GLOBULAR CLUSTERS THROUGHOUT THE LOCAL GROUP

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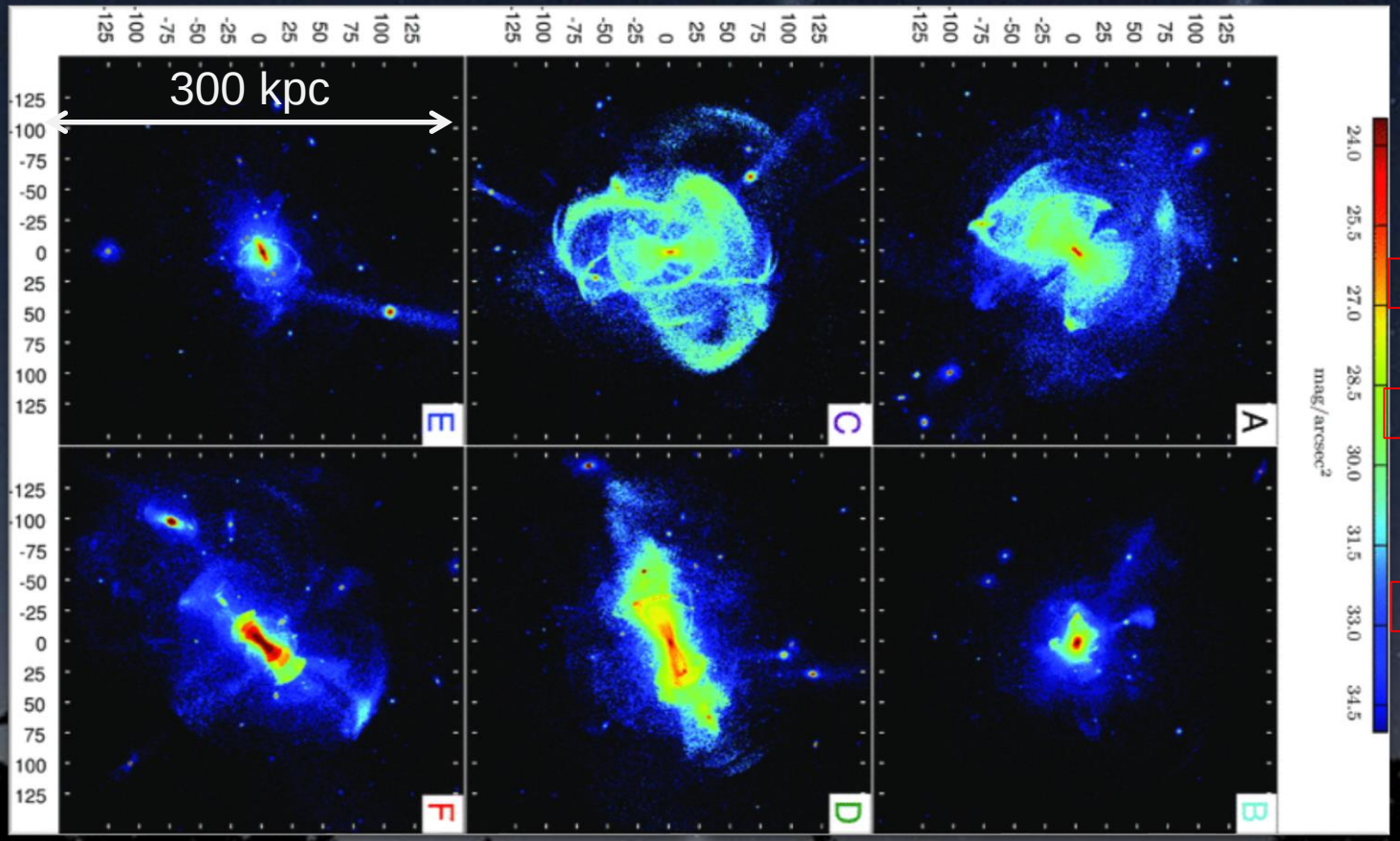
WHY ARE GCs USEFUL IN THE GALACTIC CONTEXT?

- Most GCs are ancient → they contain a record of the conditions in and around galaxies at very early epochs
- GCs are expected to form in major star formation events → their age and metallicity distributions should reflect this
- GCs are amongst the most luminous denizens of galactic halos → they offer a means to probe these enigmatic components to extreme radii and surface brightnesses
- They are found in all but the lowest luminosity galaxies, a population with which they share intriguing similarities and differences…

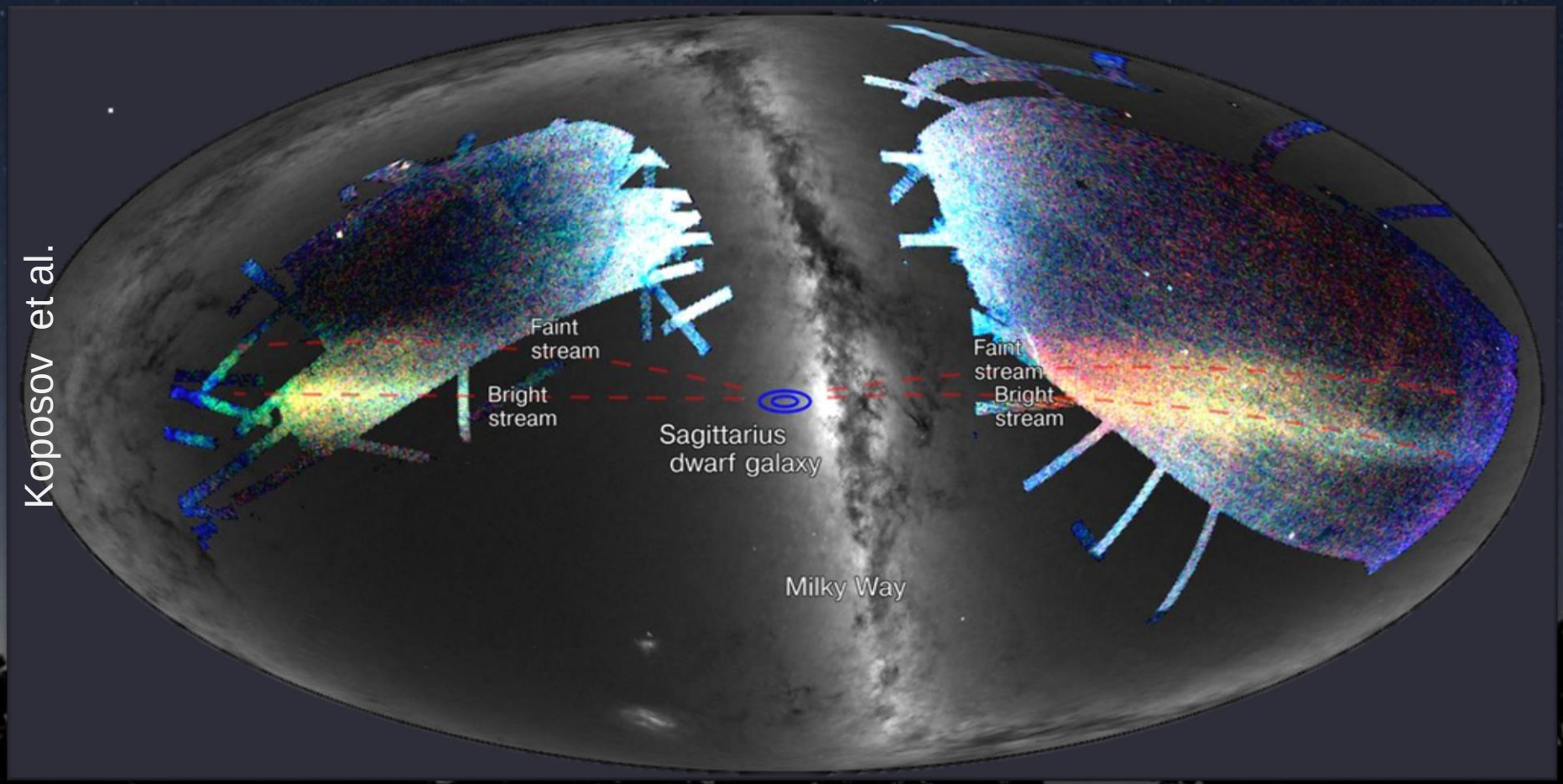
WHY ARE GCs USEFUL IN THE GALACTIC CONTEXT?



Cooper et al. 2010

Much low surface brightness substructure predicted around galaxies – both in intact satellites and disrupted ones

THE MILKY WAY IS NOT ALWAYS THE BEST TARGET



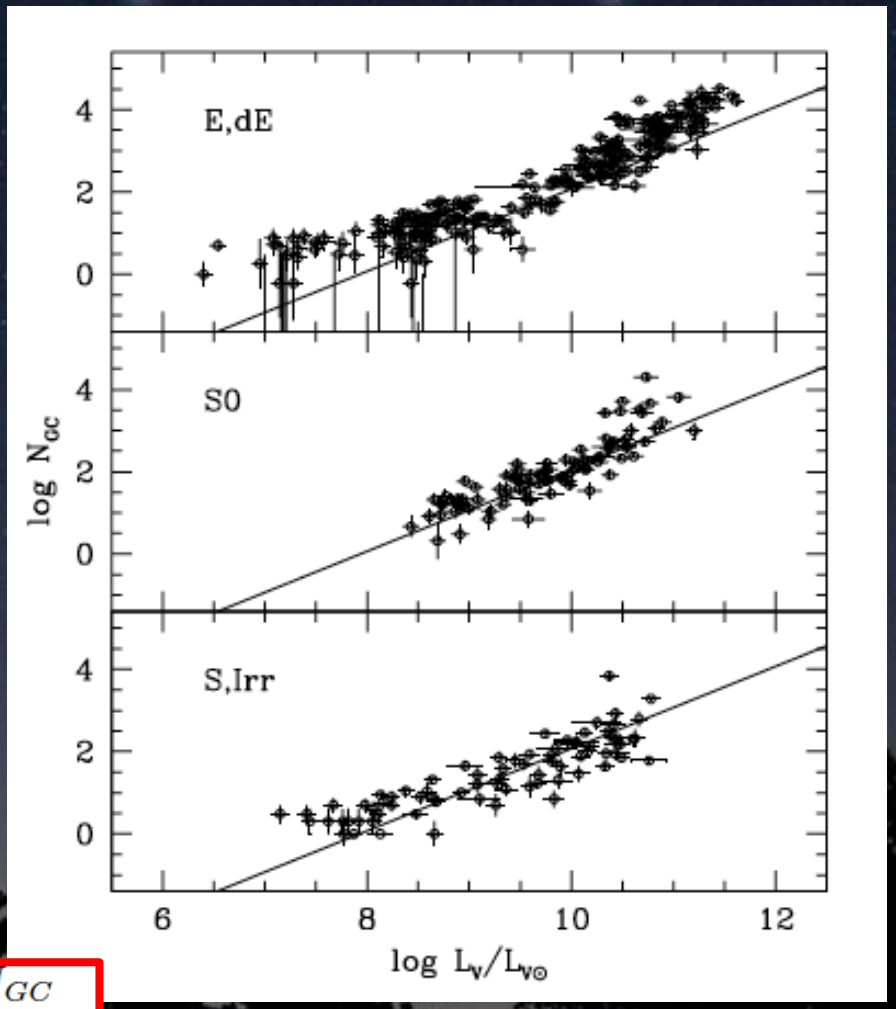
Koposov et al.

GLOBULAR CLUSTERS AND THEIR HOST GALAXIES

The number of GCs correlates strongly with host galaxy luminosity in all galaxy types

Deviations are seen at both high and low luminosities

Interpretation of this behaviour is very much an open question



Harris et al 2013

$$S_N \equiv N_{GC} \times 10^{0.4(M_V^T+15)} = (8.51 \times 10^7)\frac{N_{GC}}{L_V/L_{V\odot}}$$

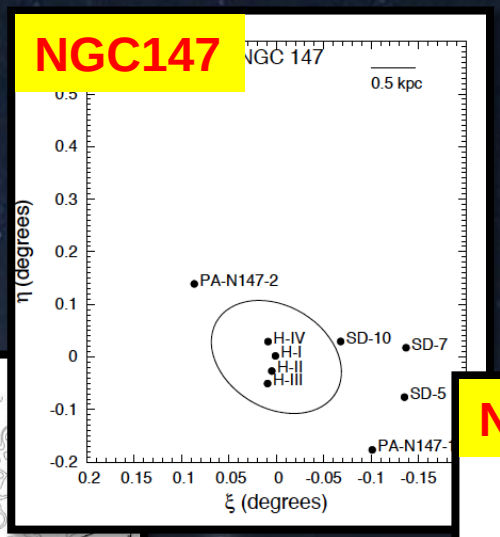
GLOBULAR CLUSTERS THROUGHOUT THE LOCAL GROUP

Huxor et al 2005, 2008, 2009, 2011, 2013a,b
Veljanoski et al. 2013, Hwang et al 2011,
Cockcroft et al 2011, de Tullio Zinn & Zinn 2013

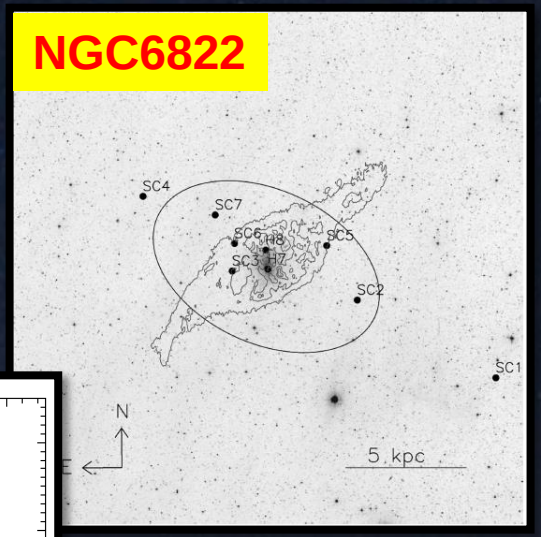
Galaxy	N_{GC}	M_V	Type
MW	160	-21.3	Sbc
M31	~450	-21.8	Sb
M33	50	-19	Scd
LMC	16	-18.4	Irr
SMC	1	-16.8	Irr
NGC205	11	-16.7	dE
M32	0	-16.5	dE
NGC6822	~8	-15.5	Irr
NGC147	10	-15.5	dE
NGC185	8	-15.4	dE
WLM	1	-14.8	Irr
Sag	6	-13.9	dSph
Fornax	5	-13.0	dSph

GLOBULAR CLUSTERS THROUGHOUT THE LOCAL GROUP

NGC147

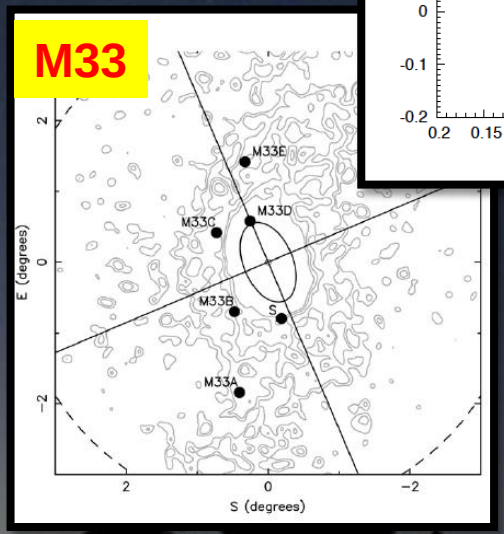


NGC6822



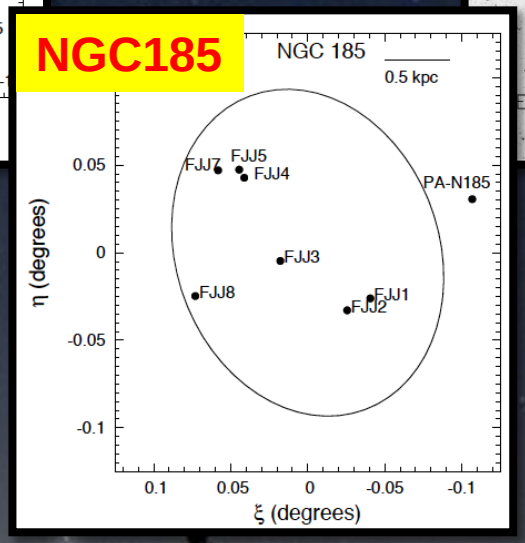
Hwang et al 2011
Huxor et al 2013

M33



Stonkute et al 2008
Huxor et al 2009
Cockcroft et al 2011

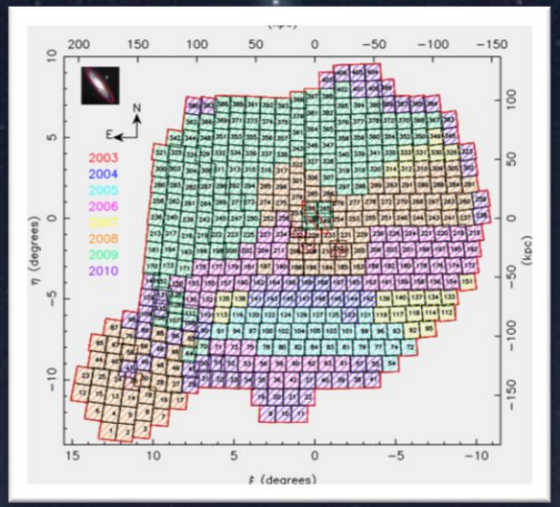
NGC185

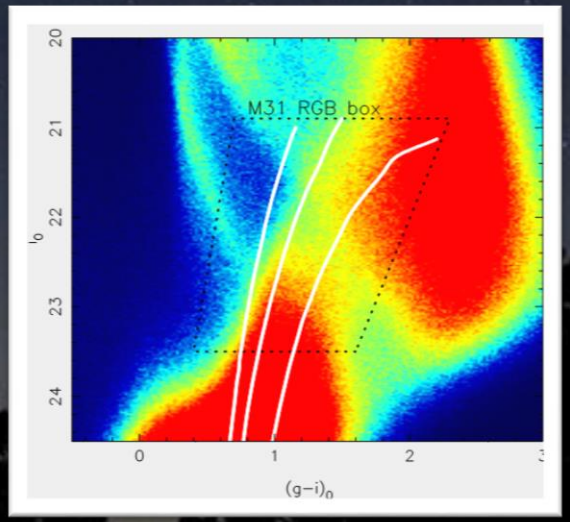


Sharina et al 2009
Veljanoski et al 2013

THE PAN-ANDROMEDA ARCHAEOLOGICAL SURVEY (PAndAS)

- CFHT Large Program, 220h over 2008-2011
- ~380 deg^2 mapped (to R_{proj}~150 kpc) with MegaCam in to g_{AB}~26.0 and i_{AB}~24.8 (5σ)
- mean seeing ~0.6-0.7”
- 96 million sources, 10 million M31 red giant branch stars

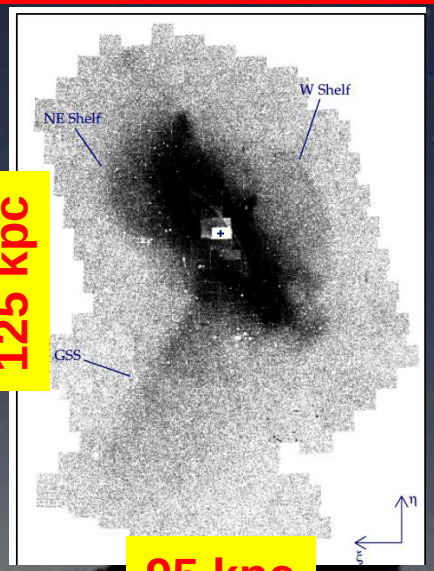




Ibata et al. 2013, Martin et al. 2013a

THE PAN-ANDROMEDA ARCHAEOLOGICAL SURVEY (PAndAS)

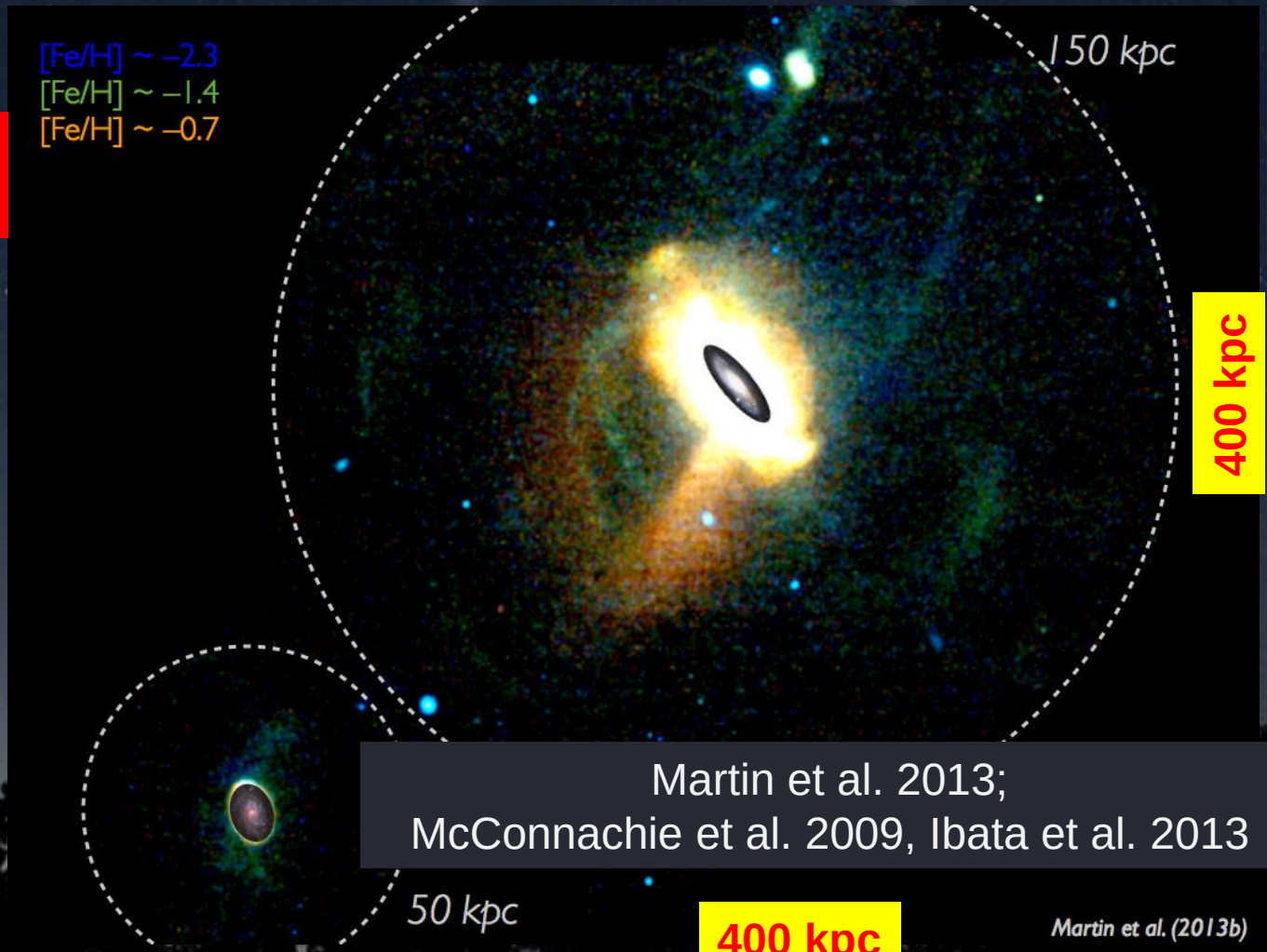
The INT/WC Survey (2000-2003)



125 kpc

95 kpc

Ferguson et al. 2002

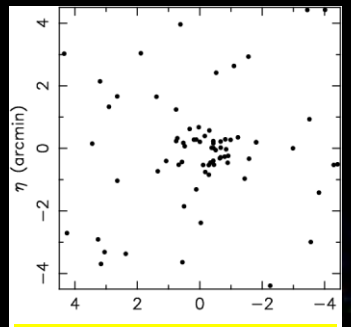


Martin et al. 2013;
McConnachie et al. 2009, Ibata et al. 2013

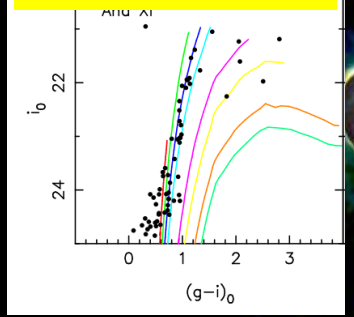
Dwarf galaxies

Zucker et al. (2004; 1)
Martin et al. (2006; 3)
Majewski et al. (2007; 1)
Ibata, Martin et al. (2007; 2)
Irwin et al. (2008; 1)
Zucker et al. (2007; 1)
McConnachie et al. (2008; 3)
Martin et al. (2009; 2)
Richardson et al. (2011, 5)
Bell, Slater & Martin (2011, 1)
Slater, Bell & Martin (2011, 1)
Martin et al. (2013a, 2)
Irwin et al. (in prep, 1)

PS1



AndXI M_V~-7.3



Martin et al. 2013

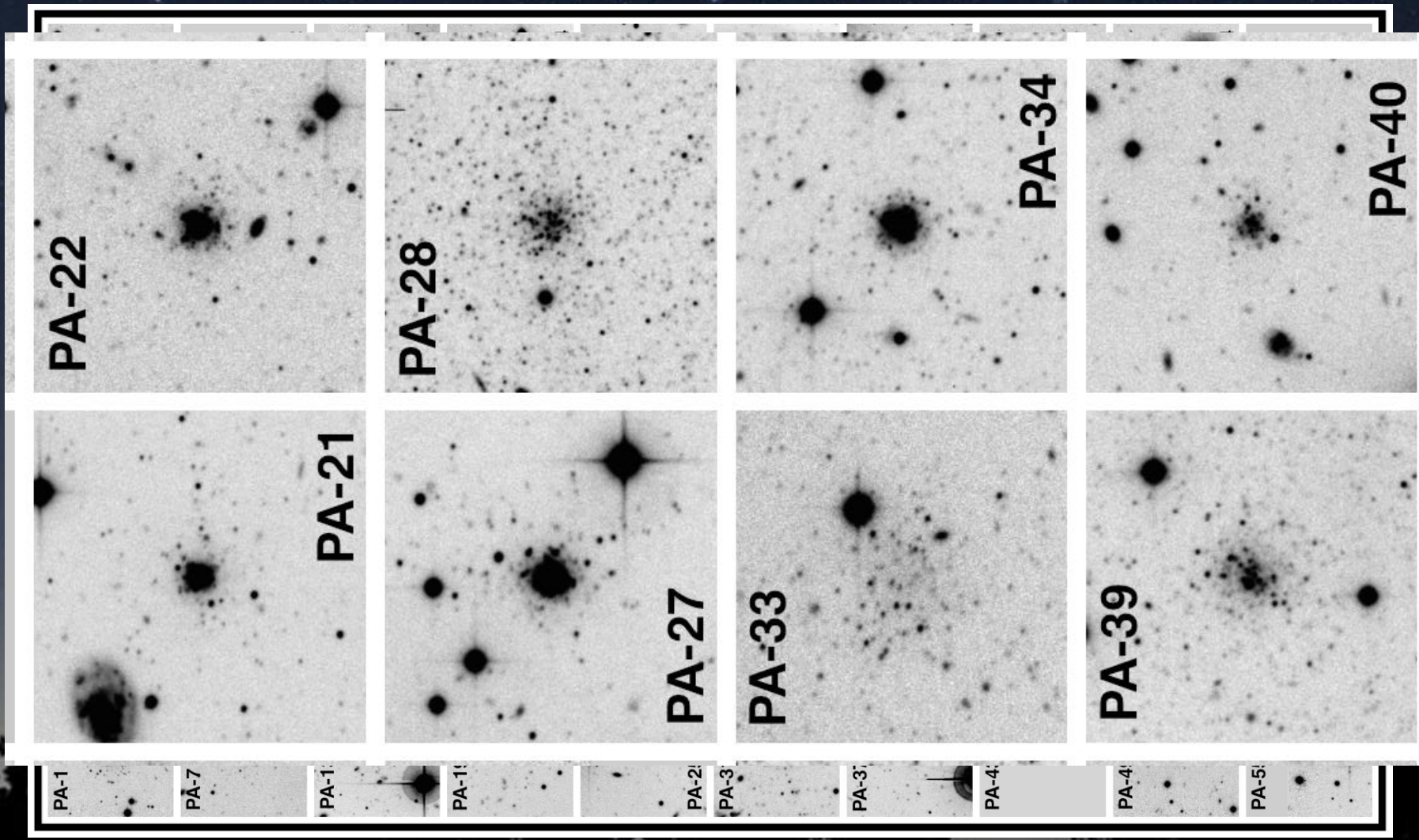
6 dSph (2004) → ~33 dSphs now
(4 SDSS+17 PAndAS + 3PS1 + 2 others)

REVEALING THE HALO GC SYSTEM OF M31

Huxor et al 2005, 2008, 2011, 2013
Mackey et al 2006, 2007, 2010, 2013a, 2013b

- Roughly 100 new halo globular clusters discovered in M31 due to INT/WFC + PAndAS, of which ~80 lie at >30 kpc [Previously, 3(0) at > 30(60) kpc]
- Found out to at least R_{proj}~140 kpc, and R_{3D}≥ 200 kpc
- Completeness tests suggest our search is 95(50)% complete to M_V~-5(-4.1) for all but most sparse/compact clusters
- Both classical (r_h~few pc) and extended GCs (r_h~few tens of pc) found

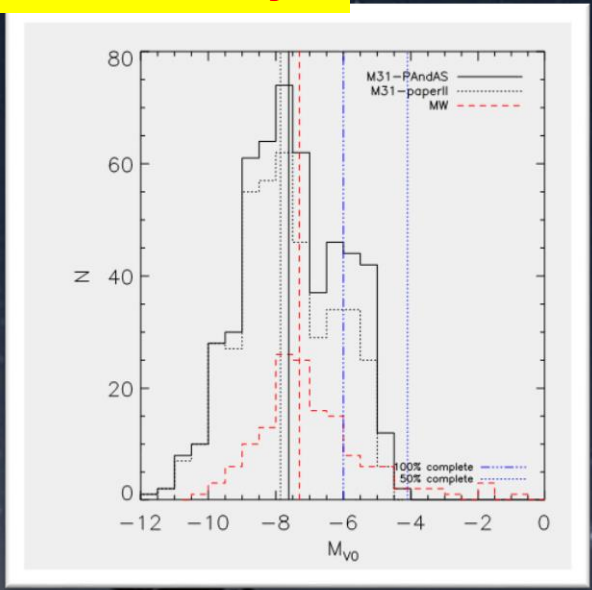
REVEALING THE HALO GC SYSTEM OF M31

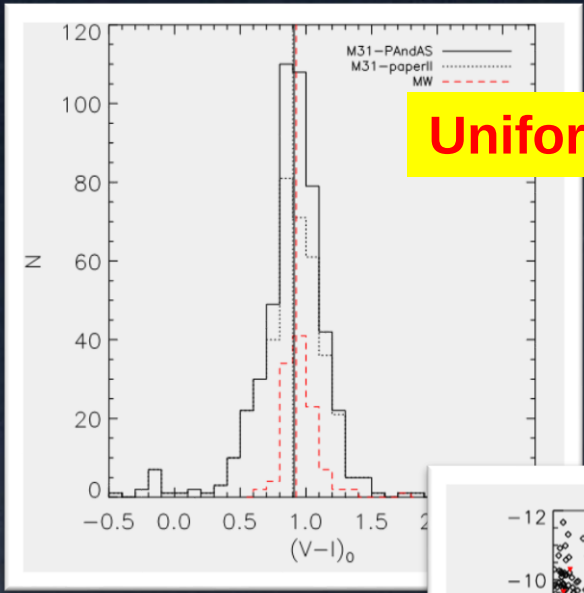


REVEALING THE HALO GC SYSTEM OF M31

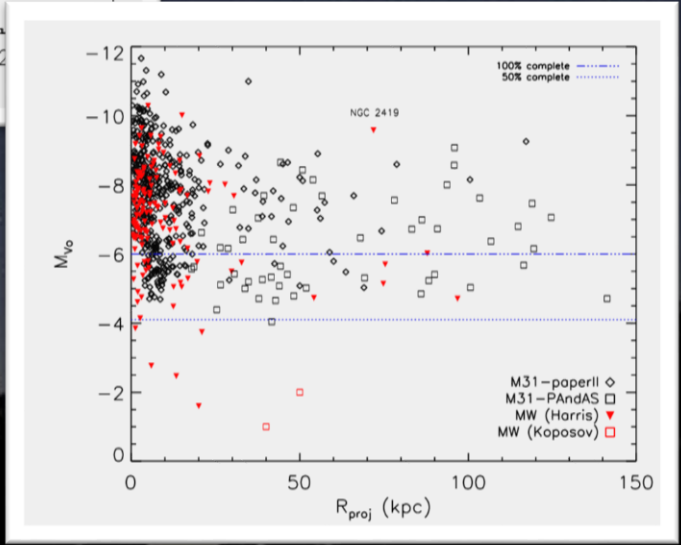
Evidence for Bimodality?

Huxor et al 2011, 2013





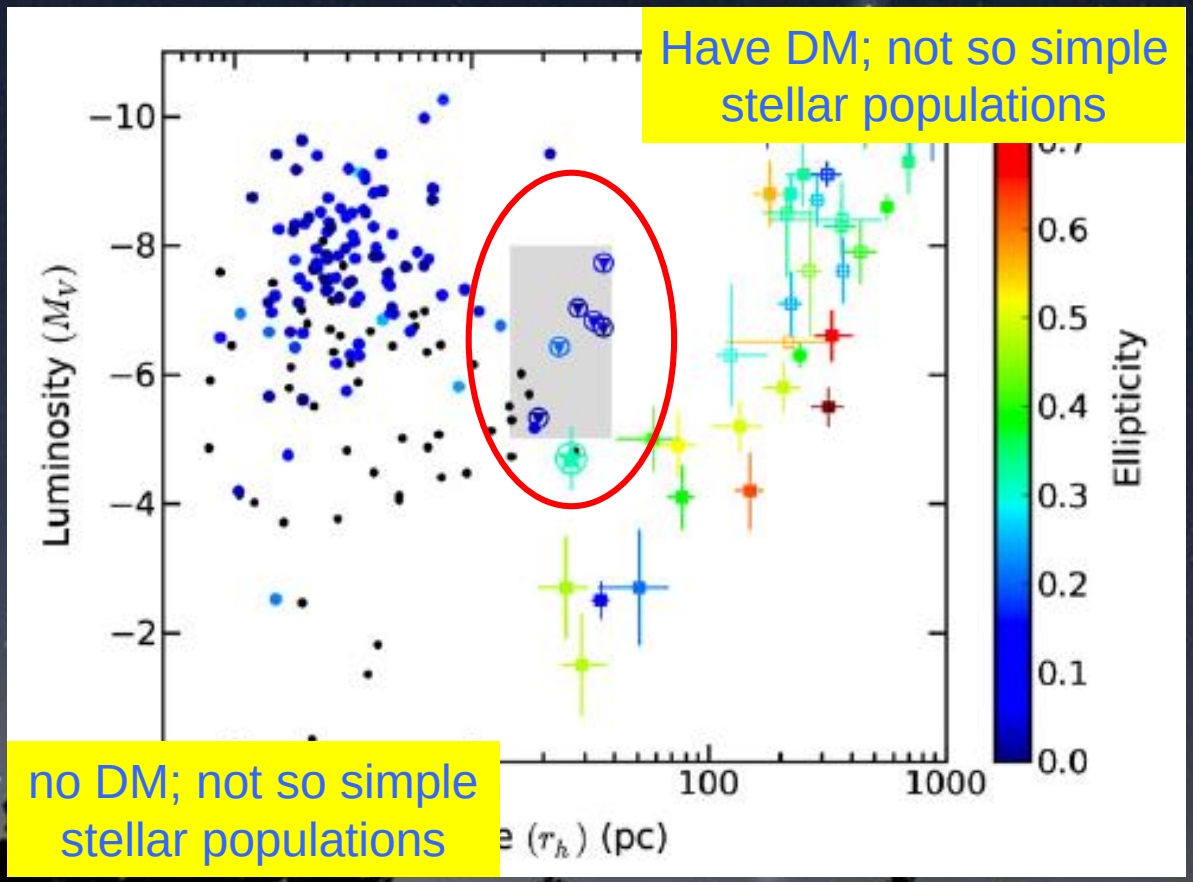
Uniform colours

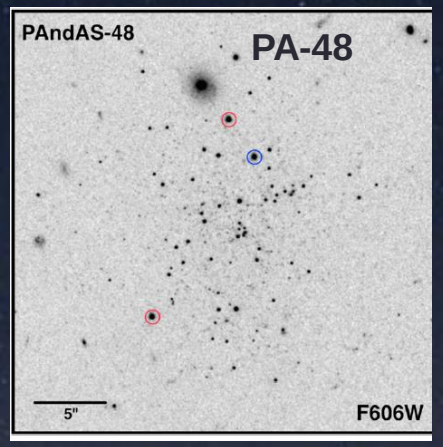


M31 has significant population of luminous outer halo GCs that is not seen in the MW

EXTENDED STAR CLUSTERS: LINK TO DSPHS?

Huxor et al 2005, Mackey et al 2006, 2013

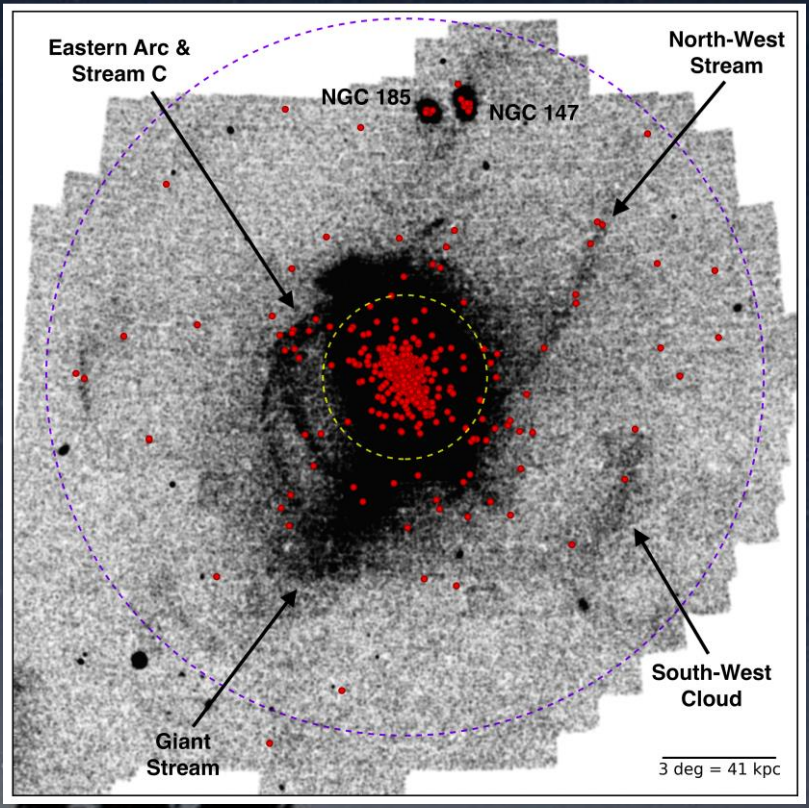




ECs also seen in M33, NGC6822 and low mass systems beyond the LG

SUBSTRUCTURE IN THE M31 GLOBULAR CLUSTER SYSTEM

Mackey et al 2010, 2013



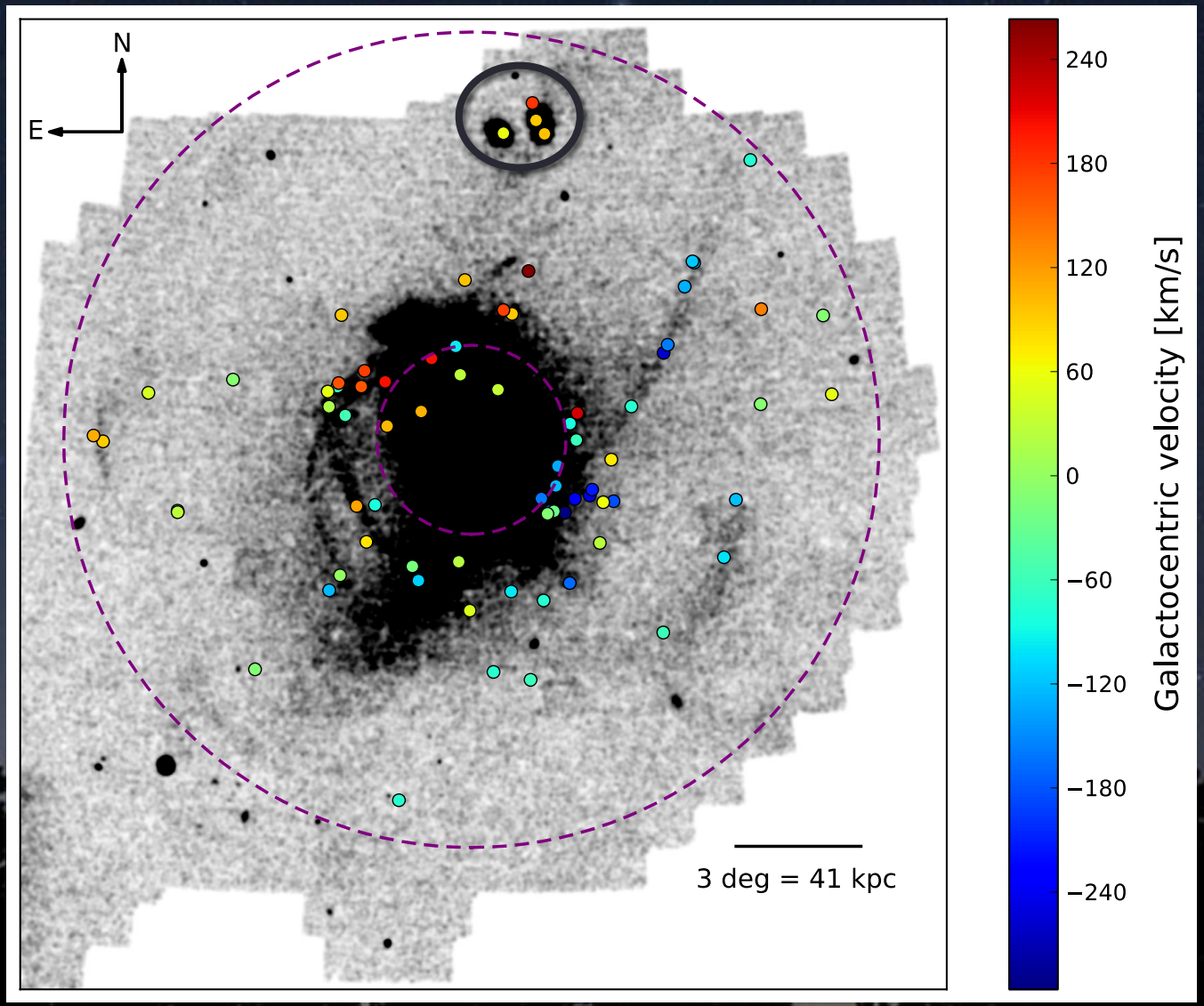
- Quantified the association of halo GCs with underlying stellar streams via Monte Carlo approach: observed alignments highly unlikely due to chance (P_{random}<0.25%)
- further support from local surface brightness levels

Most of the M31 outer halo clusters have been accreted with their dwarf host?

M31 HALO GC KINEMATICS

Jovan Veljanoski et al 2013a, 2013b

65 GC vels
KPNO
WHT
Gemini



M31 HALO GC KINEMATICS

Assume rotation axis in plane of sky and fit:

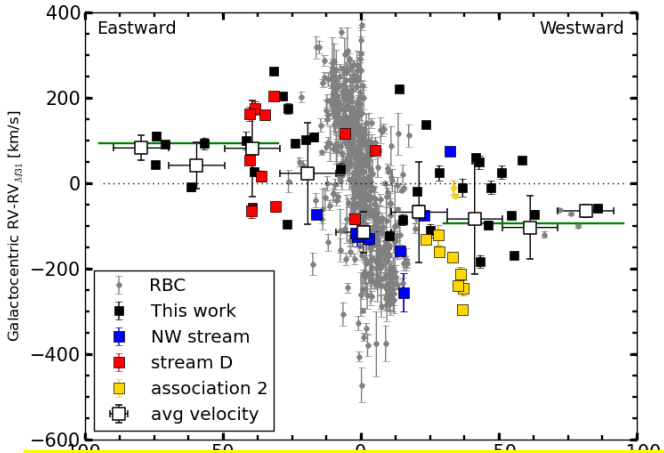
$V_{rot}=V_{sys}+A\sin(\theta-\theta_0)$

$\sigma^2=\Delta V^2 + \sigma_0^2(R/R_0)^{-2\gamma}$

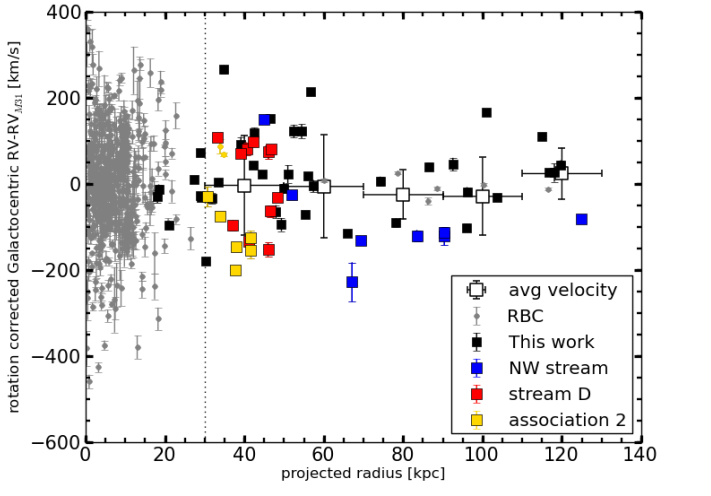
Sample Selection	Amplitude [km/s]	θ_0 [degrees]	σ_0 [km/s]	γ	N_{GC}
Full Sample	90^{+20}_{-19}	135^{+14}_{-28}	130^{+30}_{-20}	$-0.46^{+0.22}_{-0.23}$	65

Coherent rotation along minor axis in same sense as main disk!

Veljanoski et al 2013a, 2013b

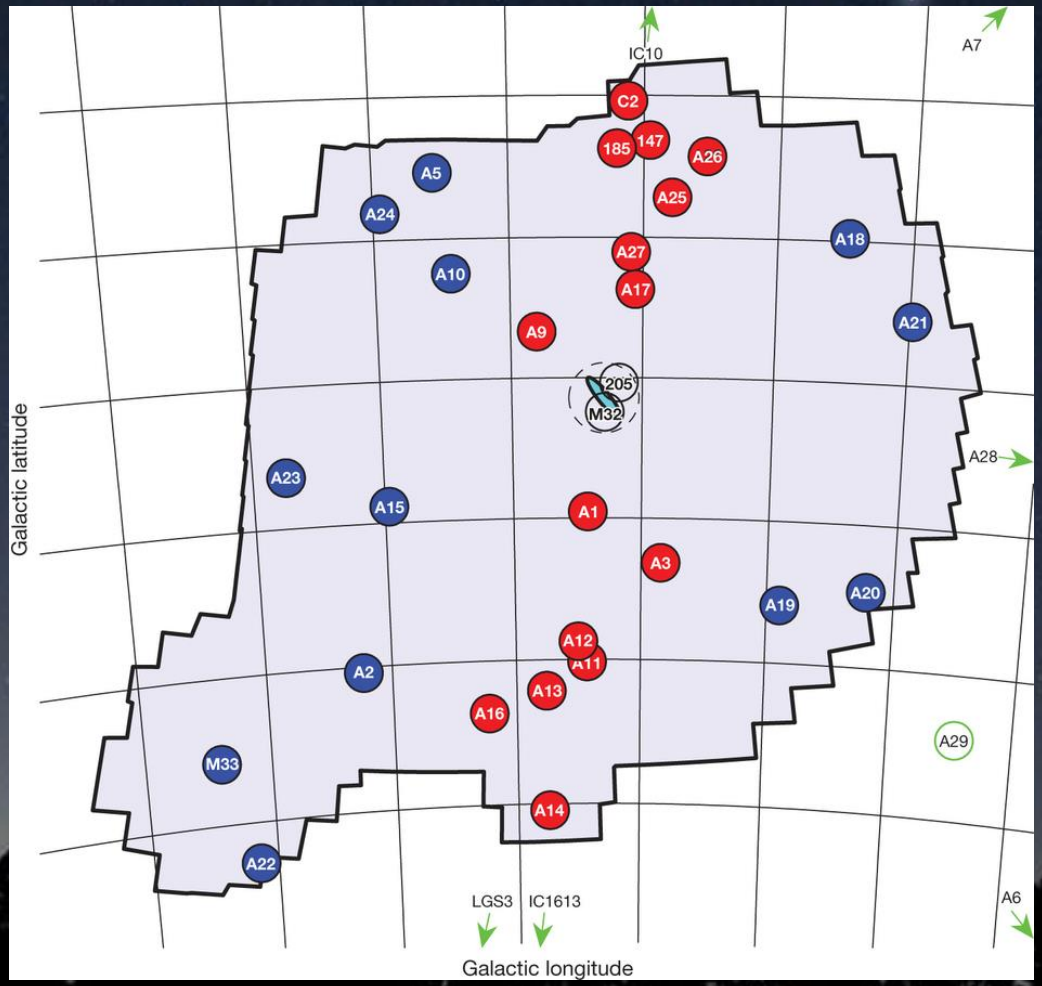


V/σ~1 to > 100 kpc?



A VAST PLANE OF DWARF GALAXIES

Ibata et al. 2013, Conn et al 2013

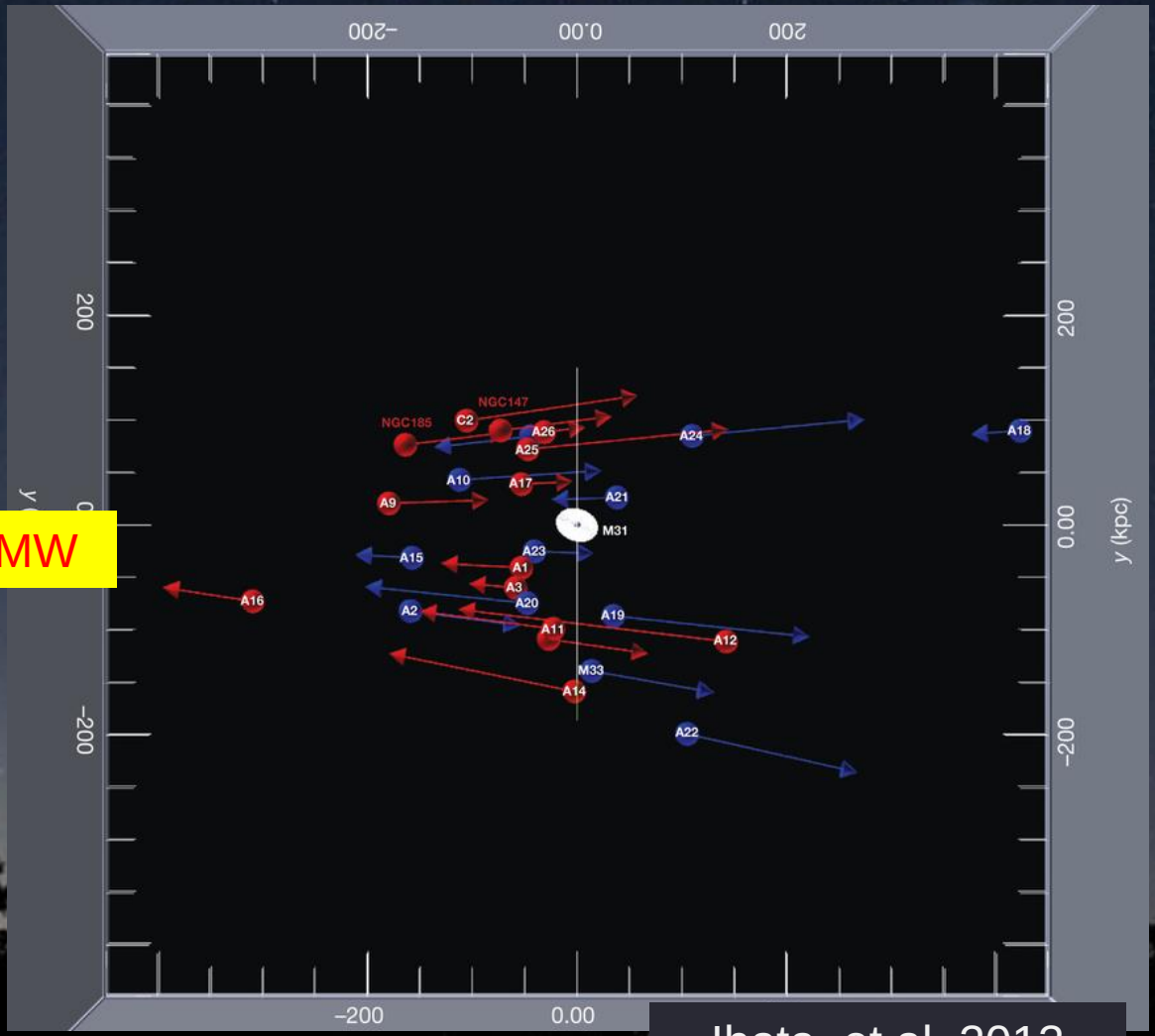


Can identify a significant plane which contains ~½ (13/27) of the known dwarf satellite population

~14 kpc thickness
~400 kpc diameter
P_{random} ~ 0.1%

Roughly perpendicular to MW disk

A VAST PLANE OF DWARF GALAXIES



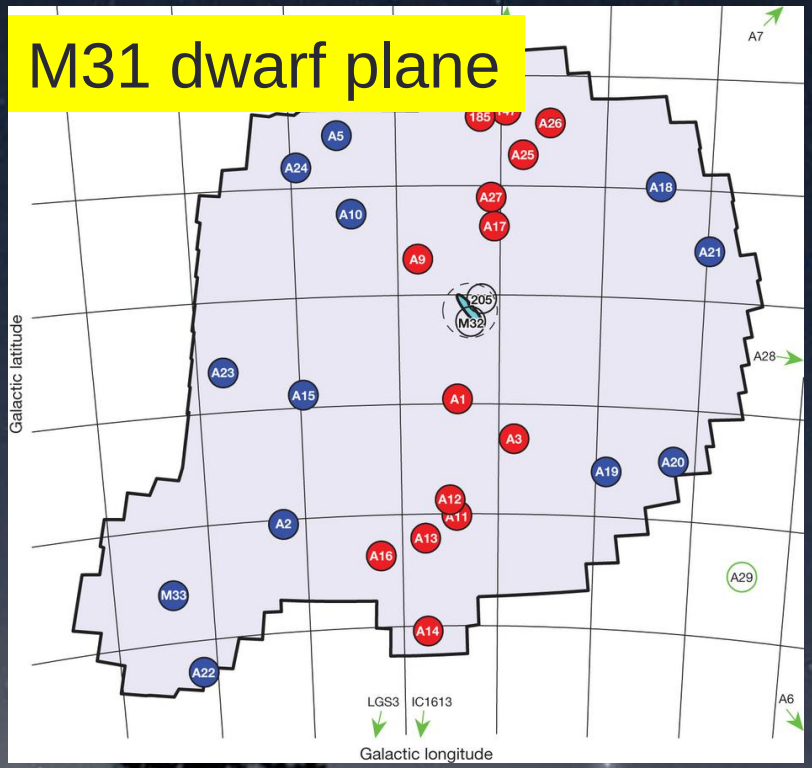
Ibata et al. 2013

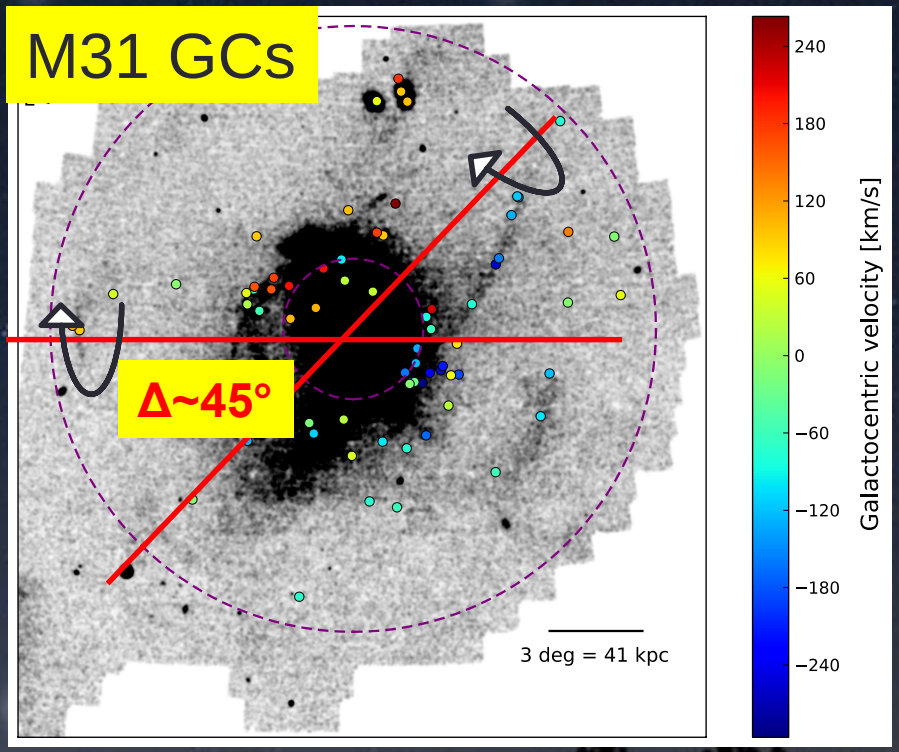
Plane satellites have motion that suggests rotation (P_{random}<0.002%)

The existence of a giant thin rotating plane of satellites may be a challenge for models

SUBSTRUCTURE AND ROTATION OF SATELLITES

Ibata et al 2013, Veljanoski et al 2013a,b





300 kpc

300 kpc

GCs and dwarf plane rotate in same sense but rotation axes slightly misaligned…clue about a similar origin?

SUMMARY

- Many GCs lurk at large galactocentric radii; we are still uncovering this population within the Local Group…
- The newly-discovered M31 halo clusters change some ensemble properties, e.g. the GCLF, the radial profile
- M31 halo GCs preferentially lie on stellar substructures, suggesting this population has been accreted along with their host galaxies
- The M31 halo GC population exhibits a high degree of rotation, in a similar sense to satellite system of dwarf galaxies: this again might support a similar accretion origin

OPEN QUESTIONS

- Given their similar global properties, why is M31's GC system so different compared to that of the Milky Way (e.g. N_{GC}, extent, LF, rotation)? Which is most representative of a typical L* galaxy?

- How can we identify GCs that have been accreted versus those that have formed in situ in the MW and in distant galaxies? Chemistry? Kinematics? Orbits? Gaia…..

- What governs the number of GCs a galaxy has? Star formation history? Accretion history? Why do so few galaxies below M_V~-13 have GCs?