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# On the cosmological evolution of the black hole–host galaxy relation in quasars

Laura Portinari,[1]⋆ Jari Kotilainen,[2] Renato Falomo[3]⋆ and Roberto Decarli[4,5]⋆

[1] *Tuorla Observatory, Department of Physics and Astronomy, University of Turku, Väisäläntie 20, FIN-21500 Piikkiö, Finland*
[2] *Finnish Centre for Astronomy with ESO (FINCA), University of Turku, Väisäläntie 20, FIN-21500 Piikkiö, Finland*
[3] *INAF – Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5, I-35122 Padova, Italy*
[4] *Universitá degli Studi dell'Insubria, Via Valleggio 11, I-22100 Como, Italy*
[5] *Max Planck Institute for Astronomy, Königstuhl 17, D-69117 Heidelberg, Germany*

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## ABSTRACT

Quasars are useful tracers of the cosmological evolution of the black hole mass–galaxy relation. We compare the expectations of semi-analytical models (SAMs) of galaxy evolution to the largest available data sets of quasar host galaxies out to $z \simeq 3$.

Observed quasar hosts are consistent with no evolution from the local $M_{\rm BH}-L_{\rm host}$ relation and suggest a significant increase of the mass ratio $\Gamma = M_{\rm BH}/M_\star(\rm host)$ from $z = 0$ to 3. Taken at face value, this is totally at odds with the predictions of SAMs, where the intrinsic $\Gamma$ shows little evolution and quasar host galaxies at high redshift are systematically overluminous (and/or have an undermassive BH). However, since quasars preferentially trace very massive black holes ($10^9$–$10^{10}\,{\rm M}_\odot$) at the steep end of the luminosity and mass function, the ensuing selection biases can reconcile the present SAMs with the observations. A proper interpretation of quasar host data thus requires the global approach of SAMs so as to account for statistical biases.

**Key words:** galaxies: active – galaxies: evolution – galaxies: formation – galaxies: high-redshift – quasars: general.

## 1 INTRODUCTION

There is evidence that every galactic spheroid (elliptical galaxy or bulge) hosts a central supermassive black hole (BH), with a strict relationship between the BH mass and the luminosity, mass, velocity dispersion, concentration and binding energy of the host (Kormendy & Richstone 1995; Magorrian et al. 1998; Ferrarese & Merritt 2000; Gebhardt et al. 2000; Ferrarese 2002; Tremaine et al. 2002; Bettoni et al. 2003; Häring & Rix 2004; Aller & Rischstone 2007; Barway & Kembhavi 2007; Graham & Driver 2007). This discovery has highlighted the close connection between the process of galaxy formation at large and the formation of the central BH, endowed with its quasar activity, and is currently one of the major observational facts that the theory of galaxy evolution has to explain. In the cold dark matter (CDM) hierarchical cosmological scenario, the usual paradigm is that (major) mergers are responsible for the joint origin and growth of BHs and galactic spheroids. Mergers trigger gas inflows feeding BH growth and quasar activity, while at the same time they modify the morphology of the galaxy into a bulge-dominated one (e.g. Kauffmann & Haehnelt 2000; Di Matteo, Springel & Hernquist 2005). Alternative mechanisms link directly the BH growth to the intrinsic star formation activity or morphological evolution of the host (e.g. Granato et al. 2001, 2004; Bower et al. 2006; Fontanot et al. 2006). All these scenarios share an important feature: a quasar marks a very specific, short but crucial phase in the evolution of a galaxy. The host is expected to be a 'young spheroid' where strong star formation (intrinsic or merger-induced) has just halted, by quasar feedback or by mere consumption of the cold gas that fed both the starburst and the quasar. Thereafter, the galaxy rapidly reddens and evolves passively, while the central BH becomes a 'dead quasar' or a 'dormant BH' (Springel, Di Matteo & Hernquist 2005a; Hopkins et al. 2008; Johansson, Naab & Burkert 2009a; Johansson, Burkert & Naab 2009b) – until, possibly, later mergers or gas infall revives star formation and/or active galactic nucleus (AGN) activity.

On the observational side, major advances have been achieved in the past few years: a suitable number of detected quasar host galaxies at redshift $1 < z < 3$ are nowadays available. Their luminosity apparently follows passive evolution, consistent with that of an elliptical galaxy formed at $z > 3$ (Kotilainen et al. 2009), in contrast with the theoretical scenario outlined above. In this paper, we aim at testing whether the predictions of current merger-based models are compatible with the available observations of quasar hosts.

Direct comparison to data on quasi-stellar object (QSO) host galaxies demands theoretical predictions on the properties of galaxies *specifically at the very phase of the optical QSO activity*, as this

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⋆E-mail: lporti@utu.fi (LP); jarkot@utu.fi (JK); renato.falomo@oapd.inaf.it (RF); decarli@mpia-hd.mpg.de (RD) is supposed to be a short but very critical phase of galaxy formation. The only explicit predictions in this sense, in the framework of semi-analytical models (SAMs), seem to date back to Kauffmann & Haehnelt (2000); here we use the most recent public mock catalogue from the Munich group to extract the expected properties of quasar host galaxies, and compare them with the latest available data.

We consider in particular recent results on the evolution of the BH mass–host mass (or luminosity) relation. Peng et al. (2006) and Decarli et al. (2010a,b) find that the BH mass–luminosity relation is roughly constant with redshift; considering the intrinsic fading of stellar populations with age, this implies that the host stellar mass $M_\star$ associated with a given BH mass $M_{\rm BH}$ decreases at high $z$. The evolution of the mass ratio $\Gamma = M_{\rm BH}/M_\star$ is an important constraint on theoretical models, especially regarding the role of quasar feedback (Wyithe & Loeb 2005; Fontanot et al. 2006).

The outline of the paper is as follows. In Section 2 we describe the SAMs in use and how quasar host galaxies are selected from the mock galaxy catalogues. In Sections 3 and 4 we discuss the evolution of the BH mass–stellar mass and of the BH mass–luminosity relation, compared to observational evidence. In Section 5 we discuss the mass function of the BH in quasars at high redshift. In Section 6 we outline our conclusions and suggestions for future studies. In Appendix A we discuss the problem of transforming observed host luminosities into stellar masses, and the significance of their apparent passive evolution.

## 2 MERGER-TRIGGERED QUASAR ACTIVITY: SEMI-ANALYTICAL MODELS

For about a decade SAMs, superposing the evolution of visible structures over that of the underlying CDM, treated galaxy formation (White & Rees 1978) and quasar activity (Efstathiou & Rees 1988) separately. After growing evidence of the BH–host bulge relation, the two lines of investigation were merged: galaxy evolution models have incorporated BH growth and AGN activity. The first ‘unified’ model was given by Kauffmann & Haehnelt (2000), followed by many others (Enoki, Nagashima & Gound 2003; Granato et al. 2004; Cattaneo et al. 2005; Bower et al. 2006; Croton, Springel & White 2006; Fontanot et al. 2006; Menci et al. 2006; Malbon et al. 2007; Marulli et al. 2008; Somerville et al. 2008; Bonoli et al. 2009; Fanidakis et al. 2011; Jahnke & Macció 2011).

Most of these models assume that the joint origin of spheroids and BHs is a consequence of mergers. In few cases, central BH accretion is (also) associated with the intrinsic evolution of the host: with its star formation activity (Granato et al. 2004; Fontanot et al. 2006) or with its morphological transformation from disc to bulge (Bower et al. 2006; Fanidakis et al. 2011). Another important distinction among the various models is whether quasar feedback at high redshift plays a key role (e.g. Granato et al. 2004; Fontanot et al. 2006; Menci et al. 2006; Somerville et al. 2008) or not.[1]

Our discussion relies on the public catalogue of SAM galaxies by the Munich group (De Lucia & Blaizot 2007), based on the Millennium Simulation (Springel et al. 2005b) and retrievable from the Millennium data base.[2] As to the ‘quasar mode’ BH accretion at high redshift, this SAM follows essentially the recipe of its prototype (Kauffmann & Haehnelt 2000; see also Croton et al. 2006). Each merger triggers a starburst, and a few per cent of the available cold gas mass $m_{\rm cold}$ accretes on to the central BH:

$$\Delta M_{\rm BH} = f_{\rm BH} \frac{m_{\rm sat}}{m_{\rm cen}} \frac{m_{\rm cold}}{1 + (280\,{\rm km\,s^{-1}}/V_{\rm vir})}. \tag{1}$$

The mass of the resulting BH is the sum of the progenitor BH masses and the (dominant) accreted mass $\Delta M_{\rm BH}$. The parameter $f_{\rm BH} = 0.03$ is tuned to reproduce the observed local BH mass–bulge mass relation at $z = 0$. The efficiency of BH growth scales with the mass ratio $m_{\rm sat}/m_{\rm cen}$ of the merging galaxies (‘satellite’ and ‘central’) so that the fractional contribution of minor mergers to quasar activity is small. BH accretion in the quasar mode is thus dominated by major mergers (mass ratio larger than 1:3) which result in the formation of a spheroid.

QSO activity in this model is always associated with a recent merger and active star formation. Quasar activity is a by-product of the merger, with no impact on the evolution of the galaxy – arguing that any quasar-induced feedback can be formally included in the strong supernova feedback accompanying the starburst. The Munich SAMs effectively belong to the no-feedback category in the quasar mode.

The Munich SAM series has been successfully tested and tuned to reproduce a wide range of observational properties of the galaxy population, such as galaxy clustering (Springel et al. 2005b); galaxy luminosity function, colour and morphology distributions, colour–magnitude, mass–metallicity and Tully–Fisher relations, cosmic star formation and BH growth history (Croton et al. 2006); the formation history of elliptical galaxies (De Lucia et al. 2006) and the properties of bright cluster galaxies (De Lucia & Blaizot 2007). This SAM is optimized to describe the galaxy population, but results on the corresponding AGN population are discussed by Marulli et al. (2008) and Bonoli et al. (2009). The cosmological evolution of the $M_{\rm BH}-M_{\rm bulge}$ relation in this model is discussed by Croton (2006).

In our study we use the available public mock galaxy catalogue of the Munich SAM (De Lucia & Blaizot 2007) to discuss the evolution of the scaling relations (BH mass versus host mass and luminosity) *as traced specifically by quasar host galaxies* up to $z = 3$.

### 2.1 Quasar host galaxies in the Munich SAM

To compare the Munich SAM with observed data on the BH–host relation in quasars, we need to know, at each redshift/snapshot of the SAM: (a) which are the active galaxies, (b) their BH masses and (c) their stellar masses and luminosities. All of this information is directly available in the public catalogue of De Lucia & Blaizot (2007), with no need for further assumptions. The active galaxies in ‘quasar mode’ are those that have just suffered a merger; we query the data base to select recent mergers following the example instructions provided on the website. ‘Recent merger’ in this case means, merged since the previous redshift snapshot, typically 1–3 × $10^8$ yr before. This is longer than the duty cycle of optical quasar

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[1] Attention has been recently focused on the role of AGNs in halting cooling flows in massive galaxies and clusters at low redshift, to better reproduce their red colours and the bright end of the local luminosity function: the ‘radio mode’, associated with low-level accretion (Kawata & Gibson 2005; Bower et al. 2006; Croton et al. 2006; Bower, McCarthy & Benson 2008). Here we refer to the feedback in the ‘quasar mode’, related to the bright phase of quasar activity at high redshift, where the bulk of BH growth and quasar energy emission occurs. Note that effective quasar feedback is directly supported by recent observations of outflows of molecular gas (Feruglio et al. 2010; Sturm et al. 2011).

[2] http://www.g-vo.org/Millennium

activity ($10^7$–$10^8$ yr) so that we can identify the very moment of quasar shining only approximately – but it is as close as we can get with the time resolution available in the public SAM catalogue.

For the recent merger/quasar mode galaxies we retrieve the following information: BH mass, stellar mass, gas mass and luminosity in various bands. We also retrieve the BH, stellar and gas mass of the progenitors: this gives us the BH mass growth $\Delta(M_{\rm BH})$ (from the mass difference between the progenitor BHs and the resulting BH) and the merger mass ratio. We also retrieve BH and galaxy properties for the overall galaxy population, to discuss differences (in luminosity mainly, see Section 4) with the quasar host subset.

The quasar population and AGN luminosity function associated with these same quasar hosts were studied by Marulli et al. (2008) by adding to the SAM various prescriptions about the quasar light curve associated with $M_{\rm BH}$ and $\Delta(M_{\rm BH})$ in each merger. Note that their (or any) additional assumptions on the quasar light curve do not affect the basic quantities [BH masses, $\Delta(M_{\rm BH})$, galaxy properties, etc.] available in the public mock catalogue, which set the scaling relations in the SAM. We comment later on the results of Marulli et al. (2008) in relation to ours, but shall not develop here a new model for the quasar population and light curves as it is not needed to study the scaling relations.

For practical reasons (avoid overload of unnecessary output data from the data base query) we impose some additional restrictions that do not affect the substance of the quasar host population.

(i) We consider mergers with a mass ratio (in cold baryons, i.e. stellar mass + cold gas mass) larger than 1:9. As major mergers 1:3 largely dominate BH growth (Croton et al. 2006), 1:9 is a very safe limit to include all significant optical QSO activity – considering that the latter does correspond to the bulk of the BH growth (Soltan 1982; Yu & Tremaine 2002). We checked that, among our final selected objects, major mergers (with a mass ratio larger than 1:3) contribute about half of the quasar hosts with $M_{\rm BH} = 10^8\,{\rm M}_\odot$ and dominate by 70–80 per cent at the massive end, $M_{\rm BH} \geq 10^9\,{\rm M}_\odot$. The quoted percentages are stable with redshift.

(ii) We restrict to galaxies hosting a BH mass $M_{\rm BH} \geq 2 \times 10^7\,{\rm M}_\odot$; this is a conservative choice that fully covers the BH mass range of the observational data set (QSO hosts at high $z$ have $M_{\rm BH} \geq 10^8\,{\rm M}_\odot$) even including the 0.4 dex error on the measured $M_{\rm BH}$, discussed later in Section 4. Besides, BH masses below our adopted limit hardly contribute to the optical quasar population (see e.g. McLure & Dunlop 2004; Shankar et al. 2010); for instance, in the latest Sloan Digital Sky Survey quasar sample of Shen et al. (2011), only 19 out of over 22 000 BH masses measured with $H_\beta$ lines are below $2 \times 10^7\,{\rm M}_\odot$.

Considering specifically the observational QSO sample of Decarli et al. (2010a), all objects at $z > 0.5$ have $M_V < -24$, which is much brighter than expected from our adopted mass cut. Indeed a BH of $2 \times 10^7\,{\rm M}_\odot$, emitting typically around 0.5 of its Eddington luminosity (McLure & Dunlop 2004; Labita et al. 2009), shines with $L_{\rm bol} = 1.3 \times 10^{38}$ W, corresponding to $M_B = -22.02$ (McLure & Dunlop 2004) or $M_V = -22.24$ (assuming a typical quasar colour $B - V = 0.22$, from Cristiani & Vio 1990). Clearly our mass cut covers both the mass and luminosity range relevant for comparison with observations.

(iii) We neglect multiple mergers of three or more progenitors, for simplicity, in the treatment of the query output (multiple mergers appear as a repeated double merger in the output list). We also neglect mergers with progenitors identified too early on (two or more snapshots before, rather than in the immediately previous snapshot) as the instant of the merger and the corresponding quasar activity is not guaranteed to be very recent, i.e. the time resolution on the quasar host phase is much worse. These two criteria together exclude less than 10 per cent of the merger events, bearing no impact on our discussion.

(iv) As the Soltan argument indicates that optical QSO activity traces the bulk of the BH growth, we test the additional requirement that the selected mergers induce a BH growth of more than 50 per cent – a simple, reasonable way to ensure that the merger corresponds to significant quasar activity. We verified that most of our conclusions are not affected when relaxing this ‘doubling’ criterion; when this is the case, both alternatives are shown (Section 5).

The selected mergers/quasar hosts represent 5–6 per cent of the global galaxy population at $z \geq 1$ and 2 per cent at $z = 0.5$. At each redshift snapshot between $z = 1$ and 3, our discussion is based on a sample of 1–3 $\times 10^4$ merger galaxies selected as above, out of a global galaxy population of 3–5 $\times 10^5$ objects.

Beyond $z \sim 1$, mergers are usually considered the main trigger of AGN activity, while at lower redshift other mechanisms are likely to contribute or even dominate (secular evolution and bar-driven instabilities; mass loss from old stellar populations; e.g. Hopkins & Hernquist 2009; Kauffmann & Heckman 2009; Cisternas et al. 2011). Therefore, our selection of recent mergers (and the underlying assumptions in the SAM about quasar activity) may not be well suited for AGN hosts at $z < 1$, but in this paper we are mostly concerned with the hosts of bright quasars at high redshift.

Furthermore, at high redshift it is observationally hard to decompose the host galaxy into its bulge/disc component, so the observed scaling relations often refer to the global host galaxy (a recent exception is Bennert et al. 2011). For consistency with this limitation, we extract from the SAM the scaling relations between BH and host galaxy, rather than host spheroid. However, as customary in the observational papers, we shall compare the high-redshift results for the host *galaxies* with the $z = 0$ relation between BH and host *bulge* (Marconi & Hunt 2003; Häring & Rix 2004).

## 3 THE BH MASS–HOST MASS RELATION

In this section we discuss SAM predictions on the evolution of the BH mass–host mass relation. Fig. 1 shows the distribution, in the $M_{\rm BH}-M_\star$(host) plane, of quasar hosts (solid contours) and of the global galaxy population (dotted contours) at various redshifts. In this plane, the two populations occupy the same loci, i.e. QSO hosts are a fair sample of the general galaxy population (at least for $M_{\rm BH} \geq 10^8\,{\rm M}_\odot$, the relevant range for high-$z$ observed quasars).

To discuss the evolution of the $M_{\rm BH}-M_\star$(host) relation, we need to specify how the relation can be defined in the models. From the physical point of view, neither the BH mass nor the host stellar mass can be selected to be the independent versus dependent variable, as they both are the result of a third process: galaxy formation and evolution. For this sort of related variables, the best statistical tracer of the intrinsic mutual relation is a bisector fit relation (Isobe et al. 1990; Akritas & Bershady 1996). This definition is also the one adopted for the observed relation in the local Universe (Marconi & Hunt 2003; Häring & Rix 2004). The ‘intrinsic’ (bisector fit) relation for the SAM galaxy catalogue (dashed lines in Fig. 1) at low redshift matches very well the local relation observed at $z = 0$ and displays little evolution with redshift. The latter is a general feature of SAMs that does not include quasar feedback (Wyithe & Loeb 2005; Fontanot et al. 2006; Malbon et al. 2007).

Note that the slope of the bisector fit relation in the $\log(M_{\rm BH})-\log({\rm M}_\star)$ plane turns out to be always close to 1;

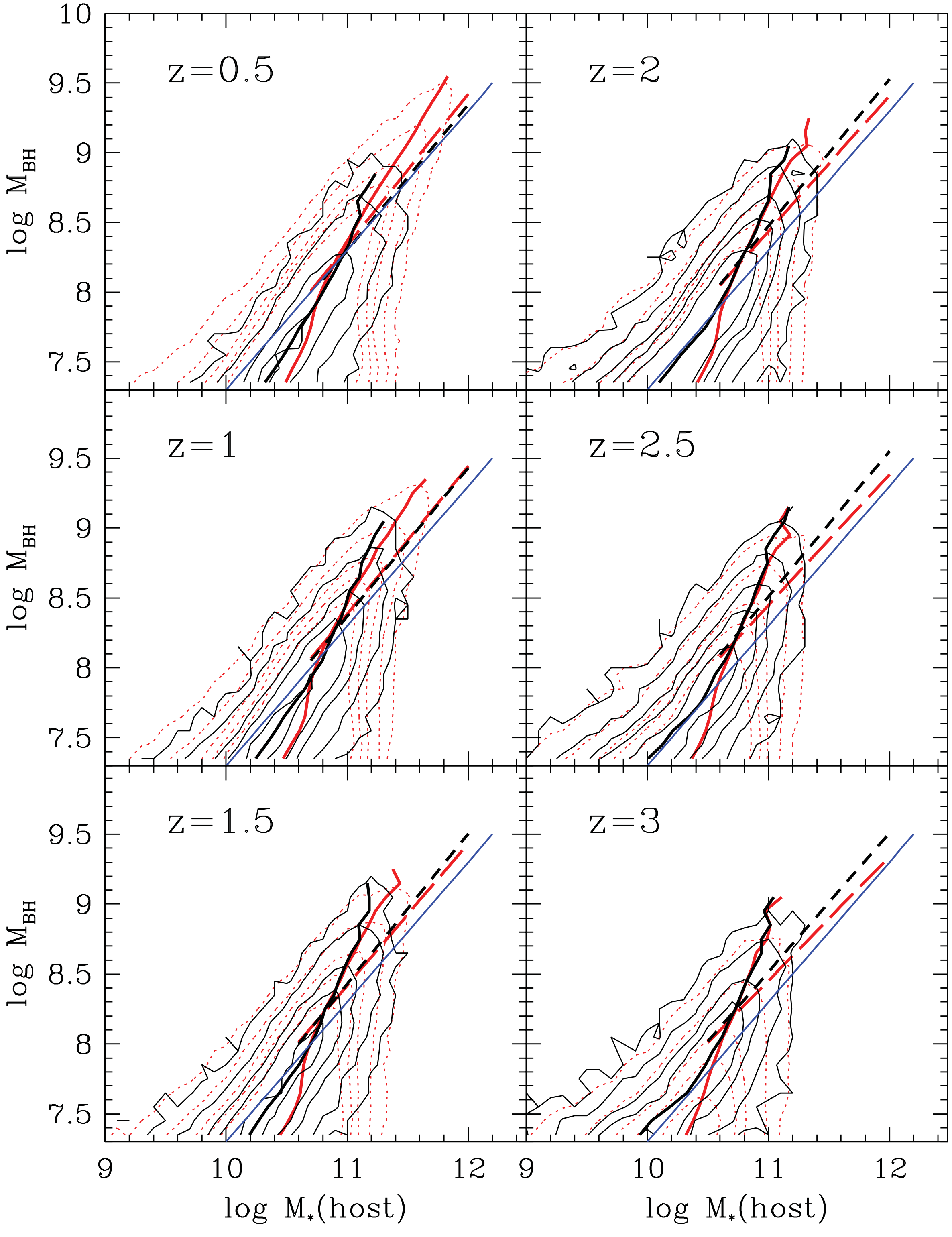

**Figure 1.** Relation between the BH mass and the host stellar mass at various redshifts, as derived from the SAM galaxy catalogue of De Lucia & Blaizot (2007) in the Millennium data base. Dotted (red) contours: isodensity contour plots for the global galaxy population. Solid contours: selected quasar hosts (recent mergers with significant BH accretion, see the text). The contour levels for the far more numerous global galaxy population are 10 times those of the quasar hosts. The solid lines trace the median host luminosity as a function of the BH mass, for the global galaxy population and for the quasar hosts. The dashed lines trace the bisector fit relations: long-dashed (red) line for the global galaxy population, short-dashed for quasar hosts; both are defined for $M_{\rm BH} \geq 10^8$ M$_\odot$(the minimum BH mass relevant for comparison with observed high-$z$ QSO hosts) but this limit is not crucial for the resulting relation. The (blue) thin straight line is the observed relation at $z = 0$: $M_{\rm BH}/M_\star$(bulge) = 0.002 (Marconi & Hunt 2003).

therefore, in practice this definition is very similar to what we would obtain with the more common approach of fixing the slope to 1 and fitting a unique value for the ratio $\Gamma = M_{\rm BH}/M_\star$ (e.g. Croton 2006; Decarli et al. 2010b). We also note that, for the same SAMs considered here, Croton (2006) reports a significant evolution in the $M_{\rm BH}-M_{\rm bulge}$ relation; this is not in contrast with our findings: most of the evolution he reports is due to the redistribution of stars from the disc to the bulge component, an effect which largely cancels out when we consider the global host galaxy.

The negligible evolution of the intrinsic (bisector fit) relation appears in contrast to observational results, when taken at face value (e.g. Peng et al. 2006; Decarli et al. 2010a,b). When comparing to high-redshift data, however, we must take into account that quasar hosts are operatively detected starting from QSO selected samples, and tend to pick out the median host mass as a function of the BH mass (solid lines in Fig. 1). The latter definition of the $M_{\rm BH}-M_\star$(host) relation mimics more closely the empirical sampling and also traces better the contour plots, which are a convolution between the intrinsic BH mass–host mass relation, its scatter and the mass function of galaxies (Lauer et al. 2007). There is a systematic bias between the two definitions of the relation: the more luminous quasars tend to trace overmassive BHs with respect to the underlying intrinsic BH–host relation. This is due to the fact that, being massive galaxies very rare, the most massive BHs are more easily found as outliers hosted in undermassive (but more frequent) hosts. This bias is discussed extensively by Lauer et al. (2007) and we shall refer to it as the Lauer bias. The bias can be defined either as an excess of BH mass at a given host mass/luminosity/velocity dispersion, or as an offset in host properties at a given BH mass. To interpret quasar host data, where the effective independent variable in the selection is the BH mass of the QSO, we prefer the latter approach: $\Delta \log M_\star$ is the offset in host mass between the median relation marginalized over the BH mass and the intrinsic (bisector fit) relation. The Lauer bias for the global galaxy population in the SAM catalogue is represented in Fig. 2 and Table 1. In these SAMs, the deviation of the distribution from the intrinsic relation is significant [$\geq 0.2$ dex in $M_\star$(host), i.e. larger than the typical dispersion] around $M_{\rm BH} = 10^9$ M$_\odot$. At this BH mass, the bias increases from 0.2 to 0.6 dex between $z = 0.5$ and 3; this is comparable to the evolution determined by Decarli et al. (2010b), considering that most of their objects at $z > 1$ indeed have $M_{\rm BH} \geq 10^9$ M$_\odot$.

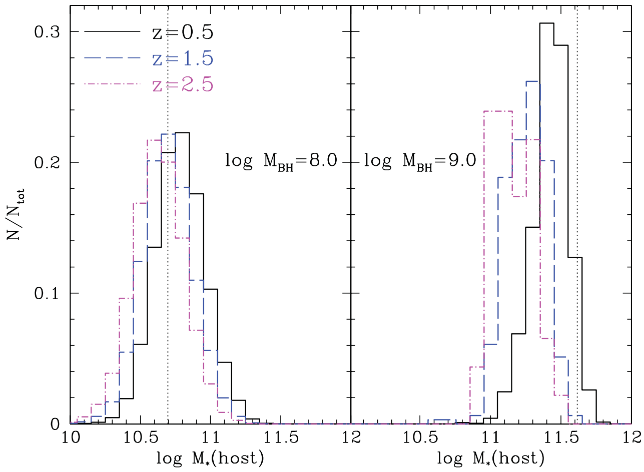

**Figure 2.** Histograms of the distribution of host galaxy masses corresponding to a given BH mass, as a function of redshift. The dotted vertical lines mark the host mass predicted by the intrinsic bisector fit relation (at $z = 0.5$, but evolution with redshift is negligible). The offset between the histograms and the vertical line represents the Lauer bias. The plot refers to the global galaxy population in the SAM catalogue; QSO hosts behave in a very similar way.

**Table 1.** Lauer bias for the global galaxy population in the SAM catalogue. We indicate the offset $\Delta \log M_\star$(host) (typically an underestimate: minus sign) of the median host stellar mass at a given BH mass, with respect to the intrinsic bisector fit relation. The dispersion is estimated from the 16th and 84th percentiles of the distribution (corresponding to 1 standard deviation for a Gaussian distribution). For the entry in the bottom-right corner ($z = 3$, $M_{\rm BH} = 10^9$ M$_\odot$), due to the small number of objects we considered the average logarithmic host mass and the extreme values in the sample.

| $z$ | $\log M_{\rm BH} = 8$ | $\log M_{\rm BH} = 8.5$ | $\log M_{\rm BH} = 9$ |
|---|---|---|---|
| 0.5 | $0.08 \pm 0.18$ | $-0.08 \pm 0.15$ | $-0.19 \pm 0.13$ |
| 1.0 | $0.09 \pm 0.18$ | $-0.09 \pm 0.14$ | $-0.23 \pm 0.15$ |
| 1.5 | $0.10 \pm 0.18$ | $-0.12 \pm 0.15$ | $-0.32 \pm 0.15$ |
| 2.0 | $0.11 \pm 0.18$ | $-0.15 \pm 0.15$ | $-0.37 \pm 0.17$ |
| 2.5 | $0.11 \pm 0.18$ | $-0.17 \pm 0.15$ | $-0.45 \pm 0.16$ |
| 3.0 | $0.11 \pm 0.18$ | $-0.21 \pm 0.16$ | $-0.58 \pm 0.09$ |

### 3.1 The evolution of Γ

The cosmological evolution of the BH/host mass ratio:

$$\Gamma = \frac{M_{\rm BH}}{M_\star({\rm host})}$$

can contribute to discriminate between different scenarios of coevolution of central supermassive BH and host galaxy: models where quasar feedback plays a prominent role predict a stronger evolution in Γ (increasing in the past) than models that do not include this effect (Wyithe & Loeb 2005), and different feedback scenarios result in different predictions for $\Gamma(z)$ (Fontanot et al. 2006). It is thus tempting to conclude that the strong evolution detected in recent observational studies favours the models that take feedback and self-regulation into account (Fig. 3). In particular, it should exclude ‘extreme merger scenarios’ where the relation between the BH mass and host mass is just the statistical outcome of the stochastic merger history, with no direct physical relation between BH and bulge formation at the level of individual galaxies (Peng 2007; Jahnke & Macciò 2010).

However, an apparent evolution of Γ is seen in the SAMs due to the Lauer bias, as the combination of two factors: (i) the slope of the median $M_{\rm BH}-M_\star$(host) relation is steeper than 1:1 (closer to 2:1) and (ii) the mass function of quasars and the Malmquist bias affect the accessible parameter range one can address as a function of redshift. We sample more luminous and massive quasars at increasing redshift and tendentially find smaller hosts and larger Γ.

Fig. 4 illustrates that, when derived from the intrinsic relation (bisector fit, dashed lines), Γ is close to the local reference value with little evolution (about 0.2 dex offset between $z = 0$ and $2-3$). In contrast, the median Γ at $M_{\rm BH} = 10^9$ M$_\odot$ shows a significant offset (a factor of 2–3 already at low redshift) and evolution with respect to the local value. This apparent evolution of Γ due to the Lauer bias is comparable to that traced by the data in Fig. 3, considering that observational samples mostly include QSOs with $M_{\rm BH} \geq 10^9$ M$_\odot$. This suggests that the Γ evolution inferred from the observations

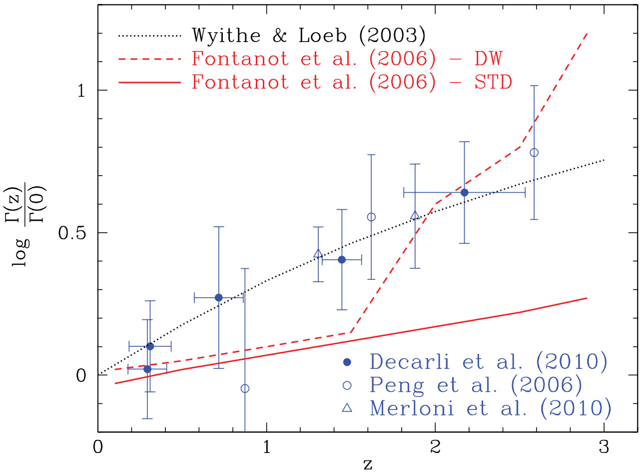

**Figure 3.** Symbols with error bars represent the evolution of the mass ratio $\Gamma = M_{\rm BH}/M_\star$ in quasar host galaxies, from various observational papers, as compiled by Decarli et al. (2010b). Lines represent the predictions of various SAMs from the literature. Wyithe & Loeb (2003) and the drying wind model of Fontanot et al. (2006) include self-regulation by quasar feedback, while the standard model of Fontanot et al. does not.

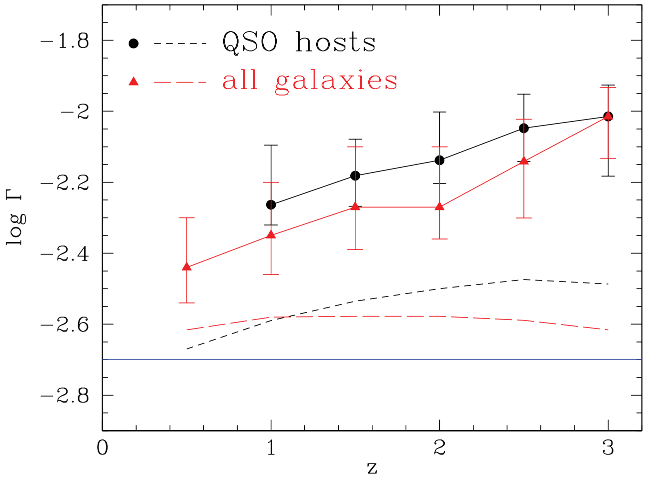

**Figure 4.** Evolution with redshift of Γ, for QSO hosts and for all galaxies in the SAM catalogue. The dashed lines refer to the bisector fit relation. Symbols connected with solid lines refer to the median Γ for objects with a BH mass around $M_{\rm BH} = 10^9$ M$_\odot$; the error bars indicate the 16th and 84th percentiles of the distribution. The horizontal line marks the local value $\Gamma = 0.002$ (Marconi & Hunt 2003).

may be largely due to the bias, and be compatible even with models that do not include effective quasar feedback.

Decarli et al. (2010b) performed a more empirically based estimate of the Lauer bias expected in their data and found it to be negligible with respect to the observed evolution. The extent of the Lauer bias depends on the luminosity/mass function of galaxies and of supermassive BHs, on the scatter of the intrinsic relation and on its evolution with redshift (Lauer et al. 2007). For the SAMs considered here, there is evidence (see Section 5) that the models underestimate the number of massive quasars at high $z$; consequently, the Lauer bias in the SAM is probably exacerbated and 'shifted' at proportionally too low BH masses. None the less, our results show that it is an important ingredient in the interpretation of the data, and the global approach provided by SAMs is needed to interpret the properties of quasar host samples.

## 4 THE BH MASS–HOST LUMINOSITY RELATION

The BH mass–host mass relation is physically more meaningful, yet the most direct comparison between models and data is for the BH mass–host luminosity relation. Observationally, in fact, we measure the luminosity of detected quasar host galaxies. Their stellar mass is then derived indirectly, typically assuming that the host is a spheroidal galaxy evolving passively since a higher formation redshift (Peng et al. 2006; Kotilainen et al. 2009; Decarli et al. 2010b). This is a quite different picture from the 'young spheroid' scenario of theoretical models. Further differences in the adopted stellar initial mass function (IMF) can easily introduce systematic offsets up to 0.3 dex in the $M_\star/L$ (Bell & de Jong 2001; Portinari, Sommer-Larsen & Tantalo 2004). The issue is further discussed in Appendix A.

Therefore, in this section we compare directly SAMs with observational data in the BH mass–host luminosity plane. We consider the rest-frame $R$-band magnitude which is the most common band of choice in the observational data sets.[3] In Fig. 5 we show the locus of SAM galaxies in the $R$-band magnitude–BH mass plane, at various redshifts. In this plane, quasar host galaxies are *not* a fair sample of the global galaxy populations: having suffered a recent merger with associated starburst, they tend to be overluminous and bluer than average. Indeed at low redshifts, quasar hosts in the SAM are systematically brighter by about 0.5 mag, at a given BH mass. At higher redshifts however ($z > 2$), due to the younger age and more intense star formation activity of the galaxy population at large, the offset between the two populations tends to vanish.

In Fig. 5, we see that at low $z$ the median relation for the global galaxy population (thick solid line tracing the dotted contours) agrees with the relation observed in the local Universe (thin straight line), while departing from it at higher redshift. Quasar hosts are always overluminous than the local relation, at any redshift. Both trends appear to be at odds with observations, which indicate a non-evolving BH mass–luminosity relation (Peng et al. 2006; Decarli et al. 2010b).

This discrepancy is evident in Fig. 6 (top panels) where we compare directly the observations of Decarli et al. (2010a,b) to the properties of SAM quasar hosts in the corresponding redshifts range. At a given BH mass, the model QSO hosts are clearly overluminous with respect to the data and/or SAMs produce an undermassive BH at given host luminosity. Even considering that the normalization of the measured BH masses is somewhat arbitrary, depending on the assumed geometry of the broad-line regions, one can hardly reconcile model predictions with the data: the minimum BH masses, corresponding to the isotropic case, would be systematically lower by 0.5 dex than the normalization adopted by Decarli et al. (2010a); but a disc-like geometry is favoured by a number of arguments (Decarli et al. 2008a,b; Graham et al. 2011, and references therein).

However, a proper comparison with observational data sets requires to convolve model predictions with observational errors.

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[3] For comparison to observational data, we have transformed Johnson $R$-band magnitudes provided for the SAMs in the Millennium data base, to Cousins $R$-band magnitudes. We have used $(V-R)_{\rm C} = 0.715\,(V-R)_{\rm J} - 0.02$ (Bessell 1983), valid up to $(V-R)_{\rm C} = 0.8$ which fully covers the colour range spanned by the SAM galaxies. Galaxies are 'fainter' in Cousins $R$ band and bluer in $(B-R)_{\rm C}$ and $(V-R)_{\rm C}$ colours; the filter corrections range between 0.1 mag for the bluest objects [QSO hosts at high redshift, with typical $(V-R)_{\rm C} \geq 0.2$] and 0.25 mag for the reddest ones [general galaxy population at $z = 0$, with typical $(V-R)_{\rm C} < 0.55$].

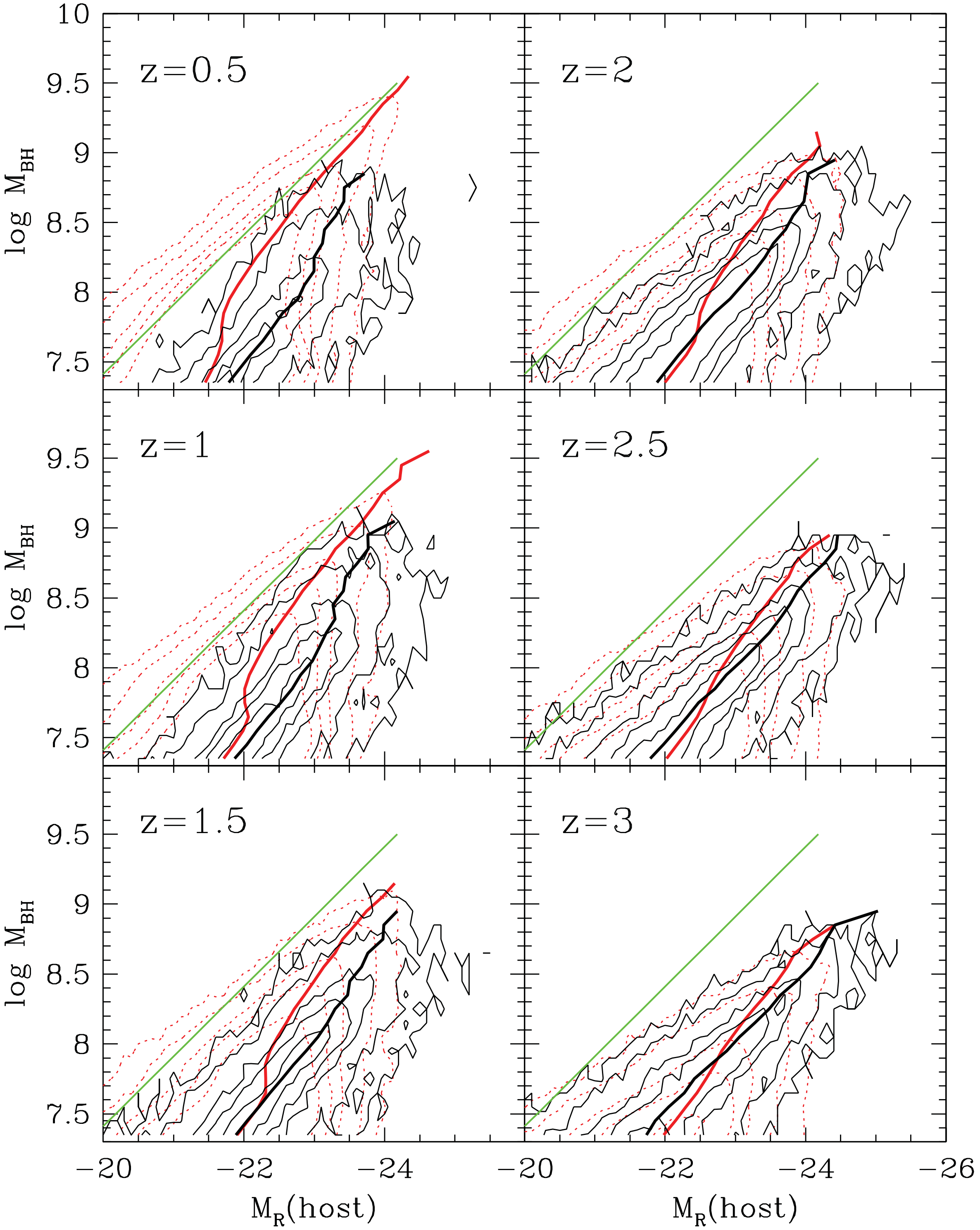

**Figure 5.** Evolution with redshift of the relation between the BH mass and the host *R*-band magnitude (including dust extinction) in the SAM galaxy catalogue. As in Fig. 1, the (red) dotted and the solid contours refer to the global galaxy population and to the QSO hosts, respectively; the solid lines show the corresponding median relations. The (green) thin straight line is the observed relation at $z = 0$ (Bettoni et al. 2003, adapted to the cosmology of the Millennium run with $h = 0.73$).

We assume typical $1\sigma$ uncertainties of 0.3 mag in host luminosity, and 0.4 dex in BH mass, determined via the virial technique (Vestergaard & Peterson 2006; Shen & Kelly 2010; Bennert et al. 2011). The corresponding quantities in the SAM galaxy catalogue are altered with randomly assigned errors in the Gaussian/lognormal distribution. The effects of error convolution are crucial, as shown in the bottom panels of Fig. 6. The models now recover the observational results, although the most massive BH masses fall somewhat short of the observed ones at the highest redshifts.

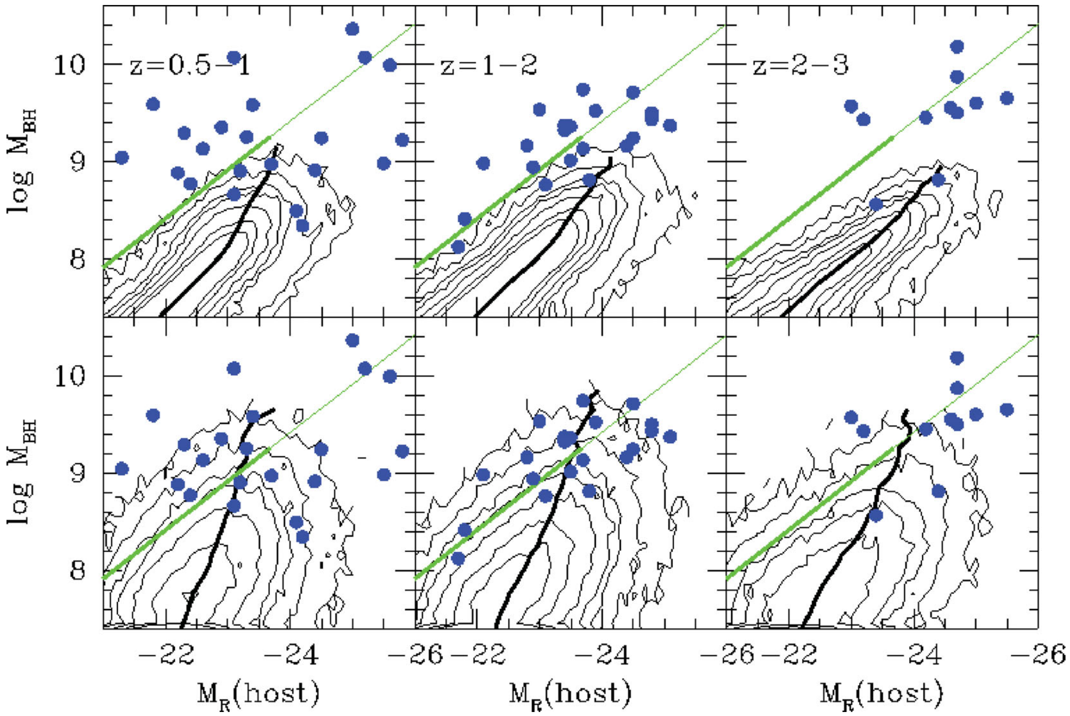

**Figure 6.** Evolution with redshift of the relation between the BH mass and the host luminosity in SAM quasar hosts, compared to observations (Decarli et al. 2010a,b; dots) in three redshift bins. The light (green) straight line is the local relation at $z = 0$ (Bettoni et al. 2003), extended with a thin line at magnitudes brighter than $M_R = -24$. Top panels: actual SAM quasar hosts; bottom panels: convolving SAM predictions with observational errors ($1\sigma$) of 0.3 mag in $M_R$(host) and 0.4 dex in log($M_{\rm BH}$).

We find that it is the error on BH masses, rather than on host luminosities, that has the main impact in altering SAM predictions. This effect was discussed by Shen & Kelly (2010; see also Shen et al. 2008; Kelly, Vestergaard & Fan 2009): observational errors on measured BH masses, combined with the steep end of the BH mass function, introduce a Malmquist-type bias that skews the sample towards much larger apparent BH masses. We shall refer to this as the Shen–Kelly bias. An analogous Malmquist-type bias at the bright end of the galaxy luminosity function has proved to help to account for the stellar mass function of high-$z$ galaxies in the hierarchical scenario (Fontanot et al. 2009, and references therein).

The evolution of the BH mass–luminosity relation, in terms of brightening with redshift at a given BH mass, is illustrated in Fig. 7. The left-hand panel shows the 'real' evolution in the SAM: the global galaxy population gets steadily brighter at increasing redshift, and quasar hosts are predicted to be much brighter at any redshift. The overluminosity depends on the BH mass: around $M_{\rm BH} \simeq 10^9\ {\rm M}_\odot$ – the most interesting BH mass range for comparison with the data set of Decarli et al. (2010a,b) – the offset is 0.7–1 mag, increasing to almost 2 mag at lower BH masses around $M_{\rm BH} \simeq 10^8\ {\rm M}_\odot$.

In the right-hand panel we show the results after error convolution: while the evolution of objects around $10^8\ {\rm M}_\odot$ is marginally affected, the scenario drastically changes at the high-mass end: for (apparent) BH masses of $10^9$–$10^{9.5}\ {\rm M}_\odot$, SAMs are consistent with no evolution within the errors and become compatible with observational results.

Altogether, the combined effect of Lauer bias and Shen–Kelly bias allows SAMs to compare successfully to the observational results. Note that both biases, acting at the massive/luminous end, produce a steepening in the slope of the BH mass–host luminosity (or host mass) relation: the apparent slope is about 1.5 dex mag$^{-1}$. Future observational investigations of the apparent slope, extending to QSOs of lower BH mass, will be a useful test for the models.

## 5 THE MASS FUNCTION OF QSOs

In the previous sections, we have seen how statistical biases dominate the interpretation of the observed evolution of the BH mass–host relation. Even with the 'aid' of bias effects, though, Fig. 6 suggests that the SAMs hardly reach the most massive BH observed in the high-redshift samples. Since the extent of the biases strongly depends on the luminosity/mass function of galaxies and BH at the high-mass end, we discuss in this section the observational constraints on the mass function of QSOs. In particular, we consider whether the lack of a massive BH in the SAM is just a statistical limit, simply due to the fact that very massive quasars are too rare objects to be included in the simulation volume.

The Millennium Simulation follows a comoving box of size $500\,h^{-1} = 685$ Mpc; from the mass function of quasars (Vestergaard & Osmer 2009), in such a volume we expect about 10 active nuclei with $10^{9.5} < M_{\rm BH} < 10^{10}\ {\rm M}_\odot$ at redshift $2 < z < 3$, while none is obtained in the simulations – not only considering the selected quasar host galaxies, but even in the global galaxy population. The left-hand panel in Fig. 8 shows the number of expected active nuclei as a function of mass and redshift (thick histogram), compared to those obtained in the SAM. The excess of low-mass QSOs in the SAM might depend on the details of our selection criterion, or to the incompleteness of the observed QSO mass function below $10^9\ {\rm M}_\odot$ (Kelly et al. 2010). More important for us here is the clear lack of quasars more massive than $10^9\ {\rm M}_\odot$ at high redshift, independent of our selection criteria – as it is confirmed looking at the global galaxy population.

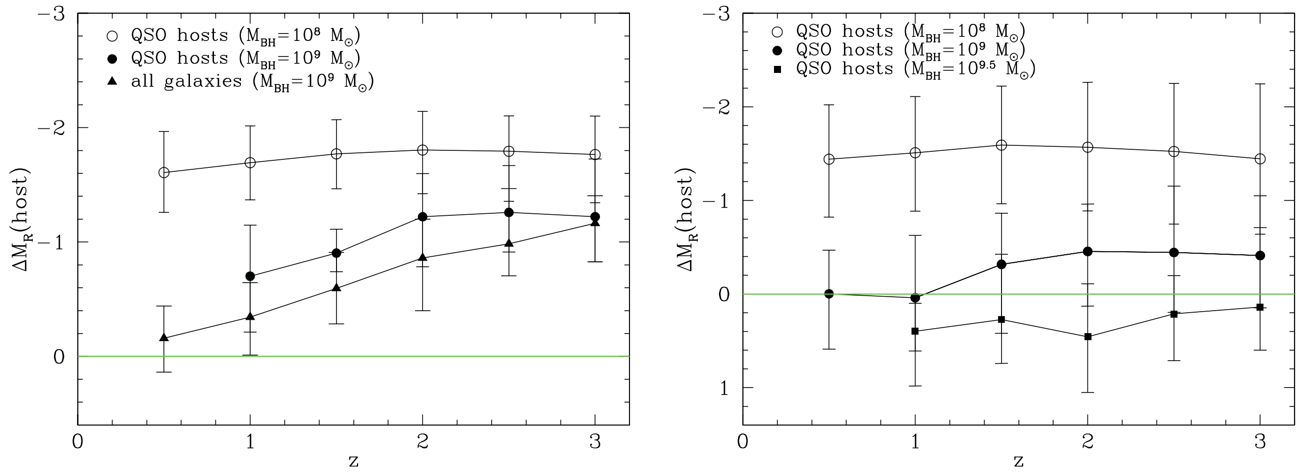

**Figure 7.** SAM predictions on the evolution of the offset $\Delta M_R$ with respect to the local BH mass–host luminosity relation (corresponding to luminosity $M_R = -21.2$, $-23.2$ and $-24.2$ for $M_{\rm BH} = 10^8$, $10^9$ and $10^{9.5}$ $\mathrm{M}_\odot$; see Fig. 5). The error bars indicate the 16th and 84th percentiles of the distribution. Left-hand panel: 'real' evolution in the SAM, for QSO hosts and for the general galaxy population; right-hand panel: including convolution with observational errors for QSO hosts.

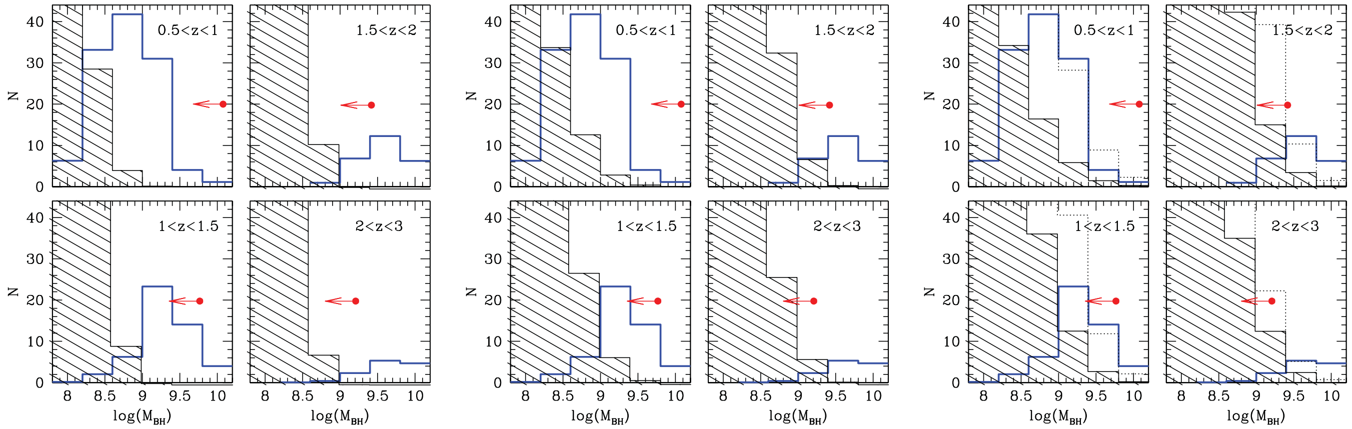

**Figure 8.** Thick (blue) histogram: BH mass function of QSOs in a volume of the real Universe equal to that of the Millennium Simulation (from Vestergaard & Osmer 2009). Thin shaded histogram: BH mass function of selected QSO hosts, scaled considering that each of the selected merger galaxies in the redshift range indicated (corresponding to 1–2 Gyr of time-span) is active as an optical QSO for only $10^7$ yr. Red dot with arrow: maximum BH mass in the global galaxy population at the lowest end of the redshift bin (i.e. at $z = 0.5$, 1, 1.5 and 2 for the various panels, respectively); it represents the maximum mass limit for QSOs that could possibly be active in that redshift bin; note the dearth of massive BHs ($M_{\rm BH} \geq 10^9$) at $z > 1.5$. Left-hand panel: actual BH mass function in the SAM. Mid panel: BH masses of QSO hosts have been convolved with a lognormal error of 0.4 dex. Right-hand panel: assuming a lognormal error of 0.55 dex; the *dotted histogram* is the (error-convolved) BH mass function of all merger galaxies (i.e. relaxing the 'doubling' criterion).

This dearth of massive BHs at high $z$ may be due to an intrinsic difficulty of hierarchical models to form massive objects at high redshift, or may demand a specific recipe for the formation of the most massive, rare BH. Marulli et al. (2008) noted an analogous mismatch with the bright end of the AGN luminosity function at $z > 1$, and suggested that an accretion efficiency increasing with redshift may cure the problem (see also Bonoli et al. 2009). It remains to be seen how the new prescription would impact the evolution of the scaling relations and the Lauer and Shen–Kelly bias in the Munich SAM. Both biases are strongest at the high-mass/luminosity end; therefore, a BH mass function depleted already at $M_{\rm BH} = 10^9$ $\mathrm{M}_\odot$ probably corresponds to an enhanced bias at that BH mass.

However, here also we must convolve model predictions with realistic observational errors. In the middle panel of Fig. 8, we show the results after convolving model BH masses with a lognormal error distribution of 0.4 dex standard deviation, similar to that adopted in Section 4. The comparison with the observed mass function at the high-mass end is improved, yet not satisfactory: the problem of an undermassive BH persists, at least above $M_{\rm BH} = 10^{9.5}$ $\mathrm{M}_\odot$. (Note that no error convolution is considered on the dot-with-arrow, i.e. on the most massive BH actually formed in the simulation; this highlights how the Shen–Kelly bias on QSO hosts can produce even higher BH masses, than actually existing in the whole simulated volume.)

However, if typical errors as large as 0.55 dex are allowed for the virial technique (Vestergaard & Osmer 2009; Vestergaard 2010; but see also Kelly et al. 2010, favouring smaller uncertainties), the discrepancy between SAMs and observed mass function is much reduced (right-hand panel in Fig. 8). Especially relaxing the 'doubling' criterion on BH masses for the selection of QSO hosts (see Section 2.1; dotted histogram) and taking into account that cosmic variance is typically two to three times the Poisson noise. All things considered, there is some evidence for a lack of a massive BH in simulated QSO hosts, but it is not compelling once observational errors are included. A deeper investigation on this issue would require a detailed simulation of the QSO light curves and luminosities, so as to extract from the SAM a sample of objects mimicking closely the observational selection.

Finally we remark that, while the Shen–Kelly bias depends only on the BH mass function and the uncertainties on measured BH masses, the Lauer bias is also sensitive to the luminosity function of galaxies: a paucity of simulated luminous, massive galaxies at high redshift would also enhance this bias. In this respect, we note that the long-standing difficulty of most SAMs with the $K$-band galaxy luminosity function at early epochs seems to be now overcome thanks to the improved treatment of the critical asymptotic giant branch phase in population synthesis models (Henriques et al. 2011).

## 6 DISCUSSION AND CONCLUSIONS

QSO host galaxies at high redshift are important tracers of the co-evolution of galaxies and BHs. Taking advantage of recent data sets extending out to $z = 3$, we have studied how the observed evolution of the BH–host scaling relations compares to theoretical SAMs; we considered specifically the publicly available SAMs of the Munich group (De Lucia & Blaizot 2007).

While at $z = 0$ the scaling relations are established for the general galaxy population, at high $z$ BH masses can only be derived for active nuclei by means of the virial technique. This introduces a number of potential biases, to be taken into account when discussing the evolution of the scaling relations.

(i) Quasar host galaxies are in a peculiar phase of their evolution: in the theoretical scenario considered here, they are ‘young spheroids’ that have just merged and suffered a starburst. Our analysis highlights the distinction between the general population and the recent mergers/quasar hosts.

(ii) At high redshift it is hard to decompose the host galaxy into its bulge/disc component so the scaling relations we analyse refer to the global galaxy; yet, for consistency with observational papers, evolution is defined with respect to the local relations derived for quiescent host spheroids.

(iii) Luminous quasars tend to trace an overmassive BH with respect to the underlying intrinsic BH–host relation (Lauer et al. 2007), so the comparison relation in the models must be defined accordingly.

(iv) The observational errors on BH masses introduce a Malmquist-type bias (Shen & Kelly 2010) that also must be taken into account, by convolving model prediction with observational errors before direct comparison to the data.

We find that the latter two bias effects dominate the interpretation of the observational results. In the Munich SAM, two basic predictions are: (i) the intrinsic (bisector fit) relation between the BH mass and the host stellar mass has negligible evolution out to $z = 3$ – as typical of models that do not include quasar feedback and self-regulation mechanisms; (ii) quasar host galaxies are systematically overluminous (and/or have systematically undermassive BHs) with respect to the local BH mass–host luminosity relation. Both predictions, taken at face value, are in stark contrast with observations. However, the Lauer bias in the SAM produces an apparent evolution of 0.6 dex out to $z = 3$, for the host stellar mass of BHs with $M_{\rm BH} \sim 10^9\ {\rm M}_{\odot}$(the typical BH masses probed by high-redshift QSOs): this is comparable to the observed evolution of $\Gamma$ (Section 3). Besides, when observations and models are directly compared in the BH mass–host luminosity plane, and models are properly convolved with observational errors, the Shen–Kelly bias compensates for the intrinsic overluminosity of SAM quasar hosts, bringing the models into agreement with the observations (Section 4).

We thus find that the observed strong evolution, with BH formation preceding the growth of the hosts, could largely be the result of statistical and selection biases, compatible with negligible real evolution of the intrinsic BH mass–host mass relation; this agrees with the conclusion of Shen & Kelly (2010). Whether a strong $\Gamma$ evolution really characterizes the general co-evolution of BH and galaxies is therefore still unclear. We note, for instance, that submillimetre galaxies tend to trace the opposite trend ($\Gamma$ decreasing at high $z$), which can be understood if different selection biases apply to different subpopulations of galaxies (Lamastra et al. 2010, and references therein).

Since biases dominate the interpretation of the results, it is of paramount importance to ascertain that SAMs predict realistic biases. As both the Lauer and the Shen–Kelly biases are related to the fact that high-$z$ quasars trace the massive/bright end of the BH and galaxy distribution functions, SAMs should reproduce these adequately at various redshifts. While the situation for the galaxy luminosity function is nowadays satisfactory (Henriques et al. 2011), there is evidence that the Munich SAM fail to reproduce the high-mass end of the BH mass function at early epochs. Indications for this come from the bright end of the AGN luminosity function at $z > 1$ (Marulli et al. 2008) and from the mass function of high-$z$ QSOs (Section 5), though this latter evidence is less compelling, if an error on observed BH masses as large as 0.55 dex is allowed and cosmic scatter is considered. A deeper investigation on this issue requires more detailed modelling of the BH accretion history and QSO luminosity curves, so as to extract from the SAM catalogue QSO samples that closely mimic the observational data sets.

A dearth of massive BHs ($M_{\rm BH} > 10^{9.5}\ {\rm M}_{\odot}$) in the simulated volume may be due to a general difficulty of hierarchical galaxy formation models to produce massive objects at high redshift, or to the fact that these massive BHs are so rare (e.g. Decarli et al. 2010b) that a separate, specific scenario is required to implement their formation in SAMs. Alternative mechanisms of BH formation in the very high redshift Universe, advocated to account for the rarest, most massive quasars at $z \simeq 6$ (e.g. Mayer et al. 2010, and references therein), may indeed also help to improve on the statistics of massive quasars at $z = 3$ and below.

Progress in the interpretation of high-redshift data also requires a better understanding of the biases in the real Universe. Both the Lauer bias and the Shen–Kelly bias act at the high end of the BH mass function, producing a steepening of the apparent BH mass–host relation with respect to the intrinsic one. Both effects are predicted to vanish around $M_{\rm BH} \leq 10^8\ {\rm M}_{\odot}$, and to be present also at low redshifts. Therefore, assuming evolution to be negligible at relatively low redshifts, comparing the relation for the local galaxy population to that for AGN hosts can constrain the actual biases. Also extending high-redshift samples to lower BH masses would be valuable.

In summary, the interpretation of the properties of quasar hosts involves a full account of the statistical properties (luminosity/mass functions) of both galaxies and quasars: on one hand quasar hosts are useful tests for SAMs, and on the other hand we need the global approach of SAMs to properly interpret the data. The SAMs considered here, although not adequately reproducing the AGN population, can still recover the observed trend of $\Gamma(z)$ in quasar host galaxies, when selection biases are included, and suggests that the underlying $\Gamma$ evolution for the general galaxy population, may be much milder. It will be worthwhile to reconsider the role of biases at the massive end of the BH populations, in the context of SAMs that better account for the properties of the quasar population.

The available observational data sets at present consist of a relatively small number of objects, but larger samples are expected to become available in the near future, based on high-resolution observations with the next generation of 30–40 m telescopes. We conclude with a 'wish-list' for future semi-analytical studies, to fully exploit the potential of quasar hosts galaxy observations to constrain the co-evolution of BH and galaxies.

(i) SAMs should include the modelling of the quasar accretion rate and light curve, so as to predict the properties of galaxies and the BH–host relations *specifically during the phase of optical quasar activity*, as in Kauffmann & Haehnelt (2000).[4]

(ii) In analysing the co-evolution of the BH mass and its host, a clear distinction should be made between an intrinsic (bisector fit) relation and a median relation at a given BH mass. The latter is affected by the Lauer bias, whose effects should be assessed separately. Error convolution, including the Shen–Kelly bias, is another mandatory step.

(iii) Besides the $M_{\rm BH}-M_\star$ relation, SAMs should provide predictions on the $M_{\rm BH}-L$ relation, which allows a more fair and self-consistent comparison to the observations.

Effort is particularly required to reproduce properly the mass/luminosity function of quasars at high redshift at the massive end: due to the importance of statistical biases, this is a crucial prerequisite to our understanding of the co-evolution of BH and galaxies as traced by quasar hosts.

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[4] Detailed BH accretion histories and AGN light curves have been modelled within the Munich SAM by Marulli et al. (2008); their effect is minor on the final scaling relations, where the total accreted BH mass matters more than the accretion time-scale. The accretion history, though, affects the properties of the host versus the instant observed quasar luminosity. This type of result was discussed by Kauffmann & Haehnelt (2000, their figs 12 and 18) but, to our knowledge, by no other more recent SAM paper, from any research group.

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## APPENDIX A: COLOUR AND MASS-TO-LIGHT RATIO EVOLUTION OF QUASAR HOSTS

The observed luminosities of quasar host galaxies are to be translated into stellar mass, in order to recover the underlying BH mass–host mass relation to be compared to the local one. In this appendix we discuss the stellar mass-to-light ratio ($M_\star/L$) necessary for the transformation.

A passively evolving starburst formed at $z = 5$ well describes the observed dimming of quasar hosts (Kotilainen et al. 2009) and was consequently assumed by Decarli et al. (2010b) to convert luminosities to stellar masses. Similar assumptions were made by Peng et al. (2006). Let us compare the colour and $M_\star/L$ evolution predicted by the SAMs to the classic assumption of passive evolution.

SAM galaxies are expected to be bluer and have lower $M_\star/L$ than a passively evolving galaxy, since in a hierarchical Universe galaxies build up progressively and are on average younger than in the monolithic scenario. Quasar hosts, selected to be recently merged objects with associated starbursts, should deviate even further from passive evolution.

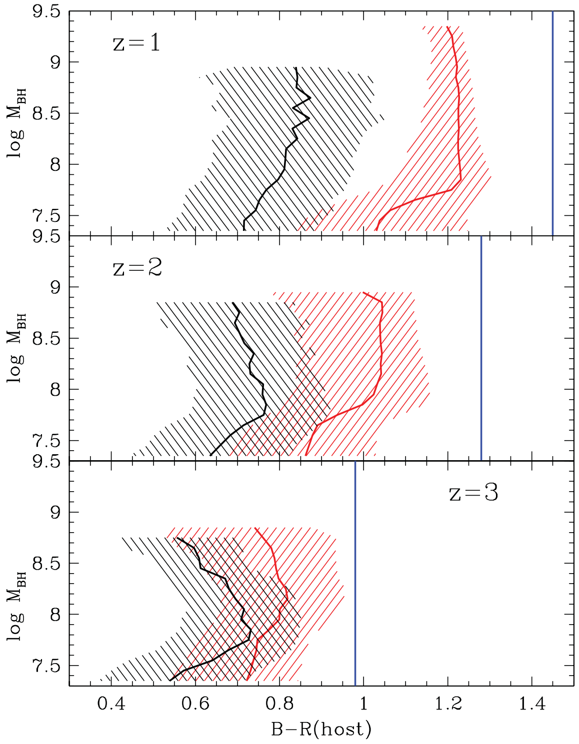

**Figure A1.** Colour distribution of galaxies at three redshift snapshots. The leftmost solid line, with shadings inclined to the left, represent the median and the 16th and 84th percentiles for the quasar host galaxies. The (red) solid line in the middle, with shadings inclined to the right, represents the analogous for the global population. The (blue) vertical line to the right shows the colours of a passively evolving starburst formed at $z = 5$.

Fig. A1 shows the $(B - R)$ colour distribution of SAM galaxies as a function of redshift. Both for the quasar hosts and for the global galaxy population, the typical colours are quite independent of the central BH mass above $M_{\rm BH} \geq 10^8$ M$_\odot$ (i.e. the median lines are roughly vertical in the plot). At $z \leq 1$, there is a significant offset in colour between the global average galaxy population and the quasar hosts that are systematically bluer by about 0.4 mag due to merger-induced recent star formation. At increasing redshift the offset decreases, as the global population gets on average bluer, faster than the quasar hosts; by $z = 3$, the offset is reduced to <0.2 mag, corresponding to only 1$\sigma$ difference between the two populations. The vertical (blue) line shows, for comparison, the much redder colours expected for passive evolution since $z = 5$.

Fig. A2 shows the evolution of the $M_\star/L$ in the rest-frame $R$ band, for the QSO hosts and the global galaxy population, respectively. We also draw the $M_\star/L$ of a passively evolving starburst formed at $z = 5$, computed by Decarli et al. (2010b) with the aid of the GALAXEV package of Bruzual & Charlot (2003) to convert their observed luminosities to stellar masses. Interestingly, the rate of $M_\star/L_R$ evolution of the SAM galaxies is very similar to the passively evolving scenario; the offset of 0.3 dex can be partly ascribed to the different stellar IMF adopted (Salpeter 1955 for passive evolution, Chabrier 2003 for the SAM galaxies); and partly to the fact that SAM galaxies are significantly bluer than a purely passively evolving galaxy (Fig. A1). Quasar hosts also define an evolutionary rate mimicking passive evolution, at least up to $z < 2.5$, with a further offset of 0.2 dex.

As the *rate* of luminosity evolution is similar in the various scenarios, the result of Decarli et al. (2010b) that quasar hosts were significantly undermassive at high redshift does not strongly depend on the passive evolution assumption. Actually, adopting the lighter $M_\star/L$ predicted by the SAMs would only strengthen their findings, with the central BH being even more overmassive, by a further 0.3–0.5 dex, with respect to their hosts.

The behaviour shown in Fig. A2 also highlights that a complex galaxy formation history may easily mimic a passively evolving case when viewed in a monochromatic band.[5] A possible way to distinguish a truly passively evolving population from a merger scenario is to use colour information (Fig. A1). Unfortunately, multiband information on quasar hosts at high $z$ is still scarce and mostly limited to $z \lesssim 1.5$ (Jahnke et al. 2009; Bennert et al. 2011). Moreover, since the host luminosity and colours have typical uncertainty of 0.3 mag one can hardly discriminate between the two scenarios beyond $z \sim 2$.

As to the adopted IMF for the $M_\star/L$ normalization, most recent theoretical models of galaxy formation adopt the 'bottom light' Chabrier (2003) prescription; however, for the most massive ellipticals that presently host the most massive BH – analogous to those traced by high-redshift QSO – recent results suggest that a Salpeter, or even 'heavier' IMF, may be more appropriate (Treu et al. 2010; Thomas et al. 2011; Van Dokkum & Conroy 2010, 2011; Tiret et al. 2011). The direct comparison in the BH mass–host luminosity plane (Section 4), however, bypasses the transformation problem.

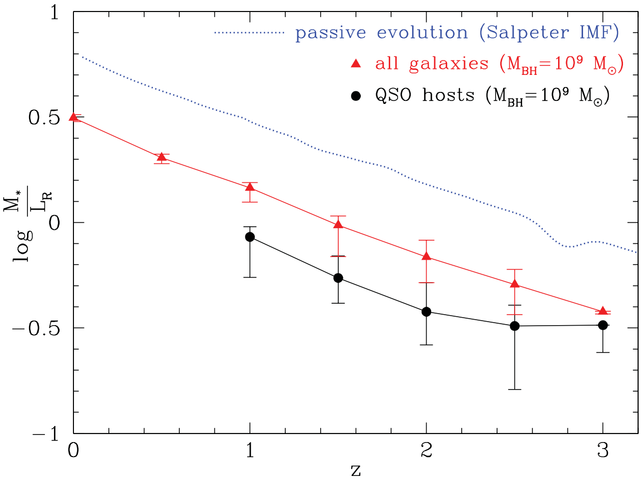

**Figure A2.** Evolution of the stellar $M_\star/L$ in the rest-frame $R$ band for SAM galaxies with a central BH mass of $10^9$ $M_\odot$(all galaxies and QSO hosts, respectively). The dotted line is the passively evolving $M_\star/L$ adopted by Decarli et al. (2010b) to transform observed luminosities into stellar masses.

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[5] Another example of this is found in the evolution of the $K$-band luminosity function (Cirasuolo et al. 2007, 2010): the characteristic luminosity of the Schechter function, $M_{K,\star}(z)$, brightens with redshift following the passive evolution of a high-redshift starburst, so as to apparently trace a population of ellipticals formed at $z > 3$. However, when the authors consider the decrease in number density of bright galaxies beyond $z = 1.5$, and the evolution of the red and blue populations separately, the apparent passive fading of $M_{K,\star}$ clearly hides a much more complex galaxy evolution history.