Empirical Constraints on the Evolution of the Relationship between Black Hole and Galaxy Mass: Scatter Matters

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ABSTRACT

I investigate whether useful constraints on the evolution of the relationship between galaxy mass ($m_{\text{gal}}$) and black hole (BH) mass ($m_{\text{BH}}$) can be obtained from recent measurements of galaxy stellar mass functions and QSO bolometric luminosity functions at high redshift. I assume a simple power-law relationship between $m_{\text{gal}}$ and $m_{\text{BH}}$, as implied by BH mass measurements at low redshift, and consider only evolution in the zero-point of the relation. I argue that one can obtain a lower limit on the zero-point evolution by assuming that every galaxy hosts a BH, shining at its Eddington rate. One can obtain an upper limit by requiring that the number of massive BH at high redshift does not exceed that observed locally. I find that, under these assumptions, and neglecting scatter in the $m_{\text{gal}}$-$m_{\text{BH}}$ relation, BH must have been a factor of $\sim 2$ larger at $z \sim 1$ and $5$–$6$ times more massive relative to their host galaxies at $z \sim 2$. However, accounting for intrinsic scatter in $m_{\text{gal}}$-$m_{\text{BH}}$ considerably relaxes these constraints. With a logarithmic scatter of $0.3$–$0.5$ dex in $m_{\text{BH}}$ at fixed $m_{\text{gal}}$, similar to estimates of the intrinsic scatter in the observed relation today, there are enough massive BH to produce the observed population of luminous QSOs at $z \sim 2$ even in the absence of any zero-point evolution. Adopting more realistic estimates for the fraction of galaxies that host active BH and the Eddington ratios of the associated quasars, I find that the zero-point of the $m_{\text{gal}}$-$m_{\text{BH}}$ relation at $z \sim 2$ cannot be much more than a factor of two times larger than the present-day value, as the number of luminous quasars predicted would exceed the observed population.

Key words: black hole physics – galaxies: formation – galaxies: evolution – quasars: general – galaxies: active – cosmology:theory

1 INTRODUCTION

The discovery of the relationship between the masses of nuclear supermassive black holes (SMBH) and the luminosity, velocity dispersion, or mass of their host galactic spheroids (Dressler 1989; Kormendy & Richstone 1995; Magorrian et al. 1998; Ferrarese & Merritt 2000; Gebhardt et al. 2000; Tremaine et al. 2002) is surely one of the most profound observational results of the past decade, if not the past century. Different methods applied to both dormant and active BH in the nearby Universe now yield consistent results and indicate that BH mass and galaxy velocity dispersion $\sigma$ are related via $m_{\text{BH}} \propto \sigma^{\beta}$, where $\beta \approx 4$–$5$ (Ferrarese & Merritt 2000; Gebhardt et al. 2000; Tremaine et al. 2002), and BH mass and galaxy mass are related via $m_{\text{BH}} \propto m_{\text{gal}}^{1.1}$ (Marconi & Hunt 2003).
intrinsic scatters of approximately 0.3 dex in $\sigma$ at fixed $L^*$ and 0.5 dex in $m_{\text{BH}}$ at fixed $L$. (Novak et al. 2004; Gültekin et al. 2004).

A large number of theoretical explanations for the origin of this observed relationship (hereafter referred to for brevity as the $m_{\text{BH}}$-$m_{\text{gal}}$ relationship) have been proposed (e.g. [Silk & Rees 1998; Burkert & Silk 2001; Adams et al. 2001, 2003; Wyithe & Loeb 2003; Robertson et al. 2006; Croton 2006; Hopkins et al. 2007a]). However, there is no widely accepted unique theoretical model, and the models differ in their predictions for the amount of evolution in the $m_{\text{BH}}$-$m_{\text{gal}}$ relationship. This quantity is therefore a potentially strong discriminator between different theoretical models, and there is great interest in obtaining robust direct observational measurements of this relationship at high redshifts. A great deal of effort and telescope time has been expended towards achieving this goal.

With currently available facilities, the masses of dormant BH can be measured via the dynamics of the surrounding gas or stars (see Ferrarese & Ford 2003, for a recent review) only for very nearby galaxies. At high redshift, it is currently possible to attempt to measure masses only for active or accreting BH. Several such studies have claimed to find evidence for significant evolution in the $m_{\text{BH}}$-$m_{\text{gal}}$ relationship, always in the sense that black holes are more massive at high redshift relative to their host galaxy (e.g. Treu et al. 2004; Peng et al. 2006; Woo et al. 2006, 2008; Salvianer et al. 2007). However, these methods rely on a set of simplified underlying assumptions and various proxies for the desired quantities, and are subject to potentially severe selection biases. Lauer et al. (2007a) have argued that if there is a moderate amount of scatter in the intrinsic $m_{\text{BH}}$-$m_{\text{gal}}$ relationship (consistent with observational constraints on the scatter in the local relation), these selection biases can account for most or all of the claimed evolution. It is therefore interesting to explore the possibility of obtaining independent empirical constraints on the evolution. Even obtaining robust upper and lower limits on the evolution could be useful.

Recently, it has become common practice to estimate the stellar masses of galaxies from multi-wavelength broadband photometry and/or spectroscopy (e.g. Bell & de Jong 2001; Bell et al. 2003; Kauffmann et al. 2003). The availability of deep multi-wavelength surveys covering substantial sky area has yielded estimates of the stellar mass functions out to high redshift, $z \sim 4-5$ (e.g. Drory et al. 2004; Fontana et al. 2004; Borch et al. 2006; Fontana et al. 2006; Pannella et al. 2006; Bundy et al. 2007; Pozzetti et al. 2007; Vergani et al. 2008; Marchesini et al. 2008; Pérez-González et al. 2008). Similarly, there has been significant progress in piecing together the evolution of the bolometric luminosity function of quasars and Active Galactic Nuclei (AGN) out to high redshift ($z \sim 6$) from multi-wavelength surveys (Hopkins et al. 2007b, and references therein; hereafter HR07).

In this paper, I explore whether one can derive useful empirical constraints on the evolution of the relationship between BH mass and galaxy mass by comparing these two sets of observed statistical distributions (galaxy stellar mass functions and QSO/AGN luminosity functions) under the basic and well-accepted ansatz that accreting BH provide the power source for AGN. The outline of the rest of the paper is as follows. In §2 I describe my basic set of assumptions. In §2.1 I present upper and lower limits on the evolution of the $m_{\text{BH}}$-$m_{\text{gal}}$ relation, assuming that there is no intrinsic scatter in the relation. In §2.2 I discuss how these constraints are impacted by the inclusion of intrinsic scatter. I conclude in §3.

## 2 UPPER AND LOWER LIMITS ON THE EVOLUTION

For nearby dormant BH, the average relationship between BH mass and galaxy mass can be characterized as $m_{\text{BH}} \propto m_{\text{gal}}^{1.1}$ (Marconi & Hunt 2003; Haring & Rix 2004). I will explore the simplest possible form for possible evolution of this relationship, namely scaling by a factor that is a function of redshift only $\Gamma(z)$. Thus the mass of a BH residing in a galaxy with mass $m_{\text{gal}}$ at redshift $z$ is given by:

$$m_{\text{BH}}(z, m_{\text{gal}}) = \Gamma(z) m_{\text{BH}}(z = 0, m_{\text{gal}}) = \Gamma(z) m_{\text{gal}}^{1.1}.$$  \hspace{1cm} (1)

I now make use of the observed galaxy stellar mass function at some redshift of interest, and assume that every galaxy hosts a SMBH with mass given by Eqn. (1). One can then obtain a reasonable lower limit on the evolution in $m_{\text{BH}}$-$m_{\text{gal}}$ (i.e. on $\Gamma(z)$) at a given redshift by assuming that 1) every BH is active at all times (has a duty cycle of unity) 2) every active BH always radiates at its Eddington luminosity. This set of assumptions will clearly maximize the number of luminous quasars for a given population of BH, under the fairly standard conjecture of Eddington-limited accretion.

One can then obtain an upper limit on the evolution by comparing the implied BH mass function at the redshift of interest with observational estimates of the present-day BH mass function. Again, under the apparently reasonable assumptions that BH masses increase monotonically with time and that significant numbers of massive BH are not somehow lost from galaxies, clearly the number of massive BH in the past cannot exceed that at the present day. To state the condition more precisely, the number density of BH, $\phi(m_{\text{BH}})$, at high redshift may not exceed the present day value for all BH masses greater than some threshold value $m_{\text{BH}} > m_{\min}$.

For the observed stellar mass function as a function of redshift, I adopt the fitting functions of Fontana et al.

\footnote{Several other equally tight relationships between BH mass and other galaxy properties have been discovered (e.g. Graham et al. 2001; Korremnd & Bender 2000). Although these relationships are intriguing, here I focus on the relationship between BH mass and galaxy mass.}

\footnote{Lauer et al. (2007b) suggest a slope of unity, but this would not significantly effect the results.}
Evolution of the $m_{\text{BH}}$-$m_{\text{gal}}$ Relationship

Figure 1. The bolometric luminosity function of quasars at $z = 1$ (left panel) and $z = 2$ (right panel). Square symbols with error bars show the estimate of the observed bolometric QSO LF from HRH07. Dashed lines show the upper limit on the QSO LF derived from the observed stellar mass function at the relevant redshift and the arguments described in the text. From left to right, the dashed lines assume that the zero-point of the $m_{\text{BH}}$-$m_{\text{gal}}$ relation has evolved by a factor of $\Gamma = 1, 2, 3, 4, 5,$ or $6$. Under these assumptions, the mass of a typical BH hosted by a galaxy of a given mass must have been larger by a factor of $\sim 2$ at $z = 1$ and by a factor of 5–6 at $z = 2$.

2.1 Constraints without Scatter

Initially, I assume that the relationship between BH mass and galaxy mass has no intrinsic scatter. It is then straightforward to derive the implied bolometric luminosity function of QSO/AGN from the observed galaxy stellar mass function under the set of assumptions outlined above, for a given value of the evolution factor $\Gamma(z)$. Figure 1 shows the observed bolometric QSO luminosity function as estimated by HRH07 along with the upper limit estimate based on the stellar mass function, for different values of $\Gamma$. This comparison is shown at $z = 1$ and $z = 2$. At QSO luminosities below the “knee” in the LF, the upper limit estimate overproduces QSOs, which can be understood as implying that these BH are not active at all times and/or are radiating at sub-Eddington luminosities. What is more interesting is that at the highest luminosities, above $\sim 10^{44}L_{\odot}$ at $z = 1$ or $10^{43.5}$ at $z = 2$, without evolution in the $m_{\text{BH}}$-$m_{\text{gal}}$ relation, the number of luminous QSOs is significantly underestimated. Assuming that these luminous QSOs are not radiating above their Eddington luminosity, and are not magnified somehow (e.g. by beaming or lensing), one can then read off the minimum amount of evolution (minimum value of $\Gamma$) required to produce enough luminous QSOs. This corresponds to $\Gamma_{\text{min}} \sim 2$ at $z = 1$ and $\Gamma_{\text{min}} \sim 5–6$ at $z = 2$. Taken at face value, then, these results require that BH were 5–6 times larger for a given galaxy mass at $z = 2$.

Now let us consider the upper limit on the evolution, or maximum allowed value of $\Gamma$. Figure 2 shows the observational estimate of the BH mass function at $z = 0$ (Marconi et al. 2004), compared with the results from the stellar mass function at $z = 2$ scaled by the same series of values of $\Gamma$. Clearly, as long as BH cannot decrease in mass or be ejected from their host galaxies, then there is an upper limit of $\Gamma_{\text{max}} \sim 6$ at $z \sim 2$. It is interesting that the lower limit from the QSO LF, discussed above, and this upper limit are so close to one another.

3 Note that the Marconi et al. (2004) estimate of the BHMF includes the effect of scatter in the local $m_{\text{BH}}$-$m_{\text{gal}}$ relation, and therefore the comparison shown here is not strictly self-consistent. However, I will consider scatter self-consistently in the next Section.
Figure 2. The mass function of SMBH. The solid green line shows the observational estimate of the BH mass function at $z = 0$ from Marconi et al. (2004). Dashed (red) lines show the BH MF implied by the observed galaxy stellar mass function at $z = 1$ (left panel) or $z = 2$ (right panel), the relationship between BH mass and galaxy mass described in the text, and evolution in the zero-point of the $m_{\text{BH}}$-$m_{\text{gal}}$ relation of a factor of $\Gamma = 1, 2, 3, 4, 5, \text{ or } 6$ (curves from left to right, respectively).

Figure 3. Left: BH mass function. Open (purple) dots show the BHMF implied by the observed $z = 2$ GSMF, no evolution in the $m_{\text{BH}}$-$m_{\text{gal}}$ relation ($\Gamma = 1$), and a scatter of $\sigma_{\text{BH}} = 0.3$; error bars are simple Poisson errors. The solid (green) line shows the observational estimate of the BH mass function at $z = 0$ from Marconi et al. (2004); the dashed (red) line shows the BH MF implied by the observed galaxy stellar mass function at $z = 2$ plus the assumed $m_{\text{BH}}$-$m_{\text{gal}}$ relation with no evolution ($\Gamma = 1$) and no scatter. To satisfy the constraint, the purple dots (prediction) should be lower than the green line (observations). Right: The QSO luminosity function. Open (purple) dots show the upper limit on the QSO LF from the same argument, but including scatter in the $m_{\text{BH}}$-$m_{\text{gal}}$ relation ($\sigma_{\text{BH}} = 0.3$); error bars are Poisson. Square (green) symbols with error bars show the estimate of the observed bolometric QSO LF at $z = 2$ from HRH07; the dashed (red) line shows the upper limit on the QSO LF derived from the observed GSMF at $z = 2$ and the arguments described in the text, for $\Gamma = 1$ and $\sigma_{\text{BH}} = 0$. Here, to satisfy the constraint, the purple dots (prediction) should be higher than the green squares (observations). The inclusion of a moderate amount of scatter has a large impact on the high-mass end of the BHMF and the high luminosity end of the QSO LF. When scatter is included, the assumption that the $m_{\text{BH}}$-$m_{\text{gal}}$ relation has not evolved since $z \sim 2$ appears to be consistent with these constraints.
2.2 Constraints with Scatter

So far I have neglected intrinsic scatter in the \( m_{\text{BH}} - m_{\text{gal}} \) relation. However, as noted by Lauer et al. (2007a), because of the very steep decline of the high-mass end of the galaxy mass or luminosity function, the highest mass black holes are actually more likely to be outliers from the \( m_{\text{BH}} - m_{\text{gal}} \) relation, hosted by galaxies of more modest mass, rather than typical BH in the much rarer high-mass galaxies that would be the sole hosts of such BH in the absence of scatter.

Novak et al. (2006) attempted to constrain the intrinsic scatter in the \( m_{\text{BH}} - \sigma \) and \( m_{\text{BH}} - L \) relations at \( z = 0 \), and concluded that due to the small sample of galaxies with reliable measurements of BH mass and uncertainties in the observational error estimates on \( m_{\text{BH}} \), only upper limits on the scatter could be obtained. They estimated these upper limits to be \( \delta_{\sigma} < 0.3 \) and \( \delta_{L} < 0.5 \), where \( \delta_{\sigma} \) is the 1-\( \sigma \) log scatter in the \( m_{\text{BH}} - \sigma \) relation and \( \delta_{L} \) is the same for the \( m_{\text{BH}} - L \) relation. Marconi & Hunt (2003) find a similar scatter in the \( m_{\text{BH}} - m_{\text{sph}} \) relation as in \( m_{\text{BH}} - \sigma \), and Haring & Rix (2004) find an observed
scatter of 0.3 dex in the $m_{\text{BH}} - m_{\text{gal}}$ relation, implying that the intrinsic scatter is presumably smaller. Recently, Gultekin et al. (2009) made a detailed study of the magnitude of the intrinsic scatter in $m_{\text{BH}} - \sigma$ and $m_{\text{BH}} - L$, finding $\sigma_\text{BH} = 0.31$ for ellipticals but a larger scatter of $\sigma_\text{BH} = 0.44$ for all galaxies (including spirals). They furthermore find that the shape of the distribution of the intrinsic residuals in $m_{\text{BH}}$ at fixed $\sigma$ is consistent with a log-normal (and inconsistent with a normal distribution).

Unfortunately, almost nothing is known about the possible evolution of the intrinsic scatter in the BH-galaxy scaling relations. Therefore, I investigate how the inclusion of representative amounts of scatter would impact the results presented in Section 2.1. In order to do this, I run Monte Carlo simulations of $\sim 10^6$ galaxies, in which I first select galaxy masses from the observed stellar mass function at the redshift of interest (using $z = 2$ as a representative case). I then assign BH masses to each galaxy according to Eqn. 2 adding a random deviate in mass selected from a log-normal distribution with root variance $\sigma_\text{BH}$, and consider the implied BH mass function and upper limit on the QSO LF as before.

Results of these experiments for various values of $\sigma_\text{BH}$ and $\Gamma$ (all at $z = 2$) are shown in Figures 3-5. Note that I cut off the galaxy stellar mass function below $10^{10} M_\odot$ because these low-mass galaxies do not provide interesting constraints and including them causes the Monte Carlo simulations to take much longer to run (for a given desired number of high-mass objects). In Figure 3 one can see that when a moderate scatter in the $m_{\text{BH}} - m_{\text{gal}}$ relation is included ($\sigma_\text{BH} = 0.3$, similar to the scatter in the observed relation at the present day), the number of luminous QSOs can be reproduced under the fairly extreme assumptions used in the lower limit exercise (all BH radiate at their Eddington limit at all times). Even a scatter half as large as the observed present-day estimates ($\sigma_\text{BH} = 0.15$), with no evolution in the normalization ($\Gamma = 1$) marginally satisfies the lower limit. With a slightly larger scatter ($\sigma_\text{BH} = 0.5$) or moderate evolution in the zero-point $\Gamma = 2$ (see Fig. 4 and 5), bright QSOs are overproduced by a factor of 10-100, leaving room for more reasonable assumptions about duty cycle and Eddington ratio.

One can try to sharpen this constraint by adopting more physically reasonable values for the duty cycles and Eddington ratios of AGN. Erb et al. (2006) and Kriek et al. (2007) find that about 20-40% of galaxies at $z \sim 2$ contain an active nucleus, and models in which such activity is merger-driven (e.g. Hopkins et al. 2008, Somerville et al. 2008) predict that this fraction is nearly constant for galaxy masses $10^9.0 \lesssim \log(m_{\text{gal}}/M_\odot) \lesssim 12.0$ (see e.g. Figure 19 of Hopkins et al. 2008). Vestergaard (2004) find that the Eddington ratios of luminous quasars at $1.5 < z < 3.5$ are in the range 0.1 < $L/L_{\text{Edd}}$ < 1, with an average value $L/L_{\text{Edd}} \sim 0.4-0.5$, while Kollmeier et al. (2006) find a fairly sharply peaked distribution of Eddington ratios with a peak at $L/L_{\text{Edd}} = 0.25$. Adopting average values for the fraction of galaxies containing active BH, $f_{\text{AGN}} = 0.3$, and the Eddington ratio $f_{\text{Edd}} \equiv L/L_{\text{Edd}} = 0.5$ (assuming that $L/L_{\text{Edd}}$ is also constant with galaxy/BH mass), produces quite good agreement with the observed QSO LF at $z = 2$ with no evolution in the zero-point or scatter of the $m_{\text{gal}}$-$m_{\text{BH}}$ relation ($\Gamma = 1$, $\sigma_\text{BH} = 0.3$, see Fig. 6).

Turning the argument around, then, if the independent observational estimates of duty cycle and Eddington ratio are correct, and if the scatter in the $m_{\text{gal}}$-$m_{\text{BH}}$ relation was not significantly smaller at high redshift than it is today, then overall evolution in the $m_{\text{gal}}$-$m_{\text{BH}}$ relation of $\Gamma \gtrsim 2$ since $z \sim 2$ is disfavored as it would overproduce the number of luminous QSOs (see Fig. 7). In particular, if the value of $\Gamma$ at $z \sim 2$ were as large as suggested by the observations of e.g. Peng et al. (2006), $\Gamma \gtrsim 4$, the number of luminous QSOs would be overproduced by more than one order of magnitude. Of course, one could reconcile these larger amounts of evolution if the duty cycle of luminous quasars is an order of magnitude smaller than what I have assumed ($\sim 2-3$ percent instead of 20–30 percent).

3 CONCLUSIONS

I have investigated whether observational estimates of the stellar mass function of galaxies, combined with observed QSO luminosity functions, can provide useful limits on the relationship between galaxies and their SMBH at high redshift. I assumed a simple relationship between galaxy mass and SMBH mass, as observed in dormant galaxies in the nearby Universe, and a simple form for the possible

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4 Note that if we included a realistic distribution of Eddington ratios, rather than a single constant value, this would again broaden the tail of the bright end of the QSO LF, leading to more very luminous QSOs.
of this relationship (see Eqn. 1), namely a shift in the zero-point of the relation by a redshift-dependent factor \( \Gamma(z) \). I then argued that one can obtain a lower limit on \( \Gamma(z) \) by making the rather extreme assumption that all BH radiate at their Eddington limit at all times, and requiring that at least the observed number of luminous QSOs be reproduced. I further argued that an upper limit on \( \Gamma(z) \) could be obtained by requiring that the number of massive BH in galaxies today should not be exceeded at high redshift.

Assuming that there is a deterministic relationship between galaxy mass and BH mass (i.e., no scatter in the \( m_{\text{BH}}-m_{\text{gal}} \) relationship), I find that in order to produce enough luminous QSOs, the zero-point of the relation must have been higher by at least a factor of \( \sim 2 \) at \( z = 1 \) and a factor of \( 5-6 \) at \( z = 2 \). At the same time, in order to avoid producing a larger number density of massive BH than what is implied by observations at \( z \sim 0 \), the upper limit on the evolution of the normalization of the \( m_{\text{BH}}-m_{\text{gal}} \) relationship at \( z = 2 \) is about a factor of six. Since both the lower and upper limits are fairly liberal, one might have expected them to lie several orders of magnitude apart, and therefore not to provide very interesting constraints on the actual evolution of the \( m_{\text{BH}}-m_{\text{gal}} \) relationship. It seems potentially quite interesting that these limits lie nearly on top of one another.

However, relaxing the assumption of a perfectly deterministic \( m_{\text{BH}}-m_{\text{gal}} \) relationship has a major impact on the results. When scatter is included in the \( m_{\text{BH}}-m_{\text{gal}} \) relation at a level similar to the intrinsic scatter in the observed relation at \( z = 0 \), I find that the majority of very massive BH are objects that live in galaxies of moderate mass but are outliers in the \( m_{\text{BH}}-m_{\text{gal}} \) relationship. This is of course due to the very steep slope of the galaxy stellar mass function at large masses. Because the constraints above arose from the most luminous QSOs, I then find that there is a strong degeneracy between the evolution of the zero-point \( \Gamma(z) \) and the scatter \( \sigma_{\text{BH}} \). For example, the QSO constraint at \( z = 2 \) can be reproduced even in a scenario in which \( \Gamma = 1 \) (no evolution in the zero-point has occurred) and \( \sigma_{\text{BH}} = 0.3 \) (the intrinsic scatter in \( m_{\text{BH}}-m_{\text{gal}} \) is similar to that in the observed relation today). Thus we are left with the very weak constraint that BH probably were no smaller at high redshift relative to their host galaxies (unless the scatter was much larger than it is today).

I tried to sharpen this constraint by adopting more physically reasonable values for the duty cycles and Eddington ratios of AGN, based on independent observational constraints. Adopting mass-independent values of \( f_{\text{AGN}} = 0.3 \) (the fraction of galaxies hosting AGN) and \( f_{\text{Edd}} \equiv L/L_{\text{Edd}} \sim 0.5 \), and assuming a scatter in \( m_{\text{BH}}-m_{\text{gal}} \) similar to that in the observed relation for dormant galaxies today (\( \sigma_{\text{BH}} = 0.3 \)), I find that BH cannot have been much more than a factor of \( \sim 2 \) more massive relative to their host galaxies at \( z \sim 2 \) than they are today. In particular, values as large as \( \Gamma(z = 2) \sim 4 \), as suggested by some observational studies (e.g. Peng et al. 2006), would overproduce the number of luminous QSOs by more than an order of magnitude.

Interestingly, Hopkins et al. (2006) also reached similar conclusions based on a somewhat different, though related argument. They pointed out that in order to avoid overproducing the total mass density in SMBH relative to the present day value, the average value of \( m_{\text{BH}}/m_{\text{gal}} \) must not have been more than about a factor of two larger at \( z \sim 2 \) than today’s value.

I have based these results on the relationship between the total stellar mass of the galaxy and the mass of the SMBH; however, there is strong evidence that the more fundamental relationship is actually between the BH mass and the mass of the spheroidal component of the galaxy (e.g. Kormendy & Richstone 1993). I made this choice because the stellar mass function of galactic spheroids is very poorly constrained at high redshift. However, at low redshift, the most massive galaxies are predominantly spheroid-dominated (e.g. Bell et al. 2003). If this was also the case at high redshift, then my conclusions will not change much as the constraints are driven by the most massive BH which are hosted by massive galaxies. If there is a significant population of disk-dominated massive galaxies at high redshift, and the BH mass indeed correlates with spheroid mass only, then this would leave more room for evolution and/or scatter in the \( m_{\text{BH}}-m_{\text{gal}} \) relation.

Another source of uncertainty arises from the fact that BH masses predicted from the \( m_{\text{BH}} \) vs. luminosity (\( m_{\text{BH}}-L \)) relationship are inconsistent with those predicted from the \( m_{\text{BH}} \) vs. velocity dispersion (\( m_{\text{BH}}-\sigma \)) relationship for the most luminous galaxies (Lauer et al. 2007b). The \( m_{\text{BH}}-m_{\text{gal}} \) relationship that I have chosen to use here is derived from the \( m_{\text{BH}}-L \) relation, which Lauer et al. (2007b) argue should be more reliable in the regime of interest, but the situation at high redshift is unknown. Currently, there are no published observational measurements of the galaxy velocity dispersion function at high redshift (of which I am aware); however, these may become available in the future. It would then be very interesting to repeat this kind of analysis using \( m_{\text{BH}}-\sigma \) instead.

Although it is disappointing that the proposed approach did not yield stronger constraints on the evolution of the \( m_{\text{BH}}-m_{\text{gal}} \) relationship, this exercise has brought out a few important lessons. First, in order to understand the relationship between galaxies and their BH, it is perhaps as important to understand the magnitude and evolution of the intrinsic scatter in this relationship as it is to understand the evolution of the zero-point of the relation itself. Second, new generations of theoretical models that attempt to simultaneously treat the formation and evolution of galaxies and their black holes (e.g. Croton et al. 2006; Bower et al. 2006; Fontanot et al. 2006; Somerville et al. 2008) must take care to properly model the dispersion in the \( m_{\text{BH}}-m_{\text{gal}} \) relationship.

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Figure 7. The QSO LF at $z = 2$ as shown in Fig. 3, with intrinsic scatter $\sigma_{\text{BH}} = 0.3$, a QSO duty cycle of $f_{\text{AGN}} = 0.3$ and an Eddington ratio of $f_{\text{Edd}} = 0.3$. Left panel: $\Gamma = 2$; Right panel: $\Gamma = 5$. Assuming that the duty cycles and Eddington ratios derived from independent observations are correct, and that the intrinsic scatter in the $m_{\text{gal}}-m_{\text{BH}}$ relation was at least as large at $z = 2$ as it is today, large amounts of evolution in the zero-point ($\Gamma \gtrsim 2$) are disfavored.

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