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## ABSTRACT

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**Key words:** keyword1 – keyword2 – keyword3

## 1 INTRODUCTION

This is a simple template for authors to write new MNRAS papers. See `mnras_sample.tex` for a more complex example, and `mnras_guide.tex` for a full user guide.

Forero-Romero et al. (2009).

## 2 ILLUSTRIS SIMULATION

Illustris-1, also known as Illustris, is a highly resolved cosmological simulation. It reproduces large-scale statistical features of the Universe, such as the galaxy population of massive clusters, as well as small-scale properties such as the morphology of galaxies and detailed values for their stellar and gas content.

This was achieved by following the evolution of  $2 \times 1820^3$  elements with dark mass resolution of  $m_{\text{DM}} = 6.26 \cdot 10^6 M_{\odot}$  and initial baryonic mass resolution of  $\overline{m}_{\text{b}} = 1.26 \cdot 10^6 M_{\odot}$  from a glass-like configuration in a periodic box of 106.5 Mpc. The  $\Lambda$ CDM cosmology of this run follows:  $\Omega_{\Lambda} = 0.7274$ ,  $\Omega_{\text{m}} = 0.2726$ ,  $\Omega_{\text{b}} = 0.0456$ ,  $\sigma_8 = 0.0809$ ,  $n_{\text{s}} = 0.963$  &  $H_0 = 70.4 \text{ km s}^{-1} \text{ Mpc}^{-1}$  which is consistent with the (last) Anisotropy Probe (WMAP)-9 ?. Illustris has a constant spatial resolution of 1.4 kpc for DM particles in comoving units, and for baryonic particles it has the same spatial resolution of DM for  $z \geq 1$ , which is later modified to 0.7 kpc in physical units for the rest of the simulation.

The evolution in time was performed with the hydrodynamic code AREPO Springel (2010), which combines a moving Voronoi tessellation with the finite volume approach. Included in the evolution algorithm, there are galaxy formation models which account for the evolution

of stars and SMBHs. Specifically, the physics followed by this model includes energetic feedback from supermassive black holes and supernovae, as well as stellar evolution and chemical enrichment. This level of detail in Illustris is advantageous for the analysis of the effect of the environment in barionic properties of galaxies. This level of resolution is hard to find among other simulations, i.e. post-processed runs with semi-analytical models which do not directly simulate baryons. (Expand) Describe Arepo more

The output of this simultaion consists of 136 snapshots. 61 of them were taken at  $z < 3$  spaced with a cosmological scale factor  $\Delta a \approx 0.02$ . The remaining 75 were taken at  $z > 3$  with spacing  $\Delta a \approx 0.01$ . Each snapshot was post-processed with a modified version of FOF Davis et al. (1985) to identify DM haloes with more than 32 particles using a linking length of 0.2 times the mean particle separation. Each output group from the 7,713,601 post-processed halos (FOF) is analyzed with the SUBFIND algorithm Springel et al. (2001) to generate, at  $z=0$ , and 4,366,546 (sub)halo catalogues with their respective characterization properties.

(HERE TALK ABOUT ILLUSTRIS-2,3 FOR RESOLUTION PURPOSES)

## 3 THE METHODOLOGY

### 3.1 Characterizing Mass Functions

A mass function is the number density  $n(M)$  of objects of determined mass  $M$ . Due to the large range of orders of magnitud in which these quantities span, the mass function is often represented in logarithmic scales on both sides. The discretization of these mass functions is simply the histogram of the logarithmic masses of the studied group of objects. In Illustris, as in all simulations, we have clear determination of volumes. This volume is constant over all the

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sample of galaxies studied and is to be taken the constant volume of the simulation  $V = (106.5\text{Mpc})^3$ . In this sense, the relation expressed by a mass function is

$$n(M)Vd\log(M) = dN \quad (1)$$

To characterize specific properties of these mass functions, we use the Press-Schechter function 2. It comes from an elaborated formalism of hierarchical formation of DM structures in an expanding Friedmann universe arriving to a self-similar state of "equilibrium" for its mass function Schechter (1976). Although its ansatz has been demonstrated to be inaccurate for our observable universe ?, the final expression is very well fitted to the mass functions of the local universe ?.

$$n(M) = n_* \left( \frac{M}{M_*} \right)^{-\alpha+1} \exp\left(-\frac{M}{M_*}\right) \quad (2)$$

The Schechter function 2 is fully defined by the three parameters  $(n_*, M_*, \alpha)$ . The number density factor  $n_*$  is just a normalization factor which varies depending on the studied system. The mass scale factor  $M_*$  may be interpreted as the mass that separates the power-law regimen  $M \ll M_*$  and the exponential regimen  $M \gg M_*$ . This transition graphically resembles a knee, which is the reason why  $M_*$  is referred as the knee-mass. The faint-end slope  $\alpha$  is directly related to the exponent of the power-law at the low-mass regime. In logarithmic scales, it is clearly interpreted as the slope of the low-mass regime.

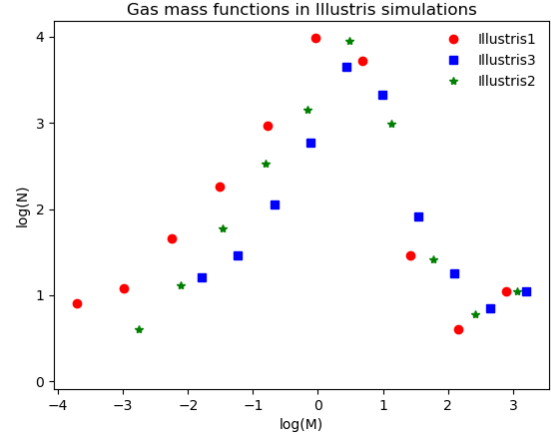
To obtain the Schechter parameters that characterize each numerical mass function, we used MCMC to obtain the fit with best likelihood. With this, we could also ...

As Illustris is a cosmological simulation, it is subject to resolution and numerical biases. The most important bias in this study is related to the minimum mass of discrete elements in the simulation. Each mass considered here is subject directly or indirectly this resolution restriction, and the effect it causes is specially evident in the produced mass functions. We used Illustris-2,3, which are less resolved copies of Illustris-1, to show this effect on the mass functions 1. Taking this into account, mass functions are heavily affected for masses below a certain cut and for this reason, only galaxies above said cut are considered in this study. This mass cut has no apparent systematical way to be calculated and therefore, we choose it having into account the performance of the respective Schechter fit.

### 3.2 Defining the environment

Given the current interest in the study of the dependence of observational HIMFs on the environment and the wide difference of the conclusions of these studies, the main scope of this work is to verify if the any results obtained observationally are supported by a similar analysis in the cosmological simulation Illustris.

For this purpose, we take two approaches to analyze the



**Figure 1.** The effect on mass resolution on mass functions of Illustris-1,2,3. (Masses have units  $10^{10}M_{\odot}$ )

dependence of mass functions on environment. On one hand, to make our study observationally-comparable, we follow the 3rd nearest neighbor (3NN) definition of environment proposed by Jones et al. Jones et al. (2016). On the other hand, to confirm our results, we use a computational and theoretical definition of environment (T-Web) of completely different nature proposed by Forero et al. Forero-Romero et al. (2009).

#### 3.2.1 The 3<sup>rd</sup> nearest neighbor definition of environment

Jones et al. Jones et al. (2016) the SDSS Aihara et al. (2011) catalogue to define the environment of galaxies in the ALFALFA Giovanelli et al. (2005) survey. This SDSS catalogue was chosen to be optically-selected and volume-limited to account for apparent lonely galaxies in ALFALFA with increasing distance. For this reason, they pre-selected galaxies brighter than  $M_r = -18.9$  in this survey.

To quantify the environment, for each reference galaxy in ALFALFA, they calculated the projected distance in the sky to the third nearest neighbor belonging to the pre-selected SDSS catalogue. This projected distance in the sky defines a numeric-surface density for each reference galaxy. To do so, first, they filtered candidate neighbors by their radial velocity relative to the reference galaxy which had to be within  $450\text{km/s}$ . According to Hubble's law, this effectively restricts the candidate galaxies to a smaller radial range, reducing apparent closer galaxies arising from the use of projected distances.

Once quantified the environment for each ALFALFA galaxy with the distance to the 3rd NN definition, they divided the group in four quartiles according this quantity. For each quartile, the respective HIMF was calculated, and with this, a Schechter fit was obtained.

As we want to replicate as closely as possible the method effectuated by Jones et. al Jones et al. (2016), we use the same specifications to calculate the environment.

We perform the analysis of the Schechter functions to gas, DM, stellar and BH mass functions. We do not perform the study directly on HIMFs because this would require some extensive calculations. We take the gas mass function as a first approximation.

### 3.2.2 The cosmic web method

To complement and verify the analysis performed with the third nearest neighbor method, we chose a complementary method of completely different nature. The chosen method was developed by Forero et al. [Forero-Romero et al. \(2009\)](#). It uses the Hessian [3](#) of the gravitational potential obtained from the smoothened DM density field to classify galaxies into four morphological environments.

$$E = mc^2 \quad (3)$$

Specifically, we diagonalize the Hessian matrix of the gravitational potential  $\phi$  obtaining three eigenvalues. This matrix encodes the local curvature of the gravitational potential. Specifically, these eigenvalues determine the concavity of  $\phi$  on the principal axes, at each point. We use these eigenvalues to interpret the tendency of mass to cluster with reference with some given threshold  $\lambda$ . Eigenvalues bigger than  $\lambda$  are interpreted as a local tendency of mass to cluster in the respective eigenaxes, and viceversa. With this characterization, clusters, sheets, filaments and voids can be defined with the number of eigenvalues above  $\lambda$ . Forero et. al. found in [?](#) that the critical value that better reproduces the correct morphological populations was  $\lambda = 0.2$ .

With these specifications, we could obtain mass functions for galaxies belonging to clusters, filaments and sheets. The amount of galaxies belonging to voids was strongly affected by the mentioned mass cuts and could not produce reasonable mass functions to analyze.

## 4 RESULTS

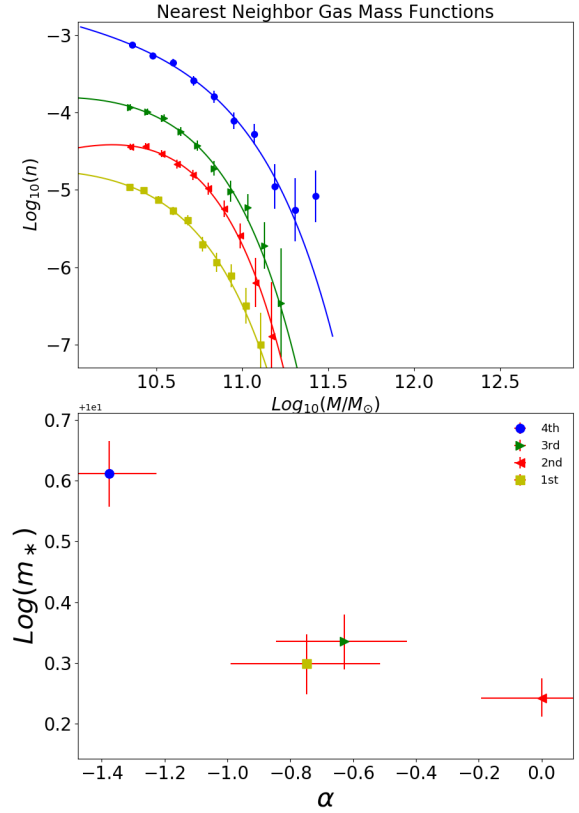
### 4.1 Preliminaries

### 4.2 Mass functions comparison

Figures and tables should be placed at logical positions in the text. Don't worry about the exact layout, which will be handled by the publishers. Figures are referred to as e.g. Fig. ??, and tables as e.g. Table ??.

## 5 CONCLUSIONS

The last numbered section should briefly summarise what has been done, and describe the final conclusions which the authors draw from their work.



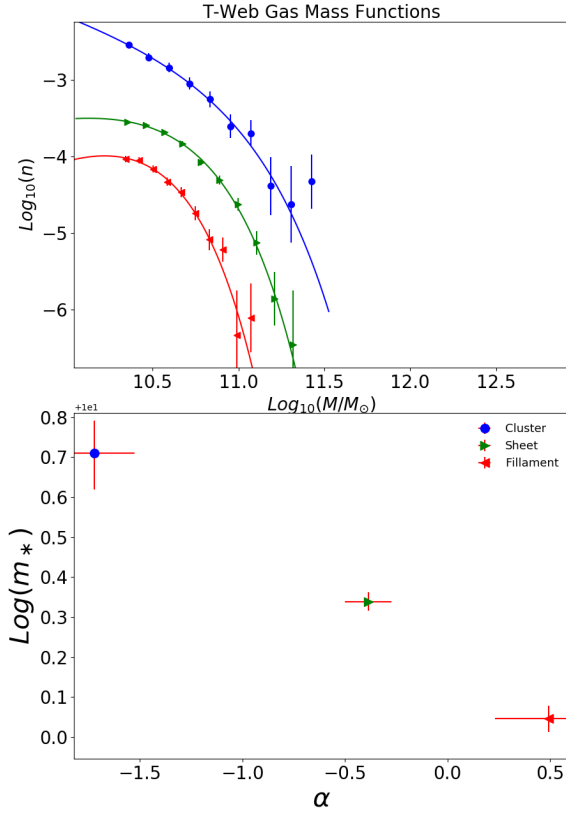
**Figure 2.** Upper side: Schechter fits of each gas mass function for each environmental quartile (tendency) using the 3rd nearest neighbor definition. Down side: Knee-mass  $m_*$  and the faint end slope  $\alpha$  values obtained from the Schechter fits for each curve shown above.

## ACKNOWLEDGEMENTS

The Acknowledgements section is not numbered. Here you can thank helpful colleagues, acknowledge funding agencies, telescopes and facilities used etc. Try to keep it short.

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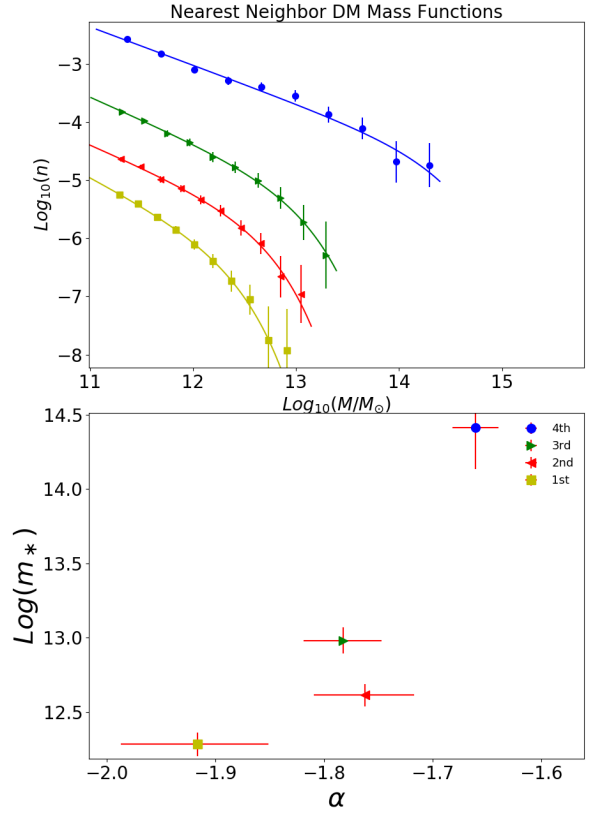


**Figure 3.** **Upper side:** Schechter fits of each gas mass function for each morphological environment characterized by the T-Web algorithm proposed by Forero et al. **Down side:** Knee-mass  $m_*$  and the faint end slope  $\alpha$  values obtained from the Schechter fits for each curve shown above.

#### APPENDIX A: SOME EXTRA MATERIAL

If you want to present additional material which would interrupt the flow of the main paper, it can be placed in an Appendix which appears after the list of references.

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**Figure 4.** Similar to figure 2 using DM.

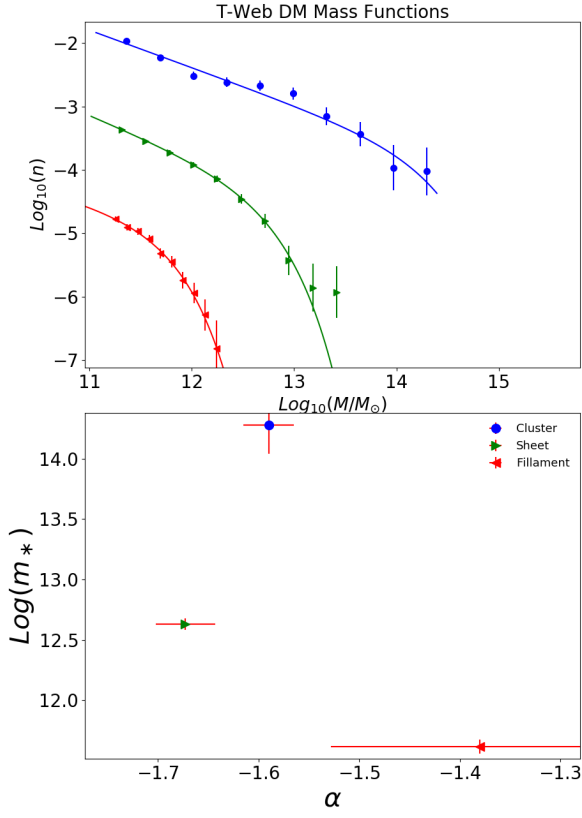


Figure 5. Similar to figure 3 using DM.

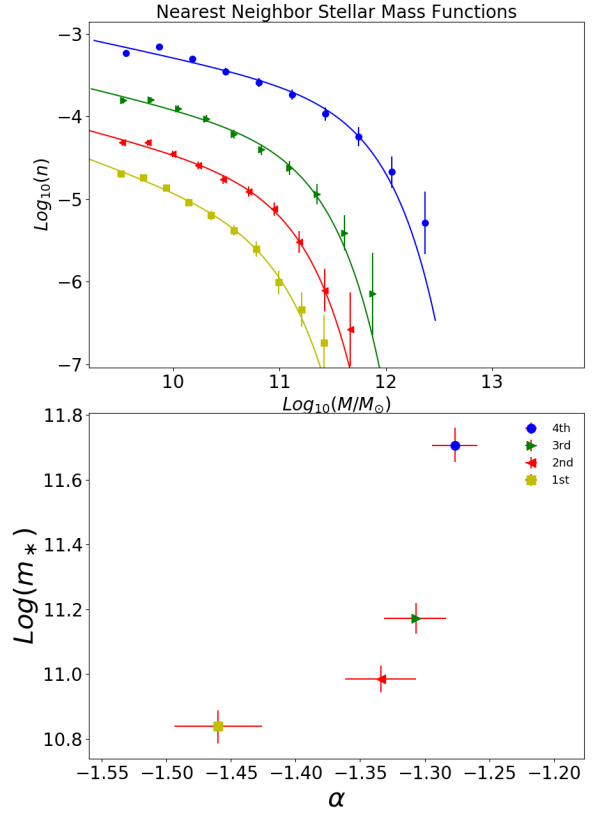
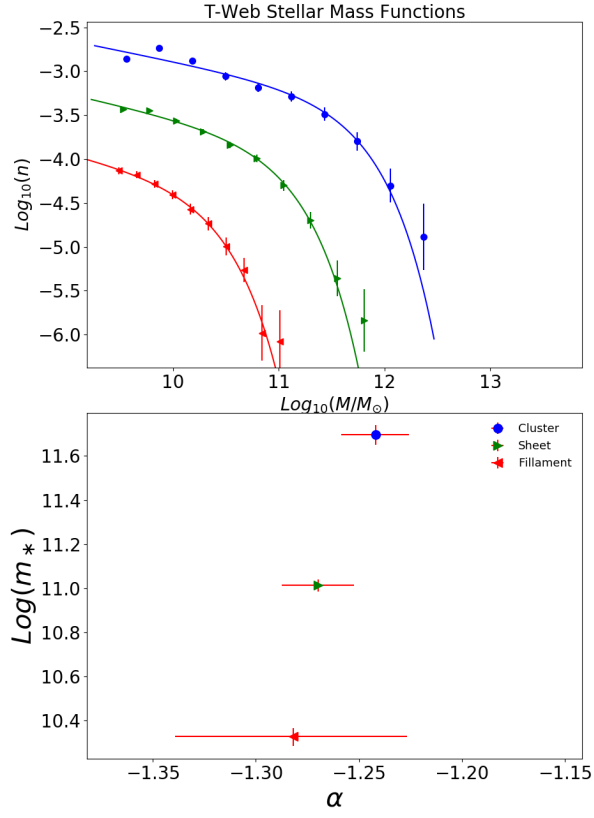
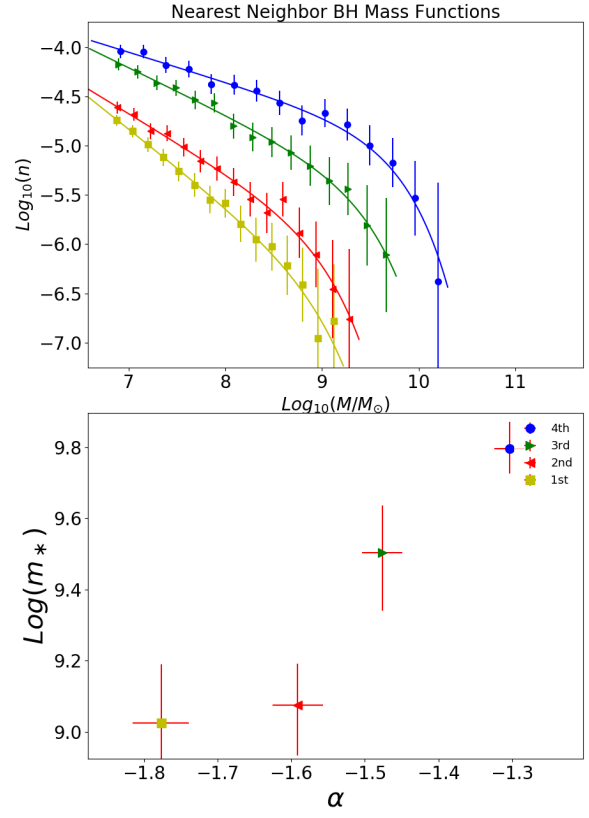


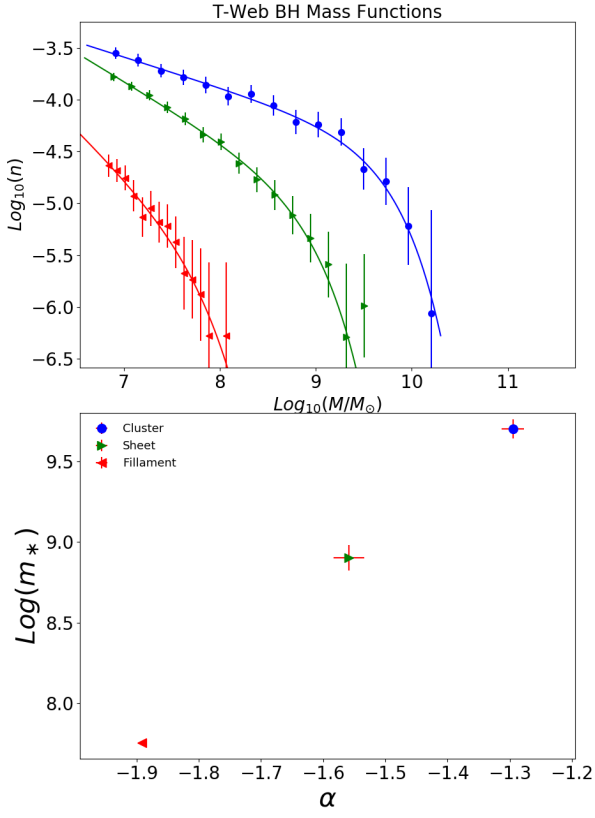
Figure 6. Similar to figure 2 using stellar mass



**Figure 7.** Similar to figure 3 using stellar mass



**Figure 8.** Similar to figure 2 using BHs mass.



**Figure 9.** Similar to figure 3 using BHs mass.