



This is a repository copy of *The galaxy's gas content regulated by the dark matter halo mass results in a superlinear $M_{BH}-M_{*}$ Relation*.

White Rose Research Online URL for this paper:
<http://eprints.whiterose.ac.uk/157616/>

Version: Accepted Version

Article:

Delvecchio, I., Daddi, E., Shankar, F. et al. (8 more authors) (2019) The galaxy's gas content regulated by the dark matter halo mass results in a superlinear $M_{BH}-M_{*}$ Relation. *Astrophysical Journal Letters*, 885 (2). L36. ISSN 2041-8205

<https://doi.org/10.3847/2041-8213/ab4e21>

© 2019 The American Astronomical Society. This is an author-produced version of a paper subsequently published in *Astrophysical Journal Letters*. Uploaded in accordance with the publisher's self-archiving policy.

Reuse

Items deposited in White Rose Research Online are protected by copyright, with all rights reserved unless indicated otherwise. They may be downloaded and/or printed for private study, or other acts as permitted by national copyright laws. The publisher or other rights holders may allow further reproduction and re-use of the full text version. This is indicated by the licence information on the White Rose Research Online record for the item.

Takedown

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.



eprints@whiterose.ac.uk
<https://eprints.whiterose.ac.uk/>

THE GALAXY'S GAS CONTENT REGULATED BY THE DARK MATTER HALO MASS RESULTS IN A SUPER-LINEAR $M_{\text{BH}}-M_{\star}$ RELATION

I. DELVECCHIO,^{1,2,*} E. DADDI,¹ F. SHANKAR,³ J. R. MULLANEY,⁴ G. ZAMORANI,² J. AIRD,⁵ E. BERNHARD,⁴
A. CIMATTI,^{6,7} D. ELBAZ,¹ M. GIAVALISCO,⁸ AND L. P. GRIMMETT⁴

¹CEA, IRFU, DAp, AIM, Université Paris-Saclay, Université Paris Diderot, Sorbonne Paris Cité, CNRS, F-91191 Gif-sur-Yvette, France

²INAF - Osservatorio di Astrofisica e Scienza dello Spazio, via Gobetti 93/3, I-40129, Bologna, Italy

³Department of Physics and Astronomy, University of Southampton, Highfield SO17 1BJ, UK

⁴Department of Physics and Astronomy, The University of Sheffield, Hounsfield Road, Sheffield S3 7RH, UK

⁵Department of Physics & Astronomy, University of Leicester, University Road, Leicester LE1 7RJ, UK

⁶University of Bologna, Department of Physics and Astronomy (DIFA), Via Gobetti 93/2, I-40129, Bologna, Italy

⁷INAF - Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, I-50125, Firenze, Italy

⁸Department of Astronomy, University of Massachusetts Amherst, 710 North Pleasant Street, Amherst, MA 01003-9305, USA

ABSTRACT

Supermassive black holes (SMBHs) are tightly correlated with their hosts but the origin of such connection remains elusive. To explore the cosmic build-up of this scaling relation, we present an empirically-motivated model that tracks galaxy and SMBH growth down to $z=0$. Starting from a random mass seed distribution at $z=10$, we assume that each galaxy evolves on the star-forming “main sequence” (MS) and each BH follows the recently-derived stellar mass (M_{\star}) dependent ratio between BH accretion rate and star formation rate, going as $\text{BHAR}/\text{SFR} \propto M_{\star}^{0.73[+0.22, -0.29]}$. Our simple recipe naturally describes the BH-galaxy build-up in two stages. At first, the SMBH lags behind the host that evolves along the MS. Later, as the galaxy grows in M_{\star} , our M_{\star} -dependent BHAR/SFR induces a super-linear BH growth, as $M_{\text{BH}} \propto M_{\star}^{1.7}$. According to this formalism, smaller BH seeds increase their relative mass faster and earlier than bigger BH seeds, at fixed M_{\star} , thus setting along a gradually tighter $M_{\text{BH}}-M_{\star}$ locus towards higher M_{\star} . Assuming reasonable values of the radiative efficiency $\epsilon \sim 0.1$, our empirical trend agrees with both high-redshift model predictions and intrinsic $M_{\text{BH}}-M_{\star}$ relations of local BHs. We speculate that the observed non-linear BH-galaxy build-up is reflected in a twofold behavior with dark matter halo mass (M_{DM}), displaying a clear turnover at $M_{\text{DM}} \sim 2 \times 10^{12} M_{\odot}$. While Supernovae-driven feedback suppresses BH growth in smaller halos ($\text{BHAR}/\text{SFR} \propto M_{\text{DM}}^{1.6}$), above the M_{DM} threshold cold gas inflows possibly fuel both BH accretion and star formation in a similar fashion ($\text{BHAR}/\text{SFR} \propto M_{\text{DM}}^{0.3}$).

Keywords: galaxies: high-redshift— galaxies: evolution— galaxies: nuclei

1. INTRODUCTION

How supermassive black holes (SMBHs) formed and evolved with cosmic time is one of the most debated issues in modern Astrophysics. One of the best known evidence supporting co-evolution between SMBHs and their host galaxies is the observed relationship at $z \sim 0$ between SMBH mass (M_{BH}) and several properties of

galaxy bulges: stellar velocity dispersion (σ_{\star}), stellar bulge mass (M_{bulge}), dark matter halo mass (M_{DM}) (e.g. Magorrian et al. 1998; Gebhardt et al. 2000; Ferrarese & Merritt 2000; Häring & Rix 2004; Gültekin et al. 2009).

Such tight (scatter ~ 0.3 dex) correlation is currently interpreted as the outcome of a long-term balance between feeding and feedback processes occurring in galaxy bulges and their central BHs (see a comprehensive review by Kormendy & Ho 2013).

Nevertheless, still unclear is whether the local $M_{\text{BH}}-M_{\text{bulge}}$ relation observed for classical galaxy bulges ($M_{\text{BH}}/M_{\text{bulge}} < 1/200$, Kormendy & Ho 2013) evolves

Corresponding author: Ivan Delvecchio
ivan.delvecchio@cea.fr

* Marie Curie Fellow

with redshift. Several studies targeting high-redshift quasars found BHs as massive as $10^9 M_\odot$ at $z > 6$, when the Universe was less than 1 Gyr old (Mortlock et al. 2011; Wu et al. 2015; Bañados et al. 2018; Vito et al. 2019). This suggests the presence of high-redshift BHs that are *overmassive* ($M_{\text{BH}}/M_\star > 1/100$) relative to local scaling relations, as found in local giant ellipticals (Lupi et al. 2019). Nevertheless, their M_{BH} measurements might be biased, since they rely on gas dynamical estimates on kpc scales, which might not hold within the BH sphere of influence. An alternative scenario is that the galaxy stellar/halo mass primarily regulates the amount of cold gas available for triggering and sustaining the central SMBH growth (see Volonteri 2010 for a review). Investigating the relationship between BH accretion rate (BHAR) and star formation rate (SFR) is crucial to shed light on the connection between both phenomena at various epochs.

A pioneering study of Mullaney et al. (2012) first proposed the idea that SMBH and galaxy growth are synchronised at all times at a universal $\text{BHAR}/\text{SFR} \sim 10^{-3}$. Recently, a number of empirical evidence argued that the BHAR/SFR ratio increases with M_\star (Rodighiero et al. 2015; Yang et al. 2018; Aird et al. 2019). This was independently corroborated in Delvecchio et al. (2019, D19 hereafter), via modeling the observed AGN X-ray luminosity function (XLF, Aird et al. 2015). In this letter, we explore the implications on the cosmic SMBH growth resulting from a M_\star -dependent BHAR/SFR trend. Particularly, assuming a seed distribution for both M_{BH} and galaxy M_\star starting at very high redshift ($z=10$), we let it evolve following the above trend. Finally, we compare their final mass build-up with observed scaling relations at $z=0$ and state-of-the-art cosmological simulations at higher redshifts.

Throughout this letter, we adopt a Chabrier (2003) initial mass function (IMF) and a flat cosmology with $\Omega_m=0.30$, $\Omega_\Lambda=0.70$ and $H_0=70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2. OUR EMPIRICALLY-MOTIVATED TOY MODEL

D19 successfully reproduced the observed AGN XLF (Aird et al. 2015) since $z \sim 3$, disentangling the relative contribution of main-sequence (MS) and starburst (SB) galaxies. The XLF was modeled as the convolution between the galaxy M_\star function and a set of “specific BHAR” ($s\text{-BHAR} = \text{BHAR}/M_\star \propto L_X/M_\star$, see Aird et al. 2012) distributions, that were normalised to match a number of empirical BHAR/SFR trends. From the derived XLF, we directly constrained the typical BHAR/SFR ratio to scale positively with M_\star , as $\text{BHAR}/\text{SFR} \propto M_\star^{0.73[+0.22, -0.29]}$, and roughly independent of redshift at $0.5 < z < 3$ (e.g. Aird et al.

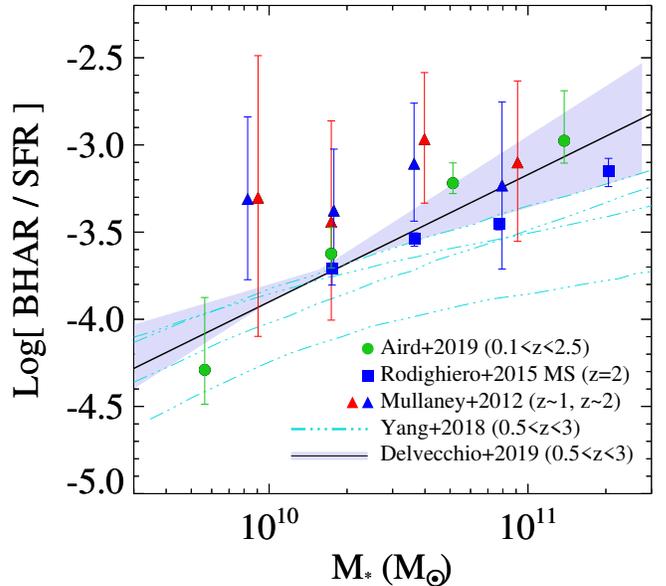


Figure 1. Compilation of various mean BHAR/SFR trends with M_\star proposed in the literature. Empirical relations for star-forming galaxies are taken from Mullaney et al. (2012, $z \sim 1$ and $z \sim 2$, red and blue triangles, respectively), Rodighiero et al. (2015, $z \sim 2$, blue squares) and Yang et al. (2018, dot-dashed lines, increasing with redshift over $0.5 < z < 3$). Datapoints from Aird et al. (2019) (green circles) are averaged over the BHAR/SFR distributions across $0.1 < z < 2.5$. Our recent trend (D19, black solid line) was obtained by reproducing the observed XLF of AGN at $0.5 < z < 3$, yielding $\text{BHAR}/\text{SFR} \propto M_\star^{0.73[+0.22, -0.29]}$ at $\pm 1\sigma$ confidence level (grey shaded area).

2019). While extrapolating this BHAR/SFR trend at $z > 3$ might suffer from uncertainties, this finding suggests that SMBHs and their hosts do not grow in lock-step over cosmic time. Fig. 1 displays our BHAR/SFR trend with M_\star (black solid line), and the corresponding $\pm 1\sigma$ scatter (grey shaded area). For comparison, in Fig. 1 we report other data and trends from the literature (Mullaney et al. 2012, Rodighiero et al. 2015; Yang et al. 2018; Aird et al. 2019) at various redshifts. In particular, Yang et al. (2018) argue for a flatter BHAR/SFR trend with M_\star , and slightly increasing with redshift. However, we stress that the redshift dependence is, at least partly, a consequence of the M_\star -independent MS relation assumed by the authors (from Behroozi et al. 2013). The absence of a bending towards high M_\star leads to slightly higher SFR, therefore lower BHAR/SFR relation, especially at low redshift where the flattening is stronger (e.g. Schreiber et al. 2015). Therefore, under the assumption of a bending MS, the above studies are all consistent with a redshift-invariant BHAR/SFR ratio.

2.1. Initial mass seed distributions

In order not to bias ourselves to any prior seed distribution, we start with a uniform sample of one thousand seeds formed at $z=10$, with masses $M_{\text{BH}}=10^{2-6} M_{\odot}$ and $M_{\star}=10^{6-10} M_{\odot}$. Such input grid spans a wide range of M_{BH}/M_{\star} , covering the mass range predicted by the main BH seed formation channels (Begelman, & Rees 1978): (i) PopIII stars remnants ($\sim 10^2 M_{\odot}$); (ii) stellar dynamical collapse ($\sim 10^3 M_{\odot}$); (iii) gas dynamical collapse ($\sim 10^{5-6} M_{\odot}$). Taking a higher (lower) initial redshift would simply yield slightly smaller (larger) M_{\star} at $z=0$. Independently of this, their M_{BH} estimates would scale accordingly (based on the BHAR/SFR trend with M_{\star}), keeping our final results and conclusions unchanged.

2.2. Setting galaxy M_{\star} growth

For each galaxy M_{\star} and redshift, we assign the corresponding SFR by following the MS relation of Schreiber et al. (2015), re-scaled to a Chabrier (2003) IMF. The MS scatter was propagated on the derived SFR by following a log-normal distribution with 1σ dispersion of 0.3 dex (Schreiber et al. 2015). The cumulative M_{\star} is simply calculated as the time-integral of the SFR. We acknowledge that a more detailed treatment of the M_{\star} build-up would require a correction for stellar mass losses (Leitner, & Kravtsov 2011), which would slightly lower our integrated M_{\star} , and consequently our M_{BH} , without affecting the overall trend. In fact, our main goal is to track the cosmic assembly of the $M_{\text{BH}}-M_{\star}$ slope and normalisation at various epochs, not to match the observed galaxy M_{\star} distribution at each redshift.

2.3. Setting BH growth

Each BH seed is assumed to gain mass via gas accretion (Soltan 1982) at a fixed radiative efficiency $\epsilon=0.1$ (e.g. Marconi et al. 2004). Because of a M_{\star} -dependent BHAR/SFR ratio, we translate the corresponding SFR into a *long-term average* BHAR, at each M_{\star} . Based on this formalism, we determine the cumulative accreted SMBH mass since $z=10$ as:

$$M_{\text{BH}}|_{z=0} = \int_{z=10}^{z=0} \text{BHAR}|_{M_{\star}(z')} \cdot \frac{dt'}{dz'} dz' + M_{\text{BH}}|_{z=10} \quad (1)$$

The corresponding Eddington ratio λ_{EDD} , at each M_{\star} (and redshift), is calculated as:

$$\lambda_{\text{EDD}}|_{M_{\star}(z')} = 4.41 \cdot 10^8 \cdot \frac{\epsilon}{1-\epsilon} \cdot \frac{\text{BHAR}|_{M_{\star}(z')}}{M_{\text{BH}}/M_{\odot}} \quad (2)$$

We iterate the above procedure down to $z=0$ with a redshift step of 0.1.

3. RESULTS

Exploring the cosmic build-up induced by a M_{\star} -dependent BHAR/SFR ratio is paramount for understanding whether the galaxy (halo) governs SMBH growth by setting the available amount of gas for fueling SF and BH accretion, or instead if early AGN feedback controls the amount of cold star-forming gas that fuels galaxy growth (Volonteri 2010).

Fig. 2 displays the evolution of one thousand M_{\star} and M_{BH} seeds (circles) since $z_f=10$, resulting from our empirical M_{\star} -dependent BHAR/SFR (D19). The colorbar indicates the seed M_{BH} distribution. For convenience, dot-dashed lines mark various M_{BH}/M_{\star} ratios. We track the evolution of M_{\star} and M_{BH} while propagating, at each time step, the dispersion of the MS relation and the uncertainty on the BHAR/SFR trend.

The positive BHAR/SFR relation with M_{\star} suggests that SMBH accretion and star formation do *not* proceed in lockstep at all cosmic epochs, whereas their build-up comes in two stages (Fig. 2).

Because of our M_{\star} -dependent BHAR/SFR trend, in small M_{\star} galaxies the BHAR is quite low relative to the SFR, therefore the SMBH lags behind the galaxy. As the galaxy steadily grows in M_{\star} , the BHAR is progressively enhanced relative to the SFR. In this regime, the BH grows super-linearly as $M_{\text{BH}} \propto M_{\star}^{1.7}$, setting along a gradually tighter $M_{\text{BH}}-M_{\star}$ locus towards higher M_{\star} . This is because two BHs with different M_{BH} but same galaxy M_{\star} have the same BHAR. Hence, while the *absolute* BH mass gained per unit time is the same, a smaller BH seed will increase its *relative* mass by a much larger factor than a bigger BH seed.

Therefore, the seed M_{\star} is the key quantity that *attracts* all seeds towards a super-linear slope, above a critical M_{\star} value (Fig. 2). Instead, the seed M_{BH} is the parameter that sets the corresponding M_{\star} threshold, increasing with seed M_{BH} , above which any prior BH seed dependence is lost.

For comparison, Fig. 2 reports predictions from cosmological simulations of a SB galaxy at $z\sim 6$ (Lupi et al. 2019, orange dot-dashed line), and of normal star-forming galaxies (Habouzit et al. 2017, magenta dotted line at $3 < z < 6$; Bower et al. 2017, cyan dot-dashed line at $z=0$). Lupi et al. (2019) used a cosmological simulation for studying the evolution of a quasar host-galaxy at $z\sim 6-7$, with seed $M_{\text{BH}}=10^6 M_{\odot}$ at $z\gtrsim 10$. Instead, the model of Habouzit et al. (2017) explores the early growth ($3 < z < 8$) of lighter BH seeds, with $M_{\text{BH}}=10^{2-3} M_{\odot}$. Finally, Bower et al. (2017) report the results from the EAGLE cosmological simulation (Schaye et al. 2015). All these models support strong Supernovae-driven winds in the early phases of galaxy growth, that evacuate the gas

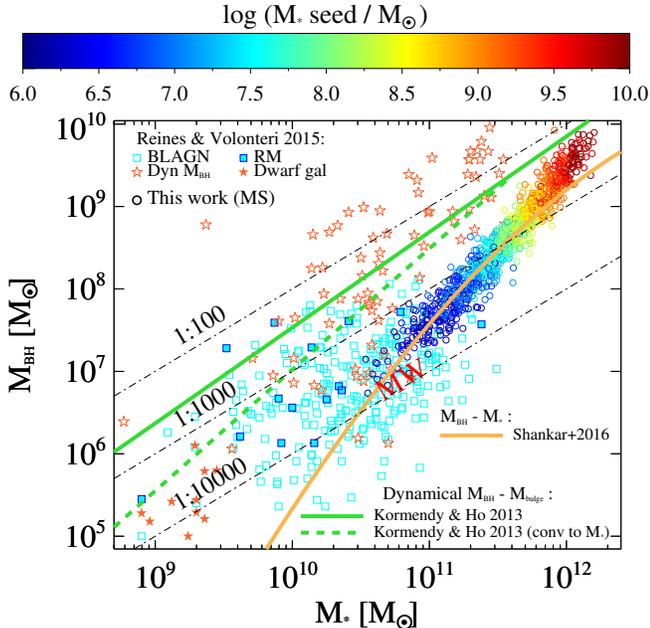


Figure 3. Final $M_{\text{BH}}-M_*$ relation at $z=0$ determined by our M_* -dependent BHAR/SFR. The colorbar indicates the seed M_* distribution at z_f . For comparison, we show the local relation from Kormendy & Ho (2013), both with M_{bulge} (green solid line) and converted to total M_* (green dashed line). Our MS wedge agrees remarkably well with the proposed de-biased $M_{\text{BH}}-M_*$ trend (Shankar et al. 2016, yellow solid line) and with the virial M_{BH} estimates for BLAGN (empty squares, Reines & Volonteri 2015). For completeness, we report $M_{\text{BH}}-M_*$ estimates collected from Reines & Volonteri (2015) for reverberation mapping AGN (RM, filled squares), dynamical M_{BH} measurements (empty stars) and dwarf galaxies (filled stars). The tag “MW” marks the mass measurements for the Milky Way.

around the central SMBH (Dubois et al. 2014), halting both BH and galaxy bulge growth. However, the rest of the galaxy keeps growing on the MS until it reaches a critical M_* , increasing with seed M_{BH} . At this stage, the galaxy potential well is deep enough to retain the ejected gas, and to drive it more effectively towards the center. The BH grows super-linearly with M_* matching the proposed de-biased $M_{\text{BH}}-M_*$ relation (Shankar et al. 2016, yellow solid line, see Fig. 3). This predicted scenario is qualitatively consistent with our empirical toy model predictions, as a natural consequence of a M_* -dependent BHAR/SFR ratio. A noteworthy difference is that the above cosmological simulations do not directly link the BHAR to the host’s properties, while our toy model assumes that BHAR depends exclusively on the galaxy’s star-forming content.

In Fig. 3 we further test our empirical predictions at $z=0$ against the local relation by Kormendy & Ho (2013), both with M_{bulge} (green solid line) and converted

to total M_* (green dashed line), by applying a M_* -dependent bulge-to-total (B/T) correction for local MS galaxies (Dimauro et al. 2018). Our MS wedge agrees remarkably well with the $M_{\text{BH}}-M_*$ of Shankar et al. (2016, yellow solid line), suggesting that our long-term averaged BHAR/SFR trend is able to recover the intrinsic $M_{\text{BH}}-M_*$ relation of MS galaxies. In addition, our trend fits very well the BLAGN sample of Reines & Volonteri (2015), who exploited 262 single-epoch M_{BH} estimates down to $\approx 10^5 M_\odot$, for which they computed the total galaxy M_* . This low-mass AGN sample contains moderate luminosity AGN ($10^{41.5} < L_{\text{AGN}} < 10^{44.4} \text{ erg s}^{-1}$), hence significantly more common than previous quasars samples. The authors found a $10\times$ lower normalisation than that inferred for dynamical $M_{\text{BH}}-M_{\text{bulge}}$ trends of inactive elliptical galaxies (Kormendy & Ho 2013), that we interpret in the next Section.

4. DISCUSSION AND SUMMARY

Our findings corroborate the idea that galaxies and their SMBHs do not grow in lockstep at all times. Cosmological simulations predict that the SMBH first starves until the galaxy reaches a critical M_* $\sim 10^9-10^{10} M_\odot$ (Bower et al. 2017; Habouzit et al. 2017; Lupi et al. 2019), corresponding to $M_{\text{DM}} \sim 10^{11-12} M_\odot$ (e.g. McAlpine et al. 2018). Later, they predict a super-linear BH growth towards $M_{\text{BH}}/M_* \gtrsim 10^{-3}$ at $M_* \gtrsim 10^{11} M_\odot$, in qualitative agreement with our findings.

The two-fold trend predicted also by our toy model can be better visualised in Fig. 4, which displays the cosmic evolution of M_{BH}/M_* (top panel), BHAR/SFR (middle panel) and λ_{EDD} (bottom panel) in MS galaxies (solid lines). Colors highlight representative cases with different seed masses. For completeness, we also show the extreme case of a continuous SB-like evolution (dashed lines), for which BH and galaxy growth proceed about $5\times$ faster than on the MS (Schreiber et al. 2015).

The typical M_{BH}/M_* ratio of MS galaxies (top panel) decreases from $z=10$ until $z\sim 2-3$, and then rises towards $z=0$. We note that smaller BH seeds increase their relative mass faster and earlier than bigger BH seeds, at fixed M_* . Above a certain critical M_* , increasing with seed M_{BH} , all seeds converge towards a similar (within a factor of two) M_{BH}/M_* ratio at $z=0$. The evolution of SB galaxies shows instead a minimum at higher redshifts, as they reach the critical M_* on about $5\times$ shorter timescales ($\propto M_*/\text{SFR}$) relative to MS analogs. For this reason, the BHAR/SFR ratio of SB galaxies appears systematically higher than for z -matched MS analogs (middle panel). We calculate the mean λ_{EDD} from Eq. 2 and display its evolution with redshift (bottom panel).

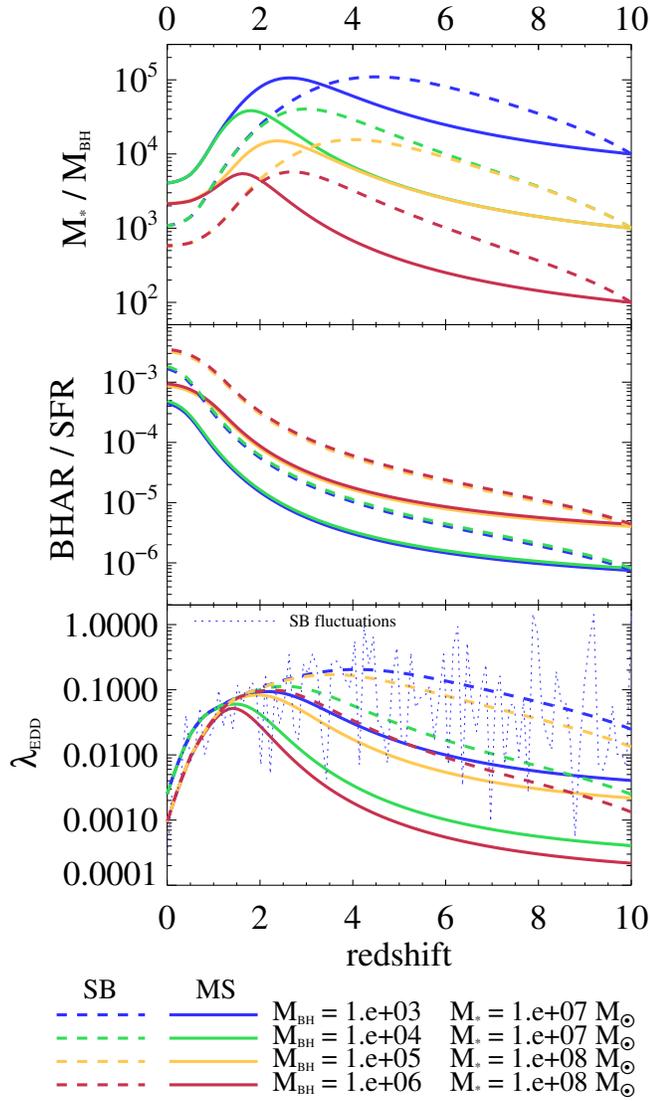


Figure 4. Redshift evolution of various SMBH- and galaxy-related parameters for four different seed masses (colored lines). The trends for MS and SB galaxies are highlighted with solid and dashed lines, respectively. Top panel: M_{BH}/M_* ratio. Middle panel: BHAR/SFR ratio. Bottom panel: Eddington ratio (λ_{EDD}). The blue dotted line marks the typical fluctuations in λ_{EDD} of a SB galaxy with seed (M_{BH}, M_*) = $(10^3, 10^7) M_\odot$ (blue dashed line) when propagating the dispersion of the MS relation and the scatter of the assumed BHAR/SFR trend.

In MS galaxies, the typical λ_{EDD} peaks at $1.5 < z < 2.5$, slightly increasing with decreasing M_{BH} seed. In comparison, SB galaxies reach a peak at higher redshifts ($2 < z < 4$). The blue dotted line indicates the typical fluctuations in λ_{EDD} of a SB galaxy with seed (M_{BH}, M_*) = $(10^3, 10^7) M_\odot$ (blue dashed line) when propagating the dispersion of the MS relation and the scatter of the assumed BHAR/SFR trend. The amplitude of such fluctuations (similar also for the other mass seeds) suggests

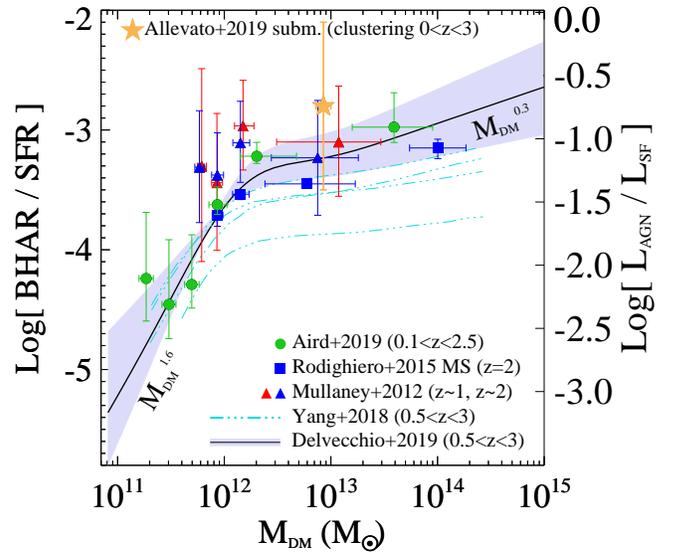


Figure 5. Compilation of various BHAR/SFR trends with M_{DM} , after applying the M_*-M_{DM} conversion for star-forming galaxies (Behroozi et al. 2019) at $z=1$. Symbols are the same shown in Fig. 1. The right y-axis shows the equivalent AGN-to-galaxy bolometric output $L_{\text{AGN}}/L_{\text{SF}}$. The clear twofold trend suggests that M_{DM} might be crucial for explaining the non-linear SMBH growth.

that SMBH accretion can vary over several orders of magnitude within the uncertainties, and it may occasionally reach Eddington-limited accretion in starbursting galaxies, consistently with high-redshift model predictions (e.g. Lupi et al. 2019).

The fact that BHAR is enhanced relative to SFR in the most massive galaxies might be also linked to the increasing compactness observed in star-forming galaxies towards higher M_* ($M_* \propto R^{0.4}$, van der Wel et al. 2014). Indeed, a higher compactness might enhance the galaxy ability to retain cold gas re-injected from stellar/AGN feedback, and eventually drive it within the BH sphere of influence.

In addition, environmental mechanisms linked to M_{DM} might help replenish and sustain BH-galaxy growth via inflows of pristine cold gas, predicted to be more effective in massive halos (Dekel et al. 2009). To test this, we adopt the M_* -dependent M_{DM}/M_* ratio for star-forming galaxies from Behroozi et al. (2019) at $z=1$ ¹, and display the BHAR/SFR trend with M_{DM} in Fig. 5. The non-linear M_*-M_{DM} conversion generates a strikingly twofold behavior that nicely resembles our empirical twofold BH-galaxy growth. In small DM halos Supernovae-driven feedback suppresses BH growth

¹ Taking the conversion at a different intermediate redshift would not affect our conclusions.

($\text{BHAR}/\text{SFR} \propto M_{\text{DM}}^{1.6}$) out to $M_{\text{DM}} \sim 2 \times 10^{12} M_{\odot}$, where baryons are most efficiently converted into stars. Above the turnover M_{DM} , AGN activity (exerting both positive and negative feedback) and cold gas inflows might enhance both BH accretion and galaxy star formation. At $M_{\text{DM}} \gtrsim 10^{13} M_{\odot}$ the BHAR/SFR ratio flattens out ($\text{BHAR}/\text{SFR} \propto M_{\text{DM}}^{0.3}$), possibly due to shock-heated gas within the DM halo (Dekel et al. 2009). We find a good agreement with the average BHAR/SFR and M_{DM} measurements obtained from clustering of X-ray AGN at $0 < z < 3$ (Allevato et al. submitted, yellow star). Therefore, we speculate that M_{DM} might be the leading physical driver of the observed non-linear BH-galaxy growth.

In Fig. 5 we link the BHAR/SFR ratio to the AGN-to-galaxy bolometric output ($L_{\text{AGN}}/L_{\text{SF}}$, right y-axis), assuming that BH accretion occurs with $\epsilon=0.1$. Instead, the galaxy bolometric power arising from star formation (L_{SF}) is calculated by converting the (obscured) SFR into rest-frame 8–1000 μm luminosity, via a (Kennicutt 1998) scaling factor. While L_{AGN} is always sub-dominant relative to L_{SF} , their ratio increases and displays a turnover in M_{DM} at $L_{\text{AGN}}/L_{\text{SF}} \approx 10\%$, above which it slowly approaches energy equipartition. Adding some contribution from unobscured star formation, particularly towards low M_{\star} , would strengthen the resulting trends. We also note that assuming L_{X} -dependent bolometric corrections for deriving the BHAR (e.g. Lusso et al. 2012) would further steepen the resulting BHAR/SFR trend with M_{\star} , amplifying the twofold behavior with M_{DM} .

We acknowledge that our toy model is not able to reproduce BHs as massive as $10^9\text{--}10^{10} M_{\odot}$ already at $z \sim 6$ (e.g. Mortlock et al. 2011), even in the unlikely scenario of continuous SB-like evolution since $z=10$. Indeed, our toy model would form BHs with $M_{\text{BH}} \lesssim 10^8 M_{\odot}$ at $z=6$, but the galaxy would overgrow in M_{\star} if extrapolating down to $z=0$ (Renzini 2009). As for local dynamical M_{BH} measurements, we believe that also high-redshift observations are likely biased towards the brightest AGN and most massive BHs that swamp the host-galaxy light, a critical condition to ensure reliable M_{BH} estimates. Therefore, we argue that such quasars at $z \sim 6$, if their M_{BH} are not overestimated (but see Mejía-Restrepo et al. 2018), must have grown at a BHAR/SFR ratio about $10\times$ higher than that assumed in this work. If such a notable ratio was followed by the overall AGN population at $z \sim 6$, we would severely overestimate the observed XLF (D19) and the declining BHAR density constrained by deep X-ray data at $z > 3$ (Vito et al. 2018). This leads us to believe that the most massive quasars at $z \sim 6$ followed very peculiar and uncommon evolutionary paths.

At $z=0$, Fig. 3 shows that our toy model agrees well with proposed de-biased $M_{\text{BH}}\text{--}M_{\star}$ relations (Shankar et al. 2016) and representative local AGN samples (Reines & Volonteri 2015). Nevertheless, we note a significant ($>10\times$) discrepancy at $M_{\star} \lesssim 10^{11} M_{\odot}$ relative to empirical $M_{\text{BH}}\text{--}M_{\text{bulge}}$ relations based on dynamical M_{BH} measurements (Kormendy & Ho 2013). This apparent conflict might arise from multiple reasons: (i) The local $M_{\text{BH}}\text{--}M_{\text{bulge}}$ relation is likely biased towards the largest BHs hosted within massive quiescent systems, for which the BH sphere of influence can be spatially resolved (Gültekin et al. 2009; Shankar et al. 2016, 2019). This biases the intrinsic $M_{\text{BH}}\text{--}M_{\text{bulge}}$ relation towards a flatter slope and higher normalization (Volonteri & Stark 2011). (ii) While in the most massive galaxies $M_{\text{bulge}} \approx M_{\star}$, at $M_{\star}=10^{10} M_{\odot}$ the B/T decreases to ≈ 0.3 for local MS galaxies (Dimauro et al. 2018). This behavior causes a M_{\star} -dependent steepening of the $M_{\text{BH}}\text{--}M_{\text{bulge}}$ relation (green dashed line in Fig. 3), though not crucial for reconciling the observed difference. (iii) A significant fraction of SMBH accretion might be heavily obscured, thus inaccessible via X-ray observations. However, this elusive contribution might boost the average BHAR by at most factor of $\lesssim 2$, thus not filling the observed gap at low M_{\star} (Comastri et al. 2015). (iv) The average radiative efficiency might be much lower than $\epsilon=0.1$ (possibly M_{\star} dependent). As a consequence, the corresponding mass accreted by SMBHs at fixed luminosity would be higher. However, the lowest theoretically-expected value of $\epsilon=0.06$ (Novikov & Thorne 1973) proves still insufficient to justify the observed discrepancy. Therefore, we favor the combination of points (i) and (ii) as possible reasons to explain the conflicting $M_{\text{BH}}\text{--}M_{\star}$ trends at $z=0$.

Concluding, the proposed empirically-motivated BHAR/SFR trend with M_{\star} (D19) enables us to describe the cosmic SMBH-galaxy assembly in normal SF galaxies, in agreement with high- z cosmological simulations and intrinsic $M_{\text{BH}}\text{--}M_{\star}$ relations at $z=0$. Our study suggests that the DM halo mass primarily regulates the amount of cold gas available for triggering and sustaining the cosmic non-linear BH-galaxy growth.

We thank the anonymous referee for a quick and constructive report. We are grateful to Paola Dimauro for sharing the median bulge-to-total ratio of MS galaxies, and Viola Allevato for sharing the clustering-based BHAR/SFR. ID is supported by the European Union’s Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement No 788679. FS acknowledges partial support from a

Leverhulme Trust Fellowship. AC acknowledges the support from grants PRIN MIUR 2015 and 2017.

REFERENCES

- Aird, J., Coil, A. L., Moustakas, J., et al. 2012, *ApJ*, 746, 90
- Aird, J., Alexander, D. M., Ballantyne, D. R., et al. 2015, *ApJ*, 815, 66
- Aird, J., Coil, A. L., & Georgakakis, A. 2019, *MNRAS*, 484, 4360
- Bañados, E., Venemans, B. P., Mazzucchelli, C., et al. 2018, *Nature*, 553, 473
- Begelman, M. C., & Rees, M. J. 1978, *MNRAS*, 185, 847
- Behroozi, P. S., Wechsler, R. H., & Conroy, C. 2013, *ApJ*, 770, 57
- Behroozi, P., Wechsler, R. H., Hearin, A. P., et al. 2019, *MNRAS*, 488, 3143
- Bower, R. G., Schaye, J., Frenk, C. S., et al. 2017, *MNRAS*, 465, 32
- Chabrier, G. 2003, *ApJL*, 586, L133
- Comastri, A., Gilli, R., Marconi, A., Risaliti, G., & Salvati, M. 2015, *A&A*, 574, L10
- Dekel, A., Birnboim, Y., Engel, G., et al. 2009, *Nature*, 457, 451
- Delvecchio et al., to be submitted, 2019, *ApJ*
- Dimauro, P., Huertas-Company, M., Daddi, E., et al. 2018, *MNRAS*, 478, 5410
- Dubois, Y., Volonteri, M., & Silk, J. 2014, *MNRAS*, 440, 1590
- Ferrarese, L., & Merritt, D. 2000, *ApJL*, 539, L9
- Gebhardt, K., Bender, R., Bower, G., et al. 2000, *ApJL*, 539, L13
- Gültekin, K., Richstone, D. O., Gebhardt, K., et al. 2009, *ApJ*, 698, 198
- Habouzit, M., Volonteri, M., & Dubois, Y. 2017, *MNRAS*, 468, 3935
- Håring, N., & Rix, H.-W. 2004, *ApJL*, 604, L89
- Kennicutt, R. C., Jr. 1998, *ApJ*, 498, 541
- Kormendy, J., & Ho, L. C. 2013, *ARA&A*, 51, 511
- Leitner, S. N., & Kravtsov, A. V. 2011, *ApJ*, 734, 48
- Lupi, A., Volonteri, M., Decarli, R., et al. 2019, *MNRAS*, 488, 4004
- Lusso, E., Comastri, A., Simmons, B. D., et al. 2012, *MNRAS*, 425, 623
- Magorrian, J., Tremaine, S., Richstone, D., et al. 1998, *AJ*, 115, 2285
- Marconi, A., Risaliti, G., Gilli, R., et al. 2004, *MNRAS*, 351, 169
- McAlpine, S., Bower, R. G., Rosario, D. J., et al. 2018, *MNRAS*, 481, 3118
- Mejía-Restrepo, J. E., Lira, P., Netzer, H., et al. 2018, *Nature Astronomy*, 2, 63
- Merloni, A., Bongiorno, A., Bolzonella, M., et al. 2010, *ApJ*, 708, 137
- Mortlock, D. J., Warren, S. J., Venemans, B. P., et al. 2011, *Nature*, 474, 616
- Mullaney, J. R., Daddi, E., Béthermin, M., et al. 2012, *ApJL*, 753, L30
- Netzer, H., Mor, R., Trakhtenbrot, B., Shemmer, O., & Lira, P. 2014, *ApJ*, 791, 34
- Novikov, I. D., & Thorne, K. S. 1973, *Black Holes (Les Astres Occlus)*, 343
- Reines, A. E., & Volonteri, M. 2015, *ApJ*, 813, 82
- Renzini, A. 2009, *MNRAS*, 398, L58
- Rodighiero, G., Daddi, E., Baronchelli, I., et al. 2011, *ApJL*, 739, L40
- Rodighiero, G., Brusa, M., Daddi, E., et al. 2015, *ApJL*, 800, L10
- Soltan, A. 1982, *MNRAS*, 200, 115
- Schaye, J., Crain, R. A., Bower, R. G., et al. 2015, *MNRAS*, 446, 521
- Schreiber, C., Pannella, M., Elbaz, D., et al. 2015, *A&A*, 575, A74
- Shankar, F., Bernardi, M., Sheth, R. K., et al. 2016, *MNRAS*, 460, 3119
- Shankar, F., Bernardi, M., Richardson, K., et al. 2019, *MNRAS*, 485, 1278
- van der Wel, A., Franx, M., van Dokkum, P. G., et al. 2014, *ApJ*, 788, 28
- Vito, F., Brandt, W. N., Yang, G., et al. 2018, *MNRAS*, 473, 2378
- Vito, F., Brandt, W. N., Bauer, F. E., et al. 2019, *A&A*, 628, L6
- Volonteri, M. 2010, *A&A Rv*, 18, 279
- Volonteri, M., & Stark, D. P. 2011, *MNRAS*, 417, 2085
- Wang, F., Wu, X.-B., Fan, X., et al. 2015, *ApJL*, 807, L9
- Wu, X.-B., Wang, F., Fan, X., et al. 2015, *Nature*, 518, 512
- Yang, G., Brandt, W. N., Vito, F., et al. 2018, *MNRAS*, 475, 1887