Composition and Kinematics of the Bulge

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HST Legacy

Funding: NSF

Bulges appear be either spheroidal (classical) or barlike (pseudobulge)

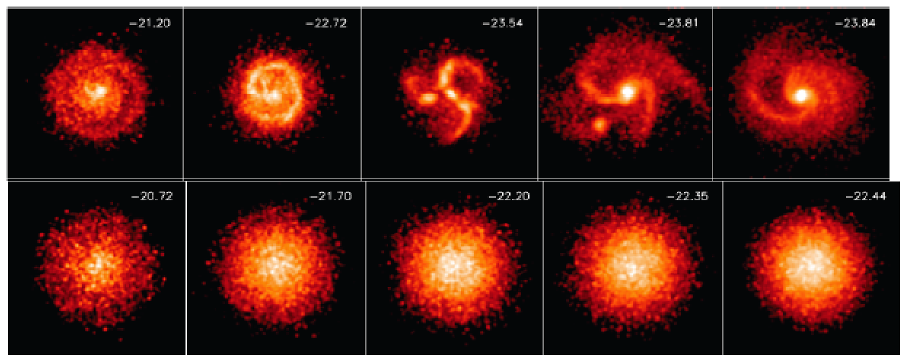
Canonical formation picture is that spheroidal forms via early mergers, while pseudobulges/bars evolve from a buckling instability over longer timescales.

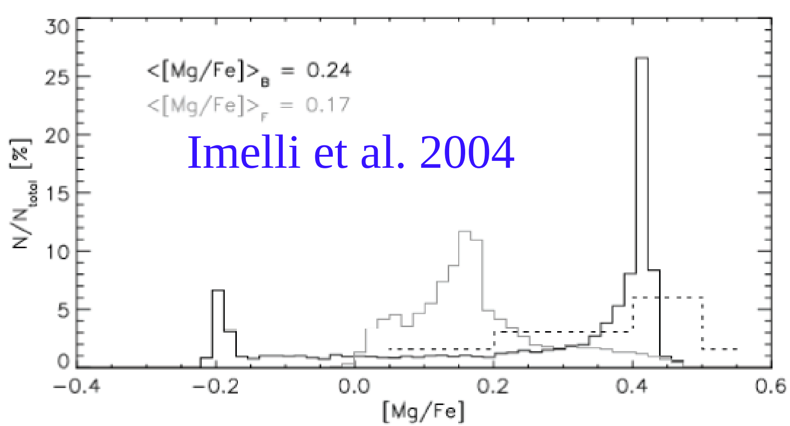
Milky Way has dynamics characteristic of pseudobulges, yet age/chemistry consistent with rapid formation.

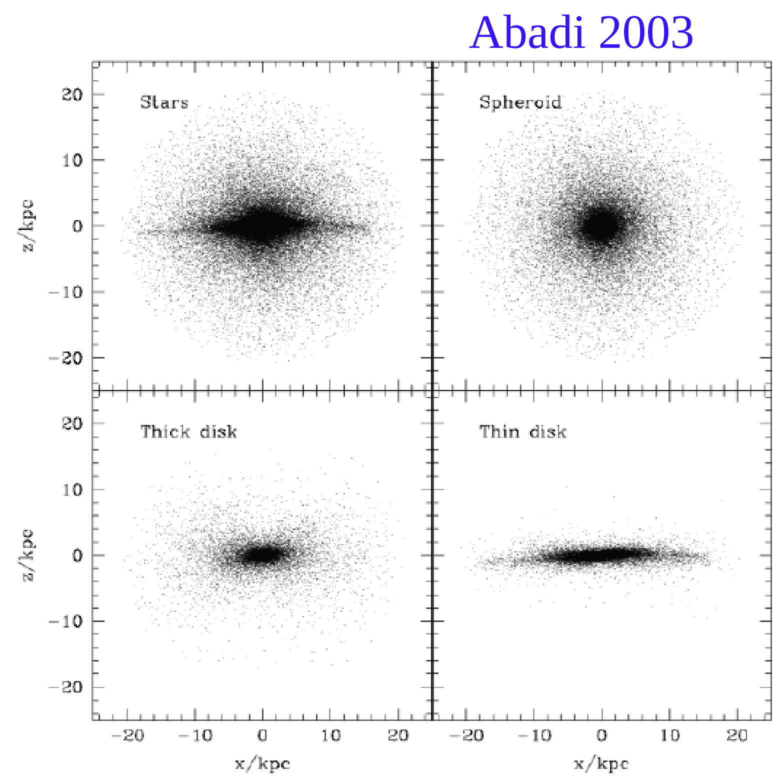
Partially based on “The Galactic Bulge” by R.M. Rich in Planets, Stars, and Stellar Systems, Vol 5 (ch. 6).

Imelli et al. 2004; Elmegreen et al. (2008) - major merger origin
Clumps dissipate rapidly into bulge or Classical early merger..

Multiple star forming clumps might produce kinematic subgroups with distinct chemical or dynamical fingerprints.







See also Inoue et al. 2013, Elmegreen et al.

N-body bar models attractive for representing the bul

However, extended formation models favored; bar survival?

Bar dissolves due to central mass (Norman et al. 1996)

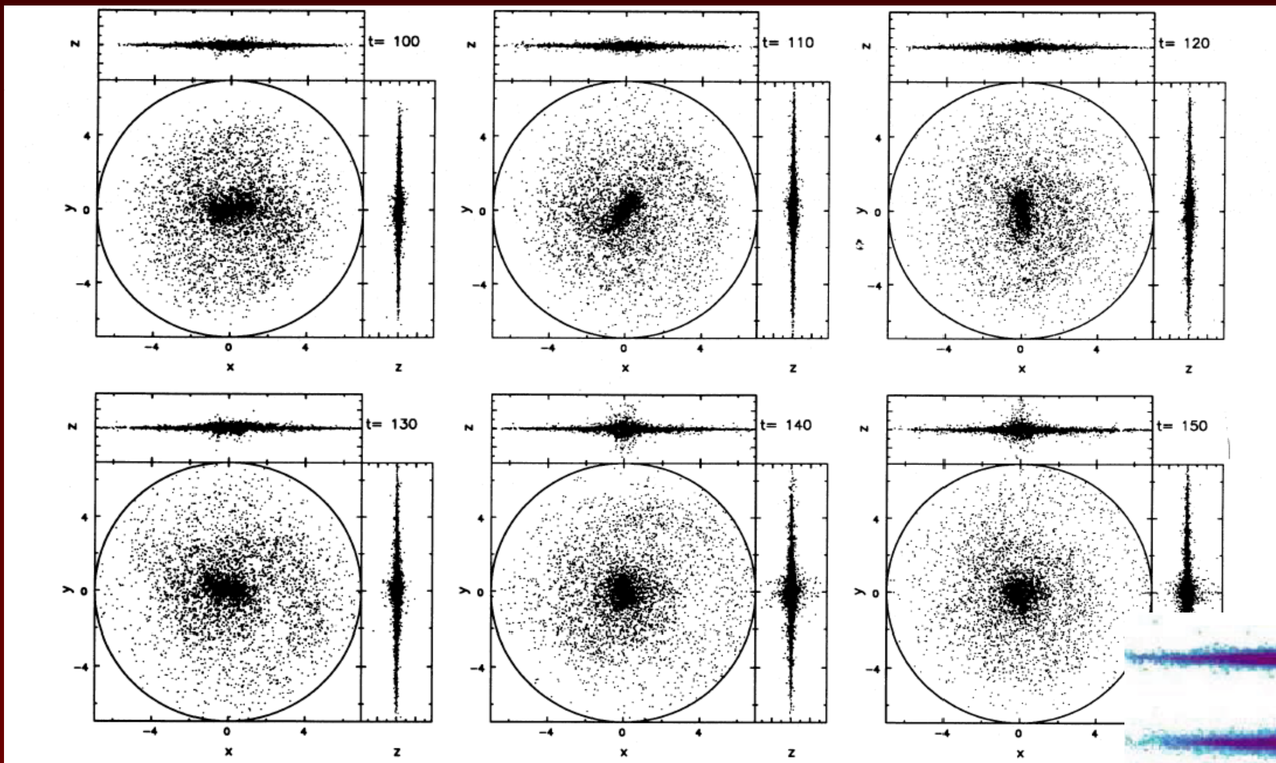
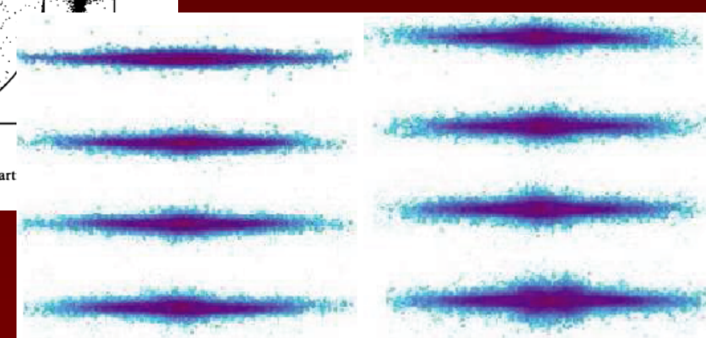


FIG. 6.—The evolution of a three-dimensional model in which a 5% central mass is grown from time 100 to time 140. The whole calculation volume is shown, but only one part
bar dissolves abruptly between times 130 and 140, forming a spheroidal bulgelike feature at the center.

Combes 09- bar resurrection via gas inflow



Vertical thickening of the bar into a bulge would leave no abundance gradient in the z-direction.

A Trip Down memory lane…
Edvardsson et al. 1993- 22 years ago. m<6.5 disk dwarfs, R=80,000, S/N>200. Rm from orbital parameters (PM+RV+integrated orbit)

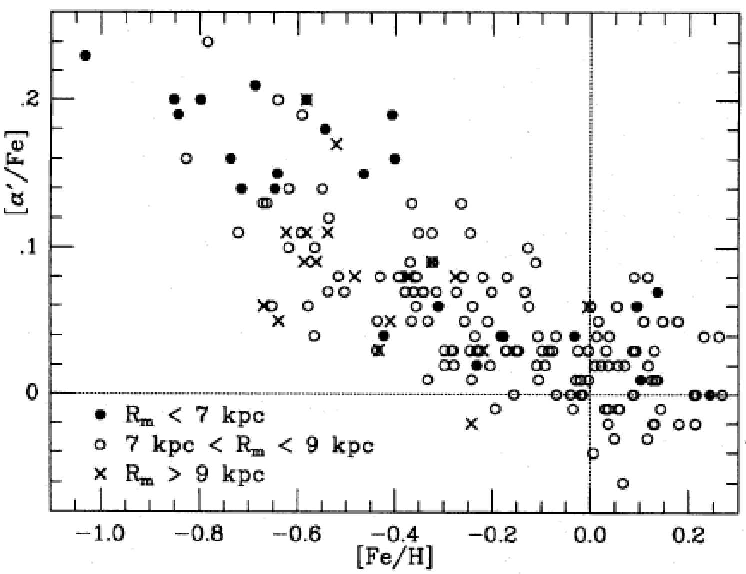


Fig. 19. The run of $[\alpha'/\mathrm{Fe}]$ vs iron abundance for all programme stars, separated in three R_m intervals

Enhanced alphas in the inner disk

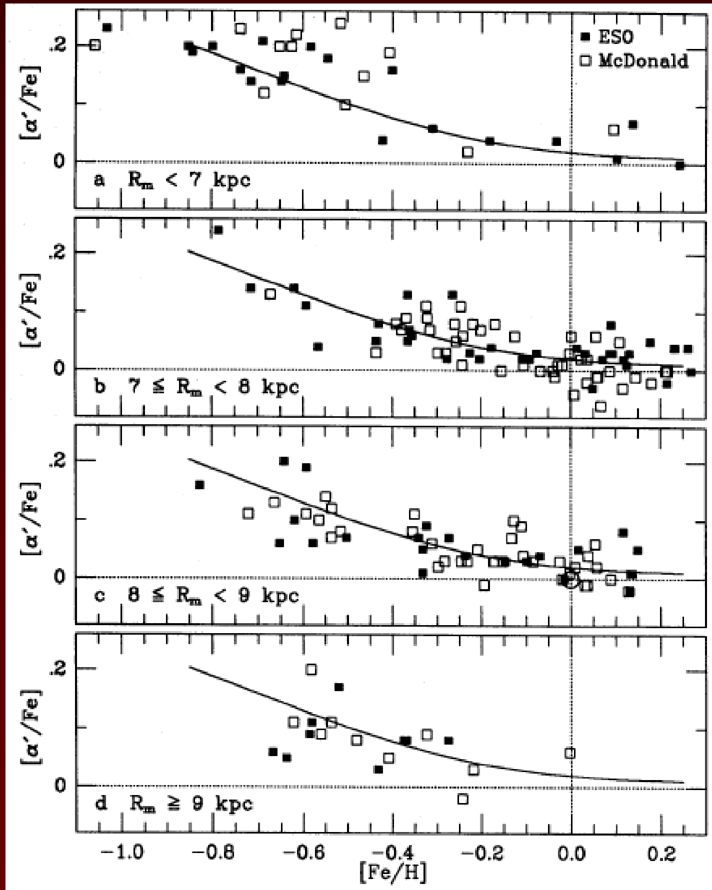
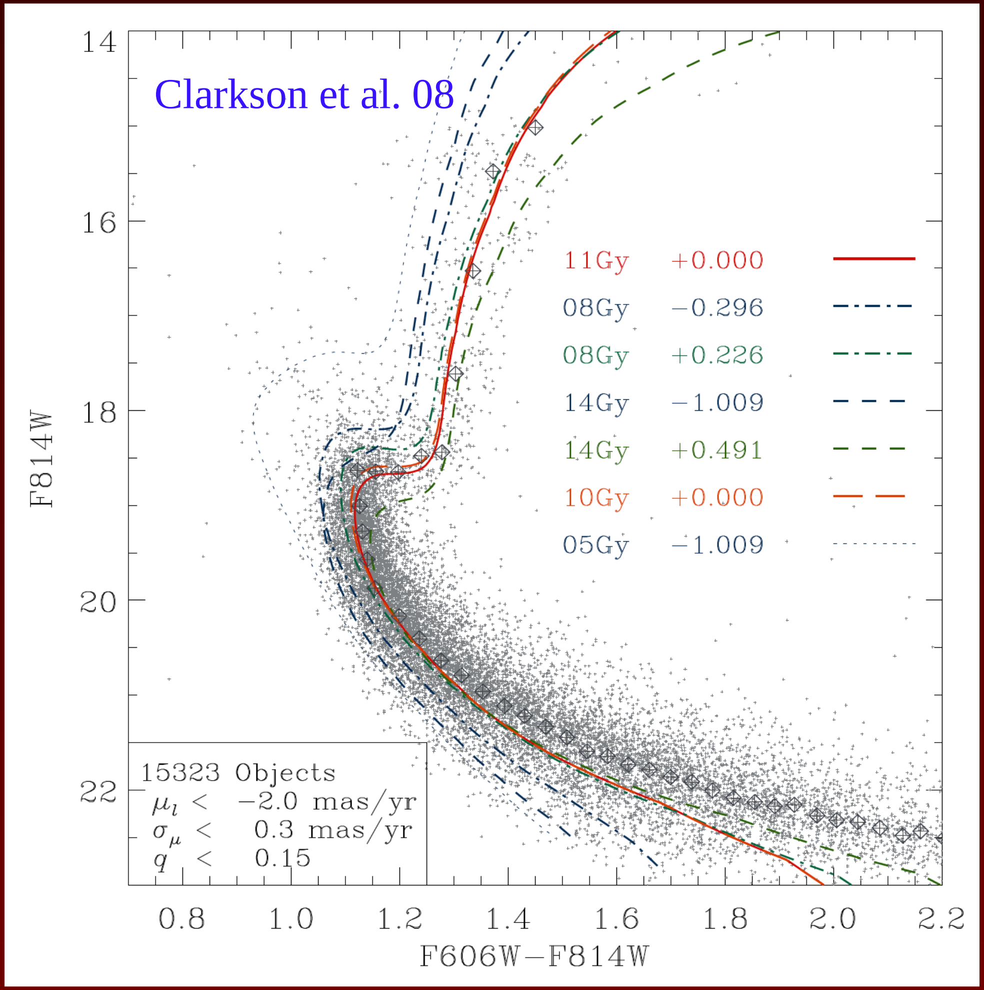


Fig. 20a–d. The run of $[\alpha'/\mathrm{Fe}]$ vs iron abundance for four ranges of R_m. The filled squares represent ESO stars and the open squares show stars observed from McDonald. The solid lines show a mean relation for all the stars. In the inner Galaxy ($R_m < 7$ kpc) $[\alpha'/\mathrm{Fe}] = 0.2$ for [Fe/H] < -0.4 and $[\alpha'/\mathrm{Fe}] = 0.03$ for [Fe/H] > -0.4. At larger distances from the galactic center there is no sign of this step in $[\alpha'/\mathrm{Fe}]$. As a result, at metallicities less than [Fe/H] $= -0.4$ the inner Galaxy is characterized by a larger $[\alpha'/\mathrm{Fe}]$ than it is further out

“classical”

“boxy/ X-shaped”

Age constraint from PM separation

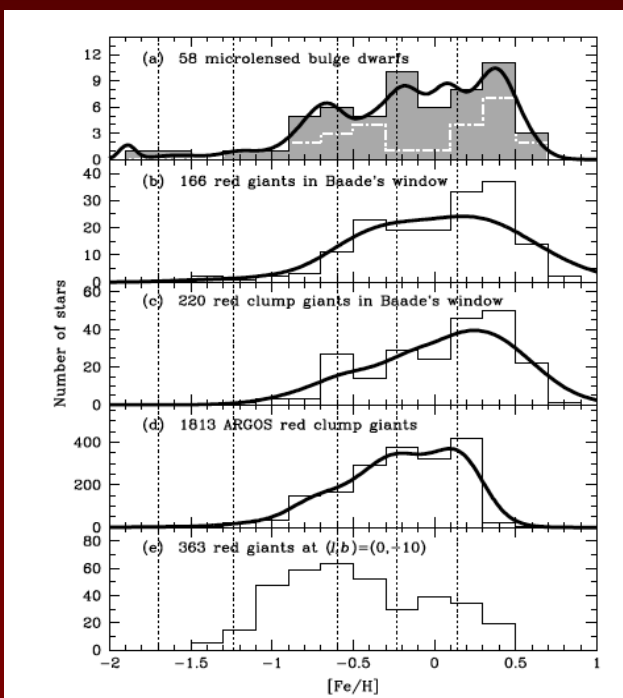


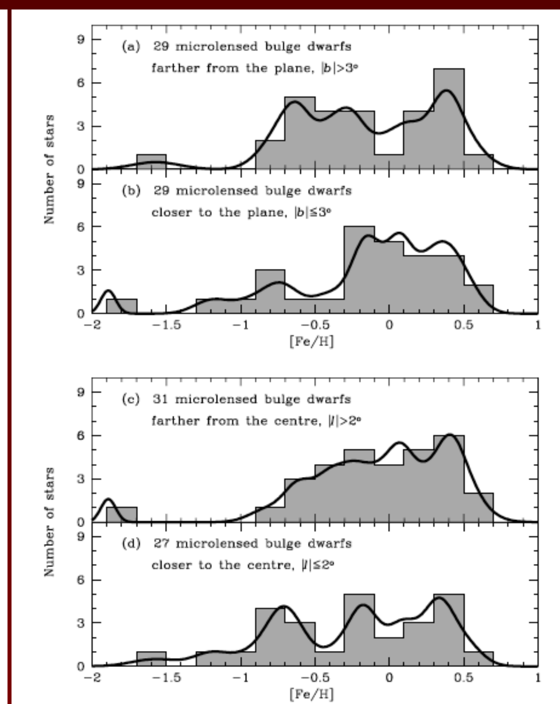
~99% of bulge older than 5Gyr; pure 10+ Gyr likely (Clarkson+ 08, 09

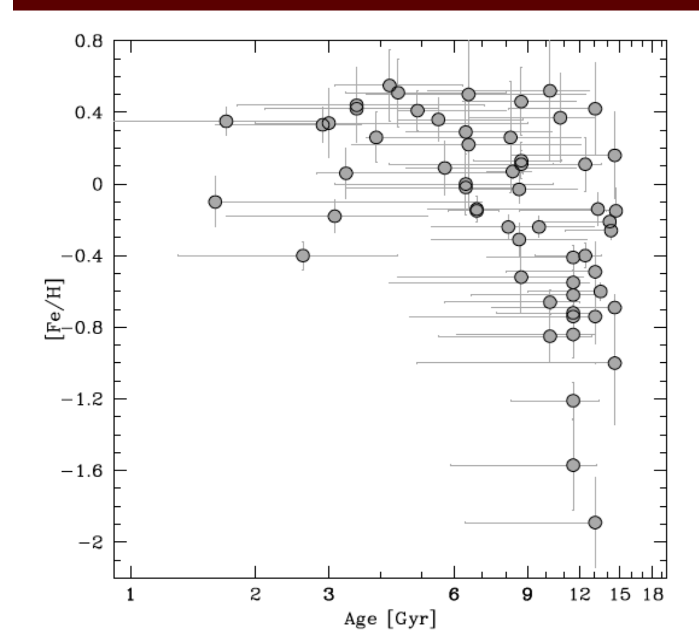
Bensby et al. 2012, 2013

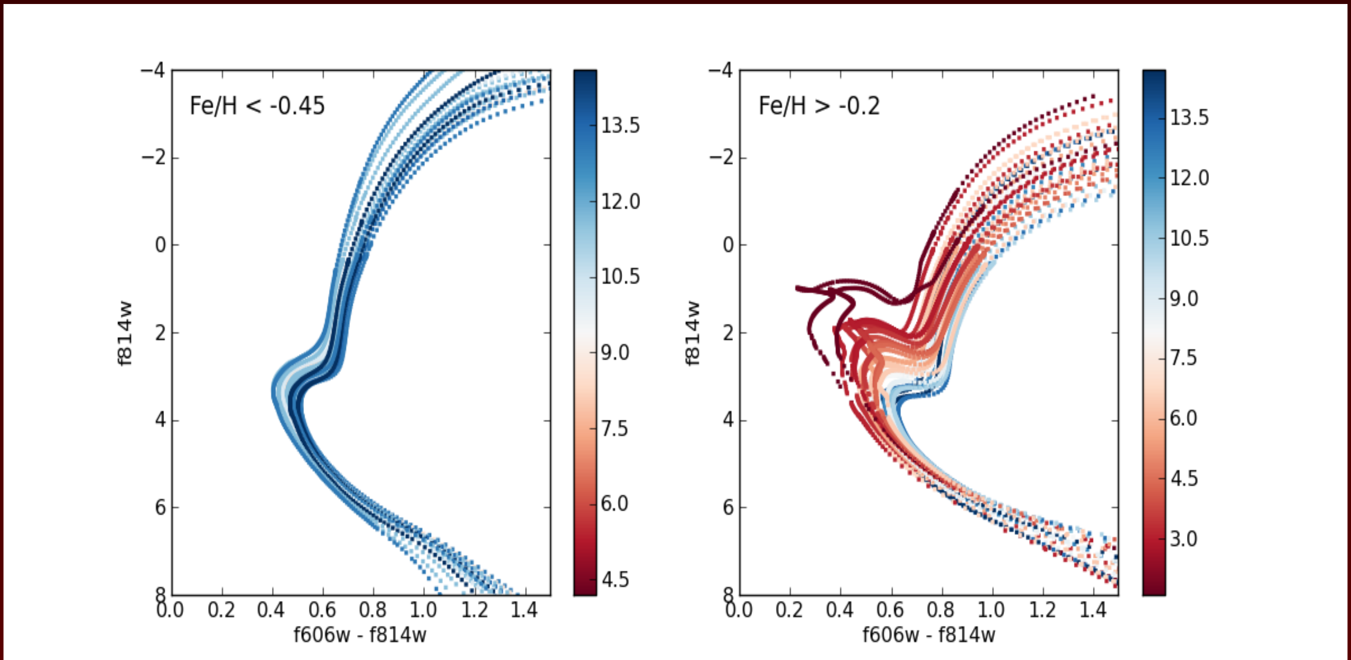
Microlensed bulge dwarfs: self-consistent log g, Teff > possible young, metal rich population, possible complexity

A major goal of composition studies is to use large K giant surveys to test the complexity of the populations

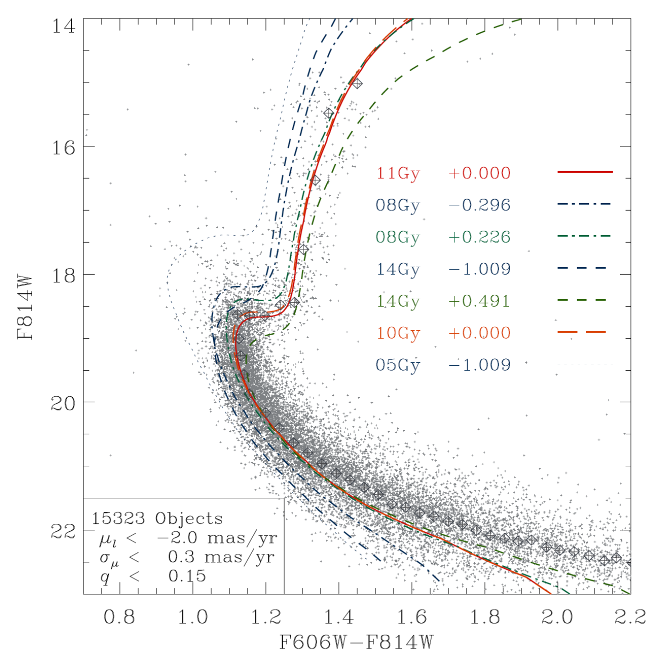




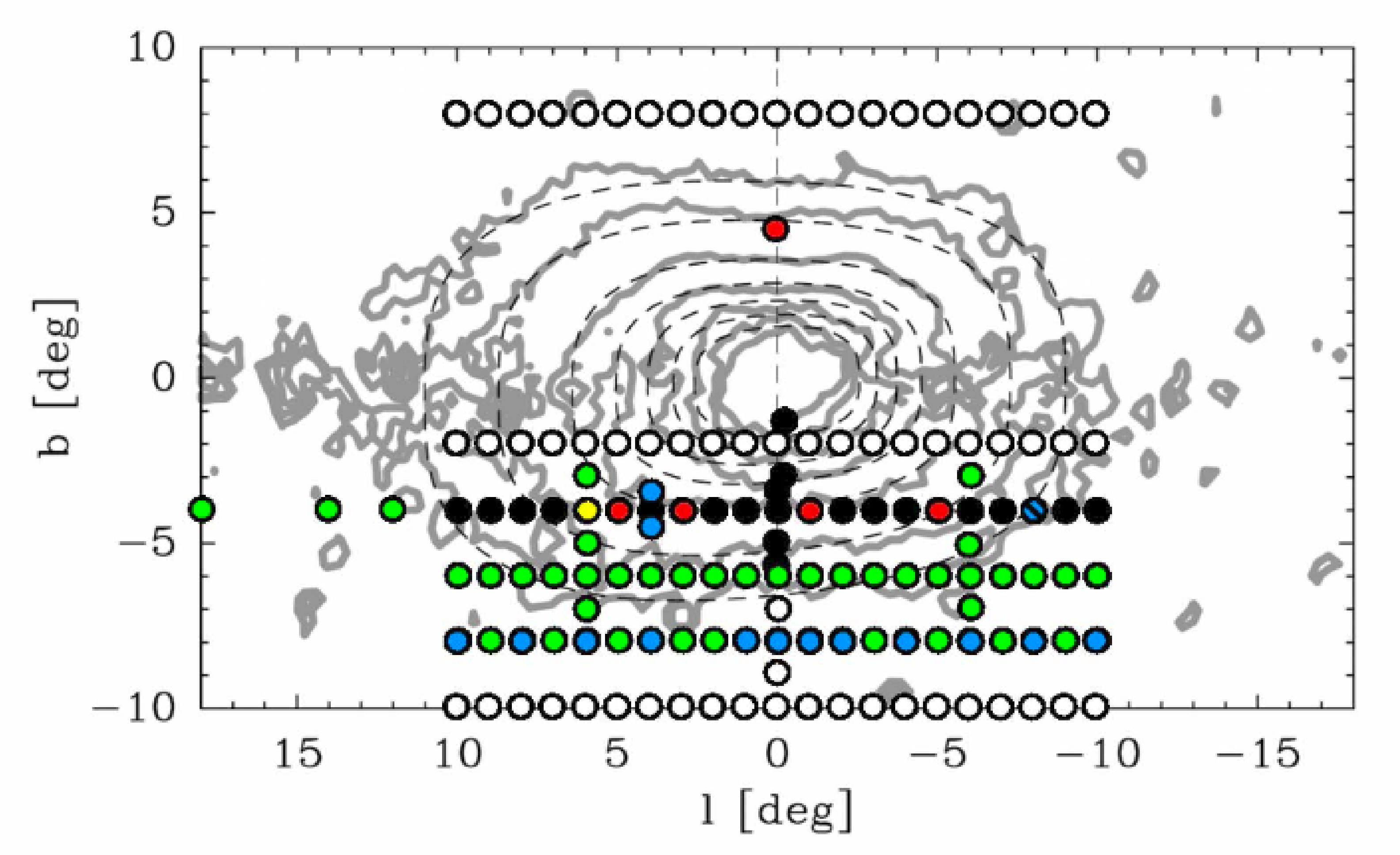




Using isochrones associated with young subdwarf populations. Young metal rich should be evident.

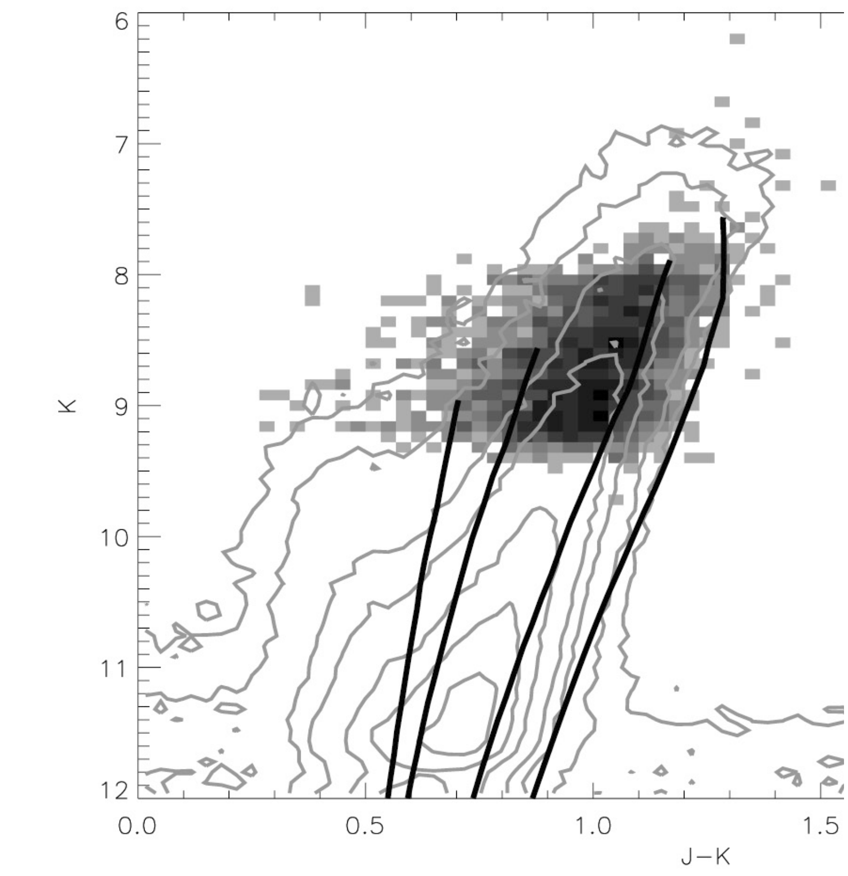


BRAVA Survey Fields 2005: blue 2006: red 2007: green

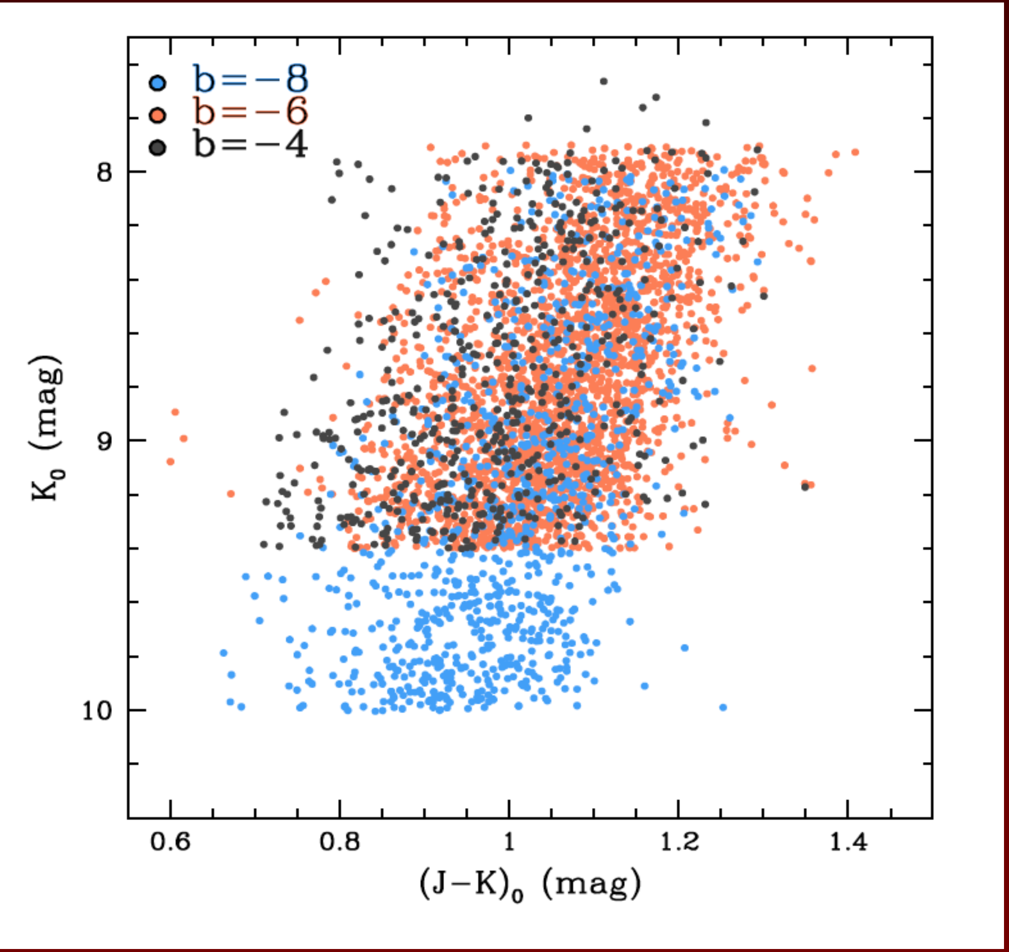


Goal: Grid of fields at 1 deg intervals, covering 10x10 deg box, pushing as close to plane as possible

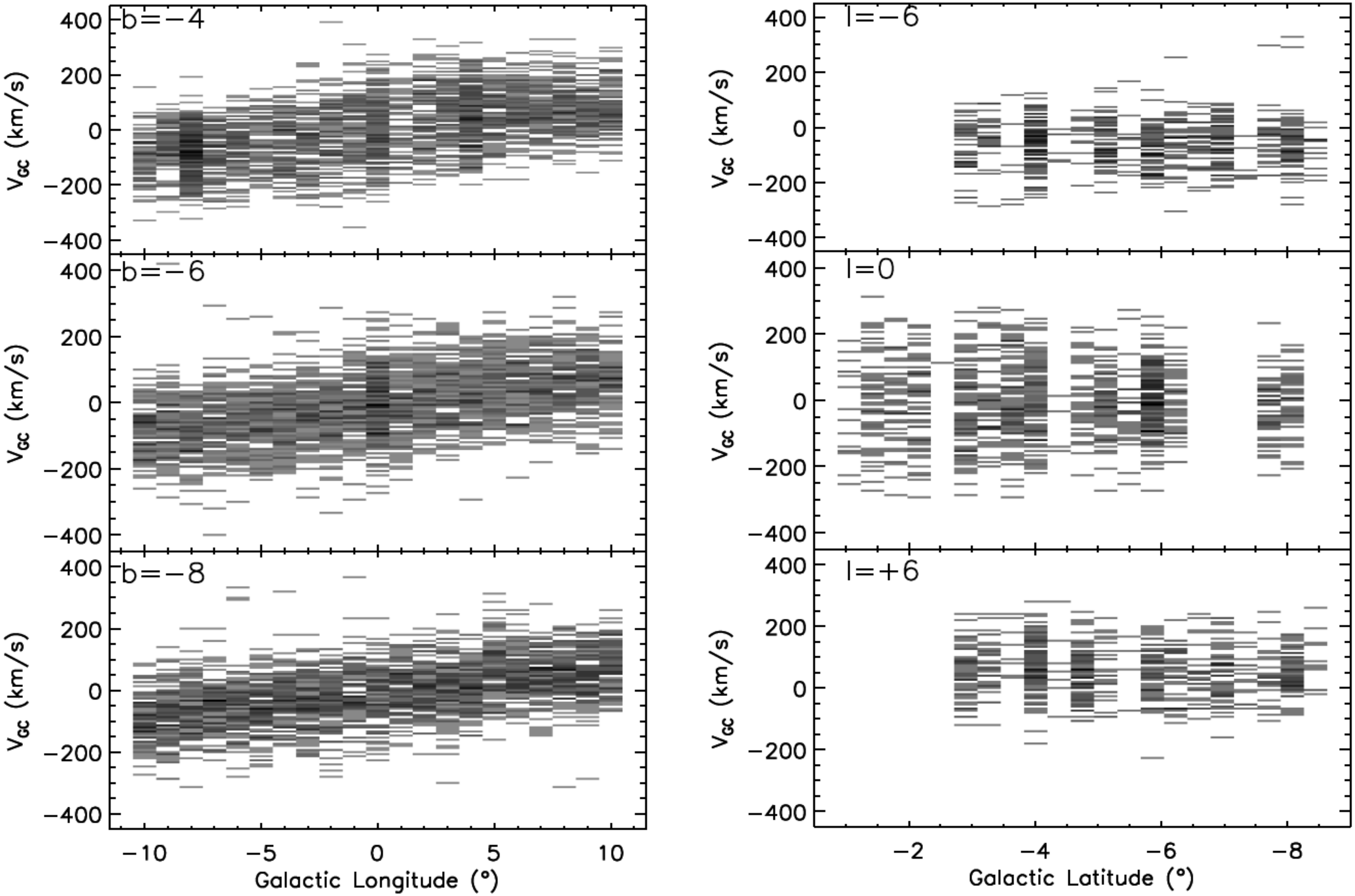
Target Selection



Howard et al. 2008 b=-4 dereddened

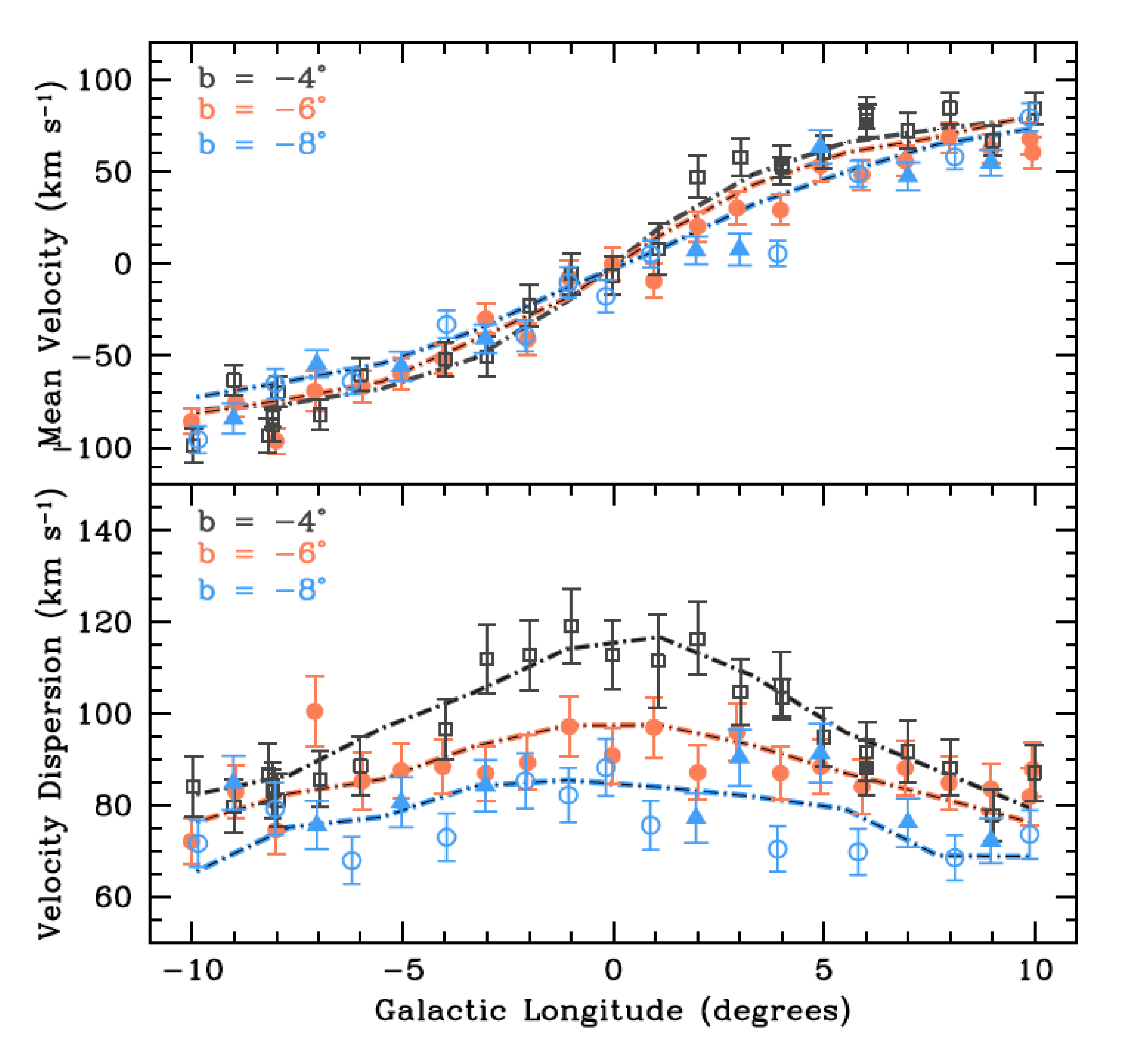


Kunder et al. 2011, new sample

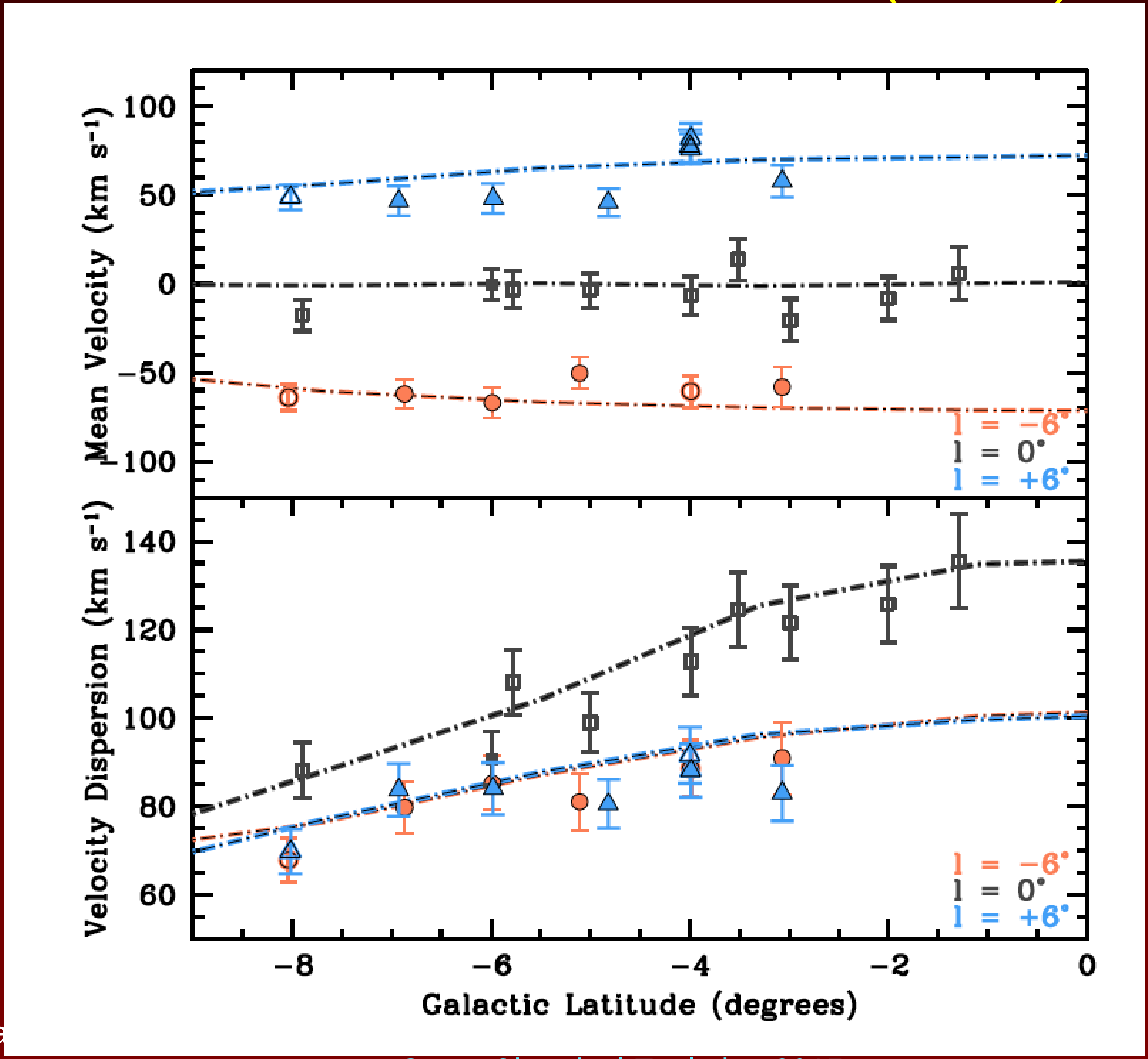


b=−4
b=−6
b=−8
l=−6
l=0
l=+6
V_{GC} (km/s)
400
200
0
−200
−400
−10
−5
0
5
10
Galactic Longitude (°)
−2
−4
−6
−8
Galactic Latitude (°)

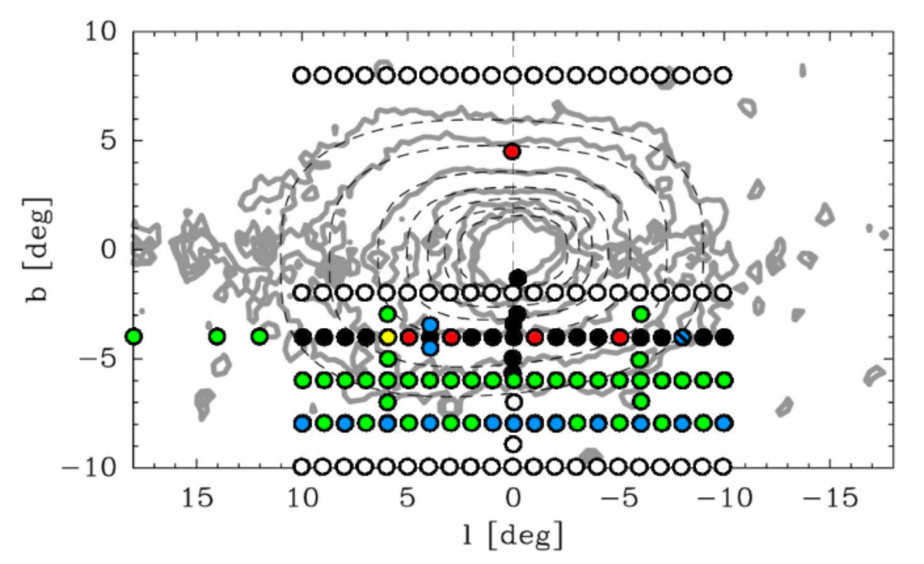
Major Axis showing cylindrical rotation (Fit is Shen et al. 2010)

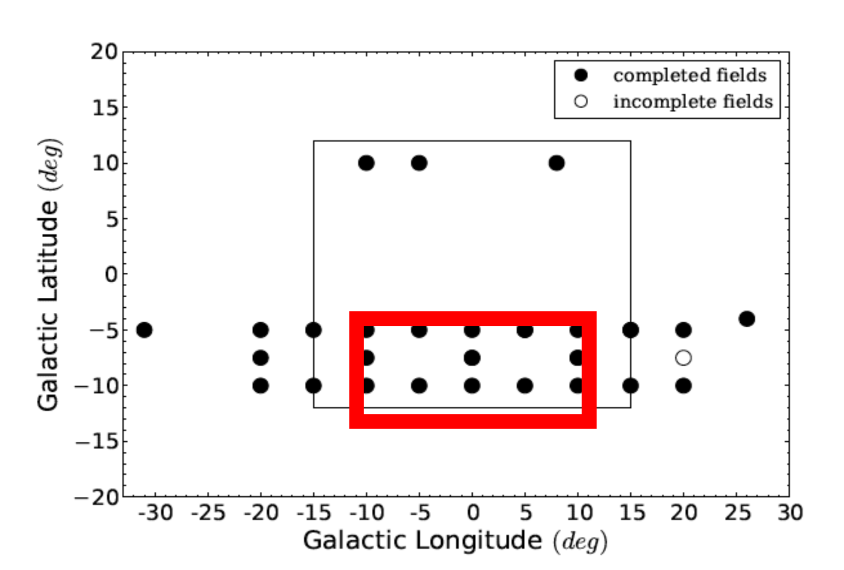


Minor axis with Shen et al. (2010) fit



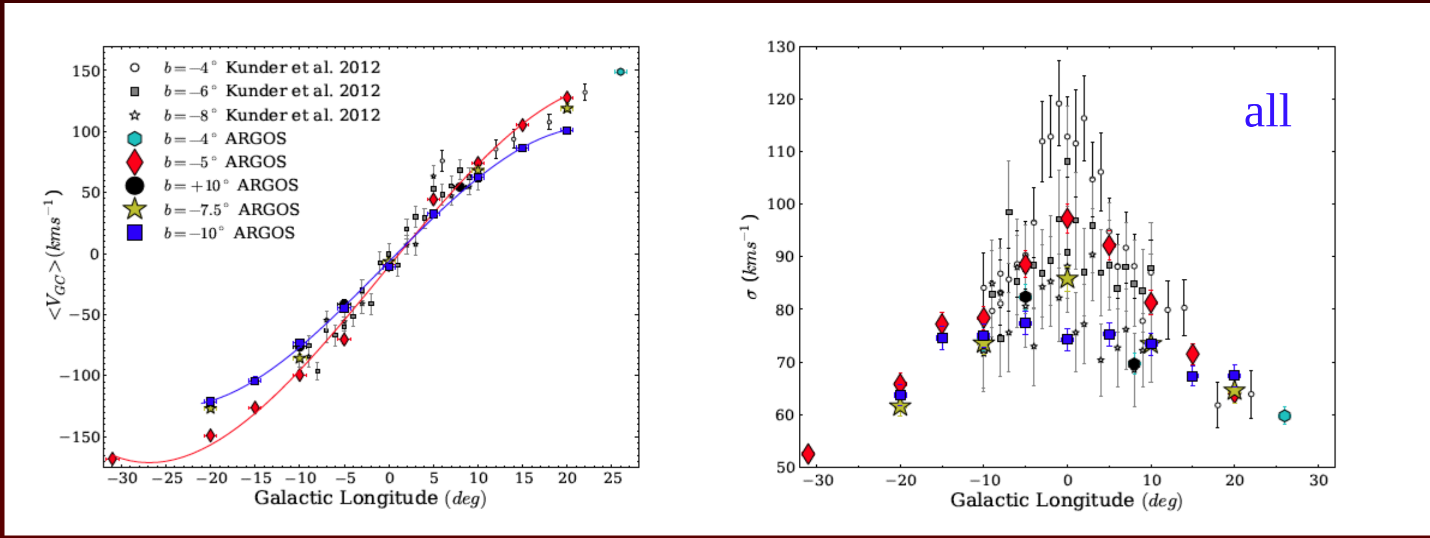
BRAVA vs ARGOS (Ness+ 13)

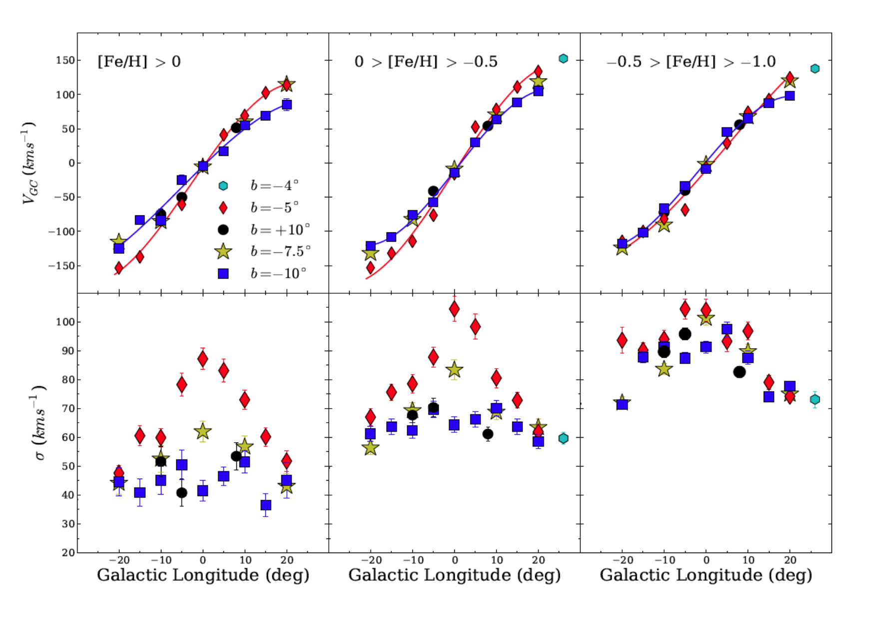


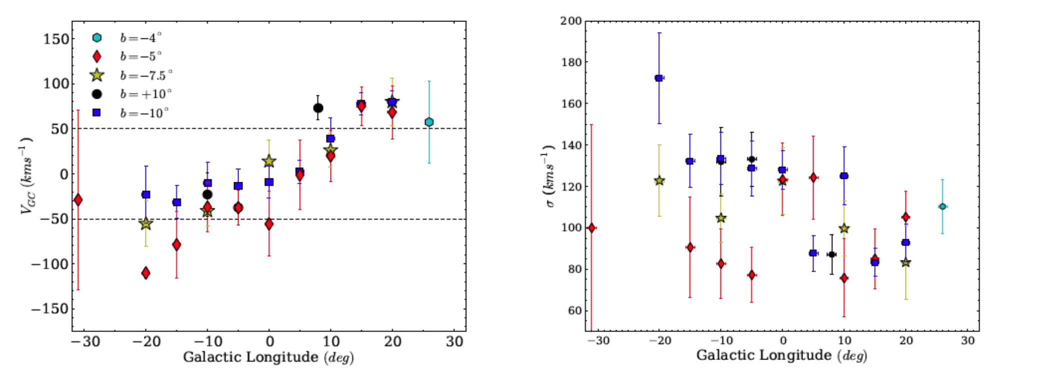


At |l|>10 are stars bulge or disk members?

ARGOS





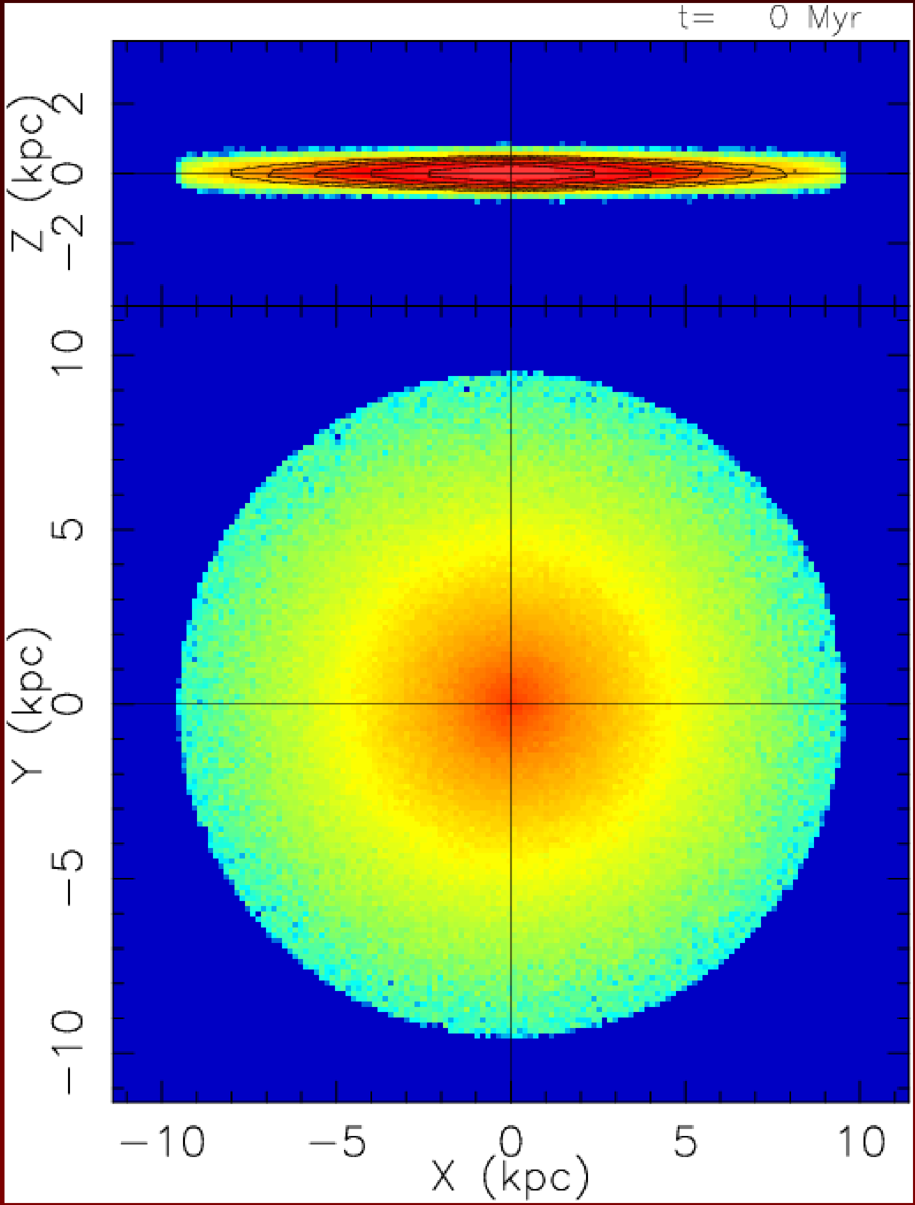


Metal Poor 5% likely inner halo members

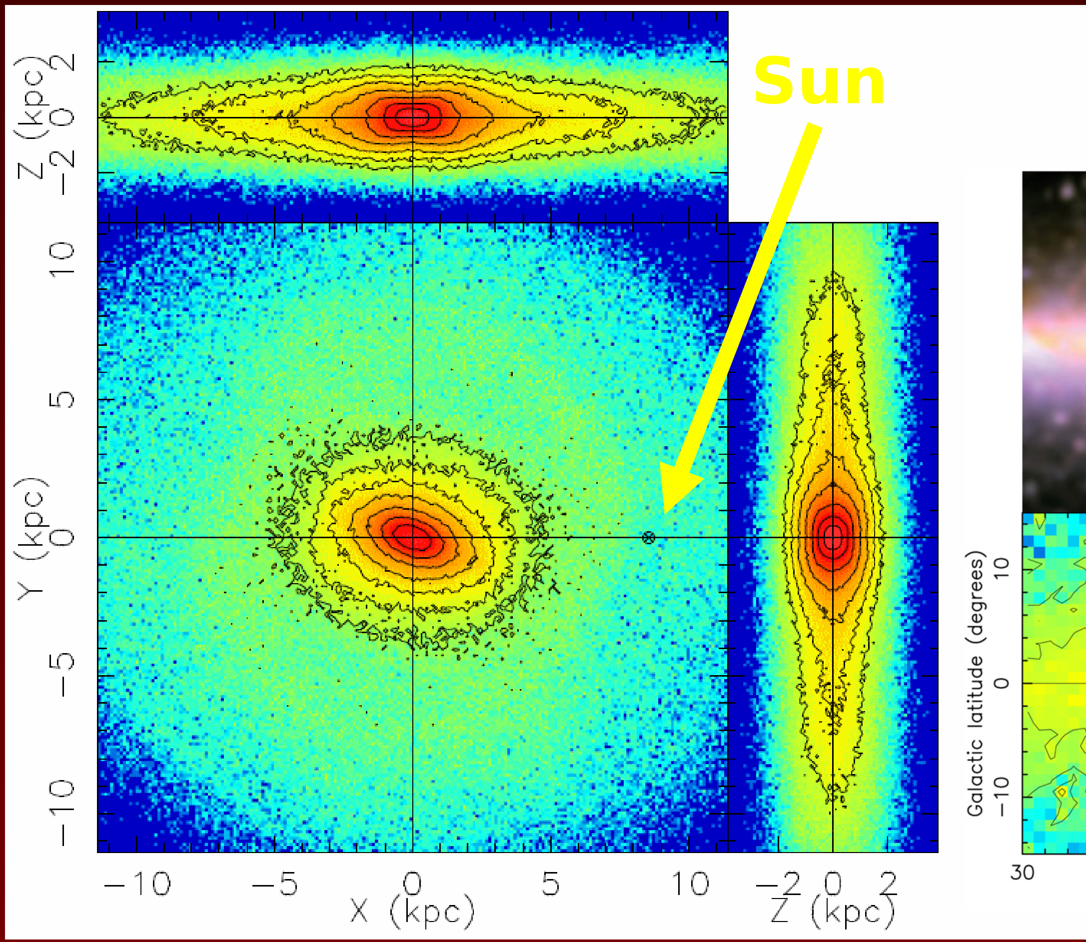
Modeling the Milky Way Bulge

Shen, Rich et al. 2010

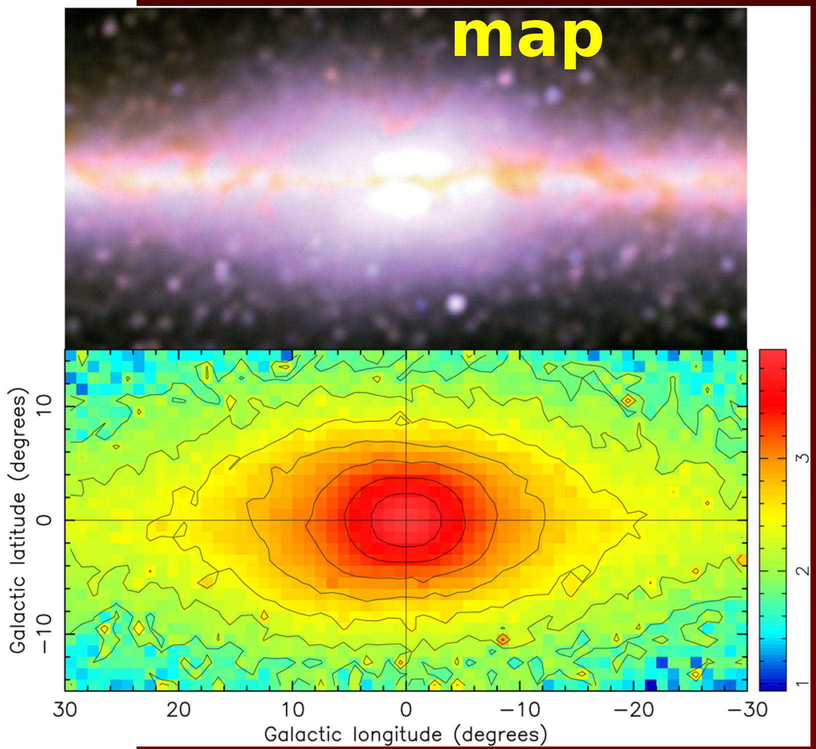
- A simple model of the Galactic bulge matches the BRAVA data extremely well in almost all aspects:
  - *b* = -4° major axis
  - *b* = -8° degree major axis
  - *l* = 0° degree minor axis
  - Surface density
  - **Shen, J., RMR, Kormendy** et al 2010, ApJL



Modeling the Milky Way Bulge ---
Surface Brightness Map

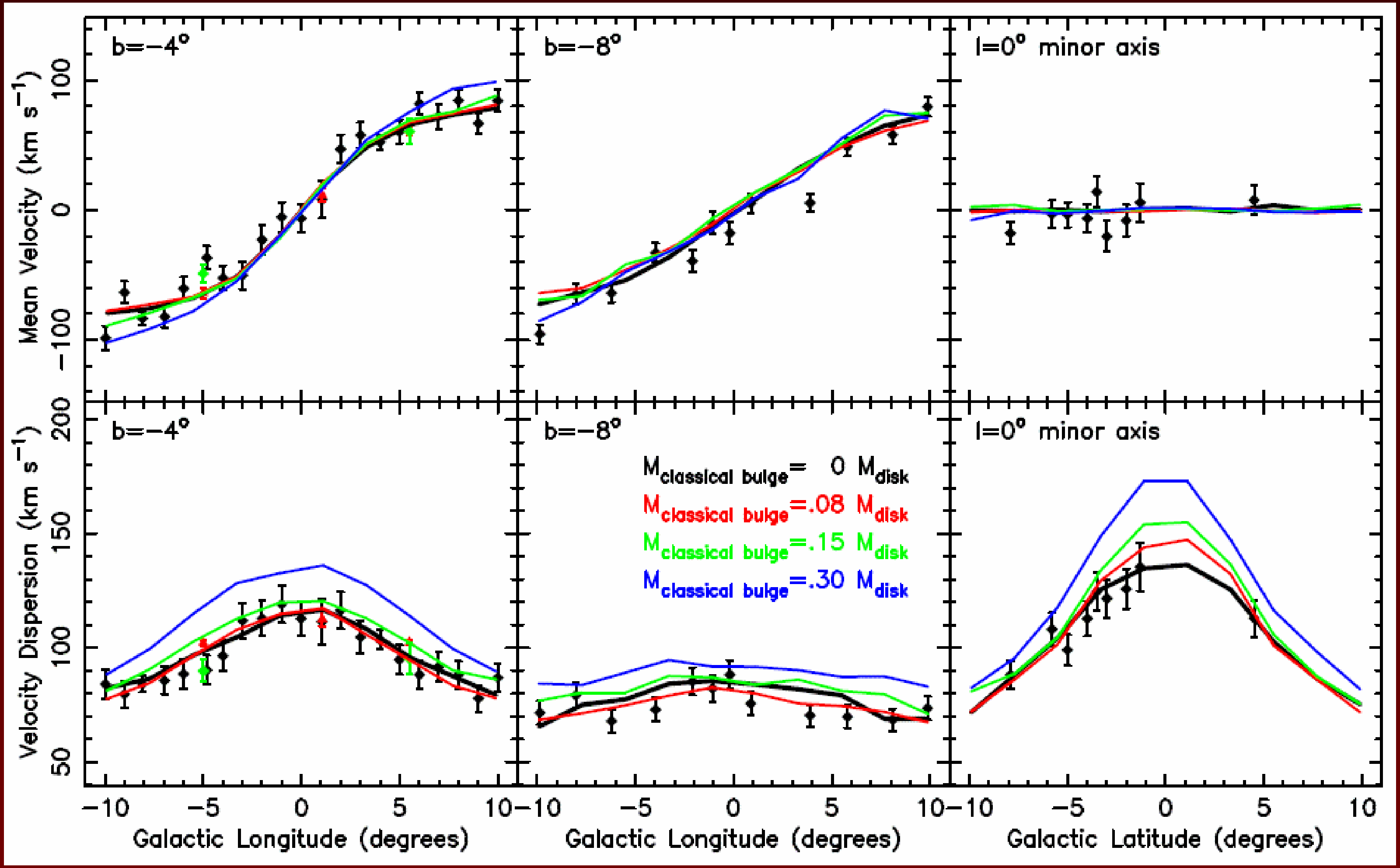


DIRBE Composite map



- The bar angle from kinematic constraint is about ~ 20^o
- The bar’s axial ratio is about 0.5 to 0.6, and its half-length is ~4kpc

A Significant Classical Bulge is Excluded

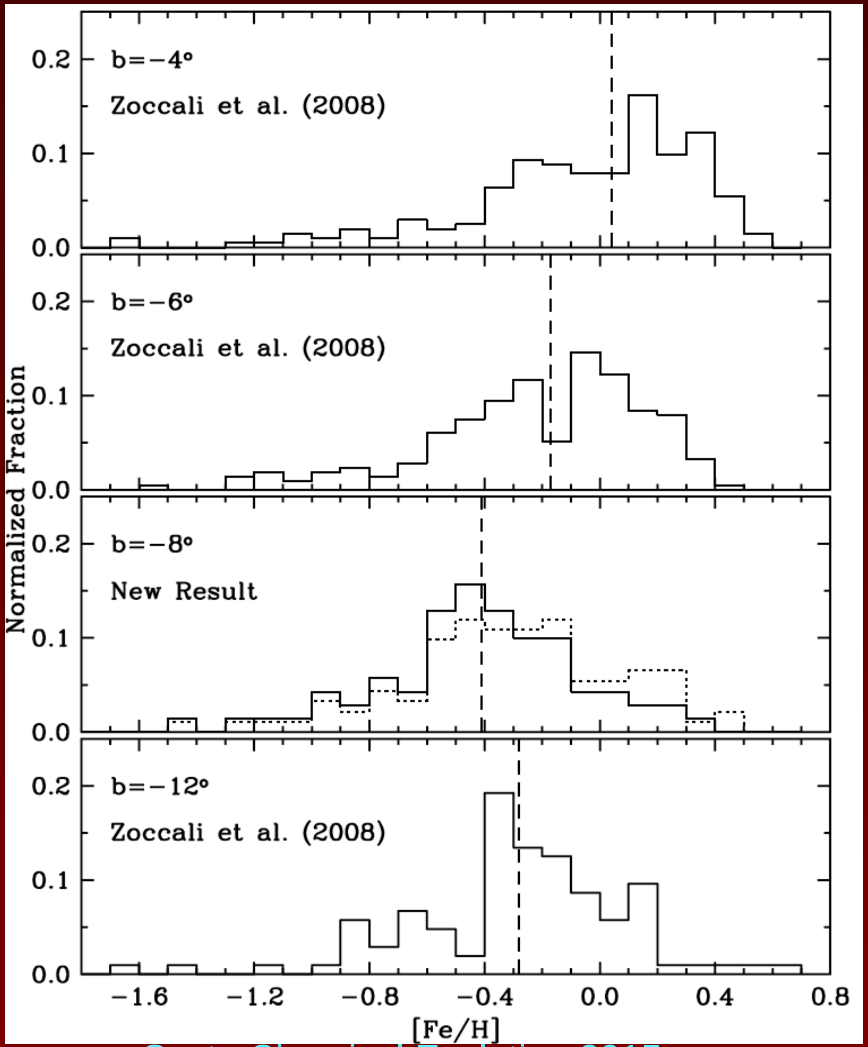


The data excludes a pre-existing classical bulge with mass >~ 10% Mdisk

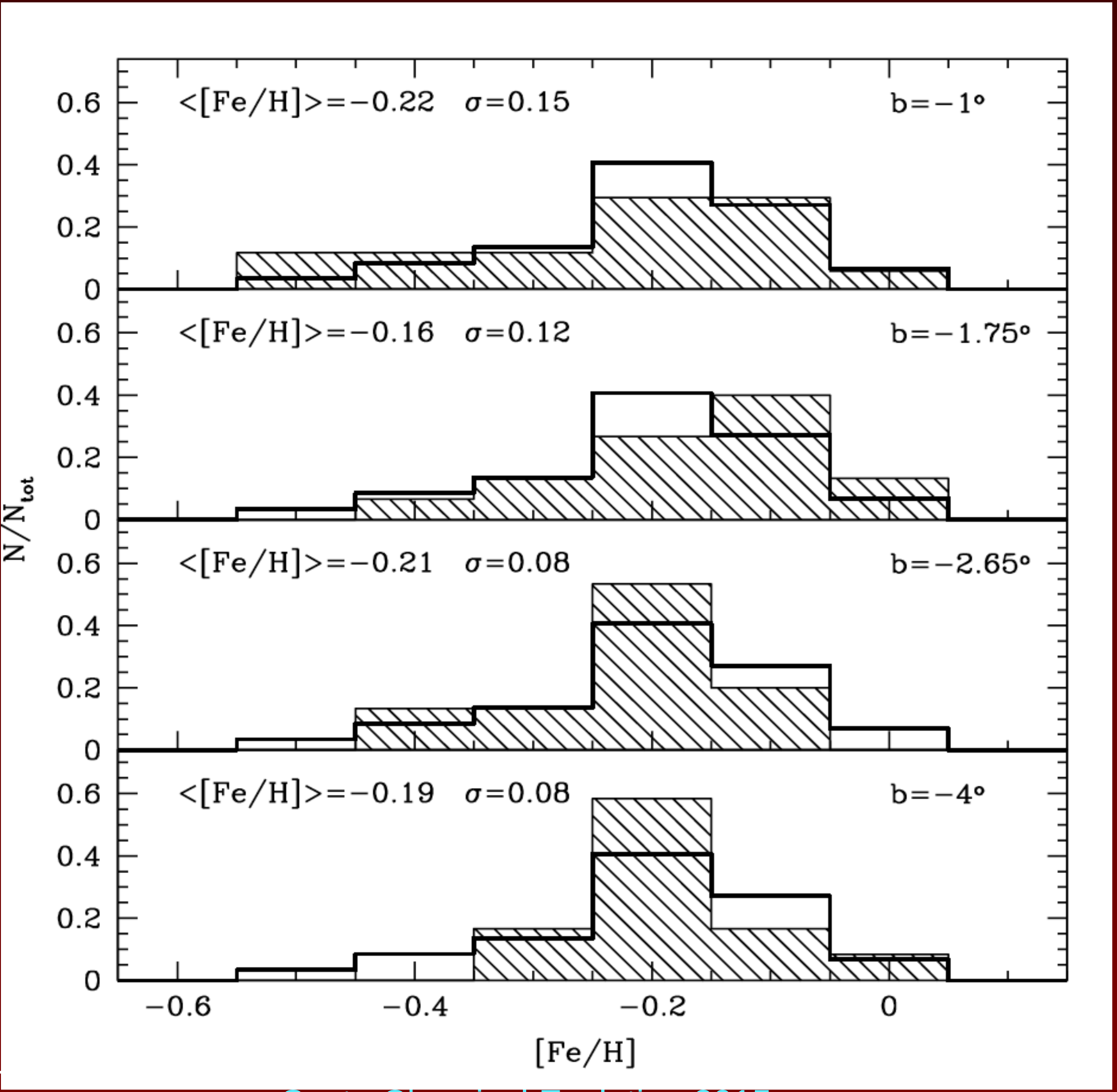
A Problem: Abundance gradient in the outer bulge

Cylindrical rotation a characteristic of pseudobulges, but should not exhibit abundance gradient, since buckling models are not dissipative. Location on Binney plot similar to NGC 4565.

Zoccali et al. 2008 with Johnson et al. 2011 for -8 deg

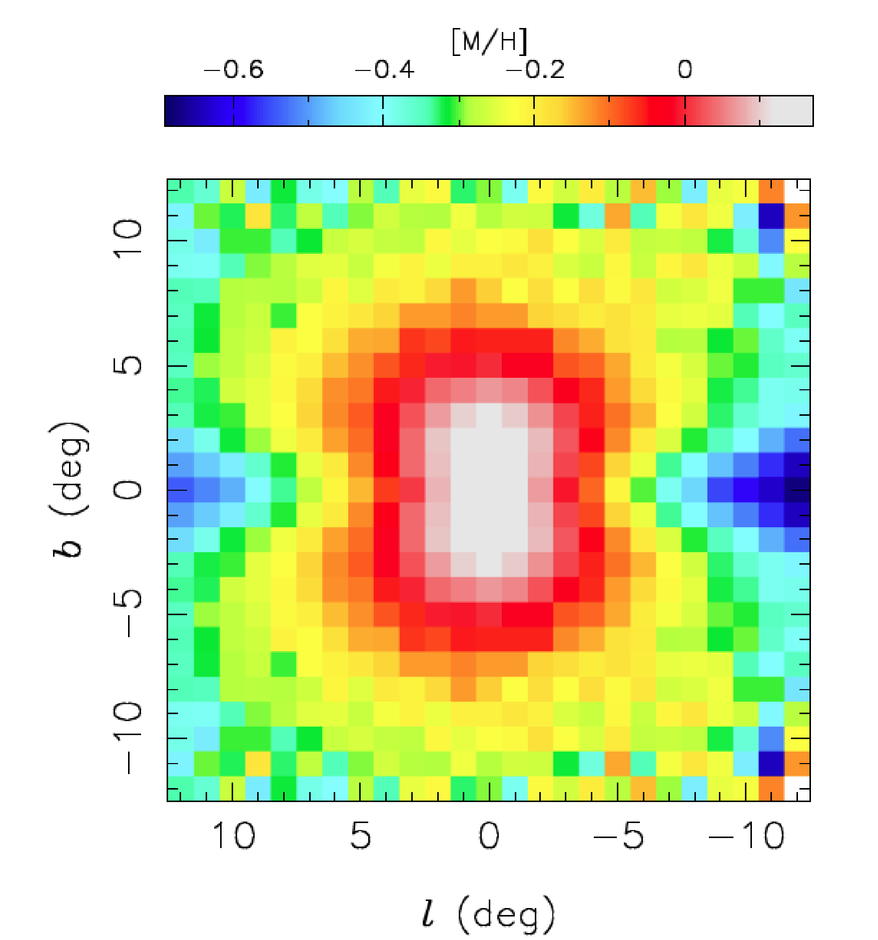


But IR spectra find no abundance gradient <4°
(Rich, Origlia, Valenti; 2011)

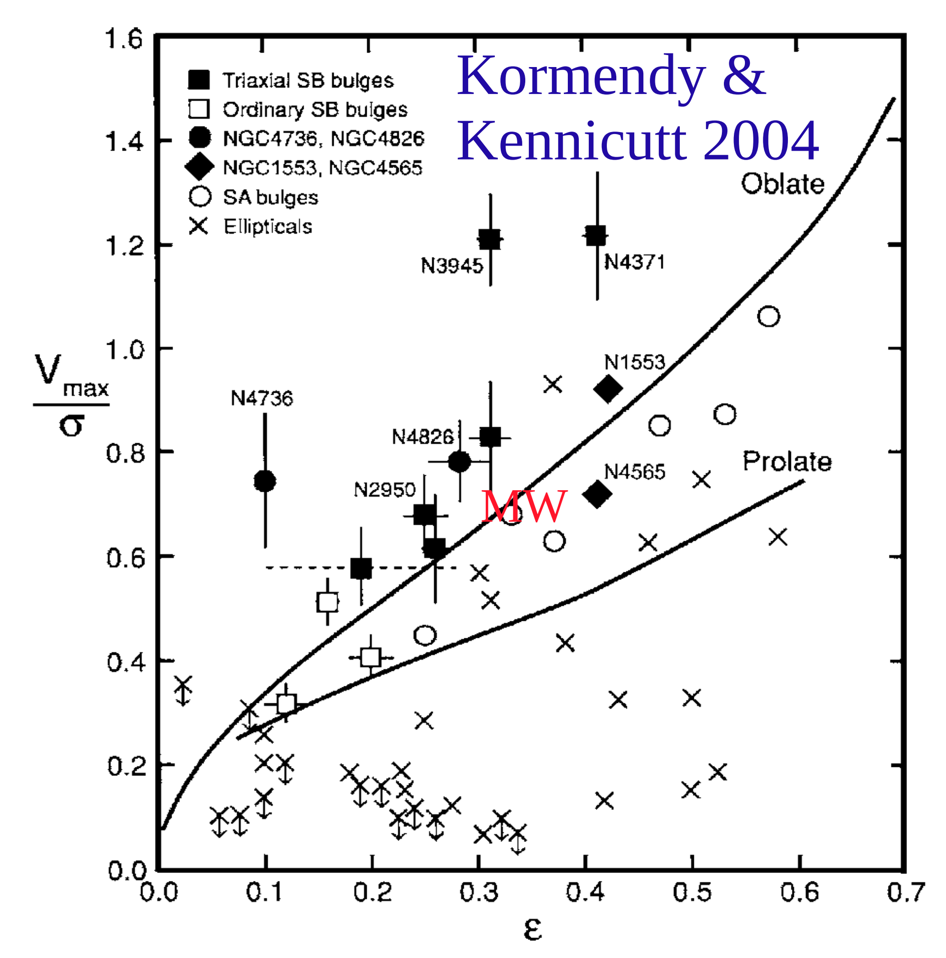


Abundance Gradient Problem solved?

Martinez-Valpuesta & Gerhard (2013) show that an N-body disk with a preexisting radial gradient can buckle and produce bar with strong vertical gradient. Loosely bound metal poor stars migrate to greater vertical distance. New finding actually overturns earlier work in the subjct.



The Milky Way shares much in common with NGC 4565 (peanut bulge, abudance gradient) BRAVA places Milky Way on Binney plot.



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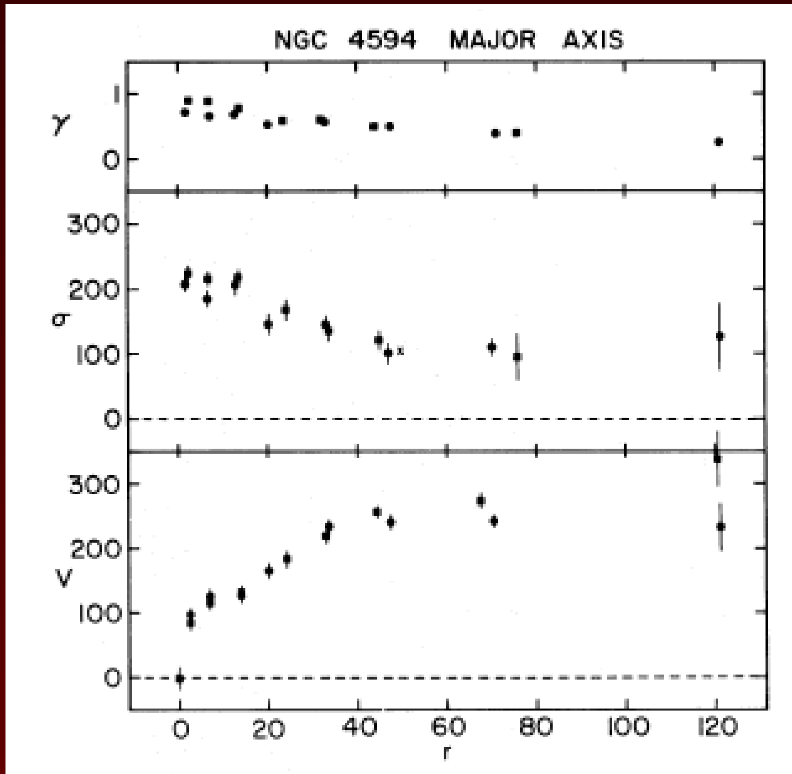
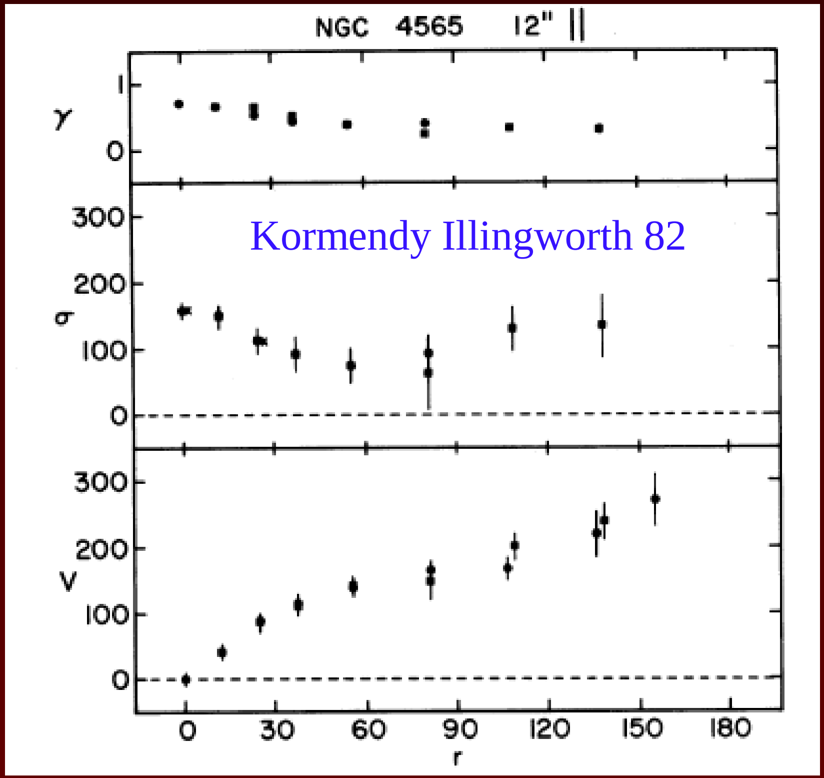
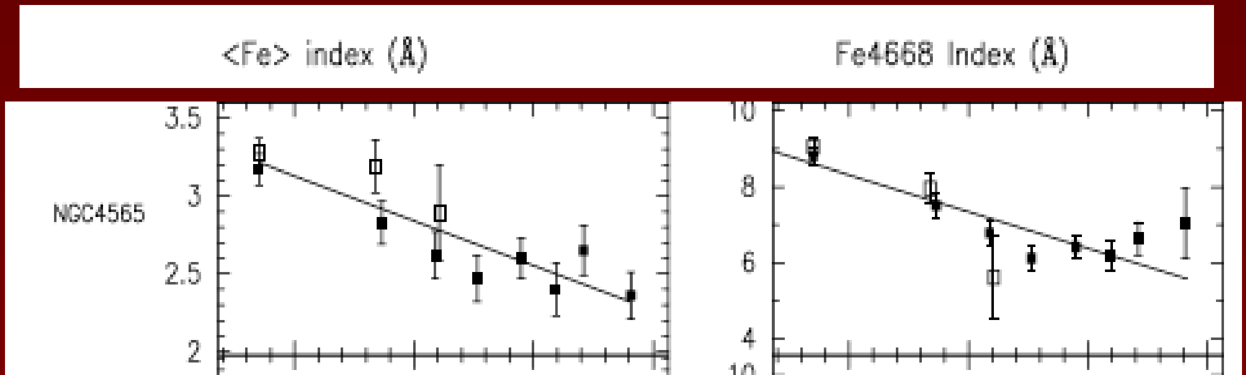




Proctor et al. 00



NGC 4565 has a boxy pseudobulge, cylindrical rotation like in the Milky Way bulge, and has a steep abundance gradient in the z direction.

Winds may be important

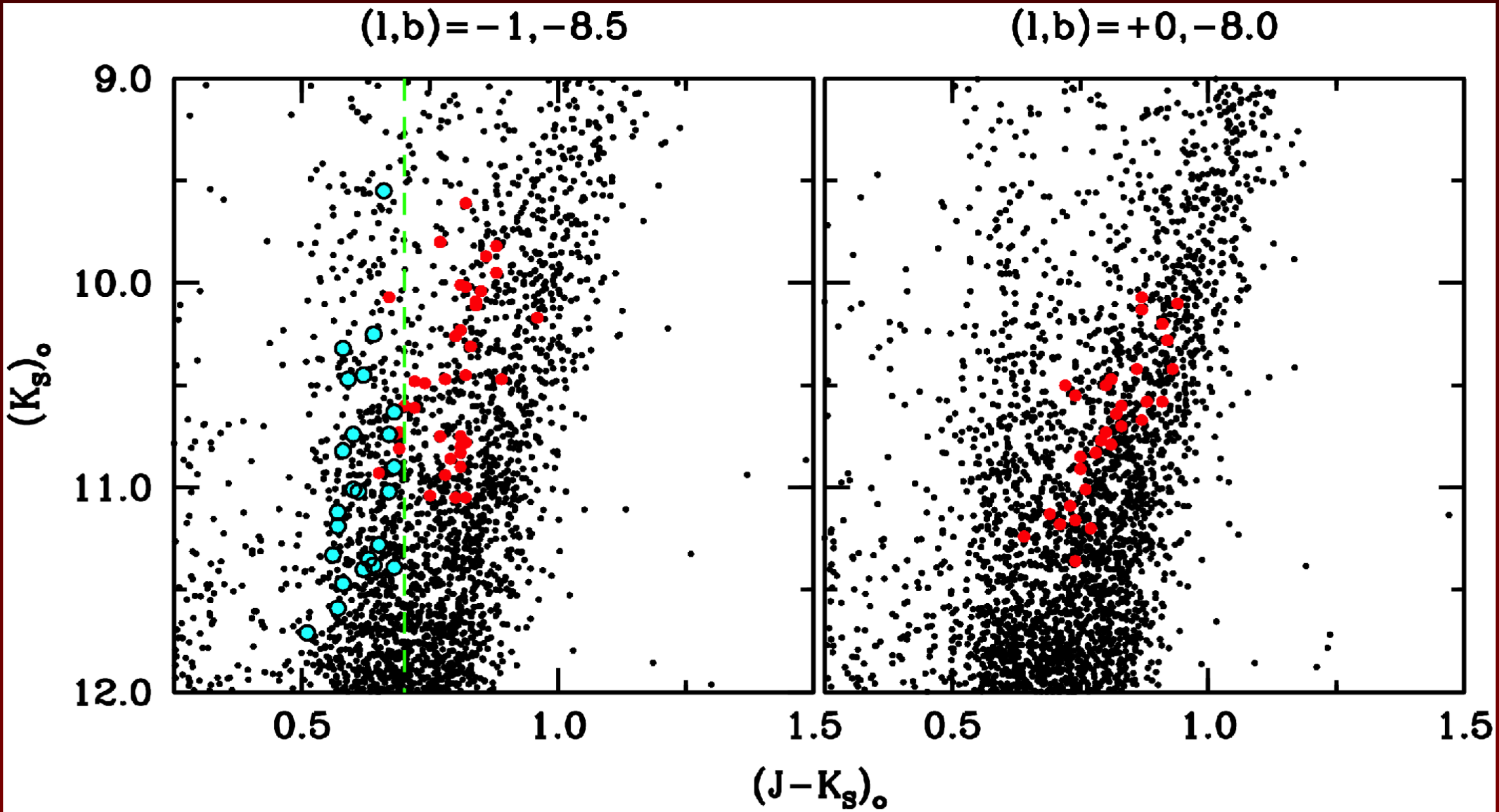
BRAVA Main Conclusions

- BRAVA is a radial velocity survey of Galactic bulge M giants
- Fully public dataset with spectra at http://irsa.ipac.caltech.edu/ as well as at UCLA: http://brava.astro.ucla.edu/.
- Survey to date has covered strips at b=-4, -6, -8, and the Southern minor axis
- Bulge rotation curve and radial velocity dispersion profile measured
- Departure from “solid body” rotation at b=-4
- Cylindrical rotation at -8
- No detection of cold streams
- Coadded datasets at b=-4, -8 are Gaussian with no evidence of dynamically independent sub populations

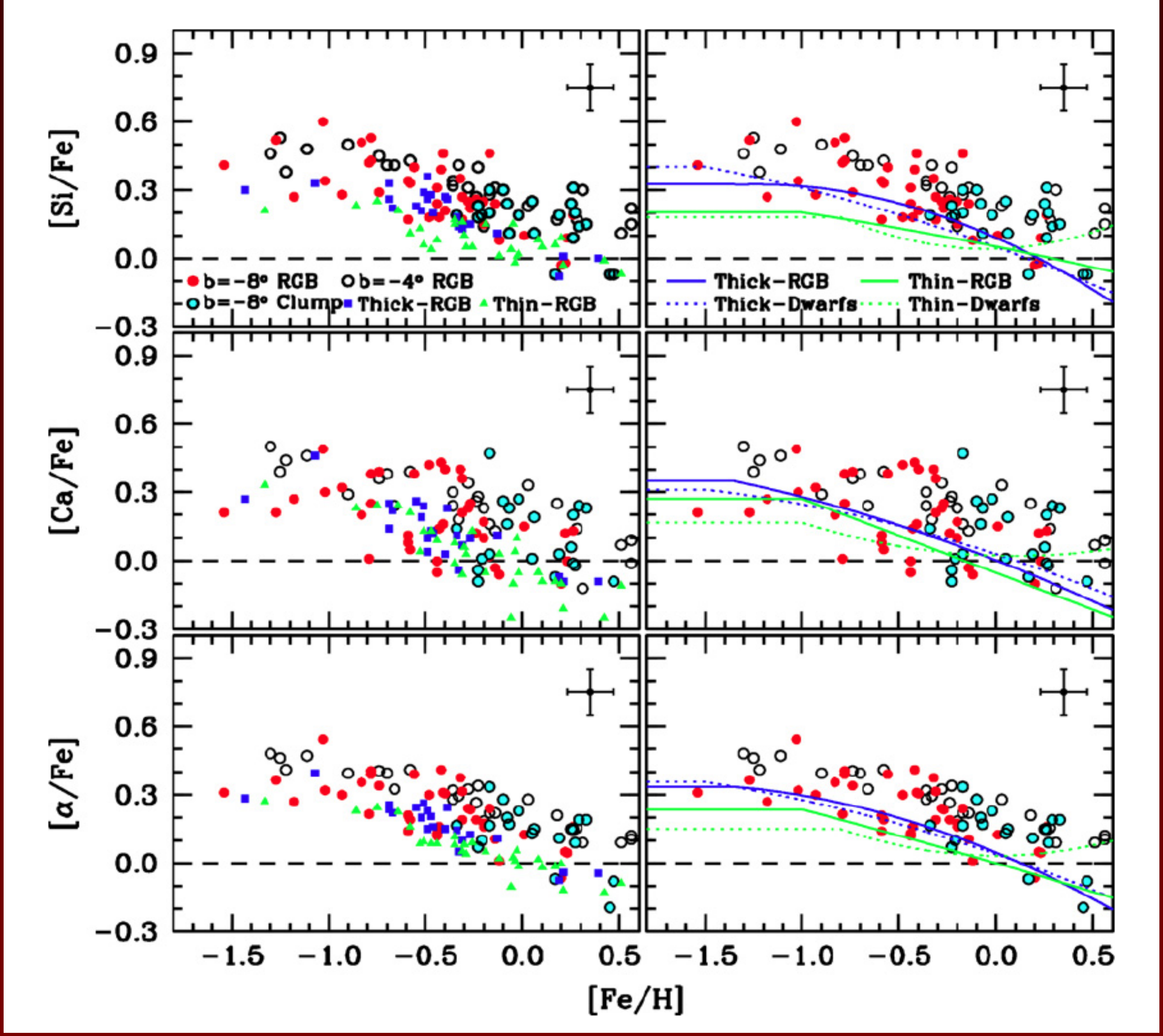
- Remarkable agreement with Shen et al. 2010 bar; “bulge”<10% Mdisk

-8° Field (Plaut's Field)

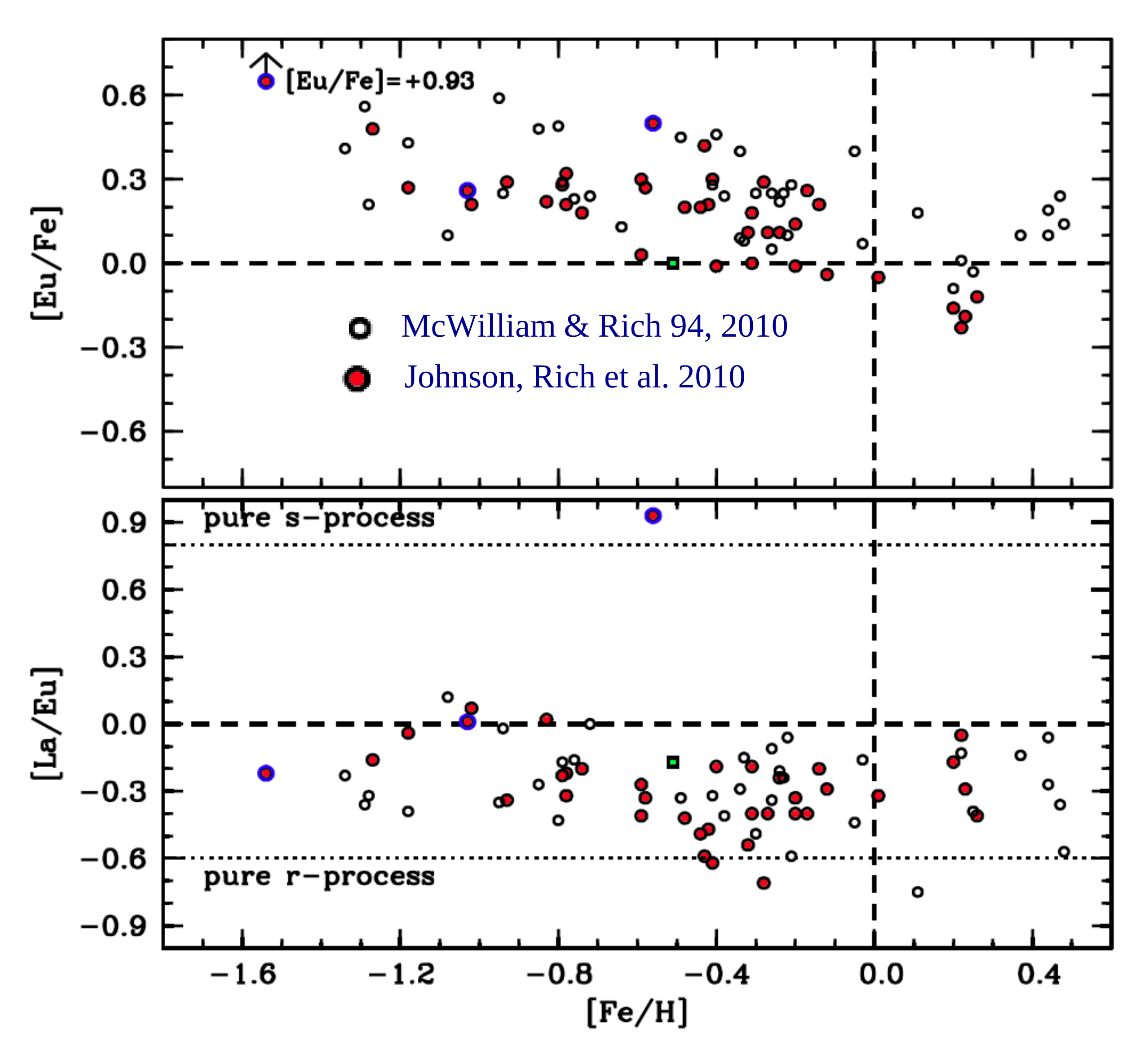
C. Johnson, Rich, Fulbright, Valenti, McWilliam (2011)
CTIO Hydra, 300 stars, 4 wavelength settings



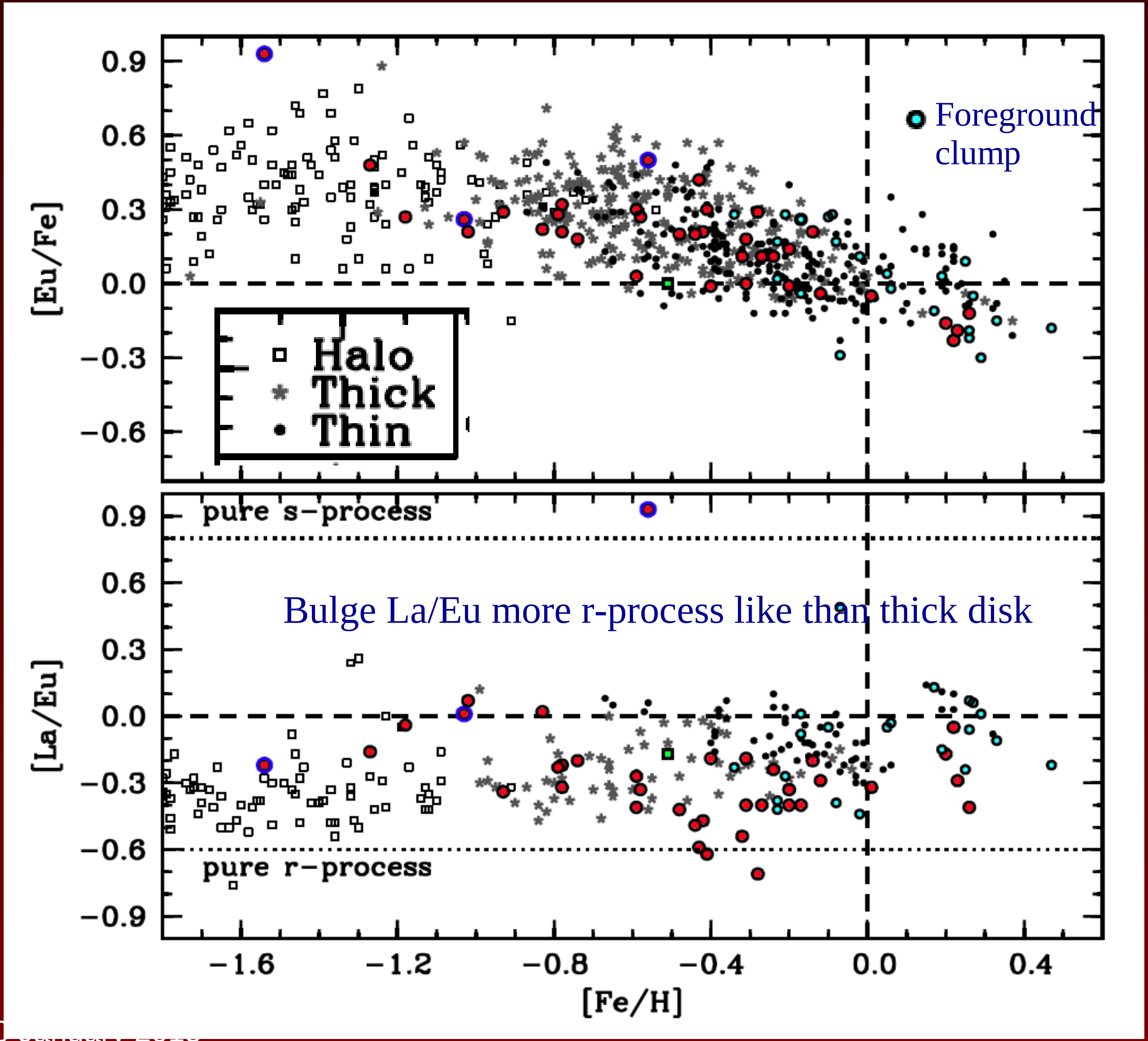
Johnson, Rich et al. 2010: alphas enhanced at -8° = 1kpc
First confirmation of high [alpha/Fe] over the whole bulge



McWilliam & Rich 2009; Johnson, Rich et al. 2012: -8° Field
Eu/Fe follows alpha-like trend; La/Eu r-process = rapid formation



Heavy element trends bulge is different from thick disk



Johnson, Rich et al. 2011

THE ASTROPHYSICAL JOURNAL LETTERS, 775:L27 (7pp), 2013 September 20 doi:10.1088/2041-8205/775

CHEMICAL ABUNDANCE ANALYSIS OF A NEUTRON-CAPTURE ENHANCED RED GIANT IN THE BULGE PLAUT FIELD

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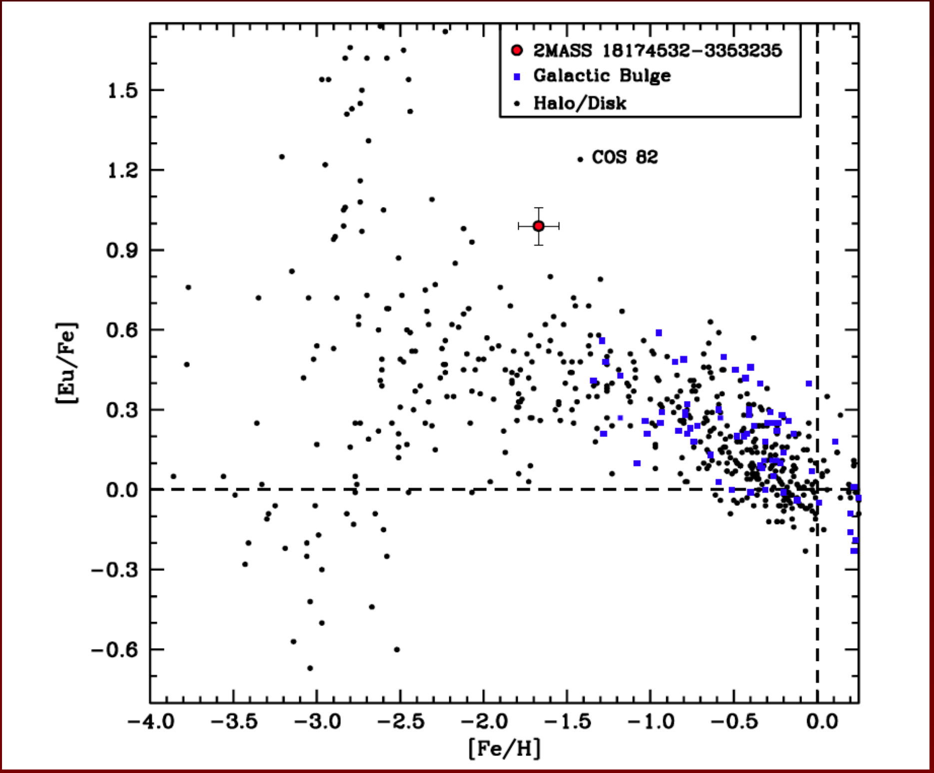
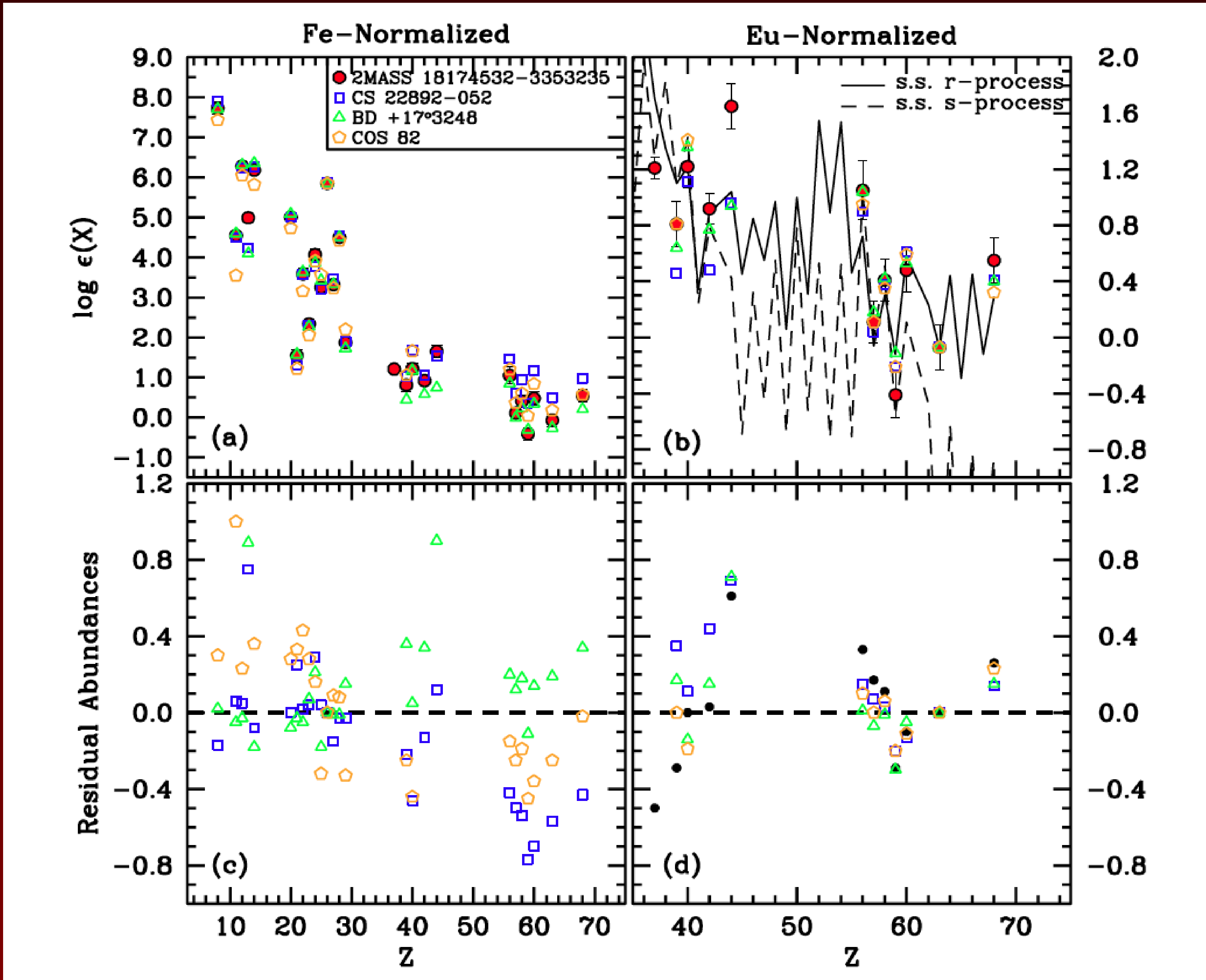
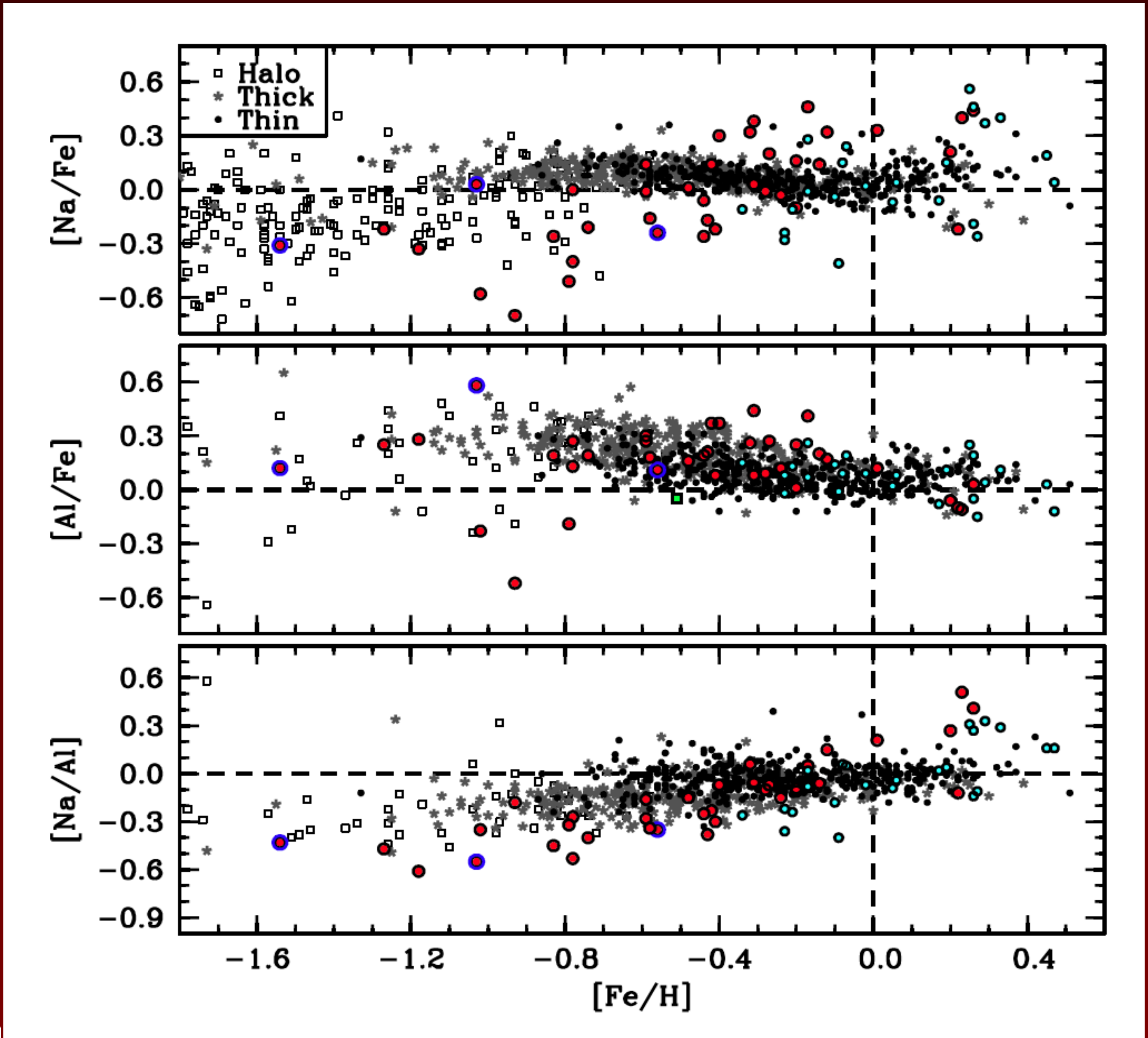
[Fe/H]=-1.67, [Eu/Fe]=+0.93 bulge giant : r-process pattern
Similar to COS 82 in the Umi dwarf spheroid (Aoki +2007) but α -enhanced





Fe−Normalized
Eu−Normalized
2MASS 18174532−3353235
CS 22892−052
BD +17°3248
COS 82
s.s. r−process
s.s. s−process
log ε(X)
Residual Abundances
(a)
(b)
(c)
(d)
Z
Z

[Na/Fe] in bulge distinct from thick disk



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doi:10.1088/0004-6256/148/4/67

LIGHT, ALPHA, AND Fe-PEAK ELEMENT ABUNDANCES IN THE GALACTIC BULGE

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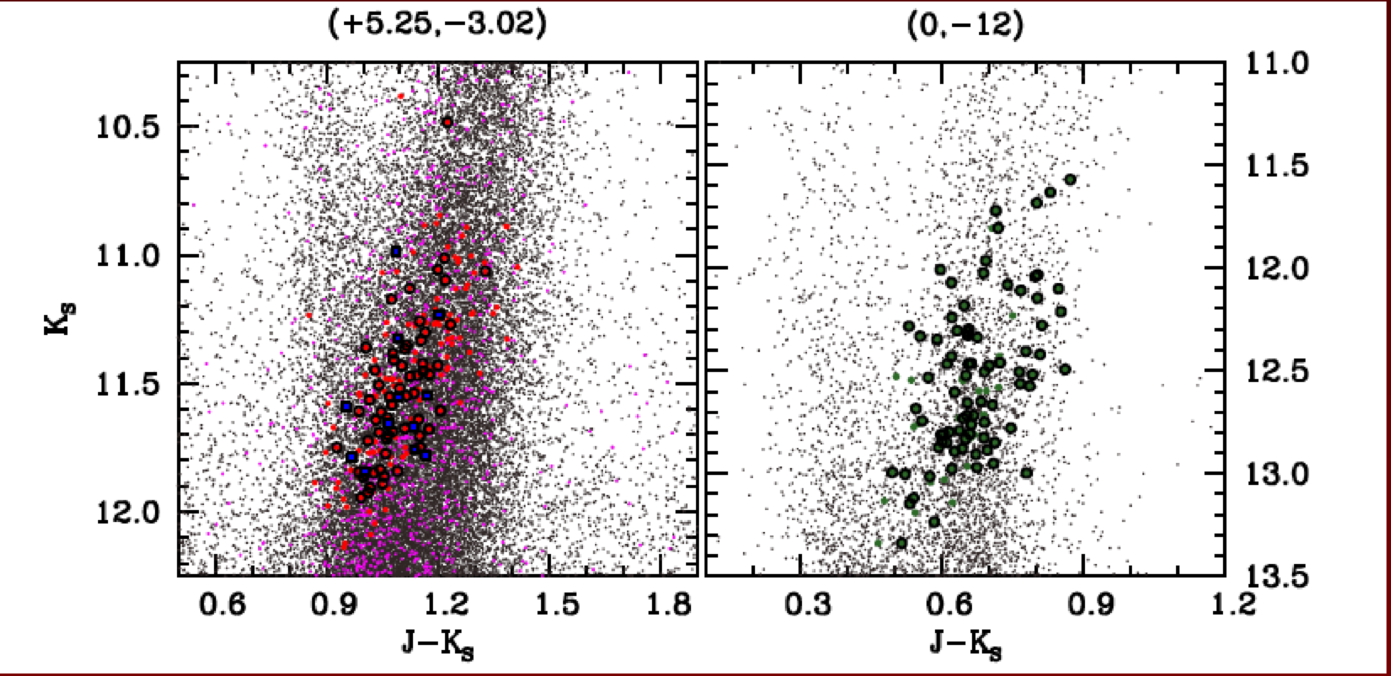
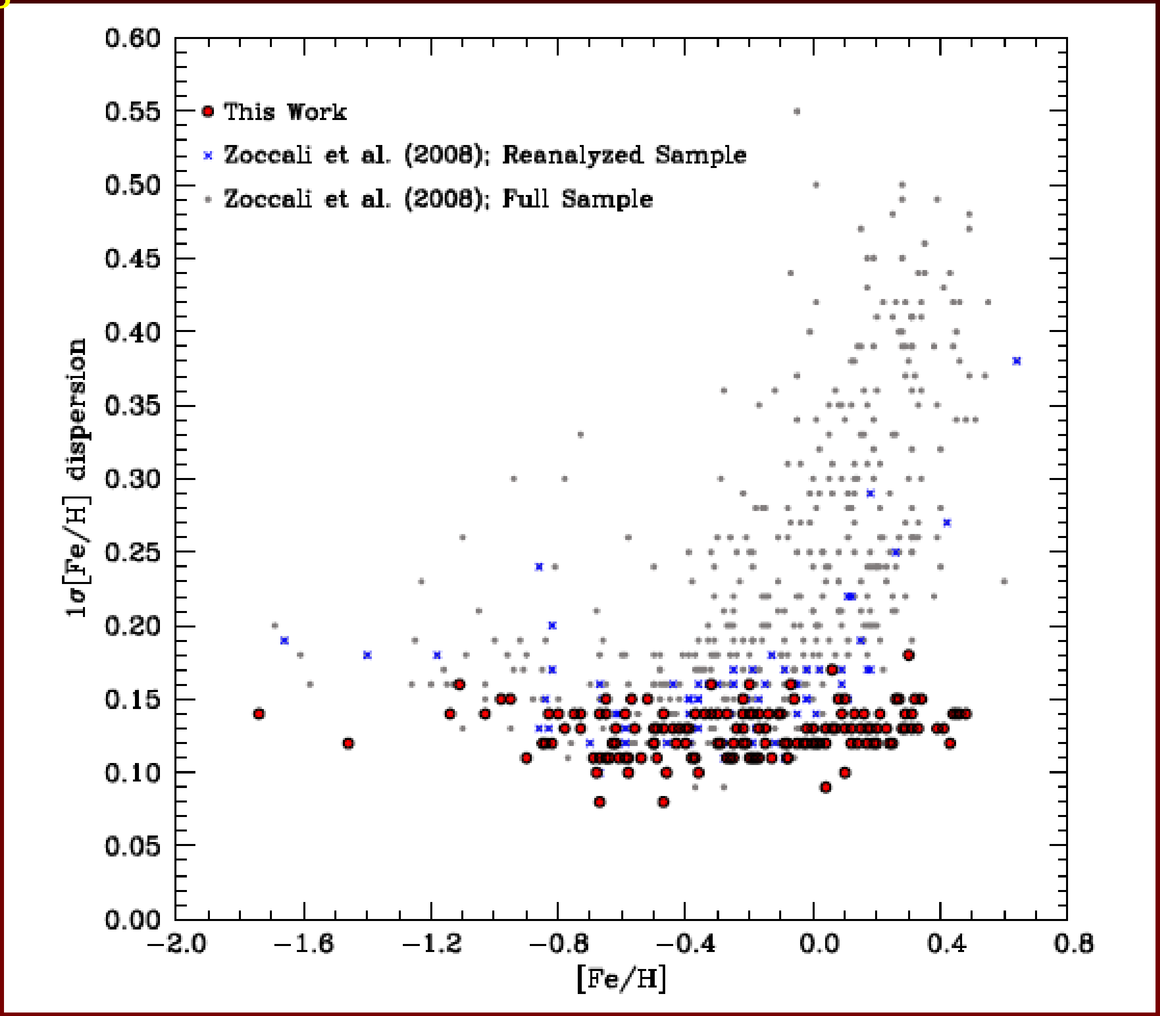
VLT Archival Data in two bulge fields

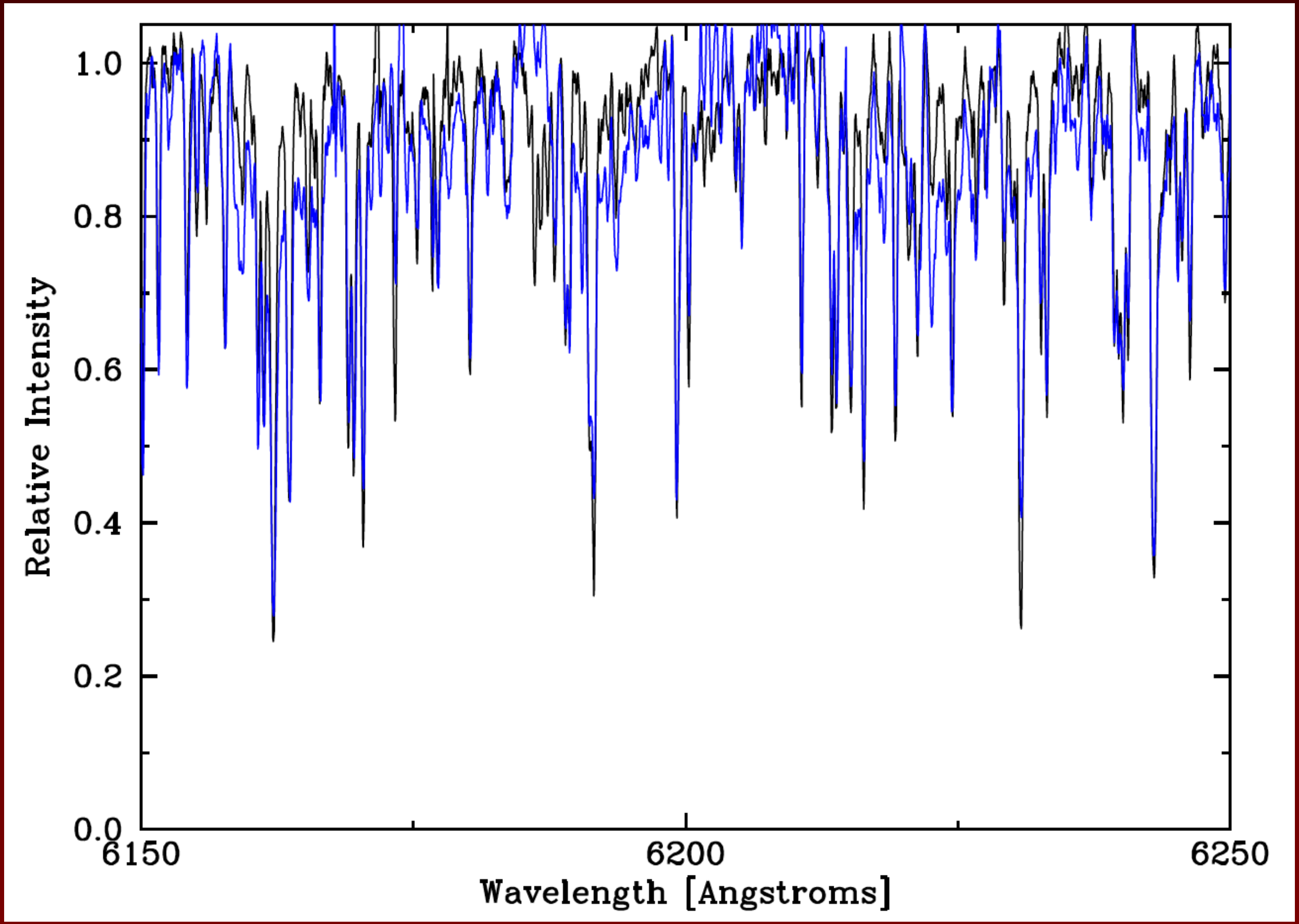


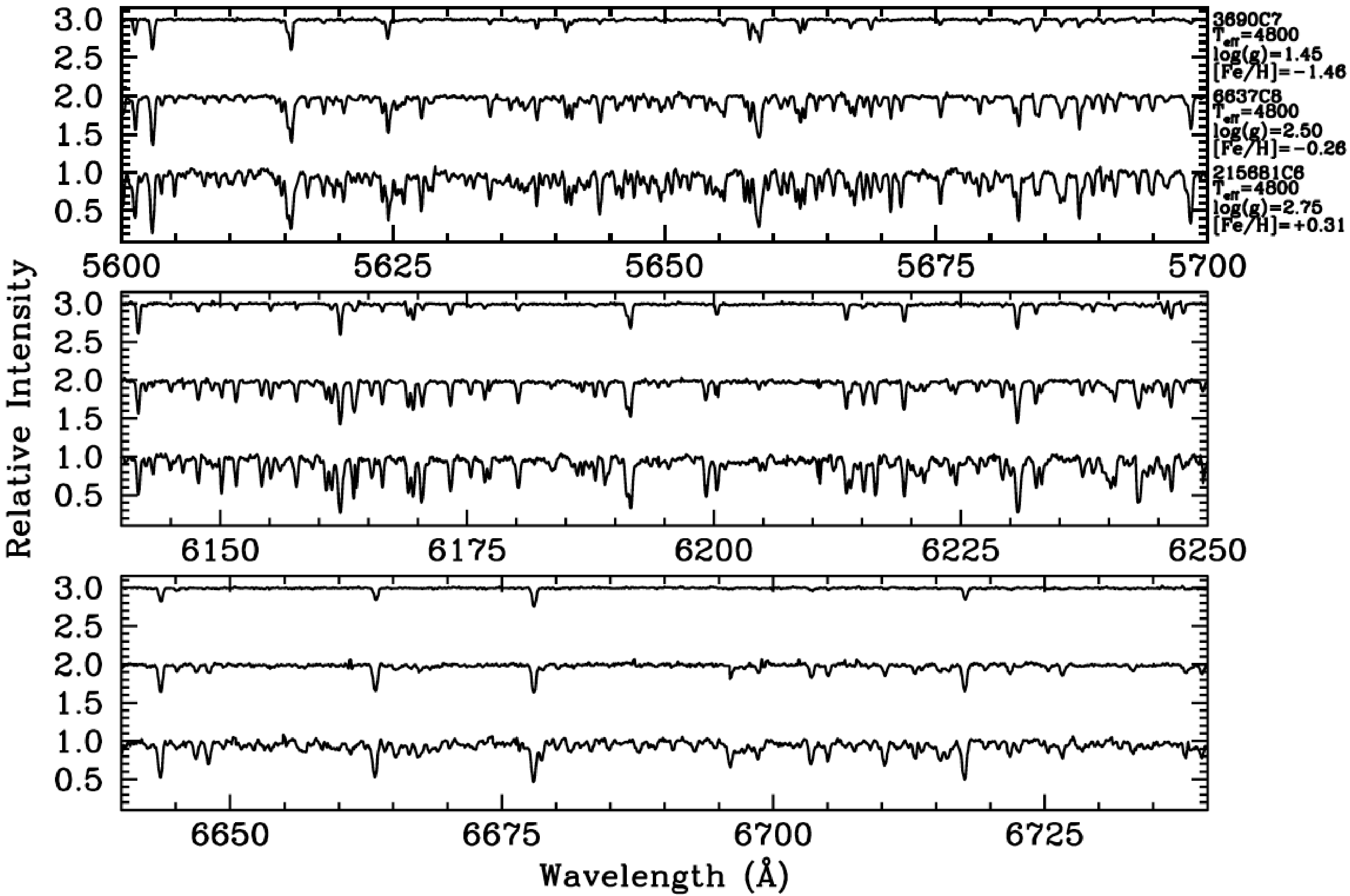
20 January 2015

Early work with FLAMES used daospec; serious errors at metal rich end; stars too cool to measure. Automated reductions are risky for cool metal rich stars



Both stars have 4200K, [Fe/H]=0.1
Blue spec heavily TiO contaminated





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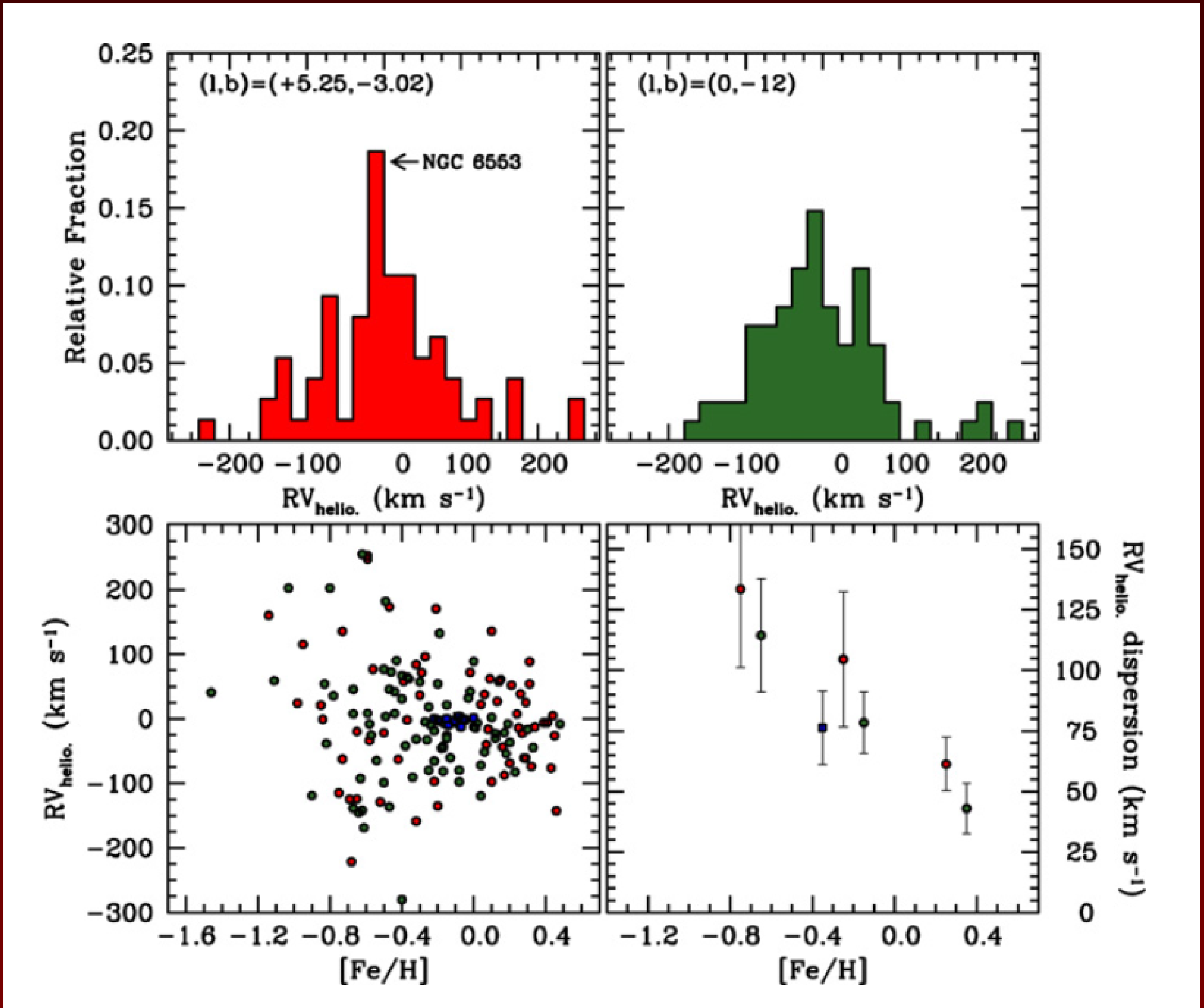
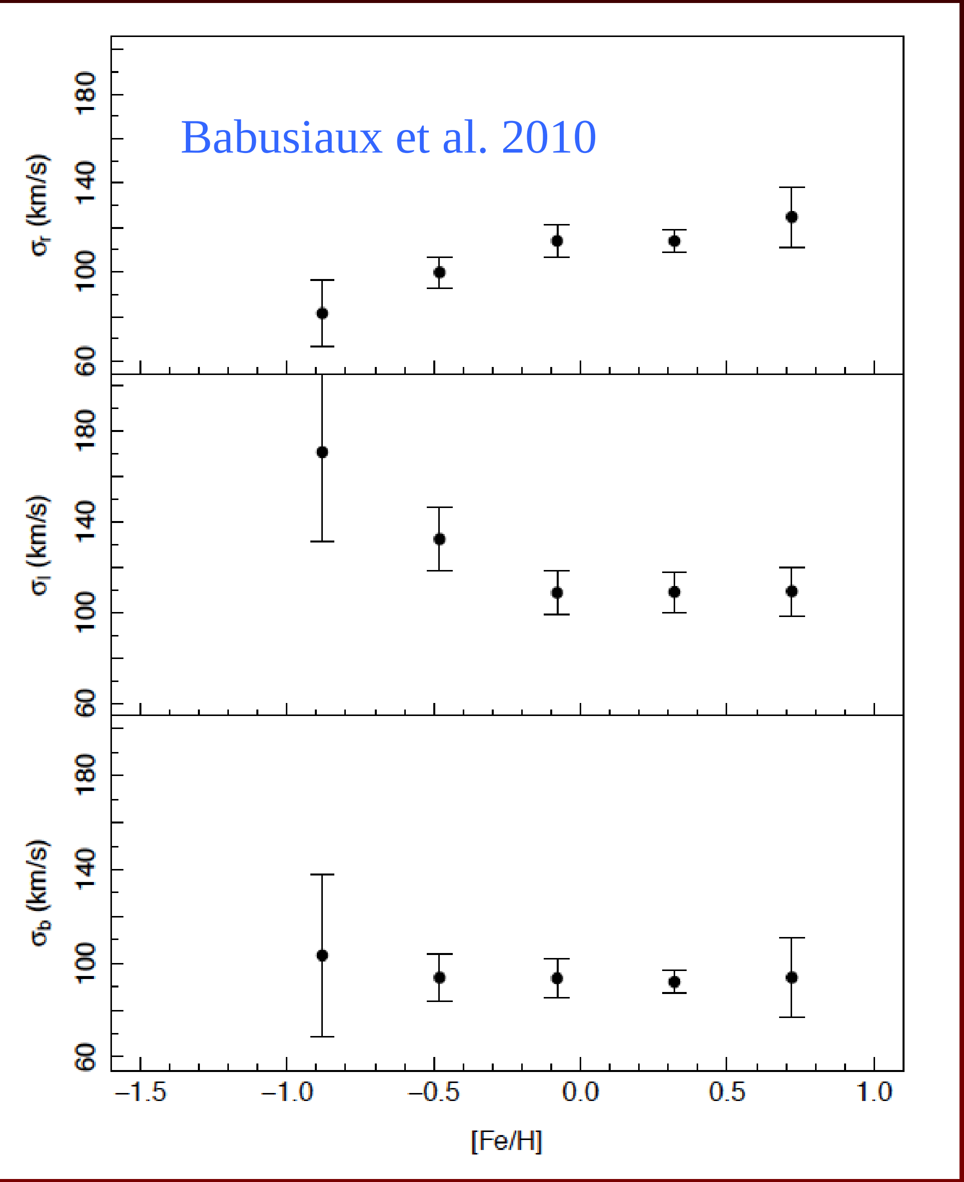
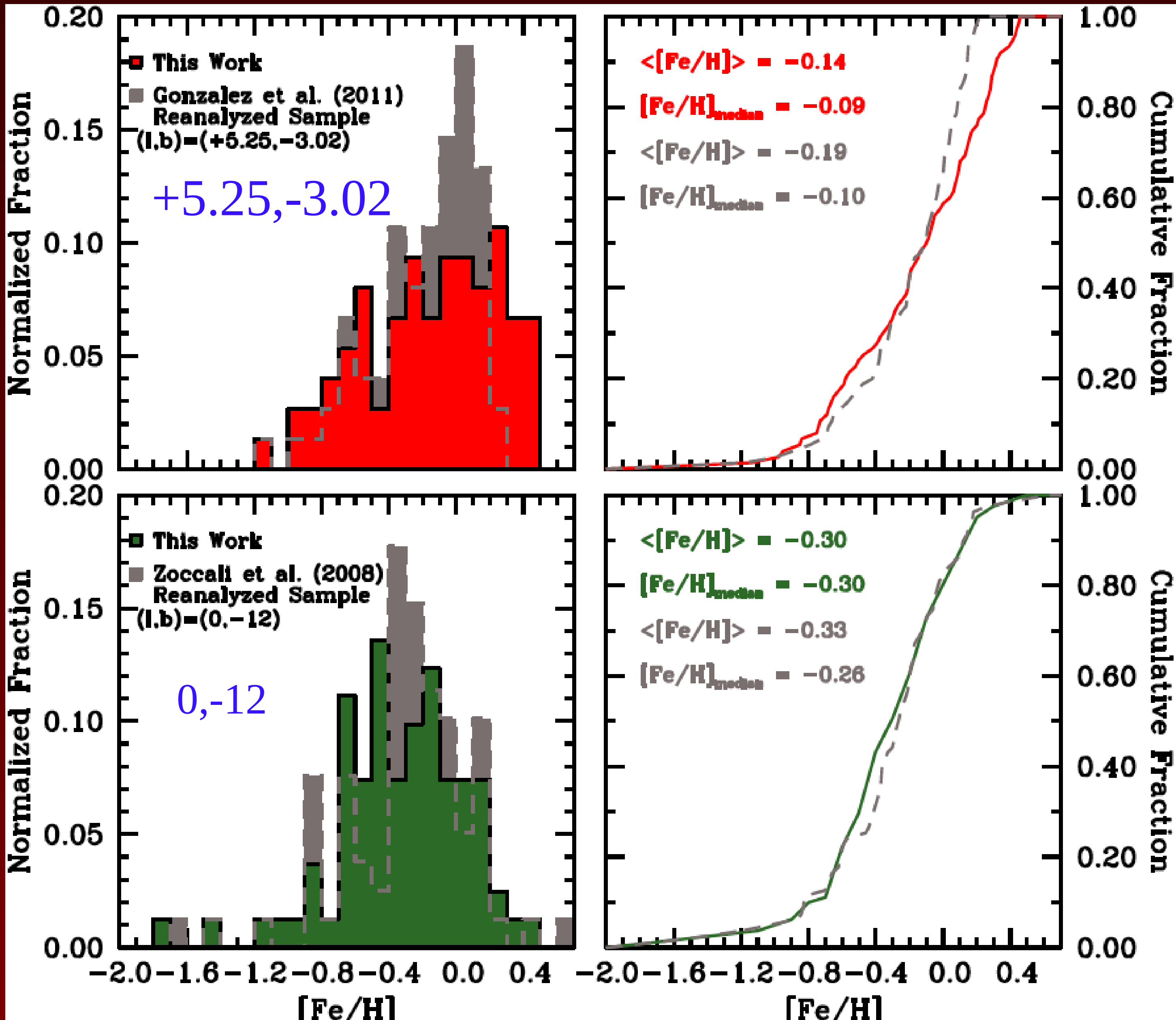
Strong sigma-Fe/H correlation

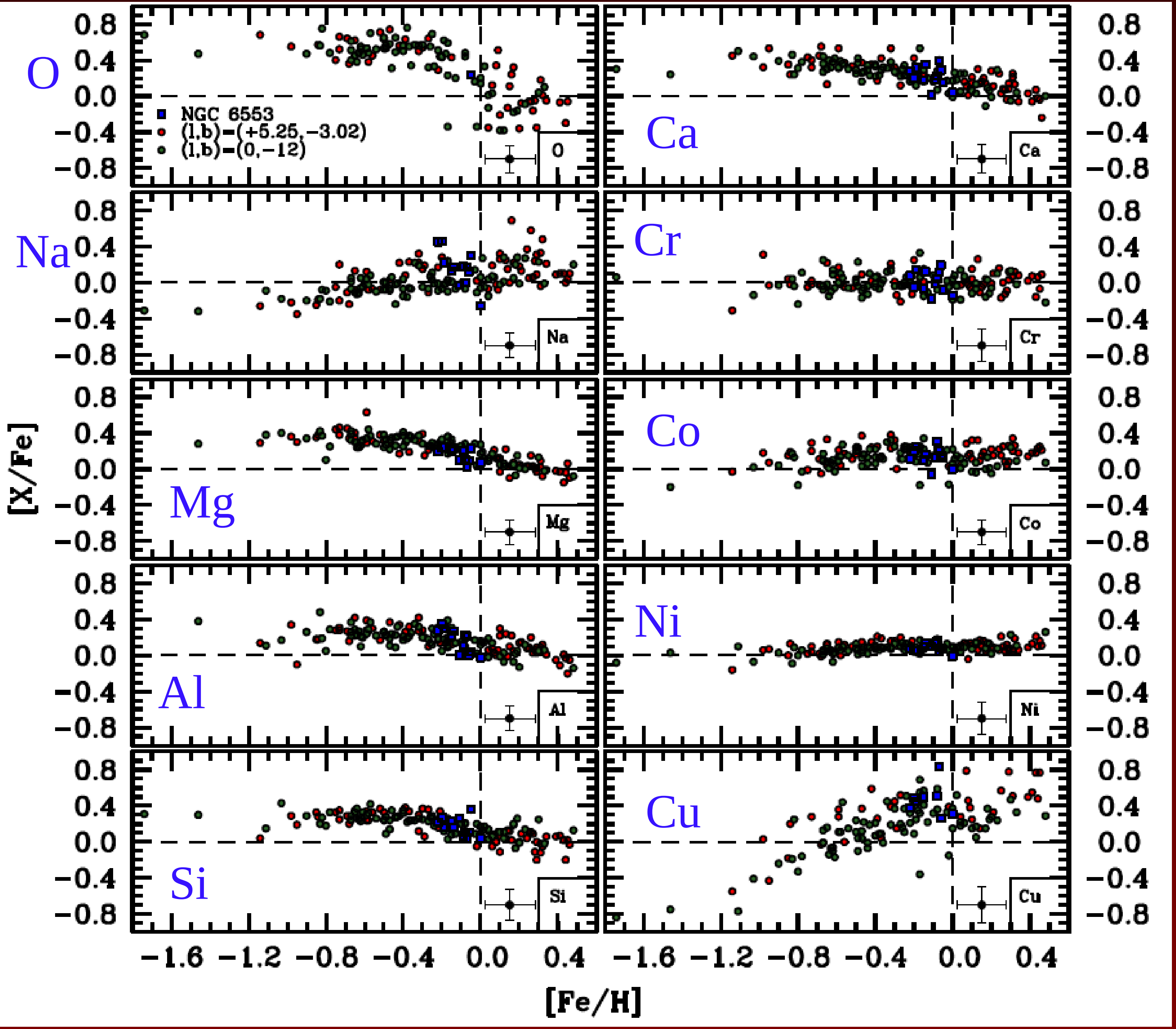


Still no confirmation of Babusiaux et al. (2010) – increased sigma with [Fe/H]

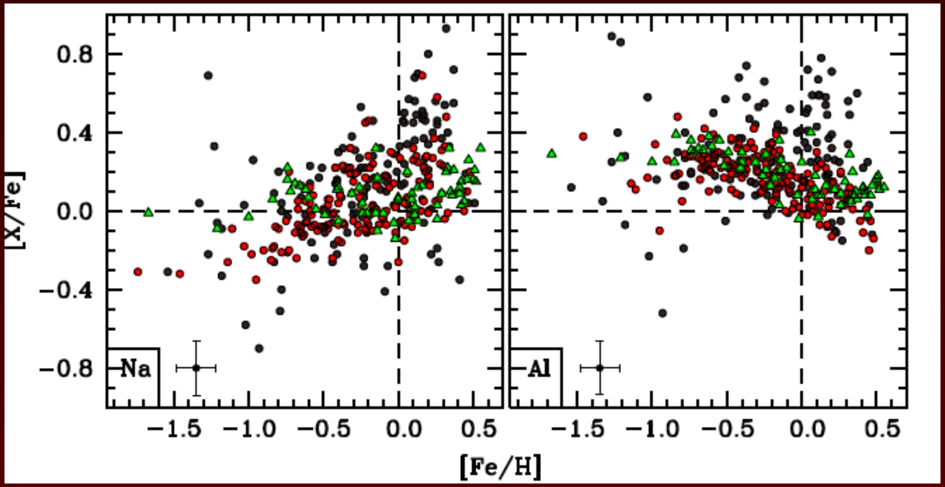


New techniques derive higher [Fe/H] at high end



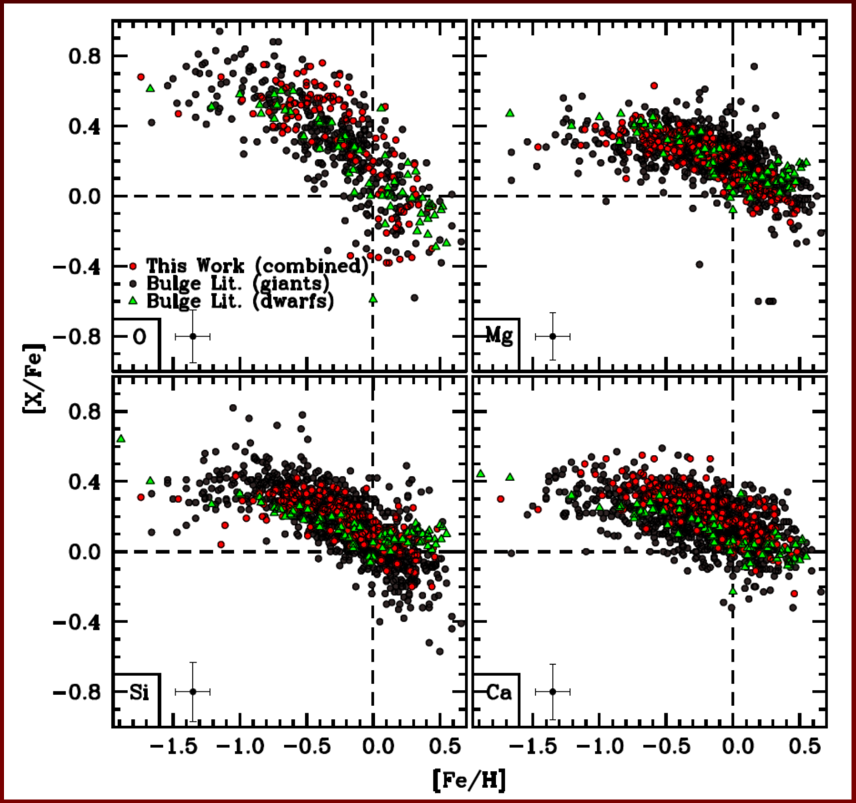


O
Na
Mg
Al
Si
Ca
Cr
Co
Ni
Cu
NGC 6553
(l,b)=(+5.25,−3.02)
(l,b)=(0,−12)
[X/Fe]
[Fe/H]

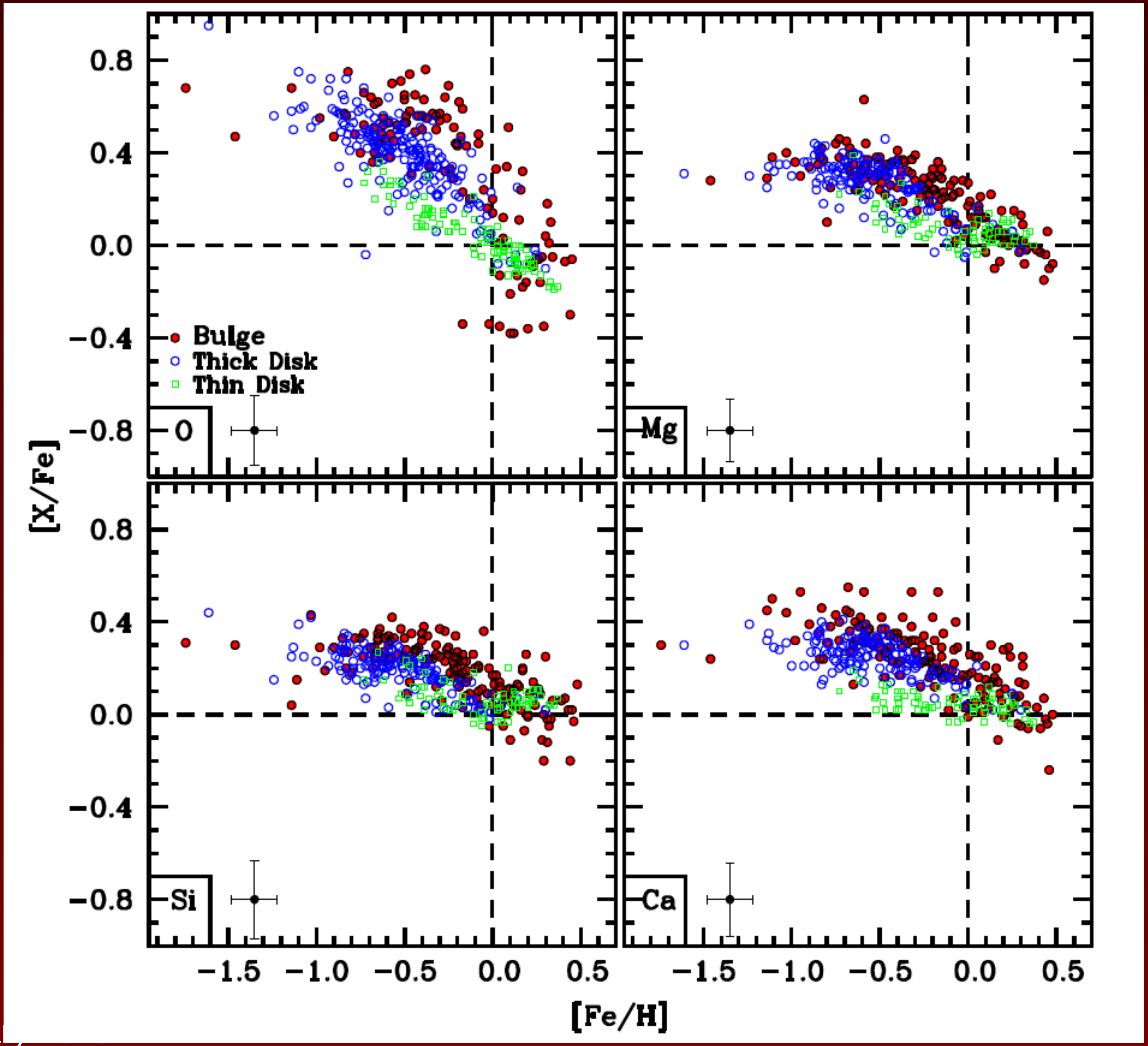


We do not confirm very high
Na, Al measurements in other work

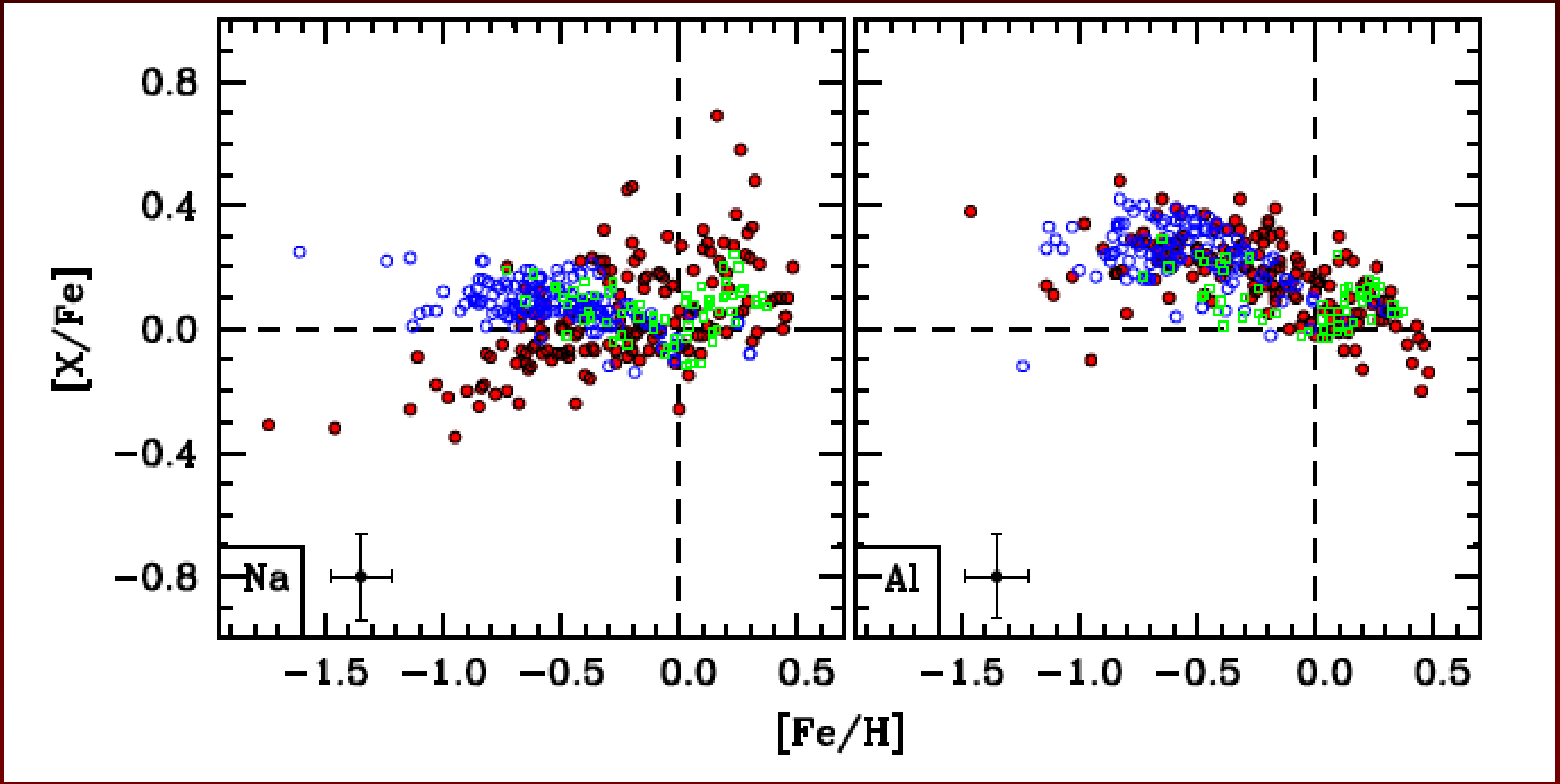
Remarkable uniformity of bulge trends implies
No significant accretion of dwarf galaxy-like objects



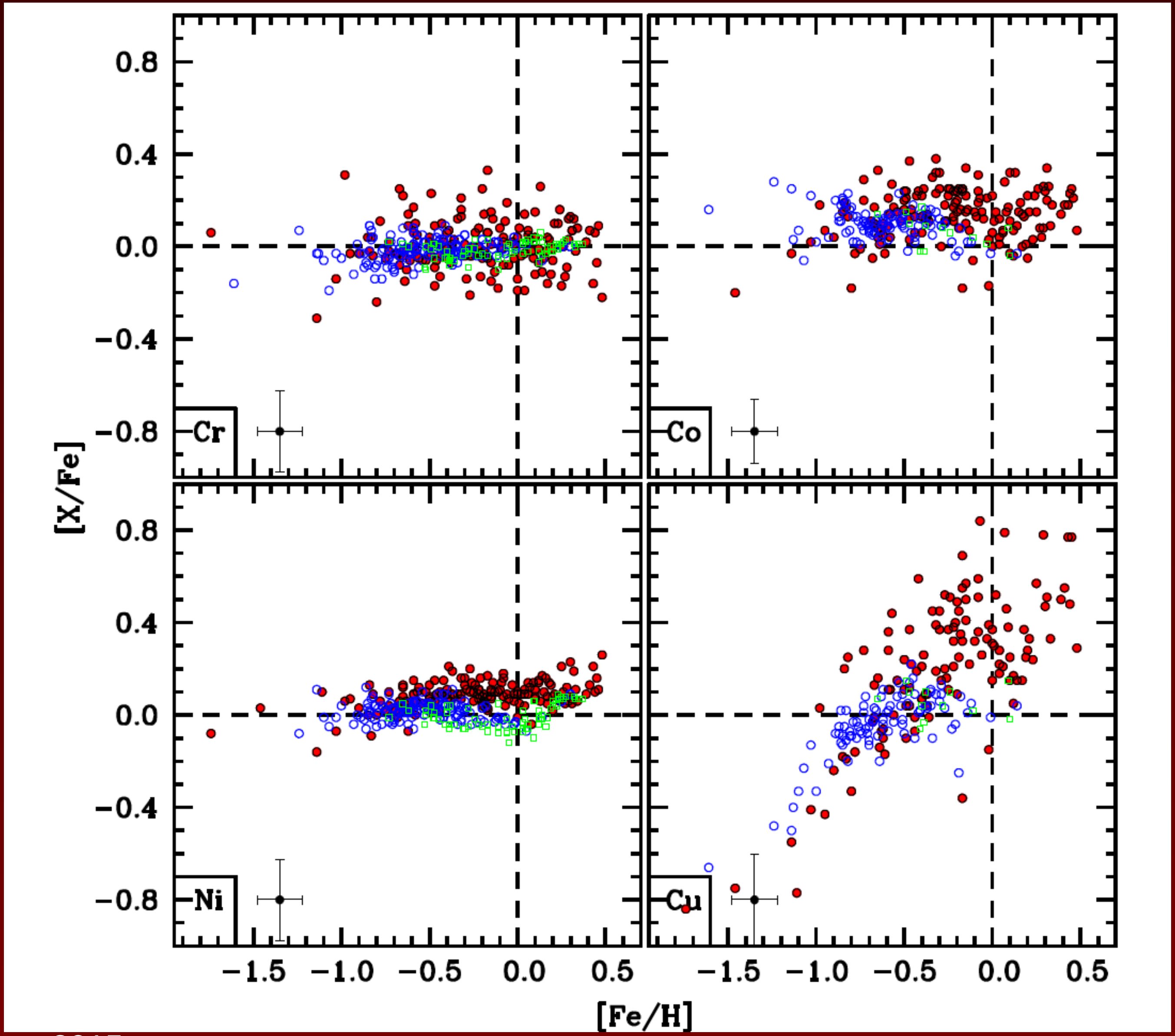
Some differences remain between bulge and thick disk.

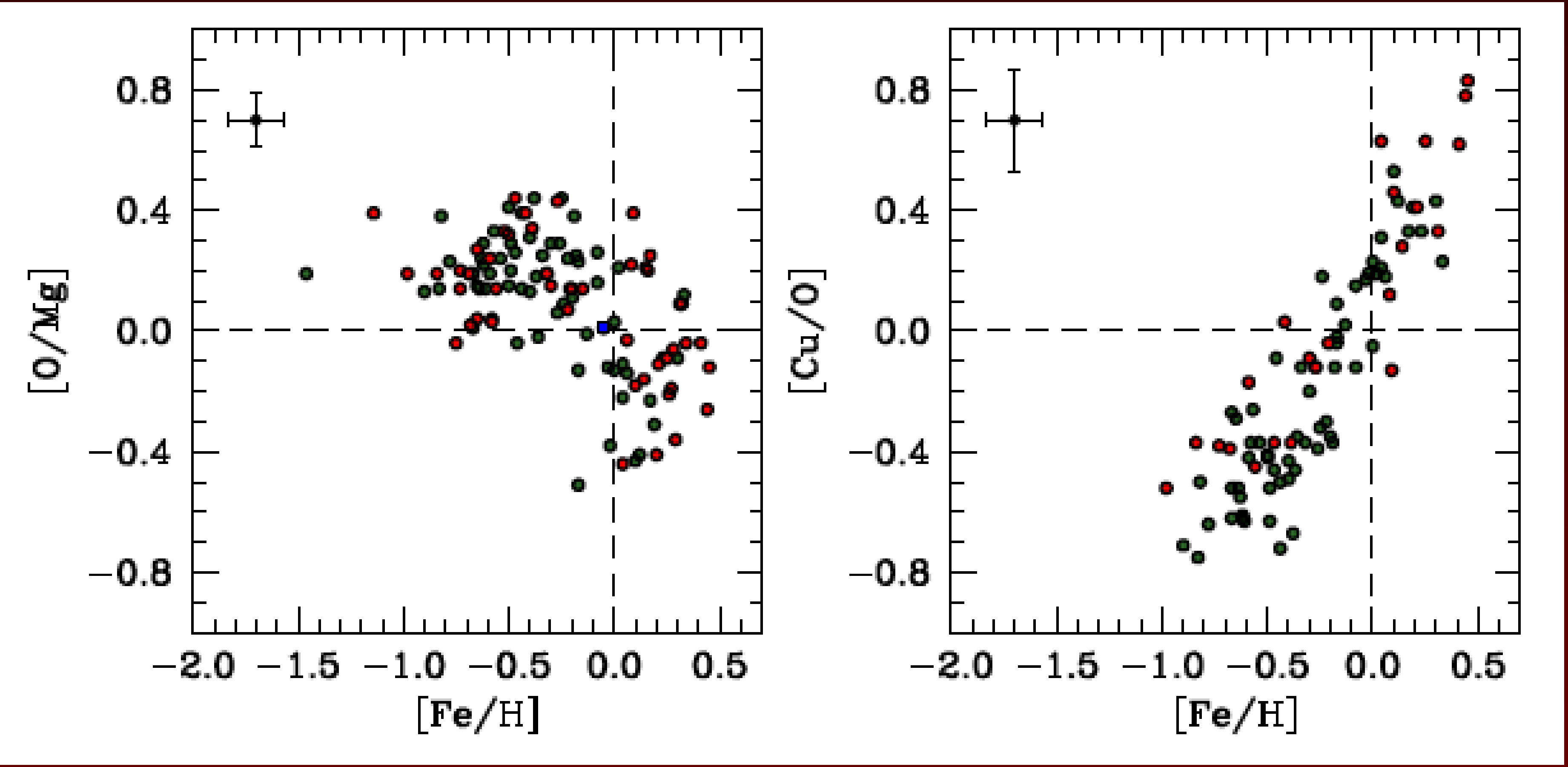


Strong Na trend is distinct from thick disk



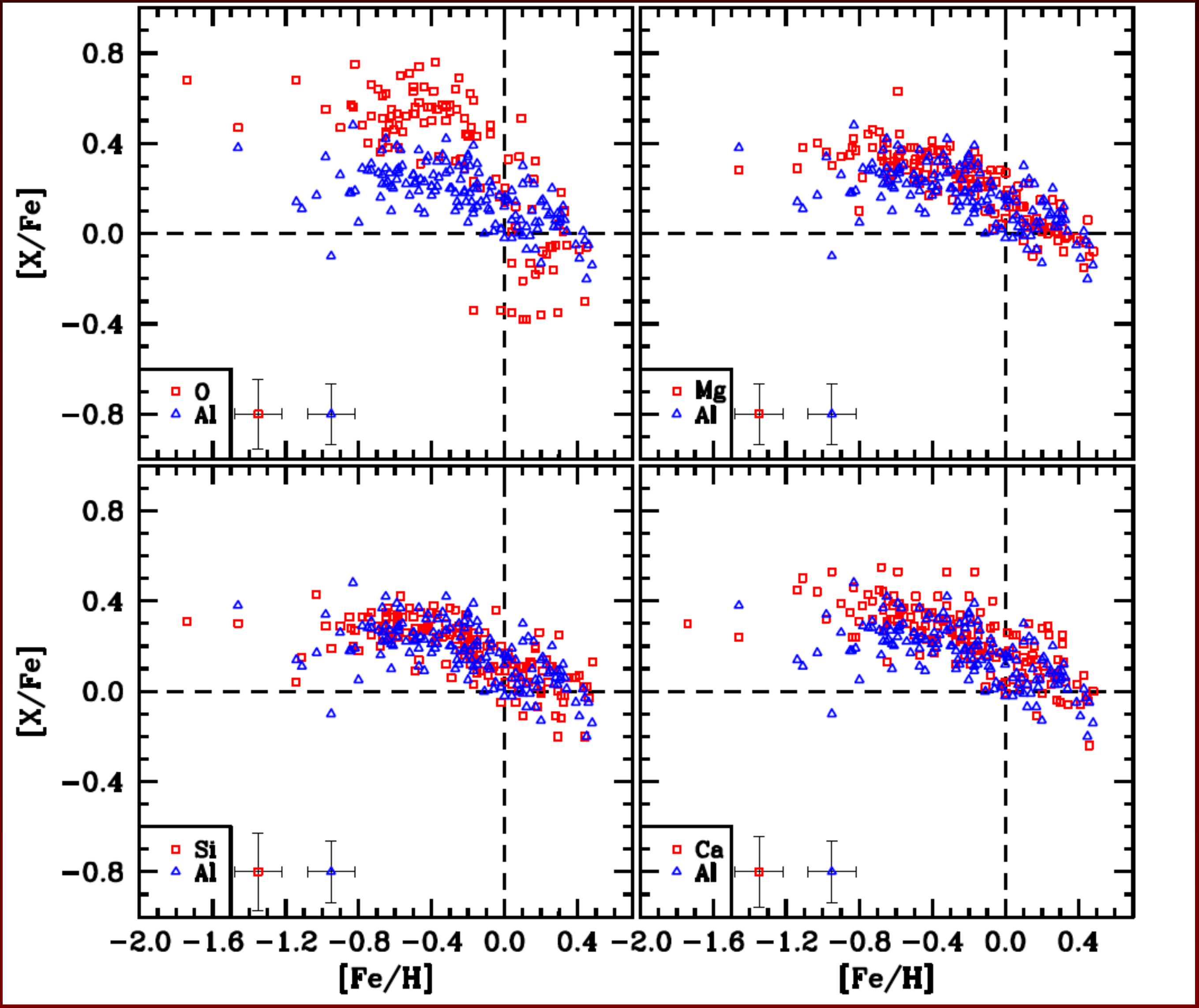
Cu, Co very different from local thick, thin disk.

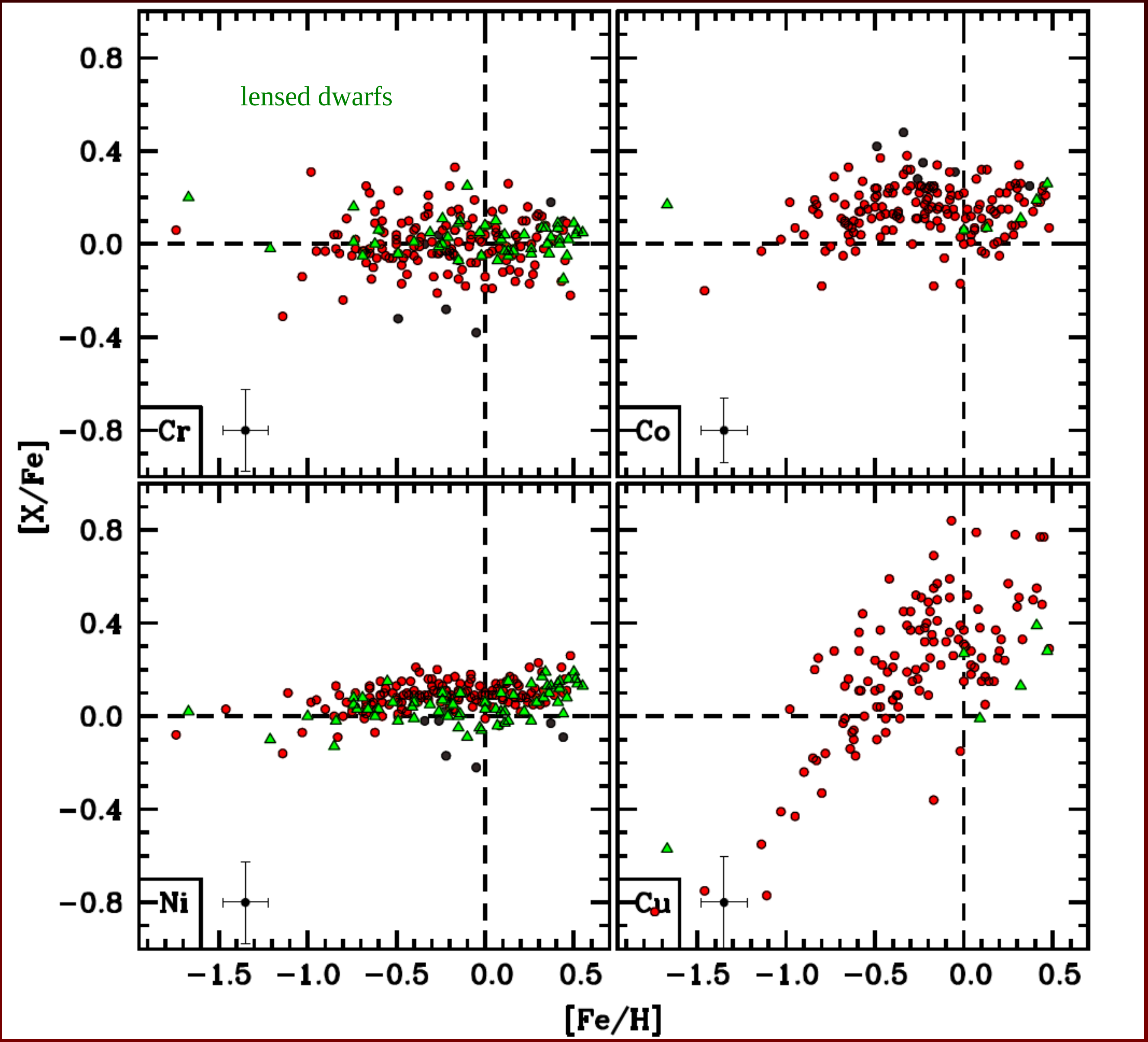




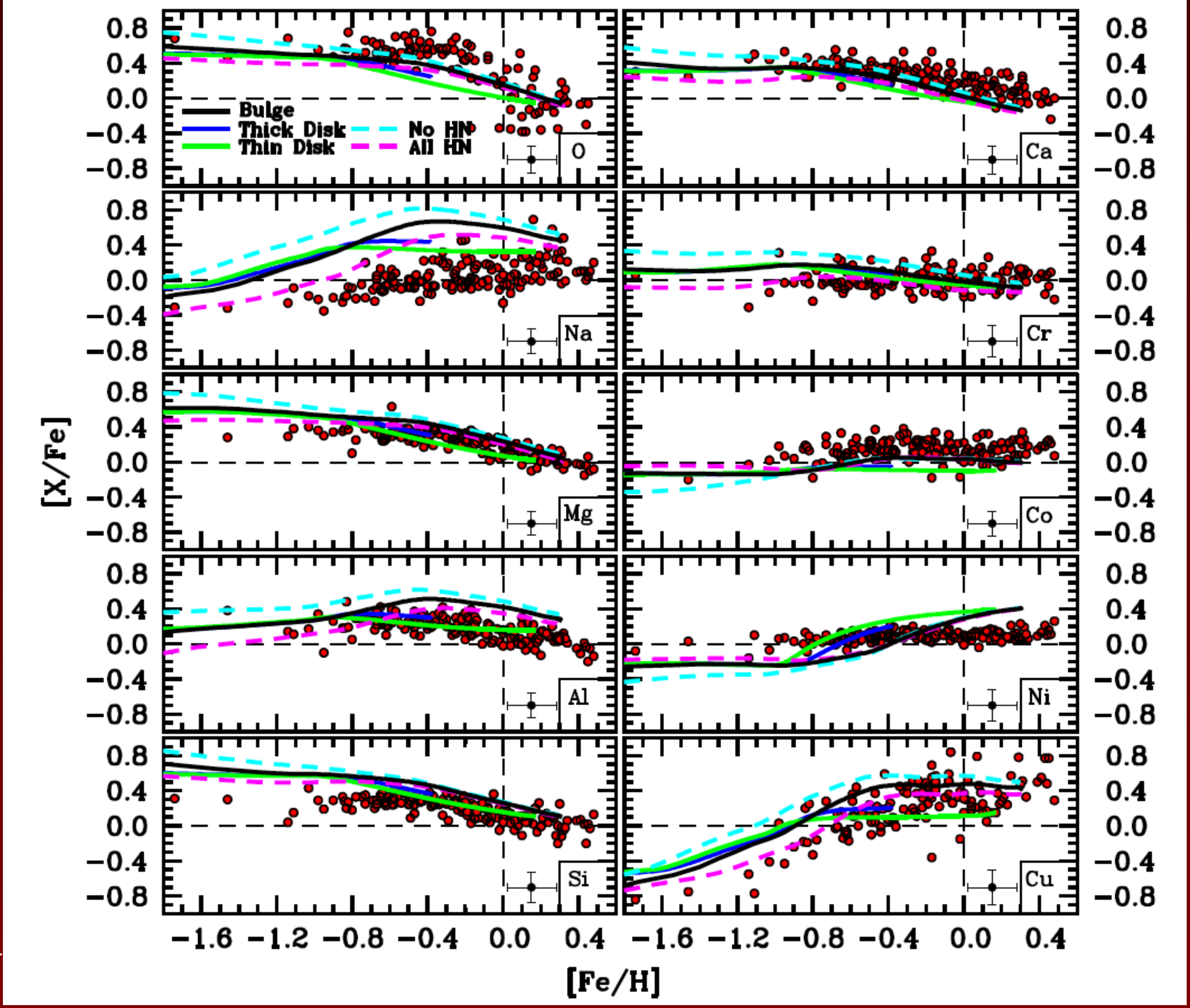
Cu/O strongly correlated with [Fe/H]. Some fraction of Cu from massive stars (s-process?) some via Type I SNe. This very strong trend suggests a single origin of Cu.

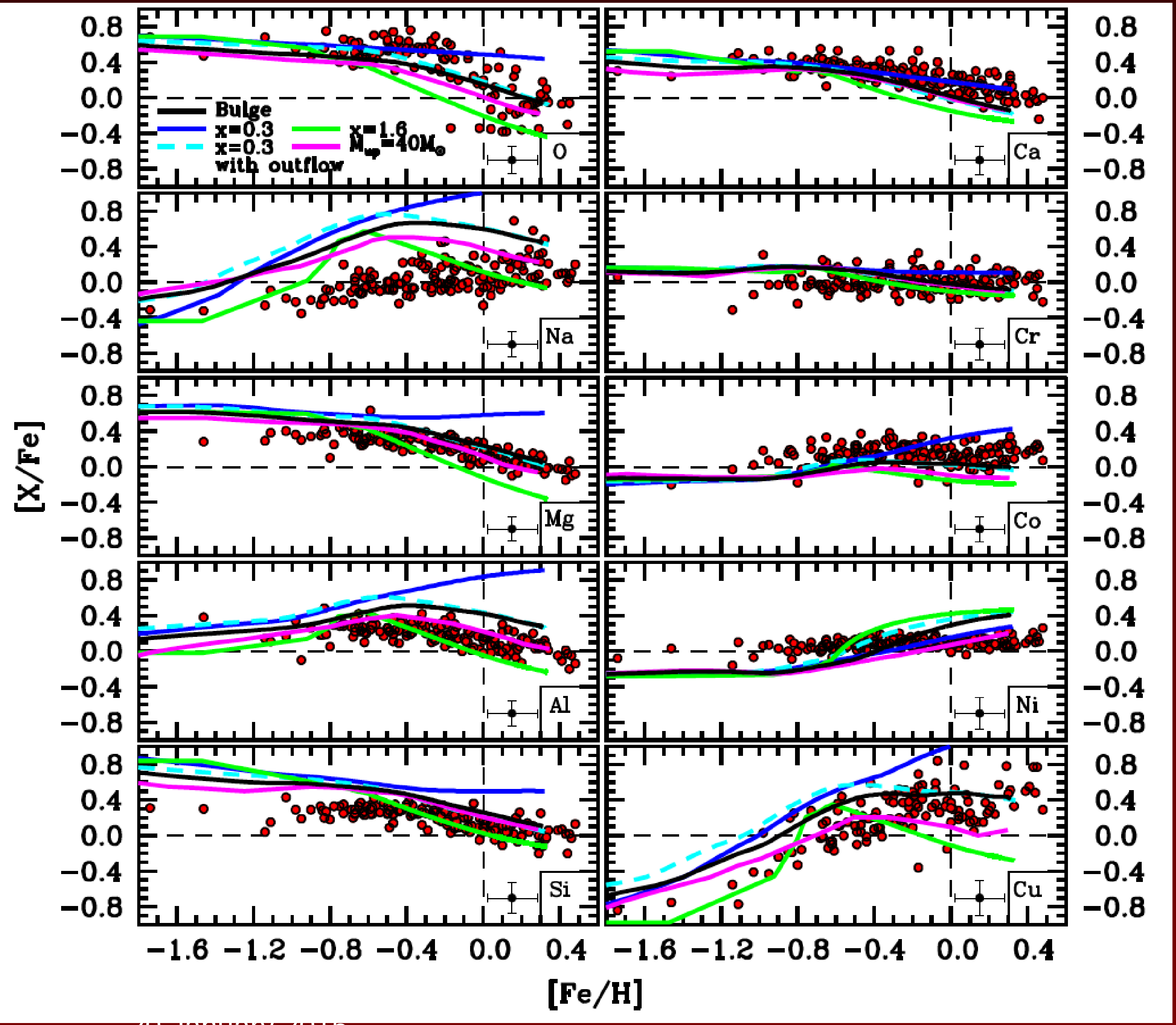
Substantial variation in alpha element trends




lensed dwarfs
Cr
Co
Ni
Cu
[X/Fe]
[Fe/H]
0.8
0.4
0.0
−0.4
−0.8
−1.5
−1.0
−0.5
0.0
0.5

Slight preference favoring hypernovae from Kobayashi models





Models don't favor either higher Type I SN rate or steeper IMF, compared to "standard" models.

Need more metal poor stars to get any leverage.

Conclusions Johnson et al. 2014

Bulge alpha, Al trends not conistent with building from dwarf galaxies.

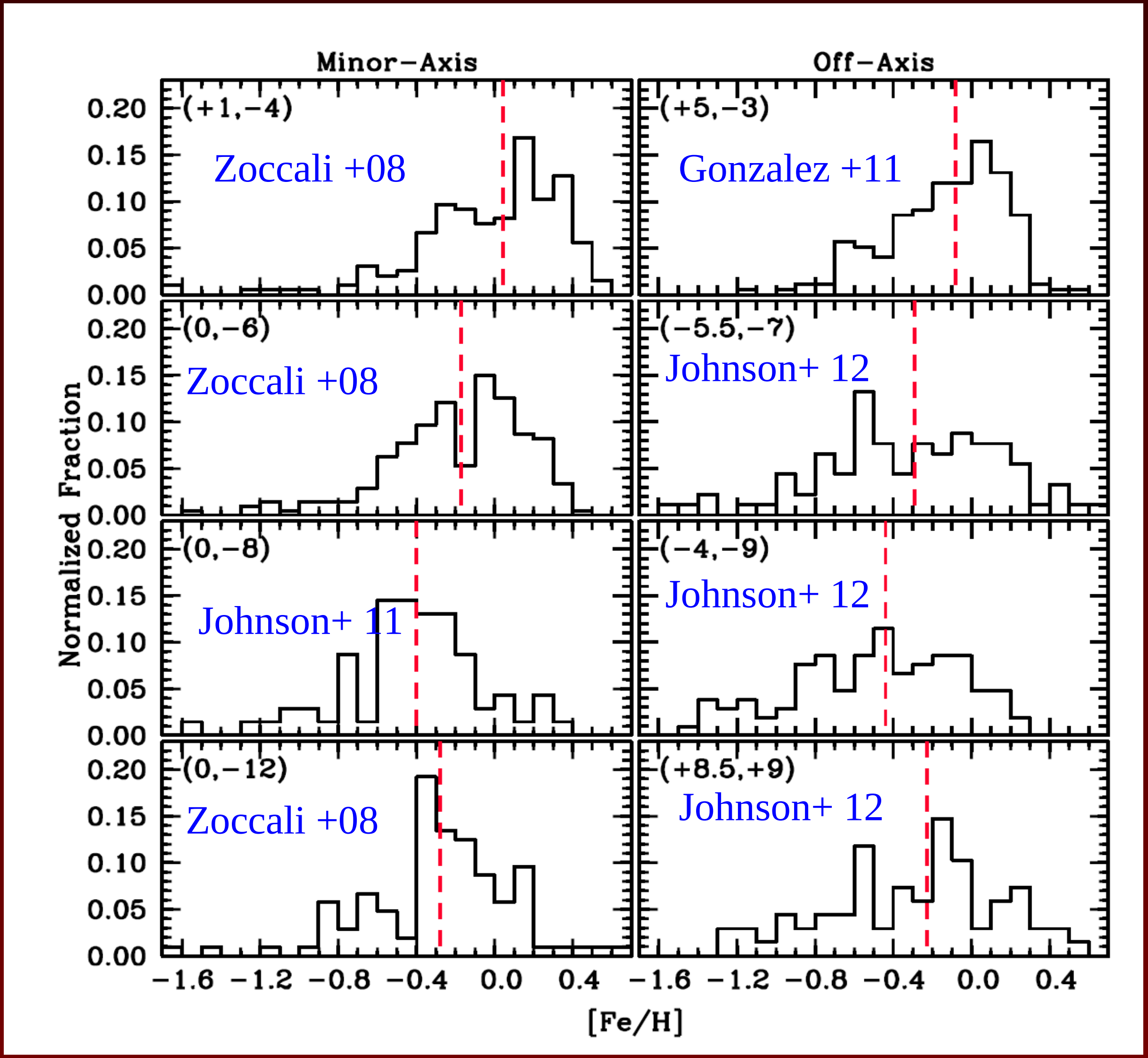
Do not confirm early high Na/Fe
Al/Fe has “alpha-like” trend, no very high Al

Na/Fe vs Fe/H has a distinct trend for the bulge; metallicity dependent yield for Na?

Cu/Fe vs Fe/H consistent with metallicity dependent yield; very high Cu at high Fe might require Type II SN contribution even at high [Fe/H].

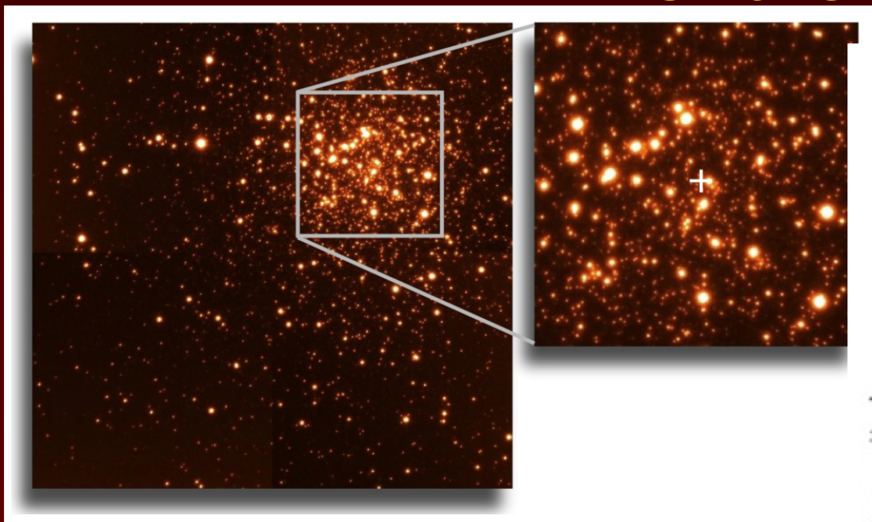
Fits of Kobayashi models to data may require Hne and do not require anomalous IMF. Need more metal poor bulge members to constrain chemical evolution models.

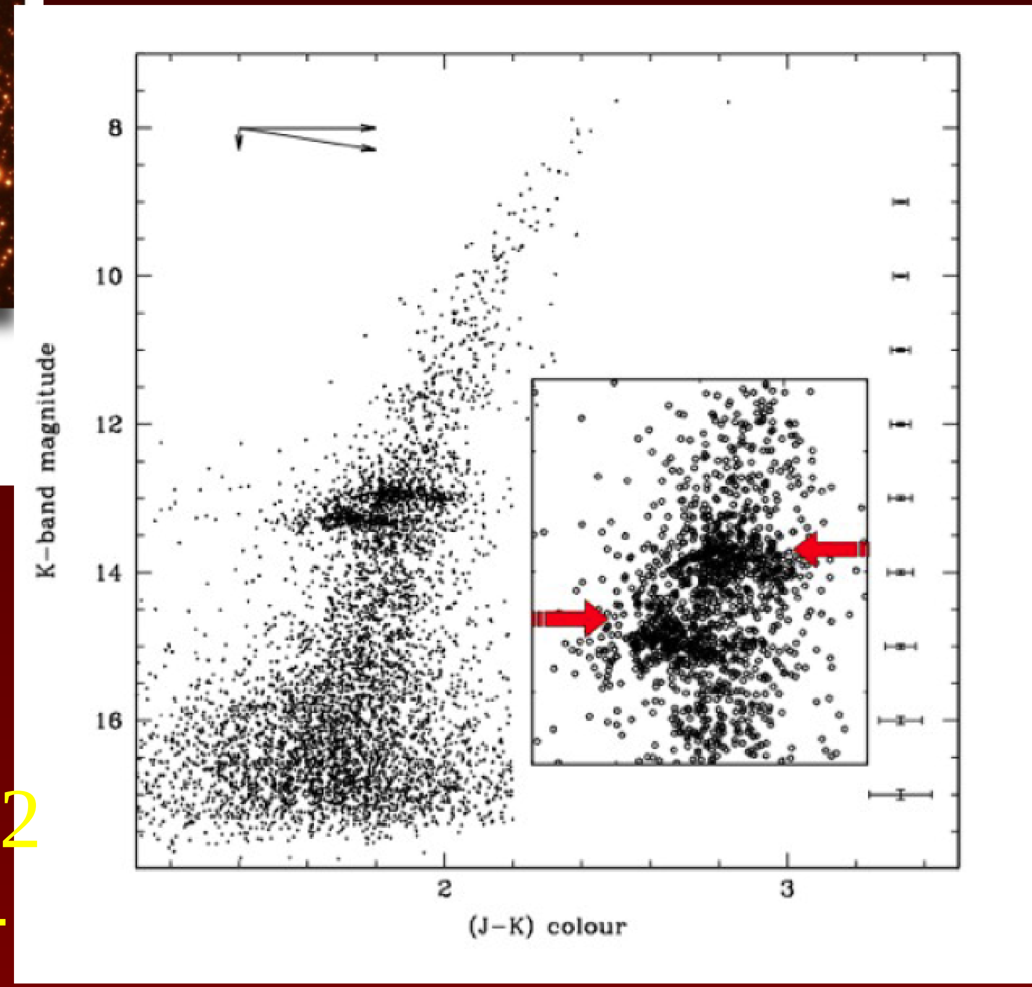
Minor axis abundance gradient clear; radial less so



Not consistent with fully dynamical N-body process
But SN wind might explain this. Also complex x-structure

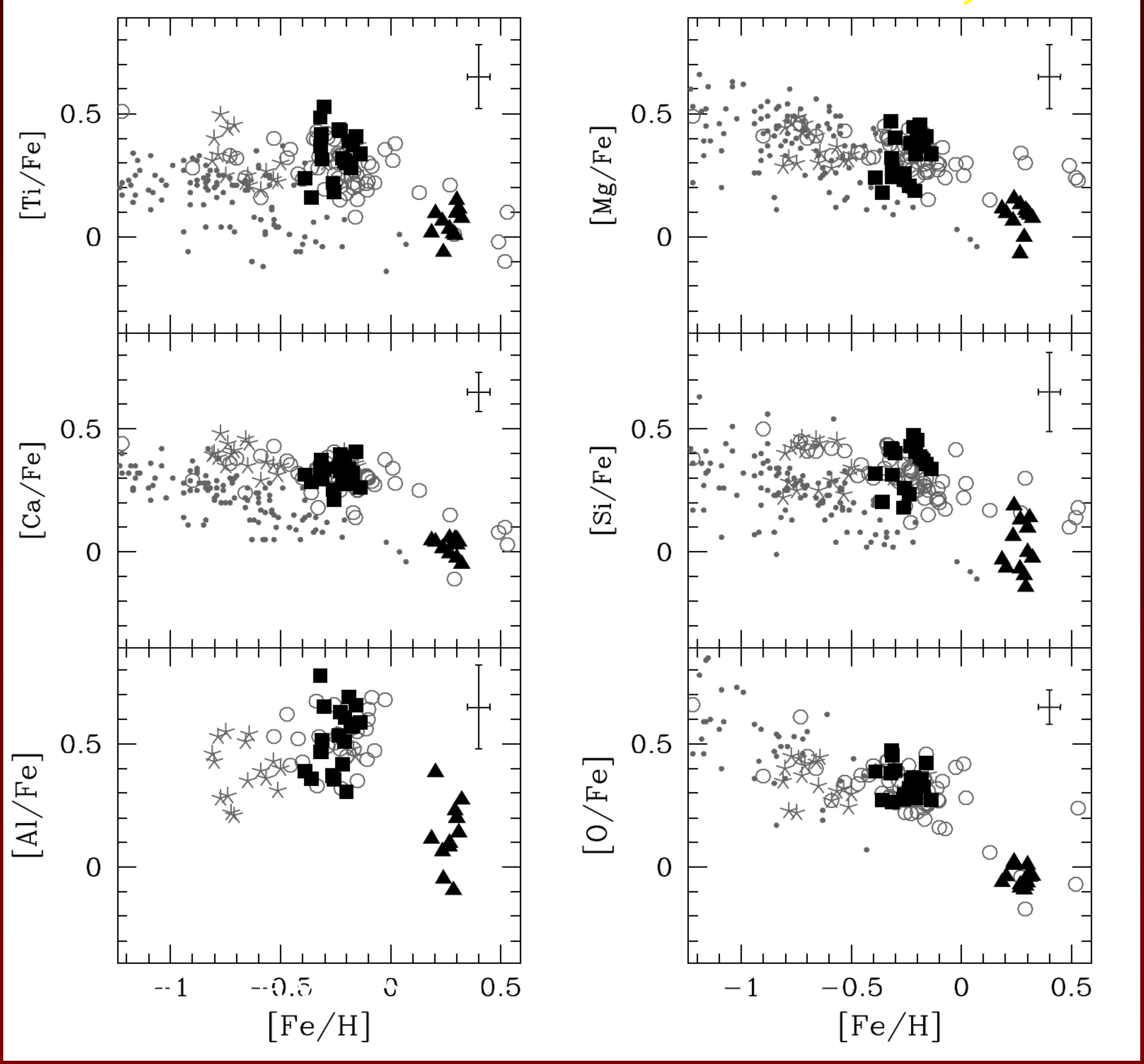
Remarkable Cluster Ter 5
Ferraro et al. 2009





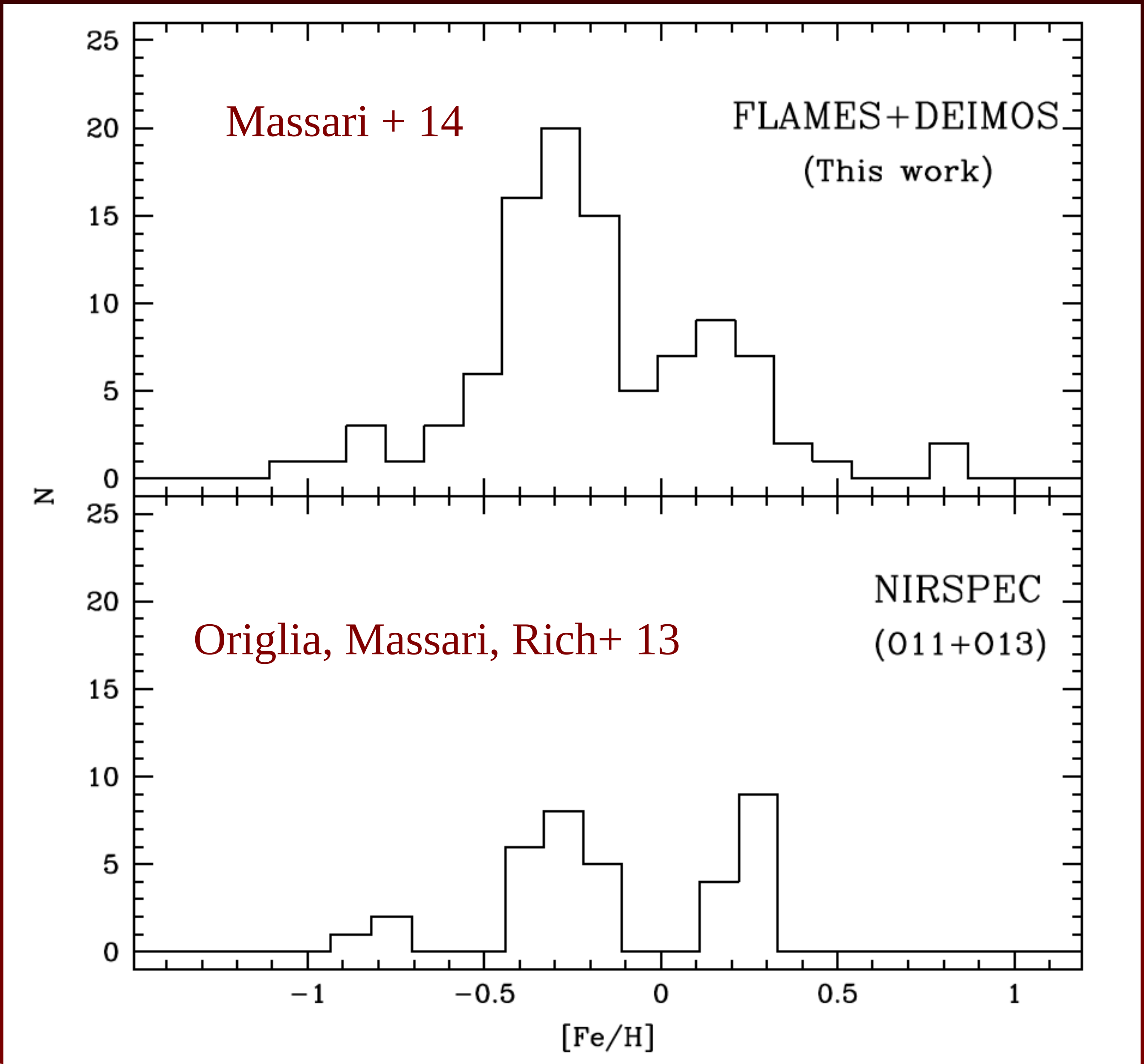
Double HB; brighter
Has [Fe/H]~+0.3
Fainter has [Fe/H]~-0.2
0.5 dex [Fe/H] spread-
Unique case.

Origlia, Rich et al. 2011
Keck + Nirspec (Mclean et al. 1998)
1.6 um window R=25,000



Two populations with striking composition difference

Metal rich part exceeds metallicity of any Galactic globular cluster


Massari + 14
FLAMES+DEIMOS
(This work)
Origlia, Massari, Rich+ 13
NIRSPEC
(011+013)
N
[Fe/H]
25
20
15
10
5
0
−1
−0.5
0
0.5
1

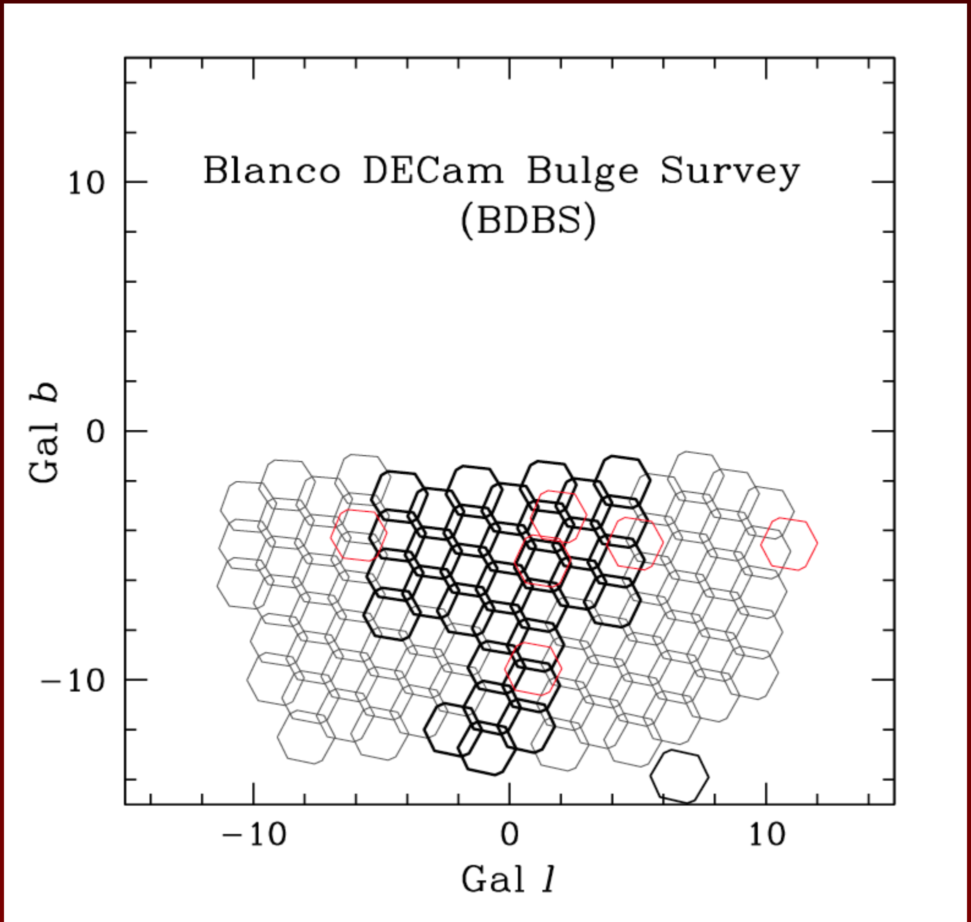
Blanco DEcam Bulge Survey

A. Kunder, C. Johnson, A. Koch, S. Michael, M. Young, W. Clarkson, M. Irwin,R.Ibata, M. Soto, Z. Ivezic, R. de Propris, A. Robin, C. Pilachowski

2013 progress on BDBS

Dark Energy Camera at CTIO Blanco 4m telescope. 3 sq. deg. field of view, 62 CCDs ugrizY SDSS colors imaging at 0.2”/pixel

20 January 2015



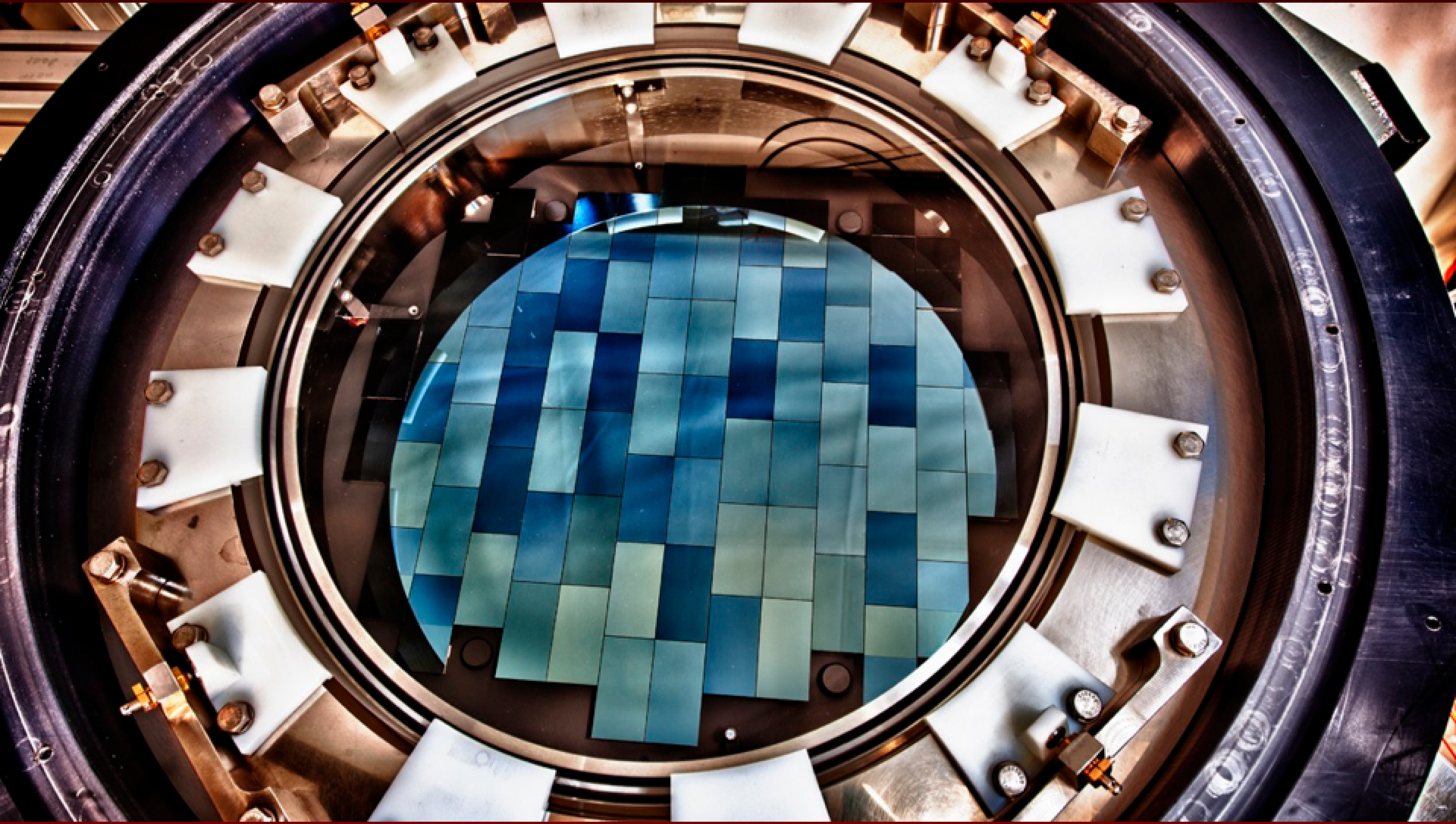
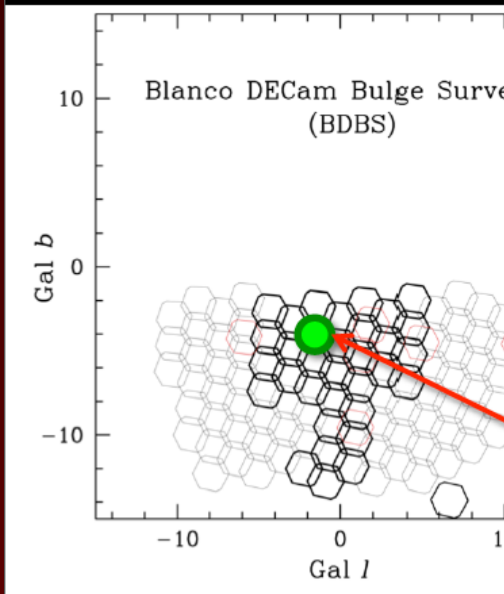
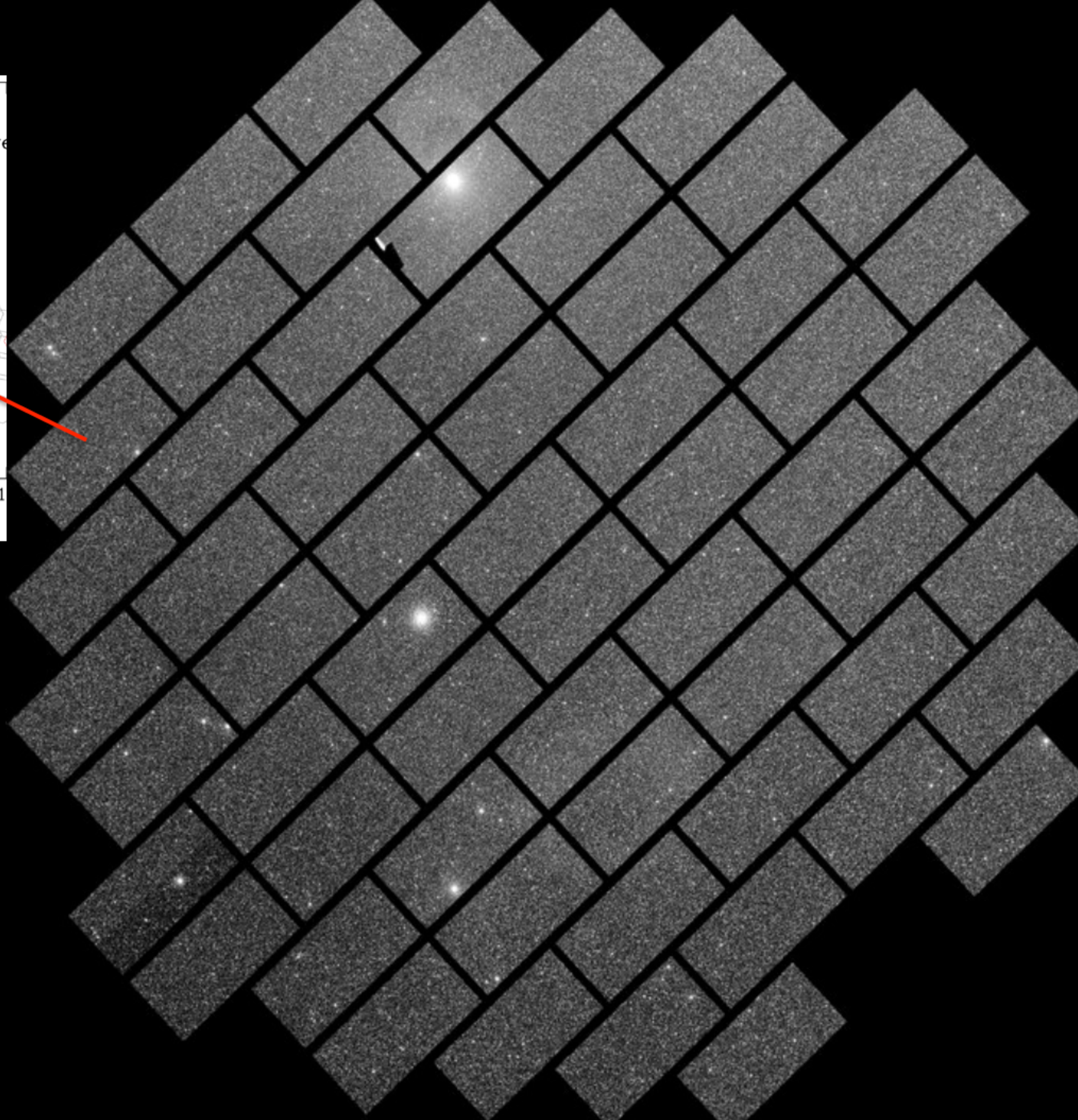


Image: W. Clarkson

20 January 2015

Image: W. Clarkson





20 January 2015

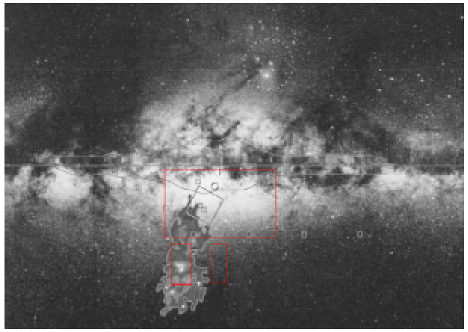
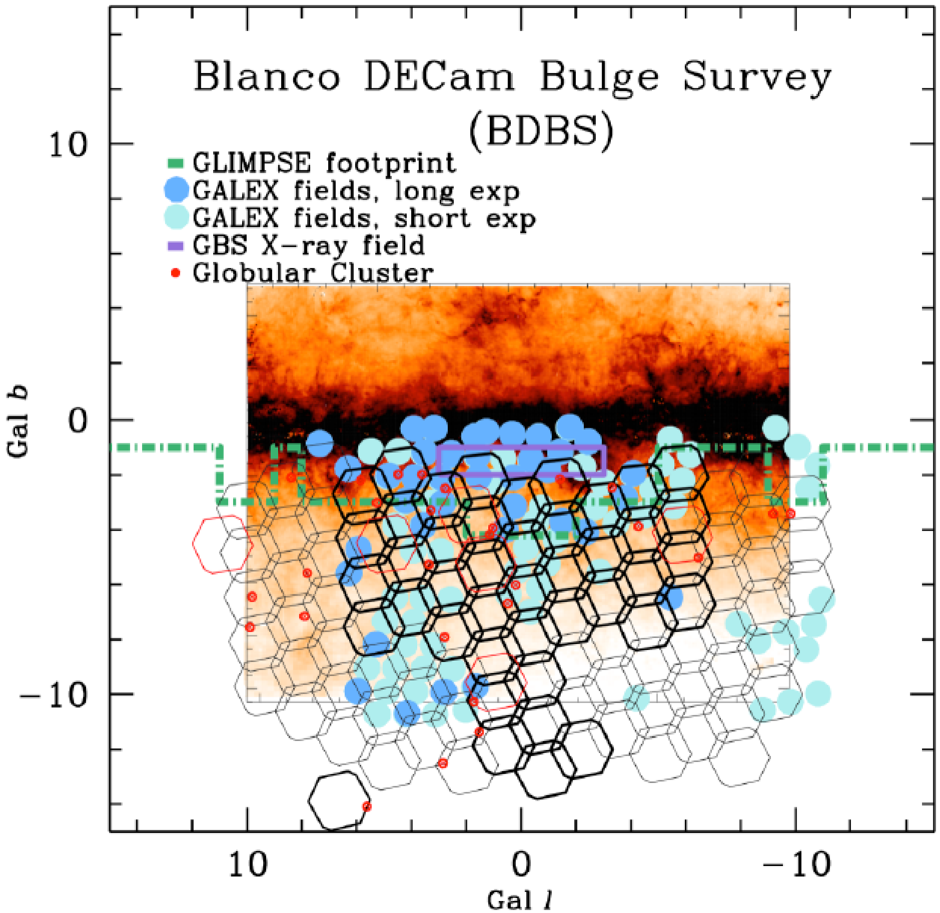
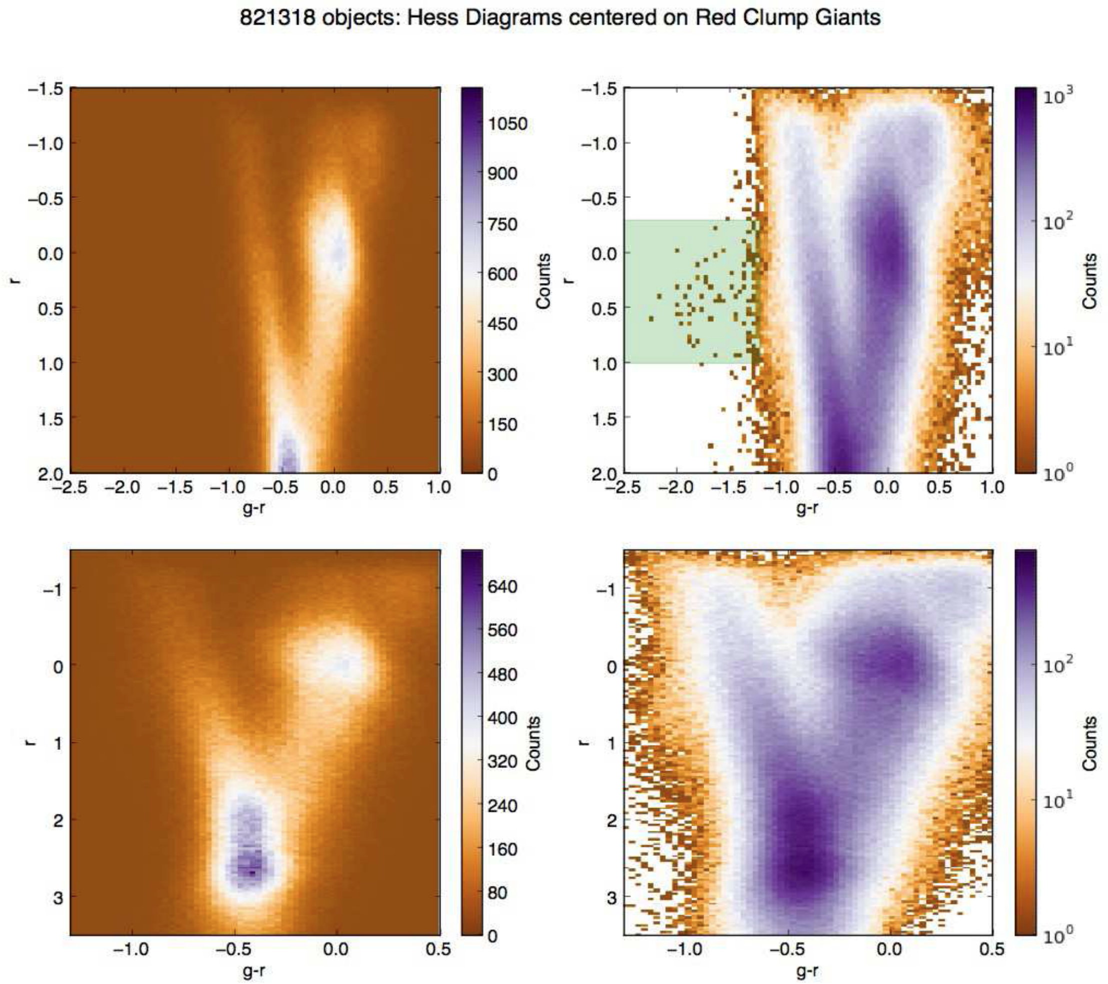


Figure 1-(Left) Visible light image of the Milky way with the bulge and Sgr dwar galaxy (illustrated as a blobby structure below the bulge) superimposed (Wyse, Gilmore, & Franx 1997). The red square regions cover the approximate location of the Blanco DECam bulge survey illustrated below.





BDBS Goals:

1. Map bulge in all 5 colors ugrizy, reaching deep enough in u to define the extreme HB.
2. Use 5 colors to map age, metallicity of bulge, separate foreground disk, define thick disk, halo
3. Search for ultra-metal poor stars
4. Multiwavelength match; Galex Spitzer, Chandra, etc.
5. High quality astrometry for population separation using Kuijken & Rich (2002) method
6. Improved map of Sgr dwarf spheroidal
7. Basic community public resource

Reductions by C. Johnson and Will Clarkson