Extremely Metal-Poor Stars in the Least Evolved Galaxies

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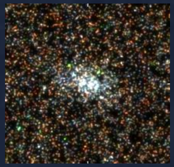
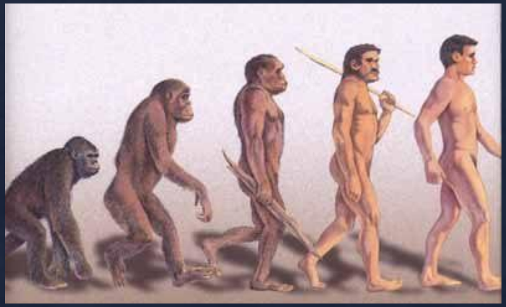
Evan Kirby (Caltech)
Steve Shectman (Carnegie)
Ian Thompson (Carnegie)

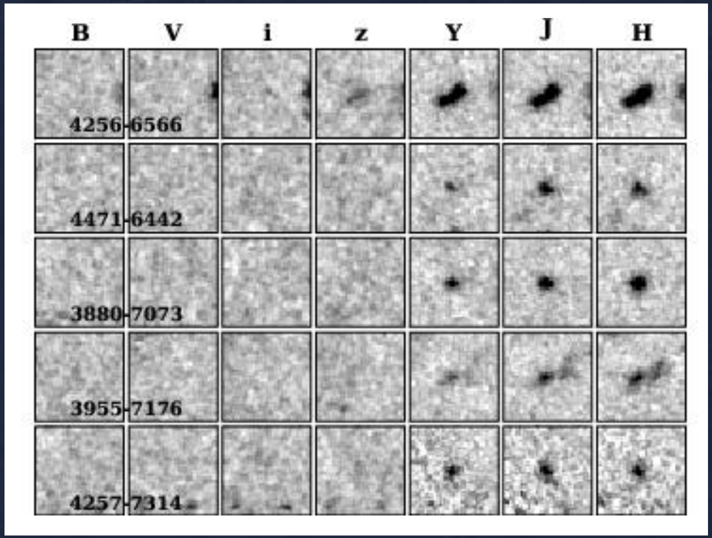




Metal-Poor Stars in Dwarfs

- Unraveling the formation of the Milky Way halo
  - Are present-day dwarfs similar to the building blocks of the halo? (Robertson et al. 2005; Frebel, Kirby, & Simon 2010)
- The first stars
  - Dwarf galaxies may be the best places to look for the most metal-poor stars (Kirby et al. 2008; Frebel et al. 2010; Simon et al. 2011)
- Nucleosynthesis and chemical evolution in the early universe (Koch et al. 2008; Simon et al. 2010)

Why Nearby Dwarfs?

z=7



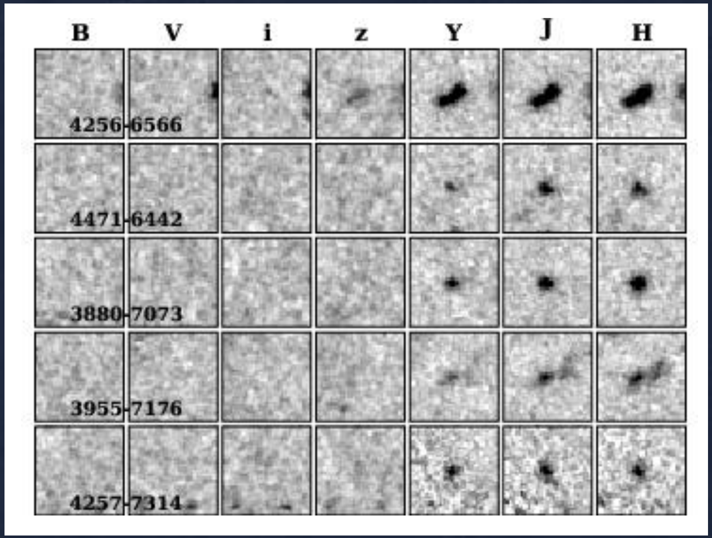
Oesch et al. (2010)

z=0

Belokurov et al. (2006b)

Why Nearby Dwarfs?

z=7



Oesch et al. (2010)

z=0

Belokurov et al. (2006b)

$1/r^2$ at z=7: 2×10^{-59}

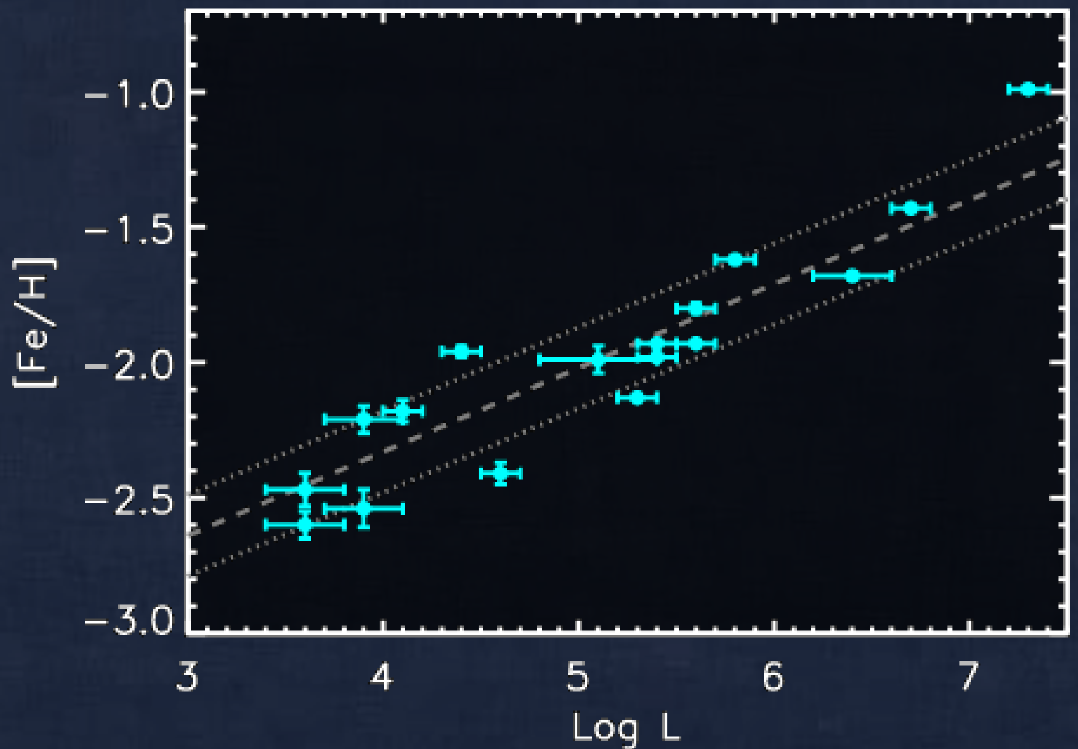
$1/r^2$ at 100 kpc: 1×10^{-47}

Where Do [Fe/H] < -3 Stars Live?

- Milky Way bulge: ?? (Tumlinson 2010)

A Hint

- Metallicity-luminosity relationship

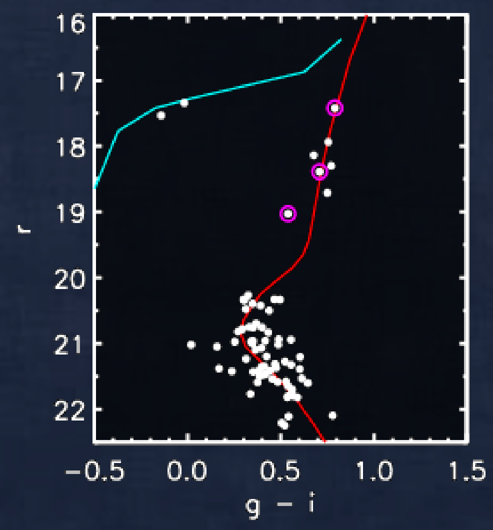


- Faint dwarfs ≠ tidally-stripped bright dwarfs
- Stars know what luminosity system they live in

Kirby et al. (2011)

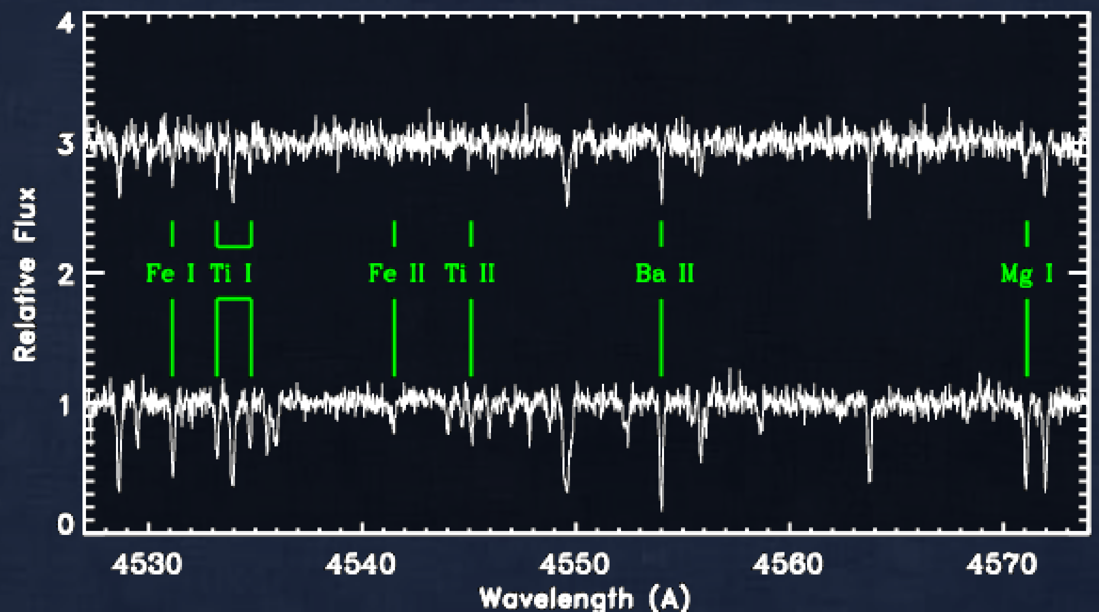
Where Do [Fe/H] < -3 Stars Live?

- Milky Way halo: <1% (Schörck et al. 2009)
- M_V < -8 dwarfs: 1-5% (Starkenburg et al. 2010)
- M_V > -8 ultra-faint dwarfs: >10% (Simon et al. 2010)
- Segue 1 (M_V = -1.5): 42% (Frebel et al., in prep.)



Measuring Abundances in Dwarfs

- High-resolution spectroscopy
  - Accurate abundances for many elements
  - Requires bright targets + long integrations



[Fe/H] = -3.24

V = 17.4, t_{exp} = 3 hr

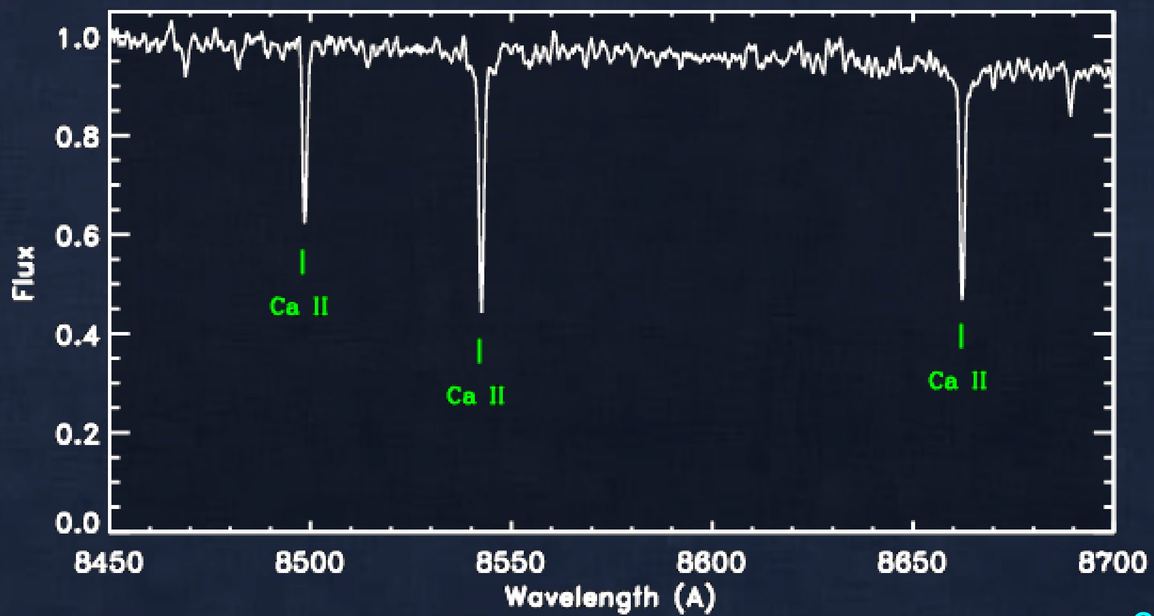
[Fe/H] = -2.34

V = 16.5, t_{exp} = 1 hr

Frebel et al. (2010)

Measuring Abundances in Dwarfs

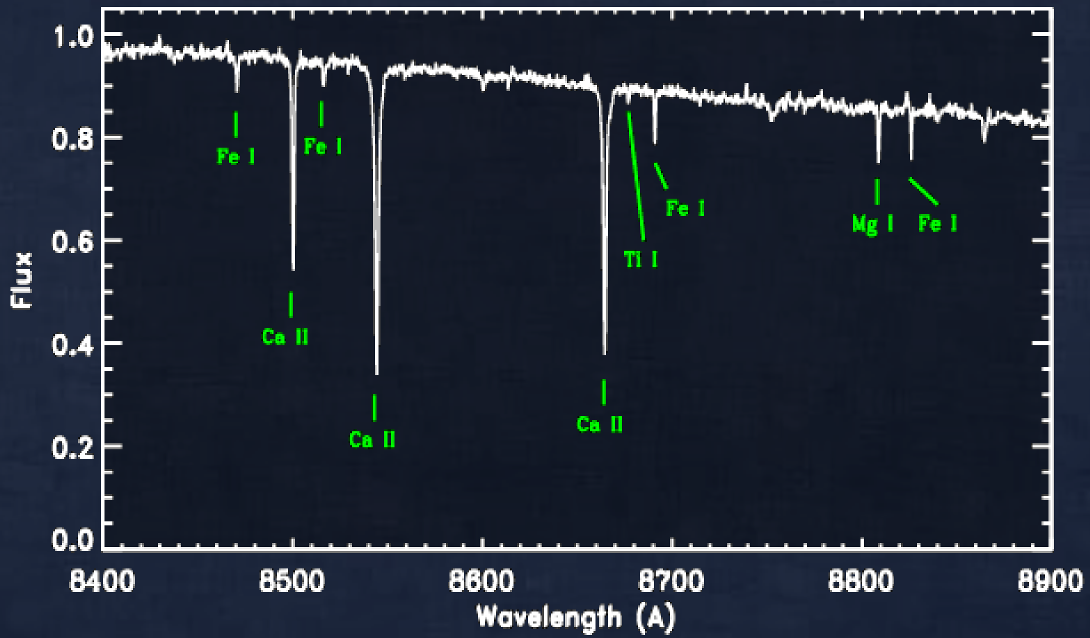
- Ca triplet
  - Requires only low/medium resolution spectroscopy
  - Can be used for much fainter stars!



e.g., Rutledge et al. (1997)

Measuring Abundances in Dwarfs

- Spectral synthesis with medium resolution spectroscopy
  - Lots of lines other than the CaT in R=6000 spectra

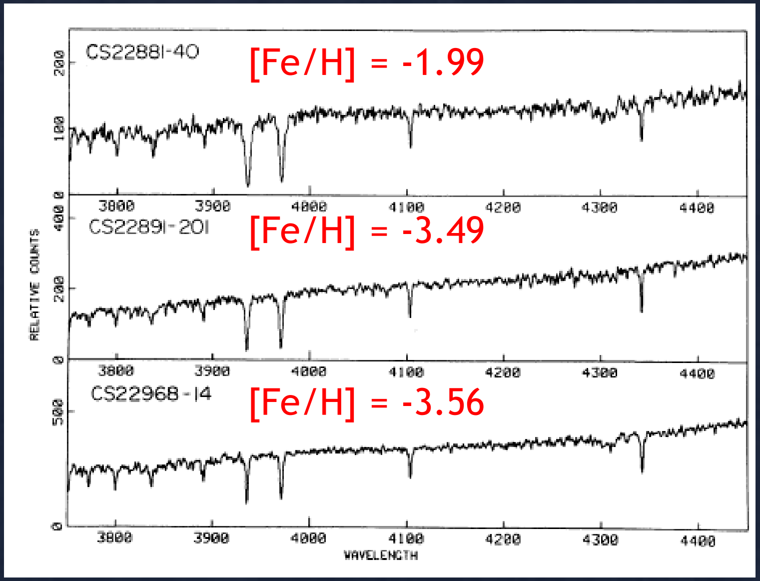


Kirby et al. (2008)

Finding the Most Metal-Poor Stars

- Spectral synthesis - requires large λ range
- Ca triplet – less sensitive at low metallicity
- Ca K - just right

BACK TO THE FUTURE



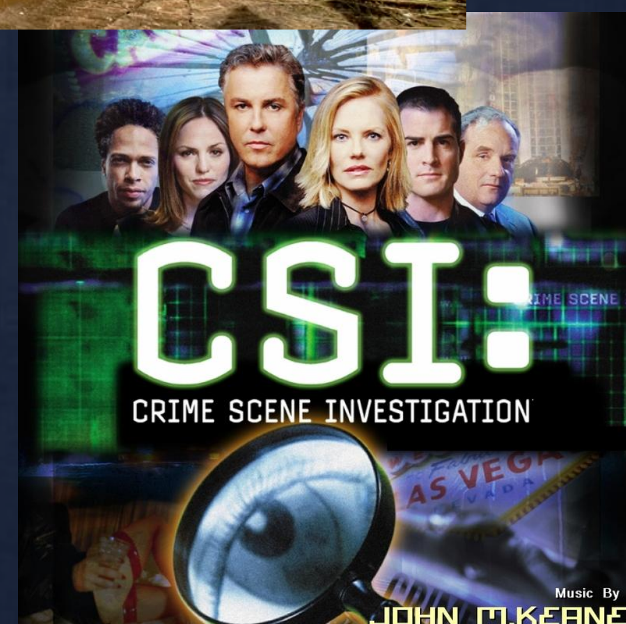
Beers, Preston, & Shectman (1985)

Ca K Survey

- Complete, magnitude limited survey (to V~20) of southern dSphs
- Uses IMACS spectrograph at Magellan

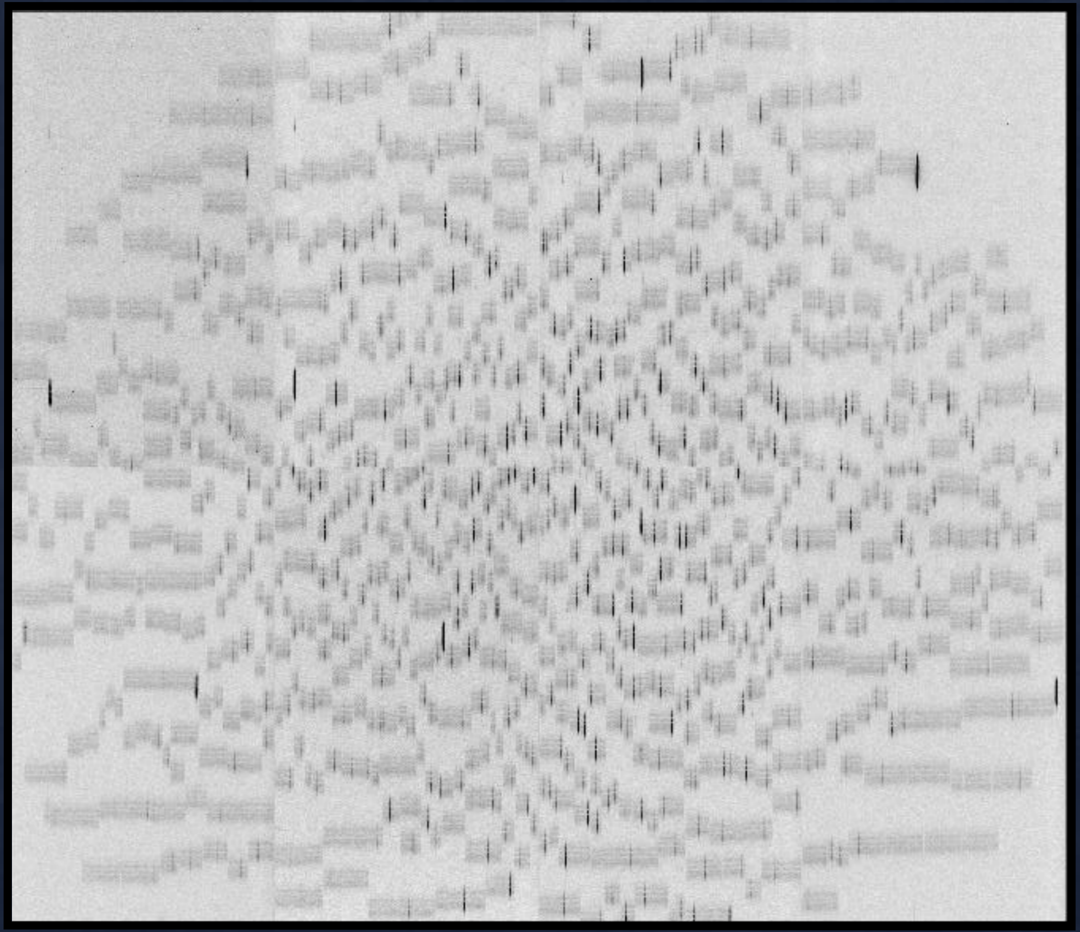
No More Acronyms!

SHARP



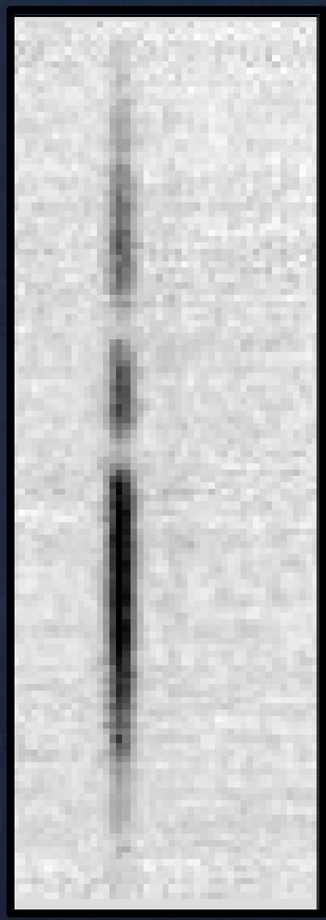
CCKSUMOMPSDG

(Complete Ca K SUrvey for the MOst Metal-Poor Stars in Dwarf Galaxies)

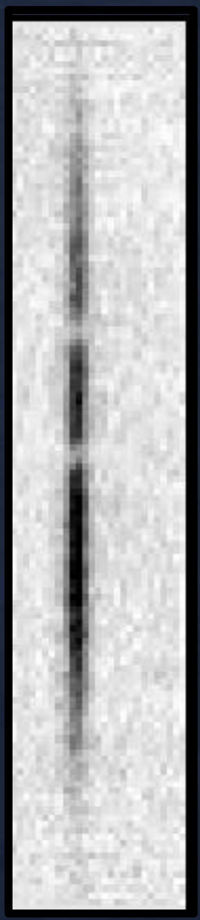


IMACS Survey Data

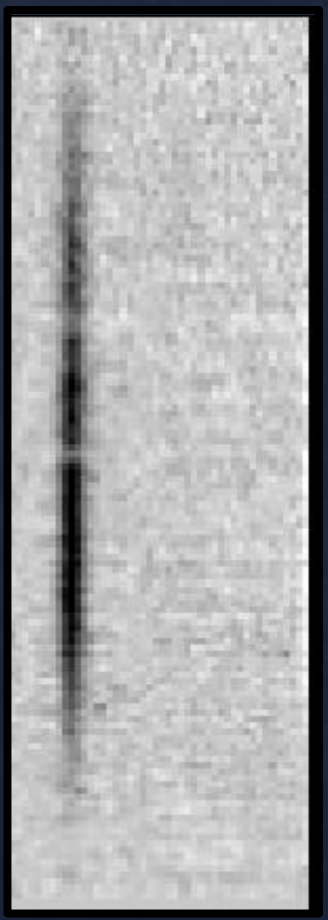
[Fe/H] = -1.5



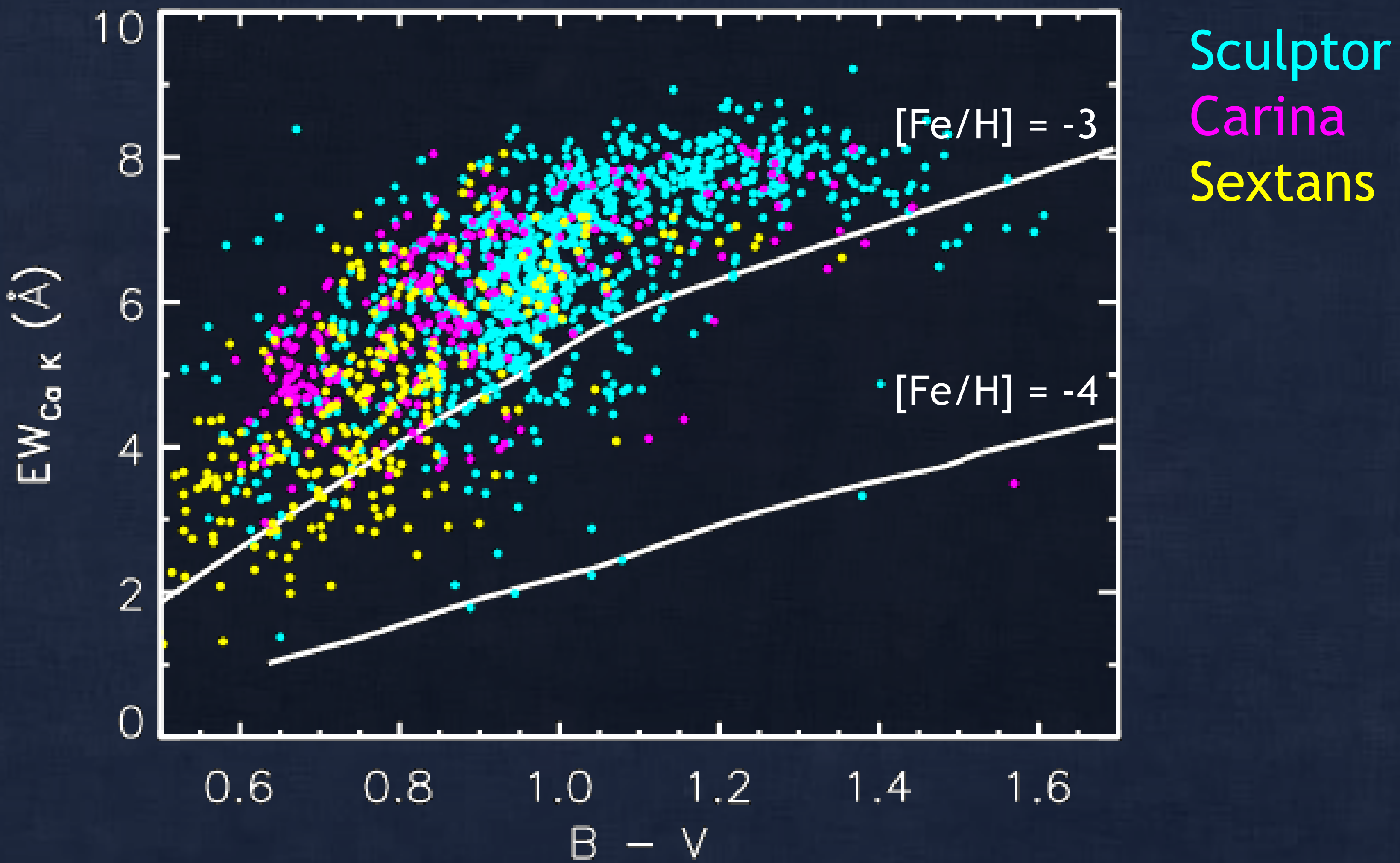
[Fe/H] = -2.5



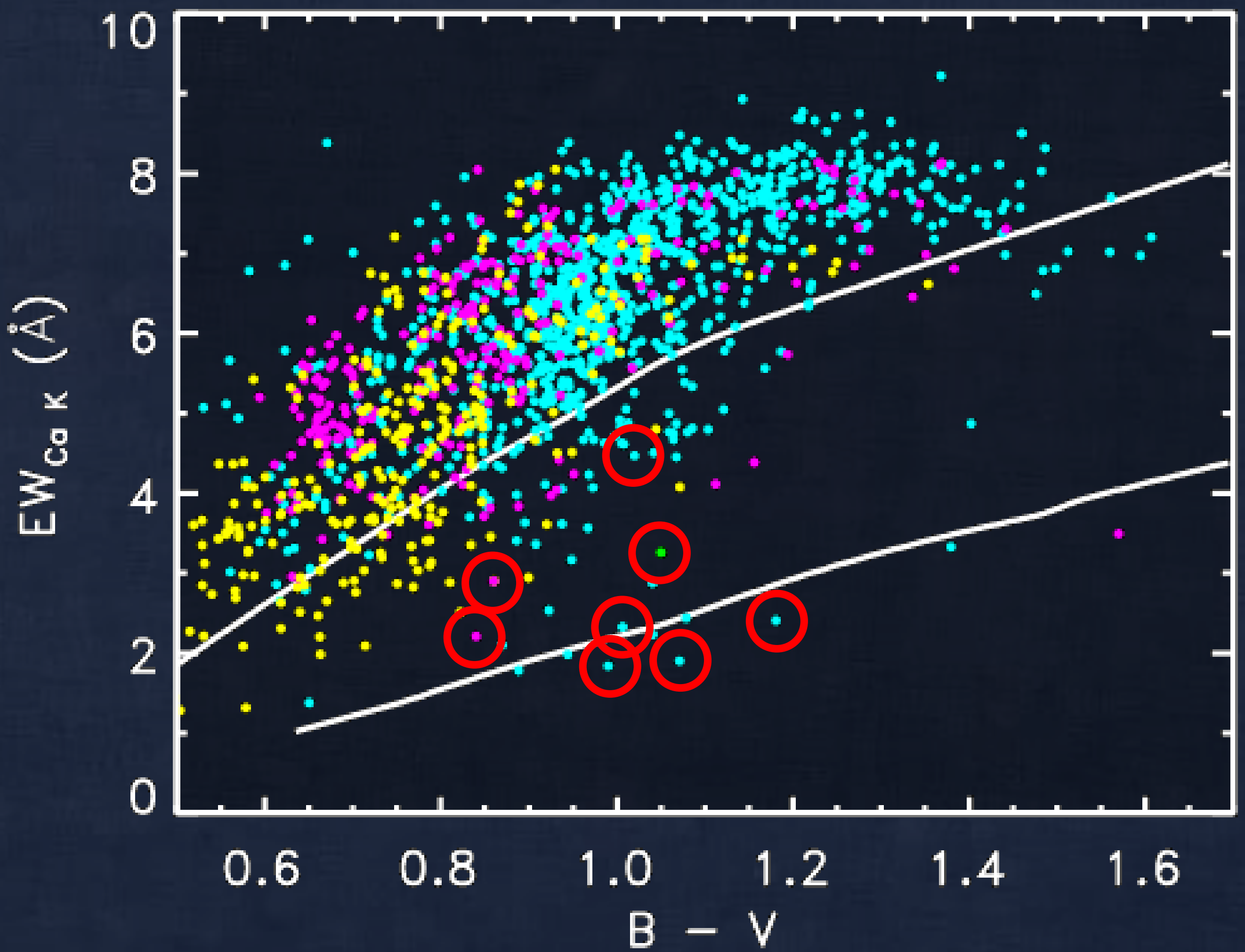
[Fe/H] = -3.8



Initial Results



Initial Results



Sculptor
Carina
Sextans
Fornax

Medium and high resolution followup:

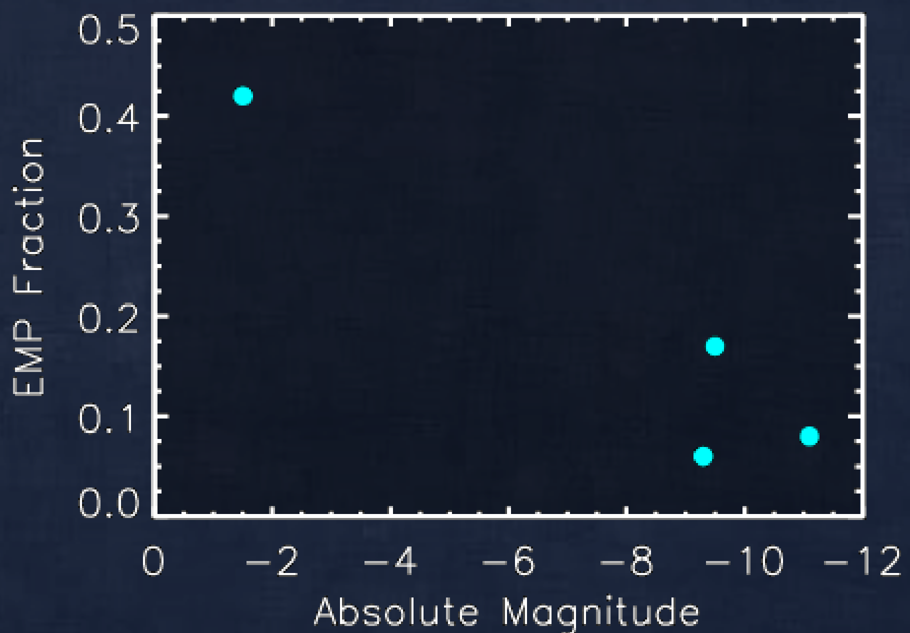
-3.1 ≤ [Fe/H] ≤ -4.0

Survey Status

- >1850 stars in Sculptor (513 in Helmi et al. 2006)
- 2912 stars in Fornax (933 in Helmi et al. 2006)
- 1294 stars in Carina (437 in Koch et al. 2006)
- 794 stars in Sextans (202 in Helmi et al. 2006)

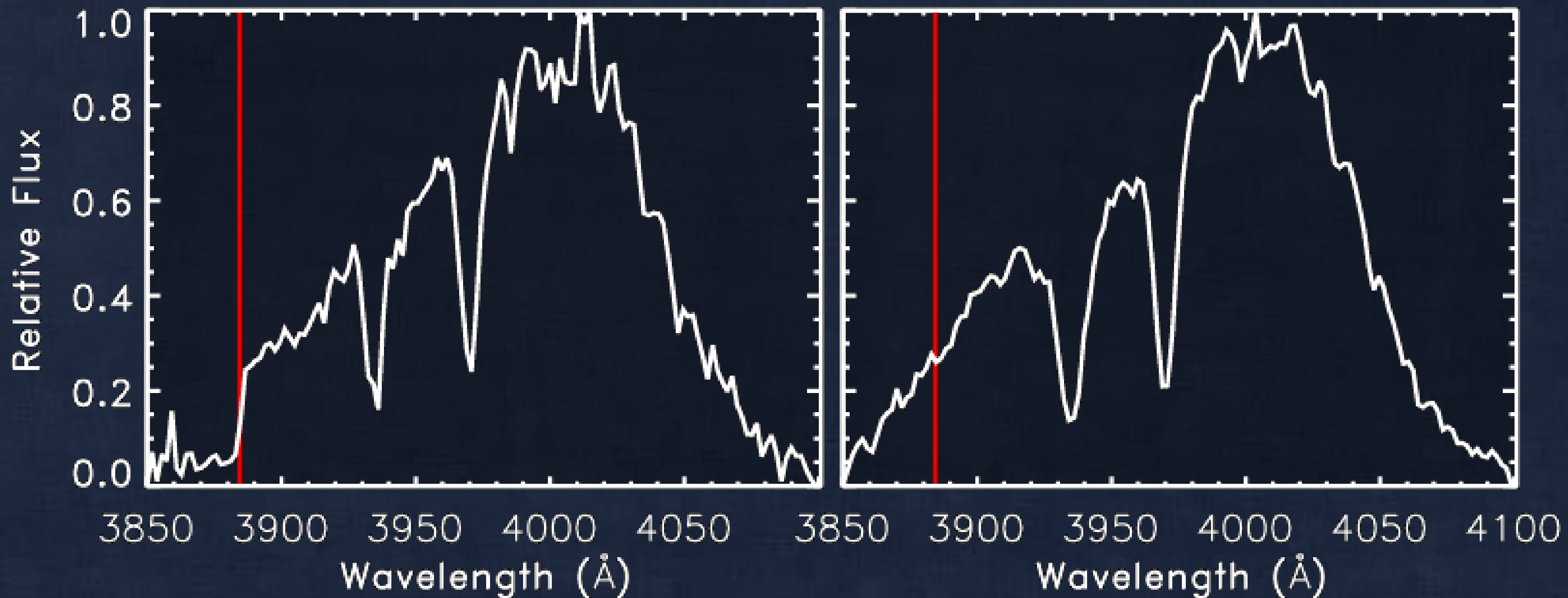
It's Full of (EMP) Stars!

- 8% of stars in Sculptor have [Fe/H] < -3
- 6% in Carina
- 17% in Sextans



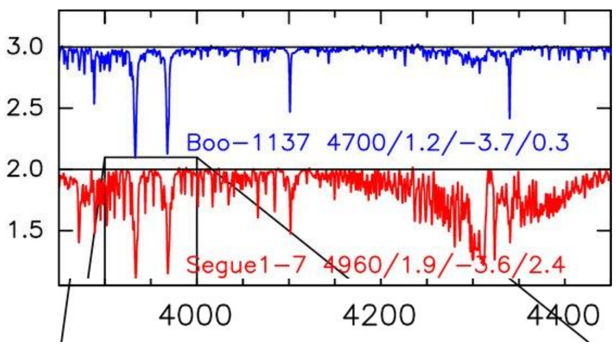
Carbon

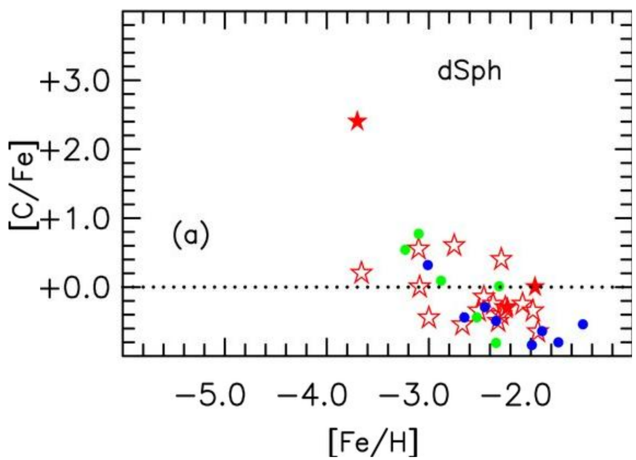
- CN bandhead at 3883 A

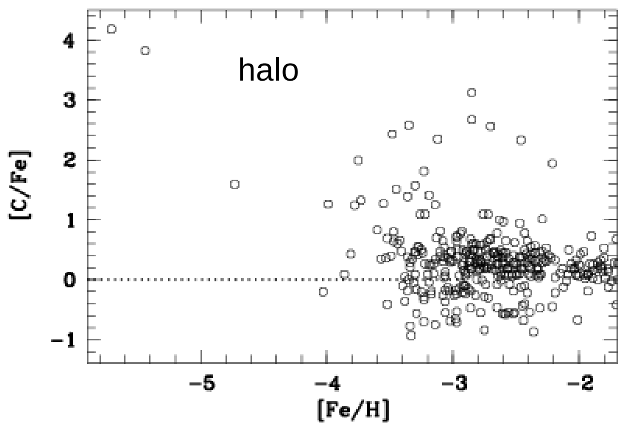


Carbon

- 20% of metal-poor halo stars are carbon-enhanced (Cohen et al. 2005; Frebel et al. 2006)

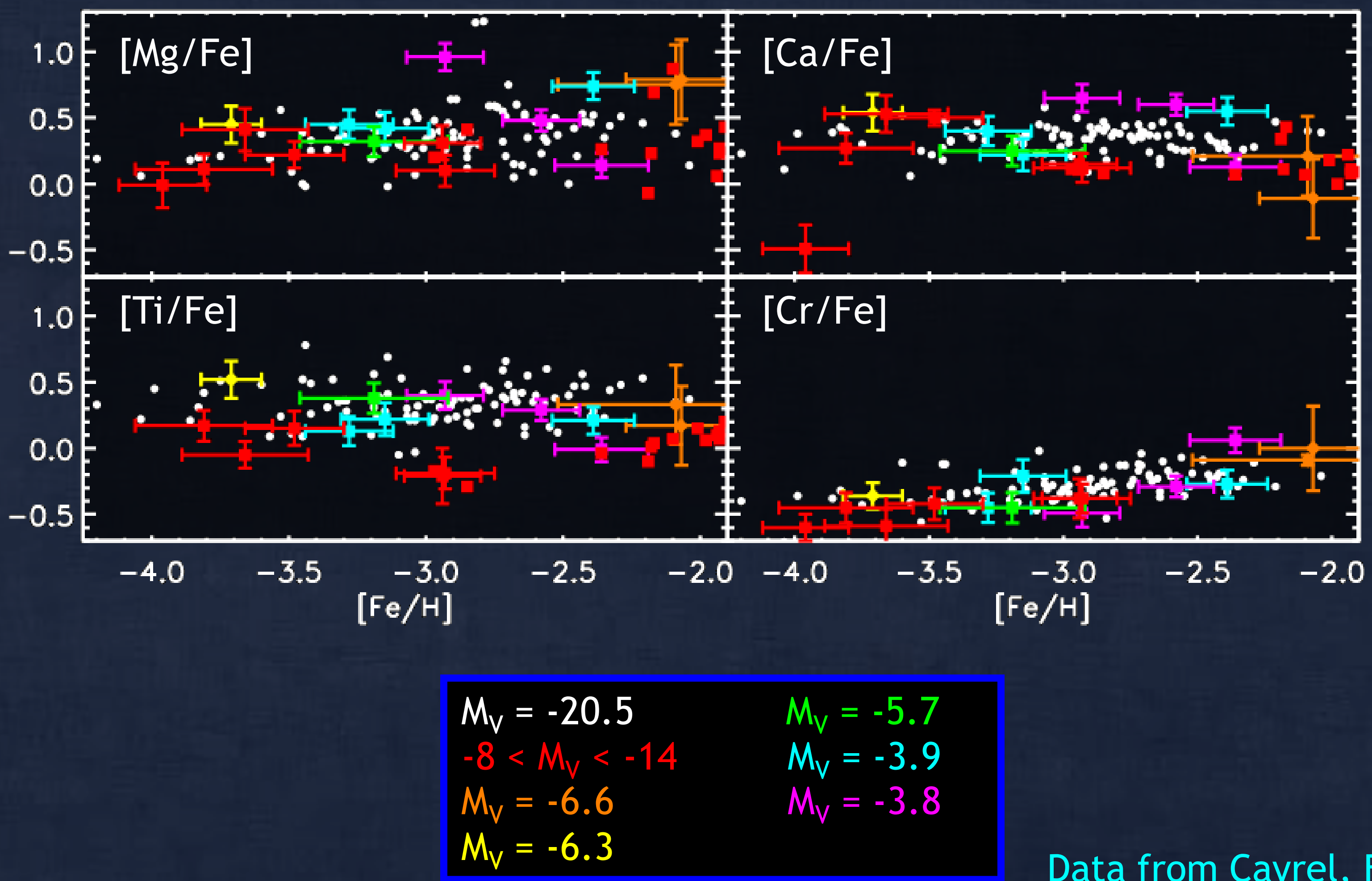






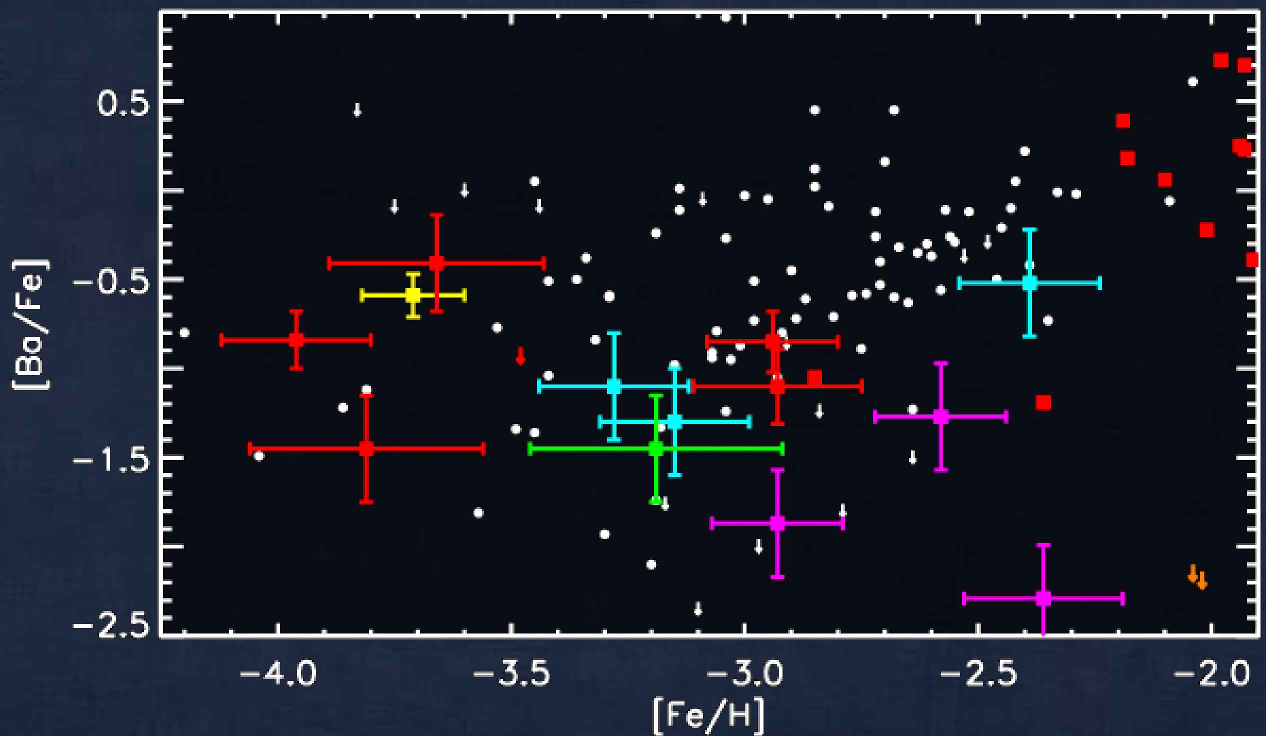
Norris et al. (2010); Frebel & Norris (2012)

Universal Early Chemical Evolution?



Data from Cayrel, Frebel, Norris, Shetrone, Simon, etc.

The Heaviest Elements



M_V = -20.5 (Francois07, Cohen04,Aoki05,Lai08)

-8 < M_V < -14 (Shetrone/ Frebel10b/Tafelmeyer10)

M_V = -6.6 (Koch08)

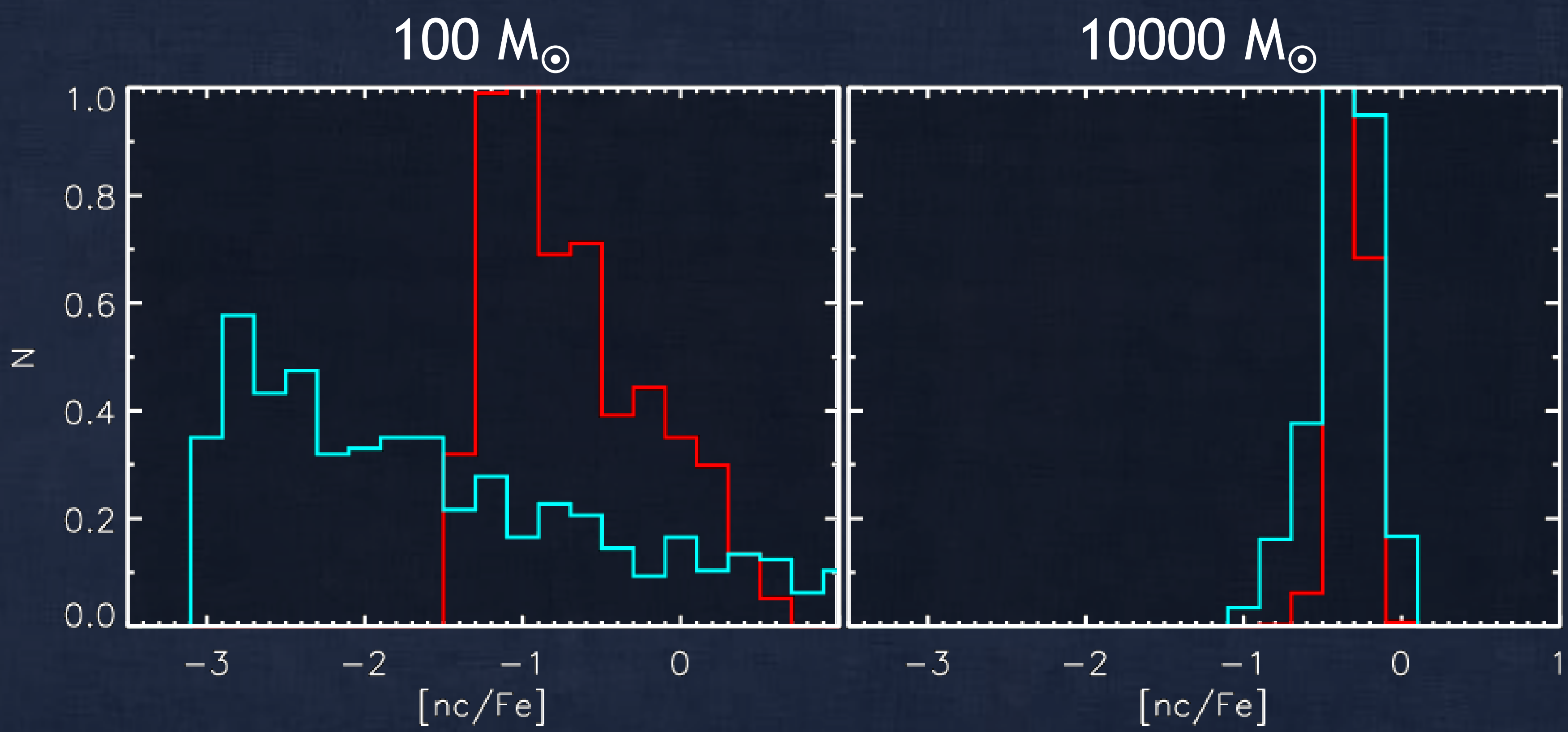
M_V = -6.3 (Norris10)

M_V = -5.7 (Simon10)

M_V = -3.9 (Frebel10a)

M_V = -3.8 (Frebel10a)

Mass Dependent SN Yields?

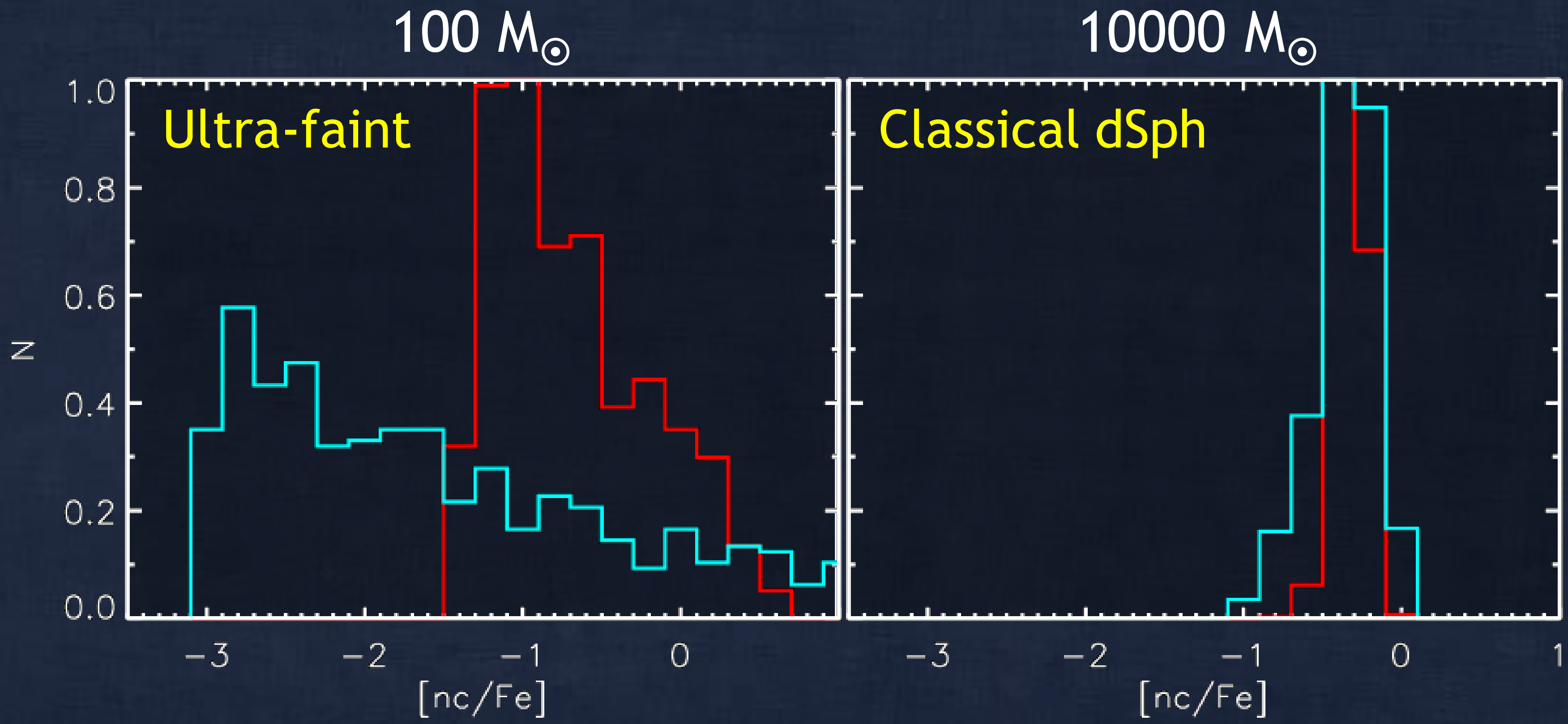


Weakly mass dependent yield

Strongly mass dependent yield

Lee et al., in prep.

Mass Dependent SN Yields?



Weakly mass dependent yield

Strongly mass dependent yield

Lee et al., in prep.

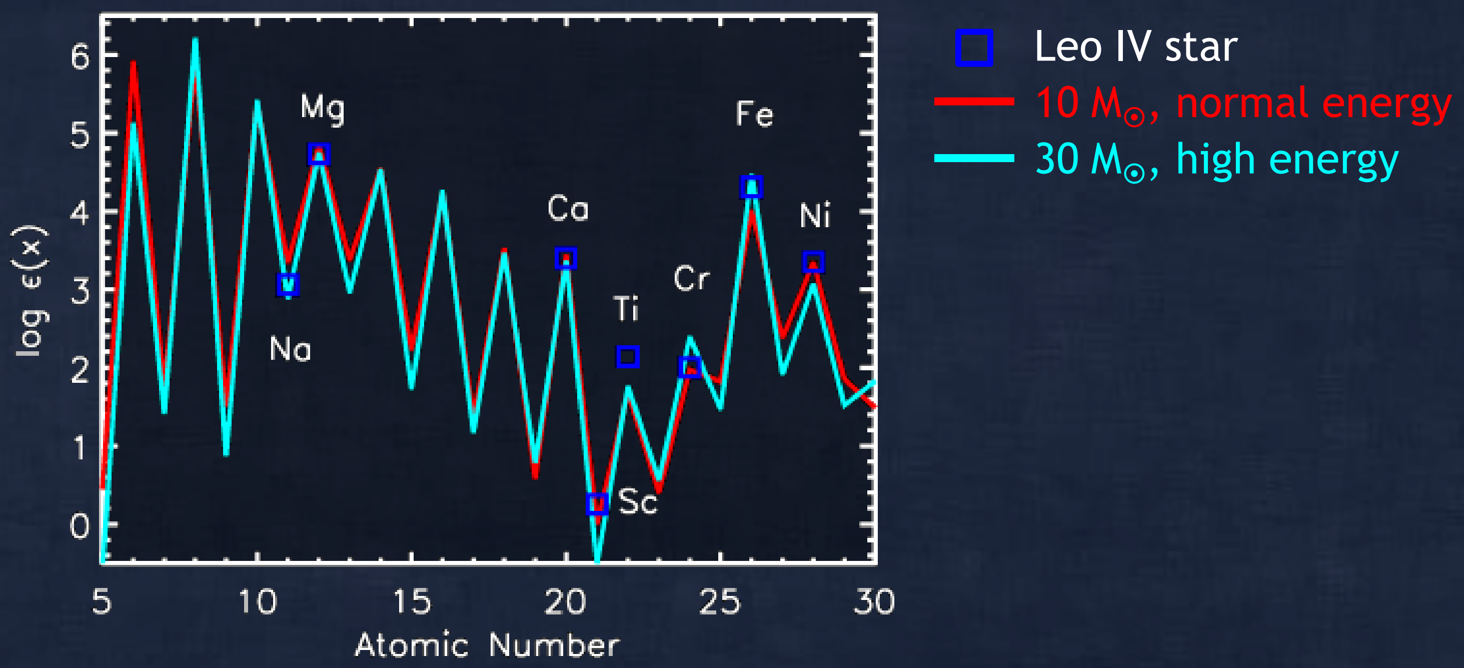
The First Supernova in Leo IV

- Leo IV has a luminosity of 14000 $L_\odot$ (Sand et al. 2009)
- Total iron content of the galaxy is 0.04 $M_\odot$
- A single Pop III supernova produces >0.03 $M_\odot$ of Fe (Heger & Woosley 2008)
- Were *all* of the metals in Leo IV synthesized by a single star??

Simon et al. (2010)

The First Supernova in Leo IV

- Leo IV abundance pattern compared to Pop III supernova models



Simon et al. (2010)

Summary

- Dwarf galaxies are home to large populations of extremely metal-poor stars
  - CCKSUMOMPSDG will find them
- Abundance patterns of these stars show:
  - Present-day dwarfs may be similar to halo building blocks
  - Early chemical evolution of galaxies appears nearly universal
  - Hints of the first supernova explosions?