A *Subaru/Suprime-Cam* wide-field survey of globular cluster populations around M87

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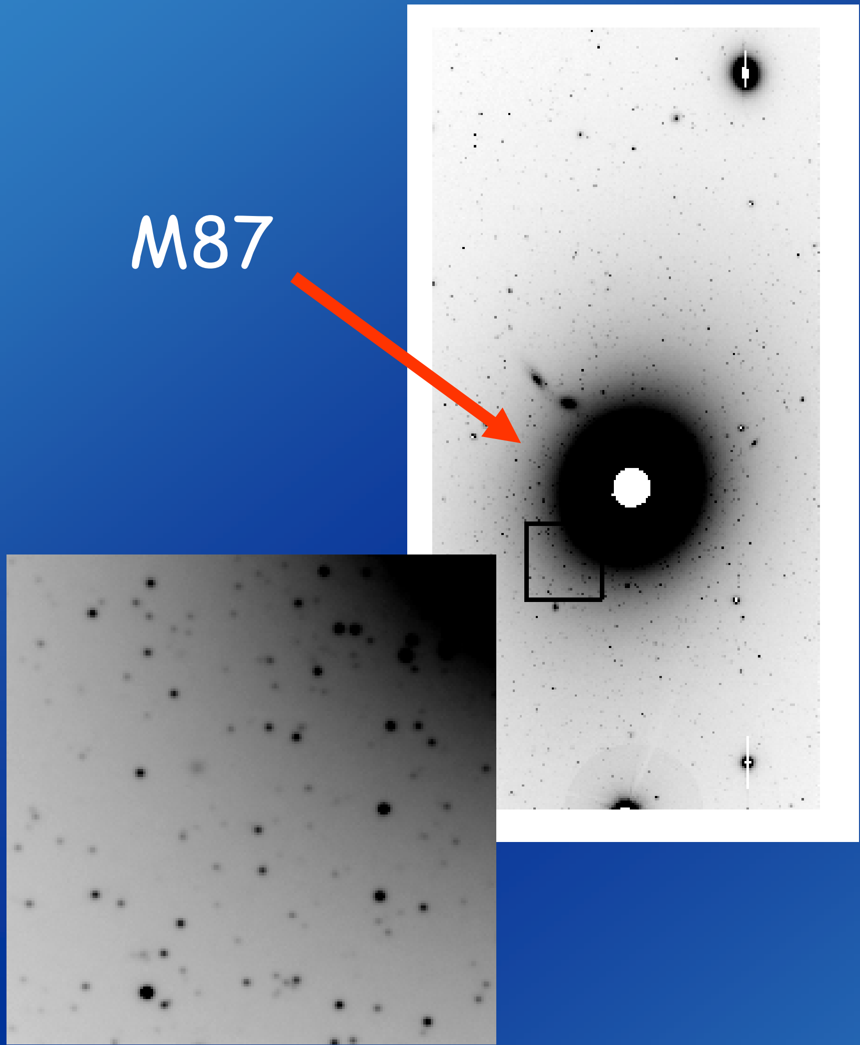
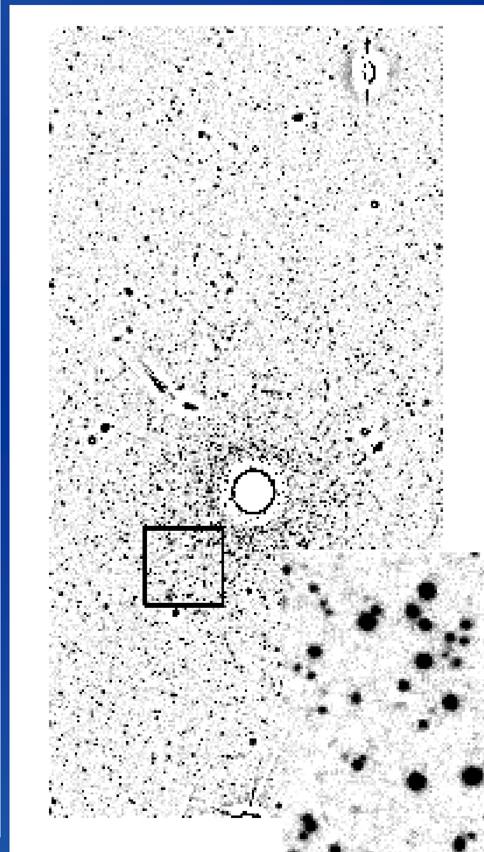
Introduction (0)

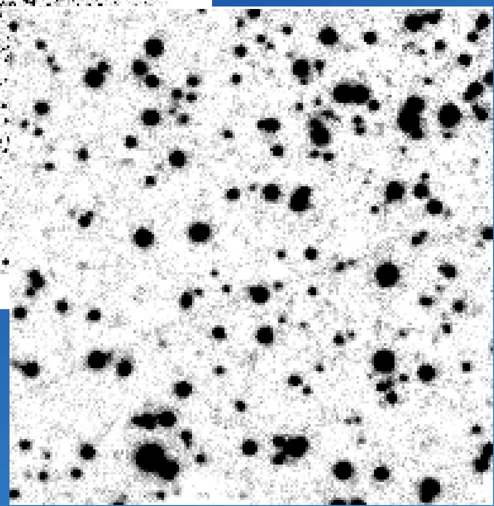
- A luminous galaxy is surrounded by a number of globular clusters (GCs)

M87





After median smoothing & subtraction



Introduction (1)

- GCs as "fossil records" of the host galaxy

The mass fraction of GCs in a galaxy is only ≤ 1%.
Nevertheless:

- There is observational evidence that when star formation occurs in a galaxy, GCs will also form (massive star clusters in starburst galaxies have been studied with HST; e.g. Holtzman et al. 1992).
- Since GC are simple stellar populations (SSPs), their photometric and spectroscopic properties are in principle simpler to interpret compared to integrated stellar light.

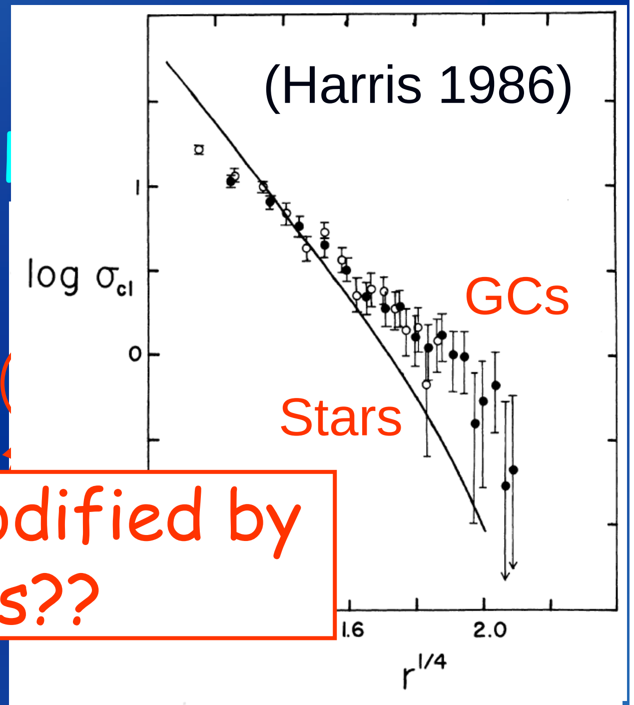
→ GCs are considered to be key probes of star formation history of the host galaxy.

Introduction (2)

- The numbers of GCs associated with el

  Environmental dependence

  GCs are extremely rich in cD galaxies & central cluster galaxies.



GC properties were substantially modified by extrinsic GCs/environmental effects??

- The spatial distribution of GCs tends to be more extended than that of galactic field stars.

↑ Capture of GCs by tidal interactions?

↑ GCs are tidally stripped from galaxies and released into the intergalactic space?

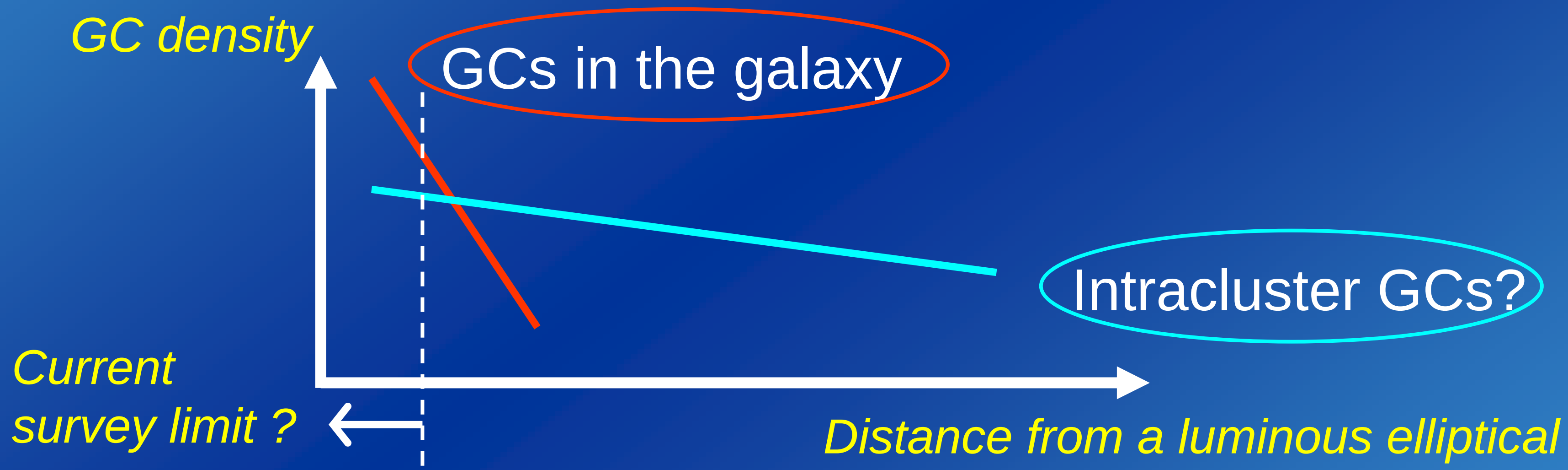
↑ Ellipticals are surrounded by intracluster GCs as well as "galactic" GCs ?

The number of GCs is apparently enhanced by intracluster GCs??

(e.g. White 1987; West et al. 1995; Cote et al. 1998)

To constrain the contribution of such GCs as extended on the cluster scale:

- Need to explore a wide field contiguously from a luminous elliptical galaxy at a cluster centre.



- Surface density of intracluster GCs is currently unknown, possibly very low.

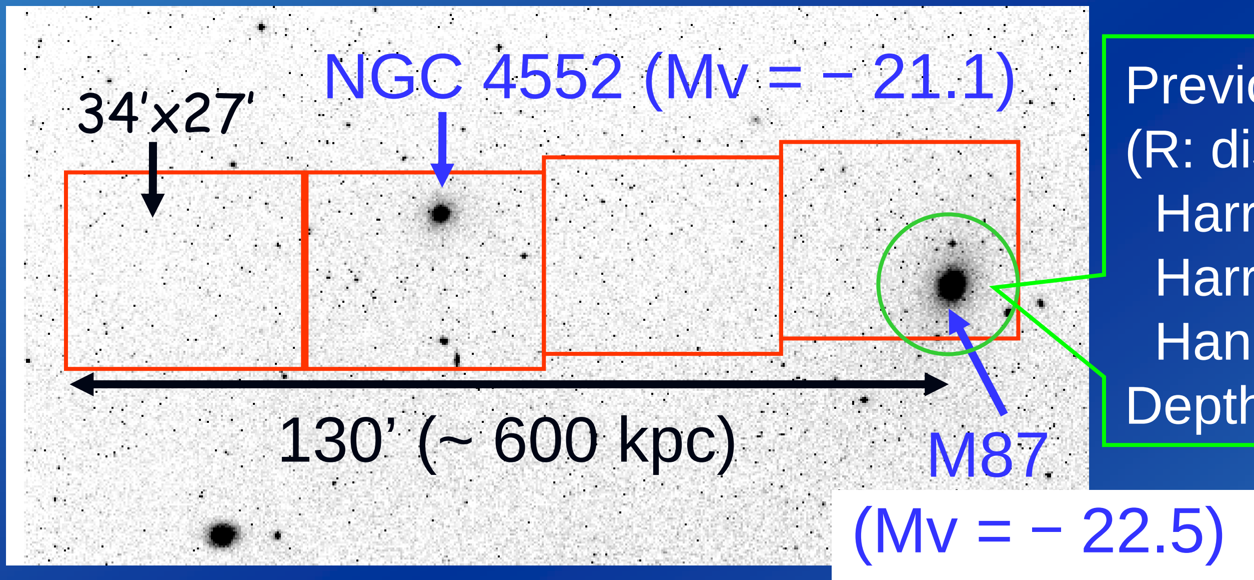
→ Need careful selection of GC candidates and statistical subtraction of contaminating objects.

The observations and data (1)

M87 region

Subaru/Suprime-Cam observation (2 nights in March 2004)

Approx. 2° x 0.5° (640 kpc x 130 kpc) through BVI filters



Previous M87 GC surveys:
(R: distance from M87)
- Harris (1986): R ≤ 20'
- Harris et al. (1998): R ≤ 10'
- Hanes et al. (2001): R ≤ 10'

Depth is V ≤ 24 or shallower.

1′ = 4.7 kpc at M87

1′ = 4.5 kpc at NGC 4552

50 % detection completeness to point source:

B ~ 25.8, V ~ 25.2, I ~ 24.5

Cf. Peak of GC luminosity function: Mv ~ -7.4 mag in Milky Way

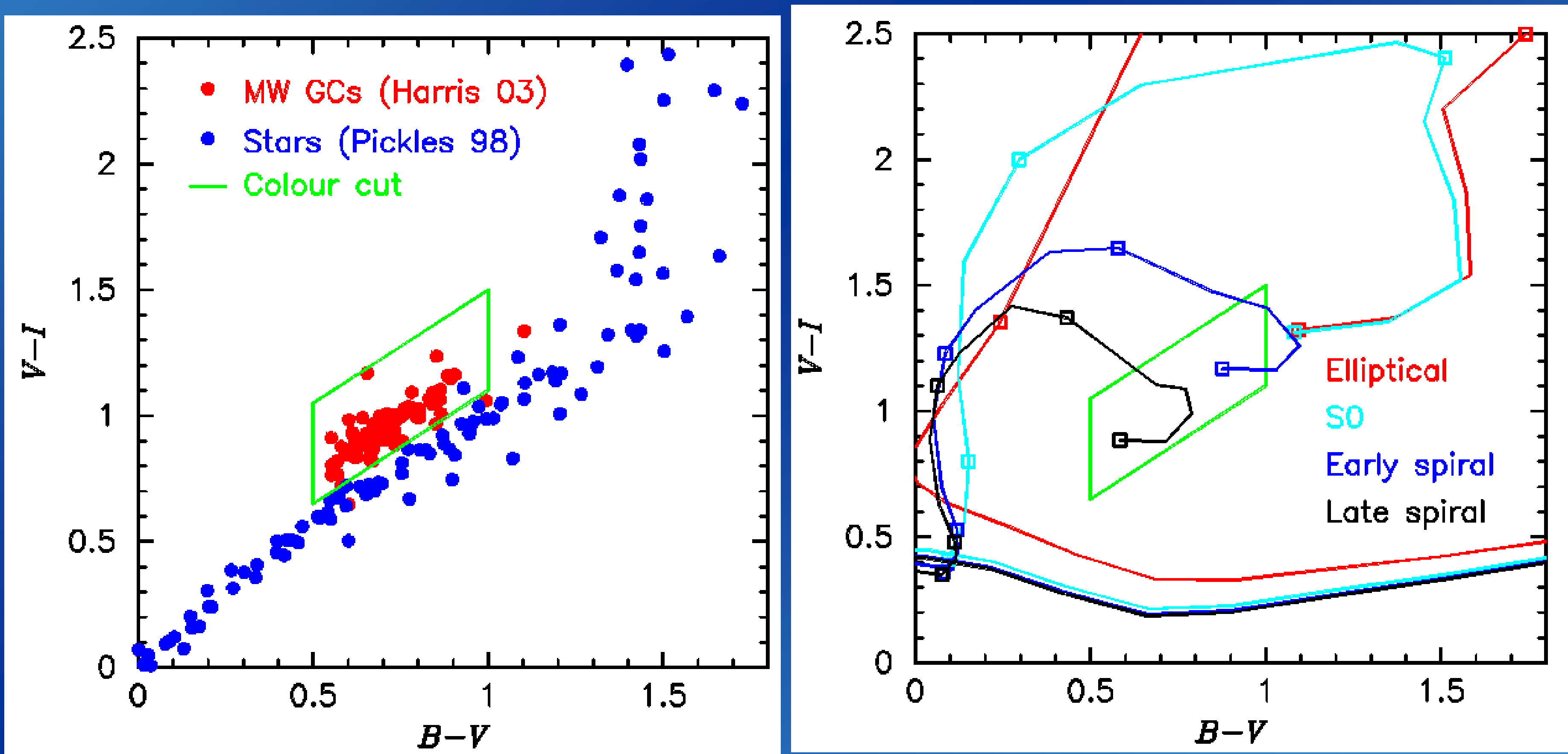
→ V ~ 23.6 mag at M87

GC selection (1): Method

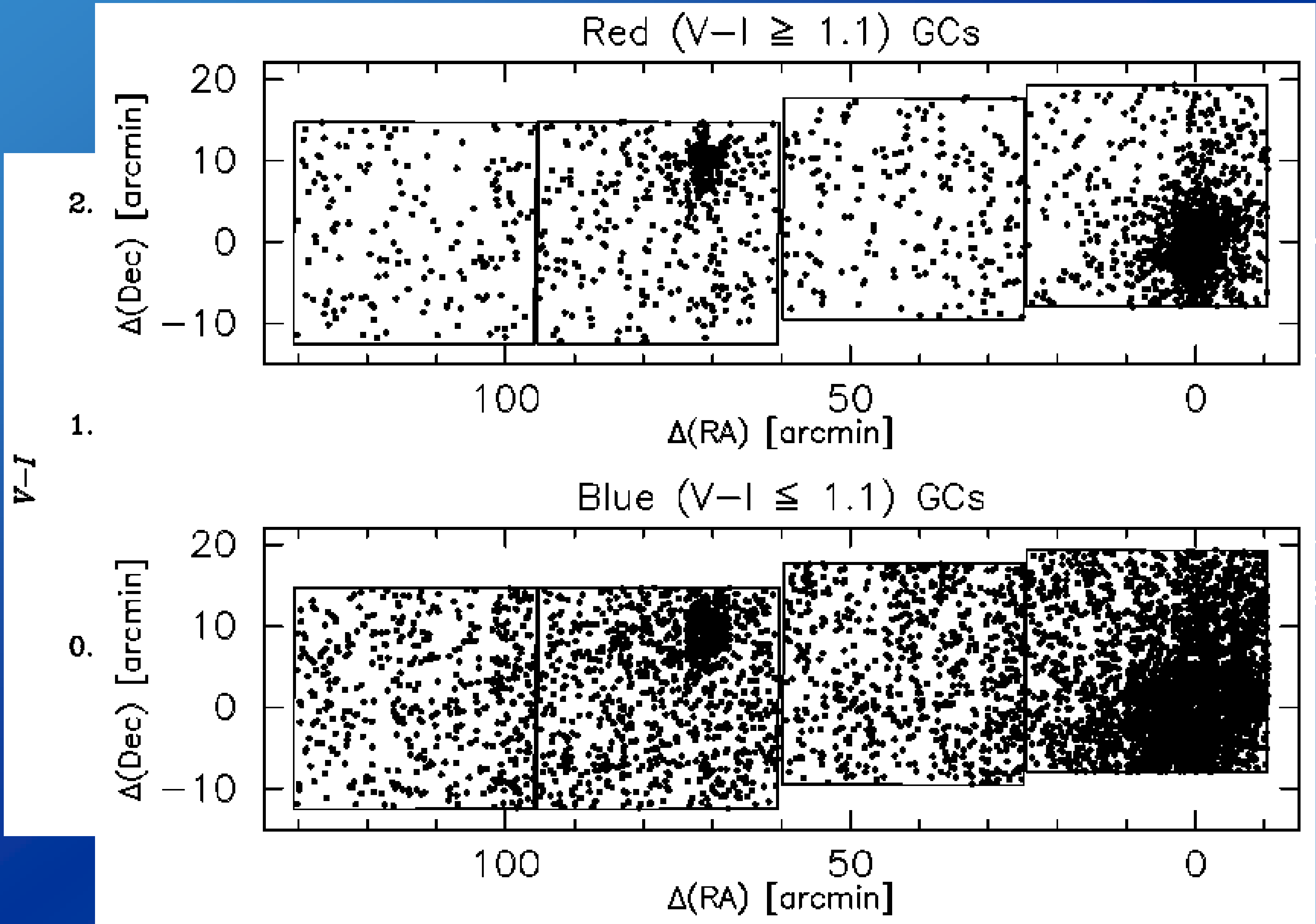
(1) Selection of unresolved objects on the V-band image with SExtractor (CLASS_STAR ≥ 0.6).

(2) PSF photometry.

(3) Colour criterion is applied to unresolved objects.



GC selection (2): Application



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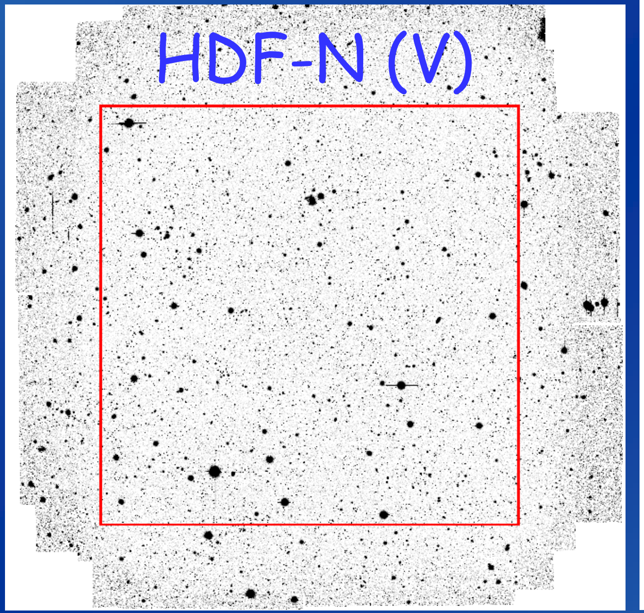
The observations and data (2)

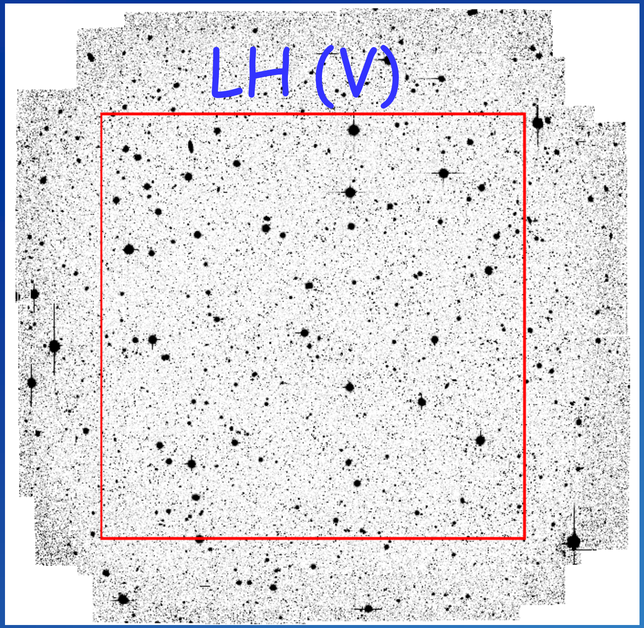
- Control fields: HDF-N & Lockman Hole

Suprime-Cam data (BVI bands) in the archive.

High galactic latitudes, similar seeing sizes, fainter limiting magnitudes compared to the data for the M87 fields.

→ Enable to pick up contaminating objects with the identical criteria to those for GCs in the M87 fields.



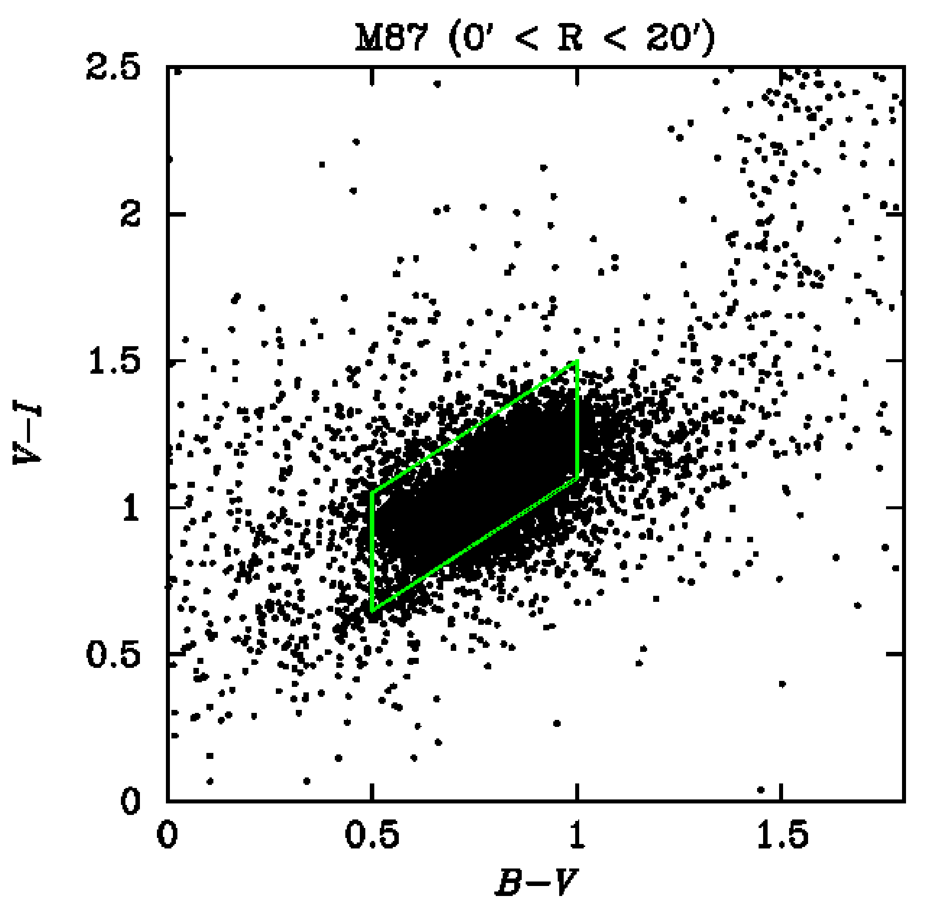


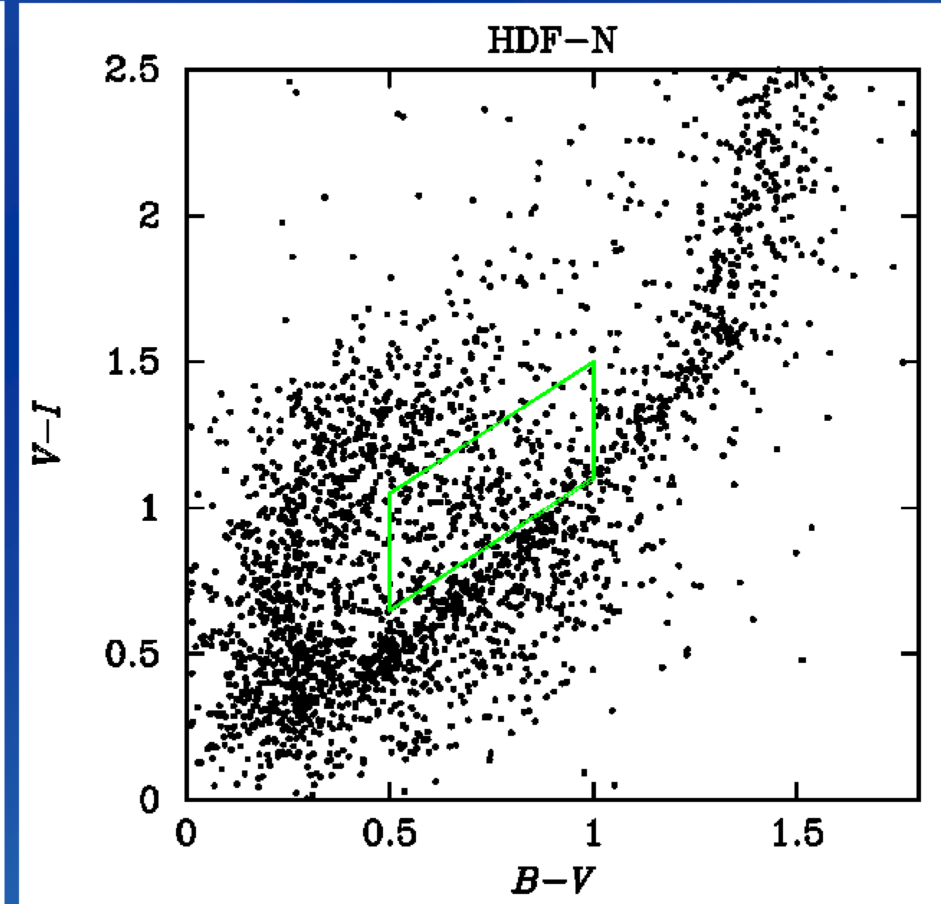
Only the central 27’ x 27’ regions (red box) are analyzed to avoid significant variations of completeness on the data.

GC selection (2): Application

Colour-colour plot of unresolved objects.

(Survey area is different.)

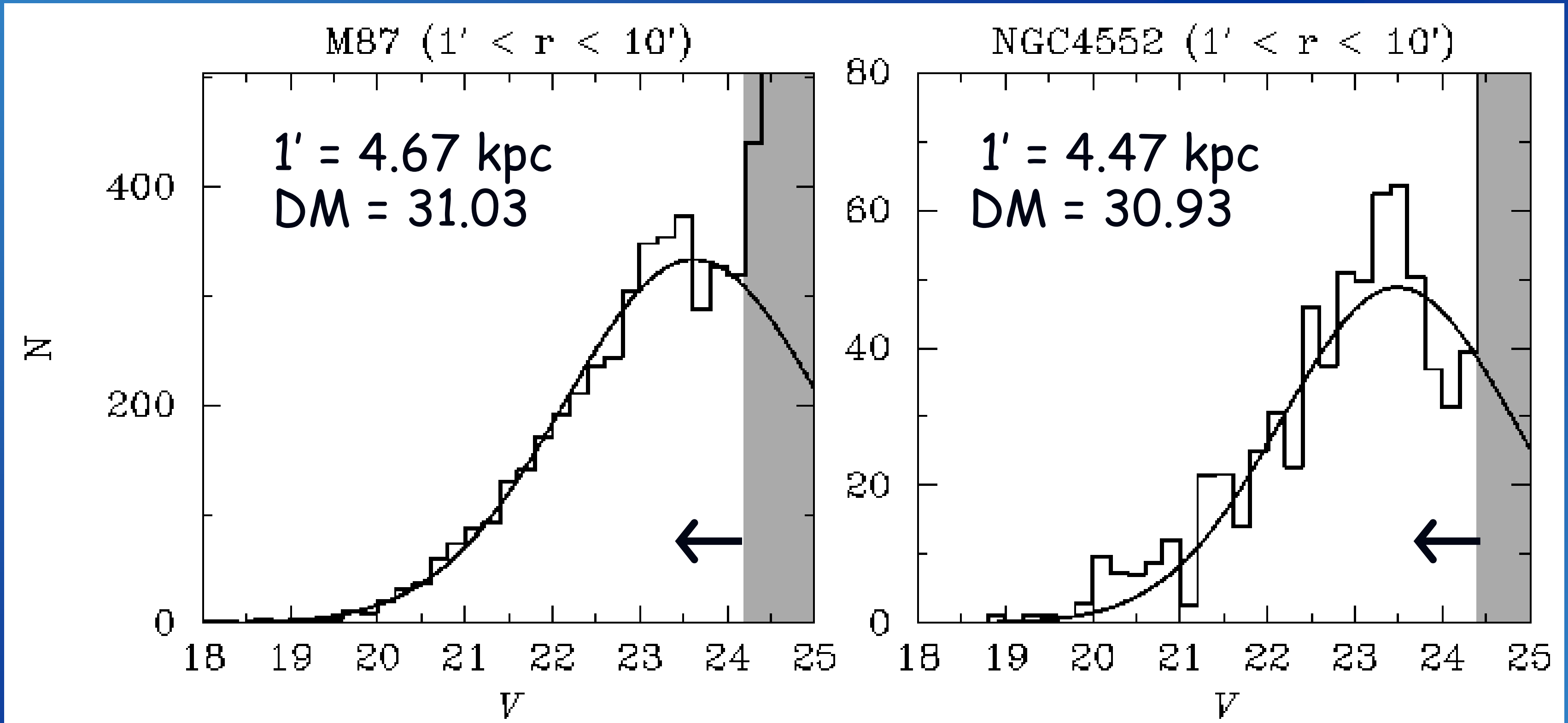




Results (1)

- GC Luminosity Function (GCLF)

Incompleteness and contamination has been corrected.



A Gaussian is fit to the LF at magnitudes with ≥ 50% completeness.

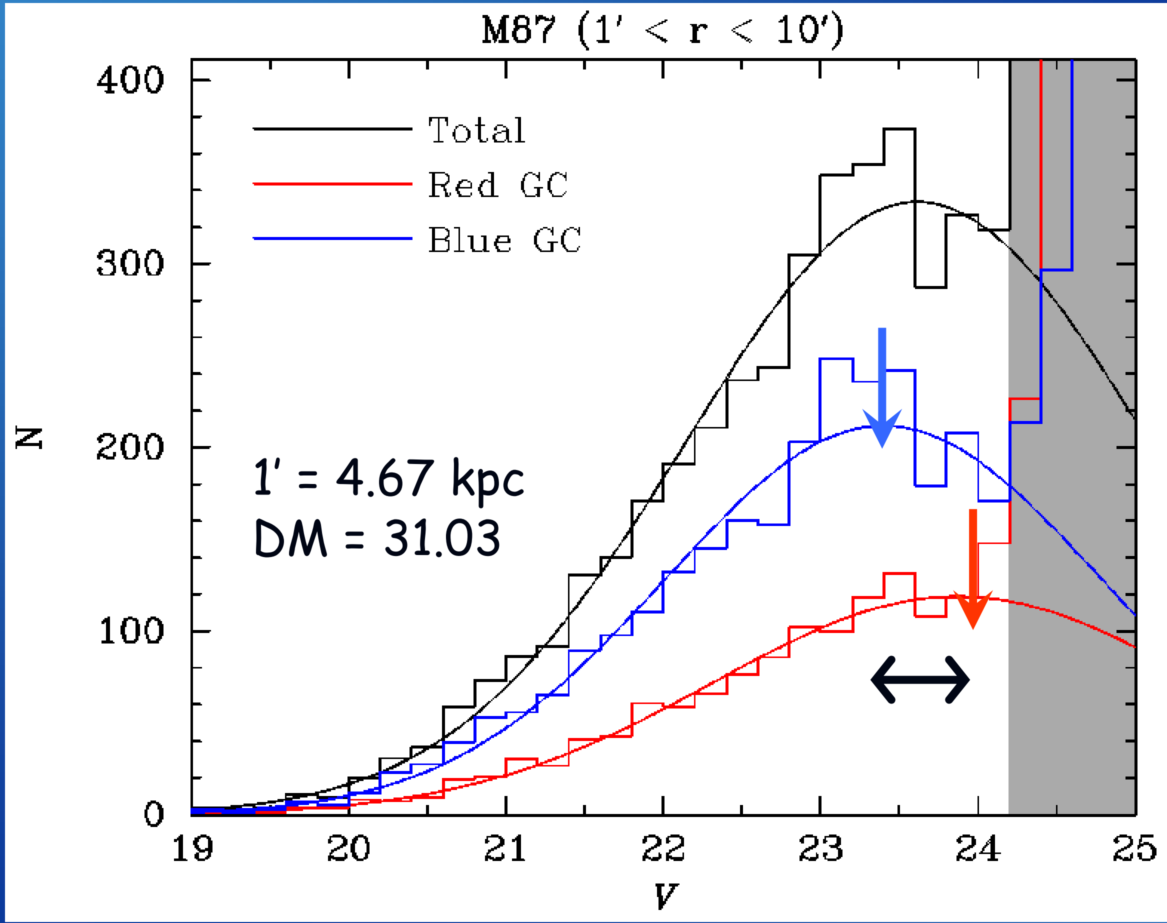
V_{peak} = 23.61±0.08 mag (M87), 23.49±0.16 mag (NGC 4552)

(Consistent with the results from HST studies;
Kundu et al. 1999; Kundu & Whitmore 2001)

Results (1)

Dependency of GCLF on GC colour

GCLFs for red GCs (V-I ≥ 1.1) and blue GCs (V-I ≤ 1.1)



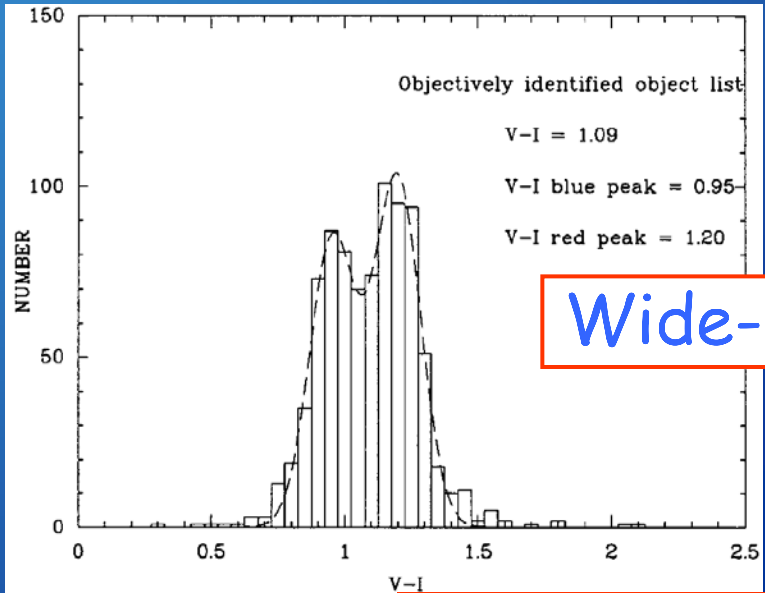
In M87, the turnover mag for the red GC subpopulation appears to be fainter by ~ 0.5 mag than that for the blue GC subpopulation.

Assuming that GCs are uniformly old, this offset can be explained by a metallicity difference between the two GC subpopulations; [Fe/H] = -0.3 (red) and -1.6 (blue) (Jordan et al. 2002).

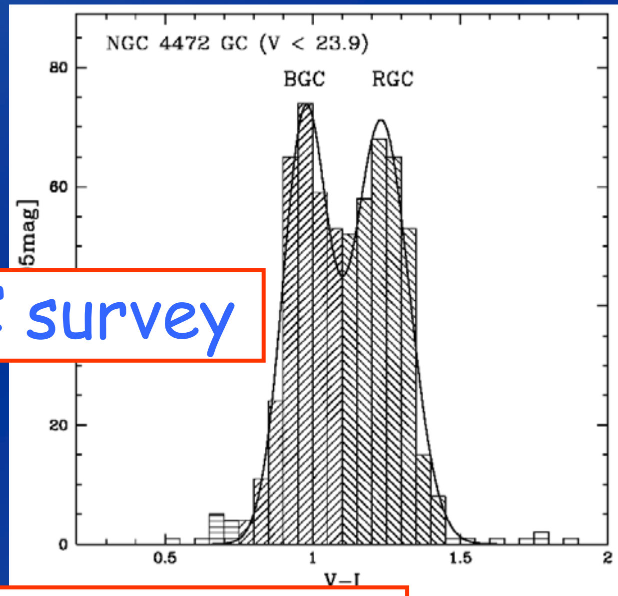
Note: In NGC 4552, GCLFs for red GCs and blue GCs appear to show no clear evidence for such difference.

Bimodal colour distributions of GCs

M87 (Kundu et al. 1999)

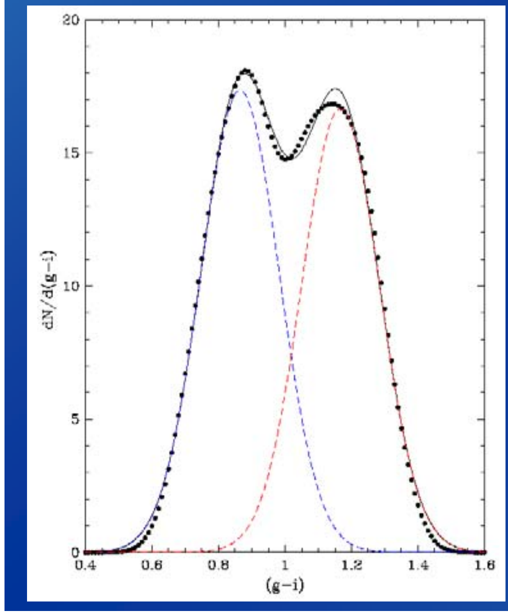


NGC 4472 (Lee & Kim 2000)



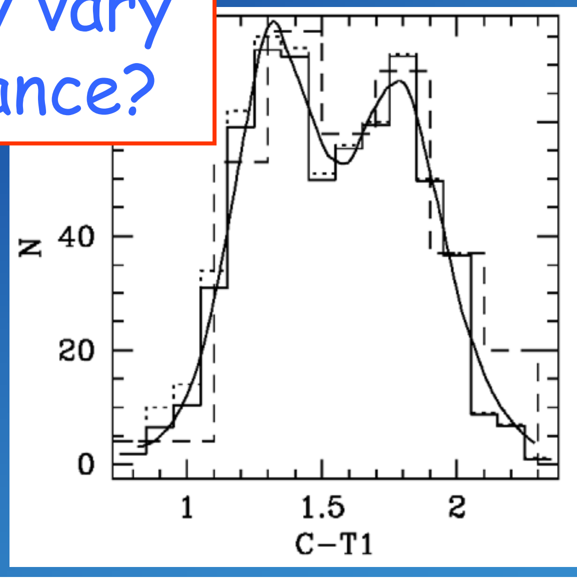
Wide-field GC survey

How does this bimodality vary with galactocentric distance?



(Forbes et al. 2004)

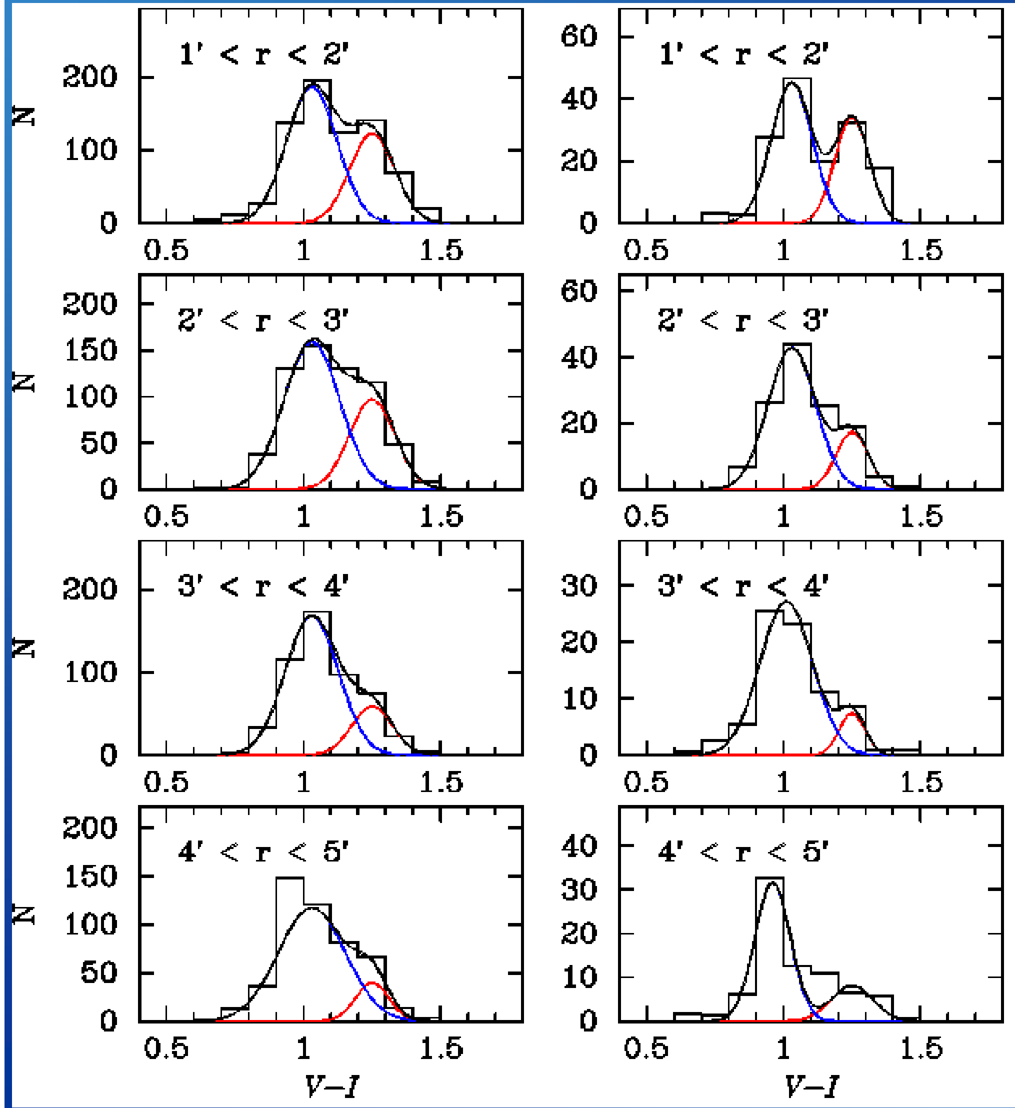
(Dirsch et al. 2003)



Results (2)

GC colour distribution (V ≤ 24 mag)

M87 *NGC 4552*



Within 5' (~ 20 – 25 kpc) from the centre.

1′ = 4.7 kpc at M87

1′ = 4.5 kpc at NGC 4552

Inner region

Outer region

- Evidence for bimodality is clearer in the inner region.
- The fraction of red GCs decreases with distance from the galaxy centre.

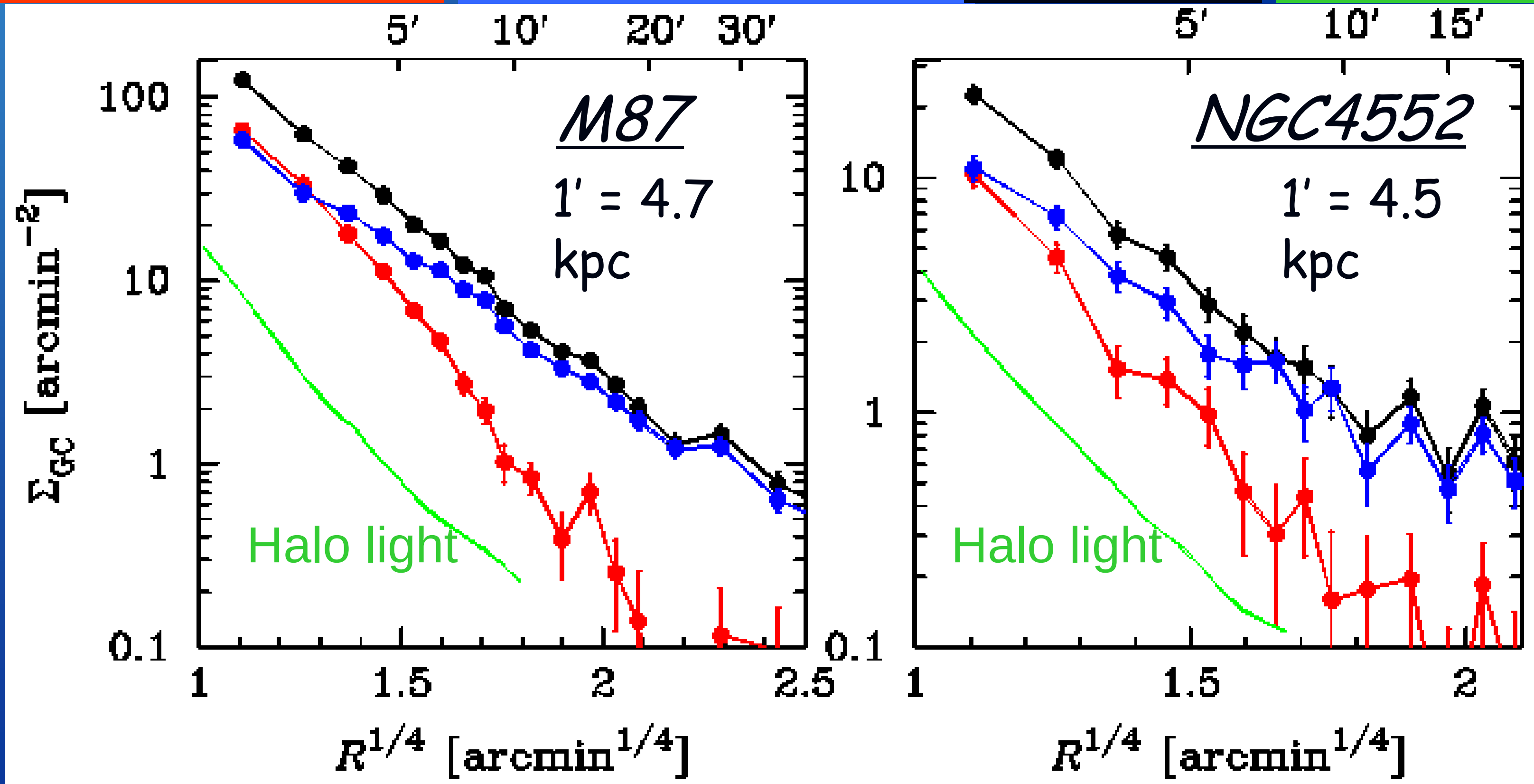
[Fe/H] = 4.3 (V-I) – 5.3

for old SSP (Vazdekis et al. 1996)

Results (3)

- Radial profiles of GC surface densities

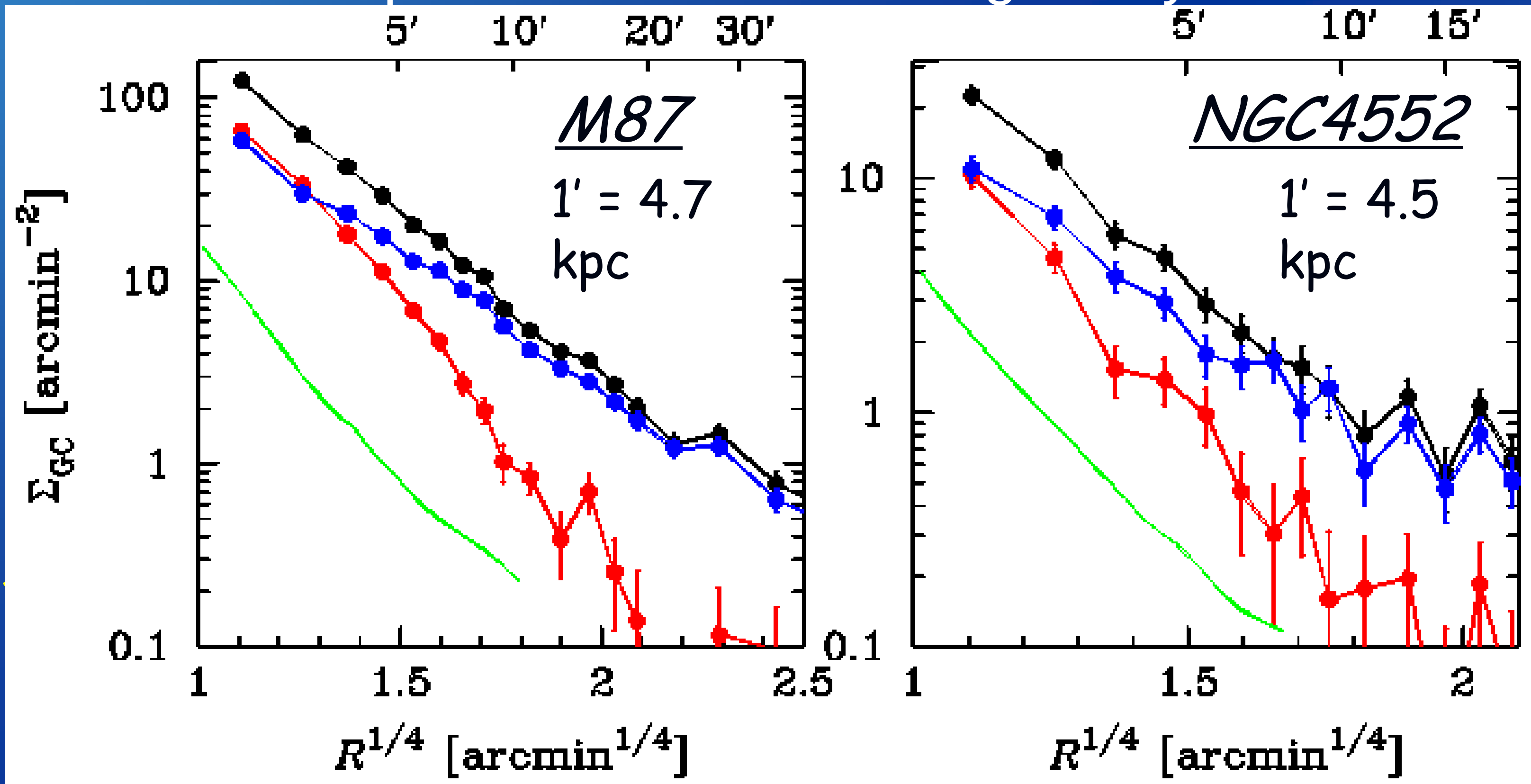
Red GCs (V-I ≥ 1.1) | Blue GCs (V-I ≤ 1.1) | Red + blue | Host galaxy



Whilst red GCs has a similar distribution to the host galaxy halo light, the blue GC distribution tends to be more extended.

To constrain the contribution of such GCs as extended over the cluster scale:

- Need to explore a wide field contiguously from a



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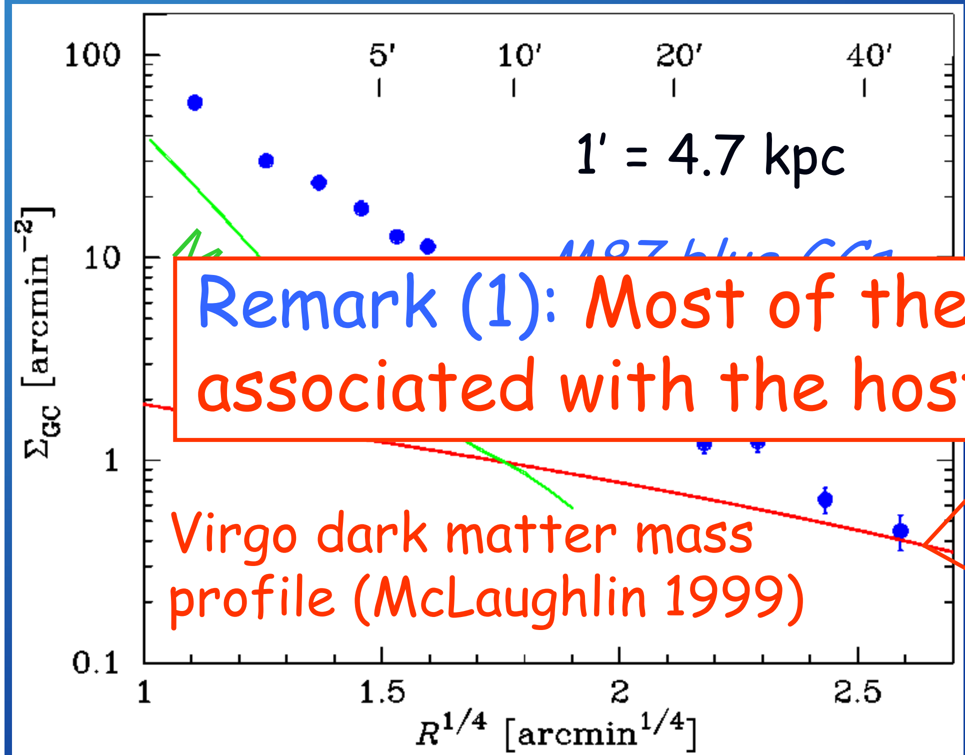
Most of the blue GCs are intracluster GCs ?

Discussion (1)

- Are the blue GCs distributed over the cluster scale?



The blue GC distribution tends to be more extended than that of the red GCs and the halo light, but it is not as

Remark (1): Most of the blue GCs must be associated with the host galaxy, not the cluster.

The best-fit Hernquist model of the dark matter distribution constrained by observations (shown here is the surface mass density with the normalization scaled).

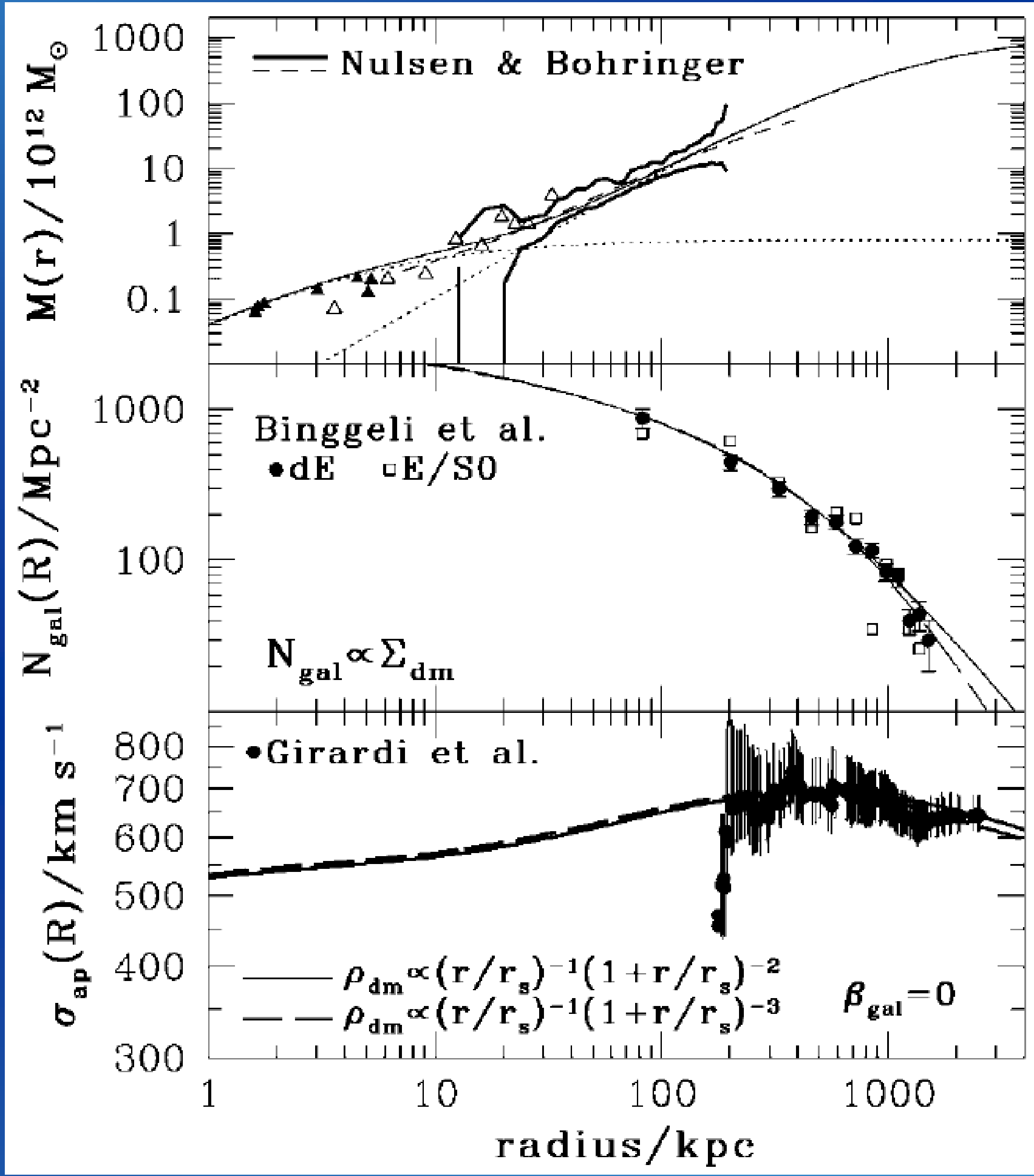
The extended nature of the blue GCs is NOT a special characteristic of central cluster ellipticals like M87 but is seen in other luminous Es: NGC 4552 (this study), NGC 4472 (Lee et al. 1998) and NGC 4649 (Forbes et al. 2004).

McLaughlin (1999)

A mass model of the Virgo cluster is obtained by using:

- M87 surface brightness profile
- X-ray hot gas distribution
- Surface number density profile of early-type galaxies
- Kinematics of early-type galaxies

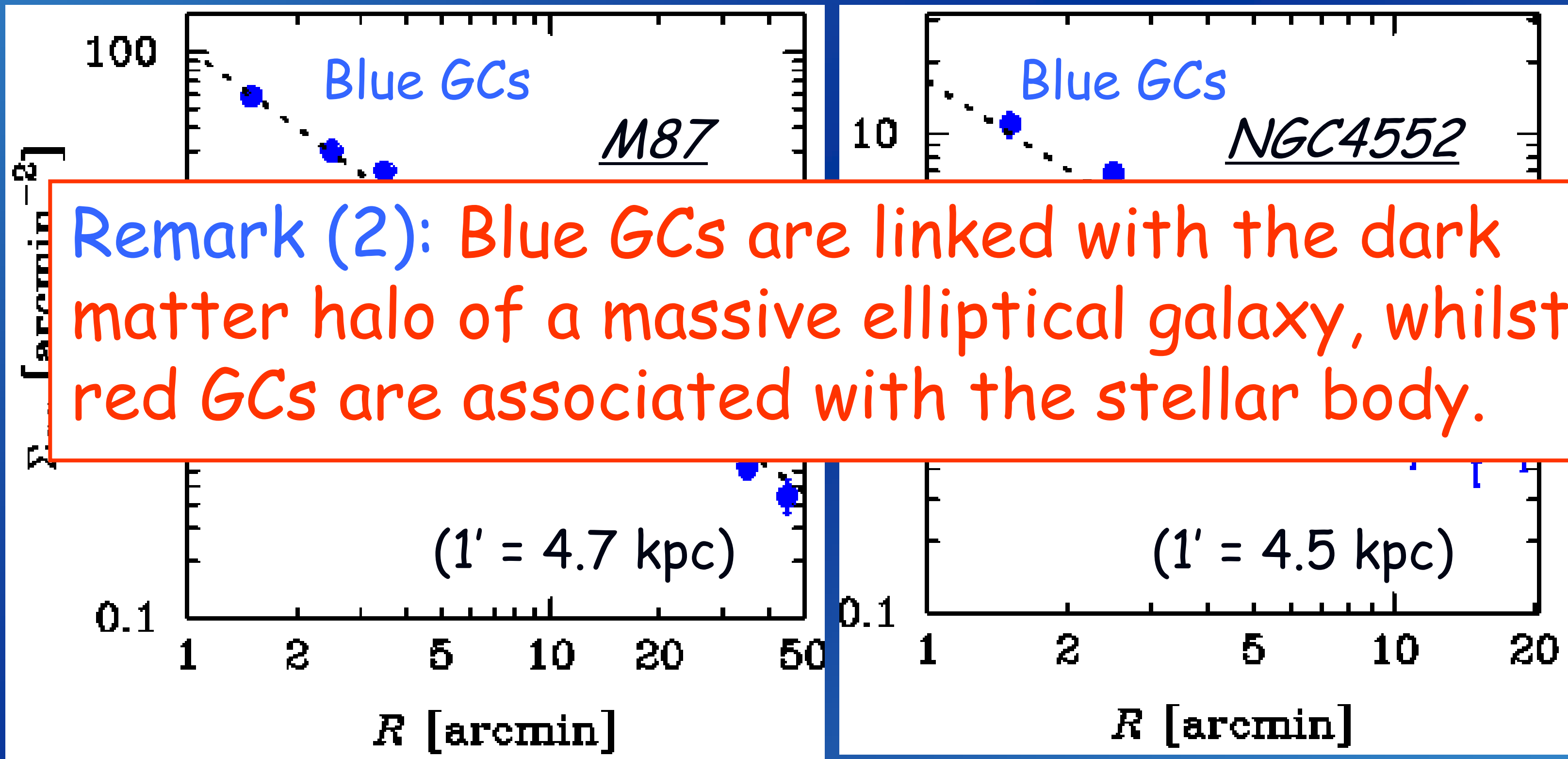
The best-fit dark matter distribution is described by a Hernquist model and NFW model.



Discussion (2)

- Origins of red & blue GC subpopulations

  - Dark matter halos of luminous Es seems to be more extended than the stellar distributions (e.g. gravitational lens analyses at intermediate z: Treu & Koopmans 2004; Ferreras et al. 2005)



Remark (2): Blue GCs are linked with the dark matter halo of a massive elliptical galaxy, whilst red GCs are associated with the stellar body.

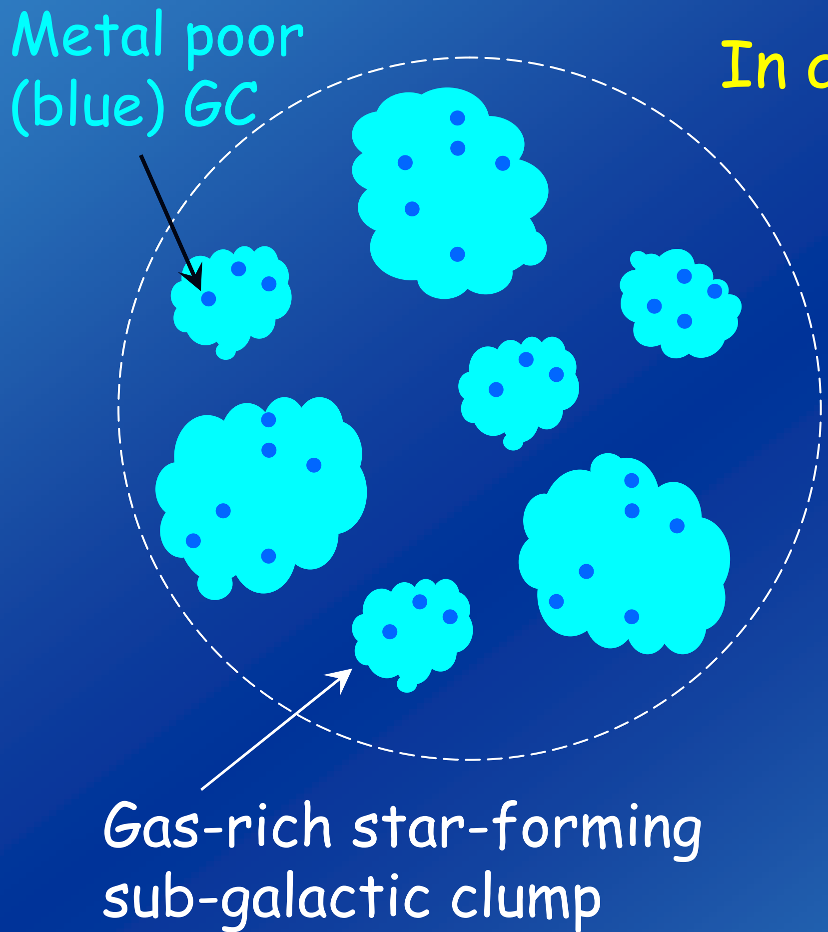
  - $\Sigma_{\text{blue GC}}(R) \propto R^{(\sim -1.3)}$, only marginally different from the projected singular isothermal sphere ($\Sigma \propto R^{-1}$).

❐ Formation of GCs & massive elliptical galaxy

Observational constraints:

The blue (metal-poor) GC distribution is more extended.

Spectroscopic ages of both metal-rich & metal-poor GCs are as old as Milky Way GCs (Strader et al. 2005)



In a cite of massive galaxy formation:

Sub-galactic clumps collapse first. (Metal-poor) GCs form therein.

These sub-galactic clumps merge into a massive elliptical galaxy.

The existing (metal-poor) GCs assemble dissipationlessly.

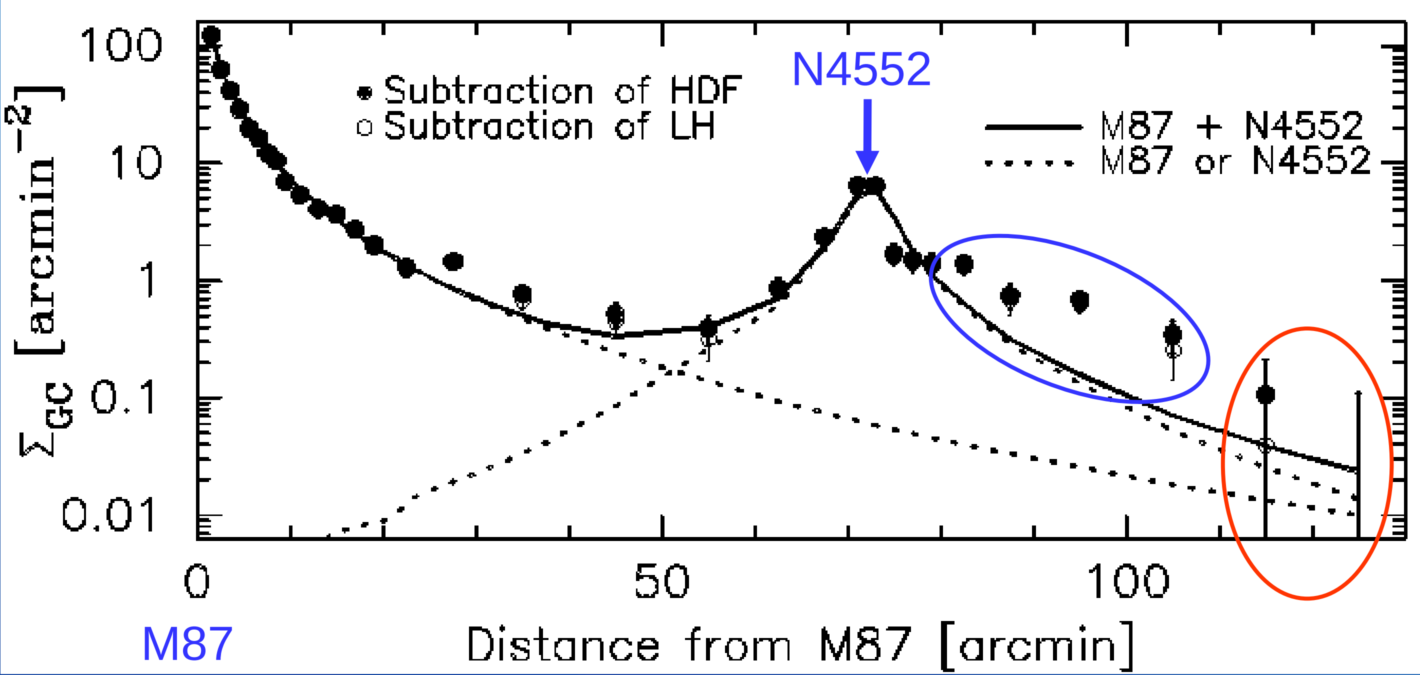
Stellar body and metal-rich GCs form dissipatively in the subsequent starbursts.

Complete at high redshift.

Discussion (4)

- Any evidence for intergalactic GCs (i-GCs)?

  Growing evidence for intergalactic stellar population in the forms of planetary nebulae (PNe), RGB stars, and diffuse light.



Excess number of GCs compared to those expected only by the M87 GCs and the NGC 4552 GCs.

Consistent with no GCs.

- Σ (i-GC) ~ 0.2 arcmin^-2 is suggested, and the distribution may have no clear trend with distance from cluster centre.

Consistent with the distribution of i-PNe (Feldmeier et al. 2004; Aguerri et al. 2005).

Discussion (5)

- Specific frequency for intergalactic GCs

The S_N for i-GCs may tell us:

(1) Main provider of intergalactic stars in the Virgo cluster

(2) Mixture of GCs & stars released by tidal interactions

Surface density of i-PNe (e.g. Feldmeier et al. 2004)

→ Luminosity density of intracluster stellar population

- Luminosity function of PNe
- Theory of stellar evolution

Surface density of i-GCs ~ 0.2 arcmin^-2 (this study)

→ S_N ~ 3, somewhat smaller than the typical value for normal Es (S_N ~ 4). Contributions from spirals (S_N ~ 1)?

→ M87 's high S_N value (~ 14) may be hard to explain by tidal capture of GCs and stars from other galaxies.

Summary

An unprecedented wide-field survey (~ 0.6 Mpc from the M87 centre) of GCs around M87 with Subaru/Suprime-Cam

- Secure selection of GC candidates with an extended source cut and a colour selection on the B-V vs. V-I diagram.
- Analyzed the Suprime-Cam data on the control fields through the BVI bands, which enable to select contaminating objects with the identical criteria to those adopted in the M87 fields.

↓ ↓ ↓

(1) Most of the blue GCs must be associated with the host galaxy, not the cluster, even in central cluster galaxies like M87.

(2) Blue GCs are linked with the dark matter halo of a massive elliptical galaxy which perhaps formed in sub-galactic clumps and assembled, whilst red GCs are associated with the stellar body formed in the subsequent starbursts.

(3) We find marginal evidence for intergalactic GCs inhomogeneously distributed in the Virgo cluster. Comparison with the surface density of intergalactic PNe suggests S_N ~3 for this GC population.