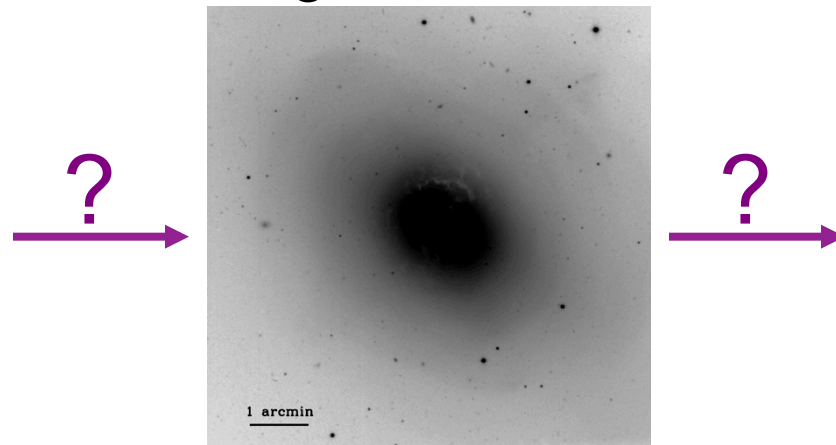


# ***Demography of Globular Clusters in the 3 Gyr-old Merger Remnant NGC 1316: Implications for the Formation History of 'old' GC systems***

Antennae



Merger Remnant



Giant E



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**Acknowledgments:** François Schweizer (OCIW), Brad Whitmore, Diane Karakla (STScI), Thomas Puzia (P.U. Católica)

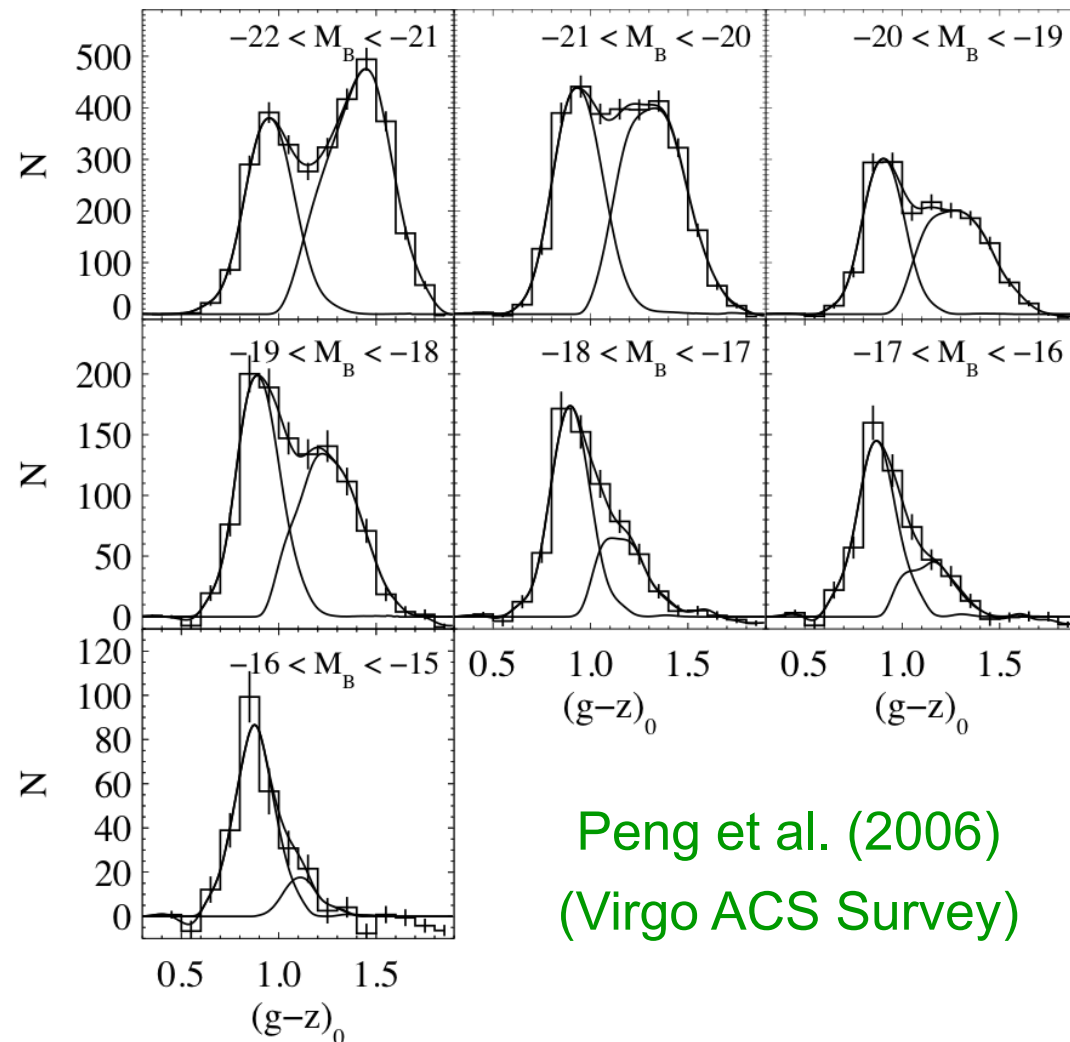
# Globular Cluster Systems: Bimodal Color Distributions

Very common in 'well-observed' giant early-type galaxies

Mainly due to  
*metallicity*

On average, **red** subpopulation shrinks with decreasing galaxy luminosity

**Red** GCs associated with spheroid component



Peng et al. (2006)  
(Virgo ACS Survey)

# GC/Galaxy Formation Models



- Formation of ellipticals / GCs in mergers  
(Schweizer 1987; Ashman & Zepf 1992)
  - Red GCs formed in high-pressure gas during major merger of gas-rich galaxies
  - Blue GCs formed in early (metal-poor) universe, now halo population
  - Predicts red GCs to be more centrally concentrated than blue ones
  
- In-situ / Multi-phase collapse  
(Forbes et al. 1997)
- Accretion / Stripping  
(Côté et al. 1998)
- Hierarchical Merging  
(Beasley et al. 2002)

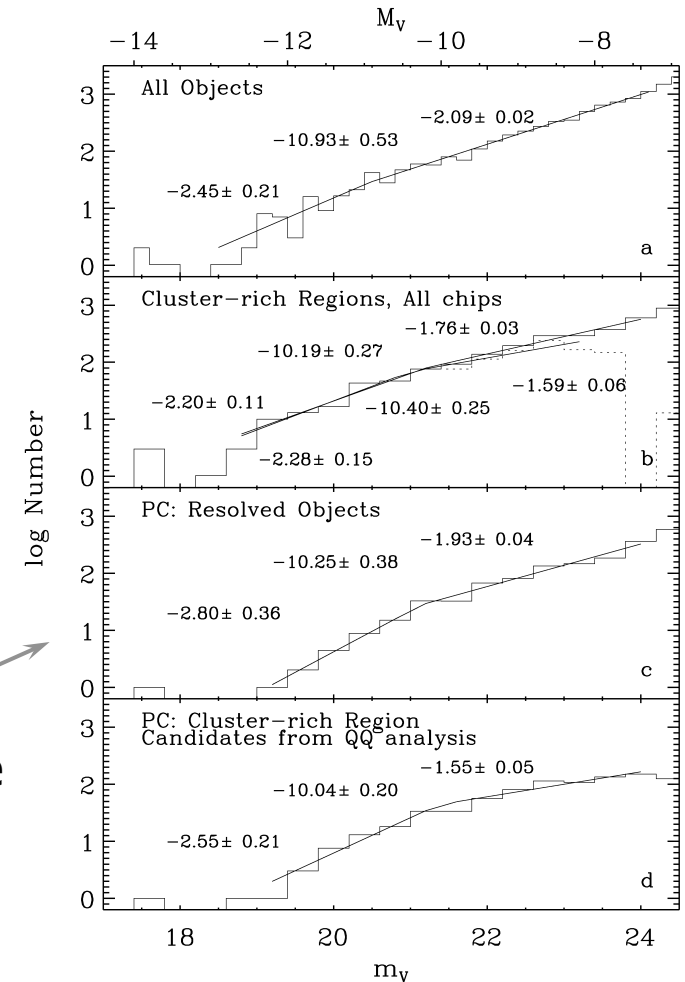
# Luminous, Young GCs found in Merger Remnants

- E.g., Antennae (NGC 4038 / 4039)



- Age  $\sim 2 - 10$  Myr from GHRs Spectra
- *Power-law Luminosity Function (LF)* with slope  $\sim -2$ , similar to GMCs

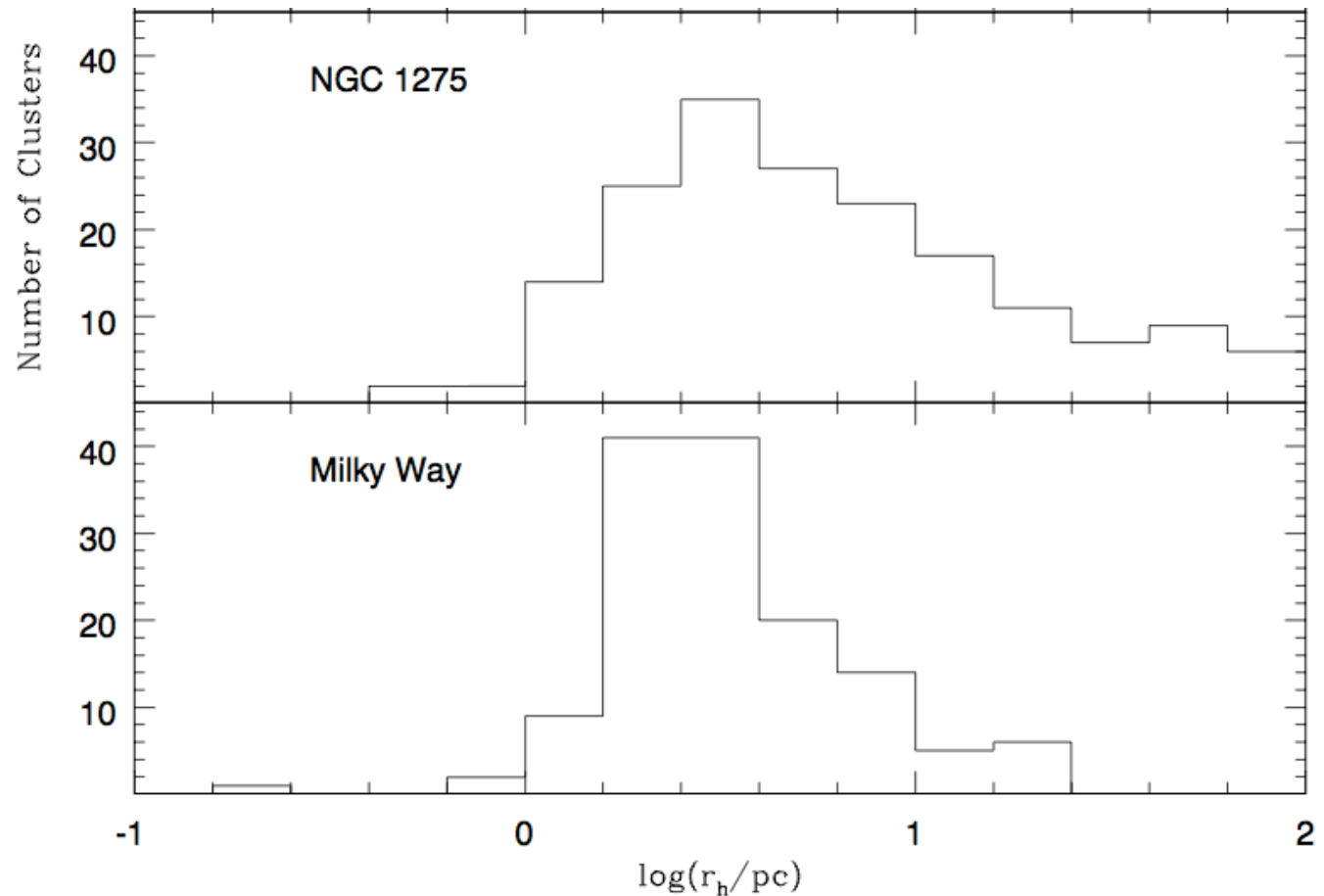
- Similar LFs in NGC 1275, 3256, 3921, 3597, 7252 (Zepf / Schweizer / Carlson et al.)
- Do these clusters become the red GCs in giant Es?



(Whitmore et al. 1999, AJ 118)

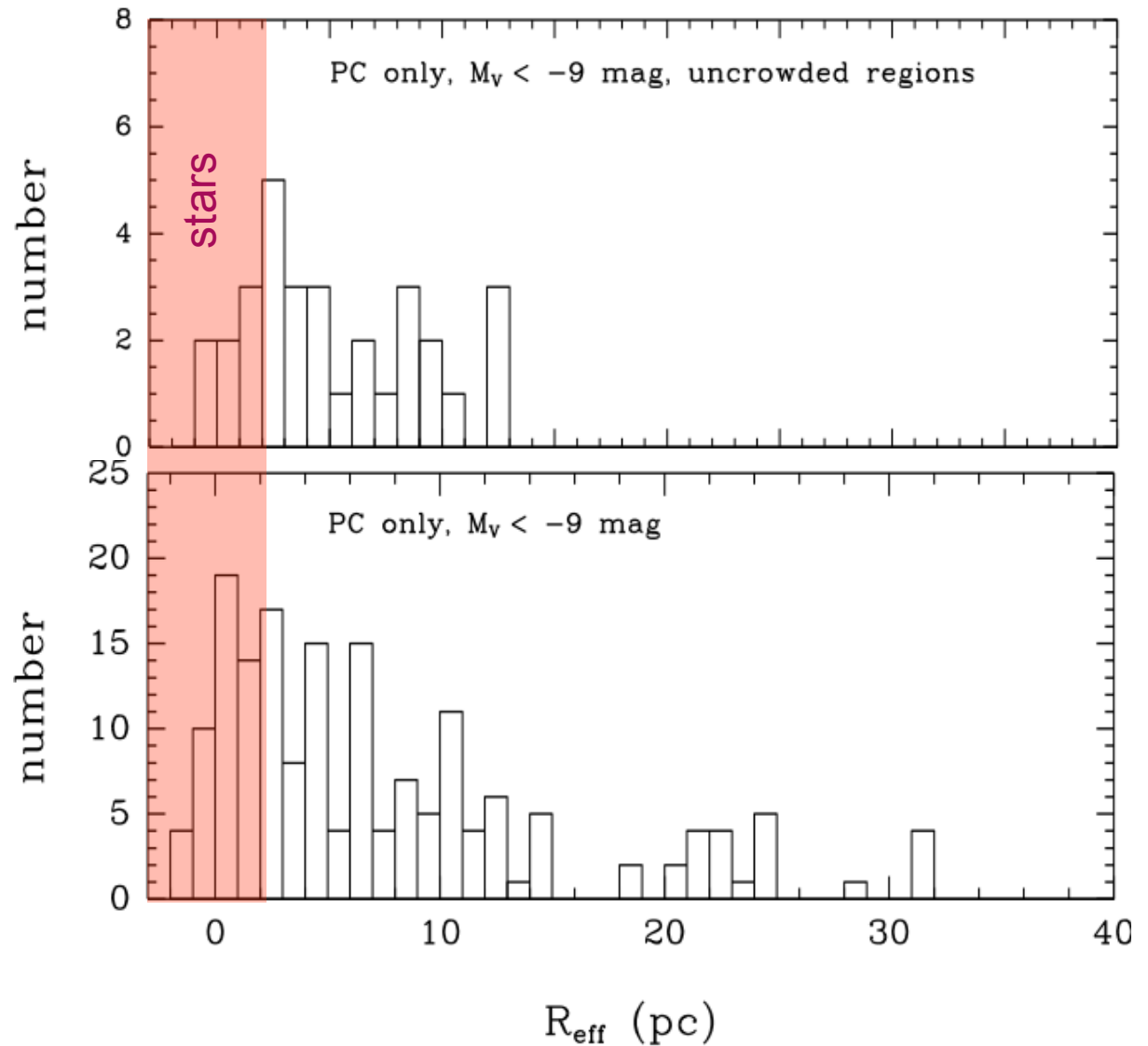
# GC demographics in mergers and young remnants

- NGC 1275 ( $\sim 500$  Myr) (Carlson & Holtzman 2001)
- $r_h$  distribution 'flatter' and reaching larger values than MW and gE galaxies



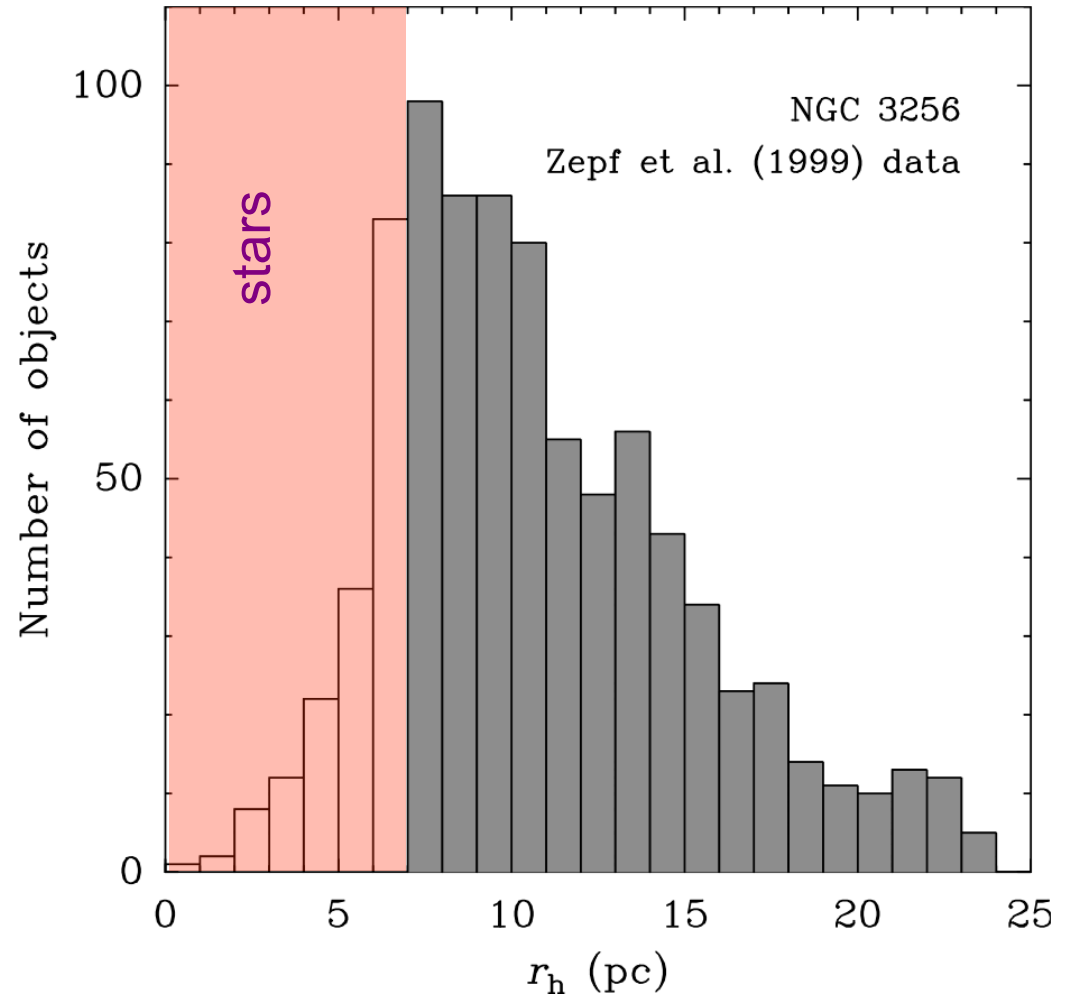
# GC demographics in mergers and young remnants

- Antennae
  - 0 – 200 Myr
  - Flattish  $r_h$  distribution up to  $\sim 15$ -20 pc
 (Whitmore et al. 1999)



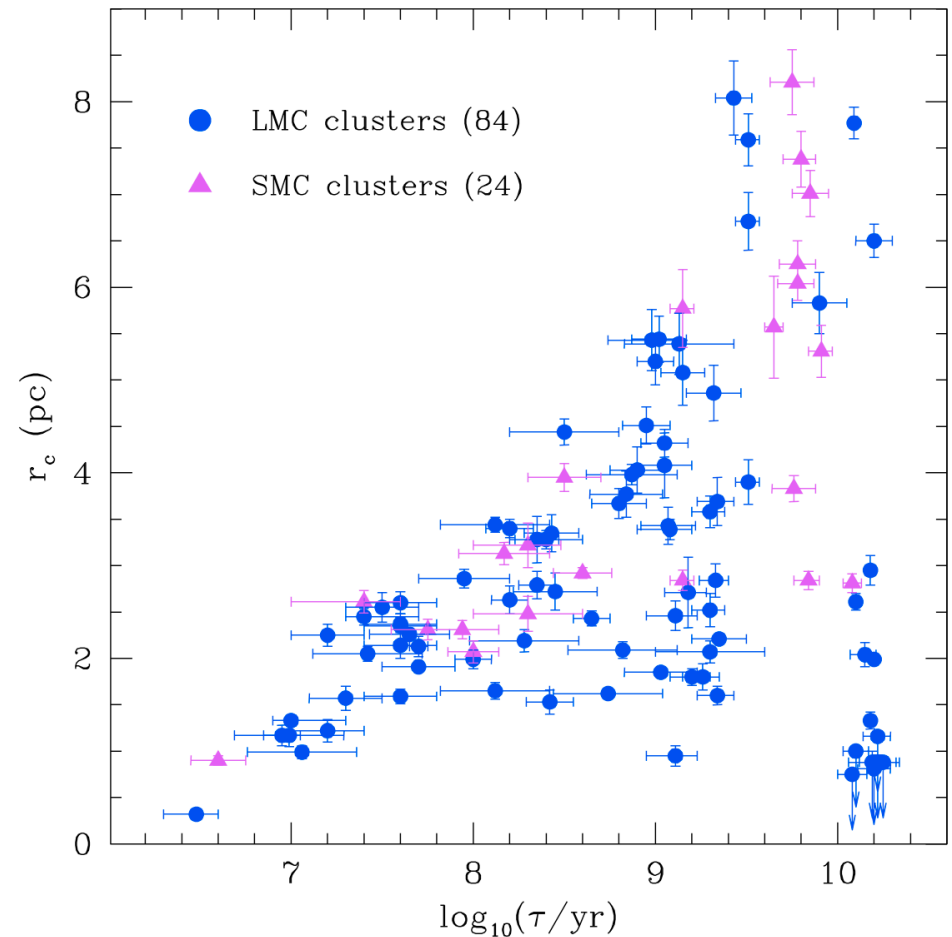
# GC demographics in mergers and young remnants

- NGC 3256 ( $\sim 100 - 200$  Myr)  
(Zepf et al. 1999)
- $r_h$  distribution again similar



# Insights from Magellanic Cloud GCs

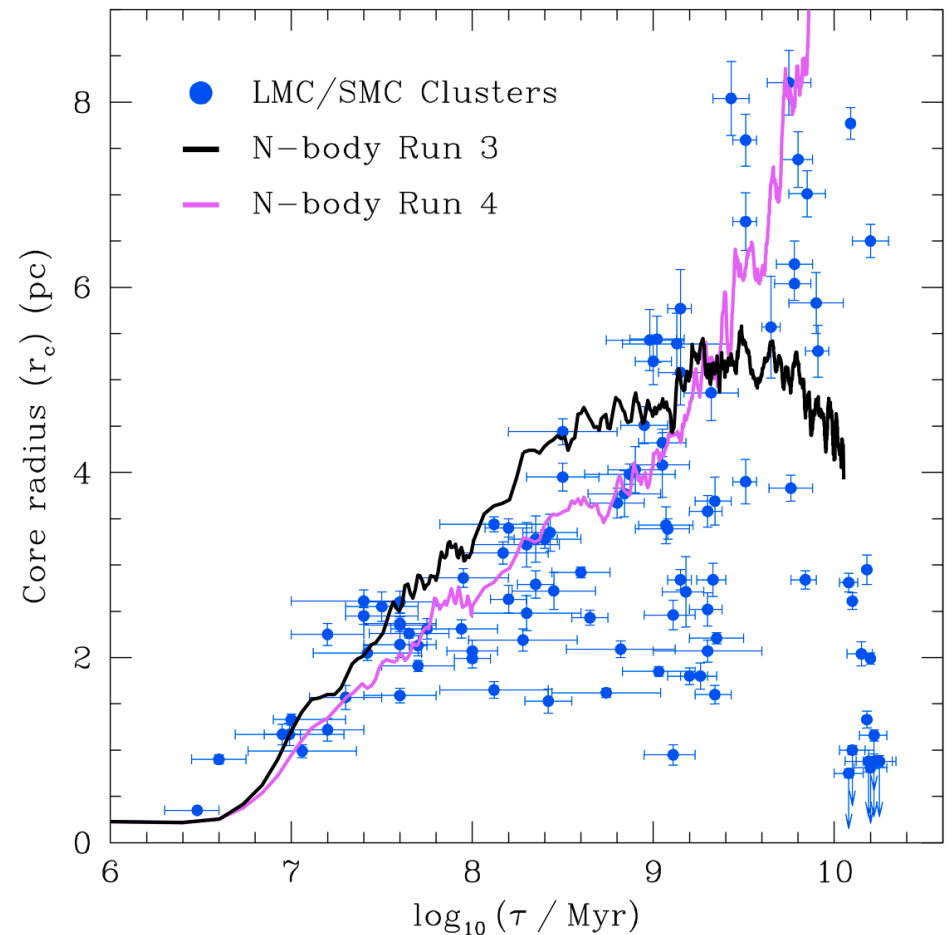
- MCs host clusters of “all ages”
- Systematic increase of maximum radius with age
- Radius distribution consistent between LMC and SMC
  - Most likely reflects “internal” effects



Mackey et al. (2008)

# Insights from Magellanic Cloud GCs

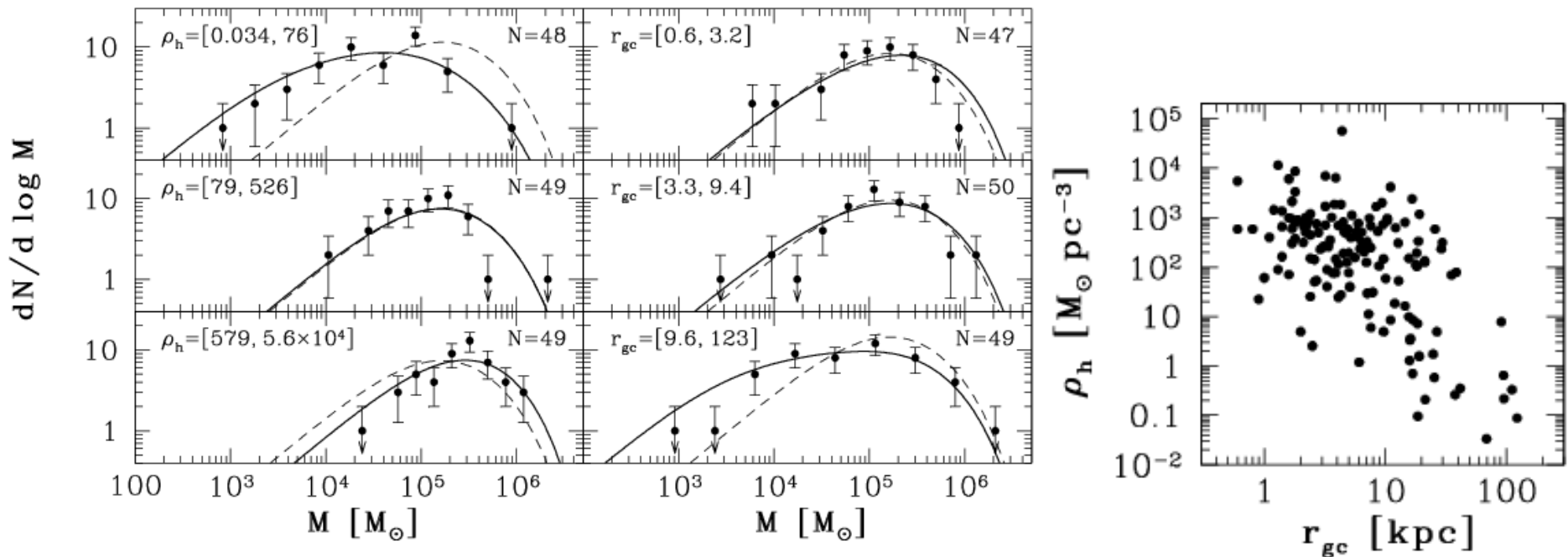
- MCs host clusters of “all ages”
- Systematic increase of maximum radius with age
- Radius distribution consistent between LMC and SMC
  - Most likely reflects “internal” effects
- Upper end of size distribution up to age  $\sim 3$  Gyr likely caused by initial mass segregation
  - Rapid mass loss in central regions, size adjusting adiabatically
- After few Gyr, mass segregation due to 2-body relaxation starts (slow) cluster contraction



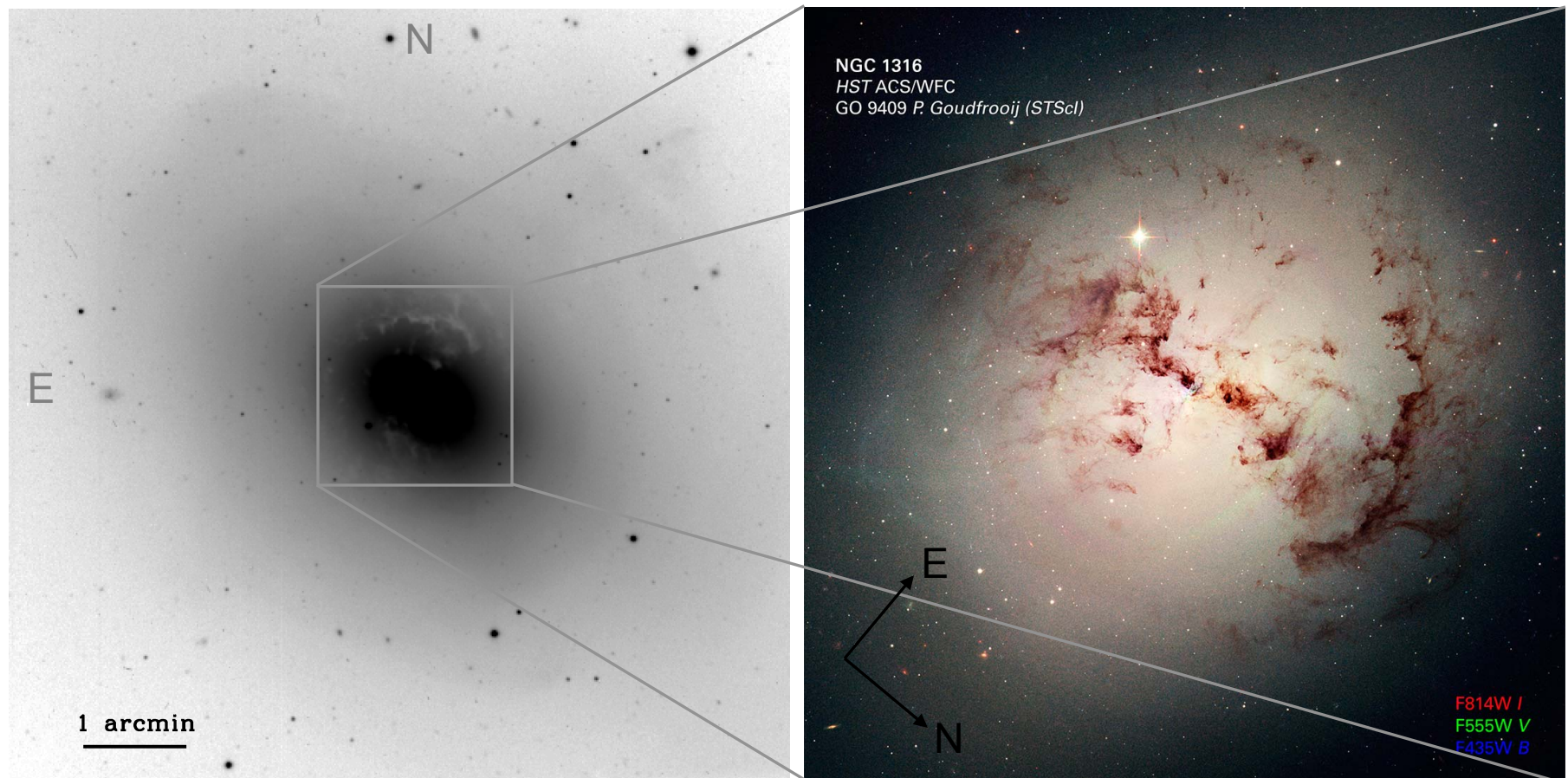
Mackey et al. (2008)

# Influence of GC Density on LFs/MFs

- McLaughlin & Fall (2008): Appearance (turnover) of MF of MW GCs depends mainly on  $\rho_h$  ; not much on  $R_{GC}$ 
  - Expected for evaporation driven by two-body relaxation ( $M_{TO} \propto \rho_h^{1/2}$ )
  - Similar picture for the Sombrero (Chandar et al. 2008)



# Testing the Merger Scenario: ACS imaging of 3-Gyr old merger remnant NGC 1316



NTT+EMMI

NGC 1316 (Goudfrooij et al. 2001, 2004)

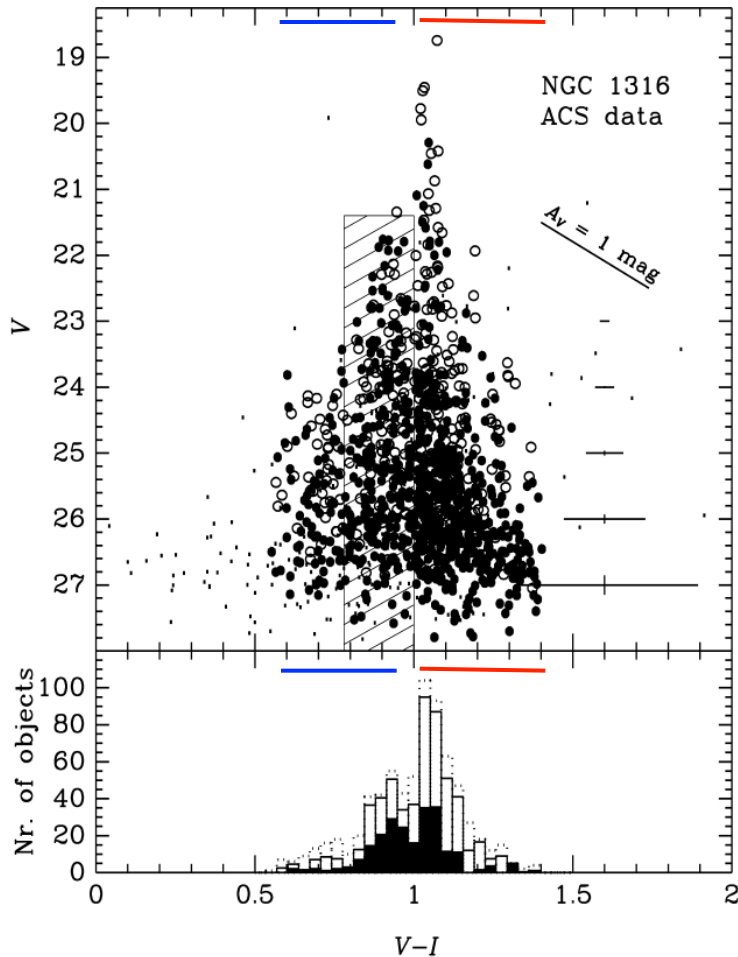
HST+ACS

ESO Workshop, April 2011

Paul Goudfrooij

4 April 2011

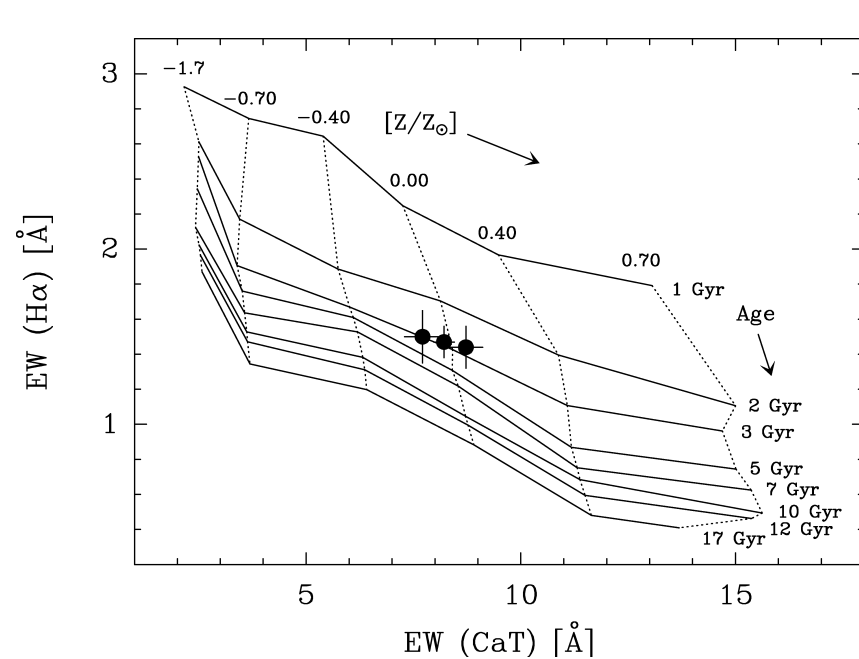
## Blue vs. Red GCs in NGC 1316



HST/ACS imaging of NGC 1316  
(Goudfrooij et al. 2004)

EW (H $\alpha$ ) vs. EW (CaT) diagram along with age-Z grid based on measurements on Bruzual & Charlot model spectra:

- The luminous red GCs are  $\sim 3$  Gyr old
- Their  $Z = Z_{\odot} \pm 0.15$  dex



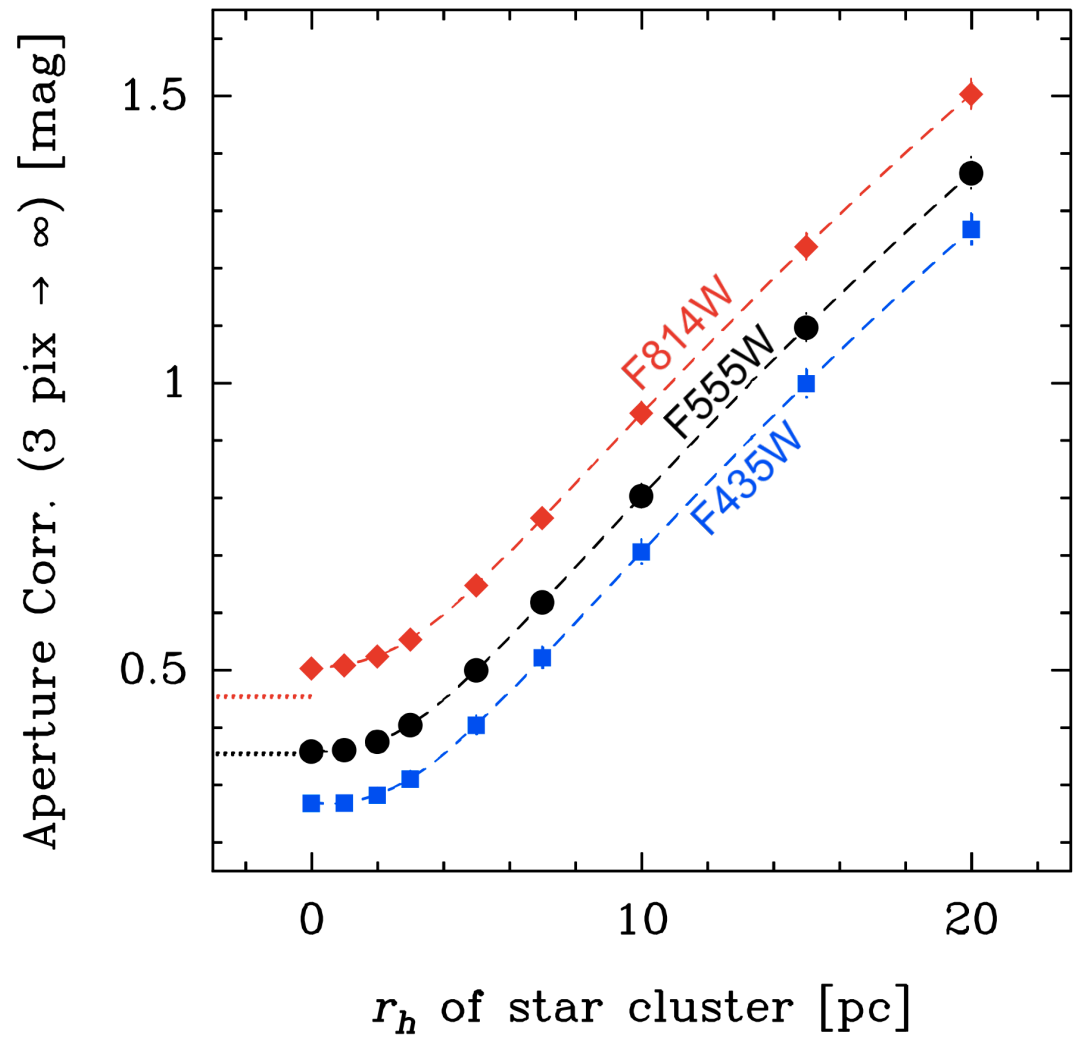
(Goudfrooij et al. 2001)

## Technical details on NGC 1316 project

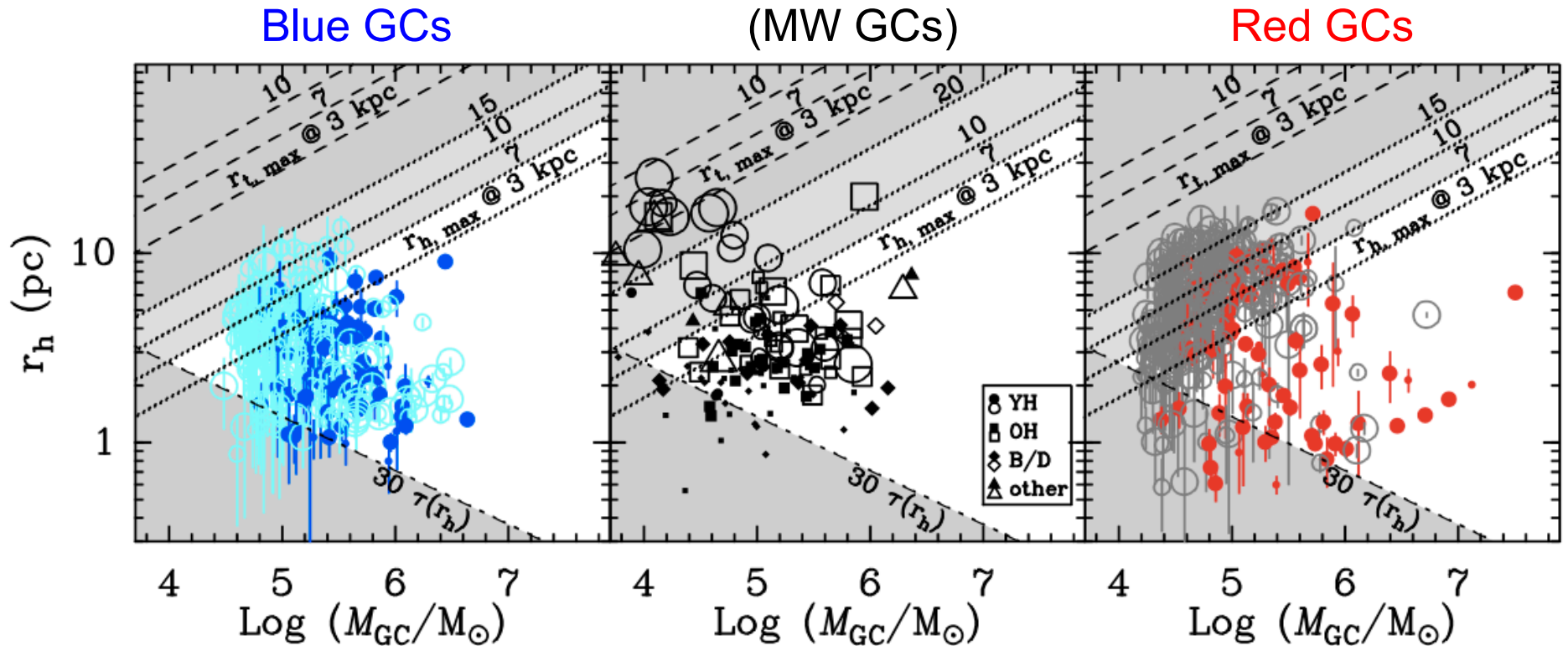
- Use ACS images of NGC 1316 (3 HST orbits; Goudfrooij et al. 2004)
  - Used S. Larsen's *ishape* program to measure GC sizes on model-subtracted images. Used Jay Anderson's *ePSF* array (on ACS \_flt images), run through MultiDrizzle just like the science images.
  - Adapted M. Paolillo's *Multiking* program to all ACS filters for which *ePSF* array available
  - Only include GCs with  $S/N > 50$  to yield robust  $r_h$  values (e.g., Kundu & Whitmore 1998, Carlson & Holtzman 2001, Larsen 2001)
- Assumptions:
  - Bruzual & Charlot (2003) SSP models for M/L ratios
  - NGC 1316 potential with  $(v^2 + \sigma^2)^{1/2} = 235$  km/s (Arnaboldi et al. 1998; Goudfrooij et al. 2001).
    - > Note MW value = 236 km/s
  - Innanen et al. (1983) spherically symmetric galactic mass distribution  $M(R_G) = \alpha R_G$ 
    - > Dispersion of MWGC  $r_t$  values around median independent of  $R_G$

# Technical details on NGC 1316 project

- Aperture correction depends **significantly** on cluster size (!)
- Same holds for completeness
- Redid both from scratch for this study
- Only consider GCs with completeness > 50% at all  $R_G$



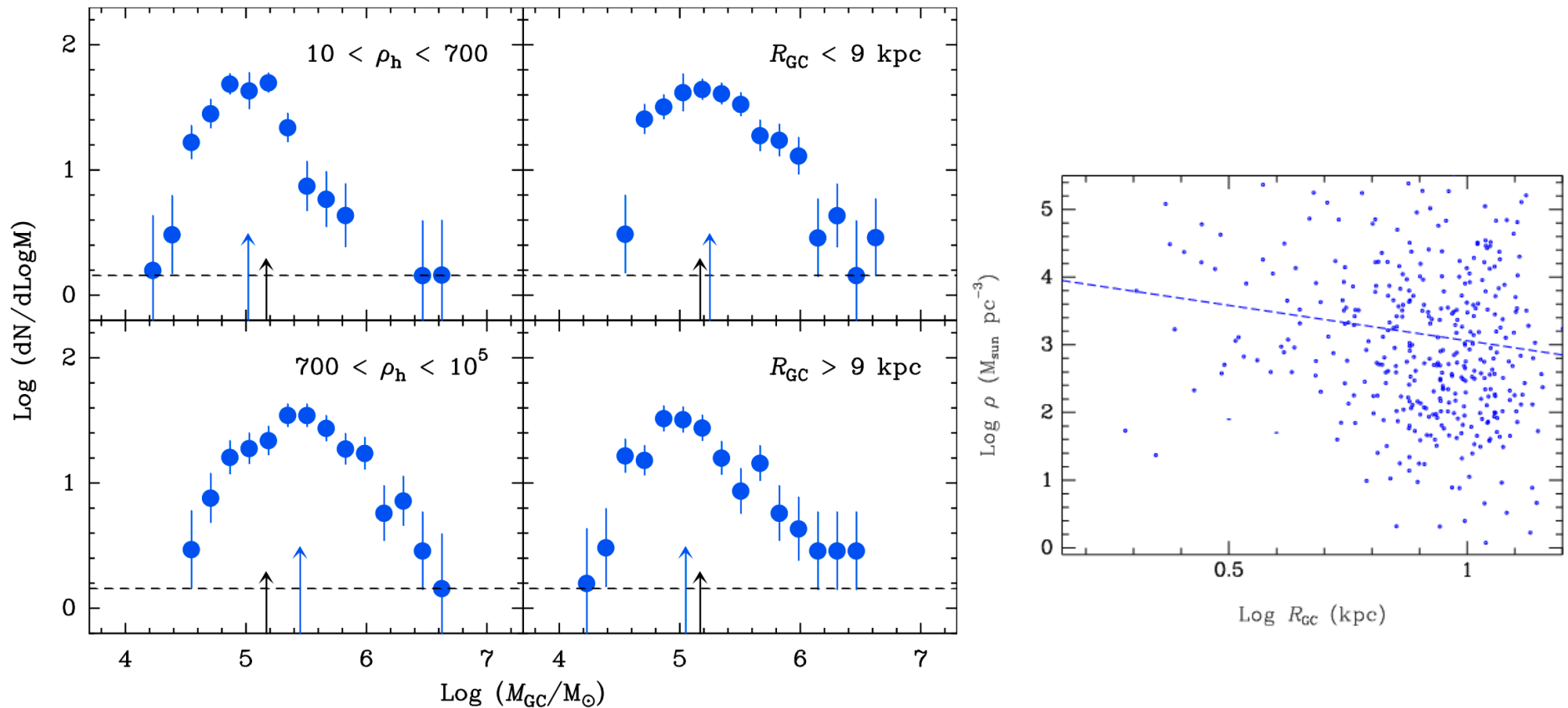
# Observed GC demography in NGC 1316



- Filled symbols:  $R_G < 3$  and 3-7 kpc
- Open symbols: 7-10 and 10-15 kpc
- Assume  $r_h = 0.12 r_t$  (true within  $\pm 0.02$  for  $10 < \text{King } c < 50$ )

# Blue GCs in NGC 1316

- Blue GCs in NGC 1316: Picture similar to MW and Sombrero
  - $M_{T0}$  increases w/  $\rho$ ; not much w/  $R_{GC}$ ;  $\rho$  only slow function of  $R_{GC}$



# 'Evolving' Red GCs in NGC 1316

## Using two "limiting" models:

### 1. No initial mass segregation

- Mass loss by stellar evolution:  $\sim 35\%$  lost by age = 400 Myr
  - > Expand  $r_h$  adiabatically during that time
- $\rho$ -dependent 2-body relaxation 'a la [McLaughlin & Fall \(2008\)](#):

$$\overline{\mu_{ev,t}} = 1100 \times \left( \frac{\rho_h}{M_\odot \text{pc}^{-3}} \right)^{1/2} M_\odot \text{Gyr}^{-1}$$

- Assume GCs with  $r_h >$  tidal limit at their  $R_G$  dissolve by age 13 Gyr

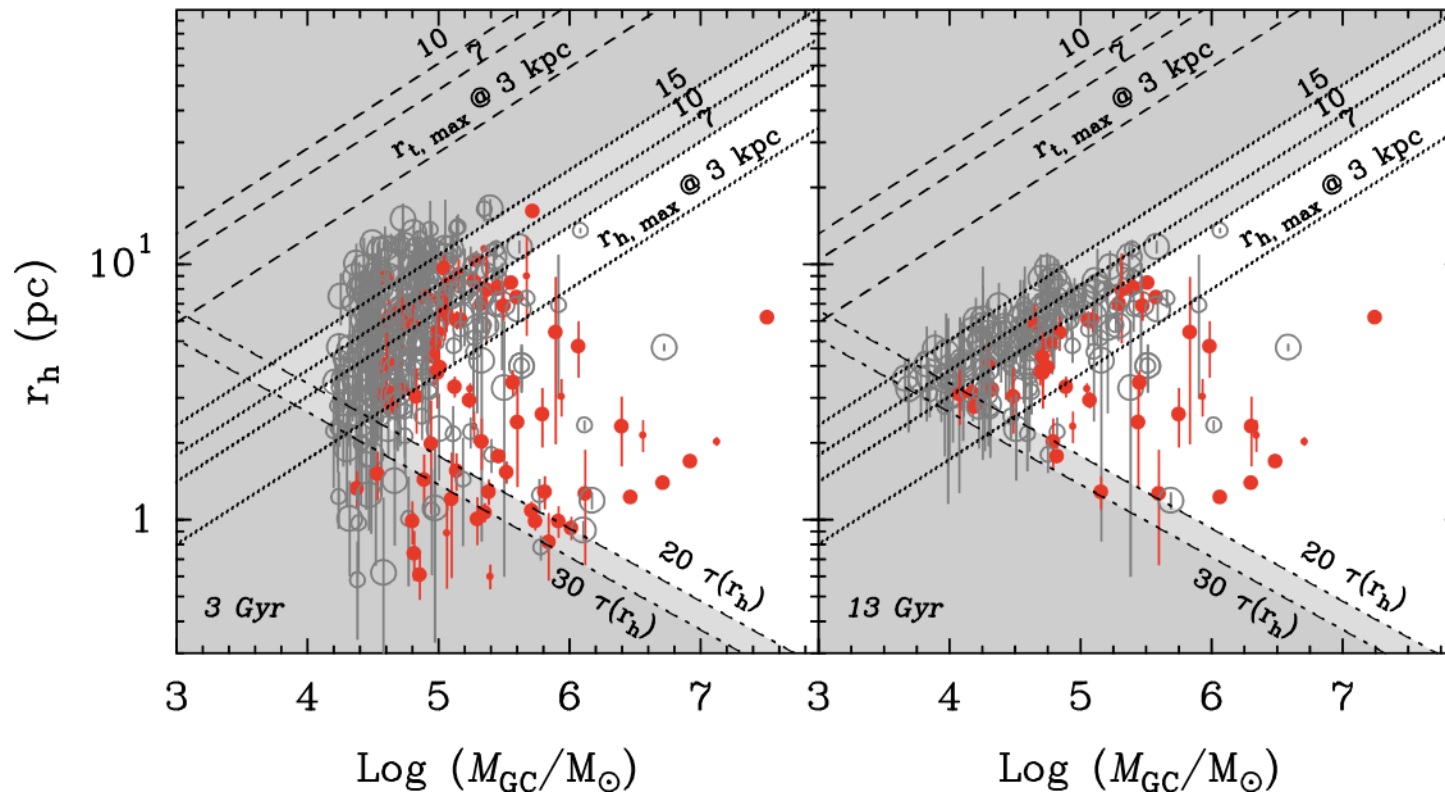
### 2. 'Moderate' initial mass segregation

- Use mass loss and  $r_h$  a.f.o. time in model *M-Rg18* of [Vesperini et al. \(2009\)](#)
- Their model with the 'strongest' mass segregation that survived 13 Gyrs of evolution

# "No initial mass segregation" model at age = 13 Gyr

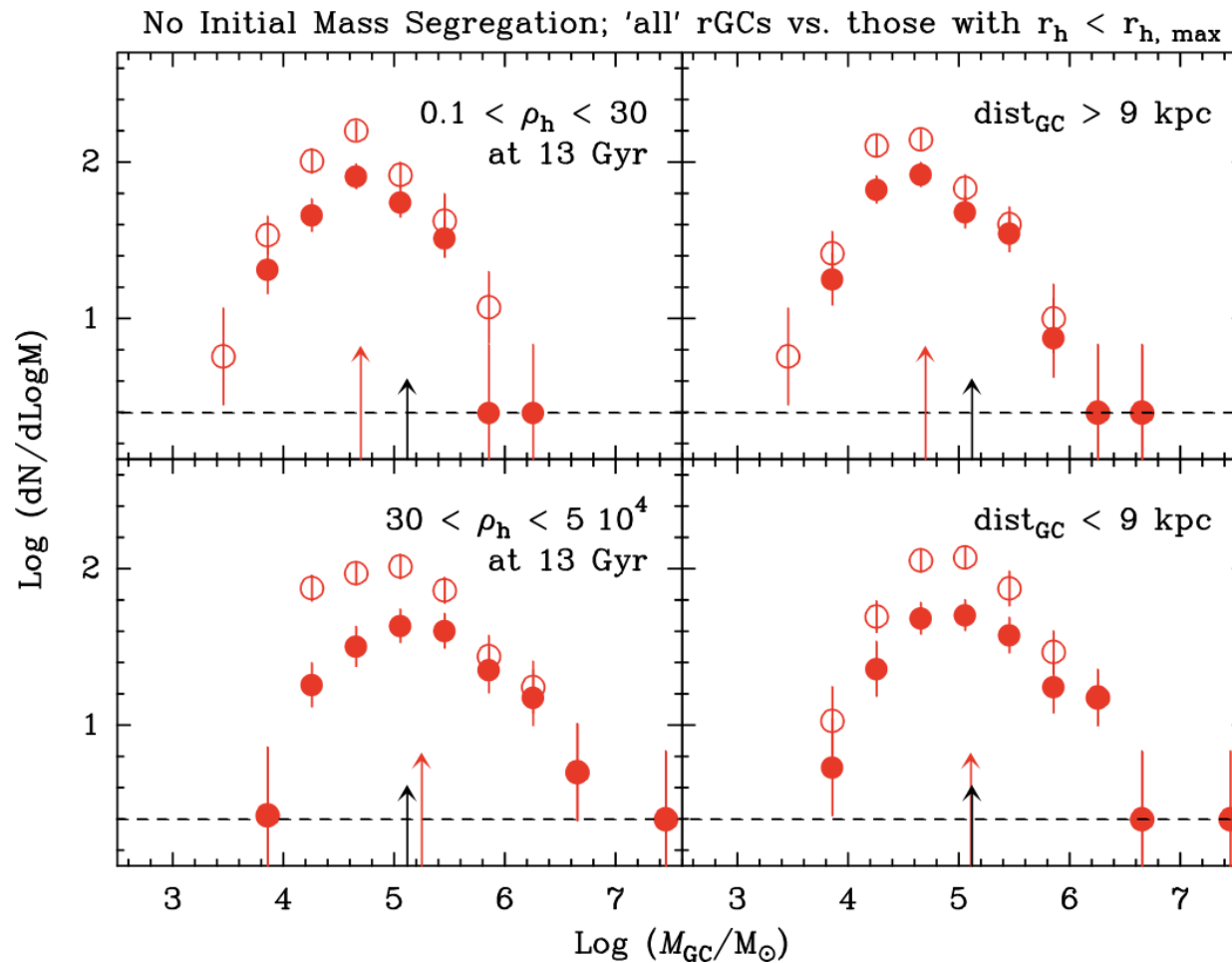
- Resulting GCs stay nicely within "survival triangle"
  - Note that going 'deeper' won't yield many more *surviving* GCs
- But  $r_h$  distribution skewed to large  $r_h$  vs. GCs in 'normal' gEs

No Initial Mass Segregation; tidal restriction on  $r_h$



# "No initial mass segregation" model at age = 13 Gyr

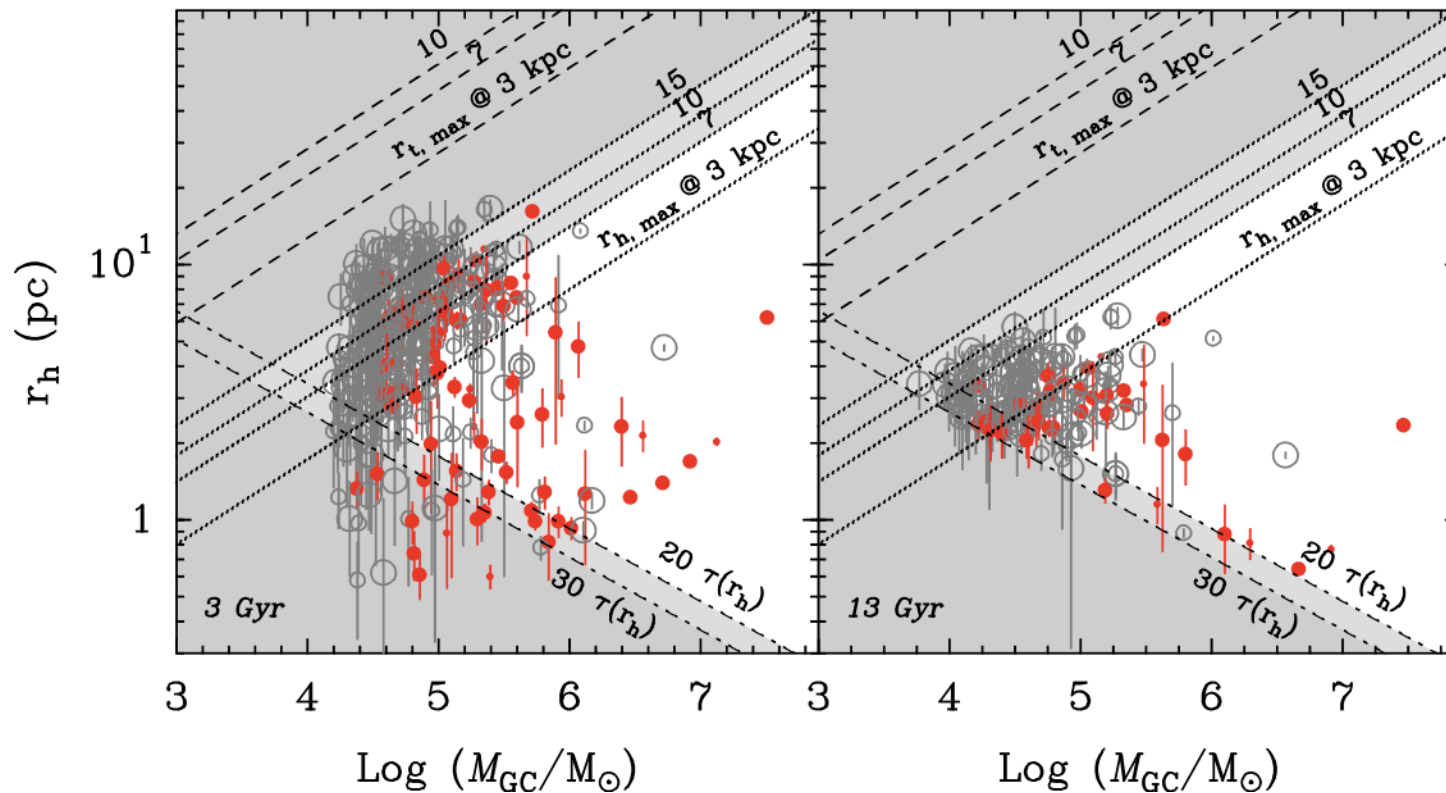
- $\rho$  dependence of mass function shows up nicely at 13 Gyr



# “Moderate initial mass segregation” model at age = 13 Gyr

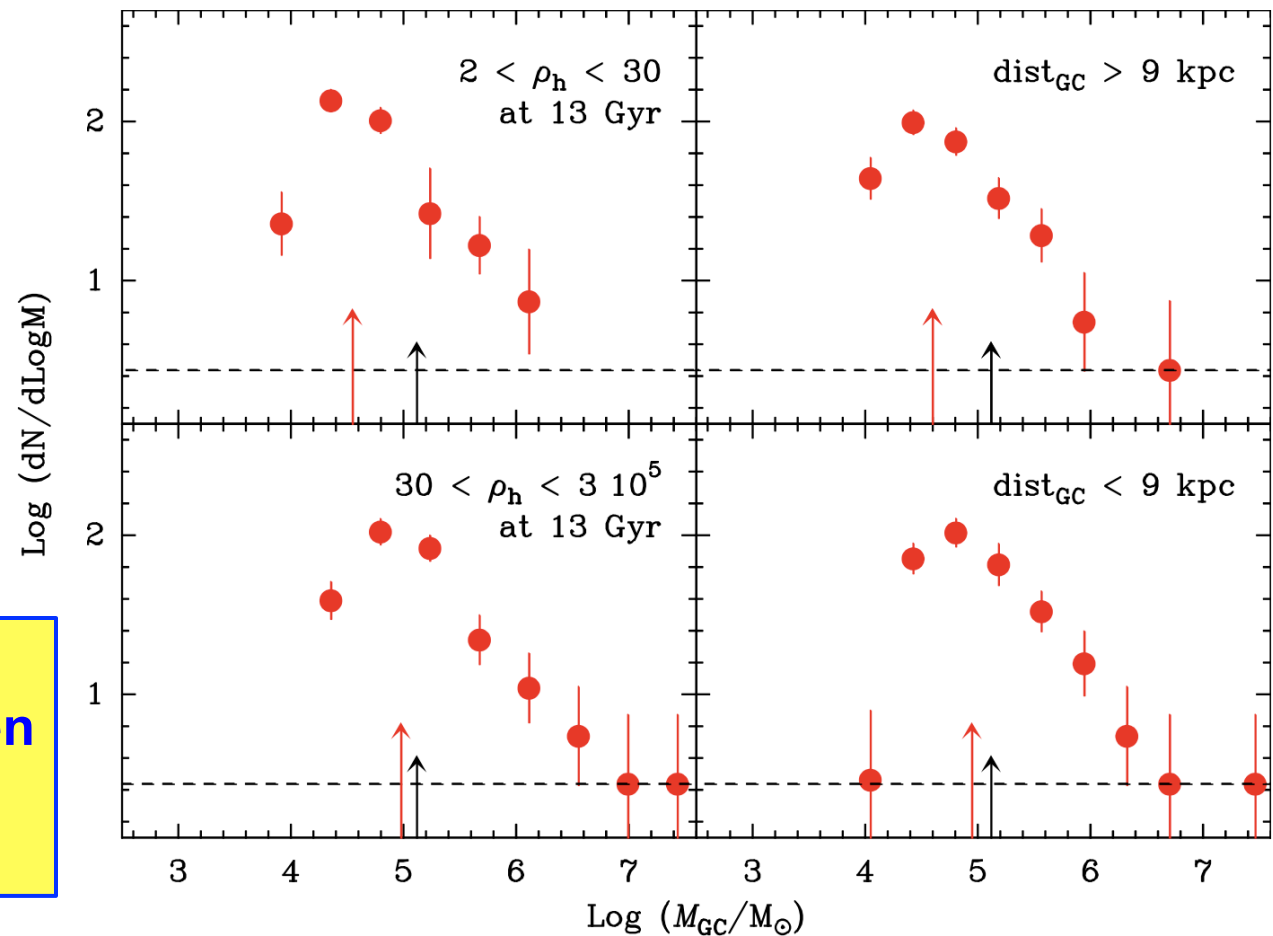
- Resulting GCs again nicely within “survival triangle”
  - Tidal limitation to  $r_h$  ‘avoided’ in this case
- $r_h$  distribution now slightly too ‘compact’ vs. in gE galaxies

Moderate Initial Mass Segregation (and *no restriction on  $r_h$* )



# “Moderate initial mass segregation” model at age = 13 Gyr

- $\rho$  dependence of mass function still there, but too many GCs eliminated at 13 Gyr



**Truth likely lies  
somewhere in between  
these two limiting  
scenarios**

## Concluding Remarks

- NGC 1316 important test bed to evaluate plausibility of forming **red** GCs in giant Es through dissipative mergers
  - Demography of metal-poor **blue** GCs consistent with those in MW and Sombrero (and probably many others as well)
    - >  $\rho$ -dependence of  $M_{TO}$  obvious, pointing to importance of evaporation
  - Size distribution of **red** GCs similar to younger remnants, as predicted by situation among Magellanic Cloud clusters
  - Two 'limiting' models to predict the MF as function of time:
    - Both predict a bell-shaped MF at 13 Gyr from observed demography
    - No initial mass segregation: Too many large GCs left
    - Moderate initial mass segregation: Too many GCs destroyed
    - 'Truth' likely lies somewhere in between, e.g. only large GCs affected by initial mass segregation, or range of mass segregation strengths.
  - Evidence favors importance of dissipative mergers during assembly history of "normal" giant ellipticals