Exploring the correlations between galaxy properties and environment in the large-scale structure of the Universe

Unnikrishnan Sureshkumar

University of the Witwatersrand
Johannesburg

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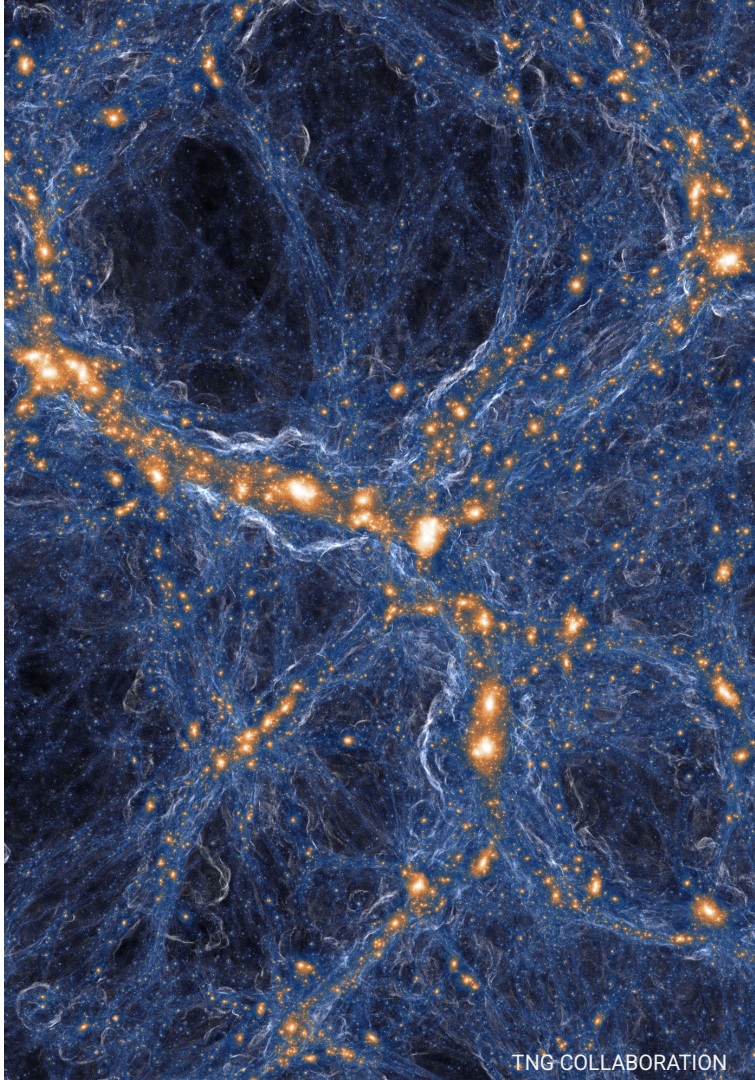
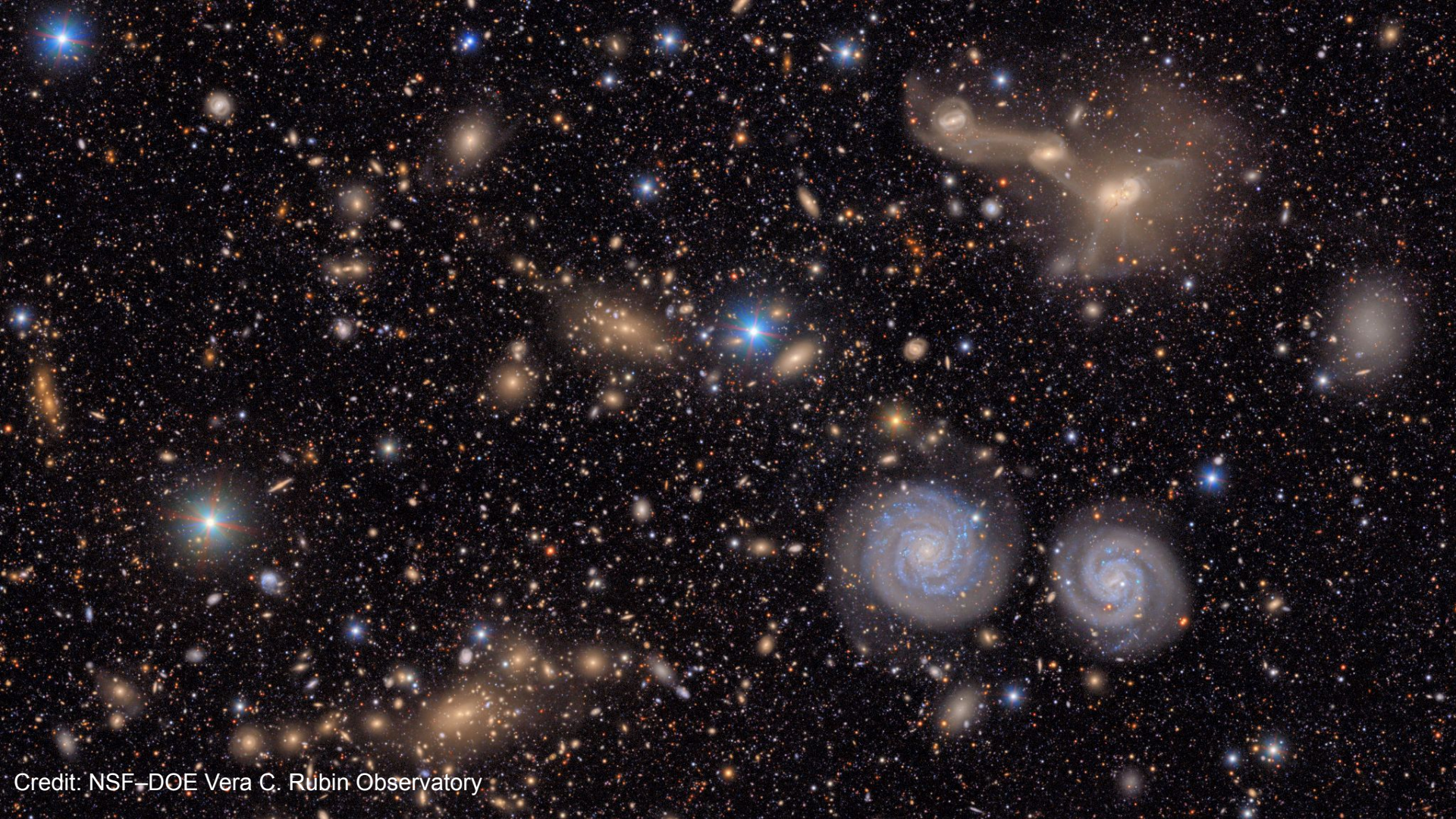



Credit: NSF–DOE Vera C. Rubin Observatory

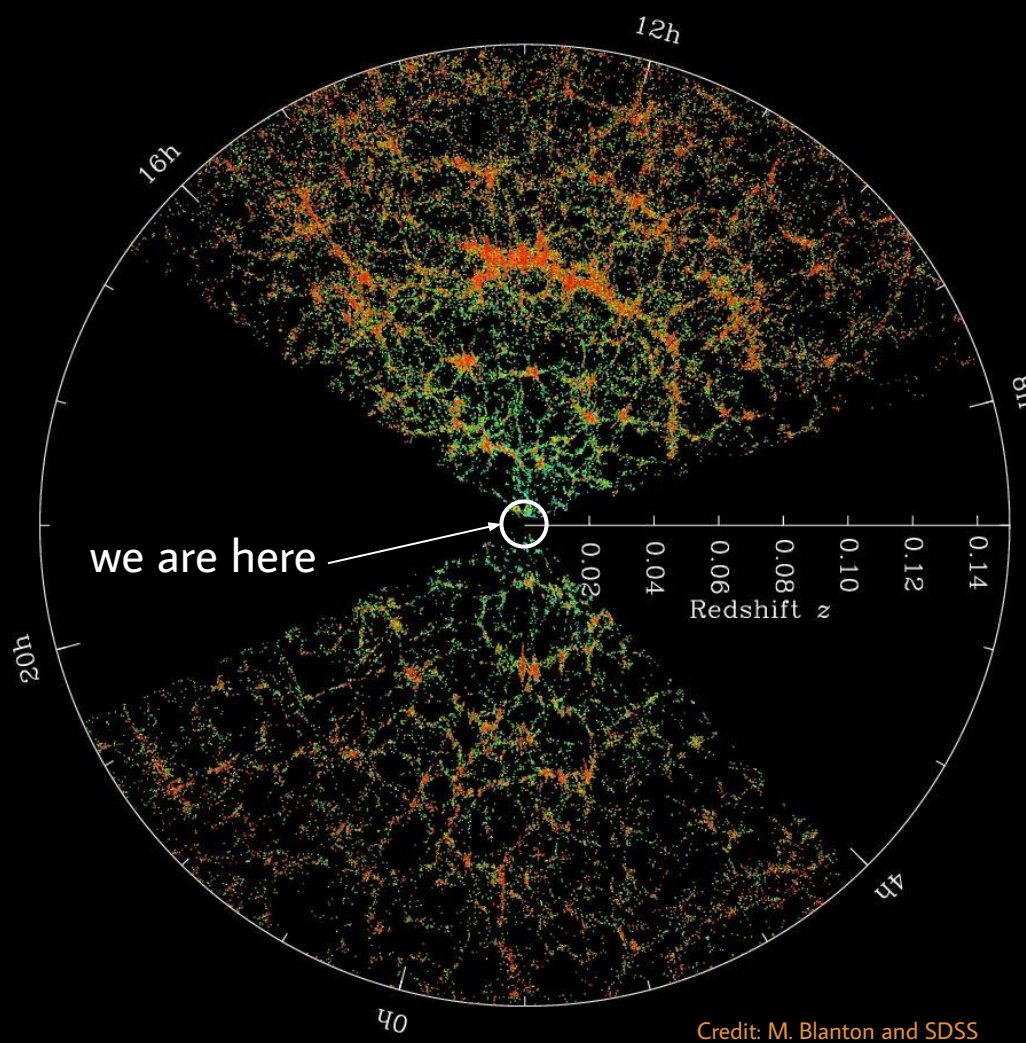
Galaxies and their properties

- **Luminosity**: brightness
- **Stellar mass**: mass of stars present
- **Star formation rate (SFR)**: total mass of stars formed per year
- **Colour**: redder the older, bluer the younger
- **Morphology**: spiral/elliptical/irregular

and so on.

Credit: NSF–DOE Vera C. Rubin Observatory

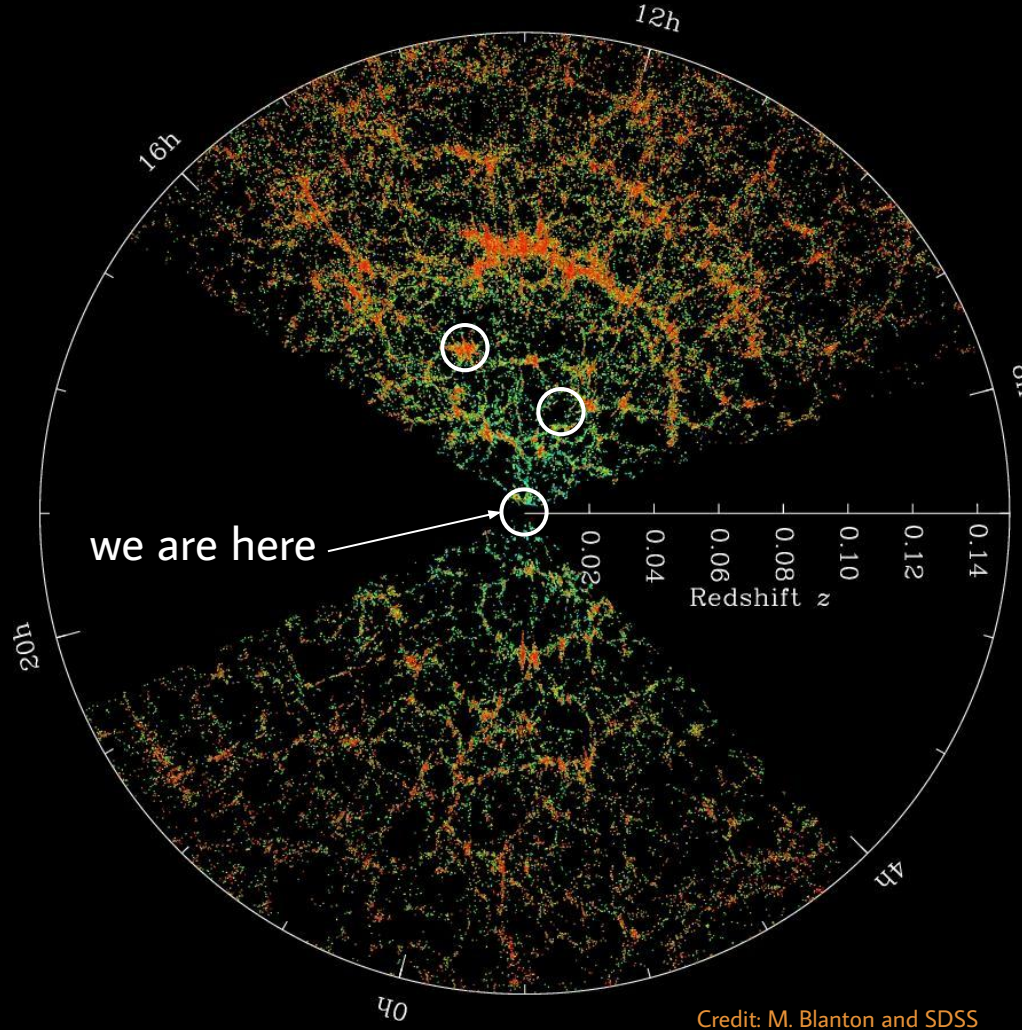
Large scale structure of the Universe



Credit: M. Blanton and SDSS

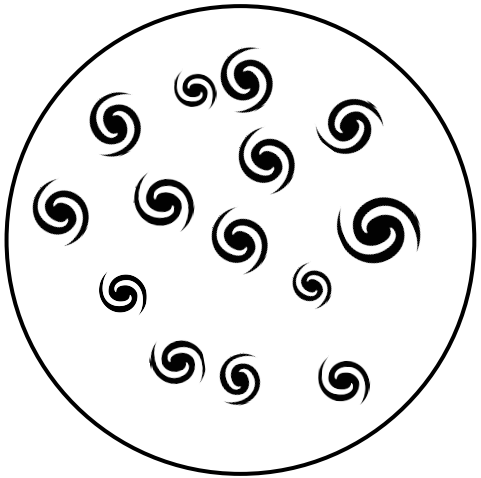
Large scale structure of the Universe

Galaxies live in different types of environments

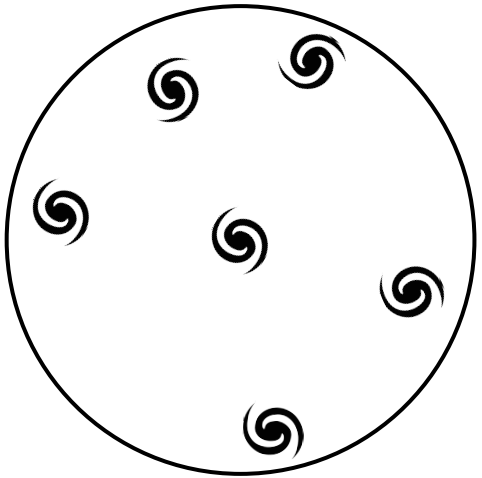


Credit: M. Blanton and SDSS

What is “Environment”?



Many galaxies existing together
→ the galaxies are in a
denser environment

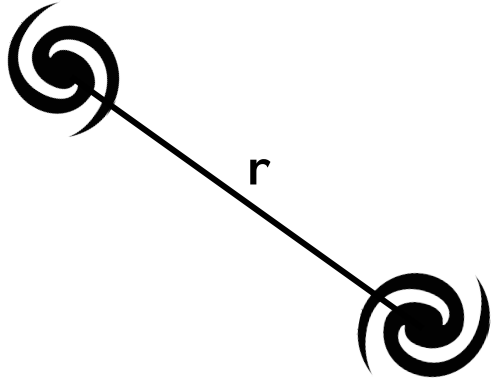


Less galaxies in a neighbourhood
→ the galaxies are in a
less dense environment

We trace the environment simultaneously for different spatial scales

Galaxy two-point correlation function

The excess probability of finding a pair of galaxies separated by a given distance, compared to a random distribution.

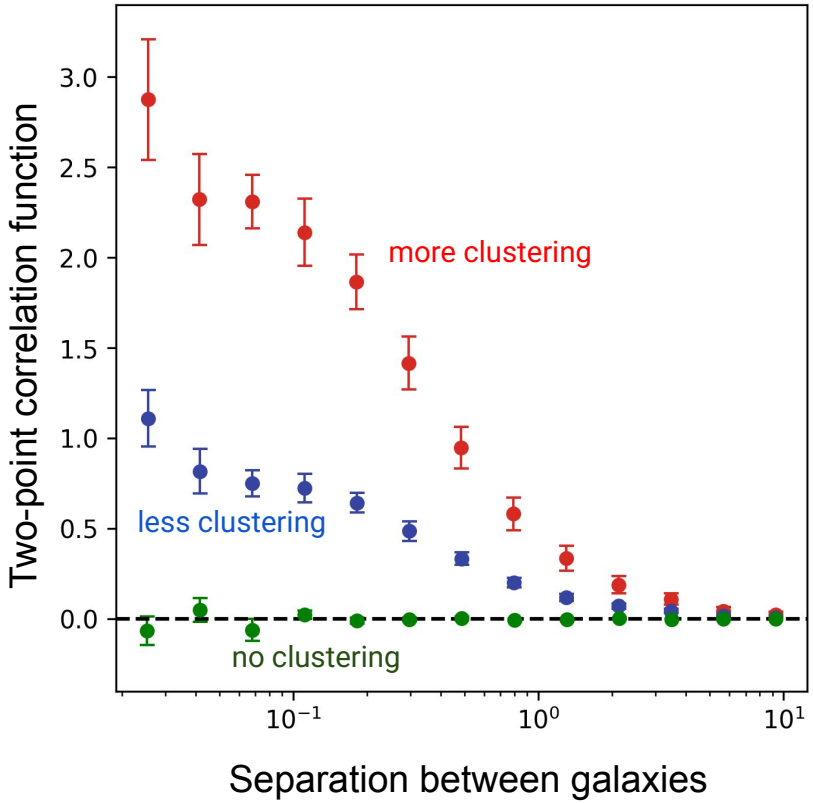


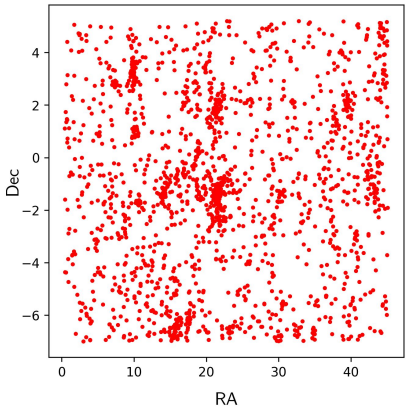
$$\text{2pCF at } r = \xi(r) = \frac{\text{Number of galaxy pairs separated by } r \text{ in the real sample (DD)}}{\text{Number of galaxy pairs separated by } r \text{ in the random sample (RR)}} - 1$$

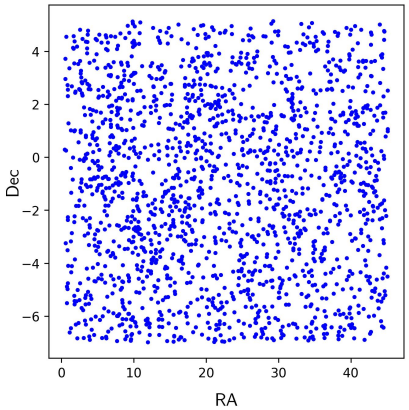
$$\xi(r) = \left(\frac{r}{r_0}\right)^{-\gamma}$$

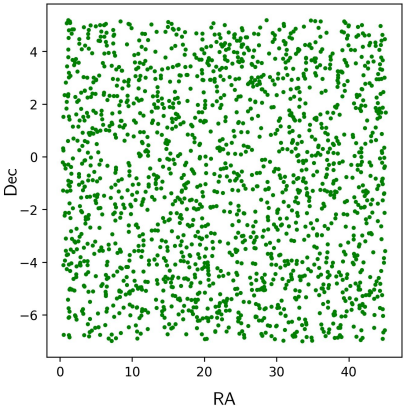
r_0 ← Correlation length

Galaxy two-point correlation function



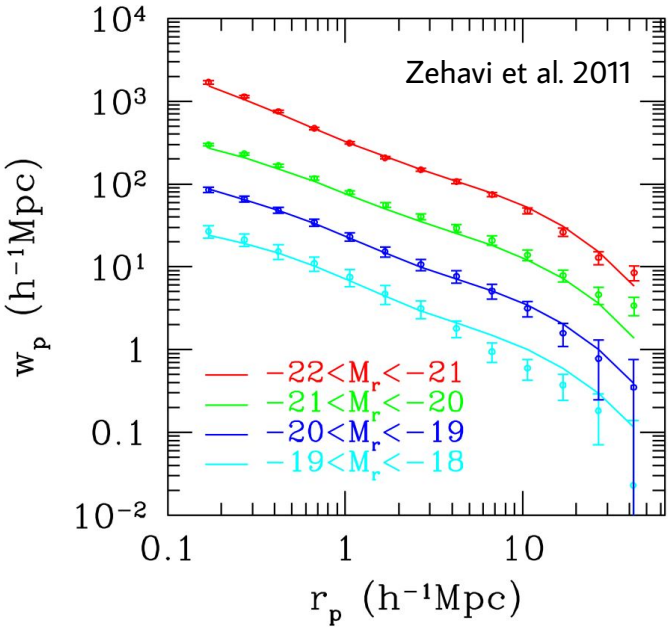




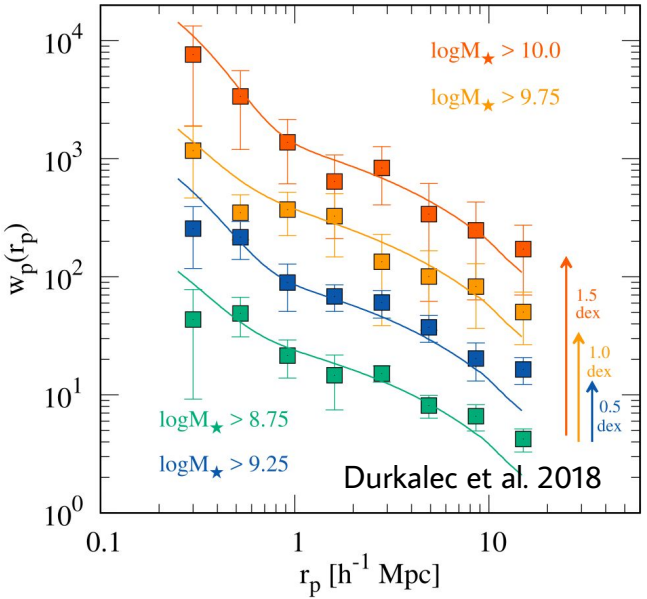


Unnikrishnan Sureshkumar
unnikrishnan.sureshkumar@wits.ac.za

Dependence of galaxy properties on environment



Norberg et al. 2001
Le Fèvre et al. 2005
Pollo et al. 2006
Zehavi et al. 2011
Farrow et al. 2015
Skibba et al. 2015
Durkalec et al. 2018
...

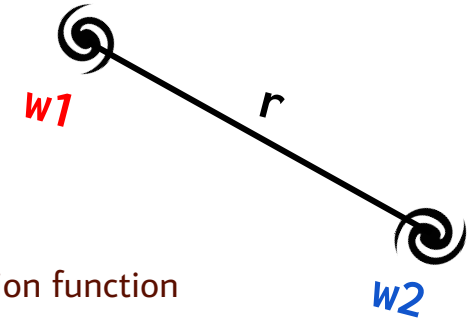


Luminous, massive, red and evolved galaxies tend to live in the denser environments of LSS than fainter, less massive, blue and young galaxies

HOW ARE DIFFERENT GALAXY PROPERTIES CORRELATED WITH THE ENVIRONMENT?

Unnikrishnan Sureshkumar
unnikrishnan.sureshkumar@wits.ac.za

Marked correlation function



★ *Mark*: property of interest (eg: luminosity, stellar mass etc.).

★ The rank of the mark is used to weight the galaxies while computing the correlation function

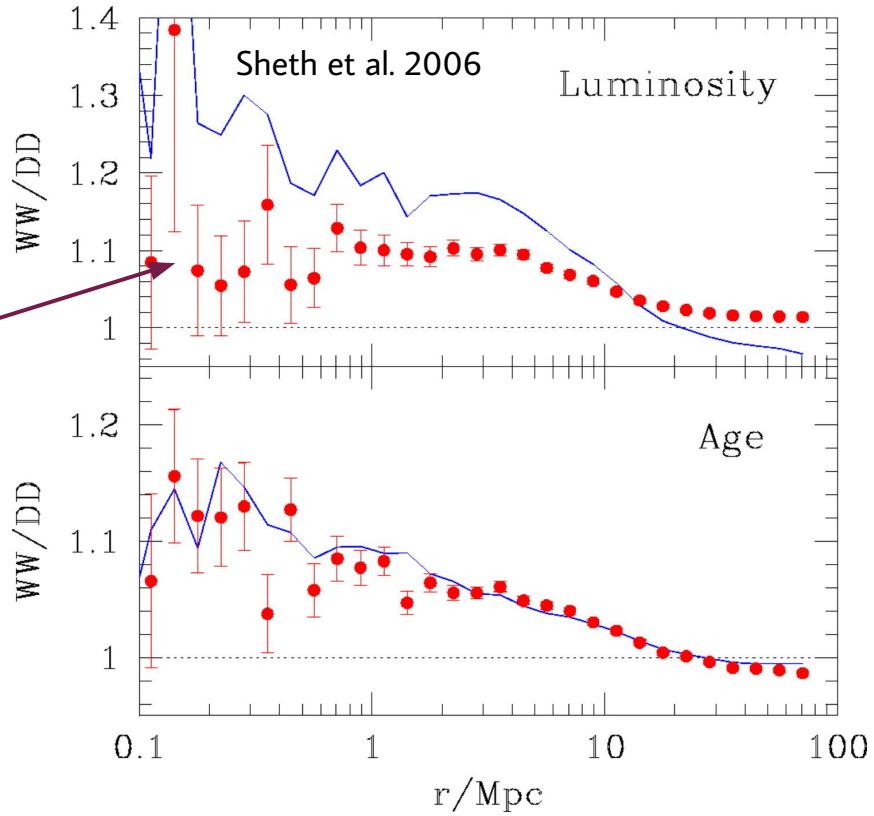
$$M_{\mathrm{prop}}(r) = \frac{1+W_{\mathrm{prop}}(r)}{1+\xi(r)}$$

$$W_{prop}(r) = \frac{\text{Weighted number of galaxy pairs separated by } r \text{ in the real sample (WW)}}{\text{Number of galaxy pairs separated by } r \text{ in the random sample (RR)}} - 1$$

Marked correlation function

The weight enhances the significance of galaxy pairs in which both galaxies have a given property more pronounced.

Greater probability of finding galaxy pairs separated by 0.1 Mpc/h with both the galaxies being relatively luminous than the mean.



★ MCF = 1 : lack of correlation,

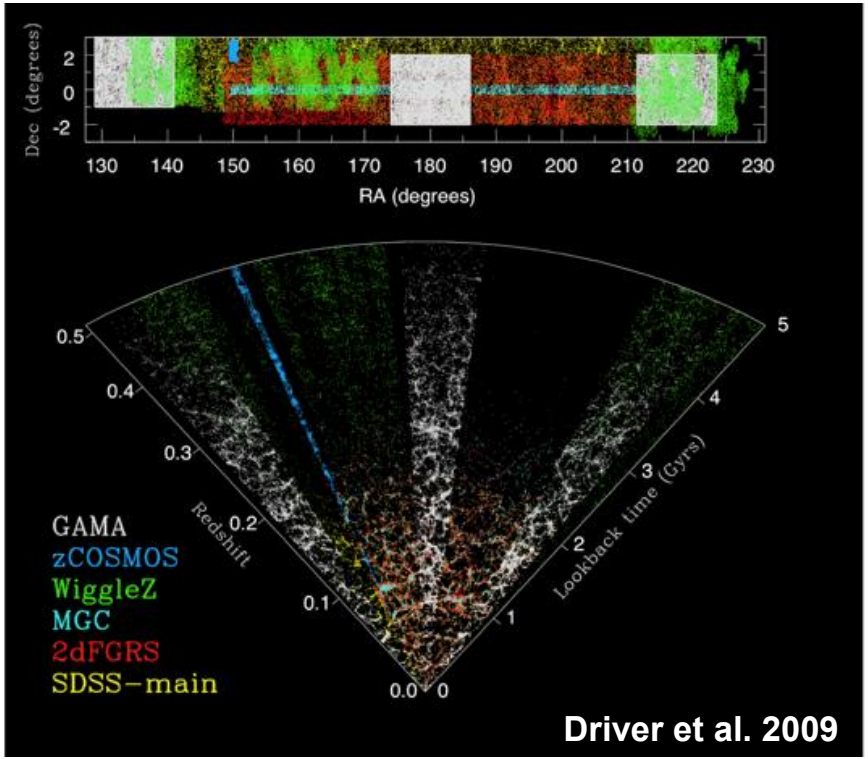
MCF > 1 : correlation,

MCF < 1 : anti-correlation

★ Strength of MCF for a property shows strength of the correlation between that property and the environment.

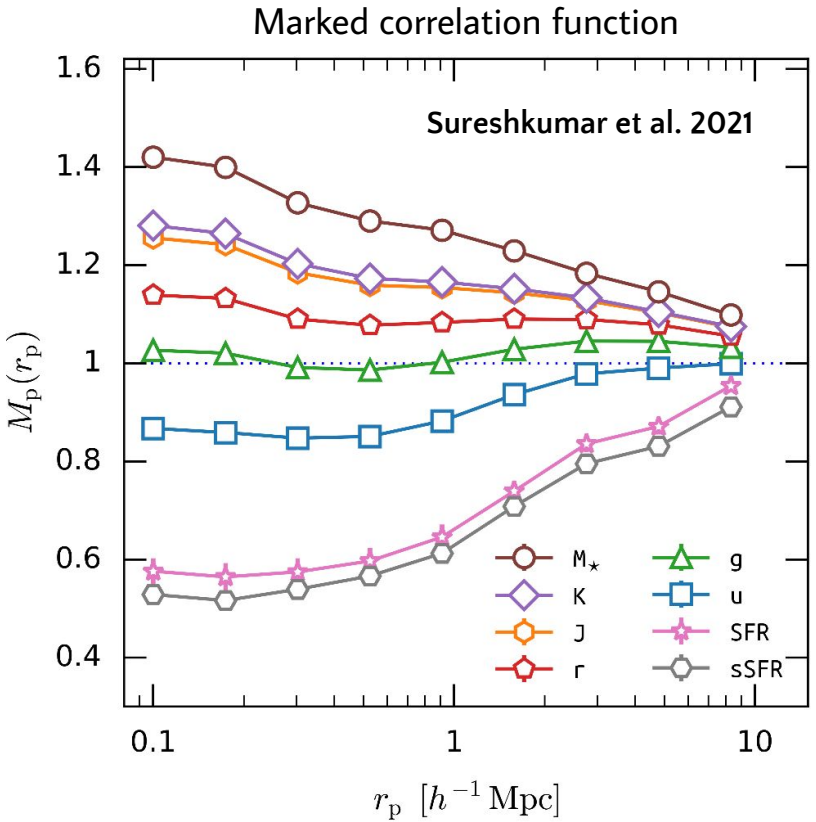
Galaxy and Mass Assembly (GAMA) survey

- spectroscopic multiwavelength galaxy survey
- Redshift z_{median} ~ 0.2
- flux limit : r < 19.8 (2 mag fainter than SDSS main galaxy sample)
- covers 5 sky regions of 60 deg^2 each: G09, G12, G15 (equatorial) and G02, G23 (southern)
- we make use of r-band limited data from GAMA II equatorial regions

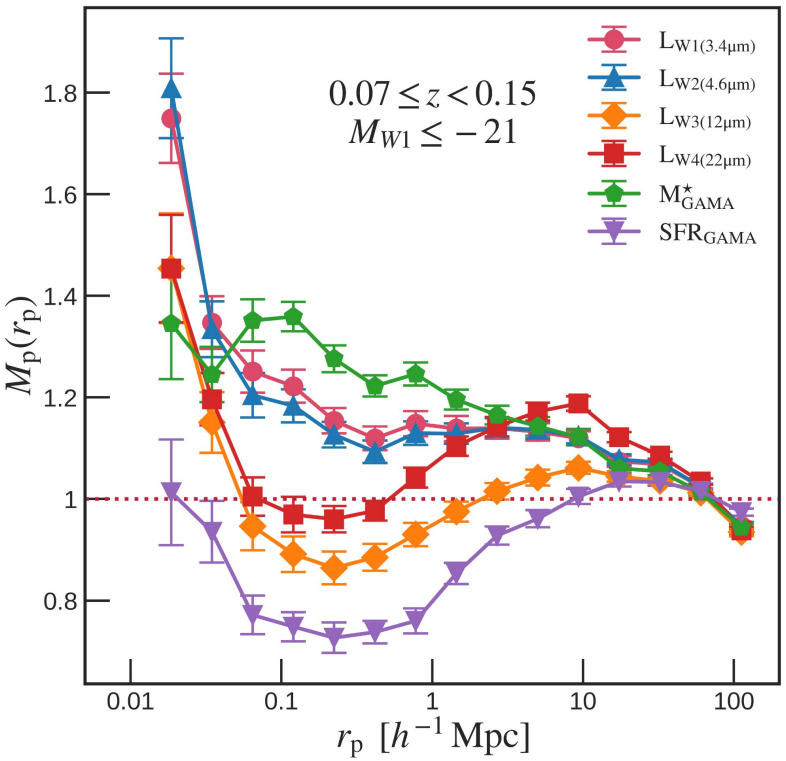


Environmental dependence of optical and near-IR properties

- ★ Stellar mass MCF is stronger than that for other properties ⇒ Stellar mass is strongly correlated with environment and hence a stronger tracer of over-density.
- ★ SFR is anti-correlated with the environment.
- ★ K-band luminosity MCF does not perfectly follow stellar mass MCF ⇒ K-band luminosity-stellar mass relation is not entirely direct and is environmental dependant.
- ★ u-band luminosity can be a good, but not a perfect proxy for star formation rate in the context of galaxy clustering.



Environmental dependence of mid-IR properties



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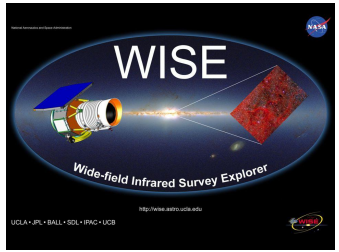
- ★ W1 - 3.4 μm
- ★ W2 - 4.6 μm
- ★ W3 - 12 μm
- ★ W4 - 22 μm



- ★ W1 and W2 bands follow stellar mass in tracing the environment.
- ★ W3 and W4 bands follow SFR.
- ★ These correlations are environmental dependent
- ★ Stronger SFR-environment correlation in smaller scales

Local environment of galaxy mergers

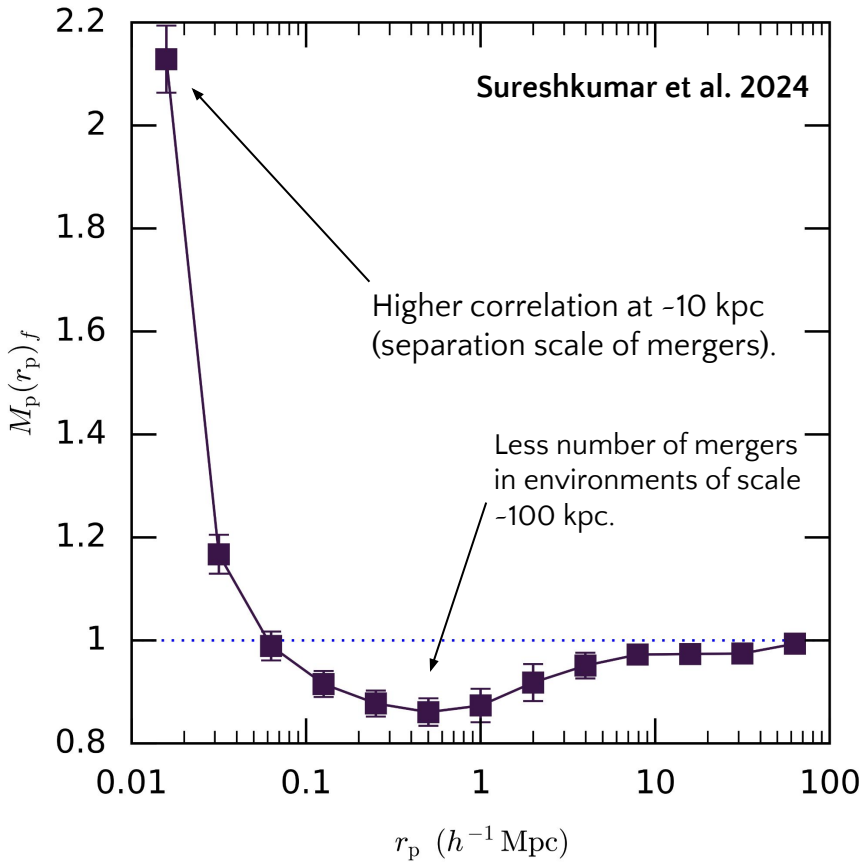
- ★ Galaxy mergers refer to the dynamic process in which two or more galaxies interact gravitationally, leading to a profound transformation of their structures and properties.
- ★ Do they prefer under-dense or over-dense environment?

Credit: NSF–DOE Vera C. Rubin Observatory

Local environment of galaxy mergers

Marked correlation function with
probability of galaxy to be a merger
as mark.

- ★ **MCF analysis shows that galaxy mergers prefer to occur in the low-dense regions of the large-scale structure.**
- ★ **The higher relative velocities of galaxies in denser environments make merger event less probable.**

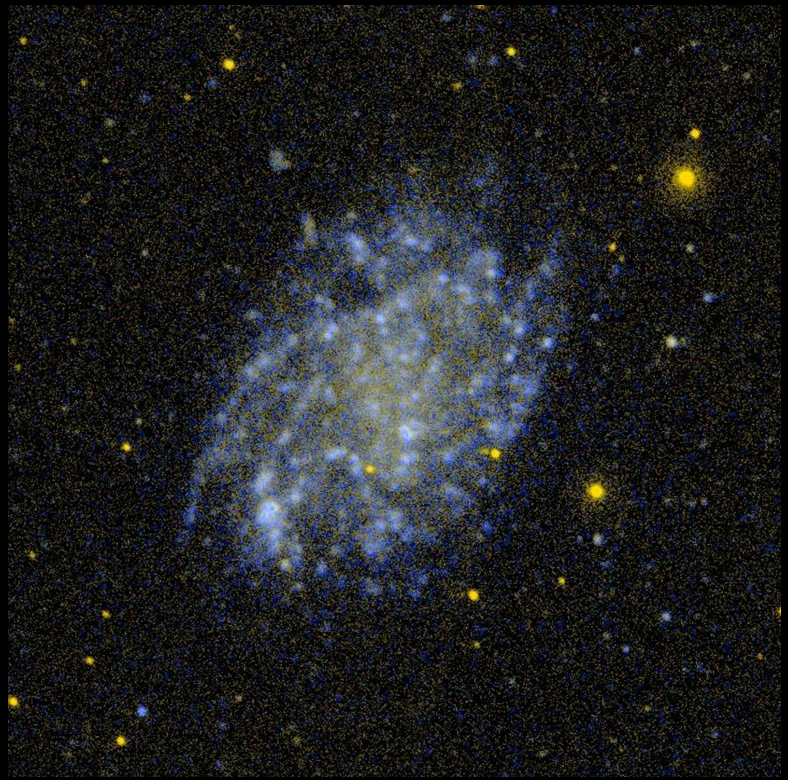


Local environment of Low surface brightness galaxies (LSBG)

- ➔ Surface brightness of a galaxy

$$\mu = m + 2.5 \times \log_{10}(2\pi r_{1/2}^2)$$

- ➔ LSBGs: surface brightness fainter than night sky.
- ➔ Account for a significant fraction of total galaxy number density.
- ➔ Crucial role in galaxy evolution.
- ➔ Are their properties correlated with their local environment?



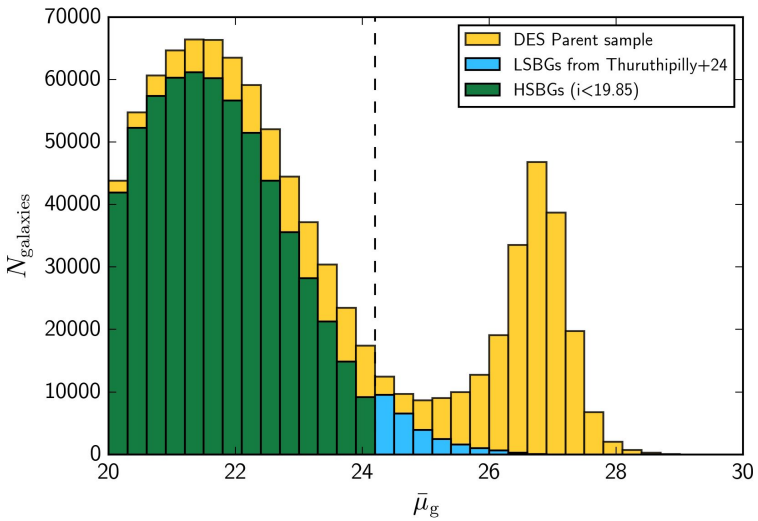
NGC 45 by GALEX

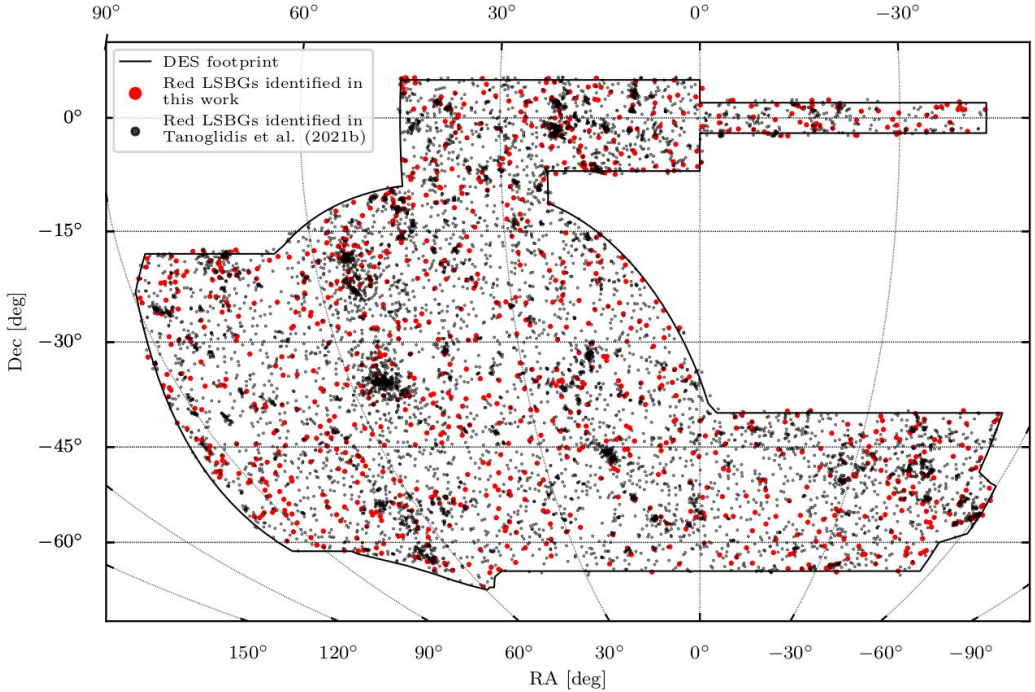
LSBGs in Dark Energy Survey

THE DARK ENERGY SURVEY

$$\bar{\mu}_g > 24.2\,\mathrm{mag/arcsec}^2$$

$$r_{1/2} > 2.5''$$





Thuruthipilly et al. 2024

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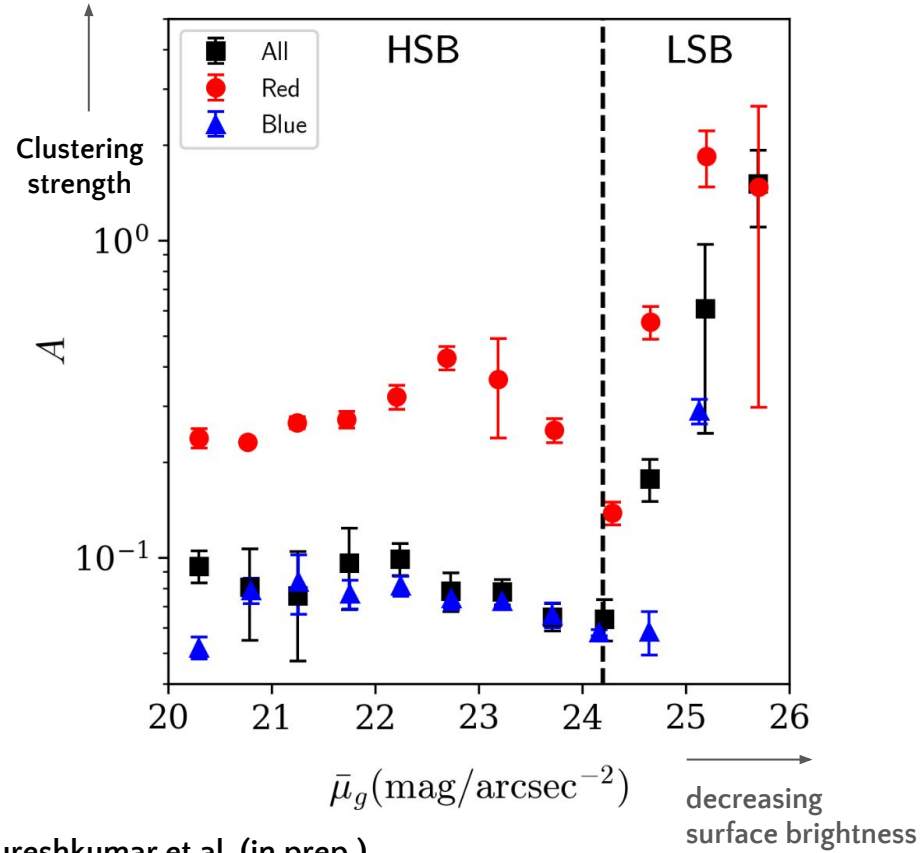

Sureshkumar et al. (in prep.)

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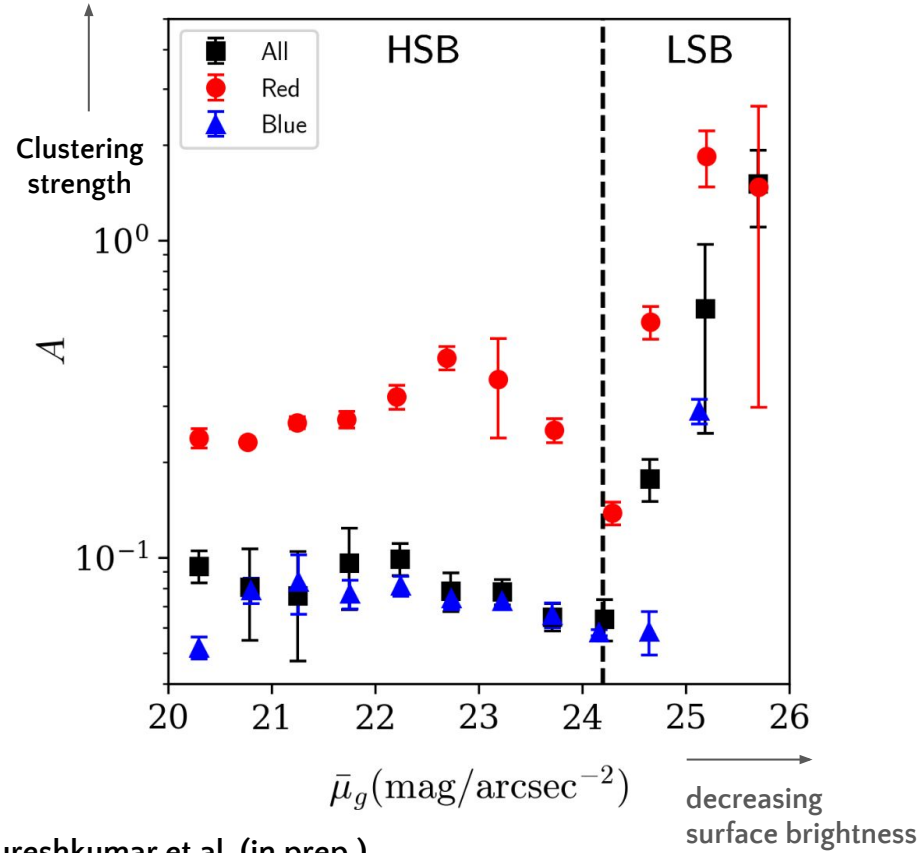

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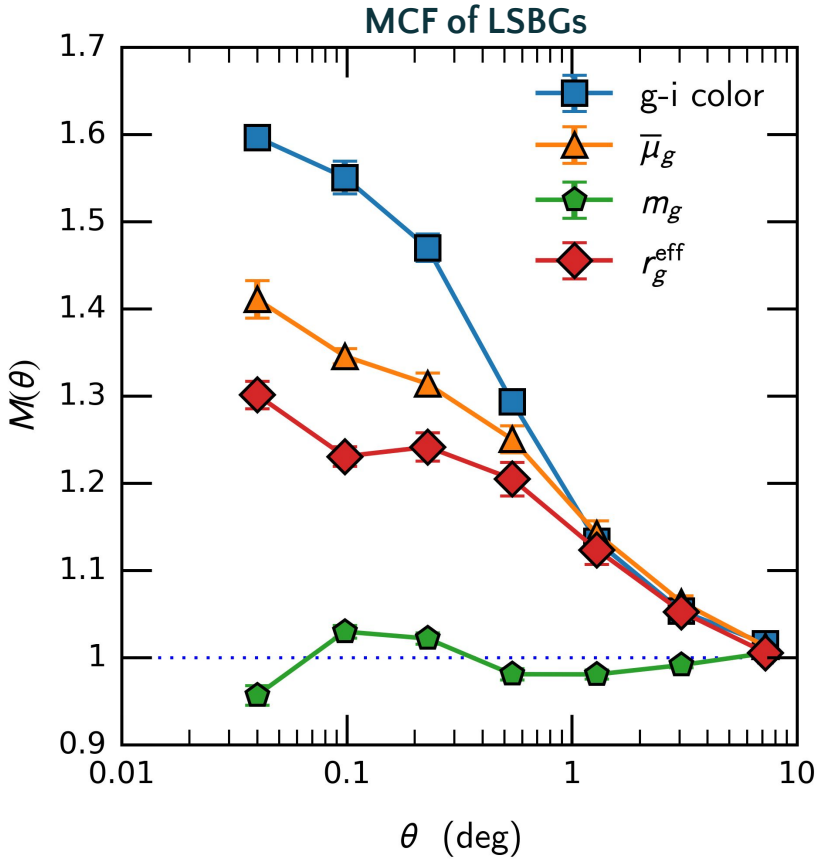
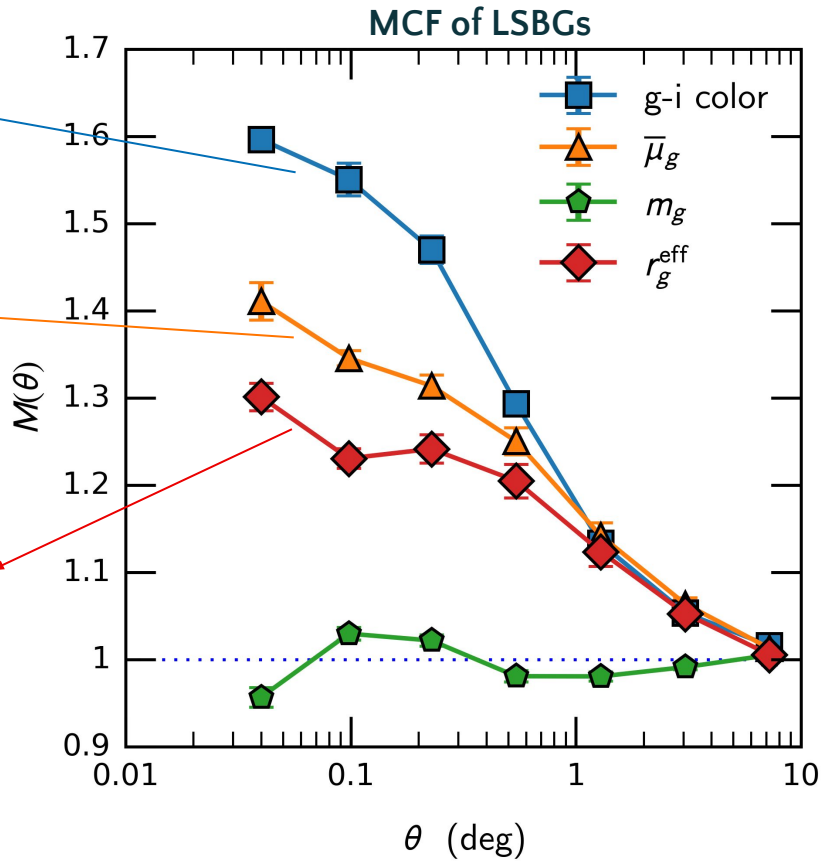


Local environment of Low surface brightness galaxies (LSBG)

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.)

Local environment of Low surface brightness galaxies (LSBG)

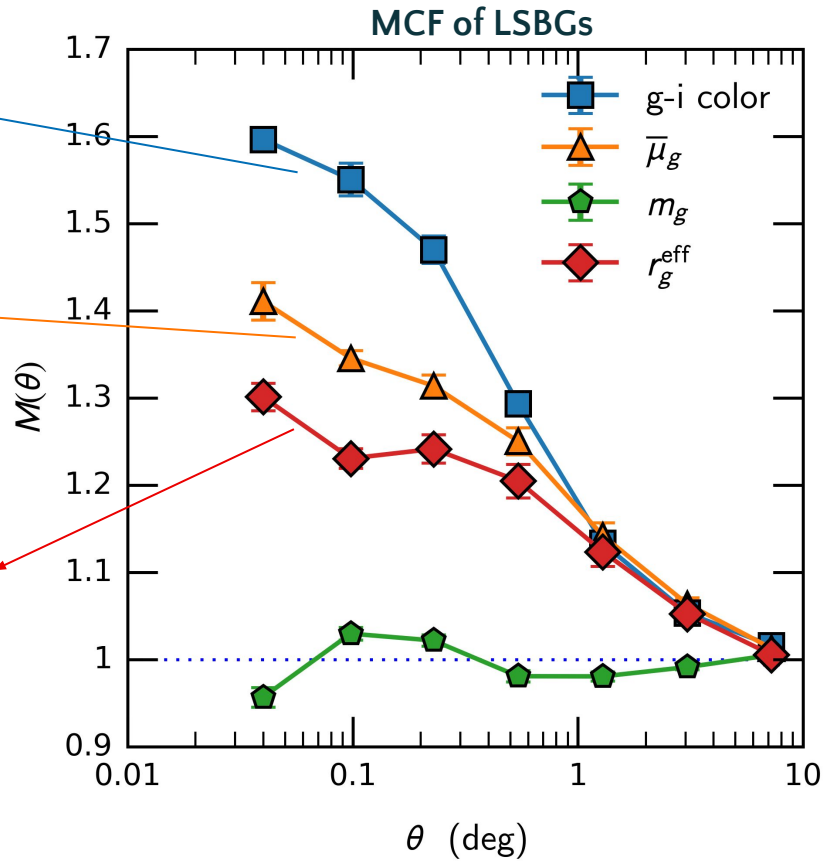
$$\mu = m + 2.5 \times \log_{10}(2\pi r_{1/2}^2)$$

LSBG–environment correlation is possibly driven by the galaxy size–environment correlation.

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.)

Summary

- Marked correlation function is an efficient tool to trace the differences in the environmental correlations of different galaxy properties.
- Stellar mass proves to be strongly correlated with the environment and SFR being anti-correlated.
- Luminosities in different bands form a hierarchy in which K (2.2 μm), W1 (3.4 μm) and W2 (4.6 μm) bands follow stellar mass and u (0.4 μm), W3 (12 μm) and W4 (22 μm) bands follow SFR in tracing the environment but NOT perfectly. That is, such correlations are scale dependent.
- Galaxy mergers prefer to exist in under-dense environments.
- Low surface brightness galaxies prefer denser environments, possibly as a result of the galaxy size-environment correlation.

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Thank you

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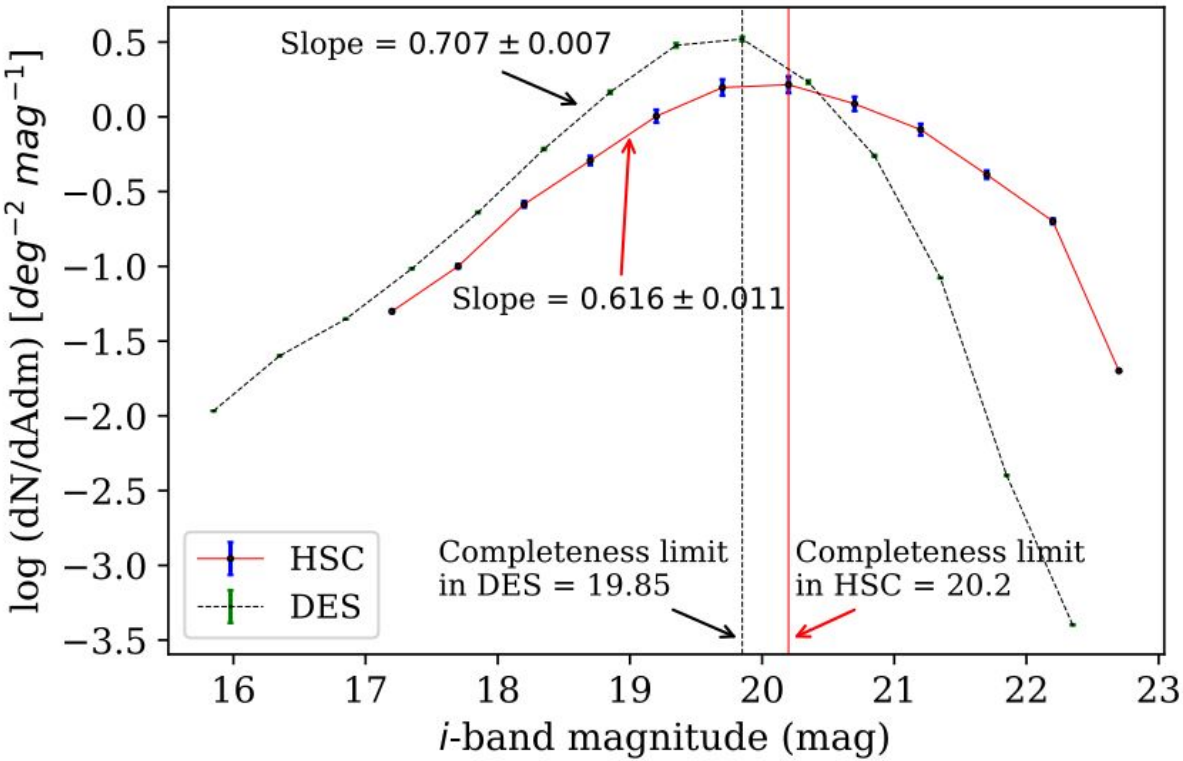
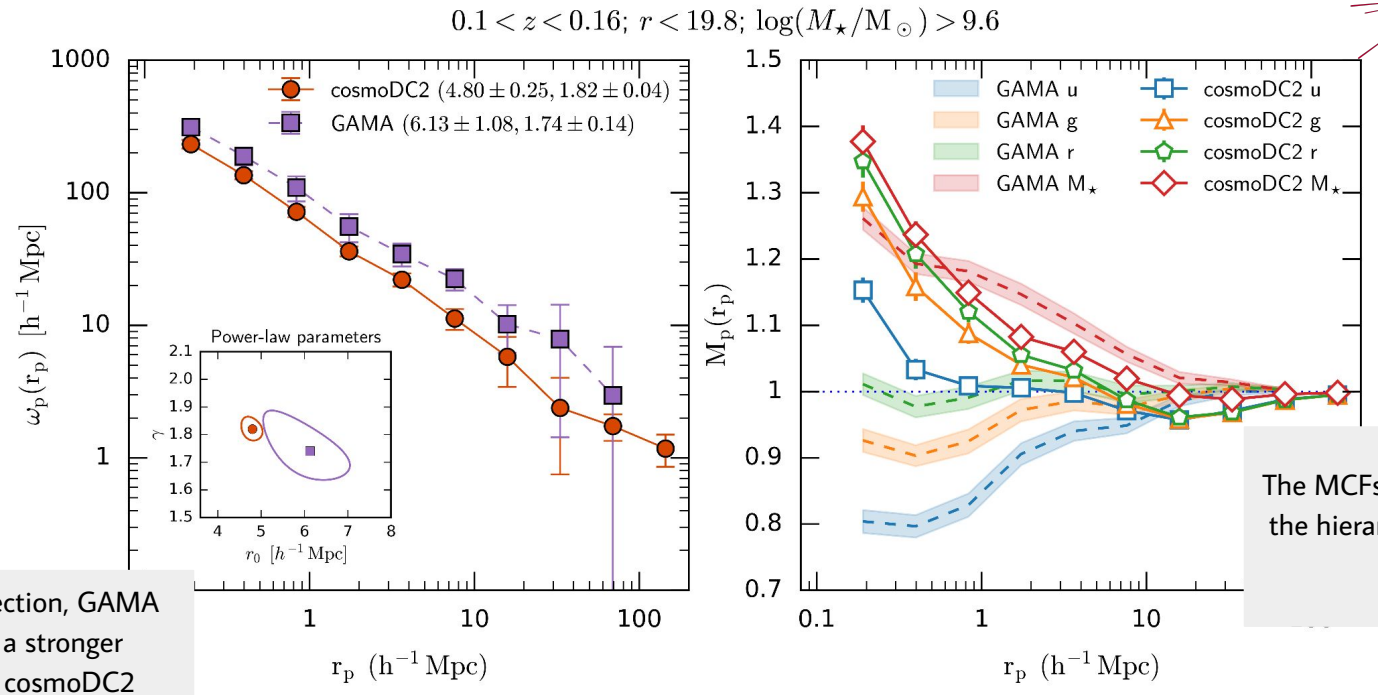
unnikrishnan.sureshkumar@wits.ac.za



Thuruthipilly+24

Measurements in cosmoDC2 catalogue



For the same selection, GAMA sample shows a stronger clustering than cosmoDC2 sample.

The MCFs in cosmoDC2 preserve the hierarchy that is observed in GAMA.

However, MCFs in cosmoDC2 behave very differently than in GAMA implying that the cosmoDC2 mock catalogue does not perfectly reproduce the environmental dependence in observed data.

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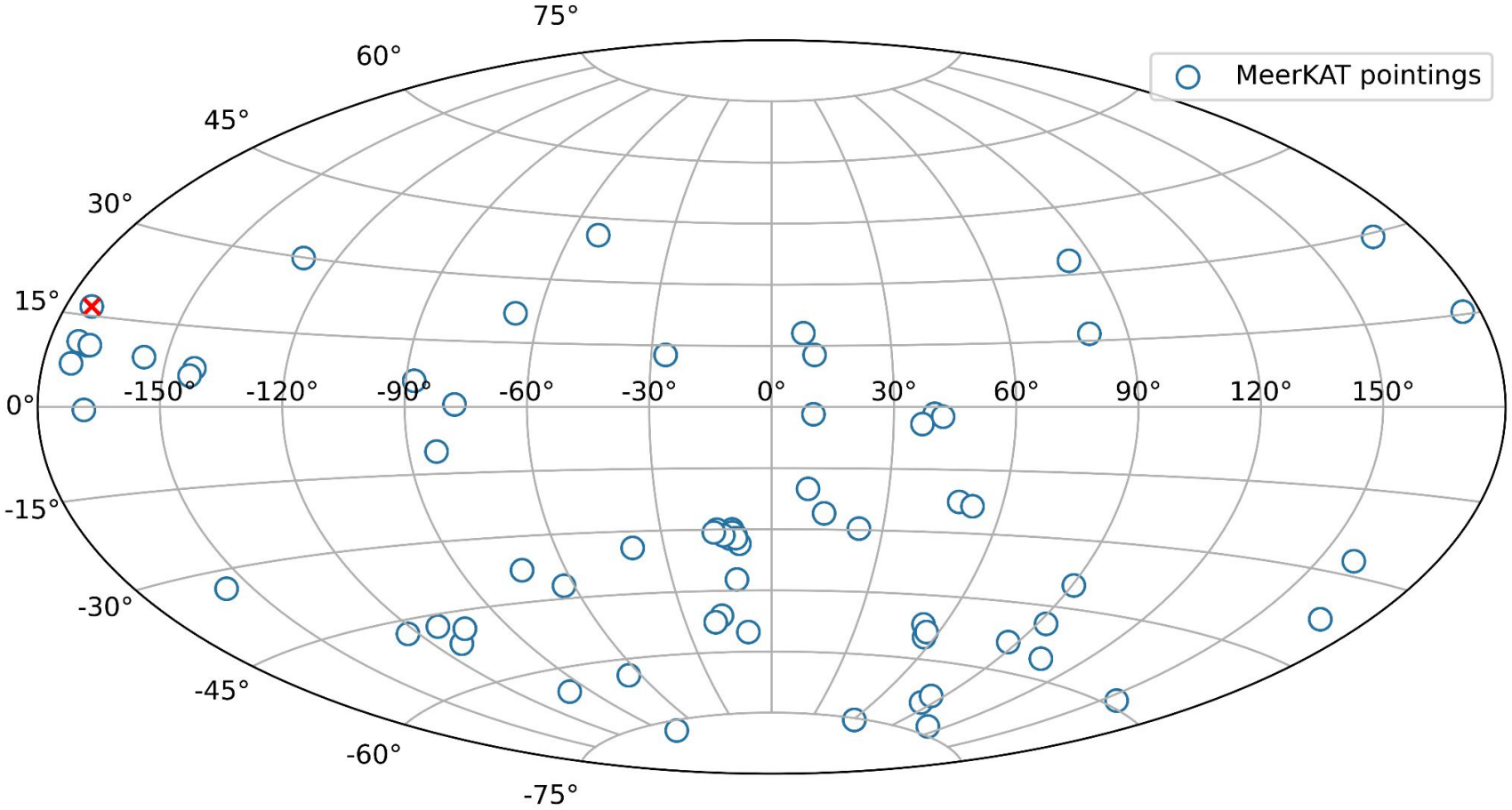
In-kind contribution to Rubin Observatory from South Africa

PI: Matt Hilton (Wits)

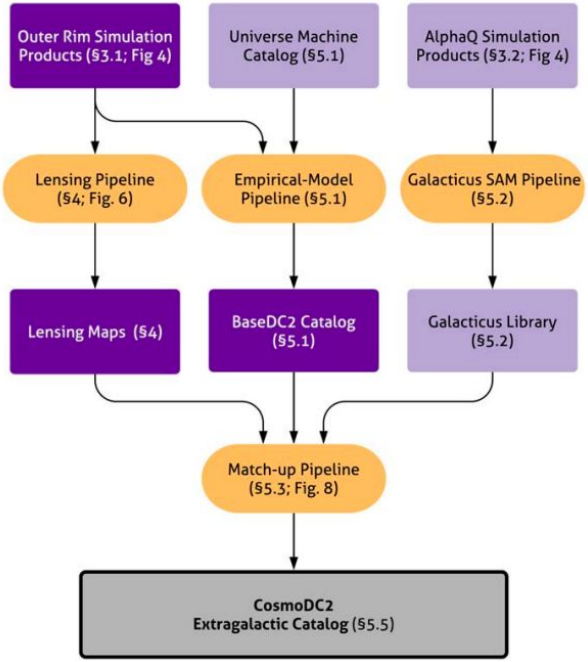
- Cross-correlate MeerKAT data with Rubin observatory
- Developing a pipeline with advanced cross-matching techniques


MeerKAT pointings
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
-150°
-120°
-90°
-60°
-30°
0°
30°
60°
90°
120°
150°

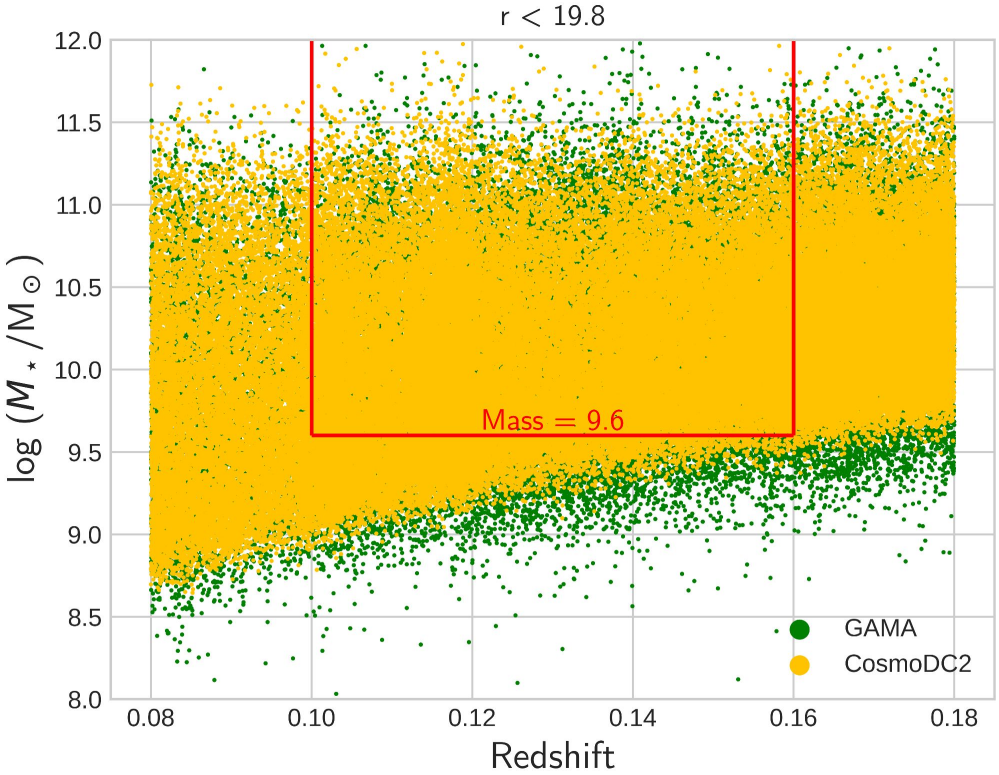
CosmoDC2 catalogue

- 8.4-meter Simonyi Survey Telescope will provide detailed imaging of millions of galaxies in the southern hemisphere sky for 10 years.
- Legacy Survey of Space and Time Dark Energy Science Collaboration (LSST DESC)
- Redshift up to 3
- Sky area : 440 sq. deg.

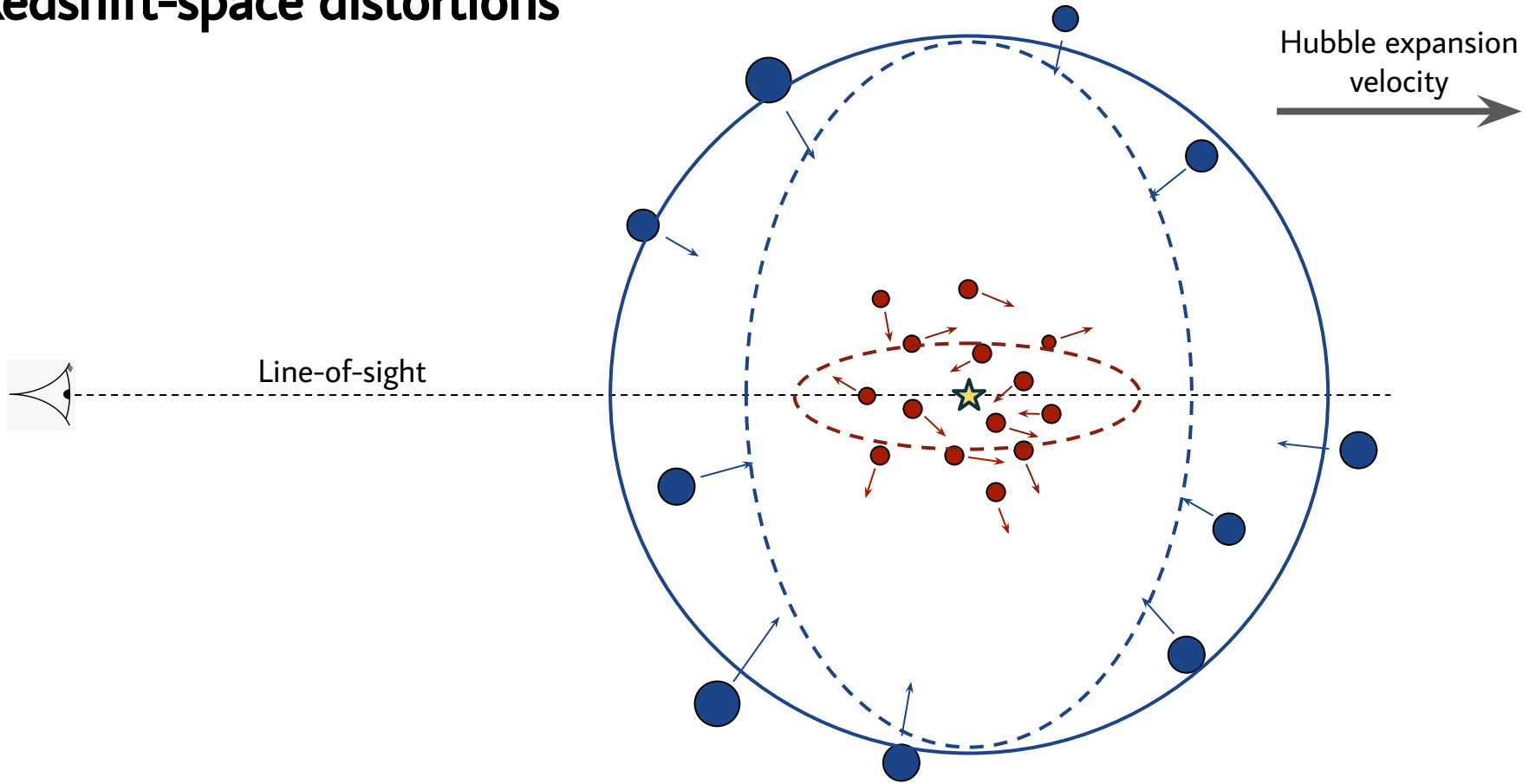
https://rubinobservatory.org/

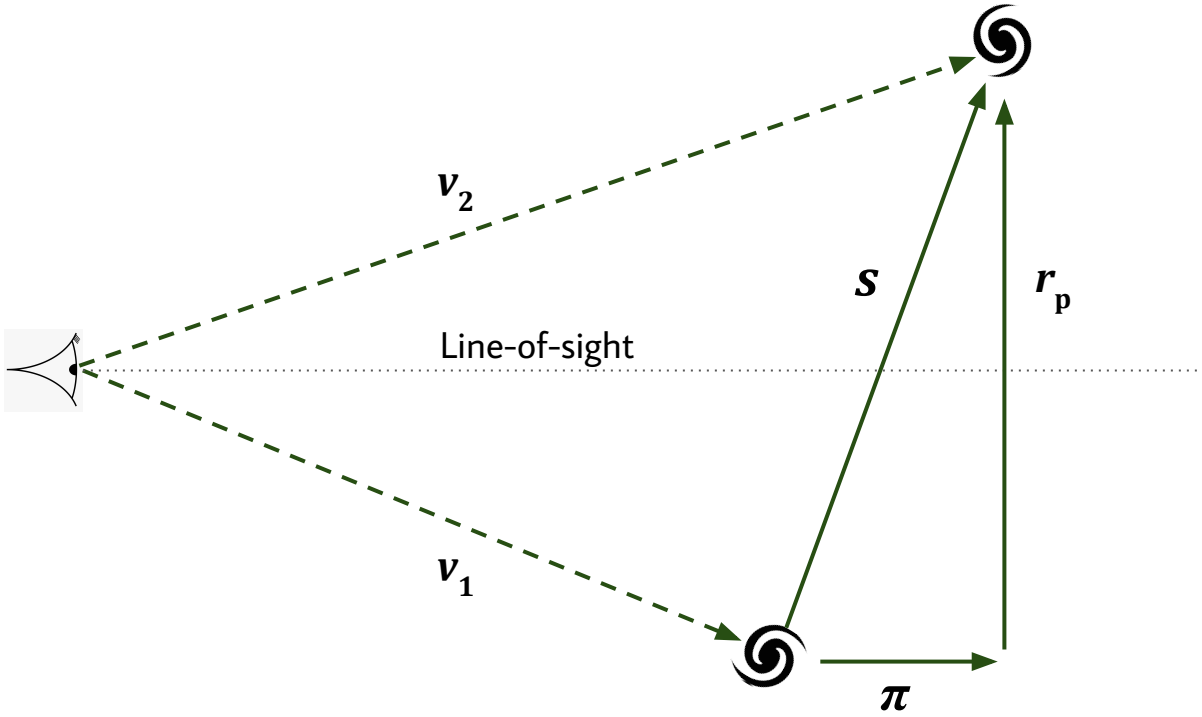


Korytov et al. 2019


r < 19.8
12.0
11.5
11.0
10.5
10.0
9.5
9.0
8.5
8.0
log (M⋆ /M⊙)
Mass = 9.6
GAMA
CosmoDC2
0.08
0.10
0.12
0.14
0.16
0.18
Redshift

Redshift-space distortions



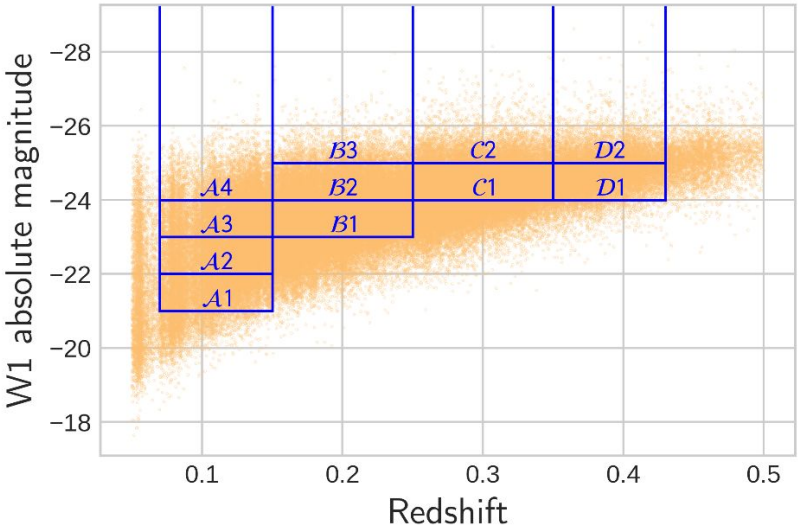


Projected two-point correlation function

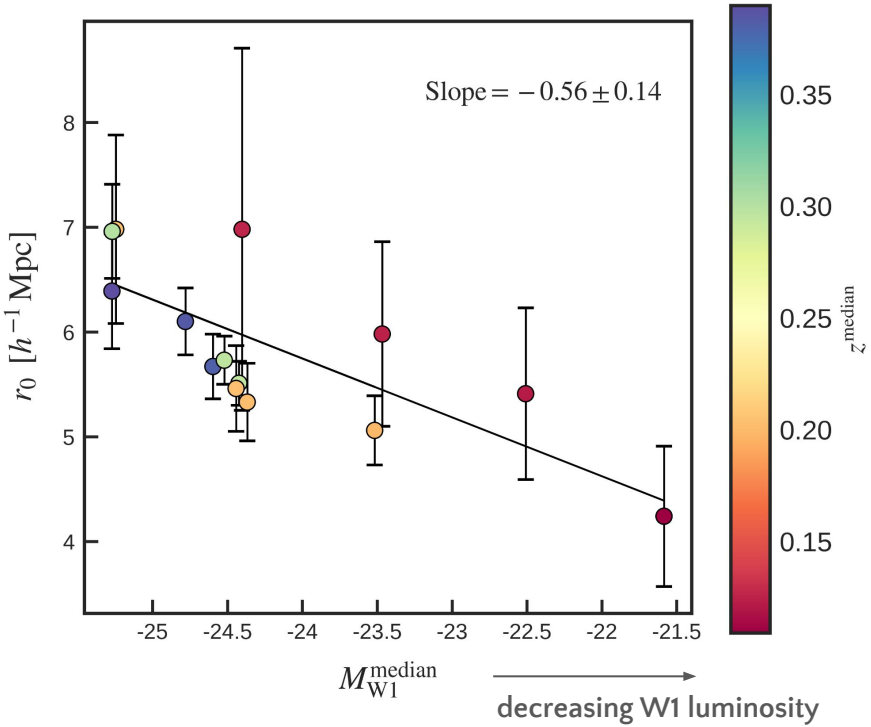
$$\omega_p(r_p) = 2\int_0^\infty \xi(r_p, \pi)\,d\pi$$

GAMA galaxies with mid-IR properties from WISE

(Cluver et al. 2014)



Galaxies brighter in W1 band are more clustered



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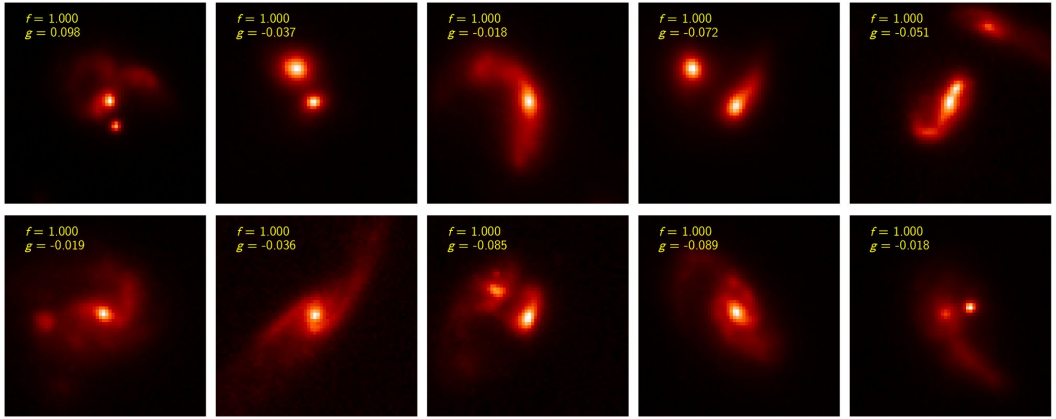
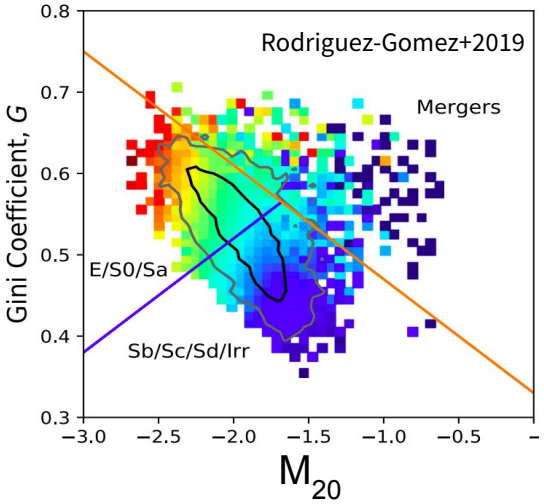
How to identify mergers?

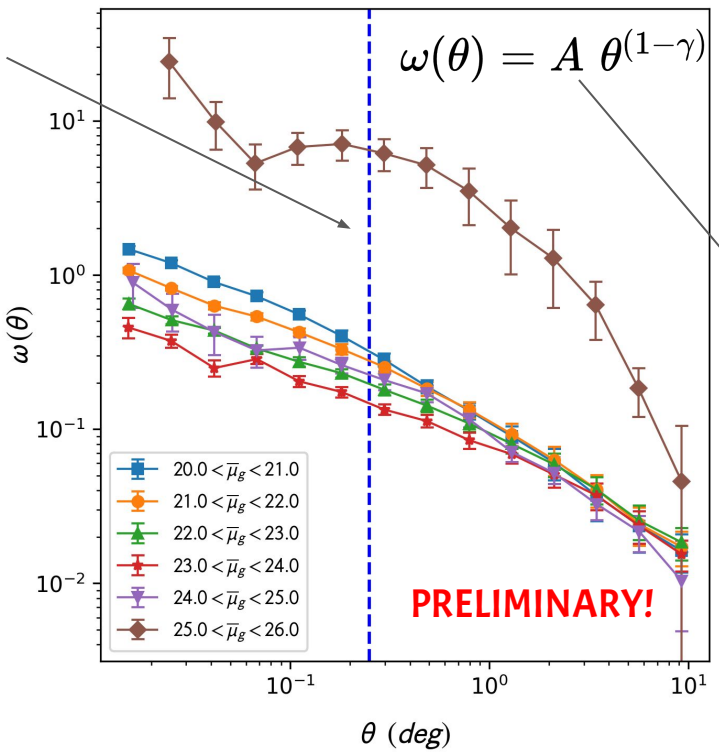
- ➔ **Visual identification**
- ➔ **Machine learning algorithms**
- ➔ **Non-parametric measures of galaxy morphology** - e.g. **Gini-M $_{20}$**

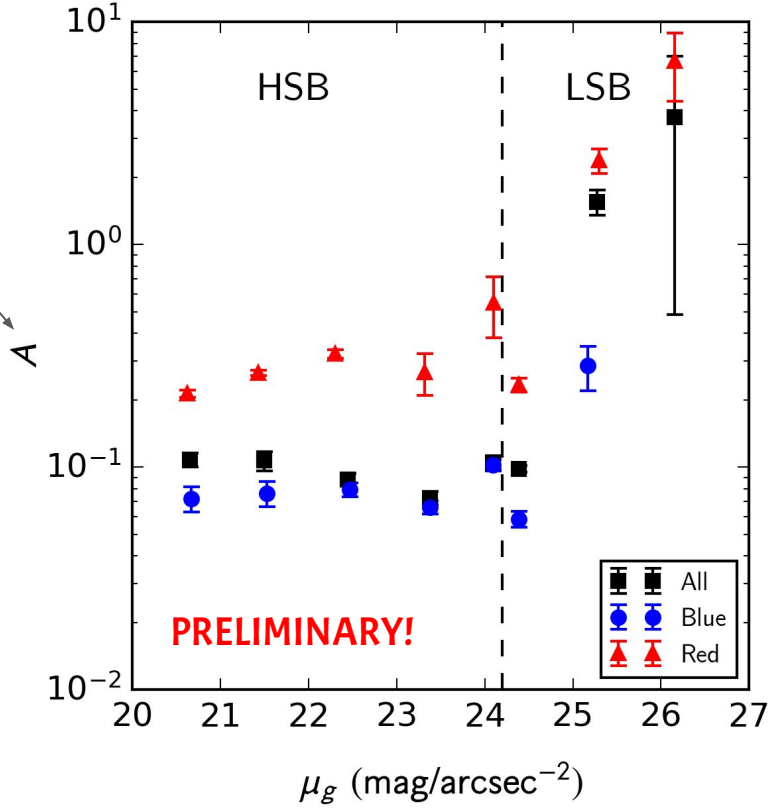




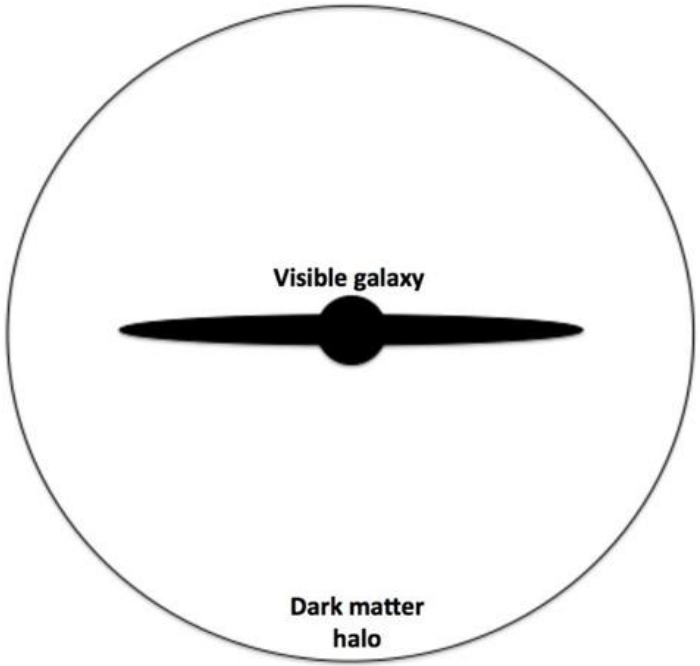
Clustering dependence on surface brightness

eq. typical scale of a galaxy cluster





Dependence of galaxy properties on environment



- ★ Galaxies live in dark matter haloes.
- ★ Galaxy properties (such as luminosity, stellar mass and star formation rate) are majorly defined by the properties of the DM halo in which they live.
- ★ The properties of DM halo correlate with environment (Sheth & Tormen 2004).
- ★ This prompts a correlation between galaxy properties and environment