Galaxy evolution, observational biases and cosmological tensions

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Galaxies are known to be good but biased tracers of the underlying dark matter field. This bias is mostly driven by the history of hierarchical clustering and galaxy/halo assembly history but is also affected by factors regulating galaxy evolution, usually environment dependent. Moreover, it is easily blurred by observational biases unavoidably present in the data. Thus, the relations between galaxy physical properties and the underlying dark cosmic web are not easy to model. At the same time, all cosmological tests are necessarily based on baryonic tracers. Thus, using galaxies for tests of cosmological models relies on our understanding of the relations between a galaxy, its DM halo, large-scale environment, their co-evolution, and observational biases in the data we use. In my talk, I will show some recent results from our group illustrating nontrivial dependencies between galaxy evolution and their environment, and pointing to the prospects - and pitfalls - with the new soon-arriving data from near-future large surveys.

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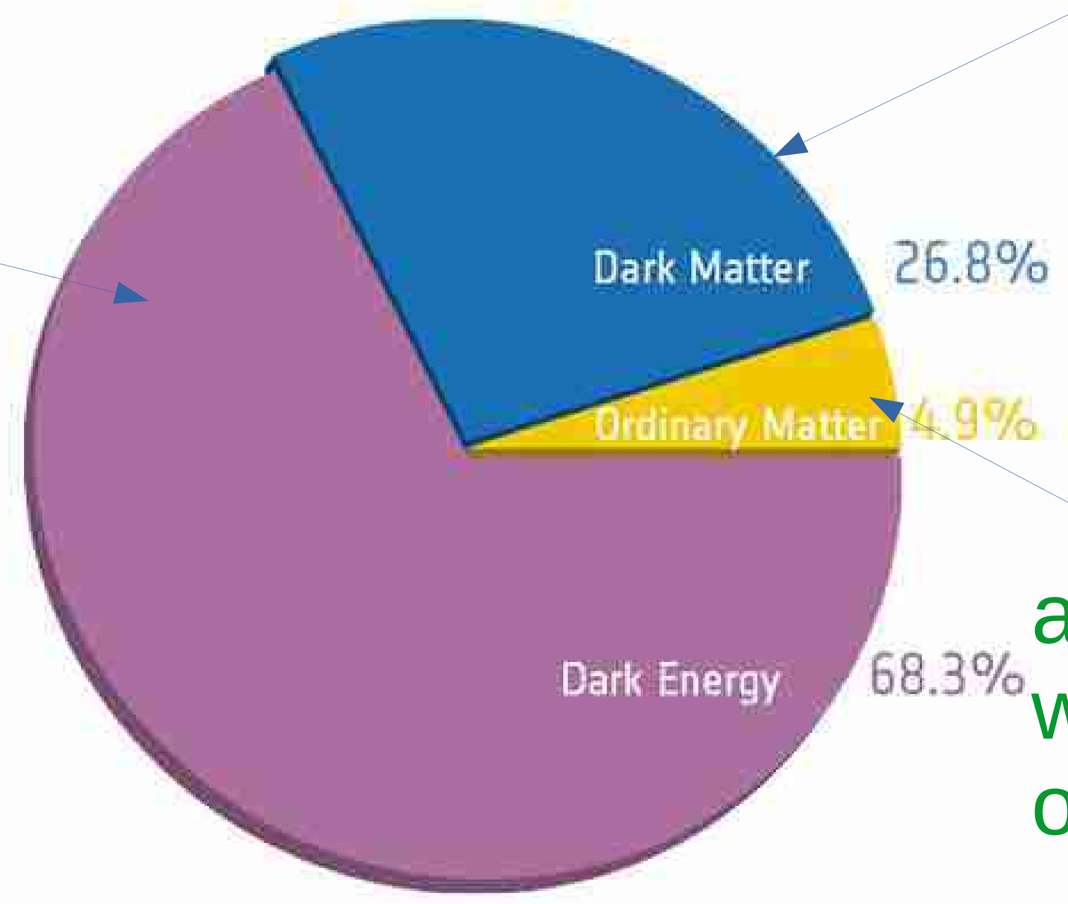
unknown



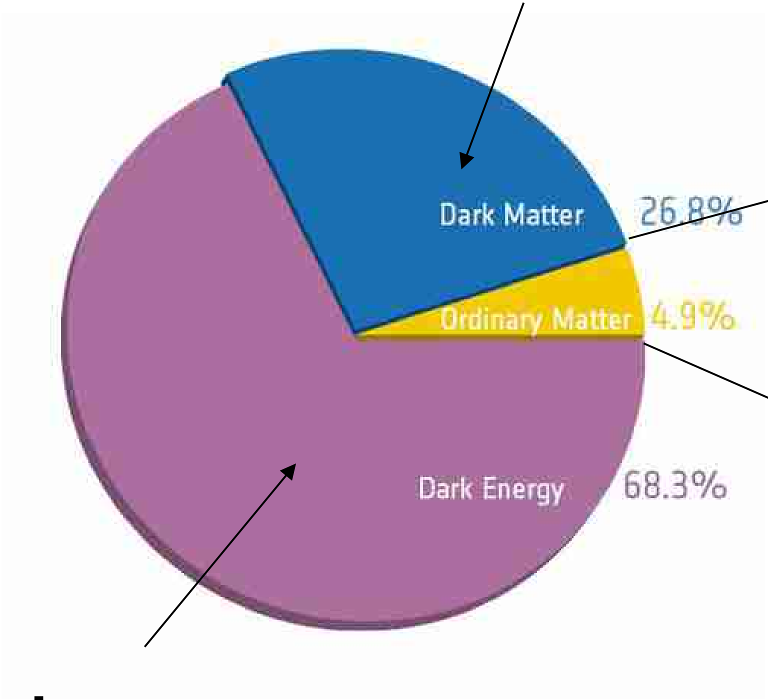
a large part went missing on the way

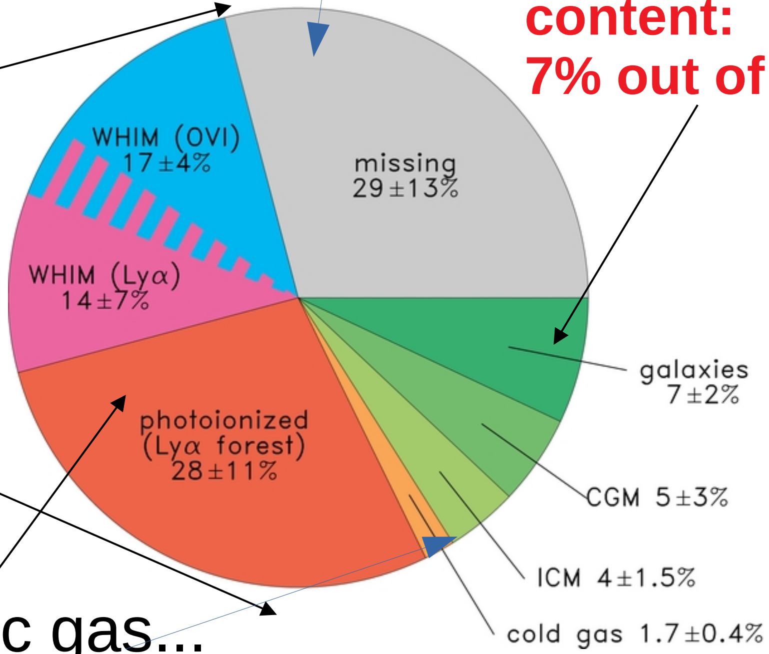
Credit: Planck collaboration

unknown again…

galaxies with their baryonic content: 7% out of 5%...

unknown





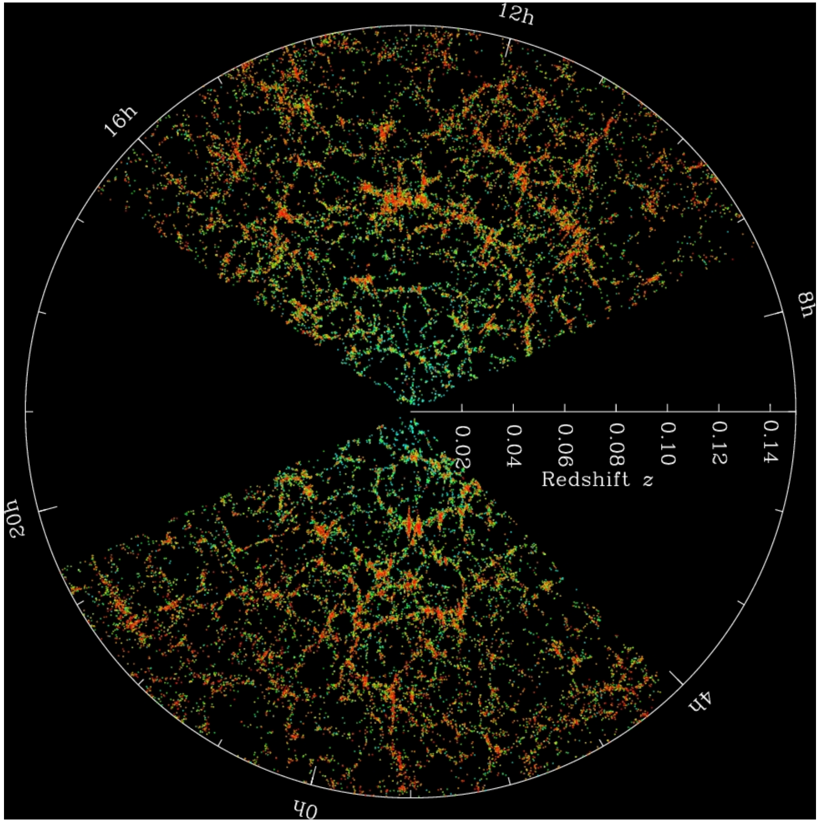
unknown

intergalactic gas...

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

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

different galaxies – different structure

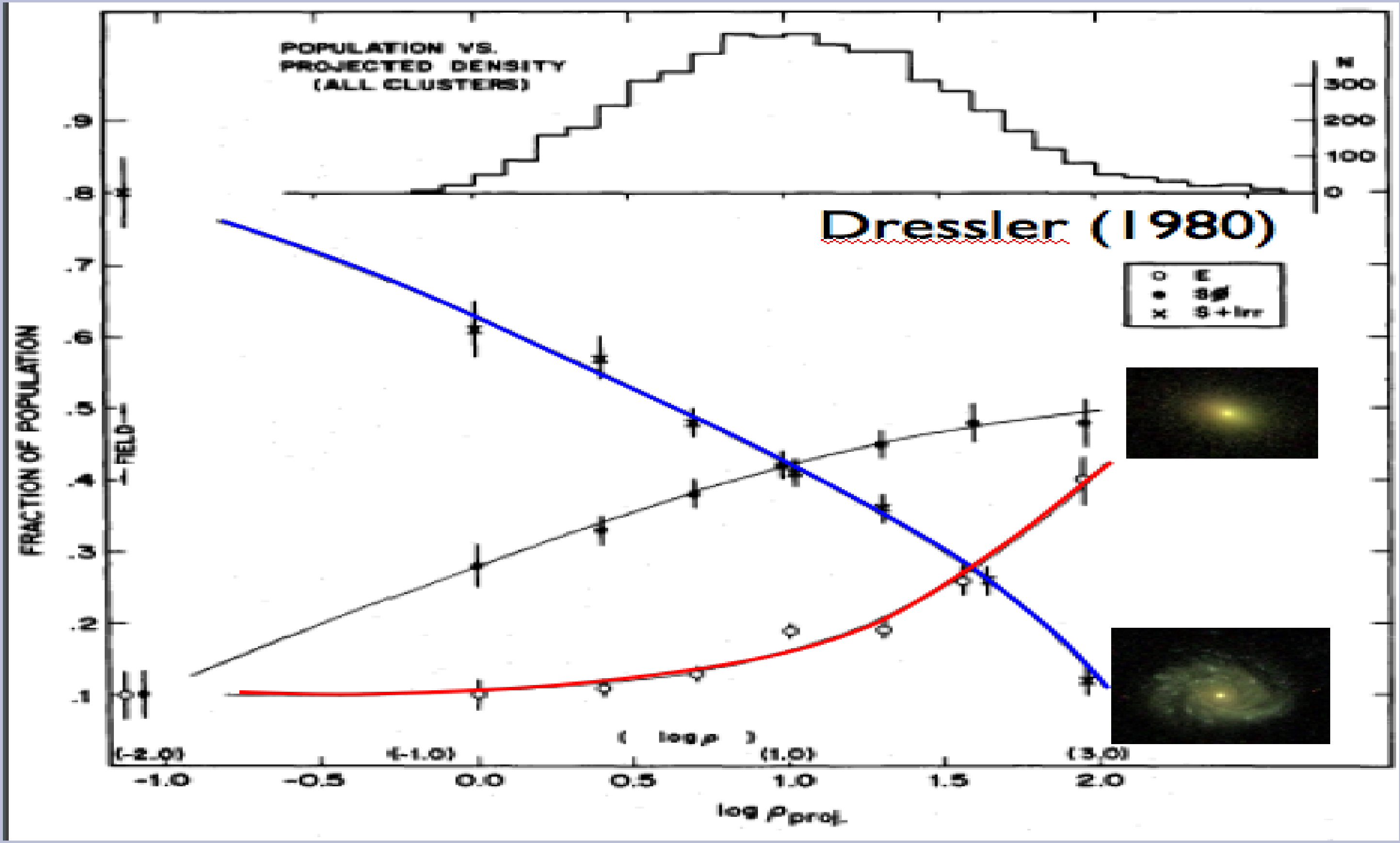


Credit: SDSS

→ 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)?

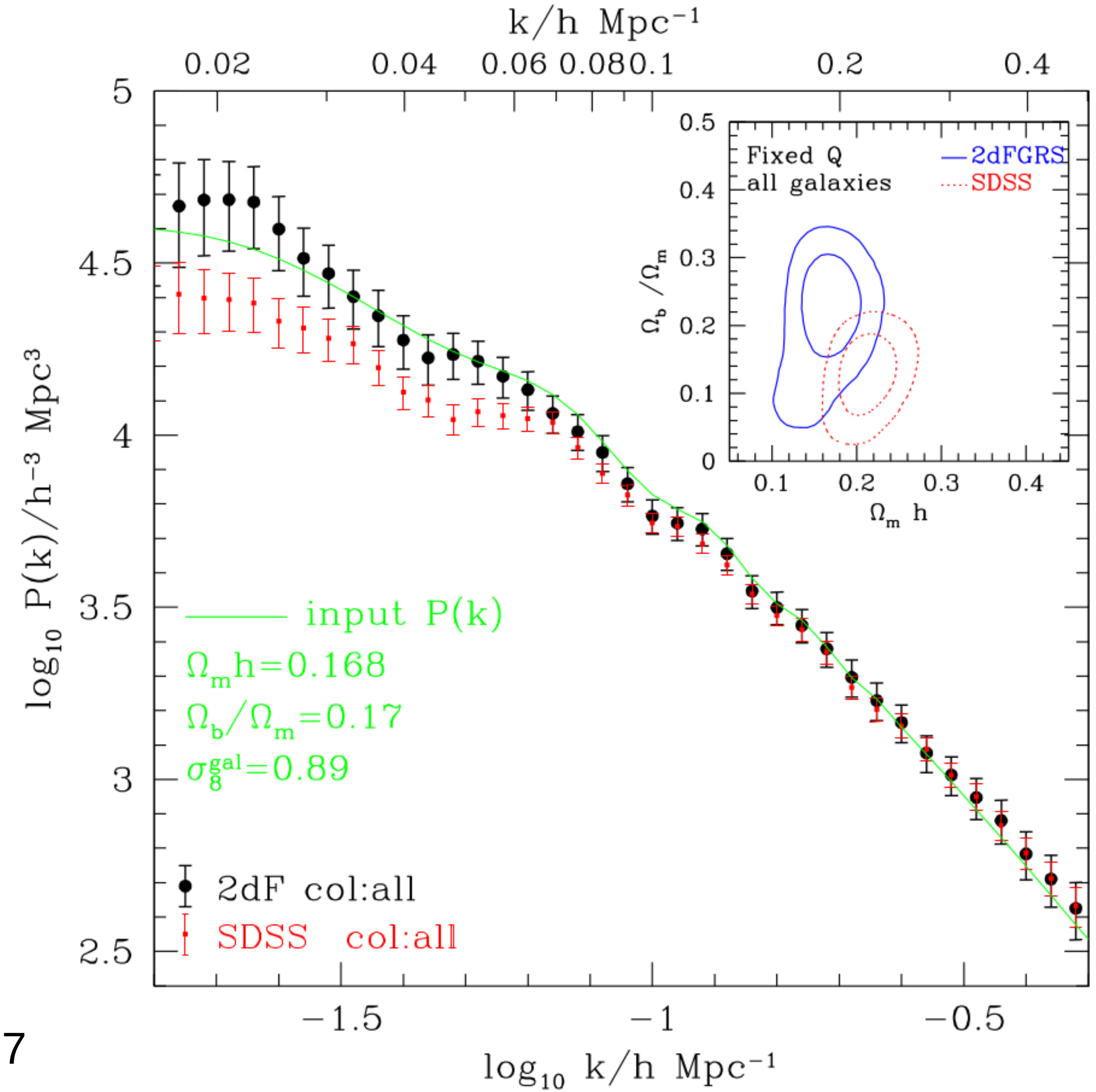
Morphological types vs local environment at z~0 different galaxies trace dark matter in a different way



A bit of (pre-)history...

Cosmic tensions from the past

SDSS
vs
2dFGRS

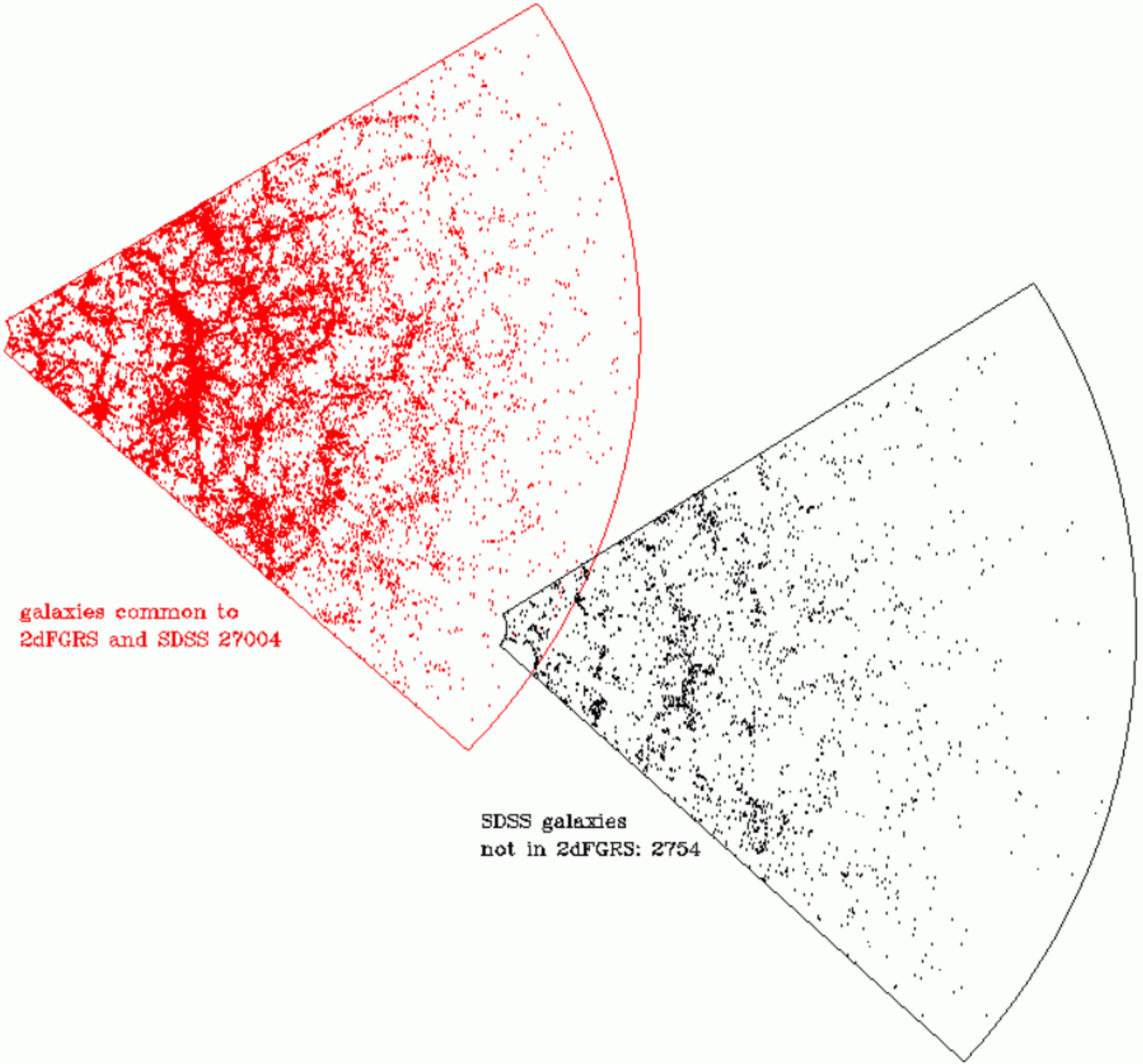


Cole et al. 2007

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

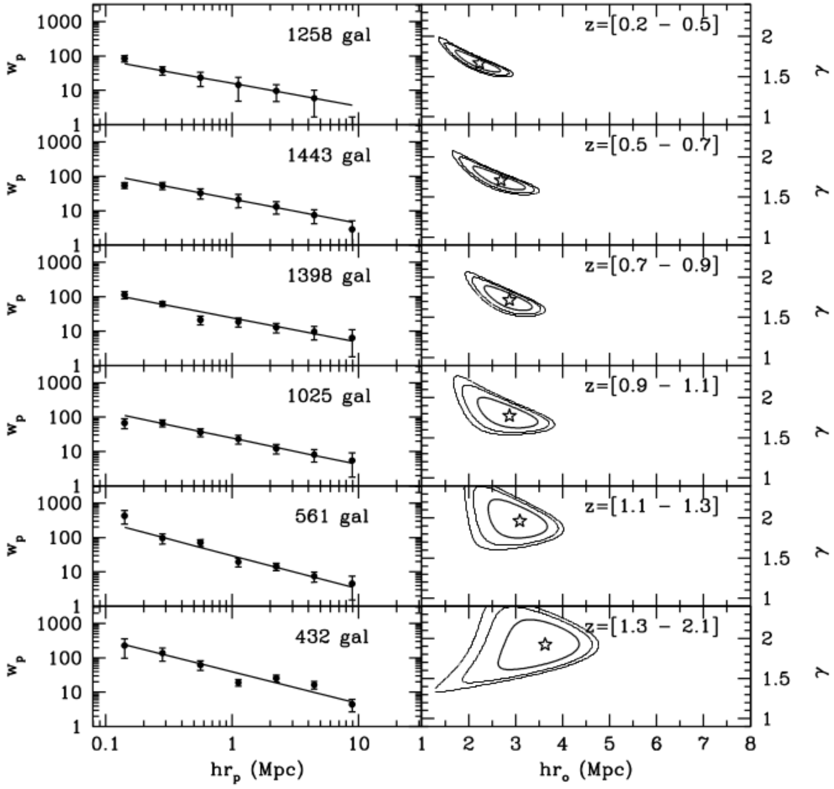


Cole et al. 2007

Cosmic conspiracies

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

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

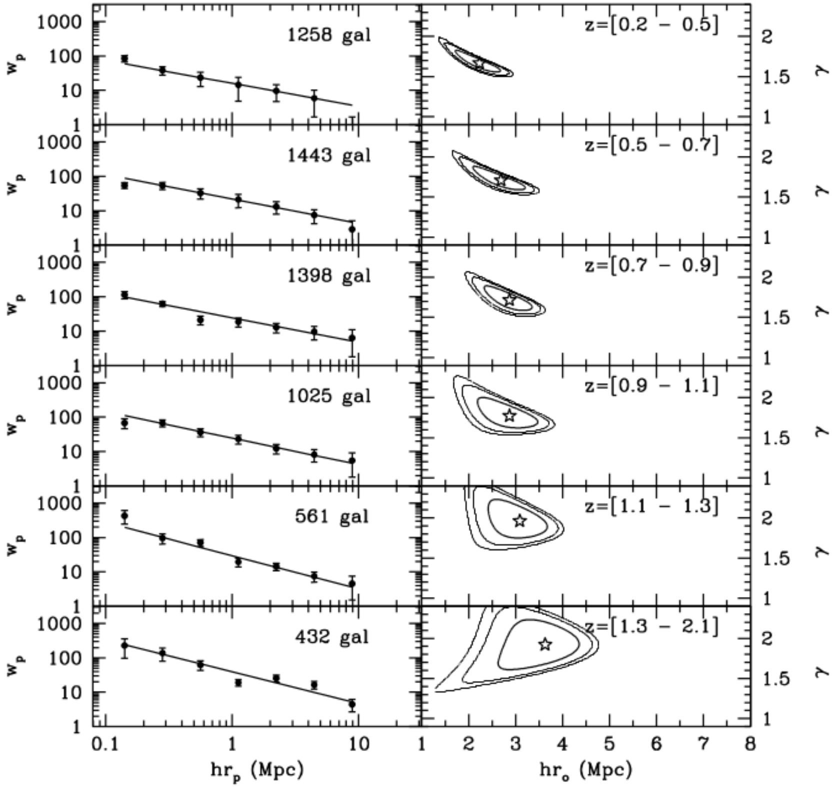


Le Fevre et al. 2005a, b; Pollo et al. 2005, 2006

Cosmic conspiracies

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

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



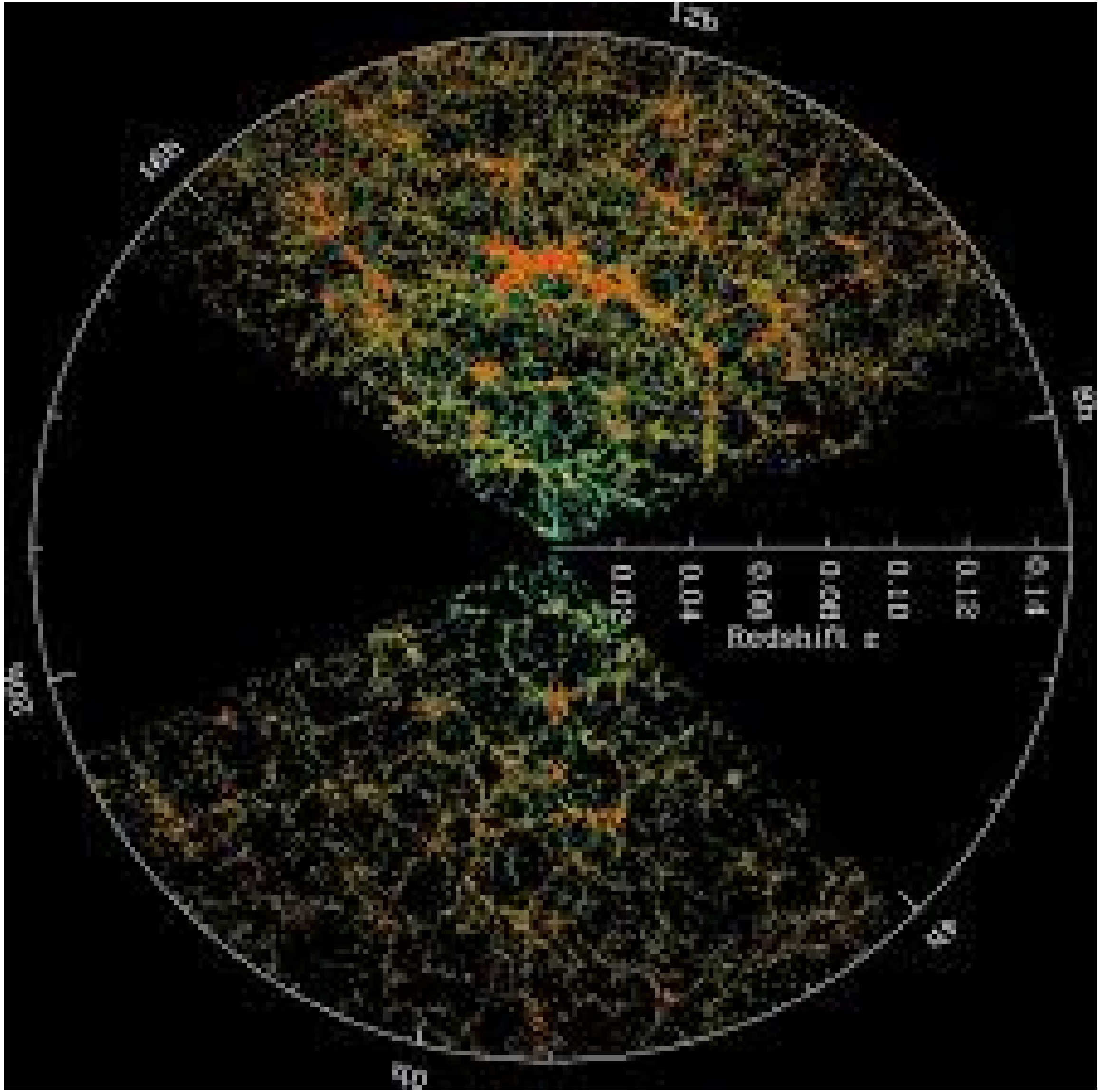
Le Fevre et al. 2005a, b; Pollo et al. 2005, 2006

Biases tend to conspire (against us)...

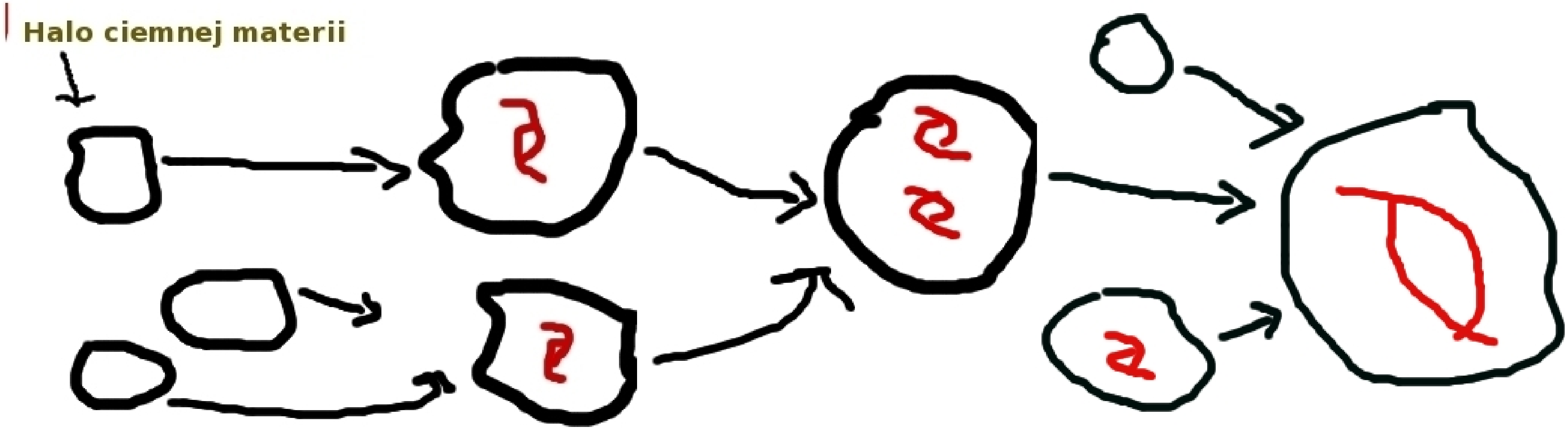
SDSS: $0<z<0.2$

Red/elliptical galaxies tend to reside in the nodes of the cosmic web (clusters)

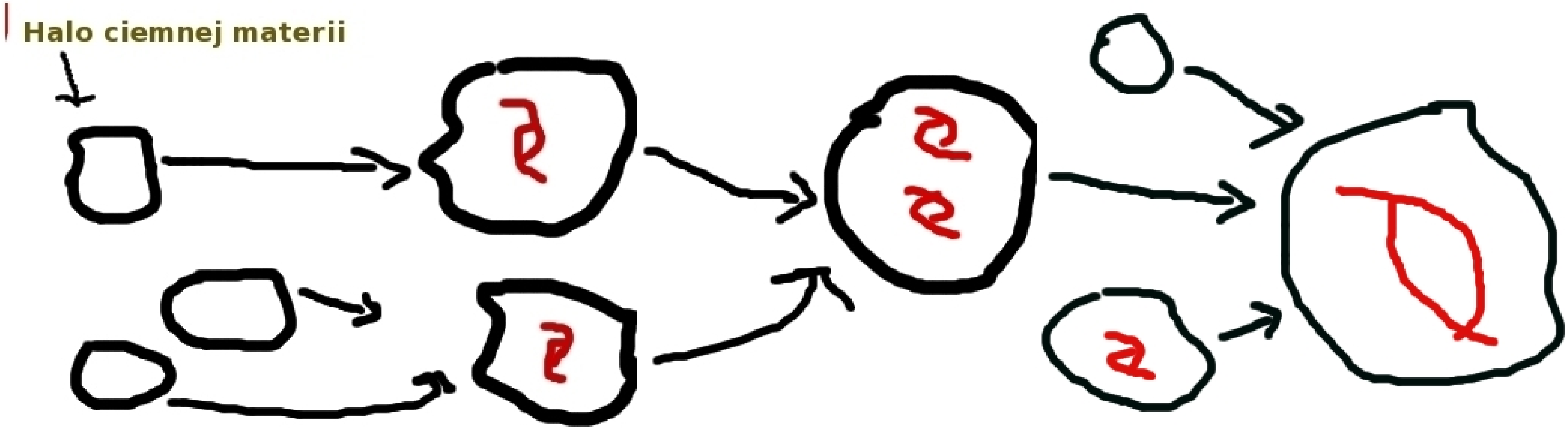
Blue/spiral galaxies are more dispersed



The hierarchical scenario of large scale structure formation: in the hierarchical scenario of the evolution of the large scale structure, dark matter haloes form starting from the strongest overdensities (→ bias) which then grow and merge depending on their spin, large scale environment etc. (→ assembly bias). Galaxies form and grow in these dark matter haloes, due to accretion and mergers.



Our understanding of a dynamics of this process and its dependence of properties of the DM halo (mass, spin) and small- and large-scale environment is still evolving. Why some galaxies are elliptical/red and some spiral/blue? When did this bimodality establish and which are the fairest tracers of DM field at different redshifts?



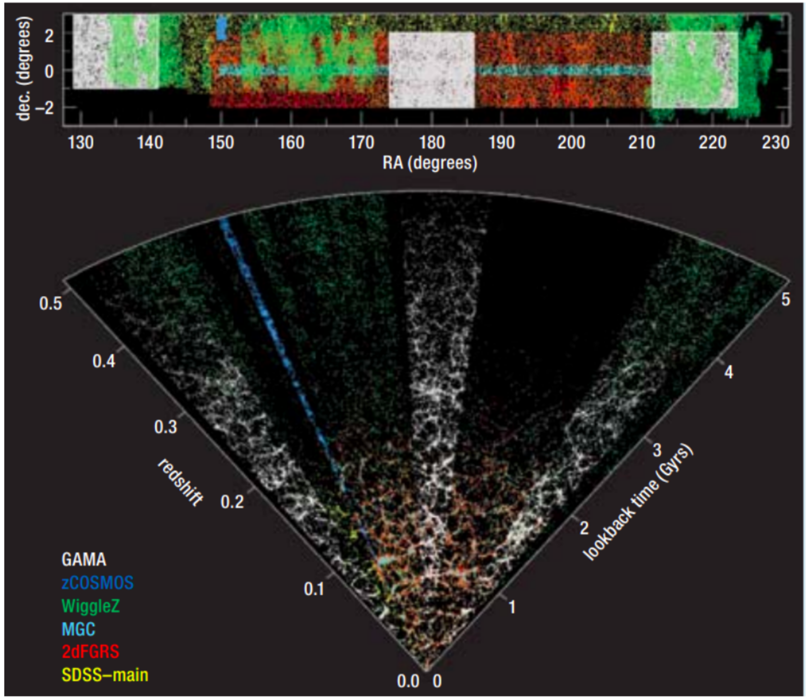
One way (and, practically, the most strightforward) to tackle these issues is the statistics of the large galaxy surveys at different redshifts – to probe large scale structure, its evolution and relations with different types of cosmological sources.

A few technicalities which may be useful for the next parts

1. One way to quantify local environment is local density measurement (→ a given scale).
2. A useful statistical tool to study galaxy clustering is galaxy (auto)correlation function (CF), or higher order correlation functions. Alternatively, their Fourier space counterparts (power spectrum, bispectrum etc.) are used.
3. In the first approximation, the shape of the CF is well fitted by the power law.
4. At a closer look, CF deviates from power law, both at large and small scales and the most strongly for the most massive/luminous samples.
5. The small scale effect is interpreted as different physics of galaxy clustering inside one DM halo; interpreted in terms of so-called HOD formalism.
6. Marked CF – weighted by selected galaxy properties to see how these properties relate to environment.

Which galaxy property is the best proxy of DM halo mass?

Galaxy and Mass Assembly Survey



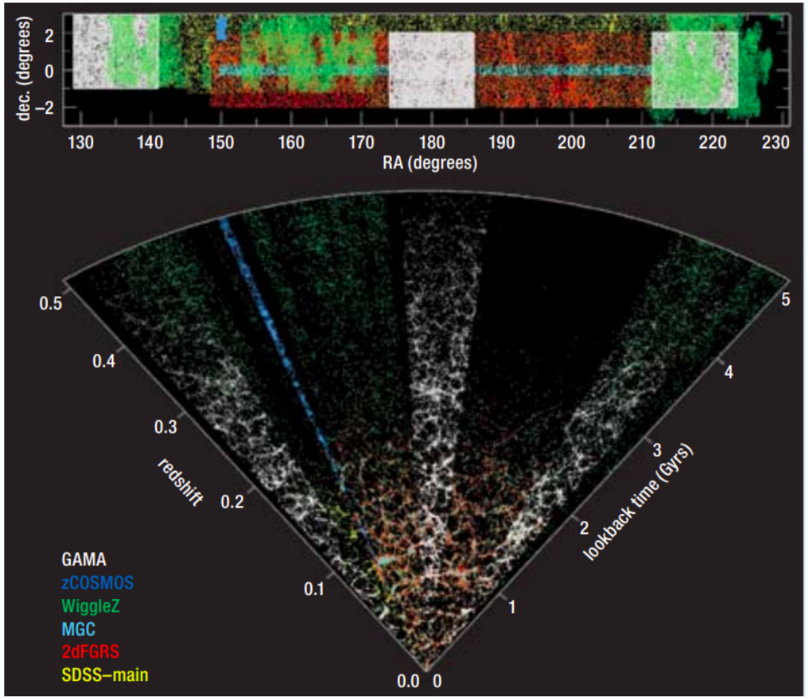
Driver et al. 2009

→ ~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

Galaxy and Mass Assembly Survey

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

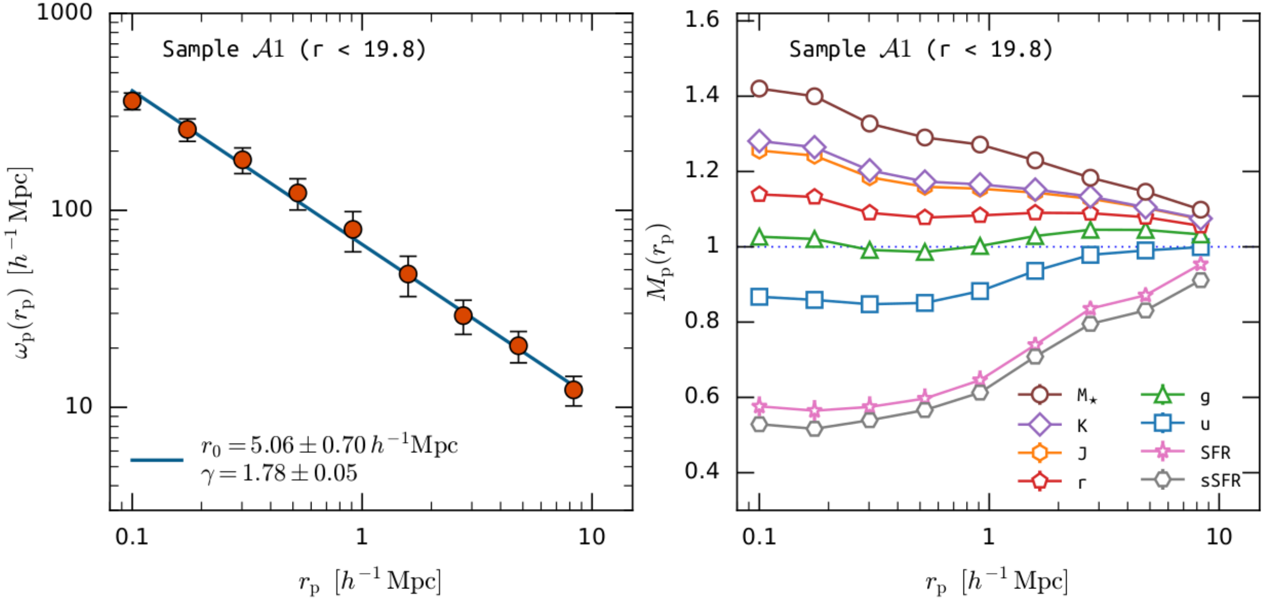
→ concept: in order to see how a given galaxy property correlates with environment and on which scale, we use this property as a weight ("mark") attached to each galaxy

→ $M = \xi_{marked}(r)/\xi(r)$

→ for comparison of different properties: "ranked MCF"

Sureshkumar et al. 2021, 2023

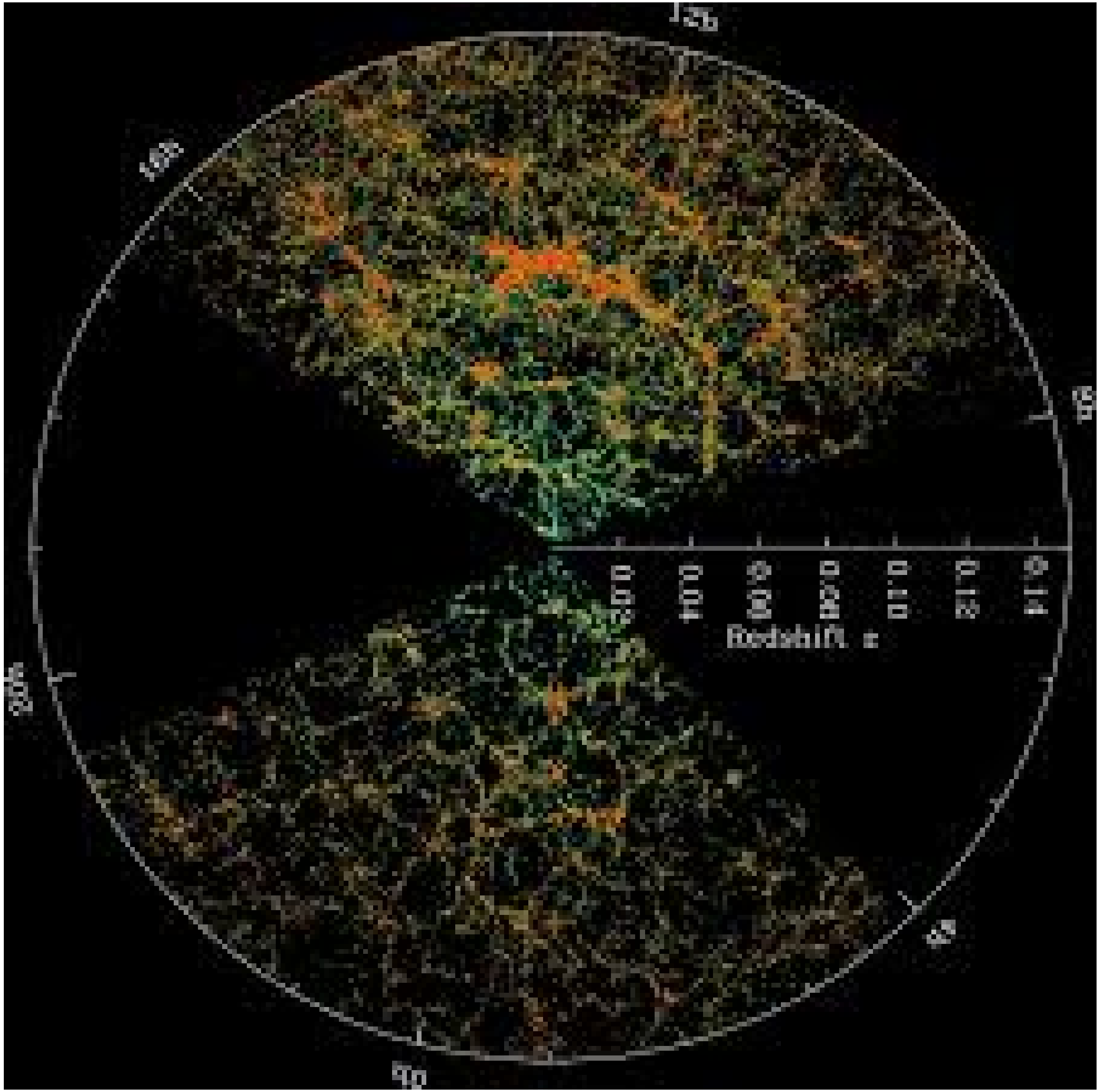
From ξ to mass-SFR-luminosity marked ξ



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)

→ The picture of the LSS we get (especially at small scales) depends on the choice of filter/color, depth, selection method etc.



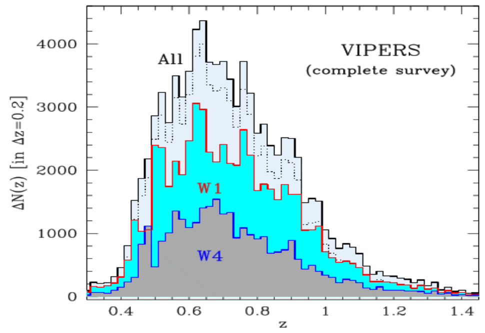
VIPERS

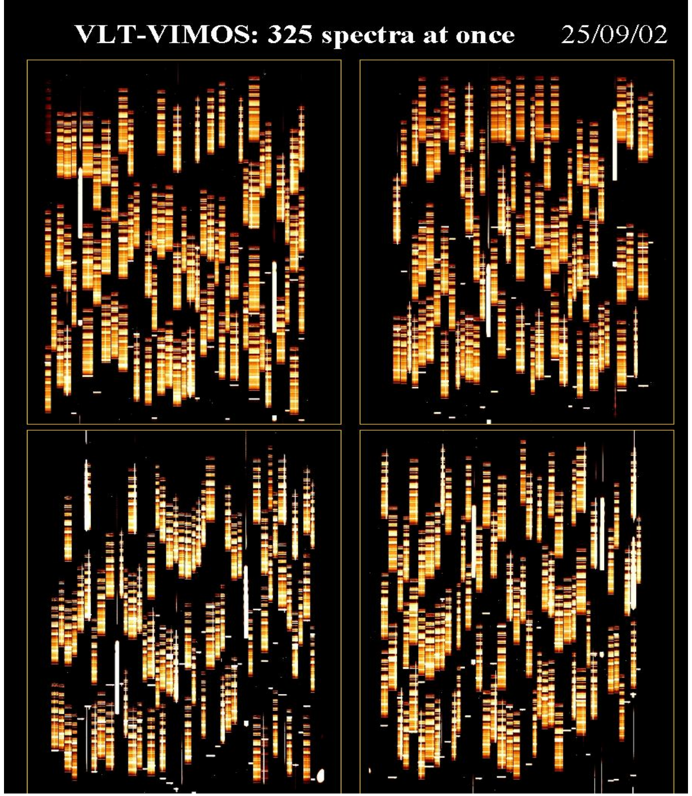
VIMOS PUBLIC EXTRAGALACTIC REDSHIFT SURVEY

SURVEY STATUS AS OF 06/11/2016

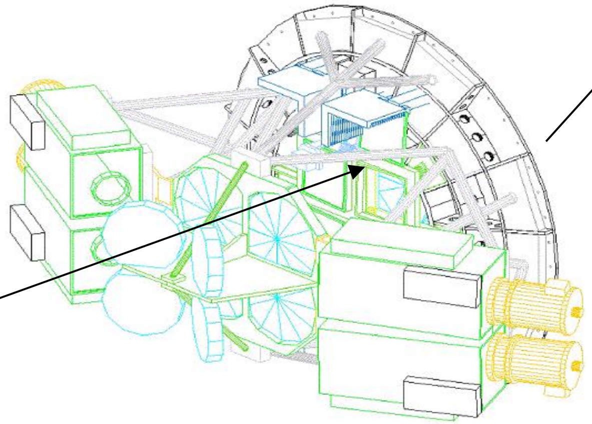
EFFECTIVE TARGETS	MEASURED REDSHIFTS	STELLAR CONTAMINATION	COVERED AREA
93252	88901	2265 (2.5 %)	100.0 %

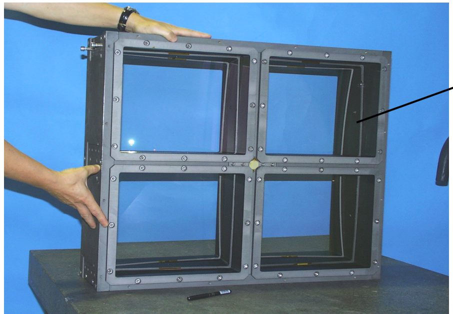
EFFECTIVE TARGETS (ET) are all the primary targeted objects with the exclusion of the ones flagged as -10 (undetected). MEASURED REDSHIFTS (MR) are the fraction of ET for which a redshift has been measured. STELLAR CONTAMINATION are the MR objects which have been identified as stars.





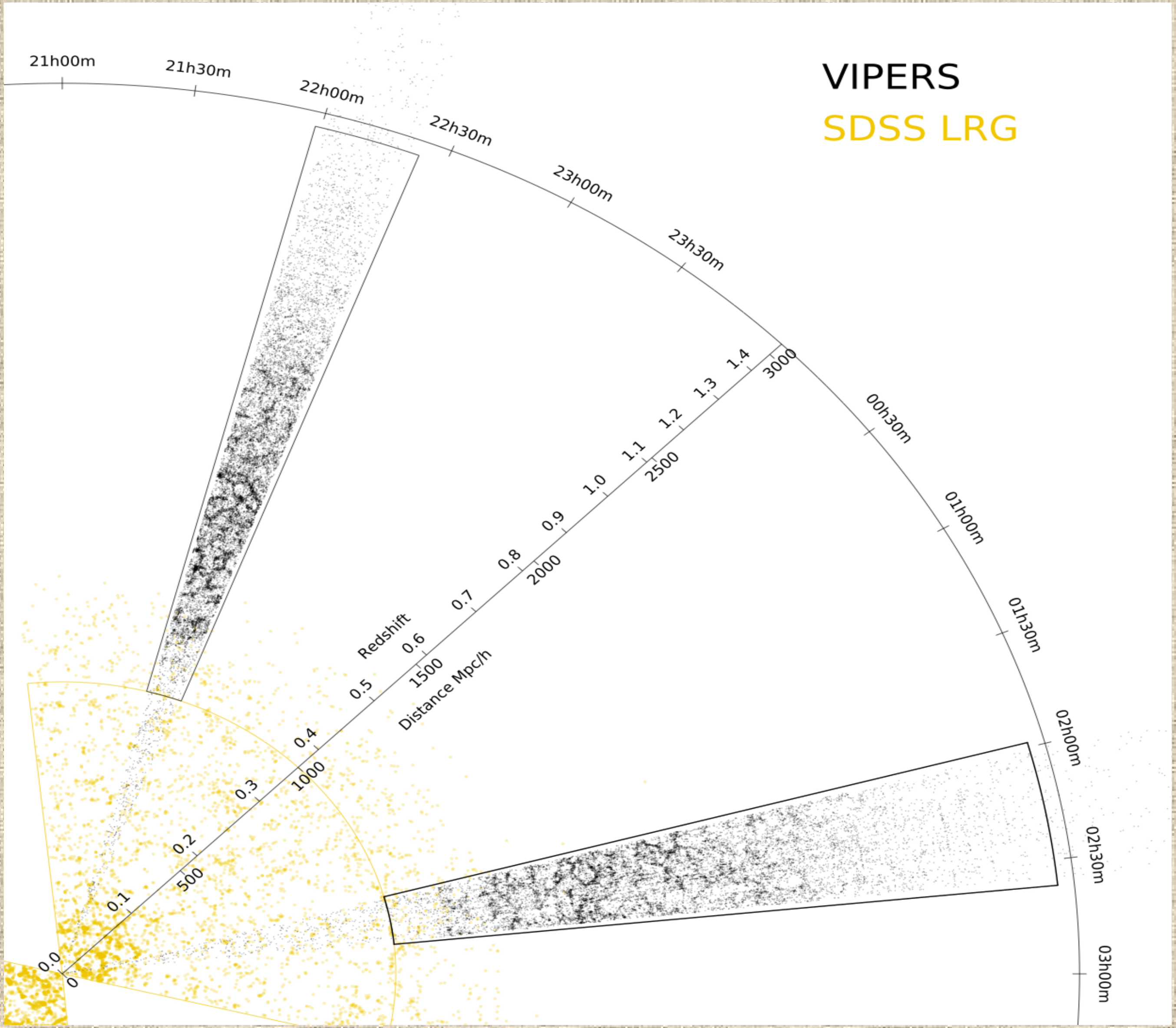
Large ESO Programme, 2008-2016



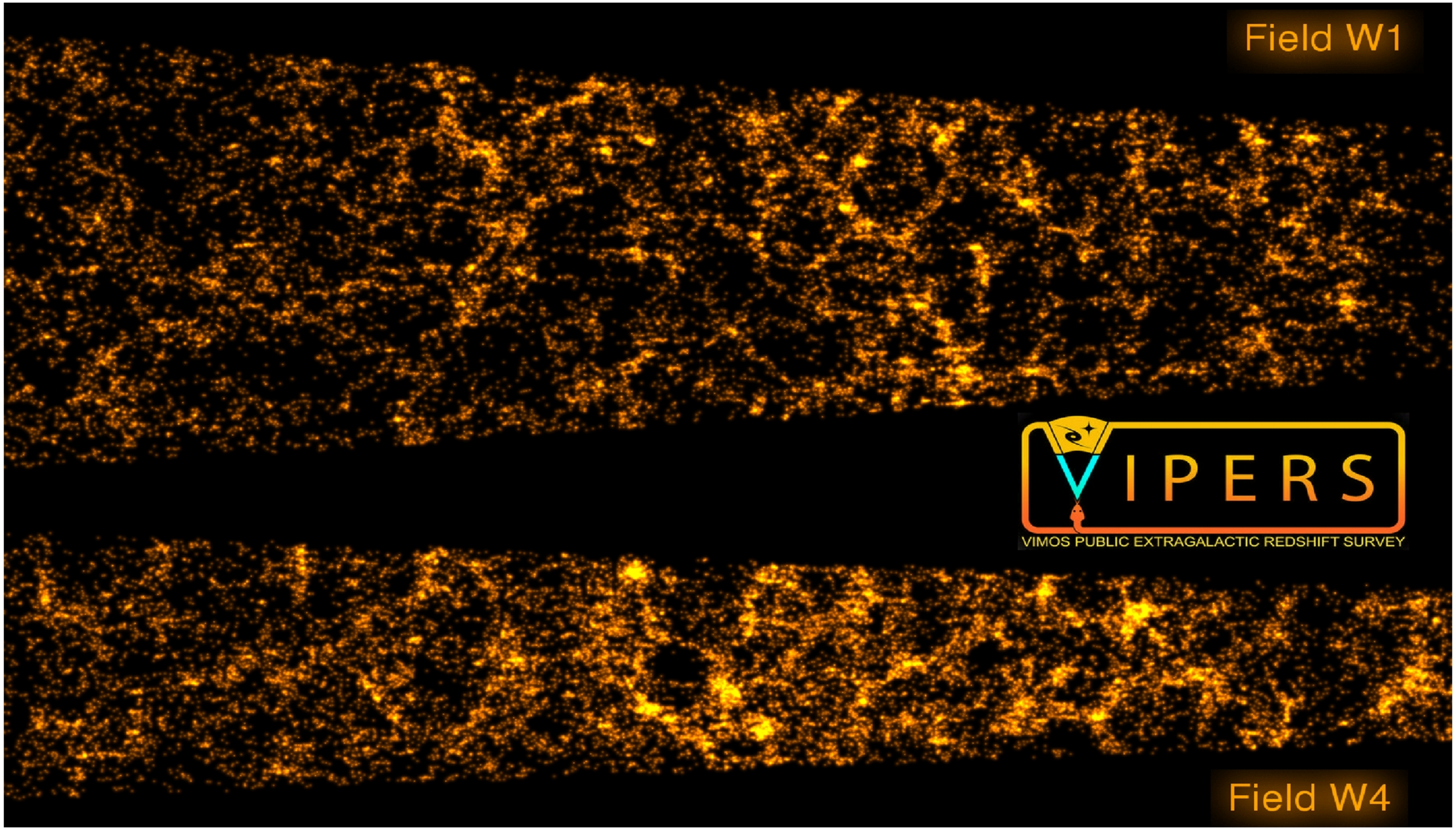


~90 000 spectra of galaxies
at **0.5<z<1.2**
2 fields on the sky, 24 deg^2

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



Courtesy Ben Granett


Field W1
VIPERS
VIMOS PUBLIC EXTRAGALACTIC REDSHIFT SURVEY
Field W4

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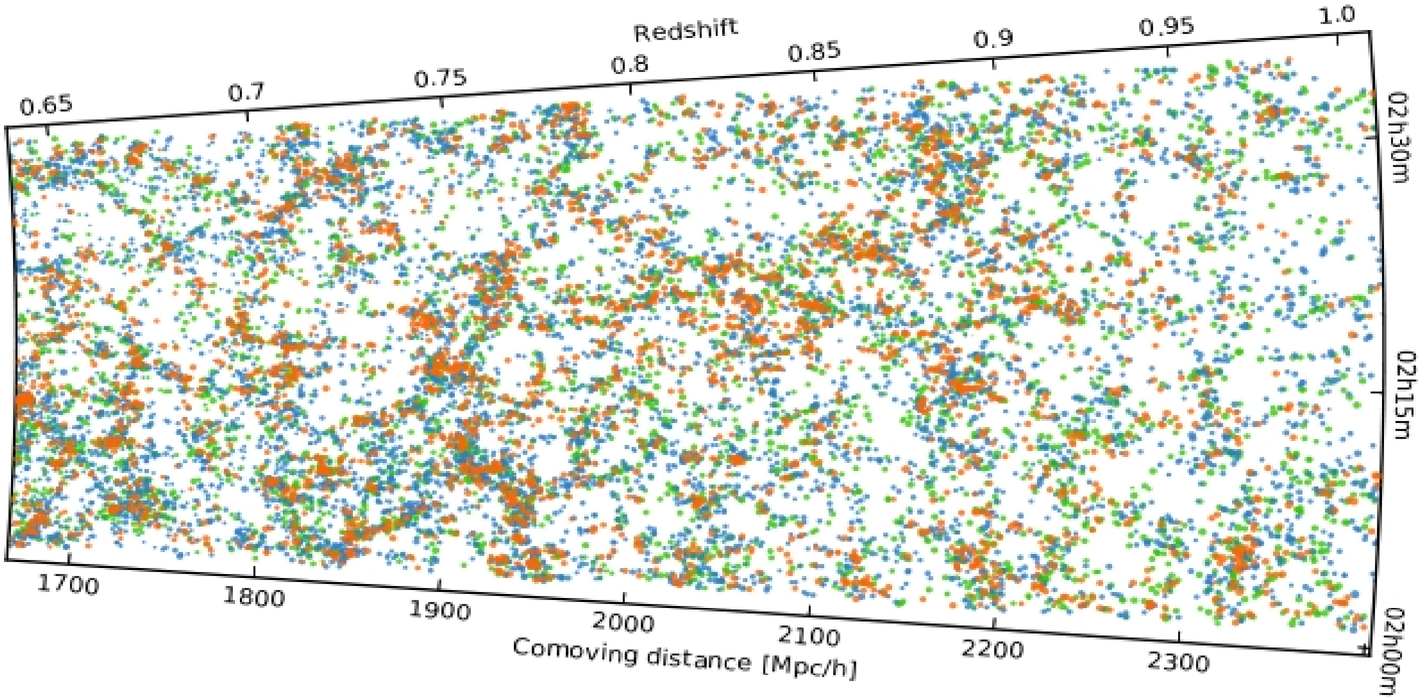
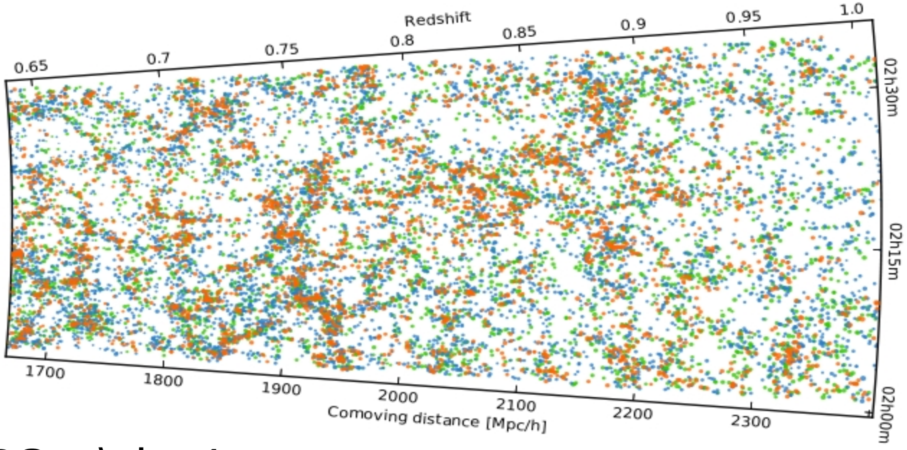
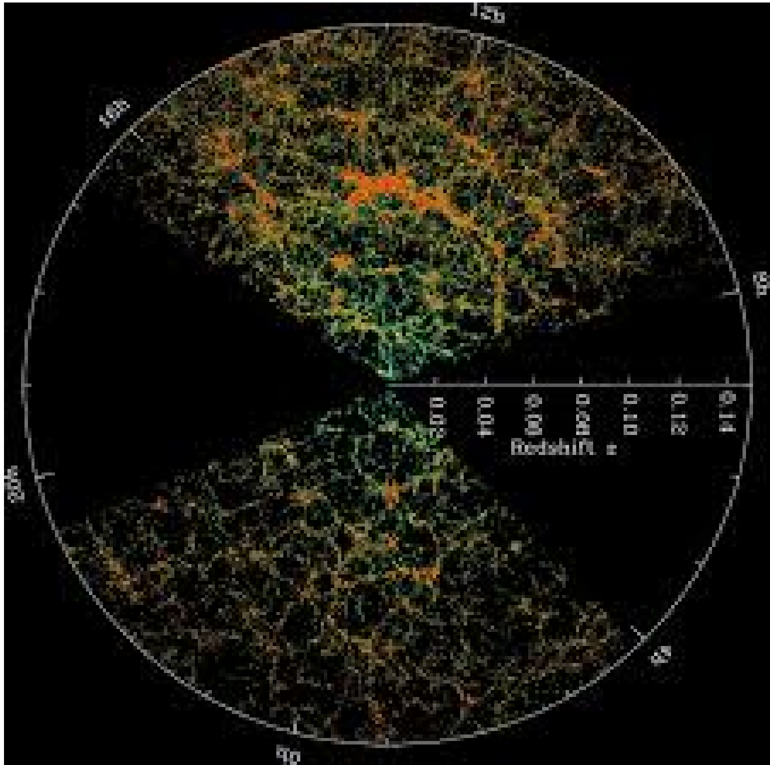


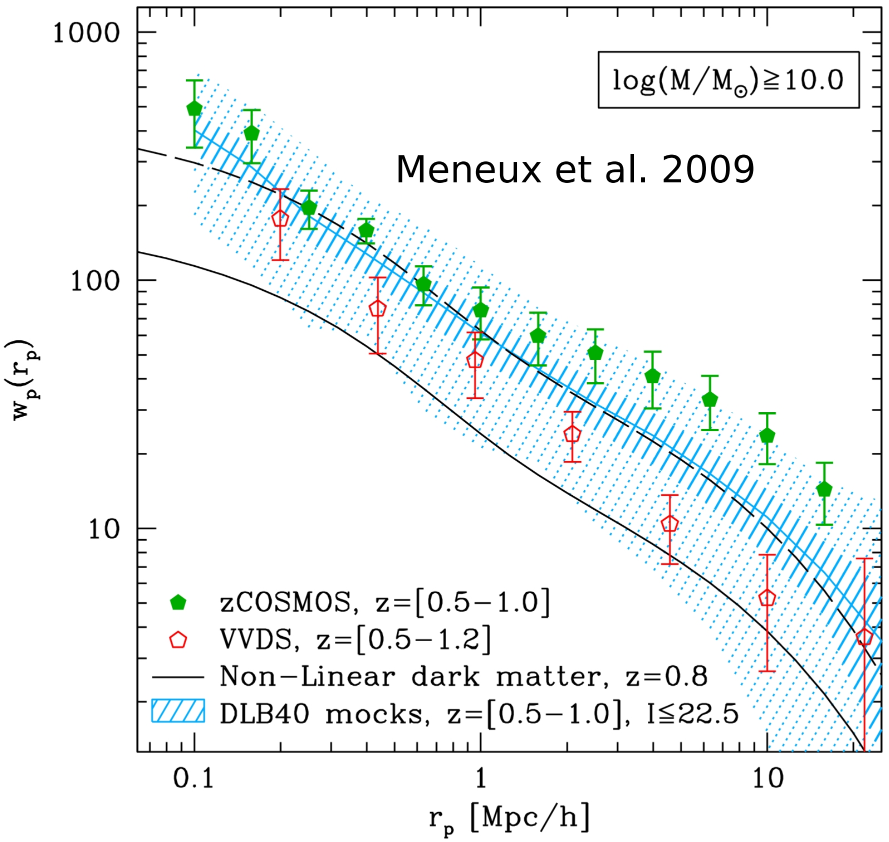


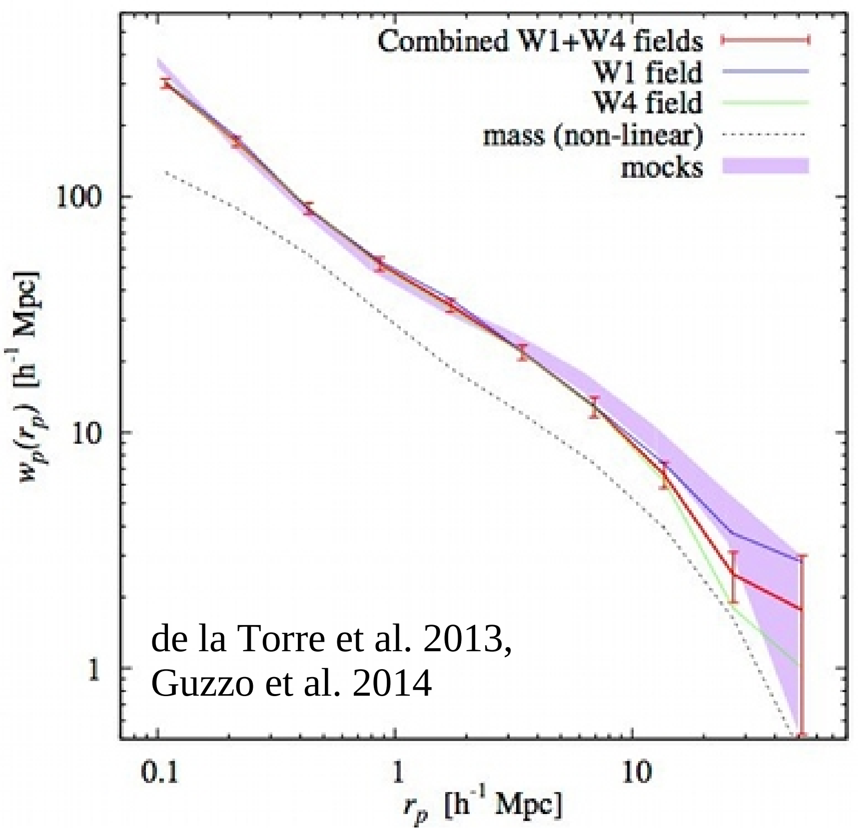
VIPERS z \sim 1



SDSS z \sim 0

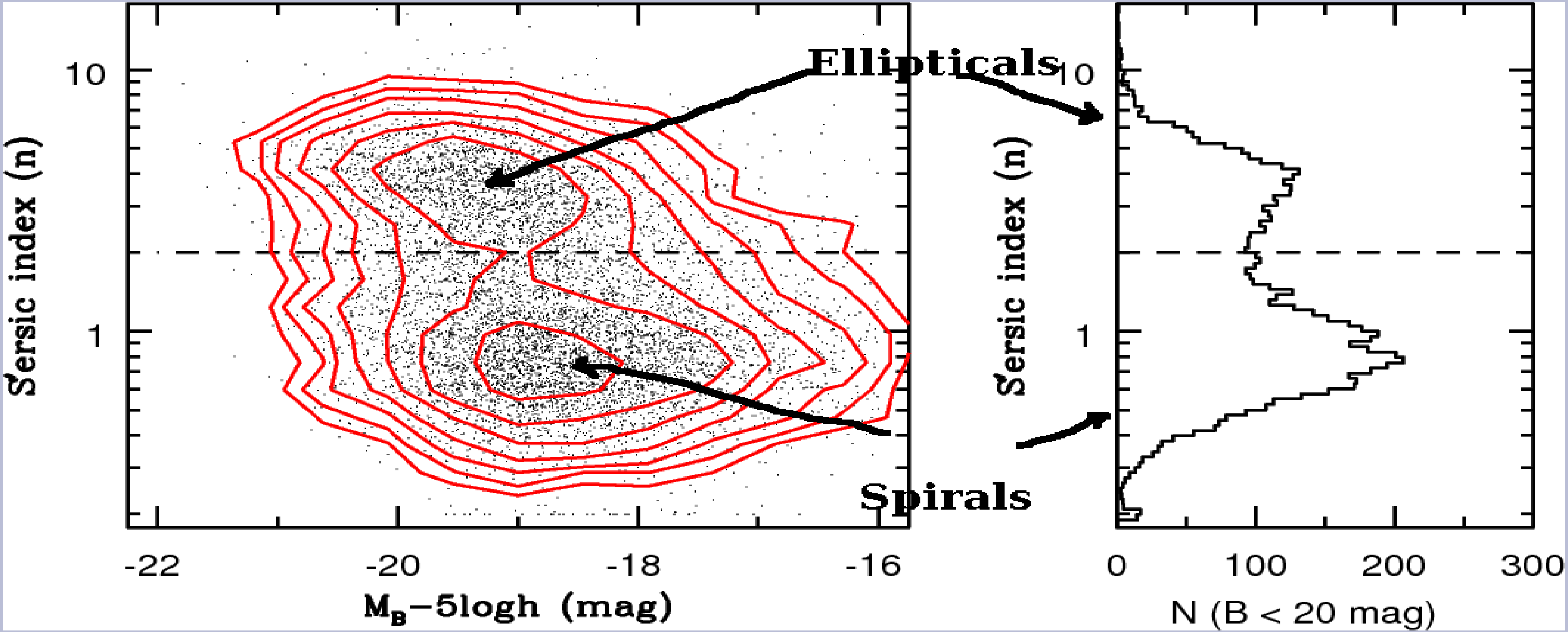
VIPERS:
be aware of cosmic variance



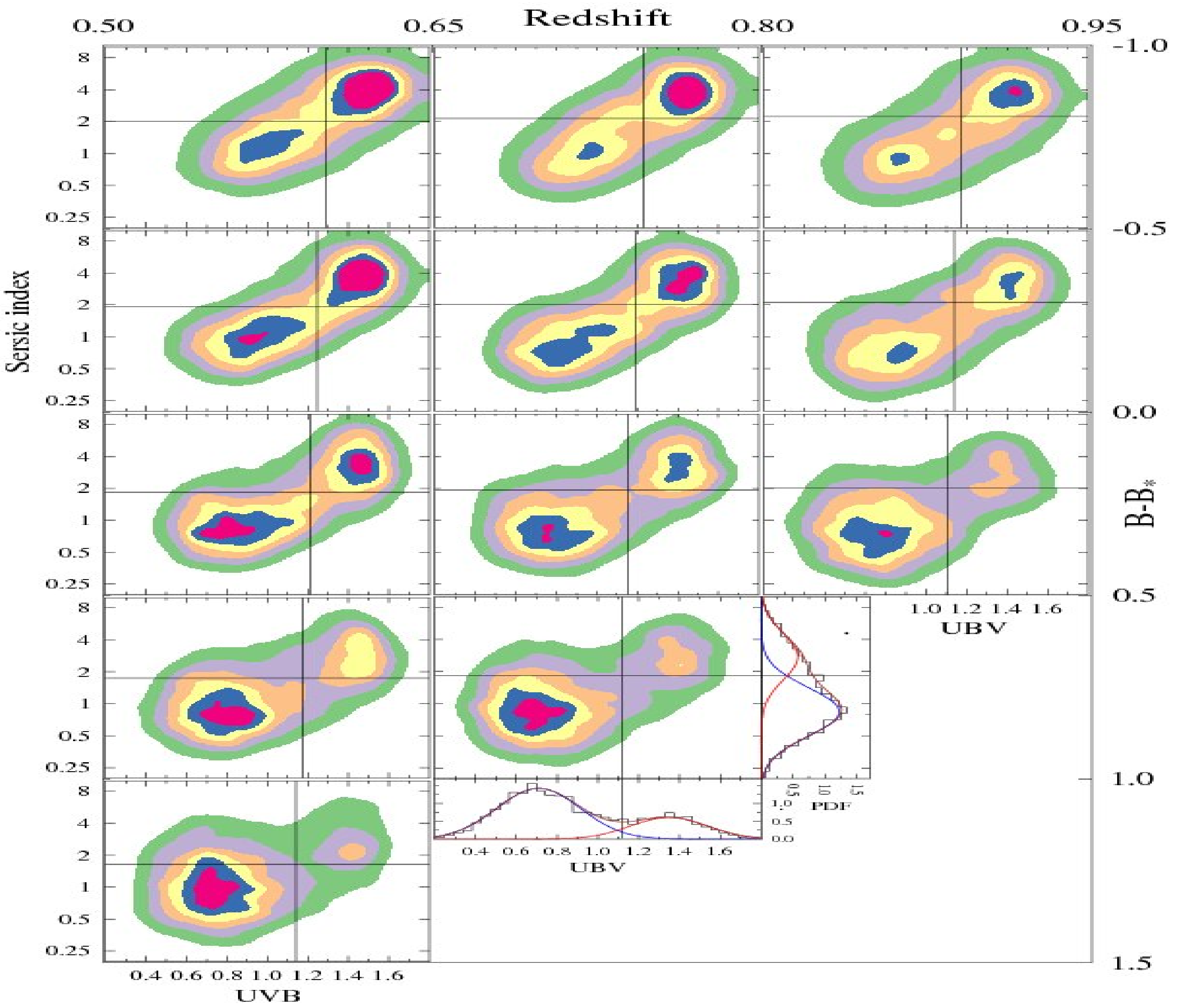


Galaxy types vs morphology:
near and far

In the local Universe (z~0)



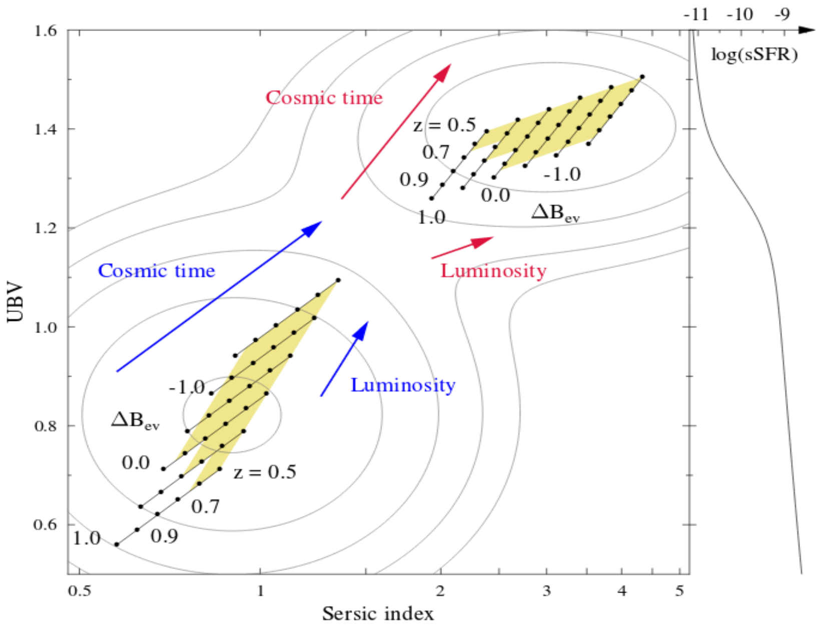
Millennium Galaxy Catalog: 10095 galaxies down to M_B = 20: Driver et al.



VIPERS galaxy morphology: bimodality both in Sersic index and colors is seen at least up to z ~ 1.2, and correlated, with a steeper evolution of a population of disk galaxies.

Krywult et al., A&A, (2017)

Morphological properties of early- and late-type galaxies at z ∼ 1



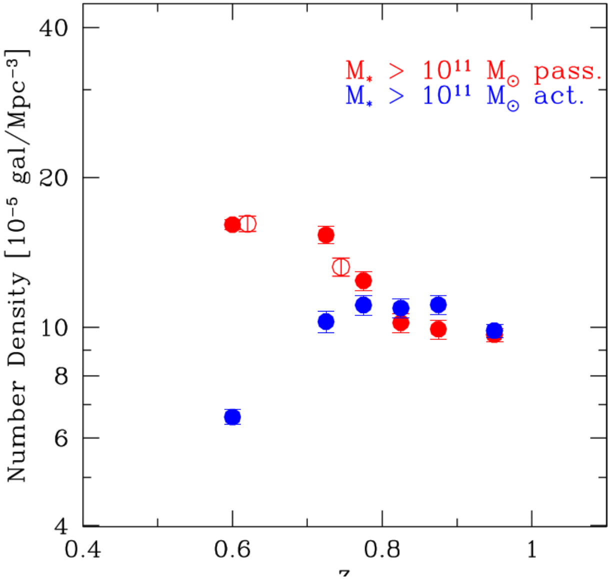
Krywult et al., A&A (2017)

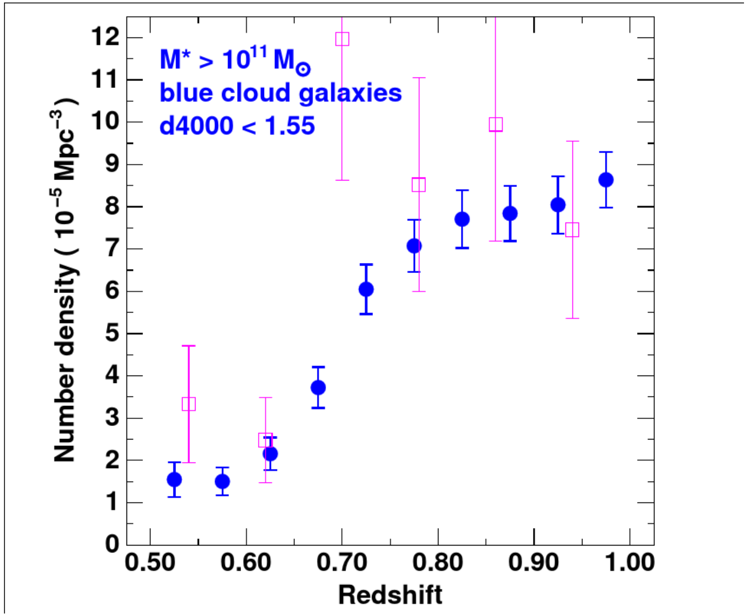
Both Early Type Galaxies (ETGs) and Late Type Galaxies (LTGs) become redder and more concentrated both with cosmic time and increasing luminosity

But: for ETGs – redden with time but concentration mostly depends on luminosities (being already established by z ∼ 1)

LTGs, in contrast, get more concentrated with time with only little evolution in color which depends mostly on their luminosities (presumably: stellar mass)

VIPERS: turning point at z ~0.7: massive blue galaxies turn red





Gargulio 2017, Heines 2017

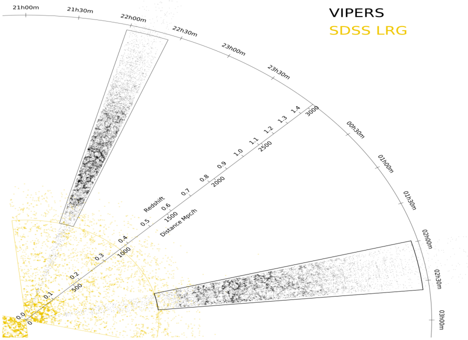
How many classes of galaxies are really there?

Bimodality…

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

How many galaxy populations are there?

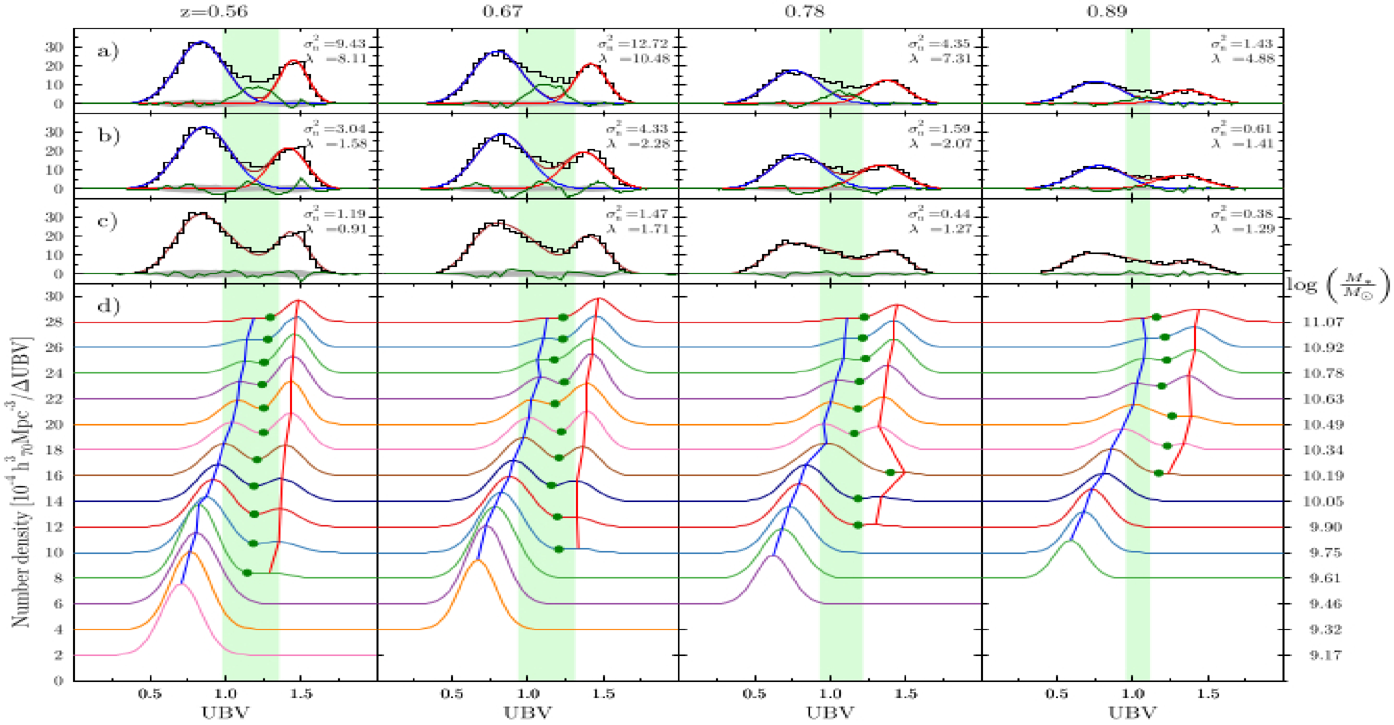
Perfect (moving) bimodality?



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.

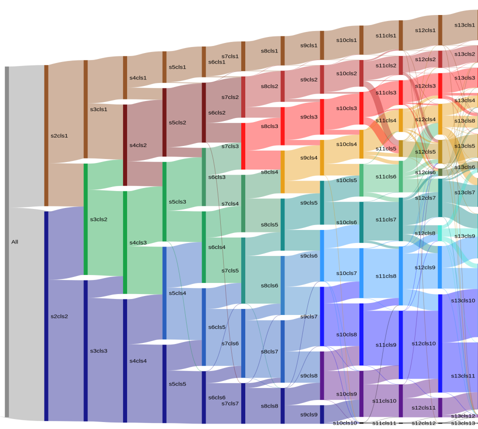


Krywult et al. in prep.

and beyond bimodality

Unsupervised classification of z ~ 1 galaxies

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



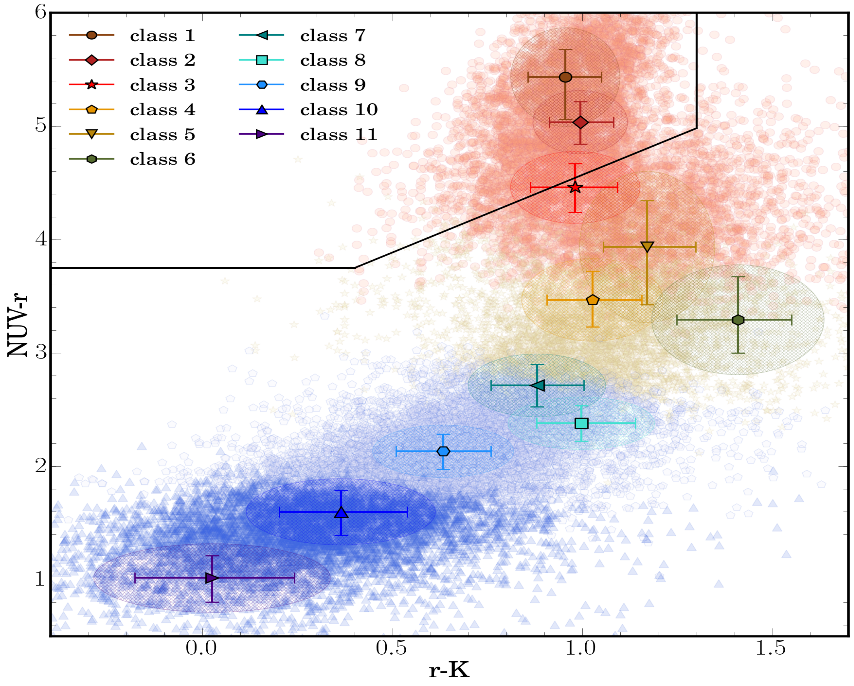
12 dimensions: absolute magnitudes + zspec

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

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

- 5 blue - 3 transitional - 3 red

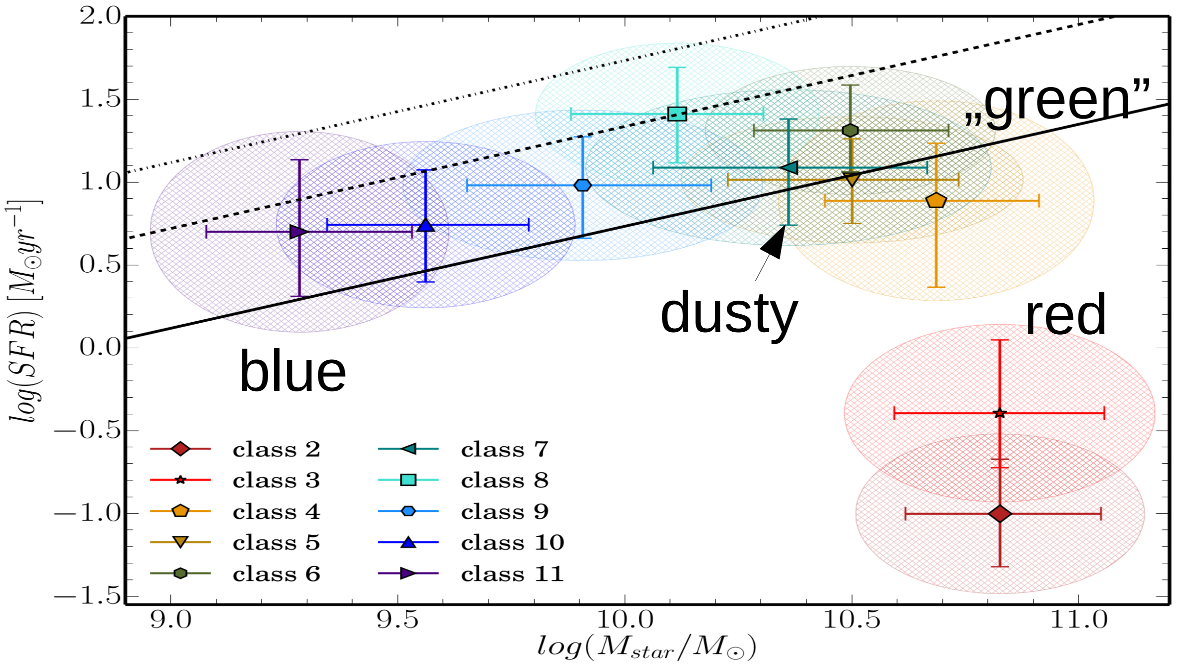
- well corresponding to galaxy classifications e.g. in NUVrK diagrams but more detailed



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.

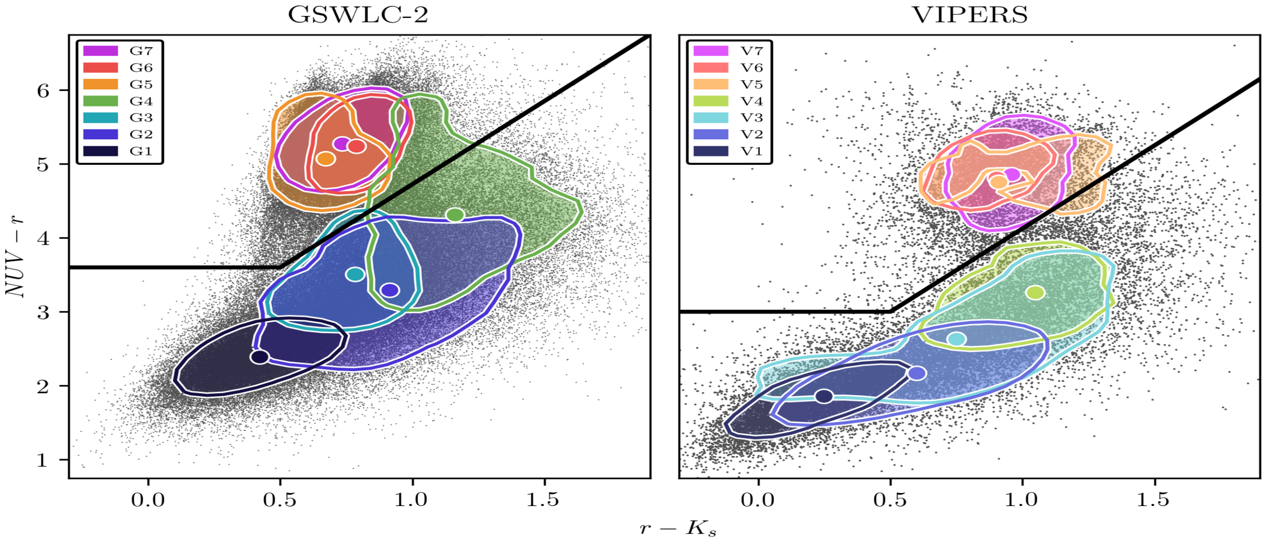


Siudek et al. 2018

How many galaxy populations are there:

However...

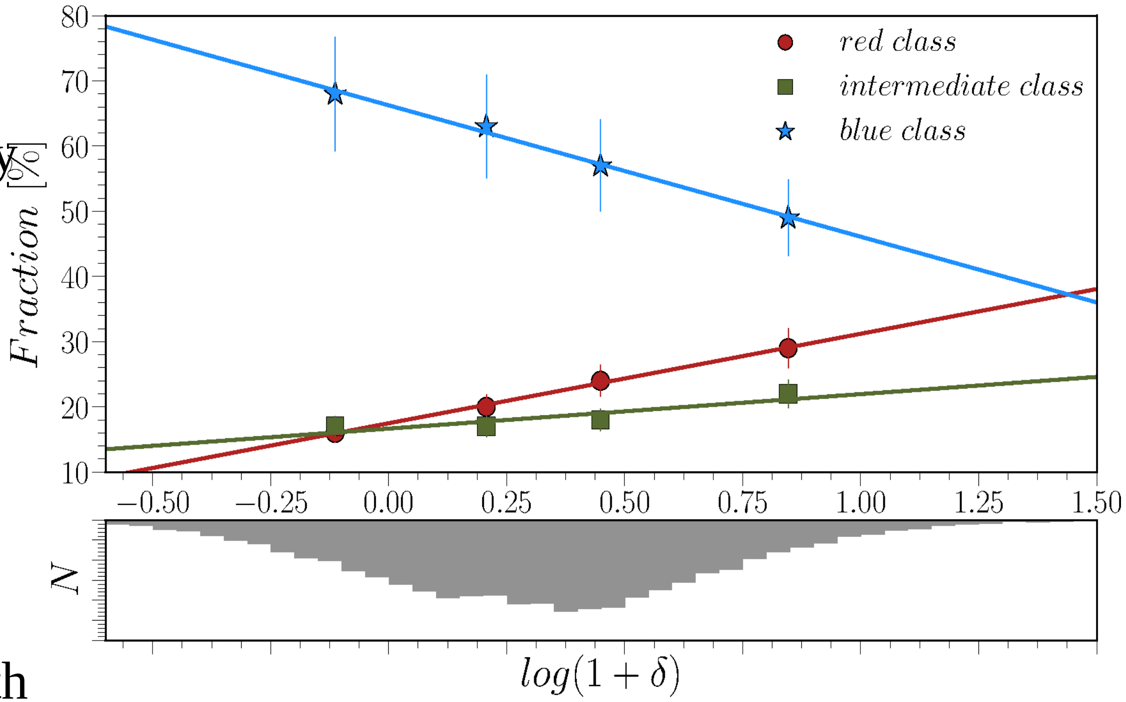
- Similarly at z~0.7 (VIPERS) and z~0 (SDSS-based GSWLC-2). Again: Fisher Expectation-Maximization unsupervised clustering algorithm but a different rest-frame colour-based parameter space)



Turner et al. 2021

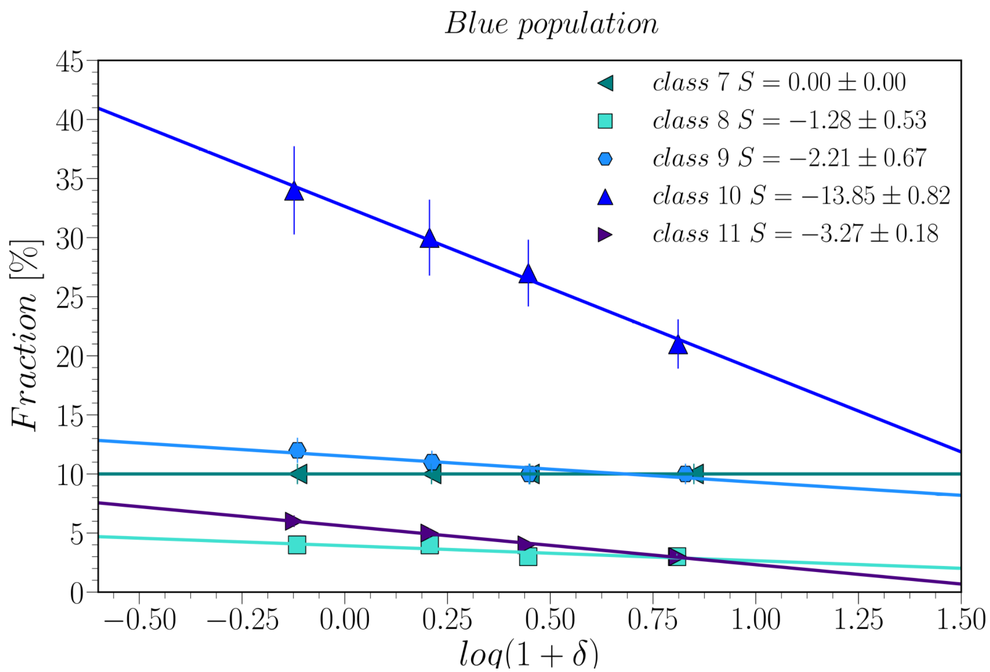
Does this 11 class division reflect actual physical information?

- 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



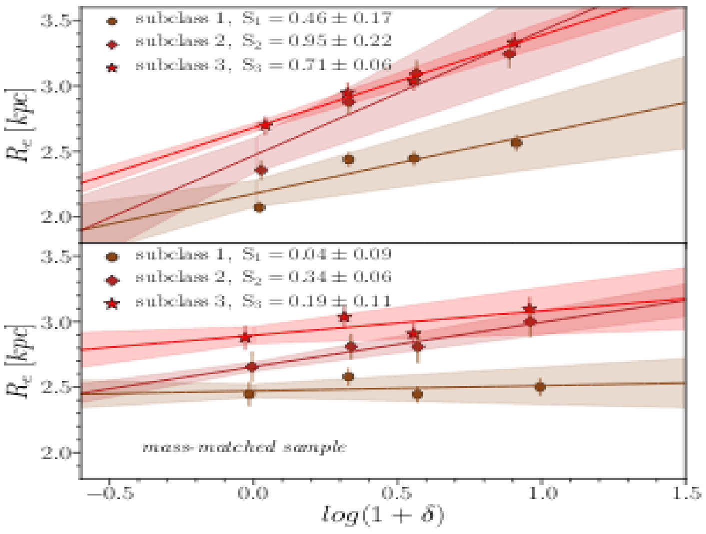
Siudek et al. 2022

→ 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



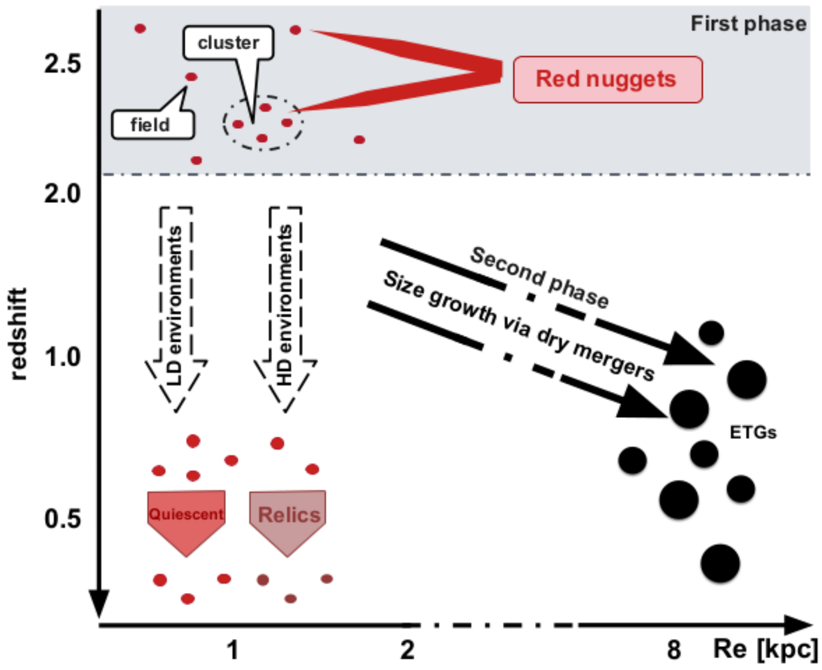
...the reddest red class:

→ 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)

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

“Red nuggets” and todays “relics”



Lisiecki et al. 2023
Siudek, Lisiecki et al. 2023

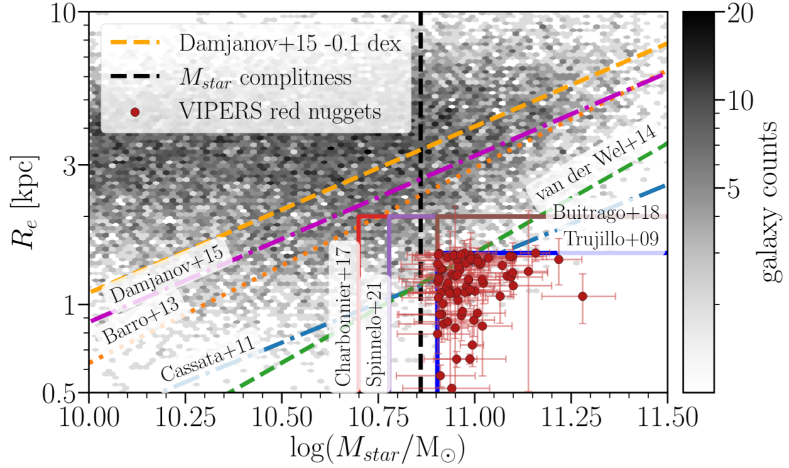
→Red nuggets: a category of rare compact red quescent galaxies found at high redshifts
→ Relics: even much rare contemporary galaxies, massive, compact and red
→ Compact ↔ not a product of merging but only passive evolution
→ ideal for “cosmic labs” and “cosmic chronomers” but extremely scarce

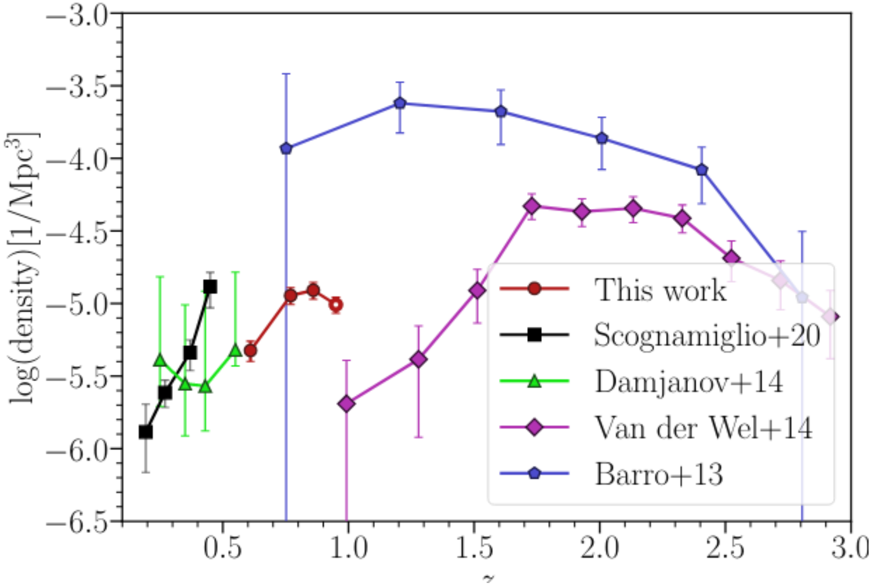
VIPERS
VIMOS PUBLIC EXTRAGALACTIC REDSHIFT SURVEY

→ 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

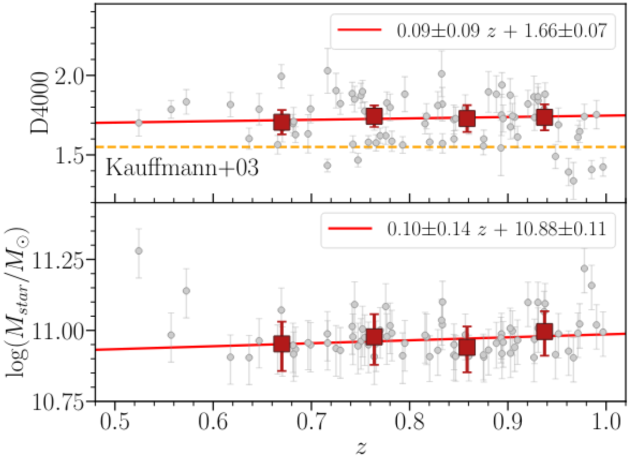


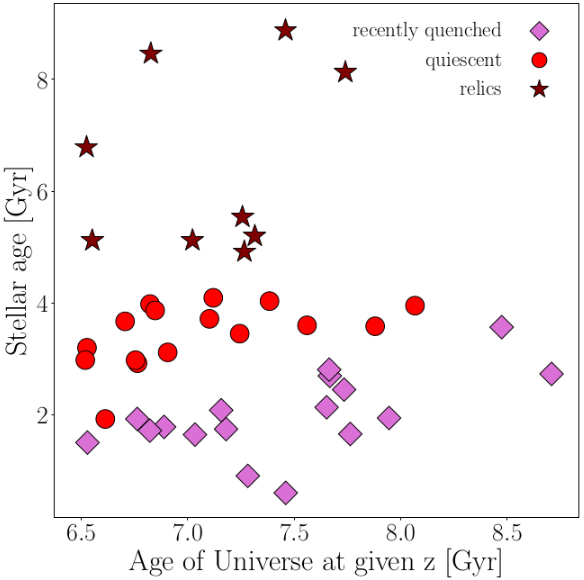


Lisiecki et al. 2023
Siudek, Lisiecki et al. 2023

VIPERS

VIMOS PUBLIC EXTRAGALACTIC REDSHIFT SURVEY





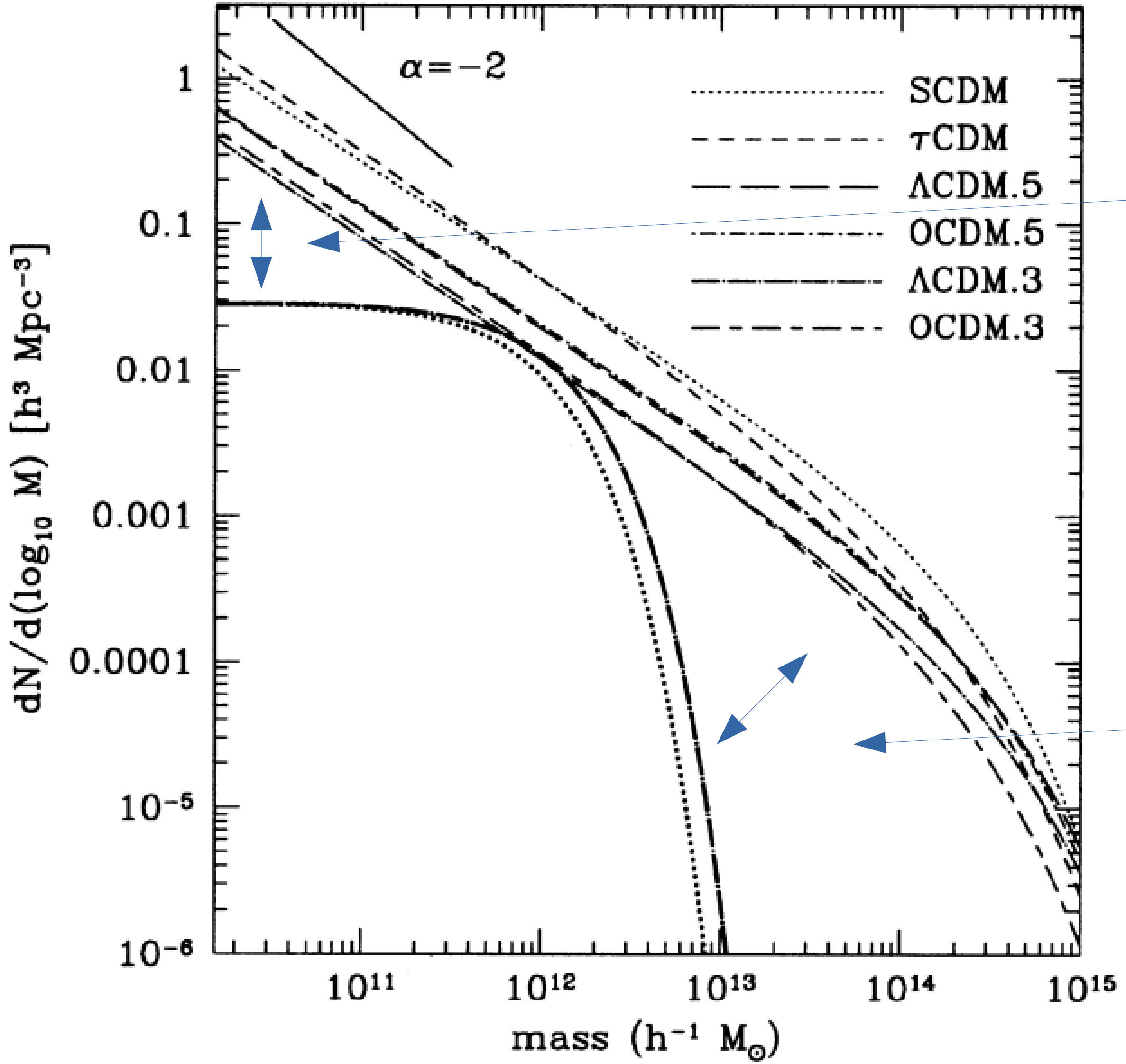
→ some of them have probably more complex star formation histories but some may be actual relics, never touched by intergalactic interactions and quenched early

→ on the way to new sample of galaxies with well controlled passive evolution histories ("cosmic chronometers")?

Lisiecki et al. 2023
Siudek, Lisiecki et al. 2023

Into the future: missing pieces in the galactic census

Faint and bright end problem of halo mass function



feedbacks
Supernovae
AGN
…
dragons

cooling time etc.

Somerville & Primack 1999

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

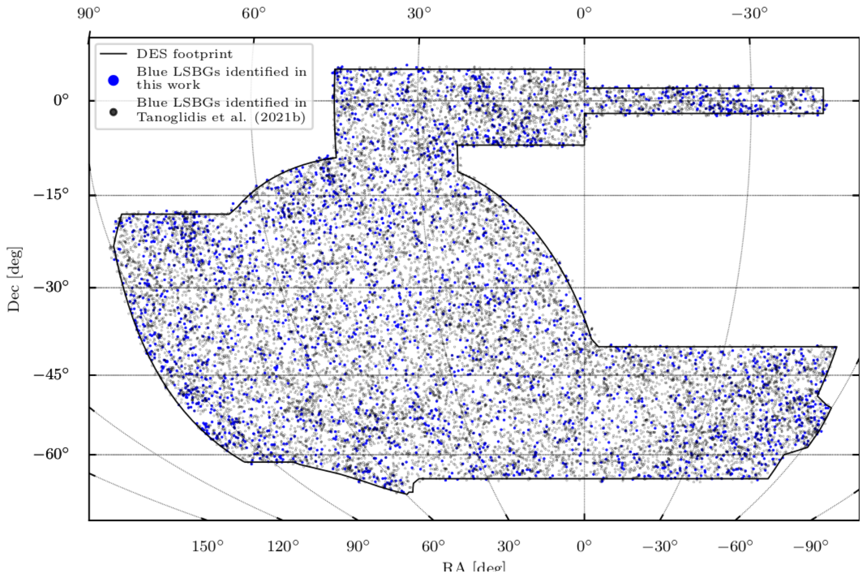
DES Y3 Gold: new catalog of LSBGs

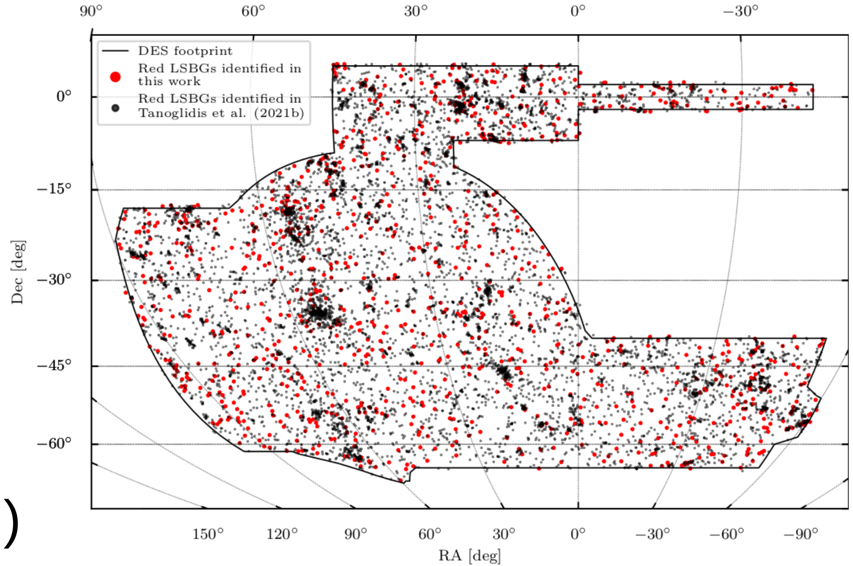
- method: self-attention-based encoder models coupled with CNN (note: with big data 1% accuracy improvement can translate to thousands of new detections)
- 27,000 LSBGs, among them 4083 new (mostly blue + extreme red, as compared to previous works)
- among them, 317 UDG candidates including 276 new ones

Thurutupilly et al. (submitted)

DARK ENERGY SURVEY

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



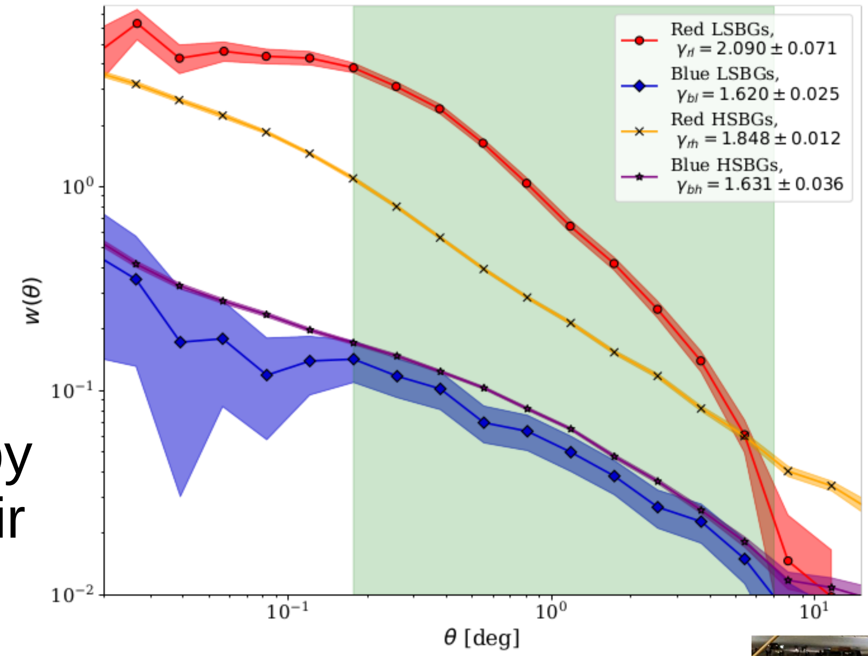


Thurutupilly et al. (submitted)

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

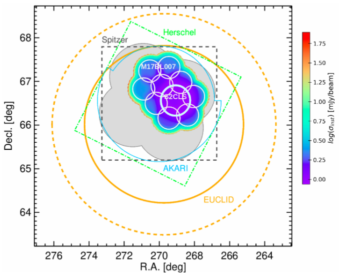
DARK ENERGY SURVEY

- 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

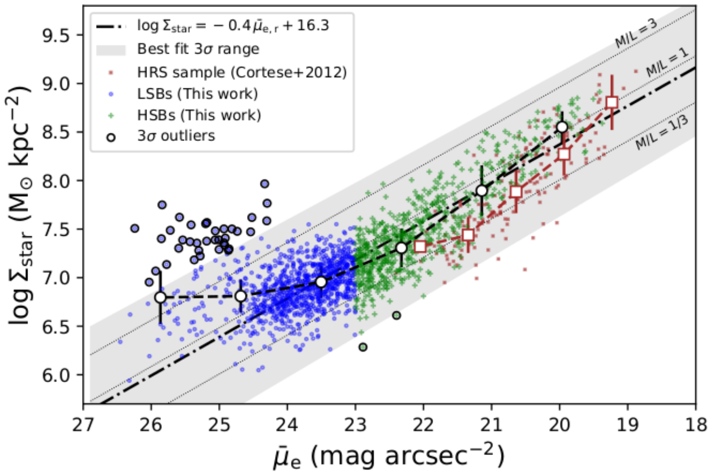


Thurutupilly et al. (submitted)

North Ecliptic Pole: dusty LSBGs?

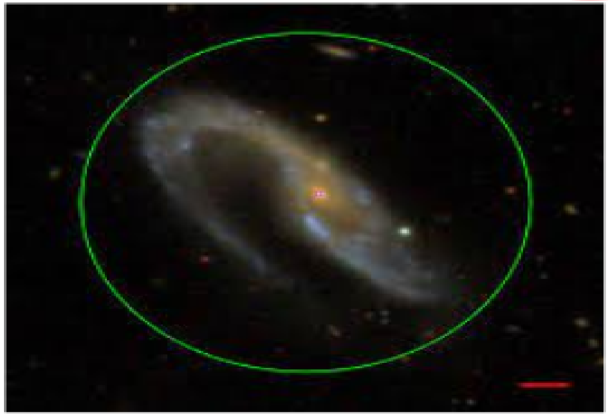


- it is generally assumed that LSBGs are dust-free
- however, they rarely have multiwavelength sets observations → properties uncertain
- NEP: 36 dusty LSBGs (2.5% of the sample)



Junais et al. 2023

Low surface brightness features of normal galaxies



Galaxy mergers

→ Very important in shaping galaxy evolution (each galaxy like Milky Was has undergone several major mergers in the past
→Very common at high redshift
→ 10-15% of merging galaxies today

→ At high(er) redshift: activators of starbursts and AGNs
→ Today: weaker/questionable contribution to star formation enhancement but still important in galaxy mass assembly

Credit: HST, NASA/ESA

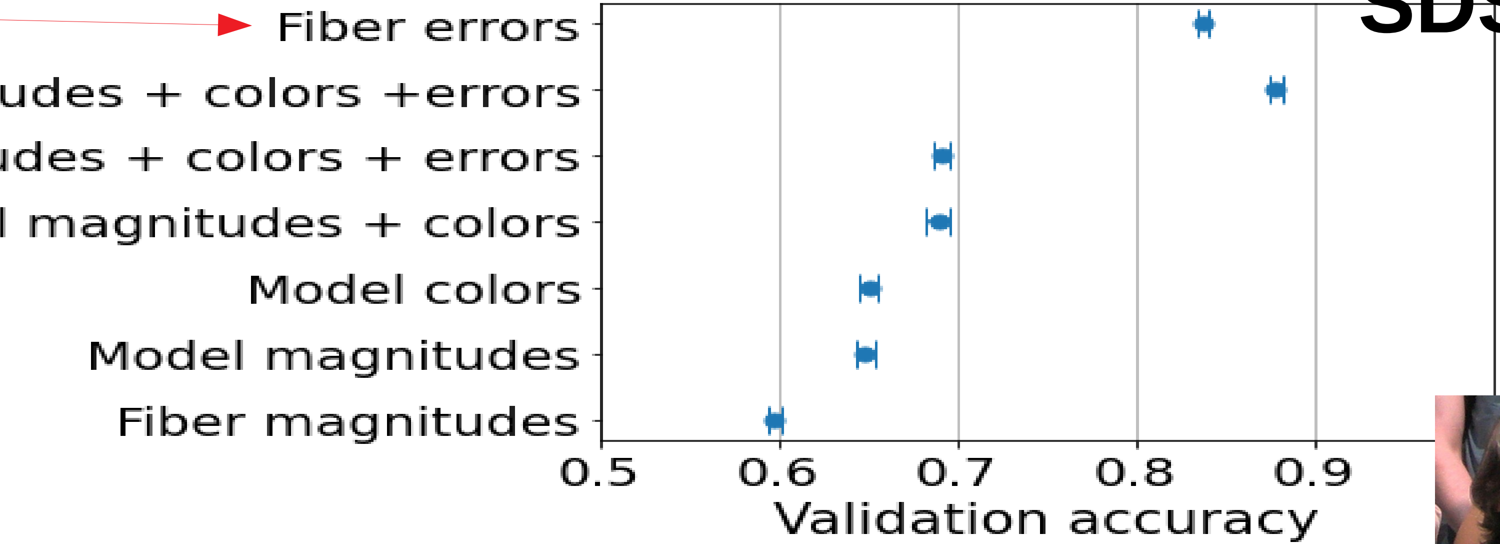
Credit: HST, NASA/ESA

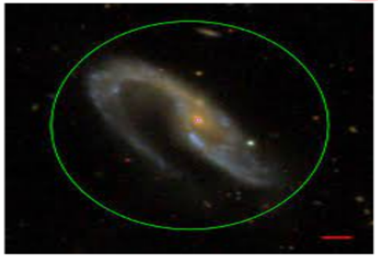
How to automatically find merging galaxies?

→ People very often use Deep Learning (with moderate success)

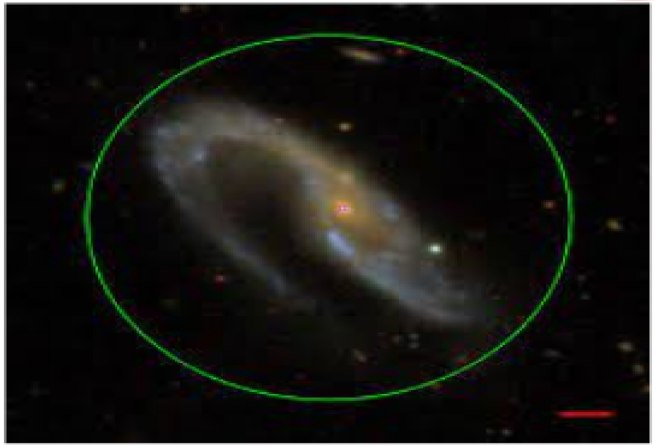
→Concept: see if we can do any good (but faster/easier/more interpretable) with photometry only (fluxes, colours, errors)

SDSS



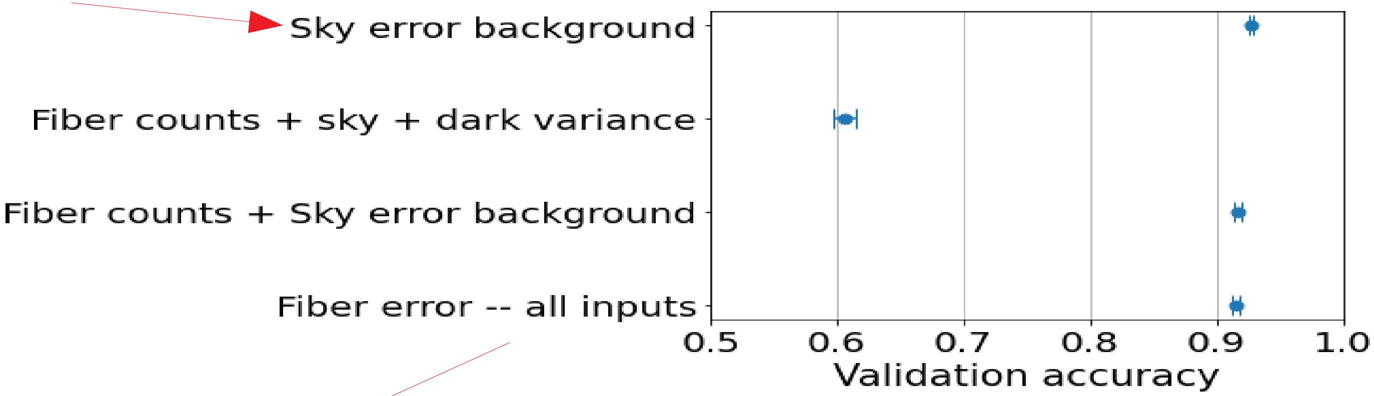


Suelves et al. 2023

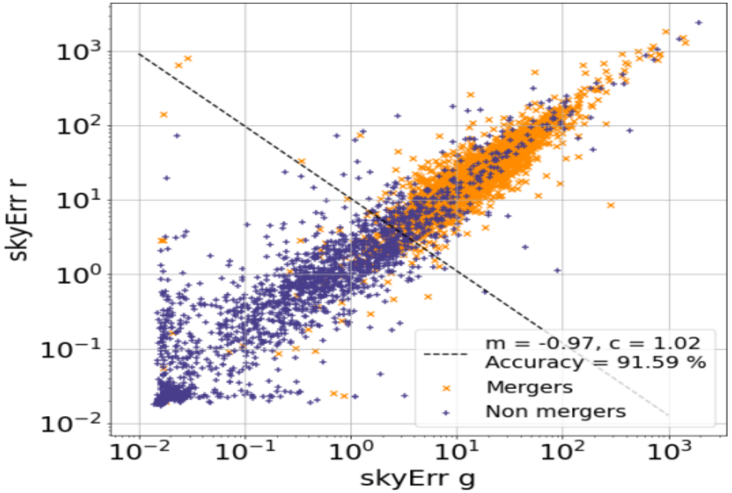


How to automatically find merging galaxies?

→ What is a magical ingredient of fiber errors?

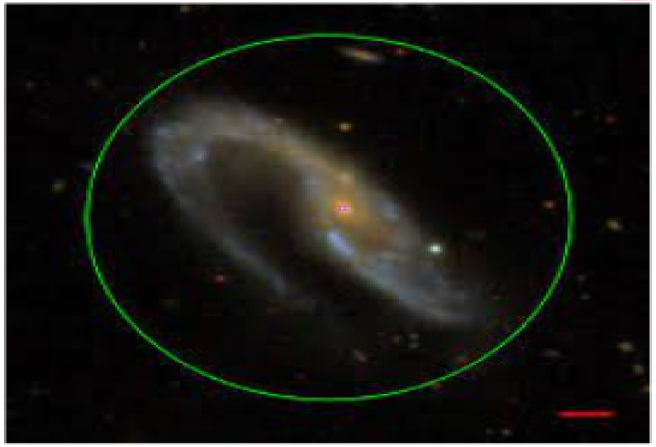


Suelves et al. 2023



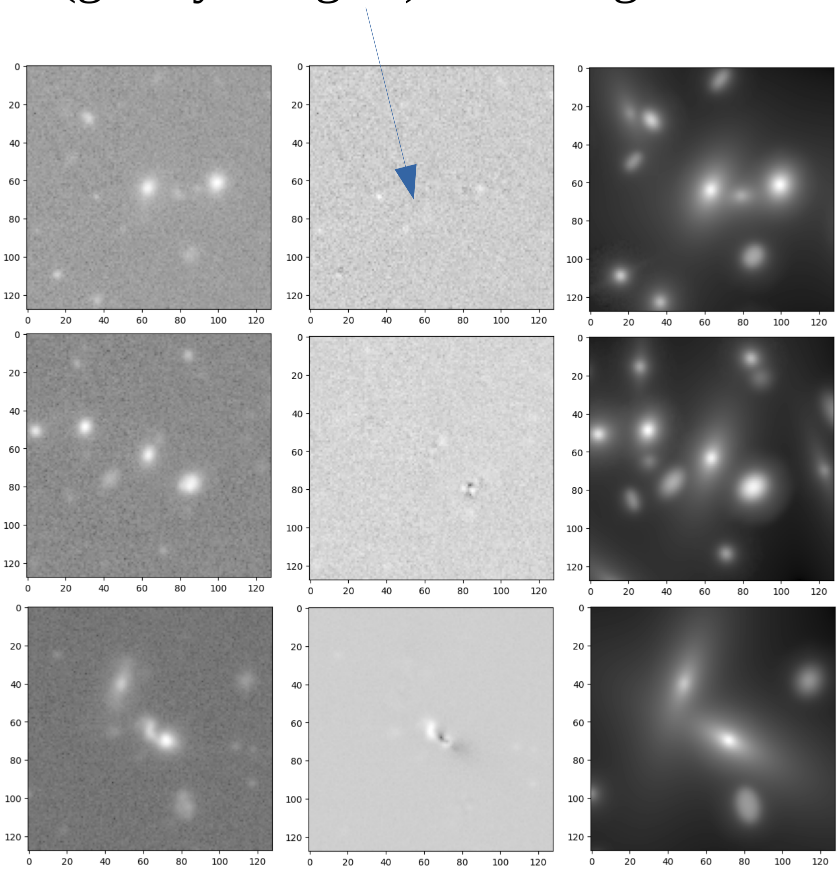
→ We do not need any ML do get ~92% accuracy – it was just about finding the key data

→ Physical implications: merging galaxies (today) do not differ that much from other galaxies – what makes them different are their surroundings (tidal tails etc.)



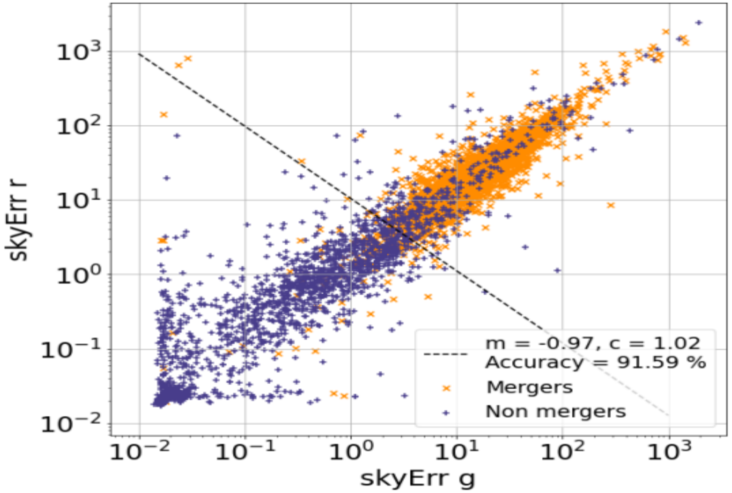
How to automatically find merging galaxies?

→ Search for galaxies (galaxy mergers) without galaxies



Chudy et al. in prep.

Suelves et al. in prep.



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)

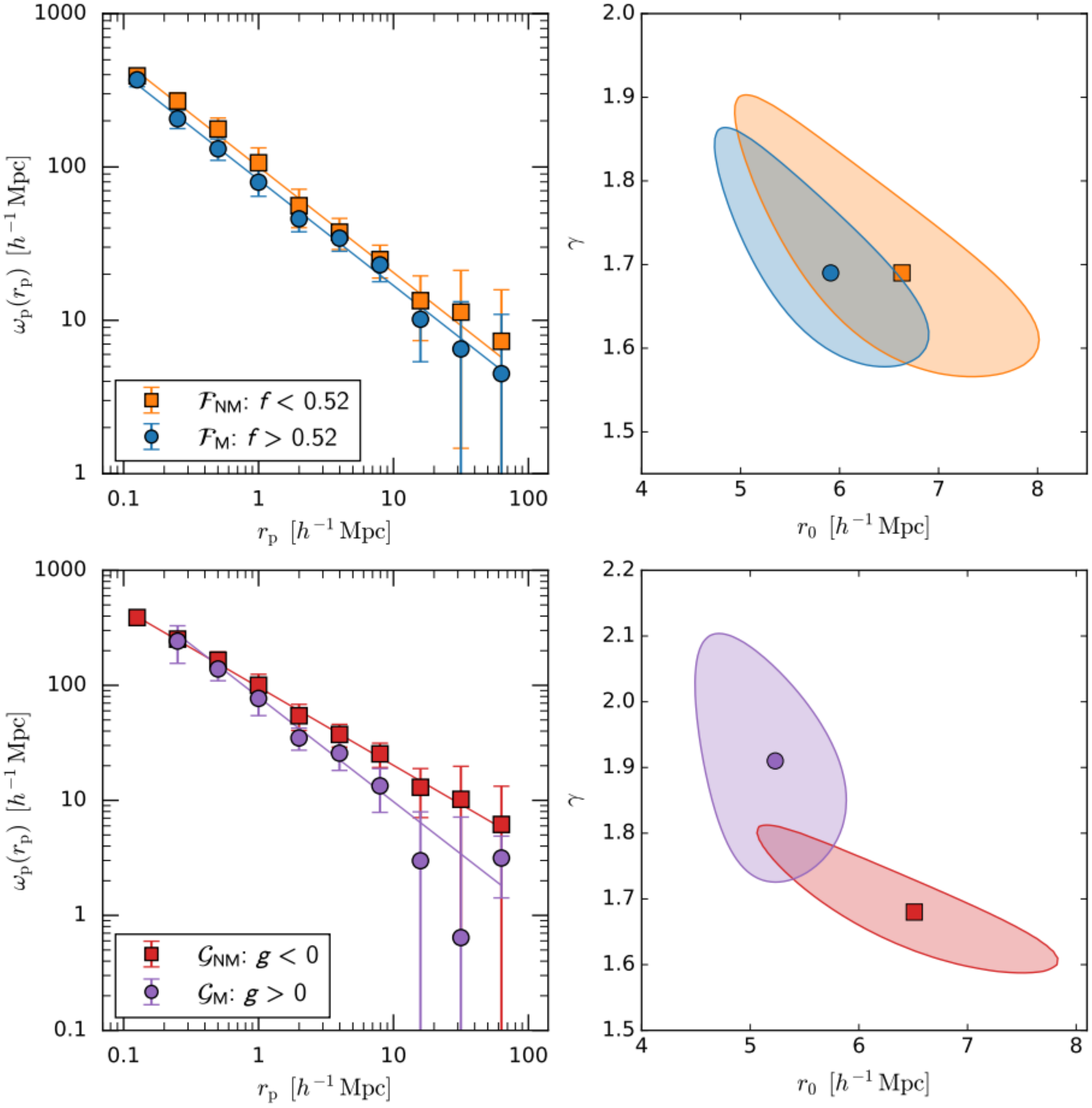
→ Method: correlation function and marked correlation function (again)

→ 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 prep.

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



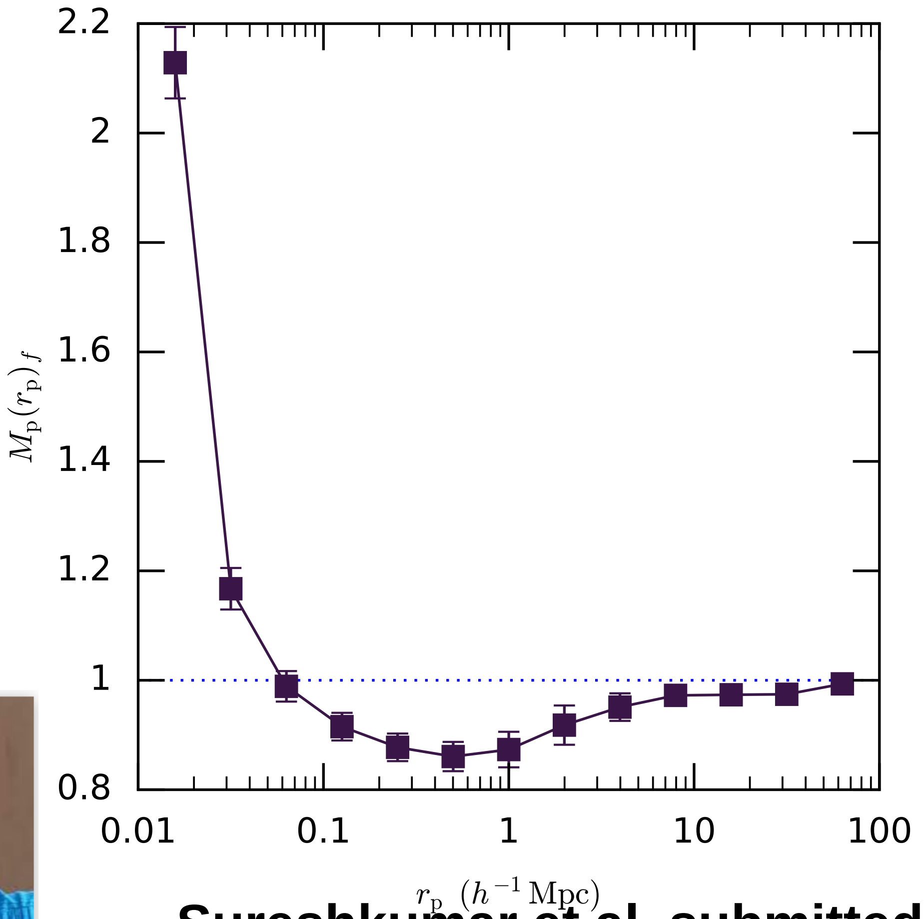
Sureshkumar et al. submitted

Galaxy and Mass Assembly Survey: where do mergers happen?

→ Merging galaxies in the present day Universe prefer underdense environments (GAMA: Sureshkumar et al. in prep., NEP: Pearson et al. in prep.)

→ No significant rise in SFR w/r to similarly massive galaxies (Pearson et al. 2019, Pearson et al. in prep.)

→ Most important is the invisible (i.e. low surface brightness features around).



Sureshkumar et al. submitted

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 universe will be one of the main topics of the nearest decade, and it may change the way we see mass census and distribution in the Universe and large scale structure