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# Evidence for merger-driven activity in the clustering of high-redshift quasars

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## ABSTRACT

Recently, a very large clustering length has been measured for quasars at a redshift of  $z \sim 4$ . In combination with the observed quasar luminosity function, we assess the implications of this clustering for the relationship between quasar luminosity and dark matter halo mass. Our analysis allows for non-linearity and finite scatter in the relation between quasar luminosity and halo mass, as well as a luminosity dependent quasar lifetime. The additional novel ingredient in our modelling is the allowance for an excess in the observed bias over the underlying halo bias owing to the merger driven nature of quasar activity. We find that the observations of clustering and luminosity function can be explained only if both of the following conditions hold: (i) the luminosity to halo mass ratio increases with halo mass; (ii) the observed clustering amplitude is in excess of that expected solely from halo bias. The latter result is statistically significant at the 99 per cent level. Taken together, the observations provide compelling evidence for merger driven quasar activity, with a black-hole growth that is limited by feedback. In difference from previous analyses, we show that there could be scatter in the luminosity–halo mass relation of up to 1 dex, and that quasar clustering cannot be used to estimate the quasar lifetime.

**Key words:** large scale structure of Universe – cosmology: theory – quasars: general.

## 1 INTRODUCTION

The Sloan Digital Sky Survey (SDSS; York et al. 2000) and the 2dF quasar redshift survey (Croom et al. 2001a) have measured redshifts for large samples of quasars, and determined their luminosity function over a broad section of cosmic history (Boyle et al. 2000; Richards et al. 2006). These surveys have also been used to constrain the clustering properties of quasars (e.g. Croom et al. 2001b, 2002, 2005; Porciani & Norberg 2006; da Ângela et al. 2008; Padmanabhan et al. 2008), including the variation of clustering length with redshift and luminosity. In the local Universe, quasars have clustering statistics similar to optically selected galaxies, with a clustering length  $R_0 \approx 8$  Mpc. The clustering length increases towards high redshift, but is only weakly dependent on luminosity. This has been interpreted as evidence for a model in which the quasar luminosity takes on a broad range of values at different stages of its evolution (Lidz et al. 2006).

In addition to the large quasar samples below  $z \sim 3$ , the SDSS has discovered luminous quasars at redshifts as high as  $z \sim 6.4$ , i.e. when the universe was less than a billion years old (Fan et al. 2001a,b, 2003, 2006). The supermassive black holes (SMBH) powering these quasars have masses of  $\gtrsim 10^9 M_\odot$ . Recently, clustering

measurements of quasars have been extended out to redshifts beyond  $z \sim 4$  using the Fifth Data Release of the SDSS (Shen et al. 2007). Quasars are shown to be significantly more clustered at high redshift relative to the more local samples, with values of  $R_0 \approx 24.1$  Mpc and  $R_0 \approx 34.7$  Mpc at  $z \sim 3$  and  $z > 3.5$ , respectively (Shen et al. 2007). White, Martini & Cohn (2008) have recently shown that this large clustering length can be associated with the observation of a very large clustering bias of  $b = 14.2 \pm 1.4$  for quasars at  $z \sim 4$ .

It was argued by Cole & Kaiser (1989), and later by Martini & Weinberg (2001) and Haiman & Hui (2001), that the quasar correlation length can be used to infer the typical mass of dark matter haloes in which quasars reside. One may then derive the quasar duty-cycle by comparing the number density of quasars with the density of host dark matter haloes. The quasar lifetime follows from the product of the duty-cycle and the time that the dark-matter halo spends in between major mergers (although there is a degeneracy between the lifetime and the quasar occupation fraction or beaming). Results from low redshift clustering have suggested quasar lifetimes of  $t_q \sim 10^6$ – $10^7$  yr, consistent with the values determined by other methods (see Martini 2003 for a review). More recently, Shen et al. (2007) have applied this analysis to their measurements of quasar clustering at high redshift. They infer lifetimes of  $t_q \sim 3 \times 10^7$ – $6 \times 10^8$  yr for quasars at  $z > 3.5$ .

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Using techniques similar to those employed at low redshift, this result has been used by White et al. (2008) to argue that the scatter in the relation between quasar luminosity and halo mass must be smaller than 0.3 dex. This small scatter poses a problem for theories of quasar growth and formation. The tightest local relation is observed between the black hole mass and bulge velocity dispersion, also with a scatter of  $\sim 0.3$  dex. However, the relation between quasar luminosity and halo mass must have several additional sources of scatter, including in the relation between halo mass and velocity dispersion, and between black hole mass and quasar luminosity. It is therefore difficult to understand how the luminosity–halo mass relation could be as tight as the black-hole mass–velocity dispersion relation.

The conclusion of White et al. (2008) arises because an increased scatter would tend to bring large numbers of low bias haloes (which are more common) into a sample of haloes at fixed quasar luminosity. The required small scatter therefore depends crucially on the assumption that the value of the observed bias truly reflects the actual bias of the quasar host galaxies. However, additional bias may exist beyond the usual halo bias for systems which are triggered by mergers, although the magnitude (and even the sign) of the effect are still being debated (e.g. Kolatt et al. 1999; Gottlöber et al. 2002; Kauffmann & Haehnelt 2002; Percival et al. 2003; Scannapieco & Thacker 2003; Gao, Springel & White 2005; Wetzell et al. 2007). Interpreting the results of simulations of the effect of mergers on bias is complicated by the small range of redshift and mass available in different studies. Furlanetto & Kamionkowski (2006) attempted to describe the clustering bias of merging systems more generally based on an analytic model. They concluded that a peak-background split approach within the extended Press–Schechter formalism cannot be used to calculate the merger bias because the large-scale density field does not enter the calculation of merger rates using this approach. Instead, Furlanetto & Kamionkowski (2006) calculated the merger bias in models where the merger rate per halo is assumed to scale with the number densities of neighbouring haloes. Since this model does not account for the large-scale density in the merger rate itself (but only in the halo densities), Furlanetto & Kamionkowski (2006) argue that it can only be considered qualitative. However, the model suggests that merging haloes are significantly more clustered than isolated haloes, by a factor of  $\sim 1.5$  for massive haloes at  $z \sim 3$ . Furlanetto & Kamionkowski (2006) also proposed a simple model in which close pairs are assumed to be merging systems, and compute the bias of those based on probabilities of separation based on clustering statistics in a variety of models, with similar results.

The possibility that the observed bias exceeds the average halo bias at a particular halo mass is not restricted to scenarios where observed objects are merger driven. A separate, but related issue concerns halo formation bias. Here, subsamples of dark matter haloes of fixed mass and redshift are shown to have clustering statistics that depend on their formation history (Gao, Springel & White 2005; Croton, Gao & White 2007; Wetzell et al. 2007). For example, if the existence of luminous quasars required that the host halo be older than a particular minimum age, then this subsample of haloes would have a clustering bias in excess of the halo population as a whole.

Since luminous quasars play an important role in the evolution of massive galaxies at high redshifts, a variety of models have been proposed to explain the high-redshift luminosity function of quasars (e.g. Haiman & Loeb 1998; Haehnelt, Natarajan & Rees 1998; Kauffmann & Haehnelt 2000; Volonteri, Haardt & Madau 2003; Wyithe & Loeb 2003; Di Matteo, Springel & Hernquist 2005; Li et al. 2007; Hopkins & Hernquist 2008; Hopkins et al. 2008). The majority of these models assume that major mergers drive the

quasar activity, implying that the observed bias should not simply reflect the bias based on the host halo mass.

In this paper, we investigate the evidence for an additional bias, beyond the spatial clustering of dark matter haloes, in the clustering data of high-redshift quasars. Wyithe & Padmanabhan (2006) showed that different models are able to reproduce the data on the high-redshift quasar luminosity function, implying a degeneracy among their input physical parameters.<sup>1</sup> For this reason, we will not attempt to model physical processes such as SMBH growth and feedback, but instead adopt the more general approach of parametrizing relations like the correlation between SMBH mass and halo mass. We are interested in the full range of allowed parameters as well as in which sets of parameters can be excluded, rather than in a particular set of parameters that is able to describe the data. This approach allows us to isolate the relationships that are constrained by the data, and to provide robust observational input for future theoretical modelling. In particular, the contribution of mergers to the observed clustering bias could be large, although its value is theoretically uncertain.

We note that while previous published suggestions for an excess merger driven bias provide motivation for our paper, we have constructed our model to be independent of the physical origin of any bias that is in excess of the usual halo clustering bias. We therefore introduce a factor relating the observed bias to the halo bias as an additional free parameter in our modelling, and examine whether or not the previously reported tensions between quasar bias and density (White et al. 2008) lead to constraints on this number.

In our numerical examples, we adopt the standard set of cosmological parameters (Komatsu et al. 2008), with values of  $\Omega_m = 0.24$ ,  $\Omega_b = 0.046$  and  $\Omega_Q = 0.72$  for the matter, baryon and dark energy fractional density, respectively, and  $h = 0.70$ , for the dimensionless Hubble constant. We assume  $\sigma_8 = 0.82$  for the *rms* amplitude of the density field fluctuations within spheres of radius  $8 h^{-1}$  Mpc linearly extrapolated to  $z = 0$ , and a power-law slope for the primordial density power spectrum of  $n_s = 0.96$ .

## 2 MODEL

Quasars are known to have a finite distribution of Eddington ratios (Kollmeier et al. 2006),  $\eta \equiv l/L_{\text{Edd}}$ , where  $l$  and  $L_{\text{Edd}}$  are the quasar and Eddington luminosities, respectively, and are thought to have a light curve that varies across a large range of luminosity during the quasar lifetime (Hopkins & Hernquist 2008). We can express this light curve as  $l(t, M_{\text{bh}}) \propto \eta(t) M_{\text{bh}}$ , where  $M_{\text{bh}}$  is the black hole mass and  $\eta$  is a dimensionless function of time. Consider now a population of quasars at a fixed instant in time. We expect to observe a range of quasar luminosity  $l$  at fixed host halo mass  $M$  because different quasars will be at a different phase of their light curve. We first compute the distribution of luminosity  $l$  at fixed halo mass and fixed black hole mass

$$\frac{dP}{dl} \Big|_{M, M_{\text{bh}}} \propto \frac{dt}{dl} \frac{dP_{\text{prior}}}{dt} \propto \left( M_{\text{bh}} \frac{d\eta}{dt} \right)^{-1} \frac{\Theta(t_{\text{lt}})}{t_{\text{lt}}}. \quad (1)$$

Here,  $(dP_{\text{prior}}/dt) = \Theta(t_{\text{lt}})/t_{\text{lt}}$  (where  $\Theta$  is the Heaviside Step function), is constant during the quasar lifetime ( $0 < t < t_{\text{lt}}$ ), and zero

<sup>1</sup> These degeneracies could be broken using the observed quasar clustering, provided that the quasar host mass could be directly connected to quasar clustering. However, as discussed in the introduction, this connection may not be direct since quasars may reside in haloes with excess bias.

at other times. The distribution of  $l$  at fixed halo mass is then

$$\left. \frac{dP}{dl} \right|_M \propto \int dM_{\text{bh}} \left. \frac{dP}{dM_{\text{bh}}} \right|_M \left. \frac{dP}{dl} \right|_{M, M_{\text{bh}}}, \quad (2)$$

where  $(dP/dM_{\text{bh}})|_M$  is the probability distribution for the black-hole mass which depends on halo mass. The mean of the logarithm of the luminosity at halo mass  $M$  can now be calculated from

$$(\log L)(M) = \int d \log l \log l \left. \frac{dP}{d \log l} \right|_M, \quad (3)$$

while the variance (in dex) can be calculated as

$$\Delta^2(M) = \int d \log l (\log l - \log L)^2 \left. \frac{dP}{d \log l} \right|_M. \quad (4)$$

In this paper, we do not use the above equations to compute the relation between the quasar luminosity,  $L$ , and host halo mass,  $M$ . Rather, we suggest a parametrized form based on the above definitions and constrain the parameters of the  $L$ – $M$  relation using the available data for high-redshift quasars. We begin by parametrizing the relation between the mean quasar luminosity,  $L$ , and host halo mass,  $M$ , as

$$\frac{L}{L_0} = \left( \frac{M}{M_0} \right)^\gamma, \quad (5)$$

where  $L_0$  and  $M_0$  are normalization constants. We then suppose that this relation has an intrinsic scatter in luminosity  $l$  at fixed halo mass  $M$  of  $\Delta$ . For simplicity, we assume that the distribution  $dP/dl|_M$  is log-normal and express its scatter in dex. Rewriting the mean relation as

$$M = M_0 \left( \frac{L}{L_0} \right)^{1/\gamma}, \quad (6)$$

we then specify the scatter in the  $M$ – $L$  relation in terms of a probability distribution for halo mass  $m$  at fixed luminosity  $L$ , that is

$$\left. \frac{dP}{d \log m} \right|_L = \frac{1}{\sqrt{2\pi}(\Delta/\gamma)} \exp \left[ -\frac{(\log m - \log M)^2}{2(\Delta/\gamma)^2} \right]. \quad (7)$$

We next specify a model for the luminosity function of quasars (i.e. the number density of quasars per unit luminosity with luminosity  $L$ ),

$$\frac{dn}{dL} = \int d \log m \left. \frac{dn}{dm} \right|_{L, M_0} \left. \frac{dP}{d \log m} \right|_L f_{\text{duty}} \left( \frac{L}{L_0} \right)^\alpha, \quad (8)$$

where  $\left. \frac{dn}{dm} \right|_{L, M_0}$  is the Sheth & Tormen (1999) mass-function for dark matter haloes of mass  $M$ , and the derivative

$$\frac{dm}{dL} = \frac{dM}{dL} \frac{dm}{dM} = \frac{m}{M} \frac{M_0}{L_0} \frac{1}{\gamma} \left( \frac{L}{L_0} \right)^{(1/\gamma)-1}. \quad (9)$$

The duty-cycle  $f_{\text{duty}} = t_{\text{lt}}/t_{\text{H}} \times f_{\text{special}}$ , where  $t_{\text{H}}$  is the Hubble time at redshift  $z$ , is the fraction of haloes that have a quasar in a luminous phase, and the last factor in equation (8) accounts for the possibility that the quasar lifetime  $t_{\text{lt}}$  is dependent on black hole mass.<sup>2</sup> The parameter  $f_{\text{special}}$  is explicitly included because our analysis allows for the possibility that only some special haloes are able to host a

<sup>2</sup> In this paper, we only consider the luminosity function and its slope at a single value of luminosity. While we have quoted a power-law form for the dependence of duty-cycle on luminosity we note that this should be thought of as a logarithmic slope at luminosity  $L$ . In general, the value of  $\alpha$  must be luminosity dependent or else the duty-cycle would exceed unity for some values of luminosity.

quasar. We return to this point below. The luminosity function has an associated logarithmic slope

$$\beta(L) \equiv \frac{d}{d \log L} \left( \log \frac{dn}{dL} \right). \quad (10)$$

We also compute the density of quasars above a limiting luminosity  $L$ ,

$$n(>L) = \int_L^\infty dL' \frac{dn}{dL'}. \quad (11)$$

The halo bias of quasars with luminosity  $L$  is given by

$$\bar{b}(L) = \frac{\int d \log m b(m) (dn/dm) (dP/d \log m)|_L}{\int d \log m (dn/dm) (dP/d \log m)|_L}, \quad (12)$$

where  $b(m)$  is the halo bias of a halo with mass  $m$ , which is computed using the fitting formula of Sheth & Tormen (1999). This bias can be used to calculate the halo bias of a sample of quasars with luminosities above a limiting value.

$$\langle b \rangle = \frac{\int_L^\infty dL' \bar{b}(L') (dn/dL')}{\int_L^\infty dL' (dn/dL')}. \quad (13)$$

As noted in Section 1, this average halo bias may underestimate the observed quasar bias if quasars are triggered by galaxy mergers (Furlanetto & Kamionkowski 2006). To account for this possibility, we introduce a free parameter  $F$ , defined as the ratio of the observed bias  $b_{\text{obs}}$  to the halo bias  $\langle b \rangle$ ,

$$F \equiv \frac{b_{\text{obs}}}{\langle b \rangle}. \quad (14)$$

A situation where  $F > 1$  implies that only a subsample of special dark matter haloes at a mass  $M$  are able to host quasars. For this reason, we have explicitly included a factor to account for the fraction of special haloes in addition to the lifetime within our definition of duty-cycle (equation 8). The inclusion of the parameter  $f_{\text{special}}$  implies that the maximum possible value of duty-cycle may be smaller than unity (unless there is more than one quasar per halo). This issue is discussed in Appendix A, where we show that unless the value of  $F$  is very large, the value of  $f_{\text{special}}$  could be of order unity. Using the results of Appendix A, we assume in this paper that the maximum allowed value of  $f_{\text{duty}}$ , which is treated as a free parameter in our modelling, is given by

$$f_{\text{max}} = \frac{(b_{\text{obs}}/F)^2 - 1}{b_{\text{obs}}^2 - 1}. \quad (15)$$

Note that the value of the black-hole mass does not enter our calculations. Thus, our conclusions are insensitive to assumptions regarding the Eddington ratio and the relation between black-hole mass and halo mass. Conversely, this means that our model is not able to address issues surrounding these relations. Nevertheless, as we show below, this simplicity does allow our model to reach some strong conclusions regarding the relationship between the observed quasar clustering and the host halo mass.

Before proceeding to analyse the implications of existing observational data, we note that the detailed results are sensitive to the form of the halo mass function. Our fiducial calculations use the Sheth–Tormen form. However, in Section 3.5, we also present results using the corresponding Press–Schechter formulation to assess the level of theoretical uncertainty in the results.

### 3 COMPARISON WITH OBSERVATIONS

The quantities  $n(>L)$ ,  $\beta$  and  $b_{\text{obs}}$  are observed properties of the quasar population, with values of  $n(>L) \sim 0.7 \times 10^{-7} \text{ Mpc}^{-1}$ ,

$\beta = -2.58 \pm 0.23$  and  $b_{\text{obs}} = 14.2 \pm 1.4$ , respectively. The quasar sample from which the clustering and corresponding density data were obtained was described in Shen et al. (2007). The bias and density for quasars at  $z \sim 4$  were discussed for this sample in White et al. (2008), and we use their calculated bias in this paper. The luminosity function slope is taken from the quasar luminosity function analysis of Fan et al. (2001b), for which the mean quasar redshift and absolute AB magnitude at  $1450 \text{ \AA}$  were  $z = 4.3$  and  $M_{1450} \approx -26$ , respectively. These quantities can be compared to the theoretical expectations described above, and hence used to constrain the free parameters,  $f_{\text{duty}}$ ,  $\alpha$ ,  $\Delta$ ,  $\gamma$  and  $F$ .

### 3.1 Results

We begin by illustrating the dependencies of the observables on the available free parameters. In Figs 1 and 2, we show contours of constant  $\langle b \rangle / F$  in the plane of  $f_{\text{duty}}$  and  $\Delta$ . Since the halo bias is related to the observed bias through an unknown constant  $F$ , we begin by showing two cases for illustration. In the first we choose  $F = 1$ , which is the standard model employed to link clustering statistics to halo mass and quasar lifetime in previous studies (Cole & Kaiser 1989; Martini & Weinberg 2001; Haimes & Hui 2001; White et al. 2008). In the second, we adopt  $F = 1.5$ , which is approximately the factor by which the observed bias exceeds the halo bias in the models of Furlanetto & Kamionkowski (2006). In Figs 1 and 2, the solid and dashed contours are plotted for values of  $F = 1.0$  and  $1.5$ , respectively. We find that there are no combinations of  $f_{\text{duty}}$  and  $\Delta$  that produce the best-fitting value of the observed bias for  $F = 1$  (White et al. 2008). In this case, we draw a contour (solid line) at the  $2\sigma$  lower limit of  $\langle b \rangle = (14.2 \pm 1.4) / F = 14.2 - 2.8 = 11.4$ . In the second case with  $F = 1.5$ , the contours (dashed lines) are drawn to correspond to the observed bias  $\langle b \rangle = (14.2 \pm 1.4) / F$ . Note that in the case of  $F = 1.5$ , only values of duty-cycle that are smaller than  $f_{\text{max}} \sim 0.4$  are viable.

In constructing these contours, for each combination of  $f_{\text{duty}}$  and  $\Delta$  the luminosity  $L$  is chosen so that the luminosity function reproduces the observed density of quasars. The duty-cycle on the  $x$ -axis corresponds to quasars with this luminosity  $L$ . For fixed values of  $F$ ,  $\gamma$  and  $\alpha$ , the contours in Figs 1 and 2 enclose the acceptable combinations of  $f_{\text{duty}}$  and  $\Delta$ , given the constraint of the observed bias. We find that smaller values of duty-cycle permit smaller values of intrinsic scatter in the  $L$ - $M$  relation. The two figures separate the effect of the parameters  $\alpha$  and  $\gamma$  on the derived constraints. In Fig. 1, we set  $\alpha = 0$  and vary the value of  $\gamma$ . In Fig. 2, we fix the value of  $\gamma = 1$  and vary  $\alpha$ . The observed bias tightly constrains the scatter in the  $L$ - $M$  relation (White et al. 2008). In particular, if  $F = 1$ ,  $\gamma = 1$ , the constraints show that  $\Delta < 0.1$  at the  $2\sigma$  level, which is tighter than the local relation between black-hole mass and velocity dispersion. The clustering and density data are not consistent with  $F = 1$  at the  $1\sigma$  level for any of the parameter sets shown. Since the scatter  $\Delta$  must be finite, the contours therefore suggest that  $F > 1$ , even at the highest possible duty-cycle.

In addition to the observed bias, our model is constrained by the observed luminosity function slope. In Figs 1 and 2, we also show the region of parameter space that is consistent with the constraint from the observed luminosity function slope (grey-scale). The predicted slope is sensitive to the value of  $\gamma$ . As a result, the values of  $f_{\text{duty}}$  and  $\Delta$  that are consistent with the observed slope are also sensitive to  $\gamma$ . Viable models must have overlapping regions of parameter space that satisfy the different constraints. Figs 1 and 2 show that unless  $\gamma$  or  $\alpha$  are large, there are no combinations of  $f_{\text{duty}}$

and  $\Delta$  that are even marginally consistent with the constraints of observed bias and luminosity function slope for  $F = 1$ .

### 3.2 Joint Likelihood distributions for pairs of parameters

To quantify the above conclusions, we next calculate the joint likelihoods for pairs of parameters, and the a posteriori probability distributions for individual parameters.

The likelihood for the parameter set  $(\Delta, \gamma, f_{\text{duty}}, F, \alpha)$  is

$$\mathcal{L}_{\Delta, \gamma, f_{\text{duty}}, F, \alpha} = \exp \left\{ -\frac{1}{2} \left[ \left( \frac{F(b) - 14.2}{1.4} \right)^2 + \left( \frac{\beta - 2.58}{0.23} \right)^2 \right] \right\} \Theta(f_{\text{max}} - f_{\text{duty}}) \quad (16)$$

Here  $\Theta(x)$  is the Heaviside step function, which imposes the constraint of a maximum possible duty-cycle at a given value of  $F$ . We then obtain marginalized likelihoods by integrating over the remaining parameters. For example, the joint likelihood for  $\Delta$  and  $f_{\text{duty}}$  is

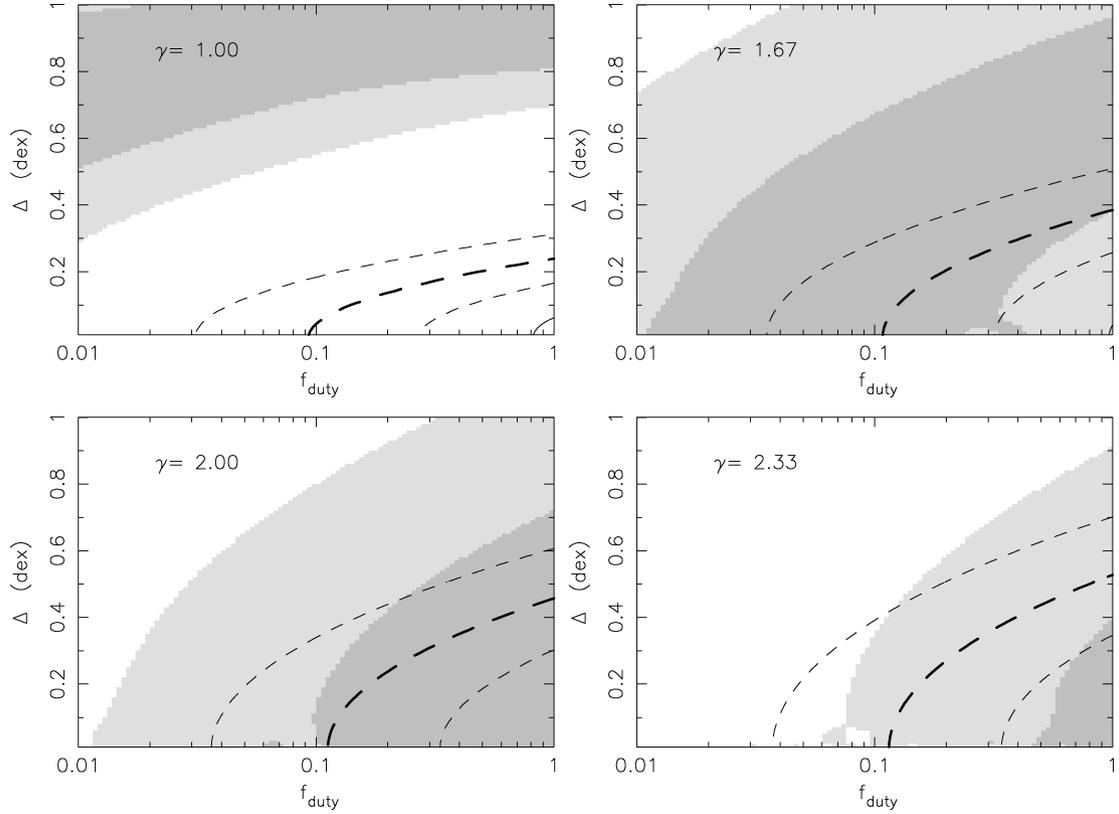
$$\mathcal{L}_{\Delta, f_{\text{duty}}} \propto \int_{\alpha_{\text{min}}}^{\alpha_{\text{max}}} d\alpha \int_{\gamma_{\text{min}}}^{\gamma_{\text{max}}} d\gamma \int_{F_{\text{min}}}^{F_{\text{max}}} dF \mathcal{L}_{\Delta, \gamma, f_{\text{duty}}, F, \alpha} \times \frac{dP_{\text{prior}}}{d\alpha} \frac{dP_{\text{prior}}}{d\gamma} \frac{dP_{\text{prior}}}{dF}, \quad (17)$$

where  $\alpha_{\text{min}}$  and  $\alpha_{\text{max}}$  are the bounding values on the finite region of the prior probability distribution  $dP_{\text{prior}}/d\alpha$  for the variable  $\alpha$ , and so on. We assume constant prior probability distributions for  $\alpha$ ,  $\Delta$  and  $\gamma$ . For  $F$  and  $f_{\text{duty}}$ , which are fractional quantities, we assume prior probability distributions that are flat in the logarithm of these quantities. We assume the prior probability to be non-zero within the following ranges:  $\alpha_{\text{min}} = -2$ ,  $\alpha_{\text{max}} = 2$ ;  $\gamma_{\text{min}} = 0$ ,  $\gamma_{\text{max}} = 2.5$ ;  $\Delta_{\text{min}} = 0$ ,  $\Delta_{\text{max}} = 2$ ;  $F_{\text{min}} = 0.5$ ,  $F_{\text{max}} = 3$ ;  $f_{\text{duty, min}} = 0.01$ ,  $f_{\text{duty, max}} = 1$ . While some of our quantitative results are sensitive to the values of these limits, our primary qualitative conclusions are robust to the choice of the prior probability distributions and their ranges.

Fig. 3 shows contours of the joint likelihood distributions for  $f_{\text{duty}}$  and  $F$  (top left panel), for  $\gamma$  and  $F$  (top right panel), for  $\Delta$  and  $\alpha$  (central left panel), for  $F$  and  $\Delta$  (central right panel), for  $F$  and  $\alpha$  (lower left panel) and for  $\gamma$  and  $\alpha$  (lower right panel). Contours are shown at 60 and 7 per cent of the maximum likelihood. Since the number of free parameters exceeds the number of observables, a unique model cannot be found. Nevertheless, the results of Fig. 3 illustrate that despite some degeneracies, several interesting statements can be made regarding the allowed parameter values.

Our main results are as follows. First, the parameter  $\alpha$  is constrained to lie within a finite range centred around  $\alpha \approx -0.3$ . In addition, lower limits can be placed on the value  $\gamma$ , which we find to be larger than unity. The value of the scatter is restricted to be  $\Delta \lesssim 1$  dex. This constraint is much less stringent than the conclusion of White et al. (2008). The difference can be traced to the fact that White et al. (2008) assumed the halo bias to be equal to the observed bias. We find that degeneracies prevent the data from imposing an upper limit on  $\gamma$  or a lower limit<sup>3</sup> on  $\Delta$  (although the latter cannot be negative). We find that the duty-cycle is unconstrained by these

<sup>3</sup> Note that the value of  $\Delta$  would be expected lie in excess of the scatter of  $\sim 0.3$  dex in the local relation between velocity dispersion and black-hole mass. Inclusion of this constraint as a prior on  $\Delta$  tightens the constraints on other parameters but does not change our qualitative conclusions.



**Figure 1.** Solid and dashed lines: contours of joint likelihood for pairs of  $\Delta$  and  $f_{\text{duty}}$  given the observed bias. The solid and dashed contours correspond to values of  $F = 1.0$  and  $1.5$ , respectively. For  $F = 1$ , the contour is drawn at the  $2\sigma$  lower limit of  $\langle b \rangle = 11.4$ . For  $F = 1.5$ , the contours are drawn at  $\langle b \rangle = (14.2 \pm 1.4)/F$ . In each case, the luminosity  $L$  corresponds to the observed density of quasars. The grey-scale shows the corresponding joint likelihood given the constraint of the observed luminosity function slope  $\beta = -2.58 \pm 0.23$ . The dark and light grey show the regions where the predicted slope is within  $1$  and  $2\sigma$  of the best-fitting value. Four examples are shown for different values of  $\gamma$ , with  $\alpha = 0$  in all cases.

observations. This result differs from previous studies (e.g. Martini & Weinberg 2001) because the parameter  $F$  removes the direct connection between halo bias and halo mass (and hence halo density). The value of  $F$  is constrained to be larger than unity, with a preferred value near  $1.5$ . This is our most important conclusion, and we will return to its implications in Section 4.

### 3.3 Constraints on individual parameters

By analogy with equation (17), the joint likelihood function  $\mathcal{L}_{\Delta, \gamma, f_{\text{duty}}, F, \alpha}$  can be marginalized over all remaining parameters to find the likelihood for a single variable. For example, the likelihood for  $\Delta$  is

$$\mathcal{L}_{\Delta} \propto \int_{f_{\text{duty}, \text{min}}}^{f_{\text{duty}, \text{max}}} df_{\text{duty}} \int_{\alpha_{\text{min}}}^{\alpha_{\text{max}}} d\alpha \int_{\gamma_{\text{min}}}^{\gamma_{\text{max}}} d\gamma \int_{F_{\text{min}}}^{F_{\text{max}}} dF \mathcal{L}_{\Delta, \gamma, f_{\text{duty}}, F, \alpha}. \quad (18)$$

The a posteriori probability density for  $\Delta$  becomes

$$\frac{dP}{d\Delta} \propto \mathcal{L}_{\Delta} \frac{dP_{\text{prior}}}{d\Delta},$$

with the normalization,

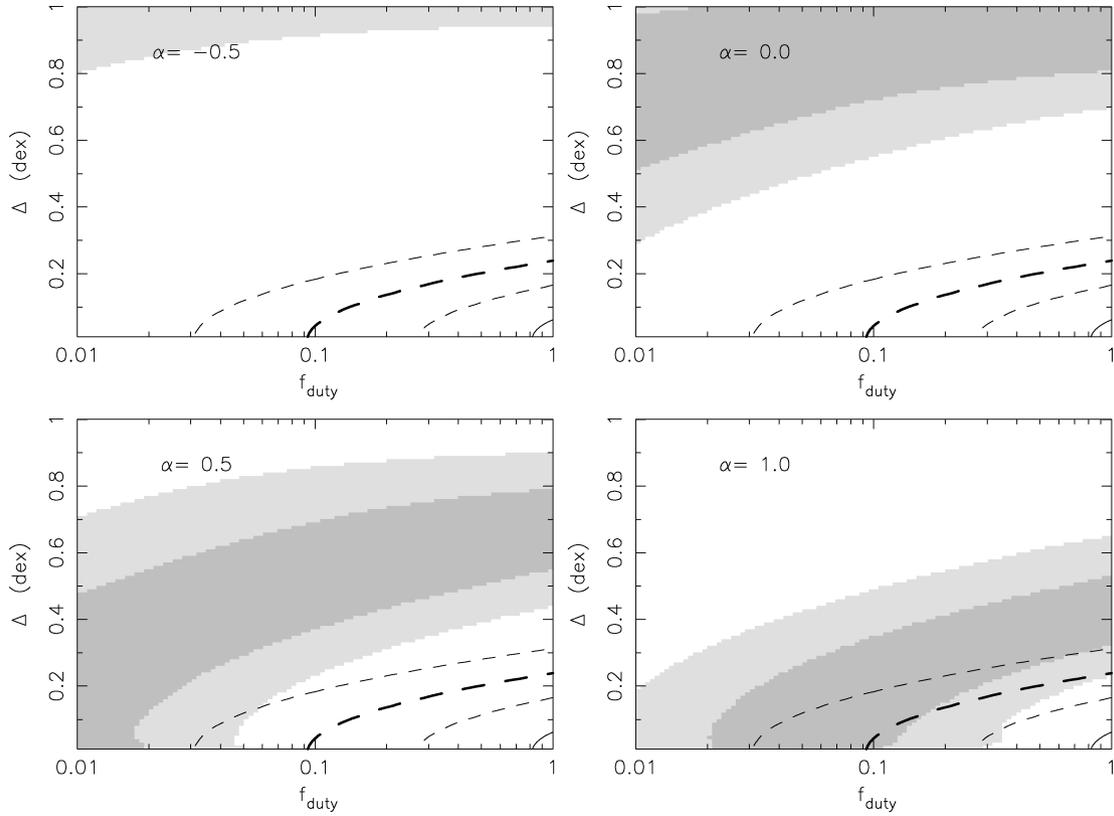
$$\int_{\Delta_{\text{min}}}^{\Delta_{\text{max}}} \frac{dP}{d\Delta} d\Delta = 1.$$

The corresponding a posteriori cumulative probability is

$$P(< \Delta) = \int_{\Delta_{\text{min}}}^{\Delta} d\Delta' \frac{dP}{d\Delta'}.$$

Fig. 4 shows the differential distributions  $dP/d\alpha$  and  $dP/df_{\text{duty}}$ . The data constrain a value of  $\alpha \approx -0.4 \pm 0.5$ , while the value of  $f_{\text{duty}}$  is weakly constrained. The left-hand panel of Fig. 5 shows the cumulative distribution for  $\gamma$ . This distribution shows that  $\gamma$  must be greater than unity at a statistical confidence of 90 per cent. Similarly, the right-hand panel shows the value of  $1$  minus the cumulative probability distribution for  $\Delta$ . At 90 per cent confidence, the scatter can only be shown to be below  $\Delta = 1$  (in difference from White et al. 2008). Finally, Fig. 6 plots the differential (left-hand panel,  $dP/dF$ ) and cumulative [right-hand panel,  $P(< F)$ ] distributions for  $F$ . The most likely value is at  $F \approx 1.7$ . The probability drops rapidly towards low values of  $F$  and we find that  $F > 1.1$  with high statistical confidence (99 per cent). Because of the upper limit on duty-cycle discussed in Appendix A, this limit on  $F$  leads to a correspondingly strong limit on  $f_{\text{duty}} < 1$ .

As noted above, our quantitative results are sensitive to the prior probability distributions because the number of free parameters is larger than the number of constraints. In particular, we find that the data do not constrain the upper limit of the parameters  $\gamma$  or  $F$ . As a result, our quantitative results are sensitive to the values chosen for the parameters of  $\gamma_{\text{max}}$  and  $F_{\text{max}}$ . However, if we increase the values of  $\gamma_{\text{max}}$  and  $F_{\text{max}}$ , permitting a greater volume of parameter space a priori, then our constraints on the lower limits for  $\gamma$  and  $F$  are improved. Therefore, our qualitative conclusions are not sensitive



**Figure 2.** As per Fig. 1, but for different values of  $\alpha$ , with  $\gamma = 1$  in each case.

to the assumed prior probability distribution. In summary, we find constraints on individual parameters of  $\alpha \approx -0.4 \pm 0.5$ ,  $\gamma > 1$  (at a statistical confidence of 90 per cent),  $\Delta < 1$  (90 per cent) and  $F > 1.1$  (99 per cent).

### 3.4 Constraints on host halo mass

Finally, we are able to use the above constraints to assess the range of halo masses that are consistent with the clustering and luminosity function data. In our formalism, the halo mass is not a free parameter. Rather, for each parameter set  $\Delta, \gamma, f_{\text{duty}}, F, \alpha$ , there is a halo mass  $M_{\Delta, \gamma, f_{\text{duty}}, F, \alpha}$ , which corresponds to the observed quasar density. Since our formalism includes scatter in the  $L$ – $M$  relationship, this mass is defined as the mean mass  $M$  at luminosity  $L$  (equation 6). This parameter combination has likelihood  $\mathcal{L}_{\Delta, \gamma, f_{\text{duty}}, F, \alpha}$ . The probability distribution for  $M$  can therefore be computed from

$$\frac{dP}{dM} \propto \int_{\Delta_{\min}}^{\Delta_{\max}} d\Delta \int_{f_{\text{duty}, \min}}^{f_{\text{duty}, \max}} df_{\text{duty}} \int_{\alpha_{\min}}^{\alpha_{\max}} d\alpha \int_{\gamma_{\min}}^{\gamma_{\max}} d\gamma \int_{F_{\min}}^{F_{\max}} dF \mathcal{L}_{\Delta, \gamma, f_{\text{duty}}, F, \alpha} \frac{dP_{\text{prior}}}{d\Delta} \frac{dP_{\text{prior}}}{df_{\text{duty}}} \frac{dP_{\text{prior}}}{d\alpha} \frac{dP_{\text{prior}}}{d\gamma} \frac{dP_{\text{prior}}}{dF} \times \delta(M - M_{\Delta, \gamma, f_{\text{duty}}, F, \alpha}), \quad (19)$$

with corresponding cumulative distribution

$$P(< M) = \int_M^{\infty} dM' \frac{dP}{dM'}. \quad (20)$$

We plot these distributions in Fig. 7. The host halo mass for the quasars in the high-redshift sample is  $M \sim 10^{13 \pm 0.5} M_{\odot}$ . In our

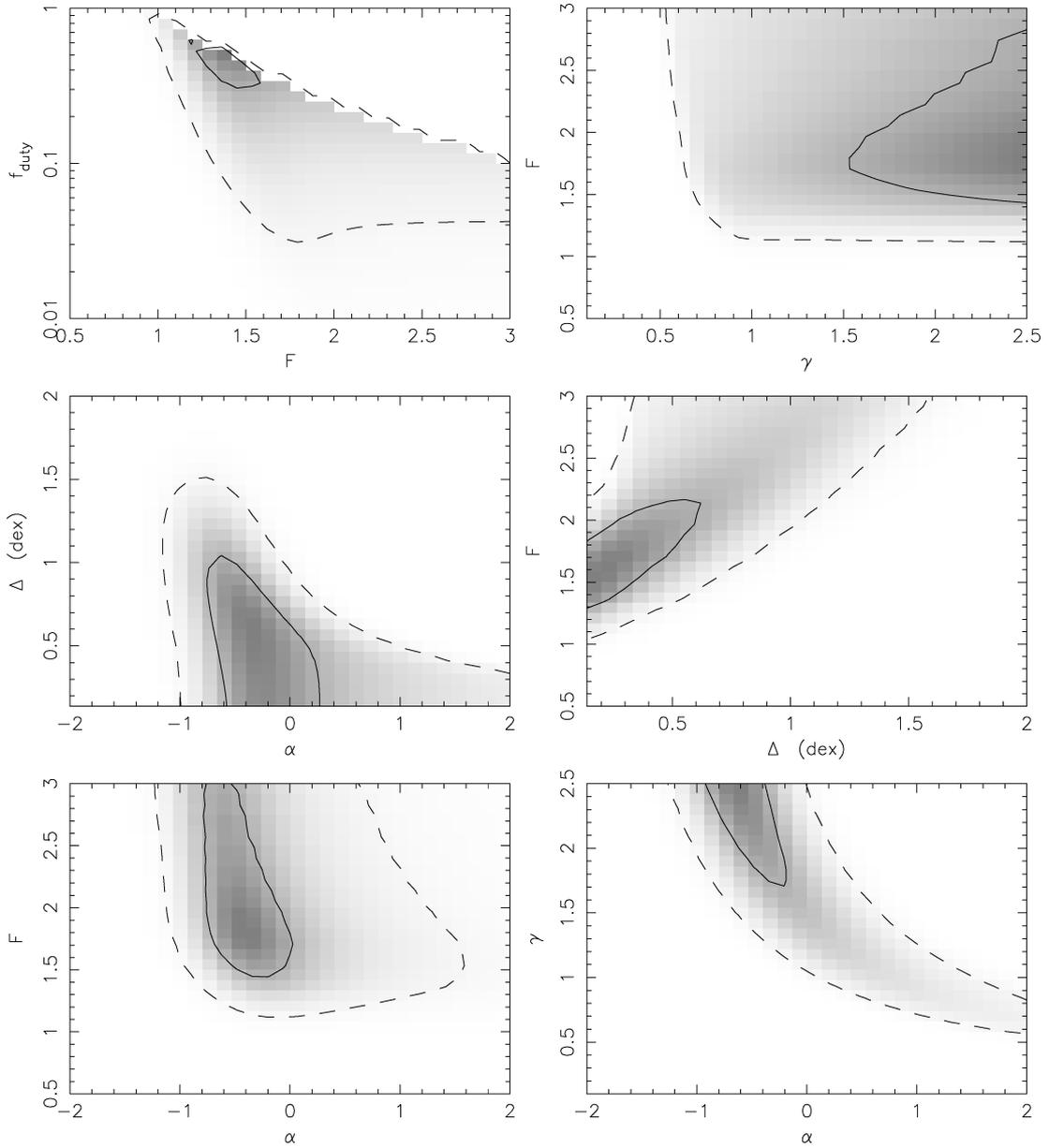
fiducial model, the halo mass is restricted to be larger than  $\sim 3 \times 10^{12} M_{\odot}$  (99 per cent). This mass range is comparable to the one ( $M \gtrsim 5 \times 10^{12} M_{\odot}$ ) quoted by Shen et al. (2007). However, note that here  $M$  refers to the halo mass corresponding to  $L$  at the mean of the  $L$ – $M$  relation. The possibility of a large intrinsic scatter means that many host haloes will have a significantly smaller mass.

The parameter constraints from our fiducial model are summarized in Table 1.

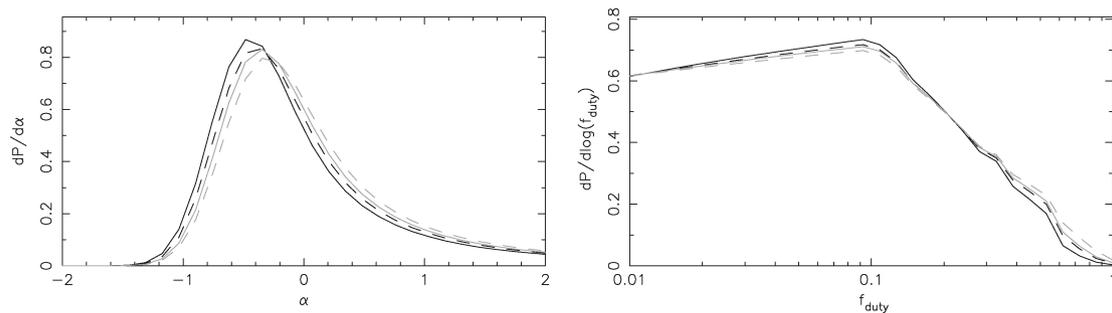
### 3.5 Theoretical uncertainties in the bias

Thus far we have presented a fiducial model using the Sheth–Tormen forms for the clustering bias (Sheth, Mo & Tormen 2001) and the mass function (Sheth & Tormen 1999). However, as demonstrated in White, Martini & Cohn (2008), the bias and density are sufficiently large as to make any quantitative conclusions sensitive to the detailed predictions of the Sheth–Tormen model. A discussion of the various analytic models and their comparison to numerical simulation is provided by White et al. (2008), who suggest that the Press–Schechter and Sheth–Tormen formalisms should bracket the expected level of theoretical uncertainty. Following this assertion, we also present results using the corresponding Press–Schechter formulation for the mass function (Press & Schechter 1974) and clustering bias (Mo & White 1996) to assess the level of theoretical systematic uncertainty in our conclusions.

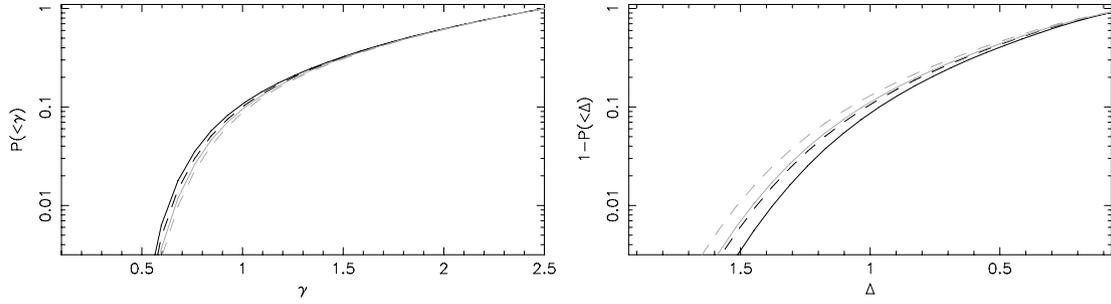
In addition to the adopted model for the statistics of the halo population, the conclusions will also be sensitive to the value of the measured space density of quasars. Shen et al. (2007) pointed out that the space density is underestimated by a factor of  $\sim 2$  for the fit of Richards et al. (2006). Following White, Martini & Cohn (2008), we have used that correction factor in our analysis above.



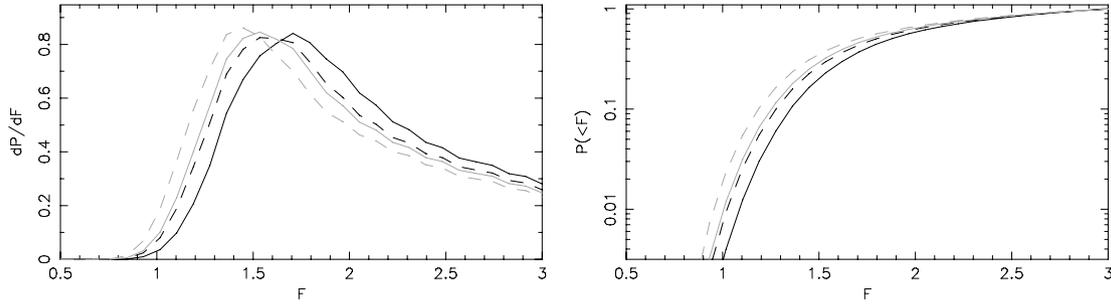
**Figure 3.** Contours of the joint likelihood distributions for  $f_{\text{duty}}$  and  $F$  (top left panel), for  $\gamma$  and  $F$  (top right panel), for  $\Delta$  and  $\alpha$  (central left panel), for  $F$  and  $\Delta$  (central right panel), for  $F$  and  $\alpha$  (lower left panel) and for  $\gamma$  and  $\alpha$  (lower right panel). Contours are shown at 60 per cent (solid) and 7 per cent (dotted) of the maximum likelihood. See text for details on the assumed prior probability distributions.



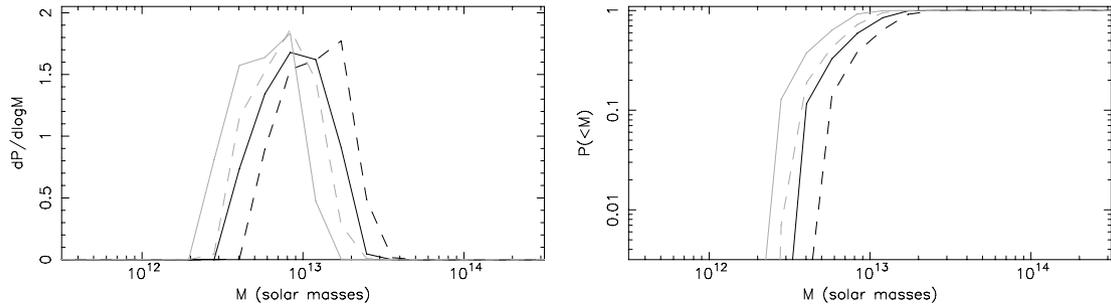
**Figure 4.** Marginalized, a posteriori differential probability distributions for  $\alpha$  (left-hand panel) and  $f_{\text{duty}}$  (right-hand panel). The black and grey lines correspond to calculations performed using the Press–Schechter and Sheth–Tormen formalisms, respectively. The solid (dashed) lines do (do not) include the correction factor of 2 in the quasar density (see text for details).



**Figure 5.** Marginalized, a posteriori cumulative probability distributions for  $\gamma$  (left-hand panel) and  $\Delta$  (right-hand panel). The black and grey lines correspond to calculations performed using the Press–Schechter and Sheth–Tormen formalisms, respectively. The solid (dashed) lines do (do not) include the correction factor of 2 in the quasar density.



**Figure 6.** Marginalized, a posteriori differential (left-hand panel) and cumulative (right-hand panel) probability distributions for  $F$ . The black and grey lines correspond to calculations performed using the Press–Schechter and Sheth–Tormen formalisms, respectively. The solid (dashed) lines do (do not) include the correction factor of 2 in the quasar density.



**Figure 7.** Marginalized, a posteriori differential (left-hand panel) and cumulative (right-hand panel) probability distributions for halo mass  $M$ . The black and grey lines correspond to calculations performed using the Press–Schechter and Sheth–Tormen formalisms, respectively. The solid (dashed) lines do (do not) include the correction factor of 2 in the quasar density.

**Table 1.** Table summarizing constraints on model parameters.

Parameter	Value	Confidence
$\alpha$	$-0.4 \pm 0.5$	(68 per cent)
$\Delta$	$< 1$	(90 per cent)
$\gamma$	$> 1.0$	(90 per cent)
$F$	$> 1.1$	(99 per cent)
$M$	$10^{13 \pm 0.5} M_{\odot}$	(68 per cent)

For comparison, we also repeat our analysis using the uncorrected value of  $N = 0.35 \times 10^{-7} \text{Mpc}^{-3}$ .

We therefore compare a set of four calculations, using combinations of the Sheth–Tormen or Press–Schechter halo statistics with the quasar density computed with or without the correction factor. In Figs 4–7, we show probability distributions for the three additional cases together with our fiducial model. The constraints on  $\gamma$

and  $\alpha$  are unaffected by these model changes since these are not directly related to the numbers of observed quasars. The lower density of quasars and the larger predicted bias of the Press–Schechter formalism (and their combination) each yield weaker constraints on  $\Delta$ ,  $F$  than our fiducial model. However, the systematic effect is mild, with limits of  $\Delta < 1$  (85 per cent), and  $F > 1.1$  (98 per cent). We find that the minimum halo mass is effected by a factor of 2 depending on the assumed combination.

## 4 DISCUSSION

In this section, we discuss some implications of our results.

### 4.1 Constraints on excess bias

We find that the value of  $F$  is constrained to be in excess of unity, that is the observed bias is in excess of the halo bias. This could be

interpreted as evidence that mergers are responsible for the quasar activity. We also find that  $\gamma > 1$ , implying that the luminosity to halo mass ratio increases with halo mass. Under the assumption that the Eddington ratio of bright quasars is nearly constant (as argued by Kollmeier et al. 2006), models of feedback limited growth through energy deposition (Haehnelt et al. 1998; Wyithe & Loeb 2003) predict a value of  $\gamma = 5/3$ . If we adopt  $\gamma = 5/3$ , then the preferred range of  $F$  (marginalized over other parameters) is  $1.5 \lesssim F \lesssim 2$ . Interestingly,  $F \sim 1.5$  is approximately the factor by which Furlanetto & Kamionkowski (2006) estimated mergers to increase the observed bias over the value of halo bias at high values of  $M$ . In our analysis, we have allowed  $F$  to be a free parameter. This approach has the promise of constraining the merger process responsible for the triggering of quasar activity. For example, Furlanetto & Kamionkowski (2006) demonstrated that if close pairs lead to mergers, then mergers are expected to be clustered differently than individual haloes. The magnitude of this difference is dependent on the clustering model, and so its measurement will constrain fundamental properties of the merger process.

In a recent complementary paper Shankar, Crocce & Miralda-Escudé (2008) investigate the constraints that can be placed on the characteristic values of radiative efficiency, Eddington ratio, and duty-cycle of high-redshift active galactic nuclei (AGN). In addition to these free parameters, the modelling also allows for free adjustment of the normalization, scatter and redshift evolution of the relation between black hole mass and halo virial velocity. In their study, these authors model measurements of the AGN luminosity function at  $z = 3-6$  in combination with the recent measurements of quasar clustering at  $z = 3-4.5$  from the SDSS that are also the corner stone of our study.

The analysis of Shankar et al. (2008) leads them to place a lower limit on the radiative efficiency of  $\epsilon > 0.7\lambda/(1 + 0.7\lambda)$ , where  $\lambda$  is the luminosity in Eddington units. However, based on estimates of black hole masses, Kollmeier et al. (2006) and Shen et al. (2007) have inferred a characteristic value of  $\lambda \sim 0.3$  for bright quasars, which given the above constraint implies that  $\epsilon > 0.17$ . This lower limit is uncomfortably high relative to the Soltan (1982) type argument presented in Shankar, Weinberg & Miralda-Escudé (2007) of  $\epsilon \sim 0.06-0.1$ . This problem is discussed by Shankar et al. (2008). We note that the argument presented in this paper, that the observed quasar bias is larger than the host halo bias, would remove this problem by allowing quasars to reside in a subsample of lower mass haloes. The larger space density of such a subsample relative to the space density of the very massive haloes needed to match the halo bias to the observed clustering permits smaller values of  $\epsilon \sim 0.06-0.1$  which are consistent with the Soltan (1982) argument as well as duty-cycles that are smaller than unity, by providing a larger number of sites where accretion required to build the local SMBH density could have occurred.

The point made in our paper is that analyses such as the one described by Shankar et al. (2008) should not necessarily be done assuming that the value of halo bias directly corresponds to quasar clustering. The allowance for the possibility of an astrophysical component of bias (through mergers or something else) eases the tension between the clustering and density that provide tight, and in some cases uncomfortable constraints on physical parameters associated with SMBH growth. Indeed, the case for excess bias seems to be born out by the results of Shankar et al. (2008) paper which are unable to reproduce the clustering and density of quasars at a simultaneously at a statistically acceptable level without invoking an unidentified systematic component of observational error in the  $z \sim 4$  sample.

In contrast to the situation at  $z \sim 4$ , at redshifts  $z \lesssim 3$  there is no tension between the observed density of quasars and the observed bias, allowing models to simultaneously reproduce both the statistics of the spatial distribution and the clustering of quasars (e.g. Wyithe & Loeb 2005; Lidz et al. 2006; Shankar et al. 2008). However, this is not evidence against a value of  $F > 1$  either at low or high redshift for the following reasons. First, while large, the halo masses of  $\sim 10^{12} M_\odot$  thought to host the luminous quasars are not on the extreme exponential tail of the halo mass function for  $z \lesssim 3$ . As a result, if the observed bias were indeed in excess of the quasar host halo bias by a factor of order 50 per cent at  $z \lesssim 3$ , this larger bias could be reproduced through a small increase in the host halo mass, while simultaneously maintaining a halo density sufficient to explain the observed quasar number counts. This is not the case at  $z \sim 4$ , as we have shown in this paper. Secondly, even if it could be shown that  $F \sim 1$  at  $z \lesssim 3$  through a clustering independent measurement of the quasar host halo mass, this would not imply that  $F \sim 1$  at high redshift since merger induced biases might be expected to be larger at earlier times (Furlanetto & Kamionkowski 2006).

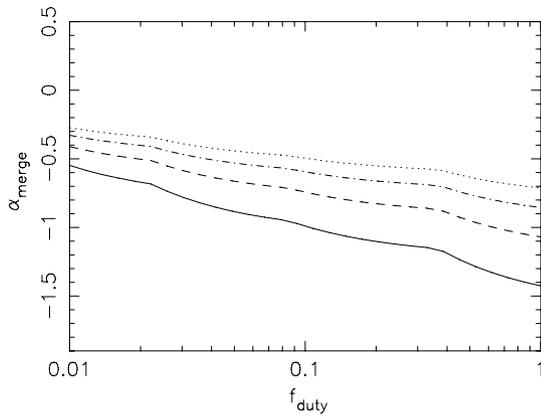
## 4.2 Consistency with merger based models for SMBH accretion

In addition to  $F$ , the value of  $\alpha$  is also well constrained. Since the constraint of  $F > 1$  may suggest that quasar activity is triggered by mergers, it is interesting to calculate the predicted value of  $\alpha$  using a model where the total duty-cycle (i.e. summing over all quasar episodes in a single host) as a function of luminosity is proportional to the rate of major mergers. We use the extended Press-Schechter formalism to evaluate the rate of mergers of haloes with mass  $M_1$  per unit mass with haloes of mass  $M_2$ ,  $d^2N/dM_1dt|M_2$  (Lacey & Cole 1993). The duty-cycle is then proportional to  $M_1 d^2N/dM_1dt|M_2 t_{\text{lt}} H$ , where  $t_{\text{lt}}$  is the lifetime of a single merger driven quasar episode and  $H^{-1}$  is the Hubble time at the redshift of interest (Wyithe & Loeb 2003). Assuming that  $t_{\text{lt}}$  is not a function of mass (as expected if the quasar episode is related to time-scales like the black-hole doubling time or the dynamical time of its host galaxy), we find

$$\alpha_{\text{merger}} \approx \frac{1}{\gamma} \frac{d}{d \log M} \left[ \log \left( M \frac{d^2 N}{dM dt} \Big|_M \right) \right], \quad (21)$$

where we have assumed major mergers with  $M_1 \sim M_2 = M$ , and the term  $1/\gamma$  originates in the conversion from  $d \log M$  to  $d \log L$  for consistency with the definition of  $\alpha$ . The resulting value of  $\alpha_{\text{merger}}$  as a function of duty-cycle is plotted in Fig. 8 for four values of  $\gamma = 1, 4/3, 5/3$  and 2 (bottom to top). While a value of  $\gamma = 5/3$  applies to feedback through energy deposition, models where the quasar drives the gas outflow from its host galaxy through momentum deposition have  $\gamma = 4/3$  (e.g. Silk & Rees 1998; Murray, Quataert & Thompson 2005; King 2003). Here, the value of  $\alpha_{\text{merger}}$  has been computed at a halo mass for which the number density times the duty-cycle is equal to the observed quasar density. We find that for this model we would expect a value of  $-1 \lesssim \alpha_{\text{merger}} \lesssim -0.3$ , with larger values of  $\gamma$  indicating less dependence of duty-cycle on luminosity. These values are consistent with our constraints on  $\alpha$ .

With respect to a merger-driven model for quasar growth, it should be noted that the two merging haloes should not each host an active quasar. The reason, as discussed in White et al. (2008), is that in this case the predicted clustering of quasars at small separations would overpredict the observed clustering at  $z \sim 2$  by Hennawi et al. (2006). This prevents the constraints on density and clustering



**Figure 8.** The theoretically expected value of  $\alpha_{\text{merge}}$  as a function of quasar duty-cycle (see text for details). Curves are plotted for four values of  $\gamma = 1, 4/3, 5/3$  and  $2$  (bottom to top).

(which have led us to conclude that  $F > 1$ ) being reconciled by increasing the duty-cycle beyond unity to account for multiple quasars in a single halo.

Several anomalies have been previously noticed in the unexpectedly high clustering of systems that may be merger driven. For example, the clustering amplitude of Lyman-break galaxies (Adelberger et al. 2005) implies a host halo mass of  $\sim 10^{12} M_{\odot}$ . However, at this mass, the density of Lyman-break galaxies then implies that the duty-cycle of vigorous star formation must be unity in all haloes. Moreover, kinematic measurements of these galaxies imply a significantly smaller mass of  $\sim 10^{11} M_{\odot}$  (Pettini et al. 2001; Erb et al. 2003). The tension between the different estimates of host mass could be alleviated if the intense star formation in Lyman-break galaxies is triggered by mergers, and if mergers in turn increase the observed bias (Furlanetto & Kamionkowski 2006). In a recent paper, Wake et al. (2008) demonstrated that a radio-loud subsample of Luminous Red Galaxies at  $z \sim 0.55$  had a clustering amplitude that is in excess of the radio-quiet subsample, despite the optical properties being identical. Wake et al. (2008) interpret this as a larger host halo mass for radio loud objects. However, it might also be appealing to assign the excess bias to a merger origin of accretion activity.

### 4.3 Alternative explanations

Of course there are alternative explanations for each of these observations. For example, dynamical measurements may only be accessing the central component of the host haloes of Lyman-break galaxies (Cooray 2005). In the case of radio loud Luminous Red Galaxies, the high bias could originate from the high bias of X-ray clusters (more massive haloes), of which the Luminous Red Galaxies would be the central member. Additionally, since clustering statistics have been shown to depend on the halo formation history (Gao et al. 2005; Croton et al. 2007; Wetzel et al. 2007), the age or structural properties the galaxy host could also effect the observed clustering. However, in each case, it is clear that the possibility of modification of the observed bias should be taken into account in interpreting clustering data for many types of galaxies, such as starburst galaxies or radio galaxies.

For example, a detailed analysis of the dependence of halo clustering on halo formation time and concentration was recently presented by Wechsler et al. (2006) using numerical simulations. These authors confirm earlier results (e.g. Gao et al. 2005) that the clus-

tering of haloes depends on formation time. Moreover, they find that clustering at a particular halo mass has a simple dependence on halo concentration. In their fig. 3, Wechsler et al. (2006) present a quantity that is equivalent to the square of our parameter  $F$  for different mass and concentration ranges. At their highest redshift considered ( $z = 2.5$ ), they find the least concentrated 25 per cent of massive haloes to have values of  $F \sim 1.1$ – $1.25$ , indicating that later forming objects are more highly clustered at this redshift range. This trend increases towards the higher redshifts  $z \sim 4$  that we are concerned with in this study. Thus, if AGN were associated with recently formed haloes, then the simulations of Wechsler et al. (2006) yield estimates of  $F$  that would be consistent with our empirical constraints. As emphasized in Wechsler et al. (2006) and elsewhere in this paper, detailed numerical simulations are required in order to reach physical conclusions given our empirical constraint on  $F$ .

### 4.4 Scatter in the luminosity–halo mass relation

We note that the scatter between quasar luminosity and host halo mass is only constrained to satisfy  $\Delta \lesssim 1$  dex. This range is significantly larger than the tight upper limit of  $\sim 0.3$  dex found in the analysis of White et al. (2008). The difference can be traced to the greater freedom in our model associated with: (i) the relation between luminosity and halo mass through  $\gamma$ ; (ii) the relation between quasar density and halo mass through  $\alpha$  and (iii) the allowance for the observed clustering bias to not directly reflect the underlying host mass for merger-driven systems. We do find that models assuming  $F = 1, \gamma = 1$  (as considered by White et al. 2008) reflect the small upper limit of  $\Delta \sim 0.3$  dex. However, in addition to this, low value of scatter being disfavoured in our more general model by the joint constraints from clustering and luminosity function, we would not expect such a tight relationship on observational grounds. In particular, an upper limit of 0.3 dex implies a scatter that is smaller than the scatter in the black hole–velocity dispersion relation measured locally ( $\sim 0.3$  dex; Tremaine et al. 2002). However, the relation between quasar luminosity and halo mass must have several additional sources of scatter, including in the relation between halo mass and bulge velocity dispersion, and between black hole mass and quasar luminosity. Hopkins et al. (2007) have investigated the scatter in relations between black-hole mass and galaxy properties including the bulge velocity dispersion. They argue that the tightness of these relations implies that any connection between black-hole mass and halo mass must be incidental. Wyithe & Loeb (2005) have modelled the black hole–halo mass relation, and have shown that the scatter in the black hole–velocity dispersion relation combined with the statistical properties of dark-matter haloes (Bullock et al. 2001) implies a scatter of at least 0.5 dex at the redshifts of interest. Moreover, any relation between luminosity and halo mass must also include a factor to account for the fraction of the Eddington rate at which the quasar accretes. Kollmeier et al. (2006) found a scatter in this distribution of 0.3 dex.

With regards to the possible value of scatter in the relation between SMBH and halo mass, the results of Shankar et al. (2008) agree with previous results of White et al. (2008). Namely, a very small value of this scatter is needed in order to make the predicted clustering consistent with the data at  $z \sim 4$  at even the  $2\sigma$  level. Shankar et al. (2008) illustrate their analysis using two cases for the scatter, 0.3 and 0.1 dex. None of the models presented with a scatter of 0.3 dex comes close to reproducing the observed clustering and so analysis of constraints on the physical parameters such as radiative efficiency and Eddington ratio concentrate on the assumption of a scatter of 0.1 dex. However, since the analysis of Shankar et al.

(2008) does not include scatter in the Eddington rate, we would argue (as detailed above) that a scatter of 0.1 dex is unphysically small. For example, the dispersion of the black hole–velocity relation is found to be quite insensitive to redshift in numerical simulations (Robertson et al. 2006). This scatter is measured locally to be 0.3 dex implying that the scatter should be comparable at  $z \sim 4$ . However, we repeat the point that the scatter in the halo–luminosity relation must also account for the fraction of the Eddington rate at which the quasar accretes, which is observed to be 0.3 dex (Kollmeier et al. 2006).

#### 4.5 Duty-cycle

Finally, we note that the quasar duty-cycle is not tightly constrained in this model. This is in difference to previous results (Cole & Kaiser 1989; Haiman & Hui 2001; Martini & Weinberg 2001; Shen et al. 2007; White et al. 2008), which have constrained the quasar lifetime from clustering. The difference originates from the fact that our model does not assume the one-to-one correspondence between observed clustering amplitude and halo mass ( $F = 1$ ). This generalization, motivated by the theoretical expectation that merging systems are likely to be more clustered than their isolated counterparts at fixed halo mass, means that a large clustering amplitude can be obtained by more common, lower mass haloes, allowing the observed density to be achieved with a smaller duty-cycle. Moreover, Fig. 3 demonstrates that even if a value of  $F \sim 1.5$  (Furlanetto & Kamionkowski 2006) is adopted, the duty-cycle remains only loosely constrained (with the exception of large values owing to the constraint that  $f_{\text{duty}} < f_{\text{max}}$ ). This is because the large value of  $F$  allows for reproduction of the data over a wide range of possible values for the scatter ( $\Delta$ ), which in turn allows the model to predict a broad range of values for the halo abundance.

#### 4.6 Constraints without luminosity function slope

In our analysis, we have included the slope of the quasar luminosity function as an additional constraint to the quasar density and clustering. Before concluding we note that the addition of this constraint does not effect quantitative conclusions regarding  $F$  or  $\Delta$ , which are derived from comparison of the halo number density and bias to the observed density and bias. We have repeated our analysis without the constraint on the luminosity function slope. We find that the addition of this constraint allows a limit to be placed on  $\alpha$  and tightens the constraint on  $\gamma$ .

### 5 CONCLUSION

The large amplitude of the observed clustering among  $z \sim 4$  quasars, combined with their density and luminosity function slope, strongly constrains the relationship between quasar luminosity and halo mass at high redshifts. We have modelled these observables using the extended Press–Schechter formalism, combined with a mean quasar luminosity ( $L$ )–halo mass ( $M$ ) relation of the form  $L \propto M^\gamma$ . We assume an intrinsic scatter (in dex) around the mean relation of  $\Delta$  at a fixed halo mass. We find that the observed clustering amplitude and luminosity function slope cannot be simultaneously reproduced unless both of the following conditions hold.

(i) The value of  $\gamma$  is greater than unity, implying that quasar luminosity is not a linear function of host mass.

(ii) The observed clustering amplitude is in excess of that expected from dark matter haloes ( $F > 1$ ), possibly implying that the observed bias is boosted because mergers trigger quasar activity.

The latter constraint on  $F$  is particularly strong. We find  $F > 1.1$  at the 99 per cent level. On the other hand, we find that the scatter in the  $L$ – $M$  relation can be constrained only to a value smaller than  $\sim 1$  dex (in difference from the recent study of White et al. 2008). We find that because of the weak constraint on the scatter the mean host mass can be only weakly constrained, to within an order of magnitude around  $\sim 10^{13} M_\odot$ . Importantly, and for the same reason, we find that clustering data combined with quasar densities do not constrain the quasar lifetime, as had been suggested previously (Cole & Kaiser 1989; Haiman & Hui 2001; Martini & Weinberg 2001).

Interestingly, the literature already contains a physically motivated model which is consistent with all of the above constraints. A scenario in which galaxy mergers drive accretion on to a central black hole, which then radiates near its Eddington luminosity until it grows sufficiently to deposit (with a  $\sim 5$  per cent efficiency) the binding energy of the surrounding gas over a dynamical time, yields an  $L$ – $M$  relation with a value of  $\gamma = 5/3$  (Wyithe & Loeb 2003). For this value of  $\gamma$ , our constraints favour a value of  $1.5 \lesssim F \lesssim 2$ , which is consistent with estimates of the expected enhancement in clustering bias for merger driven activity of  $F \sim 1.5$  (Furlanetto & Kamionkowski 2006).

In summary, the clustering statistics combined with the luminosity function of high-redshift quasars, provide compelling evidence for a scenario of merger-driven quasar activity, with black-hole growth that is limited by feedback. The resulting luminosity–halo mass relation implies that the luminosity to halo mass ratio increases with halo mass as expected in theoretical models that include feedback limited black hole growth.

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## APPENDIX A: THE FRACTION OF HALOES WITH EXTRA BIAS

Here, we discuss a simple estimate for the fraction of the total halo population that could have an excess bias.

It has been demonstrated by Shankar et al. (2008) that the analytic bias of the Sheth, Mo & Tormen (2001) fitting function describes the halo bias measured in  $N$ -body simulations to within  $\sim 10$  per cent. One might therefore assume that this limits the fraction of haloes that could possess a bias in excess of the mean population because this excess bias would be seen in simulations at a level above the analytic approximation. However, this interpretation would not be correct. To see why, we first consider the total population of haloes, for which the analytic model matches the simulations. Next, we remove a subsample of ‘special haloes’, which have a larger clustering bias than the population as a whole. Within the scenario considered in this paper, these special haloes would have the bias of the observed quasar population. The total bias can be written as

$$\langle b \rangle^2 n_{\text{tot}} = b_{\text{rest}}^2 n_{\text{rest}} + b_{\text{obs}}^2 n_{\text{special}}, \quad (\text{A1})$$

where  $\langle b \rangle$ ,  $b_{\text{obs}}$  and  $b_{\text{rest}}$ , and  $n_{\text{tot}}$ ,  $n_{\text{special}}$  and  $n_{\text{rest}}$  are the clustering biases and densities of the total halo population, of the subsample of haloes with excess clustering, and of the remainder of the population, respectively. Rearranging we find

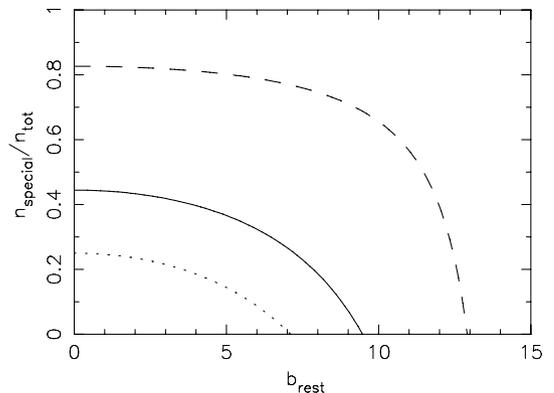
$$b_{\text{rest}}^2 (n_{\text{tot}} - n_{\text{special}}) = \langle b \rangle^2 n_{\text{tot}} - b_{\text{obs}}^2 n_{\text{special}} \quad (\text{A2})$$

where  $n_{\text{rest}} = n_{\text{tot}} - n_{\text{special}}$ , indicating that the haloes that are left over following the removal of those with excess bias have a clustering bias that is less than that of the total population. This equation suggests that there is a limit to the fraction of haloes that can have a special enhanced bias. The density of special haloes relative to the total is

$$\frac{n_{\text{special}}}{n_{\text{tot}}} = \frac{\langle b \rangle^2 - b_{\text{rest}}^2}{b_{\text{obs}}^2 - b_{\text{rest}}^2}. \quad (\text{A3})$$

Fig. A1 shows the ratio of density of haloes with excess bias relative to the total halo density as a function of  $b_{\text{rest}}$ . Three lines are shown with the excess bias parametrized according to  $b_{\text{obs}} = F b_{\text{tot}}$  and  $F = 2, 1.5$  and  $1.1$  from bottom to top. A value of  $b_{\text{obs}} = 14.2$  has been assumed, corresponding to the sample of high-redshift quasars considered in this paper.

Fig. A1 illustrates that if there is an astrophysical process (such as major mergers) which leads to a subpopulation of haloes having



**Figure A1.** The ratio between the density of haloes with excess bias relative to the total halo density as a function of  $b_{\text{rest}}$ . Three lines are shown with the excess bias parametrized according to  $b_{\text{obs}} = F \langle b \rangle$  and  $F = 2, 1.5$  and  $1.1$  from bottom to top. A value of  $b_{\text{obs}} = 14.2$  has been assumed, as appropriate for the sample of high-redshift quasars.

a larger than average bias, it is possible for these haloes to make up a significant fraction of the total population. The resulting increase in the bias of the sample relative to the average is compensated by a small value for the bias of the rest of the halo population. In this paper, our analysis has assumed a priori, that  $f_{\text{duty}}$  lies between 0.01 and 1. However, following equation (A3) we include a constraint that excludes parameter pairs of  $f_{\text{duty}}$  and  $F$  with  $f_{\text{duty}} > f_{\text{max}}$  where

$$f_{\text{max}} = \frac{(b_{\text{obs}}/F)^2 - 1}{b_{\text{obs}}^2 - 1}, \quad (\text{A4})$$

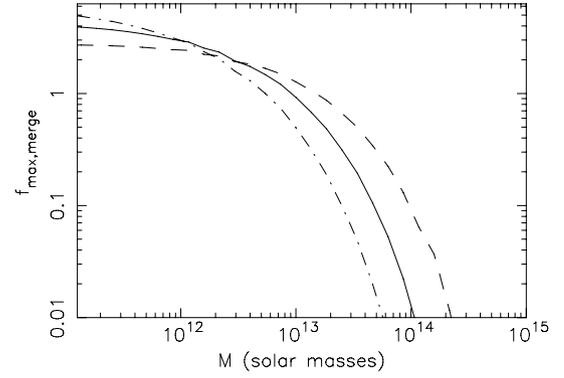
and we have assumed a minimum value for  $b_{\text{rest}}$  of unity (it can be seen from Fig. A1 that  $f_{\text{max}}$  is not sensitive to the choice for  $b_{\text{rest}}$  over a wide range.)

The above limit  $f_{\text{max}}$  is purely mathematical, and independent of any model for quasar activity. However, the upper limit on  $f_{\text{duty}}$  could also be set within a particular physical model. For example, within a merger based model it is possible to find a physically based constraint ( $f_{\text{max,merge}}$ ) on  $f_{\text{duty}}$  by calculating the fraction of haloes at a particular mass that are undergoing a major merger at a particular instant. This quantity may be estimated from

$$f_{\text{max,merge}} \sim M \left. \frac{d^2 N}{dM dt} \right|_M \Delta t_{\text{merge}}, \quad (\text{A5})$$

where  $\Delta t_{\text{merge}}$  is the duration of the merger. One estimate for this duration is the decay time of the merging satellites (the dynamical friction time-scale), which following Lacey & Cole (1993) and Colpi et al. (1999) can be approximated for equal mass progenitors as

$$\Delta t_{\text{merge}} \sim H^{-1} \min \left[ \frac{2.4}{\sqrt{178 \ln 2}} (0.5)^{0.4}, 1 \right]. \quad (\text{A6})$$



**Figure A2.** The value of  $f_{\text{max,merge}}$  as a function of  $M$  at  $z = 3$  (dotted), 4 (solid) and 5 (dot-dashed), assuming the merger based model. Equal mass progenitors and a merger lifetime corresponding to the halo orbit decay time were assumed.

In Fig. A2, we plot  $f_{\text{max,merge}}$  as a function of  $M$  at  $z = 3, 4$  and  $5$ . With the exception of the most massive haloes ( $M > 10^{13.5-14} M_{\odot}$ ),  $f_{\text{max,merge}}$  is in excess of a few 10 s of per cent in each case. This indicates that the number of merging haloes would not lead to a dearth of potential hosts for luminous quasars and so would be unlikely to limit the possible value of  $F$ .

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