# Back to the Future: The HK Survey of Beers, Preston, & Shectman

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SDSS

# Galactic Chemical Evolution

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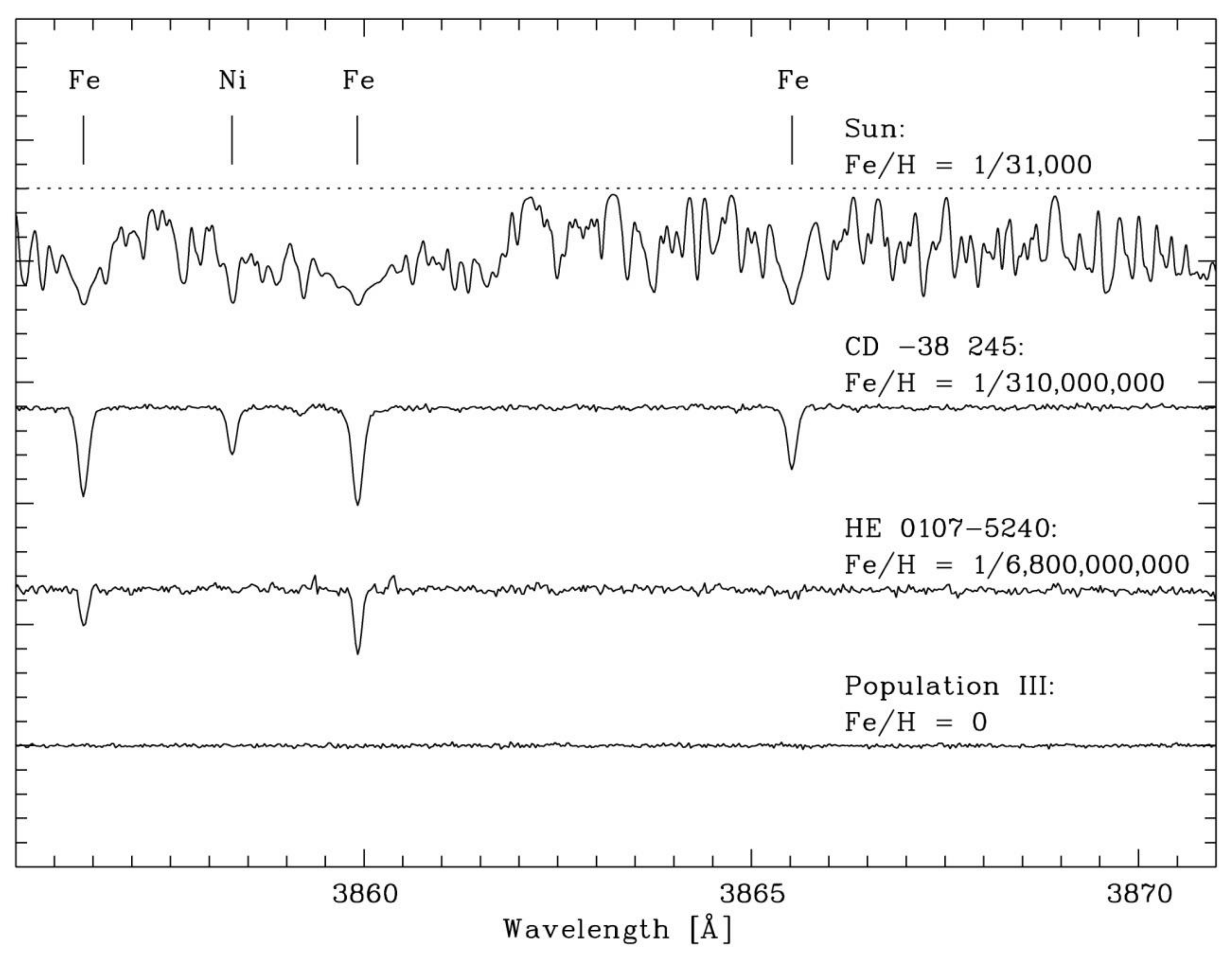


[Fe/H]= 0

[Fe/H]= −4

[Fe/H]= −5.3

[Fe/H] = -∞

# The State of Play Circa 1980

## PRIMORDIAL STAR FORMATION: THE ROLE OF MOLECULAR HYDROGEN

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### ABSTRACT

We investigate the thermal and chemical evolution of a collapsing spherical cloud composed of pure hydrogen gas. The cloud is assumed to be in pressure-free collapse. Over a wide range of initial conditions, virtually all the gas is converted to molecular form by a density $n = 10^{12}$ cm$^{-3}$. The most effective reactions are the three-body ones: $H + H + H \rightarrow H_2 + H$ and $H + H + H_2 \rightarrow 2H_2$. As a result of significant cooling from the molecules, the temperature rise is slowed, and the Jeans mass eventually falls below 0.1 $M_{\odot}$ for clouds less massive than 100 $M_{\odot}$. Such clouds should therefore be capable of fragmenting into low-mass stars. This conclusion is strengthened if angular momentum slows the collapse. We also include in a heuristic manner the effect of shock heating from colliding fragments in a turbulent collapsing cloud. With substantial heating, the Jeans mass cannot drop as far, owing to the early destruction of hydrogen molecules. The primordial stellar mass spectrum may therefore be a sensitive function of the degree and effectiveness of intercloud collisions.

# Find the Aardvark … We Needed More Metal-Poor Stars !

There is an Aardvark hiding in the back of this pickup truck. Can you find him?

The Preston-Shectman Survey for metal-poor stars (~1978) made use of an objective prism, (hand)-widened spectra, and an interference filter (to isolate the region around Ca II K, and limit sky fog and spectral overlap), in order to obtain low-res prism spectra for stars that were several mags fainter than previously achieved.

Some 60 plates were obtained, visually scanned by George Preston, and medium-res follow-up spectra obtained by Preston & Shectman, reduced and analyzed by Beers (Beers et al. 1985).

# HK Survey Telescopes

Curtis Schmidt (Cerro Tololo)

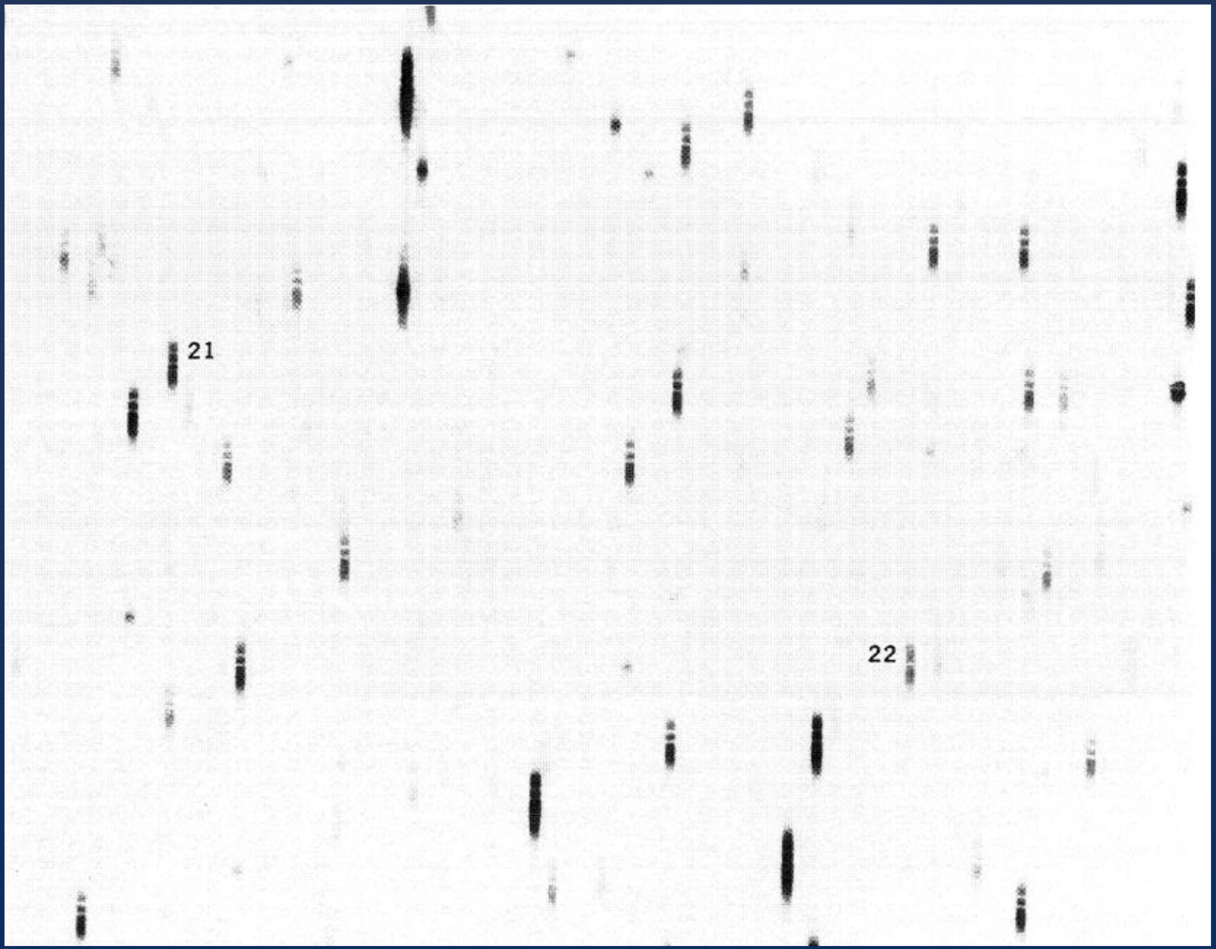
Burrell Schmidt (Kitt Peak)

# HK Survey Objective Prism Plate

Expanded by Beers (1986 – 1996) with an additional 240 plates. A total of over 300 useful plates were obtained (275 unique) in the northern and southern hemispheres.

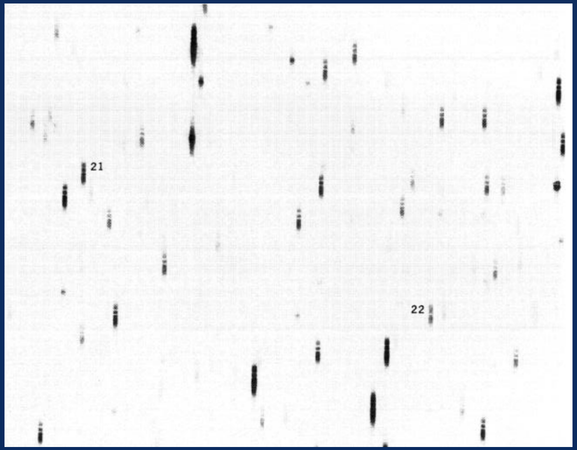
Each plate had several thousand low-res spectra, visually scanned to pick out best MP candidates.

A worldwide medium-res spectroscopic follow-up was conducted (~1985 – 2000), involving teams based in the US, Europe, and Australia.




*Enlargement of a typical HK Survey plate. Spectra are roughly 5 Å resolution, covering 150 Å . Lines of CaII K are visible, from which candidate MP stars were identified.*

# HK Survey Discovery Tools


# HK Survey Discovery Method

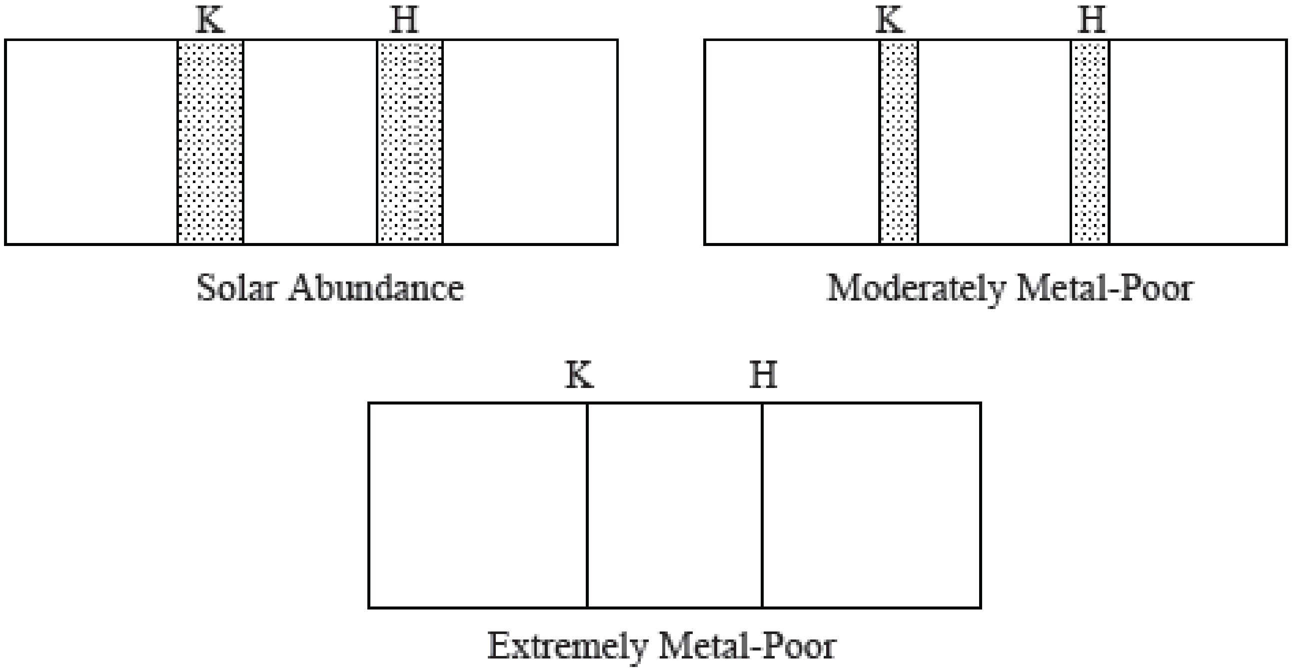
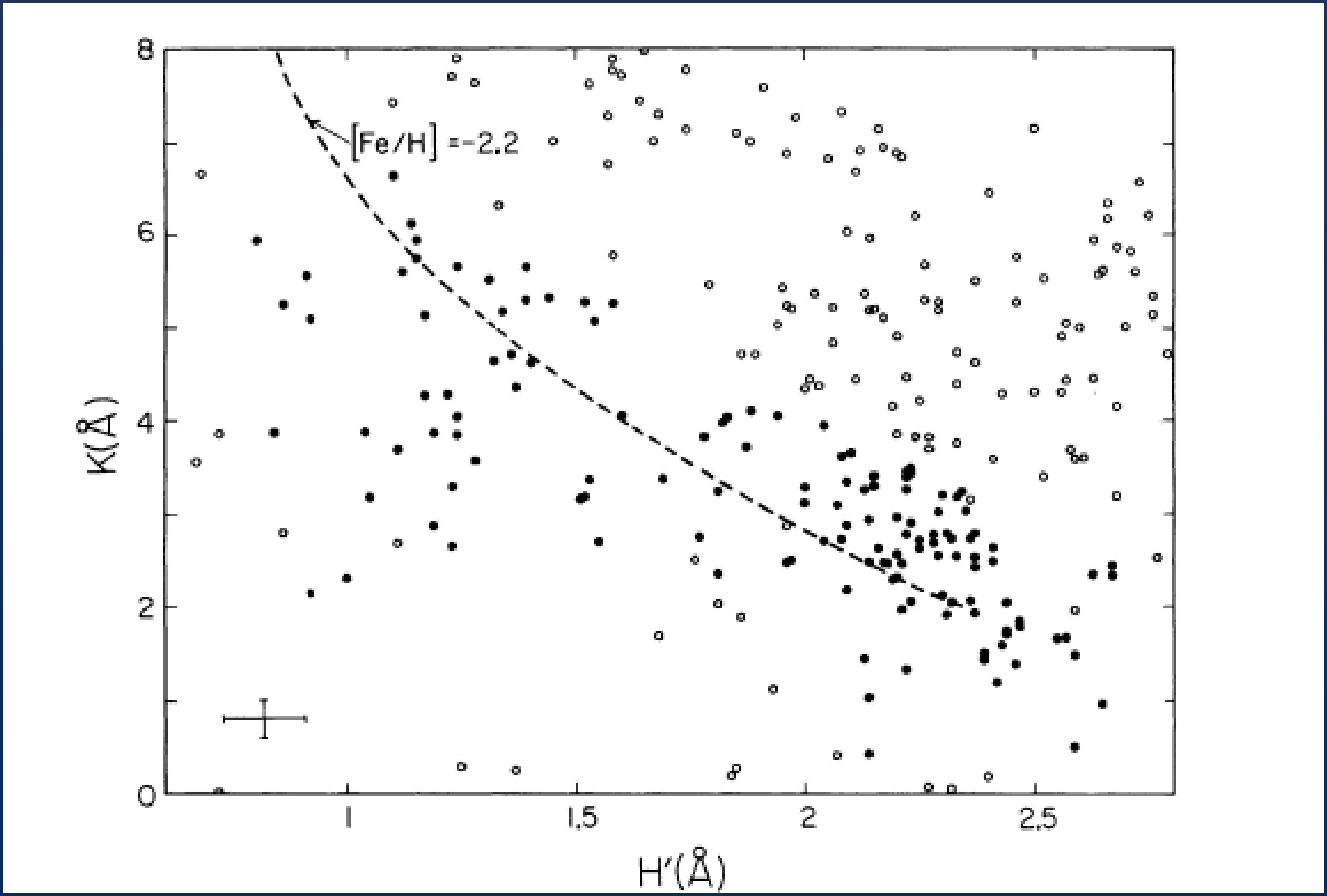



FIGURE 2. Examples of the appearance of low-resolution HK-survey spectra of solar, moderately metal-poor and extremely metal-poor candidates, over the 150 Å region covered by the prism spectra, as they would appear under a 10X microscope used in their original selection The Ca II K and H lines are labelled. Note the decrease in line-strength with declining metallicity. The examples shown are for cool stars, where both features respond sensitively to abundance. For warmer stars, only the Ca II K line decreases in strength, as the Ca II H line is blended with a rather strong Balmer Hε line.

# A Tentative Calibration



# High-Resolution Confirmation

## A new ultra metal-deficient star: CS 22876-32 ($\alpha_{1950} = 00^h05^m04\overset{s}{.}8$, $\delta_{19}$

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**Abstract.** Blue spectra, obtained with CASPEC at the 3.6 m telescope at La Silla (Chile), of the halo stars CS 22876-32 and CD $-38°245$ are analysed to derive the chemical composition. The giant CD $-38°245$ is the most deficient object presently known with [Fe/H] $= -4.5$ (Bessell and Norris, 1984), while CS 22876-32 belongs to a small group of very metal-deficient star candidates selected by Beers et al. (1985) using narrow band photometry of Ca II K line.

For CS 22876-32 we derive $T_{\rm eff} = 5900 \pm 100$ K and $\log g = 4.0 \pm 0.5$. The fine analysis with an LTE model atmosphere gives [Fe/H] $= -4.29 \pm 0.19$. Therefore this is the most metal-deficient dwarf known up to now. Abundances for five other

# HK Survey – Greatest Hits (So Far)

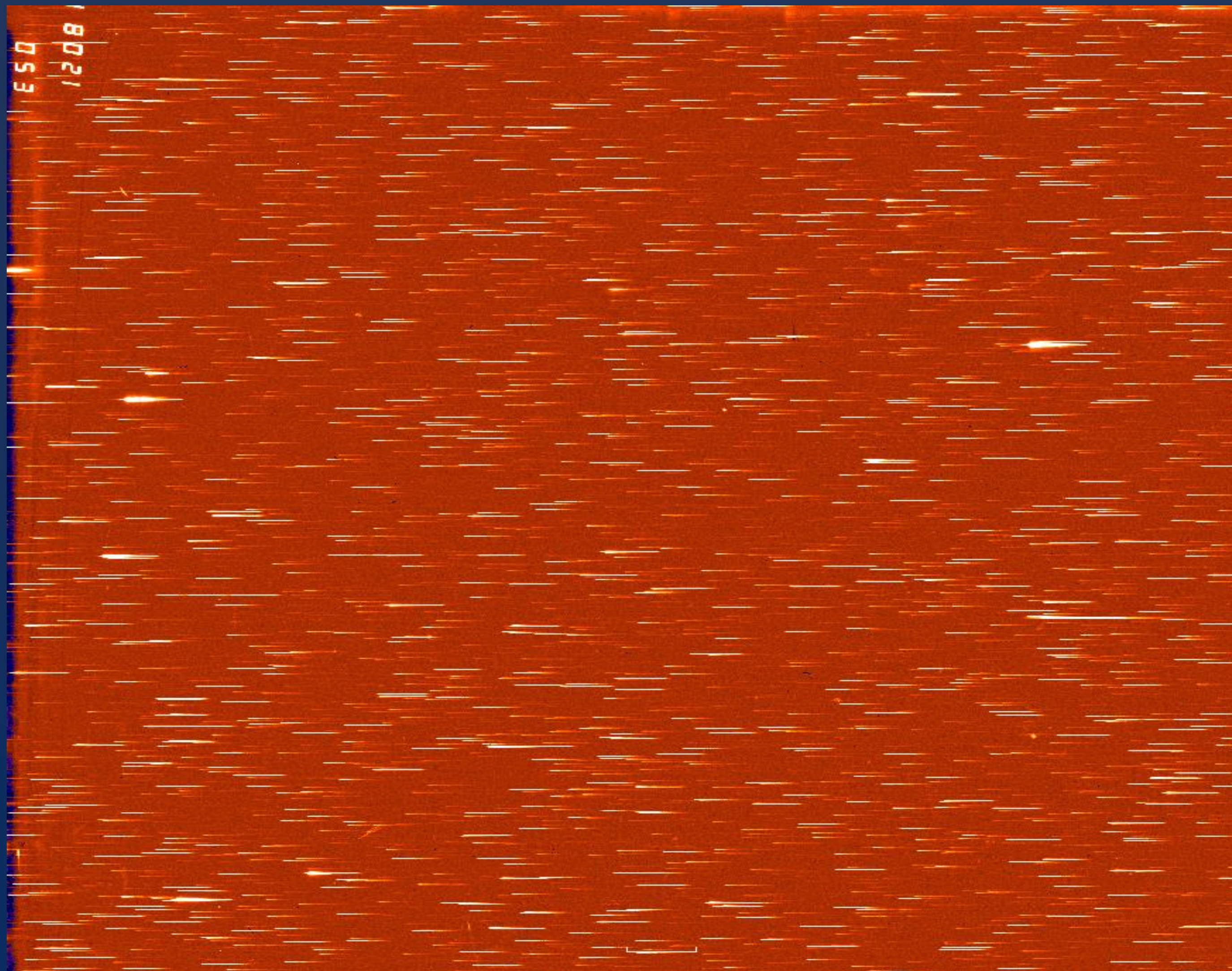
- Recognition that significant numbers of EMP stars ([Fe/H] < -3.0) exist in the Galaxy (Beers et al. 1985)
- Discovery of lowest metallicity dwarf star yet known (CS 22876-032; Beers et al. 1985)
- Derivation of change in density profile of halo (Preston et al. 1991)
- Recognition of the likely importance of Carbon-Enhanced Metal-Poor (CEMP) stars in the Galaxy (Beers et al. 1992)
- Recognition of contribution of Blue Metal-Poor (BMP) stars in the Galaxy (Preston et al. 1994)
- Recognition of r-process (McWilliam et al. 1995) and s-process-enhanced stars (Aoki et al. 2000)

# HK Survey – Greatest Hits (So Far)

- Assembly of significant numbers of EMP stars for Li studies (Ryan et al. 1999)
- First large non-kinematically selected survey of MP, VMP, EMP stars and derivation of velocity ellipsoids (Beers et al. 2000; Chiba & Beers 2000)
- Confirmation of likely presence of Metal-Weak Thick Disk (MWTD) in the Galaxy (Chiba & Beers 2000)
- Discovery of U in an EMP star (Hill et al. 2002) and the U/Th cosmo-chronometer (Cayrel et al. 2001)
- Discovery of “Actinide Boost” phenomenon (Hill et al. 2002)
- Assembly of “Gold Standard” sample of VMP stars for studies of Galactic Chemical Evolution (Cayrel et al. 2004)

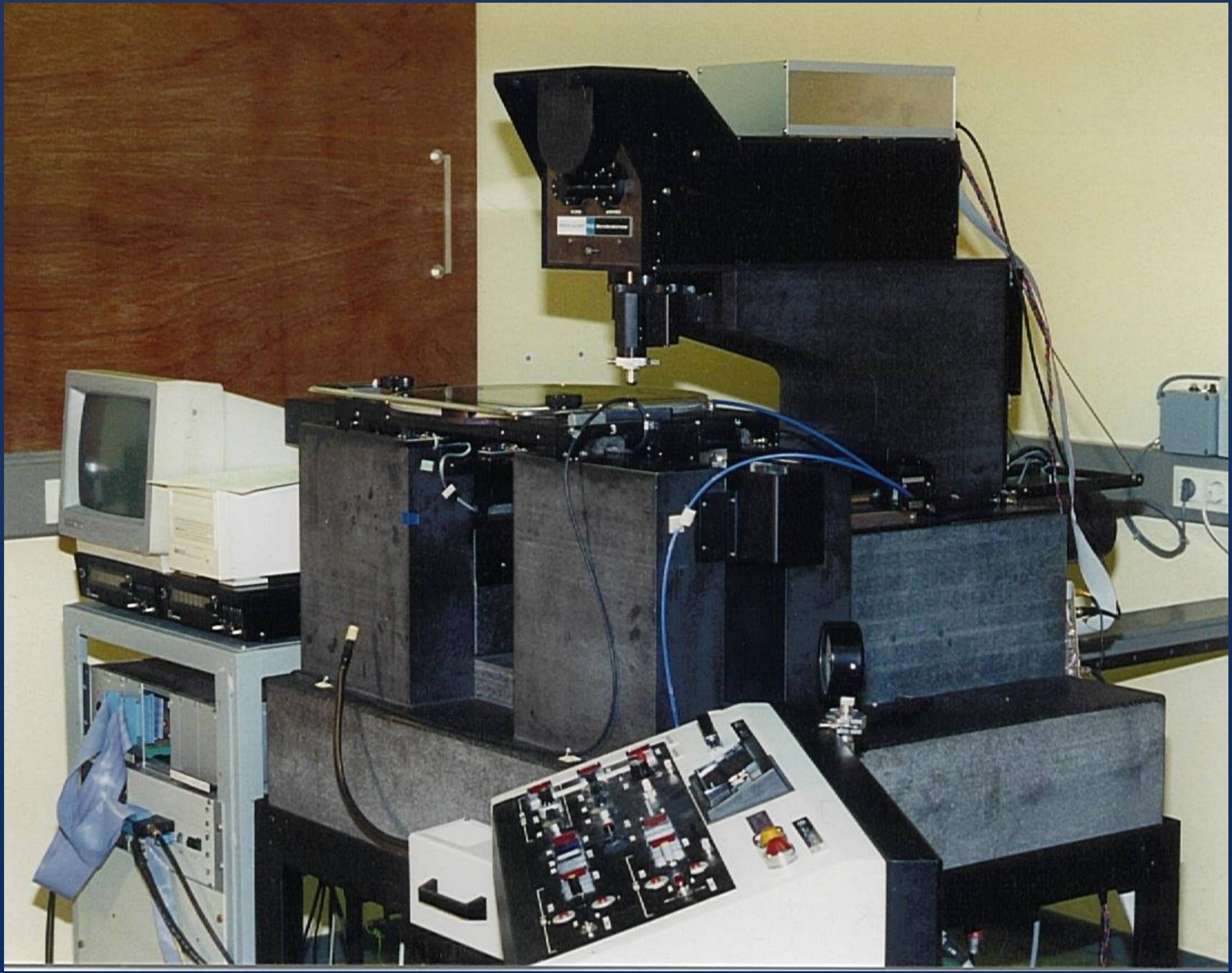
# Hamburg/ESO Searches for metal-poor stars

# Hamburg/ESO Prism Plates



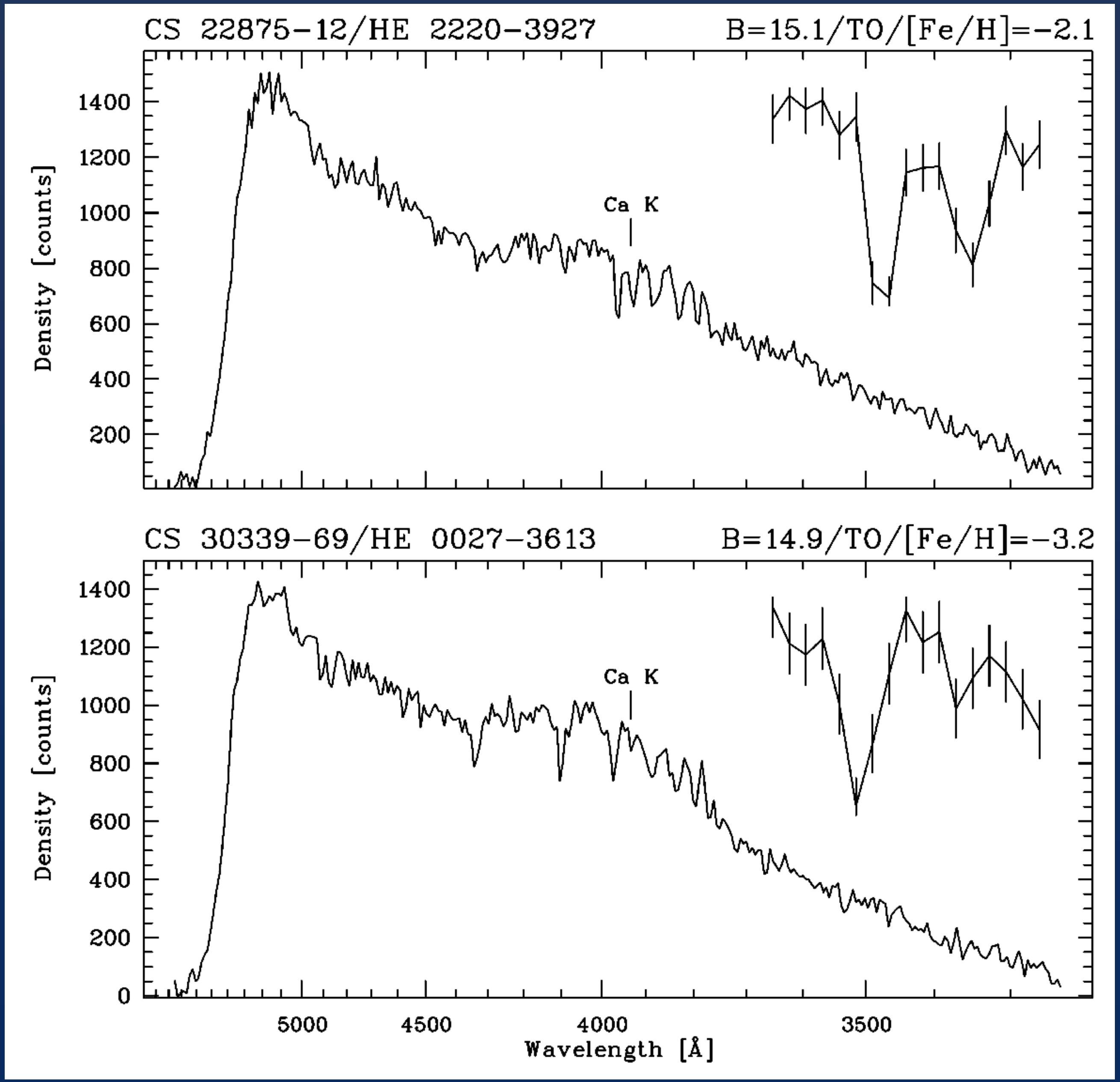

*Typical HES plate, showing spectra covering roughly 2000 Å, unwidened, at resolution of roughly 10 Å*

# HES Digitization



*Digitization of HES prism plates enables automated and quantitative selection*

# HES Spectra of Metal-Poor Stars

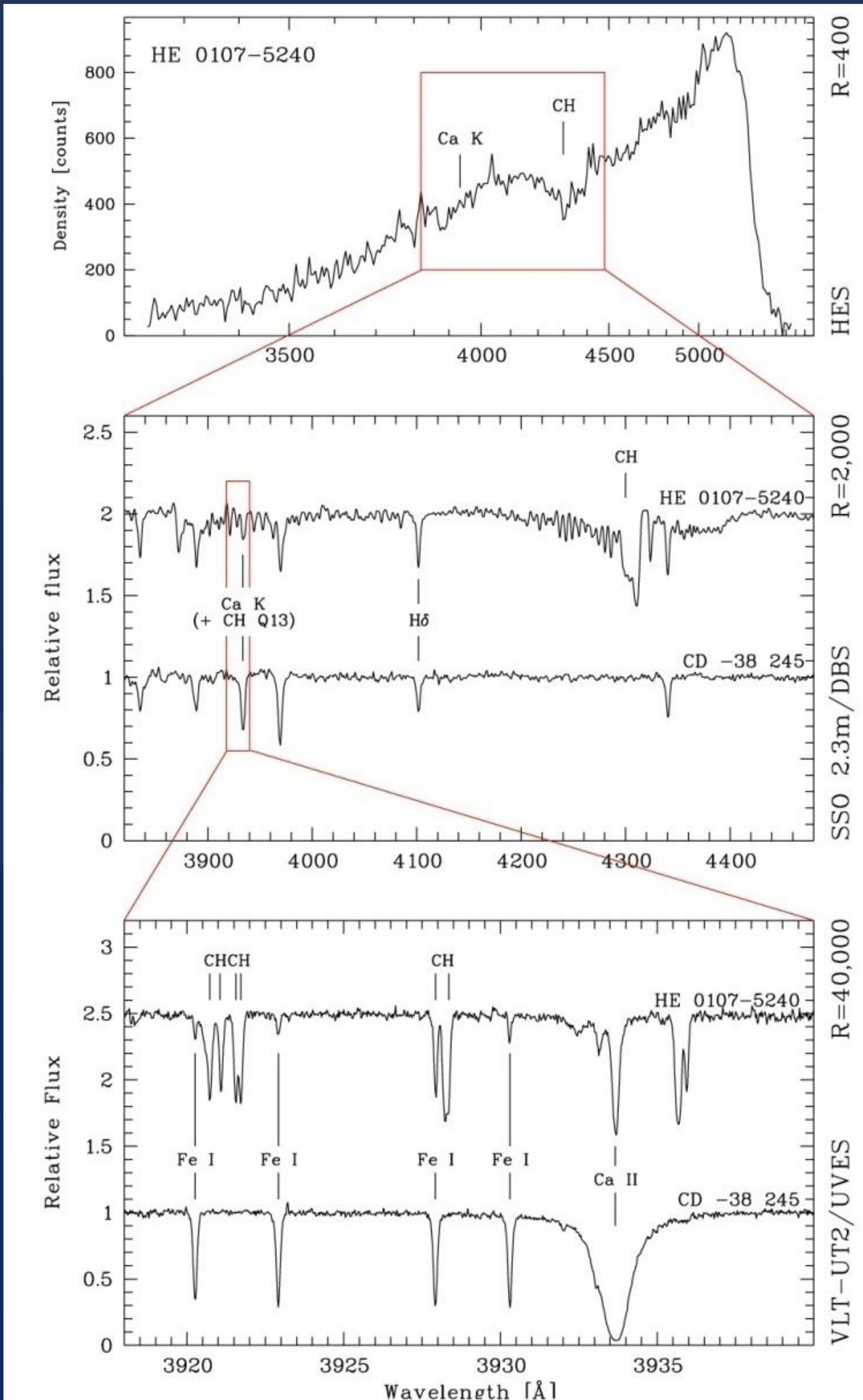


# Progression of HK/HES Observations

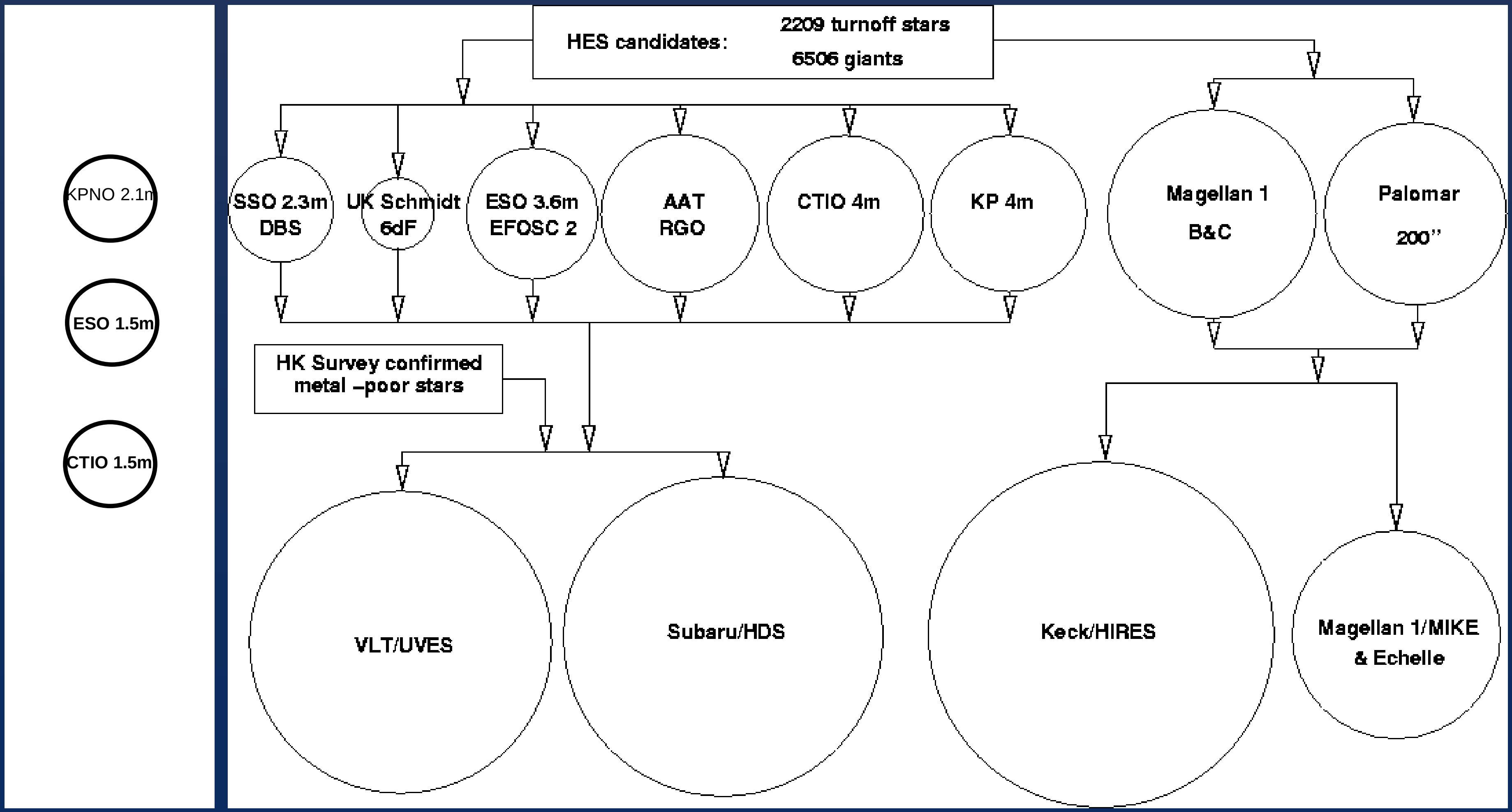
Objective Prism →

Medium Resolution →

High Resolution →



# HK/HES Metal-Poor Star Flow Chart



# Hamburg/ESO Survey – Greatest Hits (So Far)

- Discovery of the first two stars at [Fe/H] < -5.0, HE 0107-5240 (Christlieb et al. 2002), and HE 1327-2326 (Frebel et al. 2005), and detailed determination of their chemical abundance patterns.
- Discovery of 35 r-I and 8 r-II stars (Christlieb et al. 2004; Barklem et al. 2005; Frebel et al. 2007; Hayek et al. 2009; Mashonkina et al. 2010; Ren et al. 2012).
- Homogeneous abundance analysis of samples of several hundred metal-poor stars (Barklem et al. 2005; Yong et al. 2012).
- Determination of the fraction of CEMP stars as a function of [Fe/H] (Cohen et al. 2005; Lucatello et al. 2006).
- Determination of the abundance patterns of several dozen CEMP stars (Cohen et al. 2006; Goswami et al. 2006; Aoki et al. 2007).

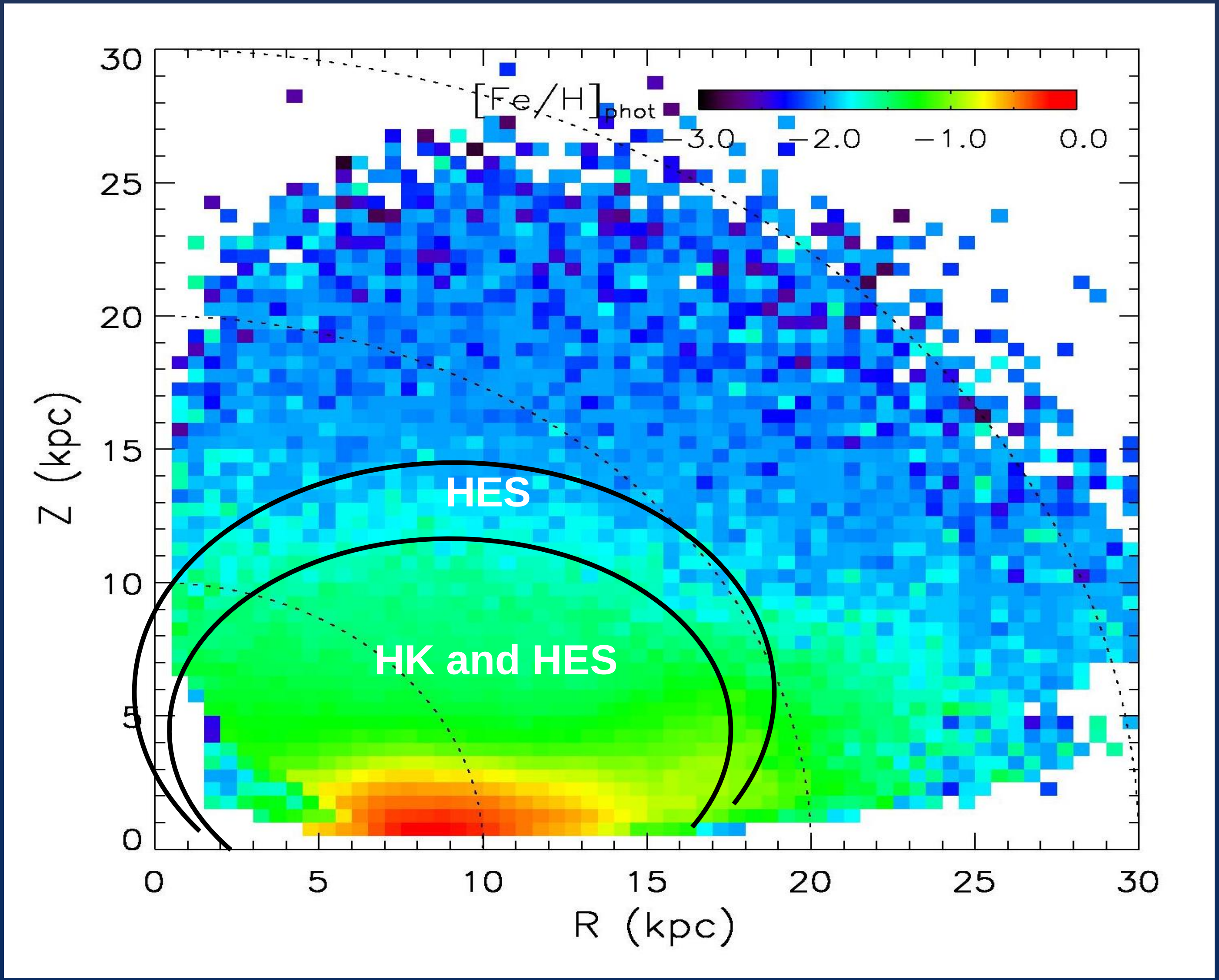
# Hamburg/ESO Survey – Greatest Hits (So Far)

- Identification of ~200 new bright stars at [Fe/H] < -2.0 (Frebel et al. 2006; Christlieb et al. 2008).
- Discovery of HE 1424-0241, an extremely metal-poor star with a large deficiency of silicon ([Si/Fe] = -1; Cohen et al. 2007).
- Most accurate measurement of the abundance of uranium in a metal-poor star, and most precise age determination by means of nucleochronometry, in the bright r-II star HE 1523-0901 (Frebel et al. 2007).
- Identification of the first star in the former "metallicity gap" of the halo MDF in the range -5.0 < [Fe/H] < 4.0: The carbon-enhanced ([C/Fe] = +1.6, ultra metal-poor ([Fe/H] = -4.8) star HE 0557-4840 (Norris et al. 2008, 2012).
- Determination of selection bias-corrected MDFs for stars with [Fe/H] < -2.5 (Schörck et al. 2009; Li et al. 2010).

# Comparison of HK/HES Surveys

| | | HK survey | HES |
|---|---|---|---|
| Telescope | north | 0.6 m Burrell Schmidt | — |
| | south | 0.6 m Curtis Schmidt | 1 m ESO Schmidt |
| Magnitude range | | $11.0 \lesssim B \lesssim 15.5$ | $14.0 \lesssim B \lesssim 17$ |
| Widened? | | yes | no |
| Area | north | $2800\,\square^\circ$ | — |
| | south | $4100\,\square^\circ$ | $7600\,\square^\circ$ |
| Objective prism | | $4^\circ$ | $4^\circ$ |
| Dispersion | | 180 Å/mm | 450 Å/mm |
| Spectral resolution | | $\sim 5$ Å | $\sim 10$ Å at Ca II K |
| Photographic emulsion | | 103a-O/IIa-O | IIIa-J |
| Filter? | | interference/Ca H+K | no |
| Wavelength range | | $3875\,Å < \lambda < 4025\,Å$ | $3200\,Å < \lambda < 5200\,Å$ |
| Candidate selection | | visual inspection | automated |

# SDSS Photometric Metallicity Map



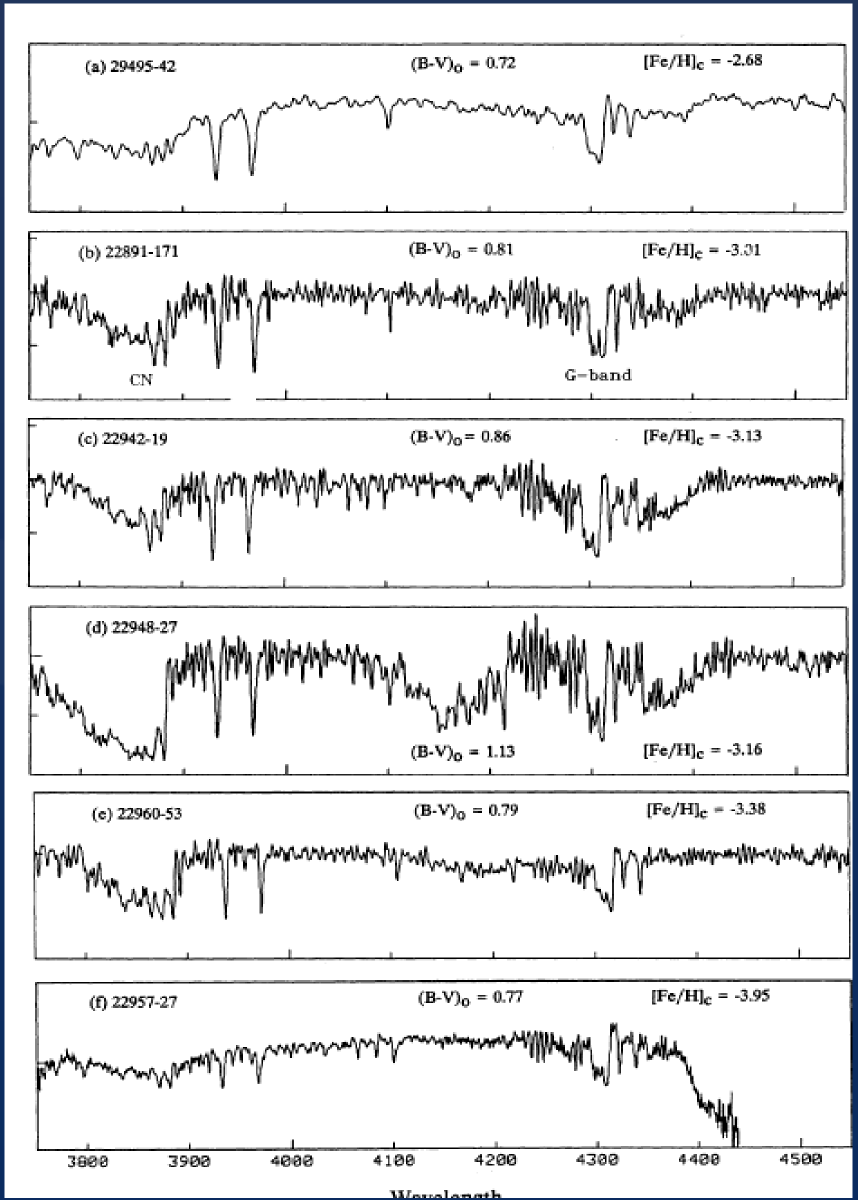
# Known MP Stars – Pre and Post SDSS/SEGUE-1/SEGUE-2

| Name | Metallicity | Pre | Post |
|---|---|---|---|
| Metal-Poor | [Fe/H] < -1.0 | 15,000 | 150,000+ |
| Very Metal-Poor | [Fe/H] < -2.0 | 3,000 | 30,000+ |
| Extremely Metal-Poor | [Fe/H] < -3.0 | 400 | 1000+ |
| Ultra Metal-Poor | [Fe/H] < -4.0 | 5 | 6 |
| Hyper Metal-Poor | [Fe/H] < -5.0 | 2 | 3 |
| Mega Metal-Poor | [Fe/H] < -6.0 | 0 | 0 |

N.B. – EMP stars probably include additional UMP and HMP stars, but wont be revealed as such until high-resolution follow-up conducted (contamination due to interstellar CaII K and/or carbon)

# The Discovery of Carbon-Enhanced Metal-Poor (CEMP) Stars

- HK Survey (Beers, Preston, & Shectman 1992)
  - Note that original selection criteria was **carbon blind**
  - Only based on **perceived weakness** of CaII H and K lines on objective prism spectra

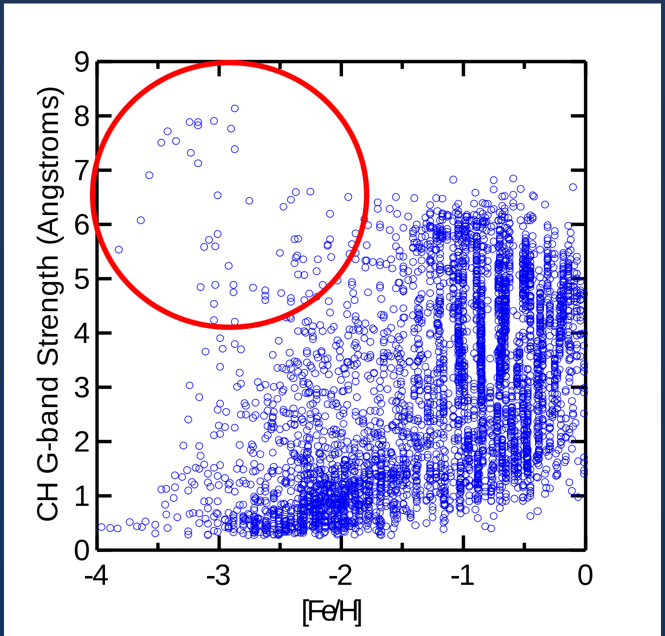


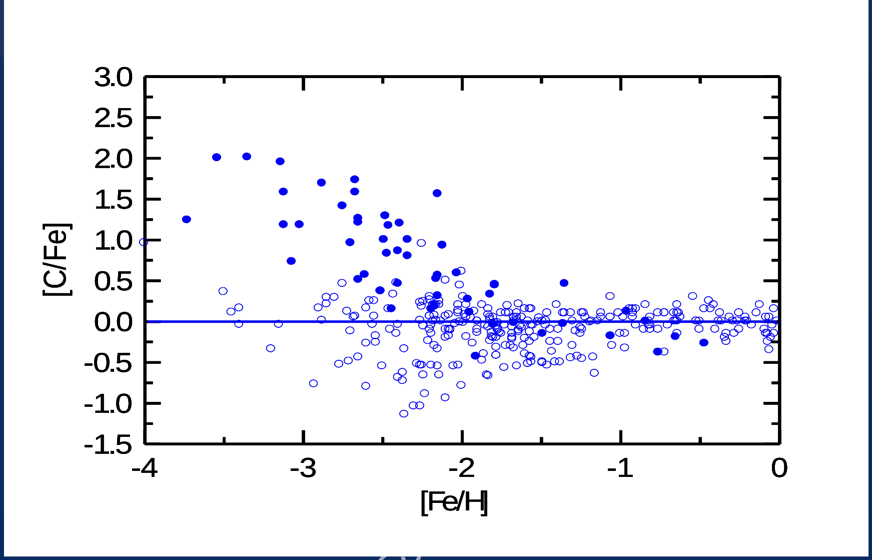
# Just How Common are These CEMP Stars ?

- The HK Survey of Beers and colleagues revealed that MANY low-[Fe/H] stars exhibit a large overabundance of carbon relative to iron **(10s of CEMP stars)**

- This realization has inspired further searches for CEMP stars, both in the HK survey and the (then) newer Hamburg/ESO prism survey **(100s of CEMP stars)**

- And by SDSS/SEGUE-1/SEGUE-2 **(1000s of CEMP stars)**



# Frequencies of CEMP Stars Based on Stellar Populations

- Carbon-Enhanced Metal-Poor (CEMP) stars have been recognized to be an important stellar component of the halo system
- CEMP stars frequencies are:
  - 20% for [Fe/H] < −2.5
  - 30% for [Fe/H] < −3.0
  - 40% for [Fe/H] < −3.5
  - 75% for [Fe/H] < −4.0
- But Why ? – Atmospheric/Progenitor or Population Driven ?
- Carollo et al. (2012) suggest the latter

# Exploration of Nature’s Laboratory for Neutron-Capture Processes

| | |
|---|---|
| Neutron-capture-rich stars | |
| r-I | $0.3 \leq [Eu/Fe] \leq +1.0$ and $[Ba/Eu] < 0$ |
| r-II | $[Eu/Fe] > +1.0$ and $[Ba/Eu] < 0$ |
| s | $[Ba/Fe] > +1.0$ and $[Ba/Eu] > +0.5$ |
| r/s | $0.0 < [Ba/Eu] < +0.5$ |
| Carbon-enhanced metal-poor stars | |
| CEMP | $[C/Fe] > +1.0$ |
| CEMP-r | $[C/Fe] > +1.0$ and $[Eu/Fe] > +1.0$ |
| CEMP-s | $[C/Fe] > +1.0$, $[Ba/Fe] > +1.0$, and $[Ba/Eu] > +0.5$ |
| CEMP-r/s | $[C/Fe] > +1.0$ and $0.0 < [Ba/Eu] < +0.5$ |
| CEMP-no | $[C/Fe] > +1.0$ and $[Ba/Fe] < 0$ |

Beers & Christlieb ARAA (2005)

# The UMP/HMP Stars are (Almost) ALL CEMP-no Stars

- Aoki et al. (2007) demonstrated that the CEMP-no stars occur preferentially at lower [Fe/H] than the CEMP-s stars
- About **80% of CEMP** stars are CEMP-s or CEMP-r/s, **20%** are CEMP-no
- Global abundance patterns of CEMP-no stars incompatible with AGB models at low [Fe/H]

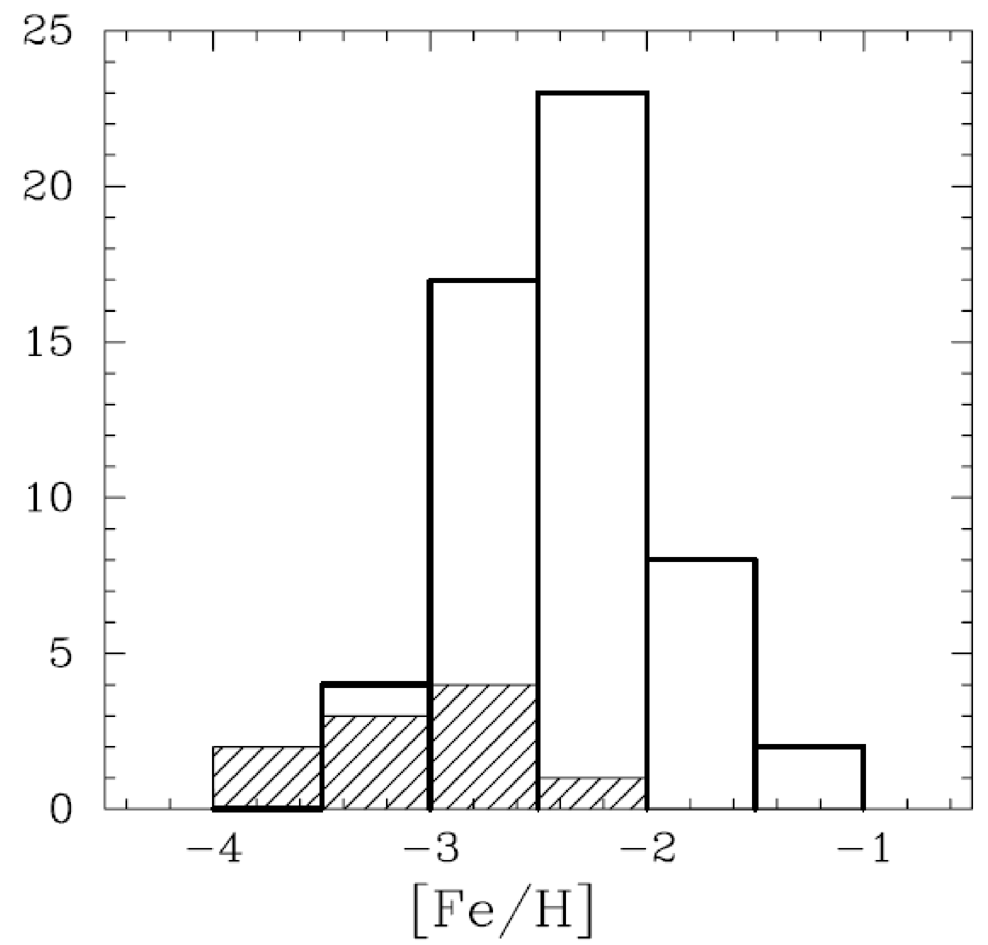
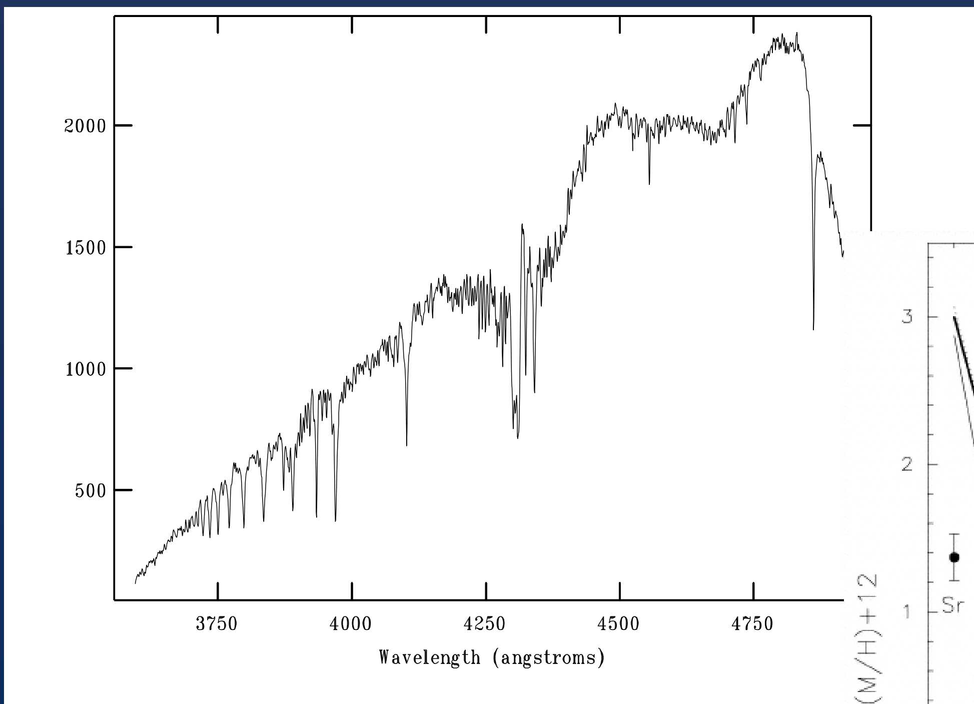
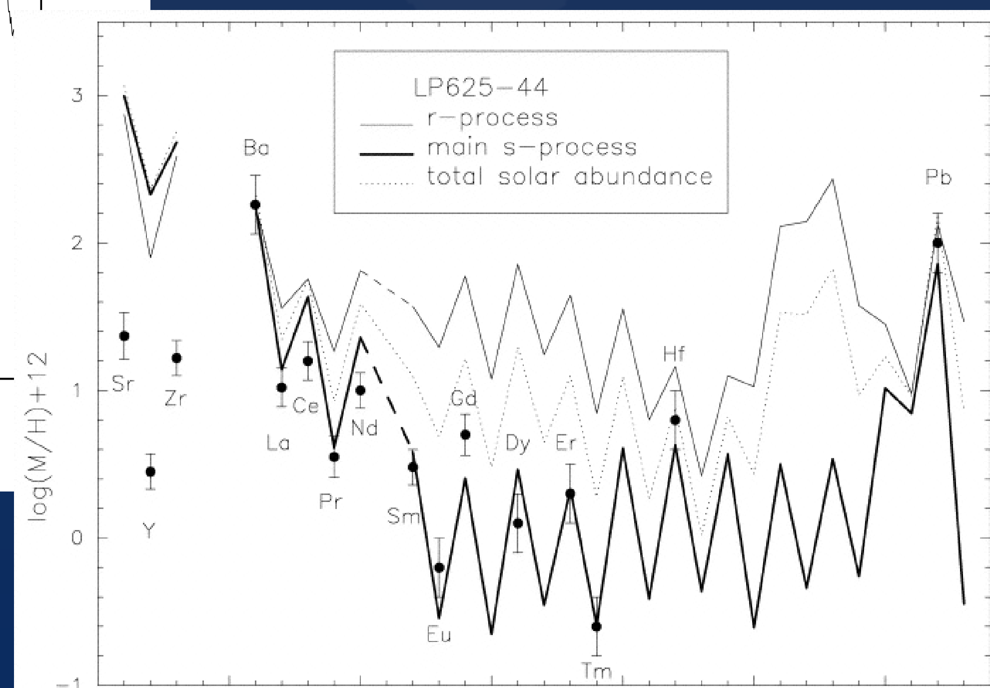



FIG. 7.—[Fe/H] distribution for CEMP stars in our expanded sample. The open histogram indicates the Ba-enhanced stars, while the hatched histogram is for the Ba-normal stars. There appears to be a clear difference in the distributions of [Fe/H] for these two classes of stars (see text).

# Carbon Enhancement Associated with s-process Patterns (Aoki et al. 2002)

LP 625-44:  [Fe/H] = -2.7; [C/Fe] = +2.0

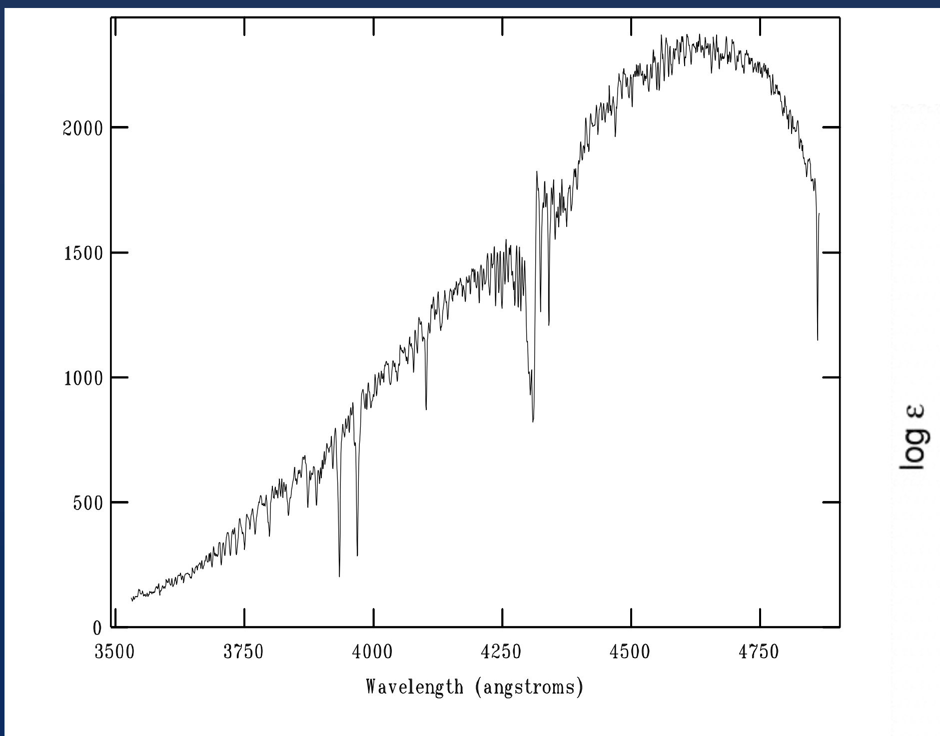


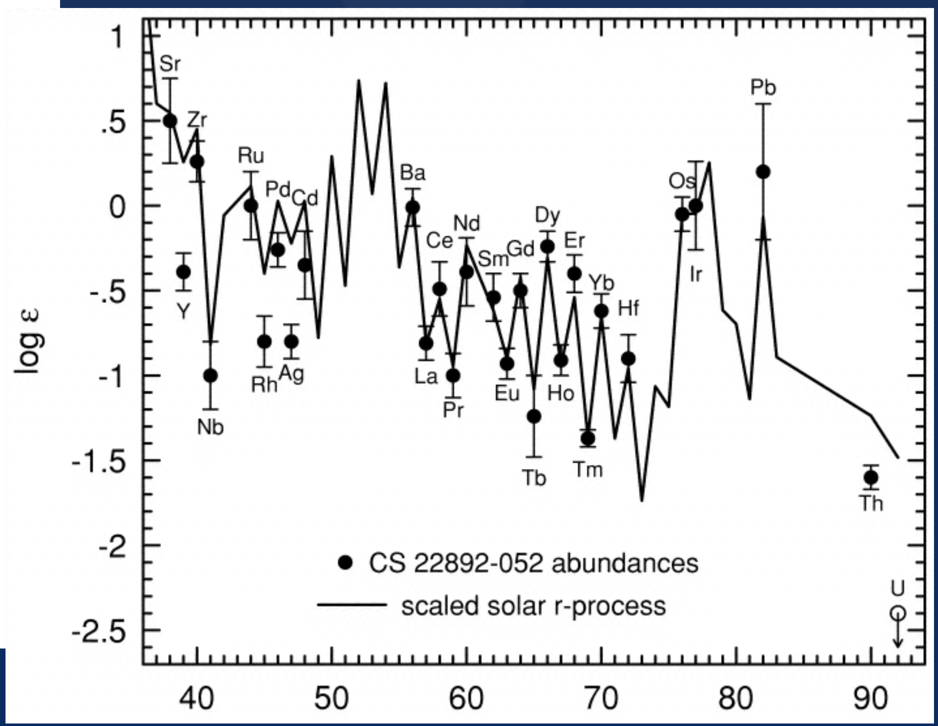




LP 625-44 was the first s-process-rich MP star with Pb measured

# Carbon Enhancement Associated with r-process Patterns (CS 22892-052; McWilliam et al. 1995; Sneden et al. 2000)

CS 22892-052: [Fe/H] = -3.1; [C/Fe] = +1.0

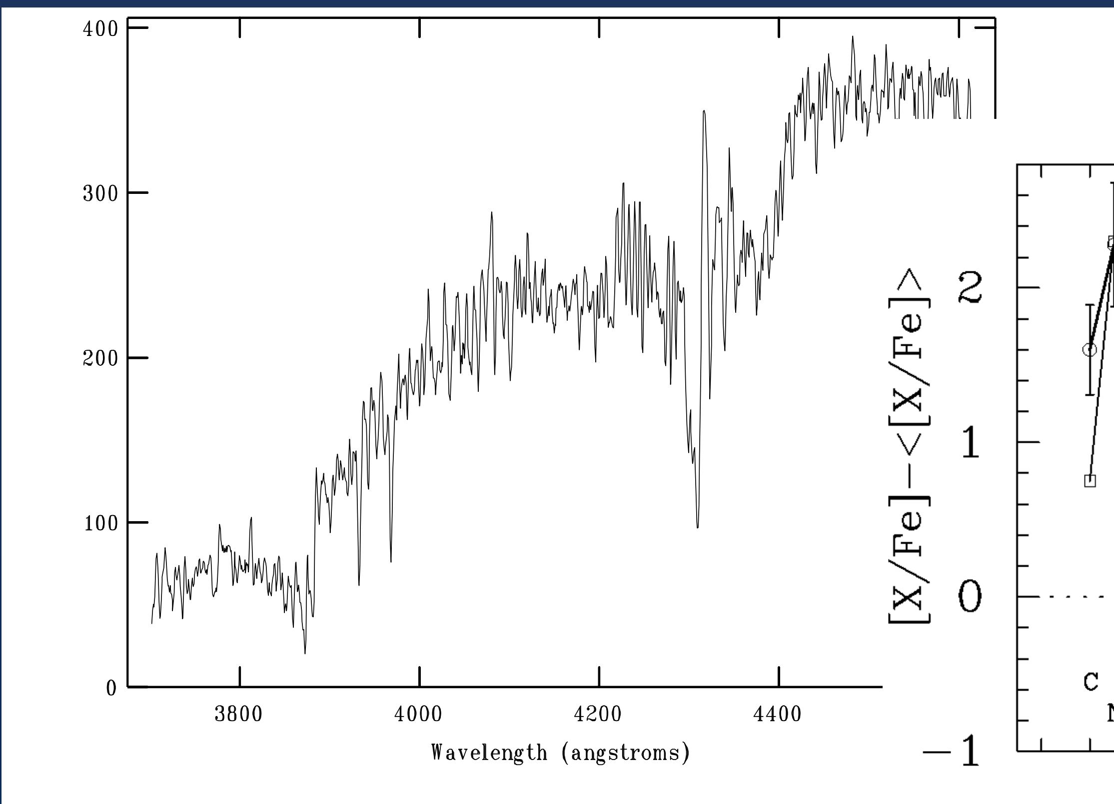


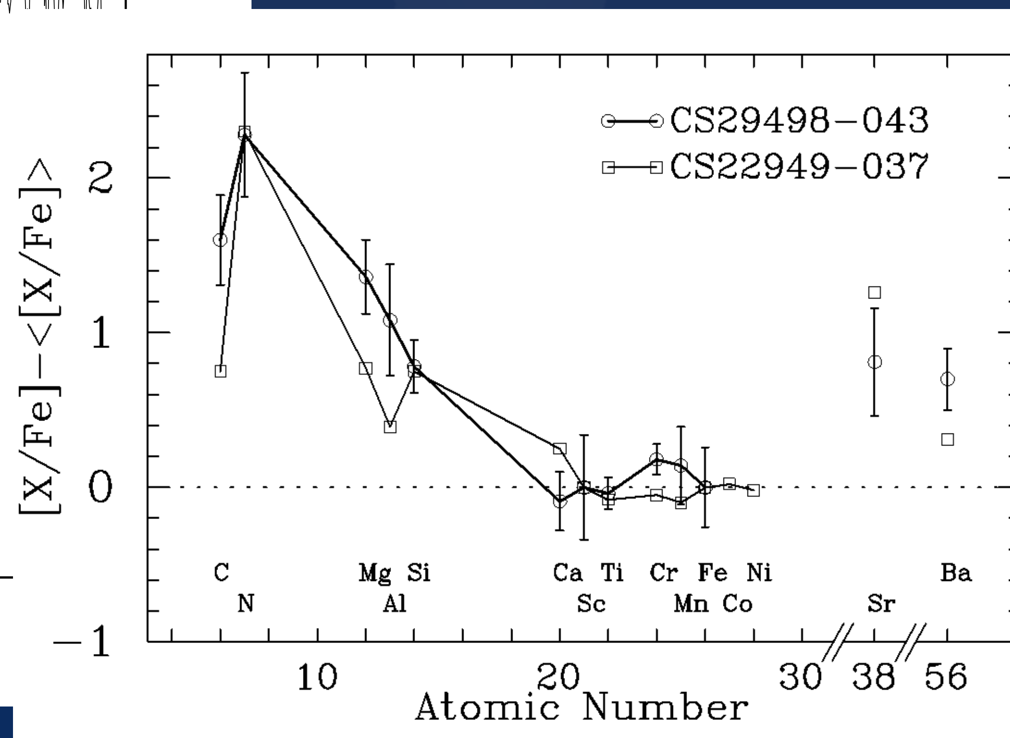




CS 22892-052 was the first highly r-process-rich MP star discovered

# CEMP-no Stars are Associated with UNIQUE Light-Element Abundance Patterns (Aoki et al. 2002)

CS 29498-043:  [Fe/H] = -3.8; [C/Fe] = +1.9

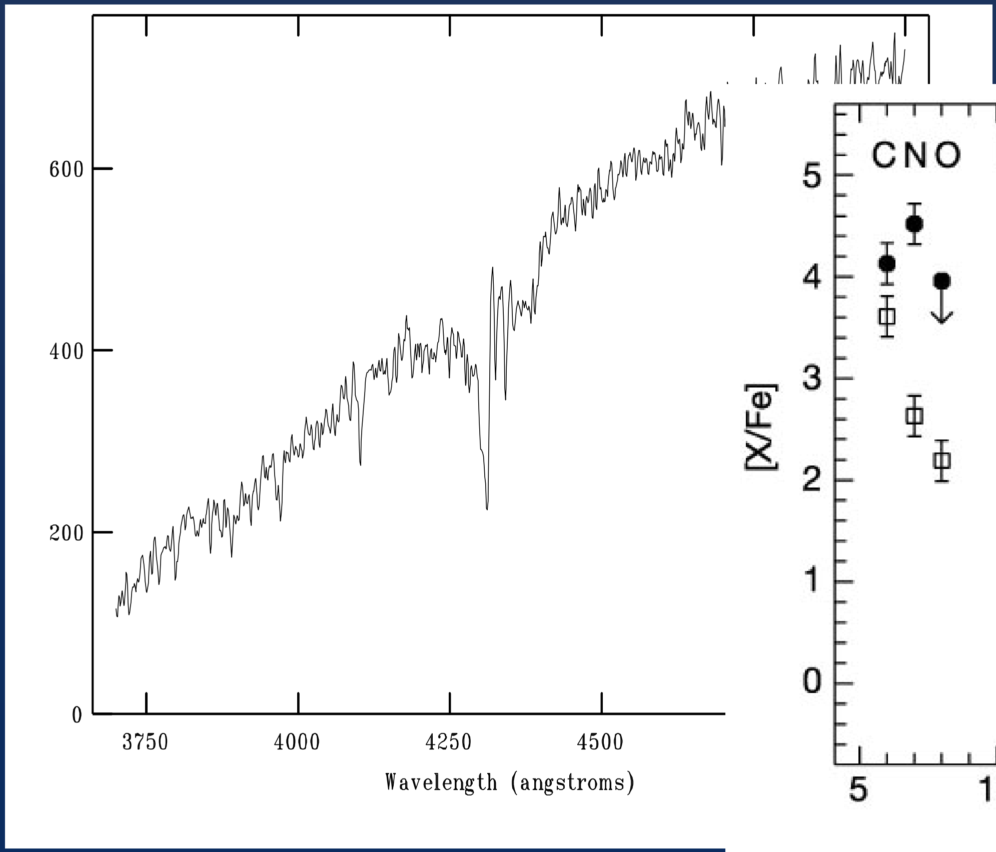


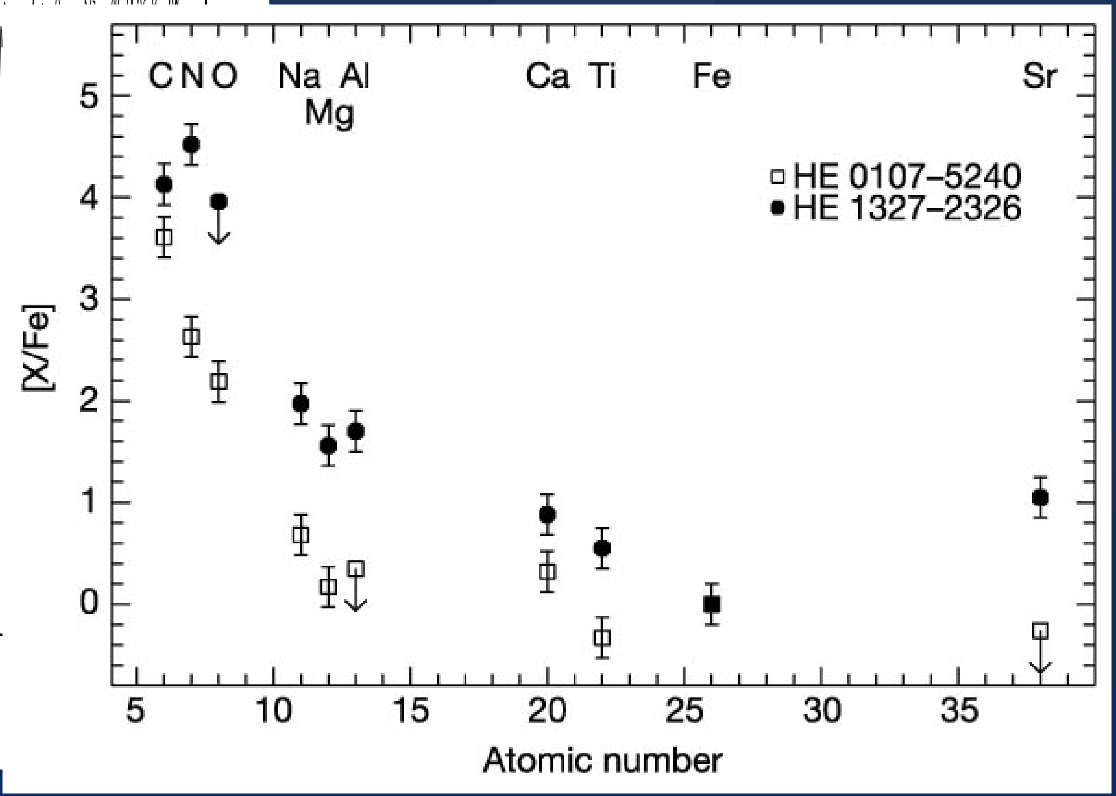




Harbingers of Things to Come!

# Last but Definitely Least… (Christlieb et al. 2002; Frebel et al. 2005)

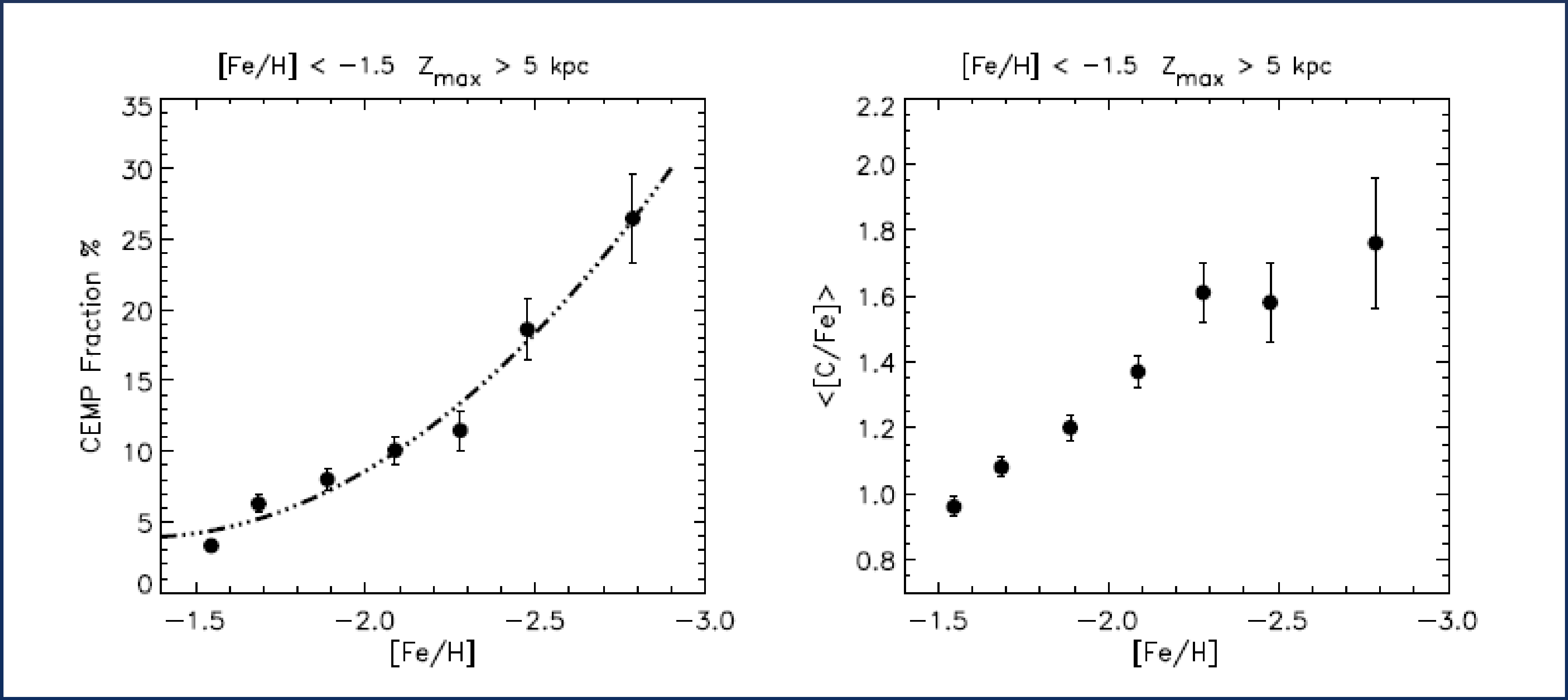
HE 0107-5240  [Fe/H] = -5.3 [C/Fe] = +3.9




It is the SAME pattern among the light elements !

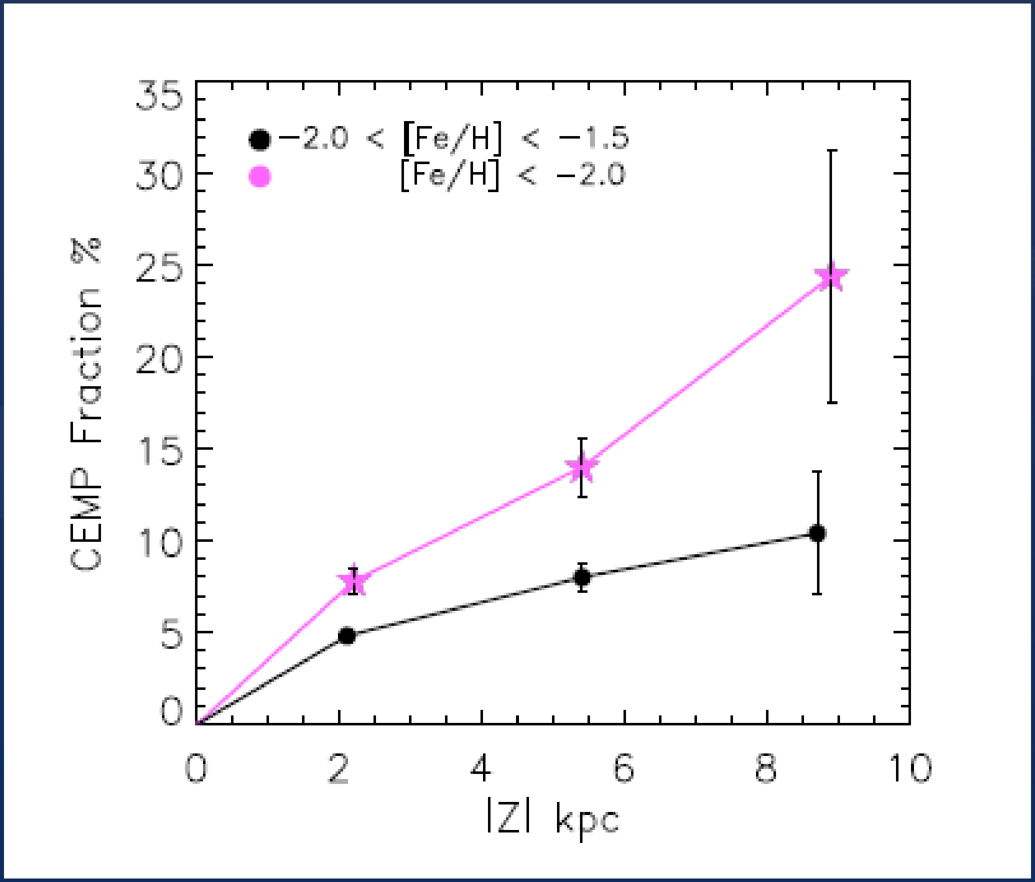
# Global CEMP Fraction and <[C/Fe]> vs [Fe/H]




Global variation shows smooth increase of *f* (CEMP) vs. [Fe/H]

Clear increase of <[C/Fe]> vs. [Fe/H]

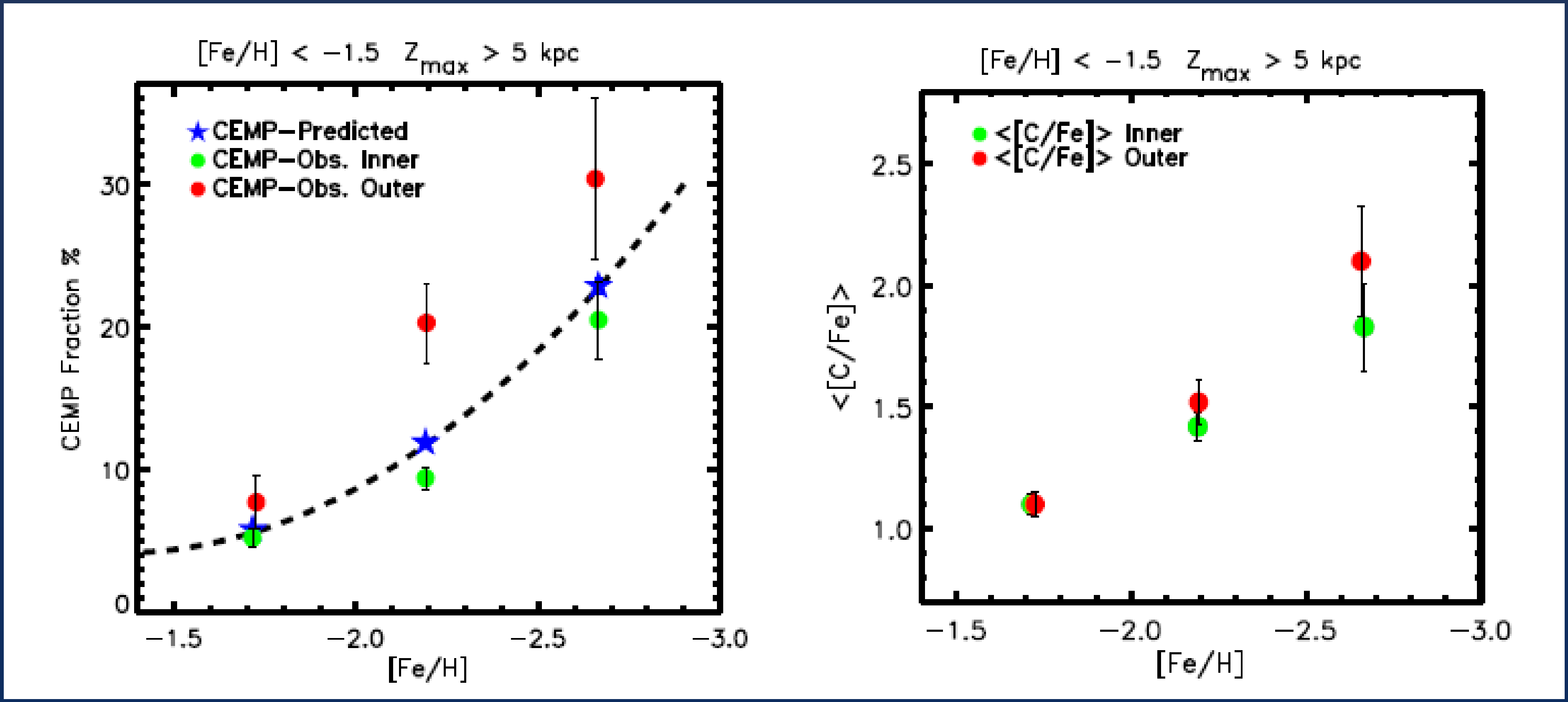
# Global CEMP Fraction vs. |Z|




Clear increase of *f* (CEMP) with |Z|

(not expected for single halo)

# Inner/Outer Halo CEMP Fractions




$f$ (CEMP)$_{OH}$ ~ 2 x $f$ (CEMP) $_{IH}$

<[C/Fe]> roughly constant IH/OH

(Carollo et al. 2012)

# Interpretation

- The distribution of CEMP stars indicates that there is likely to be more than one source of C production at low metallicity, and that the difference can be associated with assignment to inner/outer halo
- Modelers (e.g., Izzard, Pols, Stancliffe) have tried, without success, to reproduce the observed fractions of CEMP stars at low metallicity using AGB sources alone. Getting beyond 10% appears to be a real barrier
- We speculate that the majority of CEMP stars associated with the inner halo will be CEMP-s, while those associated with the outer halo will be CEMP-no

# Bottom Line

- CEMP stars in the Galaxy likely have had multiple sources of carbon production
  - CEMP-s in AGB stars
  - CEMP-no in massive (50-100 $M_o$) rapidly rotating MMP stars
  - CEMP-no in intermediate (25-30 $M_o$) “faint” SNe

- CEMP-no stars occur preferentially at the lowest metallicities, including the 3 of the 4 stars known with [Fe/H] < -4.5

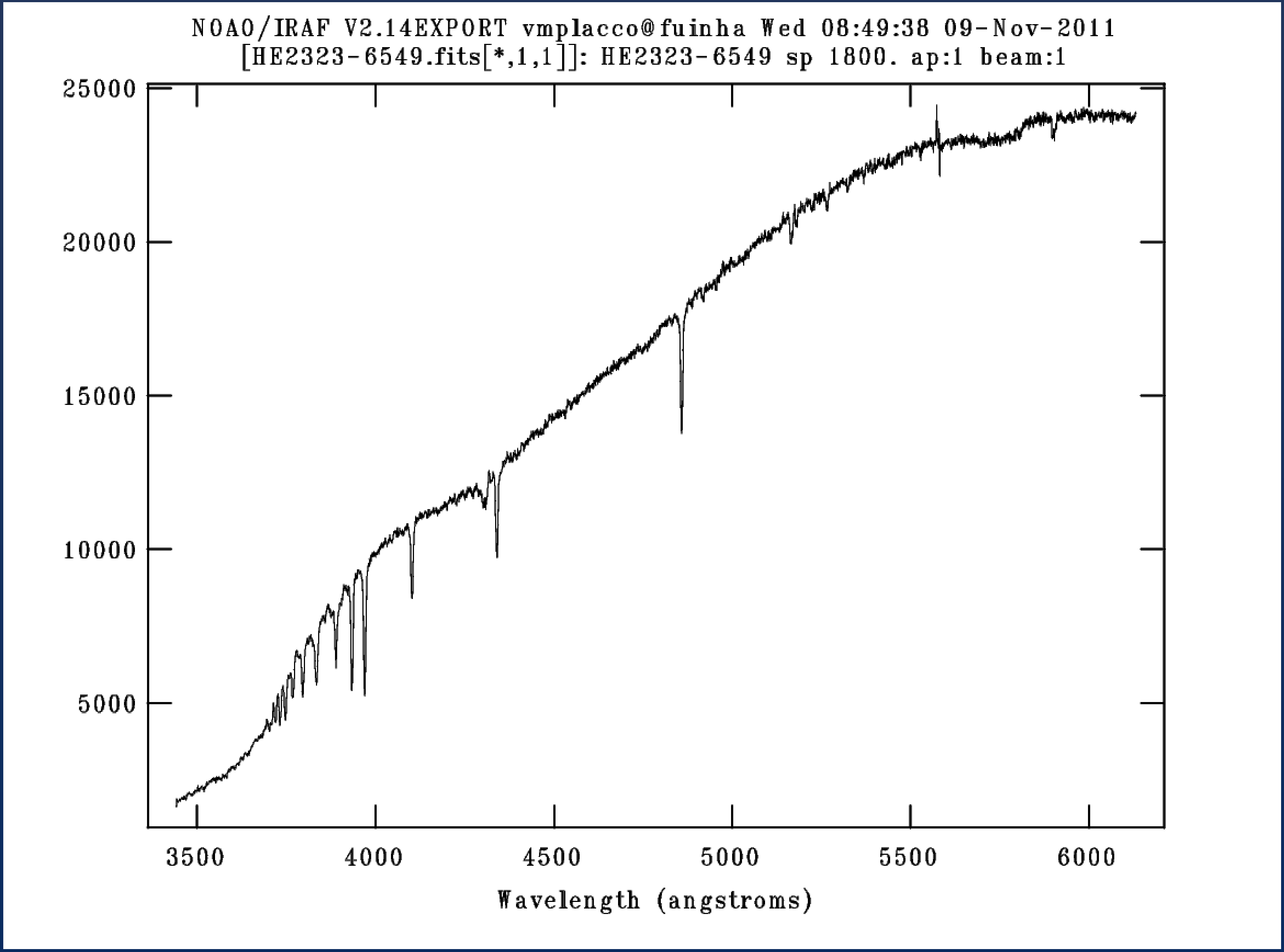
- CEMP stars are found in great number in the ultra-faint SDSS dwarf galaxies, some of which have low n-capture abundances

- High-z DLA systems exhibit similar abundance patterns as CEMP-no stars

- **We have observed (!) the nucleosynthesis products of first generation stars (Pop III)**

# New CEMP + VMP Star Survey Summary

- Placco, Beers, et al. have been using “bad weather” time on the Gemini N and S telescopes to search for NEW (formerly missed) examples of CEMP and VMP stars chosen from the HK and HES candidates
- Numerous examples of new CEMP stars found by targeting on the G-band strength of scanned HES stars
  - By taking advantage of the apparently strong correlation between large C over-abundances and declining [Fe/H], rather than on the weakness of the CaII K line for metal weakness, and obtaining C information later from medium-res spectroscopic follow-up
- Numerous examples of new VMP stars found by targeting on previously unobserved HK and HES candidates
- CEMP survey recently completed (~ 800 spectra / ~200 new CEMP stars)
- VMP survey just getting underway
- High-resolution work (AAT, Magellan, VLT/X-Shooter) – Just Starting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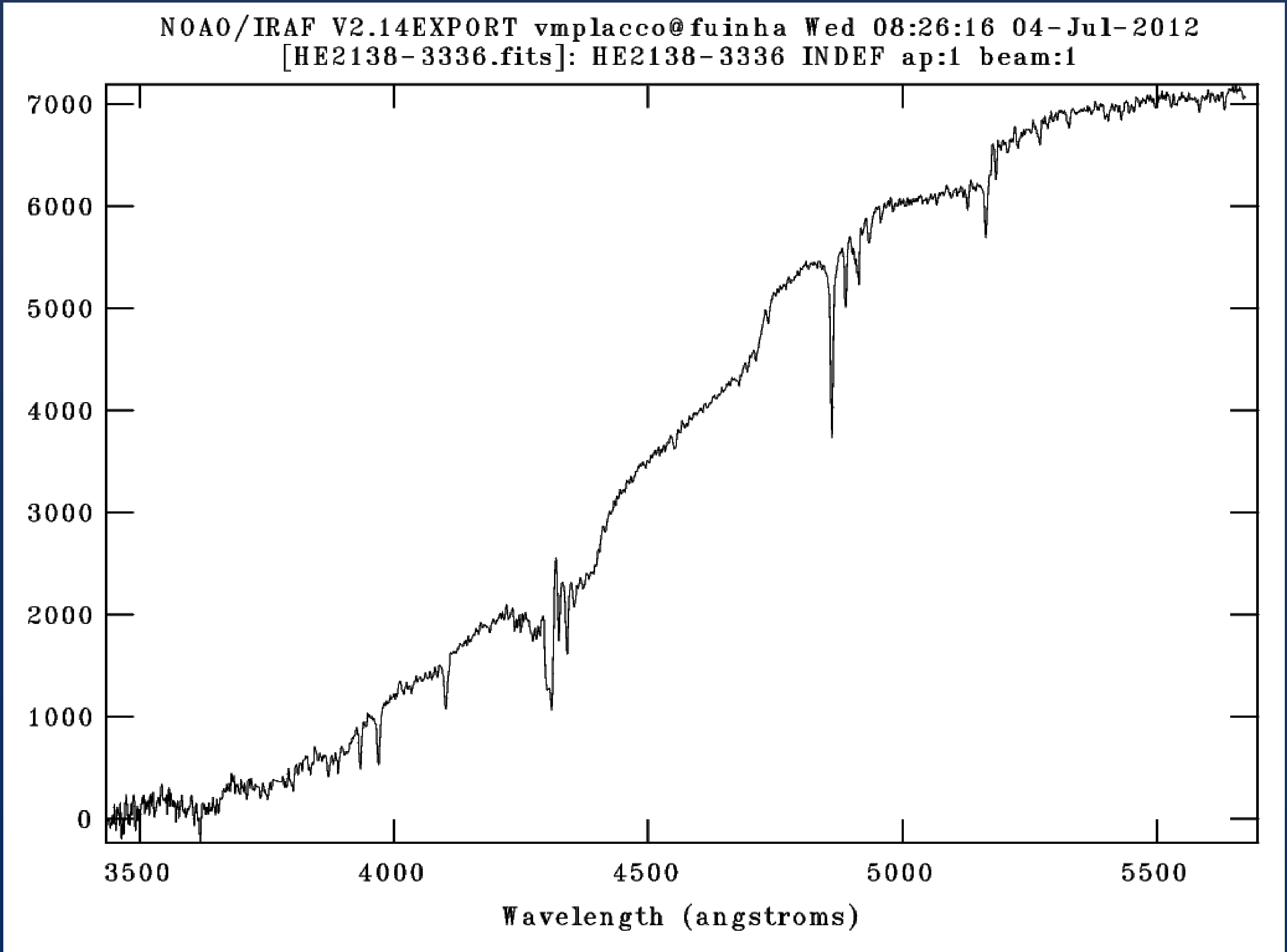
Wavelength (angstroms)



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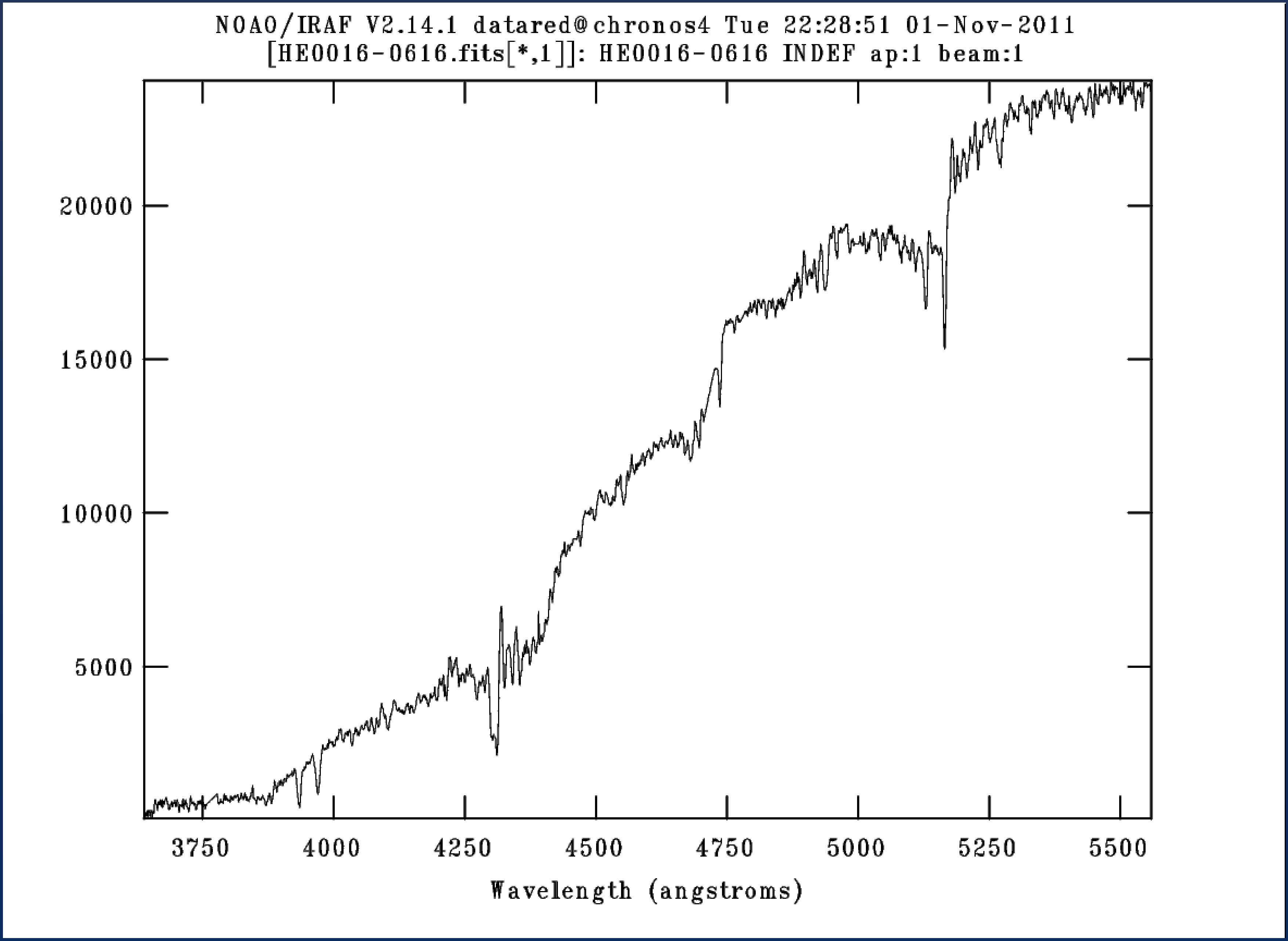
Wavelength (angstroms)



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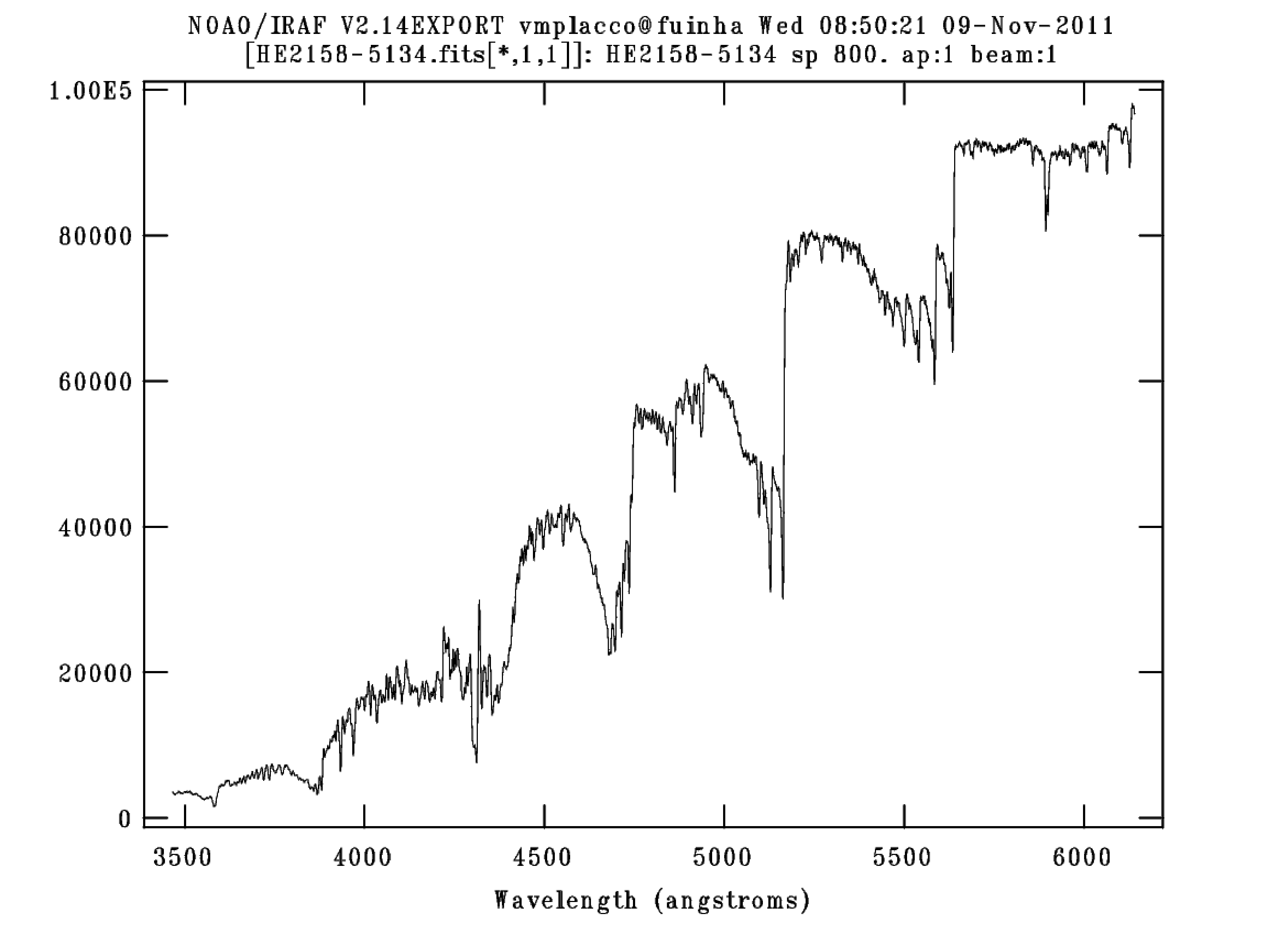
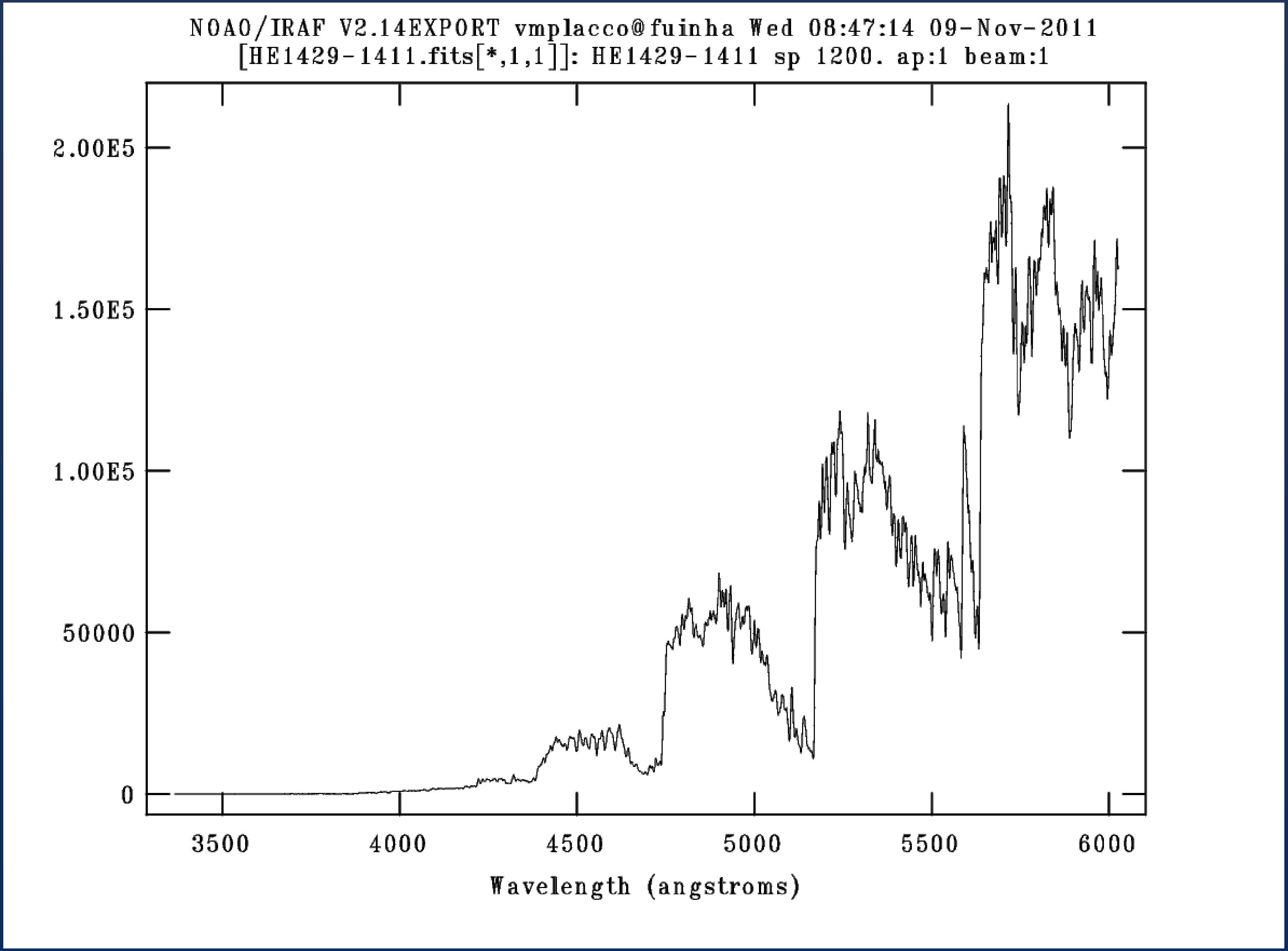
4750
5000
5250
5500
Wavelength (angstroms)


NOAO/IRAF V2.14EXPORT vmplacco@fuinha Wed 08:50:21 09-Nov-2011
[HE2158-5134.fits[*,1,1]]: HE2158-5134 sp 800. ap:1 beam:1
1.00E5
80000
60000
40000
20000
0
3500
4000
4500
5000
5500
6000
Wavelength (angstroms)


NOAO/IRAF V2.14EXPORT vmplacco@fuinha Wed 08:47:14 09-Nov-2011
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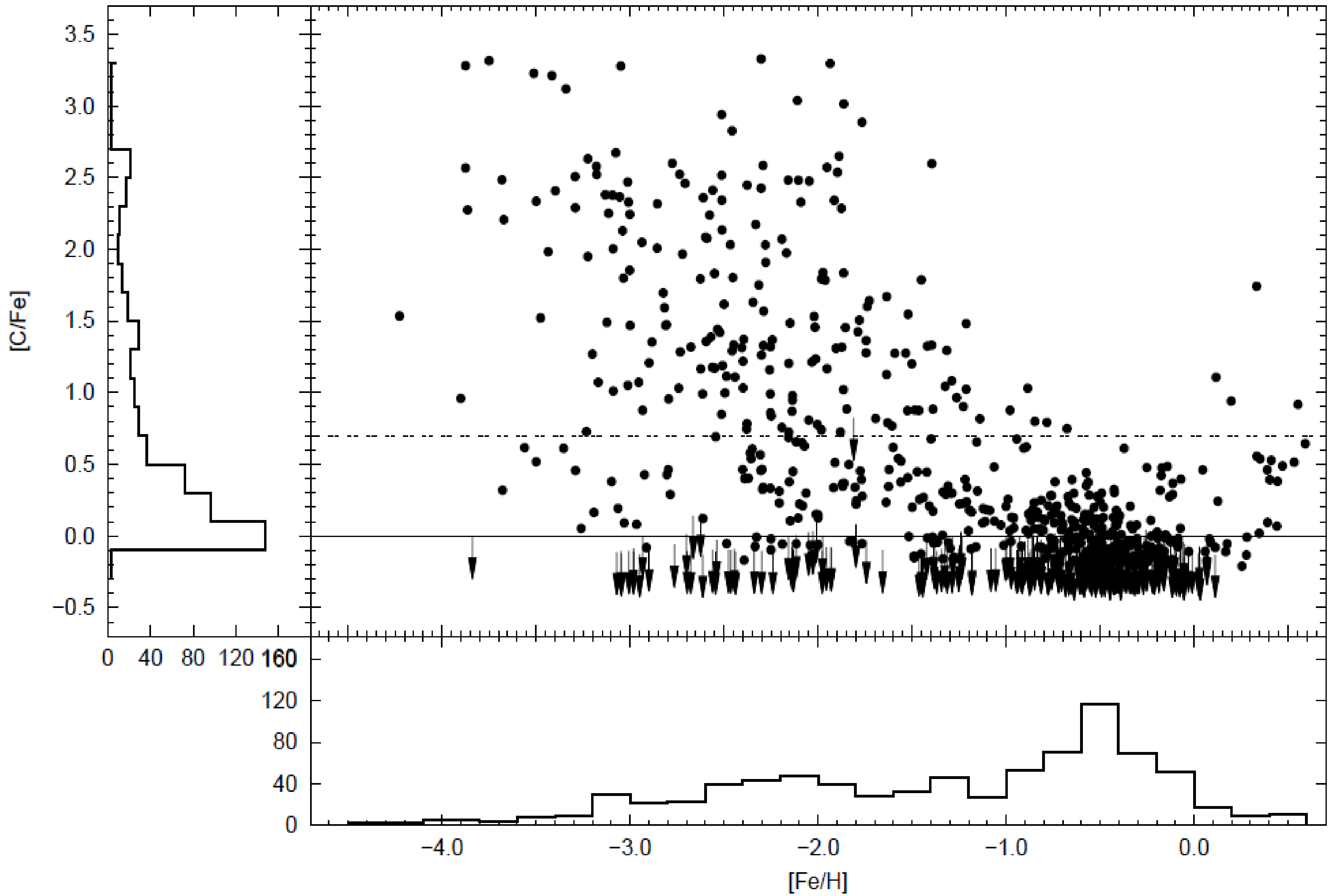
2.00E5
1.50E5
1.00E5
50000
0
3500
4000
4500
5000
5500
6000
Wavelength (angstroms)

# [C/Fe] vs. [Fe/H] (Medium-Res Results)



# The Path Forward

- Surveys for metal-poor stars have been singularly successful in revealing details of the nature of early generation stars, the structure of the Galaxy, and fundamental questions concerning the nature of chemical evolution in the early Universe

- We have gone from total numbers of VMP ([Fe/H] < -2.0) stars from a relative handful → several thousand → tens of thousands

- The coming decade will take us to numbers of VMP stars that are many orders of magnitude higher, through the efforts of numerous new surveys –- presumably with a concomitant increase in our understanding of the early Galaxy, and indeed the early Universe.

- An exciting time indeed !

# Current and Near-Future Surveys at Medium and High Spectral Resolution

- **SDSS/APOGEE** – Collecting high-res near-IR spectra for 100,000 disk/bulge/halo stars
- **AEGIS** – Collecting medium-res AAT optical spectra for 100,000 disk/halo stars (targeting from SkyMapper)
- **LAMOST** – Collecting medium-res optical spectra for 10,000,000 disk/halo stars (20 X SDSS/SEGUE)
- **Gaia-ESO** – Collecting high-res optical VLT spectra of several hundred thousand disk/halo stars for Gaia calibration
- **GALAH** – Will collect high-res optical AAT spectra of one million disk/halo stars