The correlations between galaxy properties in different environments of the cosmic web

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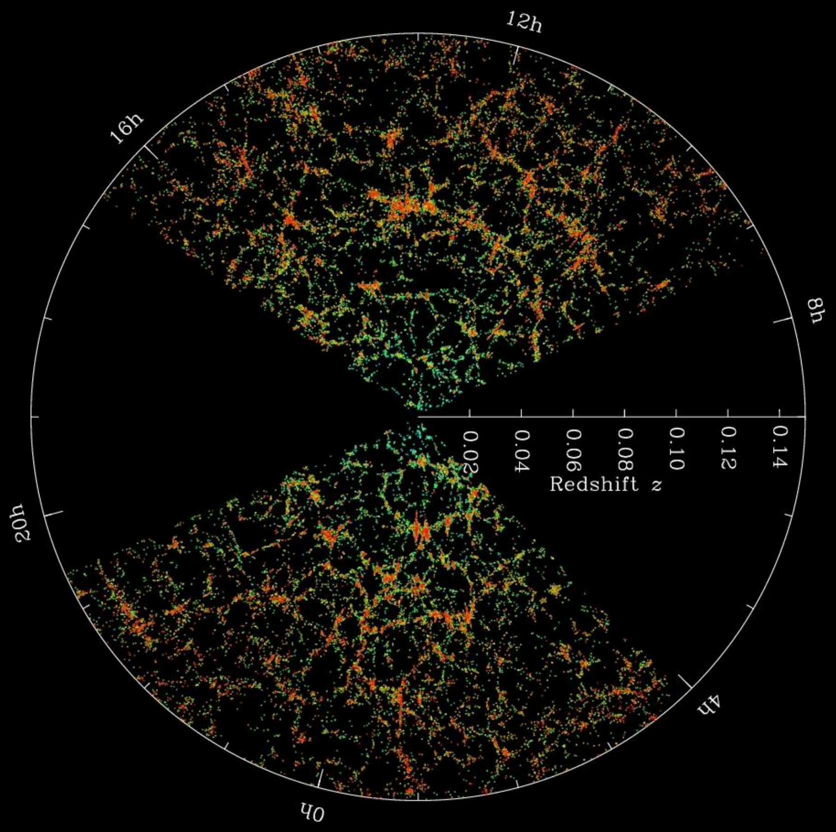
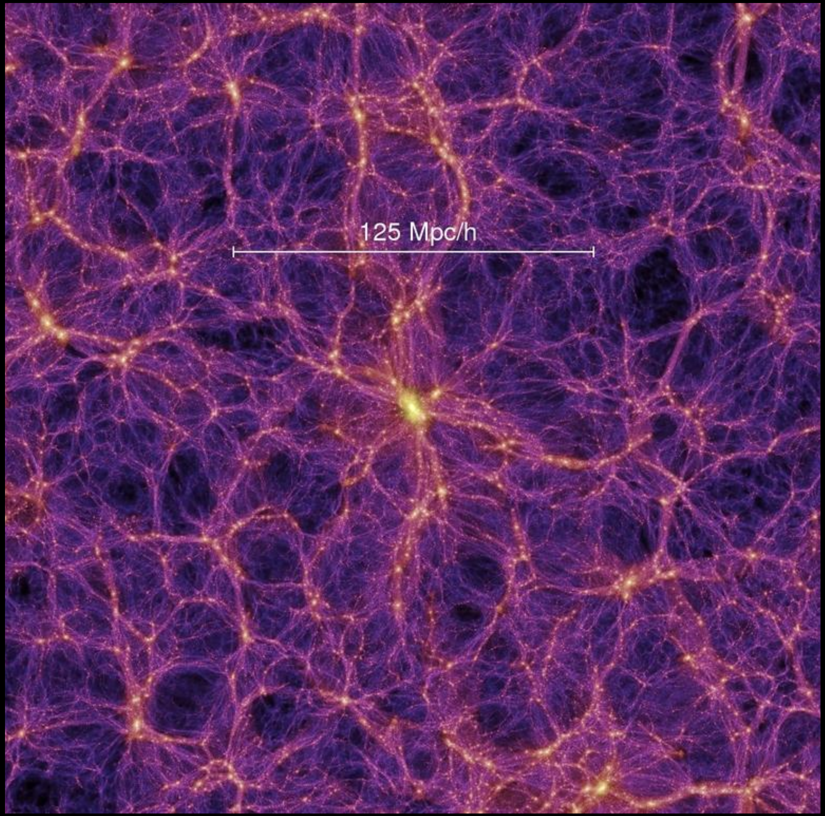
Introduction

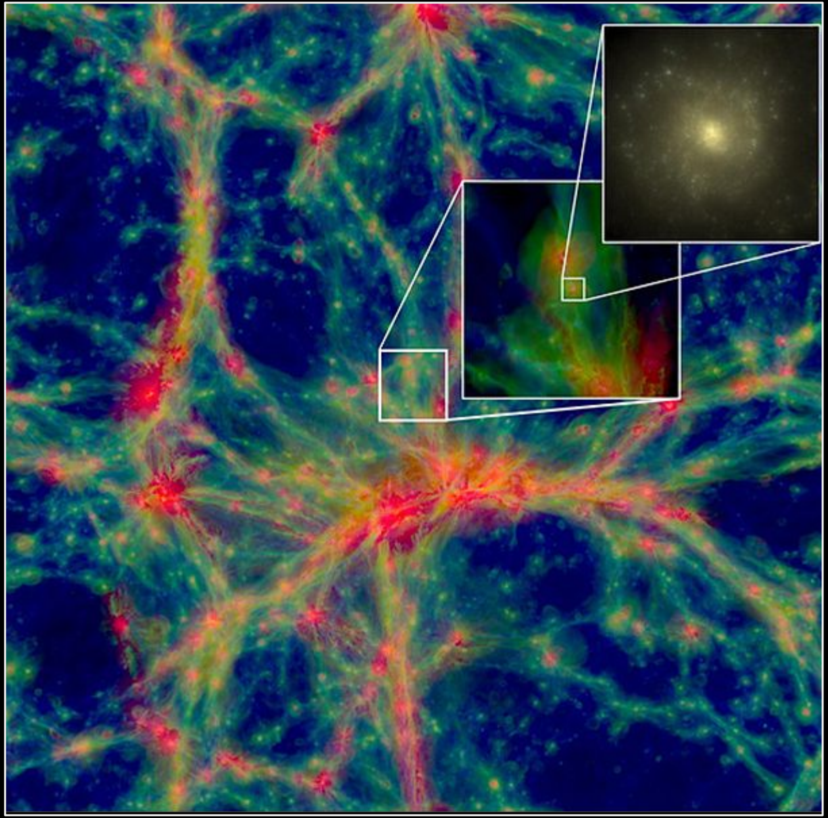


Map of the observed galaxy distribution (Credit : SDSS Collaboration)



Dark matter distribution from Millennium simulation

Introduction

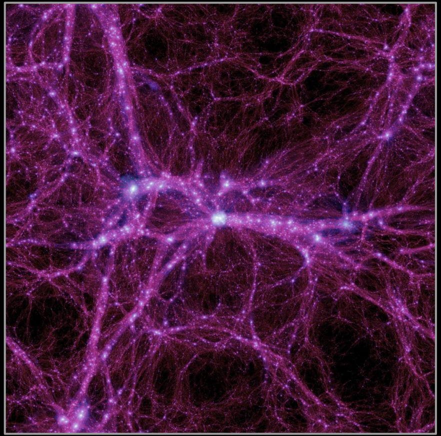


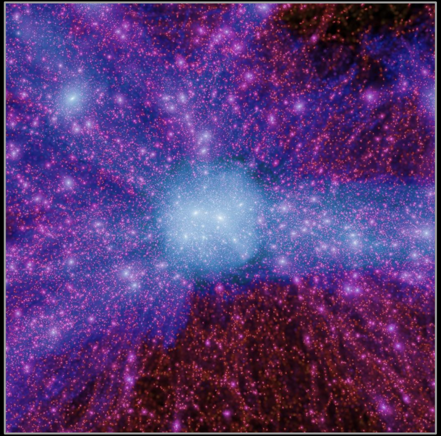
Credit : EAGLE Simulation

Distribution of matter (and galaxies) follows a network-like pattern, known as '**Cosmic Web**'.

- ❖ There are large underdense regions known as **voids**.
- ❖ Voids are surrounded by thin **sheets**.
- ❖ **Filaments** are located at the intersections of sheets.
- ❖ **Clusters** lie at the intersection of filaments.

Introduction





Credit : Millennium Simulation

Effects of large-scale environments on dark matter halo properties :

- Mass : Hahn et al. 2007, Metuki et al. 2015, Hellwing et al. 2021
- Shape : Hahn et al. 2006, Veena et al. 2018, Hellwing et al. 2021
- Spin : Aragon- Calvo et al. 2007, Zhang et al. 2009, Hellwing et al. 2021
- Halo alignment : Altay et al. 2006, Xia et al., 2017
- Halo bias: Yang et al. 2017, Fisher & Faltenbacher 2017

Introduction

Simulated dark matter in milky way halo
Credit : NASA, ESA

Effects of dark matter halo on galaxy properties :

- Mass : Behroozi et al. 2010, Rodriguez-Puebla et al. 2017
- Size: Somerville et al. 2017, Rohr et al. 2022
- SFR & Galaxy Quenching : Behroozi et al. 2019
- Galaxy morphology : Zenocratti et al. 2022
- Metallicity : Wang et al. 2023

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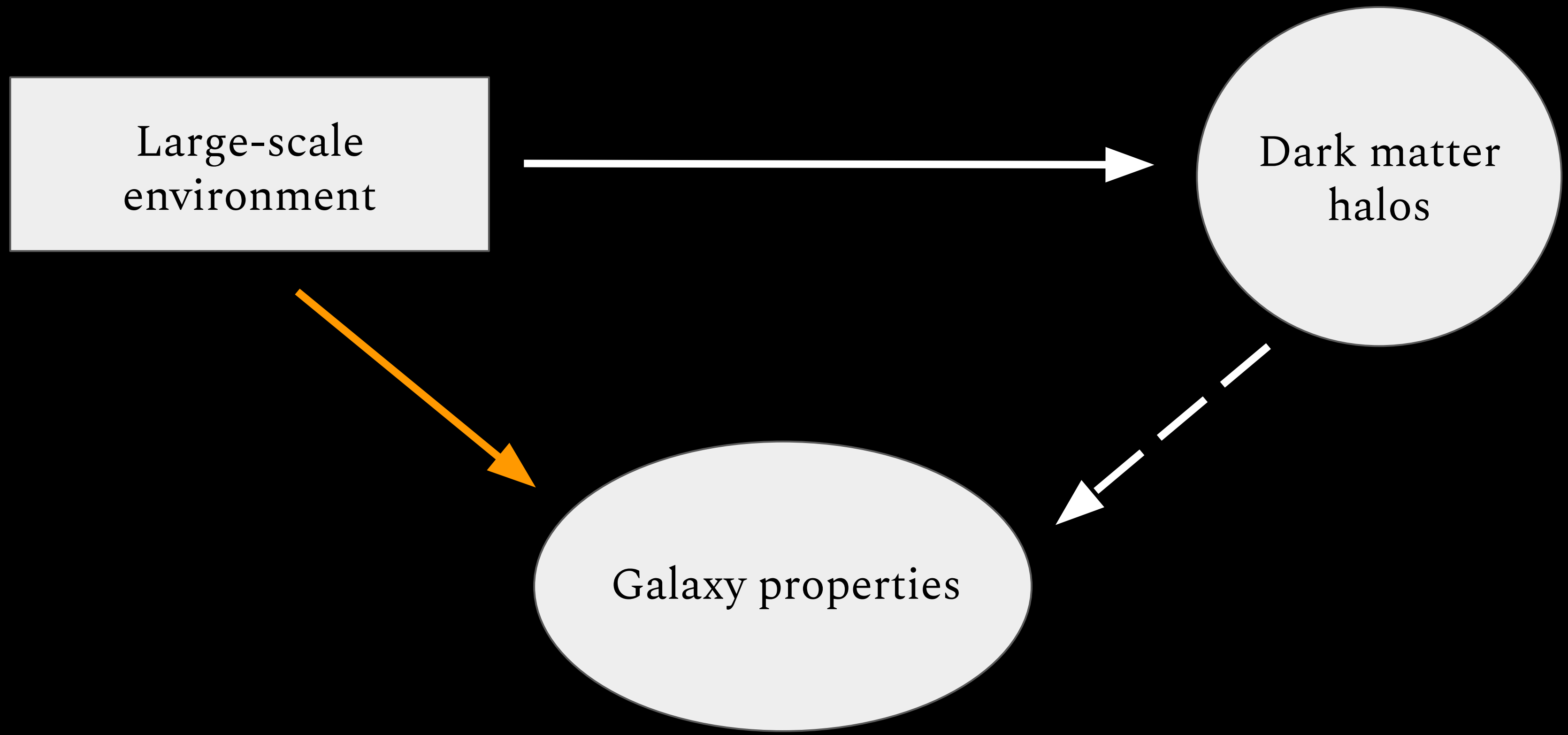
Introduction



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Introduction

Correlations of the galaxy properties with environment :

- **Colour** - Pandey & Sarkar 2020, Bhambhani et al. 2023
- **Stellar mass** - Malavasi et al. 2017, Chen et al. 2017
- **Star formation rate** - Cornuault et al. 2018, Hasan et al. 2023
- **Metallicity** - Darvish et al. 2015, Donnan et al. 2022
- **Morphology** - Pandey & Bharadwaj 2006, Kelkar et al. 2017
- **Galaxy pair alignments** - Mesa et al. 2018

Correlations between different galaxy properties :

- Star formation main sequence (SFMS) [Brinchmann et al. 2004]
- Star formation rate and morphology [Bell et al. 2012, Bomee et al. 2013]
- Stellar mass and the metallicity (MZR) [Tremonti et al. 2004, Galazzi et al. 2005]
- Size-stellar mass relation [Ichikawa et al. 2012]
- Color and stellar mass [Baldry et al. 2006]
- Gas density and star formation rate (Kennicutt-Schmidt law) [Schmidt 1959; Kennicutt 1989]

Introduction

We study the influence of cosmic-web environments on the correlations between different galaxy properties

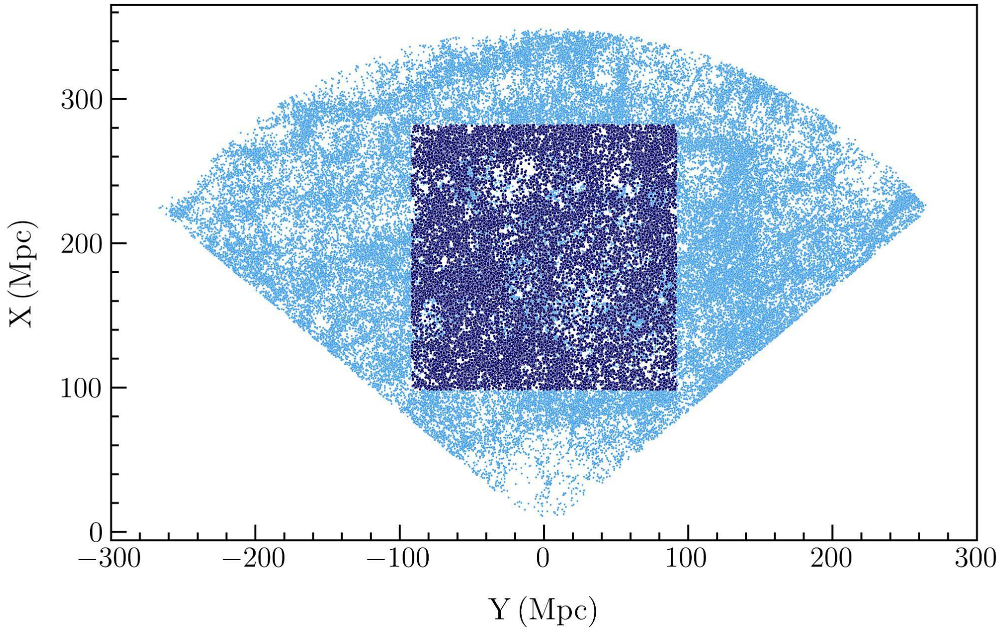
Data

- We construct a volume limited galaxy sample from the Sloan Digital Sky Survey (SDSS) data

$130^\circ \leq \alpha \leq 230^\circ$ $0^\circ \leq \delta \leq 62^\circ$

$M_r \leq -20$ $z \leq 0.08$

- Total galaxies in the volume-limited sample = 94986
- Size of the largest cube extracted from the sample : **183.50 Mpc**
- Total number of galaxies in the cube : **24146**



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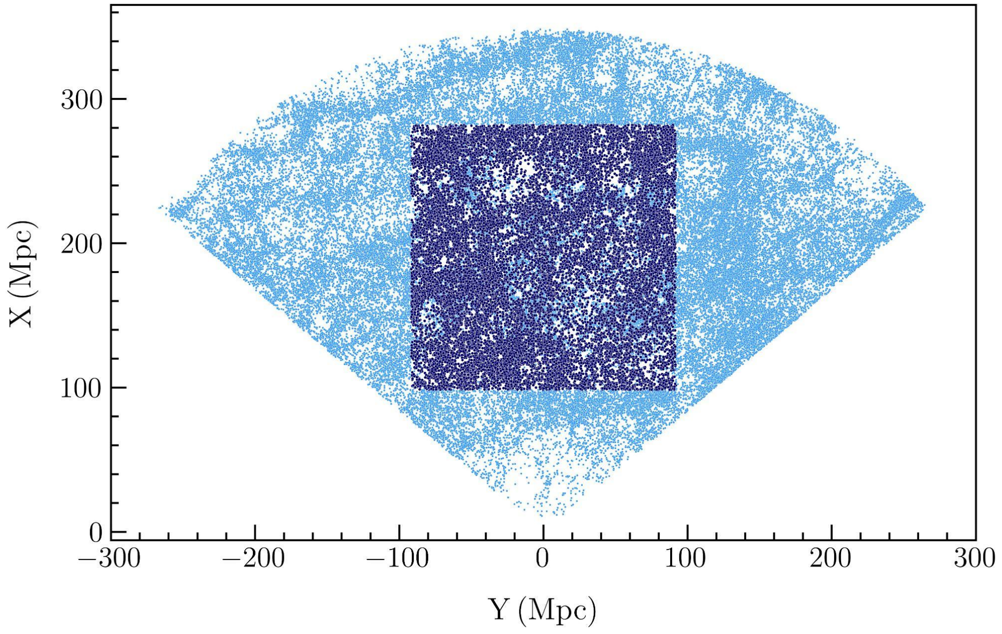

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Methodology

1. **Calculate overdensity using Cloud-In-Cell (CIC) scheme**
2. **Fourier transform of overdensity field and smoothed using a Gaussian kernel**
3. **Solve Poisson equation in Fourier space** $\nabla^2\Psi \equiv \delta$
4. **Transform gravitational potential into real space**
5. **Perform numerical differentiation to obtain deformation tensor** $T_{\alpha\beta} = \frac{\partial^2\Psi}{\partial x_\alpha \partial x_\beta}$
6. **Calculate eigenvalues of deformation tensor and sort**
7. **Identify cosic web environment based on the number of positive eigenvalues**

Number of grids along each direction = 128

Grid spacing = 1.43 Mpc

Smoothing length = 7.15 Mpc (5 grid spacing)

Intergalactic separation = 6.34 Mpc

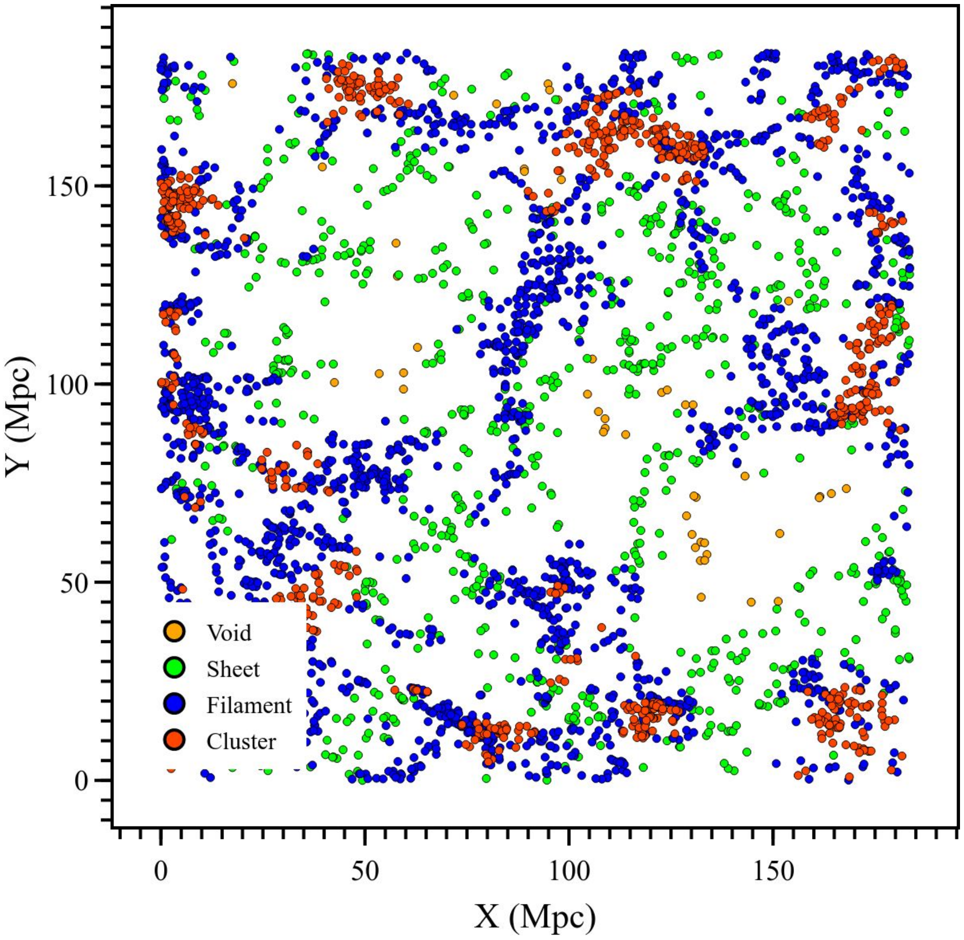
Methodology

Classification of galaxies in different cosmic web environments

- Assignment each galaxy into a particular cosmic web environment depending on the sign of the eigenvalues ($\lambda_1 \geq \lambda_2 \geq \lambda_3$) (Hahn et al., 2007)

Morphological environment	λ_1	λ_2	λ_3
Void	< 0	< 0	< 0
Sheet	> 0	< 0	< 0
Filament	> 0	> 0	< 0
Cluster	> 0	> 0	> 0

Methodology



Type of cosmic web environment	Number of recovered galaxies
Void	324
Sheet	4435
Filament	12620
Cluster	6767

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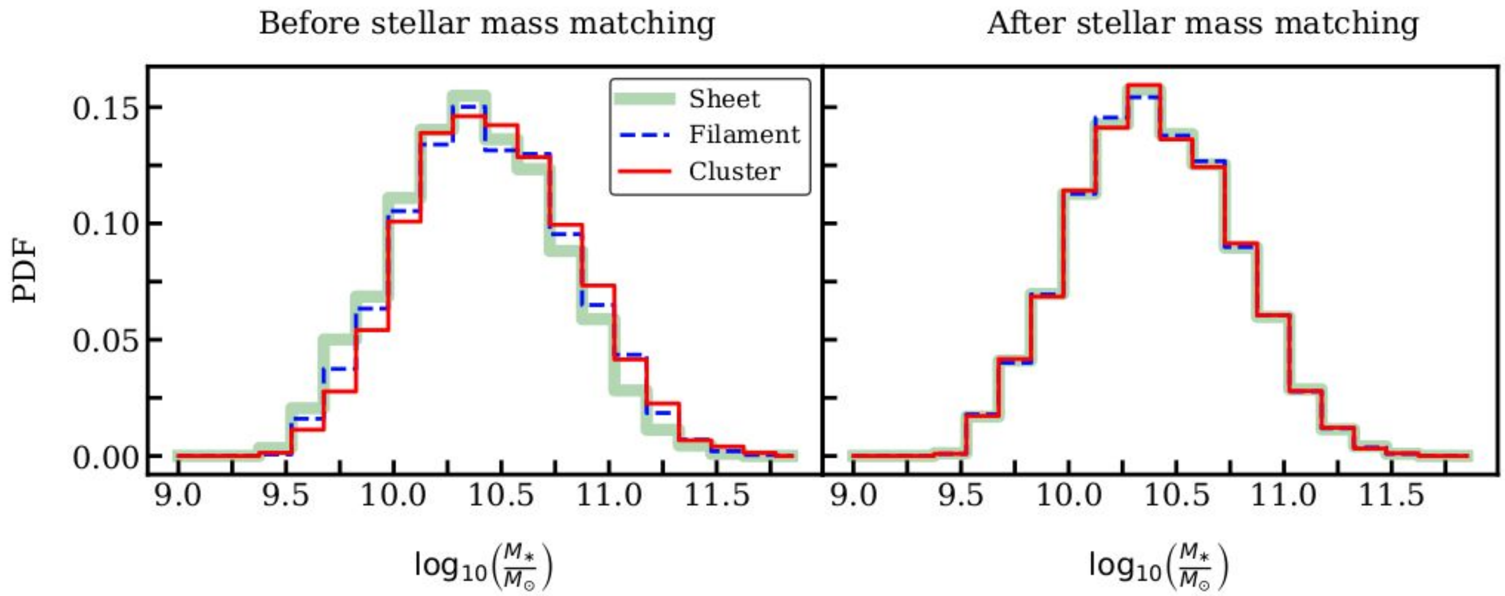
Methodology



Each environment (sheet, filament and cluster) has **4363** galaxies after stellar mass matching

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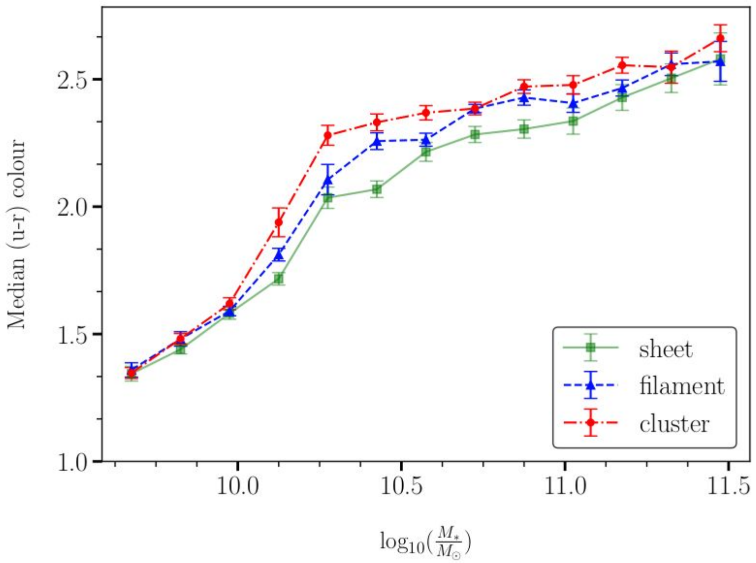
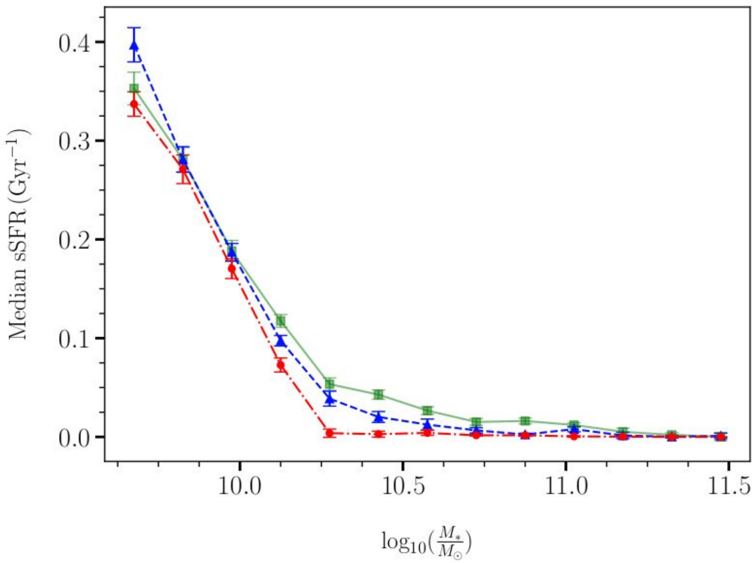
Results





Median colour of galaxies in each type of morphological environment increases with the increasing stellar mass. Enhancement of median colour with stellar mass is strongest in the cluster environment followed by the filamentary and sheetlike environments.

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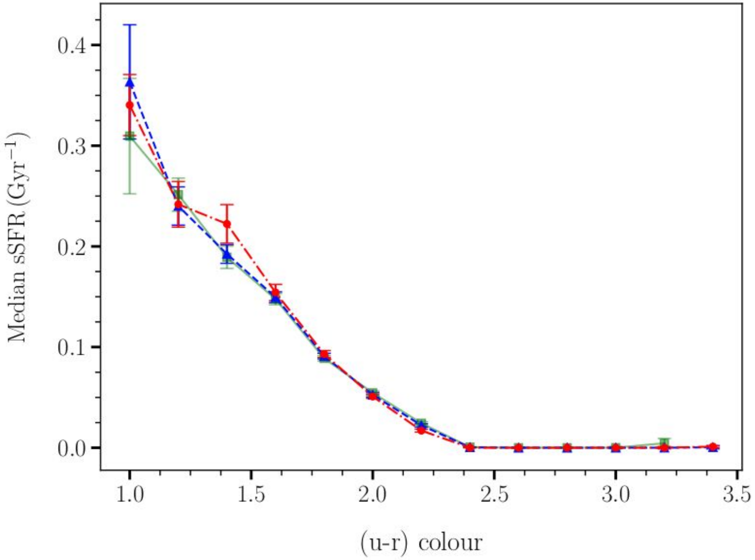
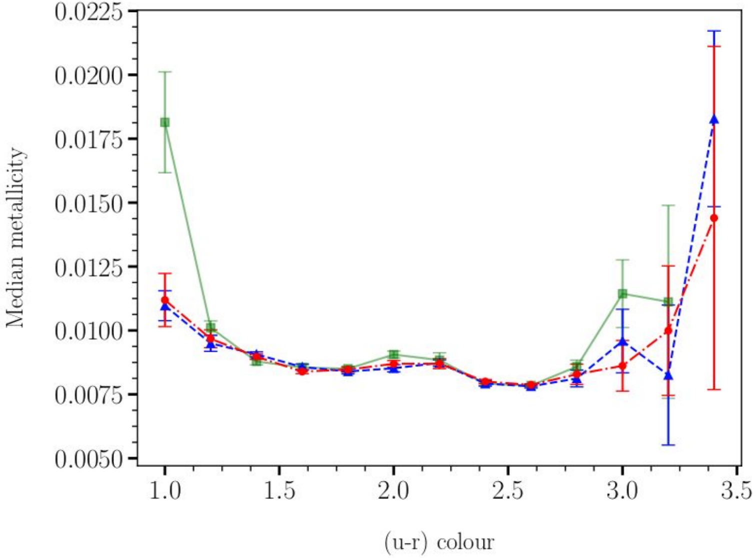
Results





sSFR and colour of galaxies are anti-correlated in all environments. Galaxies with (u − r) colour above ~ 2.3 are very low star forming.

Galaxies with redder colour have a higher metallicity in each type of morphological environment.

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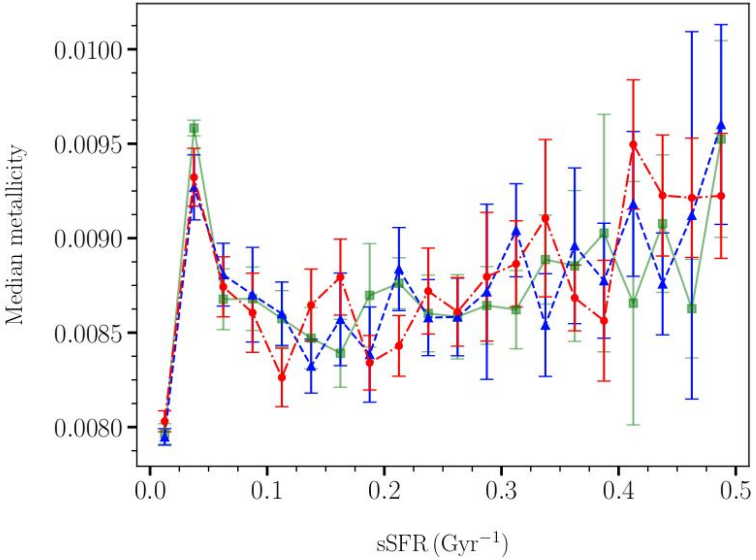
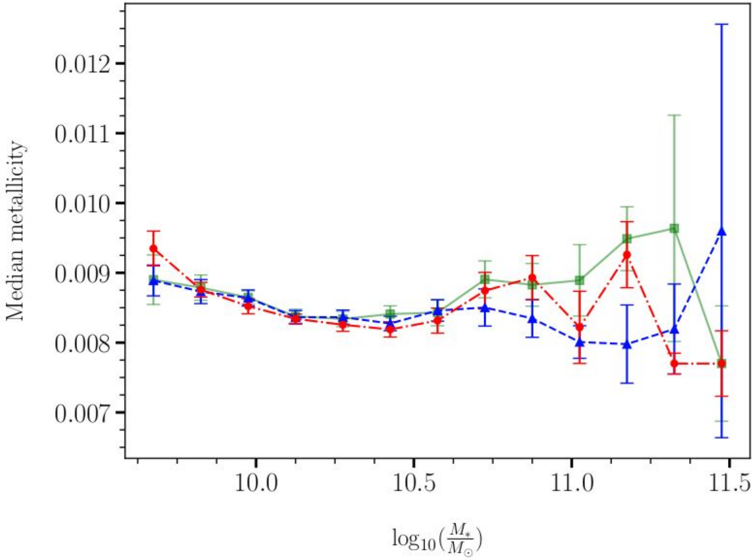
Results





Weak correlation between metallicity and sSFR in every environment. Massive galaxies tend to be metal rich in all environments.

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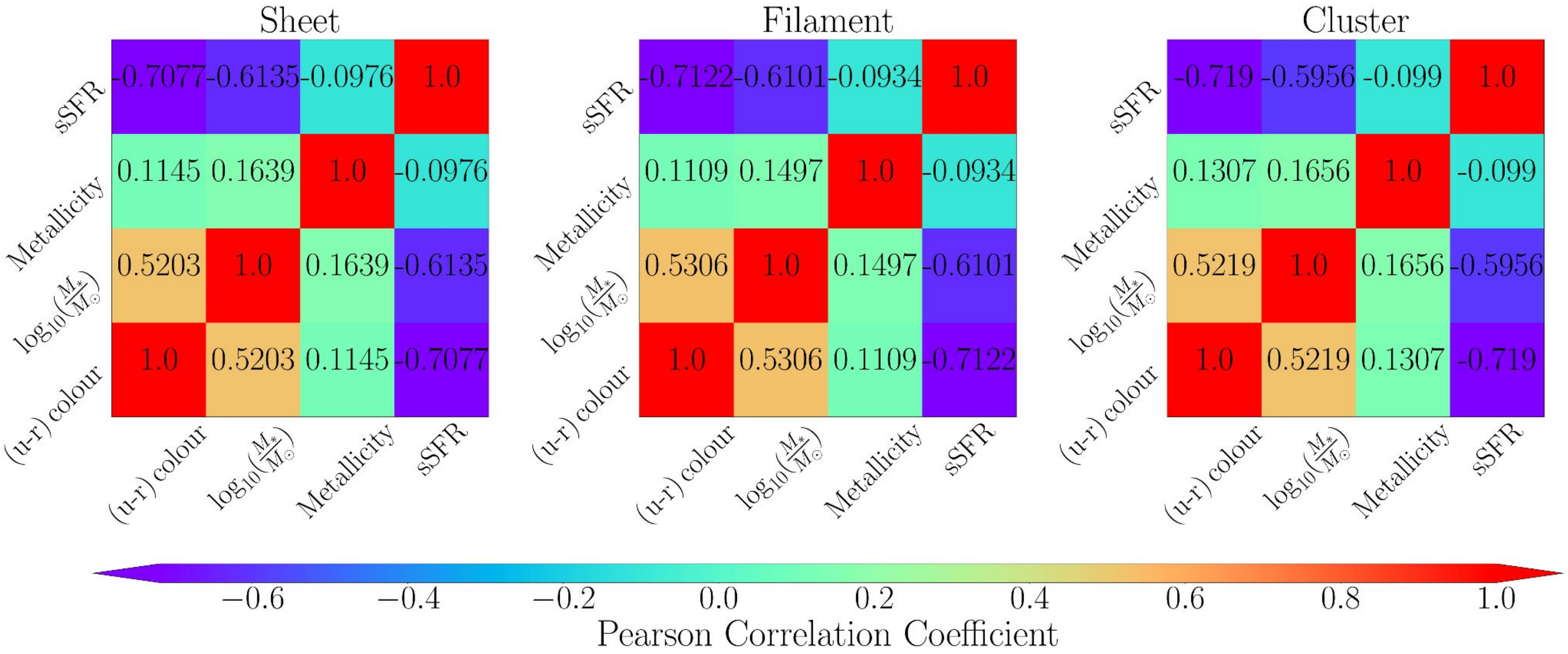
Results

Measuring correlations using Pearson correlation coefficient (PCC)



PCC for a pair of random variables (X, Y) $$r_{XY} = \frac{\sum_{i=1}^{N}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{N}(X_i - \bar{X})^2 \sum_{i=1}^{N}(Y_i - \bar{Y})^2}}$$

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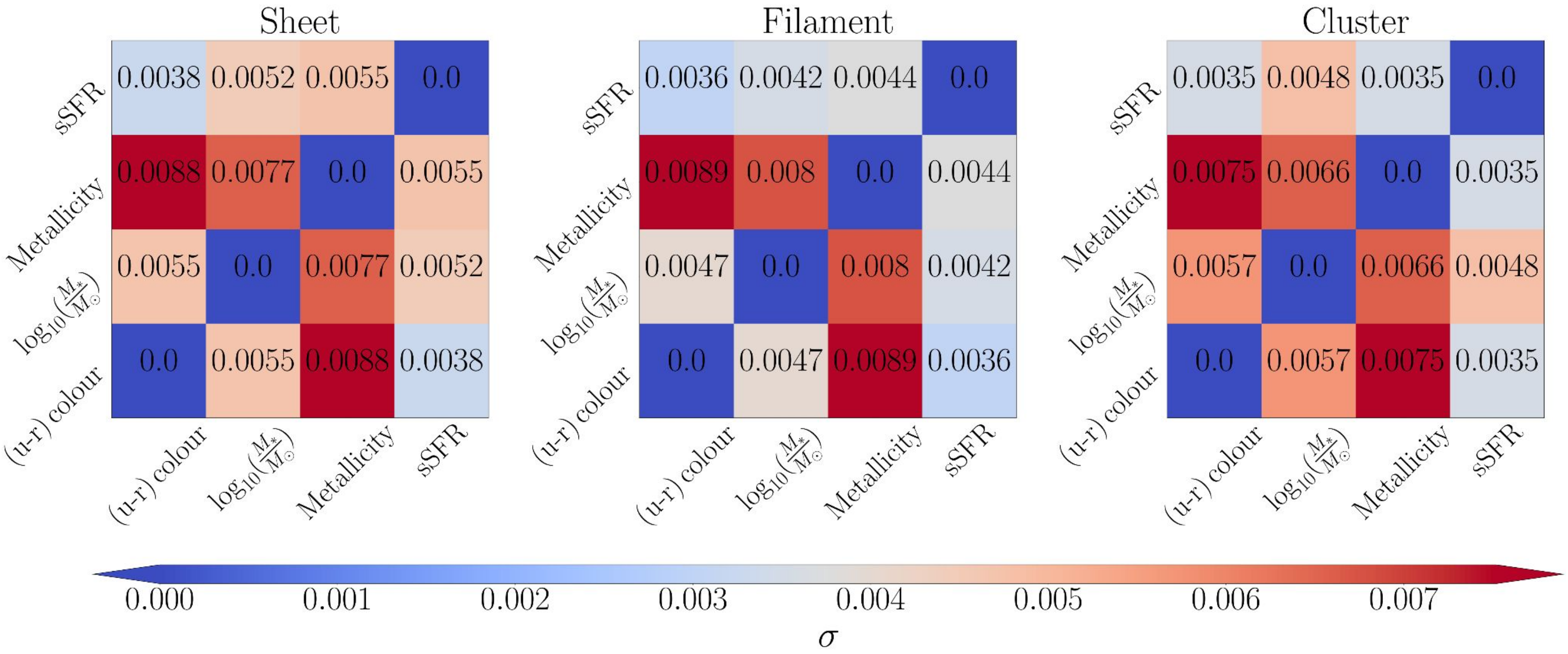

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Results

Measuring correlations using Pearson correlation coefficient (PCC)

Relations	Sheet - Filament	Filament - Cluster	Sheet-Cluster
	p value	p value	p value
colour-stellar mass	3.99×10^{-14}	2.25×10^{-14}	1.63×10^{-1}
colour-metallicity	1.85×10^{-1}	7.54×10^{-21}	1.58×10^{-17}
colour-sSFR	4.39×10^{-10}	2.71×10^{-17}	2.88×10^{-27}
stellar mass-metallicity	3.54×10^{-19}	1.23×10^{-20}	6.98×10^{-1}
stellar mass-sSFR	1.39×10^{-3}	1.36×10^{-39}	1.34×10^{-42}
sSFR-metallicity	4.54×10^{-5}	2.18×10^{-7}	5.87×10^{-1}

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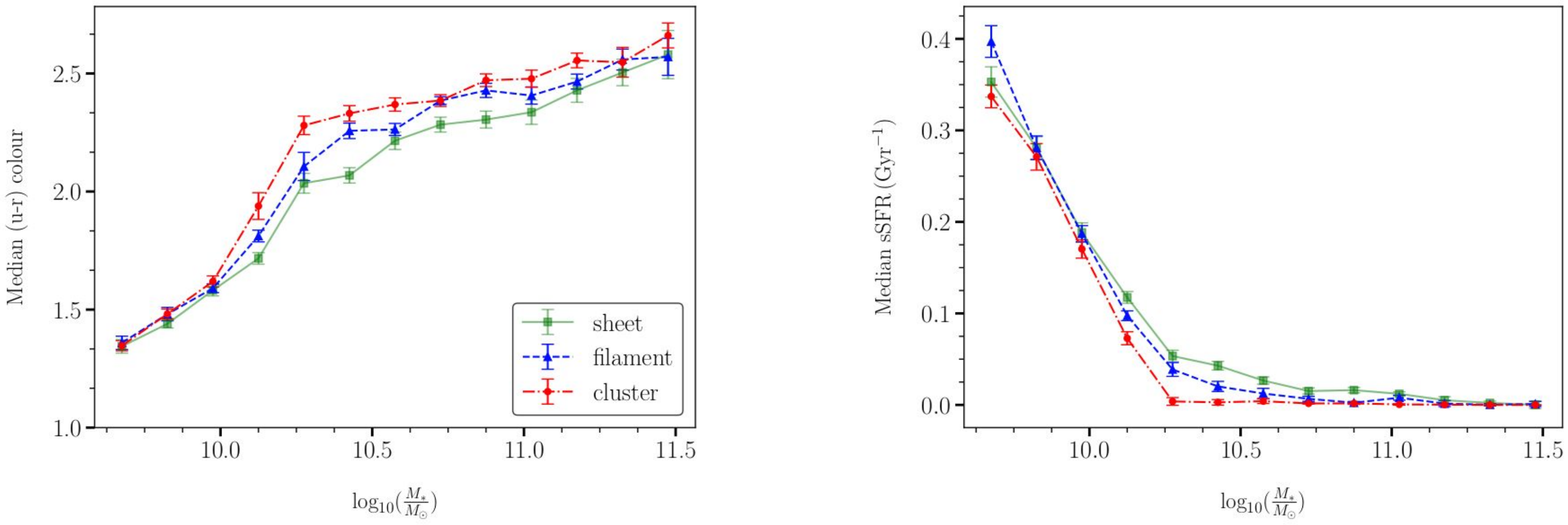
Results



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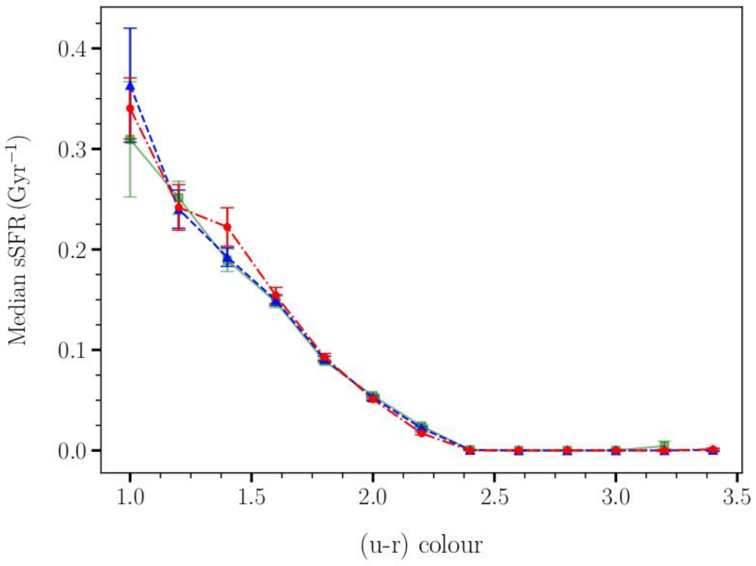

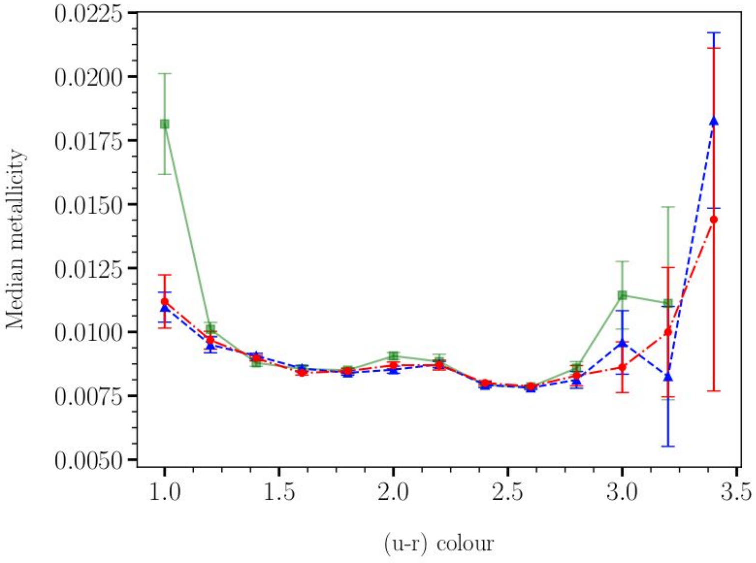

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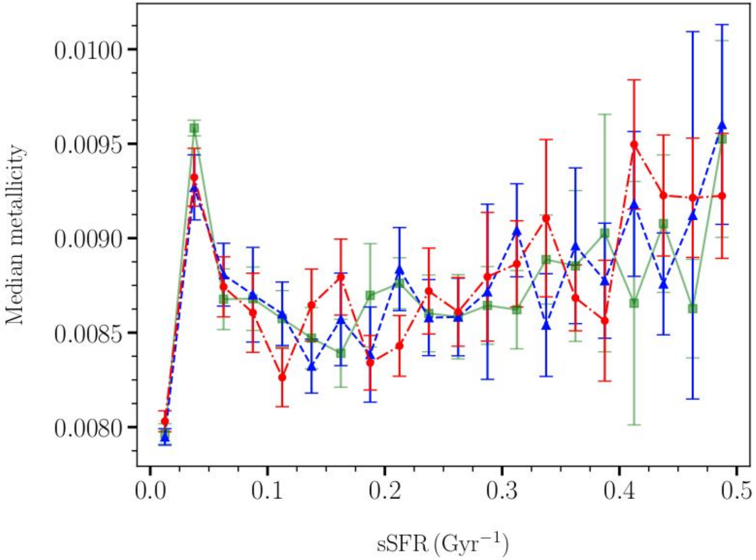

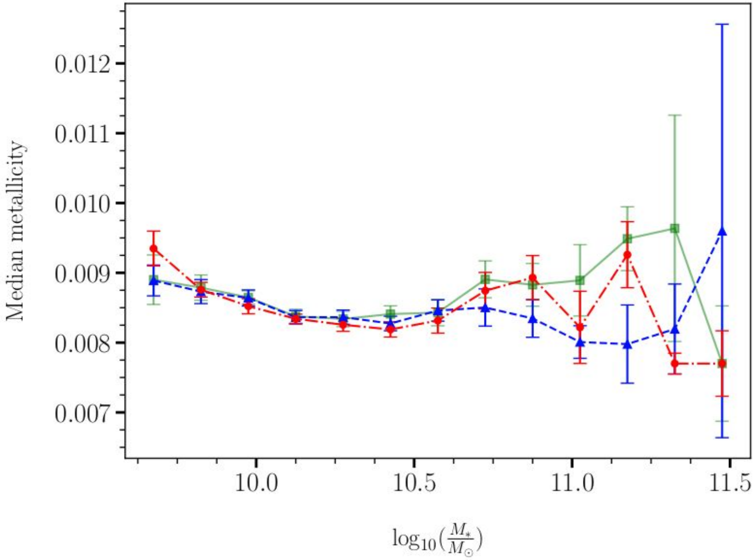

Weak correlation between metallicity and sSFR in every environment. Massive galaxies tend to be metal richin all environments.

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Results

- **Correlations between galaxy properties are non-linear and non-monotonic**
- **Normalized Mutual Information (NMI) - Information theoretic measure**

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Results

Measuring correlations using Normalized Mutual Information (NMI):

- Information entropy (Shannon, 1948) corresponding to a discrete random variable X defined as,

$$H(X) = -\sum_{i=1}^{n} P(X_i) \log P(X_i)$$

- Joint entropy for two variables X and Y,

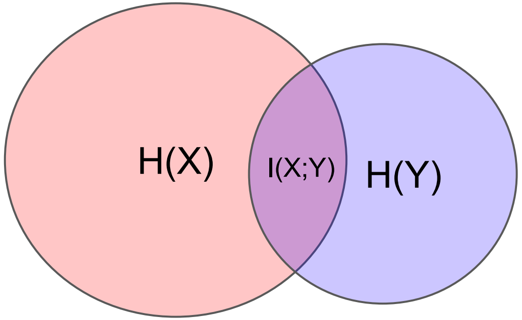
$$H(X,Y) = -\sum_{i=1}^{n_1}\sum_{j=1}^{n_2} P(X_i, Y_j) \log P(X_i, Y_j)$$

- The mutual information (MI) between X and Y,

$$I(X;Y) = H(X) + H(Y) - H(X,Y)$$

- Normalized mutual information

$$NMI(X;Y) = \frac{I(X;Y)}{\sqrt{H(X)H(Y)}}$$



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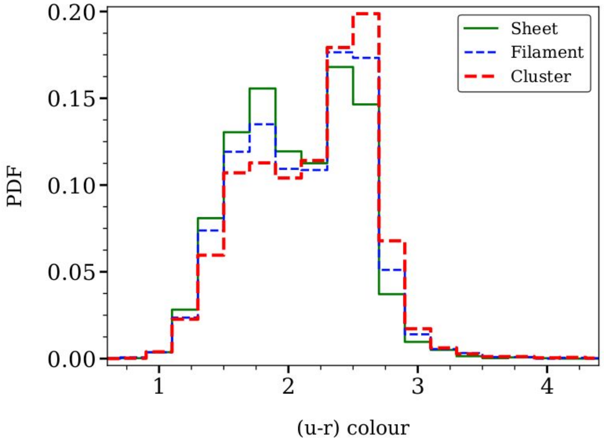

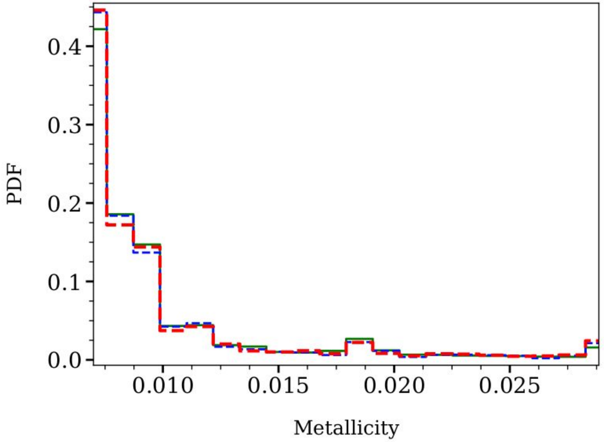

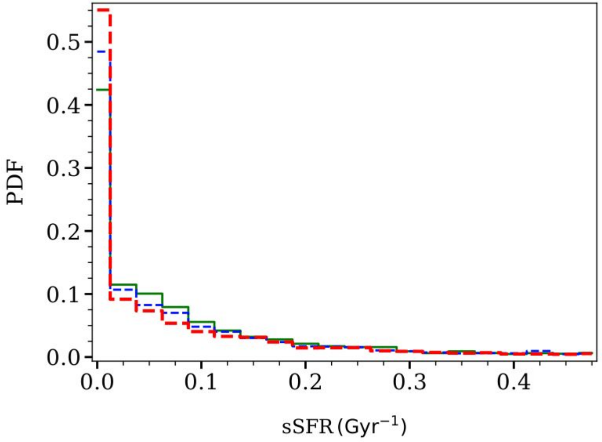

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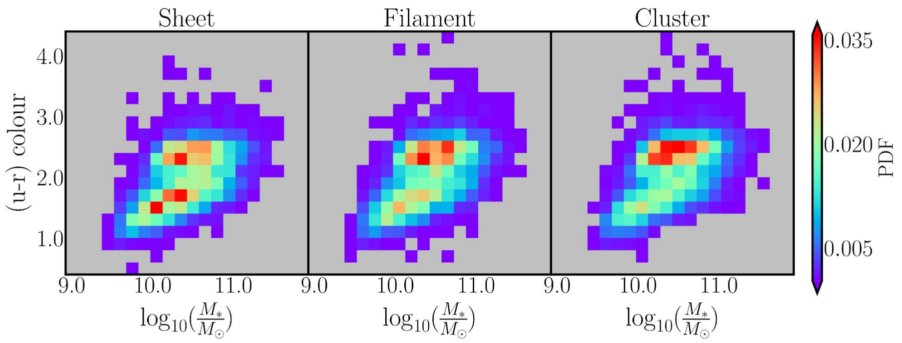

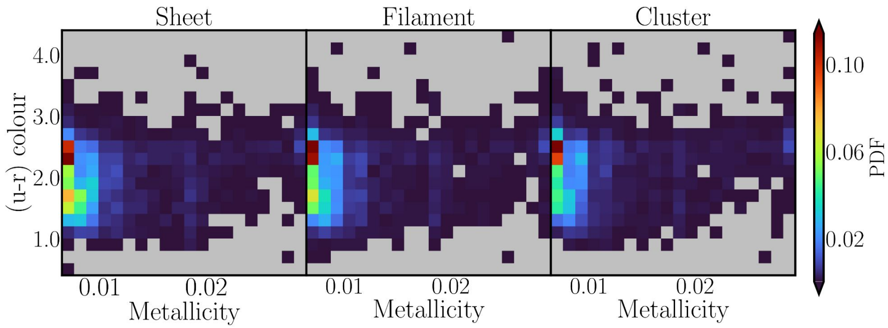

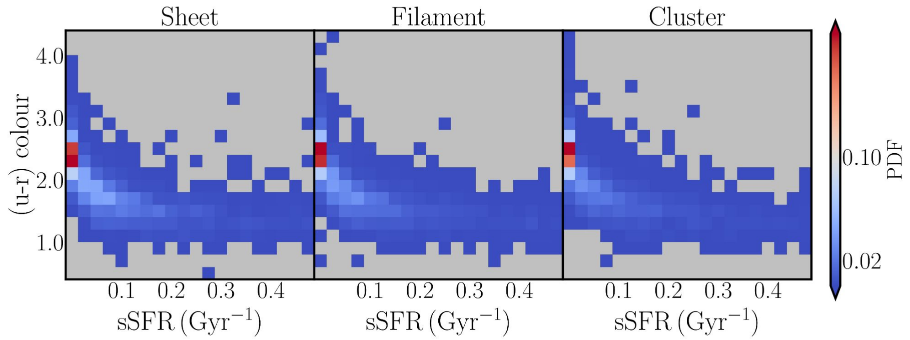

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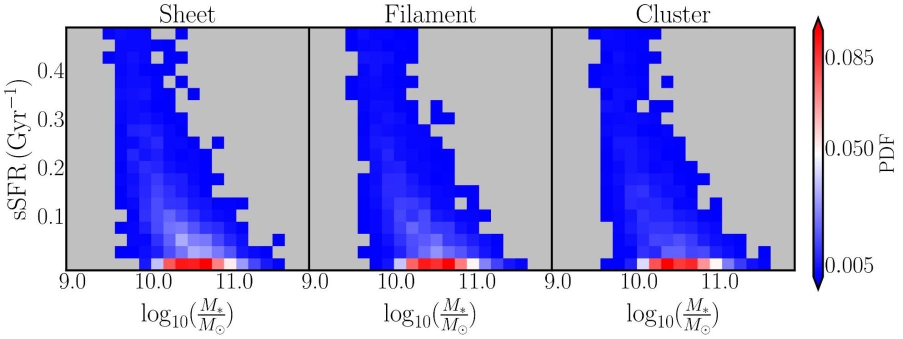

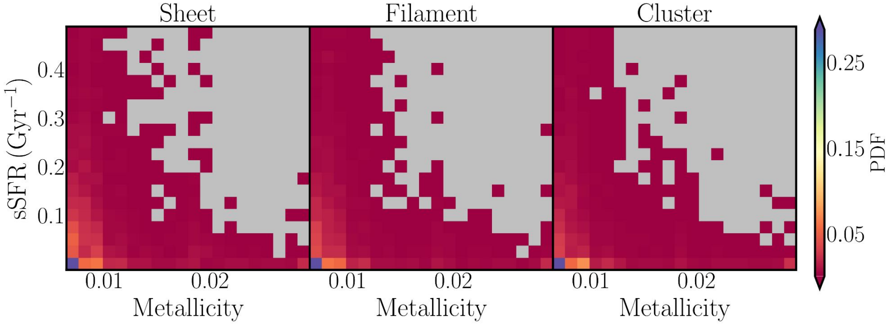

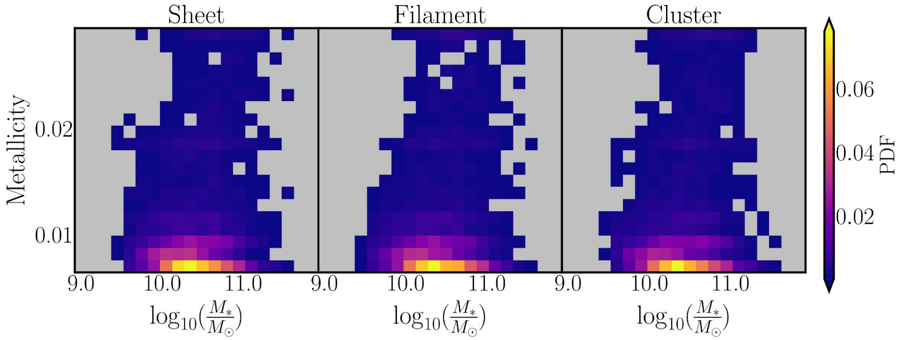

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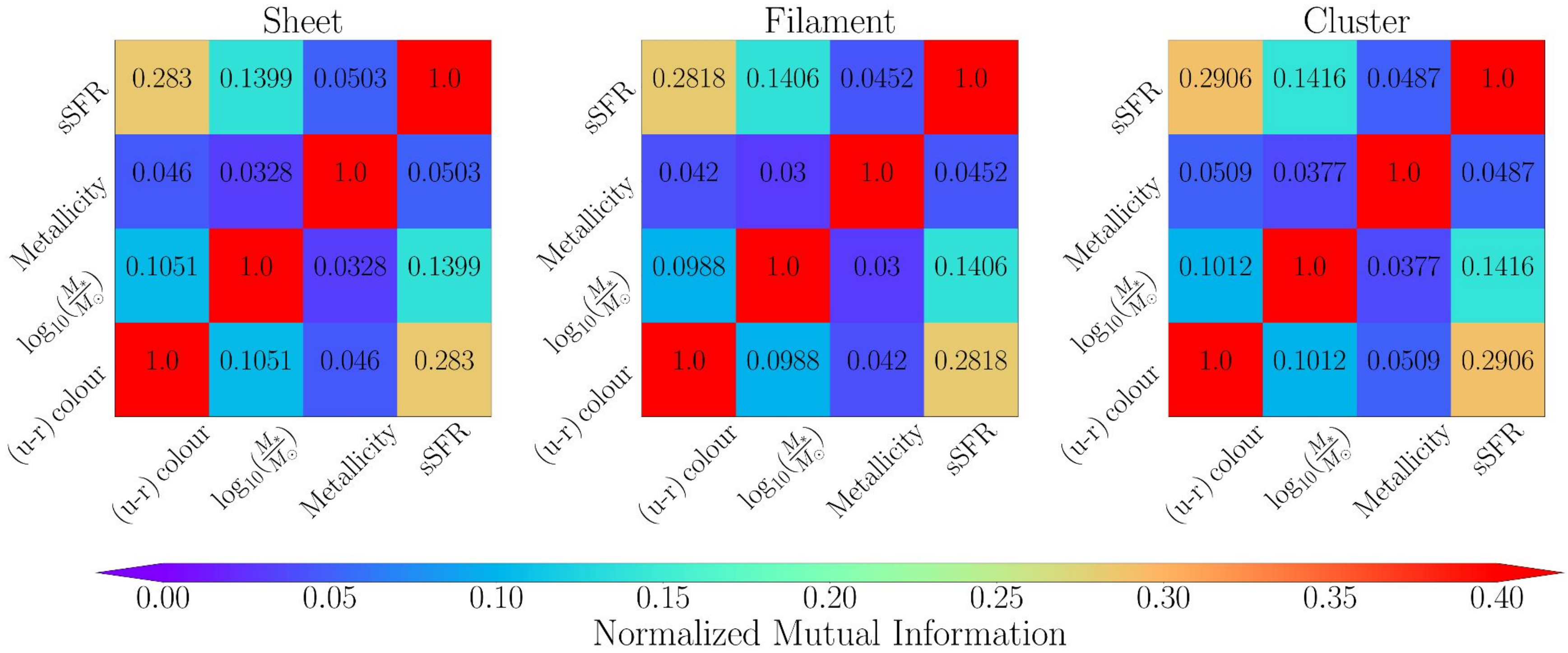

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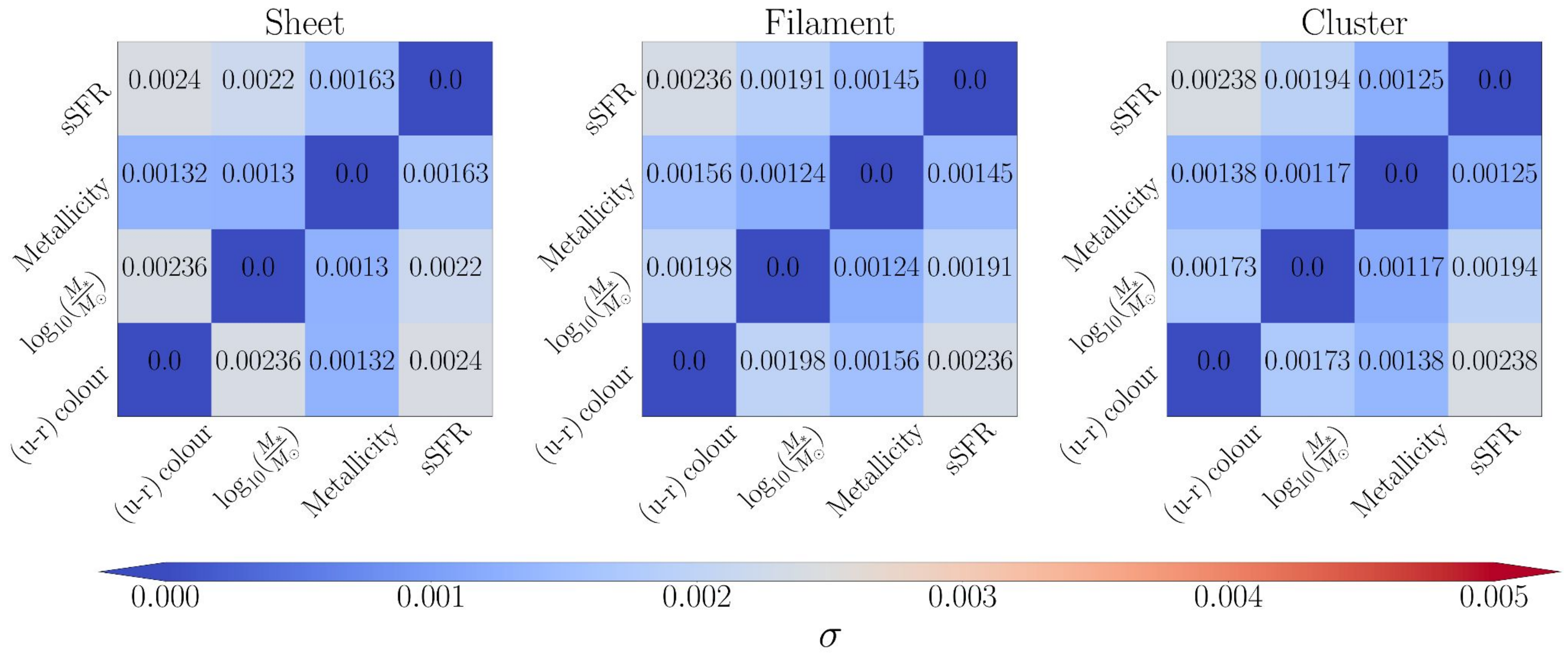

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Results

Measuring correlations using Normalized Mutual Information (NMI):

Relations	Sheet - Filament	Filament - Cluster	Sheet-Cluster
	p value	p value	p value
colour-stellar mass	9.26×10^{-25}	4.79×10^{-9}	5.09×10^{-14}
colour-metallicity	5.16×10^{-24}	4.13×10^{-51}	2.90×10^{-33}
colour-sSFR	7.68×10^{-2}	7.67×10^{-36}	2.55×10^{-32}
stellar mass-metallicity	2.29×10^{-19}	3.48×10^{-52}	1.45×10^{-33}
stellar mass-sSFR	6.54×10^{-3}	5.66×10^{-2}	1.53×10^{-5}
sSFR-metallicity	3.82×10^{-31}	2.90×10^{-24}	3.08×10^{-7}

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Conclusion

Correlations between different galaxy properties in most of the cases are strongly sensitive to the geometric environments of the cosmic web.

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Thank you

Estimation of galaxy properties :

- In this work galaxy stellar mass, specific star formation rate and metallicity are obtained from the table *StellarMassFSPSGranWideDust*, where these quantities are estimated by fitting the spectral energy distributions (SED) of galaxies using the Flexible Stellar Population Synthesis (FSPS) code (Conroy & Gunn, 2010).
- **FSPS** - a software package for stellar population synthesis (**SPS**) analysis
- **SPS** involves modelling the evolution of a group of stars and comparing the simulated spectra with observed spectra.

Metallicity

➢ Metallicity (Z) is defined as fraction of mass of the elements heavier than Helium,

$$Z = \frac{m_z}{M}$$

Petrosian magnitude

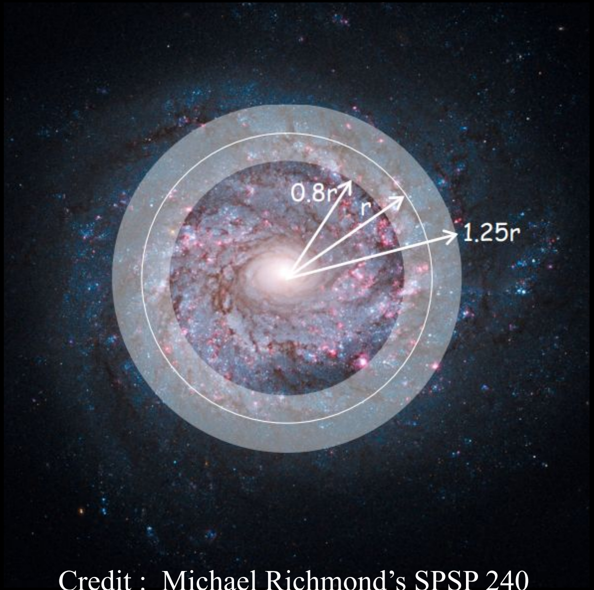
- Petrosian magnitude (V. Petrosian , 1976) estimated from Petrosian flux, measuring within $2r_P$, where r_P is Petrosian radius

- *Petrosian ratio* R_P

Ratio of the surface brightness in an annulus at r (0.8r - 1.25r),

to the mean surface brightness within r

- Petrosian radius $r_P \rightarrow R_P = 0.2$



Credit : Michael Richmond's SPSP 240 course

Student's t-test :

Statistical test to determine significance of the difference in the means of two datasets

Two-tailed t-test:

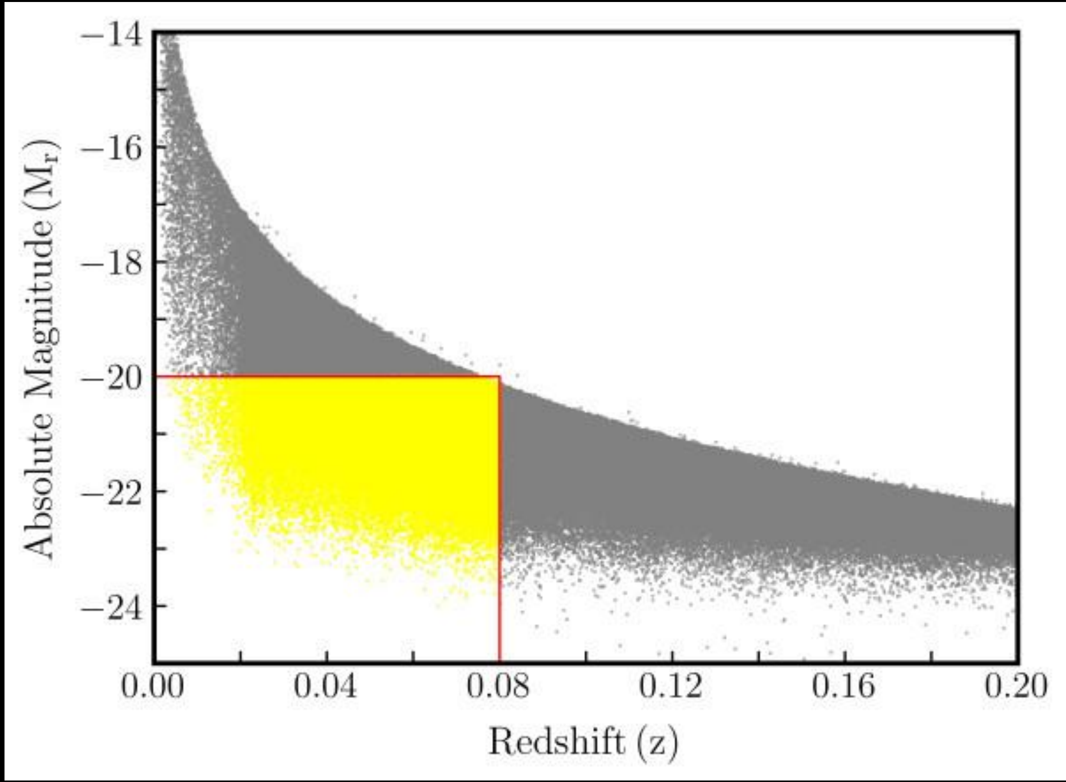
Tests for the possibility of the relationship in both directions (i.e., whether the mean of one dataset is either significantly greater than or significantly less than the mean of the other dataset)

Null hypothesis:

Means of the datasets are equal

p value:

Probability of acceptance of the null hypothesis



Definition of the volume-limited sample in redshift-absolute magnitude plane

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