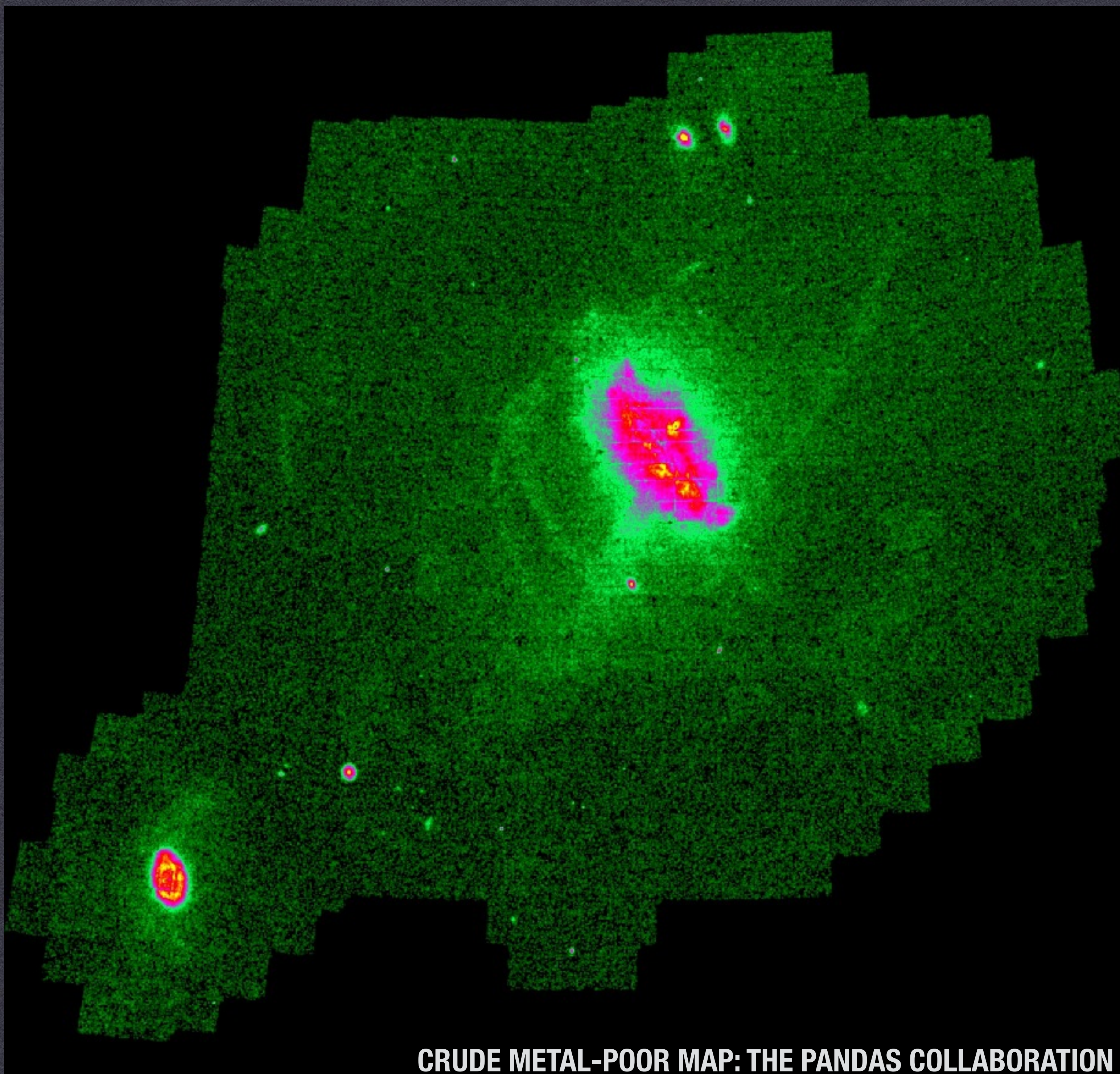
THE OUTER HALO GLOBULAR CLUSTER SYSTEM OF M31: CLUES TO GALAXY FORMATION

JOVAN VELJANOSKI
jovan@astro.rug.nl
(Kapteyn Astronomical Institute, Groningen, NL)
ANNETTE FERGUSON
(IfA, Edinburgh, UK)
DOUGAL MACKEY
(RSAA, ANU, AU)
+ THE PANDAS TEAM

PAN-ANDROMEDA ARCHAEOLOGICAL SURVEY (PANDAS)

PAndAS: The largest continuous resolved stellar populations survey of an external galaxy, mapping M31 and the lesser companion M33.



Instrument: CFHT/MegaCam.

The survey comprised ~400 distinct pointings, covering ~380 deg^2, extending out to a projected radius of ~150 kpc.

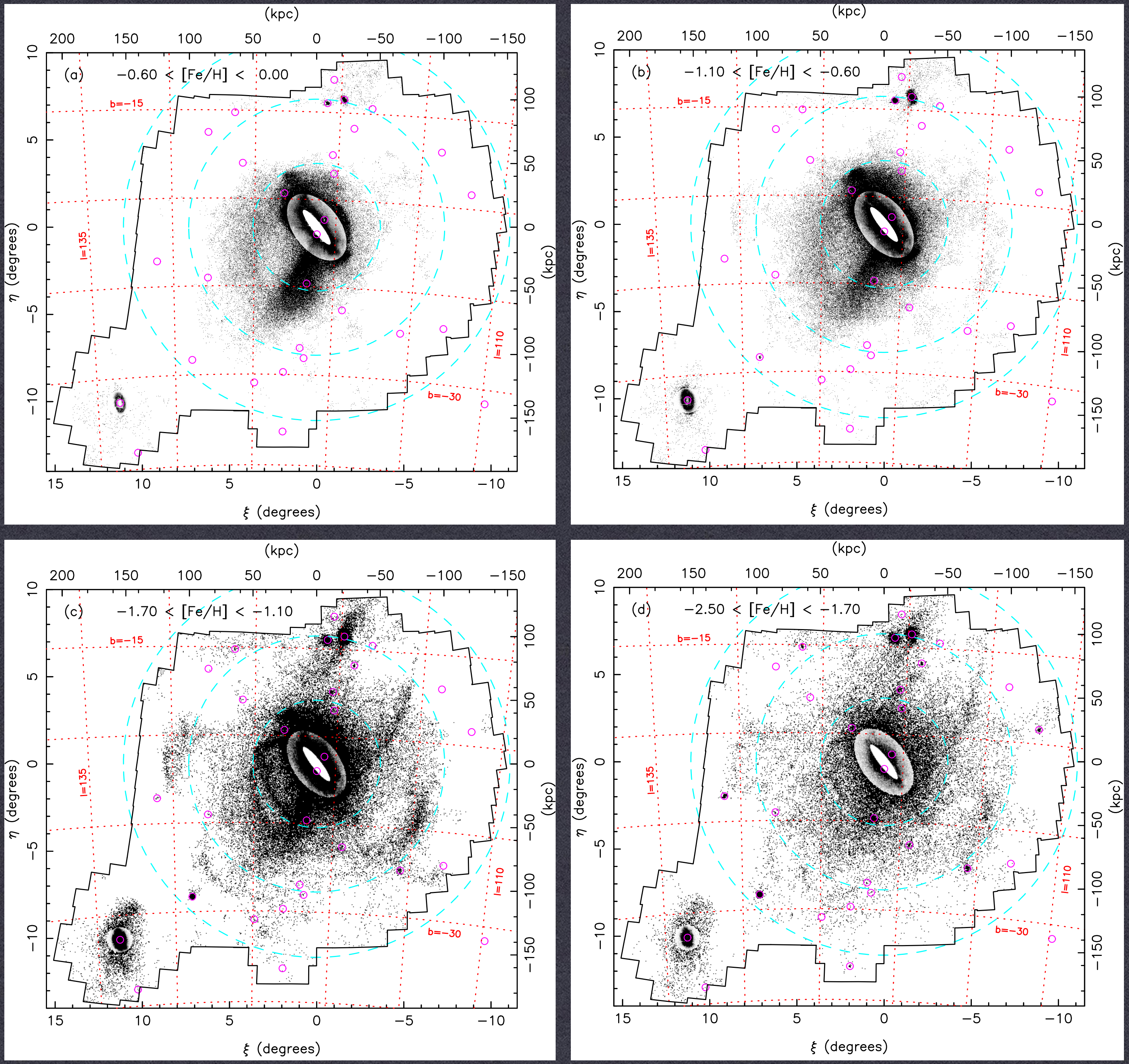
Observations are in two optical bands: *g* (depth ~25.5) and *i* (depth ~24.5).

Typical S/N of 10.

Data pre-processed by with the E*lixir* pipeline, with further processing done by the Cambridge Astronomy Survey Unit.

PANDAS RESULTS: RESOLVED STELLAR HALO

The M31 stellar halo is dominated by various tidal stellar streams, thought to be the remnants of accreted dwarf galaxies. It appears that M31 had a rich accretion history.



Photometric metallicities, assuming stars are 13 Gyr old, with [α/Fe] = 0. The applied isochrones are from Dotter et al. 2008, ApJS, 178, 89.

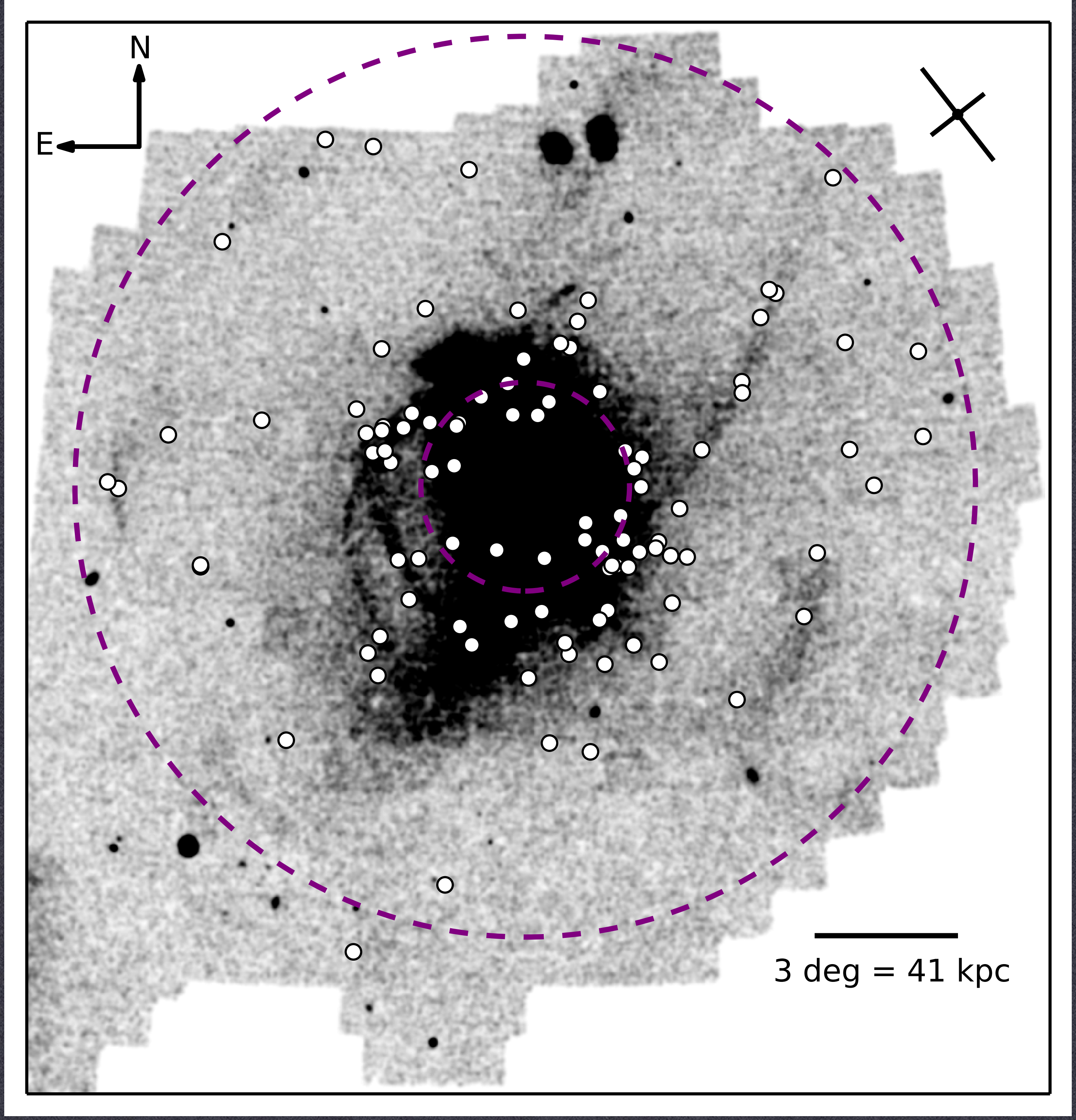
The higher metallicity halo is dominated by the Giant Stellar Stream (Ibata et al. 2001, Nature, 412, 49).

The lower metallicity halo component comprises many prominent substructures.

IBATA ET AL. 2014, MNRAS, 780, 128

PANDAS RESULTS: GLOBULAR CLUSTERS

PAndAS facilitated the search for GCs in the outer halo of M31. Using this excellent data set resulted in the discovery of 59 new GCs (Huxor et al. 2014, MNRAS, 442, 2165).



Search was conducted by visual inspection of the entire PAndAS footprint by A. Huxor (some regions were re-examined by D. Mackey and J. Veljanoski)

An automated algorithm, originally designed to search for dwarf galaxies and stellar over-densities was also applied (Martin et al. 2013, ApJ, 776, 80).

The GC search is complete down to M_V = –6.0, and 50% complete down to $M_V \approx -4.1$

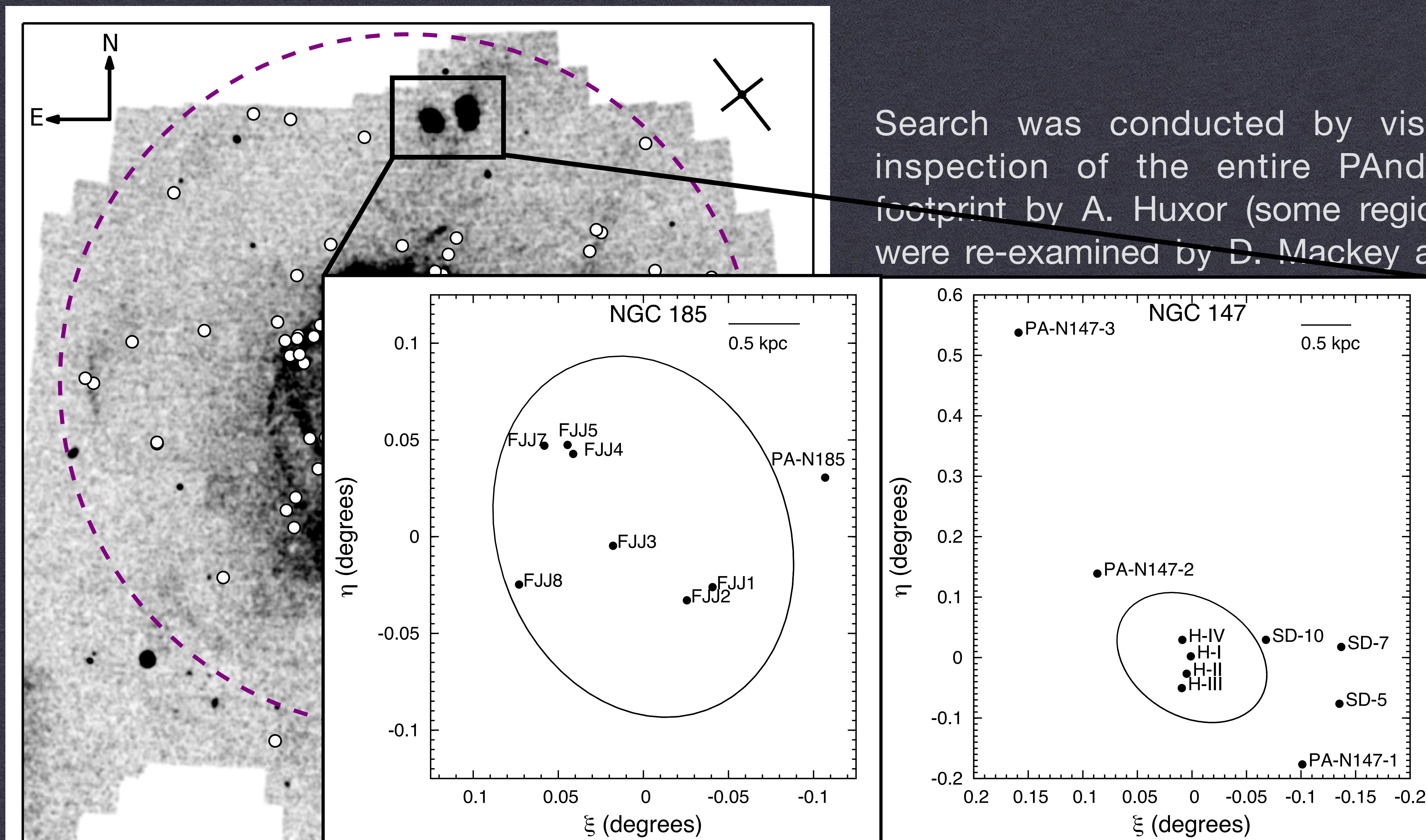
PANDAS RESULTS: GLOBULAR CLUSTERS

PAndAS facilitated the search for GCs in the outer halo of M31. Using this excellent data set resulted in the discovery of 59 new GCs (Huxor et al. 2014, MNRAS, 442, 2165).

Search was conducted by visual inspection of the entire PAndAS footprint by A. Huxor (some regions were re-examined by D. Mackey and

lly
es
so
76,

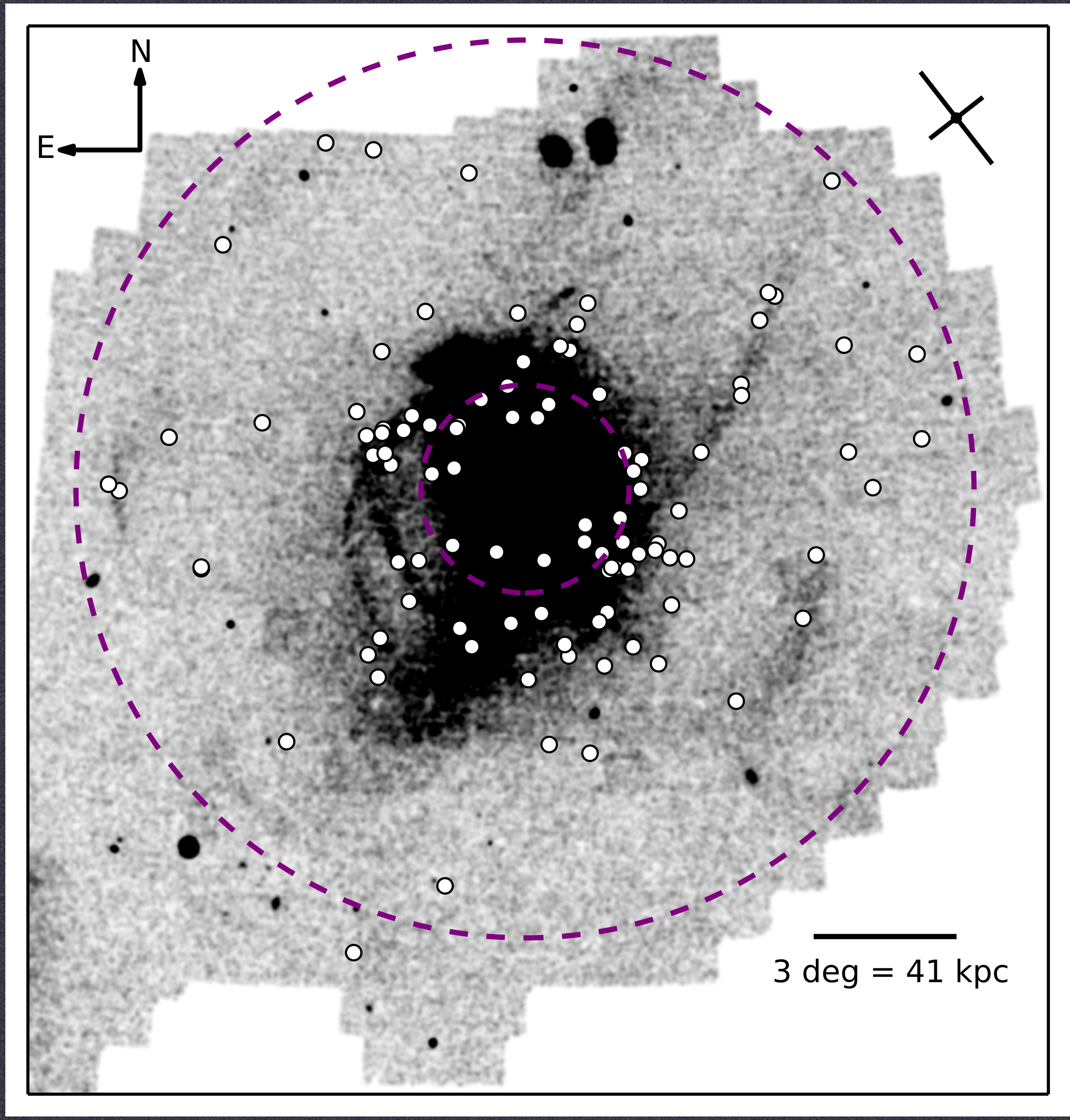
to
wn

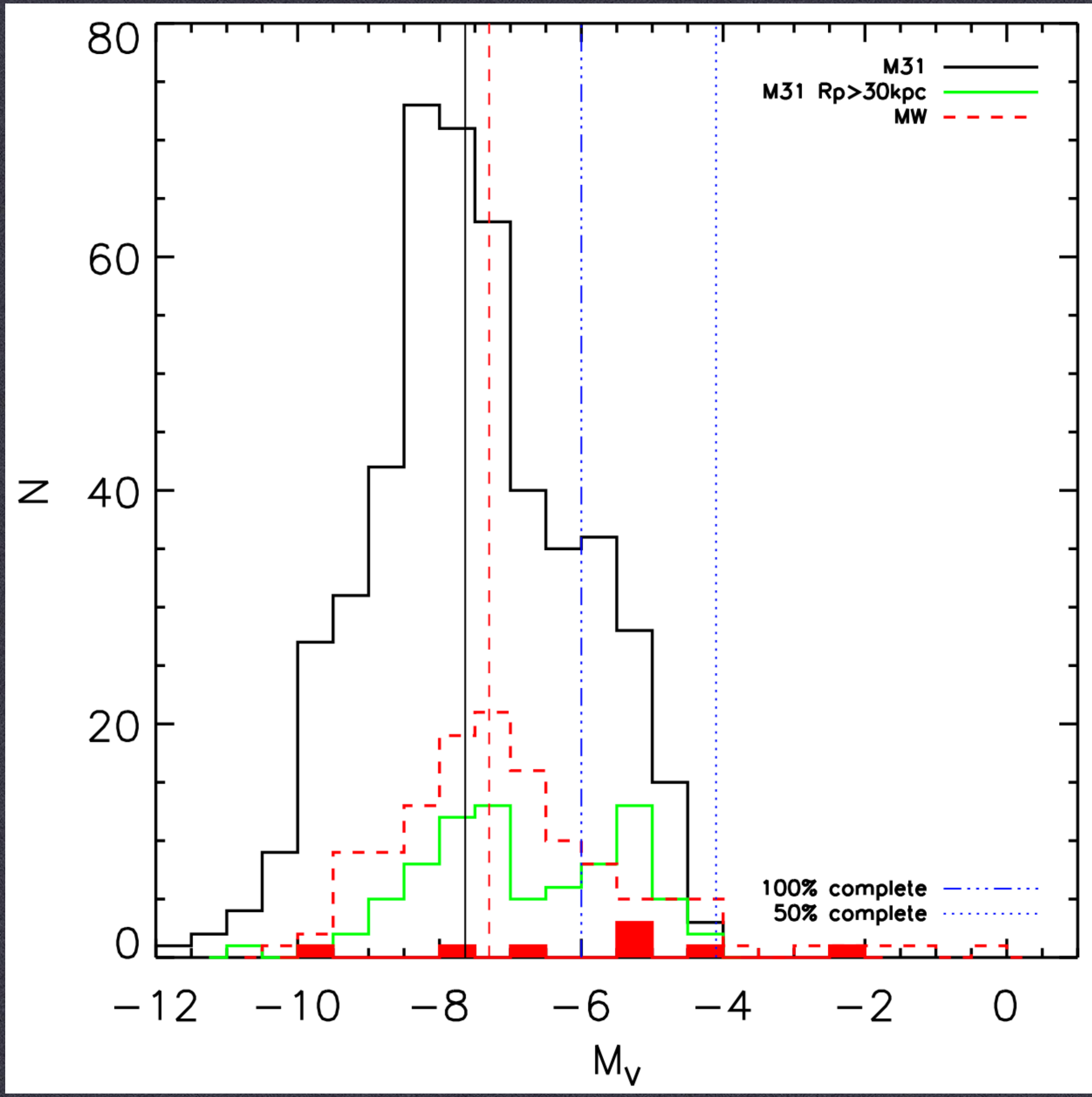


VELJANOSKI ET AL. 2013, MNRAS 435, 3654

ACCRETION ORIGIN FOR THE HALO GCS?

About 80% of the halo GCs are found to project onto stellar over-densities. Probability of a such configuration occurring by chance is <1% (Mackey et al. 2010, ApjL 717, 11). The luminosity distribution also provides a tentative support.





HUXOR ET AL. 2014, MNRAS, 442, 2165

THE M31 OUTER HALO GCS: A KINEMATICAL PERSPECTIVE

As a followup to PAndAS, we initiated a major spectroscopic campaign, targeting the M31 outer halo GCs.

Instrument	Year	GCs observed
WHT/ISIS	2005	19
WHT/ISIS	2009	12
WHT/ISIS	2010	13
Kitt-Peak/RC	2009	17
Gemini/GMOS-N	2010	4
Gemini/GMOS-N	2011	11
Gemini/GMOS-N	2012	7
Gemini/GMOS-N	2013	7

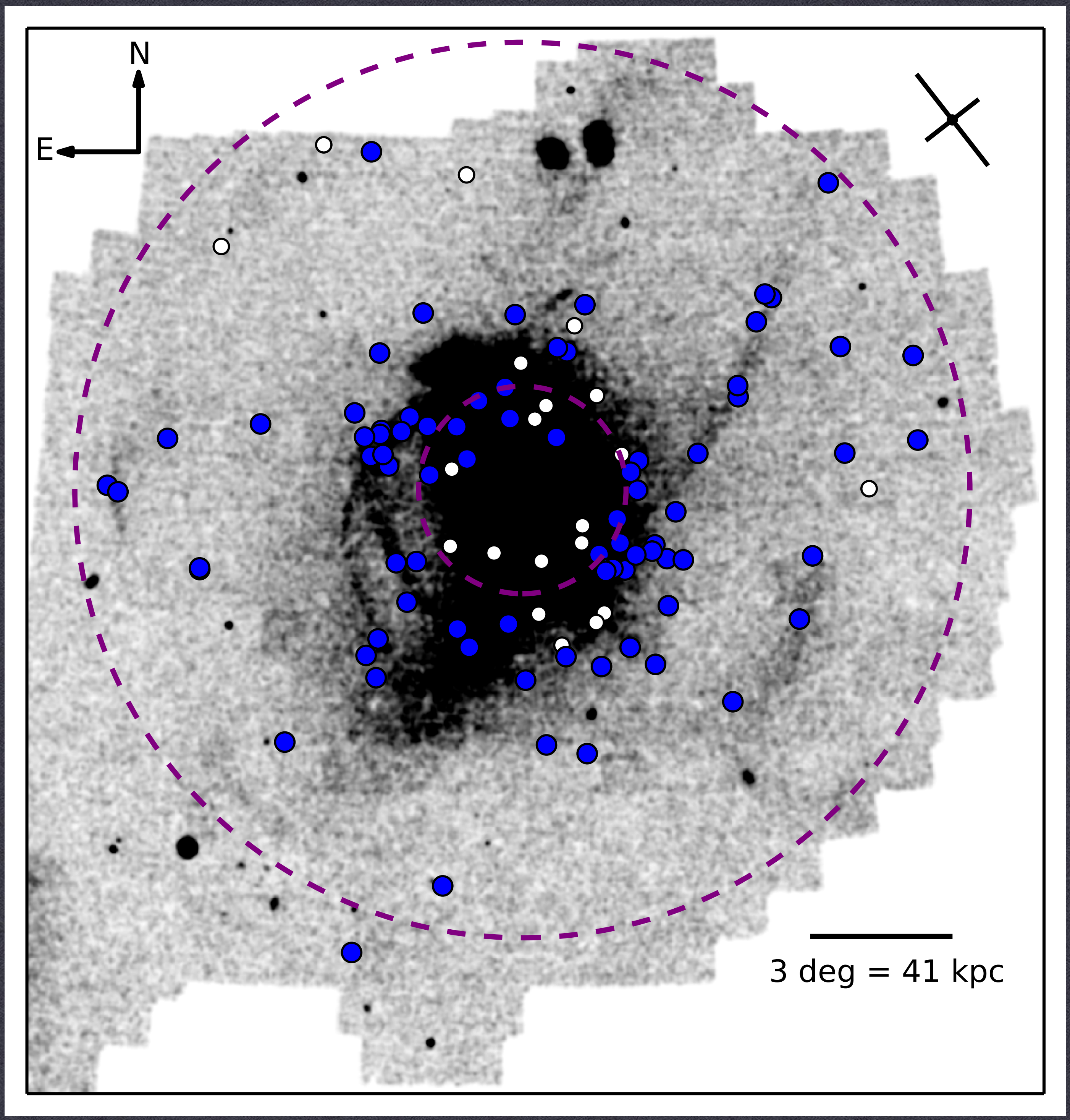
In total, observed are 78 GCs spanning projected radii between ~14—140 kpc.

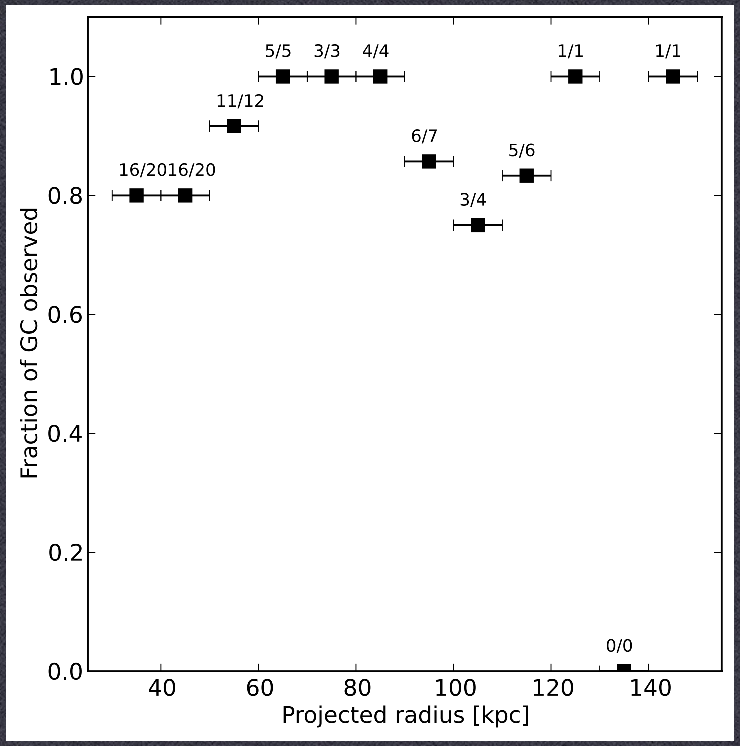
71 GCs were observed beyond 30 kpc (~85% of total number), 20 beyond 80 kpc and 10 beyond 100 kpc.

63 GCs had no previous spectroscopic information.

THE M31 OUTER HALO GCS: A KINEMATICAL PERSPECTIVE

Throughout the observations, preference was given to clusters lying on substructures are to those having larger projected distances.

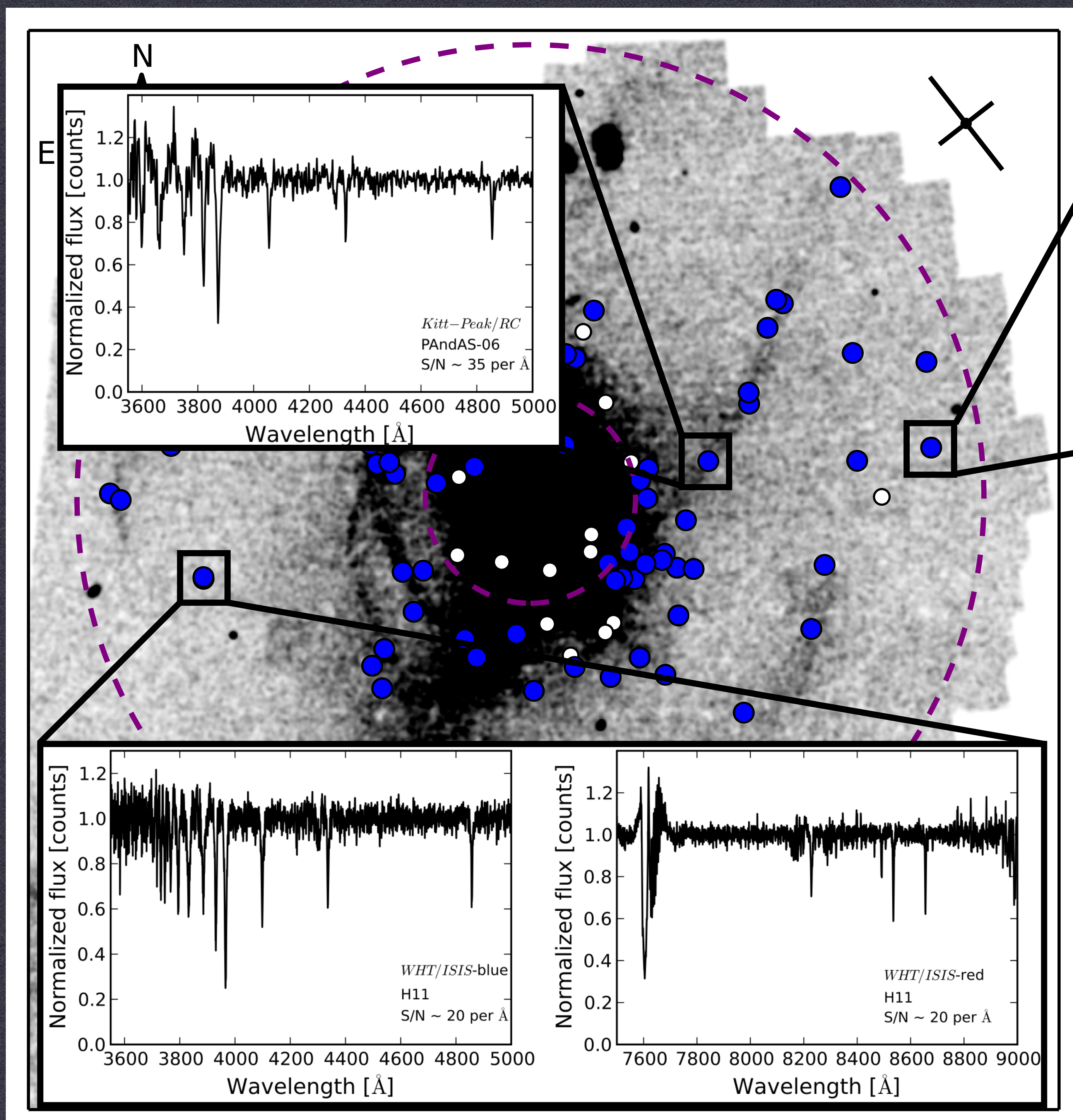


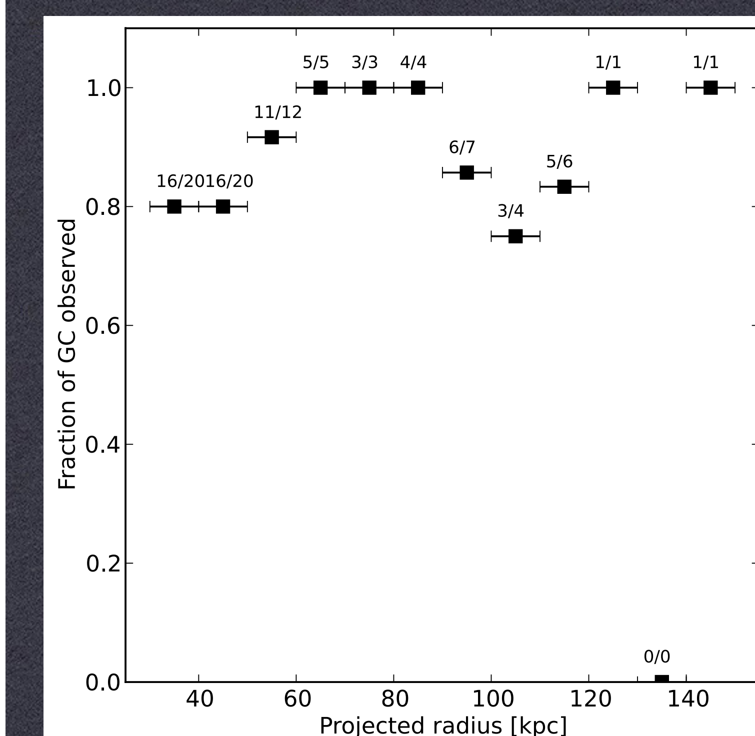


VELJANOSKI ET AL. 2014, MNRAS, 442, 2929

THE M31 OUTER HALO GCS: A KINEMATICAL PERSPECTIVE

Throughout the observations, preference was given to clusters lying on substructures are to those having larger projected distances.

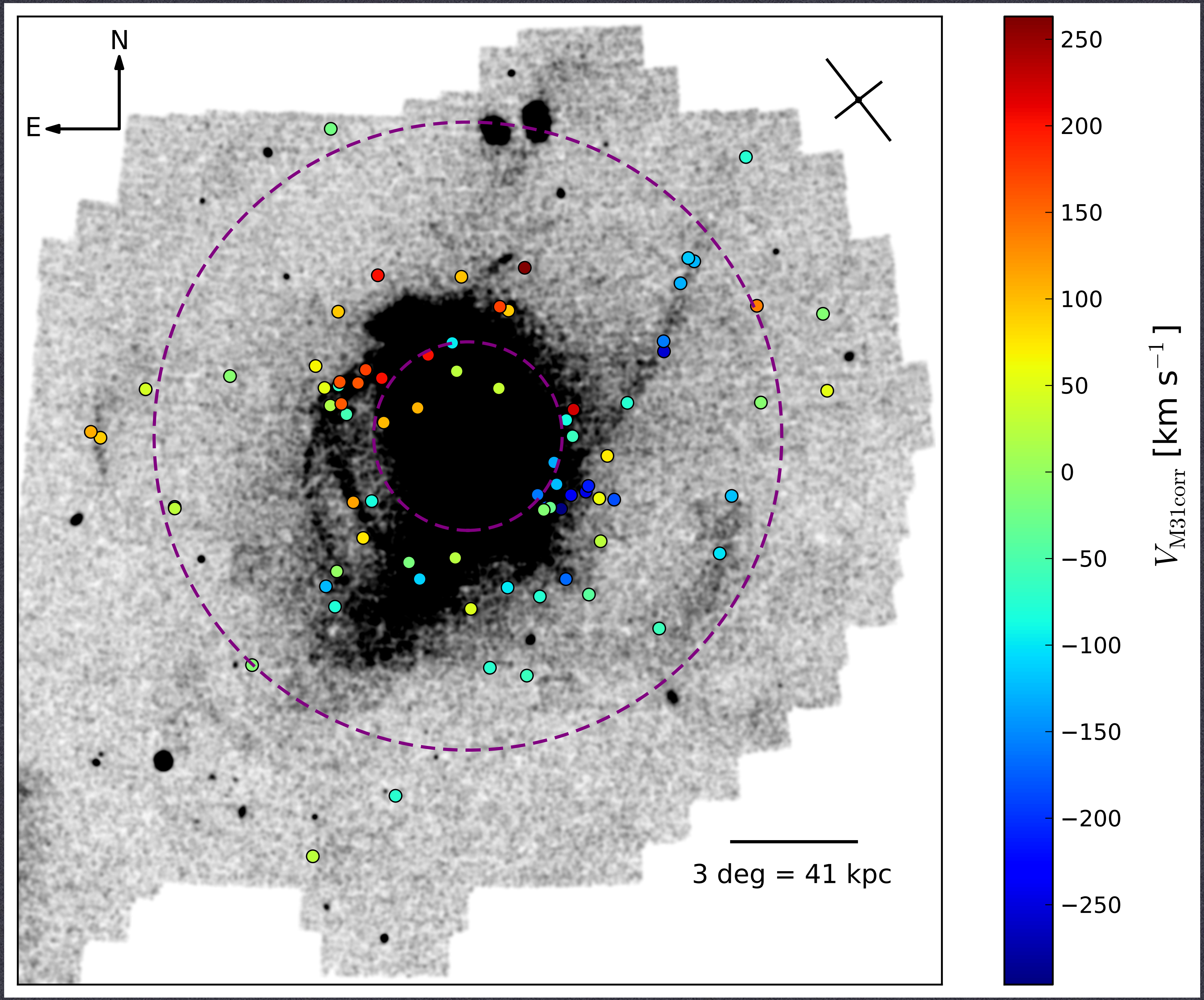




VELJANOSKI ET AL. 2014, MNRAS, 442, 2929

KINEMATICS OF THE M31 OUTER HALO GCS I

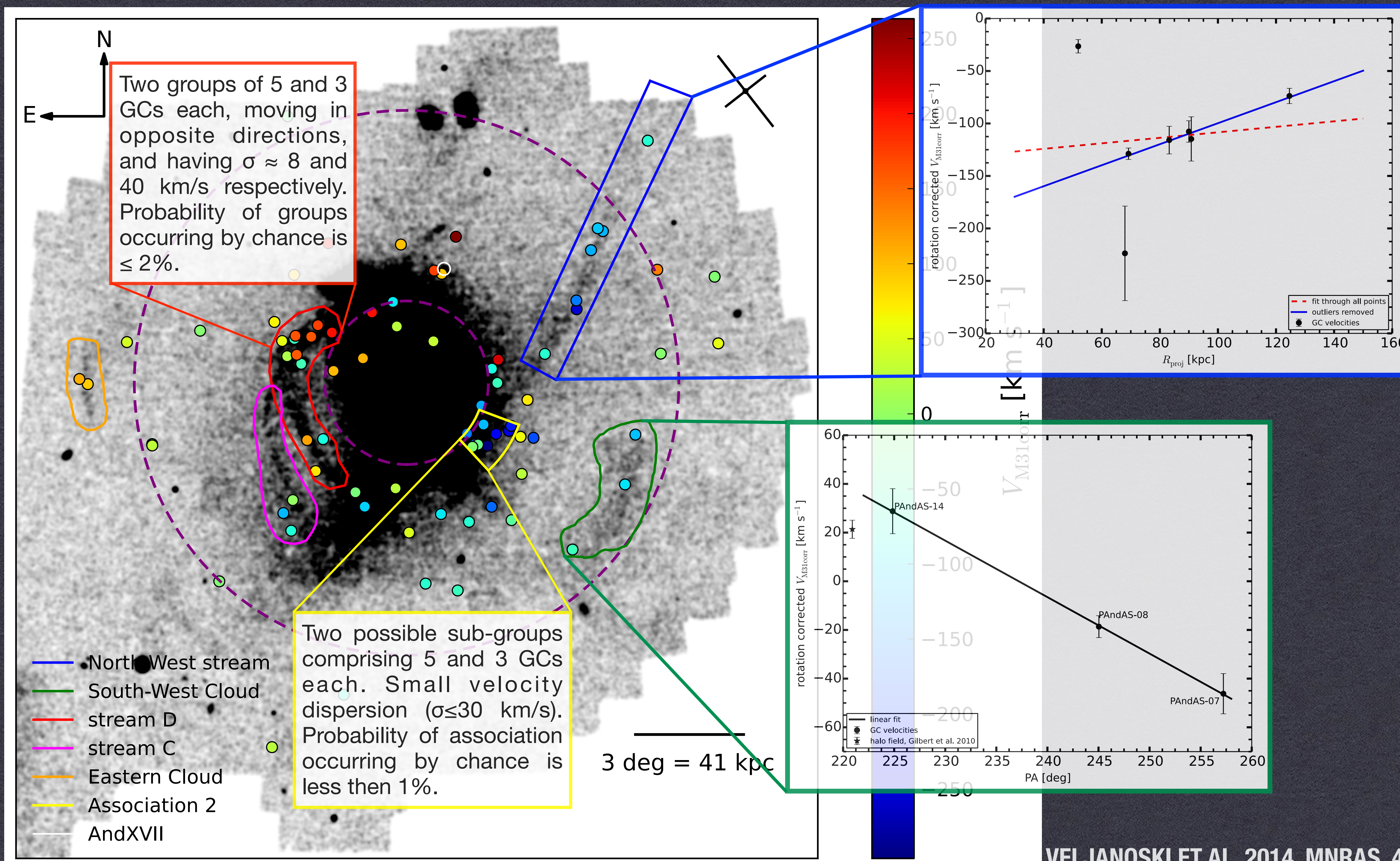
The discrete GC groups projecting on the most luminous halo streams exhibit clear kinematic patterns, supporting the accretion hypothesis. Monte Carlo tests show that this is a non-random behaviour.



VELJANOSKI ET AL. 2014, MNRAS, 442, 2929

KINEMATICS OF THE M31 OUTER HALO GCS I

The discrete GC groups projecting on the most luminous halo streams exhibit clear kinematic patterns, supporting the accretion hypothesis. Monte Carlo tests show that this is a non-random behaviour.



VELJANOSKI ET AL. 2014, MNRAS, 442, 2929

KINEMATICS OF THE M31 OUTER HALO GCS II

Modelling the overall kinematic properties of the M31 outer halo GC system in the Bayesian framework.

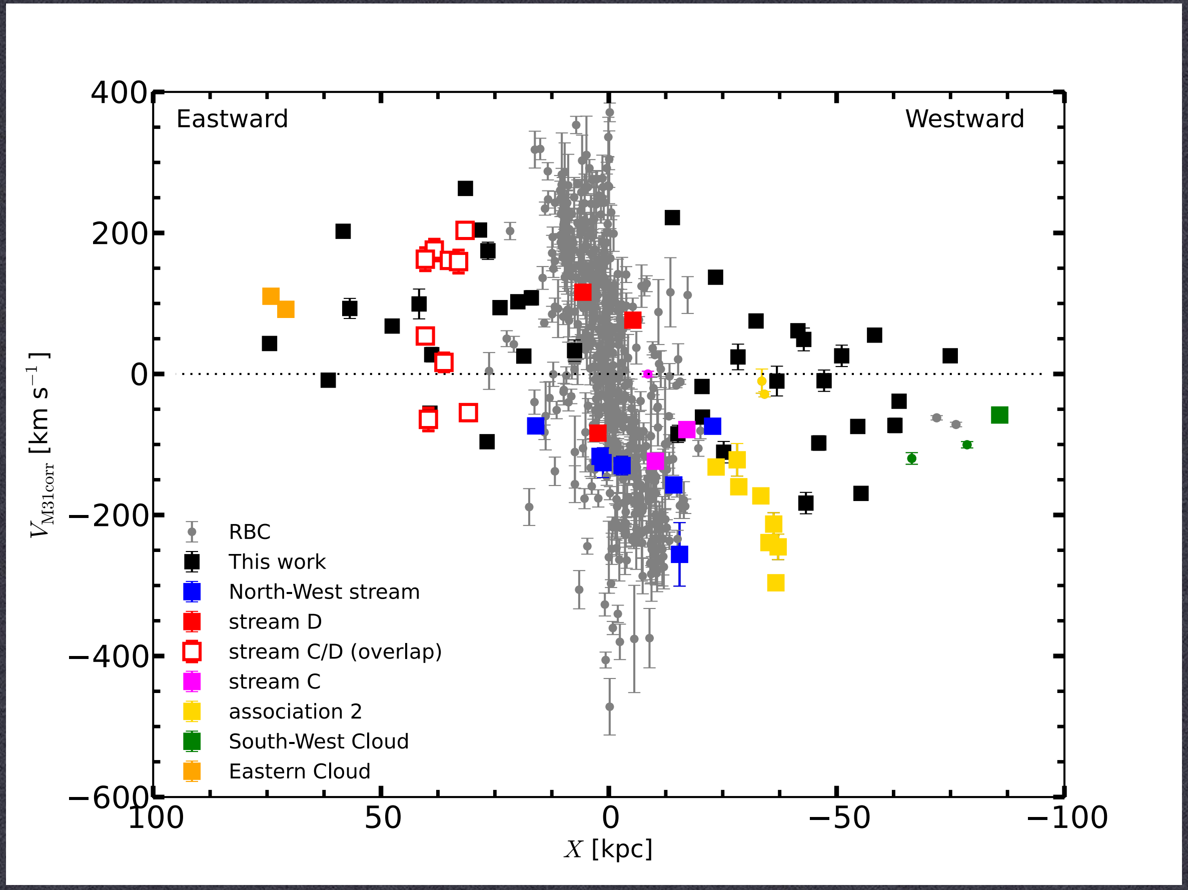
$u = v_{sys} + A\sin(\theta - \theta_0)$ Systemic rotation

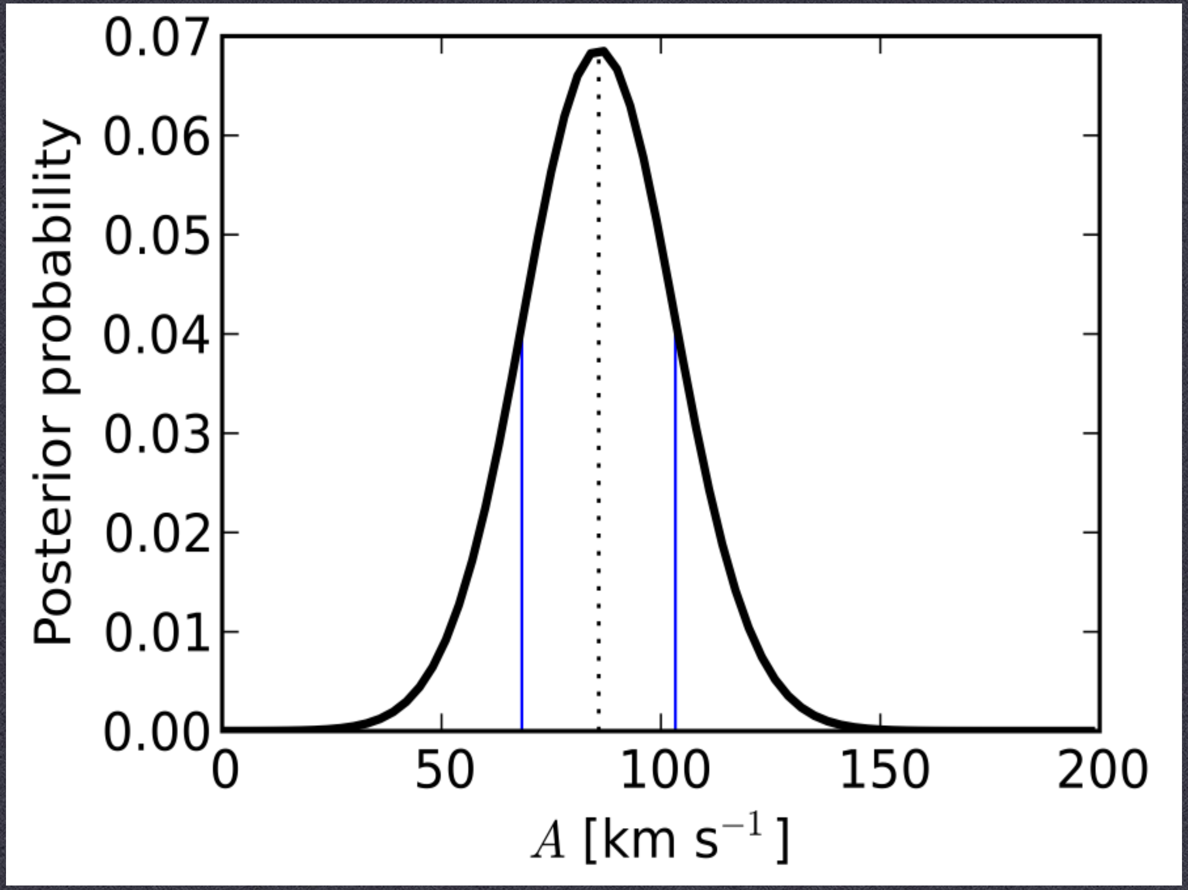
$\sigma^2 = (\Delta v)^2 + \sigma_0^2 (R/R_0)^{2\gamma}$ Velocity dispersion

$M = (2\pi\sigma^2)^{-1/2} \times \exp(-(v-u)^2/\sigma^2)$ Kinematic model

KINEMATICS OF THE M31 OUTER HALO GC III

Detected significant overall rotation. The rotation axis is nearly indistinguishable from that GCs located in the inner regions of M31.





VELJANOSKI ET AL. 2014, MNRAS, 442, 2929

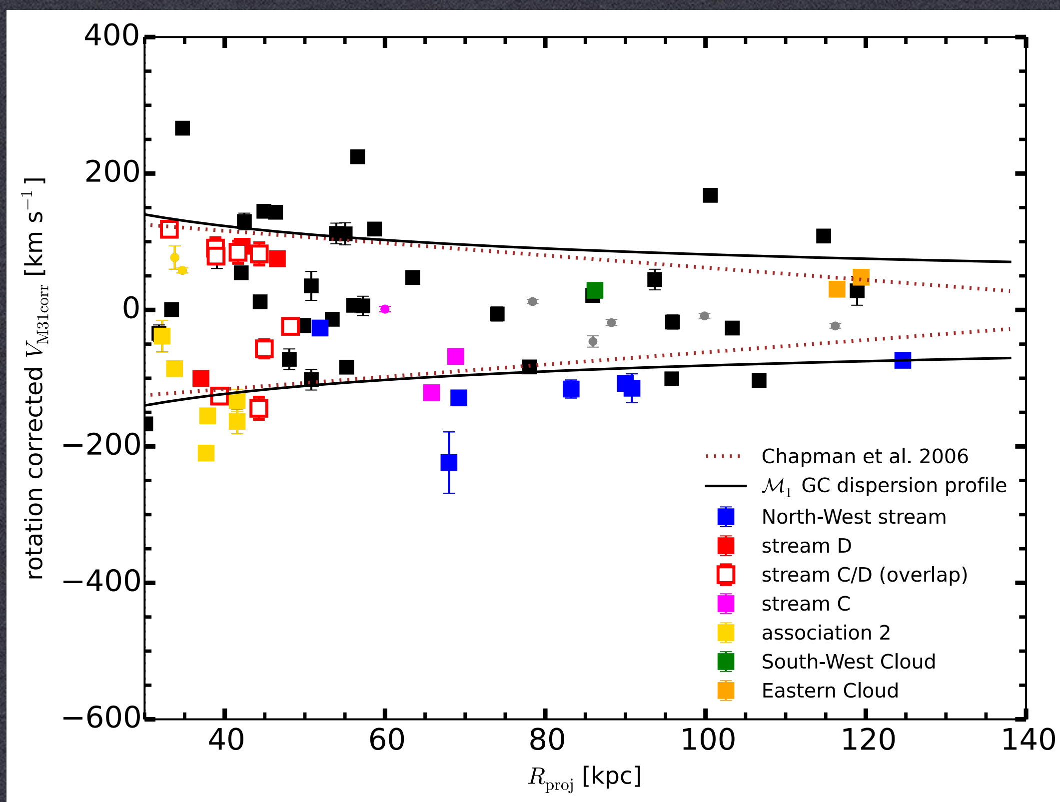
Amplitude = 86 ±17 km/s.

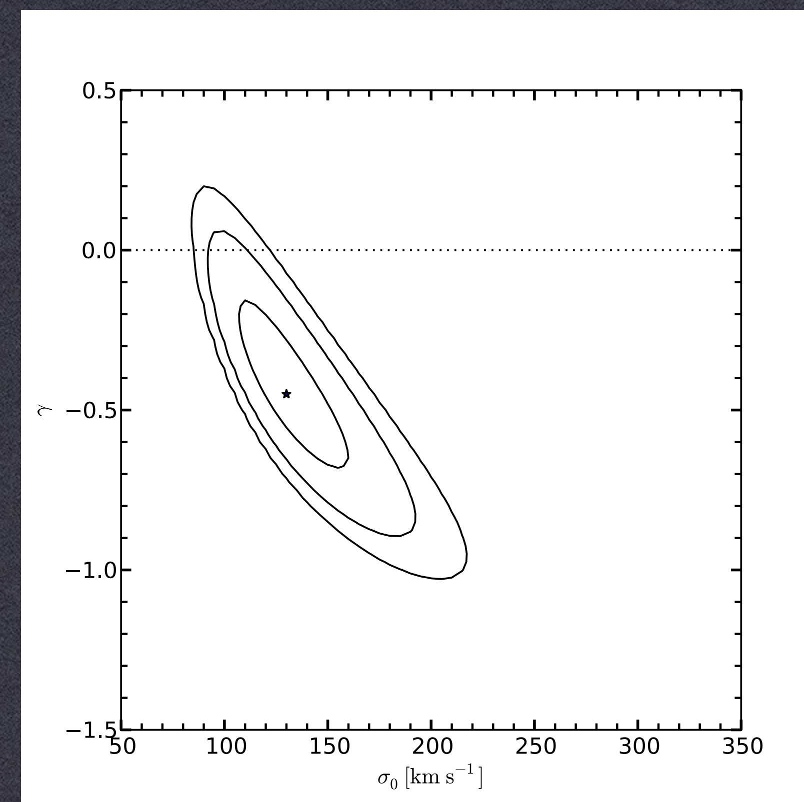
Rotation axis = 135 ± 11 deg (for reference, minor axis at 128 deg).

Rotation not solely driven by the clusters projected onto prominent substructures.

KINEMATICS OF THE M31 OUTER HALO GC IV

Detected significant overall rotation. The rotation axis is nearly indistinguishable from that GCs located in the inner regions of M31.





VELJANOSKI ET AL. 2014, MNRAS, 442, 2929

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

$\sigma_0 = 136^{+29}_{-20}$ km/s

γ = -0.45 ± 22

Close similarity is observed between the GC and stellar radial dispersion profiles, at least out to 80 kpc.

The posterior probability of measuring γ = 0, $p(\gamma = 0) < 1\%$. Thus a constant velocity dispersion as a function of projected radius can be almost entirely rejected.

PECULIAR RESULTS?

Important to understand the origin of the overall rotation of the M31 outer halo GC system, given the ample evidence for significant accretion.

Potential scenarios that might explain the spatial and kinematic properties of the M31 dwarf satellites and GCs:

- Accretion from a preferred direction(s) on the sky (e.g. Lovell et al. 2011, MNRAS, 413, 3013);
- dwarf galaxies accreted in groups (e.g. Li & Helmi 2008, MNRAS, 385, 1365);
- a single moderate mass satellite responsible for everything.

SUMMARY

I hope that I have convinced you in the importance and usefulness of studying the outer halo globular cluster system of M31.

- Measured radial velocities of 71 GCs in the true outer halo of M31;
- GCs that are projected onto tidal stellar streams are found to exhibit various velocity correlation, reinforcing the accretion hypothesis;
- Detection of a significant degree of rotation, around the optical minor axis of M31, same as the clusters in the inner regions;
- The GC velocity dispersion is found to be decreasing as a function of projected radius, similarly as for the field star component;
- This is a particularly interesting system regarding dynamical modelling and testing galaxy formation models.