# SPACE MOTIONS OF GALACTIC GLOBULAR CLUSTERS: NEW RESULTS AND HALO-FORMATION IMPLICATIONS

**Dana I. Casetti-Dinescu, Terrence M. Girard, David Herrera, William F. van Altena, Young-Wook Lee, Carlos Lopez and Danillo J. Castillo -** *Yale University, Yale Southern Observatory, Yonsei University, University of San Juan-Argentina*

## Why do we need accurate orbits of globular clusters and of satellites (surviving and undergoing disruption) ?

- We wish to find out whether there is a dynamical distinction between early, late and no accretion, and how does it all fit within the paradigm of hierarchical growth of a (disk) galaxy.

- Did dissipational collapse play a role in the formation of our Galaxy, and is it discernable ?

# Status of Observations

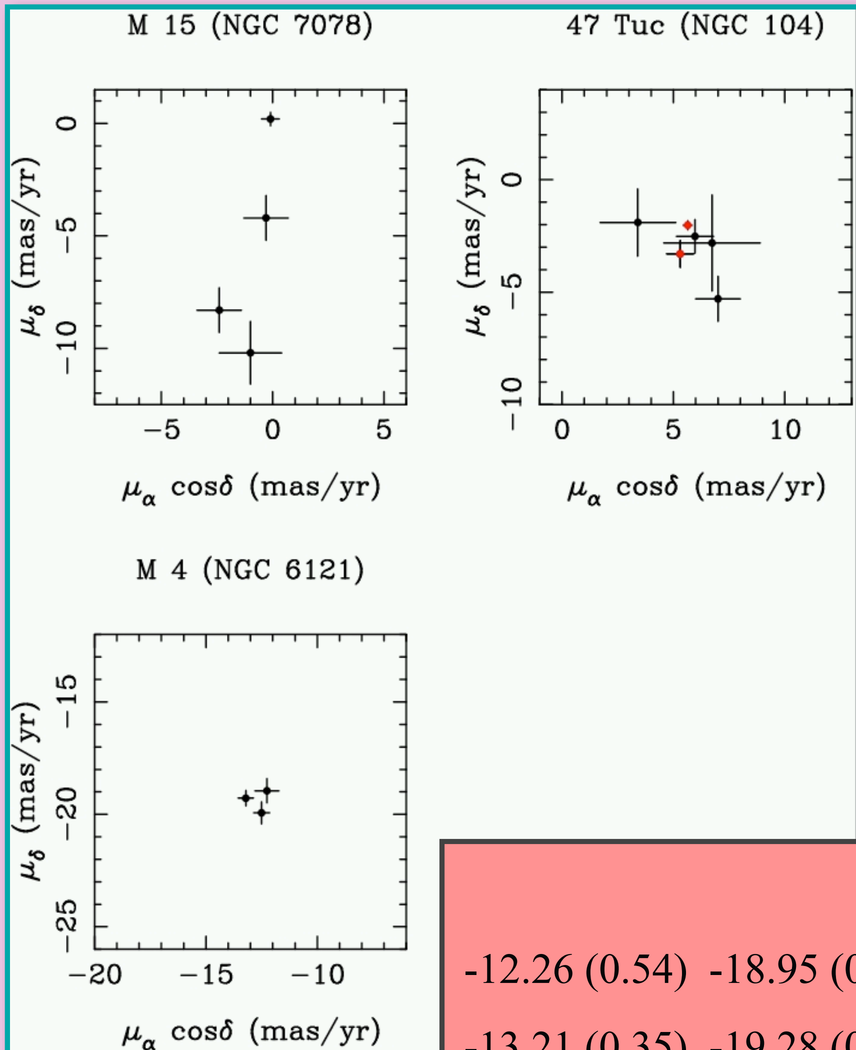
Galactic Globular Clusters (GGC):

• To date, 53 of ~ 150 GGC have measured absolute proper motions, with formal errors between 0.1 and 2.0 mas/yr; mean value ~ 0.5 mas/yr.

• Of the measured ones, 33 have one single determination, and 25 were measured by the Southern Proper-Motion Program (SPM).

• They are confined within 30 kpc from the Galactic center (only NGC 7006 is at ~ 40 kpc).

# Status of Observations: GGC (cont.)




Uncertain measurements

| NGC | D (kpc) | Δμ (mas/yr) | ΔV (km/s) |
|---|---|---|---|
| 5904 (M5) | 7.5 | 4 | 142 |
| 6205 (M13) | 7.7 | 2.5 | 91 |
| 7078 (M15) | 10.3 | 6 | 293 |
| 7089 (M2) | 11.5 | 1.5 | 82 |

**M 4**

-12.26 (0.54) -18.95 (0.54) Kalirai et al. 2004 – HST, ~12 galaxies

-13.21 (0.35) -19.28 (0.35) Bedin et al. 2003 – HST, 1 QSO

-12.50 (0.36) -19.92 (0.49) Dinescu et al. 1999 - SPM, ~100 Hipparcos stars

# Status of Observations

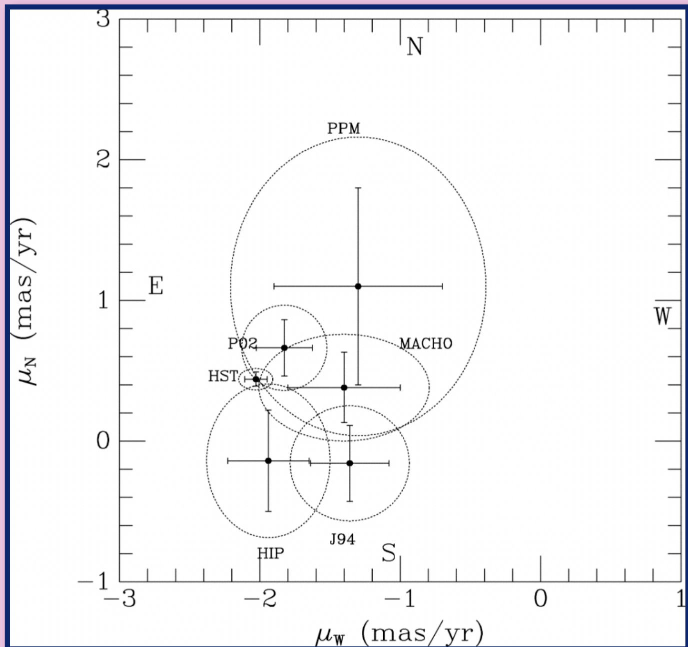
Milky-Way Satellites:

• There are determinations for 7 satellites out of some 20 known, with formal errors between 0.05 and 0.25 mas/yr; 6 of these have 2 or more measurements: ground based and HST based.

• The HST results - Piatek et al. 2002, 2003 (Fornax, Carina) before CTE correction, as well as the LMC result from Kallivayalil et al. 2006 indicate that the orbits are more energetic, more eccentric than the ground-based determinations, (larger size proper motion).

# Status of Observations: Satellites (cont.)

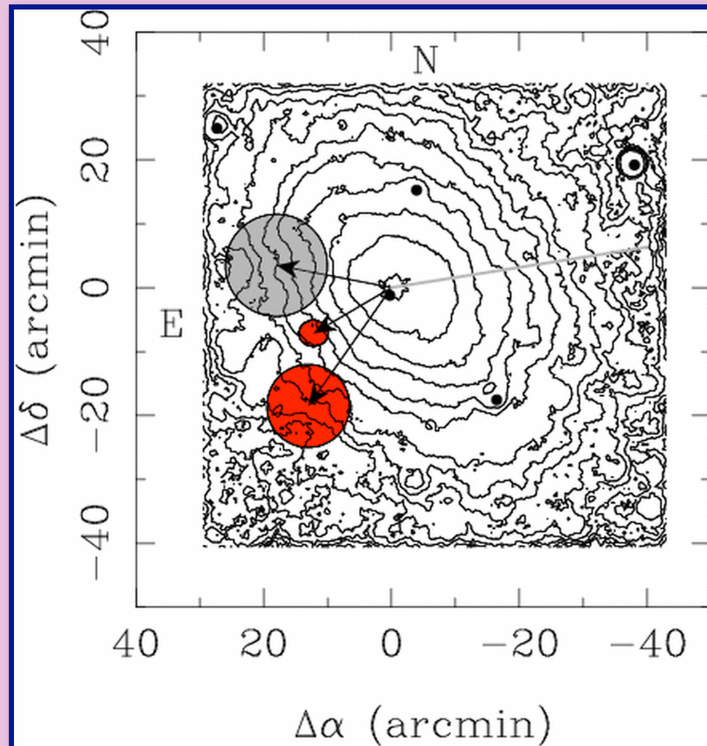
LMC - 50 kpc




Kallivayalil et al. 2006 → ecc = 0.74

Van der Marel et al. 2002 → ecc = 0.48

Fornax - 140 kpc




Piatek et al. 2002 → ecc = 0.52 (bef. CTE)

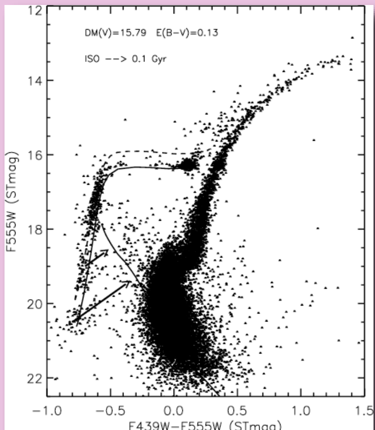
Dinescu et al. 2004 → ecc = 0.27

Piatek et al. 2006 → ecc = 0.13

# Globular Cluster Results

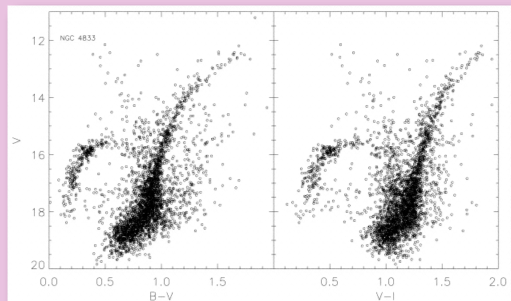
Proper-motion measurements: 53 clusters including NGC 2808, 3201, 4372, 4833, 5927, and 5986 (Casetti-Dinescu et al. 2007, AJ 134, 195), + 4 Sgr clusters (M 54, Ter 7, 8, Arp 2, proper motion same as that of Sgr) .

NGC 2808: EHB-strong



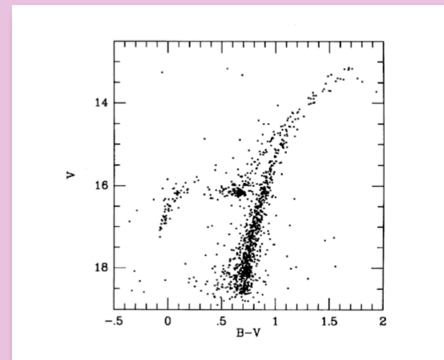

Castellani et al. 2006

NGC 4833: EHB-moderate

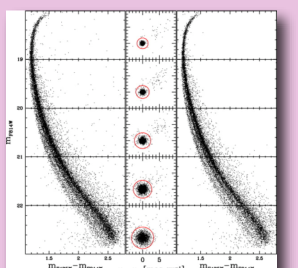



Melbourne et al. 2000

NGC 1851: bimodal




Walker 1992



Piotto et al 2007

From 94 clusters with HB classification:

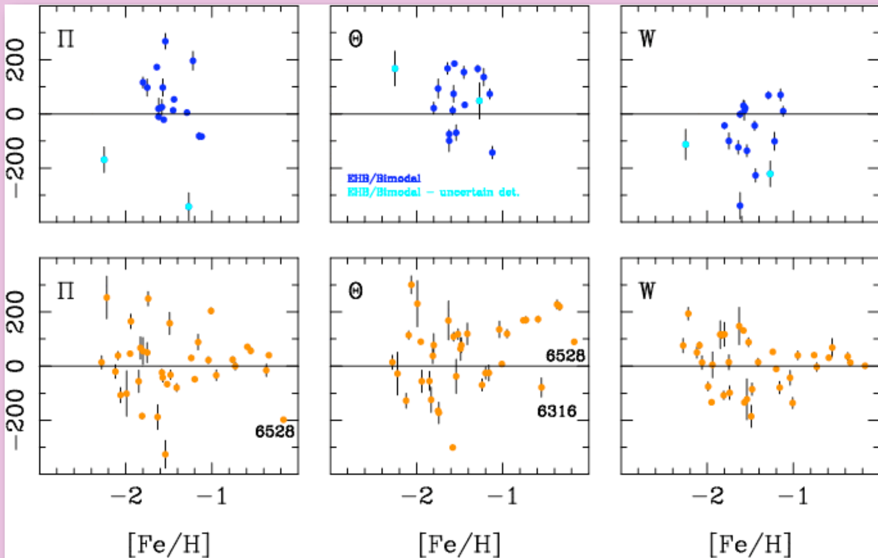
14 EHB-strong → 11 measured (including M 54, Sgr's nucleus)

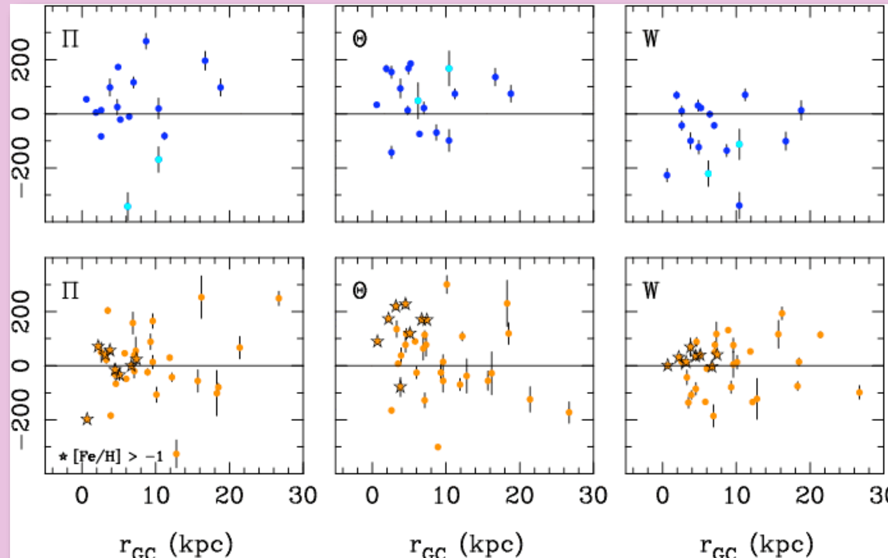
7 EHB-moderate → 4 measured

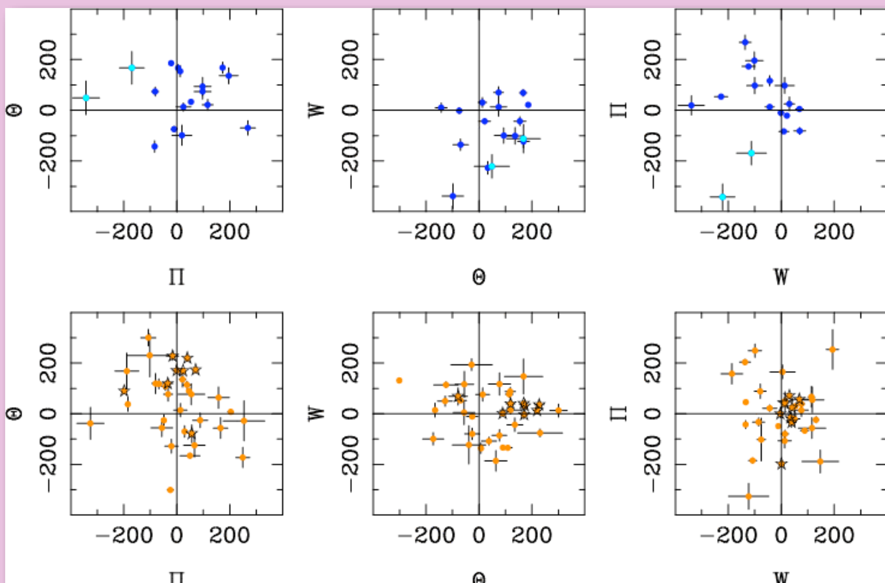
5 Bimodal HB → 3 measured

In all, there are 26 EHB clusters that **make up 53% of the total mass of the GC system**; 65% of the EHBs (58%, excluding 2 poor measurements) have orbits measured.

# Globular Cluster Results: Velocities



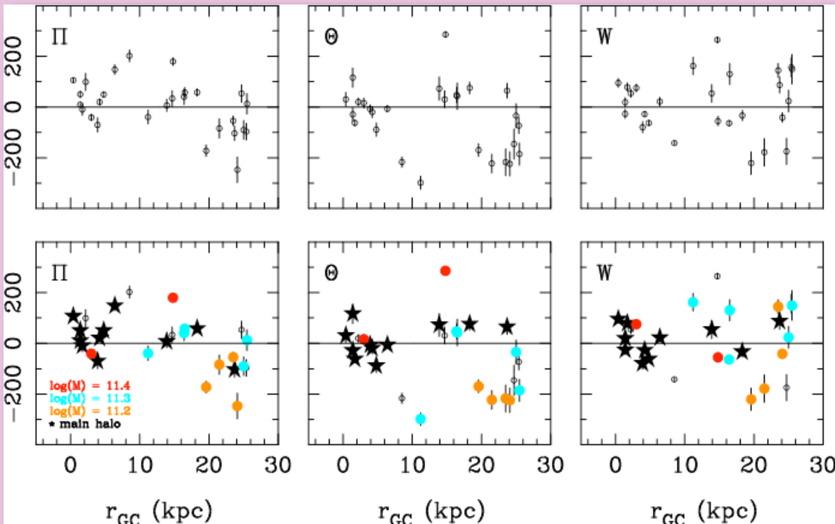




**Average velocities and dispersions (km/s)**

| Sample | N | Π | Θ | W | $\sigma_\Pi$ | $\sigma_\Theta$ | $\sigma_W$ |
|---|---|---|---|---|---|---|---|
| EHB strong | 10 | 31 (39) | 63 (36) | -62 (40) | 124 | 112 | 126 |
| EHB all | 17 | 21 (35) | 56 (25) | -75 (28) | 143 | 104 | 114 |
| EHB all - 2 poor det. | 15 | 58 (26) | 49 (27) | -60 (29) | 100 | 106 | 114 |
| Other & [Fe/H] < -1.0 | 29 | 23 (26) | 23 (24) | 14 (21) | 142 | 129 | 114 |

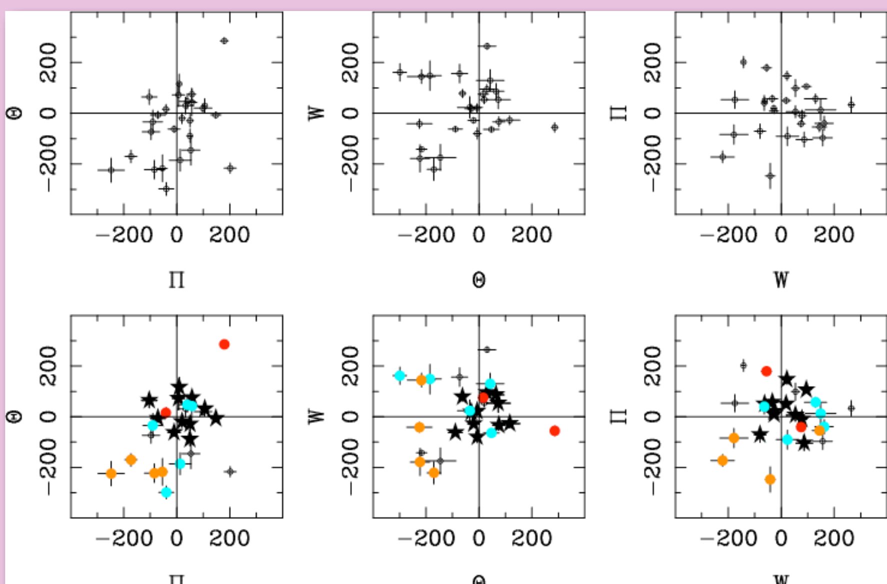
# Globular-Cluster System Model: Velocities




Prieto and Gnedin 2007

All within 30 kpc from Galactic center

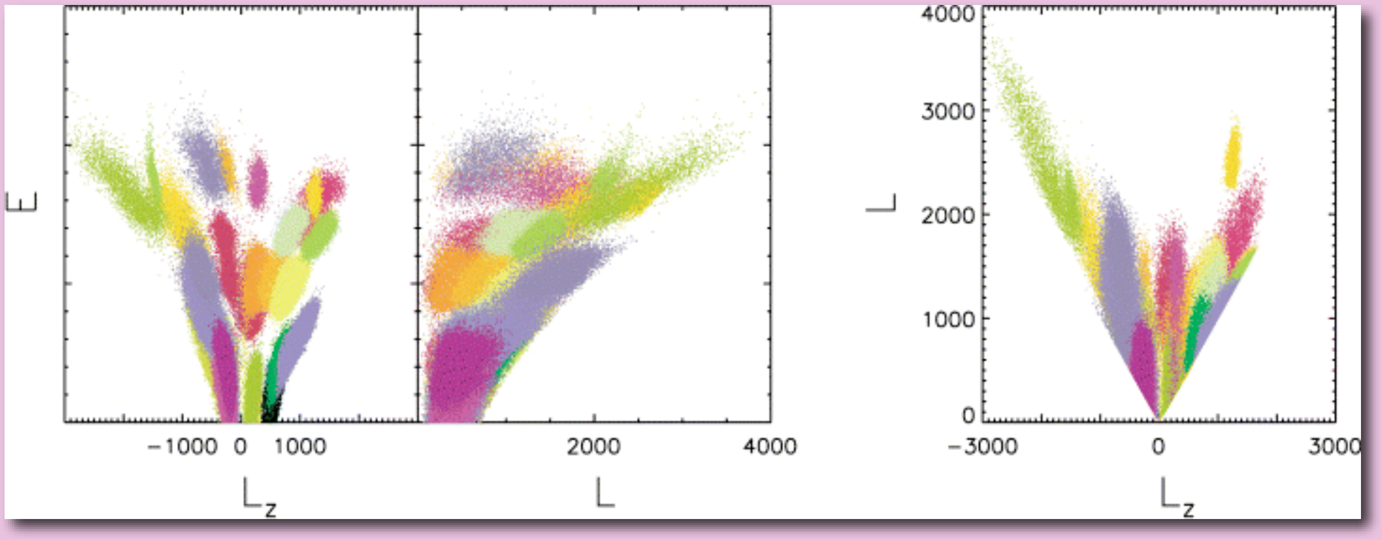
All within 30 kpc from Galactic center, and separated by initial host system



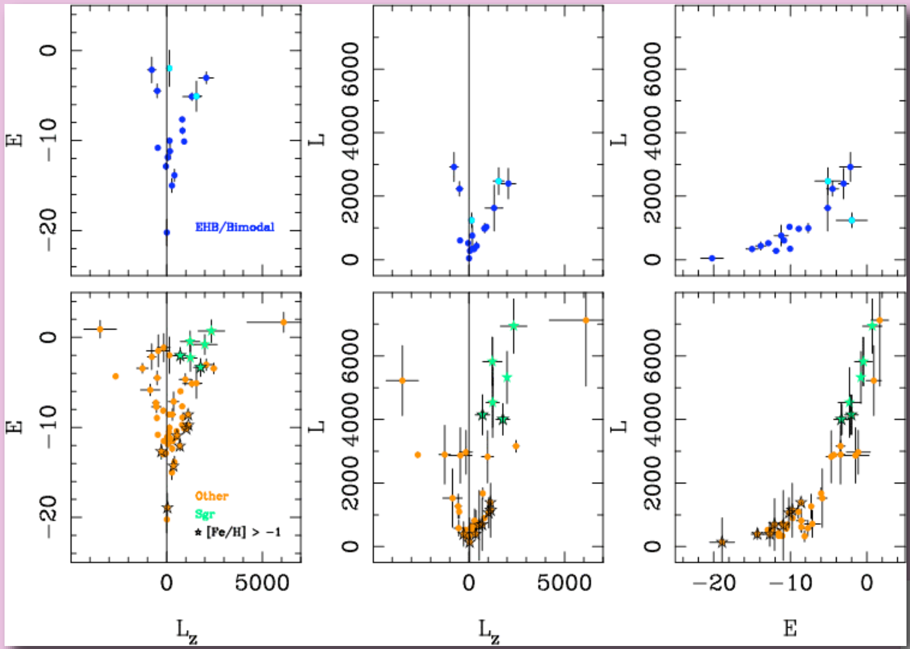

- Single episode cluster formation at z=4; model the metal-poor cluster system.
- Uncertainties: 10% in distance, 0.4 mas/yr in each proper-motion component, and 1 km/s in radial velocity.

# Integrals of Motion Diagram

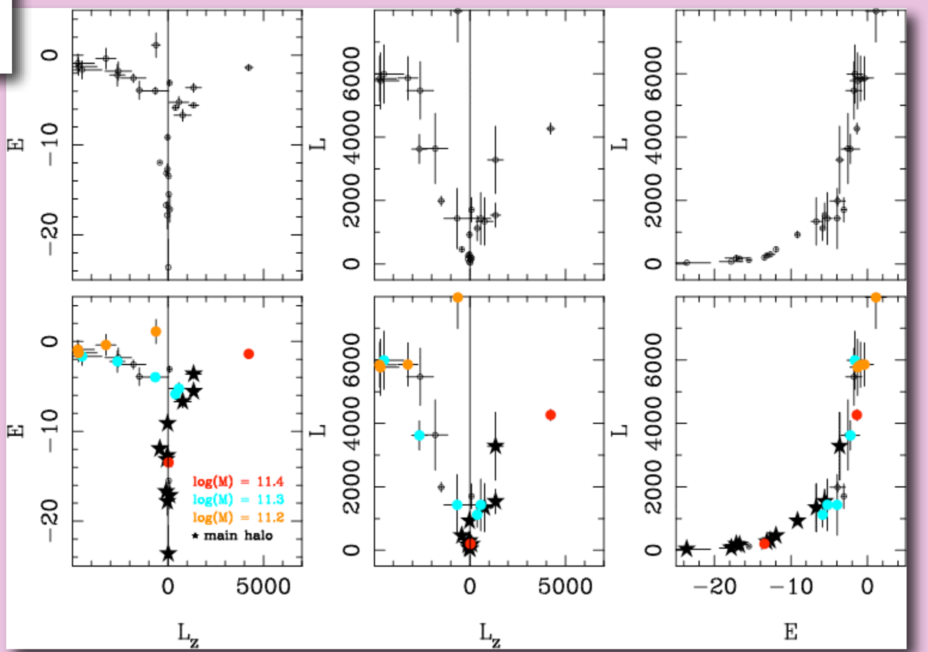
Helmi and de Zeeuw 2006



# Globular Cluster Results: Orbits

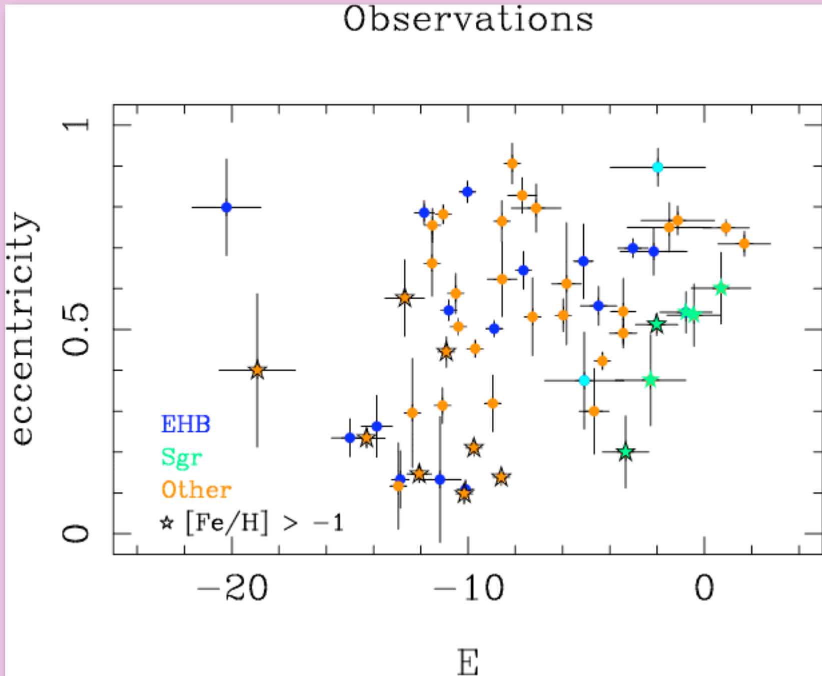


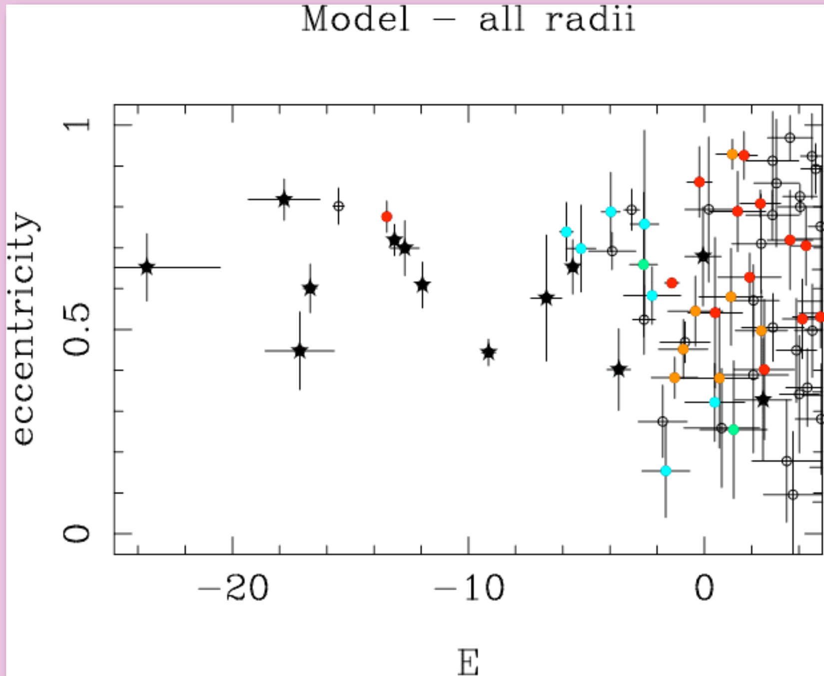

Observations




Model: within 30 kpc

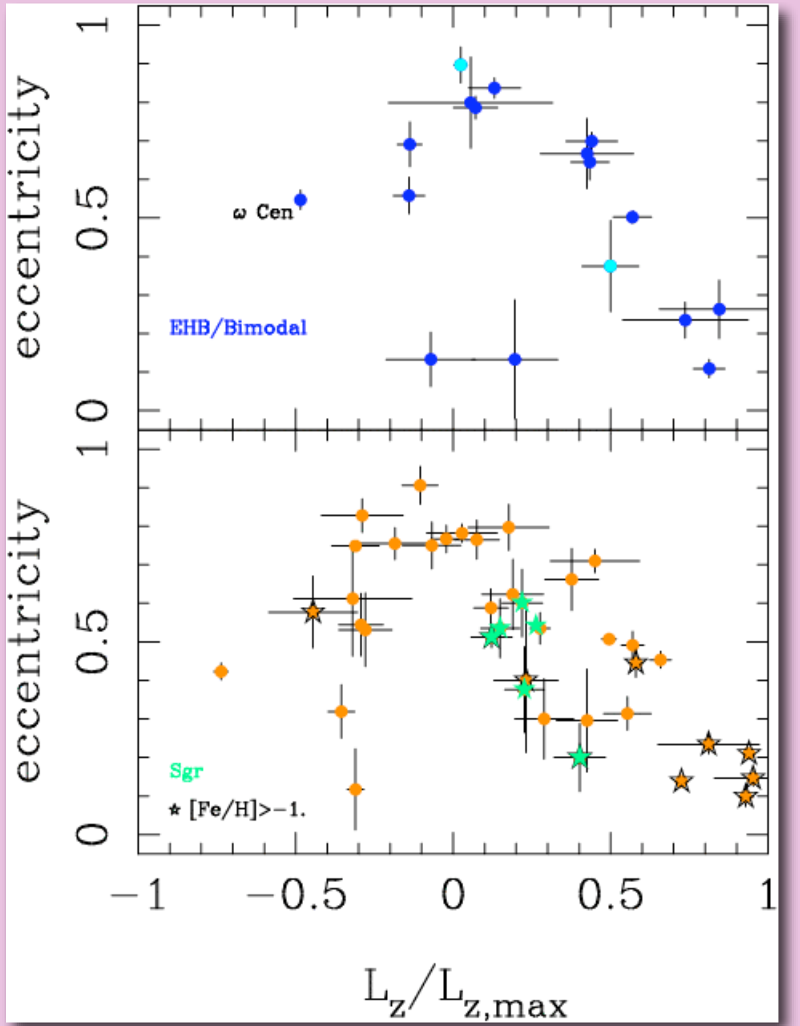
# Globular Cluster Results: Orbits (cont.)



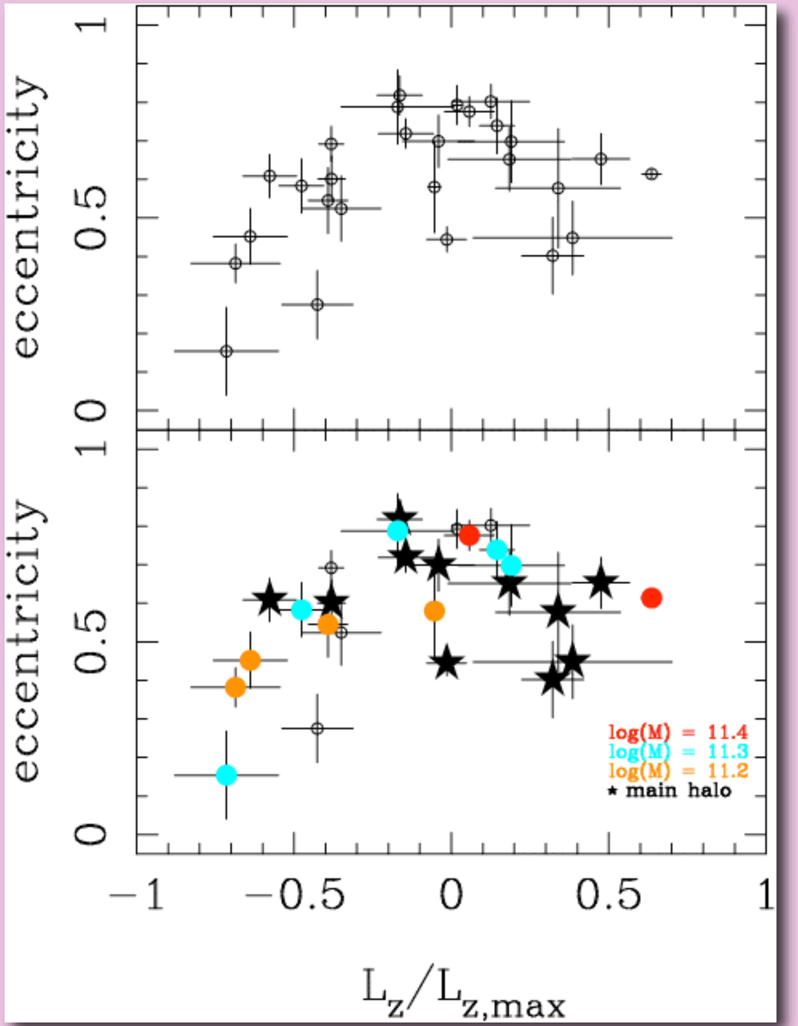



# Globular Cluster Results: Orbit shapes

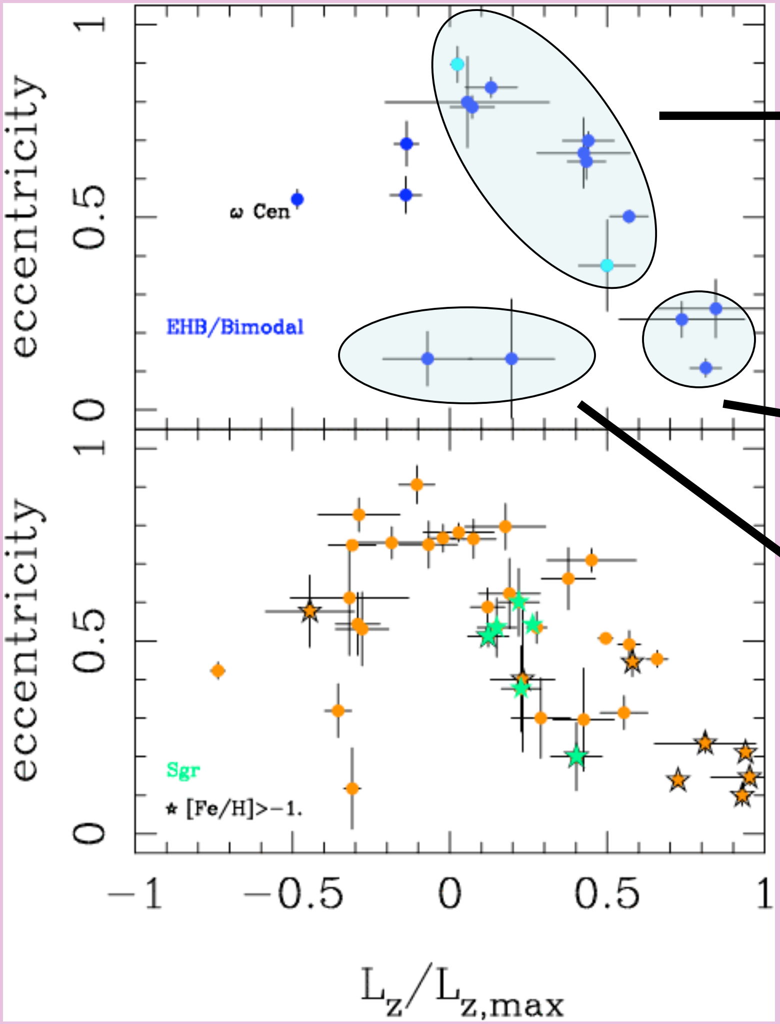
Observations




Model: within 30 kpc



# Globular Cluster Results: Orbit shapes and Groups

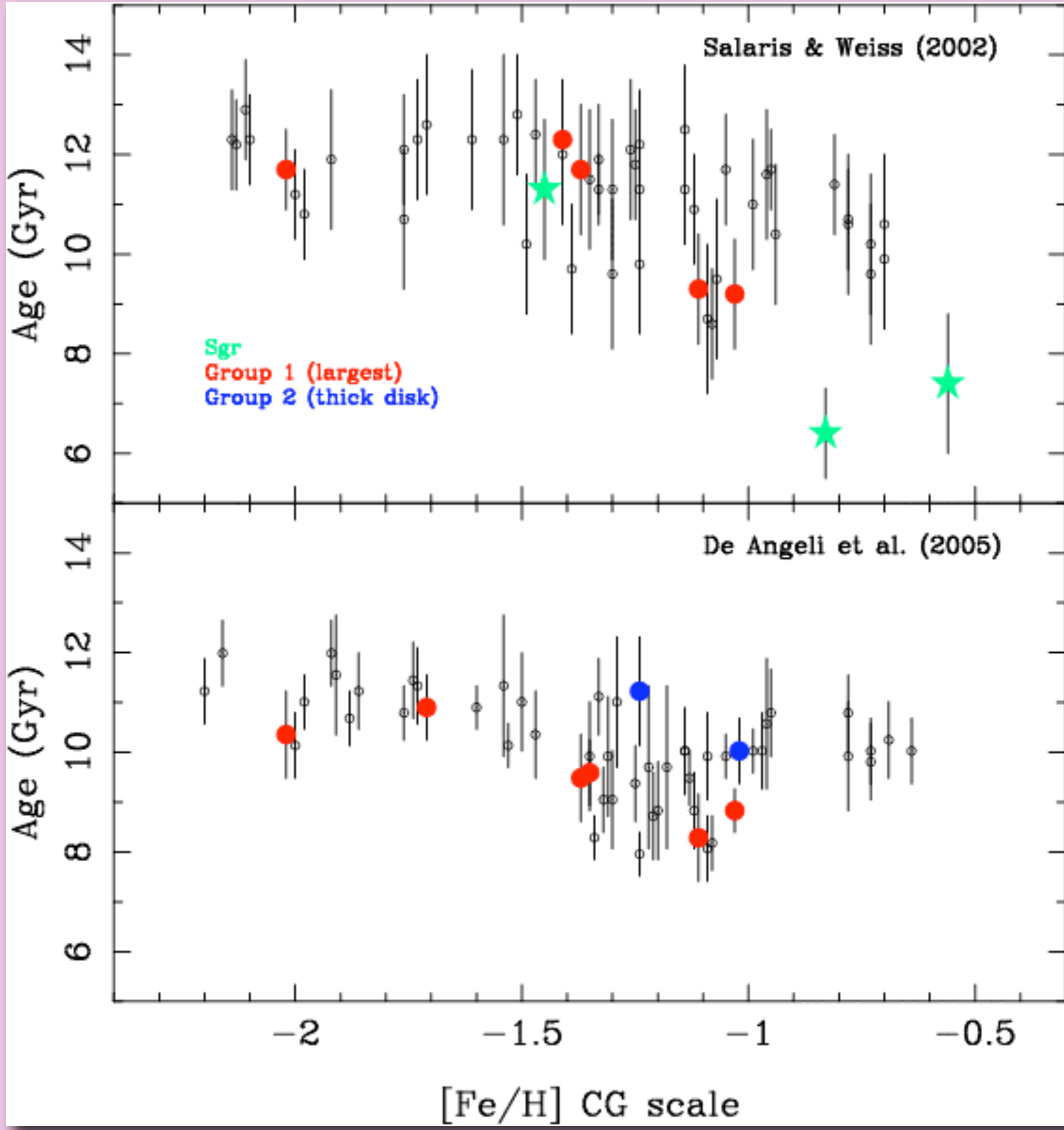



Largest possible group: 8 (excluding 5904/M5); group 1

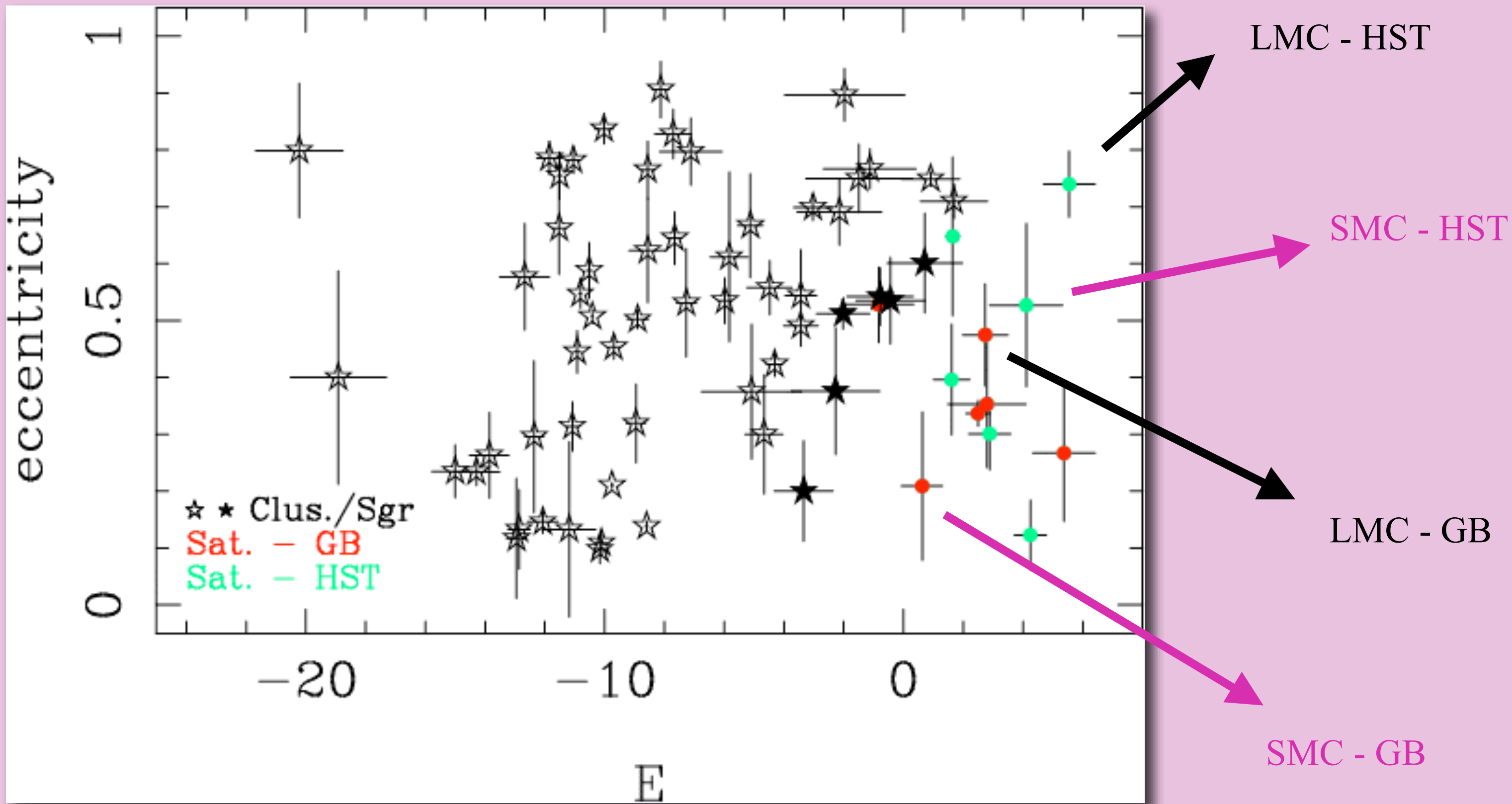
Thick-disk orbits; group 2

Polar orbits

# Age-metallicity relationships



# Globular Clusters and Satellites: Orbit properties



# Summary

• The EHB cluster system (also comprising the most massive clusters in our Galaxy), have mean velocity components different from zero, indicating that they have preserved some phase-space structure from their original parent(s) system, and therefore reinforcing their extragalactic origin. Comparison with the Prieto & Gnedin model indicates that they may come from very few initial systems (~4).

• The non-EHB clusters show a larger spread in the Lz at low orbital energies than do the model clusters. Also, the observed clusters show a larger range in eccentricity than do those of the model at low orbital energies. At high orbital energies, the observed clusters appear to have preferentially highly eccentric orbits, unlike the predictions of the model.

• From the EHB system, by selecting clusters according to their orbital characteristics, we can identify some 4 groups. For the one with the largest number of clusters, their appears to be an age-metallicity relationship. Thus, it seems that the EHB clusters were formed in a few systems, and not each in one different system.

• The proper-motion measurements of dwarf satellites appear not to be secure yet, thus making it difficult to understand them as a system.