Clustering of submillimetre galaxies in a self-regulated baryon collapse model

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ABSTRACT

We investigate anisotropies in the cosmic infrared background (CIB) using a combination of the physical evolutionary model for proto-spheroid galaxies of Granato et al. and an independent halo occupation distribution analysis. After having re-calibrated the cumulative flux function dS/dz at λ ≥ 850 μm using the available determinations of the shot-noise amplitude (the original model already correctly reproduced it at shorter wavelengths), the CIB power spectra at wavelengths from 250 μm to 2 mm measured by Planck, Herschel, South Pole Telescope and Atacama Cosmology Telescope experiments have been fitted using the halo model with only two free parameters, the minimum halo mass and the power-law index of the mean occupation function of satellite galaxies. The best-fitting minimum halo mass is log (Mmin/M⊙) = 12.24 ± 0.06, higher than, but consistent within the errors, the estimate by Amblard et al. and close to the estimate by Planck Collaboration. The redshift evolution of the volume emissivity of galaxies yielded by the model is found to be consistent with that inferred from the data. The derived effective halo mass, Meff ≃ 5 × 1012 M⊙, of z ∼ 2 submillimetre galaxies is close to that estimated for the most efficient star formers at the same redshift. The effective bias factor and the comoving clustering radius at z ∼ 2 yielded by the model are substantially lower than those found for a model whereby the star formation is fuelled by steady gas accretion, but substantially higher than those found for a merger-driven galaxy evolution with a top-heavy initial mass function.

Key words: galaxies: haloes – galaxies: high-redshift – galaxies: statistics – submillimetre: galaxies.

1 INTRODUCTION

The Herschel surveys have allowed clustering studies (Cooray et al. 2010; Maddox et al. 2010) of submillimetre (submm) galaxies with a statistics at least 1 order of magnitude better than previously possible (Blain et al. 2004; Scott, Dunlop & Serjeant 2006). These studies have been complemented by determinations of the angular power spectrum of the cosmic infrared background (CIB) anisotropies on Balloon-borne Large Aperture Submillimeter Telescope (BLAST; Viero et al. 2009), Planck (Planck Collaboration 2011) and Herschel (Amblard et al. 2011) maps. Due to the unique power of submm surveys in piercing the distant universe, thanks to the strongly negative K-correction, the clustering properties contain signatures of the large-scale structure at high redshifts and can allow us to discriminate between different formation mechanisms that have been proposed for submm galaxies. For example, merger-driven galaxy evolution models, which follow the evolution of both the disc and the spheroidal components of galaxies, predict much lower clustering strengths for submm galaxies (e.g. Almeida, Baugh & Lacey 2011; Kim et al. 2011) than models whereby the star formation is fuelled by steady gas accretion, but substantially higher than those found for a merger-driven galaxy evolution with a top-heavy initial mass function.

In this paper, building on the work by Negrello et al. (2007), we investigate the constraints set by mm and submm clustering data on the physical model worked out by Granato et al. (2001, 2004) and further elaborated by Lapi et al. (2006) and Mao et al. (2007).

A specific prediction of the model is that high-z massive protospheroidal galaxies dominate the submm counts over a limited flux density range (cf. Lapi et al. 2011). At 250 μm, the Euclidean normalized differential counts of these objects peak at ≃30 mJy; above ≃ 60 mJy and below ≃ 10 mJy the counts are dominated by z ≲ 1.5 quiescent and star-bursting late-type galaxies, less massive and less...
clustered than the high-z proto-spheroidal galaxies. The flux density range where proto-spheroidal galaxies dominate broadens and the peak shifts to brighter flux densities with increasing (sub)mm wavelength. Therefore, in this scenario, the expected clustering strengths depend on the flux density range that is being probed and on wavelength.

Several other analyses of data on the angular correlation function of (sub)mm sources and of the power spectrum of the CIB anisotropies have been carried out. They, however, use phenomenologically parametrized models for the evolution of extragalactic sources (Hall et al. 2010; Planck Collaboration 2011; Millea et al. 2012; Pénin et al. 2012) or even of the clustering power (Addison et al. 2011). Also data at different wavelengths are usually fitted separately (Ambland et al. 2011; Planck Collaboration 2011). On the contrary, the present analysis relies on a physical model for the evolution of proto-spheroidal galaxies (although the treatment of spiral and starburst galaxies is phenomenological) and aims at accounting simultaneously for clustering data over a broad range of wavelengths, from 250 μm to a few mm.

It should be noted, however, that the physical model is exploited only to compute the cumulative flux function that weights the redshift-dependent spatial power spectrum in the Limber approximation for the angular power spectrum. The halo occupation distribution (HOD), which is a statistical description of how dark matter haloes are populated with galaxies, is dealt with in a simplified manner, without including the relationship between luminosity and halo mass. A pioneering model that explicitly includes a relationship between infrared luminosity and halo mass has been presented by Shang et al. (2011).

The plan of the paper is as follows. In Section 2 we present a short overview of the evolutionary model for the relevant galaxy populations. In Section 3 we describe the halo model formalism used to compute the contributions to the power spectrum of CIB anisotropies and to the angular correlation function of detected galaxies (Section 4). Our main results are presented in Section 5 and our main conclusions are summarized in Section 6.

We adopt a standard flat Λ cold dark matter (ΛCDM) cosmology with $h = H_0/100$ km s$^{-1}$ Mpc$^{-1} = 0.70$ and a local matter density $\Omega_m = 0.27$.

2 OVERVIEW OF THE MODEL

The submm extragalactic sources are a mixed bag of various populations of dusty galaxies and of flat-spectrum radio sources (see e.g. Lapi et al. 2011).

Our model interprets powerful high-z submm galaxies as massive proto-spheroidal galaxies in the process of forming most of their stellar mass (see also Blain et al. 2004; Davé et al. 2010; Narayanan et al. 2010). It hinges upon high-resolution numerical simulations showing that dark matter haloes form in two stages (Zhao et al. 2003; Lapi & Cavaliere 2011; Wang et al. 2011). An early fast collapse of the halo bulk, including a few major merger events, reshuffles the gravitational potential and causes the dark matter and the stellar component to undergo (incomplete) dynamical relaxation. A slow growth of the halo outskirts in the form of many minor mergers and diffuse accretion follows; this second stage has little effect on the inner potential well where the visible galaxy resides.

The star formation is triggered by the fast collapse/merger phase of the halo and is controlled by self-regulated baryonic processes. It is driven by the rapid cooling of the gas within a region of $\sim 70 M_{\odot}/10^{13} M_{\odot}^{1/3} (1 + z/3)^{1/2}$ kpc, where $M_{\odot}$ is the halo mass, is regulated by the energy feedback from supernovae (SNe) and active galactic nuclei (AGNs), is very soon obscured by dust and is stopped by quasar feedback. The AGN feedback is relevant especially in the most massive galaxies and is responsible for their shorter duration ($5\sim 10^9$ yr) of the active star-forming phase. In less massive proto-spheroidal galaxies, the star formation rate (SFR) is mostly regulated by SN feedback and continues for a few Gyr.

Since spheroidal galaxies are observed to be in passive evolution at $z \lesssim 1$–1.5 (e.g. Renzini 2006), they are visible at submm wavelength only at high redshifts. Lapi et al. (2011) have shown that the Granato et al. (2004) model, as further elaborated by Lapi et al. (2006), provides a reasonably good fit to the observed counts from 250 μm to $\sim 1$ mm as well as to the luminosity functions in the range $z = 1$–4 and to the redshift distributions at $z > 1$ estimated from Herschel-ATLAS (Eales et al. 2010) data.

The fit was obtained using a single spectral energy distribution (SED) (that of the well-studied $z = 2.3$ strongly lensed galaxy SMM J2135–0102, ‘The Cosmic Eyelash’; Ivison et al. 2010; Swinbank et al. 2010) for the whole population of proto-spheroidal galaxies. This is obviously an oversimplification and indeed the Lapi et al. (2011) counts are somewhat high at mm wavelengths, especially at relatively bright flux densities. As a consequence, the model overestimates the Poisson (shot-noise) contribution to the power spectrum of intensity fluctuations since such contribution is directly related to the source counts [see equation (21)]. Consistency with the shot-noise levels estimated by Planck Collaboration (2011) at 353 GHz and measured by Hall et al. (2010), Dunkley et al. (2011) at 220 and 150 GHz is recovered scaling down the cumulative flux function $dN/dz$; [see equation (19)] of proto-spheroidal galaxies by a factor of 0.81, 0.71 and 0.55 at 353, 217 and 150 GHz (850 μm, 1.38 mm, 2 mm), respectively. No correction was applied at higher frequencies. In practice, we use the determination of the shot-noise amplitude to recalibrate the function $dN/dz$ to be used to compute the clustering power spectrum, which is measured independently. This correction mimics the effect of adopting an SED decreasing with increasing wavelength beyond the peak a bit more steeply than the one adopted by Lapi et al. (2011).

As suggested in the latter paper, the overestimate of mm-wave counts may be cured if higher-z galaxies, which yield larger and larger contributions to the bright counts at increasing mm wavelengths, have SEDs slightly hotter than SMM J2135–0102 and closer to that of G15.141 (Cox et al. 2011; see fig. 2 of Lapi et al. 2011). We have checked that indeed a good fit of the counts at all the frequencies considered here is obtained using the SMM J2135–0102 SED for galaxies at $z < 3.5$ and the SED of G15.141 at higher $z$. However, the match of the frequency spectrum of the shot-noise amplitude also improves but not enough to reach consistency with observational estimates at the longer wavelengths. Since the shot-noise amplitude can be computed directly from the counts, this suggests that there may be some small, but non-negligible, offsets between the calibration of point source flux densities and that of the diffuse background. This is not surprising since, in addition to the possibility of an imperfect photometric calibration, at mm wavelengths the recovery of the contribution of dusty galaxies to the power spectrum requires a delicate subtraction of the other components [cosmic microwave background (CMB), cirrus emission, fluctuations due to radio sources]. A rescaling to match the shot-noise spectrum seems to be the only practical way for correcting for these offsets. Since the modification is only significant at $\geq 850$ μm (in the observer frame, i.e. well beyond the peak for most sources, the impact on the bolometric luminosity, which is related to the halo mass, is minor. For galaxies at redshifts up to $z = 3.5$, accounting...
for essentially all the signal, the bolometric luminosity varies by $\leq 2$ per cent. For comparison, the coefficient of the relationship between the SFR (given by the model) and the bolometric luminosity has an uncertainty of $\sim 30$ per cent (Kennicutt 1998).

The Granato et al. (2004) model is meant to take into account the star formation occurring within galactic dark matter haloes virialized at $z_{\text{vir}} \gtrsim 1.5$ and larger than $M_{\text{vir}} \sim 10^{11.2} M_\odot$, which are, crudely, associated to massive spheroidal galaxies. We envisage disc (and irregular) galaxies as associated primarily to haloes virializing at $z_{\text{vir}} \lesssim 1.5$, which have incorporated, through merging processes, a large fraction of haloes less massive than $10^{11.2} M_\odot$ virializing at earlier times, which may become the bulges of late-type galaxies. The model, however, does not follow the formation and evolution of disc and bulge components of galaxies. For spiral and starburst galaxies, we adopt the phenomenological model described by Negrello et al. (2007). On the other hand, as shown in the following, these galaxies are essentially non-influential for the purposes of the present paper in the considered frequency range: proto-spheroids are the sine and cosine integrals, respectively:

\begin{equation}
\langle M \rangle = \int \frac{dM}{M} \frac{\langle N_{\text{gal}}(N_{\text{gal}} - 1) \rangle_{\text{gal}}}{\bar{n}_{\text{gal}}} [u_{\text{gal}}(k, M)]^2,
\end{equation}

where $\bar{n}_{\text{gal}}$ is the mean number density of galaxies: $\bar{n}_{\text{gal}} = \int \frac{dM}{M} \frac{\langle N_{\text{gal}} \rangle}{\langle N_{\text{gal}} \rangle_{\text{gal}}}$. Following Bullock et al. (2001), we approximate the dependence of the concentration $c$ on $M$ and $z$ as

\begin{equation}
c(M, z) = \frac{9}{1 + \frac{M}{M_c}} \left( \frac{M}{M_c} \right)^{-0.13},
\end{equation}

where $M_c(z)$ is the characteristic mass scale at which $c(M, z) = 1$; $M_c(z = 0) \approx 5 \times 10^{12} h^{-1} M_\odot$.

In the 1-halo term [equation (2)] we set $s = 2$, in analogy with the corresponding term for the dark matter power spectrum, if $\langle N_{\text{gal}}(N_{\text{gal}} - 1) \rangle_{\text{gal}} > 1$. Otherwise we set $s = 1$ since if the halo contains only one galaxy, it will sit at the centre. Taking into account that $\langle N_{\text{gal}}(N_{\text{gal}} - 1) \rangle_{\text{gal}} \approx 2 \langle N_{\text{gal}} \rangle_{\text{gal}}^2 + \langle N_{\text{gal}} \rangle_{\text{gal}}^2$ and that only the galaxies that are not at the centre get factors of $u_{\text{gal}}(k, M) \sim u_{\text{gal}}(k, M)$, we have

\begin{equation}
P_{\text{gal}}^{1h}(k, z) = P_{\text{gal}}^{1h}(k, z) + P_{\text{gal}}^{2h}(k, z),
\end{equation}

where $d\kappa/dM$ is the halo mass function (Sheth & Tormen 1999) and the linear matter power spectrum, $P_{\text{lin}}(k, z)$, has been computed using the CAMB code\footnote{http://camb.info/} (Lewis, Challinor & Lasenby 2000). Here, $u_{\text{gal}}(k, M)$ denotes the Fourier transform of the mass density profile of the galaxy distribution within the dark matter halo, which we assume to be approximately the same as that of the dark matter, i.e. we take $u_{\text{gal}}(k, M) \approx u_{\text{gal}}(k, M)$.

\begin{equation}
P_{\text{gal}}^{2h}(k, z) = P_{\text{lin}}(k, z) \left[ \int \frac{dM}{M} \frac{\langle N_{\text{gal}} \rangle}{\langle N_{\text{gal}} \rangle_{\text{gal}}} b(M, z) u_{\text{gal}}(k, M) \right]^2,
\end{equation}

and $\rho_{\text{gal}}/M = 3/(4\pi R^2)$. On large scales, where the 2-halo term dominates, $u_{\text{gal}}(k, M) \to 1$ and $P_{\text{gal}}^{2h}(k, z) \approx b_{\text{gal}}^2 P_{\text{lin}}(k, z)$ with $b_{\text{gal}}(z) = \int_V d\kappa f(\kappa) \left( \frac{\rho_{\text{gal}}}{M} \right) (b(M, z) \langle N_{\text{gal}} \rangle_{\text{gal}})/\bar{n}_{\text{gal}}$.

The mean mass density profile of haloes of mass $M$ is (Navarro, Frenk & White 1996)

\begin{equation}
\rho(r) = \frac{\rho_c}{(r/r_c)(1 + r/r_c)^2},
\end{equation}

where $\rho_c = \sigma^2/(2\pi G)$. The normalized Fourier transform of this profile is

\begin{equation}
\mathcal{C}(k,M) = \rho_c^2 \left[ \log(1 + c) - \frac{c}{1 + c} \right],
\end{equation}

with $c = r_{\text{vir}}/r_s$. The normalized Fourier transform of this profile is

\begin{equation}
u_{\text{gal}}(k, M) = \frac{4\pi \rho_c r_s^3}{M} \left[ (\sin(kr_s) - C_i[(1 + c)kr_s]) + \cos(kr_s) [C_i[(1 + c)kr_s] - C_i(kr_s)] - \frac{\sin(kr_s)}{(1 + c)kr_s} \right],
\end{equation}

where $\sin$ and $Ci$ are the sine and cosine integrals, respectively:

\begin{equation}
\sin(x) = \int_0^x \frac{\sin(t)}{t} dt, \quad Ci(x) = -\int_x^\infty \frac{\cos(t)}{t} dt.
\end{equation}

Following Bullock et al. (2001), we approximate the dependence of the concentration $c$ on $M$ and $z$ as

\begin{equation}
c(M, z) = \frac{9}{1 + \frac{M}{M_c}} \left( \frac{M}{M_c} \right)^{-0.13},
\end{equation}

where $M_c(z)$ is the characteristic mass scale at which $c(M, z) = 1$; $M_c(z = 0) \approx 5 \times 10^{12} h^{-1} M_\odot$.

Following Tinker & Wetzel (2010), the mean occupation functions of central and satellite galaxies are parametrized as

\begin{equation}
(N_{\text{cen}}) = \frac{1}{2} \left[ 1 + \text{erf} \left( \frac{\log(M/M_{\text{min}})}{\sigma(\log(M))} \right) \right],
\end{equation}

\begin{equation}
(N_{\text{sat}}) = \frac{1}{2} \left[ 1 + \text{erf} \left( \frac{\log(M/2M_{\text{min}})}{\sigma(\log(M))} \right) \right] \left( \frac{M}{M_{\text{sat}}} \right)^{\alpha_{\text{sat}}},
\end{equation}

where $M_{\text{min}}$, $\alpha_{\text{sat}}$, $M_{\text{sat}}$ and $\sigma(\log(M))$ are free parameters assumed to be redshift-independent. In this formalism, haloes below $M_{\text{min}}$ do not contain galaxies while haloes above this threshold contain a central galaxy plus a number of satellite galaxies with a power-law mass function with slope $\alpha_{\text{sat}}$.
We also define the effective large-scale bias, $b_{\text{eff}}(z)$, as

$$b_{\text{eff}}(z) = \int_{M} \frac{dM}{dM} \frac{\langle N_{\text{gal}} \rangle}{\bar{n}_{\text{gal}}} b(M, z),$$  \hspace{1cm} (16)

and the effective mass of the halo, $M_{\text{eff}}$,

$$M_{\text{eff}}(z) = \int_{M} \frac{dM}{dM} \frac{\langle N_{\text{gal}} \rangle}{\bar{n}_{\text{gal}}}.$$  \hspace{1cm} (17)

### 4. ANGULAR POWER SPECTRUM OF INTENSITY FLUCTUATIONS

The angular power spectrum $P(k_{\theta})$ of intensity fluctuations due to a projection of scattering of sources fainter than some flux density limit $S_{\text{lim}}$ is a projection of the spatial power spectrum of such sources at different redshifts $z$, $P_{\text{gal}}(k, z)$. In the Limber approximation, valid if the angular scale is not too large (i.e. $2\pi k_{\theta} \geq 10$), the relation between $P_{\text{gal}}(k, z)$ and $P(k_{\theta})$ is

$$P(k_{\theta}) = \int_{0}^{\infty} dz \frac{dS}{dz} P_{\text{gal}}(k = \frac{2\pi k_{\theta} + 1/2}{\chi(z)}, z) \left( \frac{dS}{dz} \right)^2 dz \frac{dV_{\theta}}{dz},$$  \hspace{1cm} (18)

where $dS/dz$ is the redshift distribution of the cumulative flux of sources with $S \leq S_{\text{lim}}$,

$$dS = \int_{0}^{S_{\text{lim}}} d\log_{10}(S) S \phi(L(S, z), z) \frac{dV_{\theta}}{dz},$$  \hspace{1cm} (19)

$\phi(L, z)$ is the epoch-dependent comoving luminosity function per unit interval of $\log_{10}(L)$, and $dV_{\theta}$ is the comoving volume element, $dV_{\theta} = \chi^2 d\chi$, $\chi(z)$ being the comoving radial distance:

$$\chi(z) = \frac{c}{H_0} \int_{0}^{z} \frac{dz'}{\Omega_{\text{m}0}(1+z')^3 + (1 - \Omega_{\text{m}0})}.$$  \hspace{1cm} (20)

Poison fluctuations add a white noise contribution to the power spectrum of fluctuations:

$$P_{\text{shot}} = \int_{0}^{S_{\text{lim}}} \frac{dN}{d\log_{10} S} S^2 d\log_{10} S,$$  \hspace{1cm} (21)

with

$$\frac{dN}{d\log_{10} S} = \int dz \phi[L(S, z), z] \frac{dV_{\theta}}{dz}.$$  \hspace{1cm} (22)

We have computed the functions $dS/dz$ for each galaxy population using the cosmological model described in Section 1 and the evolutionary models briefly described in Section 2. As mentioned in Section 2, the functions $dS/dz$ for proto-spheroidal galaxies at frequencies $\lesssim 353$ GHz ($\lambda \gtrsim 850$ $\mu$m) have been scaled down by constant factors to comply with the measurements or the best estimates of the shot-noise levels. At higher frequencies, our model accurately fits the observed source counts and therefore provides directly reliable estimates of the shot-noise level.

We have chosen to deal with the shot noise and the clustering contributions to the power spectrum of CIB fluctuations independently of each other because the former are independent of the parameters describing the clustering and are strongly constrained by the available source counts. Moreover, when only relatively low-resolution data are available, as is the case for Planck, there is a degeneracy between the shot-noise and the 1-halo clustering term. As clearly highlighted by Planck Collaboration (2011), an unsupervised least-square fit of the full CIB power spectrum measured by Planck, taking the shot-noise amplitude as a free parameter, leads to fits of similar quality with and without a substantial contribution from the 1-halo term. But fits with a low contribution from the 1-halo term imply shot-noise amplitudes far in excess of those estimated from the source counts. The higher resolution of Herschel, South Pole Telescope (SPT) and Atacama Cosmology Telescope (ACT) data breaks the degeneracy at $v \gtrsim 600$ GHz and at $v \leq 220$ GHz, respectively, allowing a direct estimate of the shot-noise amplitude.

As for the halo model, we have considered two distinct populations, i.e., proto-spheroidal galaxies and late-type galaxies, both quiescent and starbursting. Taking into account the constraints on clustering of late-type galaxies coming from IRAS data (Mann, Saunders & Taylor 1995; Hawkins et al. 2001), we find that the contribution of these sources is always subdominant and, correspondingly, their halo model parameters are very poorly constrained. Moreover, the values of $M_{\text{sat}}$ and $\sigma(\log_{10}M)$ are poorly constrained also for proto-spheroidal galaxies (Planck Collaboration 2011). We have therefore fixed $M_{\text{sat}} = 20M_{\text{min}}$ and $\sigma(\log_{10}M) = 0.6$ [within the ranges found by Tinker & Wetzel (2010) from clustering studies of optical galaxies] for both populations, and $M_{\text{min,late-type}} = 10^{11} M_{\odot}$ and $\alpha_{\text{sat,late-type}} = 1$. We are then left with only two free parameters, i.e., $M_{\text{min}}$ and $\alpha_{\text{sat}}$, for proto-spheroidal galaxies.

The angular power spectra of CIB anisotropies at 217, 353, 545 and 857 GHz on the multipole range $200 \leq \ell \leq 2000$ have been determined by Planck Collaboration (2011) using Planck maps of six regions of low Galactic dust emission with a total area of 140 deg$^2$. In the same paper, the power spectrum measurements by Amblard et al. (2011), using Herschel/SPIRE data at 250, 350 and 500 $\mu$m and extending down to sub-arcmin angular scales, i.e. up to $\ell \sim 2 \times 10^4$, were re-analysed. It was found that Amblard et al. (2011) overestimated the correction for contamination by Galactic cirrus. Moreover, the diffuse-emission calibration of SPIRE data was improved using the more accurate Planck/HFI calibration. We have used the Amblard et al. (2011) data as corrected by Planck Collaboration (2011) at 350 and 500 $\mu$m. No correction could be applied at 250 $\mu$m so that the data points at this wavelength could be underestimated.

Power spectrum measurements at mm wavelengths (around 150 and 220 GHz) have been obtained with the SPT and the ACT (Hall et al. 2010; Das et al. 2011; Dunkley et al. 2011; Shirokoff et al. 2011). The subtraction of the other components (CMB, Sunyaev–Zeldovich effect, radio sources) has been done using the best-fitting values given in the papers. Note that the units quoted as $\mu K^2$ are actually $\mu K^2$ sr$^{-1}$. The conversion factor from these units to $Jy^2$ sr$^{-1}$ is $\simeq [24.8(x^2/\sinh(x/2))]^2/[2\ell(\ell + 1)]$. The factor $[24.8(x^2/\sinh(x/2))]^2$ is $\simeq 1.55 \times 10^4$ at 150 GHz and $\simeq 2.34 \times 10^4$ at 217 GHz.

The angular correlation function $w(\theta)$ for a single source population writes, in terms of the 2D power spectrum $P(k_{\theta})$,

$$w(\theta) = 2\pi \int_{0}^{\infty} k_{\theta} P(k_{\theta}) J_0(2\pi k_{\theta} \theta) dk_{\theta},$$  \hspace{1cm} (23)

where $J_0$ is the Bessel function of order 0.

Here we have two subpopulations, proto-spheroidal and spirals+starburst galaxies, with different clustering properties. If their cross-correlations can be ignored, the signal for the whole is given by (Wilman et al. 2003)

$$w_{ps}(\theta) = f_{ps}^2 w_{ps}(\theta) + f_{ss}^2 w_{ss}(\theta),$$  \hspace{1cm} (24)

where $f_{ps}$ and $f_{ss}$ are the fractional contributions of proto-spheroidal and spirals+starburst galaxies, respectively, to the total counts:

$$f_{ps/ss} = \int dz N_{ps/ss}(z) \frac{dV}{dz}.$$

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being the redshift distribution. Ignoring the cross-correlations between the two source populations is justified because of the widely different redshift distributions implied by the adopted evolutionary model: as mentioned in Section 2, proto-spheroidal galaxies are associated with galactic-size haloes virialized at $z_{\text{vir}} \gtrsim 1.5$ while disc (and irregular/starburst) galaxies are associated primarily with haloes virializing at $z_{\text{vir}} \lesssim 1.5$.

The spatial correlation function $\xi(r, z)$ is the Fourier anti-transform of the 3D power spectrum:

$$\xi(r, z) = \frac{1}{2\pi} \int_0^{\infty} k^2 P_{\text{gal}}(k) \left( \frac{\sin(kr)}{kr} \right) dk.$$  \hfill (26)

The clustering radius $r_0(z)$ is defined by $\xi(r_0, z) = 1$.

5 RESULTS

Figs 1 and 2 compare the best-fitting model power spectrum with Planck, Herschel and SPT data in the wavelength range from 250 $\mu$m to 2 mm. The agreement is generally good except at 250 $\mu$m, where the model is consistently above the data points by Amblard et al. (2011) which, however, could be underestimated (see Section 4). As mentioned above, we have only two free parameters, i.e. the minimum mass and the power-law index of the mean occupation function of satellite galaxies of proto-spheroidal galaxies. The constraints we obtain are $\log(M_{\text{min}}/M_\odot) = 12.24 \pm 0.06$ and $\alpha_{\text{sat}} = 1.81 \pm 0.04$ (1$\sigma$). The nominal errors on each parameter have been computed marginalizing on the other and correspond to $\Delta \chi^2 = 1$.

We caution that the true uncertainties are likely substantially higher than the nominal values, both because the model relies on simplifying assumptions that may make it too rigid and because of possible systematics affecting the data.

The fact that the same values of these parameters account for the clustering data from 2 mm to 250 $\mu$m confirms the conclusion by Planck Collaboration (2011) that CIB fluctuations over this wavelength range are dominated by a single subpopulation of dusty galaxies. According to our model, this subpopulation is made of proto-spheroidal galaxies making most of their stars at $z > 1$. We find that only at 250 $\mu$m other dusty galaxy populations, normal disc and starburst galaxies, make a significant but still subdominant contribution to the clustering power spectrum. As shown by Lapi et al. (2011), according to our model, proto-spheroidal galaxies also account for the bulk of the CIB intensity in this wavelength range.

Figure 1. CIB angular power spectra $P(k_\theta)$ at submm wavelengths. Data from Planck Collaboration (2011) and Herschel/HerMES (Amblard et al. 2011). For the Herschel/HerMES data at 350 and 500 $\mu$m, we have adopted the values corrected by Planck Collaboration (2011). At 250 $\mu$m we have used the values given by Amblard et al. (2011), which may be underestimated because of an oversubtraction of the cirrus contamination and a slight overestimate of the effective beam area. The conversion from the multipole number $\ell$ used by Planck Collaboration (2011) and the wavenumber $k$ (arcmin$^{-1}$) is $k = \ell / (2 \times 180 \times 60)$. The lines show the contributions of the 1-halo and 2-halo terms for the two populations considered here [spiral and starburst (SS), and proto-spheroidal (PS) galaxies]. The magenta horizontal lines denote the shot-noise level.

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consistent with the finding by Planck Collaboration (2011) that the CIB anisotropies have the same frequency spectrum as the CIB intensity.

Our estimate of the minimum mass is higher than, but consistent, within the errors, those found by Amblard et al. (2011) considering a single galaxy population and five free parameters per frequency (but one of the parameters is unconstrained by the data within the prior range): \( \log(M_{\text{min}}/M_\odot) = 11.1_{-0.5}^{+0.2} \) at 250 \( \mu \)m, \( \log(M_{\text{min}}/M_\odot) = 11.5_{-0.3}^{+0.2} \) at 350 \( \mu \)m and \( \log(M_{\text{min}}/M_\odot) = 11.8_{-0.4}^{+0.3} \) at 500 \( \mu \)m. Our value of \( \alpha_{\text{sat}} \) is also consistent with those by Amblard et al.: \( \alpha_{\text{sat}} = 1.6_{-0.4}^{+0.2} \) at 250 \( \mu \)m, \( \alpha_{\text{sat}} = 1.8_{-0.4}^{+0.2} \) at 350 \( \mu \)m and 500 \( \mu \)m. In Planck Collaboration (2011), two or three free parameters per frequency were used; the derived minimum masses are in the range \( \log(M_{\text{min}}/M_\odot) = 11.8 \text{--} 12.5 \).

There is however an interesting difference with Planck Collaboration (2011), due to the different redshift distributions of sources. The crossover between the 1-halo and the 2-halo term occurs, according to the model by Planck Collaboration (2011), at multipole numbers ranging from \( l \simeq 800 \) at 857 GHz (350 \( \mu \)m) to \( l \simeq 1200 \) at 217 GHz (1.38 mm) corresponding to angular scales ranging from \( \theta \simeq 180 \times 60/\pi \simeq 13.5 \) arcmin at 857 GHz to 9 arcmin at 217 GHz. According to the Béthermin et al. (2011) model used in that paper, the contribution to the CIB intensity at 857 GHz peaks at \( z \simeq 1 \), where the angular scale of 13.5 arcmin corresponds to a physical linear scale \( L \simeq 6.5 \) Mpc; at 217 GHz the bulk of the CIB contribution comes from \( z > 2 \), where an angular scale of 9 arcmin corresponds to a physical linear scale \( L \simeq 4.5 \) Mpc. The non-linear masses corresponding to an overdensity \( \Delta_c = 1.68 \) on these scales are \( M_{\text{nl}}(z = 1; L = 6.5 \) Mpc) \( \simeq 7 \times 10^{13} M_\odot \) and \( M_{\text{nl}}(z = 2; L = 4.5 \) Mpc) \( \simeq 8 \times 10^{14} M_\odot \), respectively. For comparison, the characteristic non-linear masses computed from \( \sigma(M_{\ast}, z) = 1.68 \sigma(M_{\ast}, z) \) being the rms overdensity) are \( M_{\ast}(z = 1) = 2 \times 10^{11} M_\odot \) and \( M_{\ast}(z = 2) = 7.3 \times 10^{11} M_\odot \). This suggests that structures going non-linear on the considered scales are extremely rare at the corresponding redshifts. This potential difficulty is eased in our model because the crossover scales are lower by almost a factor of 2. As shown by Figs 1 and 2, the 1-halo/2-halo crossover occurs at \( \ell \simeq 450 \) at 857 GHz and at \( \ell \simeq 2100 \) at 217 GHz, corresponding to angular scales of 7.4 and 5.1 arcmin, respectively.

Our value of \( M_{\text{min}} \) implies an effective halo mass [equation (17)] at \( z \simeq 2 \) of proto-spheroidal galaxies, making up most of the CIB, \( M_{\text{eff}} \simeq 5 \times 10^{12} M_\odot \), close to the estimated halo mass of the most effective star formers in the universe. Tacconi et al. (2008) estimated their mean comoving density at \( z \sim 2 \) to be \( \sim 2 \times 10^{-4} \) Mpc\(^{-3} \). For the standard \( \Lambda \)CDM cosmology, this implies that they are hosted by dark matter haloes of \( \sim 3.5 \times 10^{12} M_\odot \) (Dekel, Sari & Ceverino 2009).

Fig. 3 compares the flux density coming from different redshifts, \( \delta S/\delta z \) [equation (19)], predicted by the model at the SPIRE wavelengths with the best-fitting estimates by Amblard et al. (2011). Planck Collaboration (2011) give (their table 7) the best-fitting values of the redshift-independent volume emissivity, \( j_{\text{eff}} \), for \( z > 3.5 \) [their equation (43)]. The values of \( j_{\text{eff}} \) given by our model (52, 175, 265 and 205 Jy sr\(^{-1} \) Mpc\(^{-1} \) at 217, 353, 545 and 857 GHz, respectively) are consistent with the best-fitting results.

As for the angular correlation function, \( w(\theta) \), of detected SPIRE galaxies, Cooray et al. (2010) reported measurements of \( w(\theta) \) for sources brighter than 30 mJy at all SPIRE wavelengths and inferred values of \( \log(M_{\text{min}}/M_\odot) \) ranging from 12.6\(^{+0.3}_{-0.6} \) at 250 \( \mu \)m to 13.5\(^{+0.3}_{-1.0} \) at 500 \( \mu \)m. On the other hand, Maddox et al. (2010) did not detect a significant clustering for their 250 \( \mu \)m selected sample with a flux limit of 33 mJy beam\(^{-1} \), but detected strong clustering at 350 and 500 \( \mu \)m, albeit with relatively large uncertainties. Our model entails a relationship between the far-IR/submm luminosity of proto-spheroidal galaxies (that provide the dominant contribution to \( w(\theta) \), see the left-hand panel of Fig. 4) and the associated halo masses (Lapi et al. 2011). For the flux density limit adopted by...
Cooray et al. (2010), 30 mJy at all SPIRE wavelengths, the model yields log \( (M_{\text{min}}/M_\odot) \simeq 12.3, 13 \) and 13.2 at 250, 350 and 500 \( \mu \)m, respectively, while for the flux density limits of Maddox et al. (2010; 33, 36 and 45 mJy), we have log \( (M_{\text{min}}/M_\odot) \simeq 12.3, 13.1 \) and 13.4. The corresponding predictions for \( \theta \) are compared with the data in Fig. 4. The agreement of the model with the data is generally good, although the situation at 250 \( \mu \)m is unclear since there is a discrepancy between the Cooray et al. (2010) and the Maddox et al. (2010) results.

**6 DISCUSSION AND CONCLUSIONS**

According to the Granato et al. (2004) model, the steep portion of submm counts is dominated by massive proto-spherical galaxies in the process of forming most of their stars on a time-scale varying with halo mass (shorter for more massive galaxies), but typically of \( \sim 0.7 \) Myr, i.e. with a duty cycle of \( \sim 0.2 \) at \( z \simeq 2 \), where their redshift distribution peaks. As shown above, this model allows us to reproduce the power spectrum of CIB fluctuations over a broad frequency range, from 250 \( \mu \)m to a few mm, with only two free parameters. The model also yields an effective volume emissivity at different redshifts consistent with observational estimates. The derived effective halo mass, \( M_{\text{eff}} \sim 5 \times 10^{12} M_\odot \), is close to that estimated for the most efficient star formers at \( z \simeq 2 \).

The multipole number at which the 1-halo contribution to the clustering power spectra ranges from \( \ell = 1450 \) at 857 GHz to \( \ell = 2100 \) at 217 GHz. These values are almost a factor of 2 higher (and, consequently, the corresponding angular scales are almost a factor of 2 lower) than those found by Planck Collaboration (2011). Since, at the redshifts where the contribution to the CIB intensity peaks, the corresponding masses are well above \( M_\ast \), this difference translates into a much larger abundance of the relevant haloes.

Alternative models make quite different predictions for the clustering properties of submm galaxies. A widespread view is that these objects are powered by major merger events. Two major theories have been worked out in this general framework. One view is that submm galaxies are massive objects, seen during a short-duration, intense, merger-induced burst of star formation (e.g. Narayanan et al. 2009). Since massive galaxies are rare at high-z and, because of the short duration of the burst, only a small fraction of them are in the submm bright phase at a given time, this scenario has difficulty in reproducing the observed counts. This difficulty may be overcome assuming an extremely top-heavy initial stellar mass function that would allow much less massive (hence far more abundant) galaxies to reach the required luminosities (e.g. Baugh et al. 2005; Lacey et al. 2010).

The clustering implied by the latter scenario has been investigated by Almeida et al. (2011) who found, at \( z = 2 \), a comoving correlation length of \( r_0 = 5.6 \pm 0.9 \) h\(^{-1}\) Mpc for galaxies with 850 \( \mu \)m flux densities brighter than 5 mJy or an effective bias factor \( b_{\text{eff}} = 2.3 \); for galaxies with \( S_{450 \mu m} > 5 \) mJy they found \( b_{\text{eff}} = 2.1 \). Our model implies log \( (M_{\min}/M_\odot) \simeq 12.4 \) for sources with \( S_{450 \mu m} > 5 \) mJy and log \( (M_{\min}/M_\odot) \simeq 13.0 \) for sources with \( S_{850 \mu m} > 5 \) mJy. The corresponding values of the clustering radius and of the effective bias factor are \( r_0 \simeq 11.2 h^{-1} \) Mpc, \( b_{\text{eff}} = 4.3 \) at 850 \( \mu \)m, and \( r_0 \simeq 7.3 h^{-1} \) Mpc, \( b_{\text{eff}} = 3.1 \) at 450 \( \mu \)m. The study by Kim et al. (2011) confirms that the clustering data require a higher amplitude of the 2-halo term, i.e. more massive haloes than implied by the major mergers plus top-heavy initial stellar mass fraction scenario.

Davé et al. (2010) investigated the clustering properties of rapidly star-forming galaxies at \( z \simeq 2 \) in the framework of a very different scenario based on cosmological hydrodynamic simulations whereby the star formation is not powered by mergers but by steady gas accretion and cooling that can fuel the star formation for several Gyr. In this scenario, typical submm galaxies at \( z = 2 \) live in massive (\( \sim 10^{13} M_\odot \)) haloes and have a duty cycle \( \sim 50 \) per cent. They are expected to be strongly clustered, with a clustering ratio \( r_0 \sim 10 h^{-1} \) Mpc and a bias factor of \( \sim 6 \). These values are well in excess of those following from our analysis which yields, for the bulk of galaxies at \( z \simeq 2 \), \( r_0 \sim 6.9 h^{-1} \) Mpc, \( b_{\text{eff}} \sim 3 \).

These results illustrate the power of accurate measurements of the CIB power spectrum and of the correlation function of galaxies at (sub)mm wavelengths to discriminate among competing evolutionary models for the population of dusty galaxies.

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Clustering of dusty galaxies
1331