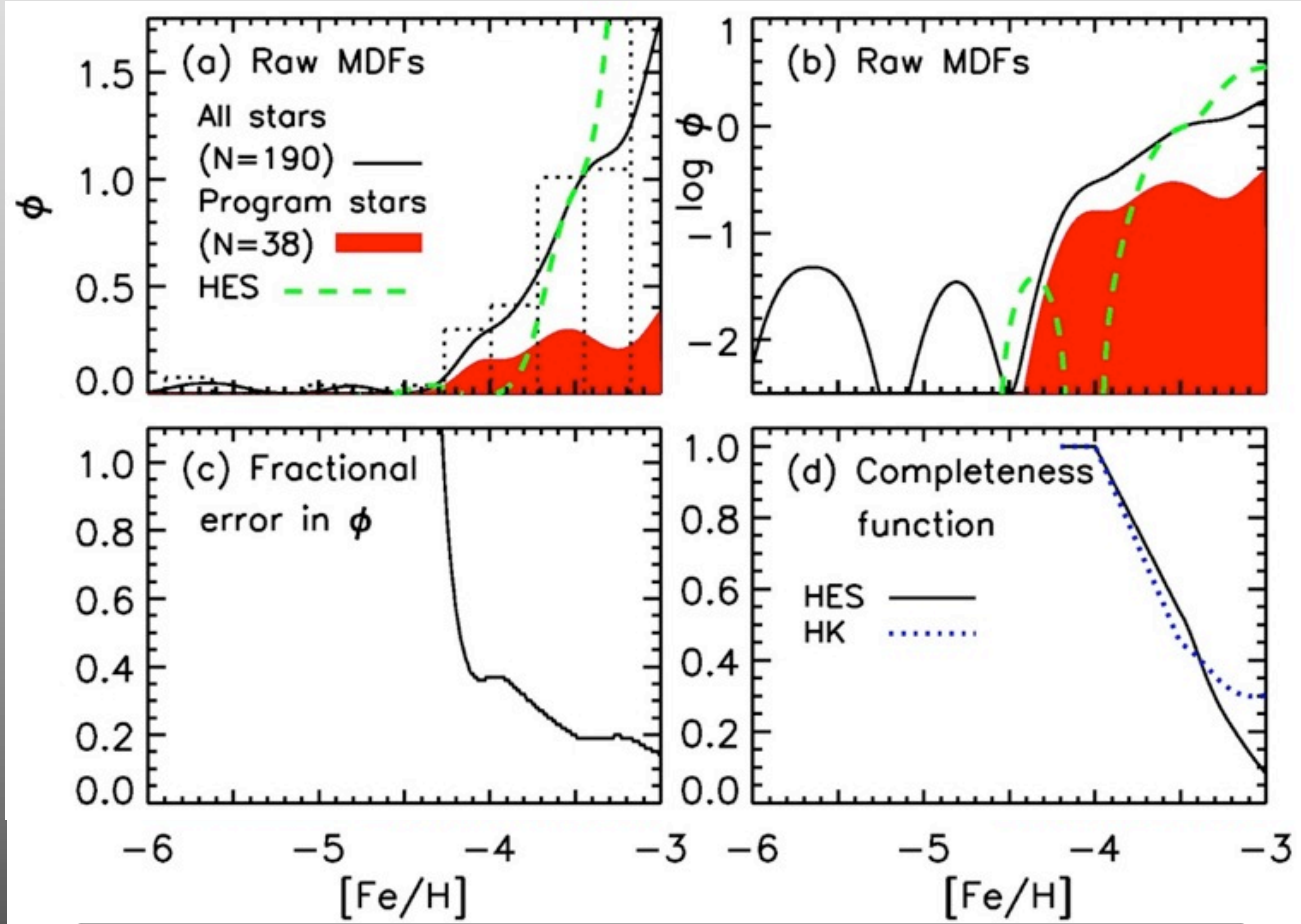
A **cutoff in the MDF**, if real, would constrain the "**critical metallicity**", below which low-mass star formation is impossible, and thereby **constrain the star formation modes of the first stars**

Raw MDF



When using a logarithmic scale, it is easier to identify the location of the “shoulder” which indicates the metallicity at which either the finite sample size becomes too small, or the MDF genuinely departs from the Galactic chemical evolution model pertaining at higher metallicity.

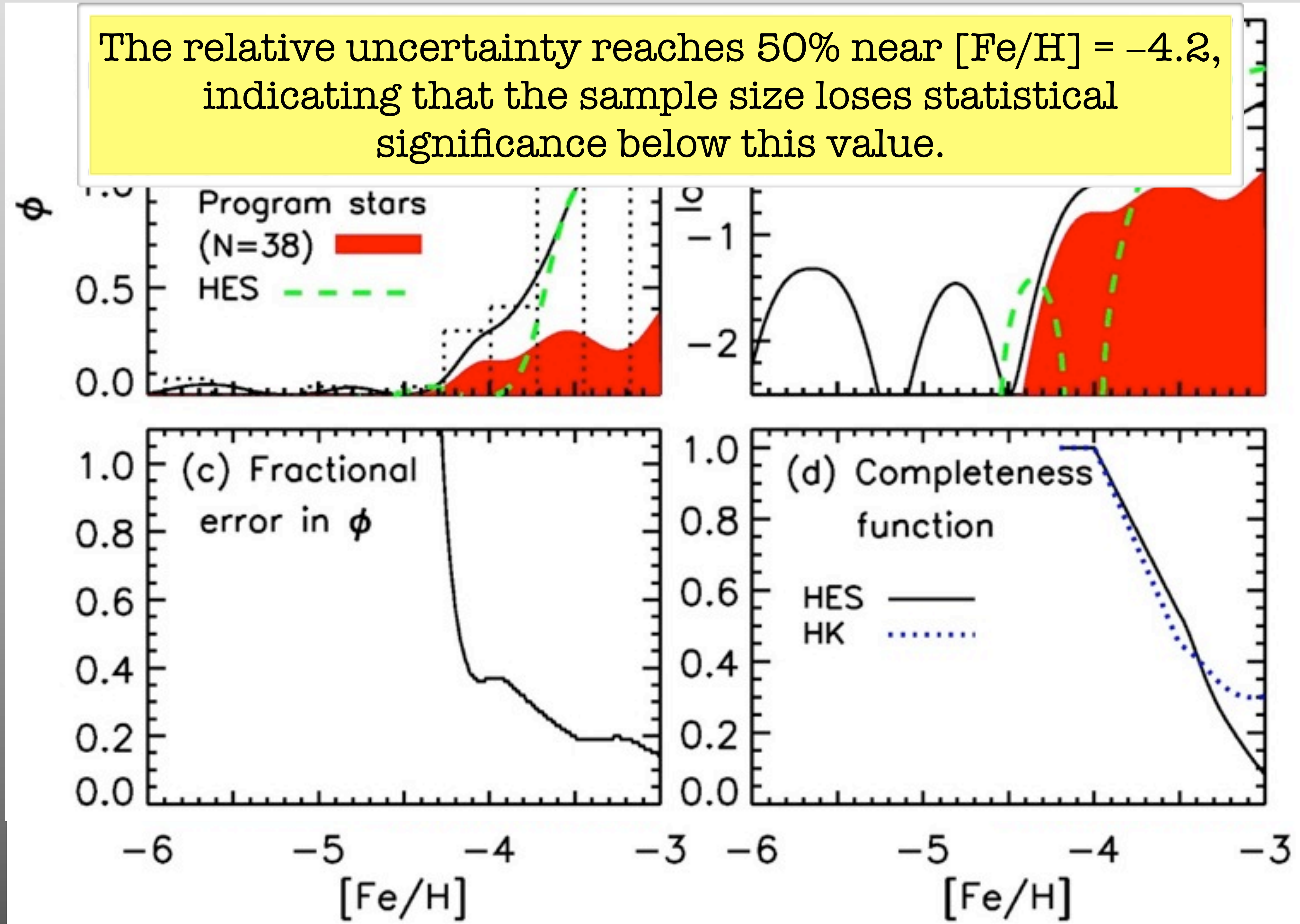
Error and Completeness



The HES is **complete** below [Fe/H] = -3.0

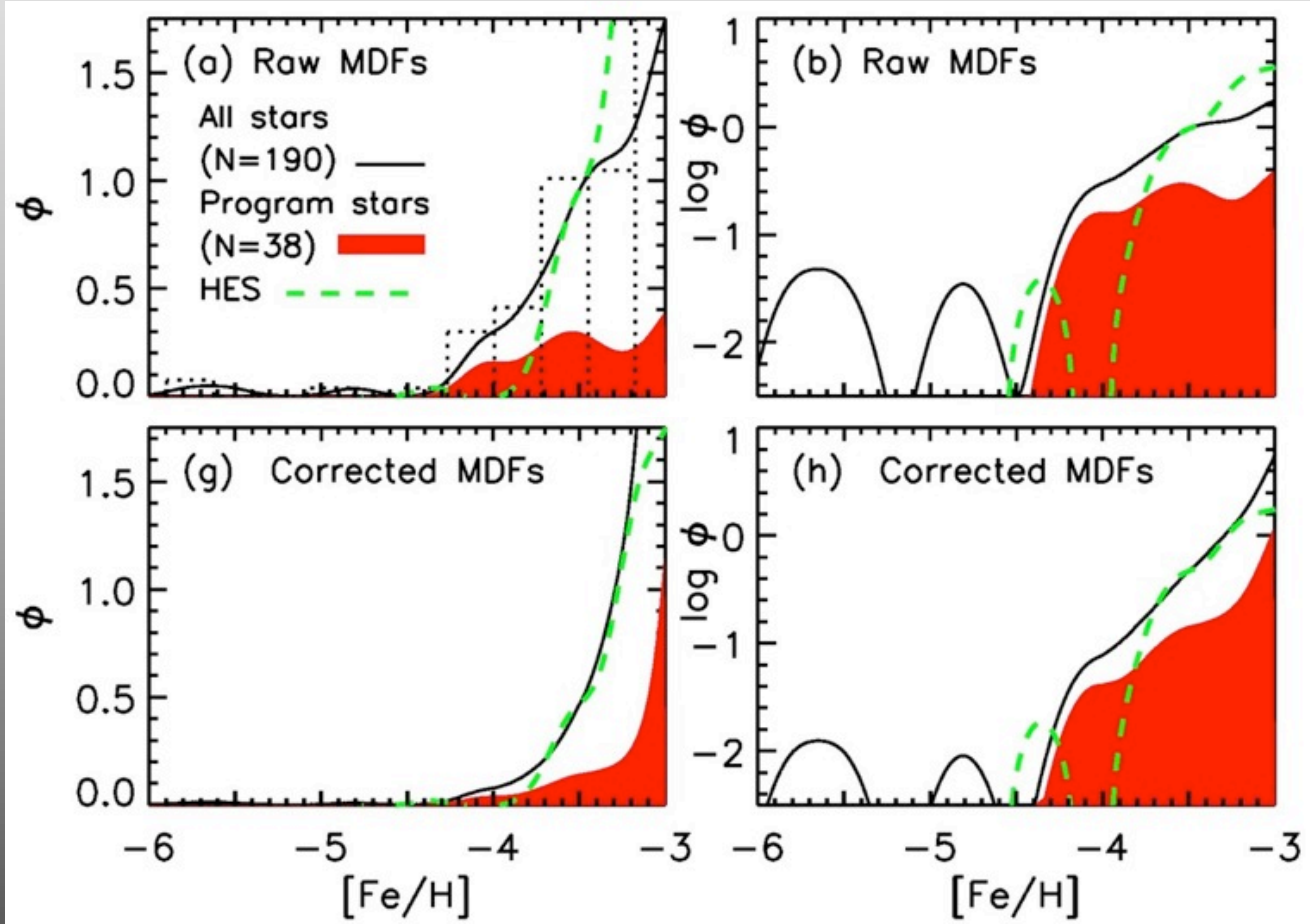
Error and Completeness

The relative uncertainty reaches 50% near [Fe/H] = –4.2, indicating that the sample size loses statistical significance below this value.

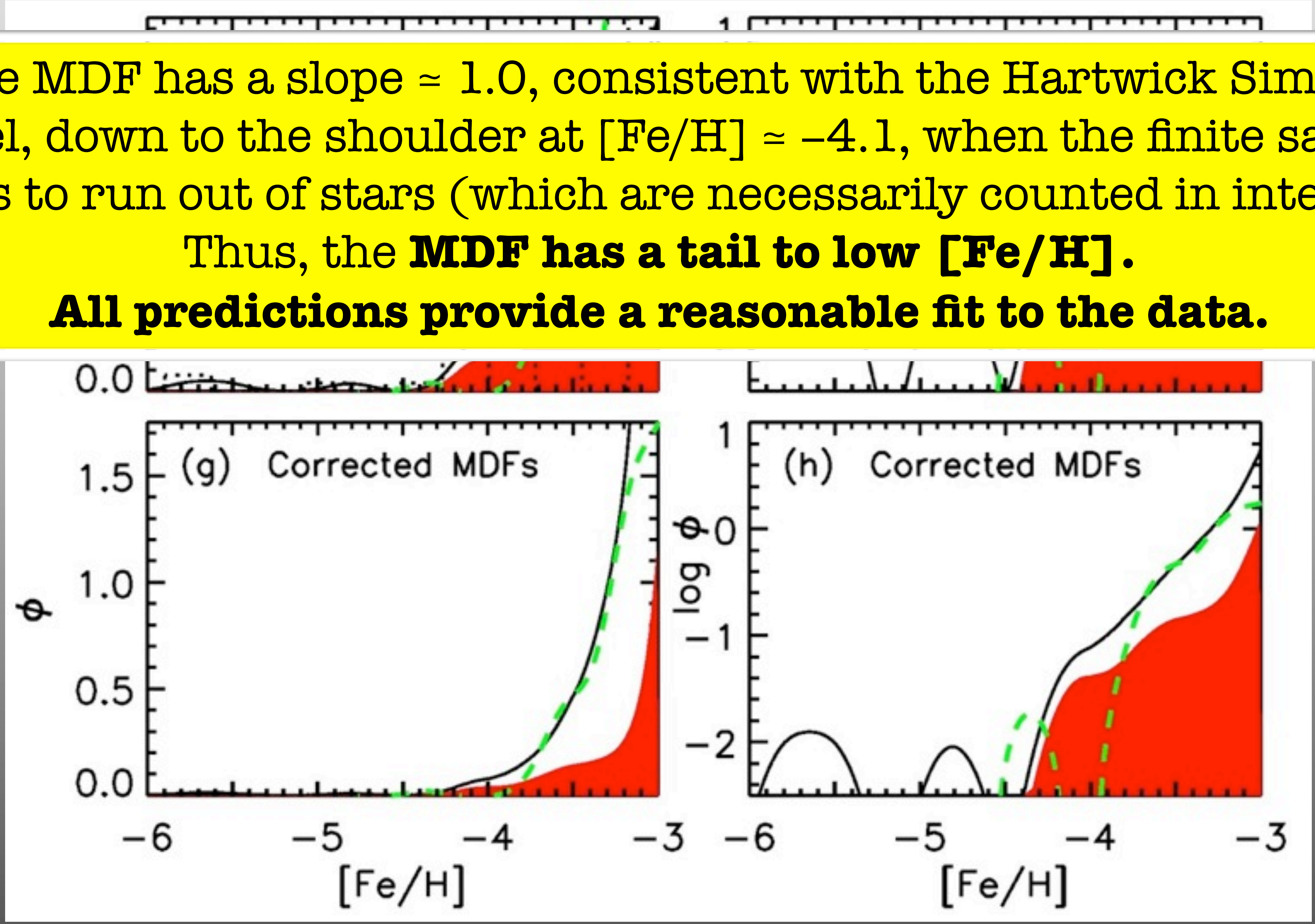


The HES is **complete** below [Fe/H] = -3.0

Raw and Corrected MDFs



Raw and Corrected MDFs



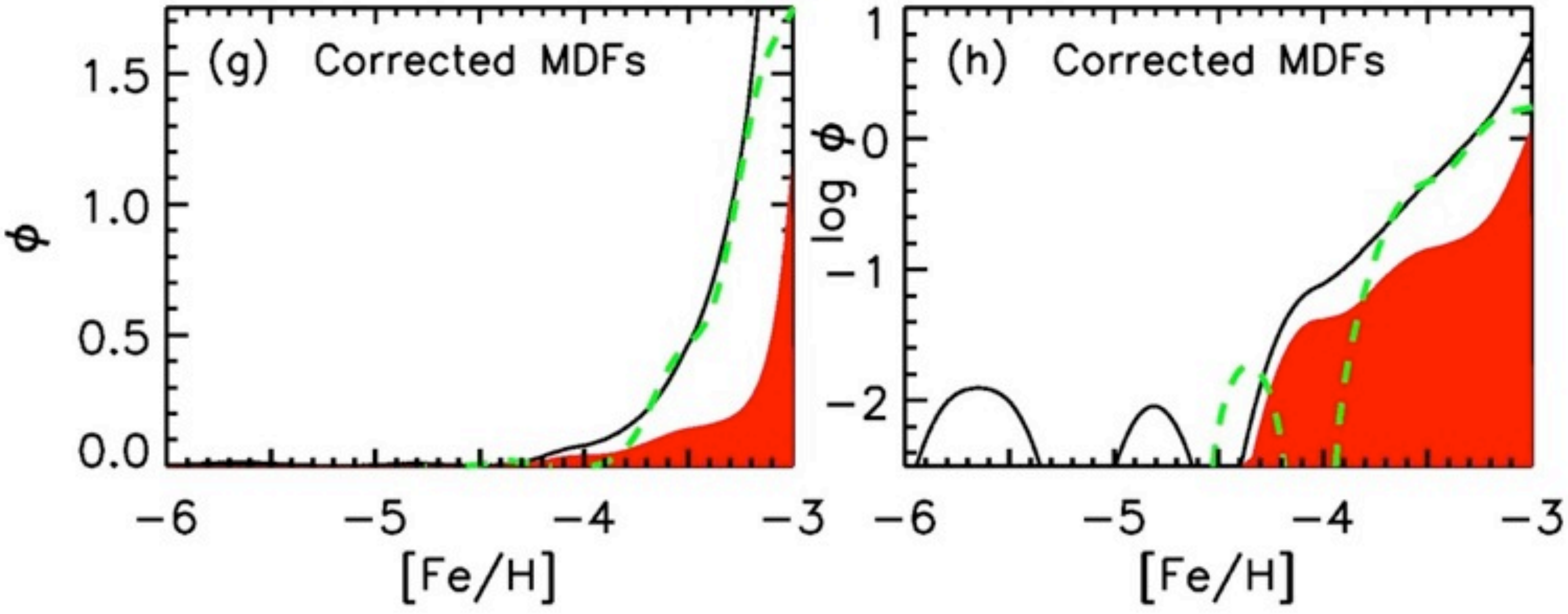
The MDF has a slope ≃ 1.0, consistent with the Hartwick Simple Model, down to the shoulder at [Fe/H] ≃ −4.1, when the finite sample begins to run out of stars (which are necessarily counted in integers). Thus, the **MDF has a tail to low [Fe/H].**

All predictions provide a reasonable fit to the data.

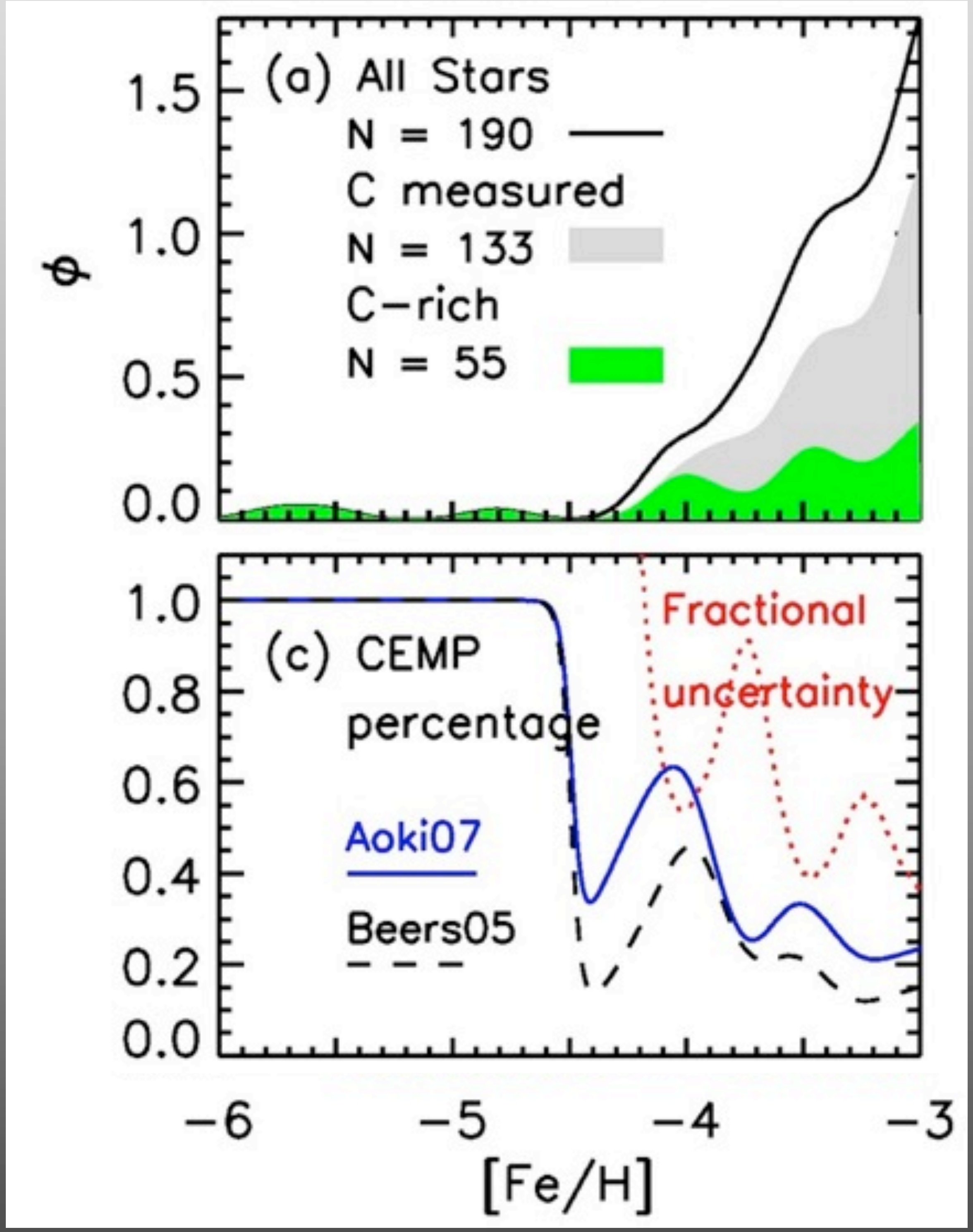
Raw and Corrected MDFs

While the **selection biases** associated with the discovery of the stars in the SAGA database are **not explicit**, the **majority carry HK-survey or HES-survey names** and thus **inherit the spectroscopic- and volume-selection biases of those works**.

Many of the HK-survey stars would also have been recovered in the HES survey, but were not renamed. Consequently, **using the HES completeness function should be a reasonable step**.



CEMP Fraction

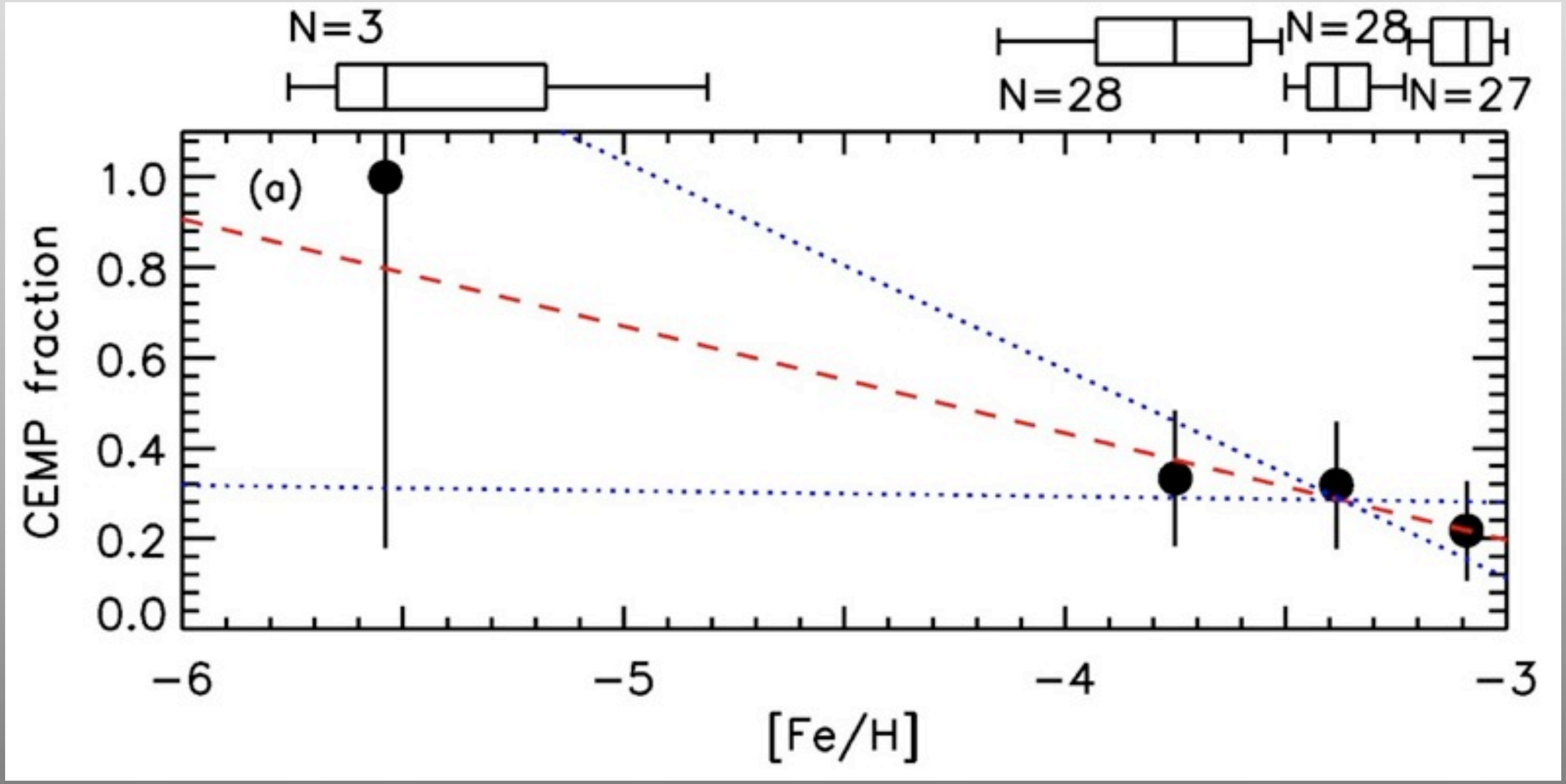


Beers & Christlieb (2005)
[C/Fe] > +1.0 (all stars)

[Fe/H]	Fraction
≤ −3.0	19 ± 5%
≤ −3.0	28 ± 6%

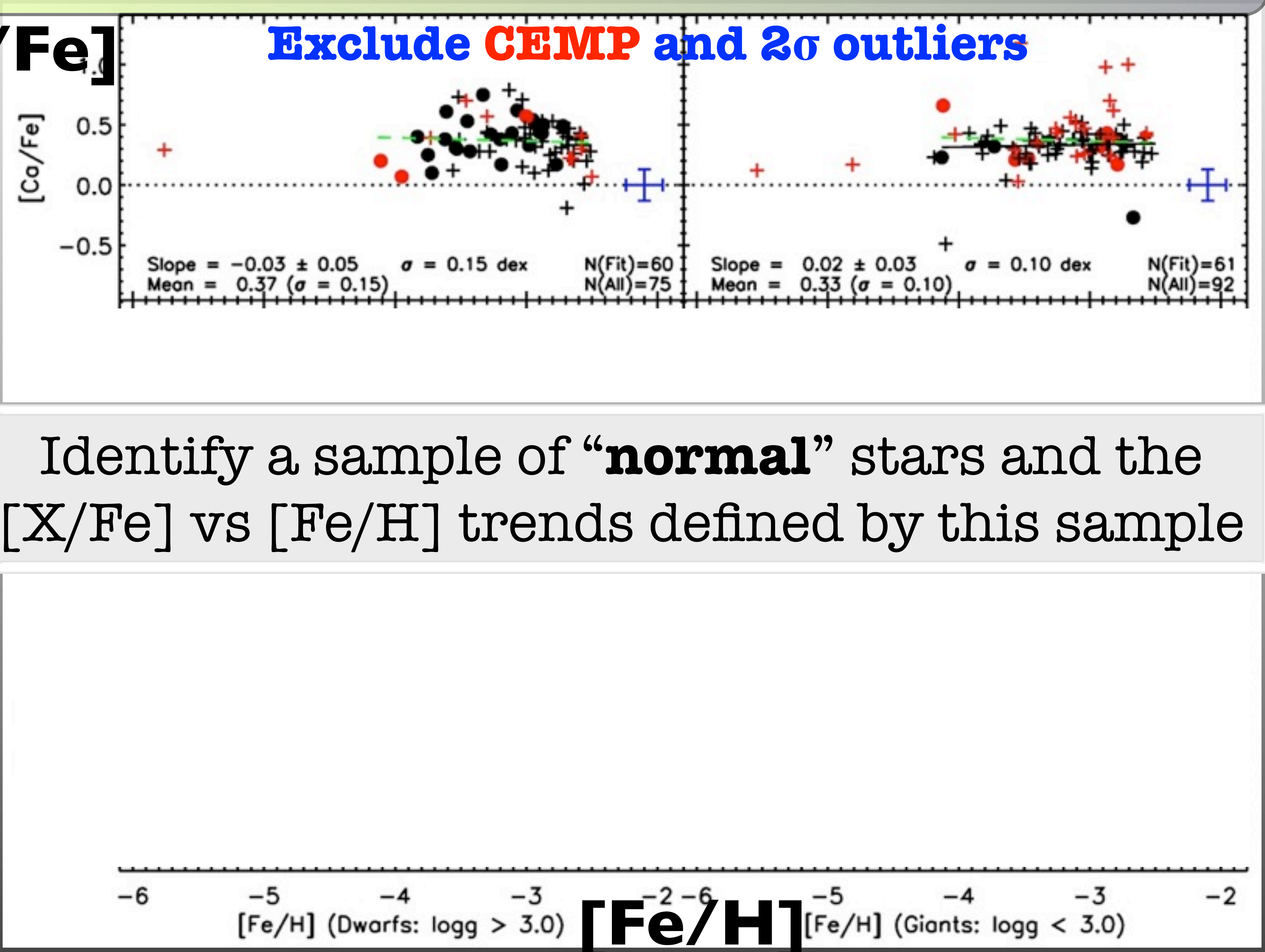
Aoki+ (2007)
[C/Fe] > +0.7
(for most stars)

CEMP Fraction



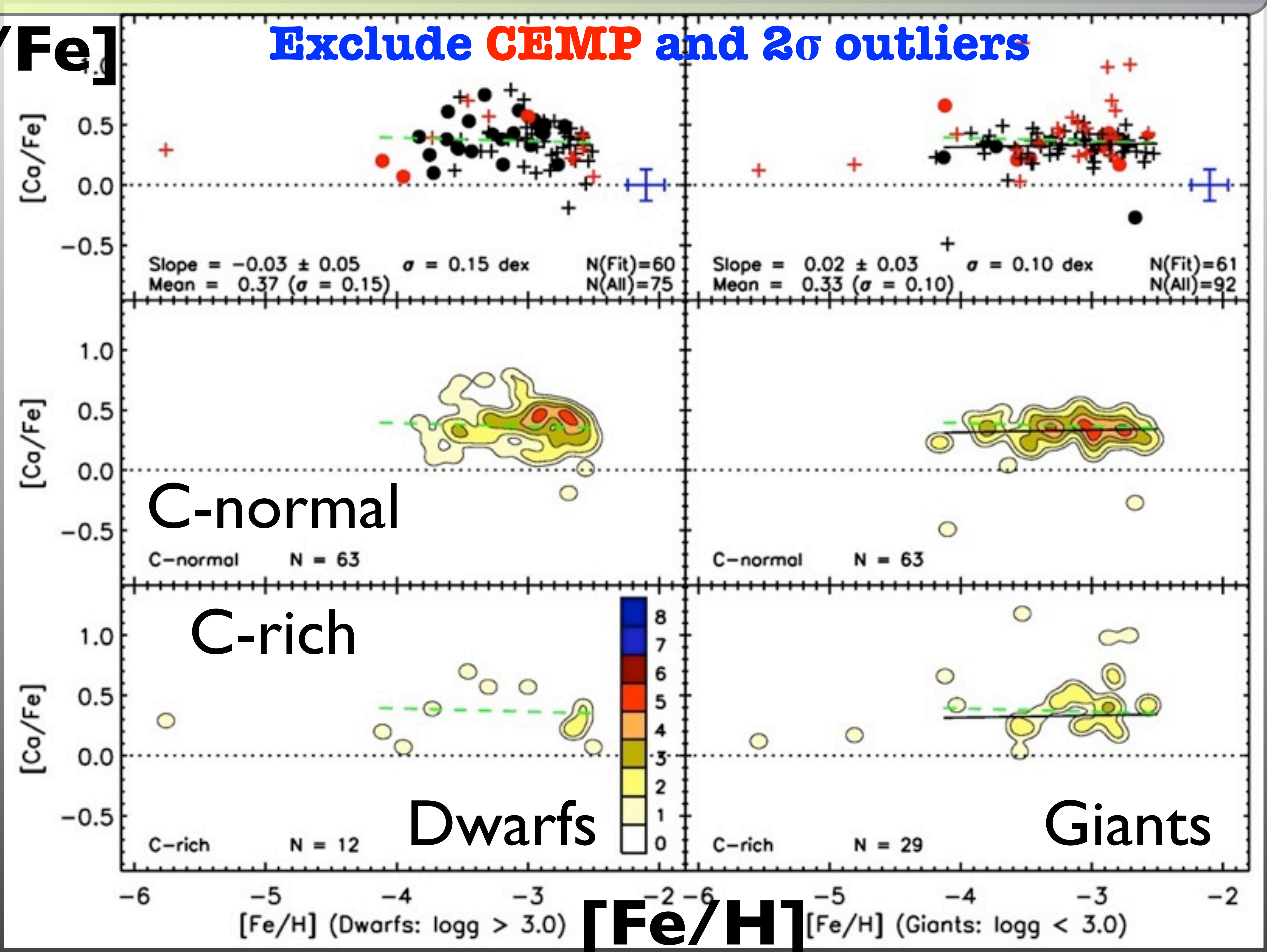
No strong evidence for an increase in CEMP fraction with decreasing [Fe/H]

Trends/scatter

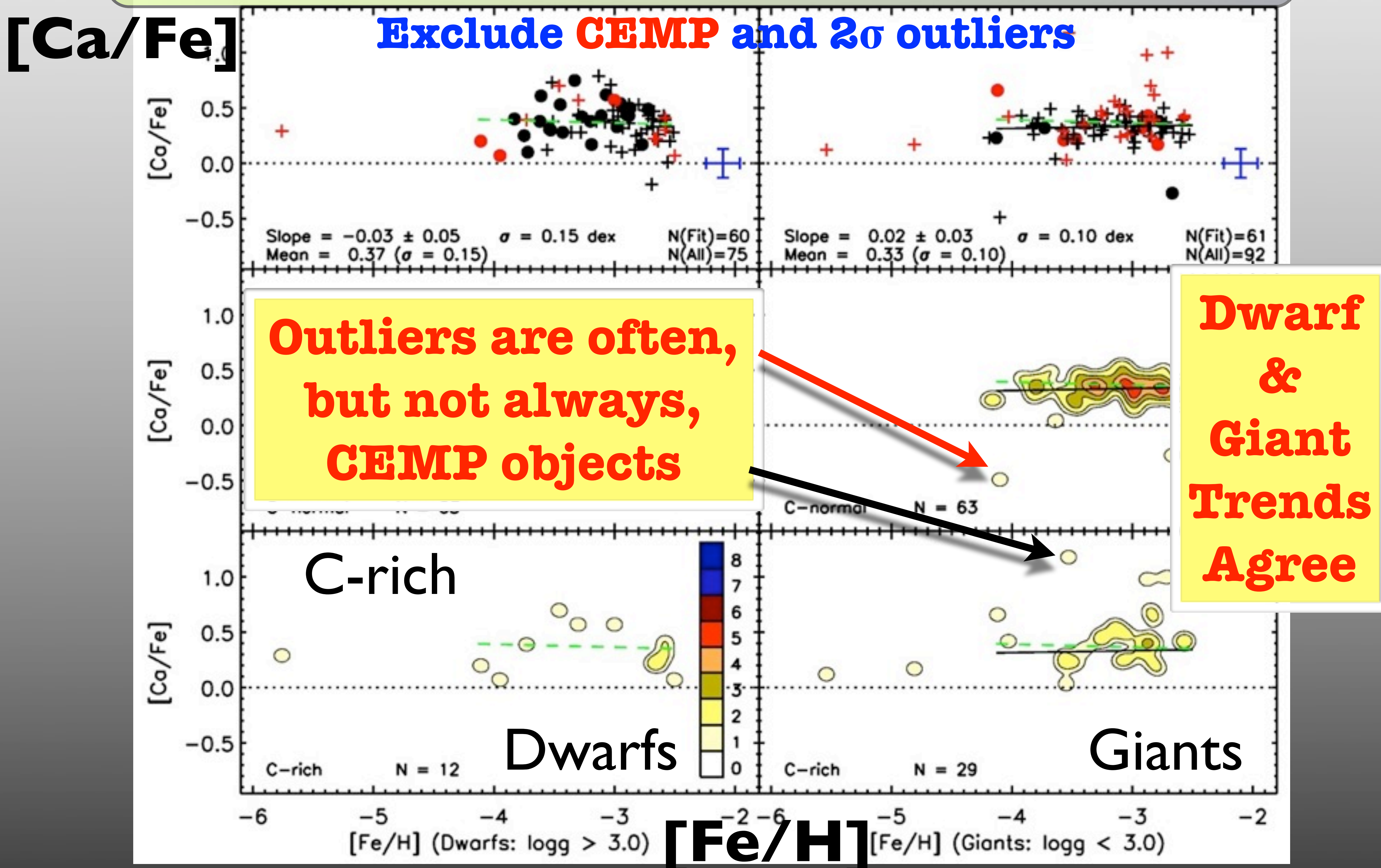


Identify a sample of "**normal**" stars and the [X/Fe] vs [Fe/H] trends defined by this sample

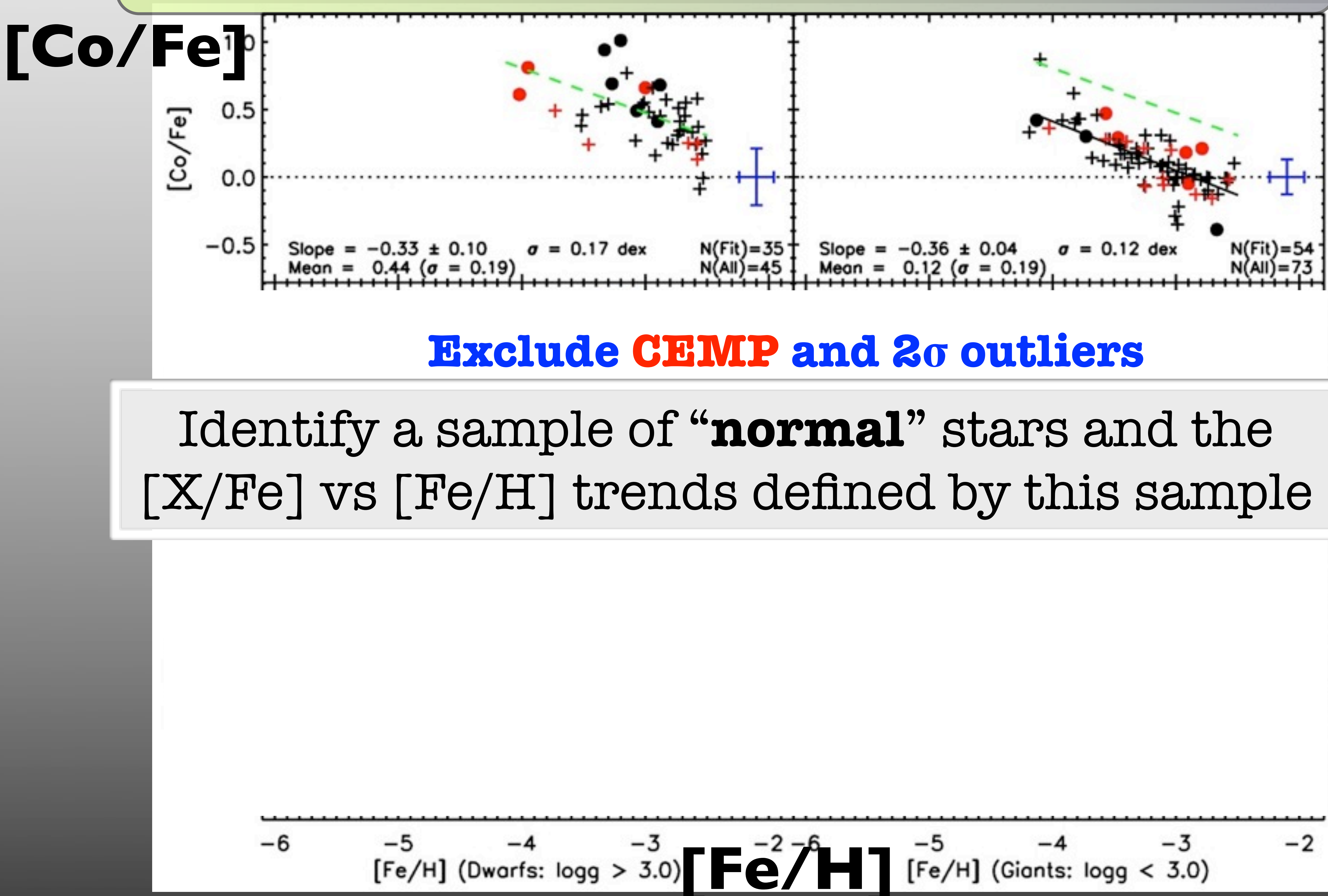
Trends/scatter



Trends/scatter



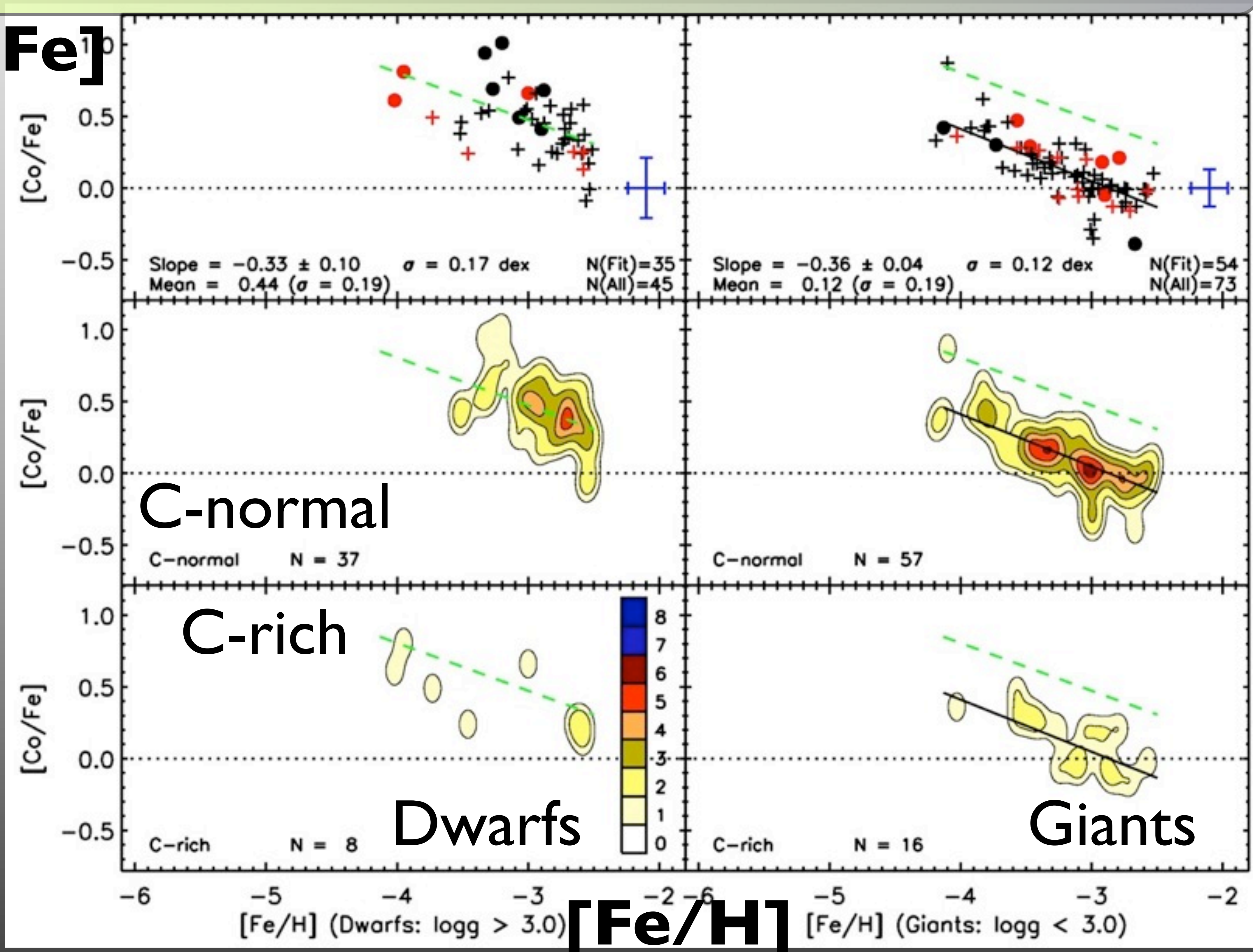
Trends/scatter



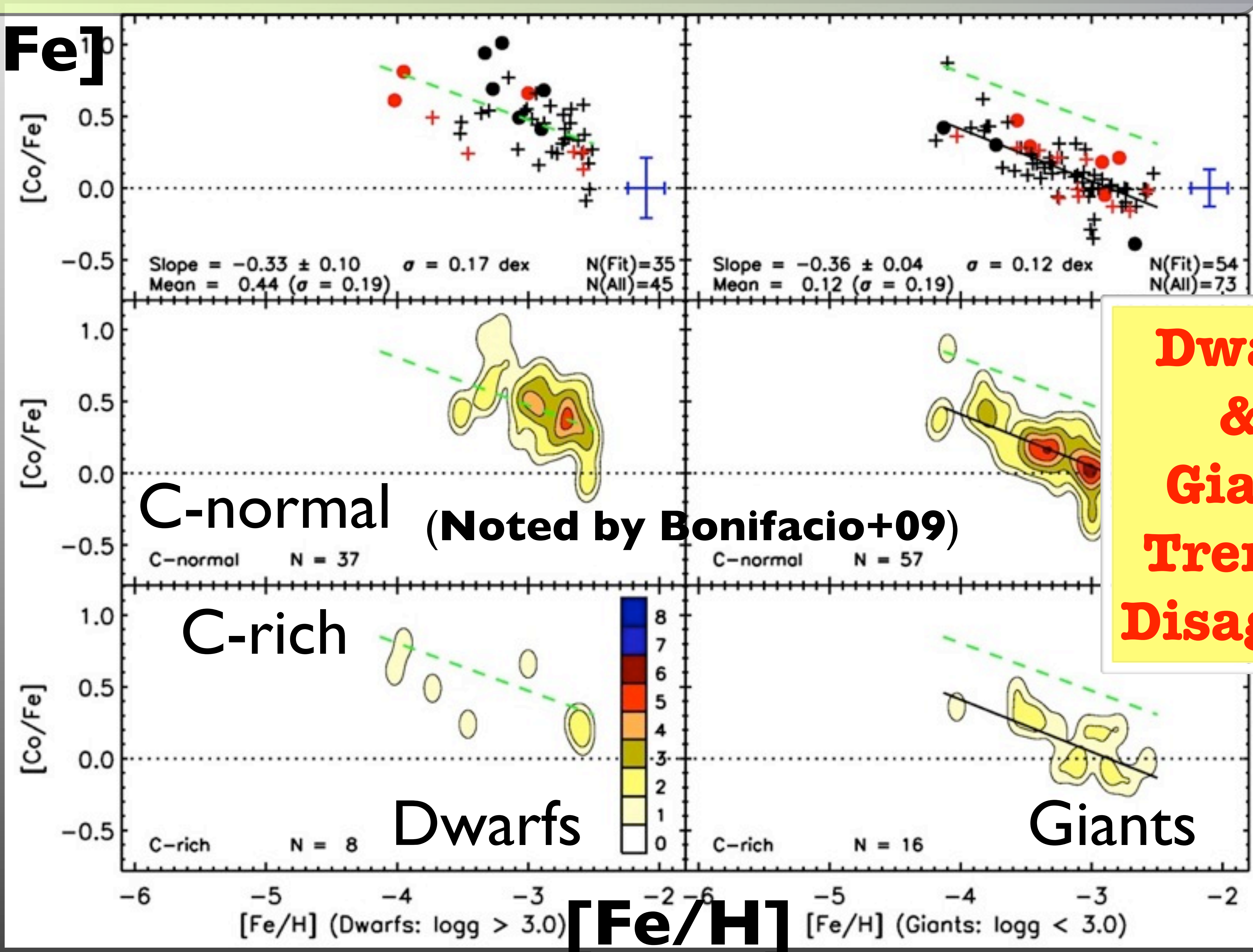
Exclude CEMP and 2σ outliers

Identify a sample of "**normal**" stars and the [X/Fe] vs [Fe/H] trends defined by this sample

Trends/scatter

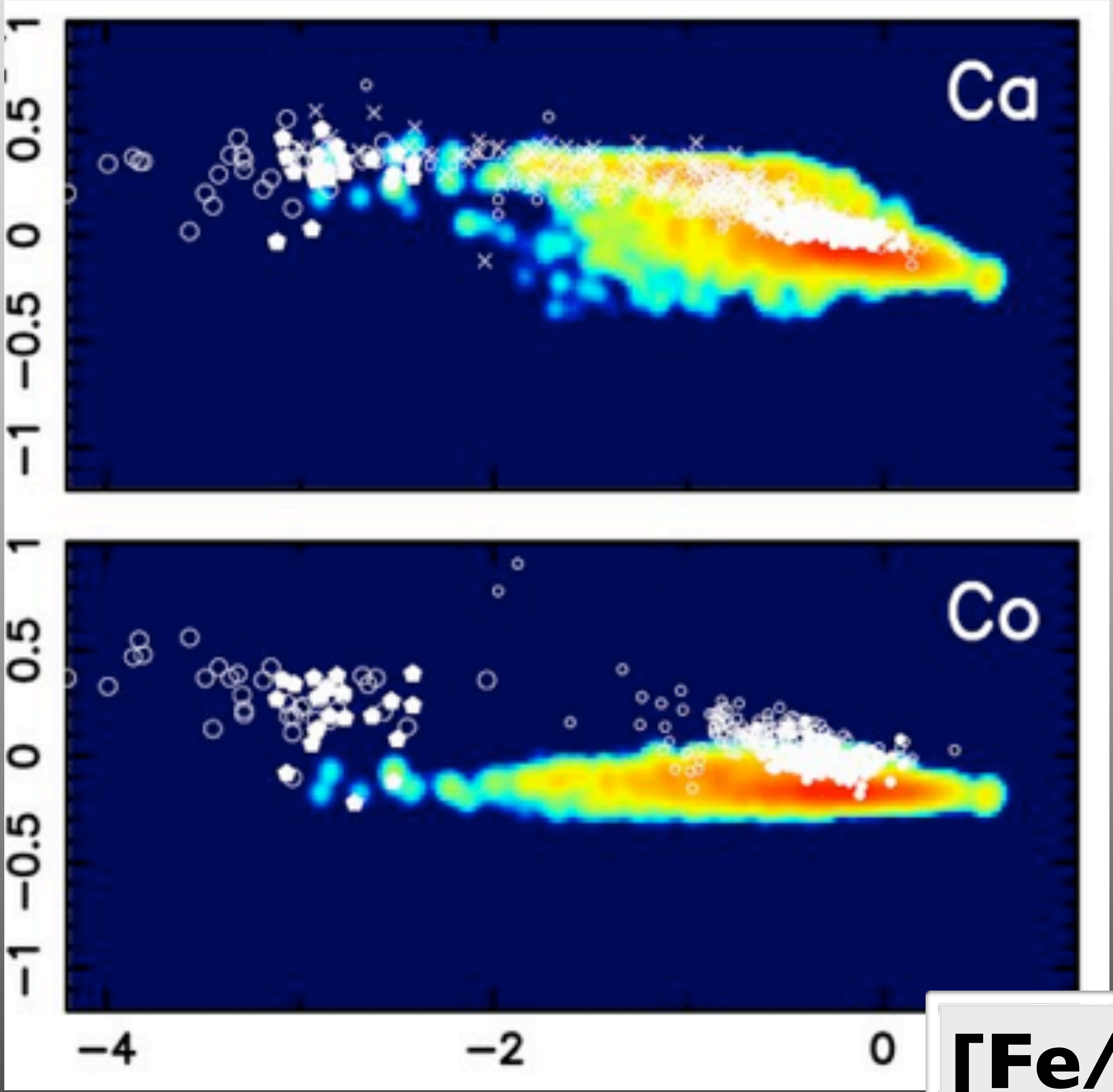


Trends/scatter



Dwarf & Giant Trends Disagree

Trends/scatter



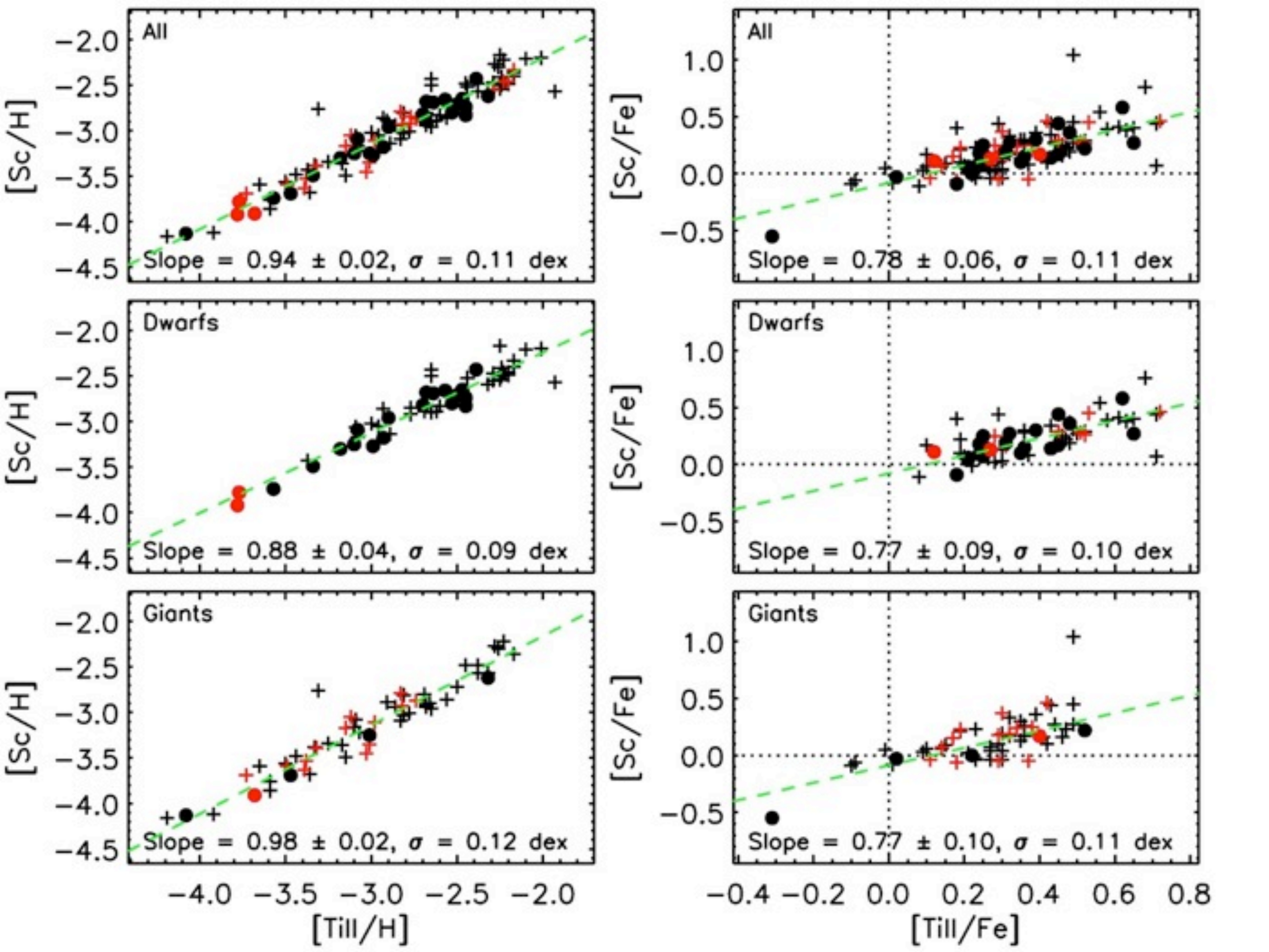
[Ca/Fe]

[Co/Fe]

[Fe/H]

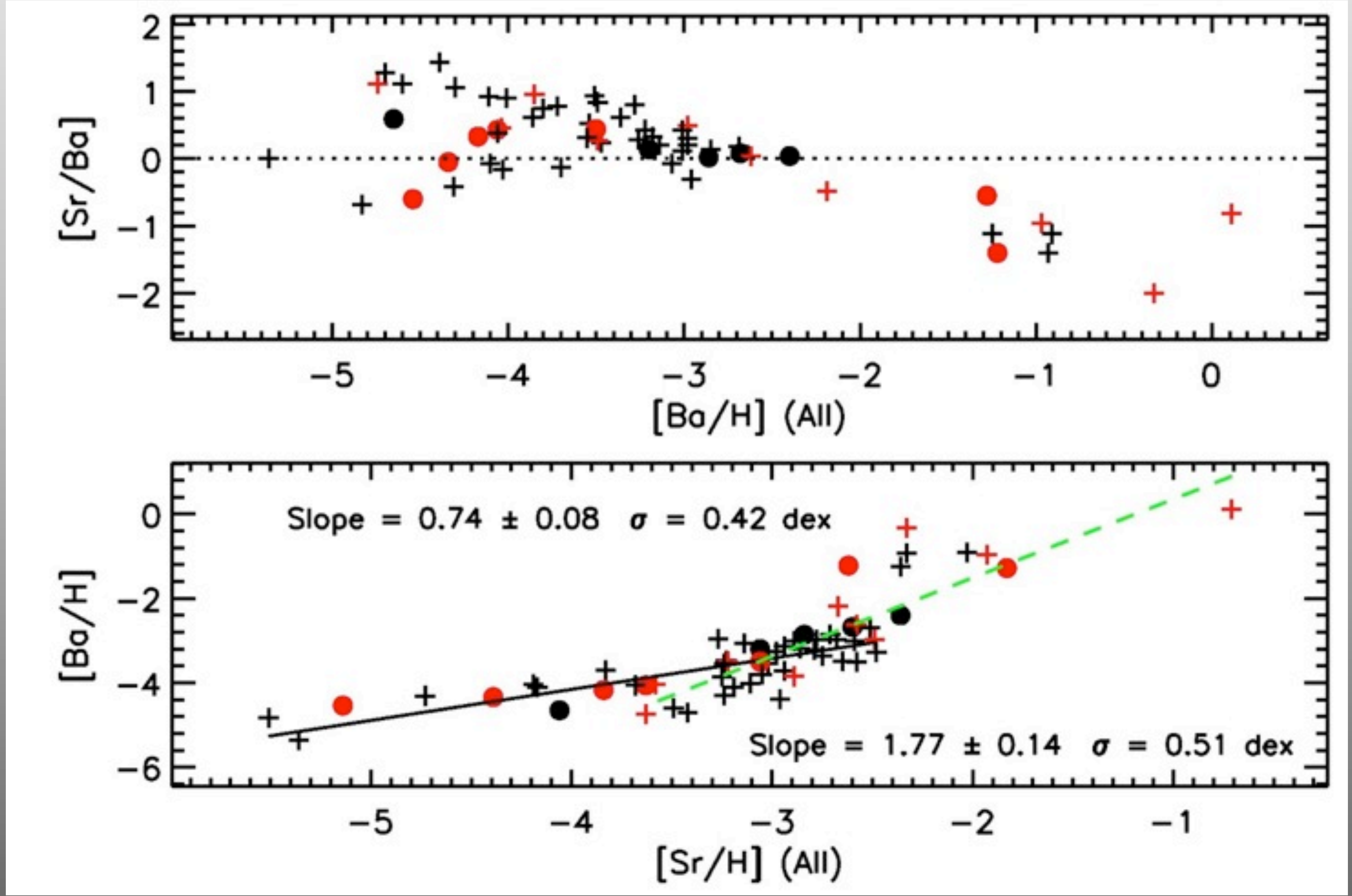
Chemodynamical simulations by Kobayashi & Nakasato 2011

Sc - Ti Correlation



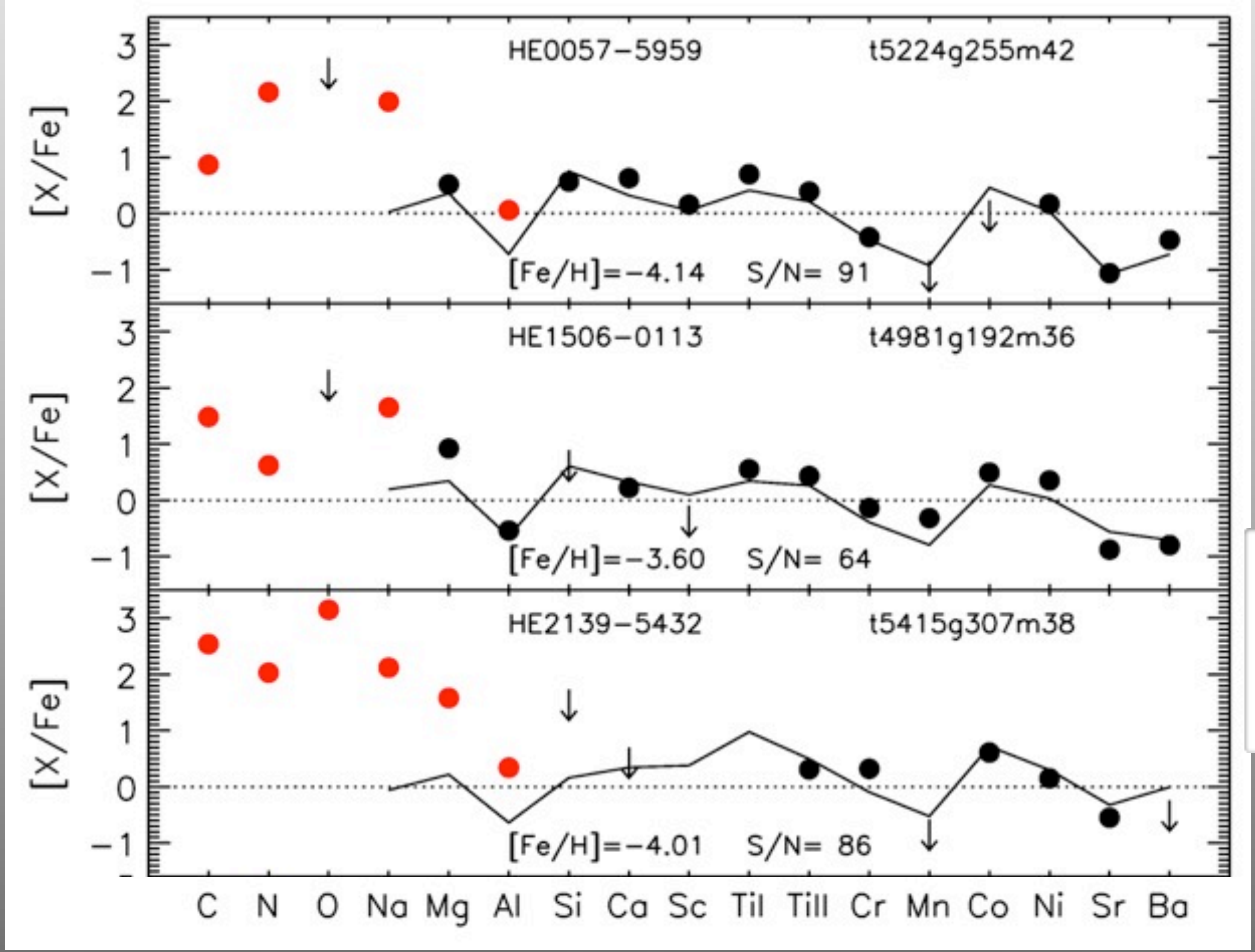
Unexpected?

Sr and Ba



Two (or more?) nucleosynthesis sites for Sr and Ba at low metallicity?

Outliers



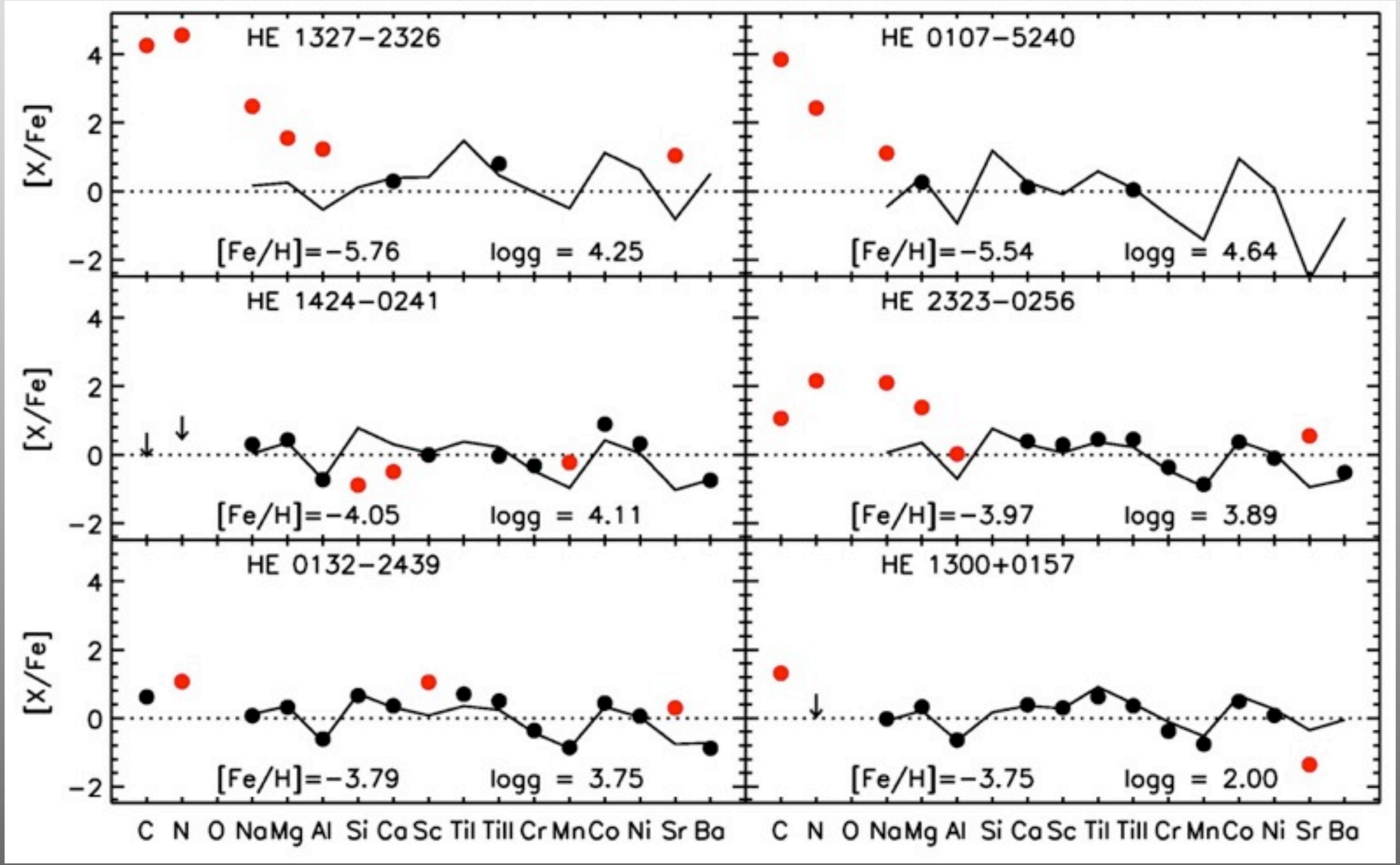
3 new CEMP-no stars with [Fe/H] < −3.5

Similar to the most Fe-poor HES stars

A new class of objects?

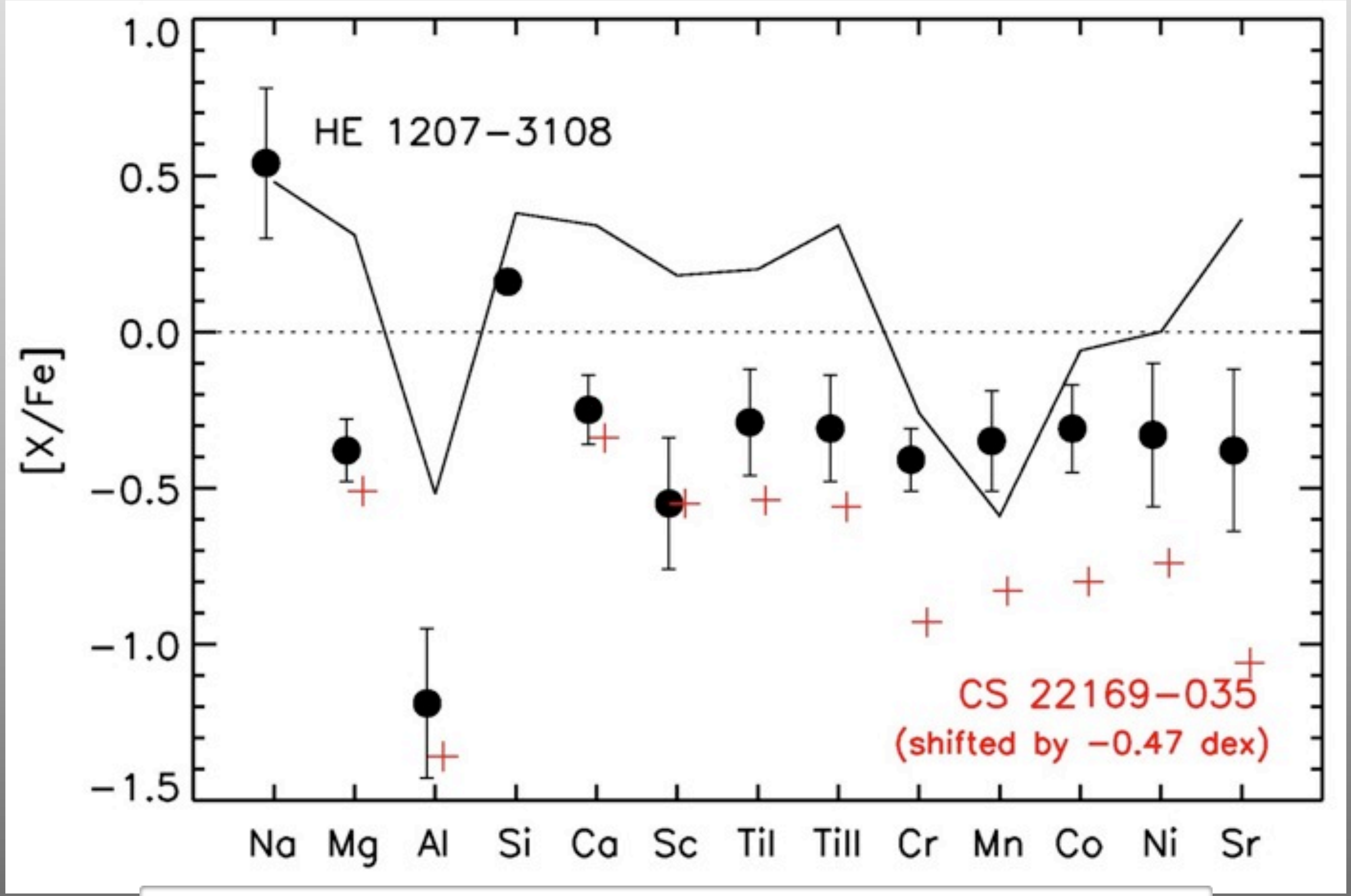
If nature can make something once ...

Outliers



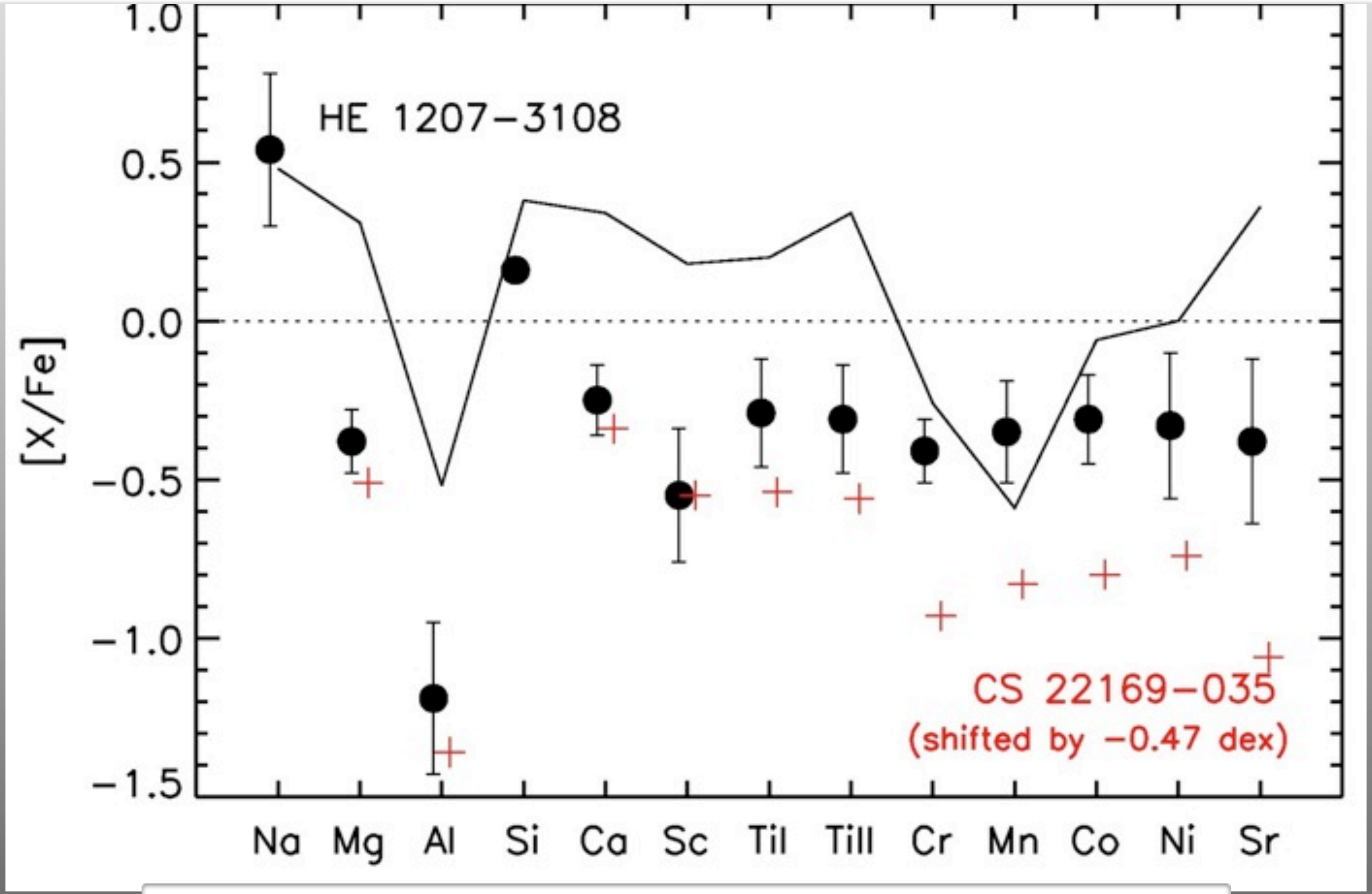
Large fraction of chemically peculiar objects at low [Fe/H]

Outliers



Stars unusually enriched in Fe

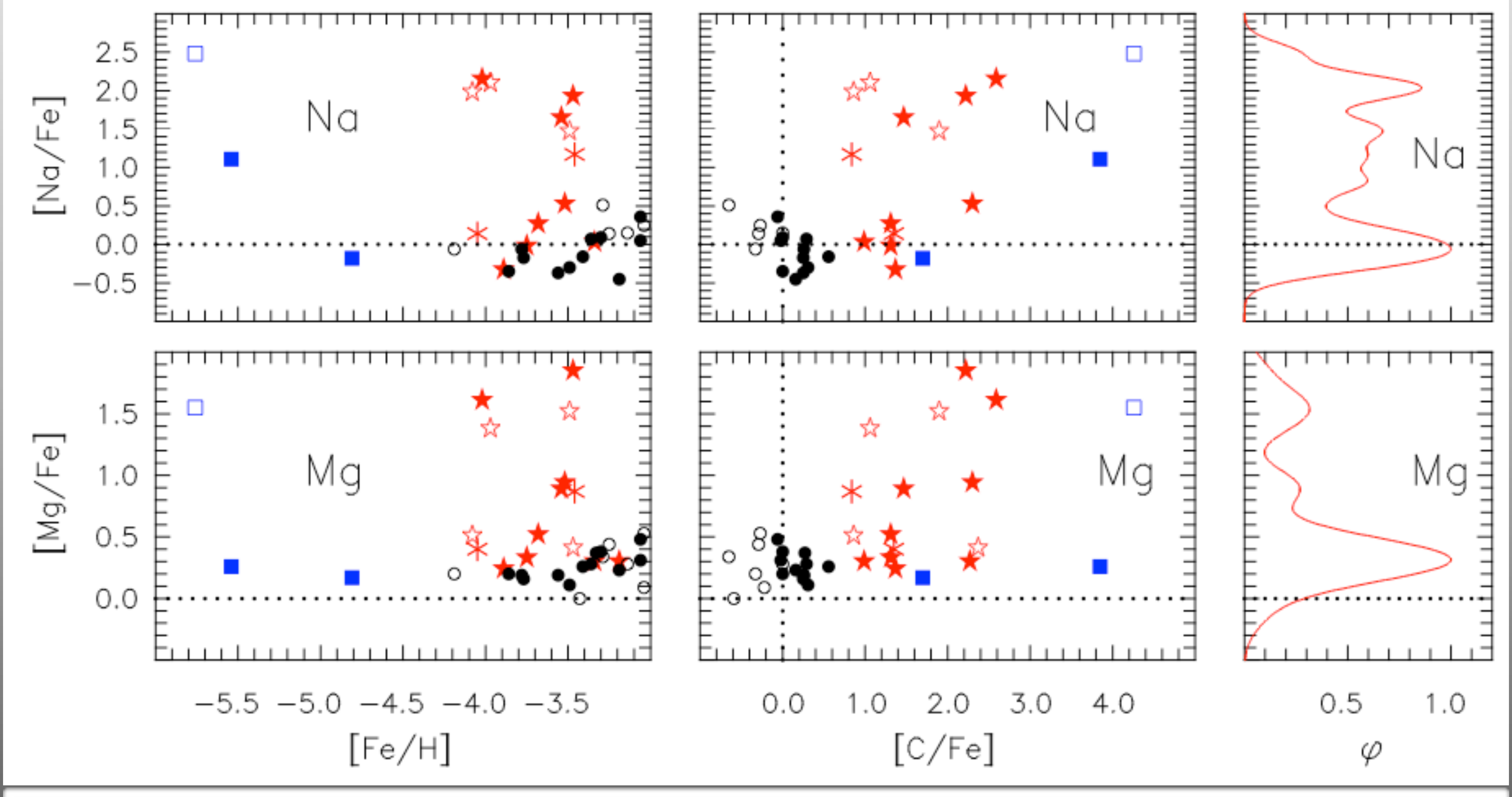
“the abundance anomalies are most simply characterized as an enhancement of Fe” (Cayrel 2004)



Stars unusually enriched in Fe

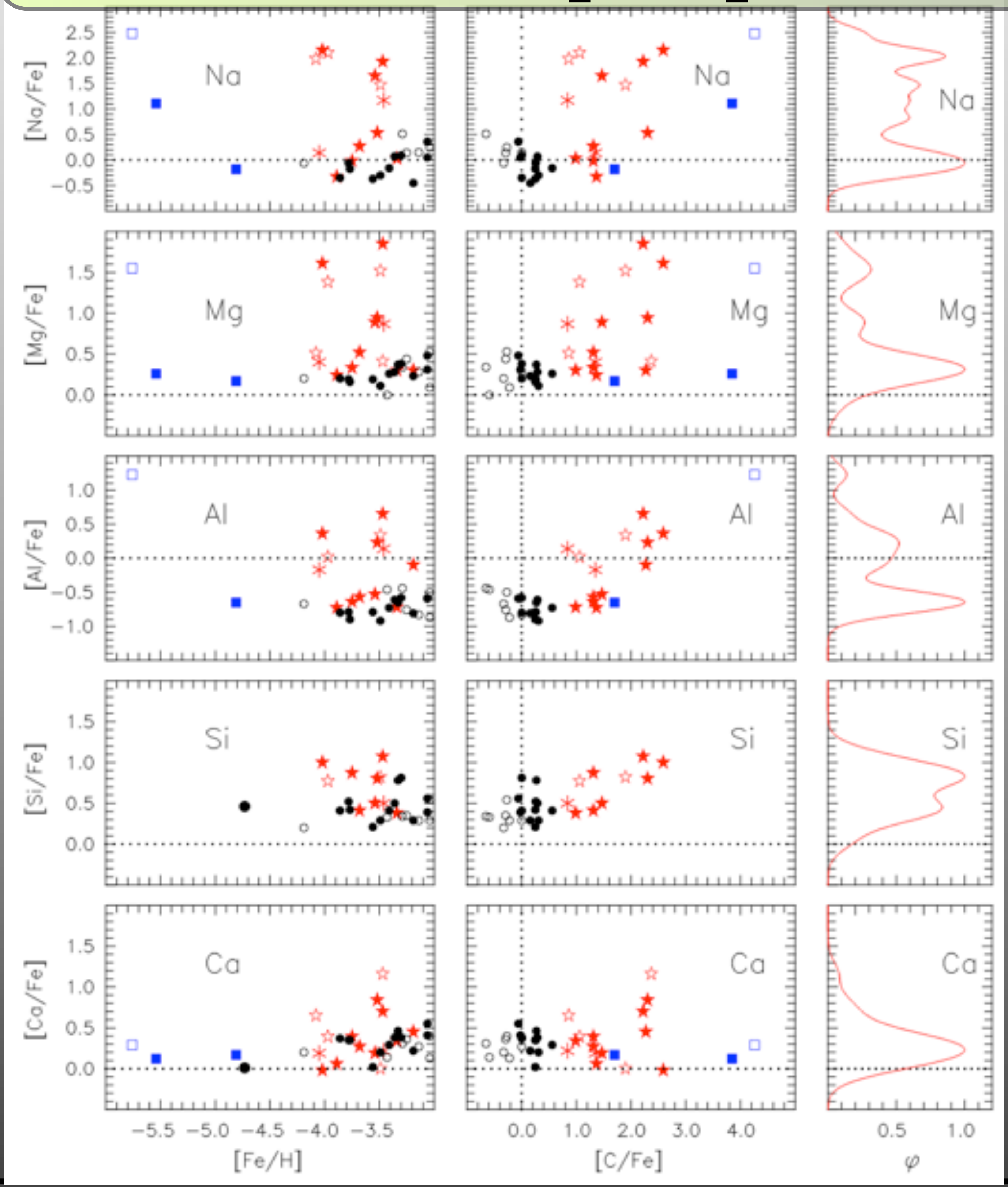
“Fe-enhanced” metal-poor star?

Two populations?

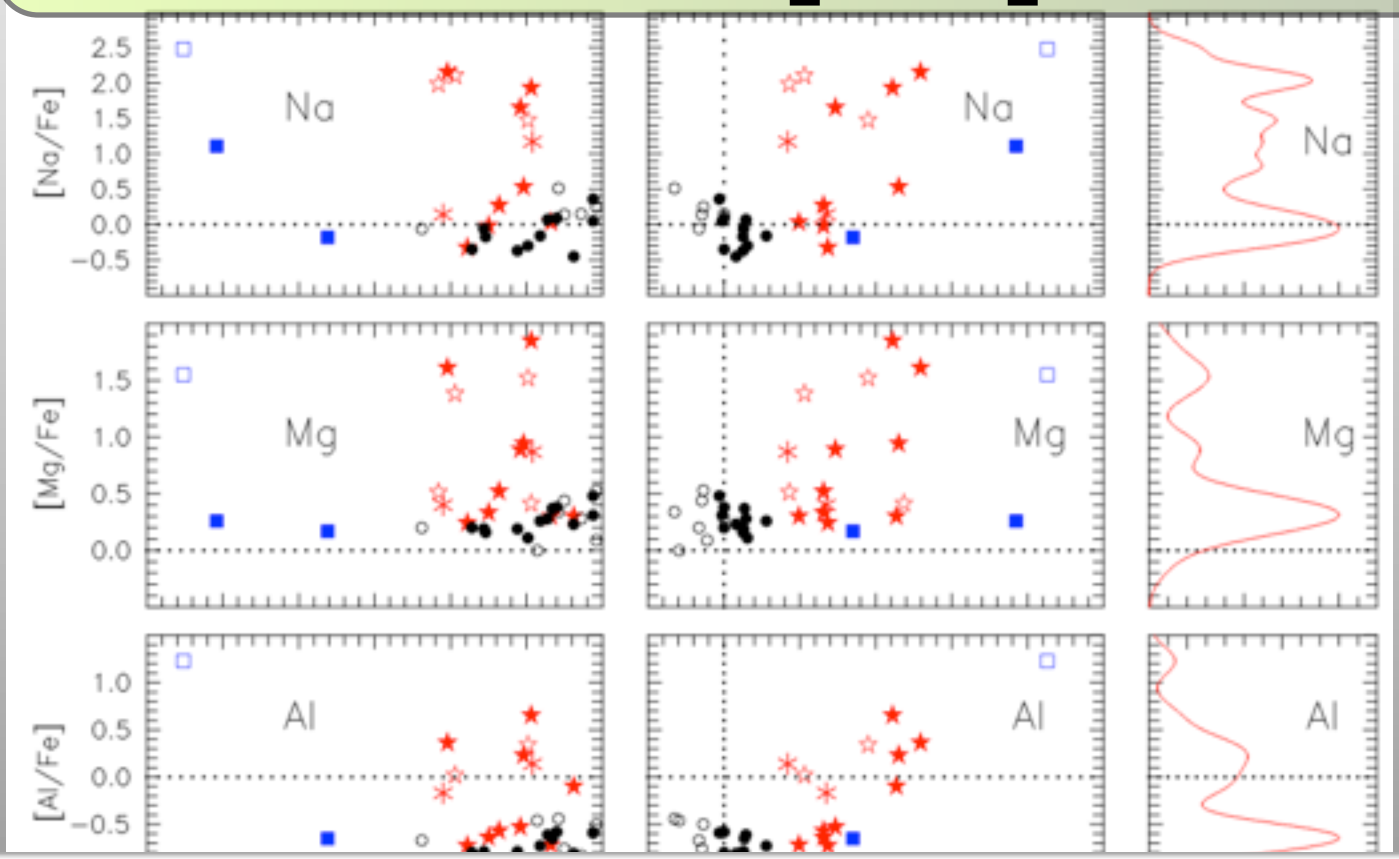


Aoki et al. (2002) first highlighted the large enhancements of Mg, Al and Si in CEMP-no stars

Two populations?



Two populations?



Of the C-rich stars with [Fe/H] < -3.0, half are enhanced in Na, Mg and Al.

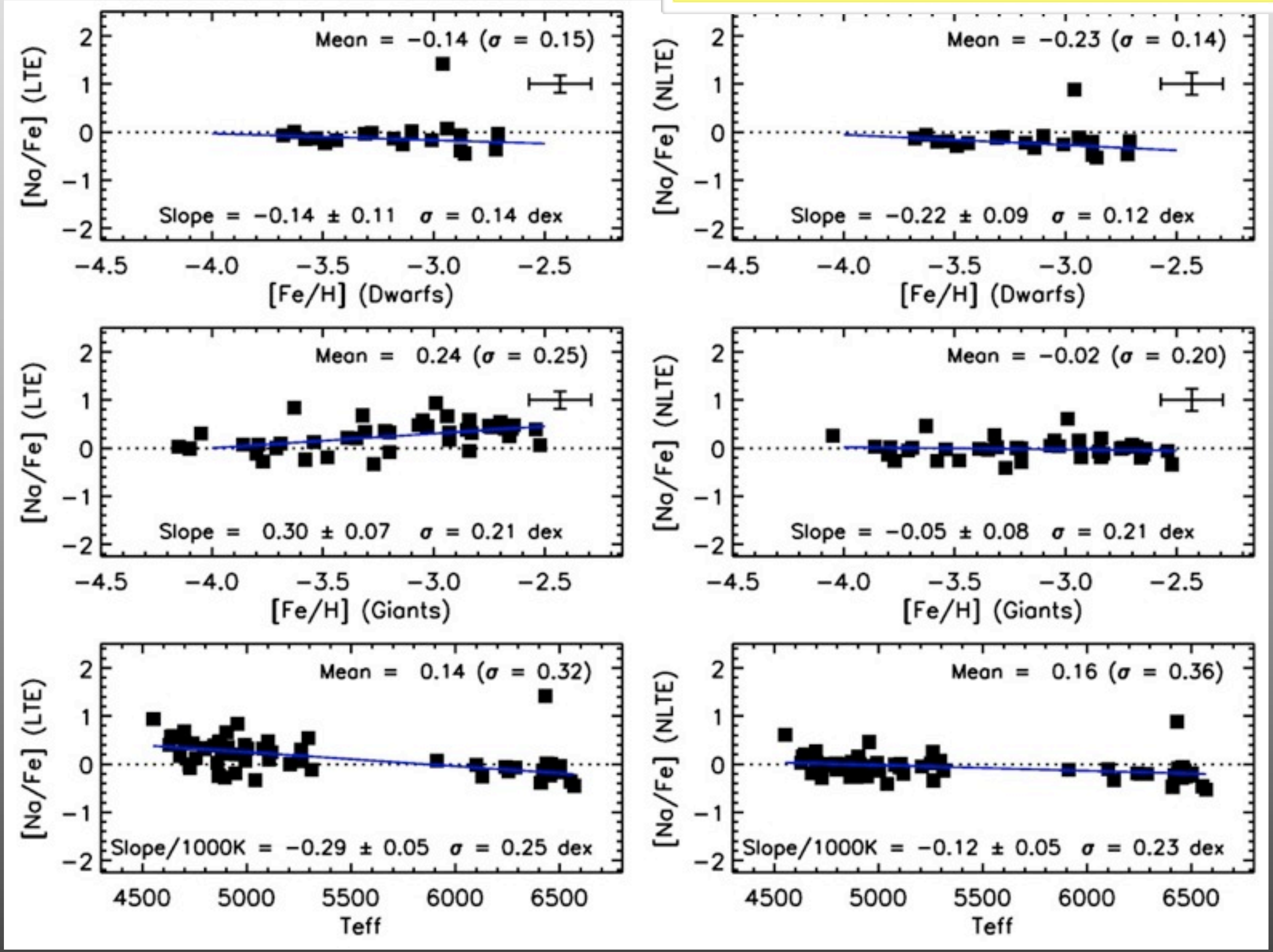
For Z > 20 (Ca), there are no enhancements

"Mixing & Fallback" (Umeda & Nomoto 2003,2005), rotation and/or jets (Tominaga et al. 2007)
(see also Fujimoto et al. 2000 and Suda et al. 2004)

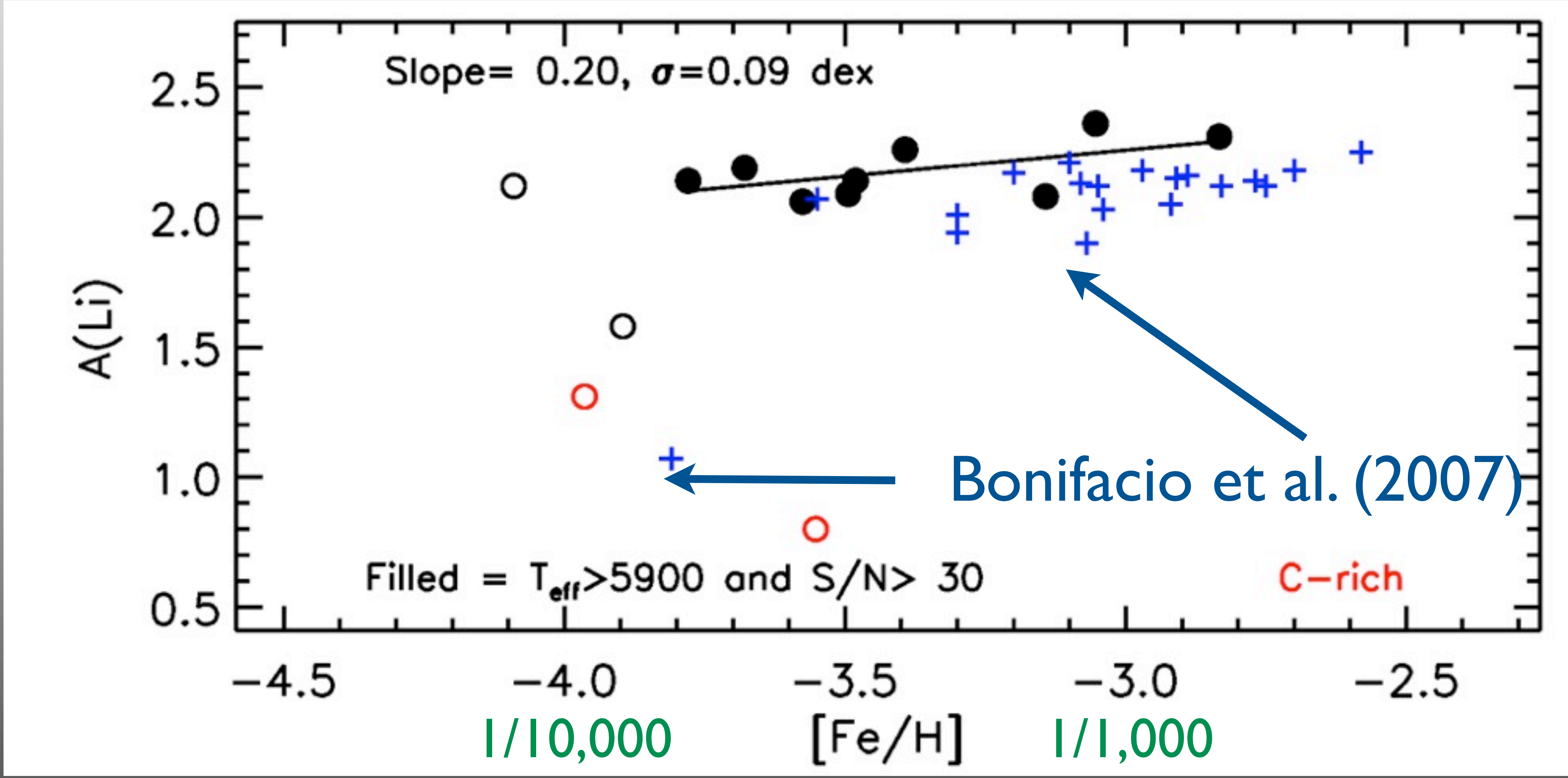
Do the C-rich and C-normal populations arise from two different gas cooling channels in the early Universe?
Fine-structure line transitions of CII and OI vs. dust-induced cooling.

NLTE

Apply the Lind et al. (2011) Na NLTE corrections



Preliminary Li results



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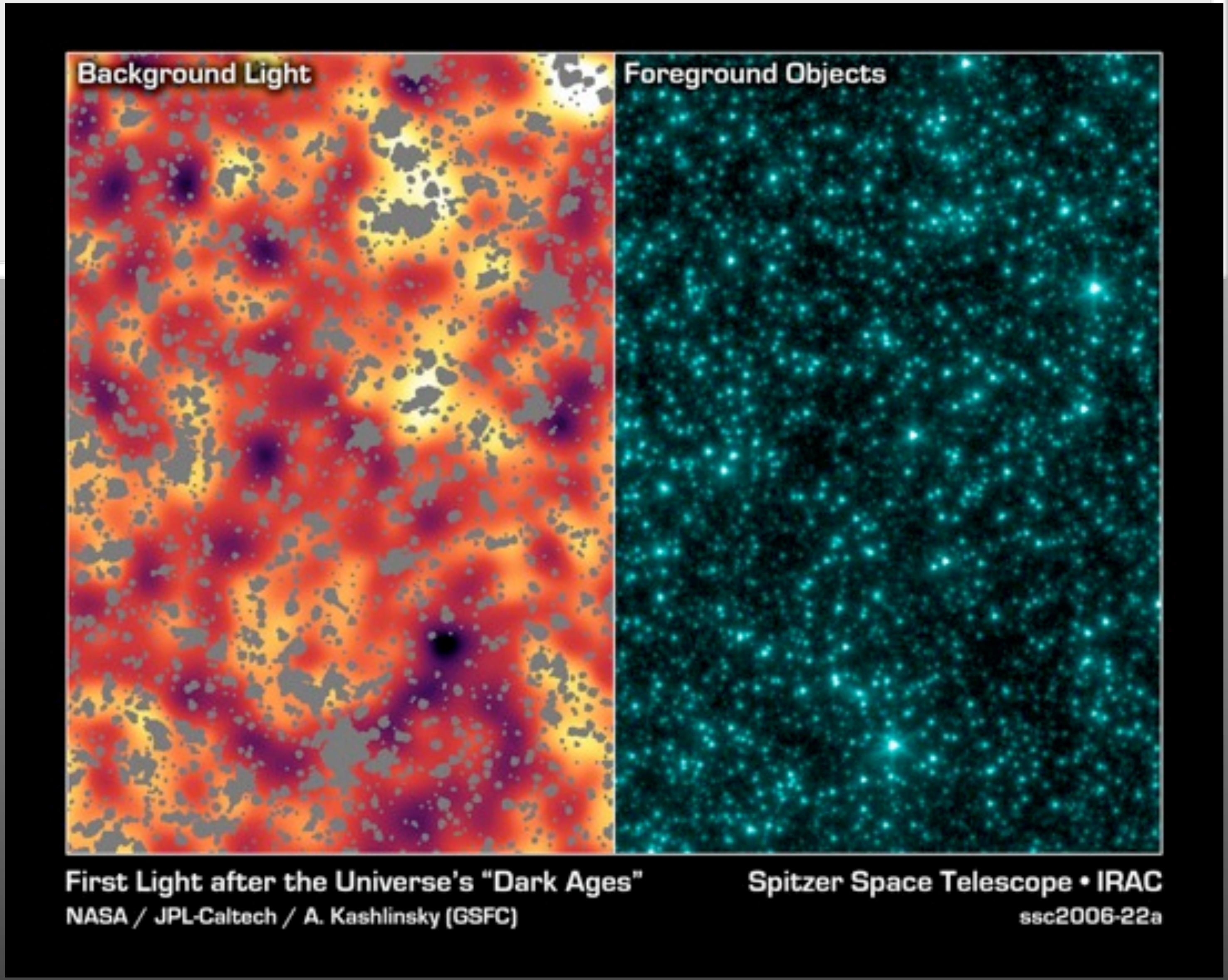

Conclusions

- **Large homogeneous** (re-)**analysis** of metal-poor stars using EWs from high-resolution, high S/N spectra
  - 86 with [Fe/H] ≤ –3.0
  - 32 with [Fe/H] ≤ –3.5
  - 9 with [Fe/H] ≤ –4.0 (... on our scale)
  - measured 16 elements (C to Ba)
- **MDF decreases smoothly** with decreasing metallicity
- **Confirm the large fraction** of **CEMP** stars
  - 32 ± 8% below [Fe/H] = –3.0 (Aoki CEMP definition)

Conclusions

- **10 new stars with −4.25 ≤ [Fe/H] ≤ −3.5**
- **Three new CEMP-no stars** with large [C, N, O, Na, Mg/Fe]
- **Numerous peculiar objects** (some of which, but not all, are CEMP stars)
- Within an **arbitrarily defined "normal" population**, the scatter can be explained by measurement uncertainties
- Confirm the **enormous scatter** in [Sr, Ba/Fe] at lowest metallicities

The Need for More Data

With more stars we can ...

- ✗ Discover the elusive Pop III star (no metals)
- ✓ Better constrain the nature of the first stars by studying more objects with [Fe/H] < –4.0
- ✓ Quantify the fraction of stars at low metallicity with anomalously large abundances of C, N, O and/or Mg
- ✗ Discover r-process enhanced stars to measure ages (Th, U)
- ✓ Measure Li to test the cosmological lithium problem

Paper V (Norris et al. in prep)

Future Directions

- Usual concerns about NLTE, 3D, using models with appropriate CNO+ compositions
- Upcoming surveys (LAMOST, SKYMAPPER) and **continued mining of existing surveys (SDSS)** will provide many additional candidates and maybe "break" the [Fe/H] = –6 'barrier'
- Improved precision? Perhaps strictly differential analysis of very high quality data to obtain errors at the <<0.05 dex level as achieved in recent studies.