FDS – the FORNAX ultra-Deep imaging Survey

A modern study of dwarf galaxies

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and the FDS-Team

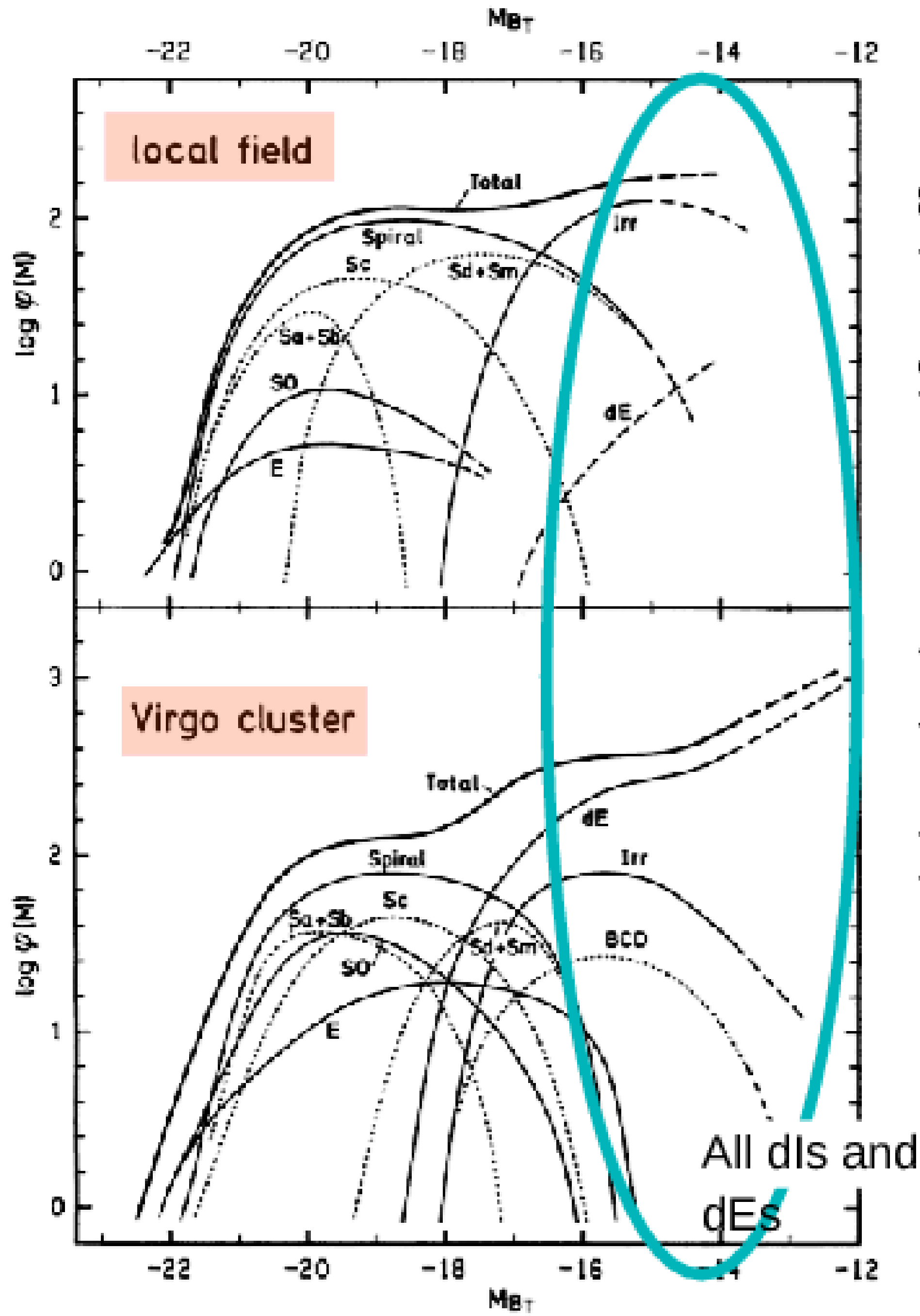
Cluster vs. Field

Luminosity function very Different (known since the 1980's)

- Dwarf galaxies dominate the Universe in numbers.

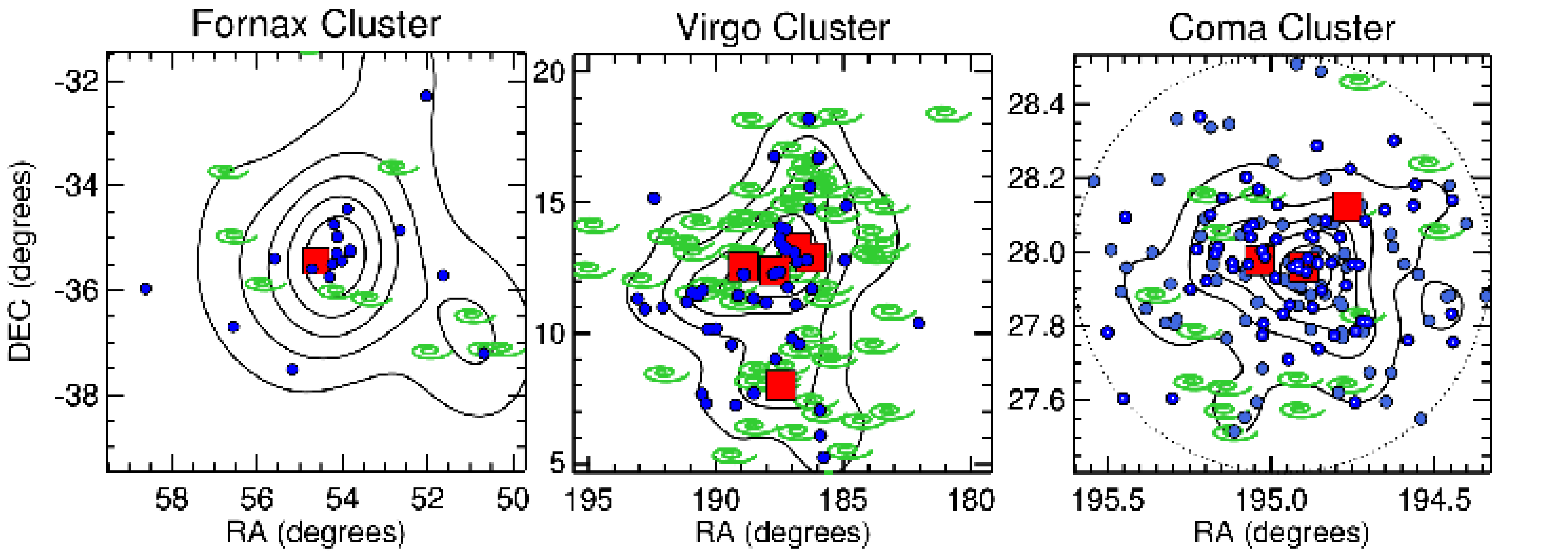
- Clusters are dominated by Quiescent Dwarfs. The field is dominated by Star Forming Dwarfs.

- We know much **less** about dwarfs than about giant galaxies.



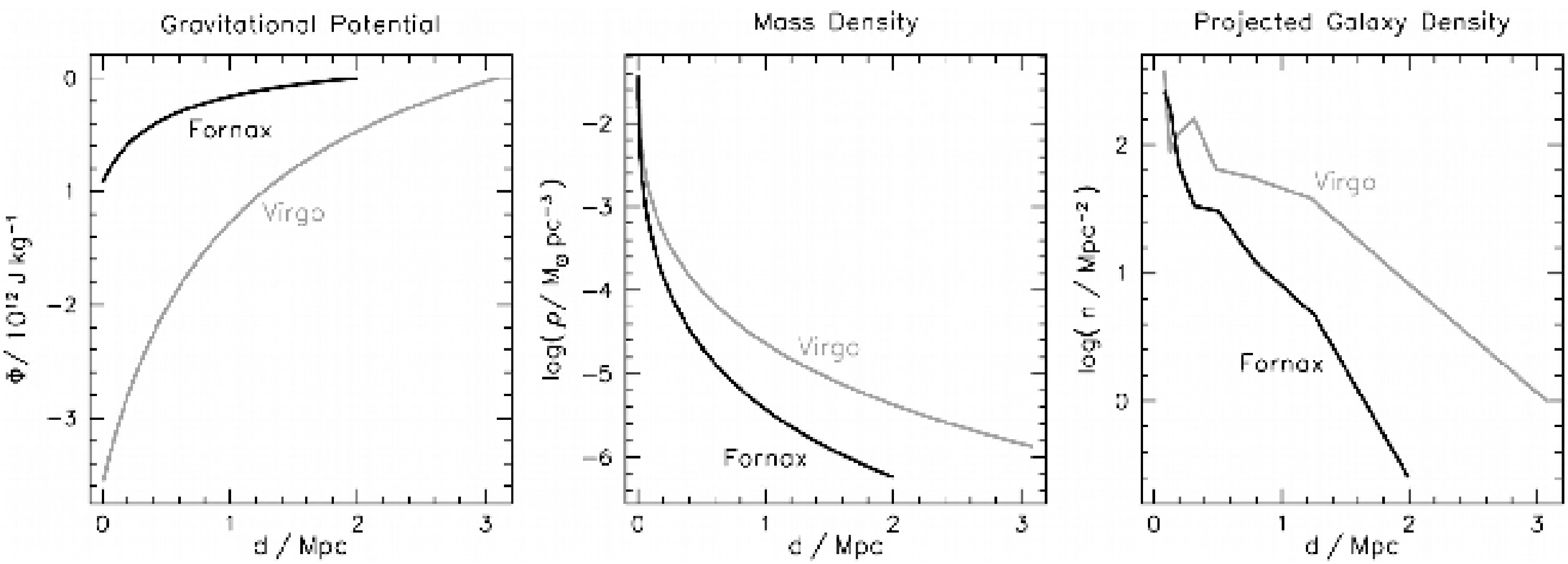
Binggeli, Sandage, Tammann ARAA (1988) ARAA, 26, 509

Spatial distribution of massive galaxies in nearby galaxy clusters



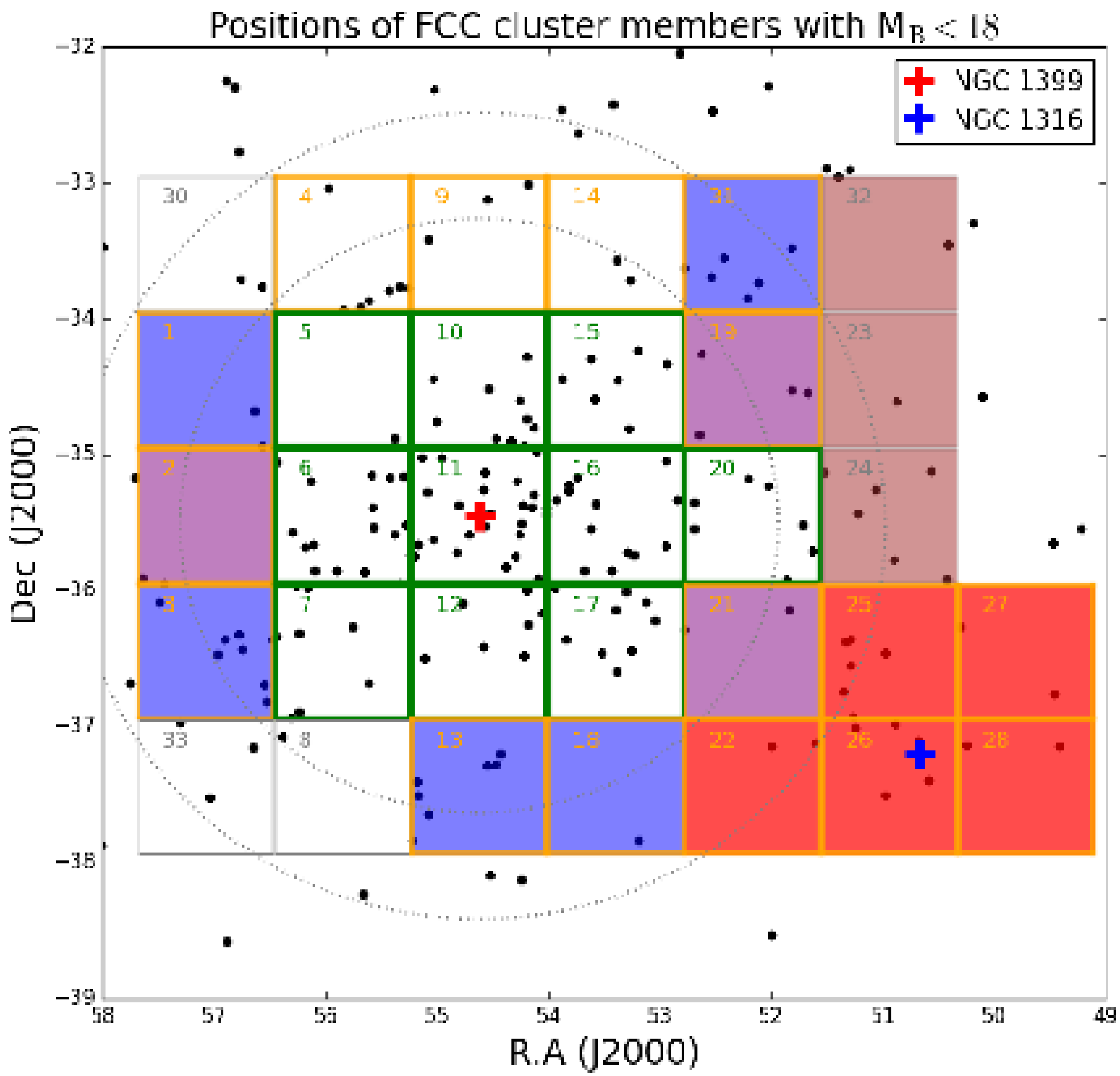
Cappellari 2016

A comparison between Virgo and Fornax



From Lisker, based on Drinkwater et al. 2001, Jordan et al., 2007, and Weinmann et al. 2011

The FDS Fornax Ultradeep Survey ESO/VST



INTEGRATION TIMES

u' – 11000s
g' – 8000s
r' – 8000s
i' – 5000s

DEPTH (SB, 1σ)

u' – 28.0
g' – 28.6
r' – 28.1
i' - 27.2

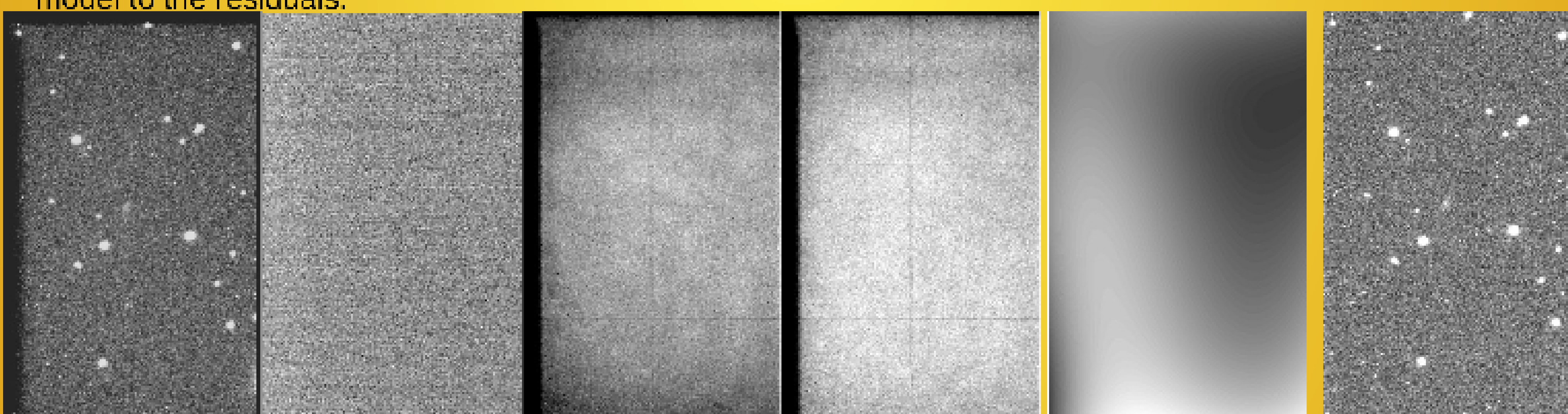
FDS: Observed in September, 2017; Finished Nov 2017

Data

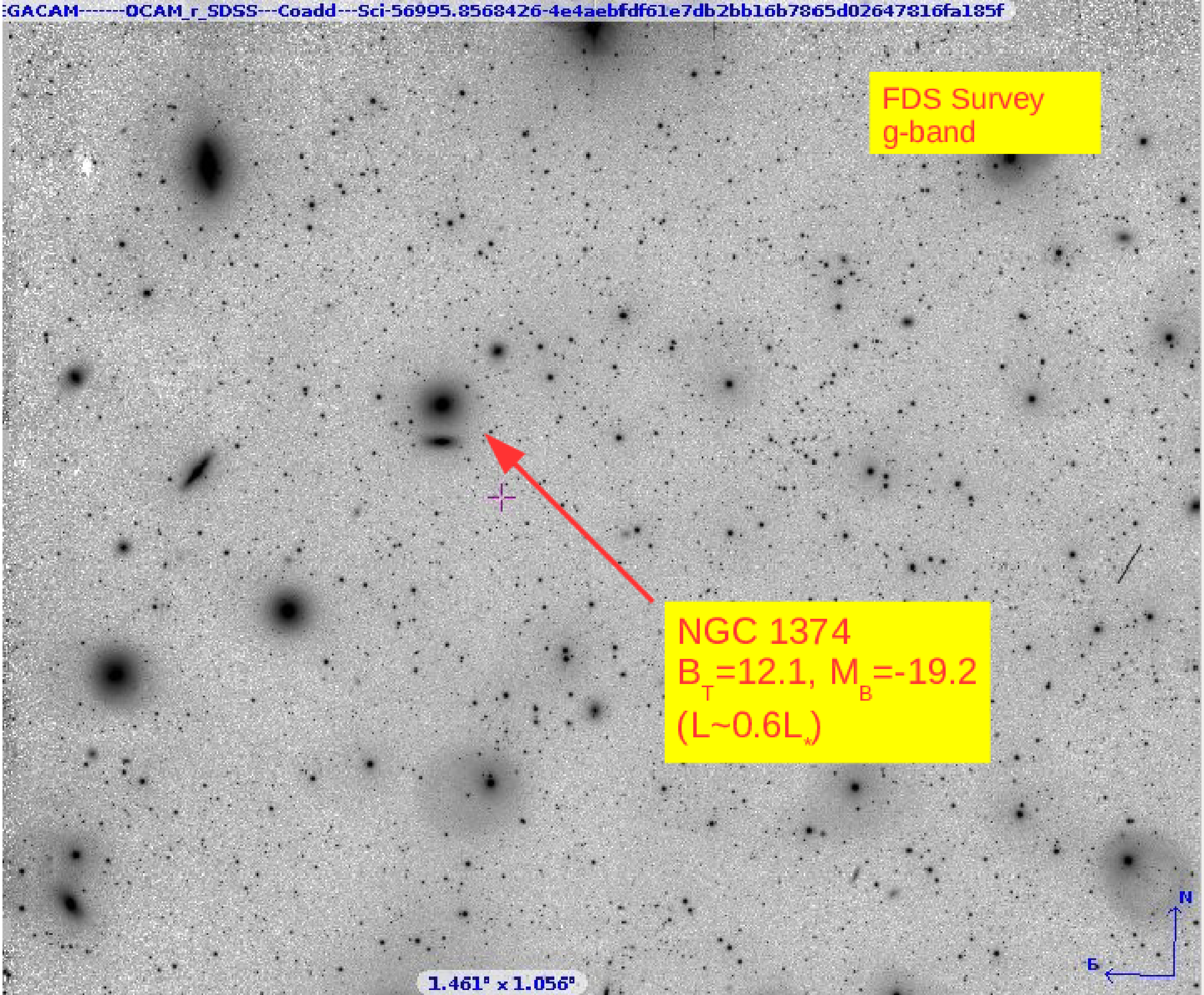
Two different reductions available: VST-tube (Naples) & AstroWISE (Groningen) both have consistent quality.

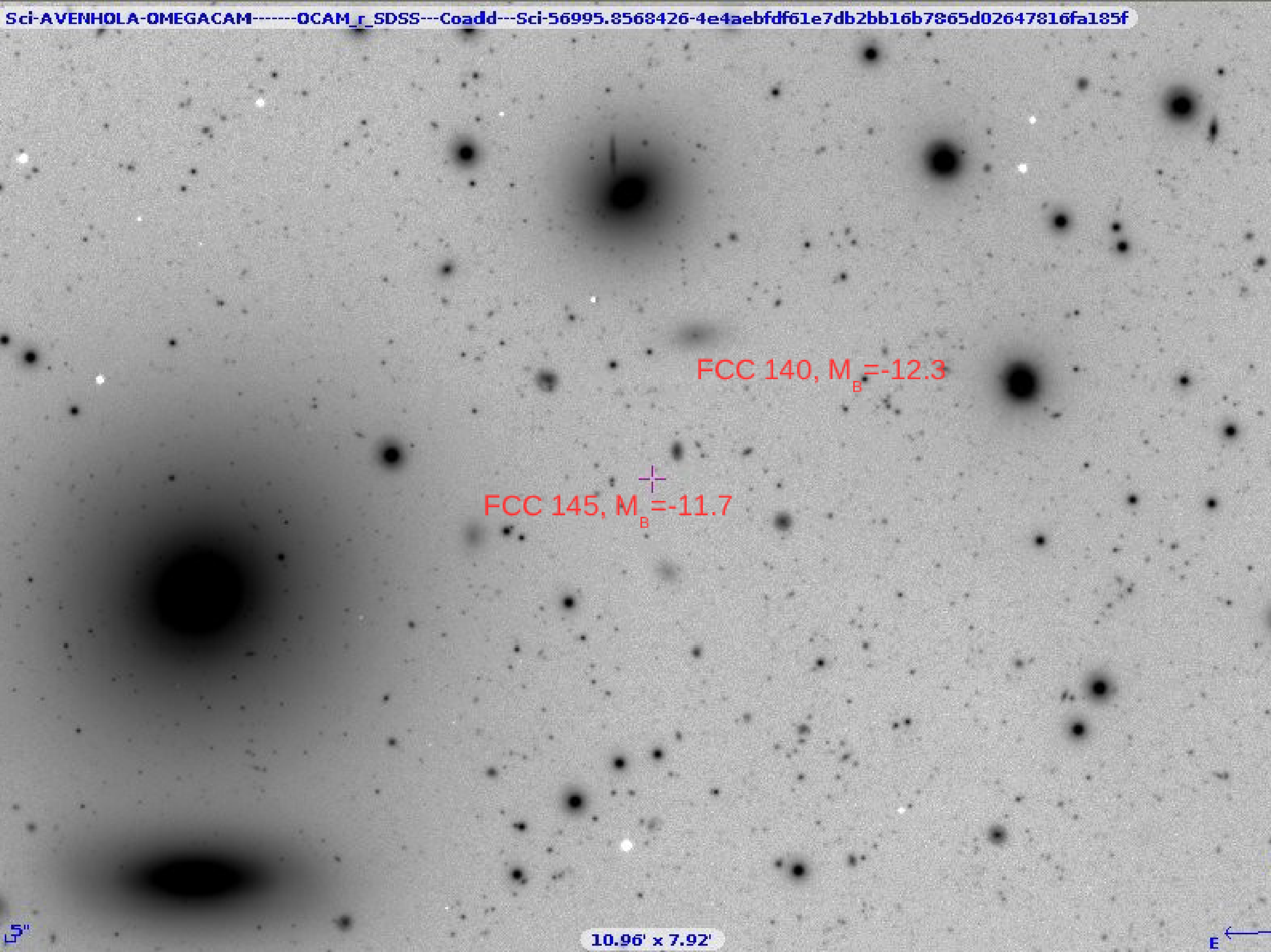
AstroWISE Reduction

- Overscan correction row-wise
- Bias subtraction – subtract median stacked master-bias
- Flatfield correction – Divide by master-flat (combined 8 dome+ 8 twilight)
- Background subtraction – Subtract background model that is stacked from 12 dithered consecutive observations
- Illumination correction – (Correction for imperfect flatfielding) Multiply exposures with a illumination correction model. The models are made by mapping the photometric residuals across the CCD array using a set of dithered Landolt Selected Area (SA) field (Landolt 1992) observations, and fitting a linear model to the residuals.



Raw - Bias / flatfield - Background *Ilumination cor. = Science


EGACAM-------OCAM_r_SDSS---Coadd---Sci-56995.8568426-4e4aebfdf61e7db2bb16b7865d02647816fa185f
FDS Survey
g-band
NGC 1374
B_T=12.1, M_B=-19.2
(L~0.6L*)
1.461° x 1.056°
N
E



Sci-AVENHOLA-OMEGACAM-------OCAM_r_SDSS---Coadd---Sci-56995.8568426-4e4aebfdf61e7db2bb16b7865d02647816fa185f
FCC 140, M_B=-12.3
FCC 145, M_B=-11.7
5"
10.96' x 7.92'
E

The Fornax Deep Survey

Collaboration based on VST OmegaCAM
GTO time of

INAF-OAC
Naples

and

NOVA/
Kapteyn

university of
groningen
faculty of science
and engineering
kapteyn astronomical
institute

PI's: **Peletier** (Kapteyn) and Iodice (INAF-OAC)

FDS Core Members

Massimo Capaccioli
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Aniello Grado
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Michael Hilker
Thorsten Lisker
Steffen Mieske
Nicola Napolitano
Maurizio Paolillo
Marilena Spavone
Edwin Valentijn
Glenn van de Ven
Aku Venhola
Gijs Verdoes Kleijn
Carolin Wittmann

Science with the FDS

A. Only FDS (until now)

1. Globular Clusters in Fornax (d'Abrusco et al. 2016)

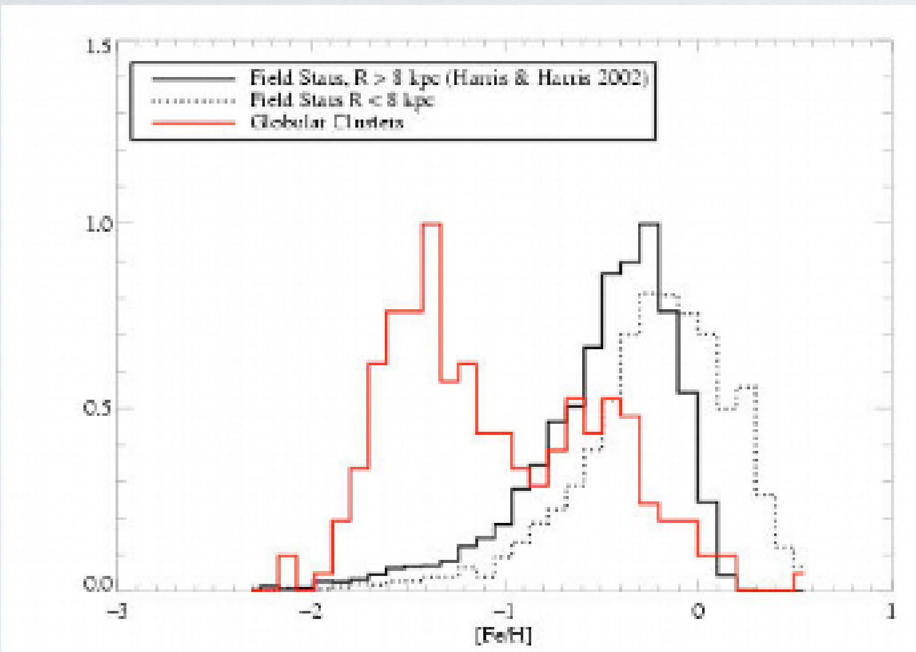
2. Deep photometry of the merger remnant NGC 1316 (Iodice et al. 2017)

3. Ultra Diffuse Galaxies in the core of the Fornax Cluster (Venhola et al. 2017)

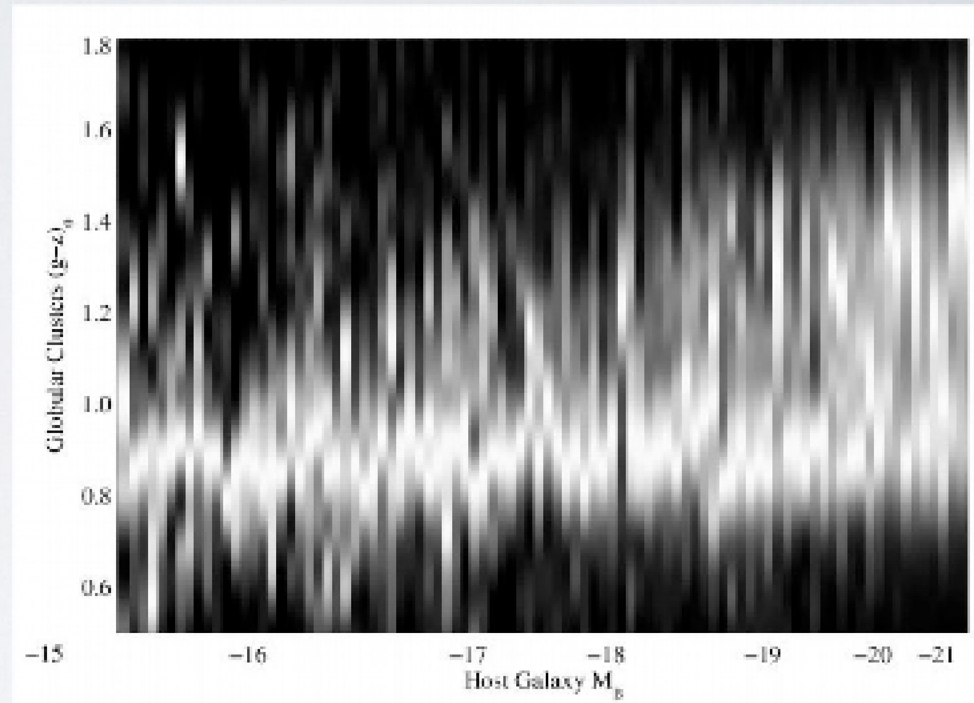
Globular clusters systems

Stars clusters are **not** faithful tracers of galactic star formation histories

Bimodal GC metallicity distributions



Harris & Harris (2004)



Peng et al. (2006)

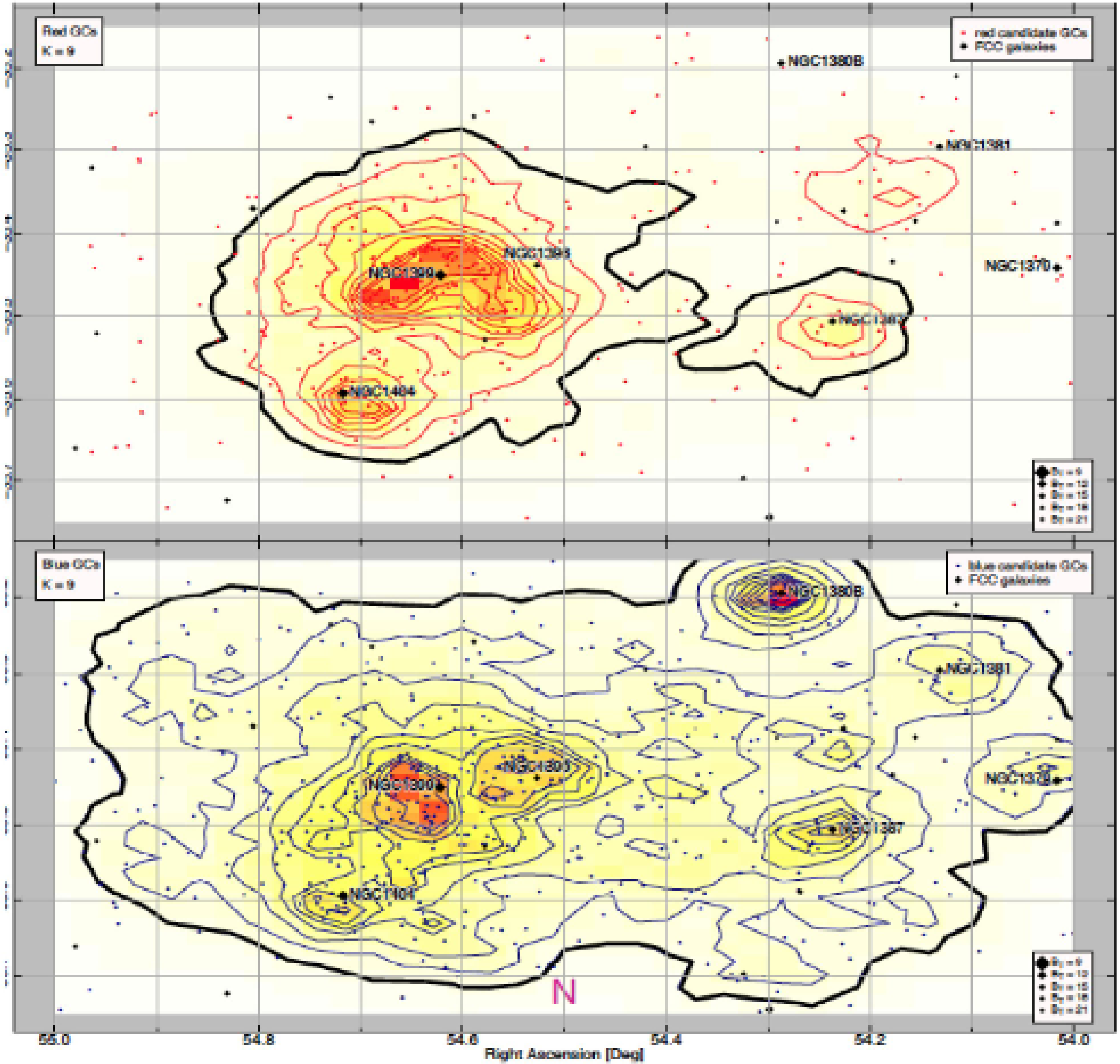
All galaxies with GCs have metal-poor GCs

Metal-rich GCs are mostly in more massive galaxies

In nearly *all* galaxies, number of metal-poor GCs *outnumbers* metal-rich GCs

Massive GC populations in central cluster galaxies are ~2/3 metal-poor

Distribution of red and blue GCs in the core of the Fornax cluster



Based on data from the Fornax Deep Survey (FDS):

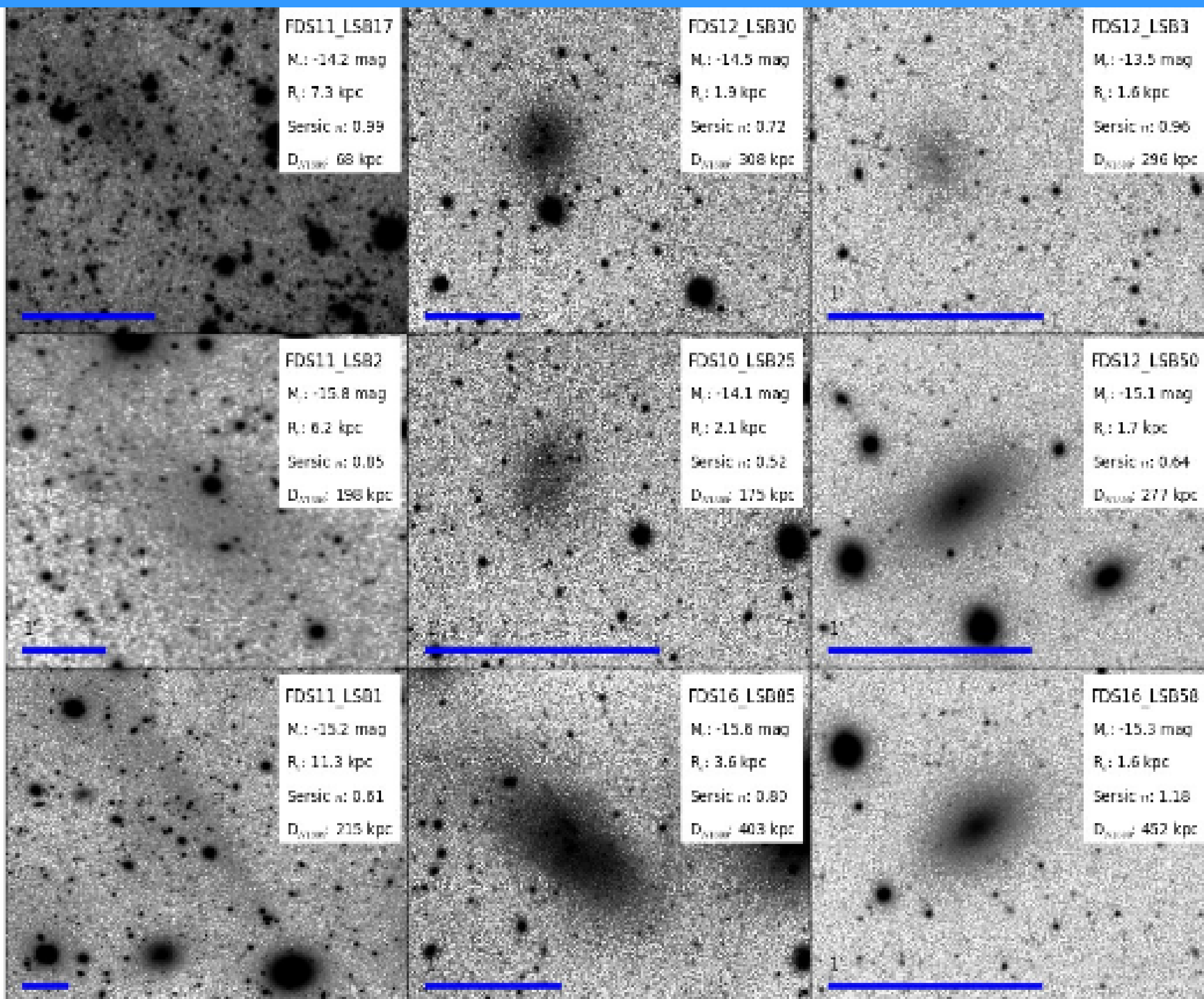
VST/OmegaCAM ugri observations

D'Abrusco et al. (2016)

UDGs

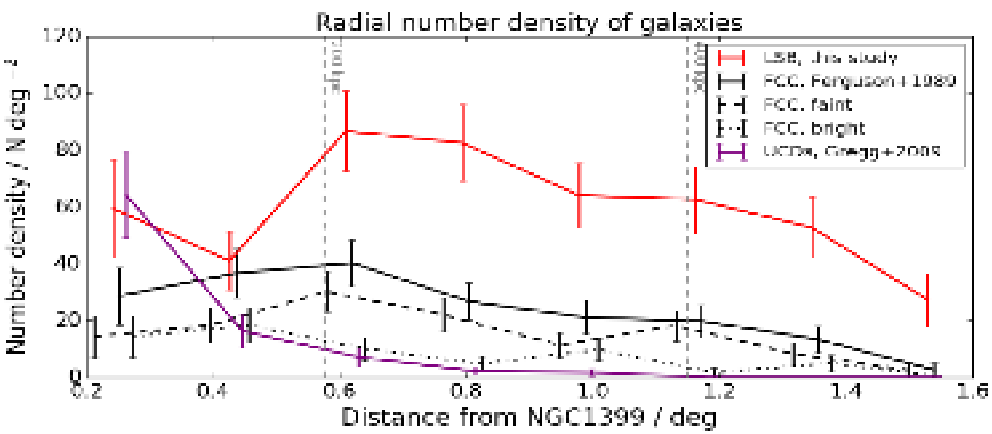
204 LSB galaxies found in inner 4 sq. degrees (Venhola et al. 2017)

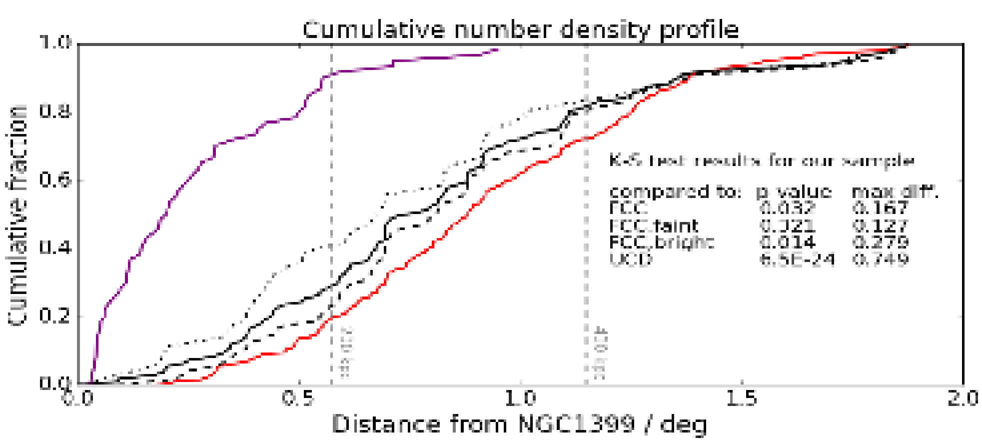
- We Identified 9 galaxies that fulfill the conditions of UDGs
- The 5 smallest UDGs are similar to the smaller LSB dwarfs by all their properties except the effective radius
- The 4 largest UDGs are elongated and one has a tidal tail.
- One UDG has a nucleus

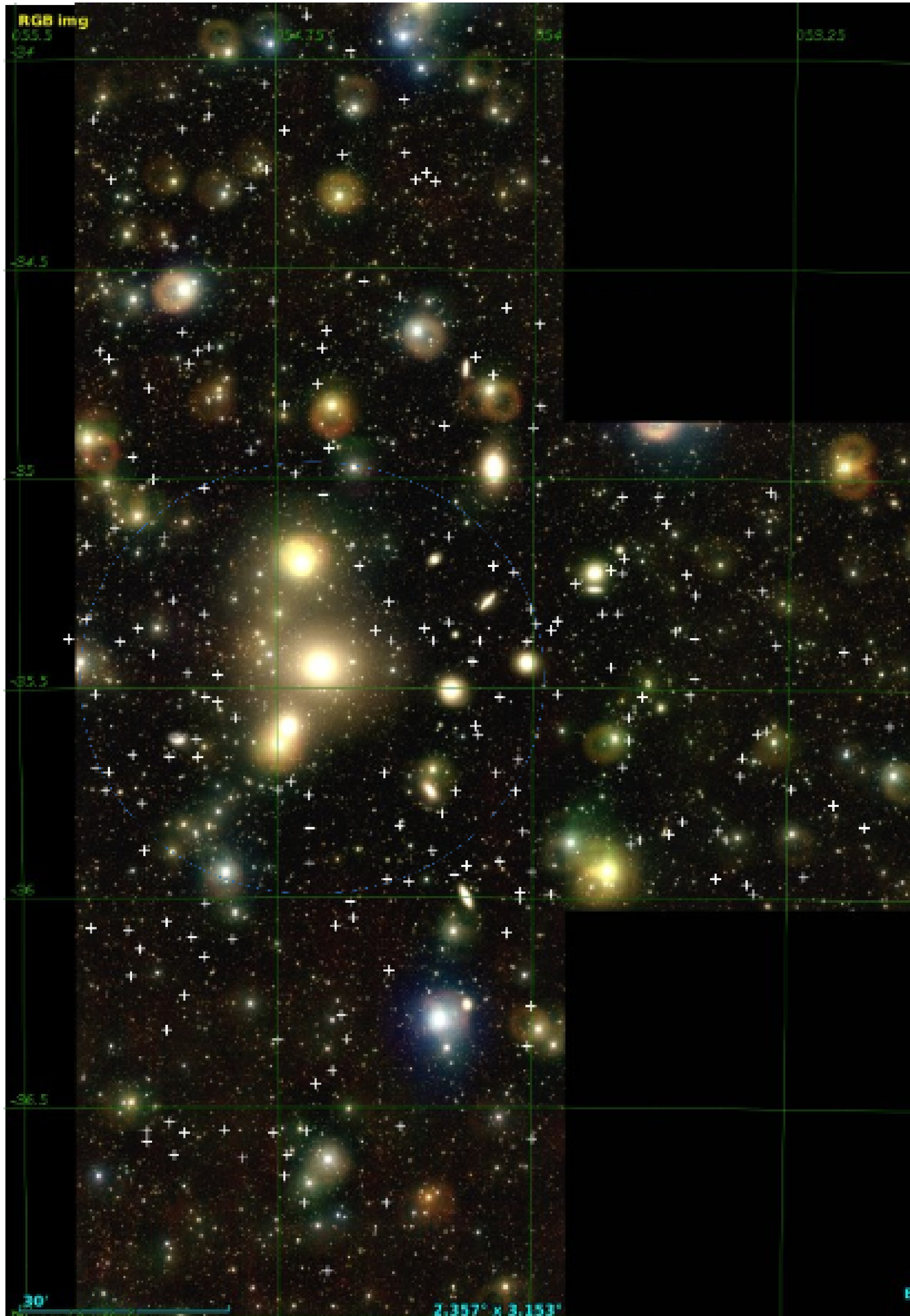


Radial distribution in the cluster

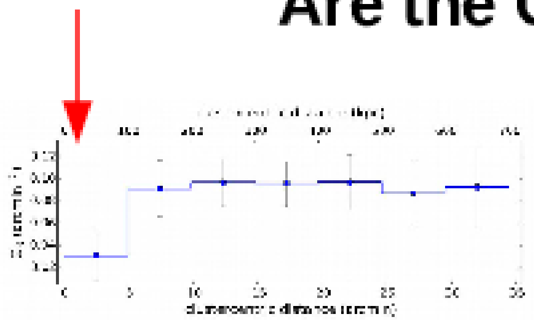
- Number density was measured in cluster centric bins and compared to FCC (Ferguson+, 1989) galaxies.
- The high surface brightness galaxies are deeper in the cluster potential than LSB
- Surface number density drops within the inner 200 kpc from the center, which can be resulting from the tidal disruption of galaxies in the cluster center.



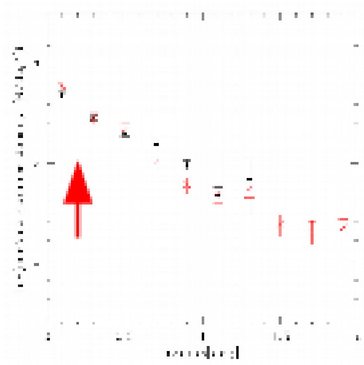




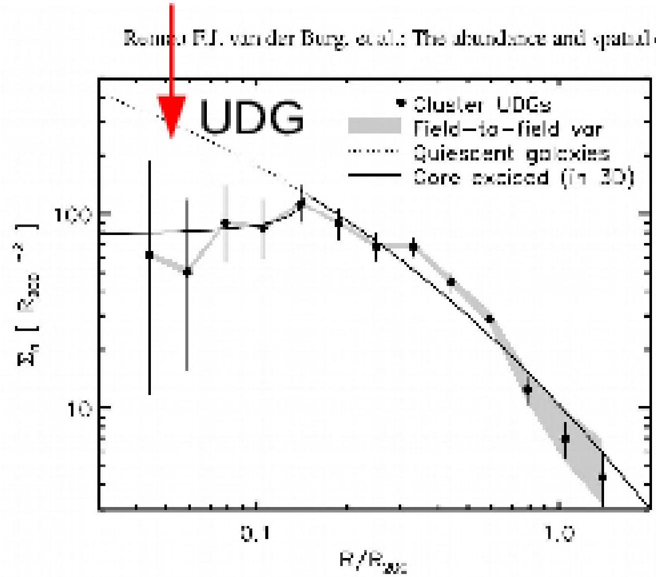
Are the Centers of Clusters really deficient in UDGs?

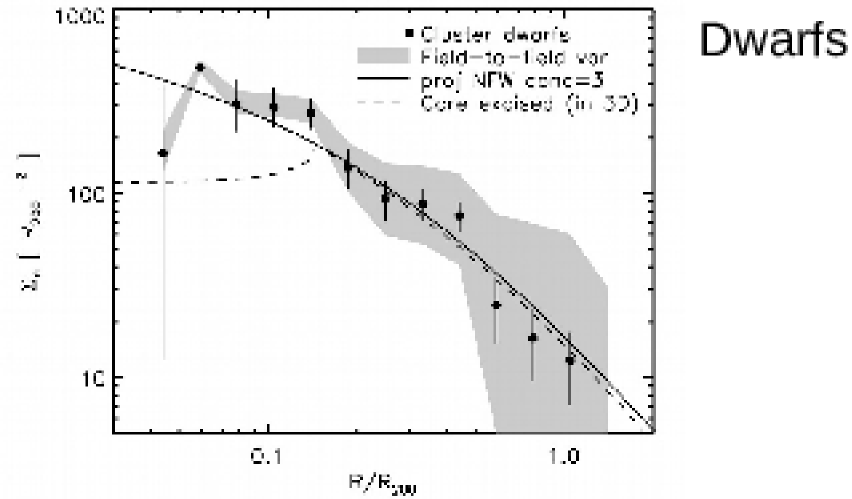


Wittmann et al. (2017)(Perseus)

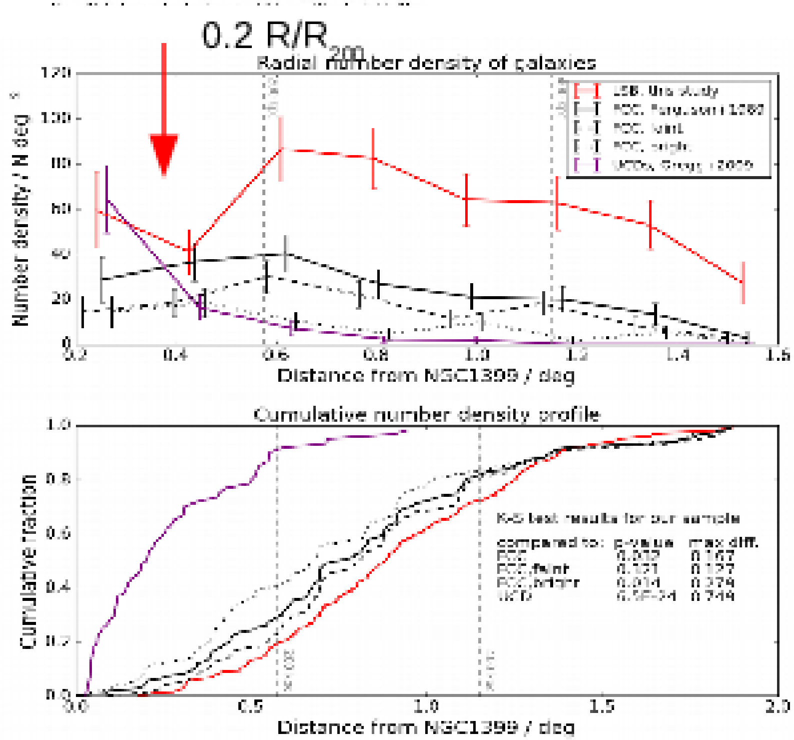


Yagi et al. (2016)(Coma)





Van der Burg et al. (2016) (KIDS)



Most papers seem to be consistent in saying that inside 0.2 R/R_{200} the number of UDGs is lower than expected from the number of dwarf or giant galaxies. Since Fornax is more nearby, the result is clearer here.

Venhola et al. (2017) (FDS)

Colors

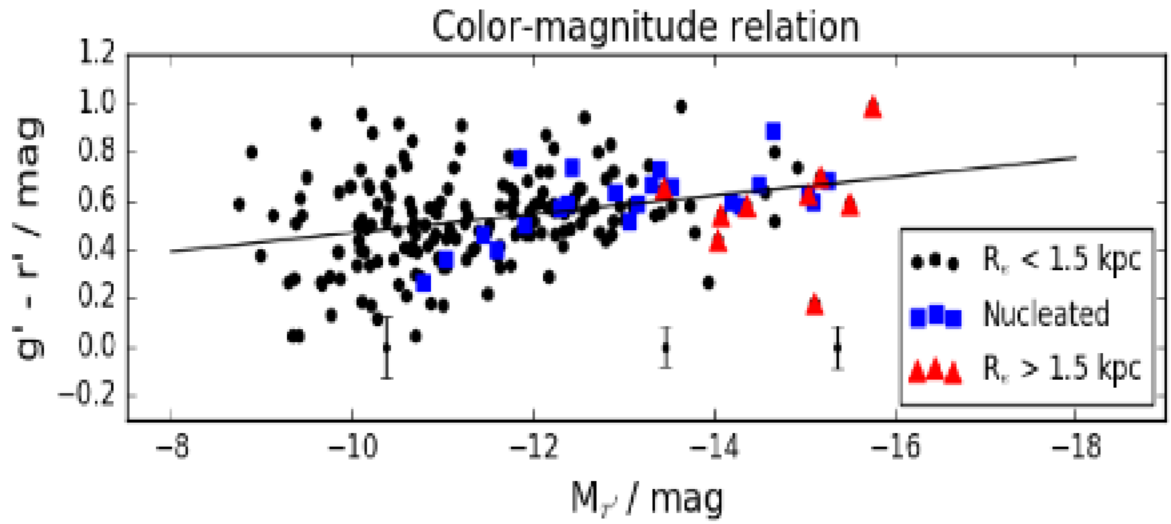
We measured aperture colors within 1 R_e for the galaxies using the profiles from GALFIT fit.

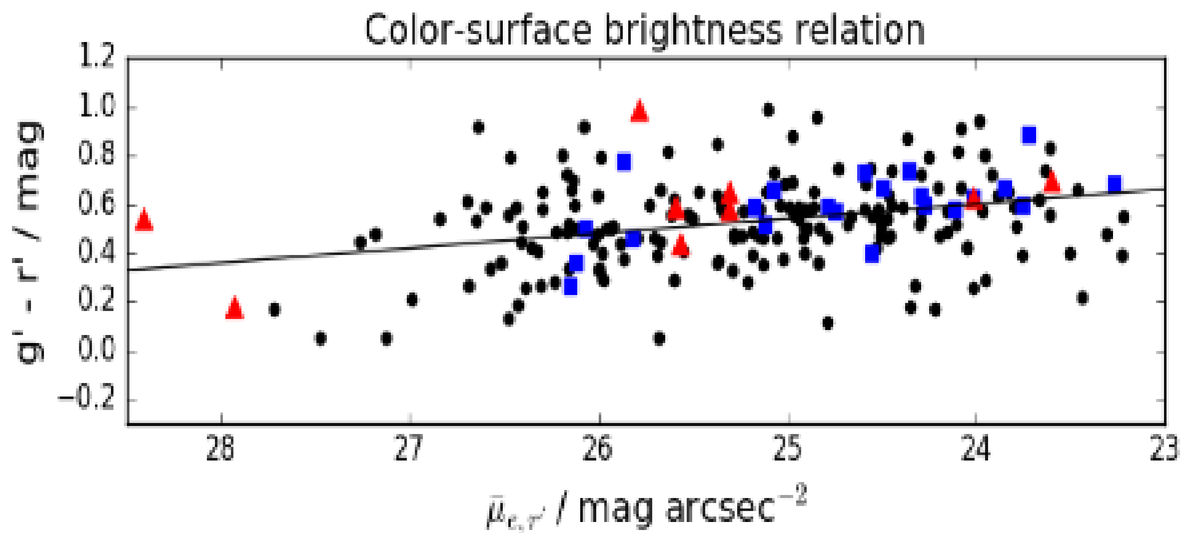
The UDGs seem to follow the same color-magnitude/SFB relation as the other LSB dwarfs (two outliers):

$g - r = -0.04(\pm 0.01) \times (M_r + 12) - 0.48(\pm 0.09)$
(consistent with Virgo dE:s)

$g - r = -0.06(\pm 0.01) \times (<\mu>_{e,r} - 24) + 0.7(\pm 0.3)$.

The median g'-r' color of the UDGs is 0.59, as in Coma where the most complete comparison sample is, the average g'-r' color is 0.68 which is not significantly different.





Conclusions - UDG

- We identify 204 LSB galaxies, of which 9 are classified as UDG

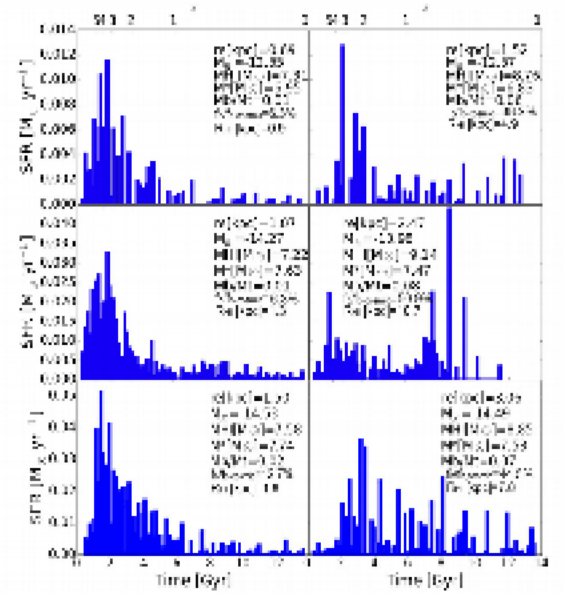
- The relative fraction of LSB galaxies drops within r=0.6 degree (180 kpc), possibly due to tidal disruption of galaxies in the center of the cluster. This is consistent with other clusters.

- UDGs have colors similar to other LSB galaxies, following the red sequence, with considerable scatter.

- When comparing the relative number of UDGs in Coma and Fornax, we find that the relative number in Fornax (0.7 +/- 0.2) is slightly higher than in Coma (0.45 +/- 0.05). This is likely due to different detection methods.

- Our observations are in agreement with high angular momentum (Amorisco & Loeb 2016) and high feedback (di Cintio et al. 2017) models, where they seem an extension of the normal dwarf population. But is there so much gas as needed for the di Cintio models?

- The elongated UDGs indicated that tidal forces must also contribute in forming some UDGs.



From di Cintio et al. 2017

Science with the FDS

B. Science in progress, including followup and complementary projects

4. Complete census of dwarf galaxies in Fornax down to M_r=-10 (Venhola)

5. Deep IFU spectroscopy of a complete sample of Fornax dwarf galaxies using the SAMI spectrograph at R=5000 **(with Nic Scott, Sara Eftekhari, Steffen Mieske)**

6. Neutral Hydrogen (HI) survey using MeerKAT (**P.I. Paolo Serra**)

7. ALMA CO-followup (P.I. Tim Davis)

8. Machine learning applications (SUNDIAL project)

9. Automated detection of faint galaxies (UDG etc.) (SUNDIAL project)

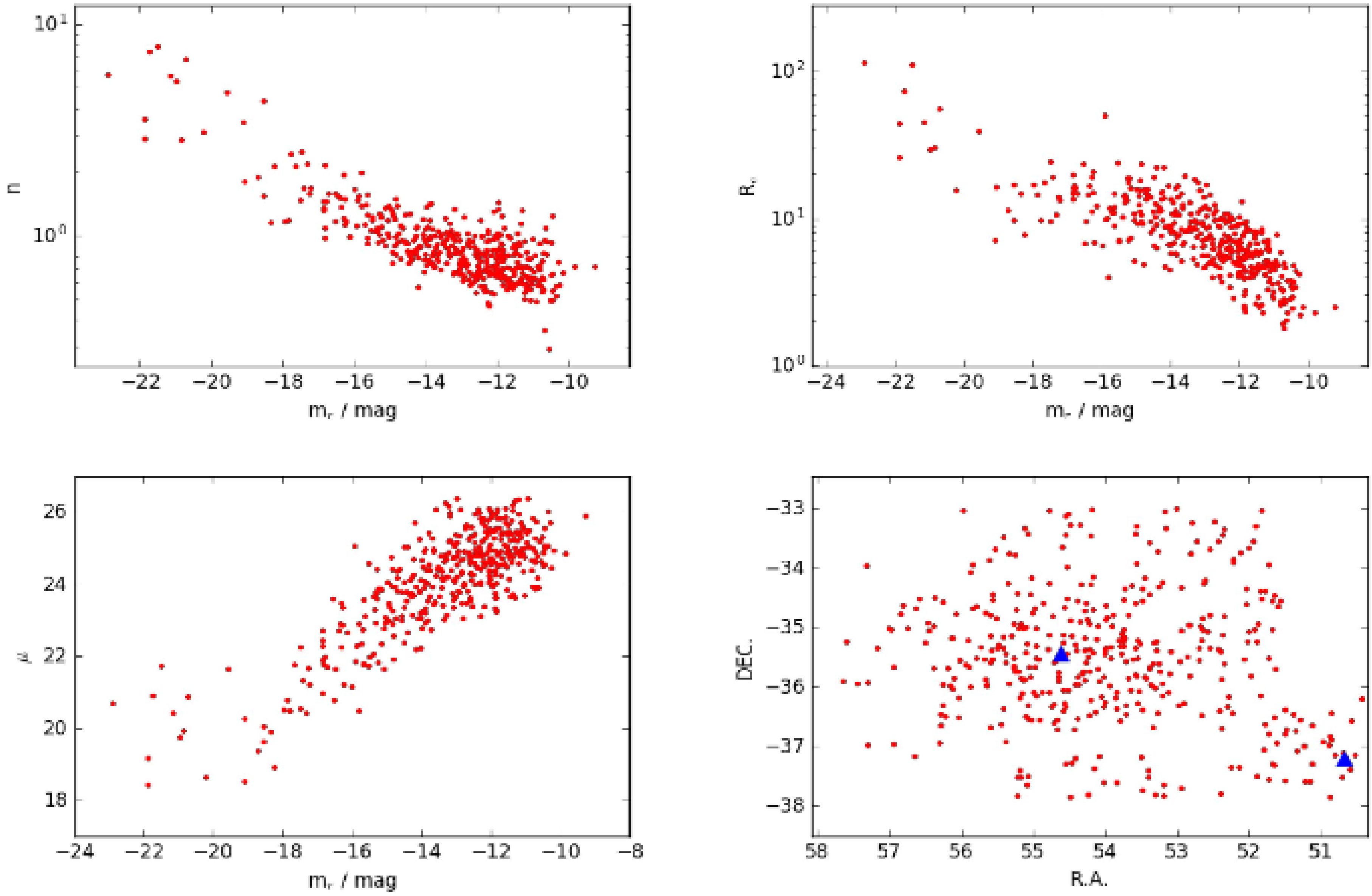
10. Cluster evolution simulations (Lead: Sven de Rijcke)

11. UV Followup of 3 areas in Fornax (with the UVIT telescope)

12. Stellar population studies of a dwarf elliptical with MUSE (Mentz et al. 2016)

13. Several other topics, including near-infrared imaging (VISTA), globular cluster studies, outer regions of massive galaxies, intracluster light, membership determination, UCDs, MUSE, etc.

The Fornax early-type galaxy sample



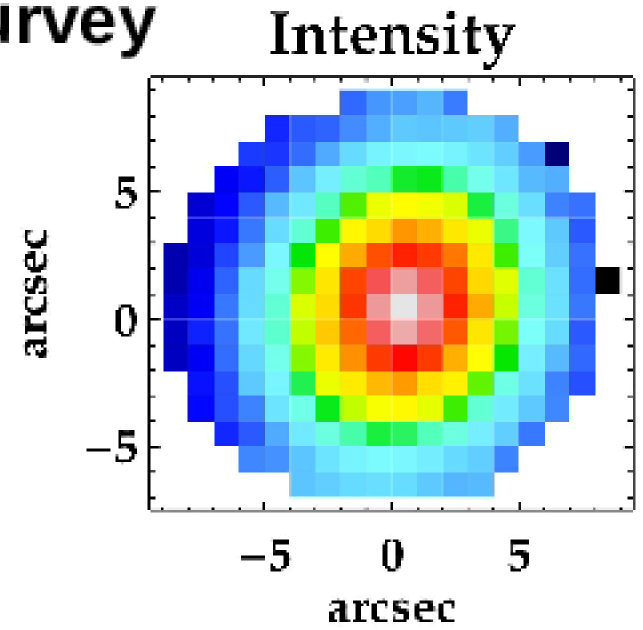
Venhola et al., in preparation

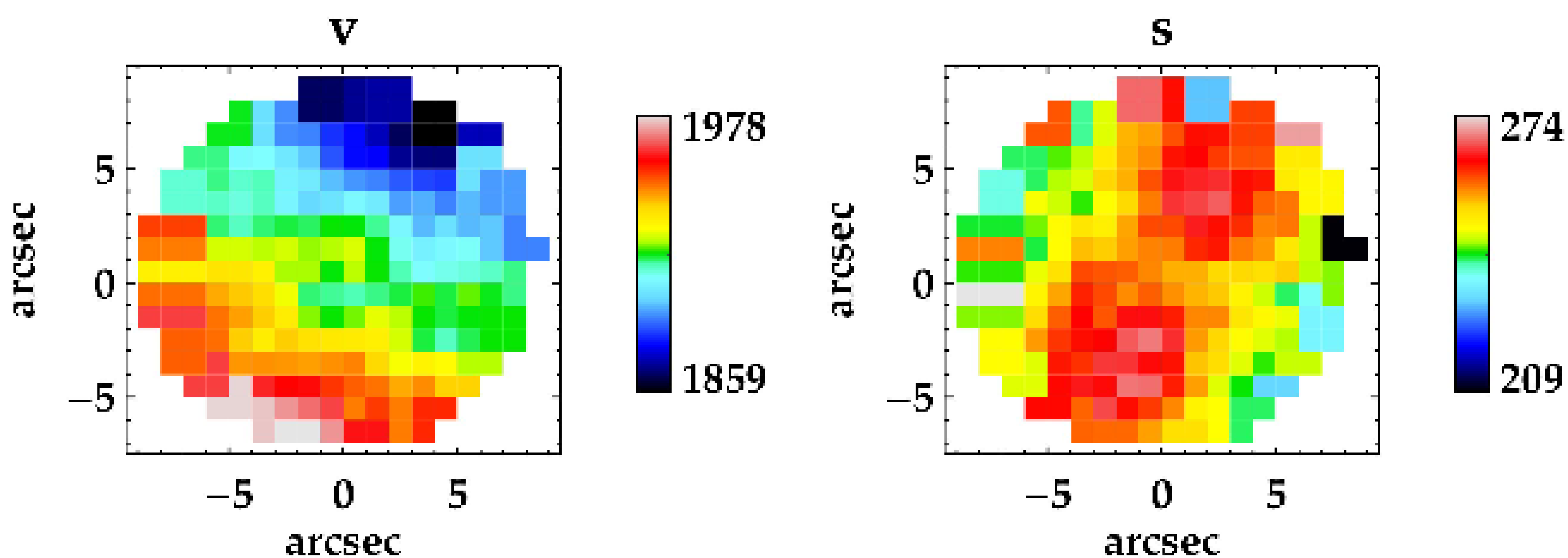
The SAMI Fornax Dwarfs Survey

Scott, Eftekhari, Peletier, Mieske

IFU Observations of 100 dE in Fornax

(Spectral resolution R=5000, so ideal
For dwarf galaxies)





The Sydney-AAO Multi-Object Integral field spectrograph (SAMI)

THE UNIVERSITY OF SYDNEY

Bundles (IFUs): 13

Sky Fibres: 26

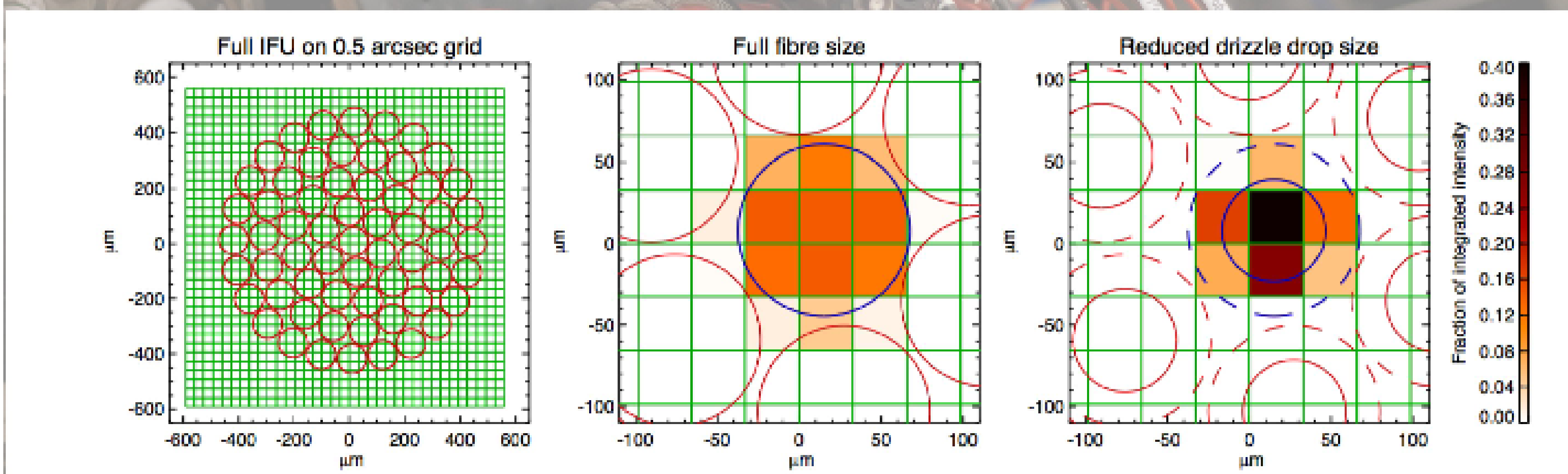
Total Fibres: 819

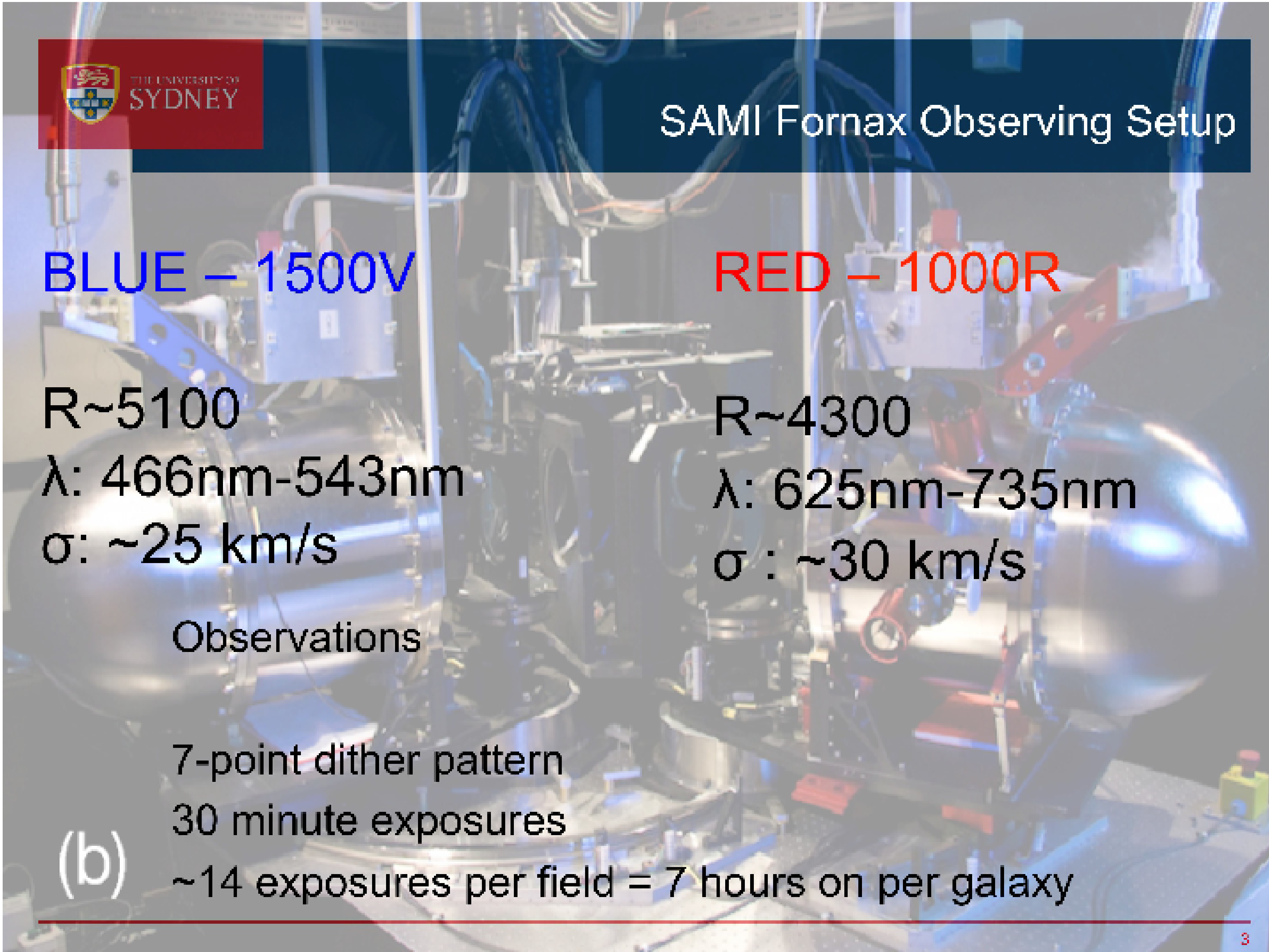
Guide Bundles: 3

Total fov: 1°

Bundle fov: 15''

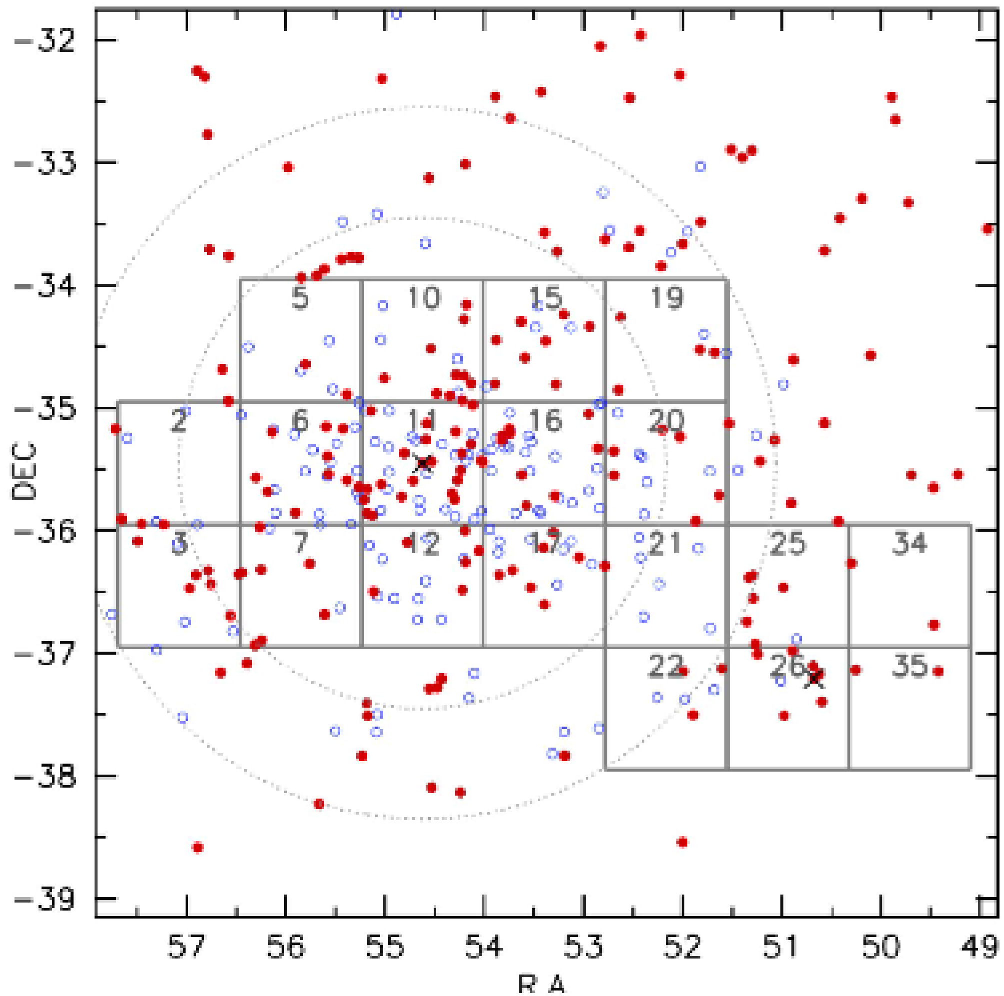
Fibre resolution element: 1.6''



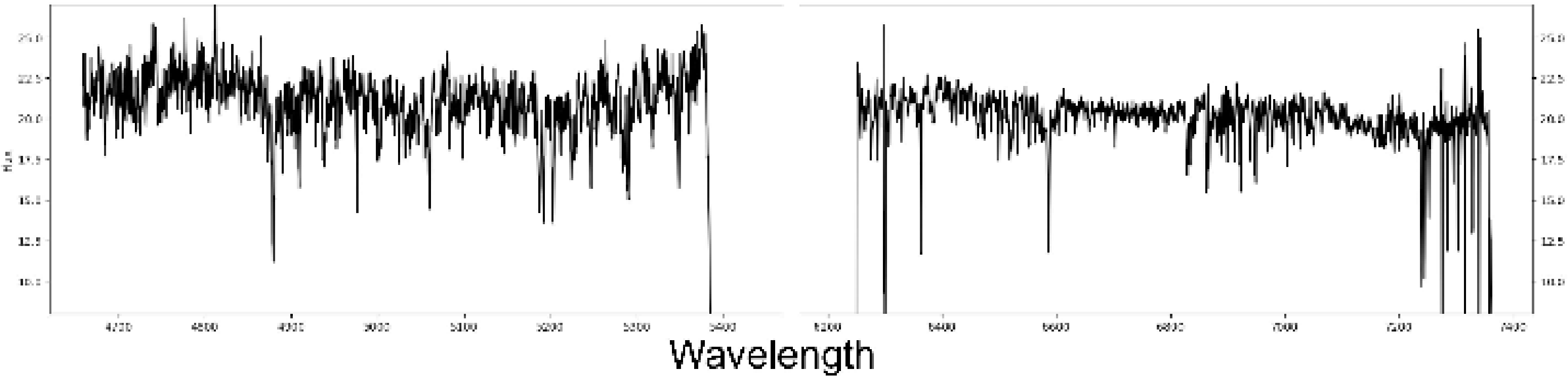

THE UNIVERSITY OF SYDNEY
SAMI Fornax Observing Setup
BLUE – 1500V
R~5100
λ: 466nm-543nm
σ: ~25 km/s
RED – 1000R
R~4300
λ: 625nm-735nm
σ : ~30 km/s
Observations
7-point dither pattern
30 minute exposures
~14 exposures per field = 7 hours on per galaxy
(b)
3

Targets

- IFU design optimal for ~12 targets per square degree
- Cluster centre requires multiple visits
- Red dots are ‘primary’ targets: Fornax cluster bright dwarfs or faint giants
- Blue dots are ‘secondary’ targets: faint dwarfs, giants or bright non-cluster galaxies
- Observations become inefficient when target density is low, i.e. cluster outskirts



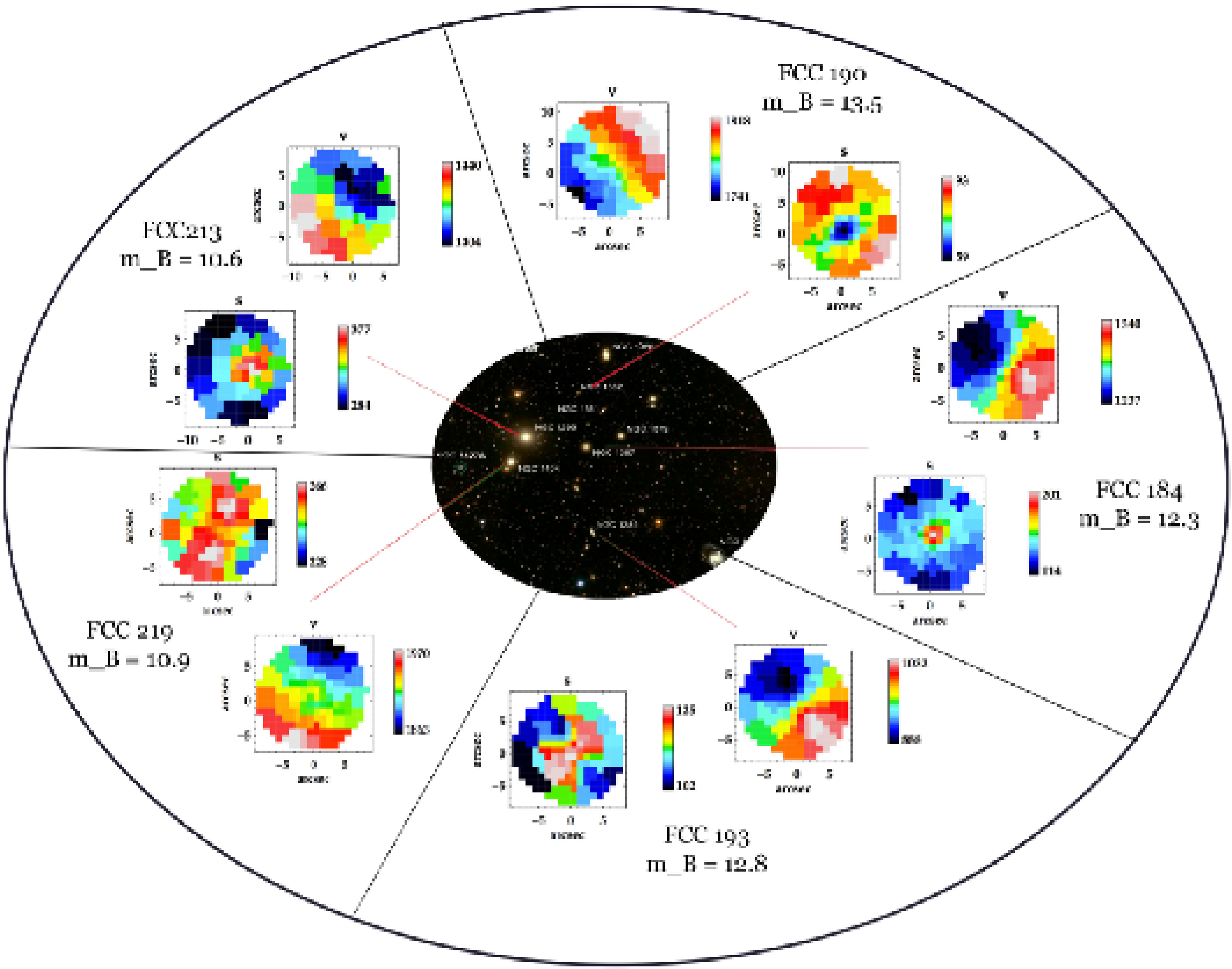
Summary of observed targets



Example spectrum for FCC203

- 12 giant galaxies
- 42 dwarf galaxies (2 observed twice)
- 4 background galaxies
- 5 F-stars for flux calibration

- Fields observed: 6, 10, 11, 15, 16, (12, 17)



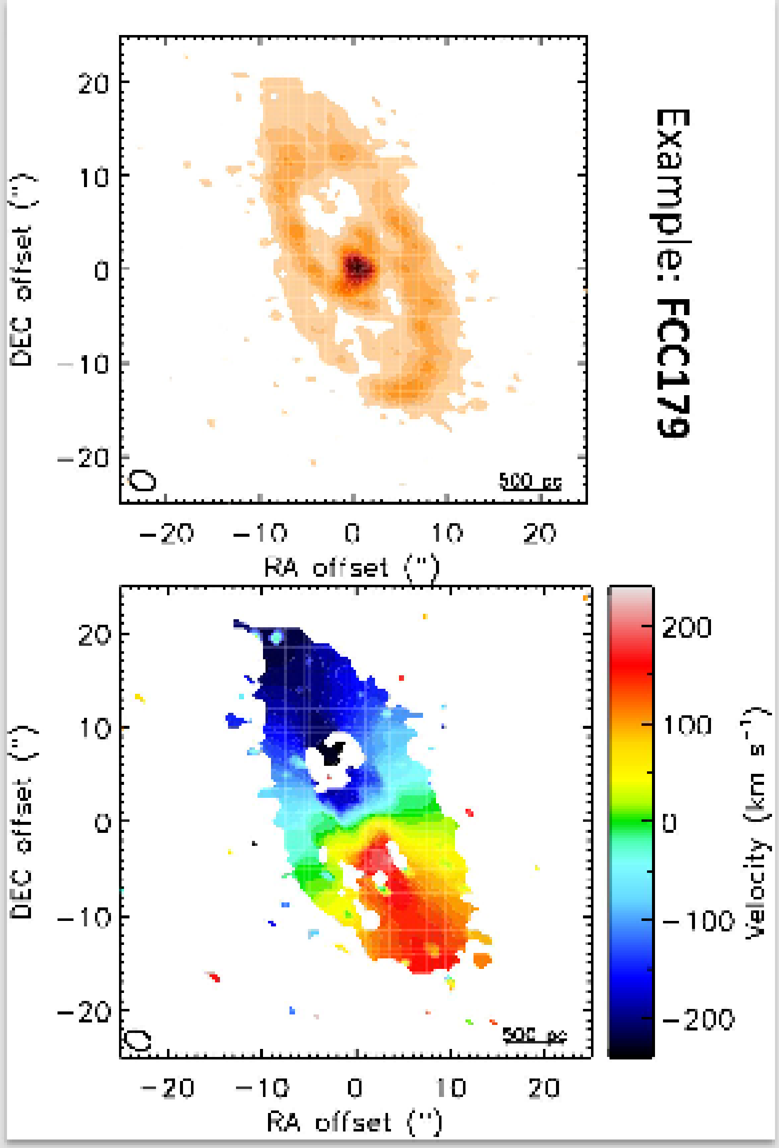
FCC 190
m_B = 13.5
FCC213
m_B = 10.6
FCC 184
m_B = 12.3
FCC 219
m_B = 10.9
FCC 193
m_B = 12.8

The ALMA Fornax Cluster Survey

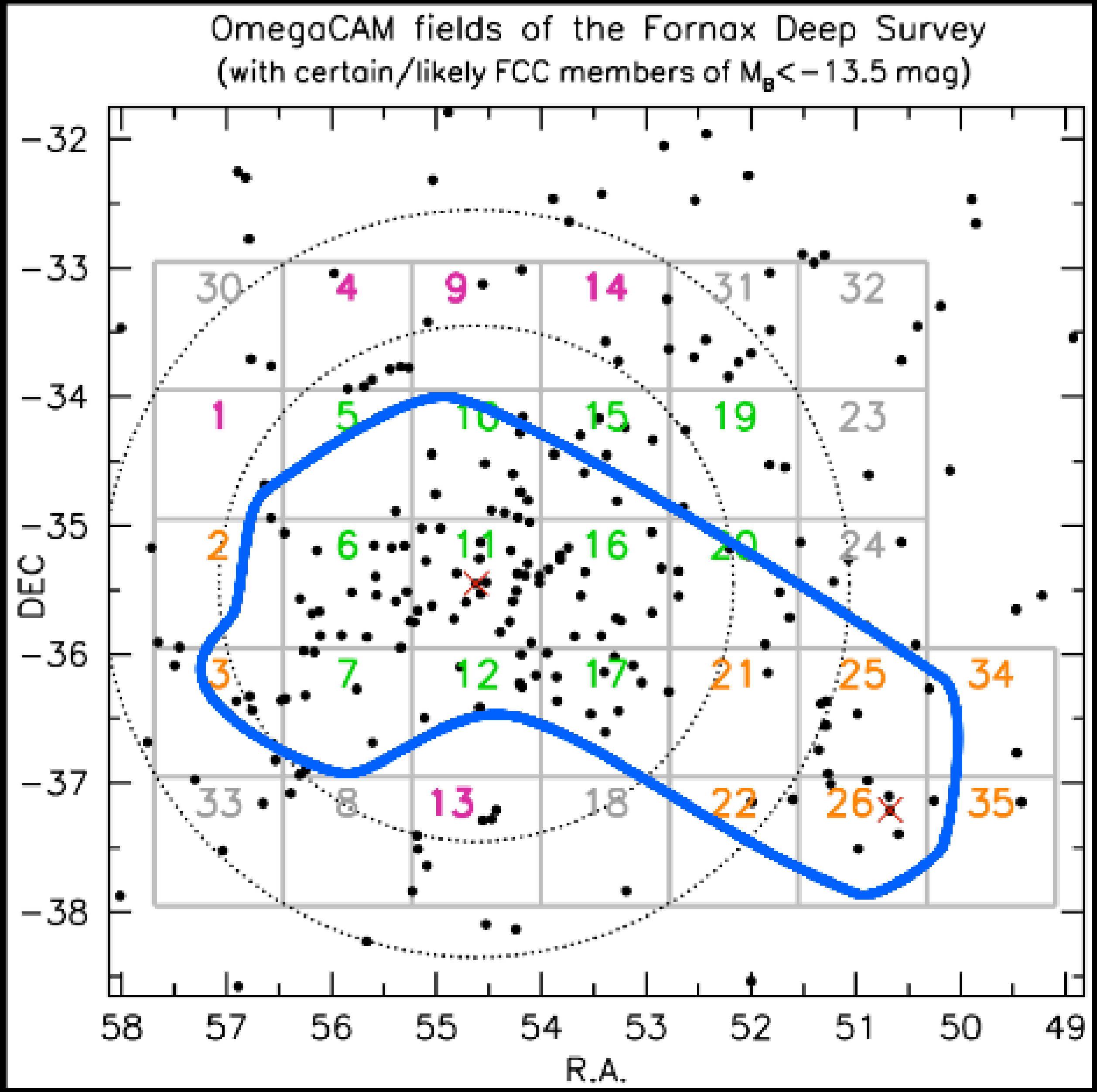
AlFoCS Overview

Use the power of ALMA to understand how environment affects cold gas, and quenches galaxies:

- CO(1-0) survey of ALL 31 Herschel detected sources in the Fornax Cluster
  - 9 Spiral, 7 ETG
  - 5 Irr, 10 dE/dS0
- ~2.4" resolution = ~200pc
- CO luminosity (→ mass) and kinematics
- 5 Msun/pc^2 sensitivity
- All observations complete



The Meerkat Fornax Survey (P.I. P. Serra)



Blue: HI coverage (Meerkat)

Conclusions:

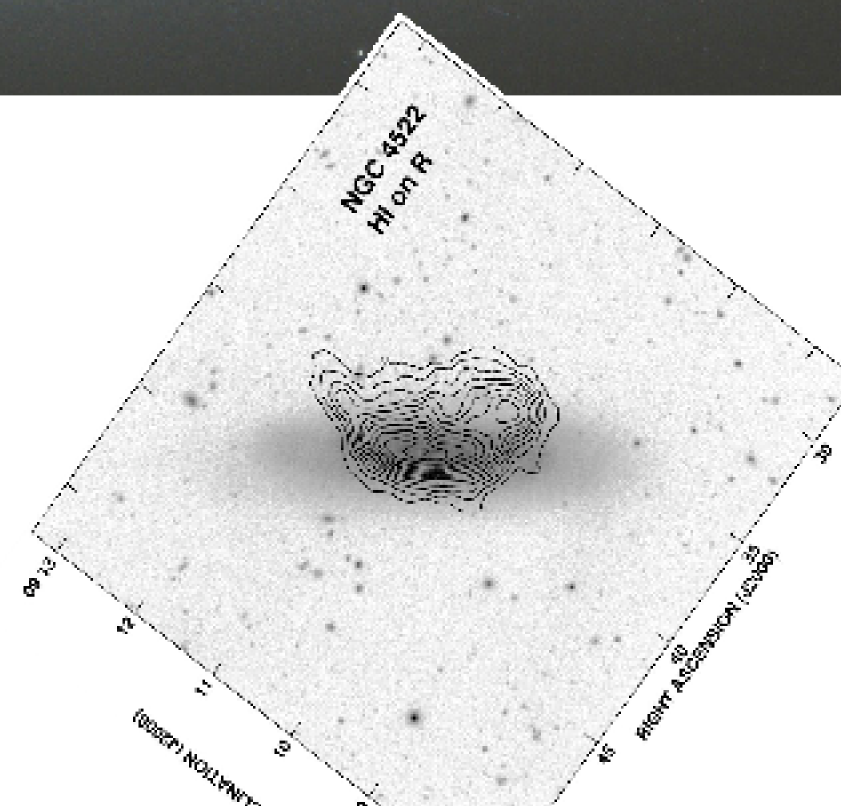
Soon, a new, deep survey of the Fornax Cluster in u'g'r'i' will be available (expected release date March 2019), offering a wealth of data to study the nature of dwarf galaxies, globular clusters, galaxy outskirts etc. in the environment of a small cluster.

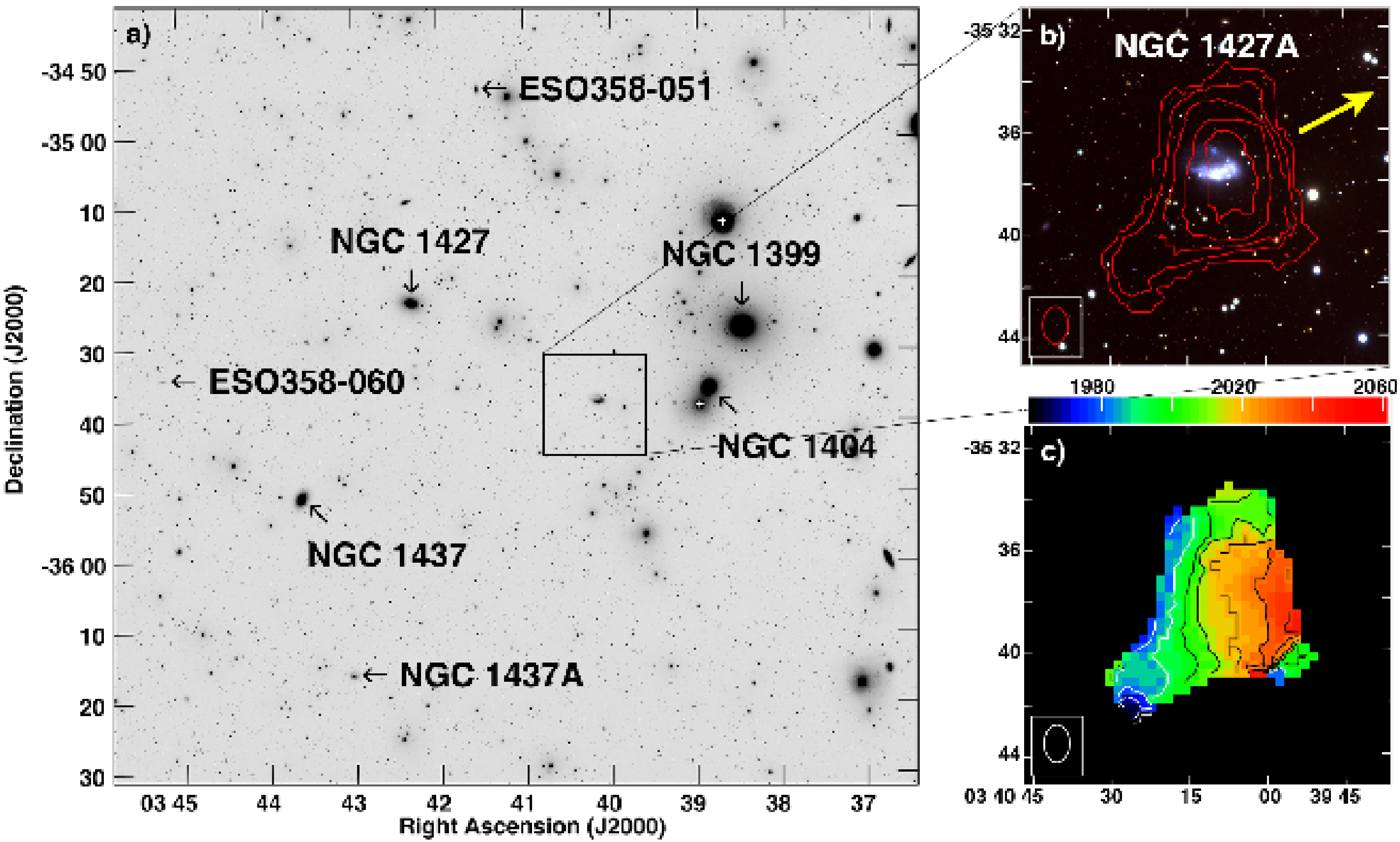
With the aid of several kinds of followup, and using existing and new simulations, we hope to learn a lot more about the physical processes that play a role during the formation and evolution of galaxies in clusters.

Intra Cluster Medium!

ngc4402 falling into centre of Virgo

ngc4522 in Virgo





a)
ESO358-051
NGC 1427
NGC 1399
ESO358-060
NGC 1404
NGC 1437
NGC 1437A
Declination (J2000)
-34 50
-35 00
10
20
30
40
50
-36 00
10
20
30
03 45
44
43
42
41
40
39
38
37
Right Ascension (J2000)
b)
NGC 1427A
-35 32
36
40
44
1980
2020
2060
c)
-35 32
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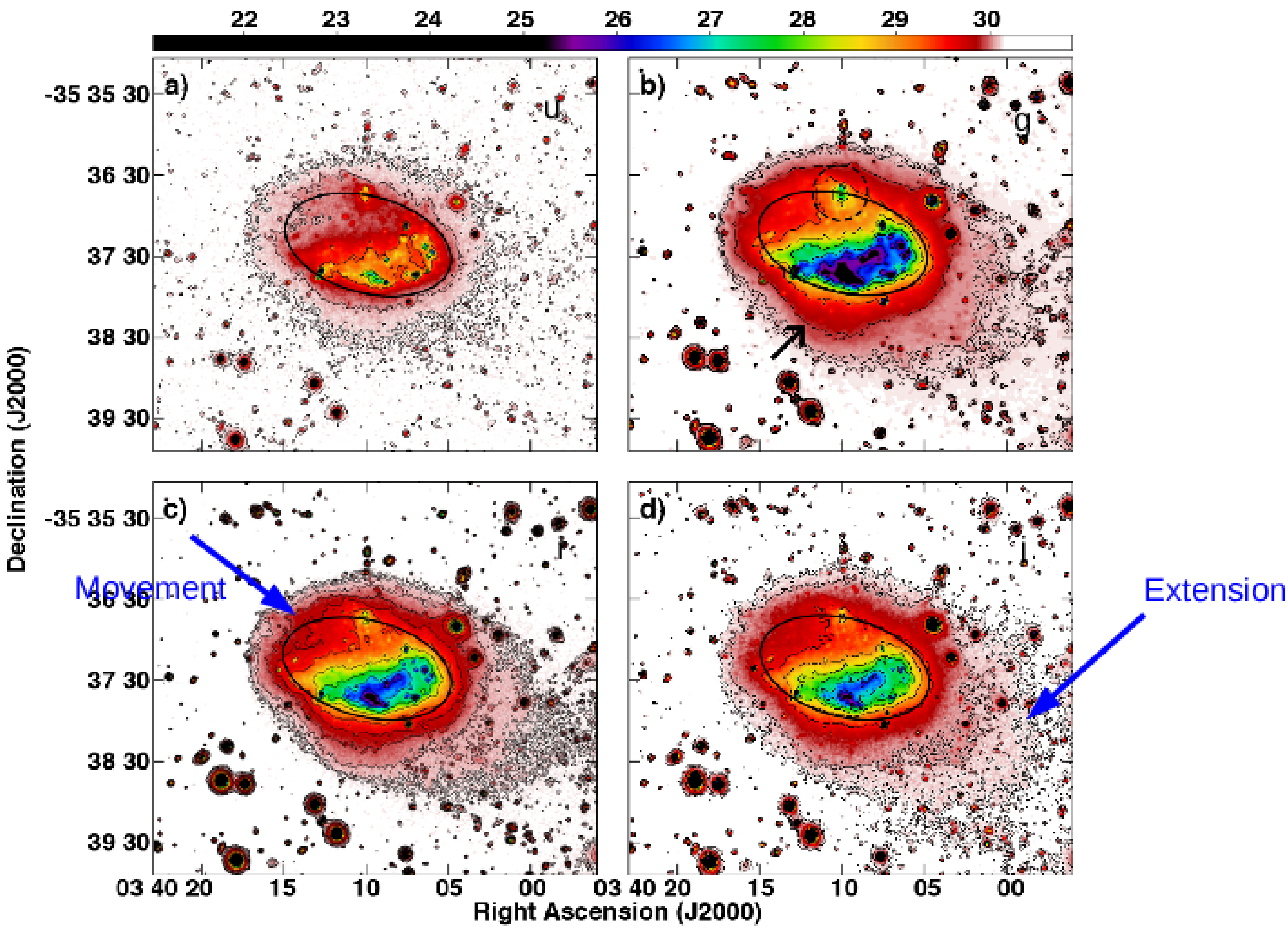
03 40 45
30
15
00
39 45



Extension on side towards which the galaxy should move argues against ram pressure stripping!