

The relation between black hole spin, star formation rate, and black hole mass for supermassive black holes

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ABSTRACT

Both theoretical models and observational evidence indicate that jets and/or outflows driven by central active supermassive black holes exert a significant feedback effect on the overall properties of their host galaxies. Theoretical models suggest that the spin of supermassive black holes drives relativistic jets. Therefore, we investigate the relationship between black hole spin, star formation rate, and black hole mass using a sample of 48 low-redshift supermassive black holes. By performing multiband fitting of spectral energy distribution, we derive the star formation rates and stellar masses of the host galaxies harbouring these supermassive black holes. Our main results are as follows: (i) For black holes with masses $M_{\text{BH}} \lesssim 10^{6.5} M_{\odot}$, the spin increases with increasing black hole mass, suggesting that black hole growth is primarily driven by gas accretion, particularly in the coherent gas accretion regime. Conversely, for black holes with masses $M_{\text{BH}} \gtrsim 10^{7.5} M_{\odot}$, the spin decreases with increasing black hole mass, indicating that growth occurs mainly through mergers, inducing chaotic accretion. (ii) At low star formation rates, black hole spin increases with increasing star formation rates, consistent with gas accretion. However, at high star formation rates, black hole spin decreases with increasing star formation rates, suggesting black hole mergers. The value of the black hole spin may be used to diagnose the star formation rate of the host galaxies through active galactic nuclei activities. (iii) Our data and analysis confirm the well-known relation between stellar mass and black hole mass, with the fitting function $\log M_{\text{BH}} = 0.57 \log M_{*} + 1.94$.

Key words. galaxies: active – galaxies: general – galaxies: star formation

1. Introduction

It is widely accepted that galaxies possess a supermassive black hole at their centre (e.g. Kormendy & Richstone 1995; Magorrian et al. 1998; Gebhardt et al. 2000; Ferrarese & Merritt 2000; Tremaine et al. 2002; Marconi & Hunt 2003; Di Matteo et al. 2003a,b; Häring & Rix 2004; Ho 2008; Di Matteo et al. 2008; Gültekin et al. 2009; Greene et al. 2010; Alexander & Hickox 2012; Kormendy & Ho 2013; Heckman & Best 2014). The origin of these supermassive black holes has remained unclear; however, it seems relatively certain that the majority of black hole growth takes place through gas accretion (Soltan 1982). The accretion process is accompanied by a significant release of energy, which is most notable in the emission of powerful quasars (Lynden-Bell 1969).

One of the significant enigmas regarding galaxy formation and evolution is the coevolution of supermassive black holes and host galaxies. The relatively close connection between the properties of the galaxy and the mass of the central supermassive black hole (e.g. Kormendy et al. 2001; Marconi & Hunt 2003; Ferrarese et al. 2006; Kormendy & Ho 2013; Heckman & Best 2014) suggests that the black hole is not just a bystander to the formation process of the galaxy (e.g. Di Matteo et al. 2000, 2001, 2003a,b, 2004, 2005, 2008, 2012), but affects it

in a decisive way (Bustamante & Springel 2019). This perspective has facilitated the incorporation of black hole evolution and feedback mechanisms into modern theories of galaxy formation (Kauffmann & Haehnelt 2000; Bustamante & Springel 2019). There are two main ways in which active galactic nuclei (AGN) feedback can impact its host galaxy. The outflow of AGN can enhance star formation (positive feedback) by compressing molecular clouds and/or interstellar medium (ISM) (e.g. Croft et al. 2006; Rodríguez Zaurín et al. 2007; Feain et al. 2007; Elbaz et al. 2009; Imanishi et al. 2011; Crockett et al. 2012; Ishibashi & Fabian 2012; Zinn et al. 2013; Schaye et al. 2015; Schutte & Reines 2022; Venturi et al. 2023). Conversely, AGN can suppress star formation (negative feedback) through mechanical energy from wind, outflow, or jets, thereby heating the surrounding ISM and preventing molecular gas from radiatively cooling, or expelling gas from the host galaxy due to AGN-driven outflow (e.g. Cresci et al. 2015; Cano-Díaz et al. 2012; Carniani et al. 2016; Bischetti et al. 2022; Chen et al. 2022; Lammers et al. 2023). Many simulation models explain the quenching transition of galaxies from star-forming blue clouds to the red sequence of elliptical galaxies due to black hole feedback (Di Matteo et al. 2005; Springel et al. 2005; Hopkins et al. 2006; Sijacki et al. 2007; Croton et al. 2006; Dubois et al. 2013; Silk 2013; Dubois et al. 2016; DeGraf et al. 2015; Hopkins et al. 2016). Subsequently, some

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numerical simulations discovered that AGN triggers star formation (Santini et al. 2012; Gaibler et al. 2012; Ishibashi & Fabian 2012; Liu et al. 2013; Zubovas et al. 2013), which implies positive feedback. Therefore, supermassive black holes are a key element in any modern theory of galaxy formation and evolution (Bustamante & Springel 2019).

Some observations have demonstrated that the interaction between the radio jets and ISM of the host galaxy can also be accountable for large outflows (e.g. Emonts et al. 2005; Morganti et al. 2007, 2013a,b; Tadhunter et al. 2014; Mahony et al. 2016), and jet-driven outflows can exert a relevant role in feedback mechanisms. The theoretical model of jet formation indicates that the jet extracts rotational energy from the black hole and the jet power (P_{jet}) depends on the spin of the black hole (a) (Blandford & Znajek 1977; MacDonald & Thorne 1982; Thorne et al. 1986; Ghisellini 2006), which implies that the spin of a black hole plays a crucial role in determining relativistic jets (Livio et al. 1999; Meier 2002; Koide et al. 2002; Garofalo et al. 2010; Tchekhovskoy et al. 2012). The black hole spin parameter ($0 \leq |a| \leq 1$) is $|a| = J_{\text{BH}}c/GM_{\text{BH}}^2$, where M_{BH} represents the black hole mass, G is the gravitational constant, and c is the vacuum speed of light. Observational evidence for the spin-enhanced jets has been reported for stellar mass black holes in X-ray binaries (Narayan & McClintock 2012; Steiner et al. 2013). Numerical simulations have also suggested that relativistic jets rely on the spin of black holes (e.g. Tanabe & Nagataki 2008; McKinney 2005). Recently, Cui et al. (2023) have discovered the precessing jet nozzle connecting to a spinning black hole in M87. Ünal & Loeb (2020) propose that the activity of a black hole depends on its spin. These aforementioned results indicate that the spin of a black hole can serve as a good indicator of the activity of a black hole. Thus, we investigated the relation between black hole spin and star formation.

In this article, we discuss how we primarily employed multi-band fitting to acquire the stellar mass and star formation rate of the host galaxy of AGN and subsequently investigated the relationship between black hole spin, star formation rate, and black hole mass. The second section delineates the sample we used, the third section presents our results and discussion, and the fourth sections provides our conclusion.

2. The sample

2.1. The sample of supermassive black holes

We collected a large sample of 48 low-redshift supermassive black holes with the spin of the black hole to study the relationship between black hole spin, star formation rate, and black hole mass. The redshift range of these supermassive black holes spans from 0.002 to 1.70. The redshift of the farthest supermassive black hole is 1.695. Hence, these supermassive black holes constituted a very local sample. We mainly focused on the sample from Reynolds (2021). The spin of the supermassive black hole was measured through X-ray reflection spectroscopy (e.g. Gallo et al. 2011; Walton et al. 2013; Risaliti et al. 2013; Lohfink et al. 2013; Brenneman 2013; Reis et al. 2014; Keck et al. 2015; Parker et al. 2018; Sun et al. 2018; Buisson et al. 2018; Walton et al. 2019; Jiang et al. 2019; Walton et al. 2020). The systematic uncertainties in X-ray reflection-based spin measurements are the uncertainties of spectral models. There are two distinct aspects to this. Firstly, the structure of the accretion disk was approximated and assumed when modelling the X-ray reflection spectrum. The second

and more serious issue is whether we correctly attributed the observed spectral structure to inner disk reflections. Despite these uncertainties, black hole spin measurements using the X-ray reflection technique show statistical robustness (Reynolds 2021). We also note that approximately 75% of the sources in our sample have relatively high black hole spins, $a \geq 0.8$. It is unlikely that the relativistic reflection method is biased towards measuring high black hole spin, as the spectral shape produced by low spin is less blurry and thus easier to distinguish from the underlying continuum (Draghis et al. 2023). Additionally, low and moderate spins are still detected by some authors (Wang et al. 2018; Draghis et al. 2021; Jana et al. 2021; Jia et al. 2022). However, one cannot exclude the possibility that there is an observational bias, which makes highly spinning black holes easier to detect. Vasudevan et al. (2016) explain that the black hole spin distribution measured in AGN is biased towards high values due to the selection effect of flux-limited observations (Brenneman et al. 2011). The black hole mass has been measured (e.g. Peterson et al. 2004; Walton et al. 2019; Bentz et al. 2006; Jiang et al. 2019; Parker et al. 2018; Nikołajuk et al. 2009; Walton et al. 2020; Sluse et al. 2012). The mass of black holes is mainly estimated by using the virial method. The uncertainty of black hole mass is approximately 0.5 dex (e.g. Gebhardt et al. 2000; Ferrarese et al. 2001; Peterson et al. 2004). We obtain the star formation rate and stellar mass of the host galaxy of a supermassive black hole by fitting multiband spectral energy distribution (SED) data. The sample is shown in Table A.1 of Appendix A.

2.2. The stellar masses and star formation rates of AGN host galaxies

We derived the stellar masses and star formation rates of the host galaxies by using version 2022.0 of the SED-fitting code CIGALE (Burgarella et al. 2005; Noll et al. 2009; Boquien et al. 2019). We adopted the optical photometry data from Pan-STARRS1-DR1 Surveys (Chambers et al. 2016; Magnier et al. 2020). The IR data were obtained from the Two Micron All Sky Survey (2MASS) (Skrutskie et al. 2006) and Wide-field Infrared Survey Explorer (WISE) (Wright et al. 2010). The far-infrared photometric data from IRAS (60 and 100 μm) were referred to in Beichman et al. (1988). As a result, we compiled a total of 14 photometric data ($g, r, i, z, y_{\text{P1}}, J, H,$ and K/K_s ; as well as at 3.4, 4.6, 12, 22, 60, and 100 μm) for the SED fitting. In our work, we utilized the templates of galaxy plus AGN to fit the SEDs of our sample. The template for galaxies consists of four modules, including star formation history (SFH), single stellar population model (Bruzual & Charlot 2003), dust attenuation (Calzetti et al. 2000), and dust emission (Draine & Li 2007; Dale et al. 2014). The module employed for the component of AGNs was Fritz et al. (2006). All these modules are included in CIGALE. We defined the CIGALE grid of model galaxy SEDs using the parameters and values given in Table 1. CIGALE identifies the best-fit SED model by minimizing the χ^2 statistic. We present examples of the best SED fitting in Figure 1. We also note that the star formation rate estimated by the SED fitting is more dependent on the star formation history model. Therefore, we used the calibration from Kennicutt (1998) to estimate the star formation rate by the IR luminosities. The IR luminosity of the host was calculated by integrating the host galaxy far-IR SED subcomponent corresponding to the cold dust emission. The star formation rate was calculated by using the formula established by Xie et al. (2021), renormalized to a Chabrier (2003) initial mass function (IMF):

Table 1. CIGALE grid parameter values adopted for the modelling described.

Parameter	Values	Description
Star formation history (SFH): Delayed		
τ_{main}	5–8000 (in steps of 10)	e-folding time of the main stellar population model (Myr).
Age	200–13 260 (in steps of 10)	Age of the oldest stars in the galaxy (Myr).
Single-age stellar population (SSP): Bruzual & Charlot (2003)		
imf	1	Initial mass function Chabrier (2003)
Metallicity	0.02	solar
Separation Age	10	Age of the separation (to differentiate) between the young and the old star populations (Myr).
Dust attenuation: Calzetti et al. (2000)		
$E(B - V)_{\text{young}}$	0.015, 0.02, 0.04, 0.06, 0.1, 0.2, 0.3, 0.9, 1.0	Color excess of the stellar continuum light for the young population.
Dust emission: dl2014		
Q_{pah}	1.12, 1.77, 2.50, 3.19	Mass fraction of PAH
U_{min}	5.0, 6.0, 7.0, 8.0, 10.0, 12.0, 15.0, 17.0, 20.0, 25.0	Minimum radiation field
A_{lpha}	2.0, 2.1, 2.2, 2.3, 2.4, 2.5, 2.6, 2.7, 2.8	the power-law distribution ($dM_{\text{d}} \propto U^{-\alpha} dU$)
Gamma	0.02	Fraction illuminated from U_{min} to U_{max}
AGN model: Fritz et al. (2006)		
$R_{\text{max}}/R_{\text{min}}$	30.0, 60.0, 100.0, 150.0	Ratio of the maximum to minimum radii of the dust torus.
τ	0.3, 0.6, 1.0, 2.0, 3.0, 6.0, 10.0	Optical depth at 9.7 μm .
β	-1.00, -0.75, -0.50, -0.25, 0.00	Beta from the power-law density distribution for the radial component of the dust torus (Eq. (3) of Fritz 2006).
γ	0.0, 2.0, 4.0, 6.0	Gamma from the power-law density distribution for the polar component of the dust torus (Eq. (3) of Fritz et al. 2006).
Opening angle (θ)	60.0, 100.0, 140.0	Full opening angle of the dust torus (Fig. 1 of Fritz et al. 2006).
ψ	0.001, 10.1, 20.1, 30.1, 70.1, 89.990	Angle between equatorial axis and line of sight.
f_{AGN}	0.0, 0.05, 0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4, 0.45, 0.5, 0.55, 0.6, 0.65, 0.7, 0.75, 0.8, 0.85, 0.9, 0.95, 0.99	Fraction of AGN torus contribution to the IR luminosity (fracAGN in Eq. (1) of Ciesla et al. 2015)

$$\text{SFR} (M_{\odot} \text{ yr}^{-1}) = 4.5 \times 10^{-44} L_{\text{IR}} (\text{erg s}^{-1}), \quad (1)$$

where L_{IR} is the 8–1000 μm rest-frame IR luminosity. Some authors have also derived the star formation rate by using the relation from [Kennicutt \(1998\)](#) for different IMF (e.g. [Molina et al. 2023](#); [Suh et al. 2019](#)), such as [Kroupa \(2001\)](#) and [Chabrier \(2003\)](#) IMFs. The differences in star formation rates that are obtained using different IMFs are minimal, typically not exceeding an order of magnitude. Following [Xie et al. \(2021\)](#), we also used Equation (1) to calculate the star formation rate of the AGN host galaxy, because the [Chabrier \(2003\)](#) IMF was assumed when fitting the SED for our sample. [Xie et al. \(2021\)](#) find that the true uncertainties in L_{IR} are approximately ~ 0.2 – 0.3 dex. Thereafter, we assumed this scatter value as the 1σ error of our star formation rate estimates.

3. Results and discussions

3.1. Relation between black hole mass and black hole spin

Constraining the primary growth mechanisms of supermassive black holes remains one of the most actively debated topics

in cosmological structure formation. Given the anticipated relationship between the evolution of supermassive black hole spin parameters and the accretion and merger histories of individual black holes ([Shakura & Sunyaev 1976](#); [Berti & Volonteri 2008](#); [Barausse 2012](#)), black hole spin may offer valuable insights into the cosmic growth of supermassive black holes.

To facilitate a more comprehensive comparison between the observed data and the black hole spin evolution model that [Bustamante & Springel \(2019\)](#) propose, we incorporated additional samples from [Mallick et al. \(2022\)](#) and [Soares & Nemmen \(2020\)](#). Specifically, the dataset from [Mallick et al. \(2022\)](#) contributed information on the spin of a low-mass black hole, while the sample from [Soares & Nemmen \(2020\)](#) pertains to the spin of a massive black hole. We also note that the black hole spin that [Soares & Nemmen \(2020\)](#) report is not directly measured via the X-ray reflection method; instead, it is inferred based on jet production efficiency. Due to the absence of multi-band data, such as far-infrared observations, for the samples from [Mallick et al. \(2022\)](#) and [Soares & Nemmen \(2020\)](#), we did not fit multiband data to obtain star formation rates and stellar masses. Figure 2 shows the relation between black hole spin and black hole mass for our sample. The observed data is similar

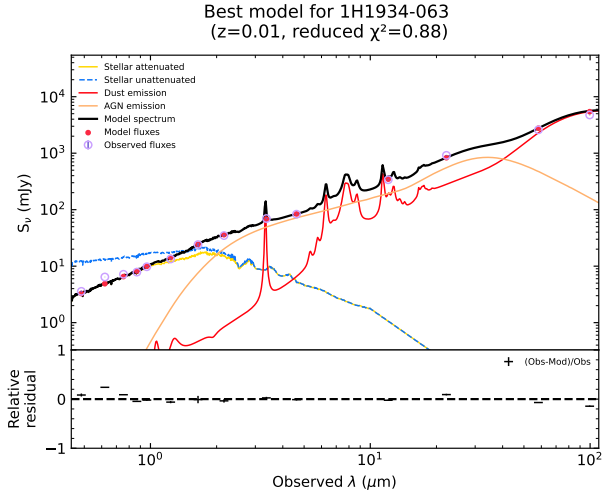


Fig. 1. Example of CIGALE SED fitting for our sample. The black line indicates the best-fitting model. The blue, orange, red, and yellow lines represent unattenuated stellar, attenuated stellar, dust, and AGN emission, respectively. The lower panel indicates the residual of the best fitting.

to the black hole spin evolution model of [Bustamante & Springel \(2019\)](#). For black holes with masses less than $10^{6.5} M_{\odot}$, the spin of a black hole increases with the mass of the black hole, which implies that the primary mechanism driving black hole growth in this mass range is gas accretion. This is consistent with the spin evolution model of [Bustamante & Springel \(2019\)](#), [Dubois et al. \(2021\)](#), and [Sala et al. \(2024\)](#). In the beginning, the spin evolution of a black hole mainly depends on the black hole mass, no matter how fast the mass accretes. The spin of a low-mass black hole can be reoriented during an accretion episode, making counterrotating accretion highly improbable and leading to continuous spin-up ([Bustamante & Springel 2019](#)). Conversely, for black holes exceeding $10^{7.5} M_{\odot}$, the spin tends to decrease to intermediate levels. This phenomenon is attributed to black hole mergers and the transition into the self-gravity regime, where the frequency of counterrotating accretion episodes is governed by the concentration parameter ([Bustamante & Springel 2019](#)). [Pacucci & Loeb \(2020\)](#) adopt a theoretical framework to assess the relative contributions of accretion and mergers to black hole growth across different mass scales and redshifts. Their findings indicate that, for black holes with masses greater than $10^{8.0} M_{\odot}$, mergers become the dominant growth mechanism, resulting in a decline in black hole spin. At this mass threshold, kinetic feedback mechanisms become significant and black hole coalescence emerges as the most efficient channel for spin evolution, surpassing the thermal quasar mode, which restricts gas accretion ([Weinberger et al. 2017](#)). We also find that the black hole spin tends to have very high values for intermediate black hole mass, but decreases for more massive black holes. Our results are also consistent with previous numerical studies of spin evolution in a cosmological context (e.g. [Dubois et al. 2021](#); [Sala et al. 2024](#)) and observational trends (e.g. [Reynolds 2021](#); [Mallick et al. 2022](#)). According to [Volonteri et al. \(2005\)](#), high spins in low-mass supermassive black hole systems suggest that these systems primarily grow through coherent accretion events. In contrast, more massive supermassive black holes ($M_{\text{BH}} > 3 \times 10^7 M_{\odot}$) with modest spins imply that their growth is predominantly driven by supermassive black holes merging. The mass dependence of black hole spins can be also seen in semianalytical models (e.g. [Berti & Volonteri](#)

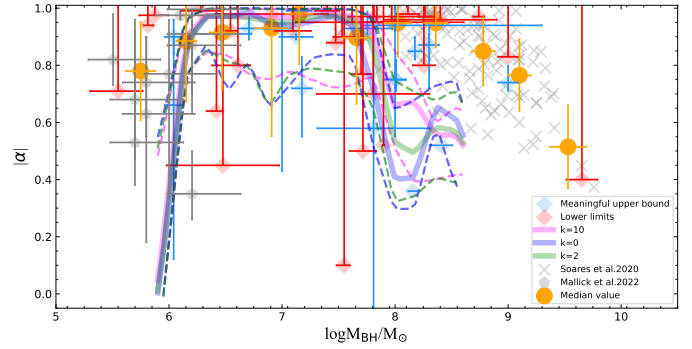


Fig. 2. Relation between black hole spin and black hole mass for a supermassive black hole. The red diamonds are the lower limits and the blue diamonds are measurements that include a meaningful upper bound. The error bars in mass are the 1σ errors from Table 1; where that was not available, we assumed a 0.5 dex ([Reines & Volonteri 2015](#); [Koss et al. 2022](#); [Reynolds 2021](#)). The solid lines are the black hole spin evolution model of [Bustamante & Springel \(2019\)](#). The dashed lines represent 25 and 75% percentiles. For completely chaotic accretion ($k = 0$), the black hole spin no longer follows the angular momentum of the gas. For a very coherent accretion ($k = 10$), the black hole behaves similarly to during the coherent regime. Medium concentrations (e.g. $k = 2$) produce a slightly intermediate behaviour, where the black hole is fairly aligned with the angular momentum of the gas, but occasionally counterrotating accretion episodes still occur. The grey pentagons are observations from [Mallick et al. \(2022\)](#) and the grey crosses are from [Soares & Nemmen \(2020\)](#). The orange circles are the median values of black hole spin in each bin.

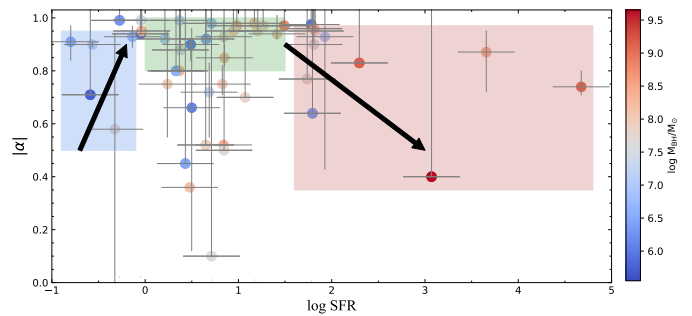


Fig. 3. Relation between the spin of the black hole and star formation rate for a supermassive black hole. All spin measurements reported here are from the X-ray reflection method. The colourbar indicates the black hole mass. The shaded areas represent low star formation rates, medium star formation rates, and high star formation rates, respectively.

[2008](#); [Fanidakis et al. 2011](#); [Barausse 2012](#); [Dotti et al. 2013](#); [Volonteri et al. 2013](#); [Griffin et al. 2019](#); [Izquierdo-Villalba et al. 2020](#); [Sesana et al. 2014](#); [Zhang & Lu 2019](#)) and hydrodynamical simulations of galaxy formation (e.g. [Dubois et al. 2014](#); [Beckmann et al. 2024](#); [Peirani et al. 2024](#)).

3.2. Relation between star formation rate and black hole spin

Figure 3 shows the relationship between the star formation rate and the spin of supermassive black holes. From Figure 3, we find that the star formation rate increases with the increase of the spin of a black hole for the sources with low star formation rates ($\log \text{SFR} < 0 M_{\odot} \text{ yr}^{-1}$). The possible explanation for the sources with low star formation rates is gas accretion. The sources with low star formation rates tend to have low black hole mass. According to Figure 2, we find that the

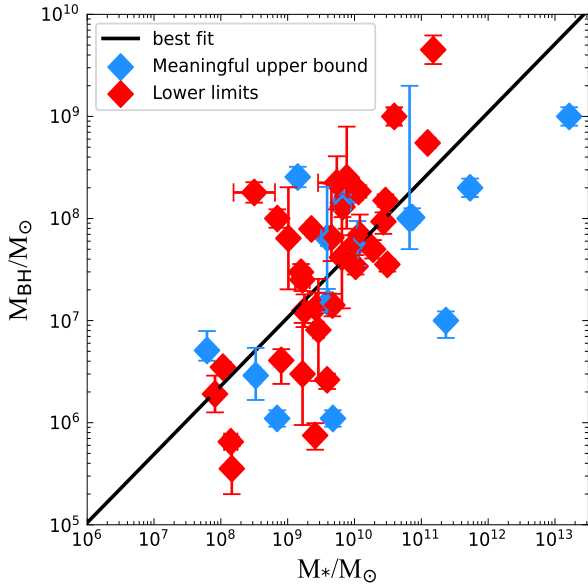


Fig. 4. Relation between the mass of the central supermassive black hole and stellar mass. The black line is the best fitting. The red diamonds are the lower limits and the blue diamonds are measurements that include a meaningful upper bound.

growth of low-mass black holes is predominantly attributed to gas accretion. The star formation rate increases as the spin of the black hole decreases for the sources with high star formation rate ($\log \text{SFR} > 1.5 M_{\odot} \text{ yr}^{-1}$). A possible explanation for the sources with high star formation rates is the merger of black holes, which is often associated with higher black hole masses. [Dubois et al. \(2014\)](#) find that the growth of massive black holes may be mainly due to the merger of black holes (their Figure 4). The black hole mergers may imply galaxy mergers. The galaxy mergers are assumed to enhance star formation (e.g. [Barnes 2004](#); [Springel et al. 2005](#); [Hopkins et al. 2006](#); [Randall et al. 2008](#); [Lin et al. 2008](#); [Kim et al. 2009](#); [Saitoh et al. 2009](#); [Rupke et al. 2010](#); [Perez et al. 2011](#); [Ellison et al. 2013](#); [Knapen et al. 2015](#); [Athanasoula et al. 2016](#); [Silva et al. 2018](#); [Wolter et al. 2023](#)). For the sources with intermediate star formation rate ($M_{\odot} \text{ yr}^{-1} 0 < \log \text{SFR} < 1.5 M_{\odot} \text{ yr}^{-1}$), we find that these sources have both high black hole spin and low black hole spin. Within this intermediate star formation rate range, where black hole masses are varied, both high and low black hole masses are present. This diversity may be caused by the combination of the merger of black holes and gas accretion, which can abruptly modify both spin magnitude and orientation ([Dubois et al. 2021](#)).

The theory of jet formation ([Blandford & Znajek 1977](#)) holds that the spin of the supermassive black hole enhances the relativistic jet. This hypothesis has been supported by observational evidence indicating that black hole spin enhances the relativistic jet ([Narayan & McClintock 2012](#); [Steiner et al. 2013](#)). [Ünal & Loeb \(2020\)](#) find that black hole activity depends on the spin of a black hole. The amplitude and orientation of the black hole spin control the efficiency of the conversion of the gas accreted onto the black hole into energy ([Bustamante & Springel 2019](#); [Sala et al. 2024](#)). Consequently, black hole spin is a critical parameter influencing jet efficiency and AGN feedback, which in turn can modulate and self-regulate black hole accretion ([Peirani et al. 2024](#)). Both theoretical models ([Silk & Norman 2009](#)) and observations (e.g. [Croft et al. 2006](#);

[Rodríguez Zaurín et al. 2007](#); [Feain et al. 2007](#); [Elbaz et al. 2009](#); [Imanishi et al. 2011](#); [Crockett et al. 2012](#); [Zinn et al. 2013](#); [Cresci et al. 2015](#); [Cano-Díaz et al. 2012](#); [Carniani et al. 2016](#); [Bischetti et al. 2022](#); [Chen et al. 2022](#); [Schutte & Reines 2022](#); [Lammers et al. 2023](#); [Venturi et al. 2023](#)) have shown that the activity of AGN impacts the star formation of host galaxies. Our above results may imply that the activity of AGN provides a feedback effect on galaxies. By considering radiation feedback, [Ishibashi et al. \(2019\)](#) investigated the influence of the spin of the central black hole on the large-scale properties of the host galaxy. Black hole spin can generate significant macroscopic effects at galactic scales, ultimately leading to large-scale feedback. The value of the black hole spin may give a diagnostic about the star formation rate of the host galaxies through the activity of AGN, which is complex. However, we also note that measuring black hole spin is more challenging compared to measuring star formation rate. We also note that, due to observation limitations, black hole spin measurements for most of our samples obtained by X-ray reflection spectroscopy are greater than 0.5, which may lead to a selective effect. In the future, our above results should be tested using large samples.

3.3. Relation between black hole mass and stellar mass

The observed correlation between the mass of the central supermassive black holes of local galaxies and their stellar mass ([McLure & Dunlop 2001, 2002](#); [Kormendy et al. 2001](#); [Marconi & Hunt 2003](#); [Ferrarese et al. 2006](#); [Kormendy & Ho 2013](#)) may imply the influence of AGN feedback on the star formation of the host galaxy. Investigating this mechanism is a primary objective in both observational and theoretical astronomy, as it could provide a crucial factor in our comprehensive understanding of galaxy formation. AGN or quasar feedback has often been invoked to explain the origin of coevolution of galaxies and supermassive black holes in the local universe ([Fabian 2012](#)). Thus, we study the relation between the mass of central supermassive black holes and their stellar mass. We used `linmix` ([Kelly 2007](#)) to fit the relation between two variables of AGN. Figure 4 shows the relation between the mass of central supermassive black holes and their stellar mass for our sample. We find that there is a strong correlation between the mass of central supermassive black holes and their stellar mass ($r = 0.65$, $p < 0.0001$; r and p are the correlation coefficient and probability for the null hypothesis of no correlation, respectively; the $p < 0.05$ is a significant correlation),

$$\log M_{\text{BH}} = 0.57(\pm 0.11) \log M_{*} + 1.94(\pm 1.05), \quad (2)$$

with an intrinsic scatter of 0.54 dex. We find that the slope of the relation between black hole mass and stellar mass for our sample is 0.57 ± 0.11 . [Beifiori et al. \(2012\)](#) reported that the slope of the relation between black hole mass and bulge stellar mass is 0.79 ± 0.26 using 46 galaxies. Our results are similar to theirs within error. [Pacucci et al. \(2023\)](#) find that the relation between black hole mass and stellar mass for high redshift active galaxies is $\log M_{\text{BH}} = 1.06(\pm 0.09) \log M_{*} - 2.43(\pm 0.83)$, with an intrinsic scatter of 0.23 dex. Our results are inconsistent with theirs, which may be due to the lower redshift of our sample compared to theirs. [Pacucci et al. \(2023\)](#) also suggest that the standard local universe relation is no longer valid in the high-redshift universe, particularly for faint AGN. [Reines & Volonteri \(2015\)](#) find that the relation between black hole mass and stellar mass for a sample of 262 broad-line AGN in the local universe is $\log M_{\text{BH}} = 1.05(\pm 0.11) \log M_{*} / 10^{11} + 7.45(\pm 0.08)$, with an intrinsic scatter of 0.24 dex. Our result is also different from

the result of Reines & Volonteri (2015). The possible explanation for this difference is that our sample size was smaller than that of Reines & Volonteri (2015).

4. Conclusions

For this study, we primarily examined the relationships between black hole spin, star formation rate, black hole mass, and stellar mass utilizing a sample of 48 supermassive black holes. The key findings of our research are summarized as follows:

(1) We find that in black holes with a mass $M_{\text{BH}} \lesssim 10^{6.5} M_{\odot}$, the black hole spin increases with the black hole mass. However, the spin of the black hole decreases with the black hole mass when the latter is $M_{\text{BH}} \gtrsim 10^{7.5} M_{\odot}$. These results may suggest that the growth of black holes from sources with low black hole mass mainly comes from coherent gas accretion events, while the growth of black holes from sources with high black hole mass mainly comes from merging events, including chaotic gas accretion.

(2) For the sources with low star formation rate ($\log \text{SFR} < 0.0 M_{\odot} \text{ yr}^{-1}$), the star formation rate increases with the spin of the black hole, which implies gas accretion. For the sources with intermediate star formation rate ($0.0 M_{\odot} \text{ yr}^{-1} < \log \text{SFR} < 1.5 M_{\odot} \text{ yr}^{-1}$), more frequent physical processes, such as the combination of black hole merger and gas accretion, are implied. For the sources with a high star formation rate ($\log \text{SFR} > 1.5 M_{\odot} \text{ yr}^{-1}$), the star formation rate increases as the spin of the black hole decreases, which implies the merger of a black hole. The value of the black hole spin may give a diagnostic about the star formation rate of the host galaxies through AGN activities, which are complex.

(3) There is a significant correlation between black hole mass and stellar mass for supermassive black holes. Our best-fitting power-law relation for the full galaxy sample is $\log M_{\text{BH}} = 0.57 \log M_{*} + 1.94$.

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References

Afanasyev, V. L., Popović, L. Č., & Shapovalova, A. I. 2019, *MNRAS*, **482**, 4985
 Alexander, D. M., & Hickox, R. C. 2012, *New Astron. Rev.*, **56**, 93
 Athanassoula, E., Rodionov, S. A., Peschken, N., & Lambert, J. C. 2016, *ApJ*, **821**, 90
 Bambi, C., Brenneman, L. W., Dauser, T., et al. 2021, *Space Sci. Rev.*, **217**, 65
 Barausse, E. 2012, *MNRAS*, **423**, 2533
 Barnes, J. E. 2004, *MNRAS*, **350**, 798
 Beckmann, R. S., Smethurst, R. J., Simmons, B. D., et al. 2024, *MNRAS*, **527**, 10867
 Beichman, C. A., Neugebauer, G., Habing, H. J., Clegg, P. E., & Chester, T. J. 1988, *Infrared Astronomical Satellite (IRAS). Catalogs and Atlases. Volume 1: Explanatory Supplement*, 1
 Beifiori, A., Courteau, S., Corsini, E. M., & Zhu, Y. 2012, *MNRAS*, **419**, 2497
 Bentz, M. C., Denney, K. D., Cackett, E. M., et al. 2006, *ApJ*, **651**, 775
 Bert, E., & Volonteri, M. 2008, *ApJ*, **684**, 822
 Bischetti, M., Feruglio, C., D'Odorico, V., et al. 2022, *Nature*, **605**, 244

Blandford, R. D., & Znajek, R. L. 1977, *MNRAS*, **179**, 433
 Boquien, M., Burgarella, D., Roehly, Y., et al. 2019, *A&A*, **622**, A103
 Brenneman, L. 2013, *Measuring the Angular Momentum of Supermassive Black Holes* (New York: Springer)
 Brenneman, L. W., Reynolds, C. S., Nowak, M. A., et al. 2011, *ApJ*, **736**, 103
 Bruzual, G., & Charlot, S. 2003, *MNRAS*, **344**, 1000
 Buisson, D. J. K., Parker, M. L., Kara, E., et al. 2018, *MNRAS*, **480**, 3689
 Burgarella, D., Buat, V., & Iglesias-Páramo, J. 2005, *MNRAS*, **360**, 1413
 Bustamante, S., & Springel, V. 2019, *MNRAS*, **490**, 4133
 Calzetti, D., Armus, L., Bohlin, R. C., et al. 2000, *ApJ*, **533**, 682
 Cano-Díaz, M., Maiolino, R., Marconi, A., et al. 2012, *A&A*, **537**, L8
 Carniani, S., Marconi, A., Maiolino, R., et al. 2016, *A&A*, **591**, A28
 Chabrier, G. 2003, *PASP*, **115**, 763
 Chambers, K. C., Magnier, E. A., Metcalfe, N., et al. 2016, ArXiv e-prints [arXiv:1612.05560]
 Chen, Z., He, Z., Ho, L. C., et al. 2022, *Nature Astronomy*, **6**, 339
 Ciesla, L., Charmandaris, V., Georgakakis, A., et al. 2015, *A&A*, **576**, A10
 Cresci, G., Mainieri, V., Brusa, M., et al. 2015, *ApJ*, **799**, 82
 Crockett, R. M., Shabala, S. S., Kaviraj, S., et al. 2012, *MNRAS*, **421**, 1603
 Croft, S., van Breugel, W., de Vries, W., et al. 2006, *ApJ*, **647**, 1040
 Croton, D. J., Springel, V., White, S. D. M., et al. 2006, *MNRAS*, **365**, 11
 Cui, Y., Hada, K., Kawashima, T., et al. 2023, *Nature*, **621**, 711
 Dale, D. A., Helou, G., Magdis, G. E., et al. 2014, *ApJ*, **784**, 83
 DeGraf, C., Di Matteo, T., Treu, T., et al. 2015, *MNRAS*, **454**, 913
 Di Matteo, T., Quataert, E., Allen, S. W., Narayan, R., & Fabian, A. C. 2000, *MNRAS*, **311**, 507
 Di Matteo, T., Johnstone, R. M., Allen, S. W., & Fabian, A. C. 2001, *ApJ*, **550**, L19
 Di Matteo, T., Allen, S. W., Fabian, A. C., Wilson, A. S., & Young, A. J. 2003a, *ApJ*, **582**, 133
 Di Matteo, T., Croft, R. A. C., Springel, V., & Hernquist, L. 2003b, *ApJ*, **593**, 56
 Di Matteo, T., Croft, R. A. C., Springel, V., & Hernquist, L. 2004, *ApJ*, **610**, 80
 Di Matteo, T., Springel, V., & Hernquist, L. 2005, *Nature*, **433**, 604
 Di Matteo, T., Colberg, J., Springel, V., Hernquist, L., & Sijacki, D. 2008, *ApJ*, **676**, 33
 Di Matteo, T., Khandai, N., DeGraf, C., et al. 2012, *ApJ*, **745**, L29
 Dotti, M., Colpi, M., Pallini, S., Perego, A., & Volonteri, M. 2013, *ApJ*, **762**, 68
 Draghis, P. A., Miller, J. M., Zoghbi, A., et al. 2021, *ApJ*, **920**, 88
 Draghis, P. A., Miller, J. M., Zoghbi, A., et al. 2023, *ApJ*, **946**, 19
 Draine, B. T., & Li, A. 2007, *ApJ*, **657**, 810
 Dubois, Y., Gavazzi, R., Peirani, S., & Silk, J. 2013, *MNRAS*, **433**, 3297
 Dubois, Y., Volonteri, M., & Silk, J. 2014, *MNRAS*, **440**, 1590
 Dubois, Y., Peirani, S., Pichon, C., et al. 2016, *MNRAS*, **463**, 3948
 Dubois, Y., Beckmann, R., Bournaud, F., et al. 2021, *A&A*, **651**, A109
 Elbaz, D., Jahnke, K., Pantin, E., Le Borgne, D., & Letawe, G. 2009, *A&A*, **507**, 1359
 Ellison, S. L., Mendel, J. T., Patton, D. R., & Scudder, J. M. 2013, *MNRAS*, **435**, 3627
 Emonts, B. H. C., Morganti, R., Tadhunter, C. N., et al. 2005, *MNRAS*, **362**, 931
 Fabian, A. C. 2012, *ARA&A*, **50**, 455
 Fanidakis, N., Baugh, C. M., Benson, A. J., et al. 2011, *MNRAS*, **410**, 53
 Feain, I. J., Papadopoulos, P. P., Ekers, R. D., & Middelberg, E. 2007, *ApJ*, **662**, 872
 Ferrarese, L., & Merritt, D. 2000, *ApJ*, **539**, L9
 Ferrarese, L., Pogge, R. W., Peterson, B. M., et al. 2001, *ApJ*, **555**, L79
 Ferrarese, L., Côté, P., Dalla Bontà, E., et al. 2006, *ApJ*, **644**, L21
 Fritz, J., Franceschini, A., & Hatziminaoglou, E. 2006, *MNRAS*, **366**, 767
 Gaibler, V., Khochfar, S., Krause, M., & Silk, J. 2012, *MNRAS*, **425**, 438
 Gallo, L. C., Miniutti, G., Miller, J. M., et al. 2011, *MNRAS*, **411**, 607
 Garofalo, D., Evans, D. A., & Sambruna, R. M. 2010, *MNRAS*, **406**, 975
 Gebhardt, K., Bender, R., Bower, G., et al. 2000, *ApJ*, **539**, L13
 Ghisellini, G. 2006, *VI Microquasar Workshop: Microquasars and Beyond*, 27.1.
 Greene, J. E., Peng, C. Y., Kim, M., et al. 2010, *ApJ*, **721**, 26
 Griffin, A. J., Lacey, C. G., Gonzalez-Perez, V., et al. 2019, *MNRAS*, **487**, 198
 Gültekin, K., Richstone, D. O., Gebhardt, K., et al. 2009, *ApJ*, **698**, 198
 Häring, N., & Rix, H.-W. 2004, *ApJ*, **604**, L89
 Heckman, T. M., & Best, P. N. 2014, *ARA&A*, **52**, 589
 Ho, L. C. 2008, *ARA&A*, **46**, 475
 Hopkins, P. F., Hernquist, L., Cox, T. J., et al. 2006, *ApJS*, **163**, 1
 Hopkins, P. F., Torrey, P., Faucher-Giguère, C.-A., Quataert, E., & Murray, N. 2016, *MNRAS*, **458**, 816
 Imanishi, M., Ichikawa, K., Takeuchi, T., et al. 2011, *PASJ*, **63**, 447
 Ishibashi, W., & Fabian, A. C. 2012, *MNRAS*, **427**, 2998
 Ishibashi, W., Fabian, A. C., & Reynolds, C. S. 2019, *MNRAS*, **486**, 2210
 Izquierdo-Villalba, D., Bonoli, S., Dotti, M., et al. 2020, *MNRAS*, **495**, 4681
 Jana, A., Naik, S., Chatterjee, D., & Jaiswal, G. K. 2021, *MNRAS*, **507**, 4779
 Jia, N., Zhao, X., Gou, L., et al. 2022, *MNRAS*, **511**, 3125
 Jiang, J., Walton, D. J., Fabian, A. C., & Parker, M. L. 2019, *MNRAS*, **483**, 2958

- Kauffmann, G., & Haehnelt, M. 2000, *MNRAS*, **311**, 576
- Keck, M. L., Brenneman, L. W., Ballantyne, D. R., et al. 2015, *ApJ*, **806**, 149
- Kelly, B. C. 2007, *ApJ*, **665**, 1489
- Kennicutt, R. C., Jr 1998, *ARA&A*, **36**, 189
- Kim, J.-H., Wise, J. H., & Abel, T. 2009, *ApJ*, **694**, L123
- Knapen, J. H., Cisternas, M., & Querejeta, M. 2015, *MNRAS*, **454**, 1742
- Koide, S., Shibata, K., Kudoh, T., & Meier, D. L. 2002, *Science*, **295**, 1688
- Kormendy, J., & Gebhardt, K. 2001, in 20th Texas Symposium on Relativistic Astrophysics, eds. J. C. Wheeler, & H. Martel, *AIP Conf. Ser.*, **586**, 363
- Kormendy, J., & Ho, L. C. 2013, *ARA&A*, **51**, 511
- Kormendy, J., & Richstone, D. 1995, *ARA&A*, **33**, 581
- Koss, M. J., Ricci, C., Trakhtenbrot, B., et al. 2022, *ApJS*, **261**, 2
- Kroupa, P. 2001, *MNRAS*, **322**, 231
- Lammers, C., Iyer, K. G., Ibarra-Medel, H., et al. 2023, *ApJ*, **953**, 26
- Lin, L., Patton, D. R., Koo, D. C., et al. 2008, *ApJ*, **681**, 232
- Liu, C., Gan, Z.-M., & Xie, F.-G. 2013, *Research in Astronomy and Astrophysics*, **13**, 899
- Livio, M., Ogilvie, G. I., & Pringle, J. E. 1999, *ApJ*, **512**, 100
- Lohfink, A. M., Reynolds, C. S., Jorstad, S. G., et al. 2013, *ApJ*, **772**, 83
- Lu, K.-X., Huang, Y.-K., Zhang, Z.-X., et al. 2019, *ApJ*, **877**, 23
- Lynden-Bell, D. 1969, *Nature*, **223**, 690
- MacDonald, D., & Thorne, K. S. 1982, *MNRAS*, **198**, 345
- Magnier, E. A., Chambers, K. C., Flewelling, H. A., et al. 2020, *ApJS*, **251**, 3
- Magorrian, J., Tremaine, S., Richstone, D., et al. 1998, *AJ*, **115**, 2285
- Mahony, E. K., Oonk, J. B. R., Morganti, R., et al. 2016, *MNRAS*, **455**, 2453
- Mallick, L., Fabian, A. C., García, J. A., et al. 2022, *MNRAS*, **513**, 4361
- Marconi, A., & Hunt, L. K. 2003, *ApJ*, **589**, L21
- McKinney, J. C. 2005, *ApJ*, **630**, L5
- McLure, R. J., & Dunlop, J. S. 2001, *MNRAS*, **327**, 199
- McLure, R. J., & Dunlop, J. S. 2002, *MNRAS*, **331**, 795
- Meier, D. L. 2002, *New Astron. Rev.*, **46**, 247
- Molina, J., Shangguan, J., Wang, R., et al. 2023, *ApJ*, **950**, 60
- Morganti, R., Holt, J., Saripalli, L., Oosterloo, T. A., & Tadhunter, C. N. 2007, *A&A*, **476**, 735
- Morganti, R., Fogasy, J., Paragi, Z., Oosterloo, T., & Orienti, M. 2013a, *Science*, **341**, 1082
- Morganti, R., Frieswijk, W., Oonk, R. J. B., Oosterloo, T., & Tadhunter, C. 2013b, *A&A*, **552**, L4
- Narayan, R., & McClintock, J. E. 2012, *MNRAS*, **419**, L69
- Nikołajuk, M., Czerny, B., & Gurynowicz, P. 2009, *MNRAS*, **394**, 2141
- Noll, S., Burgarella, D., Giovannoli, E., et al. 2009, *A&A*, **507**, 1793
- Pacucci, F., & Loeb, A. 2020, *ApJ*, **895**, 95
- Pacucci, F., Nguyen, B., Carniani, S., Maiolino, R., & Fan, X. 2023, *ApJ*, **957**, L3
- Parker, M. L., Matzeu, G. A., Guainazzi, M., et al. 2018, *MNRAS*, **480**, 2365
- Peirani, S., Suto, Y., Beckmann, R. S., et al. 2024, *A&A*, **686**, A233
- Perez, J., Michel-Dansac, L., & Tissera, P. B. 2011, *MNRAS*, **417**, 580
- Peterson, B. M., Ferrarese, L., Gilbert, K. M., et al. 2004, *ApJ*, **613**, 682
- Randall, S. W., Markevitch, M., Clowe, D., Gonzalez, A. H., & Bradač, M. 2008, *ApJ*, **679**, 1173
- Reines, A. E., & Volonteri, M. 2015, *ApJ*, **813**, 82
- Reis, R. C., Reynolds, M. T., Miller, J. M., & Walton, D. J. 2014, *Nature*, **507**, 207
- Reynolds, C. S. 2021, *ARA&A*, **59**, 117
- Risaliti, G., Harrison, F. A., Madsen, K. K., et al. 2013, *Nature*, **494**, 449
- Rodríguez Zaurín, J., Holt, J., Tadhunter, C. N., & González Delgado, R. M. 2007, *MNRAS*, **375**, 1133
- Rupke, D. S. N., Kewley, L. J., & Barnes, J. E. 2010, *ApJ*, **710**, L156
- Saitoh, T. R., Daisaka, H., Kokubo, E., et al. 2009, *PASJ*, **61**, 481
- Sala, L., Valentini, M., Biffi, V., & Dolag, K. 2024, *A&A*, **685**, A92
- Santini, P., Rosario, D. J., Shao, L., et al. 2012, *A&A*, **540**, A109
- Schaye, J., Crain, R. A., Bower, R. G., et al. 2015, *MNRAS*, **446**, 521
- Schutte, Z., & Reines, A. E. 2022, *Nature*, **601**, 329
- Sesana, A., Barausse, E., Dotti, M., & Rossi, E. M. 2014, *ApJ*, **794**, 104
- Shakura, N. I., & Sunyaev, R. A. 1976, *MNRAS*, **175**, 613
- Sijacki, D., Springel, V., Di Matteo, T., & Hernquist, L. 2007, *MNRAS*, **380**, 877
- Silk, J. 2013, *ApJ*, **772**, 112
- Silk, J., & Norman, C. 2009, *ApJ*, **700**, 262
- Silva, A., Marchesini, D., Silverman, J. D., et al. 2018, *ApJ*, **868**, 46
- Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, *AJ*, **131**, 1163
- Sluse, D., Hutsemékers, D., Courbin, F., Meylan, G., & Wambsganss, J. 2012, *A&A*, **544**, A62
- Soares, G., & Nemmen, R. 2020, *MNRAS*, **495**, 981
- Soltan, A. 1982, *MNRAS*, **200**, 115
- Springel, V., Di Matteo, T., & Hernquist, L. 2005, *MNRAS*, **361**, 776
- Steiner, J. F., McClintock, J. E., & Narayan, R. 2013, *ApJ*, **762**, 104
- Suh, H., Civano, F., Hasinger, G., et al. 2019, *ApJ*, **872**, 168
- Sun, S., Guainazzi, M., Ni, Q., et al. 2018, *MNRAS*, **478**, 1900
- Tadhunter, C., Morganti, R., Rose, M., Oonk, J. B. R., & Oosterloo, T. 2014, *Nature*, **511**, 440
- Tanabe, K., & Nagataki, S. 2008, *Phys. Rev. D*, **78**, 024004
- Tehekhovskoy, A., McKinney, J. C., & Narayan, R. 2012, *Journal of Physics Conference Series*, **372**, 012040
- Thorne, K. S., Price, R. H., & MacDonald, D. A. 1986, *Black Holes: The Membrane Paradigm* (New Haven: Yale Univ. Press)
- Tremaine, S., Gebhardt, K., Bender, R., et al. 2002, *ApJ*, **574**, 740
- Únal, C., & Loeb, A. 2020, *MNRAS*, **495**, 278
- Vasudevan, R. V., Fabian, A. C., Reynolds, C. S., et al. 2016, *MNRAS*, **458**, 2012
- Venturi, G., Treister, E., Finlez, C., et al. 2023, *A&A*, **678**, A127
- Volonteri, M., Madau, P., Quataert, E., & Rees, M. J. 2005, *ApJ*, **620**, 69
- Volonteri, M., Sikora, M., Lasota, J. P., & Merloni, A. 2013, *ApJ*, **775**, 94
- Walton, D. J., Nardini, E., Fabian, A. C., Gallo, L. C., & Reis, R. C. 2013, *MNRAS*, **428**, 2901
- Walton, D. J., Nardini, E., Gallo, L. C., et al. 2019, *MNRAS*, **484**, 2544
- Walton, D. J., Alston, W. N., Kosec, P., et al. 2020, *MNRAS*, **499**, 1480
- Wang, Y., Méndez, M., Altamirano, D., et al. 2018, *MNRAS*, **478**, 4837
- Weinberger, R., Springel, V., Hernquist, L., et al. 2017, *MNRAS*, **465**, 3291
- Wolter, I. E., Berg, M. A., & Chisholm, J. 2023, *Research Notes of the American Astronomical Society*, **7**, 232
- Wright, E. L., Eisenhardt, P. R. M., Mainzer, A. K., et al. 2010, *AJ*, **140**, 1868
- Xie, Y., Ho, L. C., Zhuang, M.-Y., & Shangguan, J. 2021, *ApJ*, **910**, 124
- Xu, Y., Pinto, C., Kara, E., et al. 2022, *MNRAS*, **513**, 1910
- Zhang, X., & Lu, Y. 2019, *ApJ*, **873**, 101
- Zinn, P. C., Middelberg, E., Norris, R. P., & Dettmar, R. J. 2013, *ApJ*, **774**, 66
- Zubovas, K., Nayakshin, S., King, A., & Wilkinson, M. 2013, *MNRAS*, **433**, 3079

Appendix A: The sample of supermassive black holes.

Table A.1. The sample of supermassive black holes.

Name (1)	redshift (2)	$\log L_{\text{IR}}$ (3)	$\log \text{SFR}$ (4)	$\log M_*/M_\odot$ (5)	$\log M_{\text{BH}}/M_\odot$ (6)	a (7)	Mass/spin Reference (8)
Mrk 359	0.0168	43.846	0.499	9.677±0.03	6.041	0.66 ^{+0.30} _{-0.54}	Bambi21
Ark564	0.0247	43.836	0.489	8.842±0.06	6.041	0.96 ^{+0.01} _{-0.06}	Rey21
Mrk 766	0.01288	43.999	0.653	8.031±0.04	6.54 ^{+0.05} _{-0.04}	>0.92	Bambi21
NGC 4051	0.00234	43.07	-0.274	7.913±0.03	6.281 ^{+0.18} _{-0.18}	>0.99	Rey21
NGC 1365	0.00546	44.612	1.265	9.655±0.02	7.81 ^{+0.53} _{-0.23}	>0.97	Bambi21
1H0707-495	0.041	43.297	-0.048	7.522±0.1	5.81 ^{+0.05} _{-0.04}	> 0.988	Bambi21
MCG-6-30-15	0.00775	42.548	-0.798	8.522±0.07	6.462 ^{+0.27} _{-0.24}	0.91 ^{+0.06} _{-0.07}	Rey21
NGC5506	0.00608	43.209	-0.137	7.022±0.04	6.70 ^{+0.19} _{-0.10}	0.93 ^{+0.04} _{-0.04}	Bambi21
IRAS 13224-3809	0.0658	45.127	1.78	9.411±0.02	5.87 ^{+0.12} _{-0.14}	>0.975	Bambi21
TON S180	0.062	44.056	0.709	9.46±0.08	6.908	> 0.98	Rey21
ESO 362-G18	0.0124	43.559	0.212	9.251±0.03	7.097 ^{+0.16} _{-0.16}	>0.92	Rey21
Swift J2127.4+5654	0.0147	44.034	0.687	9.601±0.02	7.18 ^{+0.09} _{-0.09}	0.58 ^{+0.11} _{-0.17}	Bambi21
Mrk 335	0.02578	43.716	0.369	9.669±0.05	7.15 ^{+0.11} _{-0.11}	0.99 ^{+0.01} _{-0.03}	Bambi21
Mrk 110	0.0353	43.3	-0.046	9.22±0.11	7.4 ^{+0.11} _{-0.11}	>0.99	Rey21
NGC 3783	0.00973	43.725	0.378	9.2±0.02	7.474 ^{+0.08} _{-0.08}	> 0.88	Rey21
1H0323+342	0.0629	45.156	1.809	10.017±0.06	7.531 ^{+0.12} _{-0.08}	>0.9	Rey21
NGC 4151	0.0033	42.78	-0.566	9.421±0.06	7.12 ^{+0.15} _{-0.12}	0.98 ^{+0.01} _{-0.01}	Bambi21
Mrk 79	0.022	44.192	0.846	9.957±0.02	7.72 ^{+0.12} _{-0.12}	> 0.5	Bambi21
PG1229+204	0.0636	44.19	0.843	10.045±0.06	7.756 ^{+0.22} _{-0.22}	0.93 ^{+0.06} _{-0.02}	Rey21
IRAS13197-1627	0.01654	44.419	1.072	9.011±0.02	7.806	>0.7	Rey21
3C120	0.033	44.55	1.207	10.08±0.02	7.839 ^{+0.20} _{-0.15}	> 0.95	Rey21
Mrk 841	0.03642	43.996	0.649	9.355±0.07	7.897 ^{+0.01} _{-0.01}	>0.52	Bambi21
IRAS09149-6206	0.0573	44.76	1.413	10.824±0.06	8.00 ^{+1.3} _{-0.3}	0.94 ^{+0.02} _{-0.07}	Bambi21
Ark120	0.0327	44.196	0.85	10.464±0.04	8.176 ^{+0.06} _{-0.06}	0.83 ^{+0.05} _{-0.03}	Bambi21
RBS1124	0.208	43.714	0.367	8.5±0.31	8.26 ^{+0.10} _{-0.10}	>0.97	Bambi21
1RXS J113155.4-123155	0.654	47	3.657	11.73±0.02	8.30 ^{+0.09} _{-0.09}	0.87 ^{+0.08} _{-0.15}	Bambi21
Fairall 9	0.046	44.188	0.841	9.151±0.07	8.407 ^{+0.10} _{-0.10}	>0.997	Bambi21
1H0419-577	0.104	44.517	1.171	9.821±0.07	8.11 ^{+0.10} _{-0.10}	>0.96	Bambi21
PG0804+761	0.1005	44.839	1.492	11.095±0.02	8.74 ^{+0.05} _{-0.05}	>0.97	Rey21
Q 2237+0305	1.695	48.0224	4.675	13.213±0.02	9.0 ^{+0.09} _{-0.09}	0.74 ^{+0.06} _{-0.03}	Bambi21
PG2112+059	0.459	45.643	2.296	10.595±0.1	9.0 ^{+0.09} _{-0.09}	>0.86	Bambi21
H1821+643	0.297	46.417	3.07	11.178±0.04	9.653 ^{+0.14} _{-0.14}	>0.4	Rey21
IRAS 00521-7054	0.069	45.084	1.737	10.278±0.02	7.698 ^{+0.09} _{-0.09}	> 0.77	Bambi21
IRAS13349+2438	0.108	45.274	1.927	11.368±0.02	7.00 ^{+0.09} _{-0.17}	0.80 ^{+0.2} _{-0.5}	Bambi21
Fairall 51	0.0142	43.585	0.238	8.845±0.06	8.00 ^{+0.09} _{-0.09}	0.80 ^{+0.2} _{-0.2}	Bambi21
Mrk 1501	0.087	44.33	0.983	10.06±0.07	8.26 ^{+0.06} _{-0.06}	>0.98	Bambi21
Mrk 1018	0.043	43.021	-0.325	6.873±0.3	7.81	0.58 ^{+0.36} _{-0.74}	Kos22/Vas16
Mrk 509	0.034	43.825	0.478	9.823±0.12	8.15 ^{+0.04} _{-0.04}	>0.993	Bambi21
3C382	0.055	44.174	0.827	10.864±0.06	8.01 ^{+0.09} _{-0.05}	0.75 ^{+0.07} _{-0.04}	Lu19/Wal13
PKS 0558-504	0.137	45.17	1.823	9.812±0.05	7.62	> 0.8	Kos22/Wal13
NGC 7469	0.016	45.14	1.794	9.59±0.04	6.42 ^{+0.06} _{-0.09}	>0.96	Lu19/Wal13
PDS 456	0.185	45.154	1.808	9.884±0.02	8.4	> 0.97	Wil18/Wal13
UGC 6728	0.0065	42.758	-0.588	7.951±0.05	5.55 ^{+0.22} _{-0.25}	>0.95	Lu19/Wal13
1H1934-063	0.01	43.778	0.431	9.223±0.02	6.477	>0.45	Xu22/Jia19
Mrk 279	0.03	44.293	0.946	10.433±0.02	7.97 ^{+0.09} _{-0.12}	>0.95	Lu19/Jia19
Mrk 590	0.0263	44.058	0.711	10.492±0.02	7.55 ^{+0.05} _{-0.07}	>0.1	Lu19/Jia19
NGC 4748	0.0146	43.677	0.331	8.904±0.03	6.61 ^{+0.11} _{-0.23}	>0.8	Lu19/Jia19
PG 0844+349	0.064	43.308	-0.037	7.045±0.28	8.35 ^{+0.26} _{-0.26}	>0.95	Afa19/Jia19

Notes. Columns (1) is the name of the sources; Columns (2) is the redshift; Columns (3) is the torus-subtracted IR luminosity in the 8–1000 μm band in units erg s^{-1} ; Columns (4) is SFR calculated from the torus-subtracted IR luminosity in the 8–1000 μm band, units $M_\odot \text{yr}^{-1}$; Columns (5) is stellar mass; Columns (6) is the black hole mass; Columns (7) is the black hole spin; Columns (8) is the reference of black hole mass and spin. Rey21=Reynolds (2021); Bambi21=Bambi et al. (2021); Afa19=Afanisiev et al. (2019); Kos22=Koss et al. (2022); Vas16=Vasudevan et al. (2016); Wal13=Walton et al. (2013); Lu19=Lu et al. (2019); Xu22=Xu et al. (2022); Jia19=Jiang et al. (2019). Some of the sources in the samples of Reynolds (2021) were updated from Bambi et al. (2021).