INFERENCES ON THE RELATIONS BETWEEN CENTRAL BLACK HOLE MASS AND TOTAL GALAXY STELLAR MASS IN THE HIGH-REDSHIFT UNIVERSE

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ABSTRACT

At the highest redshifts, z > 6, several tens of luminous quasars have been detected. The search for fainter active galactic nuclei (AGN), in deep X-ray surveys, has proven less successful, with few candidates to date. An extrapolation of the relationship between black hole (BH) and bulge mass would predict that the sample of z > 6 galaxies host relatively massive BHs (>10^6 M_☉), if one assumes that total stellar mass is a good proxy for bulge mass. At least a few of these BHs should be luminous enough to be detectable in the 4Ms CDFS. The relation between BH and stellar mass defined by local moderate-luminosity AGNs in low-mass galaxies, however, has a normalization that is lower by approximately an order of magnitude compared to the BH–bulge mass relation. We explore how this scaling changes the interpretation of AGNs in the high-z universe. Despite large uncertainties, driven by those in the stellar mass function, and in the extrapolation of local relations, one can explain the current non-detection of moderate-luminosity AGNs in Lyman Break Galaxies if galaxies below 10^11 M_☉ are characterized by the low-normalization scaling, and, even more so, if their Eddington ratio is also typical of moderate-luminosity AGNs rather than luminous quasars. AGNs being missed by X-ray searches due to obscuration or intrinsic X-ray weakness also remain a possibility.

Key words: galaxies: active – galaxies: evolution – galaxies: high-redshift

1. INTRODUCTION

The frontier of high-redshift galaxies and quasars has now reached a relatively large sample. Hundreds of Lyman Break Galaxies (LBGs) with colors consistent with z > 6 have been detected in deep fields (e.g., Finkelstein 2015 and references therein), and tens of luminous quasars are known at z > 6 (e.g., Fan 2012 and references therein). The population of fainter active galactic nuclei (AGNs) is still elusive. Partly, current surveys are not deep enough to detect them directly, and, partly, X-ray stacking of LBGs has led to no signal detected (Willott et al. 2012; Fiore et al. 2012; Treister et al. 2013). Searches for point sources in deep X-ray fields have also led to inconclusive results (Cappelluti et al. 2015; Giallongo et al. 2015; Weigel et al. 2015).

The X-ray non-detections have been used to estimate an upper limit on the black hole (BH) mass density at z > 6 through an analog of Soltan’s argument (Soltan 1982), and on the luminosity a putative AGN can have in these galaxies (Treister et al. 2011, 2013). With some assumptions on the Eddington ratio, this can be translated into an upper limit on the BH mass. The apparent result is that if LBGs host BHs, they are accreting at low rate, or are less massive than expected on the basis of extrapolations of the correlation between BH mass and bulge mass at z = 0 (Marconi & Hunt 2003; Häring & Rix 2004; Kormendy & Ho 2013). However, it is far from clear if high-redshift LBGs have well-developed bulges.

Reines & Volonteri (2015, hereafter RV15) have studied the relation between BH mass and total stellar mass for nearby galaxies (z < 0.055), including both galaxies with quiescent and active BHs. For the latter, the BH mass estimate is based on reverberation mapping or single-epoch virial estimates, the same technique used at higher redshifts. Likewise, their stellar mass measurements rely on mass-to-light ratios, as done on higher-redshift samples. Therefore they adopted the same methods used for mass measurements at higher redshifts, where detailed information on stellar kinematics and bulge properties is not available. They found that the relation between BH mass and total stellar mass for moderate-luminosity AGNs, predominantly hosted by lower-mass galaxies, has a normalization that is approximately an order of magnitude lower than BH–bulge mass relations largely constrained at high mass.

In this Letter, we assess whether the lower normalization identified for the low-mass galaxies, typically lacking strong bulges, can explain the lack of an X-ray detection in the stack of LBGs. We couple galaxy stellar mass functions (MFs) with BH–stellar mass relations and estimate the redshift evolution of the BH mass density and MF. We also take a complementary approach of coupling AGN luminosity functions at z = 6 with an empirical Eddington ratio distribution, derived from the high-luminosity end of the luminosity function, to determine the BHMF.

2. METHOD

Our approach resembles that taken by Shankar et al. (2004), Somerville (2009), Willott et al. (2010a), and Schulze & Wisotzki (2011). We start by paraphrasing some text from a paper by Schulze & Wisotzki (2011).

We adopt the following convention: MBH masses are given by \( \mu = \log M_{BH} \); the stellar mass is \( s \), with \( s = \log M_* \); and the luminosity is \( l = \log L_{AGN} \). Given a galaxy MF, \( \Phi_*(s) \), and a function \( g(\mu \mid s) \) that gives the probability of finding a BH of mass \( \mu \) in a galaxy of mass \( s \), the BHMF becomes

\[
\Phi_{MBH,GAL}(\mu) = \int g(\mu \mid s)\Phi_*(s)ds.
\] (1)

The integral of the BHMF then gives the mass density in BHs. Similarly, the integral of the galaxy MF gives the stellar mass density.
Based on the empirical correlation between $\mu$ and $s$, $\mu = \gamma + \alpha s$, with lognormal intrinsic scatter $\sigma$, i.e.,

$$g(\mu \mid s) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left\{ -\frac{(\mu - \gamma - \alpha s)^2}{2\sigma^2}\right\}. \quad (2)$$

A similar approach links the AGN luminosity function, $\Phi_{\text{AGN}}$, to the BHMF, through $f(\lambda)$, the probability distribution of the logarithmic Eddington ratio $\lambda$, recalling that $l = 38.11 + \lambda + \mu$, and a duty cycle, $D$:

$$\Phi_{\text{AGN}}(l) = \int Df(\lambda)\Phi_{\text{MBH,AGN}}(\mu)dl. \quad (3)$$

We consider here the $\Phi_{\text{MBH,AGN}}(\mu)$ at $z = 6$ derived by Willott et al. (2010a), starting from the quasar luminosity function by Willott et al. (2010b), with $f(\lambda)$, fitted on the sample of $z \sim 6$ quasars with estimated BH mass, described by a lognormal distribution with $\lambda = \log(0.6)$, $\sigma = 0.3$, and $D = 0.75$.

Additionally, a fraction of AGNs is obscured, and they are missed by observations. We include a luminosity-dependent correction for obscuration based on Ueda et al. (2014). Note that Ueda et al. (2014) limit their redshift evolution to $z \sim 2$. They found that the fraction of obscured quasars increases with redshift, but, conservatively, we keep the $z = 2$ value at an even higher redshift.

### 2.1. Galaxy MFs

Several different measurements and analytical fits to the galaxy stellar MF can be found in the literature. Many of them are summarized in Behroozi et al. (2013) and Madau & Dickinson (2014), where differences and uncertainties are discussed (see Figure 11 in Madau & Dickinson 2014). We will further discuss this in Section 3.

We start from the galaxy MF of Ilbert et al. (2013). We use their best-fit parameters for the full sample, and the fit for “quiescent” galaxies as a proxy for elliptical galaxies. At $z > 4$, we consider four galaxy MFs: González et al. (2011), plus the correction for nebular lines proposed by Stark et al. (2013), Duncan et al. (2014), and Grazian et al. (2015), all converted to a Chabrier initial MF for consistency with RV15. The stellar mass density for the various MFs obtained by integration for stellar masses $>10^8 M_\odot$ is shown in Figure 1. In the following, we will use as a reference the MF by Grazian et al. (2015) as “middle ground” and discuss how results change using other MFs.

### 2.2. BH–Stellar Mass Relationships

We adopt three different functional forms for the scaling between BH mass and galaxy stellar mass. The first is a simple linear scaling, so that the BH mass is $2 \times 10^{-3}$ the stellar mass:

$$\mu = s - 2.7, \quad (4)$$

as is often done in the literature, by extrapolating the BH–bulge mass relation of Marconi & Hunt (2003) and Häring & Rix (2004). This is our “vanilla” model.

We also include the two total stellar mass relationships found by RV15 for ellipticals and bulges, typically with high stellar masses:

$$\mu = 1.40s - 6.45 \quad (5)$$

and for moderate-luminosity AGNs, typically in lower-mass host galaxies:

$$\mu = 1.05s - 4.1, \quad (6)$$

“HighMass” and “LowMass” fits hereafter. Both these relationships have an intrinsic scatter of $\sim 0.5$ dex. In what follows we will adopt a scatter of $0.5$ dex for all scalings as a reference and then discuss the effect of a tighter or broader scatter. We perform a Monte Carlo experiment with 50,000 draws for each BH or galaxy mass unless otherwise stated.

### 3. RESULTS

#### 3.1. Evolution of BH Mass Density

We start by looking at an integral quantity $\rho_{\text{BH}}$, the BH mass density versus redshift, integrating $\Phi_{\text{MBH,GAL}}$ from $\mu = 5$ to $\mu = 9$. For reference, at $z = 0$ we show the mass density obtained by Shankar (2013). At $z > 0$, the main constraints come from Soltan’s argument, where the AGN luminosity function is integrated over time, from $t_{\text{max}}$ to $t(z)$, and rescaled by a (fixed) radiative efficiency, $\epsilon$, to obtain the density of mass accreted on BHs as a function of redshift:

$$\rho_{\text{BH,acc}}(z) = \frac{1 - \epsilon}{\epsilon c^2} \int_{t_{\text{max}}}^{t(z)} dt \int dL \; L \Phi_{\text{AGN}}(L, t). \quad (7)$$

We adopt as a reference the estimate by Merloni (2016) at $z < 4$, including contributions of unobscured AGNs, Compton-thin and Compton-thick AGNs, and $\epsilon = 0.1$. We also show the cases with $\epsilon = 0.06$ and $\epsilon = 0.3$. At $z > 0$, we report all the current upper limits, derived either on deep X-ray observations (Willott et al. 2011; Cowie et al. 2012; Fiore et al. 2012; Treister et al. 2013) or from the integrated X-ray background (Salvaterra et al. 2012). These upper limits do not include Compton-thick AGNs, so that in reality there may be a fraction of BHs not accounted for. We also stress that Soltan’s argument estimates the mass density accreted in luminous
phases throughout cosmic time up to \( z \). The total mass density can be higher when accounting for non-radiative BH growth, e.g., via mergers, radiatively inefficient accretion or heavily obscured accretion episodes, and when including inactive BHs. The integral of \( \rho_{MBH,GAL} \) instead provides the total mass density in BHs, irrespective of the luminosity.

In Figure 2, we summarize the main results on the redshift evolution of the BH mass density. At \( z < 1 \), there is a general consensus: taking the full MF of Ilbert et al. (2013), and assuming the vanilla fit, or including quiescent galaxies only and fit HighMass give similar results. The reason is that while the mass in galaxies locked in quiescent galaxies is about half of the total stellar mass density, the BH mass locked in elliptical galaxies dominates the full population because BHs represent a higher fraction of their stellar mass. Using the LowMass fit only, instead, leads to an underestimate of the total BH mass density.

Results become more interesting at higher redshifts. First, the fraction of stellar mass in quiescent galaxies drops significantly. Therefore, even considering that BHs represent a larger fraction of the stellar mass in ellipticals, the global contribution to the BH mass density falls. Therefore, if BHs require a bulge component, BHs represent a higher fraction of the stellar mass of the bulge at increasing redshift. Second, for the full population, the mass density in BHs is always above the limits imposed by a lack of X-ray detections in stacking of high-\( z \) galaxies, except for the LowMass fit, i.e., for the other fits to hold, X-ray limits imply most of the BH mass density was not accreted in a luminous phase.

Increasing the scatter only increases the BH mass density (Lauer et al. 2007; Somerville 2009; Volonteri & Stark 2011). Even reducing the scatter to zero, however, the vanilla or HighMass fits overestimate \( \rho_{BH,acc} \) given by the observational constraints at high-\( z \). BHs represent a smaller fraction of the stellar mass of the galaxy at higher redshift, and/or local moderate-luminosity AGNs are good proxies for the BH-host relationship at high-\( z \). A combination of the LowMass and HighMass fits (“hybrid”), using \( z = 11 \) as a dividing line (RV15), provides a reasonable evolution of the mass density at all redshifts, with only a slight tension with most upper limits at \( z > 6 \). For the same \( \mu-s \) relation of Equation (6), the uncertainty given by the unknowns in the MF amount to \( \sim 1 \) dex, with the MF by Duncan et al. (2014) requiring the strongest (negative) evolution in the \( \mu-s \) relation to accommodate observational upper limits.

In summary, the choice of the scaling relation has clear consequences for the derived BH mass density. At low redshifts, these are less marked, since massive galaxies contribute significantly to the mass density. At high redshifts, since massive galaxies are largely absent, the contribution from low-mass galaxies is more important.

### 3.2. Connection to the Quasar Population

We focus here on what the scaling relations imply for the \( z \sim 6 \) luminous quasars, at the high-mass end of the BHMF, \( \mu > 8 \). In Figure 3, we compare \( \Phi_{MBH,GAL} \) to \( \Phi_{MBH,AGN} \) at \( z = 6 \). With the vanilla and hybrid fits, \( \Phi_{MBH,GAL} > \Phi_{MBH,AGN} \) (see also the discussion in Willott et al. 2010a; Volonteri & Stark 2011), requiring, e.g., a lower duty cycle or occupation fraction. For the LowMass fit, \( \Phi_{MBH,GAL} \) is in good agreement with \( \Phi_{MBH,AGN} \) at \( \mu > 9 \).
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Figure 4. Fraction of galaxies at \( z = 6 \) hosting an AGN above a given luminosity, marked in the figure, for the LowMass and vanilla fits. Solid and dashed curves: \( \lambda = \log(0.6) \). Dotted curve: \( \lambda = \log(0.06) \), more typical of “normal” AGNs (this corresponds to the hybrid fit below \( 10^{10} M_\odot \)).

The masses of BHs powering the most luminous quasars, however, are estimated to be above the \( z = 0 \) scaling (assuming that the total dynamical mass corresponds to the stellar mass; Wang et al. 2013). To mimic their luminosity/flux limit, we associate a luminosity to BHs in \( \Phi_{\text{MBH,gal}} \) through \( f(\lambda) \), adopting the functional form and parameters given in Section 2. If, for the LowMass fit, we select only BHs with bolometric luminosity \( > 10^{45} \text{erg s}^{-1} \), similar to currently detected \( z \sim 6 \) quasars, this subset of the population, at \( s < 12 \), is described by an apparent scaling between BH mass and galaxy stellar mass:

\[
\mu = 0.40 s + 3.87,
\]

shallower and with a higher normalization than the scaling describing the full underlying population. This is a consequence of selection effects (Lauer et al. 2007; Volonteri & Stark 2011): at relatively low galaxy mass, only BHs above the mean of the intrinsic scaling can reach very high luminosity. BHs powering luminous quasars are more likely to lie above the intrinsic relation, which is recovered lowering the luminosity threshold.

3.3. Implications for Detecting AGNs in LBGs

X-ray stacking gives more direct upper limits on the luminosity of a putative AGNs in LBGs, with typical stellar masses of \( \sim 10^9 M_\odot \). According to Treister et al. (2013), at \( z = 6 \) the luminosity in the hard X-ray band is \( < 1.6 \times 10^{42} \text{erg s}^{-1} \). We show in Figure 4 the fraction of galaxies hosting an AGN detectable above a given X-ray luminosity as a function of galaxy stellar mass, where we convert from bolometric luminosity to hard X-ray using the bolometric corrections of Marconi et al. (2004). We adopt again \( \lambda = \log(0.6) \), \( D = 0.75 \), and a correction for obscuration. This Eddington ratio, however, was estimated on luminous quasars, and it is higher than the typical value for “normal” AGNs. The same applies to the duty cycle (e.g., Schulze & Wisotzki 2010). The absorbed fraction is also very conservative. We also assume that all galaxies host a BH. While today it is not clear how many galaxies with \( s \sim 9 \) have BHs (Reines et al. 2013), an LBG with \( s \sim 9 \) represented a massive galaxy at \( z \sim 6 \), and it is expected that such massive galaxies have been seeded with a BH by that time (Volonteri 2010).

Statistically, the fraction of galaxies with mass \( \sim 10^9 M_\odot \) hosting an unobscured AGN with \( L_X > 1.6 \times 10^{42} \text{erg s}^{-1} \) is only \( \sim 0.01 \) using the LowMass fit. Treister et al. (2013) stack 223 galaxies and find no detection. Therefore, the predicted luminosities are only slightly higher than the upper limit in the stack. If we select only BHs above this luminosity threshold, we can convert the MF into an expected number of AGNs in the 4Ms CDFS, covering about \( 10^{-6} \) of the sky area. Between \( z = 6 \) and \( z = 7 \), we expect \( 2.2 \times 10^{17} \) AGNs with \( L_X > 1.6 \times 10^{42} \text{erg s}^{-1} \) for the LowMass fit. The vanilla fit gives \( 4.18 \times 10^{16} \).

The accretion properties derived from luminous quasars are significantly different than the local Seyferts defining the LowMass fit, making the estimates above conservative. The median Eddington ratio for the local AGN sample is around a factor of 10 lower (using the median \( L_{\text{bol}} \) and \( M_{\text{BH}} \) from the RV15 sample). With the LowMass fit, assuming a mean Eddington ratio of 0.06 in the lognormal distribution of Eddington ratios for BHs in galaxies with \( s < 11 \), the fraction of AGNs at a given luminosity decreases (Figure 4), and between \( z = 6 \) and \( z = 7 \), we expect \( 0.15 \times 10^{17} \) AGNs with \( L_X > 1.6 \times 10^{42} \text{erg s}^{-1} \) in the 4Ms CDFS. For reference, the vanilla fit predicts \( 1.86 \times 10^{17} \) AGNs.

These results are based on the galaxy MF by Grazian et al. (2015). For the galaxy MF predicting the largest number of galaxies, thus the most difficult to reconcile with a low number of BHs and AGNs (Duncan et al. (2014), at \( L_X > 1.6 \times 10^{42} \text{erg s}^{-1} \), we find \( 3.40 \times 10^{18} \) sources in the 4Ms CDFS area for the LowMass fit and \( 5.58 \times 10^{18} \) for the vanilla fit, and in all cases, adopting \( \lambda = \log(0.6) \), making these upper limits. Assuming \( \lambda = \log(0.06) \) at \( s < 11 \), the numbers decrease to \( 0.65 \times 10^{18} \) and \( 3.06 \times 10^{17} \).

4. CONCLUSIONS

In this Letter, we have drawn inferences on high-redshift BHs and their relation to their hosts. We have tested whether the relation between BH and galaxy stellar mass found by RV15 for local AGNs \( (z < 0.055) \) can explain the lack of an X-ray detection in the stack of LBGs because of the low normalization with respect to the BH–bulge mass relation characterizing bulge-dominated quiescent galaxies. We convolve galaxy stellar MFs with BH–stellar mass relations and estimate the redshift evolution of the BH mass density and the BHMF at \( z = 6 \). We stress the speculative nature of this Letter. It is very hard to draw firm, robust conclusions given the uncertainties on the observables. Despite the uncertainties, we can highlight some trends and explain the current non-detection of moderate-luminosity AGNs in LBGs using scaling relations for BH masses and AGN luminosities derived on observational samples. The main results can be summarized as follows:

1. The fraction of stellar mass in quiescent galaxies drops significantly with redshift. If BHs require a bulge component, the ratio between BH and bulge mass must...
evolve positively with increasing redshift, in the sense that BHs represent a higher fraction of the stellar mass of the bulge.
2. The total mass density in BHs is always above the limits imposed by the lack of X-ray detections in stacking of high-z galaxies, except for the LowMass fit. Local moderate-luminosity AGNs are good proxies for the BH–stellar mass relationship at high-z, and/or BHs represent a smaller fraction of the total stellar mass of the galaxy at high-z. 
3. Using the BH–stellar mass scaling derived from local AGNs hosted by low-mass galaxies jointly with, very conservatively, the accretion properties derived only from luminous quasars (Willott et al. 2010a) is close to explaining the paucity of AGNs in LBGs. Moderate-luminosity AGNs have lower Eddington ratios than luminous quasars, which makes the scarcity of AGNs in LBGs even more reasonable.
4. If the BH–stellar mass scaling at high-z corresponds to today’s BH–bulge mass, the lack of AGNs in LBGs favors lower Eddington ratios for their BHs.

We have shown that using the empirical scaling between BH and galaxy mass, determined on local AGNs hosted by relatively low-mass galaxies, can explain the few, if any, moderate-luminosity AGNs at z > 6. One possibility is also that such AGNs are intrinsically X-ray weak (Luo et al. 2014) or that obscuration is more important than currently thought. Treister et al. (2013) also suggest alternative possibilities for such a low space density derived from the X-ray observations, among them a low BH occupation fraction at these redshift, a low AGN duty cycle, and/or BH growth through mergers.

Getting firmer constraints on the mass of the host galaxies of the current sample of luminous quasars, and pushing at the same time for detections of AGNs, e.g., using alternative techniques such as line ratios in the ultraviolet (Feltre et al. 2016) on the existing sample of LBGs would greatly help in understanding the link between BHs and galaxies at early times.

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