Draft version November 15, 2006
Preprint typeset using LaTeX style emulateapj v. 05/04/06

EVIDENCE FOR MERGING OF LUMINOUS RED GALAXIES FROM THE EVOLUTION OF THEIR CLUSTERING

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(Dated: November 15, 2006)
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ABSTRACT

The formation and evolution of massive red galaxies form a crucial test of theories of galaxy formation based on hierarchical assembly. In this letter we use observations of the clustering of luminous red galaxies from the Bootes field and N-body simulations to argue that the most luminous galaxies appear to undergo significant merging within massive halos between $z \simeq 0.9$ and $z \simeq 0.5$.

Subject headings:

1. INTRODUCTION

The assembly of the most massive galaxies is a key test of cold dark matter (CDM) models of galaxy formation, as the ongoing growth of massive galaxies via mergers is a generic feature of hierarchical CDM models. Observationally, the most massive galaxies have little ongoing star formation, and the bulk of their stellar mass was formed at $z > 2$ (e.g. Bower, Lucey & Ellis 1992; Trager et al. 2000; Cool et al. 2006, and references therein). If there is appreciable growth of these galaxies at $z < 1$, this must be due to galaxy mergers, as predicted by the hierarchical CDM models.

Evidence for the ongoing assembly of massive galaxies is inconclusive. While the stellar mass within the red galaxy population has doubled since $z = 1$ (Bell et al. 2004; Willmer et al. 2006; Brown et al. 2006a), this appears to be due to the truncation of star formation in blue galaxies, and the role of mergers is unknown. van Dokkum (2005) and Bell et al. (2006), using close galaxy pairs, conclude that $L_\star$ red galaxies grow rapidly via mergers since $z = 1$, while Masjedi et al. (2006), using similar techniques, finds the merger rate of $4L_\star$ red galaxies is only $\sim 1\%$ Gyr^{-1}. Using the galaxy space density, Brown et al. (2003) finds the stellar masses of $4L_\star$ red galaxies grow by $\simeq 20\%$ since $z \sim 0.7$, while others find no significant growth over similar redshift ranges (e.g., Bundy et al. 2006; Cimatti, Daddi & Renzini 2006; Caputi et al. 2006; Wake et al. 2006).

There is an additional route to constraining the evolution of galaxies, which is to use their clustering properties. Building upon the theoretically understood evolution of the dark matter halo population we can obtain complementary constraints which bypass the model dependence of stellar evolution or merger times as a function of projected distance. We illustrate this approach in this *Letter*, presenting preliminary evidence from the evolution of their clustering that luminous ($M_B - 5\log(h_{100}) < -20.65$) red galaxies undergo significant merging in massive halos between $z \sim 0.9$ and $z \sim 0.5$.

2. THE OBSERVATIONAL SAMPLE

We use galaxies in the $9\,\mathrm{deg}^2$ Bootes field, which has been imaged in the optical and infrared by the NOAO Deep Wide-Field (NDWFS; Jannuzi & Dey 1999) and *Spitzer* IRAC Shallow Surveys (Eisenhardt et al. 2004). We use a subset of the Bootes red galaxy sample (Brown et al. 2003, 2006b), which was selected from the Bootes imaging using empirical photometric redshifts and rest-frame optical colors. This subset has a constant comoving number density ($\bar{n} = 10^{-3}h^3\mathrm{Mpc}^{-3}$) in three redshift slices: $0.4 < z < 0.6$, $0.6 < z < 0.8$ and $0.8 < z < 1.0$ with volumes of 2.4, 3.5 and $5.2 \times 10^6\ (h^{-1}\mathrm{Mpc})^3$ respectively. Our results are based on the observed evolution of the angular clustering of these constant $\bar{n}$ samples, containing a few thousand galaxies each. We transform from models of the spatial clustering to angular clustering using a redshift distribution model which accounts for the small measured uncertainties of the photometric redshifts ($\sigma_z \lesssim 0.05$). We describe the clustering measurements and theoretical modeling in detail in Brown et al. (2006b).

3. MODELING GALAXY CLUSTERING

The galaxy samples we will model have been chosen to have constant comoving number density. Their clustering also evolves very little. We begin with a simple example to show how these two results imply that the sample must be undergoing some merging or non-passive evolution[1]. If we assume that galaxies and mass follow the same velocity field, and ignore mergers, then the continuity equation requires that $\dot{\delta}_{\rm gal} = \dot{\delta}_{\rm m}$ (Peebles 1980). If we define $\delta_{\rm gal}(z) = b(z)\delta_{\rm m}(z)$ and the growth function $D(z) \equiv \delta_{\rm m}(z)/\delta_{\rm m}(0)$ then $b(z) = 1 + D^{-1}(z)\,[b(0) - 1]$. This prediction is in good agreement with our numerical simulations with passive evolution (Figure 1). Assuming scale-independent, deterministic biasing we therefore predict that $\xi_{\rm gal}^{1/2} \propto b(z)D(z) = D + b(0) - 1$, which is not in agreement with the observed trends. In fact, we find that passive evolution cannot fit the trend of the central values of the clustering strength for any cosmology.

To go further we need a way of connecting the galaxies

[1] M.W., M.B. and A.D. thank Ravi Sheth for discussions which generated this argument.

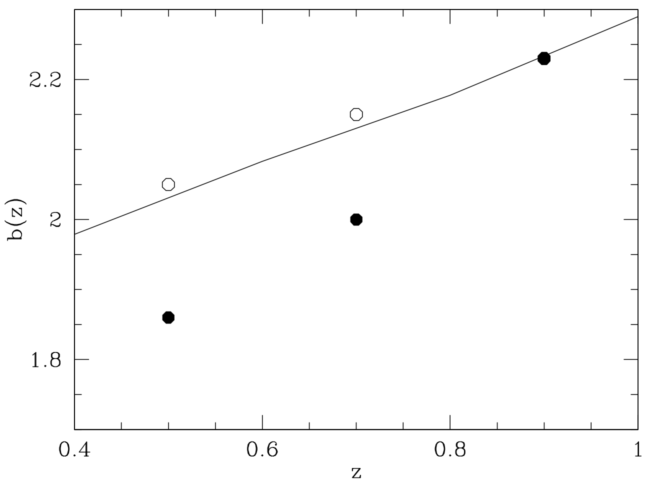

FIG. 1.— The evolution of the large-scale bias, assuming a dark matter power spectrum with $\sigma_8 = 0.8$. The solid line is $b(z) = 1 + D^{-1}[b(0) - 1]$ (see text), the open circles are measured from our "passive mocks" and the solid circles are from the mocks which best fit $w(\theta)$ at each redshift.

we observe with the host dark matter halos whose evolution theory predicts. The halo model (see e.g. Cooray & Sheth (2002) for a review) has provided us with such a physically informative and flexible means of describing galaxy bias. The key insight is that an accurate prediction of galaxy clustering requires a knowledge of the occupation distribution of objects in halos (the HOD) and their spatial distribution. In combination with ingredients from N-body simulations a specified HOD makes strong predictions about a wide array of galaxy clustering statistics. The formalism thus allows us to use observations of galaxy clustering to constrain the connection between galaxies and their host dark matter halos, and in particular to show that the luminous galaxies in the NDWFS have undergone significant merging between $z \simeq 0.9$ and $z \simeq 0.5$.

3.1. *Populating dark matter halos*

To make mock catalogs we use a halo model which distinguishes between central and satellite galaxies. We choose a mean occupancy of halos: $N(M) \equiv \langle N_{\rm gal}(M_{\rm halo})\rangle$. Each halo either hosts a central galaxy or does not, while the number of satellites is Poisson distributed about a mean $N_{\rm sat}$. We parameterize $N(M) = N_{\rm cen} + N_{\rm sat}$ with (e.g. Zheng et al. 2005)

$$N_{\rm cen}(M) = \frac{1}{2}\,{\rm erfc}\left(\frac{\log(M_{\rm cut}/M)}{\sqrt{2}\sigma}\right) \tag{1}$$

and

$$N_{\rm sat}(M) = \left(\frac{M - M_{\rm cut}}{M_1}\right)^{\alpha} \tag{2}$$

for $M > M_{\rm cut}$ and zero otherwise. Different functional forms have been proposed in the literature, but the current form is flexible enough for our purposes. Including a different low mass roll-off in the satellite term, following Tinker et al. (2005) and Conroy, Wechsler & Kravtsov (2006), does not alter our basic conclusions.

3.2. *Simulations and mock catalogs*

To model the dark matter clustering we used a high resolution simulation of a ΛCDM cosmology ($\Omega_M = 0.25 = 1 - \Omega_\Lambda$, $\Omega_B = 0.043$, $h = 0.72$, $n = 0.97$ and $\sigma_8 = 0.8$). The linear theory power spectrum was computed by evolution of the coupled Einstein, fluid and Boltzmann equations using the code described in White & Scott (1995). (A comparison of this code to CMBfast (Seljak & Zaldarriaga 1996) is given in Seljak et al. (2003).) The simulation employed 1024^4 particles of mass $8 \times 10^9\,h^{-1}M_\odot$ in a periodic cube of side $500\,h^{-1}$Mpc. Particles were initially displaced from a regular Cartesian mesh using the Zel'dovich approximation at $z = 50$ and evolved to the present using a *TreePM* code (White 2002). The Plummer equivalent softening was $18\,h^{-1}$kpc (comoving).

For each output we generate a catalog of halos using the Friends-of-Friends algorithm (Davis et al. 1985) with a linking length of $b = 0.168$ in units of the mean inter-particle spacing. This procedure partitions the particles into equivalence classes, by linking together all particle pairs separated by less than a distance b. The halos correspond roughly to all particles above a density of about $3/(2\pi b^3) \simeq 100$ times the background density and we keep all halos with more than 10 particles – though only halos with $> 10^2$ particles will be used below. We base our mass definition on the sum of the particle masses in the halo, however to obtain better correspondence between this definition of halo mass and that implicitly defined by the mass functions of Sheth & Tormen (1999) and Jenkins et al. (2000) we rescaled the masses by $M/M_{\rm fof} = 1 + 0.01\,(\ln M_{\rm fof} - 23.5)$ where $M_{\rm fof}$ is the FoF mass in $h^{-1}M_\odot$. With this redefinition the mass function in the simulation lies between those of Sheth & Tormen (1999) and Jenkins et al. (2000), differing from them by less than 10% in the mass range of interest.

Given an HOD and the halo catalogs we can produce a mock catalog in one of two ways. In each case we define a galaxy to live at the minimum of the halo potential with probability $p = \min[1, N_{\rm cen}(M)]$. Following Kravtsov et al. (2004), if $N(M) > 1$ the mean number of satellites, $N_{\rm sat} = N(M) - 1$, is computed for the halo and a Poisson random number, $n_{\rm sat}$, drawn. We then either create a satellite galaxy assuming an NFW profile (Navarro, Frenk & White 1996) with a concentration-mass relation fit to the halos in the simulation or $n_{\rm sat}$ dark matter particles, chosen at random, are anointed as galaxies. Our fiducial model thus has the satellite galaxies tracing the dark matter in the halo. The two methods produce very similar, though not identical, clustering with the biggest differences appearing at the transition between galaxy pairs in 1 halo and those in 2 halos. An analytic model (described in Zheng 2004; Tinker et al. 2005) also produces very similar results. The differences between the methods are smaller than the observational errors, so we shall neglect them henceforth.

3.3. *Comparing with data*

From the galaxy positions we compute $\xi(r)$ in real space by direct pair counting in the periodic box for separations $< 20\,h^{-1}$Mpc. Beyond $20\,h^{-1}$Mpc we extrapolate assuming a constant bias. The known photometric redshift distribution is used to convert $\xi(r)$ into $w(\theta)$ using Eq. (50) of Simon (2006) giving the predicted cluster-

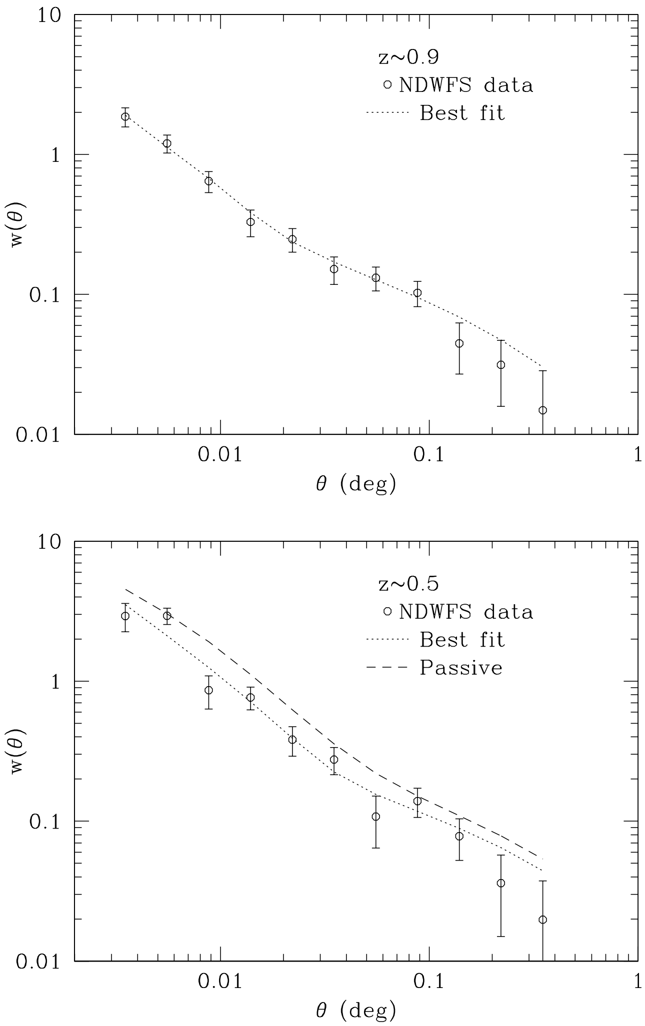

Fig. 2.— The angular correlation function, $w(\theta)$, for the $0.4 < z < 0.6$ and $0.8 < z < 1.0$ slices. Open circles with error bars represent the Bootes data, the dotted line is the best fitting HOD model prediction and (in the lower panel) the dashed line is the best fit $z \simeq 0.9$ model passively evolved to $z \simeq 0.5$.

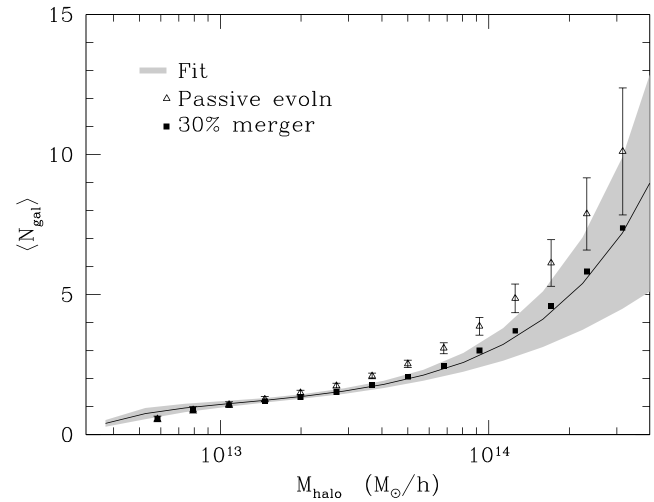

Fig. 3.— HODs for the $z \simeq 0.5$ sample. The shaded area indicates the mean and standard deviation in the HOD from the Markov chains, fit to the $w(\theta)$ data at $z \simeq 0.5$. The mass scale has been increased by 5% as described in the text. Open triangles indicate the HOD from the models at $z \simeq 0.9$ evolved to $z \simeq 0.5$ by tracking particles. Squares assume 30% of the satellites in the passively evolved mocks merge between $z \simeq 0.9$ and $z \simeq 0.5$.

ing for any set of HOD parameters. We fit to the data assuming Gaussian errors with the covariance matrices of Brown et al. (2006b), and assume a 5% error on the number density of galaxies. Figure 2 compares the best fitting HOD model predictions to the data at $z \simeq 0.9$ and 0.5.

Now we can find the set of models which best fits the data as a function of redshift and compare these to the passive evolution predictions. In order to propagate the observational errors into uncertainties in the HOD we used a Markov chain Monte-Carlo method (e.g. Gilks, Richardson & Spiegelhalter 1996) as detailed in Brown et al. (2006b). We found that the data themselves were unable to rule out models with $\sigma \gg 1$ and $\alpha \ll 1$, which we regard as unlikely for large red galaxies, so we chose to impose a prior which penalizes $\sigma > 1$ and $\alpha \simeq 0$. Tests indicate that larger surveys would not need this prior, though with this prior even our chains converged well. Because the mock catalog generation using NFW profiles is very fast and requires little memory we use this to generate the chains.

3.4. *Passive evolution*

For a subset of 250 of the models at $z \simeq 0.9$ we use the particle-based method to produce mock catalogs which we passively evolve to $z \simeq 0.5$ simply by tracking the particles based on their ID. The positions and halo memberships of these tagged particles are followed, along with the merging history of the hosting halos. We expect our results on the final halo distributions of these particles to be more robust[2] than predictions of small-scale spatial clustering coming directly from the particles, but we show the latter in Figure 2 for completeness. Looking at the difference in the HODs is also more informative, and gives us a clue as to what physics may be missing from pure passive evolution.

4. DISCUSSION

A comparison of the HOD of the passively evolved samples with the HODs which best fit the data indicates that evolution produces too many galaxies in high mass halos: Figure 3. A similar conclusion can be reached by comparing the clustering of the passively evolved models to the data in Figure 2 — the excess clustering on small scales from passive models clearly indicates that the models overpredict galaxy pairs within the same halo, i.e., they predict too many satellite galaxies in high mass halos. Another indication of the excess is that the satellite fraction in the passively evolved models is 0.24 ± 0.02 while that in the best fitting models is 0.18 ± 0.02.

There must be some physical process which reduces the number of galaxies in massive halos, and the mast natural candidate is dynamical friction which acts to merge massive satellites with the central galaxy. At high halo masses $\sim 30\%$ of the satellites in the passively evolved catalogs must have merged by $z \simeq 0.5$. In this calcu-

[2] The small-scale clustering depends on the evolution of the subhalos inside of the host halo, and due to finite force and mass resolution these may not be correctly modeled in massive halos.

lation we have not included other possible sources and sinks of red galaxies such as blue galaxies turning red or red galaxies turning blue. The existence of sources tends to strengthen our conclusions regarding the need for merging in high mass halos. A sink, e.g. red galaxies exhibiting renewed star formation, tends to weaken it.

There is one subtlety to bear in mind with these merger statistics. Since we conserve number density in our passively evolved catalogs the merger fraction is a lower limit. However, since only a small fraction ($< 10\%$) of all galaxies are merging, the lower limit is close to the true value. Phrased another way, we should really compare the passively evolved catalog (with $\bar{n} = 10^{-3}$) to a fitted one with a slightly lower number density – the "true" $z \simeq 0.5$ descendants of the $z \simeq 0.9$ galaxies. The cut-off mass scale for this catalog would be slightly larger than our fits and we should shift the mass definition in the HOD accordingly. We estimate the size of this shift, by considering the evolution of the central galaxies, to be $\approx 5\%$ and we increase the mass scale in Figure 3 accordingly.

A typical satellite galaxy could be expected to have tens of percent of the stellar mass of a central galaxy, suggesting that the central galaxy mass is increased a few tens of percent by merging over this period. To make this more quantitative we make the following simple model. Assuming that $n_{\rm h}(> M) = \Phi(> M)$ we can relate the central galaxy luminosity to halo mass. For our sample, at $z \simeq 0.5$ a halo of $10^{14}\,h^{-1}M_\odot$ hosts a central galaxy of $\approx 6\,L_\star$, with $L_{\rm cen} \propto M^{0.3}$ for massive halos. If we further assume the satellite luminosity function has the same shape as the global LF we can use our HOD models to find its normalization and integrate to find the total light in satellites. In a $10^{14}\,h^{-1}M_\odot$ halo satellites contribute $5\,L_\star$, so if 30% of the satellites merged with the central galaxy they would have contributed 40% of the current stellar mass. (This is likely to be an upper limit, because some of the mass would be lost as the satellite orbits in the host halo.) For halos of $5\times 10^{13}\,h^{-1}M_\odot$ the fraction is 25%. These numbers, while uncertain, are comparable to the 35% mass growth found by Brown et al. (2006a).

Our conclusions are necessarily tentative due to the limited volume of the NDWFS survey, which does not directly probe the mass function in the $10^{14} - 10^{15}\,h^{-1}M_\odot$ range. There are several areas where more or different data would be beneficial. Tests using models of larger surveys indicate that doubling the survey volume removes the islands of parameter space which we have excluded with priors and shrinks the errors on the HOD parameters by approximately $\sqrt{2}$, as might be expected. A measurement of the space density of groups richer than several members would shrink the errors on the high mass end of the HOD dramatically, but would require more volume than we have at present to contain a representative sample of rich groups. We also investigated the dependence of our results upon cosmology using similar simulations with different parameters. Our results remain robust within the currently allowed range of models.

This preliminary investigation shows the power of clustering measures to inform questions of the formation and evolution of galaxies. With more data from the NDWFS and future surveys we hope to be able to trace in detail the formation history of the most massive galaxies in the Universe.

We would like to thank Ravi Sheth for conversations and Jerry Ostriker for comments on an early draft. M.W. thanks the Galileo Galilei Institute for Theoretical Physics for their hospitality and the INFN for partial support during the completion of this work. This work is based in part on observations from the National Optical Astronomy Observatory and the Spitzer Space Telescope. The simulations were performed on the supercomputers at the National Energy Research Scientific Computing center. MW was supported by NASA.

REFERENCES

Bell E.F., et al., 2004, ApJ, 608, 752
Bell, E. F., et al., 2006, ApJ, 640, 241
Bower R.G., Lucey J.R., Ellis R.S., 1992, MNRAS, 254, 601
Brown M.J.I., et al., 2003, ApJ, 597, 225
Brown M.J.I., et al., 2006a, ApJ, in press [astro-ph/0609584]
Brown M.J.I., et al., 2006b, in preparation.
Bundy K., et al., 2006, ApJ, in press [astro-ph/0512465]
Cimatti A., Daddi E., Renzini A., 2006, A&A, 453, 29
Caputi K.I., et al., 2006, MNRAS, 366, 609
Conroy C., Wechsler R.H., Kravtsov A.V., 2006, ApJ, in press [astro-ph/0512234]
Cool, R. J., et al., 2006, AJ, 131, 736
Cooray, A., Sheth, R., 2002, Phys. Rep., 372, 1 [astro-ph/0206508]
Davis M., Efstathiou G., Frenk C.S., White S.D.M., 1985, ApJ, 292, 371
Eisenhardt, P. R., et al., 2004, ApJS, 154, 4
Faber S., et al., 2006, ApJ, in press [astro-ph/0506044]
Heymans C., et al., 2006, MNRAS, 371, L60
Jenkins A., Frenk C.S., White S.D.M., Colberg J.M., Cole S., Evrard A.E., Couchman H.M.P., Yoshida N., 2001, MNRAS, 321, 372
Gilks W.R., Richardson S.R., Spiegelhalter D.J., "Markov chain Monte Carlo in practice", Chapman & Hall (Florida, 1996)
Jannuzi B.T., Dey A., 1999, in ASP Conf. Ser. 191, Photometric redshifts and high redshift galaxies, ed. R.J. Weymann, L.J. Storrie-Lombardi, M. Sawicki & R.J. Brunner (San Francisco, ASP), 111
Kravtsov A.V., et al., 2004, ApJ, 609, 35.
Masjedi M., et al., 2006, ApJ, 644, 54
Navarro, J., Frenk, C., White, S.D.M., 1996, ApJ, 462, 563
Peebles P.J.E., 1980, "The large scale-structure of the universe", (Princeton, New Jersey).
Seljak U., Zaldarriaga M., 1996, ApJ, 469, 437.
Seljak U., Sugiyama N., White M., Zaldarriaga M., 2003, Phys. Rev. D68, 83507.
Sheth R., Tormen G., 1999, MNRAS, 308, 119
Simon P., 2006, A&A, in press [astro-ph/0609165]
Trager S.C., Faber S.M., Worthey G., Gonzalez J.J., 2000, AJ, 120, 165
Tinker J.L., Weinberg D.H., Zheng Z., Zehavi I., 2005, ApJ, 631, 41
van Dokkum P.G., 2005, AJ, 130, 2647
Wake D.A., et al., 2006, MNRAS, 372, 537
White M., 2002, ApJS, 579, 16
White M, Scott D, 1995, ApJ, 459, 415
Willmer C.N.A., et al., 2006, ApJ, 647, 853
Zheng Z., 2004, ApJ, 610, 61
Zheng Z., et al., 2005, ApJ, 633, 791