Clustering of SCUBA galaxies and implications for the Planck mission

M. Magliocchetti\textsuperscript{1}, L. Moscardini\textsuperscript{2}, G. de Zotti\textsuperscript{3}, G. L. Granato\textsuperscript{3}, L. Danese\textsuperscript{1}

\textsuperscript{1}SISSA, Via Beirut 4, 34014, Trieste, Italy
\textsuperscript{2}Dipartimento di Astronomia, Università di Padova, Vicolo dell’Osservatorio 2, I-35122 Padova, Italy
\textsuperscript{3}Osservatorio Astronomico di Padova, Vicolo dell’Osservatorio 5, I-35122 Padova, Italy

Abstract. The clustering properties of SCUBA-selected galaxies are investigated within the framework of a unifying scheme relating the formation of QSOs and spheroids. The theoretical angular correlation function is derived for different bias functions, corresponding to different values of the ratio $M_{\text{halo}}/M_{\text{sph}}$ between the mass of the dark halos hosting such galaxies and the mass in stars produced at the end of the major star-formation burst. SCUBA sources are predicted to be strongly clustered, with a clustering strength increasing with mass. Comparisons with the best available measurements show better fits for $M_{\text{halo}}/M_{\text{sph}} \simeq 100$. The model can also account for the clustering of Lyman-break galaxies, seen as the optical counterpart of low- to intermediate-mass primeval spheroidal galaxies. Best agreement is once again obtained for high values of the $M_{\text{halo}}/M_{\text{sph}}$ ratio. We also discuss implications for small scale fluctuations observed at different wavelengths by forthcoming experiments such as the Planck mission aimed at mapping the Cosmic Microwave Background (CMB).

1 Clustering of Scuba Sources

The theoretical expression for the angular two-point correlation function $w(\theta)$ can be derived from its spatial counterpart $\xi$ by projection via the relativistic Limber equation (Peebles 1980):

$$w(\theta) = 2 \int_0^\infty \int_0^\infty N^2(z) b^2_{\text{eff}}(M_{\text{min}}, z) \frac{dz}{dx} \frac{\xi(r, z) dz du}{[\int_0^\infty N(z) dz]^2},$$

(1)

where $x$ is the comoving radial coordinate, $r = (u^2 + x^2 \theta^2)^{1/2}$ (for a flat universe and in the small angle approximation), and $N(z)$ is the number of objects within the shell $(z, z + dz)$. The mass-mass correlation function $\xi(r, z)$ to be inserted in eq.(1) has been obtained following the work by [10] (see also [6] and [9]), which provides an analytical way to derive the trend of $\xi(r, z)$ both in the linear and non-linear regime. Note that $\xi(r, z)$ only depends on the underlying cosmology, which we fix by adopting $h_0 = 0.7$, $\Omega_0 = 0.3$, $\Lambda = 0.7$ and a COBE-normalized value of $\sigma_8 = 1$. The relevant properties of SCUBA galaxies are included in the redshift distribution of sources $N(z)$, and in the bias factor $b_{\text{eff}}(M_{\text{min}}, z)$.

The effective bias factor $b_{\text{eff}}(M_{\text{min}}, z)$ of all the dark matter haloes with masses greater than some threshold $M_{\text{min}}$ is then obtained by integrating the quantity $b(M, z)$ (whose expression has been taken from [8]) - representing the bias of individual haloes of mass $M$ - opportunely weighted by the number density $n_{\text{SCUBA}}(M, z)$ of SCUBA sources:

$$b_{\text{eff}}(z) = \int_{M_{\text{min}}}^\infty dM b(M, z) n_{\text{SCUBA}}(M, z).$$

(2)

Note that, as $n_{\text{SCUBA}}$ can be thought as the fraction of haloes hosting a galaxy in the process of forming stars, its expression can also be written as $n_{\text{SCUBA}}(M, z) = n(M, z) T_B/t_h$, where $n(M, z) dM$ is the mass spectrum of haloes with masses between $M$ and $M + dM$ ([14]), $T_B$ is the duration of the star-formation burst and $t_h$ is the life-time of the haloes in which these objects reside (see [8]).

According to [4], sources showing up in the SCUBA counts can be broadly divided into three categories: low-mass (masses in the range $M_{\text{sph}} \simeq 10^9 - 10^{10} M_\odot$), duration of the star formation burst...
Figure 1: Predictions for the angular correlation function $w(\theta)$ of forming spheroids at 850 $\mu$m for different halo-to-bulge mass ratios and different flux cuts. Solid lines are for sources brighter than 50 mJy, dashed lines for sources brighter than 10 mJy, while dotted lines correspond to $S \geq 1$ mJy. Higher curves of each type correspond to $M_{\text{halo}}/M_{\text{sph}} = 100$, lower ones to $M_{\text{halo}}/M_{\text{sph}} = 10$.

$T_B \sim 2$ Gyr, and typical fluxes $S \lesssim 1$ mJy), intermediate-mass ($M_{\text{sph}} \simeq 10^{10} - 10^{11} M_\odot$ and $T_B \sim 1$ Gyr) and high-mass ($M_{\text{sph}} \gtrsim 10^{11} M_\odot$, $T_B \sim 0.5$ Gyr, dominating the counts at fluxes $S \gtrsim 5 - 10$ mJy). Note that by $M_{\text{sph}}$ we denote the mass in stars at completion of the star formation process.

In order to evaluate the bias factor in eq. (2) we then consider two extreme cases for the ratio between the mass in stars and the mass of the host dark halo: $M_{\text{halo}}/M_{\text{sph}} = 100$ and $M_{\text{halo}}/M_{\text{sph}} = 10$. $M_{\text{halo}}/M_{\text{sph}} = 10$ roughly corresponds to the ratio $\Omega_0/\Omega_{\text{baryon}}$ between total and baryon density, where we adopted for the latter quantity the standard value from primordial nucleosynthesis; this corresponds to having assumed all the baryons to be locked into stars and, as a consequence, has to be considered as a conservative lower limit. $M_{\text{halo}}/M_{\text{sph}} = 100$ is instead related to $\Omega_0/\Omega_\star$, $\Omega_\star$ being the present mass density in visible stars: the likely value is expected to be $M_{\text{sph}}/M_{\text{halo}} = 1 - 3\%$.

Armed with the above results we can then evaluate the two-point correlation function in eq. (1) for different $M_{\text{halo}}/M_{\text{sph}}$ ratios and different flux cuts. Figure 1 presents our predictions for $w(\theta)$, respectively for a flux cut of 50 (solid line), 10 (dashed line) and 1 (dotted line) mJy. Higher curves of each kind correspond to the case $M_{\text{halo}}/M_{\text{sph}} = 100$, while lower curves refer to $M_{\text{halo}}/M_{\text{sph}} = 10$. The highest clustering amplitude is found for the brightest sources ($S \geq 50$ mJy). This is because they are associated to the most massive dark halos and are therefore highly biased tracers of the dark matter distribution. In addition, according to [4], they have a rather narrow redshift distribution so that the dilution of the clustering signal is minimum. The very sharp drop of all the curves at $\theta \simeq 1^\circ$ is due to the absence of nearby objects. This reflects the notion that the actively star-forming phase in spheroids is completed at $z > 1$.

Note that, since the clustering amplitude strongly depends on the quantity $M_{\text{halo}}/M_{\text{sph}}$, measurements of the angular correlation function $w(\theta)$ are in principle able to discriminate amongst different models of SCUBA galaxies and in particular to determine both their star-formation rate, via the amount of baryonic mass actively partaking the process of star formation, and the duration of the star-formation burst.

A first attempt to measure the angular correlation function of $S \geq 5$ mJy SCUBA sources has been recently presented by [13]. Although such measurements are dominated by noise due to small-number statistics, it is nevertheless interesting to note that – as illustrated by the left-hand panel of Figure 2 – our model (with a preference for the $M_{\text{halo}}/M_{\text{sph}} = 100$ case) shows full consistency with the data (kindly provided by S. Scott).

Another possible way to obtain some information on the nature of SCUBA sources via their clustering properties is provided by the predictions of [4] for Lyman-break galaxies to be the low-to intermediate-mass tail of primeval spheroidal galaxies, with $T_B \sim 1 - 2$ Gyr and a star-formation rate ranging from a few to a hundred $M_\odot$ yr$^{-1}$. In Figure 2 (right-hand panel) we then plotted the predicted $w(\theta)$ for those sources with $S \geq 1$ mJy (corresponding to $M_{\text{sph}} \gtrsim 10^{10} M_\odot$), expected to be found within the redshift range $2.5 \leq z \leq 3.5$, covered by the original (Steidel et al., 1996) sample. As in the former case, the higher curve is for $M_{\text{halo}}/M_{\text{sph}} = 100$, the lower one for $M_{\text{halo}}/M_{\text{sph}} = 10$. The
data points show the measurements. Even though large errors once again affect the observational findings, it is nevertheless clear that the predicted trend for $w(\theta)$ can correctly reproduce the data for high ($80 - 100$) values of the $M_{\text{halo}}/M_{\text{sph}}$ ratio. This result is consistent with the predictions by [4] and implies a well defined relationship between SCUBA galaxies and LBGs. Furthermore, it also confirms the expectations for a small fraction (on the order of a few percent) of the total mass to be confined into stars.

Finally, it is also worth noticing that our predictions are in agreement with the strong clustering of EROs recently detected by [1], since we expect these objects to be the direct descendants of SCUBA galaxies, and therefore to exhibit the same clustering properties.

2 Power Spectrum of Temperature Fluctuations

An issue intimately connected with the analysis of galaxy clustering is the study of the contribution of unresolved sources (i.e. sources with fluxes fainter than some detection limit $S_d$) to the background intensity. Its general expression is given by:

$$I = \int_0^{S_d} \frac{dN}{dS} S dS = \frac{1}{4\pi} \int_{L_{\text{min}}}^{L_{\text{max}}} d\log L \int_{z(S_d, L)}^{z_{\text{max}}} dz \frac{\Phi(L, z)}{(1+z)^2} \frac{dK}{dz}$$

(3)

(see e.g. [2]), where $dN/dS$ denotes the differential number counts, $L_{\text{max}}$ and $L_{\text{min}}$ are respectively the maximum and minimum local luminosity of the sources, $K(L, z)$ is the K-correction, $z_{\text{max}}$ is the redshift when the sources begin to shine, $z(S_d, L)$ is the redshift at which a source of luminosity $L$ is seen with a flux equal to the detection limit $S_d$, $\Phi(L, z)$ is the luminosity function (i.e. the comoving number density of sources per unit $d\log L$), and $x$ is the comoving radial coordinate.

The intensity fluctuation $\delta I$ due to inhomogeneities in the space distribution of unresolved sources is then given by eq. (3), with the quantity $\Phi(L, z)$ replaced by $\delta \Phi(L, z)$. It is easily shown that the angular correlation of such intensity fluctuations $C(\theta) = \langle \delta I(\theta', \phi') \delta I(\theta'', \phi'') \rangle$, where $(\theta', \phi')$ and $(\theta'', \phi'')$ define two positions on the sky separated by an angle $\theta$, can be expressed as the sum of two terms $C_P$ and $C_C$, the first one due to Poisson noise (i.e. fluctuations given by randomly distributed objects), and the second one owing to source clustering. It is possible to show that, in the case of highly clustered sources, the Poissonian term $C_P$ is negligible with respect to the one due to clustering. In the following we therefore only concentrate on temperature fluctuations caused by the $C_C$ term (hereafter simply called $C$).

By making use of the quantities previously defined and of eq. (3), the clustering term $C$ takes the
form:

\[ C(\theta) = \left( \frac{1}{4\pi} \right)^2 \int_{z(\theta)}^{z_{\text{max}}} dz \frac{b_{\text{eff}}^2(M_{\text{min}}, z)}{(1 + z)^4} \left( \frac{dx}{dz} \right)^2 \int_0^\infty du \, \xi(r, z), \]  

(4)

where the effective volume emissivity \( j_{\text{eff}} \) is expressed as:

\[ j_{\text{eff}} = \int_{L_{\text{min}}}^{L_{\text{max}} L(S_d, z)} \Phi(L, z) K(L, z) L \, d\log L \]  

(5).

\( C(\theta) \) in eq. (4) has been evaluated separately for the three cases of low-, intermediate- and high-mass objects, by plugging in eq. (5) the appropriate expressions for the luminosity function. The total contribution of clustering to intensity fluctuations has then been derived by adding up all the values of \( C(\theta) \) obtained for the different mass intervals and by also taking into account the cross-correlation terms between objects of different masses, according to the expression

\[ C^{\text{TOT}}(\theta) = \sum_{i,j=1}^{3} \sqrt{C_i(\theta) C_j(\theta)}, \]  

(6)

where the indexes \( i, j \) stand for high, intermediate and low masses.

Note that, the quantity \( b_{\text{eff}}^2(M_{\text{min}}, z) \) in eq. (4) should indeed be read as \( b_{\text{eff}}^2(M_{\text{min}}, M_{\text{max}}, z) \), where \( M_{\text{max}} \) is the maximum halo mass corresponding to the maximum visible bulge mass (i.e. upper limit for the mass locked into stars), which corresponds in eq. (2) to a replacement in the upper limit of the integrals of \( \infty \) with \( M_{\text{max}} \).

The angular power spectrum of the intensity fluctuations can then be obtained via (see [2]):

\[ \delta T(\theta) = \langle (\Delta T)^2 \rangle^{1/2} = \frac{\sqrt{C^{\text{TOT}}(\theta)}}{2k_b} \left[ \exp \left( \frac{h \nu}{k_b T} \right) - 1 \right]^2 \exp \left( -\frac{h \nu}{k_b T} \right) / \left( \frac{h \nu}{k_b T} \right)^2, \]  

(7)

which relates intensity and temperature fluctuations. Figure 3 shows the predicted values for the quantity \( \delta T_l = \sqrt{l(l + 1)C_l/2\pi} \) (in units of K) at respectively 353 GHz (850 \( \mu \)m – left-hand panel) and 545 GHz (550 \( \mu \)m – right-hand panel) – the central frequencies of two of the channels of the High Frequency Instrument (HFI) of the ESA’s Planck mission – as a function of the multipole \( l \) up to \( l = 1000 \). Results are plotted for two different values of the source detection limit (\( S_d = 100 \) and 10 mJy for the 353 GHz case and \( S_d = 450 \) and 45 mJy for the 545 GHz case) and the usual two values of \( M_{\text{halo}}/M_{\text{ph}} \). Also shown, for comparison, is the power spectrum of primary (CMB) anisotropies (solid line) predicted for the cosmology specified in the caption, computed with the CMBFAST code developed by [13].

At 850 \( \mu \)m, our model predicts fluctuations of amplitude due to clustering comparable to (and possibly even larger than) those obtained for primary CMB anisotropies at \( l \gtrsim 50 \). This is because most of the clustering signal comes from massive galaxies with fluxes \( S \gtrsim 10 \) mJy, which lie at substantial redshifts and are therefore highly biased tracers of the underlying mass distribution. Also the strongly negative K-correction increases their contribution to the effective volume emissivity [eq. (3)] and therefore to the fluctuations. The 550 \( \mu \)m case is even more striking, since the contribution from clustering is expected to be more than an order of magnitude greater than the one originating from primordial fluctuations, regardless of the flux detection limit.

This implies that important information on the clustering properties of faint sub-mm galaxies (and hence on physical properties such as their mass and/or the amount of baryons involved in the star-formation process) will reside in the Planck maps at frequencies greater than 353 GHz where, however, the dominant signal is expected to come from interstellar dust emission. In order to show this effect, in Figure 3 we have also plotted the expected contribution from galactic dust emission averaged all over the sky (upper dashed-dotted curves). This was derived from the IRAS maps at 60 \( \mu \)m, rescaled at the frequencies under exam by assuming a grey-body spectrum with \( T_{\text{DUST}} = 18 \) K. As already anticipated, this signal appears to be the dominant one in both the 353 and 545 GHz Planck channels.

Nevertheless, it is still possible to extract information on the nature of sub-mm galaxies if one restricts the analysis to high galactic latitude regions (i.e. \( 80^\circ \leq b \leq 90^\circ \), lower dashed-dotted curves in Figure 3), which are the least affected by galactic dust emission. In fact, as it can be seen from Figure 3, the dust contribution in this region becomes less important than the one due to the clustering of unresolved sources for \( l \gtrsim 80 \).
Figure 3: Predicted power spectrum of temperature fluctuations $\delta T_l = \sqrt{\frac{(l+1)C_l}{2\pi}}$ (in units of K) as a function of the multipole $l$ at 353 GHz (left-hand panel) and 545 GHz (right-hand panel), the central frequencies of two Planck/HFI channels. Left-hand panel: dashed lines are for a detection limit $S_d = 100$ mJy, dotted ones for $S_d = 10$ mJy. In both cases higher curves are obtained for $M_{\text{halo}}/M_{\text{sph}}=100$, lower ones for $M_{\text{halo}}/M_{\text{sph}}=10$. The solid line represents the power spectrum of primary CMB anisotropies as predicted by a standard Cold Dark Matter model for a $\Lambda$CDM cosmology ($\Lambda = 0.7$, $\Omega_0 = 0.3$, $h_0 = 0.7$). Right-hand panel: as in the former case but with flux detection limits of 450 (dashed lines) and 45 (dotted lines) mJy. The overlap observed here is due to paucity of bright ($S \sim 50$ mJy) sources. In both panels the upper dashed-dotted curve represents the contribution from galactic dust emission averaged all over the sky, while the lower one illustrates the case obtained by restricting the analysis to high galactic latitudes ($80^\circ \leq b \leq 90^\circ$).

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