# Extragalactic Globular Cluster Systems

Eric Peng
Peking University

# Why study Globular Cluster Systems?

Globular Cluster Properties

- $M \sim 10^4$-$10^6$ $M_{sun}$
- $r_h \sim 3$ pc
- single age ~ 10-13 Gyr
- -2.3 < [Fe/H] < 0.0
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Tracers of early, major epochs of star formation (z > 3)

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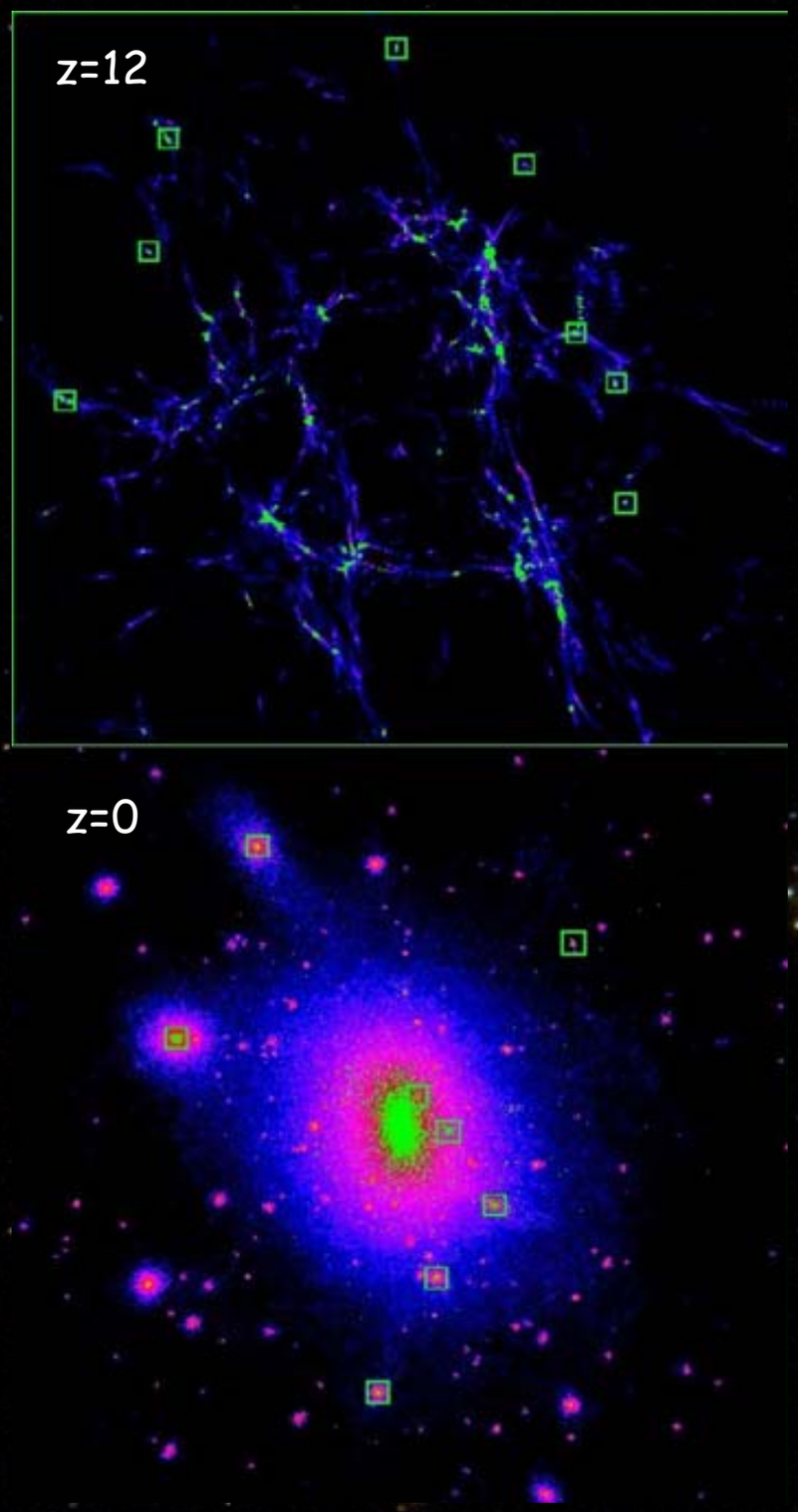


Moore et al (2006)

- Form in early collapsing dark matter halos
- Visible tracers of mass assembly on galaxy scales

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gEs

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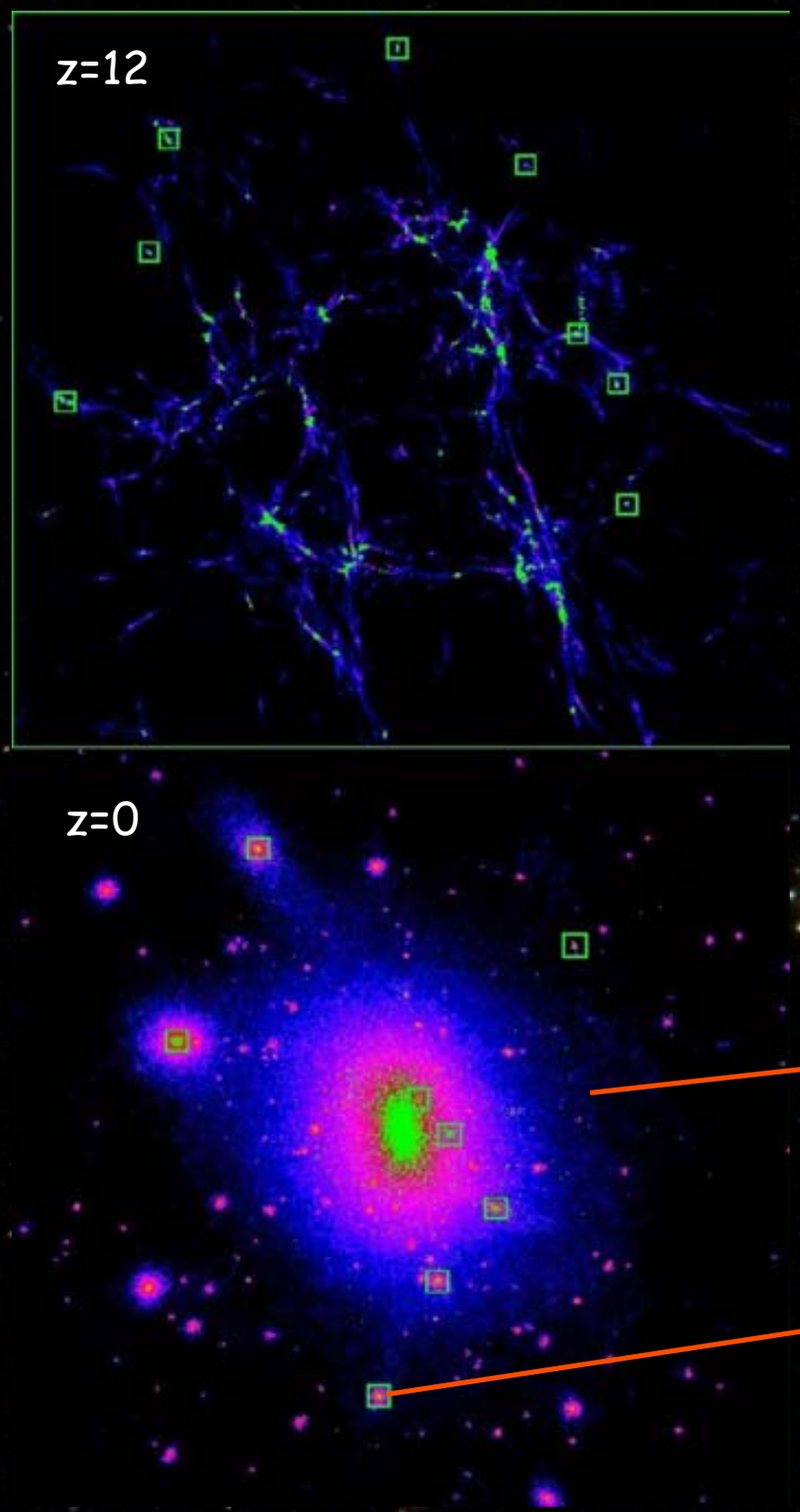


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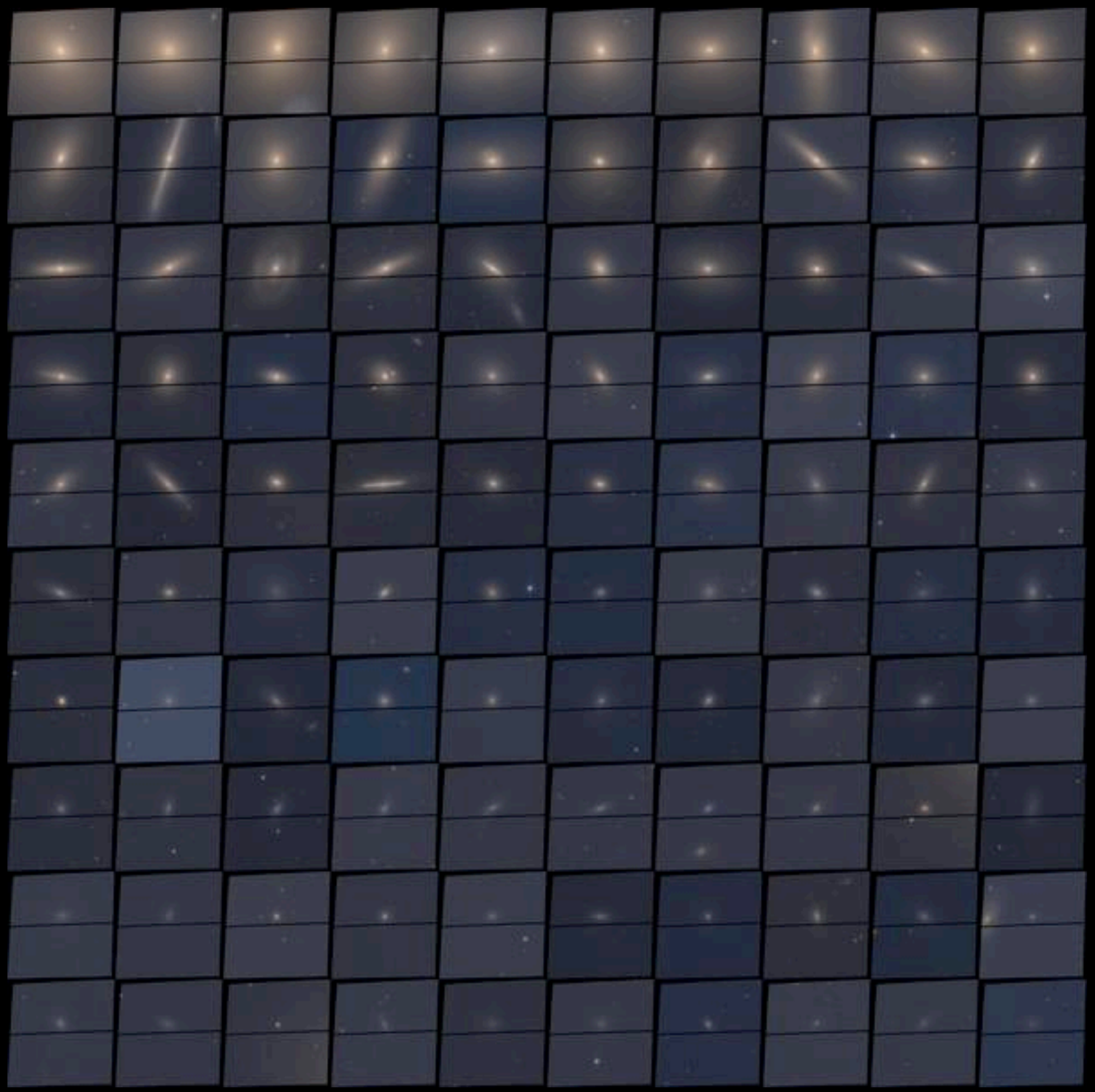

PI: Patrick Côté

- HST/ACS imaging survey in *g* and *z*
- 100 early-type galaxies
- $-22 < M_B < -15$, giants to dwarfs
- Depth: 90% of *GC* population
- 16 control fields for *GC* identification and background subtraction

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*A homogeneous survey across the mass spectrum of "surviving progenitors" and "merger products"*

# The ACS Virgo Cluster Survey


Patrick Côté (PI: Virgo)
John Blakeslee
Laura Ferrarese
Andrés Jordán (PI: Fornax)
Simona Mei
Eric Peng
John Tonry
Michael West

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Elena Dalla Bontá
Marla Geha
Monica Haşegan
Dean McLaughlin
Steffen Mieske

Chris Onken
Slawomir Piatek
Thomas Puzia
Marianne Takamiya
Andrew West


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# Data and Analysis

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- Model underlying galaxy
- Identify GC candidates
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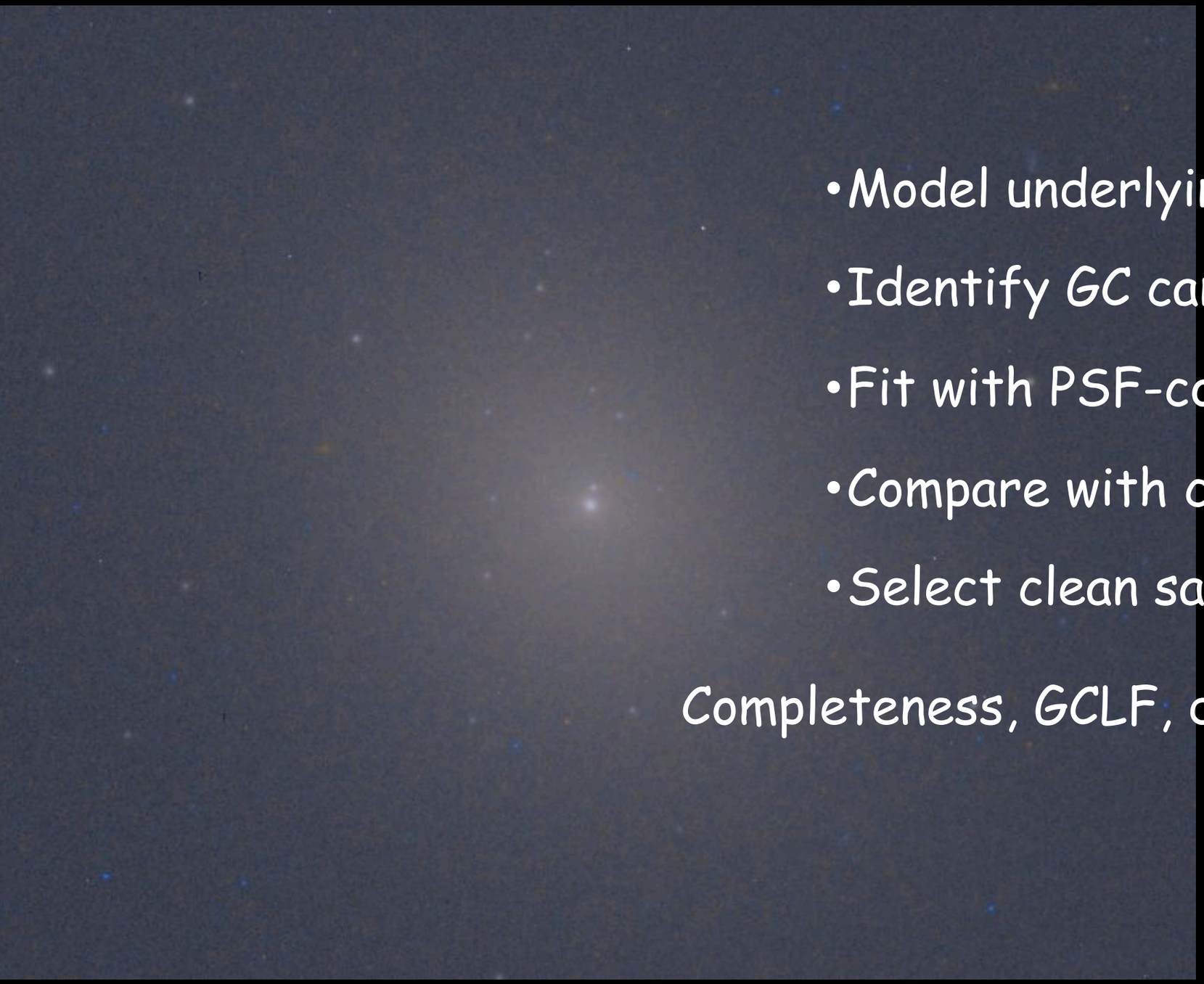

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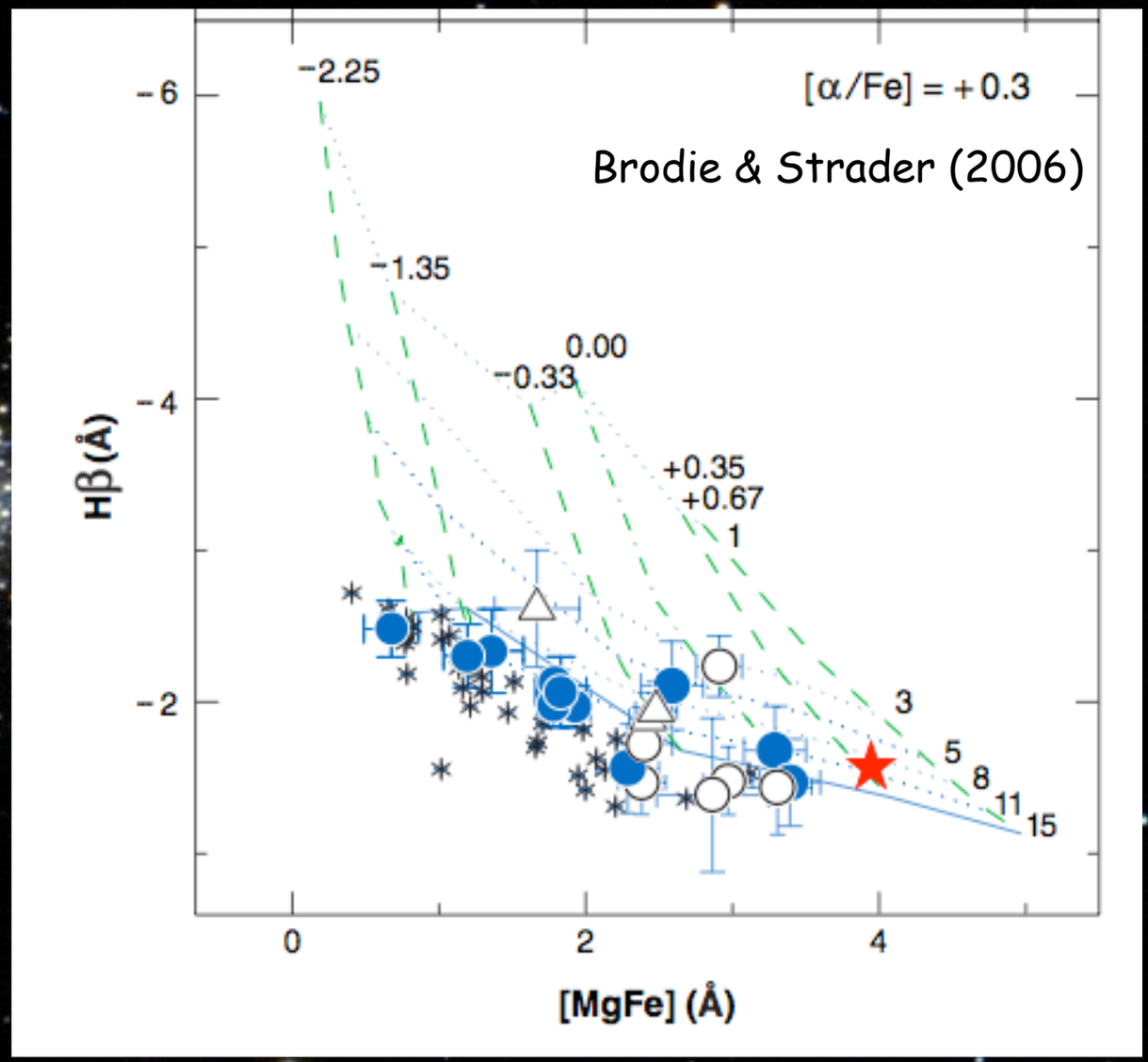
Over 11,000 GCs detected in 100 galaxies

# Globular Cluster Systems: Metallicity

- Globular cluster are predominantly old (> 8 Gyr) and metal-poor



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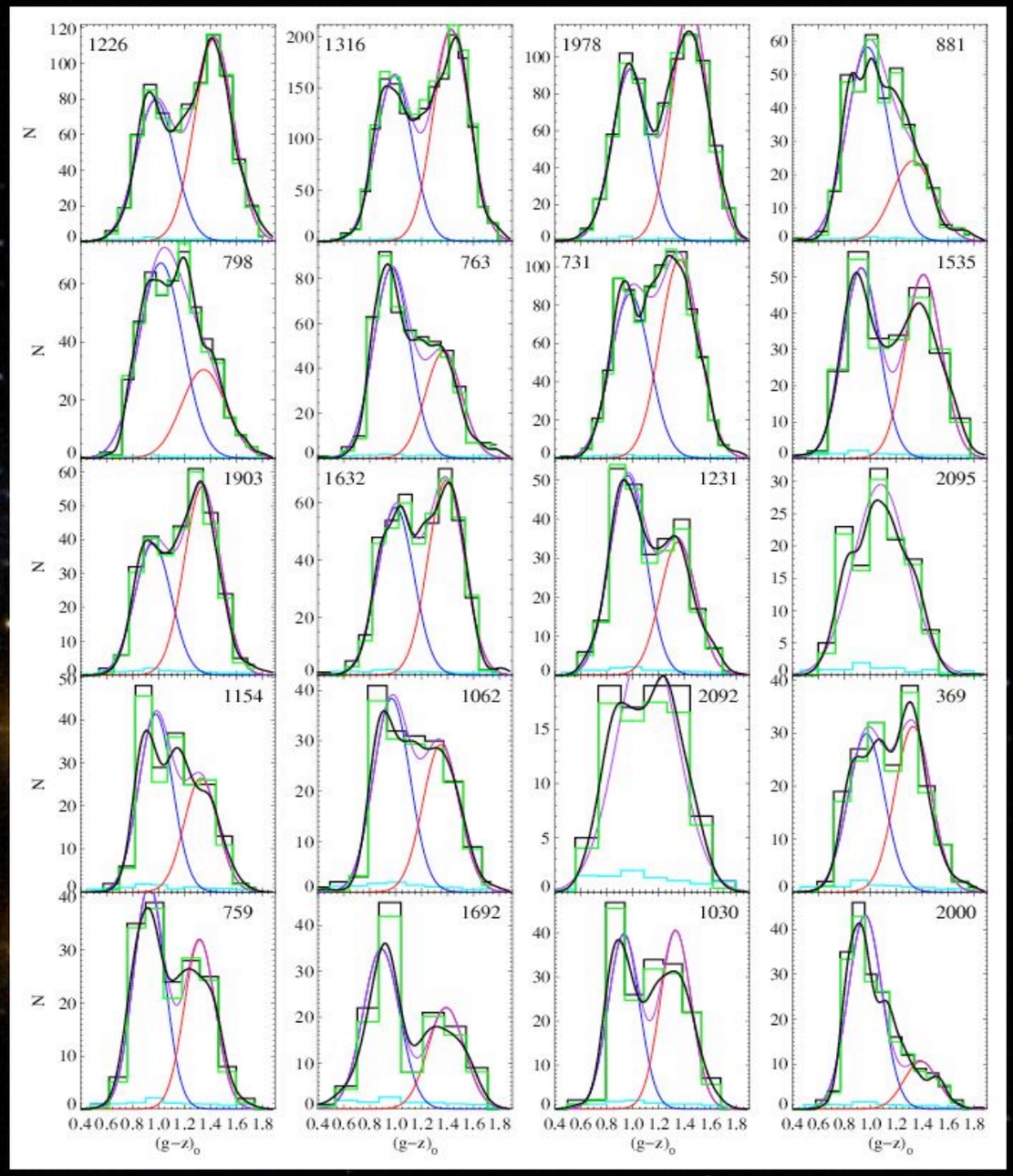
- Metal-poor (halo), metal-rich (bulge)




Peng et al. (2006)

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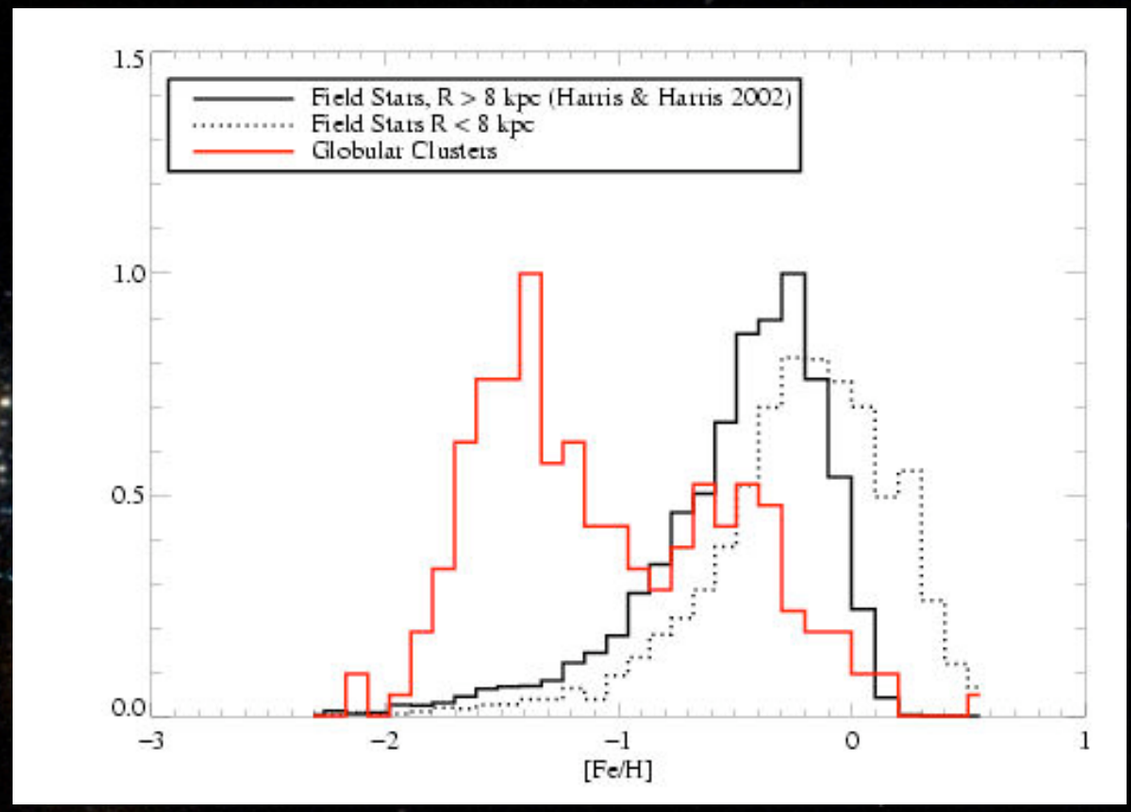


Peng et al (2004); Harris & Harris (2002)

Globular cluster formation efficiency is not constant across metallicity and age

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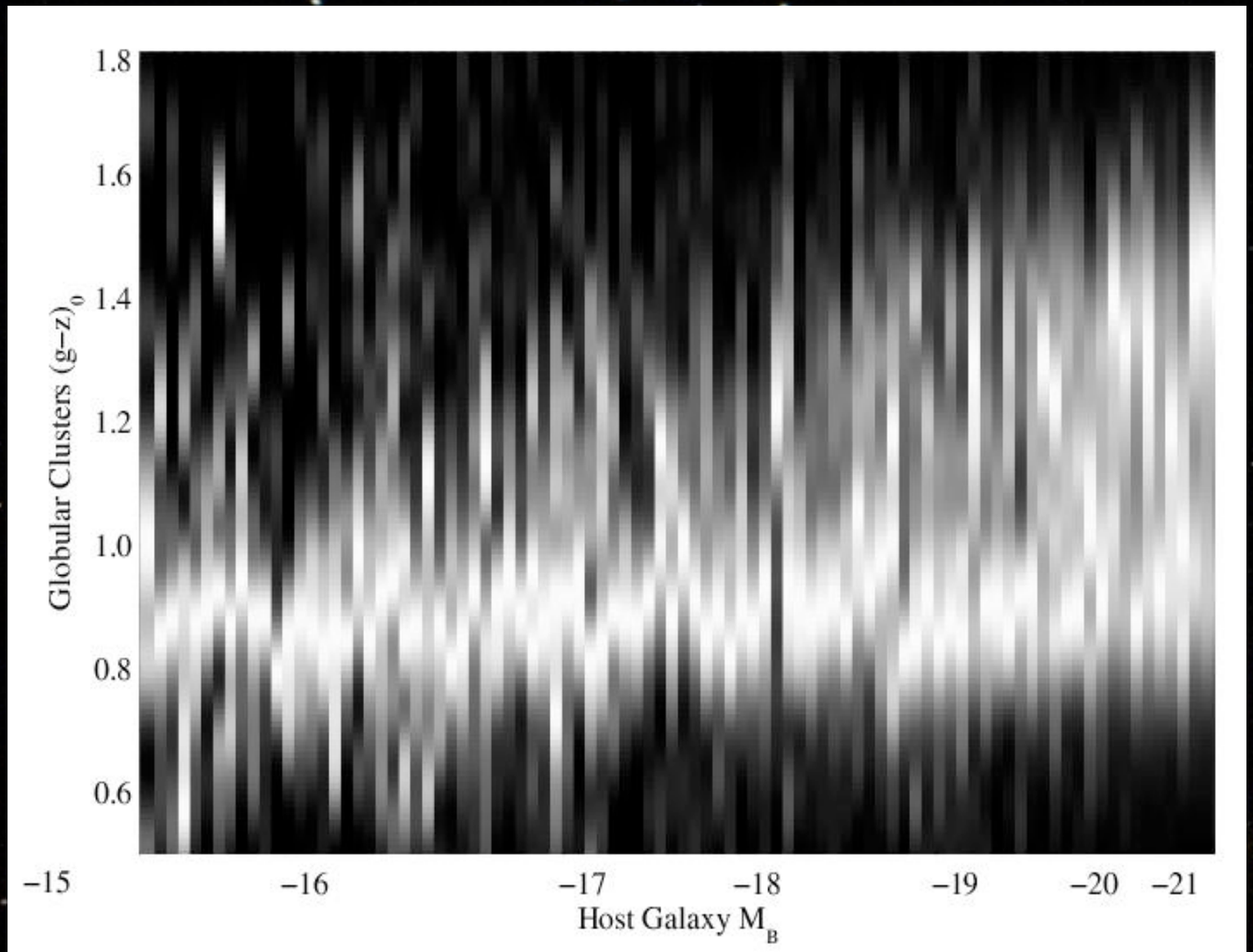


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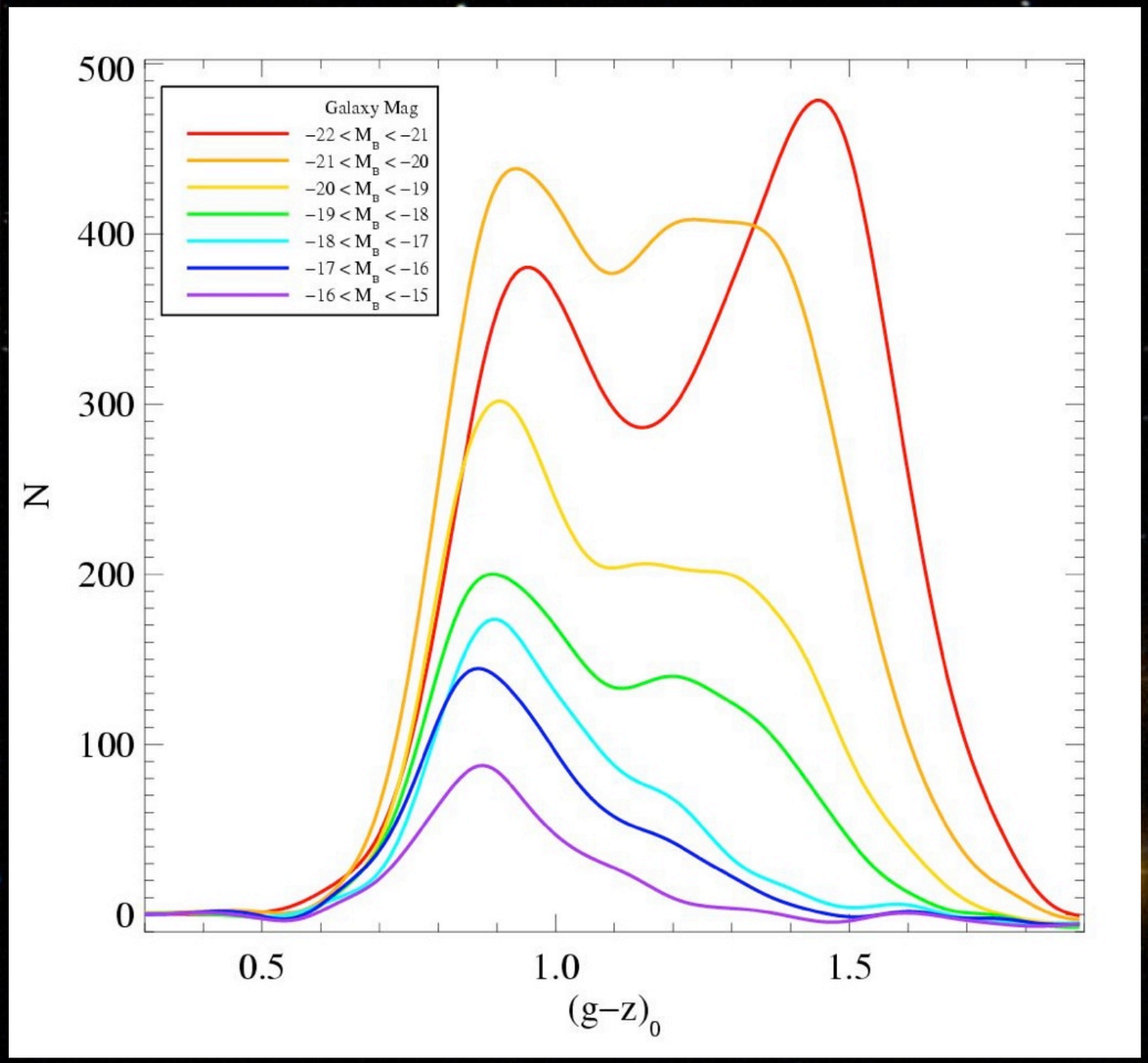


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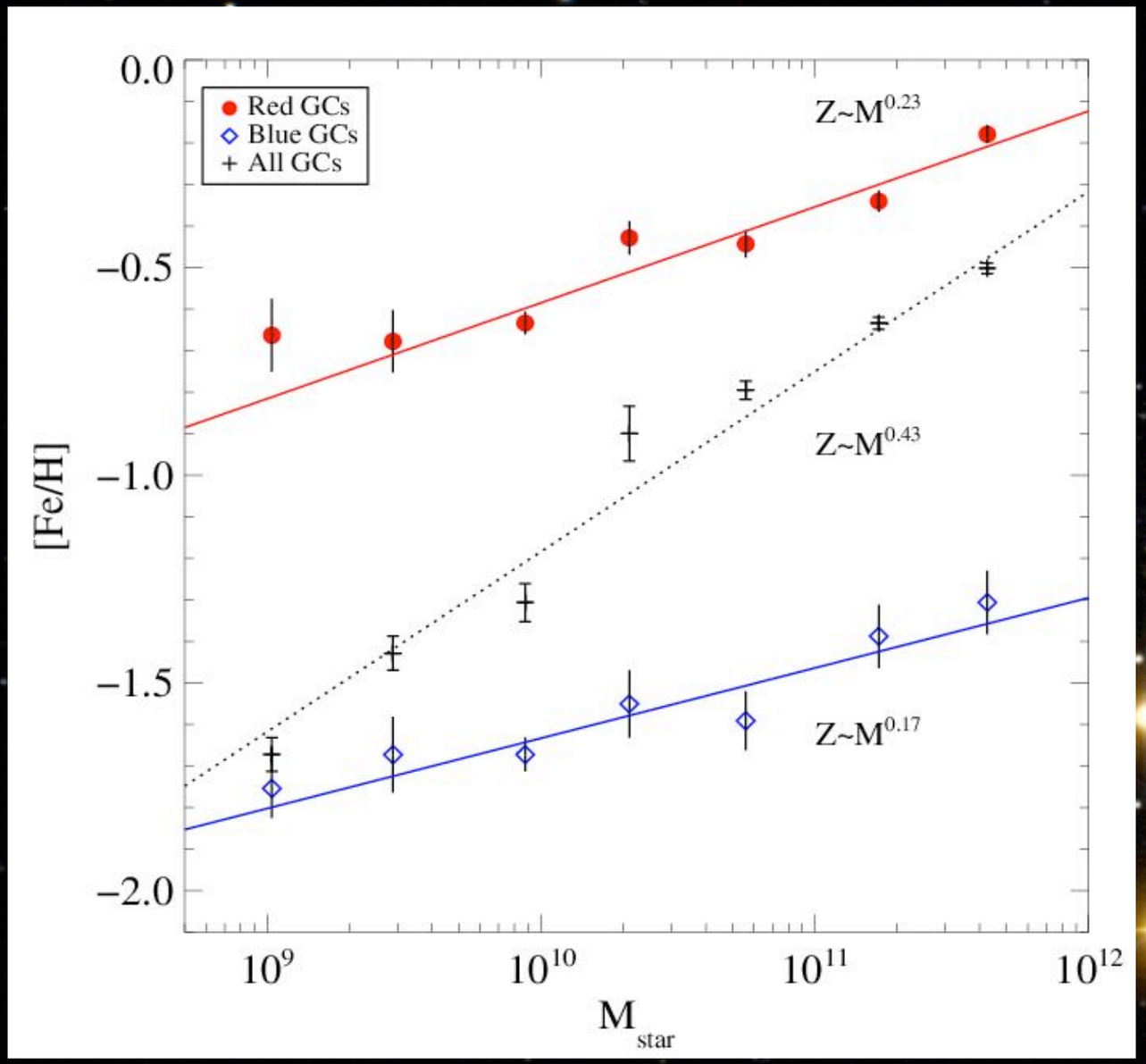


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- More massive galaxies have more, and metal-rich GCs
- Mean metallicities of both subpopulations increase with galaxy mass

# Globular Cluster Formation Efficiencies

Specific Frequency: number of GCs normalized to $M_V$=-15

$$S_N = N_{GC}\ 10^{\ 0.4(M_V+15)}$$

Purpose: "To investigate whether there is in fact a 'universal' and uniform capability for globular cluster formation." (Harris & van den Bergh 1981)

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| Spirals | $S_N$~1 |
| Ellipticals | $S_N$~5 |
| Dwarf Ellipticals | $S_N$~0-30 |
| M87 | $S_N$~14 |

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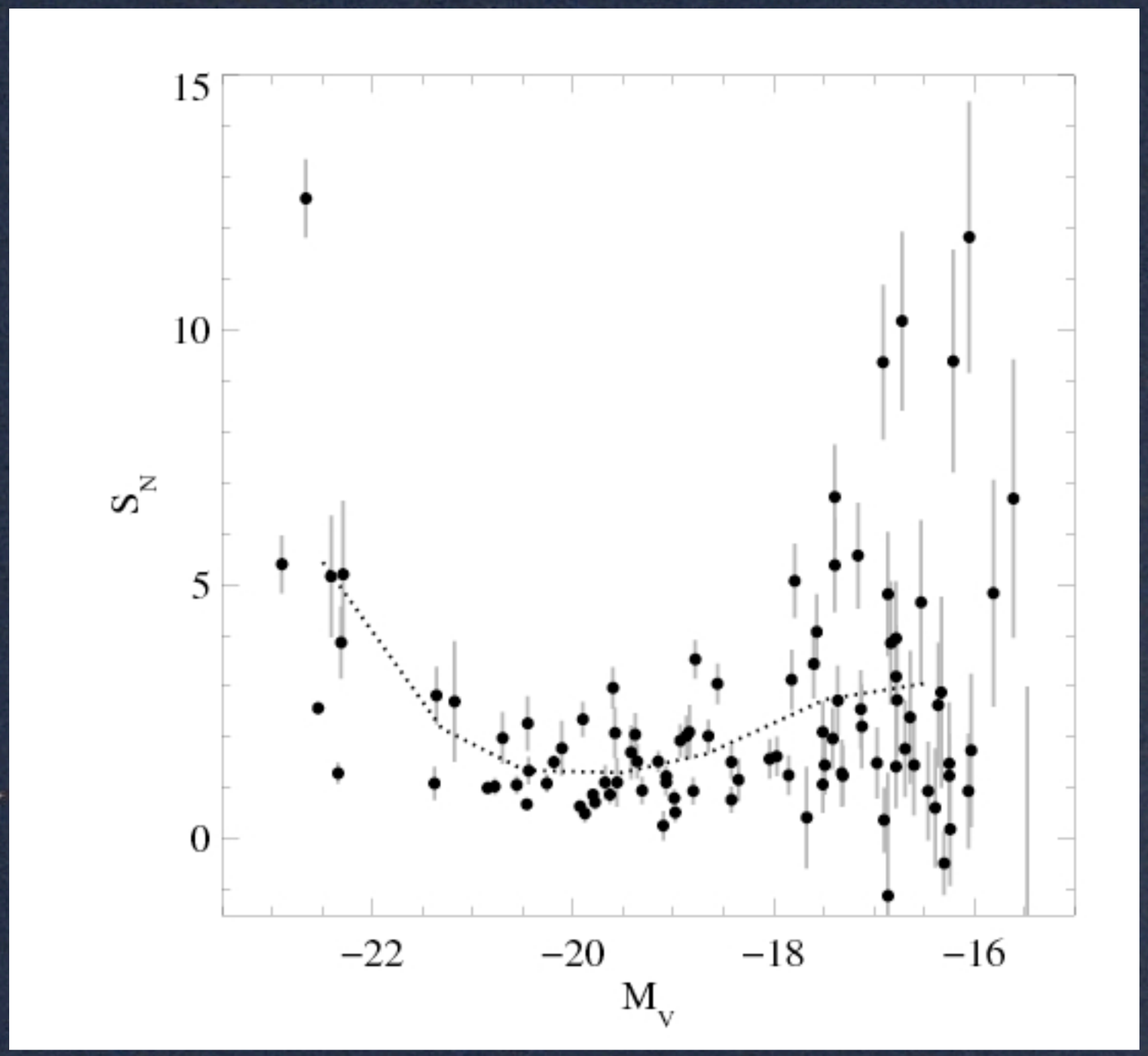
A problem? No! GC systems offer a unique and complementary view on galaxy formation.

# How does GC fraction behave across galaxy mass?




Peng et al. (2008)

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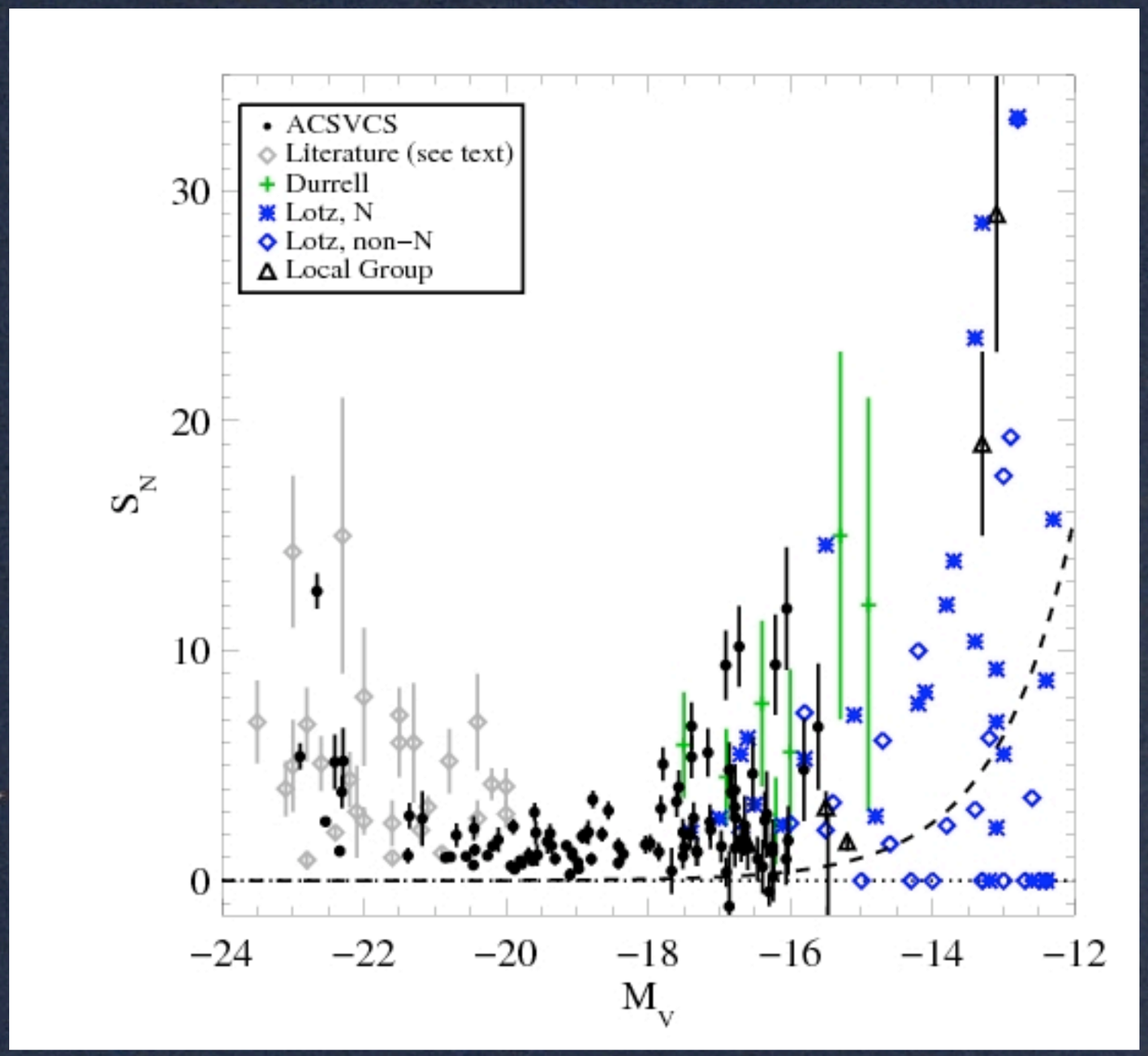


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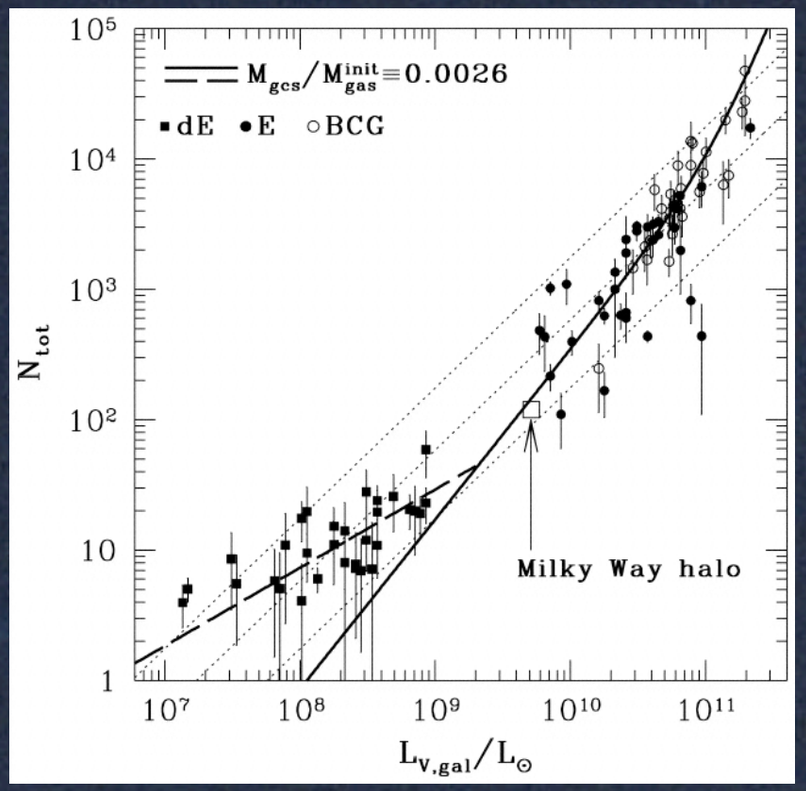
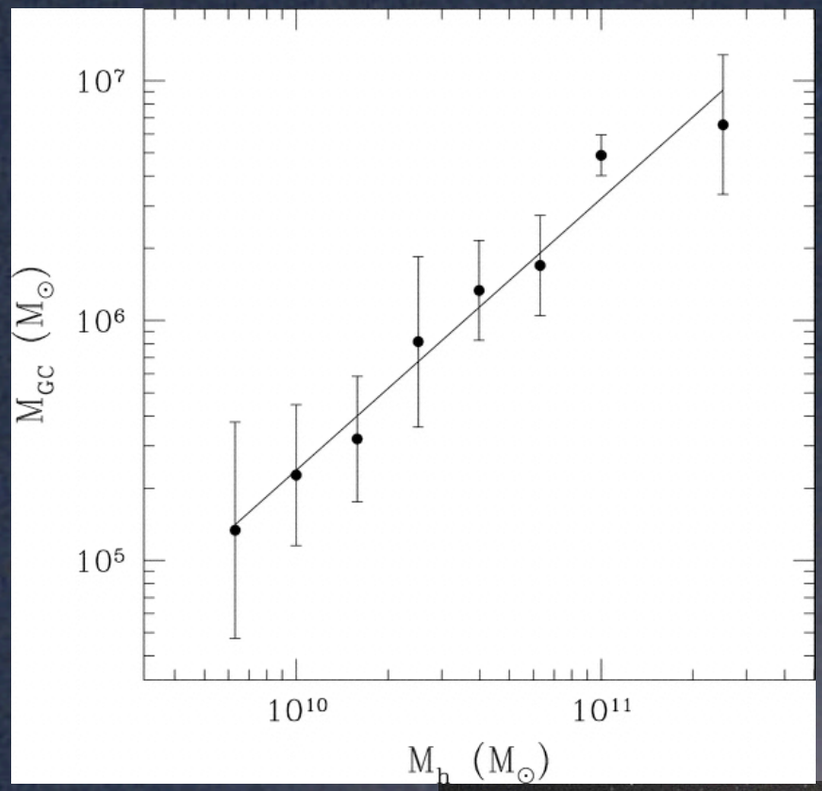
# Do Globular Clusters trace Total Mass?

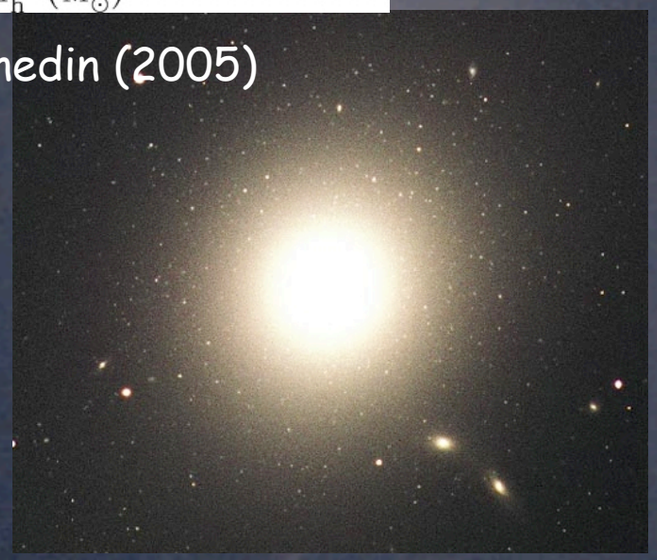
Mass in GCs may correlate with total baryonic or total dark mass




McLaughlin (1999)




Kravtsov & Gnedin (2005)



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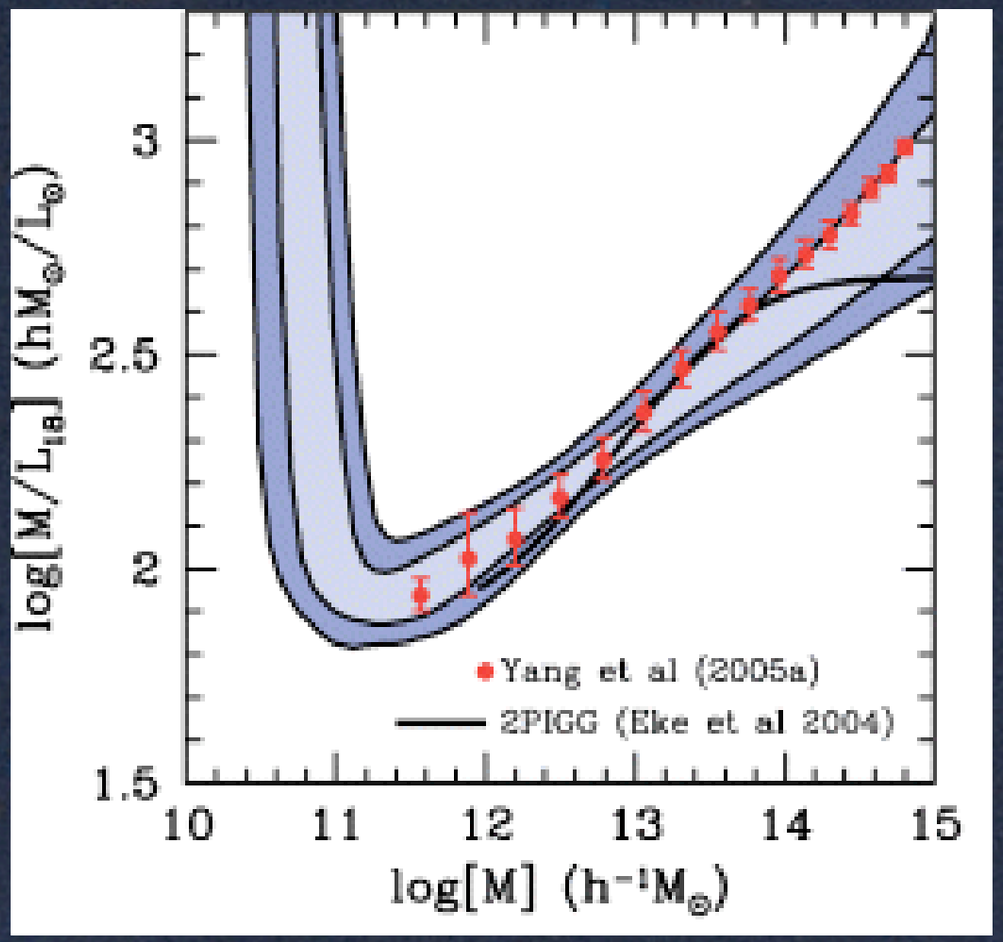


Total mass-to-light ratios of galaxies also has minimum at intermediate mass

Are globular clusters better tracers of total mass than stars themselves?

$N_{GC} \propto M_h$ or $S_M \propto M_h/L$?

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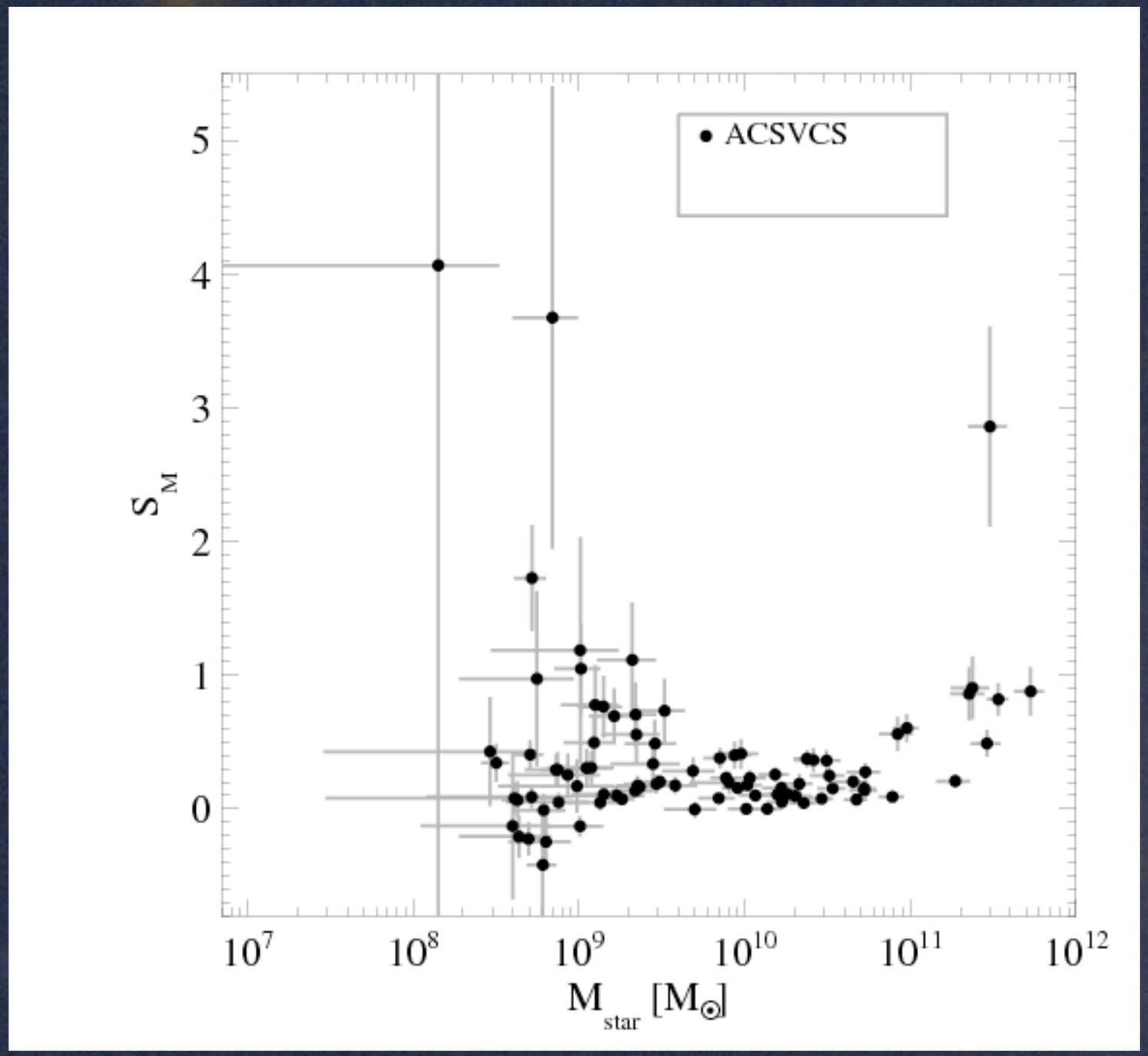


- Translate into *GC* stellar mass fraction

Peng et al. 2008

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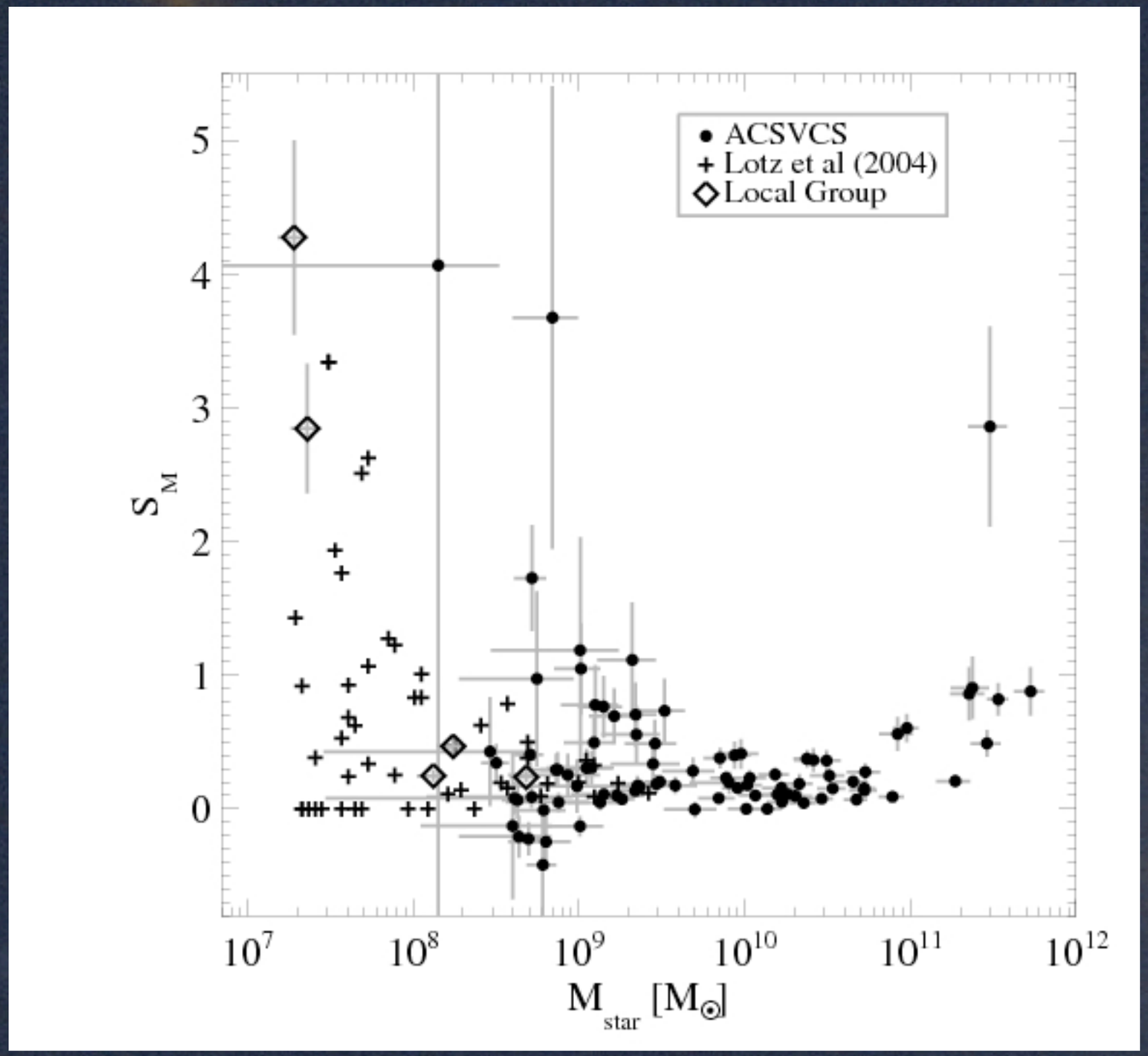


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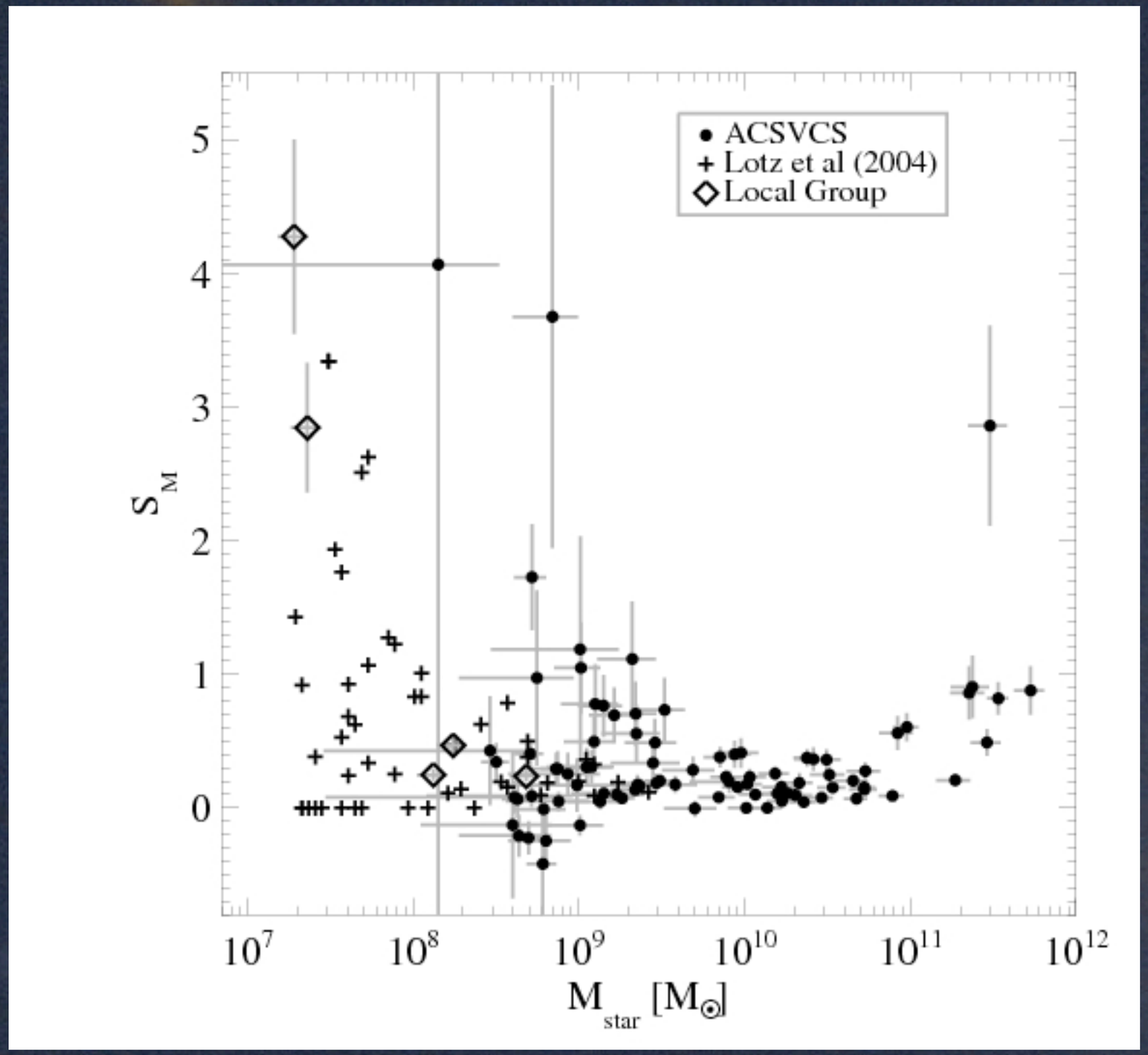
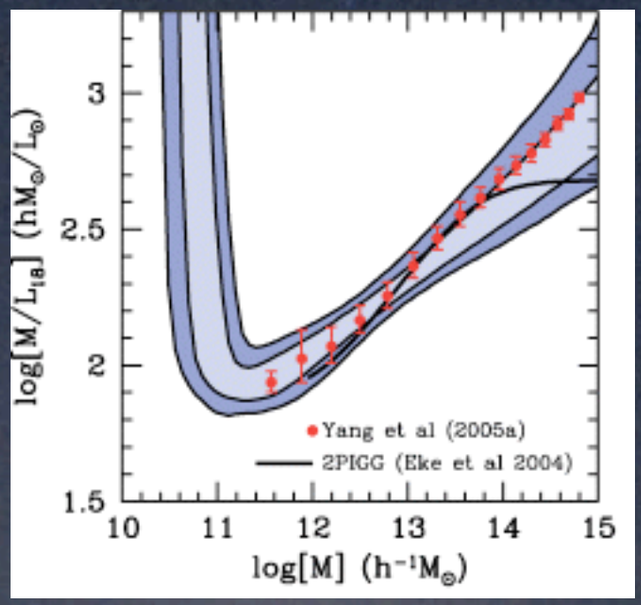



- Translate into GC stellar mass fraction
- $M_h/L$ vs $M_{gal}$ also has "U"-shaped relation

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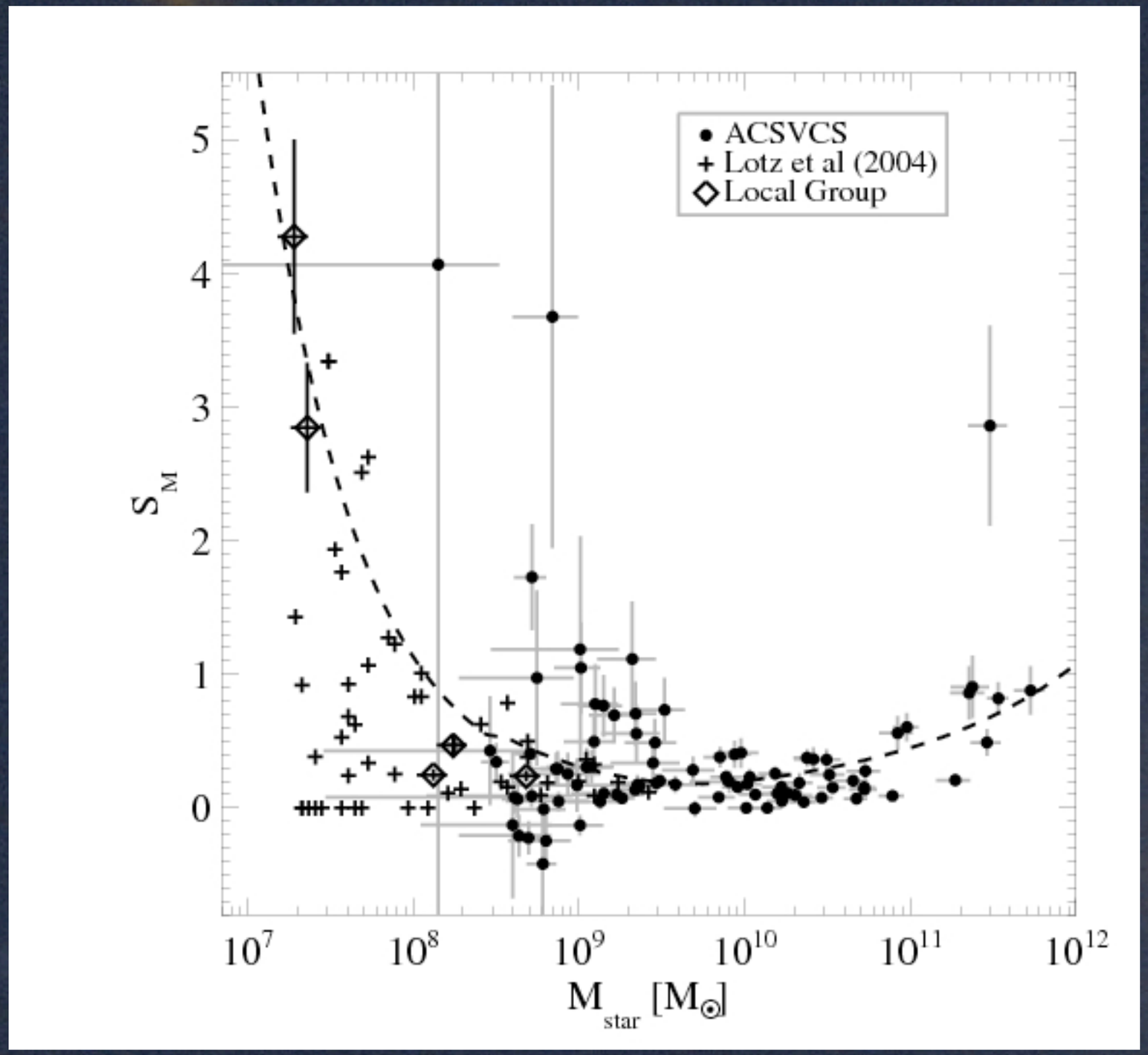


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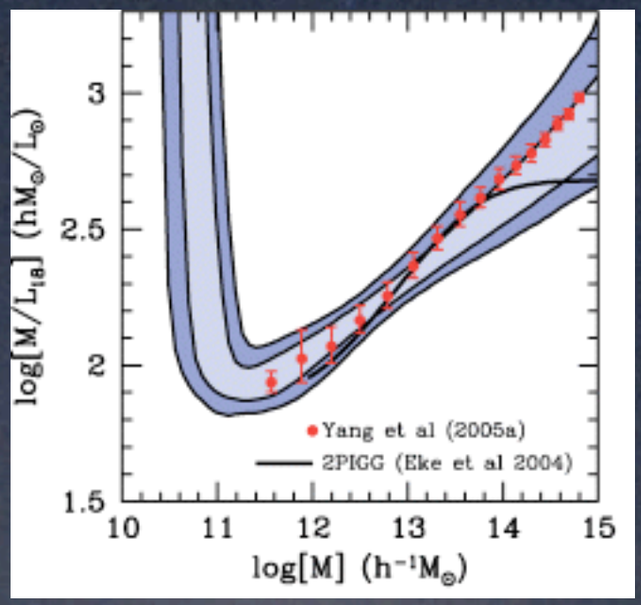


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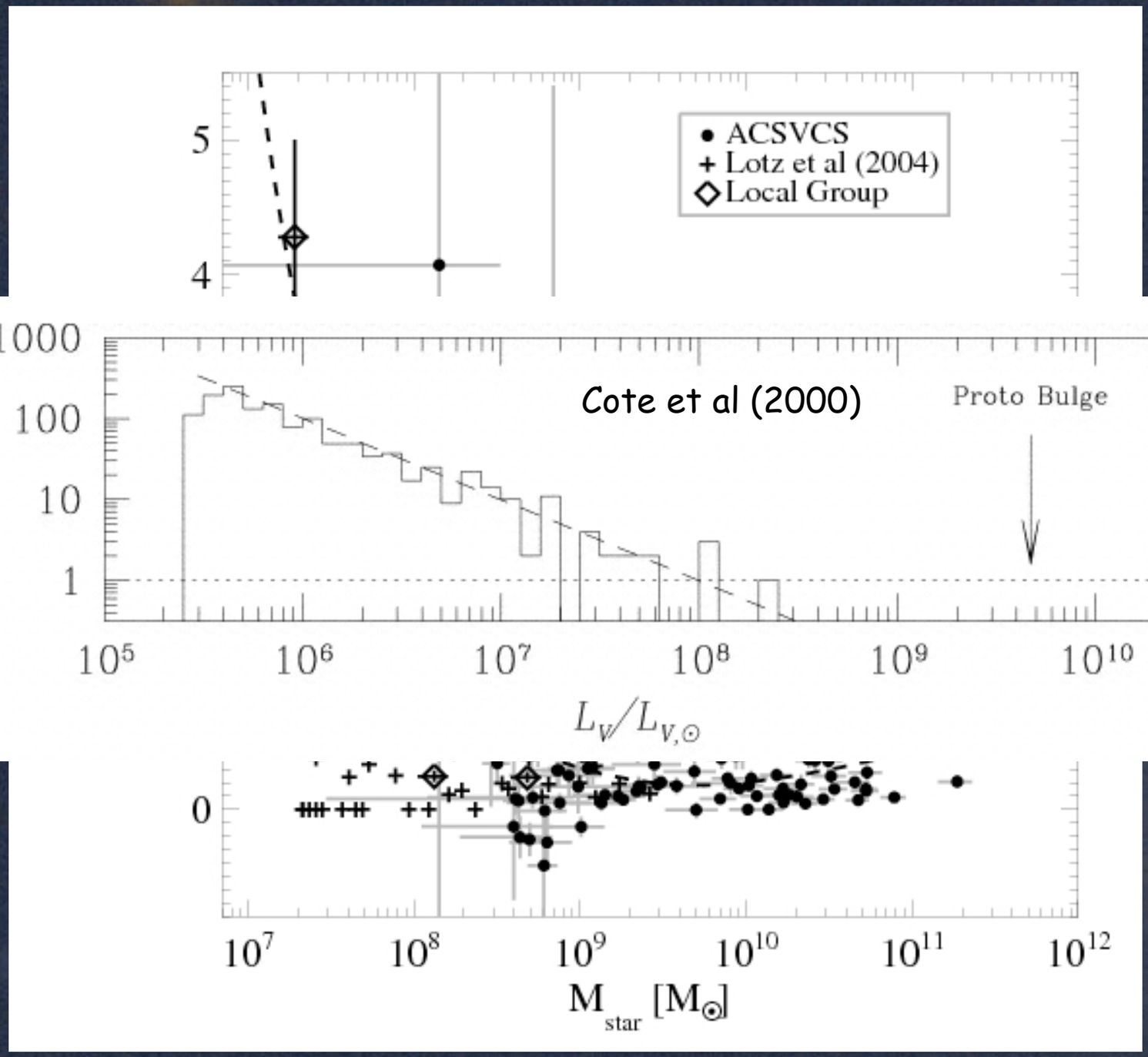


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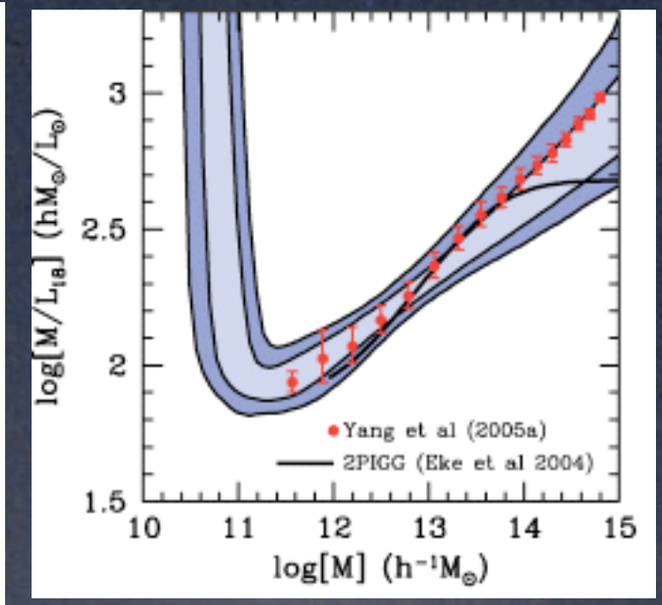


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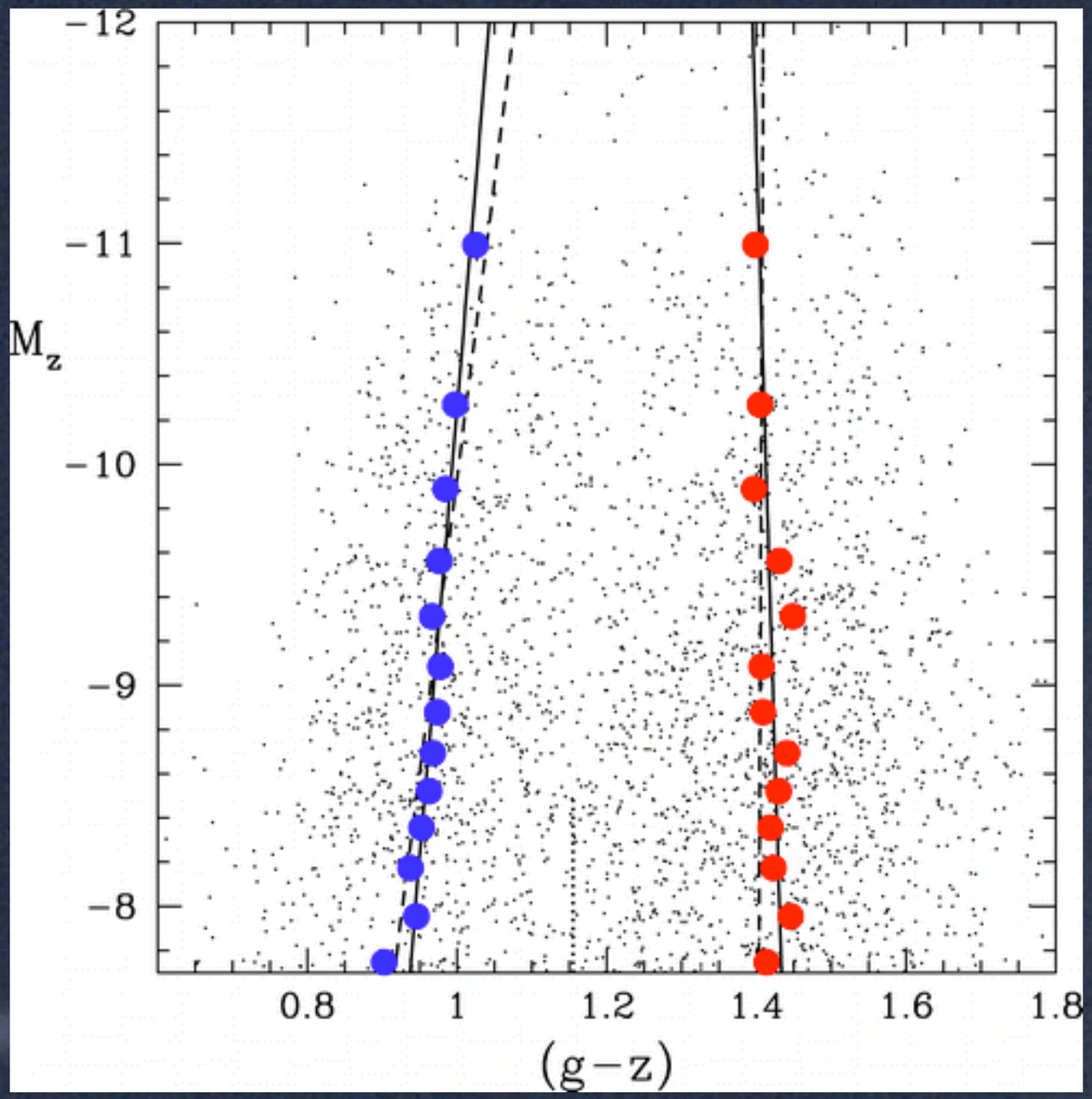
Peng et al. 2008

# Globular Clusters and Dark Matter: A connection?




Mieske et al. 2008

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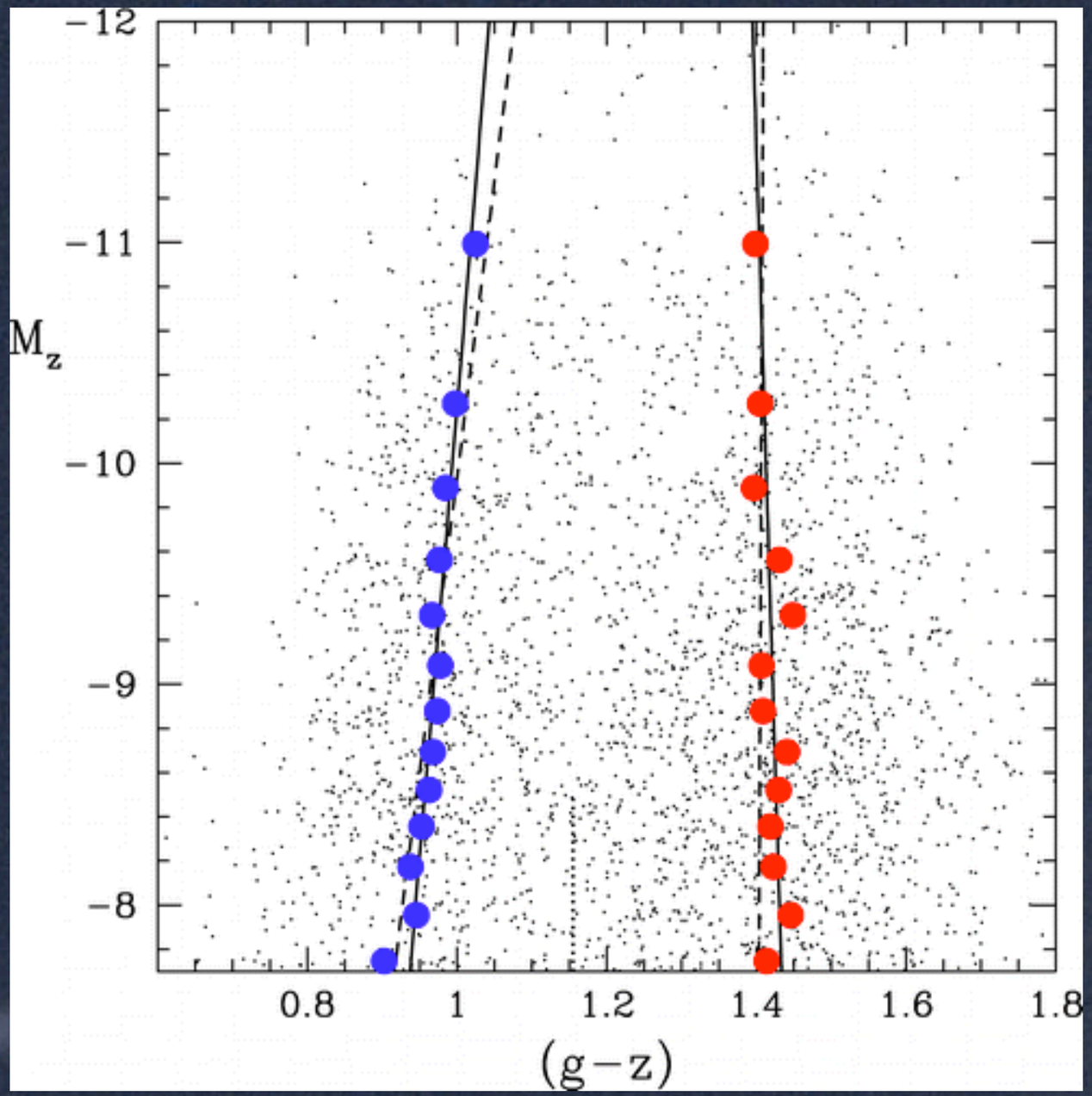


- Metal-poor Globular Clusters show color-magnitude relation (mass-metallicity)
- Self-enrichment during formation?

Mieske et al. 2008

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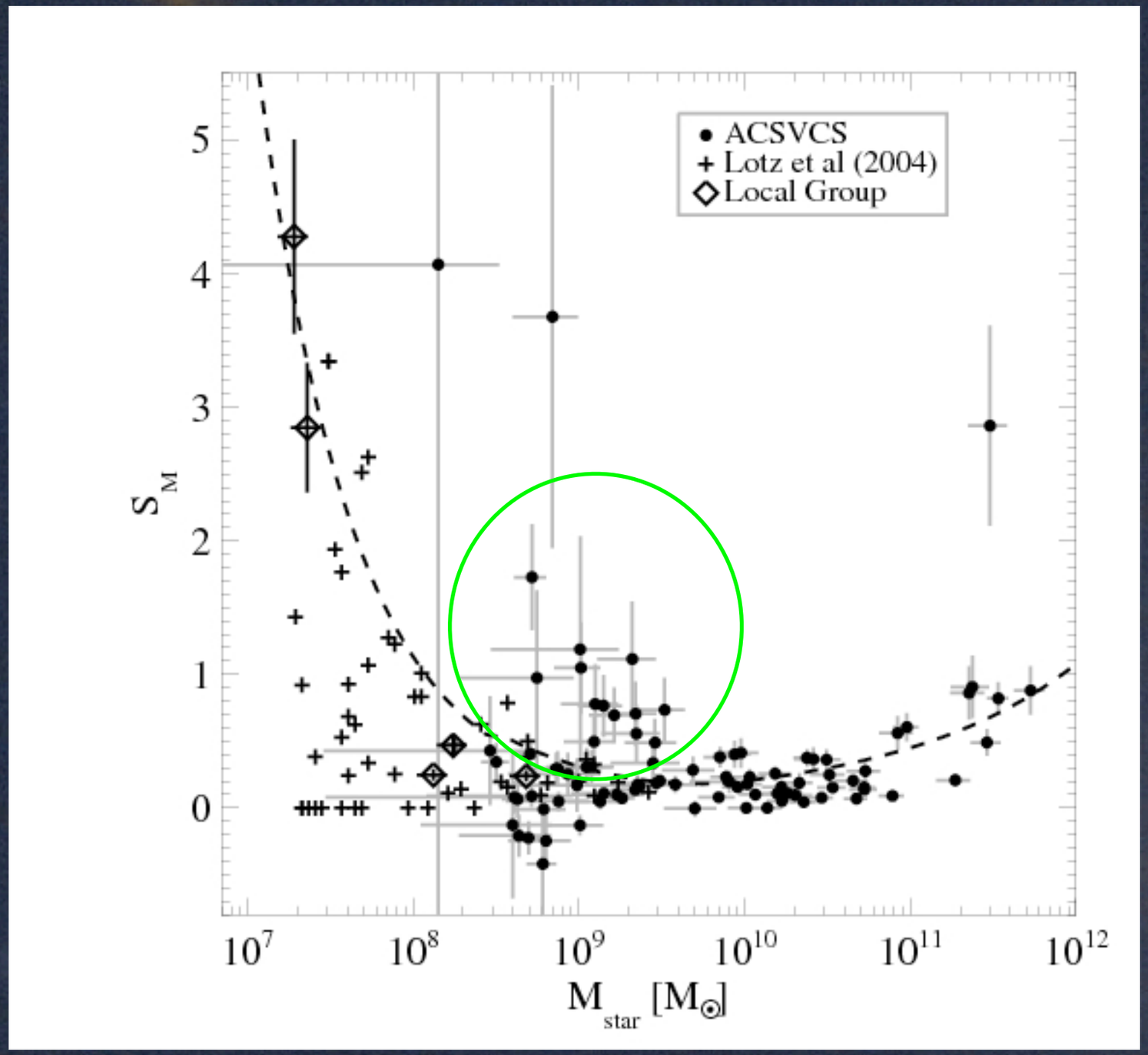


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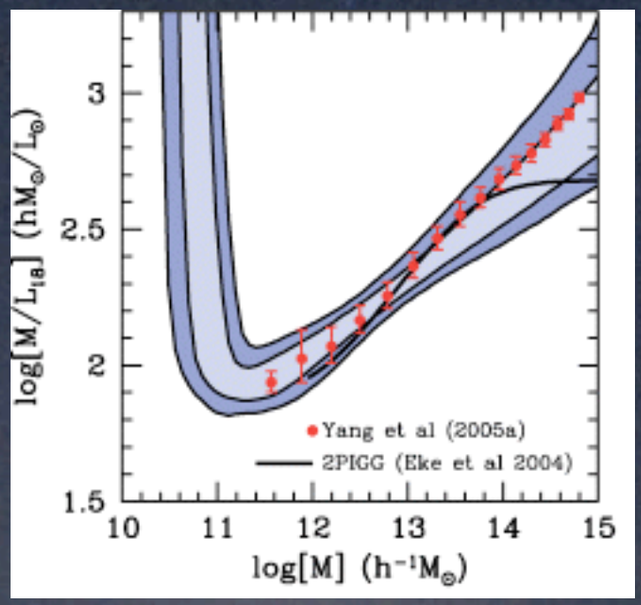


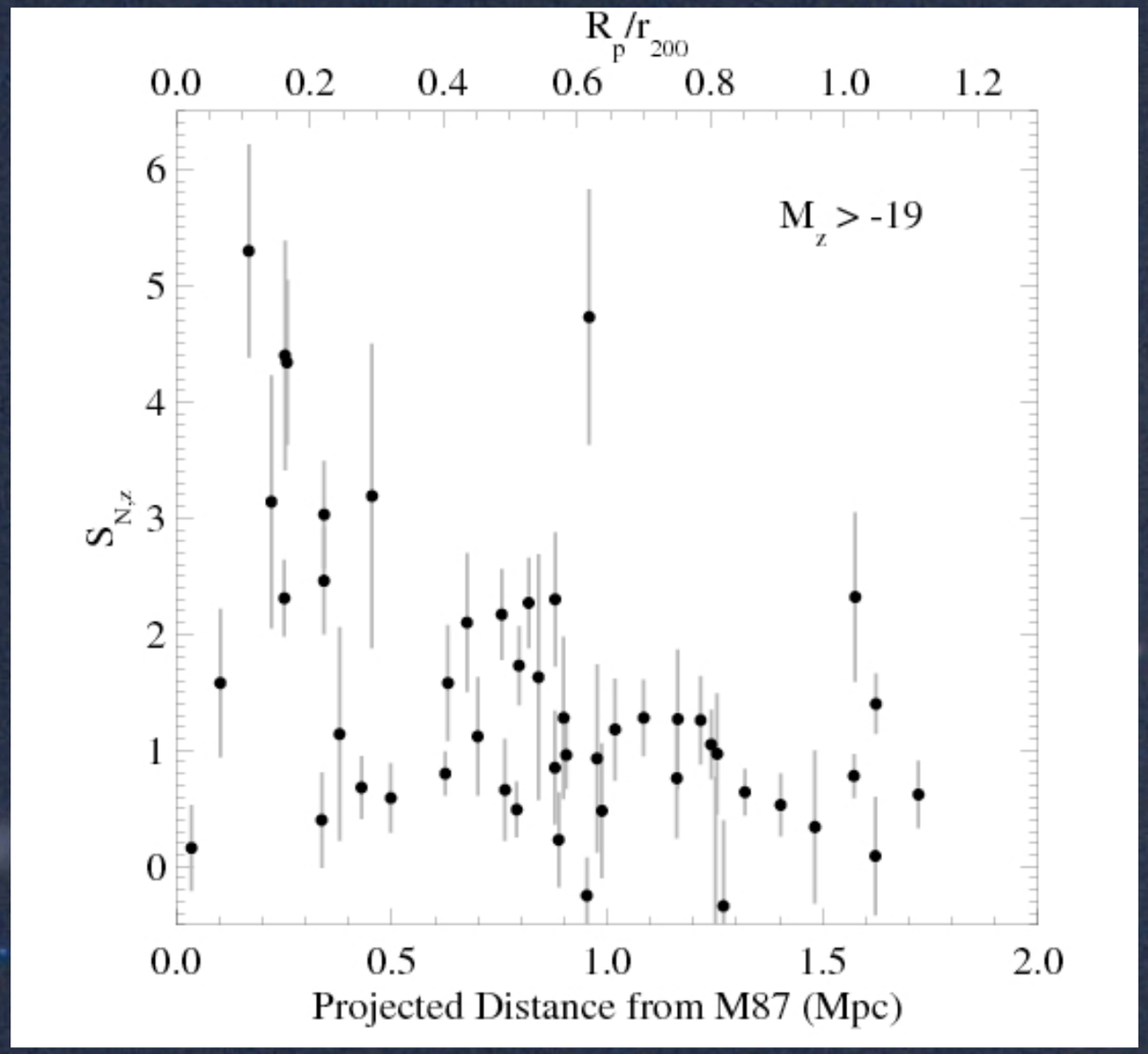

$S_M \propto M_h/L$?

- Use relation derived from HOD (van den Bosch 2007)

$N_{GC} \propto M_h$ can explain some, but not all trends in $S_M$.

Peng et al. 2008

# Globular Clusters in dEs: The Role of Environment

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- $S_N$ vs clustercentric distance

Peng et al. 2008

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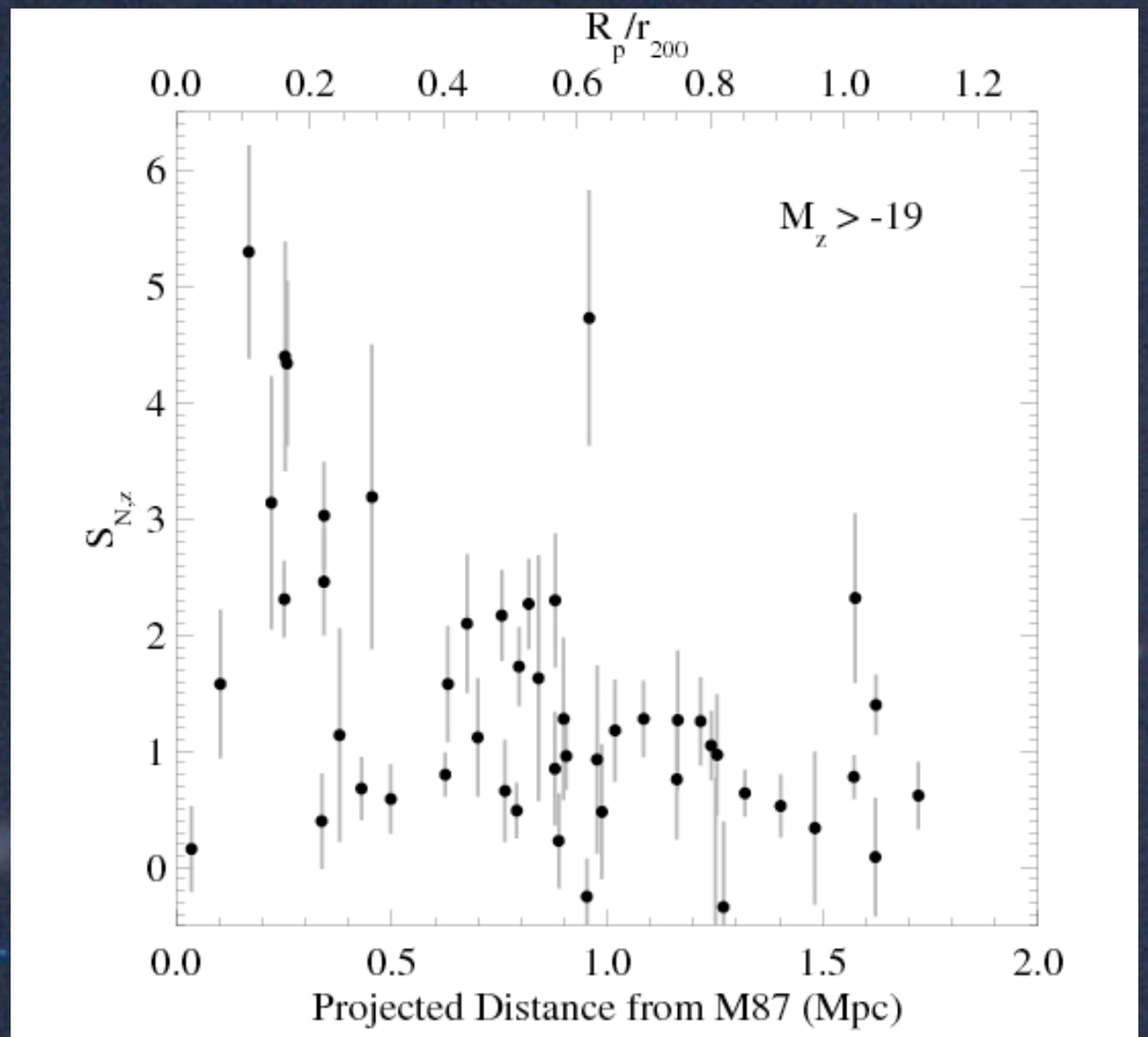


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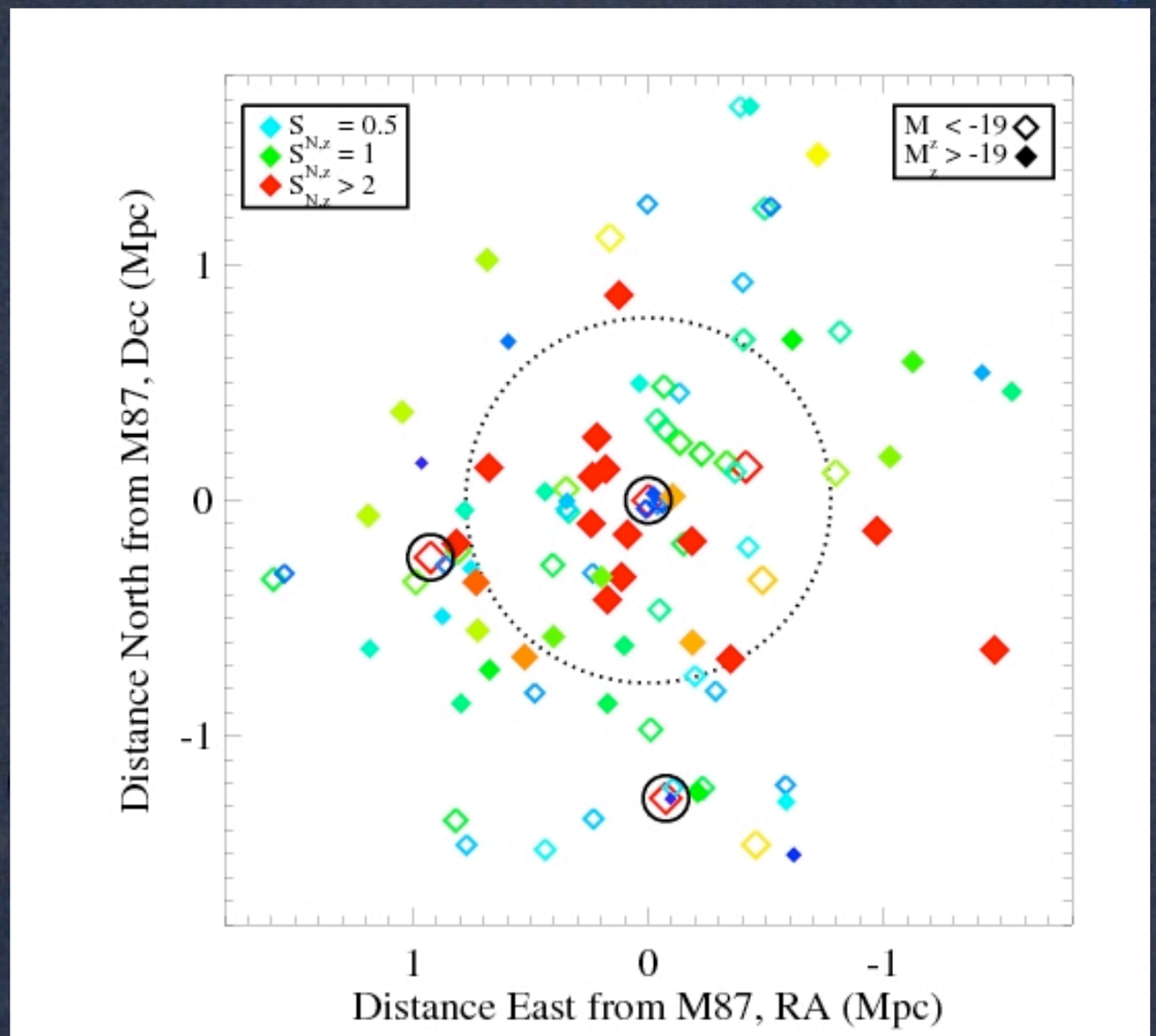
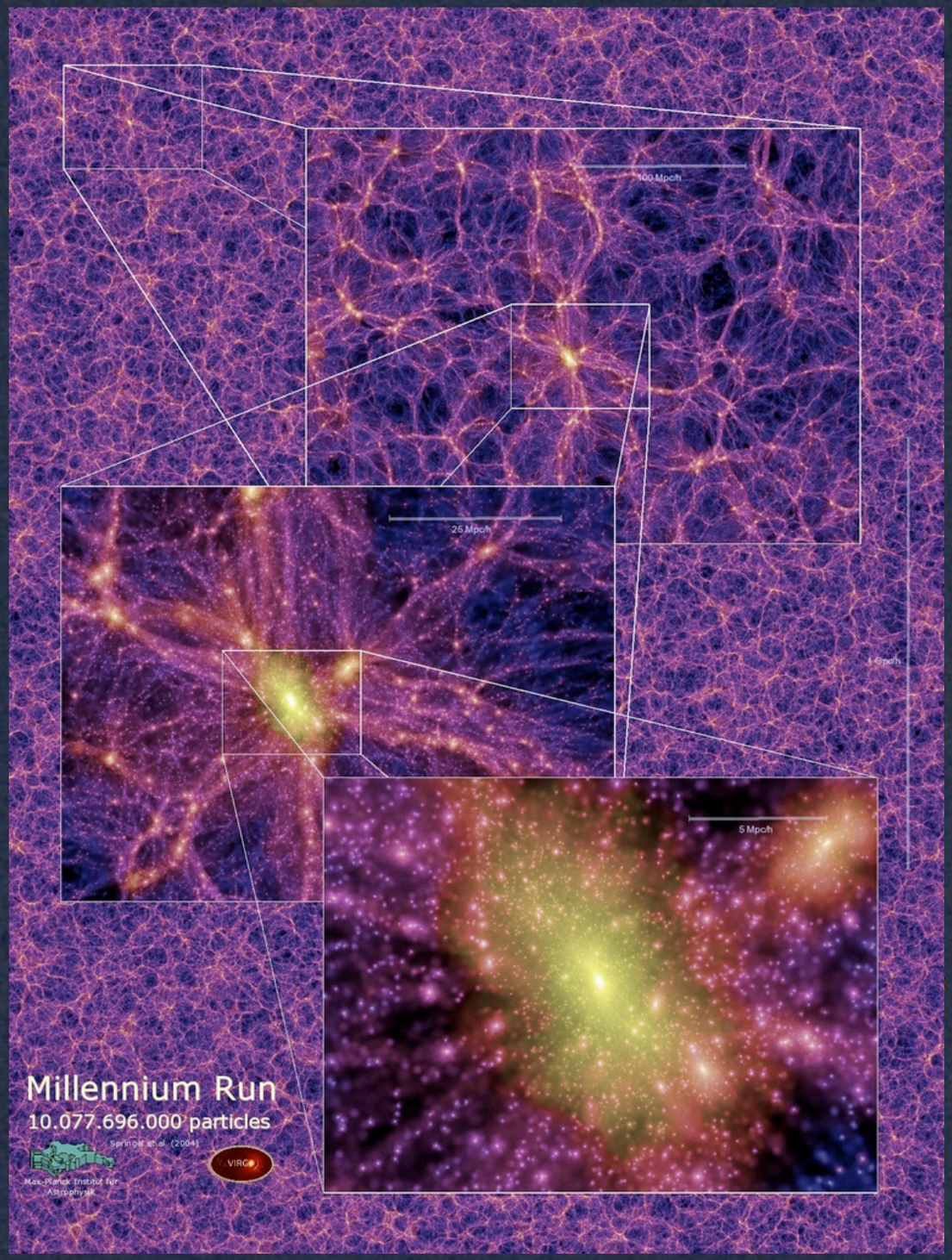



- dEs with high GC fractions are within $R_p < 1$ Mpc
- dEs within 100 kpc, stripped of GCs

Peng et al. 2008

# The Millennium Simulation

(Springel et al 2005, De Lucia et al 2006)




- $2160^3$ dark matter particles
- $500^3$ $h^{-1}$ Mpc volume
- z=127 to present
- Galaxies with stellar mass > $3x10^8$

- 126 massive galaxy clusters
- Select 15,506 simulated early-type dwarfs ($M_z$>-19 at z=0) and their progenitors
- 63 snapshots from z=12

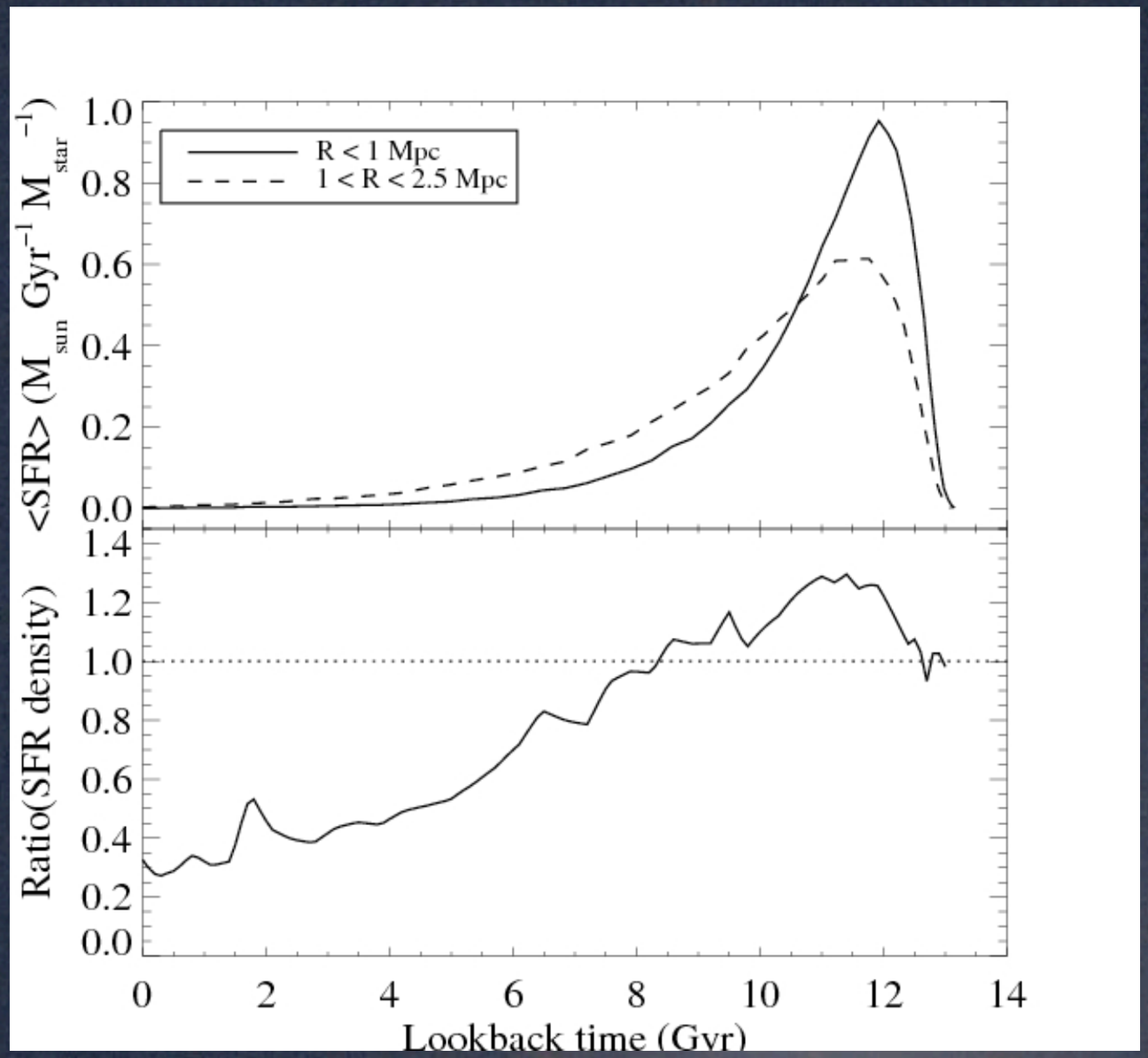
What are the properties and star formation histories of simulated early-type cluster dwarfs?

# The Millennium Simulation:
## Early-type cluster dwarfs

Average star formation rate of central dwarfs more peaked with rapid falloff

Star formation in central dwarfs occurs at higher star formation rate **density**

Higher SFR density -> higher star cluster formation efficiency



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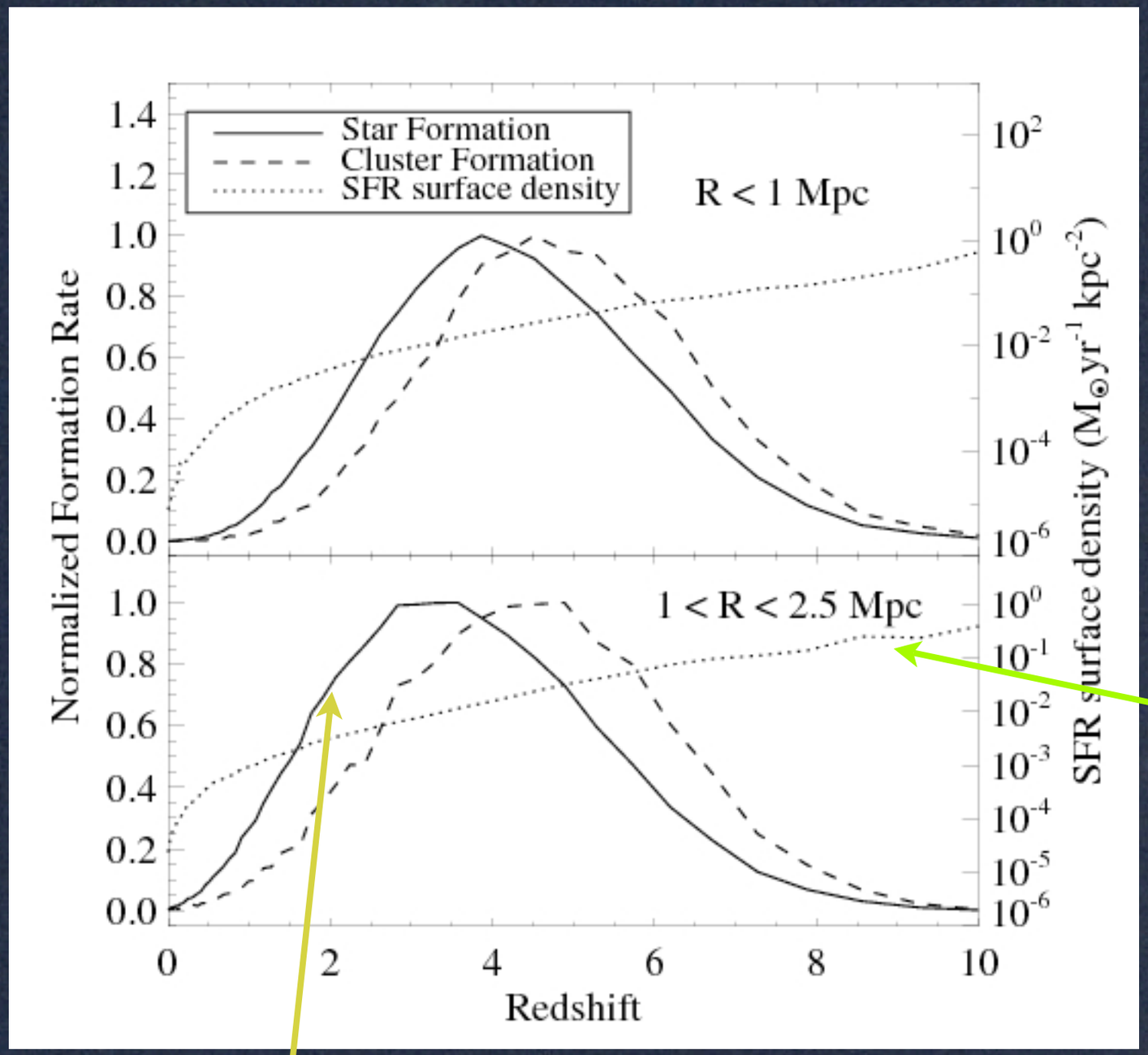


Peak formation of massive star clusters is naturally earlier than peak SFR

SFR surface density

Star Formation Rate

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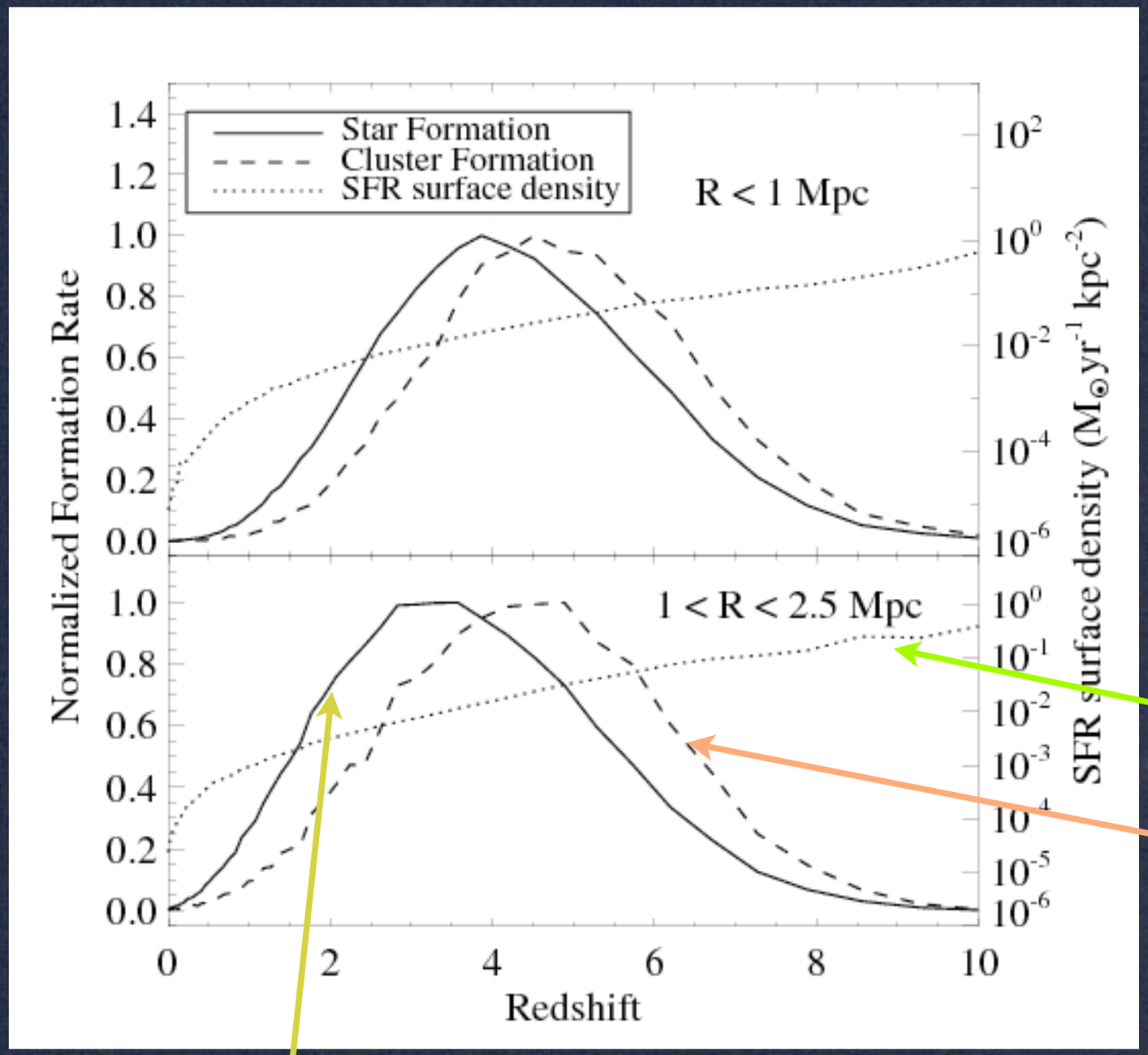


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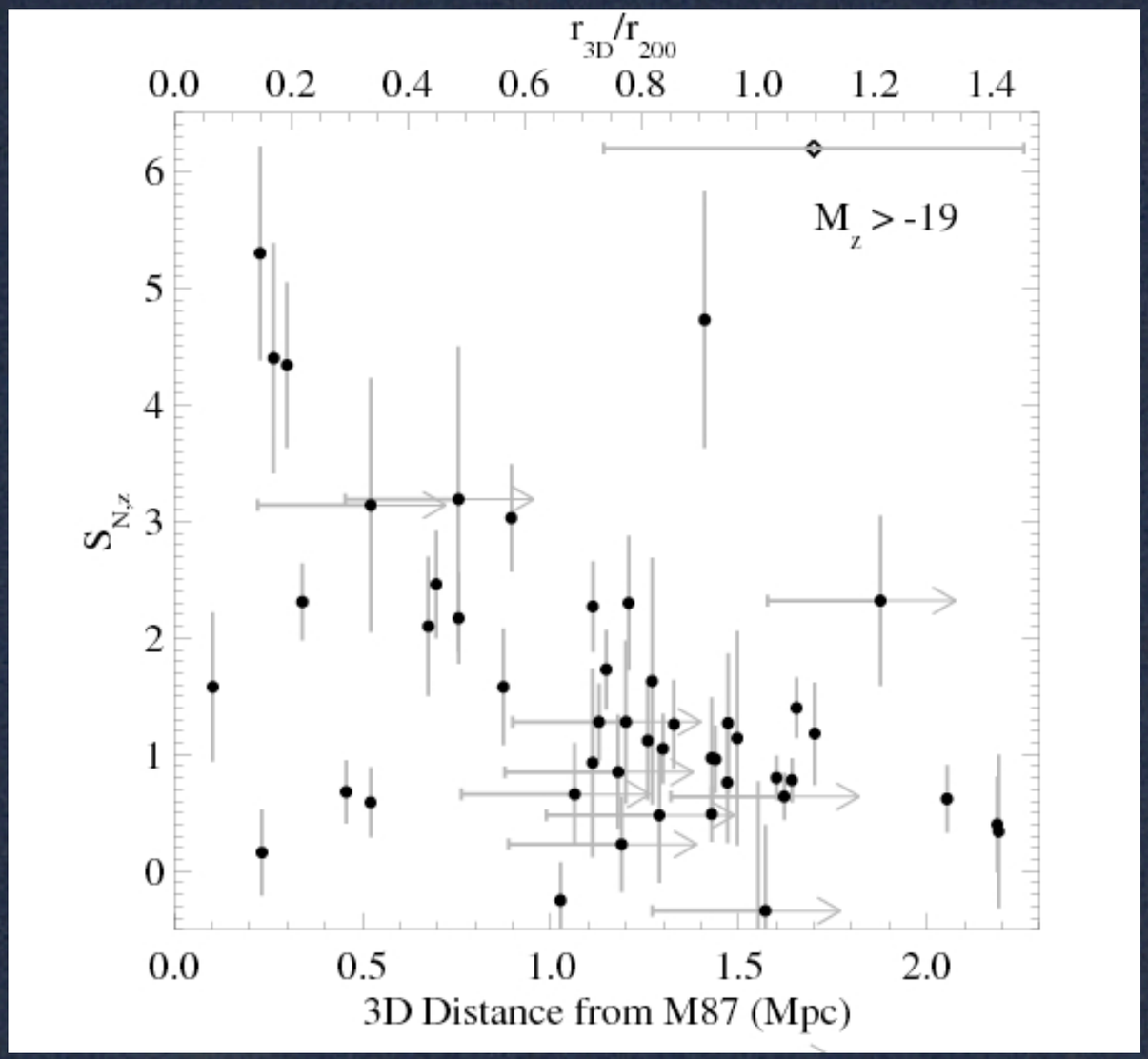


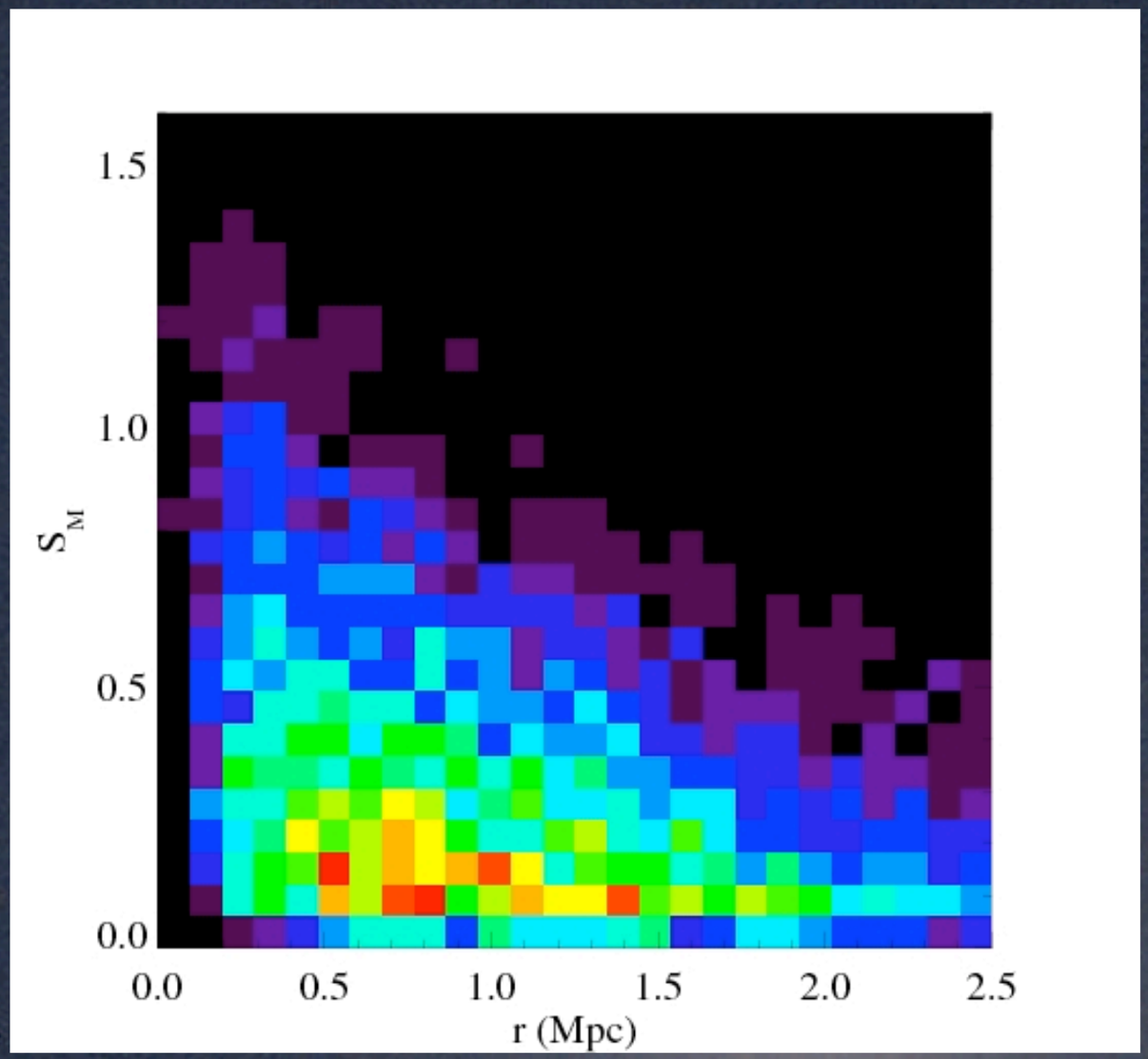

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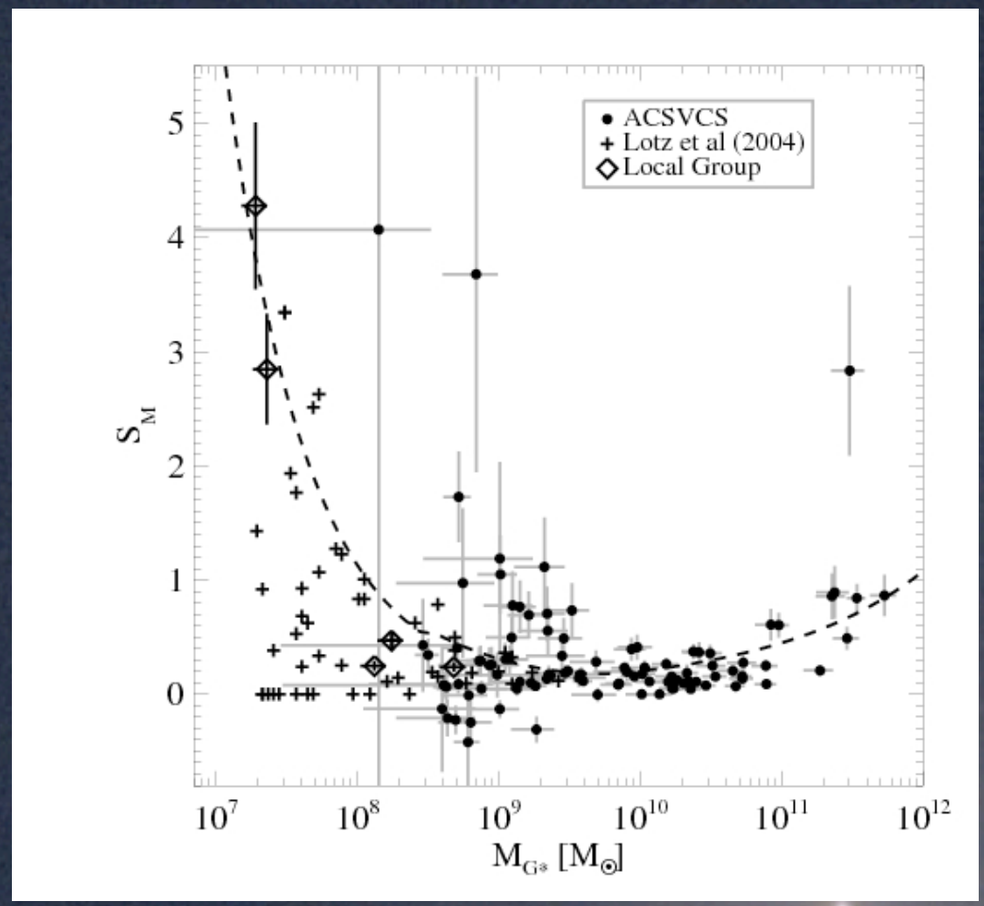

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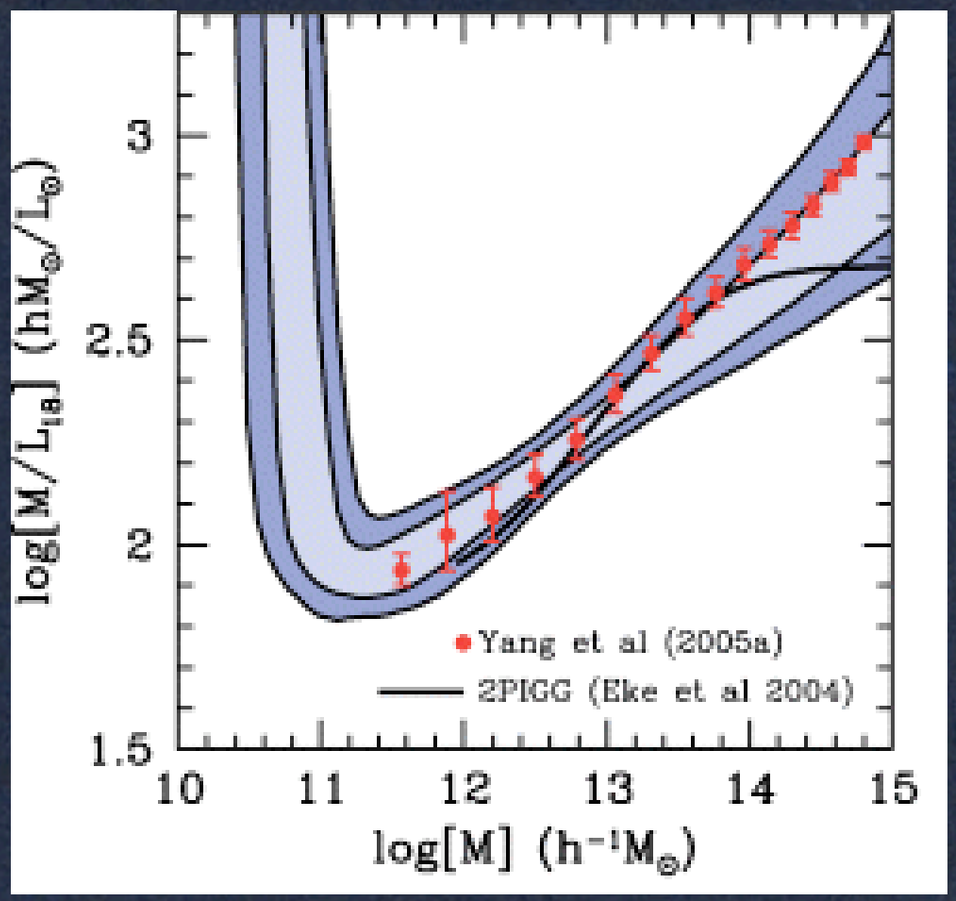
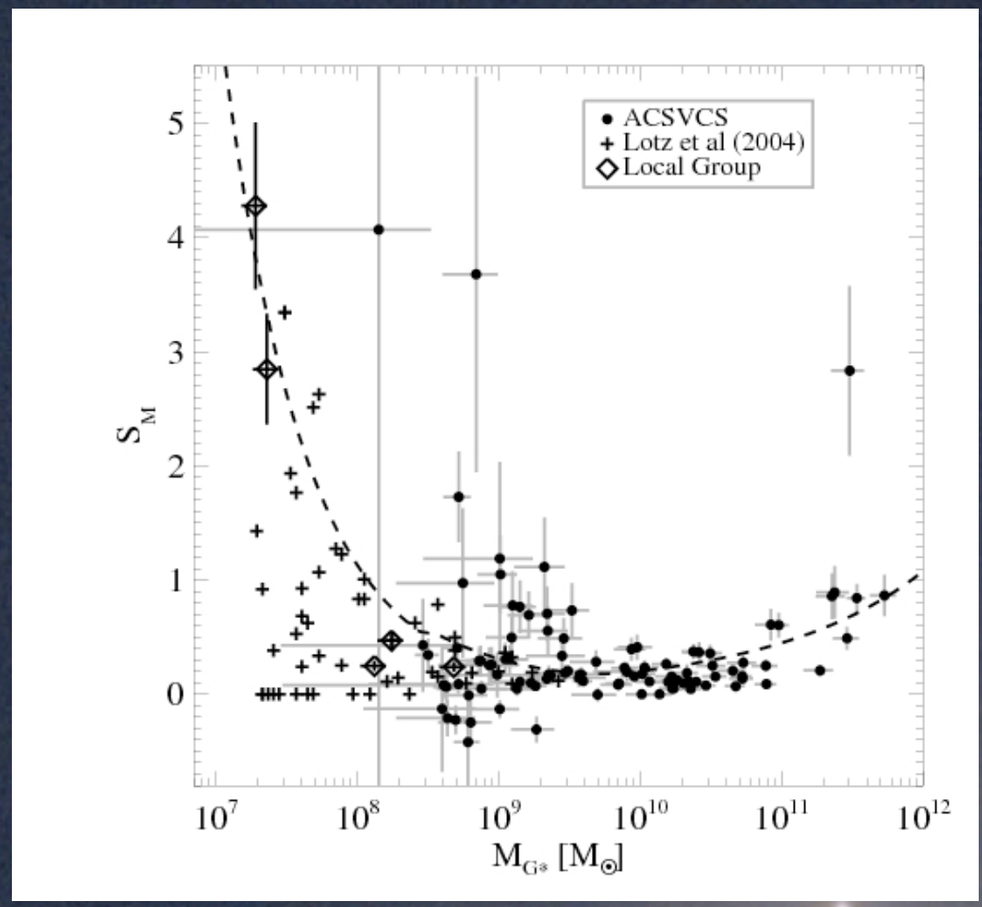
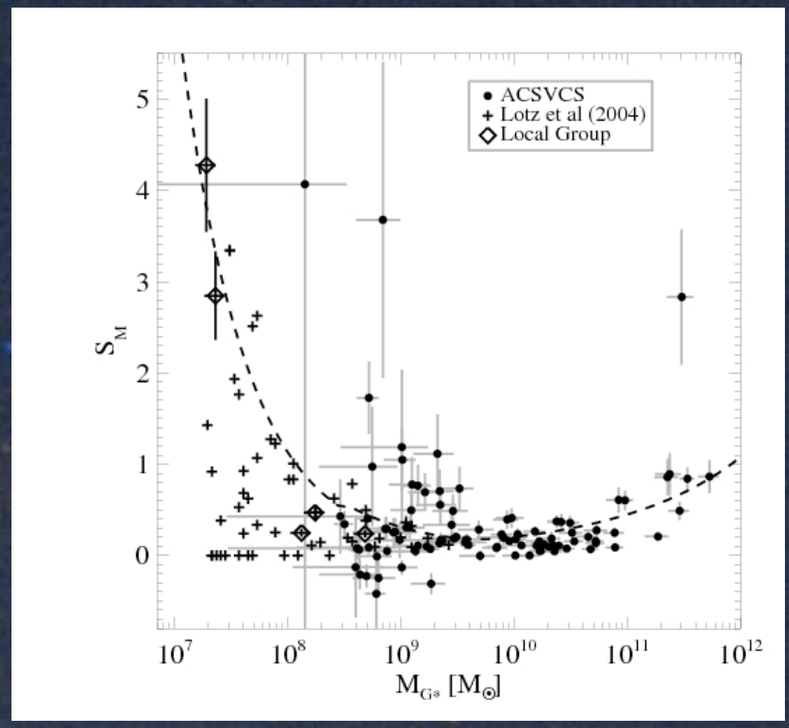
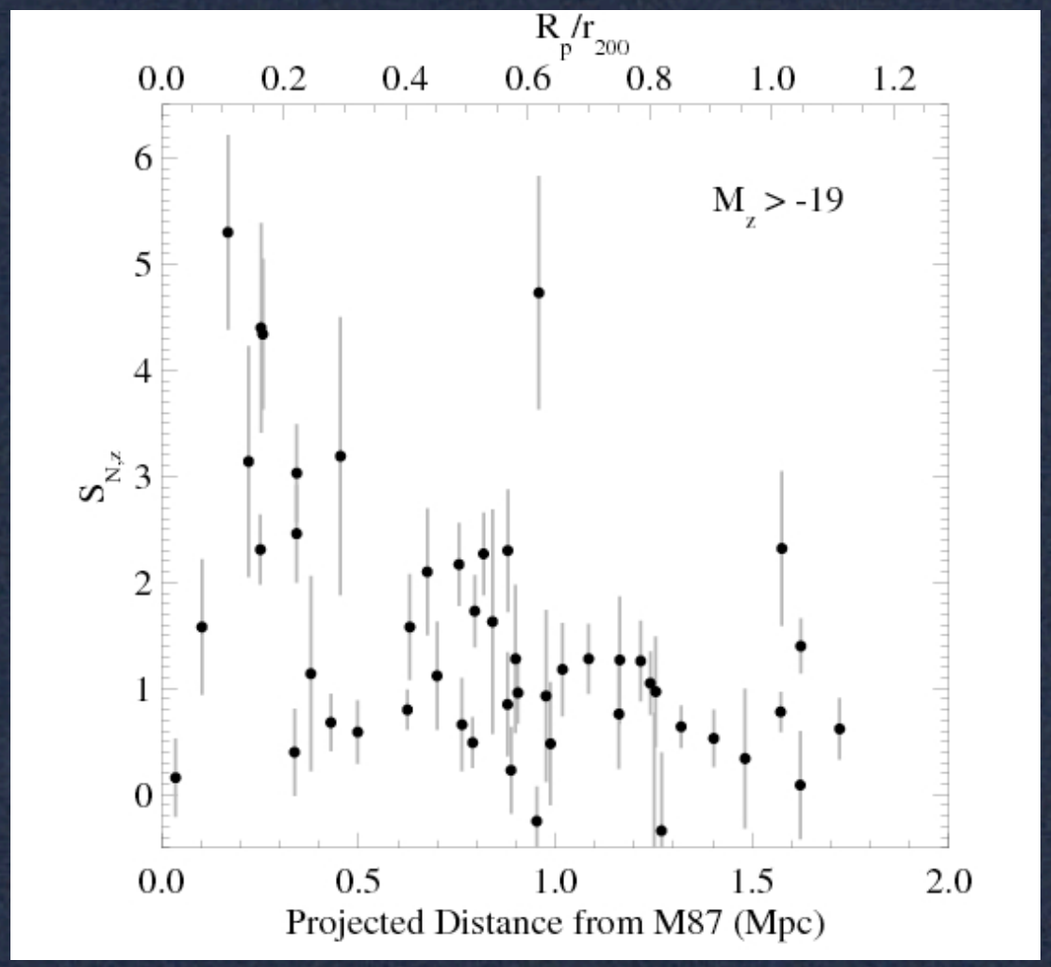


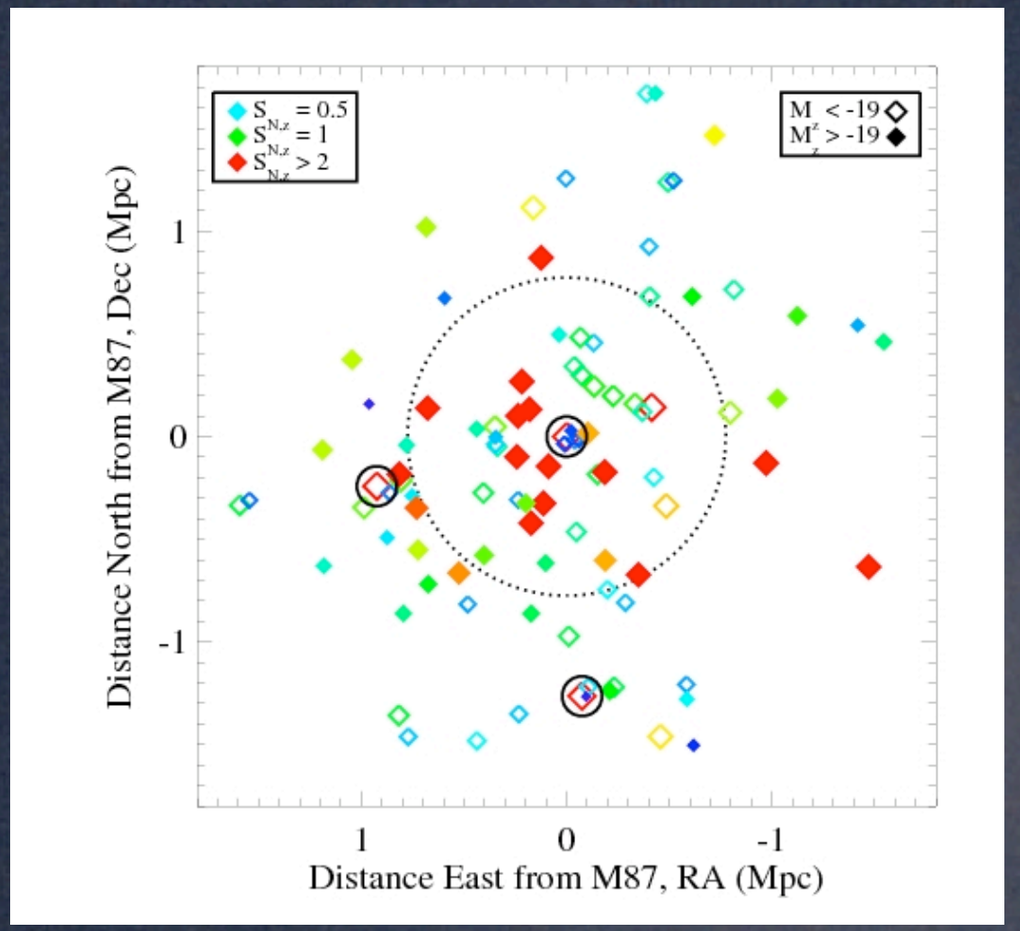



# Implications and Speculations

1. Variation in GC formation efficiency reflects (in part) formation efficiency of the field stars
2. GC formation in dEs relative to their field stars is biased toward the cluster center



# Future Directions

Observations: Imaging

- Wide-field necessary for panoramic view of GCs and dwarfs in galaxy clusters
- CFHT/Megacam, Subaru/HyperSuprime, LSST, PanStarrs, HST

Mihos et al (2006)

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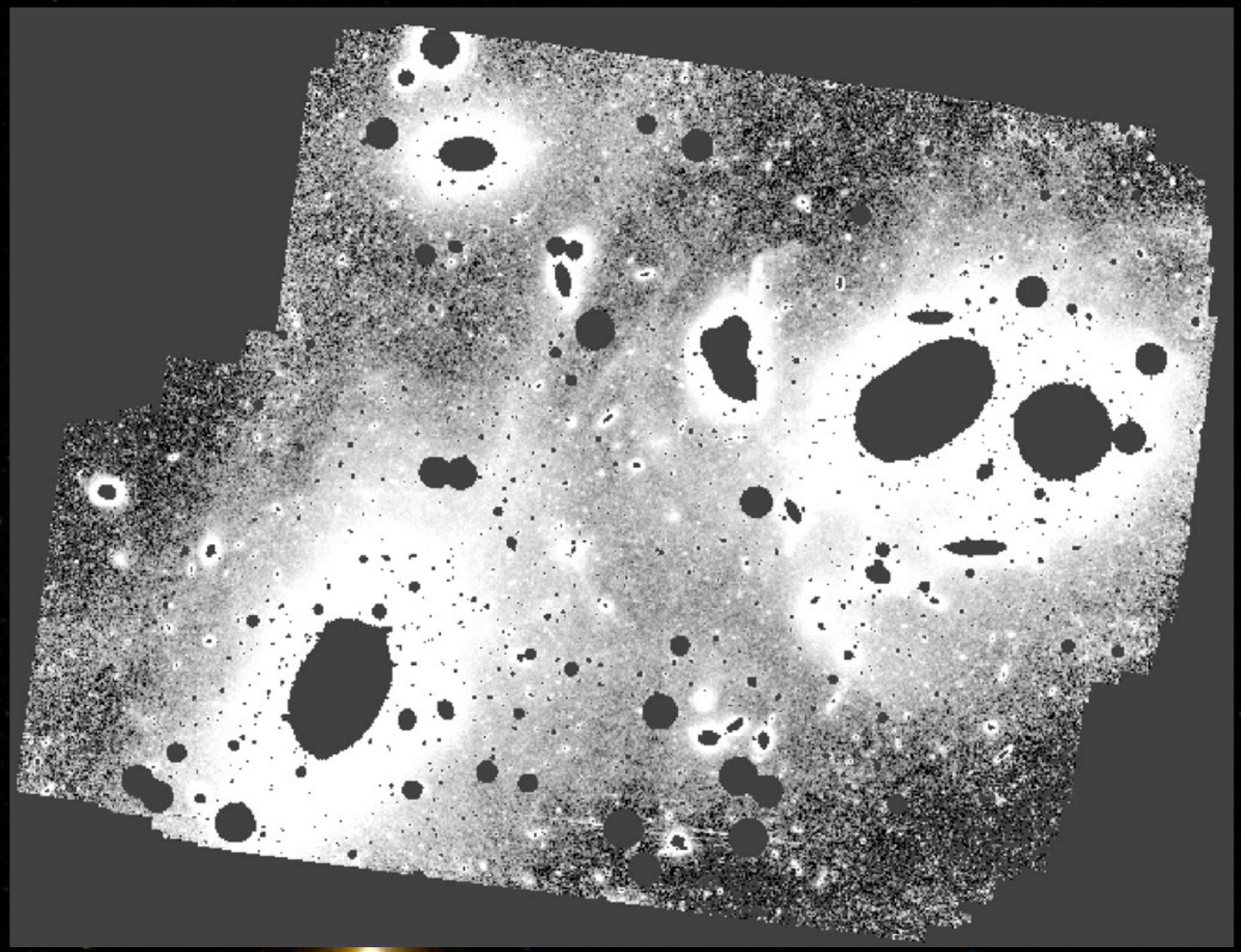

Mihos et al (2006)

# Future Directions

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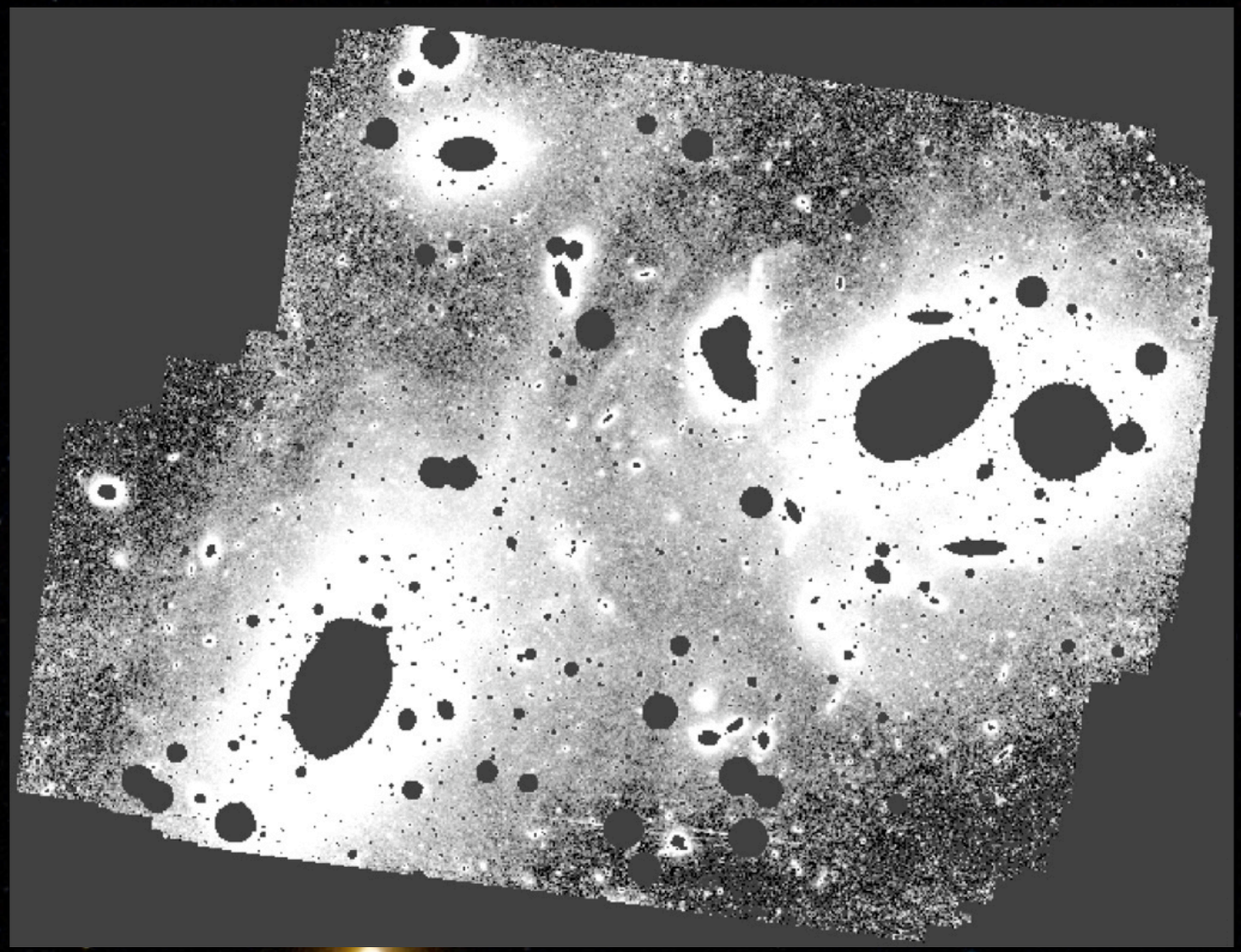
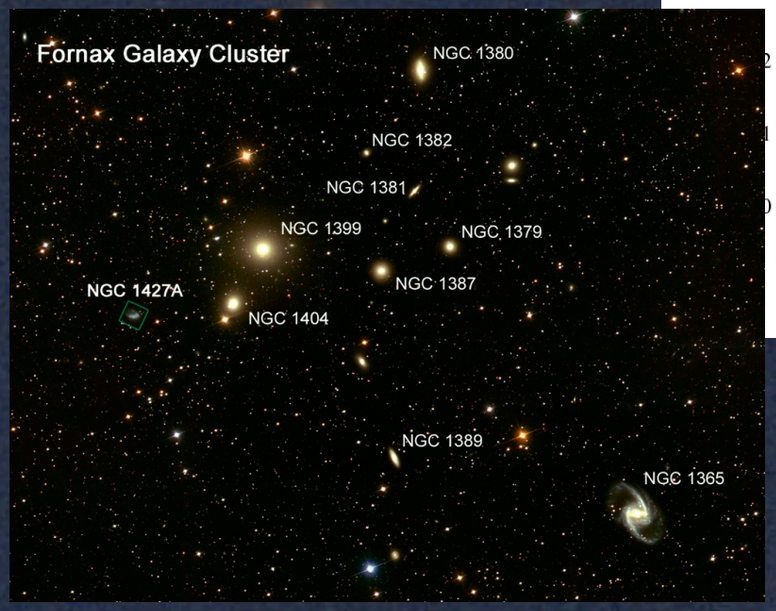
Next Generation Virgo Survey: CFHT/Megacam
Survey of 140 $deg^2$ in Virgo

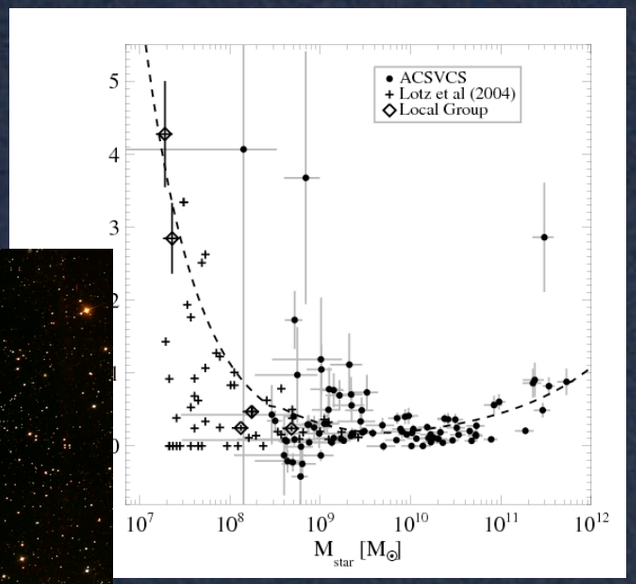


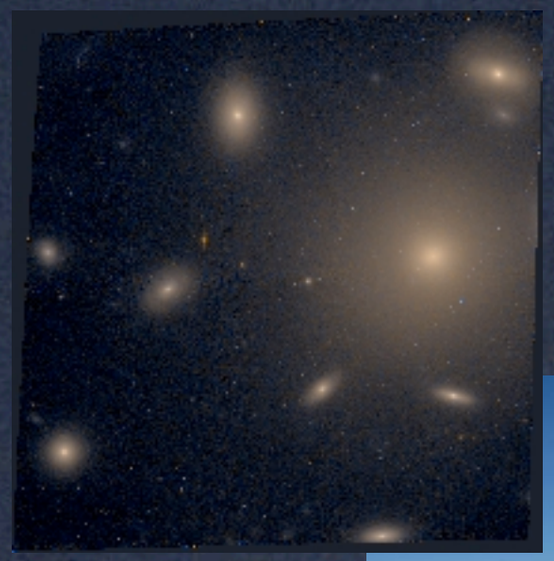
Mihos et al (2006)

- Census of baryonic content to lowest mass galaxies and star clusters
- What is the difference between a star cluster and a galaxy?

# Future Directions




- ACS Fornax Cluster Survey
- HST/ACS Coma Cluster Survey
- Spatial Distributions of Globular Clusters (Qiushi Wang, PKU)
- LAMOST : GCs are just the tip of the iceberg, a few % of stellar mass