Globular Clusters in Massive Galaxies

Patrick Durrell
(Youngstown State University)

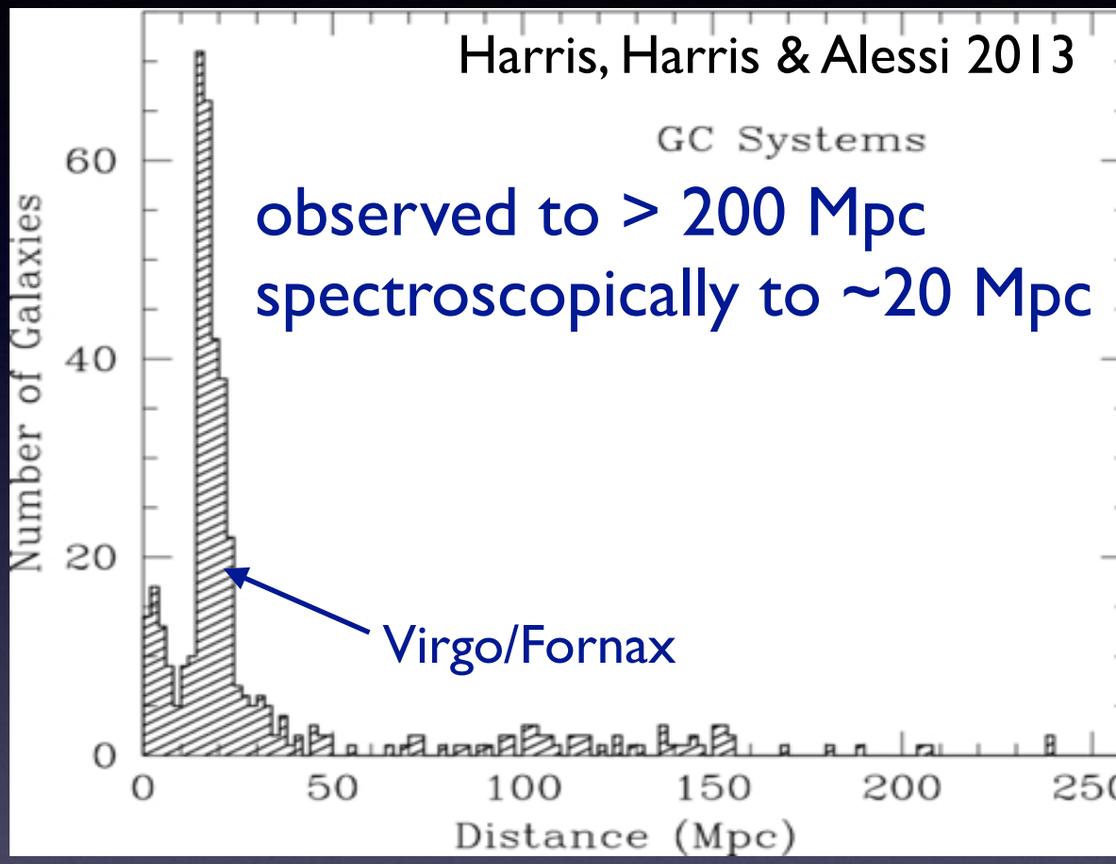
+ Pat Côté, John Blakeslee, Laura Ferrarese (Herzberg-Victoria), Eric Peng (Peking Univ)
Chris Mihos (CWRU) + NGVS Team

Globular Cluster Systems

GCs = most luminous (~10^4-$10^6 L_\odot$) discrete tracers of galaxy halos

present in all galaxies (M>10^8 $M_\odot$) in ***all*** environments

- compact (r_h~2-4pc)
- pointlike for >20 Mpc (ground)
  >80 Mpc (HST)



not-quite-so-simple
~~simple~~ stellar populations

- Complement to resolved halo star studies, PNe, diffuse light studies

  (eg. Rejkuba, Arnaboldi, Mihos, Peacock talks)

- Old (10.5-13 Gyr) ages and high masses
  product of earliest intense bursts of SF

'fossil record' of earliest stages of hierarchical galaxy formation

+ later mergers and accretion of GCs

- bimodal **color** distributions common in most luminous galaxies

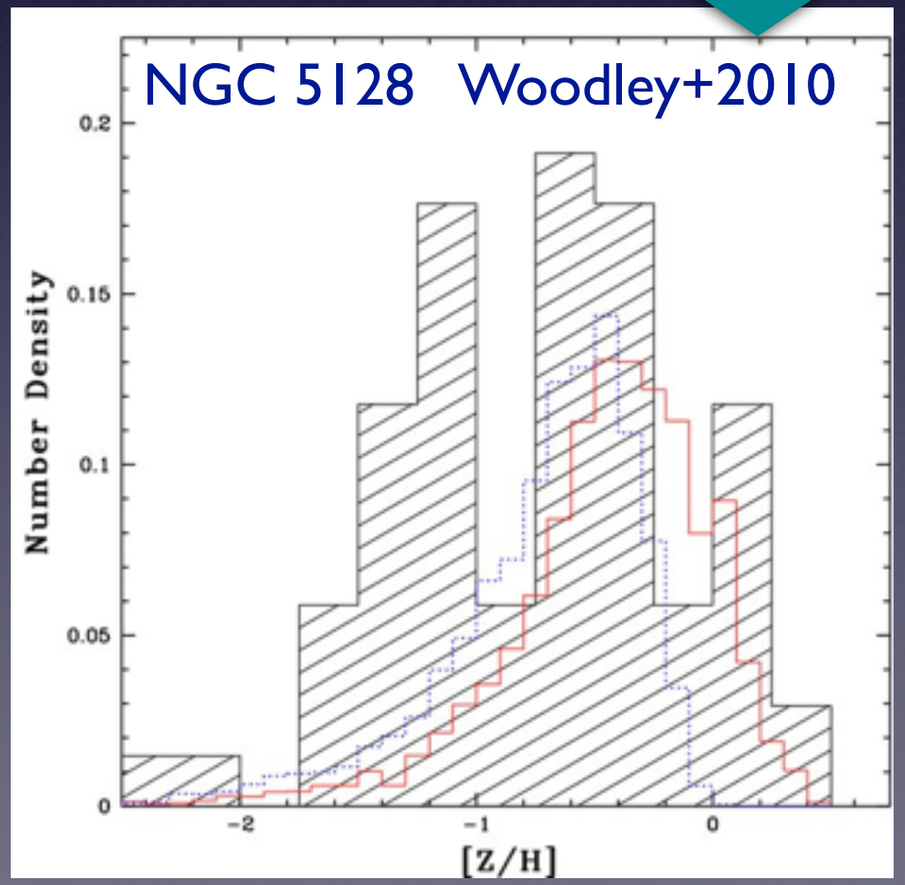
(Larsen+2001, Kundu+Whitmore 2001…)

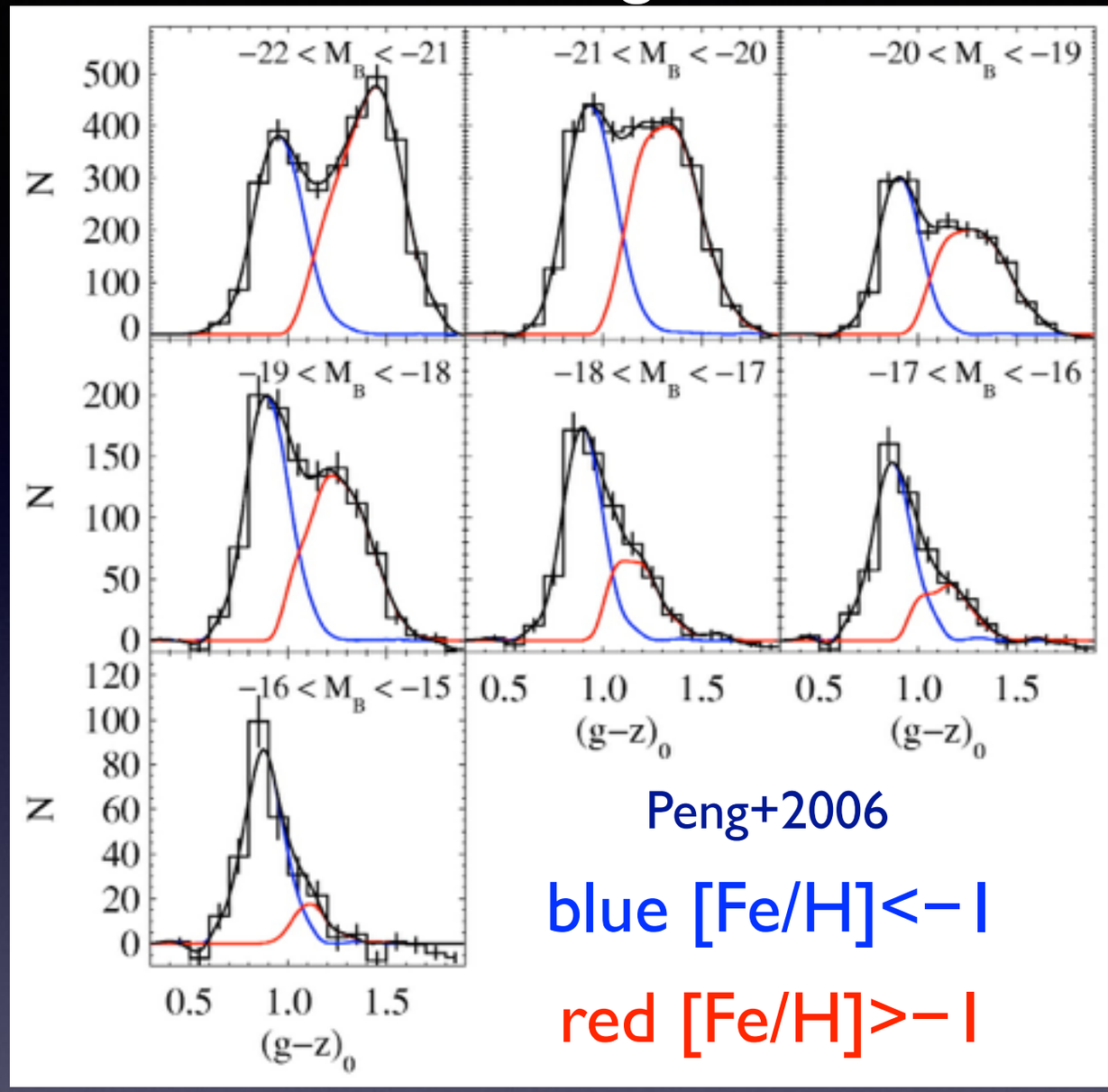
= bimodal metallicity distribution

eg. MW, NGC 3115

- comparison with stellar halo MDF?

(see also Rejkuba talk)





Peng+2006

blue [Fe/H]<−1

red [Fe/H]>−1

Blue/Red = MP/MR subpopulations

- often kinematically distinct (Brodie talk)
- relative ages constrain formation timescales

blue GC (z~4-8) red GC (z~2-4)

before most SF and feedback

GC systems in massive galaxies extend to >10-30 R_e

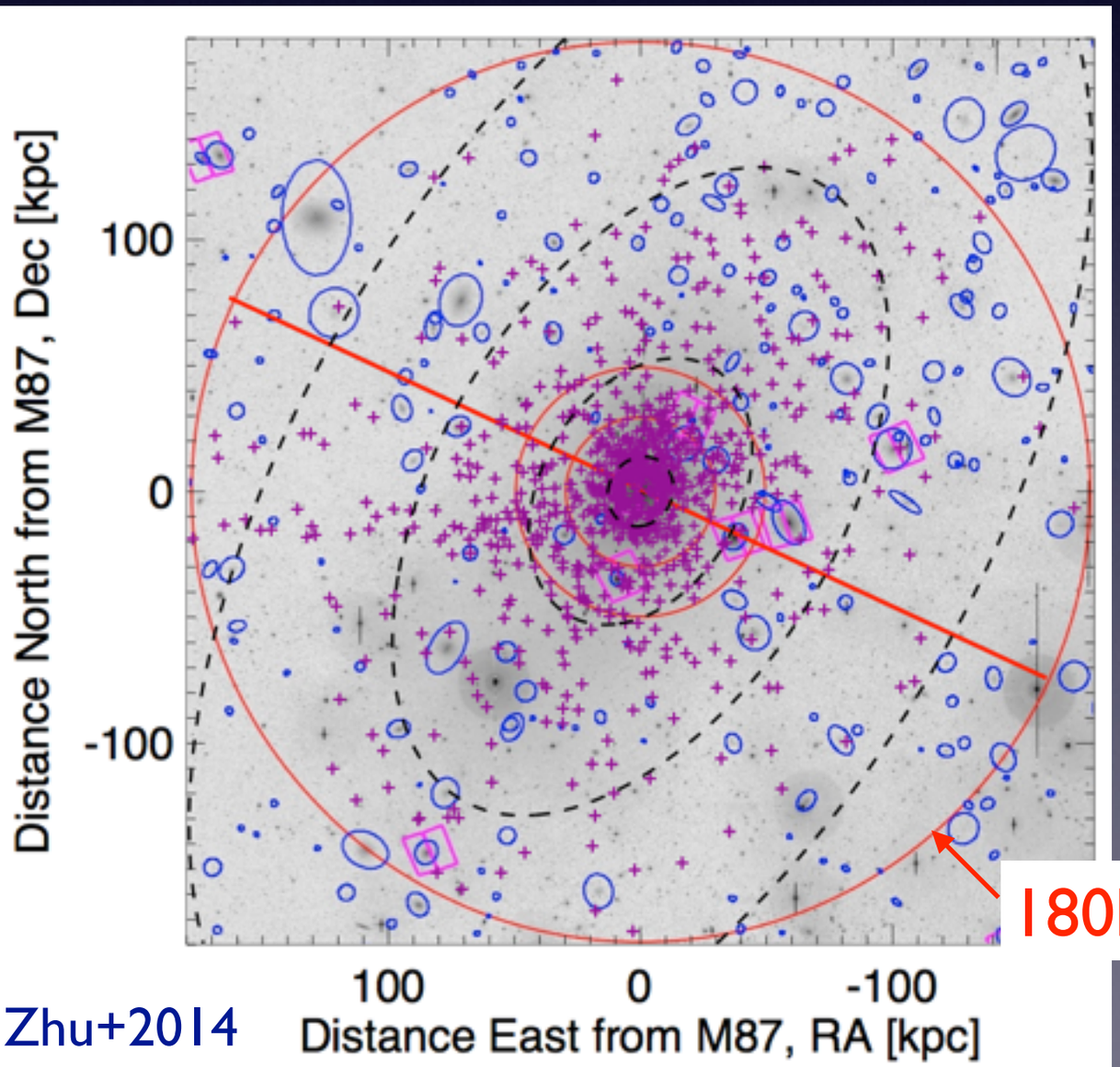
~100 kpc+ (Rhode+Zepf 2004, Bassino+2006, Peng+2011, G.Harris+2012)

- outer halo - presence of intracluster GCs? (IGCs; eg. Lee+2010,Peng+2011)

  probe the cluster potential; accretion history of massive galaxies

- relationship with UCDs = luminous GCs? nuclei of stripped galaxies?

(Voggel talk)



Zhu+2014

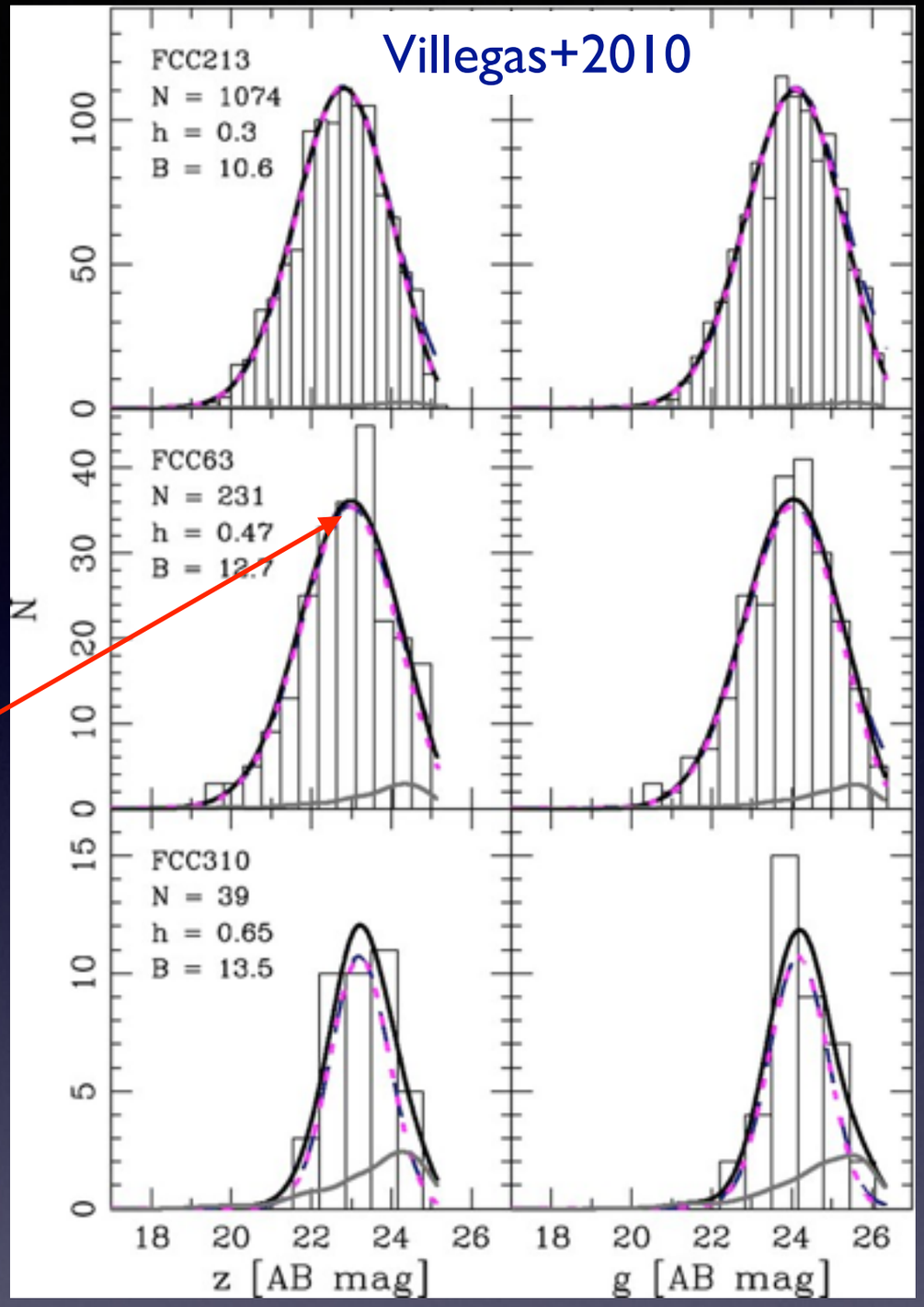
GCs important *kinematic* tracers of galaxy/cluster DM halo

- to 8-10R_e (Lee+2010; Brodie talk)
- >10 R_e (Côté+2001,Strader+2011,Zhang +2015)
- kinematic substructure in halos? (Côté+2003, Romanowsky+2012,Zhu+2014)

- GC Luminosity Function (GCLF)
  - remarkably *similar* shape in all galaxies
  - result of cluster $N(m) \propto m^{-2}$ or

    log-normal <u>initial</u> GC *mass* function
    + low-mass GC destruction

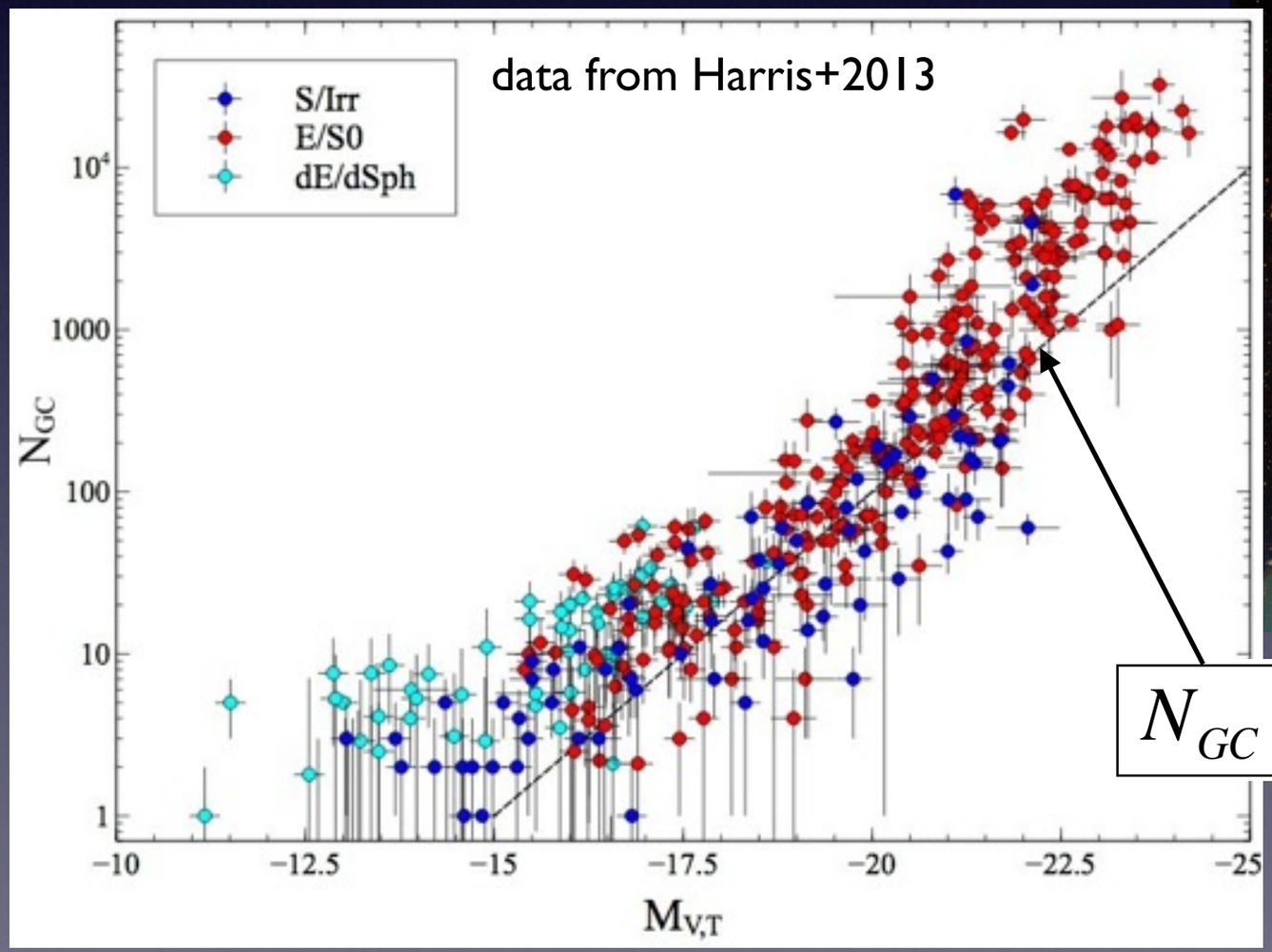
$M_{GCLF,TO} \sim 1\text{-}2\times10^5 M_\odot$

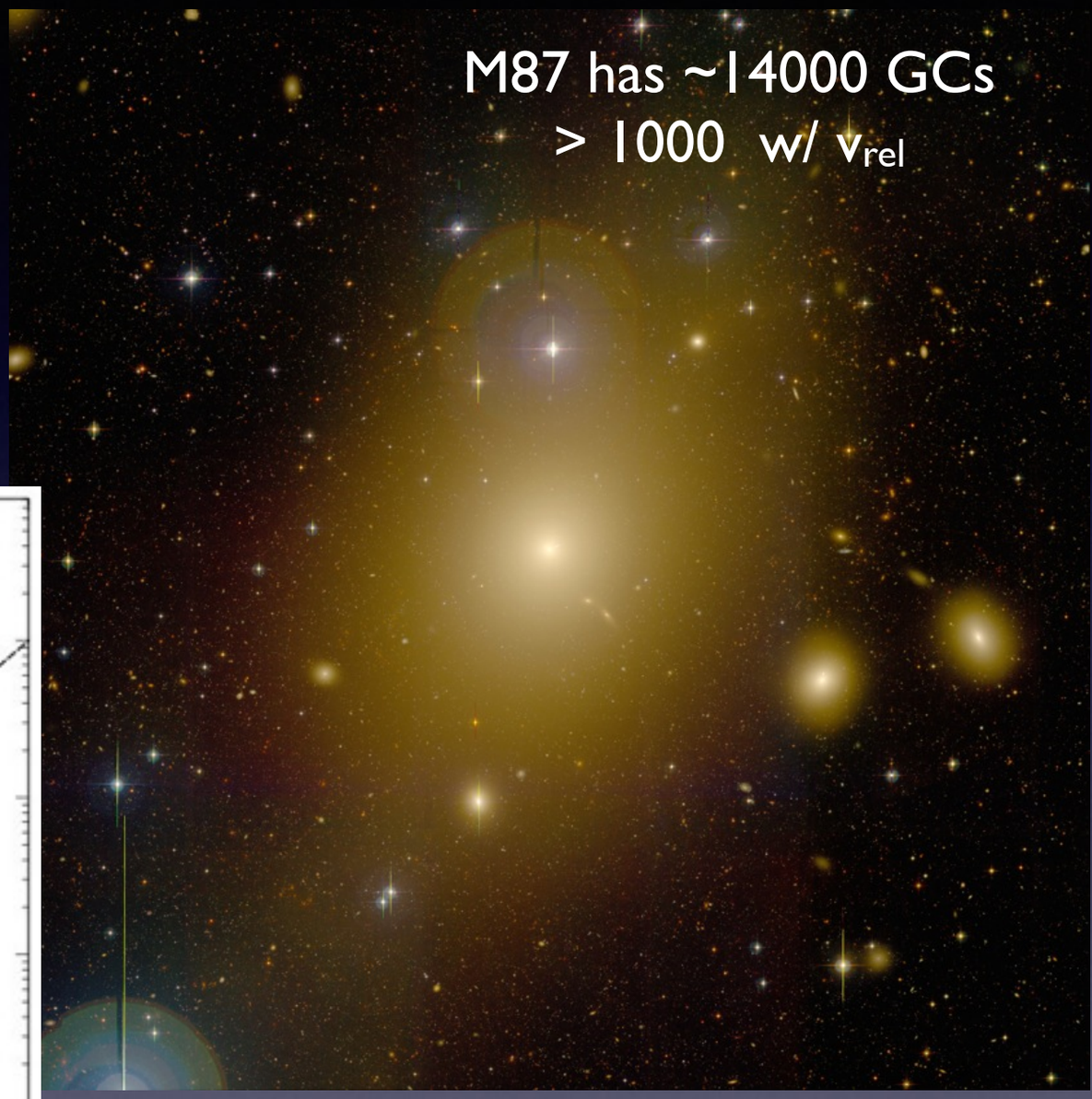


GCs useful probes over wide range of R in all galaxy types, environments

GC Numbers

- most 'accessible' observable in GCS studies
- 0,1 GC in faintest dE/dI galaxies to N_{GC} =15000-30000+
  in most luminous cD/BCG galaxies
  (eg. Alamo-Martinez+2013, Harris+2014…)





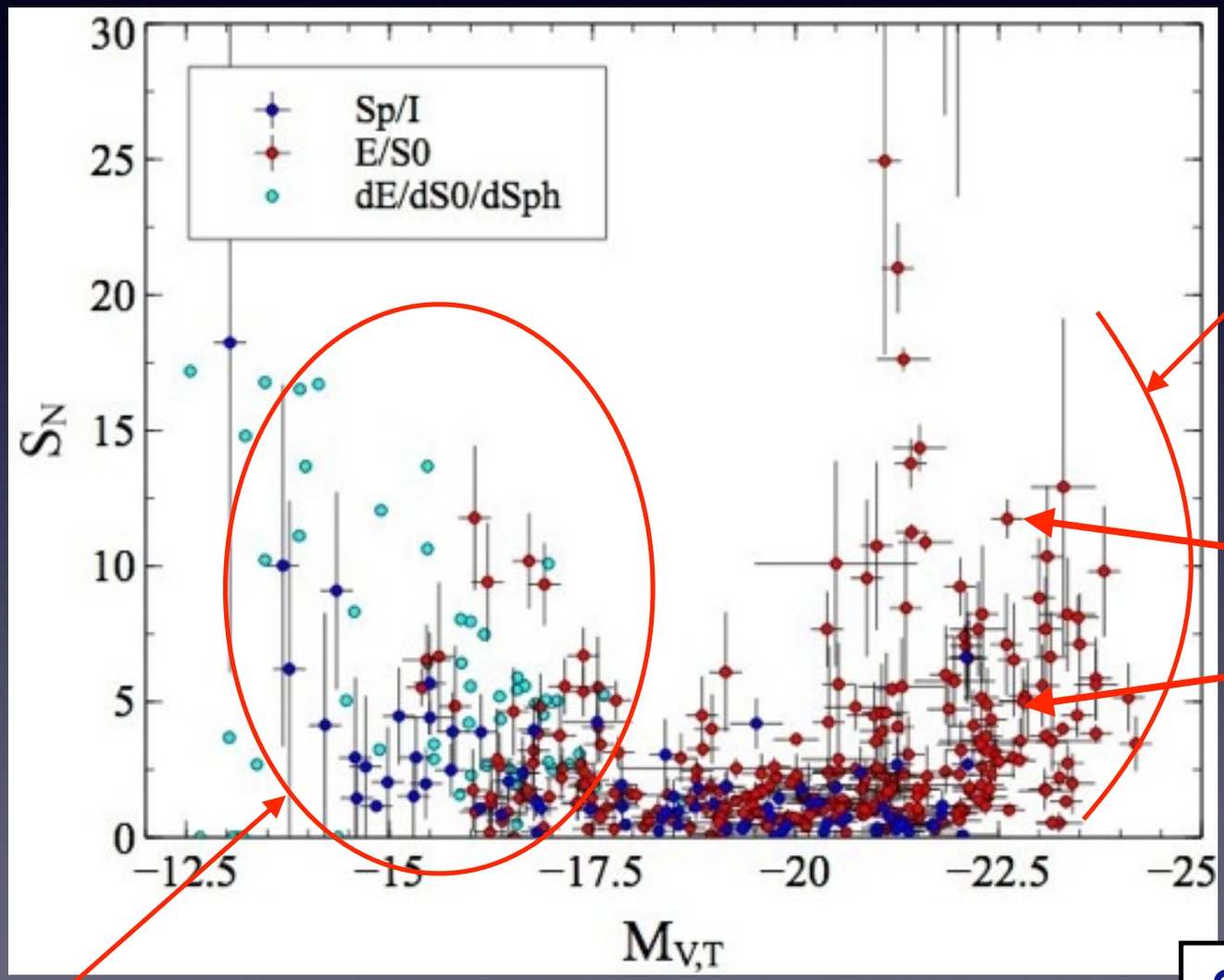
Significant deviations (at highest and lowest L) from simple N_{GC} vs. L scaling

Specific Frequency S_N

(Harris + van den Bergh 1981)

$$S_N = N_{GC} 10^{0.4(M_V+15)} = 9.6\times10^7 \frac{N_{GC}}{L_V / L_\odot}$$

- comparison of global GC formation efficiency to that of field stars
- some variation due to M/L differences b/w morphological types



wide variations of S_N in most luminous galaxies (largely ETGs)

M87

M49

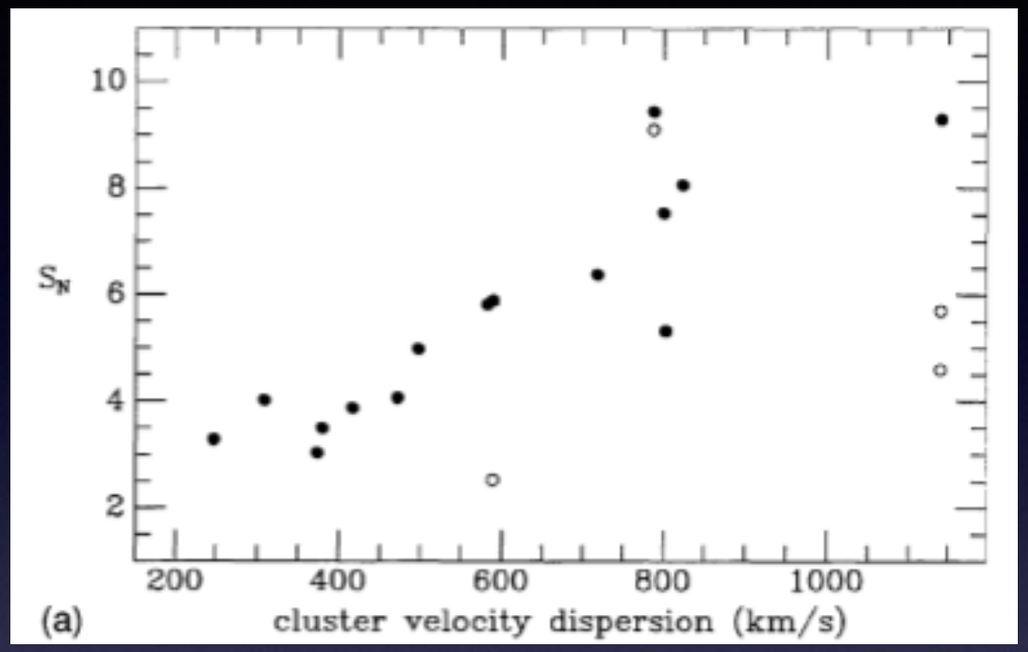
S_N variations in dwarf galaxies. SN feedback suppressing field SF? (eg. Peng+2008, Georgiev+2010)

S_N a measure of GC formation efficiency or field star SF efficiency?

Something more fundamental? **MASS**

S_N variations in massive galaxies reduced if inclusion of X-ray gas mass

GC fraction of total *baryonic* mass? (McLaughlin 1999)

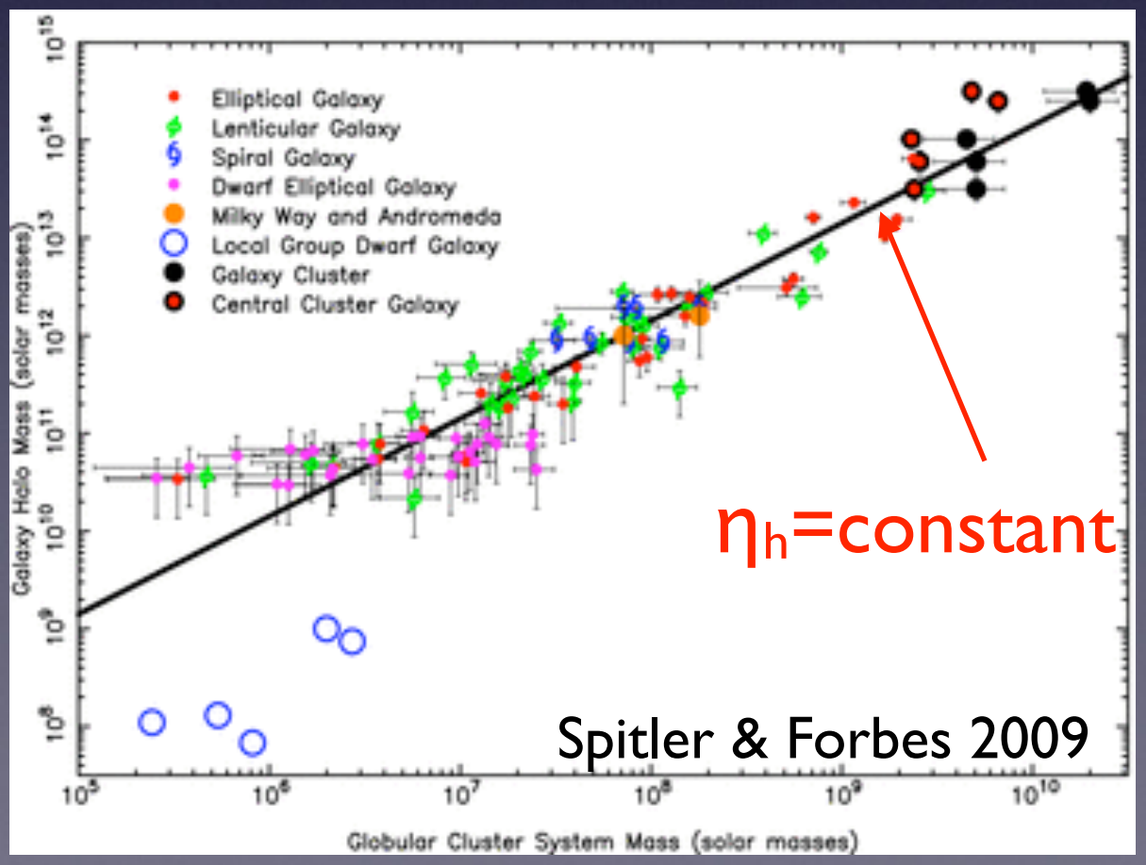


S_N increases w/ σ for BCG/cD galaxies

$N_{GCS} \Rightarrow M_{GCS}$ scales with **total** mass

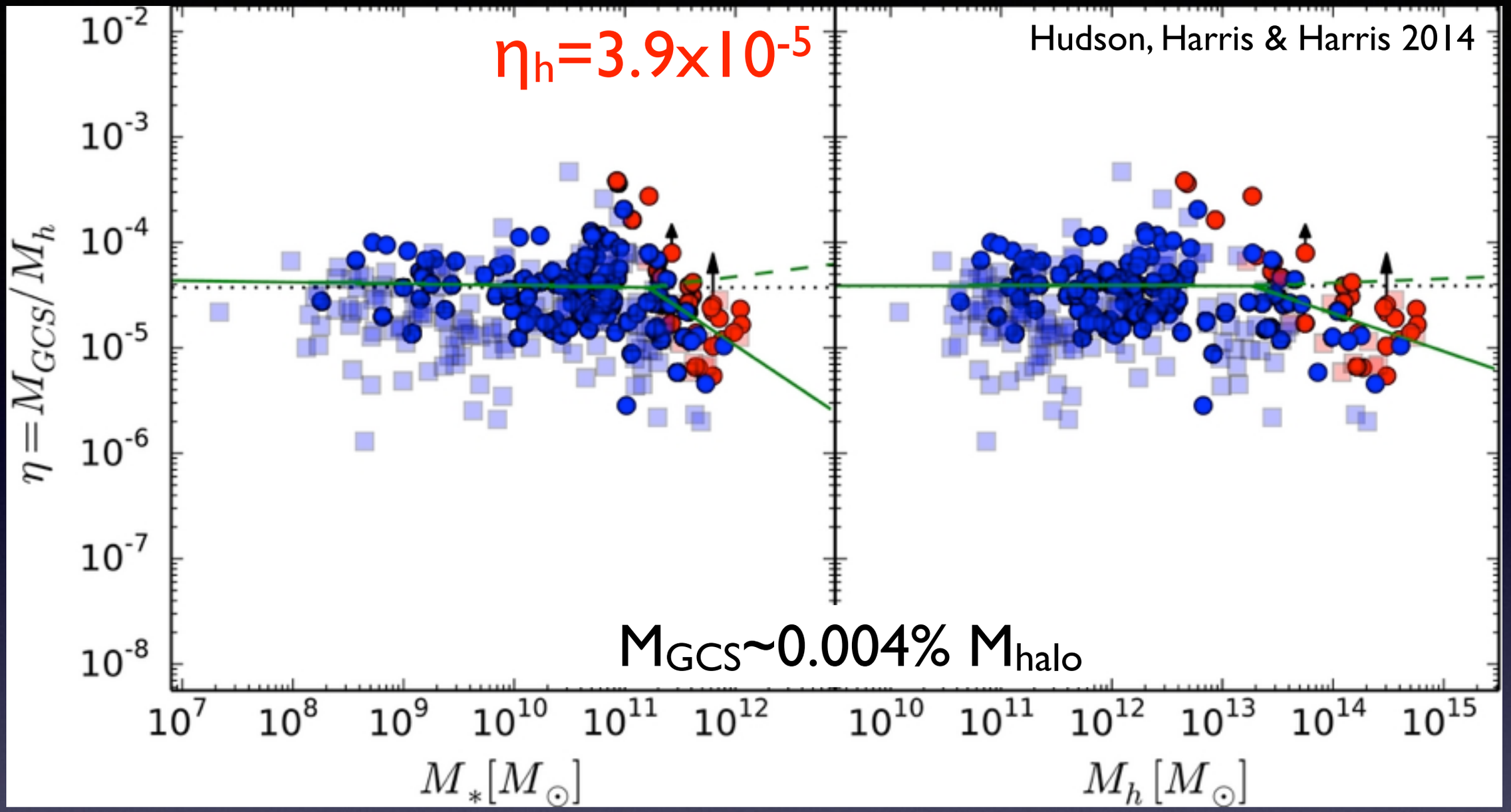
(Blakeslee+1997, Blakeslee 1999)

$$\varepsilon_h = \frac{M_{GCS}}{M_{halo}} = \frac{M_{GCS}}{M_{(DM+stars+gas)}}$$



η_h remarkably similar regardless of galaxy morphology, luminosity and environment

(Spitler+Forbes 2009, Georgiev+2010, Harris+2013 Harris talk)

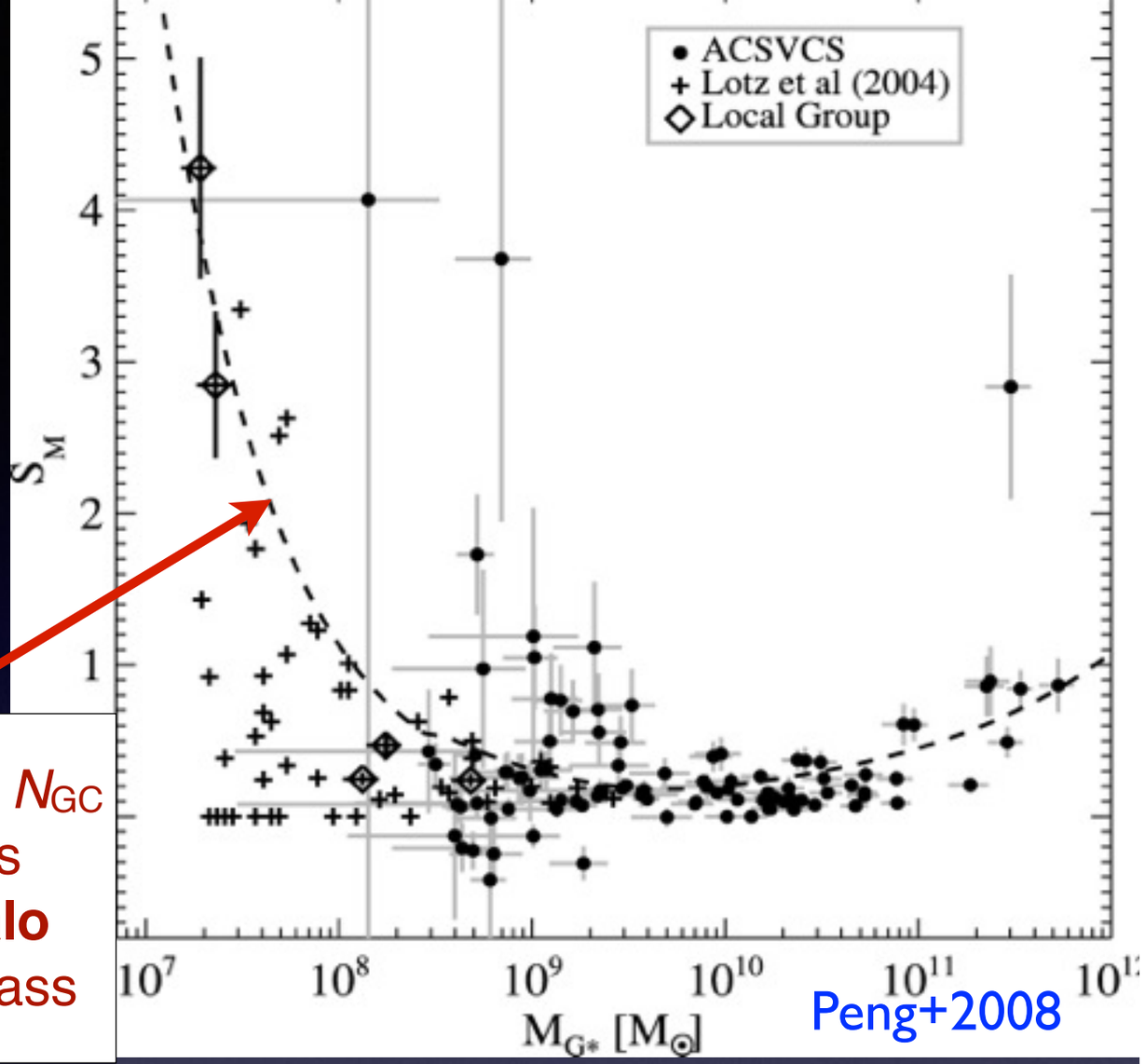


Important connection between (surviving) GCS mass and mass of DM halo at time of (early) formation (z > few)

— over almost 5 orders of magnitude in mass!

suggested by hierarchical ΛCDM models of *blue/metal-poor* GC formation

(eg. Moore et al 2006, Kravtsov+Gnedin 2005)



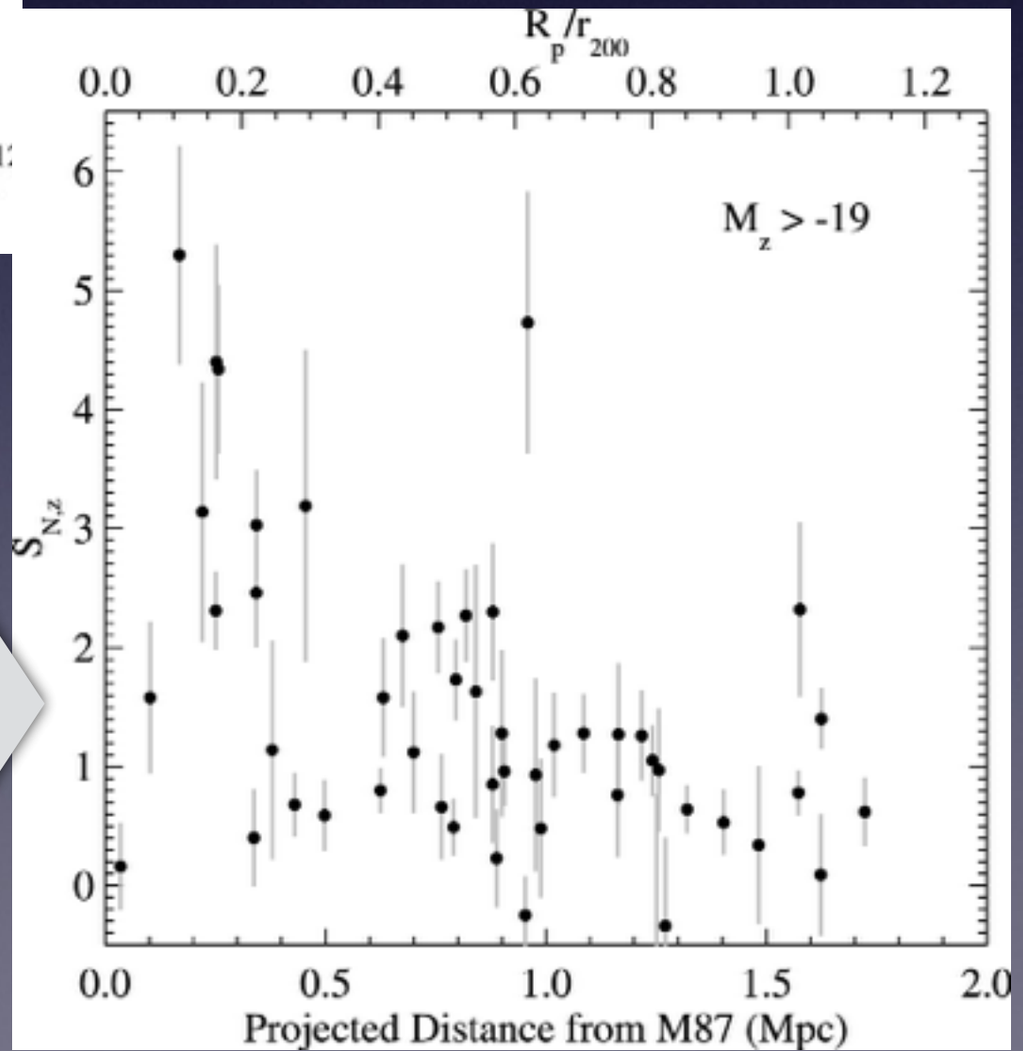
Peng+2008

Prediction if N_{GC} scales as galaxy **halo** (DM+✷) mass

With $M_{GCS} \propto M_{halo}$

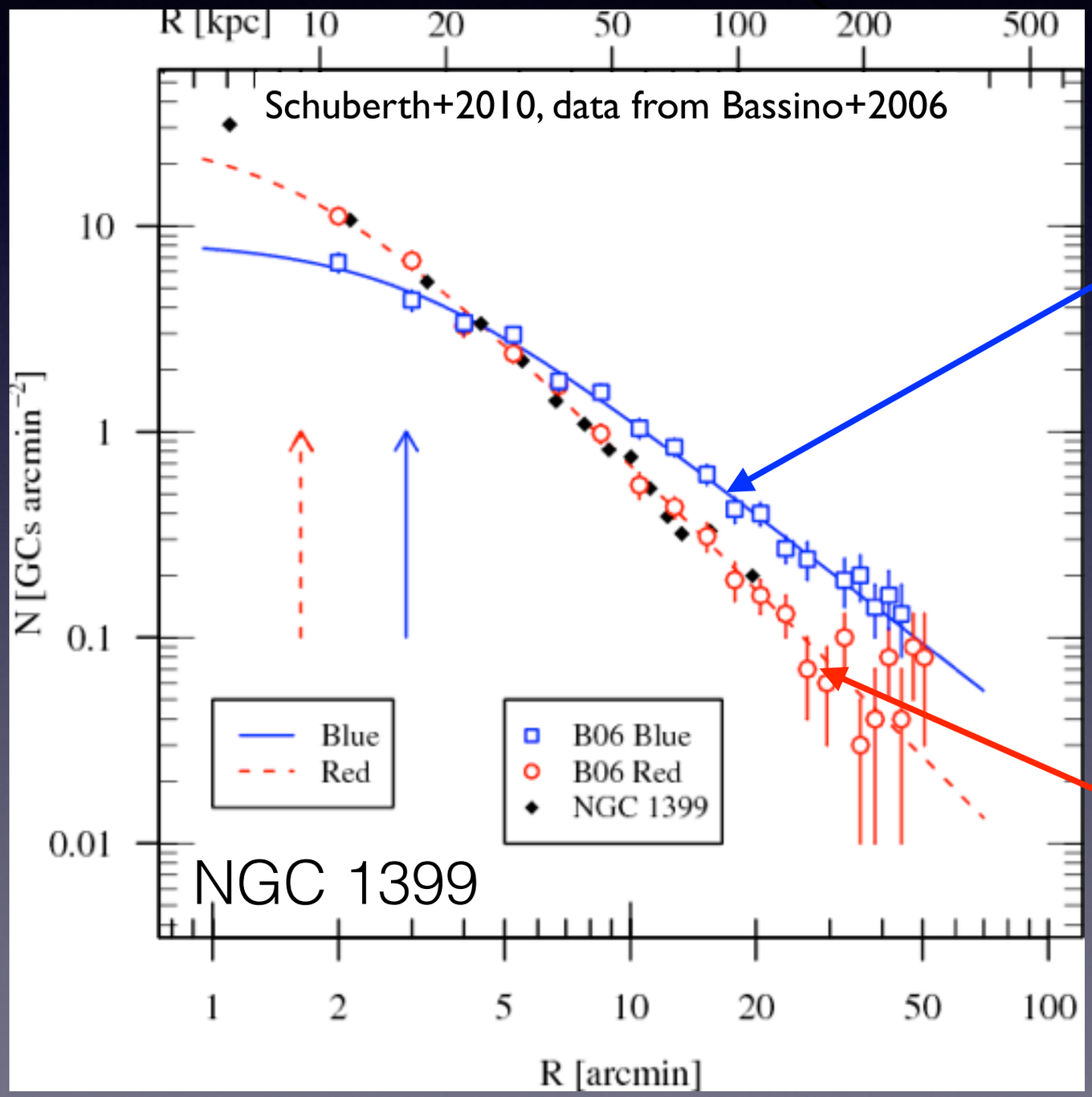
S_N variations *largely* due to field star formation efficiency
(and related feedback)
(eg. Blakeslee1997,Harris+2013)

BUT….'biased' GC formation in dwarfs near M87 (Peng+2008)



Radial Distribution of GCs

- relationship b/w GCS and spheroid, halo, DM halo
- clear differences between profiles of MP and MR GCs
  (eg. Geisler+1996, Tamura+2006, Harris2009, Schuberth+2010, Lee+2010…)

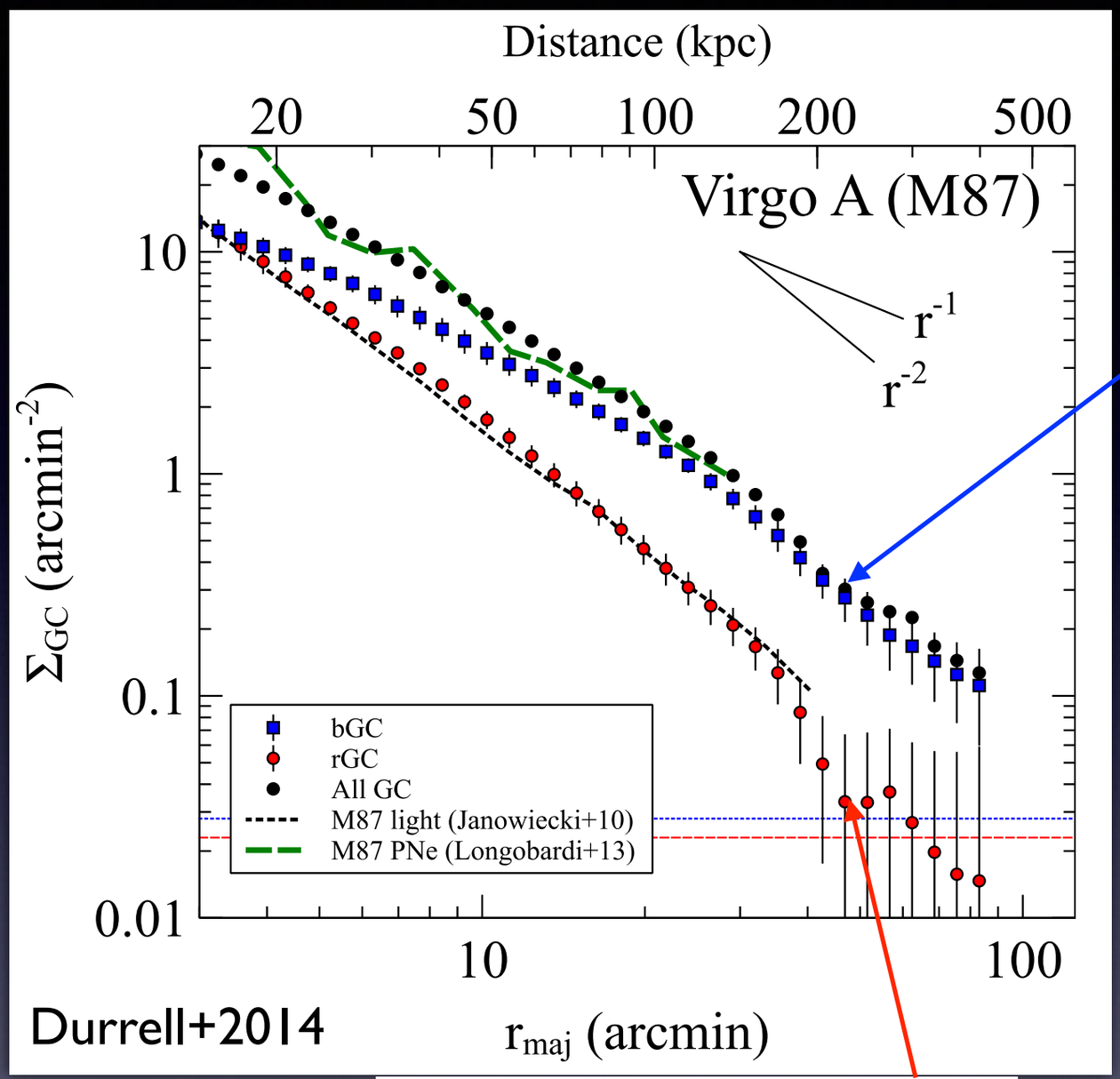


Blue/metal-poor GCs have more extended radial distribution than main spheroid

similar profile to MP *stellar* halo?
relation to galactic/cluster DM halo?

Red/metal-rich GCs more centrally concentrated matching spheroid light
coeval dissipational formation?
(eg. Forbes+1997, Forte+2005…)

Radial Distribution of blue GCs

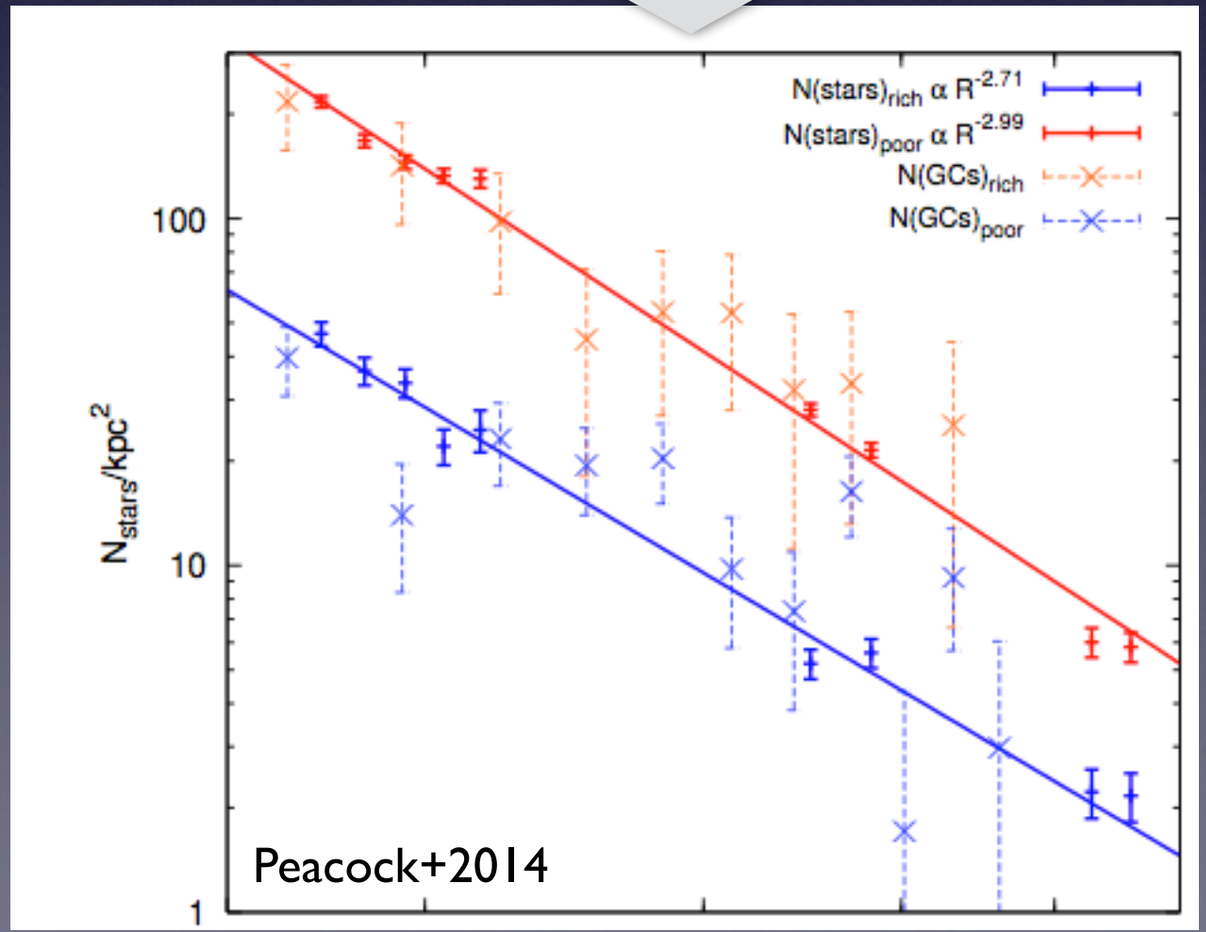


Durrell+2014

Blue/metal-poor GCs have more extended radial distribution (similar to PNe at larger r; Longobardi 2013, talk)

red GCs→0 by 200 kpc

expectation that MP halo **stars** and blue GCs should have similar profiles (eg. Moore+2006) NGC 3115

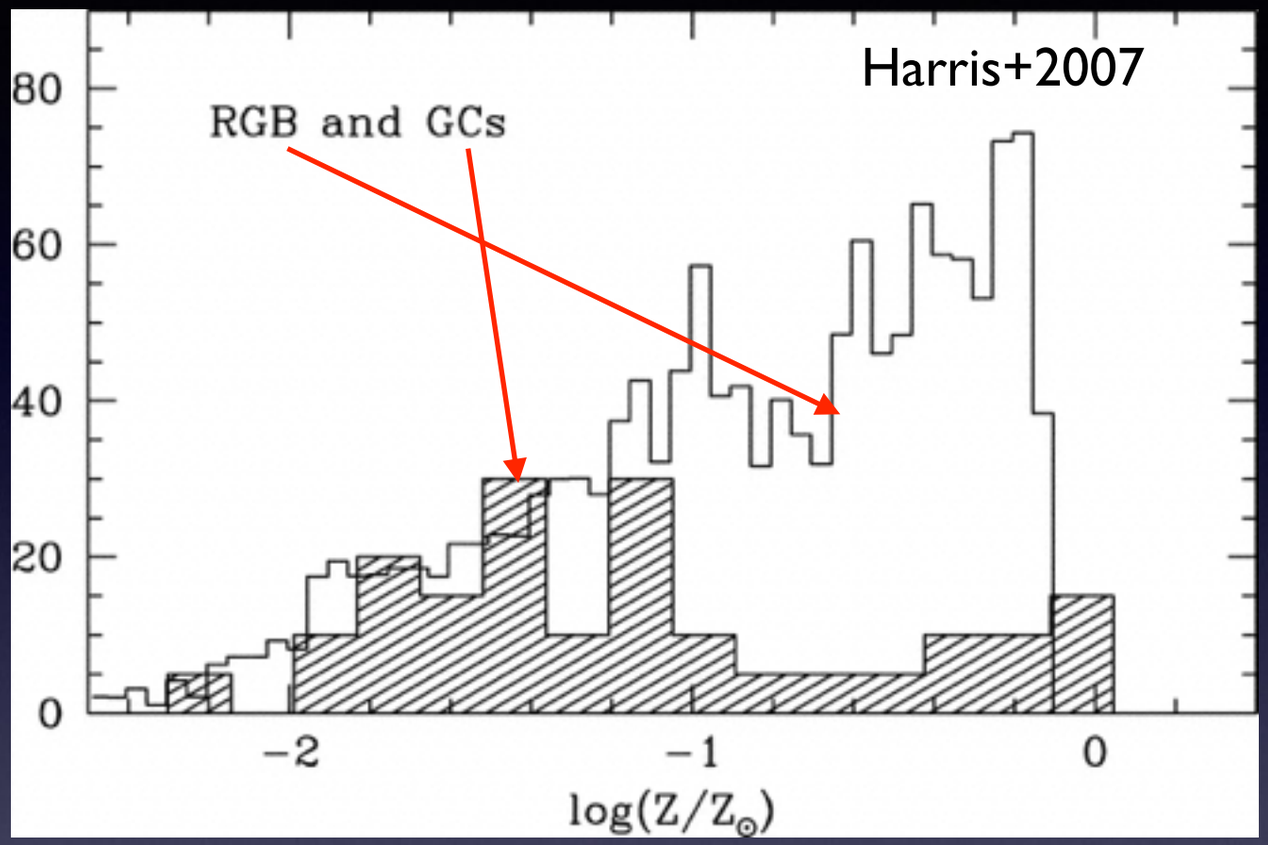


blue GCs useful probes of (proxy for?) the metal-poor *stellar* halos of galaxies

Blue GCs as tracers of outer metal-poor halos of massive galaxies

NGC3379 : MP stellar halo at ~33 kpc (10-12R_e) (Harris+2007)

NGC 5128 - MP halo stars
out to 140 kpc (~25R_e)
(Rejkuba+2014, Rejkuba, Bird talks)



For more distant galaxies:

Virgo (d=16.5Mpc) Σ_{GC}~0.20 arcmin^{-2} μ_V~28.7 mag/arcsec^2
Σ_{GC}~0.05 arcmin^{-2} μ_V~30.0 mag/arcsec^2
(S_N=6; Williams+2007)

with improved GC selection, can trace fainter SB's of metal-poor halo

GC/star ratio higher in metal-poor clusters compared to metal-rich

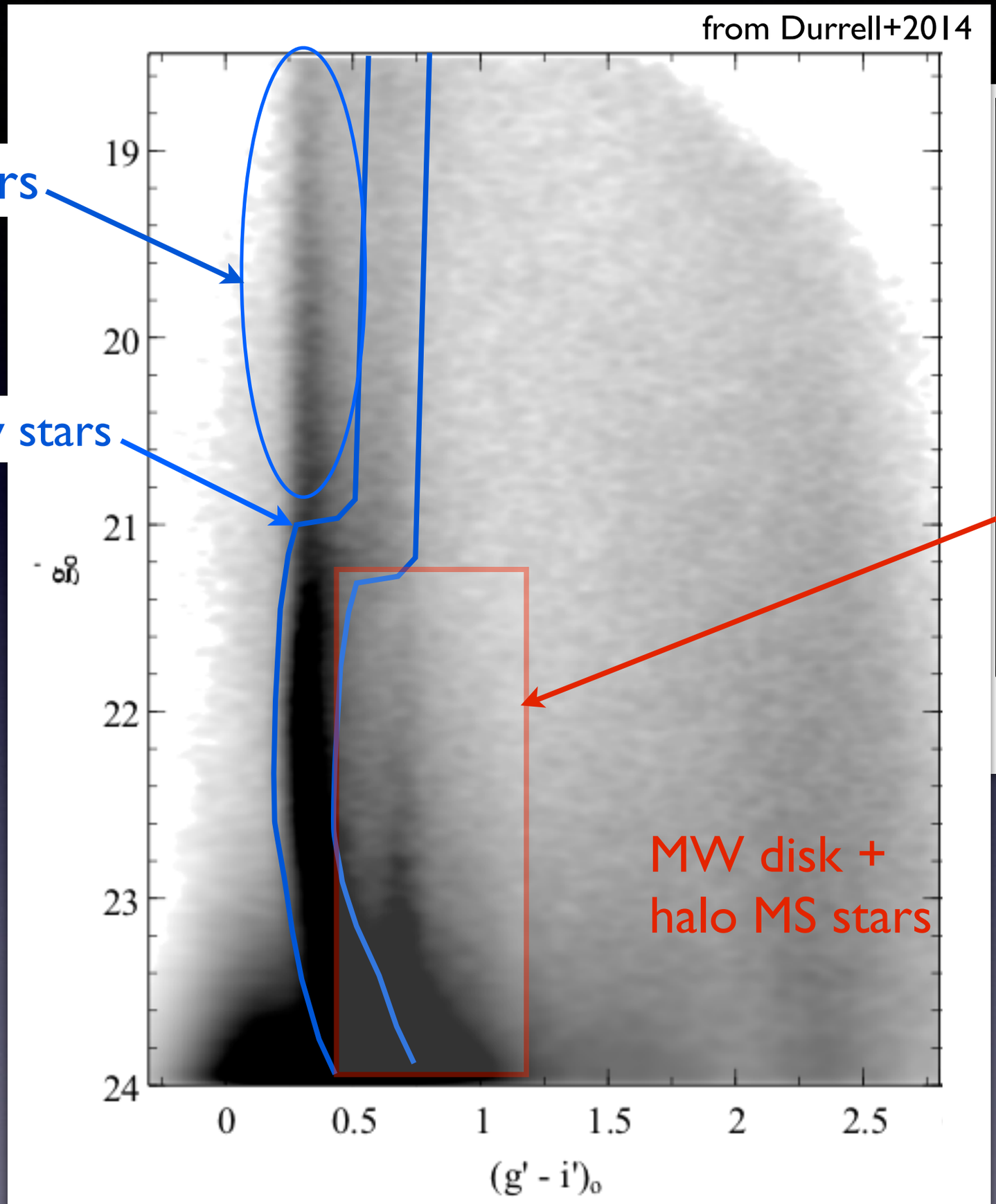
Outer Halos of Massive Galaxies: NGVS

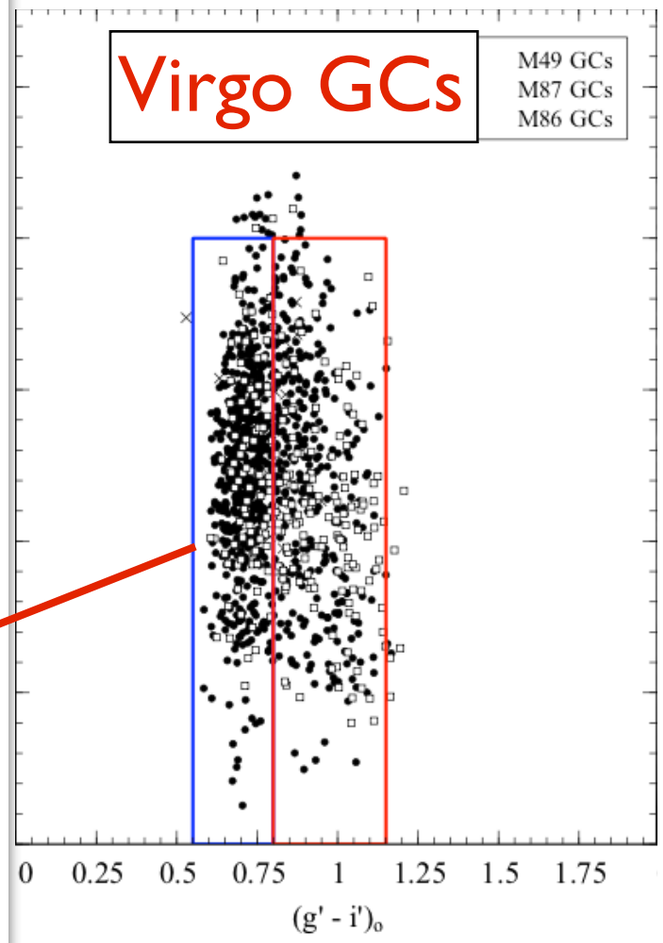
Ferrarese+2012

MW halo stars

Sgr dwarf galaxy stars

from Durrell+2014





NGVS: ~900 000 point sources

Outer Halos of Massive Galaxies

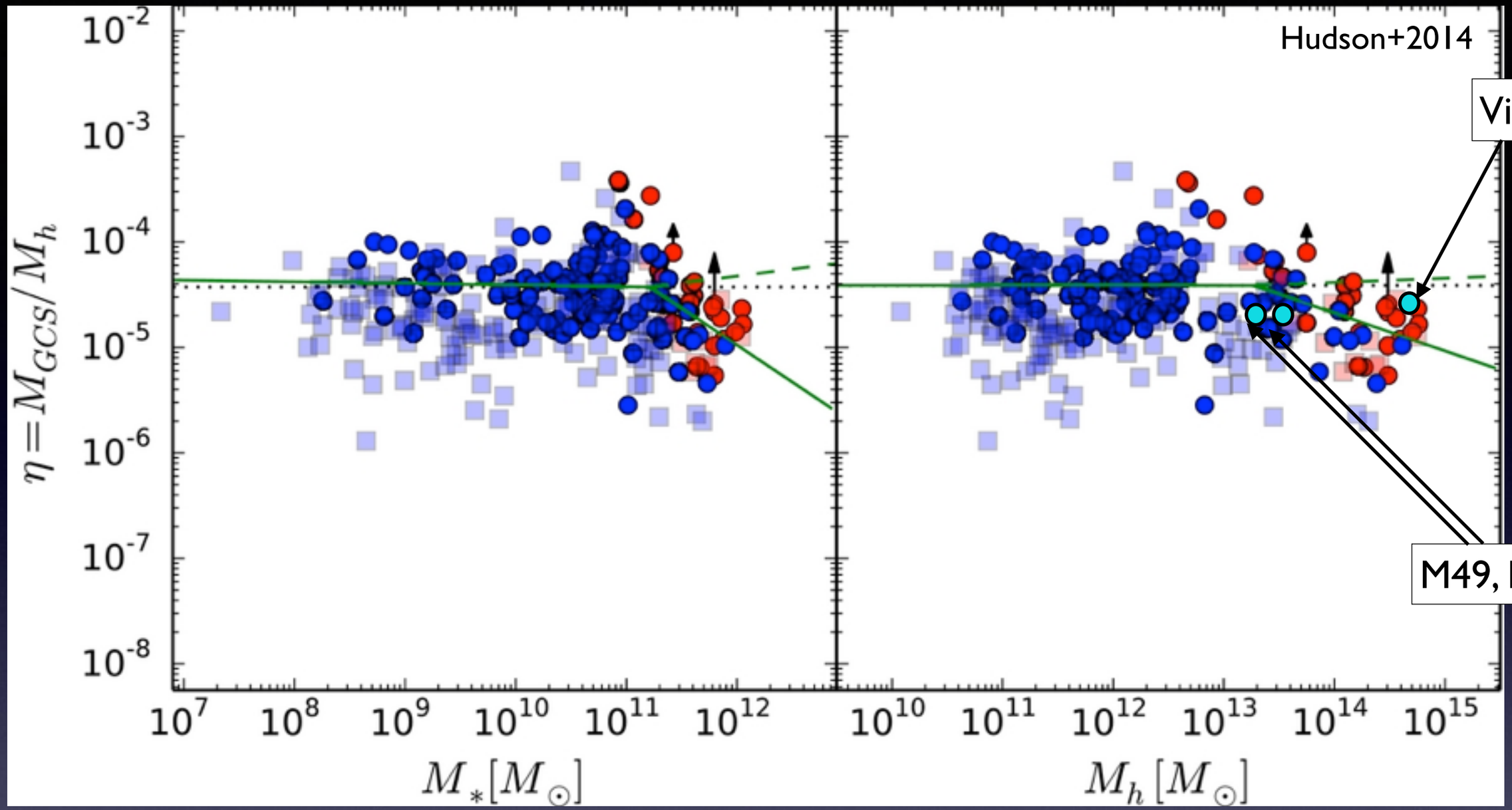
NGVS: extensive distribution of GCs throughout main subclusters
(M87, M49, M60…)

Virgo **cluster:**
N_{GC} = 67300 ± 14400
(35% in M87+M49 alone)

GCs extend to few x 100 kpc from major galaxies

Mihos+2005,2015

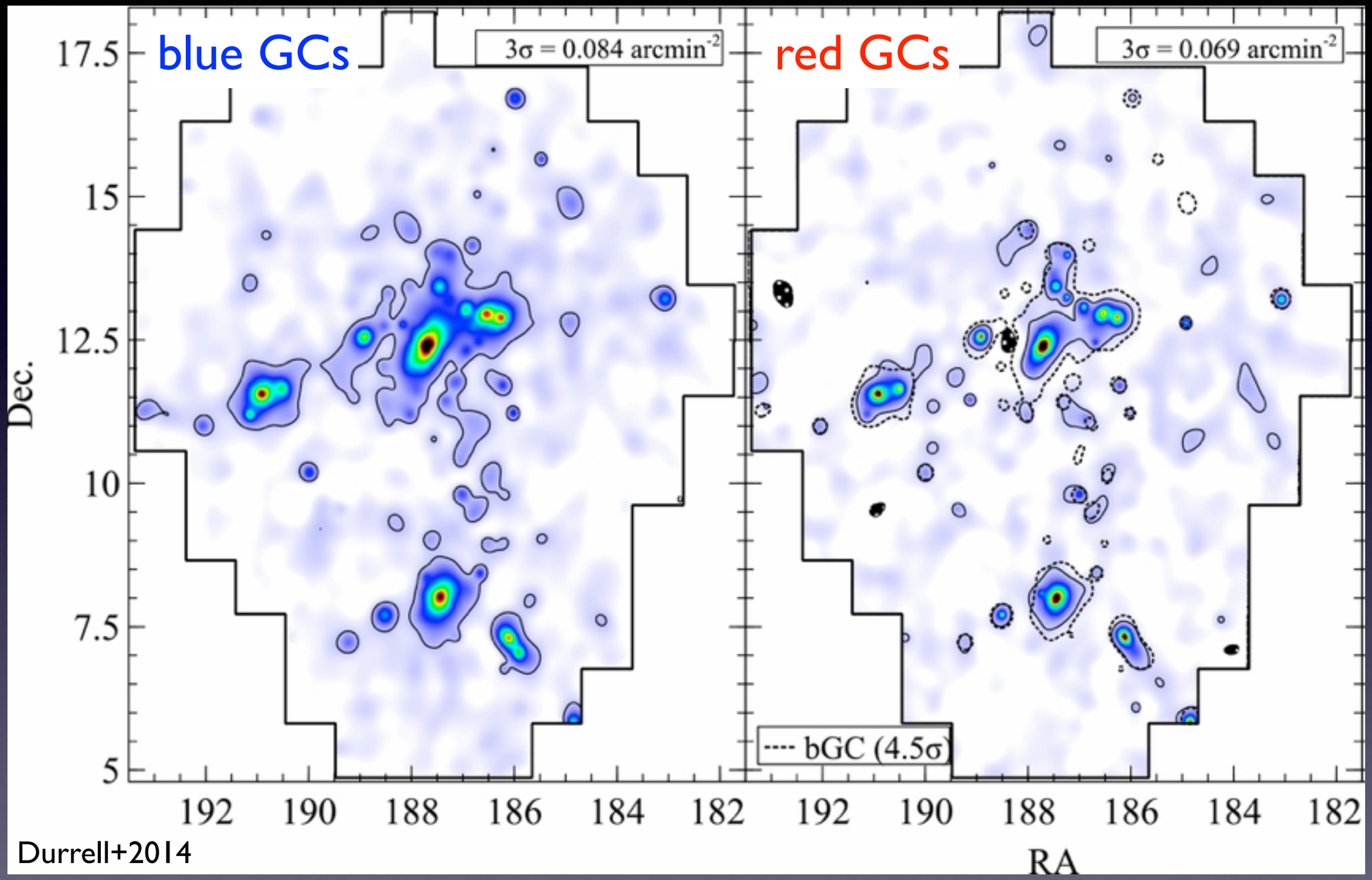
Durrell+2014



Virgo *cluster-wide* GCS : $\eta_h \sim 2.9 \times 10^{-5}$

M87/M49 (to r=200 kpc) have very similar η_h
M87 more massive, less L than M49

Outer Halos of Massive Galaxies



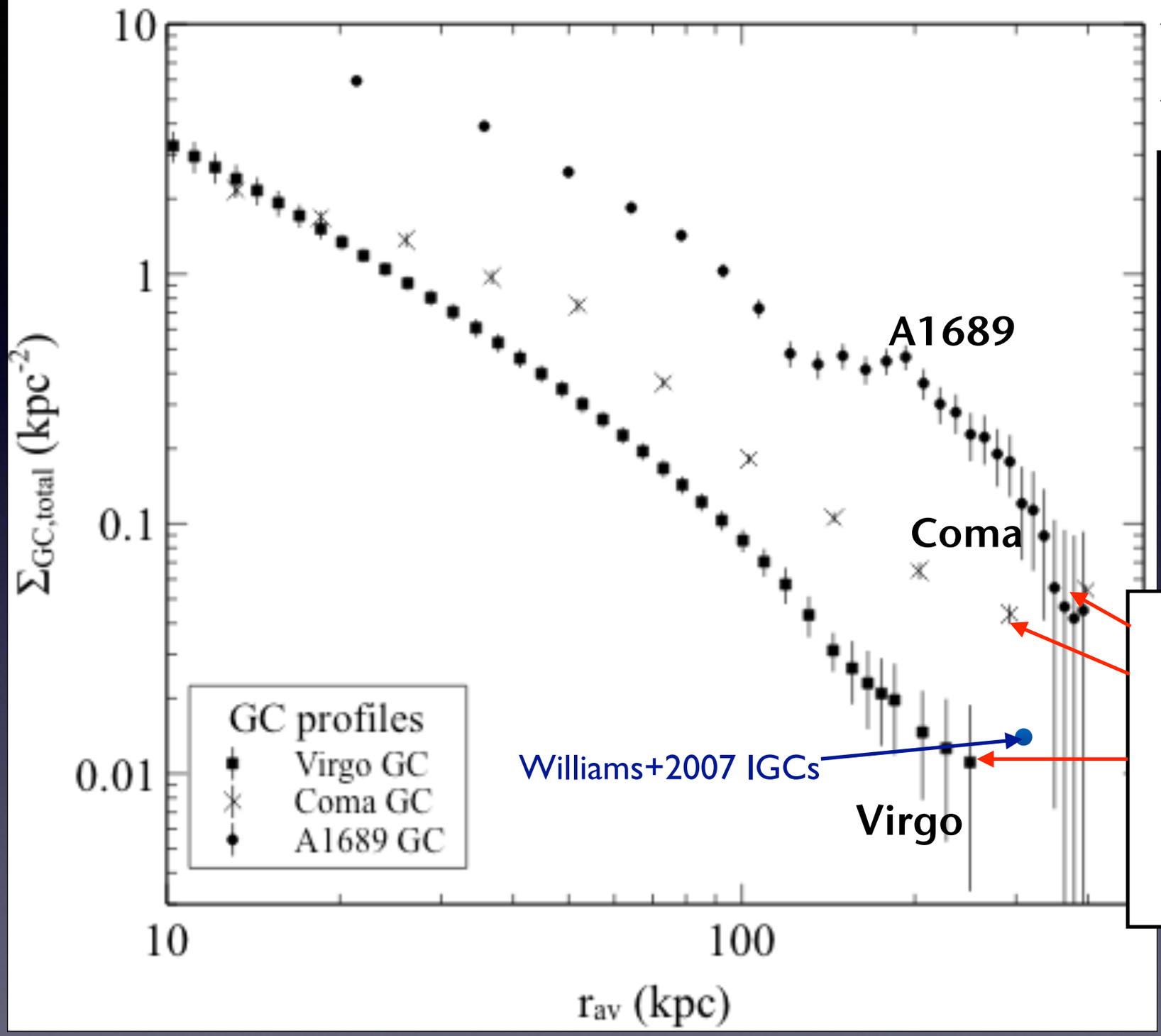
Durrell+2014

blue GCs extended (+irregular) 2D distribution surrounding massive galaxies

➡ metal-poor intracluster GCs = later/ongoing accretion?

Cluster GCS Comparison

A1689: Alamo-Martinez+2013
Coma: Peng+2011
Virgo: Durrell+ 2014



IGCs in outermost regions (r>200-300+ kpc) = trace cluster DM halo increase with dynamical state of cluster?

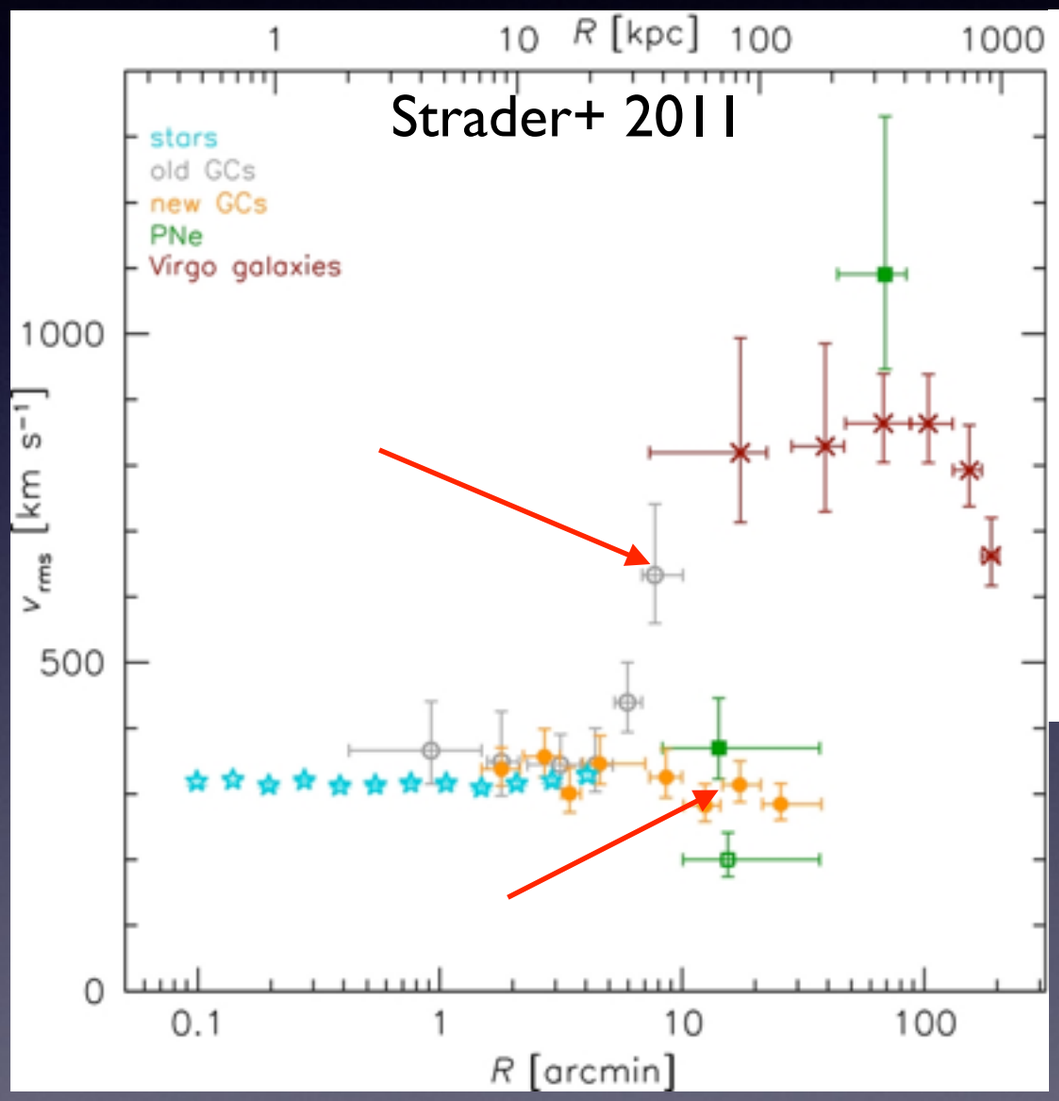
Virgo/Fornax = lower density of IGCs
Coma/A1689 = higher density of IGCs = increased tidal stripping/accretion?

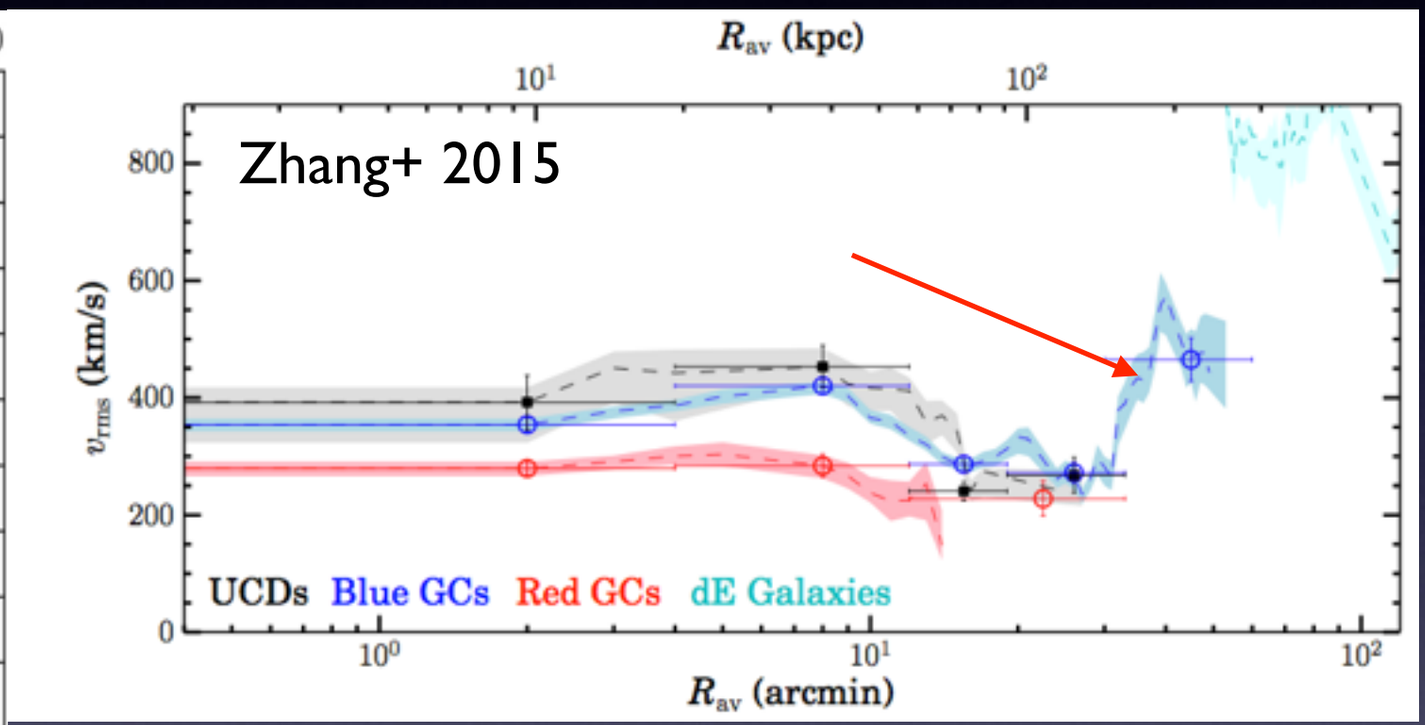
GCs in the outer halos of galaxies : **kinematics**

trace DM halo of galaxy or galaxy+cluster potential? ⇒ intracluster GCs

effects of early formation or later accretion?

M87 - intracluster PNe w/ large σ (eg. Doherty+2009, Longobardi+2013,talk)





low Σ_{GC} (~few x 0.01 kpc^{-2}) = issues with small N, θ coverage

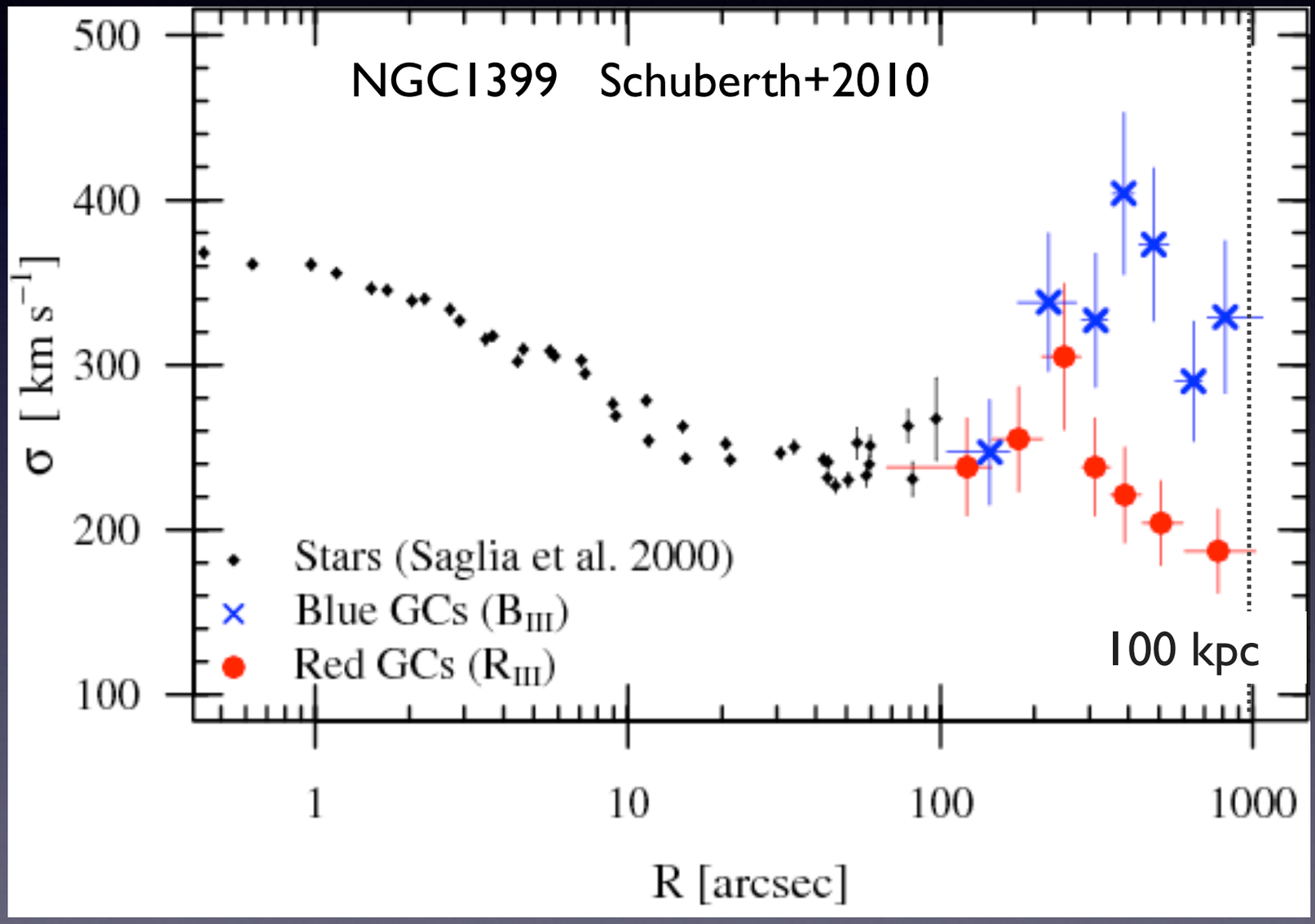
Need improved photometric selection, spectroscopic follow-up at large R

GCs in the outer halos of galaxies : **kinematics**

trace DM halo of galaxy or galaxy+cluster potential? ⇒ intracluster GCs

effects of early formation or later accretion?

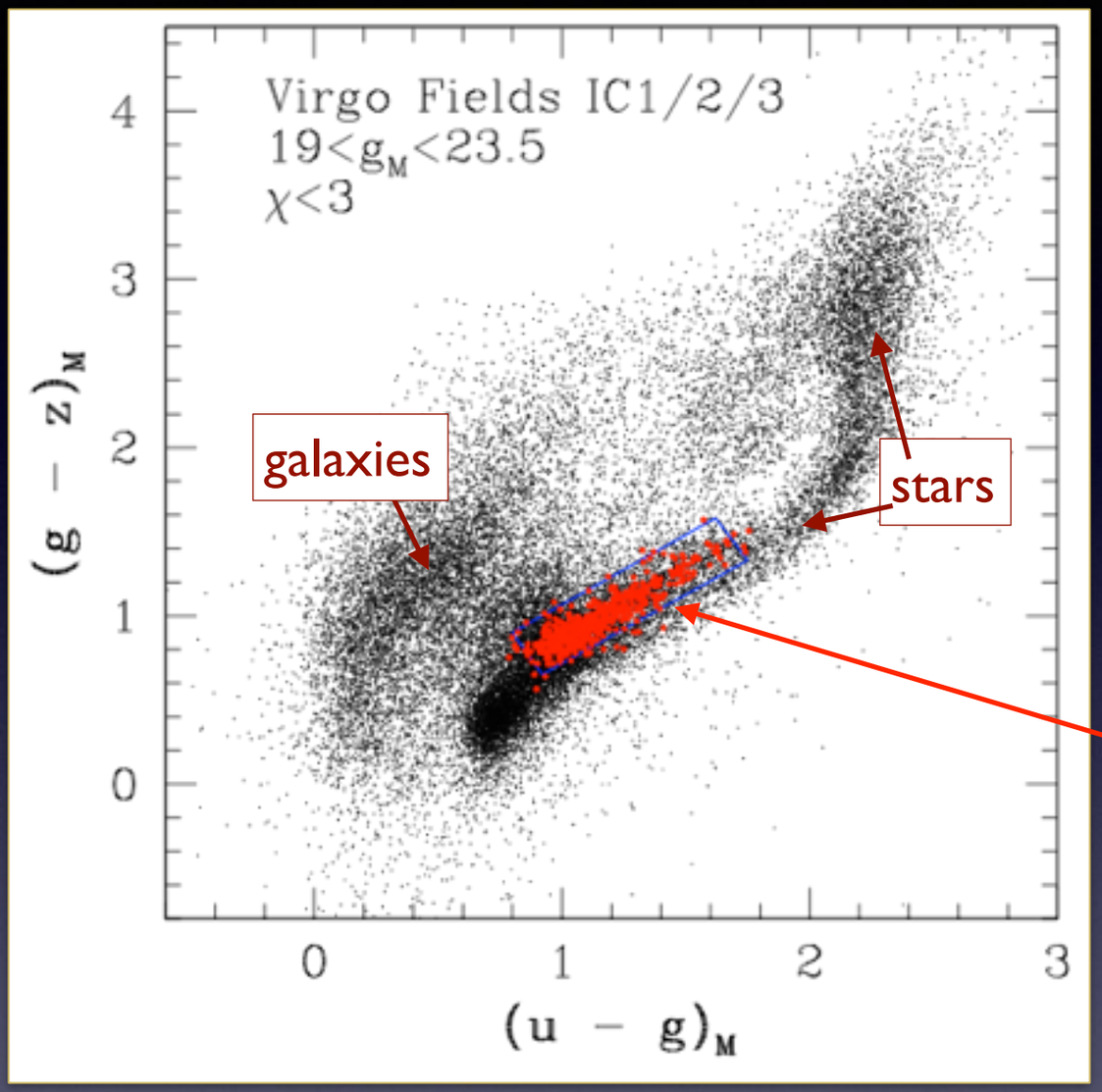
M87 - intracluster PNe w/ large σ (eg. Doherty+2009, Longobardi+2013,talk)



low Σ_{GC} (~few x 0.01 kpc^{-2}) = issues with small N, θ coverage

Need improved photometric selection, spectroscopic follow-up at large R

Photometric selection of extragalactic GCs



Virgo core MegaCam data

reduce bkg. contamination for (necessary) spectroscopic follow-up

BVR, gri v. good

(eg. Harris 2009, Rhode+Zepf 2011,Fedotov+2015)

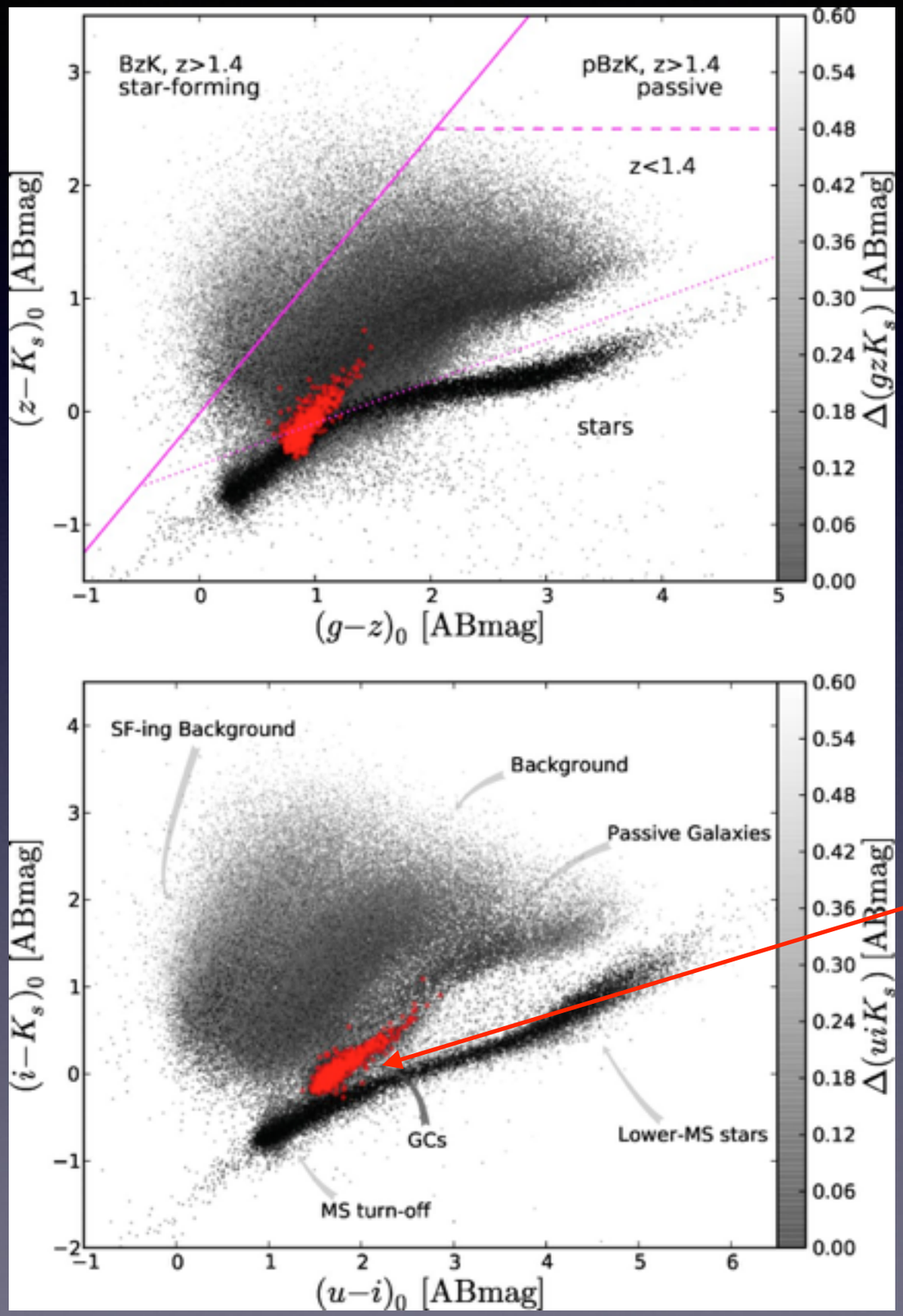
improved bkg. galaxy removal with *u*-band

(eg. Kim+2014; see also Hilker talk)

ugi/ugz shows improvement (factor few)

Photometric selection of extragalactic GCs

reduce bkg. contamination for (necessary) spectroscopic follow-up



Virgo Cluster GCs - NGVS-IR (Muñoz+2014)

BVR, gri v. good

(eg. Harris 2009, Rhode+Zepf 2011,Fedotov+2015)

improved bkg. galaxy removal with *u*-band

(eg. Kim+2014)

ugi/ugz shows improvement (factor few)

uiK for blue GCs

(which dominate outermost regions)

also, improved ground-based seeing

(eg. G.Harris+2012, NGVS:Ferrarese+2012)

Summary

- GCs effective discrete tracers of galactic halos (*and galaxy clusters)*
  - visible in many galaxies to large distances, + chemical history
- GCs formed/survived in numbers N_{GC} related to the total mass (DM+gas+stars) of the galaxy/cluster
  - S_N variations largely a reflection of field star formation efficiency
- metal-poor GCs probe stellar halos in large galaxies
  - accretion history? related to presence of IGCs
- future: studies of more GCSs to R>100-200+ kpc
  - importance of complete SED coverage UV⇒IR for GC selection
  - wide field photometry + (yet) more WF spectroscopy (!)
    eg. NGVS, MATLAS, SLUGGS, FDS, Rhode+ work