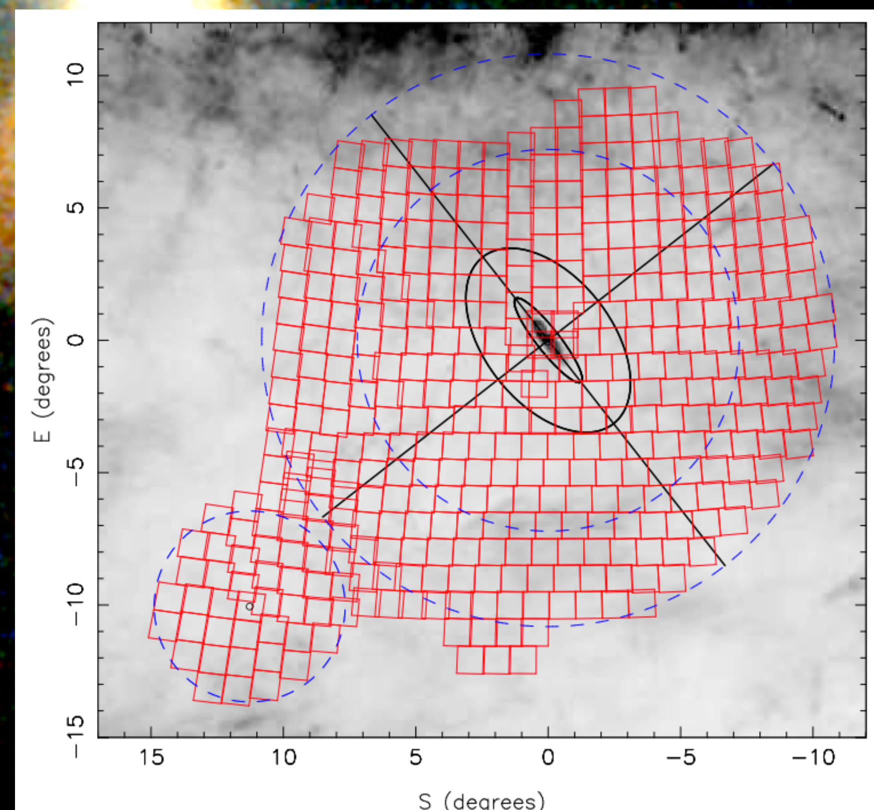
PAndAS: A retrospective

Alan W. McConnachie & the PAndAS Collaboration
(including Eduard Bernard, Pat Cote, Rodrigo Ibata, Nicolas Martin, Kim Venn and others)
Dominion Astrophysical Observatory



CFHT Users Meeting 2016
Nice, May 2 2016

Follow-up observations from

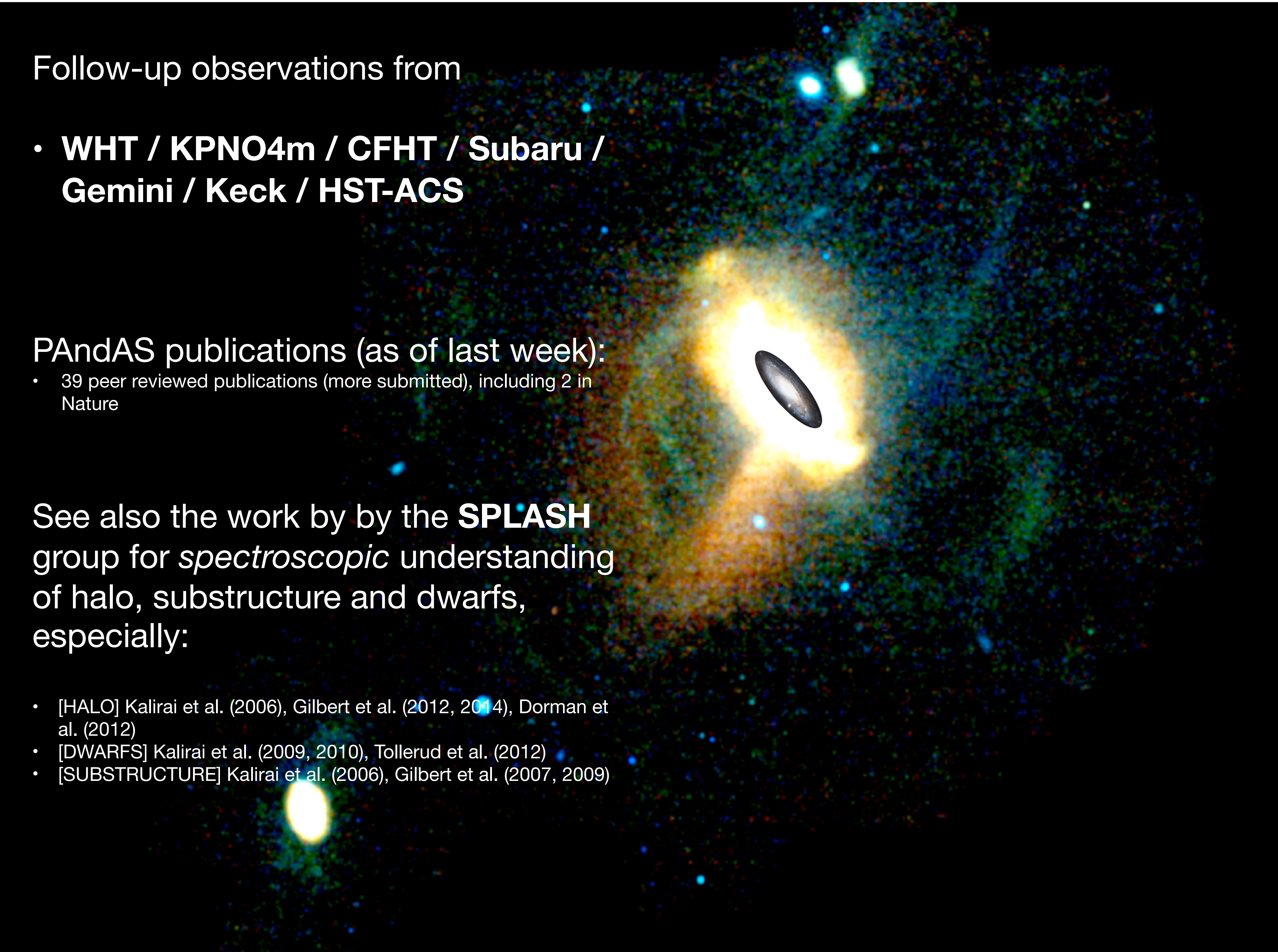
- **WHT / KPNO4m / CFHT / Subaru / Gemini / Keck / HST-ACS**

PAndAS publications (as of last week):

- 39 peer reviewed publications (more submitted), including 2 in Nature

See also the work by by the **SPLASH** group for *spectroscopic* understanding of halo, substructure and dwarfs, especially:

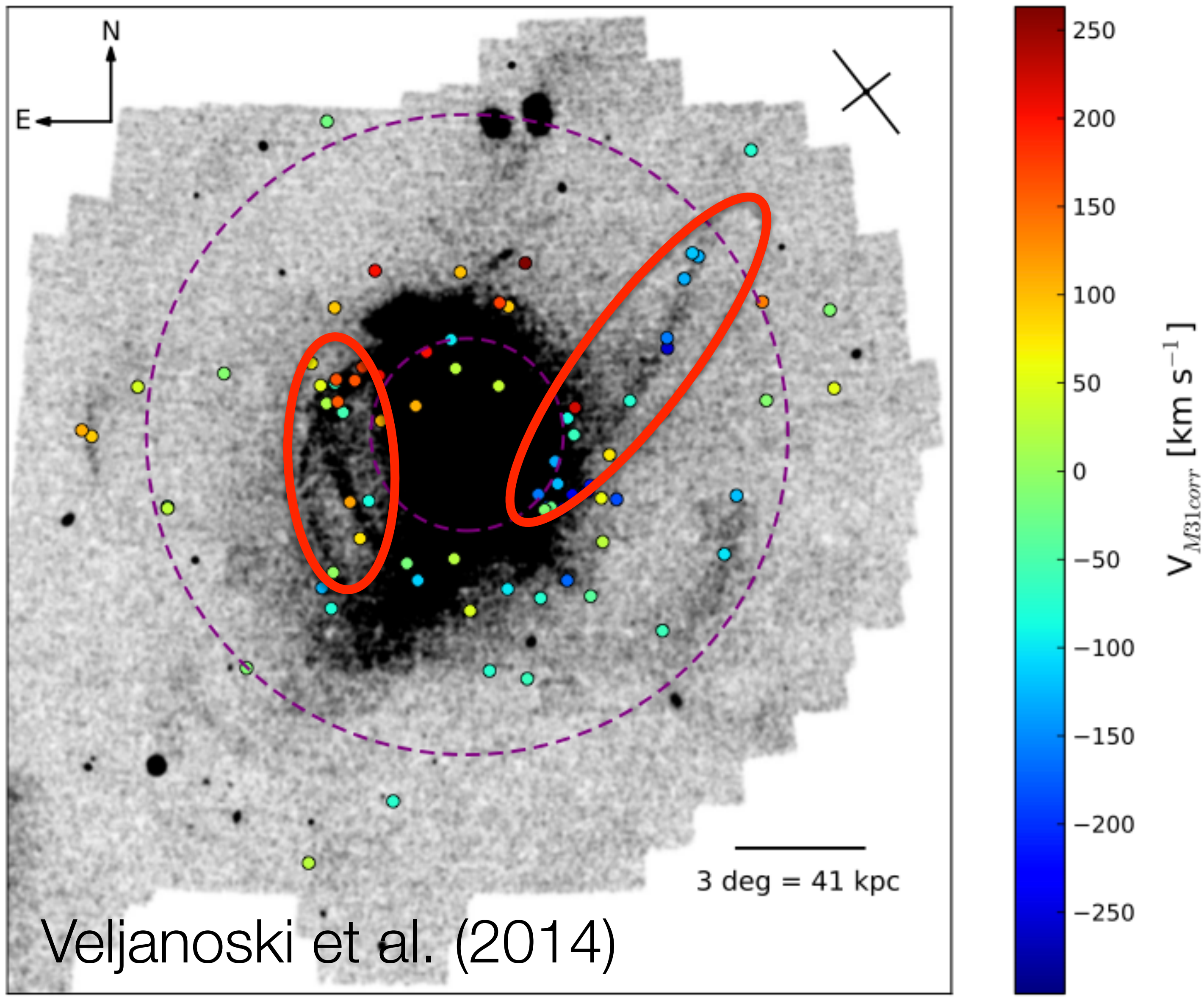
- [HALO] Kalirai et al. (2006), Gilbert et al. (2012, 2014), Dorman et al. (2012)
- [DWARFS] Kalirai et al. (2009, 2010), Tollerud et al. (2012)
- [SUBSTRUCTURE] Kalirai et al. (2006), Gilbert et al. (2007, 2009)



Substructures evident in stellar and GC distributions

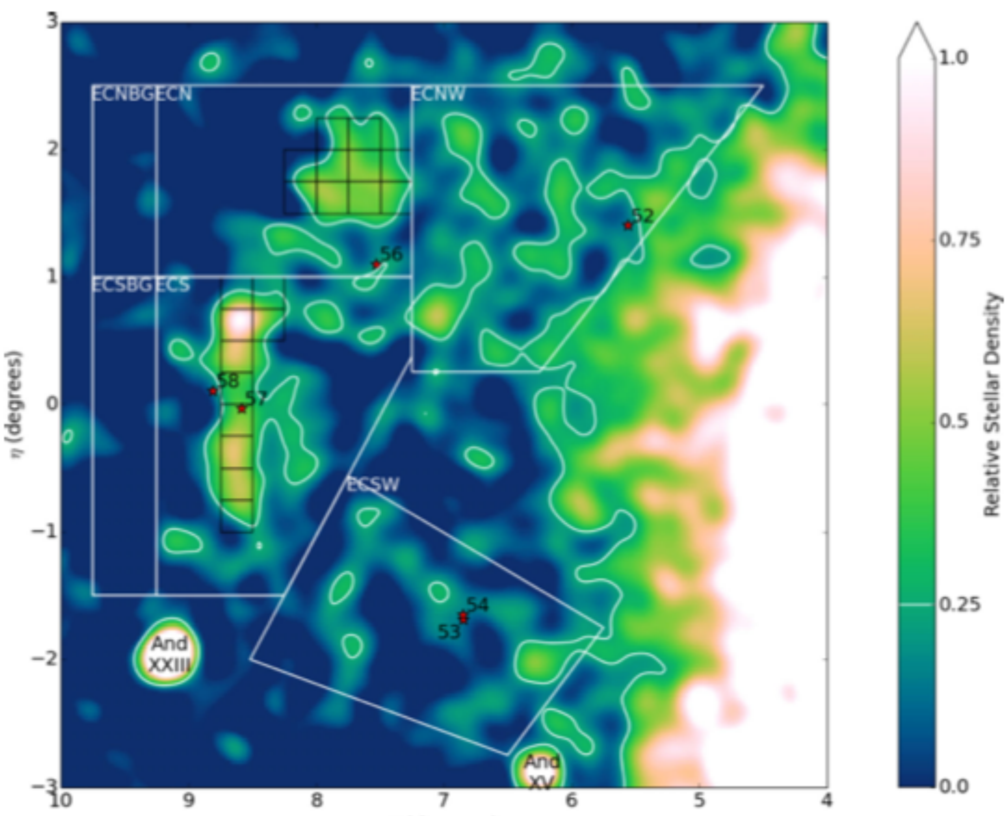
- Can identify major accretion events in the halo through the GC population ("Searle & Zinn by eye")

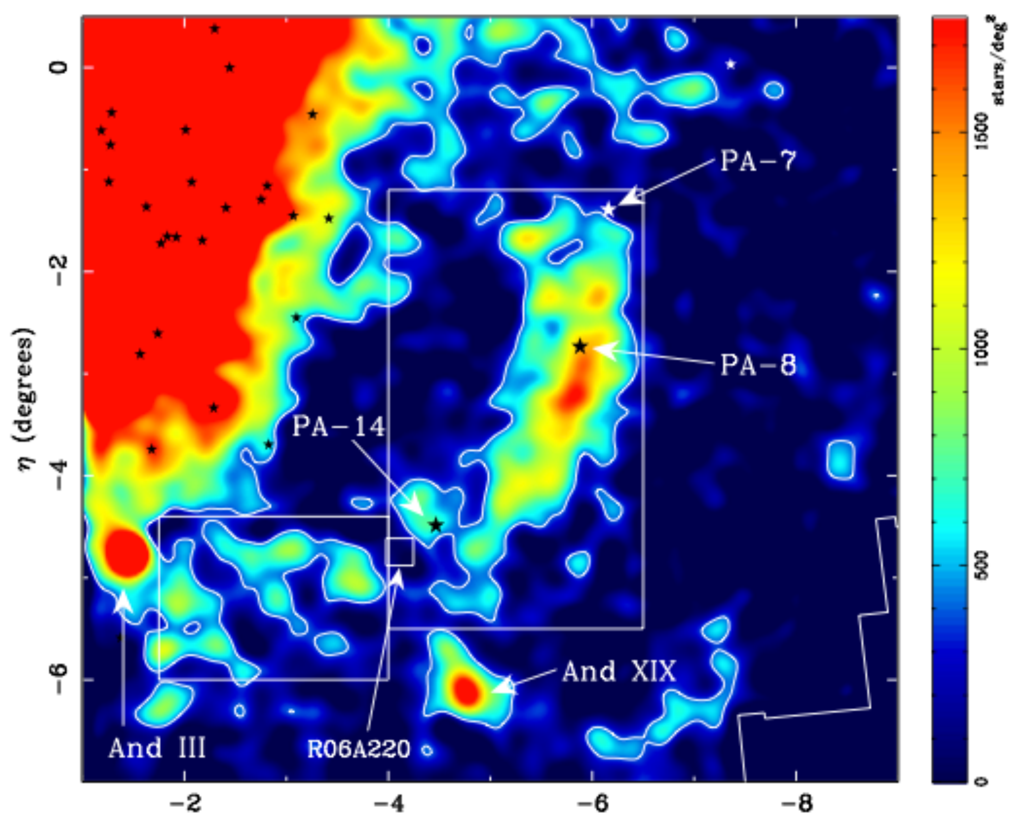
- But what other events contributed to M31's halo and how?



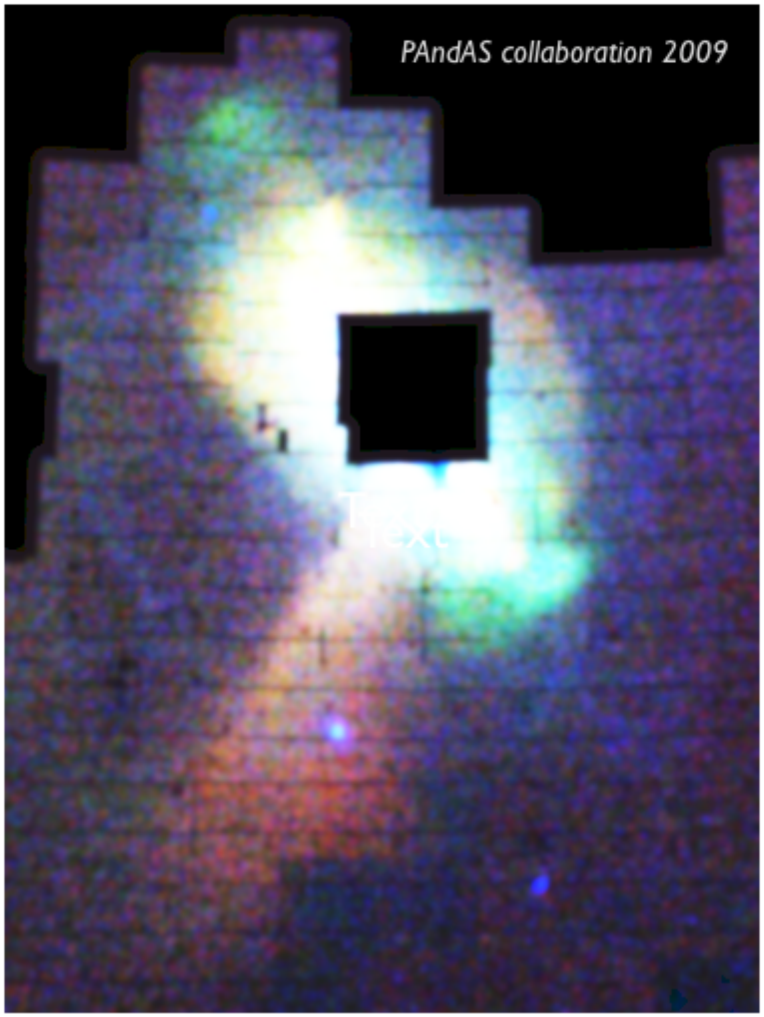
Major accretions? - The SW Cloud (Bate et al. 2014)
- The East Cloud (McMonigal et al. 2016)

- The implied metallicity for the SW (E) cloud is [Fe/H] ~ 1.35 (-1.2) dex
- Assume stellar mass - metallicity relation. Progenitor of the SW (E) cloud is implied to be ~25% (80%) more luminous than what is now observed (both Mv ~ -13 mags)
- Both the SW and E clouds have at least 2 (probably more) GCs associated (RV confirmed)

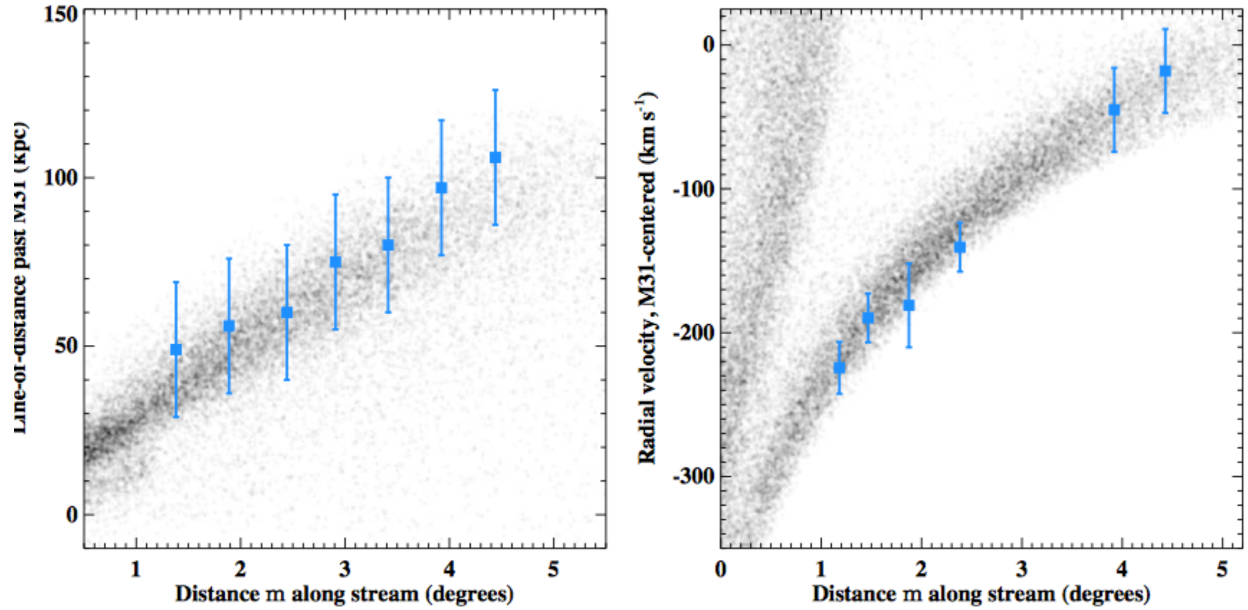




Major accretions? The giant stream



Fardal et al. 2008, 2013

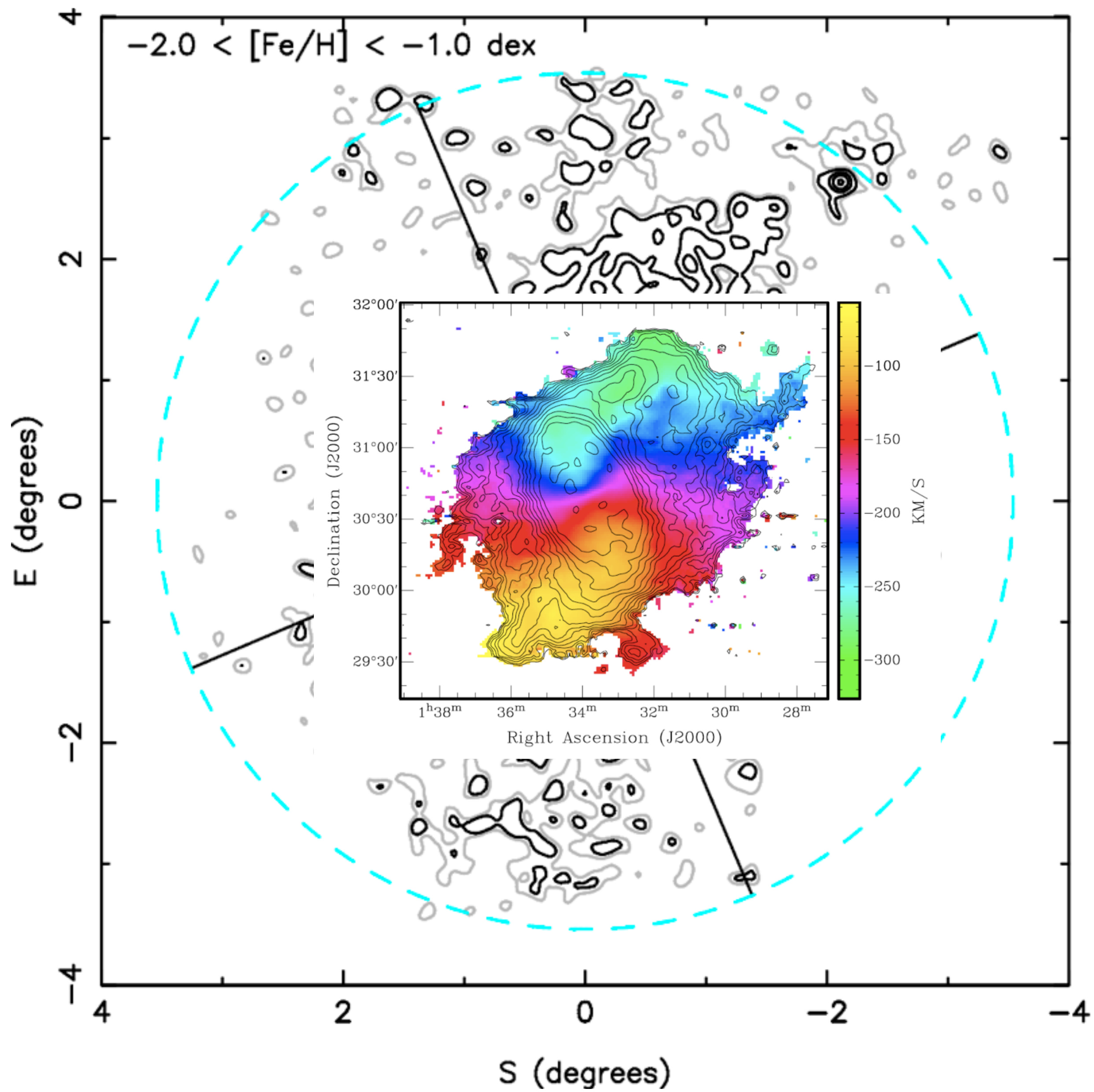


- Progenitor ~LMC mass
- Likely a rotating progenitor
- Near radial orbit, with disruptive pericenter passage of main body within last ~Gyr (750+/- 50 Myrs)
- Any remnant likely to be in the NE part of the outer disk of M31

McConnachie et al. (2010, ApJ)

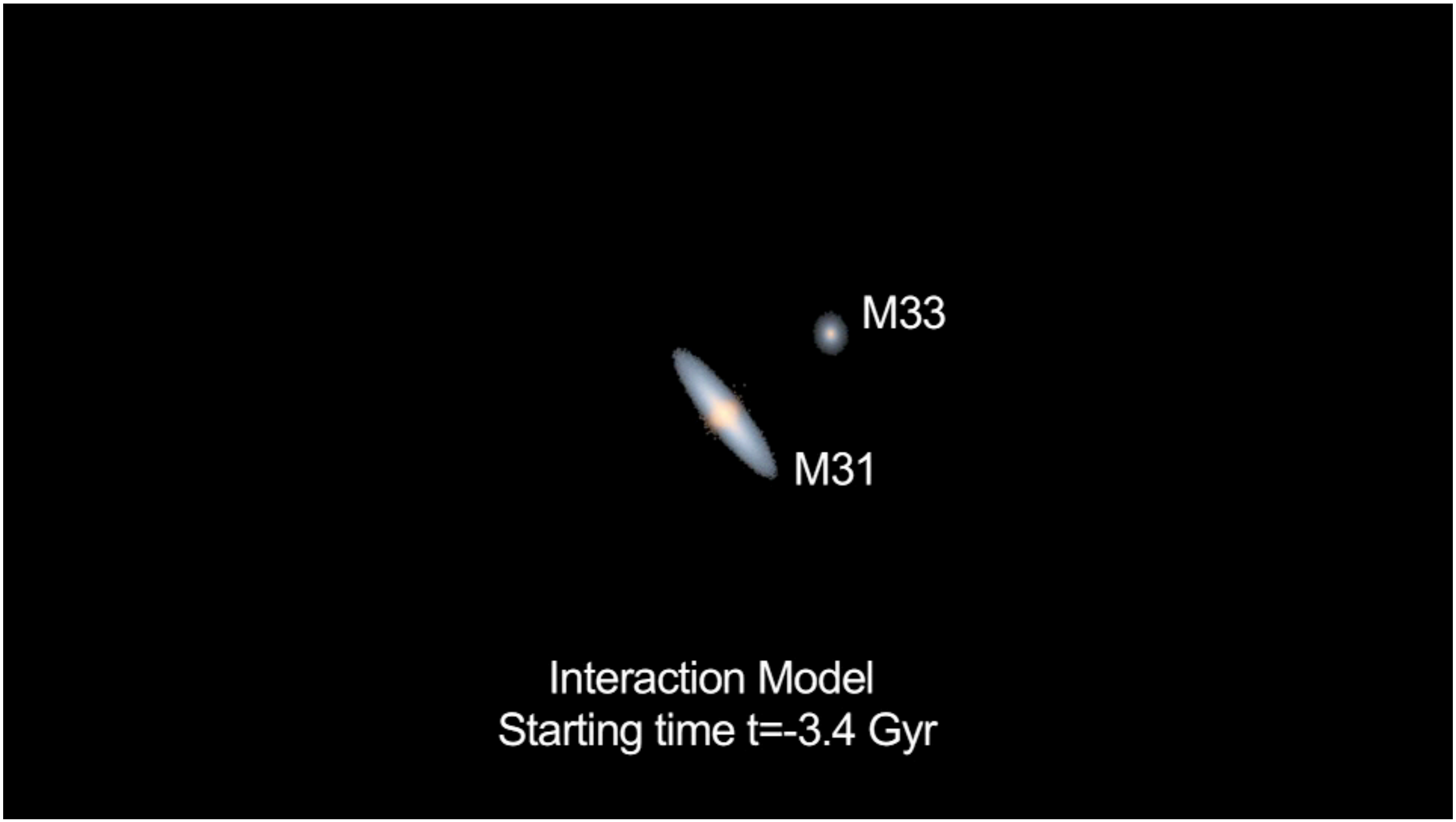
Major accretions? M33

- PAndAS reveals a giant stellar substructure surrounding M33, visible in the distribution of metal-poor RGB stars
- Integrated luminosity of substructure is Mv < -12.7+/- 0.5
- Extends out to very large radius (nearly 50kpc in projection)
- Suite of evidence suggests a tidal interaction with M31; M33 substructre due to disruption of M33 disk



Towards the interaction history of the Local Group

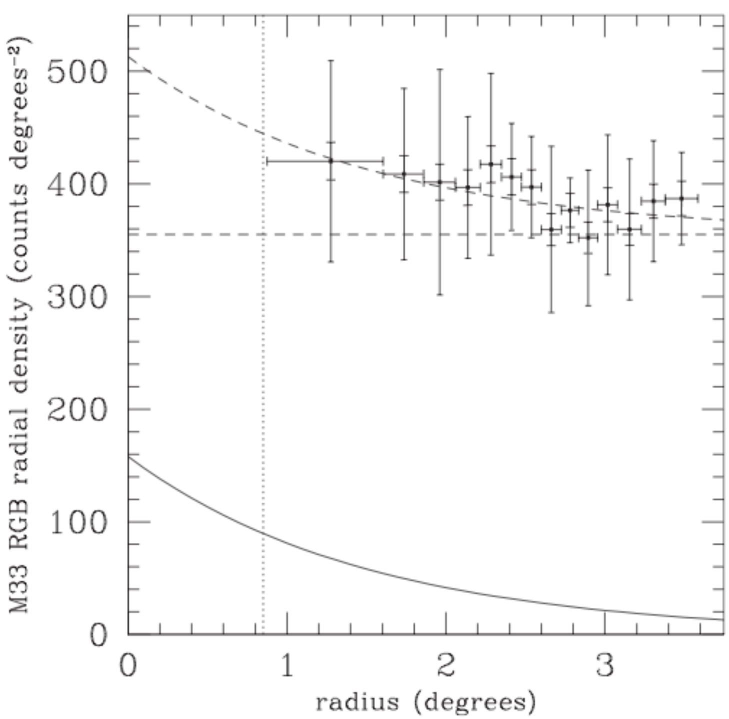
McConnachie et al. (2009)

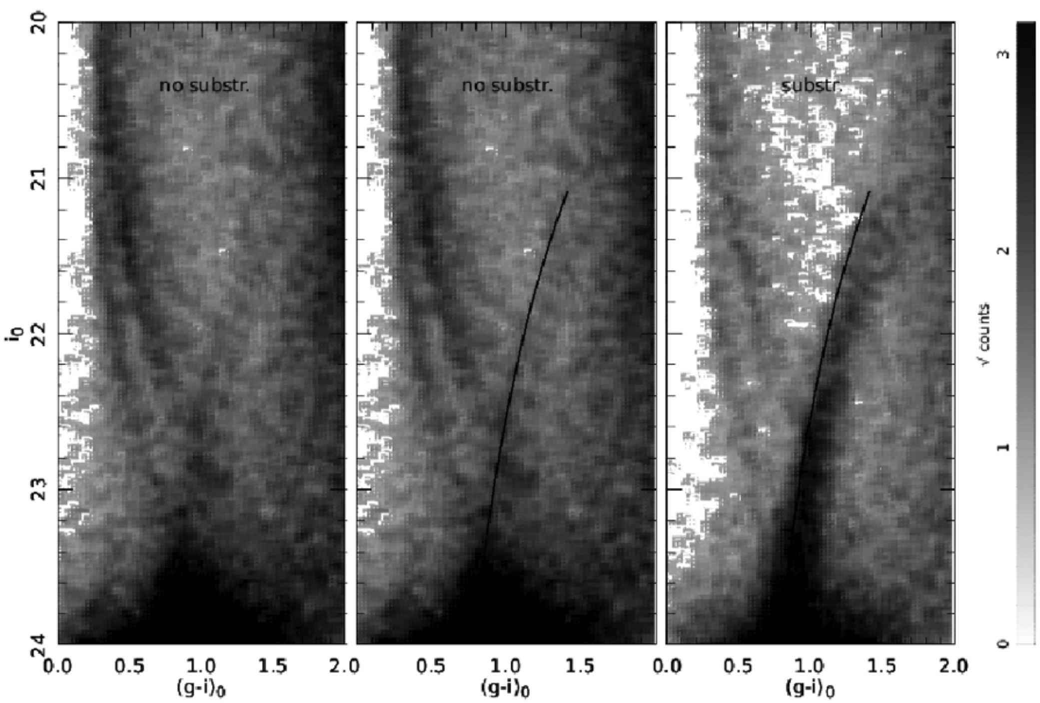


Cockcroft et al. (2013)

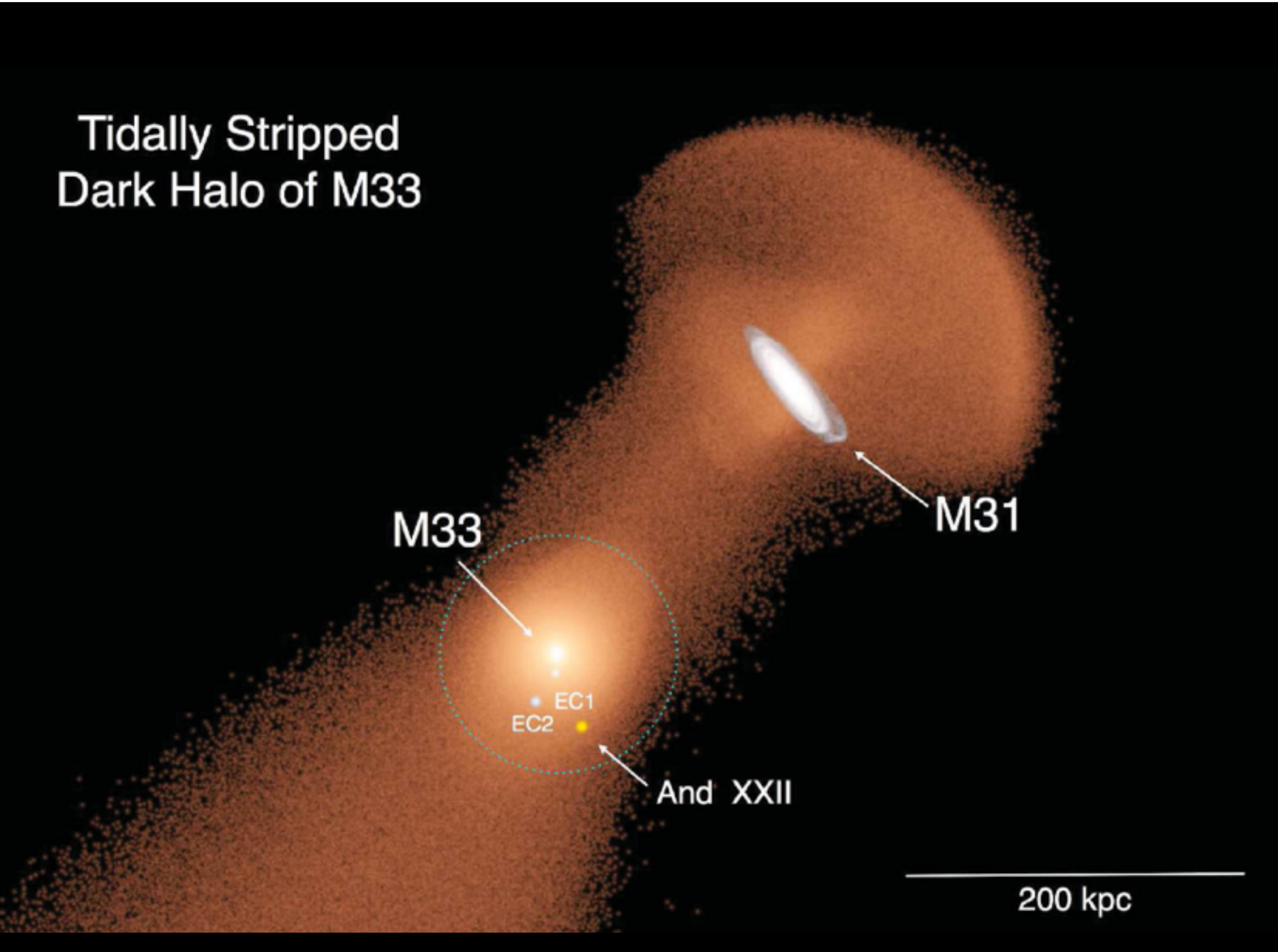
Does M33 have a "classical*" halo at large radius?

- Chandar et al. 2002: oldest star clusters have distinct kinematics from the youngest star clusters and from the HI disk. Conclude that the oldest clusters have an 85-15% halo-disk contribution
- Sarajedini et al. 2006: Bimodal metallicity distribution as implied from the period of RR Lyrae stars. Metal-poor peak attributed to halo stars
- Extremely tentative(?) evidence for very weak halo $L<4x10^6M_{sun}$, or <0.5% of M33 luminosity. Considerably fainter than 33mags/sq.arcsec



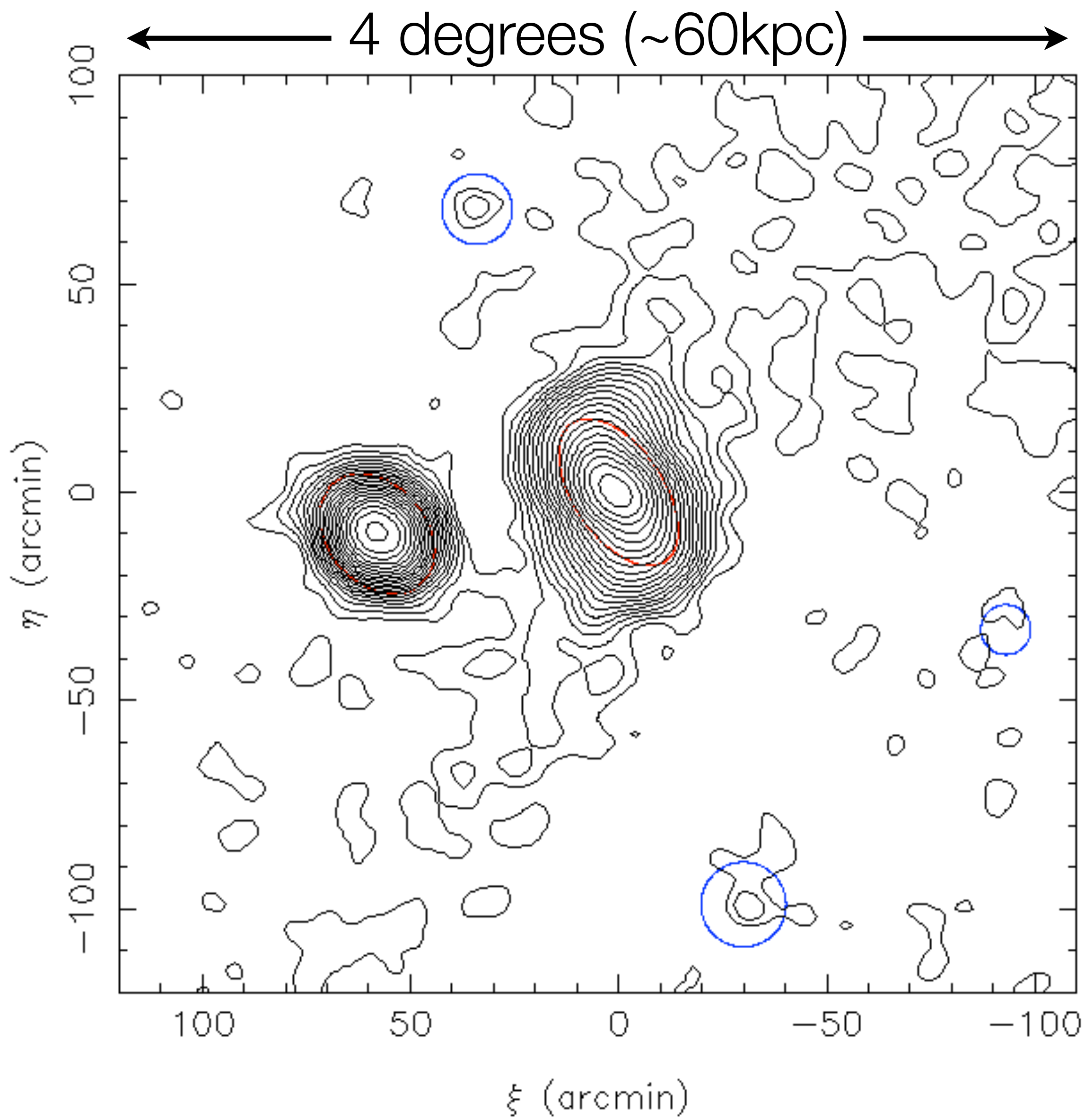


* definition unclear


Tidally Stripped
Dark Halo of M33
M31
M33
EC1
EC2
And XXII
200 kpc

Major accretions? The NGC147/185 system

- 3-D seperation ~ 60kpc
- RVs differ by 10.7km/s
    - Gaseous ISM (CO+HI) of NGC147 <2% of ‘typical’, in contrast to NGC185
    - No stars younger than ~1.5-3Gyr in NGC147, (latest burst ~40 Myr ago)
    - NGC147 has much lower central SB than NGC185



sub-sub-group

Major accretions? The NGC147/185 ~~system~~

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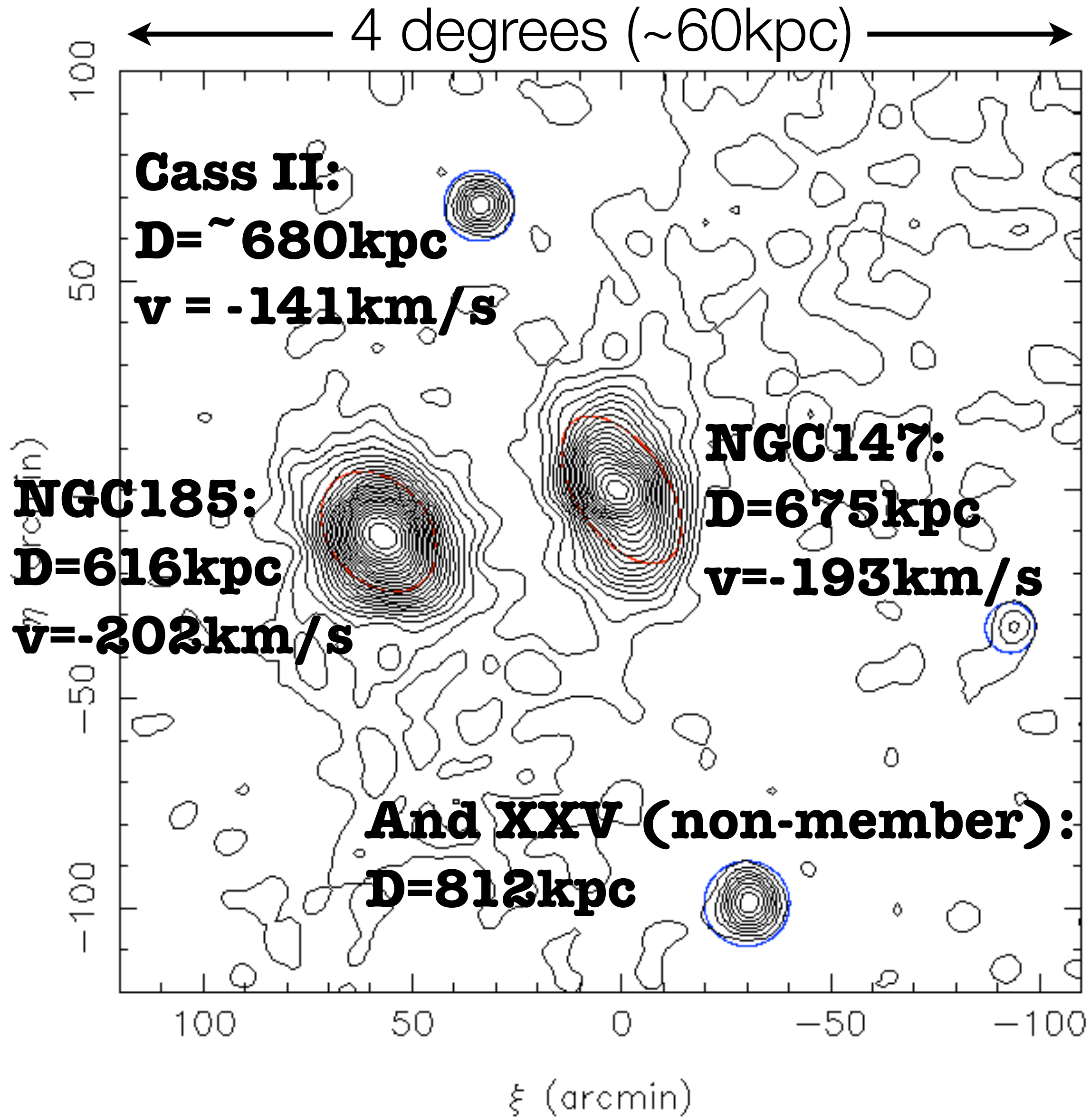
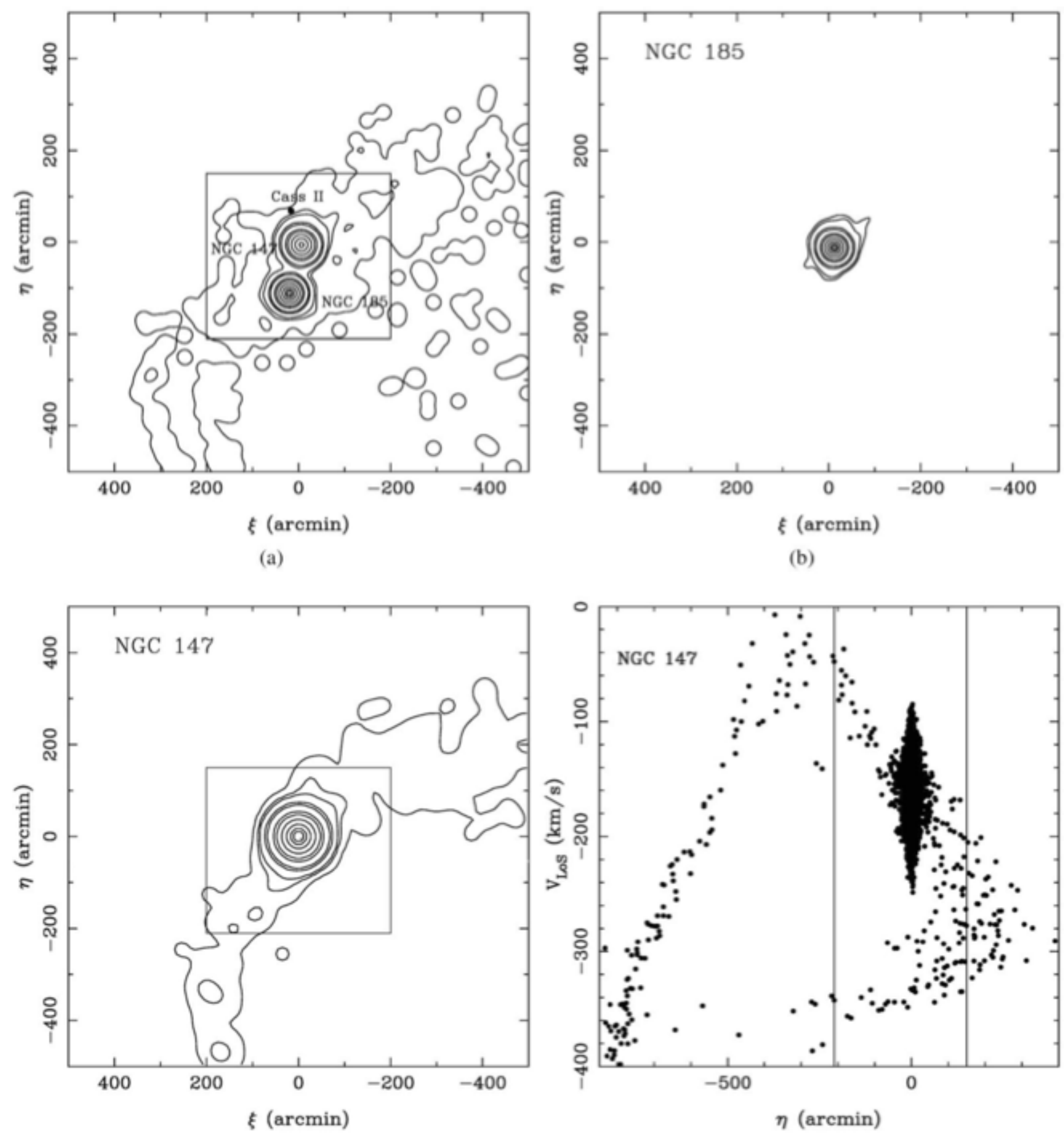
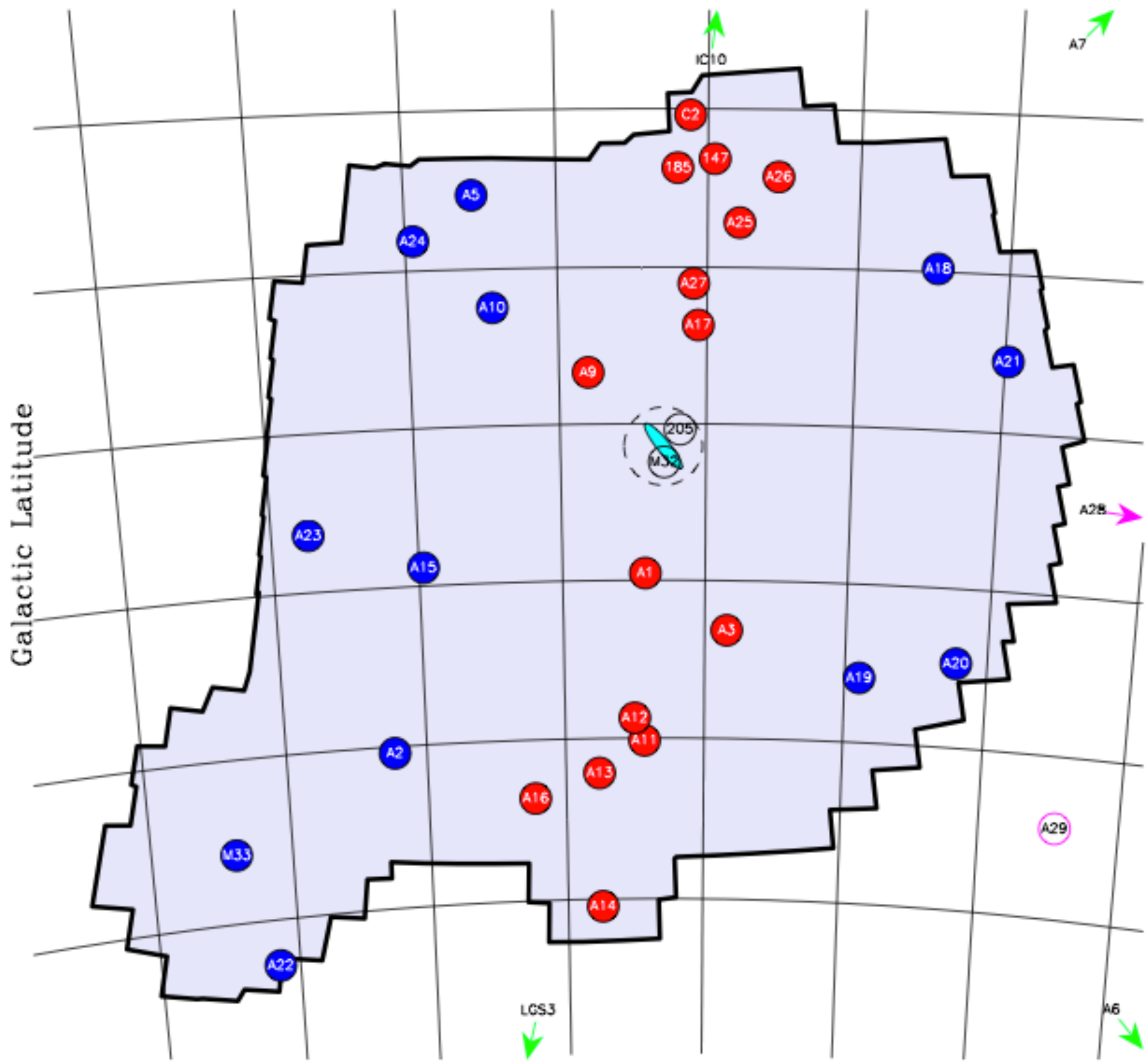


Orbital acrobatics

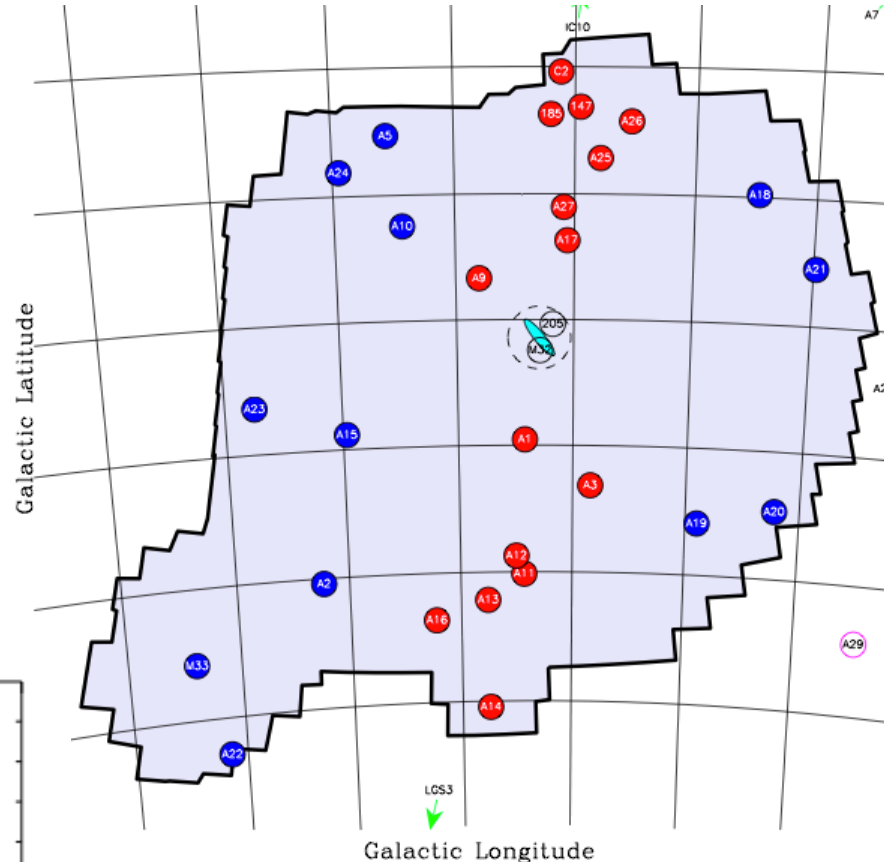
- NGC147, 185 and Cass II have similar positions and velocities projected on the sky - are they (or were they) a dynamically bound subgroup?
- Can you have a sub-group of three galaxies persist as a sub-group as they orbit M31?
- Can one member of this subgroup produce a large stellar stream, with the others showing no evidence of streams?
- Arias et al. (2016) explore parameter space looking for orbits where the group is bound at some point in the past and where NGC147 passes closest to M31

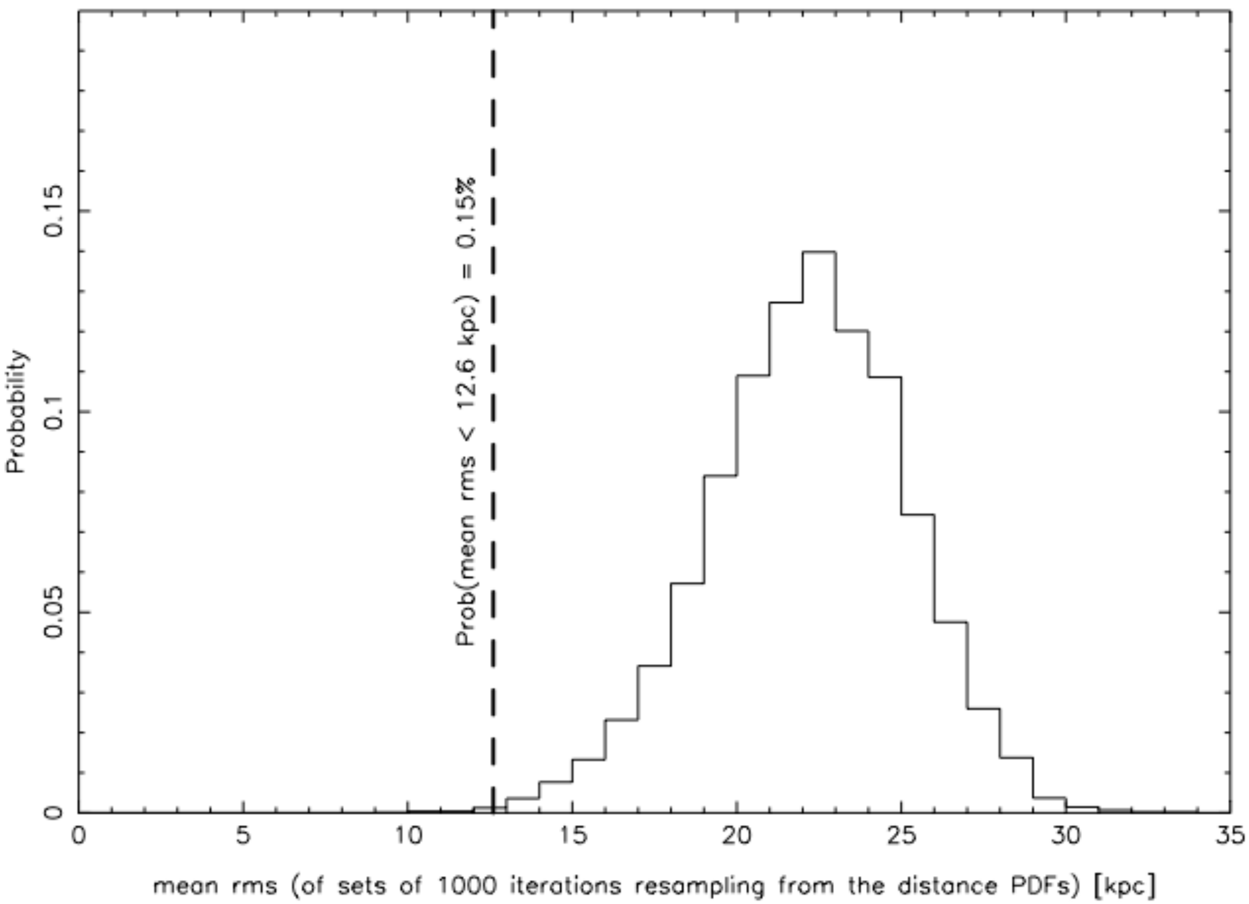


Major accretions? The disk of satellites



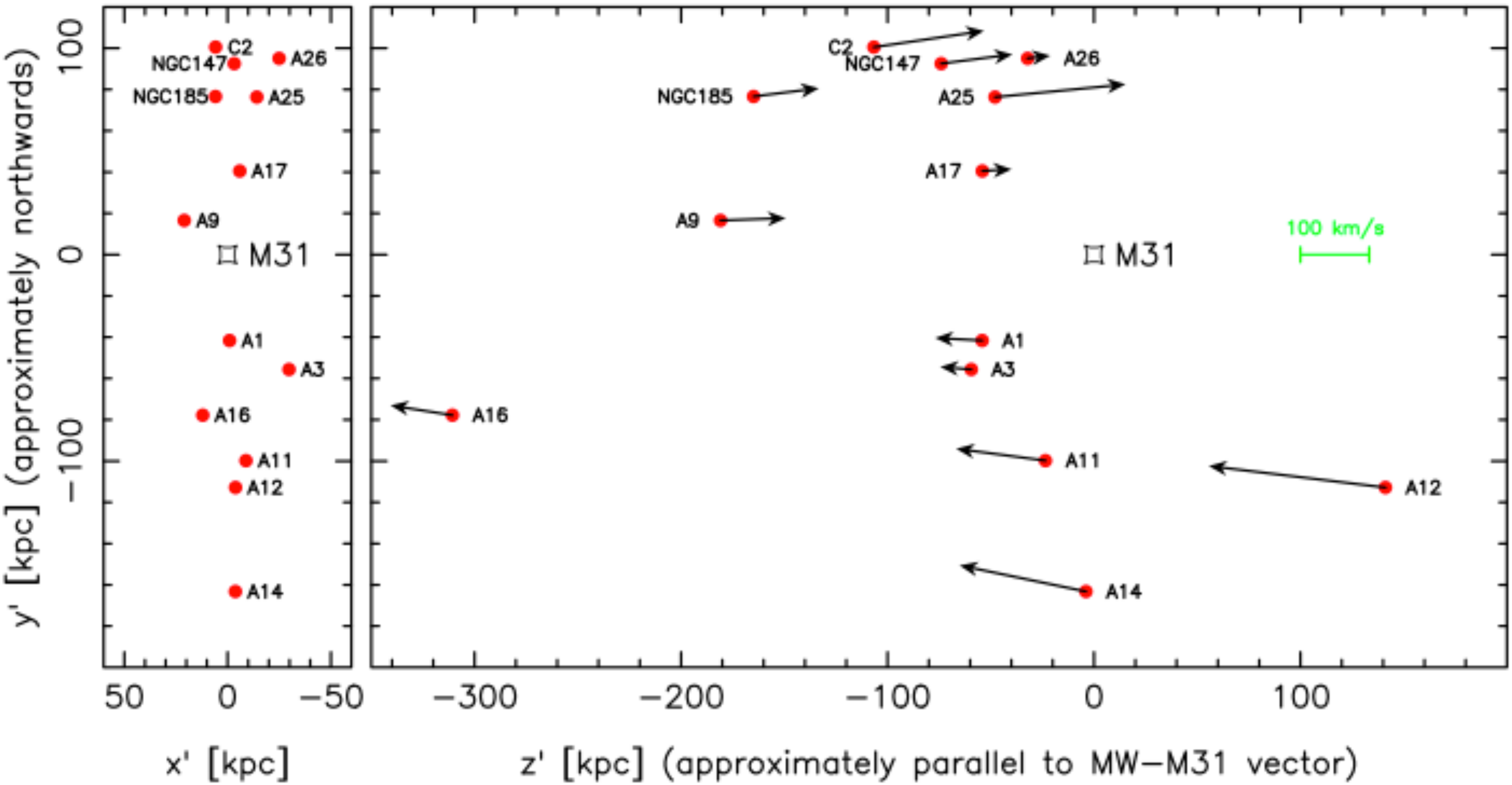
Statistics of a thin plane





- Conclude that a large number of the dwarfs are found in a statistically thin "pancake" around M31...

But what about velocities...



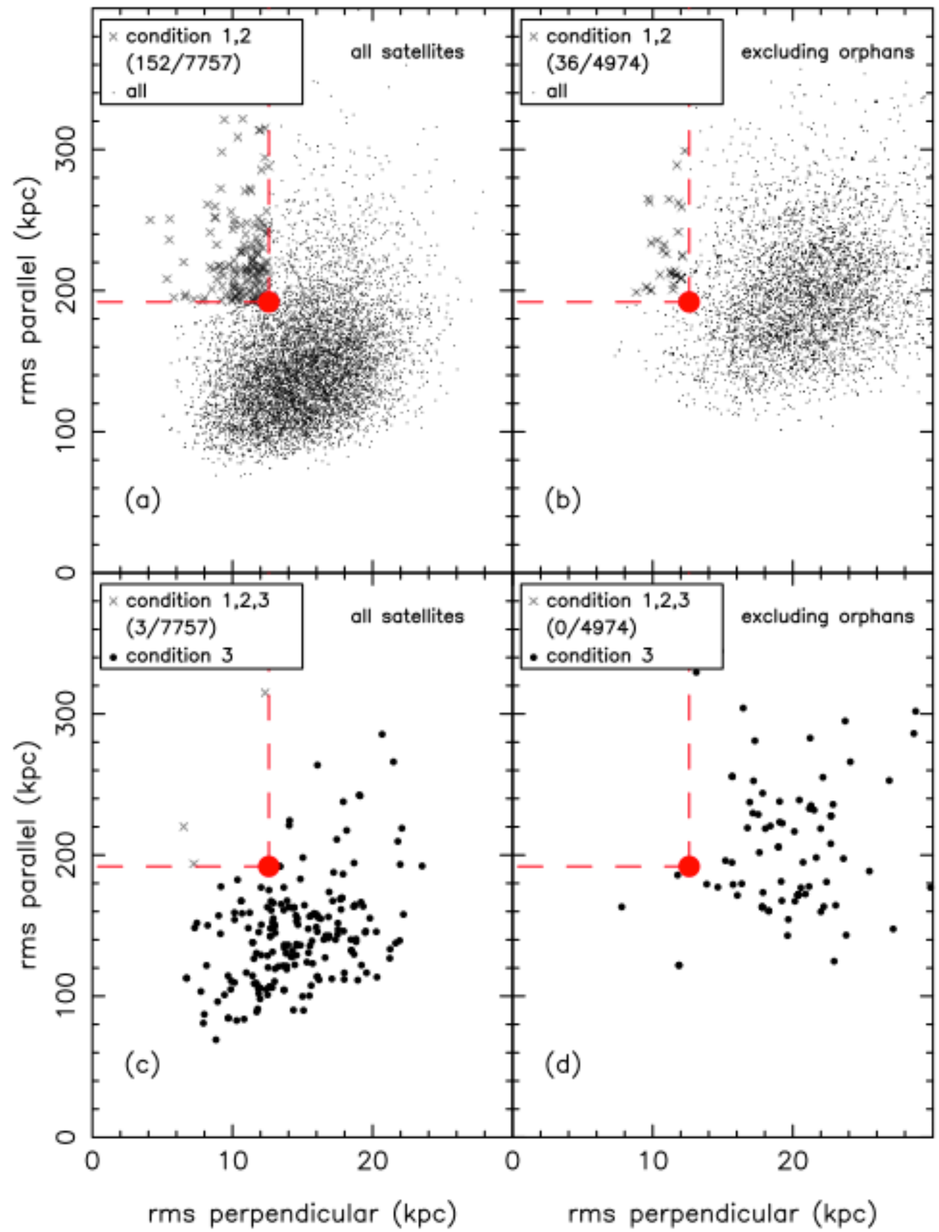
- 13 of 15 dwarfs have same sense of “rotation” - 1.4% probability

Are “planes” inconsistent with LCDM?

- ~0.04% of all galaxies in Millennium 2 simulation show planes at least as thin and rotating (Ibata et al. 2014; see also Pawlowski & Kroupa 2014, Gillet et al 2015)

- Those few (3 out of 7757) that do, the plane is a result of the accretion of a dense subgroup of galaxies

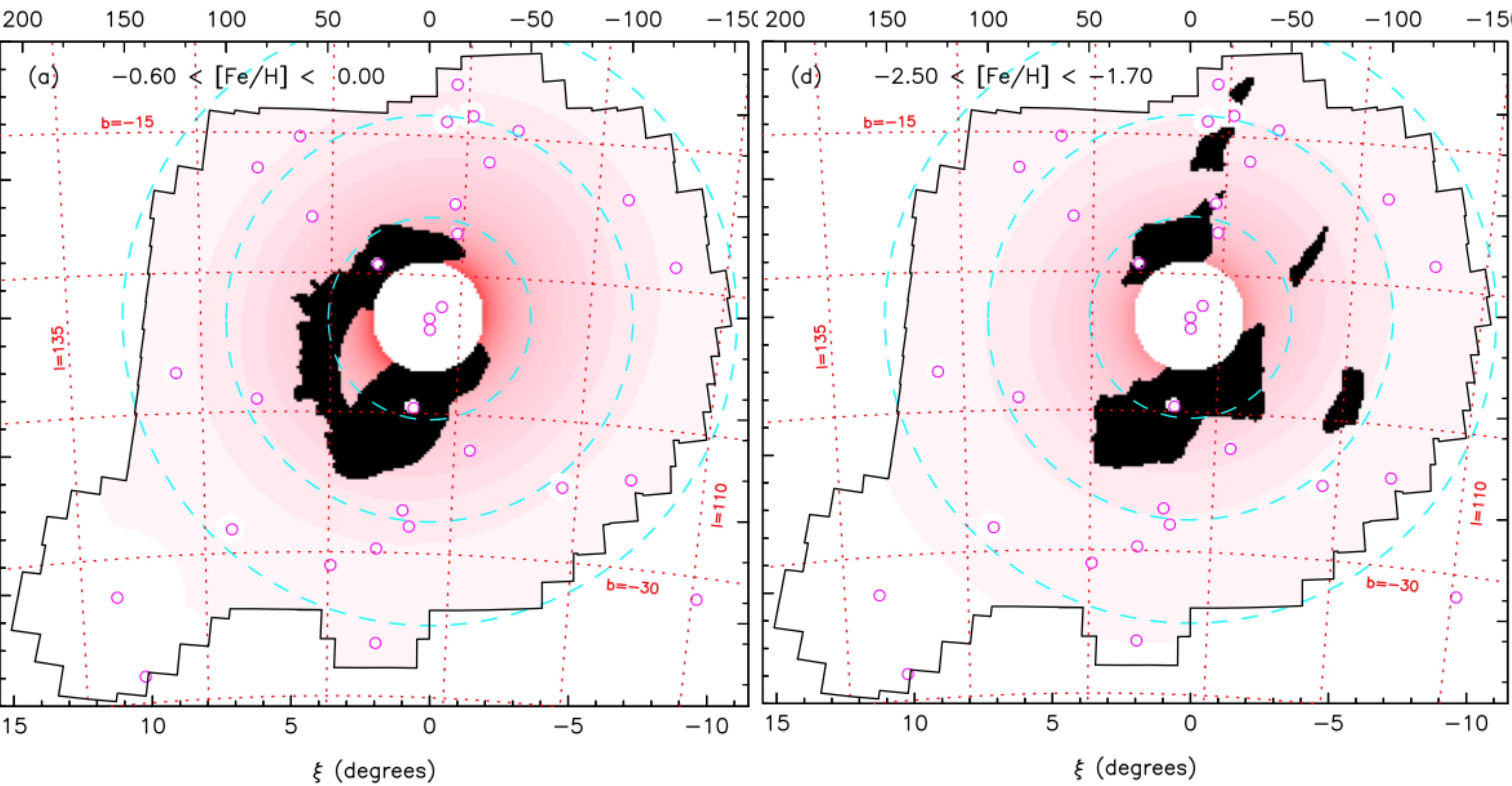
- Both the MW and M31 appear to show what is otherwise supposed to be a very rare alignment of satellites…



Ibata et al. (2014)

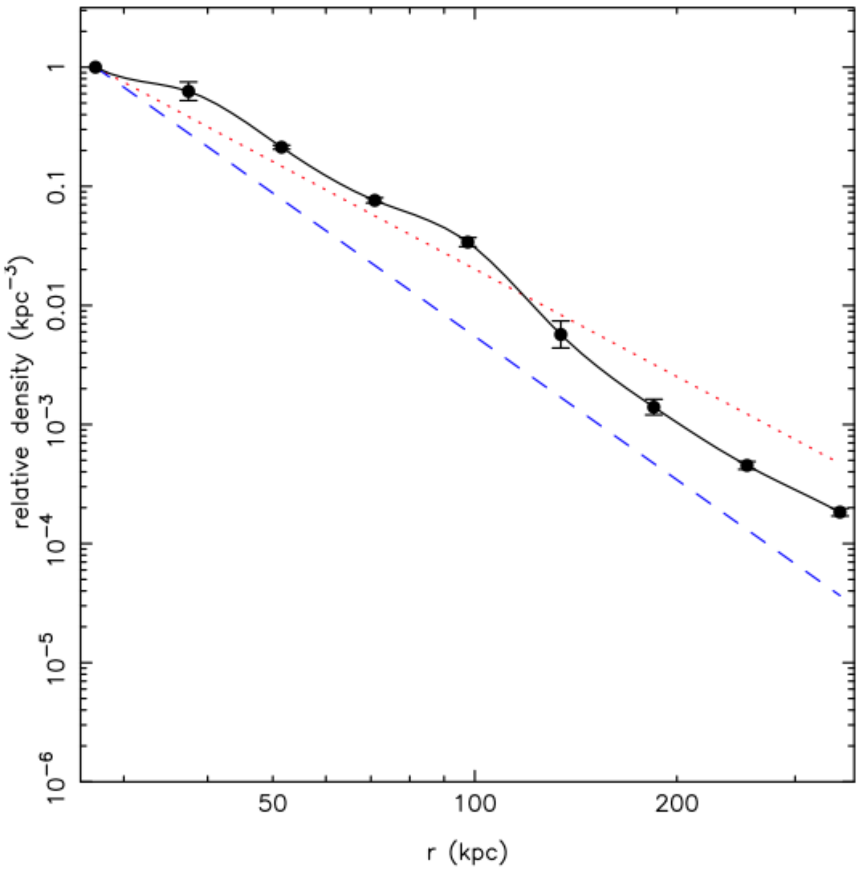
Asymmetric accretions? The smooth stellar halo

Identifying substructure as excess over underlying radially varying smooth component; use non-parametric (3D) spline fit with arbitrary anchor points.



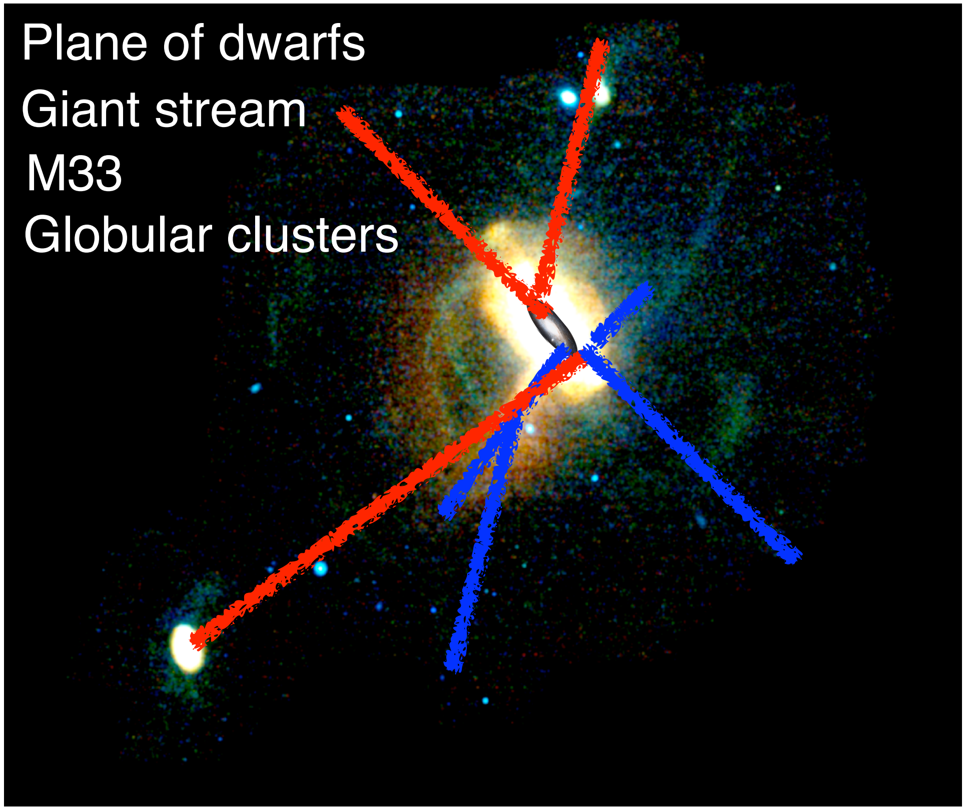
Ibata et al. (2014)

The (3D) profile of the “smooth” halo



Selection	γ	q	f_{smooth} (fraction)	$\mathcal{F}$
$-0.6 < [Fe/H] < 0.0$	-3.34 ± 0.04	1.01 ± 0.07	0.06	0.93 ± 0.04
$-1.1 < [Fe/H] < -0.6$	-3.62 ± 0.08	1.05 ± 0.04	0.06	0.91 ± 0.04
$-1.7 < [Fe/H] < -1.1$	-3.16 ± 0.06	1.07 ± 0.04	0.33	0.93 ± 0.04
$-2.5 < [Fe/H] < -1.7$	-3.08 ± 0.07	1.09 ± 0.03	0.62	0.93 ± 0.03
$-2.5 < [Fe/H] < 0.0$	-3.59 ± 0.08	1.11 ± 0.07	0.01	0.93 ± 0.03

- Nearly **spherical** power-law-esque profile for all metallicities, gamma=-3 to -4, from ~30 - 300kpc (in 3D), break at around 100kpc
- But isn’t the smooth stellar halo really just old accretions of dwarf galaxies?
- Approx 1% of halo across all metallicities appears “smooth”; strong function of metallicity, from ~6% at highest metallicities to >60% at the metal-poor end



Streams/substructures

- some dwarfs produce substructures (eg NGC147 stream, NGC205 loop?, M33 “tails”).

- the stars show the presence of substructures (more metal rich stars generally found in substructures - e.g., giant stream). Not obviously a very large number of events (~6 - 10?)

- some of the globular clusters clearly associated (spatially, radial velocity) with these visible substructures

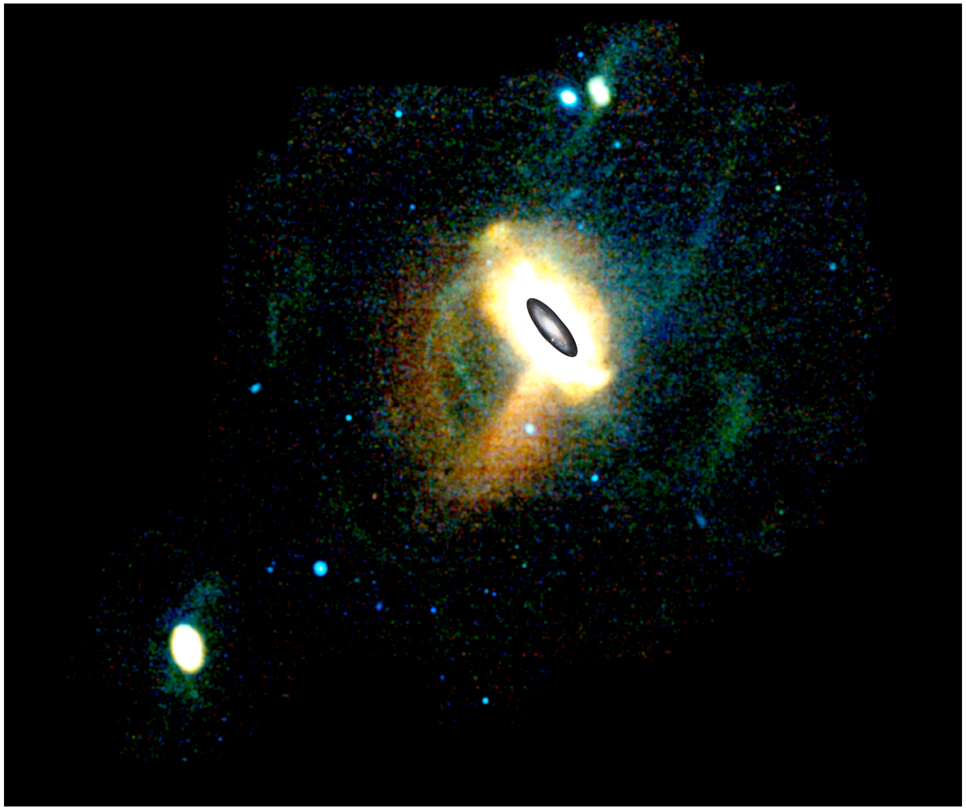
Planar distributions

- ~50% of the dwarf galaxies show a planar distribution (kinematic signature)

- stellar substructures not clearly associated with the plane (no obvious direction of preferential accretion…?)

- “smooth” stellar halo (ancient accretions?) nearly spherical (no preferential accretion direction if DM potential broadly spherical)

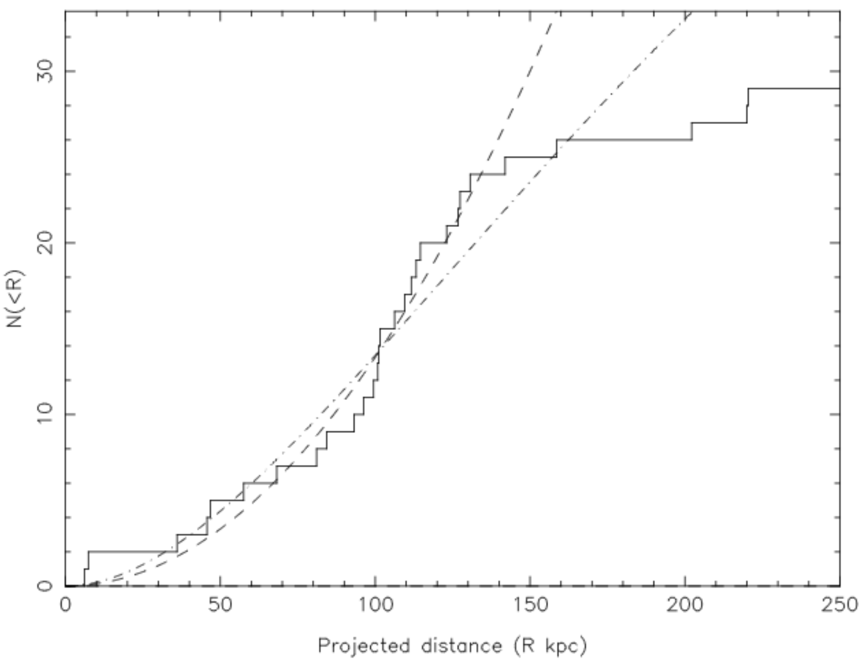
- GCs not planar (some net rotation broadly aligned with major axis though is potential evidence for preferential accretion direction)



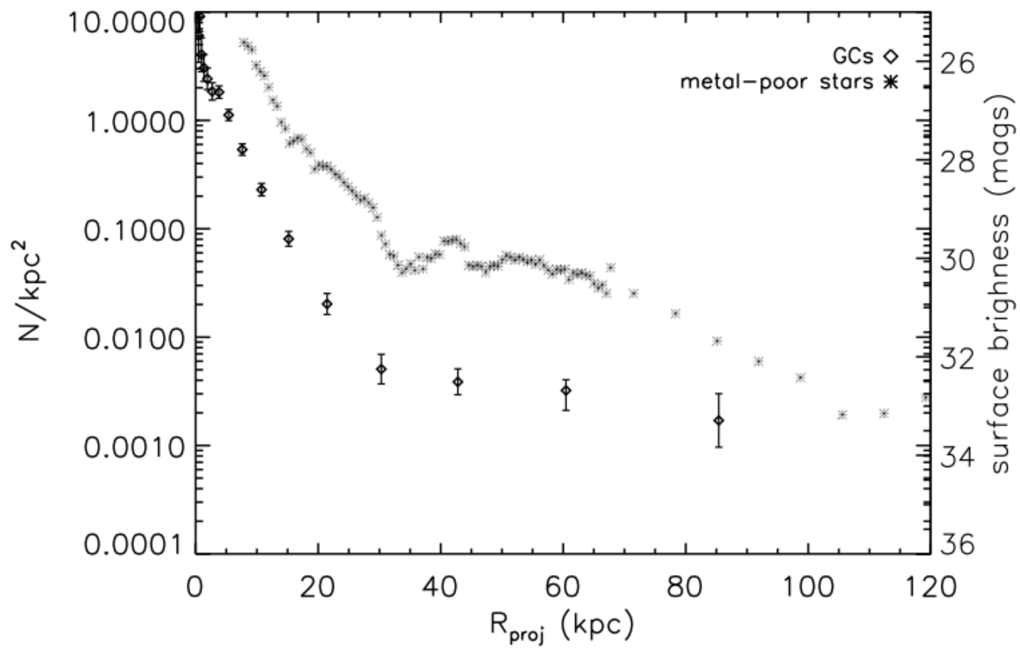
Radial profiles

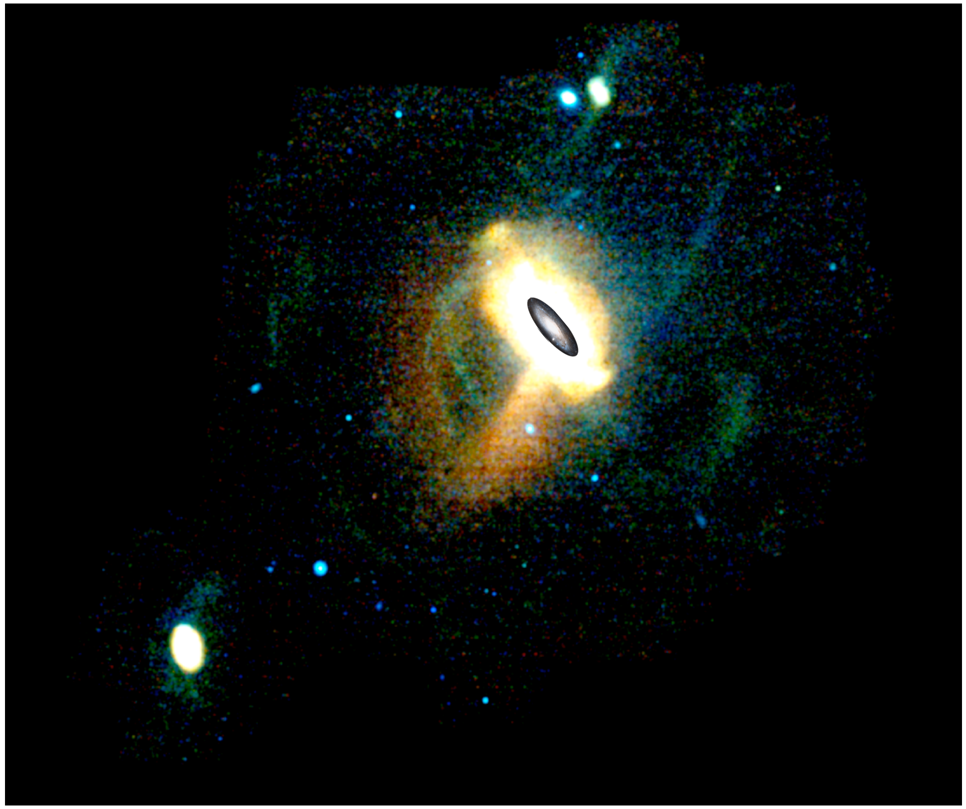
- stars follow a power law, deprojected index = -3 - 4 (Ibata et al. 2014)
- dwarf galaxies follow a power law, deprojected index = -1 (Richardson et al. 2011)
- globular clusters follow the stars (Huxor et al. 2011)
- [and they follow the stellar substructure]

Richardson et al. 2011



Huxor et al. 2011





Stellar mass budgets

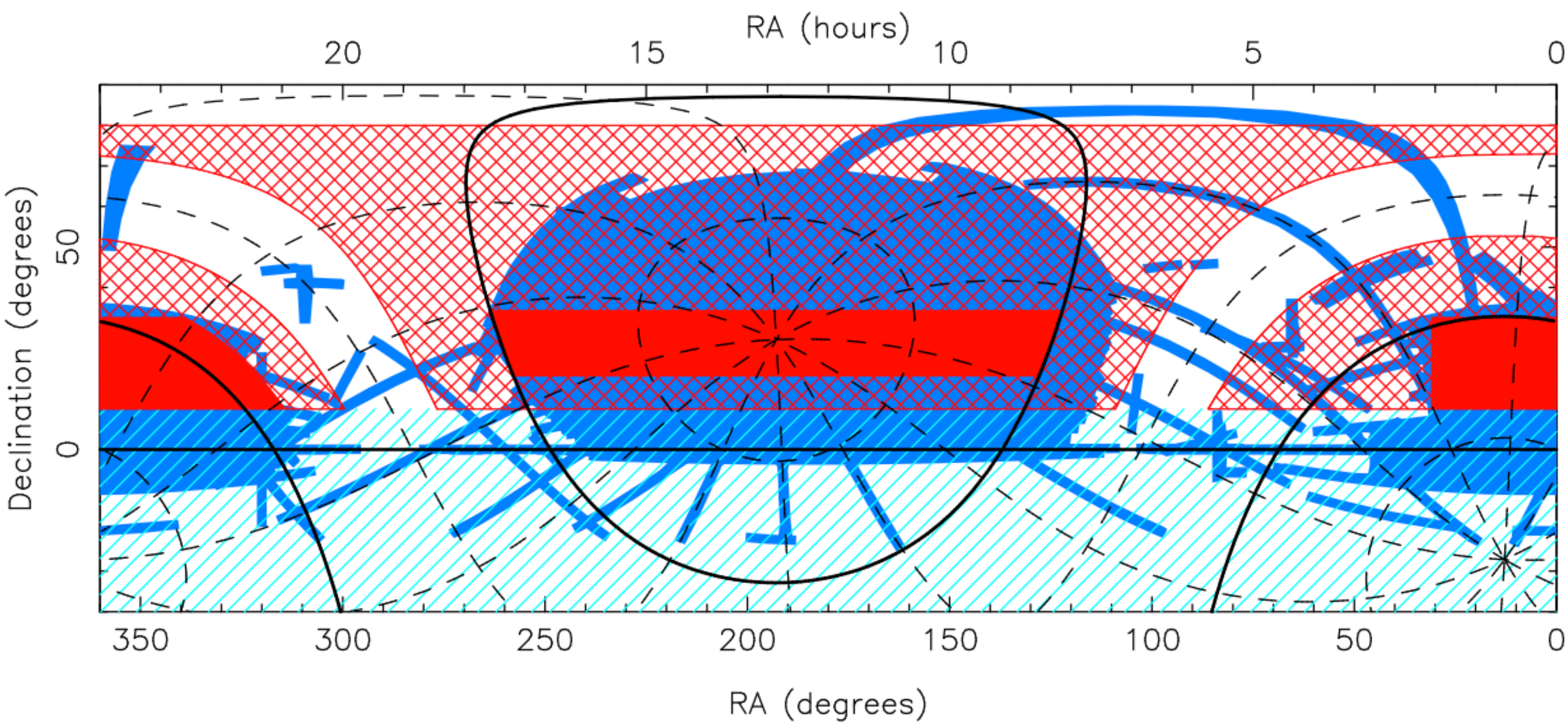
At R>~25-30 kpc (2 degrees) in PAndAS:

- the stellar halo contributes ~1.1×10^{10} M_{sun} (smooth = ~3×10^9 M_{sun})
- 28 dwarf galaxies contribute >3.5×10^9 M_{sun} (assumes M/L=1 which is obviously wrong; most is M33 (3×10^9 M_{sun}); NGC147 (3×10^8 M_{sun}), NGC185 (1.2×10^8 M_{sun})
- ~91 globular clusters contribute ~6×10^8 M_{sun} (not including M33 globular clusters)

- Stellar halo and dwarf galaxies contain about the same amount of mass; stellar halo essentially contains a few x M33 in stellar mass
- Halo GCs contain a dE-worth of stellar mass

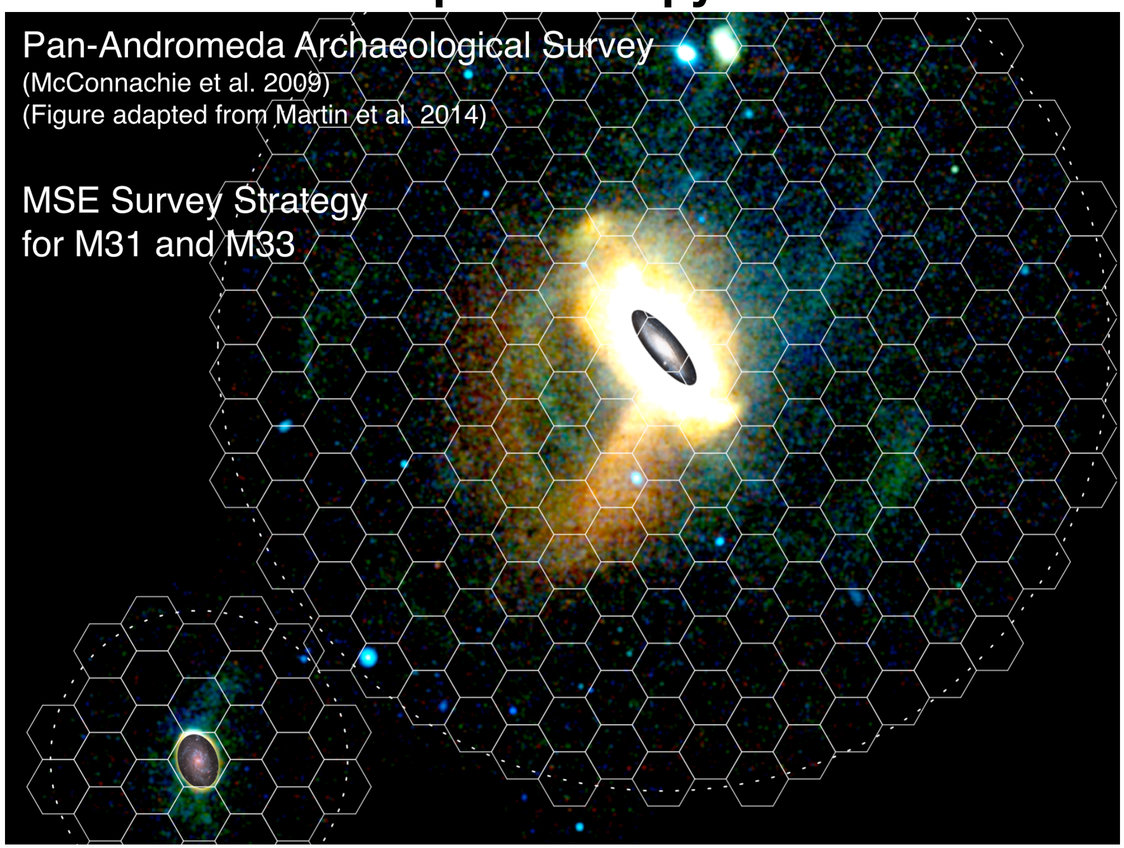
What next? The Galaxy (see talk by Rodrigo)

- New data expected for MW in coming years will represent a fantastic opportunity to advance our knowledge (understanding????) of its structure, substructure and stellar populations
- Luau (Legacy for the u band all-sky Universe) is a CFHT large program that will have surveyed ~3000 - 3500 sq.degs of sky to u=24.5 by end of this year
- Phase 2: ~10000 sq. degrees being proposed for starting January 2017



What's next? M31 halo

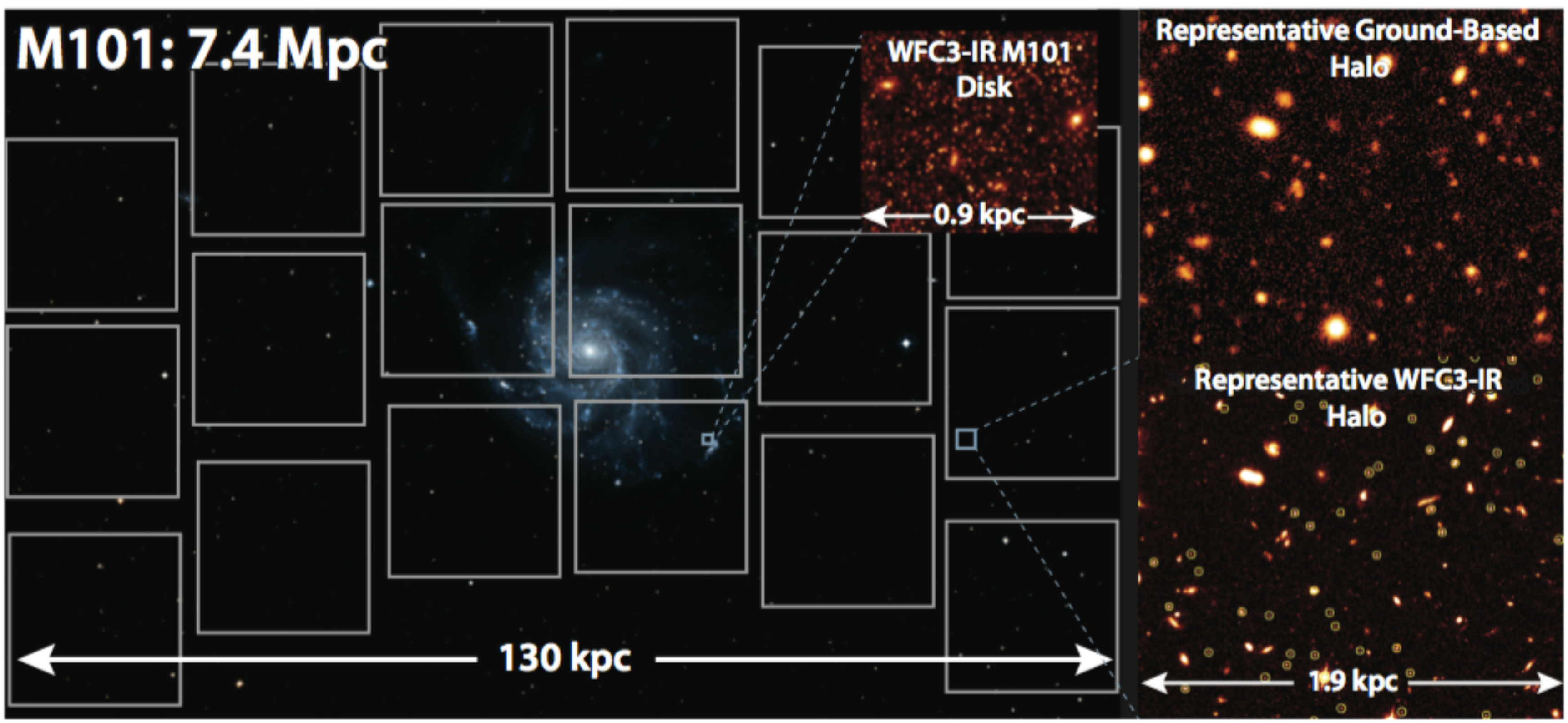
- For M31 halo, wide field imaging has been key to HST and spectroscopic followup
- HSC provides the opportunity to provide even deeper data: fainter stellar streams? dwarf-giant discrimination via narrow bands etc
- Facing Paul Weller syndrome?
  - (And the more I see - the more I know. The more I know - the less I understand)
- Really need **industrial-scale stellar spectroscopy:**



- DEDICATED WIDE
- ON A 10M CLASS

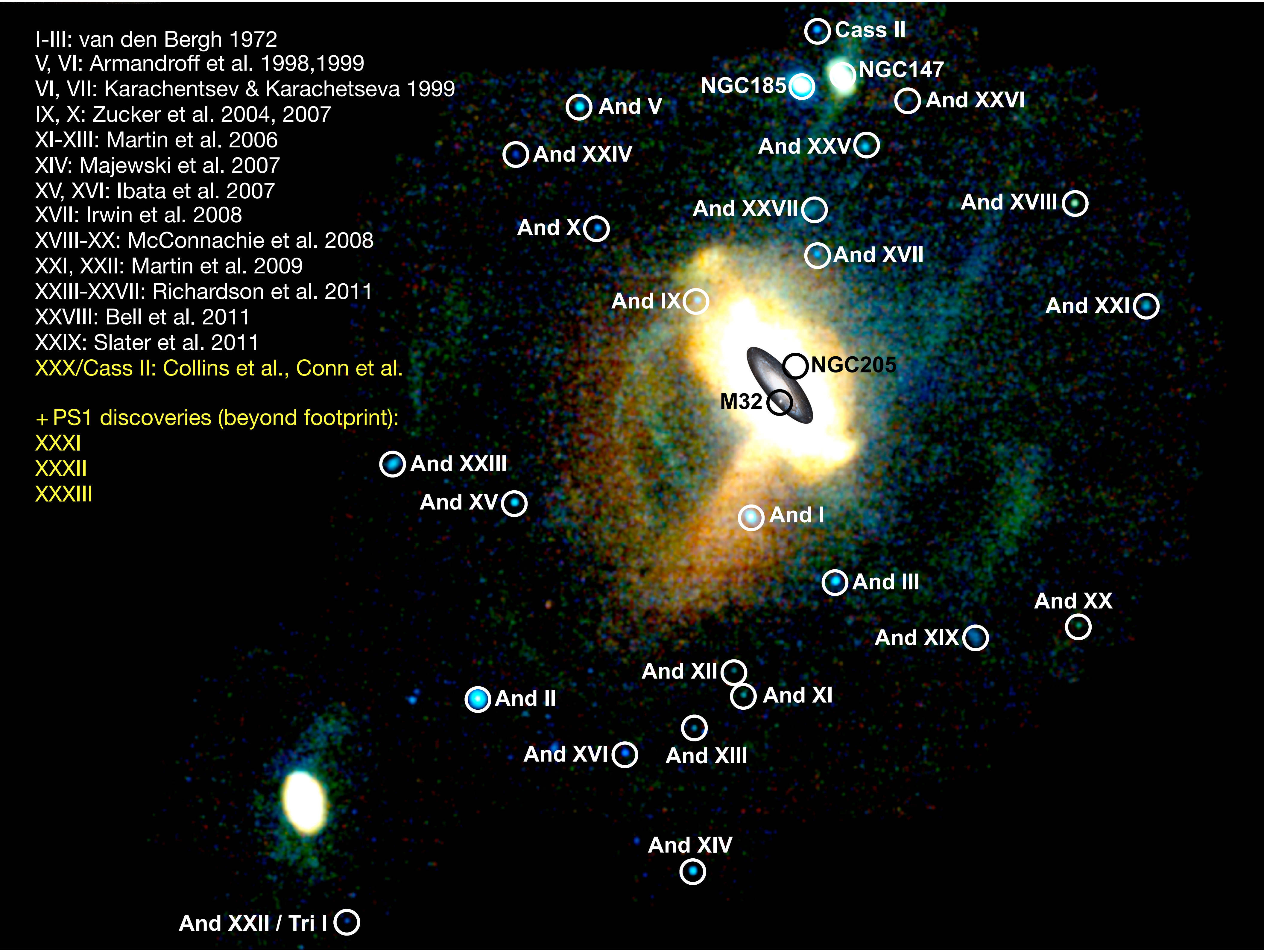
What next? The Local Volume

- Several notable programs pushing wide field mapping of resolved stellar populations into the Local Volume e.g., HST/GHOSTS, Subaru/HSC, “PISCeS”…
- Dedicated, deep, wide field imaging with very high spatial resolution required: Euclid will be the first to do this in space!
- WFIRST / WINGS: The WFIRST Infrared Nearby Galaxy Survey (P.I. Ben Williams)
  - Science definition program for WFIRST charged with designing science case and providing input to WFIRST mission design.



[redacted]

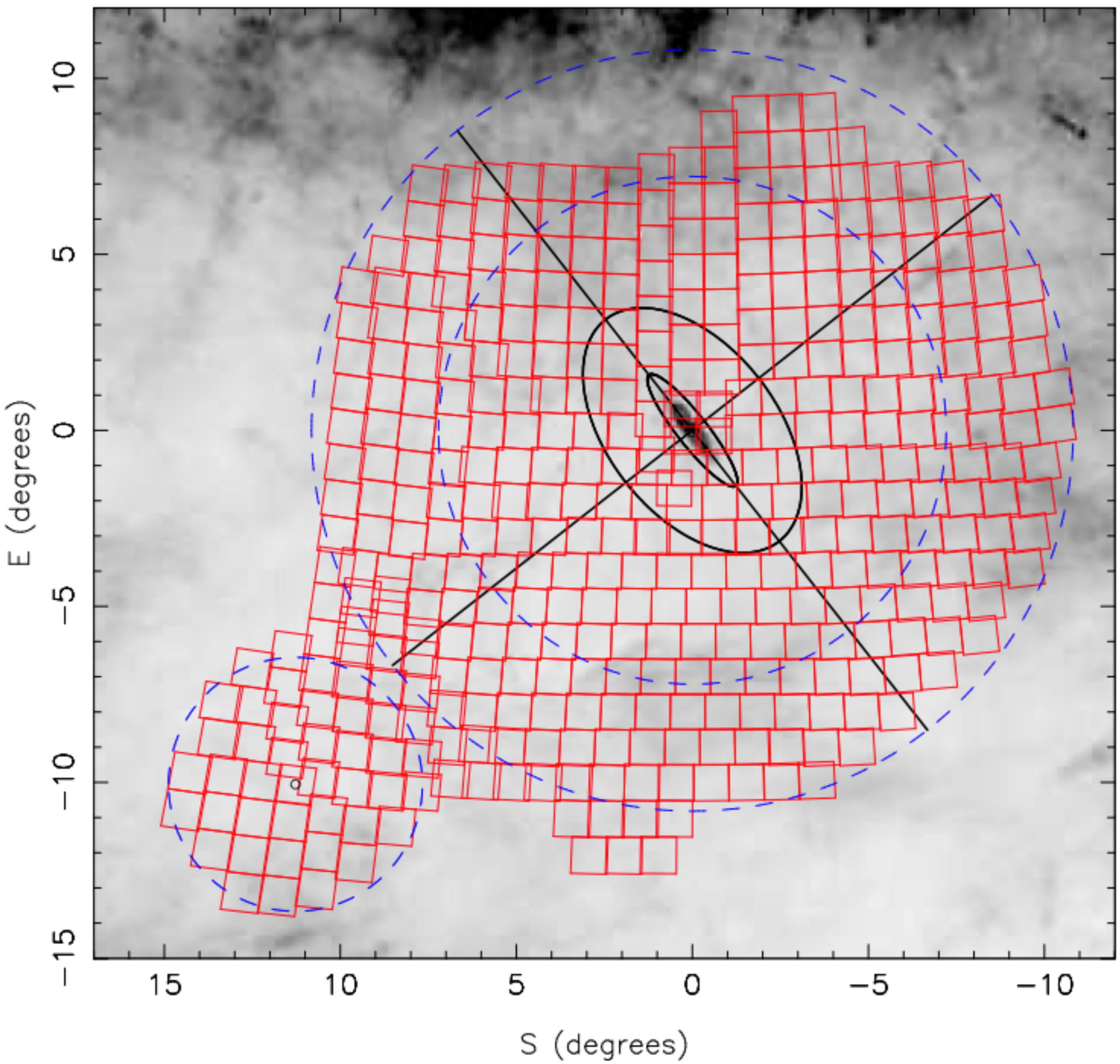
Further into the future...



I-III: van den Bergh 1972
V, VI: Armandroff et al. 1998,1999
VI, VII: Karachentsev & Karachetseva 1999
IX, X: Zucker et al. 2004, 2007
XI-XIII: Martin et al. 2006
XIV: Majewski et al. 2007
XV, XVI: Ibata et al. 2007
XVII: Irwin et al. 2008
XVIII-XX: McConnachie et al. 2008
XXI, XXII: Martin et al. 2009
XXIII-XXVII: Richardson et al. 2011
XXVIII: Bell et al. 2011
XXIX: Slater et al. 2011
XXX/Cass II: Collins et al., Conn et al.
+ PS1 discoveries (beyond footprint):
XXXI
XXXII
XXXIII
Cass II
NGC147
NGC185
And XXVI
And V
And XXIV
And XXV
And XXVII
And XVIII
And X
And XVII
And IX
And XXI
NGC205
M32
And XXIII
And XV
And I
And III
And XX
And XIX
And XII
And XI
And II
And XVI
And XIII
And XIV
And XXII / Tri I

Aquarius simulation, Springel *et al.* (2009)

PAndAS: The Survey (S08B, S09B, S10B)

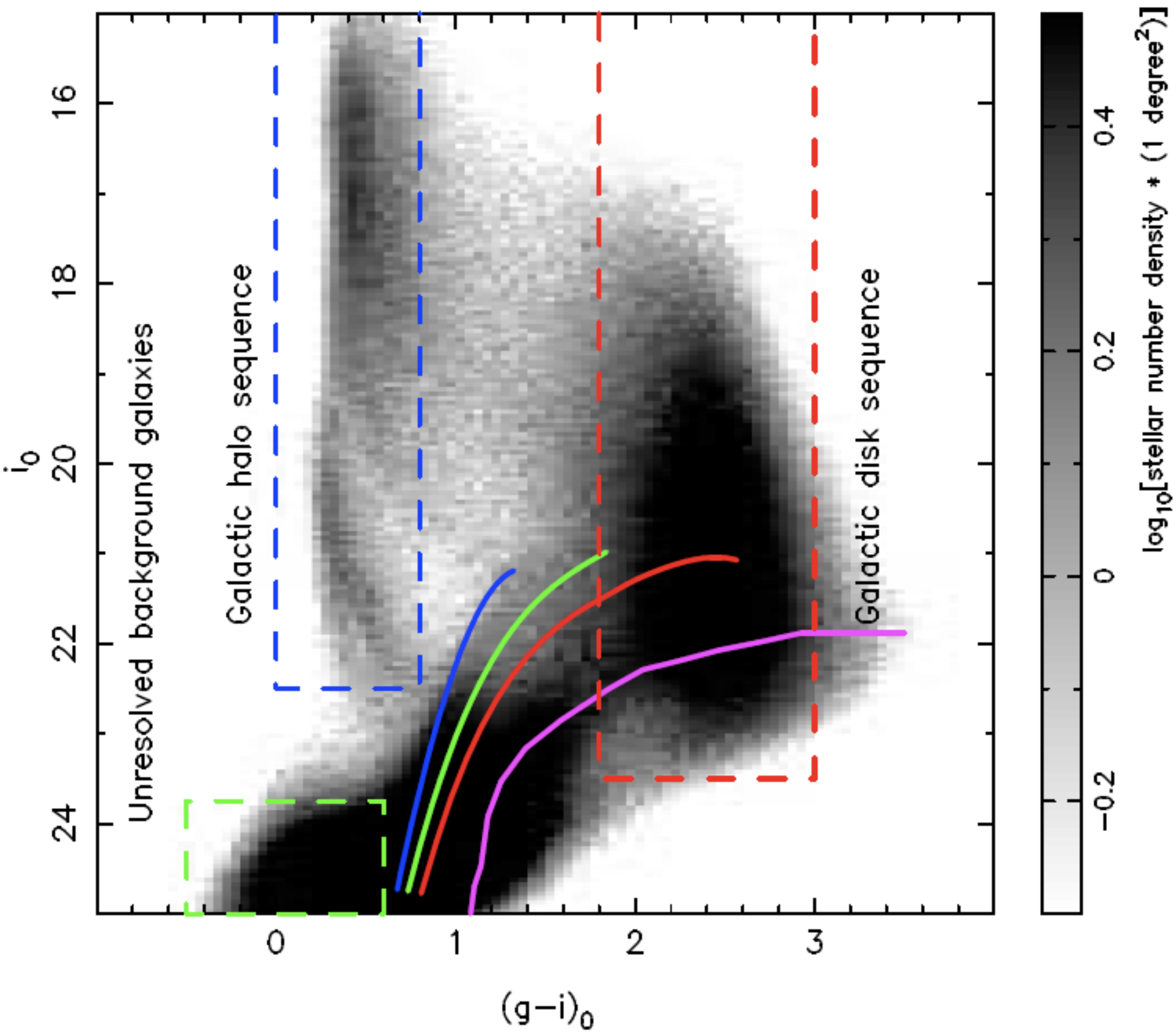


- S08B - S10B: 226 hours (41 nights) (B semesters only) on MegaCam in g and i bands

- Builds upon earlier P.I. programs by Ibata (S02B - S06B) and McConnachie (S06B - S07B)

- Total area of ~400 square degrees (~15 million cupic kpc of halo of M31/M33)

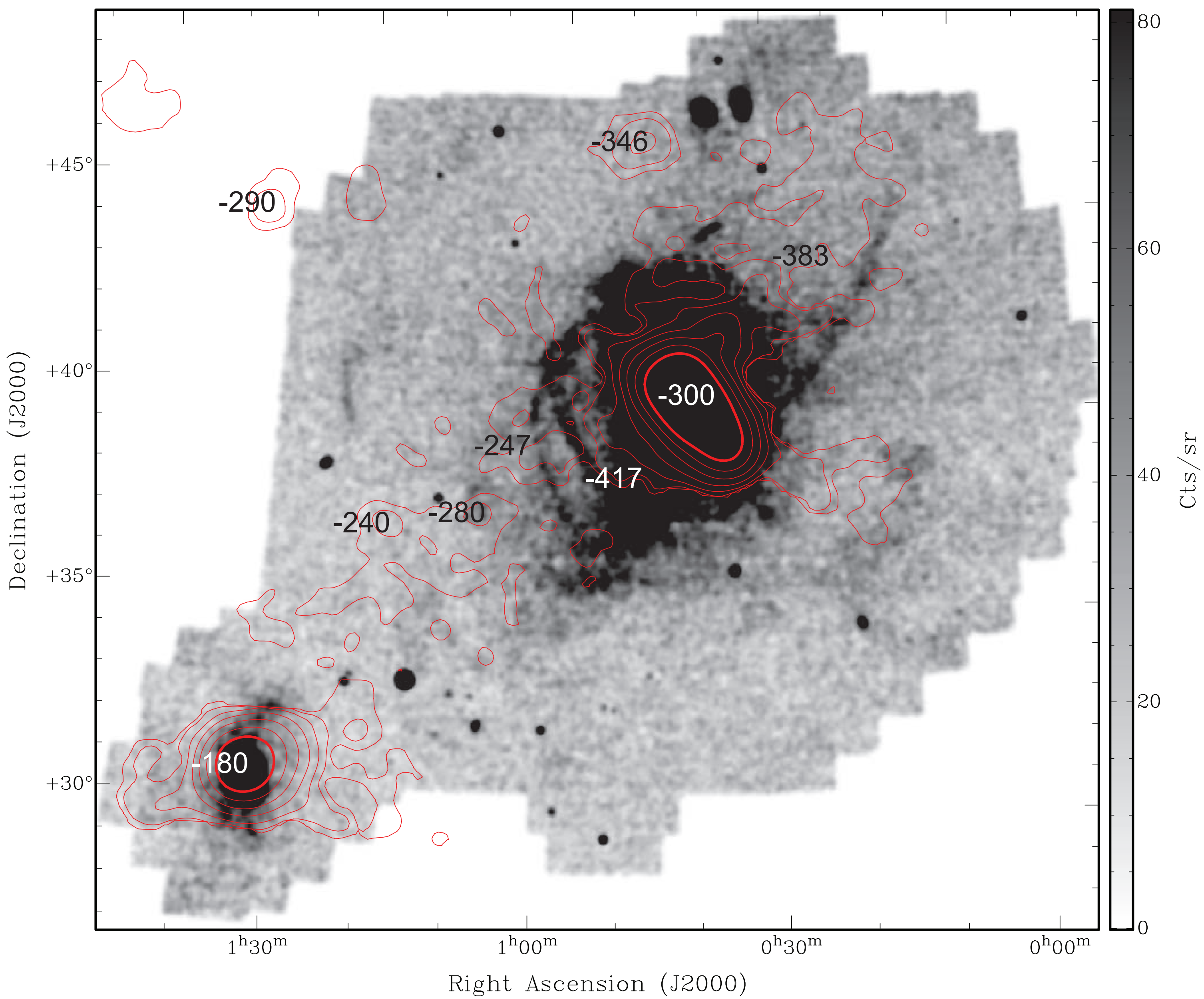
Colour - magnitude diagram



- Approx 31 million stellar objects
- Approx 10 million stellar objects consistent with red giant branch stars at the distance of M31
- S/N =10 for point sources at g = 25.5, i = 24.5

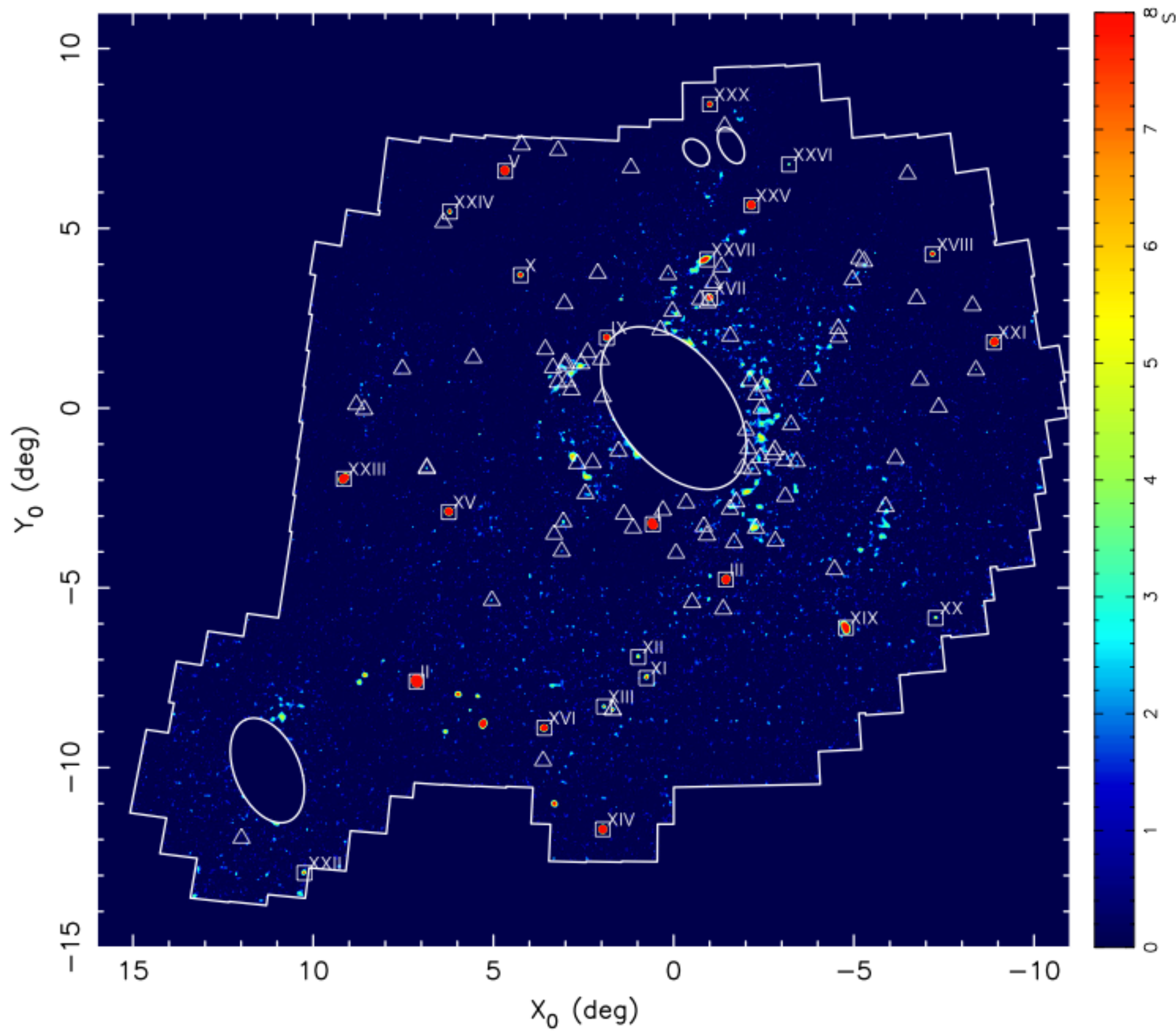
Stars - HI comparison

(Lewis et al., submitted)



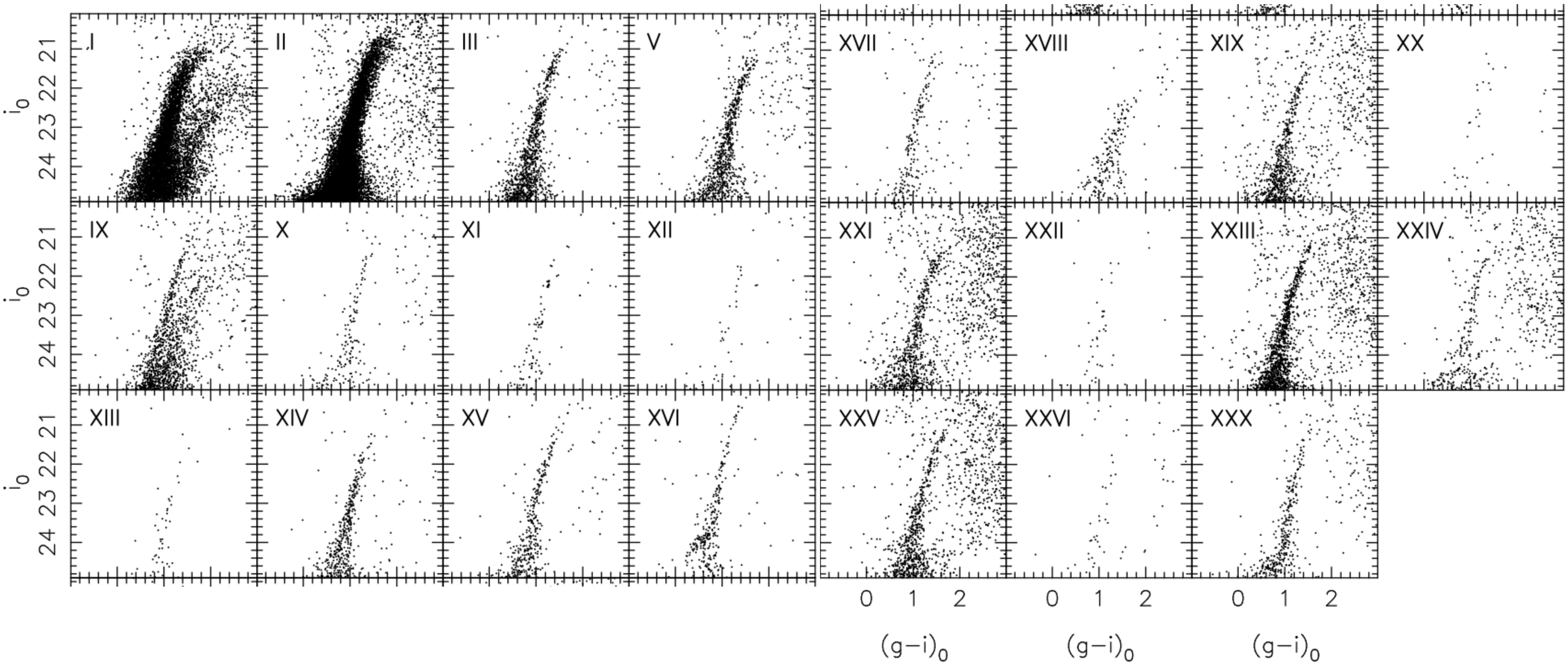
Dwarf searches

- Full statistical analysis of spatial and CMD information
    - Accounting for varying MW foreground contamination and very structured M31 “contamination”
- Automated search
    - published list of 143 most significant detections for follow up
    - will lead to completeness as function of f(X,Y,rh,[Fe/H], m-M,…) [Martin et al. in prep]



Martin et al. (2013)

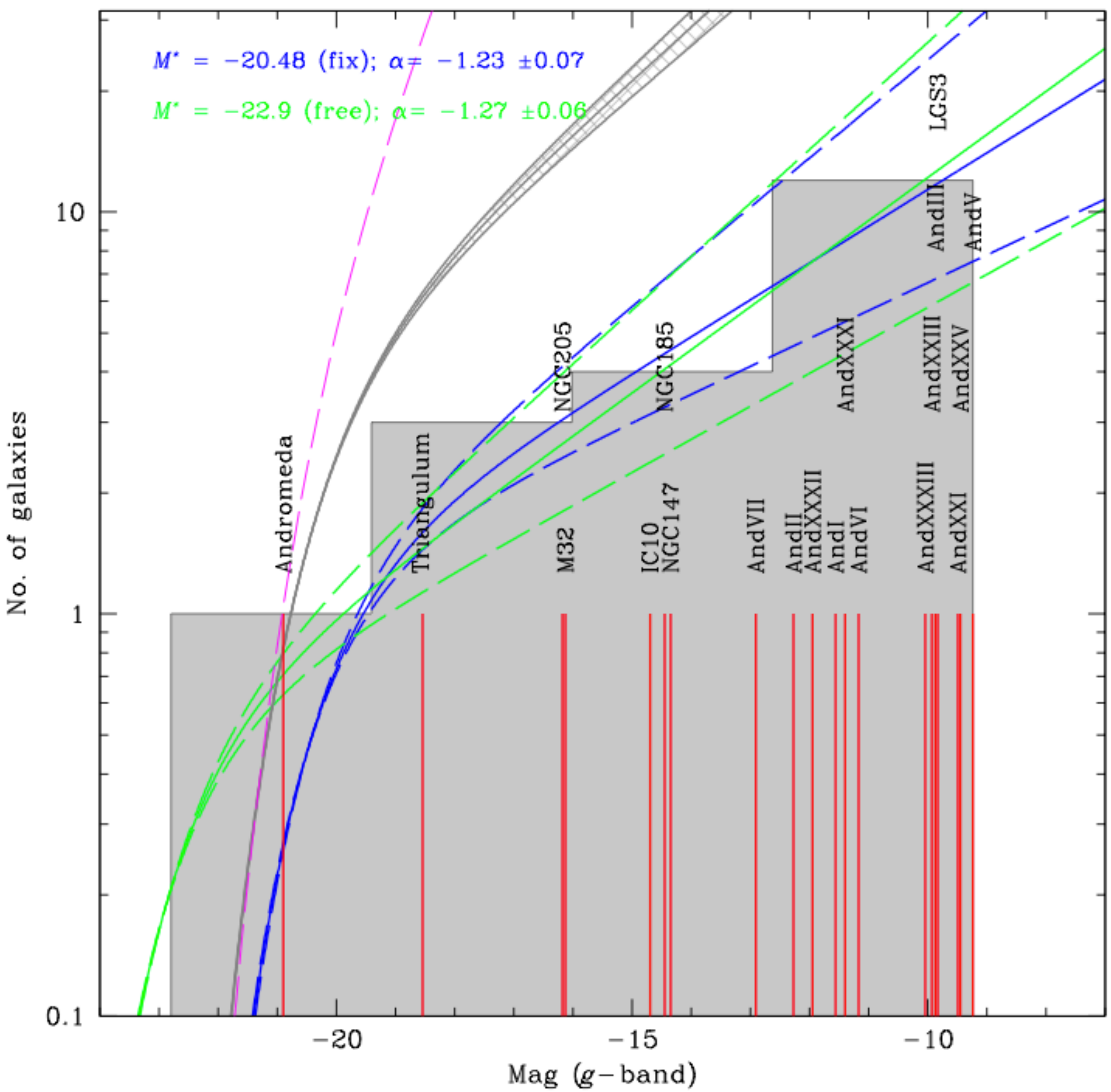
The (known) M31 dwarf galaxy satellites

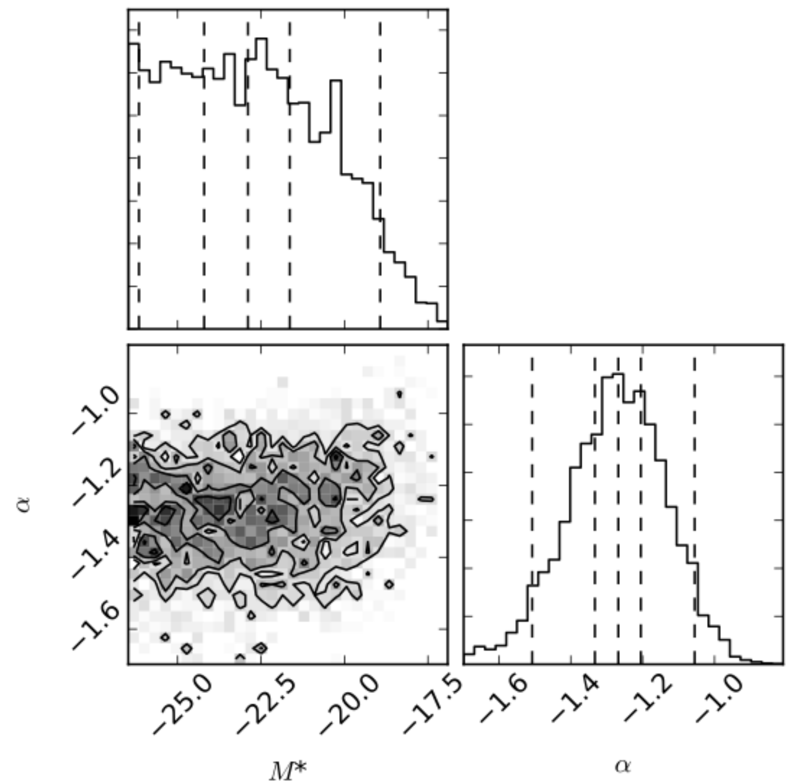


- Homogeneous (bayesian) analysis of all distances based on (bayesian) TRGB in Conn et al. (2011, 2012)
- Homogeneous (bayesian) analysis of all structural parameters in Martin et al. (2016, submitted)

Ferrarese et al. (2016, submitted)

The Andromeda dwarf luminosity function

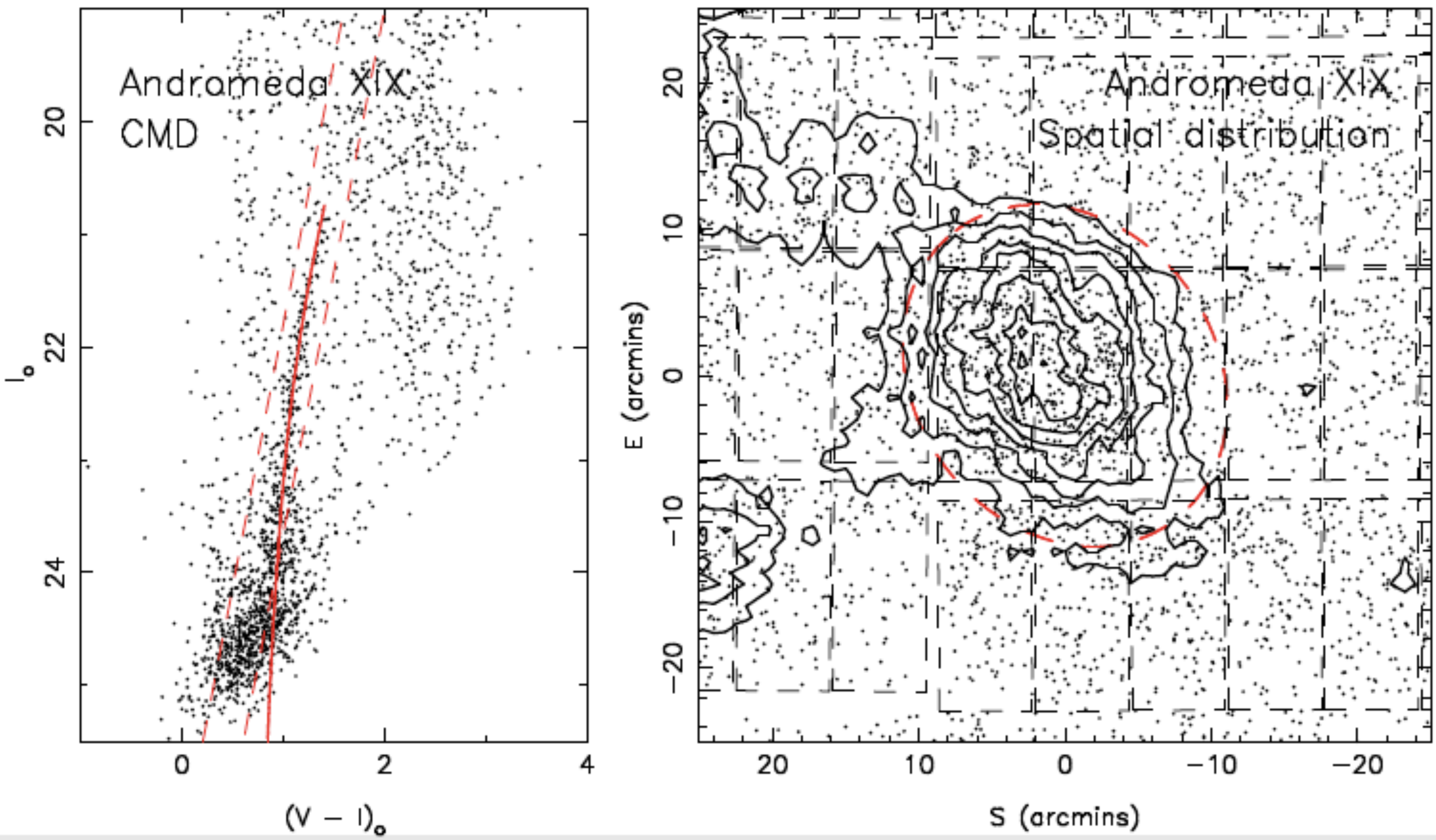




Faint end slope of alpha = -1.3

Very similar to MW (and entire LG) and the core of the Virgo cluster

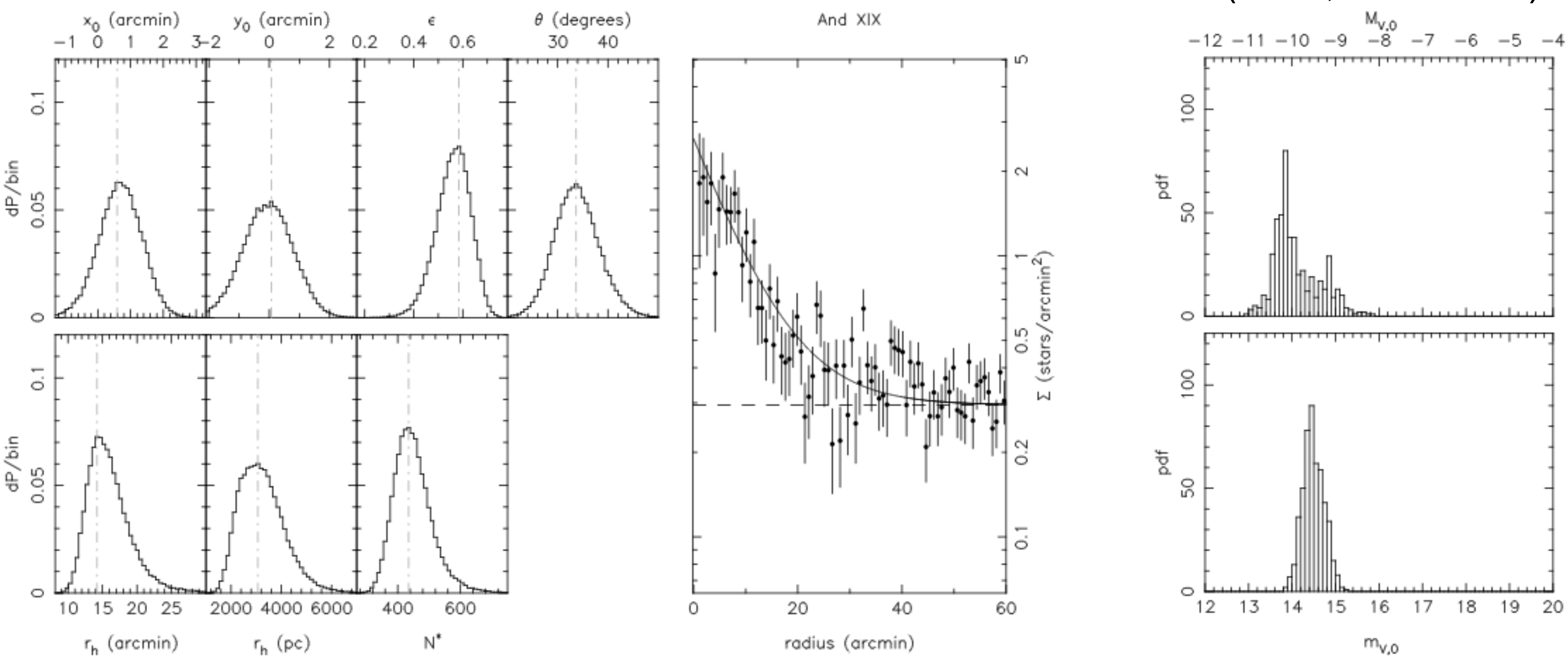
At the extremes: Andromeda XIX



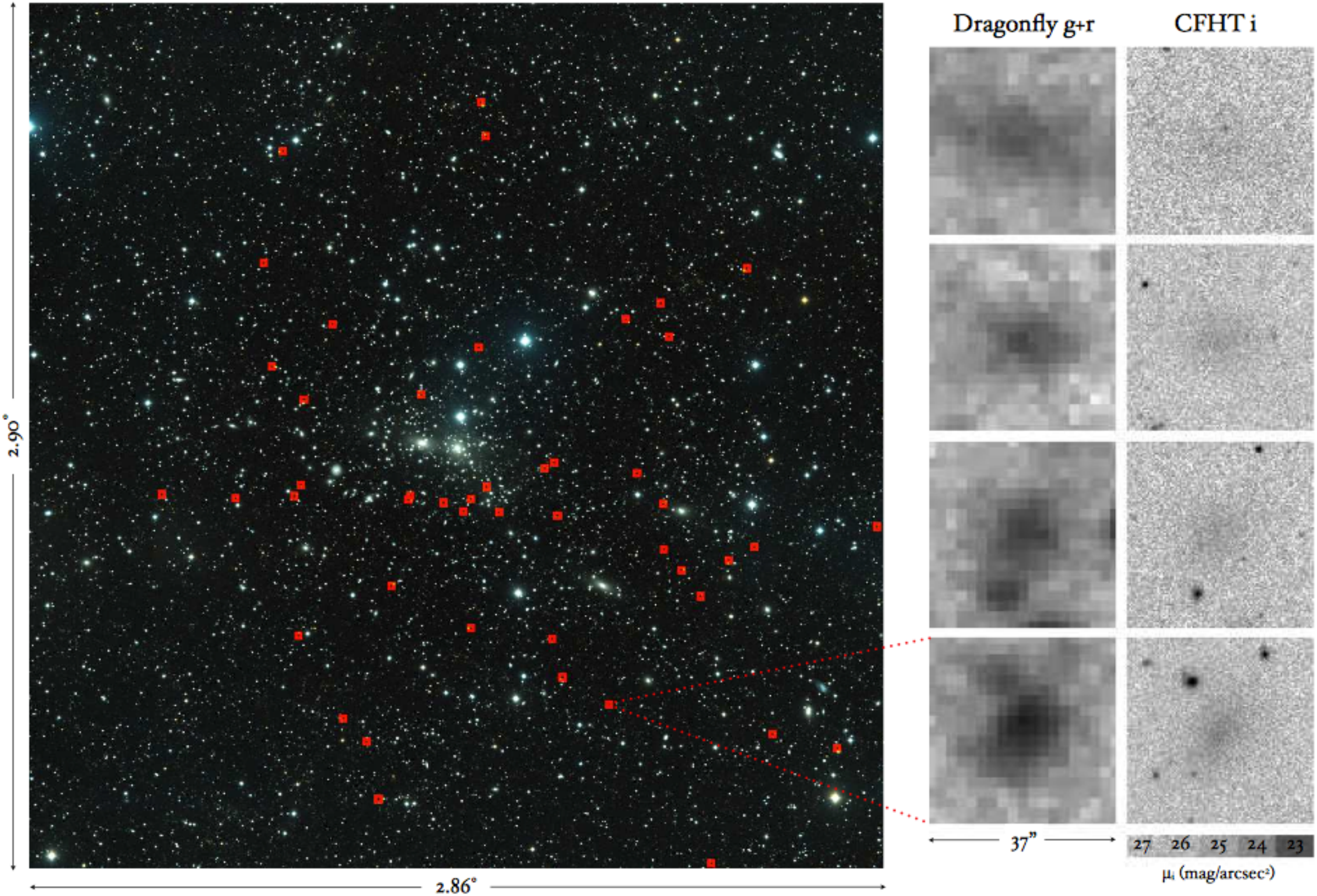
McConnachie et al. (2008)

At the extremes: Andromeda XIX

Martin et al. (2016, submitted)



- Half light radius of ~15 arcmins —> >3kpc!!!
- c.f. Dragonfly results (van Dokkum, Abraham, ApJ, 798, L45, 2015)



- c.f. Dragonfly results (van Dokkum, Abraham, ApJ, 798, L45, 2015)

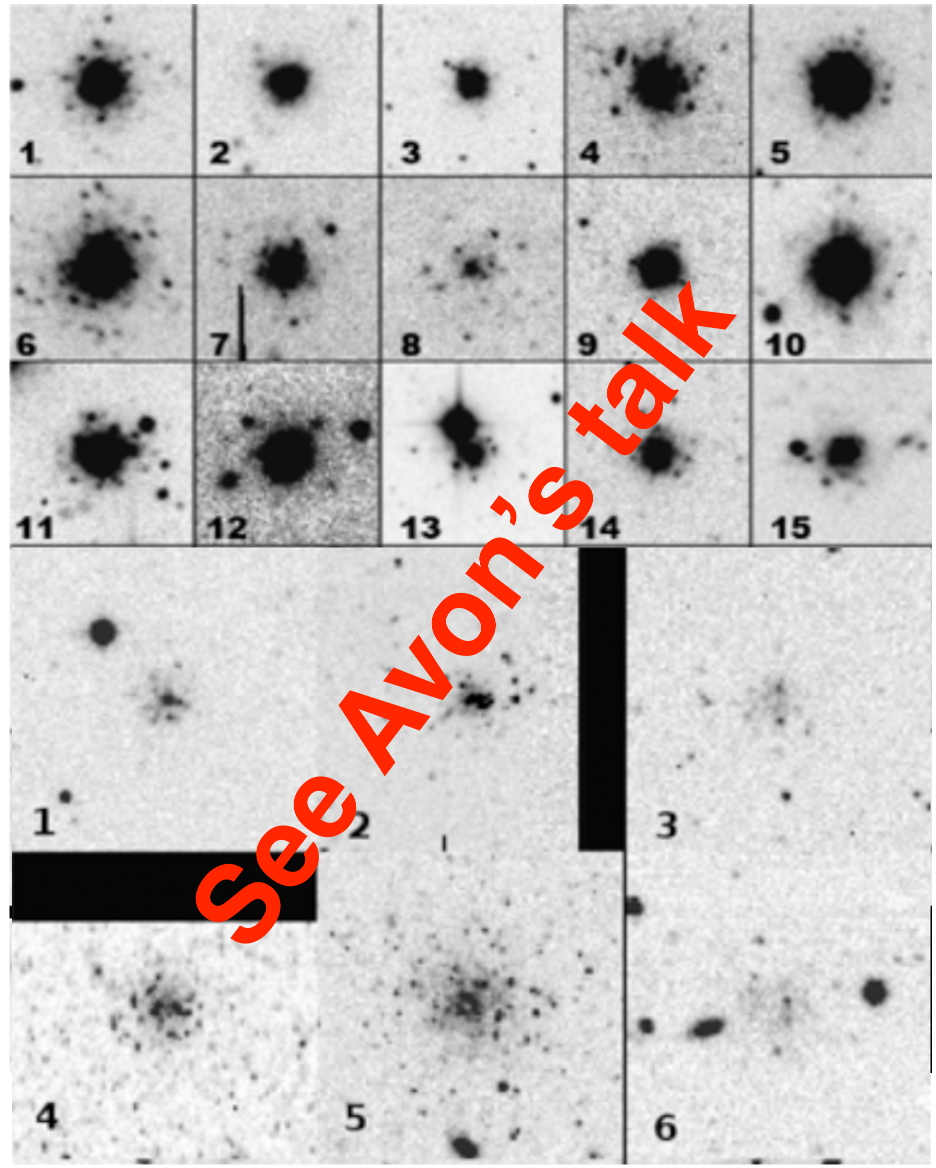
The stellar halo - globular cluster connection

- M31 now has ~450 globular clusters
- MW has ~150 globular clusters
- Some new M31 clusters are of the "extended" variety

- Prior to PAndAS and precursor surveys:
  - 34 GCs at >15 kpc
  - 3 GCs at >30 kpc.

- **PAndAS and precursor surveys have increased known GC population at large radii by 200%:**
  - 97 new GCs at >15 kpc
  - 79 new GCs at >30 kpc
  - 15 new GC at $85 < R_{proj} < 145$ kpc

- cf. MW:
  - 9 GCs at >38 kpc
  - 2 GCs at >100kpc



Huxor et al. 2005, 2008, 2015

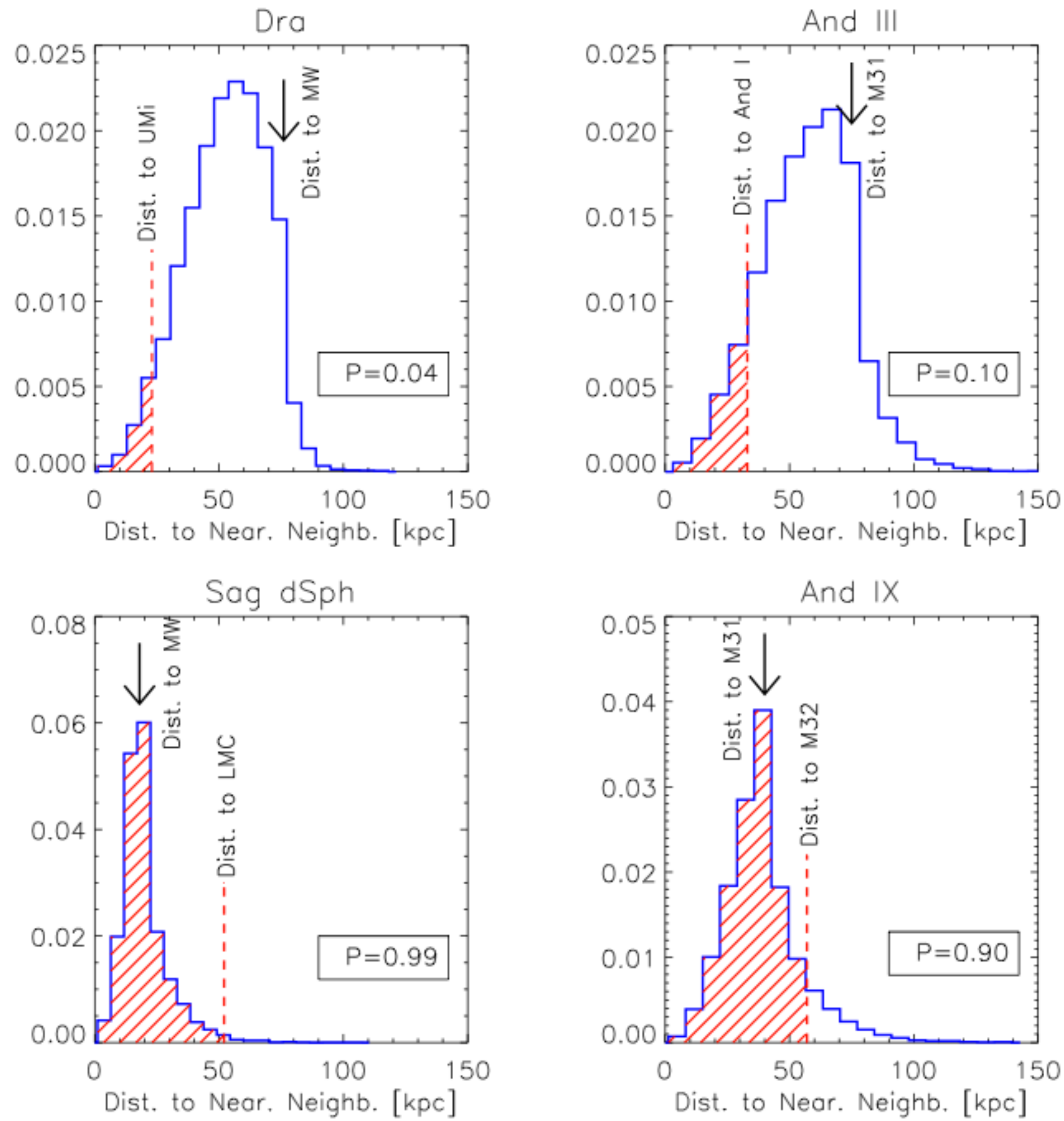
Fattahi et al. (2013, ApJ)

How common are dwarf galaxy pairs anyway?

- Search for possible pairs of galaxies, initially based only on positions

- Looking for galaxies that are “closer than they should be”, compared to randomised MW/M31 distributions with similar radial distributions

- Only look at MW/M31 satellites, and only galaxies brighter than $M_V = -8$



Fattahi et al. (2013, ApJ)

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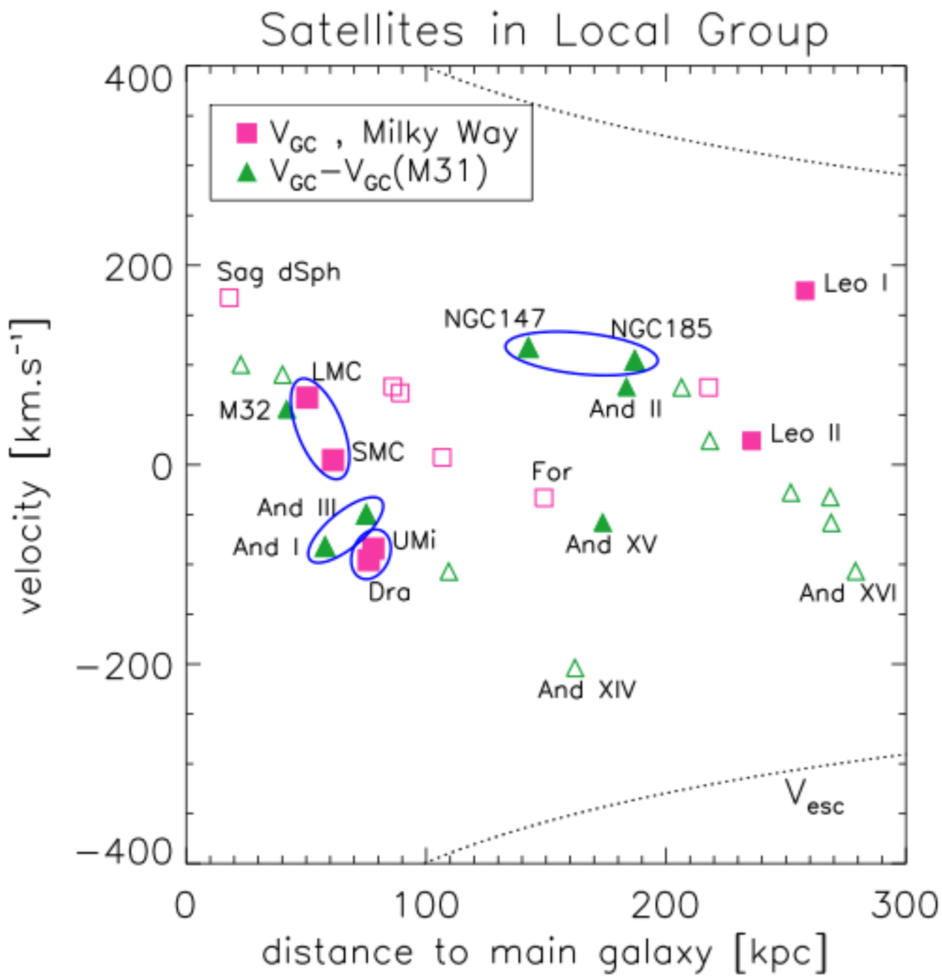
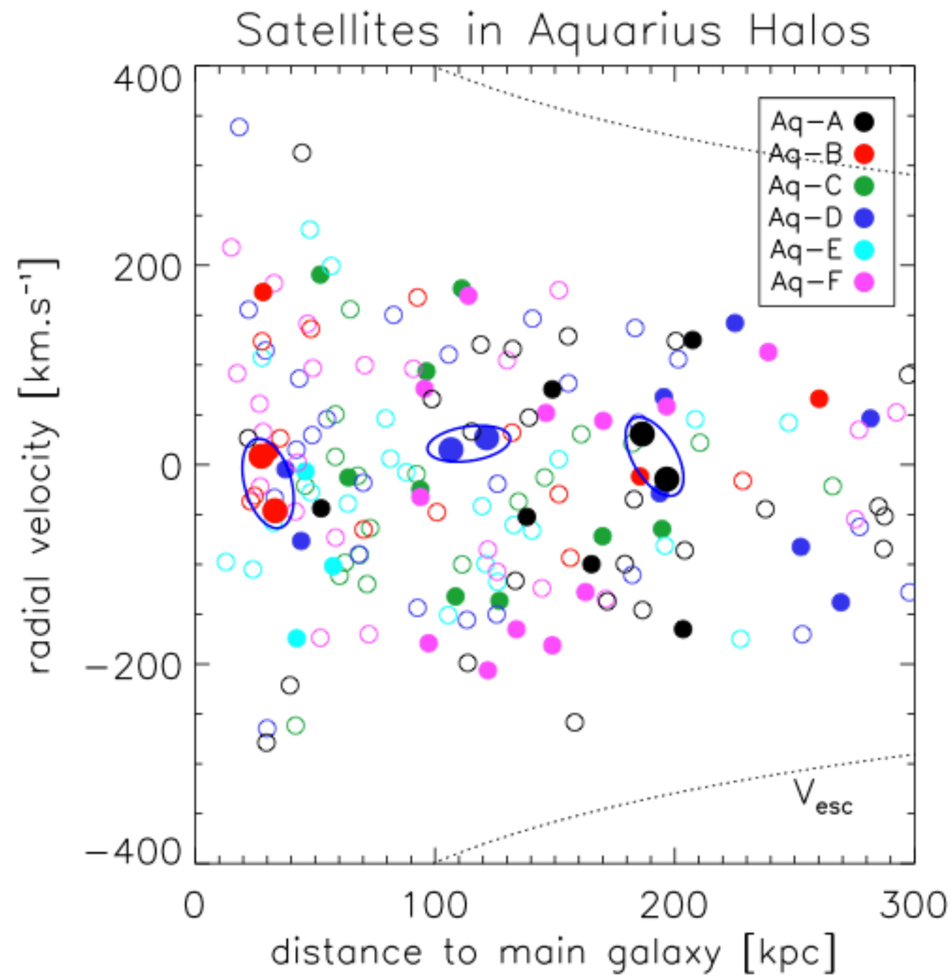
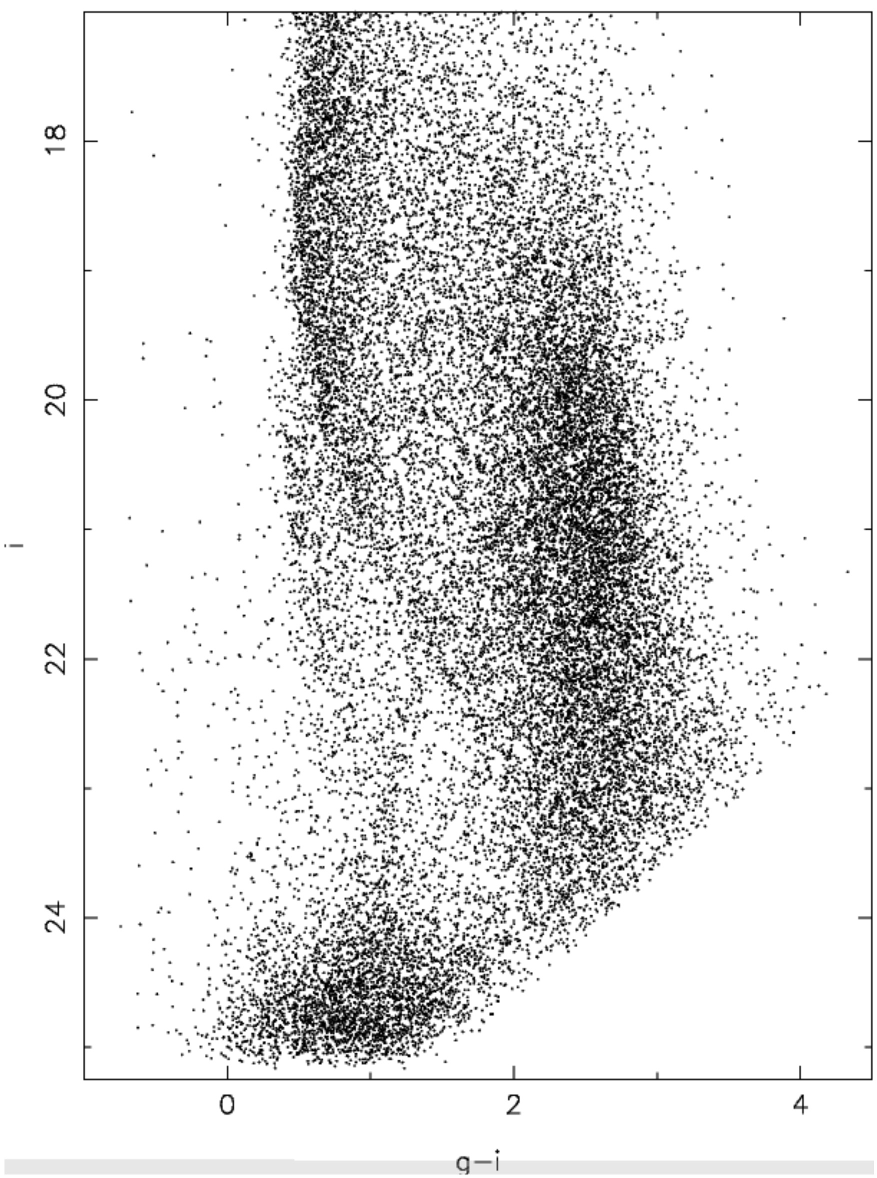


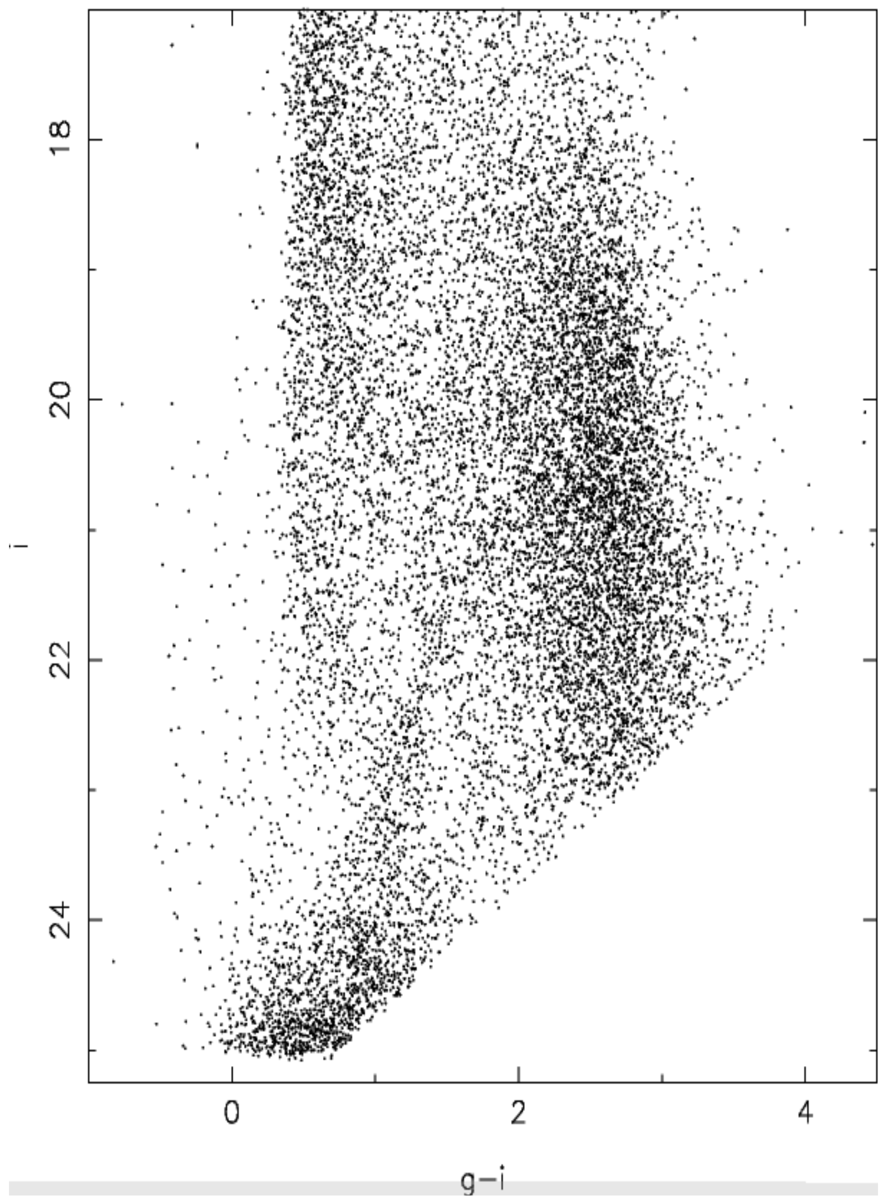


·Solid points have "companion" **closer than expected** (P<0.2); connected points also have **velocity difference < 75km/s** (based on LMC/SMC), and have **similar luminosity** (within 3 mags)

·**28% of Local Group galaxies in pairs; cf 3% from Aquarius simulations**

The Milky Way halo

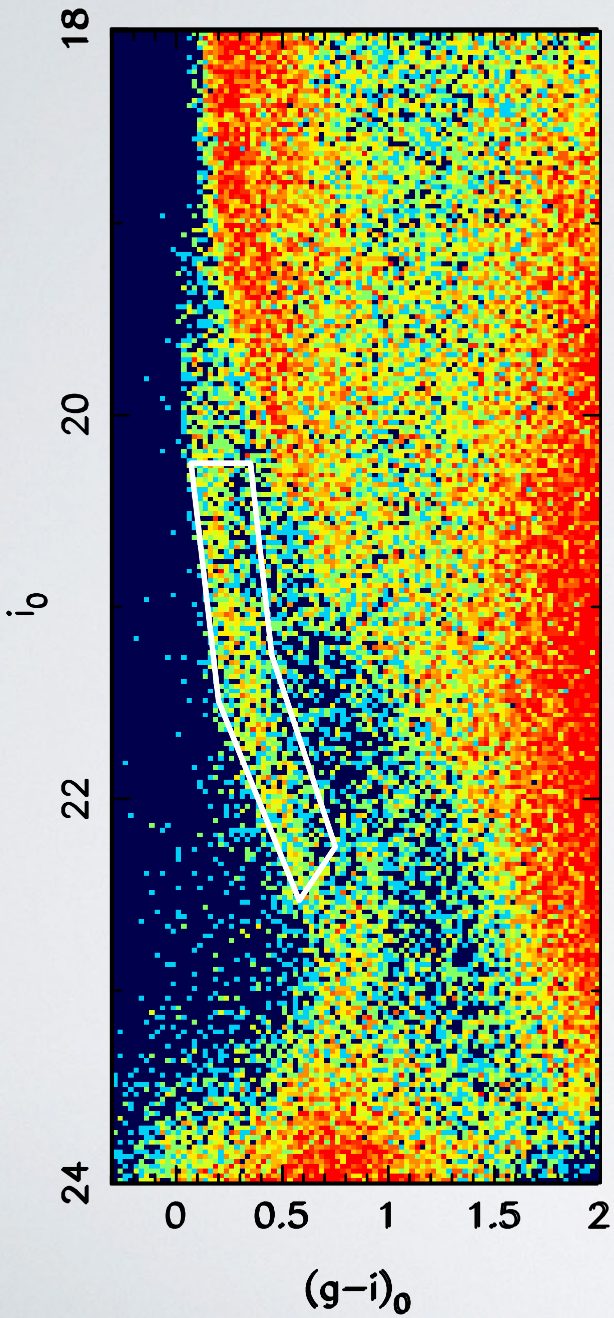


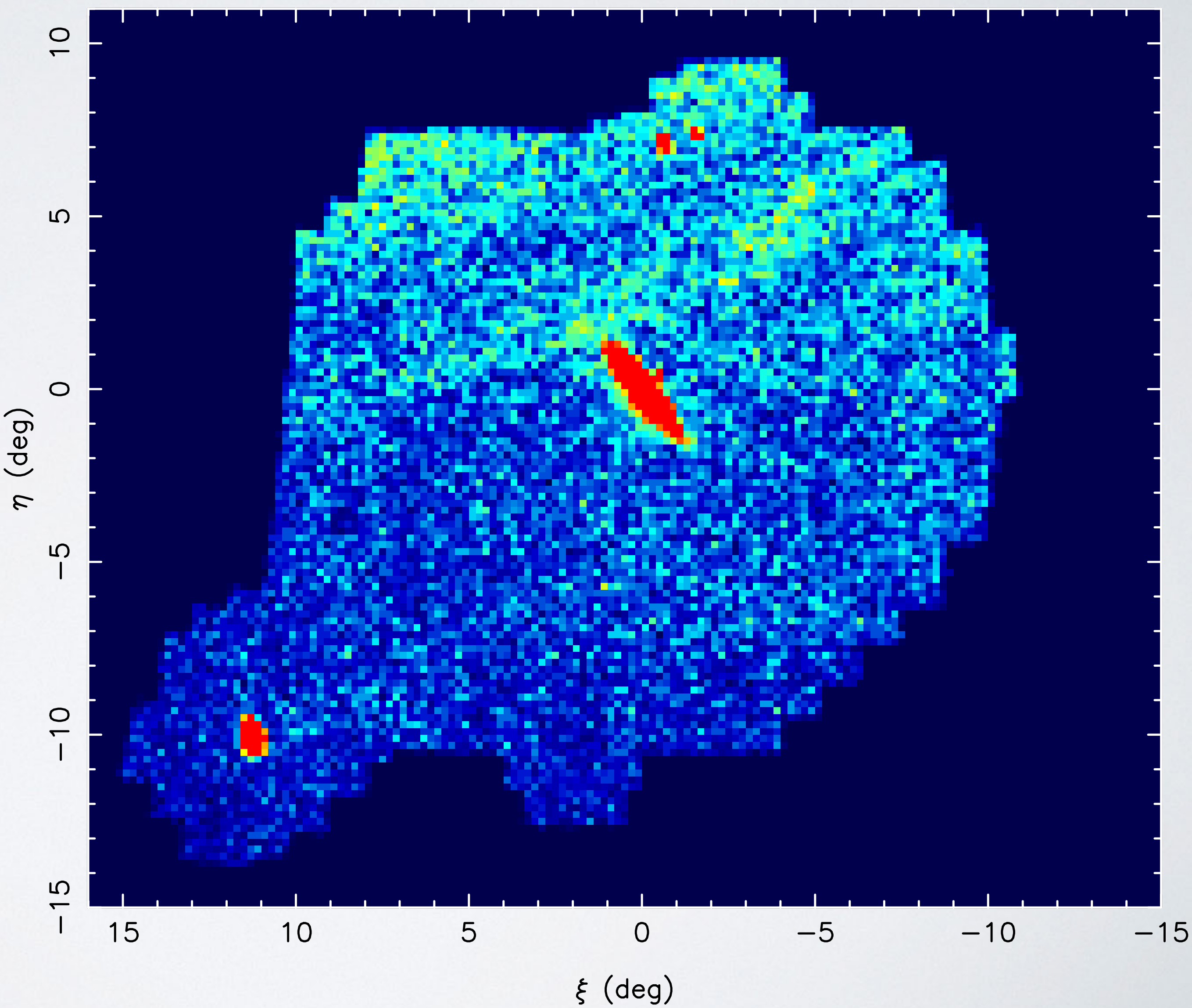


Milky Way foreground “contamination”

Martin et al. (2012)
Fardal et al. (2012)

D_{GC}~30 kpc





Rotating planes of satellites

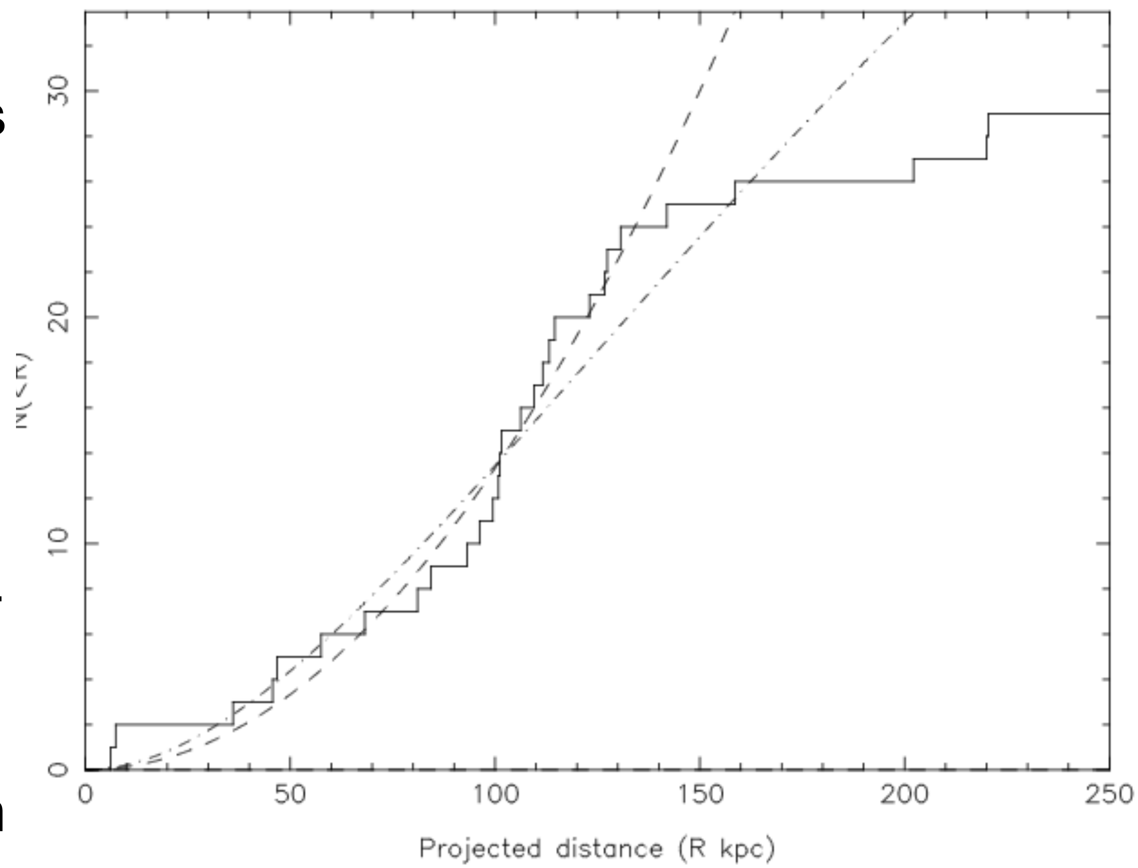
- Chance of 15 dwarfs lying in a plane as thin as we observe is 0.15%
- Chance of 13 of 15 specific dwarfs sharing same sense of “rotation” around M31 is 1.4%
- Significance of seeing a flattened plane of 15 dwarfs with coherent kinematics is therefore around 99.998%....

- A few considerations:
  - satellite distributions are relatively prolate (e.g., Zentner et al. 2005)
  - infall along preferred directions due to filaments? (e.g., Lovell et al. 2011)
  - group infall? (e.g., Sales et al. 2011, Wang et al. 2013)

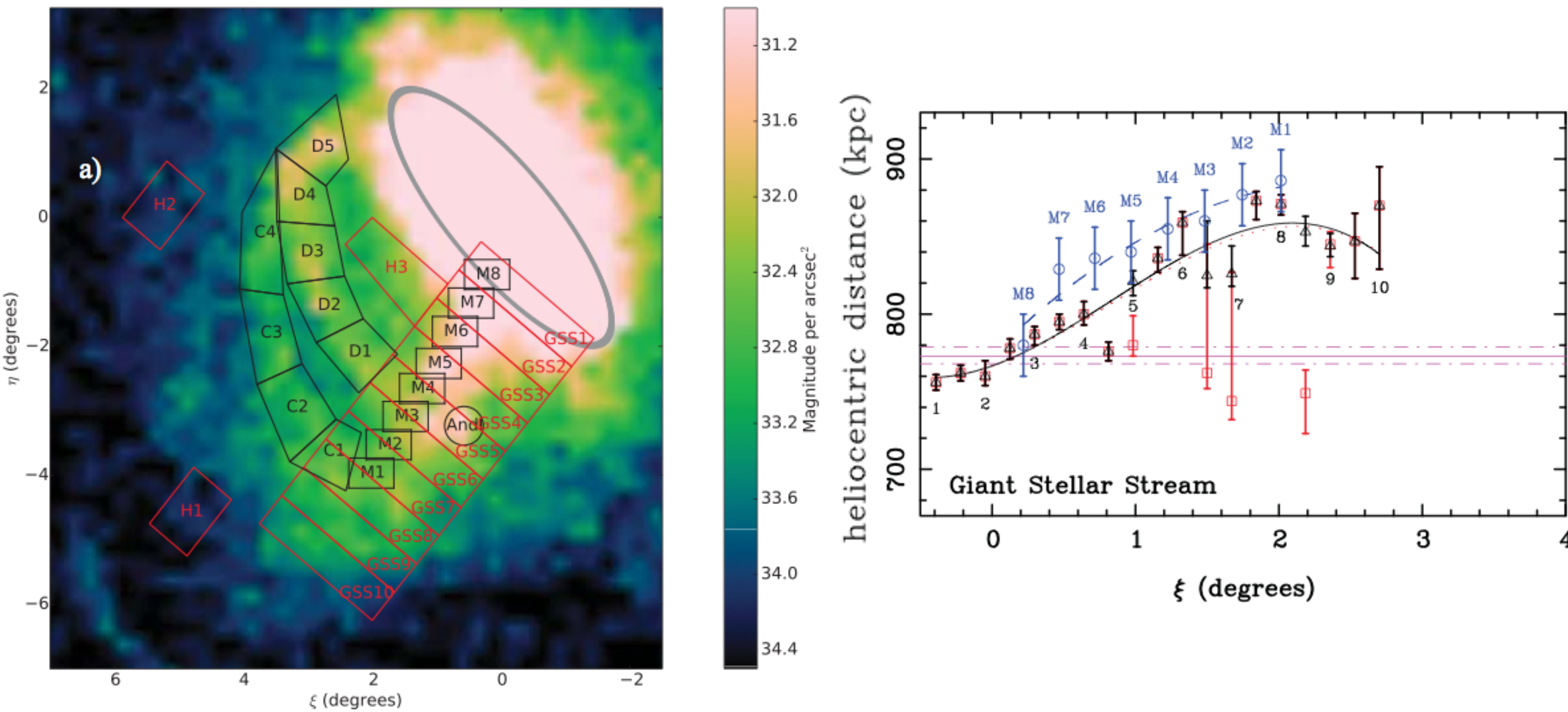
Radial distribution of M31 satellites

- (Projected) Radial distribution of M31 satellites shows no sign of declining within 150kpc. Appears more extended than MW subgroup
- Corresponds to a three-dimensional radial density distribution, $\rho(r) \propto r^{-1}$ (dashed line)
- cf cosmological simulations (dot-dashed line; prediction of sub-halo density profile based on an Einasto radial density distribution with parameters α = 0.678 and r_{-2} = 200kpc [from Figure 11 of Springel et al. 2008]).

Richardson et al. 2011



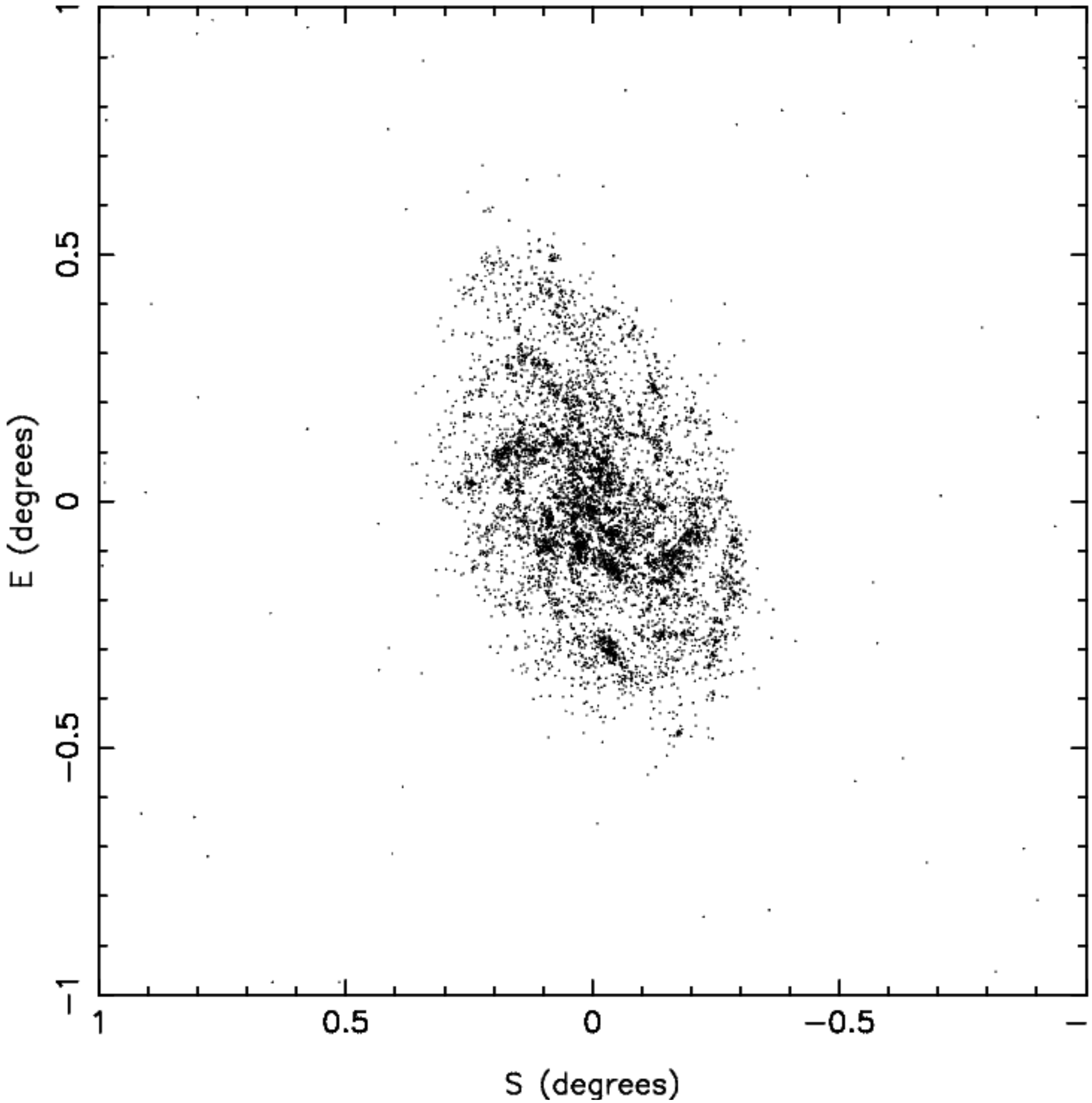
Major accretions? The giant stream



Updated geometry from Conn et al. (2016, submitted); similar gradient to McConnachie et al. (2003), although different offset

Major accretions? M33

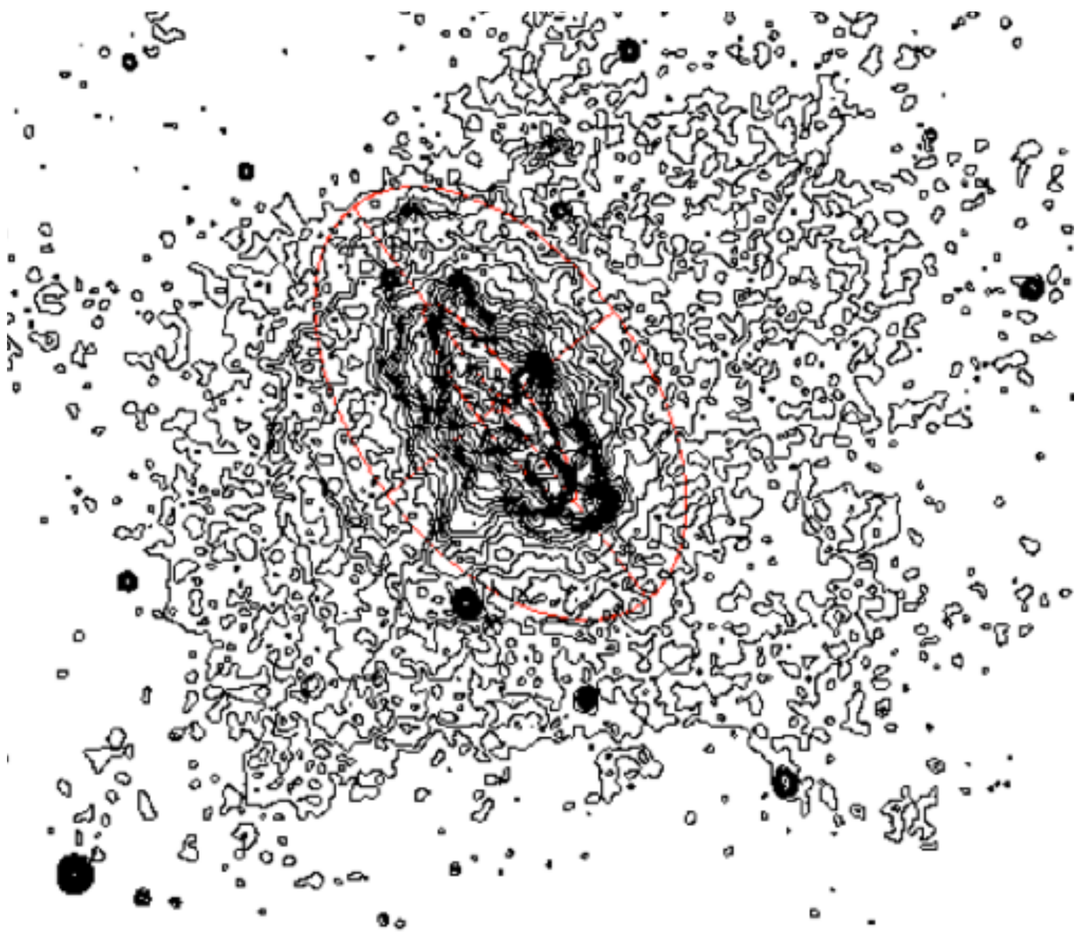
GALEX



CFHT, $(g - i)_0 < 0.0$

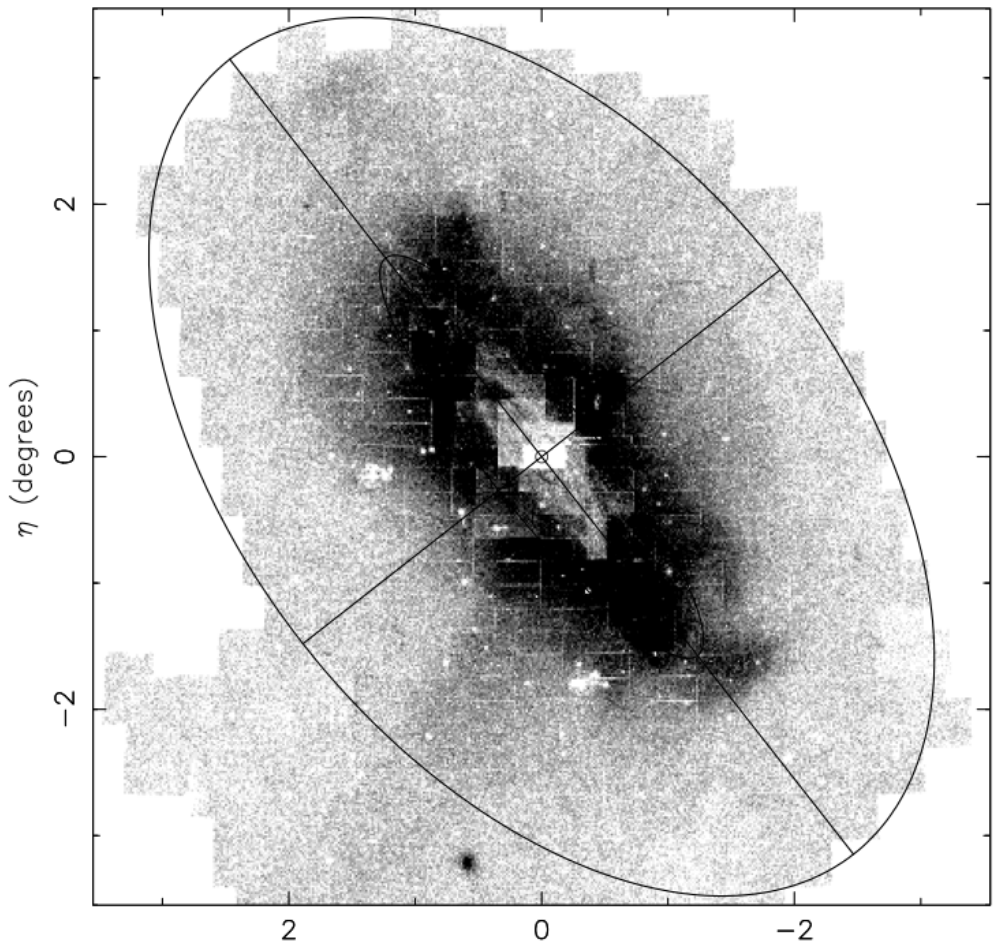
Asymmetric accretions? The smooth stellar halo

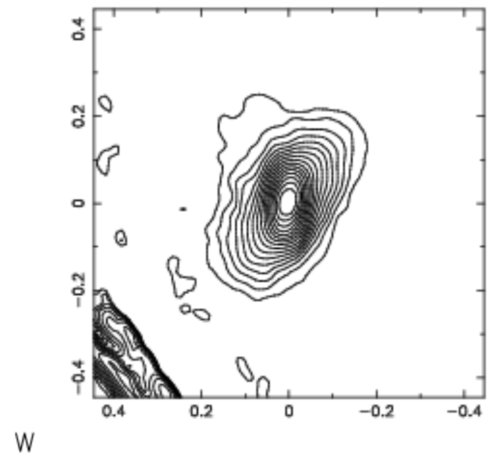
- If the plane of satellites is a result of a recent accretion, or preferential accretion from a certain direction, will the “underlying” stellar halo also show a similar alignment
- It is, after all, presumably formed via accretion, just things that were accreted earlier.

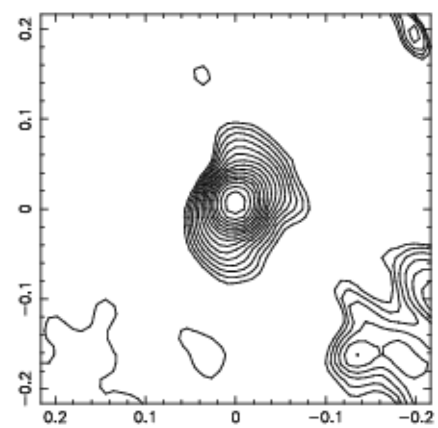


Major accretions? NGC205

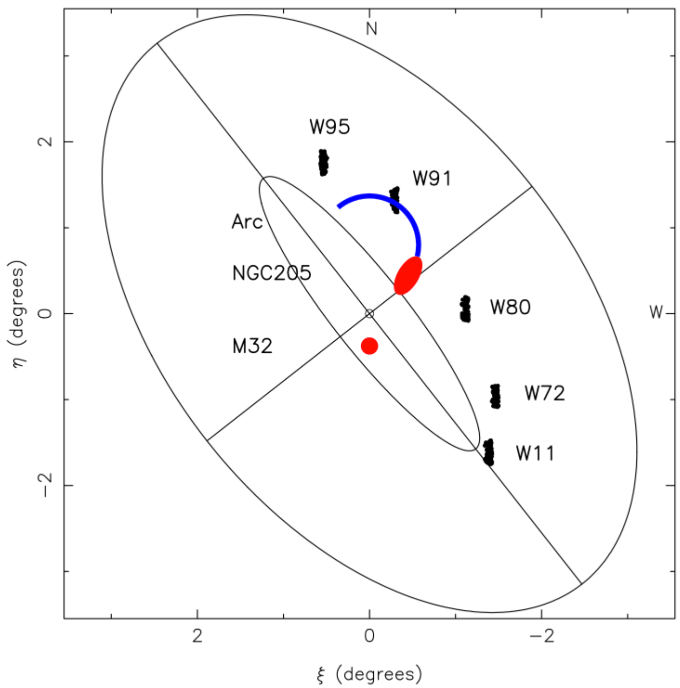
- The twisted isophotes of NGC 205 have long been known (Hodge 1973; van den Bergh in 1970 - see scan below; Choi et al. 2004)
- INT (+CFHT) imaging show a nice “arc” coming off the top of NGC205 (in projection at least; McConnachie et al. 2004)





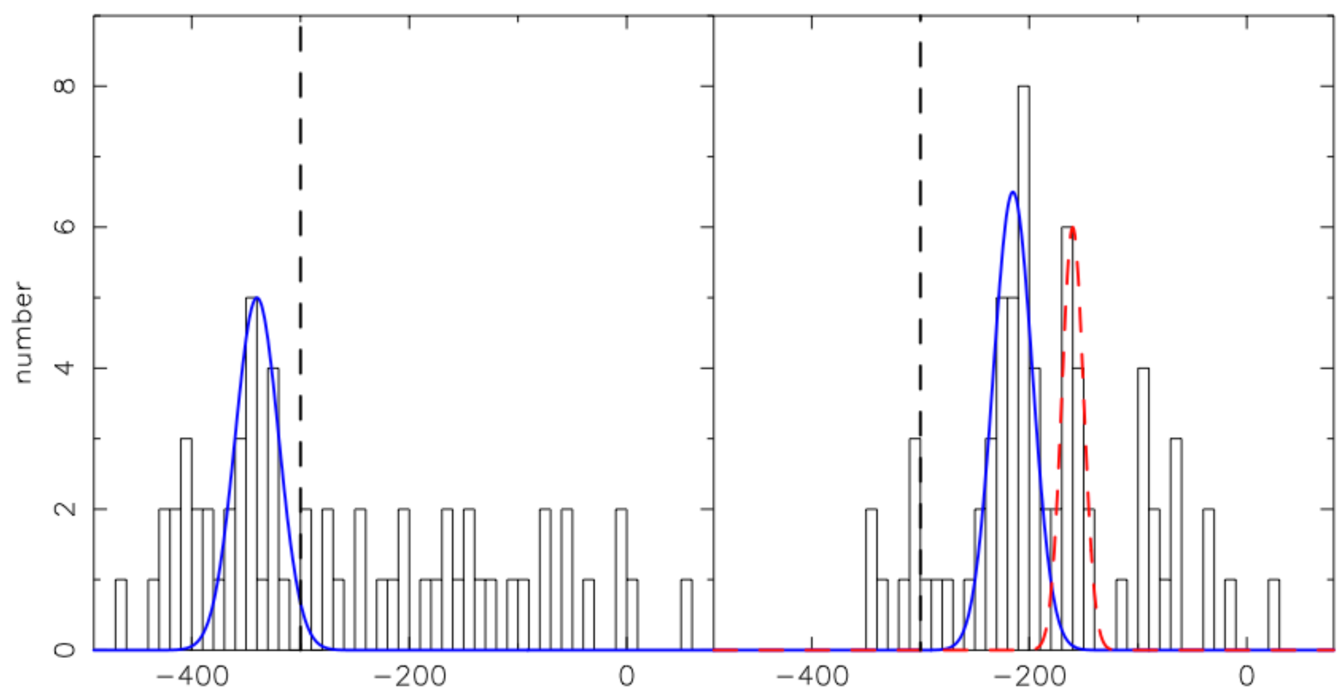


Major accretions? NGC205

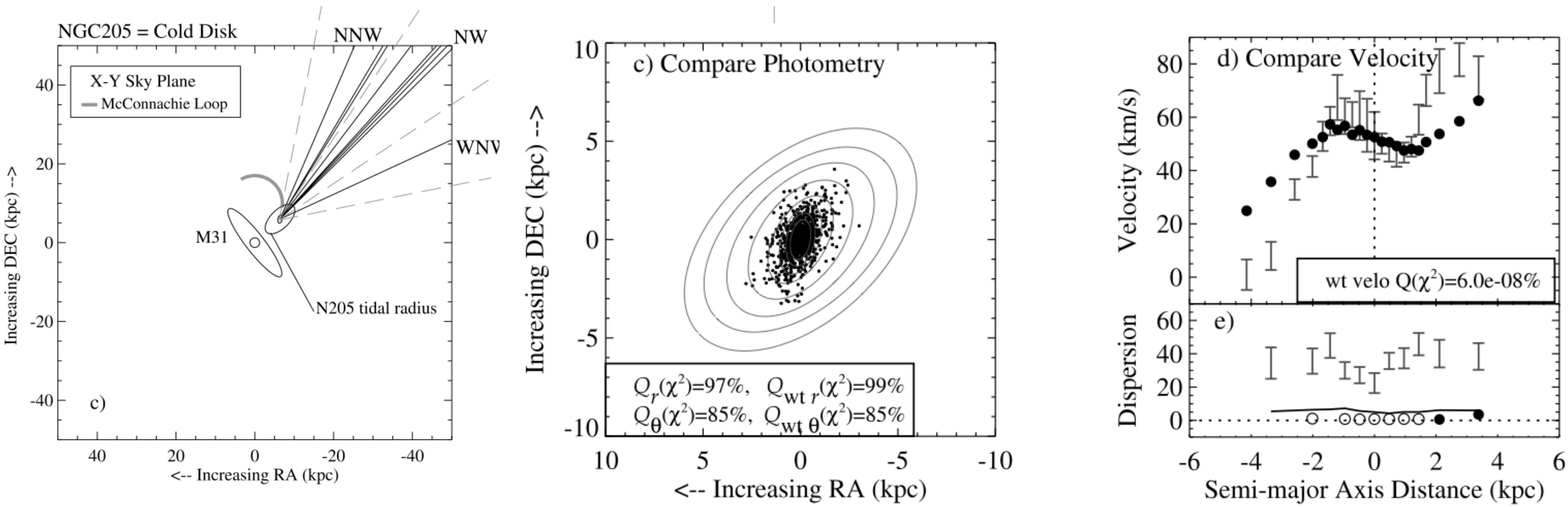


Two Keck DEIMOS fields observed in 2002 (W80 and W91). W91 shows evidence for an additional component relative to W80

Is this the loop?



Dynamical modelling of NGC205



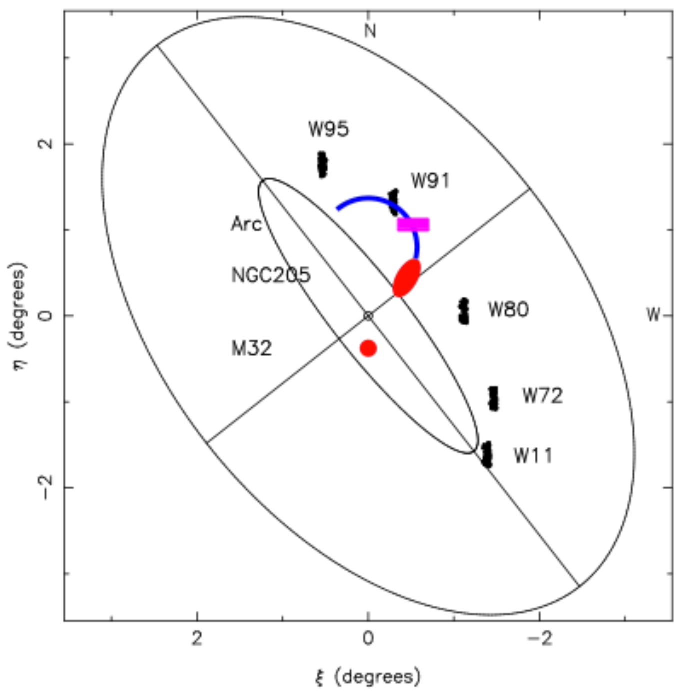
Howley et al. (2008) dynamically model the orbit of NGC205 using the twisted photometry of Bender et al. and kinematics of the main body of NGC205 (Geha et al. 2006) as constraints

They conclude that

the loop is not associated with the orbit of NGC205

NGC205 is moving at a velocity of 300 - 500 km/s relative to M31 on a primarily radial orbit i.e., near the escape velocity of M31, “signifying NGC205 is likely on its first M31 passage”

More kinematics



- Addition field midway between NGC205 and W91 observed in 2004. Shows same feature shifted to velocity of NGC205
- What you would expect if
  - the kinematic feature previously identified is associated with the loop
  - the loop was associated with NGC205. Not definitive but suggestive