Galaxy evolution, observational biases and cosmological tensions

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Quy Nhon, 14.08.2025

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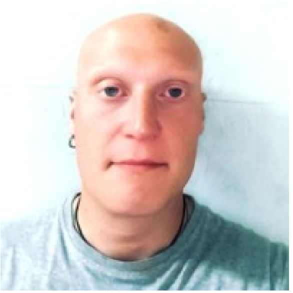
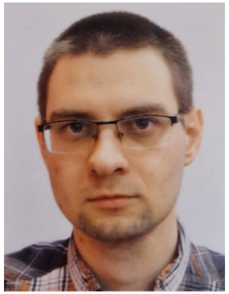


Antonio Vanzanella



Michal Vrabel

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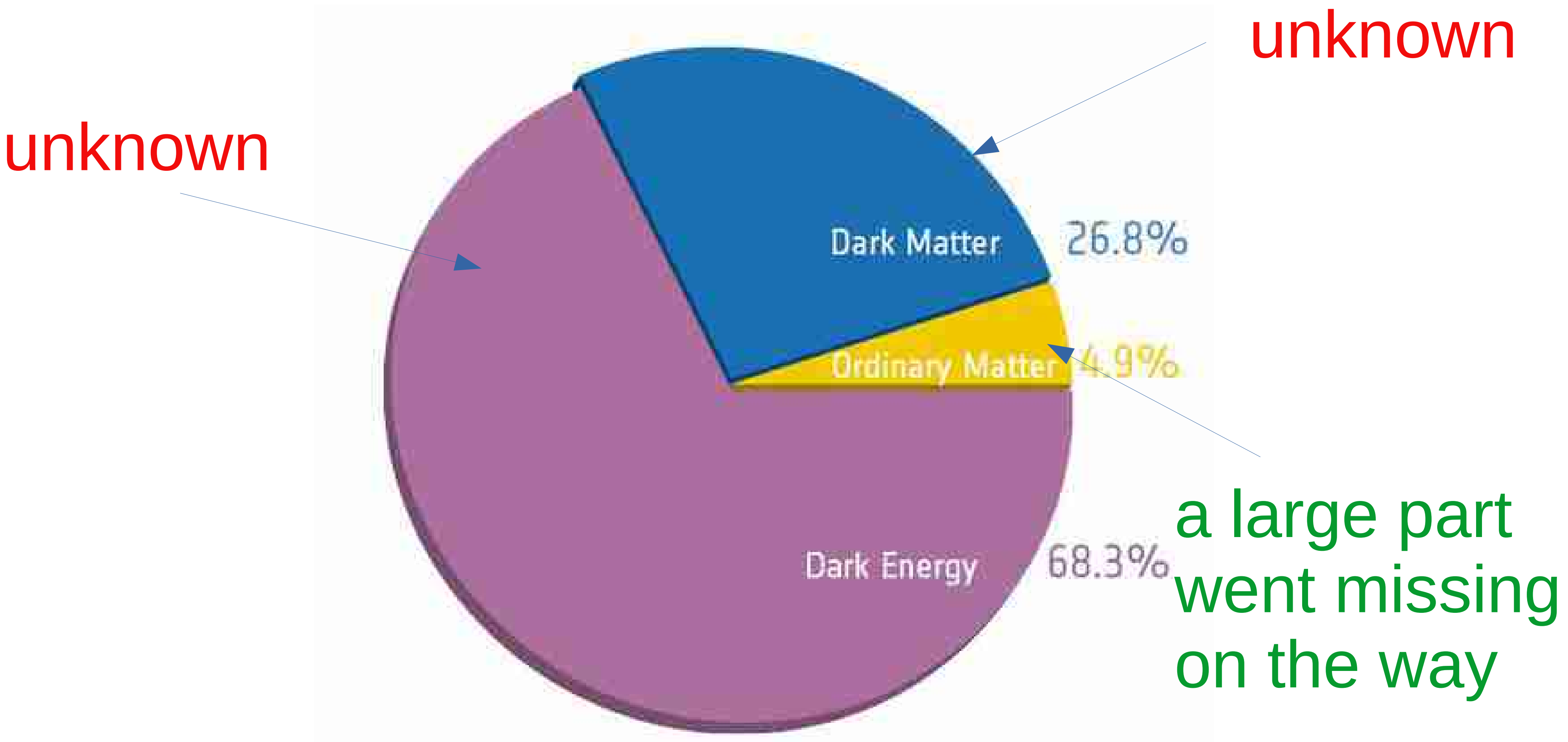
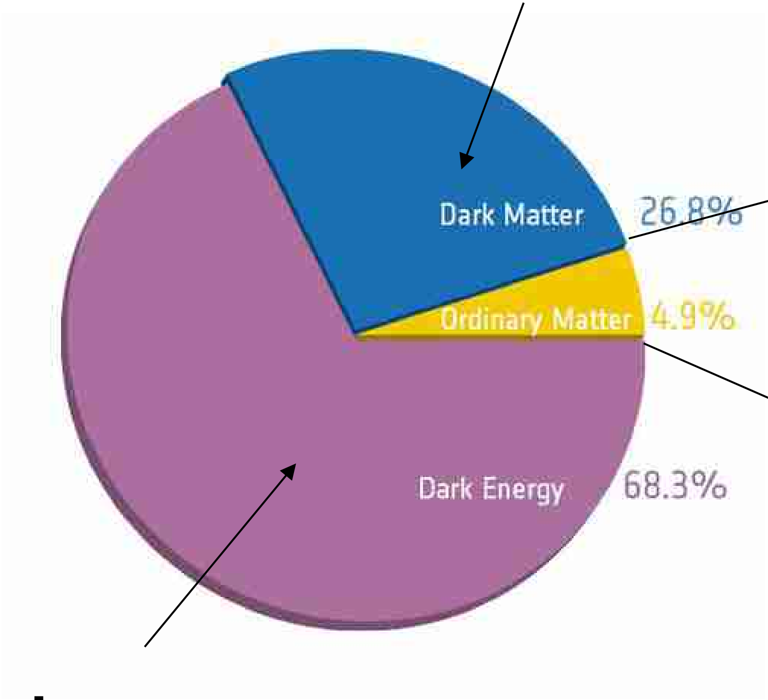


Credit: Planck collaboration

unknown again…

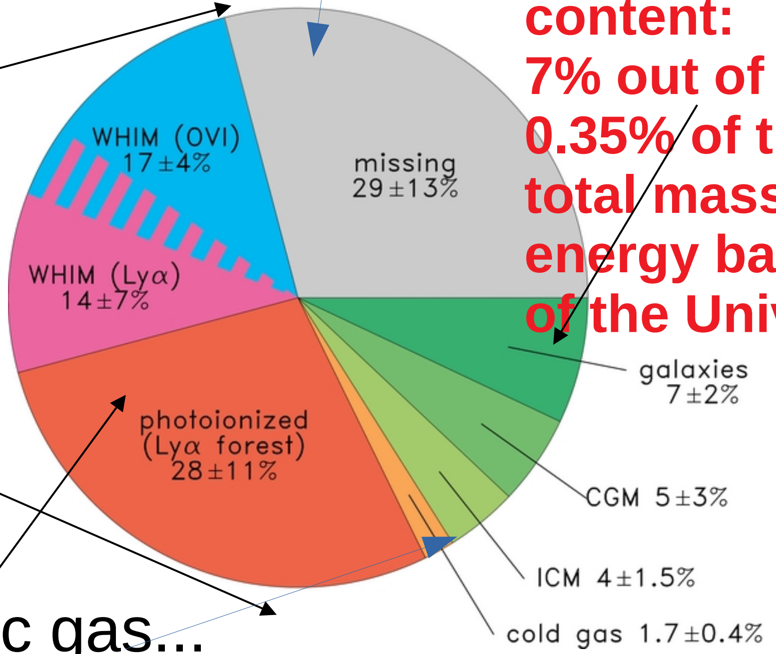
galaxies with their baryonic content: 7% out of 5% = 0.35% of the total mass-energy balance of the Universe

unknown



unknown

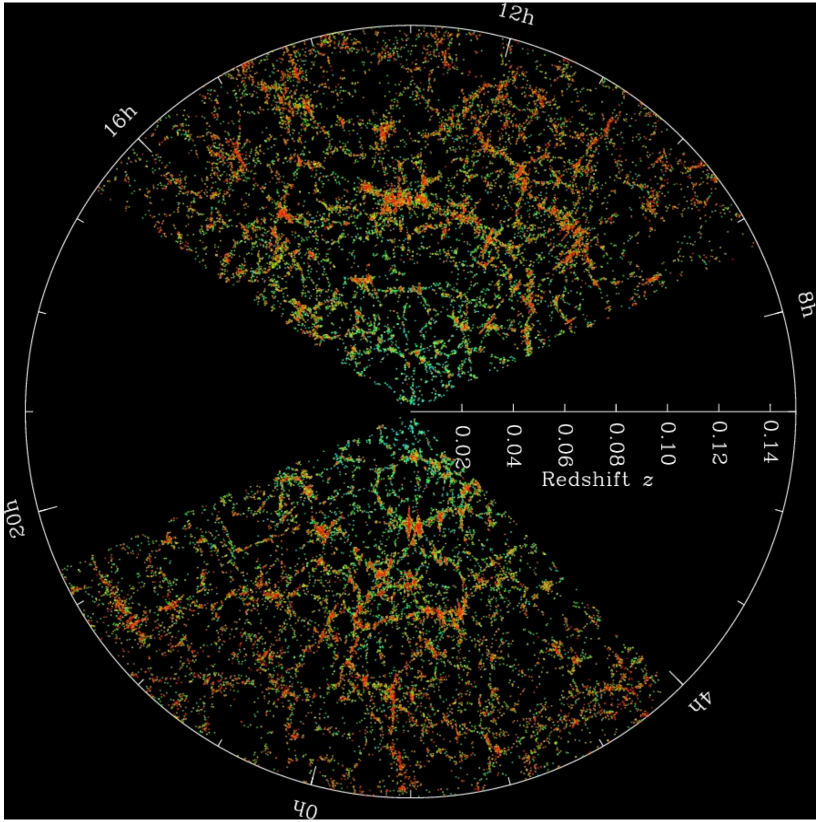
intergalactic gas...



Parameters of LCDM, DM (and DE), new physics, alternative cosmological model or whatever is behind → baryonic matter is a tracer (moreover, only very selected pieces of of baryonic matter)

→ reconstruction only as good as our understanding of **biases** of baryonic tracers

different galaxies – different structure



Credit: SDSS

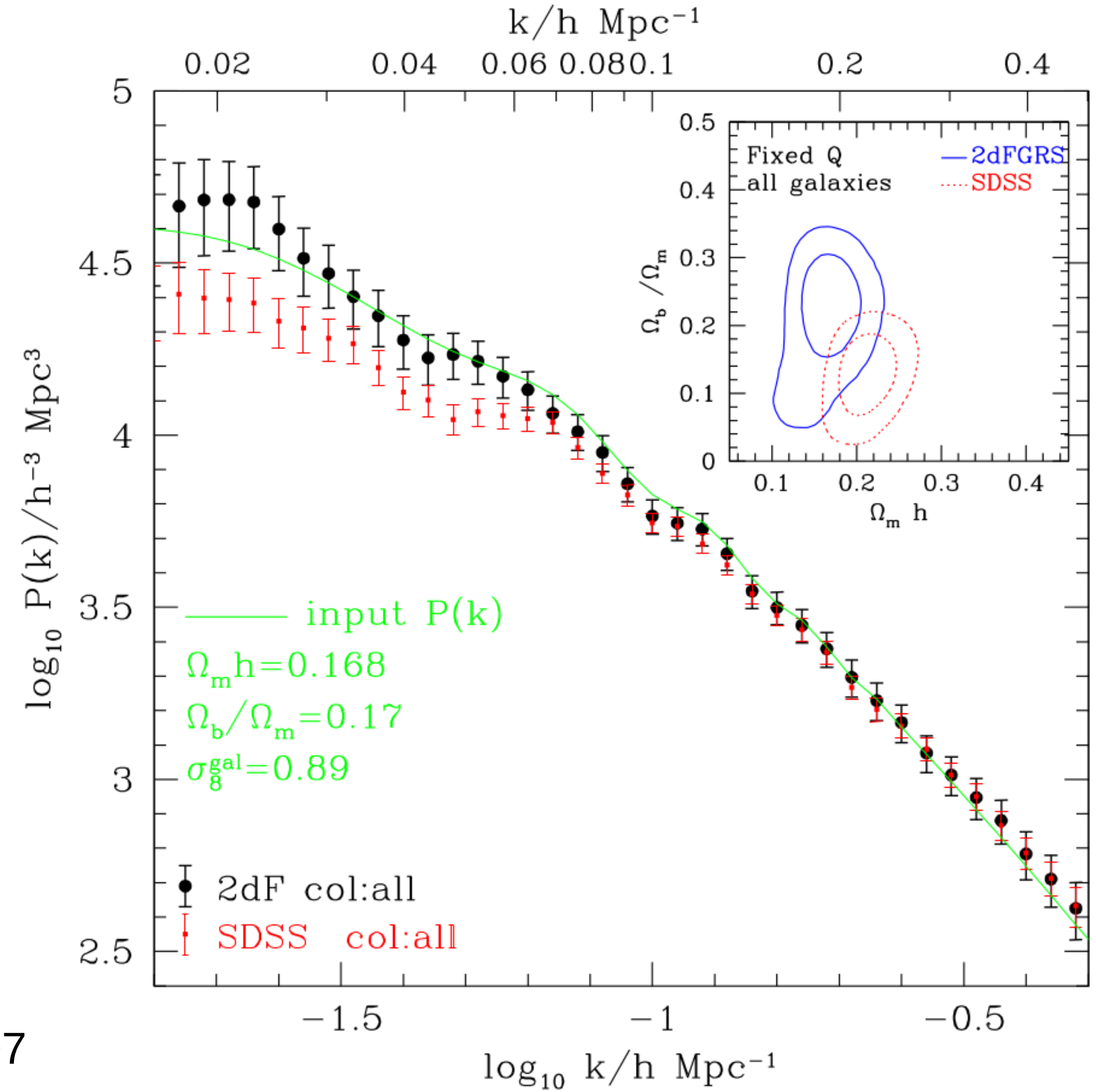
→ How many different types of galaxies there are and how differently are they tracing LSS?

→What is the imprint on the galaxy clustering measurements (and derived quantities)?

A bit of (pre-)history...

Cosmic tensions from the past

SDSS
vs
2dFGRS

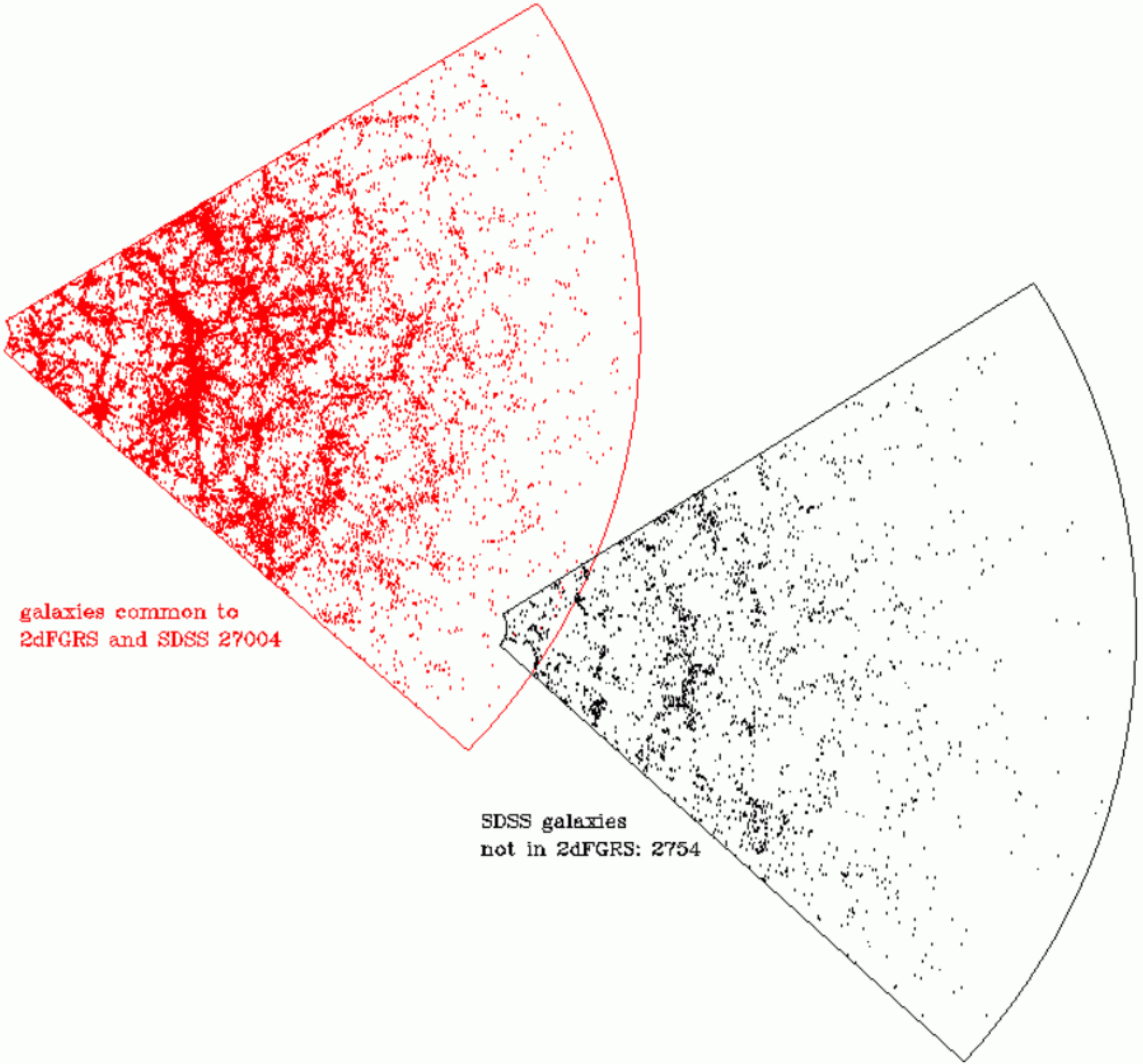


Cole et al. 2007

Cosmic tension: SDSS vs 2dFGRS

* SDSS: r-selected
* 2dFGRS: b_J-selected

→result: 10% more galaxies in SDSS
   + these galaxies being redder
→result: different cosmological parameters

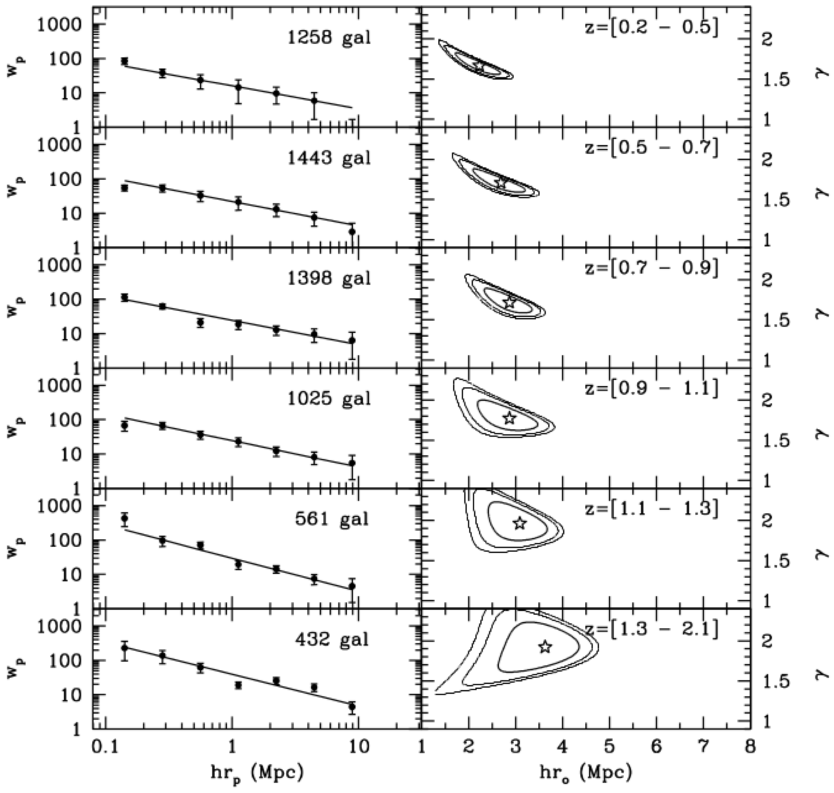


Cole et al. 2007

Cosmic conspiracies

* VVDS-Deep
* 6000 galaxies 0<z<2.1

* Evolution of the correlation function… wait, where is the evolution?

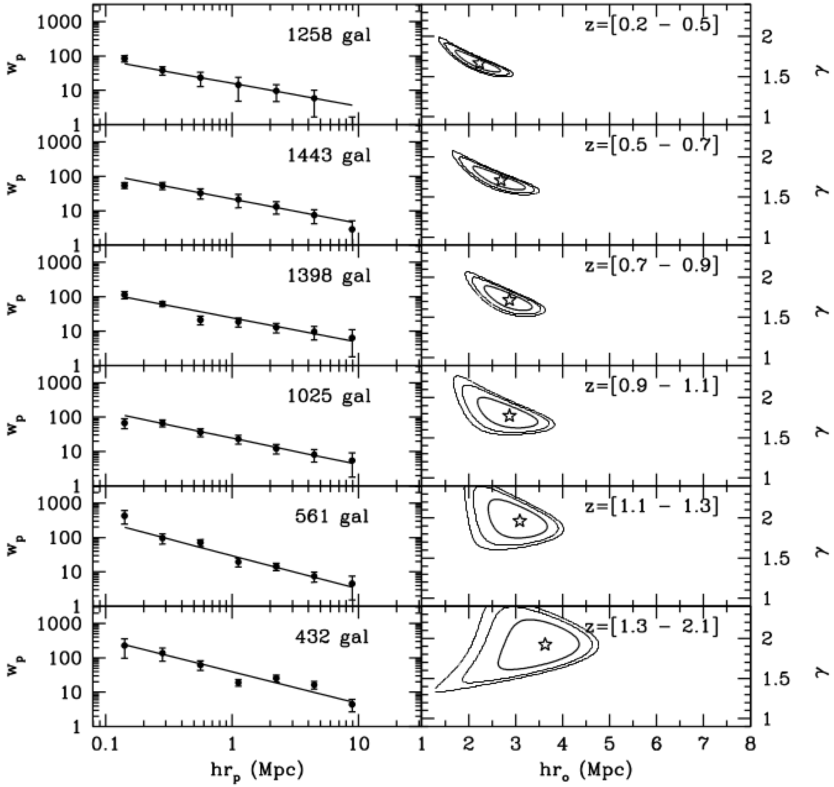


Le Fevre et al. 2005a,b; Pollo et al. 2005, 2006

Cosmic conspiracies

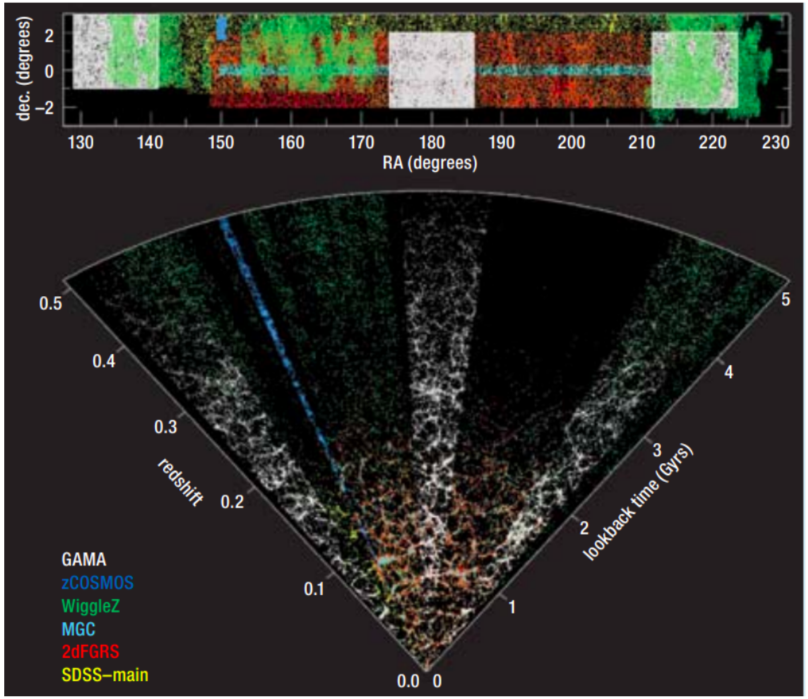
* VVDS-Deep F02
* 6000 galaxies 0<z<2.1

* Explanation:
structure evolution →
stronger clustering with
decreasing z
Malmquist bias → brighter
(hence more clustered)
galaxies at higher z
→ almost perfectly
canceled out



Le Fevre et al. 2005a, b; Pollo et al. 2005, 2006

Back to today: galaxy properties vs environment – going beyond (auto)correlation function



Driver et al. 2009

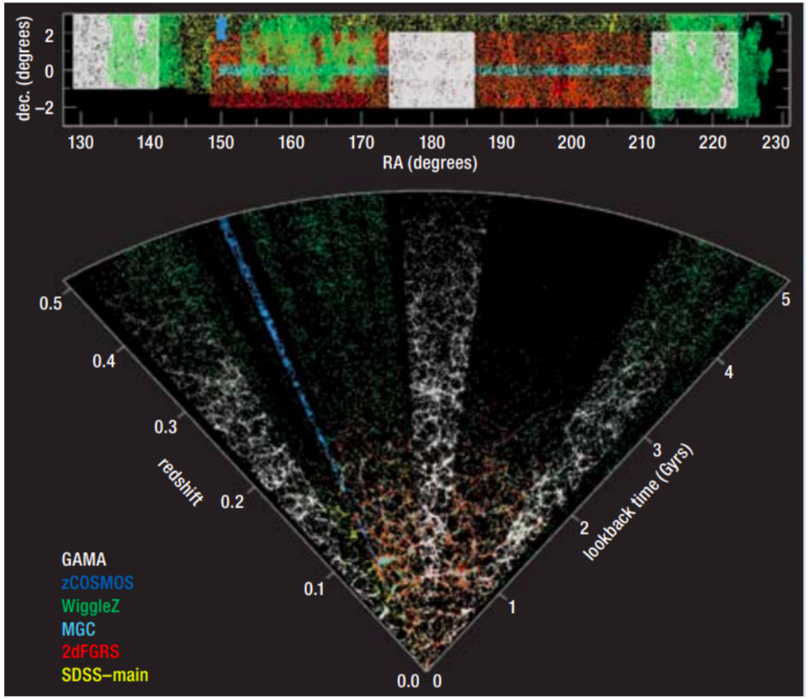
Galaxy and Mass Assembly Survey

→ ~300,000 spectroscopically measured galaxies down to $r < 19.8$ mag over ~286 deg2

→ Perfect for studies of galaxy clustering vs galaxy properties for (almost) local bright galaxies

→ we selected a set of volume limited sample(s) in the redshift range $0.1<z<0.16$

Sureshkumar et al. 2021, 2023



Driver et al. 2009

Sureshkumar et al. 2021, 2023

Galaxy and Mass Assembly Survey

GAMA

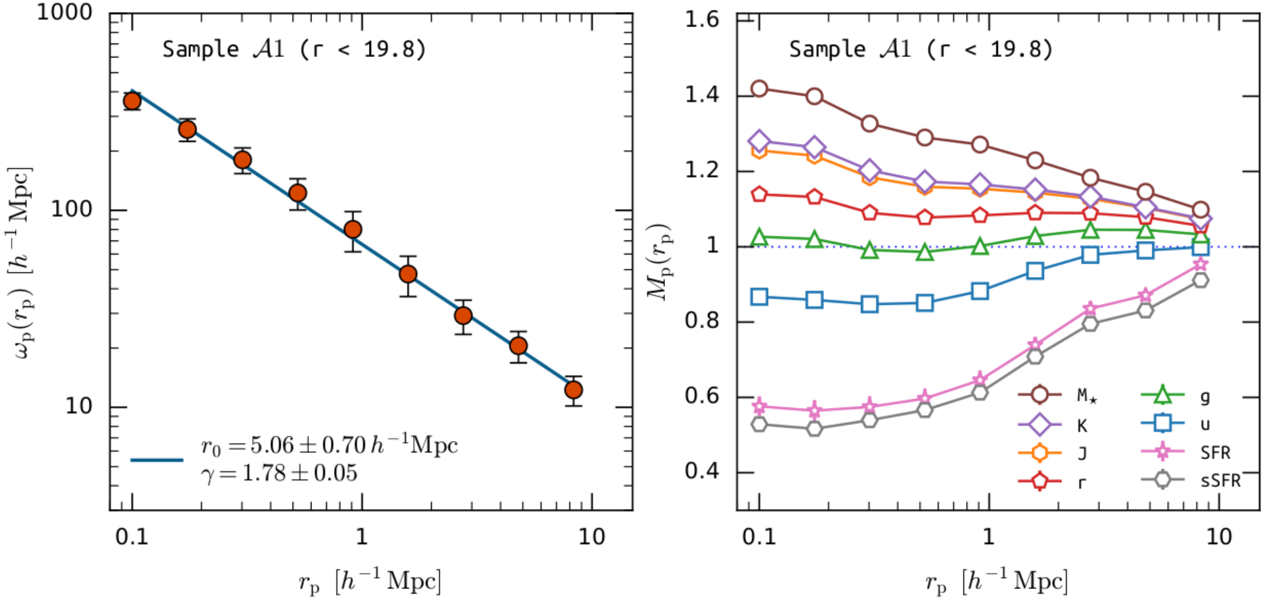
→ Method: marked correlation function (Skibba, Sheth et al. 2006, 2009, 2013)

→ concept: in order to see how a given galaxy property correlates with environment and on which scale, we use this property as a weight (“mark”) attached to each galaxy

→ M = ξ_marked(r)/ξ(r)

→ for comparison of different properties: “ranked MCF”

From ξ to mass-SFR-luminosity marked ξ



Sureshkumar et al. 2021

→ Different properties differently mark LSS at small scales
→ the strongest overdensity traces is the stellar mass, the weakest sSFR, luminosities from red to blue form a hierarchy in between
→ monotonously steepening galaxy spectral slope ("redness") when moving to small scales (dense environments)

Galaxy and Mass Assembly Survey: mergers in the large scale structure, or where do mergers happen?

Pearson et al. 2019

→ Galaxy merger catalogs in the GAMA survey (selected → by ML and → according to the Gini parameter)

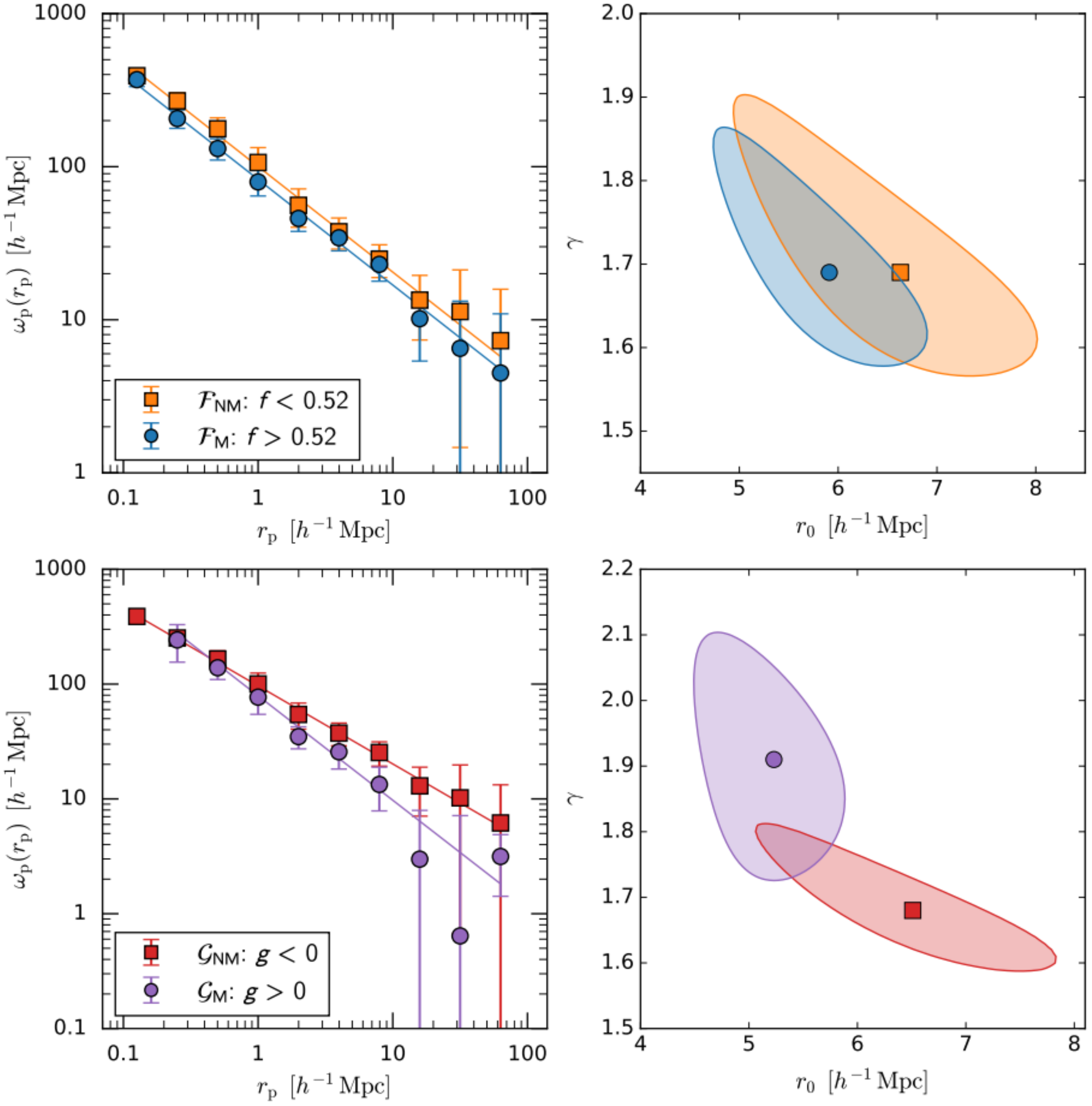
→ Method: correlation function and marked correlation function (again)

→ concept: probability of a galaxy to be a merger (according to CNN) can be regarded as a measure of galaxy "mergeriness" and then used as a weight ("mark")

→ $0.1<z<0.16$, volume limited sample(s)

Sureshkumar et al. in 2024

Galaxy and Mass Assembly Survey: mergers in the large scale structure, or where do mergers happen?



Sureshkumar et al. 2024

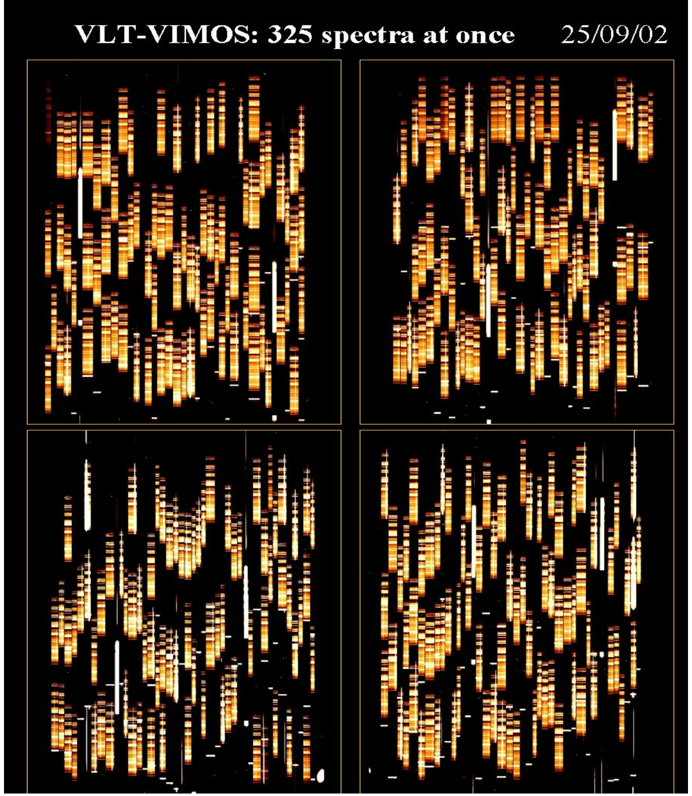
Galaxy and Mass Assembly Survey: where do mergers happen?

→ Merging galaxies in the present day Universe prefer underdense environments (GAMA: Sureshkumar et al. 2014, NEP: Pearson et al. 2024)
→ No significant rise in SFR w/r to similarly massive galaxies (Pearson et al. 2019, Pearson et al. 2024)
→ Most important is the invisible (i.e. low surface brightness features around).

Sureshkumar et al. 2024

How many types of galaxies are really there?

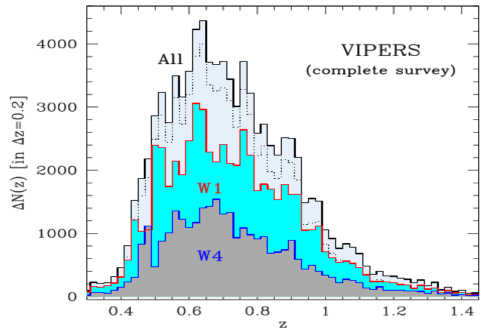
VIPERS
VIMOS PUBLIC EXTRAGALACTIC REDSHIFT SURVEY



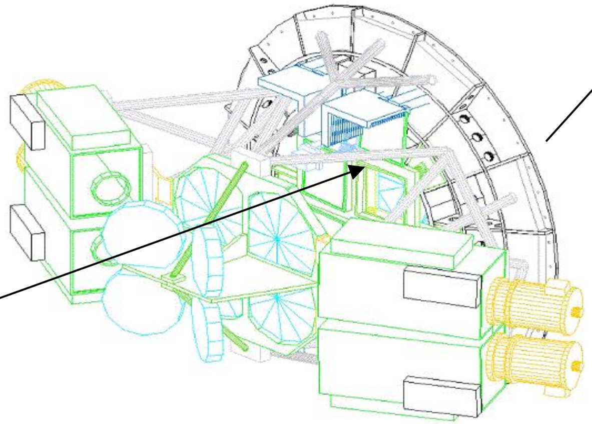
SURVEY STATUS AS OF 06/11/2016

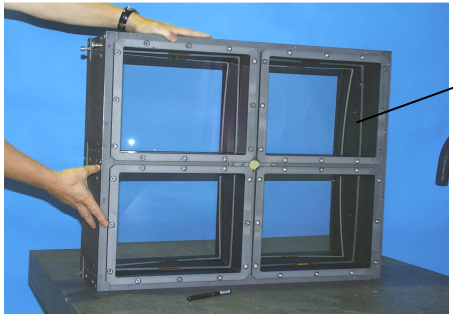
EFFECTIVE TARGETS	MEASURED REDSHIFTS	STELLAR CONTAMINATION	COVERED AREA
93252	88901	2265 (2.5 %)	100.0 %

EFFECTIVE TARGETS (ET) are all the primary targeted objects with the exclusion of the ones flagged as -10 (undetected). MEASURED REDSHIFTS (MR) are the fraction of ET for which a redshift has been measured. STELLAR CONTAMINATION are the MR objects which have been identified as stars.



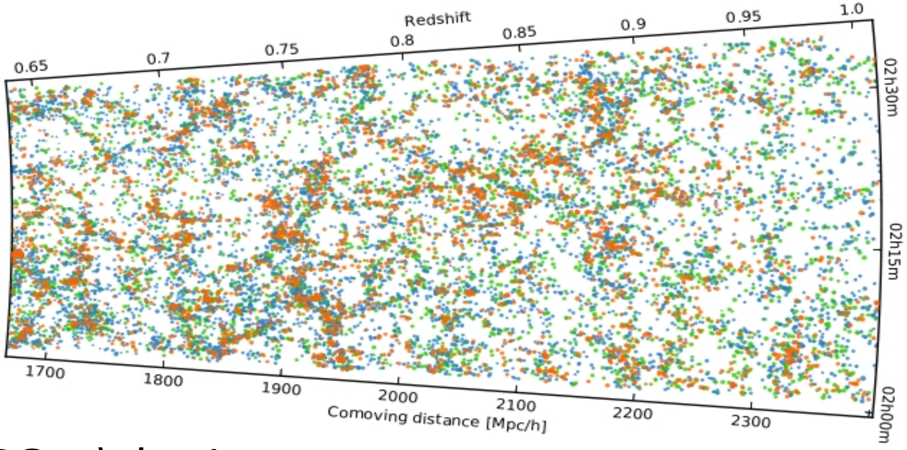
Large ESO Programme, 2008-2016



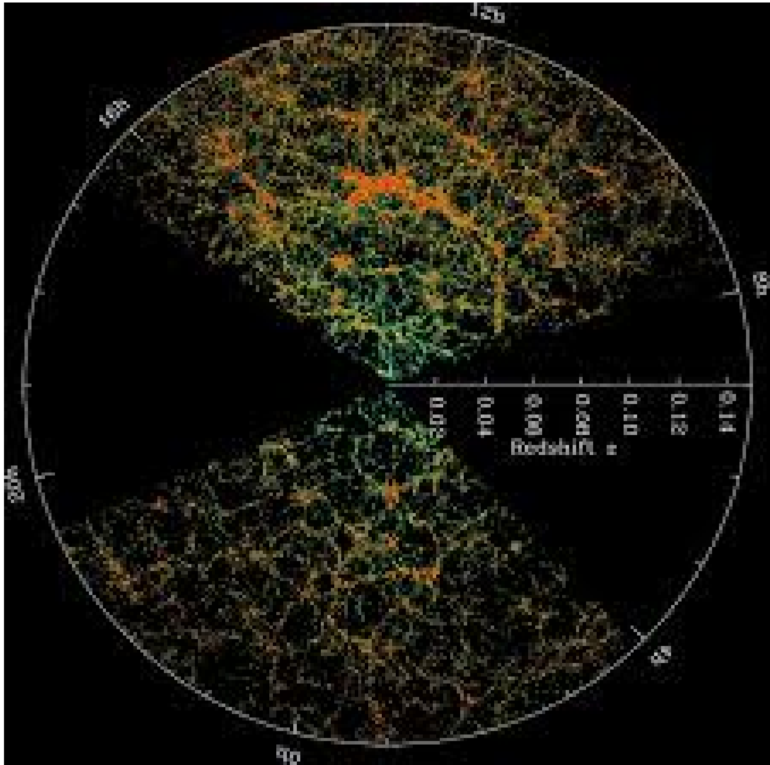


~90 000 spectra of galaxies
at **0.5<z<1.2**
2 fields on the sky, 24 deg^2

Guzzo et al. 2014, 2017, Scodeggio et al. 2018



VIPERS z \sim 1



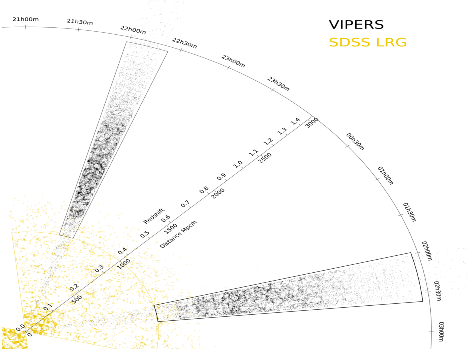
SDSS z \sim 0

Bimodality…

http://vipers.inaf.it/rel-pdr2.html

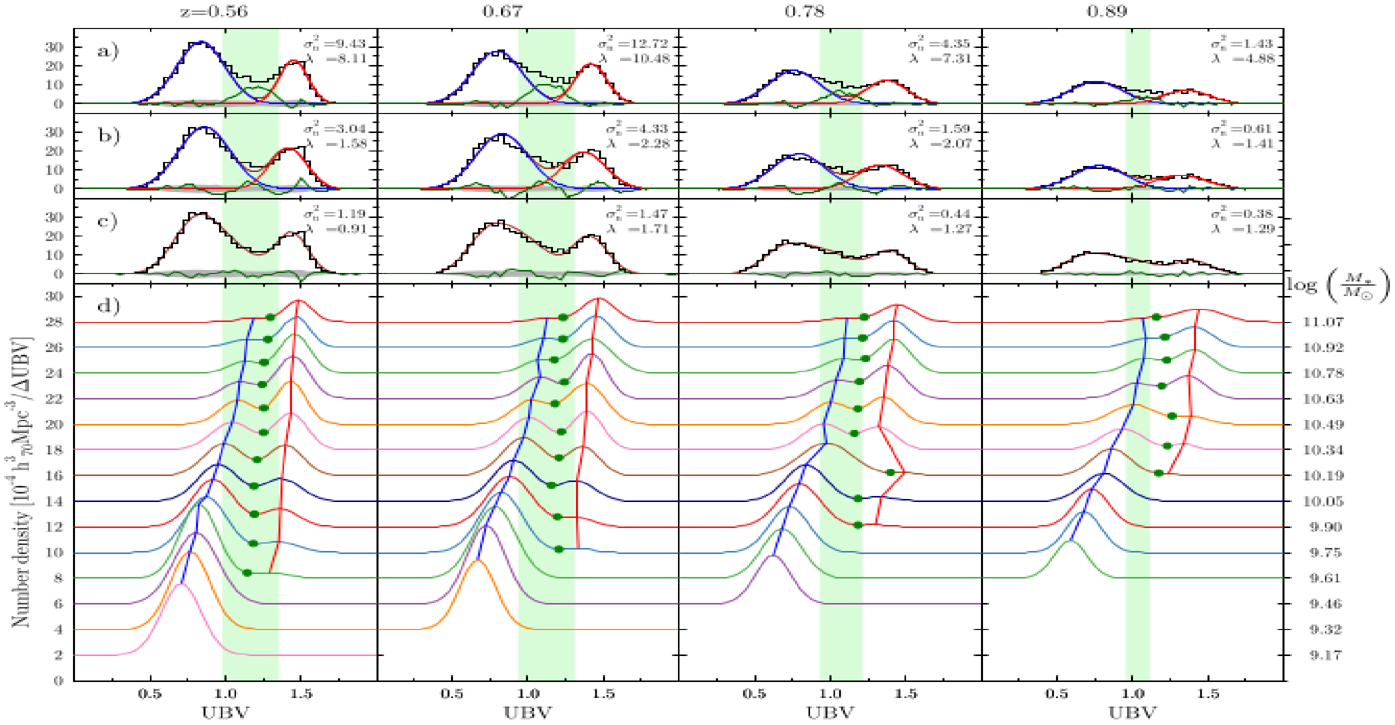
How many galaxy populations are there?

Perfect (but moving) bimodality?



Courtesy Ben Granett

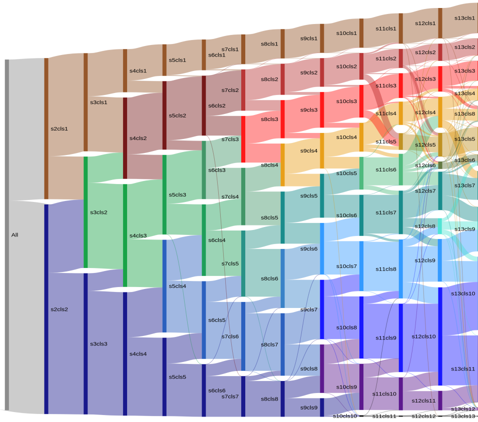
- VIPERS: ~90,000 spectroscopically measured galaxies at 0.5<z<1.2 in 2 fields of 24 deg^2
- Galaxy colour (and not only) distribution: slight deviations from bi-Gaussianin large redshift and mass bins in the „green" area between red and blue populations seem to be rather an effect of mass-and-redshift dependence of otherwise perfectly bi-Gaussian distributions.



Krywult et al. in prep.

and beyond bimodality

Unsupervised classification of z ~ 1 galaxies



Unsupervised classification of VIPERS galaxies based on their distribution in a multidimensional absolute magnitude space

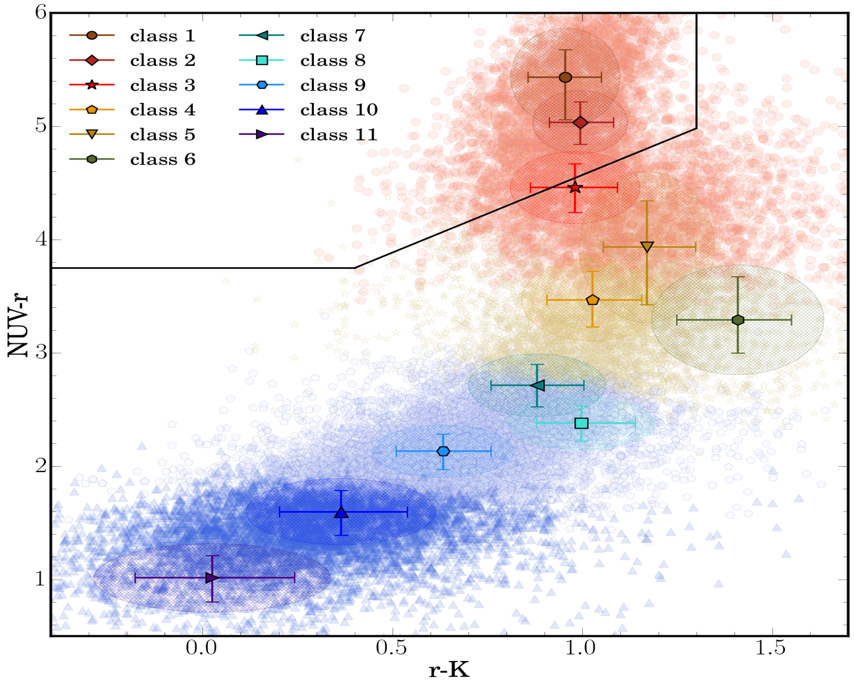
12 dimensions: absolute magnitudes + zspec

→ **blind separation** (no training sample nor other hints) →

11 classes of mid-redshift galaxies + one class of outliers:

- 5 blue - 3 transitional - 3 red

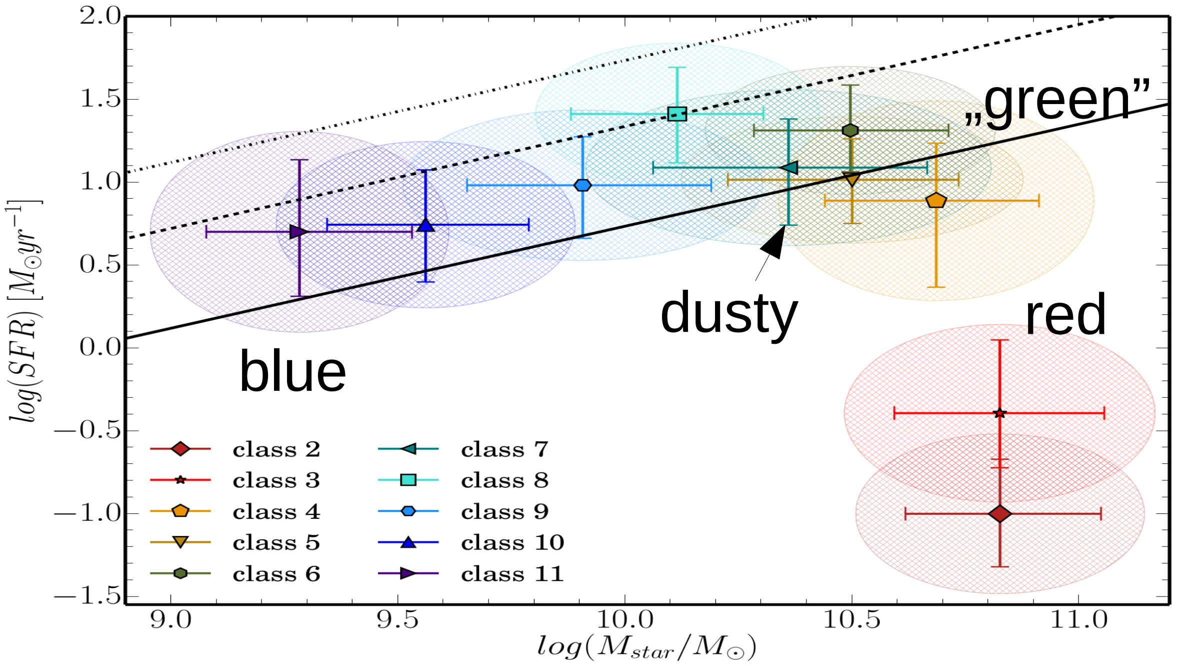
- well corresponding to galaxy classifications e.g. in NUVrK diagrams but more detailed



Siudek et al. 2018

How many galaxy populations are there:

Inside two main Gaussian populations many subpopulations exist, forming a sequence but distinguishable only in multidimensional feature space.

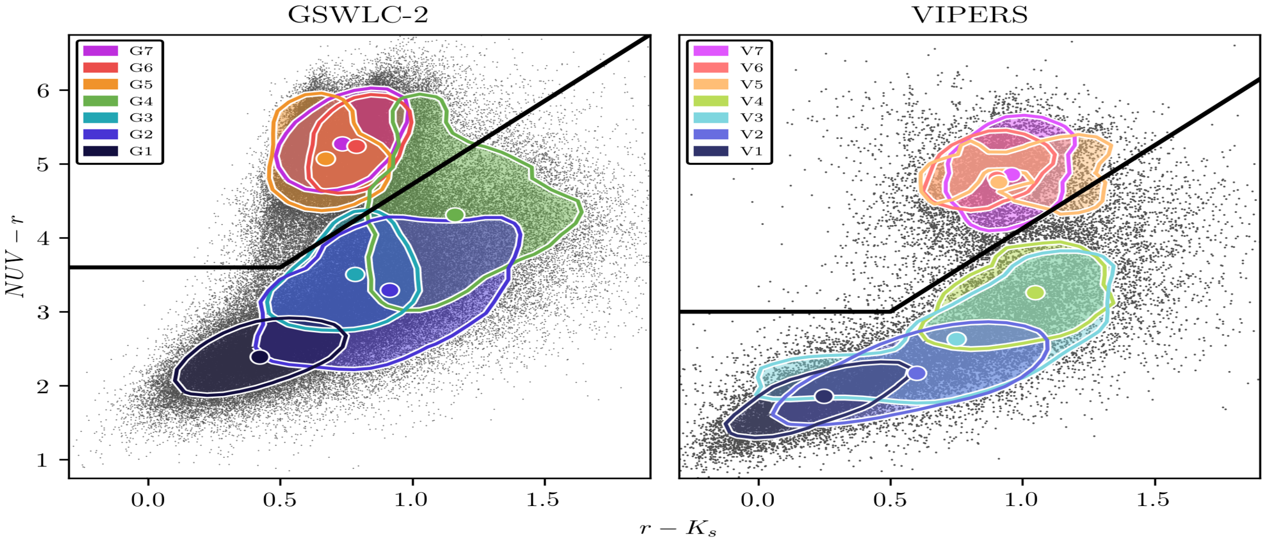


Siudek et al. 2018

How many galaxy populations are there:

However...

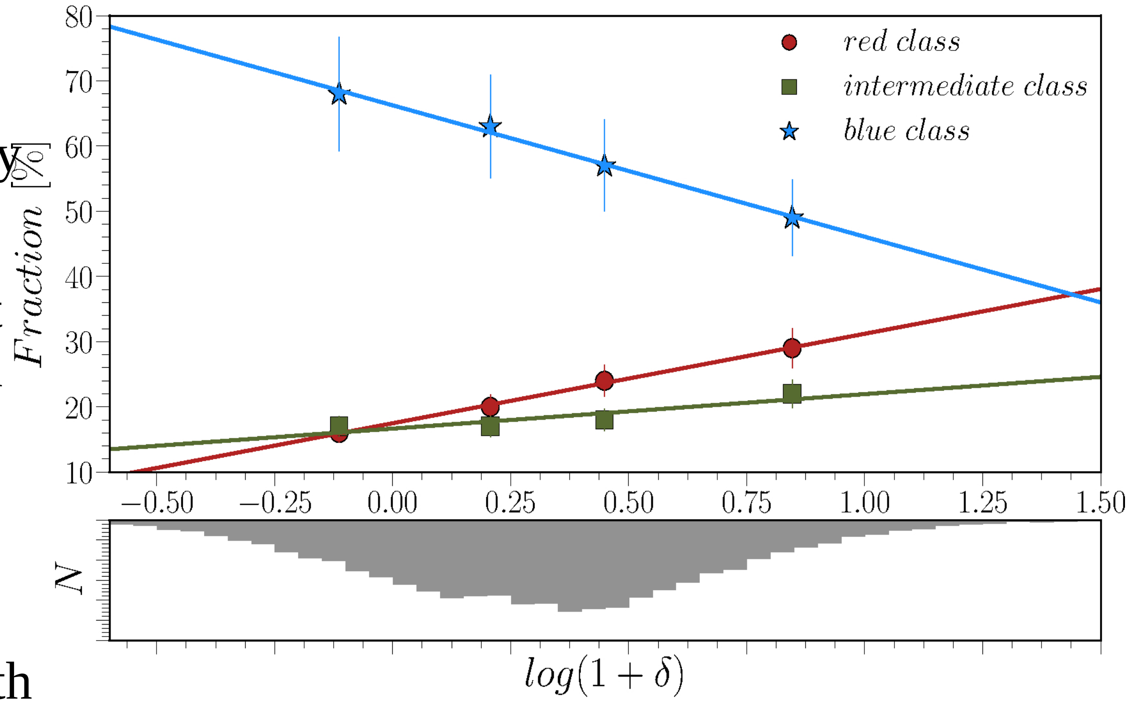
- Similarly at z~0.7 (VIPERS) and z~0 (SDSS-based GSWLC-2). Again: Fisher Expectation-Maximization unsupervised clustering algorithm but a different rest-frame colour-based parameter space)



Turner et al. 2021

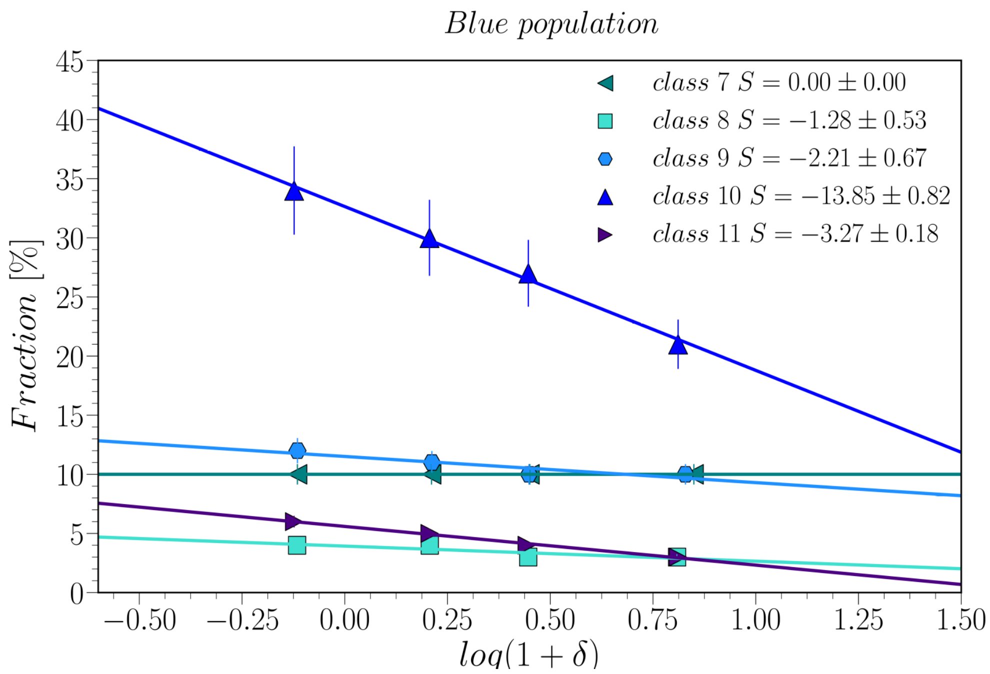
Does this 11 class division reflect actual physical information?

- Traces of different galaxy evolutionary paths seen in multi-color space?
- See what happens when quantities not related to classification are introduced
- Environment: environmental dependence → biases and differences in how galaxies trace LSS
- Global tendency at z~1 consistent with local: red galaxies are most aboundant in the dense environments, blue ones dominate the field → downsizing and mass-driven evolution



Siudek et al. 2022
density field: Cucciati et al. 2014

Looking into details: blue



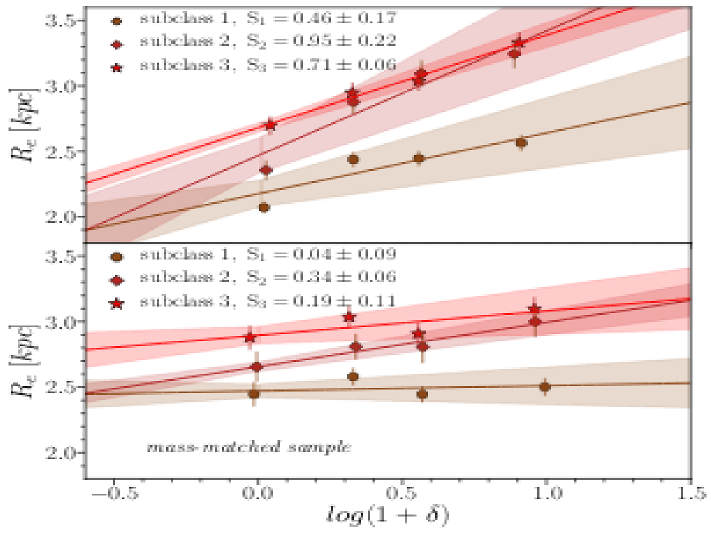
Siudek et al. 2022

→ Blue galaxies at z~1: not all follow the downsizing trend!

→ For blue galaxy populations: the downsizing trend is mostly driven by only one (admittedly, the largest) subpopulation (and in this case it it consistent with mass-driven passive evolution)

→ the fractions of other blue SF galaxies are much less mass/environment-dependent – environmental effects play a role in keeping them blue

Looking into details: red

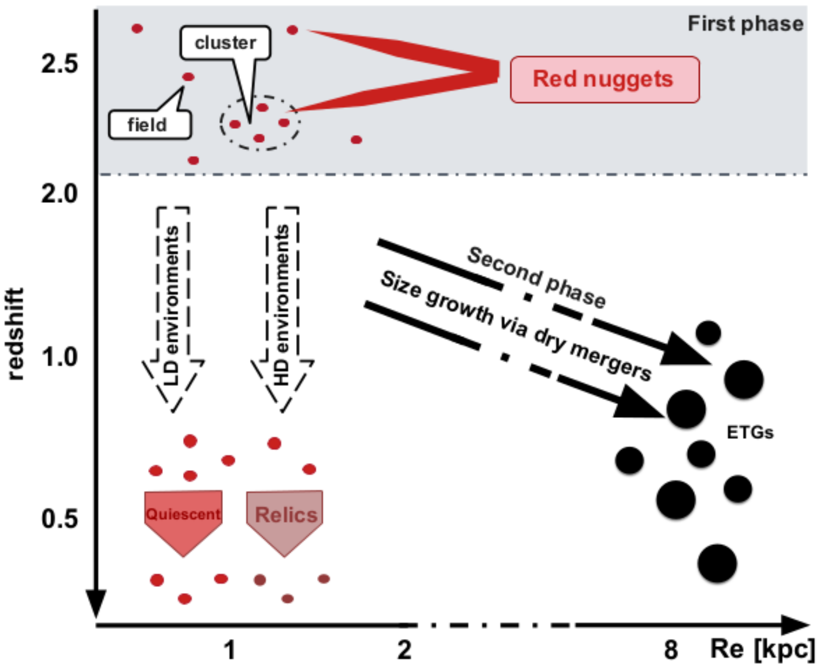


Siudek et al. 2022;
morphology: Krywult et al. 2018

...the reddest red class:
→ the smallest in size (on average 20% smaller than other red galaxies of the same mass)
→ size does not depend on environment (independently on stellar mass): may be a product of early fast quenching (while the other two classes might have grown also through mergers)

VIPERS
VIMOS PUBLIC EXTRAGALACTIC REDSHIFT SURVEY

"Red nuggets" and todays "relics"



→Red nuggets: a category of rare compact red quiescent galaxies found at high redshifts

→ Relics: even much rare contemporary galaxies, massive, compact and red

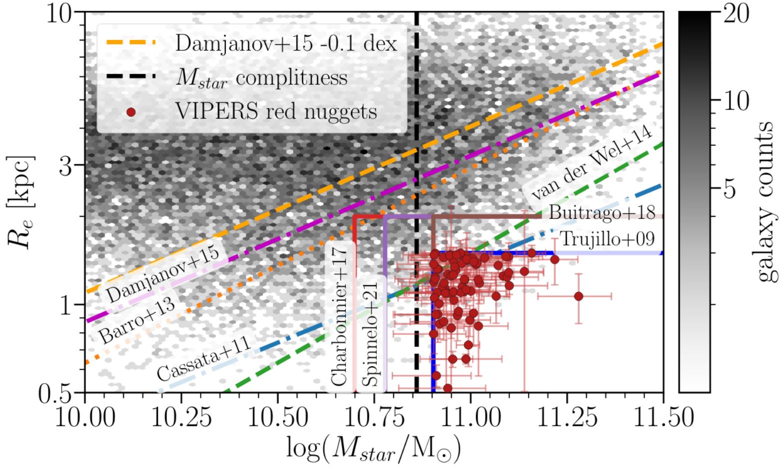
→ Compact ↔ not a product of merging but only passive evolution

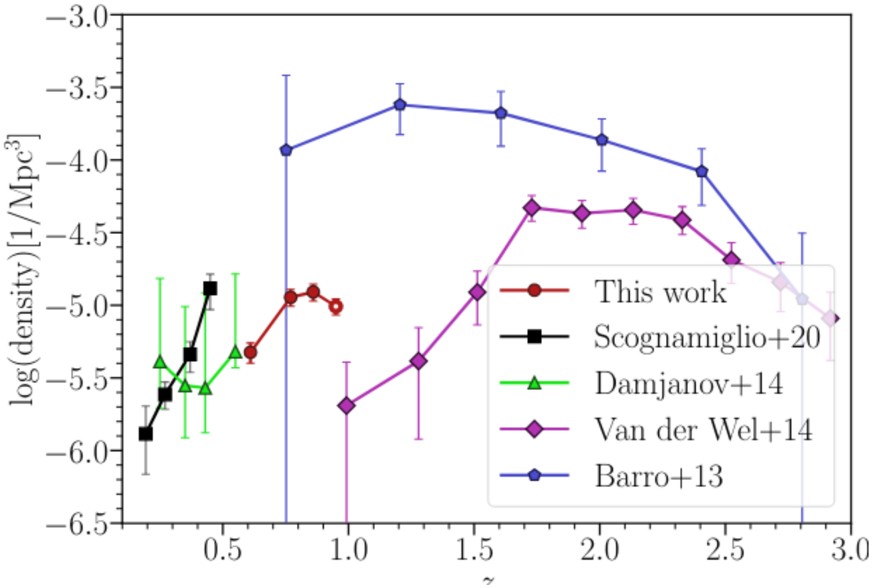
→ ideal for "cosmic labs" and "cosmic chronomers" but extremely scarce

Lisiecki et al. 2023
Siudek, Lisiecki et al. 2023 +
Lisiecki et al. in prep

VIPERS
VIMOS PUBLIC EXTRAGALACTIC REDSHIFT SURVEY

→ the first mass complete catalog of 77 “**red nuggets**” at z~0.7
→ filling the gap between high z “red nuggets” and low-z “relics”
→ properties only weakly dependent on environment

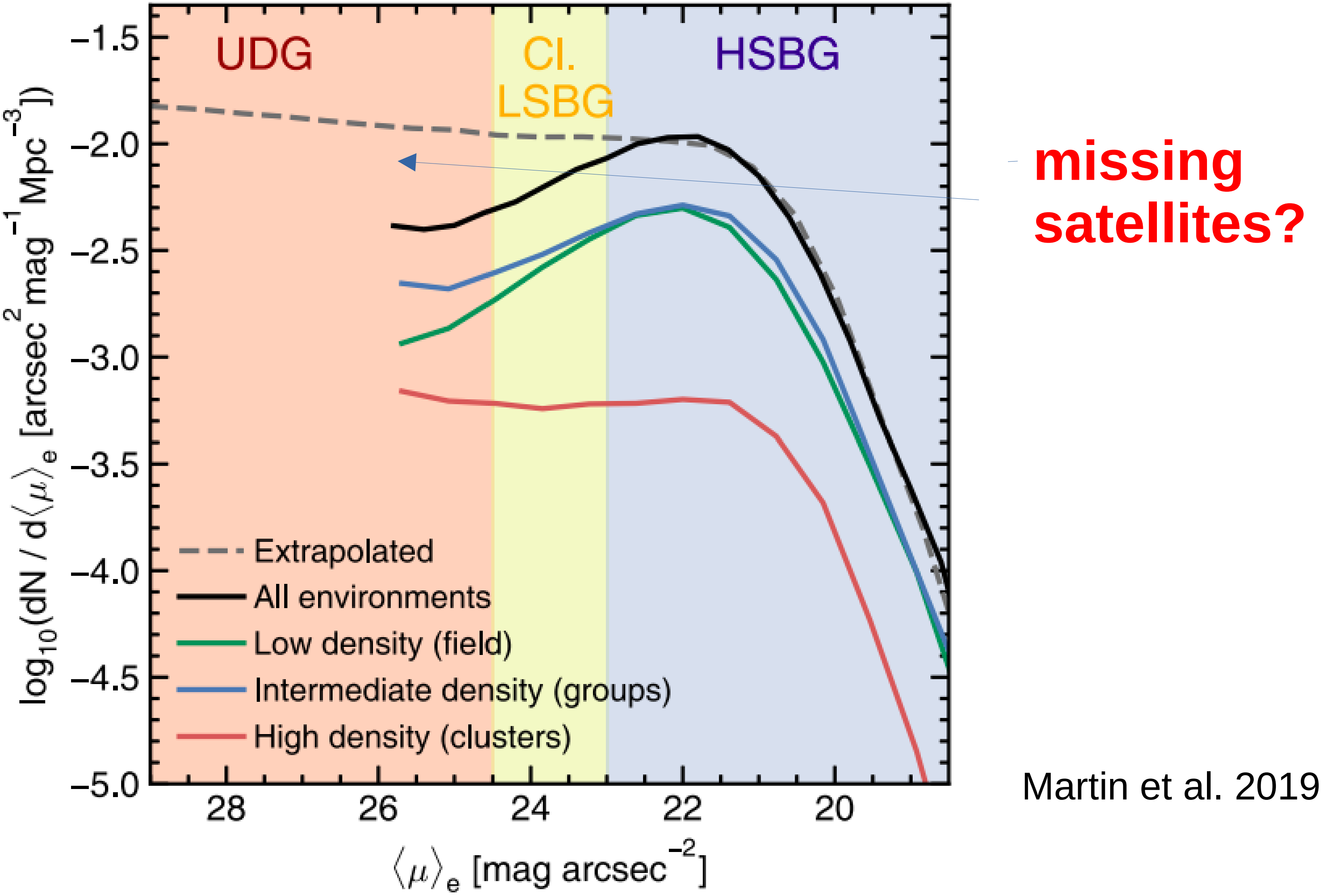




Lisiecki et al. 2023
Siudek, Lisiecki et al. 2023 +
Lisiecki et al. in prep.

Into the future: missing pieces in the galactic census

Faint end problem of luminosity /mass function



Martin et al. 2019

Low surface brightness Universe

→ Galaxies with surface brightness below the background level
→ now estimated to be around 30-60% of the total number density of galaxies and 15-20% of the total dynamical mass contained in galaxies
→ mostly dwarfs but also giant massive galaxies like Malin 1
→ different colors, properties… most likely also evoluitionary paths
→ Ultra Diffuse Galaxies are a sub-category of LSBGs
→ Low surface brightness features surround also normal galaxies – needed to understand mass aggregation, inflows and outflows

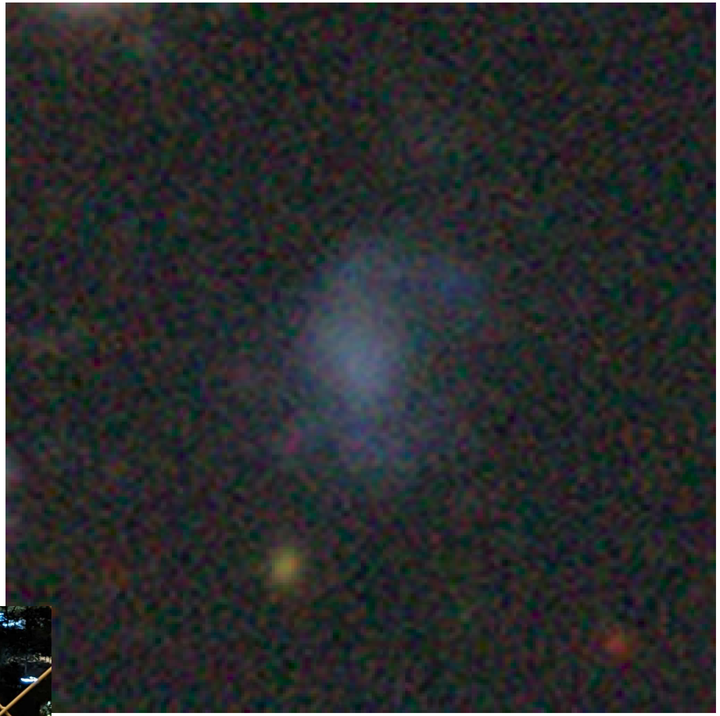
Boissier/A&A/ESO/CFHT

Why are we interested in LSBGs?

- “Missing ingredient” in the large scale structure reconstruction
- Faint and (mostly) low mass → fill the faint end of the luminosity/mass function
- Extremely sensitive to environment → explain the role of feedbacks in the galaxy formation and evolution
- Low mass and having extreme relations with their host DM haloes → allow to test non-CDM DM models

DES Y3 Gold: new catalog of LSBGs

- method: self-attention-based encoder models coupled with CNN (note: with big data 1% accuracy improvement can translate to thousands of new detections)
- 27,000 LSBGs, among them 4083 new (mostly blue + extreme red, as compared to previous works)
- among them, 317 UDG candidates including 276 new ones



Thurutupilly et al. 2024

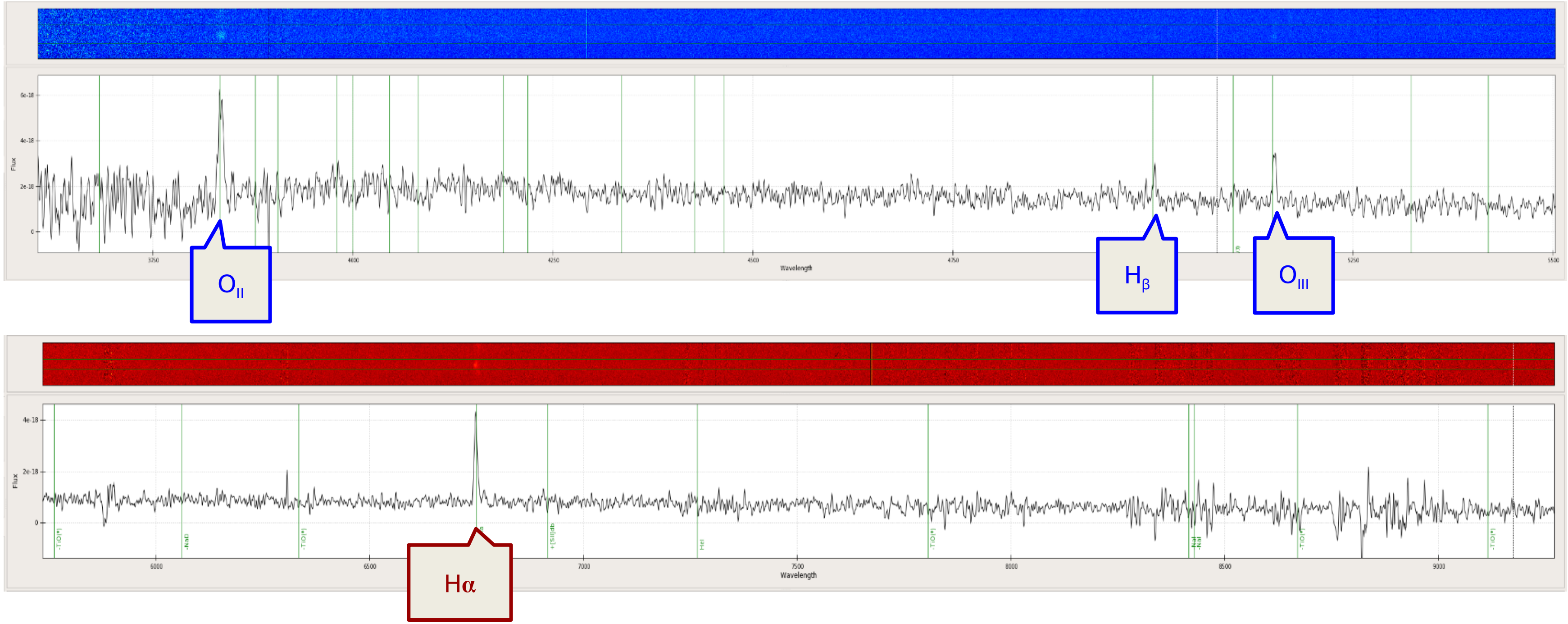
Are these LSBG candidates really LSBGs?

A subsample of UDGs from Thuruthipilly et al. (2024) spectroscopically observed by the Large Binocular Camera (LBC):

Vanzanella in prep.

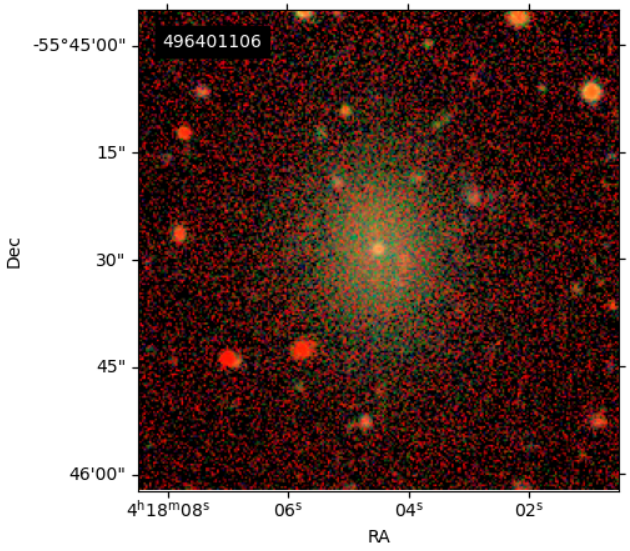
spectroscopic redshift=0.0282 → **confirmed** LSB/UDG

DES DR1 RGB

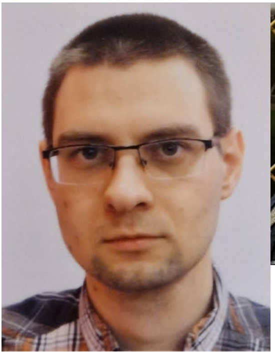


Slide credit (with modifications): Kasia Małek

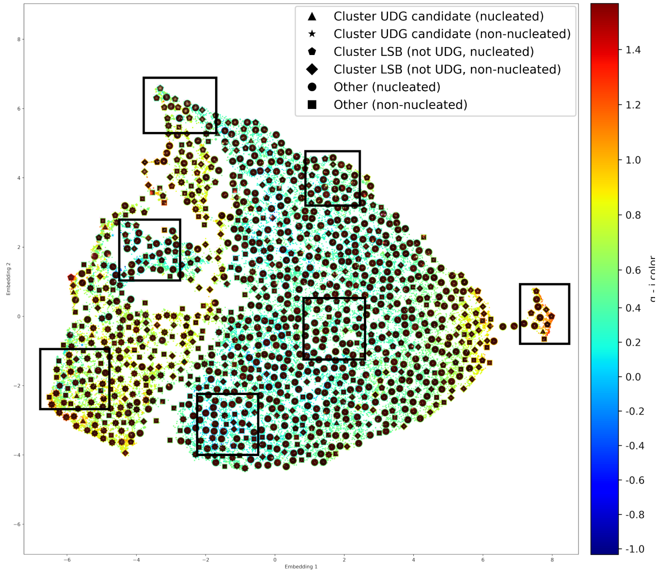
Ongoing: a new updated catalogue inclluding nucleated sources



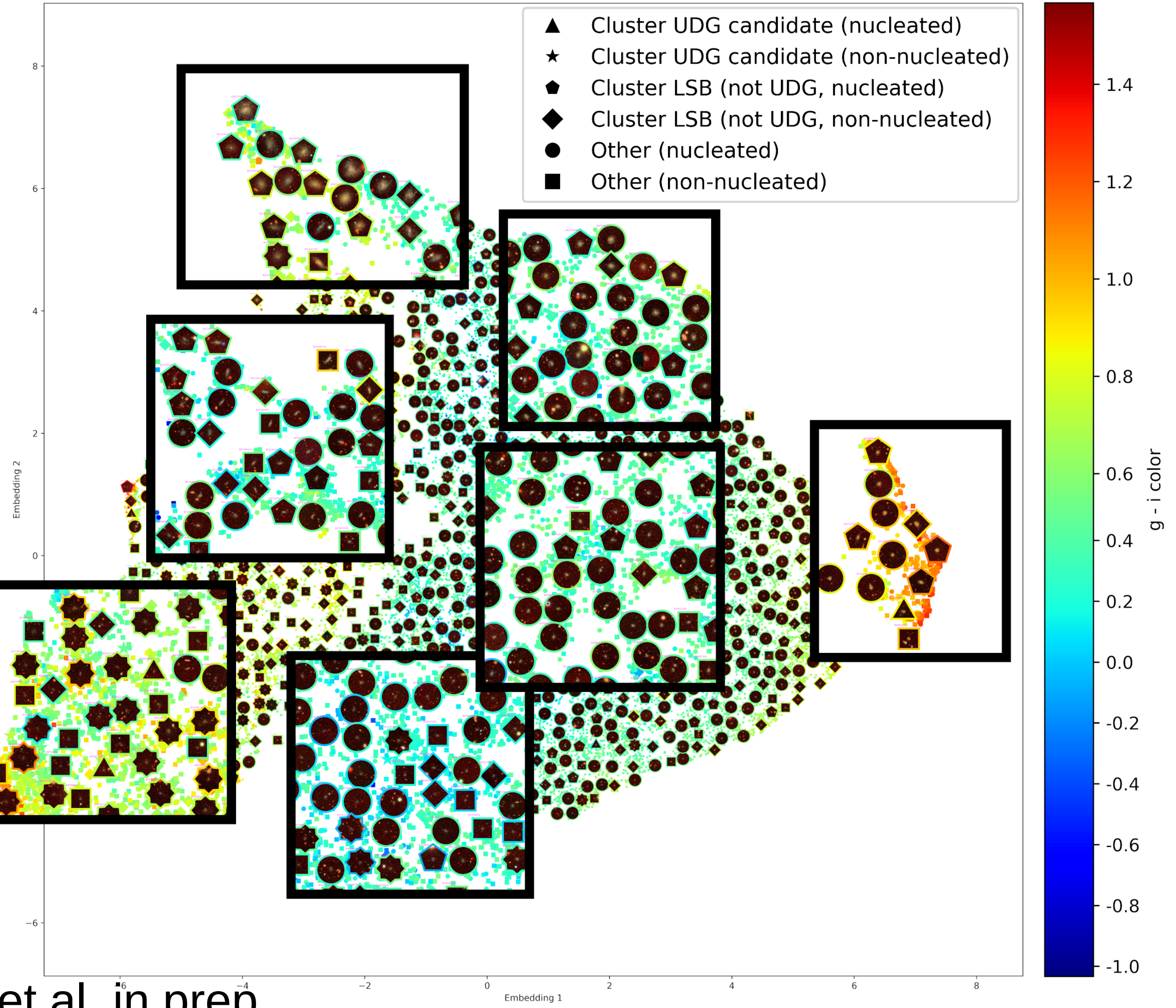
- In the Thurutupilly et al (2024) paper only objects with good quality Sersic fit were included.
- Ongoing: adding objects well fitted with double Sersic profile ("nucleated")
- 27,000 LSBGs → ~50,000 LSBGs (tests of the sample ongoing).

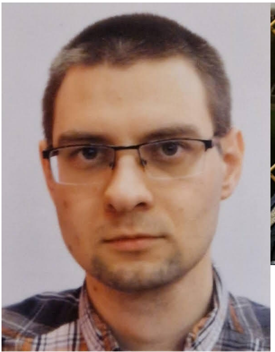


Vrabel, Thurutupilly et al. in prep.



A complex zoo of LSBG sub-types





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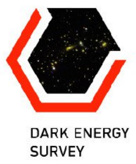
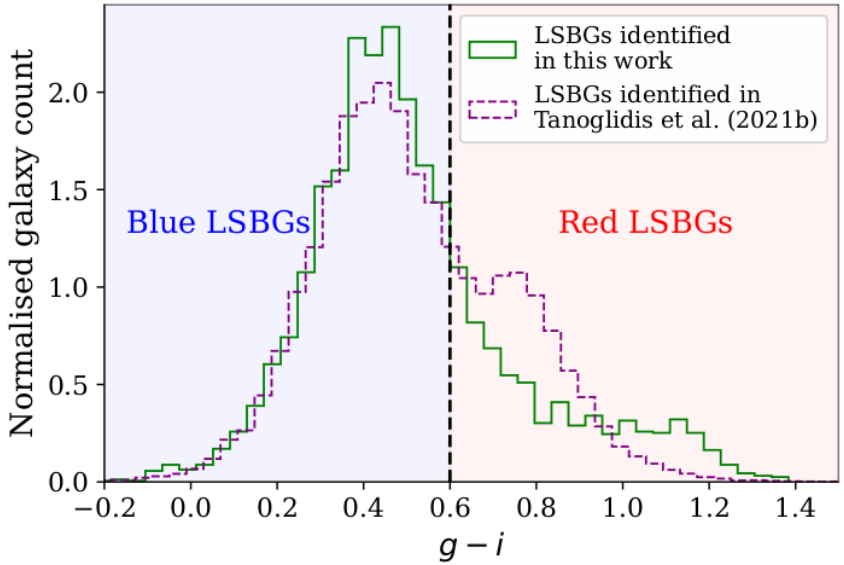
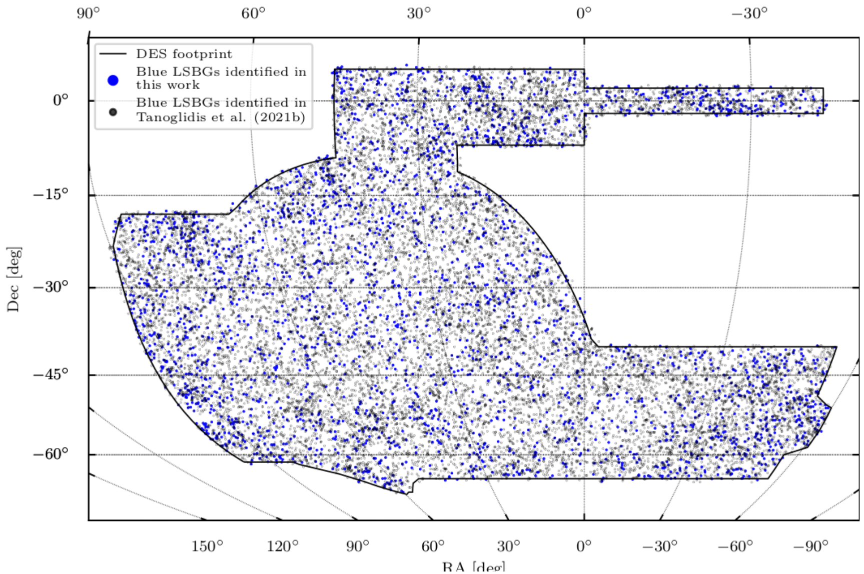
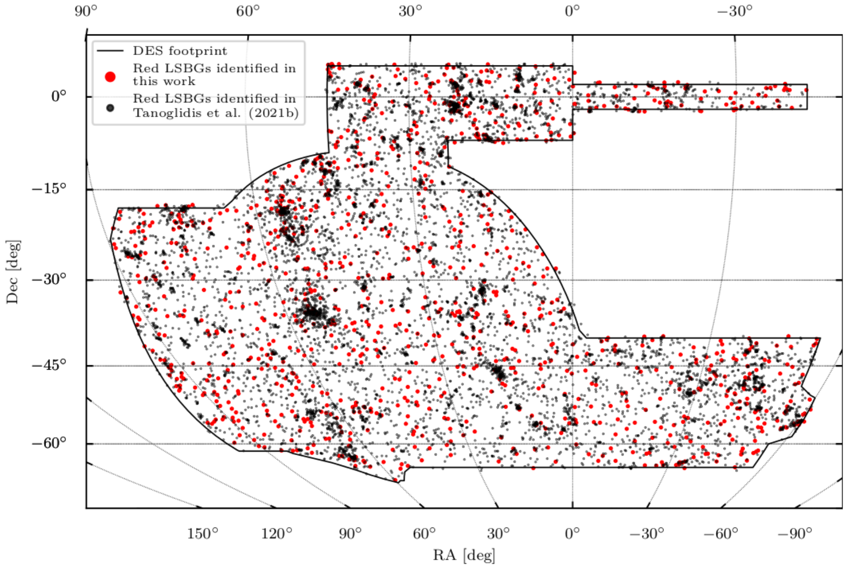






Maps of blue and red LSBGs (old and new) in the DES field

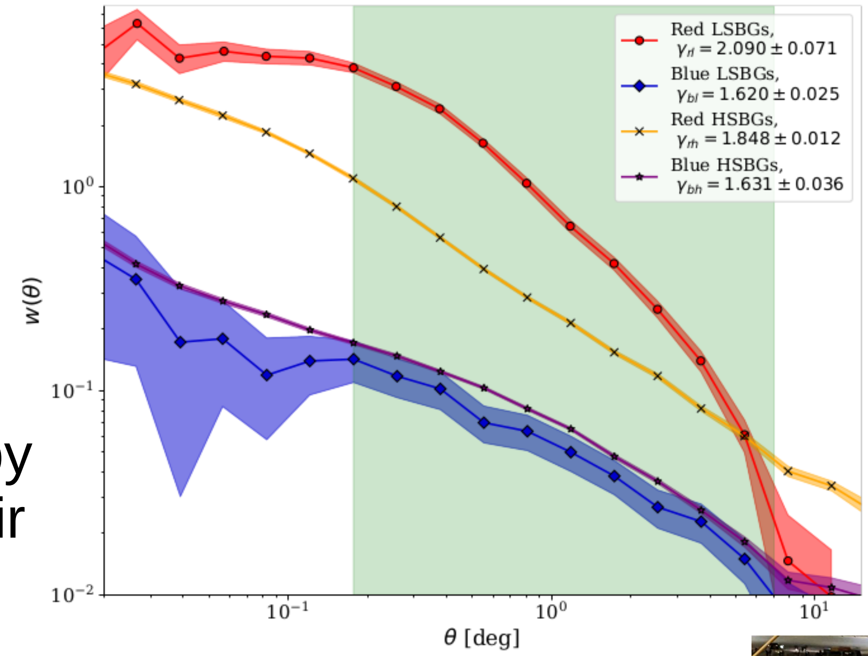


Thurutupilly et al. 2024

Clustering of LSBGs vs HSBGs in the similar z and luminosity range

DARK ENERGY SURVEY

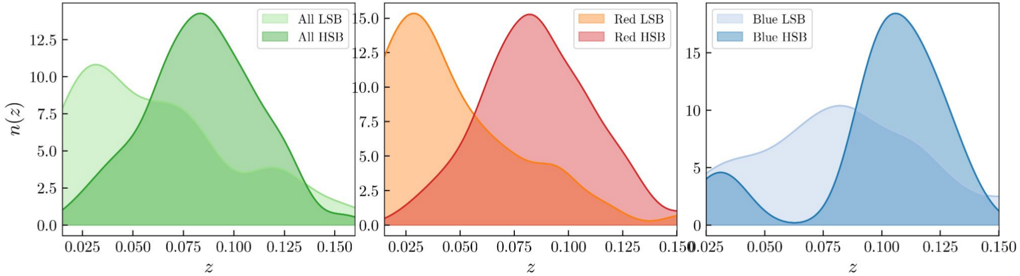
- red and blue LSBG trace LSS in a completely different way
- blue: low clustering, very similar to their HSB counterparts → occupy small haloes typical for their stellar mass range; avoid clusters
- red: very strongly clustered → occupy much more massive haloes than their HSB counterparts and → aboundant in clusters (and groups?) but not in their centers, rather surroundings/outskirts



Thurutupilly et al. 2024

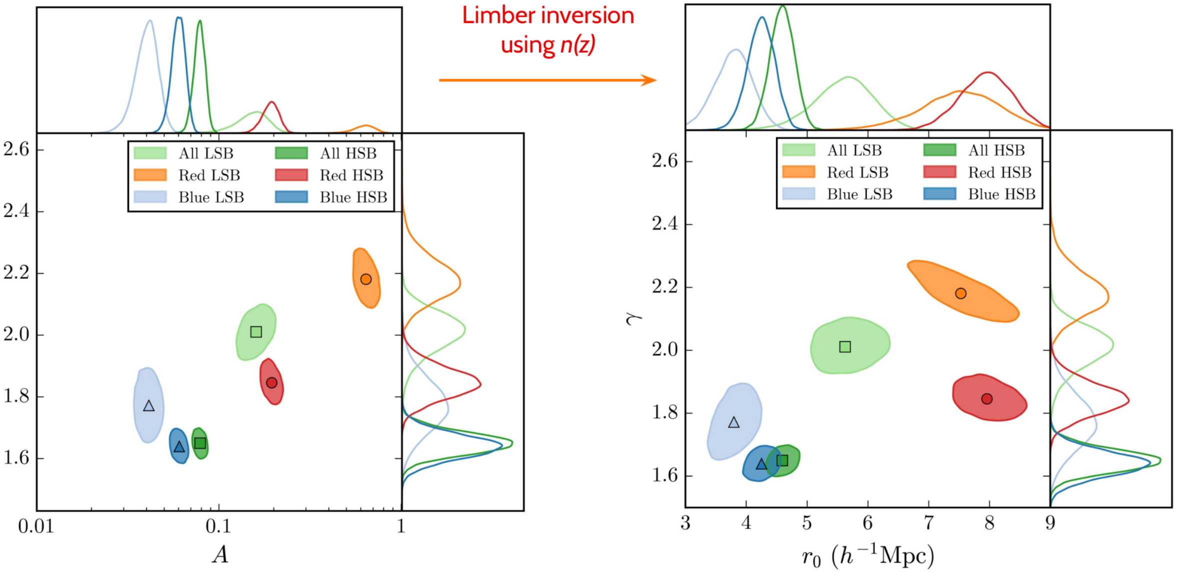
Clustering of LSBGs vs HSBGs in the similar z and luminosity range

DARK ENERGY SURVEY



Sureshkumar et al. in prep

- Moving to 3D we get the differences smaller but blue and red LSBGs still are at opposite (and further than their HSB counterparts) ends of the clustering range



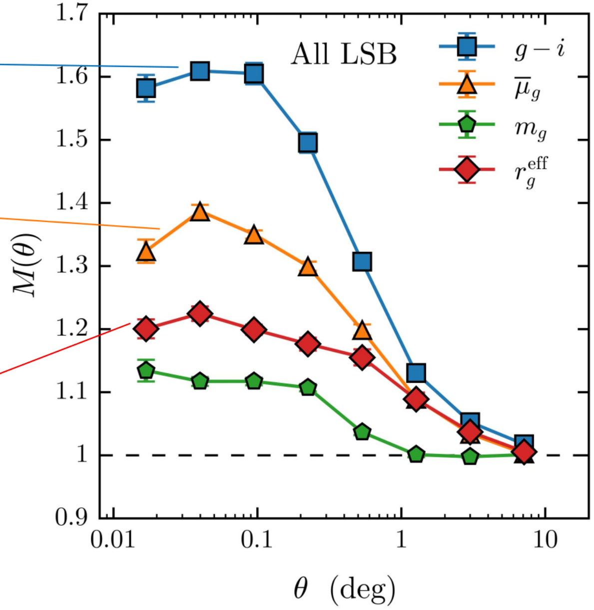
Clustering of LSBGs - MCF: dependence of properties on the evvironment

DARK ENERGY SURVEY

Redder LSBGs prefer denser environment

LSBGs with higher value of surface-brightness magnitude (lower surface-brightness) prefer denser environment

Larger LSBGs prefer denser environment

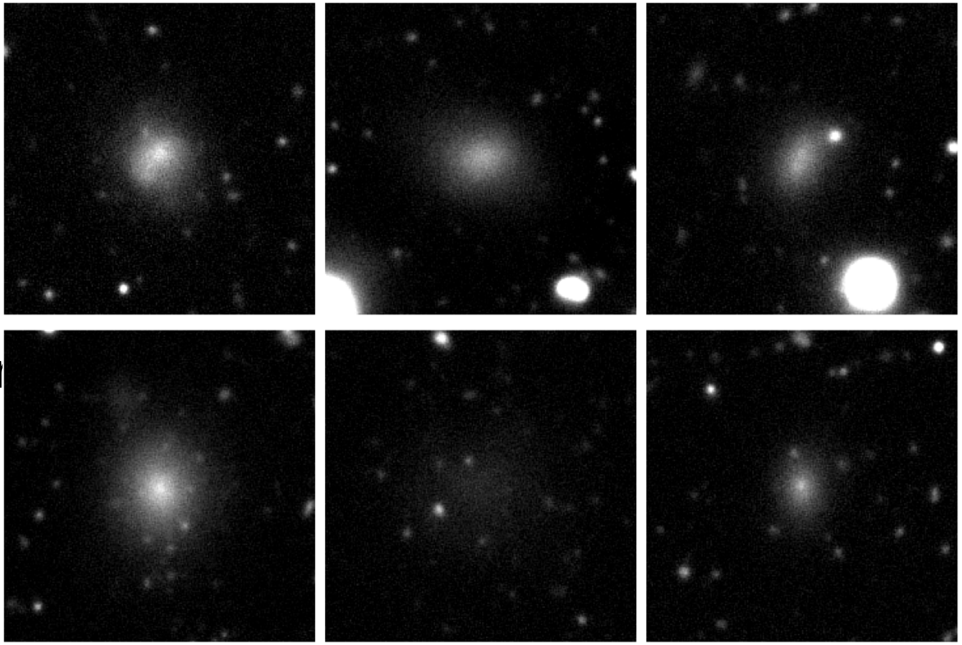


Sureshkumar et al. in prep

How effectively can the DES experience be transferred to other data (LSST included)?

- Transformer models + DES-identified LSBGs (with pixel values → surface brightness, to account for instrument differences)
- 171 LSBGs found, among them 87 new discoveries (159 identified using transformer models, and 12 additional LSBGs found through visual inspection).
- Among them 28 UDGs.
- The transformer model achieves a true positive rate of 93% in HSC data without any fine-tuning: successful transfer learning.

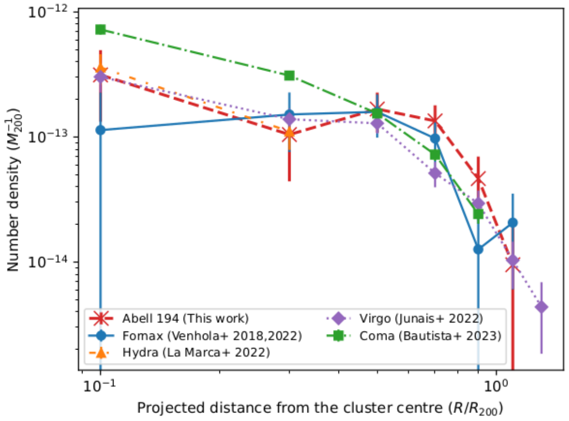
DES to HSC: the case of Abell 194

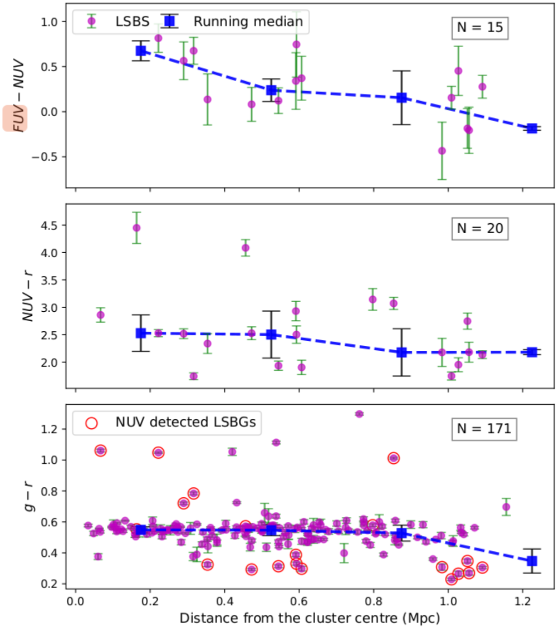


Thurutupilly, Junais, Koda, Pollo et al. 2025

DES to HSC: the case of Abell 194

- Number density of LSBGs decreases towards the center of the cluster → LSBGs prefer cluster outskirts (→ flattening of CF at small scales)
- Towards cluster centre, LSBGs become redder in UV → signature of quenching (→ scale dependence of properties)





Thurutupilly, Junais, Koda, Pollo et al. 2025

Summary

- → Different evolutionary paths of different galaxies depend (also) on their environments → superficially similar galaxies may have quite different histories, and quite different relations with environment
- → ...which implies they trace the LSS differently which may lead to different cosmological conclusions (especially at the “precision cosmology” level)
- → small scale dependence of clustering on galaxy properties on environment – monotonic change of average galaxy properties with scale instead of bi/multi-modality
- → Low surface brightness galaxies as the missing piece of galactic census - may change the way we see galaxy distribution and evolution in the Universe and large scale structure