The Bulge Radial Velocity/Abundance Assay

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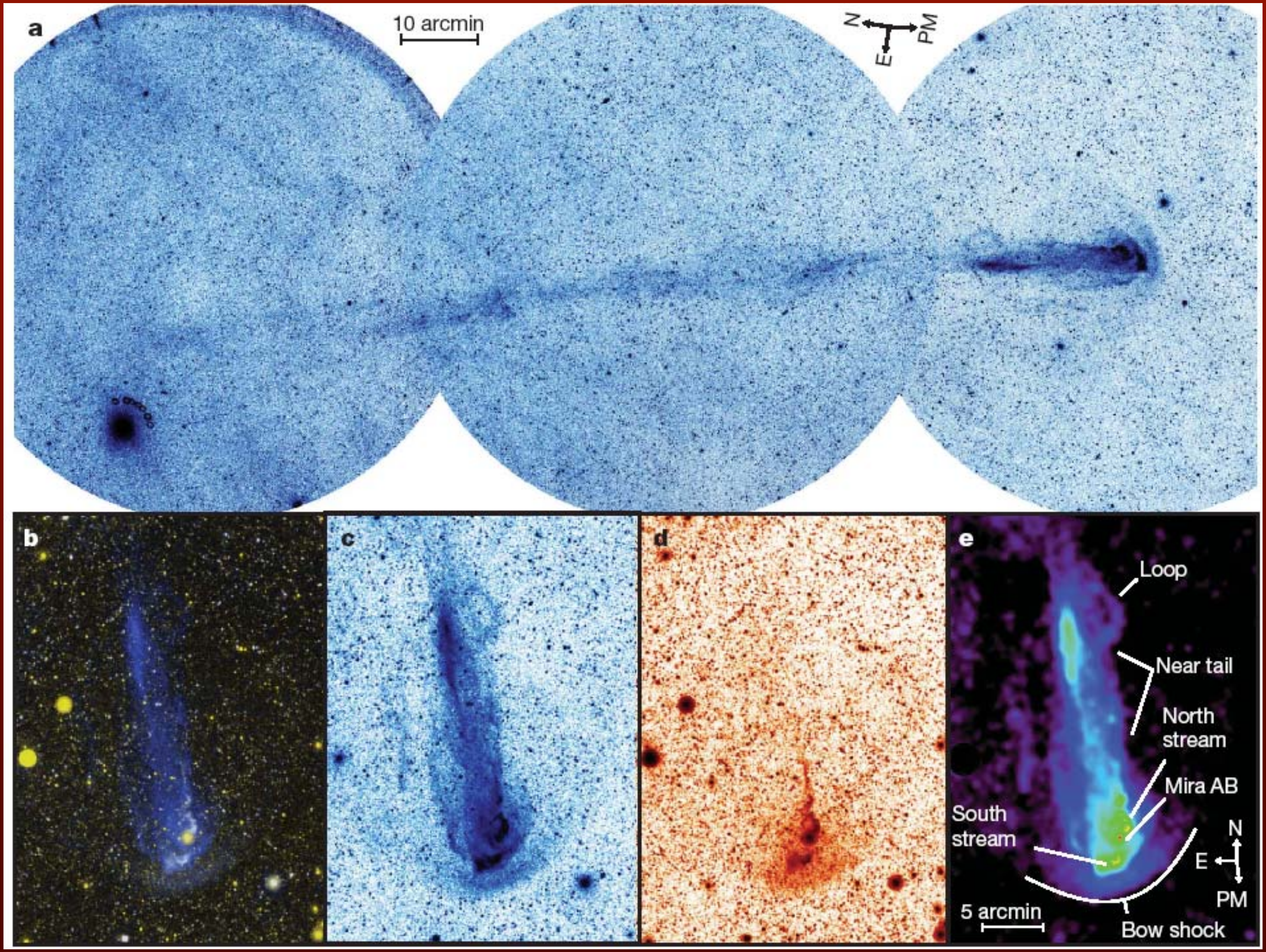
Roberto de Propris (CTIO), Andy McWilliam (Carnegie), Jon Fulbright(JHU), Livia Origlia (Bolo

My other telescope is a 0.5m… GALEX



Mira Tail Martin, Seibert et al. 2007, Nature, 448, 780

Motivation

- "Spheroids" 50-70% of stellar mass in local Universe. (Fukugita et al. 1998)
- Lyman-break (z > 3) galaxies metal-rich star formation and evidence for metal-rich winds. Chemical evolution.
- Epoch, population of bulge formation?? EROs?

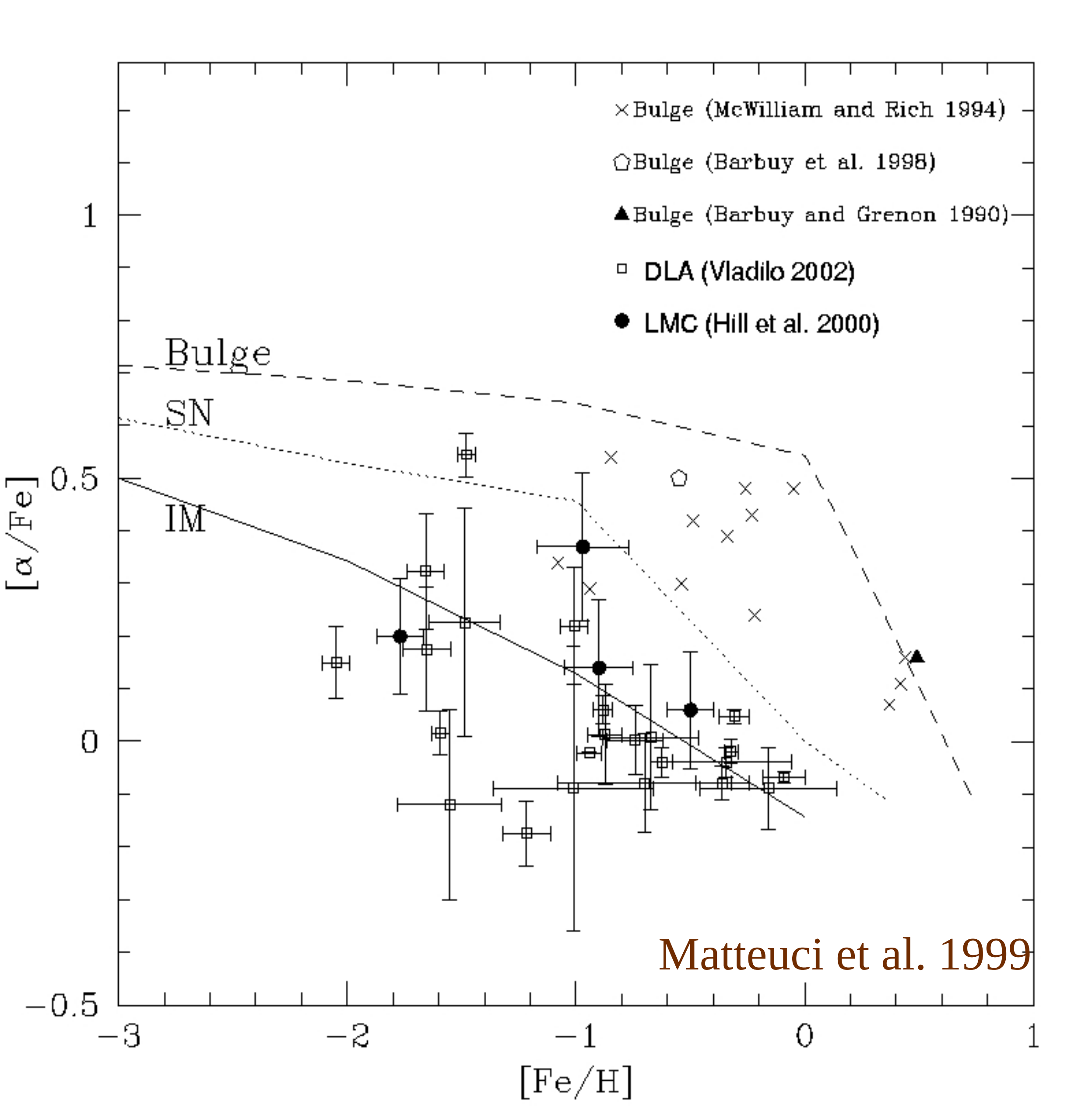
  BzK, LBG? Other?
- Unique formation history, stellar population (link to

  extragalactic spheroids, high Mg_2 index (Worthey et al. 199
- Bulges host supermassive black holes. Formation process sti unknown. Related to bulge formation? (Gebhardt et al., Ferrarese et al., Ghez et al.).
- Metal rich halos are widespread: M31 (Durrell 1994, Rich 1996) other galaxies (Mouhcine et al. 2005).
- ~15 hot Jupiter transit planets discovered using HST imaging of Bulge field (Sahu et al. 2006).

Composition is a window into galaxy formation and chemical/dynamical evolution

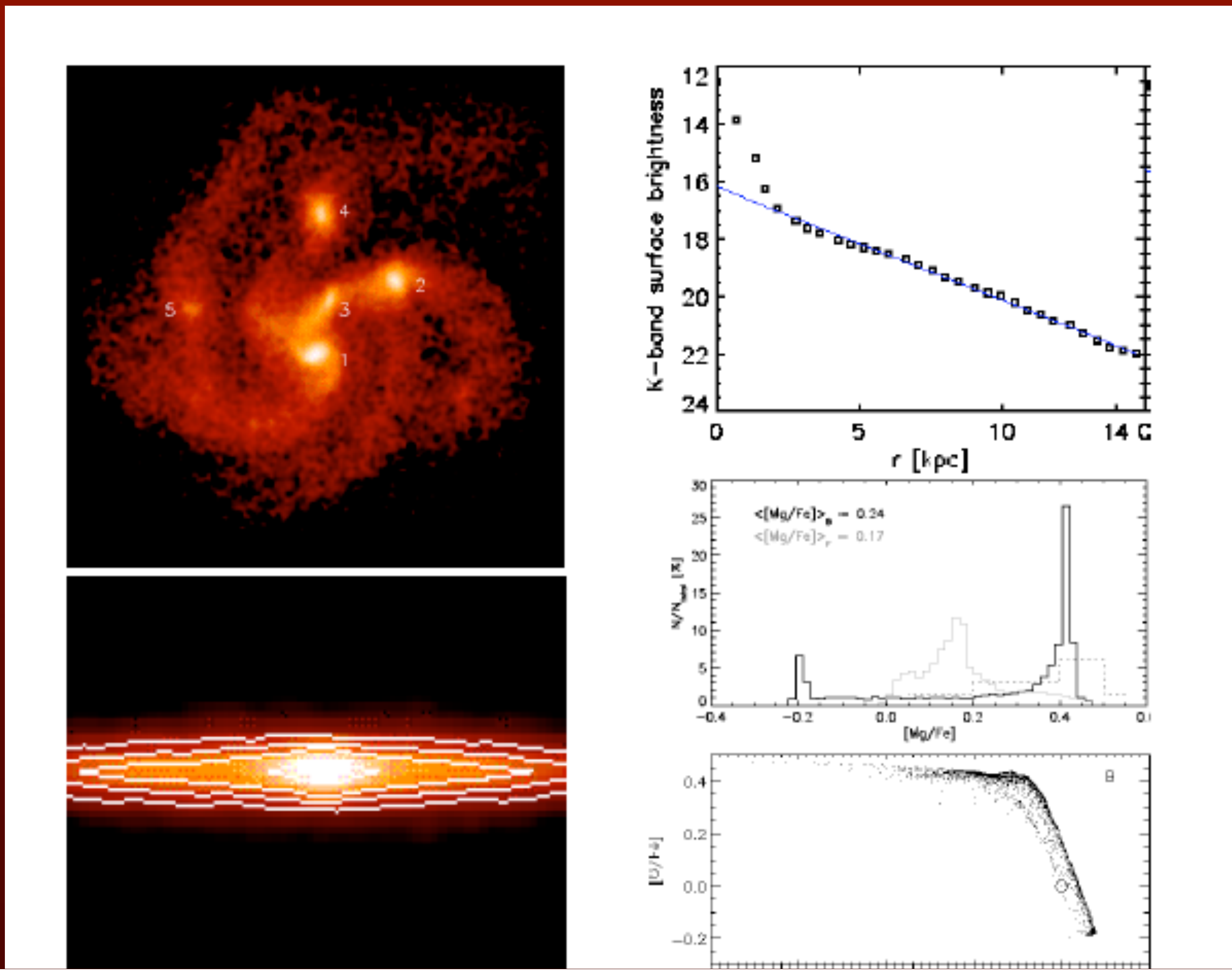
- Type II supernovae are produced by massive stars (>8 $M_\odot$) on very short (10^7 to 10^8 yr) timescales.
- Type I supernovae produce Fe-peak elements on longer ~10^9 yr timescales.
- Produce large amounts of the elements through the Fe-group ($Z < 31$) and probably some r-process.
- Known for high α-element (O, Mg, Ne, Si, S, Ar, Ca, Ti) to Fe yields.
- Detailed production dependent on progenitor mass:
  - O, Mg primarily produced by $M > 25\ M_\odot$ progenitors.
  - Si, S produced in the 15-25 $M_\odot$ range.
  - Ca, Ti through Zn produced over nearly all masses.

High [O/Fe] reflects early burst of star formation

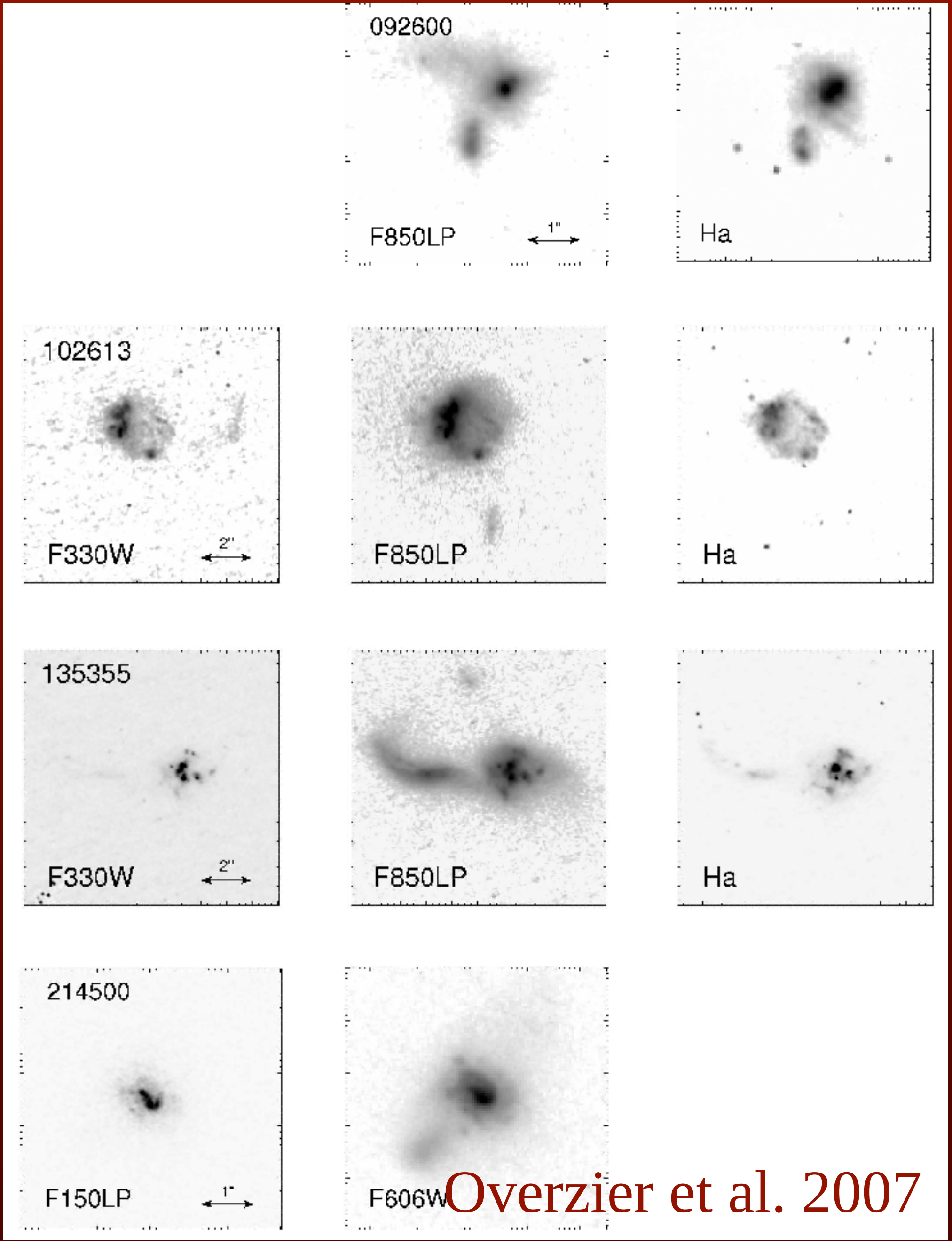


Imelli et al. 2004 - major merger origin
Clumps dissipate rapidly into bulge

Multiple star forming clumps might produce kinematic groups with distinct chemical fingerprints.



UV-Luminous Galaxies in the Local Universe (Lyman Break Galaxy Analogs)



Overzier et al. 2007

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

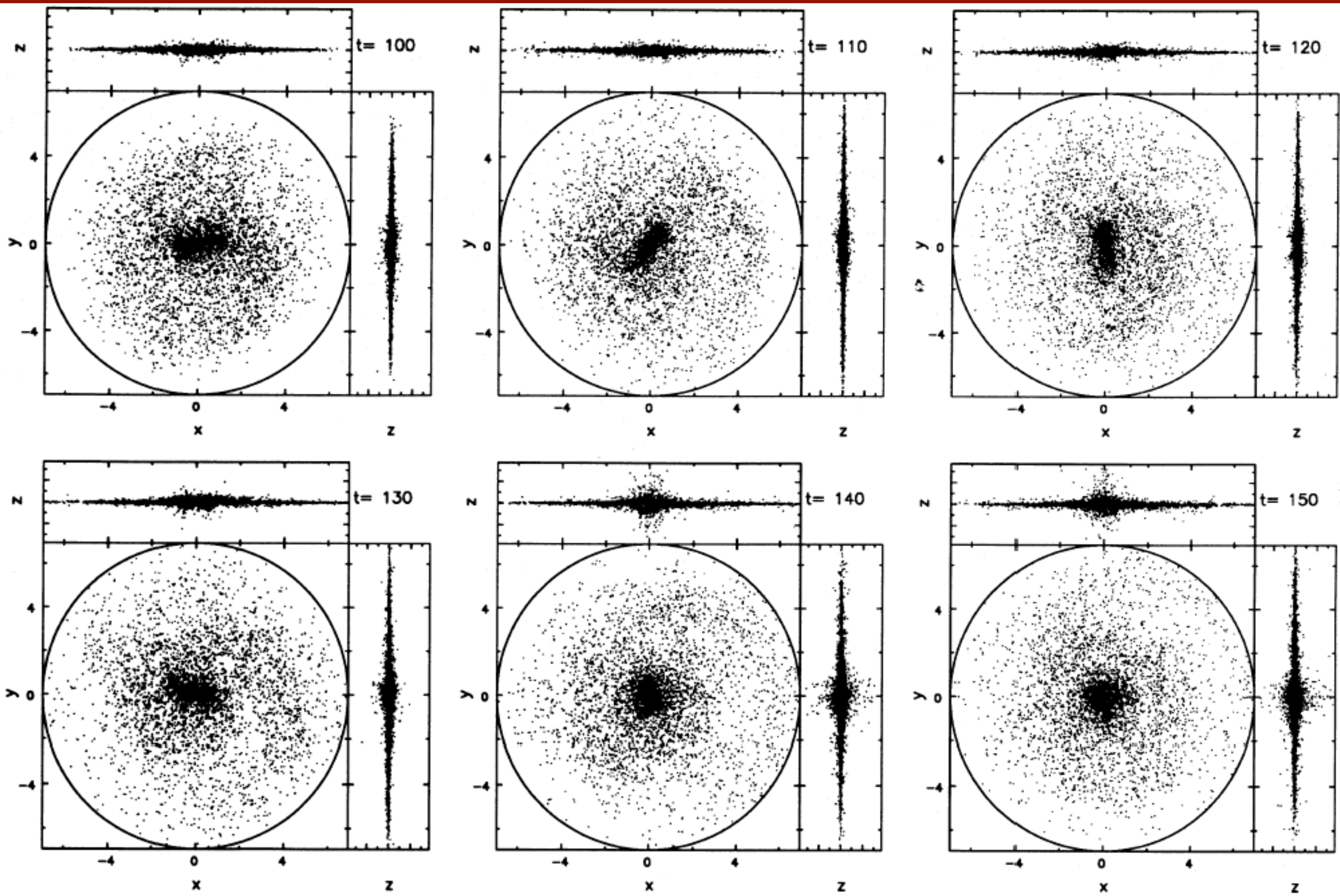
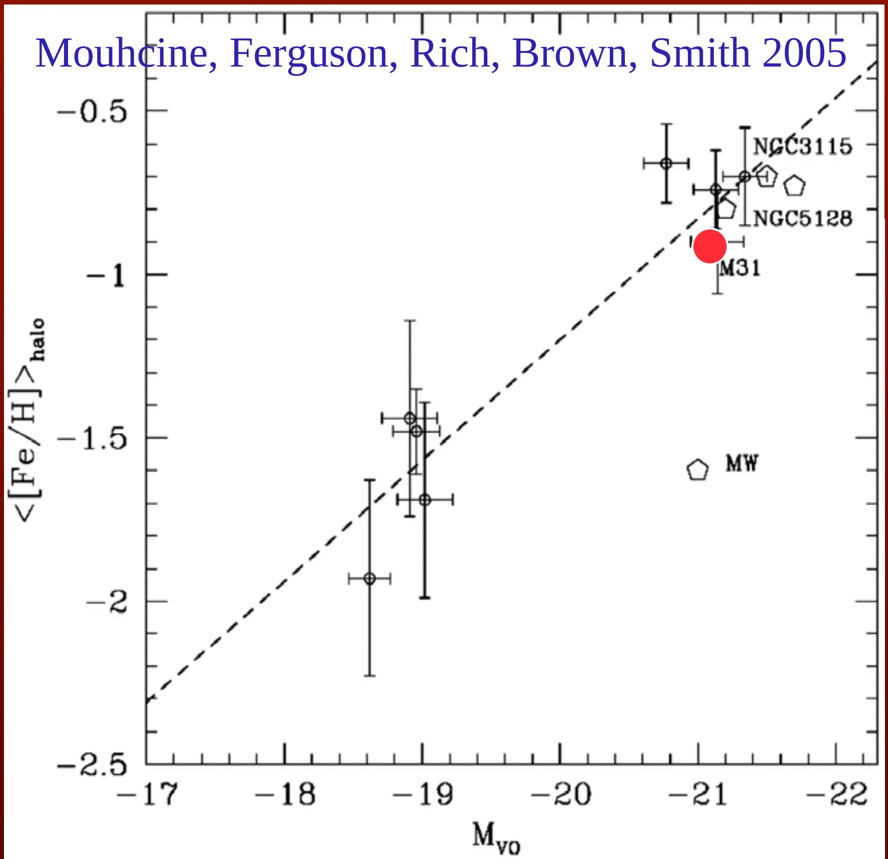
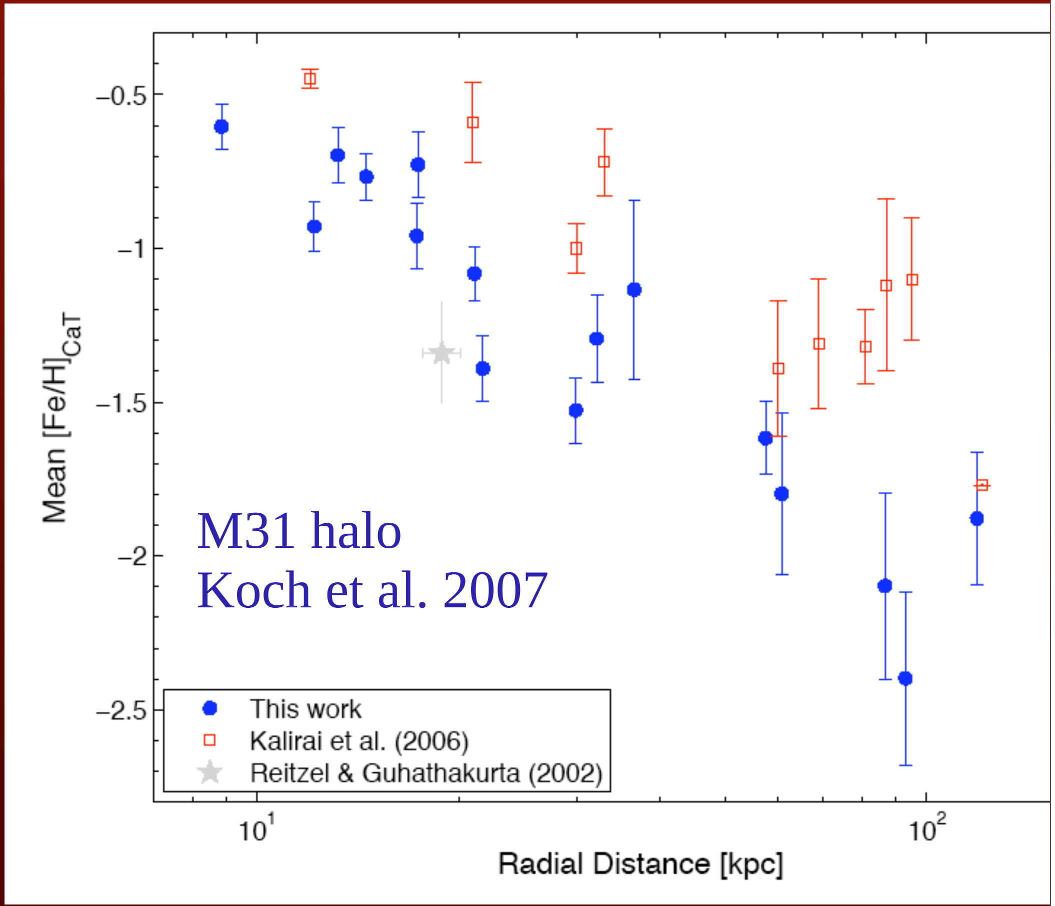


FIG. 6.—The evolution of a three-dimensional model in which a 5% central mass is grown from time 100 to time 140. The whole calculation volume is shown, but only one particle in 40 is plotted. The bar dissolves abruptly between times 130 and 140, forming a spheroidal bulgelike feature at the center.

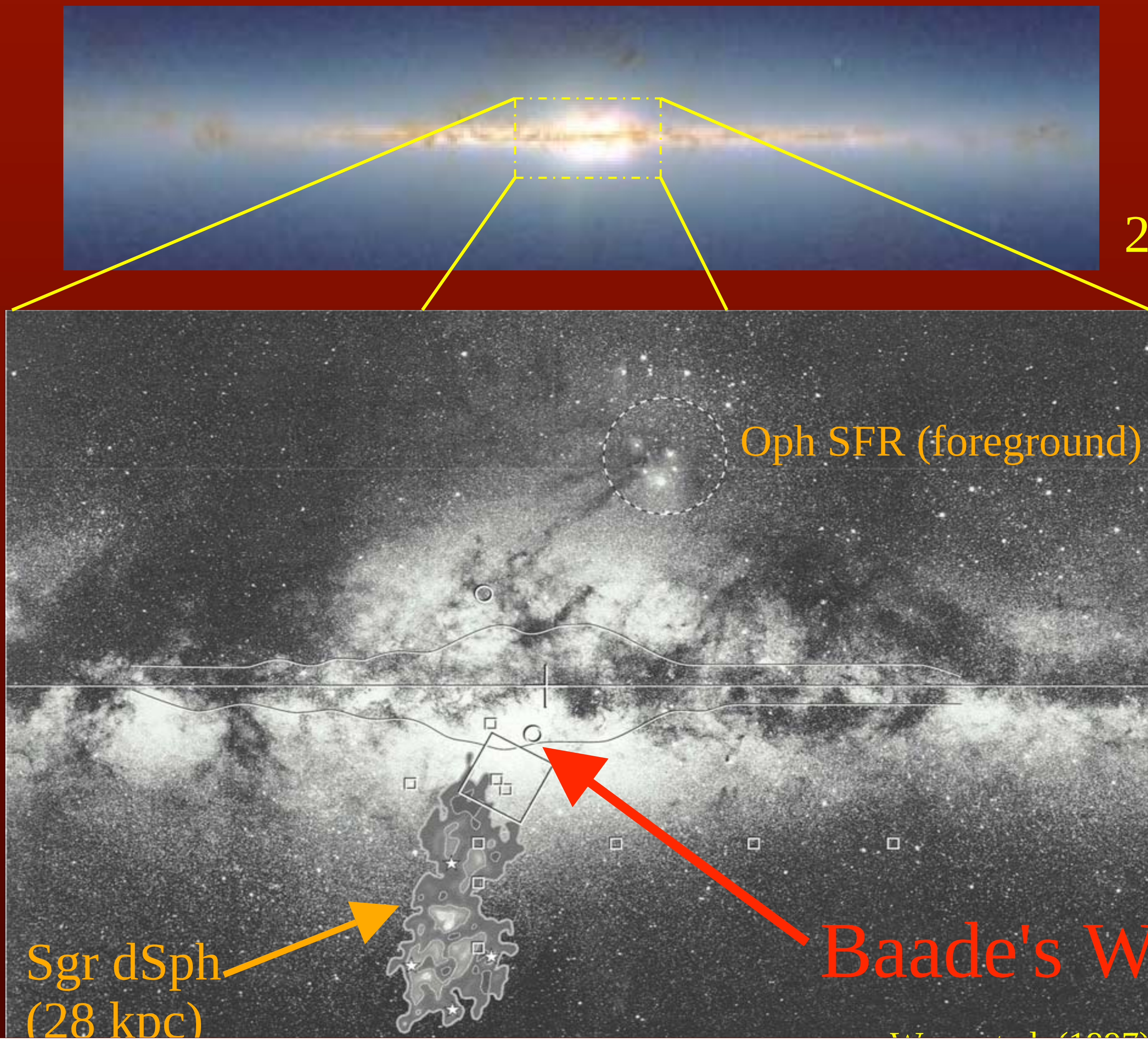
Vertical thickening of the bar into a bulge would leave no abundance gradient in the z-direction.

Do some bulges populate halos?
Do bulge debris populate halos?



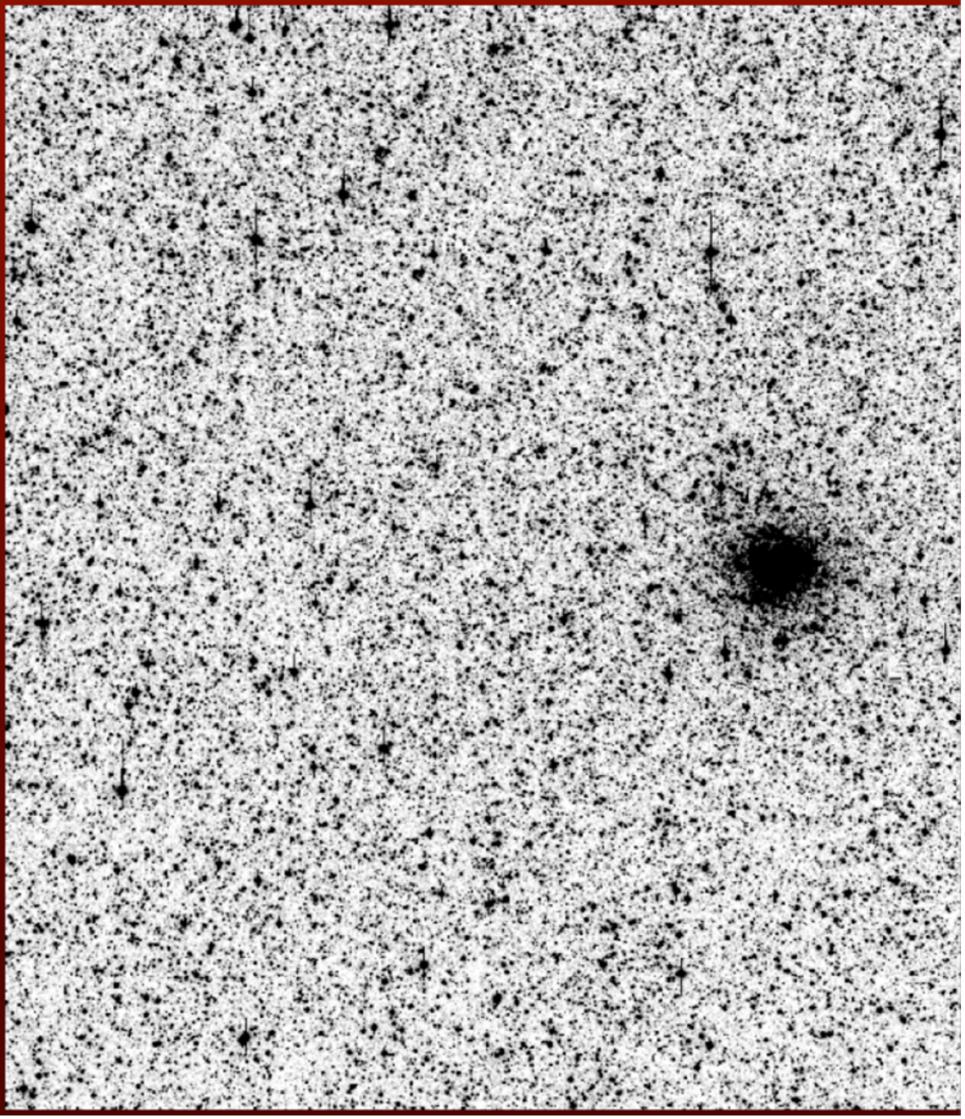


Bulge in Context



Baade's Window

- Located at (l,b)=(-1°,4°)
- "Low" reddening:
  $E(B-V) = 0.45 \pm 0.10$
  $A_V = 1.3$ to 1.6 mag
- Line of Sight passes ~500 pc (~1 scale length) from Galactic Center.
- Has been heavily studied (OGLE, low-res, etc.).



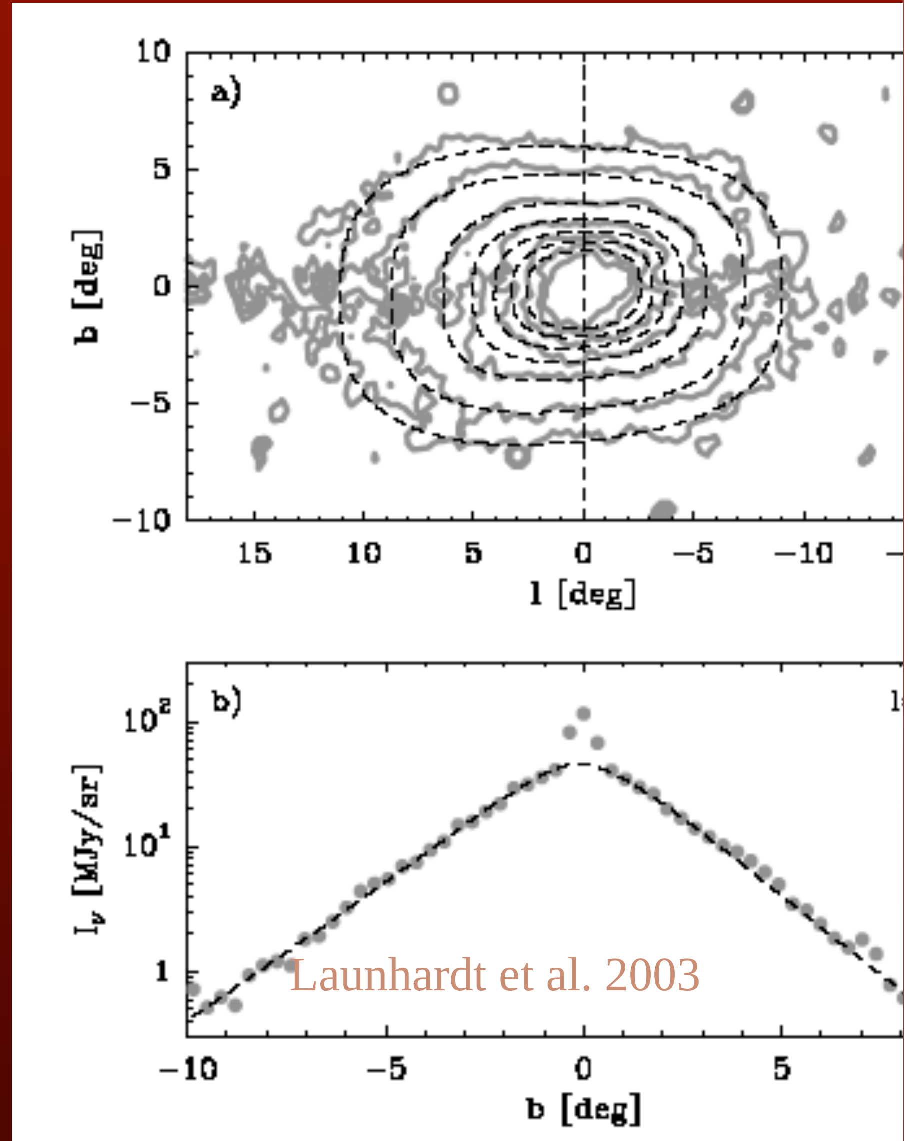
The Inner Bulge < 200 pc: A complex picture

Outside of 200 pc the bulge is dominated by old stars; bar angle ~20^o (Gebhardt et al. 2002); bar has 3 kpc length

The Galactic Center region has star formation, supermassive black hole

Serabyn & Morris (1996) argue that the nuclear region is dominated by the r^-2 cusp. Launhardt et al. 2002 map it.

Nuclear region has continuous star formation but has some old stars.



Launhardt et al. 2003

the inner Galaxy: the bulge ...

structure:

$-20^o < l < +20^o$ → 3 kpc

$-10^o < b < +10^o$ → 1.5 kpc

triaxial/oblate

<u>inner bulge</u> (COBE-DIRBE)

$-10^o < l < +10^o$

$-5^o < b < +5^o$

boxy/peanut shaped → barred

physical parameters:

$L_{bol} \cong 5 \times 10^9\ L_o$ (25%)

$M \cong 2 \times 10^{10}\ M_o$ (20%)

Bar angle ~20^o

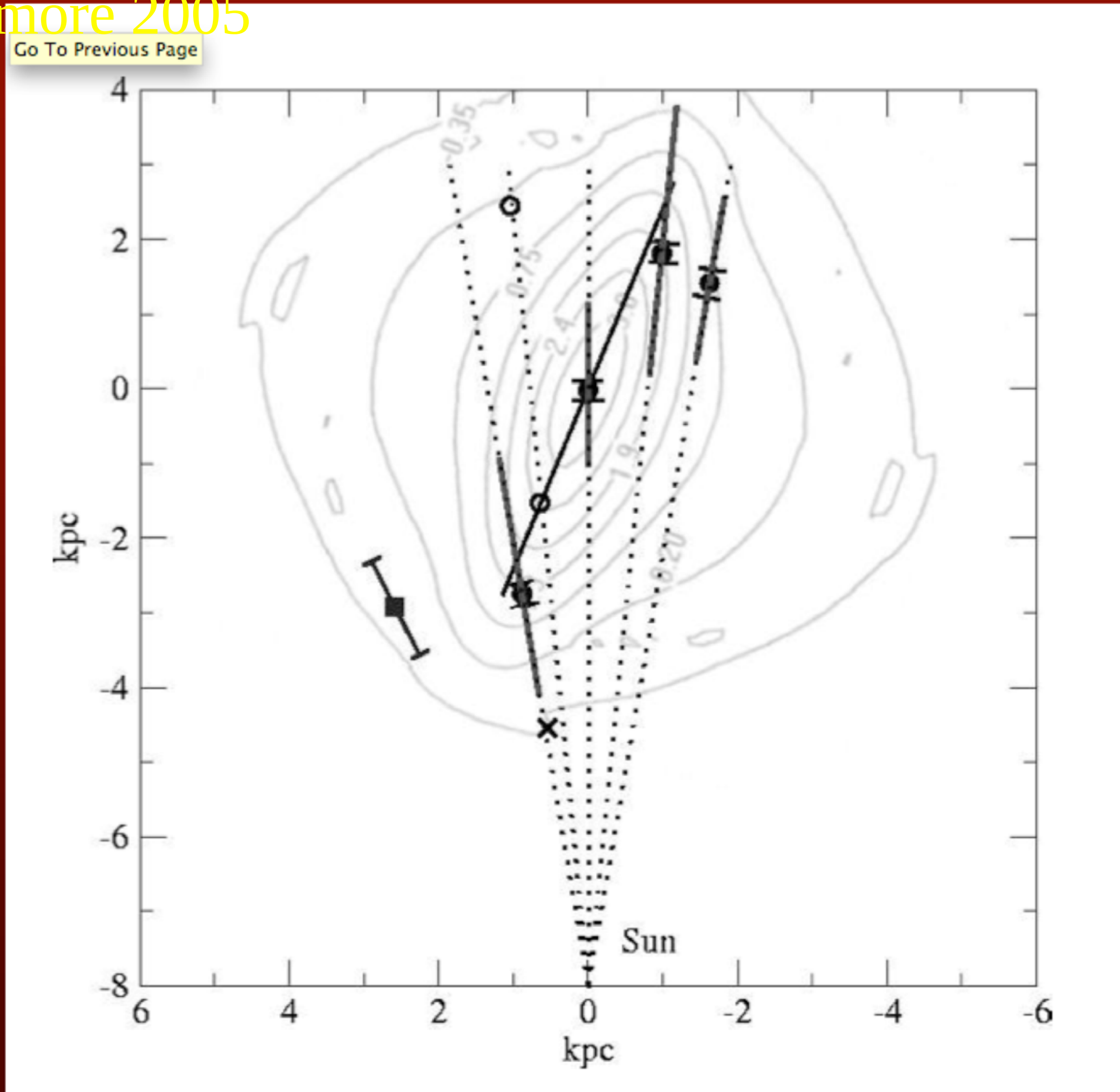
(See Babusiaux & Gilmore 05,
reviews by Gerhard 02,
new work by Benjamin (GLIMPSE)

surface brightness:
power-law (large $r^{1/4}$ bulges) or
exponential (small bulges in late type galaxies) ?

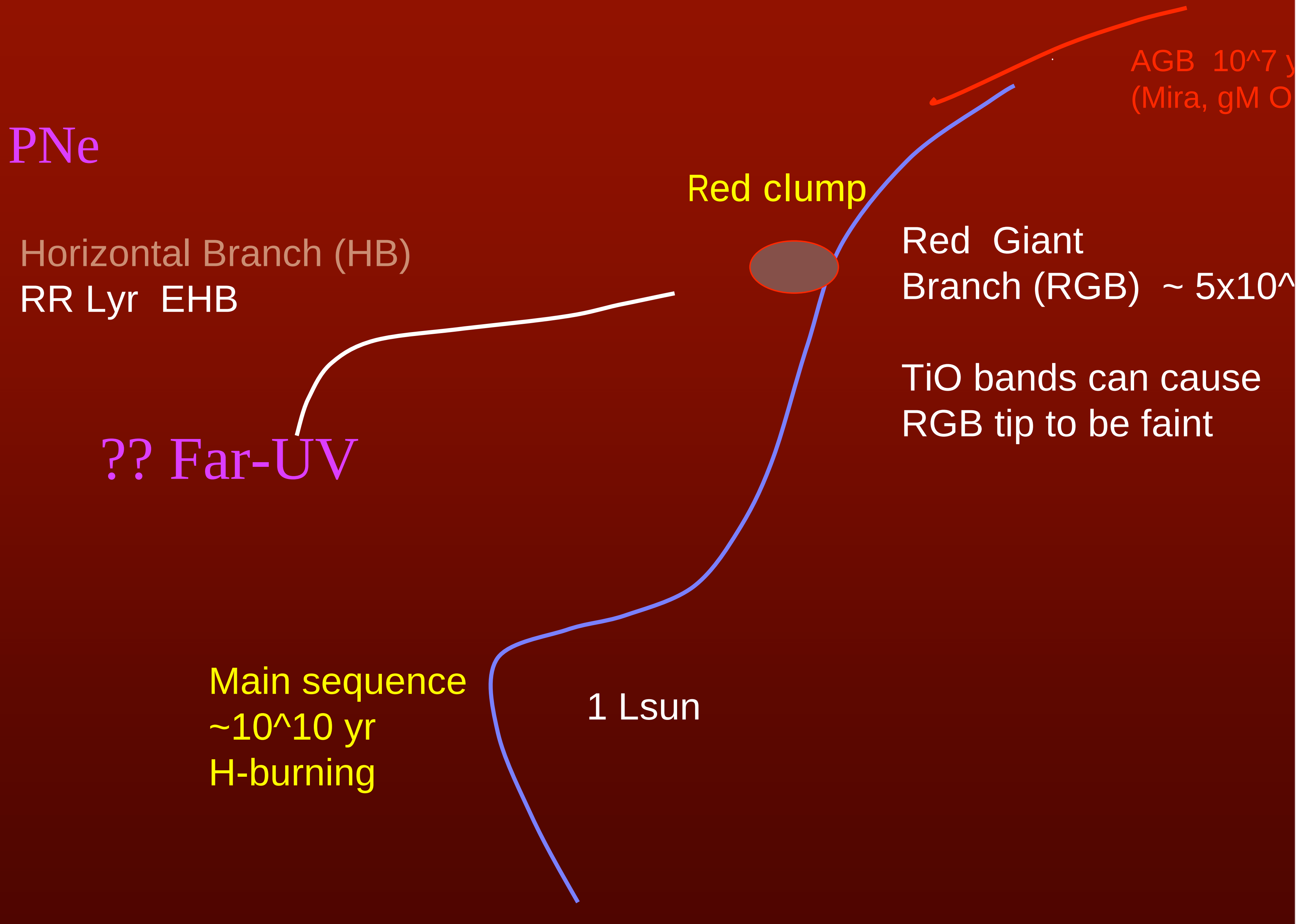
Dwek et al. 2005

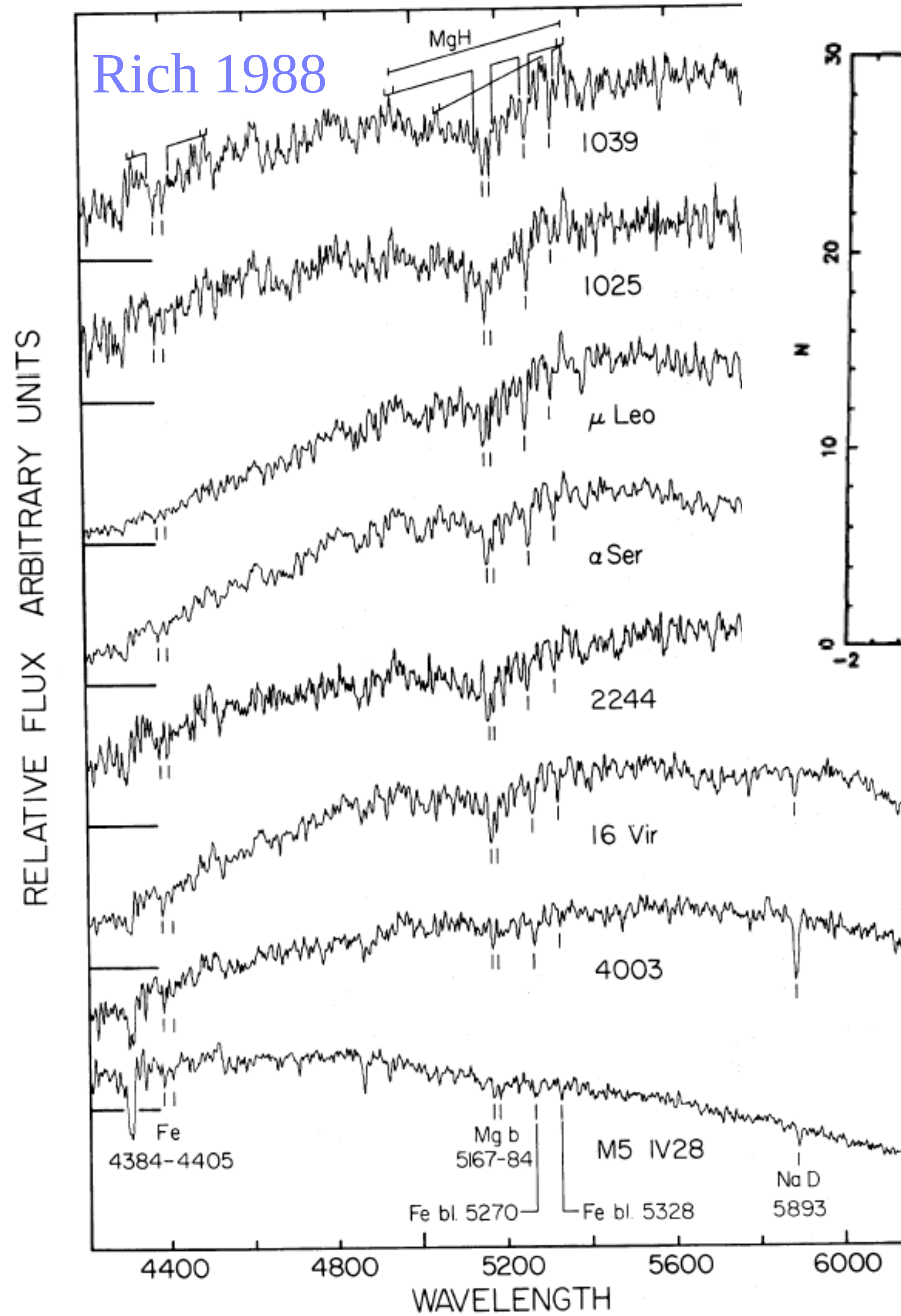
Slide courtesy L. Origlia

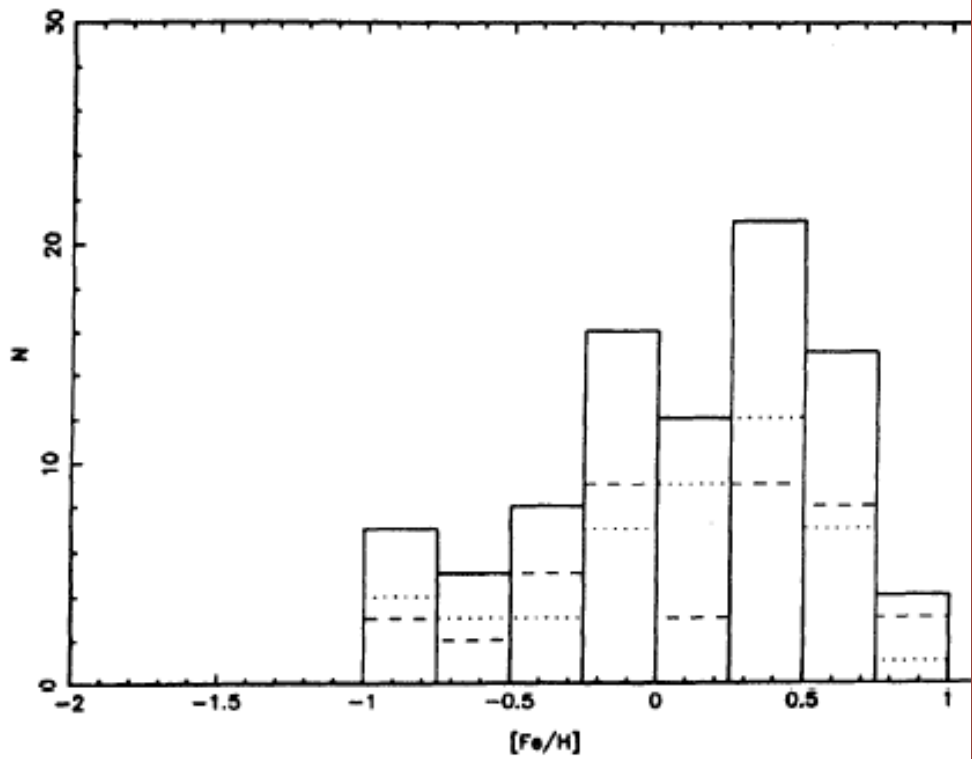
Bar structure from red clump distance; Babusiaux & Gilmore 2005

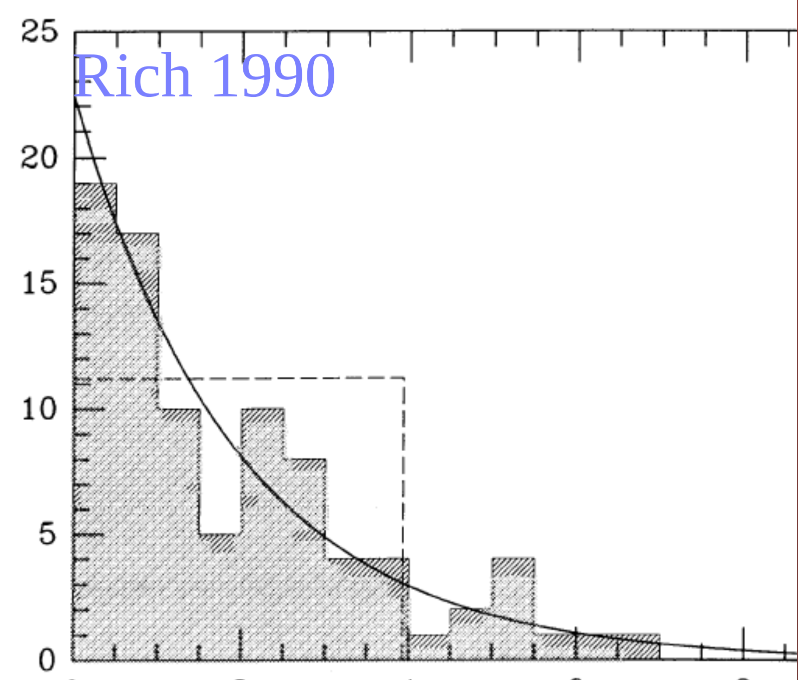


Stellar Evolution in the Bulge

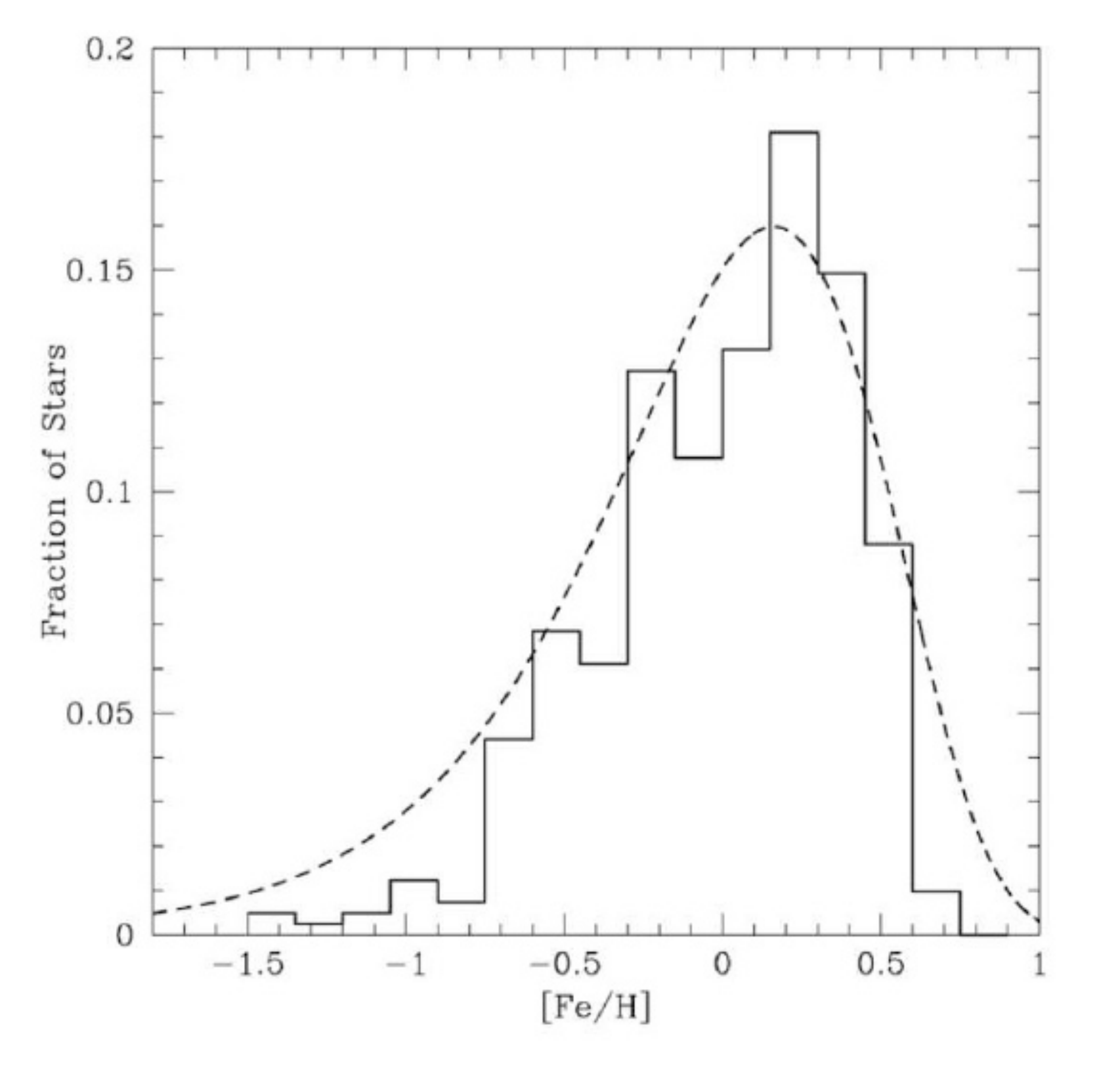



Rich 1988
MgH
1039
1025
μ Leo
α Ser
2244
16 Vir
4003
Fe
4384-4405
Mg b
5167-84
M5 IV28
Na D
5893
Fe bl. 5270
Fe bl. 5328
RELATIVE FLUX ARBITRARY UNITS
4400
4800
5200
5600
6000
WAVELENGTH


N
0
10
20
30
−2
−1.5
−1
−0.5
0
0.5
1
[Fe/H]


Rich 1990
25
20
15
10
5
0

Simple model fit (Rich et al. 07)to Zoccali et al. 2008 data at -6º



BRAVA
First proposal 2003

Rich et al. 2007 ApJ 658, L29
Rich+ 2007 astro-ph/0710.5162
Howard et al. 2007 astro-ph 0807.3967; ApJ in press.

Strategy: Use M giants brighter than clump that can be observed even in high extinction fields

Select M giants from 2MASS survey (excellent, uniform, astrometry and photometry; ease of developing links to spectra for a public database

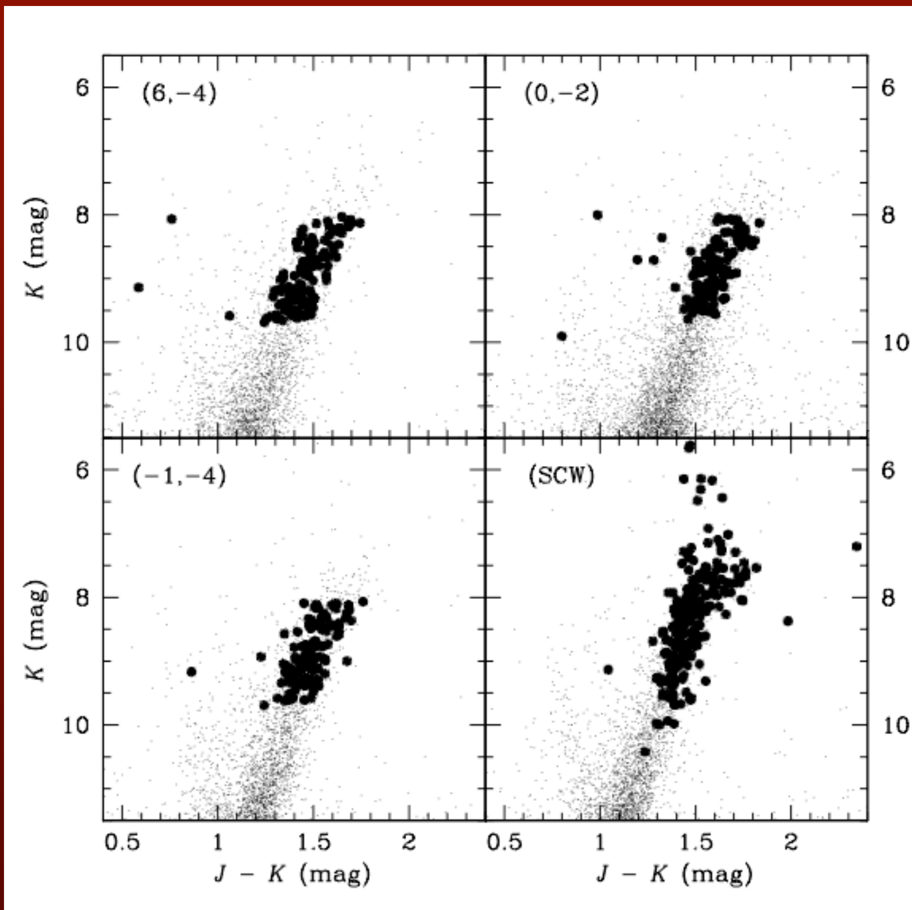
Clear red giant branch easily seen in 2MASS data

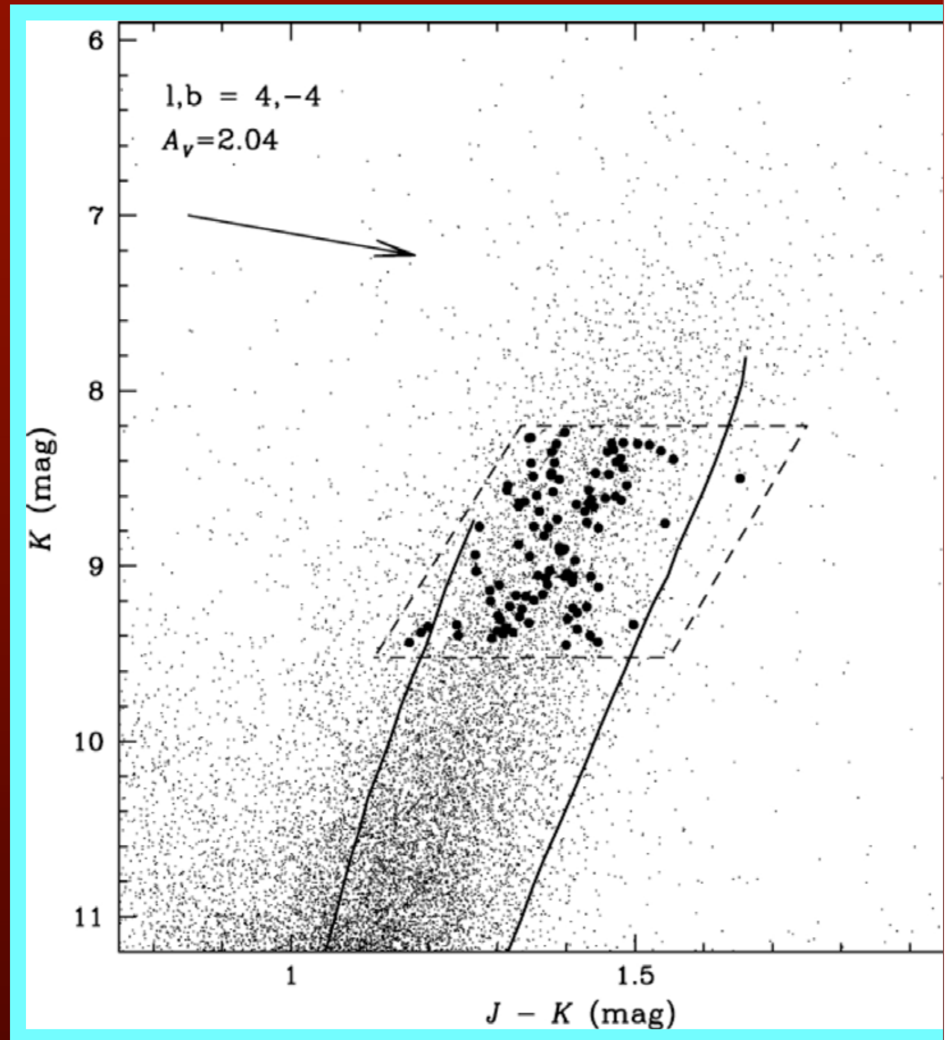
Cross correlation from 7000 - 9000A (include Ca IR triplet)

Abundances from either future IR studies or from modeling of optical spectra

3x10 min exposures with Hydra fiber spectrograph at CTIO Blanco 4m; ~100 stars/field R~4000

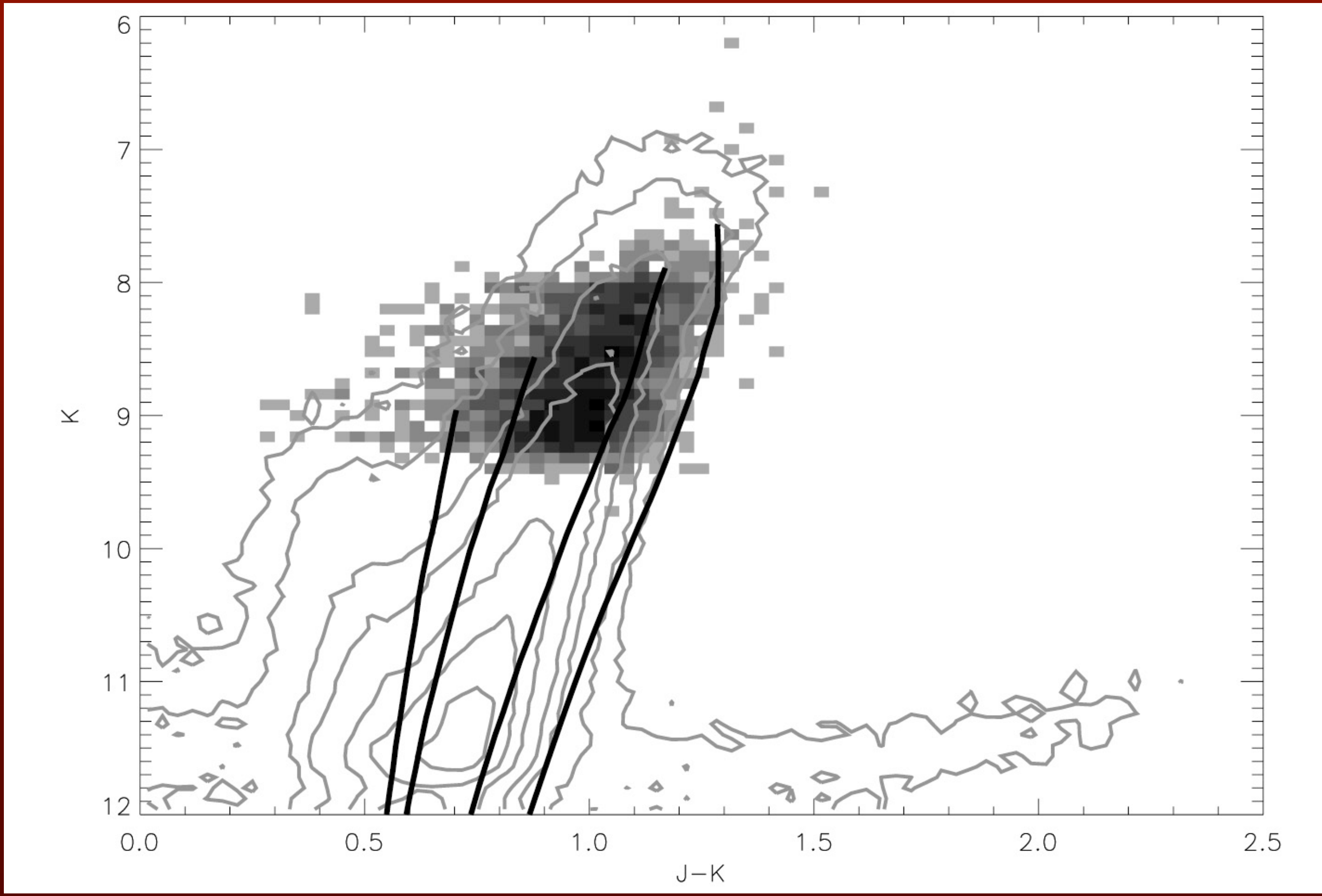
All stars pass through K/M giant phase; avoid region of CMD with overlap from disk and nearby red clump



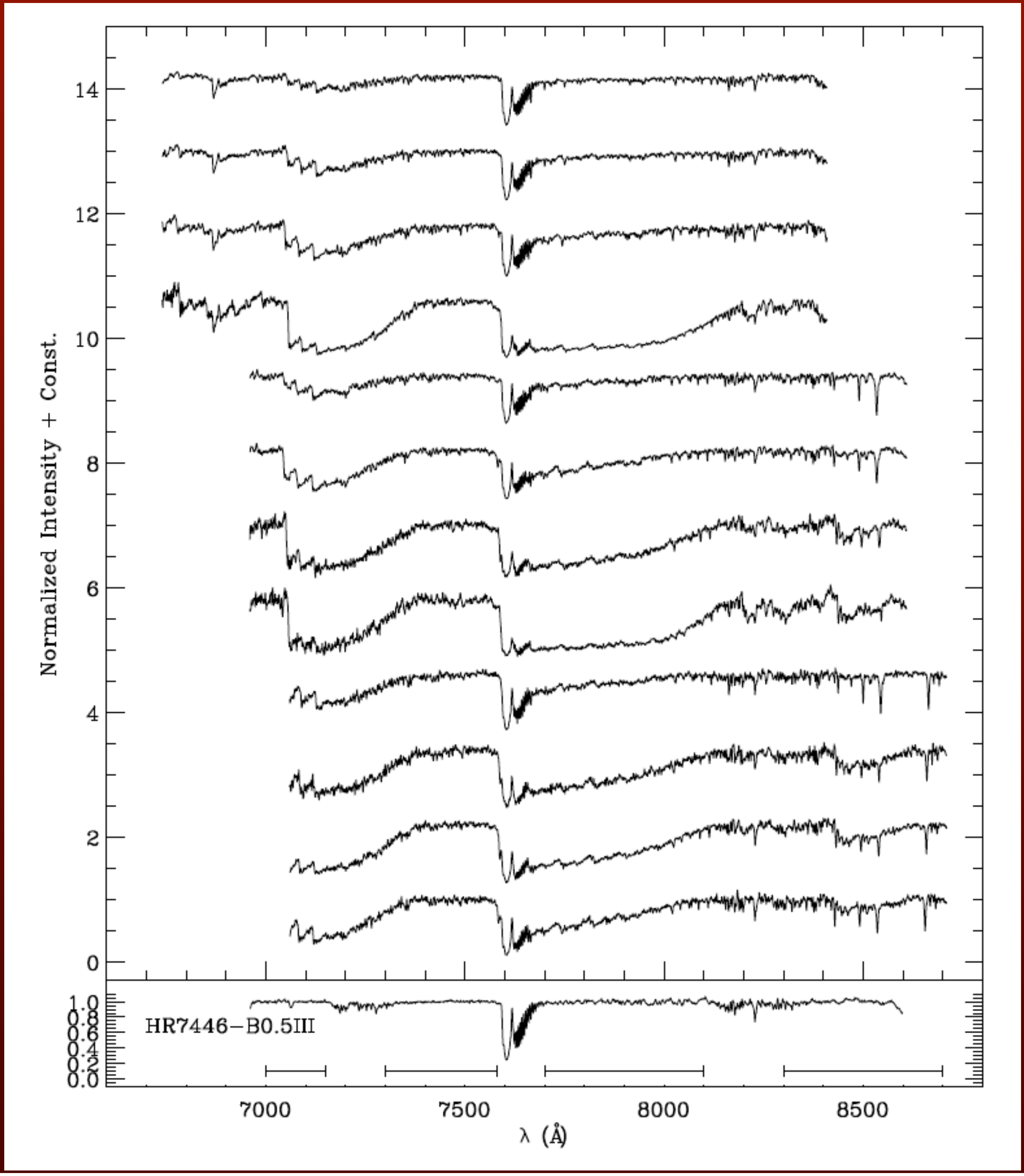


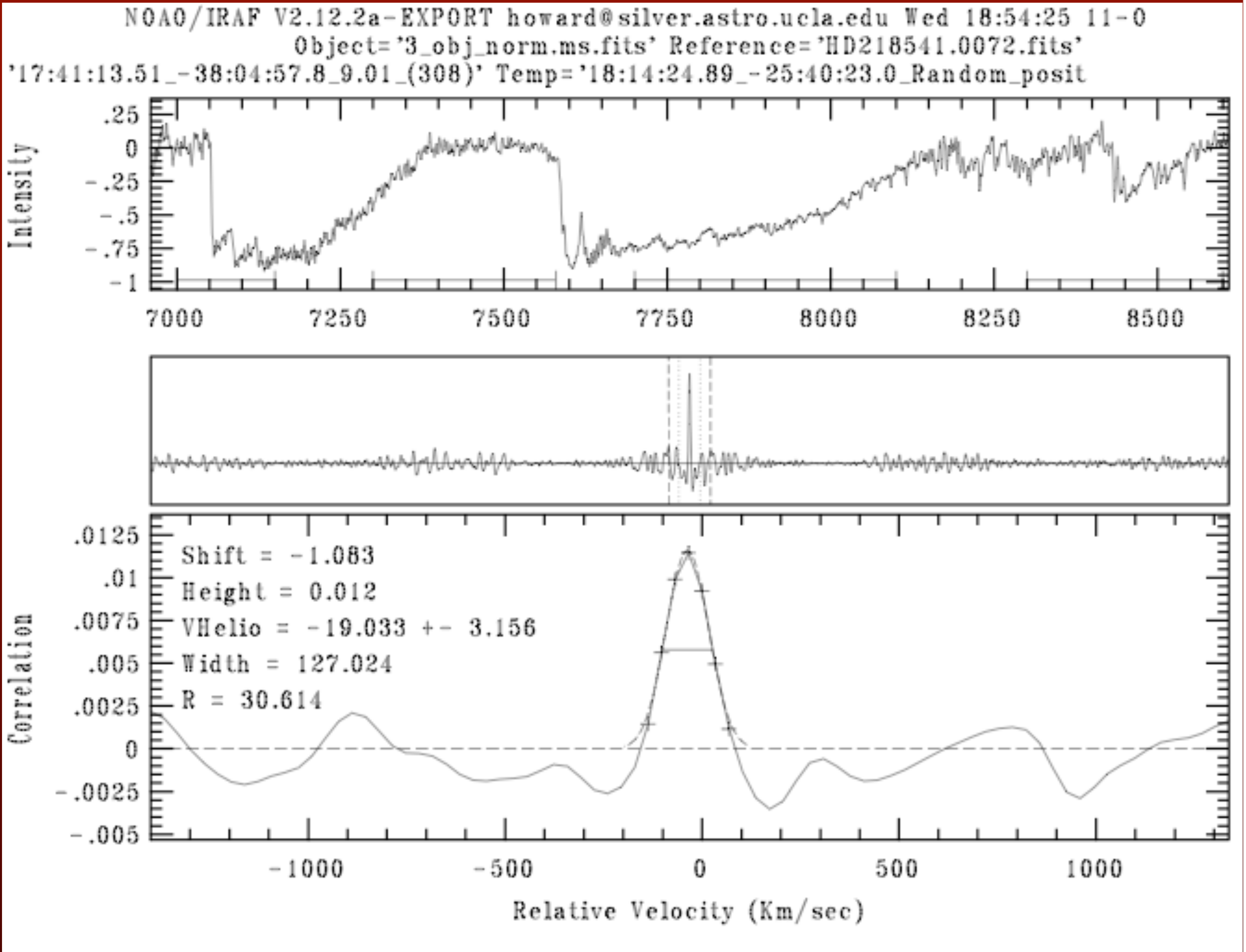
[Fe/H]=-1.3 and +0.5 RGB
Adjust selection for reddening

Full sample, dereddened



Sample BRAVA spectra




NOAO/IRAF V2.12.2a-EXPORT howard@silver.astro.ucla.edu Wed 18:54:25 11-O
Object='3_obj_norm.ms.fits' Reference='HD218541.0072.fits'
'17:41:13.51_-38:04:57.8_9.01_(308)' Temp='18:14:24.89_-25:40:23.0_Random_posit
Intensity
.25
0
-.25
-.5
-.75
-1
7000
7250
7500
7750
8000
8250
8500
Correlation
.0125
.01
.0075
.005
.0025
0
-.0025
-.005
Shift = -1.083
Height = 0.012
VHelio = -19.033 +- 3.156
Width = 127.024
R = 30.614
-1000
-500
0
500
1000
Relative Velocity (Km/sec)

Beaulieau et al. 2000

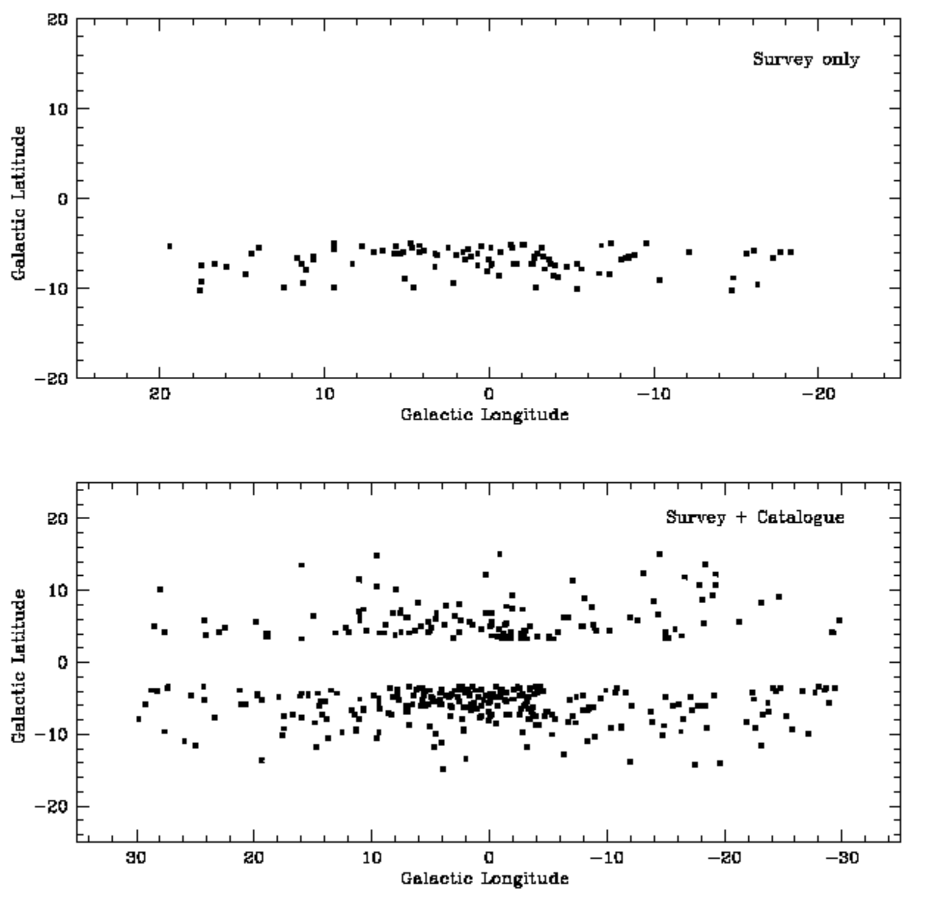
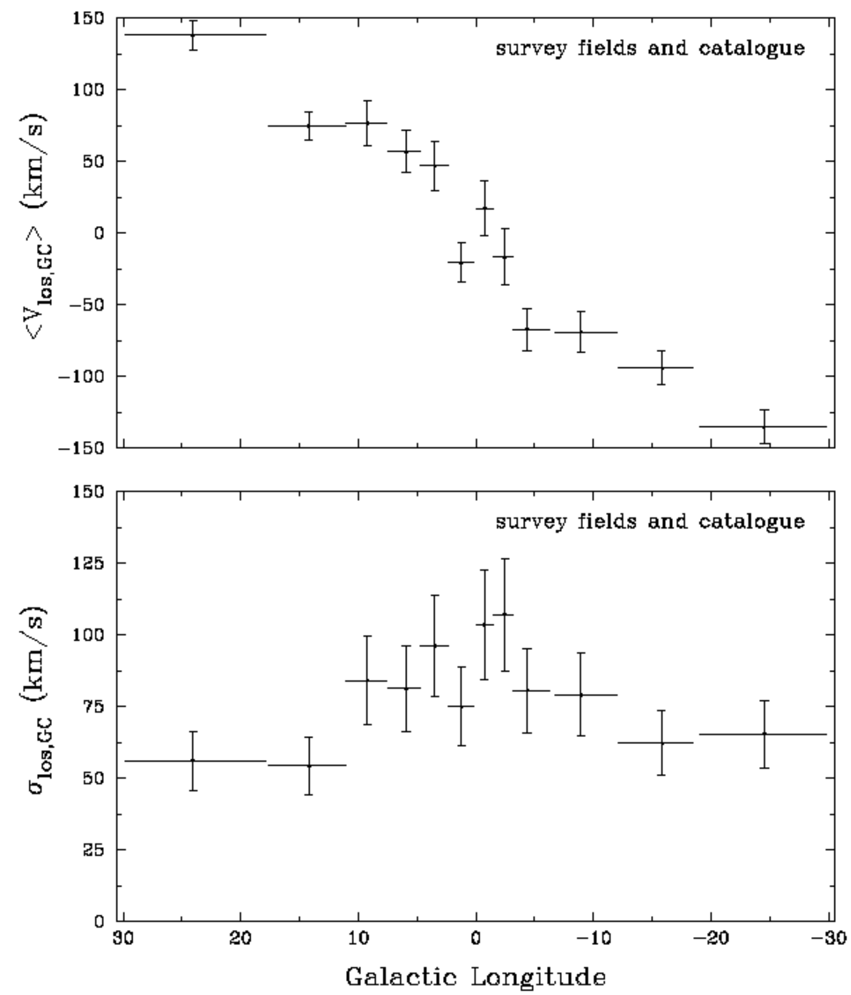


FIG. 2.—(*l*, *b*) distributions for the Survey fields only sample (*top panel*) and the Survey fields + Catalogue sample (*lower panel*).



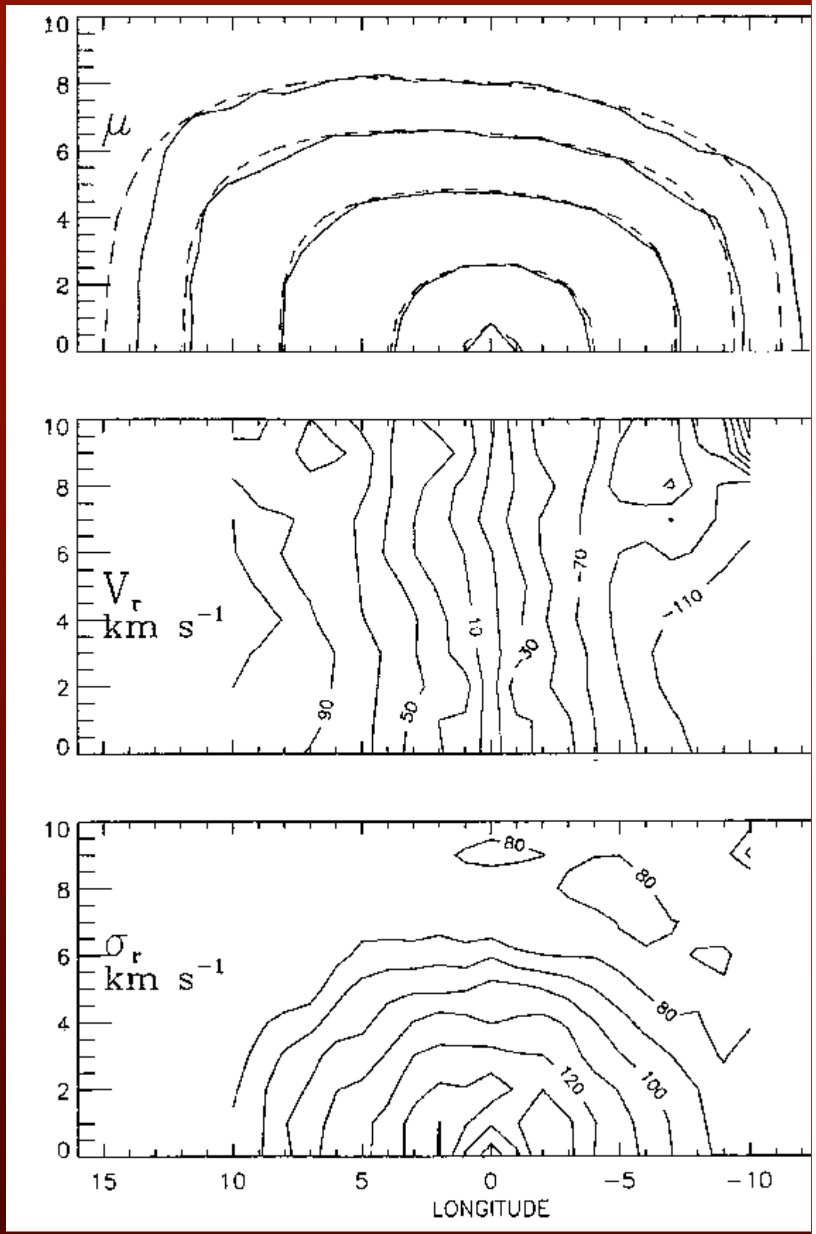
Zhao (1996) self-consistent Rotating Bar model

Schwarzschild method

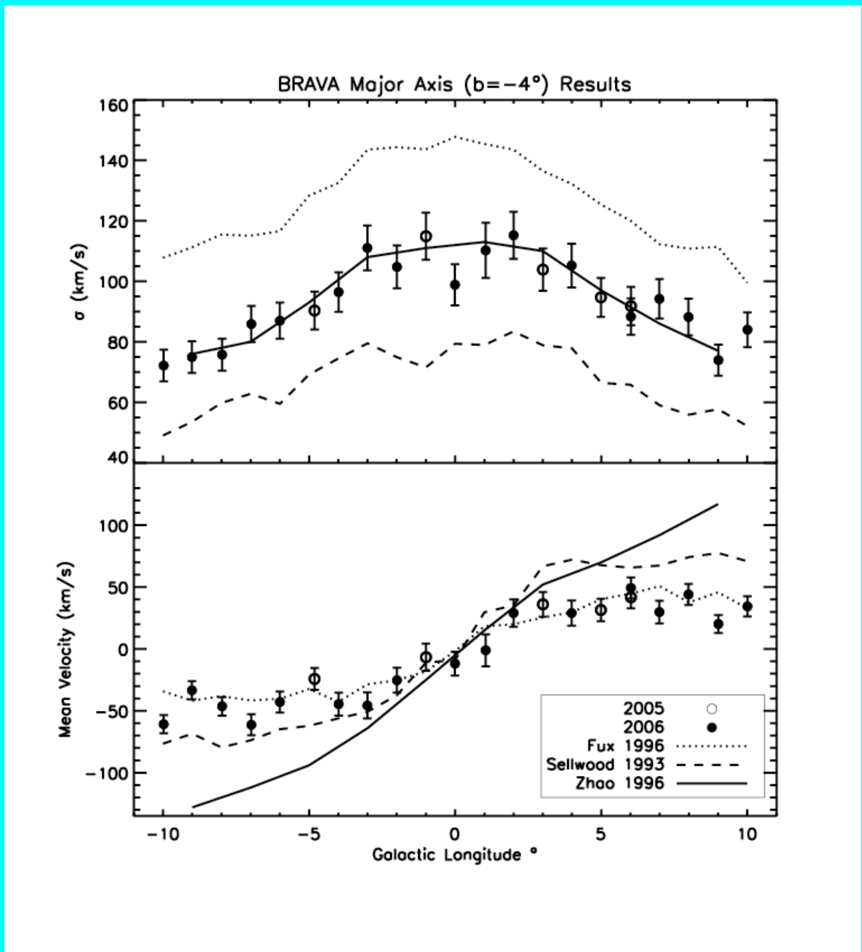
Surf brightness, dynamics constrain orbit families

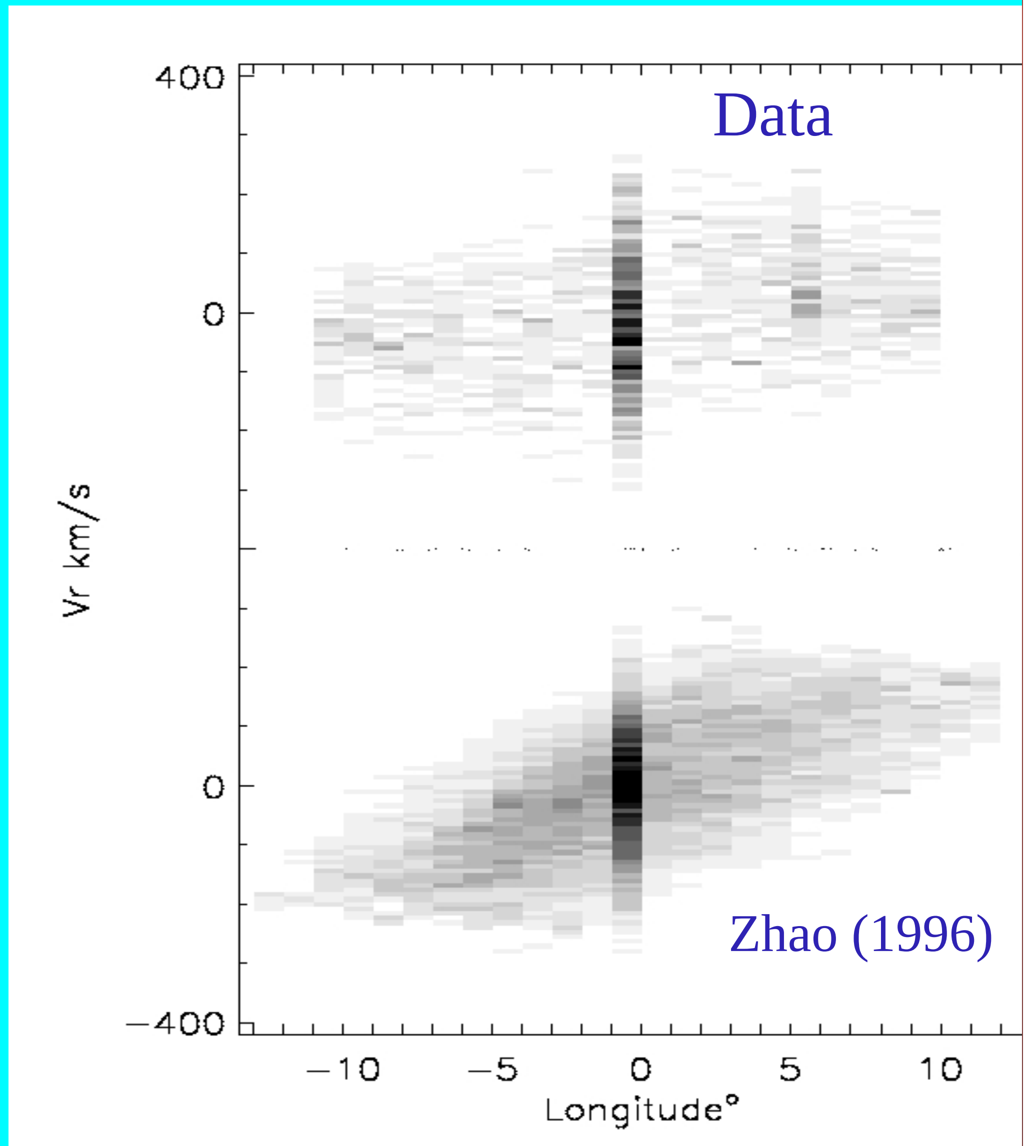
Can populate N-body bar with particles launched according to the model prescription

Model can be modified to respond to new data

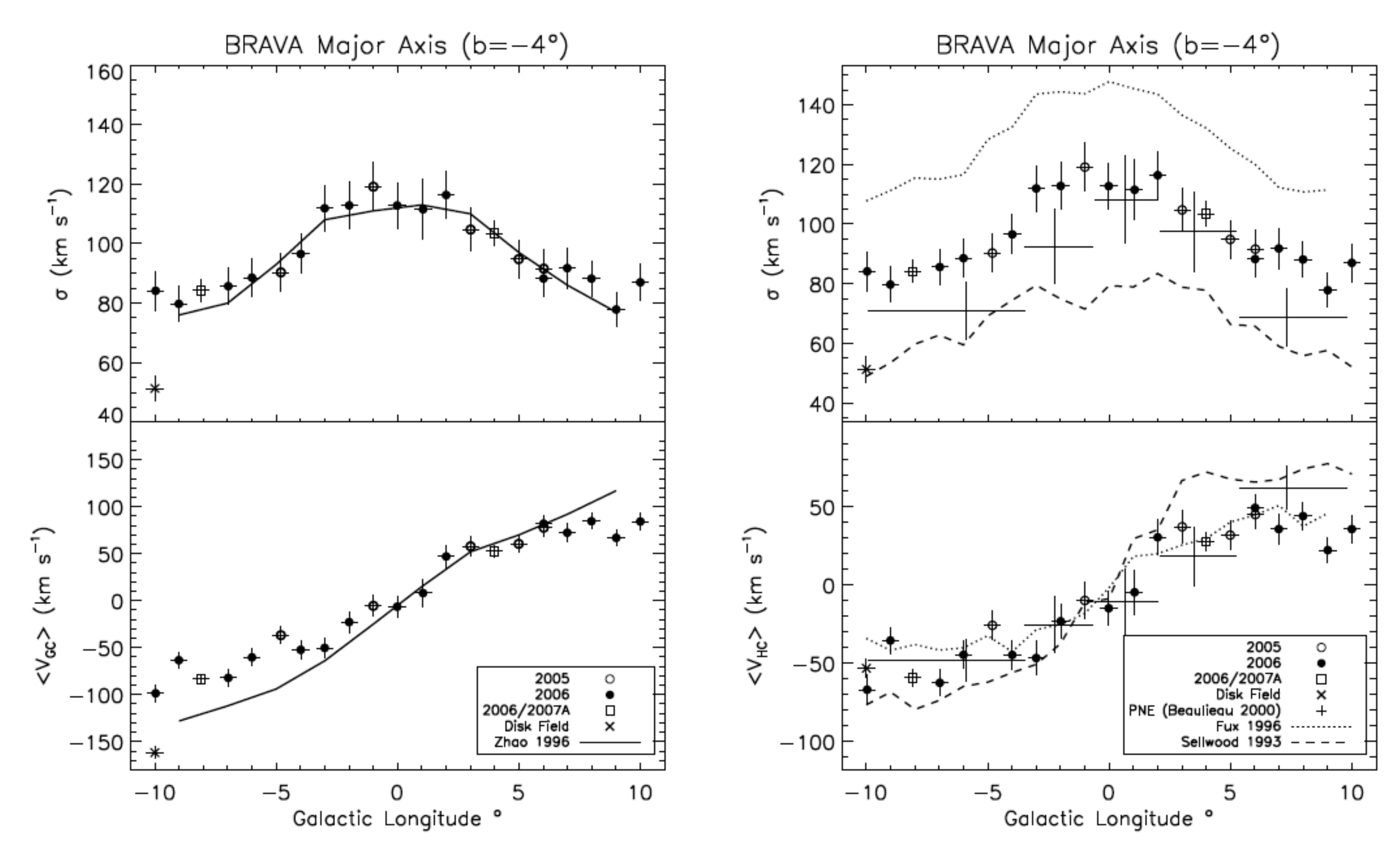


Solid body rotation not present at -4º; Zhao model needs more retrograde orbits

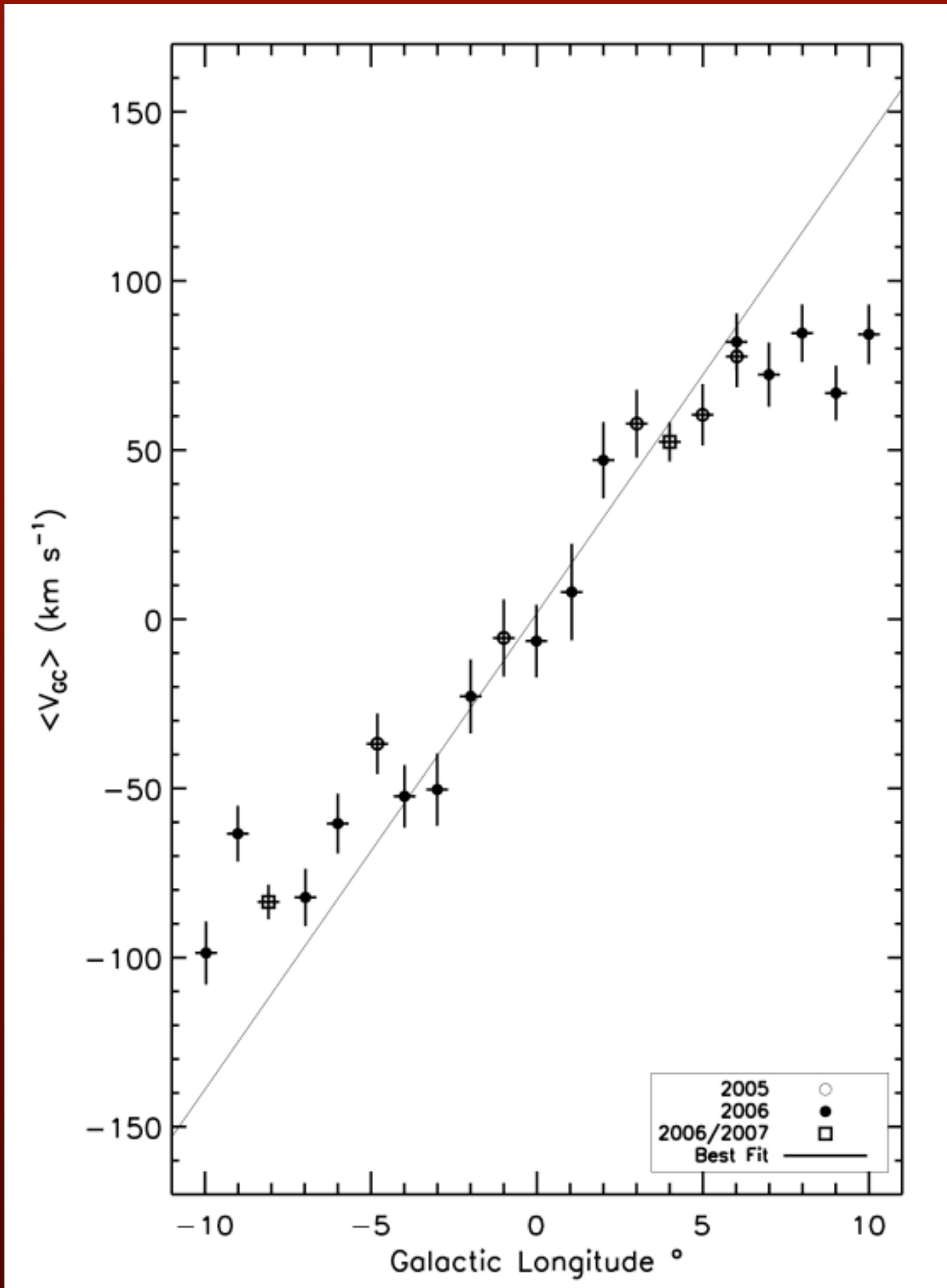




Rebinned Beaulieau data (light open crosses) show Pne agree well with rotation curve but dispersion curve low.

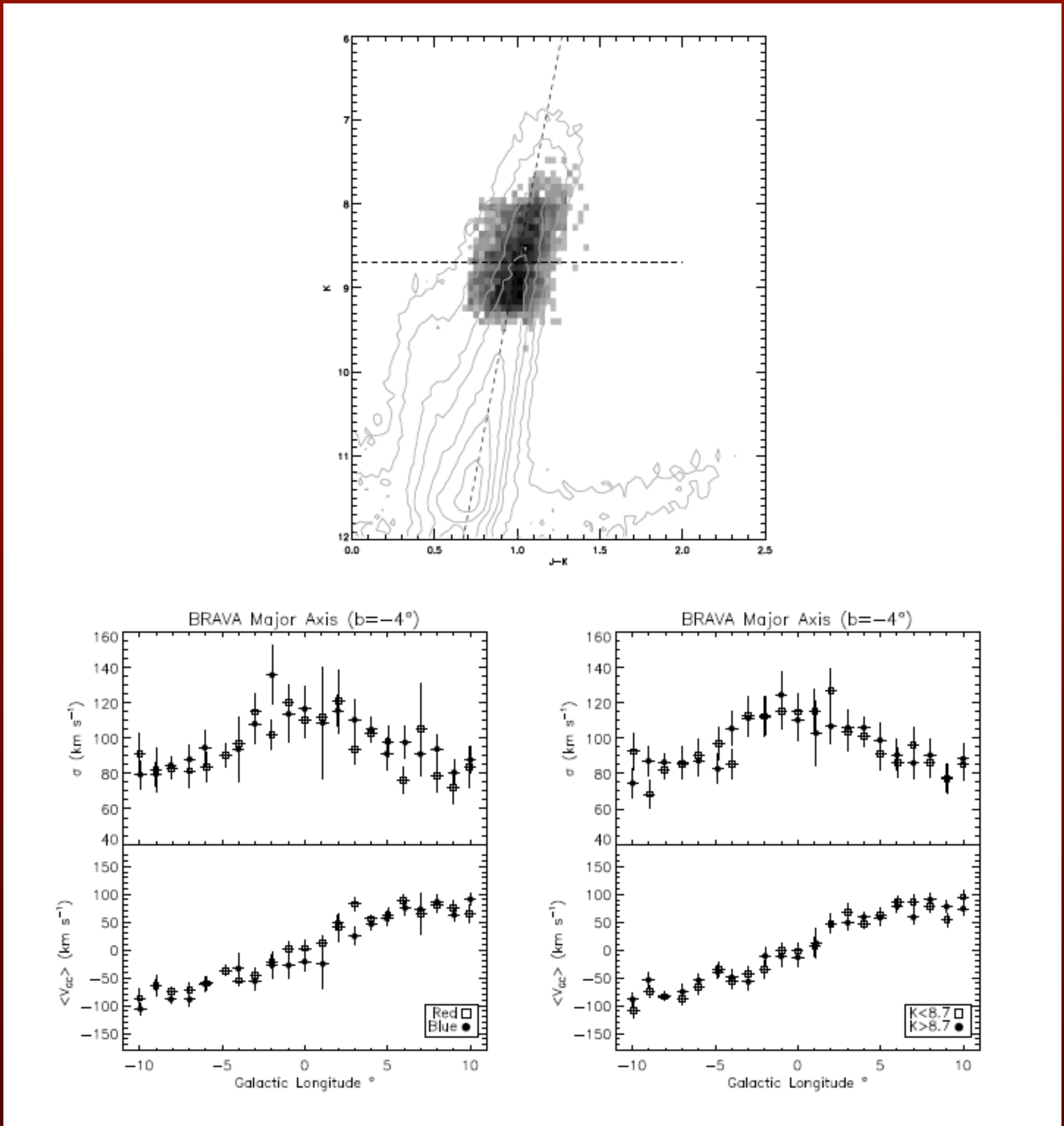


Pne data courtesy S. Beaulieau

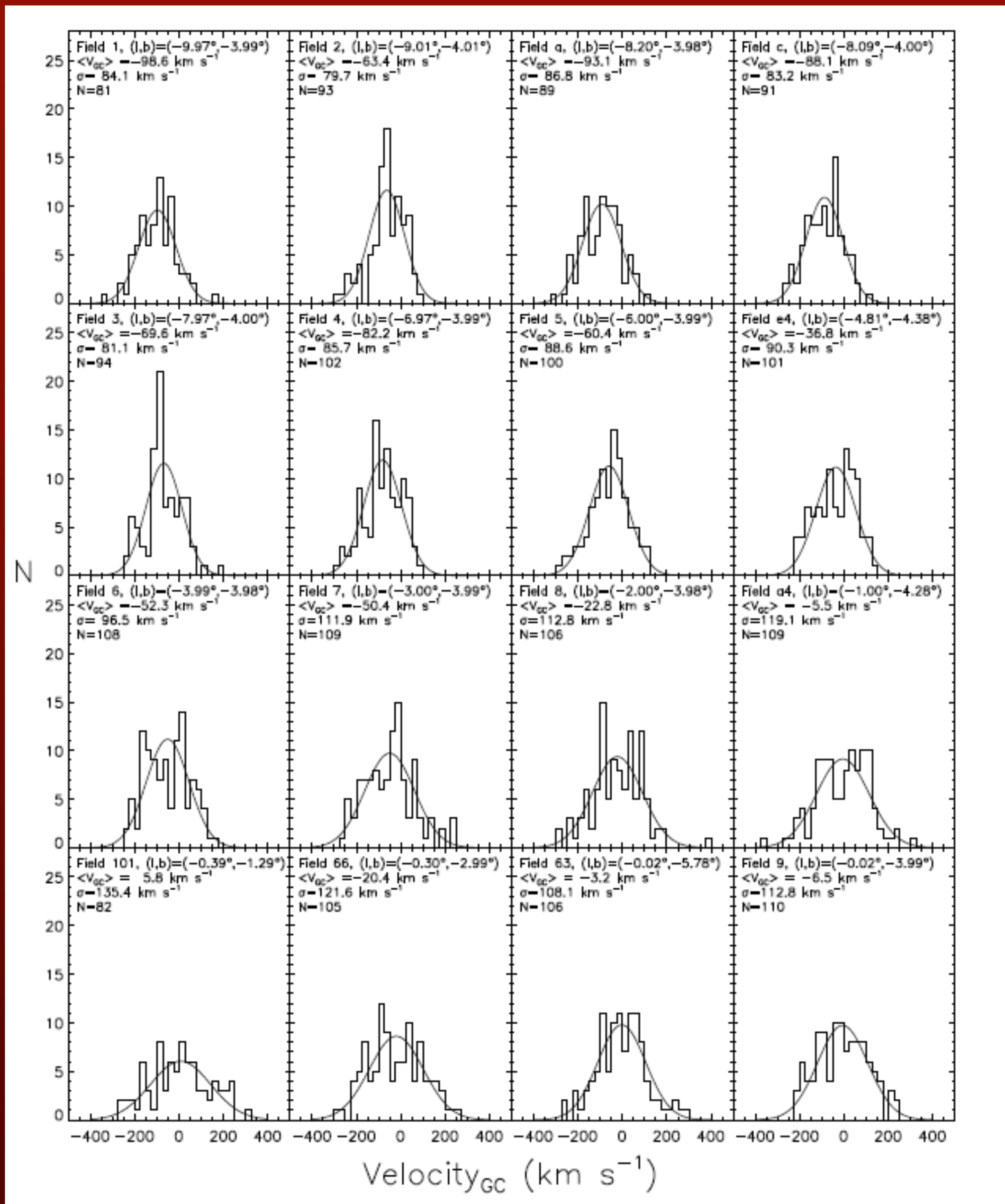


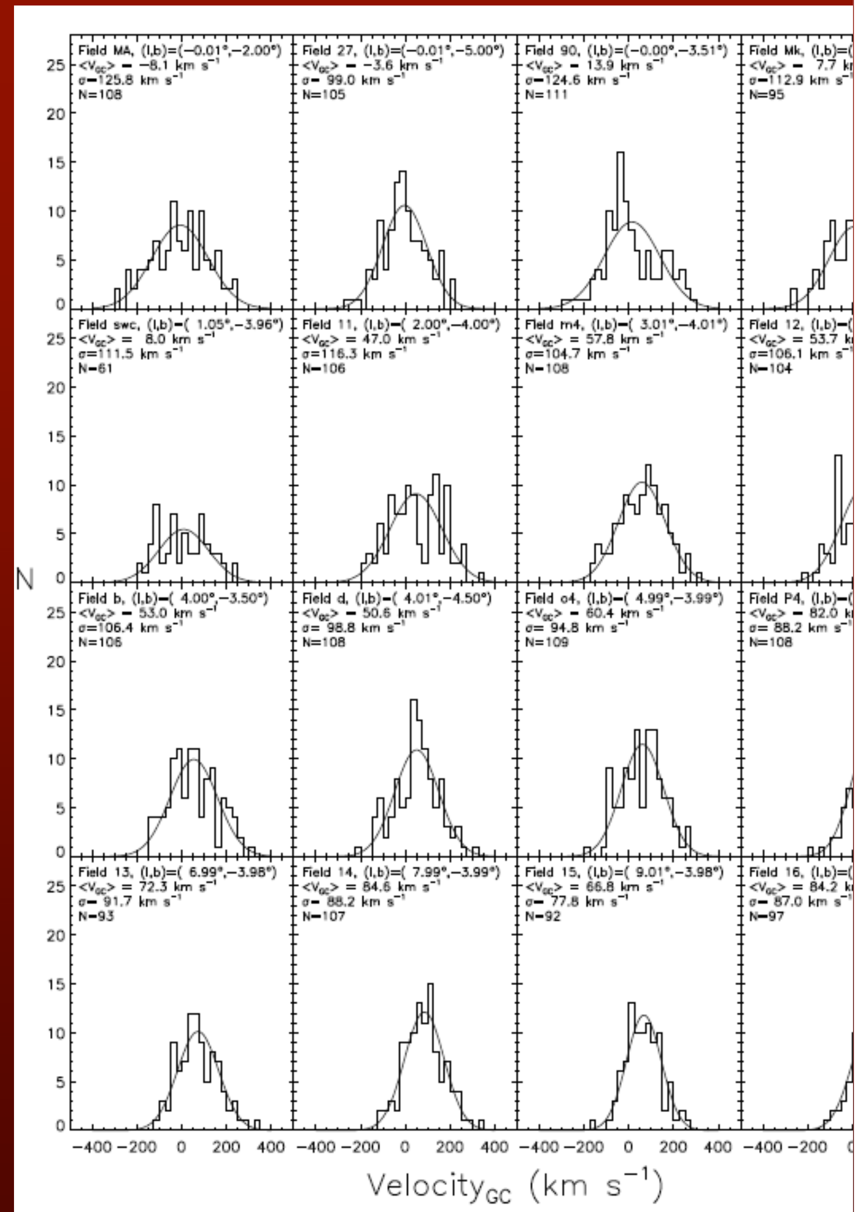
150
100
50
0
−50
−100
−150
−10
−5
0
5
10
Galactic Longitude °
<V_GC> (km s^-1)
2005
2006
2006/2007
Best Fit

Kinematics does not change with color, luminosity

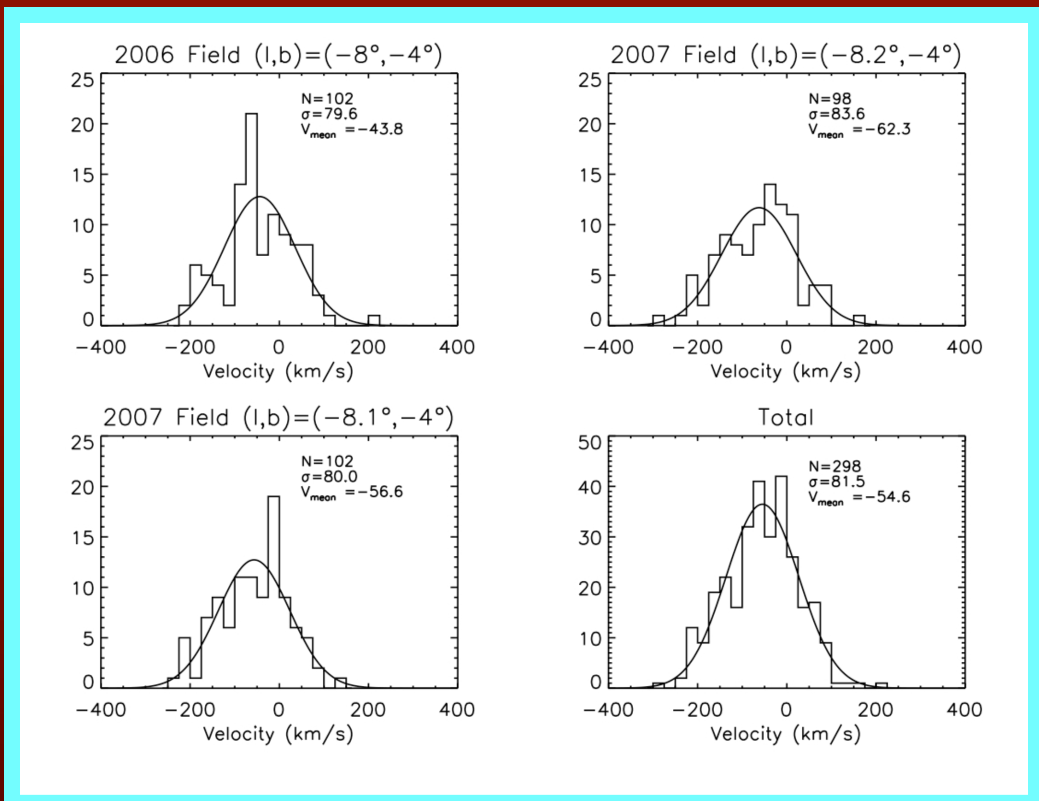


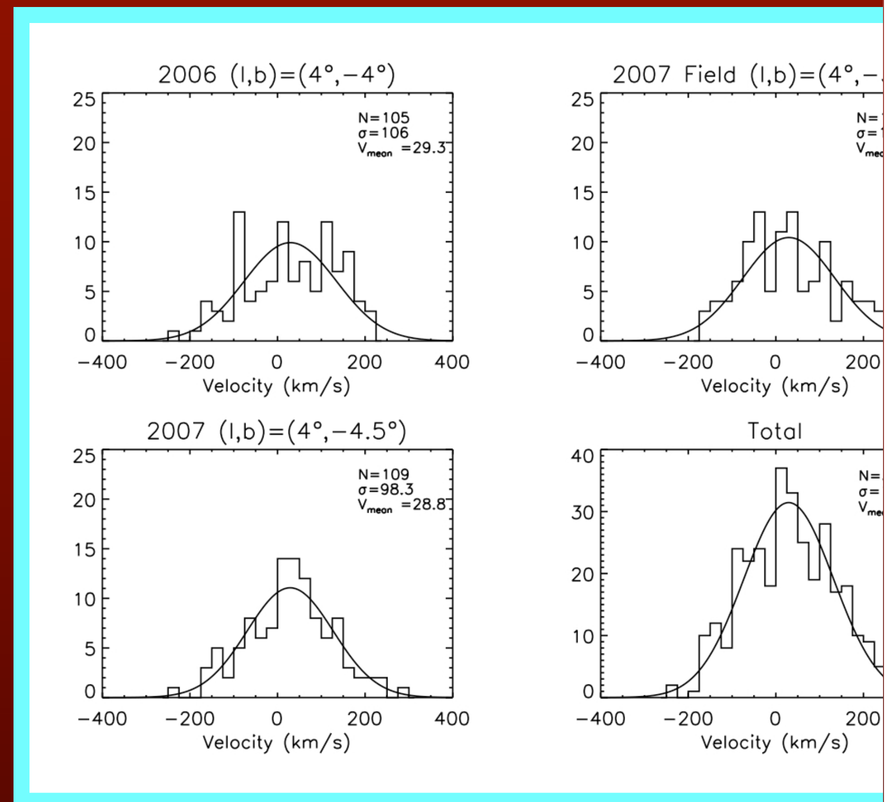
-4° velocity distributions





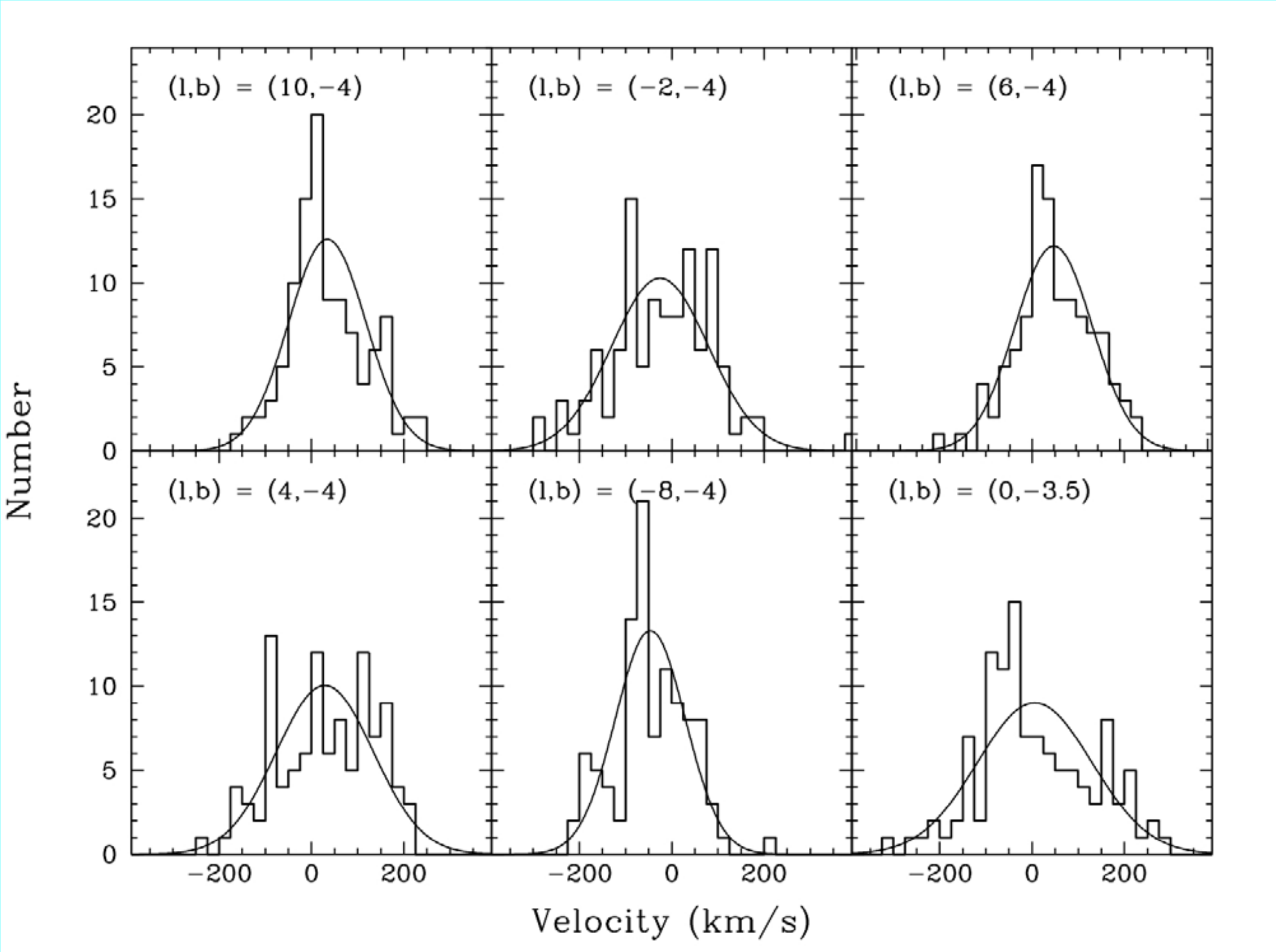
Larger samples have not confirmed 2 stream candidates; all candidates will be followed up. Reitzel et al. (2007) simulations suggest ~1 “real” stream

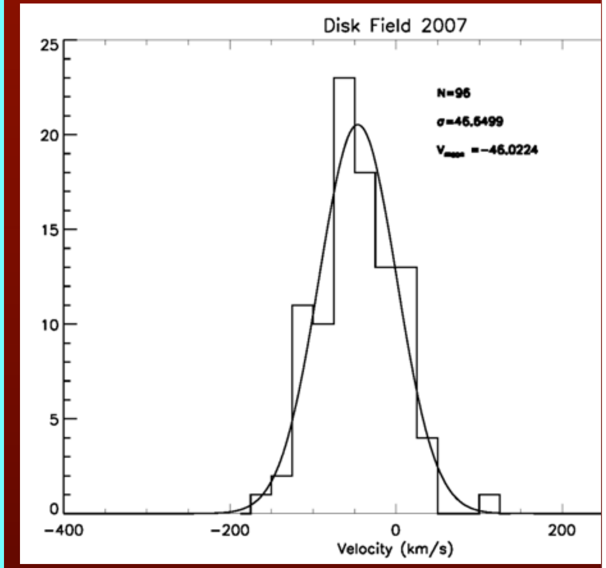




Stream followup important. Possible origins from disrupted globular clusters or dwarf galaxies, groups of stars in unusual orbit families; all candidates presently assumed to be Poisson statistics caused.

Cold streams?



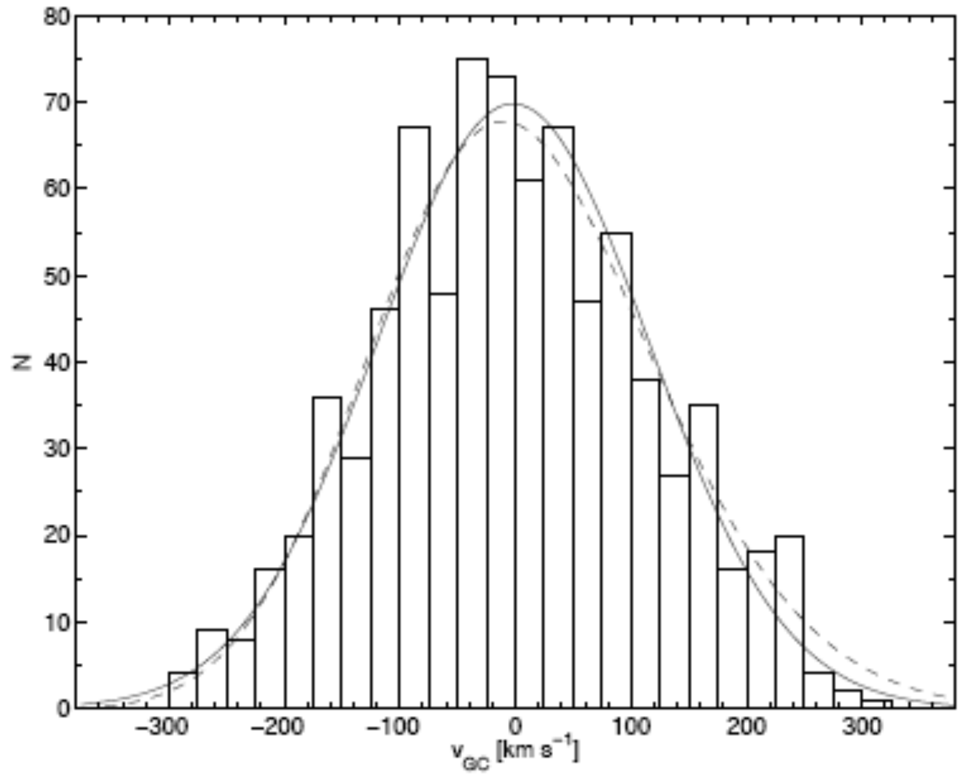


Disk l=-30; sigma 46 km

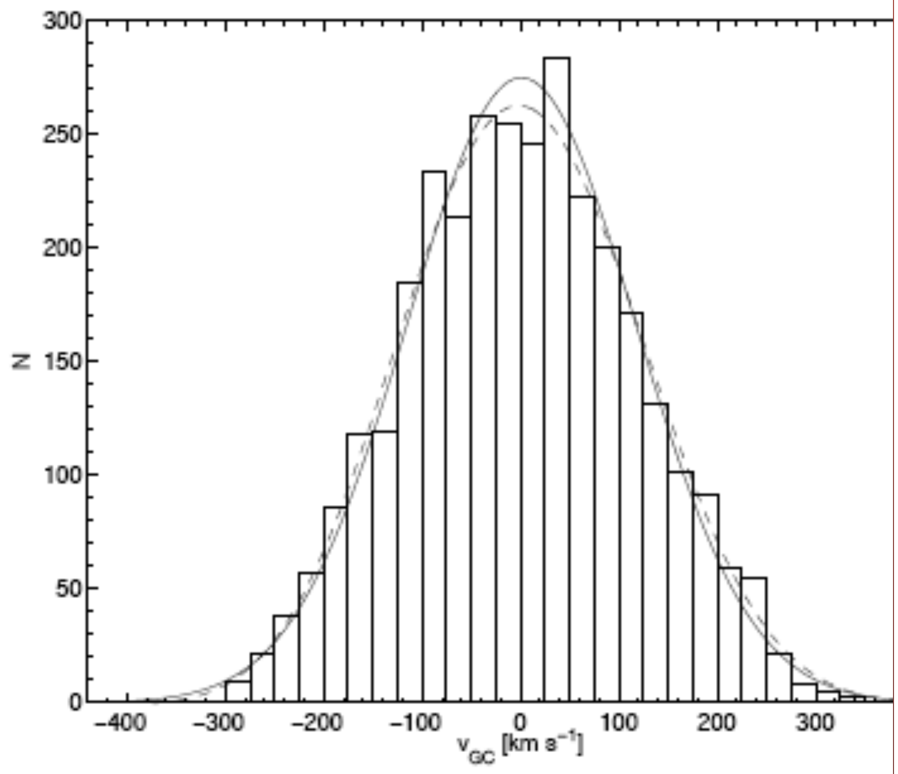
No coincidence with Sgr dwarf at +140 k/s

Summed and shifted data show no departure from Gaussian: No evidence of cold (disky) or hot (halo-like) subcomponents

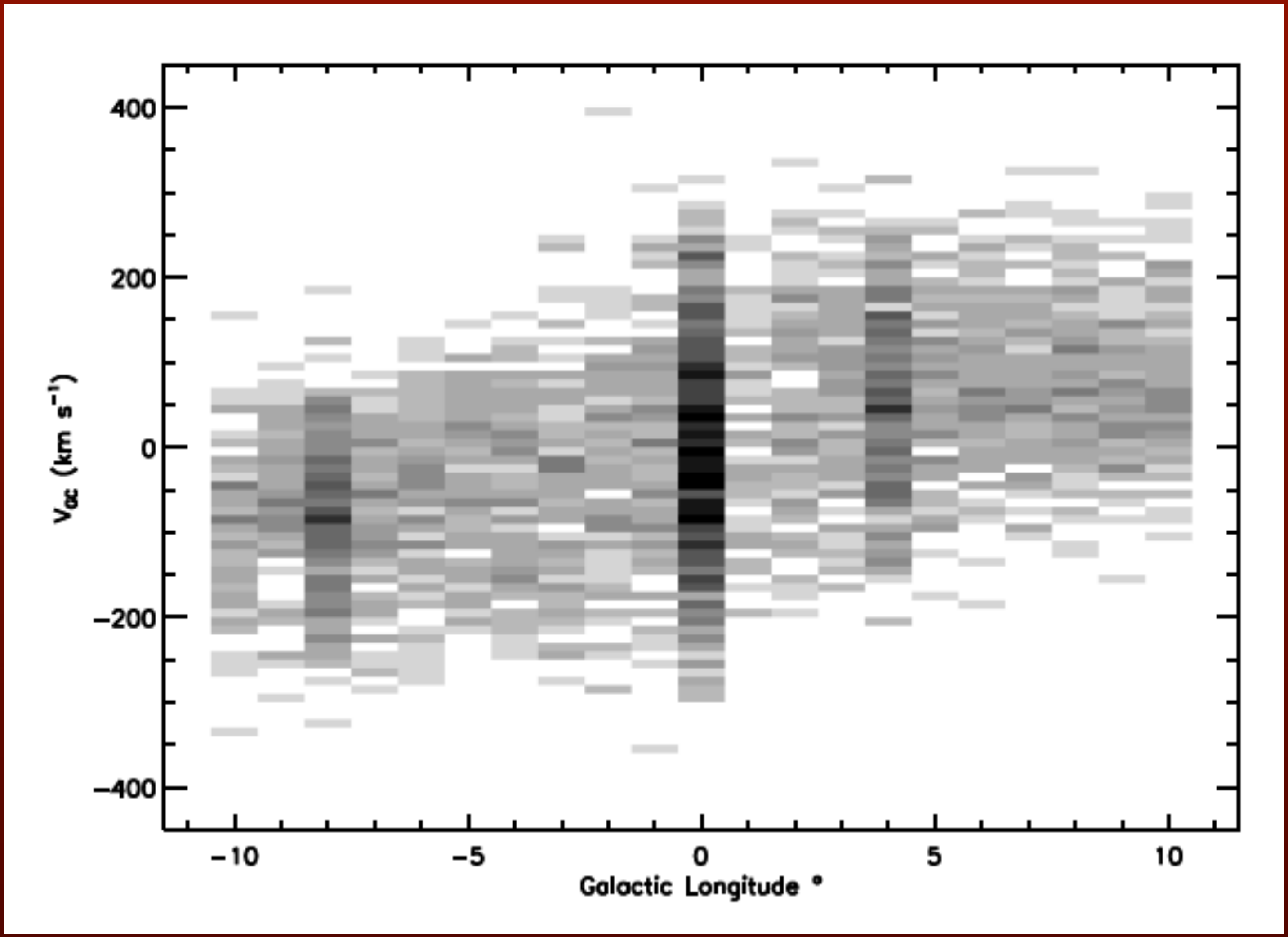
Minor axis, N=822



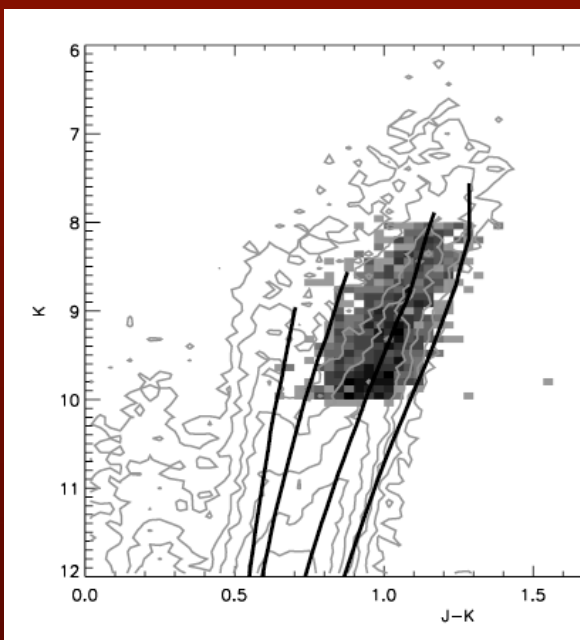
Minor + *b=-4^o^* major, N=30

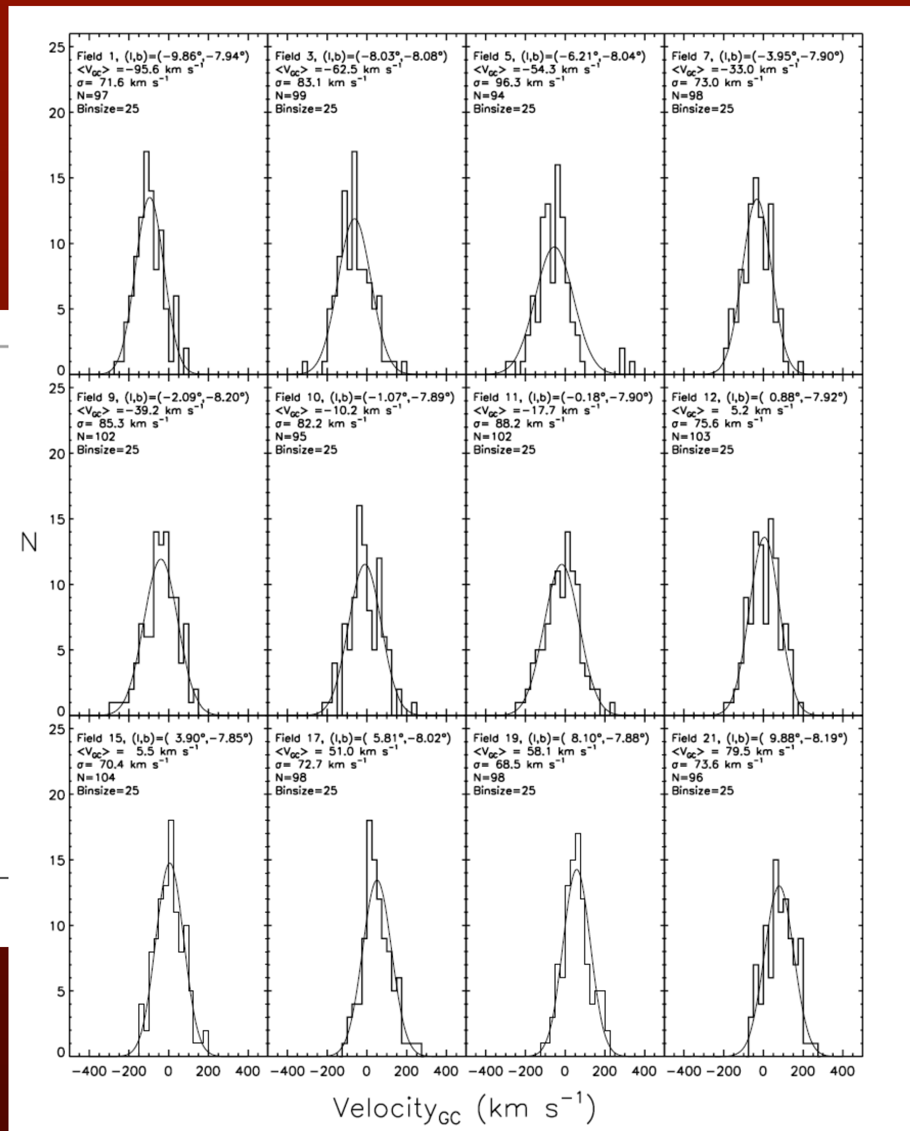


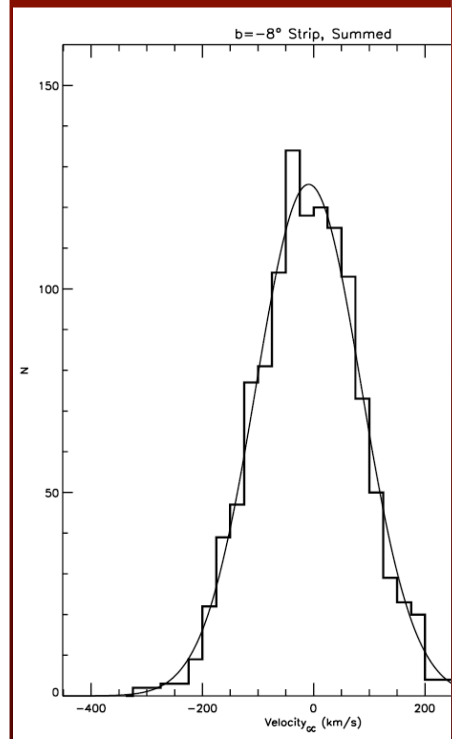
l-v plot also shows no cold (disk) or hot (spheroid) components

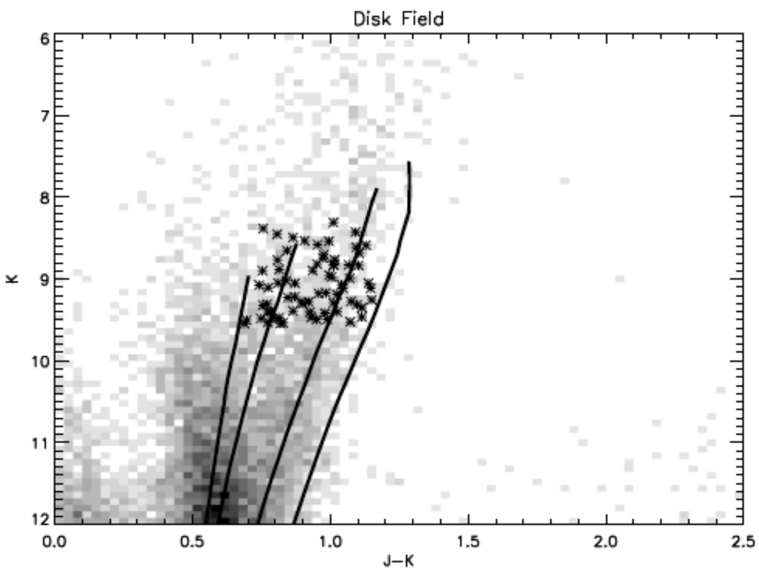


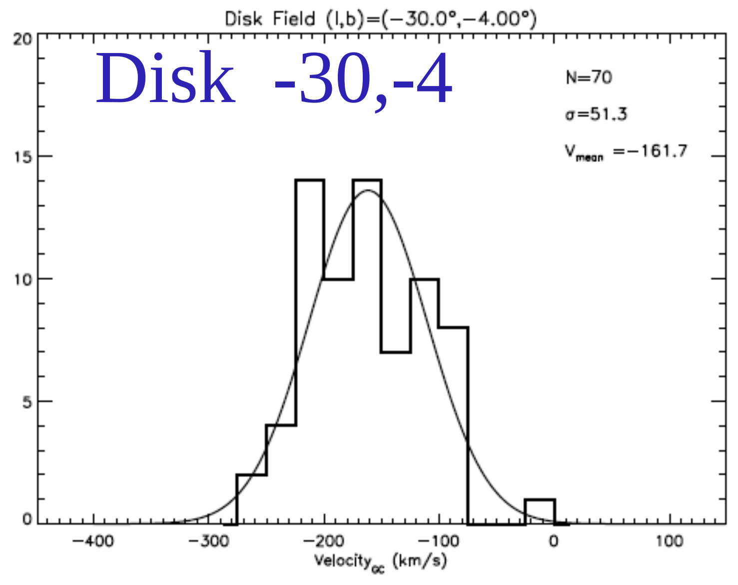
New Results at -8°



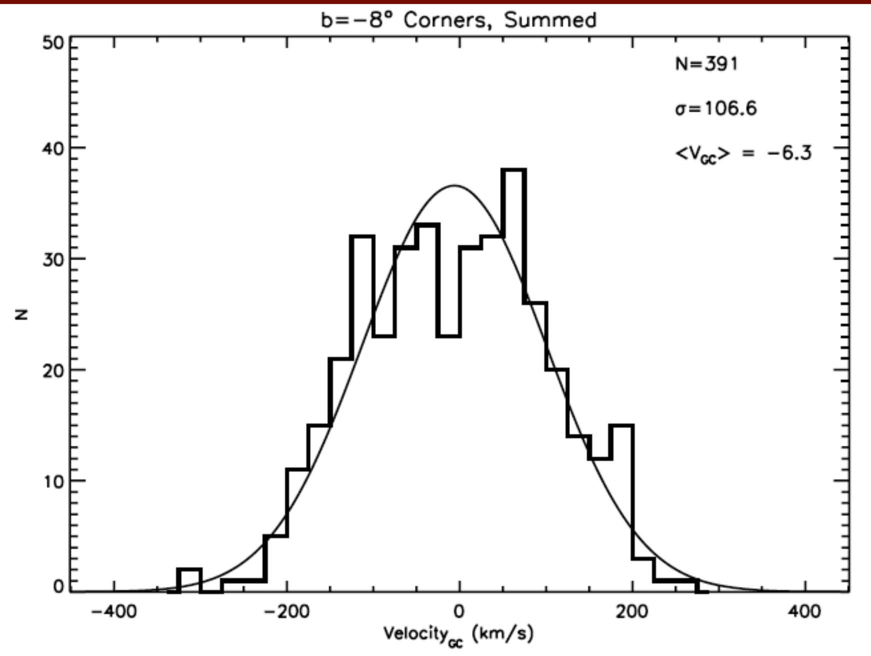


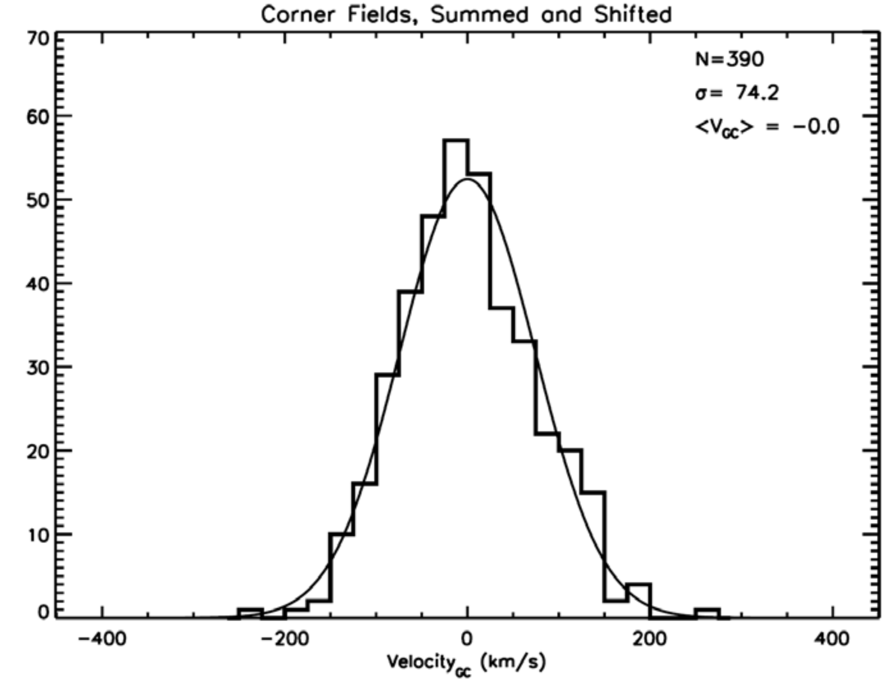




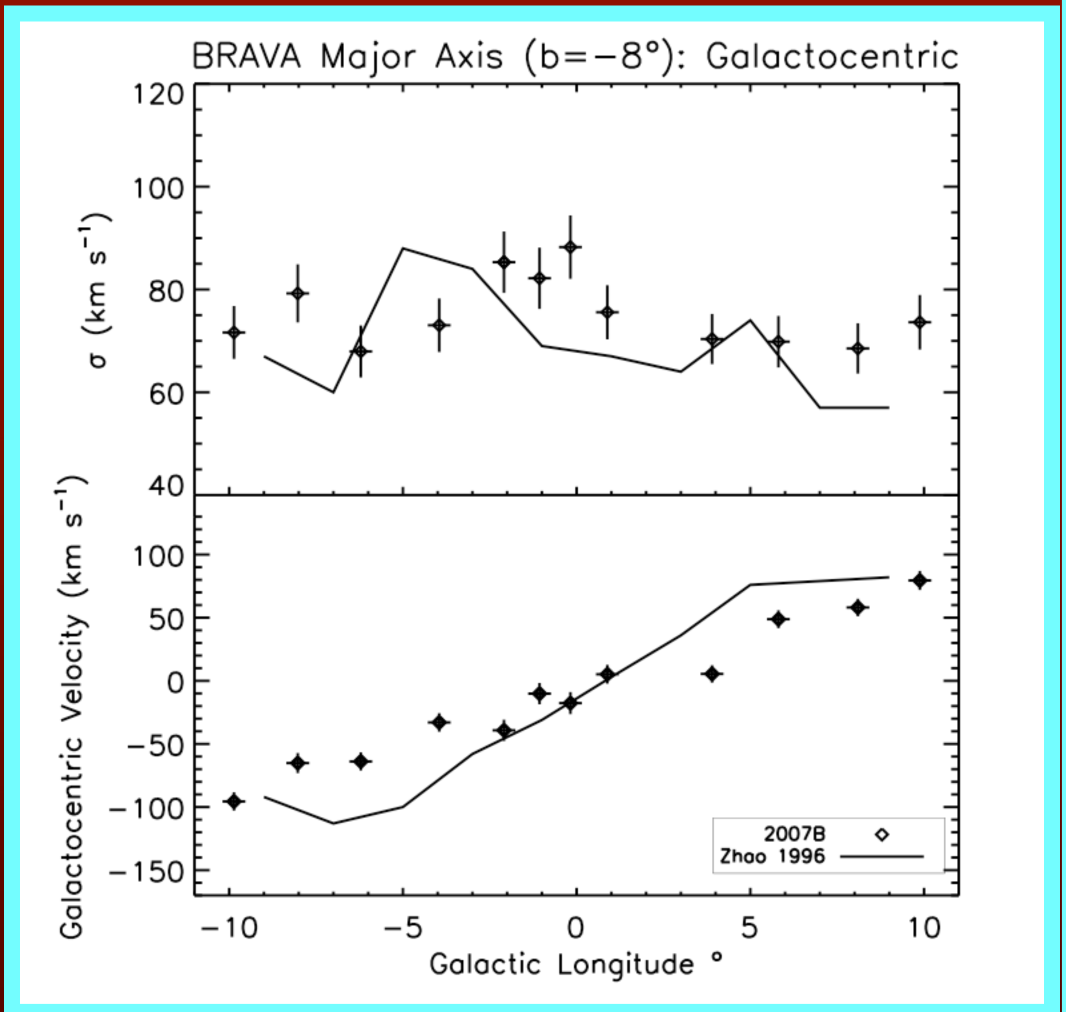


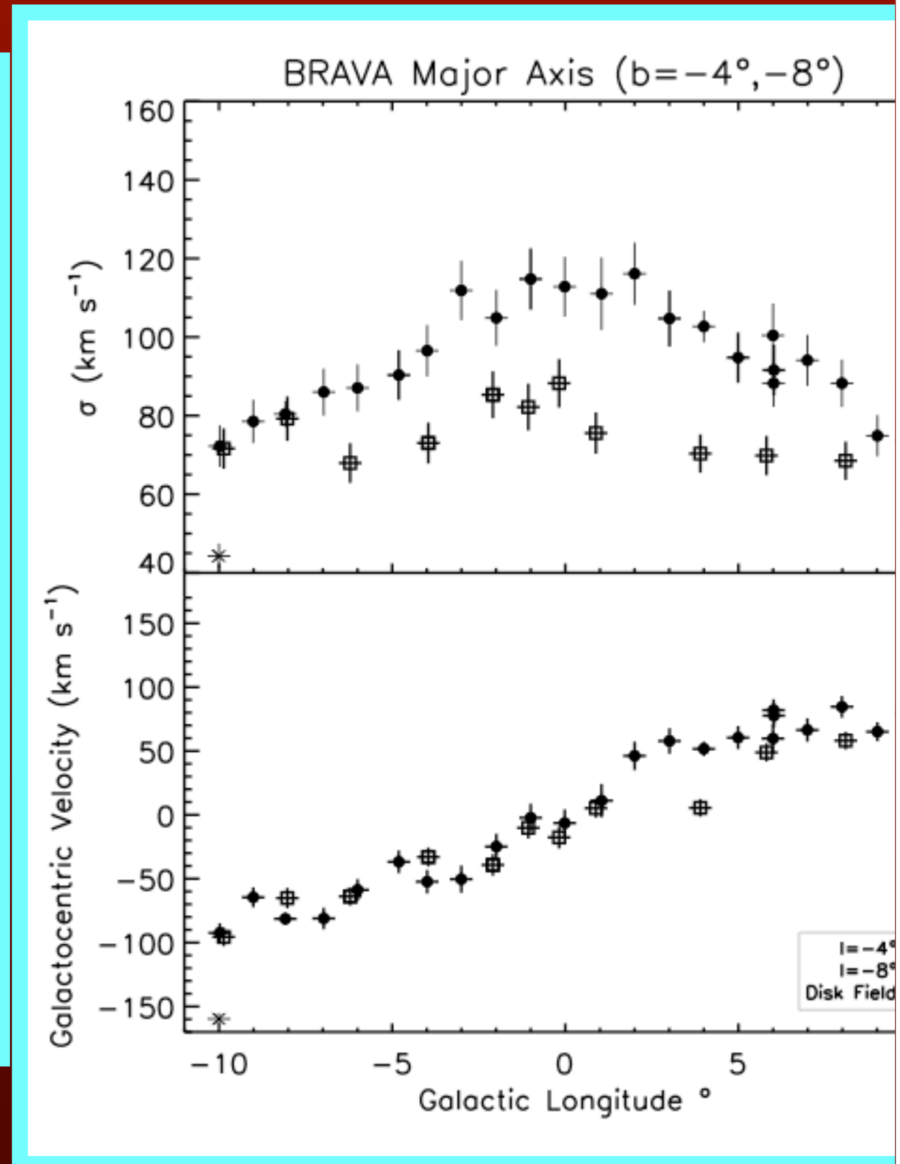
The -8º field has a clear bulge-like population, even at the corners





BRAVA data at -8º (1kpc): Evidence of cylindrical rotation? Also note solid-body like rotation field at -8

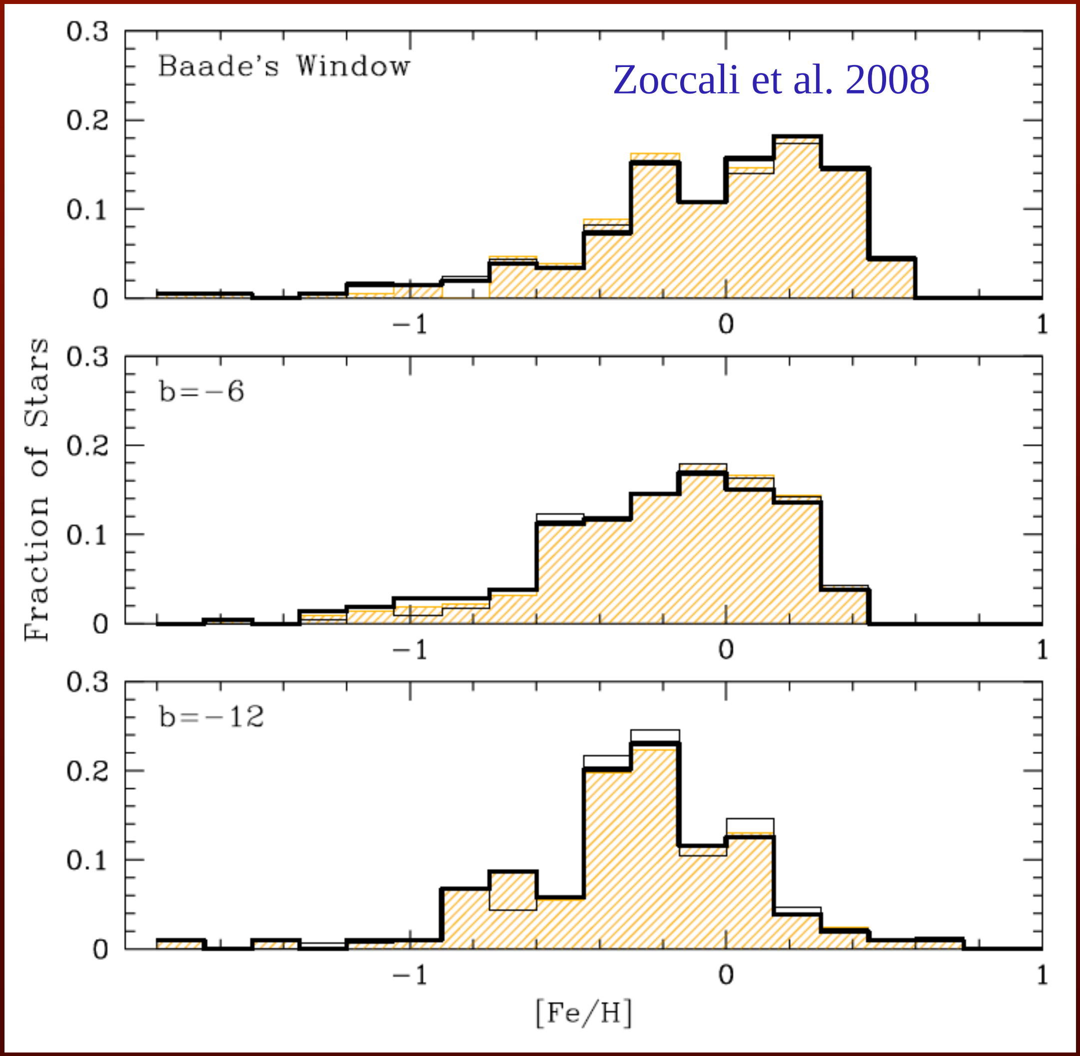




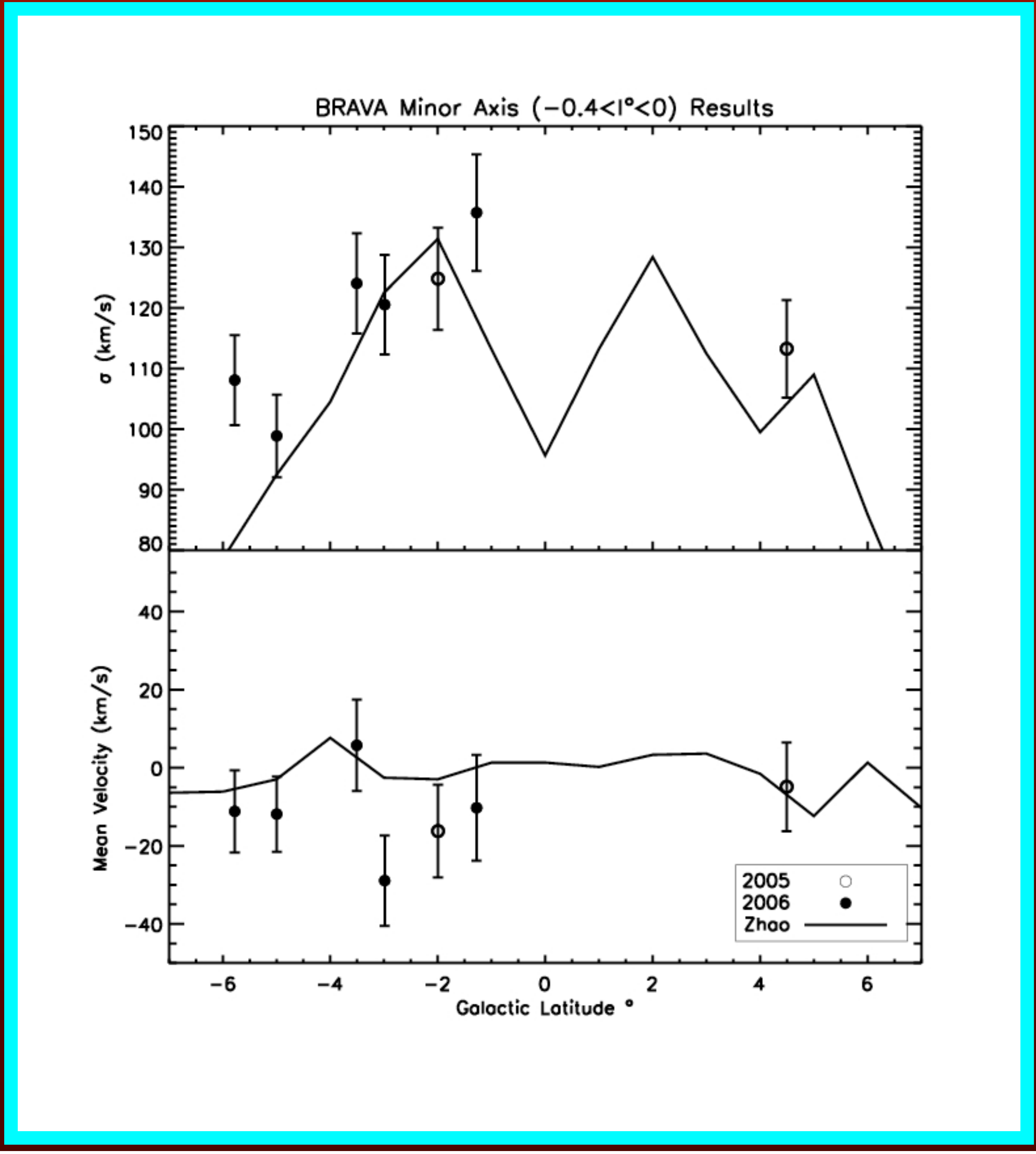
Howard et al. 2008

Contradiction: Abundance gradient in the outer bulge

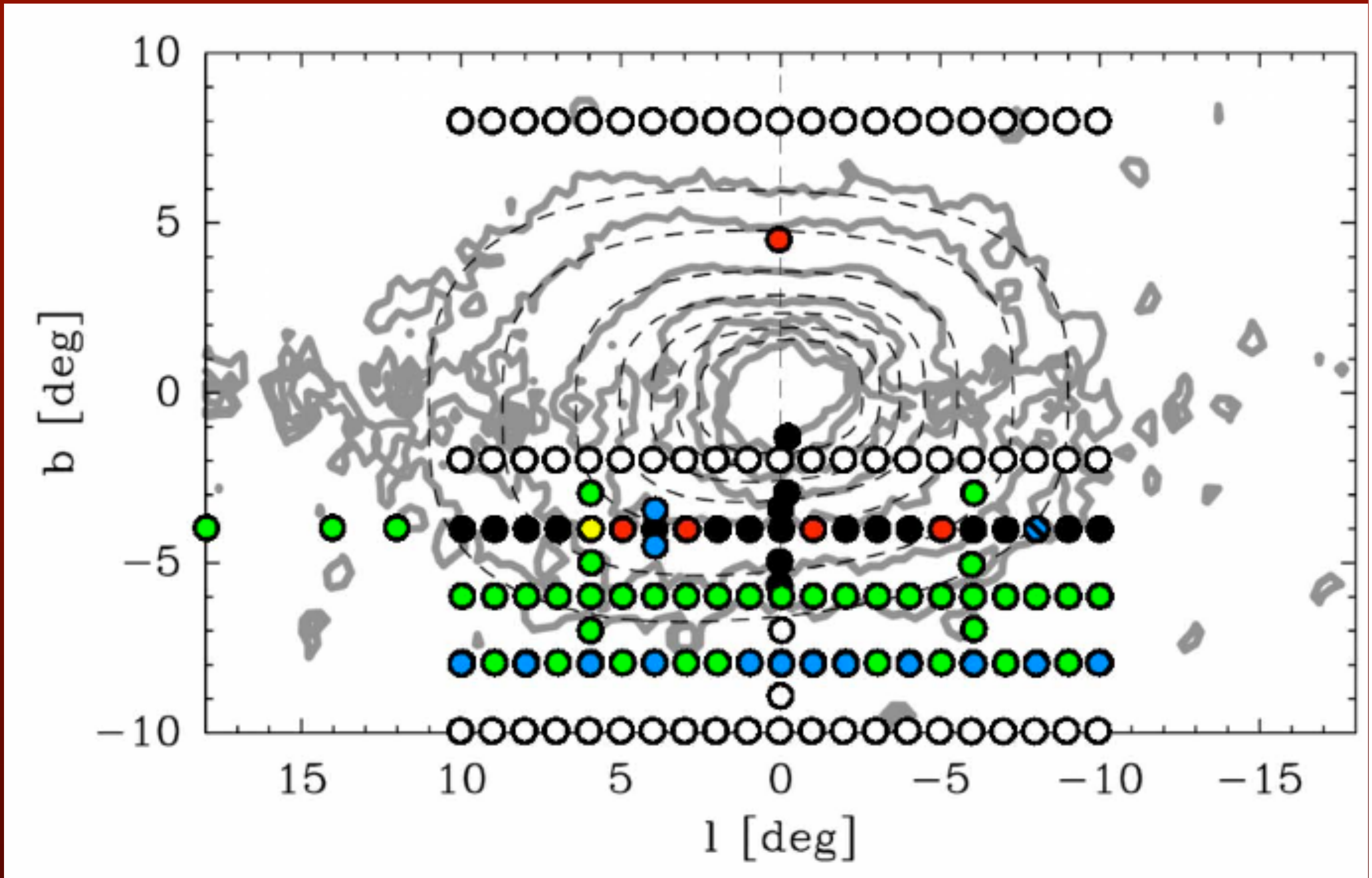
Cylindrical rotation a characteristic of pseudobulges, but should not exhibit abundance gradient, since buckling models are not dissipative. Location on Binney plot similar to NGC 4565.



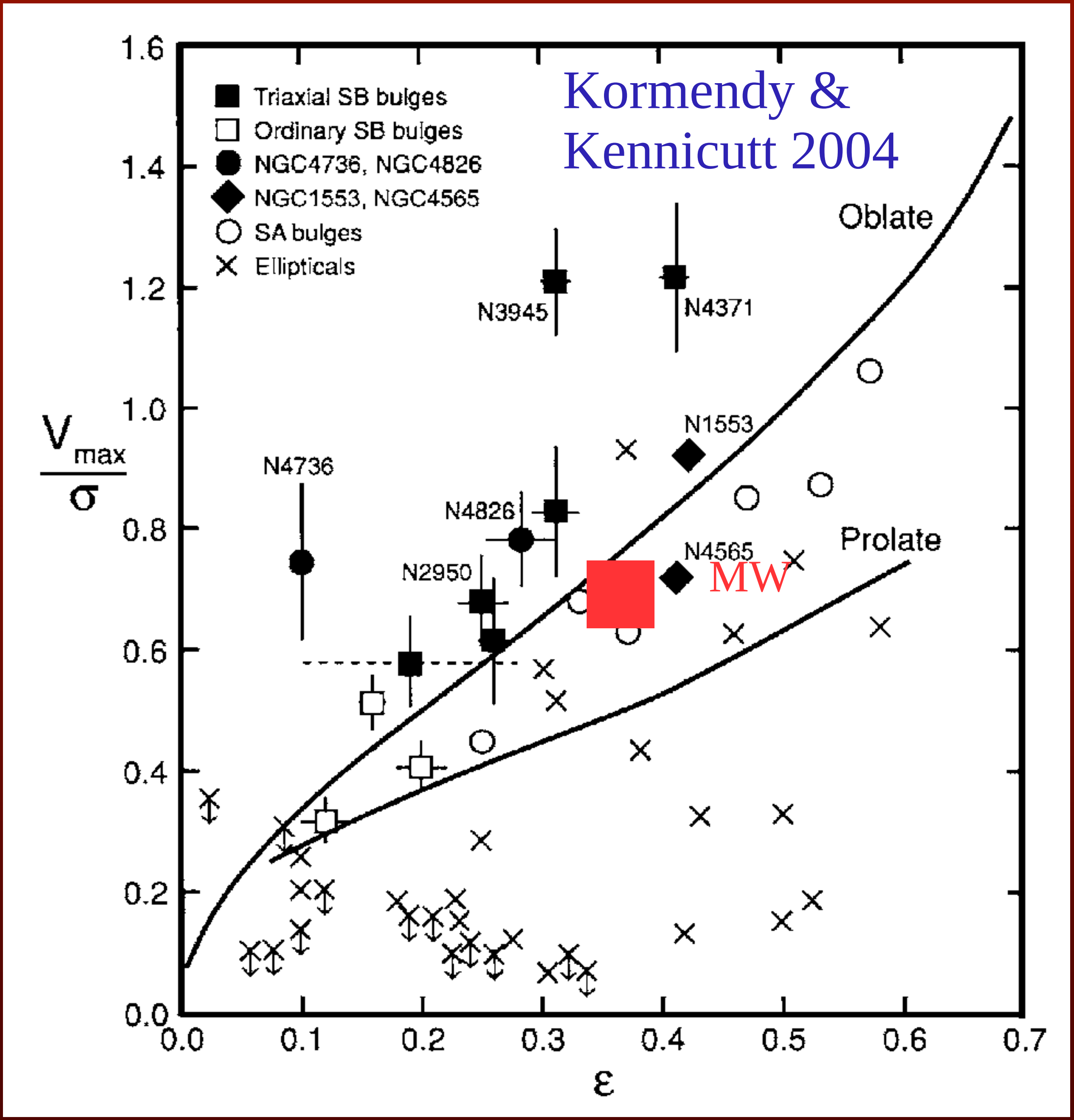
No minor axis rotation; more data needed



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


Kormendy & Kennicutt 2004
Triaxial SB bulges
Ordinary SB bulges
NGC4736, NGC4826
NGC1553, NGC4565
SA bulges
Ellipticals
Oblate
Prolate
N3945
N4371
N1553
N4736
N4826
N4565
N2950
MW
V_{max}/σ
ε
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7

Bulge Spectroscopy Before Keck

Low resolution spectroscopy; challenging due to high extinction, stellar crowding, high metallicity.

High resolution spectroscopy almost impossible (McWilliam & Rich 1994 analyzed CTIO echelle spectra of 11 giants). R=16,000,S/N=30

Galactic globular clusters, disk, and halo composition well understood; bulge remains as last frontier.

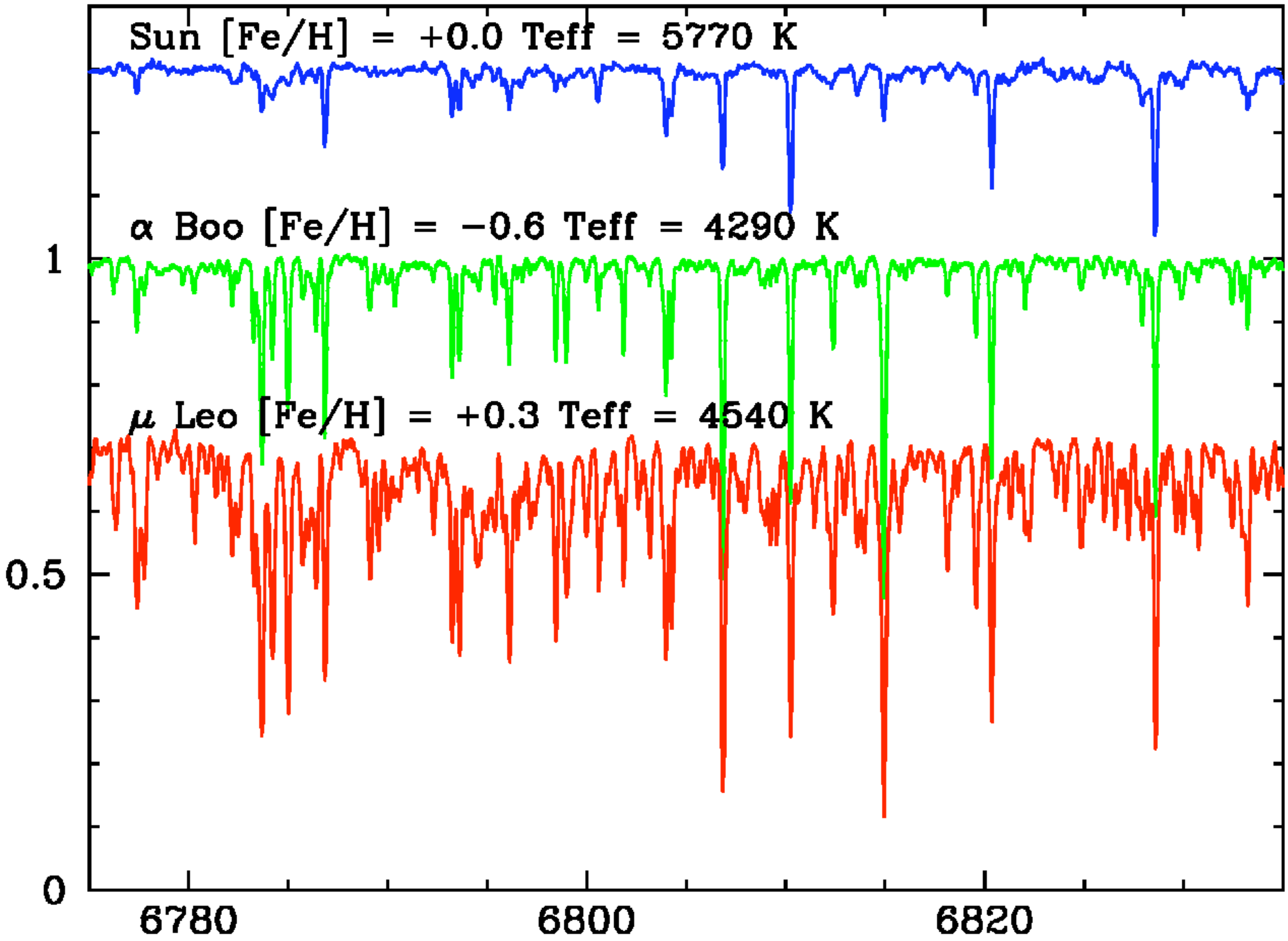
Bulge Spectroscopy After Keck

HIRES: R=45,000 and higher, S/N~60: metal rich giants feasible

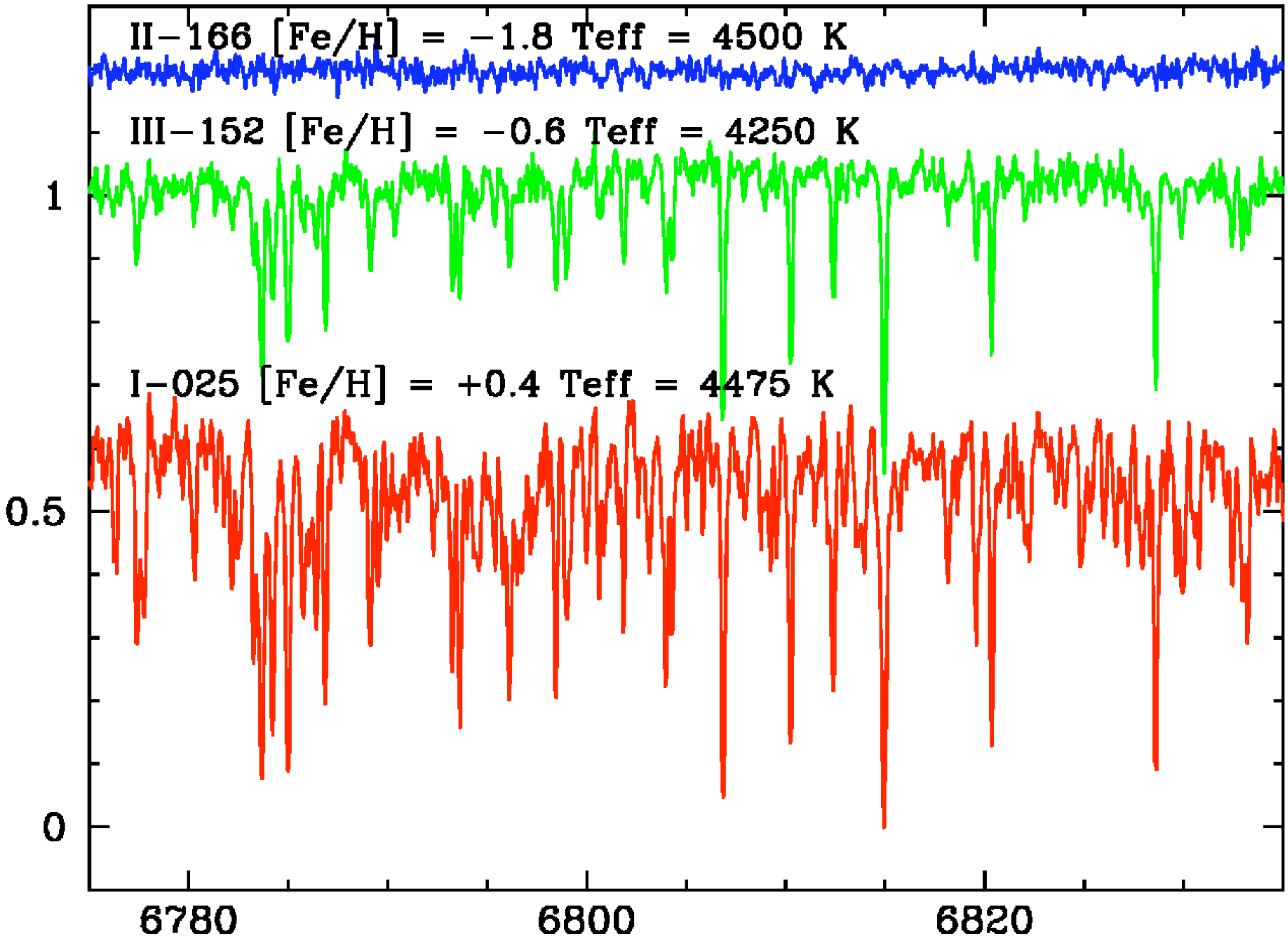
NIRSPEC: R=25,000 cross-dispersed infrared echelle, opens both cool red giants and optically obscured stars

Note: NIRSPEC remains as *the only* cross-dispersed infrared echelle spectrograph with R>20,000 on an 8-10m class telescope. Need for atmospheric dispersion standard star, flat field, arcs, for each wavelength setting makes other IR echelles (Phoenix, CRIRES) far less efficient, especially for faint stars.

Sample Spectra:



Keck Bulge Giants: Baade's Window



A New Approach to Abundance Analysis

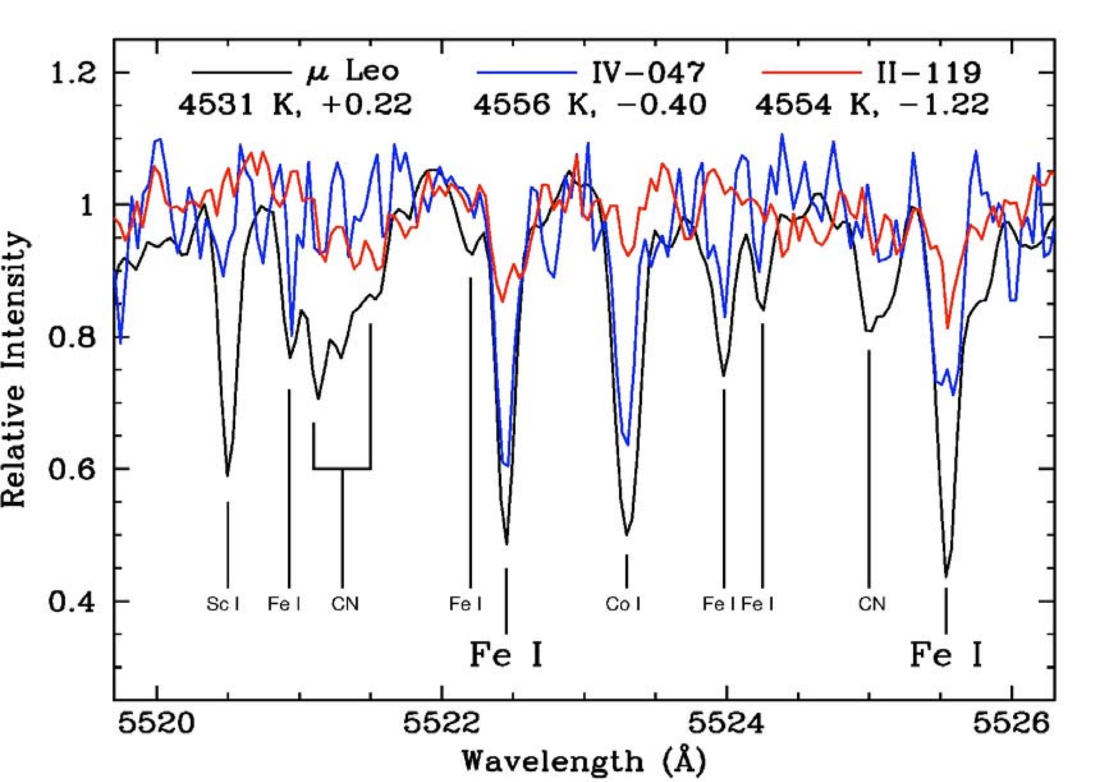
- Use the thick disk giant Arcturus, not the Sun, as the abundance standard.

- Issues like non-plane parallel atmosphere, mass loss, CN molecule opacity, etc. are similar between Arcturus and the bulge giants.

- Derive Arcturus-based gf values for weak iron lines that remain on the linear part of the curve of growth even in metal rich stars. Confirm the line list with the local metal rich giant mu Leo.

- Result: robust iron abundance scale, and confirmation of stars with [Fe/H]=+0.5

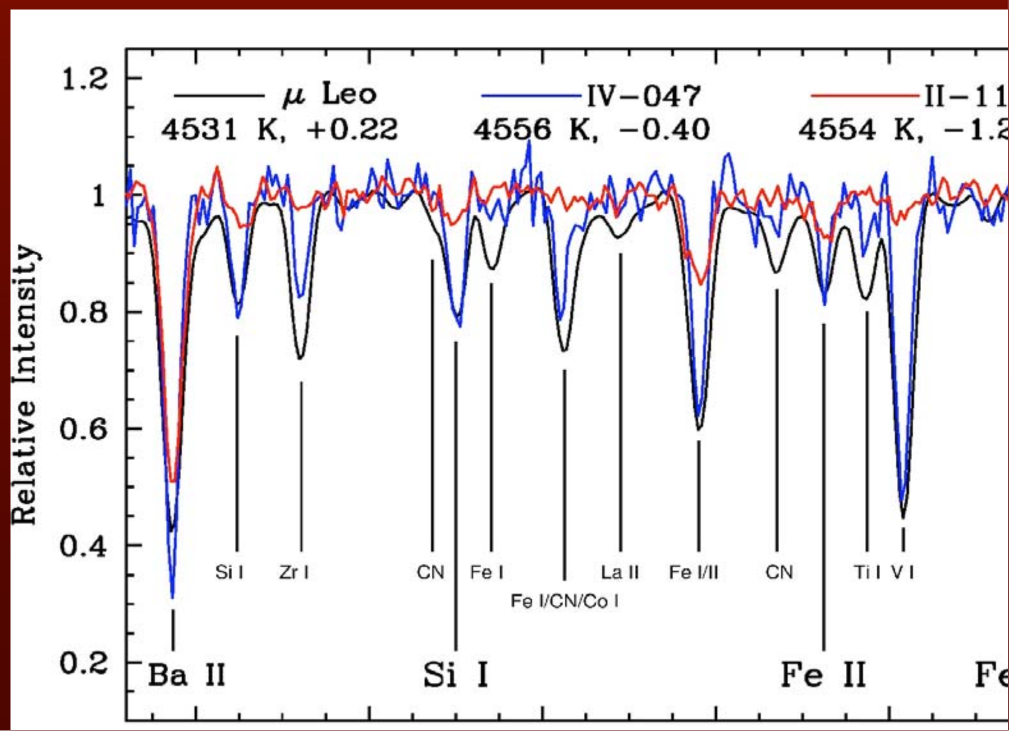
- Method also adopted by Lecureur et al. 2007.



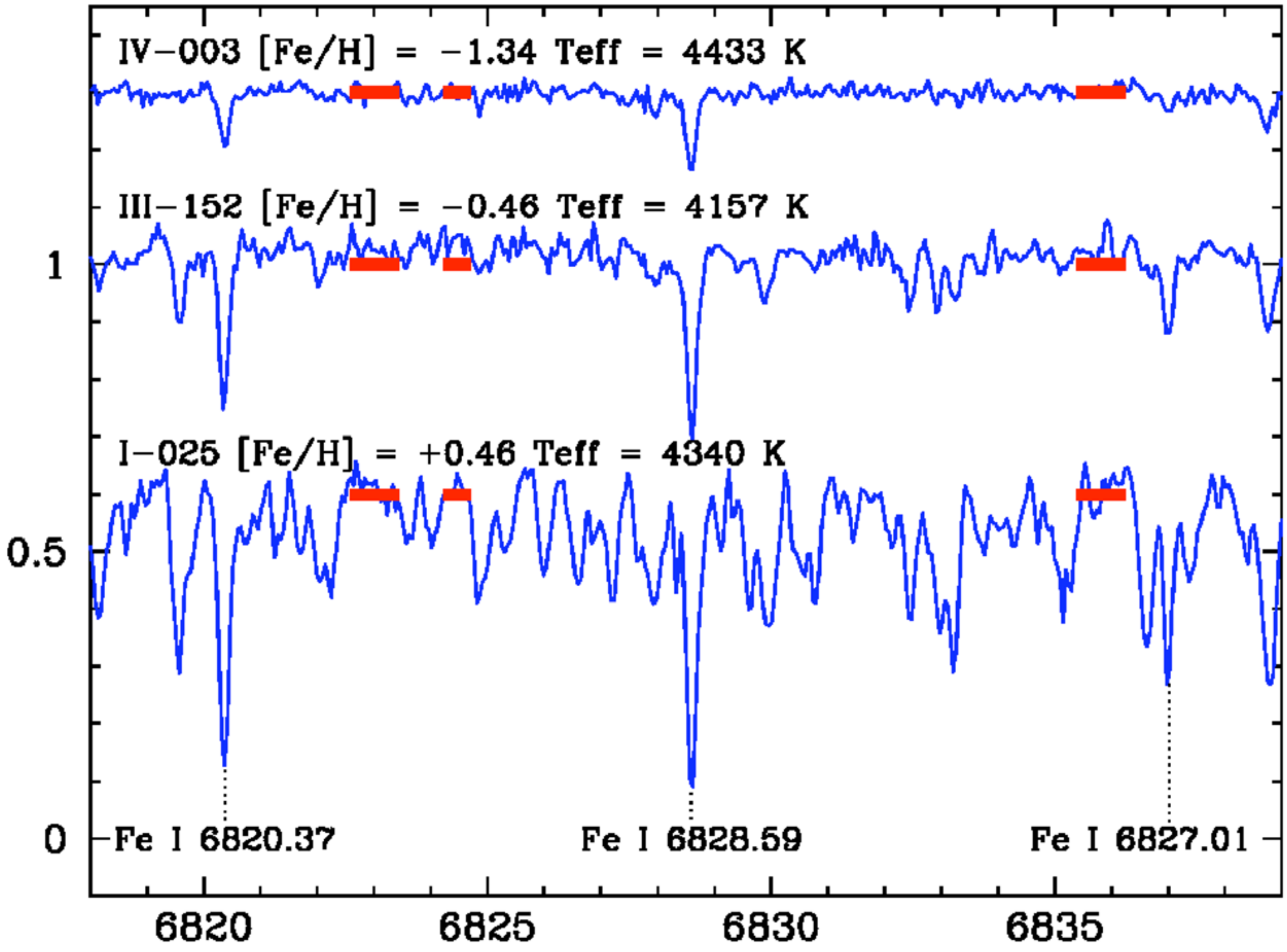
Fulbright, McW, Rich 2006 definitive bulge iron abund relative to Arcturus.

New linelist is usable over the full abundance range of our sample.

Fe I	2119	4047	uLeo	1039
m/H	-1.22	-0.40	0.32	0.51
5522	25	68	83	92
5525	28	66	102	106
6152	60	102	127	…

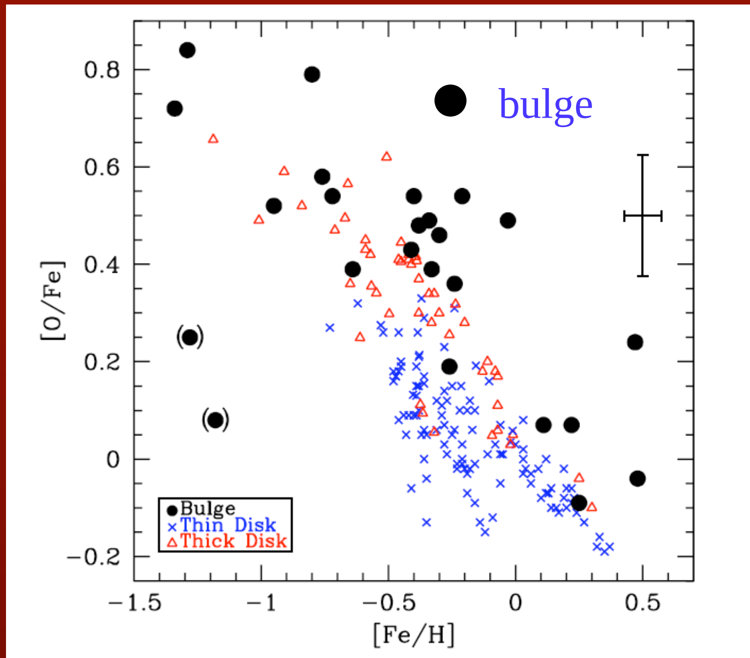


Sample Continuum Regions & Lines:

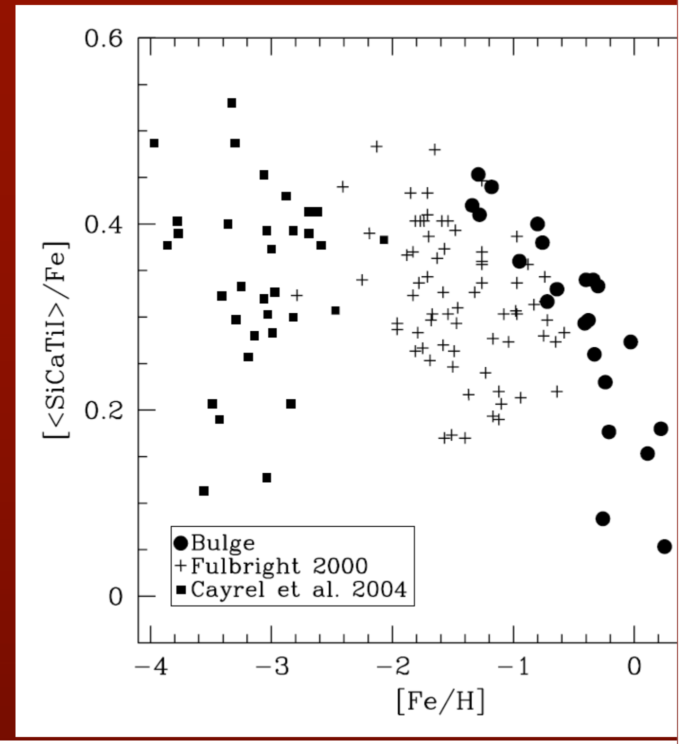


NEW [Fe/H] scale (FMR 2006) leads to.. Fulbright, McWilliam, & Rich 2007

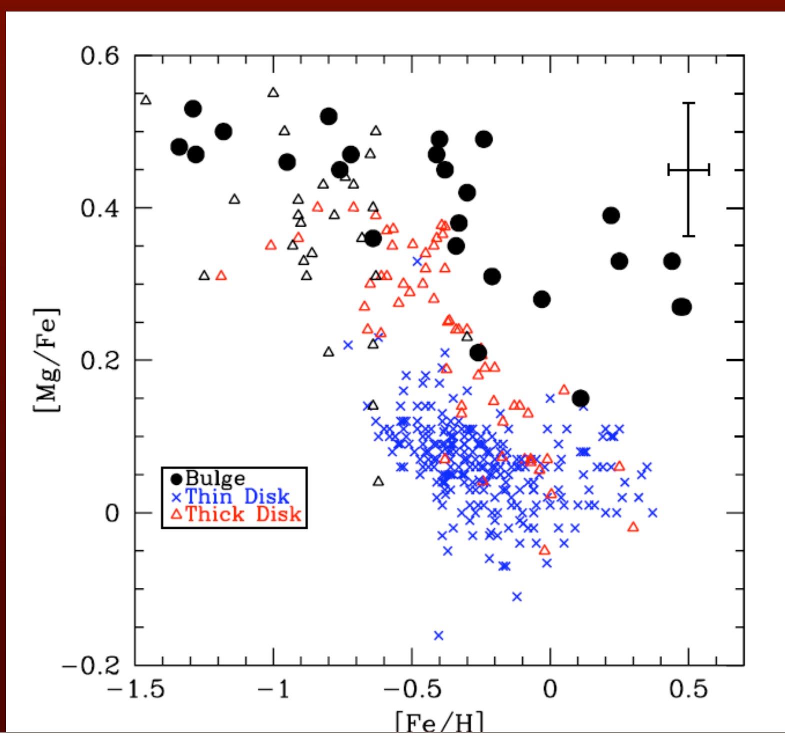
[O/Fe]



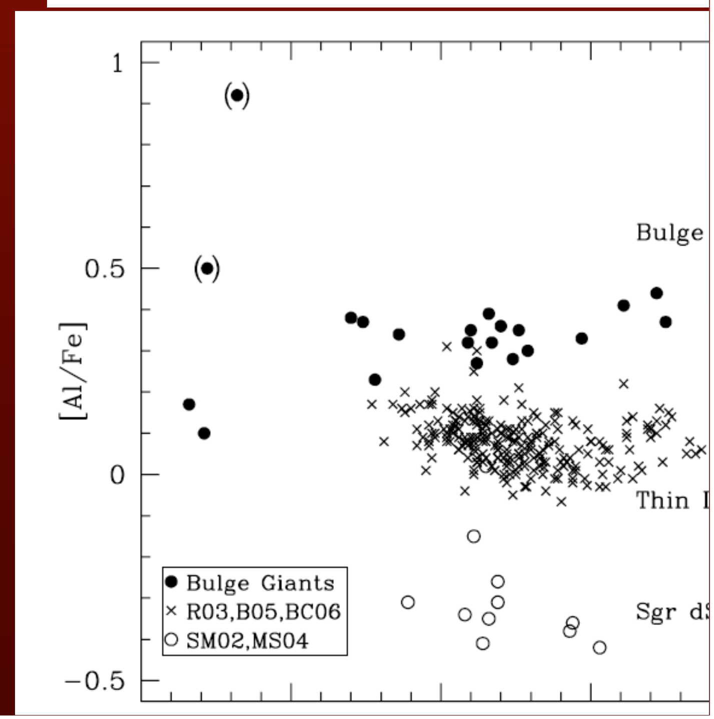
[<SiCaTi>/Fe]



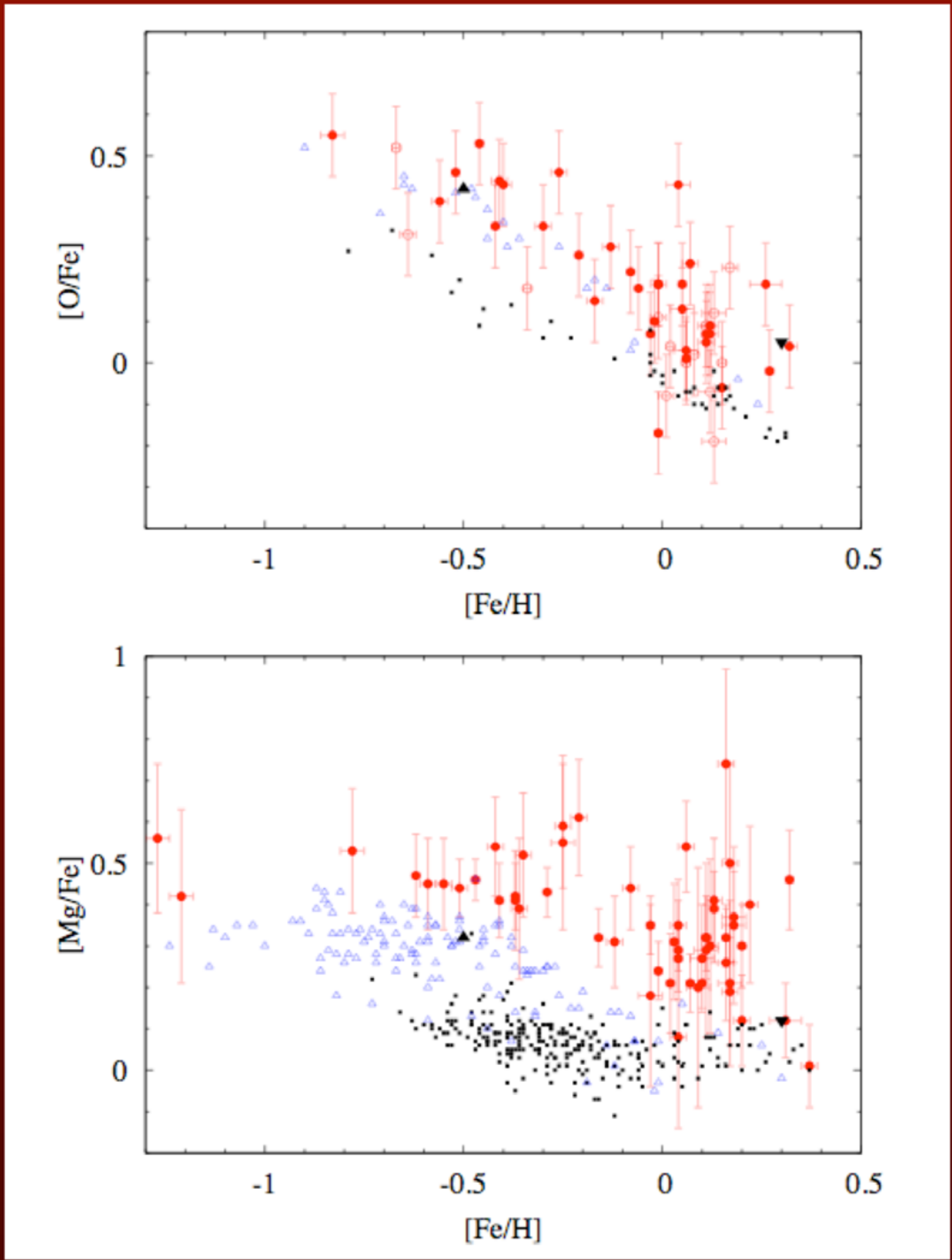
Mg/Fe



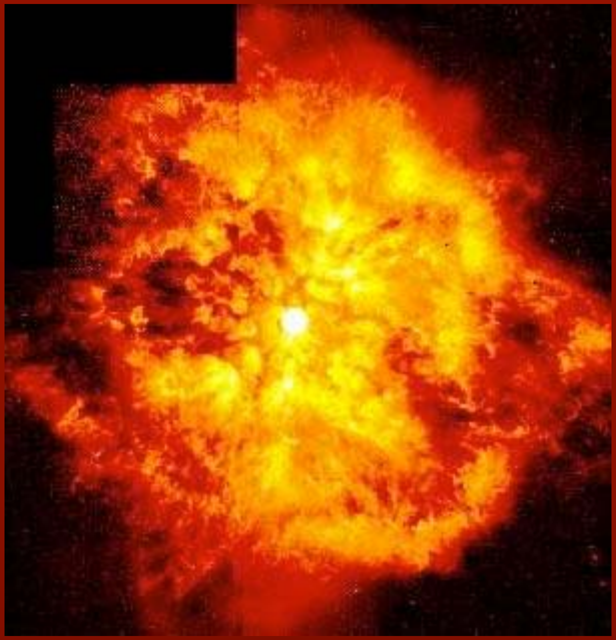
[Al/Fe]



Confirmation: Lecureur et al. 2007



Mg confirms
McWilliam &
Rich 1994



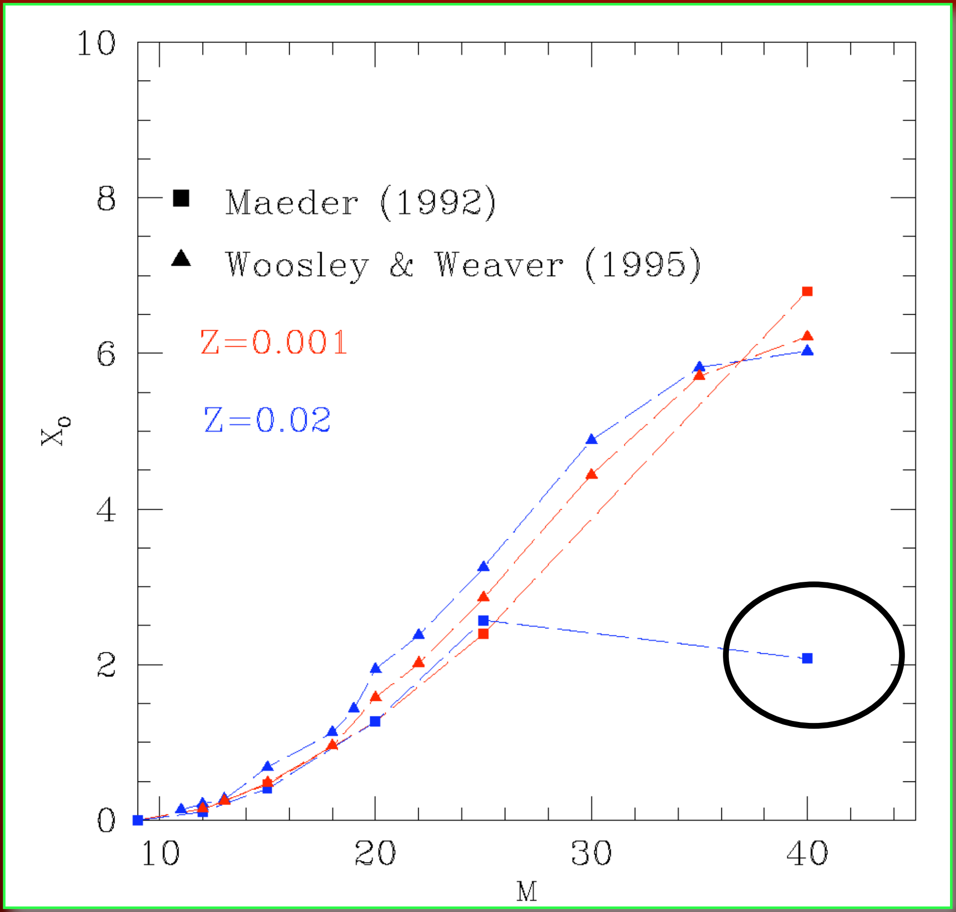
WR124 (Grosdidier et al. 1998)

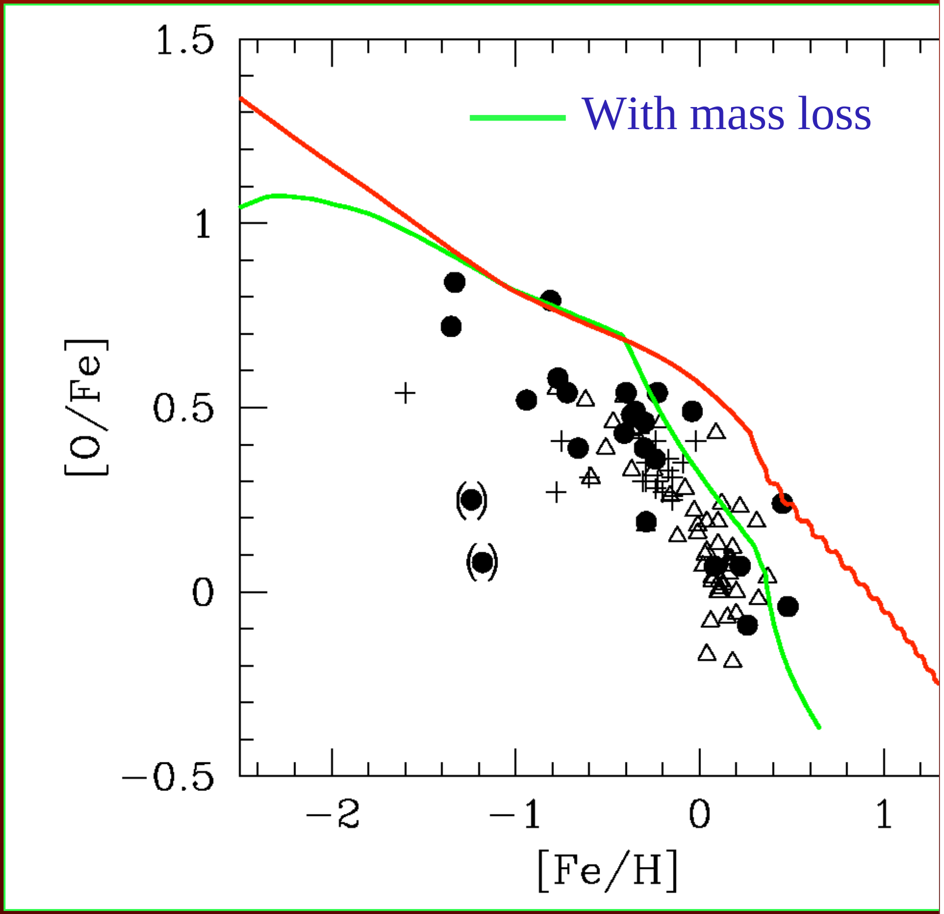
What is the matter with Oxygen?

N2359 (Berlind & Challis,

- Wolf-Rayet stars are believed to be evolved, very massive ($M > 30\ M_{\odot}$) and metal-rich ($> 1/3\ Z_{\odot}$).
- Extreme mass loss (dM/dt up to $10^{-4}\ M_{\odot}$ /yr) at high velocities (up to 2000 km/s). Total mass loss can be a significant fraction of the ZAMS mass.
- Occurs during He-core burning, so later burning stages are affected. Could this stop O production?

Mass loss in metal rich massive star progenitors (Maeder 1992) may explain the [O/Fe] decline





Maeder models have lower O yields, due to mass loss of outer layers, preventing He, C from being synthesized to O.

McWilliam, Matteucci, Balero, Rich, Fulbright, & Crescutti 2007 astroph; ApJ in pre

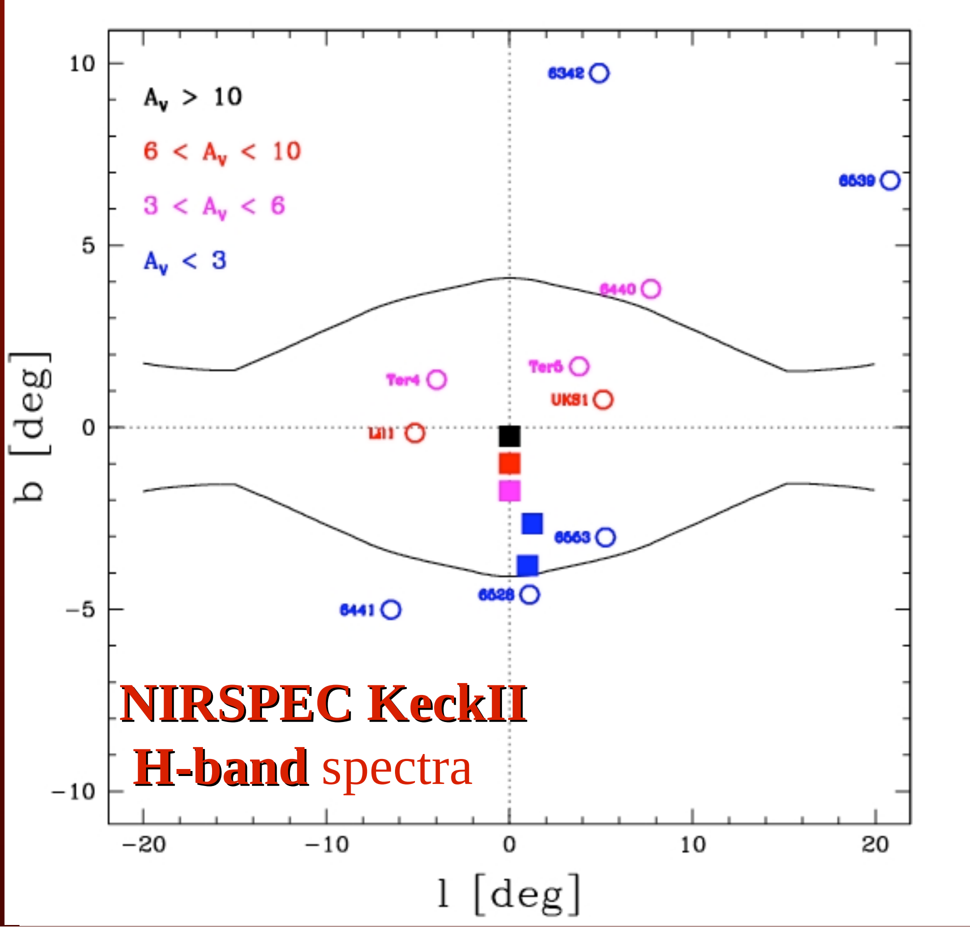
Infrared Spectroscopy of Bulge M giants

L. Origlia, E. Valenti Bologna Obs.

Keck II with Nirspec/ echelle R=25,000, 1.6μm

Region has OH lines and Fe, Mg, Si, Ca

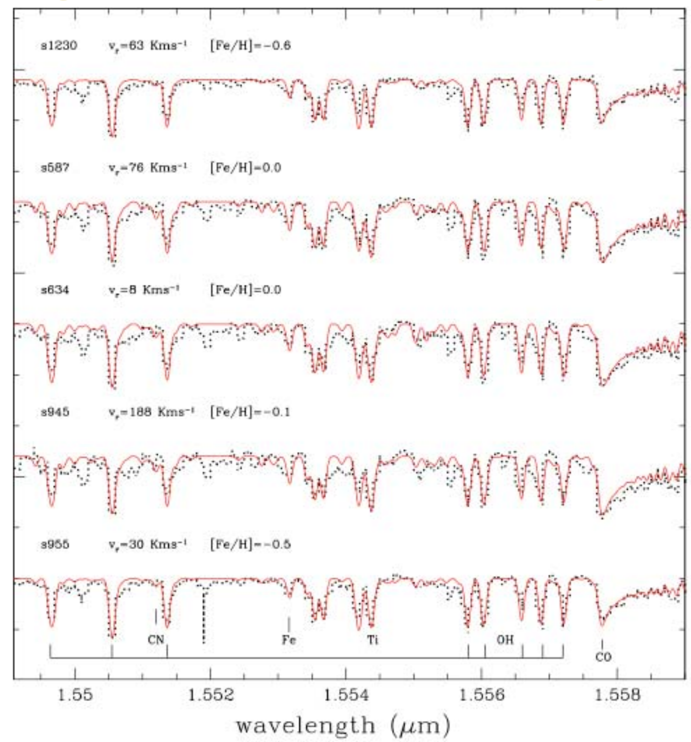
Origlia et al. ’02,’04,’05,‘08



NIRSPEC KeckII

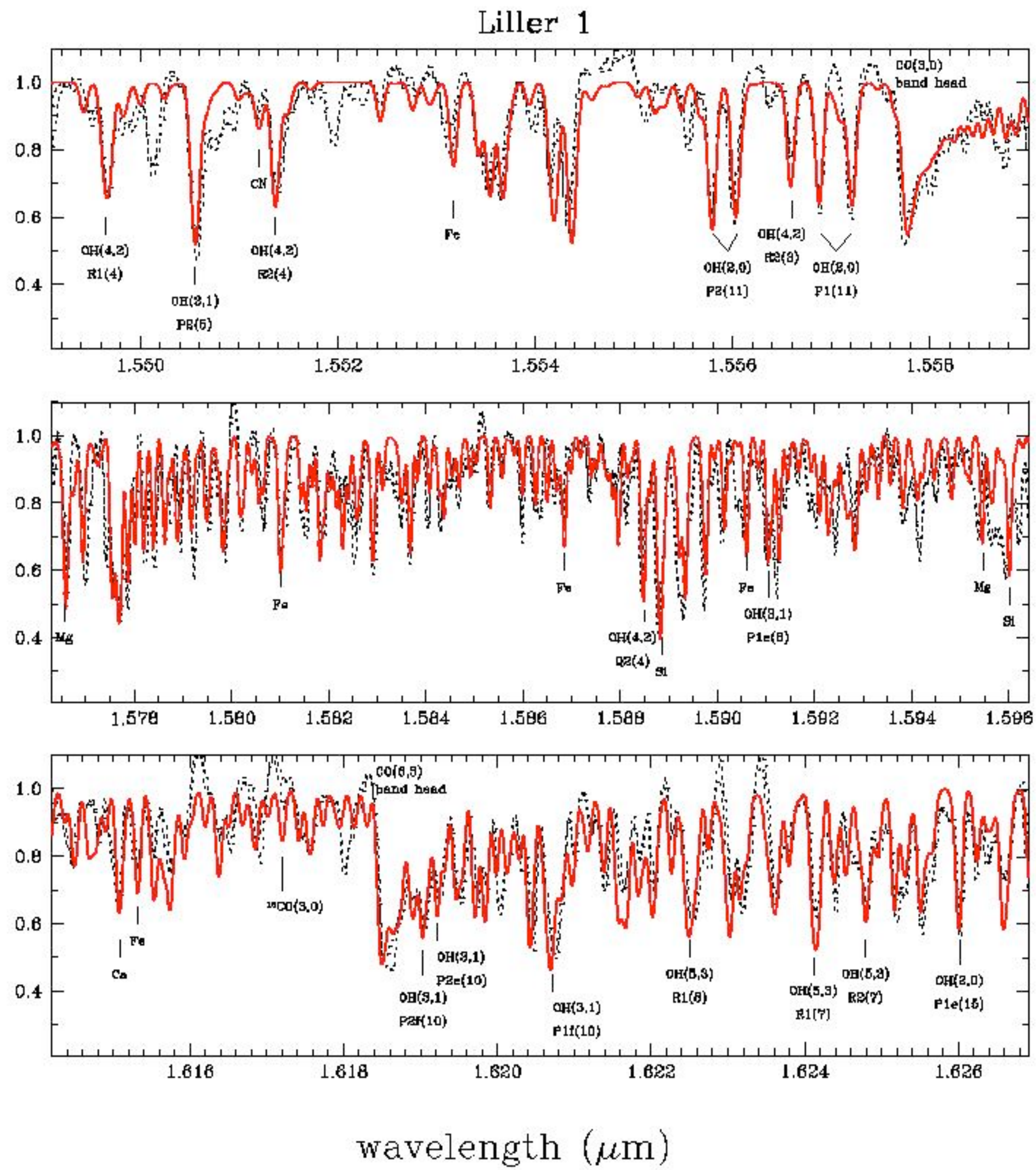
H-band spectra

M giants from field at -0.25 deg



Extend abundance analysis to cool stars, obscured regions.

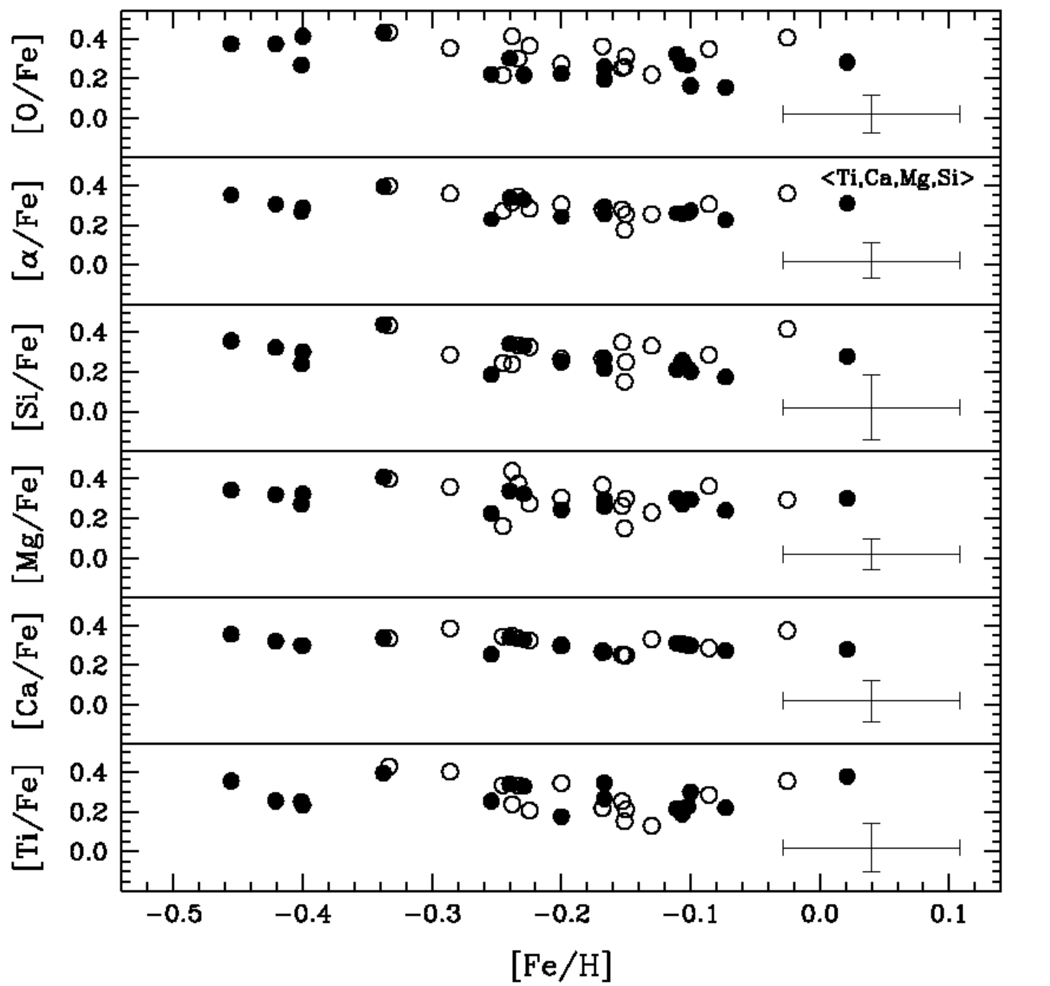
Origlia, Rich and Castro (2002)

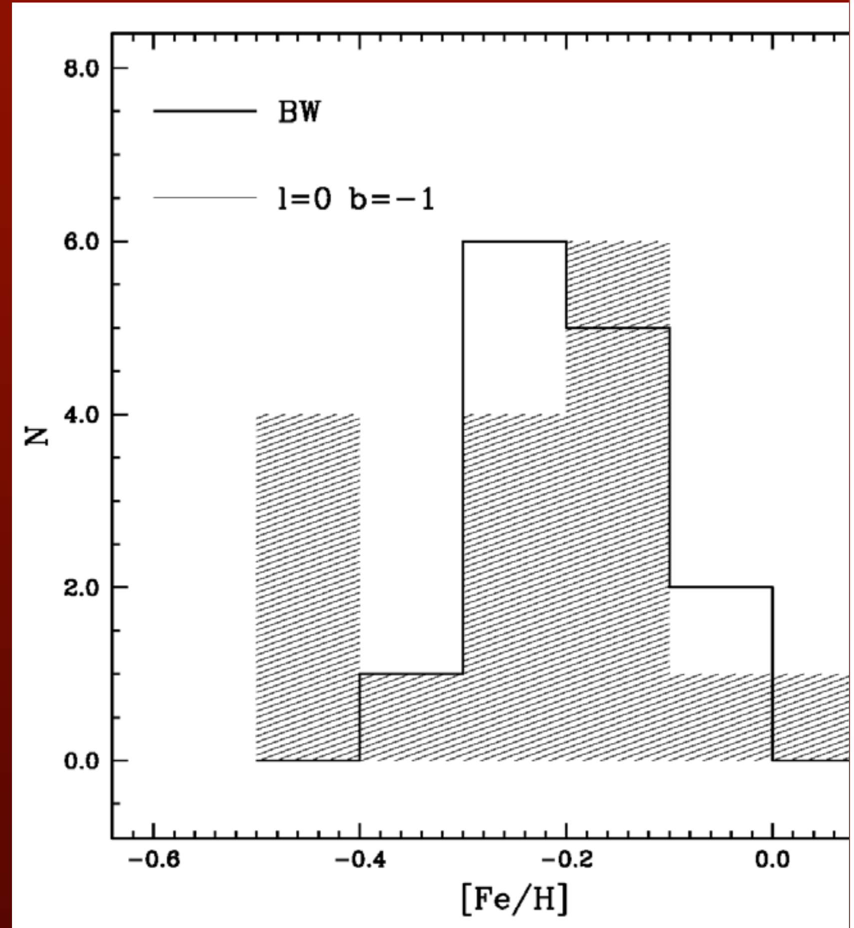


- Spectrum synthes
using Johnson,
Bernat, Krupp (19
atmospheres and
Origlia code
- Verified using
NEXTGEN
atmospheres
- Full error analysi
Origlia & Rich 20
- Multiple OH line
advantage, but oth
alpha element line
are on damping pa
of the curve of
growth.
- Need phot for ste
parameters

First detailed abundances of bulge M giants in Baade's Window and (l,b)=(0,-1)

Rich & Origlia 2005 ApJ; Rich, Origlia, Valenti 2007 ApJ Lett

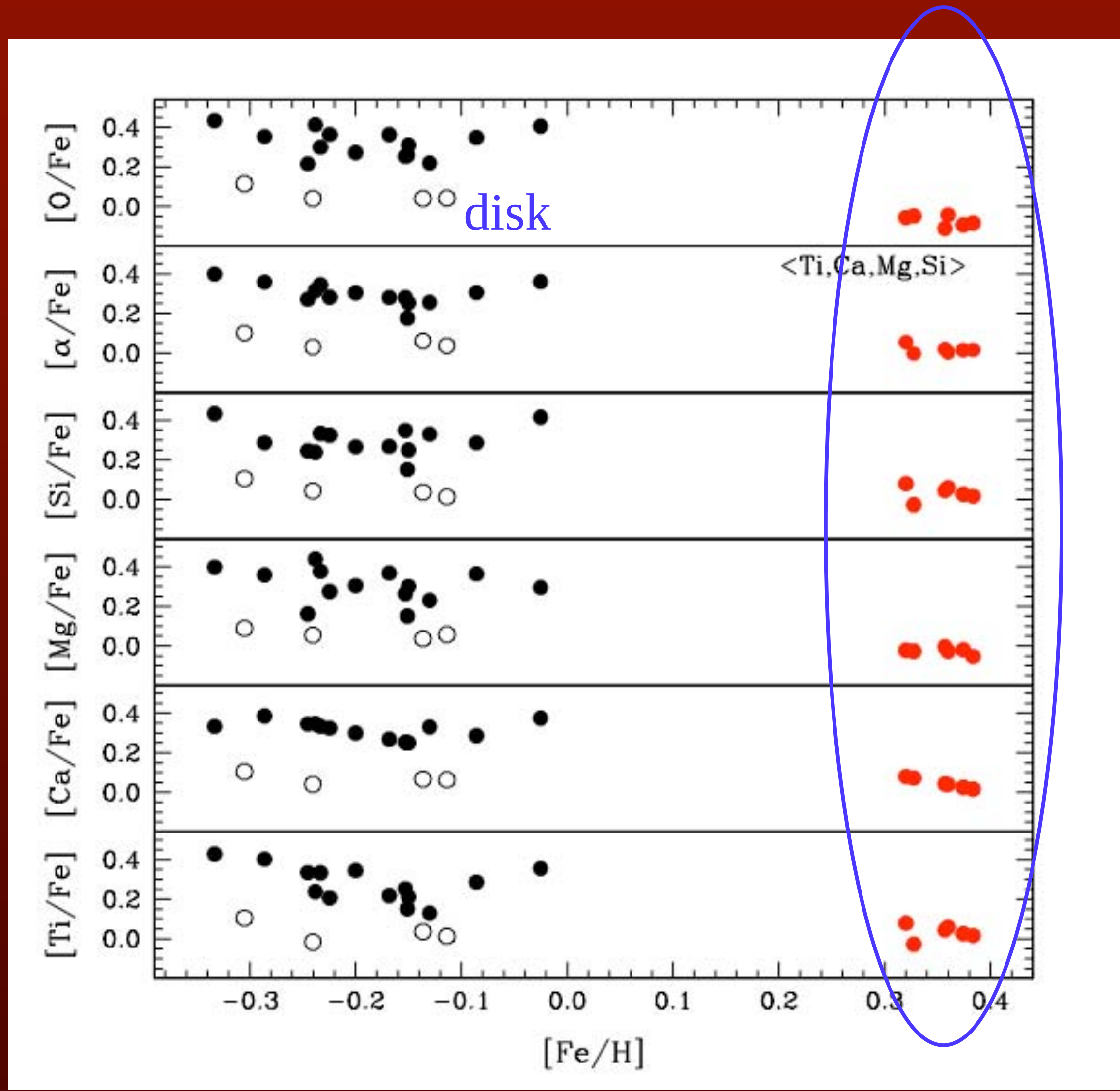




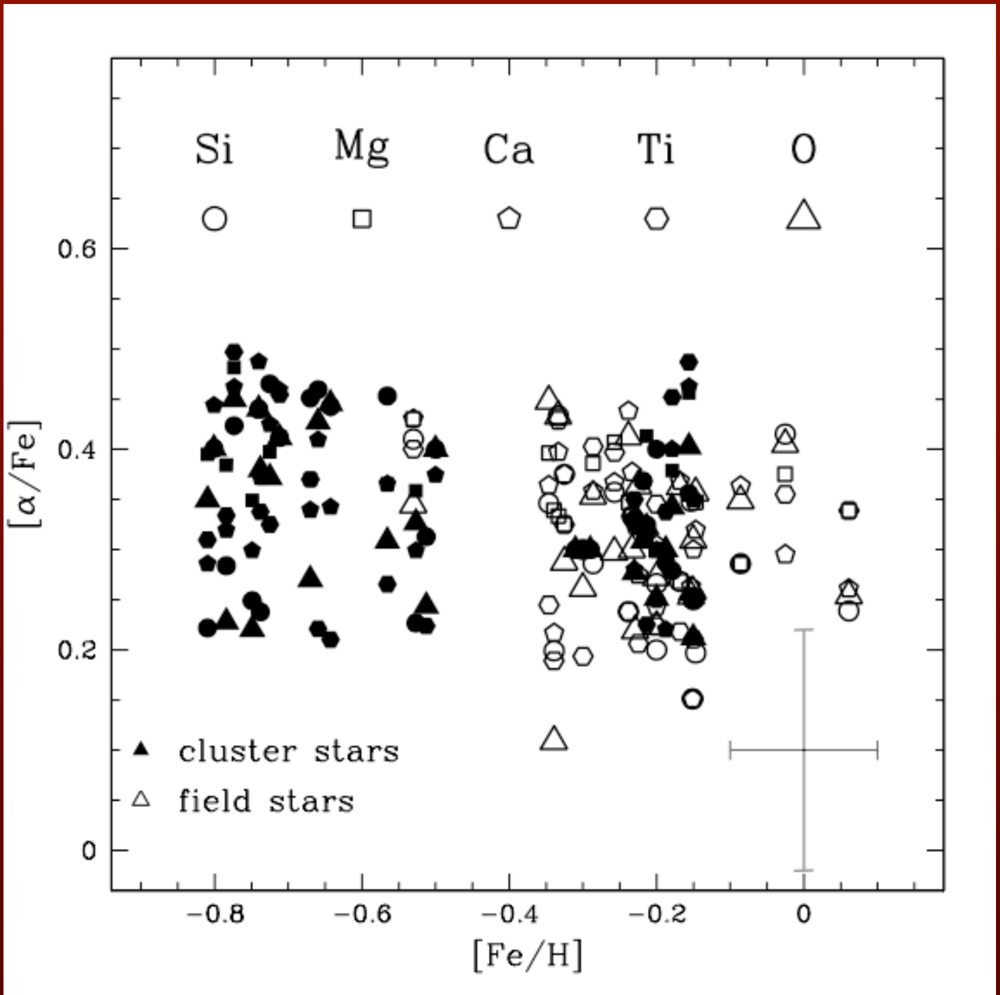
No gradient between field

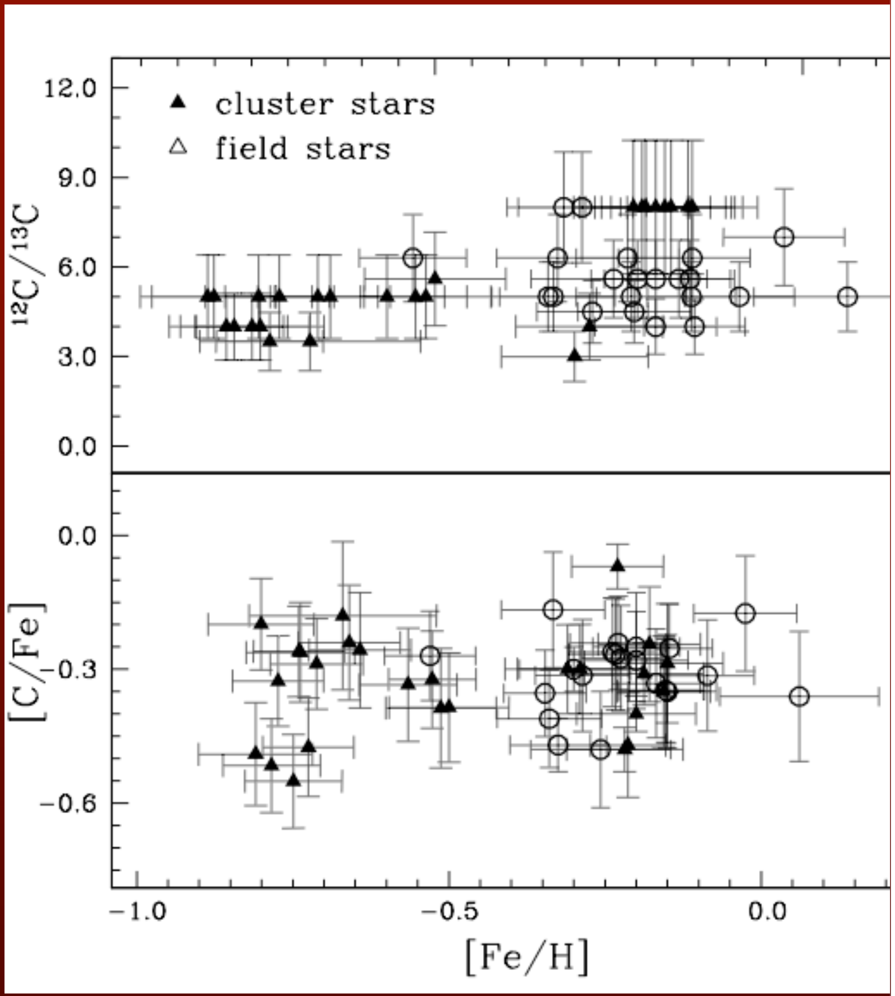
Open circles; Baade's Window (1,-4)
Filled circles: (0,-1): no composition gradient

NGC 6791 (Origlia et al. 2006) is metal rich and has low (disk-like) alphas; why no bulge M giants this metal rich? Are most metal rich stars truncated by mass loss?

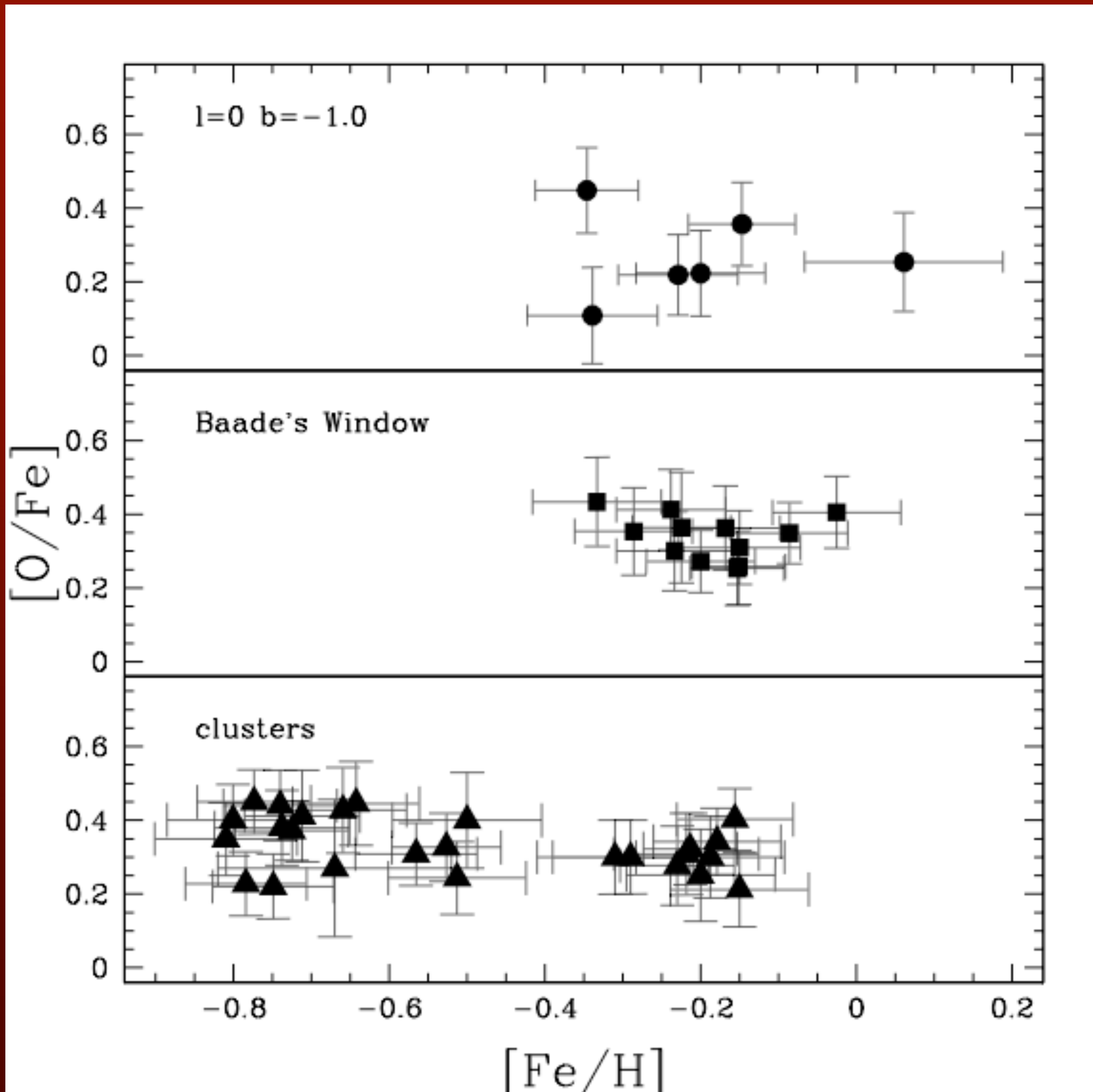


Bulge globular clusters and field stars show similar enhancement



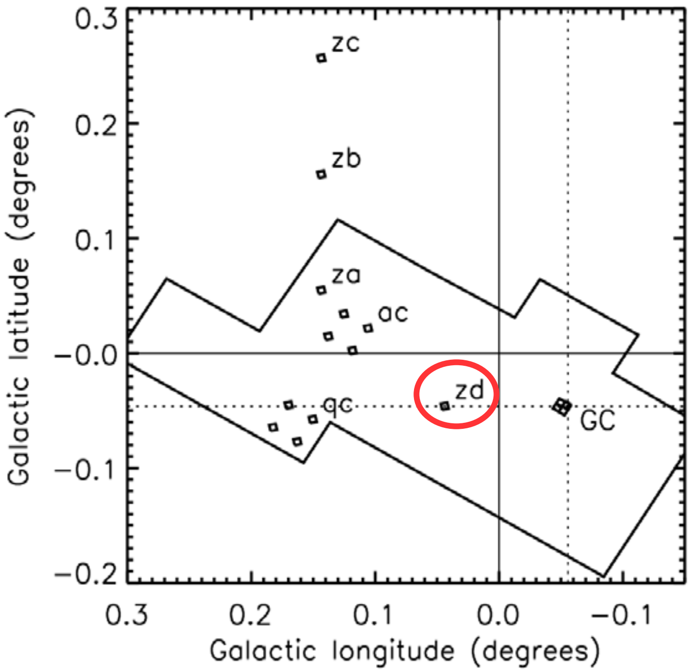


All light elements are enhanced the same, but our samples lac metal rich bulge M giants (we do not see O decline).

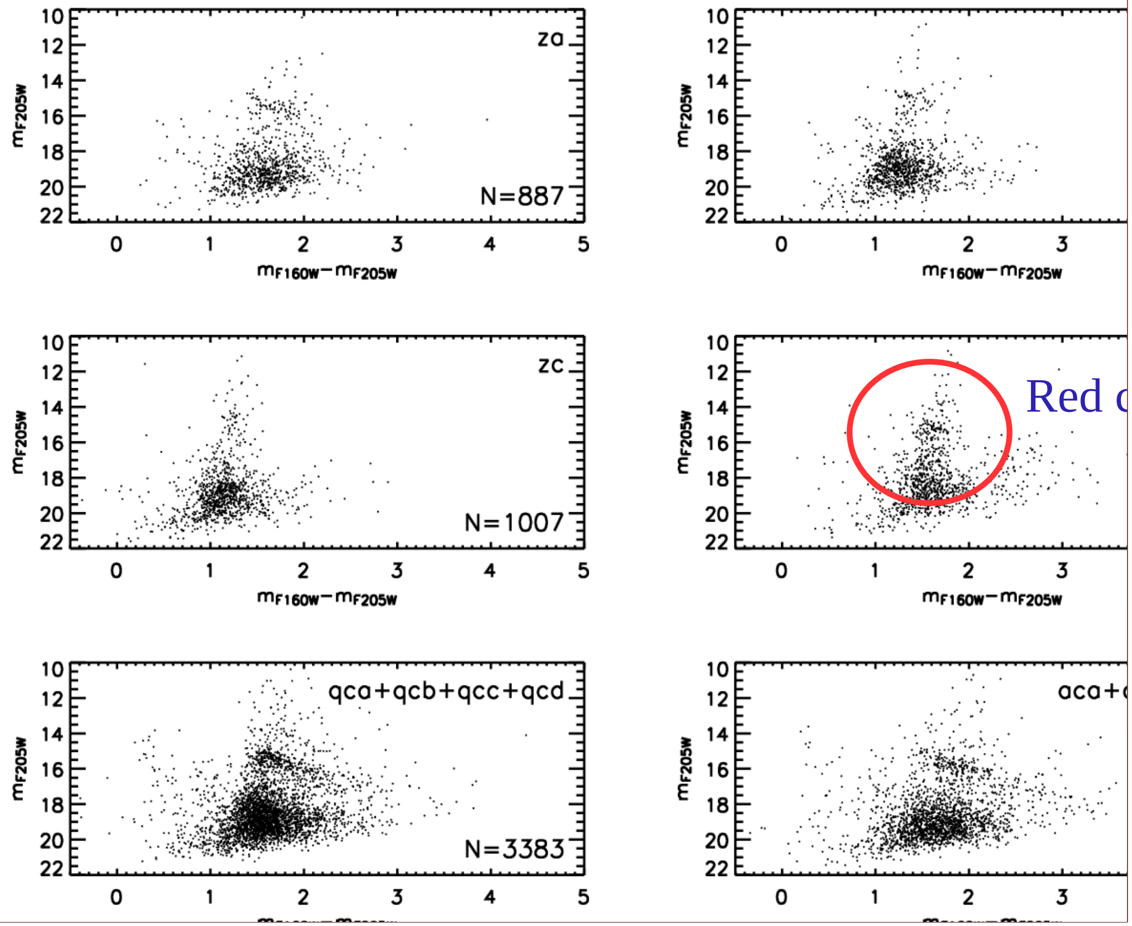


l=0 b=−1.0
Baade's Window
clusters
[O/Fe]
[Fe/H]
0
0.2
0.4
0.6
−0.8
−0.6
−0.4
−0.2
0
0.2

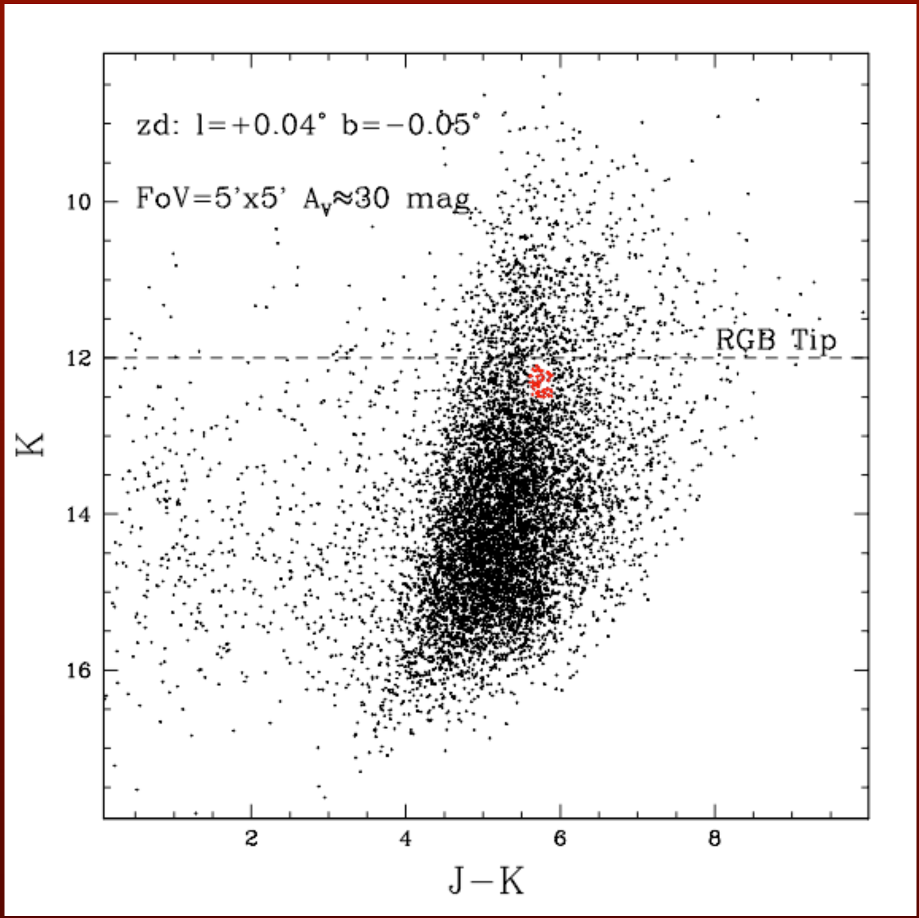
Pushing abundance analysis toward the Galactic Center

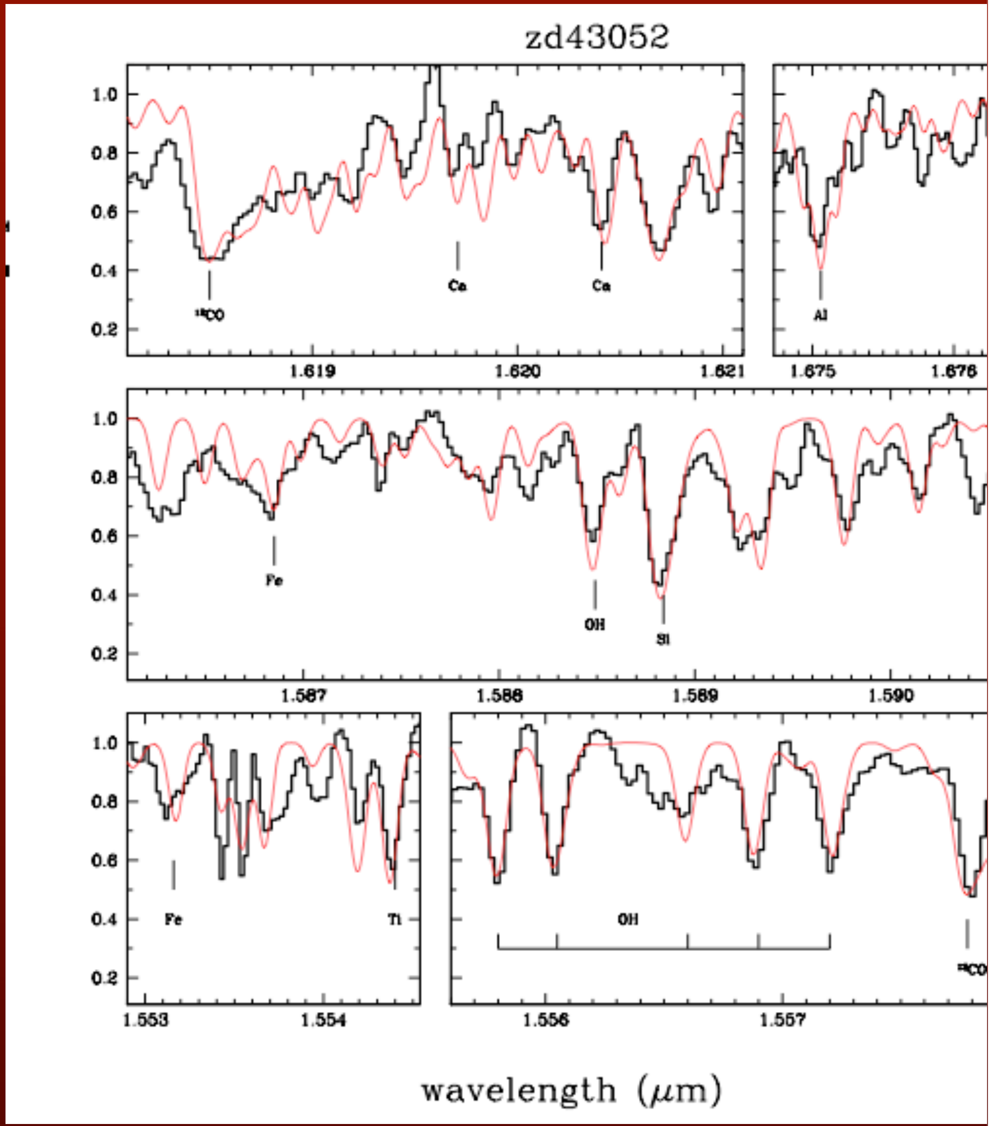


Figiger et al. 2004



Rich, Origlia, Valenti in prep.





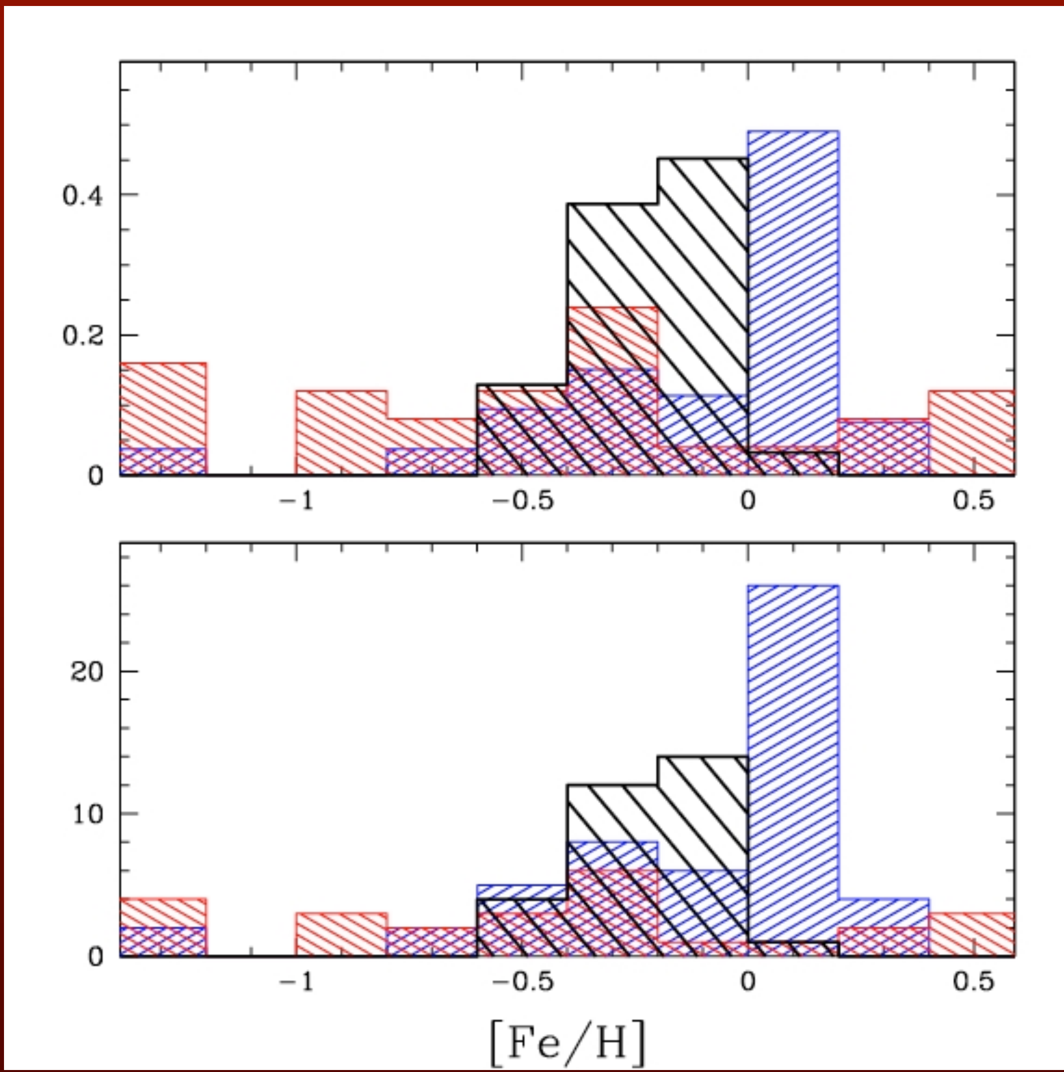
log g=0.5, *ξ*=2 km/s, T_{eff}=3800K

[Fe/H]=-0.2

[O,Si,Ti/Fe]=+0.3

[Al/Fe=+0.4]

[Fe/H] distribution - bulge



Red: Fulbright, McWilliam, Rich (1996)

Blue: Lecureur et al. 2007

Black: Rich, Origlia, Valen

M giants appear to lack t most metal rich stars

Is there a problem with bulge abundances?

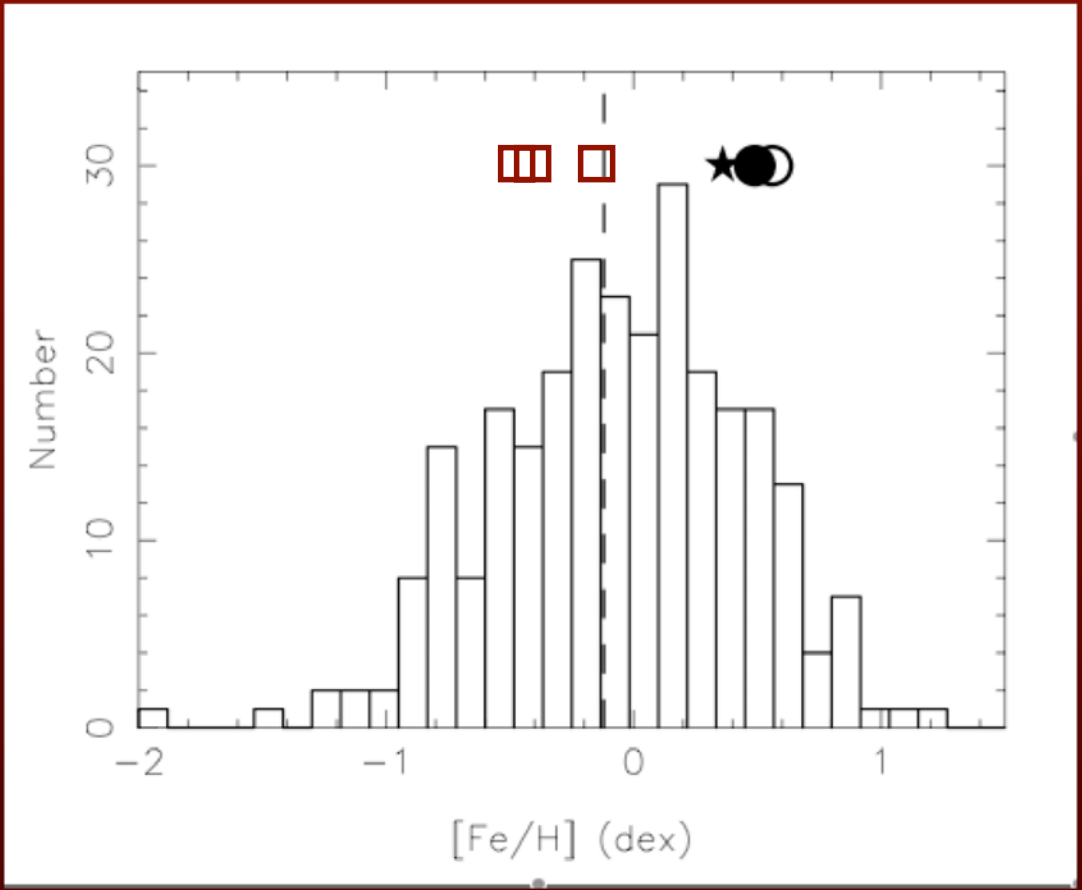
Cohen et al. 2008 observe a microlensed metal rich ([Fe/H]=+0.51) bulge dwarf. 2 other bulge dwarfs, also microlensed, are metal rich (but 3 ther bulge dwarfs are Solar and metal poor).

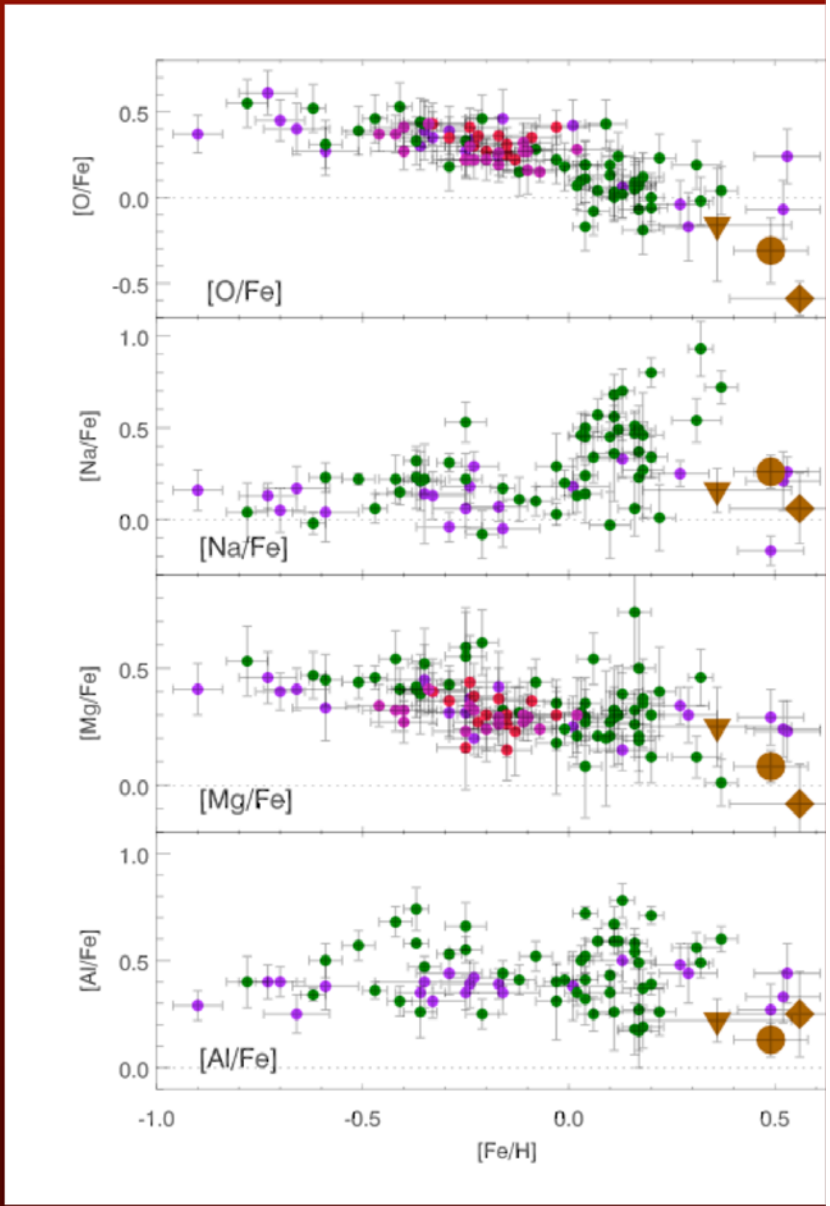
Cohen proposes that most metal rich giants are not present, not represented, due to mass loss.

Bulge actually has [Fe/H]~+0.3?

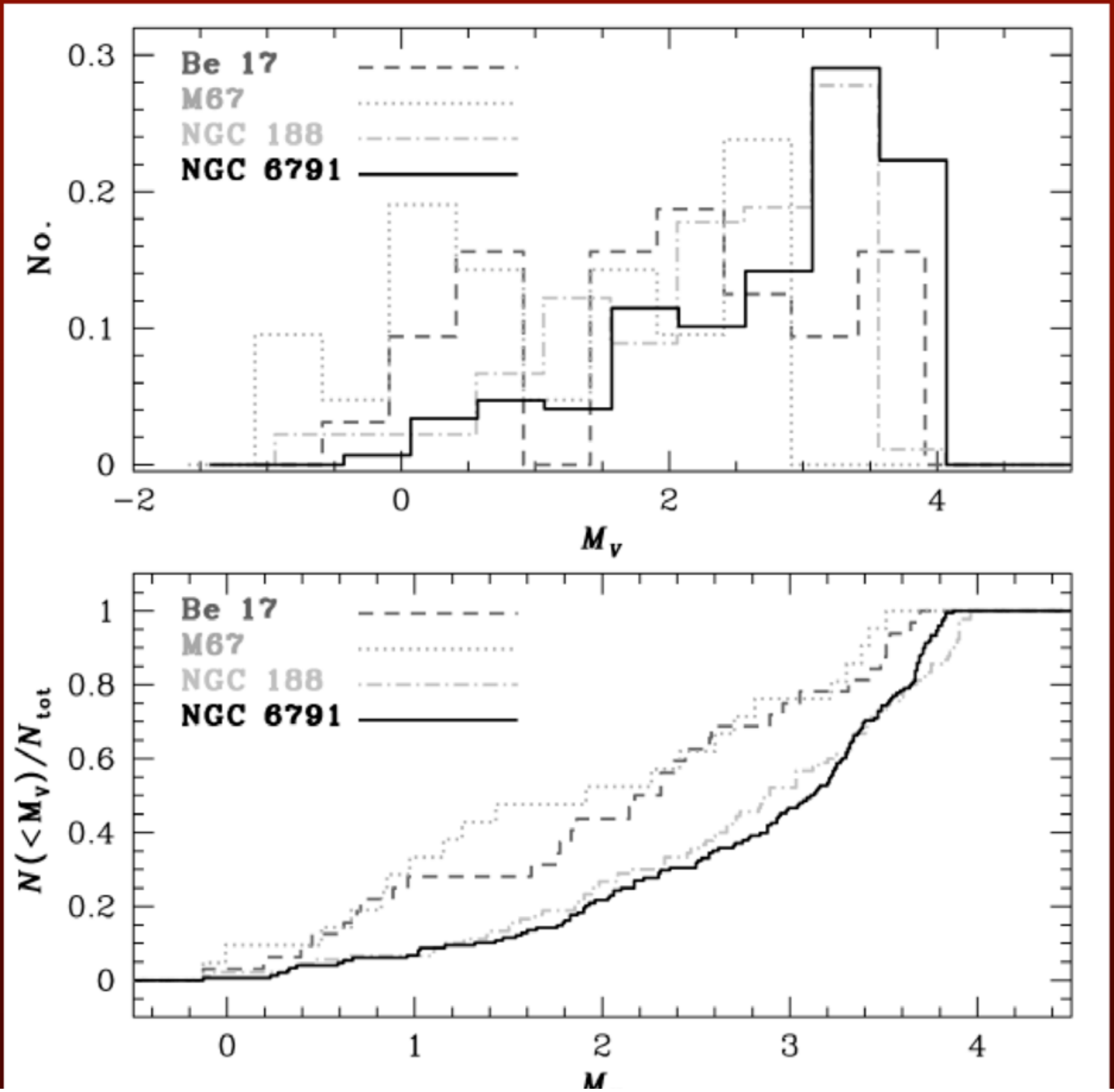
Figures from Cohen et al. 2008

3 added lensed bulge dwarfs from Cavallo et al. 2002





Kalirai et al. (2007) suggest that mass loss may deplete RGB in metal rich populations, helping to account for UV-bright populations. Only marginal effect and NGC 188 has Solar metallicity while 6791 is +0.4 - same RGB LF.



We disagree with Cohen et al. 2007; we believe that there is no problem with a red-giant derived abundance scale in the bulge.

Conclusions (Abundances)

1. Concluding a six year effort, Fulbright et al. (2006) develop a new iron abundance scale for the bulge. A new line list of weak iron lines, with Arcturus-based gf values, is used to verify the abundance scale at the metal rich end.

2. Fulbright et al. (2007) confirms original abundance trends (enhanced alphas) found in McWilliam & Rich (1994) are confirmed; oxygen is a enhanced but far less than Mg/Fe (analysis in progress).

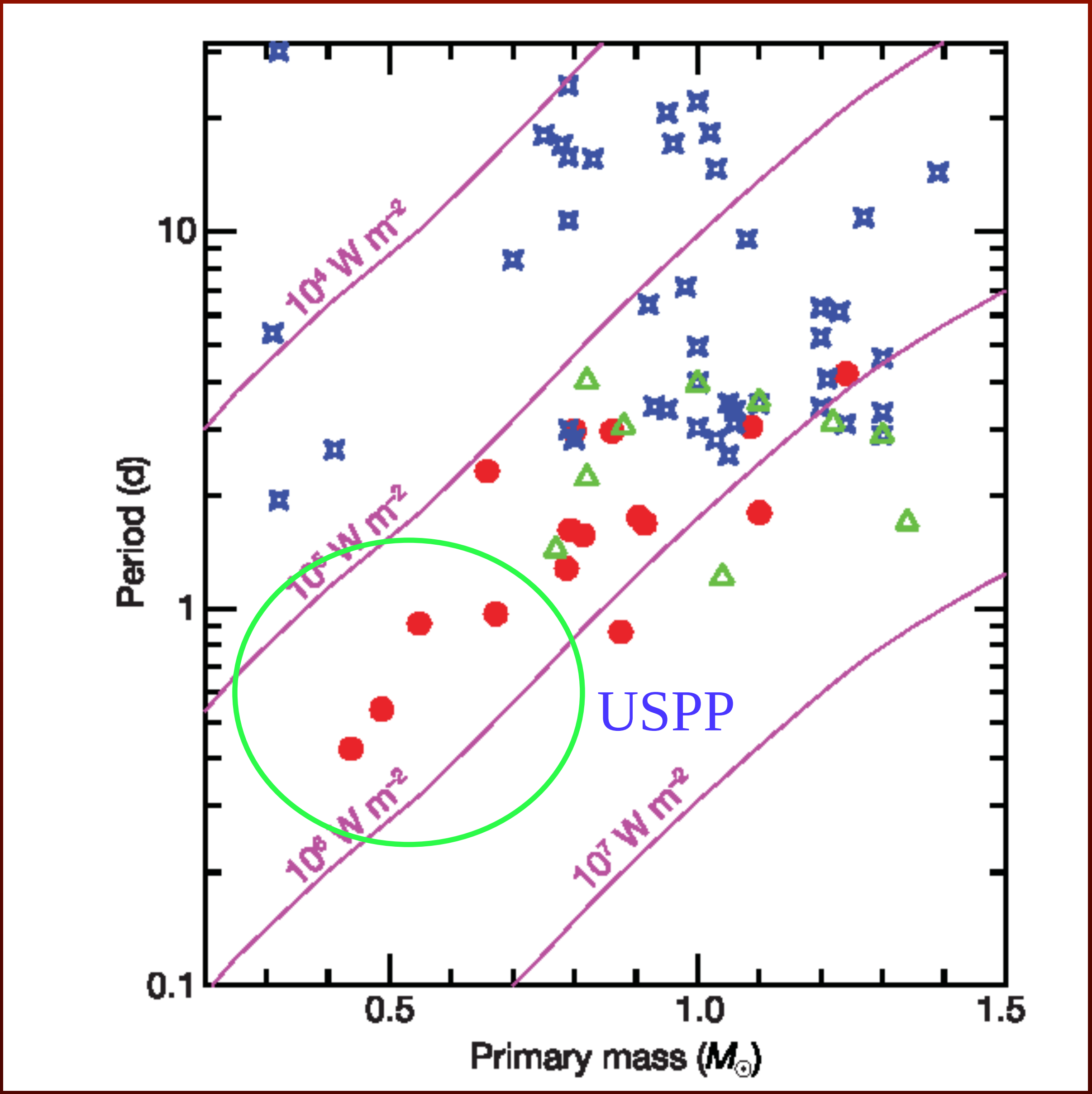
3. The bulge and halo are separated in <Ca+Si+Ti>/Fe vs [Fe/H]

4. [Al/Fe] ranks cleanly the bulge, Solar vicinity, and Sgr dwarf.

5. New studies of M giants 100 pc from the nucleus find no abundance or composition gradient relative to Baade's Window, but metal rich M gia are lacking.

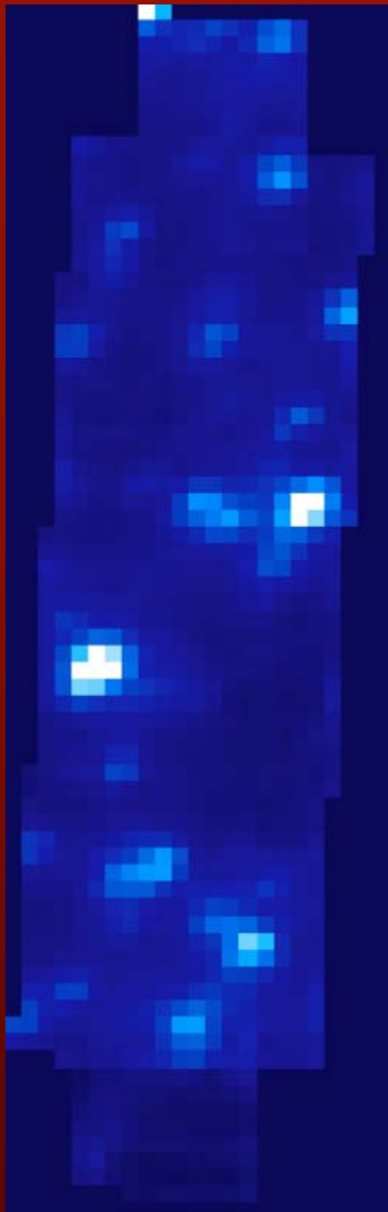
6. We believe that K giant studies have adequately and correctly sampled bulge abundane distribution.

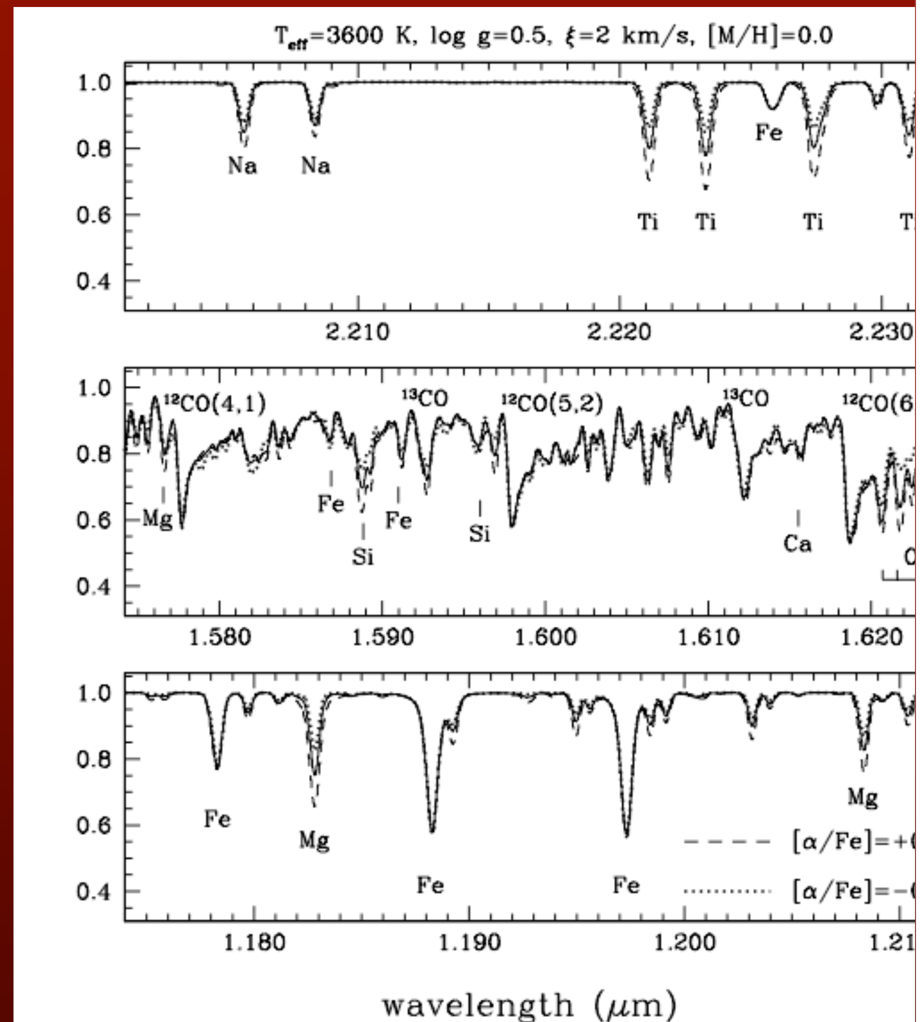
Sahu et al. 2006: Ultra-short Period Planets in the bulge



Hot Jupiter population discovered orbiting M dwarfs, at similar irradiati levels (but smaller orbits)

OSIRIS in M31 Bulge





M31 bulge 300 pc S of the nucleus (roughly
Equivalent to the Sgr I window in the Milky Way
Obtained in Hbb (1.6 um). K=16 mag giants

Spectrum synthesis (Origlia
at R=3,800