Dynamical Evolution of Star Clusters

- Star clusters & stellar birth
- Dynamical evolution of a star cluster
- Outstanding issues/some latest studies

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Star Formation = Cluster Formation

Stars are formed in groups out of dense molecular cloud cores, and planets are formed, at the same time as the stellar birth, in dusty circumstellar disks.

Giant Molecular Clouds

$D = 20\sim100$ pc; $\mathcal{M} = 10^5\sim10^6\ \mathcal{M}_\odot$;
$\rho \approx 10\sim300\ \mathrm{cm}^{-3}$; $T \approx 10\sim30$ K;
$\Delta v \approx 5\sim15\ \mathrm{km}^{-1}$

Molecular clumps/ clouds/condensations

$n \sim 10^3\ \mathrm{cm}^{-3}$, $D \sim 5$ pc, $M \sim 10^3\ \mathrm{M}_\odot$

Dense molecular cores

$n \geq 10^4\ \mathrm{cm}^{-3}$, D ~ 0.1 pc, $M \sim 1\text{-}2\ \mathrm{M}_\odot$

李建德 dust formation
姜博識 brown dwarfs
黃柏傑 young dusty disk

Jeans Mass $\mathcal{M}_{\mathrm{J}} \propto T^{3/2}/\rho^{1/2}$ in cgs and solar units

If $\mathcal{M}_{\text{cloud}} > \mathcal{M}_{\mathrm{J}}$ (critical mass) ➔ cloud collapse

GMCs $\mathcal{M}_J \approx 100 \sim 1000\ \mathcal{M}_\odot$ But stars $\sim$0.08 to 120 $\mathcal{M}_\odot$

Cloud collapse → $\rho \uparrow$, and if sufficient cooling, $T \approx$ const (isothermal)

denser → more collisions/excitations/line emission → if photons escape → cooling

→ $\mathcal{M}_{\mathrm{J}} \downarrow$, i.e., easier to exceed ➔ **fragmentation** to clumps/cores

… until a core very dense, so no longer optically thin (adiabatic)

→ $T \uparrow$ ➔ formation of a star or two for each core ➔ a **star cluster**

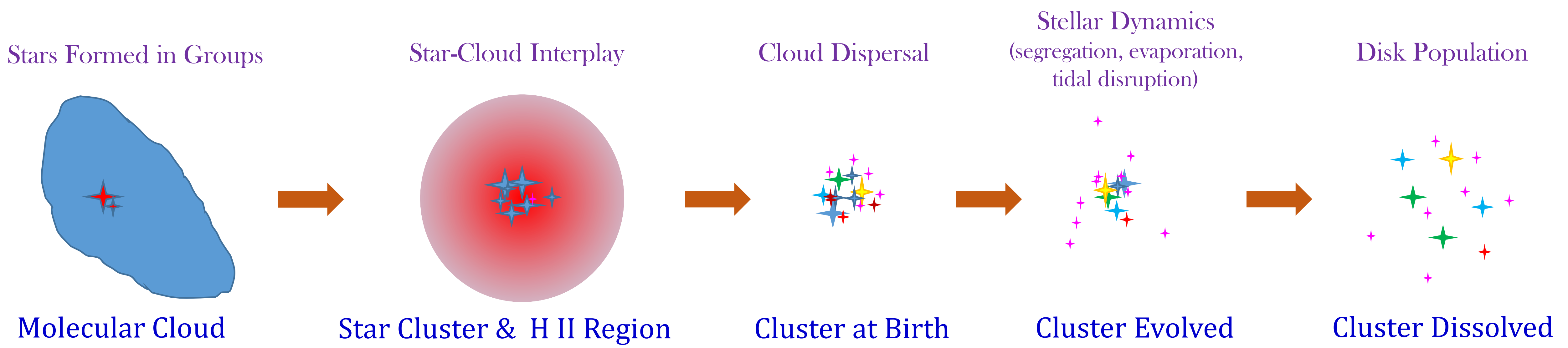
- Member stars in a star cluster have the same age, same chemical abundances, and at the same distance from us. … **well, almost**

Evolution of Star Clusters

Chen, Chen & Shu, 2004, AJ, 128, 2306
Chen & Chen, 2010, ApJ, 721, 1790

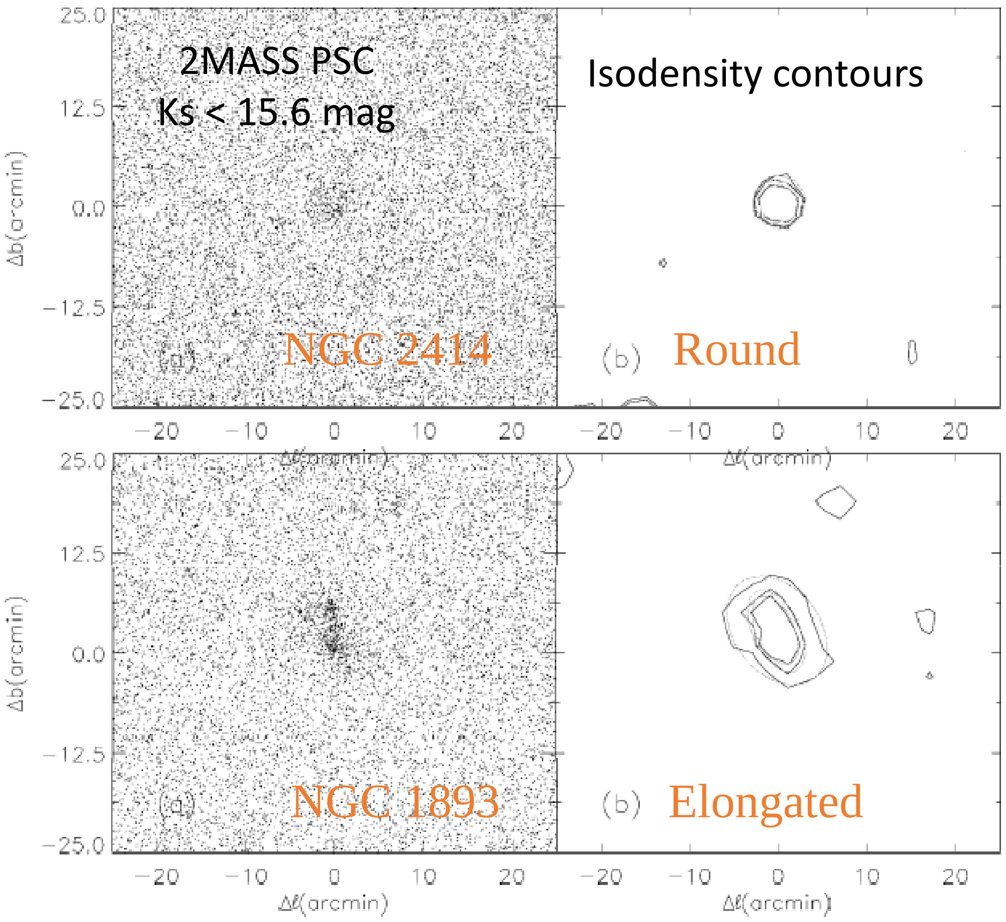
- (Initial) Molecular clouds are clumpy and filamentary; so are the youngest star clusters.
- (Internal) Mutual gravitational interaction among members tend to virializes the cluster into a spherical shape (relaxation), with more massive stars concentrating more toward the center (mass segregation). Lowest-mass members are vulnerable to ejection out from the system (stellar evaporation).
- (External) Eventually Galactic perturbations (tidal forces, differential rotation) distort and rip apart the star clusters. Then-members supply the Galactic disk population.
- A recently dissolved system in the solar neighborhood may be recognized as a moving (star) group.

陳長耀 moving groups


Stars Formed in Groups
Star-Cloud Interplay
Cloud Dispersal
Stellar Dynamics
(segregation, evaporation, tidal disruption)
Disk Population
Molecular Cloud
Star Cluster & H II Region
Cluster at Birth
Cluster Evolved
Cluster Dissolved

Shape Morphology

Probabilistic star counting --- weighting each star by the number of neighbors



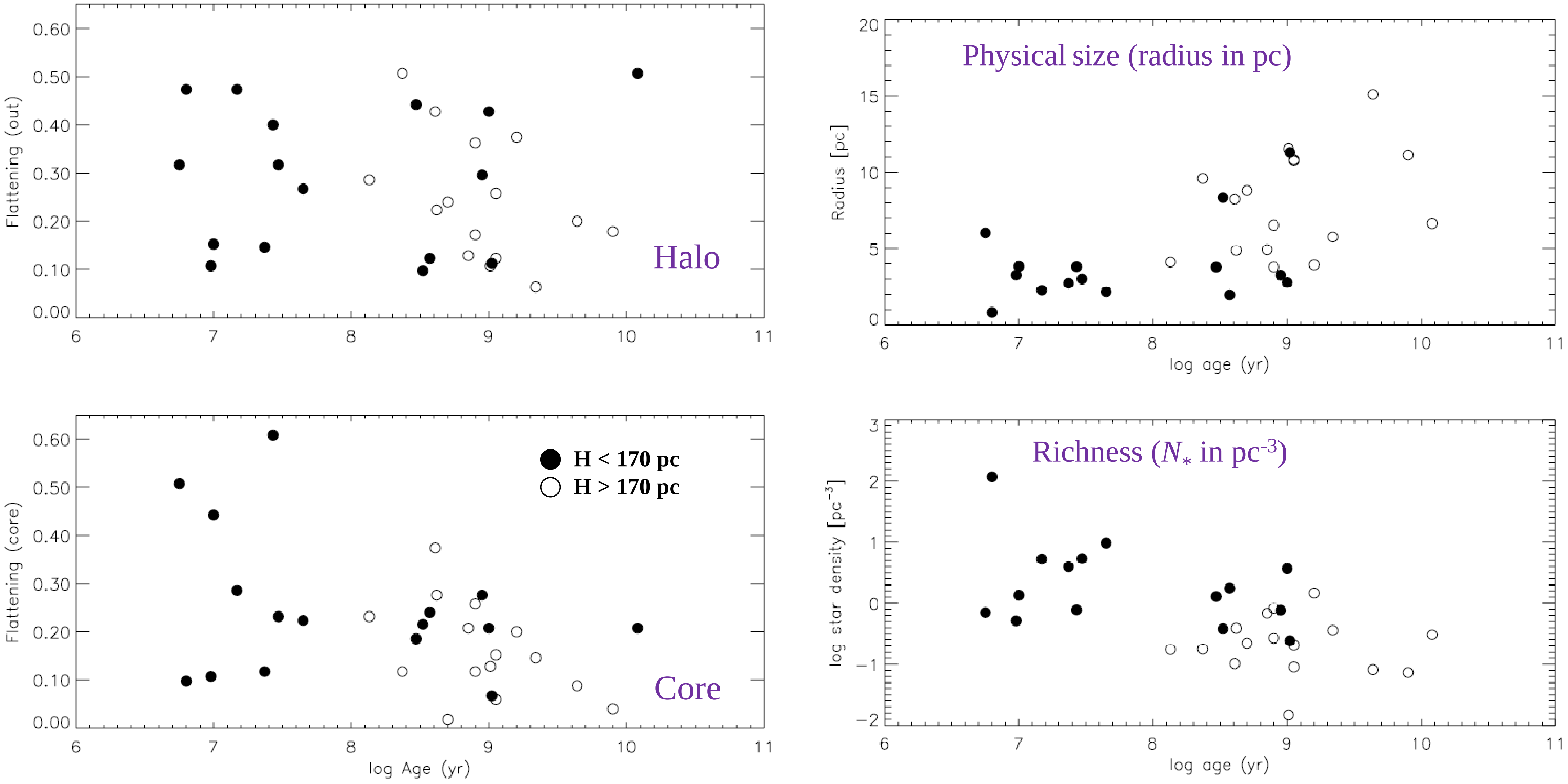
Core:

1/3 max density

Halo:

3 times field fluctuation

OCs are in general flattened, even among the youngest ones of a few Myr. As an OC ages, its core becomes circularized by stellar dynamics; the overall size expands and stellar density drops.



Globular Clusters are flattened

Axial Ratios of 116 GCs

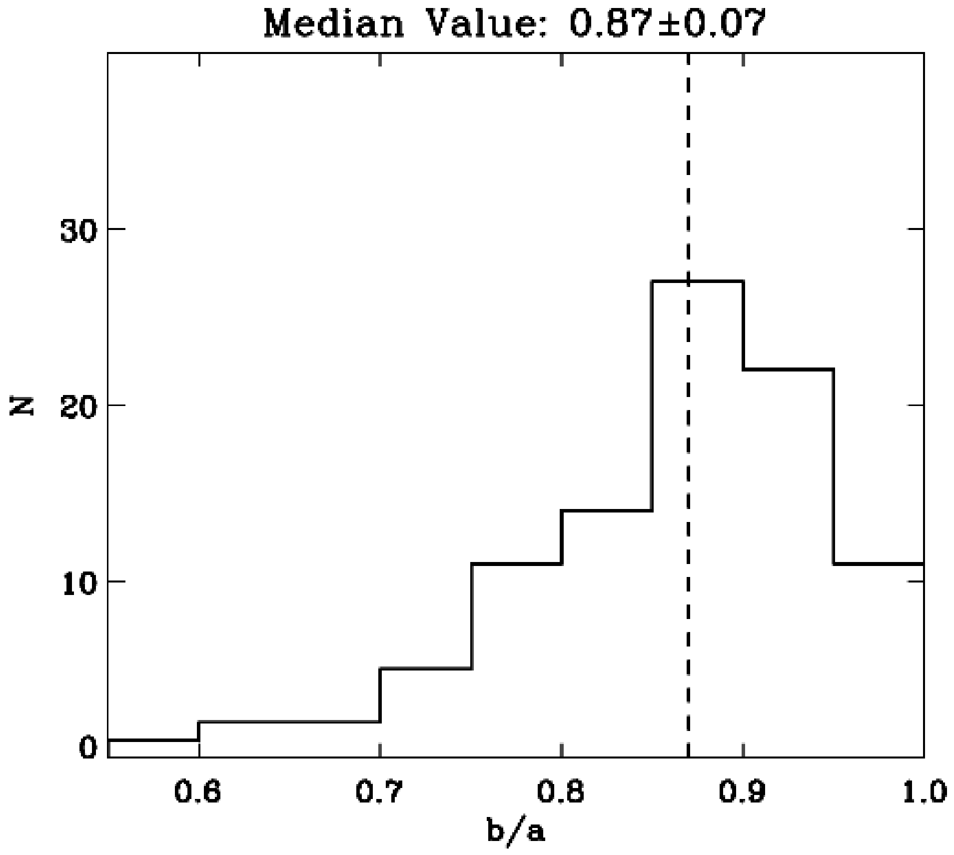


Fig. 6.— The distribution of the axial ratios of the 95 Galactic globular clusters with reliabile measurements. The dashed line indicates the median value of 0.87 of the sample.

(CW Chen & WP Chen, 2010)

Dynamical Relaxation of a Stellar System

Spitzer (1988)
Shu (1984)

$$\tau_{\rm cross} = \frac{D}{v}$$

$$N_{\rm cross} = \frac{0.1\,N}{\ln N}$$

$$\tau_{\rm relax} = \tau_{\rm cross} \cdot N_{\rm cross}$$

$$\tau_{\rm evap} \approx 96\,\tau_{\rm relax}$$

where

$\tau_{\rm cross}$ … time for a star to move across cluster = dynamical time scale

D … diameter of the cluster

v … velocity of the star

N … number of stars in the cluster

$N_{\rm cross}$ … number of crossings

$\tau_{\rm relax}$ … relaxation time scale

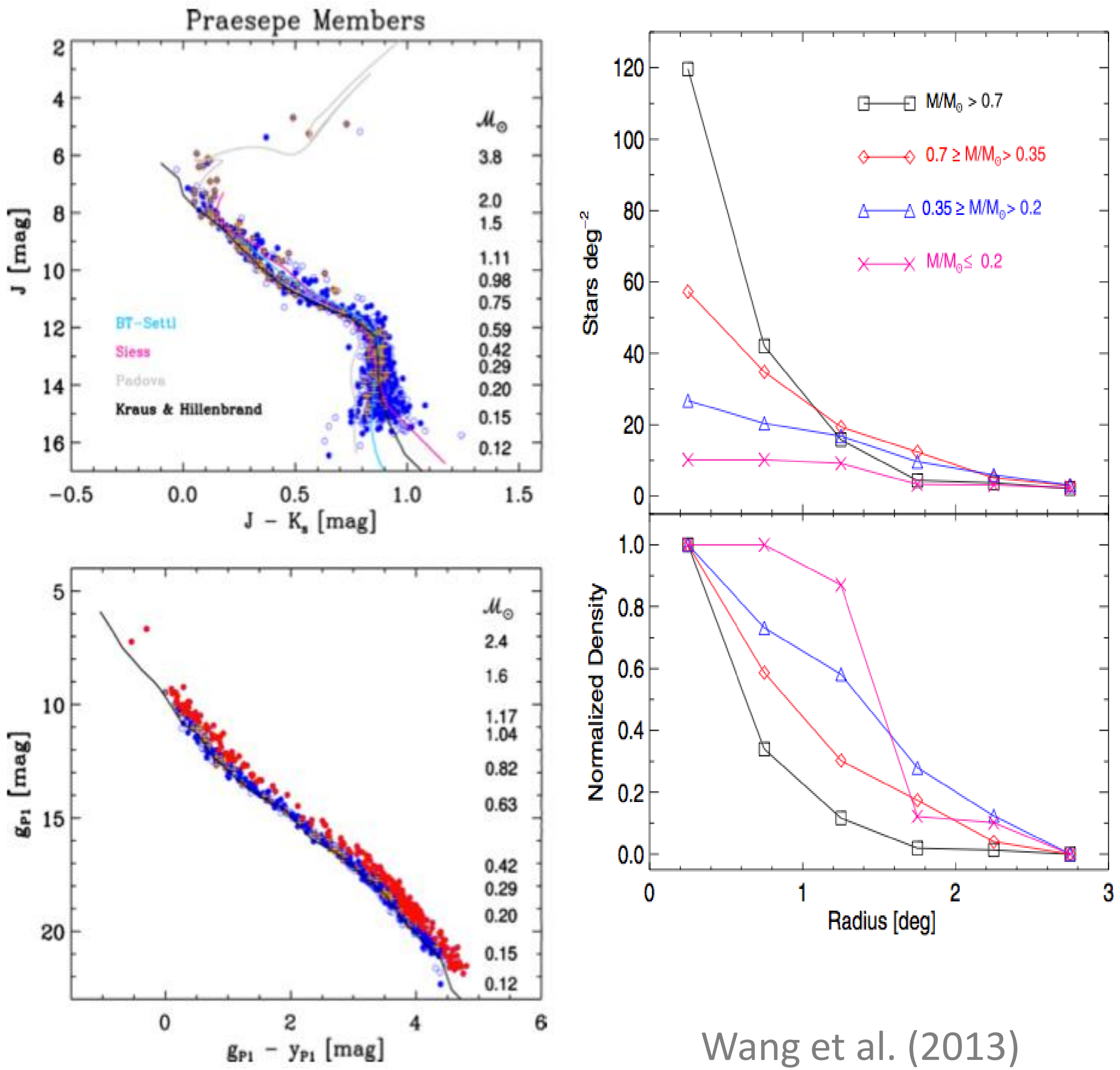
$\tau_{\rm evap}$ … stellar evaporation time scale

For a typical GC, $\tau_{\rm relax} \approx 10^8 \sim 10^9$ yr **Most GCs have been relaxed.**

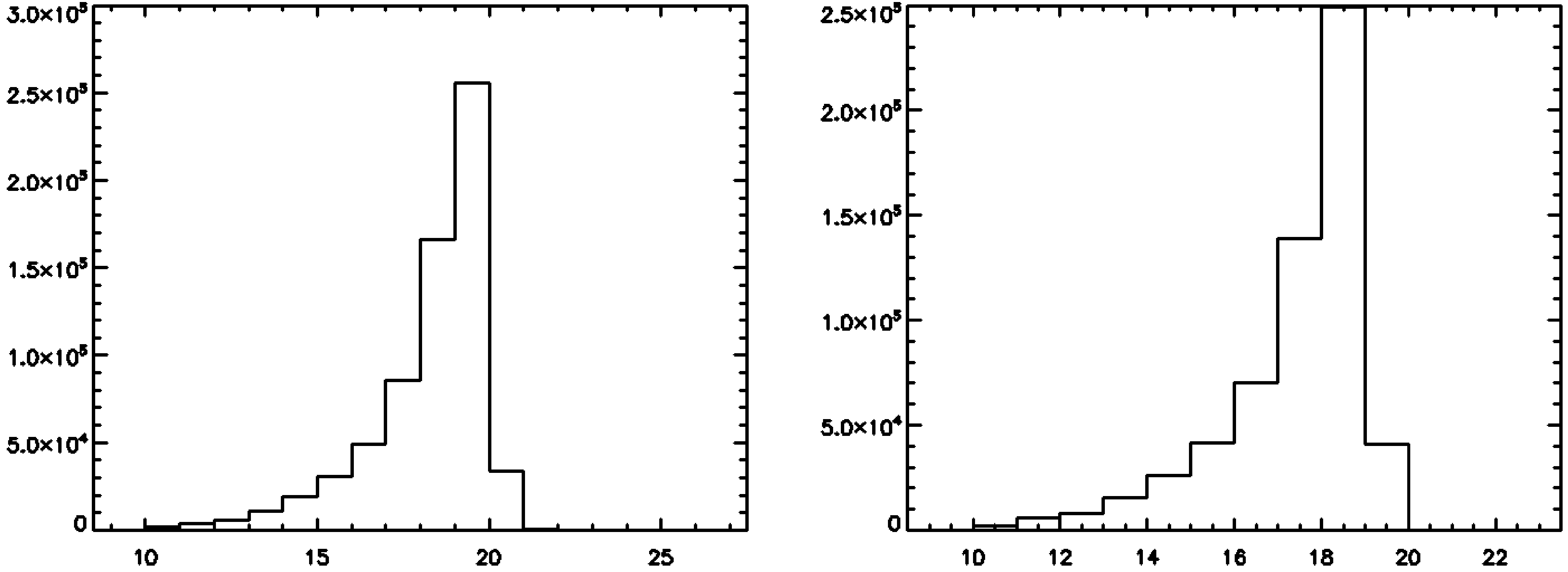
For a typical OC, $\tau_{\rm relax} \approx 10^6 \sim 10^7$ yr **Young OCs are being relaxed.**

Praesepe (M44, 750 Myr, 179 pc)

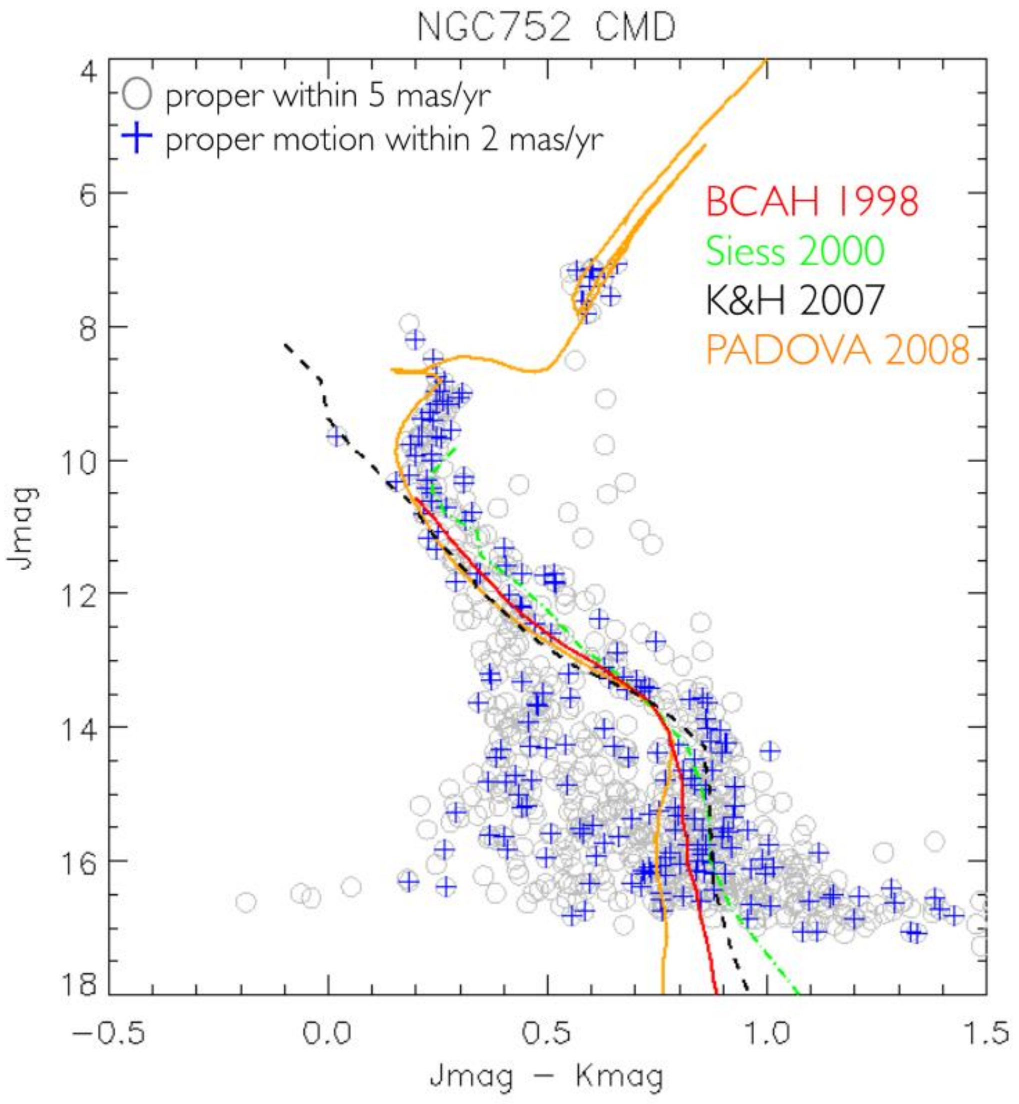
- A secured list of 1040 member candidates to test stellar evolutionary models
- 20-40% binary freq. with a preference of similar-mass pairs
- Mass segregation with the lowest mass members ($< 0.2\ M_\odot$) being stripped away
- The cluster being dissolved

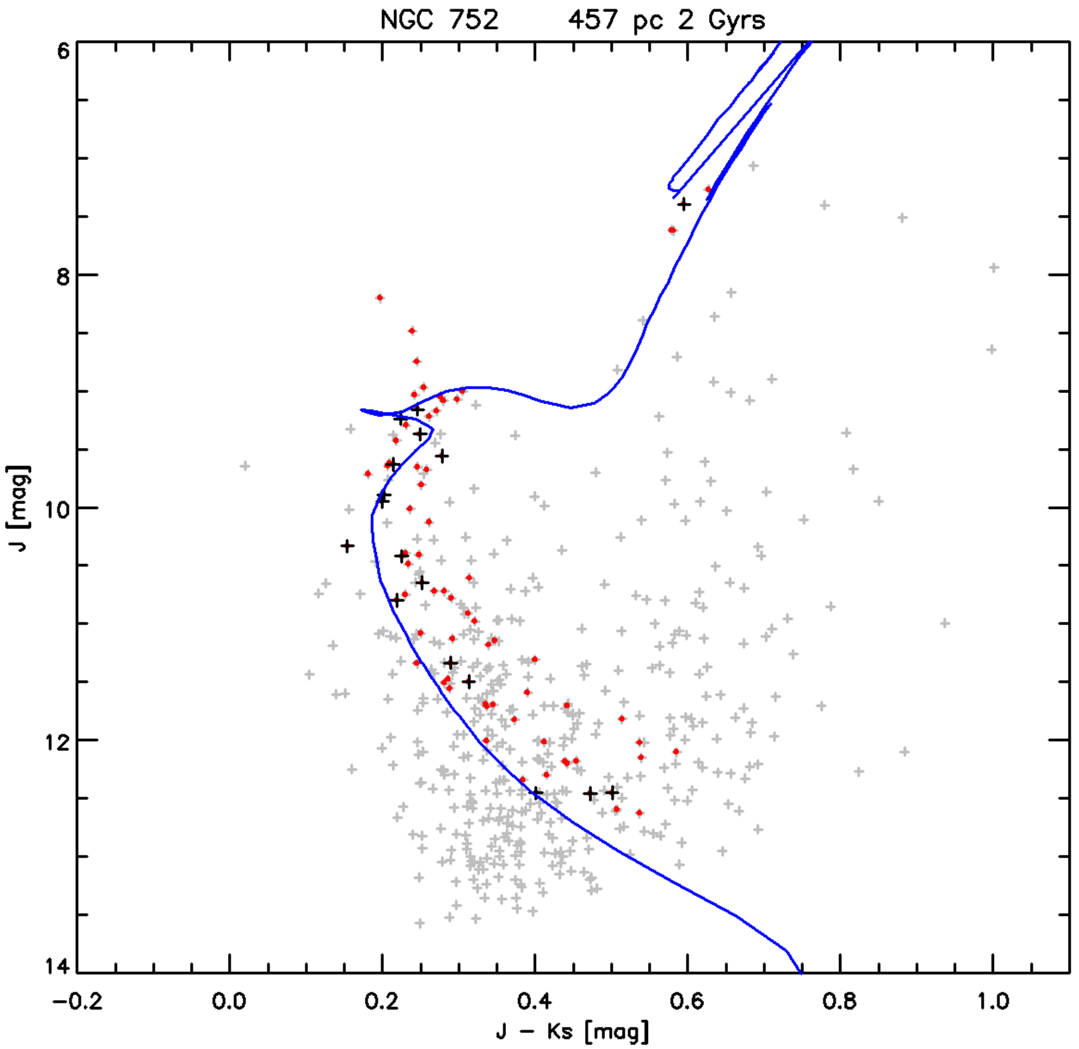


Wang et al. (2013)



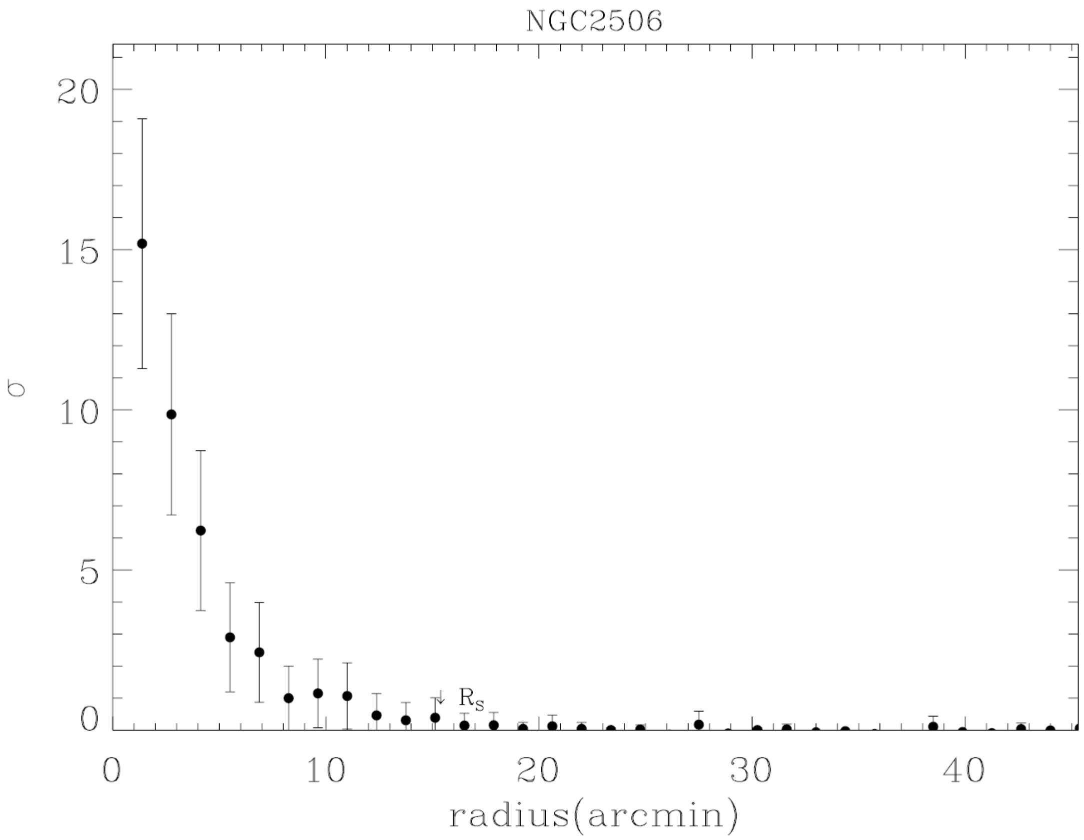
UKIDSS J and K data can probe much fainter (substellar) members

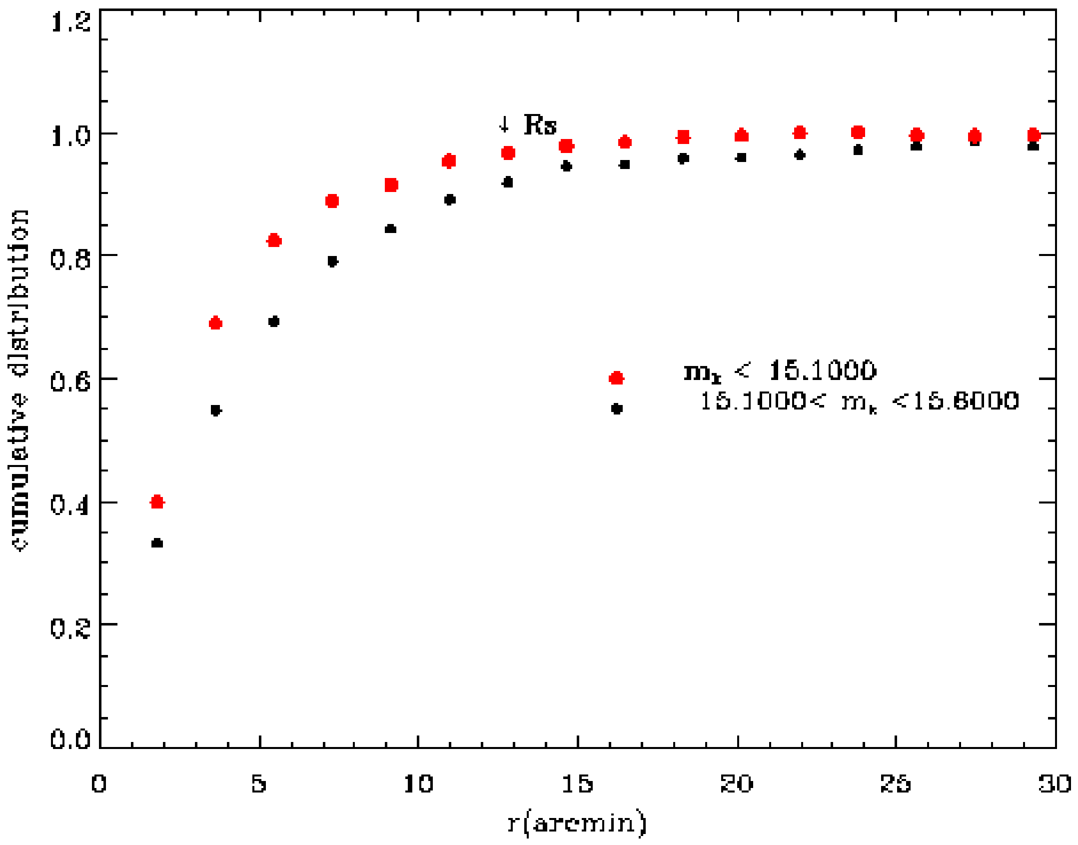




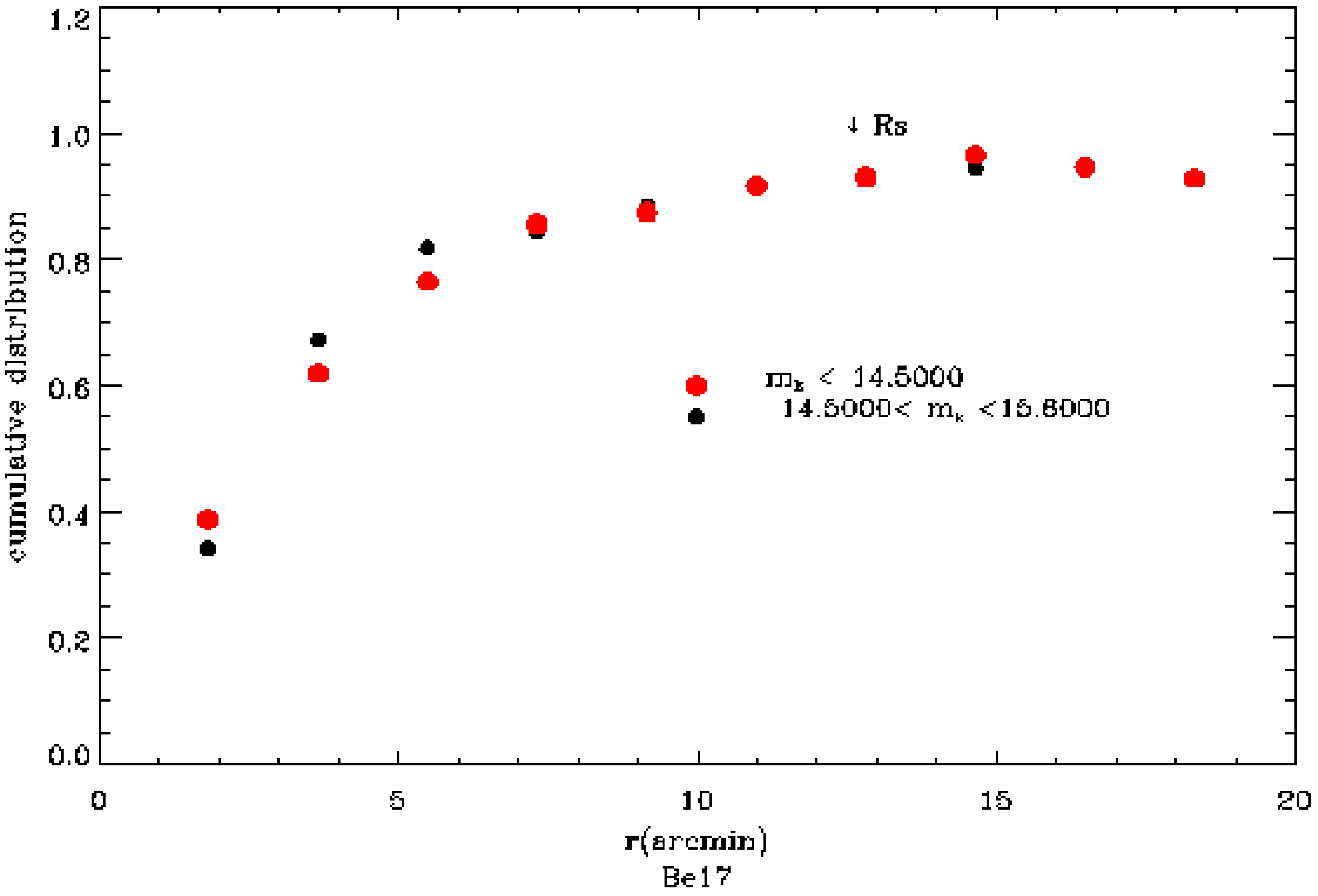
Member selection by (1) Position, (2) Proper Motions, (3) Isochrone (distance), and (4) Radial Velocity

Dynamical Evolution



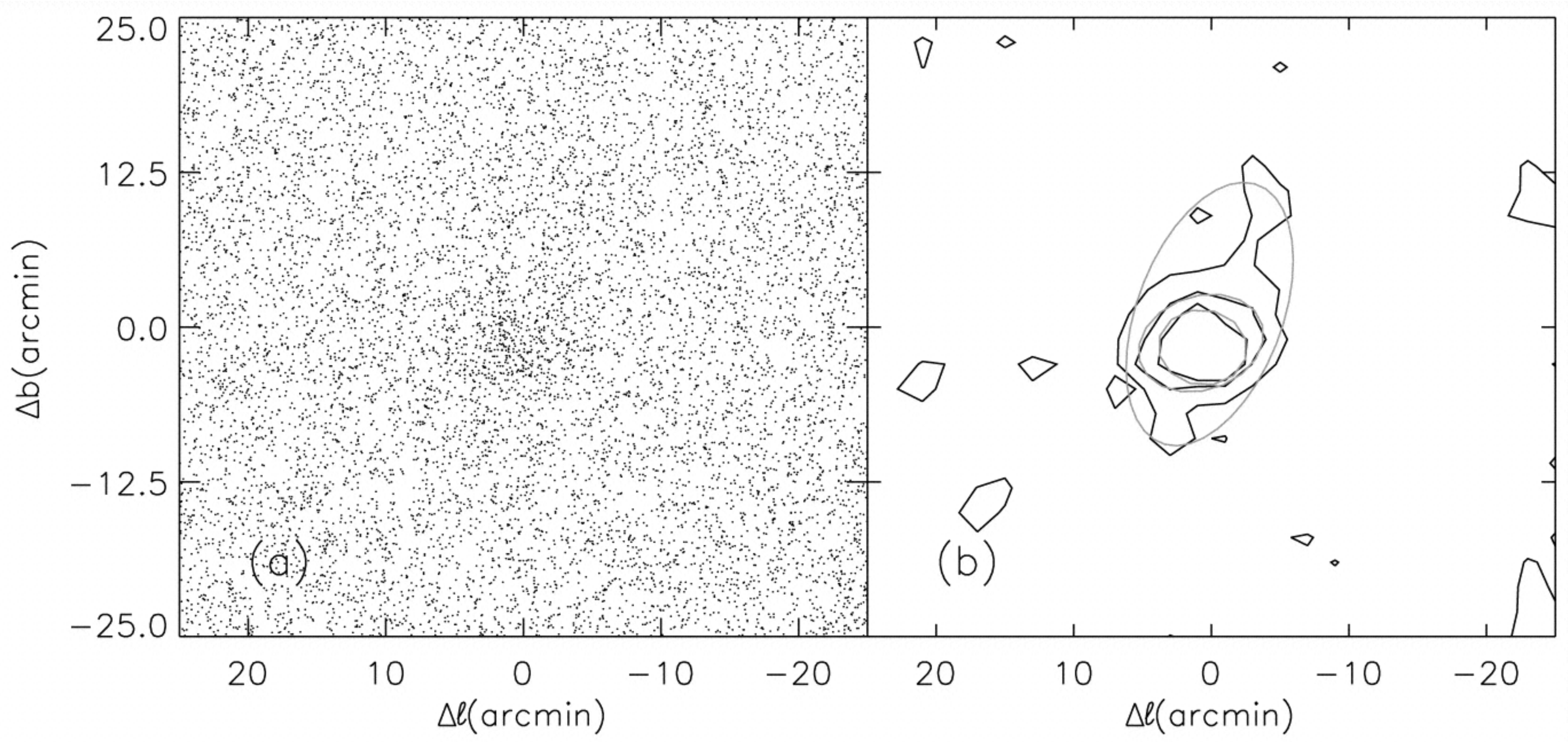


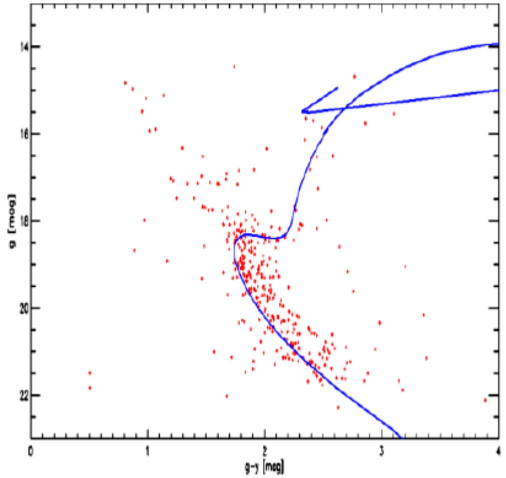
Cumulative stellar density profiles for NGC 2506, showing clear evidence of **mass segregation**

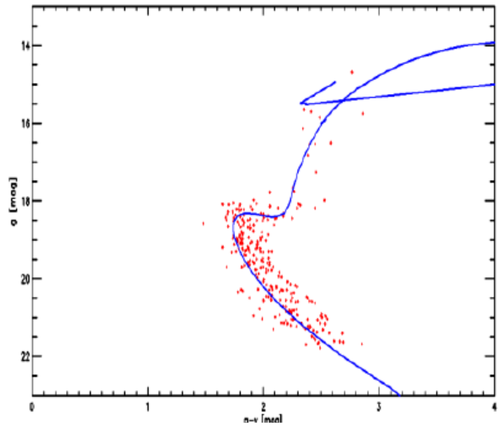


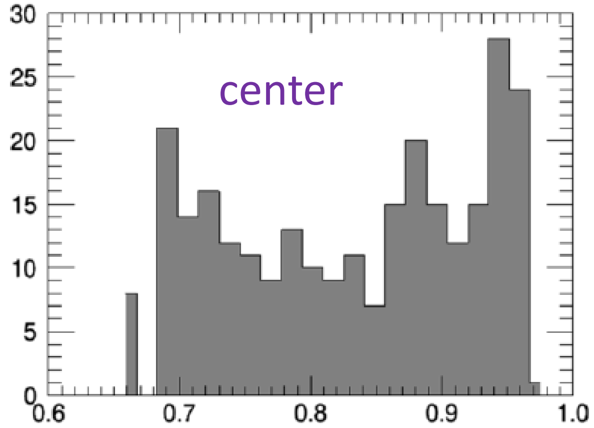
… while the old OC (log (age [years]) = 10) Berkeley 17 does not show mass segregation.

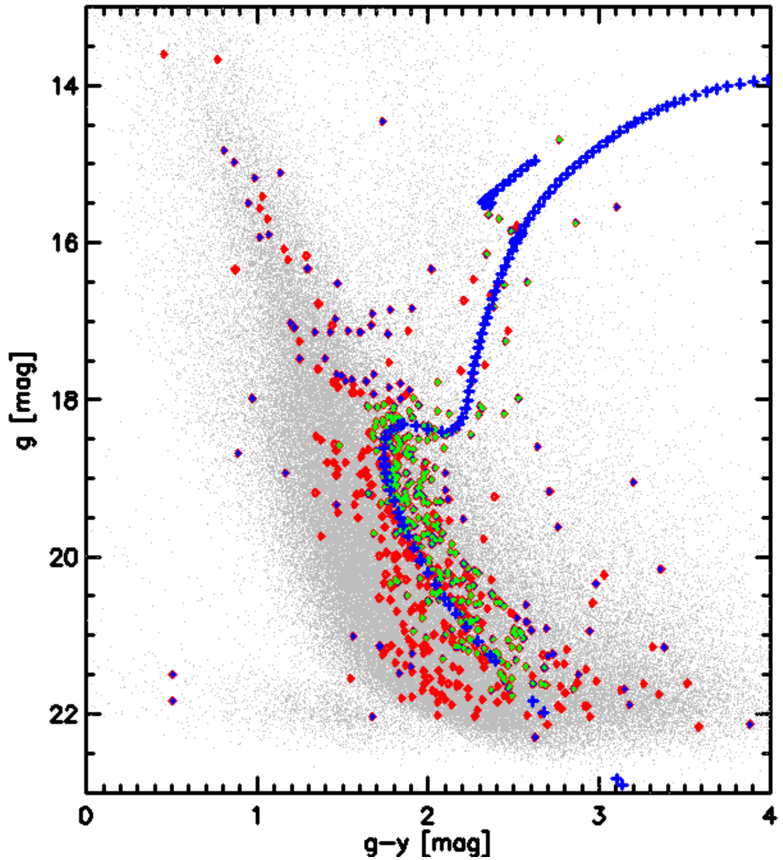
Eventually tidal force and Galactic differential rotation tear the cluster apart.



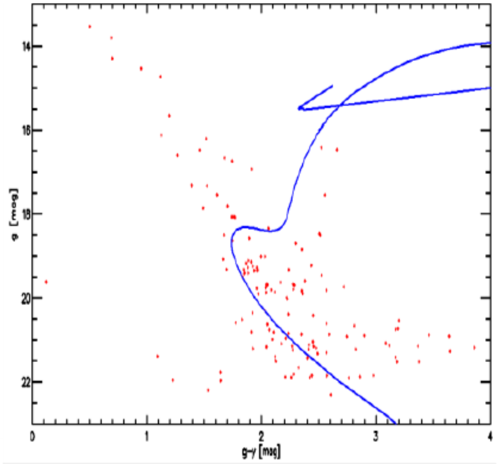


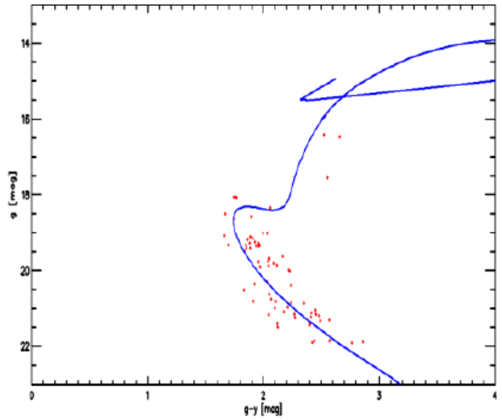


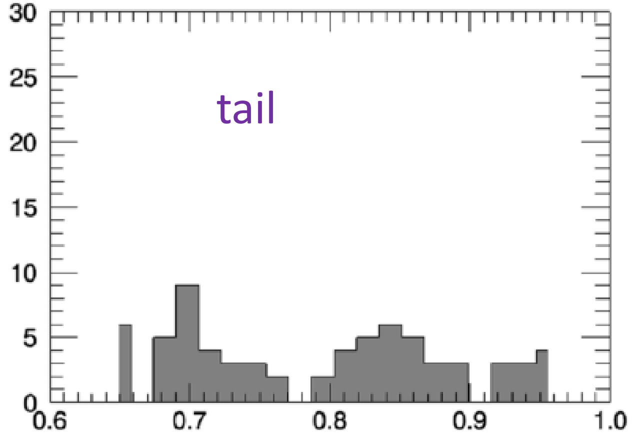




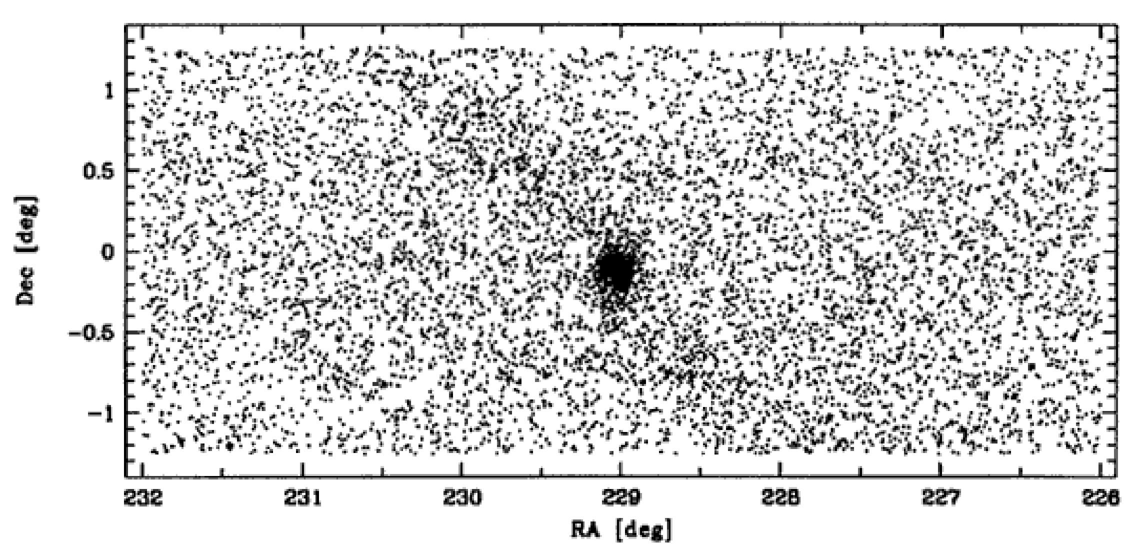
Statistically cleaned CMDs
→ member stars in the tail systematically less massive than those in the core

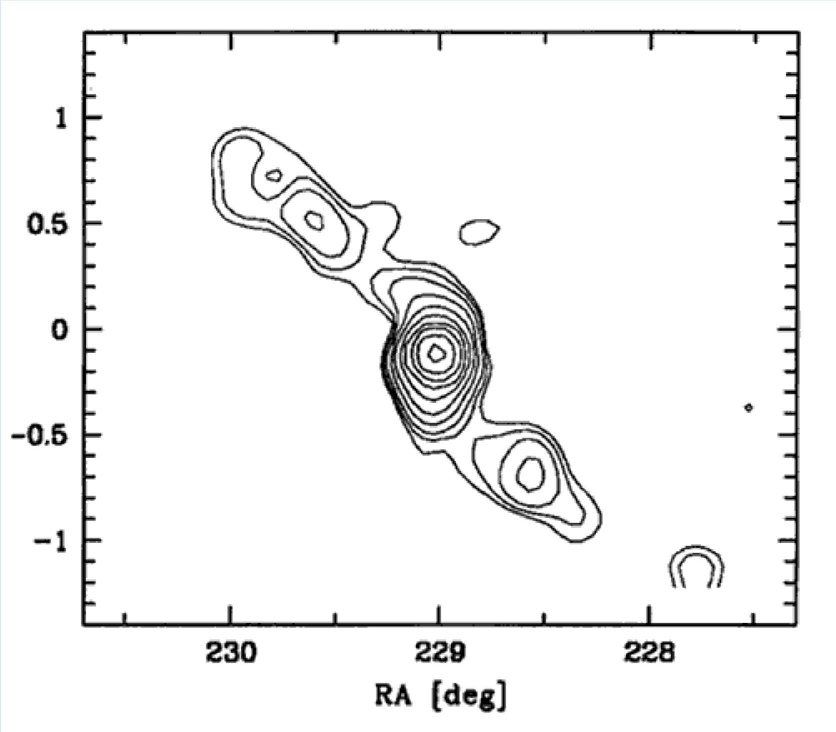


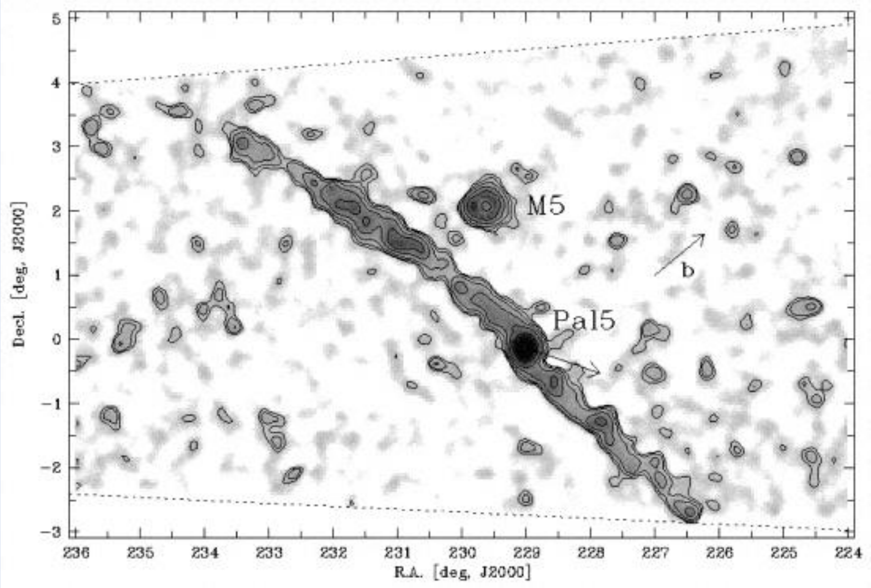




Tidal Tails







The "archetype" of globular cluster tidal tails -- those found by the digital sky survey on the globular cluster Palomar 5. Upper panels from Odenkirchen et al. (2001, AJ, 548, L165) showing initial discovery in the SDSS equatorial strip data. Lower panel is an extended view of 10 degree tails from Sloan in Odenkirchen et al. (2003, AJ, 126, 2385).

http://www.astro.virginia.edu/class/majewski/2007/astr551/lectures/globular_clusters/life_cycle.html

Tidal Tails

Chen, CW, et al. (2010)

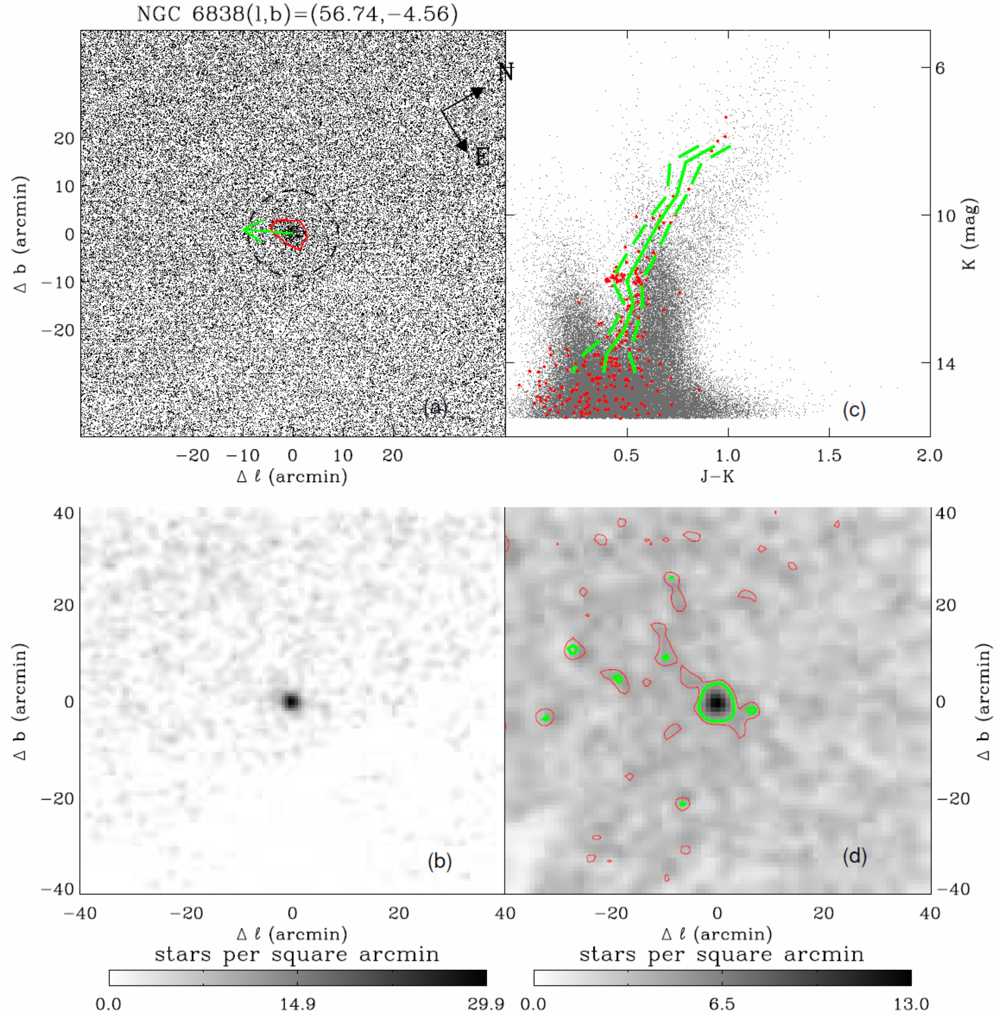


Figure 30. Same as Figure 19 but for the halo GC NGC 6838, for which the axial ratio is determined to be 0.68 ± 0.02.

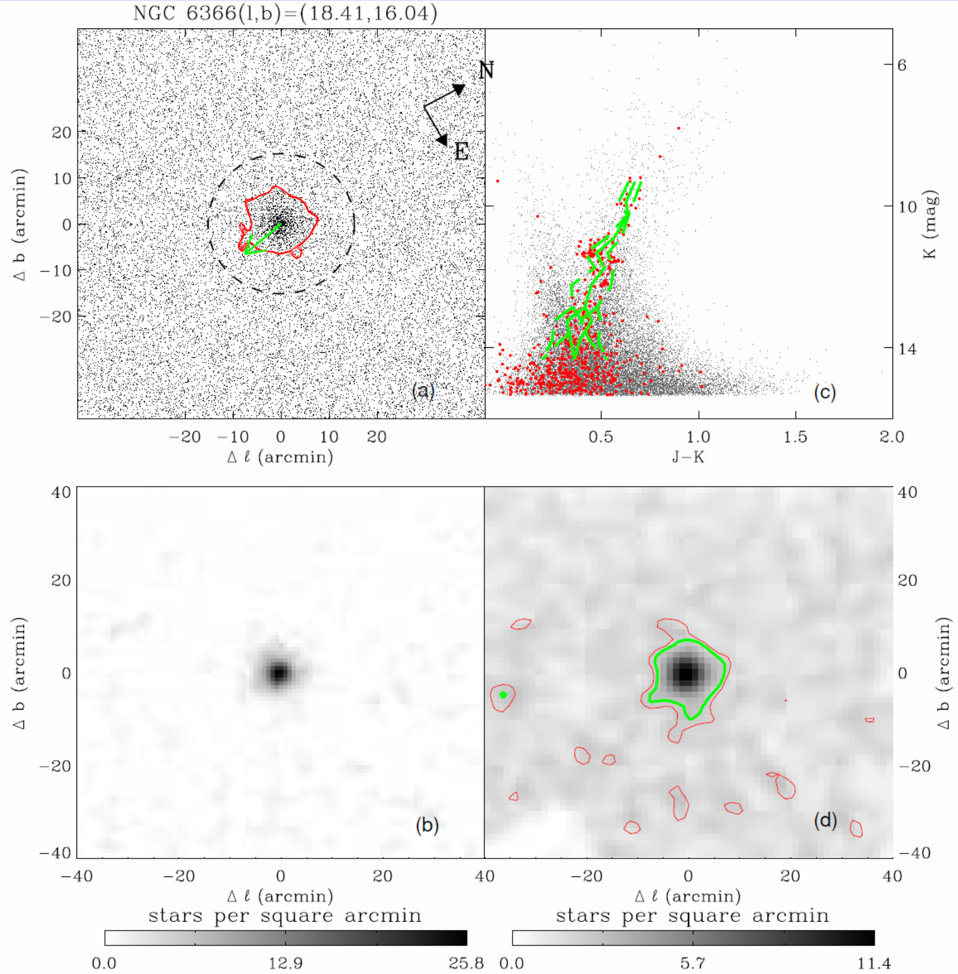


Figure 35. Same as Figure 19 but for the bulge GC NGC 6366, whose probable member stars selected by the color–magnitude method (see the text) show clumpiness around the cluster.

Conclusion

So stay tuned …

- Nothing of an “old” topic
- Time ripe to study star clusters in quality and in quantity; formation conditions and survival
- Gaining ever more knowledge than before of the long known and studied star clusters, with new answers and new questions---larger *vs* smaller systems; much massive *vs* very low-mass members; systems in MW *vs* beyond.
- An expanded sample of star clusters to probe stellar evolution and Galactic structure/evolution