The Pan-Andromeda Archaeological Survey

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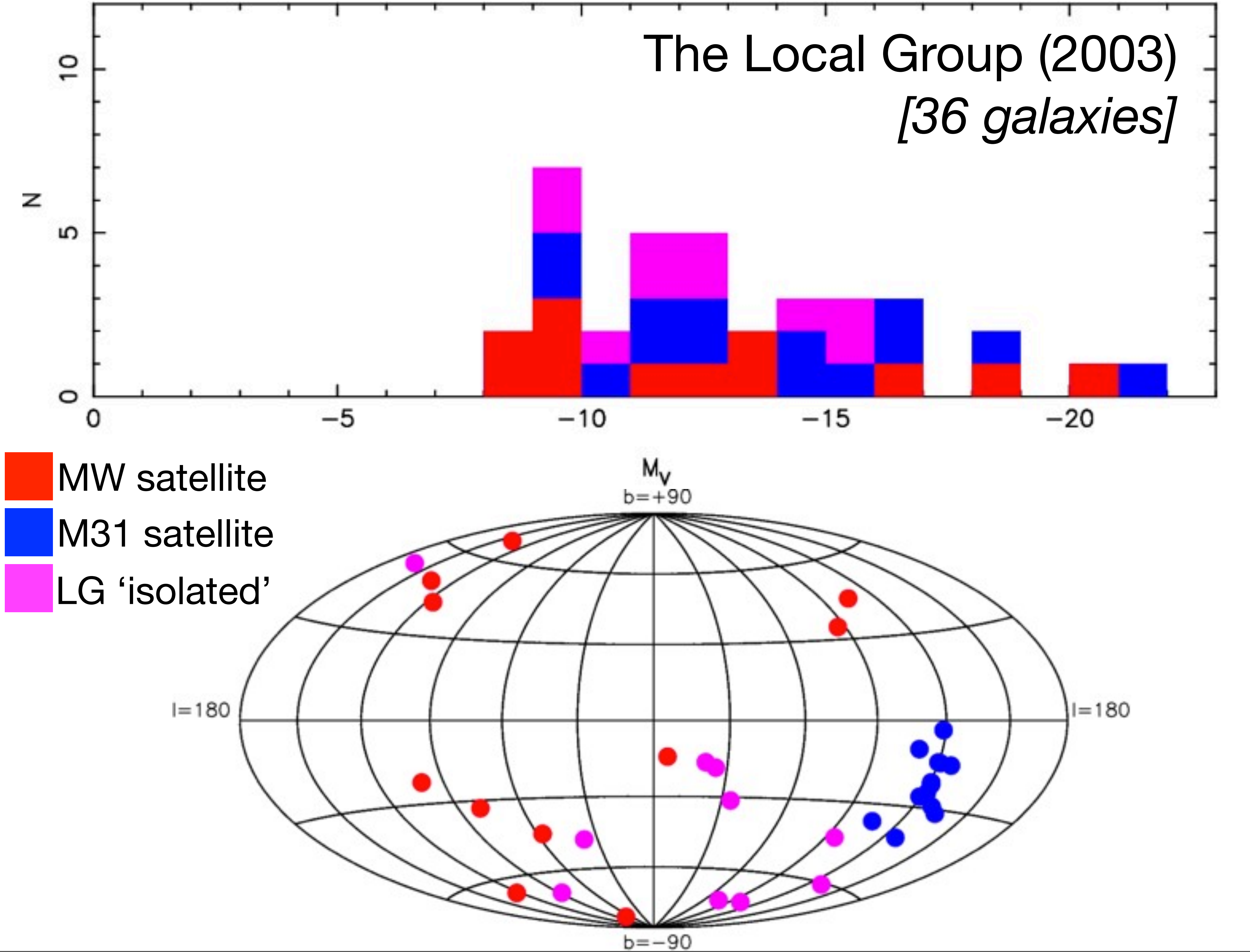
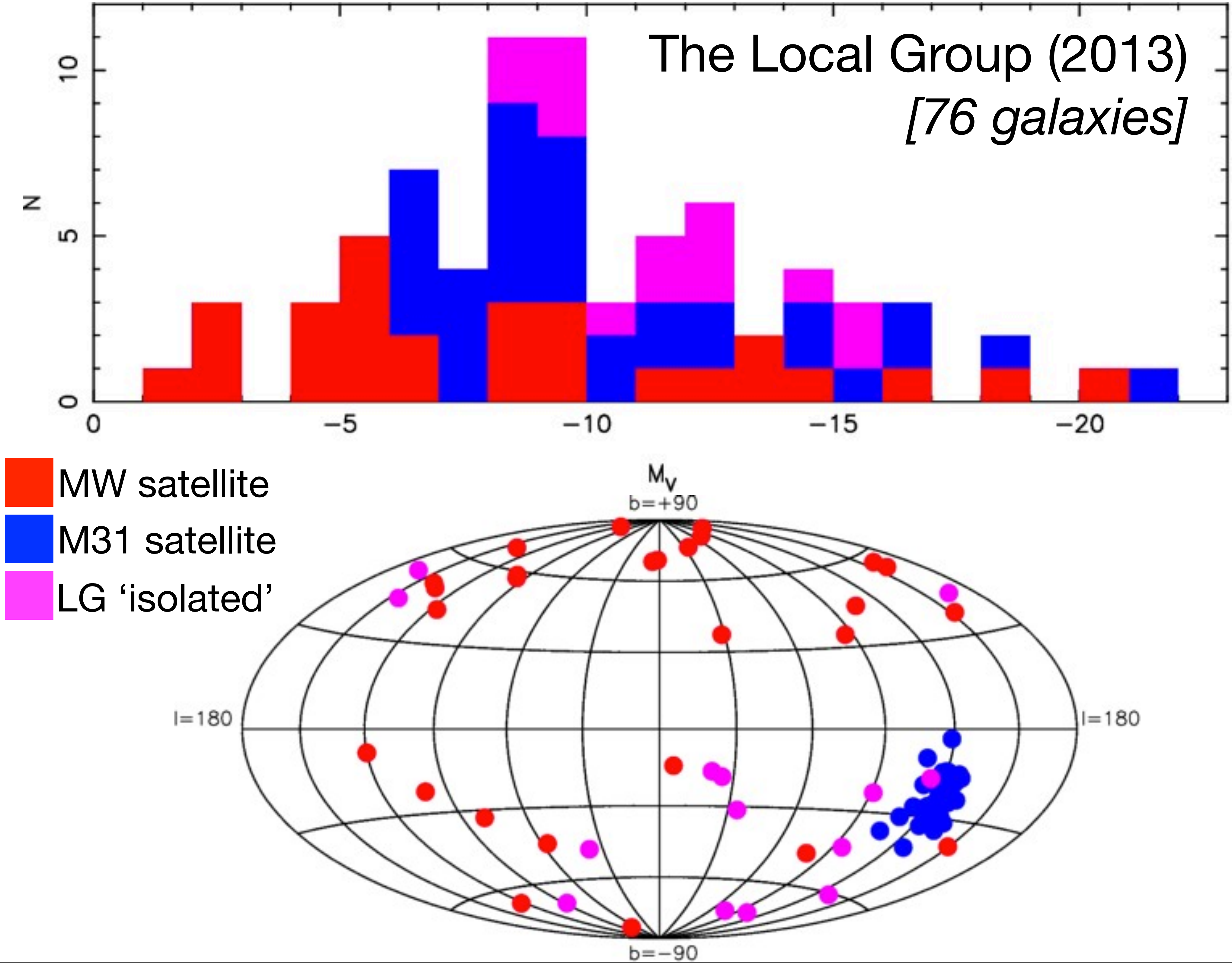
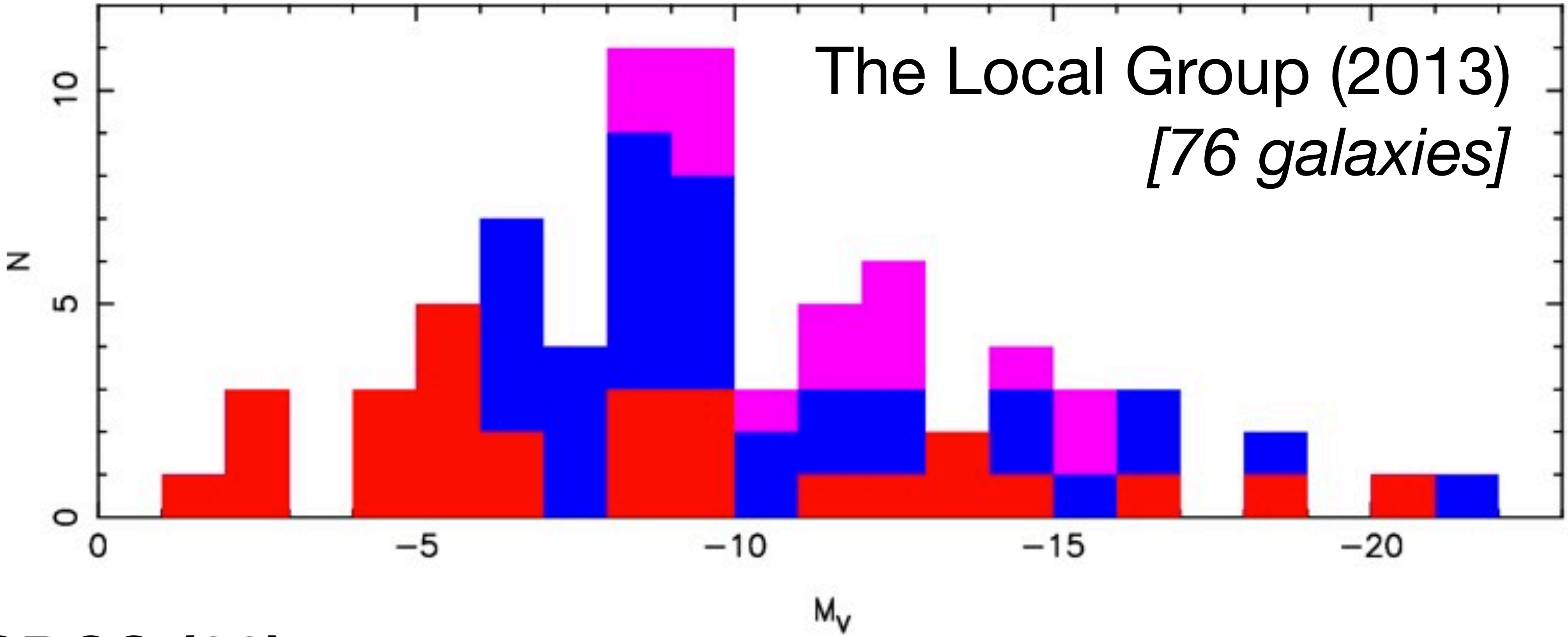
CFHT Users Meeting 2013
Campbell River



The Local Group (2003)
[36 galaxies]
N
0
5
10
0
−5
−10
−15
−20
M_V
MW satellite
M31 satellite
LG ‘isolated’
b=+90
b=−90
l=180
l=180



The Local Group (2013)
[76 galaxies]
N
0
5
10
0
−5
−10
−15
−20
M_V
MW satellite
M31 satellite
LG 'isolated'
b=+90
l=180
l=180
b=−90



SDSS (20):

Segue I, II, Ursa Major I, II, Bootes I, II, III, Willman I, Coma Berenices, Hercules, Leo IV, V, Leo T, Canes Venatici I, II, Pisces II, Andromeda IX, X, XXVIII, XXIX

PAndAS (17):

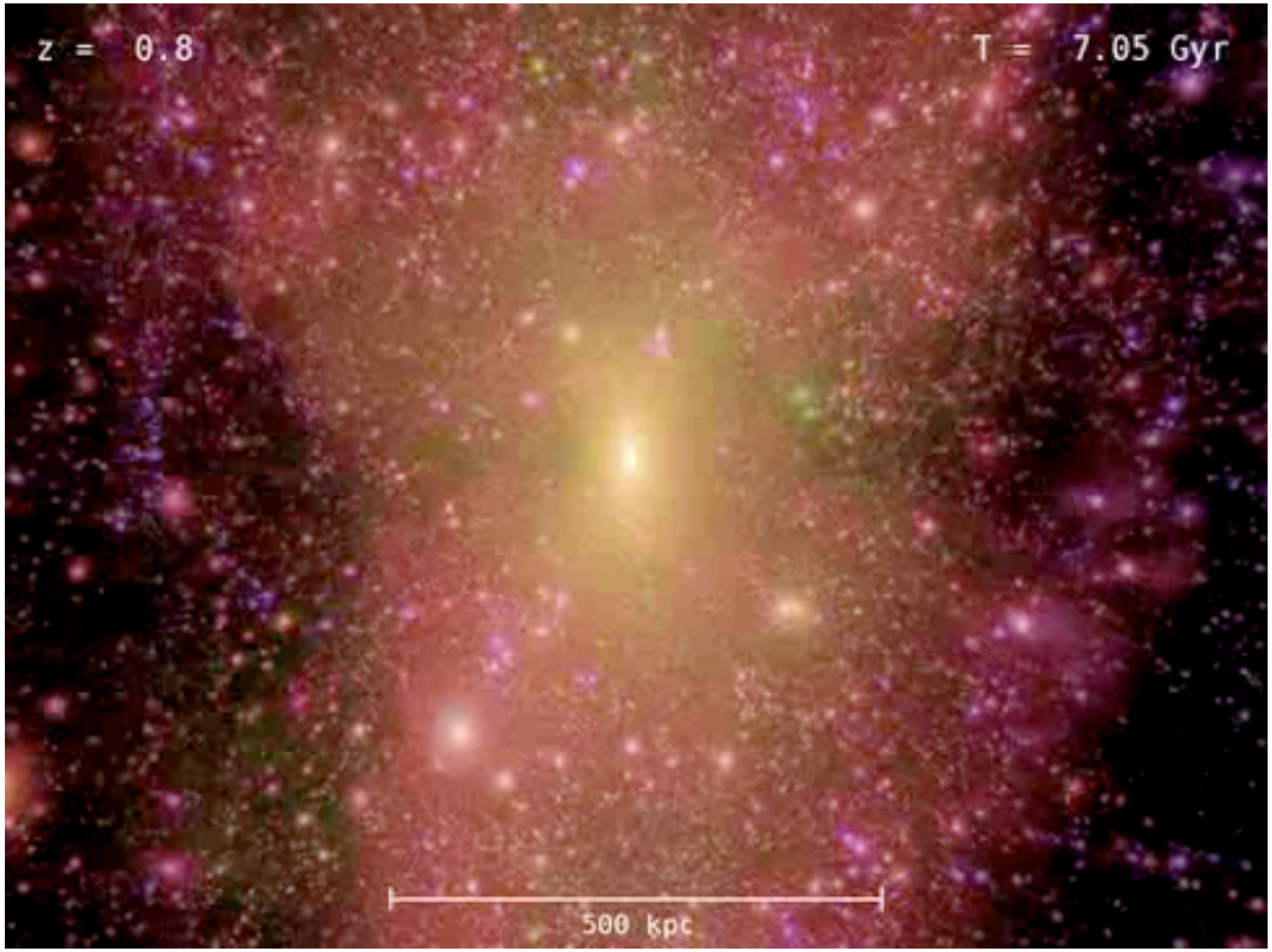
Andromeda XI, XII, XIII, XV, XVI, XVII, XVIII, XIX, XX, XXI (Tri I), XXII, XXIII, XXIV, XXV, XVI, XXVII, *XXX (Cass II)*

Others (3):

Canis Major [controversial], UGC4879 [new distance], And XIV [Majewski]

Cosmology on galactic scales

- Cosmology (structure formation) on large scales reasonably well modelled within a Lambda Cold Dark Matter paradigm
- Predicts that typical L*-ish galaxy halos should be surrounded by many (>1000s) of low mass sub-halos
- Detailed probes of individual galaxies provide (one of?) the best means to probe cosmology on small scales



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

Survey strategy and science drivers

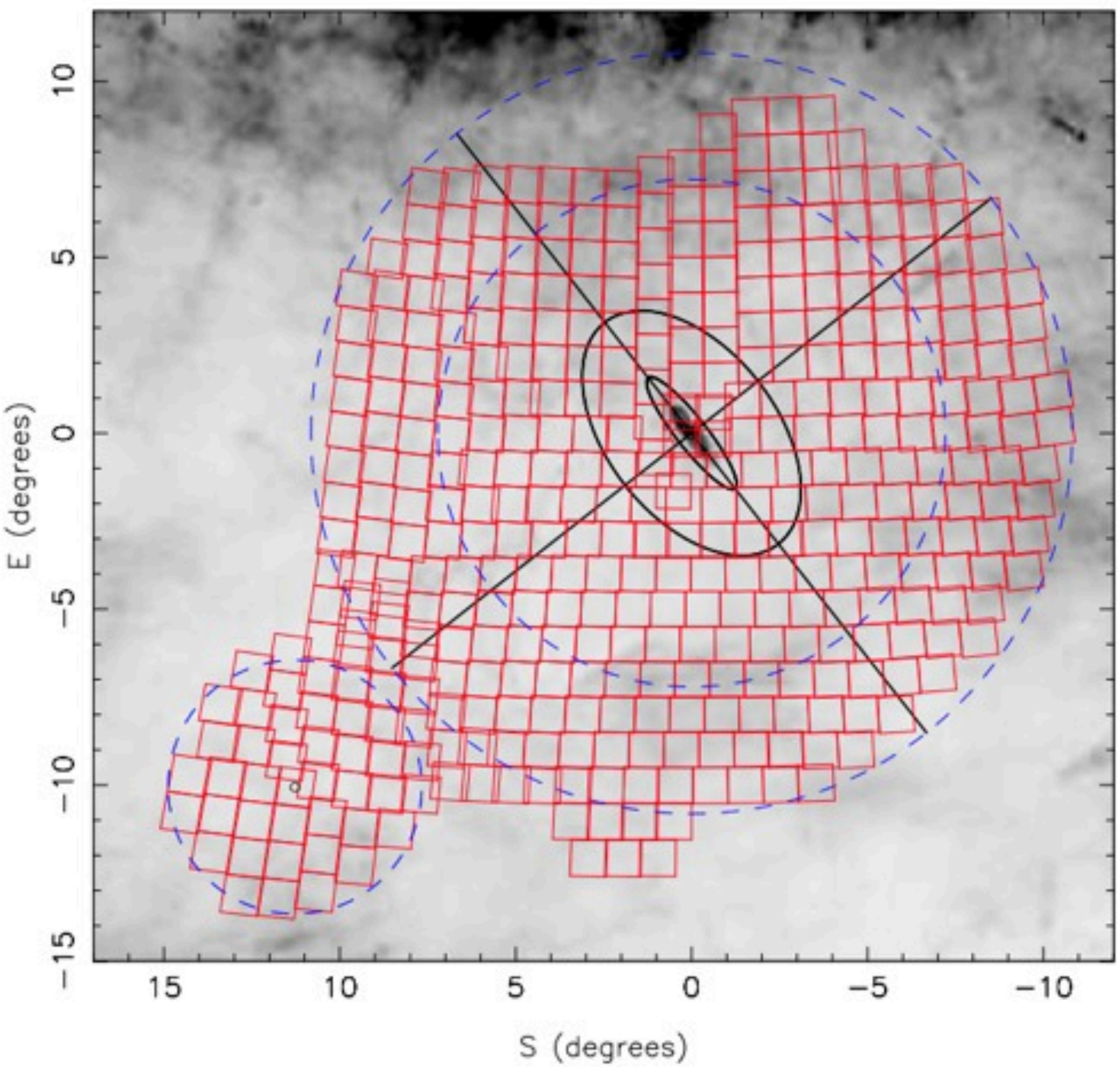
- Basic requirements / strategy
  - Haloes expected to extend out to beyond 100kpc - large area survey
  - Low surface brightness - obtain stellar photometry of top several magnitudes of RGB
  - Chemodynamical structures - maximise metallicity sensitivity (optical/blue bands)
  - Large area of discovery space / Manageable survey duration - two-filter photometry used for main survey; additional filters, pointed observations, obtained as follow-up as required

- Key science drivers:
  - What is the relation between globular clusters and halo stars?
  - What is the overall shape of the stellar halo of a large galaxy?
  - What is the degree and morphology of substructure in the stellar halo?
  - What is the luminosity function of an entire galaxy sub-group, down to extremely faint magnitudes?
  - What is the parameter space occupied by dwarf galaxies, and what is their spatial distribution?
  - How is the light in the stellar halo distributed between surviving dwarfs, substructure and the “smooth” component?

The Pan-Andromeda Archaeological Survey

- 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)
- Contiguous and panoramic view complimentary to more detailed studies of MW

The Pan-Andromeda Archaeological Survey



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Papers to date

(i) The remnants of galaxy formation from a panoramic survey of the region around M31 *McConnachie & PAndAS 2009, Nature, 461, 66*

(ii) PAndAS cubs: Discovery of two new dwarf galaxies in the surrounding of the Andromeda and Triangulum galaxies *Martin et al. 2009, ApJ, 705, 758*

(iii) Evidence for an accretion origin for the outer halo globular cluster system of M31 *Mackey et al. 2009, ApJL, 717, 11*

(iv) The photometric properties of a vast stellar substructure in the outskirts of M31 *McConnachie et al. 2010, ApJ, 723, 1038*

(v) The M33 globular clusters with PAndAS data: the last outer halo clusters? *Cockcroft et al., 2011, ApJ, 730, 112*

(vi) PAndAS progeny: Extending the M31 dwarf galaxy cabal *Richardson et al., 2011, ApJ, 732, 76*

(vii) Density variations in the M31 north-west star stream *Carlberg et al, 2011, ApJ, 731, 74*

(viii) A Bayesian approach to locating the red giant branch tip magnitude I *Conn et al., 2011, ApJ, 740, 69*

(ix) A Bayesian approach to locating the red giant branch tip magnitude II *Conn et al., 2012, ApJ, 758, 11*

(x) PAndAS in the Mist: Correlating the stellar and gaseous mass within the halos of M31 and M33 *Lewis et al. 2013, ApJ, 763, 4*

(xi) Unearthing foundations of a cosmic cathedral: searching the stars for M33's halo *Cockcroft et al. 2013, MNRAS, 428, 124*

(xii) A vast thin plane of corotating dwarf galaxies orbiting the Andromeda galaxy *Ibata et al. 2013, Nature, 493, 62*

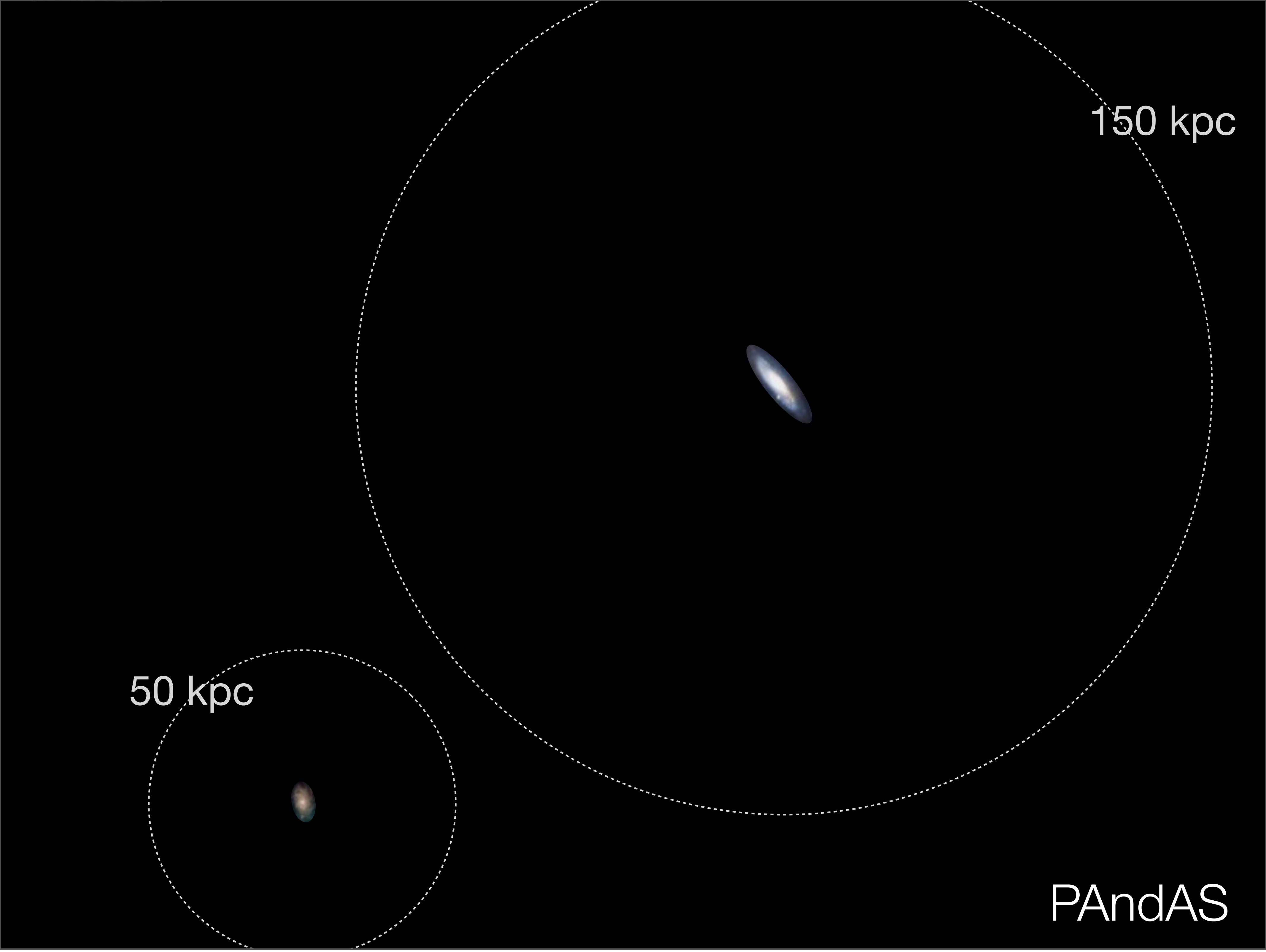
(xiii) The three dimensional structure of the M31 satellite system: strong evidence for an inhomogeneous distribution of satellites Conn et al. 2013, ApJ, 766, 120

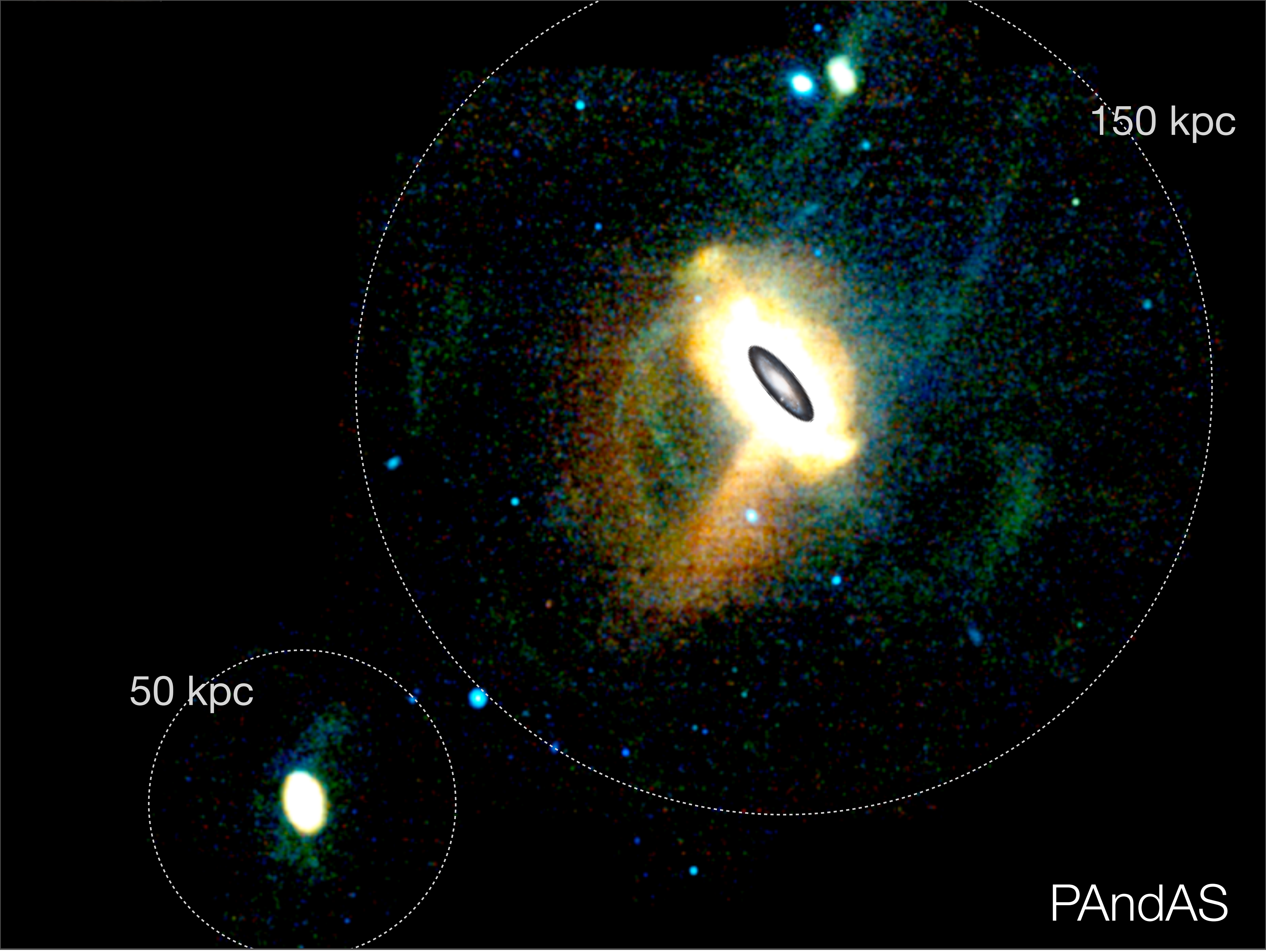
Follow-up Observations

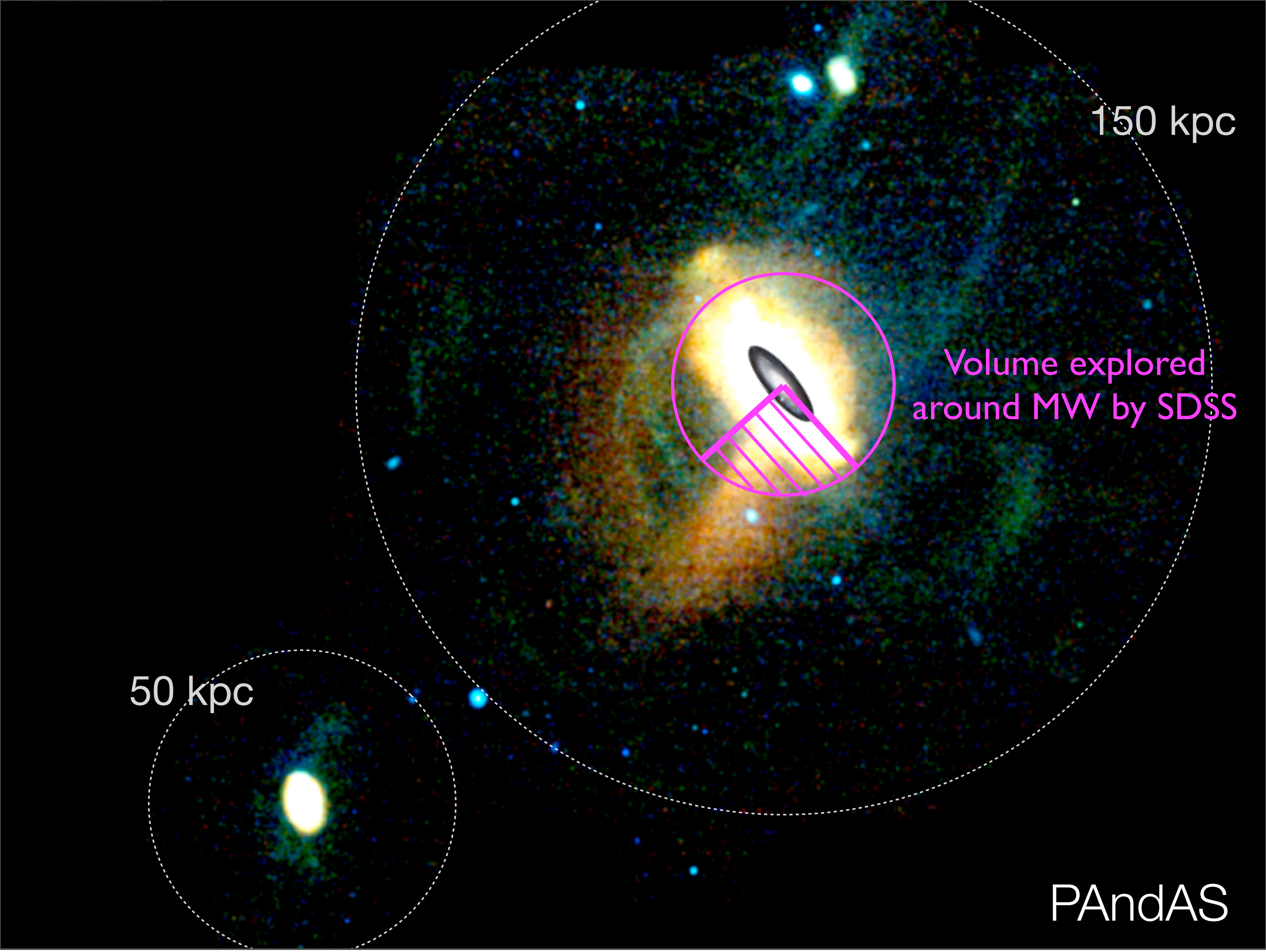


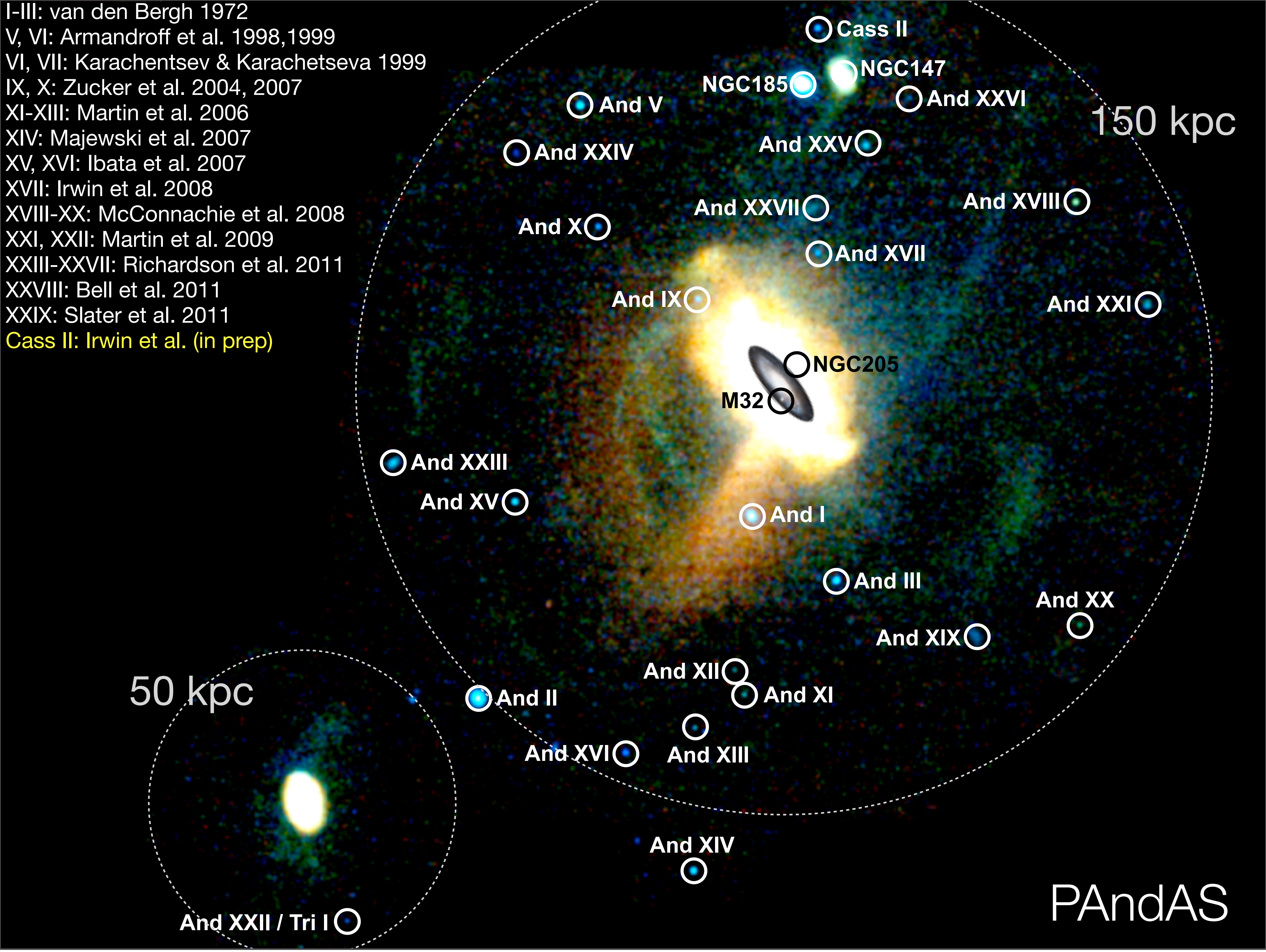

Since 2009B, over 30 accepted follow-up proposals on WHT, KPNO4m, CFHT, LBT, Subaru, Gemini, Keck & HST, leading to ~14 additional papers so far...



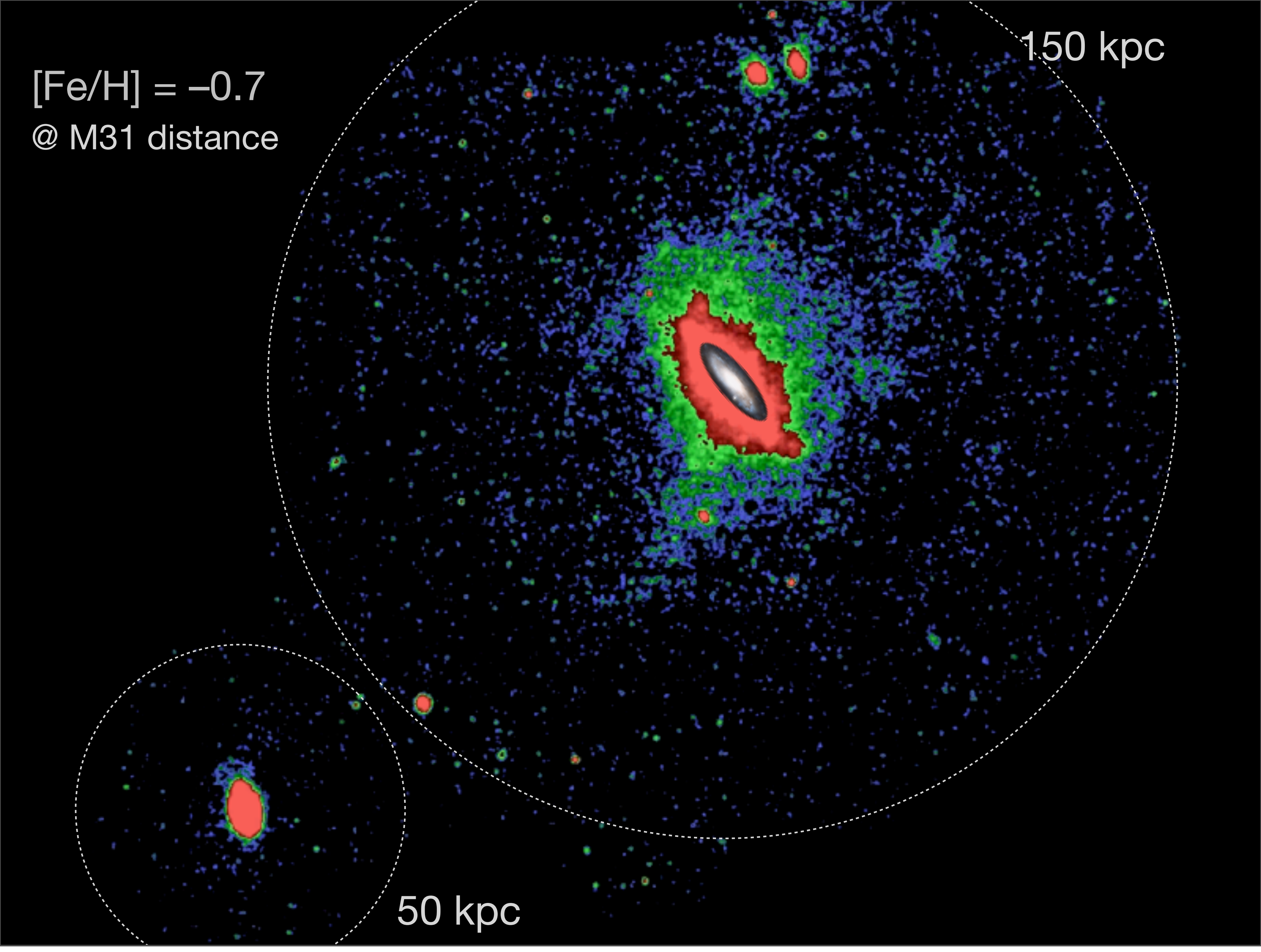


150 kpc
50 kpc
PAndAS


150 kpc
50 kpc
PAndAS


150 kpc
Volume explored
around MW by SDSS
50 kpc
PAndAS


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
Cass II: Irwin et al. (in prep)
Cass II
NGC147
NGC185
And XXVI
And V
150 kpc
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
50 kpc
And II
And XVI
And XIII
And XIV
PAndAS
And XXII / Tri I


150 kpc
[Fe/H] = −2.3
@ M31 distance
50 kpc


[Fe/H] = –0.7
@ M31 distance
150 kpc
50 kpc

What we wanted to do,
and what we’ve actually
done

a brief update

What is the relation between globular clusters and halo stars?

- 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.

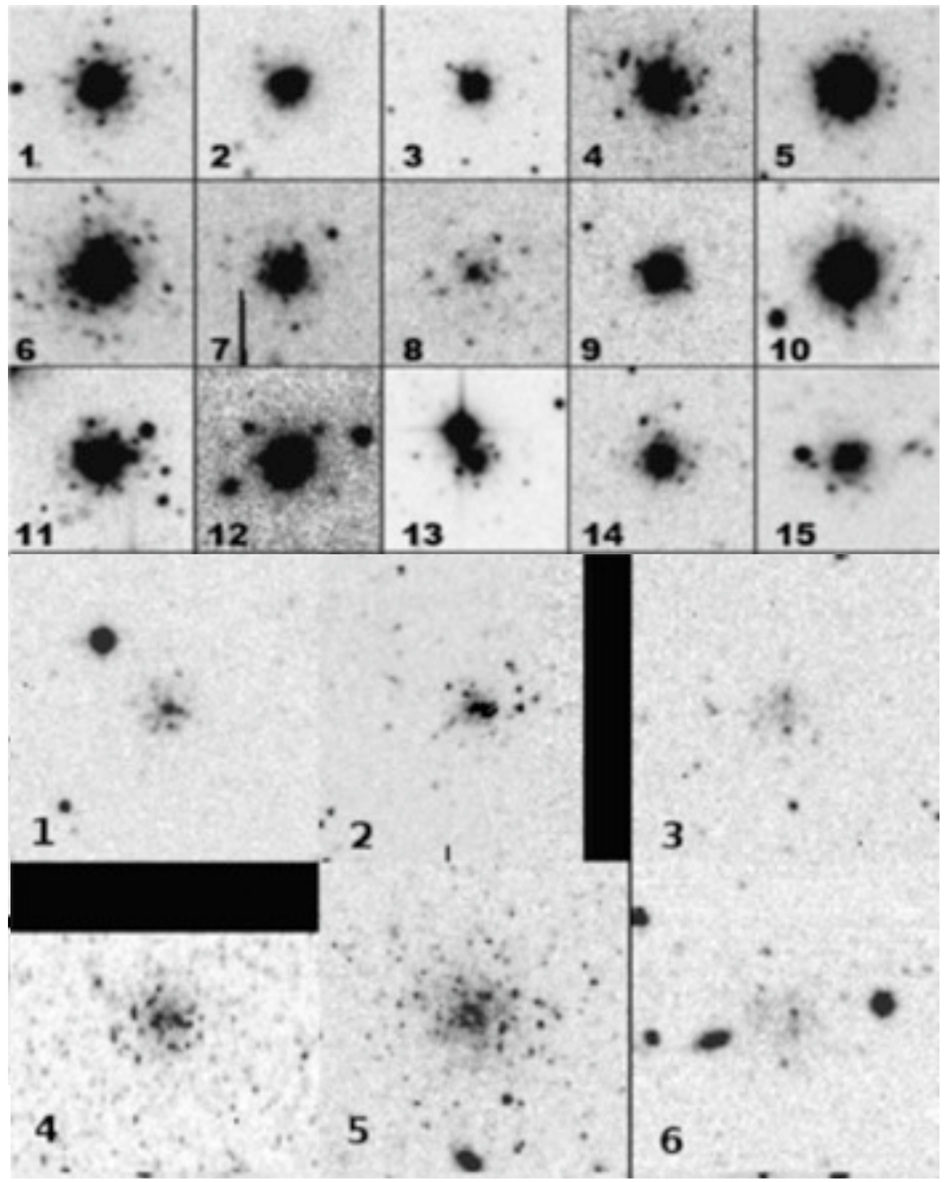
What is the relation between globular clusters and halo stars?

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

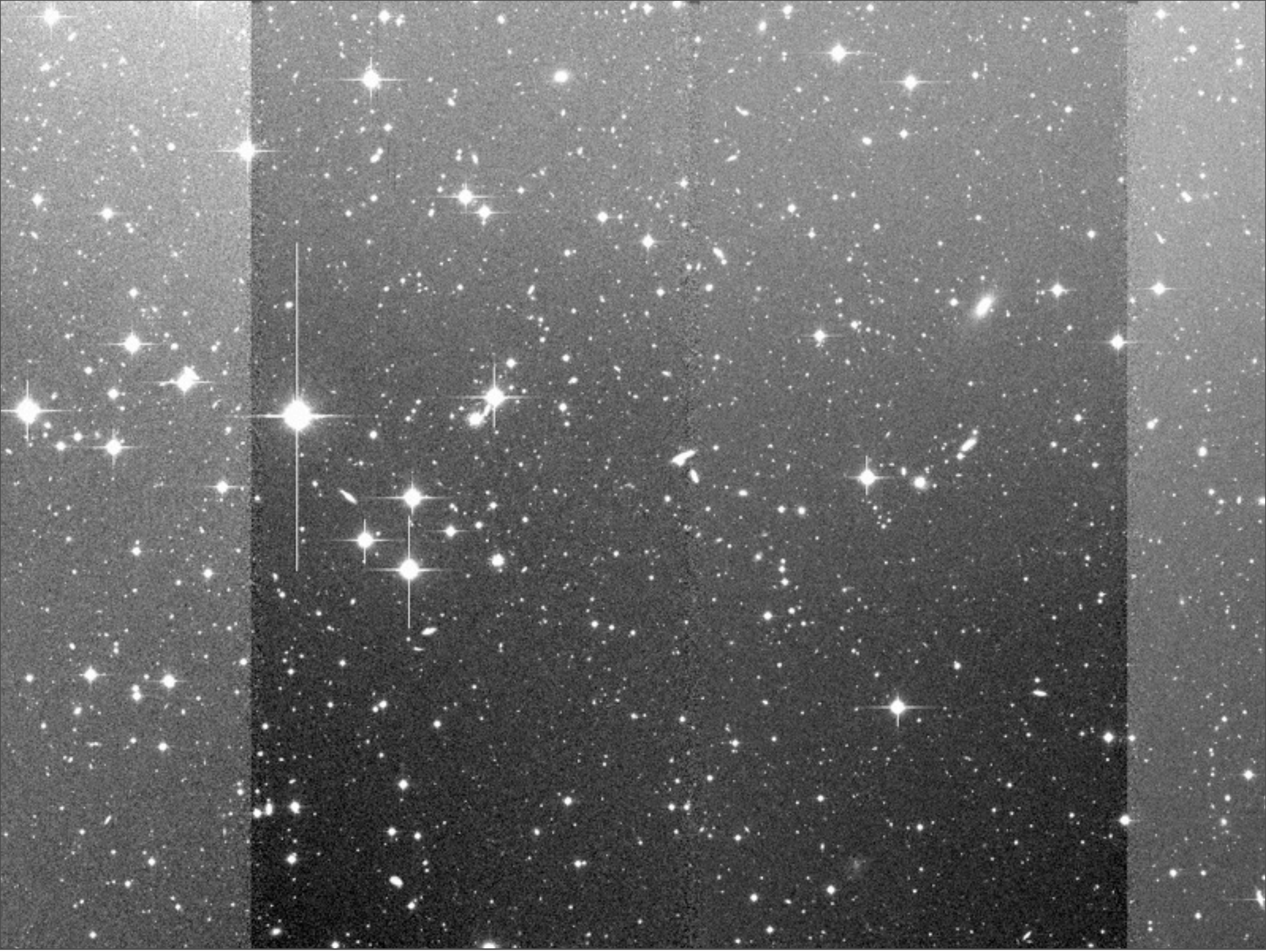
•Prior to PAndAS and precursor surveys:
- •34 GCs at >15 kpc
- • 3 GCs at >30 kpc.

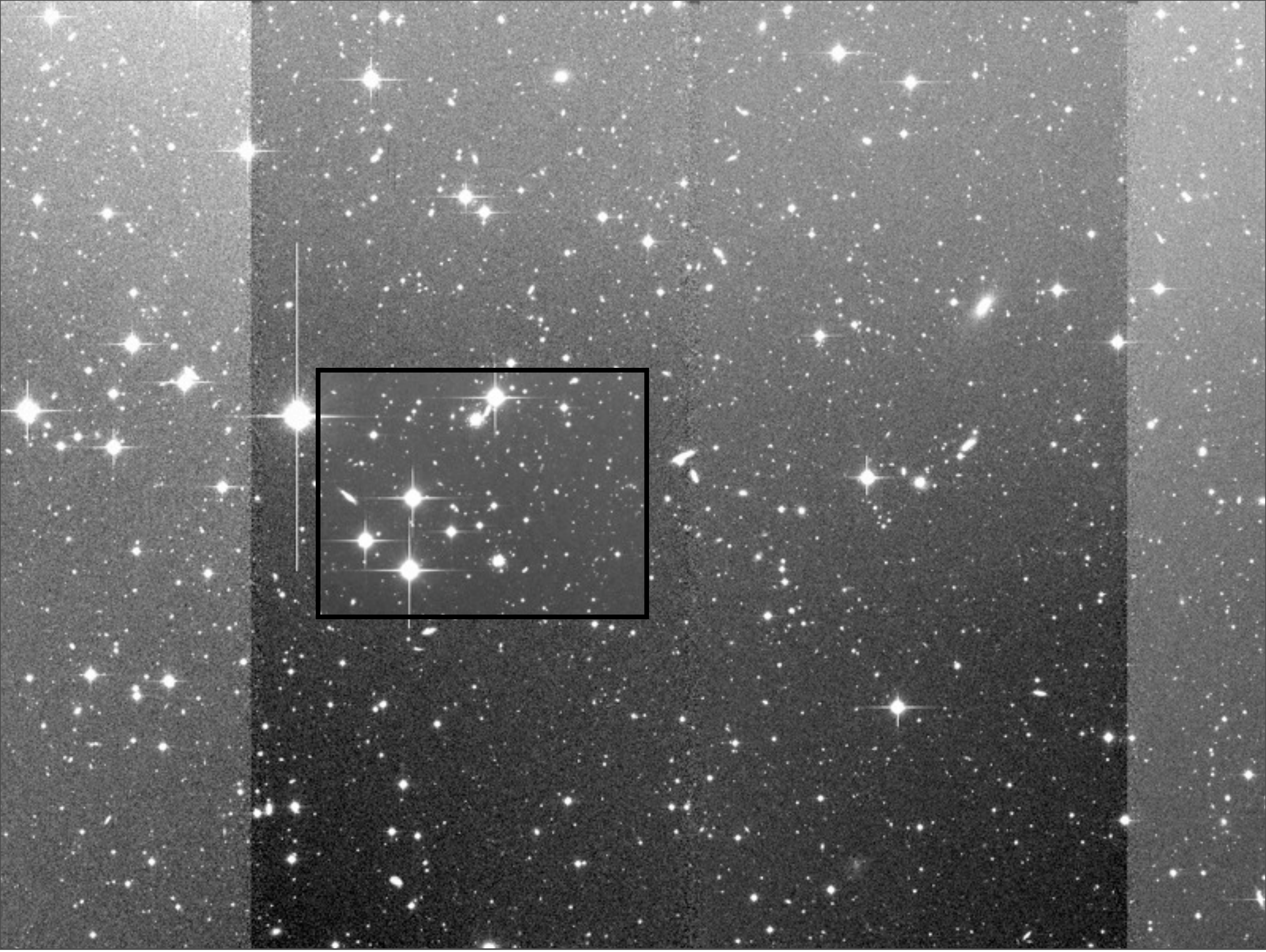
•PAndAS and precursor surveys have increased known GC population at large radii by 200%:
- •100 new GCs at >15 kpc
- •79 new GCs at >30 kpc
- •15 new GC at 85 < R_{proj} < 145 kpc

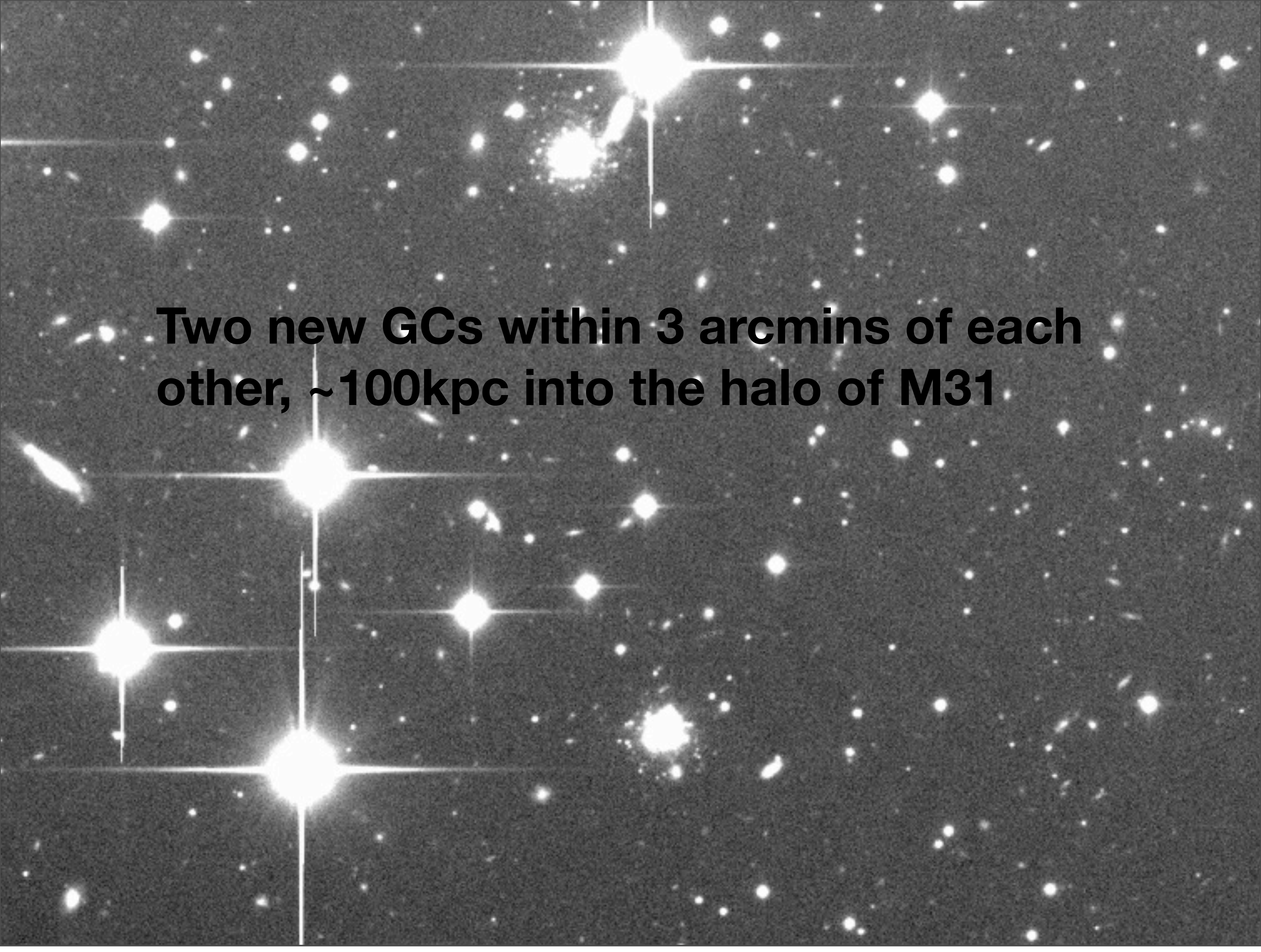
•cf. MW:
9 GCs at >38 kpc
2 GCs at >100kpc

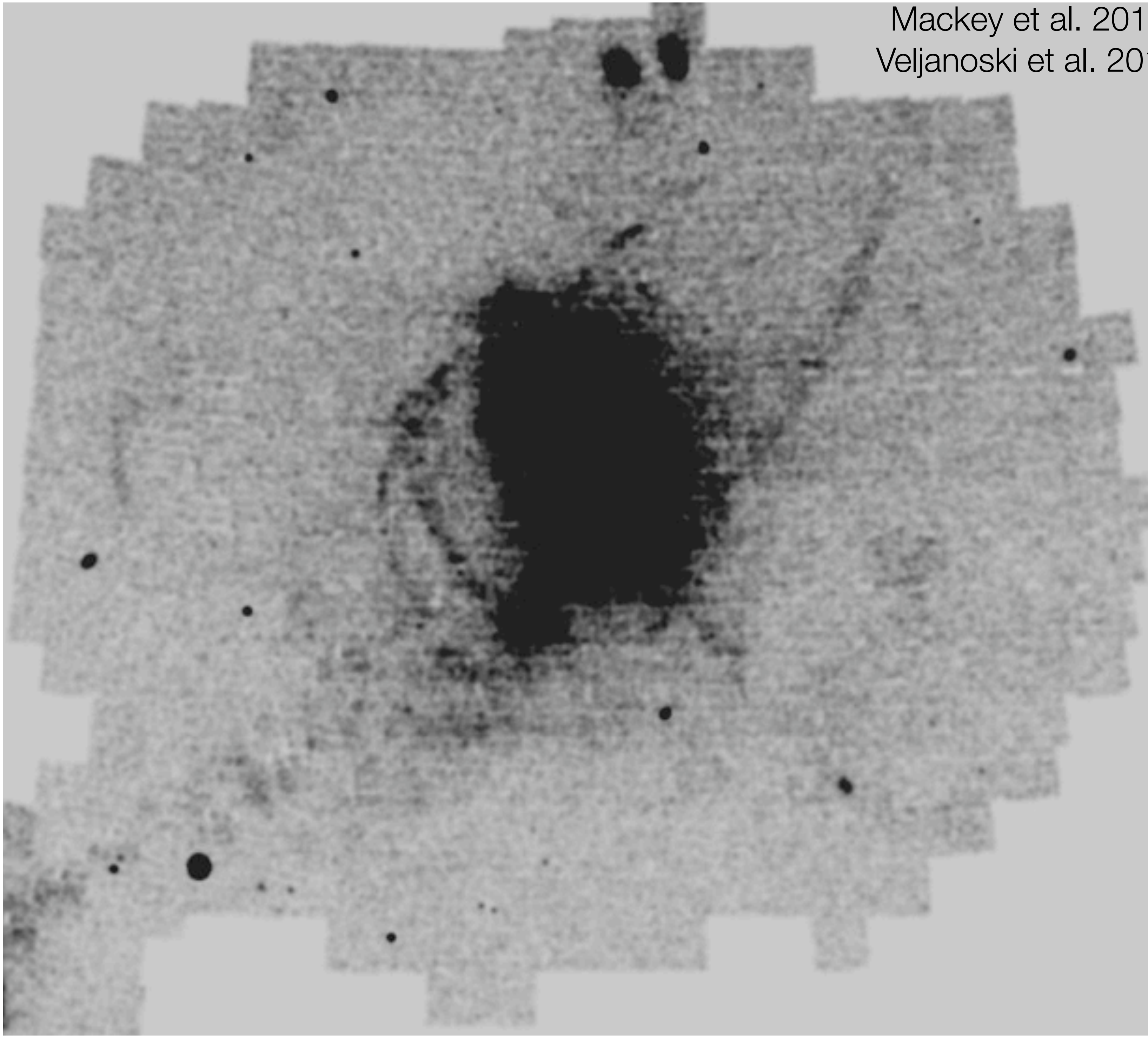


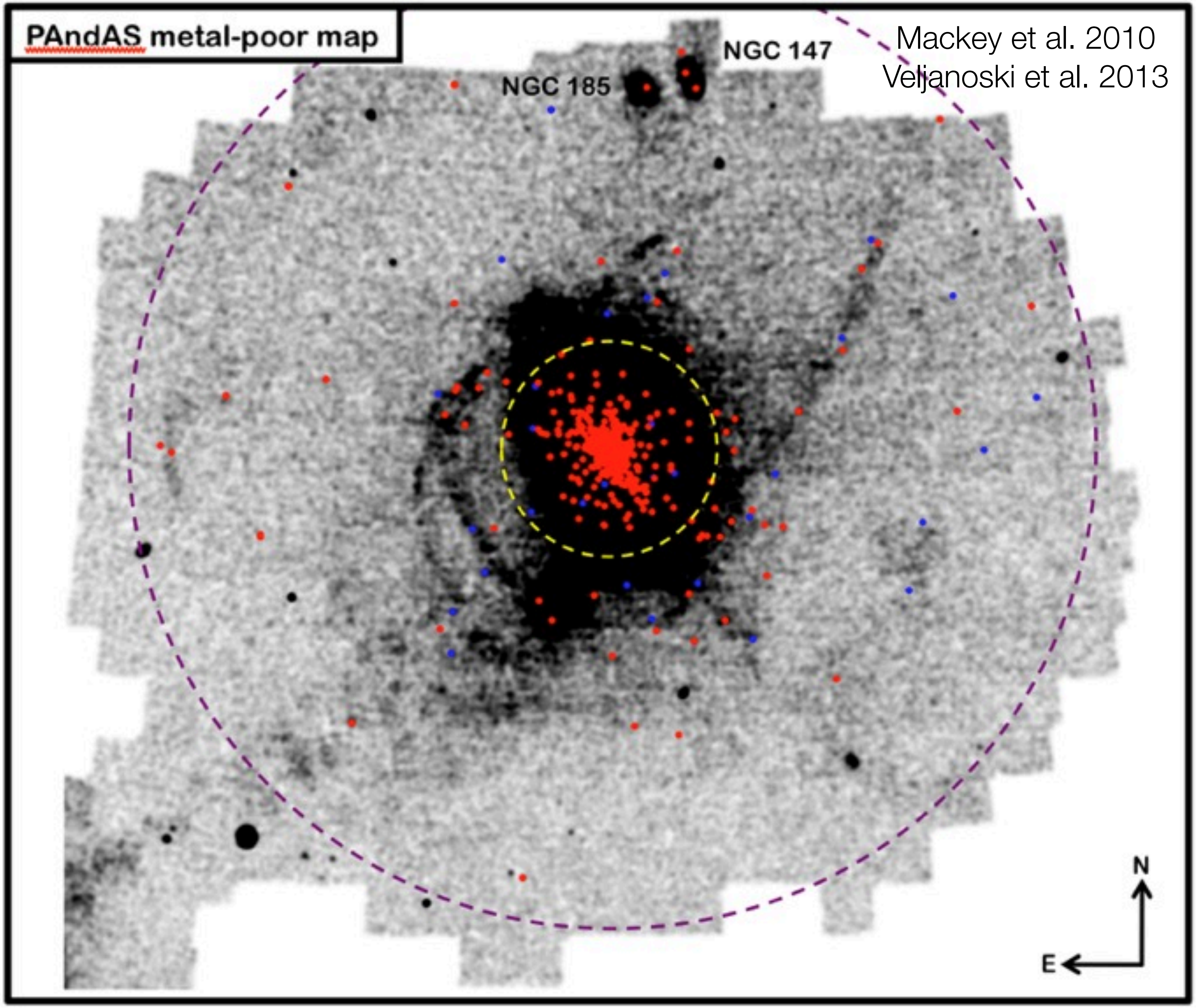
Huxor et al. 2005, 2008, 2013 (in prep)





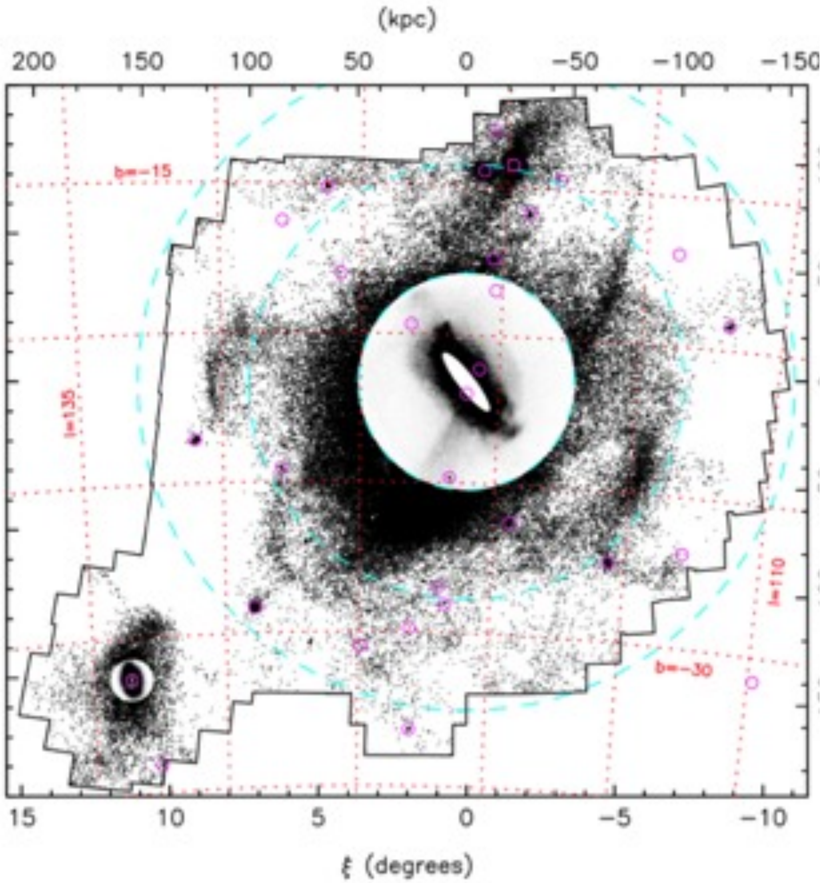

Two new GCs within 3 arcmins of each
other, ~100kpc into the halo of M31

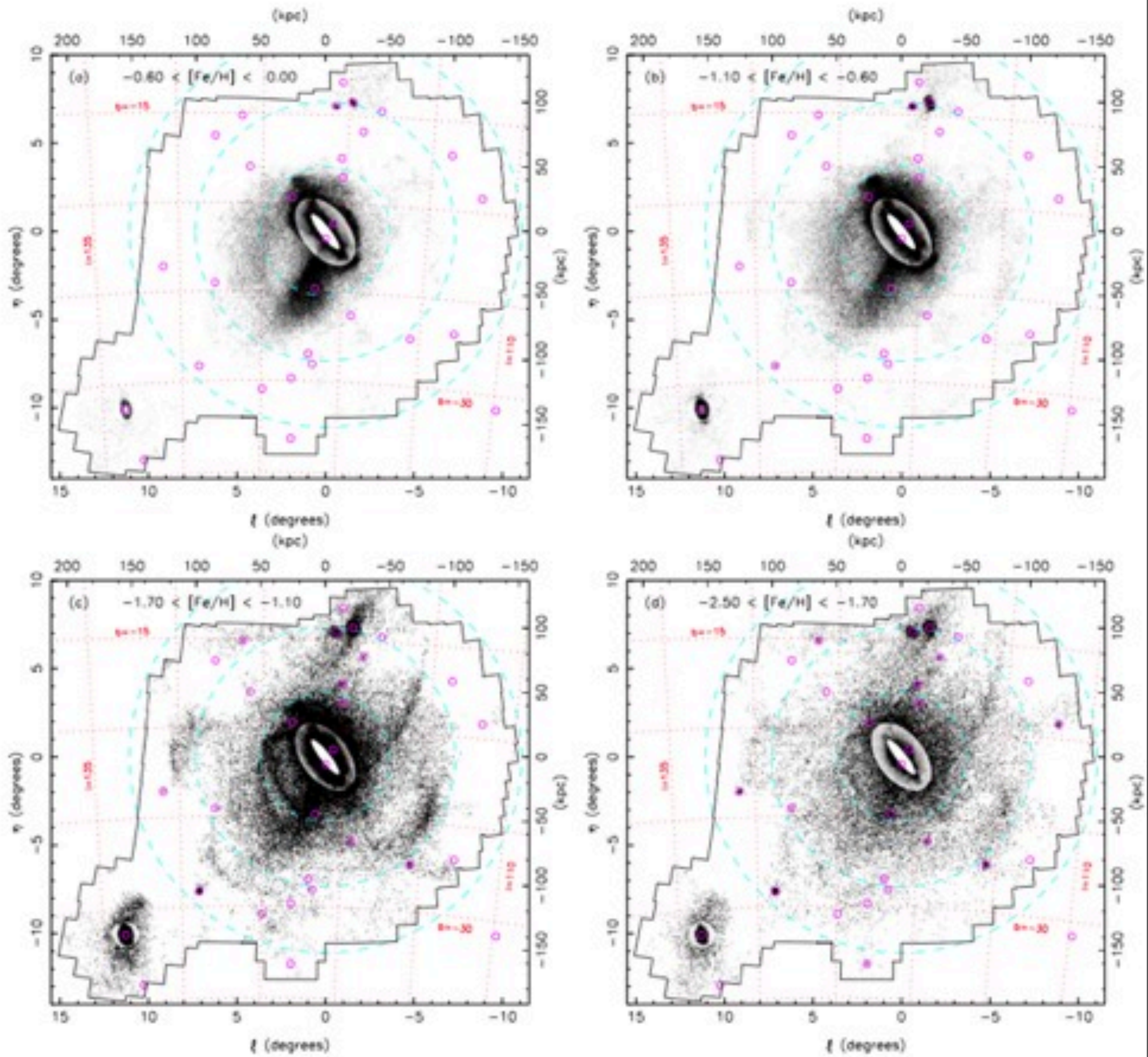

Mackey et al. 2010
Veljanoski et al. 2013


PAndAS metal-poor map
NGC 147
NGC 185
Mackey et al. 2010
Veljanoski et al. 2013
N
E

What is the overall shape of the stellar halo of a large galaxy?
[See next talk!]

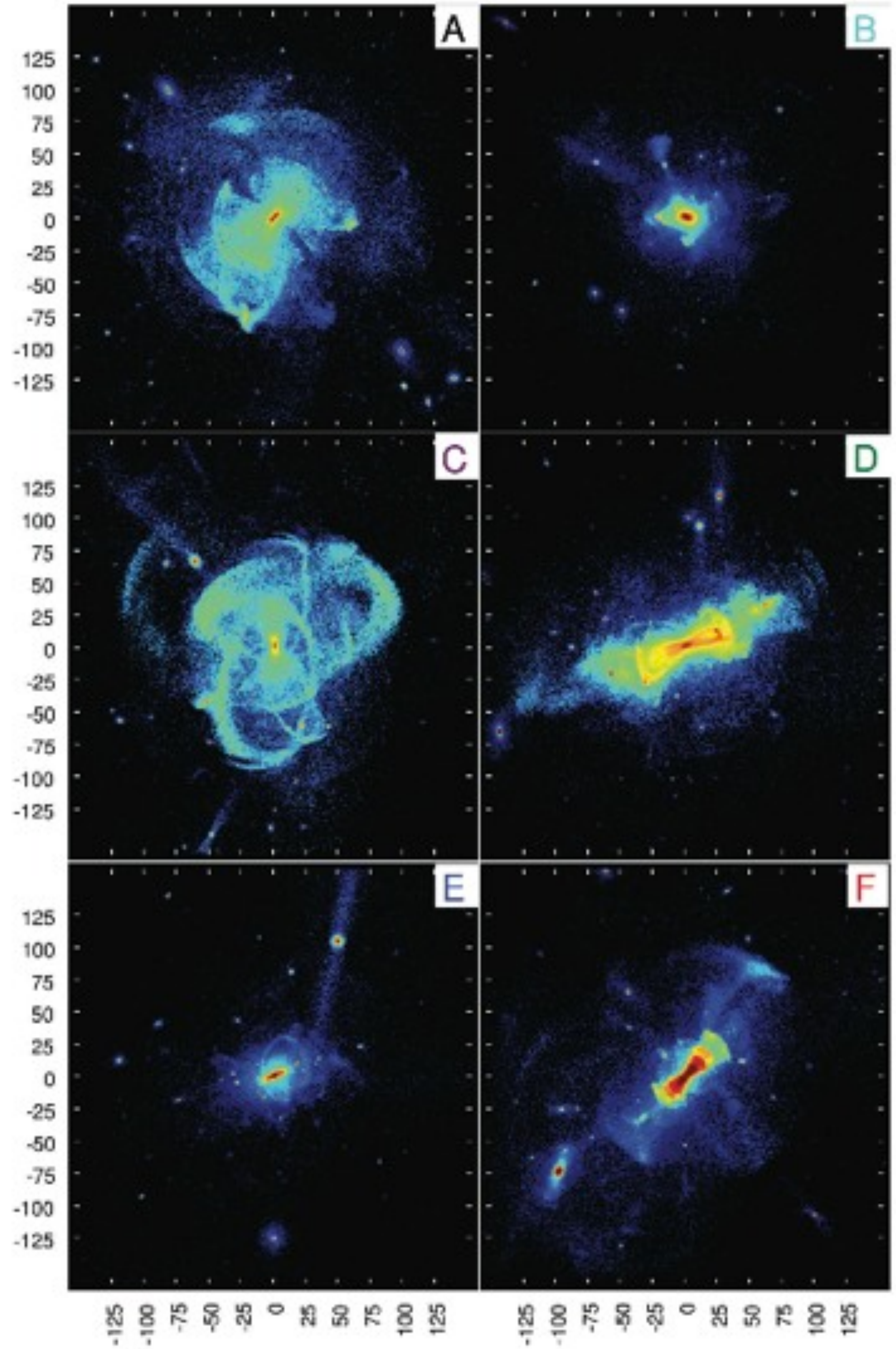
- Ibata et al. 2013 (to be submitted)



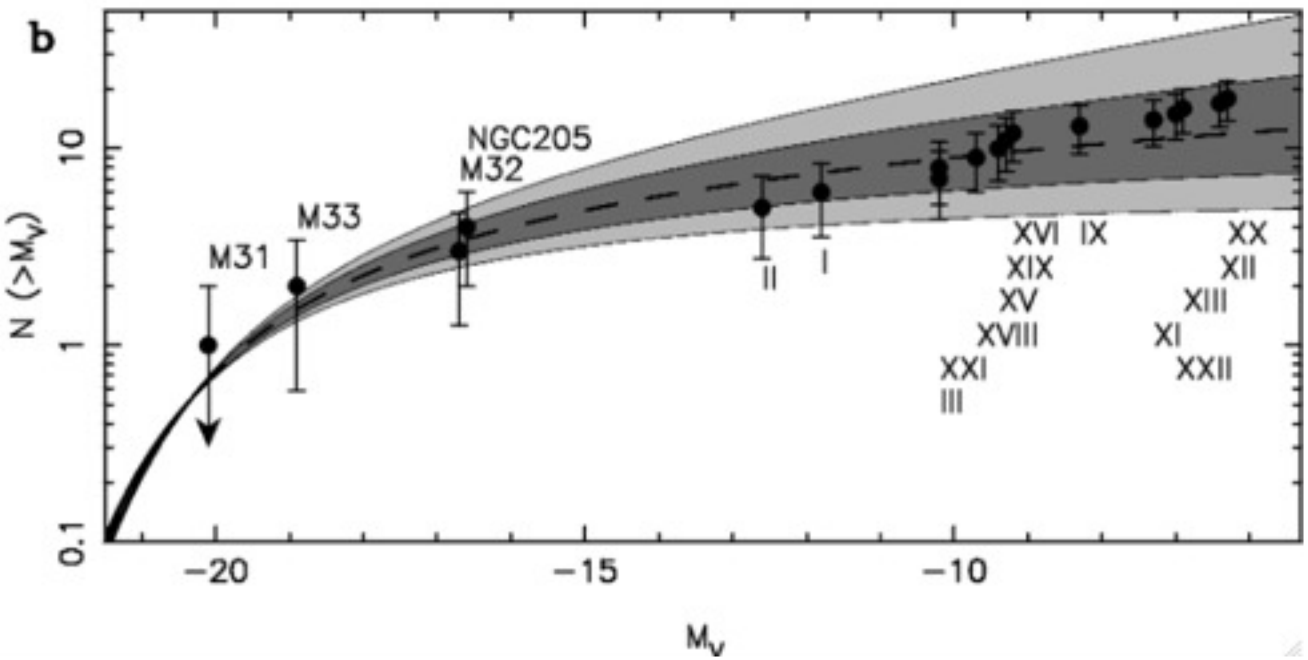


What is the degree and morphology of substructure in the stellar halo?

- McConnachie et al. (2013, nearly in prep)
- Examine distribution of residuals (ie substructure on all scales); decompose into basis functions
- Compare power spectrum to Cold Dark Matter simulations (right, from Cooper et al. 2010) and Warm Dark Matter simulations
- In collaboration with the Aquarius Collaboration (Navarro, Frenk, et al.)

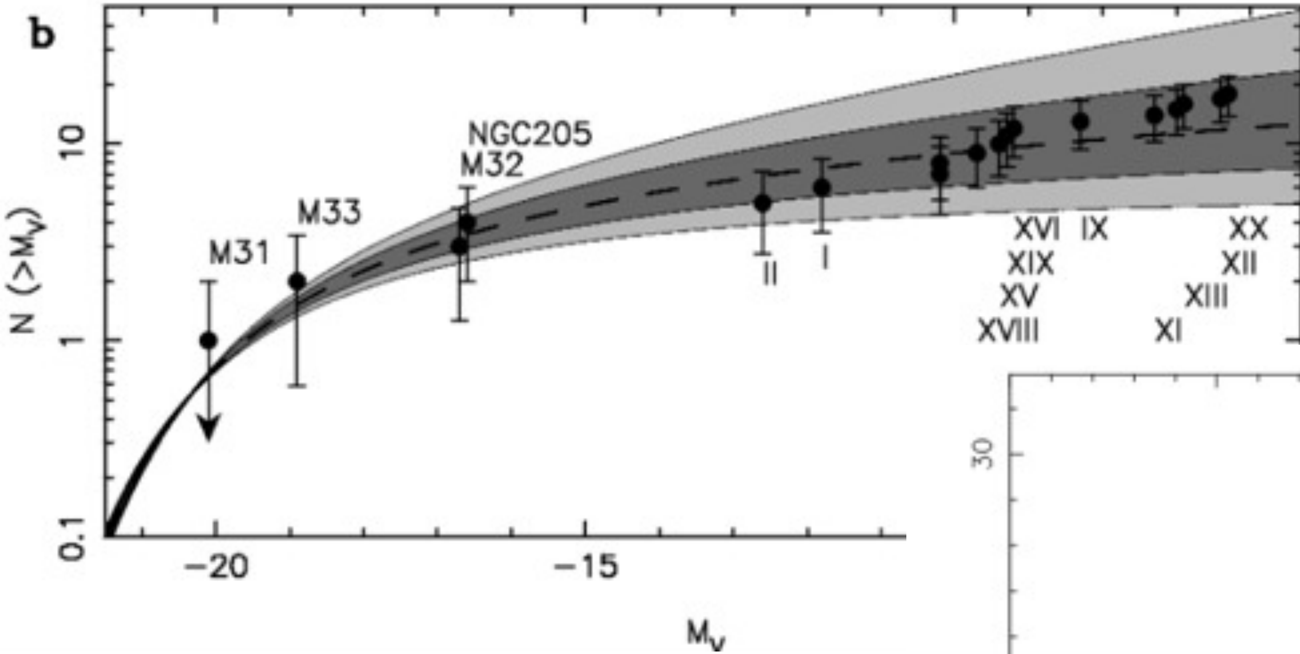


What is the luminosity function of an entire galaxy sub-group, down to extremely faint limits?
What is the parameter space occupied by dwarf galaxies, and their spatial distribution?



- Luminosity function (2009)
  - Best-fit Schecter function has faint-end slope alpha = -0.98 +/- 0.07
  - McC+2009

What is the luminosity function of an entire galaxy sub-group, down to extremely faint limits? What is the parameter space occupied by dwarf galaxies, and their spatial distribution?



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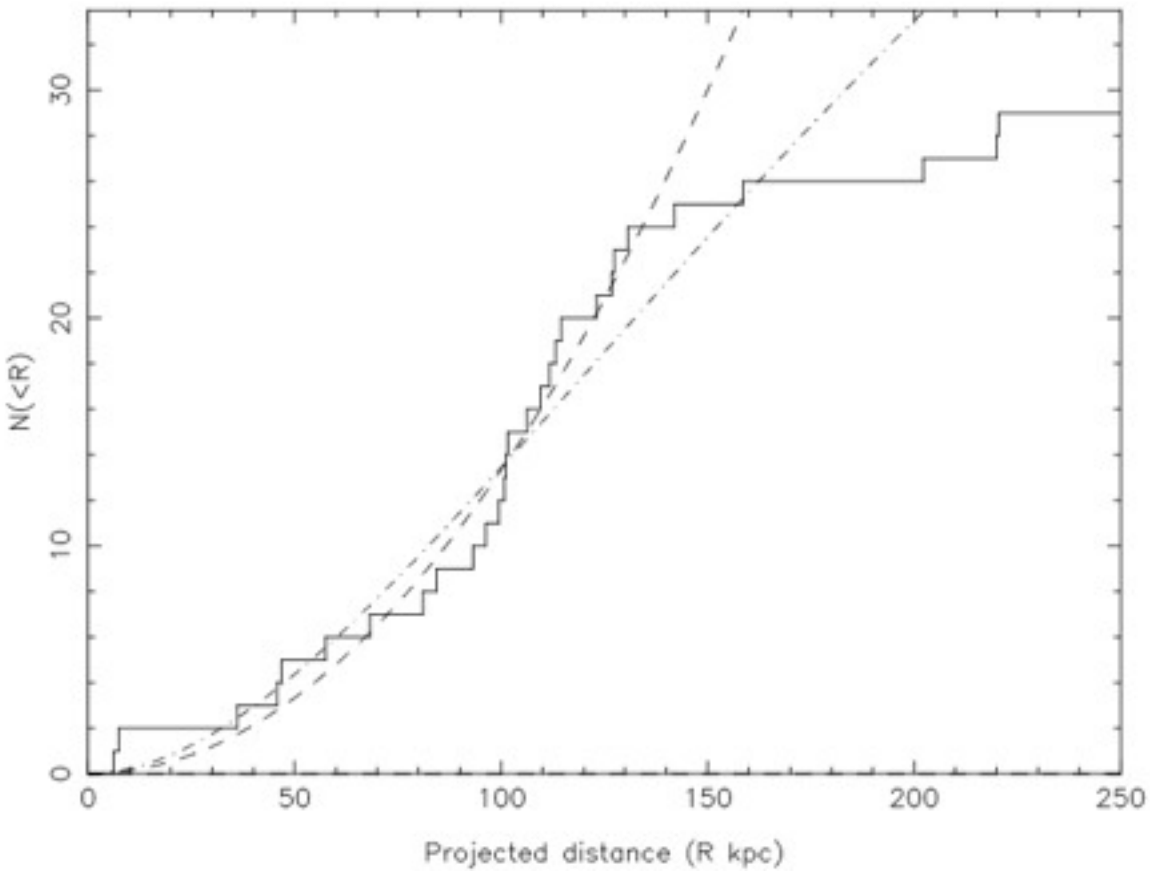
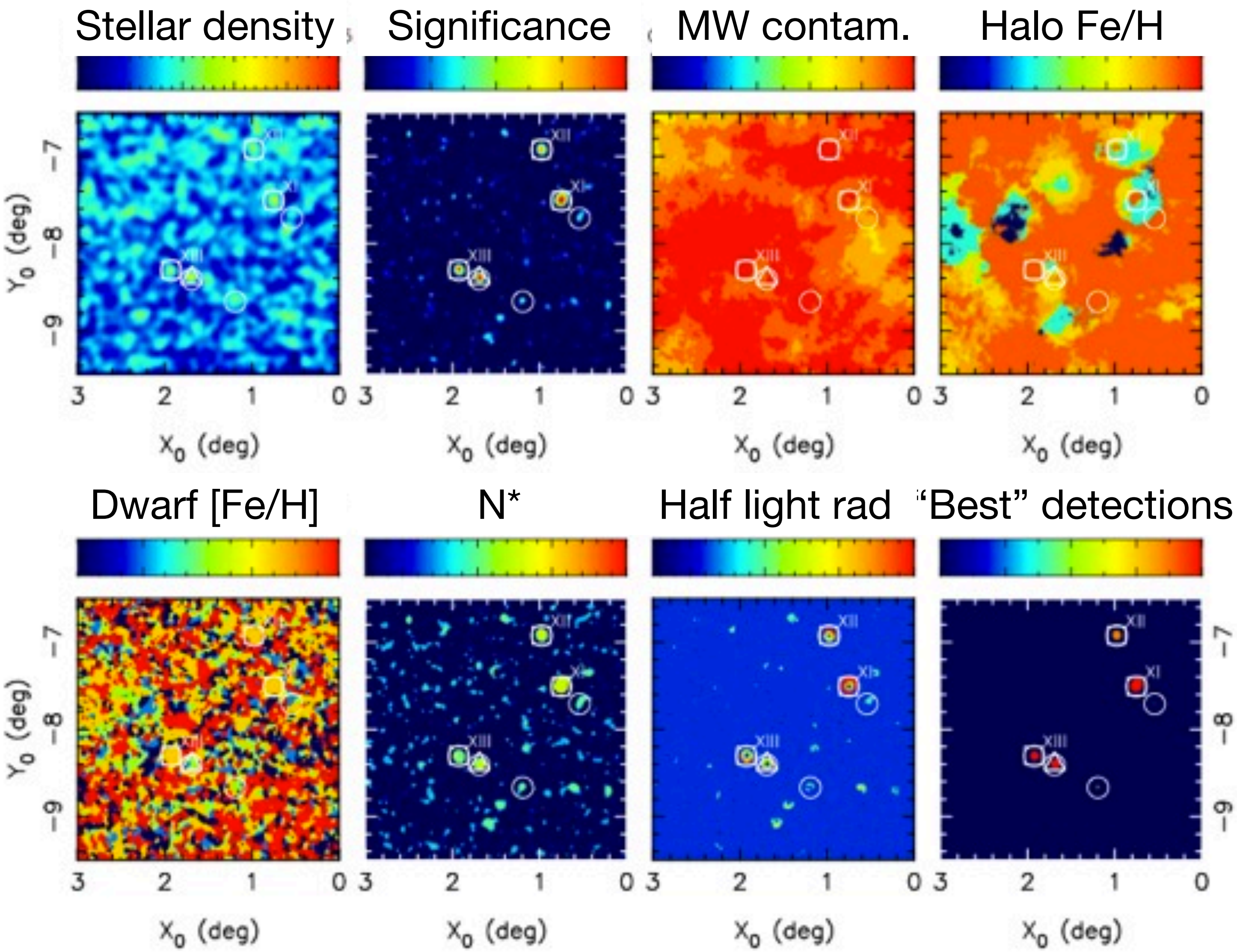


- Radial distribution (2011)
  - Flat distribution in projection
  - Corresponds to a 3D density distribution, $\rho(r) \propto r^{-1}$ (dashed line)
  - cf cosmological simulations (dot-dashed line)
  - Richardson et al. 2011

What is the luminosity function of an entire galaxy sub-group, down to extremely faint limits?
What is the parameter space occupied by dwarf galaxies, and their spatial distribution?

- Martin et al. (2013ab, to be submitted; 2013/4 in prep)



- Bayesian maximum likelyhood technique to search for overdensities of stars that follow a well-defined density distribution, both on the sky and in color-magnitude space
- f(X,Y,rh,[Fe/H], N*)

What is the luminosity function of an entire galaxy sub-group, down to extremely faint limits? What is the parameter space occupied by dwarf galaxies, and their spatial distribution?

- All known dwarf galaxies (and many GCs) identified with high significance. One new GC identified.
- Numerous high probability candidates in need of deeper follow up
- Allow robust derivation of parameter distributions; benchmark for simulations

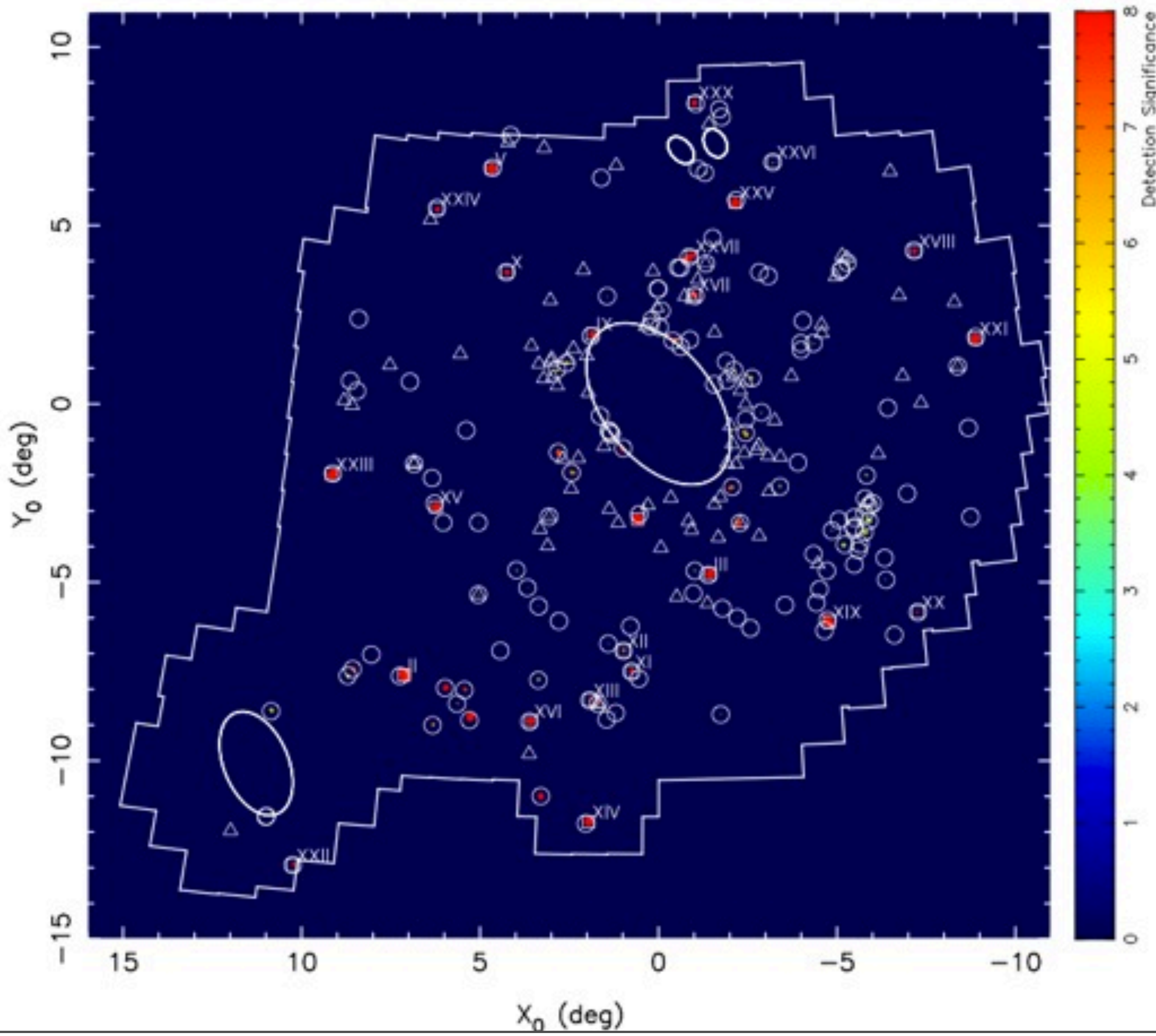


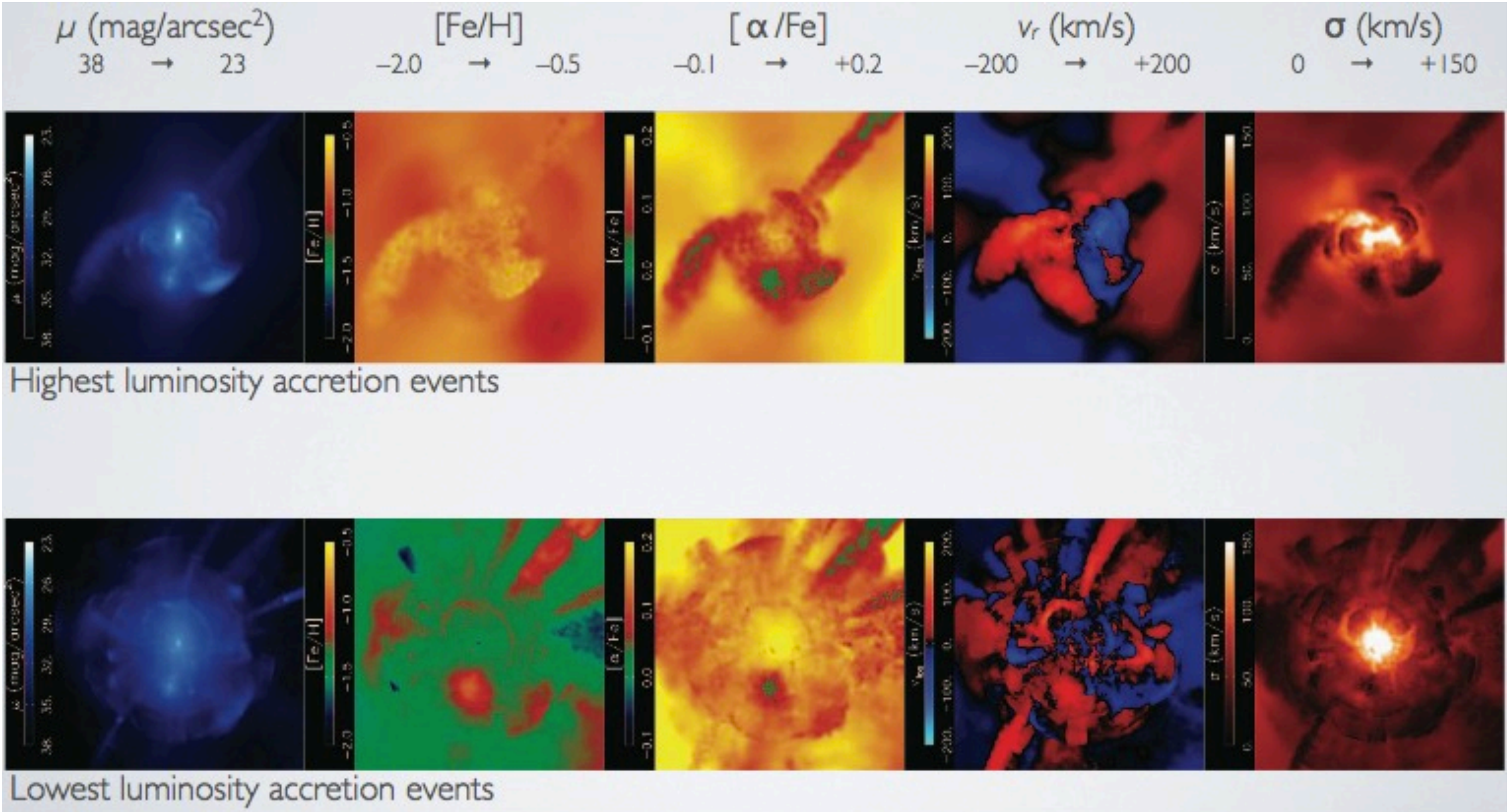
TABLE 1

List of significant detections

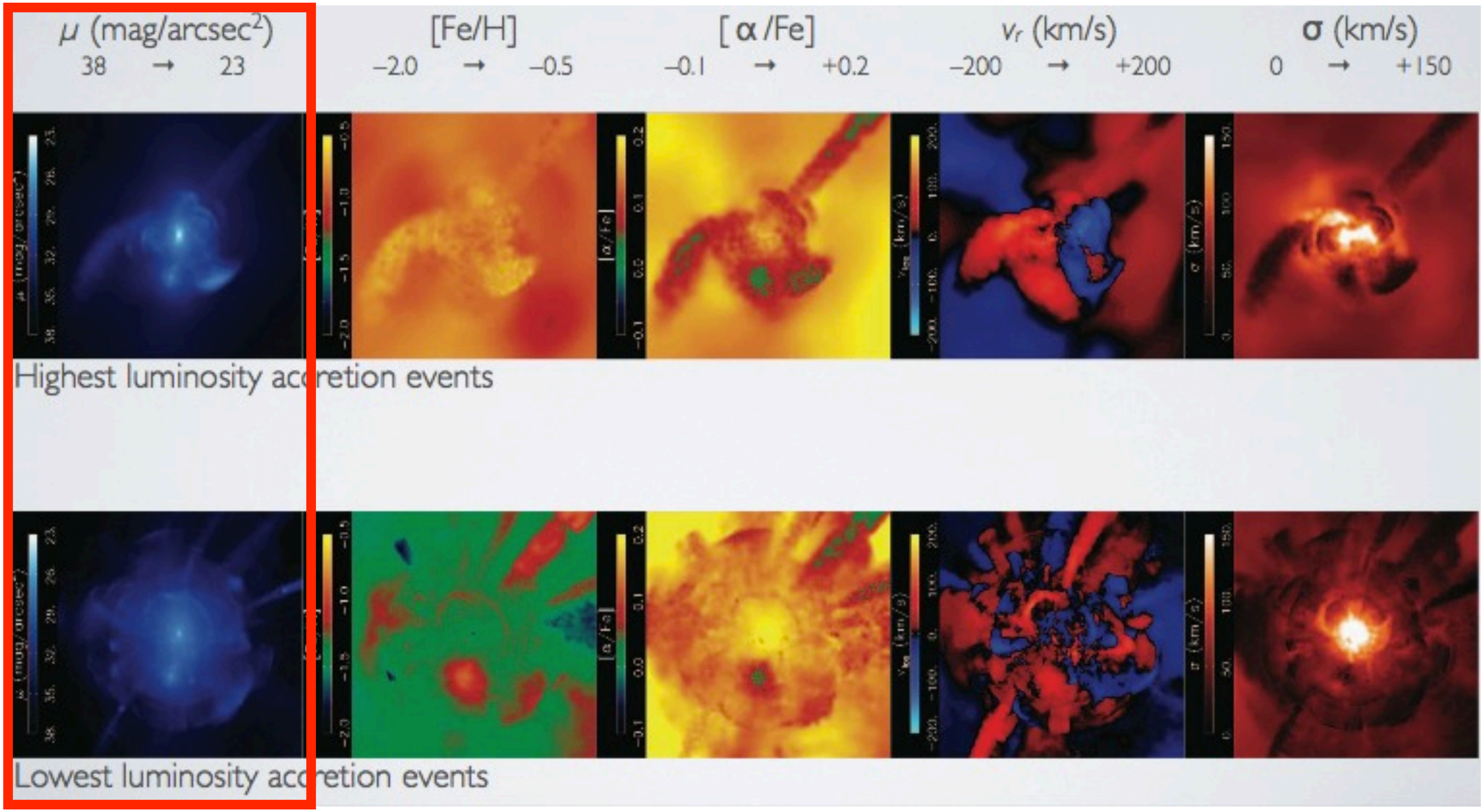
Detection	α (J2000)	δ (J2000)	X_0 (deg)	Y_0 (deg)	S	S_{th}	Remark
Detection 1	00:19:45	+35:05:36	-4.7	-6.1	> 8.5	3.5	And XIX
Detection 2	00:35:49	+36:28:20	-1.4	-4.8	> 8.5	3.7	And III
Detection 3	01:10:07	+47:38:55	4.6	6.6	> 8.5	3.2	And V
Detection 4	01:17:00	+33:23:19	7.2	-7.6	> 8.5	4.0	And II
Detection 5	01:07:27	+32:19:31	5.3	-8.9	> 8.5	4.0	GC system of background galaxies (NGC 382, 383, 384, 385, 386)
Detection 6	23:54:43	+42:30:28	-8.9	1.9	> 8.5	3.2	And XXI
Detection 7	00:30:03	+46:55:09	-2.2	5.7	> 8.5	3.0	And XXV
Detection 8	01:29:13	+38:44:08	9.1	-2.0	> 8.5	3.2	And XXIII
Detection 9	00:36:21	+49:36:40	-1.0	8.4	> 8.5	3.2	Cas II/And XXX
Detection 10	00:51:55	+29:38:53	2.0	-11.8	> 8.5	4.0	And XIV
Detection 11	00:45:28	+38:10:28	0.5	-3.1	> 8.5	4.6	And I
Detection 12	00:59:38	+32:21:55	3.6	-8.9	> 8.5	3.2	And XVI
Detection 13	00:37:53	+45:22:06	-0.9	4.1	> 8.5	3.7	And XXVII
Detection 14	00:36:59	+44:17:12	-1.0	3.0	> 8.5	4.6	And XVII
Detection 15	01:06:42	+44:47:42	4.3	3.7	> 8.5	4.3	And X
Detection 16	01:14:32	+38:12:23	6.3	-2.8	> 8.5	3.0	And XV
Detection 17	00:02:22	+45:06:37	-7.2	4.3	> 8.5	3.2	And XVIII
Detection 18	00:53:07	+43:08:06	1.9	1.9	> 8.5	4.5	And IX
Detection 19	01:18:30	+46:23:26	6.2	5.5	> 8.5	3.2	And XXIV
Detection 20	00:57:44	+30:21:07	3.3	-11.0	> 8.5	4.0	GC system of background galaxy (NGC 315)
Detection 21	00:46:20	+33:48:16	0.8	-7.5	> 8.5	3.5	And XI
Detection 22	00:50:44	+32:54:31	1.7	-8.4	> 8.5	3.2	M06GC
Detection 23	01:10:57	+33:09:28	6.0	-8.0	> 8.5	3.2	GC system of background galaxy (NGC 410)
Detection 24	01:27:40	+28:05:53	10.2	-12.9	> 8.5	4.5	And XII
Detection 25	00:51:51	+33:00:07	1.9	-8.3	8.5	3.2	And XIII
Detection 26	00:47:54	+40:00:59	1.0	-1.2	7.8	4.2	overlap with M31 inner halo stellar structure
Detection 27	00:07:30	+35:07:52	-7.3	-5.8	7.8	3.2	And XX
Detection 28	01:23:16	+33:27:28	8.6	-7.4	7.7	4.0	GC system of background galaxies (NGC 495 and 499)
Detection 29	00:31:10	+37:54:00	-2.3	-3.3	7.5	3.7	GC Bol 514 [† **ref**]
Detection 30	00:40:32	+43:01:48	-0.4	1.8	7.5	4.2	overlap with M31 inner halo stellar structure includes new EC PAndAS-31, see § 4.2.1
Detection 31	01:08:24	+33:08:07	5.4	-8.0	7.5	3.2	GC system of background galaxies (NGC 392, 394, 397)
Detection 32	00:57:23	+39:50:58	2.8	-1.4	7.4	4.6	overlap with minor axis stream D (Ibata et al. 2007)
Detection 33	00:32:09	+38:54:41	-2.1	-2.3	7.1	4.6	overlap with M31 inner halo stellar structure
Detection 34	01:12:11	+32:07:28	6.3	-9.0	6.9	4.0	GC system of background galaxy (NGC 420)
Detection 35	00:47:27	+34:22:34	1.0	-6.9	6.9	3.0	And XII

Detection 104	00:15:04	+37:52:55	-5.5	-3.2	3.6	3.0	overlap with SW cloud
Detection 105	00:21:05	+35:35:11	-4.4	-5.6	3.6	3.5	overlap with SW cloud
Detection 106	00:18:17	+37:33:42	-4.9	-3.6	3.6	3.0	
Detection 107	00:07:18	+38:25:23	-7.0	-2.5	3.5	3.5	
Detection 108	00:15:33	+36:34:51	-5.5	-4.5	3.5	3.5	overlap with SW cloud
Detection 109	00:31:59	+49:13:25	-1.8	8.0	3.5	3.2	overlap with NGC 147 stream
Detection 110	00:45:20	+33:36:34	0.5	-7.7	3.5	3.5	see Figure 10 (bottom panels)
Detection 111	23:57:34	+40:02:45	-8.7	-0.7	3.5	3.2	
Detection 112	00:52:11	+47:32:55	1.6	6.3	3.5	3.0	star forming regions in background NGC 278
Detection 113	00:17:13	+37:50:46	-5.1	-3.3	3.4	3.0	
Detection 114	00:49:33	+32:28:53	1.5	-8.8	3.4	3.2	
Detection 115	00:10:56	+34:33:30	-6.6	-6.5	3.3	3.2	
Detection 116	00:36:12	+47:48:29	-1.1	6.6	3.3	3.0	overlap with NGC 147 stream
Detection 117	01:28:33	+41:20:35	8.6	0.6	3.3	3.2	
Detection 118	01:28:30	+43:04:24	8.4	2.4	3.3	3.2	
Detection 119	01:00:48	+36:02:39	3.7	-5.2	3.3	3.0	overlap with stream B
Detection 120	00:49:31	+34:34:02	1.4	-6.7	3.3	3.0	
Detection 121	00:21:05	+36:56:28	-4.3	-4.2	3.3	3.0	overlap with SW cloud
Detection 122	00:19:23	+36:27:28	-4.7	-4.7	3.3	3.0	overlap with SW cloud
Detection 123	01:27:22	+41:05:23	8.4	0.4	3.3	3.2	
Detection 124	01:08:11	+37:46:21	5.0	-3.3	3.3	3.0	
Detection 125	00:46:34	+35:03:09	0.8	-6.2	3.3	3.0	
Detection 126	00:59:08	+35:32:51	3.4	-5.7	3.2	3.0	overlap with stream B
Detection 127	00:32:22	+49:26:17	-1.7	8.3	3.2	3.2	overlap with NGC 147 stream
Detection 128	01:07:32	+48:34:51	4.1	7.5	3.2	3.2	at the edge of PAndAS
Detection 129	00:08:50	+40:50:43	-6.4	-0.1	3.2	3.0	bright star
Detection 130	00:12:14	+38:13:41	-6.0	-2.8	3.1	3.0	overlap with SW cloud
Detection 131	00:20:34	+35:57:35	-4.5	-5.2	3.1	3.0	overlap with SW cloud
Detection 132	00:33:57	+35:31:51	-1.8	-5.7	3.1	3.0	
Detection 133	01:15:15	+38:54:29	6.3	-2.1	3.1	3.0	
Detection 134	00:30:14	+34:58:00	-2.6	-6.3	3.1	3.0	
Detection 135	00:15:14	+37:34:10	-5.5	-3.5	3.1	3.0	overlap with SW cloud
Detection 136	01:19:49	+41:30:57	7.0	0.6	3.1	3.0	
Detection 137	00:14:05	+44:46:07	-5.1	3.7	3.1	3.0	
Detection 138	00:15:11	+37:37:06	-5.5	-3.5	3.0	3.0	overlap with SW cloud
Detection 139	00:56:18	+35:09:26	2.8	-6.1	3.0	3.0	
Detection 140	00:14:33	+37:07:43	-5.6	-3.9	3.0	3.0	
Detection 141	01:13:05	+37:41:59	6.0	-3.3	3.0	3.0	
Detection 142	00:13:31	+37:58:29	-5.8	-3.1	3.0	3.0	overlap with SW cloud
Detection 143	00:25:24	+35:34:20	-3.5	-5.6	3.0	3.0	

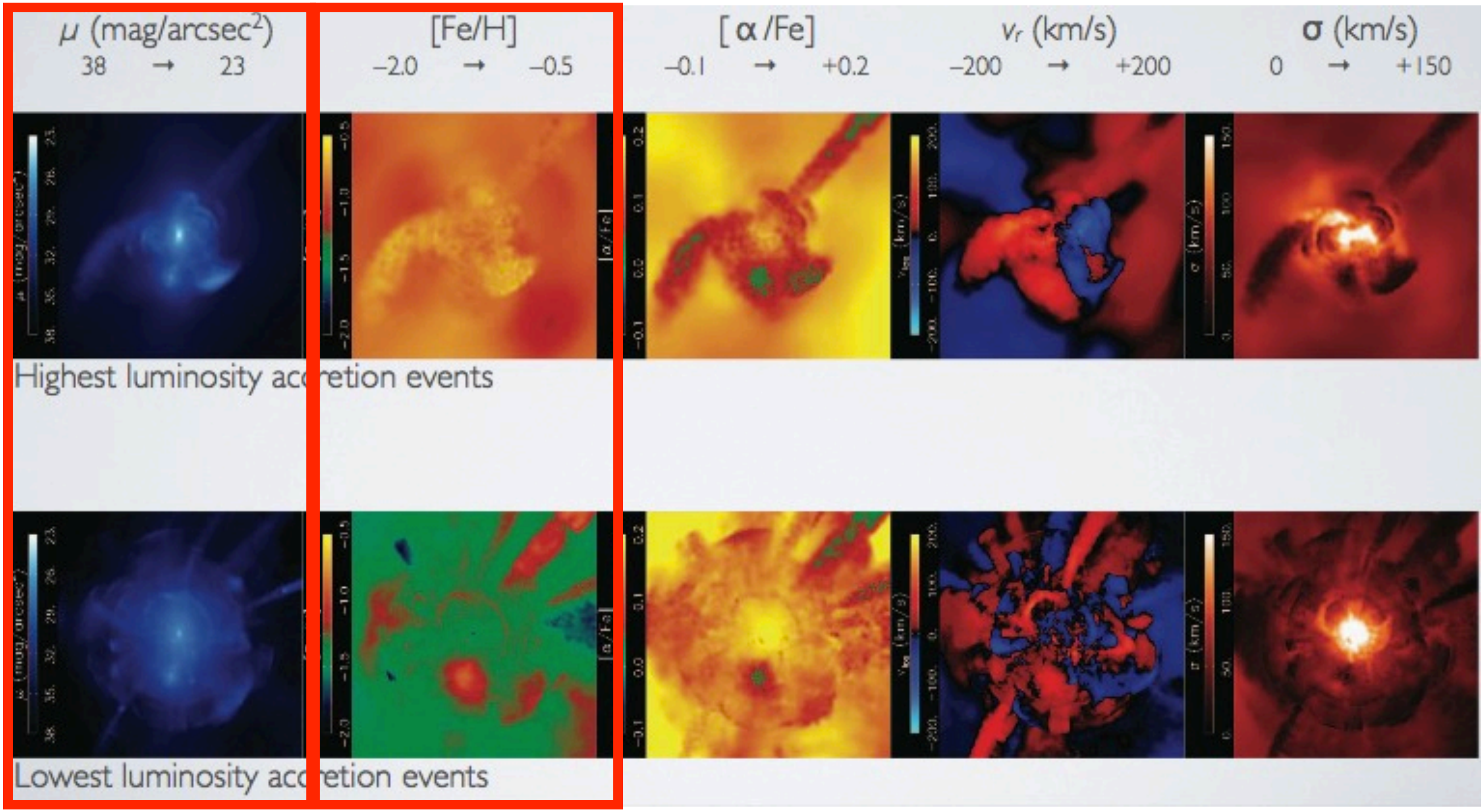
Where do we go from here? [from N. Martin, ngCFHT workshop]

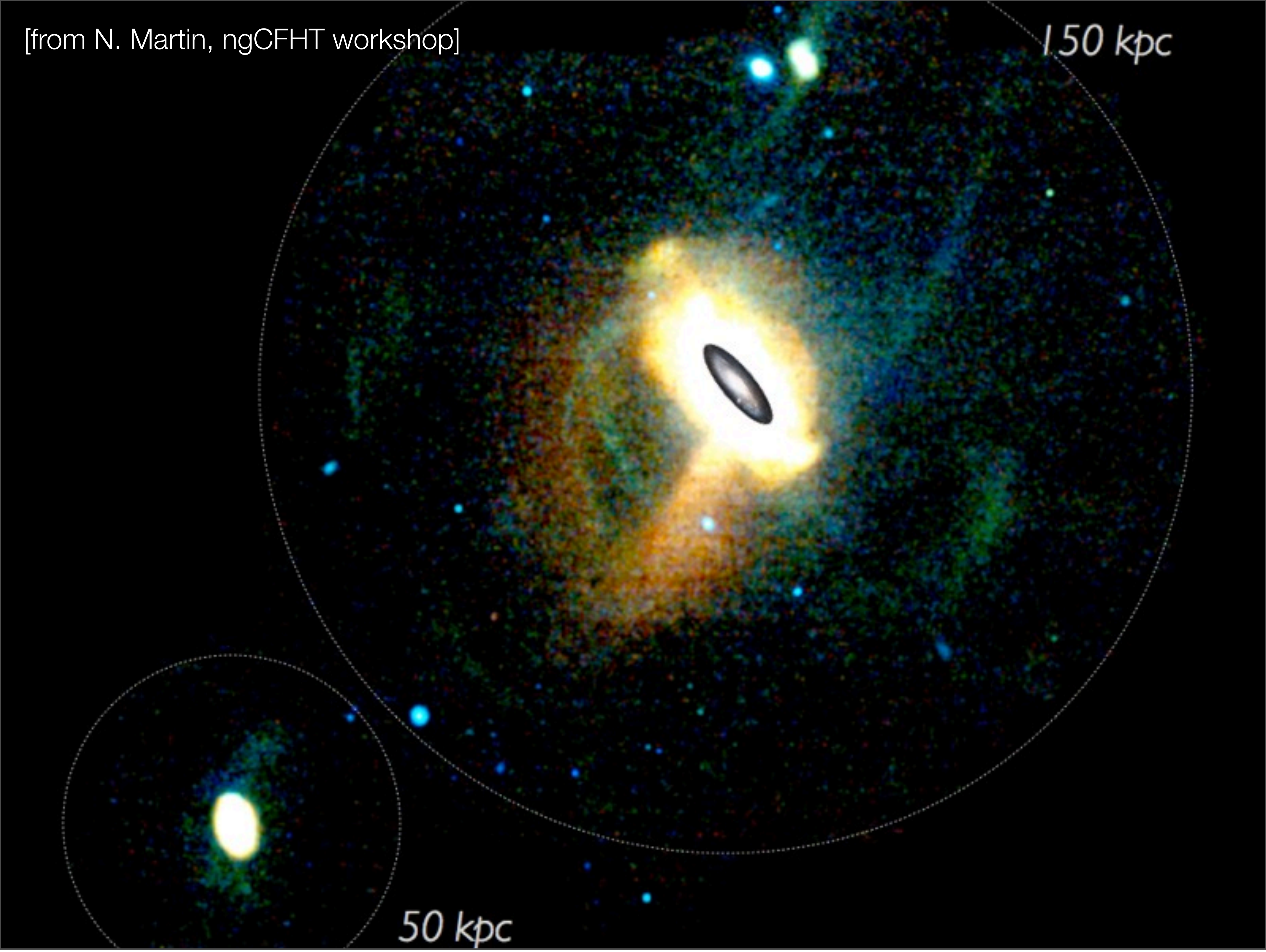


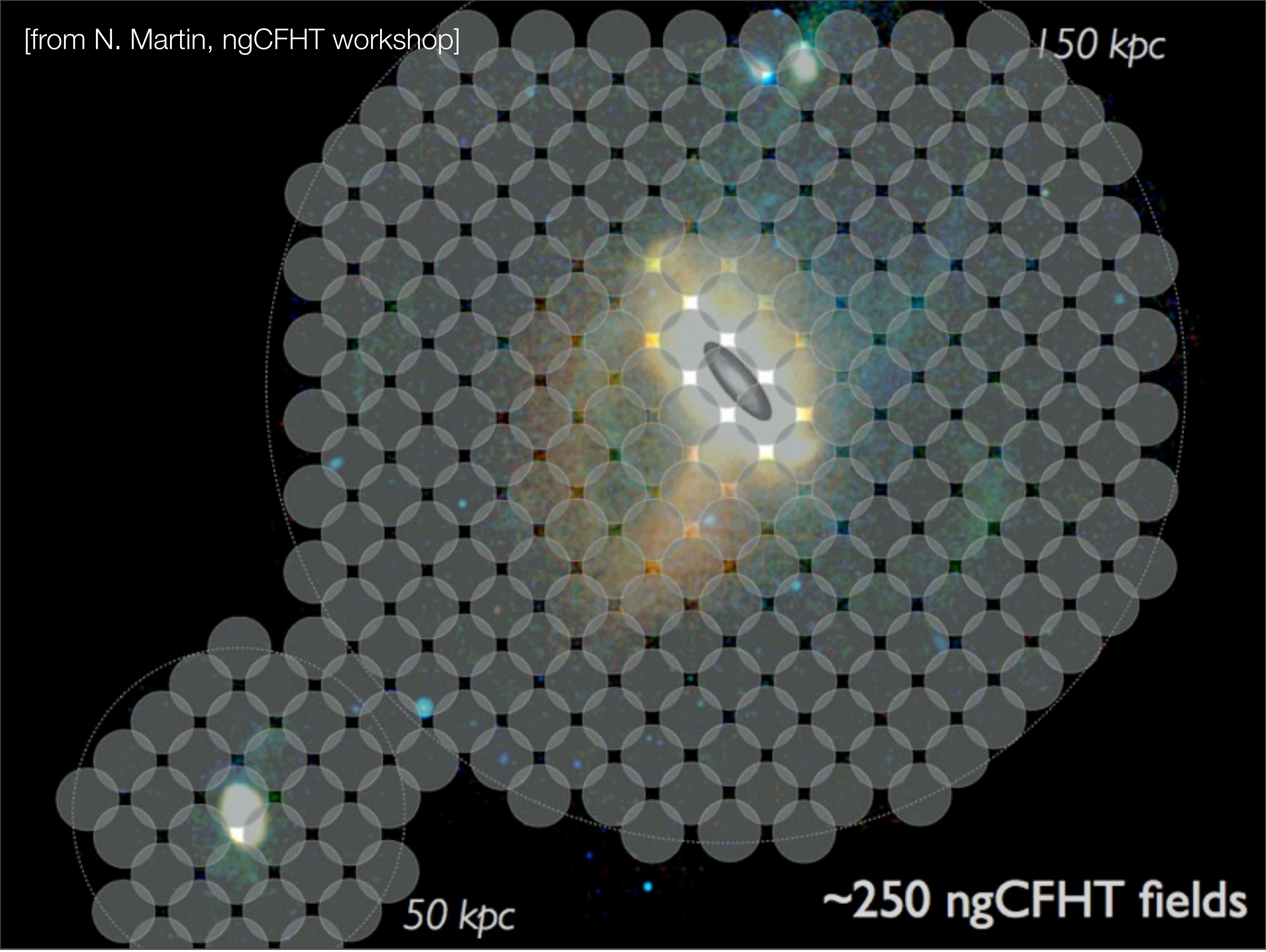
Where do we go from here? [from N. Martin, ngCFHT workshop]



Where do we go from here? [from N. Martin, ngCFHT workshop]




[from N. Martin, ngCFHT workshop]
150 kpc
50 kpc


[from N. Martin, ngCFHT workshop]
150 kpc
50 kpc
~250 ngCFHT fields

ngCFHT Workshop, UHilo, 27 - 29 March 2013

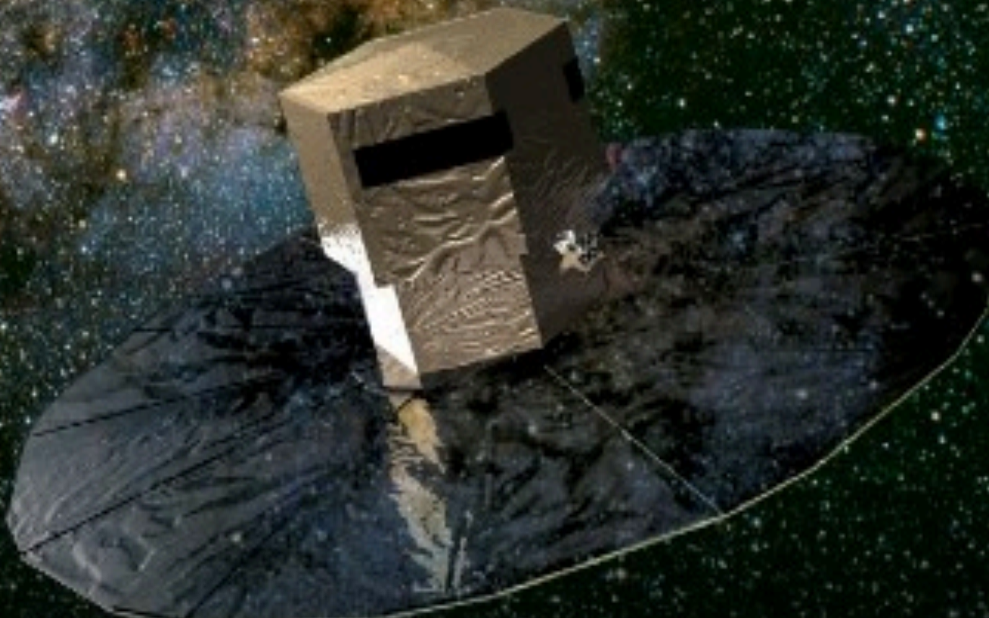
- 96 participants from 11 countries (including CFHT, JAC, Keck, Subaru, Gemini participants)
- Discussion on the scientific and technical development of the ngCFHT project, and on the formation of the expanded partnership required to deliver ngCFHT to the international astronomy community.

http://ngcfht.org/

The ESA Gaia mission and its synergies with ngCFHT

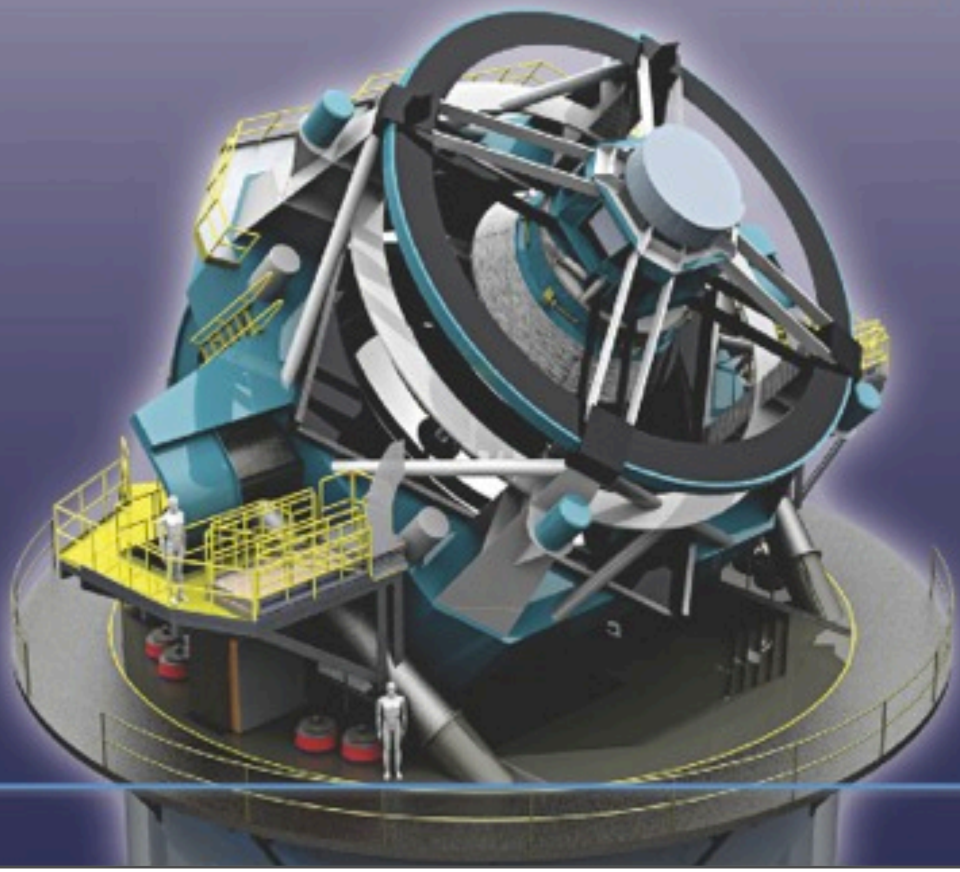
Catherine Turon
Observatoire de Paris
GEPI / UMR CNRS 8111

ngCFHT workshop
27-29 March 2013
Hilo, Hawaii



The Large Synoptic Survey Telescope, spectroscopic followup and the ngCFHT

Michael Strauss
Princeton University



Thursday, June 20, 13

Summary

- PAndAS complete observations at the start of 2011. Final calibration complete. All data publicly available, with high level data products to be made public within the year.

- **Globular clusters:** 100 new systems; outer halo clusters show spatial coincidence with stellar streams (and kinematic clustering).

- **Dwarf galaxies:** ~17 dwarf galaxies discovered around M31 by PAndAS/ precursors. Flat luminosity function and extended radial profile. ML method to search for all dwarfs and dwarf candidates for follow-up; quantify selection effects to derive correction functions for major parameters.

- **Stellar halos:** measured two dimensional shape of “smooth” stellar halo an L* galaxy (see next talk); robust quantification of substructure proceeding, for comparison to predictions from different cosmologies (initially, Cold and Warm Dark Matter).

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 $\alpha = 0.678$ and r_{-2} = 200kpc [from Figure 11 of Springel et al. 2008]).

Richardson et al. 2011