Globular Clusters with the Extended Horizontal-Branch as Remaining Cores of Galaxy Building Blocks

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Formation of the MW Galaxy: Milestones

1. ELS 1962; Larson 1974 (Collapse)
2. Searle & Zinn 1978; Toomre 1977 (Accretion)
3. Zinn 1993; van den Bergh 1993 (Collapse+Accretion)
4. Sagittarius dwarf, halo substructures, ΛCDM simulations...
5. Remaining question:

   Where are the building blocks predicted by ΛCDM?

   → "Missing satellites" problem (Moore+99; Klypin+99)

   → Early reionization could alleviate part of the problem (Bullock+00)

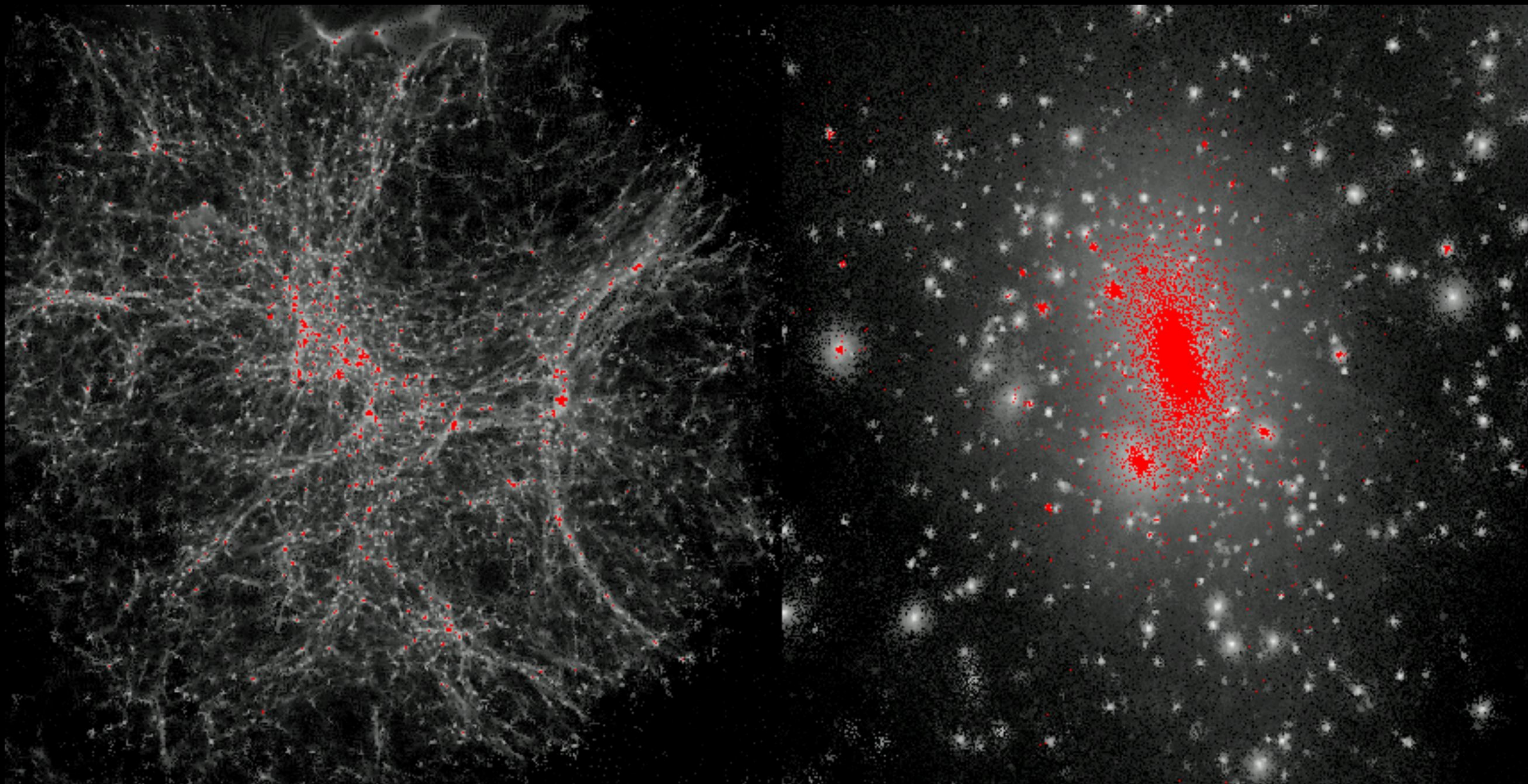
   → But stellar halo & bulge are there…

   dSph's appear to have little to do with halo formation (e.g., [α/Fe]).

   Where are the relicts of building blocks that formed Galaxy?

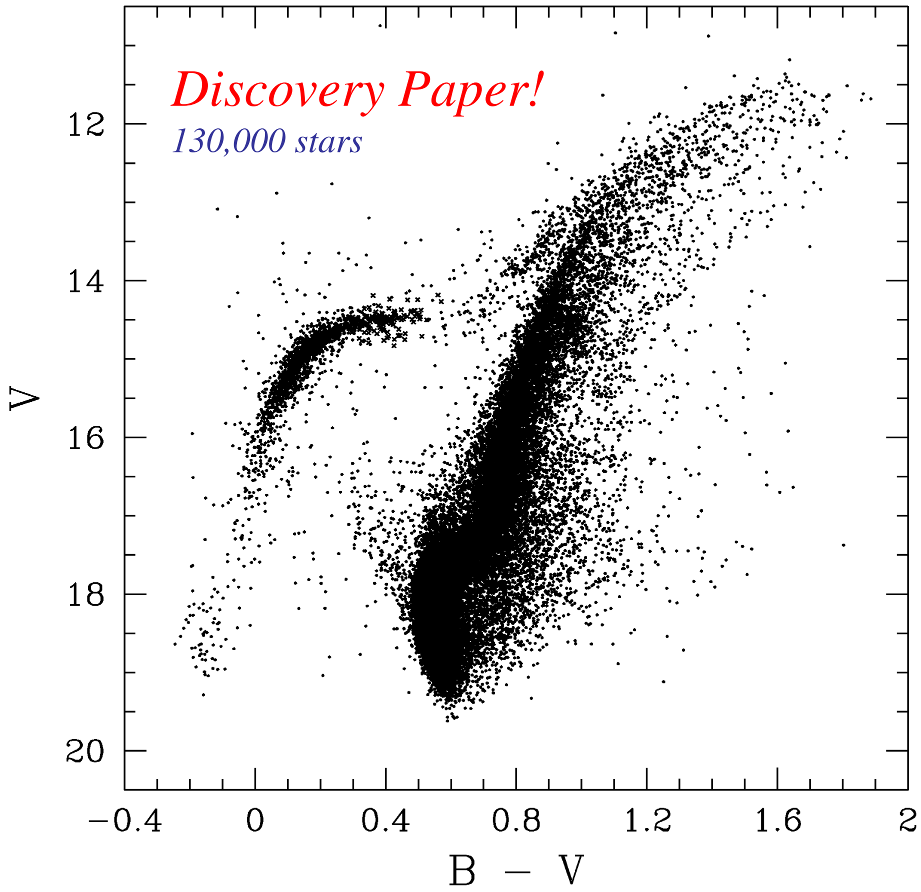
The Milky Way Then and Now

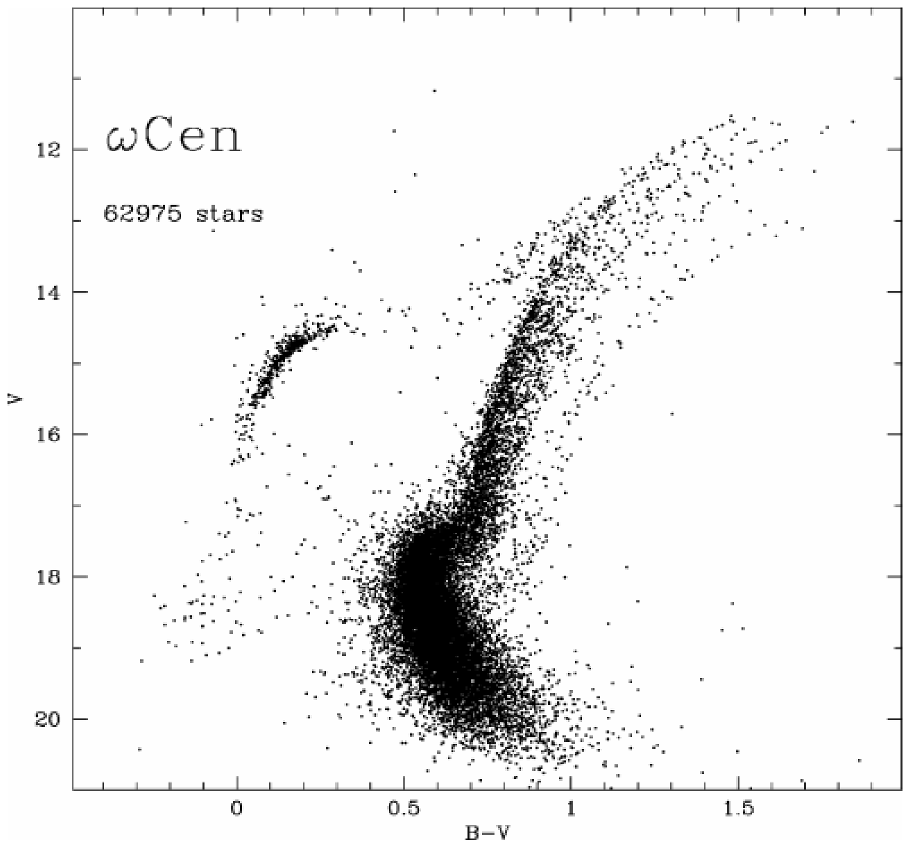
0.4 Gyr old ($z = 10$) 13.4 Gyr old ($z = 0$)



Courtesy Ben Moore
University of Zurich

Clues from the Multiple Populations in ω Cen



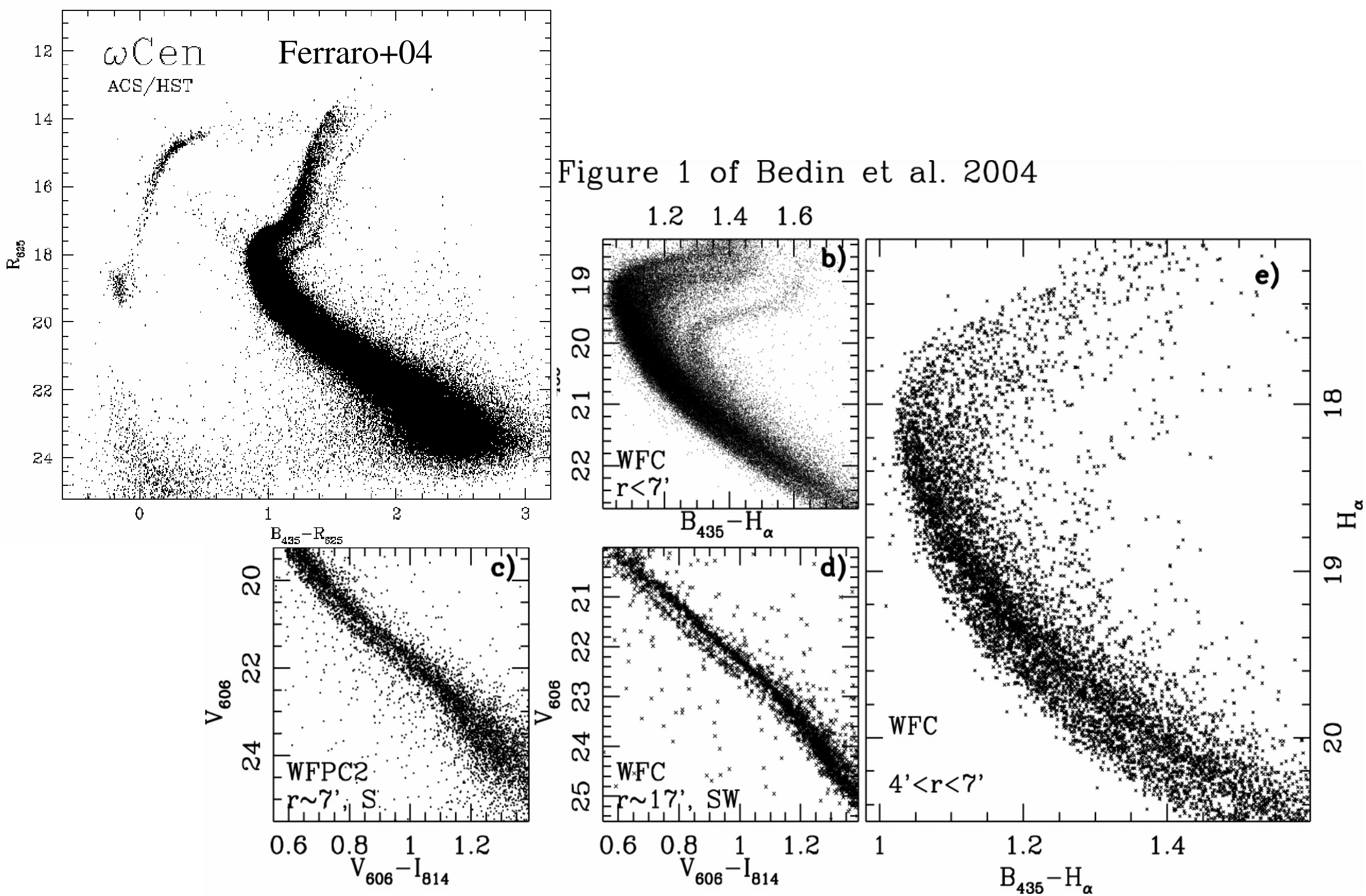


CTIO **0.9m + 760** frames!
Lee, Rey, Sohn et al. 1999, Nature, 402, 55

"This was the first time that multiple populations were found in a GC."

VLT **8.2m + ~ 30** frames
Sollima, Ferraro et al. 2005
(see also Pancino+2000)

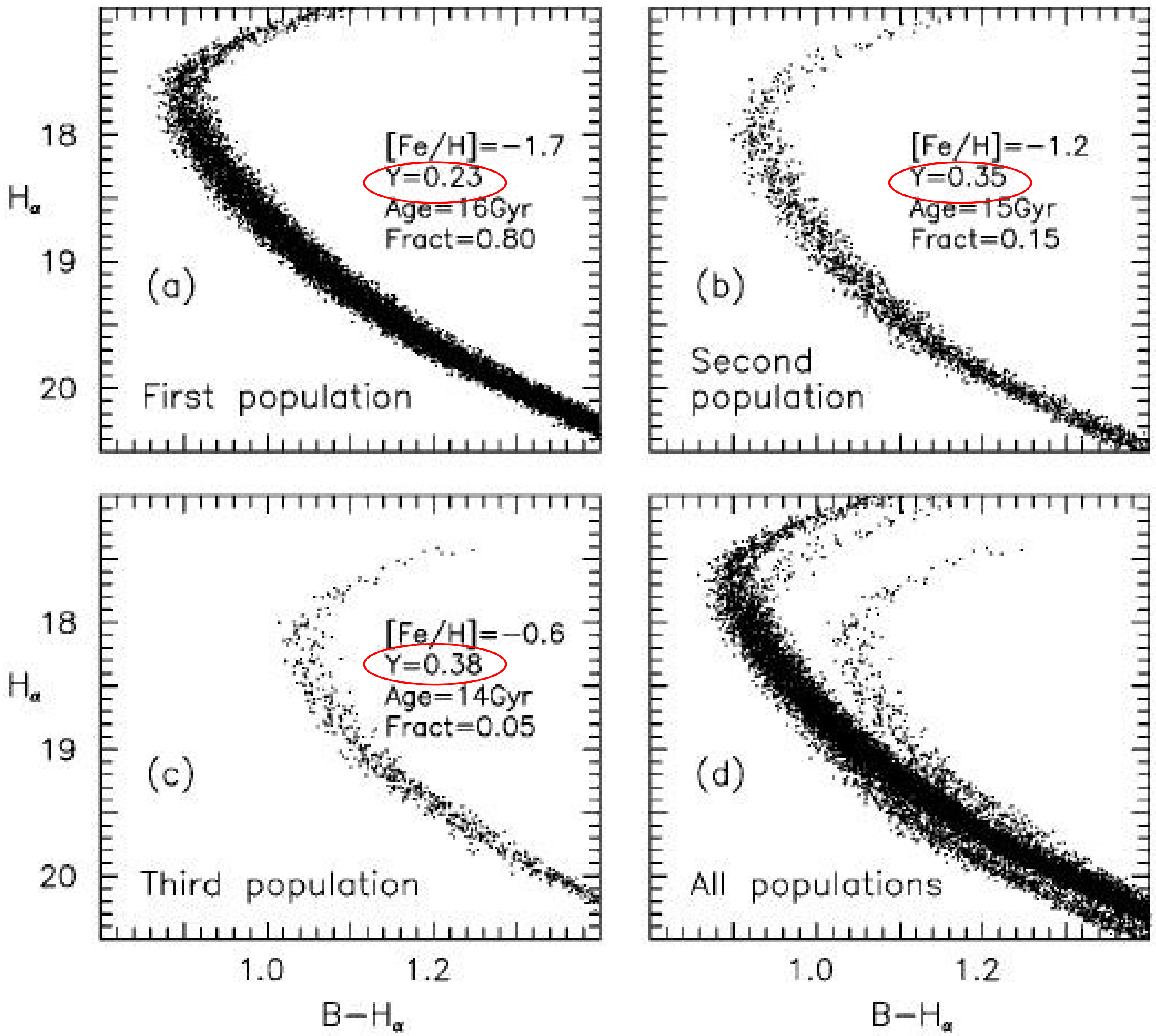
Recent HST Observations of ω Cen



Presence of Double Main Sequence!

Super-He-rich Subpopulations in ω Centauri

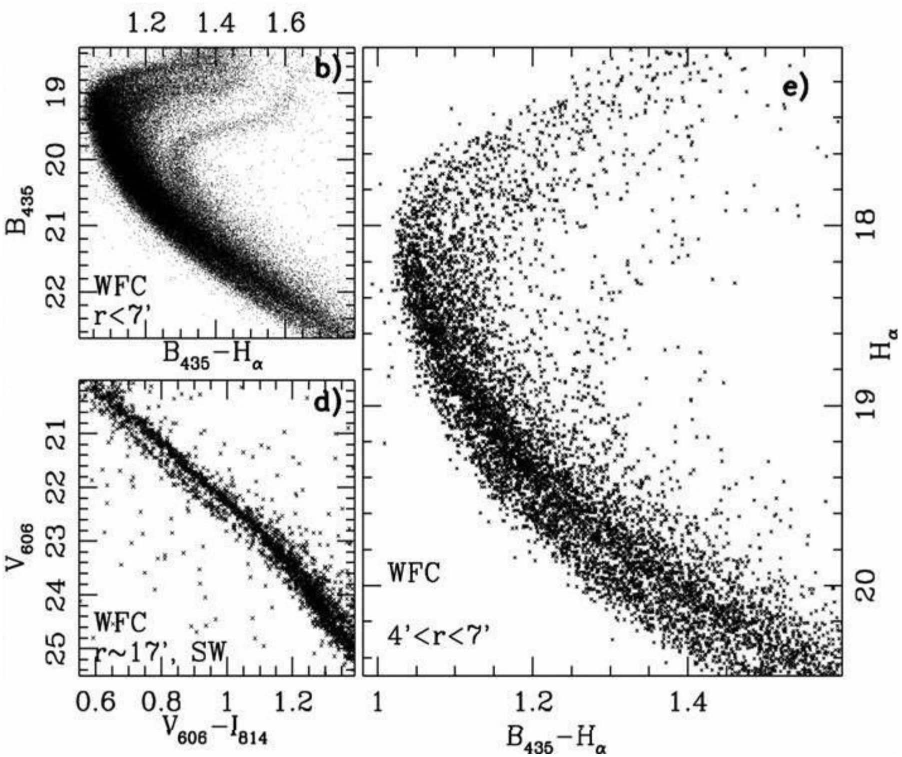
Analysis based on the old (1987) Yale Isochrones



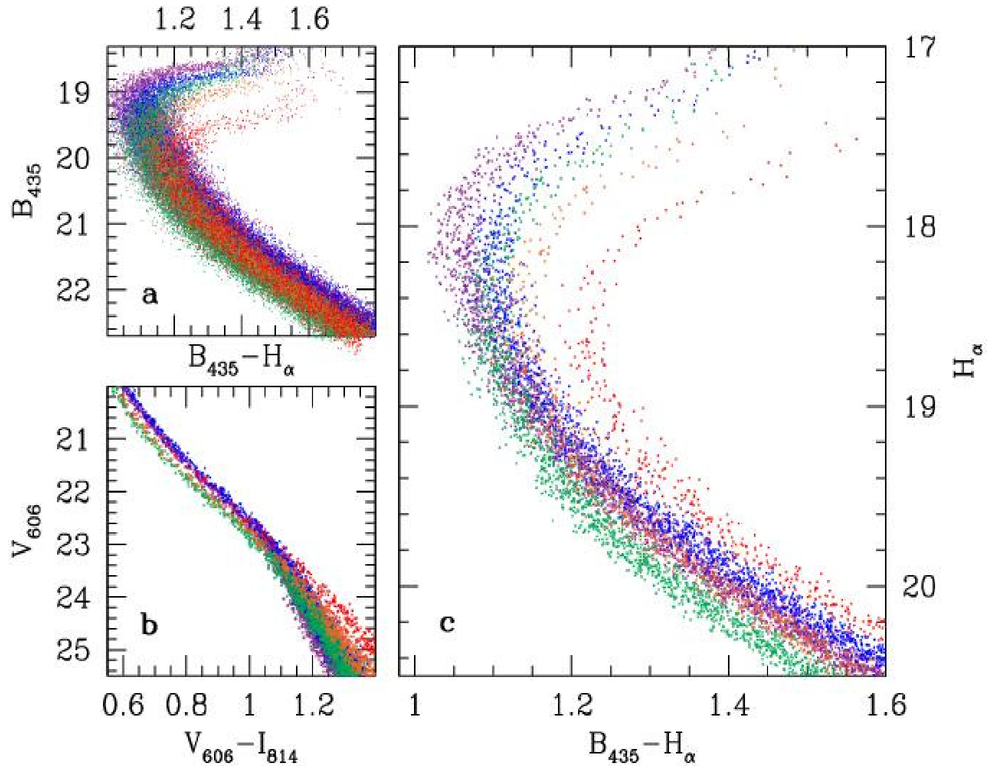
Norris 2004

Super-He-rich Subpopulations in ω Centauri

Evidence from MS & New Y^2 Isochrones



Observation: Bedin et al. 2004



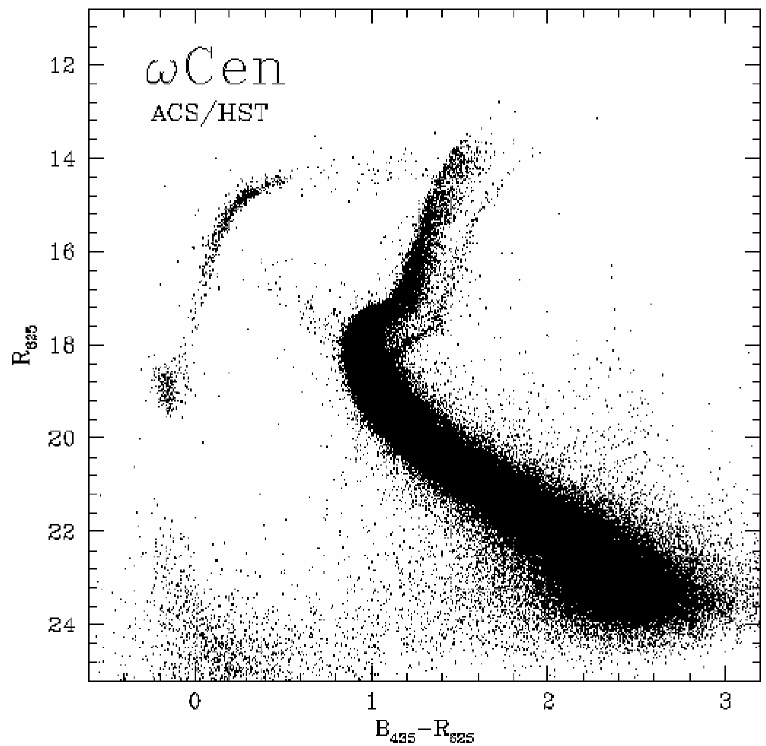
Model: Lee et al. 2005

See also
Norris 04; Piotto+05;
Sollima+06

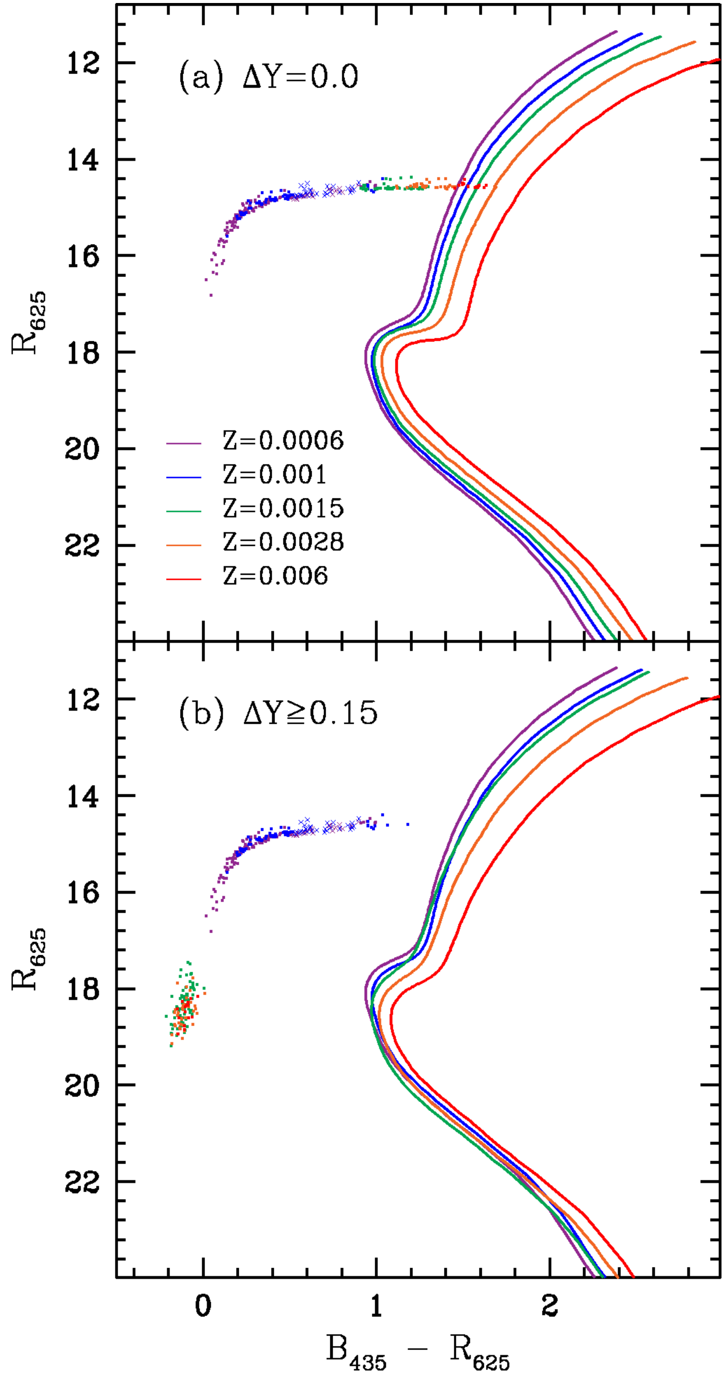
Population	Z	Y	Age [Gyr]	Fraction
—	0.0006	0.231	13	0.42
—	0.001	0.232	13	0.27
—	0.0015	0.38	12	0.17
—	0.0028	0.40	11.5	0.08
—	0.006	0.42	11.5	0.05

Super-He-rich Subpopulations in ω Centauri

Evidence from Extended HB

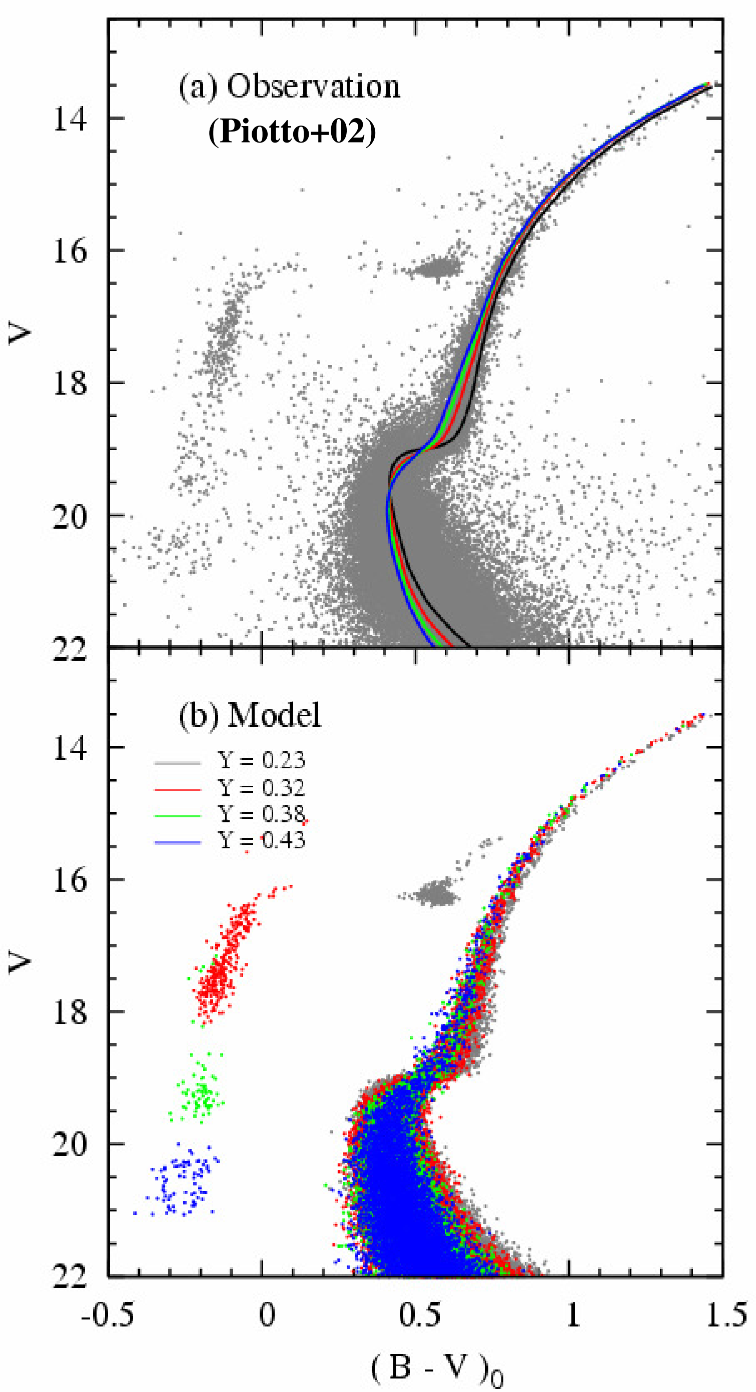


Observation:
Ferraro et al. 2004



Model:
Lee et al. 2005

Super-He-rich Subpopulations in NGC 2808
Evidence from Extended HB & MS



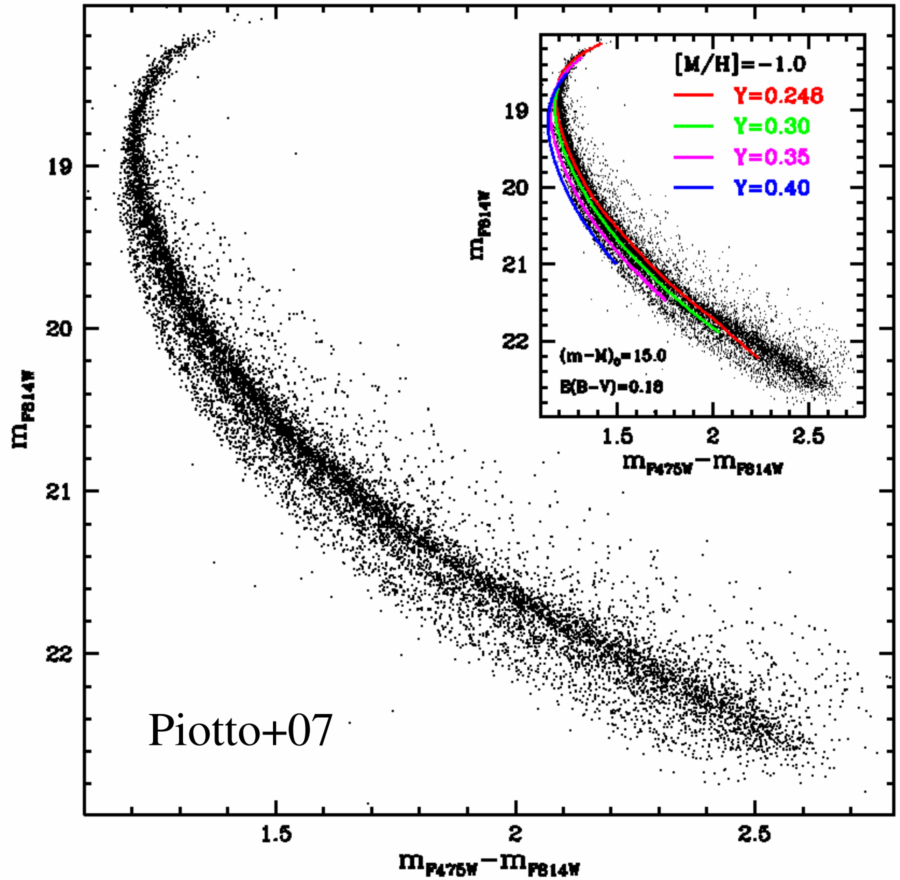


Fig. 2.— A zoom of the proper-motion-selected, differential-reddening-corrected CMD of the right-hand panel of Fig. 1. In the inset the observed CMD is fitted with four 12.5 Gyr isochrones, with different He content.

Lee+05 Prediction: EHB is a strong signature of the presence of multiple populations in a GC!
(see also D'Antona+05)

Super-He-rich Subpopulations in EHB Globular Clusters

1. D'Antona & Caloi 2004: from HB models of NGC 2808
2. Bedin, Piotto+2004: double MS of ω Cen
3. Norris 2004: from MS models of ω Cen
4. Lee+2005: HB and MS-RGB models of ω Cen & NGC 2808, UV photometry of EHB stars
5. Piotto+2005: Spectroscopy of MS stars in ω Cen
6. D'Antona, Caloi, Fusi Pecci, Rood+2005: MS photometry of NGC 2808
7. Sollima, Ferraro+2006, 2007: MS photometry of ω Cen
8. Moehler & Sweigart 2006: Spectroscopy of BHB stars in NGC 6388
9. Yoon+2007: from HB shapes & RR Lyrae periods of NGC 6388/6441 (see also Caloi & D'Antona 07; Catelan+06; Moehler & Sweigart 06; Pritzl+02)
10. Piotto+2007: MS photometry of NGC 2808
11. Castellani+07: Star counts of ω Cen
12. …

Where does the Helium come from?

1. Ejecta from AGB stars of 4-6$M_{\odot}$ (D'Antona & Caloi 04)
2. Wind from massive rotating stars (Maeder & Meynet 06)
3. Mini SNe (Piotto et al. 05): "Mass of ω Cen was just right to allow the ejecta of high-mass SNe to escape, while retaining the ejecta of ~10$M_{\odot}$ SNe"

Origin of He-enhancement is not fully understood yet, although this appears to be a consequence of more than one epoch of star formation.

Significant fraction of He-enriched subpopulation (> 25%, ω Cen & NGC 2808) is not easily reproduced from the yields of 1st generation (normal He) without ad-hoc assumptions! (Bekki & Norris 06; Karakas+06; Choi & Yi 07; Romano+07)

→ We may need to consider different environments, such as central regions of dwarf galaxies!

GCs with "extended HB (EHB)" as remaining cores of disrupted "building blocks"?

1. Origin of He-enrichment?: Significant fraction of He-enriched subpopulation is only possible at the core of ancient dwarf galaxy! (Bekki & Norris 06; Bekki 06; Romano+07)

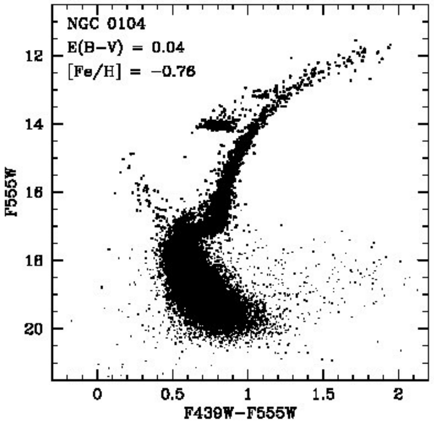
   NB. Radial gradient of extreme HB & blue MS! (Rey+04, Sollimar+06)
2. Hints from ω Cen, M54, NGC2419, & G1: They are suspected as cores of disrupted dwarfs (Freeman 93; Sarajedini & Layden 95; Lee+99; Meylan+01; Bekki & Freeman 03), and they all have EHB!
3. Working hypothesis: GCs with EHB as remaining cores of disrupted building blocks (dwarfs, satellites, subsystems)?
4. Survey of 114 GCs with good CMDs suggests ~28 (~25%) have EHB! (Lee+07)
5. LF, kinematics & other properties of EHB GCs?

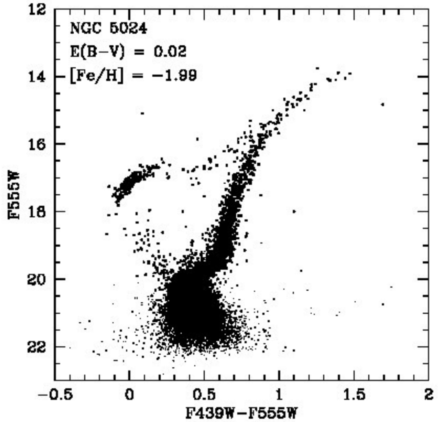
Classification of GCs with EHB

(CMD from Piotto+02 & Y.-W. Lee's compilation w/ H.-Y. Lee)

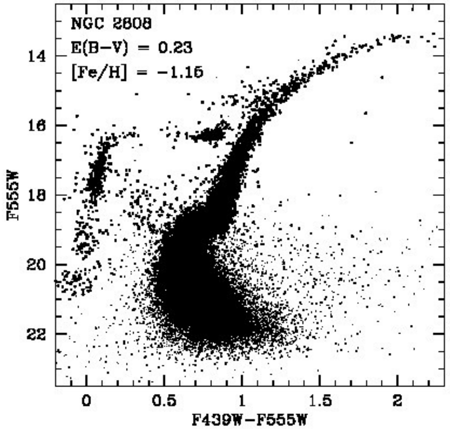
~ 25% (28/114) of Milky Way GCs have Extended HB (EHB)!

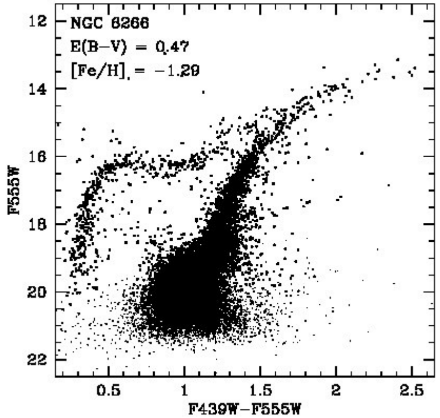
- **Normal HB**





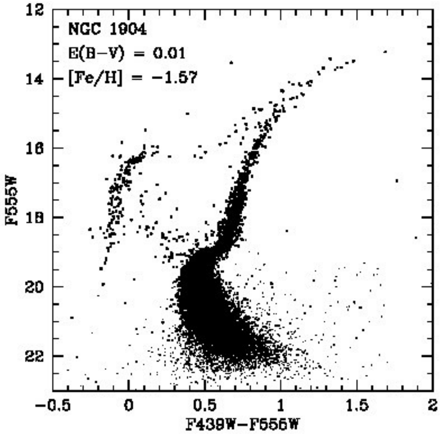
- **Strongly EHB** ($\Delta V_{HB} \geq 3.5$)

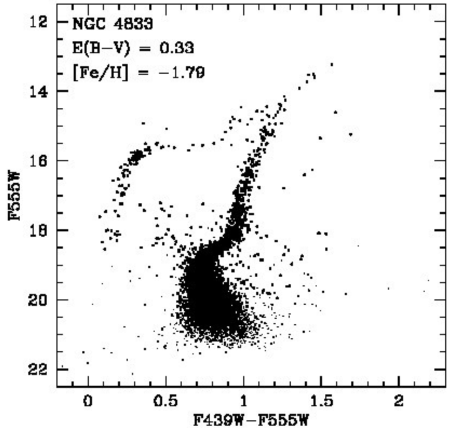




- **Moderately EHB**

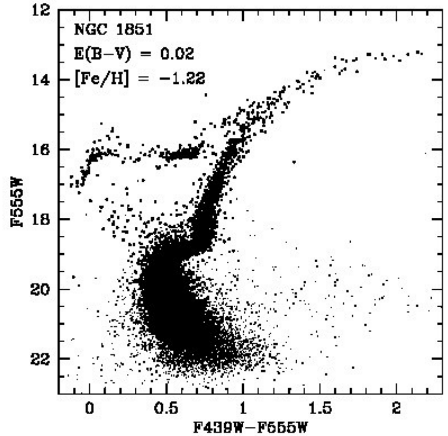
($3.0 \leq \Delta V_{HB} < 3.5$ with gap or blue extension)

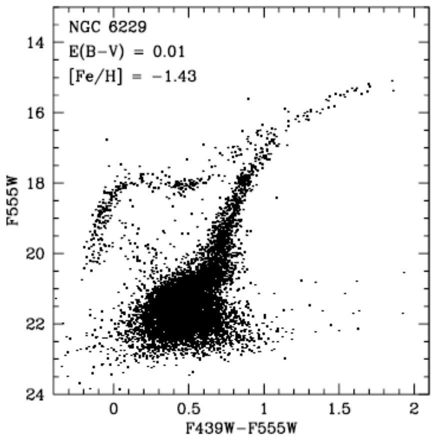




- **Bimodal HB**

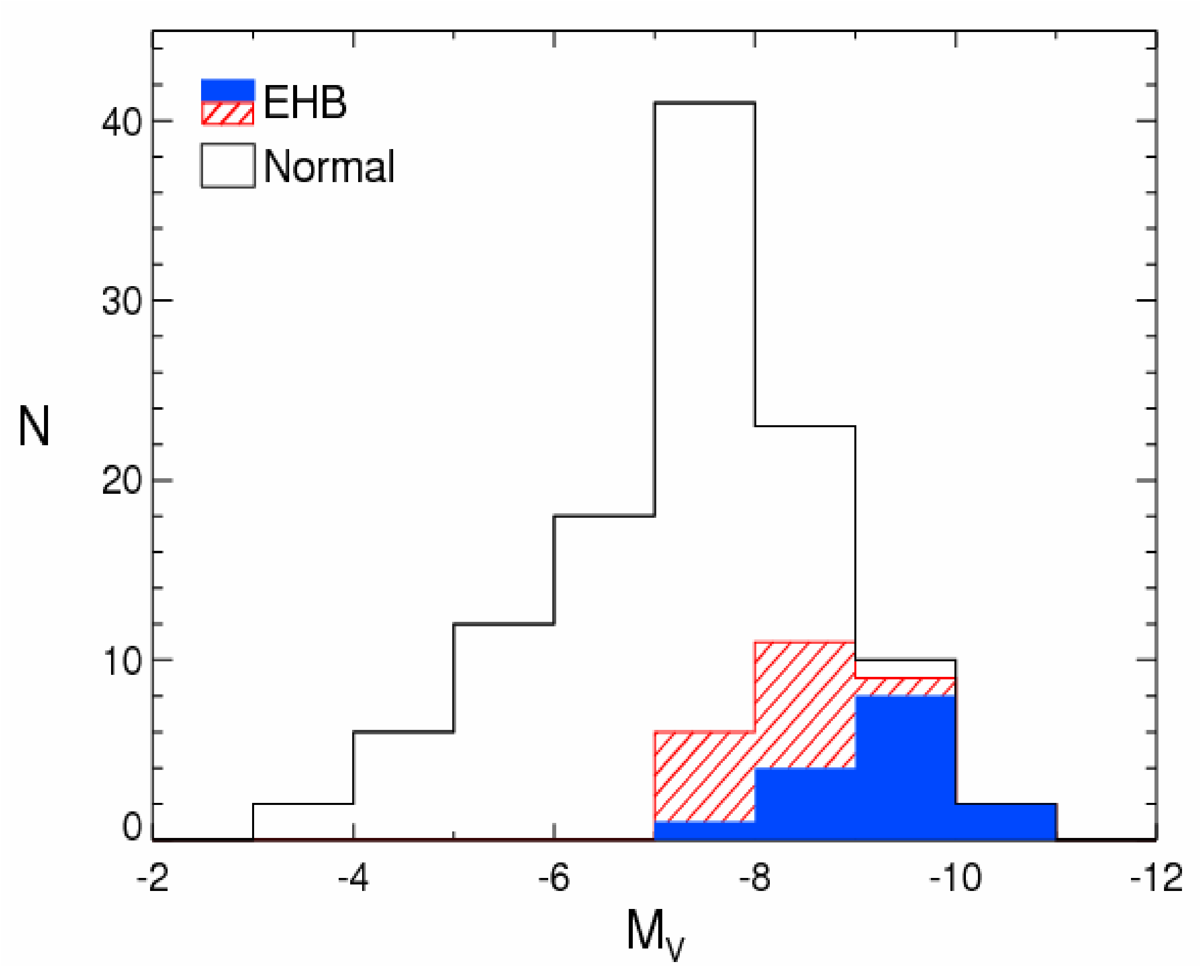
($\Delta(B-V)_{HB} \geq 0.78$ with clear color bimodality)





"Extended HB (EHB)" GCs are more massive than normal GCs!

(Lee, Gim & Casetti-Dinescu 2007, ApJ, 661, L49)



Early hints:
Fusi Pecci+1993
Ree+2002
Recio-Blanco+2006

NB.
1. Inferred mass of EHB GCs is comparable to low-luminosity dwarf galaxies.
2. Most GCs belonging to dwarf satellite galaxies are fainter than M_v = - 8 (Mackey+vdB 05) & have no EHB!

➔ EHB GCs might have a unique origin?

Subdivision of GCs for Kinematic Analysis

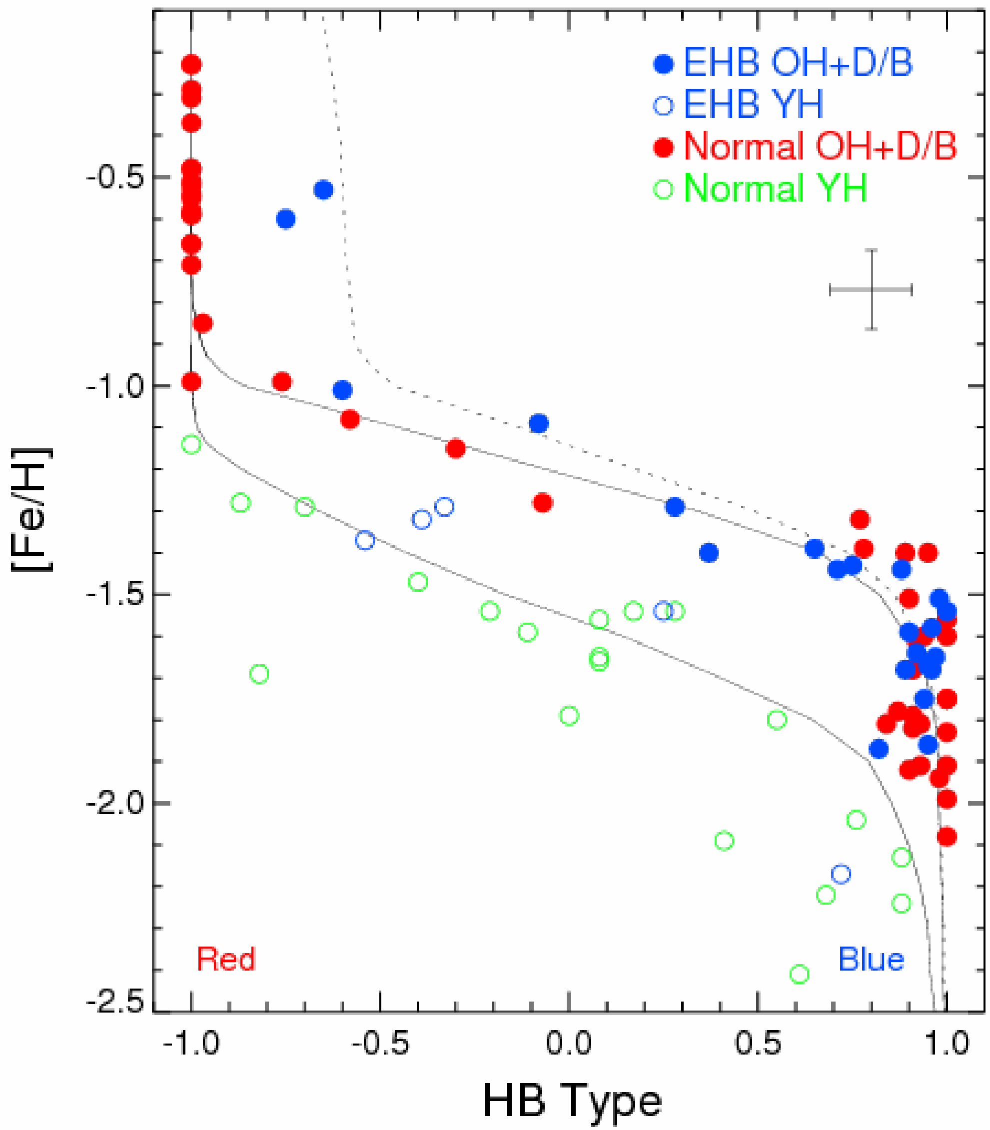
1. Following Zinn (1993):

Filled Circles = “Old Halo” (OH)
+ metal-rich “Disk/Bulge” (D/B)

Open Circles = “Young Halo” (YH)

The majority (80%) of OH GCs are in the inner halo (R_{gc} < 8Kpc), while most (94%) YH GCs are in the outer halo (R_{gc} > 8 Kpc).

2. Kinematics of GCs with & w/o EHB ?



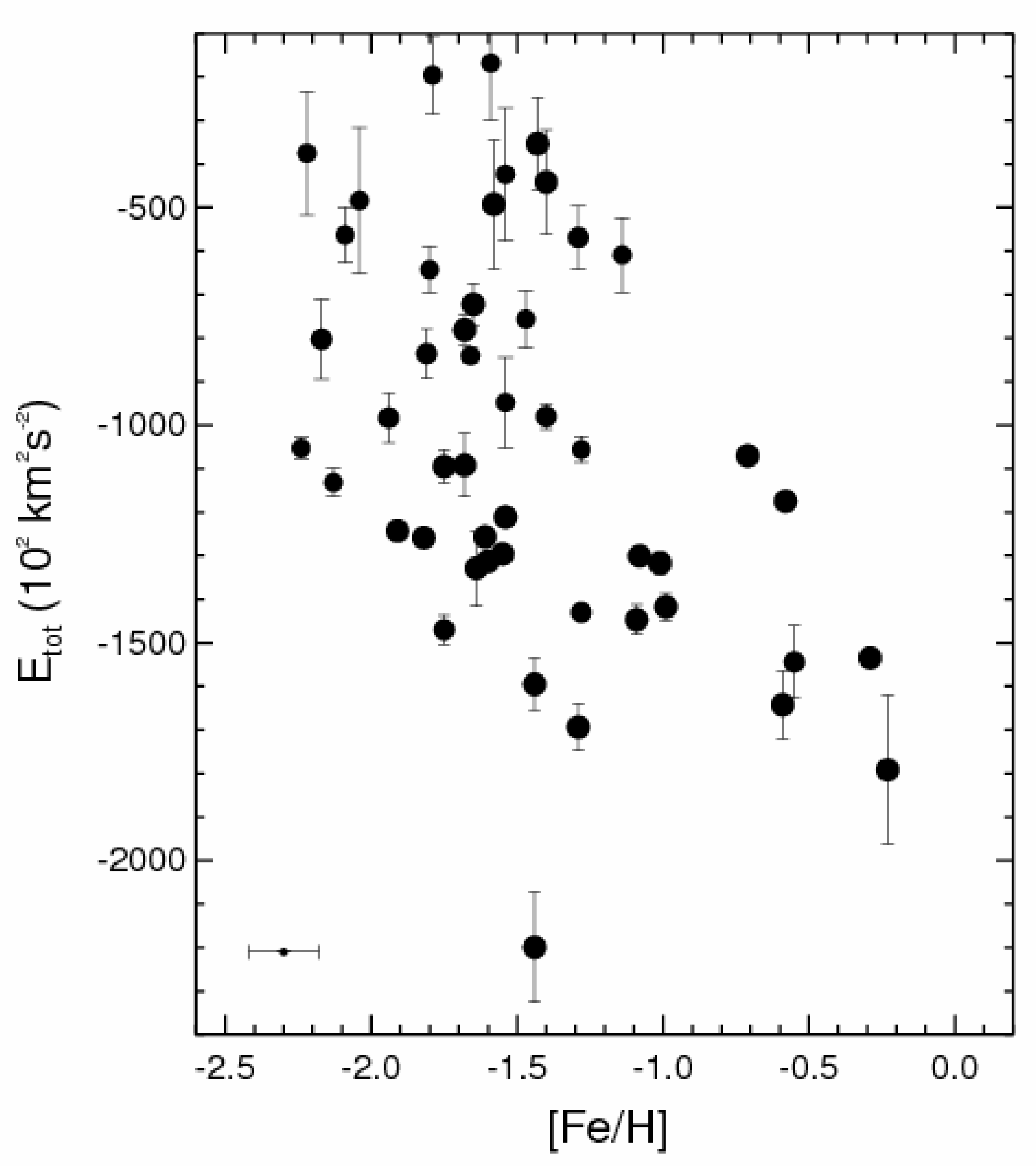
Based on Harris 2003 database

Kinematics of Globular Clusters based on Radial Velocity alone

Group	N	V_{rot} [km s^{-1}]	σ_{los} [km s^{-1}]	V_{rot}/σ_{los}
All GCs				
All Halo	**71**	**25±27**	**124±10**	**0.20±0.22**
YH	**25**	**-18±66**	**153±22**	**-0.12±0.43**
OH	**46**	**40±27**	**104±11**	**0.38±0.26**
D/B	**14**	**168±28**	**65±12**	**2.57±0.65**
EHB				
All EHB	**24**	**10±32**	**93±13**	**0.11±0.34**
OH	**18**	**4±35**	**91±15**	**0.05±0.38**
Normal GCs				
All Halo	**48**	**32±39**	**137±14**	**0.24±0.29**
YH	**20**	**-42±80**	**162±26**	**-0.26±0.49**
OH	**28**	**70±39**	**111±15**	**0.63±0.36**
D/B	**13**	**188±22**	**48±9**	**3.94±0.89**
Normal (M_V < -6)				
All Halo	**39**	**37±44**	**139±16**	**0.26±0.32**
YH	**17**	**-69±81**	**160±27**	**-0.44±0.51**
OH	**22**	**105±42**	**103±15**	**1.02±0.43**
D/B	**11**	**195±27**	**52±11**	**3.76±0.95**

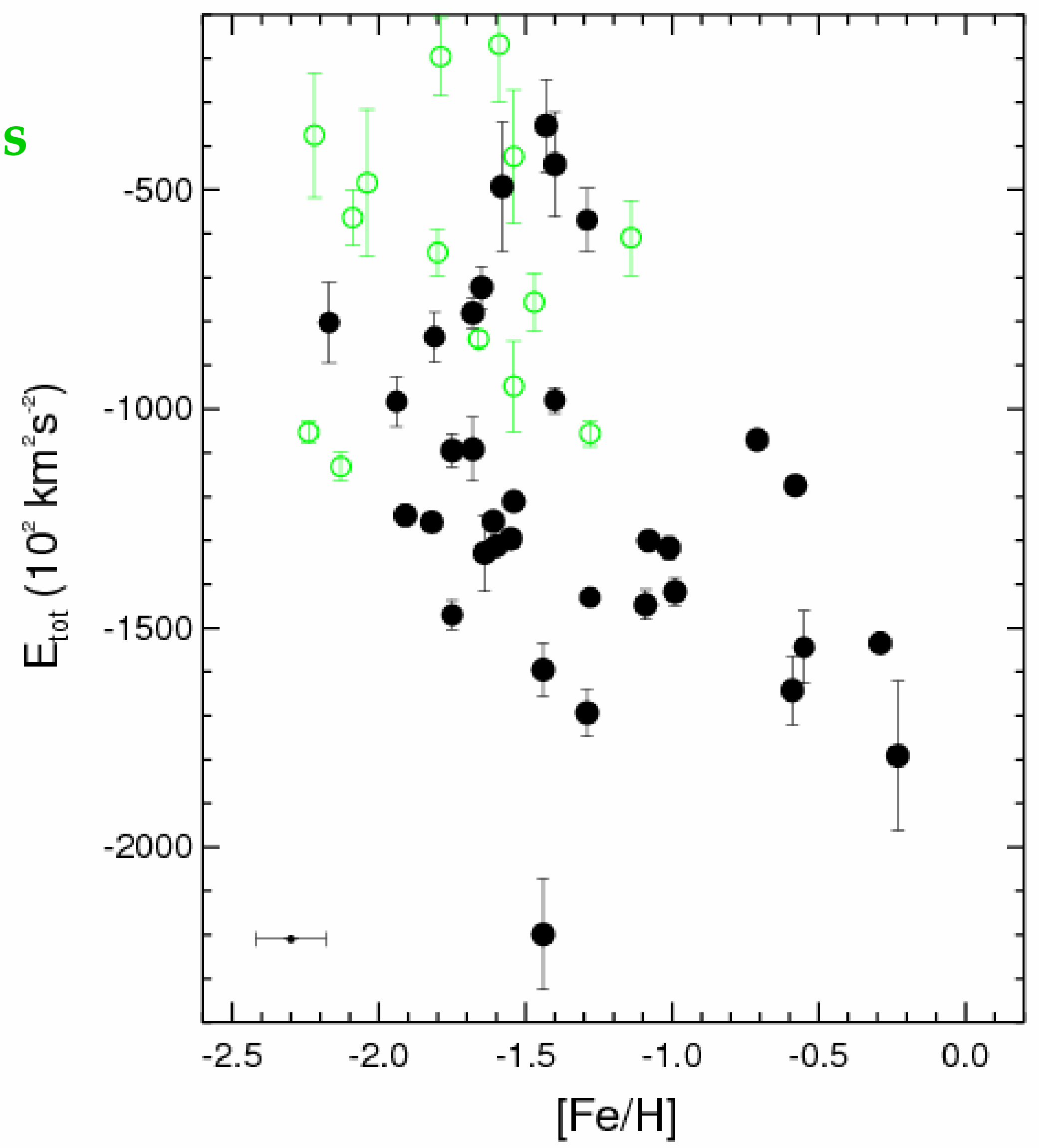
Full Spatial Motions & Orbital Parameters for 49 GCs from Dinescu+1999, 2003, 2007

All GCs



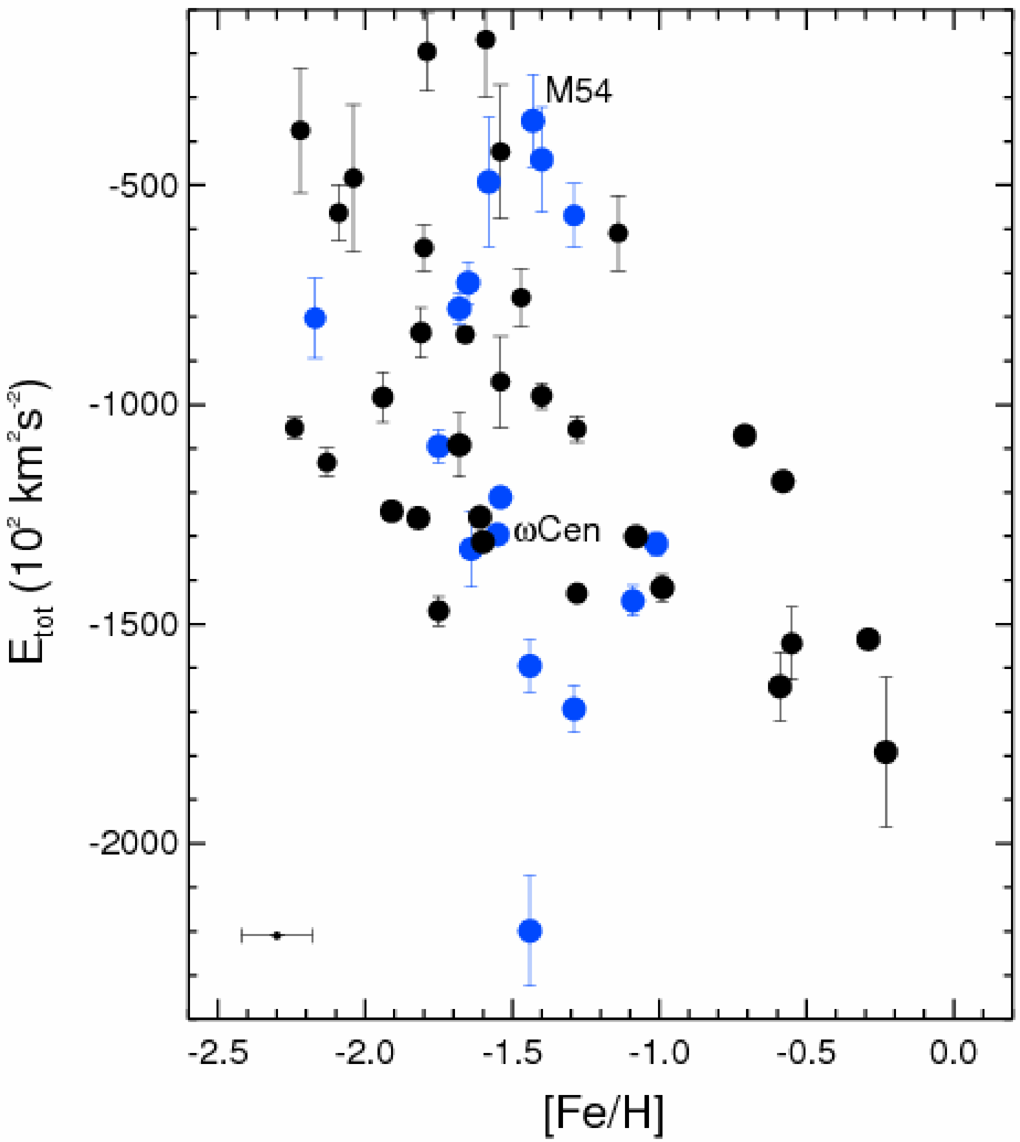
E_{tot} vs [Fe/H]

Normal YH GCs



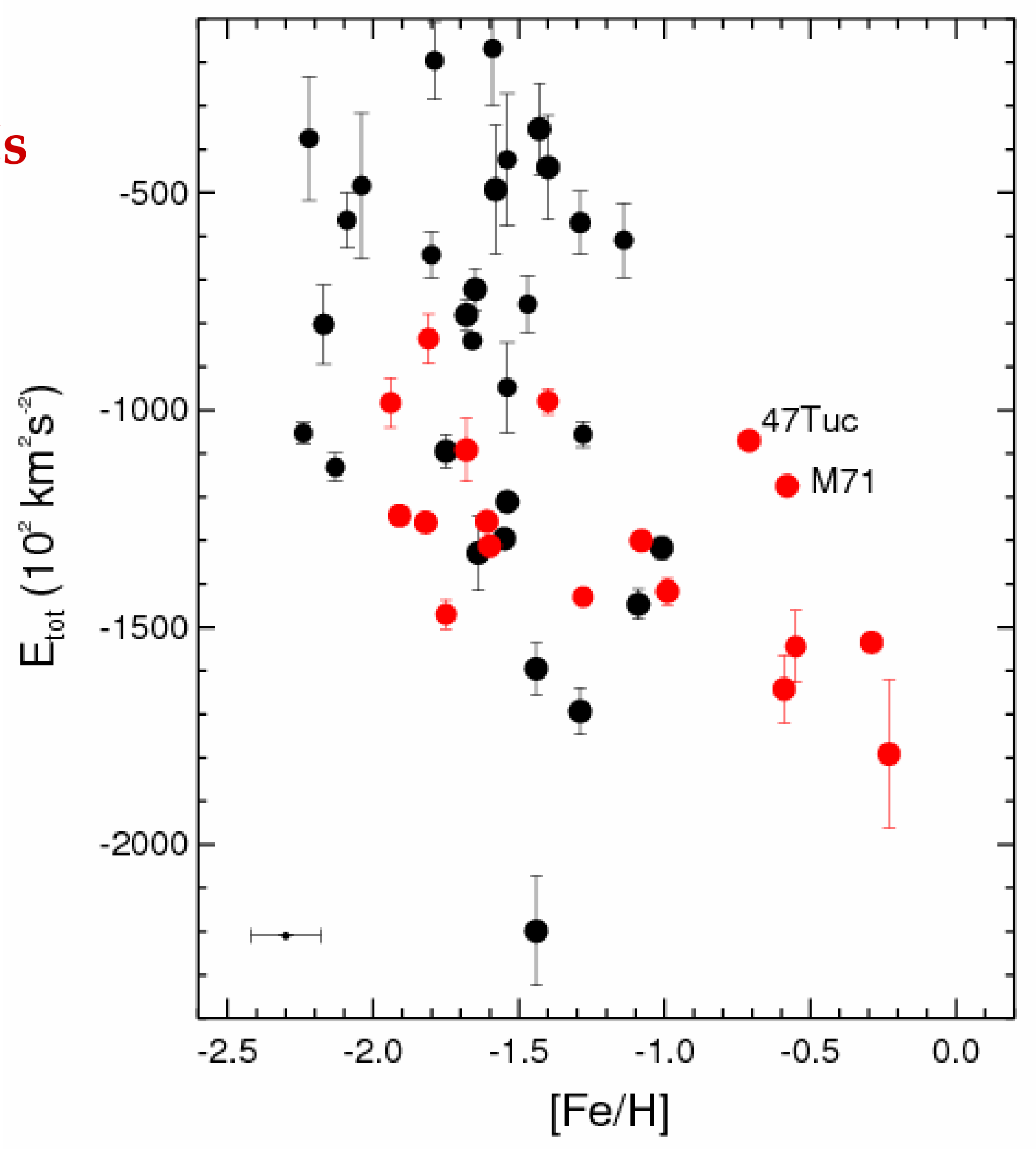
E_{tot} vs [Fe/H]

EHB GCs



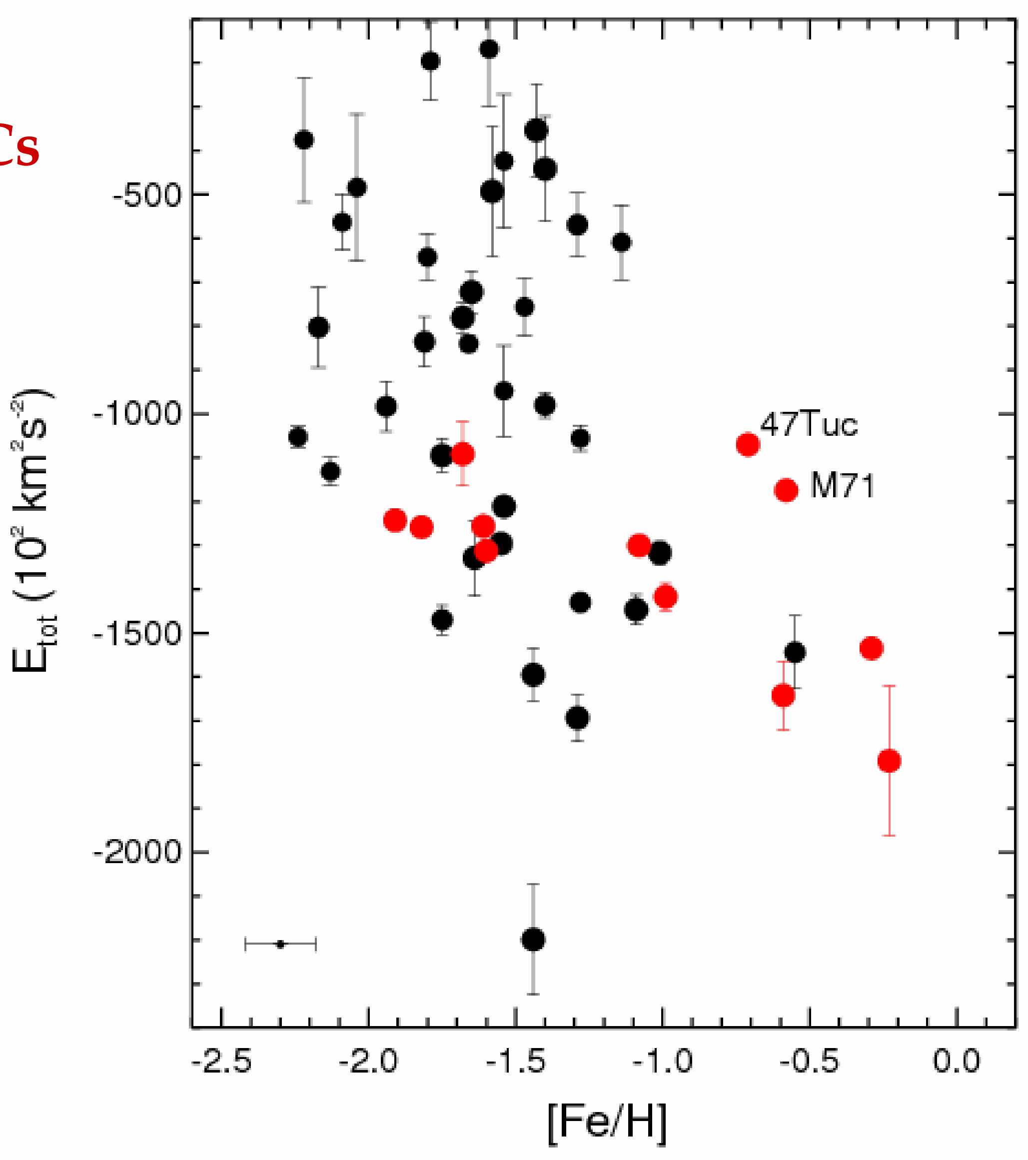
E_{tot} vs [Fe/H]

Normal OH GCs



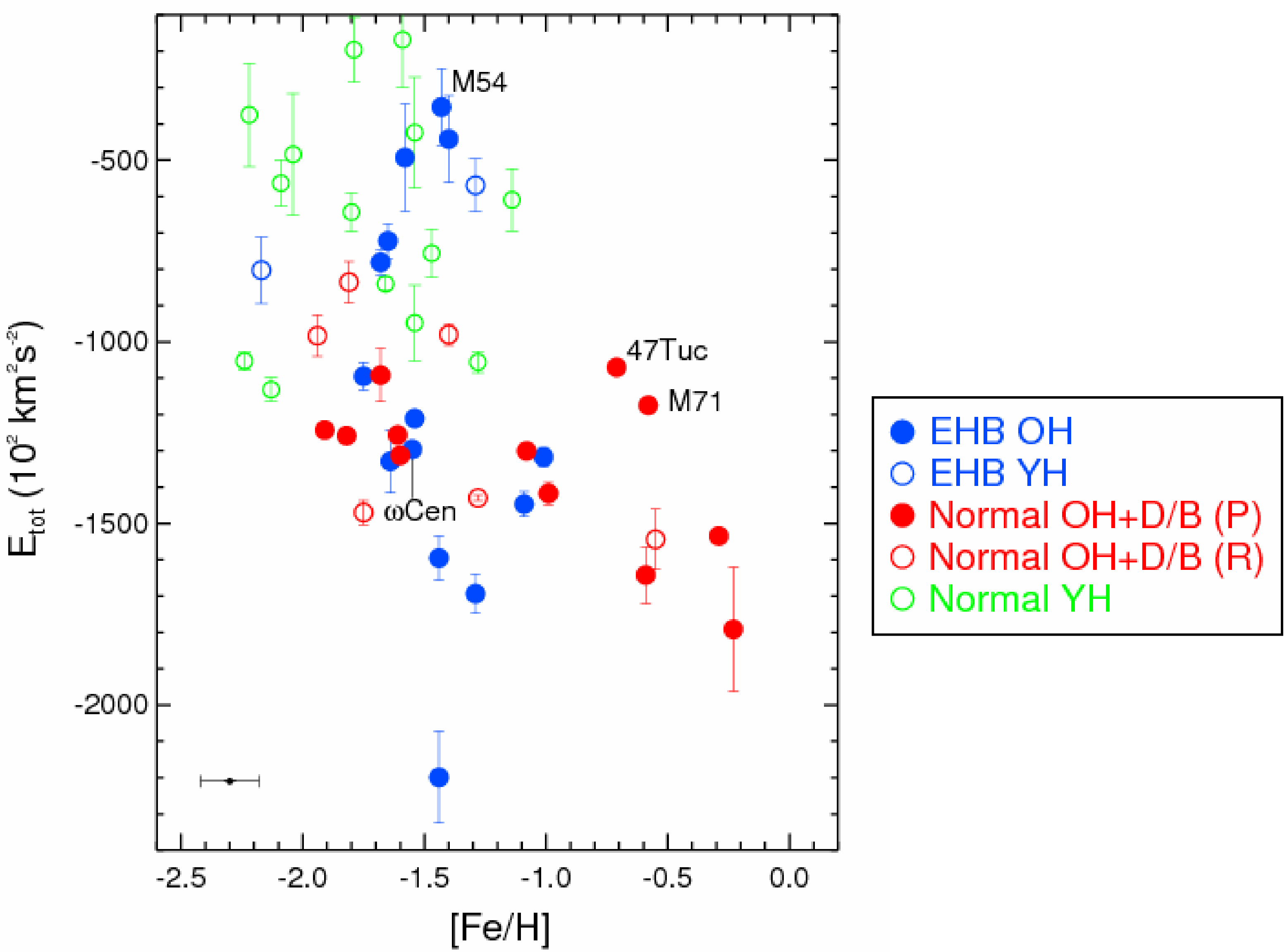
E_{tot} vs [Fe/H]

Normal OH GCs (Prograde)



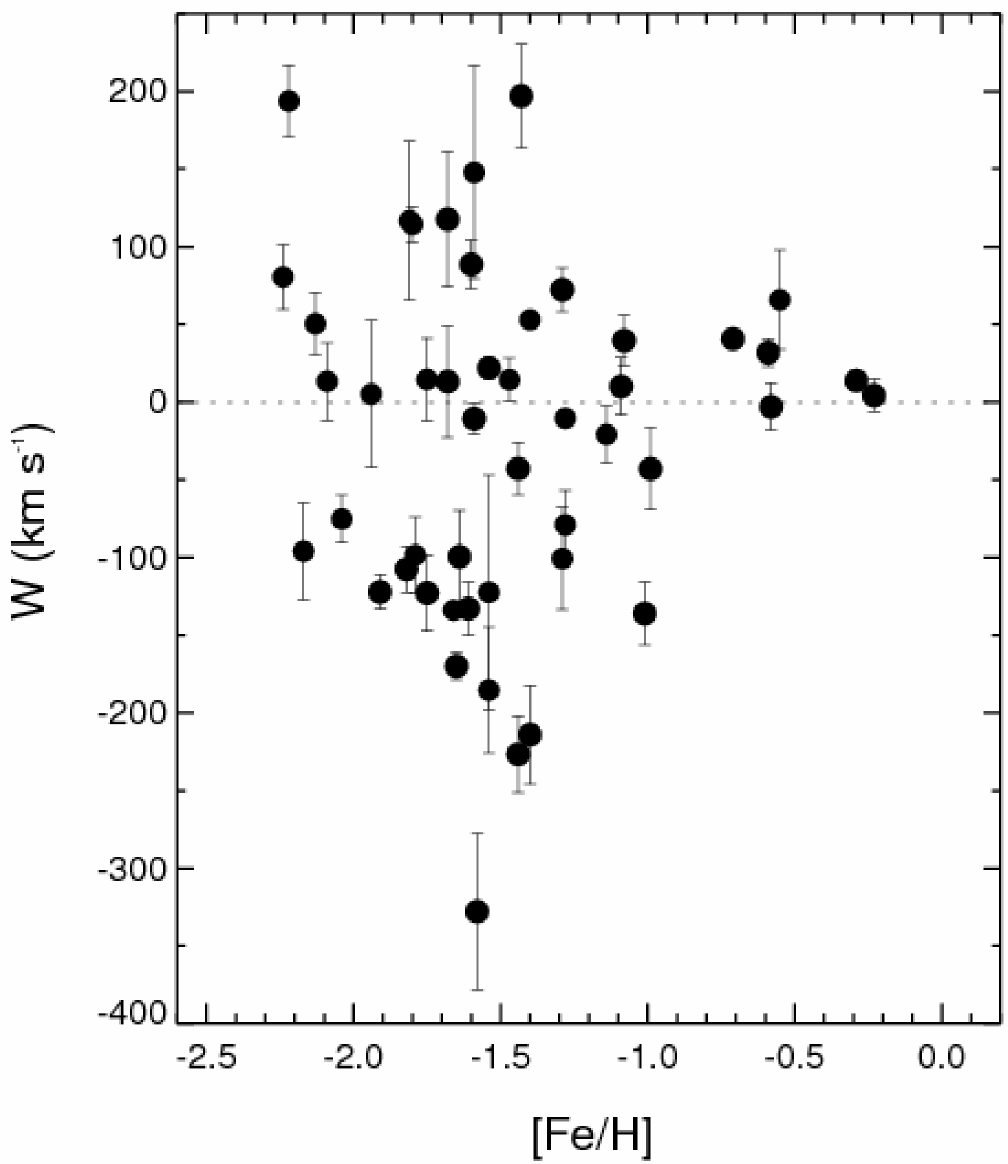
E_{tot} vs [Fe/H]

Lee, Gim & Casetti-Dinescu 2007, ApJ, 661, L49



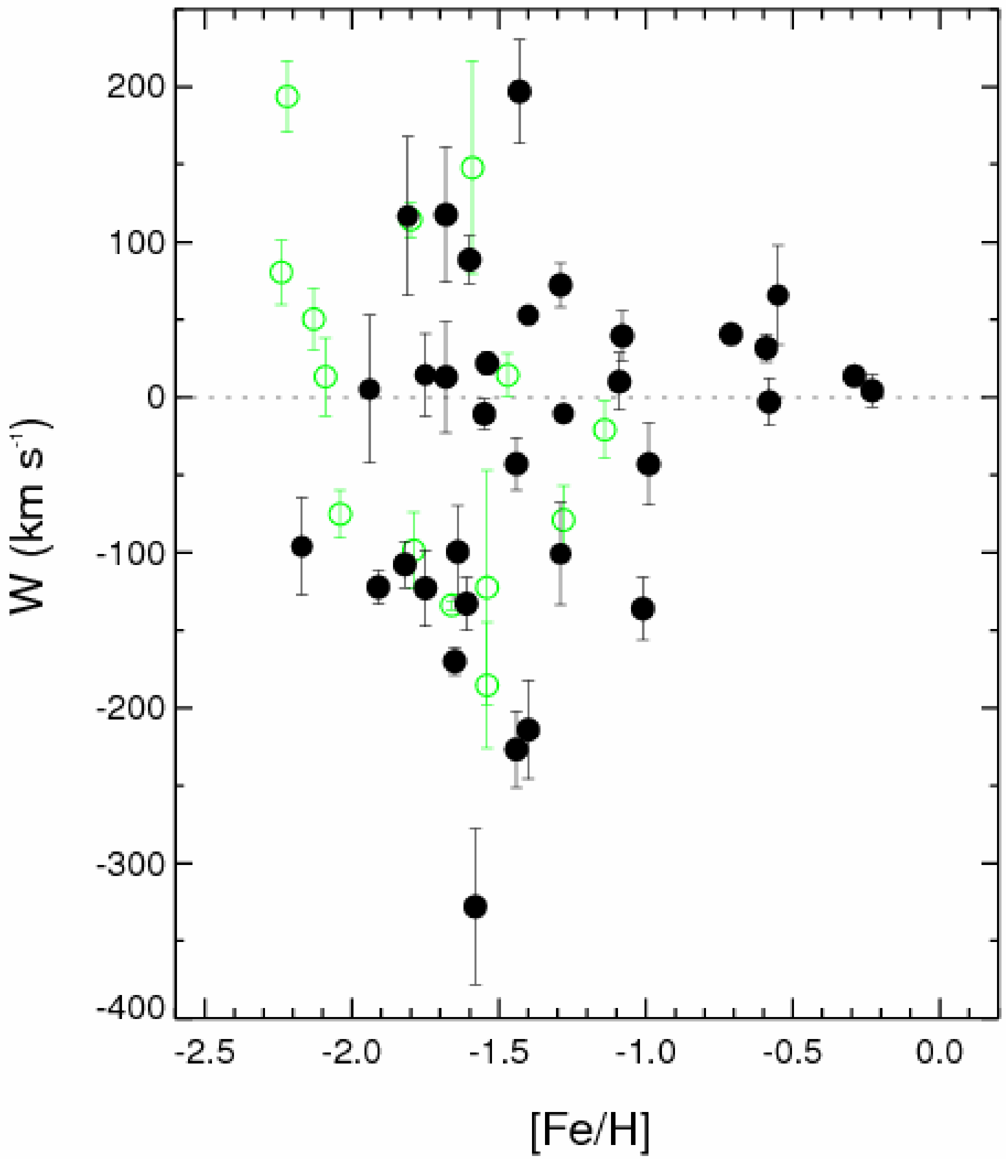
E_{tot} vs [Fe/H]

All GCs



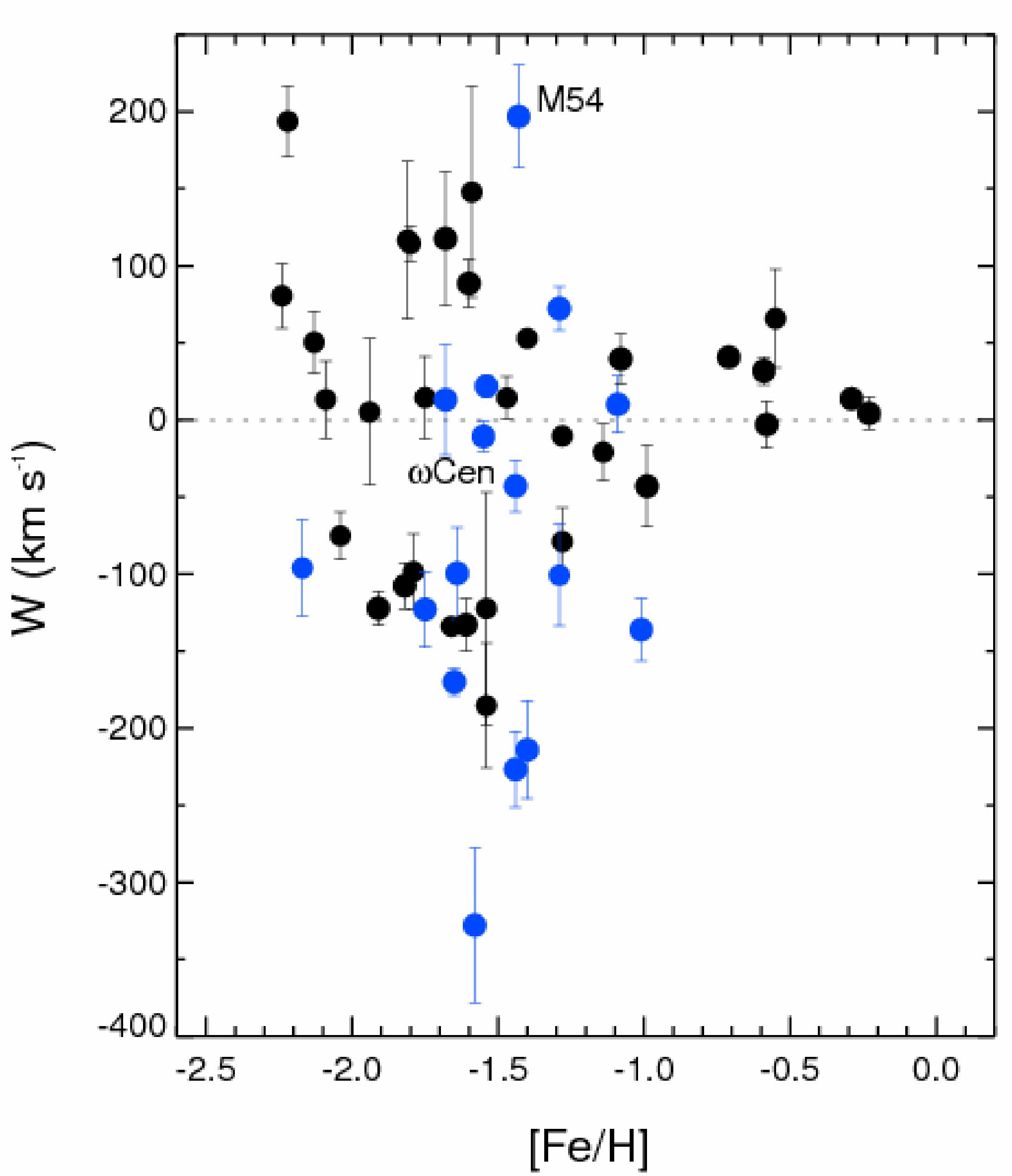
W vs [Fe/H]

Normal YH GCs



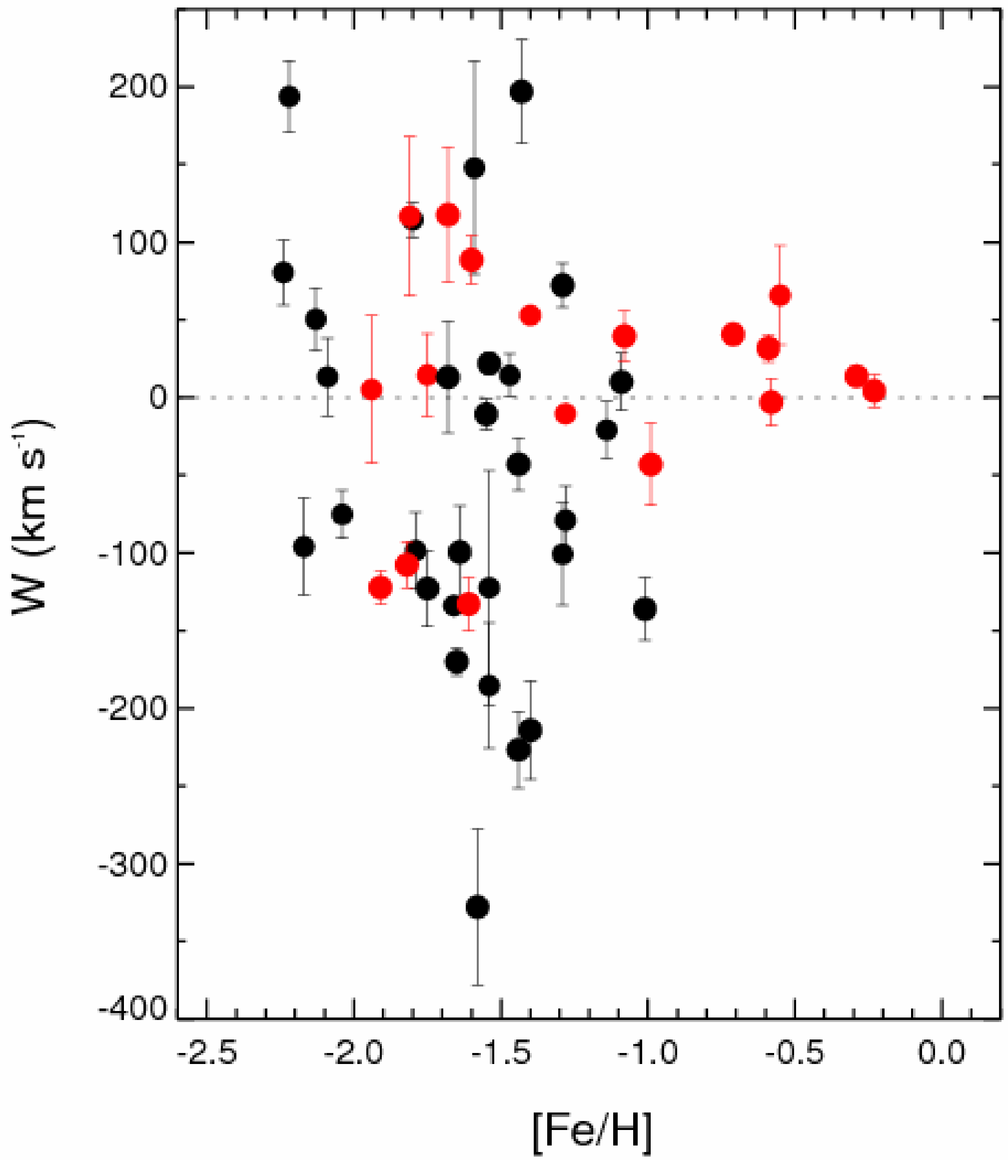
W vs [Fe/H]

EHB GCs



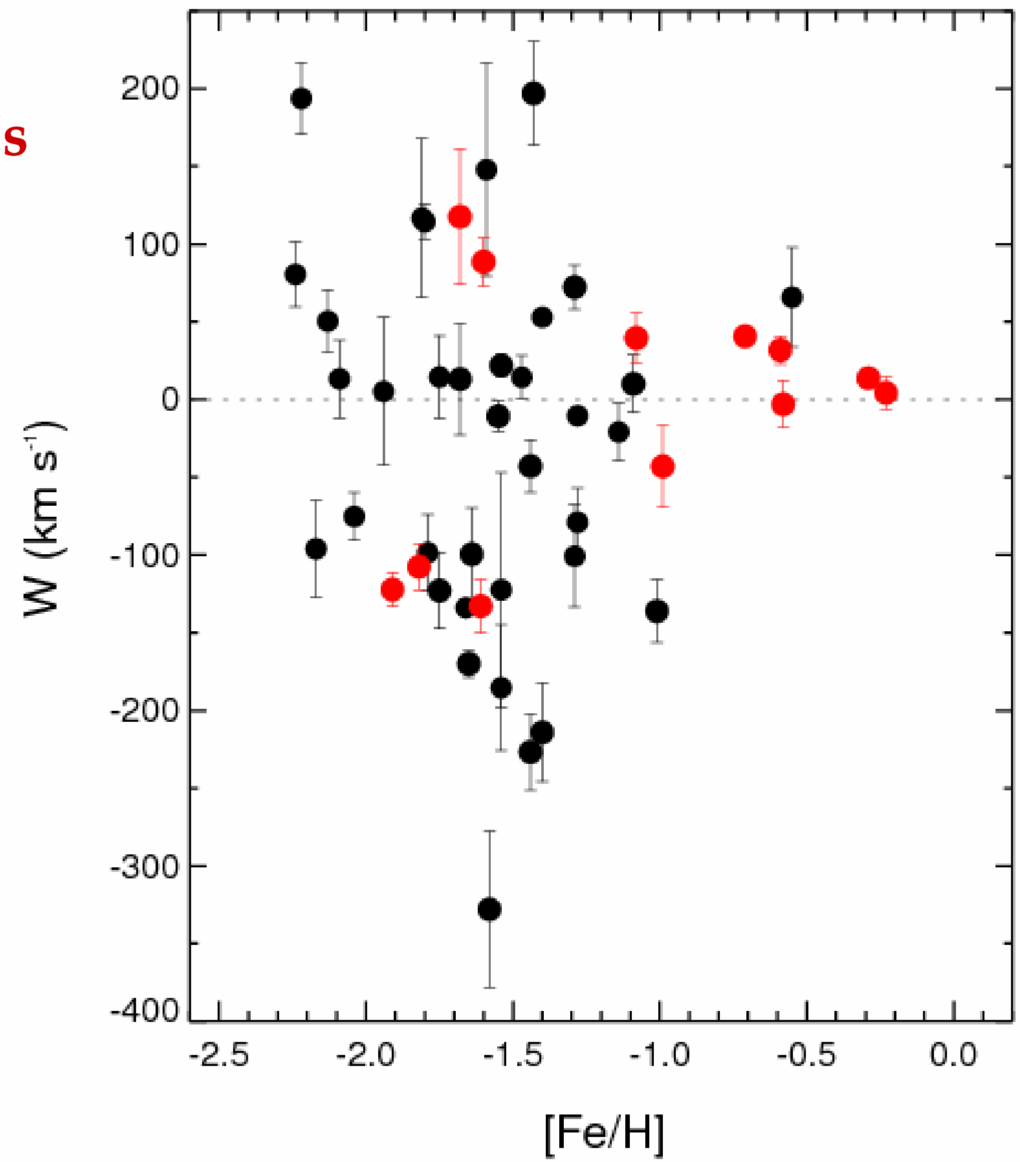
W vs [Fe/H]

Normal OH GCs



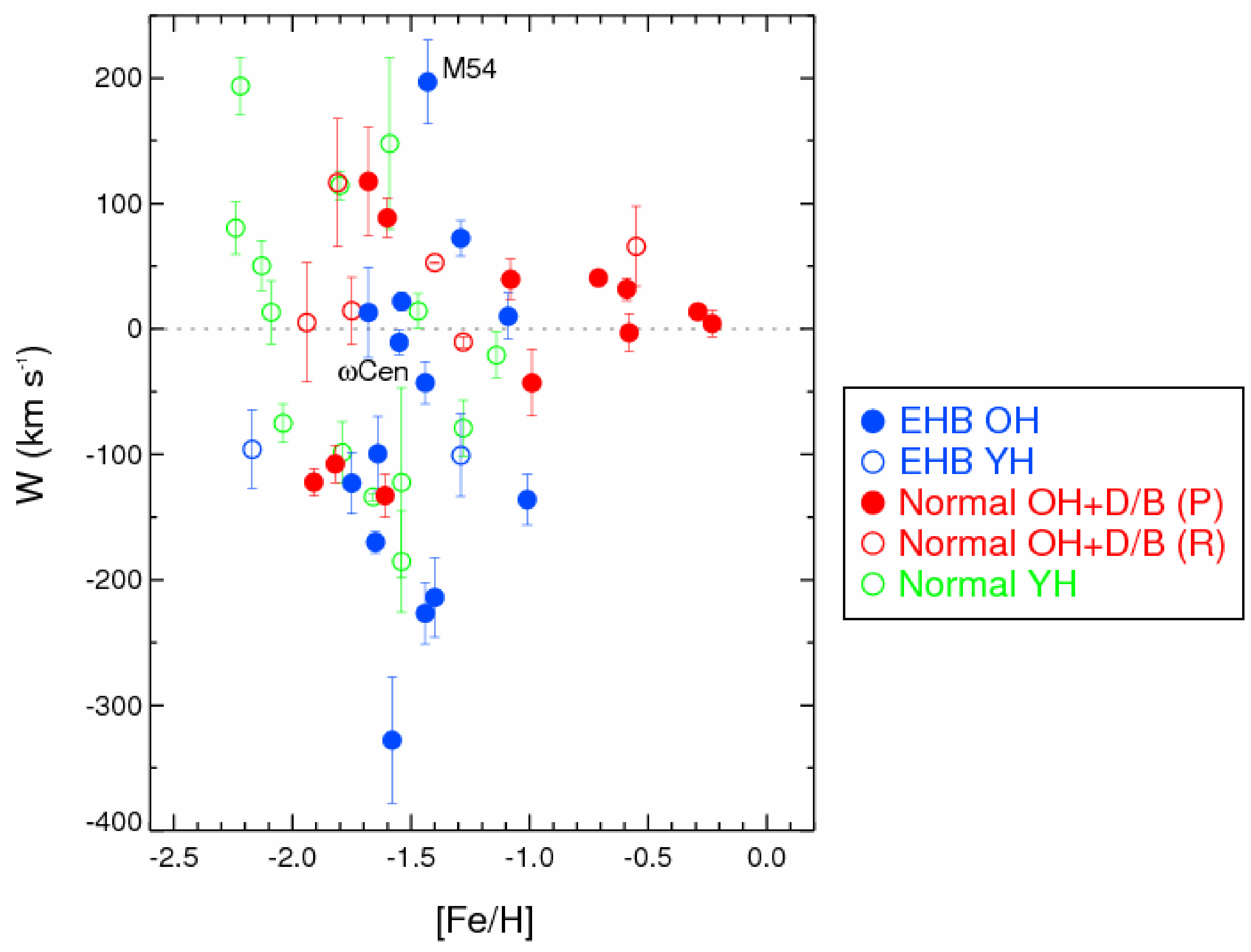
W vs [Fe/H]

Normal OH GCs (Prograde)



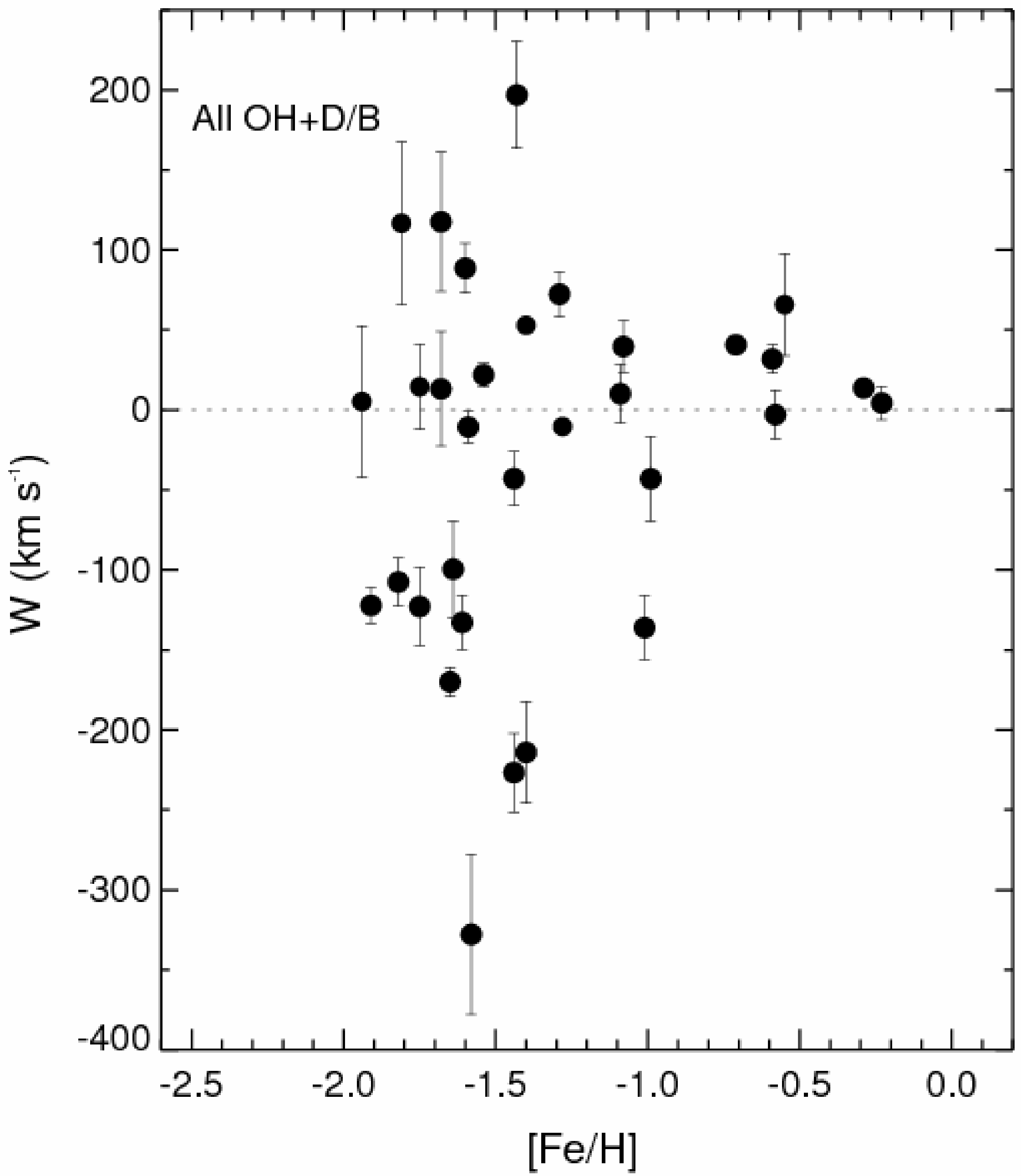
W vs [Fe/H]

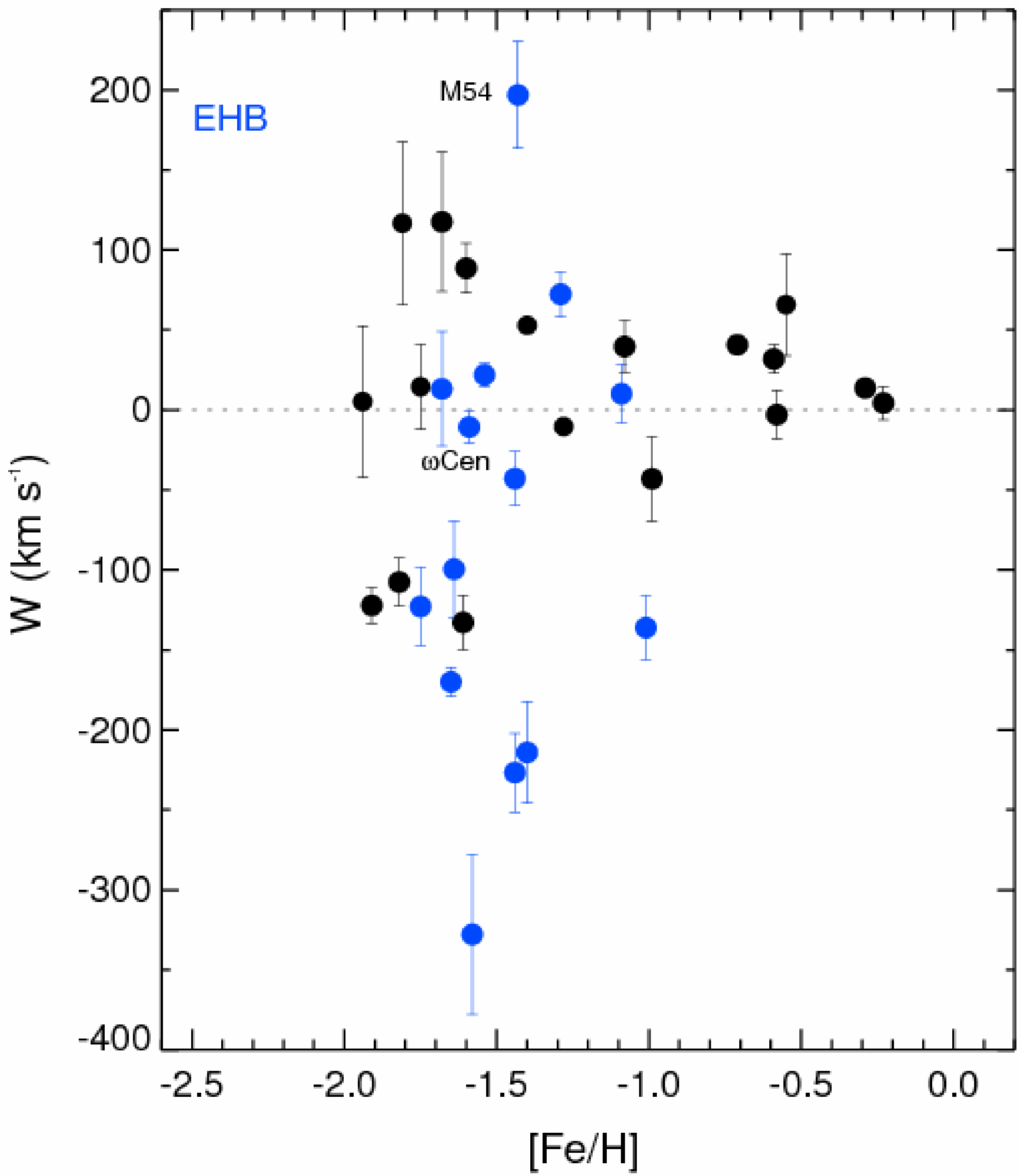
Lee, Gim & Casetti-Dinescu 2007, ApJ, 661, L49



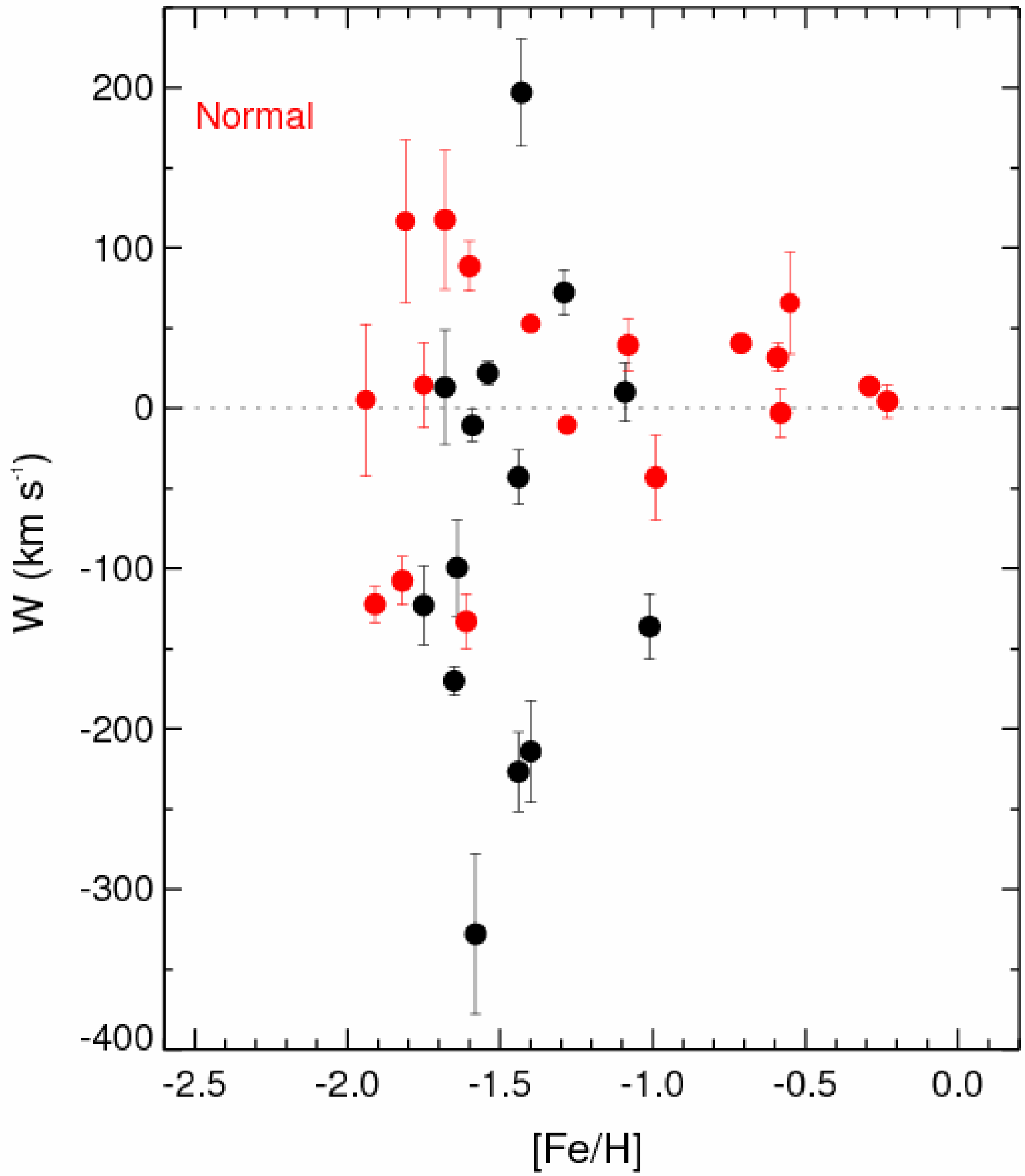
W vs [Fe/H]

OH GCs only
(most of them are
in the inner halo)

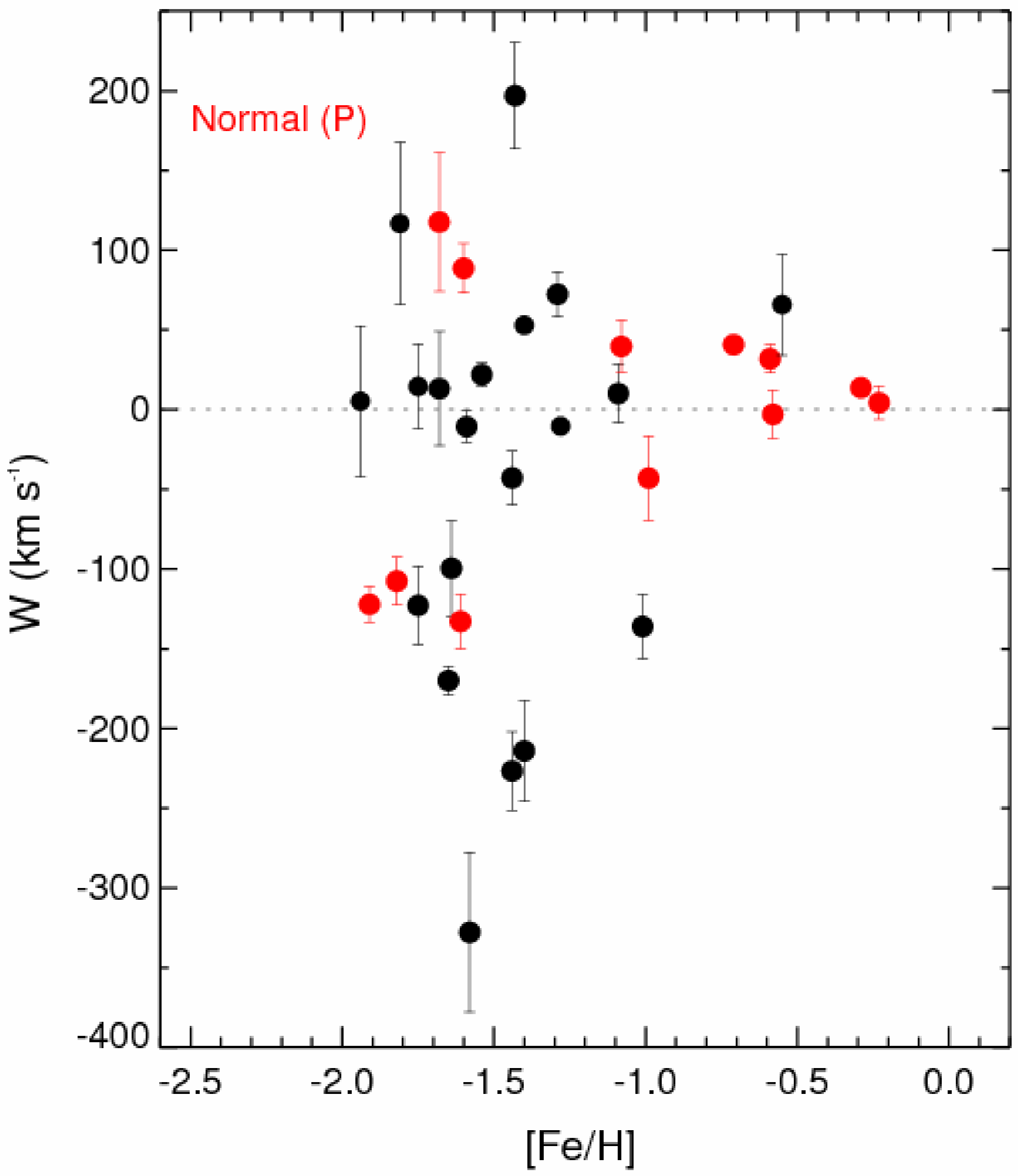




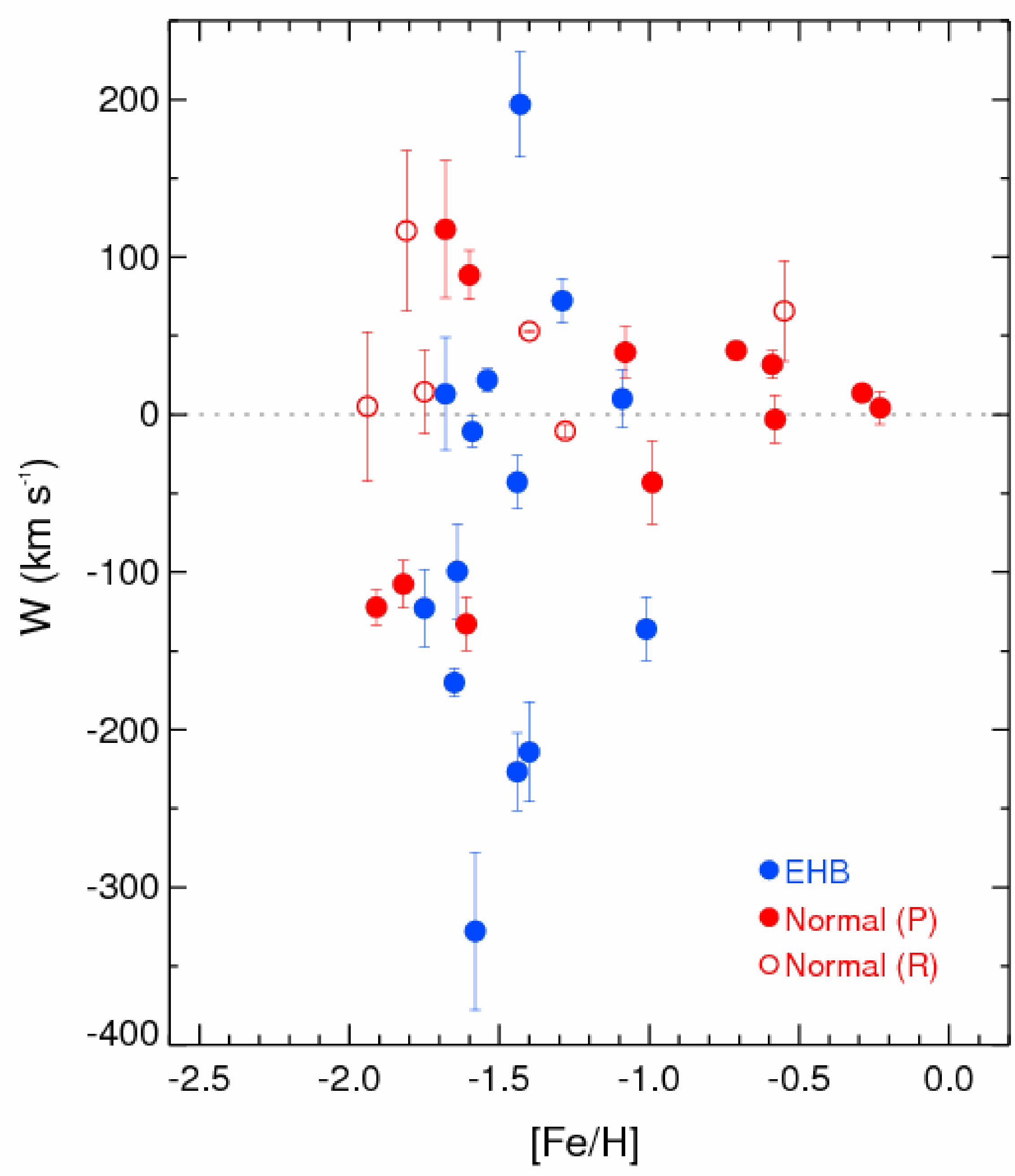
EHB
M54
ωCen
W (km s^{-1})
[Fe/H]
200
100
0
-100
-200
-300
-400
-2.5
-2.0
-1.5
-1.0
-0.5
0.0



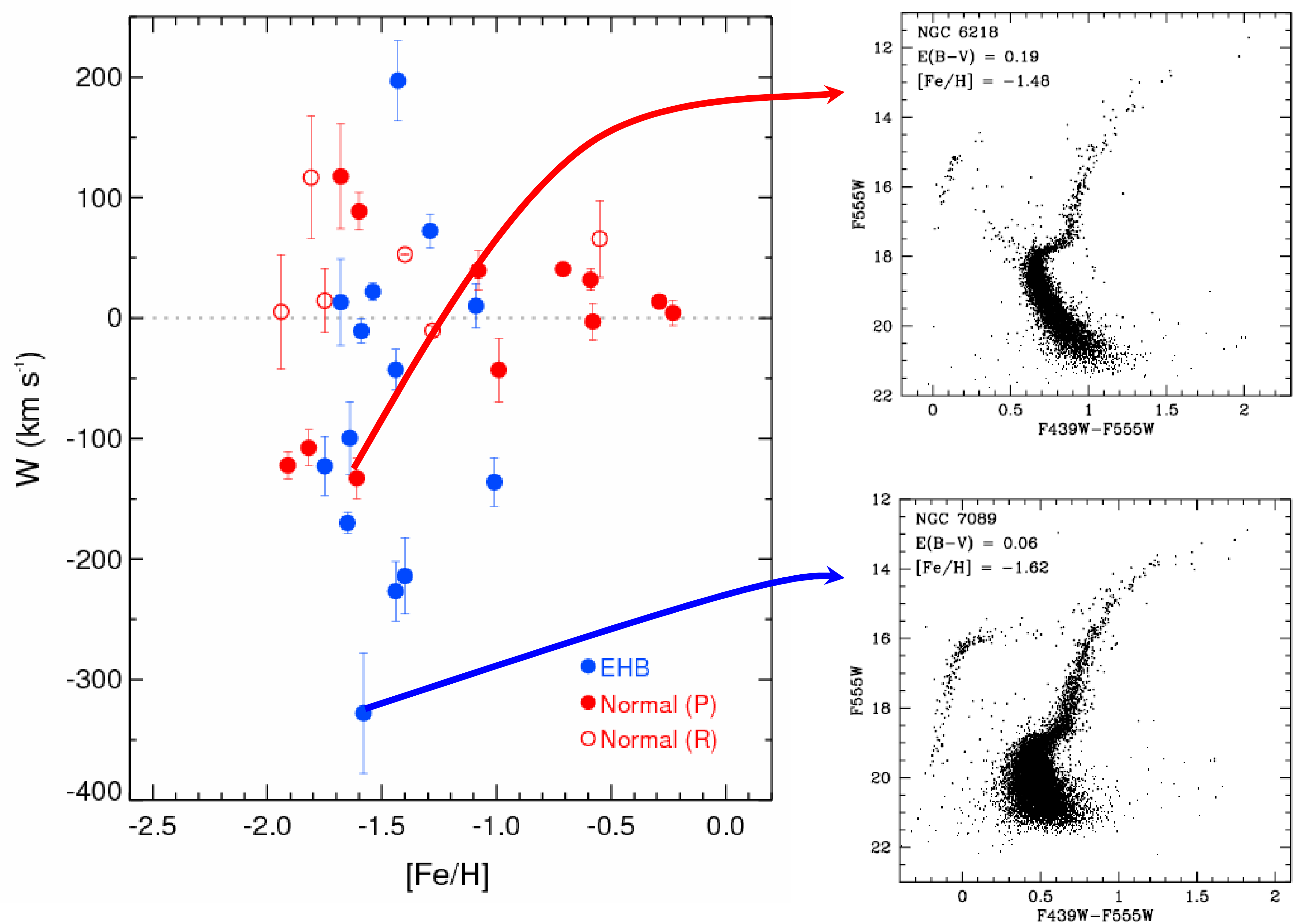
Normal
200
100
0
-100
-200
-300
-400
W (km s^{-1})
-2.5
-2.0
-1.5
-1.0
-0.5
0.0
[Fe/H]



Normal (P)
W (km s^{-1})
[Fe/H]
200
100
0
-100
-200
-300
-400
-2.5
-2.0
-1.5
-1.0
-0.5
0.0

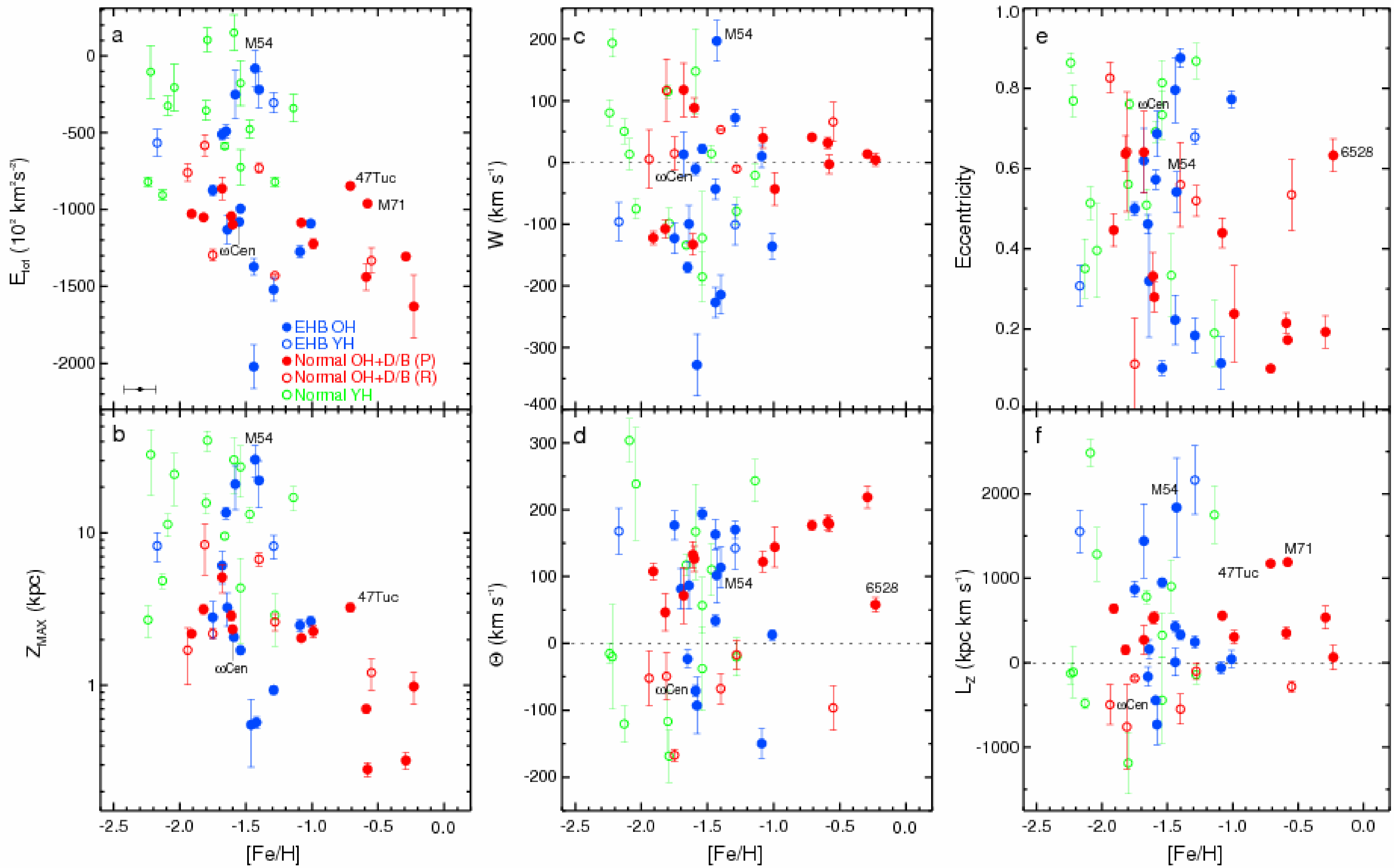


Monte-Carlo Simulations:
Occurrence of this by random selection < $1/10^5$ (0.001%) !



CMDs from Piotto+02

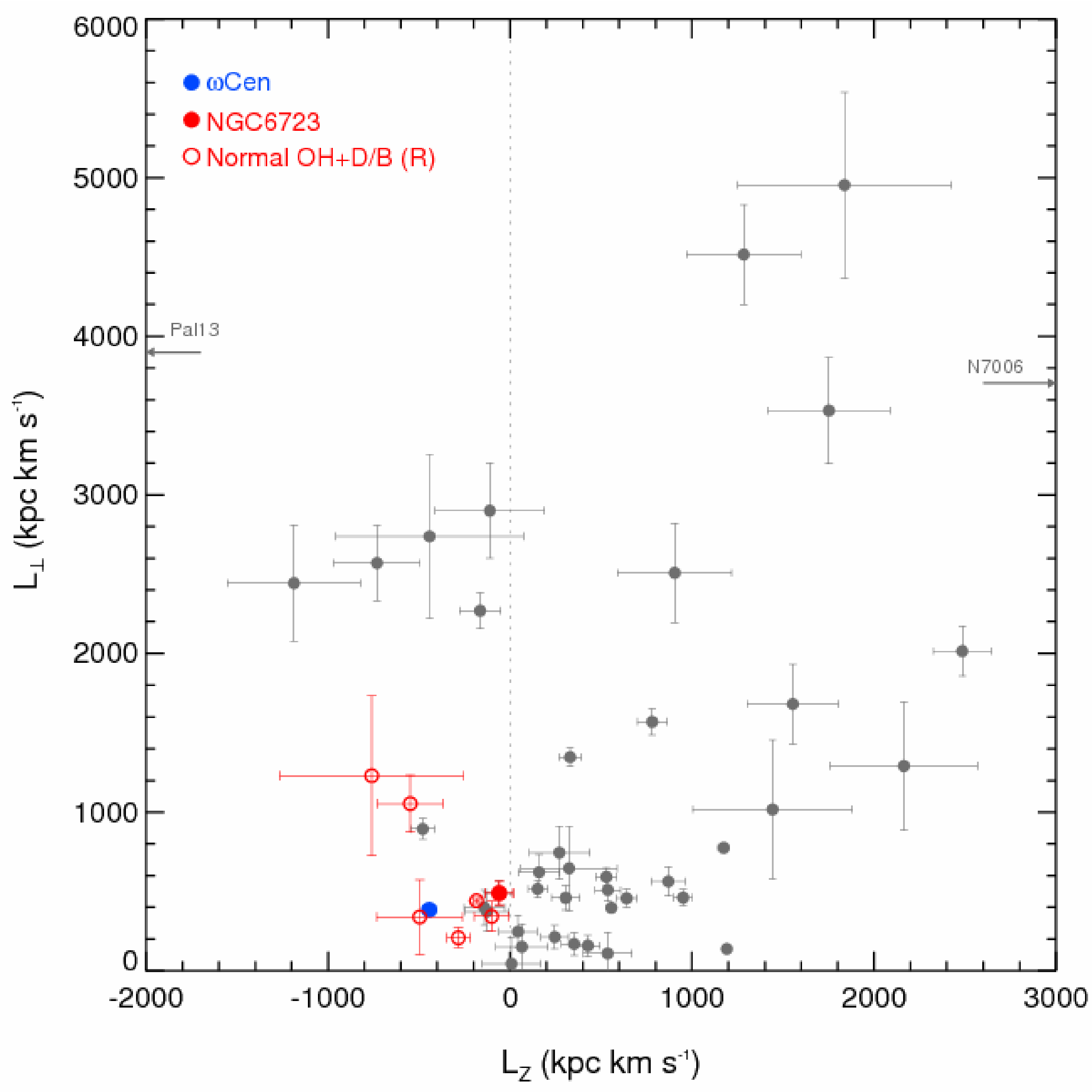
Lee, Gim & Casetti-Dinescu 2007, ApJ, 661, L49



EHB GCs: $r = -0.02$ to -0.31, p-values = 0.25 to 0.95

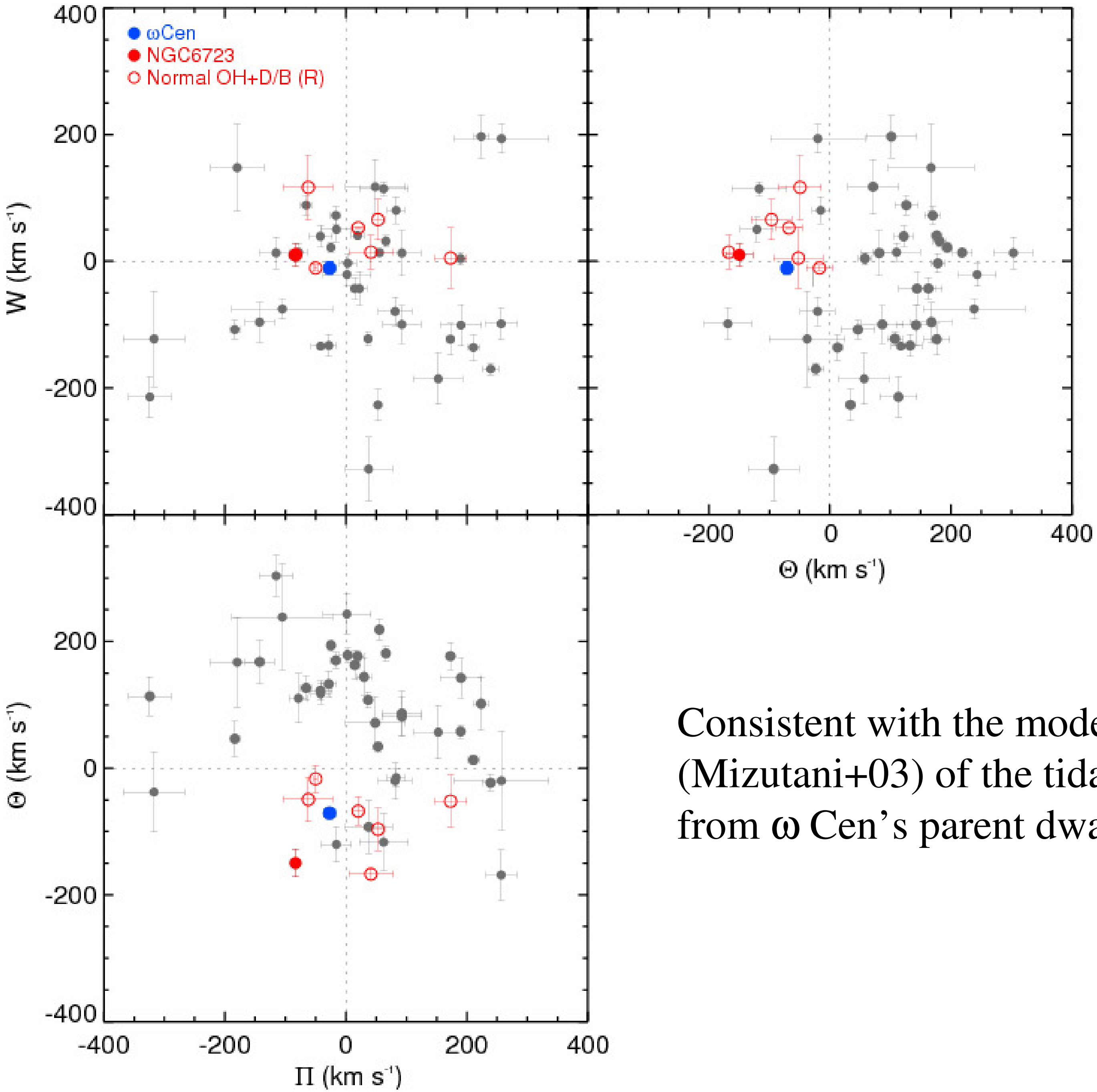
Normal OH (P): $r = -0.71$ to -0.95, p-values = 0.000003 to 0.01 (except L_z, $r = 0.17$ & p-value = 0.59), excluding N6528 in panels (d) & (e)

Six OH GCs with retrograde rotation: Originated from ω Cen?



If originated from the same parent system, clumping is expected in the angular momentum phase space (Helmi+99).

NB. $L_\perp$ is not fully conserved in an axisymmetric potential



Consistent with the model prediction (Mizutani+03) of the tidal debris from ω Cen's parent dwarf system!

Kinematics of GCs with & w/o EHB

1. Spatial motion of EHB GCs is dominated by random motion with no correlation between kinematics and metallicity.

2. However, most normal GCs in the inner halo (OH) show clear correlations between kinematics and metallicity, which is consistent with the dissipational collapse.

3. Normal GCs in the outer halo (YH) share their kinematic properties with the EHB GCs, in consistent with the accretion origin.

EHB GCs are distinct from normal GCs in:

1. Mass (Brightness)
2. Kinematics (in the inner halo)
3. Presence of super-He-rich subpopulations (multiple populations)

→ different origins!

Conclusion

MW Formation: Merger, Collapse, & Accretion

Present-day Galactic GCs are ensemble of heterogeneous objects originated from three distinct phases of the Milky Way formation!

(1) EHB GCs: remaining cores or relicts of building blocks that first assembled to form the nucleus and halo of the proto-Galaxy

(2) OH+D/B GCs with normal HB: genuine GCs formed in the dissipational collapse of a transient gas-rich inner halo system that eventually formed the Galactic disk (ELS 1962)

(3) YH GCs with normal HB: genuine GCs formed in the outskirts of outlying building blocks that later accreted to the outer halo of the Milky Way (Searle & Zinn 1978)

References

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