Galaxies and Clusters of Galaxies as Peak Patches of the Density Field

Masataka Fukugita,1,2* Hans Böhringer3,4

1 Kavli Institute for the Physics and Mathematics of the Universe, University of Tokyo, Kashiwa 2778583, Japan
2 Institute for Advanced Study, Princeton, NJ08540, USA
3 Universitätssternwarte München, Ludwig-Maximilians-Universität, Scheinerstr. 1, D-81679, München, Germany
4 Max-Planck-Institut für extraterrestrische Physik, D-85748 Garching, Germany.

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

The mass function of galaxies and clusters of galaxies can be derived observationally based on different types of observations. In this study we test if these observations can be combined to a consistent picture which is also in accord with structure formation theory. The galaxy data comprise the optical galaxy luminosity function and the gravitational lensing signature of the galaxies, while the galaxy cluster mass function is derived from the X-ray luminosity distribution of the clusters. We show the results of the comparison in the form of the mass density fraction that is contained in collapsed objects relative to the mean matter density in the Universe. The mass density fraction in groups and clusters of galaxies extrapolated to low masses agrees very well with that of the galaxies: both converge at the low mass limit to a mass fraction of about 28% if the outer radii of the objects are taken to be \( r_{200} \). Most of the matter contained in collapsed objects is found in the mass range \( M_{200} \sim 10^{12} - 10^{14} h^{-1} M_\odot \), while a larger amount of the cosmic matter resides outside of \( r_{200} \) of collapsed objects.

Key words: galaxies: general, galaxies: clusters, cosmology: observations, cosmology: large-scale structure of the Universe

1 INTRODUCTION

In modern theory of cosmological structure formation, it is supposed that galaxies and clusters of galaxies formed from peak patches of the density field of matter in the Universe (Bardeen et al. 1986). In cosmological simulations the primary reference objects which are populated by galaxies and galaxy clusters are dark matter halos and their abundance is described by the dark matter halo mass function (e.g. Jenkins et al. 2001, Tinker et al. 2008). Observationally galaxies and galaxy clusters have very different appearances. Galaxies just mark the central region of the dark matter halo and the extent of their embedding dark matter halo can only be traced by weak gravitational lensing. On the contrary the dark matter halos of clusters of galaxies are filled by a hot, X-ray luminous intrachuster plasma, which can easily be observed with X-ray telescopes (e.g. Sarazin, 1986) and through the Sunyaev-Zeldovich effect in the cosmic microwave background (Sunyaev & Zeldovich, 1972). In this way the gravitational potential of the dark and baryonic matter halo can be visualised more directly.

In this note we explore if the observational data on galaxies and groups and clusters of galaxies can be described consistently in the from of a continuous halo mass function, even though the observational signatures of these objects are very different. We test in this way the validity of structure formation theory and the correctness of the interpretation of the observational data. In the present study we show as representation of the object mass distribution mostly the fraction of the cosmic matter density made up by galaxies and clusters, which is a direct reflection of the cumulative mass function. This provides us in addition with the interesting information where the major parts of matter are located in our Universe.

For all calculations depending on the cosmological model, we use a flat cosmic geometry and the parameters, \( \Omega_m = 0.282 \) (Böhringer et al. 2017) and \( H_0 = 70 \) km s\(^{-1}\) Mpc\(^{-1}\). We retain \( h = h_{100} \) for some values quoted from the literature. This mass density is compared to the density of the 2015 result of Planck (Planck Collaboration 2016) and to the WMAP 9 year result (Bennett et al. 2013). The specific value for \( \Omega_m \) is chosen because

\[ \Omega_m = \frac{c_s^2}{c_s^2 + \Omega_{\text{cdm}}} \]

The uncertainty of \( \Omega_m \) is degenerate with that of \( c_s^2 \) and can be represented as \( c_s^2(\Omega_m/0.3)^{0.57} = 0.75 \pm 0.03 \) (Böhringer et al. 2014).
2 Galaxy and Cluster Data

To assign a definite mass to galaxies and their dark matter halos and to galaxy clusters, we need to define an outer radius up to which the mass distribution in the systems is integrated. In an analysis of gravitational lensing around galaxy halos it is indicated that the mass of galaxies is distributed beyond the pseudovirial radius of galaxies, which was operationally defined as the radius, $r_{200}$, which encircles a mass corresponding to 200 times the critical density (Masaki et al. 2012; hereafter MFY). The analysis indicates that the distribution of mass around galaxies is extended to a few Mpc, to the middle to neighbouring galaxies: there seems no boundary in the mass distribution. Also for galaxy clusters the mass profile continues to increase well beyond a radius of $r_{200}$; see e.g. Ettori et al. (2019). Since there is no clear, natural outer edge to these collapsed objects, a common fiducial outer radius has to be adopted for the comparison of the galaxy and cluster matter density content. Here we use $r_{200}$ in our further analysis, which approximately describes the boundary between the partly virialised material inside and the mostly infalling matter outside.

The mass function of galaxy halos for our study was obtained in the following way. The luminosity function of galaxies is now accurately known (Blanton et al. 2001; 2003; Folkes 1999) to $L > 10^{5.5} L_\odot$. Here we use the Blanton et al. 2001 luminosity function, which refers to the standard $ugriz$ photometric system. McKay et al. (2001; 2002) measured the mass of galaxies encircled by haloes to $260 h^{-1}kpc$ by measuring weak lensing shear around galaxies for the Sloan Digital Sky Survey (SDSS) spectroscopic sample. Their measurement gives $(M/L_r) \approx 170 \pm 21 h^{-1}$ for the $r$-band for the mass of galaxies encircled by haloes to $260 h^{-1}kpc$, which is thought to be well beyond the virial radius of galaxies and thus to stand for the mass associated with galaxies. Their data show that the mass-to-light ratio does not depend on galaxy luminosity for an interval of a decade, $5 \times 10^9 - 8 \times 10^{10} L_\odot$. They also find the dynamical mass from the virial velocity for the same sample to be $(M/L_r) \approx 145 \pm 34 h^{-1}$, with a reasonable agreement with their lensing estimate. For our analysis we adopted $160 \pm 30 h^{-1}$ at the radius of $260 h^{-1}kpc$, but scaled to the pseudovirial radius.

With the aid of the N-body simulation result for haloes of galaxies, the average pseudovirial radius ($r_{200}$) of galaxies that match the SDSS sample, which is estimated to have a lower mass cutoff $M_{low} \approx 2 \times 10^{11} h^{-1} M_\odot$, is approximately $120 h^{-1}kpc$, and so the radius McKay et al. measured corresponds to $\approx 2.2 r_{200}$ (MFY). As $260 h^{-1}kpc$ is significantly larger than $r_{200}$, this is taken as evidence that the mass distribution extends much beyond $r_{200}$; $r_{200}$ comprise only a fraction of mass associated with galaxies. For the comparison with clusters, we scale the average mass measured at $260 h^{-1}kpc$ to that at $r_{200}$, using the weak lensing scaling result, which approximately reads $M \propto r^{3.6}$ beyond the pseudovirial radius (MFY). This yields $(M/L_r)_{r_{200}} \approx 90 \pm 20 h^{-1}$. This is the value we have adopted to estimate the mass of galaxies.

We remark that this radius dependence of the mass profile is consistent with that expected for the Navarro-Frenk-White (NFW, Navarro et al. 1995, 1997) profile with the core radius $r_c$ in units of $r_{200}$ to be $c = r_{200}/r_c = 5 - 10$, which is the value compatible to that derived for clusters $c \approx 5$ and for haloes of galaxies $c \approx 10 - 15$ from inner profiles, typically, for $r \leq r_{200}$. This means that the NFW profile stands also for a good description of galaxy haloes extended beyond the virial radius. Combining the galaxy luminosity function with the mass-to-light ratio from weak lensing we construct the galaxy halo mass function.

In our preceding work (Böhringer et al. 2017) we have computed the mass function of clusters and groups of galaxies down to $3 \times 10^{12} h^{-1} M_\odot$, using an X-ray selected cluster-group sample. We find that this mass function agrees well with that obtained from optical cluster samples (Bahcall & Cen 1993), when the cluster mass is standardised to a universal definition, say by adopting $r_{200}$. The mass function of groups and clusters in (Böhringer et al. 2017) was derived from the cluster catalogue compiled in the REFLEX II survey which was based on X-ray detections of clusters in the ROSAT All Sky Survey in the south-
ern sky (Böhringer et al. 2013). Since X-ray luminosity is tightly correlated with the cluster mass, the X-ray selection of the galaxy clusters is a good basis for the construction of the cluster mass function. The cluster sample fulfills another important requirement being statistically highly complete (95%) and described by a well understood selection function. The cluster catalog is flux-limited with a minimum unabsorbed X-ray flux of function. The cluster catalog is flux-limited with a minimum unabsorbed X-ray flux of $(2015)$.

The cluster sample covers the redshift range $z = 0 - 0.4$ and has a median redshift of $z = 0.1$, very similar to the SDSS galaxy sample. The important observational census on which the further work is based is the X-ray luminosity function (Böhringer et al. 2014).

The mass function was determined from the luminosity function in two different ways. Cluster masses were estimated by means of the X-ray luminosity – mass relation determined for smaller subsamples (Vikhlinin et al. 2009, Pratt et al. 2009). By this means the X-ray luminosity function was converted into the cluster mass function. In the second approach to constrain the cluster mass function we use our observational data to fit them to cosmological model predictions for the X-ray luminosity function of clusters. This fit was used in Böhringer et al. (2014) to constrain cosmological model parameters. The predictive theory of the cluster X-ray luminosity function for a given set of cosmological parameters involved the following steps: we adopt a $\Lambda$CDM cosmological model with flat geometry, the matter density distribution power spectrum was determined with CAMB (Lewis et al. 2000)$^3$. We take a parametrized form of the halo mass function derived from N-body simulations by Tinker et al. (2008) to construct the prediction for the cluster mass function. The empirical cluster mass - X-ray luminosity relation with its scatter and uncertainties is used to finally compare to the observed X-ray luminosity function.

The statistical uncertainty of the most critical cosmological parameters, $\Omega_m$ and $\sigma_8$ (Böhringer et al. 2017, Fig. 1), and the errors on the $L_X - M$ scaling relation in the fit determines the uncertainty range of the mass function. The two ways to obtain the mass function are in good agreement, as shown in Böhringer et al. (2017, Fig. 2).

For the present work we use the constraints on the cluster mass function from the method that involves the fit to the cosmological model predictions for two reasons: this method provides tighter constraints since it includes our knowledge about cosmic structure formation, and second the theoretical framework allows us to extrapolate the mass function beyond the observational limits. The observational data of the cluster sample cover the mass range $M_{200} = 7 \times 10^{12}$ to $3 \times 10^{15} h^{-1} M_\odot$. In the present work we add the uncertainty of the numerically derived mass function, which is in the range of 5 - 10%, (Tinker et al. 2008) as an additional uncertainty of conservatively 10% to the resulting mass function. For the comparison with the galaxy data we use the mass function derived for a redshift of $z = 0.1$, which is also the fiducial redshift for the galaxy sample. We compare these results to the mass function obtained using other parametrisations for the halo mass function from the literature (e.g. Watson et a. 2013, Despali et al. 2016), finding that differences lie well within our uncertainty.

### 3 THE COMBINED MATTER DENSITY FRACTION

From the galaxy and cluster mass function determined as described above, we derive the matter fraction contained in all collapsed objects inside $M_{200}$ above a certain limiting mass. For these calculations we have taken $\Omega_m = 0.282$ consistent with the best fit to the cluster abundance (Böhringer et al. 2017). The matter fraction was calculated from $\rho_m = \int \frac{dn}{dm} dm$, where $dn/dm$ is the differential cluster mass function. Fig. 1 shows the mass fraction in collapsed objects from galaxies to groups and clusters of galaxies. The dashed part of the cluster mass function shows the regime where the mass function is extrapolated to masses lower than covered by the observational data. The galaxy halo mass fraction was estimated from the luminosity function of galaxies (Blanton et al. 2001) multiplied with the mass-to-light ratio, $\rho_m = \bar{\rho}_m \times \langle M/L \rangle$, where $\langle M/L \rangle \simeq 90 \pm 20 h^{-1}$ and $\bar{\rho}_m$ is the galaxy luminosity density in the $r$ band. The galaxy halo mass function is observationally constraint to $M > 10^{11.2} M_\odot$. We note that at the low masses the two functions match perfectly, even though they have been derived from very different observational data sets$^4$.

In Fig. 2 we show the differential form of the matter function derived from galaxy group and cluster observations. It is derived from the mass function through $\frac{dn}{dm}$, giving the mass fraction in $m$ interval. This curve illustrates, which object population contributes most to the matter density. We see a broad maximum for the mass range $M_{200} \sim 10^{12} - 10^{14} h^{-1} M_\odot$.

Fig. 3 shows the local power law index (logarithmic slope) of the cumulative mass function and of the function

---

$^3$ CAMB is publicly available from http://www.camb.info/CAMBsubmit.html

$^4$ The luminosity function is still uncertain and this nearly perfect match would be disturbed up to 30% if we adopt Blanton et al 2003. The results, however, would still be consistent within the combined error limits.
of the matter fraction of groups and clusters of galaxies. We find that the matter fraction saturates at masses lower than about $10^{11} M_\odot$, with a further increase of not more than 1%. This originates from a flattening of the cumulative mass function. In our previous study we have fitted a Schechter function as an approximation to the observed cumulative function. In our previous study we have fitted a Schechter function. In our previous study we have fitted a Schechter function.

We find that the matter fraction saturates at masses lower than about $10^{11} M_\odot$, with a further increase of not more than 1%. This originates from a flattening of the cumulative mass function. In our previous study we have fitted a Schechter function as an approximation to the observed cumulative function. In our previous study we have fitted a Schechter function.

Figure 3. Logarithmic slope of the cumulative mass function (solid line) and the matter density fraction (dashed line) of groups of clusters.

4 DISCUSSION AND CONCLUSION

We see in Fig. 1 that the matter density fraction in galaxy halos and clusters match well at the low mass end, as well as the underlying cumulative mass functions. The mass fraction of the galaxy group and cluster fraction reaches a saturation value of $\Omega_{\text{cluster,virial}}/\Omega_m = 0.28(1 \pm 0.02)$ and the galaxy luminosity function leads to $\Omega_{\text{galaxy,virial}}/\Omega_m = 0.28(\pm0.08)$. This provides a convergent answer for the mass contribution of collapsed objects if the region considered is restricted to the pseudovirial radius. This means that the bulk of mass is in the intergalactic space. We note that the result for galaxy halos does not change when we use the values relevant to other colour bands. With other colour band results (Blanton et al. 2001; McKay et al. 2002), we obtain the mass density $u : t : v : z = 0.64 : 1.14 : 1 : 0.99 : 0.03$, where we have normalised the values to the $r$-band result. With the exception of the $u$-band, which is strongly affected by star formation, we have a convergent answer with variations well within the uncertainties, and we can take the value from the $r$-band as the representative mass of haloes within the pseudovirial radius of galaxies.

It is interesting to see that the cluster-group mass fraction function departs from the galaxy mass fraction for $M > 3 \times 10^{11} h_{70}^{-1} M_\odot$, indicating that cooling processes, which are essential for galaxy formation, become less effective for masses larger than this limit. This leads to the observed high-mass cutoff of the mass function from galaxies, while the high mass cutoff for clusters and groups is purely set by the initial condition and the gravitational physics.

We see in Fig. 2 that most of the mass is contained in objects in the mass range $M_{200} \sim 10^{12} - 10^{14} h_{70}^{-1} M_\odot$. It is worth noting, that this is the range of structures where the variance of the density fluctuations in the linearly extrapolated density fluctuation field, usually designated by $\sigma(M)$, is close to unity. For the quoted mass range we find $\sigma(M) = 0.8 - 1.9$. Since we determine the structure formation model that fits our observations best, we also derive the variance of density fluctuations as a function of filter radius, $\sigma(M(R_f))$. We find $\sigma(M) = 1$ at $M_{200} \sim 5 \times 10^{13} h_{70}^{-1} M_\odot$. This is the mass scale where most object formation takes place at the present epoch and it is thus not surprising to find most matter in collapsed objects in this mass range.

The observations imply that substantially more mass is distributed beyond the pseudovirial radius of $r_{200}$, for both galaxies and clusters while it is custom to adopt $r_{200}$ to define the cluster. The pseudovirial sphere contains only 28% of the matter density in the Universe. This is in good agreement with the N-body result, which gives 26% for the mass fraction contained within $r_{200}$ (MFY). This increases to 45% within $2.2 r_{200}$ and increase to 70% if the radius of sphere is taken to be 10 times $r_{200}$ (MFY). Our results exhibit that galaxies and clusters live at the peak patches of the density field, and most of the mass is present in intergalactic space. We stress that this differs from the distribution of the luminous component (stars), which should have an edge of the distribution, corresponding to the cooling radius of the baryons. We expect that the hot gas behaves similarly to dark matter at cosmological scales, where we see, at large radii, no reasons to segregate gas from dark matter. So the fractions we discussed here are likely to apply similarly to the distribution of baryons.

ACKNOWLEDGEMENTS

MF thanks late Yasuo Tanaka for the hospitality at the Max-Planck-Institut für Extraterrestrische Physik and also Eiichiro Komatsu at Max-Planck-Institut für Astrophysik in Garching, where the bulk of this work was done. He also wishes his thanks to Alexander von Humboldt Stiftung for the support during his stay in Garching. He received in Tokyo a Grant-in-Aid (No. 15430000110) from the Ministry of Education in Japan. H.B. likes to thank Gyoung Chon for her role in the compilation and construction of the REFLEX data and for discussions.

REFERENCES

Blanton, M. R., & Cen, R., 1993, ApJ, 407, L49
Bardeen, J. M., Bond, J. R., Kaiser, N., & Szalay, A. S. 1986, ApJ, 304, 15
Bennett, C. L., Larson, D., Weiland, J. L., et al. 2013, ApJS, 208, 20
Blanton, M. R., Dalcanton, J., Eisenstein, D., et al. 2001, AJ, 121, 2358
Blanton, M. R., Hogg, D. W., Bahcall, N. A., et al. 2003, ApJ, 592, 819
Böhringer, H., Schuecker, P., Guzzo, L., et al., 2004, A&A, 425, 367
Böhringer, H., Chon, G., Collins, C.A., et al., 2013, A&A, 555, A30
Böhringer, H., Chon, G., Collins, C.A., et al., 2014, A&A, 570, A31
Böhringer, H., Chon, G., & Fukugita, M. 2017, A&A, 608, A65
Despali, G., Giocoli, C., Angulo, R.E., et al., 2016, MNRAS, 456, 2486
Ettori, S., Ghirardi, V., Eckert, D., et al., 2019, arXiv1805.00035
Folkes, S., Ronen, S., Price, I., et al. 1999, MNRAS, 308, 459
Hildebrandt, H., Viola, M., Heymans, C., et al. 2017, MNRAS, 465, 1454
Jenkins, A., Frenk, C.S., White, S.D.M., et al., 2001, MNRAS, 321, 372
Lewis, A., Challinor, A., Lasenby, A., 2000, ApJ, 538, L473
Masaki, S., Fukugita, M., & Yoshida, N. 2012, ApJ, 746, 38
McKay, T. A., Sheldon, E. S., Racusin, J., et al. 2001, arXiv:astro-ph/0108013
McKay, T. A., Sheldon, E. S., Johnston, D., et al. 2002, ApJ, 571, L85
Navarro, J.F., Frenk, C.S., White, S.D.M., 1995, MNRAS, 275, 720
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1997, ApJ, 490, 493
Planck Collaboration, Ade, P. A. R., Aghanim, N., et al. 2016, A&A, 594, A13
Pratt, G.W., Croston, J.H., Arnaud, M., et al., 2009, A&A, 498, 361
Sarazin, C.L., 1986, Rev. Mod. Phys., 58, 1
Schechter, P.L., 1976, ApJ, 203, 297
Sunyaev, R. A. & Zeldovich, Y.B., 1972, Comm. Astrophys. Space Phys., 4, 173
Tinker, J., Kravtsov, A. V., Klypin, A., et al. 2008, ApJ, 688, 709
Vikhlinin, A., Kravtsov, A., Burenin, V., et al., 2009, ApJ, 692, 24
Watson, W.A., Iliev, I.T., D’Aloisio, A., et al., 2013, MNRAS, 433, 1230

This paper has been typeset from a \TeX/\LaTeX file prepared by the author.