Filling up the mass-size plane of low-mass stellar systems in M31

Dougal Mackey

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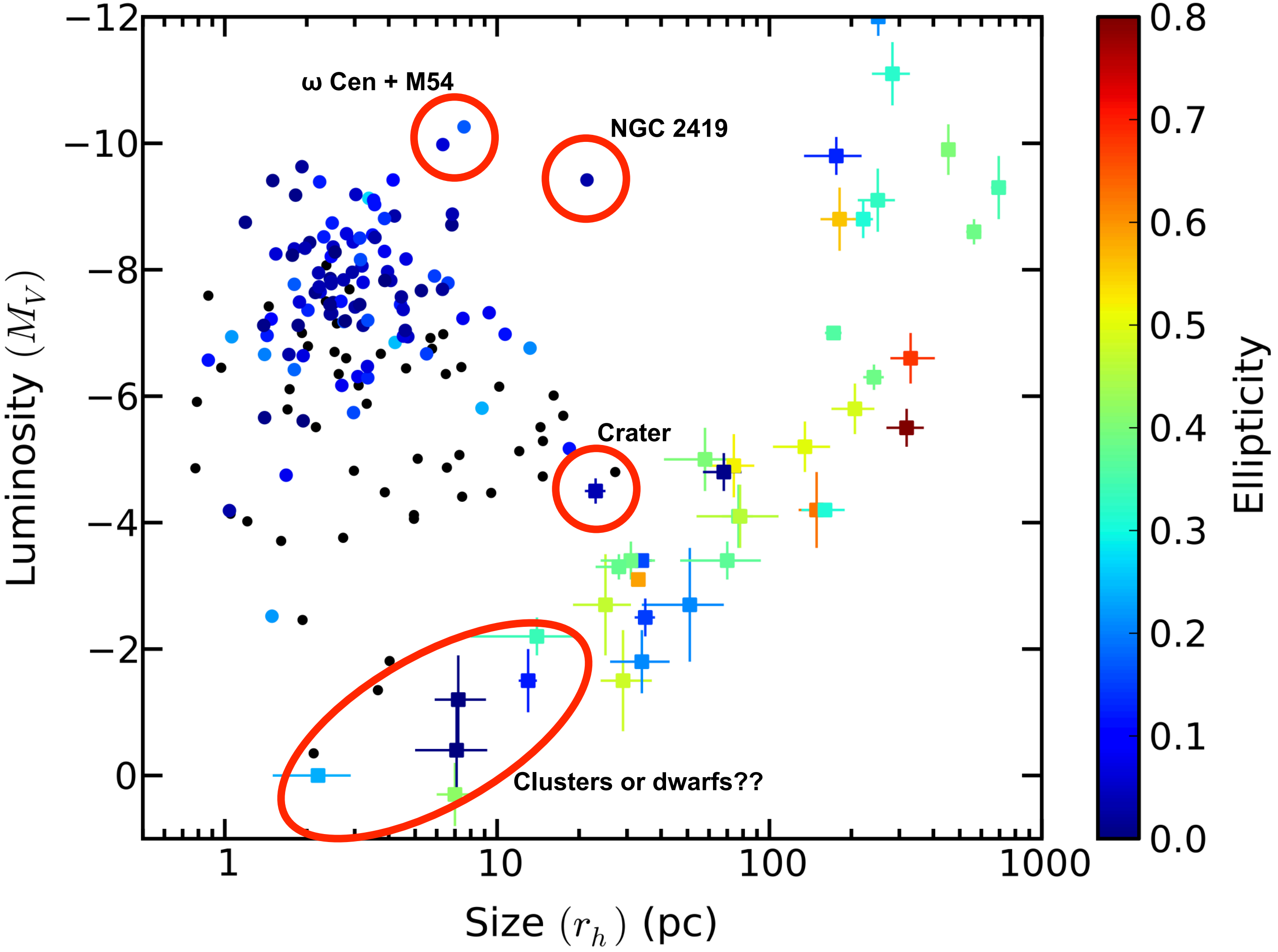
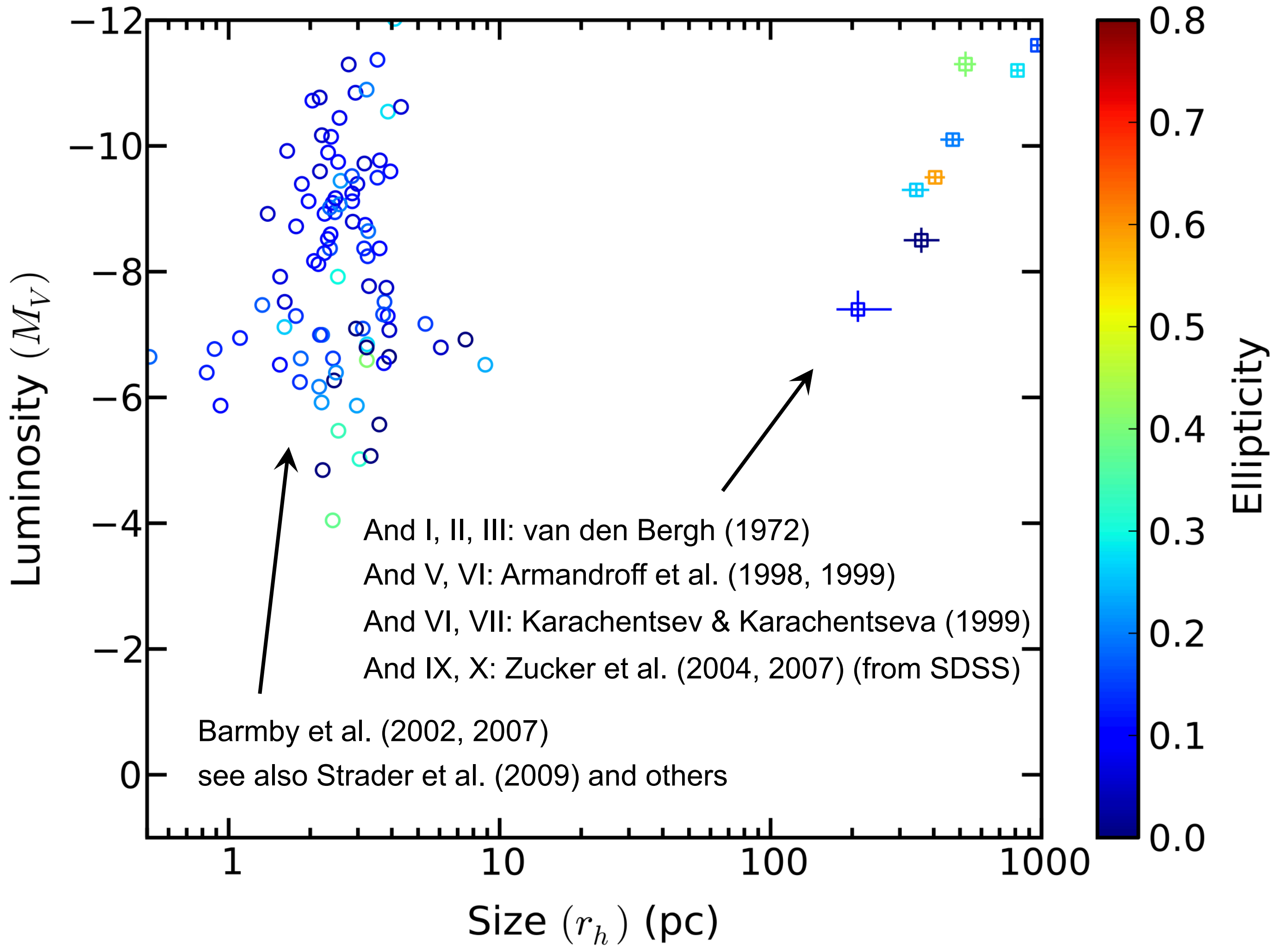
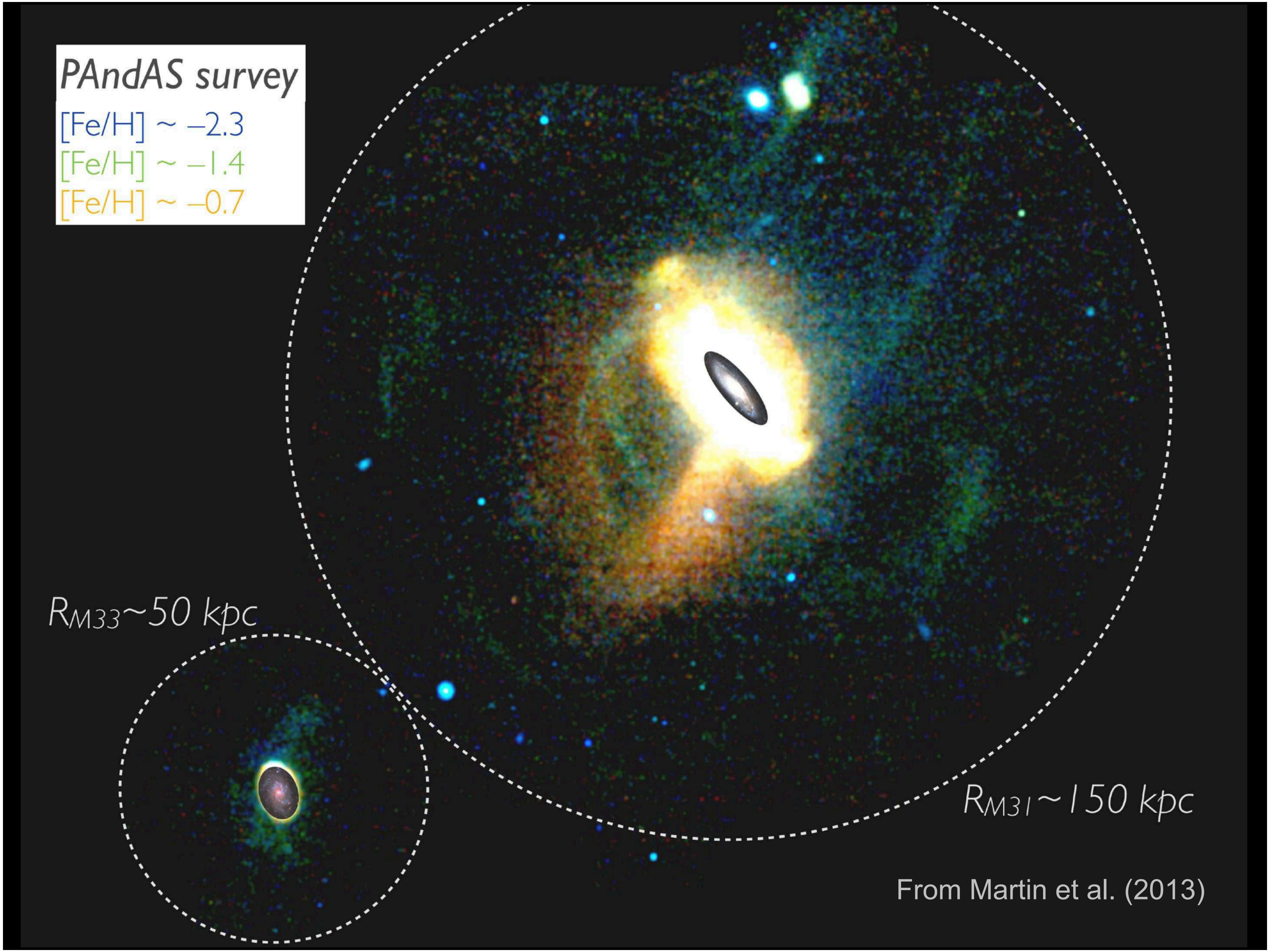
Image credit: R. Andreo

Size-luminosity plane in the Milky Way



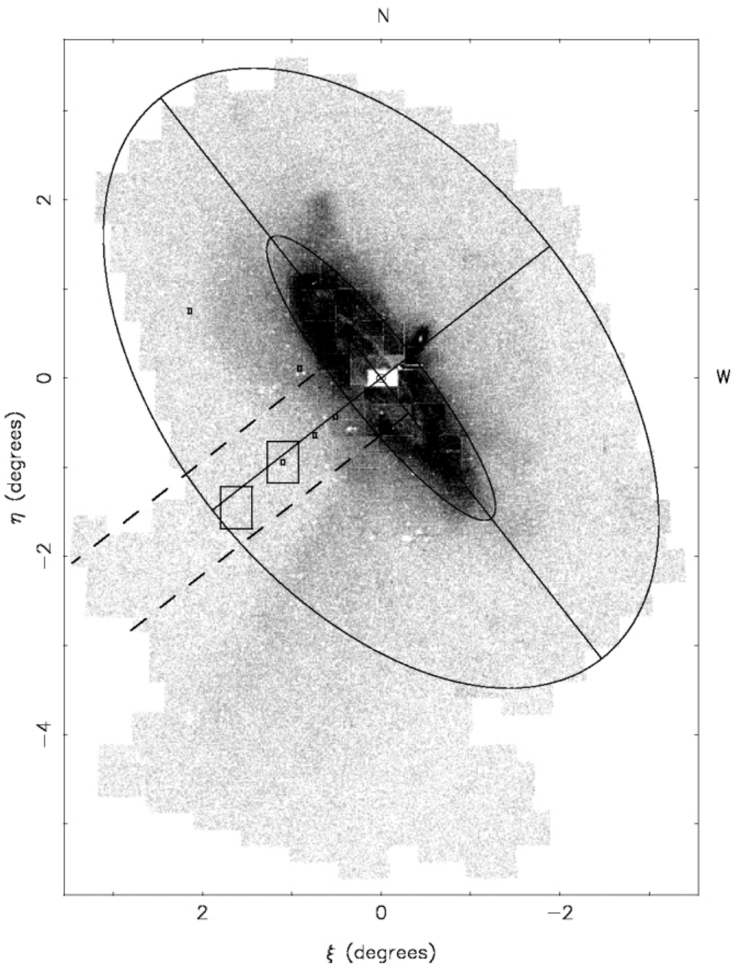
Size-luminosity plane in M31 (circa 2005)

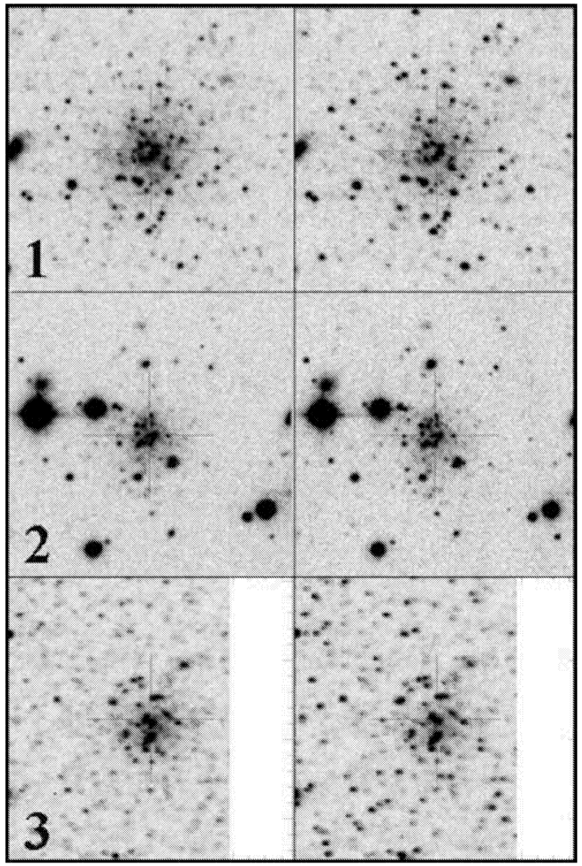




PAndAS survey
[Fe/H] ~ –2.3
[Fe/H] ~ –1.4
[Fe/H] ~ –0.7
R_{M33}~50 kpc
R_{M31}~150 kpc
From Martin et al. (2013)

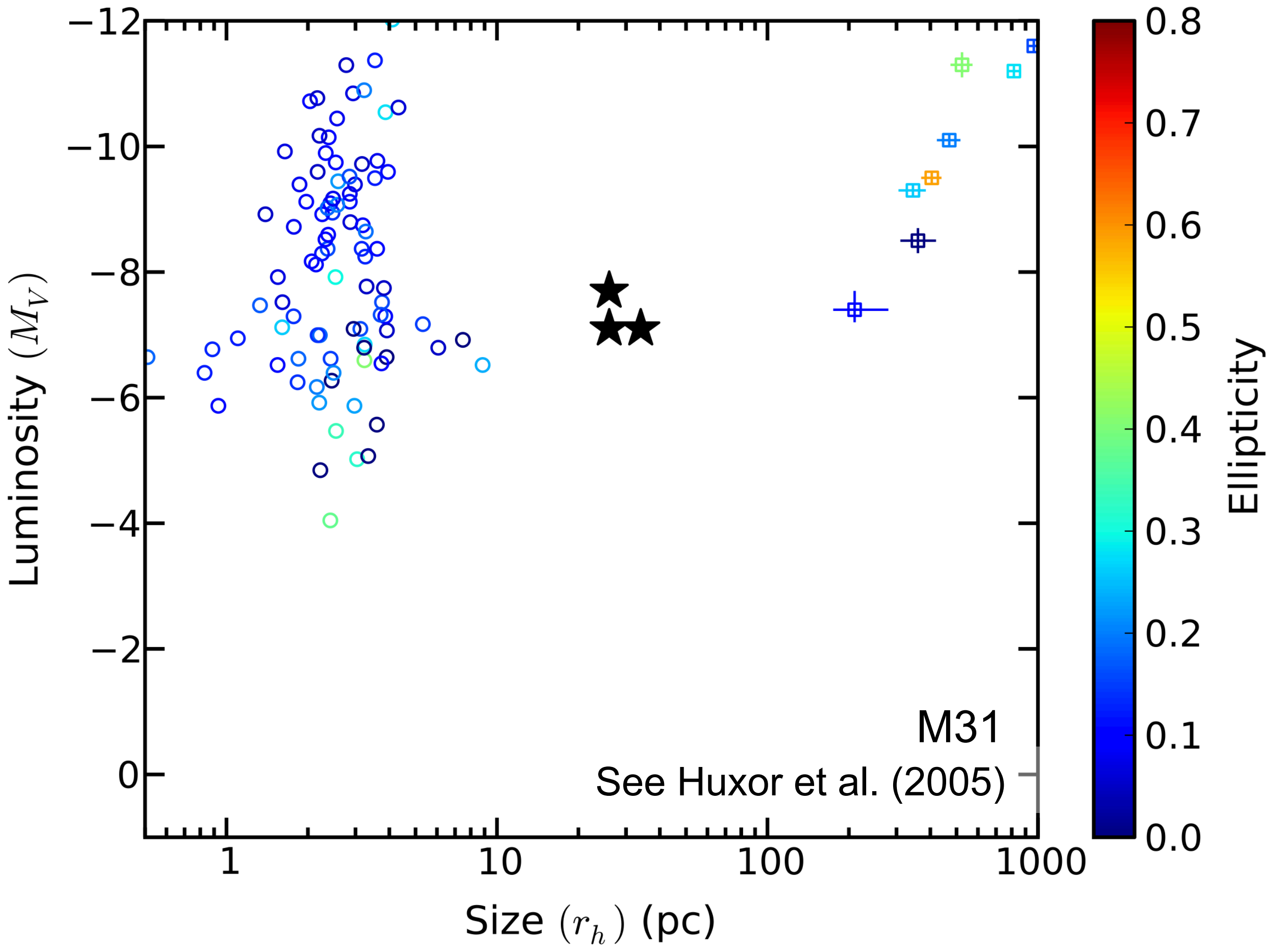
“Extended” clusters in the M31 halo





See Huxor et al. (2005)

Extended clusters on the size-luminosity plane



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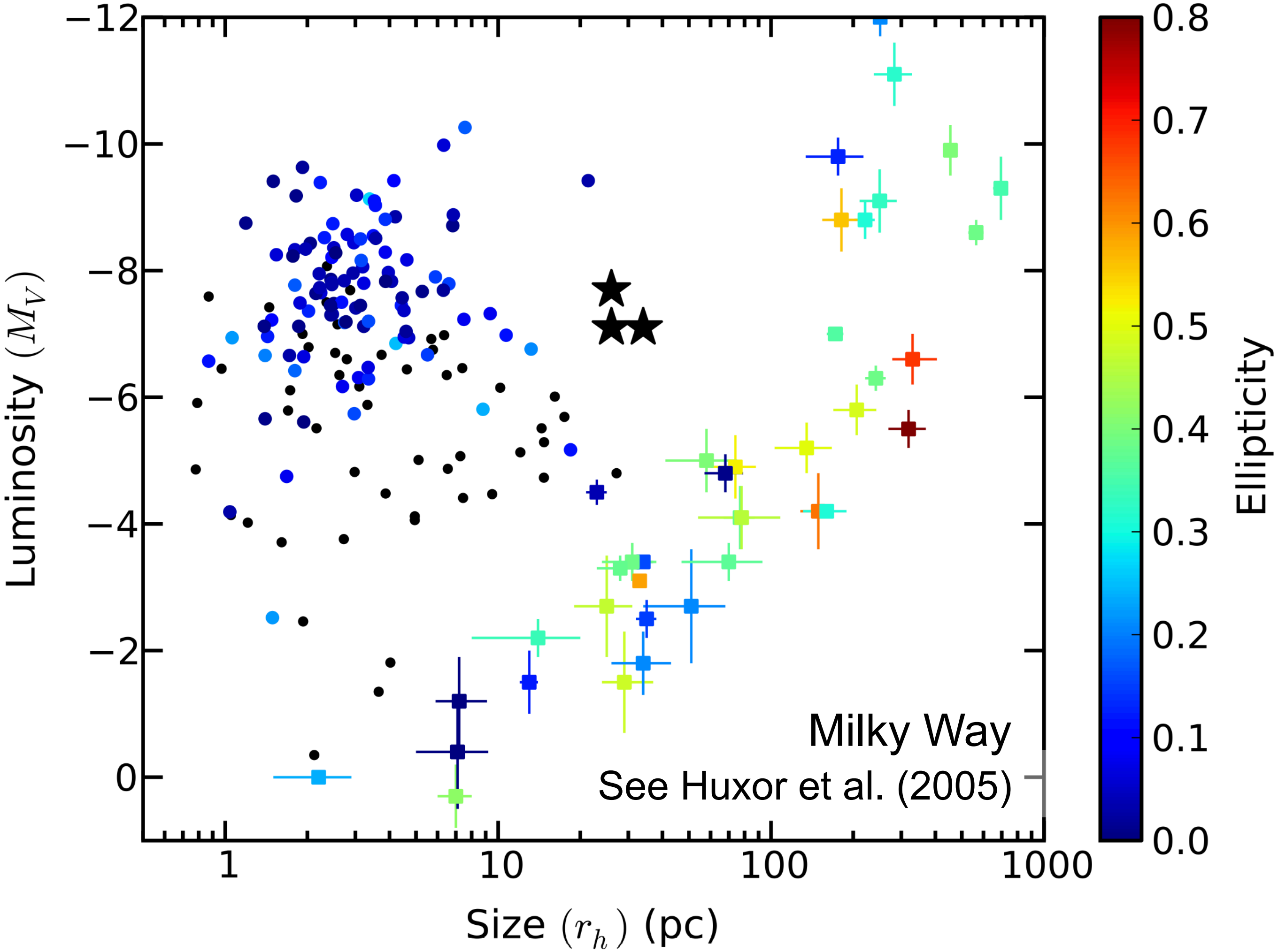
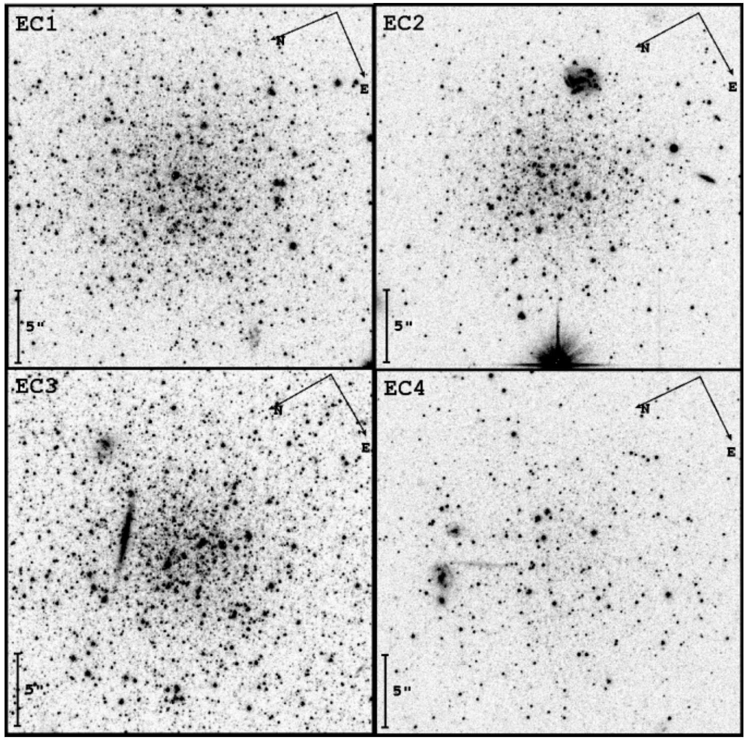
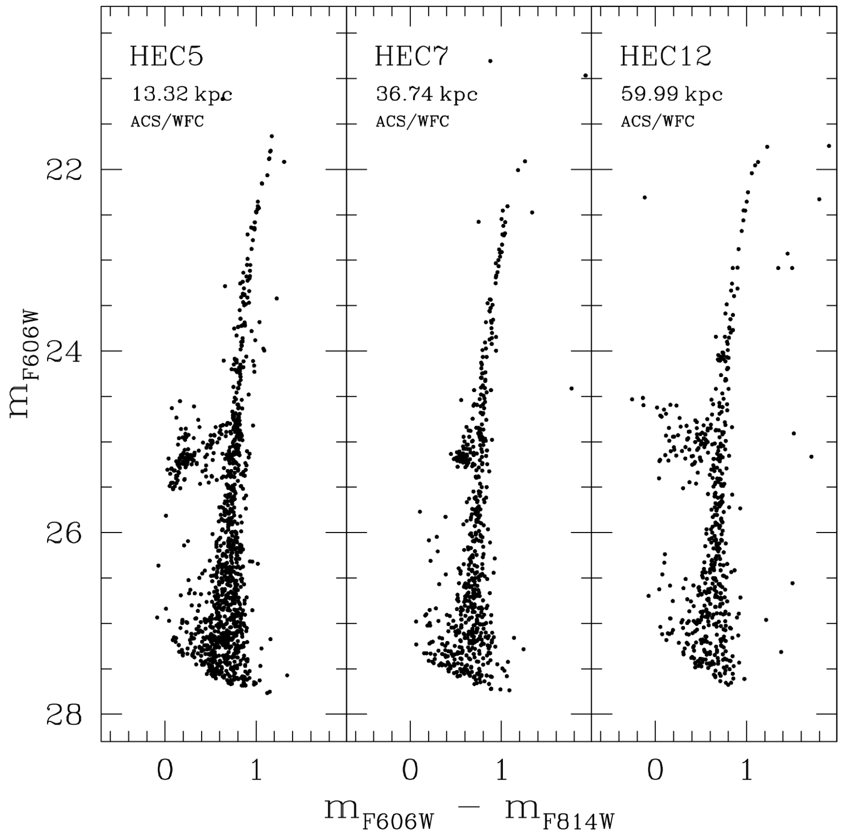


What is the nature of these objects?





Mackey et al. (2006): HST imaging shows stellar populations completely consistent with these objects being globular clusters.

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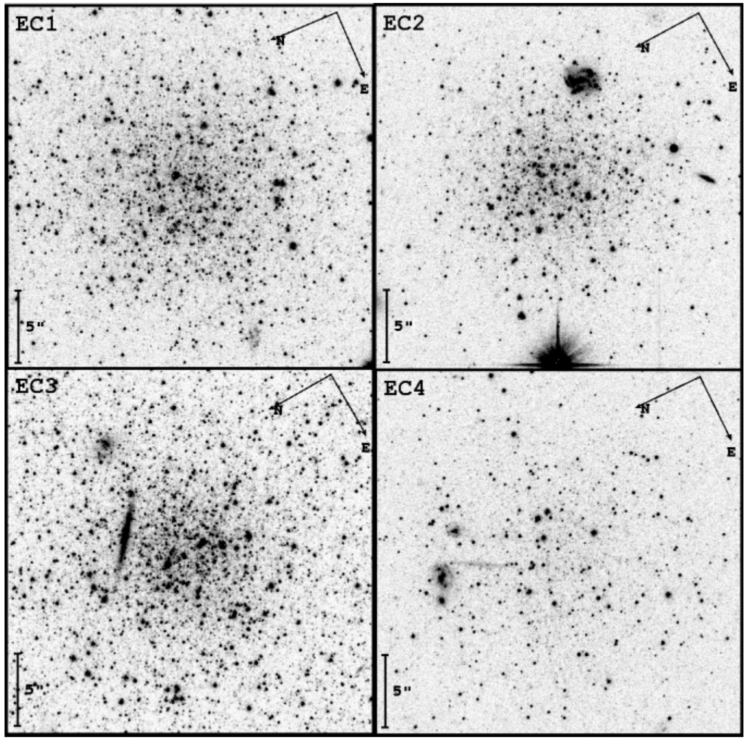

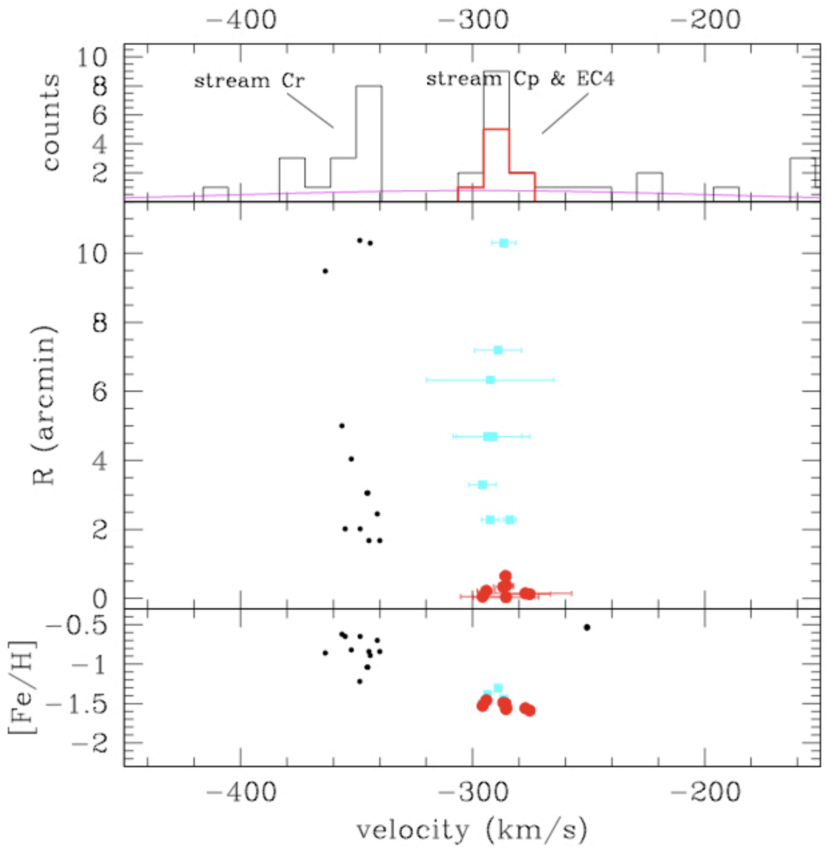

Collins et al. (2009): Keck DEIMOS stellar velocities show evidence for a kinematic association with an underlying stream (more later)

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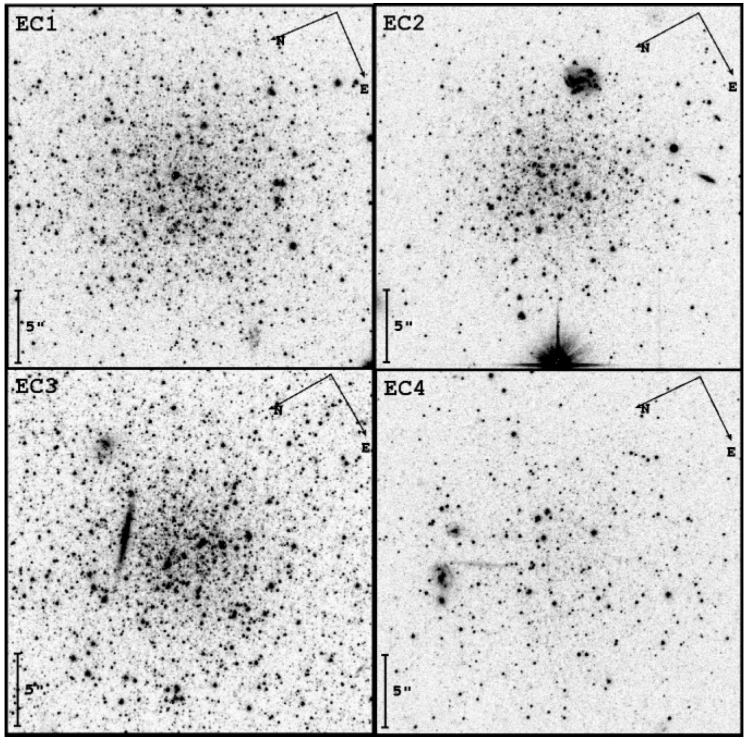
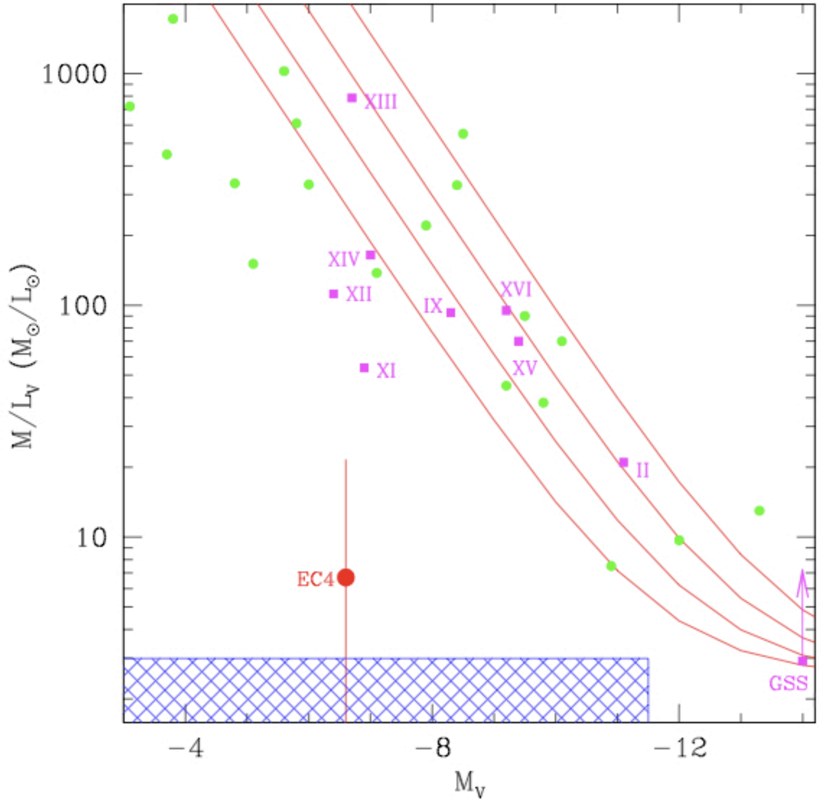
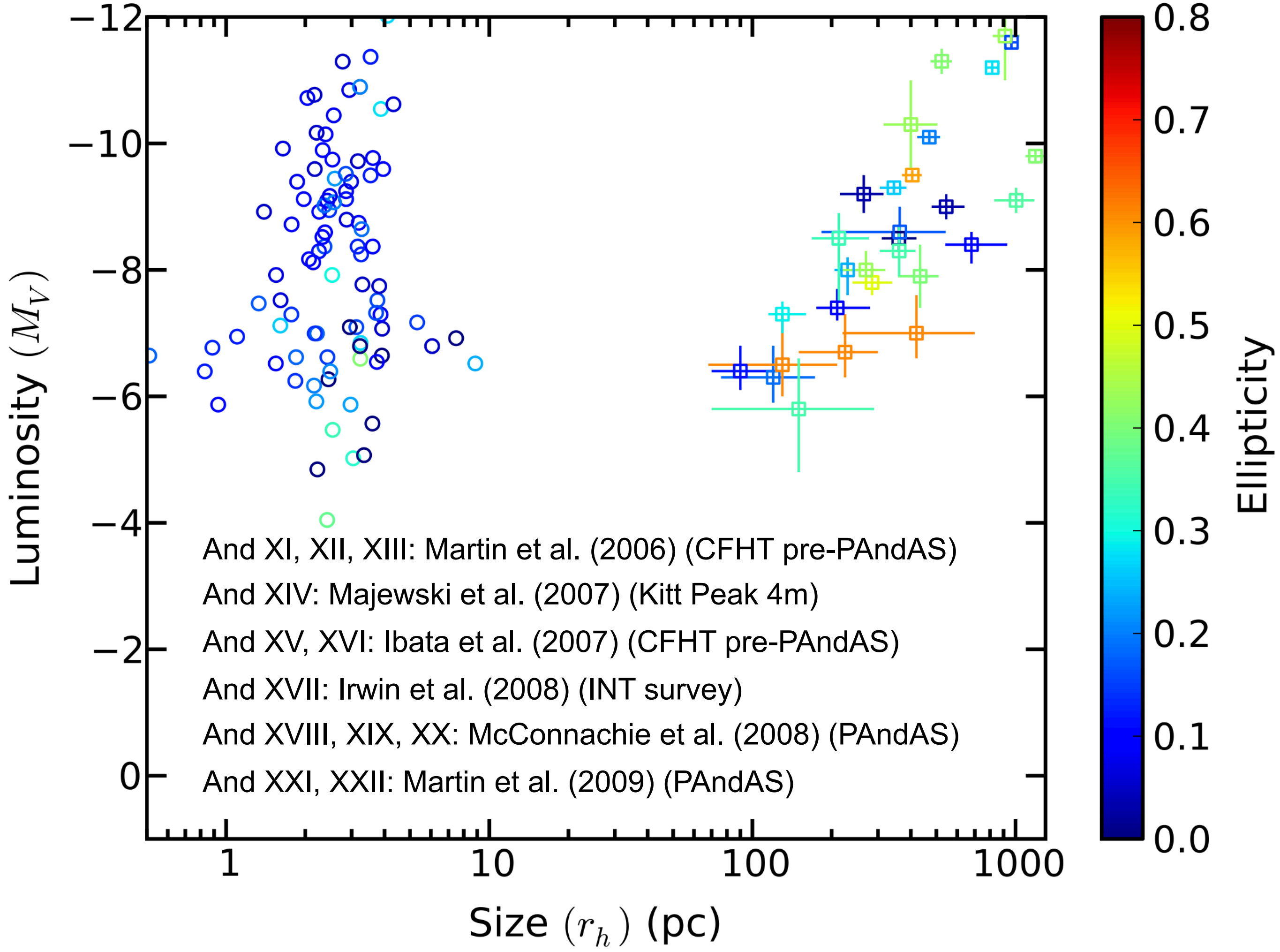




Collins et al. (2009): Implied mass-to-light ratio from dispersion is $6.7^{+15}_{-6.7}$
Completely consistent with that expected for a GC, not dwarf

Lots (and lots) of new M31 dwarf satellites



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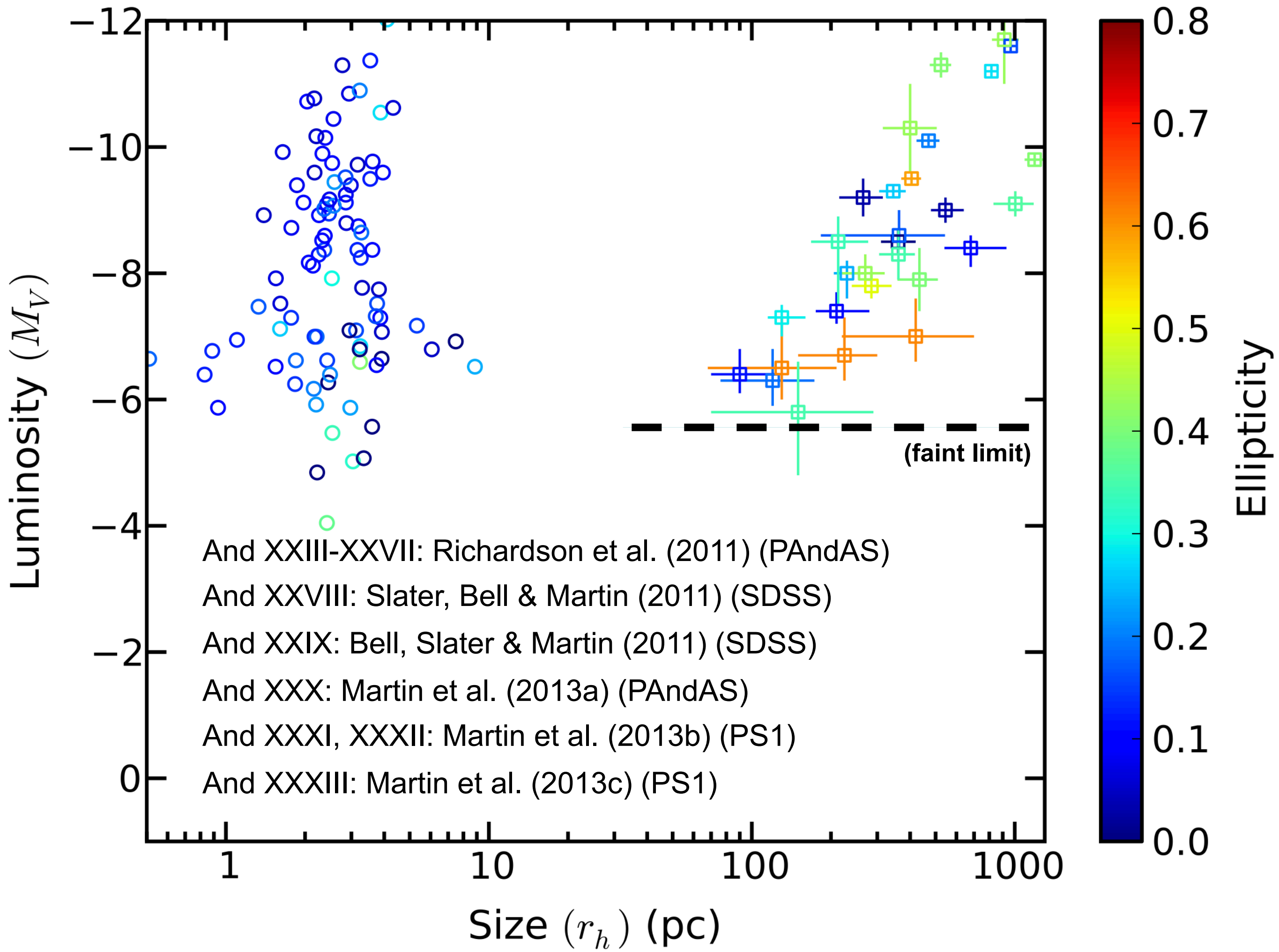

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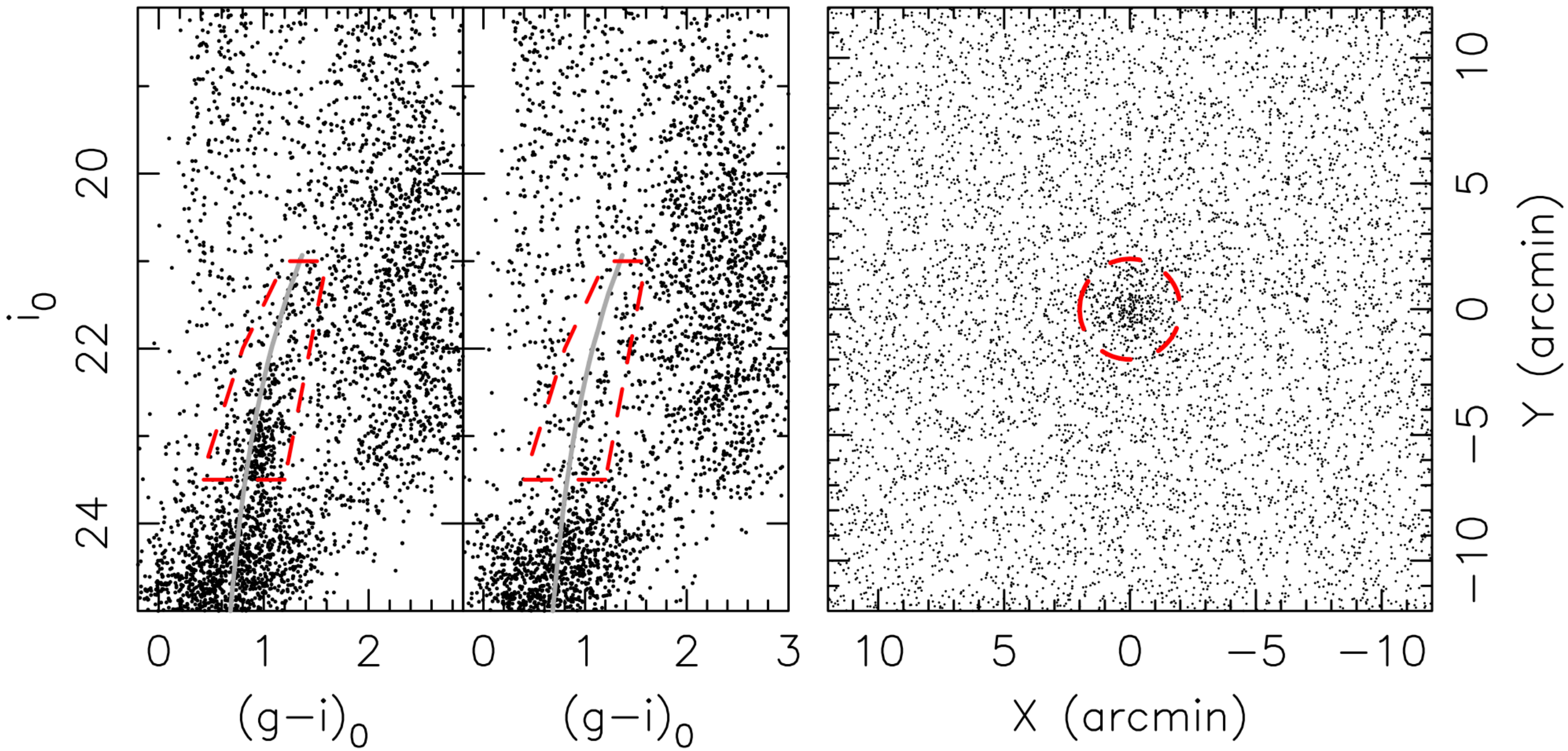
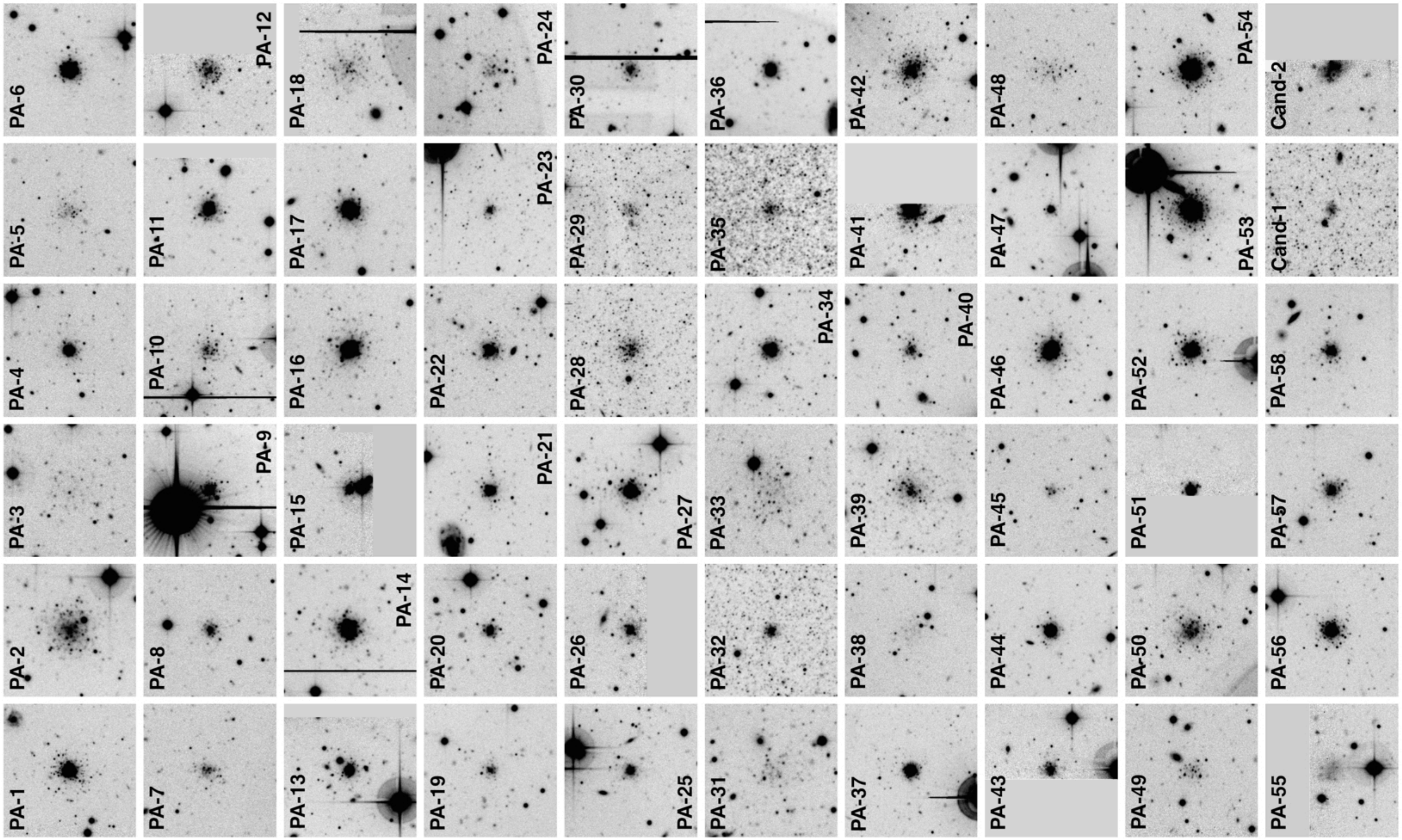


Martin et al. (2013): Search algorithm on PAndAS data finds all known dwarfs plus 39 isolated candidates below faint limit (here stacked).

Globular clusters in PAndAS

- Until (very) recently, only GCs in the very inner regions (~ disk) of M31 had been studied.
- Prior to PAndAS++, 34 (of ~ 450) known GCs at > 15 kpc, of which just 3 > 30 kpc.
- We have discovered 97 GCs outside 15 kpc, of which 80 lie outside 30 kpc (to 145 kpc!)
- For comparison, in the Milky Way, just ~12(?) GCs are known beyond 38 kpc (= 30 x 4/π).
- See Huxor et al. (2008); Huxor, Mackey, Ferguson, et al. (2014), MNRAS, 442, 2165

- Also, 22 independent discoveries from SDSS(!) – some overlap with PAndAS catalogue.
- See di Tullio Zinn & Zinn (2013, 2014, 2015)



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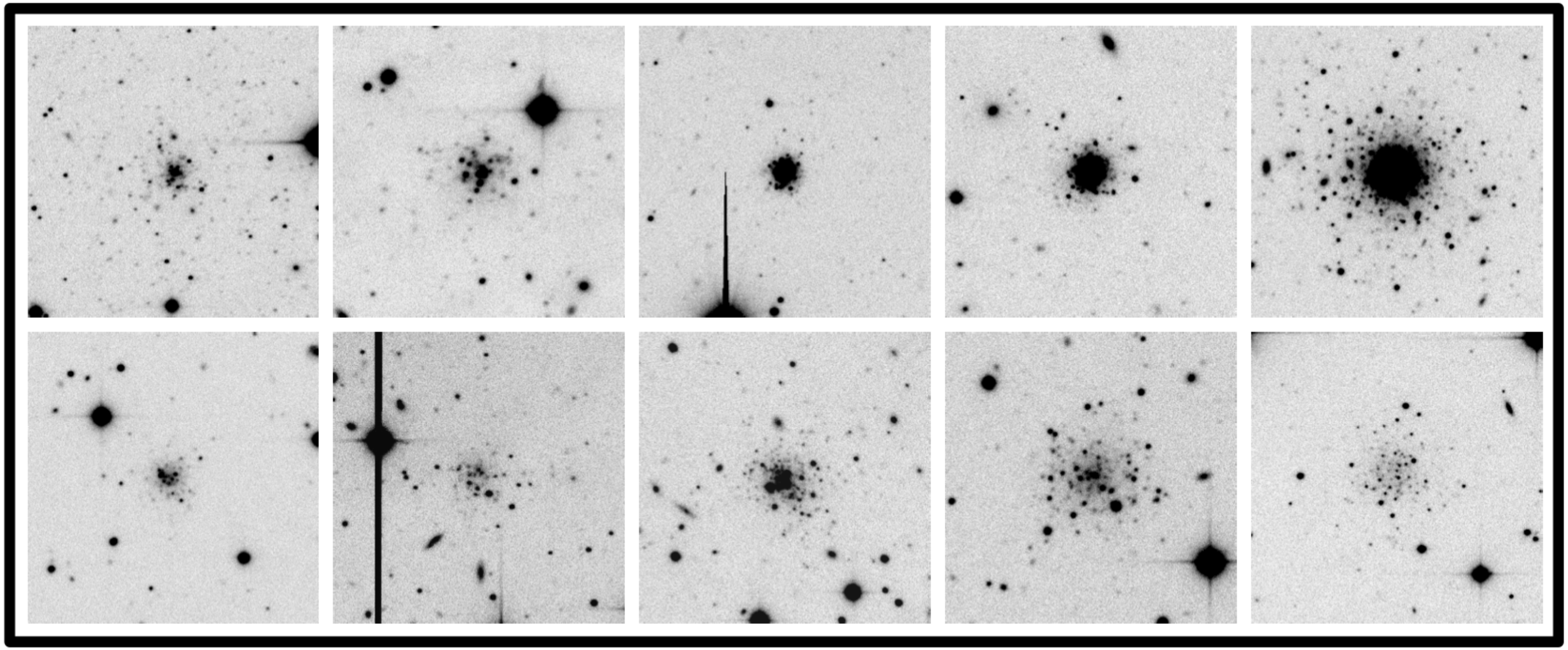

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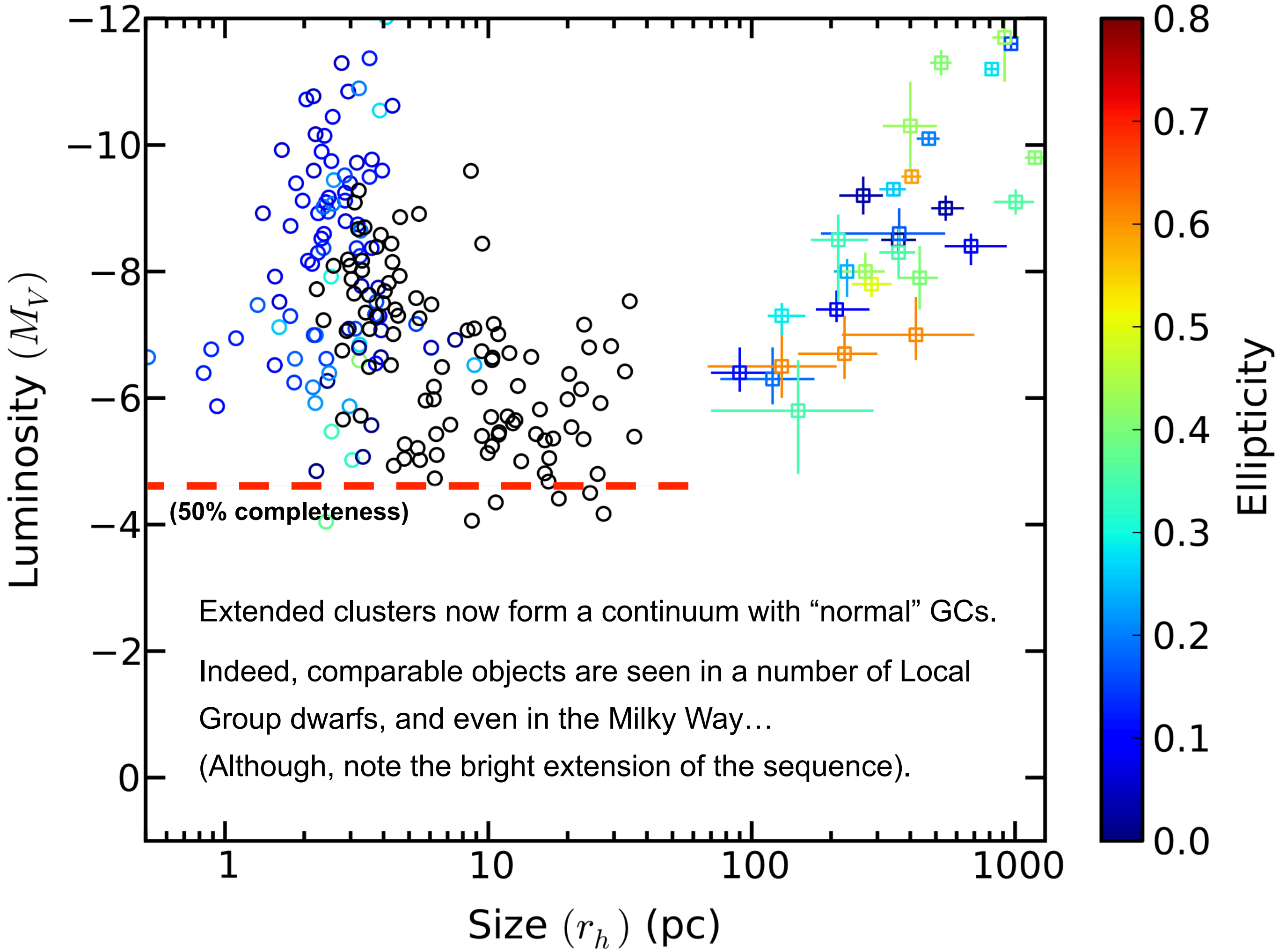
PAndAS clusters on the size-luminosity plane



Extended clusters now form a continuum with "normal" GCs.

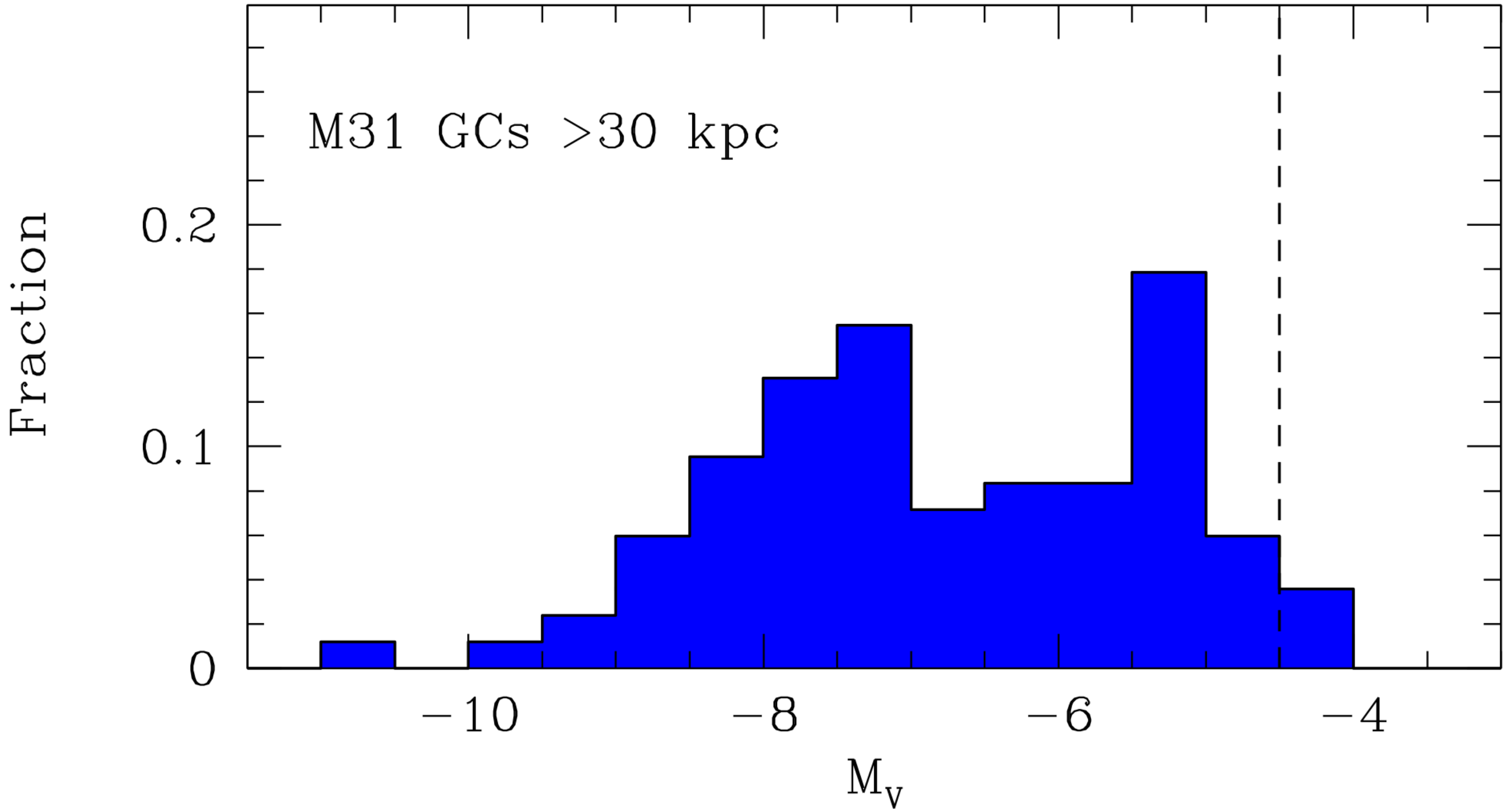
Indeed, comparable objects are seen in a number of Local Group dwarfs, and even in the Milky Way…

(Although, note the bright extension of the sequence).

Luminosity function for M31 outer halo GCs

Has a second (faint) peak, quite different from the “universal” LF

See Huxor et al. (2014)



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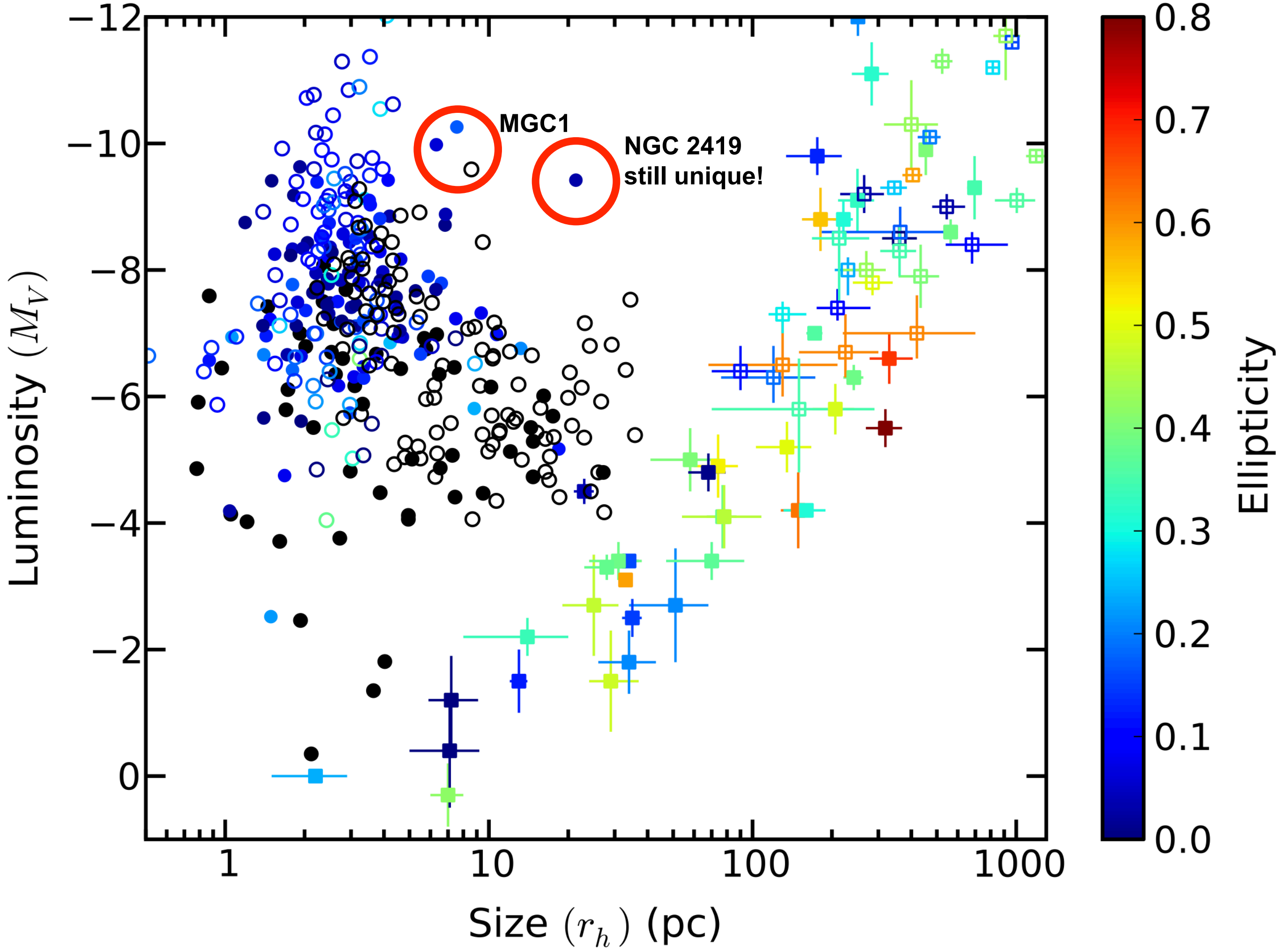
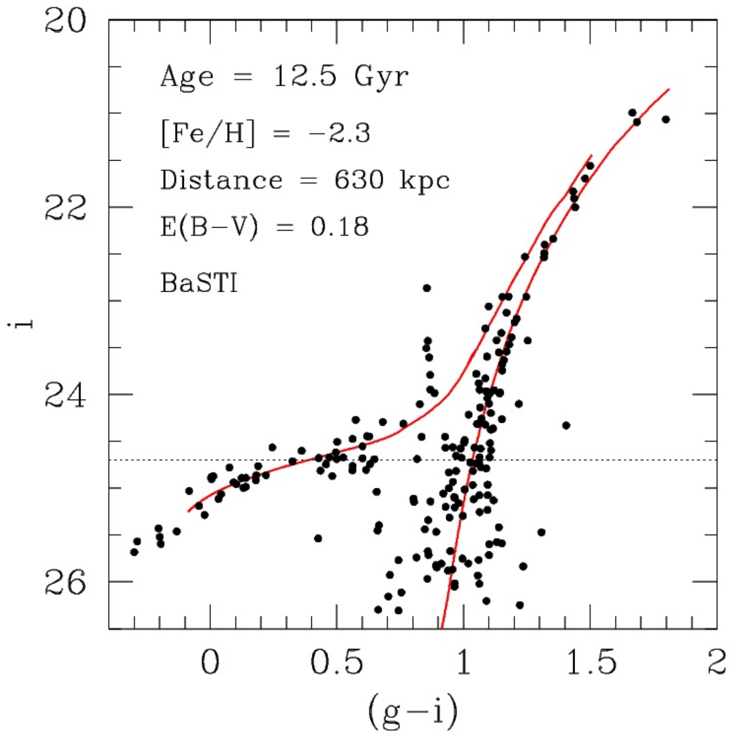
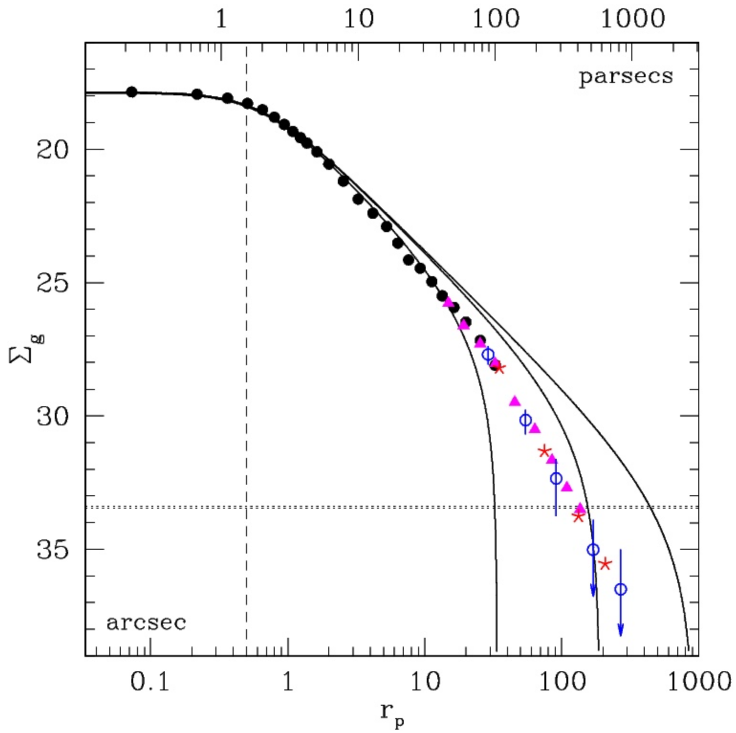


The extremely isolated cluster MGC1

Discovered by Martin et al. (2006), deep imaging by Mackey et al. (2010)





Lies at 200 kpc from M31, very metal poor, King model cannot fit density profile.

Conroy, Loeb & Spergel (2011) – profile rules out that it has a dark matter halo.

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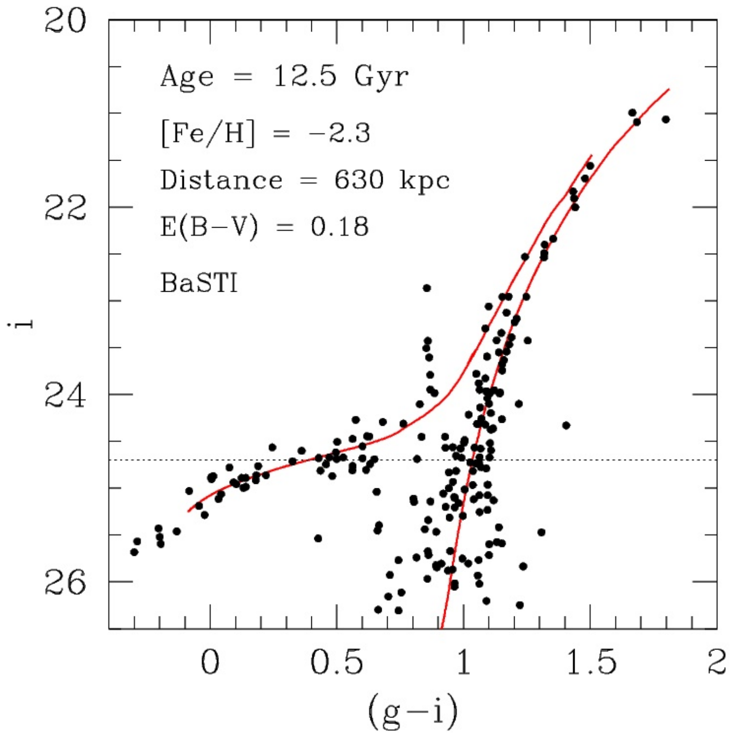

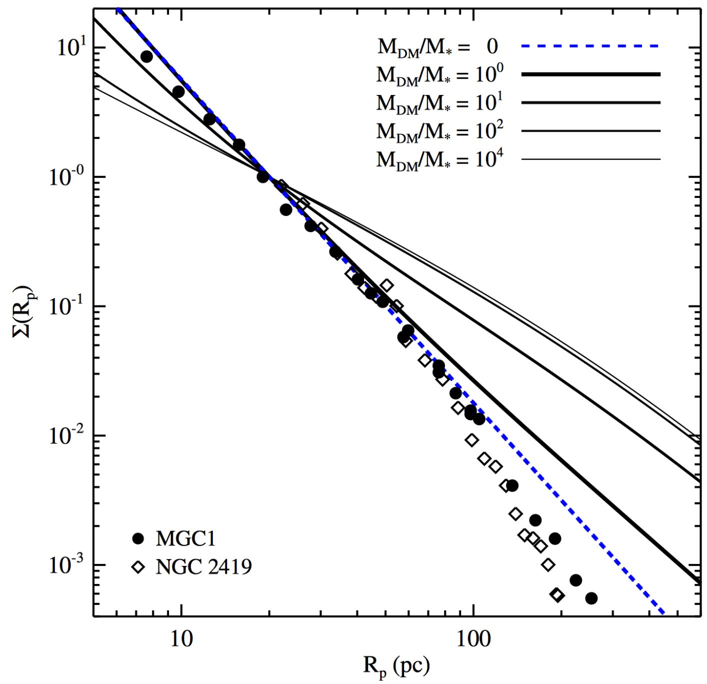

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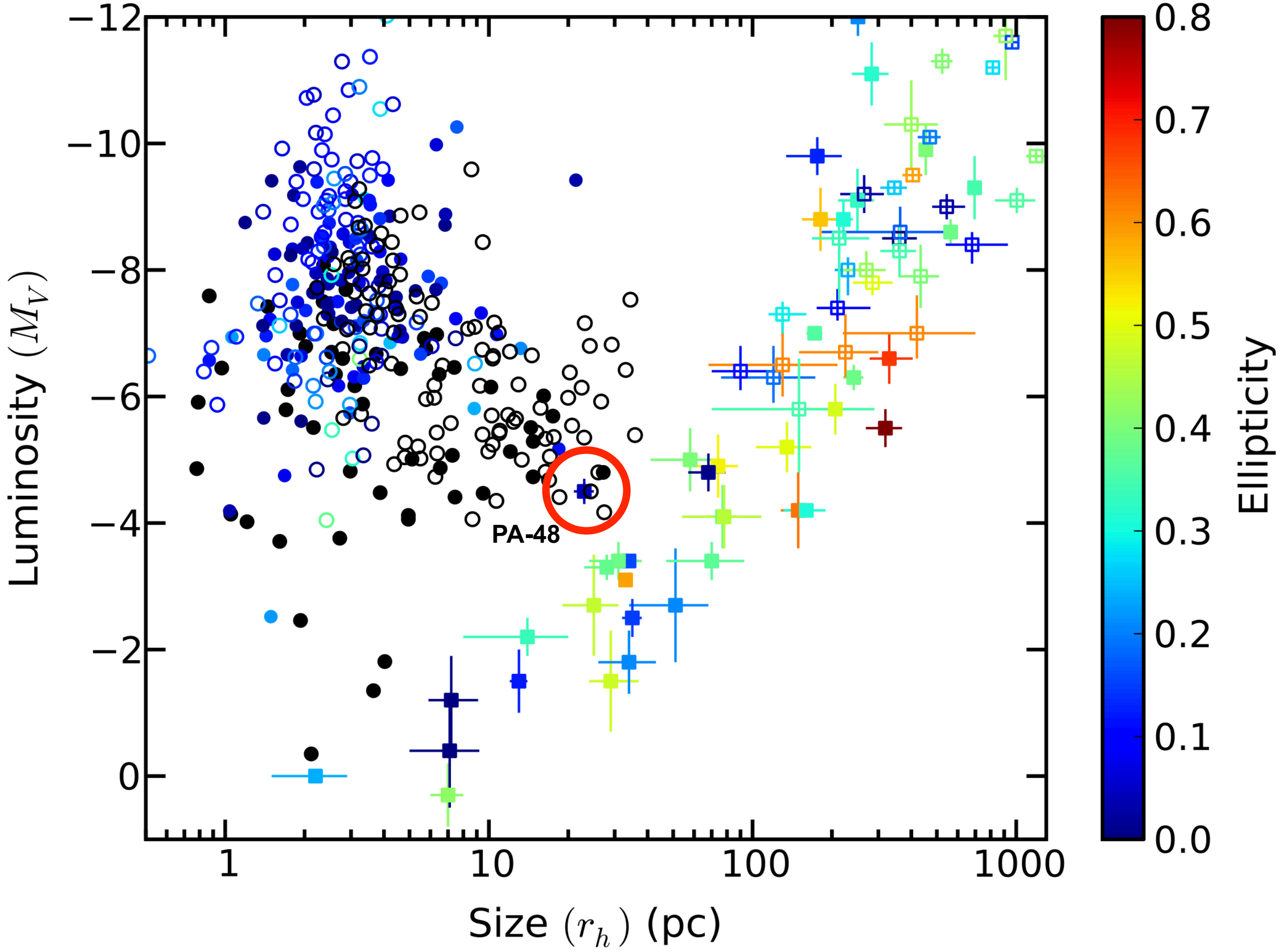
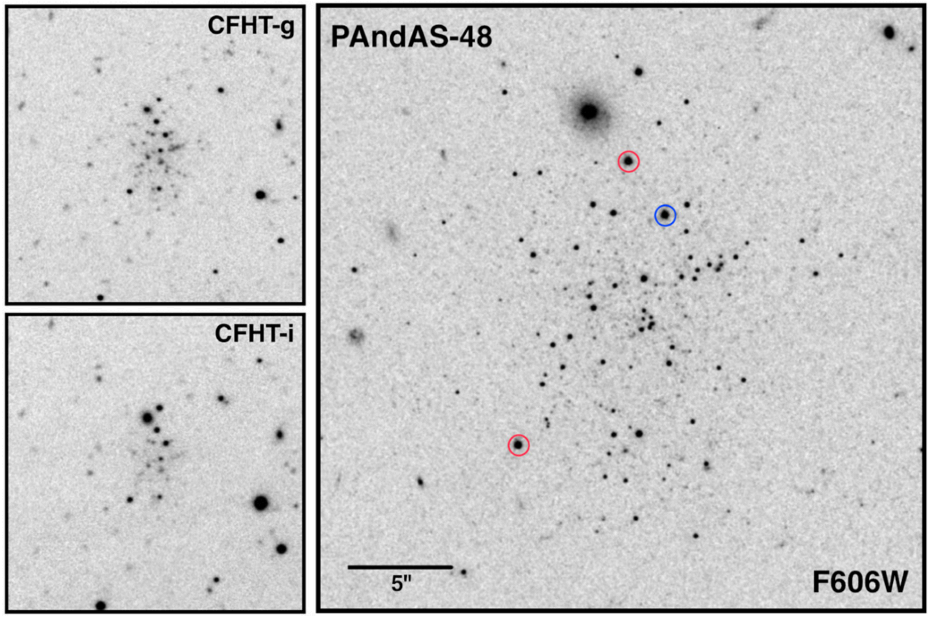
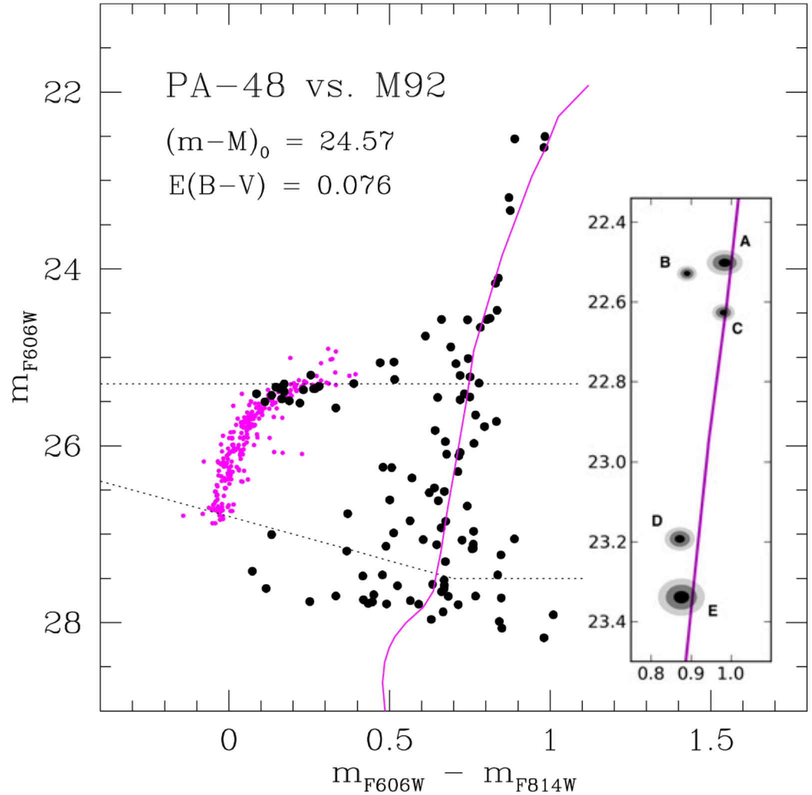


The unusual cluster(?) PA48

A faint (M_V ~ -4.5) stellar system lying at 150 kpc from the centre of M31
Very metal-poor, with [Fe/H] < -2.3 (fits luminosity-metallicity relationship)
Object is more elliptical than almost all known GCs (e ~ 0.3)





Mackey et al., 2013, ApJ, 770, L17

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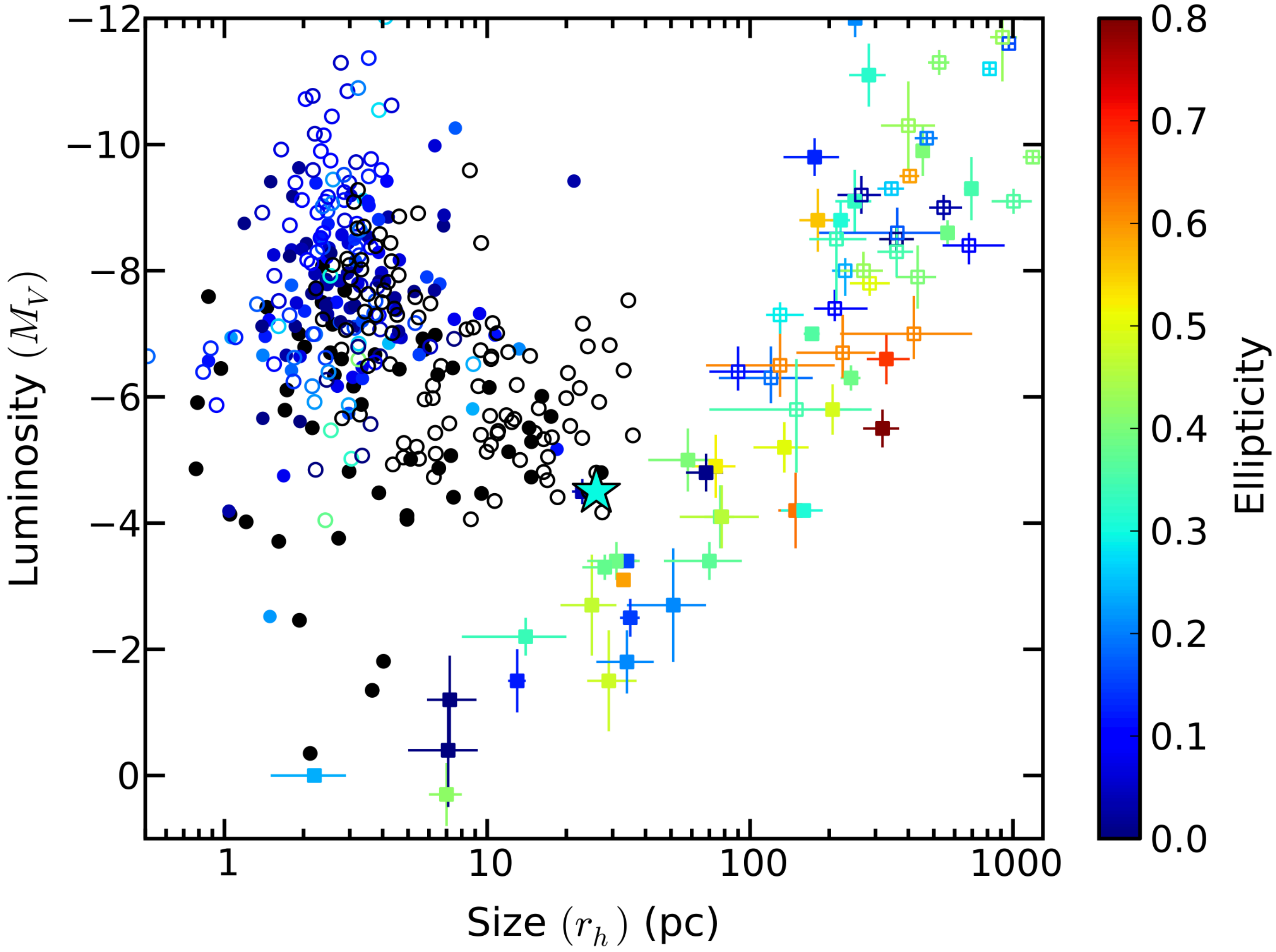

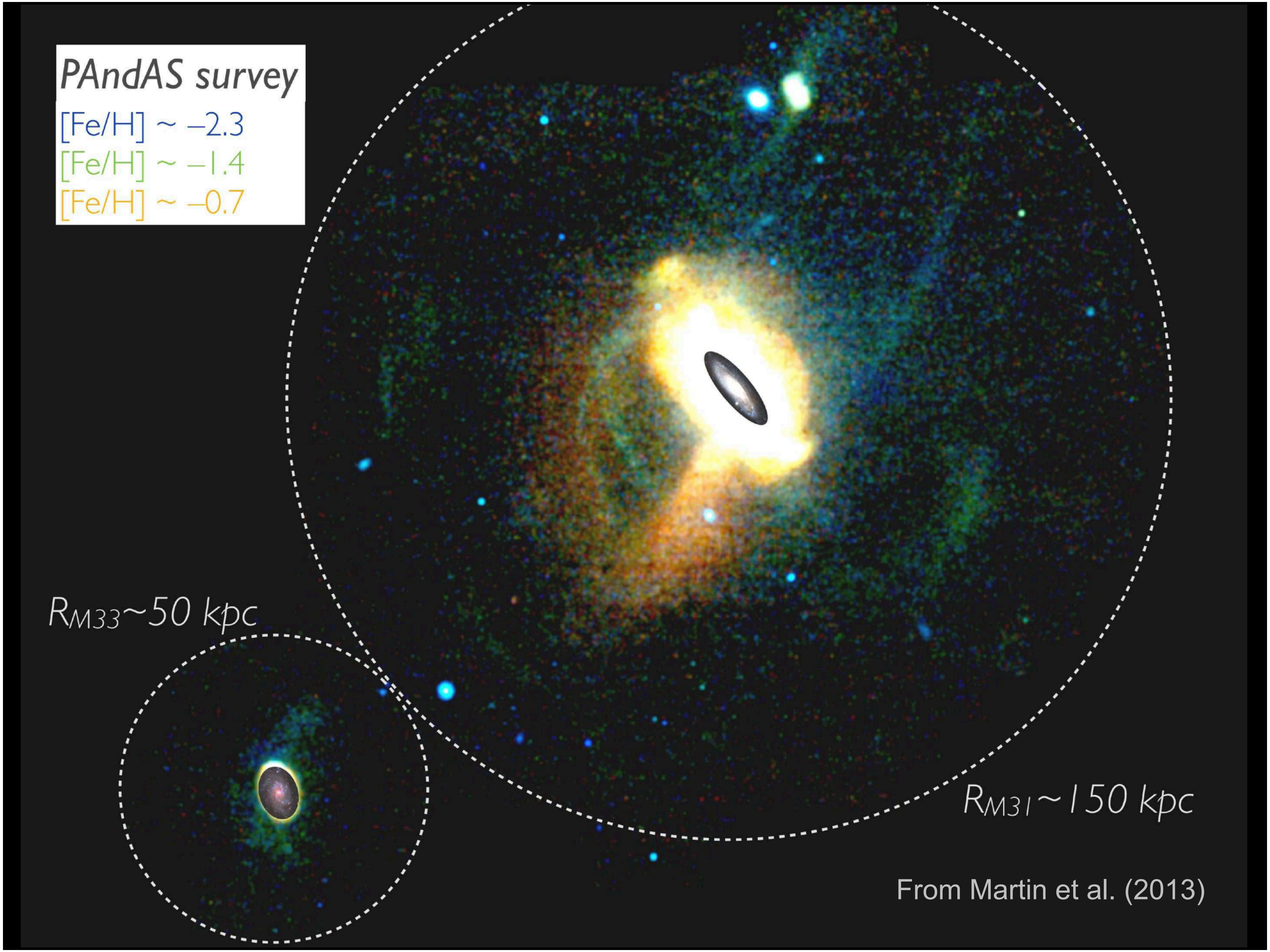

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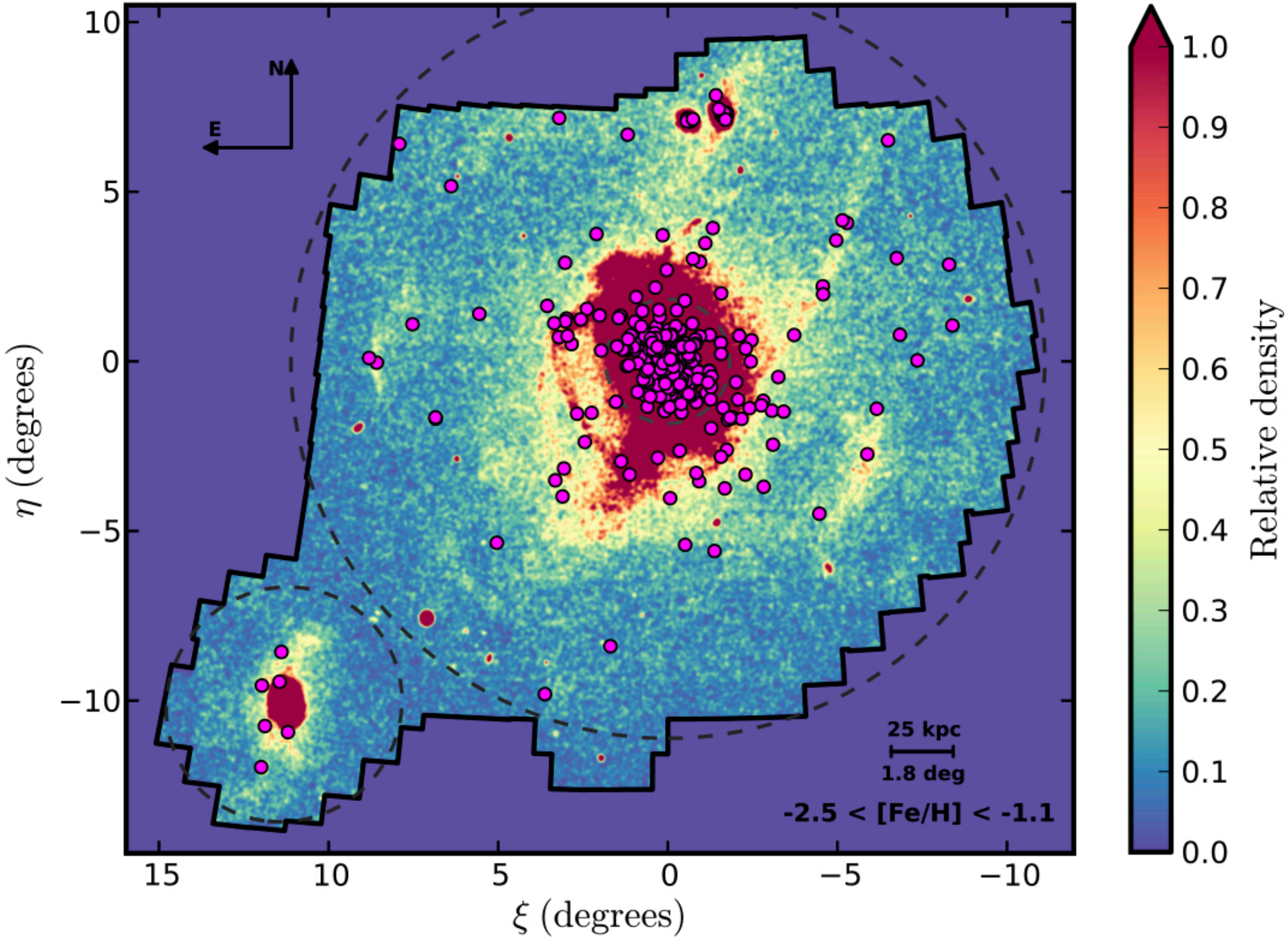


(Mackey et al., 2010, ApJ, 717, L11; Mackey et al., 2015, MNRAS, in prep.)

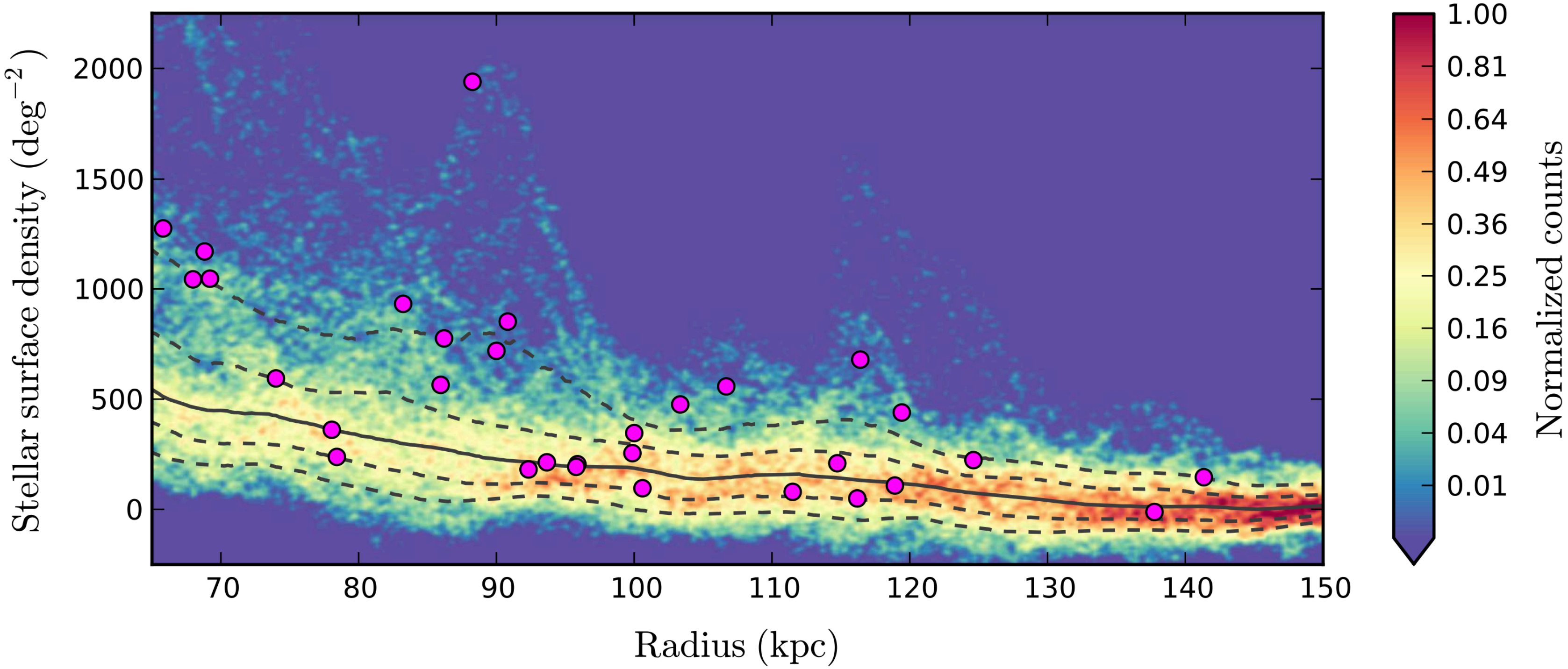
GC-stream association in M31

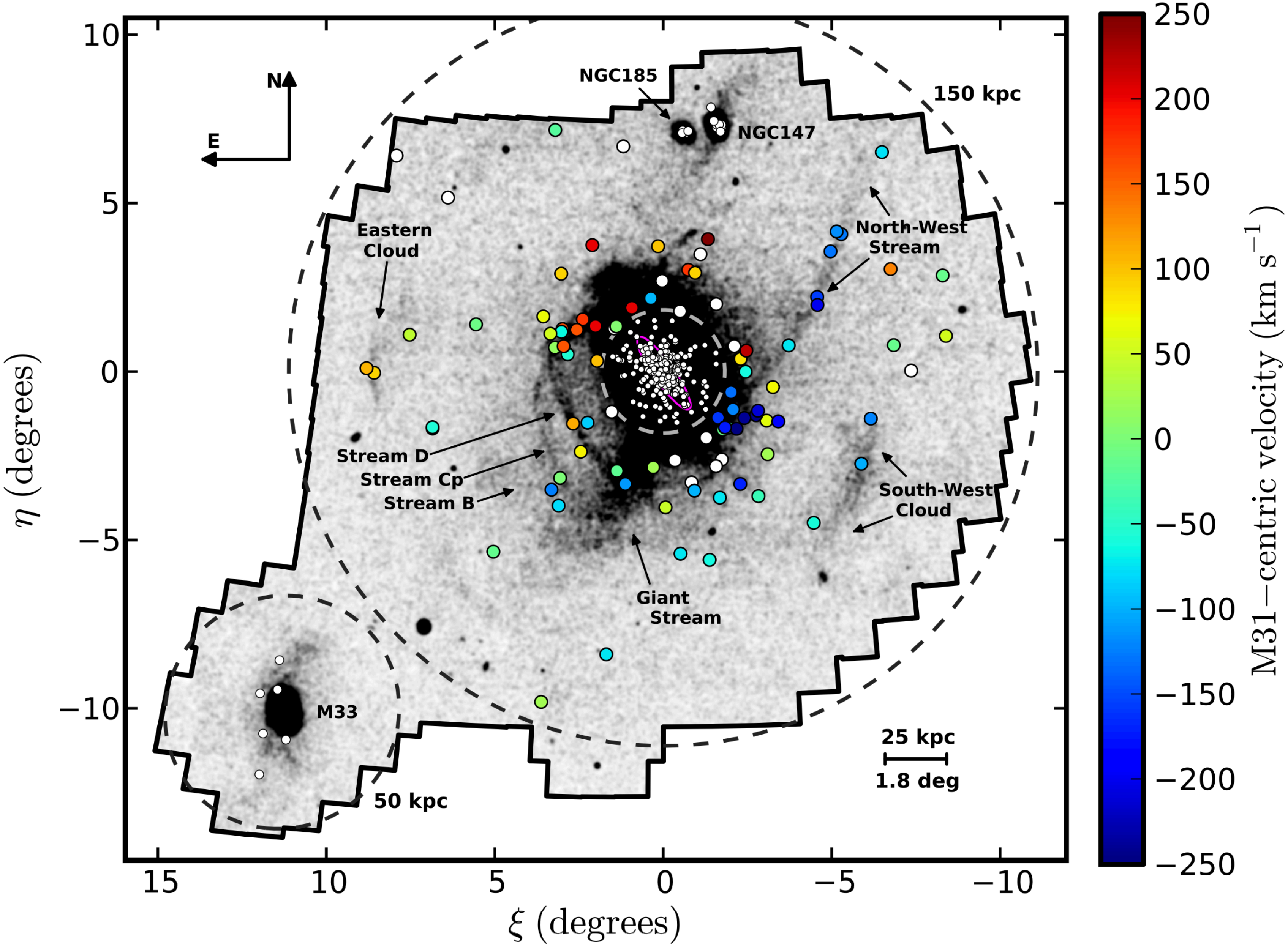
Count M31 metal-poor RGB stars around each GC (correct for contamination).

Compare to distribution for all locations at a given radius, many GCs have excess

In fact, 45% of GCs >30 kpc sit in top 25th percentile; 25% in top 10th percentile

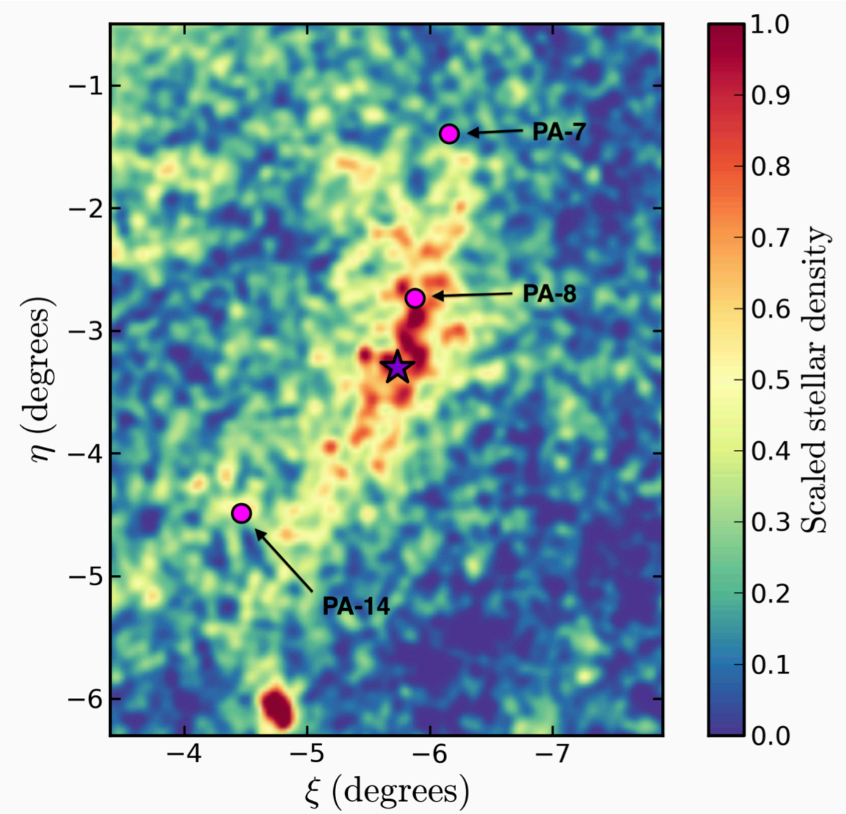
Chance of this happening randomly in a smooth GC distribution << 1%

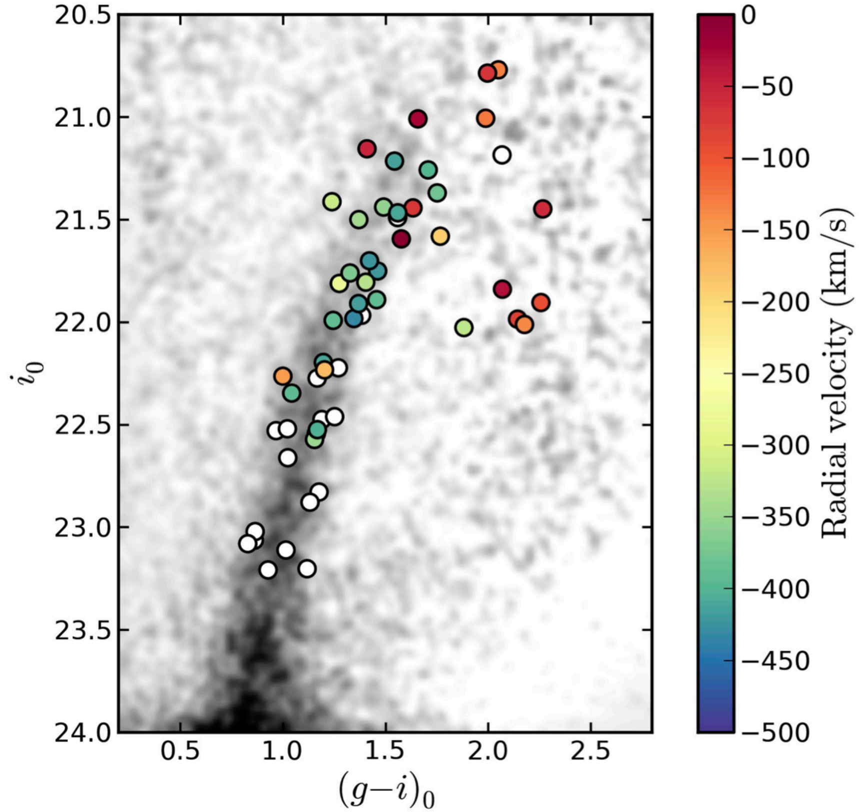




(Veljanoski et al. 2013, ApJ, 768, L33; Veljanoski et al. 2014, MNRAS, 442, 2929)

Kinematics of M31 halo GCs





(Mackey, Lewis, Collins, et al., 2014, MNRAS, 445, L89)

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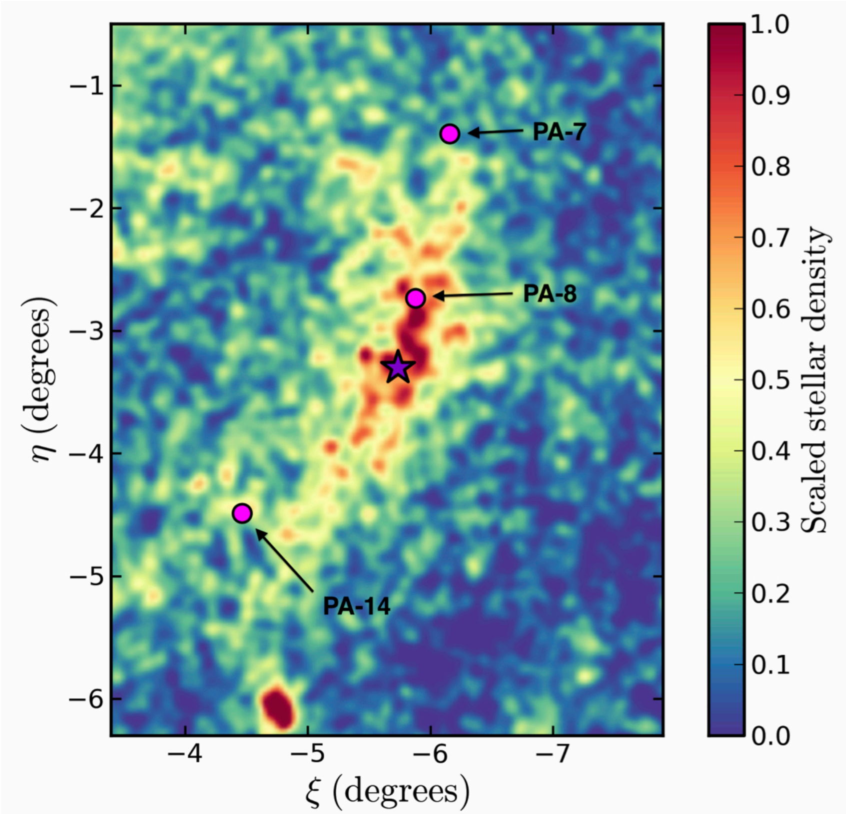
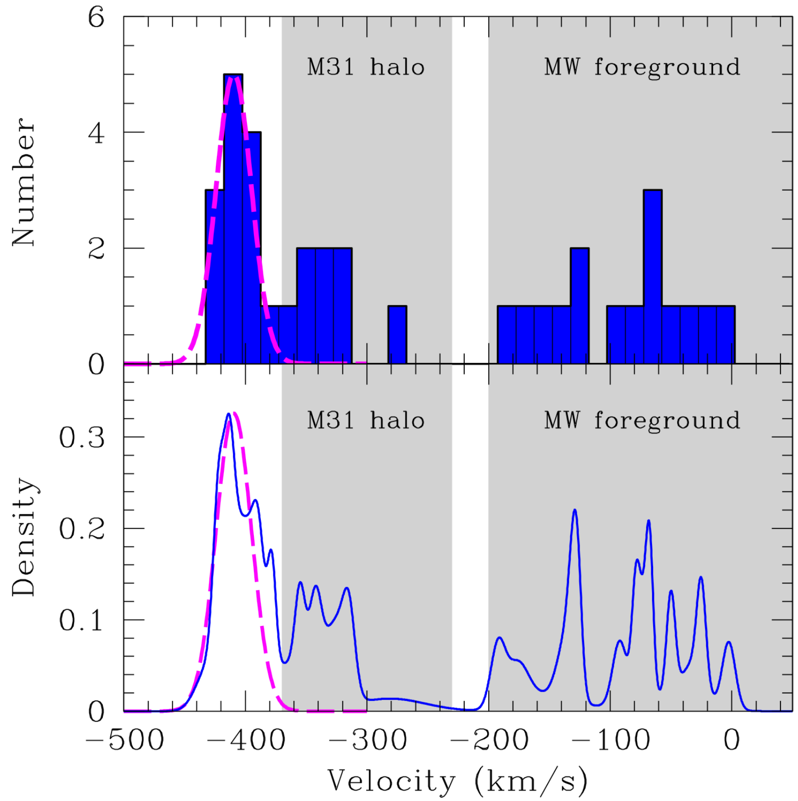




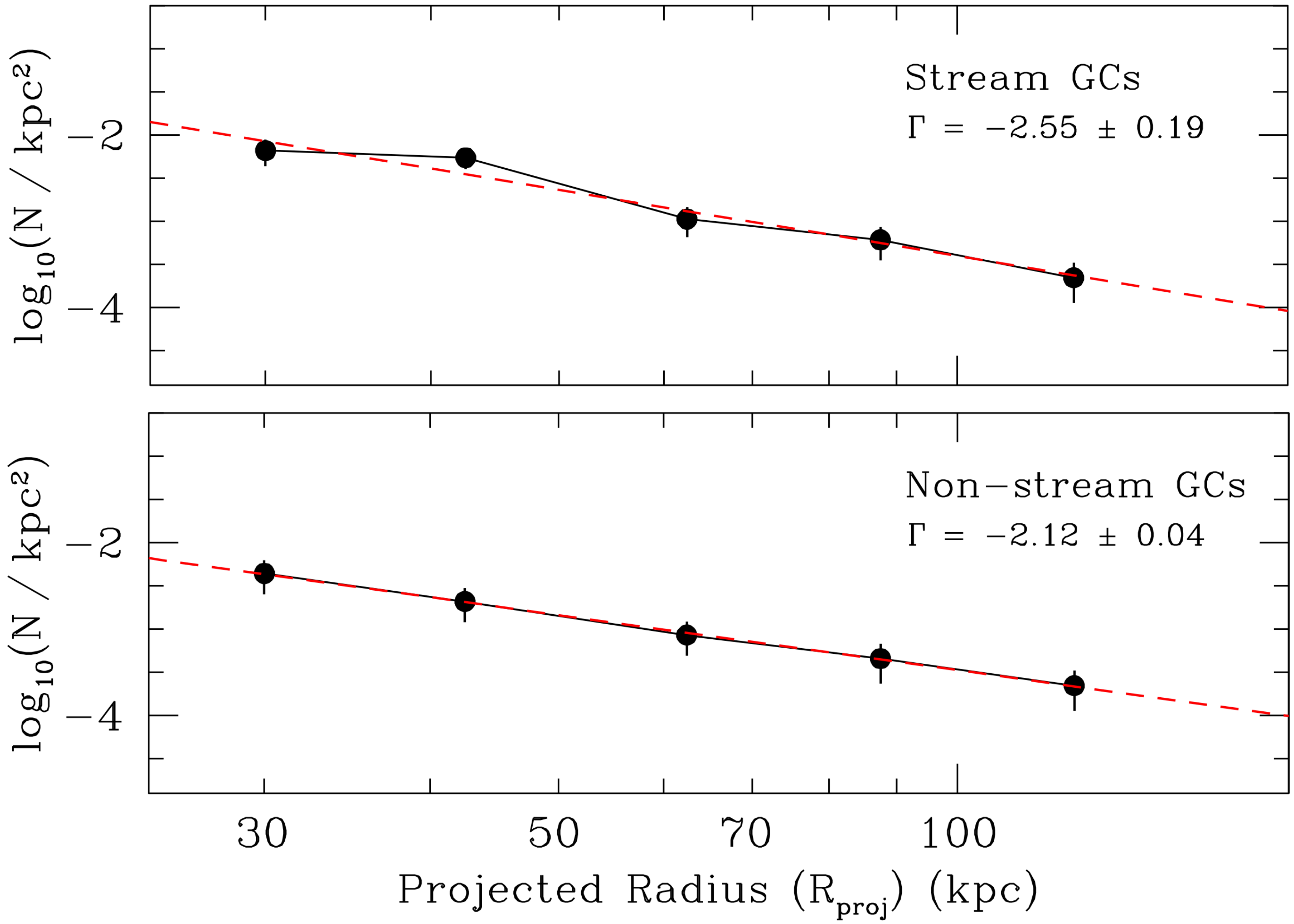
- Measure velocity = -408 ± 3 km/s → PA-8 has velocity = -411 ± 4 km/s.
- Dispersion ~ 13 ± 3 km/s. (Can this tell us about disruption of progenitor?)

 (Mackey, Lewis, Collins, et al., 2014, MNRAS, 445, L89)

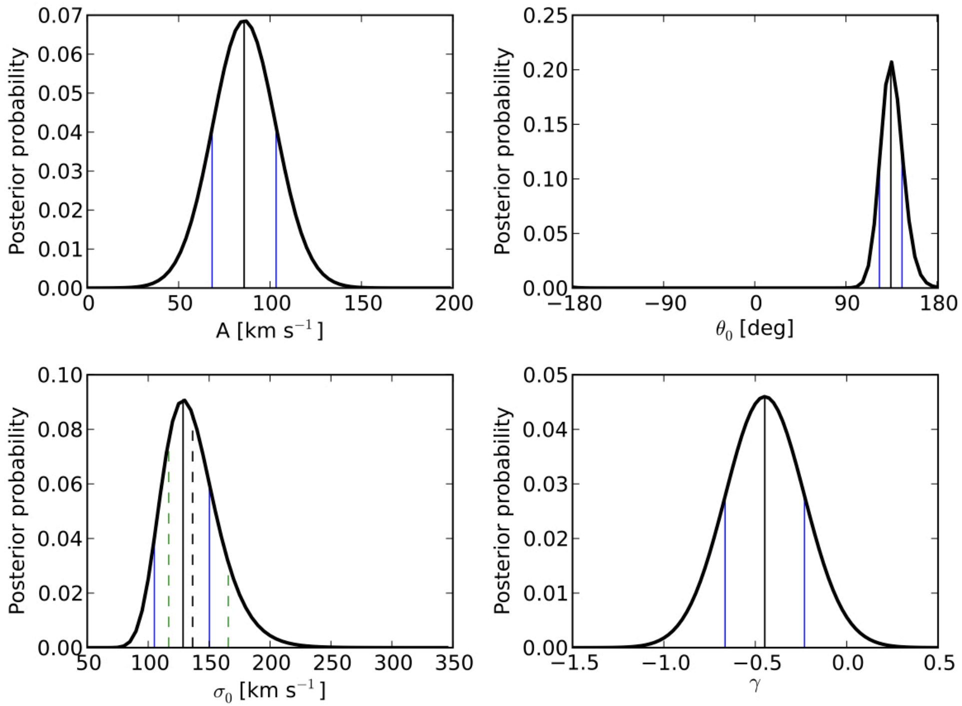
Stream and non-stream GC subgroups

- Use local densities and velocities to split the outer halo GC population
- This can be done pretty unambiguously with present data – (hopefully) clean samples
- The split is 60-40 into “stream” and “non-stream” sub-populations
- Within the uncertainties, this fraction remains constant with radius outside ~30 kpc.
- Global properties (luminosity, size distributions) largely indistinguishable.

Stream and non-stream GC subgroups



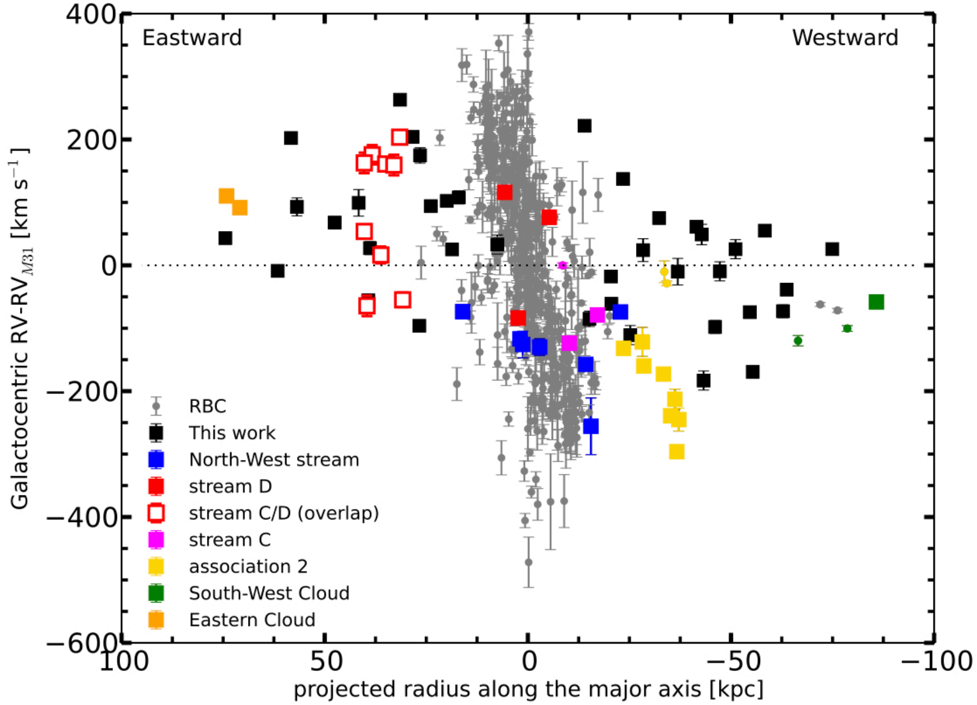
Global kinematic properties



- Set up a simple four-parameter model for the GC halo kinematics…
- Constant rotation amplitude, fixed PA, power-law velocity dispersion with radius.
- Use a maximum likelihood method to find the “best” values of these given the data.

(Veljanoski et al., 2014, MNRAS, 442, 2929)

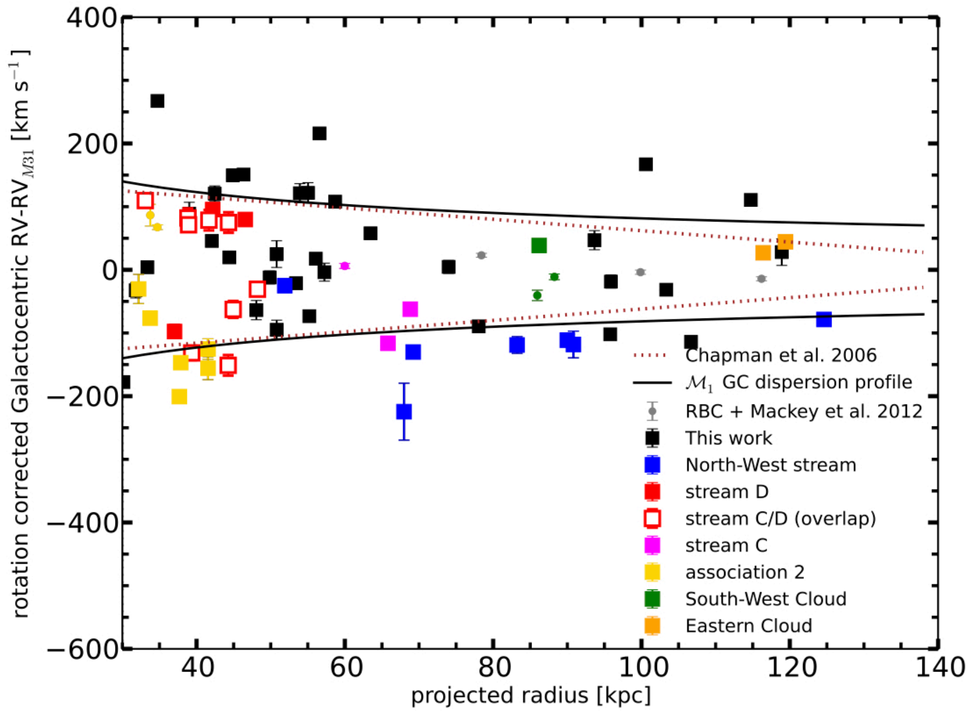
Global kinematic properties



- Rotation amplitude = 86 ± 17 km/s; zero rotation ruled out at very high significance.
- Position angle = 135 ± 25 deg east of north, matches precisely the M31 minor axis.
- The rotation is not driven solely by GCs sitting either on or off major substructures.

 (Veljanoski et al., 2014, MNRAS, 442, 2929)

Global kinematic properties



- Velocity dispersion at R_p = 30 kpc is 130 ± 23 km/s.
- The dispersion appears to decrease with radius: Υ = -0.45 ± 0.22 (negative at ~2σ)
- Very similar behaviour to the field halo, at least to outermost measurements (~70 kpc).

 (Veljanoski et al., 2014, MNRAS, 442, 2929)

Summary

- The M31 size-luminosity plane is getting quite full (thanks to various wide-field surveys)
- More clusters (both in the centre and halo) and more (luminous) satellite dwarfs
- So, a greater variety of objects than in the MW, but occupied regions very consistent

- Extended clusters are just that – globular clusters with unusual structures

- GCs in the M31 outer halo trace streams – around 60% fall into a “stream” subgroup
- Stream GCs have a steeper radial fall-off than non-stream GCs
- Non-stream GCs fall-off precisely like the metal-poor smooth halo component

- Globally, the GC system rotates out to large radii, axis aligned with that of the disk
- Difficult to reconcile with “chaotic” accretion suggested by GC-stream alignment