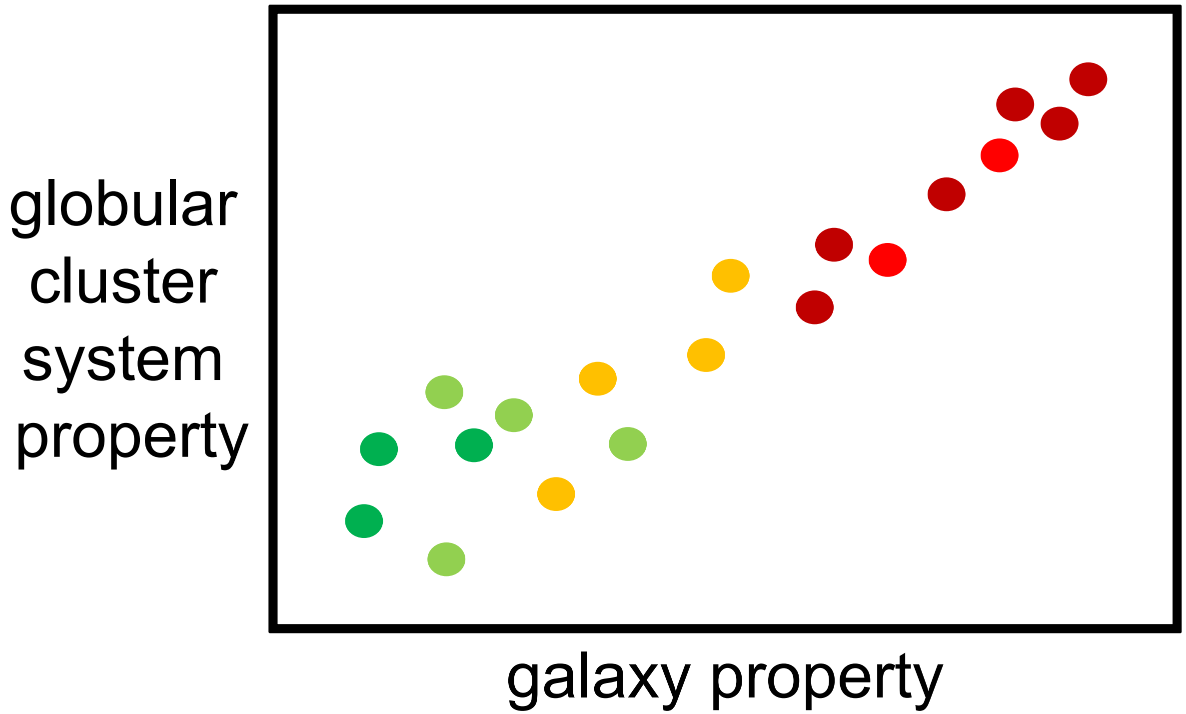
# GC scaling relations

## An observational perspective





Michael Hilker (ESO, Garching)


KITP Globular Clusters 2020

# Observables for ensemble properties of extragalactic GCSs

## Photometry

- Numbers → total numbers, specific frequency
- Spatial distribution → GCS effective radius, gradients
- Luminosity distribution → luminosity function, mass function (via M/L), GCS total mass
- Color distribution → bimodality, color gradients, (metallicity/age distribution/gradients)
- Size distribution → compact vs. extended GCs, UCDs

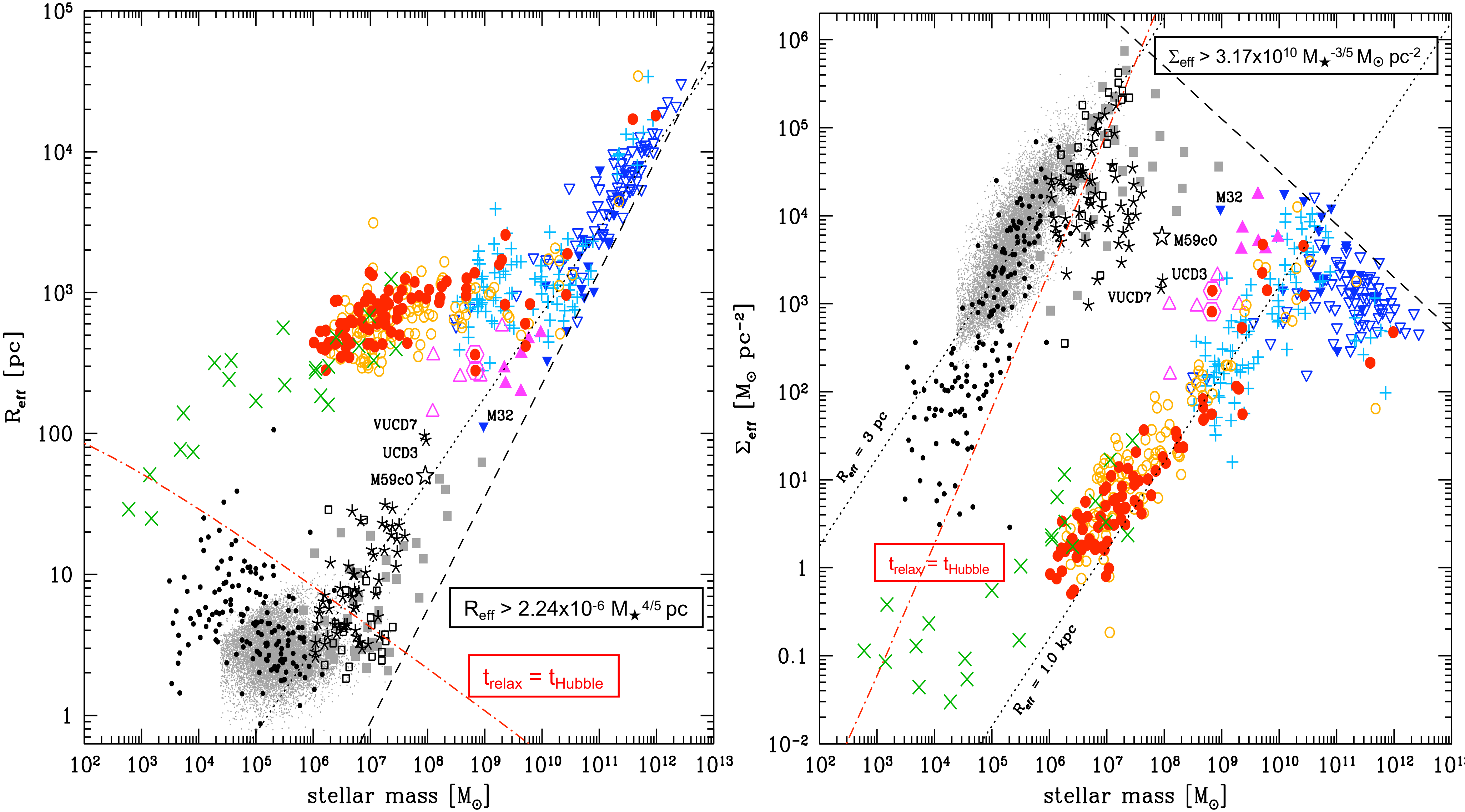
→ for blue and red GCs

## Spectroscopy

- LOS velocity distribution → higher order moments: dispersion, anisotropies (radial/tangential orbits)
- Line strengths distribution → metallicity distribution/gradients, [Fe/H], [α/Fe], other elements, age distribution/gradients
- Internal velocity dispersions → dynamical mass distribution, unseen mass (SMBHs, DM)

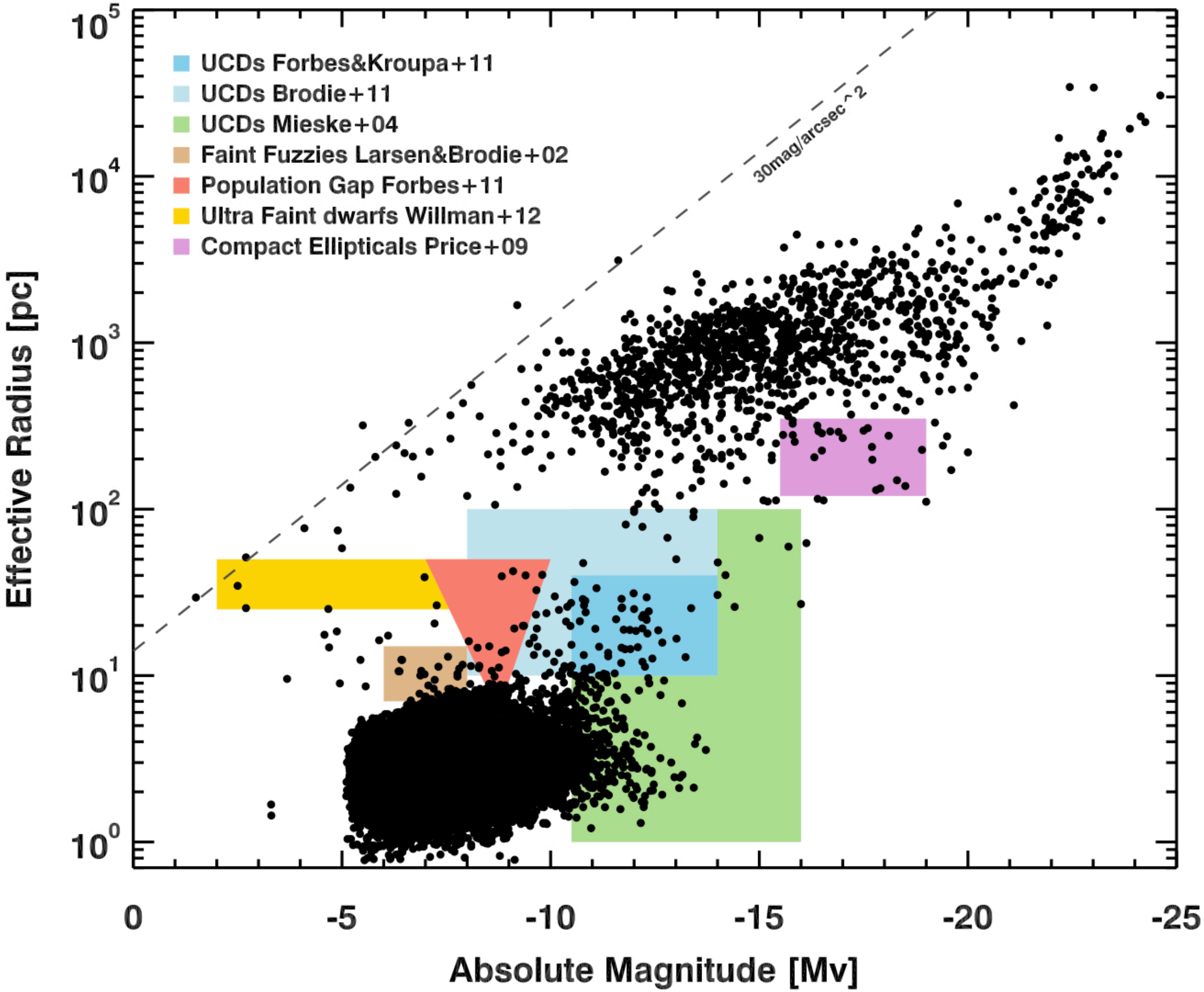
Scaling relations: compare GCS properties as function of galaxy mass, halo mass, galaxy type, environment, etc.

# The star cluster – galaxy context (2010)



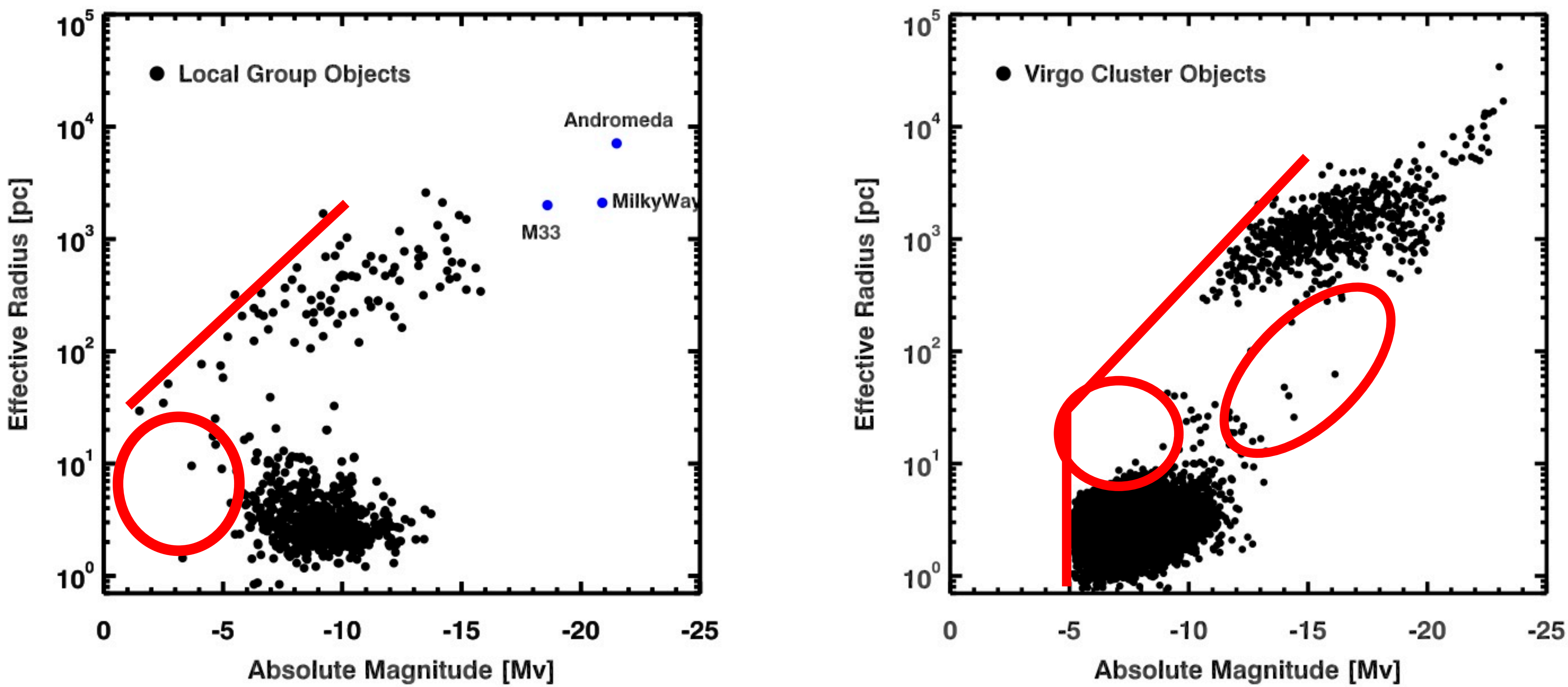

**Misgeld & Hilker (2011),** see also Dabringhausen et al. 2008

# The star cluster – galaxy context – the ‘special’ star clusters




Voggel (PhD thesis), based on Misgeld & Hilker (2011)

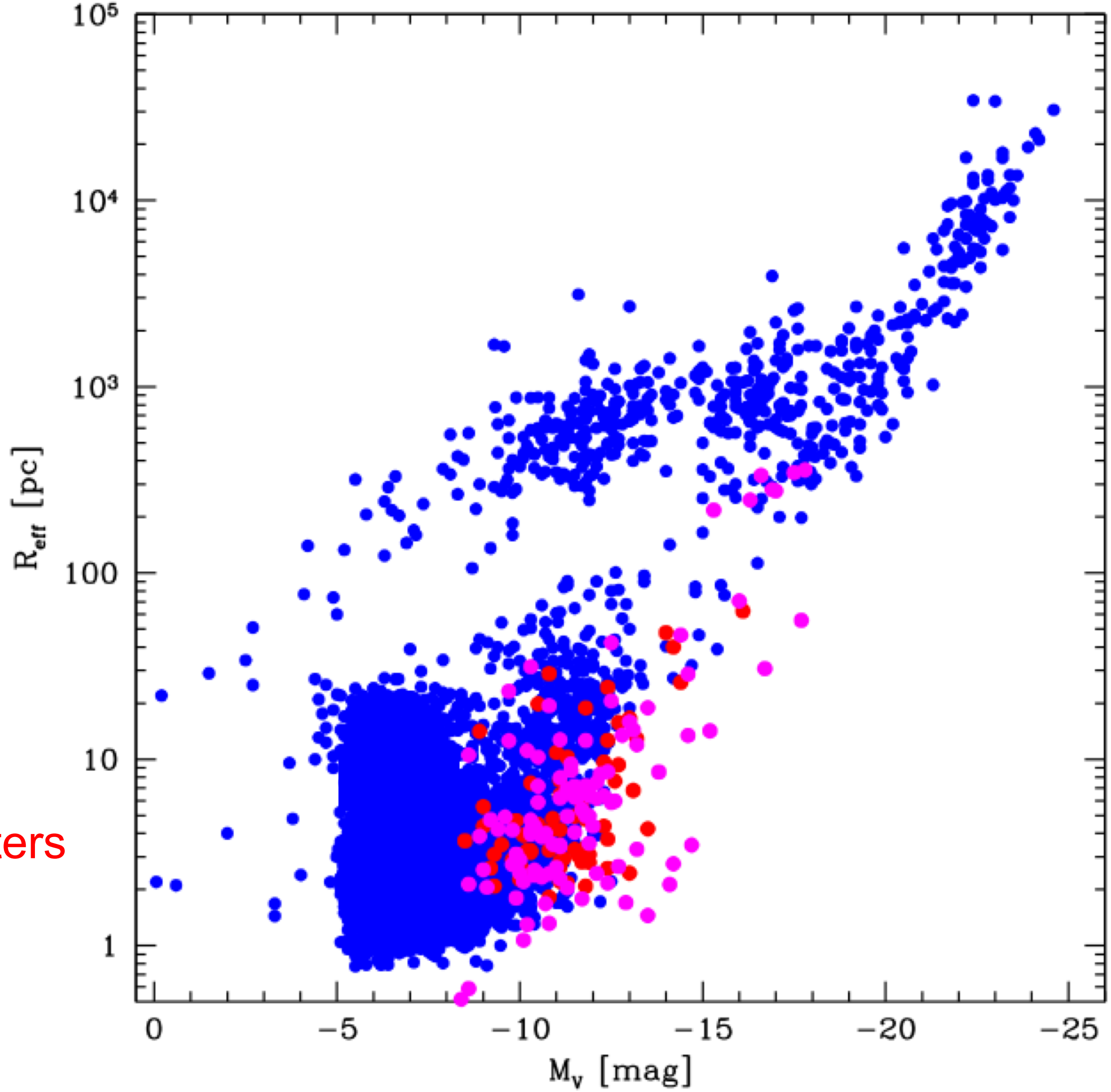
# The star cluster – galaxy context – divided by environment




Observational detection limits/biases

Voggel, Hilker (~2015, never published)

# The star cluster – galaxy context (‘everything plot’, 2014)

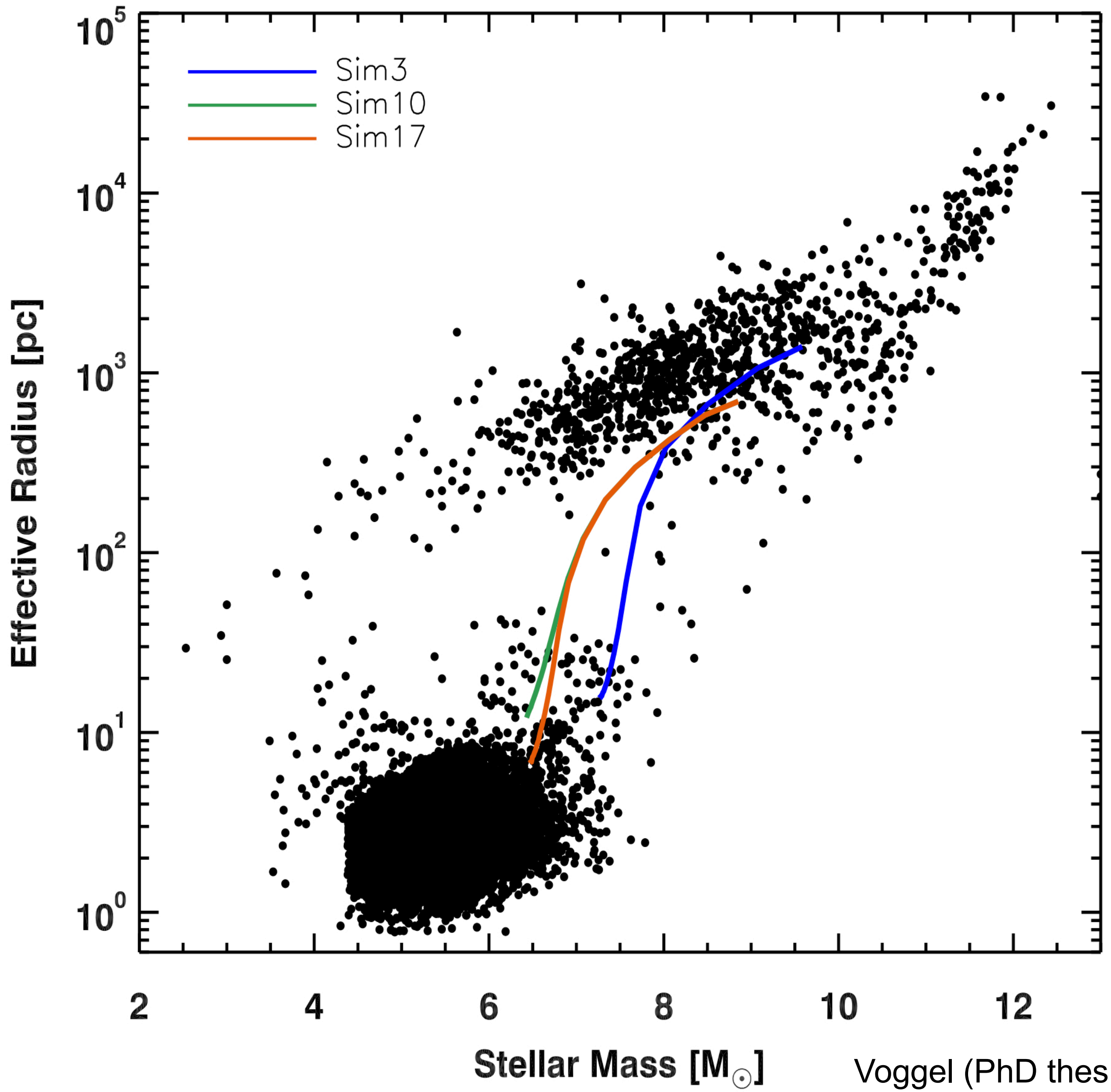



adapted from Misgeld & Hilker (2011)
Brodie et al. (2011)
Brüns & Kroupa (2012),
plus nuclear star clusters from
Böker et al. (2004)
Rossa et al. (2006)
Côté et al. (2006)
Georgiev & Böker (2014)

see also:
Norris et al. (2014)

adding nuclear star clusters (NSCs)

# Stripping tracks in the mass-size plane



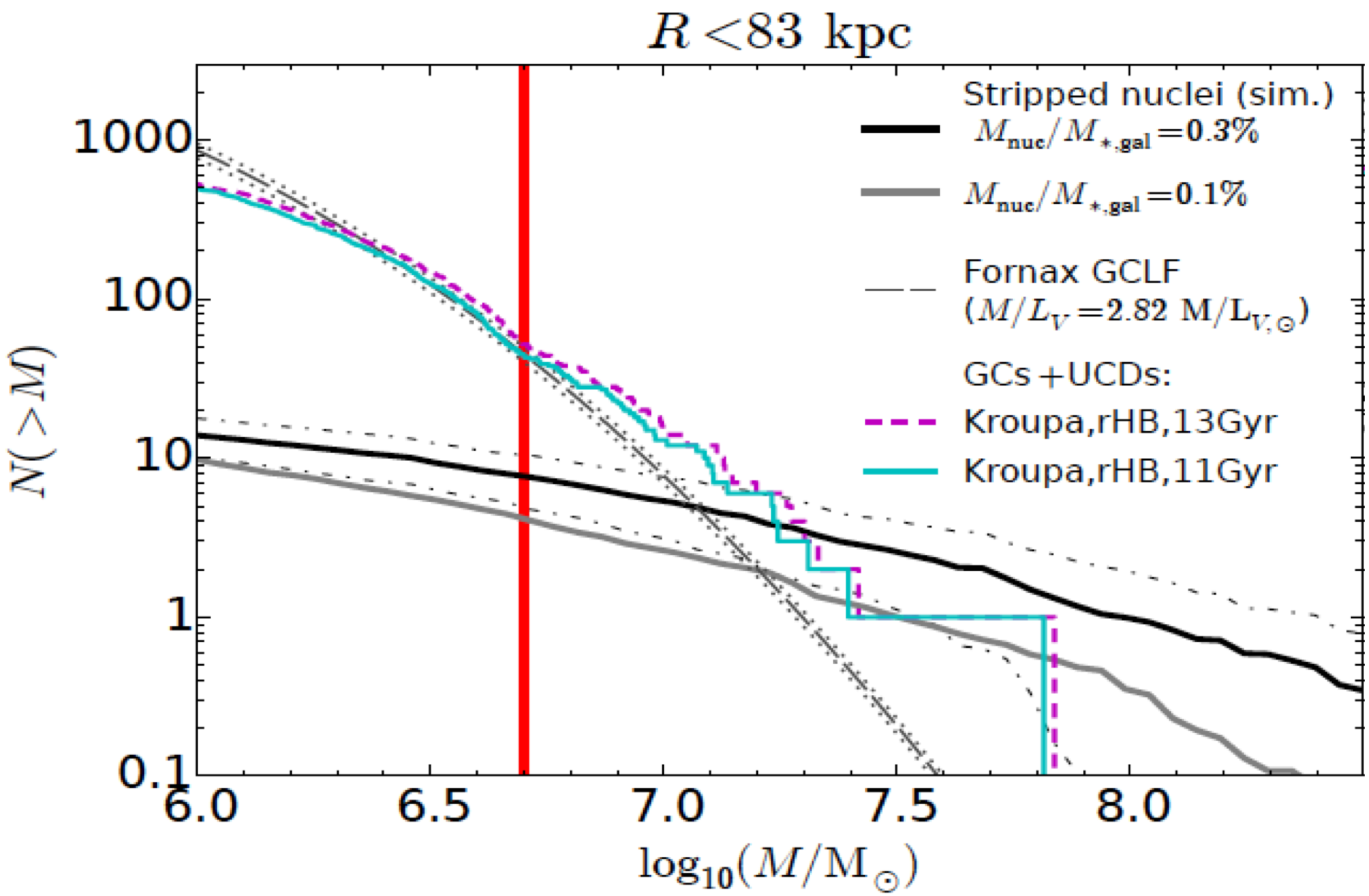

Voggel (PhD thesis) based on Pfeffer & Baumgardt (2013)

Pfeffer & Baumgardt 2013: disruption of nucleated galaxies with box orbits around host galaxy (to mimic complex cluster potential)

Pfeffer et al. 2014: stripping of nucleated galaxies in a cosmological context (Millenium 2 + Guo semi-analytical model)

Pfeffer et al. 2016: comparison of stripping simulations to observed UCDs in the Fornax and Virgo clusters

# Mass function of stripped nuclei and GCs/UCDs: observations vs. simulations

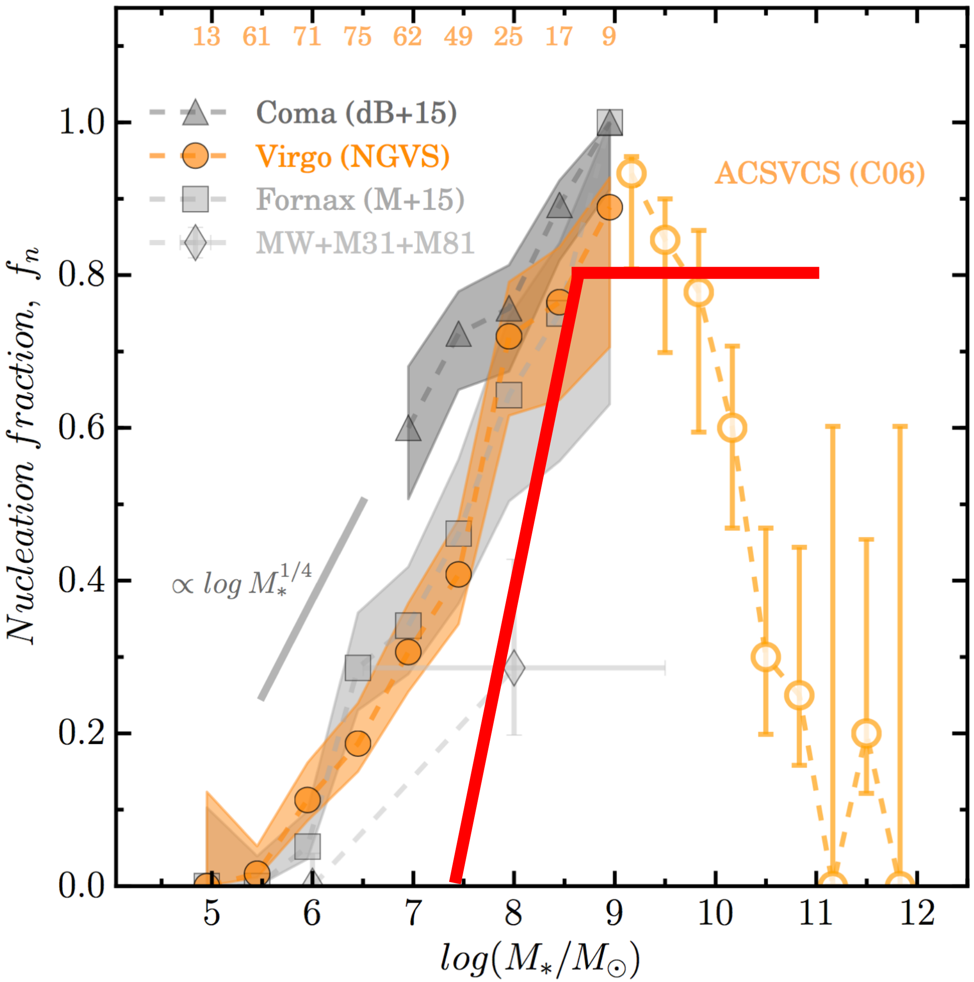


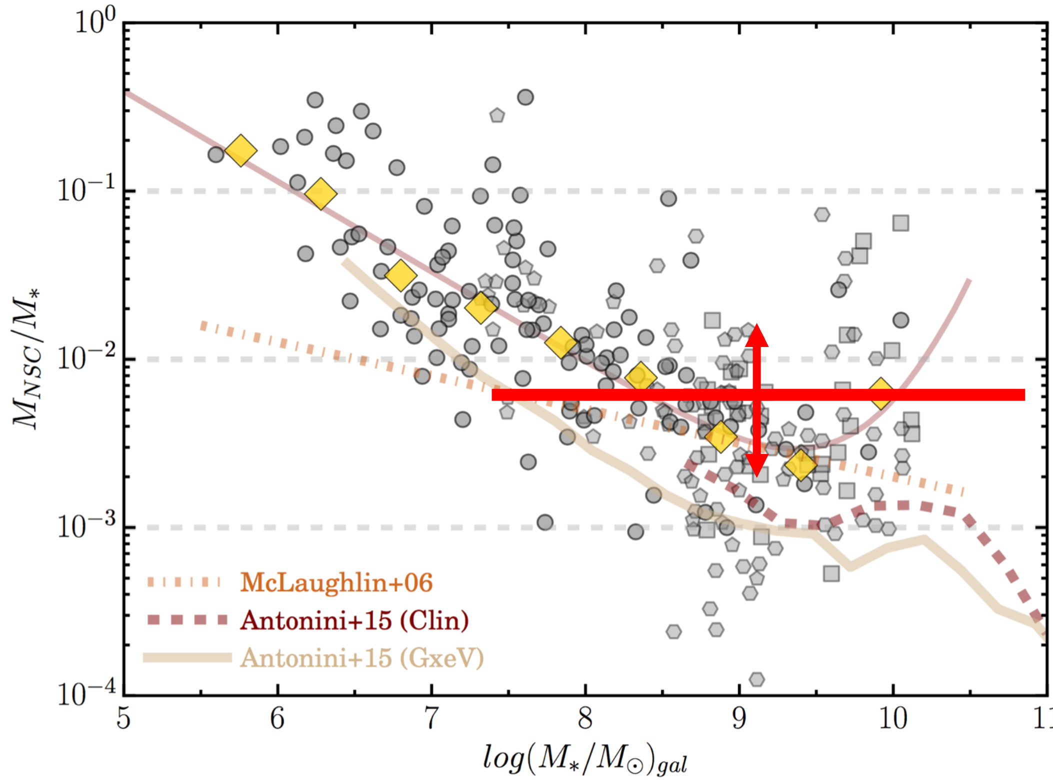

<20% of all UCDs in Fornax with masses larger than $2x10^6\ M_o$ and

~40% of those with masses larger than $10^7\ M_o$ are compatible with being stripped nuclei

Pfeffer, Hilker, Baumgardt & Griffen (2016)

# Observed nucleation fraction and nuclei mass fraction

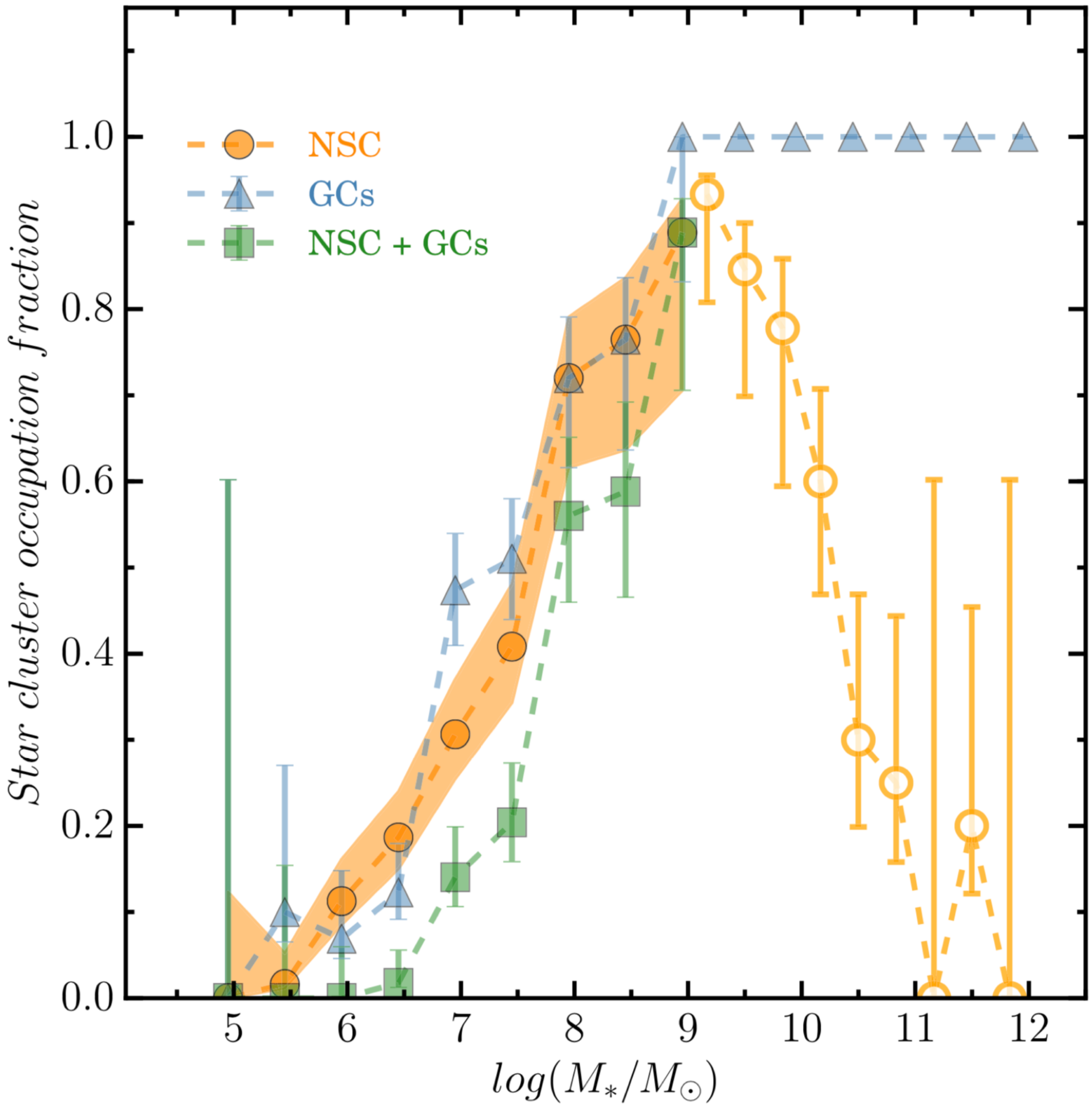



assumed nucleation fraction and NSC/galaxy mass ratio in Pfeffer et al. (2014, 2016)

Next Generation Virgo Survey (Sanchez-Janssen et al. 2019)

# Star cluster occupation fractions od Virgo galaxies

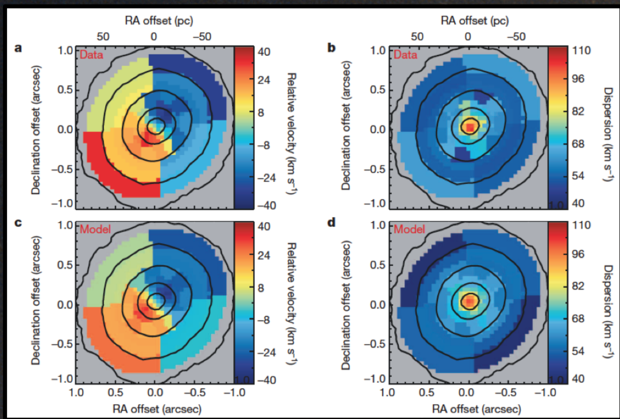


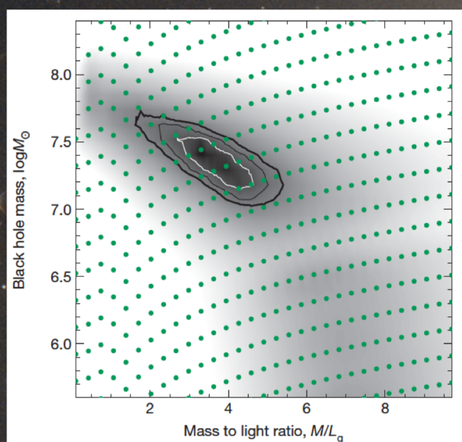

Sanchez-Janssen et al. (2019)

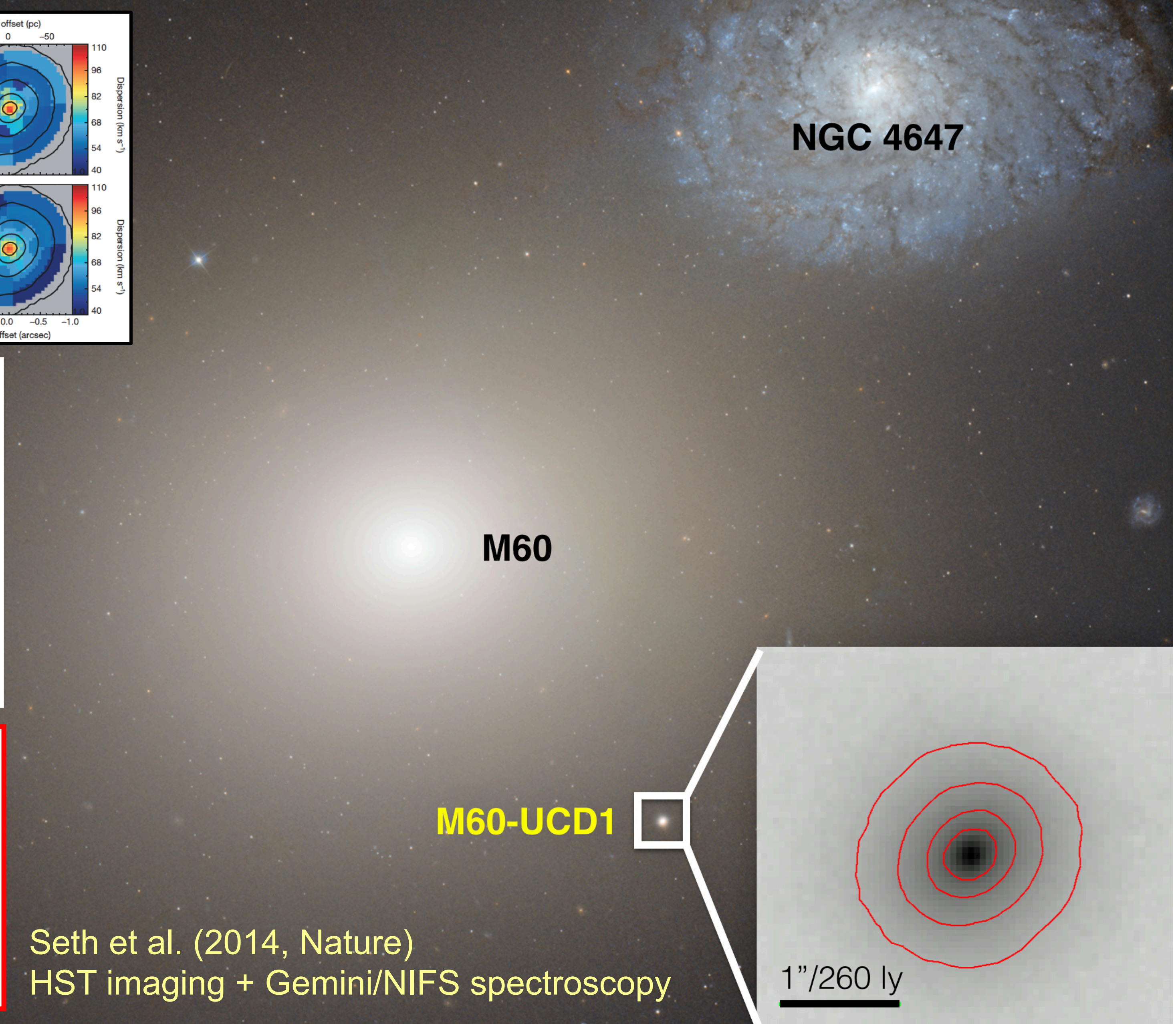
Close connection between NSCs and GC systems at low galaxy masses.

Fraction of galaxies that host both types, NSCs and GCs, is a bit lower.

# Super-massive black holes in UCDs




Best-fit model:

$M_{UCD}$ = 1.2x10$^8$ $M_☉$

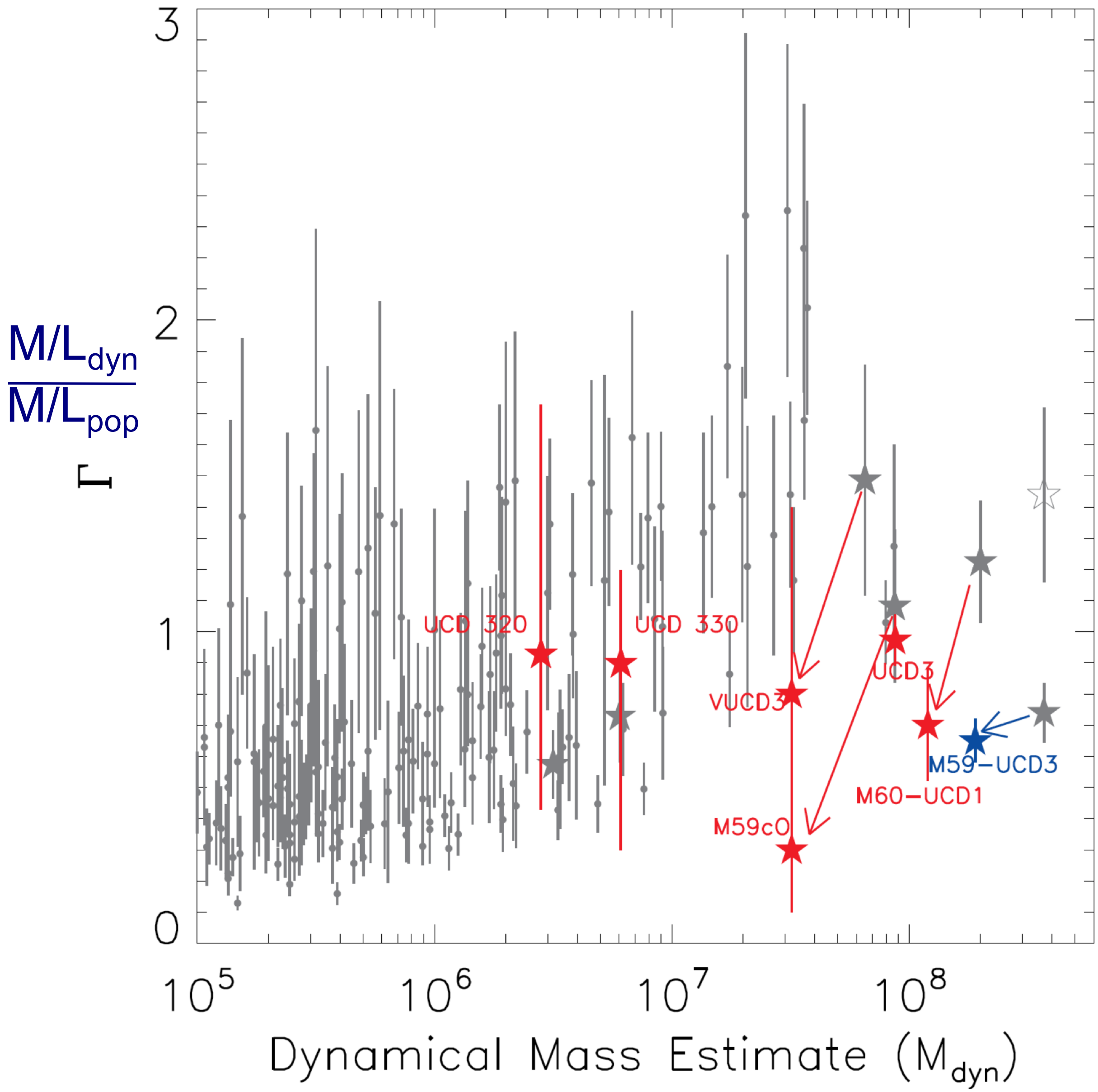
$M_{BH}$ = 2.1x10$^7$ $M_☉$

SMBH has 15% of UCD's total mass!

Seth et al. (2014, Nature)

HST imaging + Gemini/NIFS spectroscopy

# Super-massive black holes in UCDs

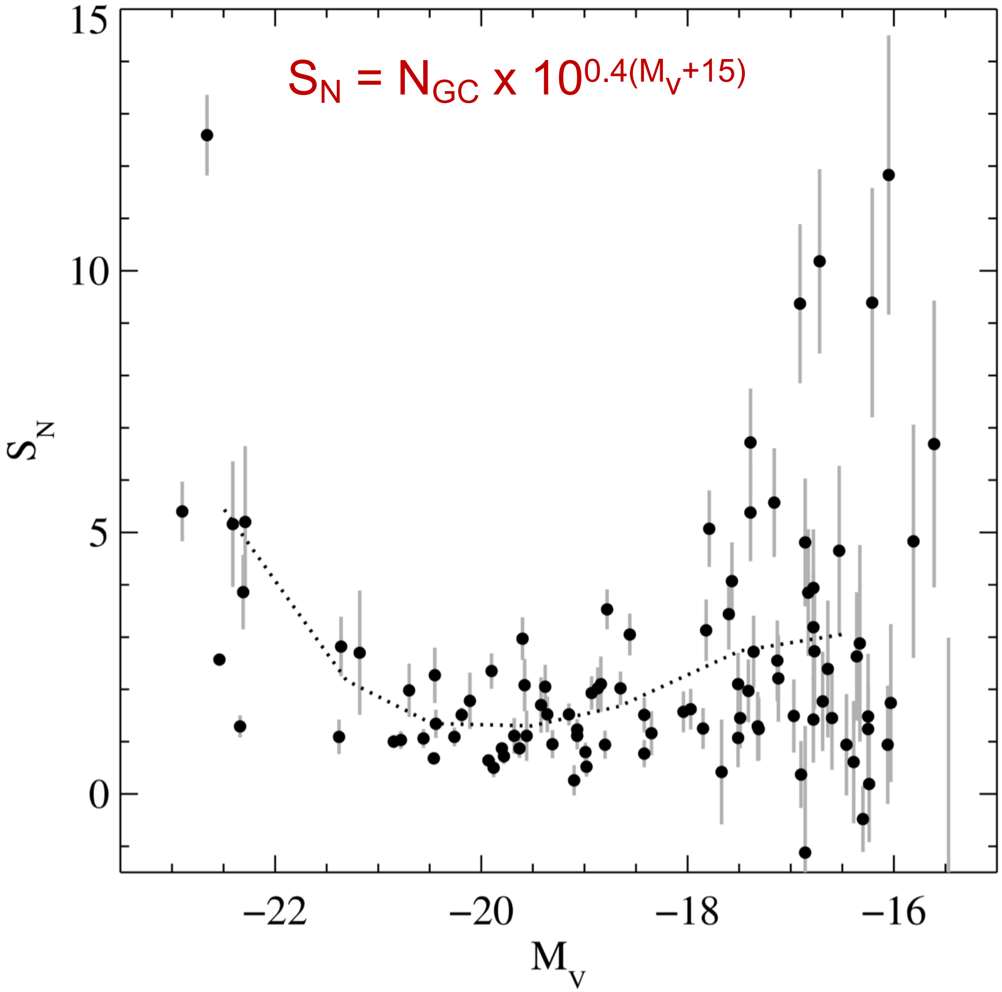


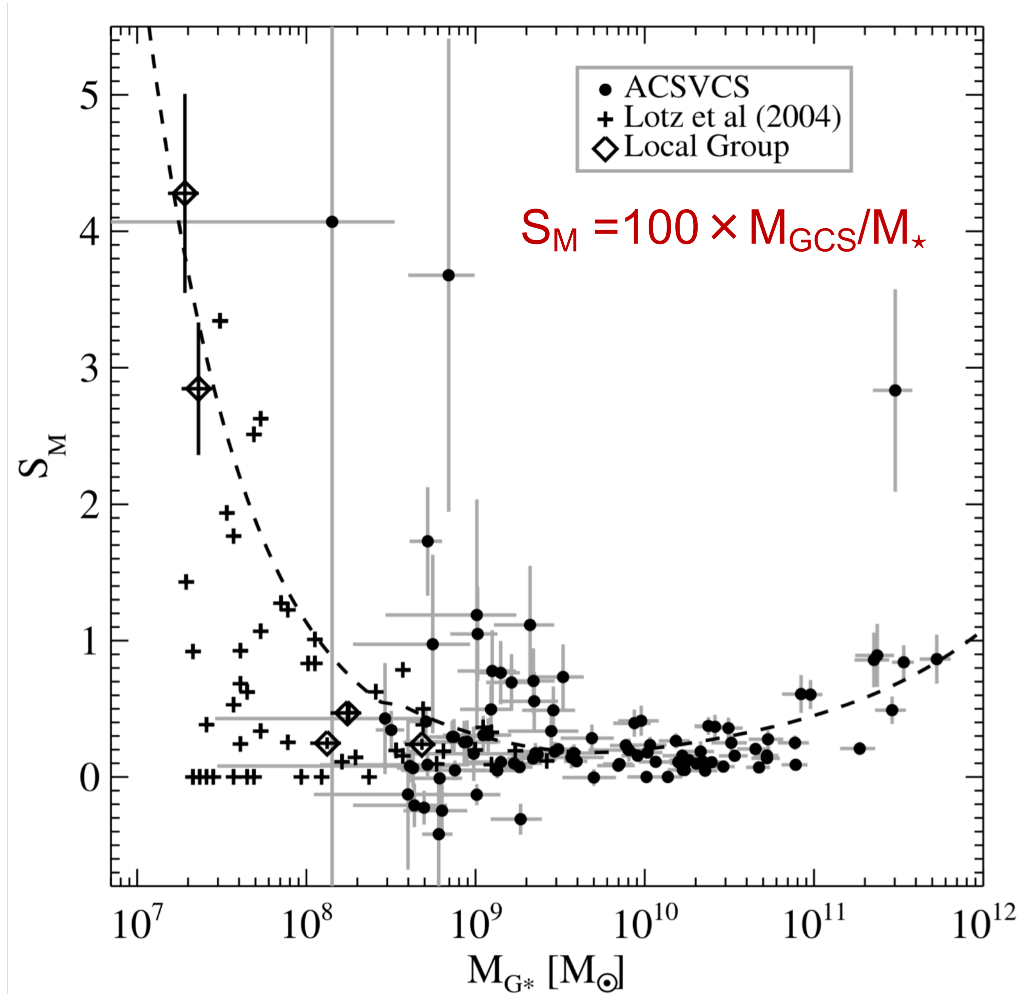

5 UCDs with $M>10^7$ $M_o$ in the Virgo and Fornax clusters have significant SMBHs (2-18% of UCD mass)

2 Cen A UCDs/GCs with $M<10^7$ $M_o$ are compatible with no BH

Seth et al. (2014)
Ahn et al. (2017)
Voggel et al. (2018) – Cen A
Ahn et al. (2018) – Virgo
Afanasiev et al. (2018) – Fornax

# Specific frequencies/mass of (mainly) early-type galaxies

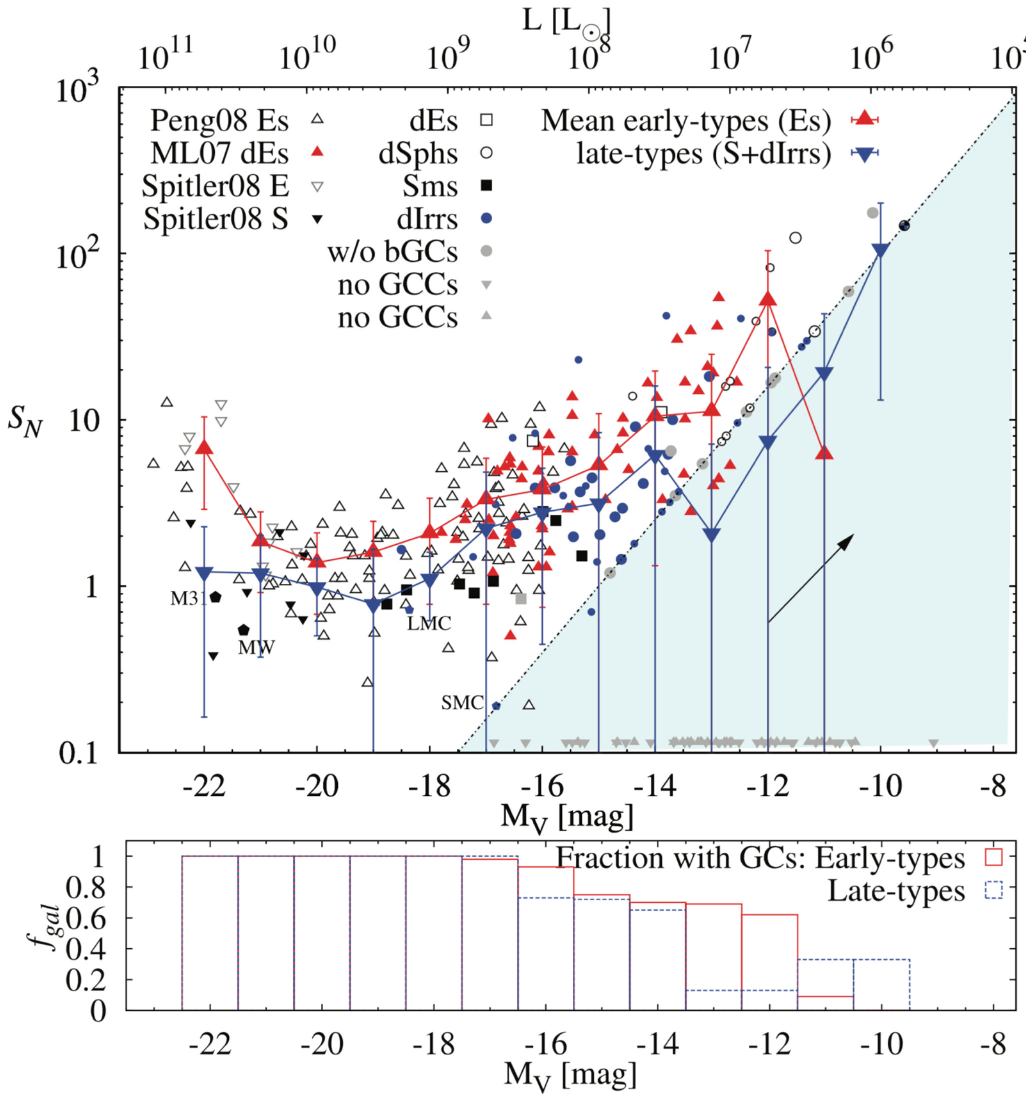


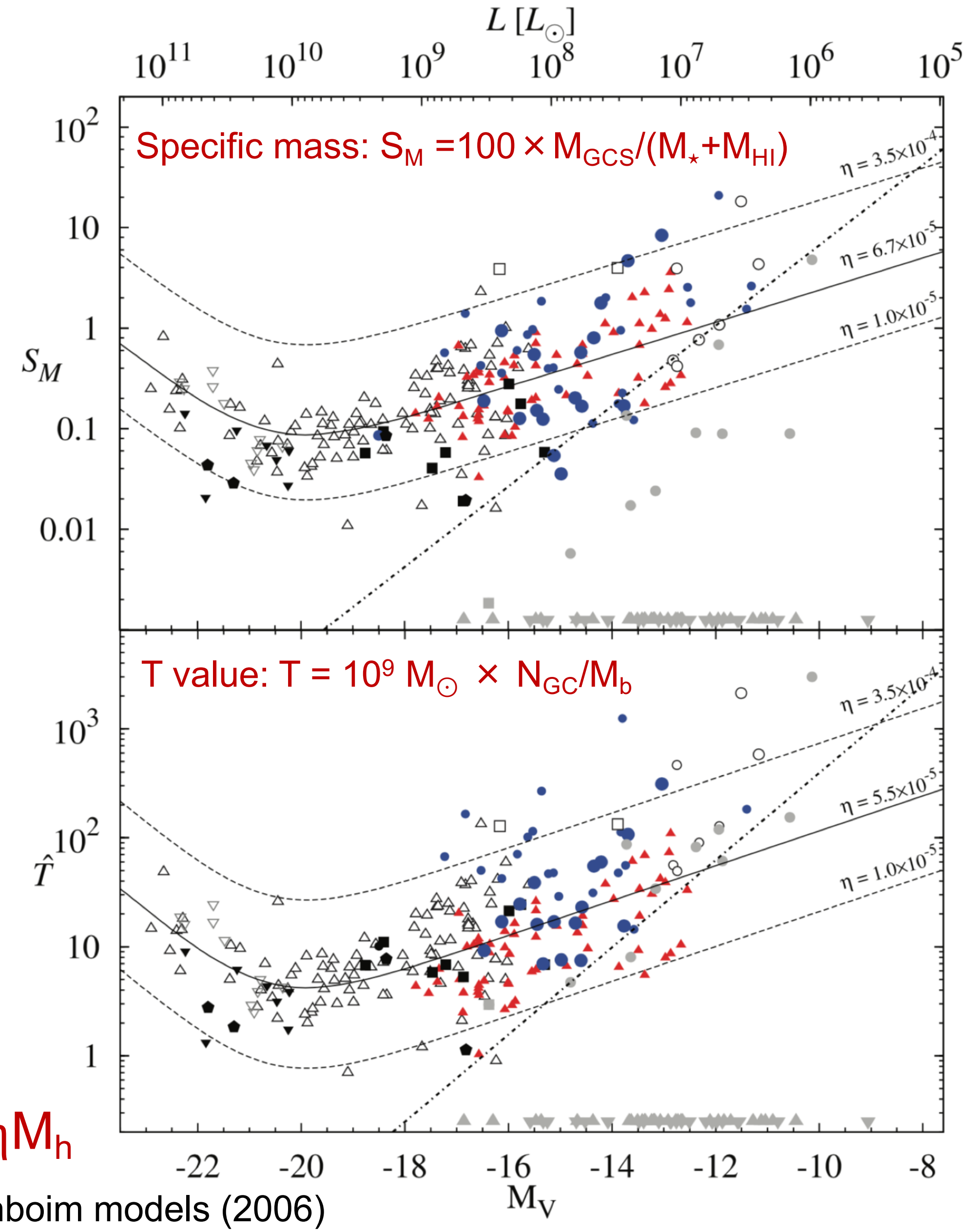

Luminosity

ACS Virgo Cluster Surveys: Peng et al. (2008)

# Specific frequencies/mass of early- and late-type galaxies



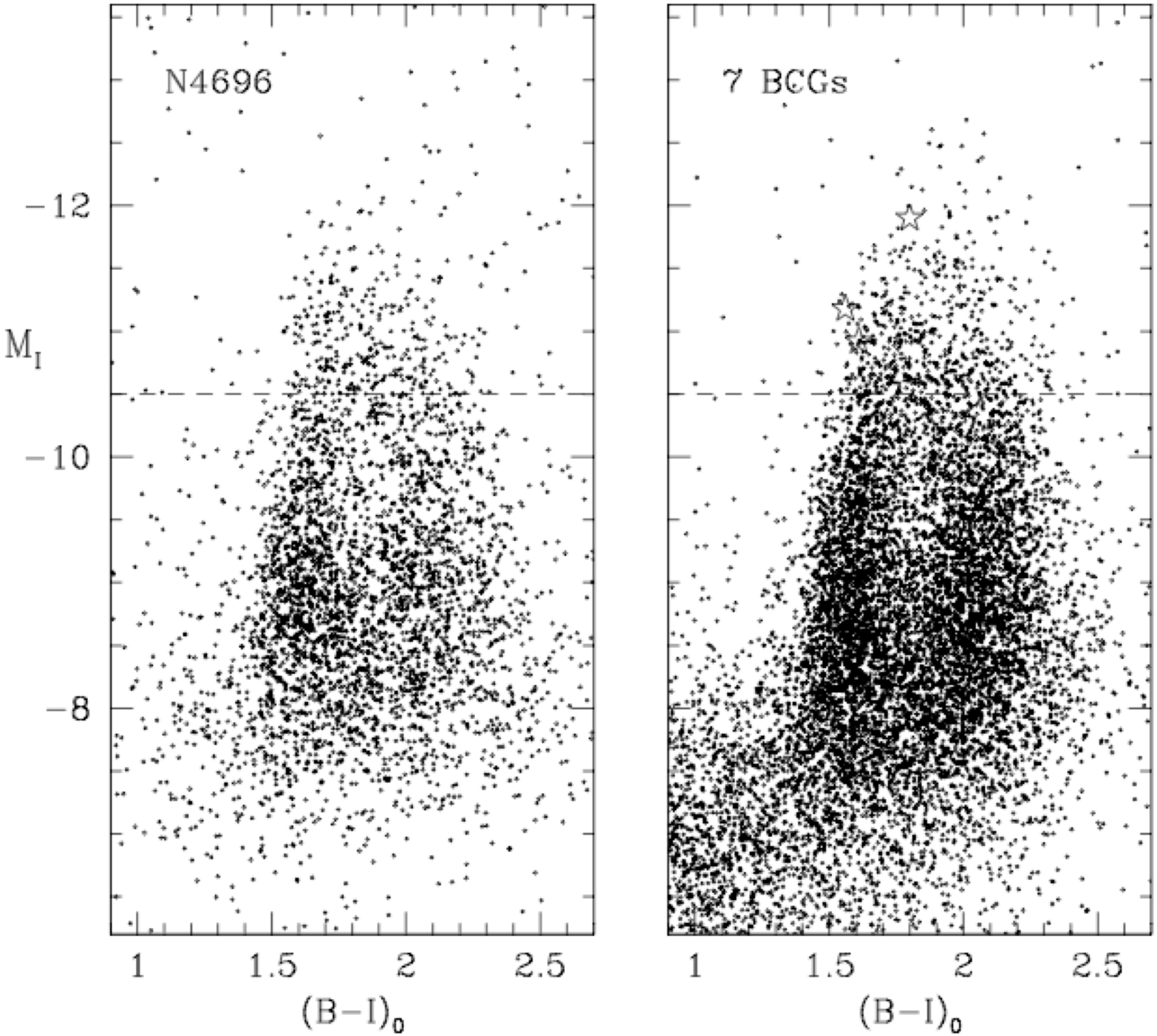

Georgiev et al. (2010)




$M_{GCS} \equiv \eta M_h$

Dekel & Birnboim models (2006)

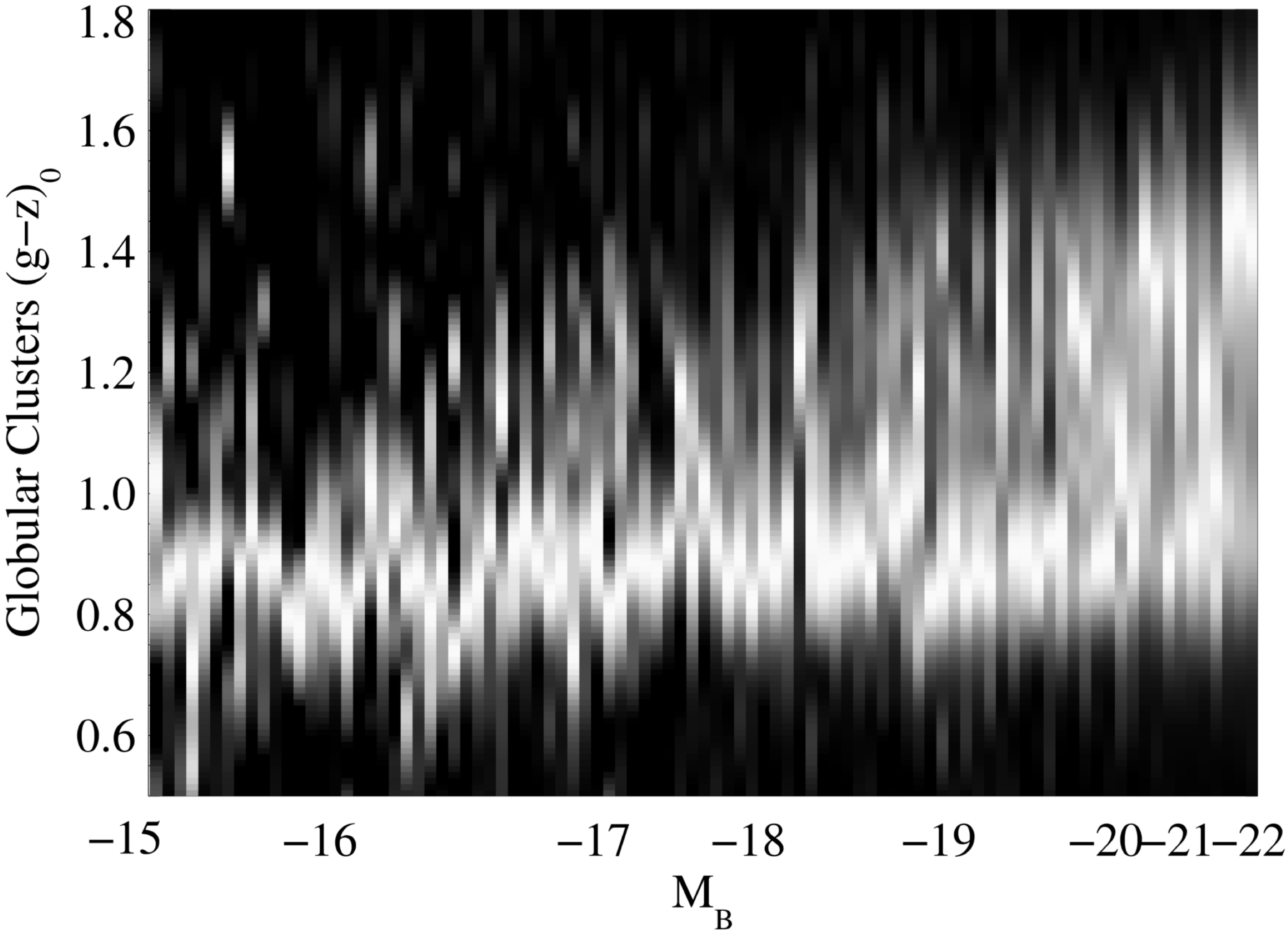
# Color distributions of GCs




Brightest cluster galaxies have bimodal color distribution for GCs less massive than ω Centauri ($M_V$>10.5 mag)

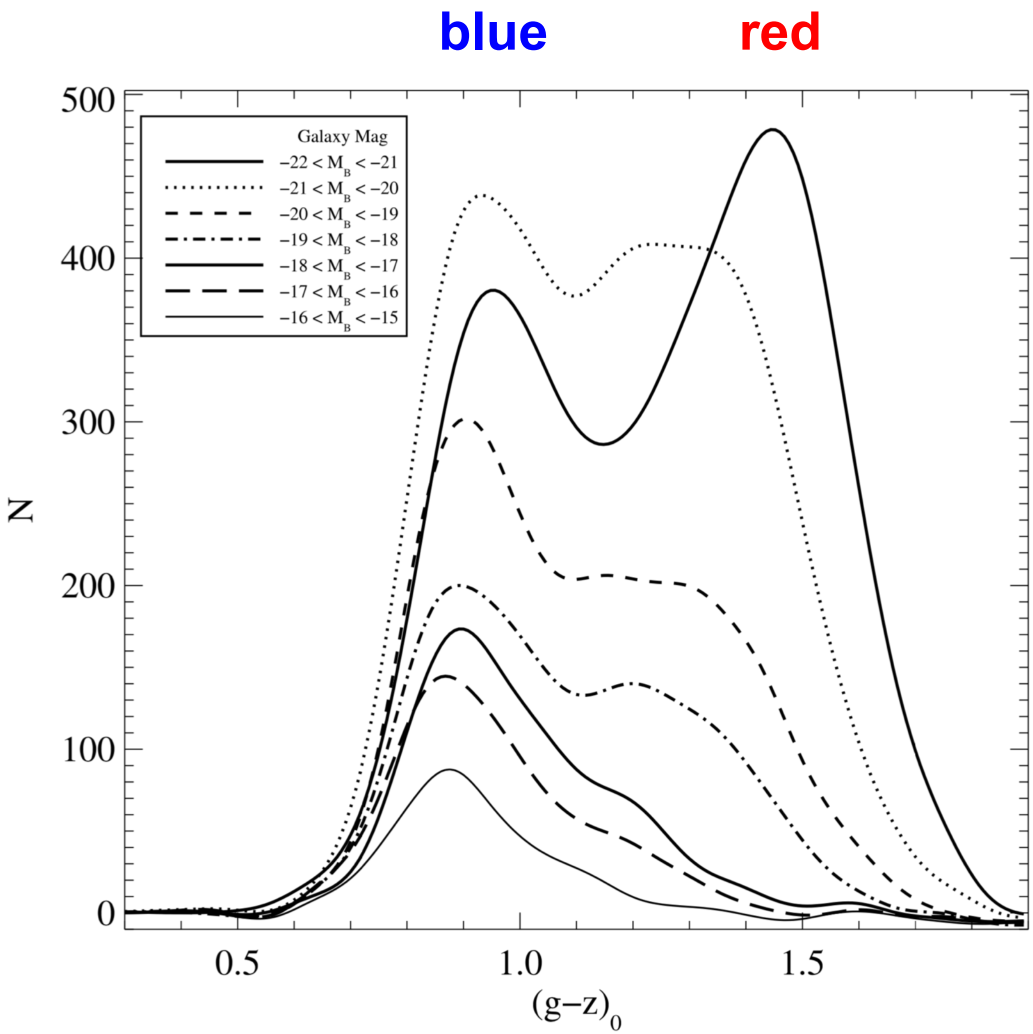
Harris et al. (2006)

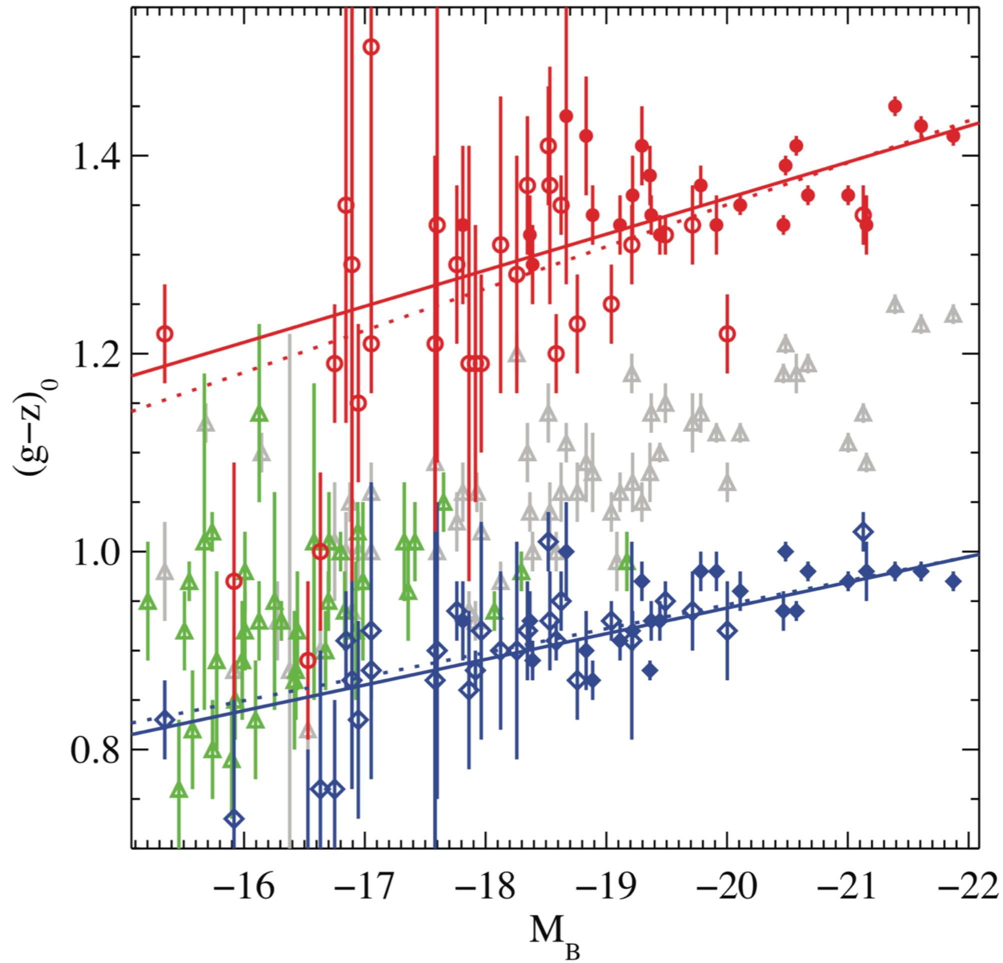
# ACS Virgo Cluster Survey: GC colors vs. galaxy's magnitude




Peng et al. (2006)

# ACS Virgo Cluster Survey: GC color bimodality vs. galaxy luminosity

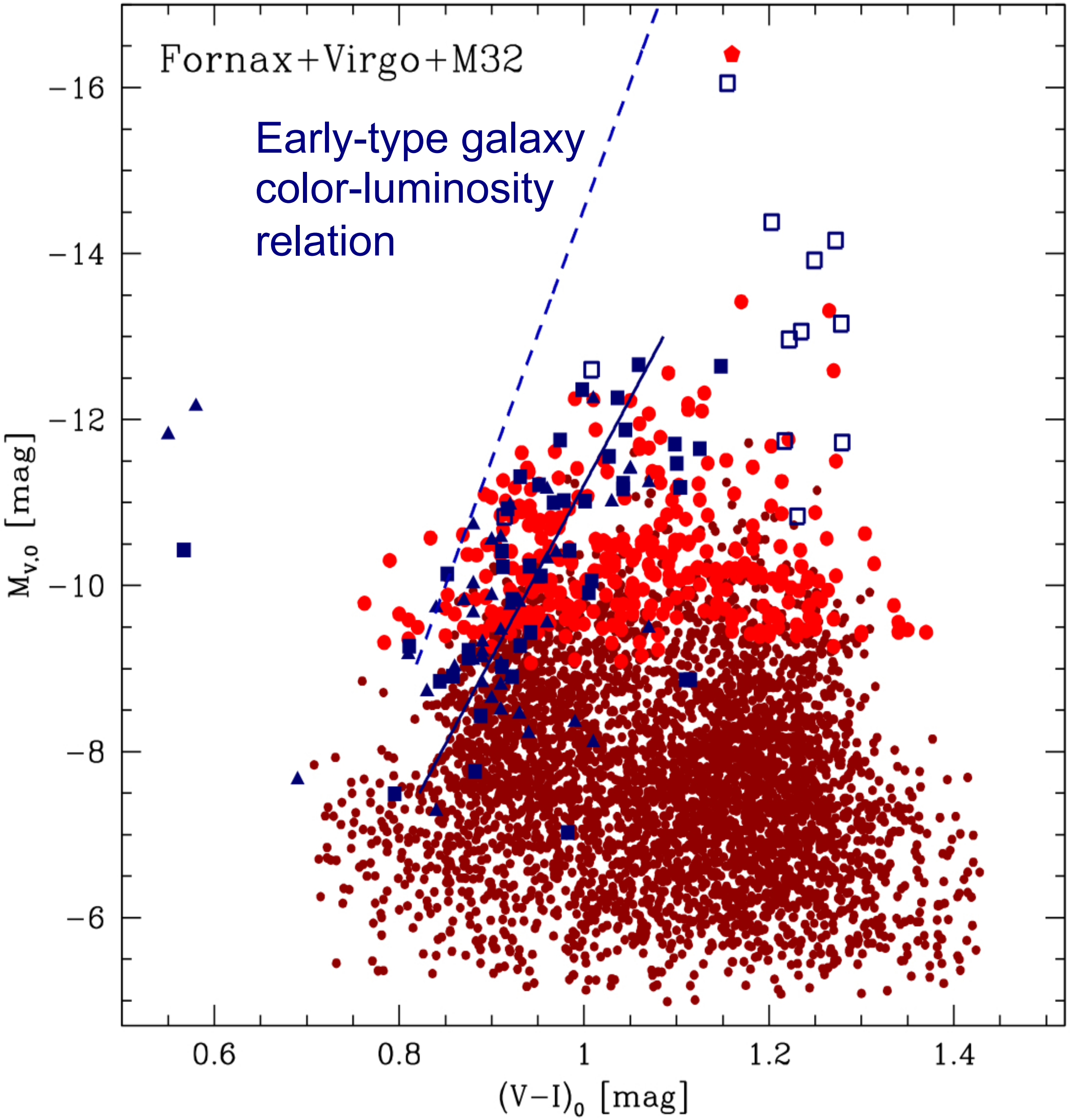



Colors of blue and red peaks depend on galaxy luminosity

Peng et al. (2006)

# CMD for massive GCs, UCDs, dE nuclei and NCs of spirals



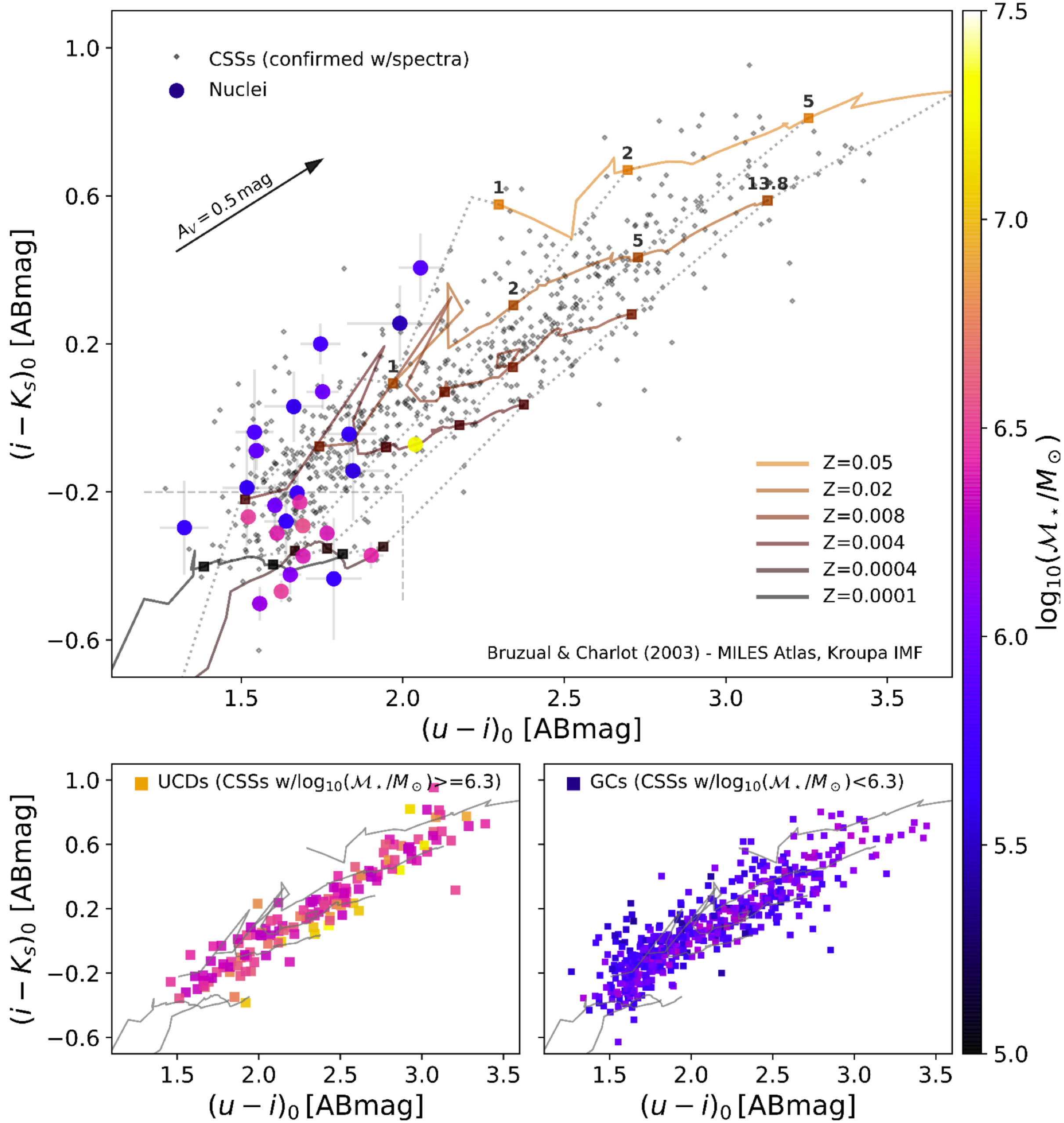

GCs of NGC 1399, NGC 1404 and M87 from the Fornax and Virgo ACS surveys (Jordan, Côté)

Radial velcocity confirmed UCDs and GCs in Fornax and Virgo (Hilker, Drinkwater, Mieske, Richtler, …)

Nuclear star clusters from Virgo ACS survey (Côté et al. 2006) and Lotz et al. (2004) sample

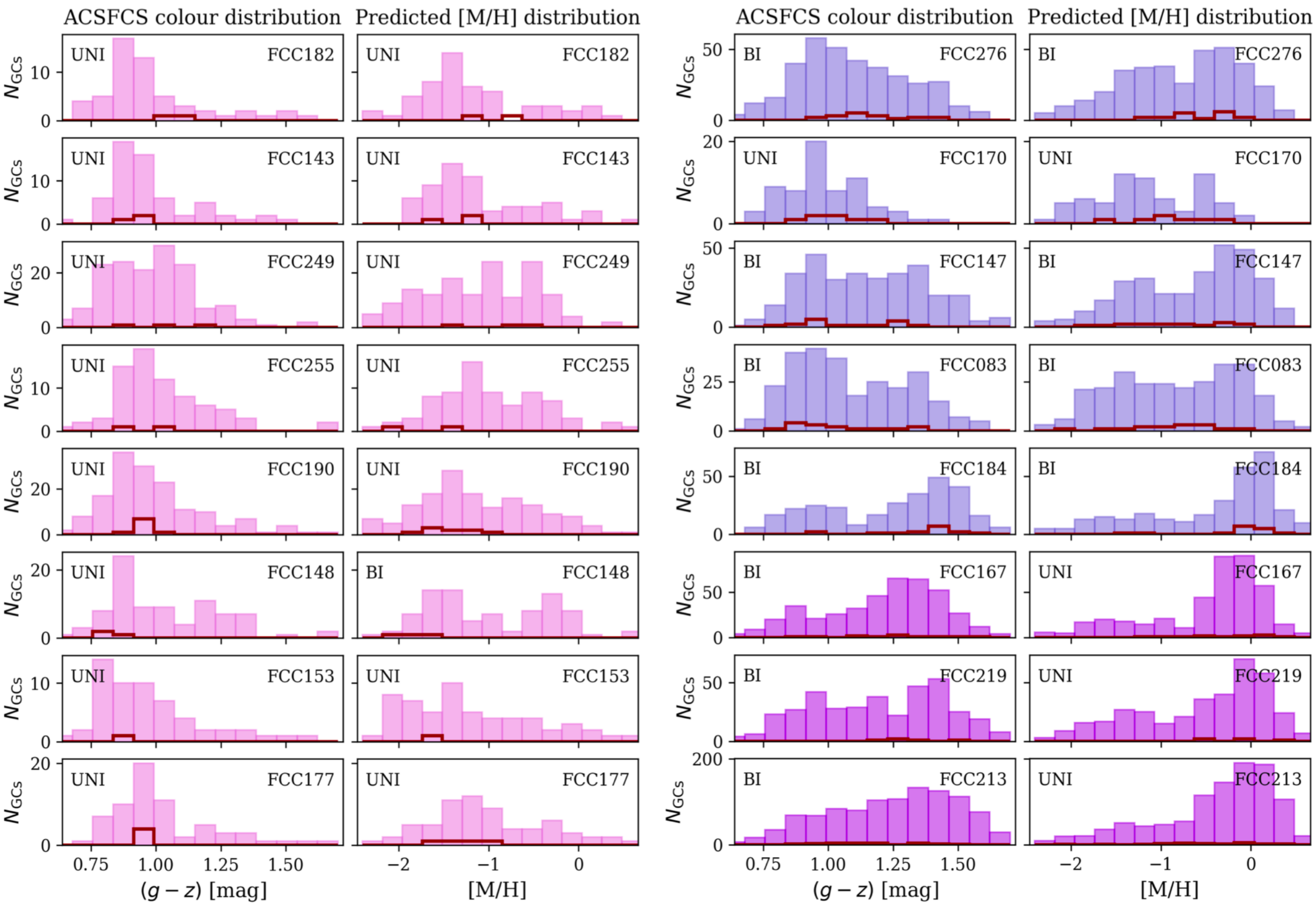
# NSCs, UCDs and GCs of the Fornax cluster in the 2-color diagram

→ uiKs plane is promising to disentangle age and metallicity distribution

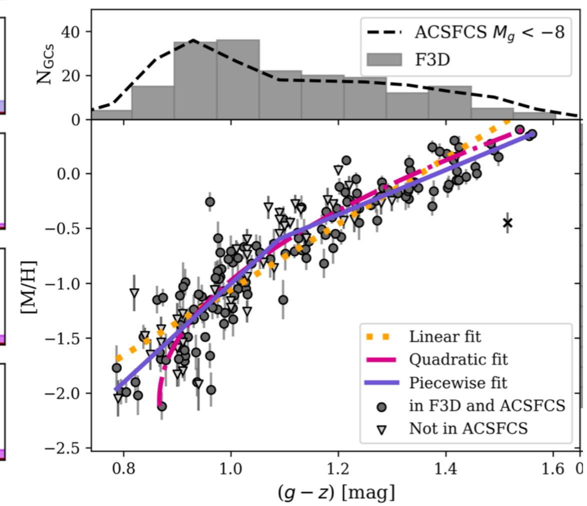



Next Generation Fornax Survey (NGFS): Ordenes-Briçeño et al. (2018)

# From color to metallicity distributions …



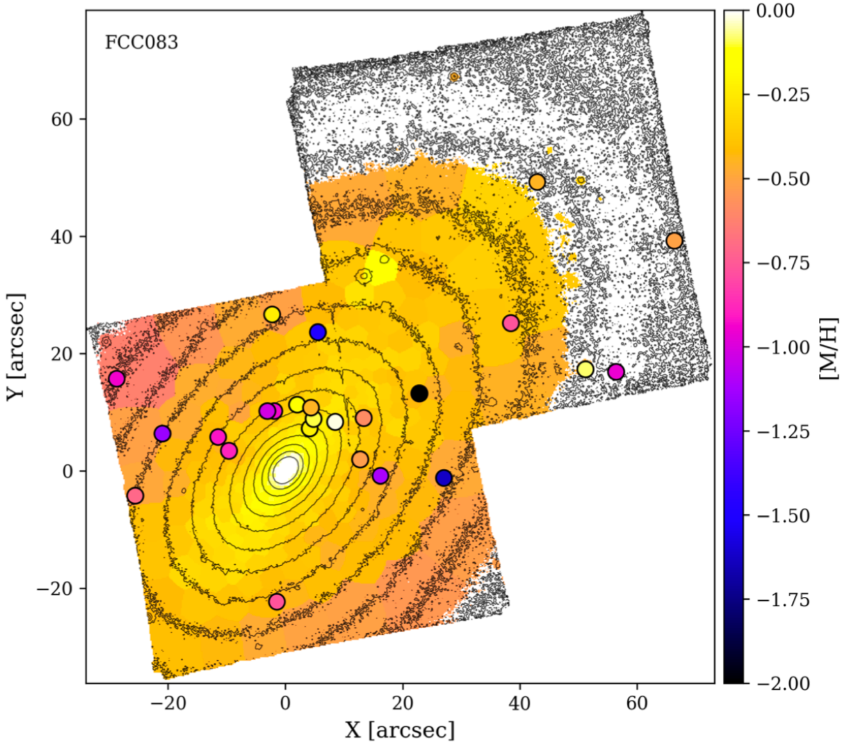

… based on a non-linear color-metallicity relation

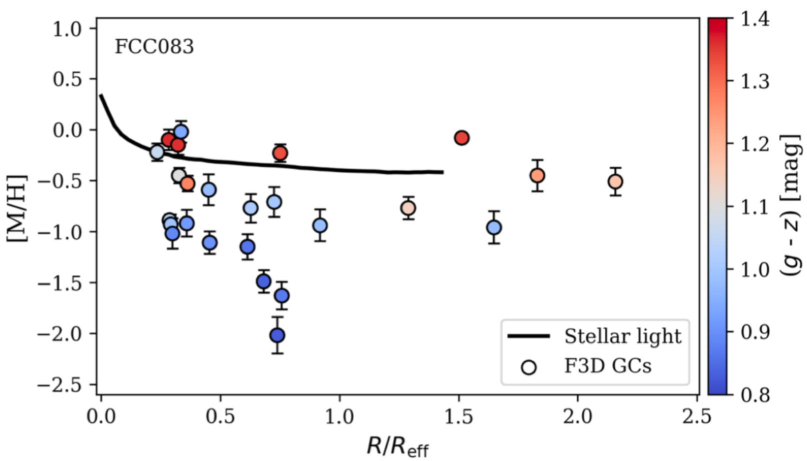



→ increasing galaxy mass

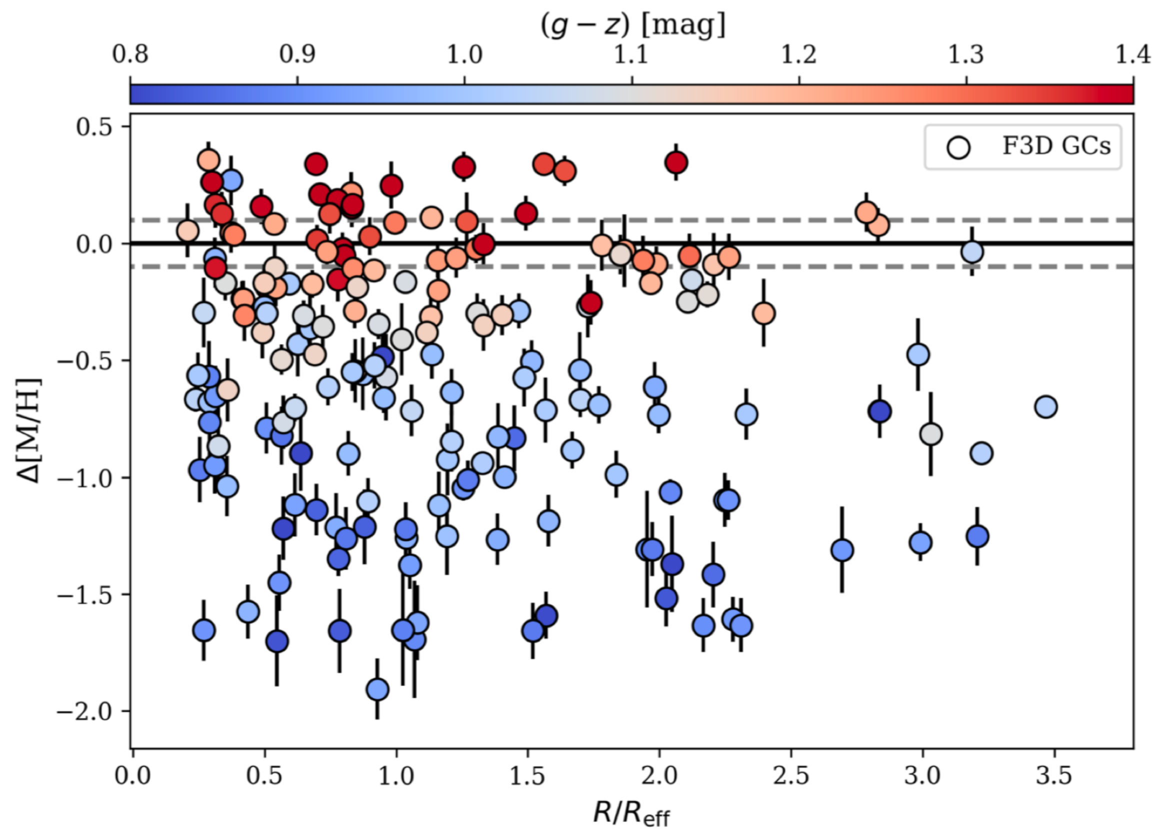
Fahrion et al. (2020) – F3D survey with MUSE

# Metallicity difference of GCs and their host galaxies



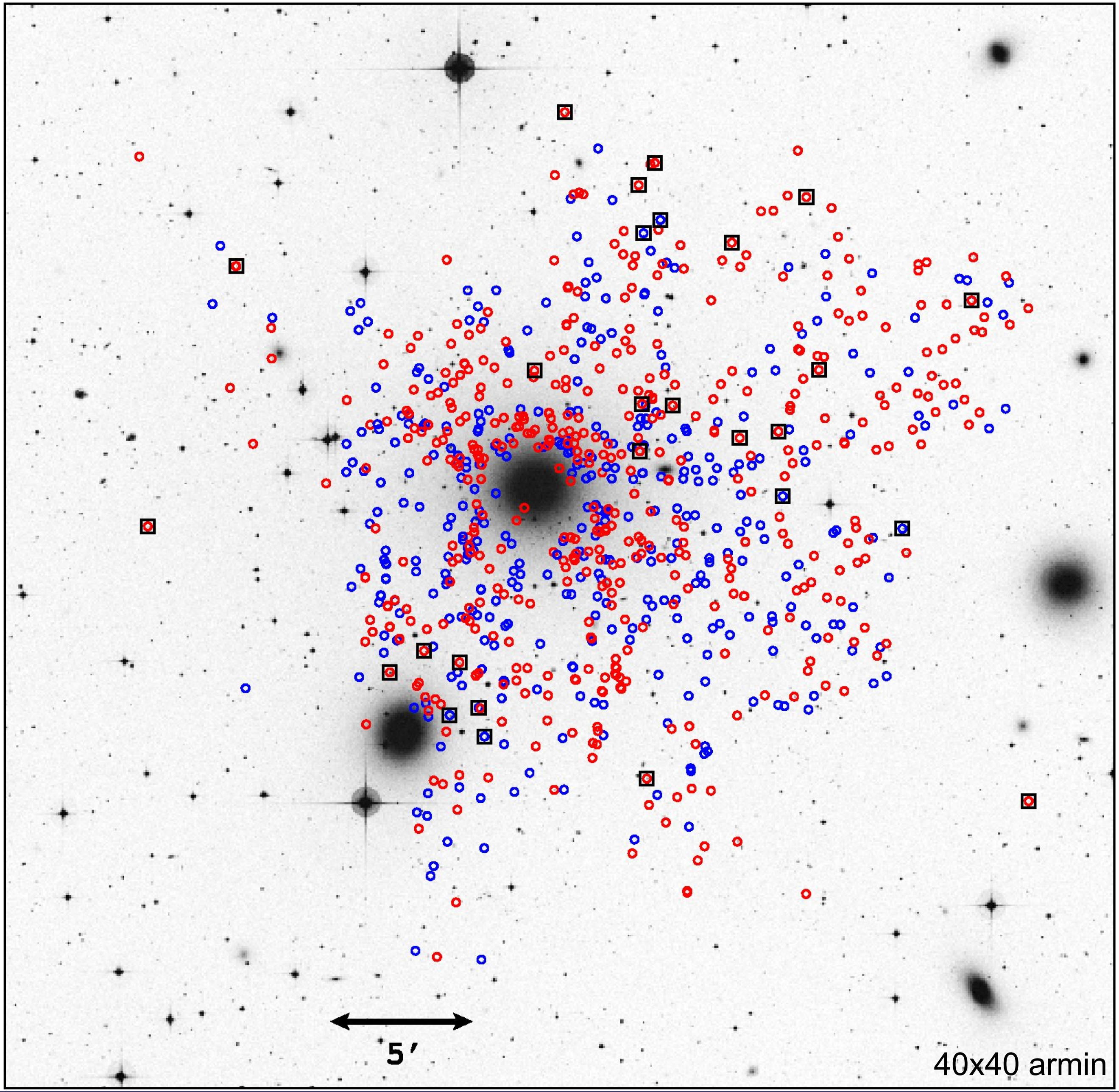

238 GCs in 26 galaxies




Red (metal-rich) GCs follow the metallicity trend of their host galaxy

Fahrion et al. (2020) – F3D survey with MUSE

# Spectroscopic survey of ~700 globulars around NGC 1399




□ bright compact objects: R<19.5 (~ $M_V$<-11.5)

$M_V$<-8.5

Schuberth et al. (2005, 2006)

Richtler et al. (2004, 2005)

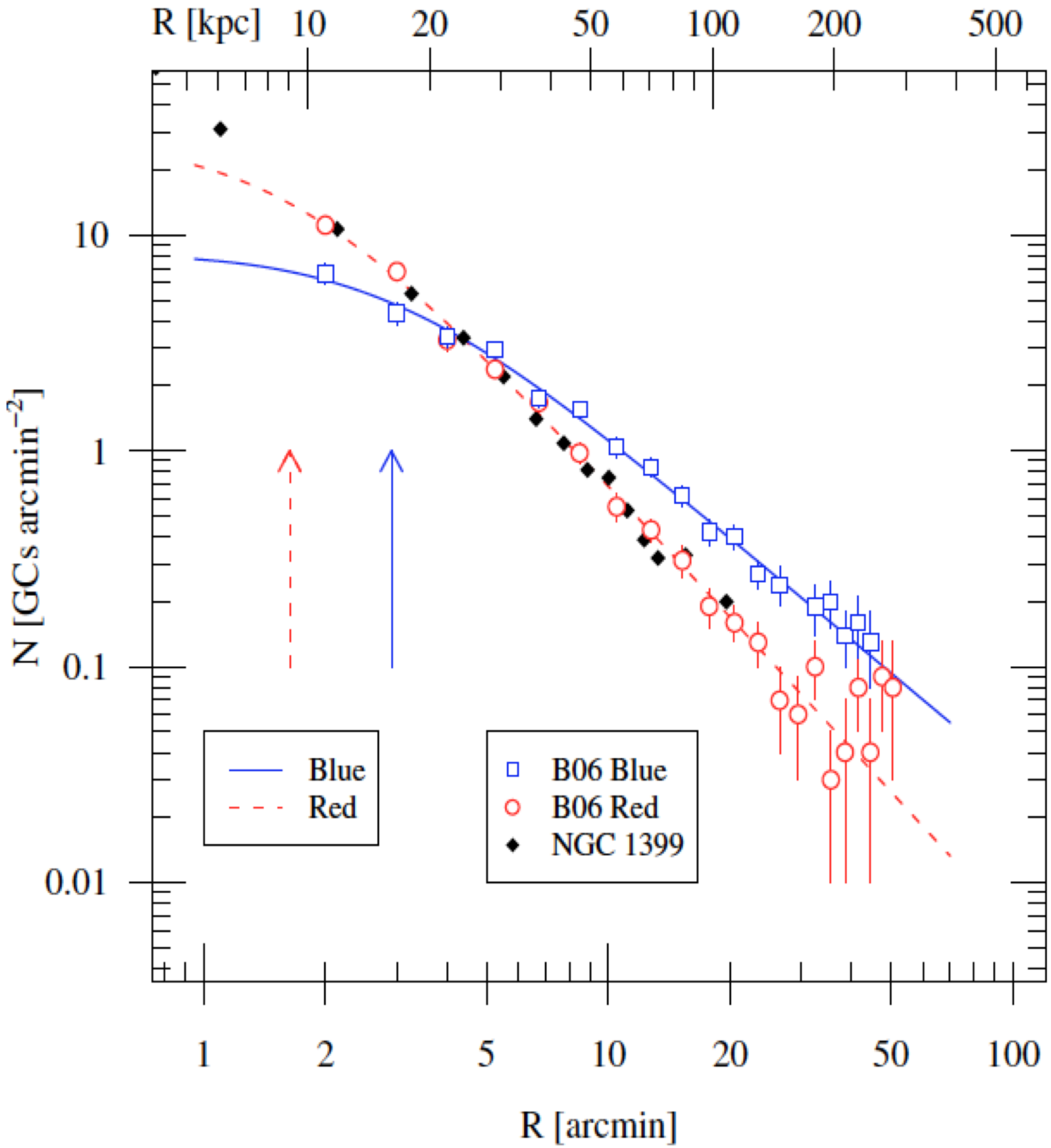
Dirsch et al. (2004)

Mieske et al. (2002, 2004)

Drinkwater et al. (2000, 2003)

Hilker et al. (1999)

# Number density profiles of red and blue GCs around NGC 1399 in the Fornax cluster

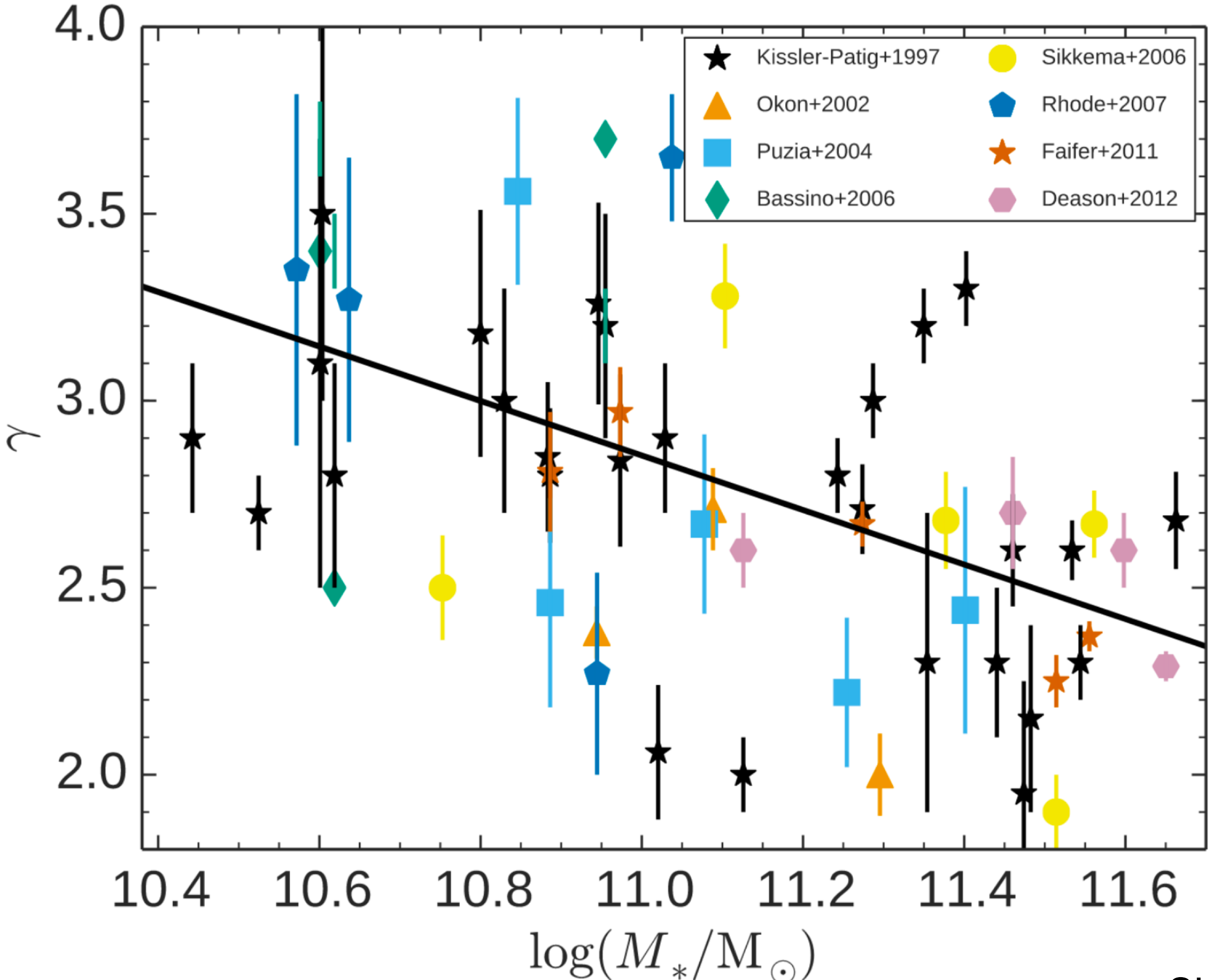



Red GCs do follow the properties of the spheroid stellar population.

Blue GCs dominate in the halo of NGC 1399.

Schuberth et al. (2010)

# Power-law slope of the deprojected GC density profile




2d projected profile:

$N(R) \sim R^{-(\gamma-1)}$

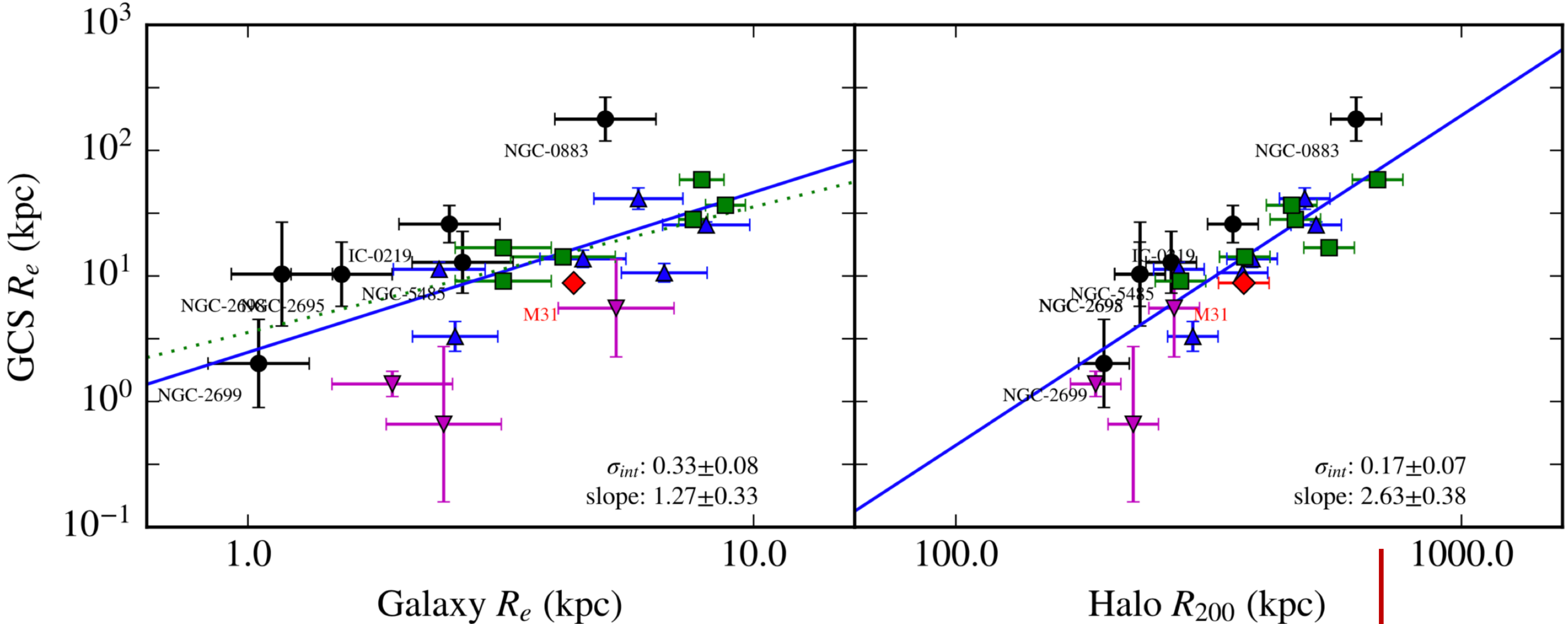
3D deprojected profile:

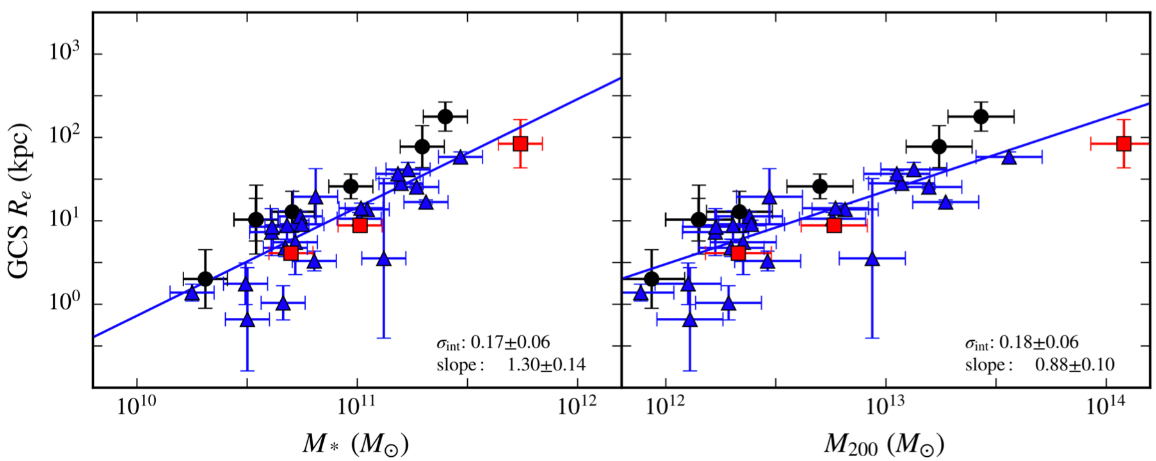
$n(r) \sim r^{-\gamma}$

More massive ETGs have shallower profiles than lower mass ETGs

SLUGGS: Alabi et al. (2016)

# GCS size - halo size relation

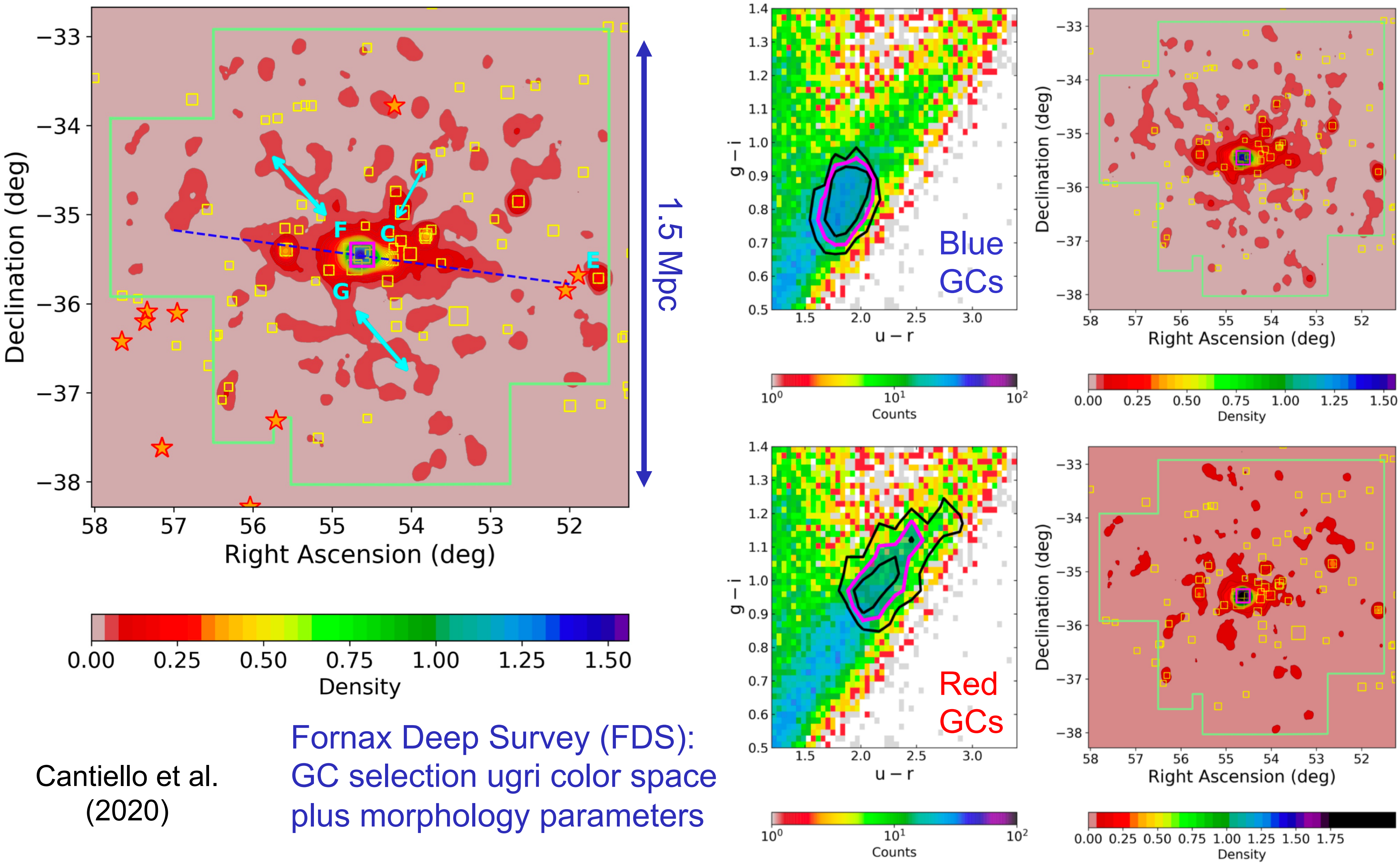



Hudson et al. (2018)

Hierarchical assembly of GCSs?!

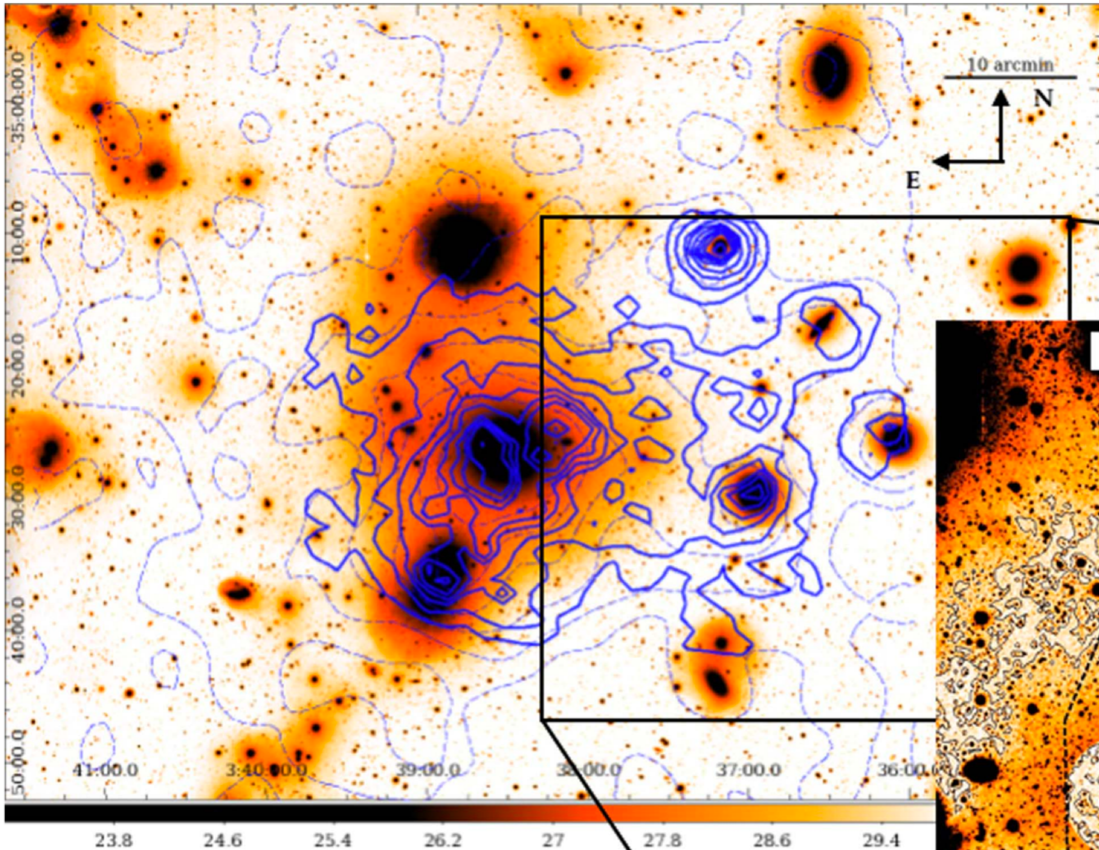
# Spatial distribution of GCs in the Fornax cluster

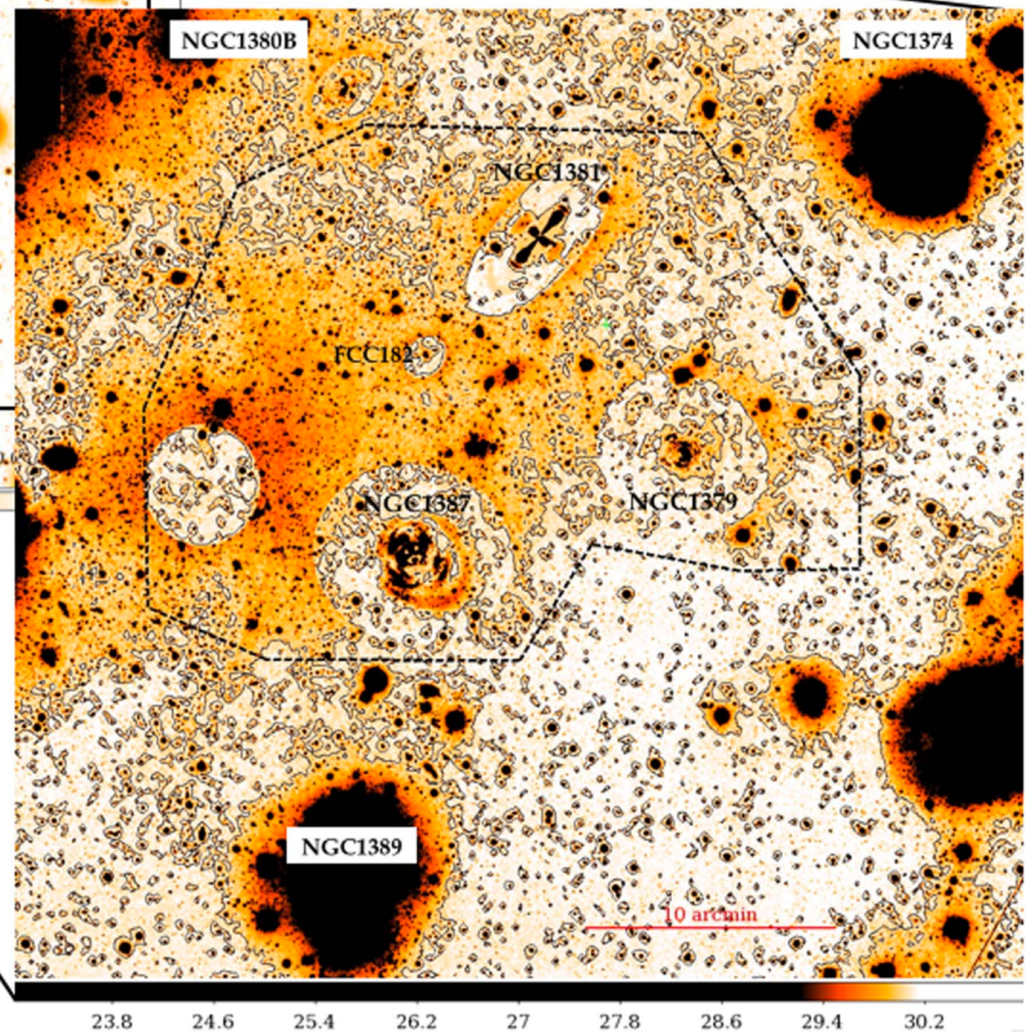



Cantiello et al. (2020)

Fornax Deep Survey (FDS): GC selection ugri color space plus morphology parameters

# GCs tracing intra-cluster light in the Fornax cluster



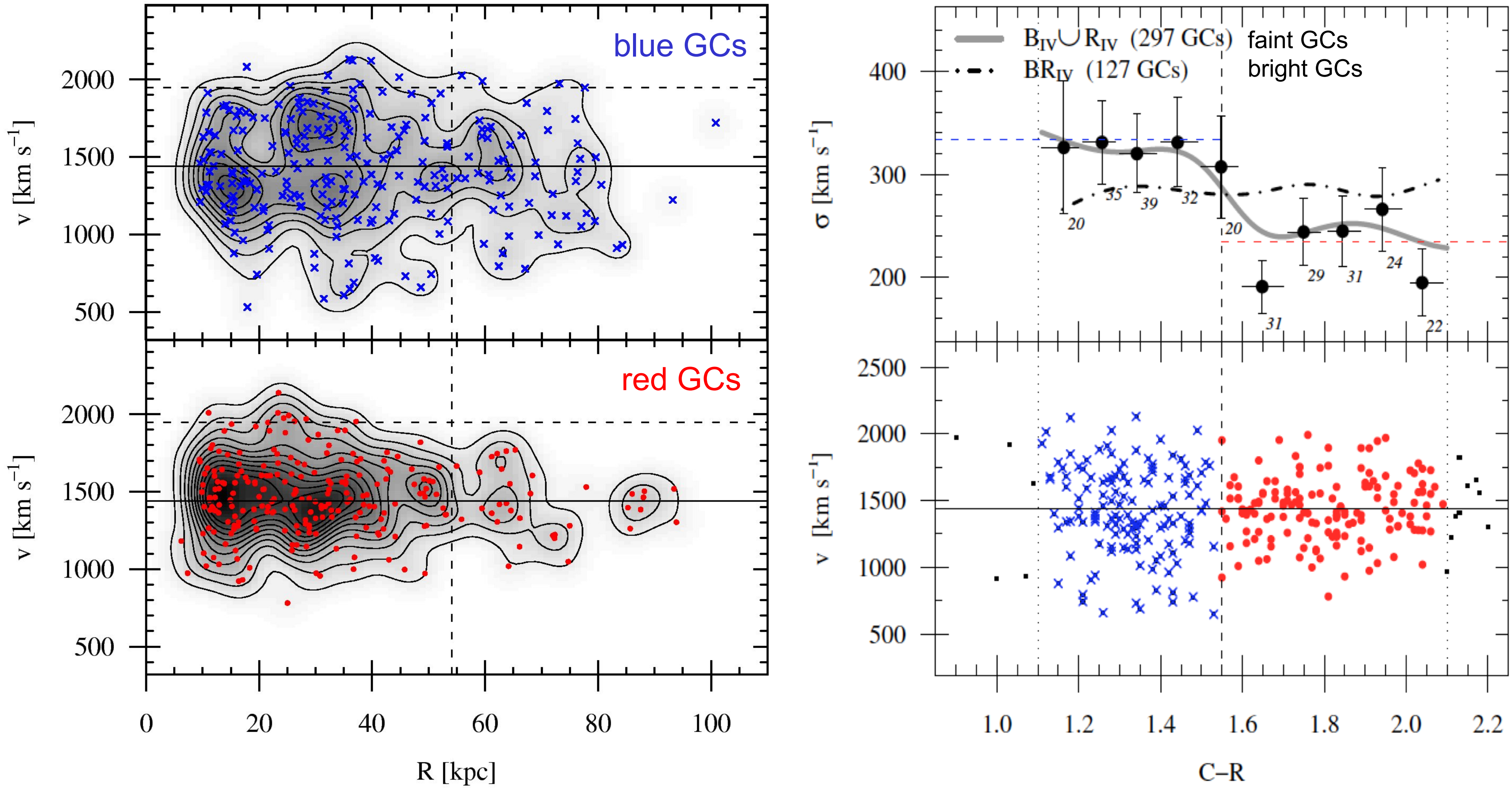




Contours: GC number density

→ There is hope to be able to connect intra-cluster GCs to ‚accreted light' of galaxies

Fornax Deep Survey (FDS):
Iodice et al. (2010)

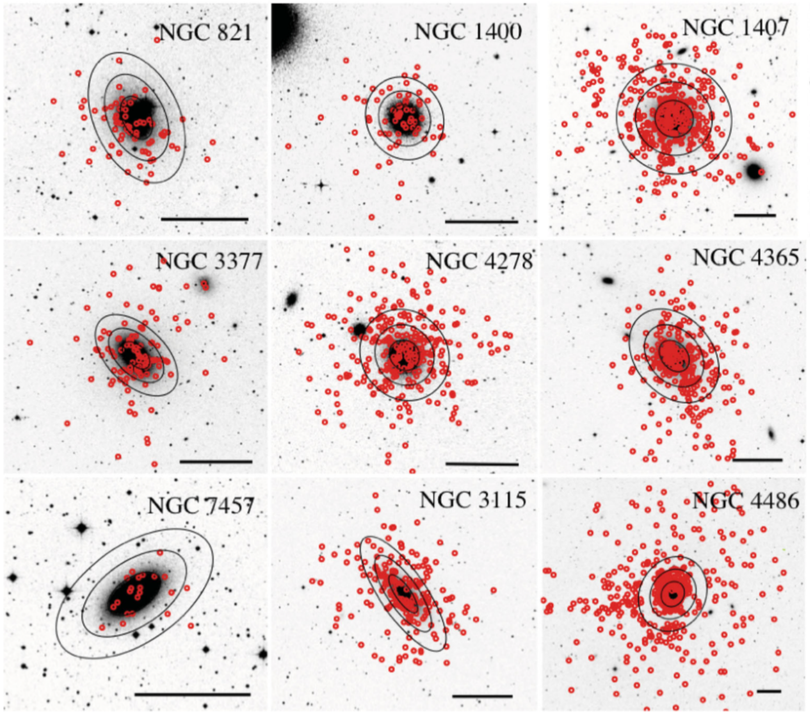
# Phase space, velocity and velocity dispersion vs. color

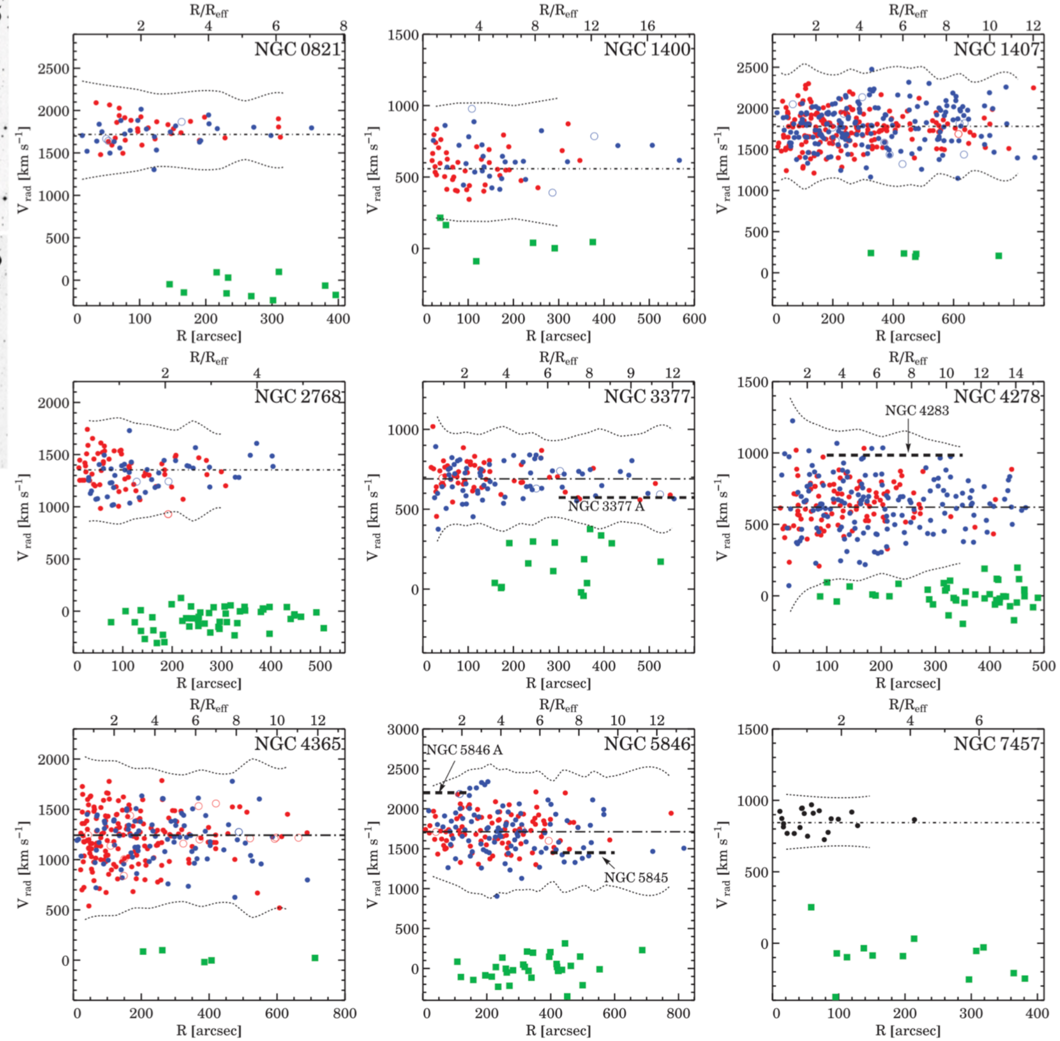



Blue and red GCs trace the same potential: Jeans analysis reveals that the orbits of red GCs are consistent with isotropy (maybe slightly radial), while those of blue GCs show a tangetial bias.

Schuberth et al. (2010)

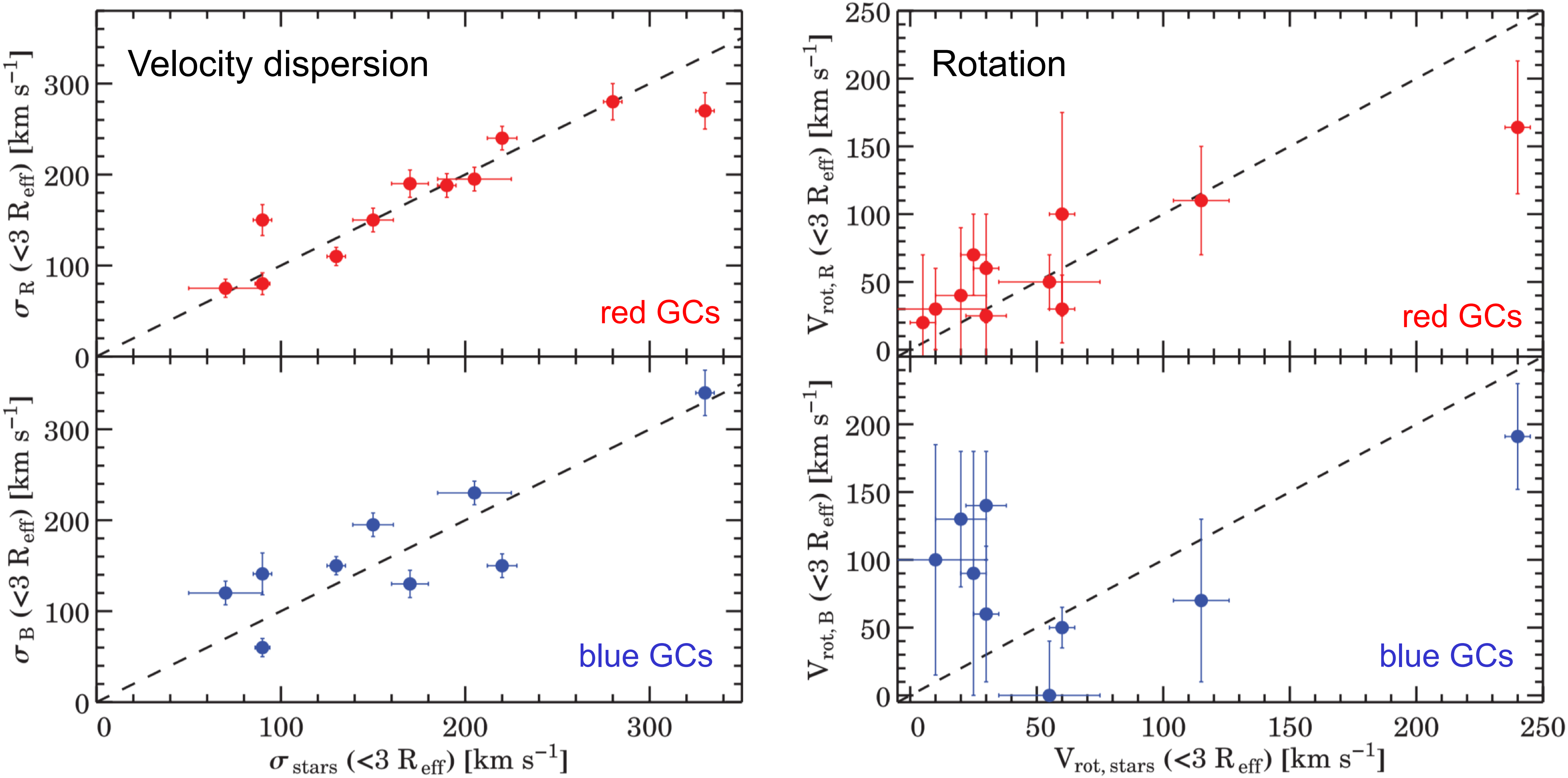
# SLUGGS: kinematics of ~2500 GCs around 12 early-type galaxies




SLUGGS: Pota et al. (2013)

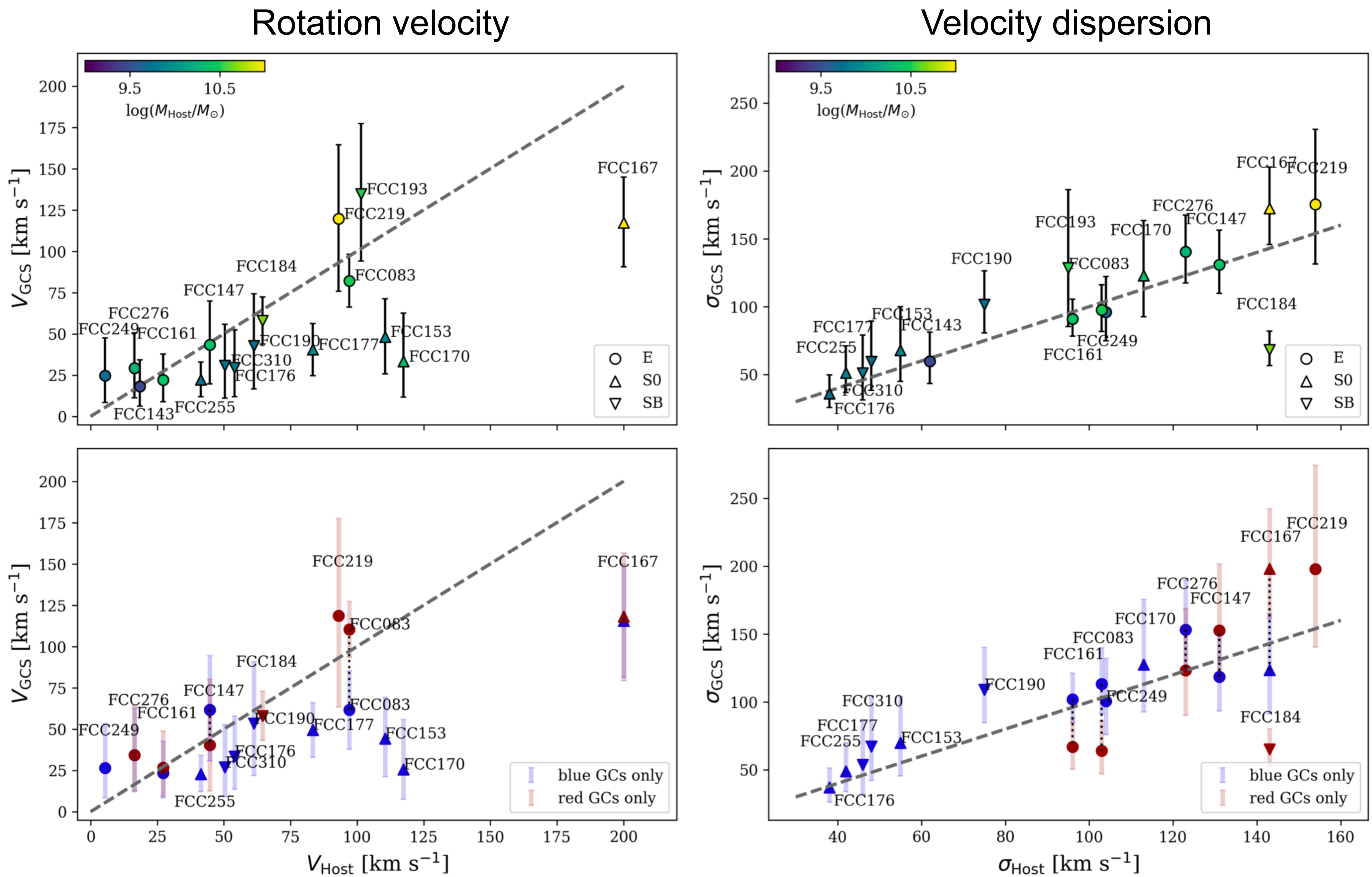
# SLUGGS: GCS kinematic properties vs. galaxy kinematics




Pota et al. (2013)

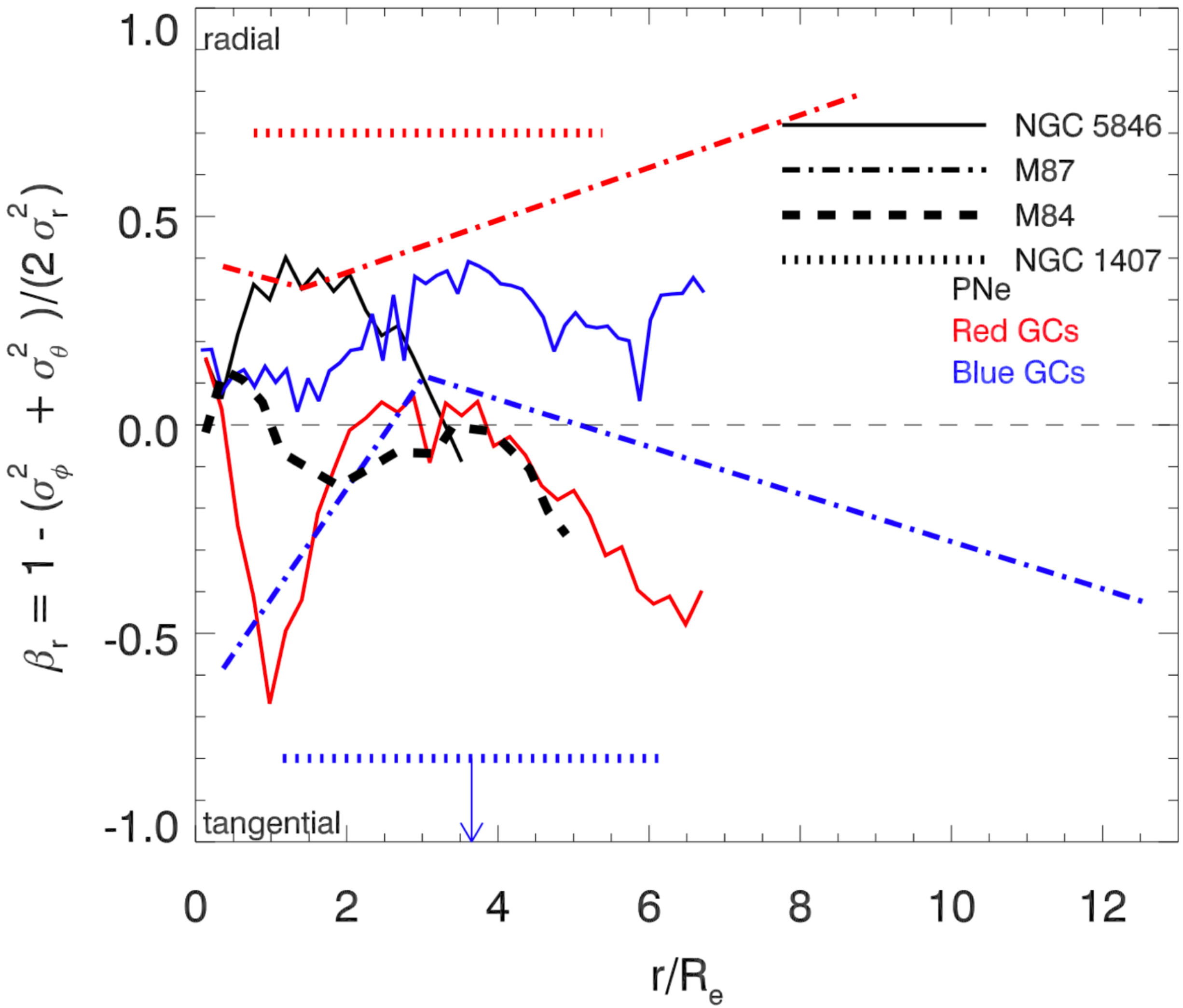
# Inner (<3 $R_{eff}$) kinematics of GCSs and their host galaxies in Fornax

Red and blue GCSs



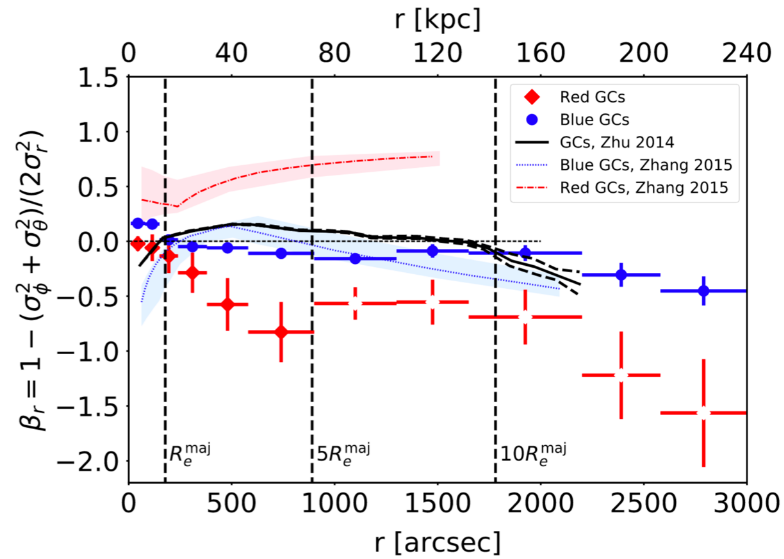

Fahrion et al. (2020) – based on MUSE observations of the F3D survey

# Orbital anisotropies of blue and red GCs: β-profiles




Zhu et al. (2016)

## New results for M87:

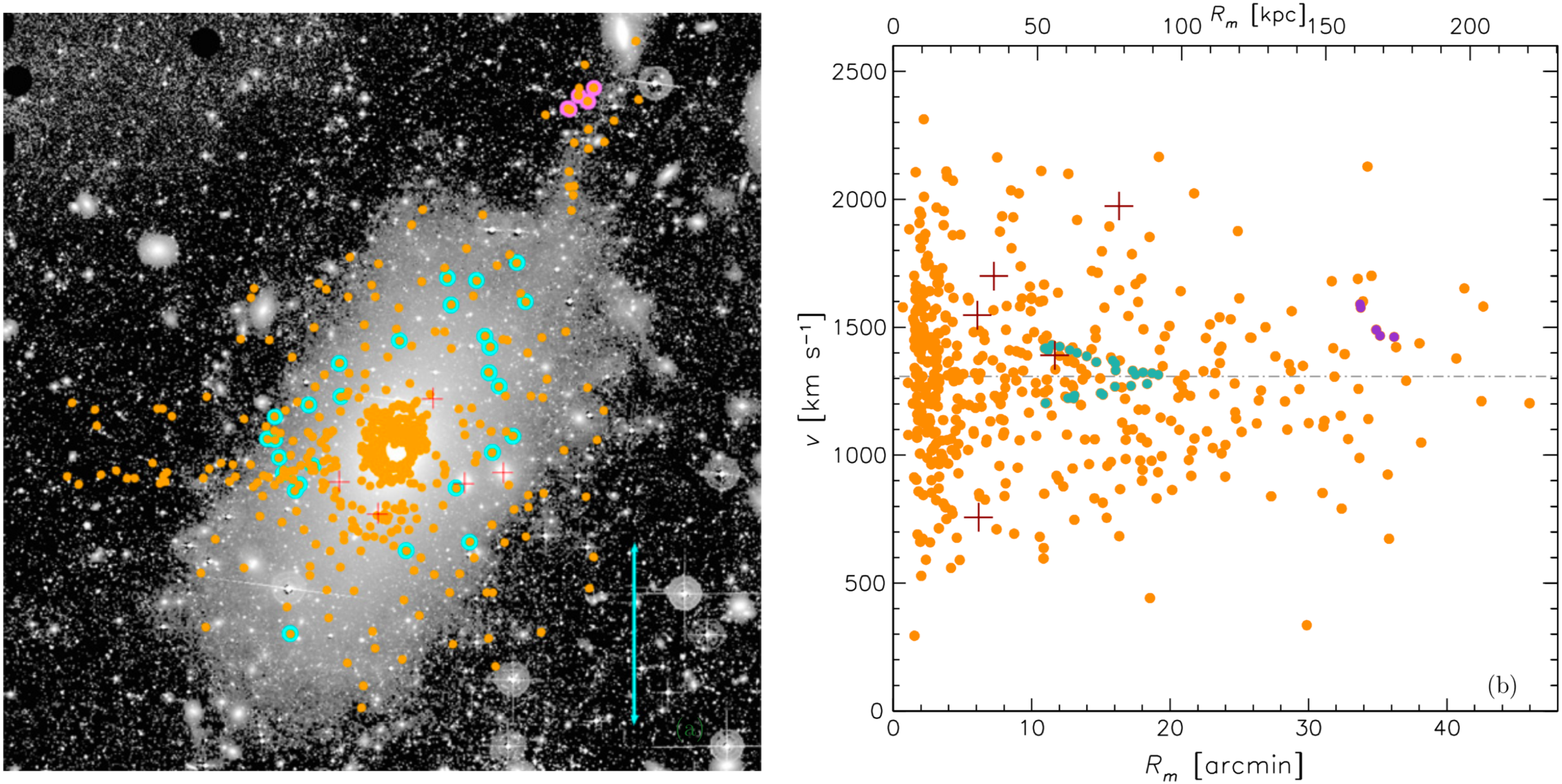



Li et al. (2020)

## Discrepancy for red GCs:

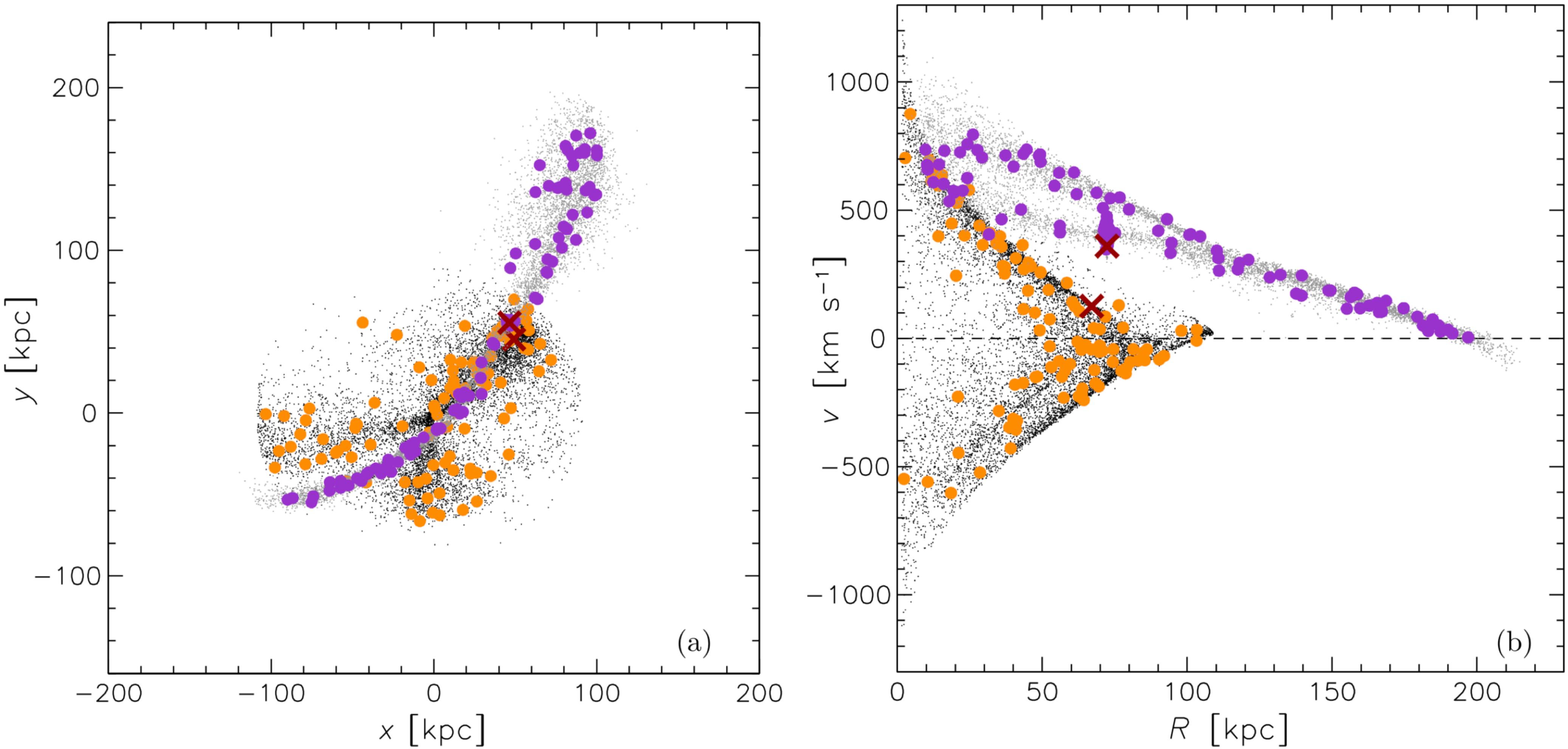
Spherical Jeans modelling
in Zhu et al. (2016)
versus
Axisymmetric Jeans modelling
in Li et al. (2020)

# Galaxy assembly traced by GC kinematic sub-structure around M87




Romanowsky et al. (2012)

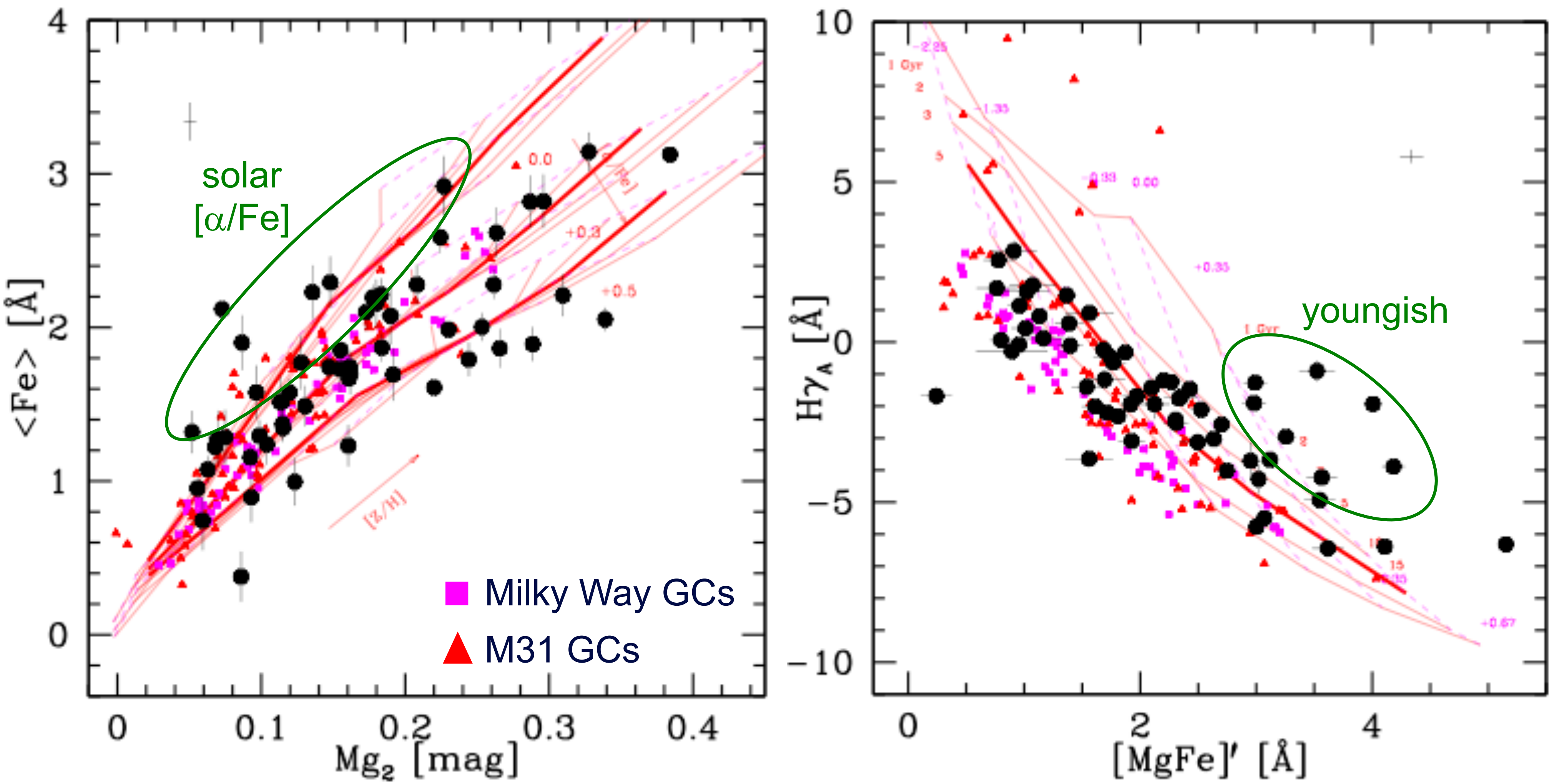
# Galaxy assembly traced by GC kinematic sub-structure around M87




Simulations of galaxies falling into an idealized central cluster potential

Romanowsky et al. (2012)

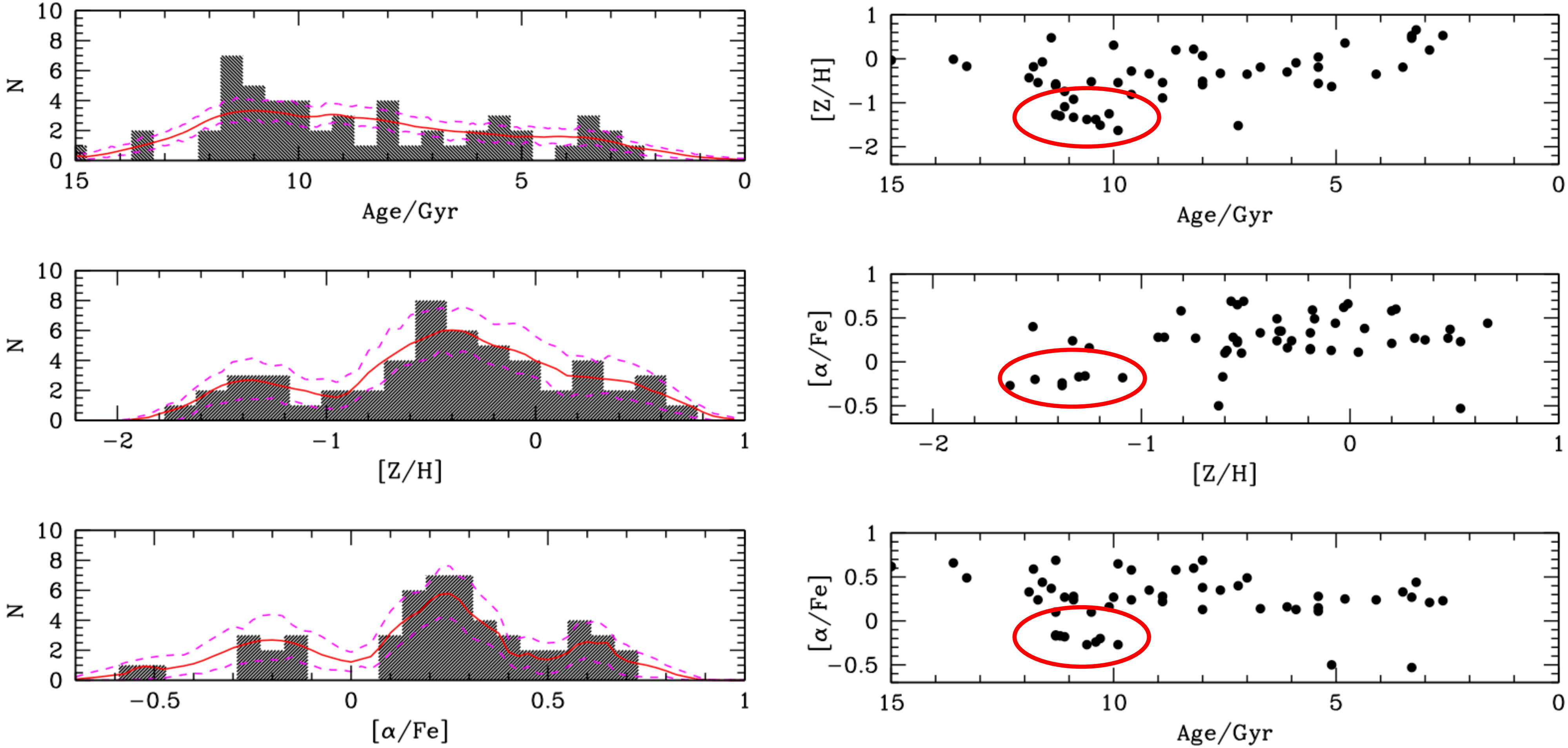
# Abundances and ages of GCs/UCDs in the Fornax cluster




High S/N VLT/FORS spectra of ~60 bright GCs/UCDs in Fornax ($M_V$<-9.5)

Hilker, Puzia et al. (in prep.)

# Abundances and ages of GCs/UCDs in the Fornax cluster




Puzia, Hilker et al. (in preparation)

Sub-group is located in narrow ring around NGC 1399
→ coherent sub-structure from accretion event?

# Discussion points

- What is the best color combination for conversion to metallicity/age distributions? – including infrared/UV?
- ‘SLUGGS’ survey for nearby (<10 Mpc) spirals – which (future) spectrographs to use?
- Chemo-dynamical modelling – using multi-dimensional phase-space: RA, DEC, $d_{gal}$, $v_{los}$, $mass_{GC}$, color, [Fe/H], [$\alpha$/Fe], age
- NSC contribution to UCDs/GCs in state-of-the-art simulations – E-MOSAICS 35 Mpc volume?
- GCS database – supaHarris facility?
- Simulations database – providing ‘observables’ to compare with