The Galactic Bulge

Dedicated to Victor M. Blanco and A.E. Whitford

R. Michael Rich (UCLA),

Christian Johnson (UCLA), Andreas Koch (ZAH), Juntai Shen (Shanghai Observatory), HongSheng Zhao (St. Andrews), John Kormendy (UT Austin), Will Clarskon (UCLA) Roberto de Propris (ESO and FINCA), Livia Origlia (Bologna) Annie Robin (Besancon), Mario Soto (STScI), Christian Howard (Google Inc)

HST Legacy

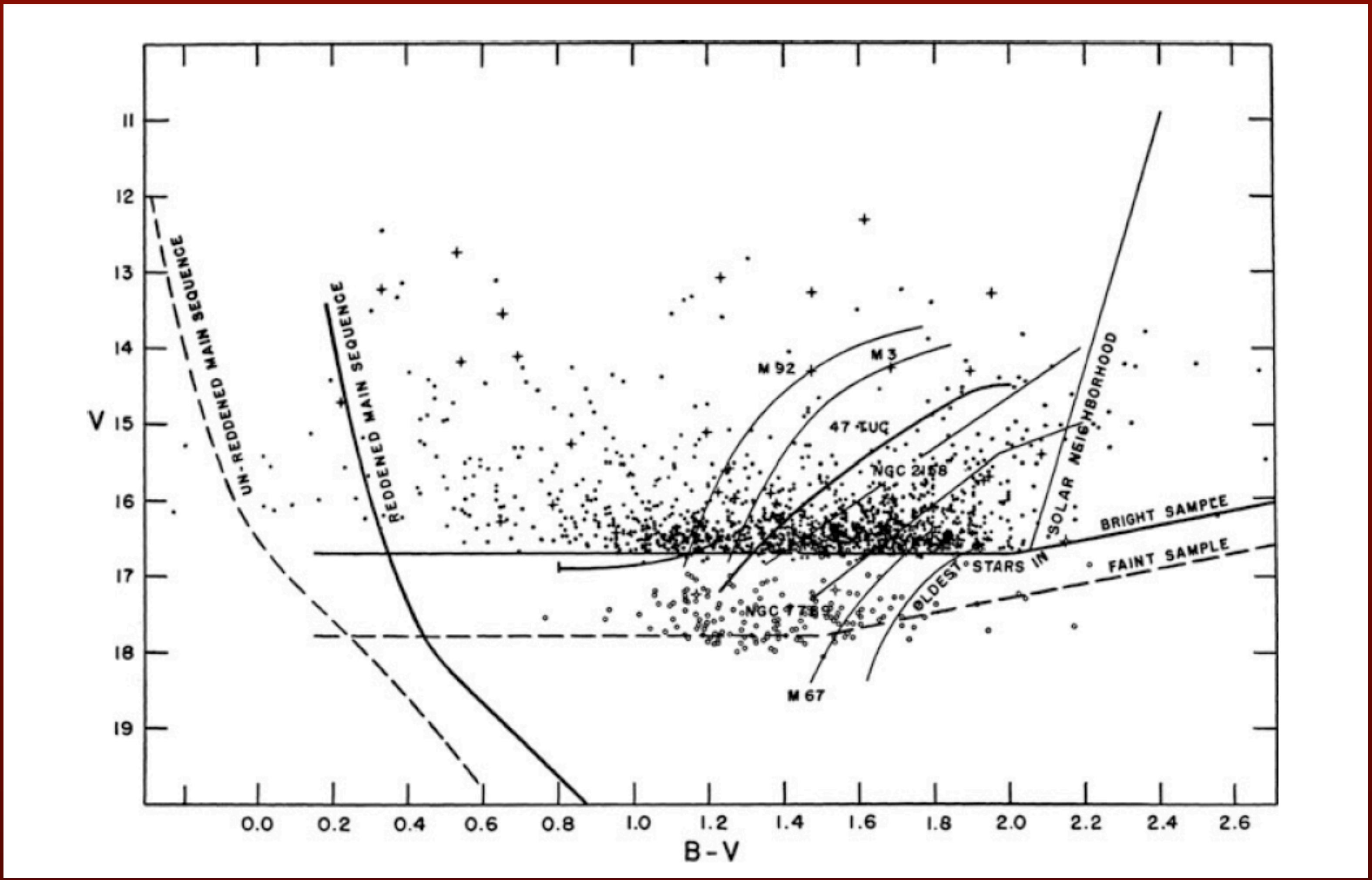
6 May 2013

CTIO 50

Funding: NSF AST-0709479

Historical Perspective

Prior to CTIO, we had rough distance to bulge from RR Lyrae, globular clusters… Arp (1965) photographic CMD



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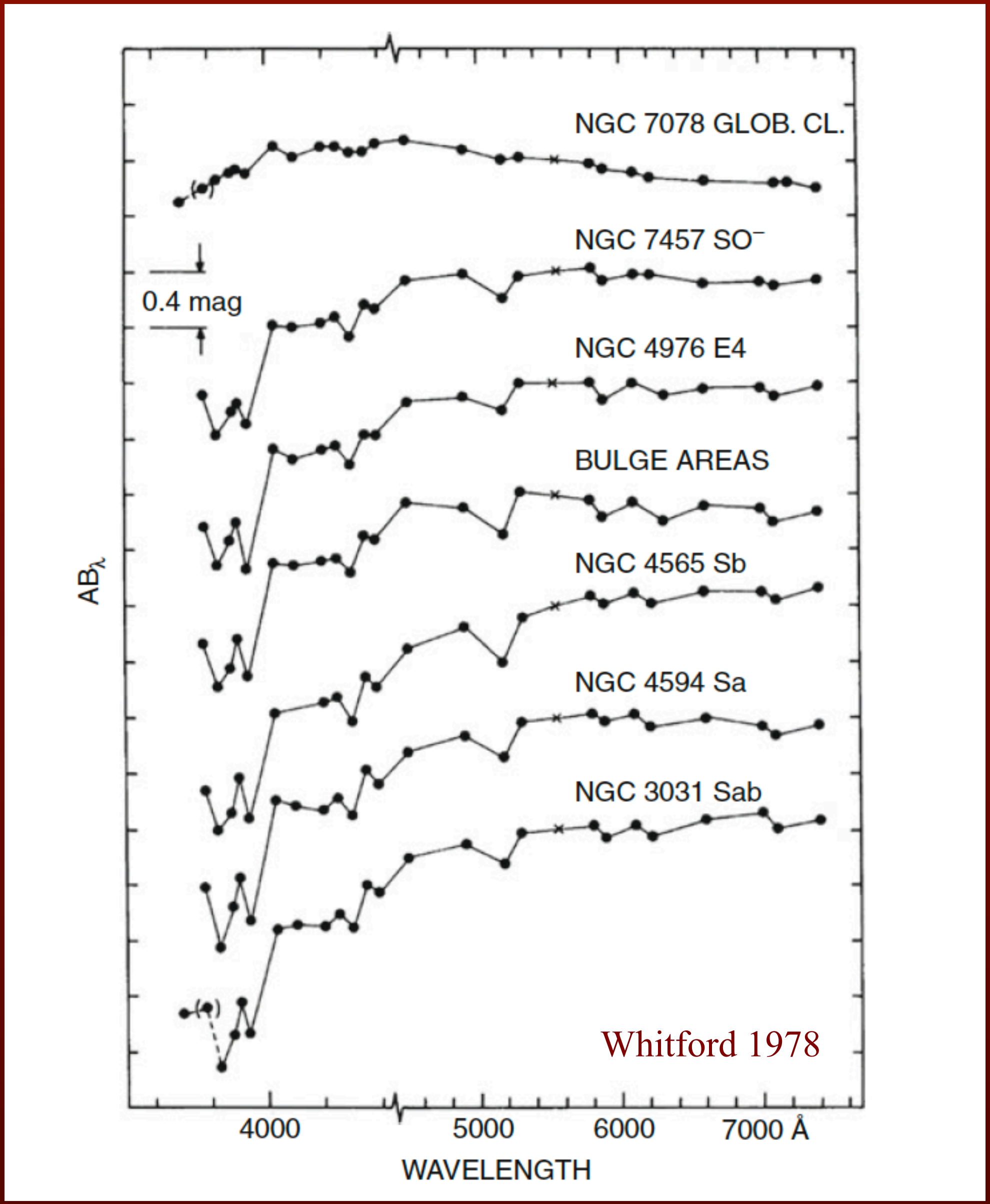
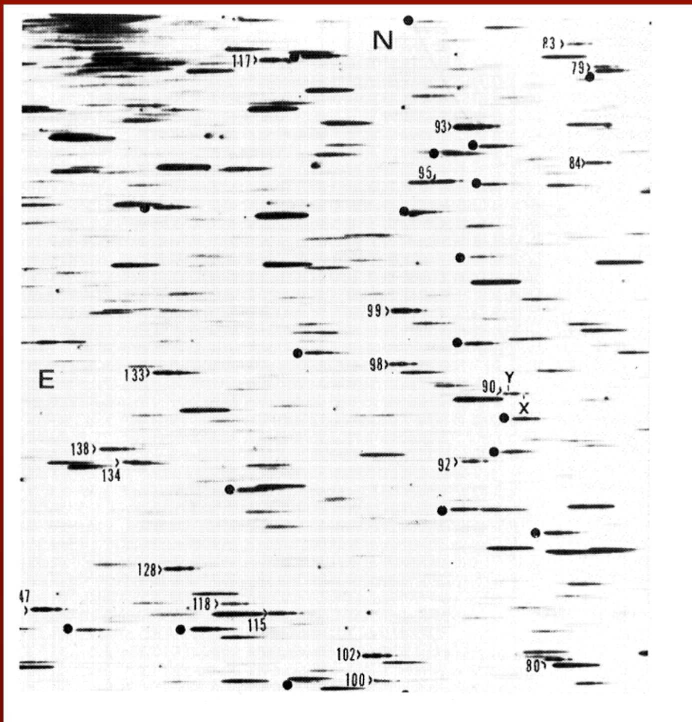


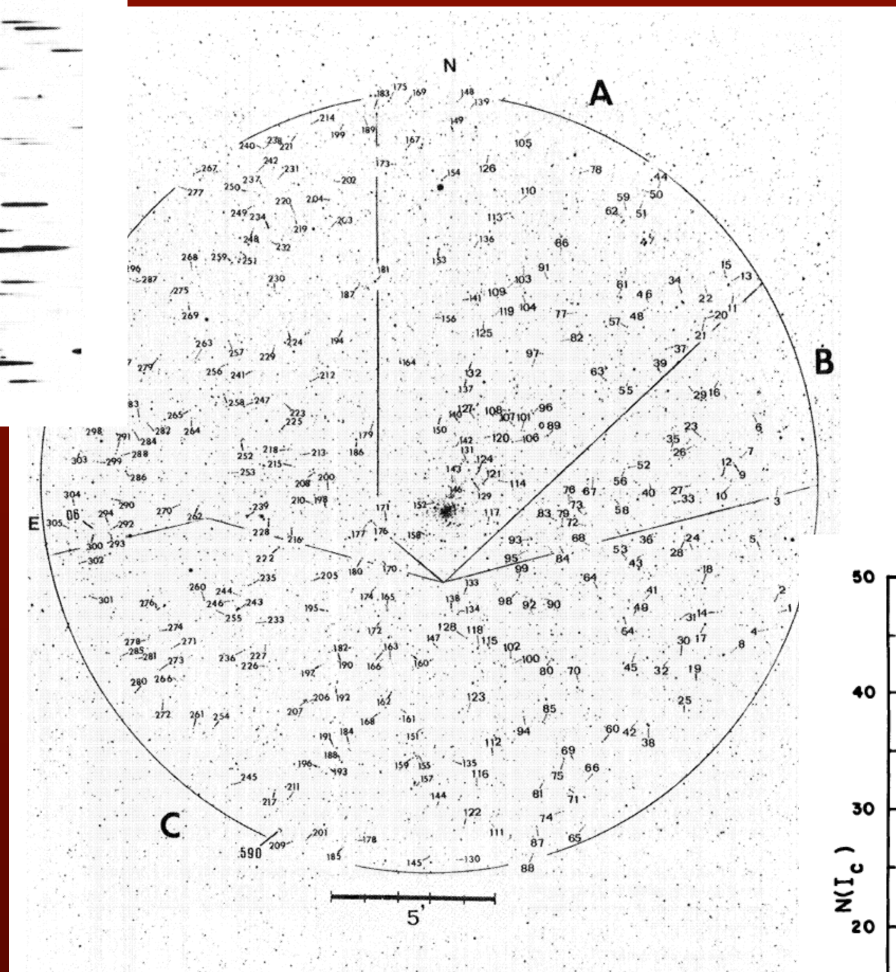
CTIO enabled breakthroughs in study of the bulge

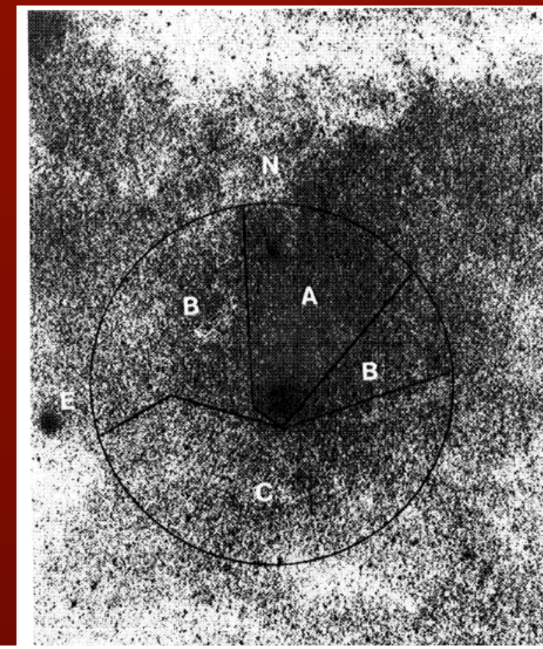
Whitford (1978) used photoelectric scanner on CTIO 1.5m to compare bulge spectrophotometry to external galaxies

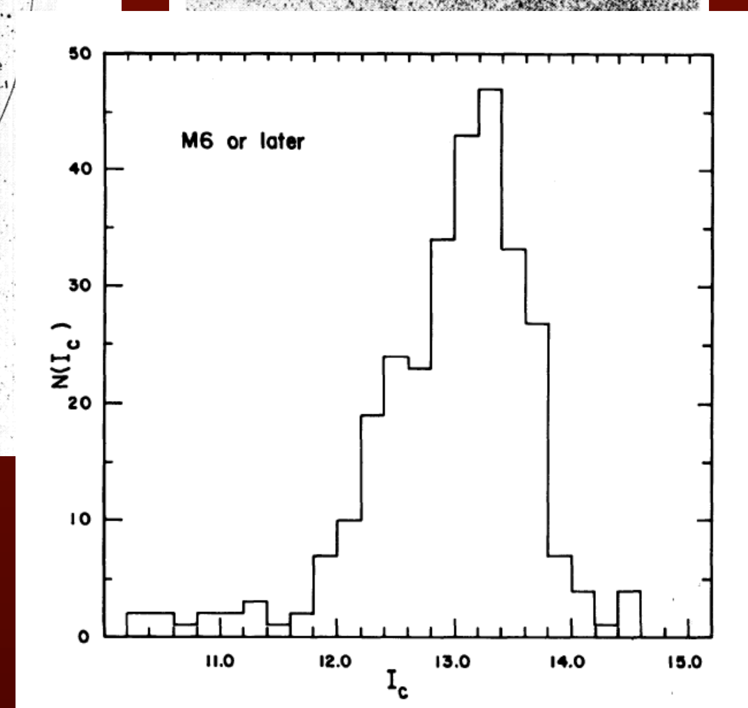
Established bulge population of Milky Way resembled other galaxies

Red giant surveys of Blanco, McCarthy, & Blanco









Using Low resolution grating/prism at prime focus of CTIO 4m telescope (now Blanco 4m telescope) M giants are bright: 12<I < 14

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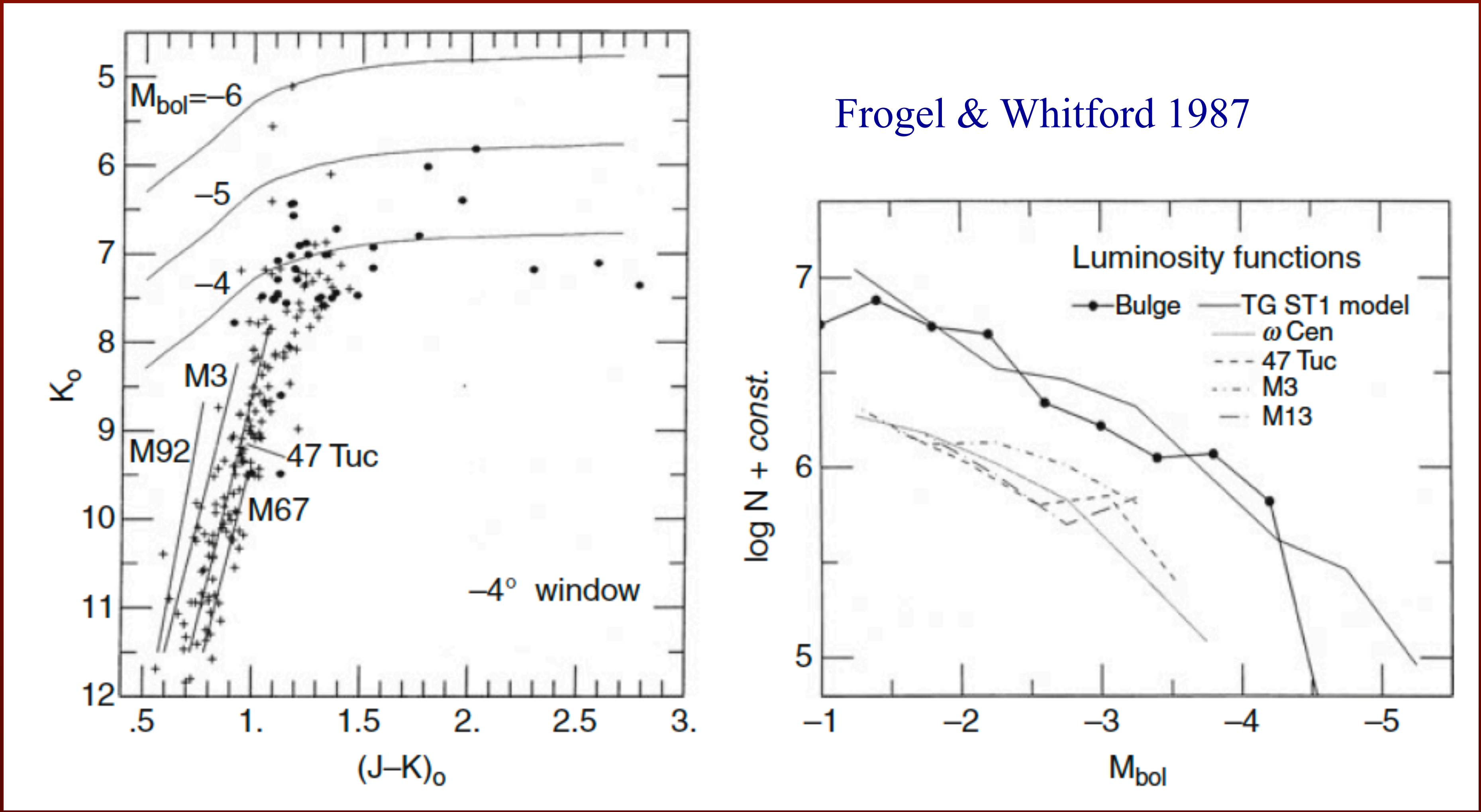
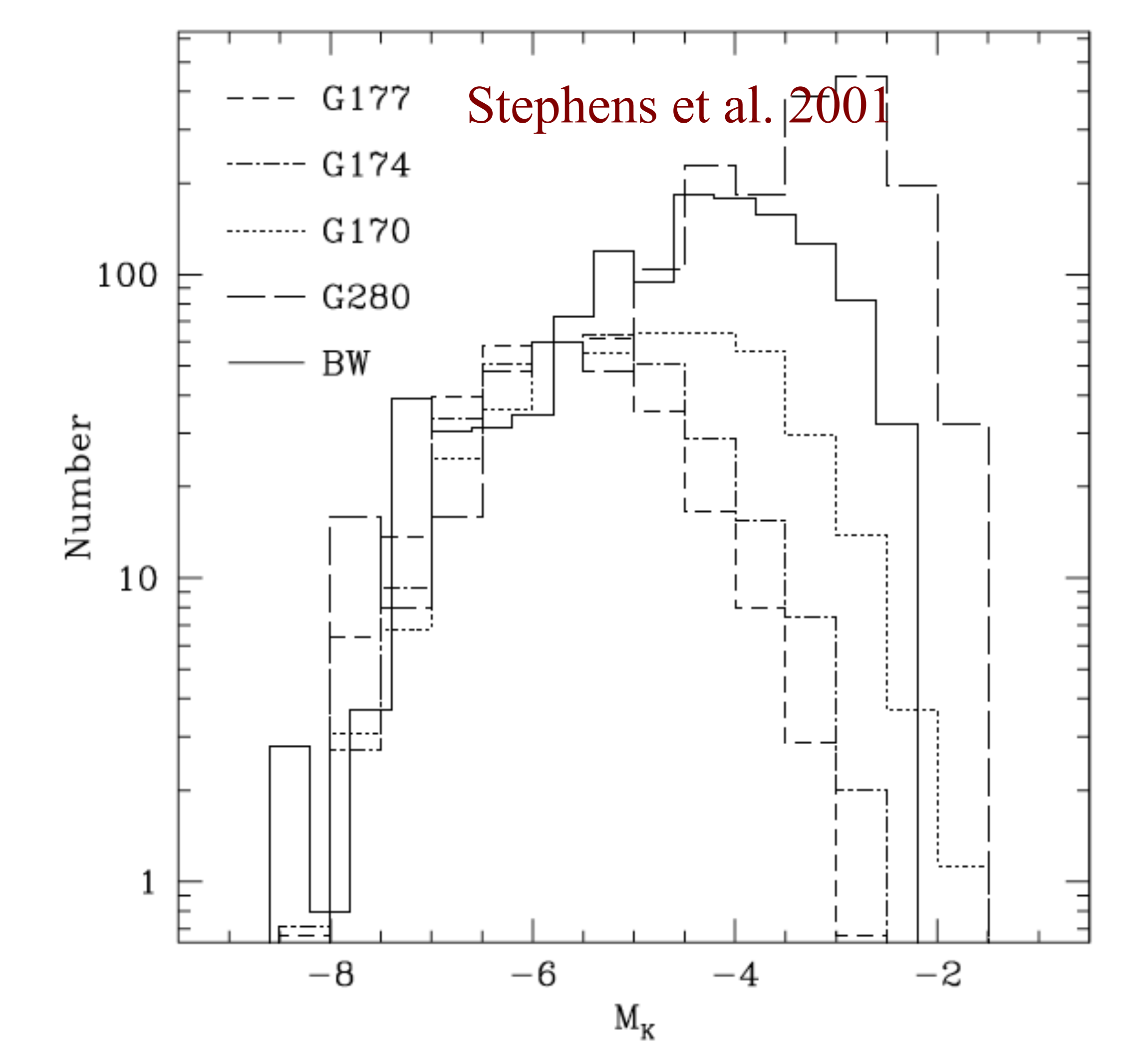
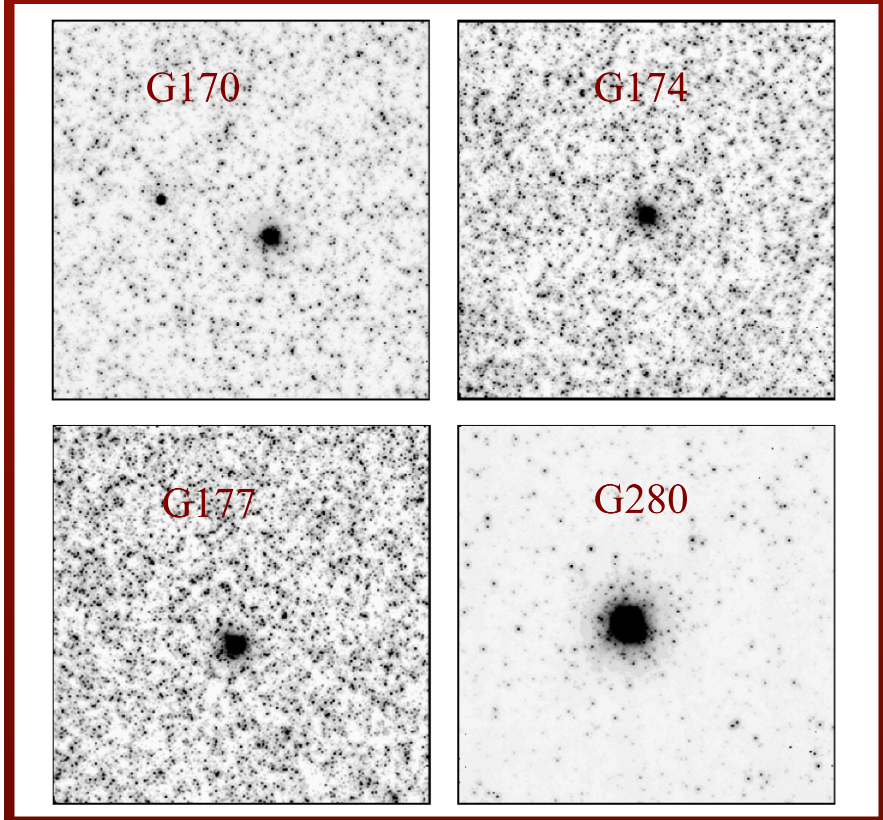
Blanco Surveys give new perspective: M giants for IR surveys; R, I color-magnitude diagram produces clean red giant branch for K giant surveys at Las Campanas



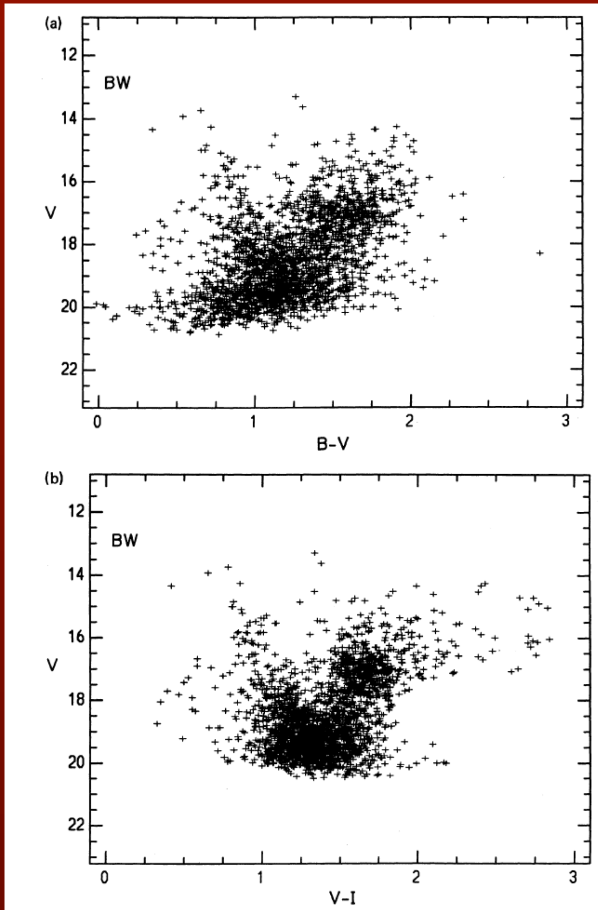
Important series of papers on M giants at latitudes from -2 to -12° Frogel, Blanco, Terndrup, Whitford in 1990s

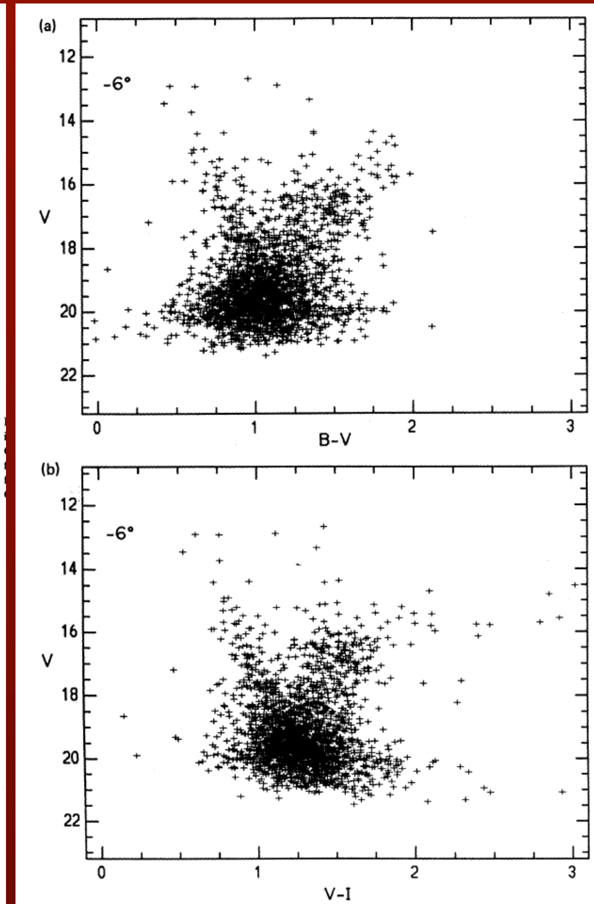


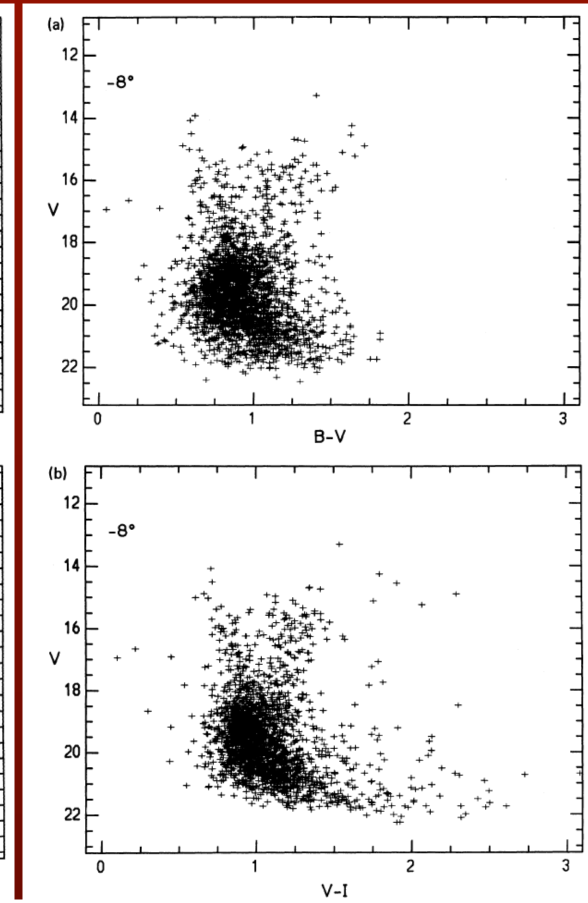


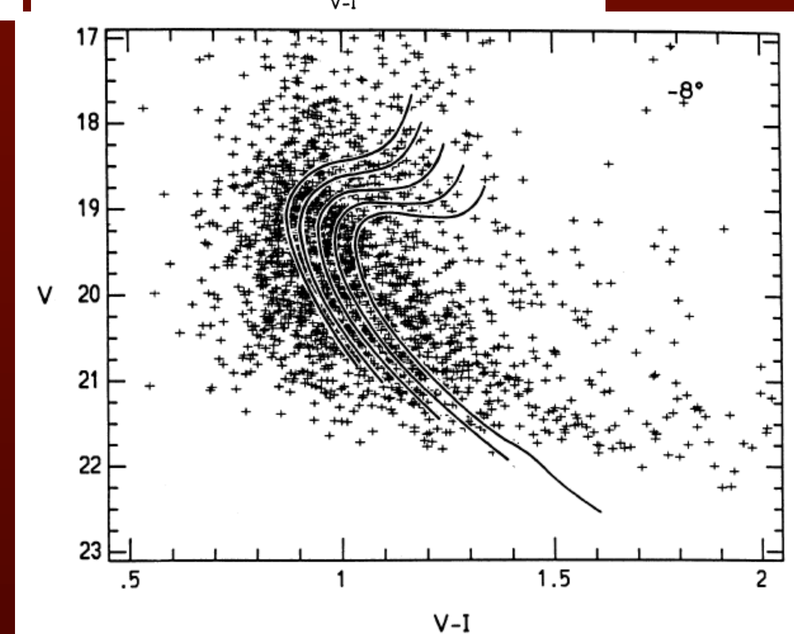
The CTIO IR photometry helped place the IR population of the M31 bulge, observed using HST/NICMOS, in context; FW87 also informs new Gemini AO based studies (Olsen et al. 2006).

Whitford 90th meeting at UC Santa Cruz March 1996



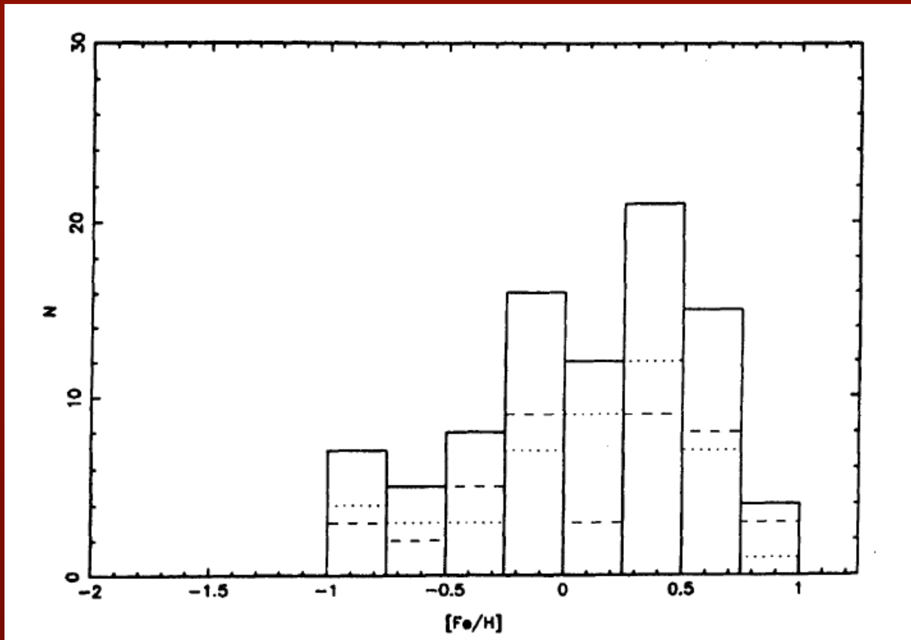






Terndrup (1988) color-magnitude diagrams and age constraint for the bulge (CTIO 4m prime focus). First definition of the red clump in the bulge, population/abundance gradient, and age constraint (globular cluster-age).

Rich 1988



(Sample selected from Blanco & Whitford R,I photometry from 4m plates

R88 > McWilliam & Rich 1994 R=16,000

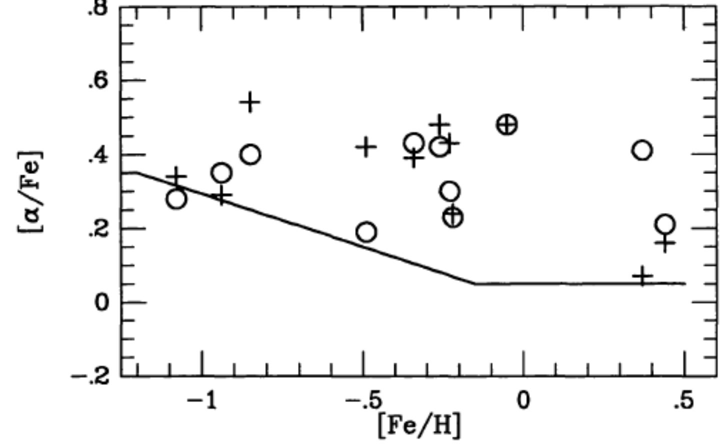
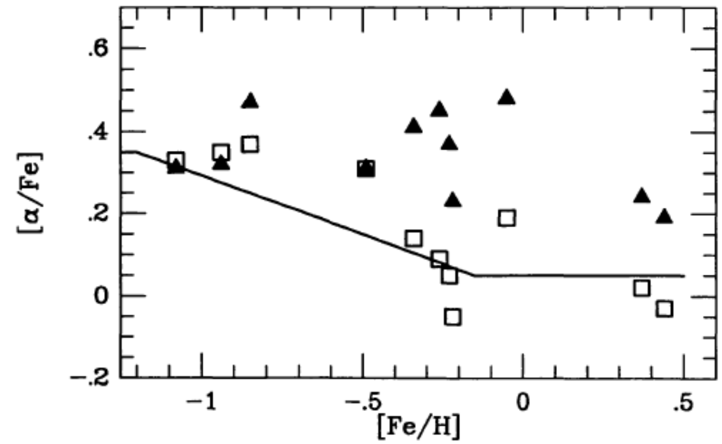


FIG. 20a

Prove high [Fe/H]; Mg, Ti/Fe high



HE FIRST DETAILED ABUNDANCE ANALYSIS OF GALACTIC BULGE K GIANTS IN BAADE'S WINDOW

ANDREW MCWILLIAM[1,2]
Observatories of the Carnegie Institution of Washington, 813 Santa Barbara Street, Pasadena CA 91101; e-mail: andy@marmite.ociw.edu
AND
R. MICHAEL RICH[1,3]
Department of Astronomy, Columbia University, 538 W. 120th Street, New York NY 10027; e-mail: rmr@cuphya.phys.columbia.edu
Received 1993 April 8; accepted 1993 August 13

AAS Pierce Prize McWilliam

2. OBSERVATIONS AND REDUCTIONS

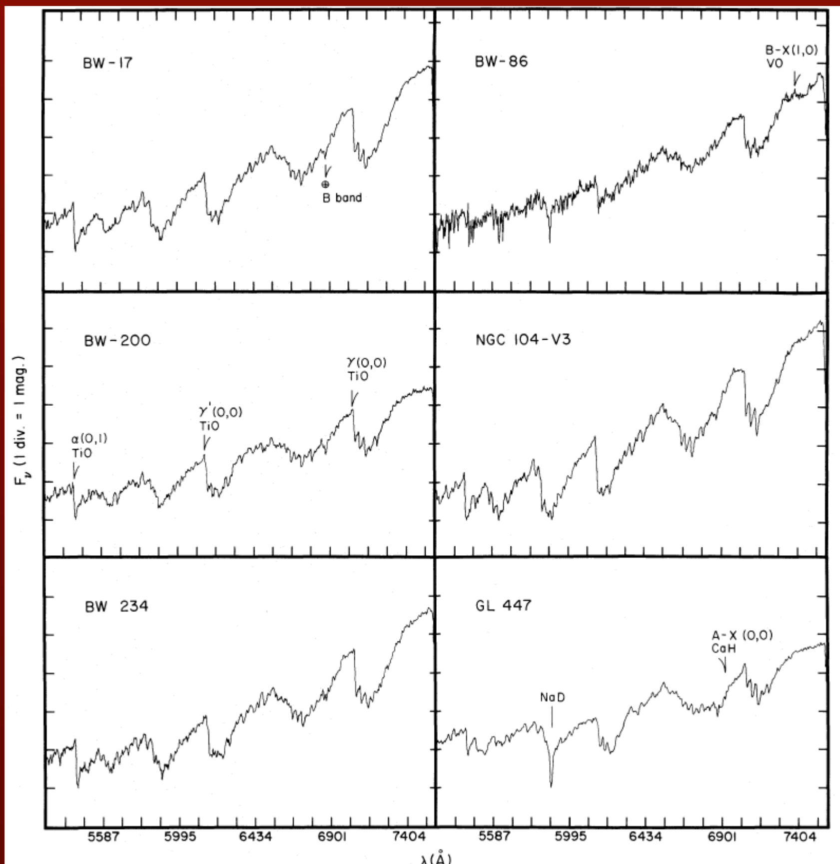
Spectra of 12 Galactic bulge K giants were taken using the CTIO 4 m echelle spectrograph with the Air Schmidt camera on one night in 1990 June and four nights in 1991 May. The

Results confirmed at Keck, VLT

300 min exposures

6

Mould (1983) obtains radial velocities of Blanco M giants, pioneering kinematic studies of the bulge



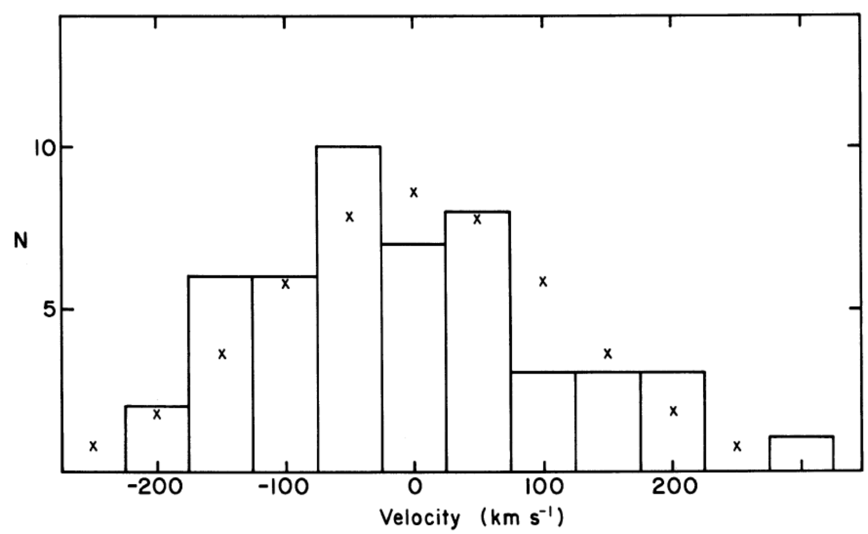


FIG. 5.—Radial velocity distribution of M giants in Baade's window (*histogram*). The crosses represent the best fitting normal distribution.

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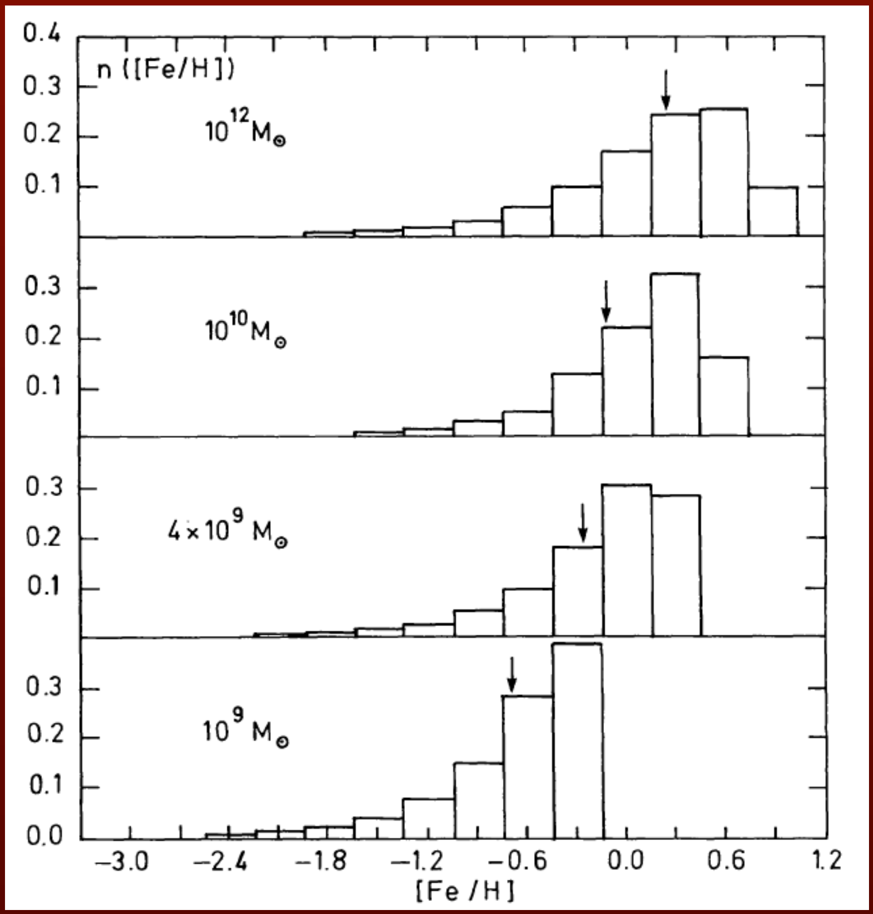
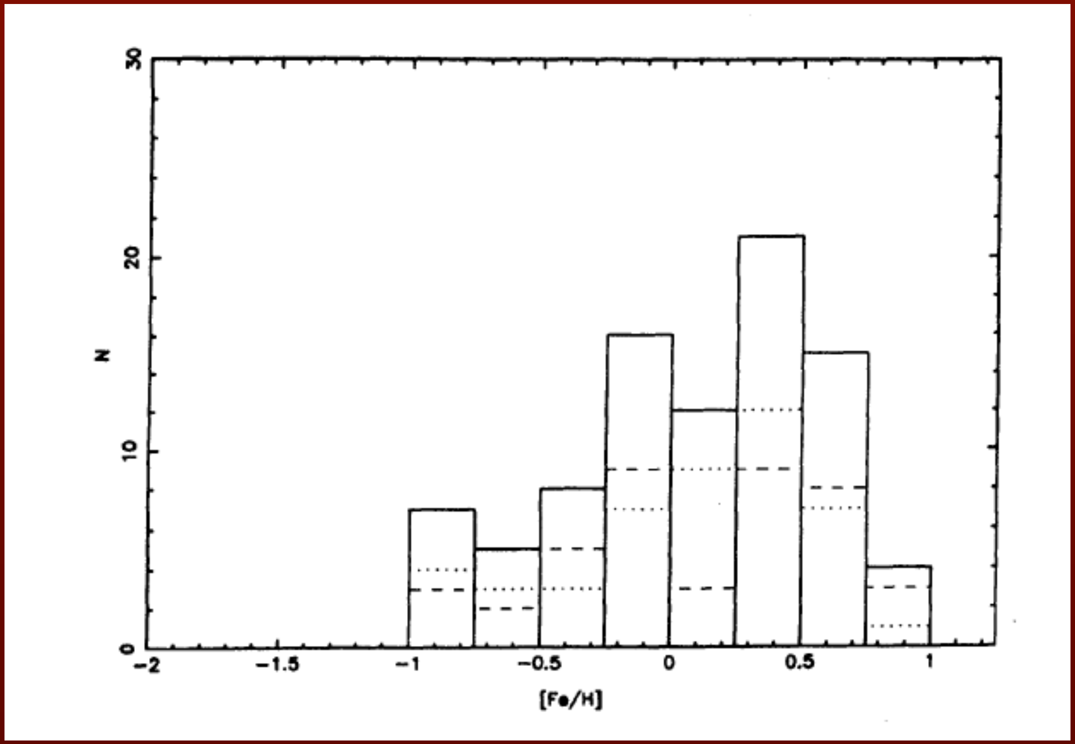
Chemical and photometric properties of SN-driven galactic wind model for elliptical galaxies

Arimoto & Yoshii 1987, A&A 173, 23

Rich 1988 AJ 95, 828 (Ph.D. Thesis); J. Mould





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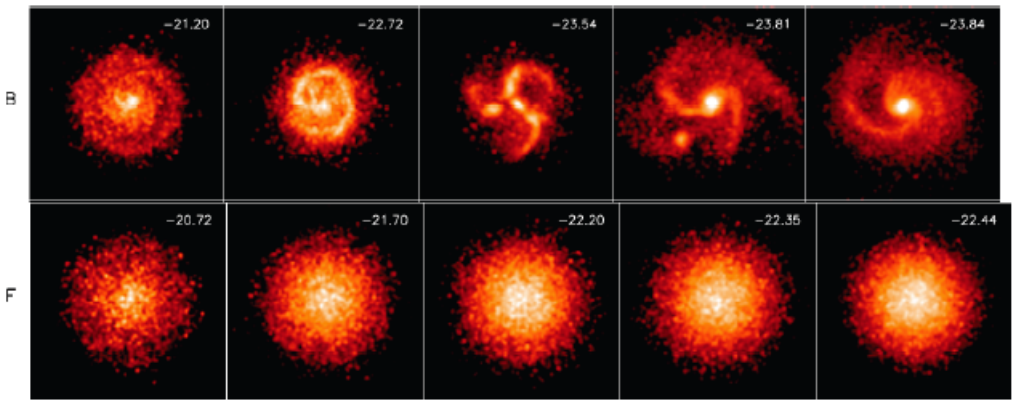
Bulges appear be either spheroidal (classical) or barlike (pseudobulge)

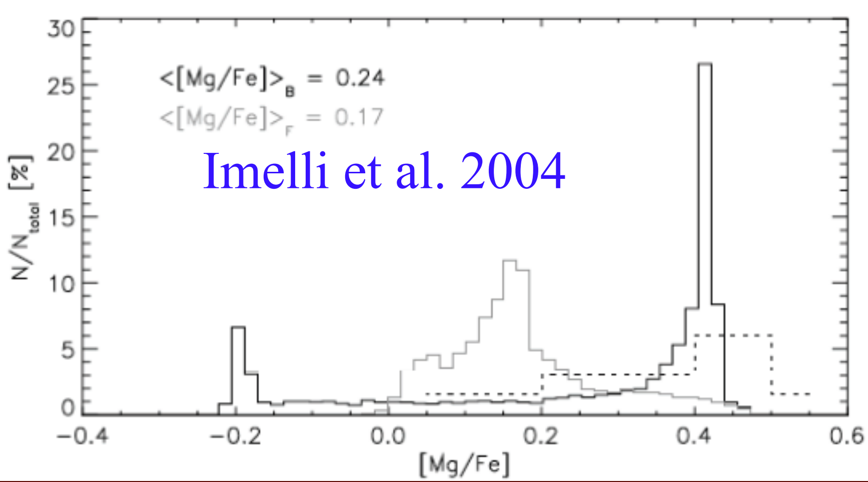
Canonical formation picture is that spheroidal forms via early mergers, while pseudobulges/bars evolve from a buckling instability over longer timescales.

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

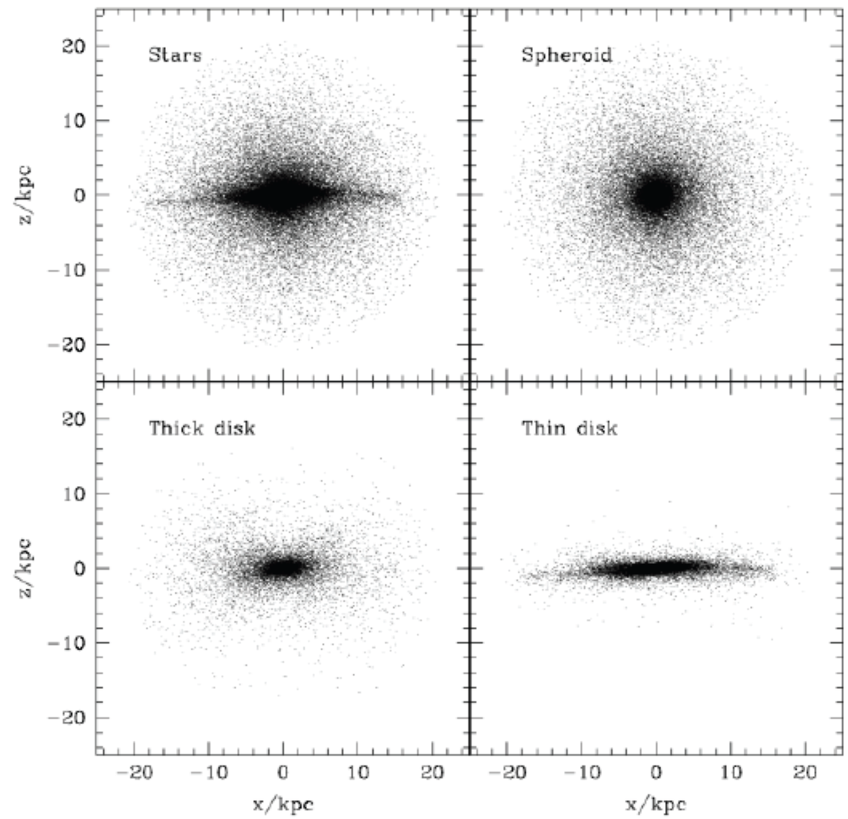
Imelli et al. 2004; Elmegreen et al. (2008) - major merger origin
Clumps dissipate rapidly into bulge or Classical early merger..

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





Abadi 2003



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N-body bar models attractive for representing the bulge

However, extended formation models favored; bar survival?

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

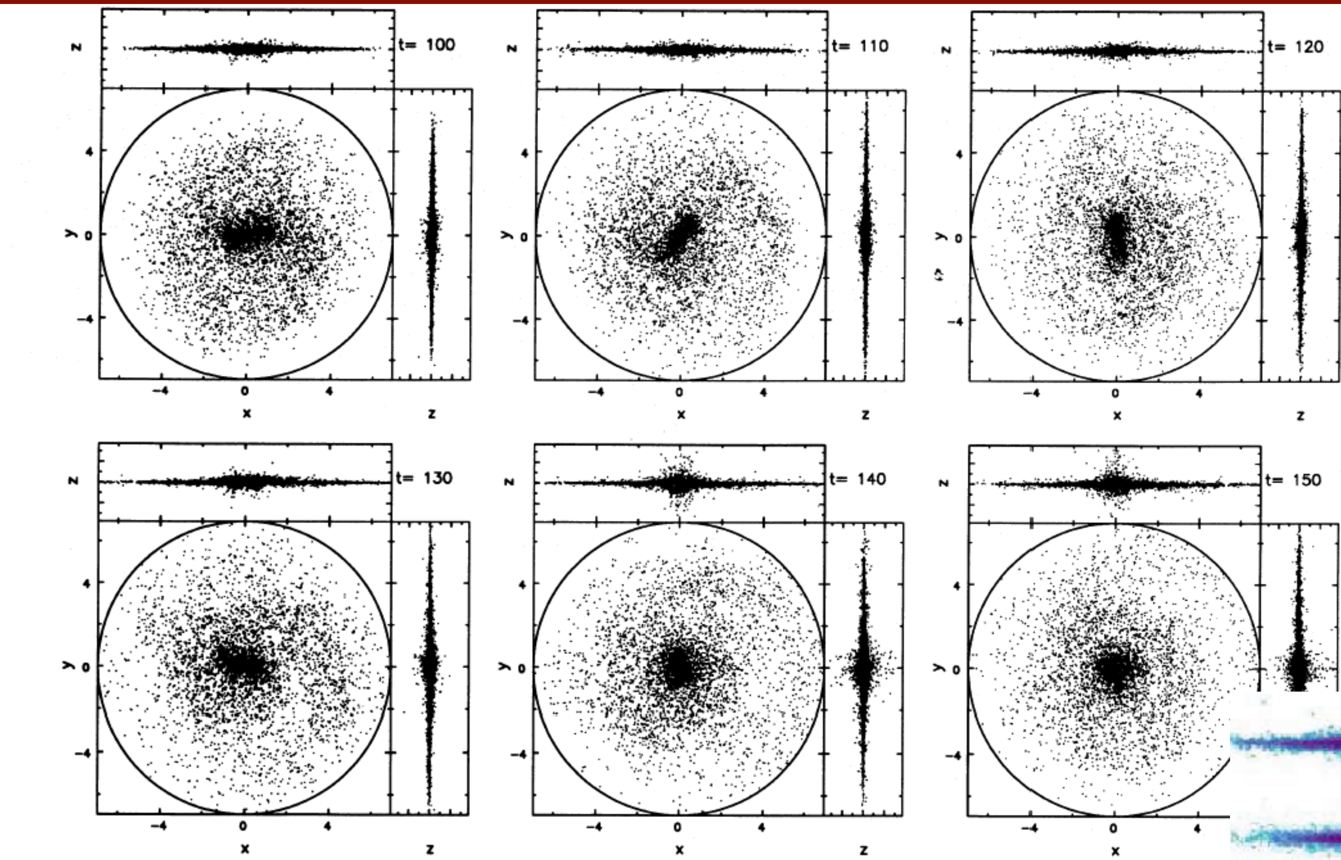
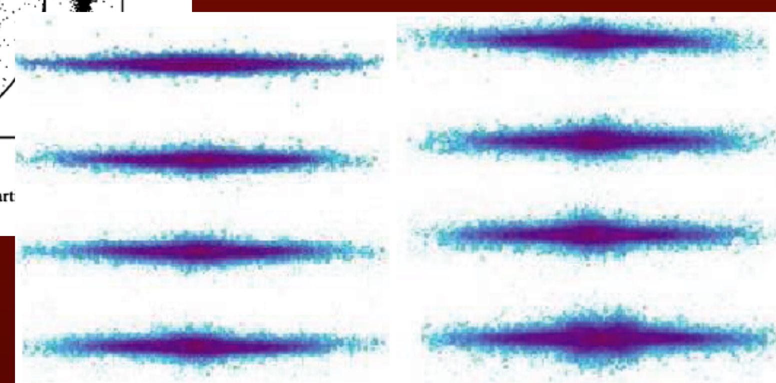


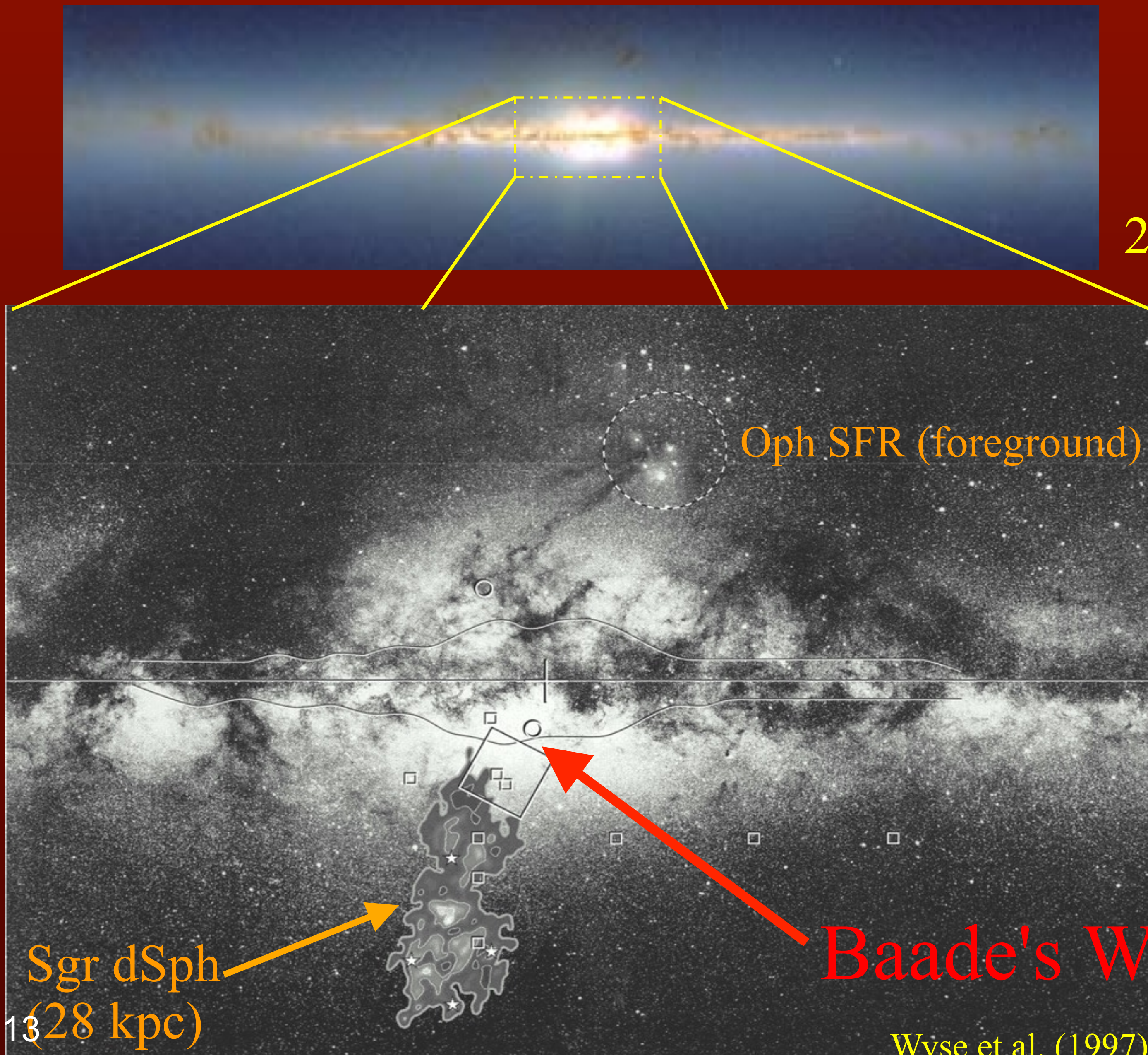
FIG. 6.—The evolution of a three-dimensional model in which a 5% central mass is grown from time 100 to time 140. The whole calculation volume is shown, but only one part
bar dissolves abruptly between times 130 and 140, forming a spheroidal bulgelike feature at the center.

Combes 09- bar resurrection via gas inflow



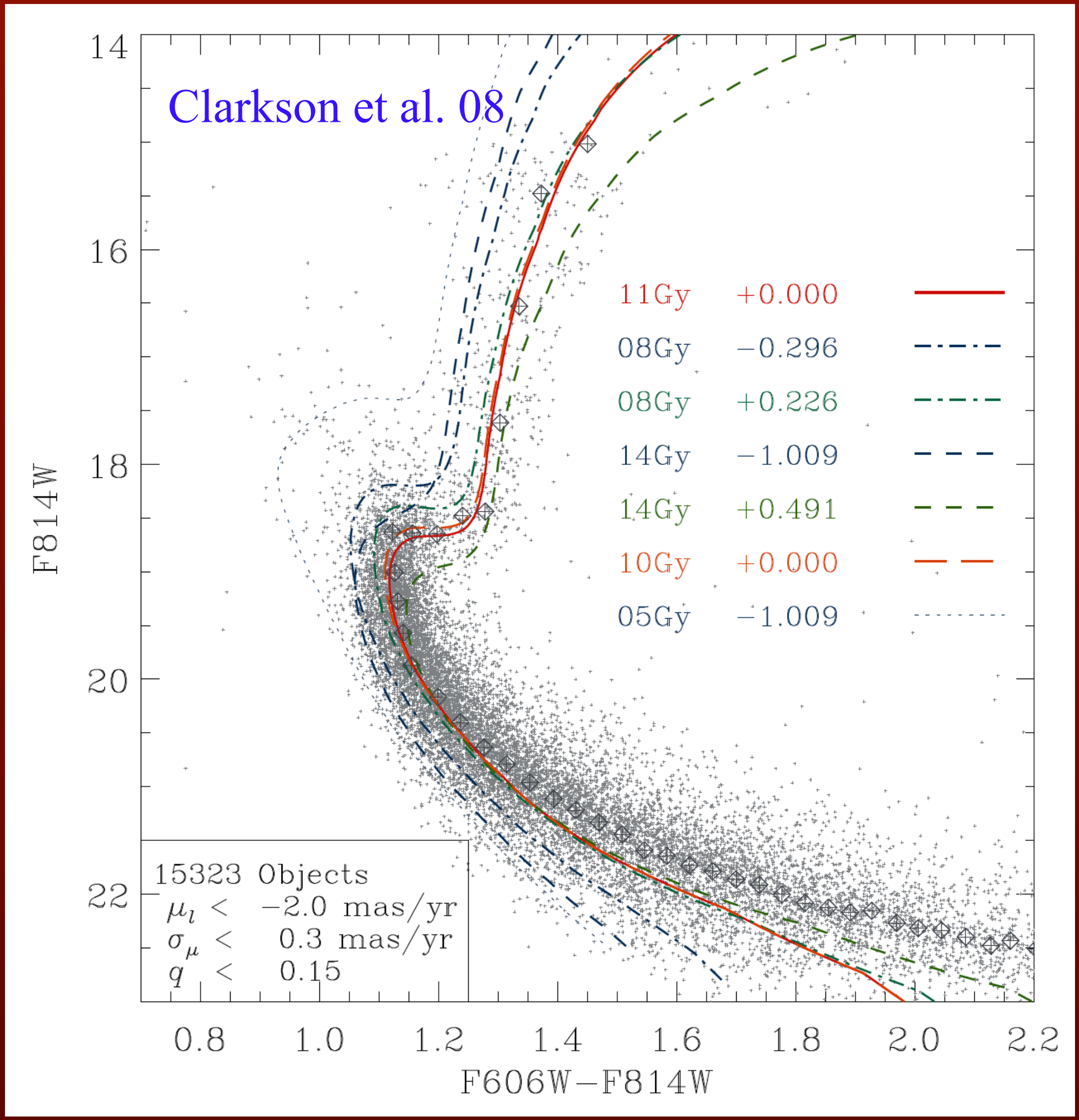
Vertical thickening of the bar into a bulge would leave no abundance gradient in the z-direction.

Bulge in Context



Courtesy J. Fulbright

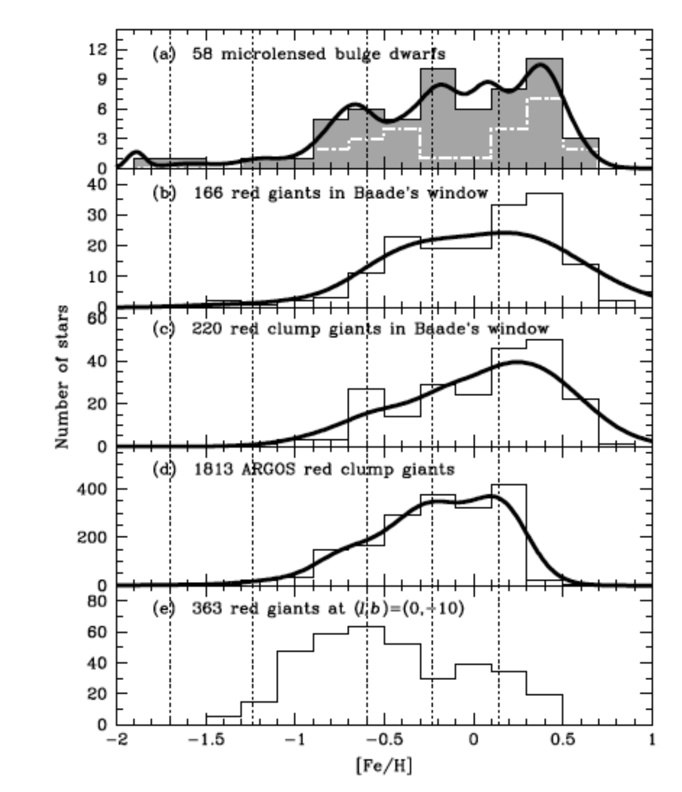
Age constraint from PM separation

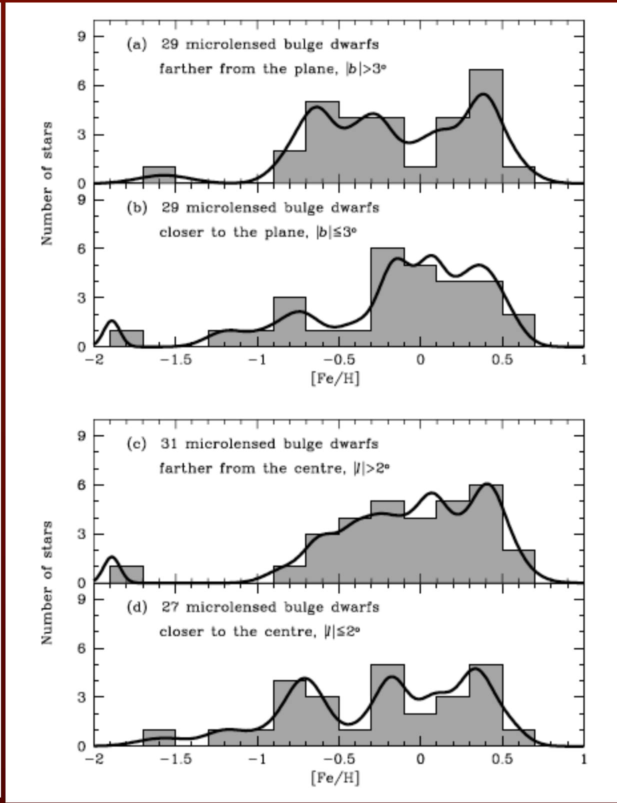


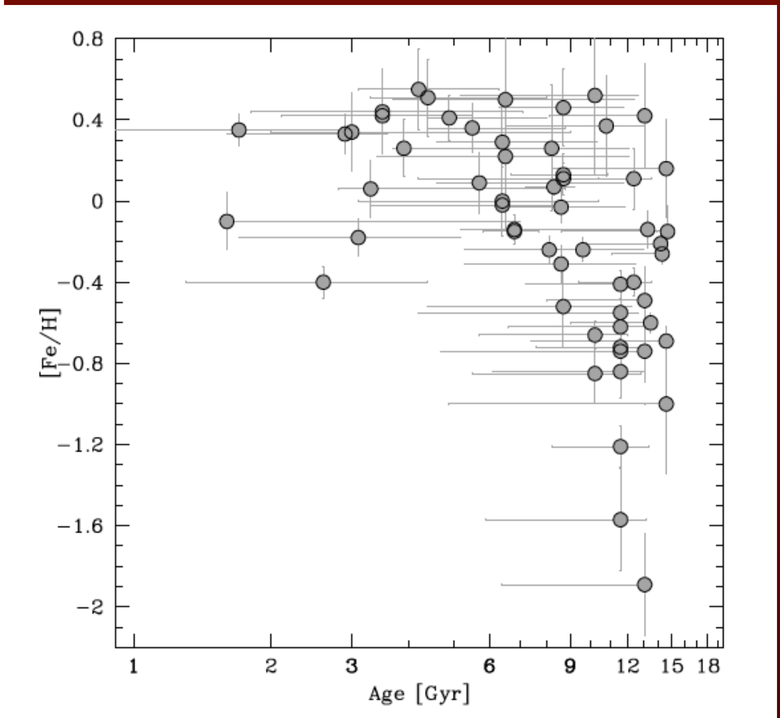
~99% of bulge older than 5Gyr; pure 10+ Gyr likely (Clarkson+ 08, 09

Bensby et al. 2012

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







Kinematics

PNe Beaulieau et al. 2000

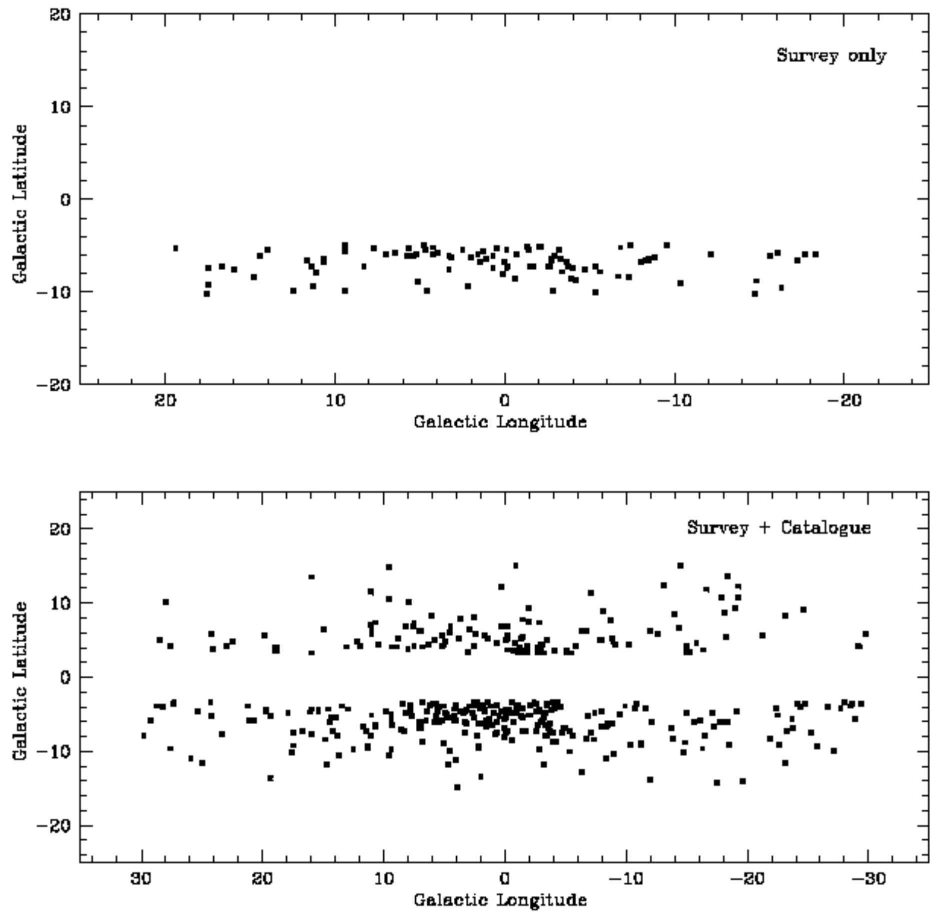
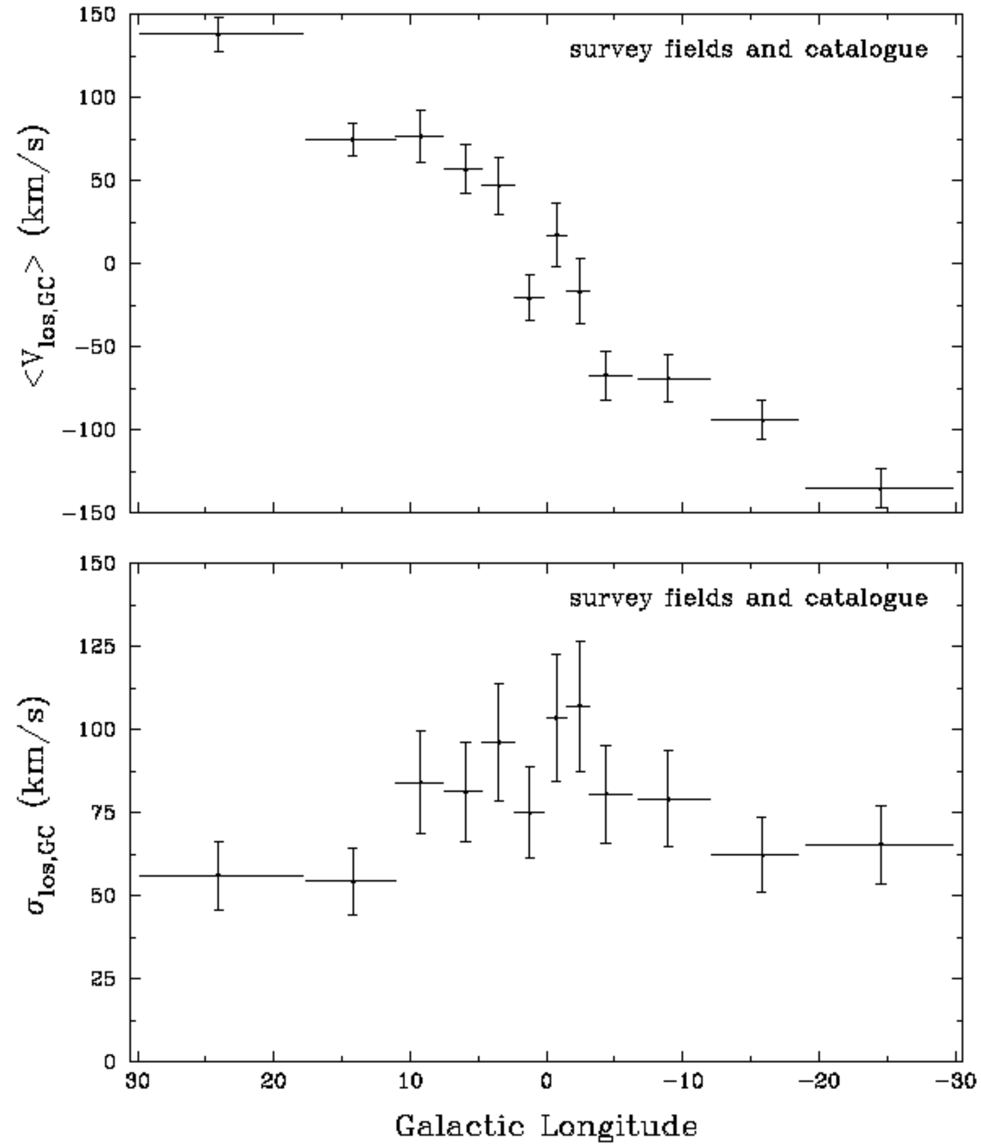


FIG. 2.—(*l*, *b*) distributions for the Survey fields only sample (*top panel*) and the Survey fields + Catalogue sample (*lower panel*).



Trailblazing survey used to explore a range of bar models, constrain orientation of bar

BRAVA
First proposal 2003

Rich et al. 2007 ApJ 658, L29
Rich+ 2007 Howard et al. 2008 , 2009 ApJ
Shen et al. 2010 ApJ; Kunder et al. 2011 AJ

Special thanks to Roberto de Propris and Andrea Kunder

Strategy: Use M giants brighter than clump that can be observed even in high extinction fields. M giants also trace the 2um light of the bulge

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; bulge membership

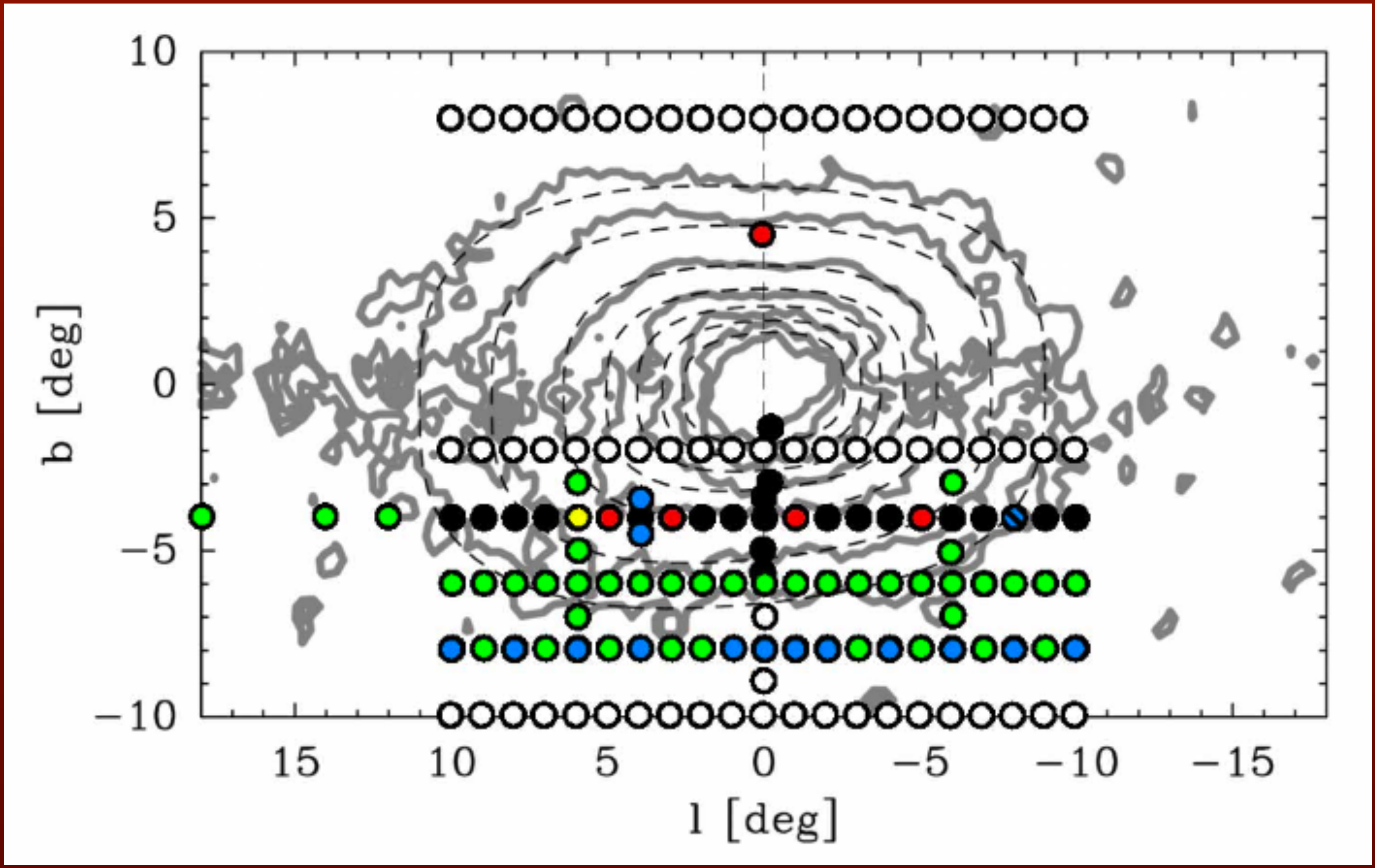
Cross correlation from 7000 - 9000A (include Ca IR triplet)

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

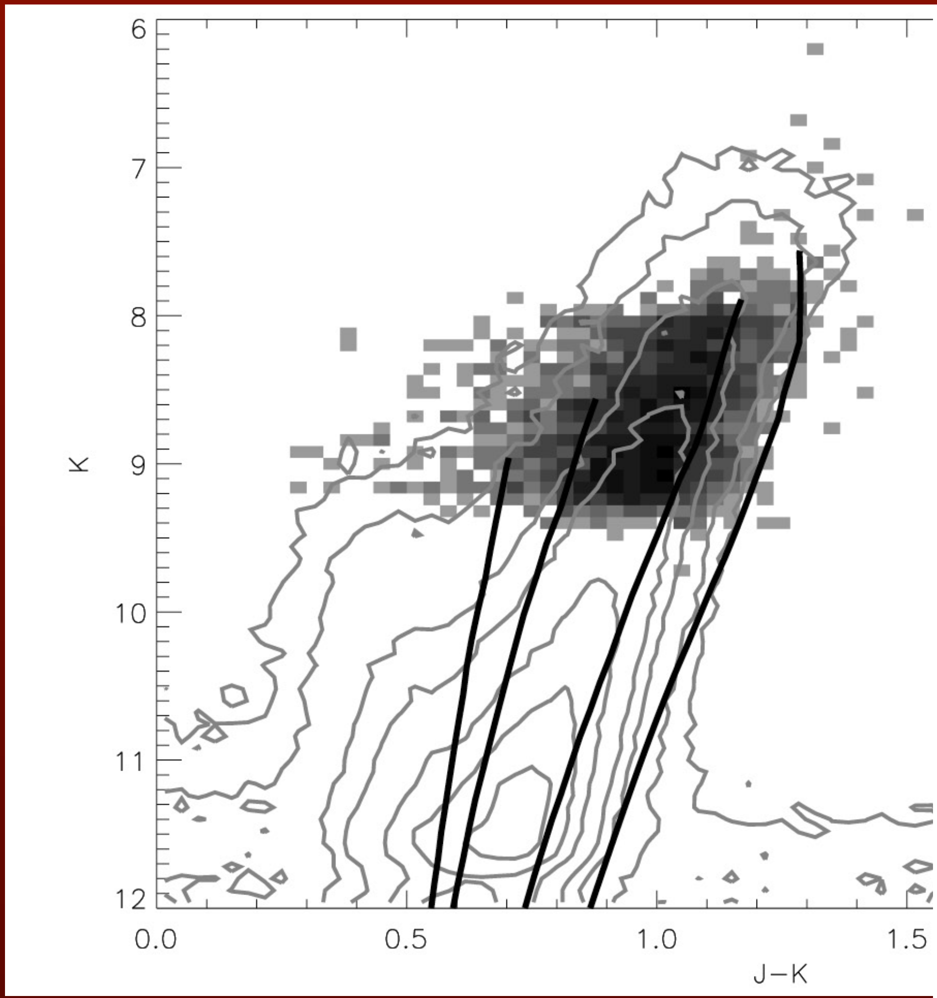
9,000 stars to date; website and public data release aim for 2010

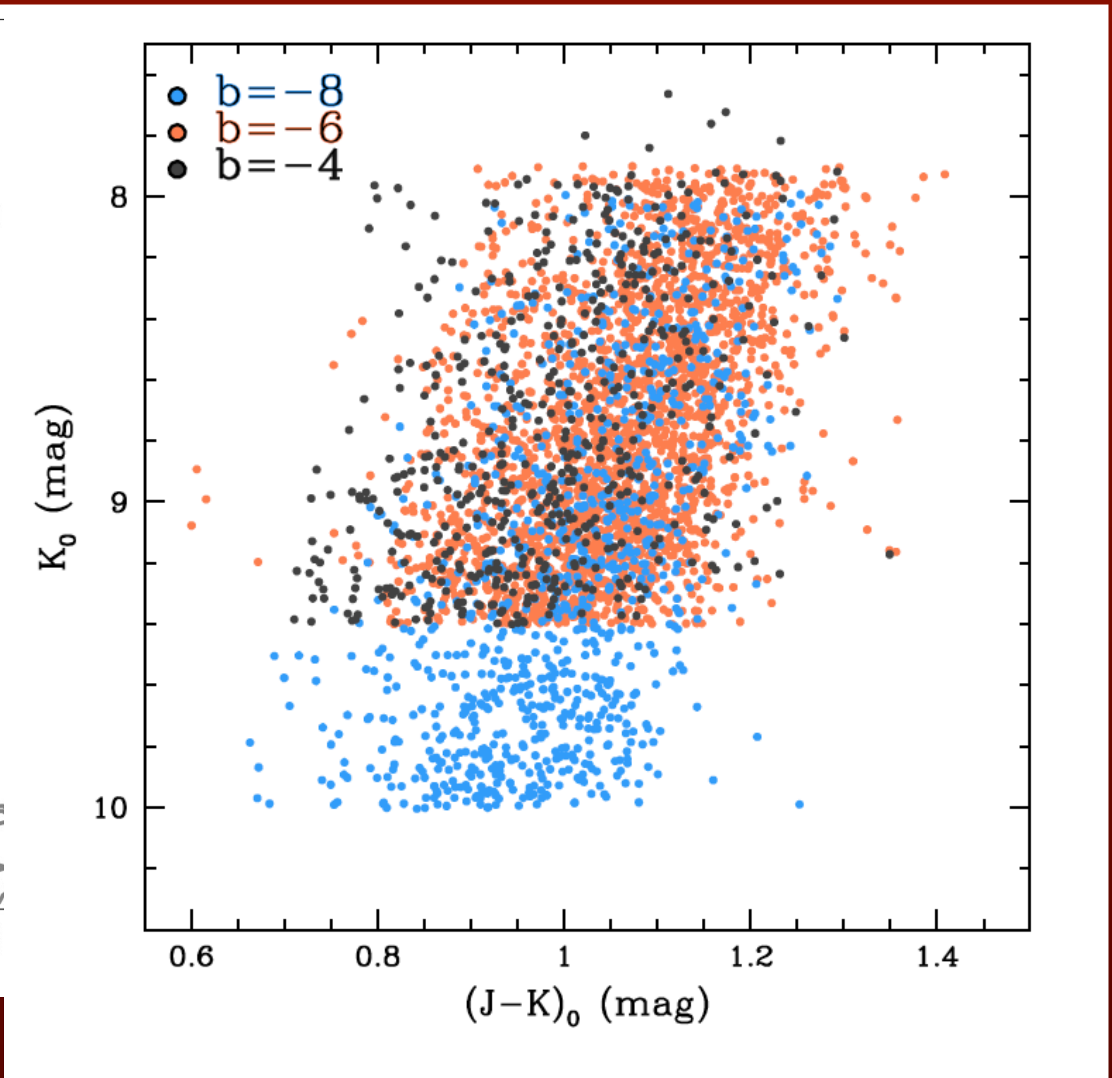
Survey Fields 2005: blue 2006: red 2007: green



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

Target Selection

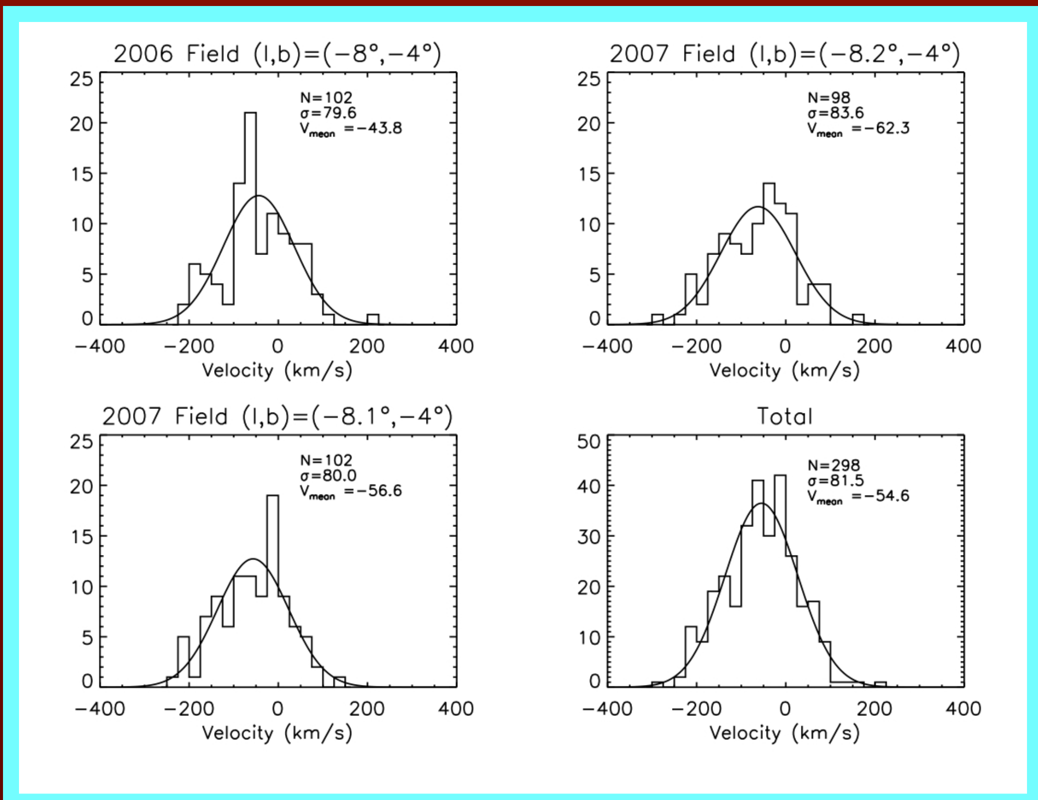


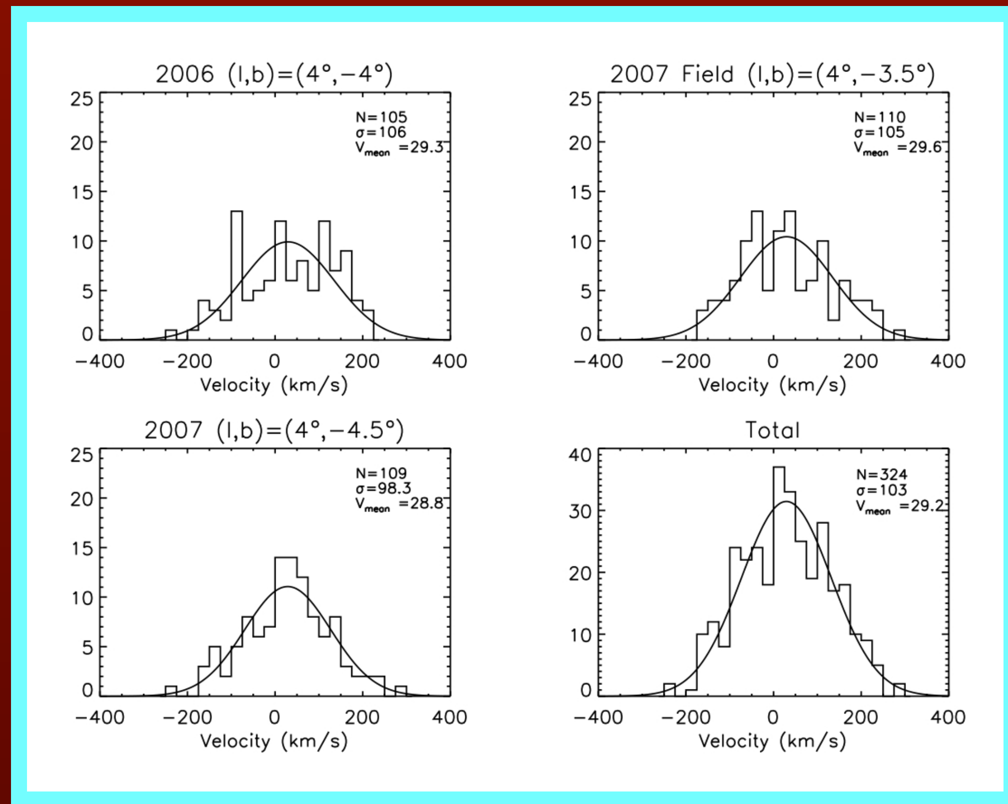


Howard et al. 2008 b=-4 dereddened

Kunder et al. 2011, new sample

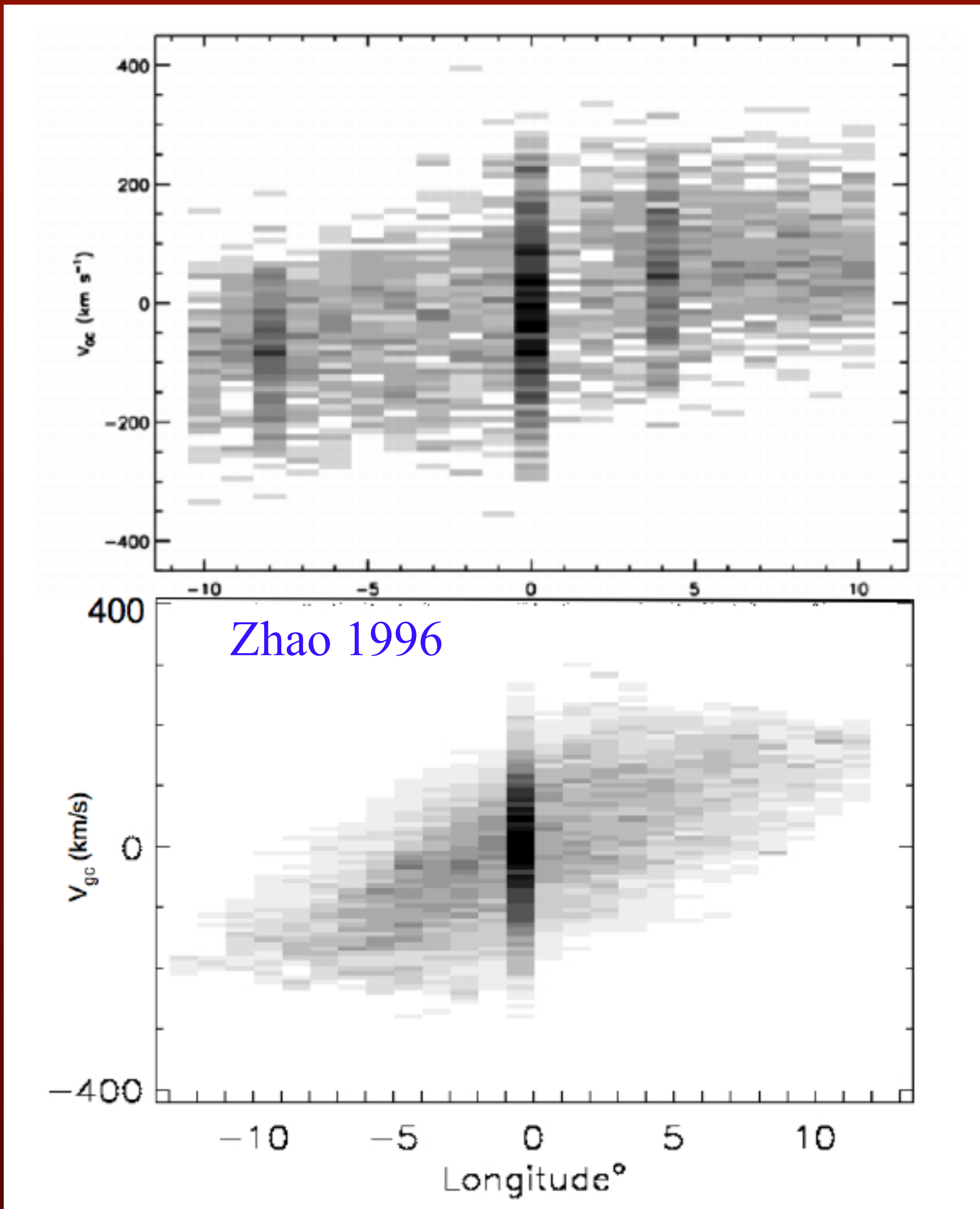
Larger samples have not confirmed 2 stream candidates; all candidates will be followed up. Reitzel et al. (2007) simulations suggest ~1 “real” stream



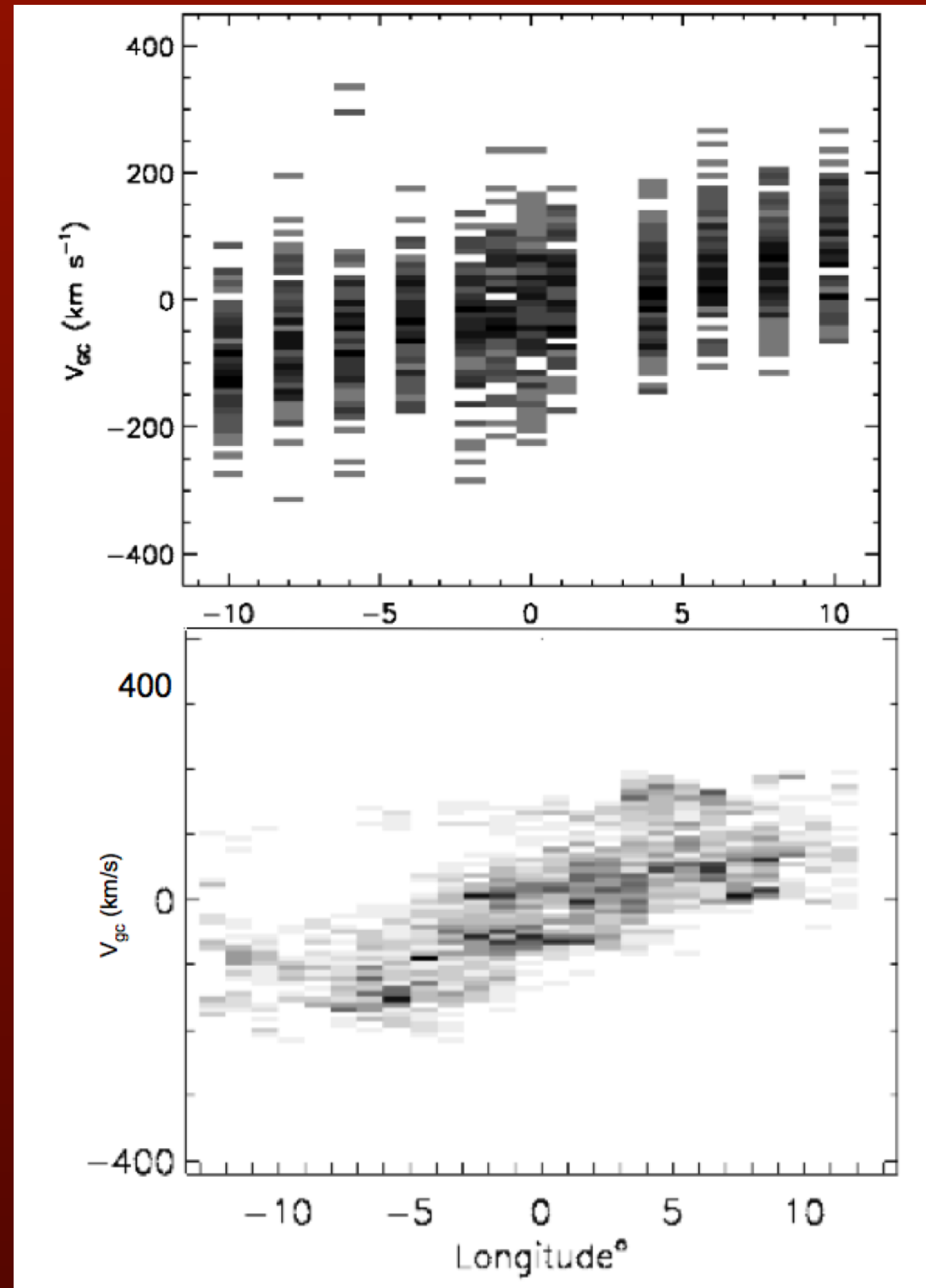


Stream followup important. Possible origins from disrupted globular clusters or dwarf galaxies, groups of stars in unusual orbit families; all candidates presently assumed to be Poisson statistics caused.

-4


400
200
0
−200
−400
V_{GC} (km s^{-1})
−10
−5
0
5
10
Zhao 1996
400
0
−400
V_{gc} (km/s)
−10
−5
0
5
10
Longitude°

-8


400
200
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V_{GC} (km s^{-1})
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V_{gc} (km/s)
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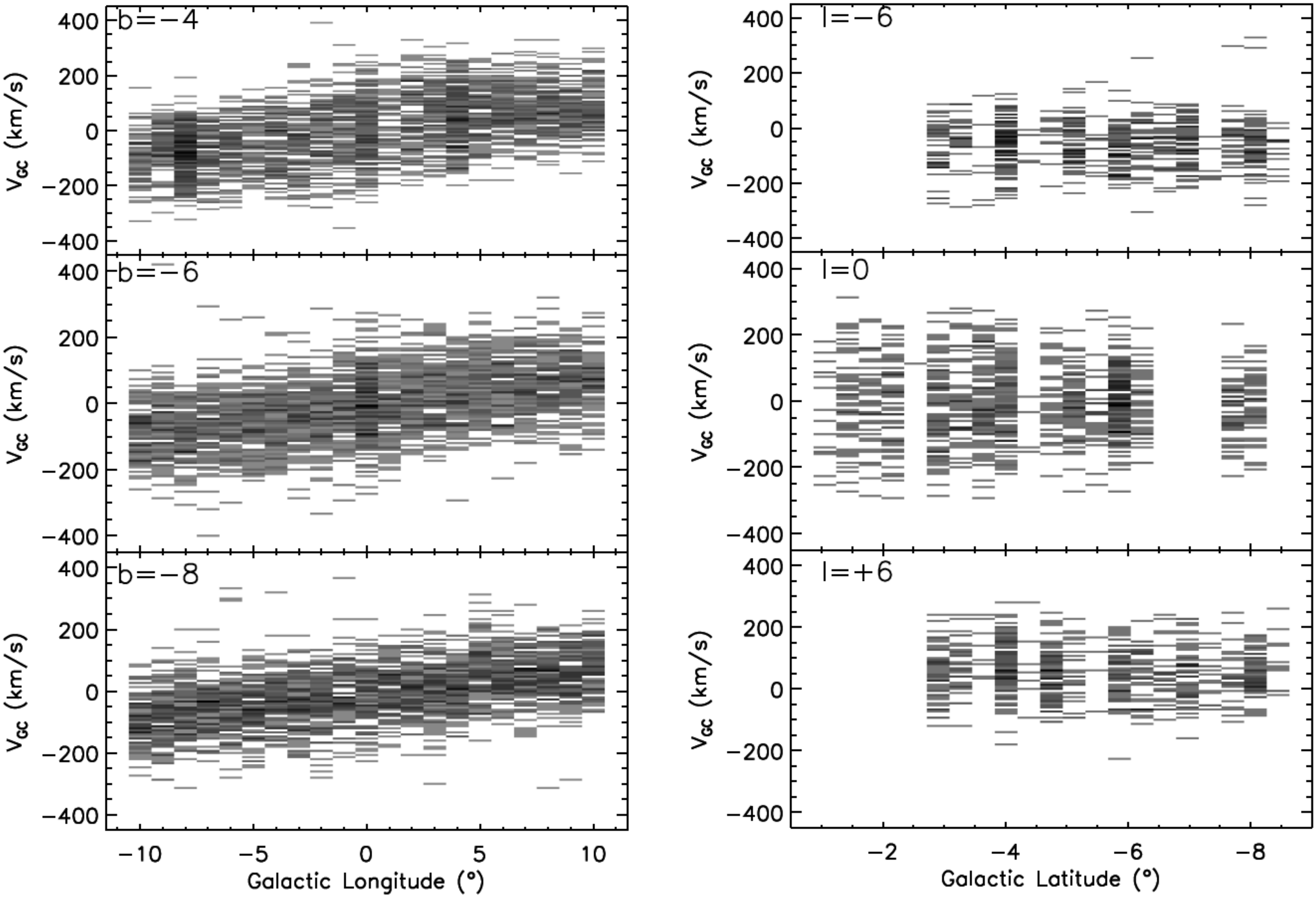
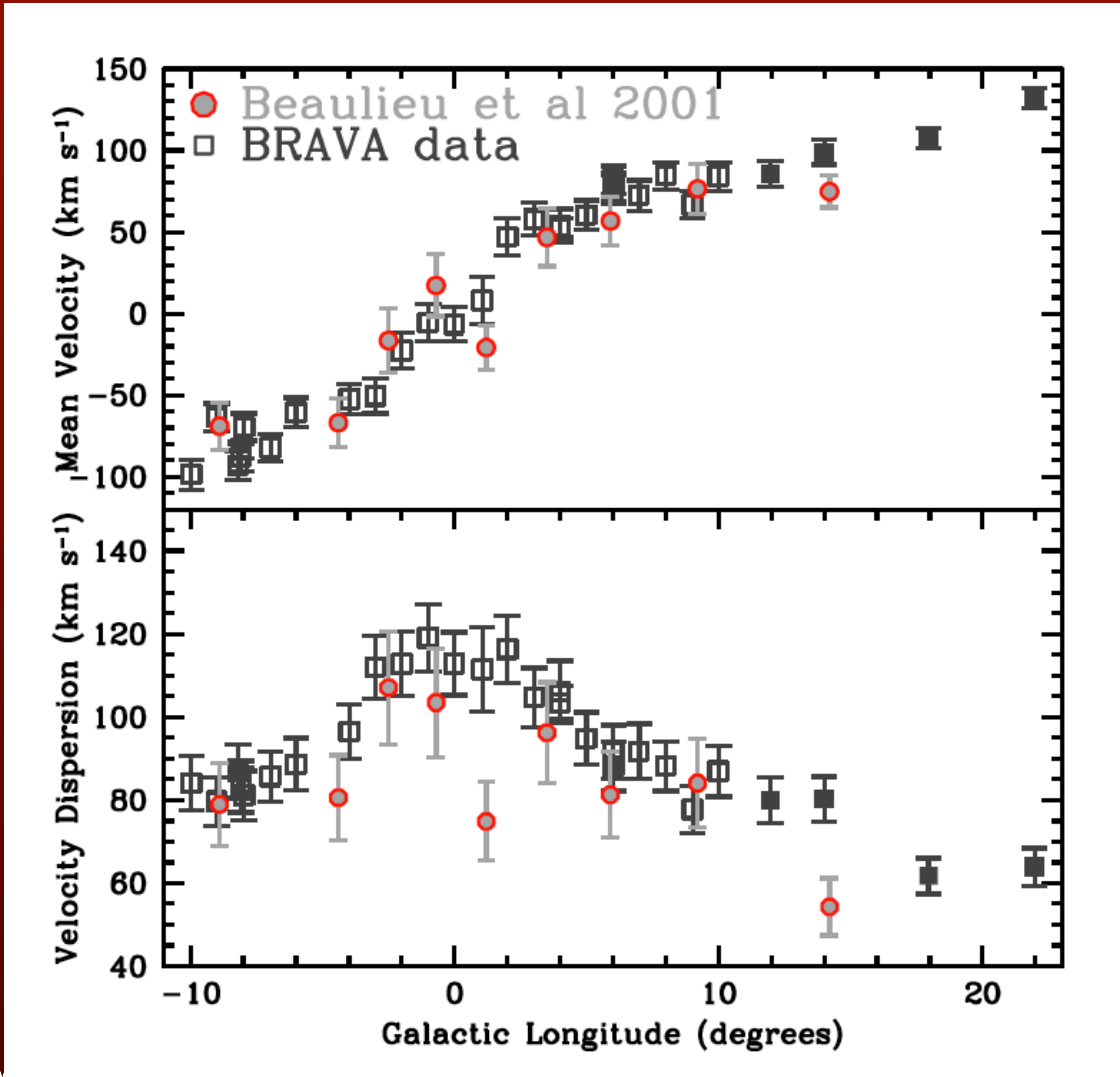
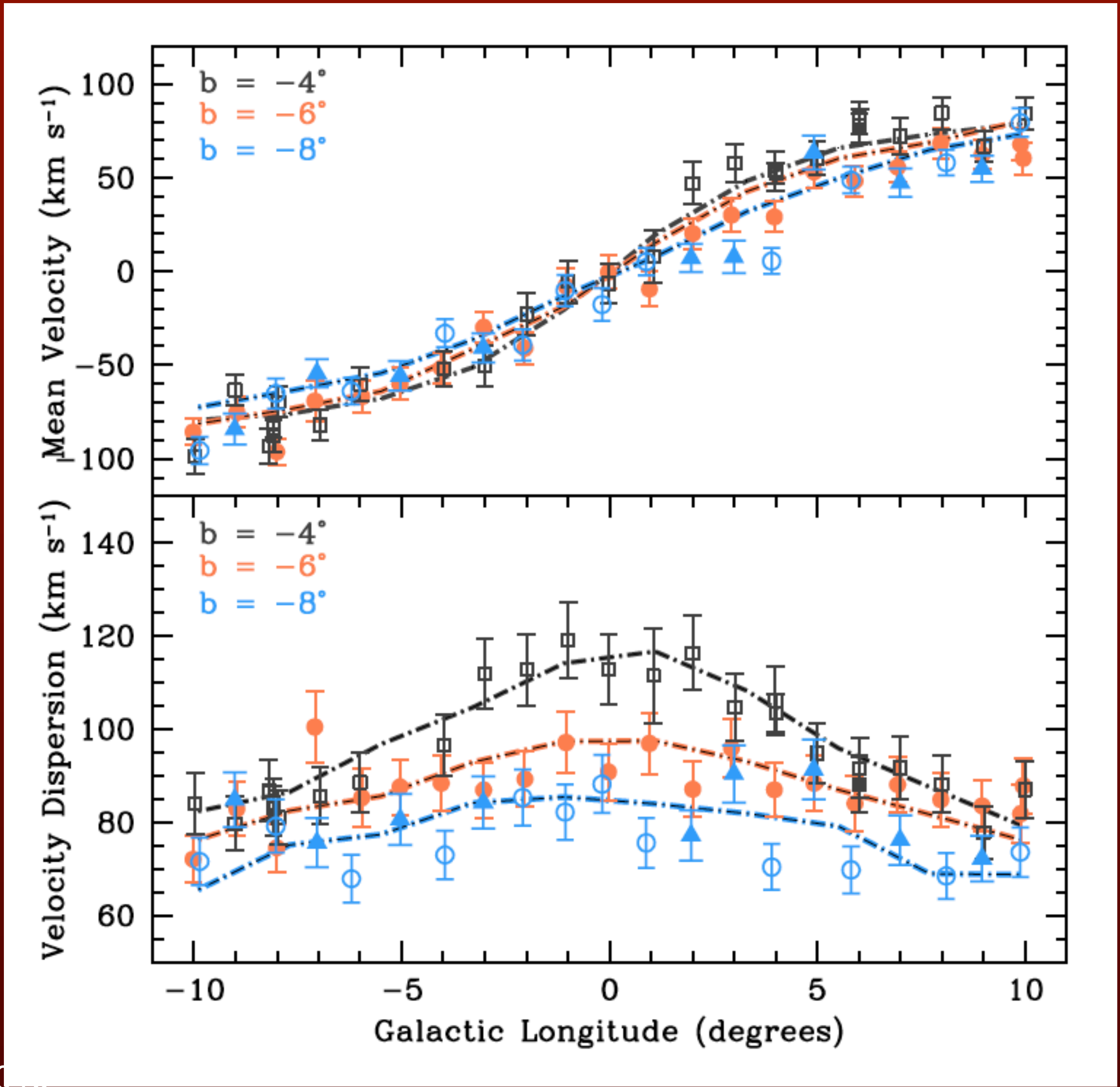
5
10
Longitude°


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

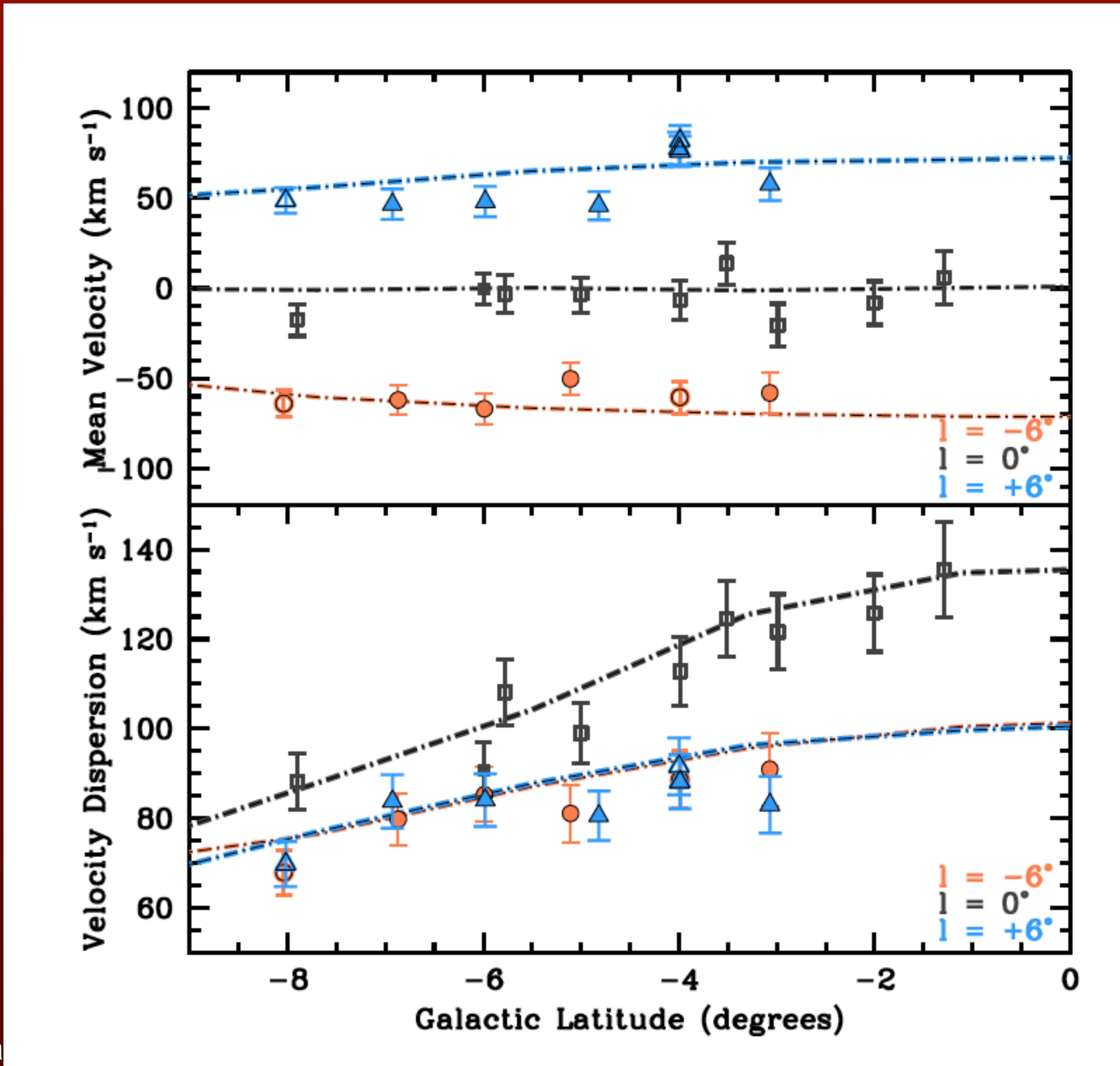
Most recent results (Kunder et al. 2011)



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



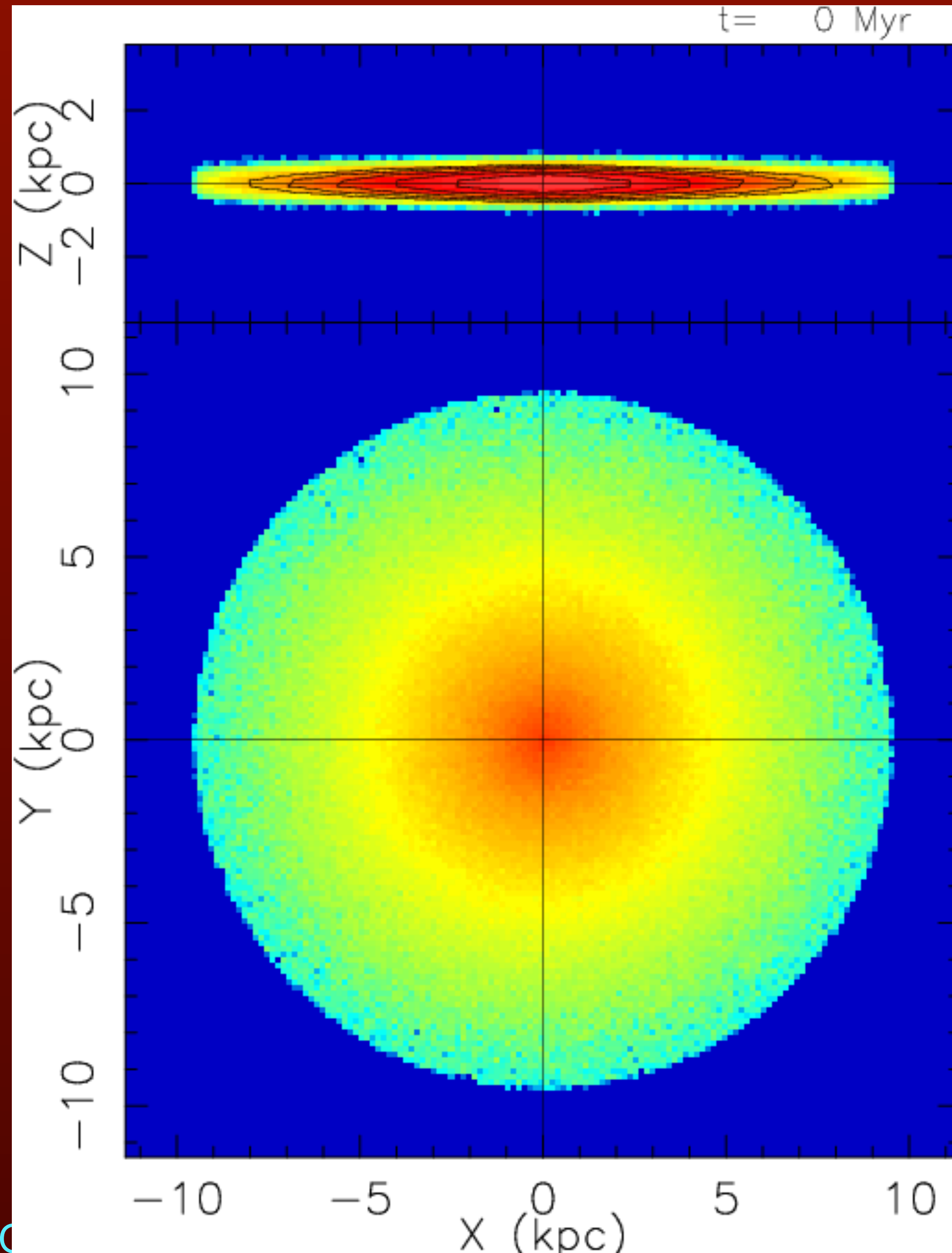
Minor axis with Shen et al. (2010) fit



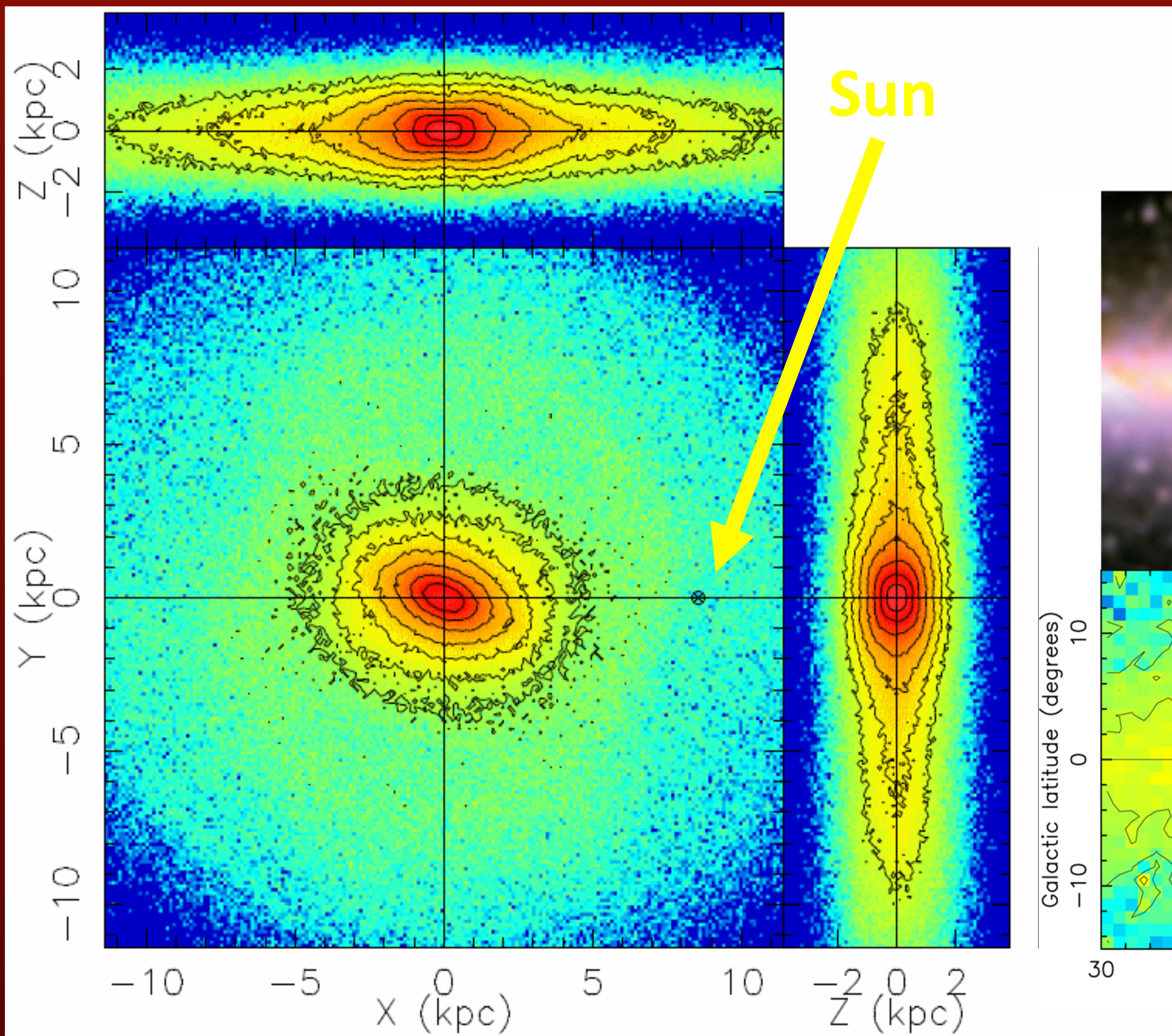
Modeling the Milky Way Bulge

Shen, Rich et al. 2010

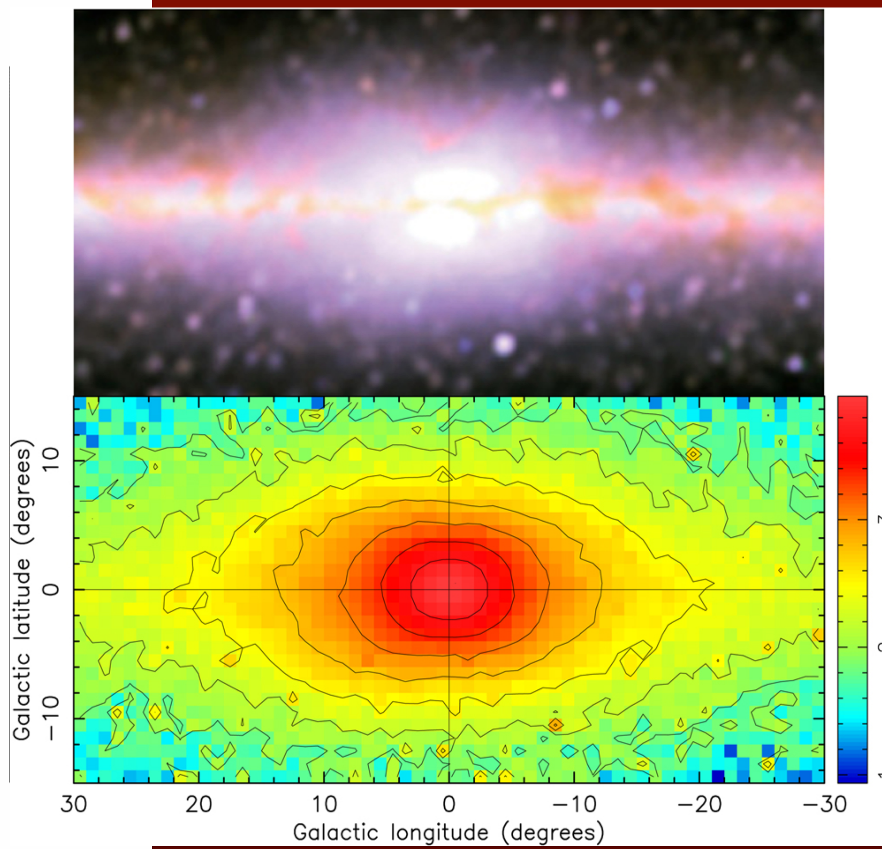
- A simple model of the Galactic bulge matches the BRAVA data extremely well in almost all aspects:
  - *b* = -4° major axis
  - *b* = -8° degree major axis
  - *l* = 0° degree minor axis
  - Surface density
  - **Shen, J., RMR, Kormendy** et al 2010, ApJL submitted, arXiv:1005.0385



Modeling the Milky Way Bulge ---
Surface Brightness Map



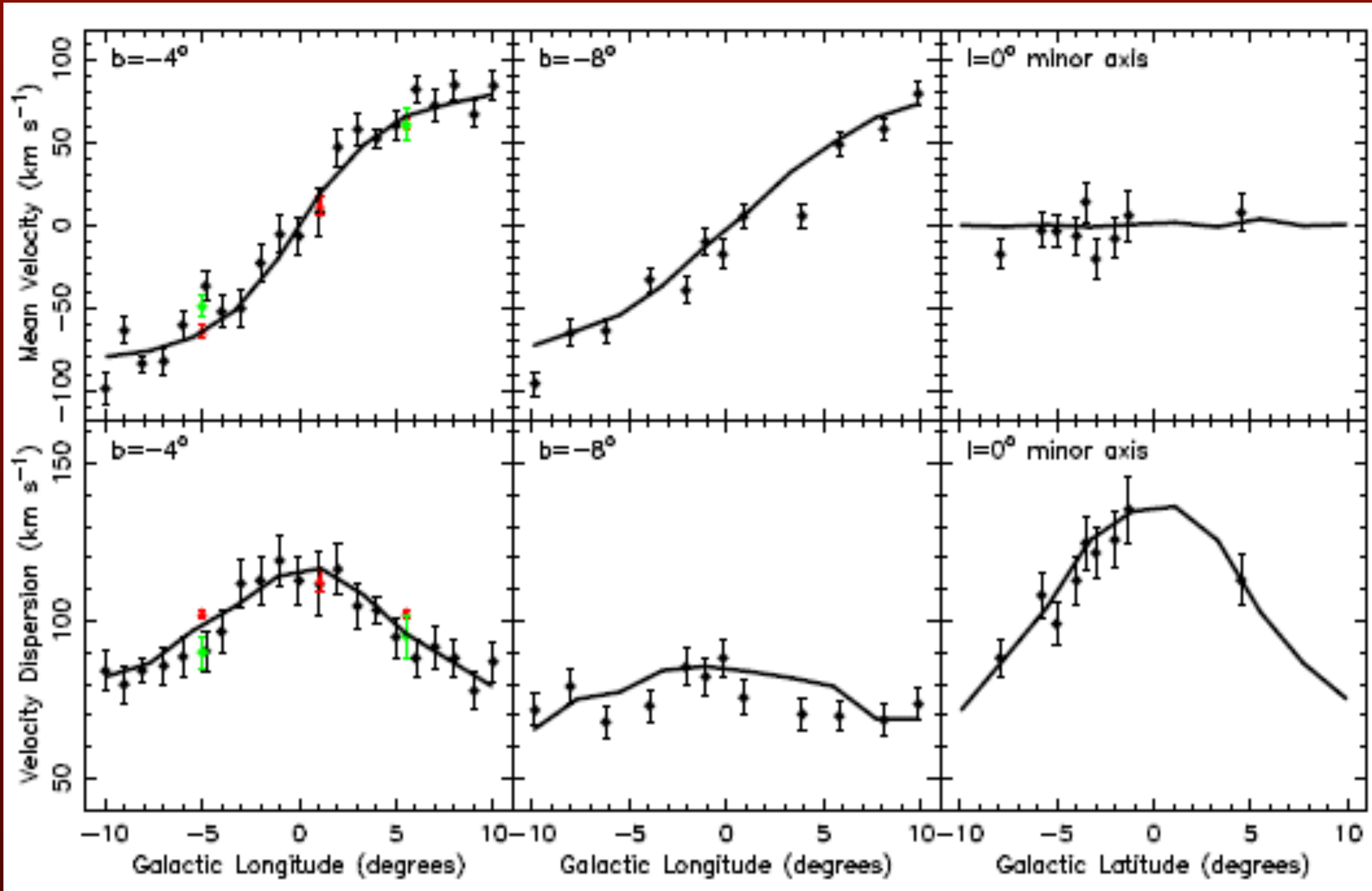
DIRBE Composite map



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

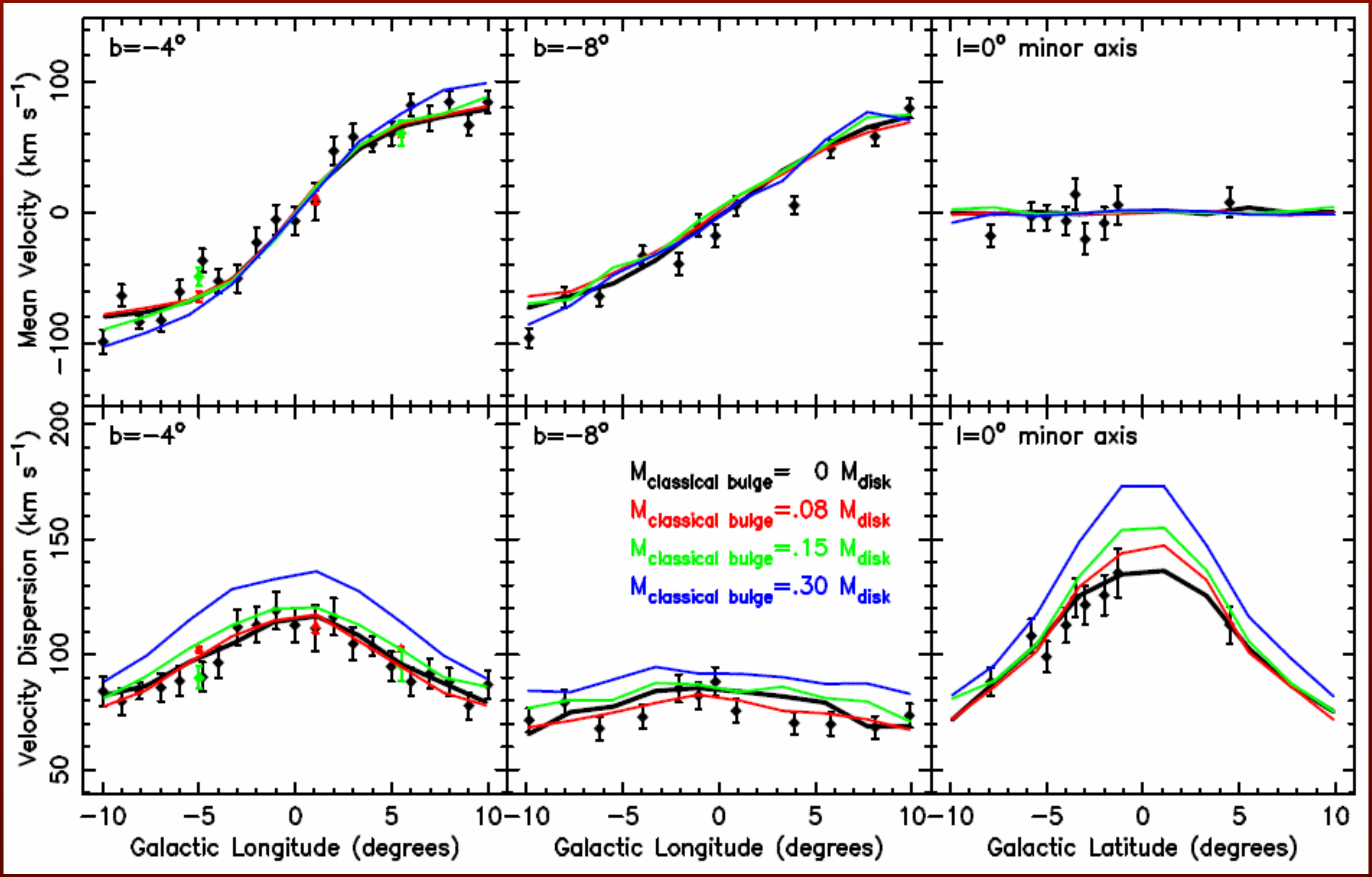
Modeling the Milky Way Bulge ---

Match stellar kinematics in all strips strikingly well



Black line = model; it is not a fit of data points

A Significant Classical Bulge is Excluded

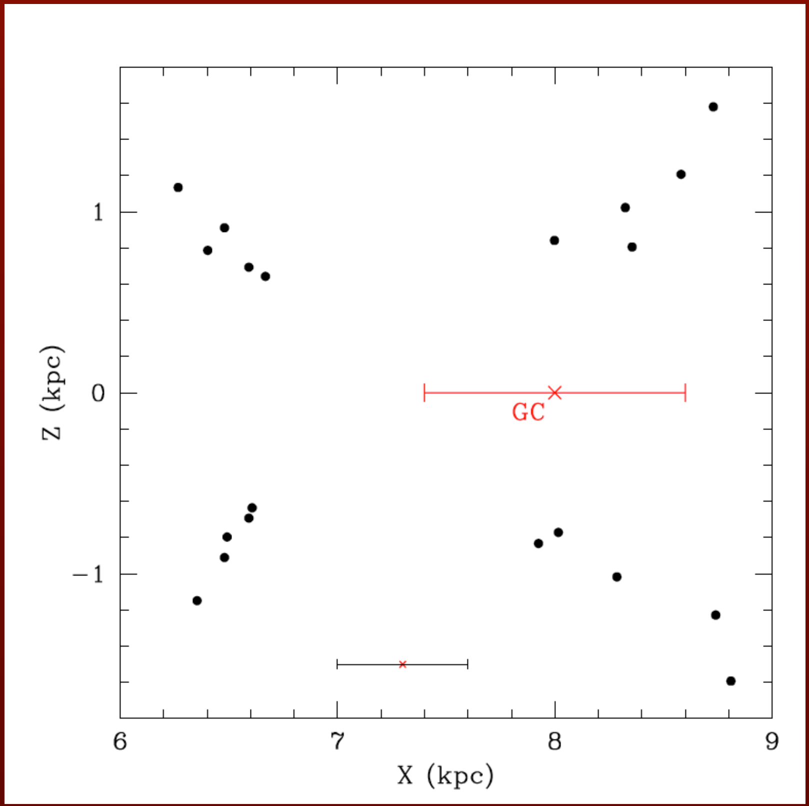


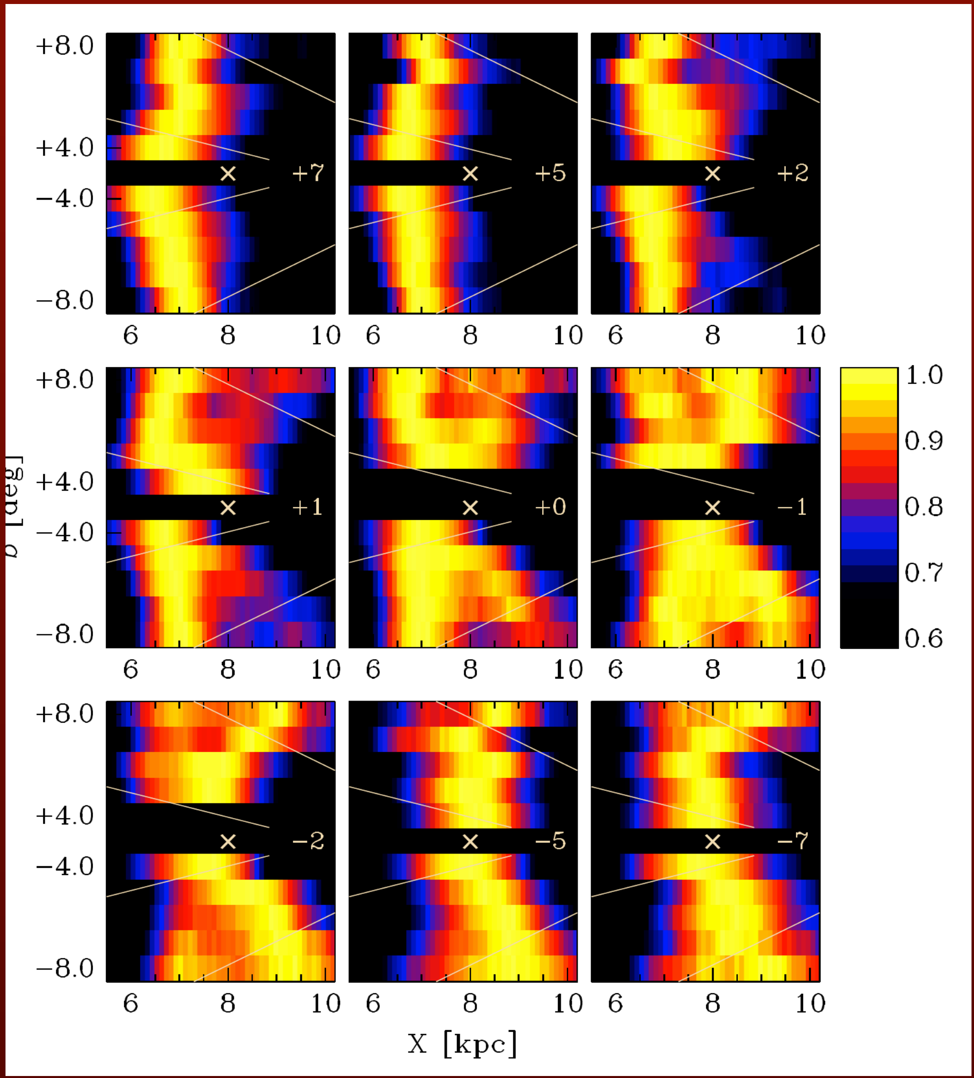
The data excludes a pre-existing classical bulge with mass >~ 10% Mdisk

Modeling on the MW bulge – Model Setup

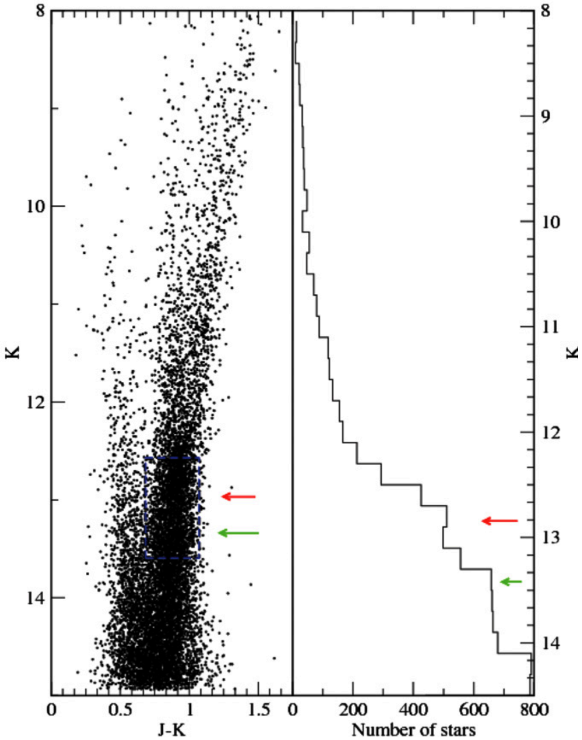
- High resolution N-body simulations with millions of particles
- Cold massive disk, initial Q ~ 1.2
- A pseudo-isothermal rigid halo with a core which gives a nearly flat rotation curve of ~220 km/s from 5 to 20 kpc

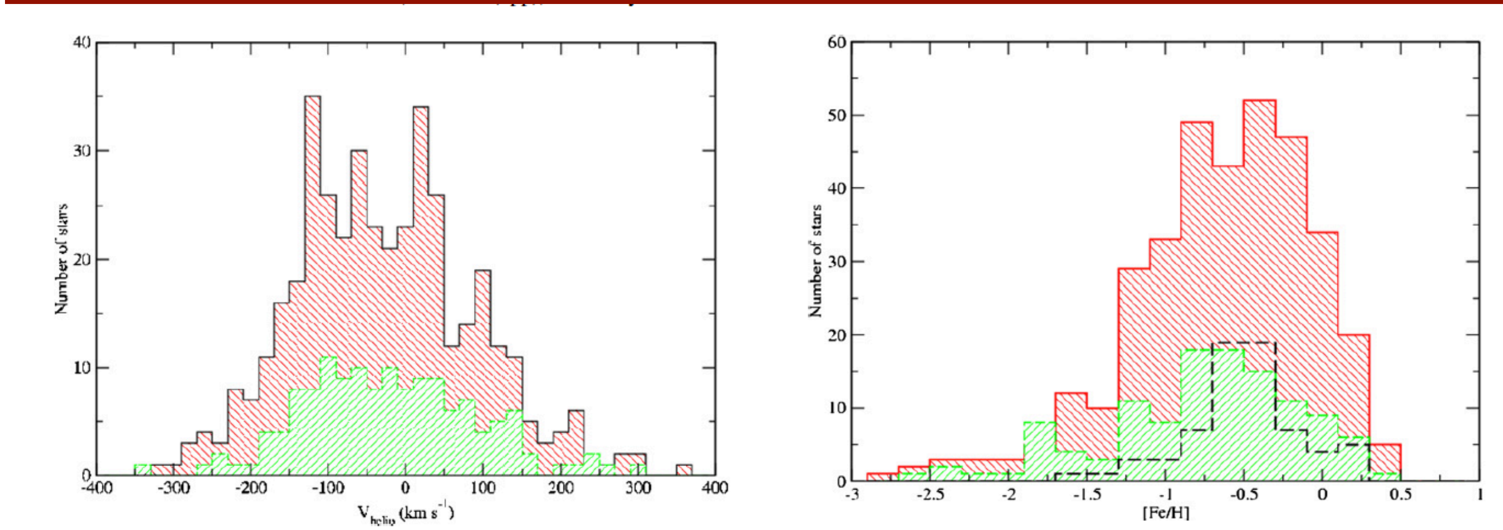
X-shaped bulge (McWilliam & Zoccali 2010)

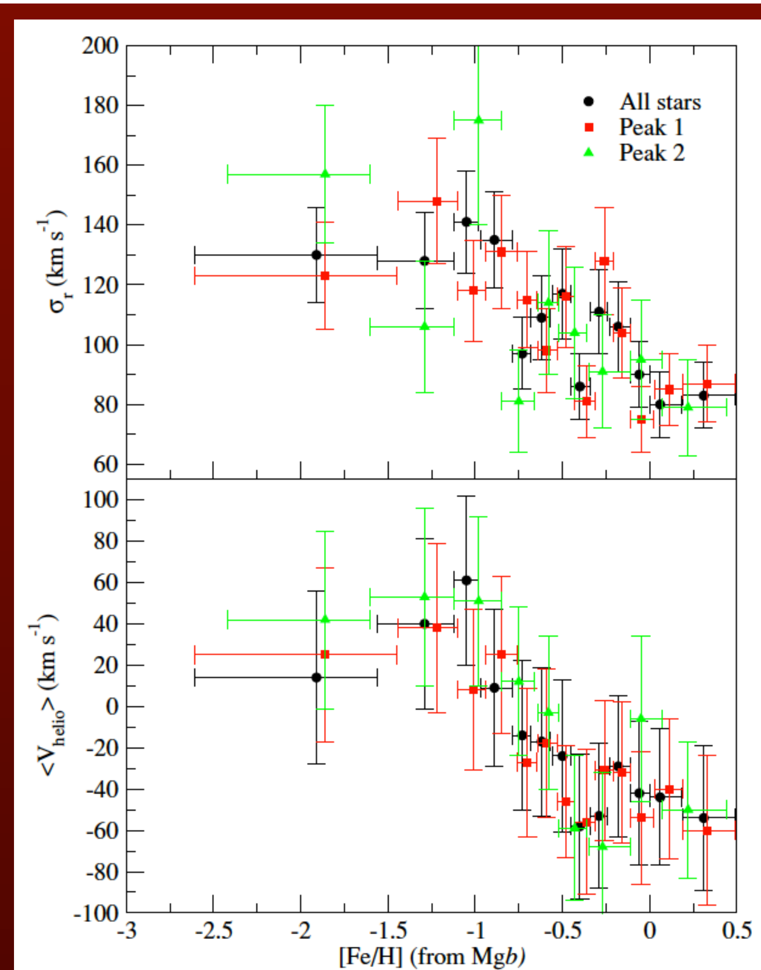




Saito et al. 2011







De Propris, Rich, et al. 2011
Kinematics and Abundances in the two clumps are identical

The Shen et al. 2010 model has an X-shaped structure

Li & Shen 2012 astro-ph

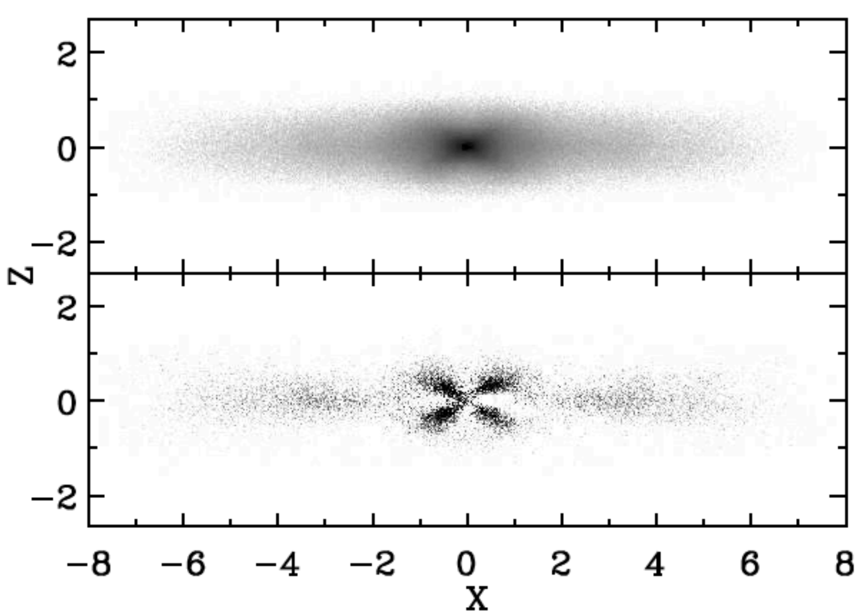
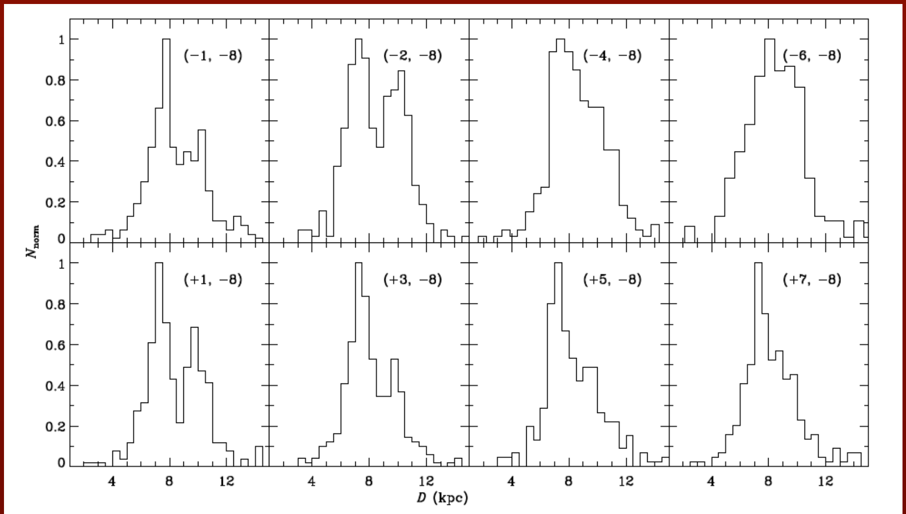
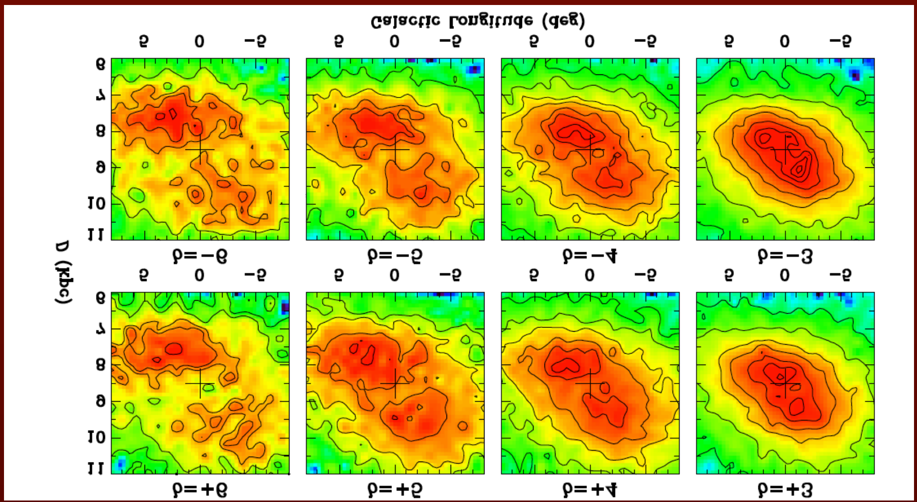


FIG. 1.— The upper panel shows the side-on view of the bar in our model. The lower panel shows the residual after subtracting the underlying smooth light contribution. The vertical X-shaped structure is highlighted in this residual image. The length unit is $R_{d,0} = 1.9$kpc.





Summary from modeling of the BRAVA kinematics

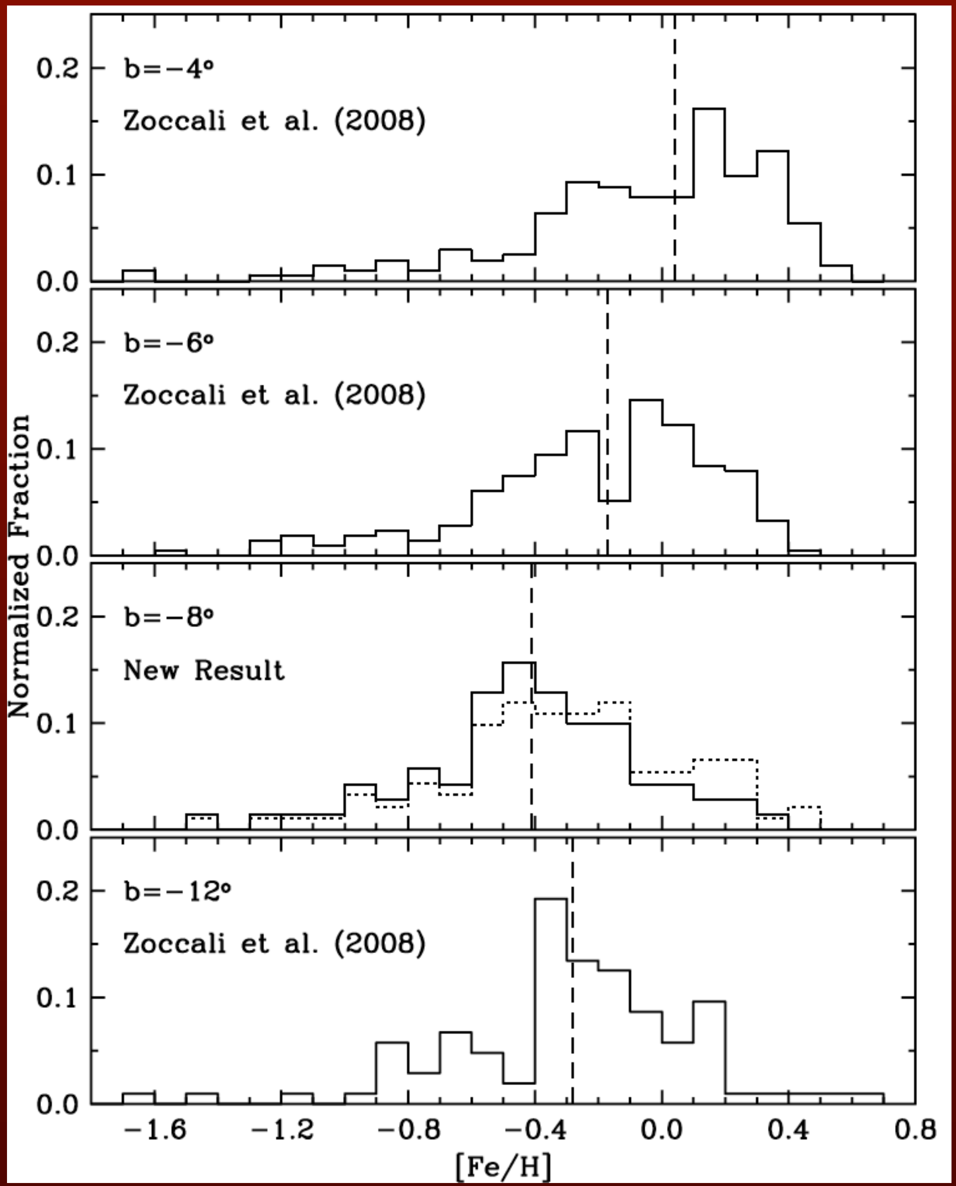
- Our simple, but realistic, model can match BRAVA kinematics of the Galactic bulge strikingly well
  - No need for a contrived model with many free parameters
- The bulge is simply the bar viewed edge-on; it is part of the disk, not a separate component.
- A significant classical bulge is excluded, so **our MW is an nearly pure-disk galaxy**
- Giant, pure-disk galaxies like our own MW present a major challenge to the standard picture in which galaxy formation is dominated by hierarchical clustering and galaxy mergers
- Fraction of pure disk galaxies in local U. (Kormendy & Barentine 2010; Kormendy et al. 2010)

Shen, J., RMR, Kormendy et al 2010, ApJL submitted, arXiv: 1005.0385

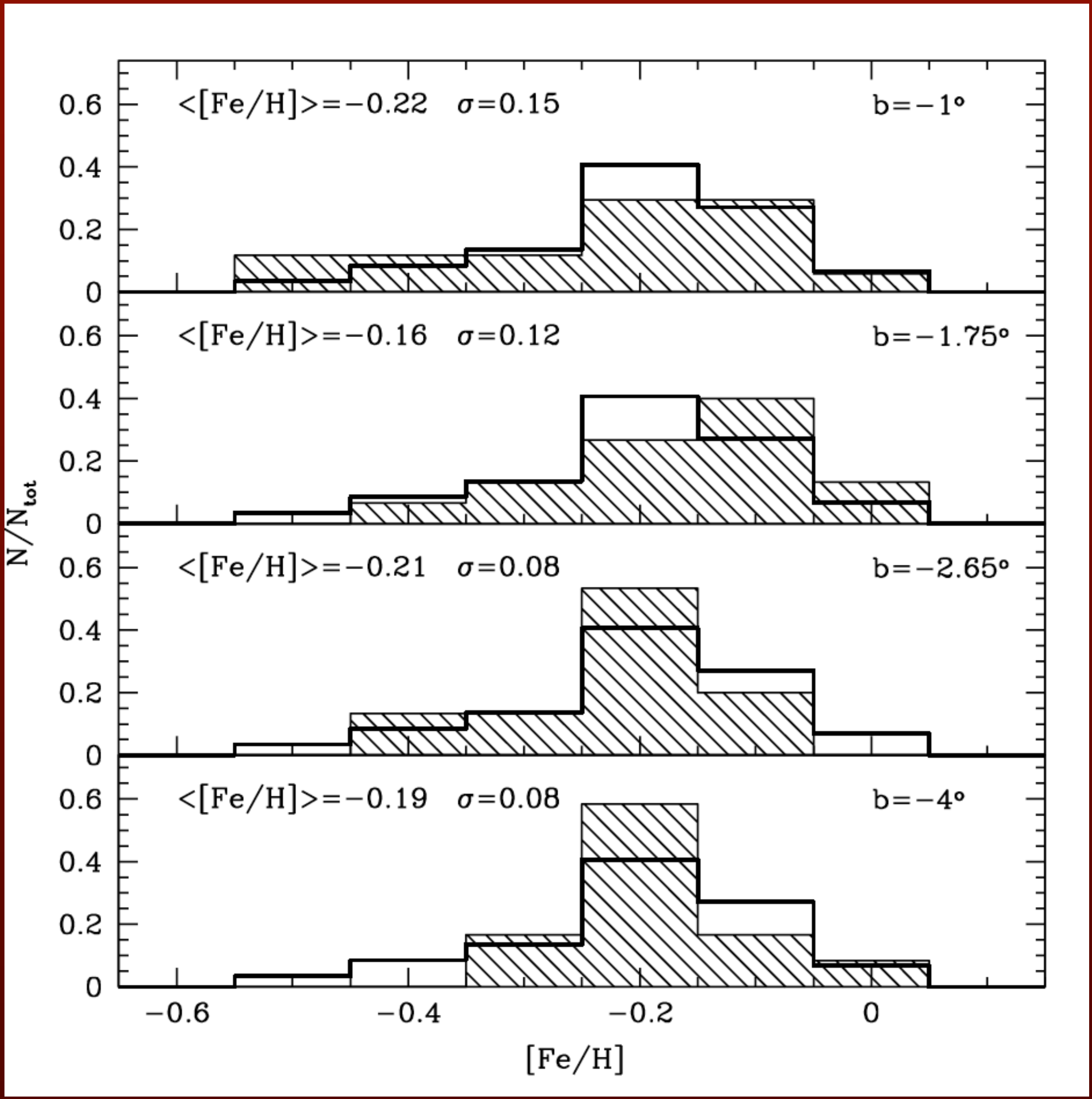
A Problem: Abundance gradient in the outer bulge

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.

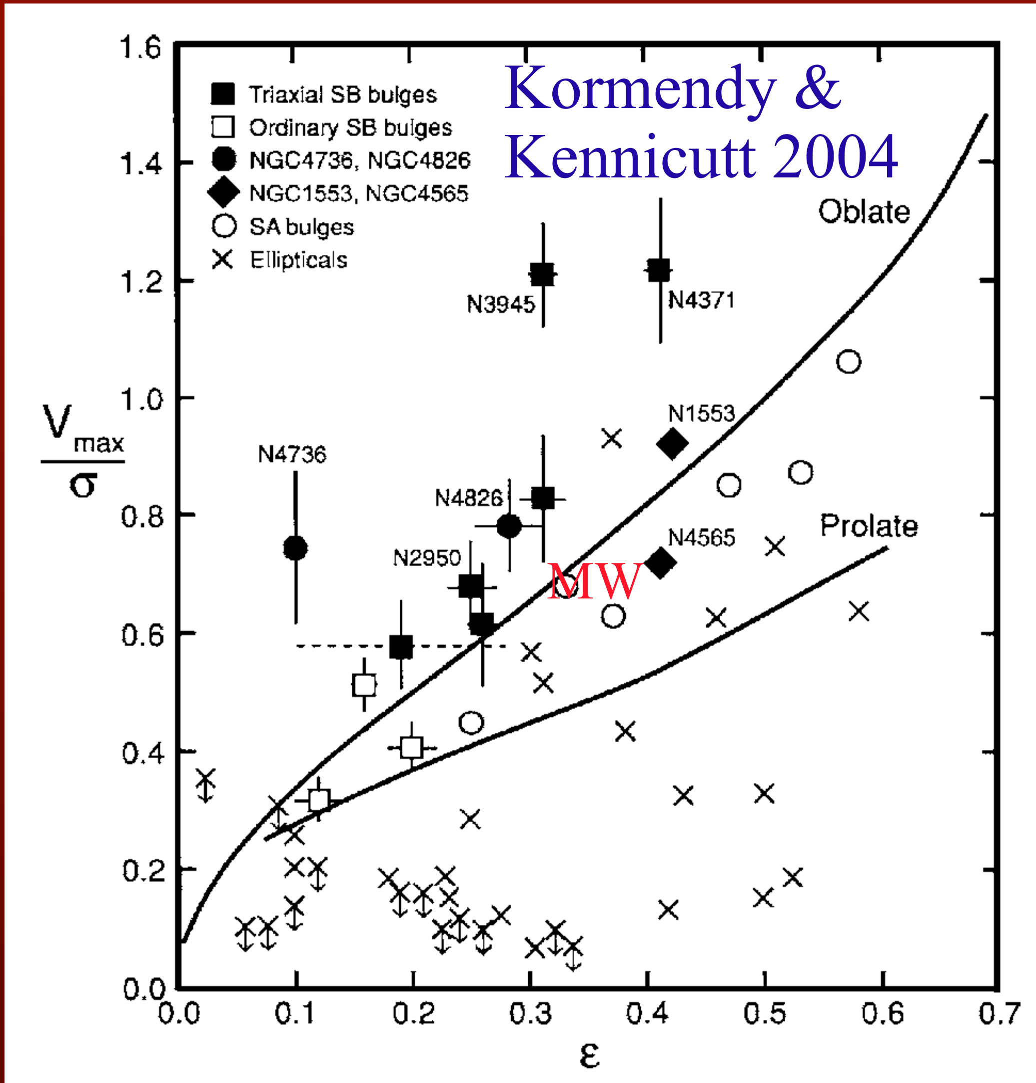
Zoccali et al. 2008 with Johnson et al. 2011 for -8 deg

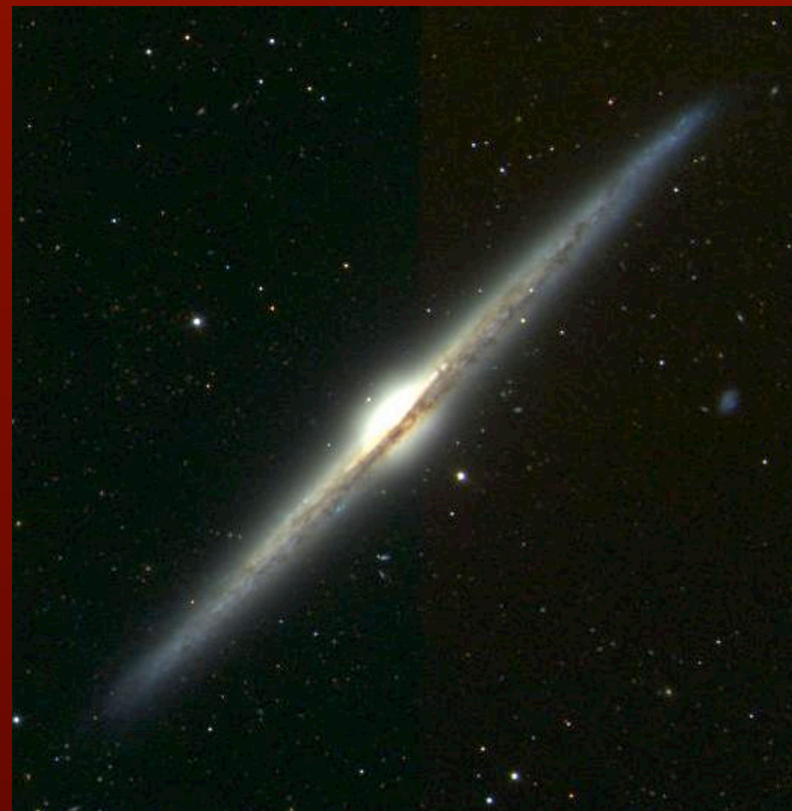


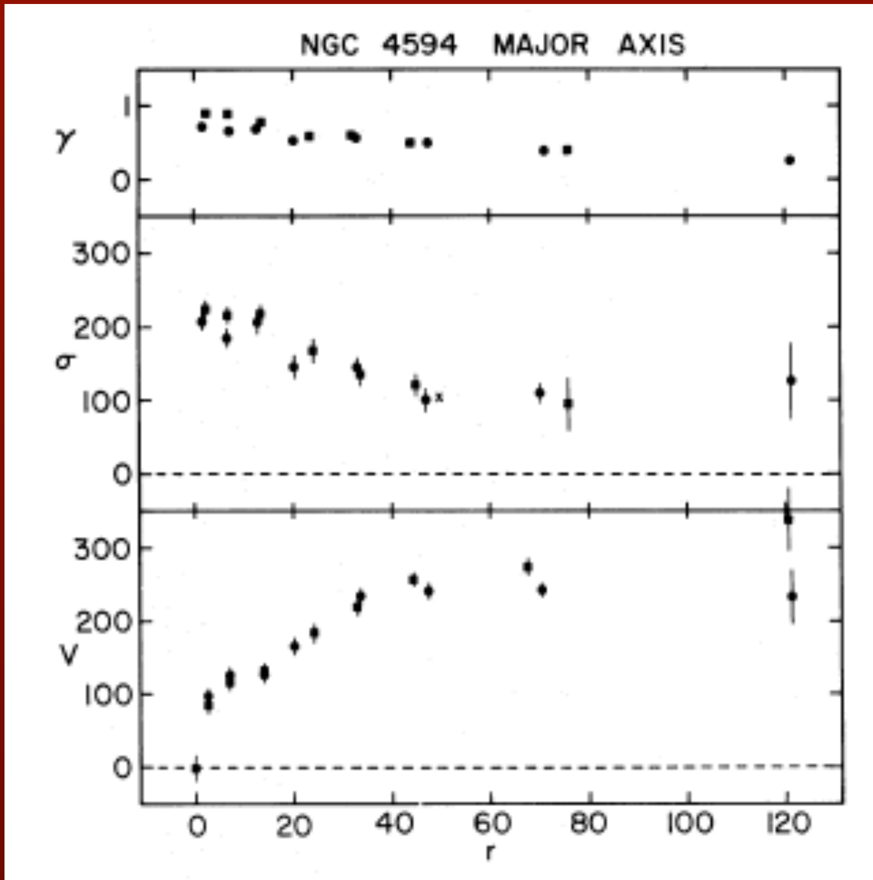
But no abundance gradient <4° (Rich, Origlia, Valenti; 2011)

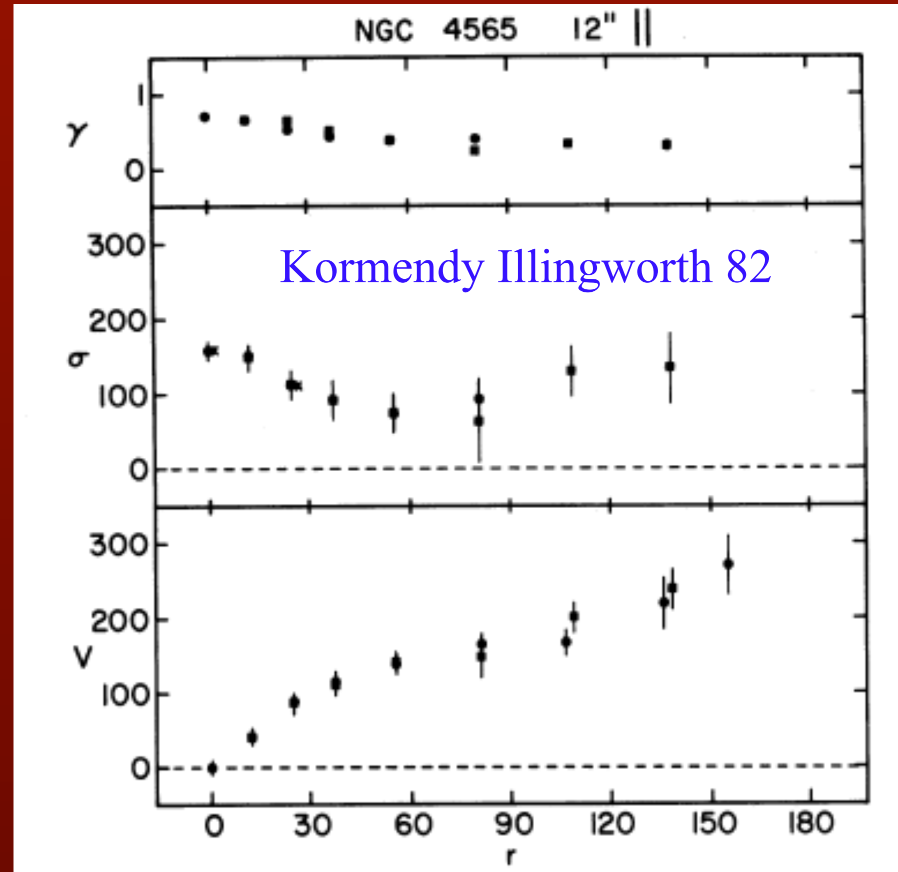


The Milky Way shares much in common with NGC 4565 (peanut bulge, abudance gradient)

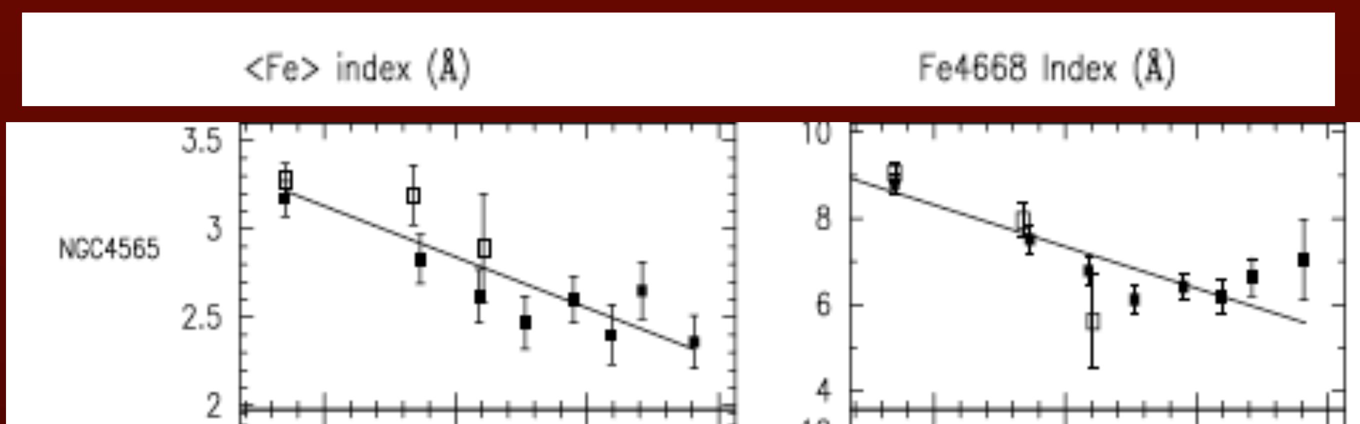








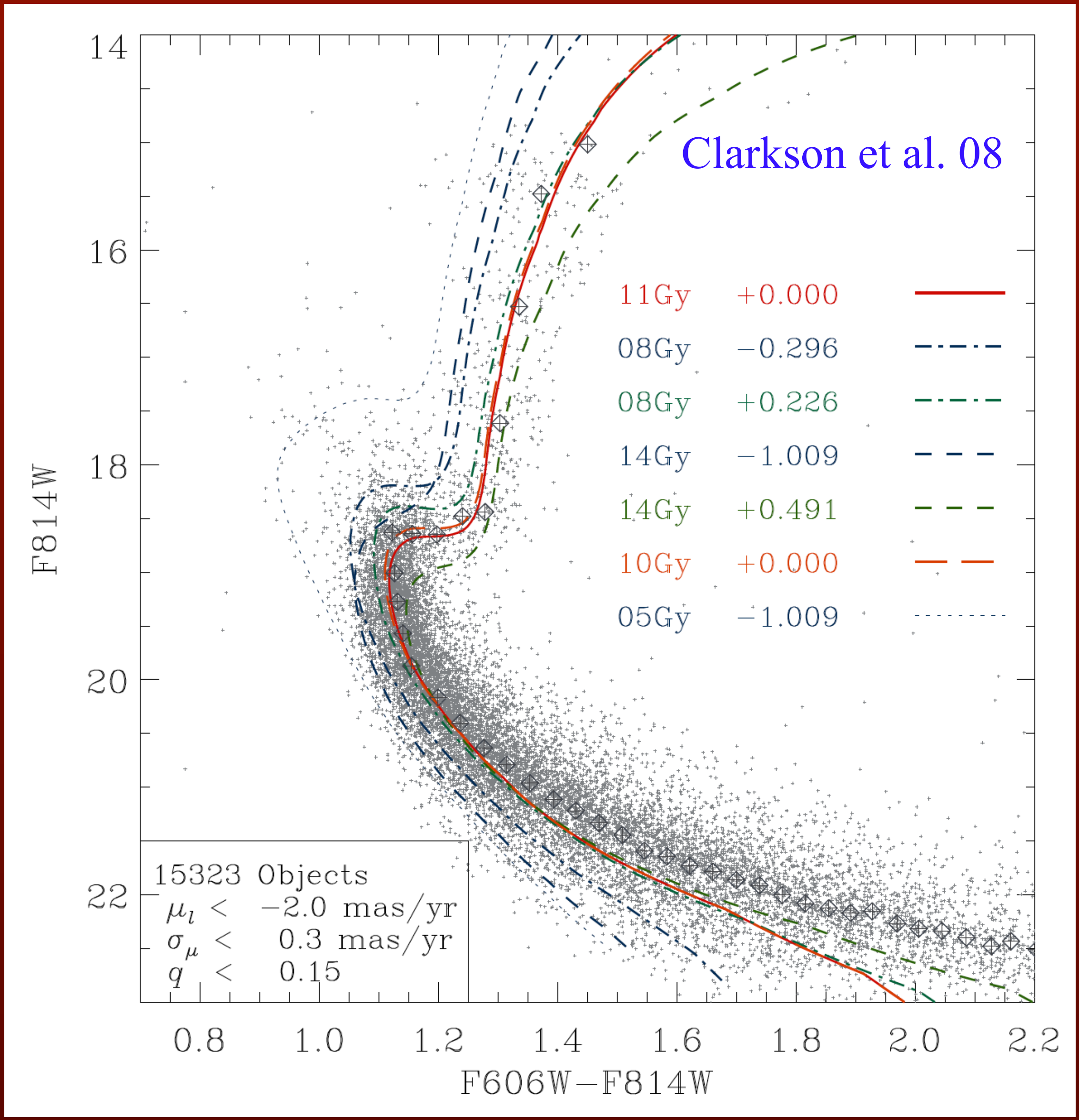
Proctor et al. 00



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

The Age/Pseudobulge Paradox



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

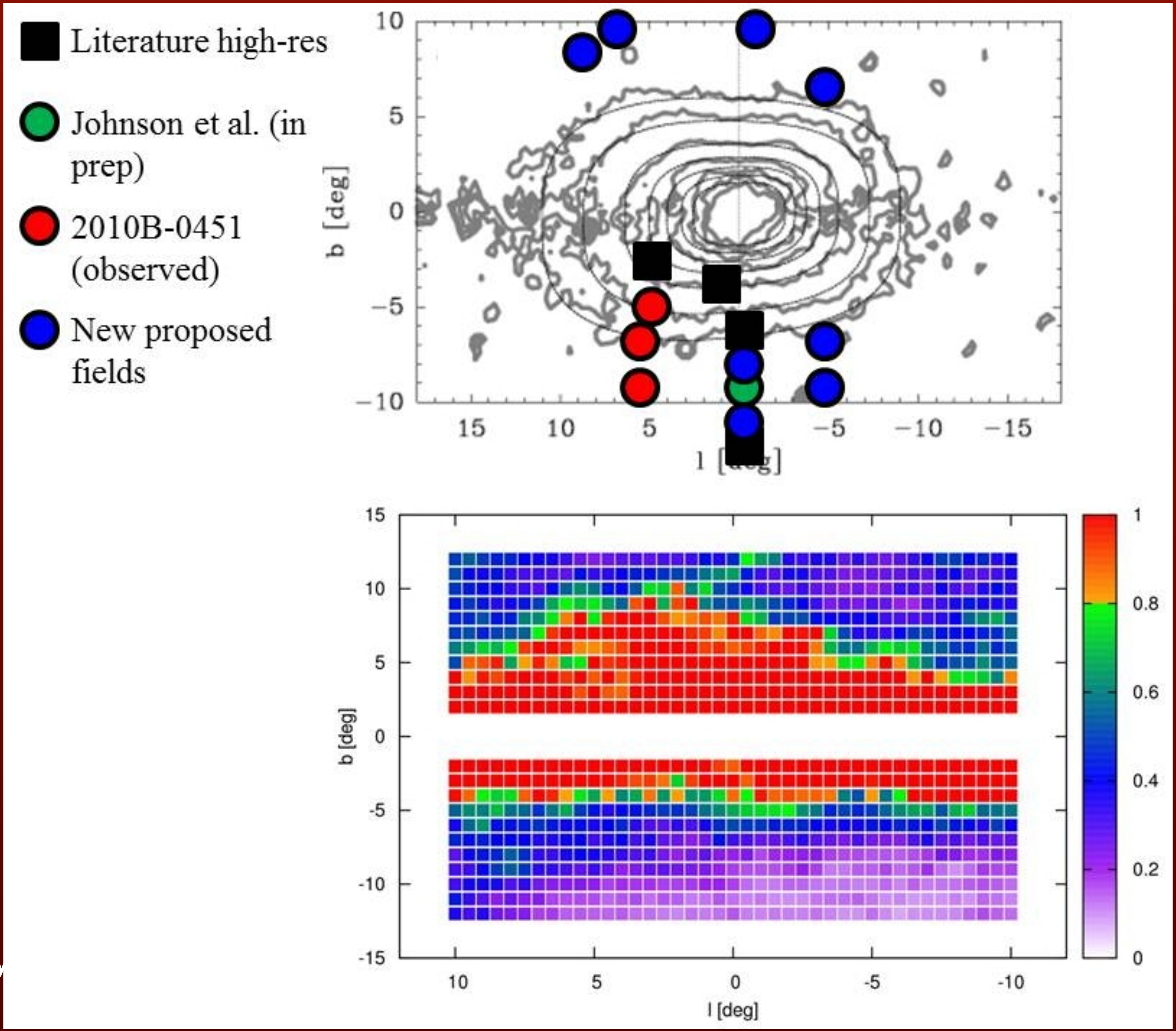
Cylindrical rotation, morphology, consistent with pseudobulge (young?)

Abundance gradient of MW, NGC 4565 – but how? If N-body models?

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

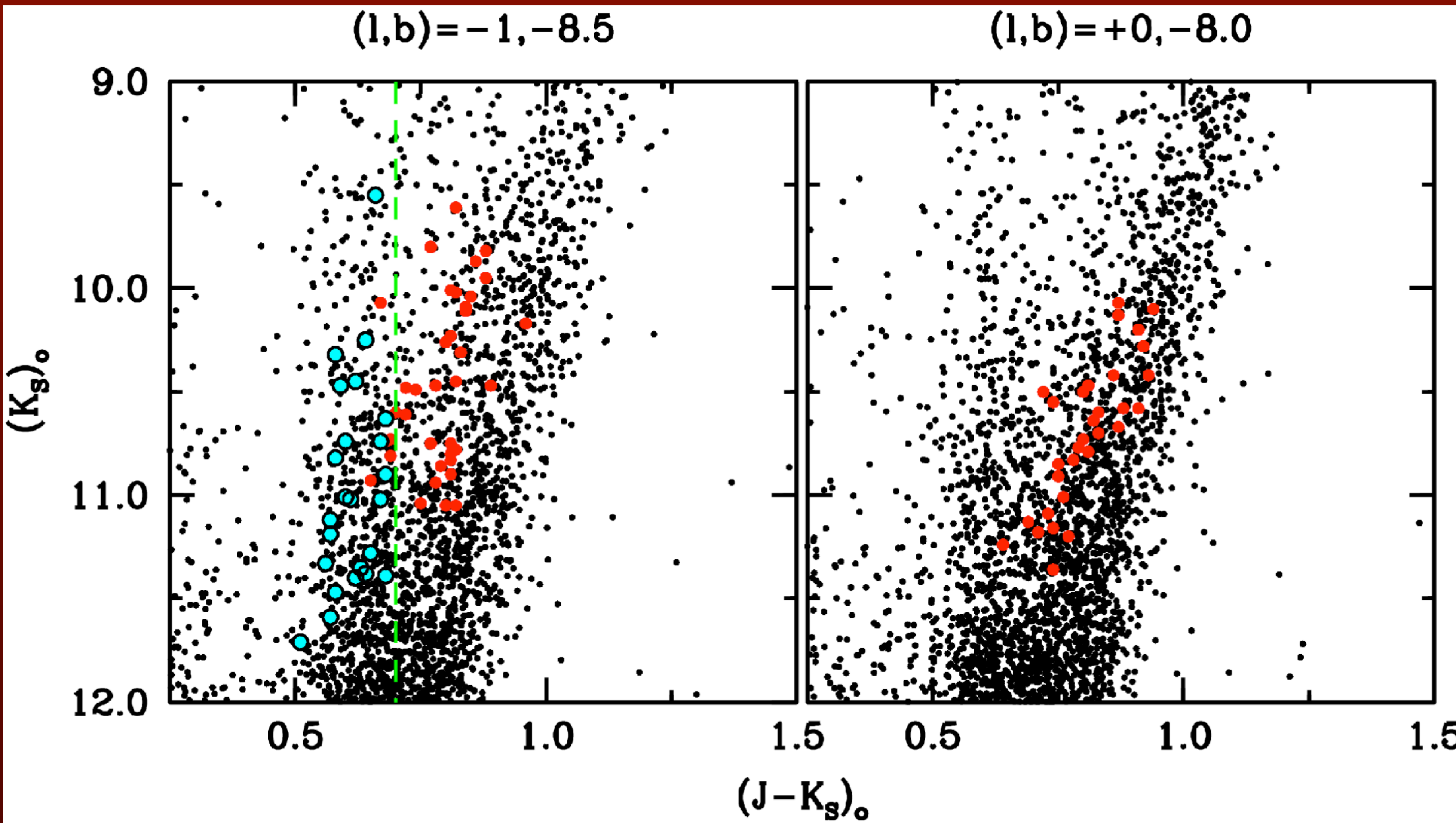
Hydra echelle survey ongoing Johnson, Rich et al. 2011



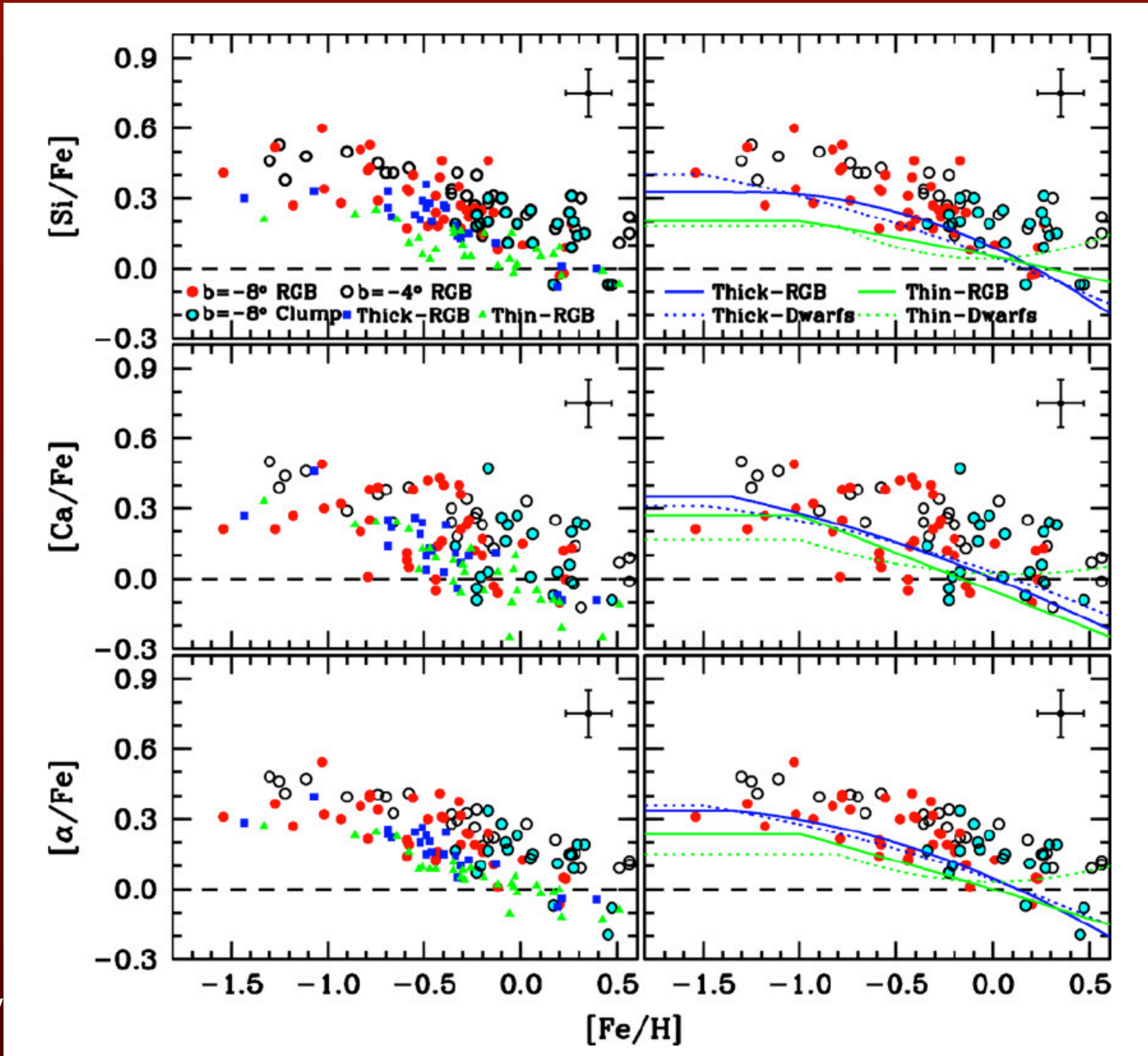
-8° Field (Plaut's Field)

C. Johnson, Rich, Fulbright, Valenti, McWilliam (2011)

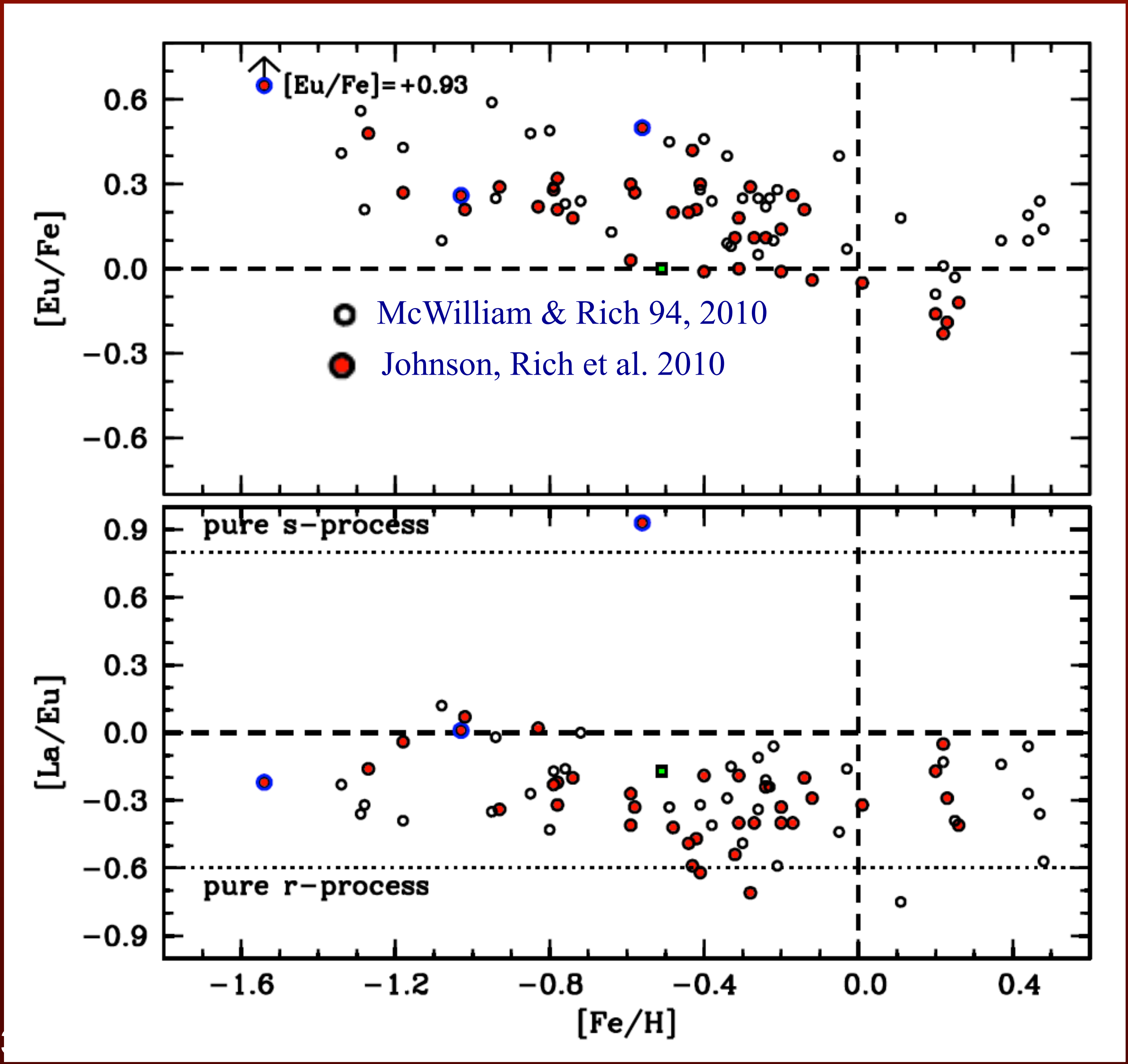
CTIO Hydra, 300 stars, 4 wavelength settings



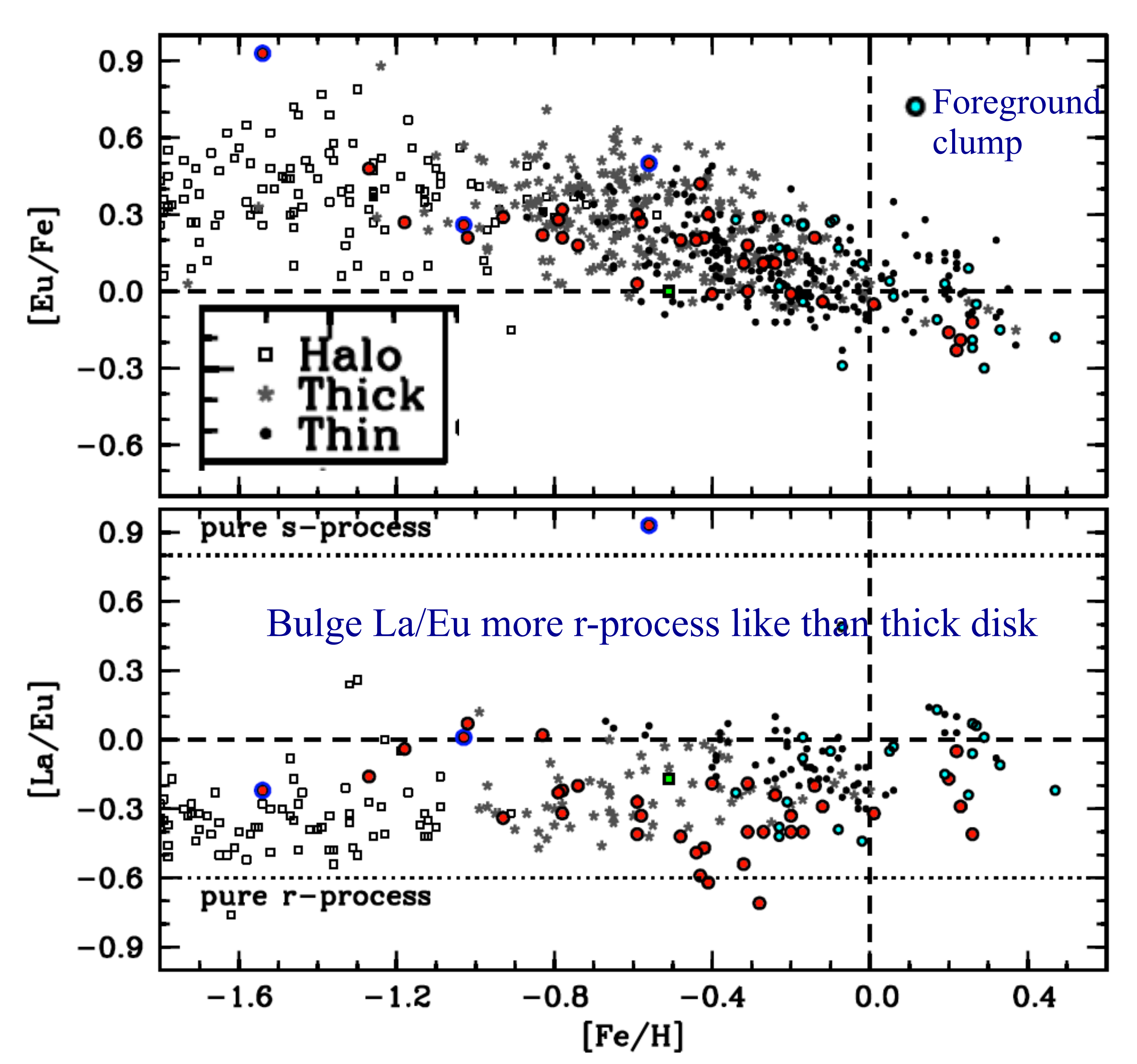
Johnson, Rich et al. 2010: alphas enhanced at -8^o = 1



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

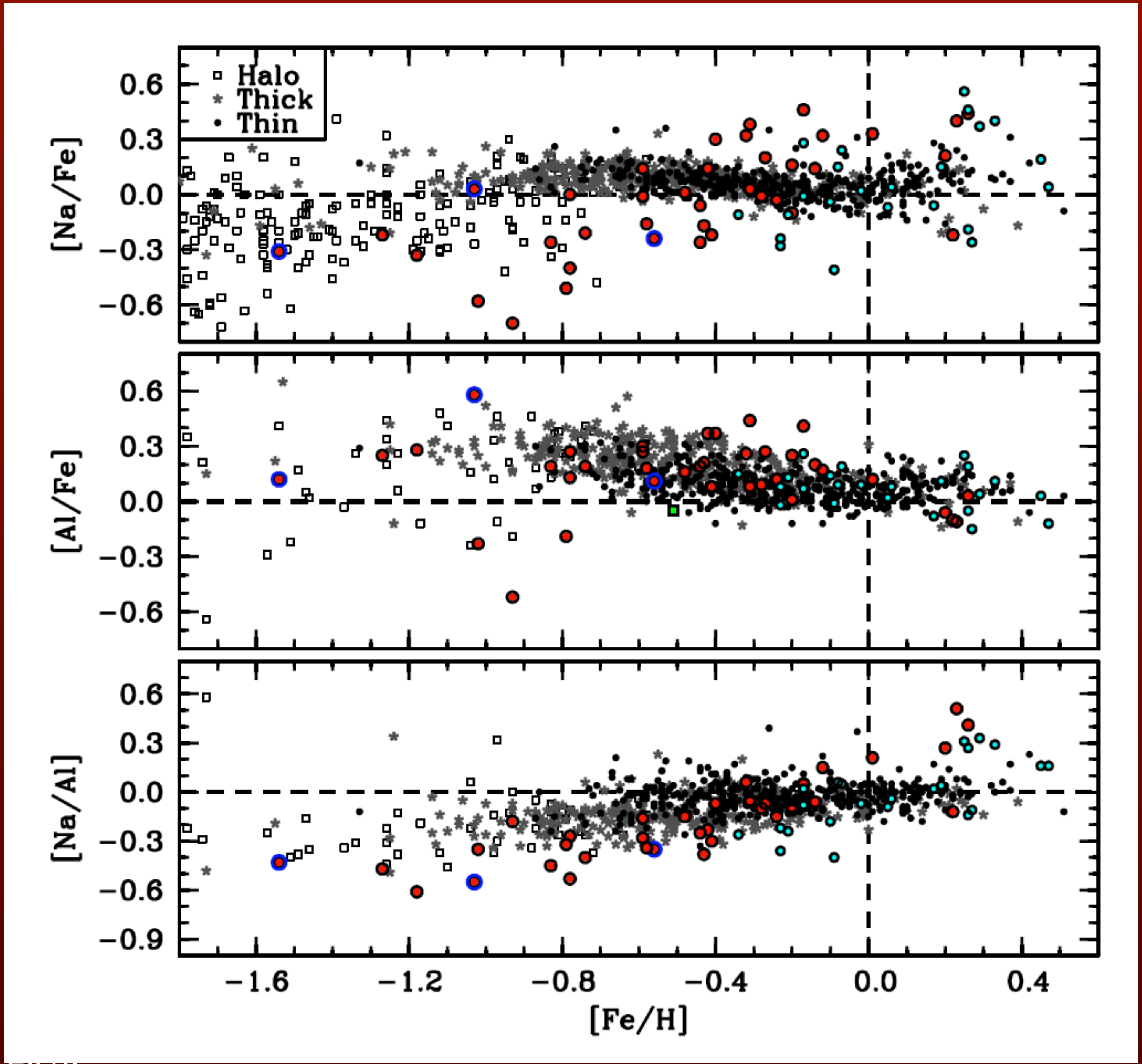


In terms of heavy elements, bulge is different from thick disk

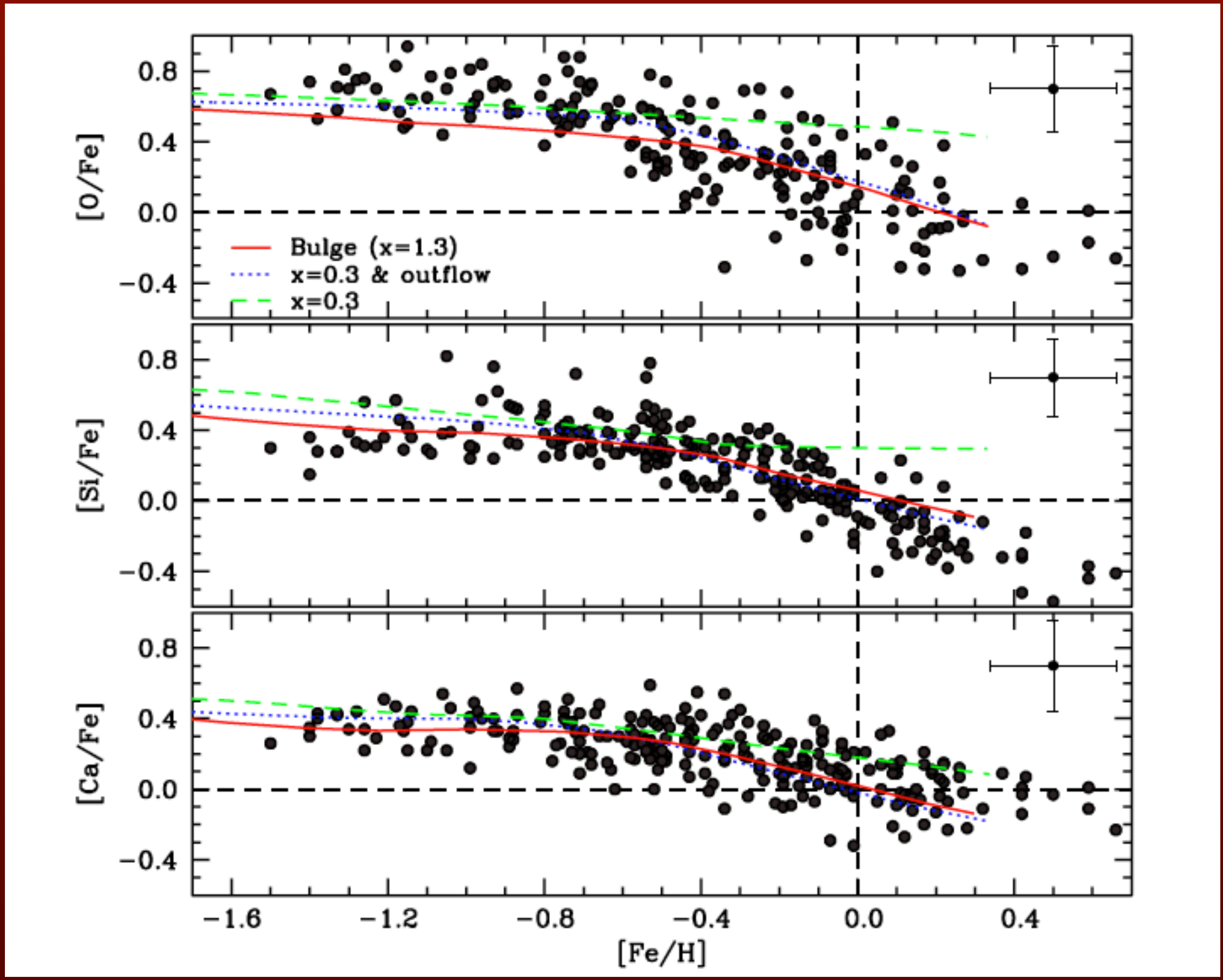


Johnson, Rich et al. 2011

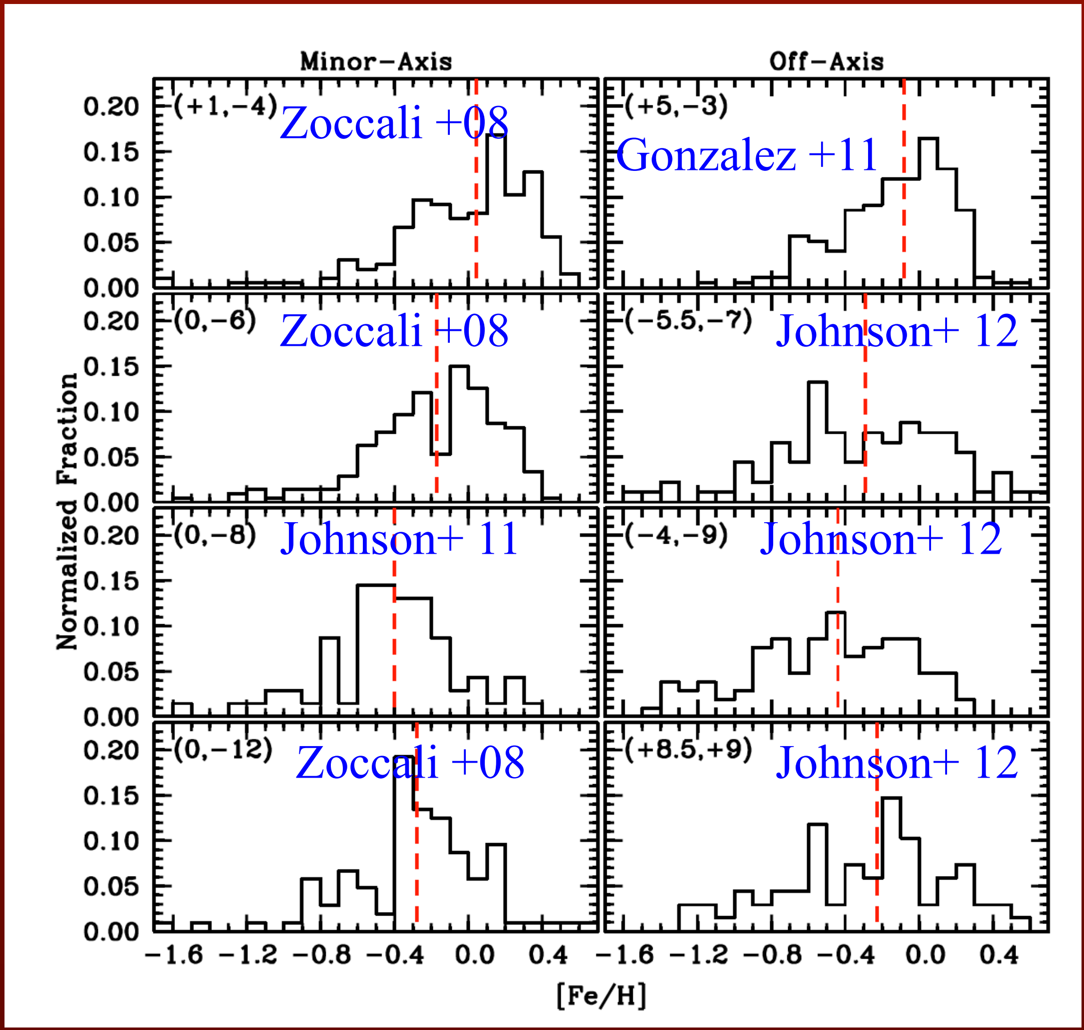
[Na/Fe] in bulge distinct from thick disk



Johnson, Rich et al. 2013

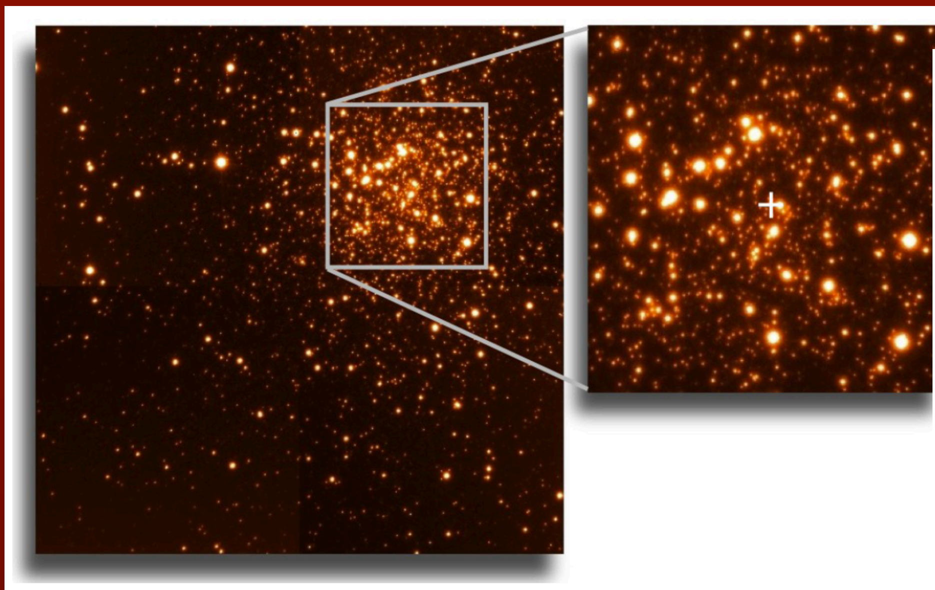


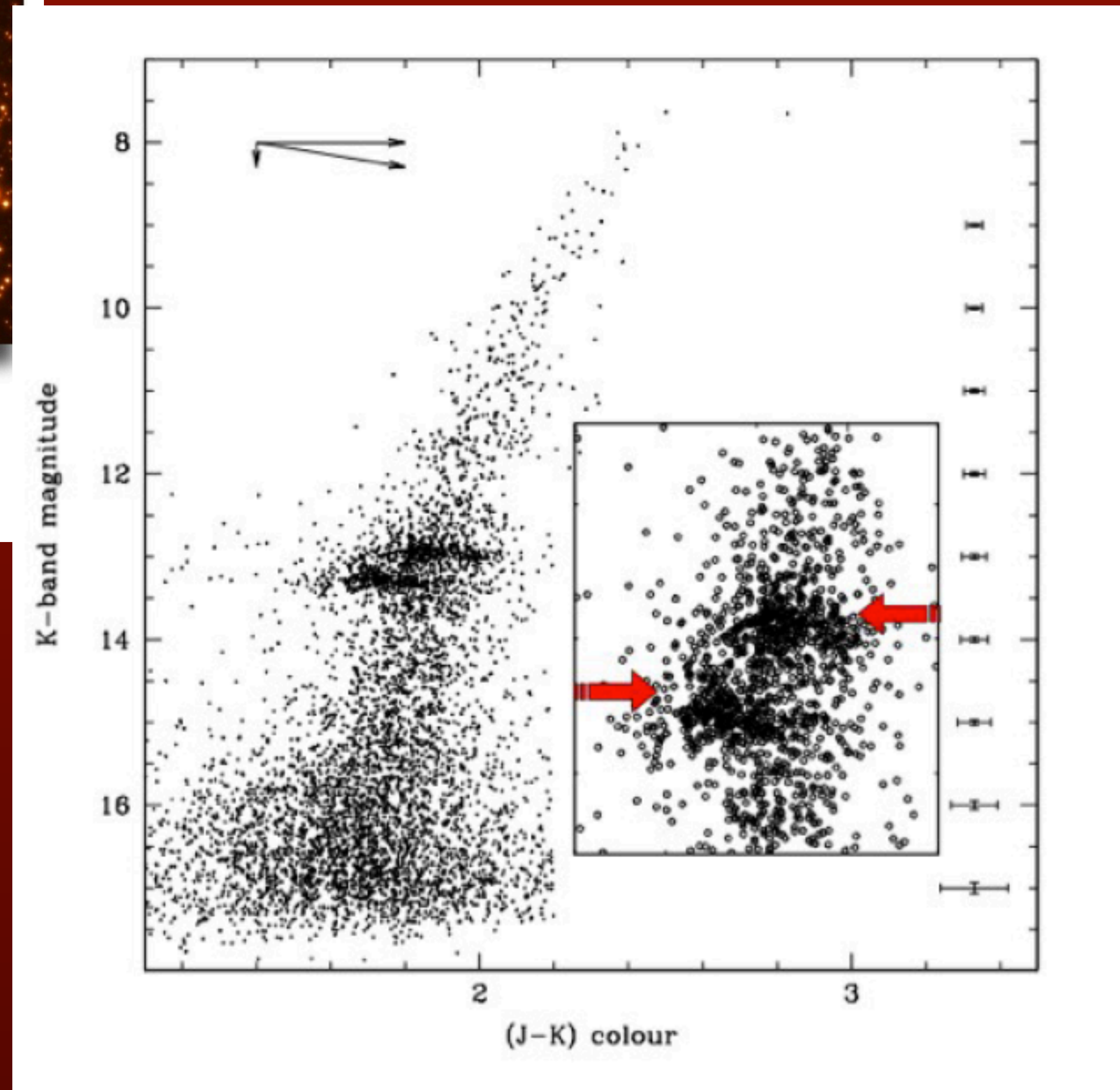
Minor axis abundance gradient clear



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

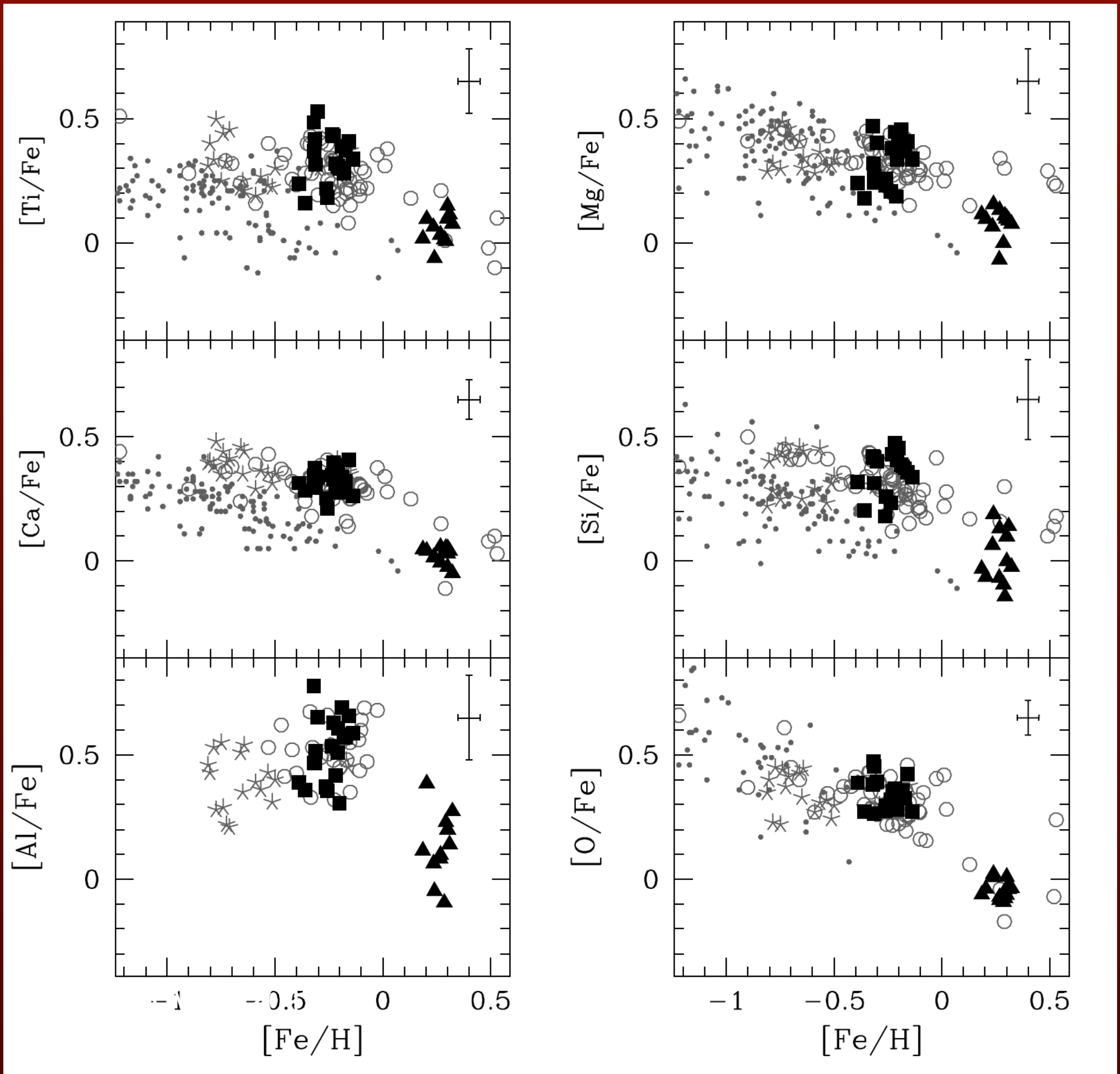
Remarkable Cluster Ter 5
Ferraro et al. 2009





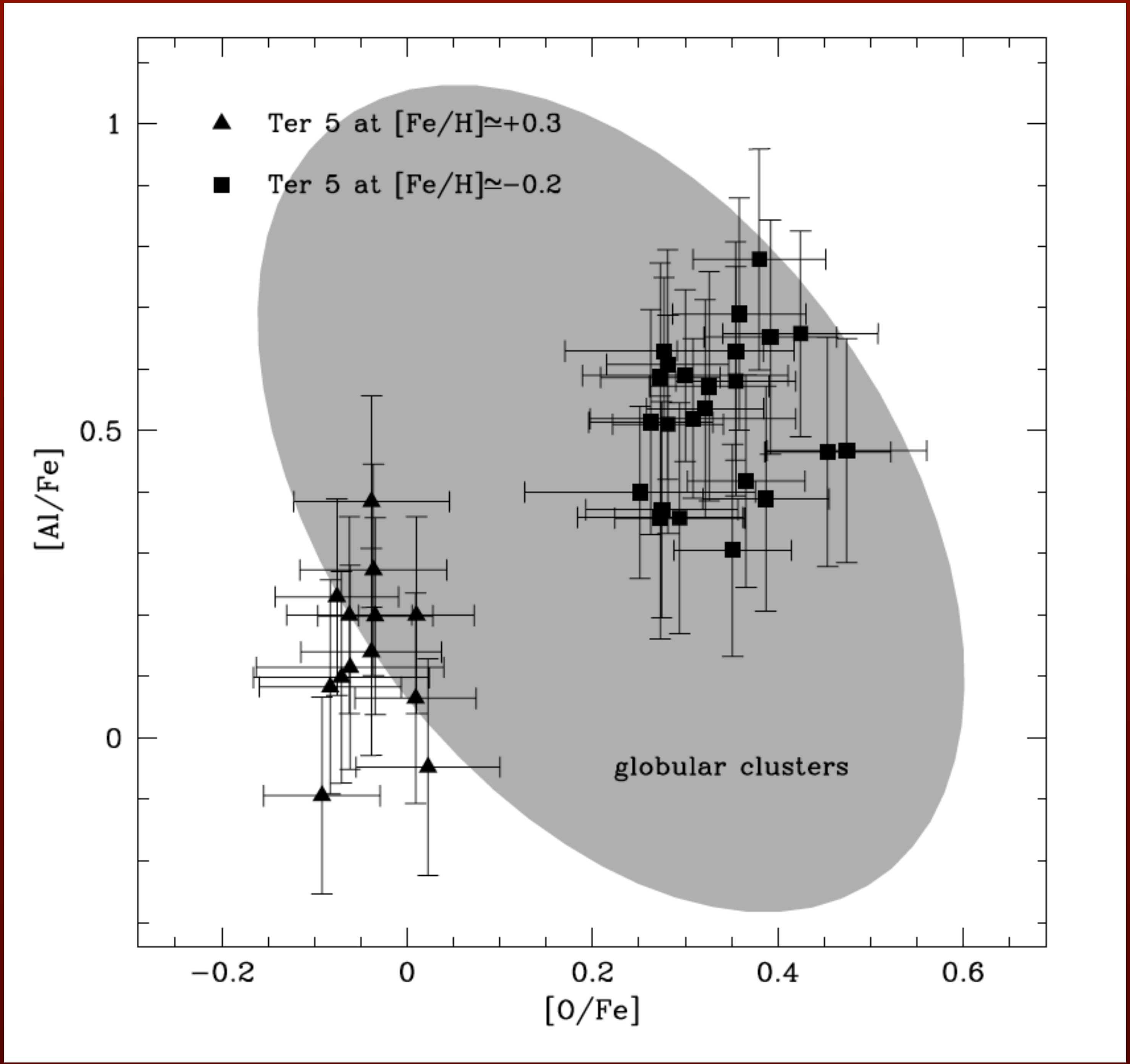
Double HB; brighter
Has [Fe/H]~+0.3
Fainter has [Fe/H]~-0.2
0.5 dex [Fe/H] spread-
Unique case.

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


Ter 5 at [Fe/H]≃+0.3
Ter 5 at [Fe/H]≃−0.2
globular clusters
[Al/Fe]
[O/Fe]
1
0.5
0
−0.2
0
0.2
0.4
0.6

BRAVA Implications

The M giant population shows kinematic uniformity on large scales

The agreement with two independent N-body bar models is striking.

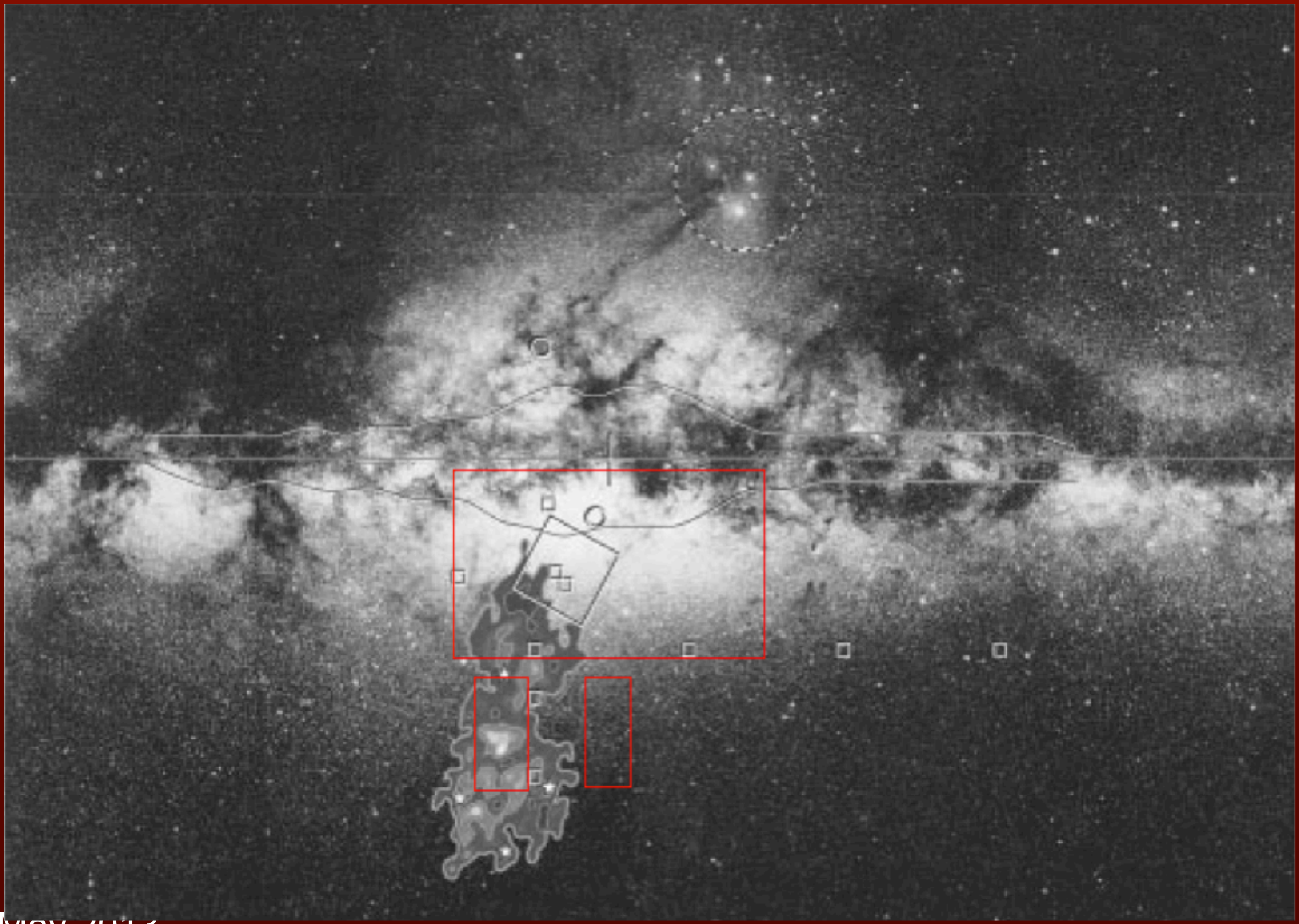
The dynamical processes responsible for creating a bar should accelerate stars without respect to abundance; the existence of an abundance gradient cannot be explained by N-body bar models.

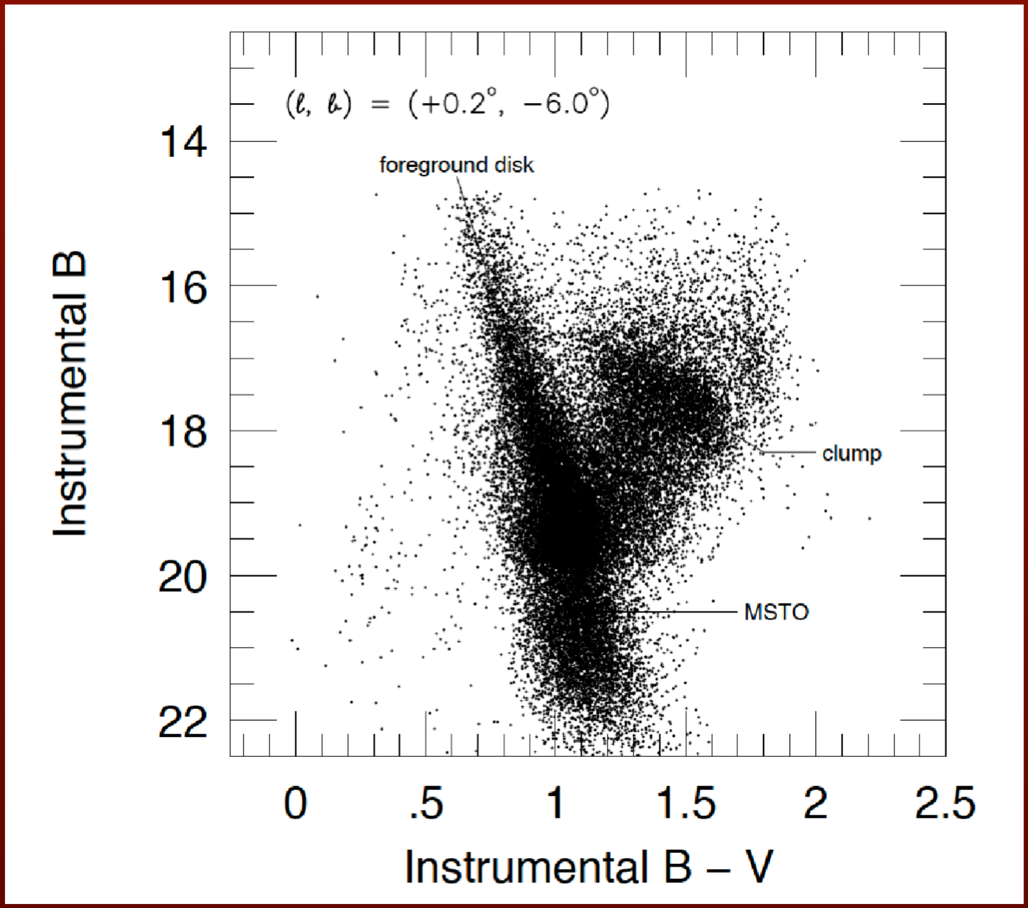
There is no transition in population from “bar” to “bulge/spheroid” at b=-8, that might help explain the gradient.

Growing evidence (alpha/Fe, La/Eu, photometric) for early, rapid, bulge formation. However, composition alone does not rule out a younger sub population at [Fe/H]>0

Blanco DEcam Bulge Survey

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





Terndrup et al. 2004

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