Metal-poor stars towards the bulge: a mixed bag of chemical enrichments

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Galactic Components

M104 (HST) – unbarred spiral with ca. 30% of MW extent

Disk(s)
Halo: stars, globular clusters, satellite galaxies, dark matter
Central bulge (bars)

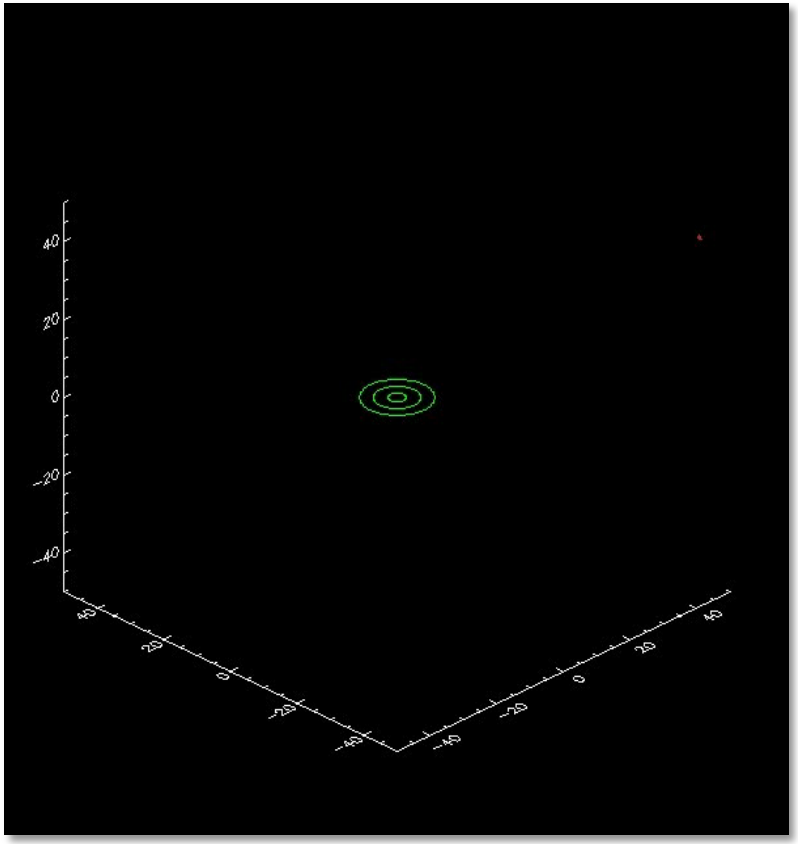
Halo formation

ΛCDM: hierarchical halo formation via accretion of dark matter dominated fragments.

Metal-poor halo stars were probably donated from satellite accretion.

Some stars in the dwarf satellites show chemical imprints from *individual* SNe (→ Pop III).
→ clues to the earliest enrichment phases.

What about the bulge?

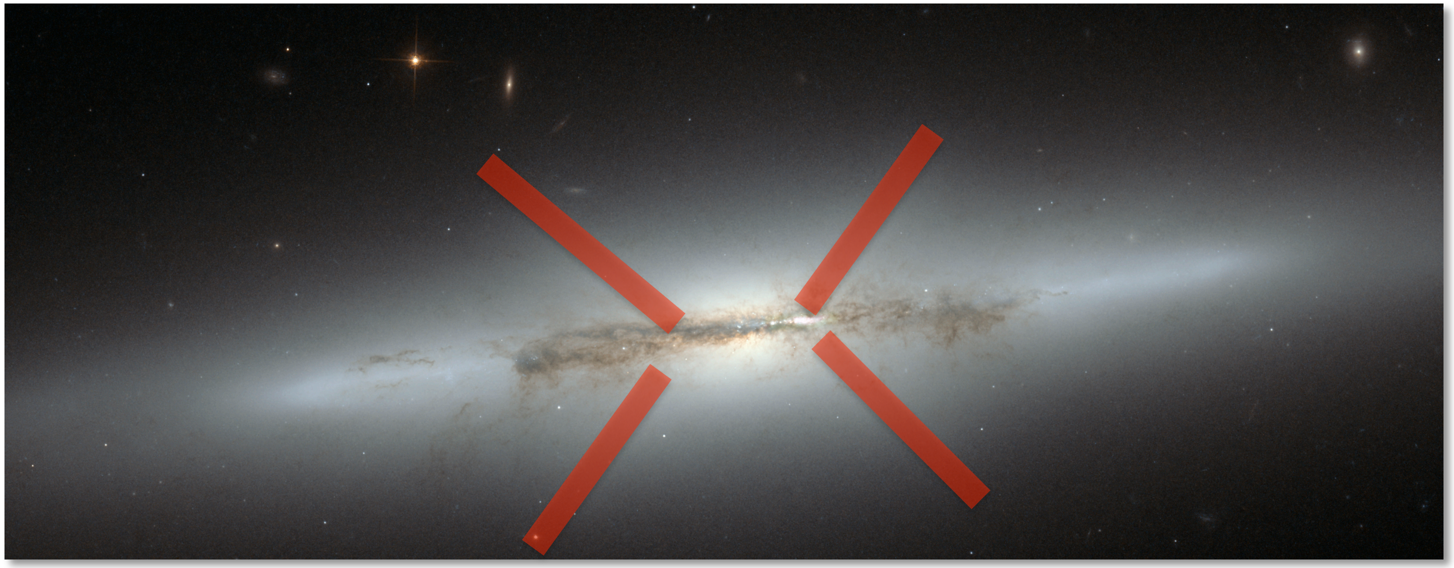


Bullock & Johnston (2005)

AK et al. 2008; Tolstoy et al. (2009); Simon et al. (2010); **AK** & Rich (2014)

Bulges

- 25% of the light in the local universe comes from bulges.
- Inhomogeneous class of objects with different formation channels:
    1) Spheroidal (“classical”) bulges form rapidly via early mergers. Bulge forms before disk.
    2) Pseudo-bulges / bars evolve from a buckling instability over longer timescales (>1 Gyr).



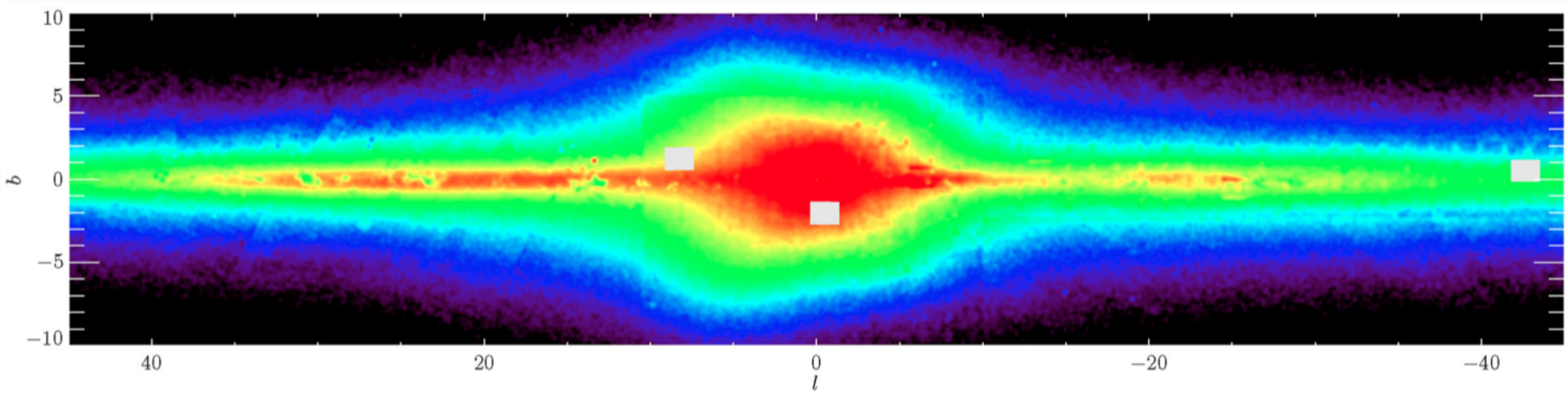
NGC 4710 (HST); McWilliam & Zoccali (2010); Rich (2012)

(Galactic) bulge formation

- **The bulge is old and metal rich, yet very complex**
  (e.g., McWilliam & Rich 1994; Clarkson et al. 2008; Bensby et al. 2013).

- **Dynamical formation, where bulge == bar** (e.g., Shen et al. 2010; Wegg et al. 2015) **? Prominent X-shape** (McWilliam & Zoccali 2010)

- **No evidence for kinematic substructures (streams), although hyper-velocity stars exist.**
  (e.g., Howard et al. 2008; Kunder, **AK**, et al. 2012; Kunder et al. 2014, 2015; C.J. Hansen, **AK**, et al. subm.).

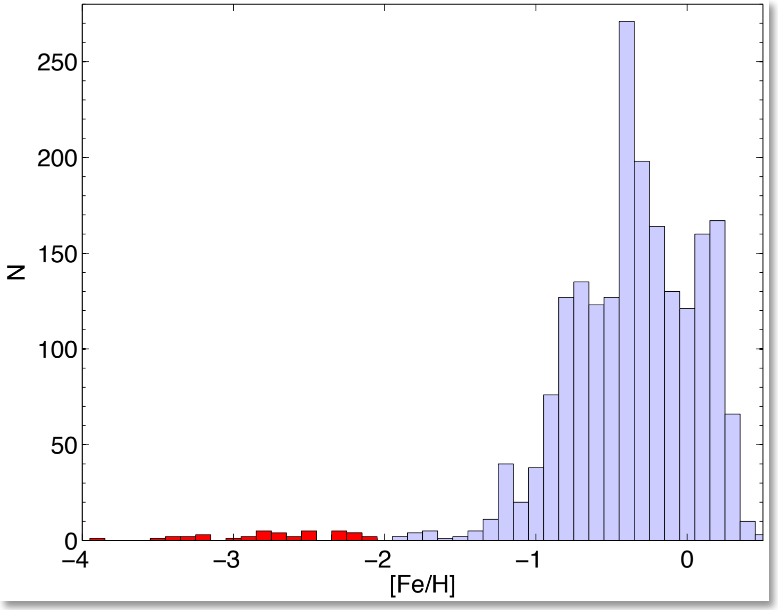


Wegg et al. (2015)

Bulge vs. halo formation

- **Oldest stars with [Fe/H] < −3 (*z* > 6 - 10) are predicted on tight orbits in the *innermost* halo, due to inside-out nature of CDM: *"In the bulge, not of the bulge"* (Tumlinson 2010).**

- **E.g., ARGOS bulge survey: non-rotating, metal-poor tail; attributed to the inner halo (R_{GC} < 3.5 kpc; Ness et al. 2013)**

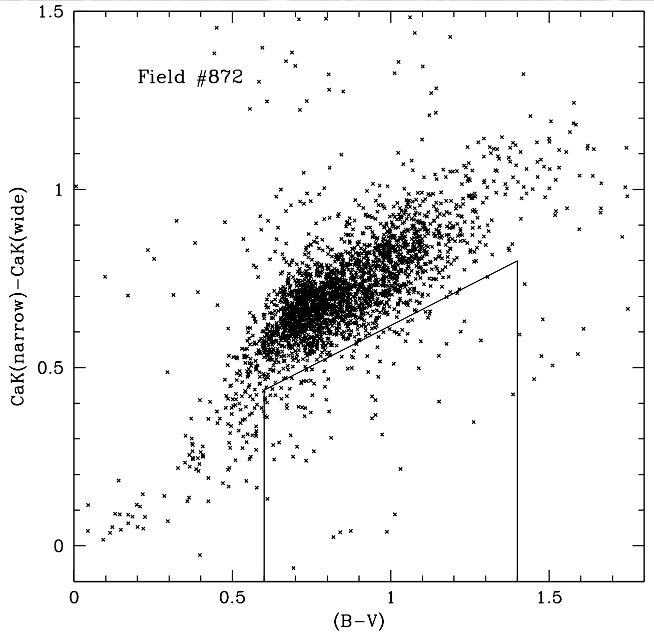


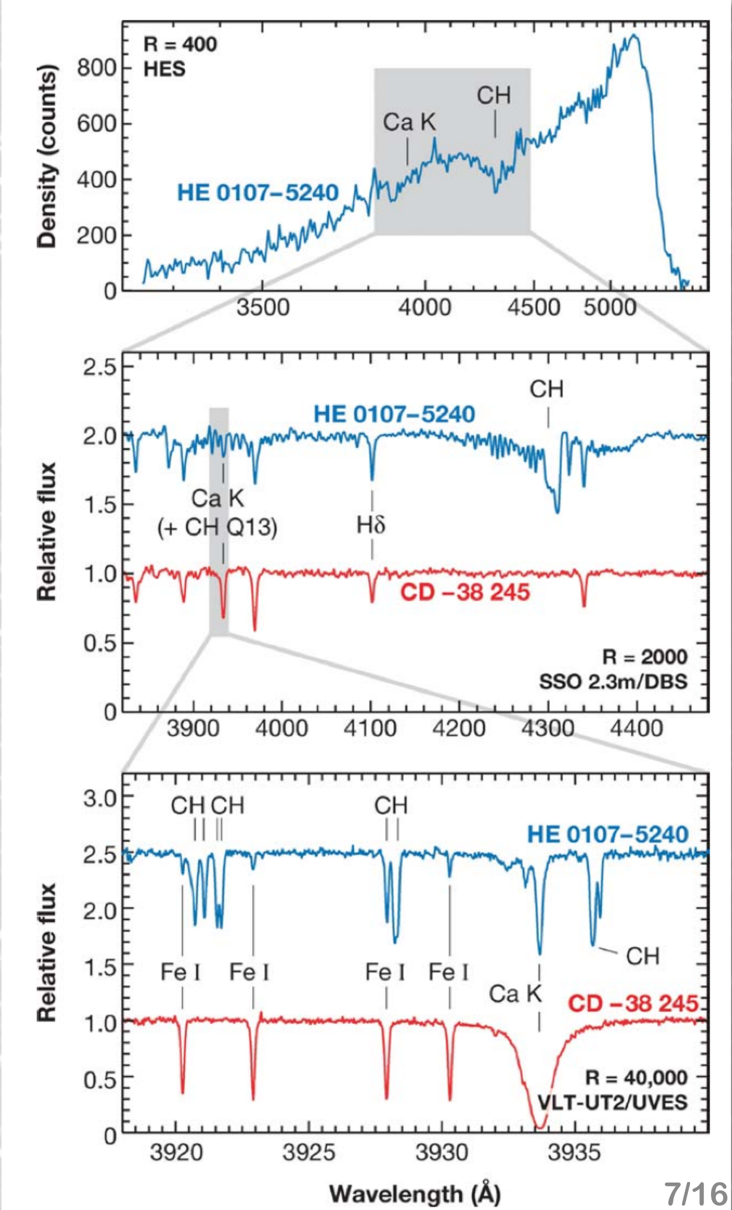
To date: 55 stars between -2 and -4 dex in surveys of several 10000s stars

(Ness et al. 2013; García Pérez et al. 2013; Howes et al. 2014, 2015; Casey & Schlaufman 2015, AK et al. 2016)

Target selection

- **EMP candidates from narrow-band Ca K photometry (20 Å line, 200 Å continuum, at 3933 Å).**
- **T_{eff}-sensitivity from BVI imaging.**
- **Calibrated against known EMP stars.**



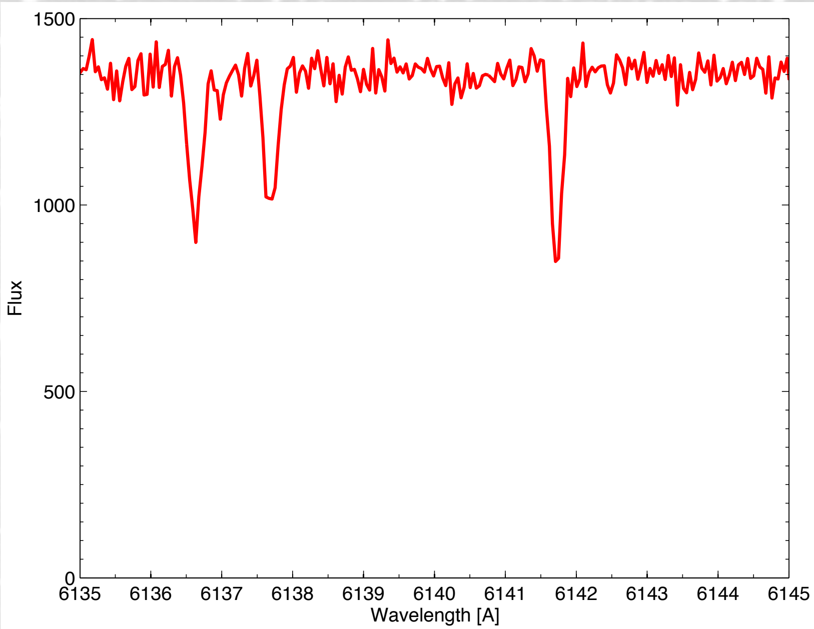


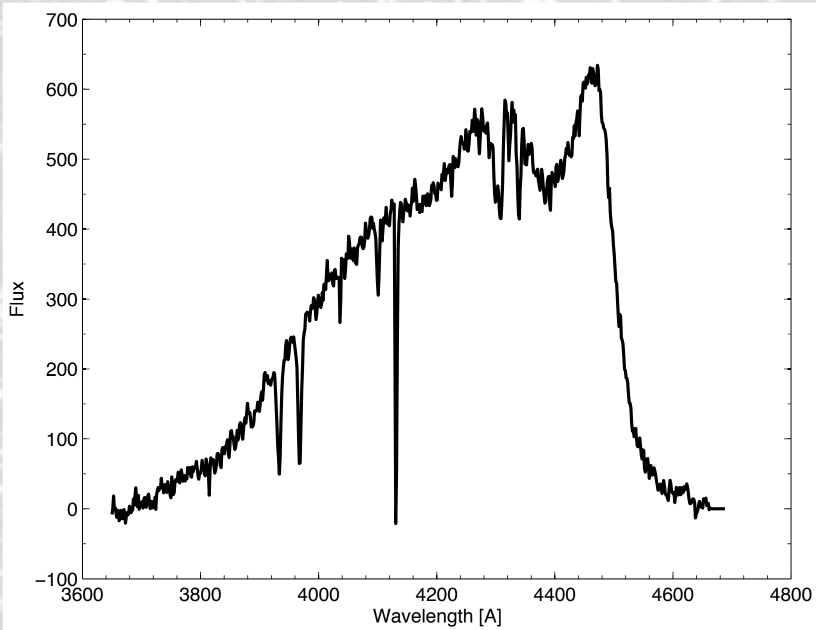
Beers & Christlieb (2005)

Target selection

- Problems: CR hits, diffraction spikes, TiO in cold M-stars.
- → low-res (R~2000) follow-up of ~150 stars (WFCCD grism)

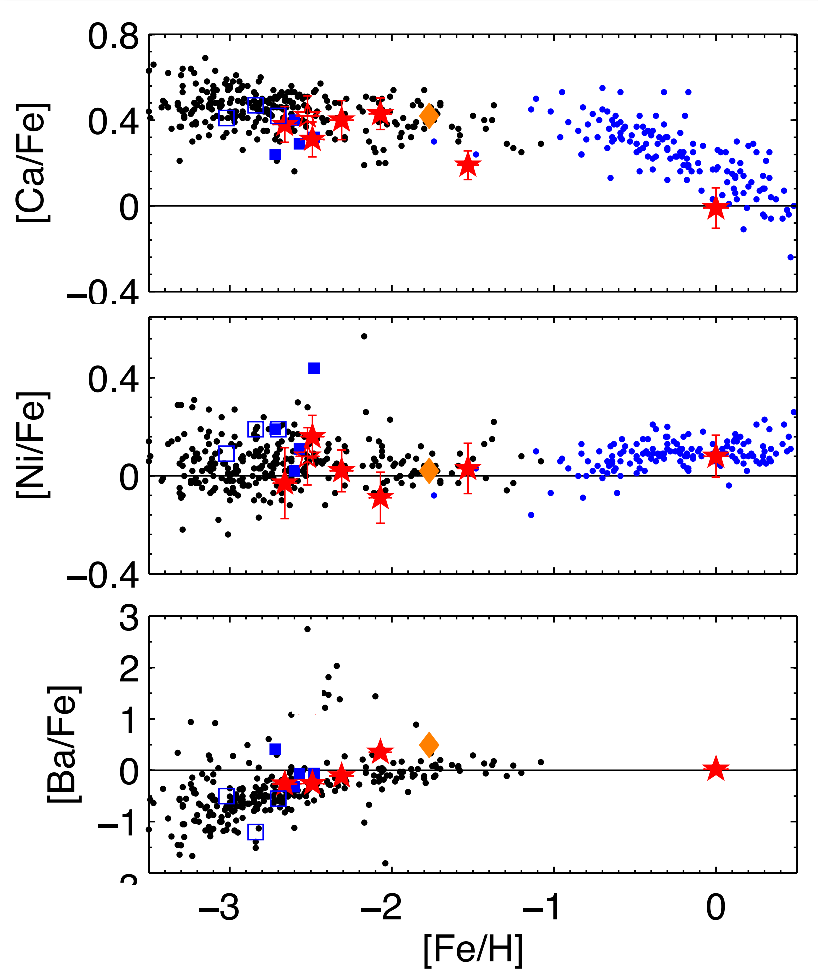
  → high-res (R~45000) follow-up of 8 stars (MIKE @Magellan)





Abundance results

- One metal-rich (Solar) bulge star
- The majority of (23) species for the rest of the stars is compatible with *halo* abundances!



Metal-poor Halo (Roederer et al. 2014)

Bulge (Johnson et al. 2012, 2014)

Metal-poor "bulge" (Casey & Schlaufman 2014; Howes et al. 2014)

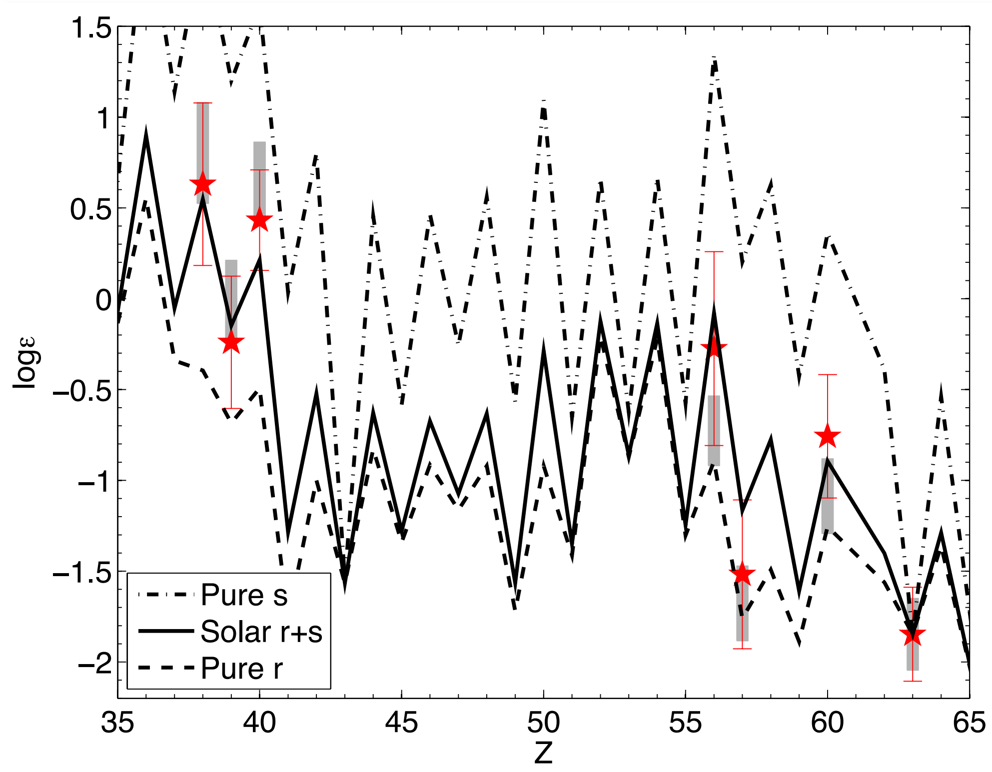
r-process enhanced bulge (Johnson et al. 2013)

This work (AK et al. 2016)

AK et al. 2016, A&A, in press (arXiv:1511.01490)

Normal halo-(like) stars ?!

- The majority of (23) species for the rest of the "bulge" stars is compatible with *halo* abundances and points to standard enrichment processes !



Mean abundances of all stars compared to Solar r/s pattern (Simmerer 2004).

HD 122563, weak r-process star (Honda 2006)

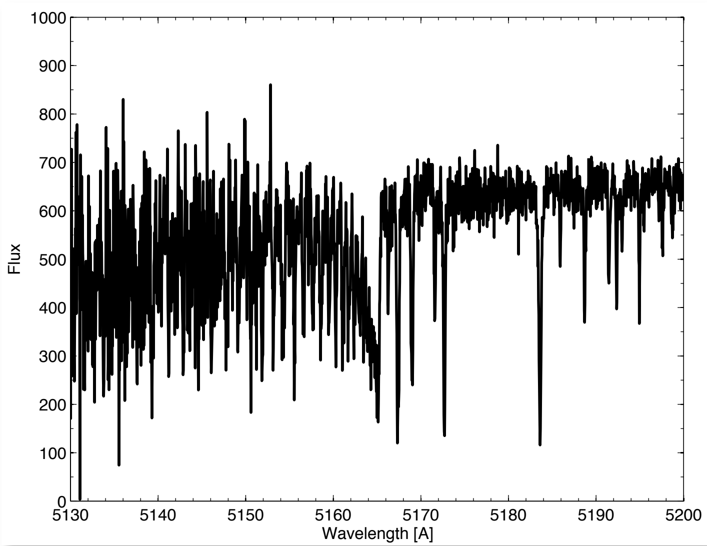
AK et al. 2016, A&A, in press (arXiv:1511.01490)

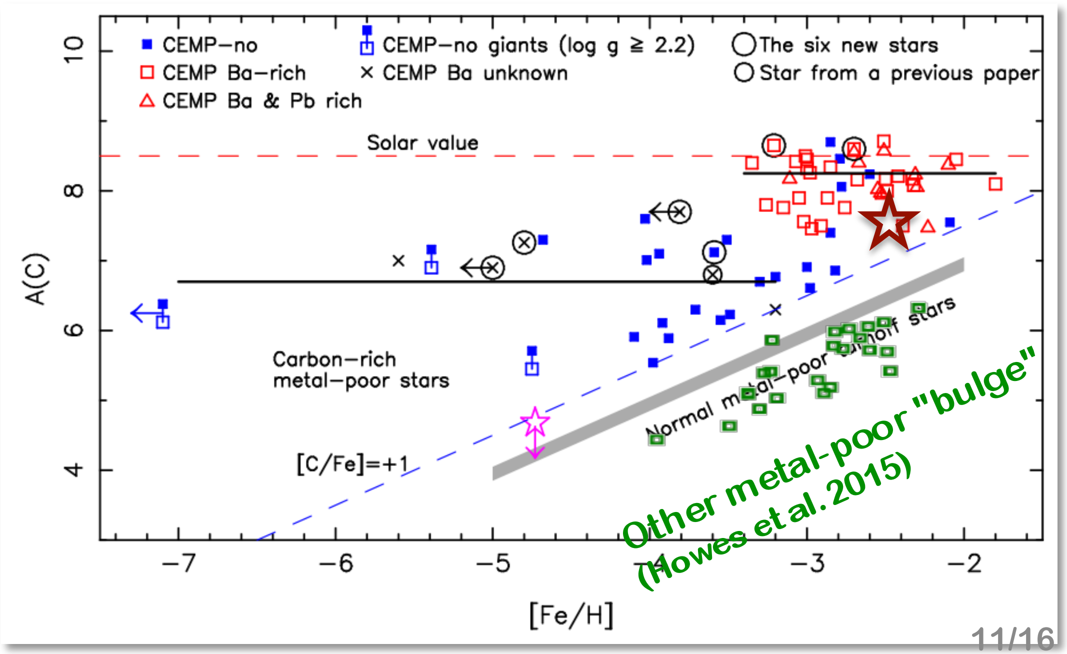
Some special guests

- one **CEMP-*s*** ([Fe/H] = -2.5, [C/Fe] = 1.4, [Ba/Fe] = 1.3)
- one **Ba-**star ([Fe/H] = -1.5, [C/Fe] = 0.4, [Ba/Fe] = 1.3)

No evidence for binarity (no velocity variations, but no representative time coverage); **abundances indicate origin of C-enhancement from AGB transfer.**

First contenders of this class towards the bulge.

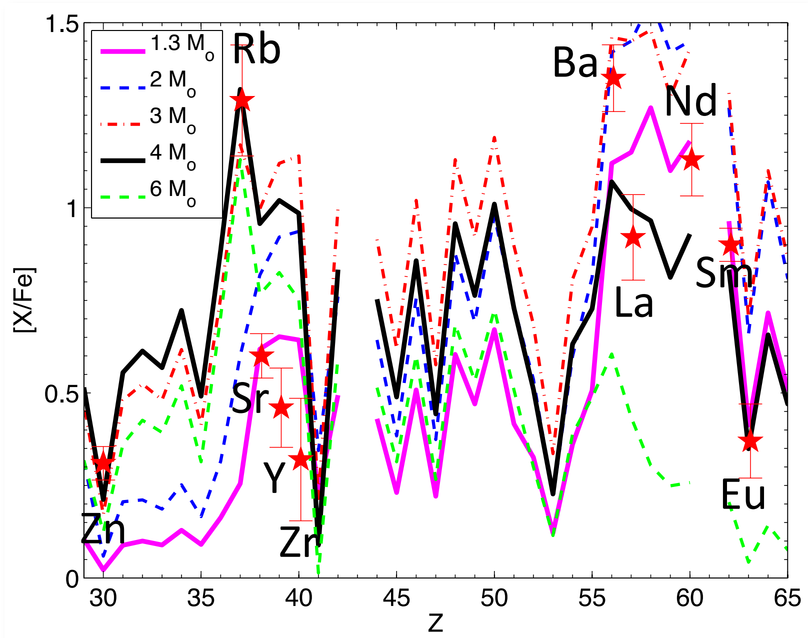




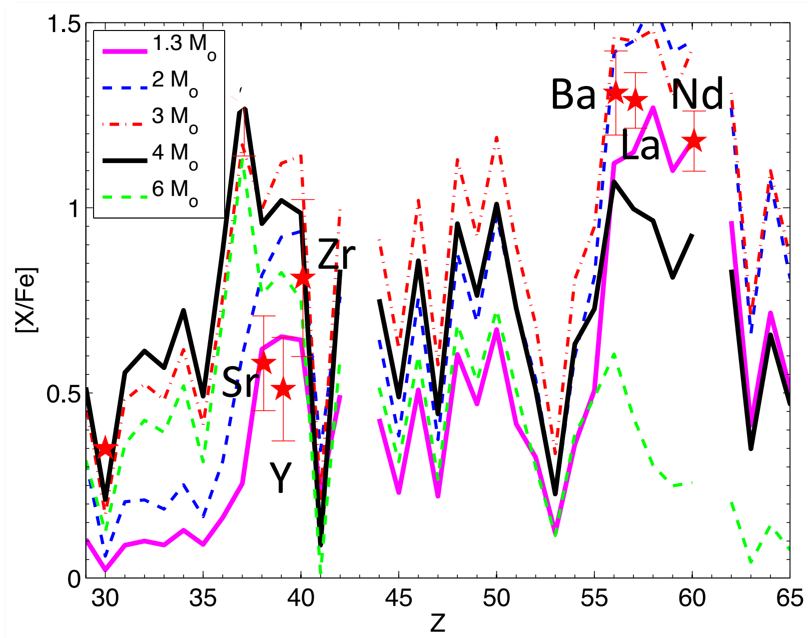
Bonifacio et al. (2015); C.J. Hansen et al. (2016)

Bulge CEMP-s and CH

- Ba-star: High Rb/Zr ratio (0.99), [hs/ls] = 0.41, low La, Y
- Low-metallicity (Z=0.0001 – 0.0003) AGB models indicate ~4 $M_\odot$ progenitor for Ba-star, ~1.3 $M_\odot$ for CEMP-s.
- [Fe/H] of -2.5 coincident with peak of halo-CEMP MDF



[Fe/H] = -1.5

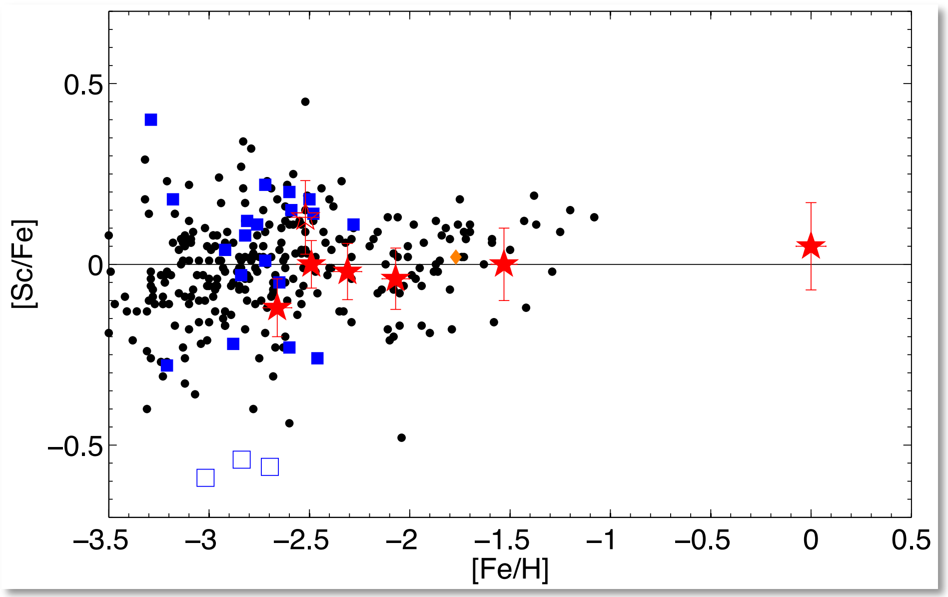


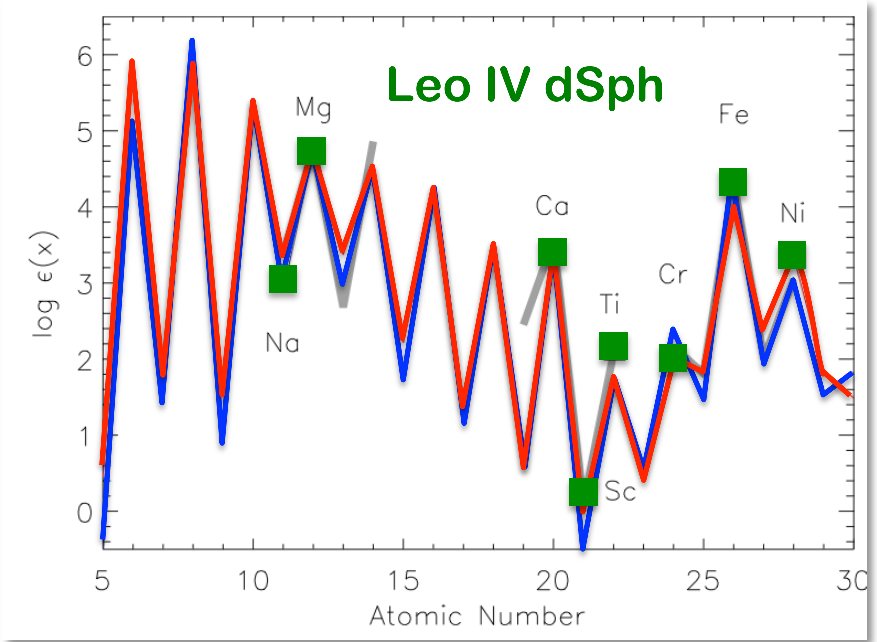
[Fe/H] = -2.5

F.R.U.I.T.Y. (Cristallo et al. 2011)

No Population III

- Regular (Solar) [Sc/Fe] values are in contrast to predicted depletions in Sc from Pop III nucleosynthesis.
- Cf. observations of ultrafaint dwarf spheroidals
  (AK et al. 2008; Simon et al. 2010)





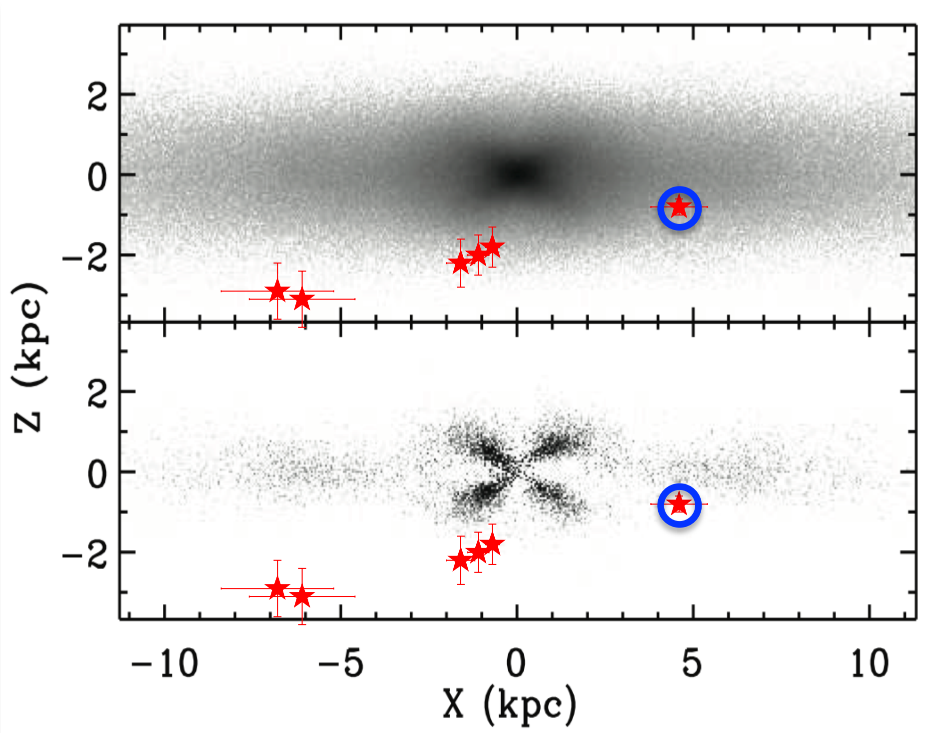
Low-Sc *was* suggested in bulge
(Casey & Schlaufman 2015)

→ Localized enrichment ?
→ Low-numbers ?

Metal-free, high-explosion model of a 30 $M_\odot$ star (Heger & Woosley 2010).
Or 10 $M_\odot$ with less dilution

Bulge or halo? – Location

- Location indicates three members on the far side of the X.
- Sample contains stars out to $R_{GC} \sim 6$ kpc, $|z| \sim 3$ kpc. Combined with the regular chemistry this conforms with an overlapping inner halo, in line with Tumlinson (2010).



← Model of smooth component

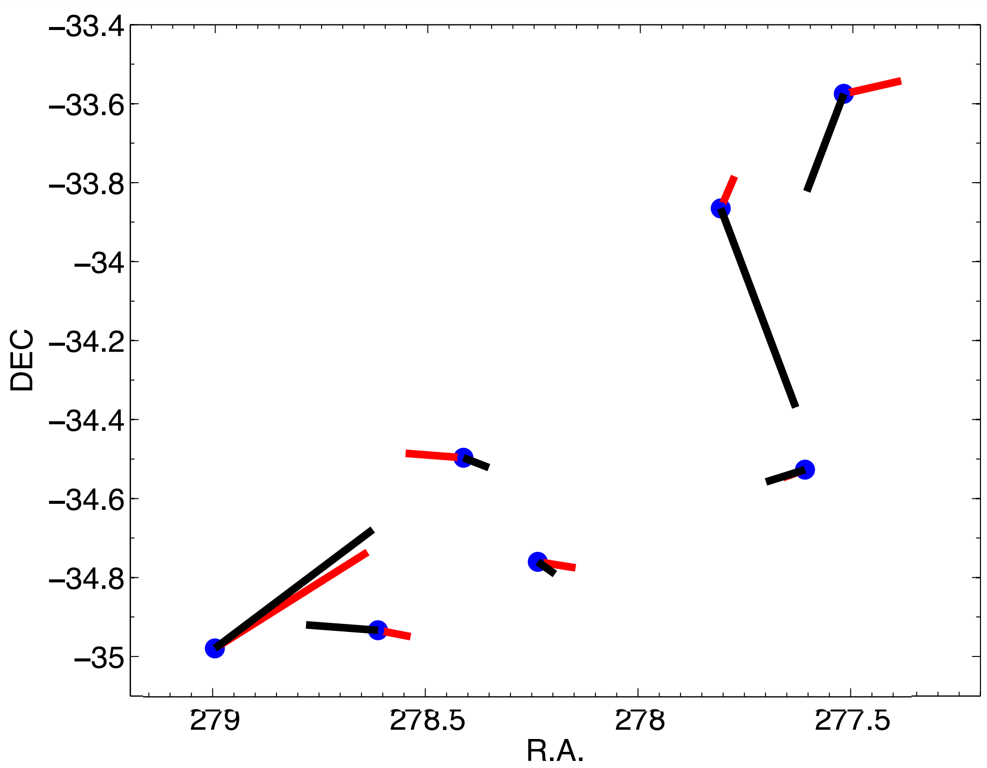
← Model of X-shaped bulge component

Metal rich star

Li & Shen (2010); McWilliam & Zoccali (2010)

Bulge or halo? – Kinematics

- **Often, metal-poor "bulge" stars found to be on tight or eccentric orbits** (Howes et al. 2014, 2015; Casey & Schlaufman 2015).
- **Usually based on various sets of proper motions (SPM4, UCAC4, OGLE), which can grossly disagree!**



UCAC4

SPM4

Bulge or halo? – Kinematics

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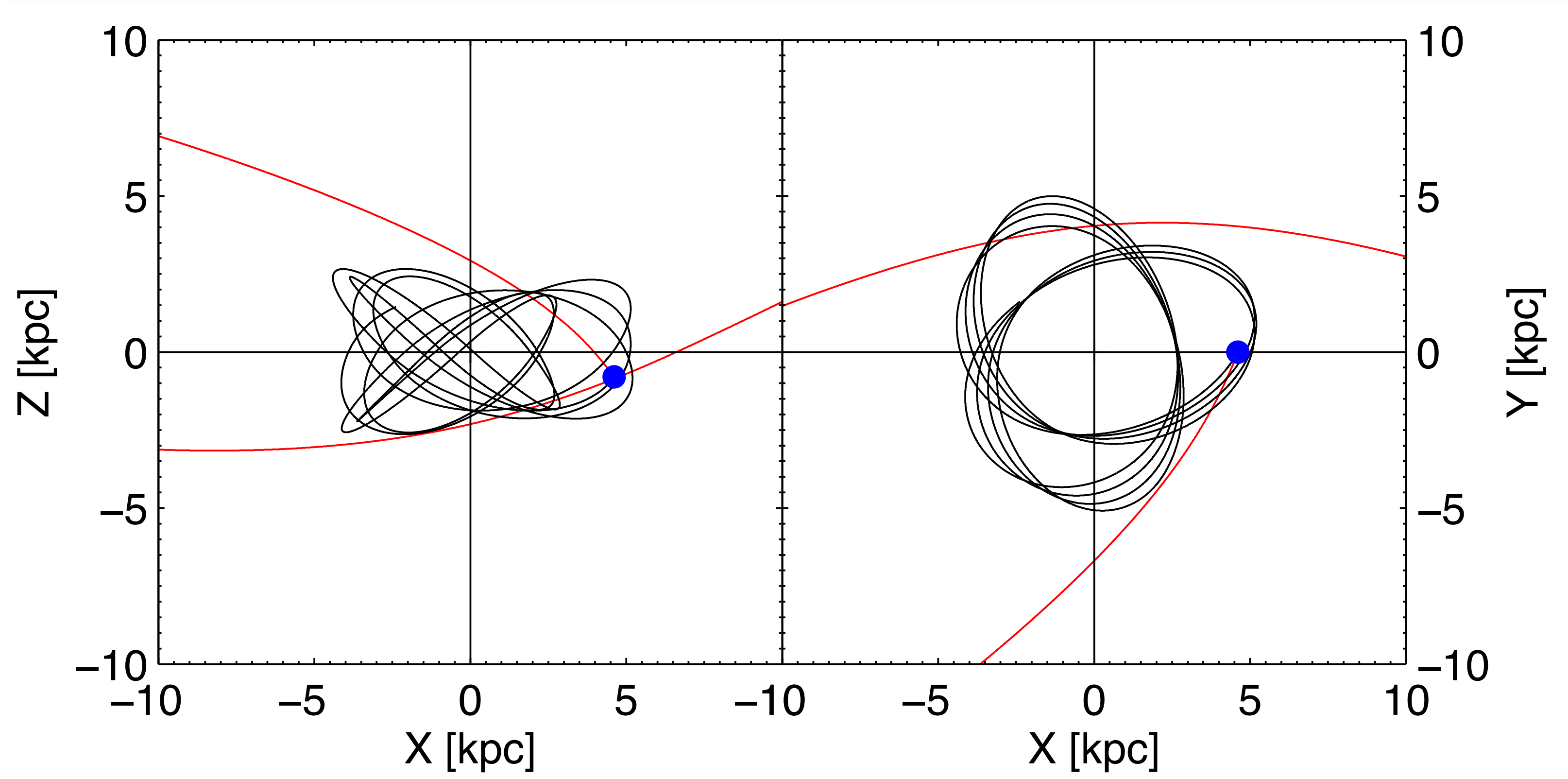
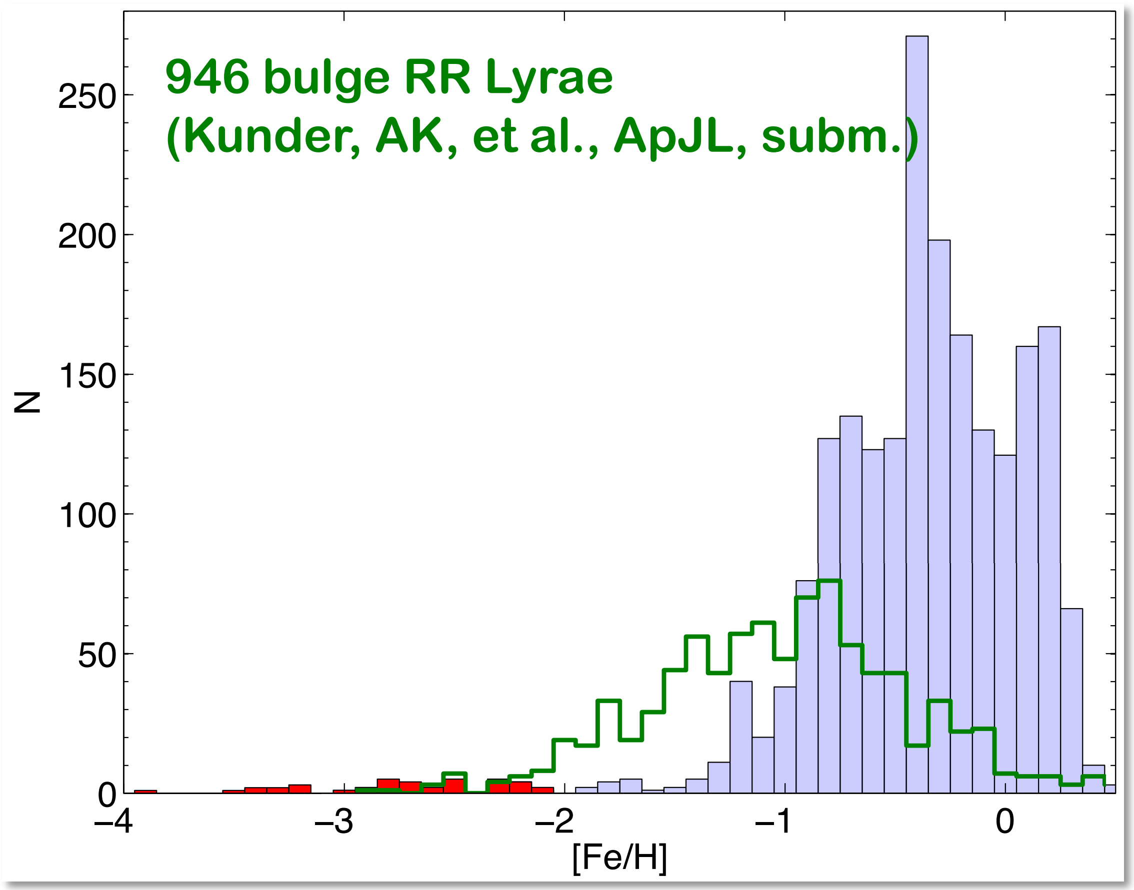


Summary

- We detected "metal-poor" stars *towards* the "bulge", down to -2.7 dex.
- No evidence for Pop III enrichment (normal Sc/Fe), nor extraordinarily massive AGB.
- First CEMP and Ba-stars in that population.
- Kinematics are inconclusive due to uncertain proper motions.

  → Caution with a true, metal-poor bulge – how to distinguish from halo stars passing through ?! Yet consistent with the notion that anicent objects (z>10) are to be found in the central regions of the Milky Way.
- Improved target selection methods desirable, e.g., using (2MASS+WISE) IR and optical colors (Schlaufman & Casey 2014).

Summary


946 bulge RR Lyrae
(Kunder, AK, et al., ApJL, subm.)
N
250
200
150
100
50
0
–4
–3
–2
–1
0
[Fe/H]