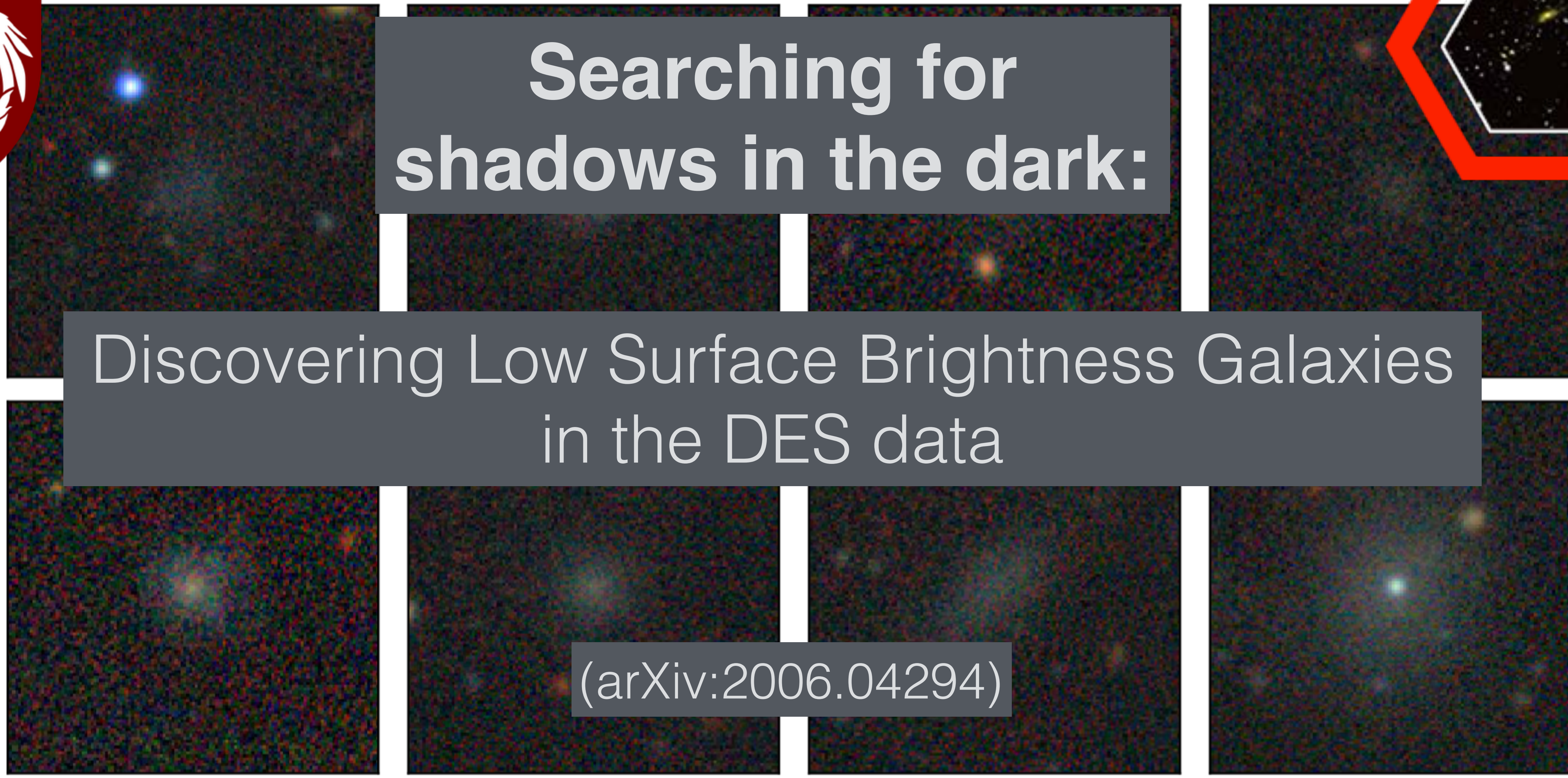
Searching for shadows in the dark:

Discovering Low Surface Brightness Galaxies in the DES data



(arXiv:2006.04294)

Dimitrios Tanoglidis

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LIneA webinar

13/08/2020

Low Surface Brightness Galaxies (LSBGs)

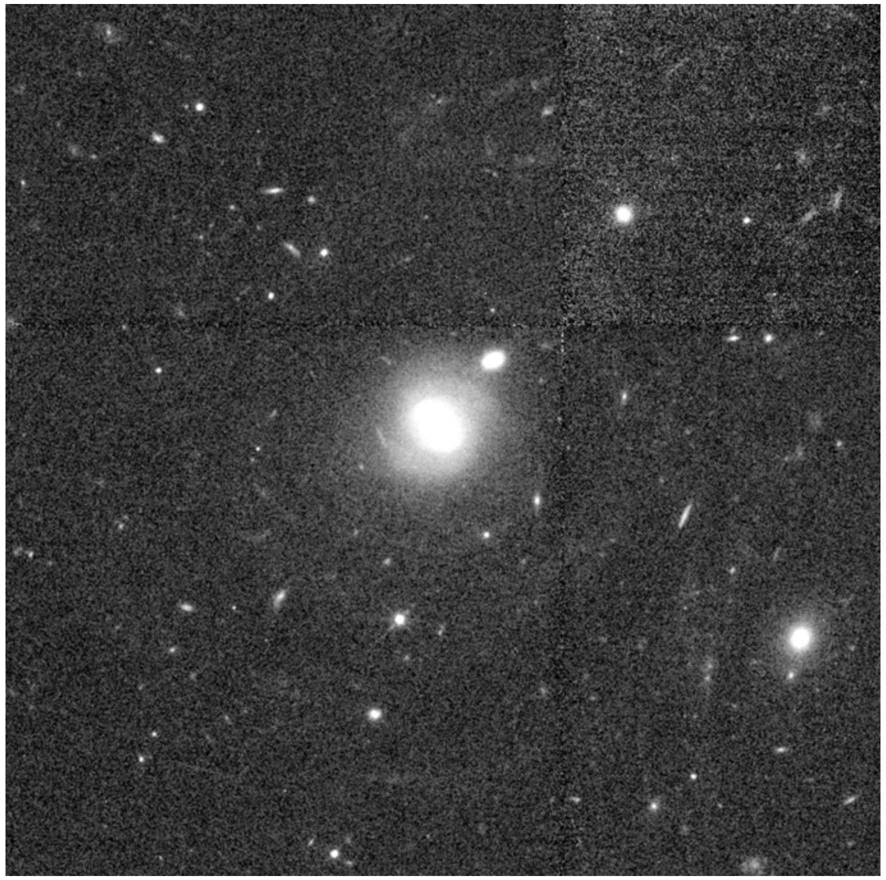
Definition: Diffuse galaxy with a surface brightness at least one magnitude fainter than the ambient sky.

Dark Sky: $\mu \sim 22 \text{ mag arcsec}^{-2}$

We are **interested** in objects > 5x fainter: $\mu > 24 \text{ mag arcsec}^{-2}$

- LSBGs are difficult to detect.
- Difficult to study over a wide sky area and in different environments (clusters vs field).
- Test models of galaxy formation and the galaxy—halo connection.
- Renewed interest in Ultra Diffuse Galaxies (UDGs) defined as LSBGs with large physical sizes.

Part I: The "Past"



Malin 1, from HST

Origins

Malin 1 1986

Mike Disney 1976

Visibility of galaxies

It is well known that our counts of galaxies could be seriously biased by selection effects, largely determined by the brightness of the night sky. To illustrate this, suppose the Earth were situated near the centre of a giant elliptical galaxy, then the mean surface brightness of the sky would appear some 8–9 mag brighter than is observed from our position in the Galaxy ($\sim$23 V mag (arc s)$^{-2}$ looking toward the galactic pole, discounting atmospheric and zodiacal contributions[1,2]). Optical astronomers would then find extragalactic space an empty void; spiral and irregular galaxies would be quite invisible and all they would easily detect of galaxies would be the core regions of ellipticals very similar to their own. They would be blinded to much of the Universe by the surface brightness of their parent

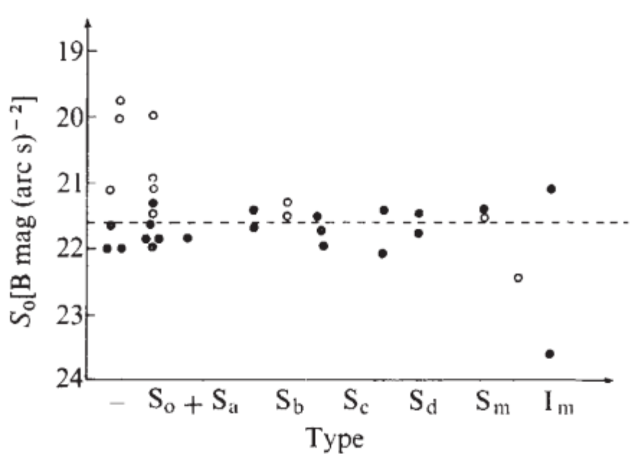


Fig. 1 Central surface brightnesses S_0 of exponential disks of spiral and irregular galaxies taken from Freeman[2] plotted against galactic type. Filled circles show most reliable data, open circles less reliable. Some of the original points, subsequently shown to be incorrect (K. C. Freeman, personal communication) have been removed. (————) is at 21.65 B mag (arc s)$^{-2}$.

DISCOVERY OF A HUGE LOW-SURFACE-BRIGHTNESS GALAXY: A PROTODISK GALAXY AT LOW REDSHIFT?

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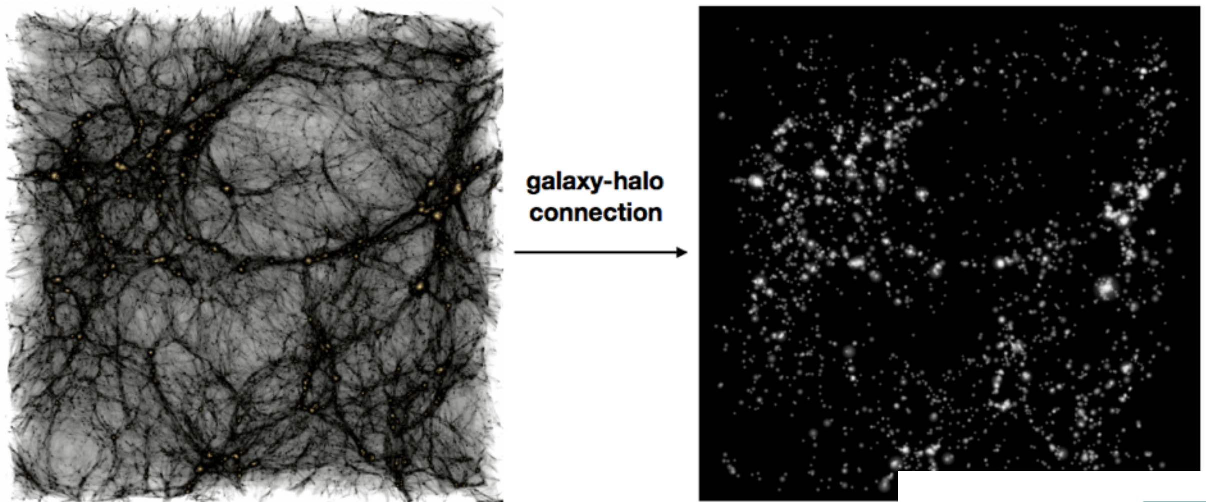
Received 20 February 1987

ABSTRACT

We report on the *accidental* discovery of an extremely large, extremely H I-rich low-surface-brightness galaxy located at a redshift of $z = 0.083$. Its nuclear spectrum exhibits broad, low-level emission lines. Surface photometry at V indicates the presence of a bulge component and a very extended disk, with scale length of $\approx 45''$ (55 kpc for $H_0 = 100$) and with central surface brightness of $V(0) \approx 25.5$ mag arcsec^{-2}. The total amount of H I is at least $1.0 \times 10^{11} \mathscr{M}_\odot$. This amount of H I is at least 5 times more H I than any spiral galaxy previously observed. If disk formation is a quiescent process, then it is likely that we have caught a disk in the process of formation. We also point out that the properties of this disk are

However, LSB regime largely unexplored



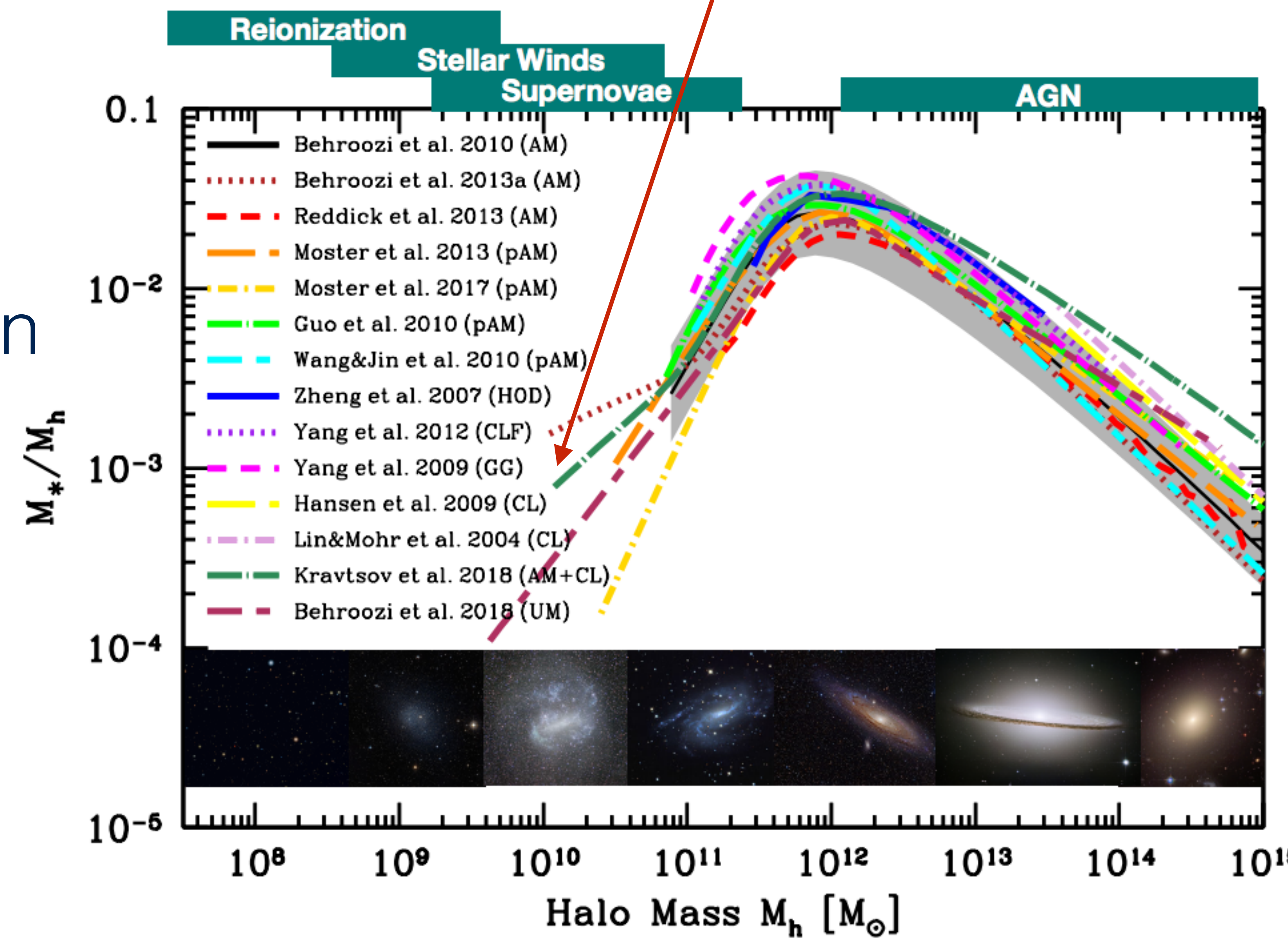
Wechsler & Tinker 2018

Galaxy-Halo connection

Expected to be dominated by LSBGs

Martin+ 2019, arXiv: 1902.04580

Dalcanton+ 1997, arXiv: 0705088



Behroozi+ 2018

Renewed interest in UDGs : A special class of LSBGs

Ultra Diffuse Galaxies (UDGs) : LSB + extended (physical radius)

Surf. brightness: $\mu \gtrsim 24 \text{ mag arcsec}^{-2}$

Effective radius: $R_{\text{eff}} > 1.5 \text{ kpc}$

FORTY-SEVEN MILKY WAY-SIZED, EXTREMELY DIFFUSE GALAXIES IN THE COMA CLUSTER

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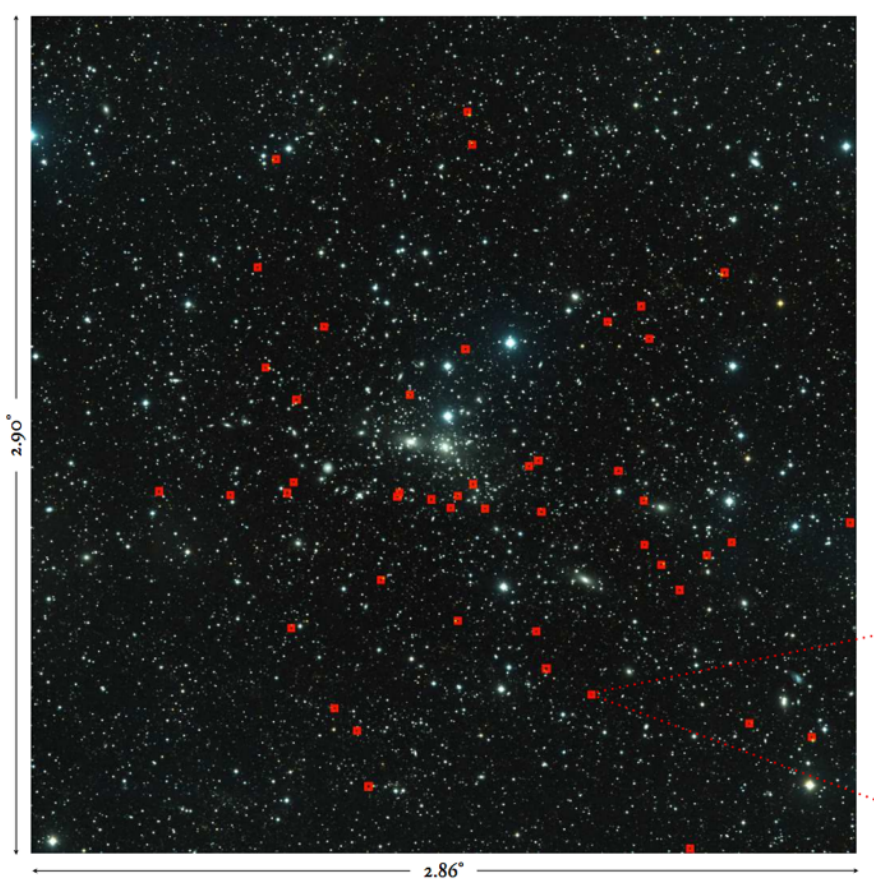
ABSTRACT

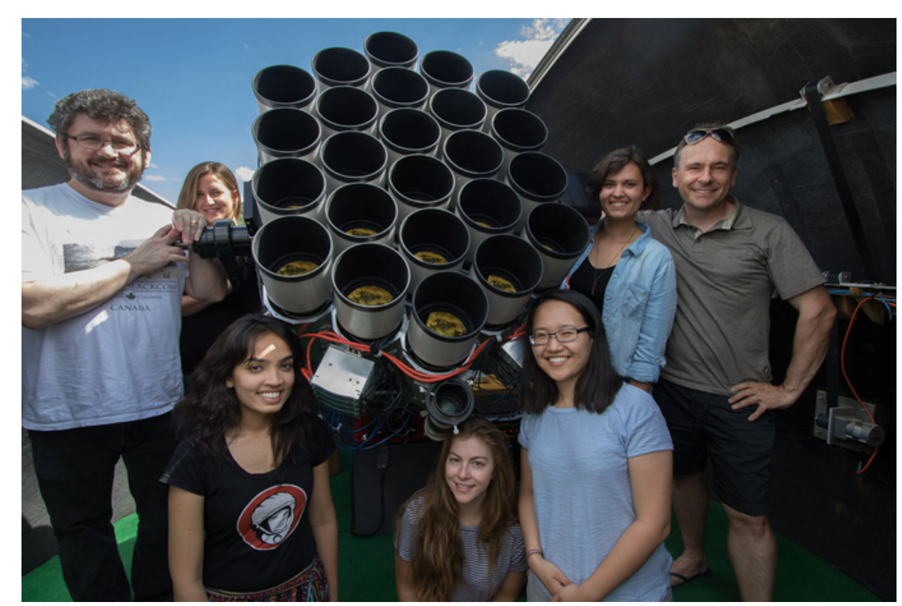
We report the discovery of 47 low surface brightness objects in deep images of a $3° \times 3°$ field centered on the Coma cluster, obtained with the Dragonfly Telephoto Array. The objects have central surface brightness $\mu(g,0)$ ranging from 24 – 26 mag arcsec^{-2} and effective radii $r_{\text{eff}} = 3'' - 10''$, as measured from archival Canada France Hawaii Telescope images. From their spatial distribution we infer that most or all of the objects are galaxies in the Coma cluster. This relatively large distance is surprising as it implies that the galaxies are very large: with $r_{\text{eff}} = 1.5$ kpc – 4.6 kpc their sizes are similar to those of L_* galaxies even though their median stellar mass is only $\sim 6 \times 10^7 M_\odot$. The galaxies are relatively red and round, with $\langle g-i \rangle = 0.8$ and $\langle b/a \rangle = 0.74$. One of the 47 galaxies is fortuitously covered by a deep Hubble Space Telescope ACS observation. The ACS imaging shows a large spheroidal object with a central surface brightness $\mu_{475} = 25.8$ mag arcsec^{-2}, a Sersic index $n = 0.6$, and an effective radius of $7''$, corresponding to 3.4 kpc at the distance of Coma. The galaxy is not resolved into stars, consistent with expectations for a Coma cluster object. We speculate that these "ultra-diffuse galaxies" (UDGs) may have lost their gas supply at early times, possibly resulting in very high dark matter fractions.

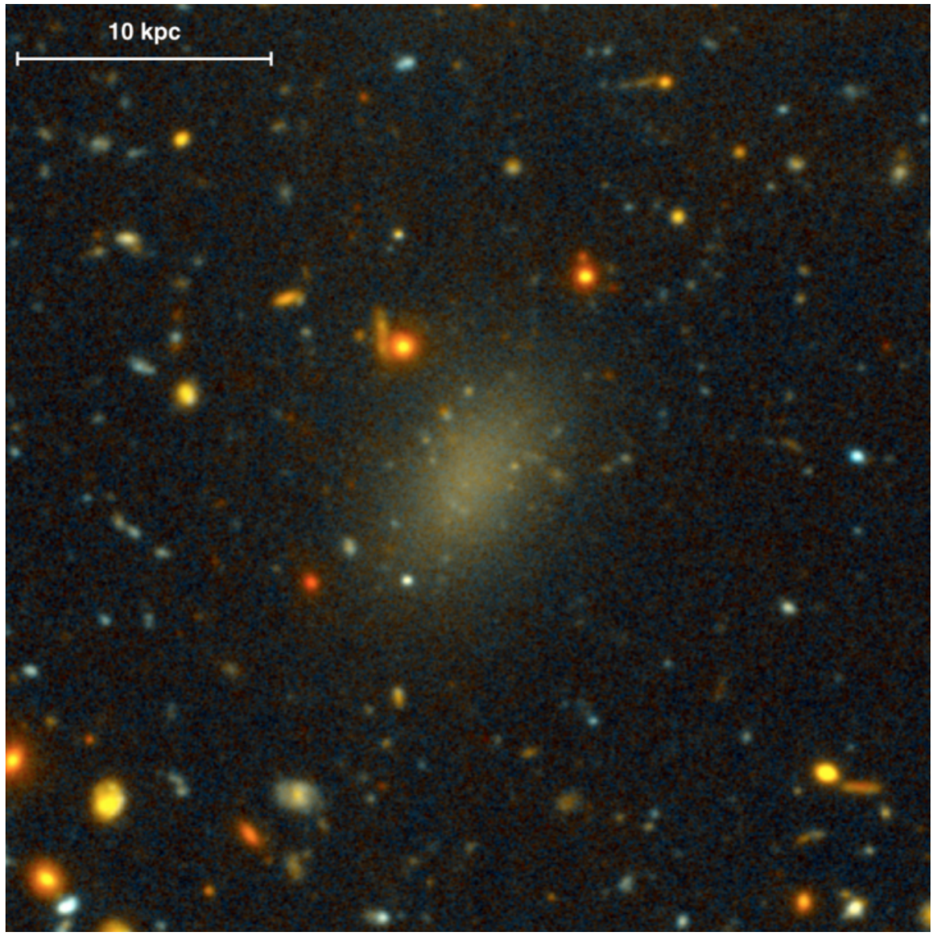
Size ~ Milky Way
Stellar content ~ 1000 times less

Van Dokkum+15, arXiv: 1410.8141



Dragonfly Telephoto Array





Most UDGs discovered in clusters

No signs of tidal effects

Using stellar kinematics: $M_h \sim 10^{12}\ M_\odot$

Are UDGs failed L* galaxies?
In such host masses, galaxy formation -> effective

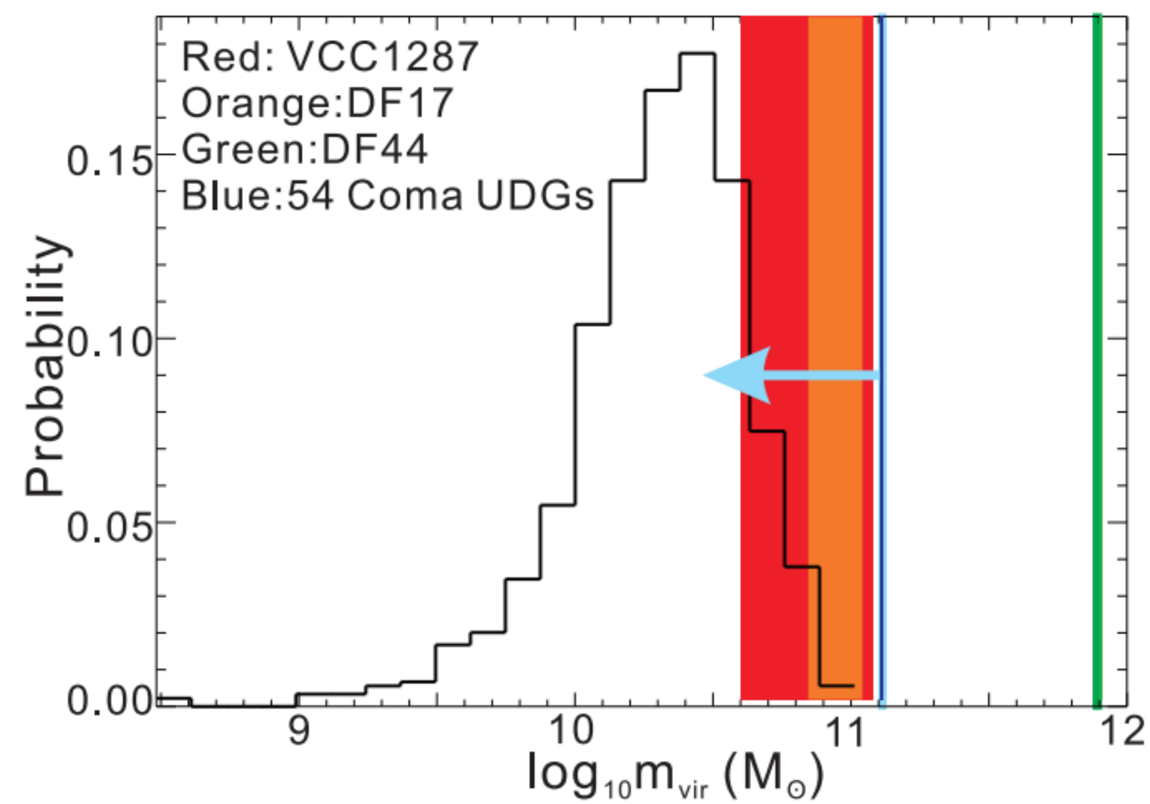
Dragonfly 44, Coma Cluster,
Van Dokkum+16, arXiv: 1606.06291

Other observations: $M_h \sim 10^{10}\ M_\odot$

UDGs "normal" UDG dwarfs?
Can be explained if:

- Formed late
- High spin

(Amorisco & Loeb, 2016
Rong et. al. 2017,
Conselice 2018)



Rong+17, arXiv: 1703.06147

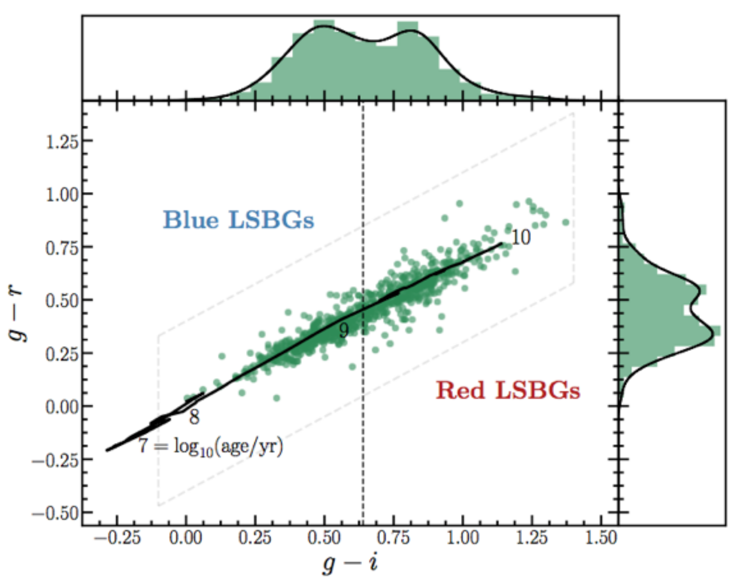
State of the Art in Wide-Field Surveys searches for LSBGs: Hyper-Supreme-Cam (HSC)

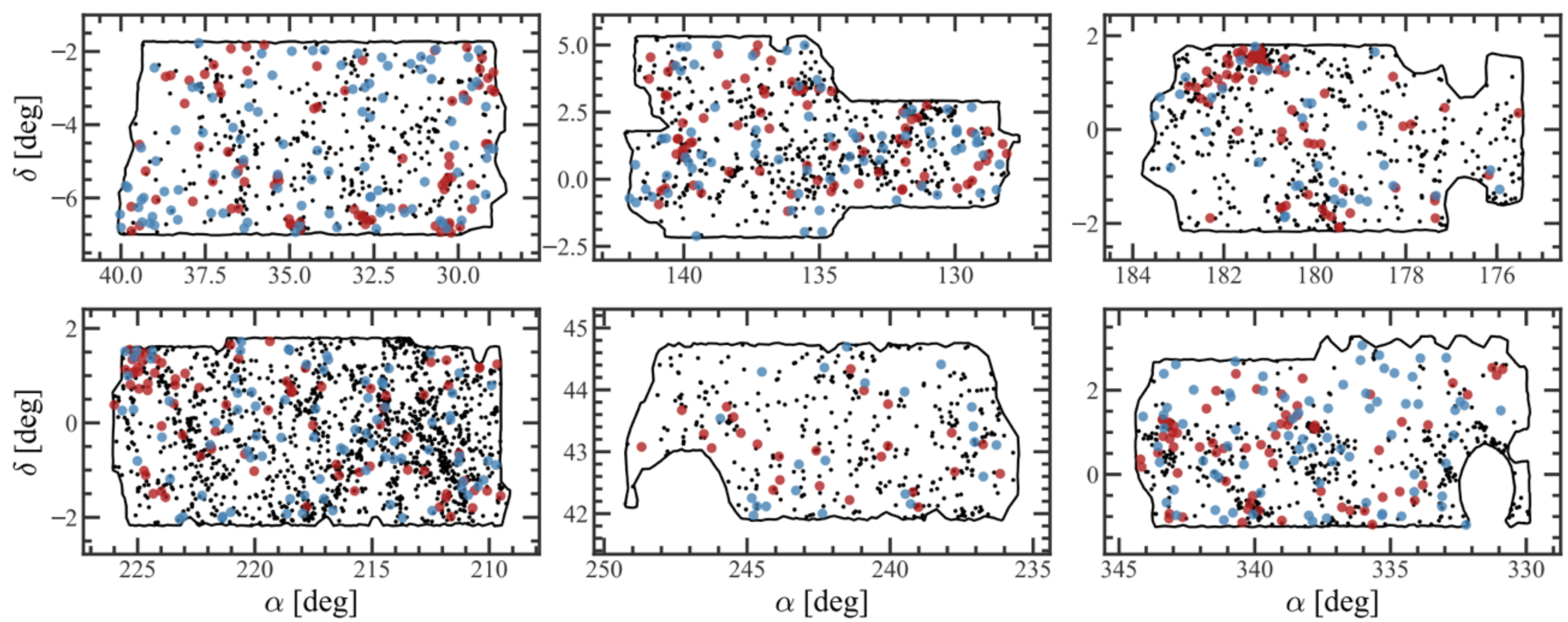
(Greco+18, arXiv 1709.04474)

Analysis of the first ~200 deg^2

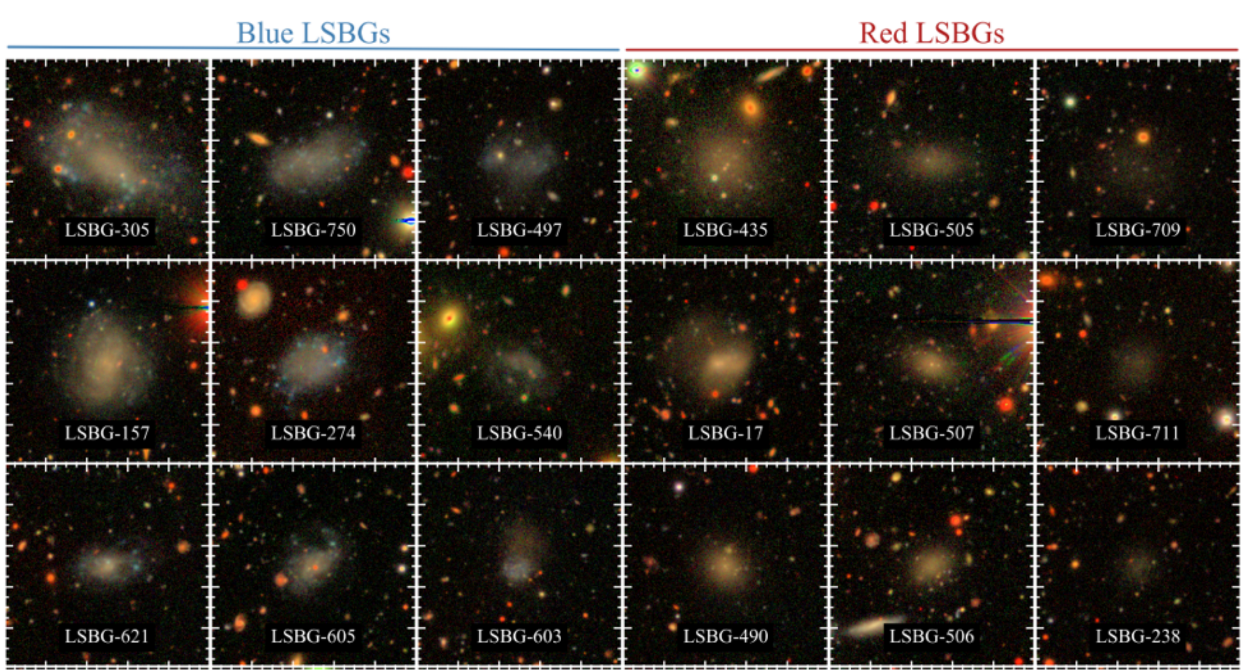
781 LSBGs

Depth, *i* ~ 26 (point source)





Signs of spatial clustering for red LSBGs



Dwarf spheroidals and UDGs to gas-rich irregulars and giant LSB spirals

Part II: The Present

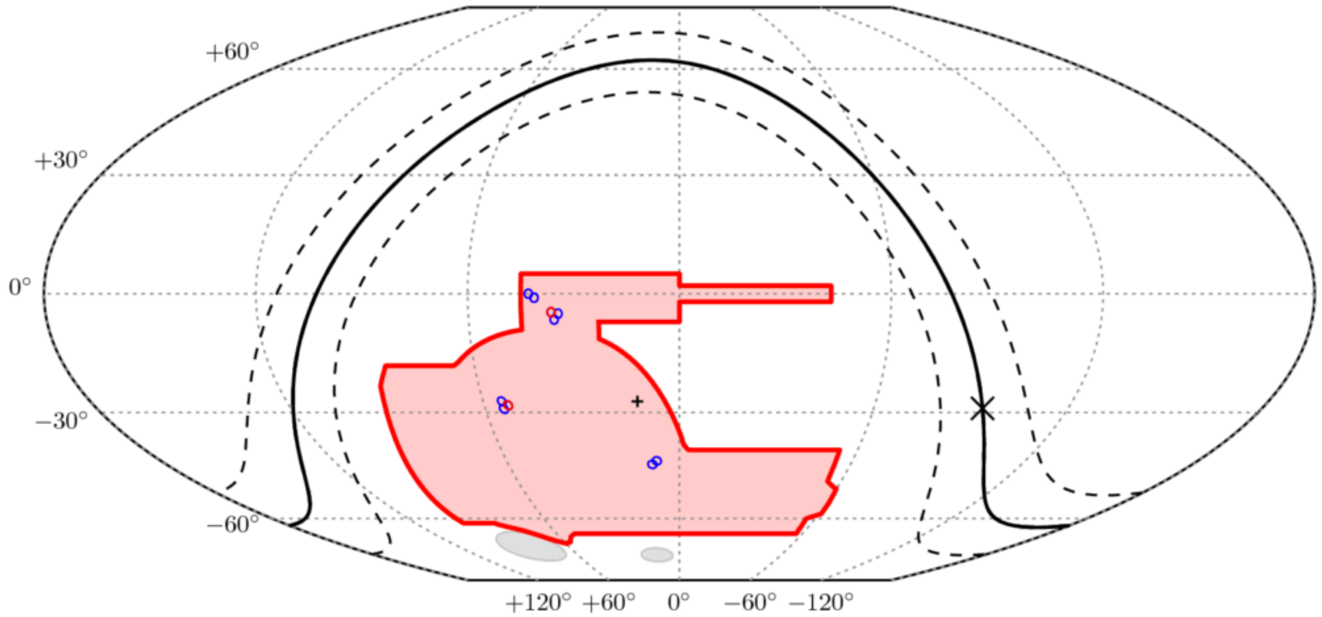
LSBGs in DES

The Dark Energy Survey (DES)

- Optical - Near IR survey
- 4m Blanco Telescope, CTIO, Chile
- ~5000 deg^2 footprint
- Five photometric bands: *g,r,i,z,Y*

(Median limiting magnitudes
$g = 23.52$, $r = 23.10$, $i = 22.51$, $z = 21.81$,
$Y = 20.61$)

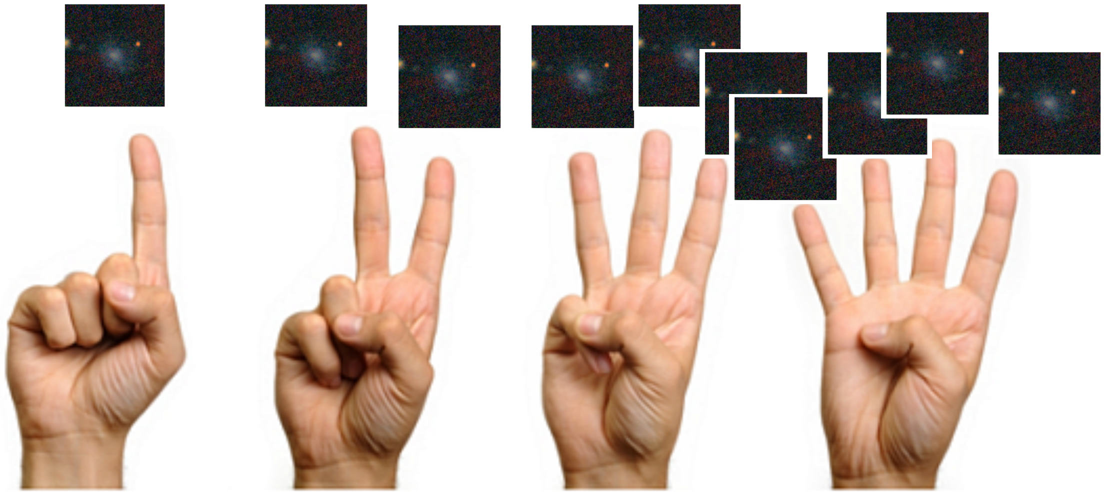
- 758 observing nights, ~6 years, last observations: Jan 9th, 2019
- > 300M objects (closer to ~400M objects)



DES Footprint ~5000 deg^2
the "tank"

A Catalog of LSBGs in 4 steps

From the first three years (Y3) of DES data



Step 1: Catalog cuts on the SExtractor-derived parameters

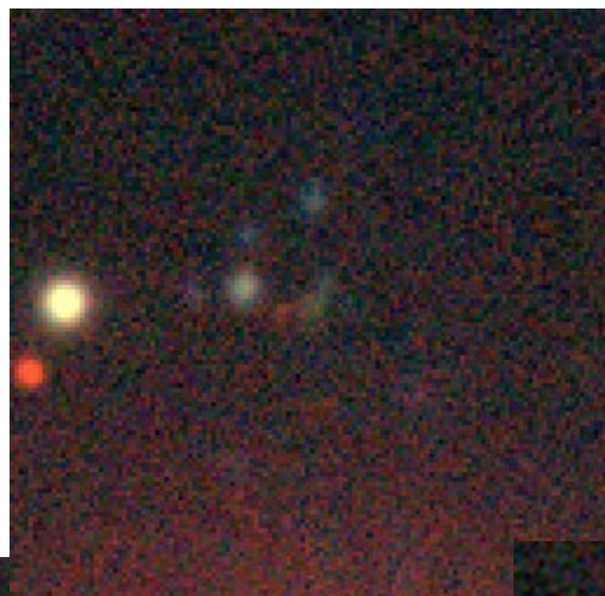
- Mean surface brightness: $24.3 < \bar{\mu}_{\text{eff}}(g) < 28.8 \text{ mag arcsec}^{-2}$
- Flux radius: $r_{1/2}(g) > 2.5''$
- + star/galaxy separation cuts, ellipticity, color cuts

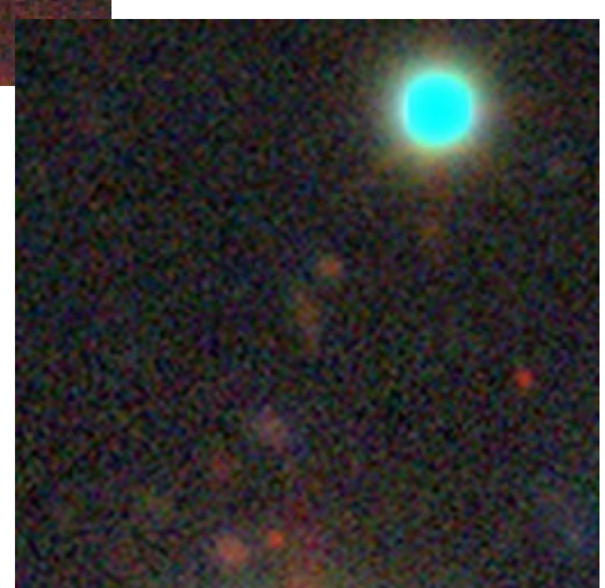
(Cuts motivated by a similar analysis on HSC
Greco et. al. 2018, arXiv: 1709.04474)

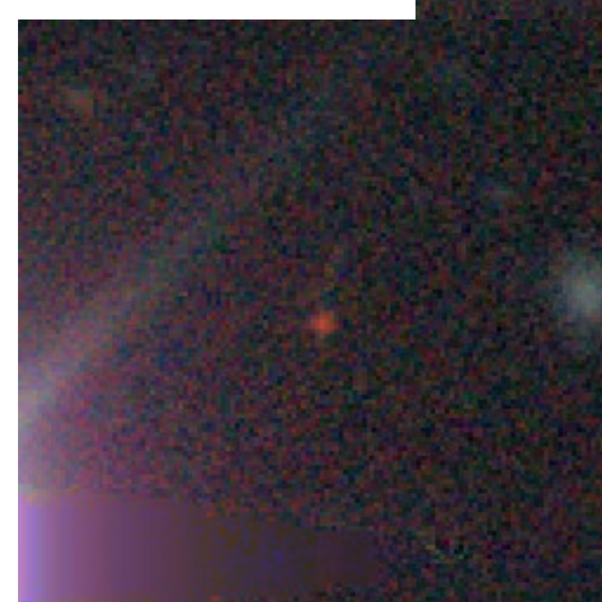
413,608 candidates

413,608 LSBGs?

~ **90%** false detections







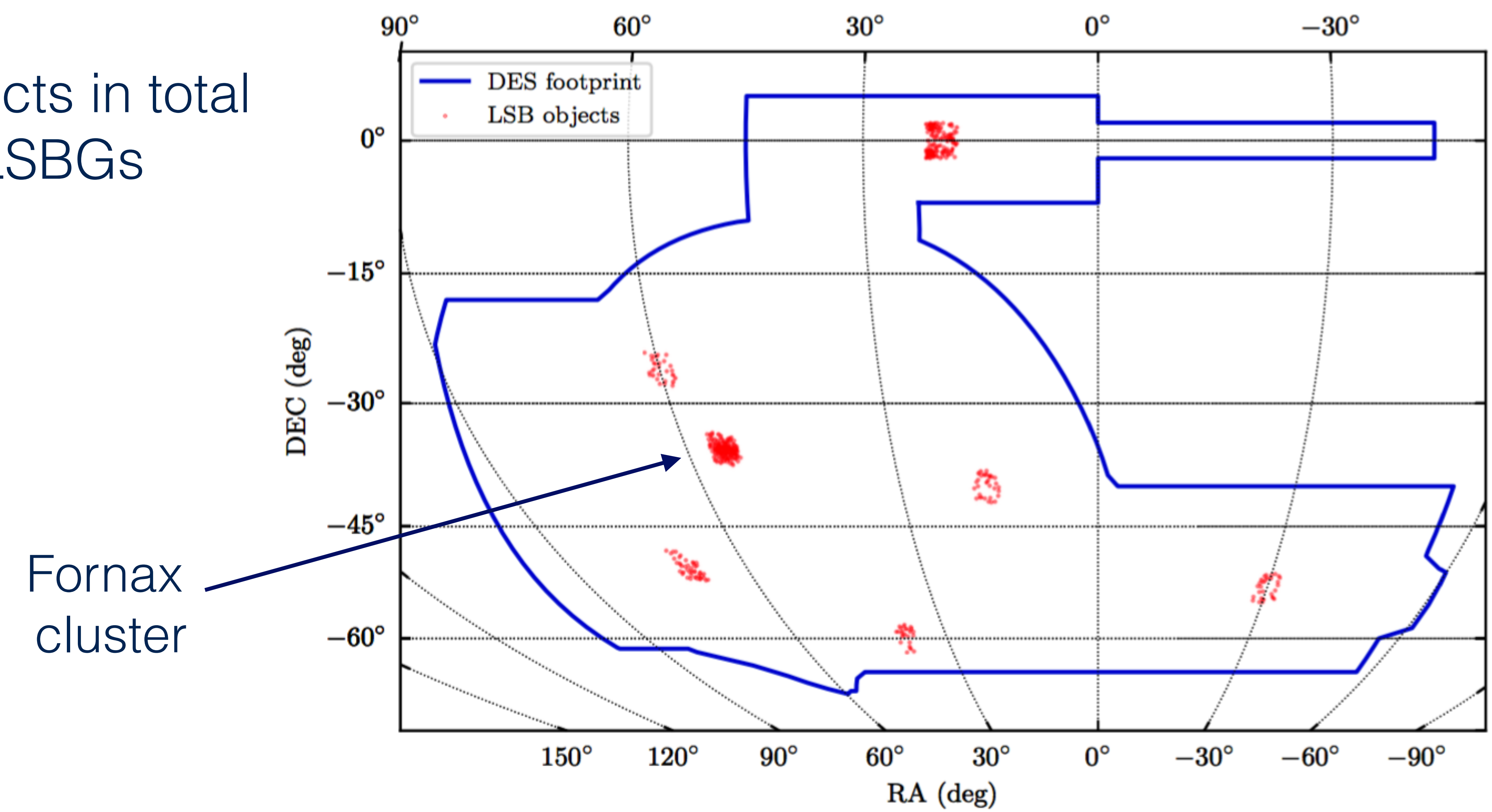
Step 2: Machine Learning Classification

Problem: Training set?

Solution: Create a set of objects with labels determined by visual inspection:

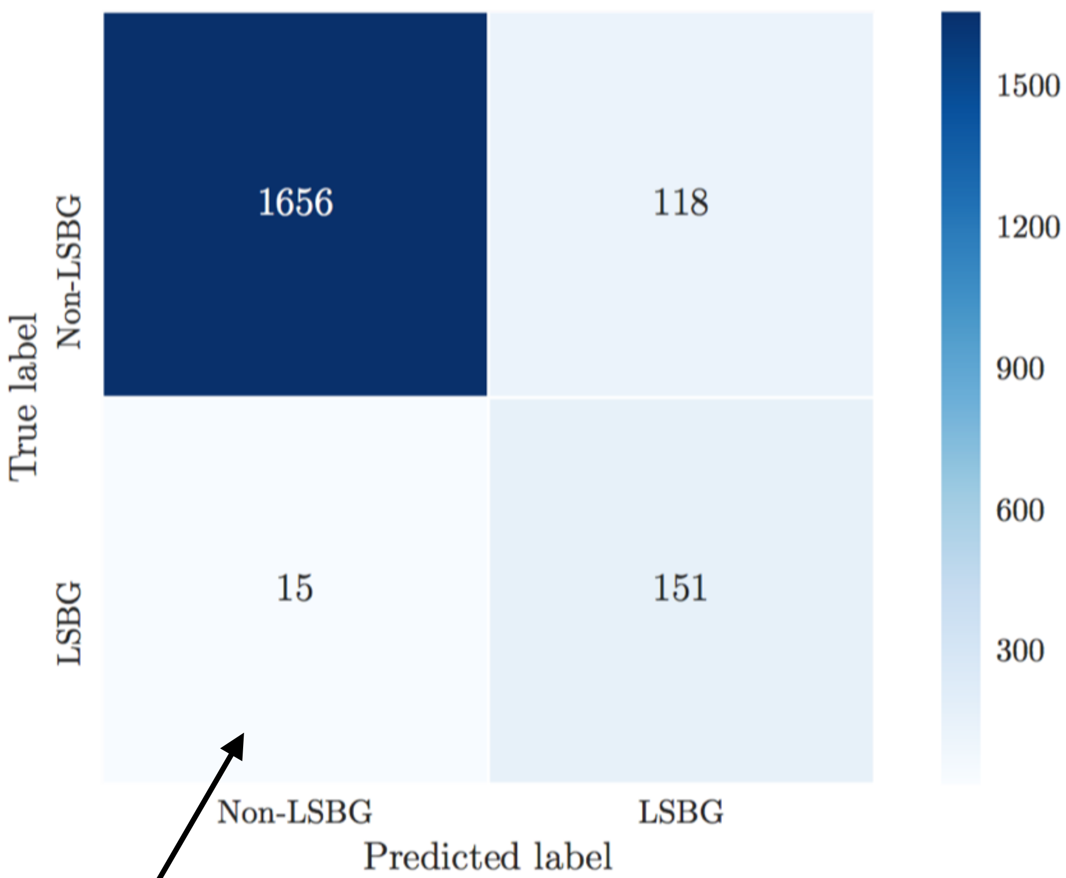
- 7   4 x 4 degree regions

- 7760 objects in total
- 640 true LSBGs



SVM classifier

Select classifier with minimum False Negative Rate
- completeness over purity



False Negatives

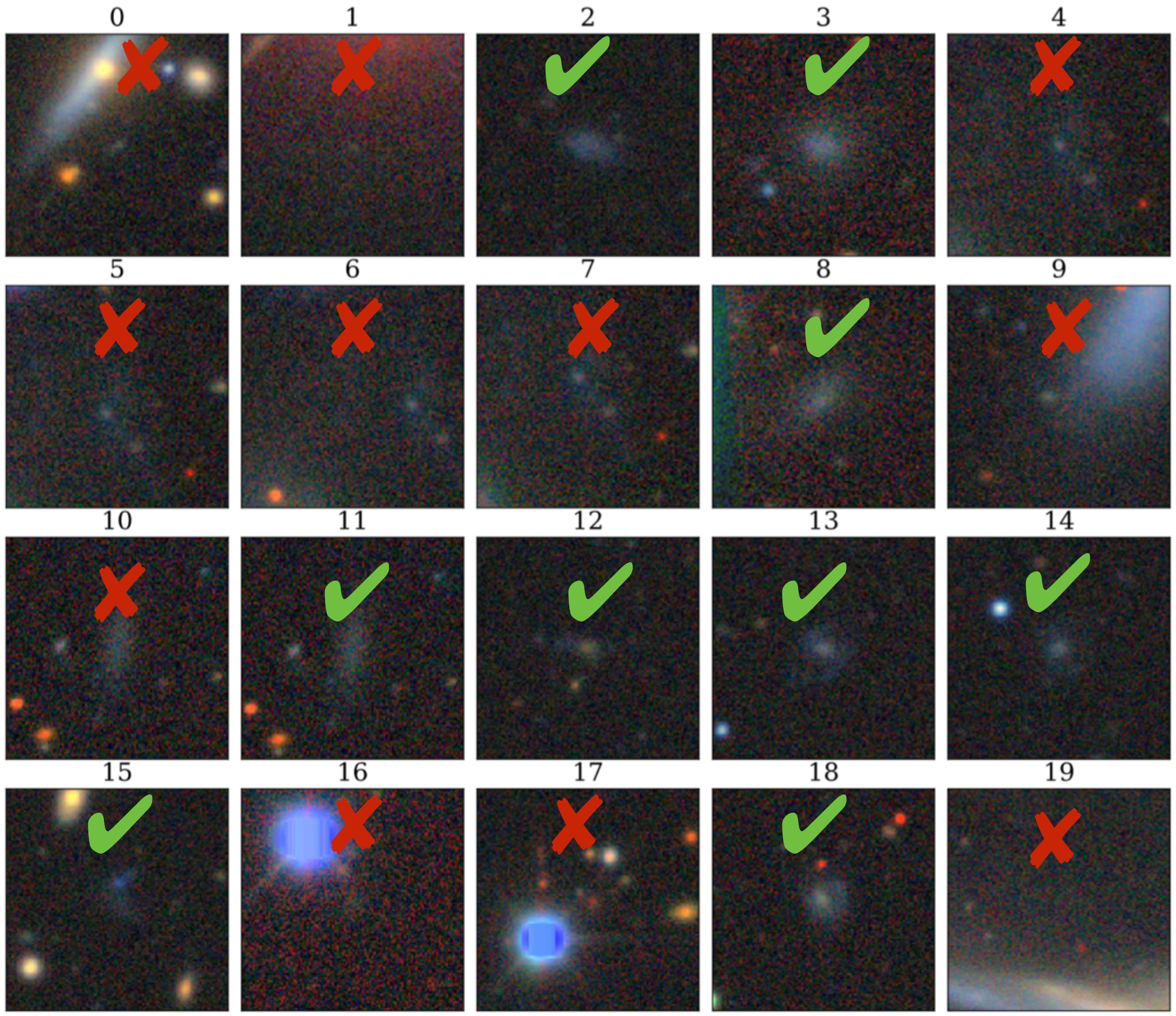
Completeness: **~90.1%**

Purity: **~56.1%**

40,820 candidates

Feature importance (RF classifier)

Step 3: Visual Inspection



Reject remaining false positives

21,286 Galaxies

Step 4: Galfit modeling and extinction correction

- Recalculate photometric (magnitudes) and structural (eff. radius, Sérsic index) parameters using Galfit
- Correct for Galactic extinction based on the position of each object and the E(B-V) map (Schlegel et. al. 1998)
- Perform cuts based on the updated parameters

Final Catalog:
20,977
radially extended **LSBGs**

How efficient are we? Comparison with external dwarf catalogs

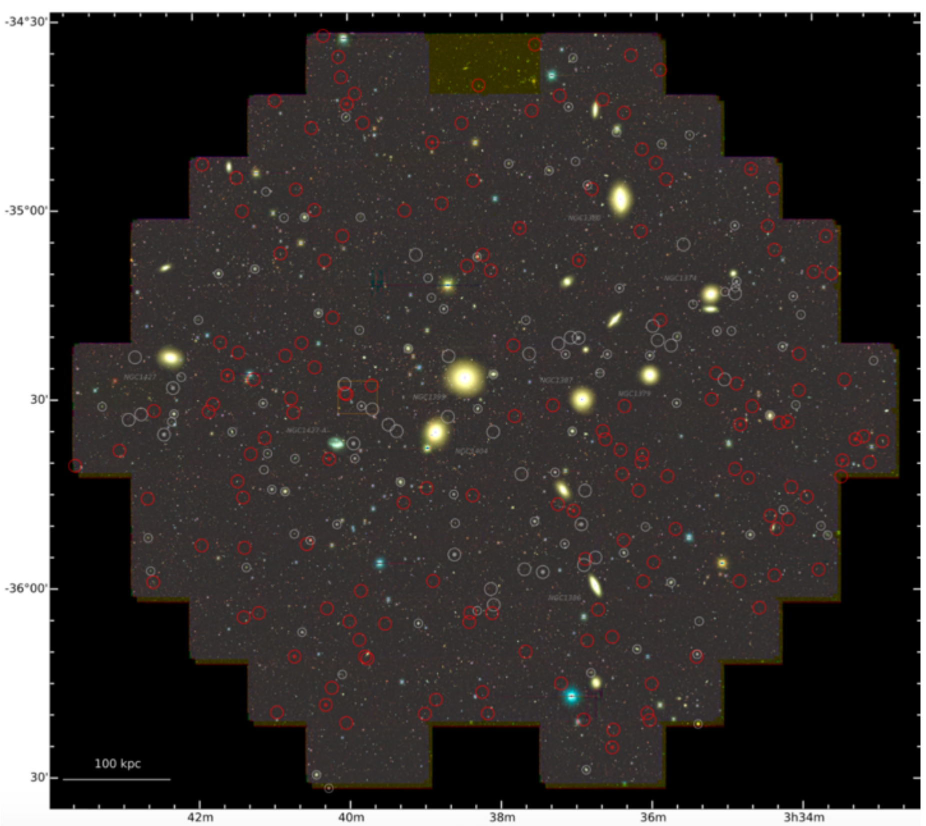
Next Generation Fornax Survey

DECam, ~ 30 deg^2 around Fornax, ~2 mag deeper than DES

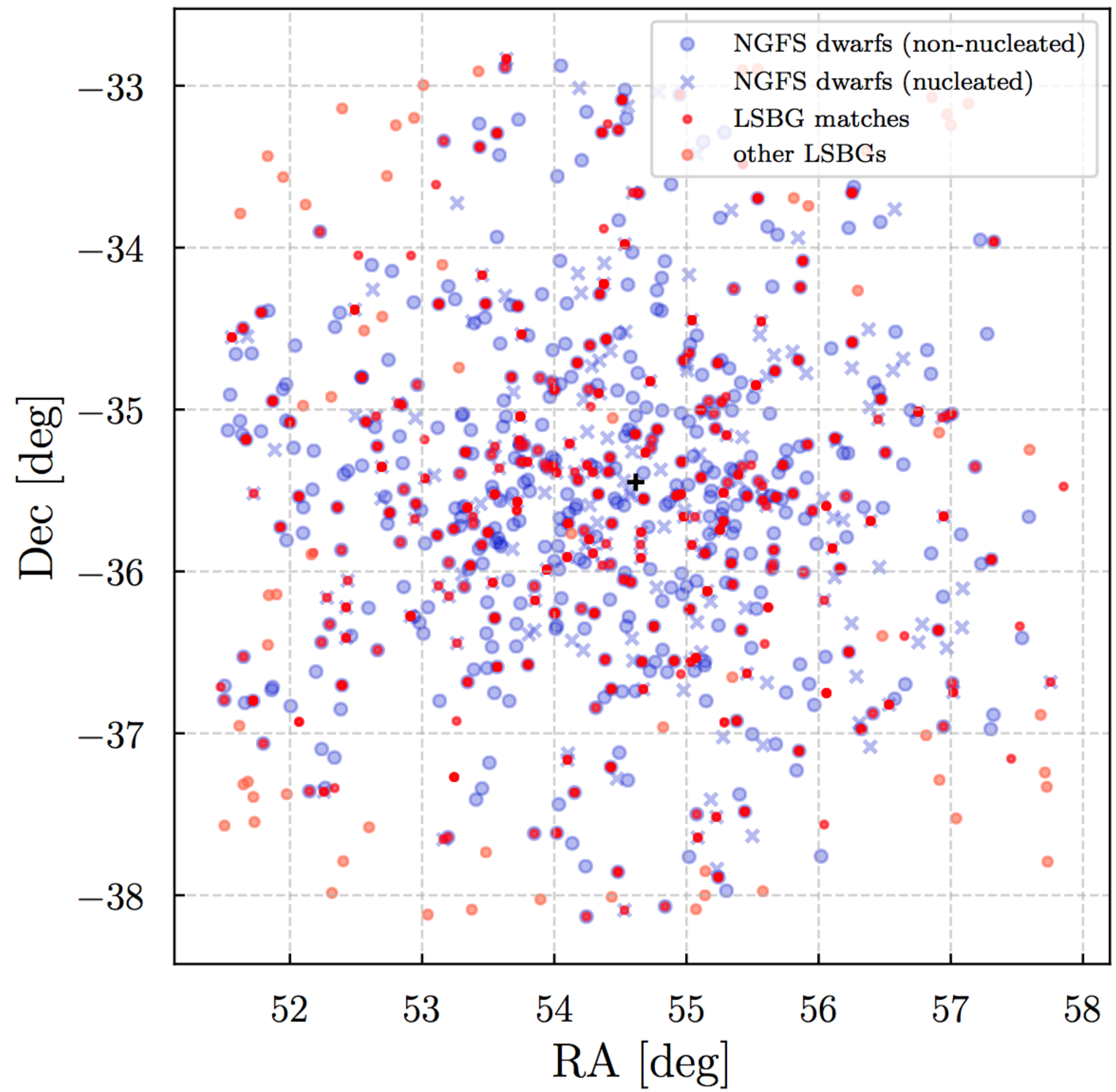
643 dwarf galaxies:

- 181 nucleated
- 462 non-nucleated

(Eigenthaler et al. 2018; Ordenes-Briceño et al. 2018)



R. Munoz et. al. ,1510.02475



Use the full DES catalog around Fornax

Apply the different cuts,
match with the NGFS catalog

matching radius: 3”

~ 8 objects within NGFS footprint,
detected by us but not by them

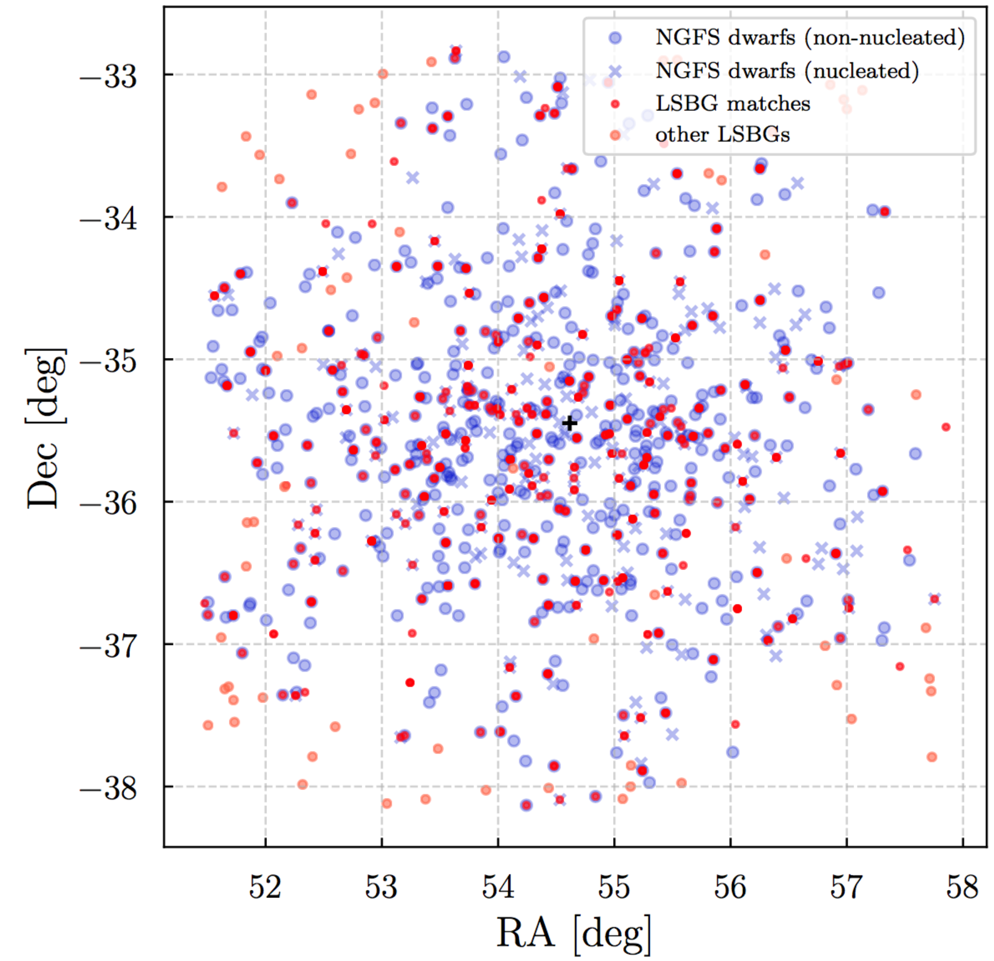


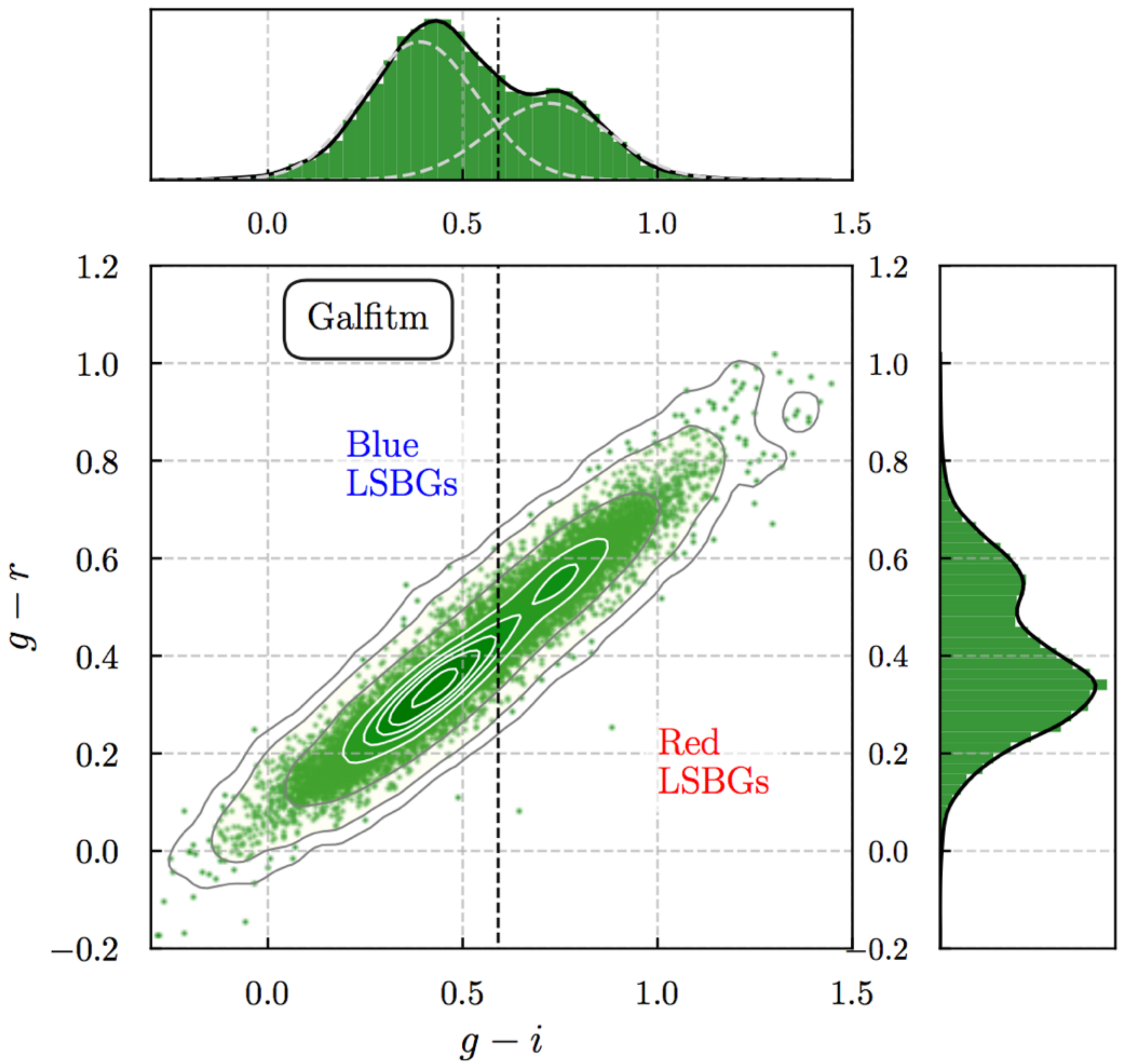
Table 1. Detection efficiency around the Fornax Cluster

Cuts applied	All galaxies	Nucleated	Non-nucleated
No cuts	76.6%	89.5%	71.6%
Surface brightness cut only	61.7%	54.7%	64.4%
Angular size cut only	56.4%	81.8%	46.4%
Both cuts	42.4%	48.6%	39.9%
Final result (After ML/Vis. inspection)	36.8%	43.6%	34.1%

Exploring the Sample

Colors
(stellar populations)

Bimodiality in *g-i* - *g-r* color-color space



Split into blue and red LSBGs

Separation: GMM in *g-i*

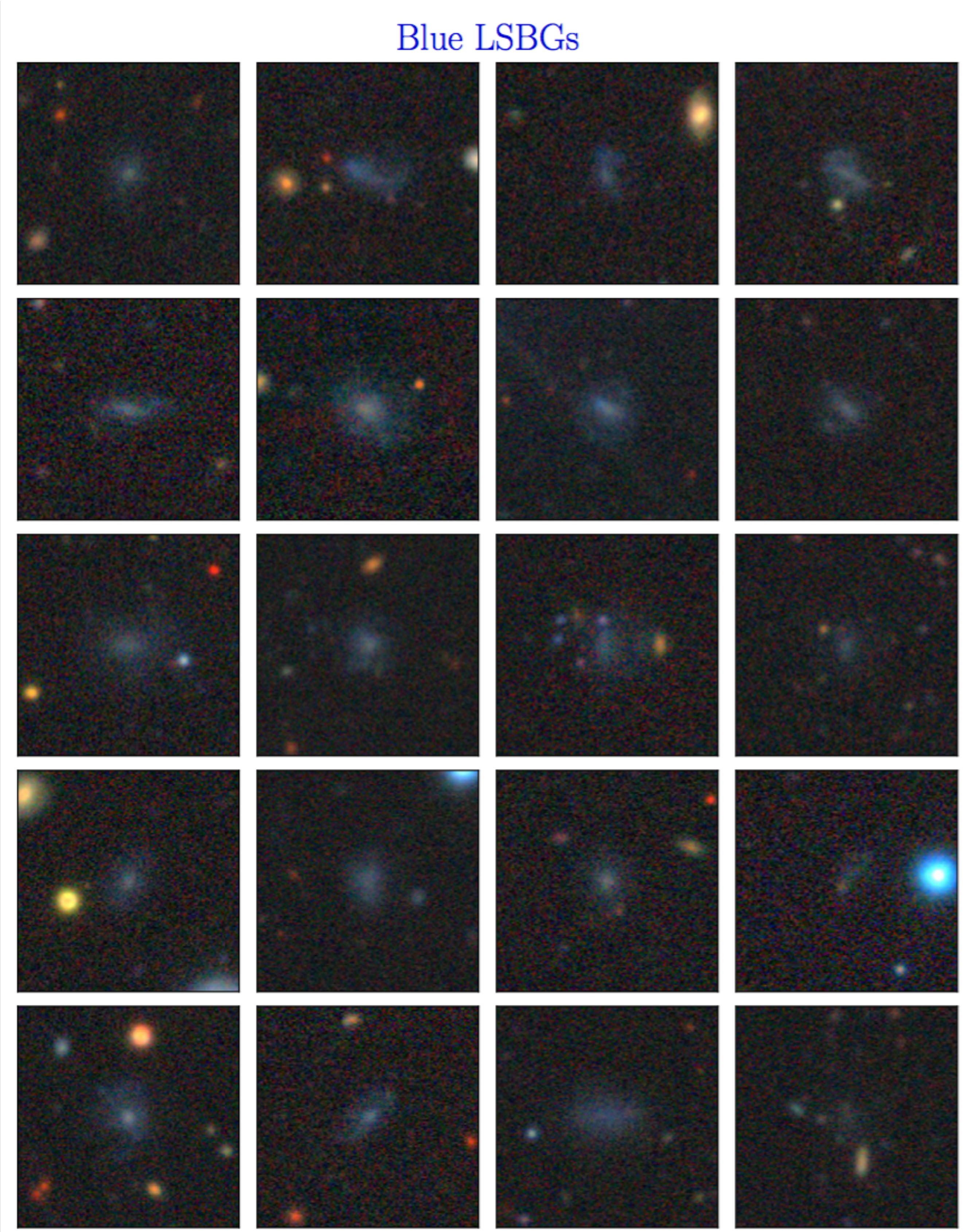
$$g - i = 0.59$$

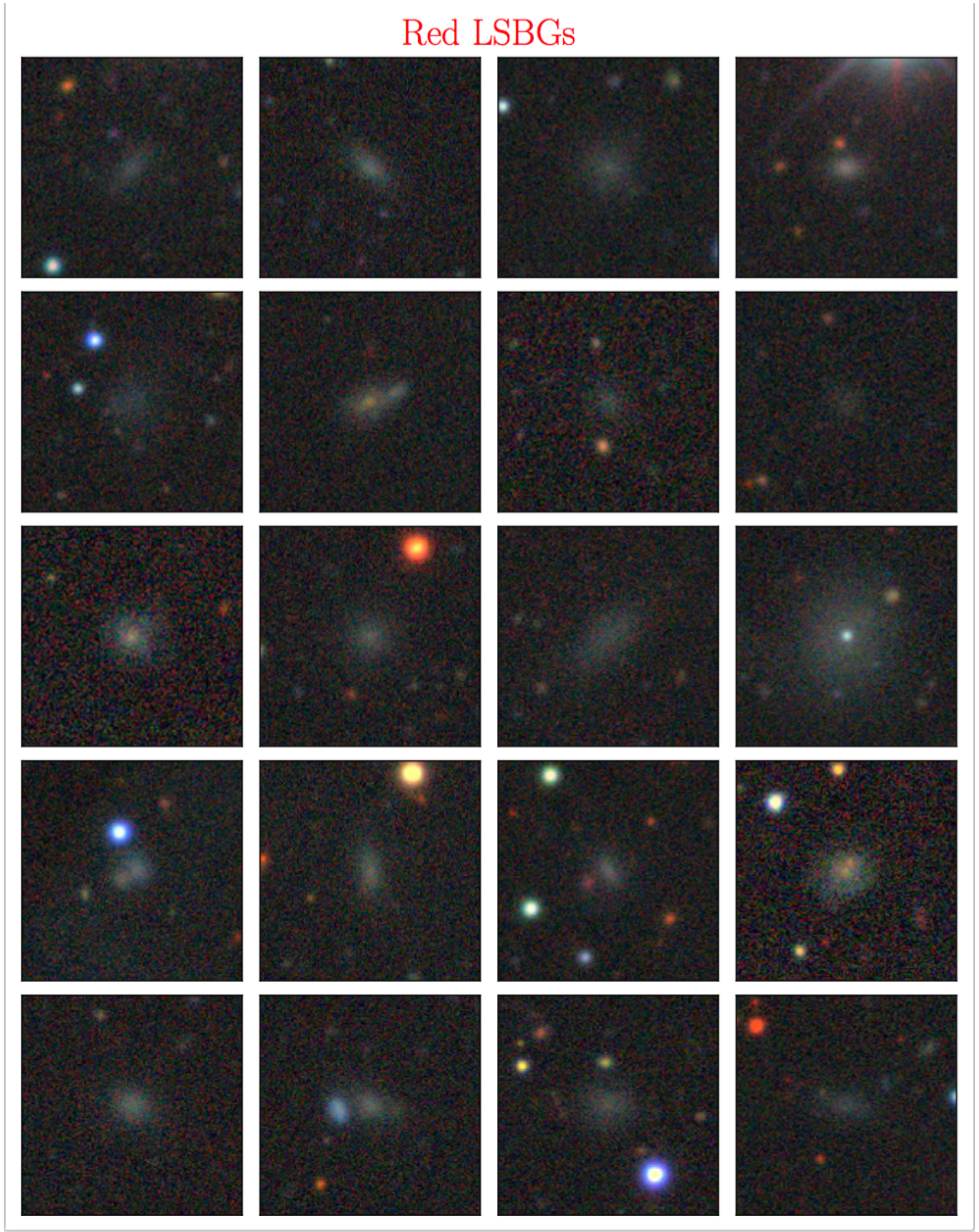
13,829 LSBGs

7,148 LSBGs

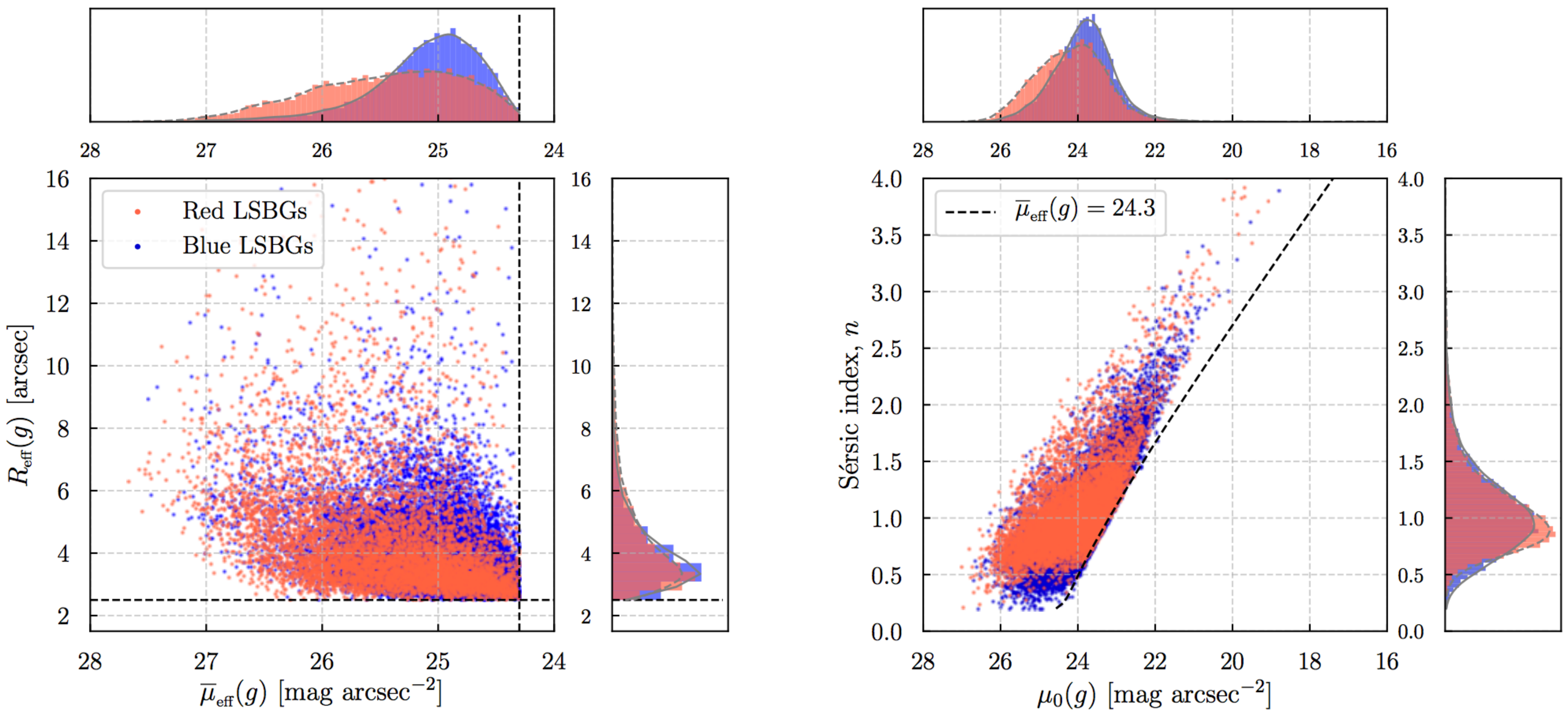
Dimitrios Tanoglidis: dtanoglidis@uchicago.edu

Morphological differences



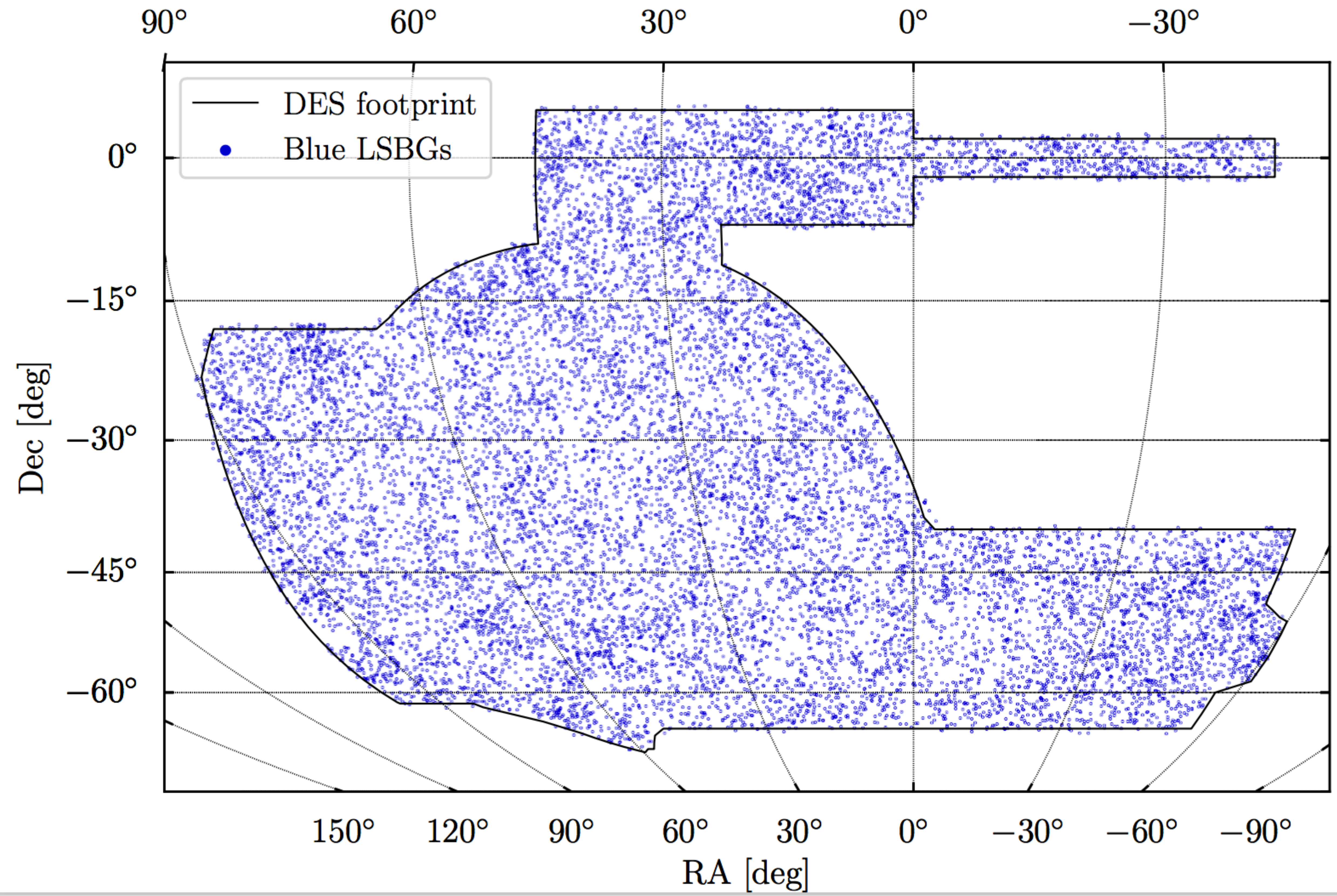


Distribution of structural/photometric parameters



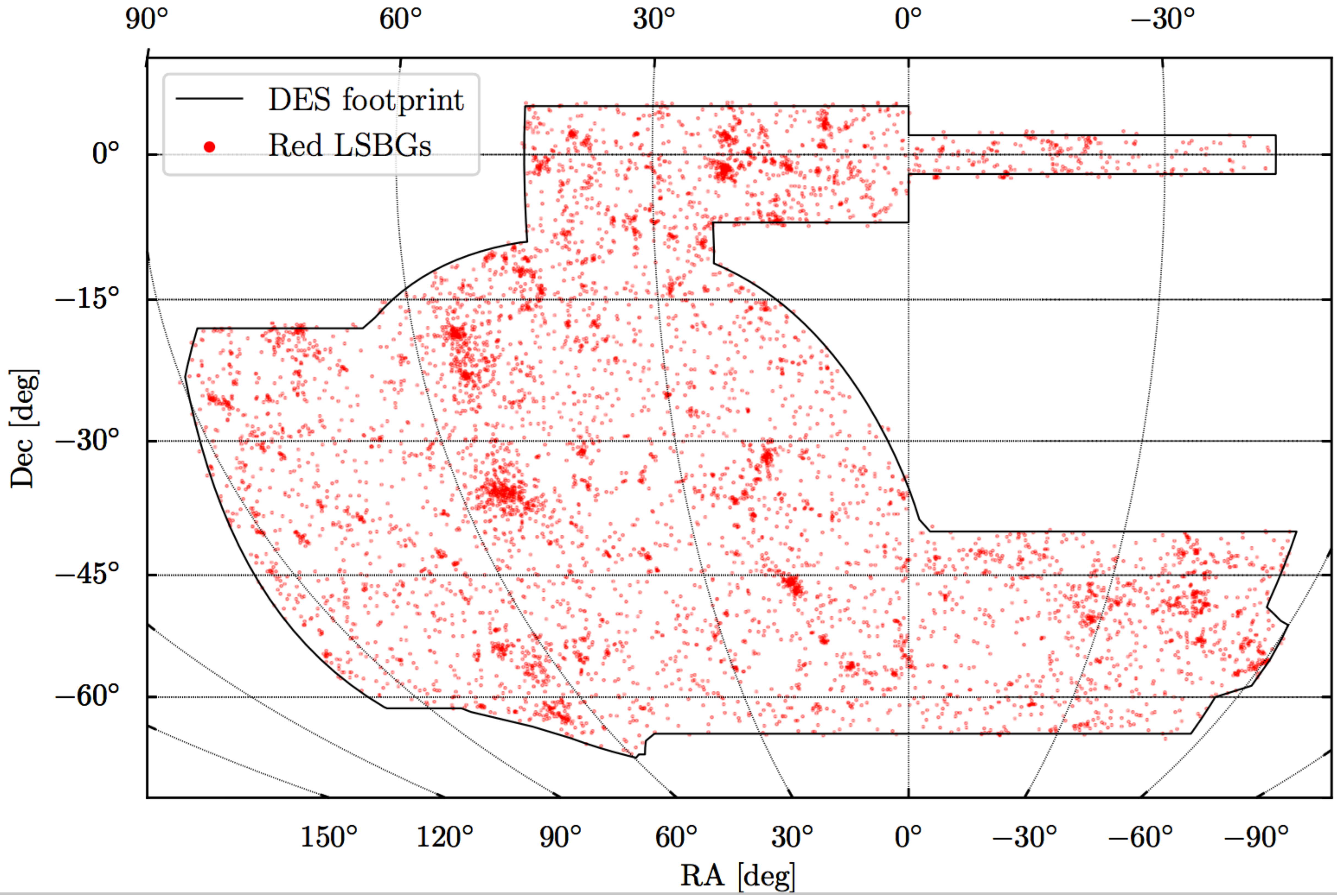
Blue galaxies brighter

Spatial distribution: blue LSBGs



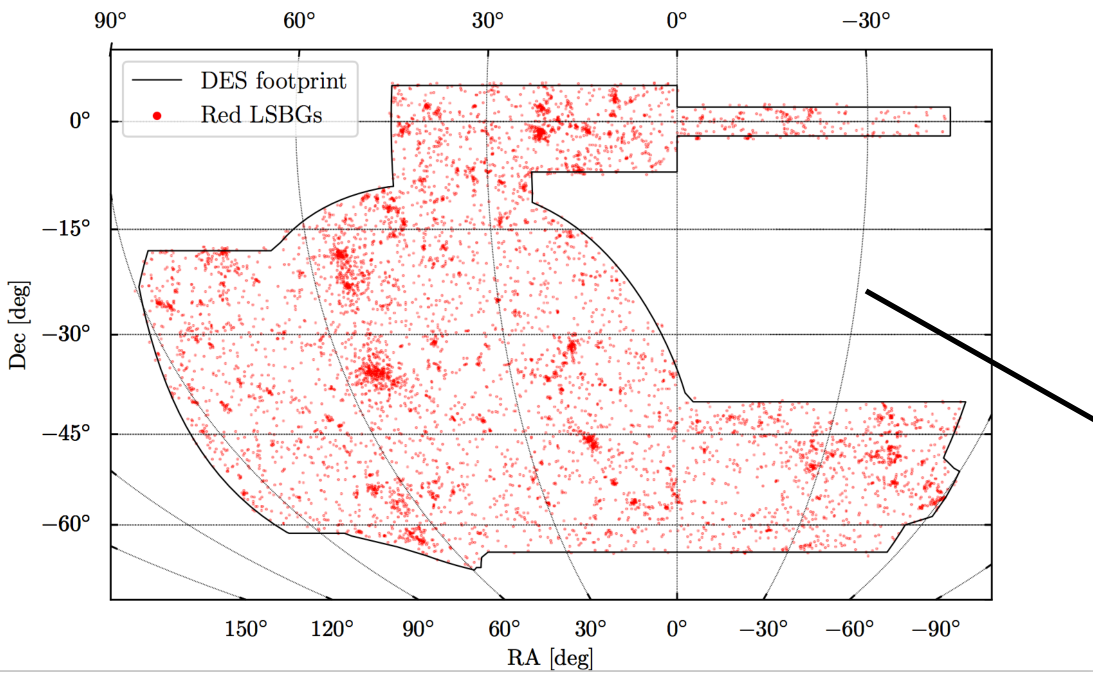
13,829 LSBGs

Spatial distribution: red LSBGs



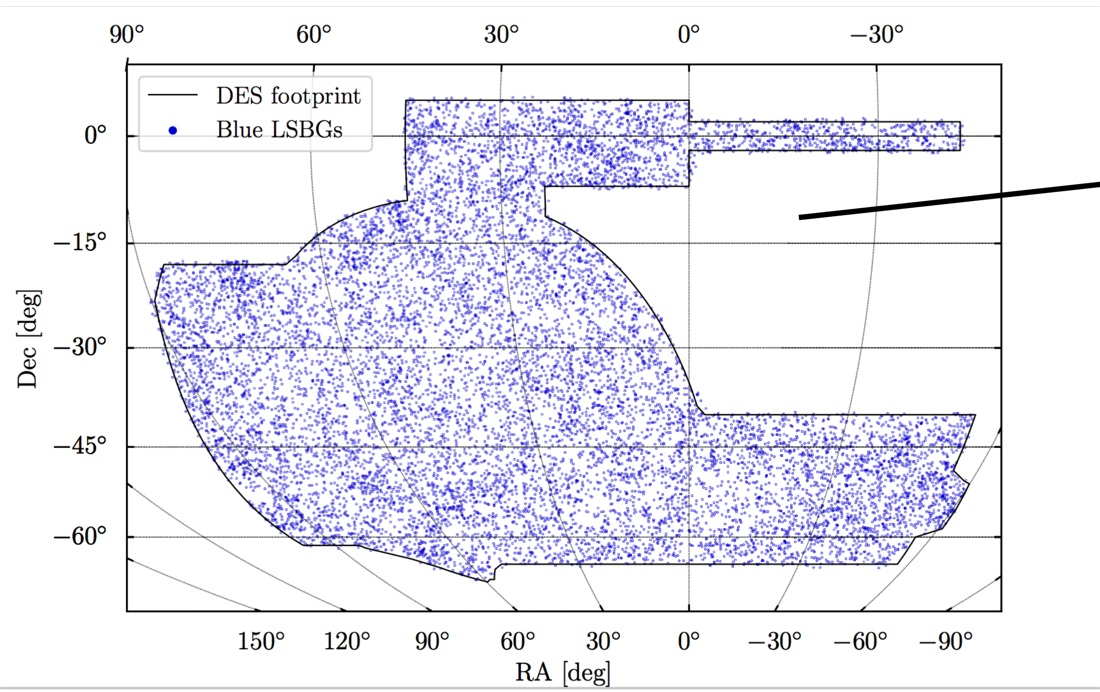
7,148 LSBGs

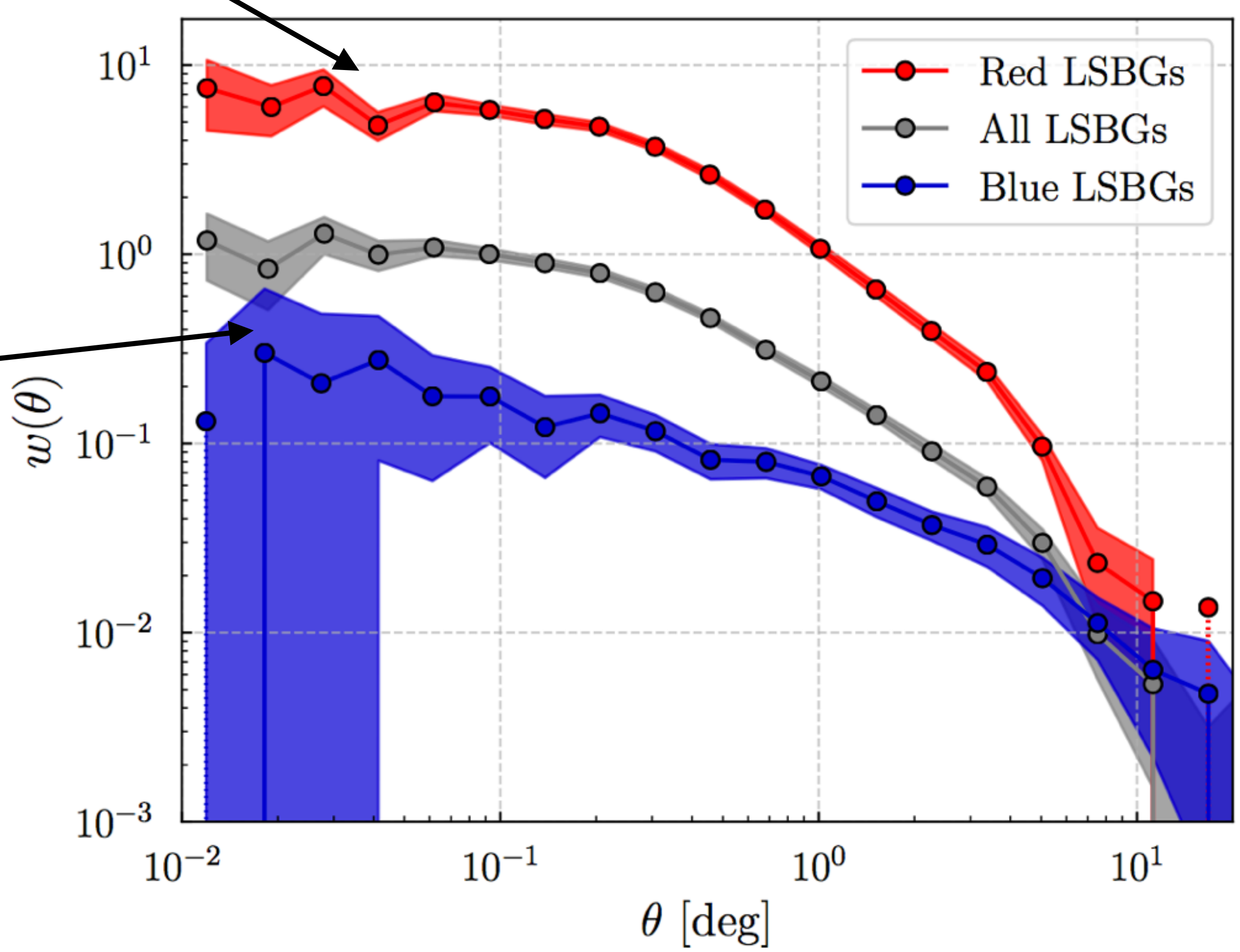
Spatial distribution: Clustering properties quantified



Overdensities as a function of (angular) scale quantified through the 2pt function:

$$w(\theta) = \langle \delta_g(\hat{n}) \delta_g(\hat{n} + \theta) \rangle$$





Spatial distribution: Comparison with HSB catalogs

Two samples:

- A HSB sample from DES data, with:

$$20.0 < \bar{\mu}_{\text{eff}}(g) < 22.0 \text{ mag arcsec}^2$$

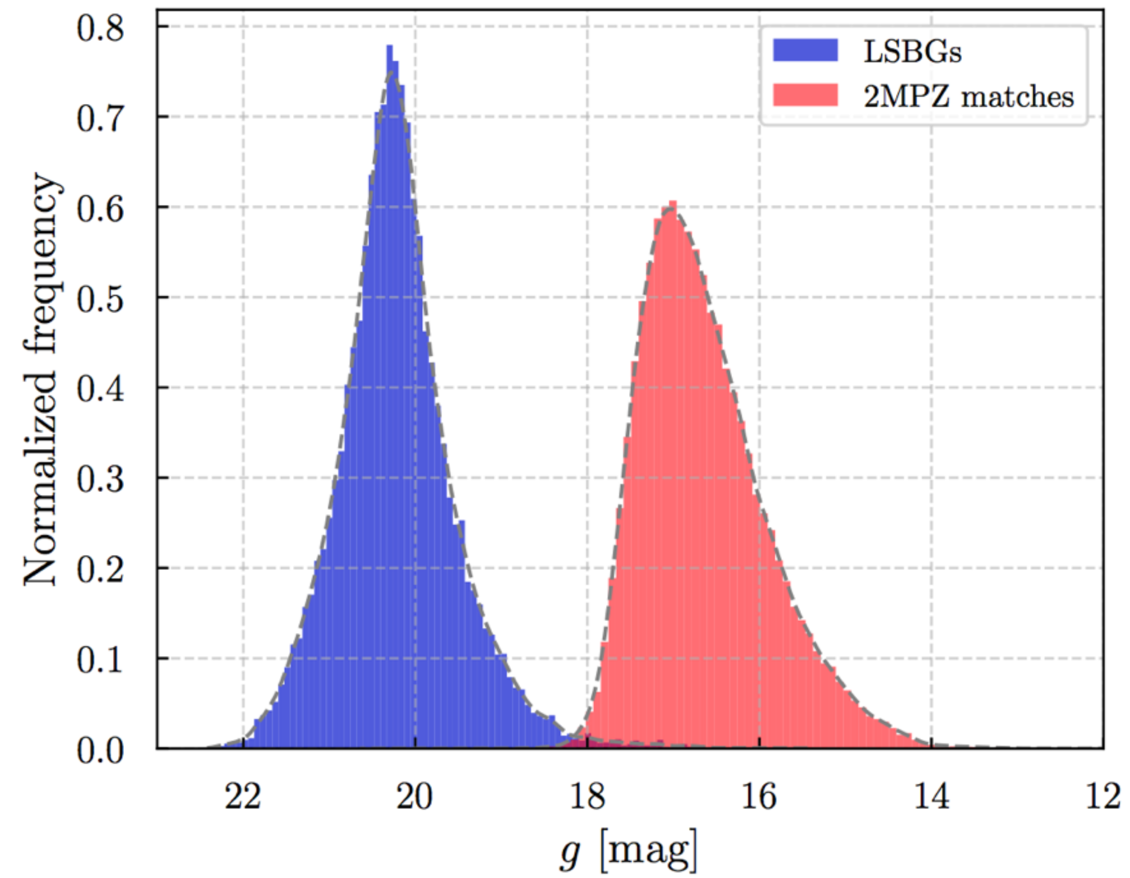
and the same magnitude distribution

- A sample from the 2MPZ catalog

$$19.0 < \bar{\mu}_{\text{eff}}(g) < 23.0 \text{ mag arcsec}^2$$

2MPZ catalog (Bilicki+14)
Local (peak z~ 0.07) accurate photo-z sample (σ ~ 0.015)

Magnitude distributions



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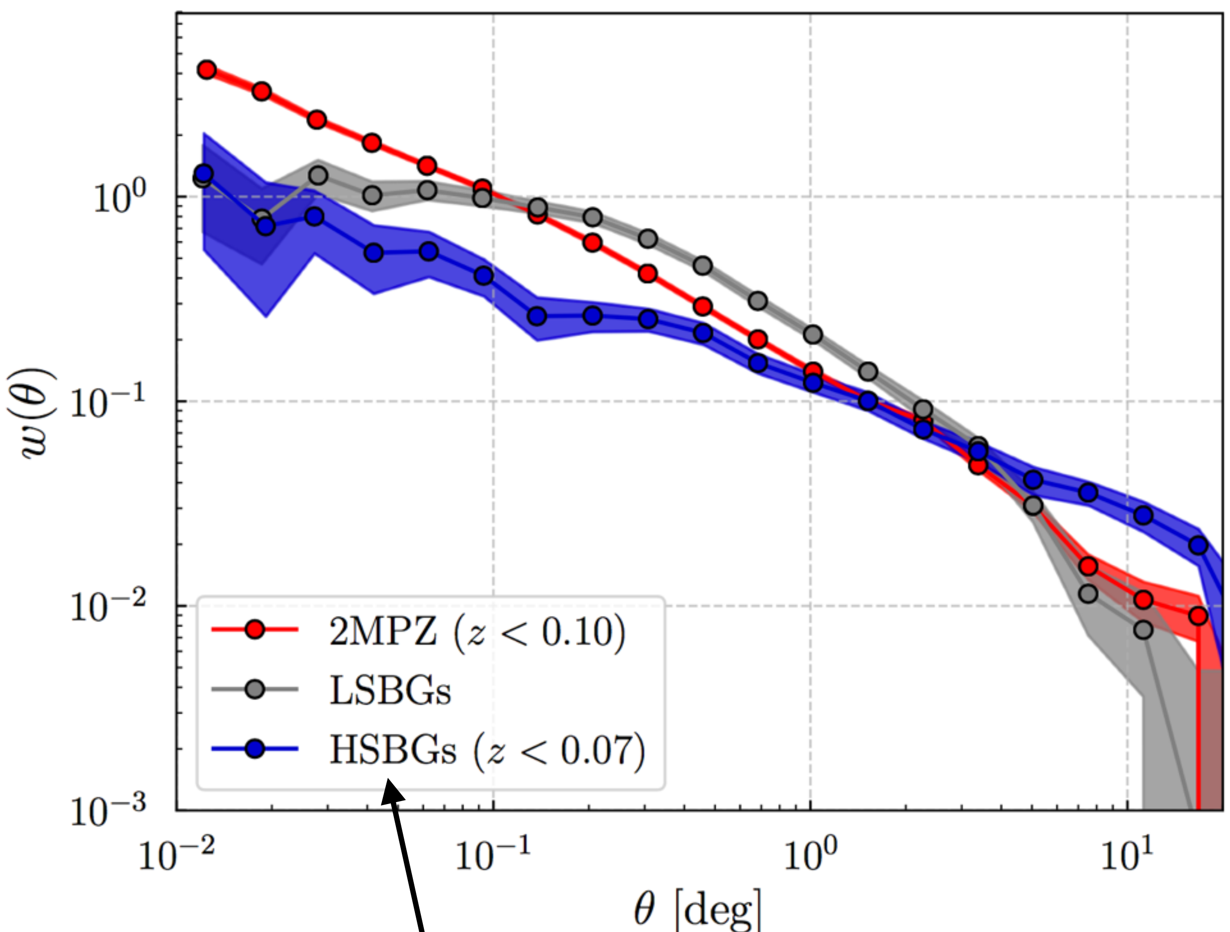
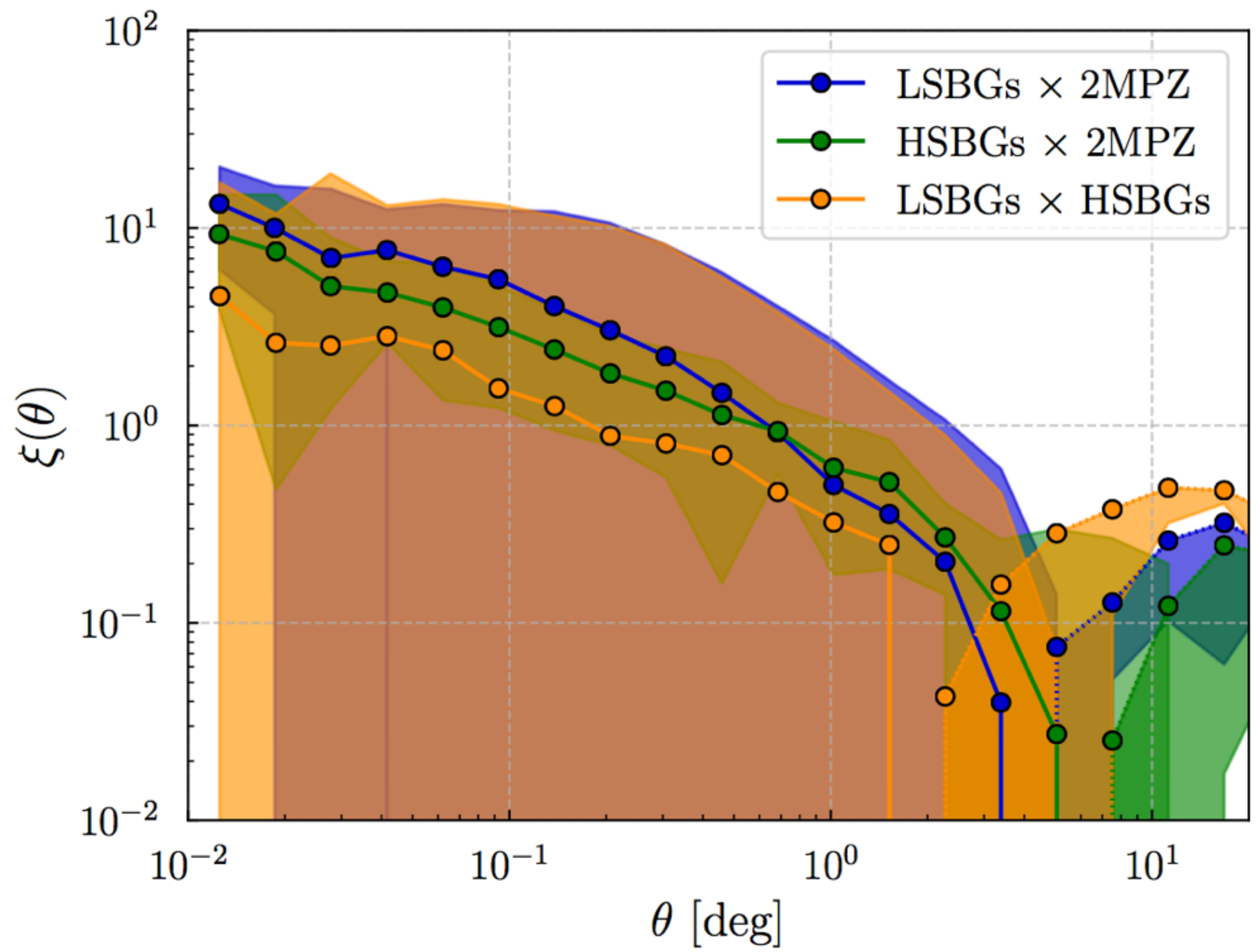
Spatial distribution: Comparison with HSB catalogs

Auto-correlation 2pt functions



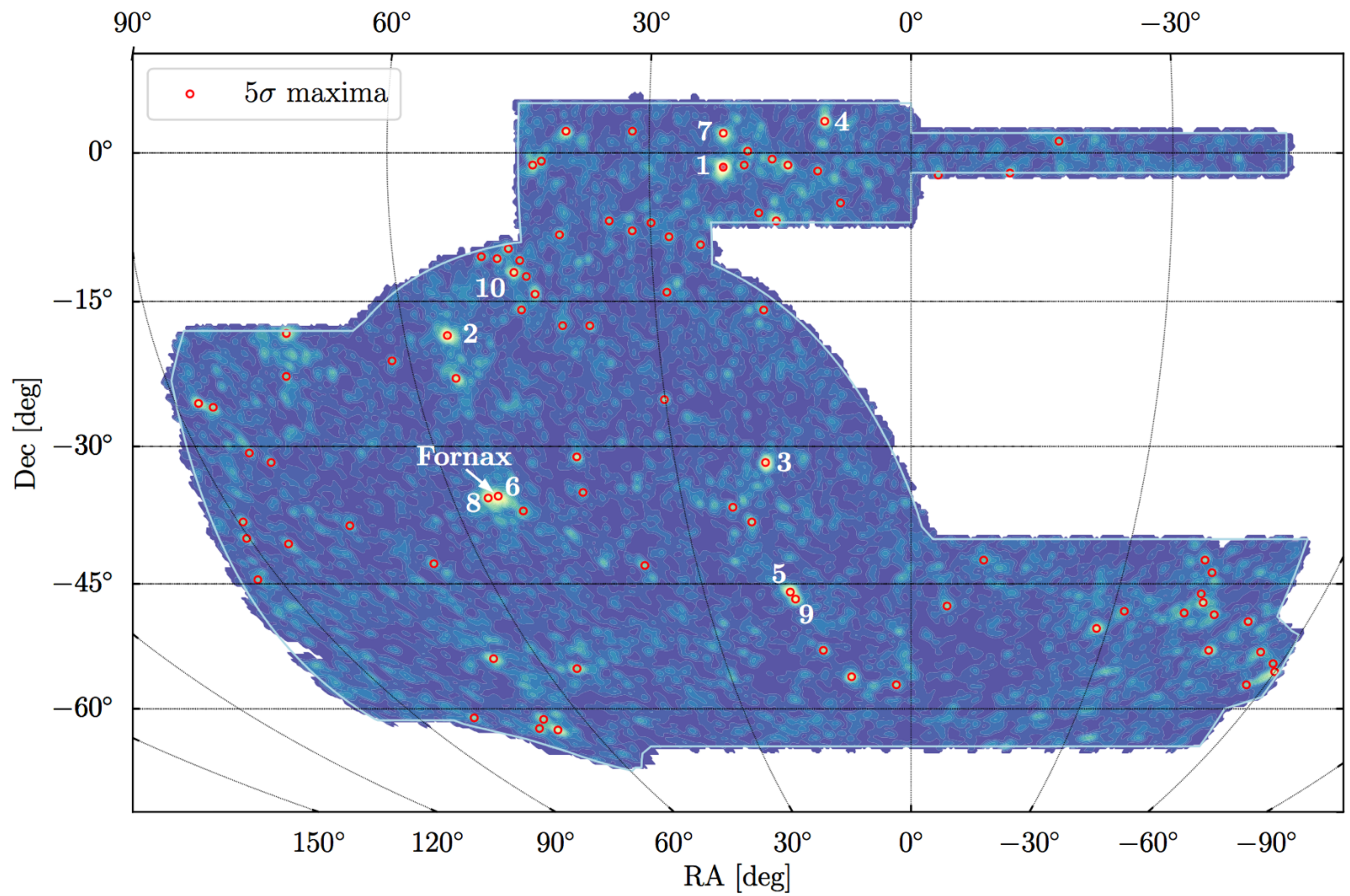
Cross-correlation 2pt functions



Apply redshift cuts

extended LSBGs -> low redshifts

Associating peaks with clusters



KDE map of the LSBG distribution with a **0.3 deg** kernel width

88 peaks 5σ > mean

Associating with clusters, groups and large galaxies provides:

distance information!

Associating peaks with clusters

88 peaks 5σ > mean

- Abell : 32
- NGC: 18
- RXC: 10
- 2Mass: 12
- No assoc: 16

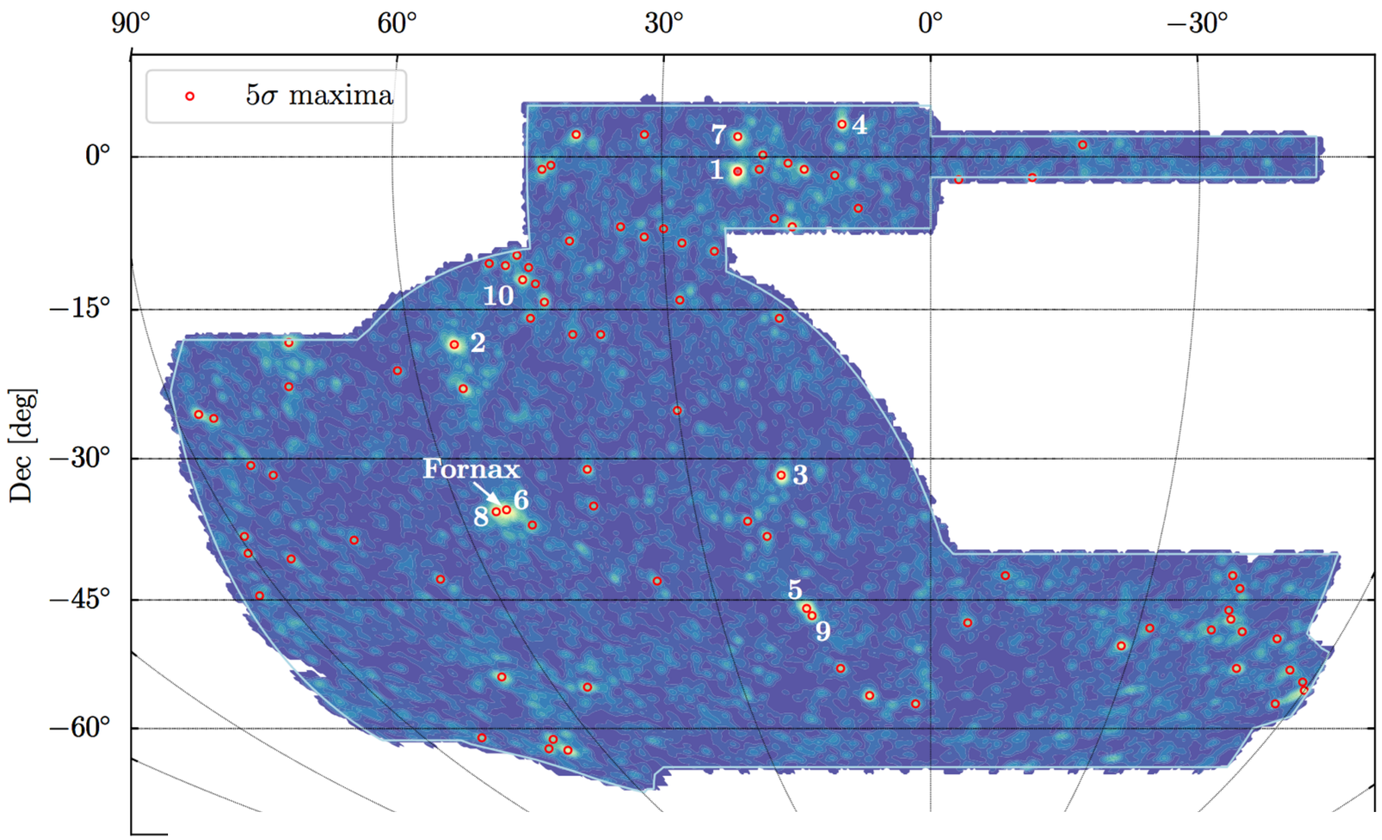
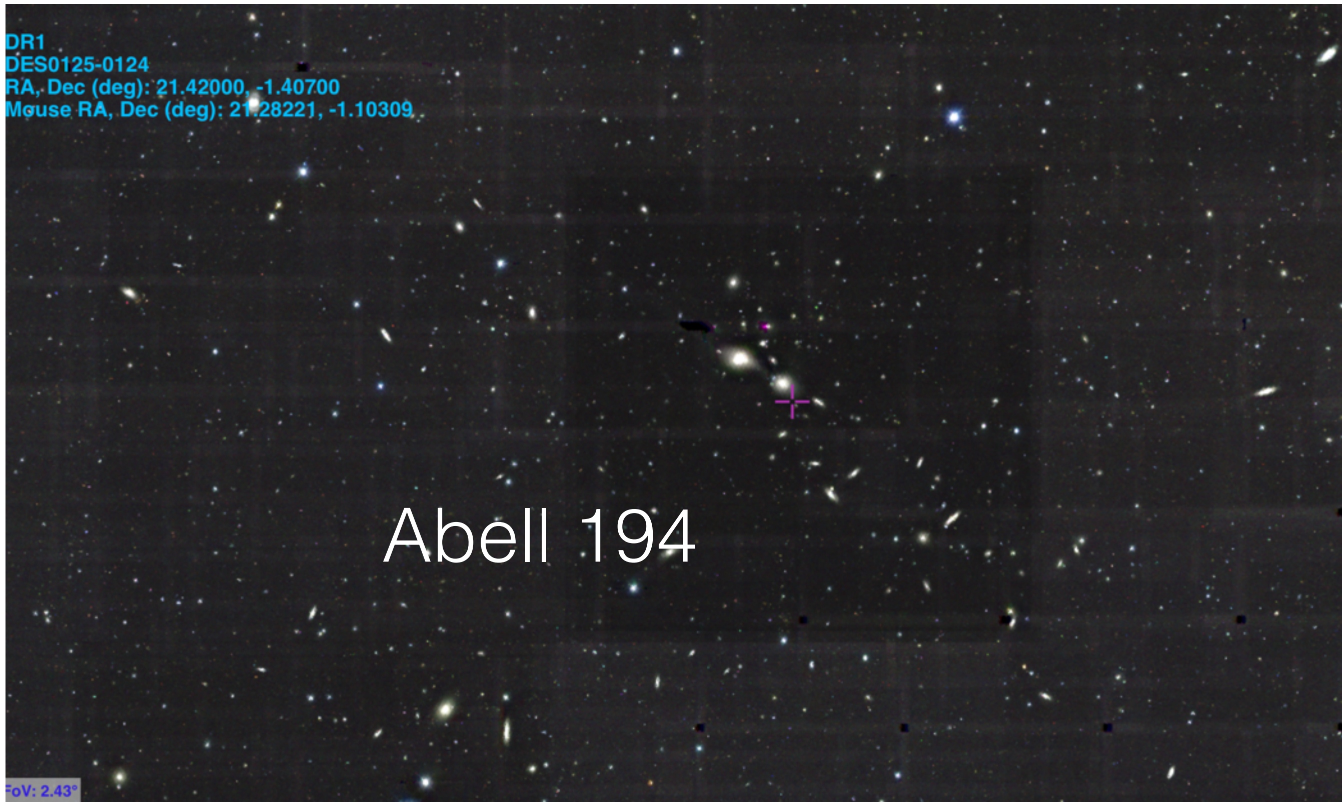
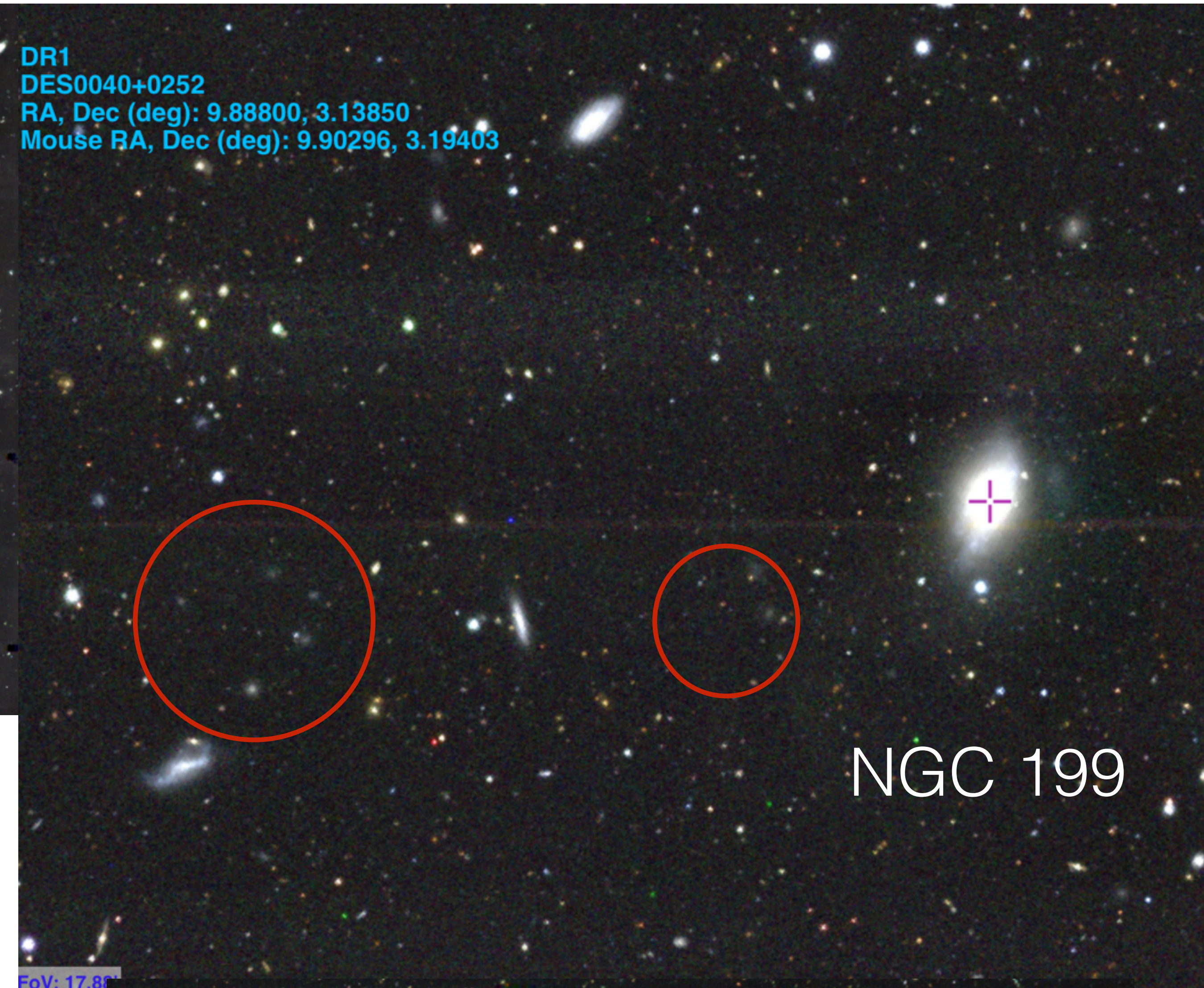


Table 2. Characteristics of the ten most prominent density peaks and their associations

Peak Number	$(\mathrm{RA,Dec})_{\mathrm{peak}}$ (deg,deg)	Best Association	$(\mathrm{RA,Dec})_{\mathrm{assoc}}$ (deg,deg)	Redshift z	Distance (Mpc)	$N(< 0.5^{\circ})$
1	(21.5012, -1.4286)	Abell 194	(21.4200, -1.4072)	0.018	75.07 ± 5.26	65
2	(54.9388, -18.4712)	RXC J0340.1-1835	(55.0475, -18.5875)	0.0057	23.41 ± 1.64	45
3	(18.4983, -31.7043)	Abell S141	(18.4758, -31.7519)	0.020	84.80 ± 5.94	41
4	(9.8887, 3.1829)	NGC 199	(9.8882, 3.1385)	0.0153	62.81 ± 4.41	39
5	(17.4972, -45.9398)	Abell 2877	(17.6017, -45.9228)	0.0247	106.61 ± 7.45	39
6	(53.9377, -35.3133)	Fornax (Abell S373)	(54.6162, -35.4483)	0.0046	18.97 ± 1.33	32
7	(21.5017, 1.7794)	RXC J0125.5+0145	(21.3746, 1.7627)	0.01739	72.32 ± 5.10	34
8	(55.3393, -35.5138)	Fornax (Abell S373)	(54.6162, -35.4483)	0.0046	18.97 ± 1.33	27
9	(16.8965, -46.7418)	Abell 2870	(16.9299, -46.9165)	0.0237	102.03 ± 3.89	30
10	(46.1290, -12.0551)	NGC 1200	(45.9770, -11.9918)	0.01305	57.03 ± 4.01	30

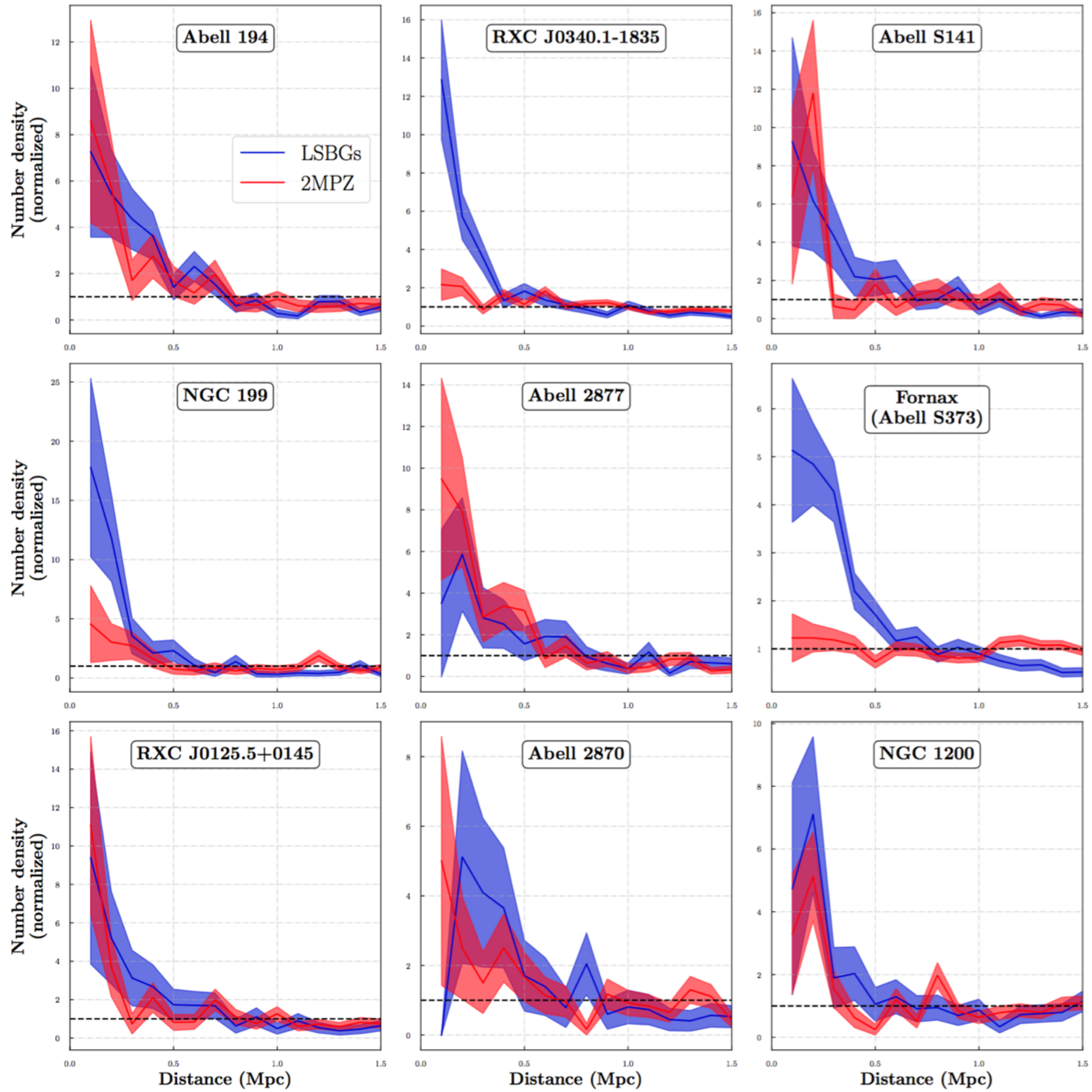

DR1
DES0125-0124
RA, Dec (deg): 21.42000, -1.40700
Mouse RA, Dec (deg): 21.28221, -1.10309
Abell 194
FoV: 2.43°


DR1
DES0040+0252
RA, Dec (deg): 9.88800, 3.13850
Mouse RA, Dec (deg): 9.90296, 3.19403
NGC 199


DR1
DES0557-3749
RA, Dec (deg): 89.37708, -38.12030
Mouse RA, Dec (deg): 89.44769, -38.05467
???
FoV: 35.97'


?

Application I:Radial Profiles



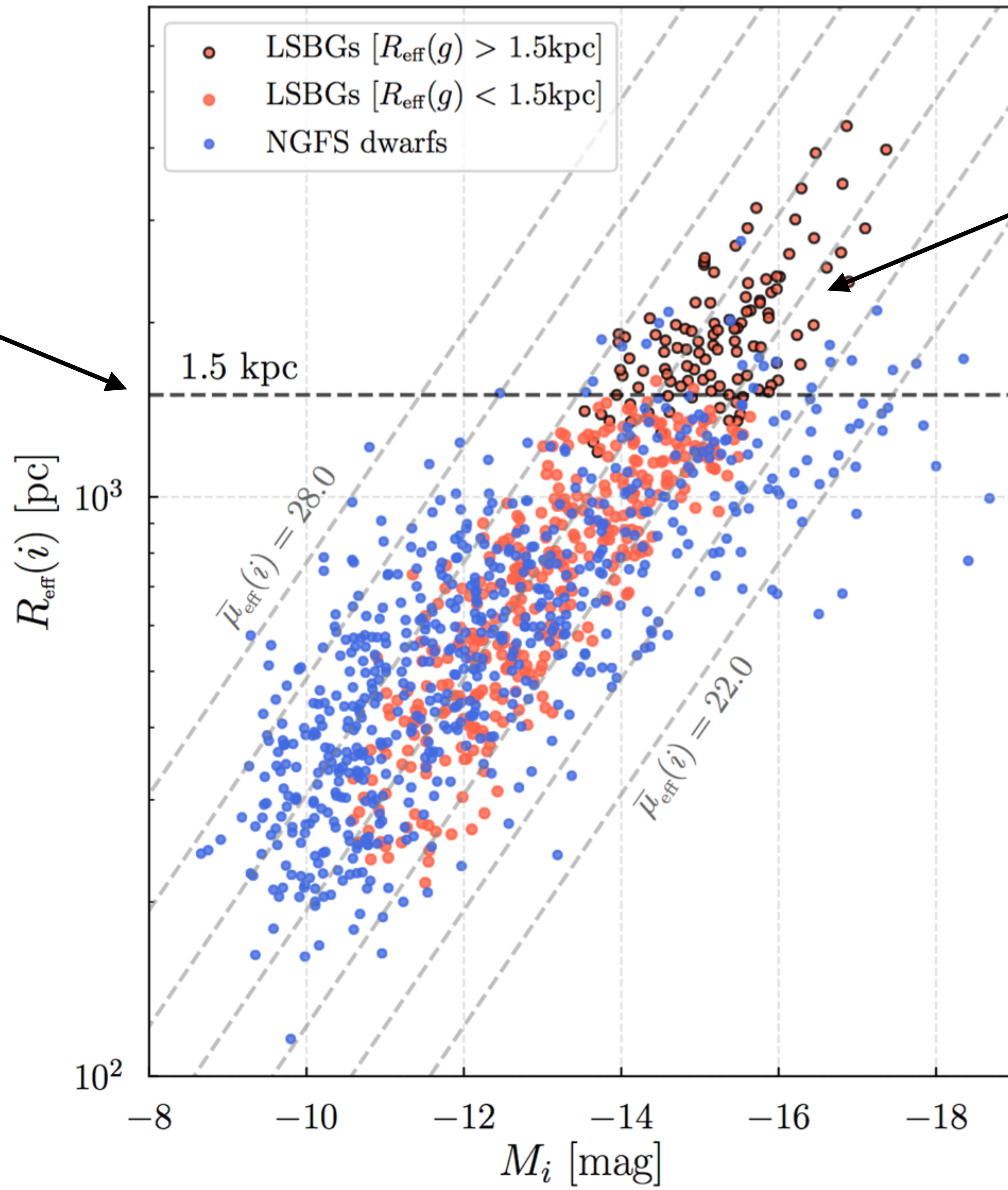
Distribution of LSB and HSB galaxies: similar in most cases

Application II: Size-Luminosity Relation

Distance information —> physical size of the LSBGs

Natural continuation of the dwarf population

UDG limit

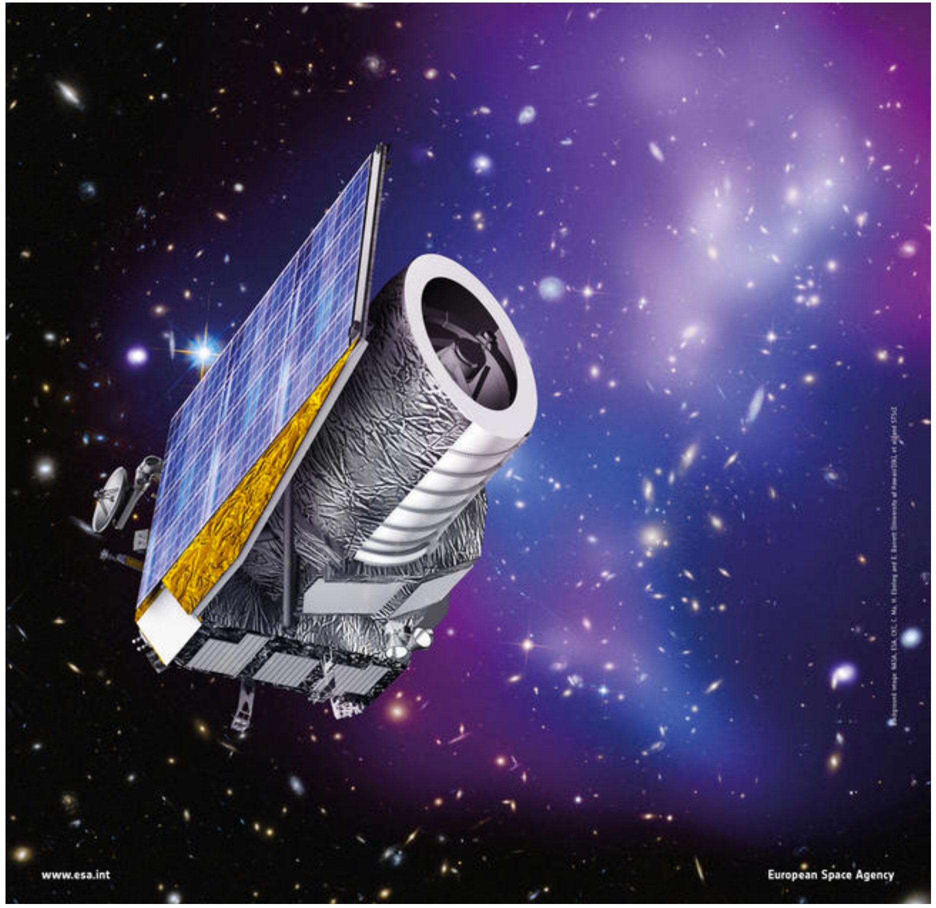


Comparison
with the NGFS dwarfs

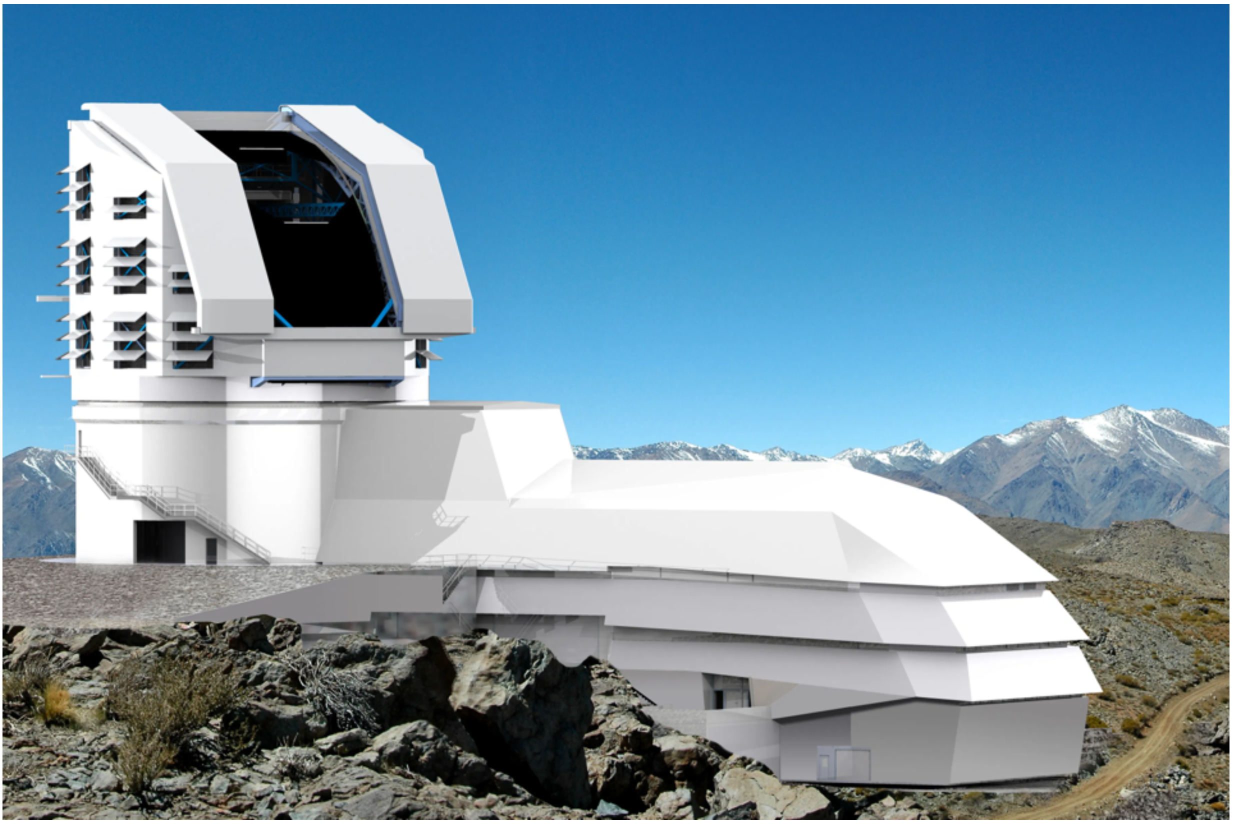
108 UDGs

According to the physical size definition

Part III: The Future

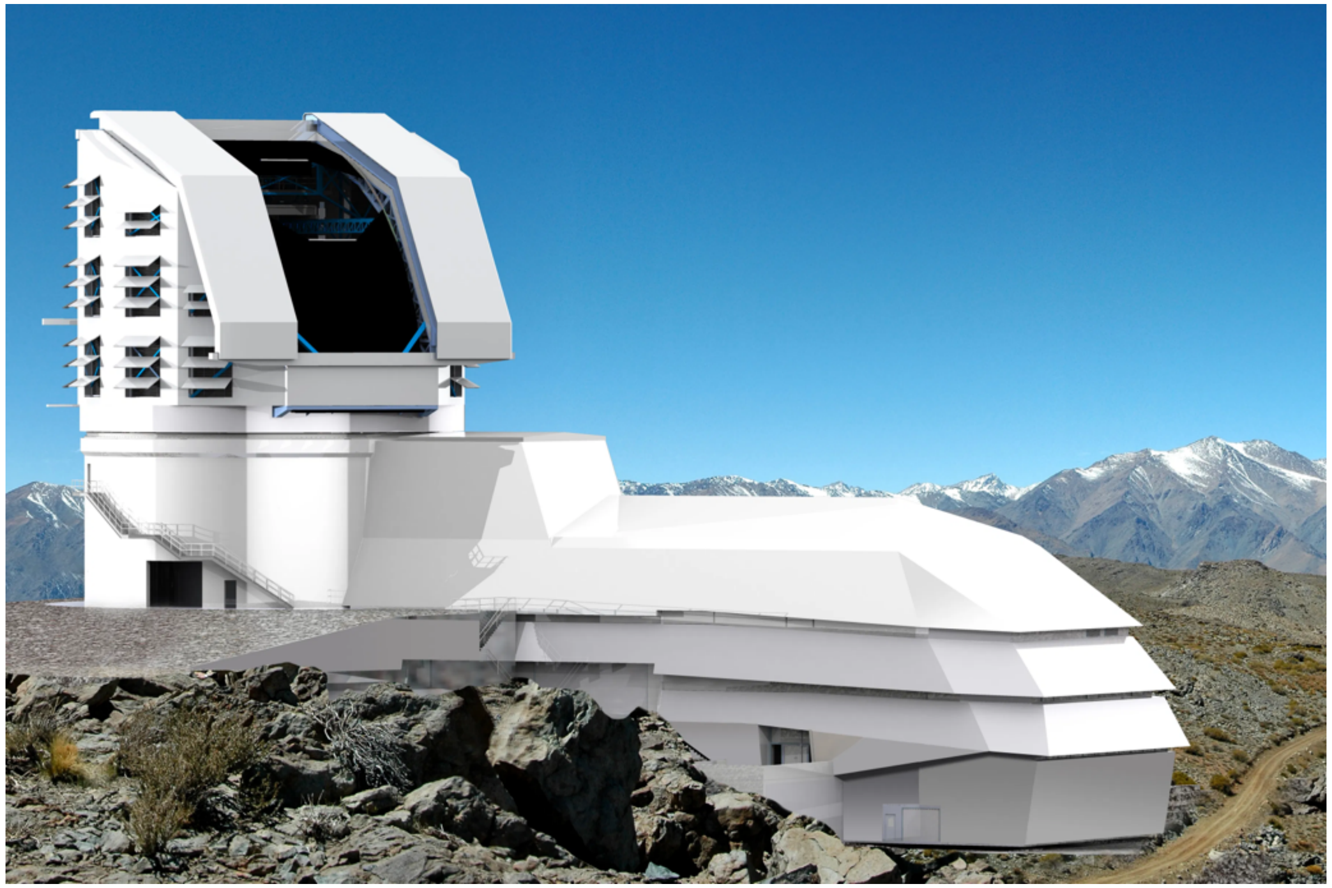


Euclid survey



Vera C. Rubin observatory

Legacy Survey for Space and Time (LSST)
on the
Vera C. Rubin Observatory



Area ~ 2000 deg^2

u,g,r,i,z,Y optical survey

5-σ point source depth:
$g \sim 27.4$, $i \sim 26.8$

Data: 20TB/night

20 Billion galaxies after 10 years!

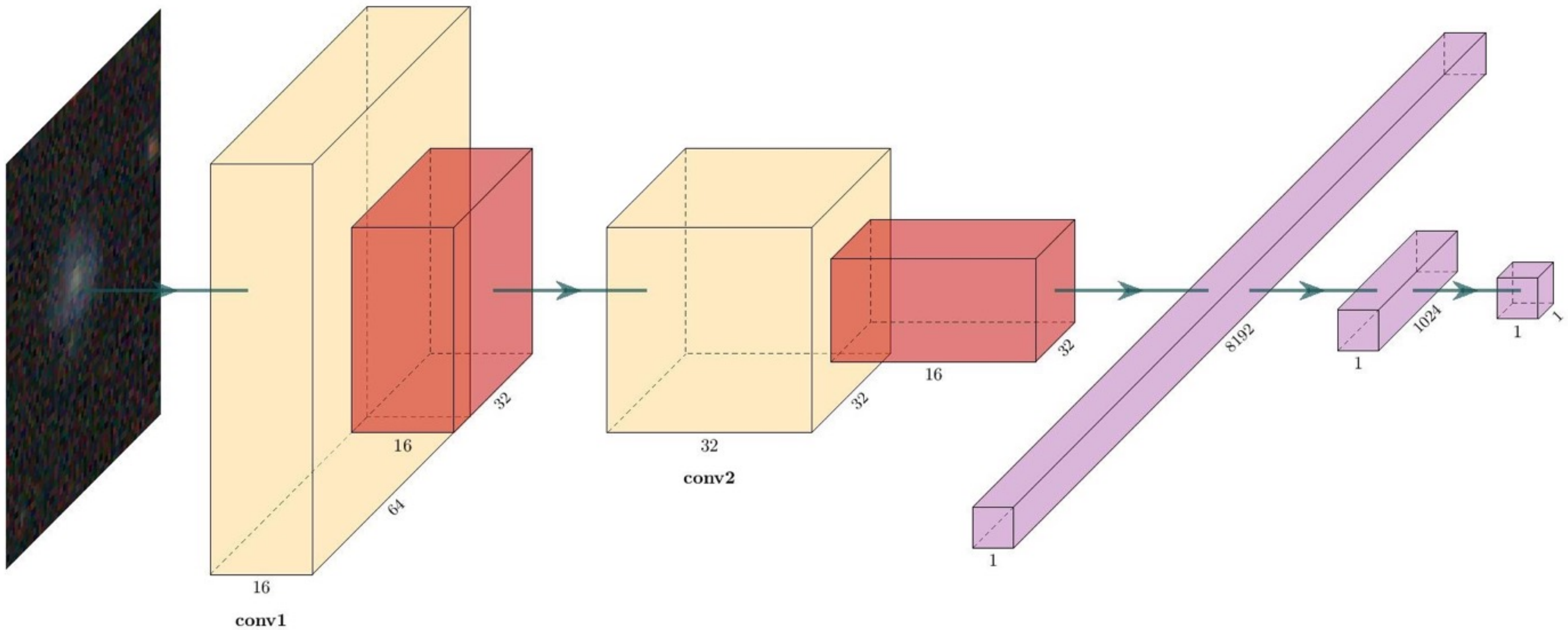
BIG data

Visual inspection??

Source: https://www.lsst.org/scientists/keynumbers

Convolutional Neural Networks

(LeCun+ 98)



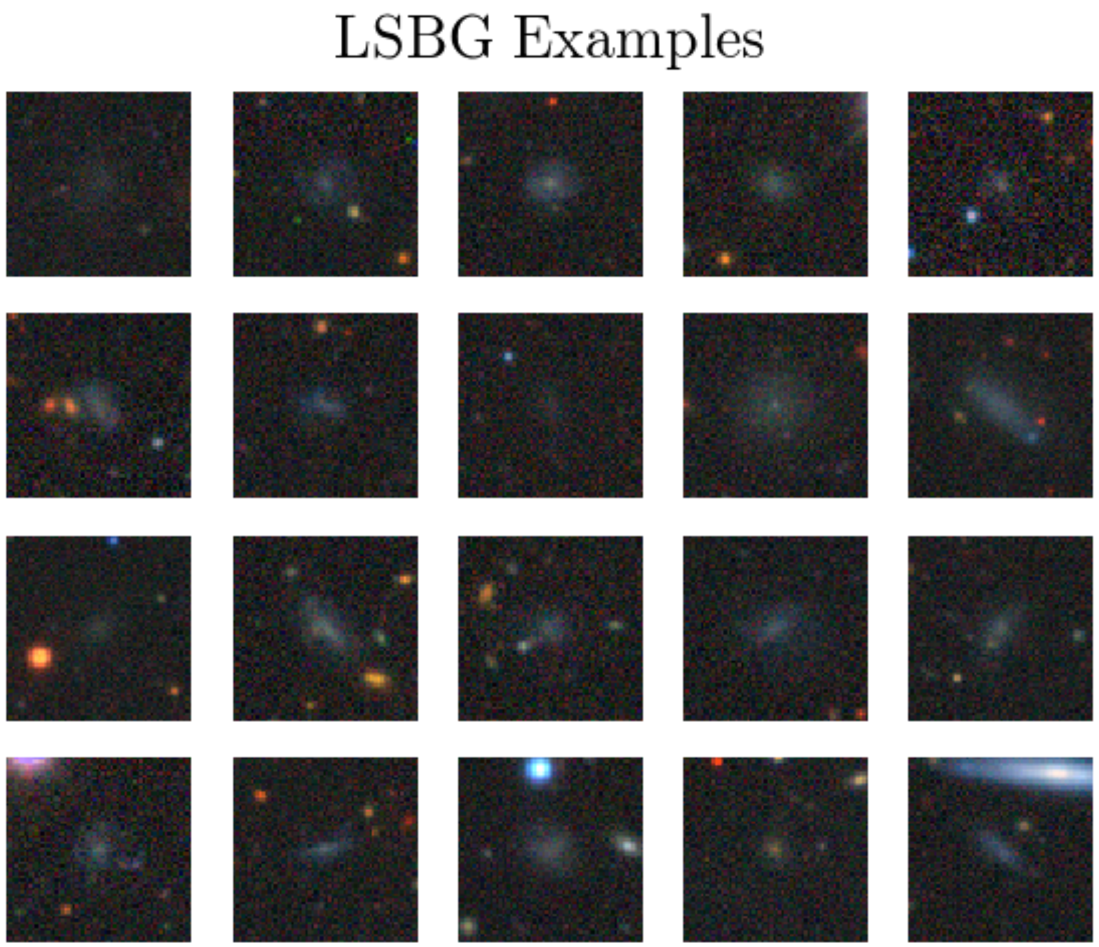
Automatic Classification at the image level

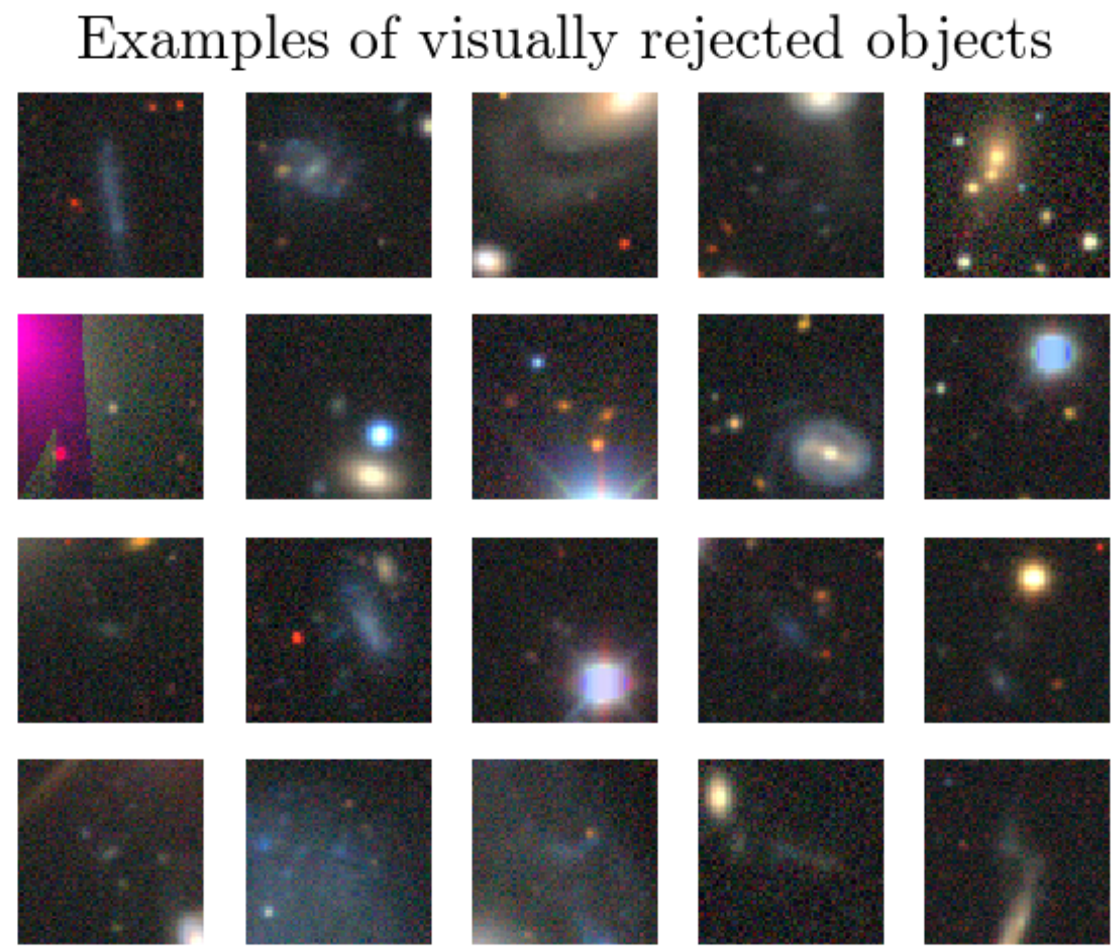
Applications in astronomy:

- Star-galaxy separation
- Strong lensing identification
- Merging galaxies
- ....

Requires a **large** number of labeled training instances (examples)

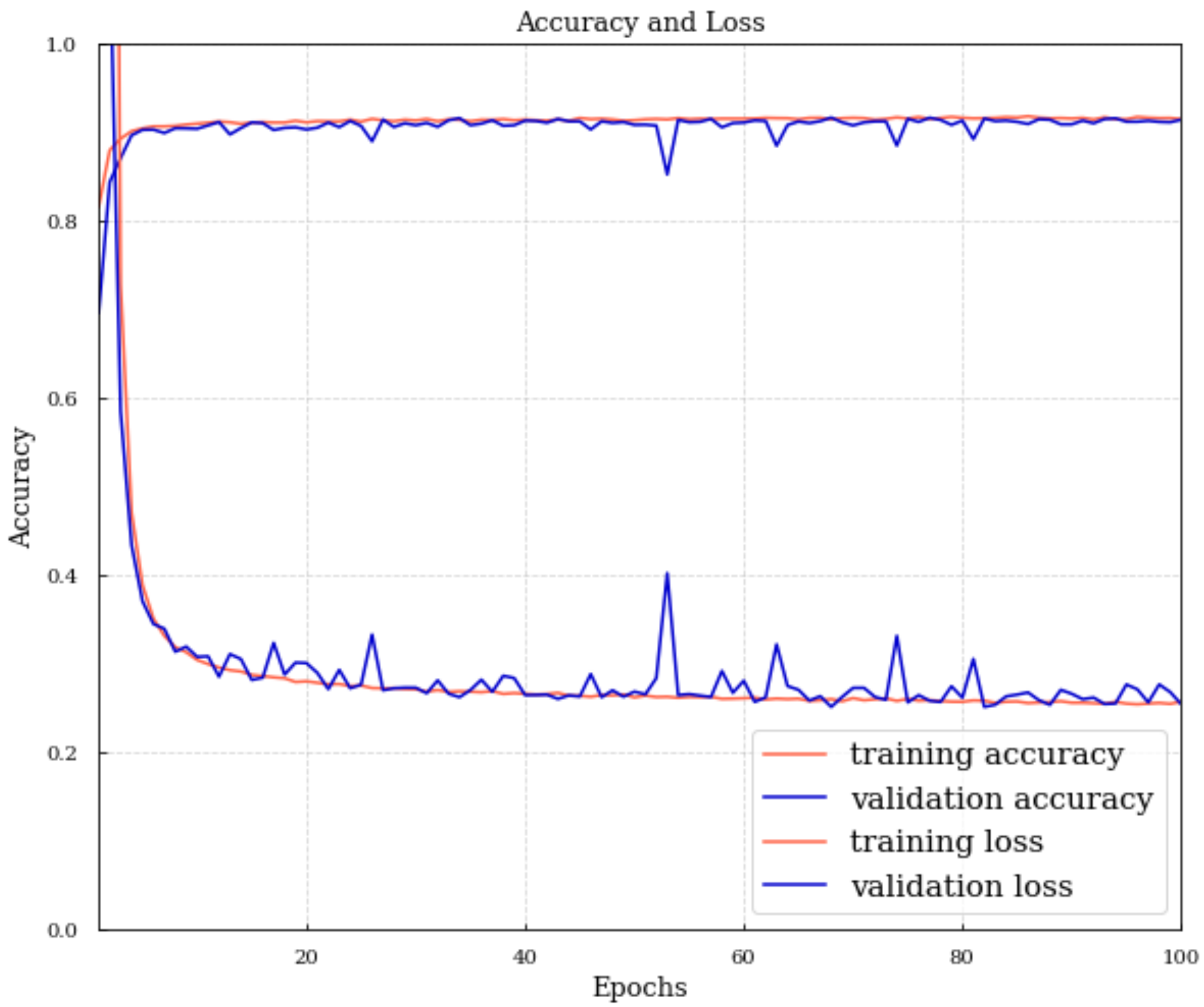
CNNs require a **large** number of labeled training instances (examples)

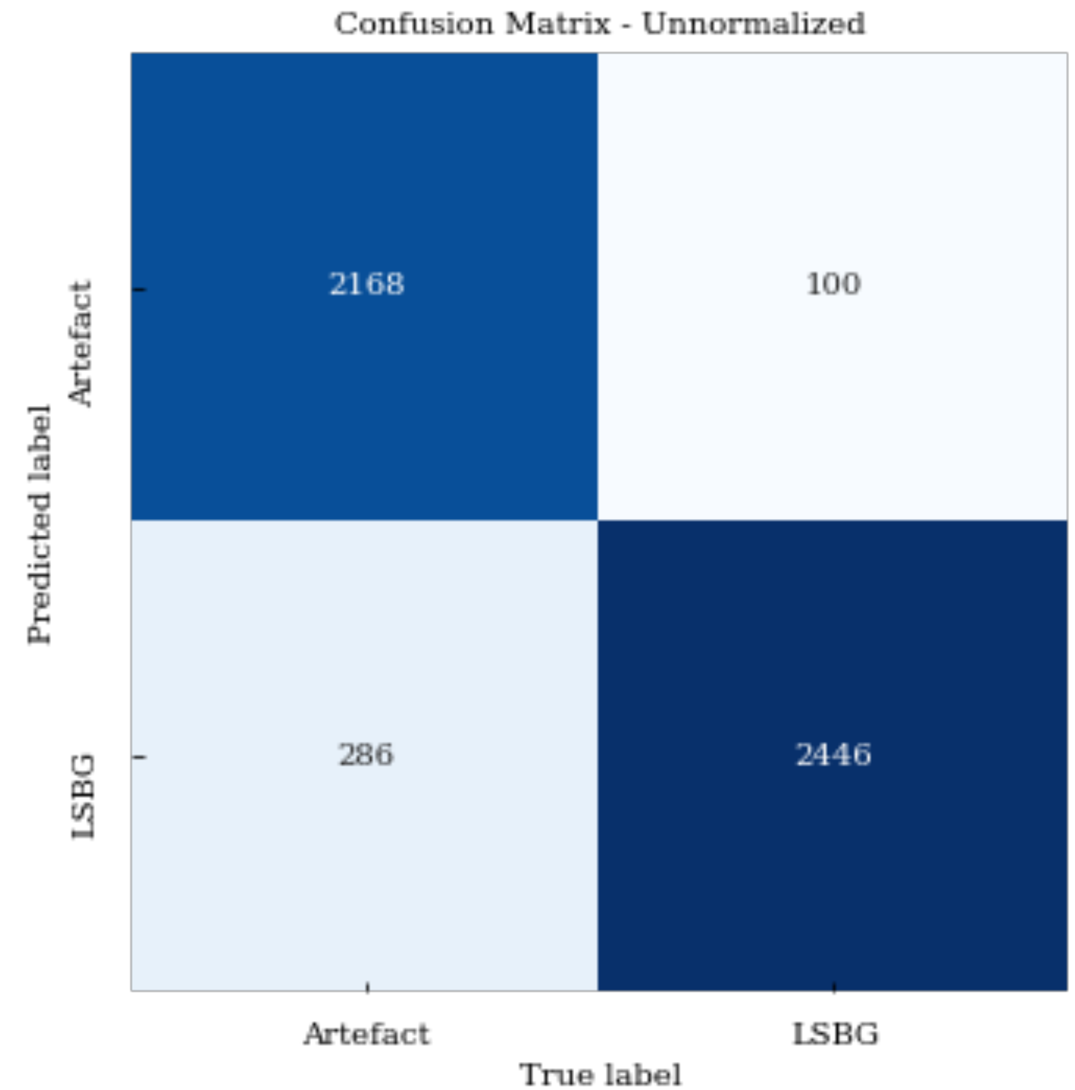




20000 positive + **20000** negative examples
(manually classified/annotated)

Preliminary results





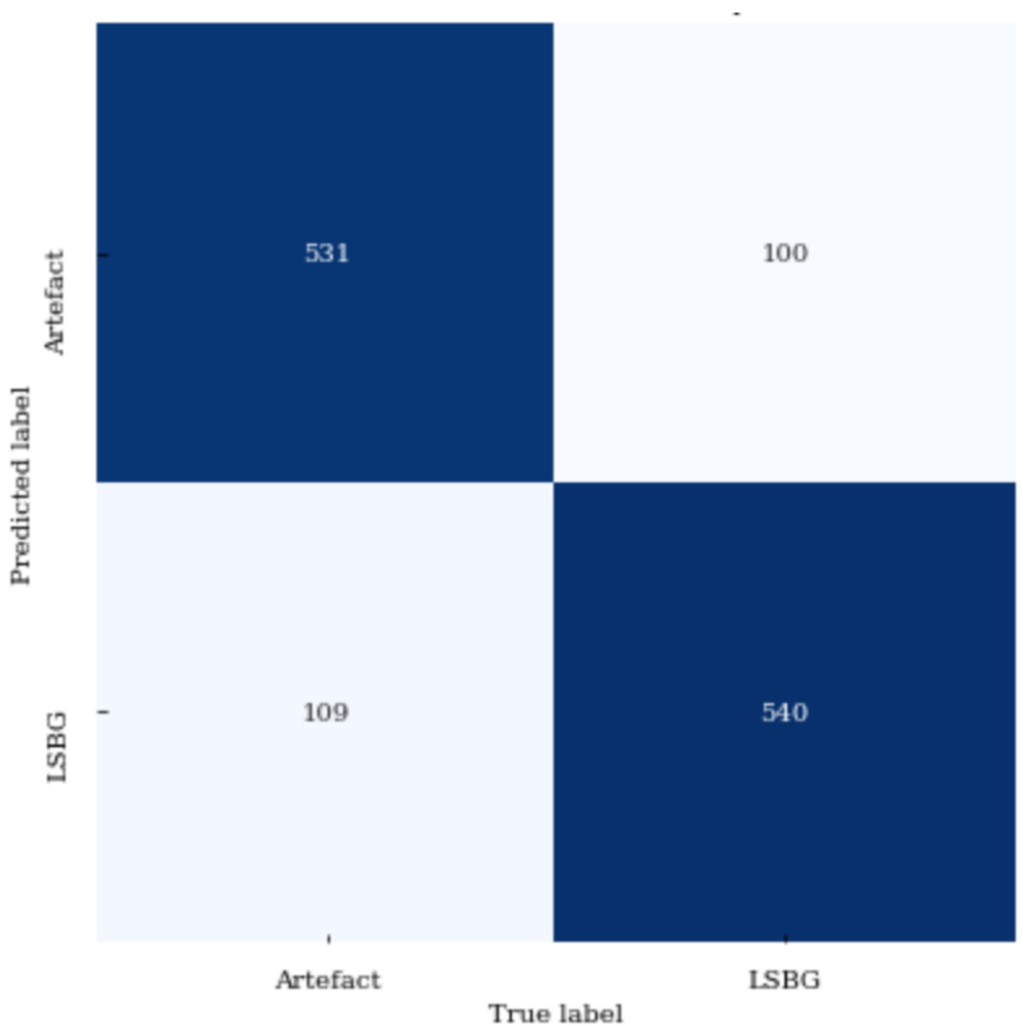
Train for 100 epochs

Training set: **30000**
Validation set: **5000**
Test set: **5000**

Accuracy ~ **92.3%**
Purity ~ **89.5%**

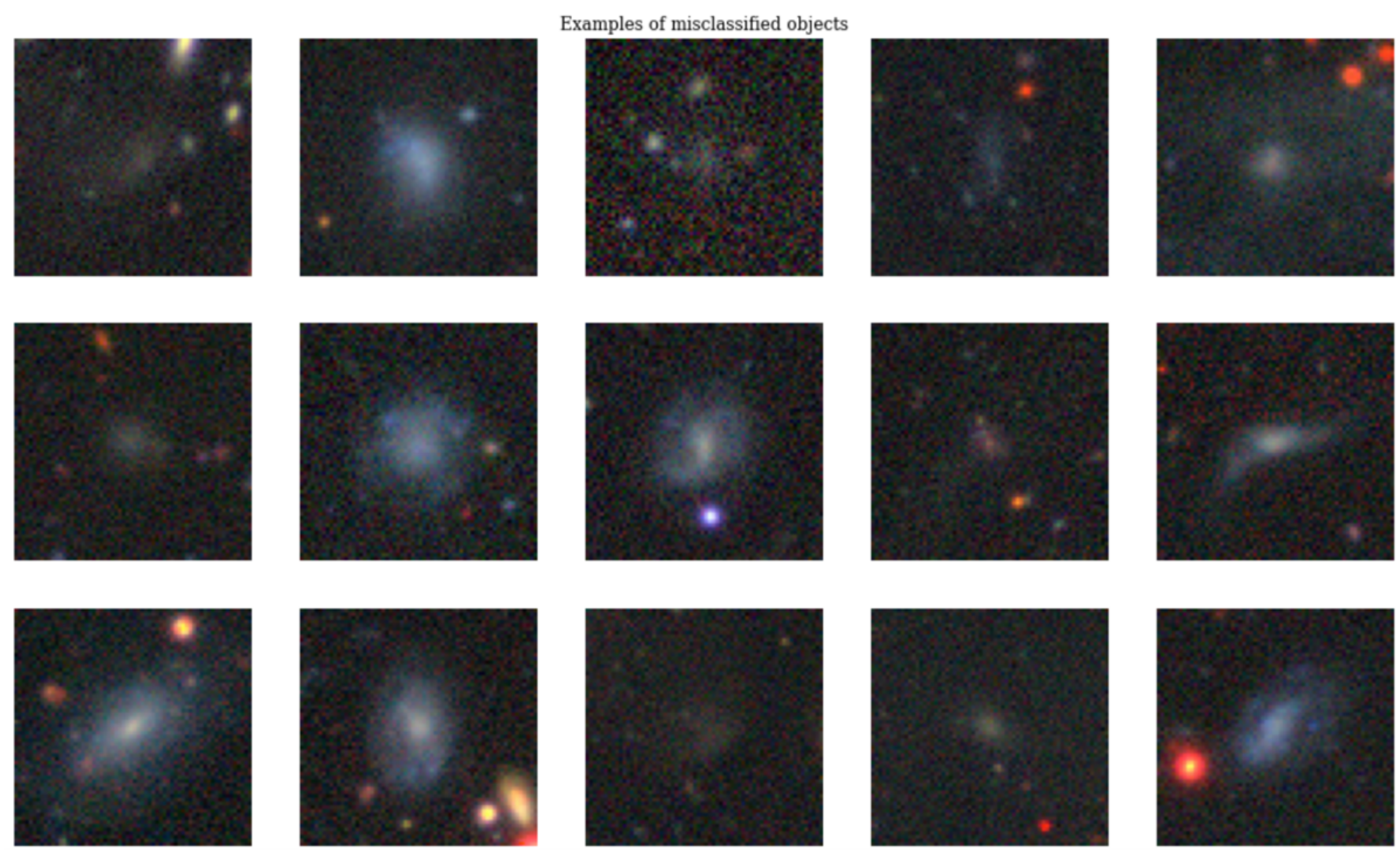
Transfer learning

Train on DES, classify HSC examples



Accuracy ~**83.7%**
Purity ~ **83.2%**

Misclassified (?)



Improvement:
domain adaption

Other future directions

- Photometric redshift (distance) estimation for LSBGs
- Mass estimation through weak lensing
- LSBG clusters?
- Comparison with theory / galaxy formation models
- Spectroscopy for dynamical mass estimates
- Distances from cross correlations

The future is **FAINT!**

A great collaboration!

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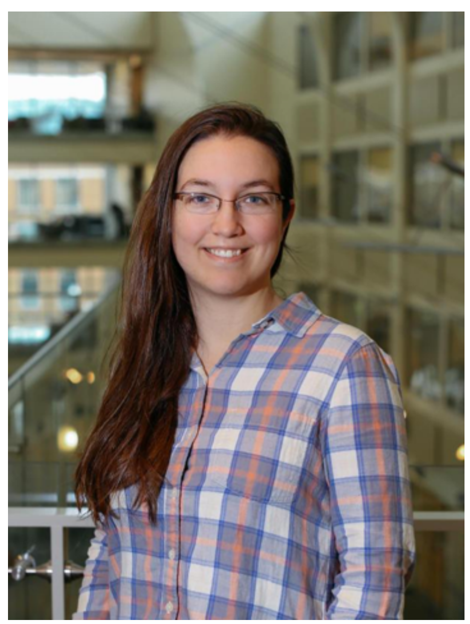
Kuang Wei (UChicago)

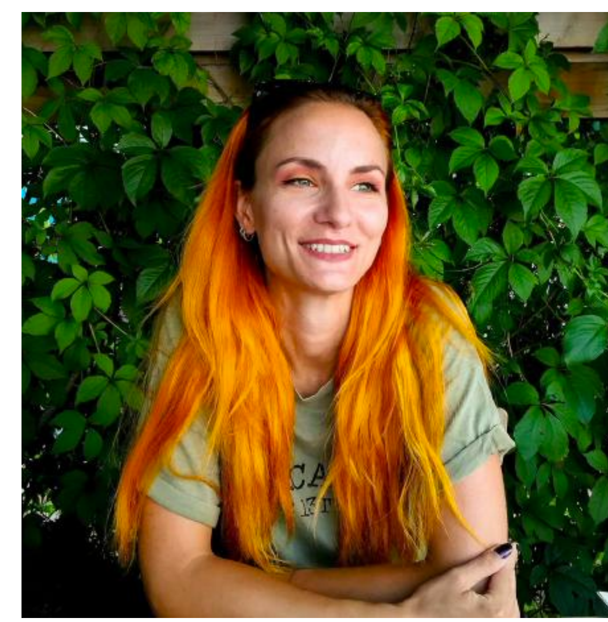
Ting S. Li (Carnegie/Princeton)

J. Sanchez Lopez
(FNAL)



A. Peter (OSU)

A. Feldmeier-Krause
(UChicago)



A. Ćiprijanović (FNAL)

+ DES IC reviewers + DES builders + the broader DES collaboration


LSBG
galaxies
We
blue
clusters
galaxy
radii
sample
brightness
extended
redshift
effective
distribution
Reff
properties
system
surface
Red
DES
groups
physical
model
calculate
environment
clustered
low
identify
Based
evolution
divide
prominent
classified
define
nearby
formation
projected
diffuse
constitute
component
Energy
band
identified
bright
ultra
Redder
three
fit
find
years
area
host
objects
mean
space
deg2
For
imaging
arcsec
within
rsic
color
bimodal
assuming
kpc
populations
associated
derived

Thank you!!!