

New Breakthroughs in the Battle of the Bulge Using Globular Clusters



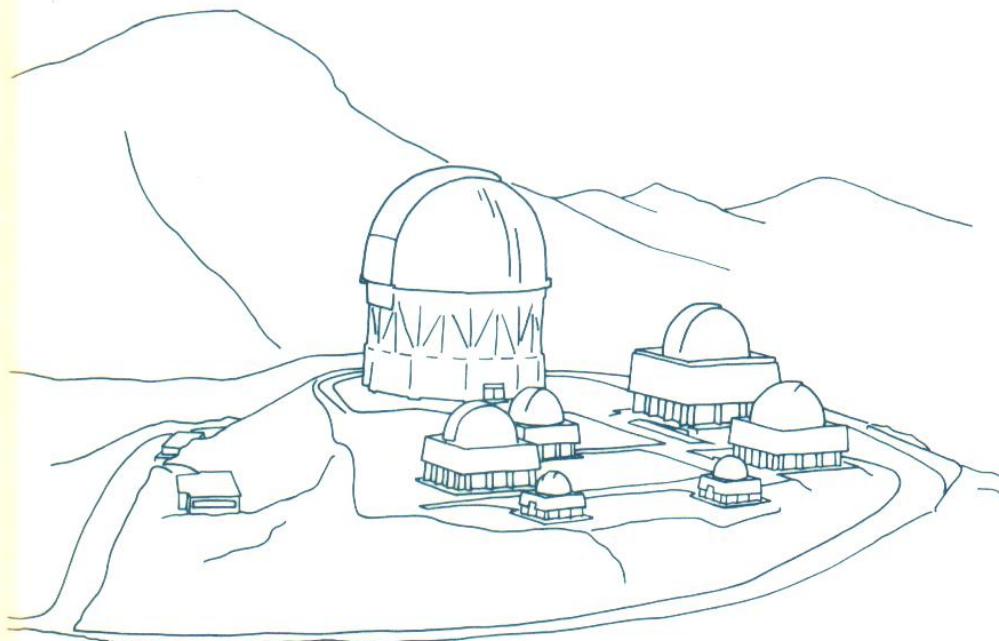
F. Mauro, C. Moni Bidin, R. Cohen, A. Chene,
S. Villanova, J. Cummings, A. Gormaz, D. Geisler
Universidad de Concepcion

D. Minniti, J. Alonso-Garcia, M. Hempel (PUC) and VVV Team





PROGRESS AND OPPORTUNITIES IN SOUTHERN HEMISPHERE OPTICAL ASTRONOMY



CTIO 25th Anniversary Symposium
Edited by V. M. Blanco and M. M. Phillips



A wild party at Cerro Tobolo, err Loboto....



ESO/CTIO Workshop on

BULGES OF GALAXIES

La Serena, Chile, 16 – 19 January 1990

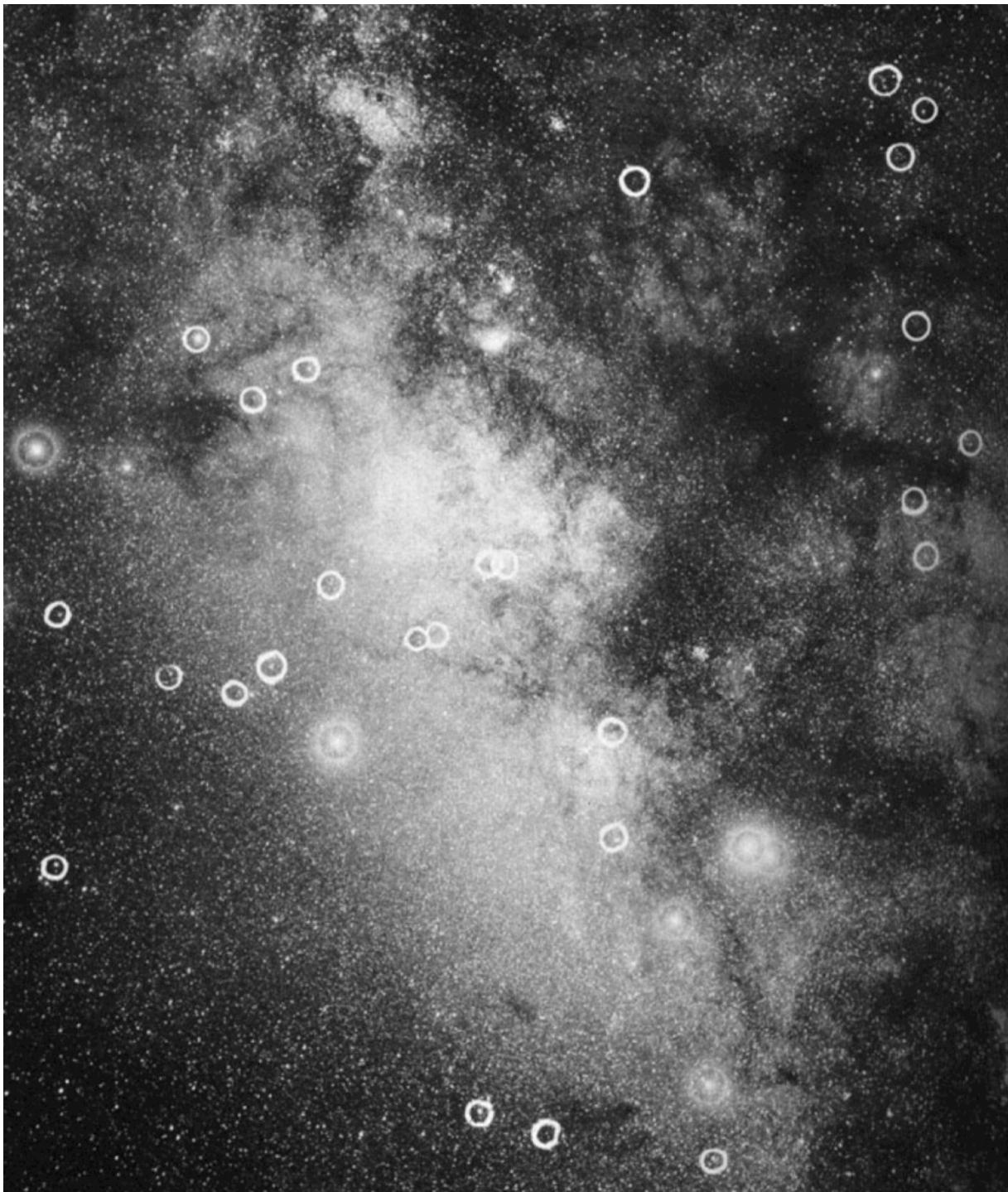


PROCEEDINGS

Edited by B.J. Jarvis and D.M. Terndrup

GOBIERNO REGIONAL

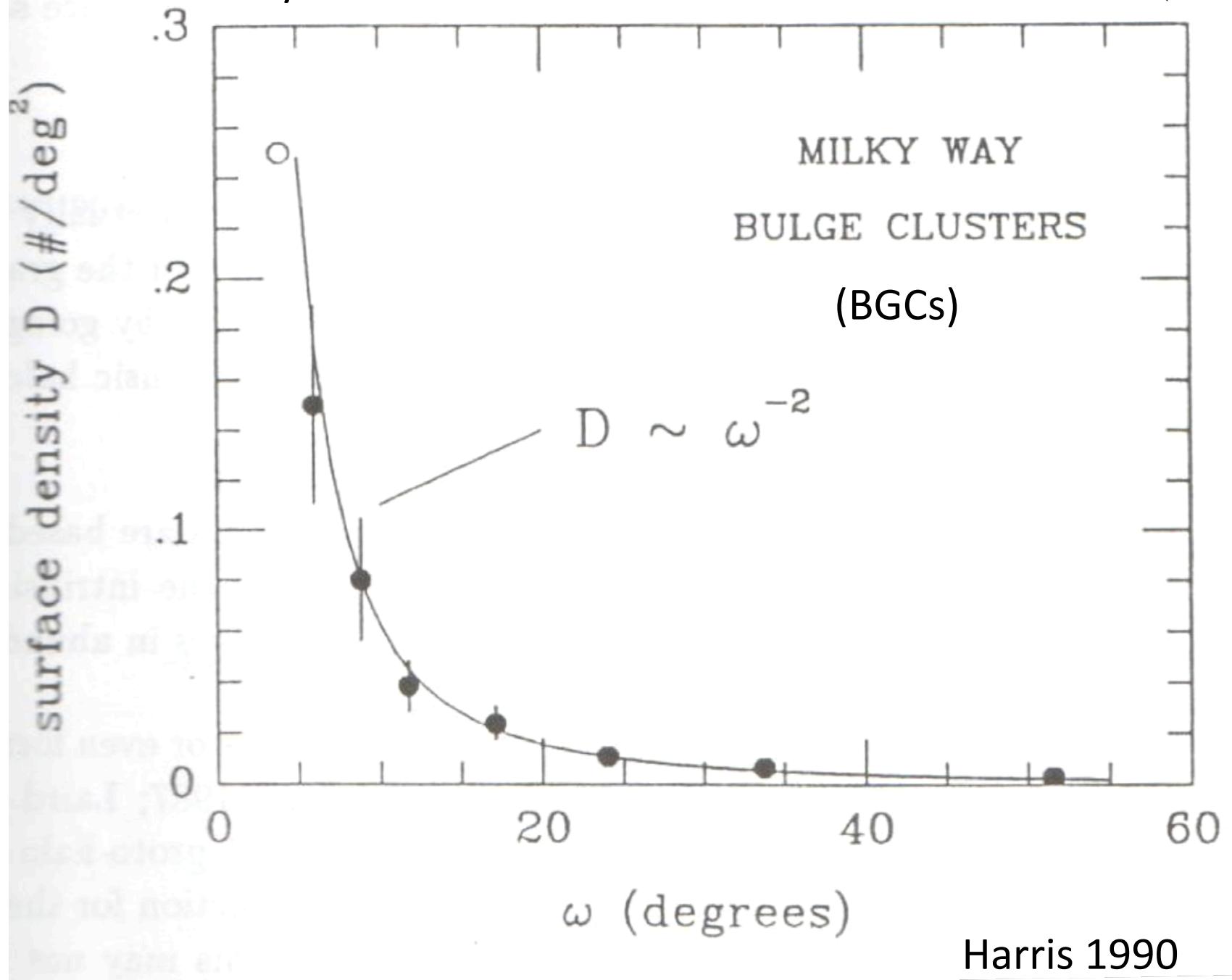




Shapley 1918:
Globular Clusters
(GC) concentrated
towards Galactic
center!

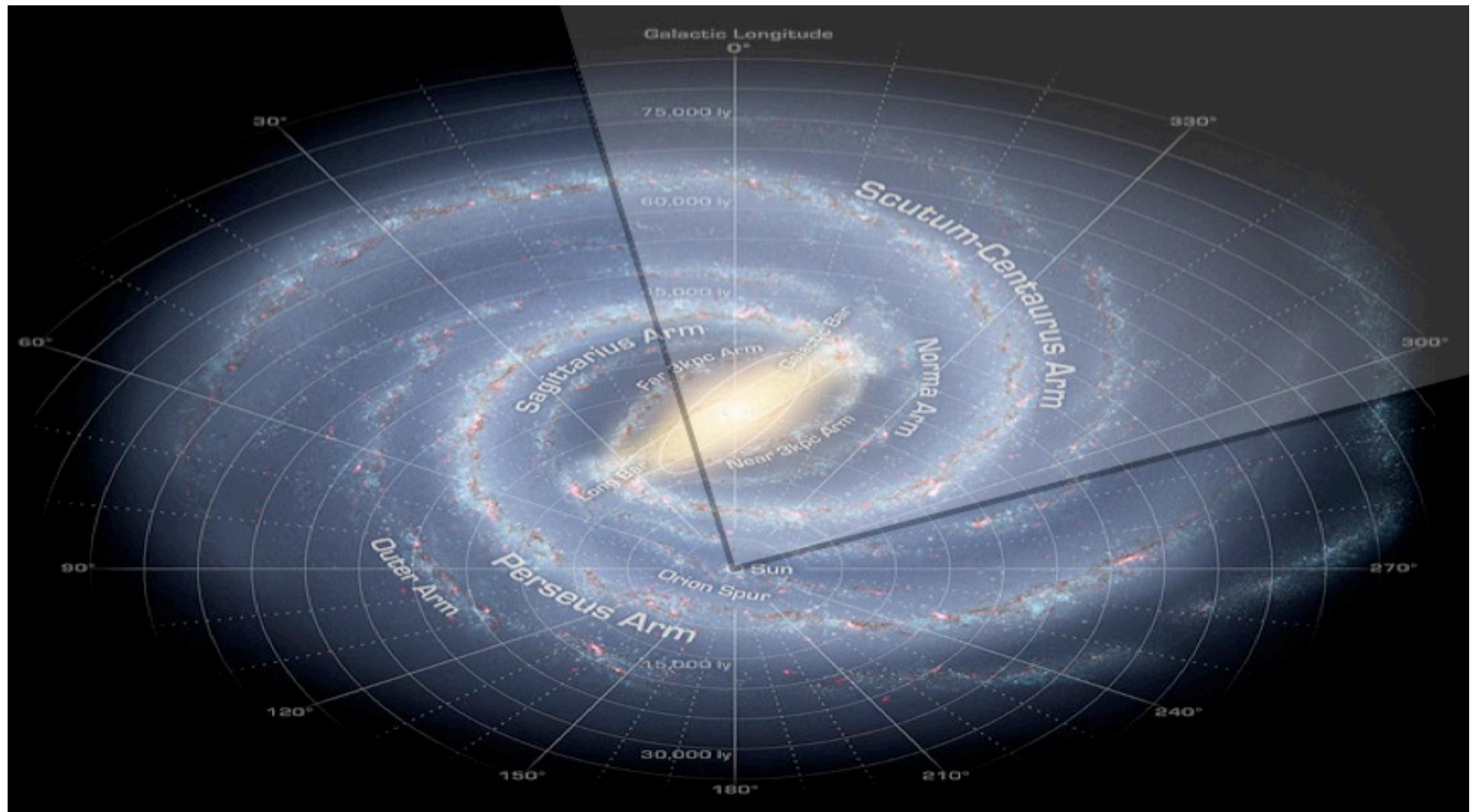
But note **zone of avoidance**
where there are no GCs –
extinction! Also crowding.
Hard work!

50% of Galaxy's ~150 GCs within 25° of Galactic center (5% of sky)

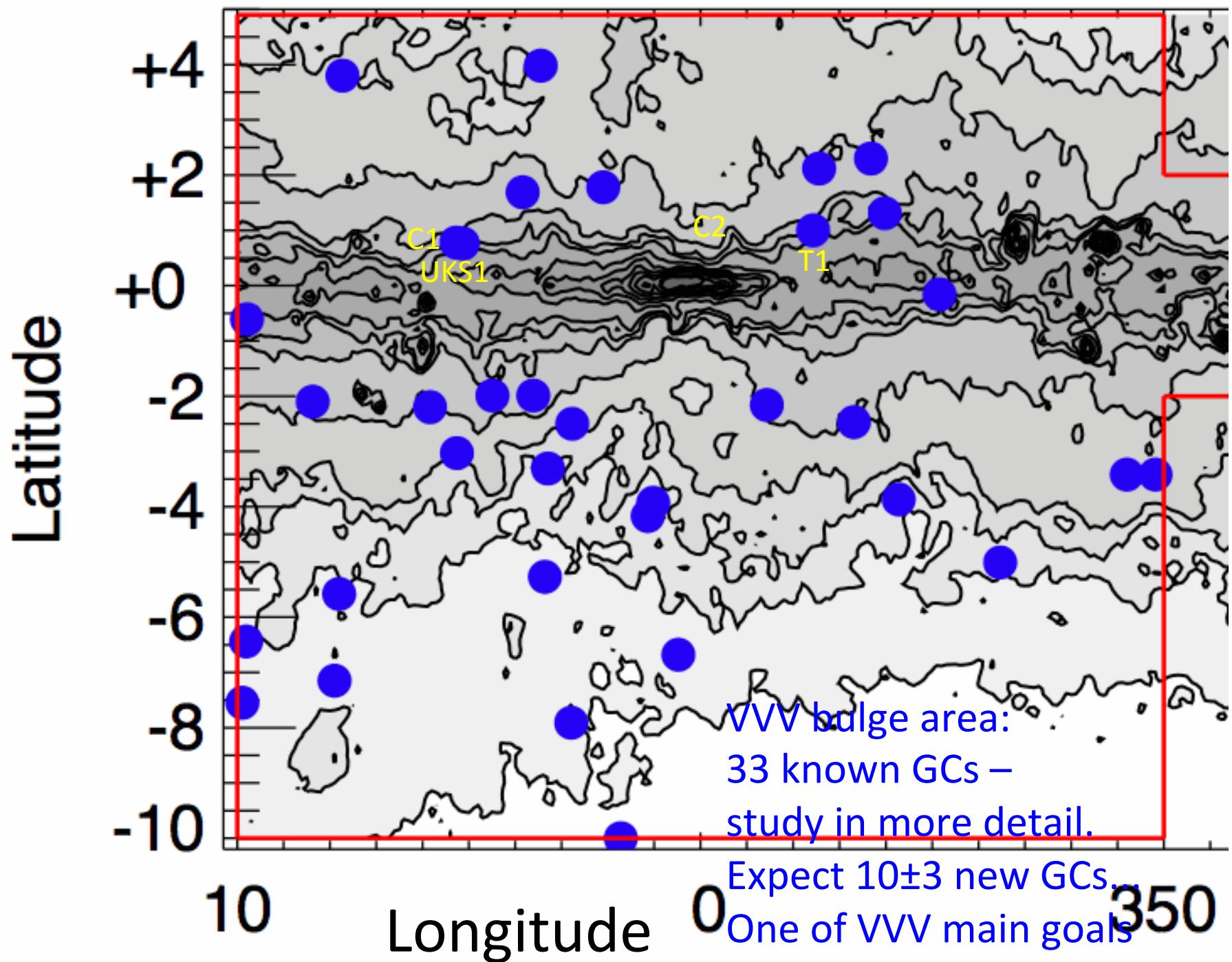


Vista Variables in the Via Lactea (D. Minniti, PI)

$\mathcal{V}\mathcal{V}\mathcal{V}$ Minniti et al. (2010)



- 1920h with VISTA over 5 yrs
- Observations started Feb. '10
- 520 sq deg bulge/plane
- ZYJHK_S
- 10^9 point sources
- 10^6 variables



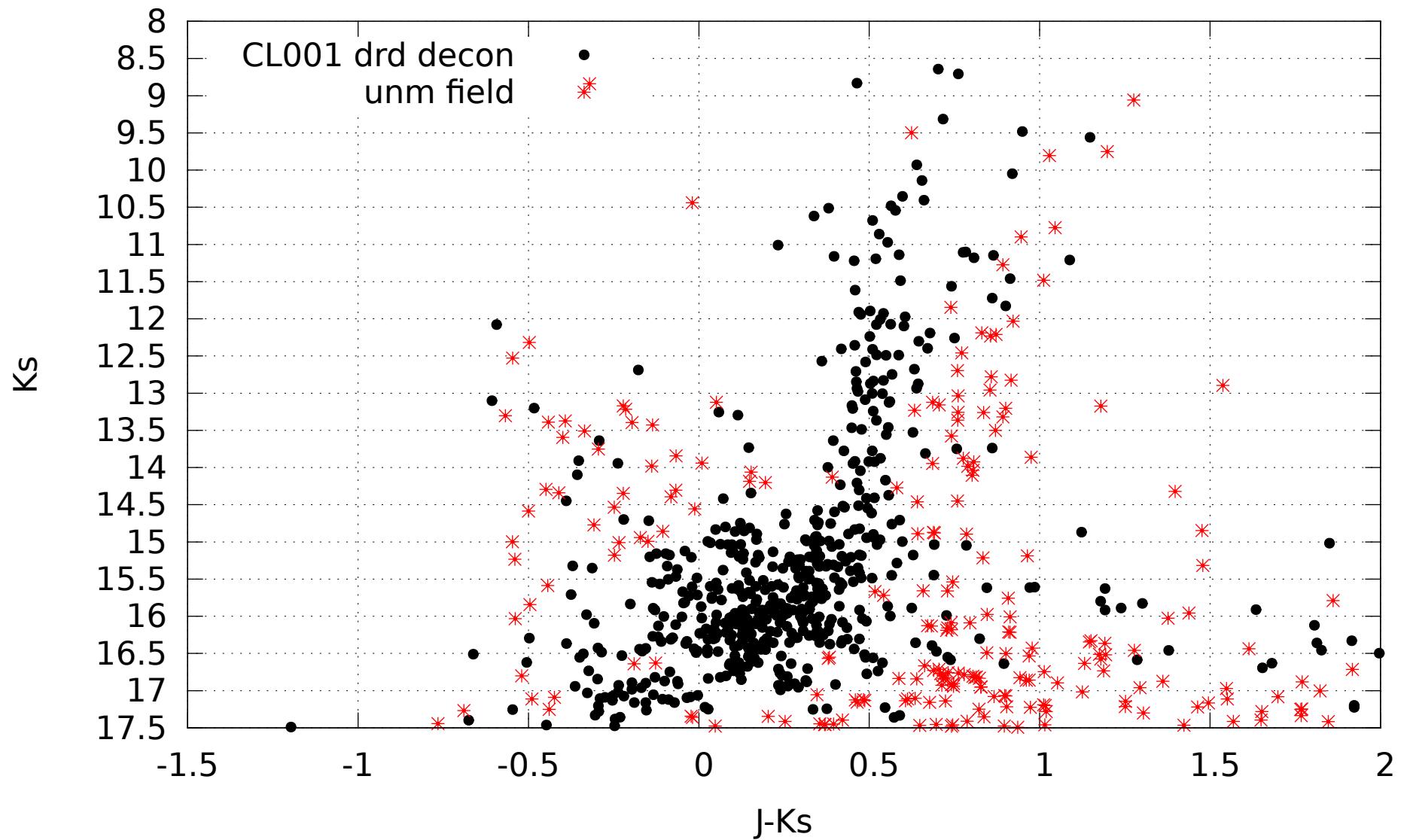
New Bulge(?) GCs!

Minniti 1 (VVV-CL001)

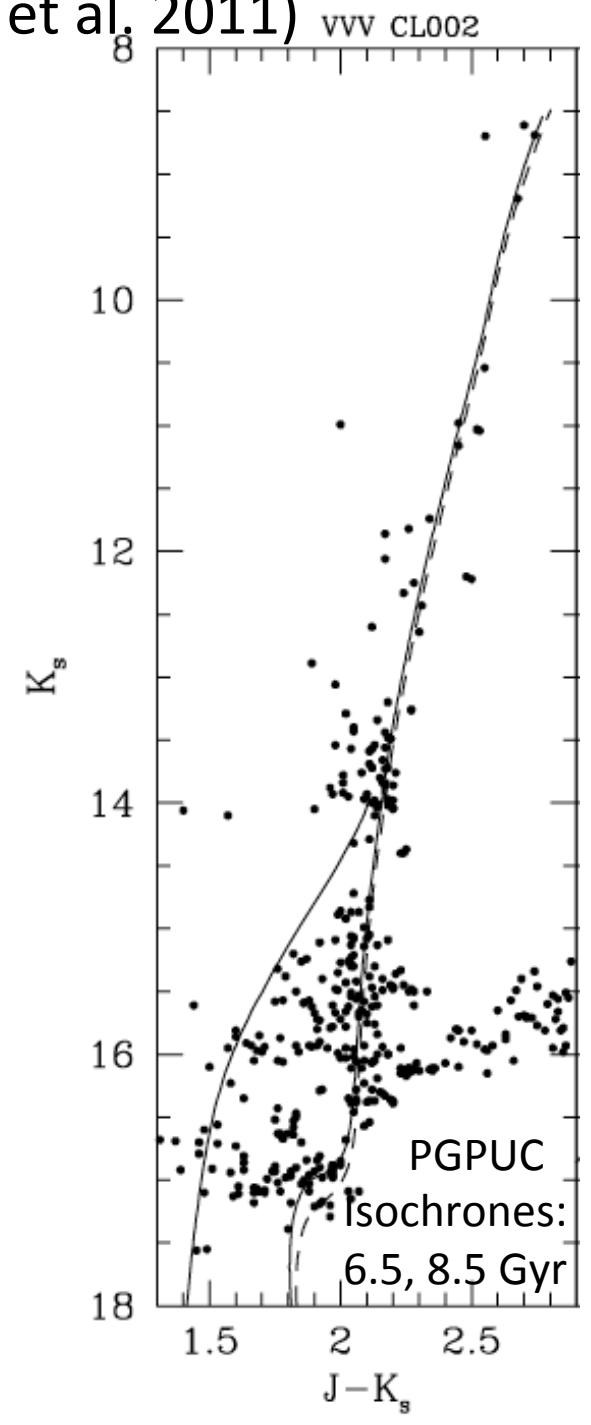
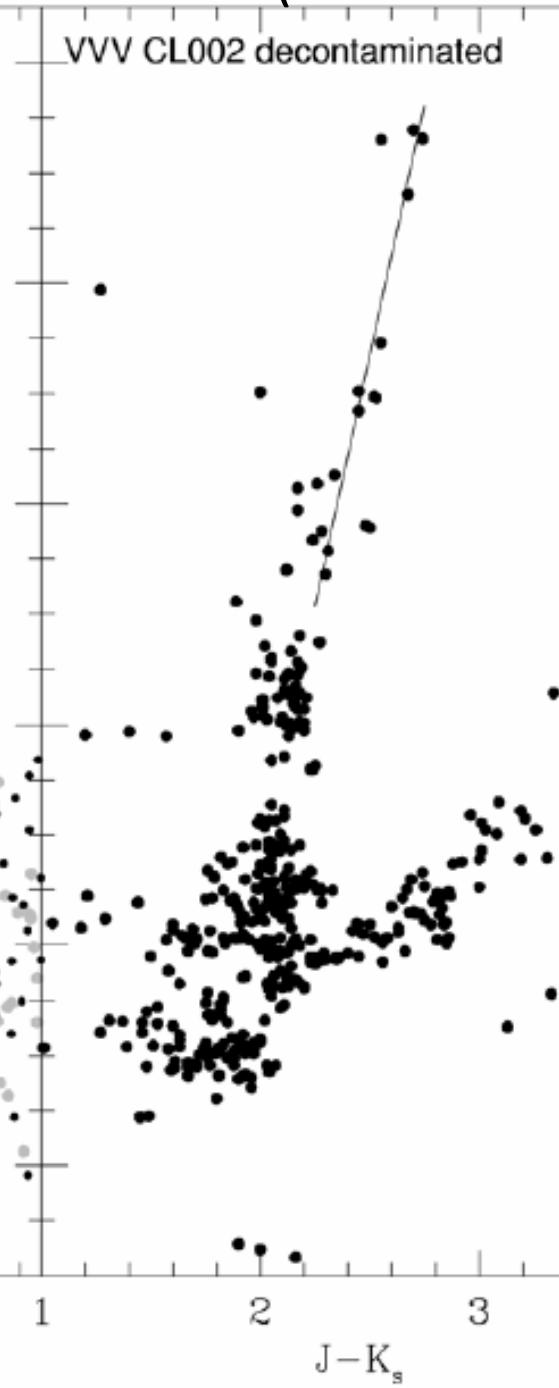
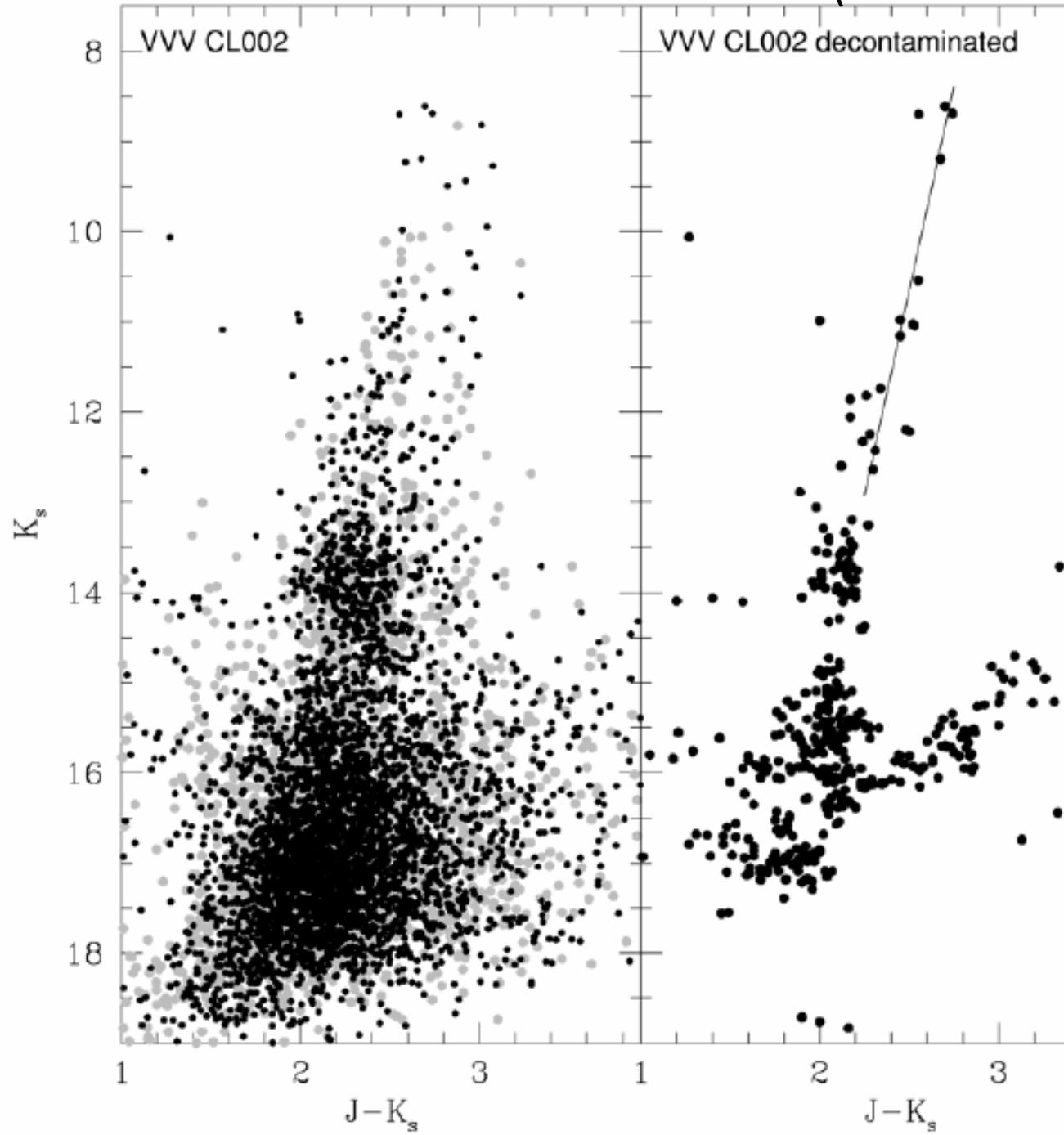


Only 8' from known GC! Closest pair of GCs in the Galaxy! Binary?!
Minniti et al. 2011 – both possibly beyond far end of bulge but d very ???

New SkZ pipeline CMD: inner 30" dereddened and decontaminated



Another one! VVV CL002 (Moni Bidin et al. 2011)

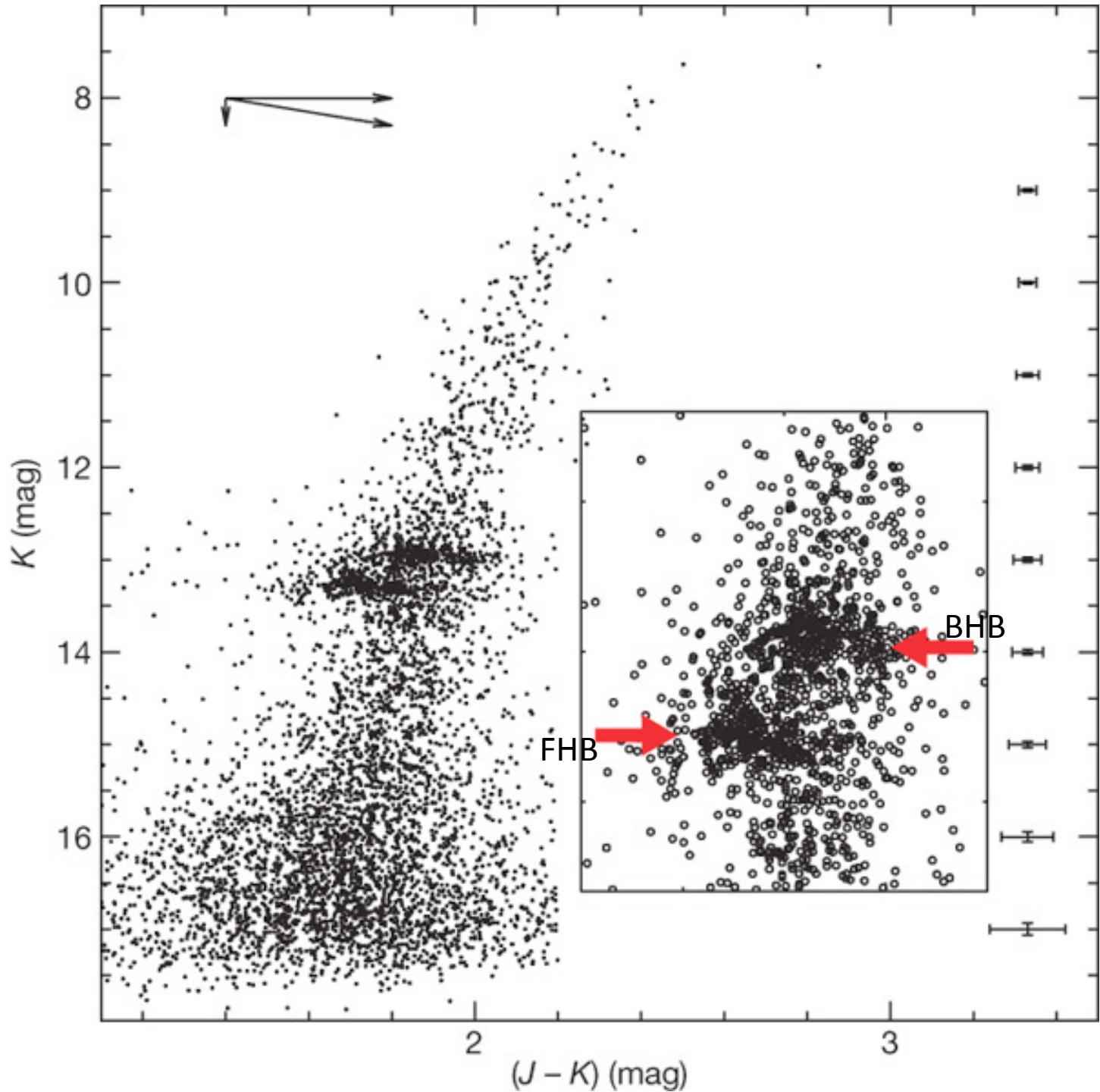


Derived parameters of the two cluster candidates.

	VVV CL002	VVV CL003
r_h (')	0.75 ± 0.10	0.6 ± 0.1
r_h (pc)	1.6 ± 0.3	2.3 ± 0.4
r_t (')	1.8 ± 0.1	1.8 ± 0.1
r_t (pc)	3.8 ± 0.5	6.8 ± 0.4
$c = \log(r_h/r_c)$	0.65 ± 0.26	0.56 ± 0.21
$(m - M)_0$	14.32 ± 0.23	15.57 ± 0.16
d (kpc)	7.3 ± 0.9	13.0 ± 1.0
R_{GC} (kpc)	0.7 ± 0.9	5.0 ± 1.0
z (pc)	113 ± 13	166 ± 14
$E(J - K_s)$	1.50 ± 0.15	1.48 ± 0.15
$E(B - V)$	2.88 ± 0.29	2.85 ± 0.29
[M/H]	-0.16 ± 0.2	-0.1 ± 0.2
[Fe/H]	-0.4 ± 0.2	-0.1 ± 0.2
M_V	-3.4 ± 0.3	–
Age (Gyr)	≥ 6.5	–

Derive distances,
metallicities,
velocities, etc. for
CL1, UKS1, CL2, CL3...

One of closest
BGCs to Galactic
center!
First disk cluster
on far side of
Galactic center!



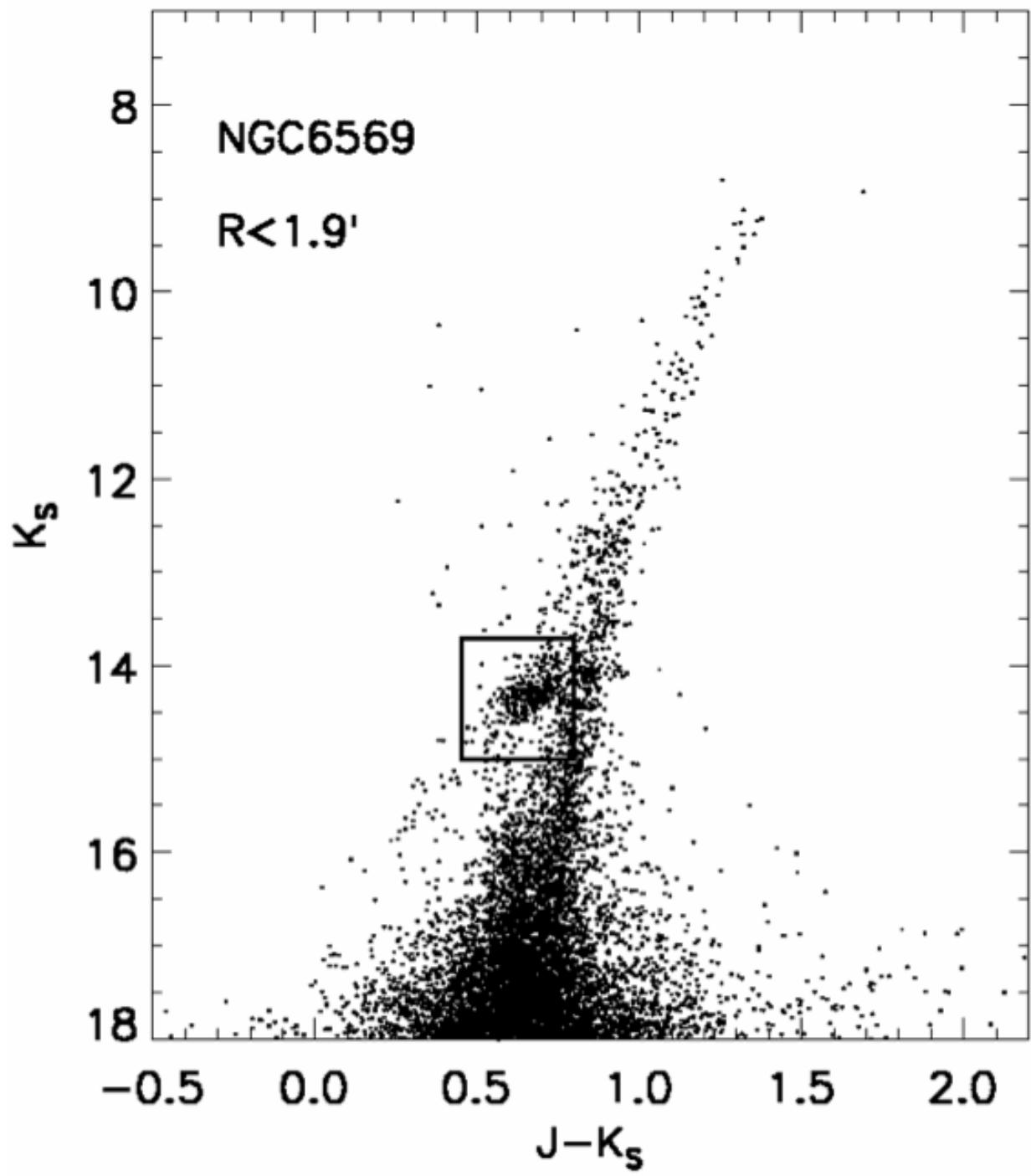
Bulge Building
Blocks (BBB):

Ferraro et al. 2009
Terzan 5: 2 RCs!!!
 $\Delta K = 0.3$ mag
NOT instrument,
diff redd, field.
Also in ACS VI

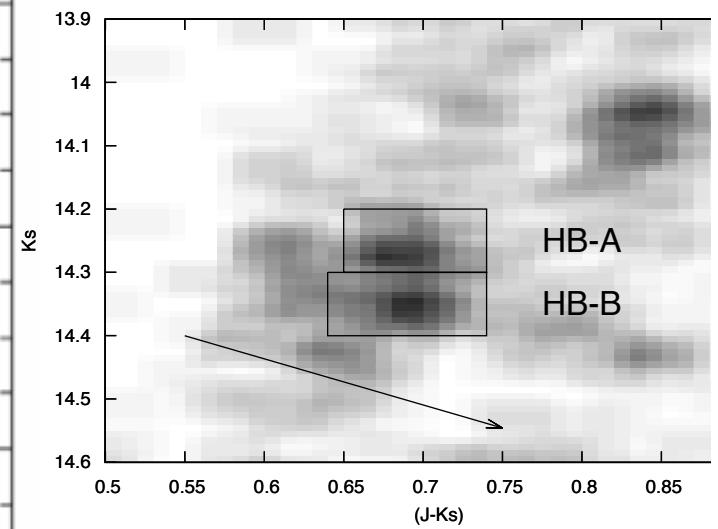
Structural parameters for Terzan 5 (Lanzoni et al. 2010)

Bimodal met (& [α/Fe] dist), covering bulge met range, no Al:O anticor. – range of met, α and age - not just another BGC: BBB?

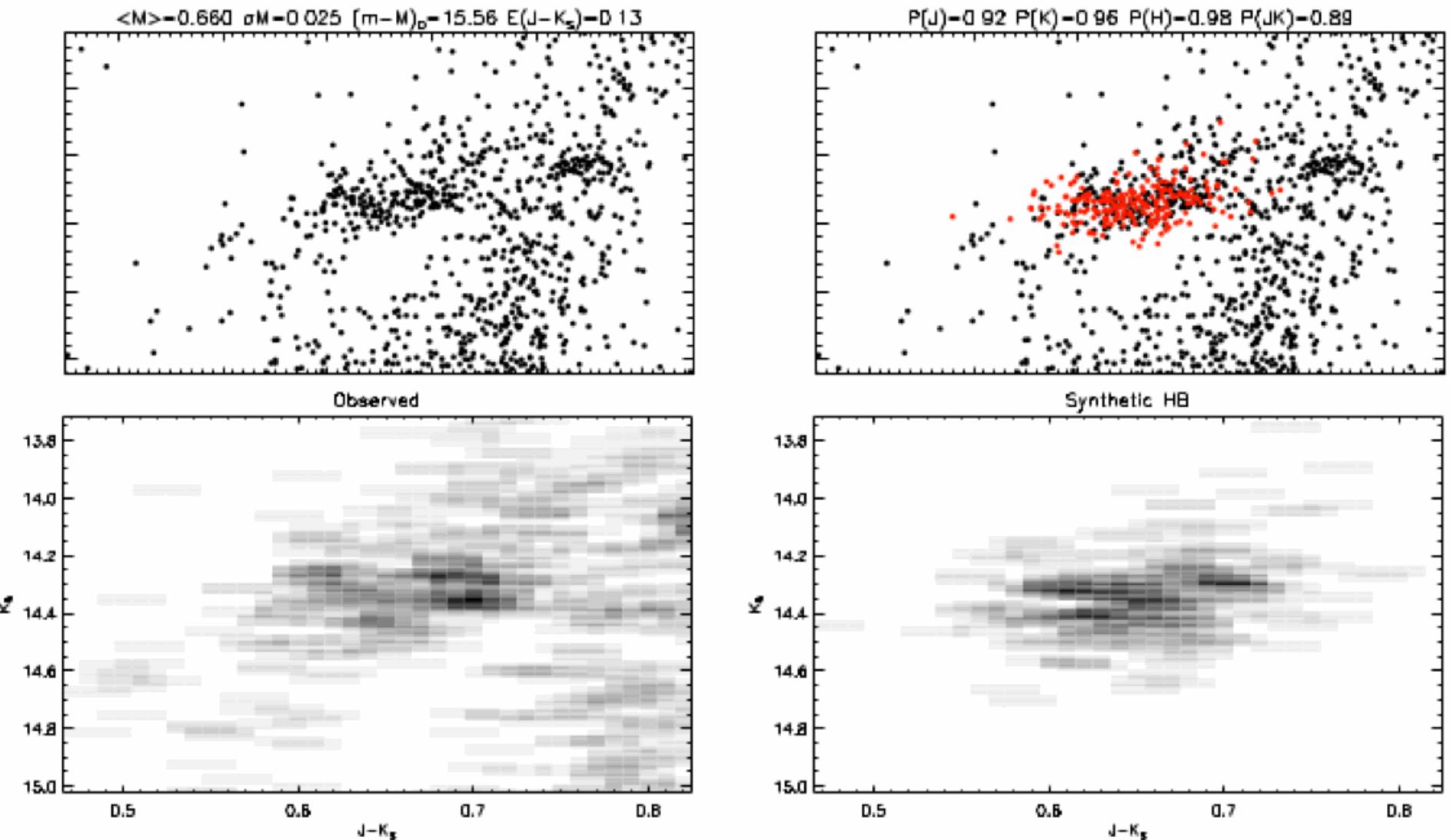
Center of gravity	$\alpha_{\text{J}2000} = 17^{\text{h}} 48^{\text{m}} 4.85^{\text{s}}$
	$\delta_{\text{J}2000} = -24^{\circ} 46' 44.6''$
Reddening [†]	$E(B - V) = 2.38 \pm 0.055$
Distance [†]	$d = 5.9 \pm 0.5 \text{ kpc}$
Core radius	$r_c = 9'' = 0.26 \text{ pc}$
Concentration	$c = 1.49$
Total luminosity	$L_{\text{bol}} \simeq 8 \times 10^5 L_{\odot}$
Total mass	$M_{\text{T}} \simeq 2 \times 10^6 M_{\odot}$ ~ΩCen!!
Central mass density	$\rho_0 \simeq 4.1 \times 10^6 M_{\odot}/\text{pc}^3$
Central <i>K</i> -band SB	$\mu_K(0) = 9.85 \text{ mag/arcsec}^2$
Central <i>I</i> -band SB	$\mu_I(0) = 15.87 \text{ mag/arcsec}^2$
Central <i>V</i> -band SB	$\mu_V(0) = 20.54 \text{ mag/arcsec}^2$



Mauro et al. 2012:
discovery of 2 new
dual RC BGCs in VVV data:
NGC 6440 and 6569.
More BBBs?
But ΔK only 0.1 mag...

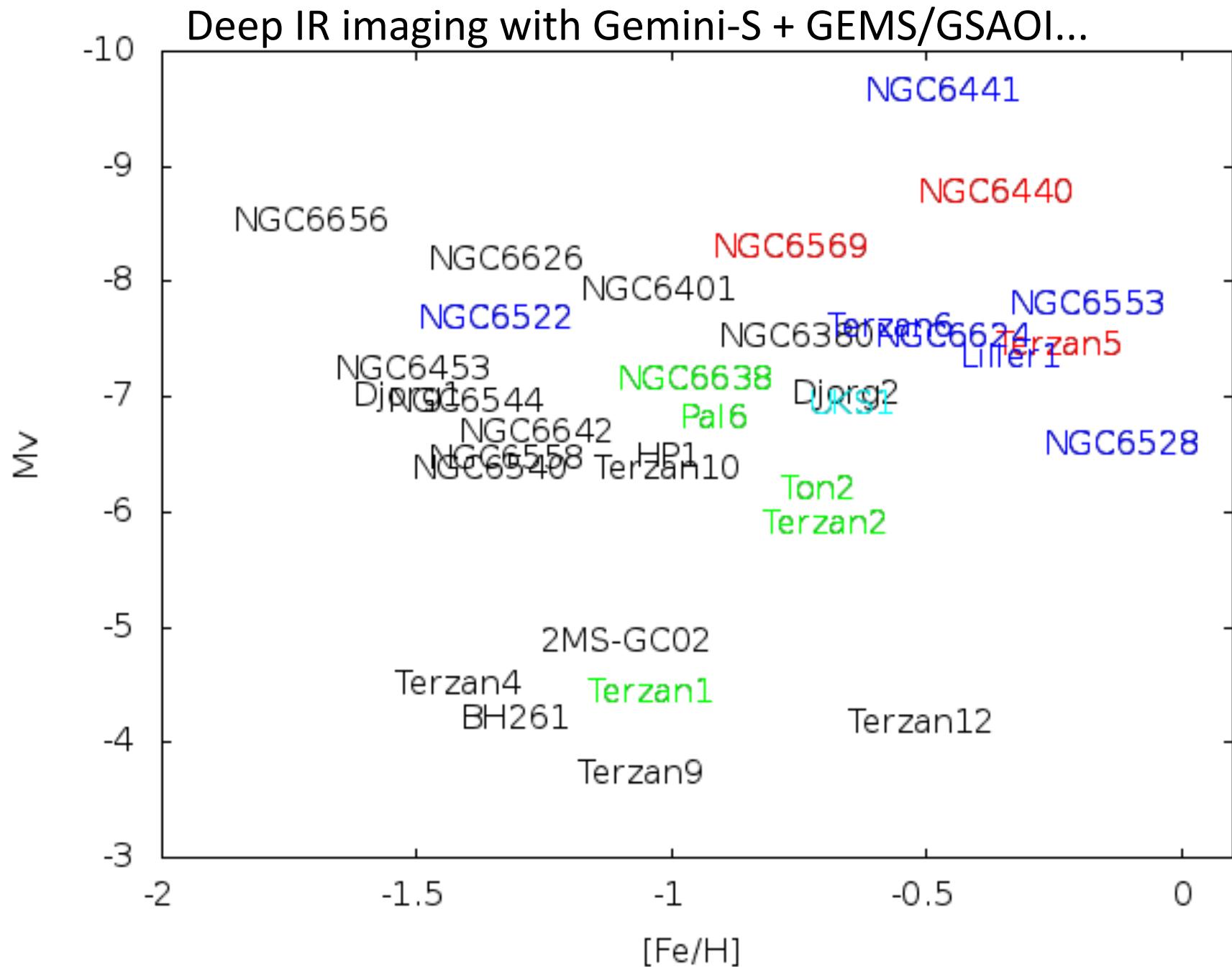


Be careful! MAY be able to explain at least some "dual" RCs by stellar evolution or simply photometric errors &/or diff. redd...



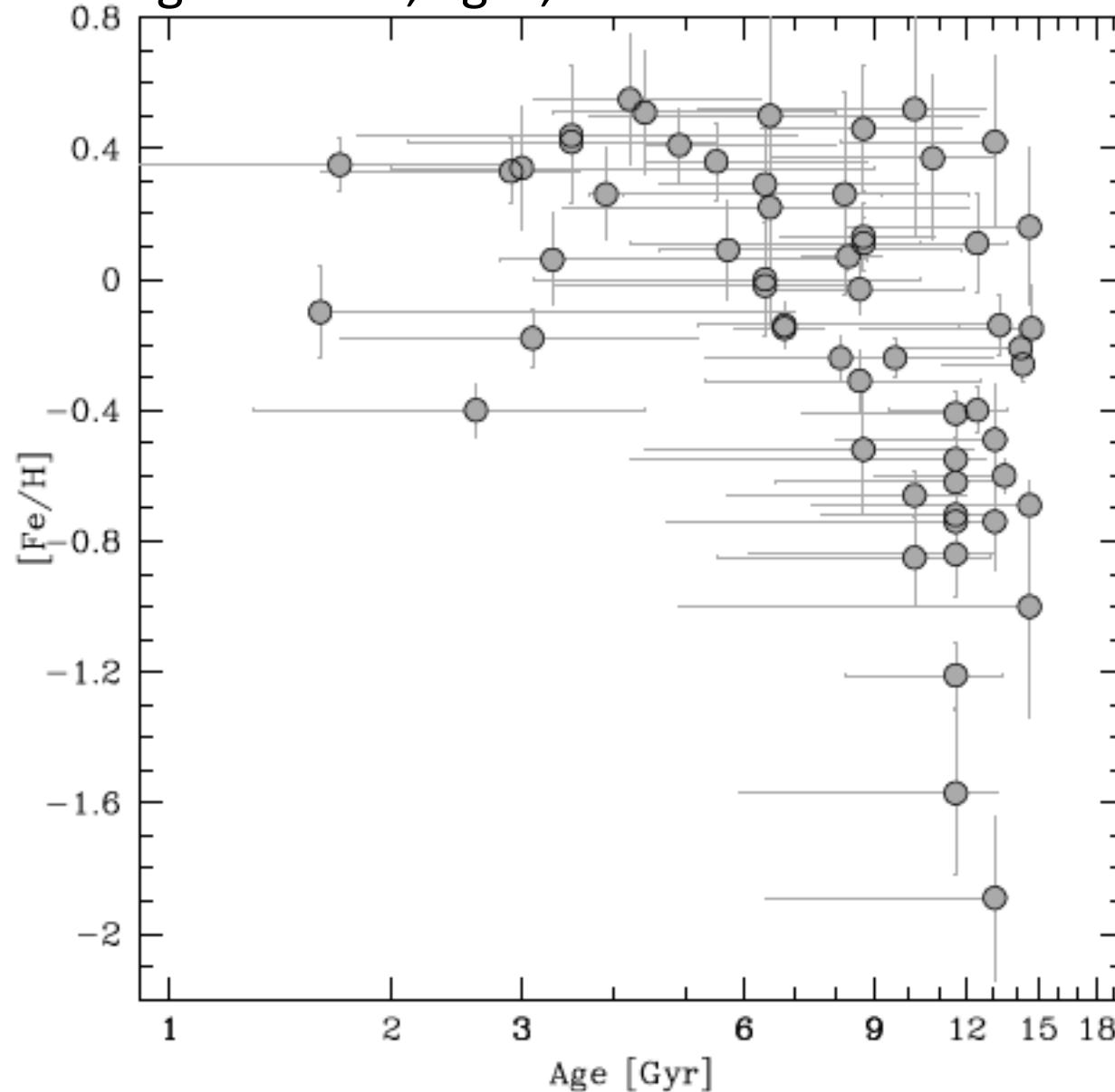
Cohen et al. 2013

So far, dual RC BGCs are among the most massive and metal-rich...



Bulge is getting VERY complicated – at least 2, maybe ≥ 4 pops...

Need good mets, ages, kinematics for BGCs....



Bensby et al. 2013: 58 microlensed bulge dwarfs/subgiants



CaT metallicities & velocities

- ♦ Brightest stars are giants: peak flux in IR
- ♦ RGB stars have three broad Ca II absorption lines (CaT)
- ♦ CaT are strongest lines in IR: EW a few Å – low resolution
- ♦ Easy to correct for log g
- ♦ Easy to measure [Fe/H]
- ♦ Observe many stars simultaneously
 - ♦ Remove distance & redd effects using relative photometry
 - ♦ Metallicity calibration good for wide age and met. range

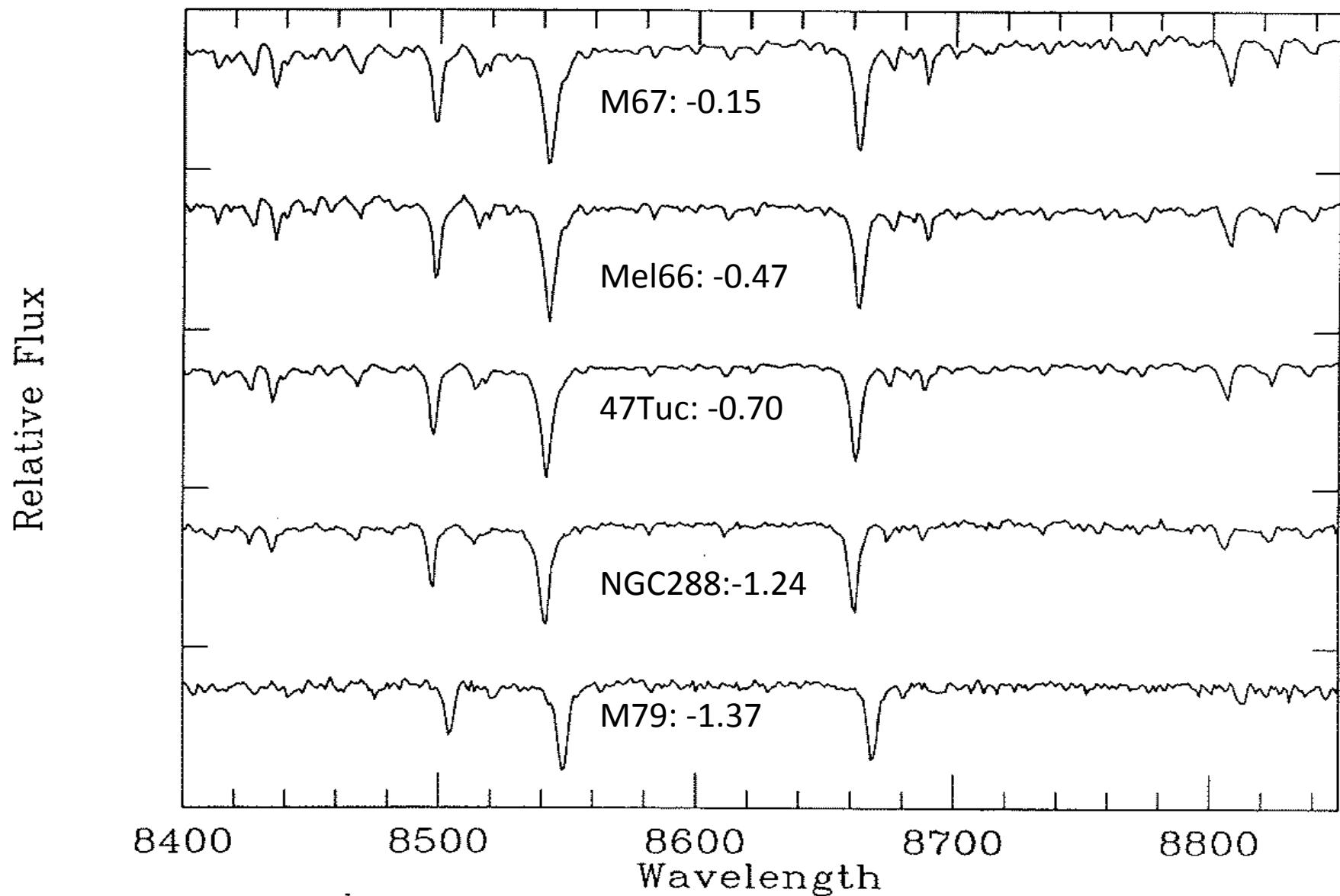
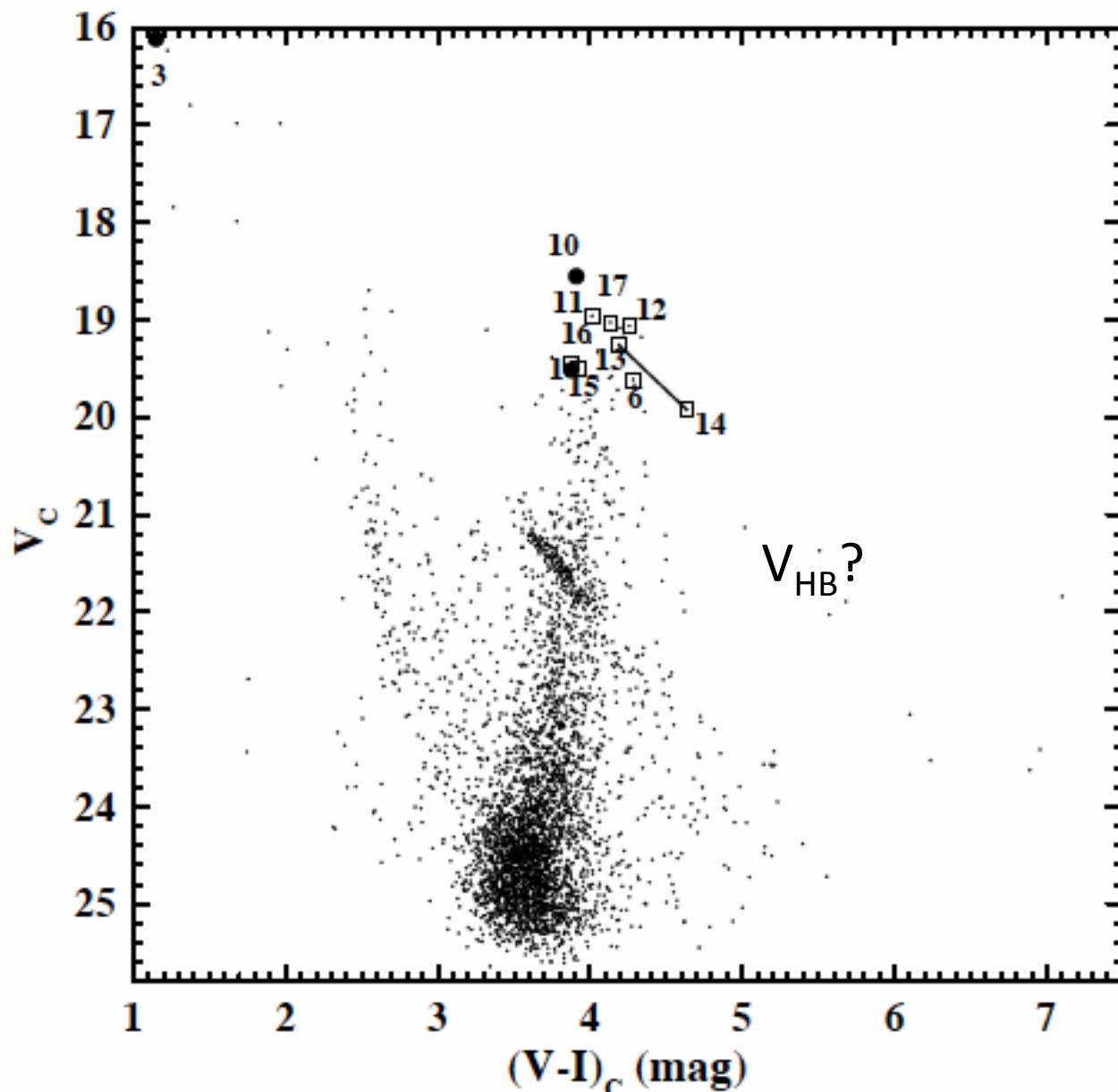
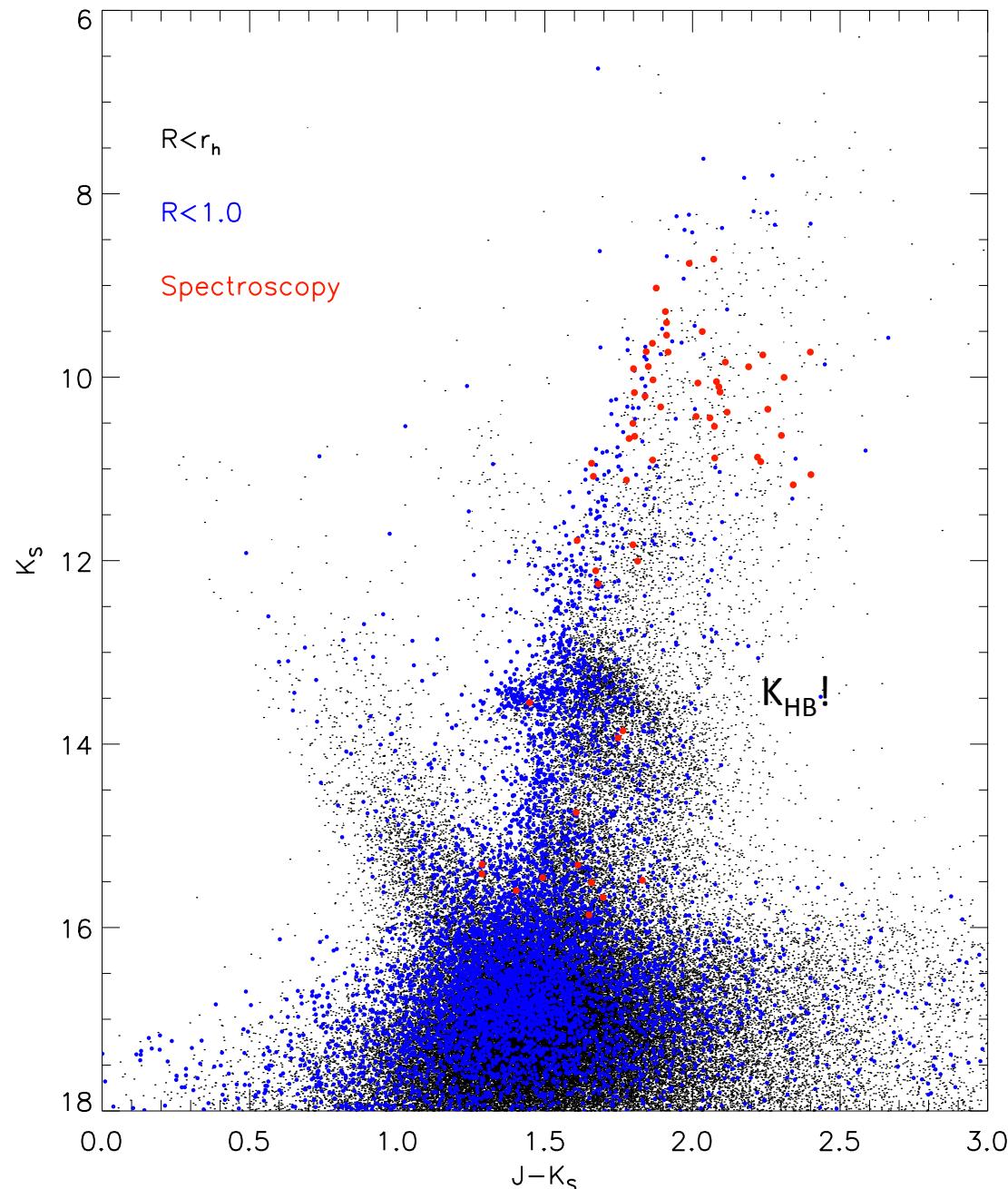


FIG. 2. Spectra of Galactic globular and open cluster giants in the region of the Ca II triplet. These spectra show the variation in line strength, at fixed absolute magnitude (M_{8600}), from very metal poor at the bottom ($[\text{Fe}/\text{H}] = -1.7$), increasing in metallicity, to solar metallicity at the top. From the bottom to top, the spectra are M79 237, NGC 288 20C, 47 Tuc 5312, Melotte 66 1242, and M67 IV-202. The Ca II triplet lines appear at $\lambda\lambda$ 8498, 8542, 8662 Å. Each of the five spectra are plotted with a relative flux of 0.35 at the lower tick mark, and 1.2 at the upper tick mark.

BUT requires seeing & measuring V_{HB} – HARD for BGCs!
1/2 of BGCs don't have met derived from individual spectra!

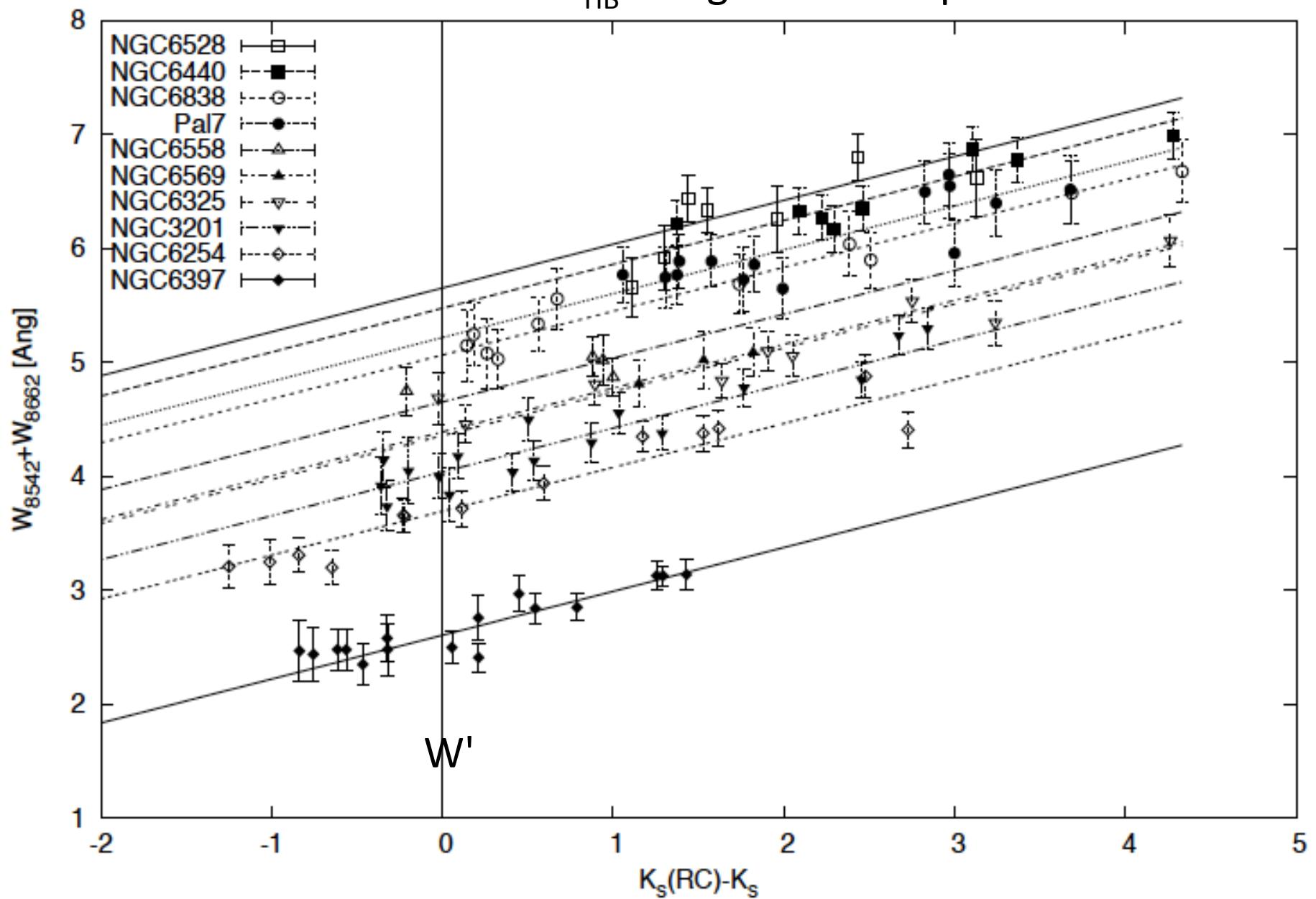


Idiart et al. (2002): optical HST CMD of Terzan1 (T1). $E(B-V)=2.0-2.5!$



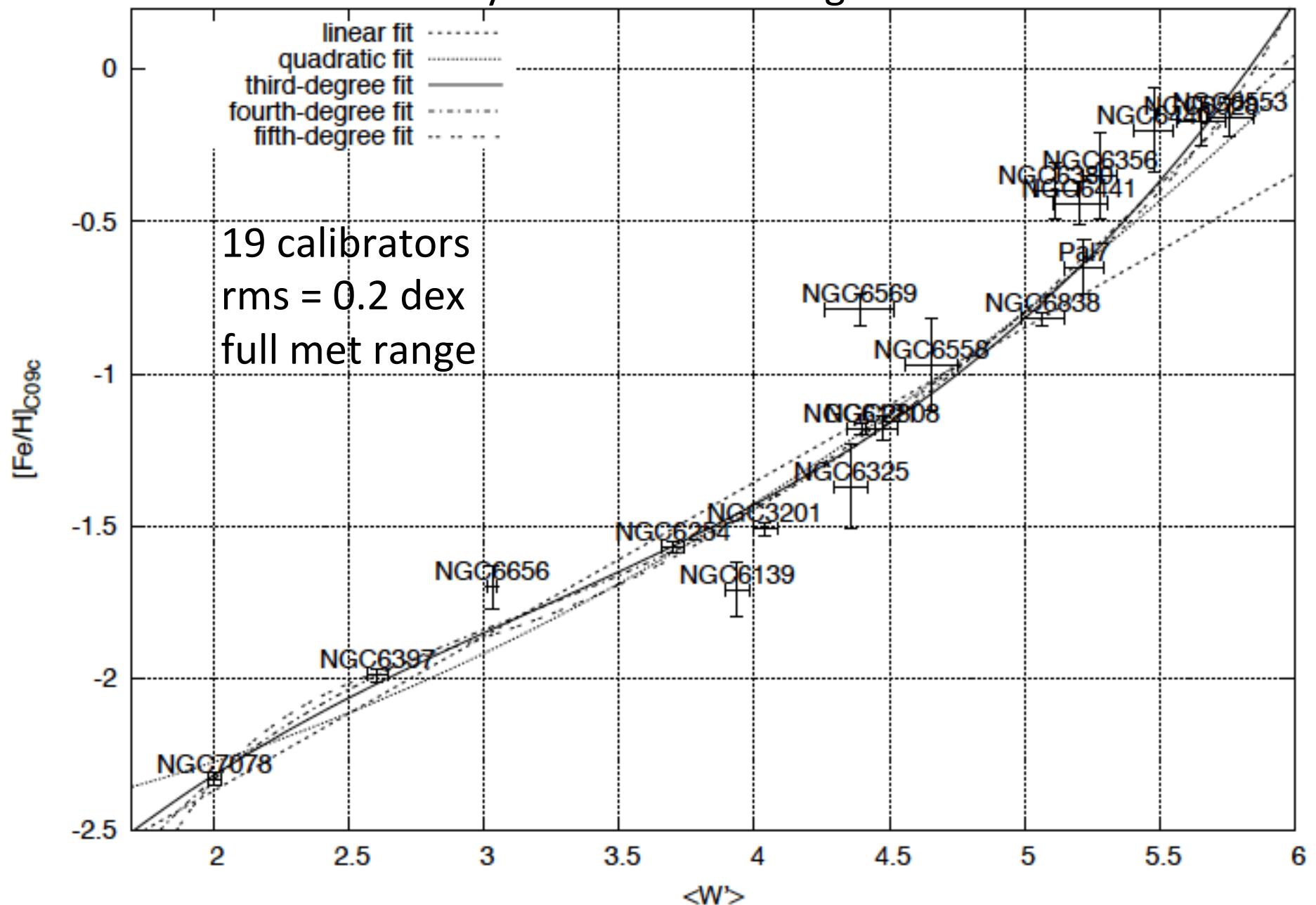
VVV CMD for Terzan 1 - Cohen et al. 2013

Derive calibration as for V_{HB} using reduced equivalent width W'



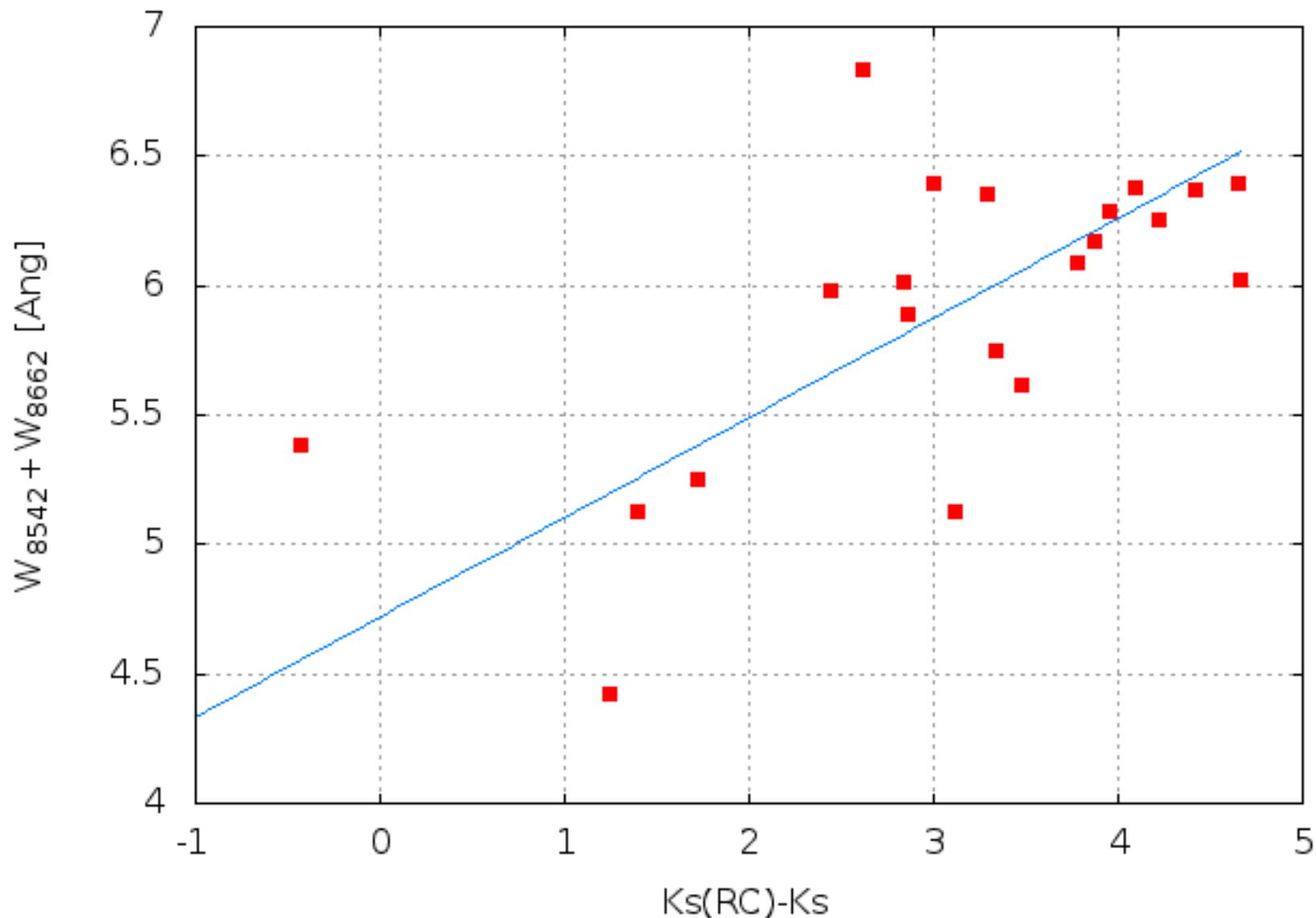
Mauro et al. 2013

Metallicity calibration looks good!



Mauro et al. 2013

Terzan 1



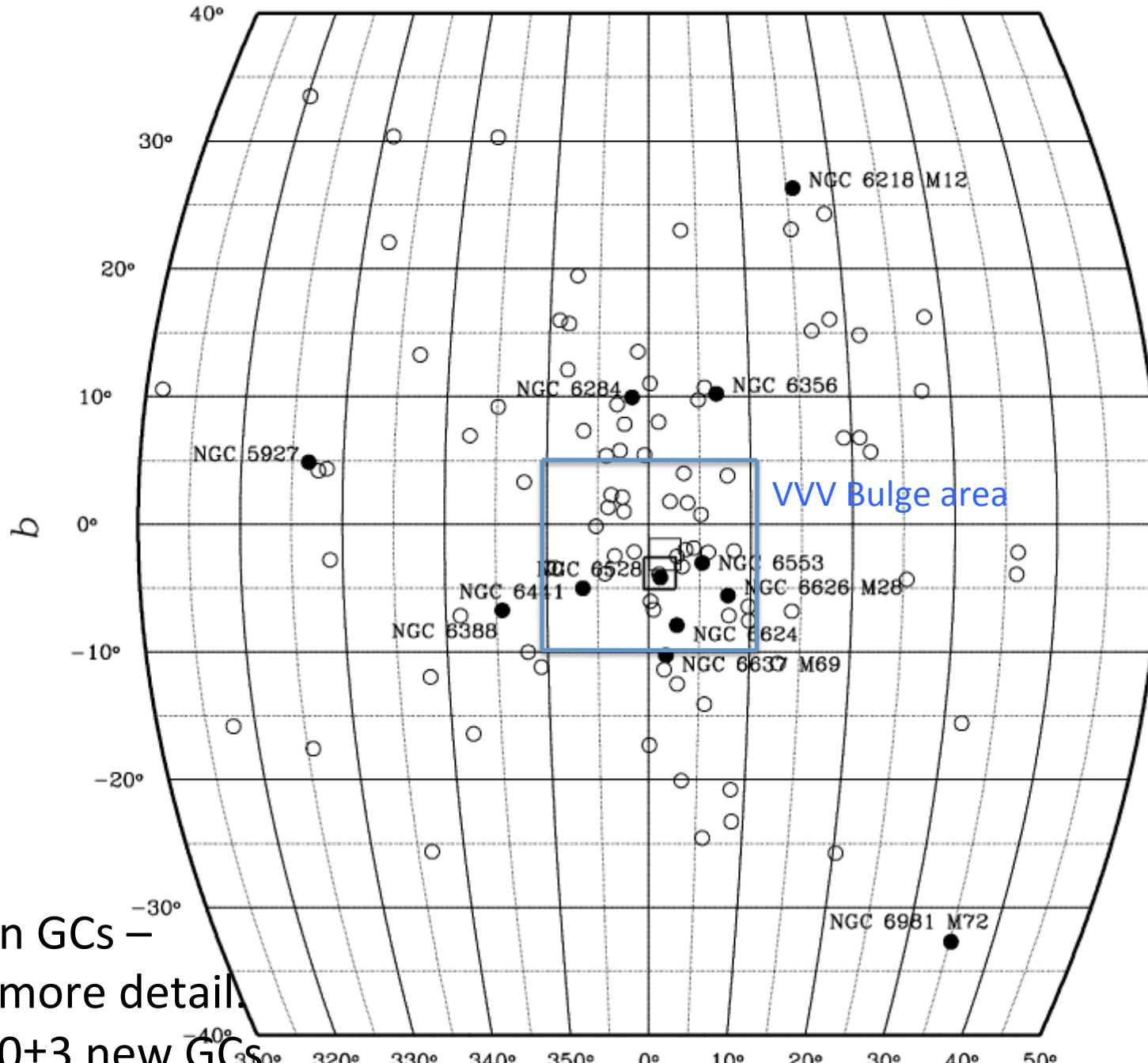
Cummings et al. 2013 preliminary result:
 $\langle [Fe/H] \rangle = -1.04 \pm 0.03$ from 21 velocity members

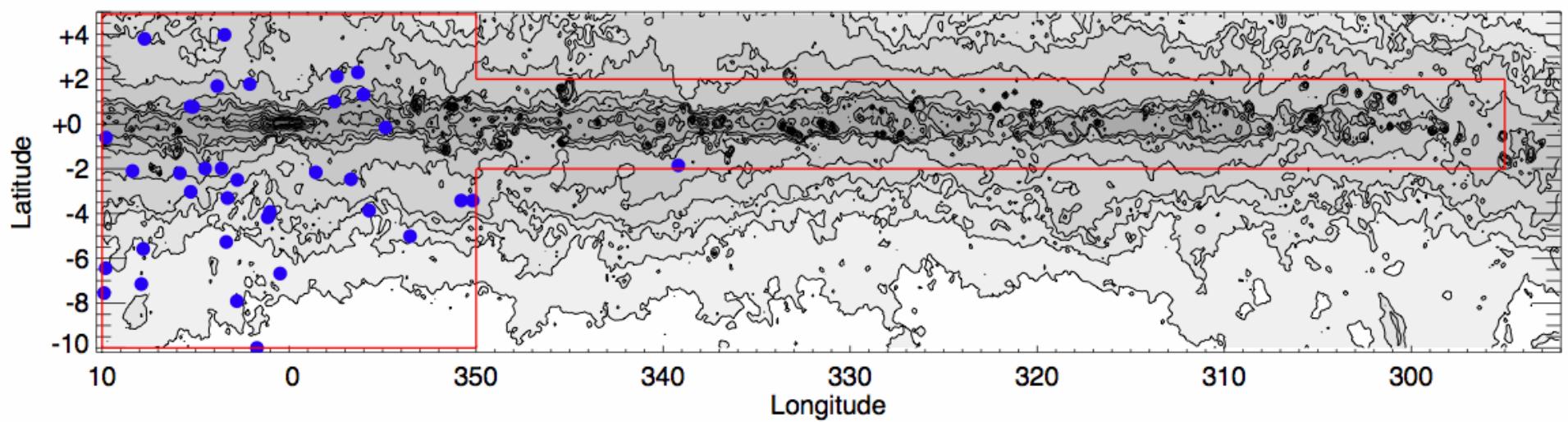
Conclusions

- VVV goldmine - changing census of BGCs
- Are dual RC BGCs BBBs?
- Need deep IR photometry for ages
- IR CaT technique is excellent for good mets, vels
- Revolutionize knowledge of BGCs shortly

Happy Birthday Tololo!
and many more to come...

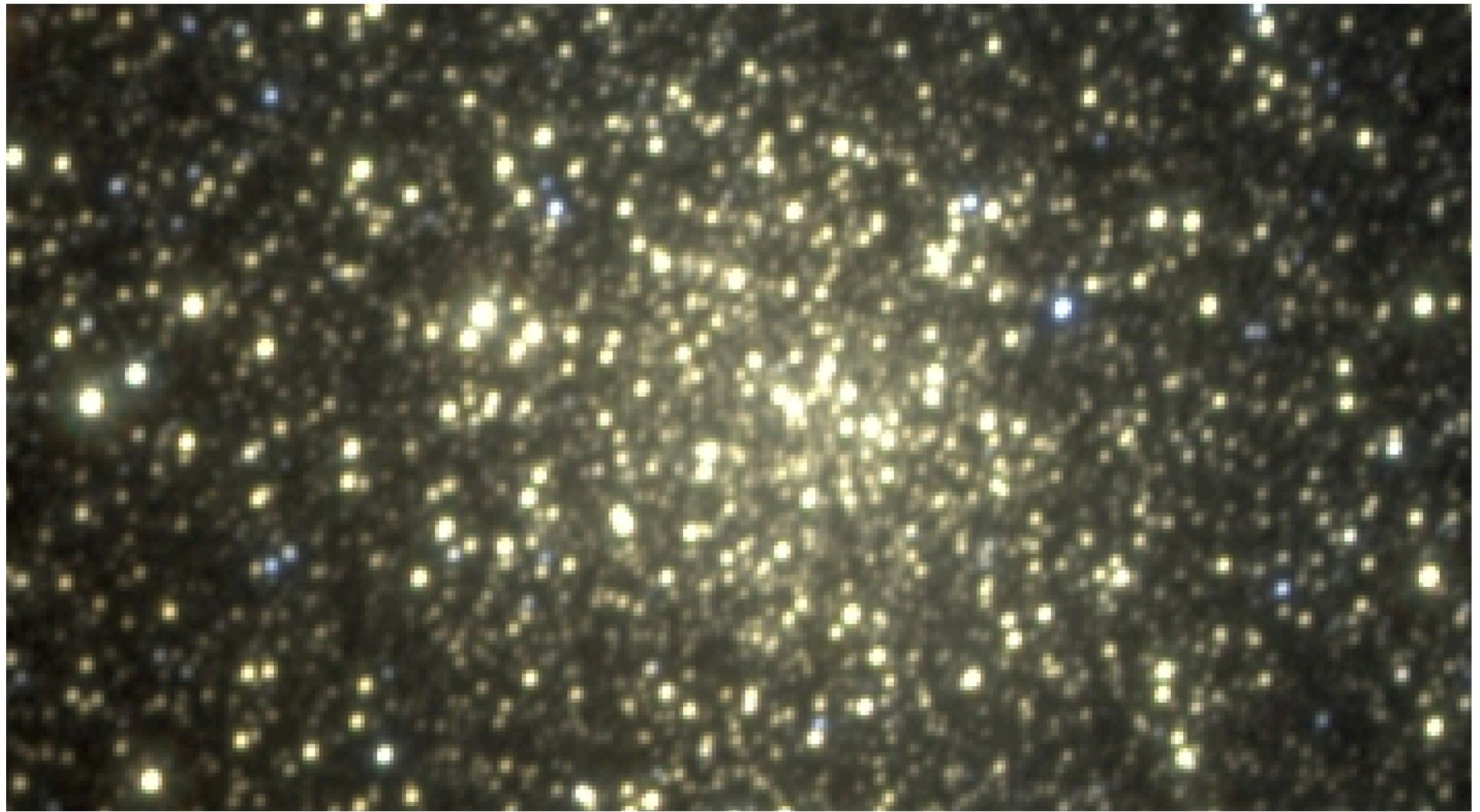


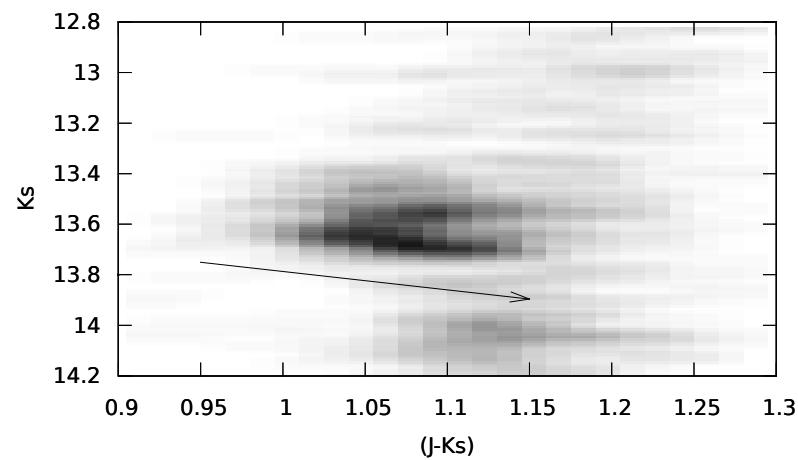




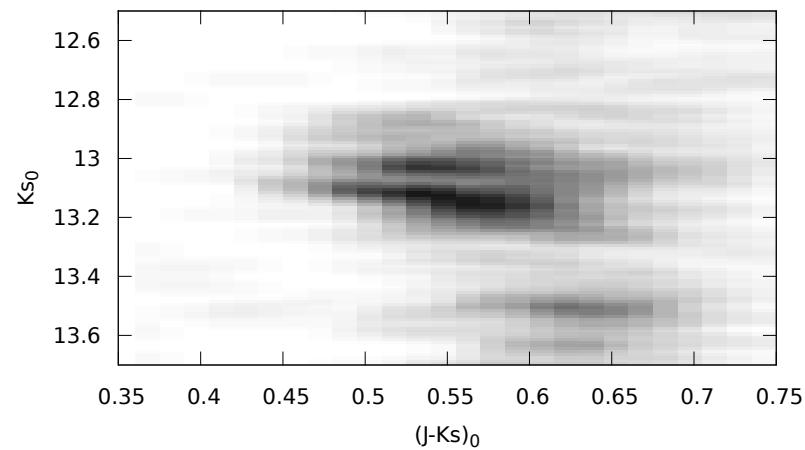


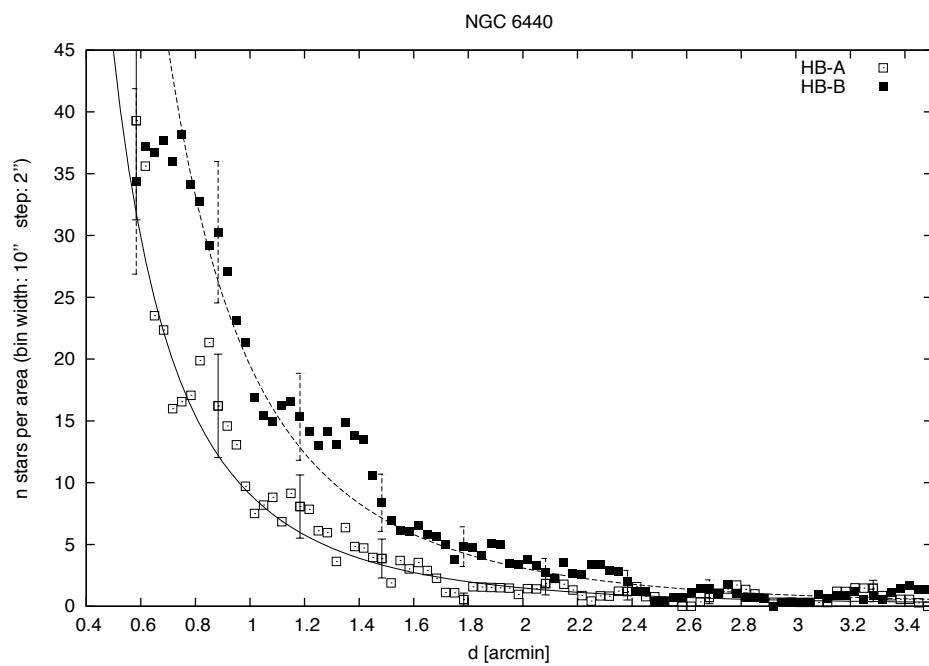
UKS1

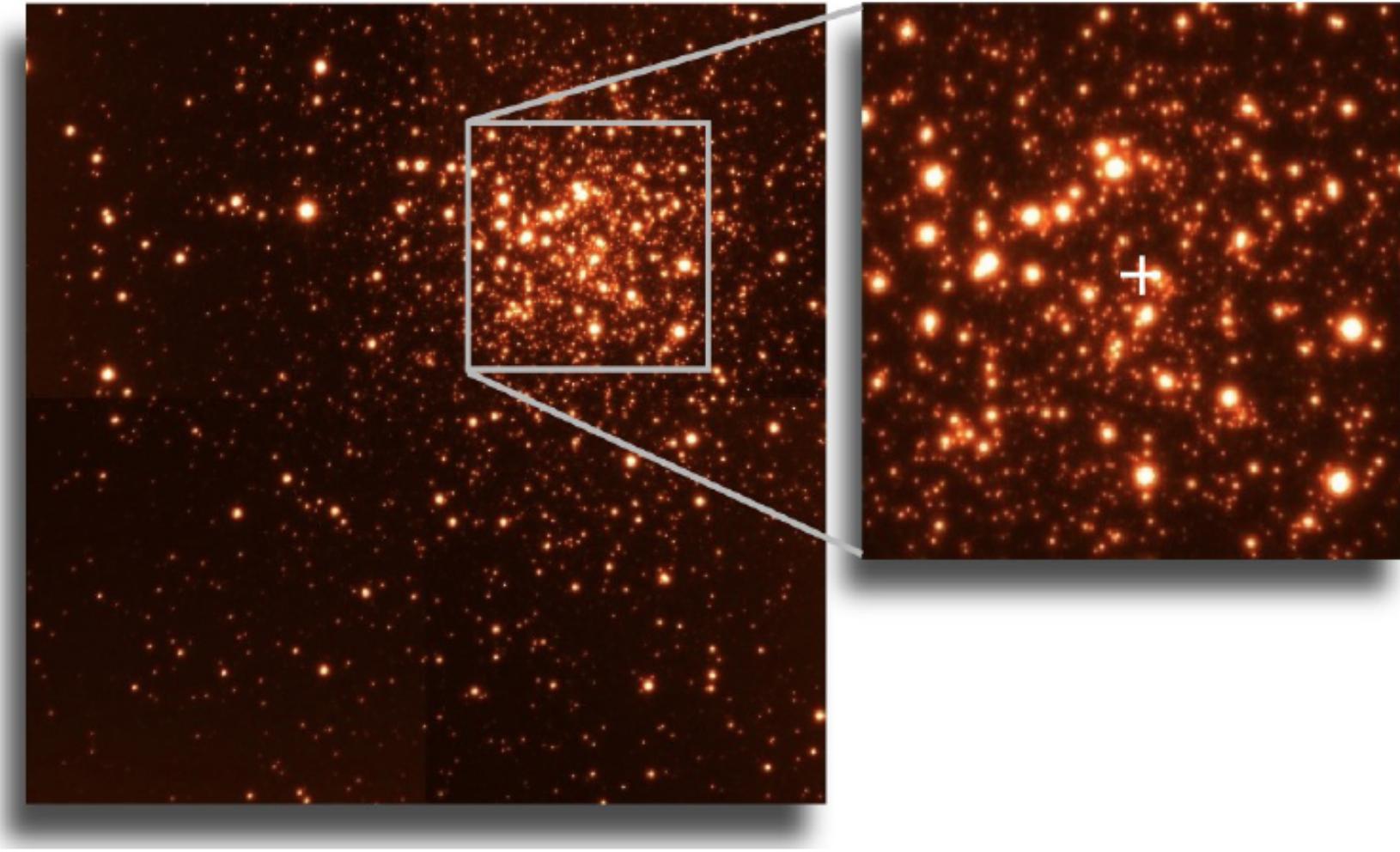




N6440...



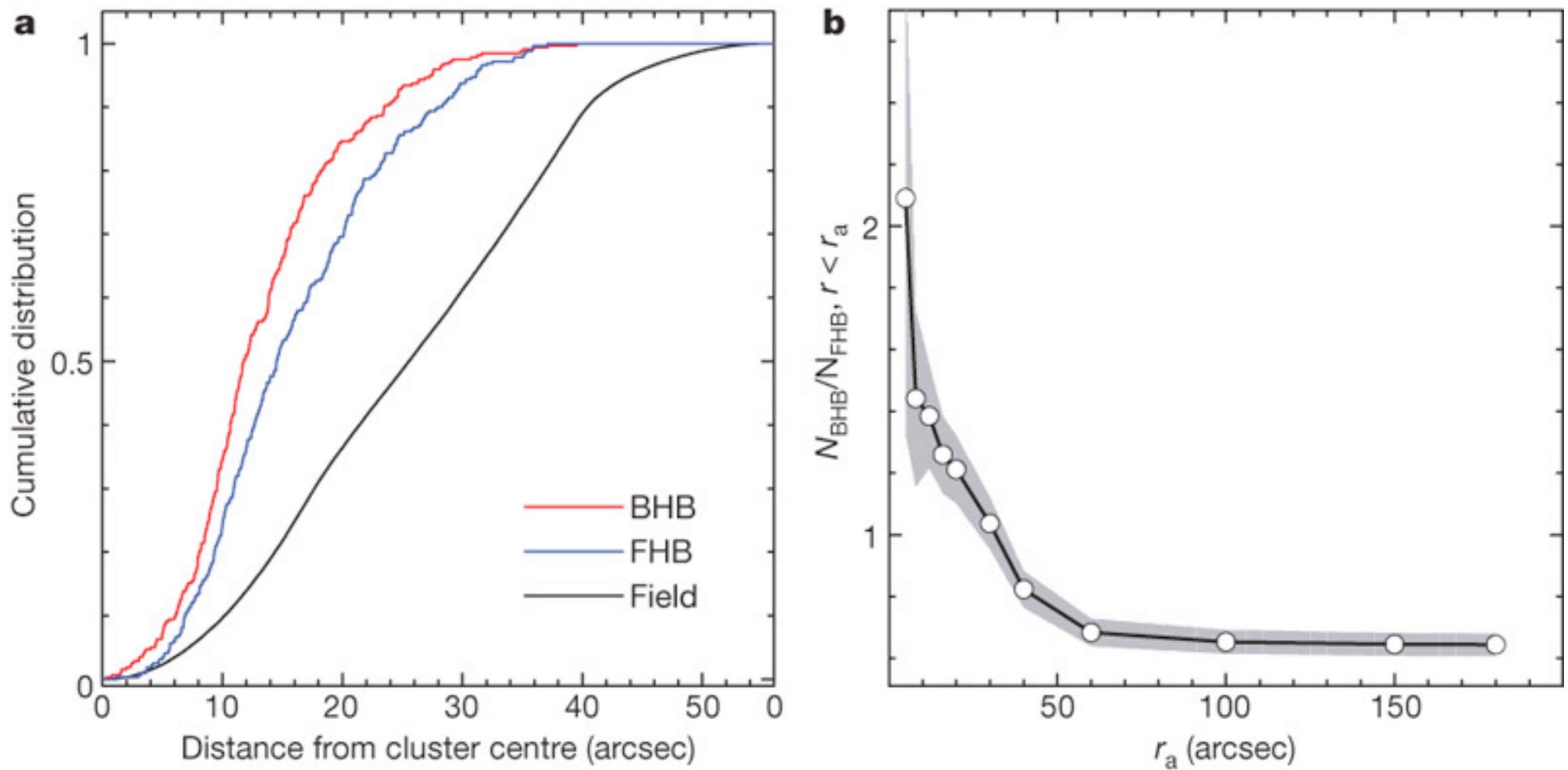




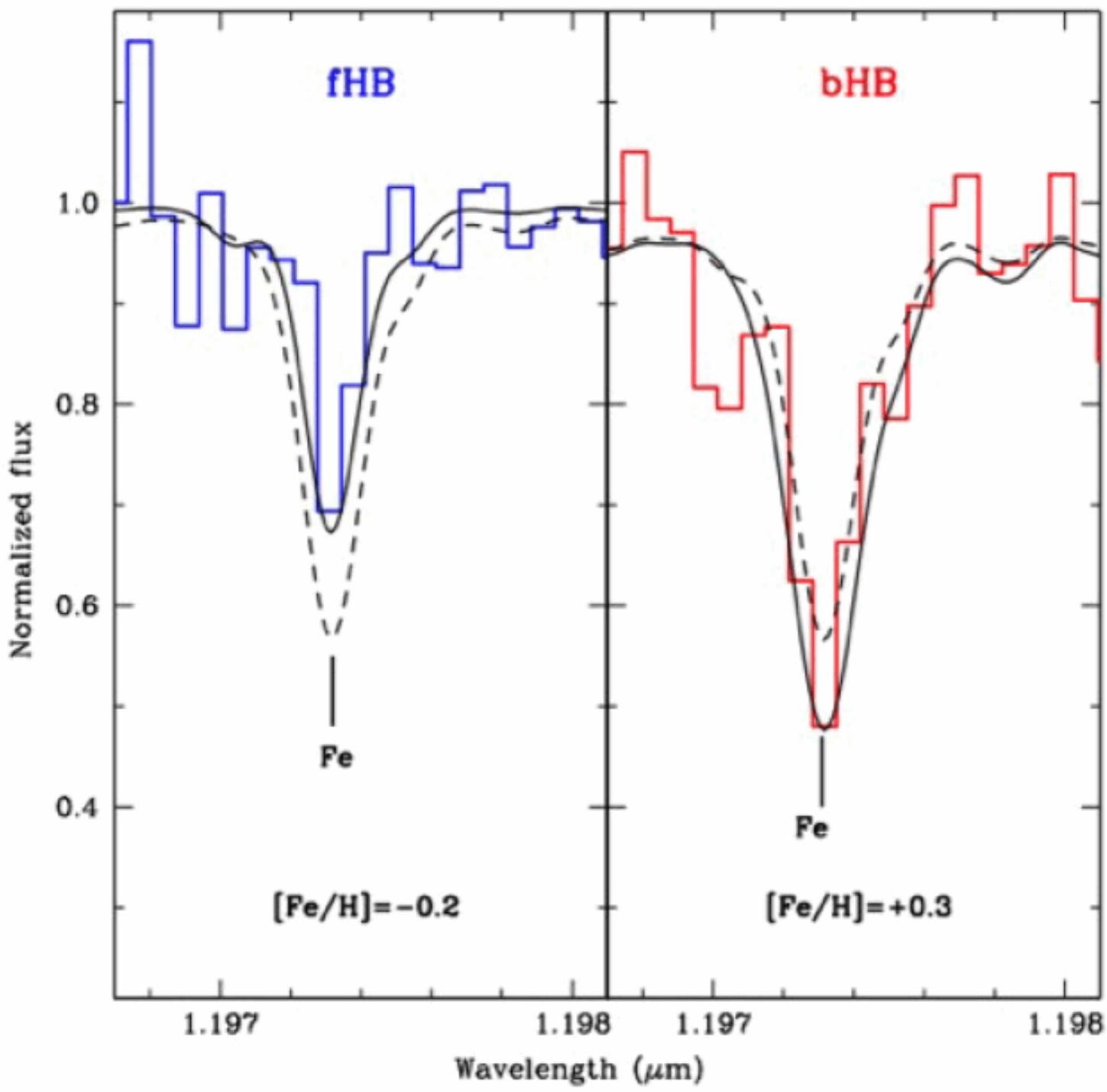
Terzan 5: MCAO 0.1" K - Ferraro et al. (2009)

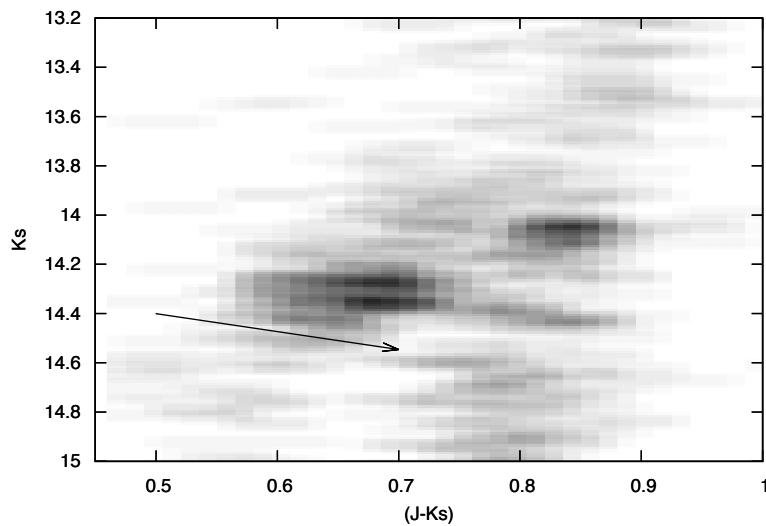
Fig. 1. MAD image of Terzan 5 in the *K* band. Observations were performed at the ESO-VLT (Paranal, Chile) on August 2008, through *J* and *K* filters. Exposure times were about two minutes in each filter. Shown is the best image obtained in the *K* band (the image size is 1'x1', north is up, east is left). The

Ferraro et al. (2009):

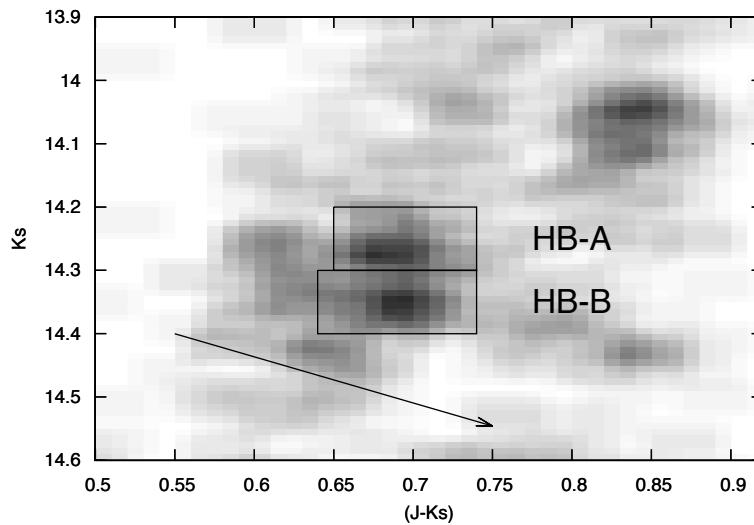


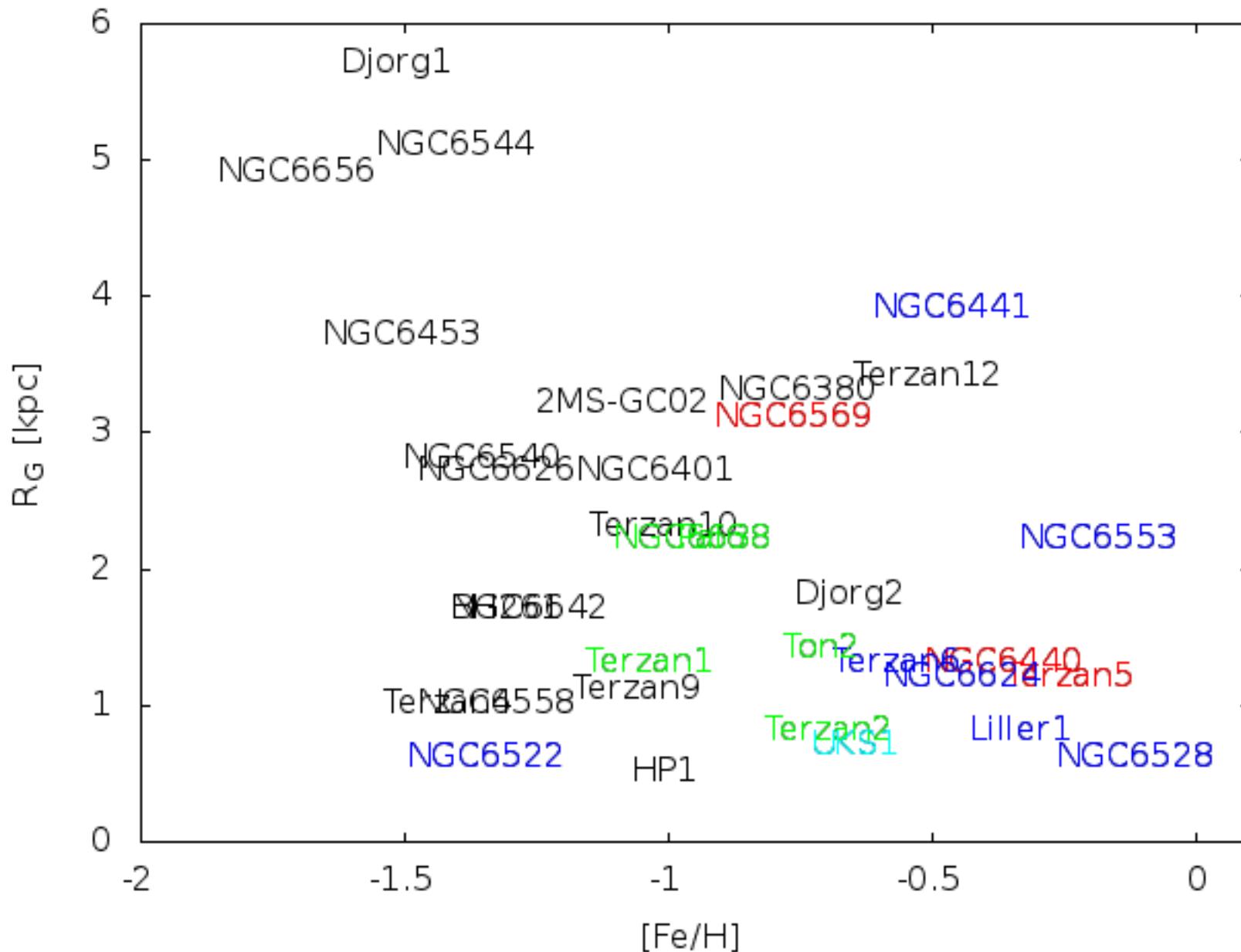
- BHB more centrally concentrated than FHB! BHB disappears $>50''$
- Spectra suggest BHB has $[\text{Fe}/\text{H}] \sim +0.3!!$, FHB $\sim -0.2!!$
- Not enough to explain ΔK – also require BHB $\sim 6\text{Gyr}$, BHB $\sim 12\text{Gyr}$
- Ω Cen of the bulge! – remnant nucleus of dwarf galaxy...



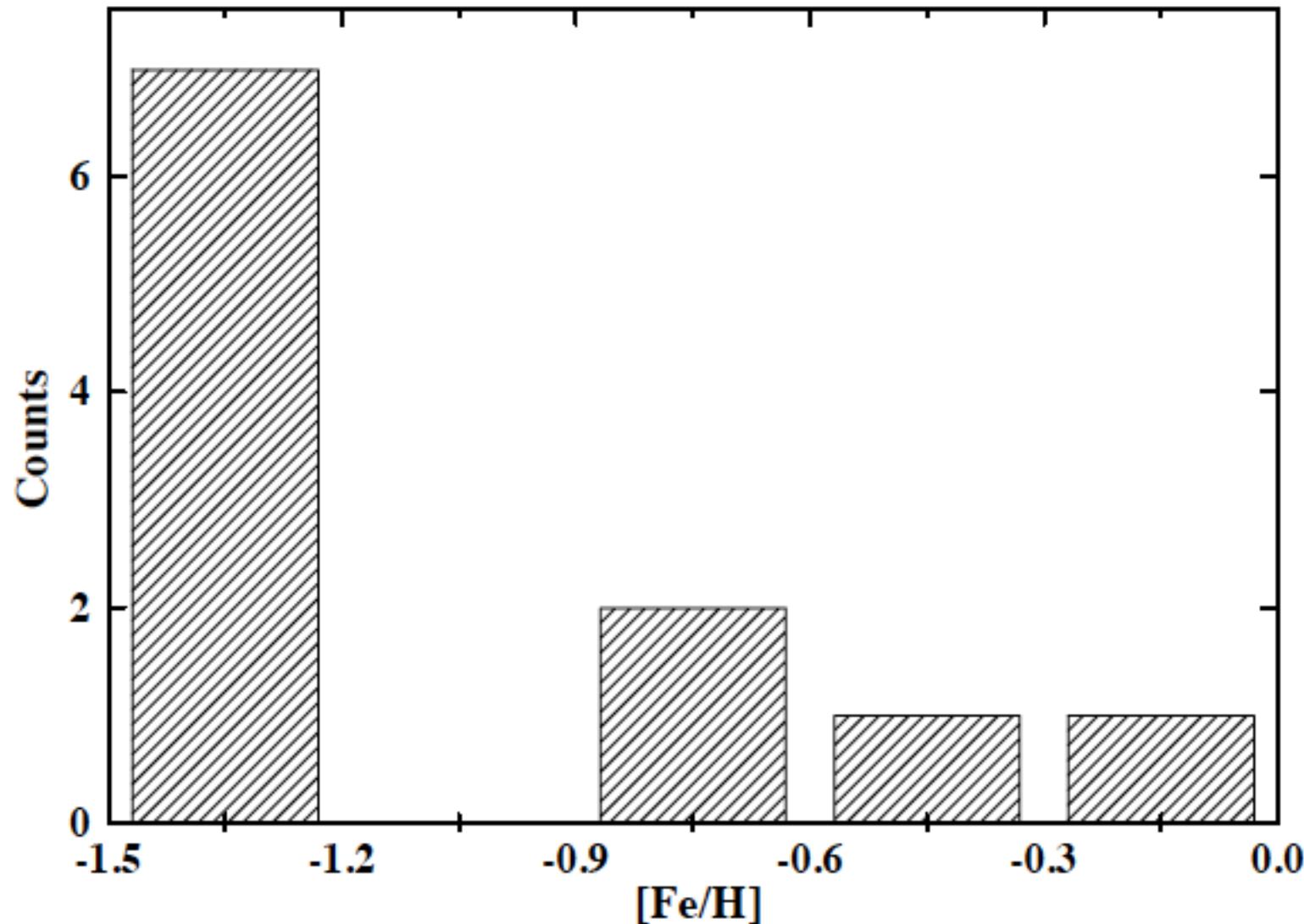


N6569...



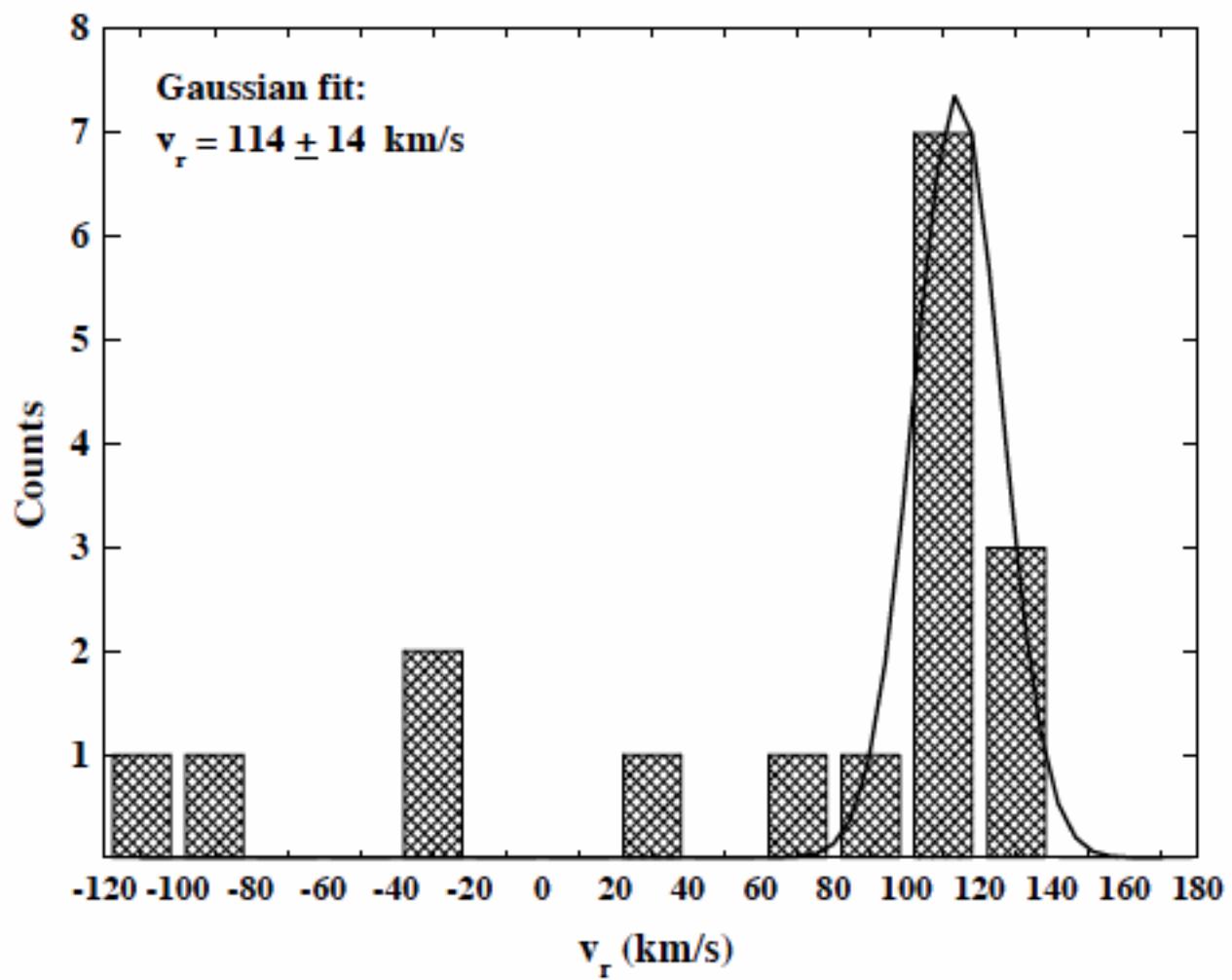


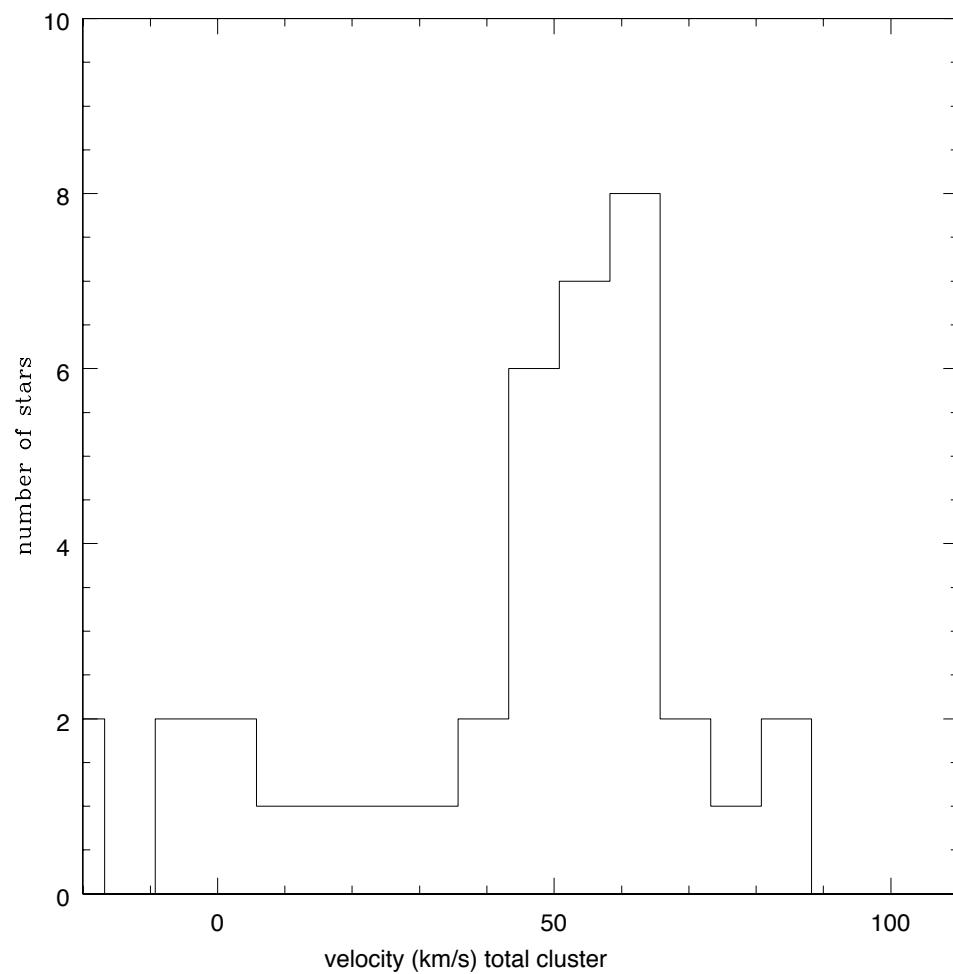
Hard to derive abundances for large sample...



Idiart et al. (2002) T1: heavy field contamination!

Typical error 0.2dex, $\langle \text{[Fe/H]} \rangle = -1.27 \pm 0.05$ for 11 velocity members





Valenti et al. 2010: Terzan IR phot. [Fe/H]=-1.11

