A&A 452, 47–50 (2006)
DOI: 10.1051/0004-6361:20054465

Astronomy & Astrophysics

The baryon mass function for galaxy clusters

S. E. Nuza[1] and A. Blanchard[2]

[1] Instituto de Astronomía y Física del Espacio, C.C. 67, Suc. 28, 1428, Buenos Aires, Argentina
e-mail: sebasn@iafe.uba.ar
[2] Laboratoire d'Astrophysique de Toulouse-Tarbes, 14 avenue E. Belin, 31400 Toulouse, France
e-mail: alain.blanchard@ast.obs-mip.fr

Received 3 November 2005 / Accepted 17 January 2006

ABSTRACT

Context. The evolution of the cluster abundance with redshift is known to be a powerful cosmological constraint when applied to X-ray clusters. Recently, the evolution of the baryon mass function has been proposed as a new variant that is free of the uncertainties present in the temperature-mass relation. A flat model with $\Omega_{\rm M} \simeq 0.3$ was shown to be preferred in the case of a standard cold dark matter scenario.

Aims. We compared the high redshift predictions of the baryon mass in clusters with data for a more general class of spectra with a varying *shape* factor Γ without any restriction to the standard cold dark matter scenario in models normalized to reproduce the local baryon mass function.

Methods. Using various halo mass functions existing in the literature we evaluated the corresponding baryon mass functions for the case of the non-standard power spectra mentioned previously.

Results. We found that models with $\Omega_{\rm M} \simeq 1$ and $\Gamma \simeq 0.12$ reproduce high redshift cluster data just as well as the concordance model does.

Conclusions. Finally, we conclude that the baryon mass function evolution alone does not efficiently discriminate between the more general family of flat cosmological models with non-standard power spectra.

Key words. cosmology: cosmological parameters – cosmology: large-scale structure of Universe – cosmology: observations

1. Introduction

The growth of structure in the Universe is believed to be the result of gravitational collapse generated by the existence of tiny departures from homogeneity and isotropy (presumably generated during inflation) in the primordial distribution of matter (see e.g., Peacock 1999). The overdensity of matter in a particular comoving scale l evolves according to linear theory until it reaches a value of $\delta_k \sim 1$, where we have used $k \equiv |\boldsymbol{k}|$ with $\boldsymbol{k}$ the comoving *wavevector* that satisfies the relation $|\boldsymbol{k}| = 2\pi/l$. For later times the evolution is highly nonlinear and the formation of bound structures like galaxies and galaxy clusters takes place. It is believed that this hierarchical process of structure formation is still at work today. Press & Schechter (1974, hereafter PS) developed a semianalytical formulation to deal with this regime and eventually predict the number of collapsed objects (often called *virialized* objects) of a given mass M (associated with the scale l) at a given redshift z, i.e. to determine the so-called *mass function*. Interest in the PS approach has grown in recent years because it appears to reproduce the results of numerical simulations well (e.g. Efstathiou et al. 1988; White et al. 1993; Lacey & Coley 1994) where the nonlinear regime can be tested unambiguously inside the limits imposed by the resolution of the simulation. Sheth & Tormen (1999) obtained a different expression for the mass function by assuming an *ellipsoidal* collapse instead of a *spherical* one (as assumed in the PS theory) and found better agreement between the model and the numerical results. Sheth et al. (2001, hereafter SMT) present an improved version of their 1999 work. Instead of working out a semianalytical approach Jenkins et al. (2001, hereafter J01) have introduced several fits to the numerical simulations using different algorithms for the halo finder and for several kinds of cosmologies. Further analyses have been made of these matters such as, White (2002) and Warren et al. (2005). Of particular interest is the evolution of the mass function with redshift that has been shown to be sensitive primarily to the mass density of the Universe (Blanchard & Bartlett 1998). This high sensitivity allows us to use the evolution of the abundance of X-ray clusters as a powerful cosmological test (Oukbir & Blanchard 1992). Recently, the *baryon* mass function (i.e., the number density of comoving objects with a given baryon mass) has been advocated by Vikhlinin et al. (2003, hereafter V2003) as an useful alternative and cosmological constraints were derived in the context of standard cold dark matter (hereafter CDM) spectrum. V2003 have consequently concluded that cluster data favors a concordance-like Universe. This analysis seems to conflict with the study made by Blanchard et al. (2000) and with the recent *XMM-Newton* Ω-project (Vauclair et al. 2003), which is somewhat surprising because Sadat et al. (2005) found that gas fraction in distant clusters within the *XMM-Newton* Ω-project was consistent with a high-density Universe and not with a concordance model. These two sets of analyses therefore suggest that the baryon mass fraction should also be consistent with a high-density Universe. The present paper aims to clarify this issue. Here we study the more general class of spectra with a varying *shape* factor Γ, without any restriction to the standard CDM model. In Sect. 2 we briefly review the PS formalism and recall the results of SMT and J01. In Sect. 3 we introduce the temperature-mass (hereafter $T-M$) relation, and we use the different available expressions for the baryon mass function, normalized to local cluster data, to compare them with the high redshift observations provided by V2003. Finally, we discuss our main conclusion that data on the baryon mass function of clusters can also be reproduced in a critical Universe with $\Omega_\Lambda \simeq 0$, indicating that there is no discrepancy in both approaches.

2. Mass functions of galaxy clusters

2.1. The PS formalism

The PS approach is based on the assumption of an initial *Gaussian* overdensity field $\delta(\boldsymbol{x}, z_i)$ and a *spherical* model for the subsequent collapse (Partridge & Peebles 1967). Let $n(M, z)$ be the comoving number density of objects with mass M at a given redshift z. Then,

$$n(>M, z) = \int_M^{+\infty} \frac{dn(M', z)}{dM'} dM' \quad (1)$$

is the number of collapsed objects of mass greater than M at redshift z. The *mass function* resulting from these priors reads as (for a detailed discussion see e.g. Blanchard et al. 1992)

$$\frac{dn(M, z)}{dM} = \frac{\rho_0}{M} \frac{d\nu}{dM} \mathcal{F}(\nu). \quad (2)$$

In this formula, ρ_0 is the comoving background density of the Universe, $\nu \equiv \delta_c/\sigma(M, z)$, where δ_c is the *linear* overdensity evaluated at the virialization time, $\sigma(M, z)$ is the rms amplitude of the matter fluctuations at a given mass scale M, and $\mathcal{F}(\nu)$ is a function taken as

$$\mathcal{F}(\nu) = \sqrt{\frac{2}{\pi}} \exp\left(-\frac{\nu^2}{2}\right) \quad (3)$$

in the original PS work. For an Einstein-de Sitter Universe, the value for δ_c is approximately 1.69. This value is normally assumed because of the weak cosmological dependence of the linear overdensity at virialization (e.g. Colafrancesco & Vittorio 1994). In order to evaluate $\sigma(M, z)$ one has to smooth the density field $\delta(\boldsymbol{x}, z)$ with some known *window function* W_k for a given k. The expression for $\sigma(M, z)$ results in

$$\sigma^2(M, z) = \int_0^{\infty} \frac{dk}{2\pi^2} k^2 |\delta_k(z)|^2 F^2[W_k], \quad (4)$$

where $F[W_k]$ is the Fourier transform of W_k, and $|\delta_k(z)|^2$ is the power spectrum of $\delta(\boldsymbol{x}, z)$. The most popular election for W_k is a spherical top-hat in real space such that the relation between the mass scale M and the comoving linear scale l is given by $l^3 = 6M/\pi\rho_0$. From Eqs. (2) and (4), it is easy to see that all cosmological dependence enters through the evolution of the *linear* overdensity field of matter, so by setting its value adequately one can apply this formalism to any cosmology of interest.

2.2. Improvements to PS theory

As mentioned in the introduction, SMT have introduced an improved version for the mass function of collapsed objects. Their approach is similar to that of PS, but instead of assuming a spherical model for virialization, they used elliptical collapse and obtained a somewhat different expression that agrees better with N-body numerical simulations. The SMT expression reads as follows

$$\frac{dn(M, z)}{dM} = c\sqrt{\frac{2a}{\pi}} \frac{\rho_0}{M} \frac{d\nu}{dM} \left(1 + \frac{1}{(a\nu^2)^p}\right) \exp\left(-\frac{a\nu^2}{2}\right), \quad (5)$$

Table 1. Different fits for $f(\sigma, z)$ provided by J01 for different cosmological models and various halo finders. CM and HF stands for Cosmological Model and Halo Finder respectively. $fof(a)$ refers to a *friend of friend* algorithm with an interparticle separation a and $so(\Delta)$ refers to a *spherical overdensity* algorithm with contrast density Δ (respect to the background). *All* means all cosmological models listed in Table 2 of J01 paper.

#	A	B	C	CM	HF	Δ
1	0.307	0.61	3.82	τCDM	*fof*(0.2)	≃180
2	0.301	0.64	3.88	ΛCDM	*fof*(0.164)	≃324
3	0.301	0.64	3.82	τCDM	*so*(180)	180
4	0.316	0.67	3.82	ΛCDM	*so*(324)	324
5	0.315	0.61	3.80	*All*	*fof*(0.2)	≃180

with $a = 0.707$, $c = 0.3222$, and $p = 0.3$. Setting $a = c = 1$ and $p = 0$ in this formula leads to the PS formalism. More recently, J01 have found several fits to the mass function using the results of their N-body numerical simulations. Specifically, they consider the quantity

$$f(\sigma, z) \equiv \frac{M}{\rho_0} \frac{dn}{d\ln\sigma^{-1}} \quad (6)$$

that is parametrized assuming the following functional form motivated by the *ansatz* given by Eqs. (2) and (5):

$$f(\sigma, z) \equiv A \exp\left(-\left|\ln\sigma^{-1} + B\right|^C\right), \quad (7)$$

with A, B, and C the fitting parameters. In particular they use two distinct ways of object grouping, namely *friend-of-friend* and *spherical-overdensity* halo finders, for various types of cosmologies (see their paper for details). In Table 1 we give the different values of the fitting parameters in these several situations. An important quantity related of these halo finders is the cluster density with respect to the background Universe density (or *contrast* density). In general, its value depends on the cosmology and redshift. J01 assume a *constant* value for the contrast density (see Δ in Table 1) in order to get their fits.

3. Determination of Ω_0

3.1. The temperature-mass relation

An unavoidable ingredient in the determination of the mass function for galaxy clusters was until recently the use of the $T-M$ relation, i.e. the relation between the cluster total (virial) mass and the (observed) X-ray temperature. It allows determination of the mass function so that its evolution can then be used to constrain the value of Ω_0 (e.g. Oukbir & Blanchard 1992, 1997). Standard scaling laws (e.g. Kaiser 1986) allow us to write the $T-M$ relation as follows

$$T_X = A_{TM} \left(\Omega_M \frac{\Delta(\Omega_M, z)}{178}\right)^{1/3} M_{15}^{2/3} h^{2/3} (1+z), \quad (8)$$

where $\Delta(\Omega_M, z)$ is the contrast density mentioned in 2.2 and h the present Hubble constant in units of 100 km s^{-1} Mpc^{-1}. The subscript 15 means that masses are taken in units of $10^{15}\ M_\odot$. A_{TM} is a normalization factor in that case. A known uncertainty exists in A_{TM} because the value that results from numerical simulations is significantly different from the one based on the hydrostatic equation (Roussel et al. 2000). Despite this, the $T-M$ relation has been applied in the past to link cluster observations ($\propto T_X$) with cluster mass. A conservative approach to this was assumed by Vauclair et al. (2003) when using two extreme normalizations in their analysis of the *XMM-Newton* Ω-project (Lumb et al. 2004). In particular, their conclusions are roughly independent of the A_{TM} value. However, Blanchard & Douspis (2005) have recently introduced a procedure to remove this uncertainty. In the next subsection we review the recent proposal by V2003 to avoid the $T - M$ normalization problem applied to the constraint of Ω_0.

3.2. The baryon mass function

This method relies on the standard assumption that the baryon fraction within the virial radius in clusters should be close to the average value in the Universe, i.e. $f_b \simeq \Omega_b/\Omega_M$ (White et al. 1993). Using the baryon mass at a radius of constant baryon contrast density (e.g. Vikhlinin et al. 1999) and the fact that, to a first order, the baryon and total mass in clusters are trivially related by $M_b = M f_b$, one can deduce the functional form $N_b(M_b)$ of the baryon mass function as

$$N_b(>M_b) = N\left(>M_b f_b^{-1}\right), \qquad (9)$$

where $N(M)$ is the total mass function. Equation (9) allows us to evaluate the baryon mass functions for different models according to the various expressions presented in Sect. 2. By studying the evolution of $N_b(M_b)$ for high-z cluster data, we can constrain the density parameter previous adjustment of the mass function to the local cluster observations. In this last procedure, the shape factor Γ of the power spectrum and the σ_8 parameter (formula (4) evaluated on a scale of 8 h^{-1} Mpc) can be fixed. It is worth noting that the baryon fraction universality implies, for a cluster, that the total matter density contrast equals the baryonic matter contrast, i.e. $\Delta = \Delta_b$, where b stands for *baryonic*. The most obvious advantage of this method is that the baryonic mass is a quantity that can be measured directly. We refer the reader to V2003 for details.

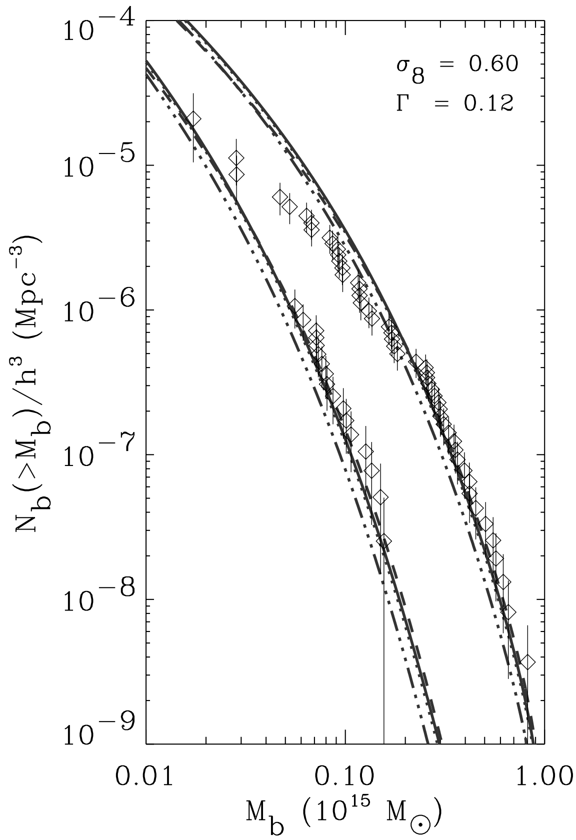

Fig. 1. Low and high redshift cluster data ($z \simeq 0.05$ and $z \simeq 0.5$ respectively, $h = 0.5$) compared with various theoretical baryon mass functions (dotted line: J01 # 1, dashed 3-dotted line: J01 # 3, solid line: J01 # 5, dashed line: SMT, see Sect. 2). A Universe satisfying (Ω_M, Ω_Λ) ≃ (1,0) clearly fits the data for non-standard power spectra with Γ = 0.12.

3.3. Standard CDM vs. Γ-varying spectra

In order to make the comparisons mentioned above, we used the local ($z \simeq 0.05$) and high-z (≃0.5) cluster observations from Voevodkin & Vikhlinin (2004, see their Table 1) and V2003 respectively, where data is defined for $\Delta_b = 324$. When comparing the reliability of a particular cosmology to cluster observations, the value of h can be taken arbitrarily, because once the baryonic mass data is scaled properly ($M_b \propto h^{-2.25}$, Voevodkin & Vikhlinin 2004), the only factor that determines the fit inside the context of a particular cosmology, is the redshift evolution of the mass function (previous constraint of the Γ and σ_8 parameters using local cluster data, see Sect. 3.2). In our comparison we adopted two fiducial models: a concordance model with $\Omega_M = 0.3$, $\Gamma = 0.2$, $\sigma_8 = 0.71$, $\Omega_b = 0.04$, $h = 0.71$ and a model with $\Omega_M = 1$, $\Gamma = 0.12$, $\sigma_8 = 0.6$, $\Omega_b = 0.105$, $h = 0.5$. The first model is close to the preferred one according to V2003 when fitted to the baryon mass function and its evolution. The second one is the best fit model to X-ray cluster data proposed by Vauclair et al. (2003). The baryon fractions were taken to be the apparent value after computing the corrections of depletion and clumping (Sadat & Blanchard 2001) using the analysis of local clusters by Sadat et al. (2005), i.e.: $f_b = \Upsilon \cdot \Omega_b/\Omega_M \simeq 1.14 \cdot \Omega_b/\Omega_M$. When using a particular mass function that assumes another value for Δ_b a correction must be applied because of the distinct cluster mass definition. To achieve this, a Navarro-Frenk-White (Navarro et al. 1996, NFW96) universal profile for the structure of the CDM halos in clusters was used assuming $C = 5$ (where C is the concentration parameter defined in Eq. (3) of NFW96), giving typical corrections for the baryonic mass on the order of 20%. The results of our comparisons can be seen in Figs. 1 and 2 where we have plotted various of the expressions for the baryon mass function (see Sect. 2) in each graph. As can be seen in the figures, the different functions lead to nearly identical behaviour for the same values of Γ and σ_8 up to $z \simeq 0.5$. To get total agreement, only a tiny change in these parameters is needed for each expression. We checked that in such a case the various expressions lead to a very similar level of evolution, since almost identical. We also noticed that V2003 have used a Υ varying parameter with X-ray temperature that leads to better agreement in the predicted mass function at low masses. The validity of such a variation with X-ray temperature is questionable (Sadat et al. 2005) and does not modify our conclusions. The most noticeable result obtained in the comparison is that the evolution of the baryon mass function in an Einstein-de Sitter cosmology ($\Omega_\Lambda \simeq 0$) is clearly consistent with the high redshift cluster data. Although the amount of evolution is clearly not the same between different cosmologies the baryon masses inferred from high redshift data also differ in a way that accidentally compensates for the evolution abundance effect.

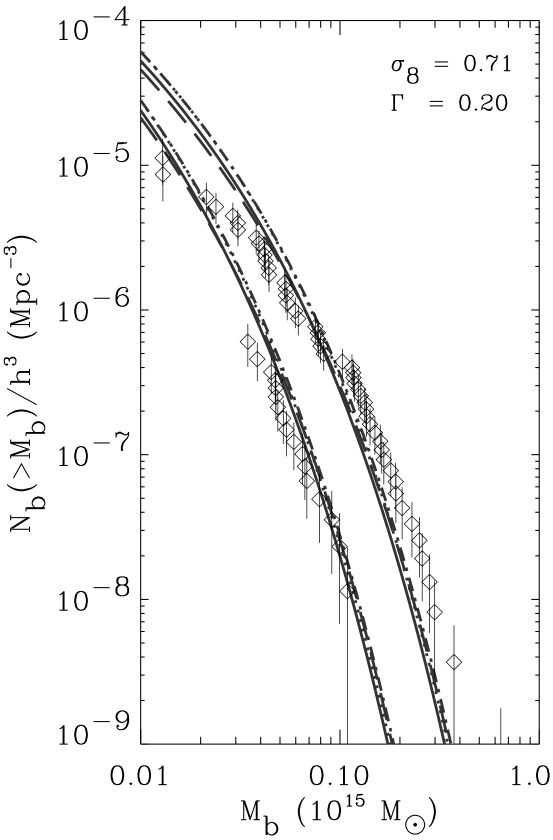

Fig. 2. Same as Fig. 1 but for the case of a *fiducial* concordance cosmology with $h = 0.71$ (dotted line: J01 # 2, dashed dotted line: J01 # 4, solid line: J01 # 5, dashed line: SMT, see Sect. 2).

4. Discussion

We have found that a non-standard (Γ-varying) spectra can reproduce the observed baryon mass distribution function both for local and high redshifts in the case of an Einstein-de Sitter cosmology just as well as the concordance model does. For this, we used several formulas for the baryon mass function and found that the results are essentially insensitive to the expression used. It is important to recall that the V2003 analysis is based on the assumption of standard CDM power spectra for matter and on a particular value of the Hubble constant. This assumption fixes the value of the shape factor essentially in $\Gamma \simeq \Omega_0 h$ (e.g. Peacock & Dodds 1994). Furthermore, as they have used $h \simeq 0.65$, i.e. a Hubble constant value near the Hubble Key Project result (Freedman et al. 2001), they would get a shape factor of $\Gamma \simeq 0.65$ in an Einstein-de Sitter Universe, which is very far from the value we get here for the same cosmology, i.e. $\Gamma = 0.12$. It is well known that the standard CDM model is ruled out in an Einstein-de Sitter cosmology, which is the reason for needing a non-standard CDM spectra in the $\Omega_M \simeq 1$ case. This difference explains the apparently conflicting conclusions between V2003 and the present work. While the Einstein-de Sitter and concordance models produce distinct cluster number counts for a flux limited survey (Vauclair et al. 2003) or for the temperature distribution function evolution (Blanchard et al. 2000), once models are properly normalized at low redshift, the baryon mass function does not differentiate among flat cosmologies, because the inferred baryon masses are different, and this difference accidentally and roughly compensates for the effect of number evolution. This kind of non-standard spectra with lower Γ on cluster scales could have originated from different hypotheses on the dark matter content and/or from the existence of some unknown phase in the evolution of the Universe (like hot dark matter or quintessence) that could drive different power spectra for matter. The initial power spectrum could also be altered from a single power law by physics at the inflation period. We are therefore lead to the final conclusion that present baryon cluster data can be described equally well by either a concordance or an Einstein-de Sitter (with a non-standard Γ value on cluster scales) Universe implying that the baryon mass function is not as effective as the evolution of the temperature function. This removes the apparent discrepancies between the conclusions inferred from the *XMM-Newton* Ω-project (Vauclair et al. 2003; Sadat et al. 2005) and V2003.

Acknowledgements. S.E.N. acknowledges M. Douspis for useful discussions and hospitality during a recent visit at LATT. He also thanks R. Pelló, L. Ferramacho, and M. Treguer for hospitality and the LENAC (Latin American-Europe Network for Astrophysics and Cosmology) project and CONICET for financial support. We are grateful to A. Vikhlinin for useful discussions and for providing us with an electronic version of the baryonic mass data. We also acknowledge the anonymous referee for several comments that helped to improve this paper.

References

Blanchard, A., & Bartlett, J. G. 1998, A&A, L332, 49
Blanchard, A., & Douspis, M. 2005, A&A, 436, 411
Blanchard, A., Valls-Gabaud, D., & Mamon, G. 1992, A&A, 264, 365
Blanchard, A., Sadat, R., Bartlett, J. G., & Le Dour, M. 2000, A&A, 362, 809
Colafrancesco, S., & Vittorio, N. 1994, ApJ, 422, 443
Freedman, W. L., Madore, B. F., Gibson, B. K., et al. 2001, ApJ, 553, 47
Efstathiou, G., Frenk, C. S., White, S. D. M., & Davis, M. 1988, MNRAS, 235, 715
Jenkins, A., Frenk, C. S., White, S. D. M., et al. 2001, MNRAS, 321, 372 (J01)
Kaiser, N. 1986, MNRAS, 222, 323
Lacey, C., & Cole, S. 1994, MNRAS, 271, 676
Lumb, D. H., Bartlett, J. G, Romer, A. K., et al. 2004, A&A, 420, 853
Markevitch, A. 1998, ApJ, 504, 27
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1996, ApJ, 462, 563
Oukbir, J., & Blanchard, A. 1992, A&A, 262, L21
Oukbir, J., & Blanchard, A. 1997, A&A, 317, 10
Partridge, R. B., & Peebles, P. J. E. 1967, ApJ, 147, 868
Peacock, J. A. 1999, Cosmological Physics (Cambridge University Press)
Peacock, J. A., & Dodds, S. J. 1994, MNRAS, 267, 1020
Press, W. H., & Schechter, P. 1974, ApJ, 187, 425
Roussel, H., Sadat, R., & Blanchard, A. 2000, A&A, 361, 429
Sadat, R., & Blanchard, A. 2001, A&A, 371, 19
Sadat, R., Blanchard, A., Vauclair, S. C., et al. 2005, A&A, 437, 31
Sheth, R. K., & Tormen, G. 1999, MNRAS, 308, 199
Sheth, R. K., Mo, H. J., & Tormen, G. 2001, MNRAS, 323, 1 (SMT)
Vauclair, S. C., Blanchard, A., Sadat, R., et al. 2003, A&A, 412, L37
Vikhlinin, A., Forman, W., & Jones, C. 1999, ApJ, 525, 47
Vikhlinin, A., Voevodkin, A., Mullis, C. R., et al. 2003, ApJ, 590, 15 (V2003)
Voevodkin, A., & Vikhlinin, A. 2004, ApJ, 601, 610
White, M. 2002, ApJS, 143, 241
White, S. D. M., Efstathiou, G., & Frenk, C. 1993, MNRAS, 262, 1023
White, S. D. M., Navarro, J. F., Evrard, A. E., & Frenk, C. 1993, Nature, 366, 429
Warren, M. S., Abazajian, K., Holz, D. E., & Teodoro, L. 2005, ApJL, submitted [arXiv:astro-ph/0506395]