By studying the bispectrum of the galaxy distribution in the 2dF galaxy redshift survey (2dF-GRS), we have shown that 2dFGRS galaxies are unbiased tracers of the mass distribution. This allows us to break the degeneracy intrinsic to power spectrum studies, between the matter density parameter $\Omega_m$ and the bias parameter $b$, and to obtain an accurate measurement of $\Omega_m$: $\Omega_m, z_{\text{eff}} = 0.27 \pm 0.06$, a measurement obtained from the 2dFGRS alone, independently from other data sets. This result has to be interpreted as $\Omega_m$ at the effective redshift of the survey $z_{\text{eff}} = 0.17$. Extrapolated at $z = 0$ we obtain $\Omega_m = 0.2 \pm 0.06$ for the $\Lambda$CDM model. This constraint on the matter density parameter when combined with cosmic microwave background constraints on the flatness of the Universe, show firm evidence that the Universe is dominated by a vacuum energy component.

1 What’s bias

We are confident that the Universe started off almost uniform with very small primordial perturbations as we can see for example in the Cosmic microwave background at redshift $\sim 1100$, with a distribution very close to gaussian (cf. Heavens, Wu and Sanz contributions). Given these properties of the initial conditions and a set of cosmological parameters, it is possible to predict the statistical properties of the large scale mass distribution in the local Universe (at $z \sim 0$) via e.g. N-body simulations. If we could observe the mass distribution in the local Universe this would be a very powerful tool to/we could discriminate between different cosmological models. Unfortunately, we cannot observe the mass distribution directly, what we can easily observe is the distribution of objects that “light up” as for example the galaxy distribution in the 2dF galaxy redshift survey (2dFGRS; fig. 1 left panel). It is well known that different kind of luminous objects show different clustering properties (e.g., Peacock and Dodds 1994). Thus different
kind of luminous objects cannot be all faithful tracers of the underlying mass distribution, and
galaxies might be biased tracers of the mass: on large scales we might say $\delta_g = b \delta_m$, where
$\delta \equiv \delta \rho / \rho$ the subscripts $g$ and $m$ stand for galaxy and mass, and $b$ denotes the (linear) bias
parameter. The concept of bias was introduced by Kaiser (1984), originally to explain the clustering properties of Abell clusters, but the concept was a key element to reconcile the theoretical prejudice of an $\Omega_m = 1$ Universe with the observations of large-scale structure. Today we know that the Universe is not Einstein-de Sitter, so in principle we do not need galaxy bias, but 'the genie is out of the bottle'.

1.1 Why measure it
We could say that bias encloses our ignorance about the complicated process of galaxy formation, so we could learn about galaxy formation by measuring it. However, there is a more important reason to measure it: there is a degeneracy intrinsic to linear theory large-scale structure studies (i.e. power spectrum or correlation function studies) between the effect of gravity driven by $\Omega_m$ and the effect of bias; these studies can only yield $\beta \simeq \Omega_m^{0.6} / b$, thus we need to know, or measure, the bias parameter $b$ to get the real “prize”, $\Omega_m$. The 2dF team has measured this parameter from the survey obtaining $\beta = 0.43 \pm 0.07$ (Peacock et al. 2001).

1.2 How to disentangle gravity from bias
Gravity leaves its own signature on the distribution of mass density. In fact non-linear gravity
skews the field (because of the requirement that $\delta_m \geq -1$). Bias can also introduce skewness, but the effect of gravity on the shape of the cosmological structures is different from that of biasing: gravity creates very characteristic sheets and filaments in the mass distribution (e.g. Zeldovich pancakes). If we succeed in measuring how much gravity signature there is in the galaxy distribution, we can disentangle gravity from biasing. The statistical tool most effective to pick up this signature of gravity is the bispectrum.

2 Bispectrum
The bispectrum, $B(k_1, k_2, k_3)$, is the Fourier space counterpart of the three point correlation function, more precisely: $\langle \delta_{k_1} \delta_{k_2} \delta_{k_3} \rangle = B(k_1, k_2, k_3) \delta^3 (k_1 + k_2 + k_3)$ where $\delta^3$ denotes the Dirac delta function. Due to the presence of the Dirac delta function we see that the bispectrum is defined on triplets of $k$-vectors that form triangles. The bispectrum is zero for a gaussian field, but, even if the Universe started off with gaussian initial conditions, we should expect to detect non-zero bispectrum today on non-linear scales. In particular, the expression for the bispectrum is easy to obtain in the mildly non-linear regime i.e. in second order perturbation theory in $\delta$. (The theory of the bispectrum has been developed by e.g., Fry 1994, Matarrese Verde Heavens 1997, Verde et al 1998, Scoccimarro et al 1998, Scoccimarro et al 1999). To be consistent one has to expand also the bias to second order (i.e. $\delta_g = b_1 \delta + m + 1/2 b_2 \delta_m^2 + ...$). The expression for the galaxy bispectrum thus becomes:

$$B_g(k_1, k_2, k_3) = \left[ \frac{1}{b_1} J(k_1, k_2) + \frac{b_2}{b_1^2} \right] P_g(k_1) P_g(k_2) + \text{cyc.} \quad (1)$$

where $P_g$ denotes the (measurable) galaxy power spectrum, $B_g$ the (measurable) galaxy bispectrum and $J$ is a known function of the $k$-vectors. The shape information, that is the signature of gravity in the large scale structure distribution is enclosed in this function $J$.

The form of equation (1) implies that it is possible to extract the linear and quadratic bias parameters ($b_1$ and $b_2$) via a likelihood analysis.

* $\Omega_m$ denotes the present-day matter density of the Universe in units of the critical density.
3 The bias of 2dF galaxies

The 2dFGRS, when finished, will provide a 3D map of 250,000 galaxies. The bispectrum analysis presented here is based on only 130K of them. Equation (1) applies only on mildly non-linear scales, and, more importantly, only in a very idealized case (survey of infinite volume, the distance of galaxies is accurately known, no discreteness effects etc.). In the case of the 2dFGRS there are many real-world effects to account for (redshift space distortions, discreteness, window function, selection function etc.). We can model all these effects (for details see Verde et al. 1998, Verde et al. 2002) and assess the performance of the bispectrum method with a Monte Carlo approach, by performing the analysis on several mock 2dFGRS catalogs with known bias parameters.

We analyzed the bispectrum signal of 80 million triangles configurations from the galaxy distribution of the 2dFGRS obtaining: $b_1 = 1.04 \pm 0.11$, $b_2 = -0.05 \pm 0.08$. The 2dF galaxies on large scales are thus unbiased tracers of the mass distribution. This result is in agreement with the findings of Lahav et al. 2002 (see Lahav contribution), but has been obtained with a completely independent method and entirely from the 2dFGRS alone, independently of other data sets. The fact that the quadratic bias parameter is consistent with being zero argues powerfully that 2dFGRS galaxies indeed trace the mass on large scales.

We also find no evidence for scale dependence bias. At some level non-linear/scale dependent bias must appear on small scales, but these scales might be too small for the perturbative method used here to be valid. Note that this results applies to 2dF galaxies or more specifically to 1.9$L_*$ galaxies at $z \sim 0.17$. Because of the tendency of bias to approach unity with time, this results does not rule out the biased galaxy formation picture: galaxies might have had a significant bias at formation time.

4 The density of the Universe

By combining the 2dFGRS measurement of the $\beta$ parameter with the measurement of the bias presented here, we obtain a determination of the matter density of the Universe $\Omega_{m,z_{eff}} = 0.27 \pm 0.06$. We stress here that this result has been obtained from the 2dFGRS alone, independently of other data sets. Note that the effective depth of the survey is $z = 0.17$, thus our measurement should be interpreted as $\Omega_m$ at this epoch. The extrapolation at $z = 0$ is model dependent. In the right panel of fig. 1 the blue shaded areas show the 1,2 and 3 sigma confidence contours in the $\Omega_m$, $\Omega_\Lambda$ plane (here $\Lambda$ denotes the cosmological constant). For comparison we also show the 1,2 and 3 sigma constraints from the Boomerang data (de Bernardis 2001) and supernovae 1A (Perlmutter et al 1999). The dotted line denotes flat Universe. The solid lines show the joint confidence contours for Boomerang and 2dF. It is quite remarkable that three different experiments (subject to very different systematics) agree so well (Heavens, Verde, Percival 2002) and point towards the same cosmological model.

5 Conclusions

We have demonstrated that the optically selected galaxies from the 2dFGRS trace the dark matter density extremely well on large scales. This allows us to break the degeneracy, intrinsic to power spectrum studies, between gravity and biasing. We obtain a measurement of the matter density parameter at $z_{eff} = 0.17$ of $\Omega_{m,z_{eff}} = 0.27 \pm 0.06$. The extrapolation of this quantity at $z = 0$ is model dependent, however the constraints of cosmological parameters obtained from 2dFGRS, Cosmic microwave background and Supernovae agree remarkably well. Thus we can cosncude that we are converging towards a cosmological model where the Universe is

for more details see Lahav contribution in these proceedings or [http://www.mso.anu.edu.au/2dFGRS/]
flat, is dominated by a vacuum energy component ($\Lambda = 0.8 \pm 0.08$) and the matter density is $\Omega_m = 0.2 = \pm 0.06$.

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