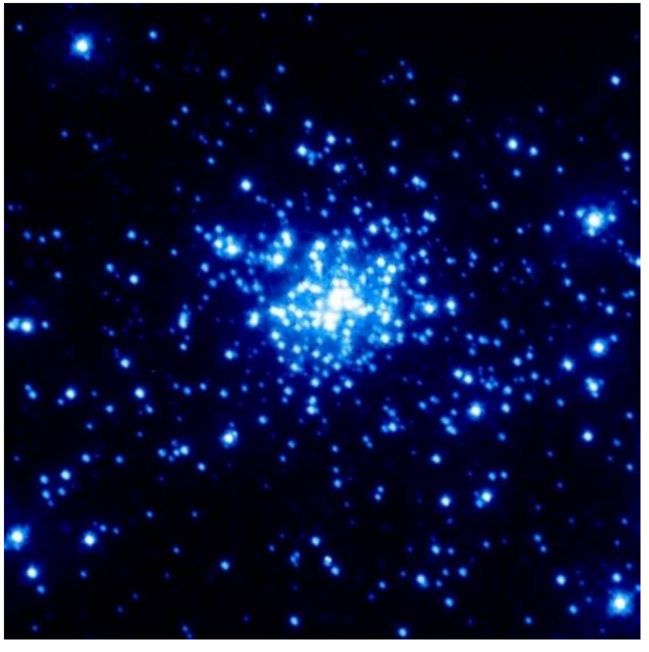
Formation of Star Clusters and Dwarf Galaxies

Oleg Gnedin

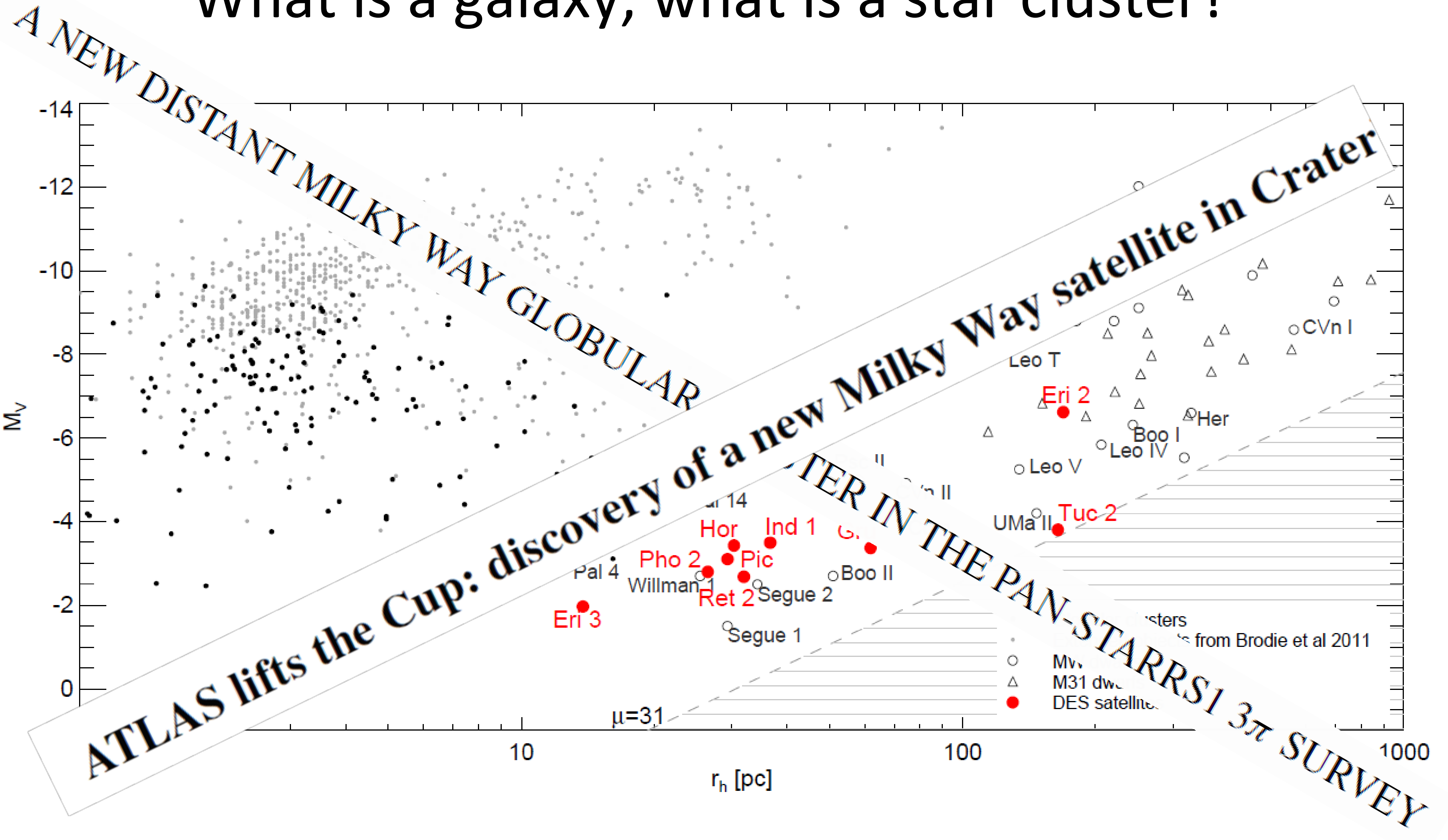
(University of Michigan)



star cluster

dwarf galaxy (Leo IV)

What is a galaxy, what is a star cluster?



Koposov et al. 2015

The Astronomical Journal, 129:148–159, 2005 January

DISCOVERY OF A SOLITARY DWARF GALAXY IN THE APPLES SURVEY

Anna Pasquali
Institute of Astronomy, ETH Hönggerberg, HPF, CH-8093 Zürich, Switzerland; and ESO/Space Telescope European Coordinating Facility, Karl-Schwarzschild-Strasse 2, D-85748 Garching bei München, Germany

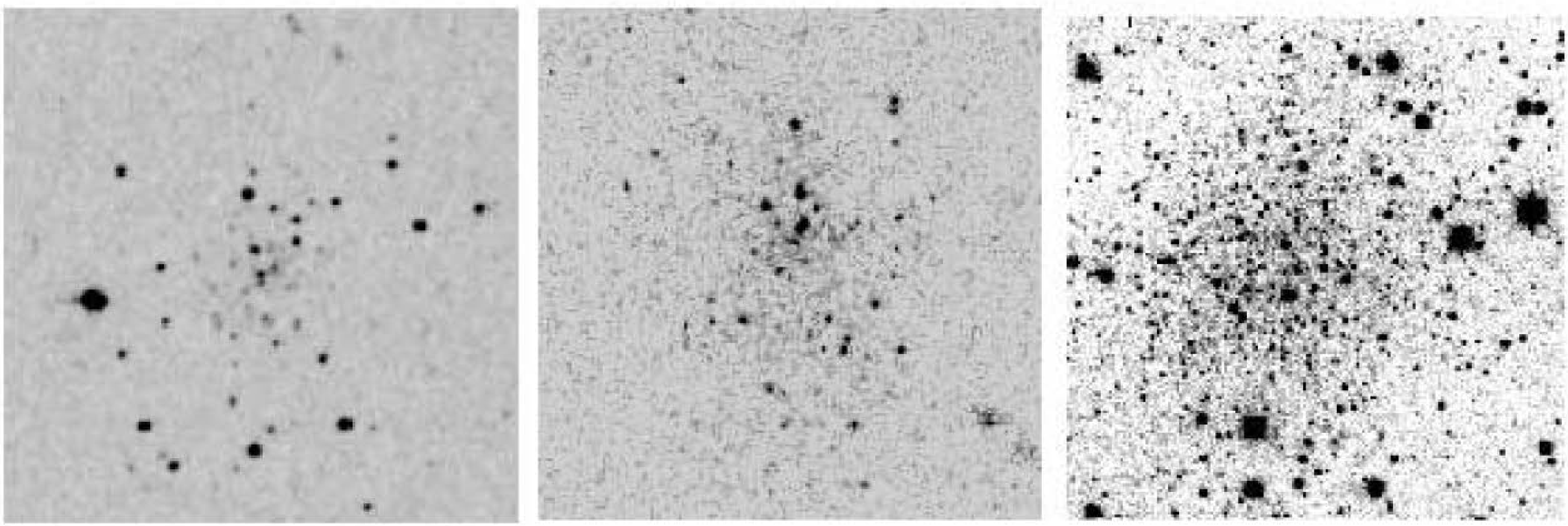
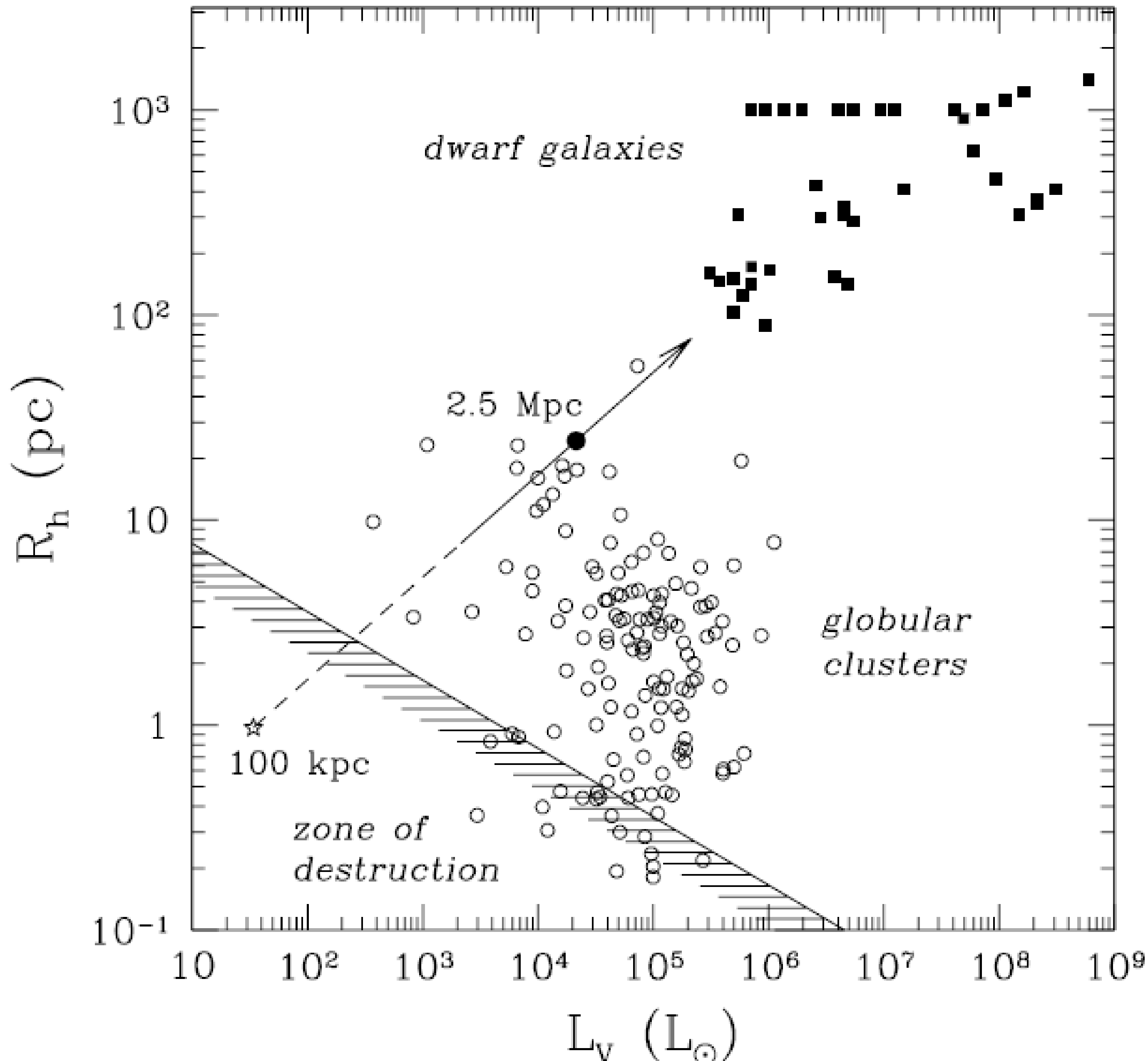
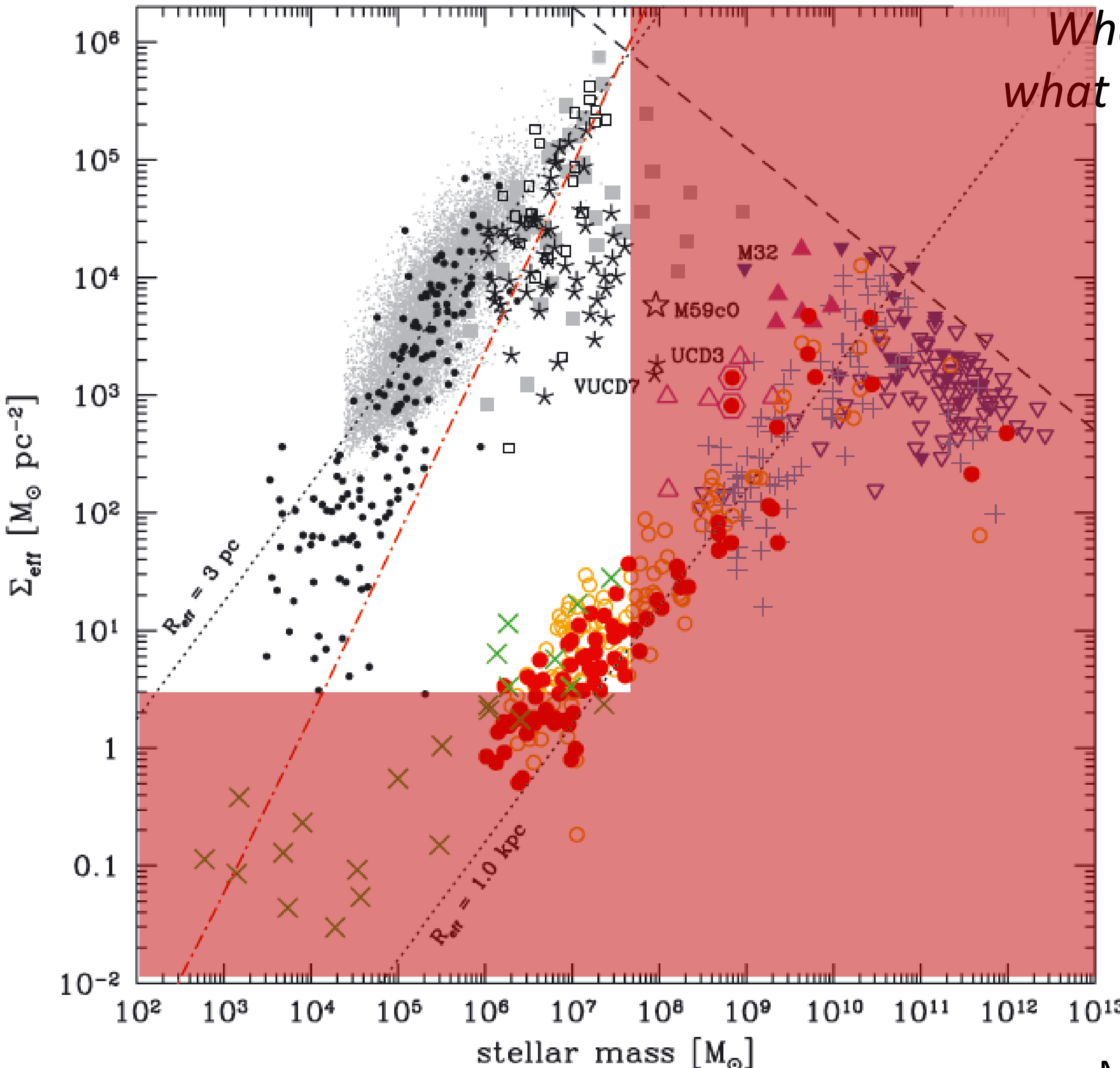


Fig. 1.—F775W image of APPLES 1 (*middle panel*, $9'' \times 9''$, i.e., $\sim 440 \times 440$ pc^2) compared with the DSS image of the globular cluster Pal 13 in the Galactic halo (*left panel*, $5' \times 5'$, i.e., $\sim 130 \times 130$ pc^2) and a *V*-band image of the dwarf galaxy And V (*right panel*, $3' \times 3'$ equivalent to 640×640 pc^2) by Armandroff et al. (1998).



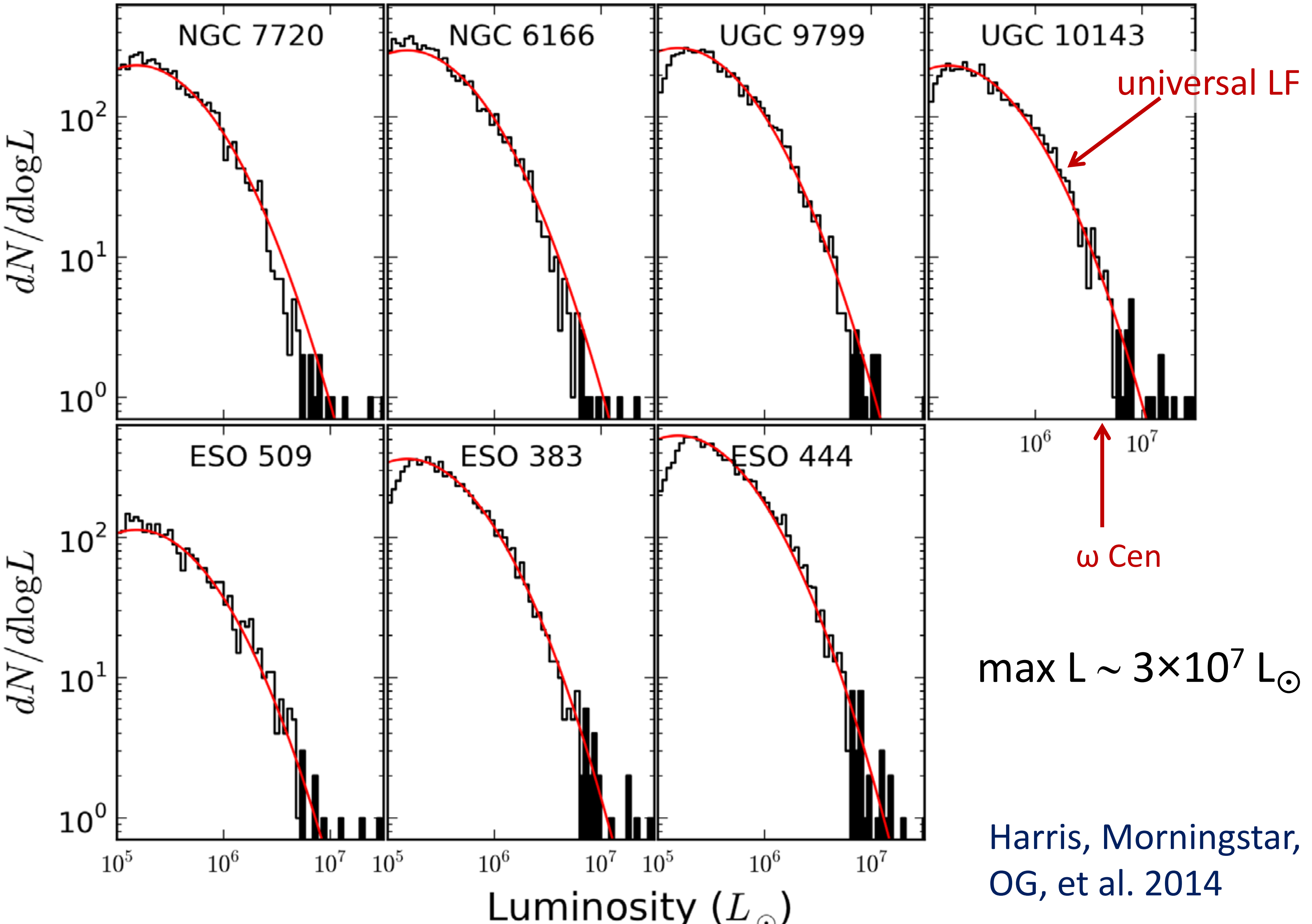
Pasquali et al. 2005

What is a galaxy, what is a star cluster?



Misgeld & Hilker 2011

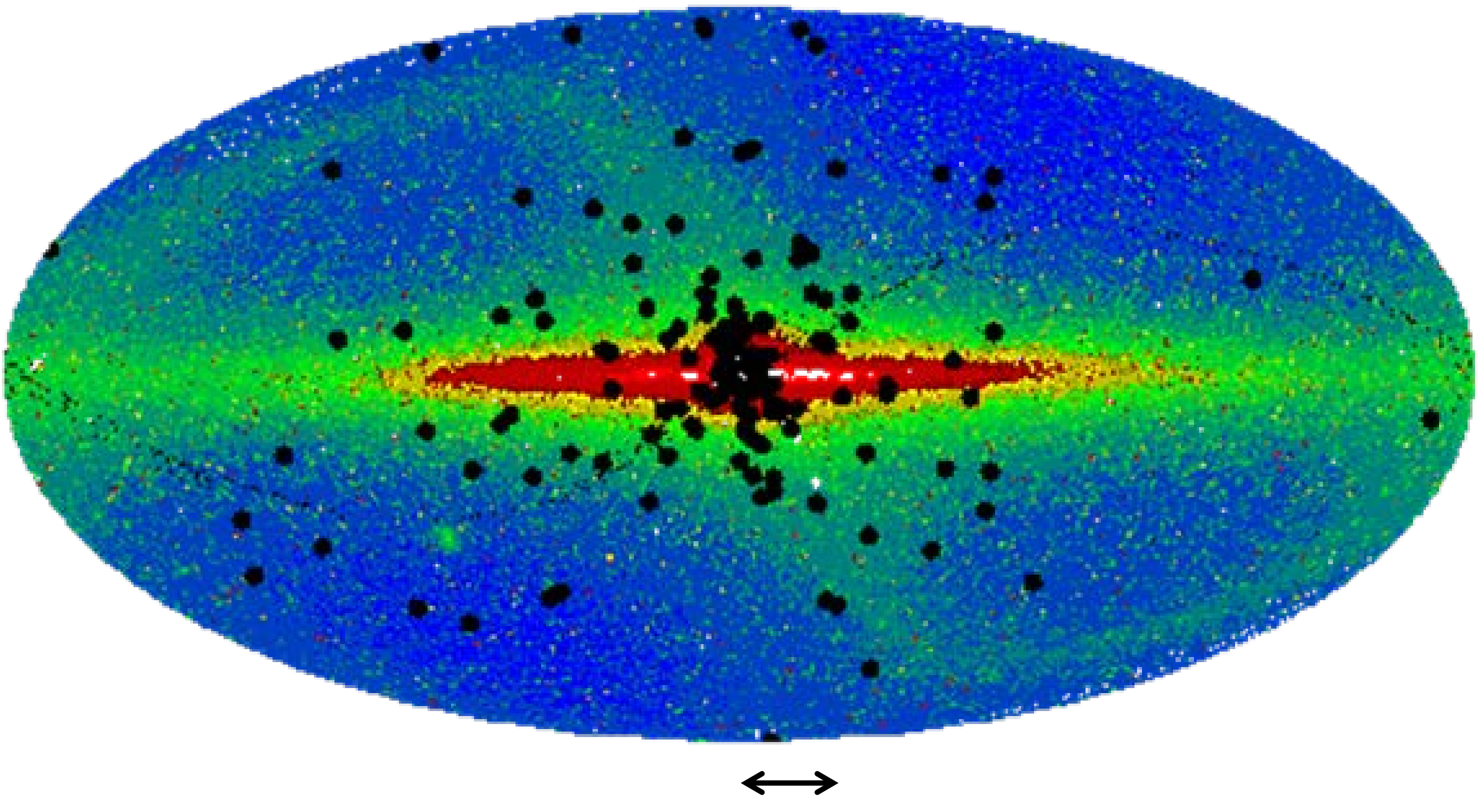
Globular Cluster Systems of *Brightest Cluster Galaxies* out to 200 Mpc



max L ~ 3×10^7 $L_\odot$

Harris, Morningstar, OG, et al. 2014

Let's focus on globular clusters in the Milky Way.
They have the best data on mass, size, age, metallicity.
Also: *Spatial and kinematic distributions*

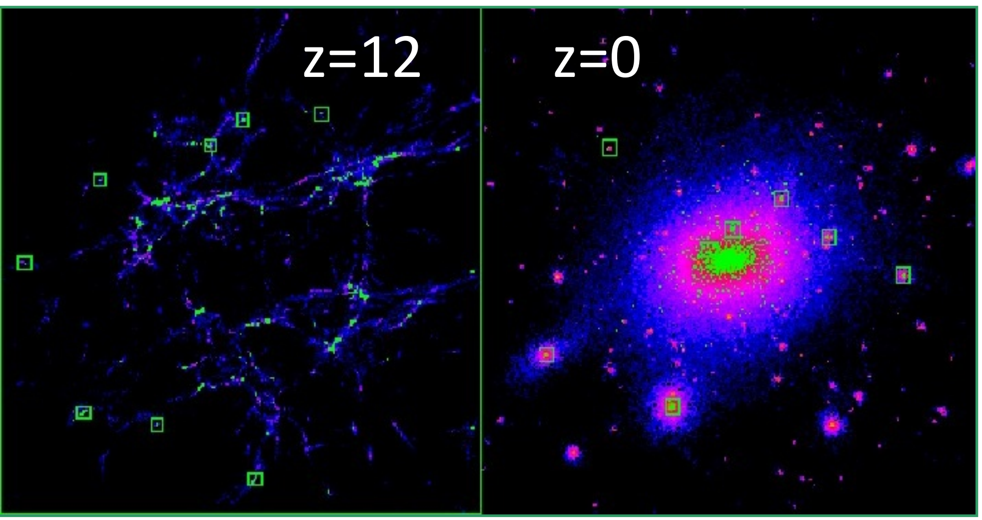


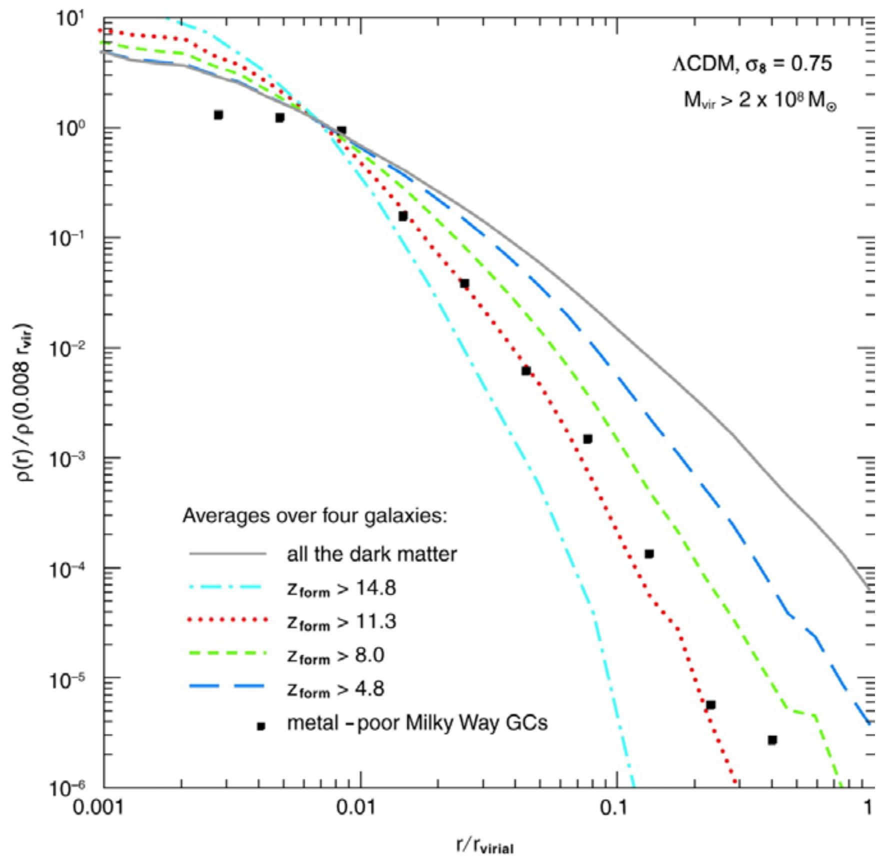
half of Galactic GCs are within 5 kpc of Galactic center: much closer than dark matter satellite halos

From N-body simulations we know that early-forming sub-halos are closer to the eventual center of galaxy than late-forming sub-halos

$\Rightarrow$ match spatial distribution of GCs to pick "right" halos

Placing one blue GC per dark matter halo requires $z_{form} \sim 12$





Moore, Diemand,..., Stadel 2006

Issues? Globular clusters are both dense <u>and</u> massive:

$\rho_h \sim 10^3$–$10^5\ M_\odot\ pc^{-3}$ $\quad M \sim 10^5$–$10^7\ M_\odot$

Not so simple… spatial distribution of halos depends on their mass

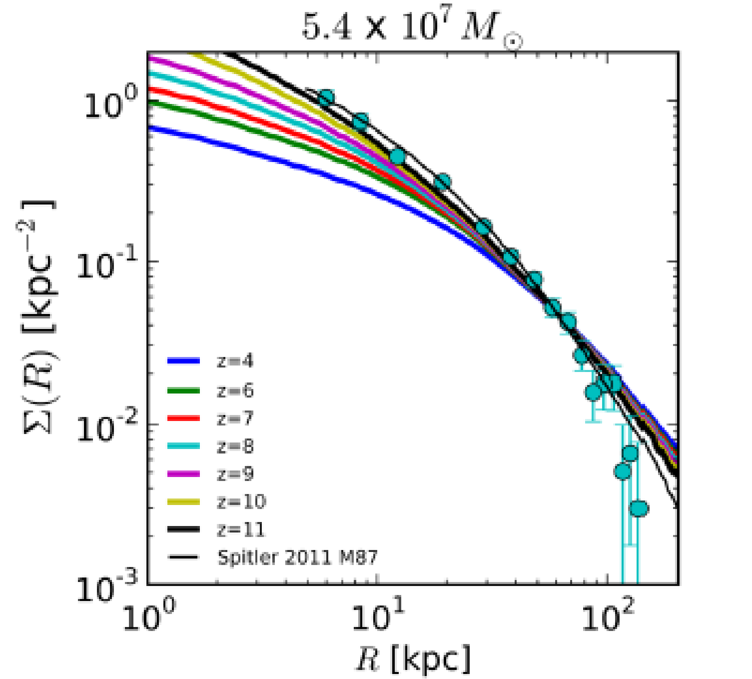
Higher mass halos are more concentrated at a given epoch

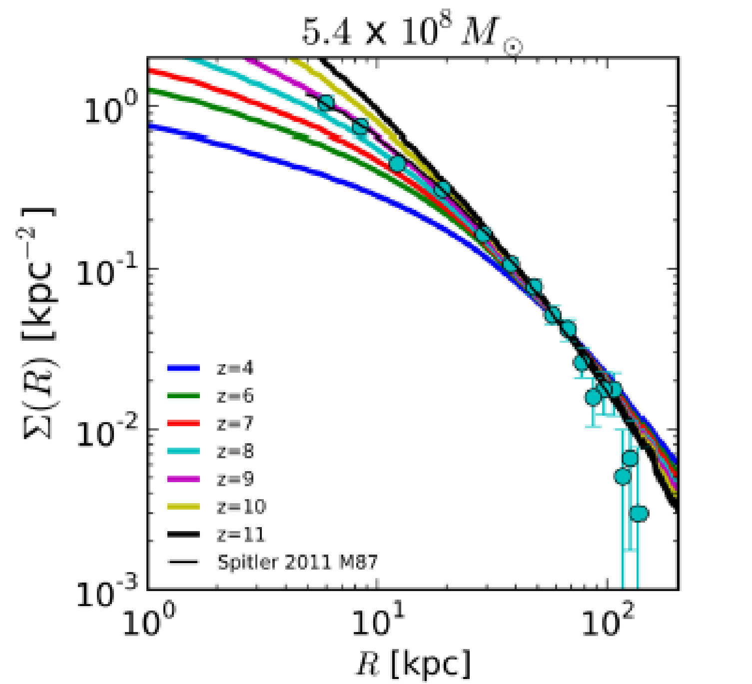
$\Rightarrow$ "their clusters" can match the observed spatial distribution with lower formation redshift,

$\Rightarrow$ so let's put GCs in more massive halos

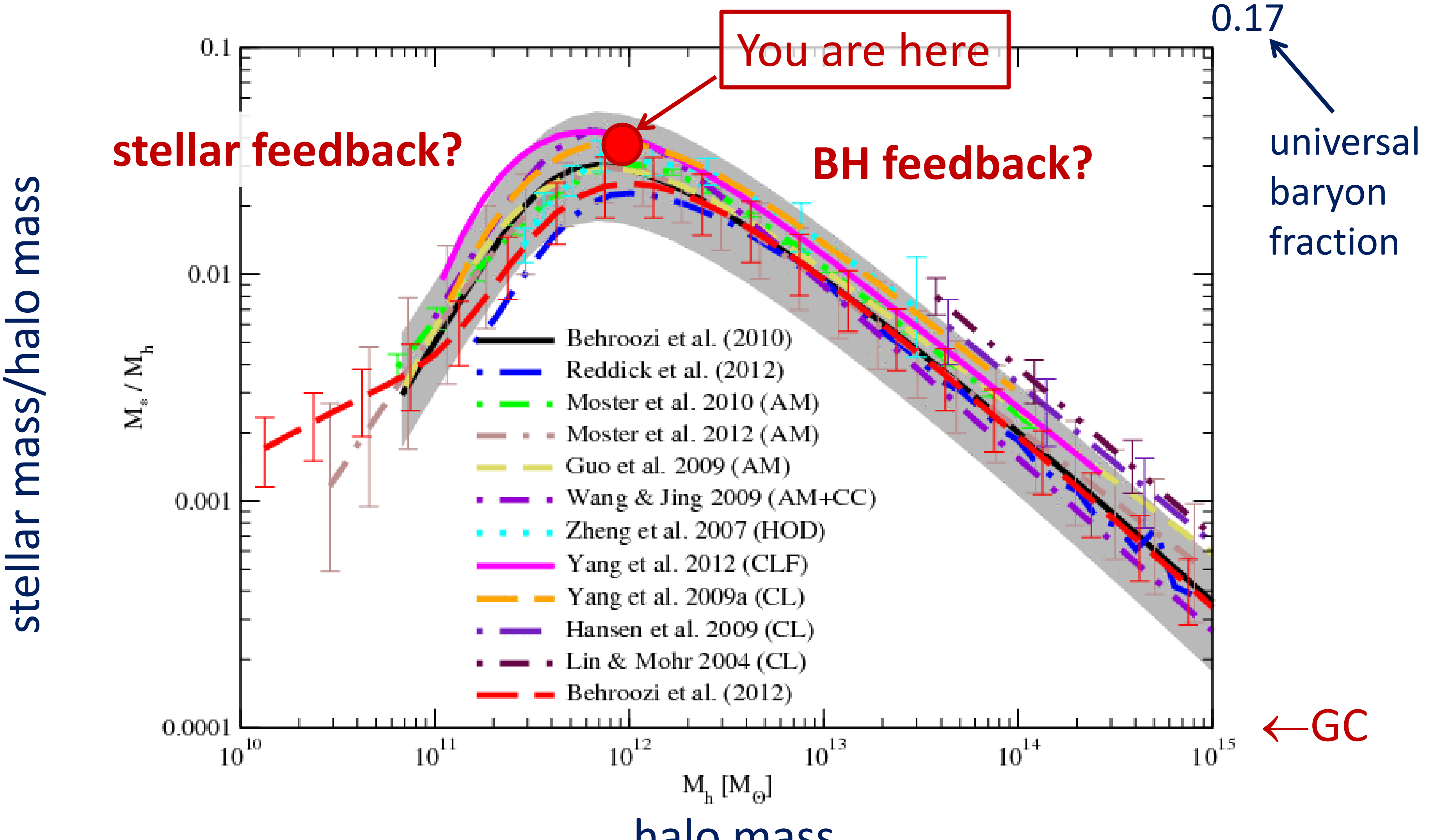
This is good! Because it is so much harder to form stars in small halos.

Boley, Lake, Read, Teyssier 2009
Griffen et al. 2010
Spitler et al. 2012
Corbett Moran, Teyssier, Lake 2014





Matching numbers of halos and galaxies indicates that star formation is inefficient, especially at low and high masses

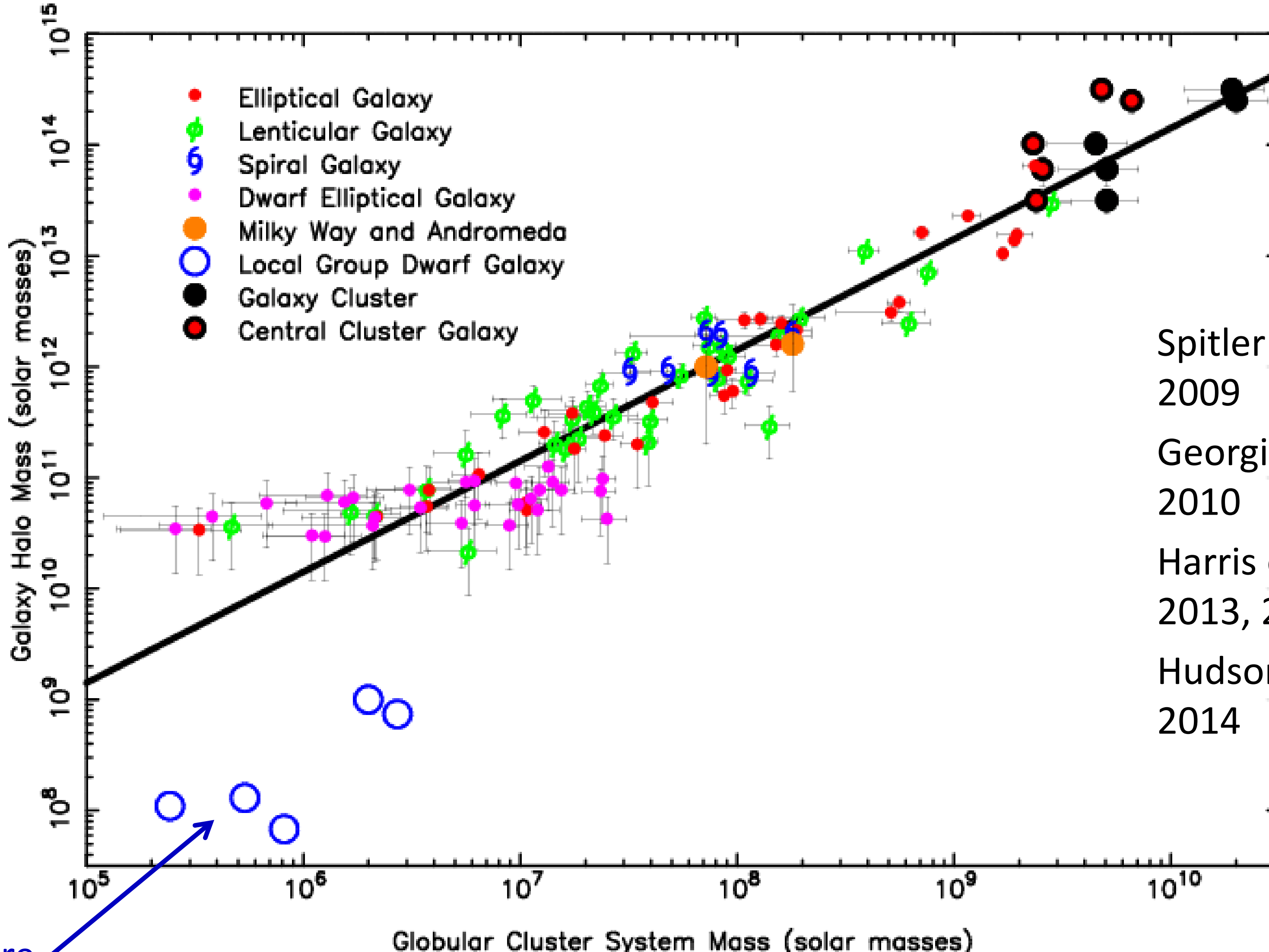


Conroy et al. 2006,
Behroozi et al. 2012

fraction of galaxy mass in its globular cluster system is similar in galaxies of (almost) any type and environment, over 5 orders of magnitude in mass

group environment

single galaxy environment



Spitler & Forbes 2009

Georgiev at al. 2010

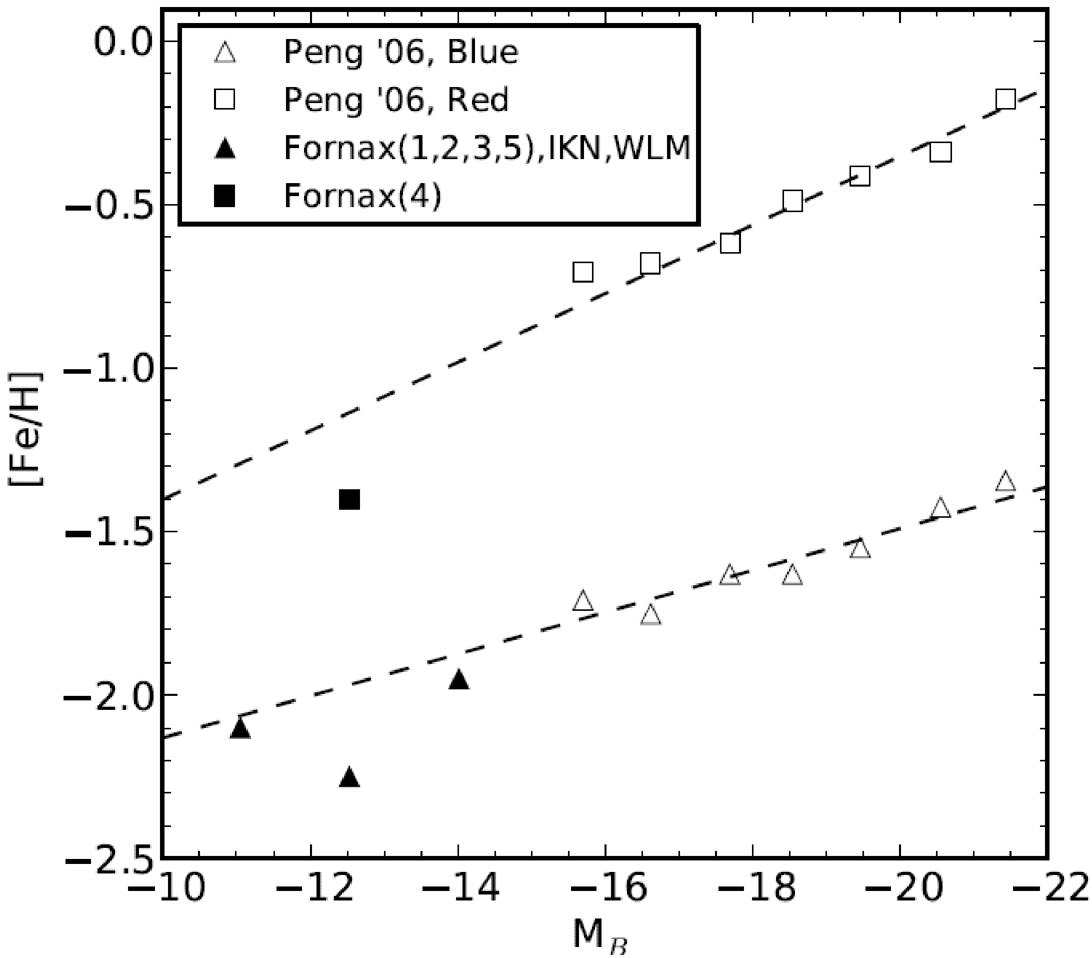
Harris et al. 2013, 2015

Hudson et al. 2014

dwarfs are different

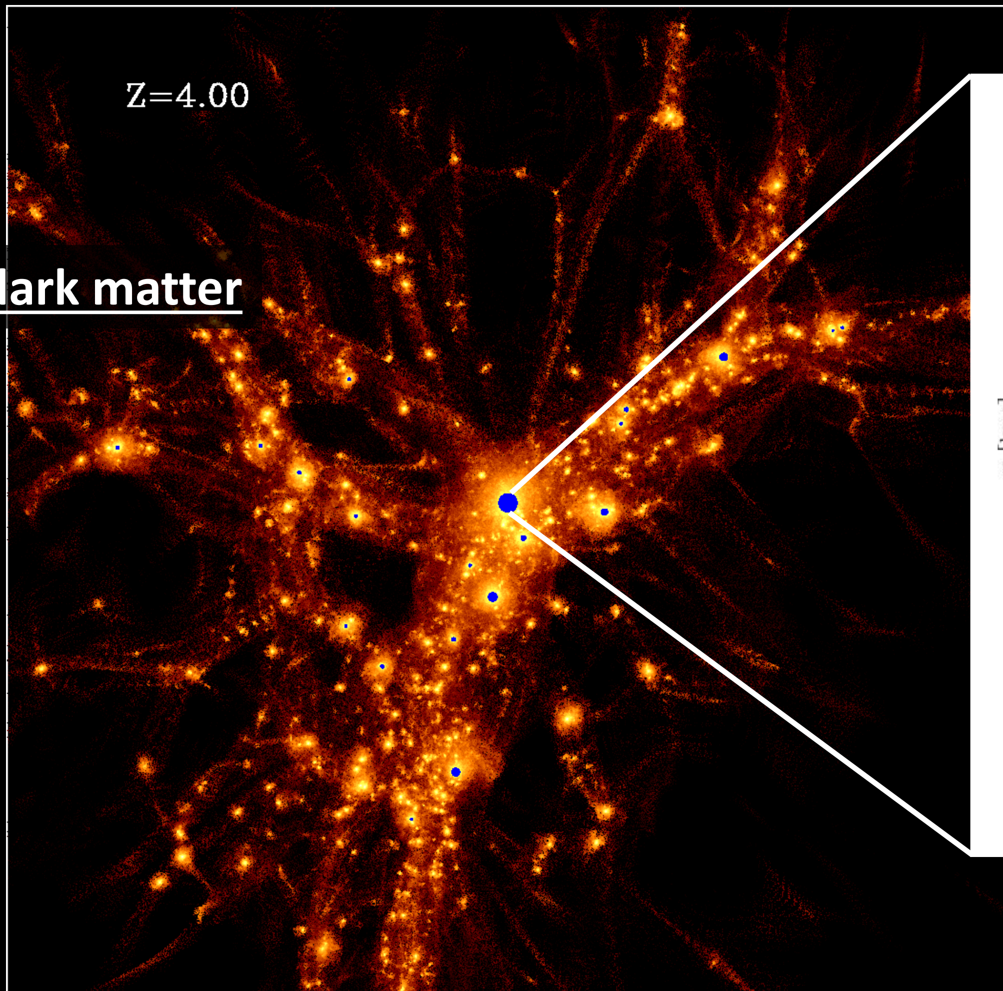
$$M_{GC} \approx (1\text{-}5)\times10^{-3}\, M_* \approx (0.3\text{-}1)\times10^{-4}\, M_{host}$$

Metal-poor clusters contain a large fraction (10-20%) of all metal-poor stars in those dwarf galaxies where they exist: this places constraints on the possible initial mass of GCs



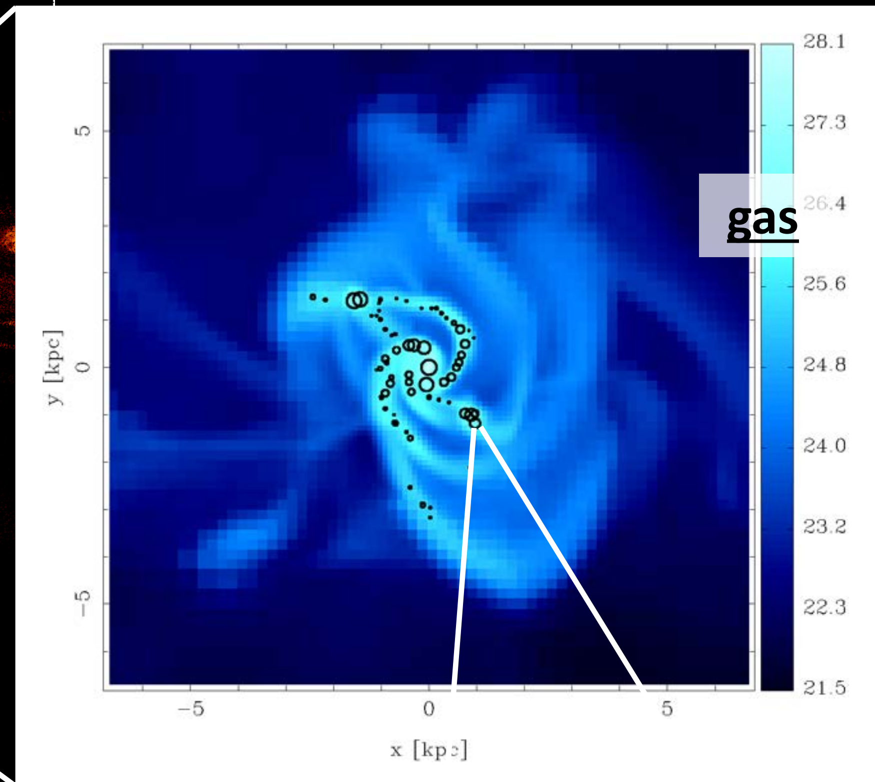
Larsen et al. 2014

Explore cluster formation: use cosmological AMR simulations to look for gas clouds dense and massive enough to host GCs



300 kpc (physical)

14 kpc

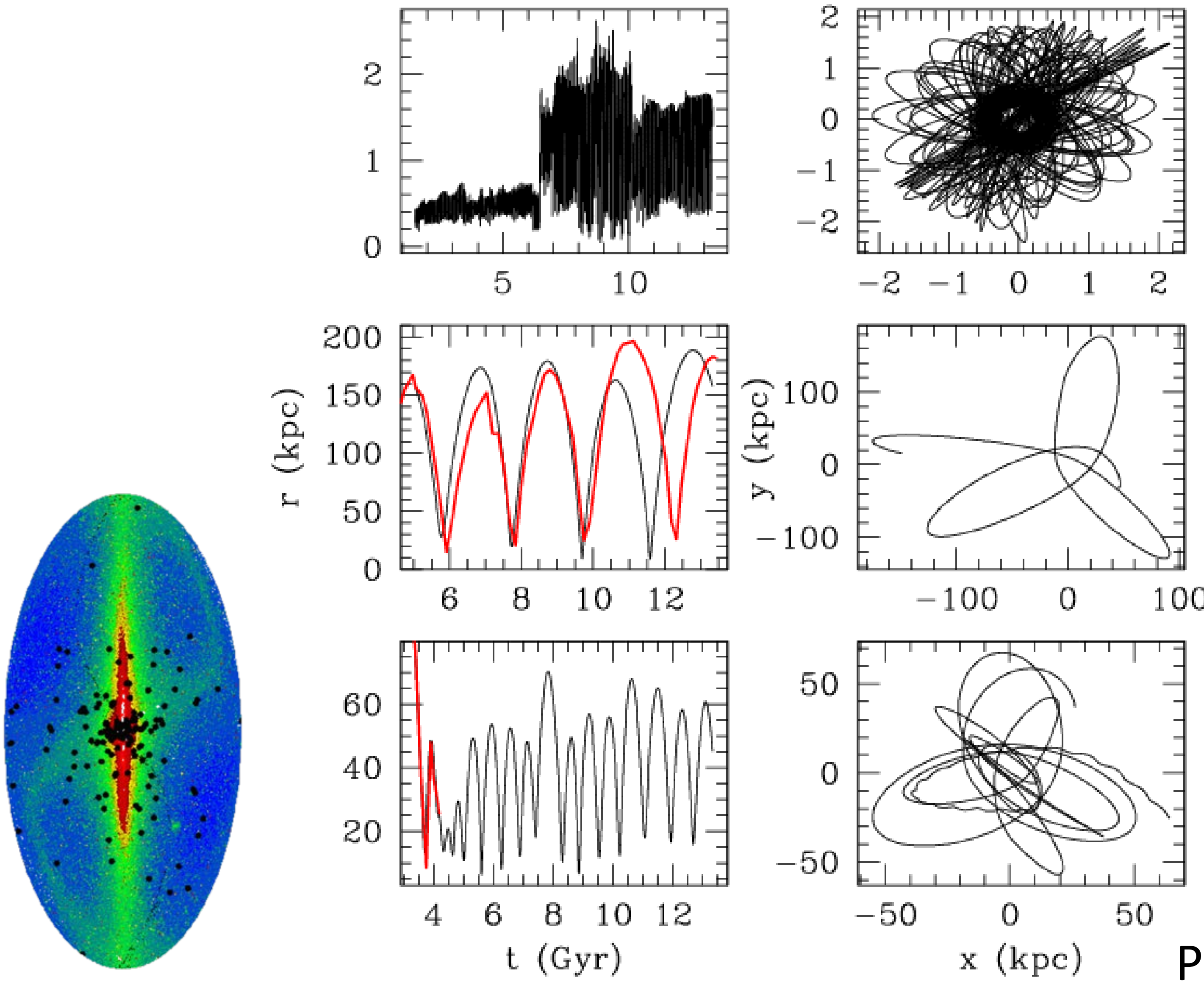


20 pc

Kravtsov & OG (2005): $M_{GC} \approx 10^{-4} M_{host}$

power-law mass function $dN/dM \propto M^{-\beta}$, $\beta \approx 2$

The globular cluster system of the Milky Way is gradually built up by the contributions of the central and satellite galaxies



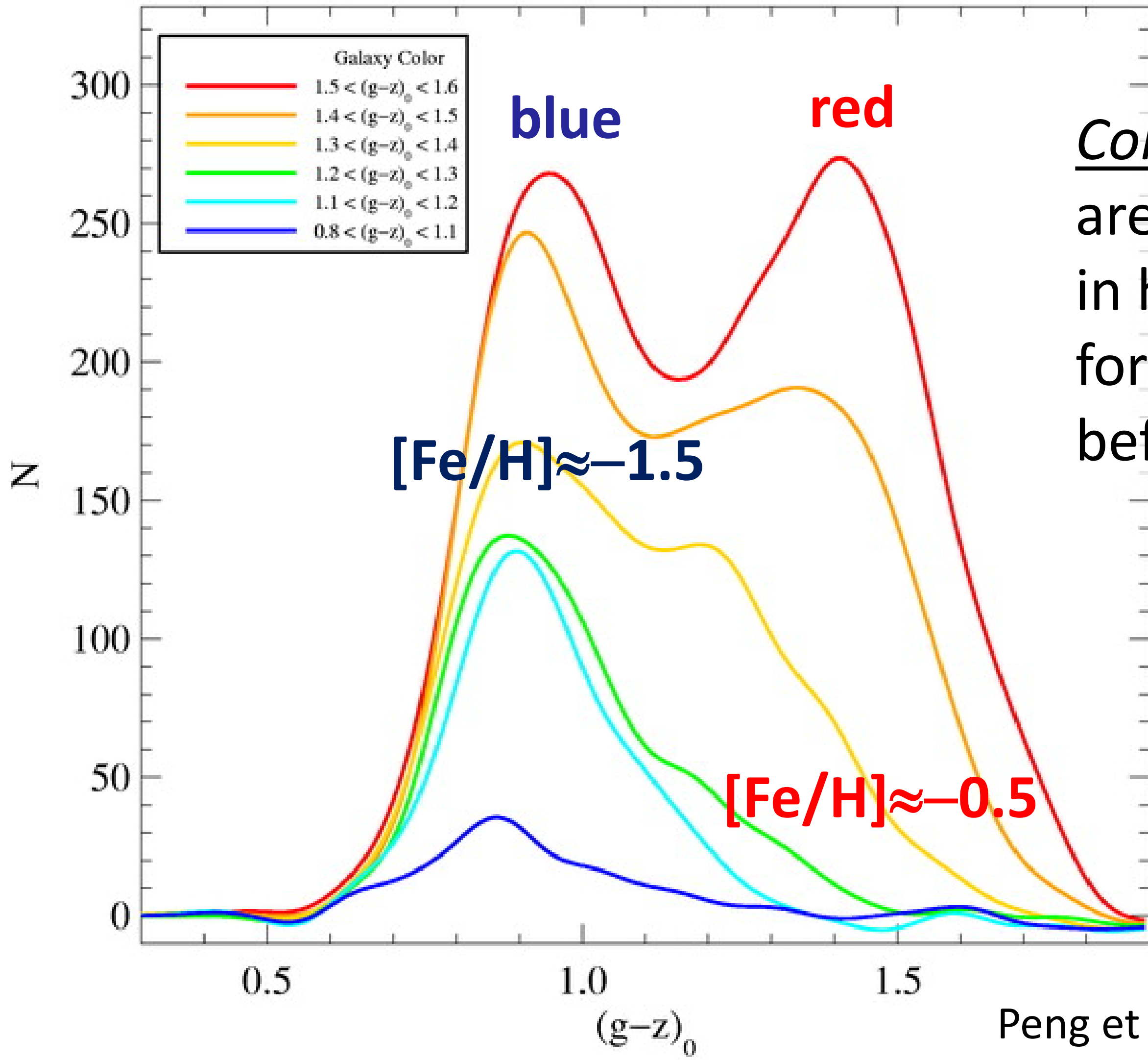
central galaxy
(thick disk
clusters)

surviving
satellite galaxy
(galaxy in red)

disrupted
satellite galaxy

Prieto & OG 2008

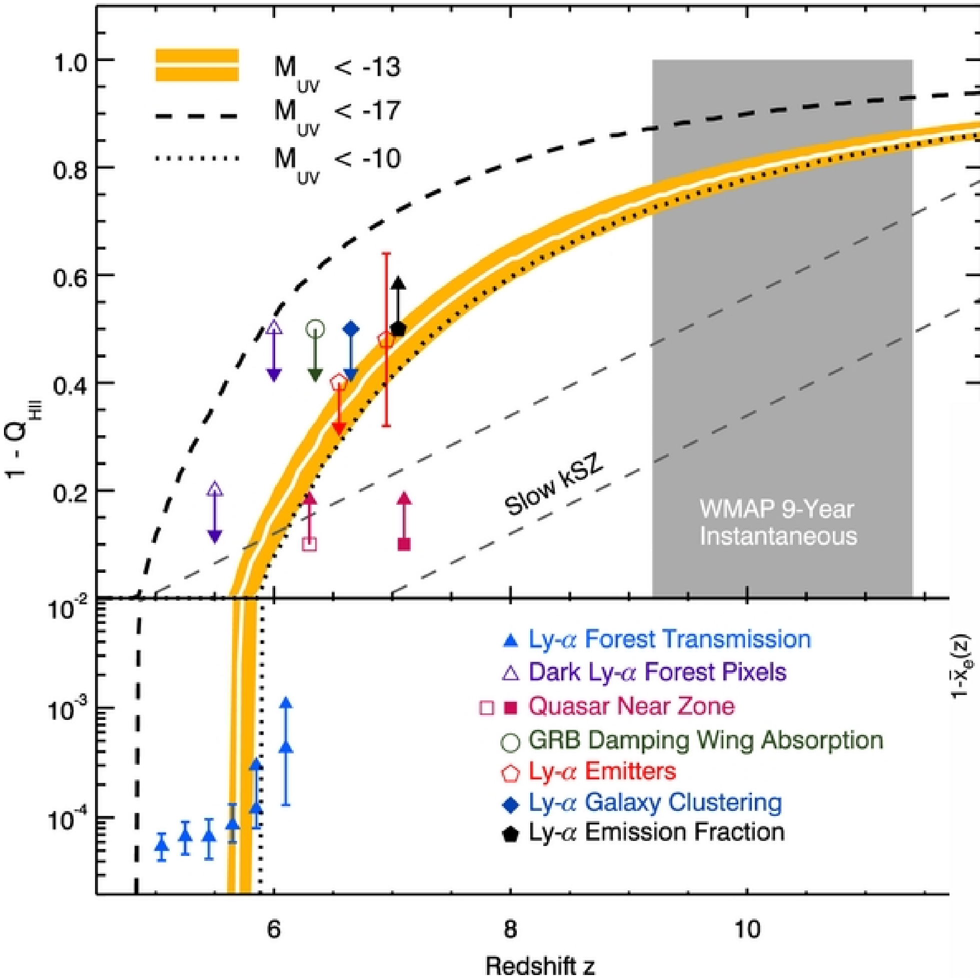
Metallicity distribution encodes the conditions of the galactic ISM at the time of cluster formation: *many galaxies display multi-modality*



Common view: red clusters are associated with field stars in host galaxy, blue clusters formed earlier, possibly before cosmic reionization

Peng et al. 2006 – HST Virgo Cluster Survey

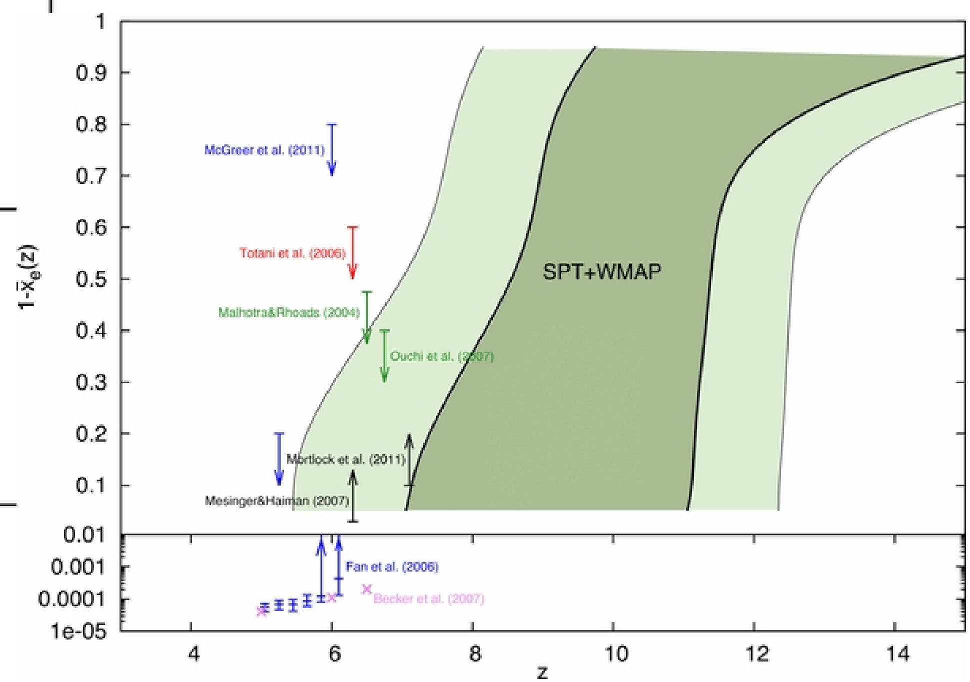
Any relevance of reionization of cosmic hydrogen?



Robertson et al. 2013
(optical tracers)

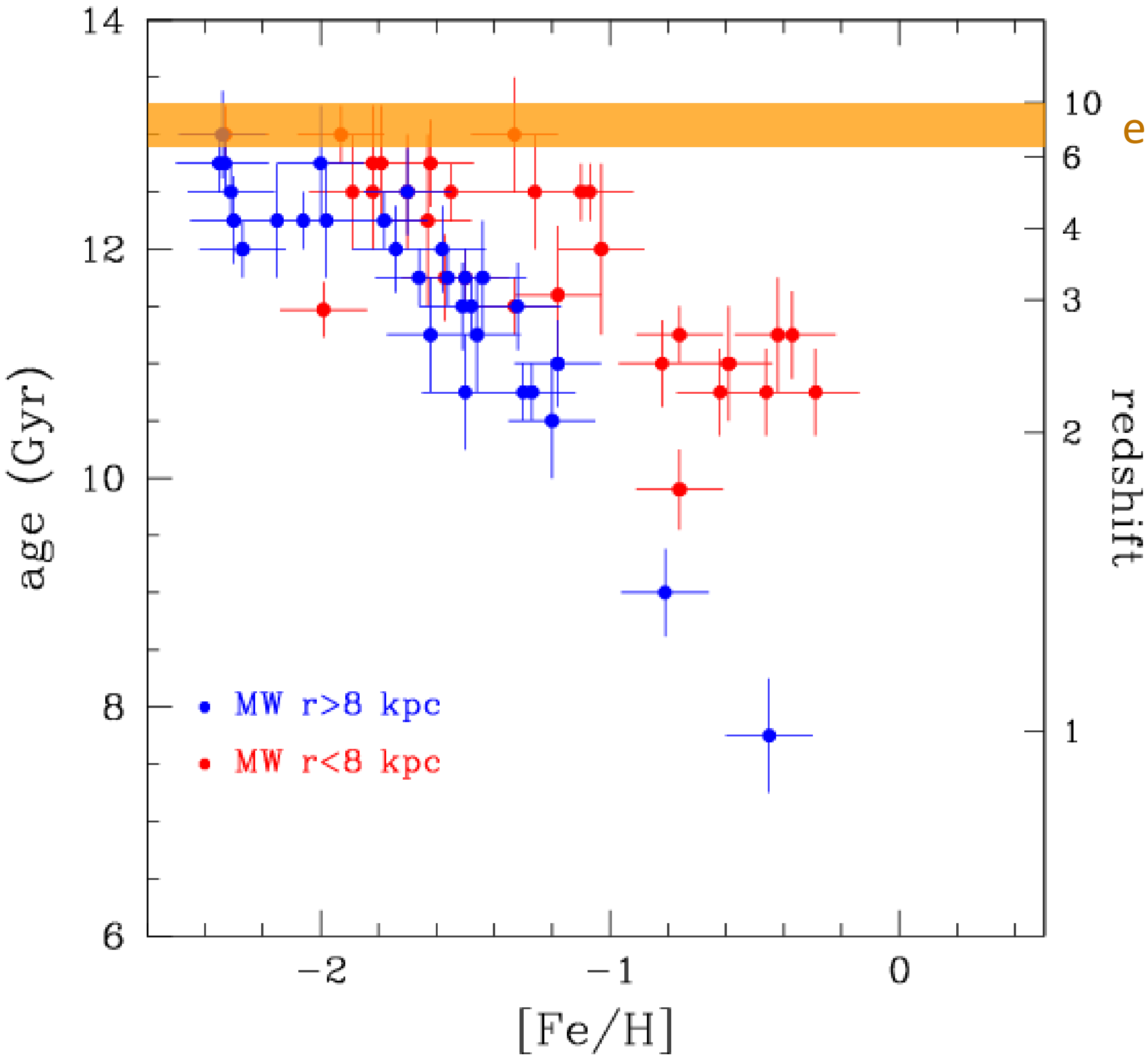
reionization is responsible for creating fossil dwarf galaxies (ultrafaints)

age of the universe at
the end of reionization
≈ 600 – 900 Myr



Zahn et al. 2012
(kinetic SZ effect)

Age-metallicity relation for globular clusters in the Milky Way



epoch of cosmic reionization

globular clusters form later

Resolved CMD with HST in Milky Way:

Marín-Franch et al. 2009

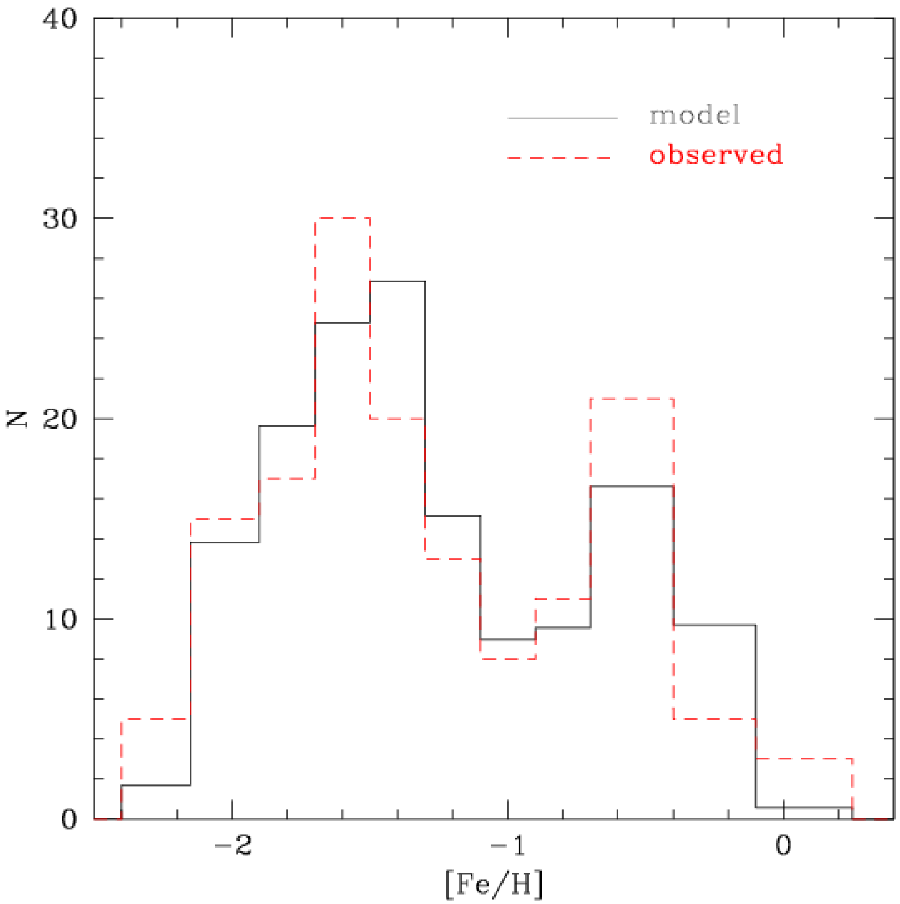
Dotter et al. 2011

Vandenberg et al. 2013

Leaman et al. 2013

Can a single formation mechanism produce bimodality? Yes
Model: GC formation is triggered by gas-rich mergers

(mergers are only needed to mark GC formation before the bulk of field stars)



begin with cosmological simulations of halo formation

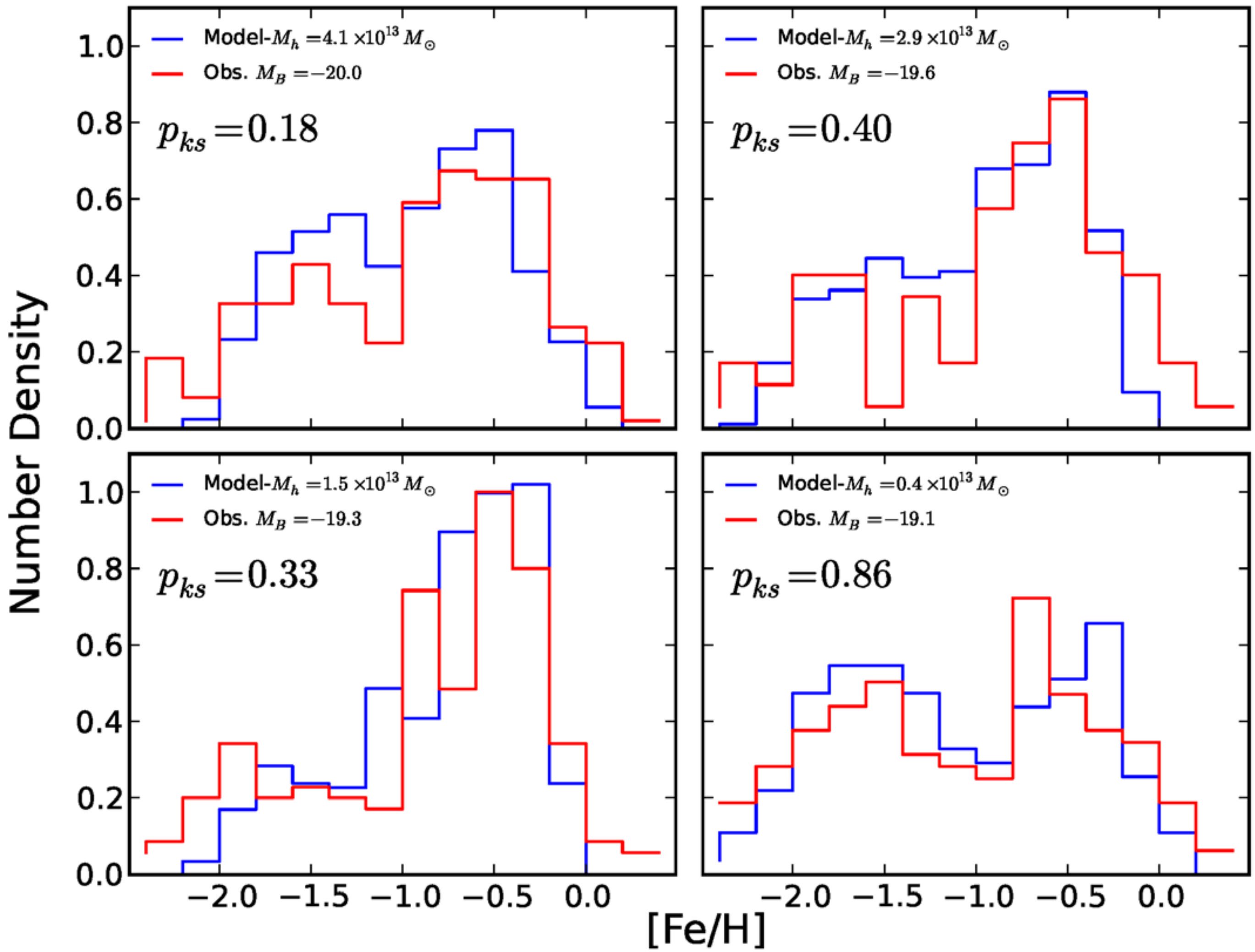
supplement halos with cold gas mass based on observations

use M_{GC} - M_{gas} relation from hydro simulations

metallicity from observed M_*-Z relation for host galaxies, include evolution with time

Galactic GCs: Muratov & OG 2010

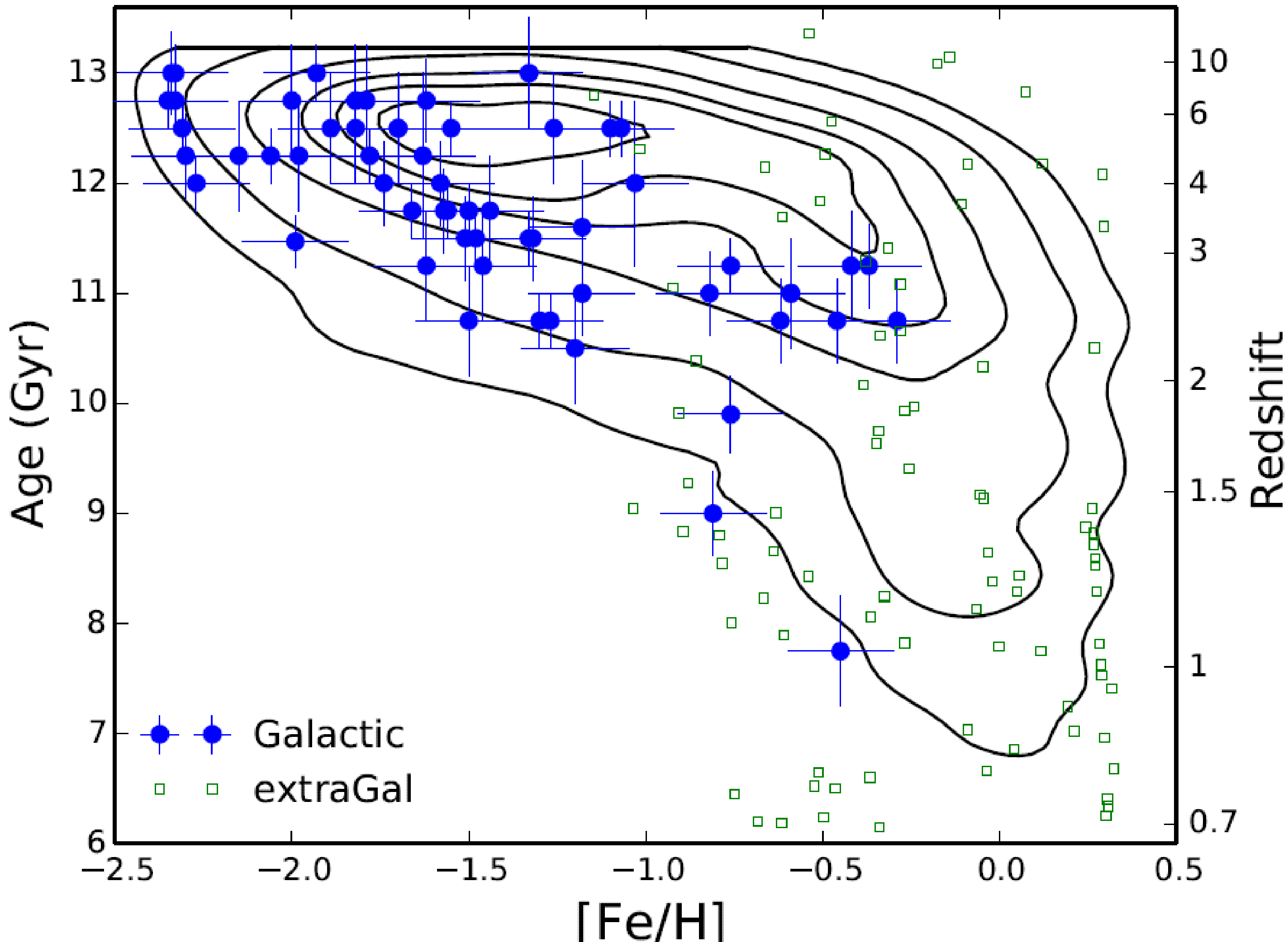
Also matching mass and metallicity distributions of GCs in elliptical galaxies of the Virgo cluster



Li & OG 2014

Model age-metallicity relation

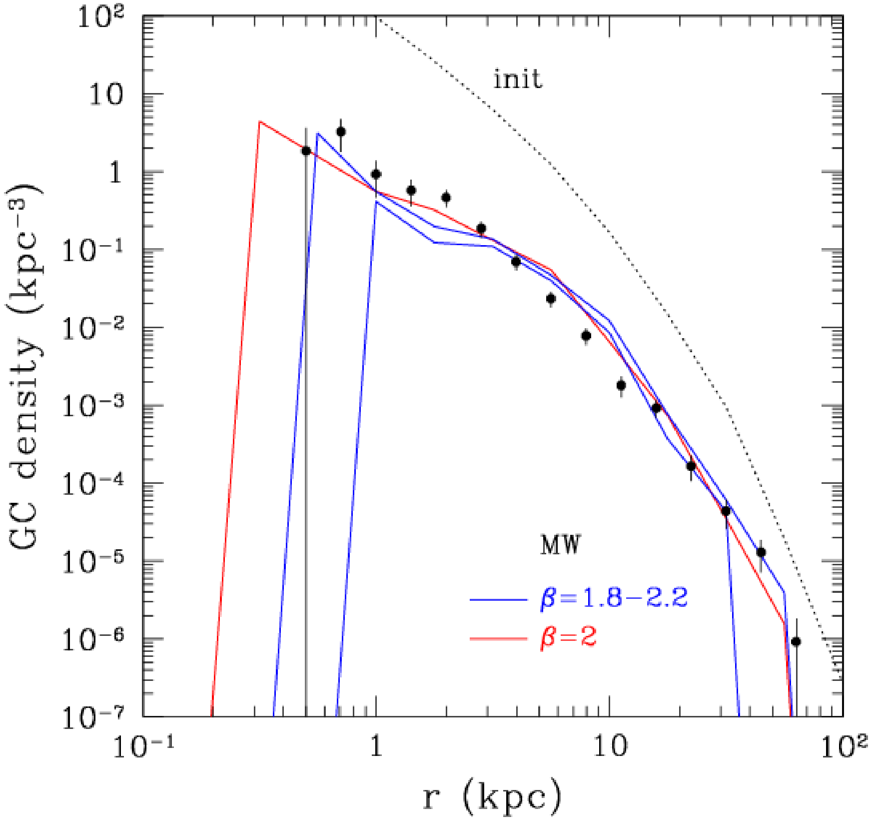
Theoretical prediction – let's test it!



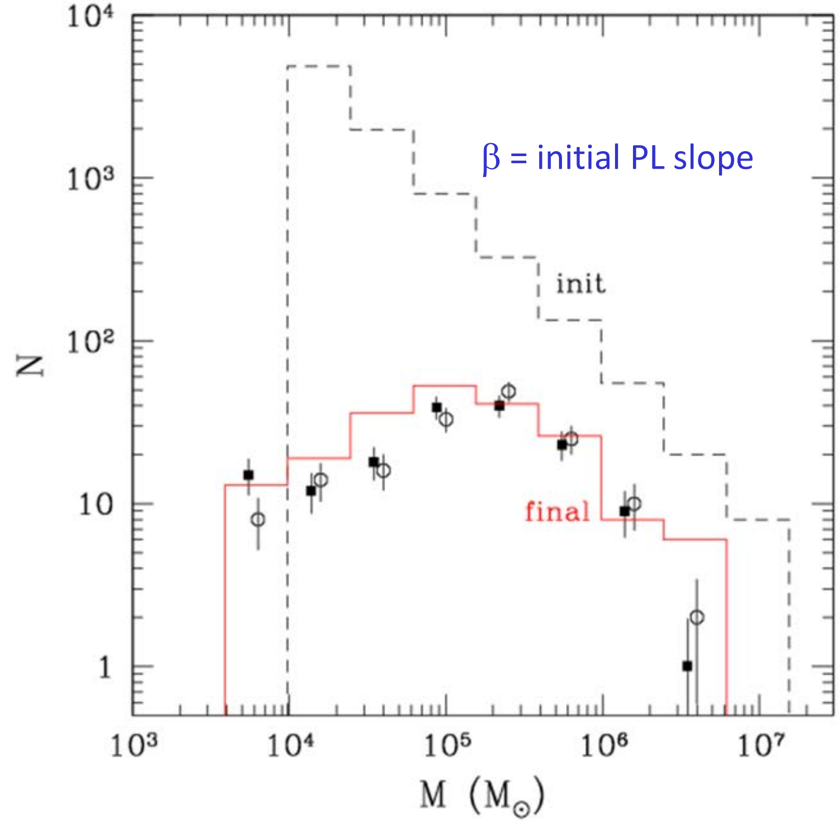
Li & OG 2014

Inner globular clusters could have merged into a NSC

Simple model: assume GCs in the Galaxy initially follow stellar density, migrate inward by dynamical friction, and tidally disrupt along the way.



Choose normalization such that surviving clusters match the observed density profile of Galactic clusters

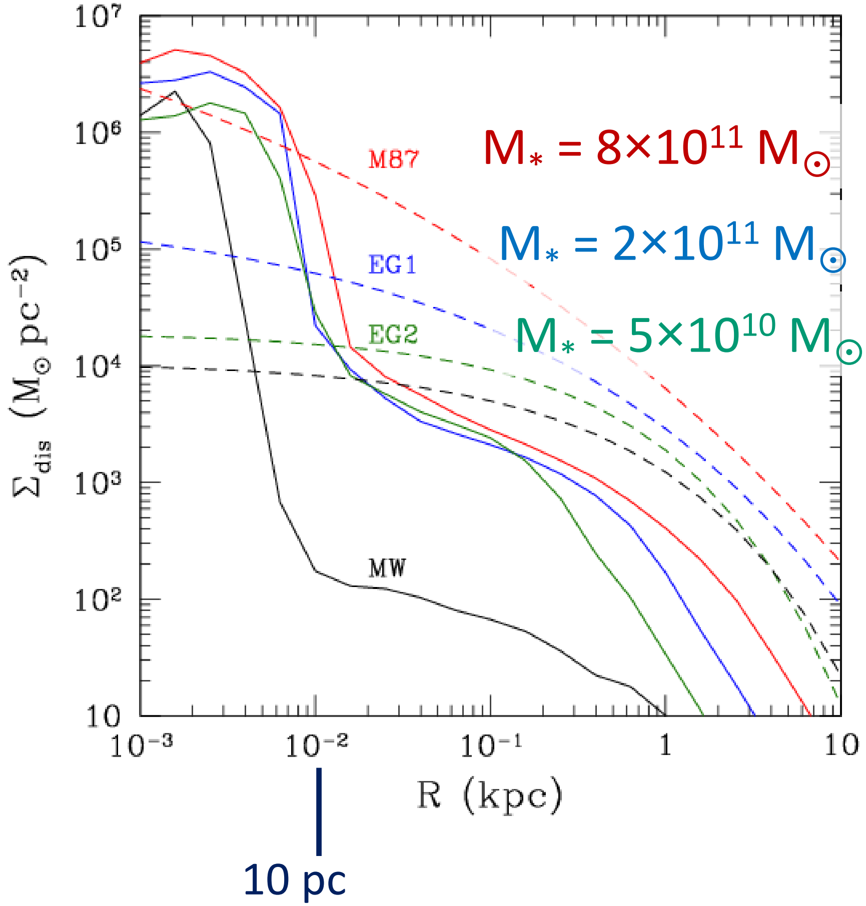


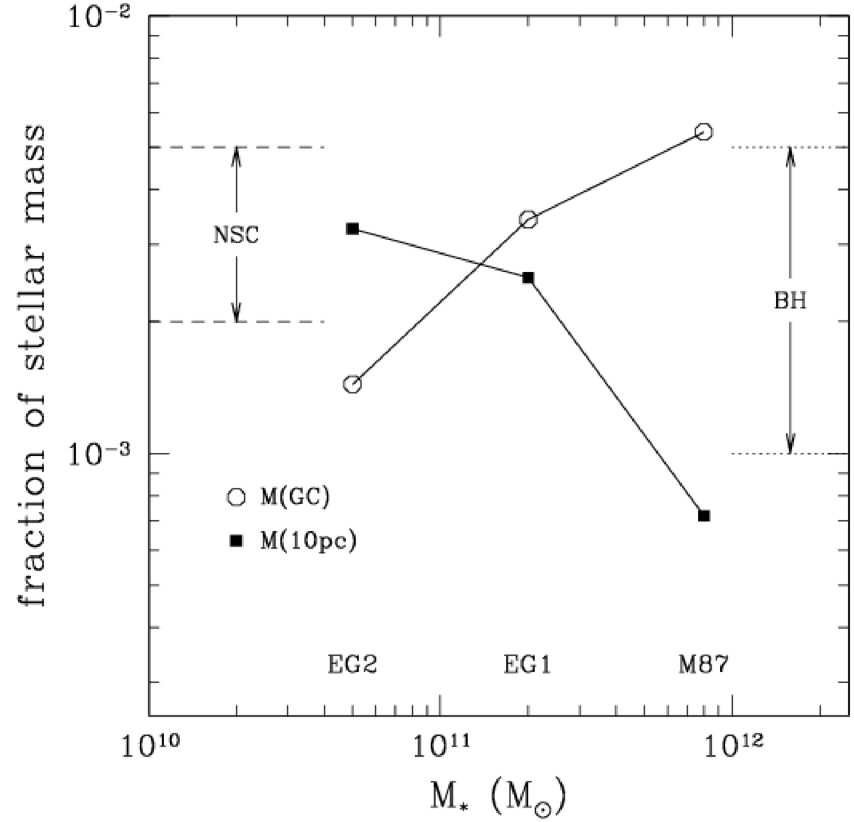
…and reproduce the observed cluster mass function

OG, Ostriker & Tremaine 2014

Part of Nuclear Star Cluster built by GCs is higher in lower-mass galaxies (< 10^{11} $M_\odot$) than giant E,

while the in-situ formed part is likely to be higher in more massive galaxies





Additional mass from in-situ star formation (50% more, Antonini et al. 2015)

Remaining GC system is similar to SMBH mass – *coincidence*?

Summary

- Massive star clusters have much higher density than dwarf galaxies

- Observed age-metallicity relation indicates that GCs continued to form until $z \sim 1$-2

- *Red clusters* form in intermediate-*z* gas-rich mergers, *blue clusters* form in early mergers *and* later massive mergers

- GC luminosity function is consistent with universal log-normal

- Lower-mass galaxies can build up a significant *Nuclear Star Cluster* within 10 pc from disrupted globular clusters