EVOLUTION OF THE NON-LINEAR GALAXY BIAS UP TO REDSHIFT $z=1.5$

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Deep redshift surveys of the universe provide the basic ingredients to compute the probability distribution function (PDF) of galaxy fluctuations and to constrain its evolution with cosmic time. When this statistic is combined with analytical CDM predictions for the PDF of mass, useful insights into the biasing function relating mass and galaxy distributions can be obtained. In this paper, we focus on two issues: the shape of the biasing function and its evolution with redshift. We constrain these quantities by using a preliminary sample of galaxies spectroscopically surveyed by the Vimos-VLT Deep Survey in a deep cone $0.4 < z < 1.5$ covering $0.4 \times 0.4$ sq. deg. We show that the ratio between the amplitude of galaxy fluctuations and the underlying mass fluctuations declines with cosmic time, and that its evolution rate is a function of redshift: biasing evolution is marginal up to $z \sim 0.8$ and more pronounced for $z > 0.8$.

1 Introduction

If cold dark matter (CDM) exists, it is collisionless, and interacts only gravitationally, then it is fair to say that we fully understand its spatial arrangement and clustering properties on large scales. In particular we know how to characterize the distribution properties of the mass density contrast $\delta$, the fundamental variable for Large Scale Structure studies. Somewhat less clear, from a theoretical point of view, is our quantitative understanding of the complex mechanisms which, on various cosmological scales, regulate the formation and the evolution of luminous structures within the underlying dark-matter distribution. In other terms, we still lack a reliable theoretical description of the distribution properties of the galaxy density contrast $\delta_g$. At present, only observations seem to offer the most promising way to constrain the statistics of $\delta_g$.

A related crucial issue is the understanding of physical dependence of $\delta_g$ on the underlying dark matter fluctuation field $\delta$ on large scales. A comprehensive description of the "biasing scheme", i.e. of the functional relationship between galaxies and the underlying dark matter density fluctuations, lies at the hearth of all interpretations of Large Scale Structure (LSS) theo-
retical models. Since structure formation models all predict the distribution of mass, the role of biasing is pivotal in mapping observations back onto the theoretical models.

While there is general observational consensus on the broad picture, i.e. that primordial massive galaxies form inside dark matter halos whose spatial distribution is highly biased with respect to the underline mass distribution and that biasing must decrease as time goes by, the elucidation of the finer details of this evolution as well as any meaningful comparison with specific theoretical predictions is still far from being secured. Since clustering depends on morphology, color and luminosity, and since most high redshift samples have been selected according to different colors or luminosity criteria, it is not clear, for example, how the very different classes of objects (Ly-break galaxies, extremely red objects or ultraluminous galaxies), which populate different redshift intervals, can be considered a uniform set of mass tracers across different cosmic epochs. Furthermore, one must note that the biasing relation is likely to be nontrivial, i.e. non-linear and scale dependent, especially at high redshift.

Many approaches have been used to characterize the clustering of galaxies and to understand its relation with the clustering of matter. A complete specification of galaxy clustering may be given by the full set of galaxy N-point correlation functions. This approach has been explored over the past decade as better and deeper redshift surveys have become available.

An alternative description may be given in terms of the probability distribution function (PDF) of a random field. A PDF of the cosmological density fluctuations is the most fundamental statistic characterizing the large-scale structure of the universe. In principle, it encodes much of the information contained within the full hierarchy of correlation functions, thus providing valuable information about gravitational evolution of density fluctuations. While the shape of the PDF of mass fluctuations at any given cosmic epoch is theoretically well constrained from CDM simulations, little is known about the observational PDF of the general population of galaxies in the high redshift universe. Even locally, this fundamental statistic has been often overlooked.

Using the first-epoch Vimos-VLT Deep Survey data we have derived the functional shape of the PDF of galaxy overdensities studying its evolution over the wide redshift range $0 < z < 1.5$. In particular we have shown how to derive the biasing relation $\delta_{g} = b(z, \delta, R)\delta$ between galaxy and mass overdensities from their respective PDFs $g(\delta_{g})$ and $f(\delta)$. As a matter of fact, assuming a one-to-one mapping between mass and galaxy overdensity fields, conservation of probability implies

$$\frac{d\delta_{g}(\delta)}{d\delta} = \frac{f(\delta)}{g(\delta_{g})}.$$  \hspace{1cm} (1)

The advantage over other methods is that we can explore the functional form of the relationship $\delta_{g} = b(z, \delta, R)\delta$ over a wide range in mass density contrasts, redshift intervals and smoothing scales $R$ without specifying any a-priori parametric functional form for the biasing function.

## 2 The First-Epoch VVDS Redshift Sample

The Vimos-VLT Deep Survey (VVDS) is a spectroscopic survey primarily designed for measuring more than 100,000 galaxy redshifts in the range $0 < z < 5$. The VVDS is an ambitious observational program to study how different was the universe when half its current age. Fig 1 is an evocative picture which best tell us what VVDS is: a genetic laboratory where we can hope to decode important information about the complex physical status of the present day universe by studying the Large Scale Structure in its embryonic form.

The VVDS studies the evolutionary sequence of galaxies, clusters and AGNs with a double observational strategy: a) with a wide survey which covers 16 deg$^2$ down to the limiting mag-
Figure 1: 3D overdensity field traced by the galaxy distribution in the VVDS deep field. In order to obtain this geographical map of the distant regions of the Universe we have used data in the redshift interval $0.83 < z < 0.93$. The galaxy distribution in this redshift range is continuously smoothed using a Top Hat window function with radius $R = 2h^{-1}\text{Mpc}$. The metric has been computed assuming a ΛCDM cosmology and the correct axis ratio between transversal and radial dimensions has been preserved. The approximate transverse and radial dimensions of the volume are shown in the figure.
nitude $I_{AB} = 22.5$ and $b$) with a deep survey covering about 1.3 deg$^2$ down to $I_{AB} = 24$. The strength of the VVDS, compared to other currently undergoing deep surveys of the universe, is that it has been conceived as a purely flux-limited survey, i.e. no target pre-selection according to colors, morphology or compactness is implemented. As a consequence its selection function is simple to understand and it allows a direct and easier comparison between the high-z and low-z samples of galaxies.

The analysis presented in this paper is based on data collected in the deep VVDS-02h field. In this field (0.4 x 0.4 sq. deg.) VIMOS observations have been performed using 1” wide slits and the LRRed grism which covers the spectral range 550 < $\lambda$(nm) < 940 with an effective spectral resolution $R \sim 227$ at $\lambda = 750$nm. The accuracy in redshift measurements is $\sim 275$ km/s. Details on observations and data reduction are given elsewhere\textsuperscript{5}\textsuperscript{18}.

For the purposes of this study we have defined a VVDS sub-sample with galaxies having redshift $z < 1.5$. Even if we measure redshifts up to $z \sim 5$, the conservative redshift limits bracket the range where we can sample in a denser way the underlying galaxy distribution and, thus, minimize biases in the reconstruction of the density field. This subsample contains 3448 galaxies with secure redshift and the redshift sampling rate is $\sim 30\%$ i.e., down to $I_{AB} = 24$, we measure redshifts for nearly one over three galaxies.

It is worth to emphasize that the VVDS is probing the high redshift domain at $I \leq 24$ in the VVDS-02h-4 field with the same sampling rate of pioneer surveys of the local Universe such as the CFA (at $z \sim 0$) and, more recently, the 2dFGRS\textsuperscript{9} (at $z \sim 0.1$).

3 Method

It seems now well established\textsuperscript{10}\textsuperscript{11} that, in the local universe, the distribution of baryonic matter does form a faithful representation of the spatial properties of the dominant species of matter (i.e. collisionless weakly interacting dark matter). On the contrary, very little is known about the rate of evolution as a function of redshift of the biasing relationship. Even less it is known about possible deviations, on large scales, from the simple linear parameterization which is almost universally adopted in order to describe of the biasing function on large scales (i.e. $R > 5h^{-1}$Mpc).

By using $\delta_g(\delta) = b(z, \delta, R)\delta$, into eq. \textsuperscript{11}, we have derived the redshift-, density-, and scale-dependent biasing function $b(z, \delta, R)$ between galaxy and matter fluctuations in a $\Lambda$CDM universe as the solution of the following differential equation

\[
\begin{cases}
\delta_g(-1) = -1 \\
b'(\delta)\delta + b(\delta) = f(\delta)g(\delta_g)^{-1}
\end{cases}
\] (2)

where the prime denotes the derivative with respect to $\delta$, $f(\delta)$ and $g(\delta_g)$ are the PDF of mass and galaxy fluctuations respectively, and the initial condition has been physically specified by requiring that galaxies cannot form where there is no mass.

With this computational approach, we loose information on a possible stochasticity characterizing the biasing function. The advantage is that we can provide a preliminary measure, on some characteristic scales $R$, of the local, non-linear, deterministic biasing function over the continuous redshift interval 0.4 < $z$ < 1.5.

Note that in our computational scheme, we explicitly assume that the mass PDF is described, to a good approximation, by a log-normal distribution\textsuperscript{13}

\[
f(\delta) = \frac{(2\pi\omega^2)^{-1/2}}{1 + \delta} \exp \left\{ - \frac{[\ln(1 + \delta) + \omega^2/2]^2}{2\omega^2} \right\}
\] (3)

characterized by a single parameter ($\omega$) that is related to the variance of the $\delta$-field as
Figure 2: The observed biasing function (solid-line) recovered for the density field smoothed on scales $R = 8h^{-1}$Mpc and for different redshift bins (from left to right) in the volume-limited VVDS sample ($M_B = -20 + 5\log h$). The dotted line represents the linear biasing model $\delta_g = b_L\delta$ while the no-bias case ($b_L = 1$) is shown with a dashed line. The central cross is for reference and represents the $\delta_g = \delta = 0$ case. The shaded area represents $1\sigma$ errors in the derived biasing function but do not include uncertainties due to cosmic variance

$$\omega^2 = \ln[1 + (\delta^2)]$$ (4)

Particular attention has been paid to devise an optimal strategy so that the comparison of the PDFs of mass and galaxies can be carried out in an objective and accurate way. First we have tested the statistical reliability of the observationally inferred PDF of VVDS galaxy fluctuations. By applying the VVDS observational selection functions to GALICS semi-analytical galaxy simulations we have explored the region of the parameter space where the PDF of VVDS-like densities traces in a statistically unbiased way the parent underlying PDF of the real distribution of galaxy overdensities. We have shown that the observed PDF of galaxy density contrasts is an unbiased tracer of the underlying distribution up to redshift $z = 1.5$, on scales $R \gtrsim 8h^{-1}$ Mpc.

Second, we have corrected the log-normal approximation, which describes the mass density PDF, in order to take into account redshift distortions induced by galaxy peculiar velocities at early cosmic epochs, i.e. when the mapping between redshifts and comoving positions is not linear. In this way, the theoretically predicted mass PDF can be directly compared to the corresponding observational quantity (galaxy PDF) directly in redshift space.

Finally, we note that, in pursuing our approach, we have assumed that the current theoretical understanding of how clustering of DM proceeds via gravitational instability in the expanding universe is well developed, i.e. the PDF $f(\delta)$ of mass fluctuations can be safely derived via analytical models or N-body simulations. In particular, in what follows, we will consider a $\Lambda$CDM background mass distribution locally normalized to $\sigma_8(z = 0) = 0.9$.

4 Results

We have obtained the biasing function $b(\delta)$ by numerically integrating the differential equation (2) i.e. without a-priori parameterizing the form of the biasing function. We have solved eq. (i) in different redshift intervals, ii) using matter and galaxy PDFs obtained by smoothing the density fields on $R = 8h^{-1}$Mpc and iii) using a volume-limited sub-sample of galaxies with absolute magnitude $M_B < -20 + 5\log h$.

Results are presented in Fig. 2 where we show that the biasing function has in general a non trivial shape and where we trace its evolution across different cosmic epochs. The main conclusions inferred by analyzing the solution of eq. [1] are presented and discussed in detail by Marinoni et al. 2005 [7]. Here we briefly summarize our main findings.
Figure 3: The redshift evolution of the linear biasing parameter on a 8$h^{-1}$Mpc scale for the volume-limited ($M_B < -20 + 5 \log h$) VVDS subsample (filled squares) is shown. The triangle represents the $z \sim 0$ bias inferred for 2dFGRS galaxies having median $L/L^* \sim 2$ (i.e. the median luminosity of the volume-limited VVDS sample). Our measurements are also compared to various theoretical models of biasing evolution. The dotted line indicates the conserving model (Fry 96), the solid and dashed lines represent the star forming (Mo & White 1996) and merging (Blanton et al. 2000) models.

i) In general, the linear approximation offers in general a poor description of the richness of details encoded in the biasing function, i.e. the linear biasing function (dotted line in Fig.2) poorly describes the observed scaling of the $\delta_g$ vs. $\delta$ relation (solid line). Non-linear effects in the biasing relation are detected at a level of $\lesssim 10\%$. In particular the ratio between the quadratic and linear term of the biasing expansion

$$\delta_g = \sum_{k=0}^{2} \frac{b_k}{k!} \delta^k. \quad (5)$$

is nearly constant in the redshift range $0.7 < z < 1.5$ and different from zero at a confidence level greater than $3\sigma$ (we find $b_2/b_1 \sim -0.15 \pm 0.04$ for $R = 8h^{-1}$Mpc). This result confirms a general prediction of CDM-based hierarchical models of galaxy formation\(^2\). However, such non-linear distortions of the biasing function are not observed locally in the 2dFGRS sample\(^1\). The fact that the $b_2/b_1$ ratio is not only different from zero but also remains constant over all the redshift intervals investigated in the range $0.7 < z < 1.5$ is even more difficult to reconcile with the "null" result of local measurements.

ii) Non-linear effects bend the biasing function in such a way that the $\delta_g$ vs. $\delta$ relation is steeper in underdense regions (the local slope is $b(\delta) > 1$) than in overdense ones. In particular, Fig. 2 shows that below some finite mass density threshold the formation efficiency of galaxies brighter than $M_B < -20 + 5 \log h$ drops to zero. Moreover the mass-density threshold below which the formation of bright galaxies ($M_B < -20 + 5 \log h$) seems to be inhibited decreases as a function of time. This trend suggests that galaxies of a given luminosity were tracing systematically higher mass overdensities in the early Universe, and that as time progresses, galaxy formation begins to take place also in lower density peaks. Stated differently, the assembling of luminous galaxies in low density regions becomes more efficient as time goes by.
We do not observe the imprints of scale-dependency in the biasing function a behavior in agreement with results derived from local surveys\textsuperscript{10} at $z \sim 0$.

By representing the biasing function in linear approximation\textsuperscript{14}, i.e. by compressing all the information contained in the $\delta_g$ vs. $\delta$ relation into a single scalar parameter $b_L$ using the equation

$$b^2_L \equiv \frac{\langle b^2(\delta) \delta^2 \rangle}{\langle \delta^2 \rangle} \quad (6)$$

it is easier to compare our results with those of other authors (who often “a-priori” adopt a linear parameterization for describing galaxy bias) and also with predictions of theoretical models. With this approximation, we have found that the linear biasing parameter evolves with cosmic time. It appears that we live in a special epoch in which the galaxy distribution traces the underlying mass distribution on large scales ($b_L \sim 1$), while, in the past, the two fields were progressively dissimilar and the relative biasing systematically higher. The difference between the value of $b_L$ at redshift $z \sim 1.5$ and $z \sim 0$ for a population of galaxies with luminosity $M_B < -20 + 5 \log h$ is significant at a confidence level greater than $3\sigma$ ($\Delta b_L \sim 0.5 \pm 0.14$).

Over the redshift baseline investigated, the rate of biasing evolution is a function of redshift: $z \sim 0.8$ is the characteristic redshift which marks the transition from a “minimum-evolution” late epoch to an early period where the biasing evolution for a population of $M_B < -20 + 5 \log h$ galaxies is substantial ($\sim 33\%$ between redshift 0.8 and 1.4).

Even at past epochs, brighter galaxies were more strongly biased than less luminous ones. Moreover the dependence of biasing on luminosity at $z \sim 0.8$ is in good agreement with what is observed in the local universe\textsuperscript{15}. In other terms even at high redshift, luminous galaxies avoid mass underdense regions while fainter ones are found also in low density environments.

By comparing our results to predictions of theoretical models for the biasing evolution, we have shown that the galaxy conserving model\textsuperscript{16} and halo merging\textsuperscript{17} model offer a poor description of our data (See Fig 3). This result could suggest that the gravitational debiasing or the hierarchical merging of halos alone may not be the only physical mechanisms driving the evolution of galaxy biasing across cosmic epochs. At variance with these results, the star forming model\textsuperscript{18} seems to describe better the observed redshift evolution of biasing. However the conclusion we can draw is that these three different models which are based on simplifying hypothesis, if considered alone, are far from being realistic. we need a more complex modeling of biasing evolution. Our analysis seems to suggest the apparent need of more complex biasing mechanisms to explain the observed biasing evolution.

The red sample is systematically a more biased tracer of mass than the blue one in every redshift interval investigated, but the relative biasing between the two populations is nearly constant in the redshift range $0.7 < z < 1.5$ ($b^{red}/b^{blue} \sim 1.4 \pm 0.1$), and comparable with local estimates (see also Meneux et al. 2006\textsuperscript{19}). Moreover, we have found that the bright red subsample is biased with respect to the general red population in the same way as the bright sample of blue objects is biased with respect to the global blue population thus indicating, that biasing as a function of luminosity might be, at first order, independent of colors.

Due to the large errorbars which still affect our results, the bias of our sample of bright and moderately red objects at $z \sim 1$ is not statistically dissimilar from that expected for EROS of similar luminosity, even if the EROS biasing appears to be systematically larger.

One key aspect of this study is the measure of evolution in the distribution properties of galaxy overdensities from a continuous volume sampled with the same selection function over a wide redshift baseline. In a different paper (Marinoni et al. in prep.) we discuss the cosmological implications of our results namely by testing the standard assumption that the structure we see
today are the results of the gravitational amplification and collapse of small primordial matter density fluctuations. As the volume sampled is still limited, errors on the analysis presented in this paper are dominated by cosmic variance. The technique presented here will be applied to a larger sample as the VVDS observational program progresses.

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References

1. Sigad, Y., Branchini, E., Dekel, A., 2000, ApJ, 540, 62
2. Somerville, R. S., Lemson, G., Sigad, Y., Dekel, A., Kauffmann, G., White, S. D. M., 2001, MNRAS 320, 289.
3. Davis, M. & Peebles, P. J. E. 1977 ApJS, 34, 425
4. Ostriker, J. P., Nagamine, K., Cen , R., Fukugita, M., 2003, ApJ, 597, 1
5. Le Fèvre, O., et al. 2005, A&A, 439, 845
6. Marinoni, C. & Hudson, M., 2002, ApJ, 569, 101
7. Marinoni, C., et al. 2005, A&A, 442, 801
8. Le Fèvre, O., et al. 2004, A&A, 428, 1043
9. Colless, M. M., 2001, MNRAS, 328, 1039
10. Verde, L., et al., 2002, MNRAS, 335, 432
11. Lahav, O., et al. 2002, MNRAS, 333, 961
12. Hatton,S., Devriendt, J. E. G., Ninin, S., Bouchet, F. R., Guiderdoni, B., & Vibert, D. 2003, MNRAS, 373, 75
13. Coles, P., & Jones, B. 1991, MNRAS, 248, 1
14. Dekel, A., & Lahav, O. 1999, ApJ, 520, 24
15. Norberg, P. et al. 2001, MNRAS, 328, 64
16. Fry, J. N. 1996, ApJ, 461, L65
17. Mo, H., White, S. D. M., 1996, MNRAS, 282, 347
18. Blanton, M., Cen, R., Ostriker, J. P., Strauss, M. A., Tegmark, M., 2000, ApJ, 531, 1
19. Meneux, B., et al. 2006, A&A, 452, 387