The Evolution of $M_*/M_{\text{BH}}$ Between $z=2$ and $z=0$

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ABSTRACT
We propose a novel method to estimate $M_*/M_{\text{BH}}$, the ratio of stellar mass ($M_*$) to black hole mass ($M_{\text{BH}}$) at various redshifts using two recent observational results: the correlation between the bolometric luminosity of active galactic nuclei (AGN) and the star formation rate (SFR) in their host galaxies, and the correlation between SFR and $M_*$ in star-forming (SF) galaxies. Our analysis is based on $M_{\text{BH}}$ and $L_{\text{bol}}$ measurements in two large samples of type-I AGN at $z\approx 1$ and $z\approx 2$, and the measurements of $M_*/M_{\text{BH}}$ in 0.05$<z<0.2$ red galaxies. We find that $M_*/M_{\text{BH}}$ depends on $M_{\text{BH}}$ at all redshifts. At $z\approx 2$, $M_*/M_{\text{BH}}\sim 280$ and $\sim 40$ for $M_{\text{BH}}=10^8$ and $M_{\text{BH}}=10^9M_\odot$, respectively. $M_*/M_{\text{BH}}$ grows by a factor of $\sim 4-8$ from $z\approx 2$ to $z=0$ with extreme cases that are as large as 10–20. The evolution is steeper than reported in other studies, probably because we treat only AGN in SF hosts. We caution that estimates of $M_*/M_{\text{BH}}$ evolution which ignore the dependence of this ratio on $M_{\text{BH}}$ can lead to erroneous conclusions.

Key words: galaxies: active – galaxies: nuclei – galaxies: evolution – quasars: general.

1 INTRODUCTION
Study of the co-evolution of Active Galactic Nuclei (AGN) and their host galaxies provides important clues about the growth of super massive black holes (SMBHs) and the star formation (SF) history of the Universe. In the local universe one finds a tight correlation between the SMBH mass ($M_{\text{BH}}$) and the mass of the bulge of its host, $M_{\text{bulge}}$ (Marconi & Hunt, 2003; Haring & Rix 2004, hereafter HR04), or alternatively with the stellar velocity dispersion $\sigma_*$ (Ferrarese & Merrit 2000; Gebhardt et al. 2000). Typically $M_{\text{bulge}}/M_{\text{BH}}\sim 500–1000$. $M_{\text{bulge}}/M_{\text{BH}}$ must have been smaller at high redshift. For example, $M_{\text{BH}} \sim 10^{9-10}M_\odot$ are often observed at $z=3-6$ (e.g. Netzer 2003; Shenmer et al. 2004; Fan et al. 2006), yet galaxies that are 500-1000 times more massive are never observed at $z>0.5$ and are very rare even at $z\approx 0$.

The evolution of the $M_{\text{BH}}-\sigma_*$ relationship has been studied in numerous papers. Examples are Shields et al. (2003) who find no evolution up to $z\approx 2$, and Woo et al. (2008) who suggest that $M_{\text{bulge}}/M_{\text{BH}}$ has increased by a factor of $\sim 3$ since $z=0.6$. The uncertainties in all such measurements are very large due to the difficulties in measuring $\sigma_*$ or $M_{\text{bulge}}$ in high-redshift AGN hosts. While measuring $M_{\text{bulge}}$ in high-redshift galaxies is difficult, the total stellar mass, $M_*$, is easier to obtain. This is achieved by multiband spectral energy distribution (SED) fitting, which is used to constrain $M_*/L_*$. However, obtaining $M_*/M_{\text{BH}}$ for AGN hosts is severely limited by the problematic subtraction of the bright point-like continuum in type-I AGN and the estimation of $M_{\text{BH}}$ in type-II AGN.

Several recent studies used deep imaging to estimate $M_*/M_{\text{BH}}$ (or $L_{\text{host}}/M_{\text{BH}}$) in $z\sim 0.5–3$ AGN by resolving the host galaxy emission and by careful PSF modelling (e.g. Kukula et al. 2001; Peng et al. 2006; Kotilainen et al. 2007; Bennert et al. 2010). The measured host luminosity was translated to $M_*$ by assuming a certain $M_*/L_\odot$ ratio. A common assumption is that AGN hosts are “red and dead”, with a stellar population which evolves passively from a high formation redshift, e.g. $z_{\text{form}} \approx 5$. A detailed study of this type, including a summary of many earlier findings, is given in Decarli et al. (2010; hereafter D10) who find that $M_*/M_{\text{BH}}$ evolves following $(M_*/M_{\text{BH}}) \propto z^{-0.28}$. The assumption of non-SF AGN hosts may describe some objects, but many studies find that hosts of luminous AGN often contain much younger stellar populations (e.g., Kauffmann et al. 2003; Jahnke et al. 2004; Silverman et al. 2009; Merloni et al. 2010, and references therein).

In this Letter we suggest a novel method to estimate the evolution of $M_*/M_{\text{BH}}$. Our approach makes use of the known relationships between star formation rate (SFR) and $M_*$ in SF galaxies (SFGs), and between the bolometric luminosity of AGN ($L_{\text{bol}}$) and the SFR in their hosts. We describe these relationships in 2 and use them to estimate $M_*/M_{\text{BH}}$ in SF galaxies at $z\approx 0.15$, $z\approx 1$ and $z\approx 2$ in 3. In 4 we discuss the implications to the co-evolution of SMBHs and their hosts. Throughout this work we assume a standard ΛCDM cosmology with $\Omega_\Lambda=0.7$, $\Omega_M=0.3$ and $H_0=70\text{km s}^{-1}\text{Mpc}^{-1}$.
2 SFR-\(M_\ast\) AND SFR-\(L_{\text{bol}}\) CORRELATIONS

Our work is based on two empirical correlations. The first is the well established, redshift dependent, SF sequence (a correlation between SFR and total stellar mass, \(M_\ast\)) in SF galaxies. There are numerous papers on this issue and the following is only a partial list which is most relevant to our work. Brinchmann et al. (2004; hereafter B04) studied a large sample of low redshift SFGs in the Sloan Digital Sky Survey (SDSS). They show a clear relationship of the form \(SFR \simeq 8.7 \left(M_\ast/10^{11}\right)^{0.77}\). The result was later confirmed by Salim et al. (2007) who used a combination of SDSS and GALEX data. Similar relationships at higher redshifts, based on mid-IR and UV observations and multi-wavelength SED modelling, are reported in Elbaz et al. (2007; hereafter E07), Daddi et al. (2007; hereafter D07), Noeske et al. (2007), Drory & Alvarez (2008) and several other papers (see a more complete list in Dutton et al. 2009). E07 and D07 used the combined \(HST\), \(Spitzer\) and ground-based photometry of the GOODS field. E07 studied blue \((U − g \lesssim 1.5)\) galaxies at \(z=0.8−1.2\) and found \(SFR \simeq 57 \left(M_\ast/10^{11}\right)^{0.9} M_\odot \text{yr}^{-1}\). D07 studied \(BzK\)-selected galaxies at \(z=1−3\). For \(z=2\) they find \(SFR \simeq 200 \left(M_\ast/10^{11}\right)^{0.8} M_\odot \text{yr}^{-1}\). The scatter around both relations is \(\sim 0.3−0.4\) dex. Noeske et al. (2007) reports \(SFR \propto M_\ast^{0.7}\) for \(z=0.2−0.7\) AEGIS galaxies. Drory and Alvarez (2008) studied the FORS Deep field up to \(z=4.5\) and find similar trends, albeit with systematically lower SFR. Much of the differences between the various SFR-\(M_\ast\) relations can be attributed to the selective inclusion of extremely low-SFR galaxies in the samples under study.

There is mounting evidence that many, perhaps most AGN hosts are actively forming stars. This relates to the issue of whether such hosts are “blue”, “red”, or “green valley” sources (e.g., Brammer et al. 2009 and references therein). This is especially important at high redshift due to the known tendency for the fraction of blue galaxies to increase with redshift (e.g. E07 and references therein). Works like Salim et al. (2007) show that low-\(z\) AGN hosts populate the more massive part of the SF sequence. These high masses, in turn, mean that the apparent “green” colours of many AGN hosts are the consequence of low specific SFR (SSFR), not a low SFR. Moreover, Branner et al. (2009) show that many green valley galaxies belong to the blue sequence once reddening is properly taken into account. While such ideas are well supported for low redshift AGN, there is a need for more evidence at high-\(z\). Some such data already exists, e.g. the Silvermann et al. (2009) work that claims that the SFR and \(M_\ast\) in AGN hosts at \(z=0.7\)−1 are indistinguishable from those of inactive SF galaxies. Given all the above, our first assumption is that the hosts of most luminous, optically-selected AGN are part of the SF sequence at all redshifts. This assumption is further justified in Fig.1.

Our second assumption is that there exists a significant correlation between the bolometric luminosity of AGN (\(L_{\text{bol}}\)) and the SFR of their hosts. This correlation is hinted at in various intermediate and high redshift studies (Netzer et al. 2007; Lutz et al. 2008) and in low redshift type-II AGNs (Netzer 2009; hereafter N09). Here we adopt an updated version of the correlation presented in N09, by excluding LINERs from the group of low-\(z\) AGN. This gives

\[
SFR \simeq 32.8 \left(L_{\text{bol}}/10^{46} \text{ergs s}^{-1}\right)^{0.7} M_\odot \text{yr}^{-1}.
\]

This equation is not a fit to the data but rather a line that goes through the points. As discussed in N09, there is no simple way to derive a best fit function to this inhomogeneous data set.

Since the above correlation is crucial for our study, we show the data used here in Fig.1. In addition to the samples presented and discussed in N09, this version also includes two additional groups of zCOSMOS type-II AGNs at \(z=1\) and \(z=2\), kindly provided by V. Mainieri. These are X-ray selected sources where \(L_{\text{bol}}\) is estimated from \(L(2−10 \text{keV})\) and the SFR is based on multi-wavelength SED fitting. The two groups lie on the above relationship with a scatter in SFR of about 0.4 dex, comparable to the overall scatter. There are several reasons for this scatter. At the low-\(L_{\text{bol}}\) end, the scatter is related to the inaccuracies in SFR and \(L_{\text{bol}}\) determination as well as real scatter in these properties. At \(z=1\) and \(z=2\), the scatter reflects the uncertainty in SED modelling and the range of \(M_\ast\) across the SF sequence. At the high-\(L_{\text{bol}}\) end, much of the scatter is due to observational uncertainties, the incompleteness of the high redshift AGN samples and, perhaps, the extreme SFR in mergers. A more complete account of these issues can be found in N09.

The following analysis relies on the combination of the above correlations for SF AGN hosts. Given \(L_{\text{bol}}\), we can determine SFR (Eq.1) and this, in turn, can be translated to \(M_\ast\) given the redshift dependent SFR-\(M_\ast\) correlations.

3 THE REDSHIFT EVOLUTION OF \(M_\ast/\mathcal{M}_{\text{BH}}\)

3.1 \(M_\ast/\mathcal{M}_{\text{BH}}\) at low and high redshift

To explore \(M_\ast/\mathcal{M}_{\text{BH}}\), we define several samples of both AGN and non-AGN galaxies. The first is a large sample of \(0.05<z<0.2\) galaxies from the value-added MPA/JHU SDSS DR4 database. This includes photometry, \(M_\ast\), SFR and \(\sigma_\text{v}\) for all sources (B04). To justify the use of the \(\mathcal{M}_{\text{BH}}-\sigma_\text{v}\) relation of Tremaine et al. (2002), we choose only red galaxies, following the colour cut of Baldry et al. (2004). The number of such sources, after applying some basic quality criteria, is 210,158. They cover the range \(5\times10^9 < M_\ast/\mathcal{M}_\odot < 6\times10^{11}\).
and $10^9 < M_{\text{BH}}/M_\odot \lesssim 2 \times 10^9$ (the latter lower limit was chosen to filter out dubious measurements). $M_\ast$ is derived from the SDSS photometry and thus the flux limit of the sample ($r_{\text{petro}} < 17.7$) affects the number of low-$M_\ast$ galaxies. Here we deal mostly with the larger $M_\ast$ systems and these limitations do not affect our general conclusions.

The work involves also four AGN samples: type-I and type-II samples at $0.1 < z < 0.2$, a type-I sample at $z=1$ and a type-I sample at $z=2$. The first two provide little new information but serve to test and to justify the general new method presented here. The $0.1 < z < 0.2$ redshift range is chosen to enable proper measurements of type-I and type-II AGN (see details in N09). The type-II AGNs are “strong AGN” (Seyfert 2s or S2s but not LINERs) drawn from the local SDSS sample. $L_{\text{bol}}$ for these 1152 AGN is determined by the [O~III] and [O~II] method of N09. The 2814 type-I AGN are drawn directly from the SDSS/DR7 (Abazajian et al. 2009) database and are analyzed in a way similar to the one presented in Netzer & Trakhtenbrot (2007; hereafter NT07). Here $M_{\text{BH}}$ is estimated from the monochromatic luminosity at 5100Å ($L_{5100}$) and the FWHM of the Hβ line. $L_{\text{bol}}$ is determined from $L_{5100}$, using the bolometric correction factors of Marconi et al. (2004). To avoid selection biases, we apply a common observed flux limit for the type-I and type-II samples, such that only sources with F([O~III]) $> 4 \times 10^{-16}$ ergs cm$^{-2}$ s$^{-1}$ are included. Assuming a typical bolometric correction of 2500 (Netzer et al. 2006, NT07), this translates to $L_{\text{bol}} > 2.5 \times 10^{43}$ ergs s$^{-1}$.

We constructed the SF sequence for our type-II low redshift sample and compared it with the SF sequence presented in B04. The agreement is very good, with about 70% of the AGN hosts lying on the sequence. We also confirm earlier results (e.g. Salim et al. 2007) which suggest that AGN hosts concentrate at somewhat higher $M_\ast$. We find that despite their apparently red colours, the majority of the red S2 hosts are actively forming stars and are situated on the SF sequence. These S2 hosts are, in fact, mostly green valley sources, with lower SSFR. Some 30% of the AGN are not part of the SF sequence. We suspect that the fraction of such sources at higher redshift is smaller but have no way to check it qualitatively. The remaining of the paper and the results concerning $M_\ast/M_{\text{BH}}$ refer only to those AGN that are on the SF sequence.

Next, we translate $L_{\text{bol}}$ to SFR for the $0.1 < z < 0.2$ type-I AGN using Eq.~[1] This is then converted to $M_\ast$ using the low redshift SF sequence of B04. Combined with the measured $M_{\text{BH}}$, we obtain $M_\ast/M_{\text{BH}}$ for all these sources. This can be compared with $M_\ast/M_{\text{BH}}$ measured directly for the type-II $z=0.1-0.2$ AGN. The overall good agreement justifies the use of a similar procedure for higher redshift AGN samples. We selected two higher redshift type-I AGN samples from the SDSS/DR7. We chose sources in the range $0.9 < z < 1.1$ and $1.8 < z < 2$ (5330 and 4352 objects, respectively), which are the nominal redshift ranges of the SFG samples of E07 and D07. Full details of the sample selection, line fitting and related analysis will be given in a forthcoming publication. In short, we use a similar procedure to the one described in NT07 and in Shen et al. (2008) to measure the Mg~IIλ2798 emission line complex. The FWHM of the line and the adjacent continuum luminosity ($L_{3000}$) are combined to estimate $M_{\text{BH}}$ using the relation of McLure & Dunlop (2004). We calculate $L_{\text{bol}}$ from $L_{3000}$ by calibrating $L_{3000}$ against $L_{5100}$ in a separate sub-sample where the two continuum bands are observed in the spectrum. We then estimated the SFR by using Eq.~[1] The distribution of inferred SFRs (not shown here) clearly shows that these AGN hosts are actively forming stars at rates that are comparable to the non-AGN SFGs at those redshifts. In particular, 99% of the $z=2$ sources have SFR $\gtrsim 42 M_\odot$ yr$^{-1}$, the median SFR in the SF sequence of D07. While most (not all, see earlier comments) high redshift AGN hosts are expected to lie on the SF sequence, the range in SFR and in $M_\ast$ can be very different from those found for non-AGN samples because of the differences in properties of the observed samples, in particular different flux limits. To examine this in detail, we focus on our $z=2$ type-I AGN sample. We compare the range of derived SFR and possible range of $M_\ast$ to the same properties in the D07 sample, using data kindly provided by Emanuele Daddi. Such a comparison involves two crucial factors. First, the D07 sample includes much fainter sources. As explained above, almost all our type-I AGN occupy only the upper part of the $z=2$ SF sequence. This is a direct consequence of the SDSS flux limit. Second, one can consider two approaches to deduce typical values of $M_\ast$ for the $z=1$ and $z=2$ samples, by either (1) converting each individual SFR to $M_\ast$ through the best fit SF sequence, at the appropriate redshift (i.e. E07 and D07), or (2) sampling the distribution of $M_\ast$ per given SFR (in the high-redshift SF sequences), for each deduced value of SFR. By definition, the latter will result in a considerably broader distribution of the derived $M_\ast/M_{\text{BH}}$, due to the wide range of properties in the observed samples. In the following analysis we only use the first approach, i.e. we derive $M_\ast$ for each $z=1$ and $z=2$ AGN host, by converting its (derived) SFR through the E07 and D07 relations, respectively. We note that the ~0.4 dex scatter in these relations is a real uncertainty on our high-redshift results. The $z=2$ sample covers $9.5 \times 10^7 \lesssim M_{\text{BH}}/M_\odot \lesssim 5 \times 10^9$ and $1.7 \times 10^{10} \lesssim M_\ast/M_{\text{BH}} \lesssim 2 \times 10^{11}$, while the $z=1$ sample covers $3.8 \times 10^9 \lesssim M_{\text{BH}}/M_\odot \lesssim 2.5 \times 10^9$ and $2.8 \times 10^{10} \lesssim M_\ast/M_{\text{BH}} \lesssim 2.9 \times 10^{12}$. Clearly, the varying ranges of $M_\ast$ and $M_{\text{BH}}$ in the different local and high-redshift samples prohibit a simplistic comparison of the mean $M_\ast/M_{\text{BH}}$. In what follows we thus preform a more careful comparison.

### 3.2 $M_\ast/M_{\text{BH}}$ evolution

Standard galaxy evolution scenarios suggest that the end phase of many high redshift SF galaxies are massive, red ellipticals. Therefore, we use our data to compare the properties of the $z=1$ and $z=2$ AGN hosts to those of red galaxies in the local Universe. Fig.~[2] shows the entire sample of 0.05$<z<0.2$ red galaxies, as a gray scale density map. The galaxies form a well-defined band in the $M_\ast/M_{\text{BH}}$-plane that follows the approximate relationship $M_\ast/M_{\text{BH}}\propto M_{\text{BH}}^{-0.7\pm0.1}$. Also shown is the sample of the $0.1 < z < 0.2$ type-II AGN that follows a similar trend. Fig.~[2] also shows data for the 30 local galaxies from HR04 with dynamically measured $M_{\text{BH}}$. In this case we plot $M_{\text{BH}}$ rather than $M_\ast$. All $M_{\text{BH}}$ are taken directly from HR04 except those of M87, NGC~4649 and NGC~4697 where we used new measurements reported in Gebhardt & Thomas (2009), Shen & Gebhardt (2010) and Forestell et al. (2010). This sequence extends up to $M_{\text{BH}} \approx 6 \times 10^9 M_\odot$, and $M_\ast/M_{\text{BH}}\sim100$ and shows a clear dependence on $M_{\text{BH}}$, sim-
Figure 2. $M_*/M_{\text{BH}}$ for different local and high redshift samples: local red galaxies (gray scale density map), type-II AGN (red points), the HR04 sources (green circles) and $z \simeq 2$ type-I AGN (blue points). The arrows demonstrate simple scenarios where only $M_*$ or both $M_*$ and $M_{\text{BH}}$ grow by a factor of 2.

Figure 3. The distributions of $M_*/M_{\text{BH}}$ at different redshift, for the three $M_{\text{BH}}$ sub-groups discussed in the text.

![Image](image-93x541 to 245x687)

shift. This is obviously an over-simplification of the evolution of most galaxies and significant epochs of SF at $z<4$ (e.g. D07; E07; Drory & Alvarez 2008; van Dokkum et al. 2010, and references therein). Accounting for younger stellar populations would result in lower $M_*$ and thus lower $M_*/M_{\text{BH}}$ (see D10 and Peng et al. 2006).

(ii) The D10 sample represents the minority of the AGN population, as hinted by two biases. First, the majority of the D10 sources lie in the top 15% of the $M_{\text{BH}}$ distributions corresponding to their redshift. Second, the selection criteria for the D10 HST observations could have been biased towards large, resolved galaxies with large $M_*$.

(iii) The mean $M_{\text{BH}}$ in high redshift AGN samples is systematically larger than the corresponding low redshift $M_{\text{BH}}$. For example, in our large sample of red galaxies, 99% of the sources show $M_{\text{BH}} < 10^{8.5}M_\odot$ while 20% of the $z \simeq 1$ and 57% of the $z \simeq 2$ AGN have larger $M_{\text{BH}}$. All the $z \simeq 2$ sources in D10 have $M_{\text{BH}} > 10^{8.7}M_\odot$. Such objects should only be compared with local galaxies which host BHs that are at least as massive. As Fig. 2 shows, this corresponds to $M_*/M_{\text{BH}}=100$–200, instead of the commonly used $\sim 700$.

In conclusion, while our work applies to most AGN, the D10 sample probably represents the remaining sources.

The results presented here point to a scenario where many galaxies have to increase their mass by factors of 4-8 (2-4) since $z \simeq 2$ ($z \simeq 1$). The growth factors for the most massive BHs are not well determined since the number of very massive galaxies in the local universe is not large enough to reliably extend the results of Fig. 2 beyond $M_{\text{BH}} \simeq 10^{8}M_\odot$. These numbers represent the requirement for the galaxies to over-grow their SMBHs by the above factors. This seems to be consistent with models which suggest that the high mass SMBHs observed at $z \simeq 2$ could have accumulated most of their mass by that redshift (Marconi et al. 2004). On the other hand, it may be in contradiction with at least some scenarios linking AGN activity to the shut-down of SF in their host galaxies (see Somerville et al. 2008; Cattaneo et al. 2009 and references therein).

While a full discussion of the various growth scenarios of $M_*$ is beyond the scope of this Letter, we comment briefly on some of these ideas. Major galaxy mergers would increase both $M_*$ and $M_{\text{BH}}$, either through starbursts and
gas accretion in “wet mergers” or the possible coalescence of the two SMBHs involved in “dry mergers”. However, theoretical and observational arguments (e.g. Lotz et al. 2008; Genel et al. 2009) suggest a low rate of such events for $z < 2$ galaxies. Thus, major mergers cannot change $M_*/M_{\text{BH}}$ by more than a factor of $\sim 2 - 3$ between $z=2$ and $z=0$. Small “dry mergers” may help. For example, Naab, Johansson & Ostriker (2009) show that present-day massive red ellipticals gain $\sim 40\%$ of their mass through accretion of smaller companions since $z \sim 2$. Intense SF in outer parts of galaxies due to external source of cold gas which does not find its way to the centre (e.g. van Dokkum et al. 2010), is another possibility. More possibilities and more references are discussed in Benson & Devereux (2009). The $M_*/M_{\text{BH}}$ distributions presented here suggest an increase in $M_*/M_{\text{BH}}$ by factors beyond what is suggested in many theoretical studies.

Finally, we comment on the possibility that the suggested evolution of $M_*/M_{\text{BH}}$ could be due to two wrong assumptions. First, many more AGN hosts may not lie on the SF sequence or may not obey the $L_{\text{bol}}$-SFR correlation used here. This is unlikely to be the case at low redshift, where SDSS type-II AGNs are used. However, the selection of at least some of the most luminous, high redshift high-$L_{\text{bol}}$ sources in Fig. 1 may be biased towards high FIR luminosity, high SMBH hosts (e.g. Zheng et al. 2009) in particular if these are found in mergers that are not part of the SF sequence. Herschel observations of well-defined AGN samples are likely to resolve this issue. Second, the Drory & Alvarez (2008) work shows a decline in SFR at the high-$M_*$ end for $z<2$ galaxies. Thus, some of our $L_{\text{bol}}$-based SFR estimates might be associated with considerably larger values of $M_*$.

We conclude that there is a steep evolution in $M_*/M_{\text{BH}}$ from $z \sim 2$ to $z=0$ for SF AGN hosts. This trend is barely consistent with some, but not all galaxy and BH evolution models. We have also demonstrated the crucial importance of considering different $M_{\text{BH}}$ groups separately when evaluating the $M_*/M_{\text{BH}}$ evolution.

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