arXiv:2401.04159v1 [astro-ph.GA] 8 Jan 2024

The Redshift Evolution of the $M_\bullet - M_\star$ Relation for JWST's Supermassive Black Holes at $z > 4$

Fabio Pacucci [ID][1,2] and Abraham Loeb [ID][1,2]

[1] Center for Astrophysics | Harvard & Smithsonian, Cambridge, MA 02138, USA
[2] Black Hole Initiative, Harvard University, Cambridge, MA 02138, USA

ABSTRACT

JWST has detected many overmassive galactic systems at $z > 4$, where the mass of the black hole, $M_\bullet$, is $10 - 100$ times larger than expected from local relations, given the host's stellar mass, $M_\star$. This Letter presents a model to describe these overmassive systems in the high-z Universe. We suggest that the black hole mass is the main driver of high-z star formation quenching. SMBHs globally impact their high-z galaxies because their hosts are physically small, and the black holes have duty cycles close to unity at $z > 4$. In this regime, we assume that black hole mass growth is regulated by the quasar's output, while stellar mass growth is quenched by it and uncorrelated to the global properties of the host halo. We find that the ratio $M_\bullet/M_\star$ controls the average star formation efficiency: if $M_\bullet/M_\star > 8 \times 10^{18}(n\Lambda/f_{\rm Edd})[(\Omega_b M_h)/(\Omega_m M_\star) - 1]$, then the galaxy is unable to form stars efficiently. Once this ratio exceeds the threshold, a runaway process brings the originally overmassive system towards the local $M_\bullet - M_\star$ relation. Furthermore, the $M_\bullet - M_\star$ relation evolves with redshift as $\propto (1 + z)^{5/2}$. At $z \sim 5$, we find an overmassive factor of ~ 55, in excellent agreement with current JWST data and the high-z relation inferred from those. Extending the black hole horizon farther in redshift and lower in mass will test this model and improve our understanding of the early co-evolution of black holes and galaxies.

1. INTRODUCTION

During the first year of operations of the James Webb Space Telescope (JWST), one of the most remarkable discoveries was the detection of a population of lower-mass ($10^6 - 10^8 \, {\rm M}_\odot$), lower-luminosity ($10^{44} - 10^{46} \, {\rm erg \, s}^{-1}$) supermassive black holes (SMBHs) at $z > 4$ (Harikane et al. 2023; Maiolino et al. 2023a; Übler et al. 2023; Stone et al. 2023; Furtak et al. 2023; Kokorev et al. 2023; Yue et al. 2023; Bogdán et al. 2023), reaching up to a redshift of $z = 10.6$ with GN-z11 (Maiolino et al. 2023b). A comparison to the properties of the most distant quasar in the pre-JWST era, with a mass of $M_\bullet = (1.6 \pm 0.4) \times 10^9 \, {\rm M}_\odot$ at $z = 7.6$, (Wang et al. 2021), clarifies how much JWST has expanded our view on the early population of black holes, both upward in redshift and downward in mass.

The lower luminosity of these SMBHs allowed the detection of starlight from their hosts (see, e.g., Ding et al. 2023) and estimate some of their properties, e.g., their stellar and dynamical mass and (gas) velocity dispersions. Some of these SMBHs were identified in the so-called "little red dots" (Matthee et al. 2023), containing "hidden little monsters" (Kocevski et al. 2023), which are low-luminosity, strikingly red objects. Recently, Greene et al. (2023) used spectroscopy from the JWST/UNCOVER program to argue that $\sim 60\%$ of these objects are dust-reddened AGN: young galaxies hosting a low-luminosity SMBH at their center.

The discovery of a lower-luminosity population of SMBHs and their hosts' properties led to an additional, unexpected discovery. In the local Universe, well-known relations connect the mass of the central SMBHs with physical properties of their hosts (see, e.g., Magorrian et al. 1998; Ferrarese & Merritt 2000; Gebhardt et al. 2000; Kormendy & Ho 2013). For example, the $M_\bullet - M_\star$ relation links the SMBH mass and the stellar mass of the host. Reines & Volonteri (2015) found that the mass of the central SMBH is $\sim 0.1\%$ of the stellar mass of their hosts, with a scatter of ~ 0.55 dex, or a factor ~ 3.5.

A significant wealth of data from numerous JWST surveys indicates the detection of SMBHs at $z > 4$ that are $10 - 100$ times overmassive when compared to the stellar content of their hosts (Harikane et al. 2023; Maiolino

et al. 2023a; Übler et al. 2023; Stone et al. 2023; Furtak et al. 2023; Kokorev et al. 2023; Yue et al. 2023). The mass of these SMBHs is not $\sim 0.1\%$ of the stellar mass of their hosts, but rather $1\% - 10\%$, or even close to $\sim 100\%$ in some cases (Bogdán et al. 2023).

A detailed statistical analysis of these data, with an MCMC algorithm that takes into account observational biases (e.g., see Lauer et al. 2007), finds that this population of lower-mass SMBHs at $z > 4$ violate the $M_\bullet - M_\star$ relation at $> 3\sigma$ (Pacucci et al. 2023). Interestingly, Maiolino et al. (2023a) notes that while the SMBHs are overmassive with respect to the $M_\bullet - M_\star$ relation, other scaling relations, such as the $M_\bullet - \sigma$ and the $M_\bullet - M_{\rm dyn}$ relations (with the velocity dispersion and the dynamical mass, respectively), hold at $4 < z < 7$. Altogether, recent JWST data suggests that the $M_\bullet - \sigma$ and the $M_\bullet - M_{\rm dyn}$ relations are "fundamental and universal" because they are powered by the depth of the gravitational potential well generated by the central SMBH. Instead, the $M_\bullet - M_\star$ relation could evolve with redshift.

The $M_\bullet - \sigma$ and the $M_\bullet - M_{\rm dyn}$ relations are linked, so it is not surprising that once one holds, the other follows. Instead, the host's stellar mass is measured independently. Despite significant uncertainties affecting stellar mass and black hole mass measurements, Pacucci et al. (2023) find that, unless most overmassive SMBHs found so far are characterized by errors of a factor ~ 60 in their black hole mass or their stellar mass all in the same direction (i.e., all increasing $M_\star$ or decreasing $M_\bullet$), this result holds. Note that typical reported errors, at 1σ, are of a factor ~ 3 in $M_\bullet$ and a factor ~ 4 in $M_\star$ (see, e.g., Maiolino et al. 2023a).

Theoretical predictions, dating back 20 years, suggest that scaling relations evolve with redshift. For instance, Wyithe & Loeb (2003) argued that the ratio $M_\bullet/M_\star$ should scale as $\propto (1 + z)^{3/2}$, due to self-regulation via quasar (Silk & Rees 1998) and supernova feedback. Quasar activity is efficient in quenching star formation via the effect of strong outflows or by heating the gas (e.g., Fabian 2012; Heckman & Best 2014; King & Pounds 2015), although there is at least one example of a black hole triggering star formation in a dwarf galaxy (Schutte & Reines 2022).

Other works have studied the redshift evolution of scaling relations using numerical simulations (e.g., Robertson et al. 2006; Di Matteo et al. 2008; Sijacki et al. 2015), semi-analytic models (e.g., Malbon et al. 2007; Kisaka & Kojima 2010), observations (e.g., Peng et al. 2006; Decarli et al. 2010; Merloni et al. 2010; Trakhtenbrot & Netzer 2010; Bennert et al. 2011), or combinations of those (e.g., Booth & Schaye 2011), especially at $z \lesssim 2$. More recently, Caplar et al. (2018) developed

a phenomenological model, based on observations, and found that the ratio $M_\bullet/M_\star$ scales as $\propto (1+z)^{1.5}$ at $z < 2$, in agreement with Wyithe & Loeb (2003).

In this Letter, we present a model that explains the evolution at $z > 4$ of the $M_\bullet - M_\star$ relation for SMBHs in JWST data. Furthermore, we develop a condition on the ratio $M_\bullet/M_\star$ to probe whether the quasar feedback stunts star formation. The model makes predictions that can be tested with future JWST data.

2. MODEL PRINCIPLES

We start with the principles of our model for high-z overmassive systems. The model we present is valid only in the high-z Universe, where the typical growth time for black holes, t_g, is similar to the age of the Universe: $t_g \sim t_{age}$.

The basis of our model is that the *black hole mass is the primary parameter that controls high-z star formation quenching.* This premise is supported by recent analyses of JWST/CEERS data with cosmological simulations (Illustris TNG and EAGLE), showing that high-z galaxy quenching is primarily regulated by the mass of the SMBH (Piotrowska et al. 2022; Bluck et al. 2023). Previous cosmological simulations already showed that star formation quenching should scale with energy input from the central SMBH over the entire lifetime of the galaxy, which is proportional to the black hole mass (Terrazas et al. 2020; Bluck et al. 2023). Active SMBHs in $z > 4$ galaxies discovered by JWST are effective at quenching star formation for at least two reasons.

First, *high-z galaxies are physically small*; the ionized bubble generated by active SMBHs likely extends to the entire galaxy. Typical physical sizes of galaxies detected by JWST at $z = 7-9$ are characterized by effective radii of $80 \, {\rm pc} < r_e < 300 \, {\rm pc}$, with a mean value of $r_e \sim 150$ pc (Baggen et al. 2023). This typical physical size has to be compared with the radius of the ionization bubble created by a SMBH accreting at its Eddington rate. For a $\sim 10^7 \, {\rm M_\odot}$ SMBH, as typically found in these overmassive systems (Pacucci et al. 2023), this radius can extend as much as ~ 700 kpc (see, e.g., Cen & Haiman 2000; Madau & Rees 2000; White et al. 2003). Regions of high-density gas presumably present in the high-z galaxies could effectively shield the radiation from the SMBH and still allow localized star formation; this would, however, be ineffective in generating large-scale star formation. Hence, SMBHs were effective in quenching star formation because they had a global impact on the entire host. Note that previous studies (e.g., Chen et al. 2020) already highlighted the importance of the radius of star-forming galaxies in determining the growth of their SMBHs.
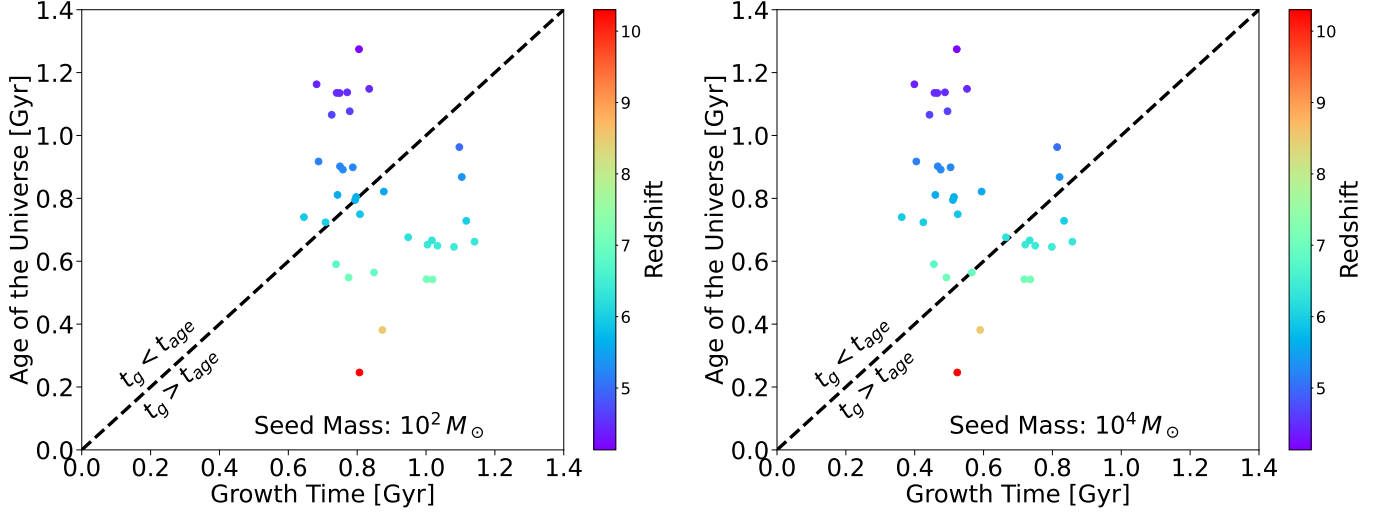
Figure 1. Left panel: Comparison between the growth time (assuming a light seed of $100\,\mathrm{M_\odot}$) and the age of the Universe at detection, for the overmassive systems detected by JWST thus far. The dashed line indicates where the growth time equals the Universe's age at that detection redshift. The data points are colored according to their detection redshift, shown in the color bar. **Right panel:** same as the left panel, but the growth time assumes a heavy seed of $10^4\,\mathrm{M_\odot}$.

Second, *in the high-z Universe, the growth time of black holes is comparable to the age of the Universe.* Hence, central SMBHs at a given redshift z are active for a time comparable to the Hubble time $t_{age}(z)$, if $z > 4$. Figure 1 shows, for the high-z overmassive systems detected thus far by JWST, a comparison between the age of the Universe (at detection) and growth time. This latter time is calculated assuming a continuous growth from a seeding redshift of $z = 25$ (see, e.g., Barkana & Loeb 2001) at the Eddington rate, assuming a light seed of $100\,\mathrm{M_\odot}$ (left panel) or a heavy seed of $10^4\,\mathrm{M_\odot}$ (right panel). At higher redshift, the age of the Universe is comparable to, or even shorter than, the growth time (for those two specific seeding scenarios); hence, the "activity duty cycle" for those specific SMBHs has to be close to unity. Because their duty cycle is close to unity, these SMBHs are constantly injecting energy into the primeval galaxy and heating the cold gas necessary to produce stars. Once the age of the Universe is $\gtrsim 1$ Gyr, the SMBH is active only for a fraction of the Hubble time and stars can then form from cold molecular gas, which becomes widely available in the galaxy.

This hypothesis is further confirmed by a recent analysis of $4.5 < z < 12$ galaxies in the JWST/CEERS survey (Cole et al. 2023), showing a higher variability of star formation activity at high redshift. Stars form primarily in short periods of starburst activity, with star-forming duty cycles of only 20% at $z \sim 9$, and 40% at $z \sim 5$. The study also suggests a smoother star formation activity at $z < 4.5$, when the age of the Universe is > 1 Gyr and the quasar duty cycle drops significantly below unity.

2.1. Assumptions on the Growth of $M_\bullet$ and $M_\star$

The two assumptions in our model for high-z overmassive systems are the following (v_c is the circular velocity of the galactic halo, see Barkana & Loeb 2001):

1. Black hole mass growth is regulated by the quasar output. This leads to the scaling $M_\bullet \propto v_c^5$.

2. Stellar mass growth is quenched by the quasar output and uncorrelated with v_c: $M_\star \not\propto v_c$.

The first scaling is easily demonstrated as follows (see the same derivation in Wyithe & Loeb 2003). Assume that the central SMBH of mass $M_\bullet$ is emitting energy at a fraction η of the Eddington luminosity, L_{Edd}, with $L_{\mathrm{Edd}} \propto M_\bullet$. Let us further assume that a fraction $\mathcal{F}$ of ηL_{Edd} is trapped by the gas within the galaxy. The self-regulation hypothesis predicts that the growth of the central SMBH shuts off when the total luminosity output of the SMBH, absorbed by the gas over a dynamical time t_{dyn}, is equal to the binding energy of the host halo of total mass M_h:

$$\eta L_{\mathrm{Edd}}\mathcal{F} = \frac{1}{2}\frac{\Omega_b M_h v_c^2}{\Omega_m t_{\mathrm{dyn}}}, \qquad (1)$$

where Ω_b/Ω_m is the baryon fraction.

From Barkana & Loeb (2001), we derive the dependence of the circular velocity of stars with respect to the halo mass M_h and the redshift z:

$$v_c = 245\left(\frac{M_h}{10^{12}M_\odot}\right)^{1/3}[\xi(z)]^{1/6}\left(\frac{1+z}{3}\right)^{1/2}\ \mathrm{km\ s^{-1}}, \qquad (2)$$

where the factor $\xi(z)$ is defined as:

$$\xi \equiv \frac{\Omega_m}{\Omega_m^z}\frac{\Delta_c}{18\pi^2},$$

$$\Omega_m^z \equiv \left[1 + \left(\frac{\Omega_\Lambda}{\Omega_m}\right)(1+z)^{-3}\right]^{-1},$$

$$\Delta_c = 18\pi^2 + 82d - 39d^2,$$

$$d = \Omega_m^z - 1$$

As $M_h \propto v_c^3$, our previous self-regulation equation implies that $M_\bullet \propto v_c^5$.

Regarding the second assumption, it is essential to note that the circular velocity v_c depends on the total mass of the halo, not on its stellar mass. We argue that the total halo mass corresponding to a given circular velocity v_c is in place. However, it is not forming stars efficiently because their growth is inhibited by high-duty cycle quasar activity in a small-size galaxy.

This second assumption can be tested experimentally. From JWST observations at redshift $4 < z < 7$ (see, e.g., Maiolino et al. 2023a), there is no relation between the stellar mass of the host and the measured velocity dispersion of the galaxy. While the σ values vary in the Maiolino et al. (2023a) dataset in a range of 0.3 dex, the stellar masses vary for 2.5 dex. A Pearson's (2-tailed) correlation test yields no correlation (p-value ~ 0.03) at 5% significance. Hence, $M_\star \propto \sigma^0 \propto v_c^0$. At these redshifts and for these stellar masses, there is no indication that the stellar mass growth is regulated by either supernova or the quasar feedback. In this regard, our treatment is fundamentally different from Wyithe & Loeb (2003).

3. RESULTS

Next, we derive our results: a condition on the ratio $M_\bullet/M_\star$ for the average star formation rate to be effectively quenched at high-z (Sec. 3.1) and a prediction for the redshift evolution of the $M_\bullet - M_\star$ relation at $z > 4$ (Sec. 3.2).

3.1. A Condition for Star Formation Quenching

We have developed a theoretical condition on the ratio $M_\bullet/M_\star$ to understand if quasar feedback is efficient in quenching star formation and to which extent. We then test this hypothesis with the 35 overmassive systems discovered by JWST at $z > 4$ (Harikane et al. 2023; Maiolino et al. 2023a; Übler et al. 2023; Stone et al. 2023; Furtak et al. 2023; Kokorev et al. 2023; Yue et al. 2023; Bogdán et al. 2023).

Before proceeding, we note that galaxies meeting the condition for star formation quenching developed here are *not prevented* from forming stars *altogether*, or even at the observation time. After all, the 35 overmassive systems studied here contain $10^8 - 10^{11}\,\mathrm{M_\odot}$ in stars, which must have formed at some point. Likely, the existing stellar masses were formed when the black hole mass was small, and the quasar feedback was weak. Our condition on the ratio $M_\bullet/M_\star$ prevents star formation from being efficient over the entire lifetime of the galactic system, up to detection. In other words, the criterion we developed applies to the *time average of the star formation rate*, not to its instantaneous value. Despite this note, it is reassuring to report that out of the 35 overmassive systems studied here, only 3 display large far-infrared luminosities, which may indicate ongoing star formation (Stone et al. 2023).

We assume that star formation is quenched once the SMBH injects sufficient energy into the system to raise the temperature above the virial one. Recently, Gelli et al. (2023) used a similar formalism to argue that supernova feedback fails to quench star formation in high-z galaxies. This finding supports our model principles detailed in Sec. 2.

A simple model to describe the energetics of a primordial galaxy includes $\mathcal{H}$ and $\mathcal{C}$: the rate of energy injection (heating) and the rate of energy subtraction (cooling).

The power injected into the system, for a SMBH accreting at Eddington ratio f_{Edd} (defined as the ratio between the actual accretion rate and the Eddington rate), is

$$\mathcal{H} = f_{\mathrm{Edd}}\frac{4\pi G M_\bullet m_p c}{\sigma_T}, \tag{3}$$

where G is the gravitational constant, m_p is the proton mass, c is the speed of light, and σ_T is the Thomson cross section.

The energy of a gas characterized by pure translational kinetic energy, at the virial temperature T_{vir}, is $E = \langle 3/2\rangle N k_B T_{\mathrm{vir}}$, where N is the total number of particles and k_B is the Boltzmann constant. Expressing the cooling time as $t_{\mathrm{cool}} \simeq 3k_B T_{\mathrm{vir}}/(\Lambda n)$, where Λ is the cooling function and n is the gas number density (see, e.g., Rees & Ostriker 1977; Barkana & Loeb 2001), we can express the cooling rate as:

$$\mathcal{C} = \frac{1}{2}\frac{n\Lambda}{\mu m_p}M_g. \tag{4}$$

Here, $\Lambda(T_{\mathrm{vir}}, Z)$ is the cooling function in terms of the virial temperature and metallicity, $\mu = 0.6$ is the mean molecular weight for ionized gas, and M_g is the gas mass. This last term can be expressed as the baryon mass of the halo minus the mass in stars: $M_g = (\Omega_b/\Omega_m)M_h - M_\star$. Note that the cooling function Λ has units $\mathrm{erg\,s^{-1}\,cm^3}$.

The condition that feedback heats the gas mass above its virial temperature in the small, high-z galaxy is: $\mathcal{H} > \mathcal{C}$. This condition can be expressed in terms of the ratio $M_\bullet/M_\star$ as follows:

$$\frac{M_\bullet}{M_\star} > \frac{1}{8\pi} \frac{n\Lambda\sigma_T}{Gc\mu m_p^2 f_{\rm Edd}} \left(\frac{\Omega_b}{\Omega_m}\frac{M_h}{M_\star} - 1\right). \qquad (5)$$

Expressing the constants in numerical form (with units equal to the reciprocal of $\rm erg\,s^{-1}$), this translates into:

$$\frac{M_\bullet}{M_\star} > 8 \times 10^{18}\, \frac{n\Lambda}{f_{\rm Edd}} \left(\frac{\Omega_b}{\Omega_m}\frac{M_h}{M_\star} - 1\right). \qquad (6)$$

We adopt $f_{\rm Edd} = 1$ for our calculations because overmassive systems discovered by JWST are estimated to be accreting at rates $0.1 < f_{\rm Edd} < 5$ (Harikane et al. 2023; Maiolino et al. 2023a). Furthermore, we use the median cooling function for the gas metallicity range $0.1 < Z/Z_\odot < 0.3$ and the mean gas number density ($\sim 0.5\,{\rm cm^{-3}}$) calculated for simulated galaxies in the redshift range $5 < z < 10$ by Robinson et al. (2022). The metallicity range used is justified by a recent study with JWST of $z \sim 6$ galaxies with masses $\sim 10^{10}\,{\rm M_\odot}$, showing typical values $12 + \log({\rm O/H}) \sim 8.2$, which is $\approx 25\%$ of the solar value (Nakajima et al. 2023). Finally, we assume the values of the cosmological parameters from Planck Collaboration et al. (2020) and the halo mass to stellar mass ratio from Behroozi et al. (2019).

In Fig. 2, we show the condition on the ratio $M_\bullet/M_\star$. First, we note that *for large stellar masses* ($M_\star > 10^{11}\,{\rm M_\odot}$) *the threshold ratio tends to the local one:* $\log_{10}(M_\bullet/M_\star) \sim -3$. This indicates that quasar quenching of overmassive systems at high-z leads naturally to a ratio similar to the one implicit in the local relation. Central SMBHs grow until feedback self-regulates it, or the available gas runs out. Then, when the quasar's duty cycle drops below unity, efficient star formation can resume; mergers with other galaxies also bring additional mass in stars. Eventually, stellar mass growth by in-situ formation and mergers pushes the system below the threshold and towards the local $M_\bullet - M_\star$ relation.

Note that *this threshold can only be crossed once in the downward direction.* If a SMBH is overmassive, it will decrease the average star formation efficiency until it shuts off. Once stars begin to form again, the system will move downward and eventually cross the threshold. At that point, star formation is not quenched anymore; a runaway process occurs that pushes the system more into the star-forming region. This process ends with the system close to the local $M_\bullet - M_\star$ relation.

Figure 2 shows the location of the aforementioned 35 overmassive systems discovered by JWST at $z > 4$. All these systems are either well inside the area where star formation is quenched or close to the threshold value. Typically, higher redshift systems (i.e., with $z > 5$, see the ones by Kokorev et al. 2023 and Bogdán et al. 2023) are deeper into the quenching regime than lower redshift ones, with $z \sim 4$. The only system whose location is marginally compatible with the threshold, possibly indicating that the galaxy is about to restart efficient star formation, is CEERS 01665, at $z = 4.483$ (Harikane et al. 2023).

In Fig. 2 we also show a sample of local $z \sim 0$ galaxies from Reines & Volonteri (2015), which are used to infer the local $M_\bullet - M_\star$ relation. Although the threshold ratio $M_\bullet/M_\star$ is computed for high-z systems and not necessarily valid in the local Universe, it is reassuring to see that most of the local galaxies on the $M_\bullet - M_\star$ relation reside well into the regime where star formation is active, or close to the boundary. This fact further suggests that high-z overmassive systems migrate towards the local $M_\bullet - M_\star$ relation by crossing the threshold once. Some of the $z \sim 4$ overmassive systems share their locus in the diagram with these local galaxies.

3.2. The Redshift Evolution of the $M_\bullet - M_\star$ Relation

We now derive a function to describe the redshift evolution of the $M_\bullet - M_\star$ relation. Based on the two principles described in Sec. 2, we obtained the following scaling for $M_\bullet$ and $M_\star$ as a function of the circular velocity of the host halo: $M_\bullet \propto v_c^5$ and $M_\star \propto v_c^0$. Hence, $M_\bullet/M_\star \propto v_c^5$. Given the scaling of the circular velocity with redshift (Eq. 2), we obtain:

$$\frac{M_\bullet}{M_\star} \propto \xi(z)^{5/6}(1+z)^{5/2} \qquad (7)$$

Note that $\xi(z)$ is a weakly varying function of the redshift; the main scaling is with the term $(1+z)^{5/2}$. We define a redshift evolution function $\mathcal{E}(z)$:

$$\mathcal{E}(z) = \frac{\xi(z)^{5/6}(1+z)^{5/2}}{\xi(0)^{5/6}}, \qquad (8)$$

and note that $\mathcal{E}(z)$ indicates how much SMBHs at redshift z are overmassive when compared to what is expected from local ($z = 0$) relations. The value of $\mathcal{E}(z)$ for $0 < z < 15$ is shown in Fig. 3.

For example, for typical overmassive systems at $z \sim 5$ (Pacucci et al. 2023), we obtain $\mathcal{E}(5) \approx 55 \approx 1.74\,{\rm dex}$ (see Fig. 3). This indicates that SMBHs in the sample should be ~ 55 times overmassive compared to the local $M_\bullet - M_\star$ relation. Equation 8 implies that $M_\bullet \sim M_\star$ by $z \sim 30$, in agreement with standard scenarios for the formation of black hole seeds (Barkana & Loeb 2001).
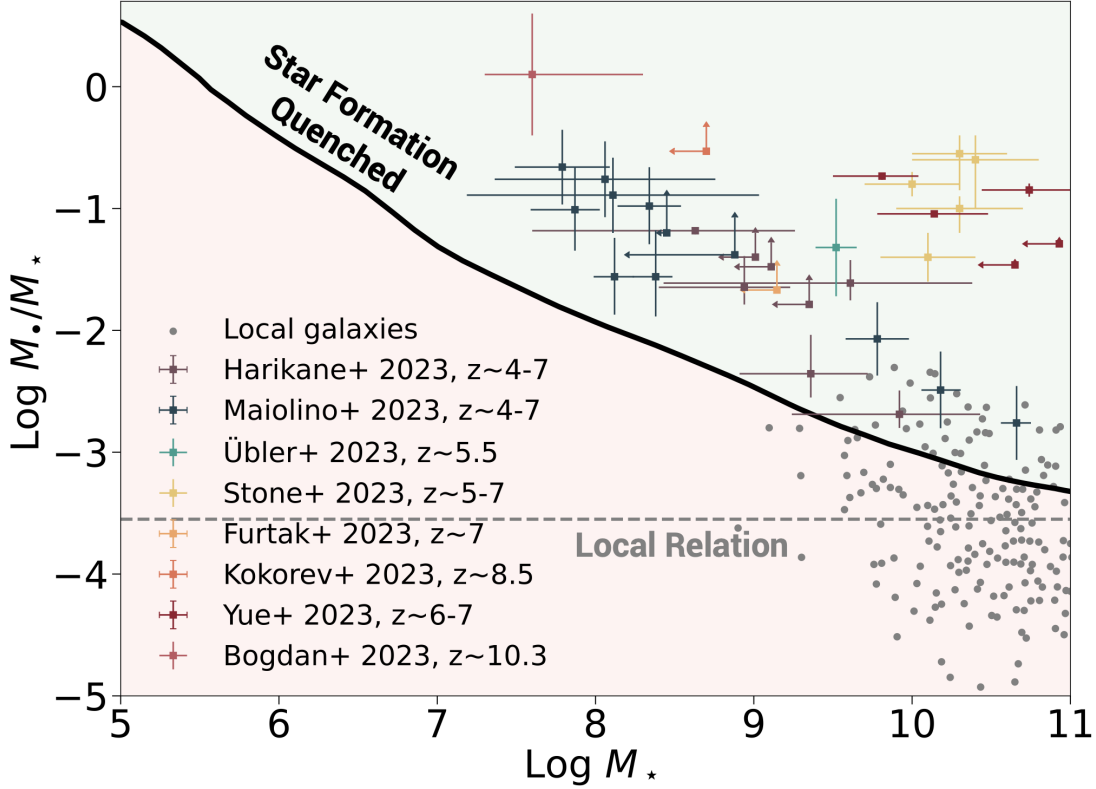
Figure 2. Condition on the ratio $M_\bullet/M_\star$ for quasar feedback to suppress the *average* star formation efficiency. Active galaxies that reside in the green area, with a ratio $M_\bullet/M_\star$ above the threshold (indicated with a black line), experience quasar activity that increases the gas temperature above the virial value. Colored symbols indicate overmassive systems discovered by JWST at $z > 4$, as the legend indicates. Gray symbols indicate local galaxies on the $M_\bullet - M_\star$ relation from Reines & Volonteri (2015), whose ratio $M_\bullet/M_\star$ is shown as a dashed line.
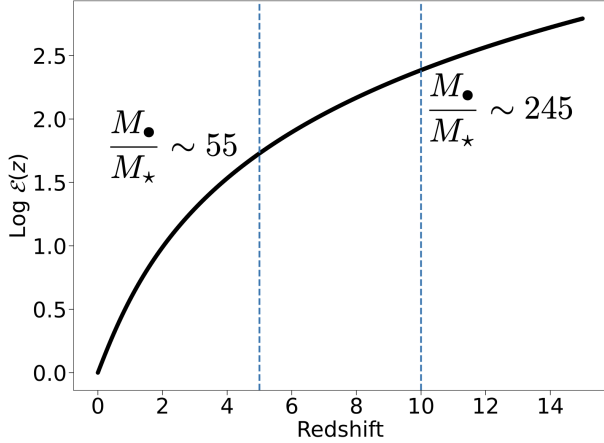
Figure 3. Value of the logarithm in base 10 of $\mathcal{E}(z)$ for $0 < z < 15$. The values for $z = 5$ and $z = 10$ are marked and indicated.

In Fig. 4, we use the factor $\mathcal{E}(z)$ to rescale the local relation (Reines & Volonteri 2015) to higher redshifts. The scaling-up to $z = 5$, the median redshift of the sample of overmassive systems used by Pacucci et al. (2023), agrees remarkably well with the inferred relation deter-mined by the same study. We also scale up the local relation to $z = 10$ (i.e., a factor of 245). This scaled-up relation is still too low to explain the extremely overmassive system at $z \sim 10$ described by Bogdán et al. (2023). Uncertainties in its black hole and stellar mass could explain the discrepancy.

4. DISCUSSION AND CONCLUSIONS

Before the Hubble Space Telescope performed its first deep field image, it was argued that it would not re-veal significantly more galaxies than ground telescopes (Bahcall et al. 1990).

A similar surprise came during the first year of JWST, which unraveled many galaxies at $z > 4$ hosting a SMBH. Line diagnostics and X-ray detections suggest typical SMBH masses of $\sim 10^6 - 10^8\,M_\odot$. With bolo-metric luminosities $1-2$ orders of magnitude lower than the bright quasars discovered thus far at $z > 6$, their relative faintness allowed the detection of starlight from their hosts. For the first time, observers could inves-tigate the relation between black hole and stellar mass at high-z. The data led to the conclusion that high-z
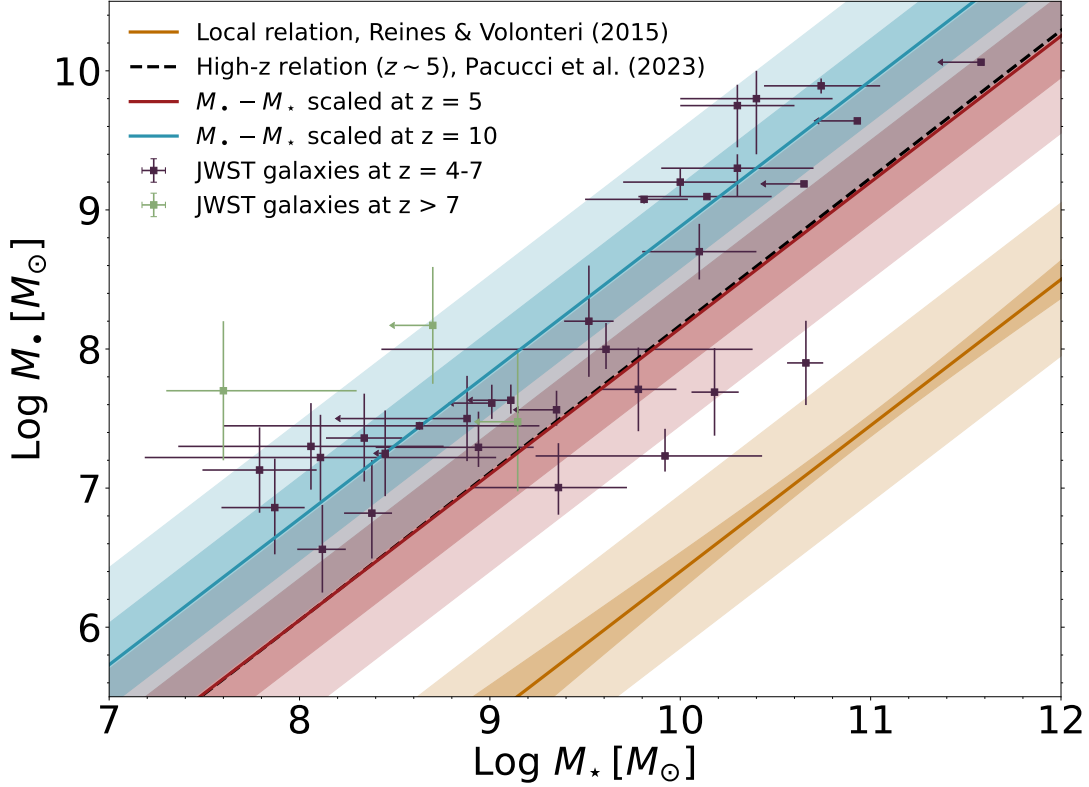
Figure 4. The $M_\bullet - M_\star$ plane is populated with the overmassive systems discovered by JWST at $z > 4$ (categorized into two groups: $4 < z < 7$ and $z > 7$). The local relation (Reines & Volonteri 2015) is shown in yellow and scaled up at $z = 5$ (red) and $z = 10$ (blue), according to Eq. 8. The dashed, black line indicates the high-z relation inferred from JWST data by Pacucci et al. (2023). Our model for the redshift evolution of the $M_\bullet - M_\star$ relation predicts the trend remarkably well.

SMBHs are $10 - 100$ times overmassive with respect to the stellar mass of their hosts (Pacucci et al. 2023).

Significant uncertainties affect the determination of the stellar mass, derived from SED fitting to galaxy templates, and the SMBH mass, derived from single-epoch virial estimators, based, for example, on the width of the Hα line of the broad line region (see, e.g., Greene & Ho 2005). These methods are calibrated in the local Universe ($z \ll 1$) and have yet to be thoroughly tested at higher redshift (see, e.g., the discussion in Maiolino et al. 2023a). Notwithstanding these uncertainties, to retrieve the local scaling relations, the black hole masses (stellar masses) of these high-z overmassive systems would need to be overestimated (underestimated) by a factor ~ 60 (Pacucci et al. 2023).

If further data confirms this result, it opens up an important question. Why are these high-z black holes so overmassive with respect to the stellar mass of their hosts while other relations, such as the $M_\bullet - \sigma$, hold (Maiolino et al. 2023a)?

In this Letter, we have developed a model to explain high-z overmassive systems. The overarching idea is that SMBHs exert an outsized influence on their host galaxies at high-z because their hosts are small, and the

black holes have duty cycles close to unity at $z > 4$. Hence, the black hole mass is the primary parameter responsible for high-z star formation quenching. It follows that black hole mass growth is regulated by its energy output, while the stellar mass growth is quenched by it, and its instantaneous value is uncorrelated to the global properties of the host halo.

Our main results are as follows:

- In the high-z Universe, the ratio $M_\bullet/M_\star$ controls the average star formation efficiency. If $M_\bullet/M_\star > 8 \times 10^{18} (n\Lambda/f_{\rm Edd})[(\Omega_b M_h)/(\Omega_m M_\star) - 1]$, star formation is quenched by quasar feedback. Once this threshold is crossed, a runaway process brings the originally overmassive system close to the local $M_\bullet - M_\star$ relation.

- The local $M_\bullet - M_\star$ relation evolves with redshift as $\mathcal{E}(z) = \xi(z)^{5/6}(1+z)^{5/2}/\xi(0)^{5/6} \propto (1+z)^{5/2}$, where $\xi(z)$ is weakly dependent on redshift. We find a value of $\mathcal{E}(z = 5) = 55$, which is in excellent agreement with current JWST data and the high-z relation inferred by Pacucci et al. (2023).

Our model suggests that early SMBHs, primarily if formed as heavy seeds of initial mass $\sim 10^4 - 10^5 \, \mathrm{M}_\odot$

(see, e.g., Ferrara et al. 2014), affect the evolution of the entire host. Eventually, the activity duty cycle of the quasar drops significantly below unity, and efficient star formation can resume. Once the galaxy grows via mergers, more stars and cool gas are added. Eventually, stars catch up with the SMBH mass, self-regulation of star formation occurs (see, e.g., Wyithe & Loeb 2003), and the system reaches the local $M_\bullet - M_\star$ relation.

Understanding the high-redshift evolution of the scaling relations is fundamental for two reasons. First, it informs us about the physical processes that regulate the growth of the black hole and stellar component (see, e.g., Vogelsberger et al. 2014; Schaye et al. 2015; Weinberger et al. 2017; Nelson et al. 2018; Terrazas et al. 2020; Piotrowska et al. 2022; Bluck et al. 2023). Second, it may inform us of the seeding mechanism that formed the central black hole in the first place. In fact, several studies have shown that a high ratio $M_\bullet/M_\star$ may be indicative of the formation of a heavy seed (see, e.g., Agarwal et al. 2013; Natarajan et al. 2017; Visbal & Haiman 2018; Scoggins et al. 2023; Natarajan et al. 2023) at $z > 20$. The study of the properties of central SMBHs and their hosts at high-z, as well as the detection of extremely massive, and rare SMBHs at $z > 10$, will determine if heavy seed formation channels were active in the high-z Universe (Pacucci & Loeb 2022).

JWST and upcoming facilities such as Euclid, the Rubin Observatory, and the Roman Space Telescope are pushing the observable horizon for black holes farther in redshift and lower in mass. The discovery of still undetected populations of compact objects will ultimately clarify how all the black holes in the Universe formed.

REFERENCES

Agarwal, B., Davis, A. J., Khochfar, S., Natarajan, P., & Dunlop, J. S. 2013, MNRAS, 432, 3438, doi: 10.1093/mnras/stt696

Baggen, J. F. W., van Dokkum, P., Labbé, I., et al. 2023, ApJL, 955, L12, doi: 10.3847/2041-8213/acf5ef

Bahcall, J. N., Guhathakurta, P., & Schneider, D. P. 1990, Science, 248, 178, doi: 10.1126/science.248.4952.178

Barkana, R., & Loeb, A. 2001, PhR, 349, 125, doi: 10.1016/S0370-1573(01)00019-9

Behroozi, P., Wechsler, R. H., Hearin, A. P., & Conroy, C. 2019, MNRAS, 488, 3143, doi: 10.1093/mnras/stz1182

Bennert, V. N., Auger, M. W., Treu, T., Woo, J.-H., & Malkan, M. A. 2011, ApJ, 742, 107, doi: 10.1088/0004-637X/742/2/107

Bluck, A. F. L., Conselice, C. J., Ormerod, K., et al. 2023, arXiv e-prints, arXiv:2311.02526, doi: 10.48550/arXiv.2311.02526

Bogdán, Á., Goulding, A. D., Natarajan, P., et al. 2023, Nature Astronomy, doi: 10.1038/s41550-023-02111-9

Booth, C. M., & Schaye, J. 2011, MNRAS, 413, 1158, doi: 10.1111/j.1365-2966.2011.18203.x

Caplar, N., Lilly, S. J., & Trakhtenbrot, B. 2018, ApJ, 867, 148, doi: 10.3847/1538-4357/aae691

Cen, R., & Haiman, Z. 2000, ApJL, 542, L75, doi: 10.1086/312937

Chen, Z., Faber, S. M., Koo, D. C., et al. 2020, ApJ, 897, 102, doi: 10.3847/1538-4357/ab9633

Cole, J. W., Papovich, C., Finkelstein, S. L., et al. 2023, arXiv e-prints, arXiv:2312.10152, doi: 10.48550/arXiv.2312.10152

Decarli, R., Falomo, R., Treves, A., et al. 2010, MNRAS, 402, 2453, doi: 10.1111/j.1365-2966.2009.16049.x

Di Matteo, T., Colberg, J., Springel, V., Hernquist, L., & Sijacki, D. 2008, ApJ, 676, 33, doi: 10.1086/524921

Ding, X., Onoue, M., Silverman, J. D., et al. 2023, Nature, 621, 51, doi: 10.1038/s41586-023-06345-5

Fabian, A. C. 2012, ARA&A, 50, 455, doi: 10.1146/annurev-astro-081811-125521

Ferrara, A., Salvadori, S., Yue, B., & Schleicher, D. 2014, MNRAS, 443, 2410, doi: 10.1093/mnras/stu1280

Ferrarese, L., & Merritt, D. 2000, ApJL, 539, L9, doi: 10.1086/312838

Furtak, L. J., Labbé, I., Zitrin, A., et al. 2023, arXiv e-prints, arXiv:2308.05735, doi: 10.48550/arXiv.2308.05735

Gebhardt, K., Bender, R., Bower, G., et al. 2000, ApJL, 539, L13, doi: 10.1086/312840

Gelli, V., Salvadori, S., Ferrara, A., & Pallottini, A. 2023, arXiv e-prints, arXiv:2310.03065, doi: 10.48550/arXiv.2310.03065

Greene, J. E., & Ho, L. C. 2005, ApJ, 630, 122, doi: 10.1086/431897

Greene, J. E., Labbe, I., Goulding, A. D., et al. 2023, arXiv e-prints, arXiv:2309.05714, doi: 10.48550/arXiv.2309.05714

Harikane, Y., Zhang, Y., Nakajima, K., et al. 2023, ApJ, 959, 39, doi: 10.3847/1538-4357/ad029e

Heckman, T. M., & Best, P. N. 2014, ARA&A, 52, 589, doi: 10.1146/annurev-astro-081913-035722

King, A., & Pounds, K. 2015, Annual Review of Astronomy and Astrophysics, 53, 115, doi: 10.1146/annurev-astro-082214-122316

Kisaka, S., & Kojima, Y. 2010, MNRAS, 405, 1285, doi: 10.1111/j.1365-2966.2010.16530.x

Kocevski, D. D., Onoue, M., Inayoshi, K., et al. 2023, ApJL, 954, L4, doi: 10.3847/2041-8213/ace5a0

Kokorev, V., Fujimoto, S., Labbe, I., et al. 2023, ApJL, 957, L7, doi: 10.3847/2041-8213/ad037a

Kormendy, J., & Ho, L. C. 2013, Annual Review of Astronomy and Astrophysics, 51, 511, doi: 10.1146/annurev-astro-082708-101811

Lauer, T. R., Tremaine, S., Richstone, D., & Faber, S. M. 2007, ApJ, 670, 249, doi: 10.1086/522083

Madau, P., & Rees, M. J. 2000, ApJL, 542, L69, doi: 10.1086/312934

Magorrian, J., Tremaine, S., Richstone, D., et al. 1998, AJ, 115, 2285, doi: 10.1086/300353

Maiolino, R., Scholtz, J., Curtis-Lake, E., et al. 2023a, arXiv e-prints, arXiv:2308.01230. https://arxiv.org/abs/2308.01230

Maiolino, R., Scholtz, J., Witstok, J., et al. 2023b, arXiv e-prints, arXiv:2305.12492, doi: 10.48550/arXiv.2305.12492

Malbon, R. K., Baugh, C. M., Frenk, C. S., & Lacey, C. G. 2007, MNRAS, 382, 1394, doi: 10.1111/j.1365-2966.2007.12317.x

Matthee, J., Naidu, R. P., Brammer, G., et al. 2023, arXiv e-prints, arXiv:2306.05448, doi: 10.48550/arXiv.2306.05448

Merloni, A., Bongiorno, A., Bolzonella, M., et al. 2010, ApJ, 708, 137, doi: 10.1088/0004-637X/708/1/137

Nakajima, K., Ouchi, M., Isobe, Y., et al. 2023, ApJS, 269, 33, doi: 10.3847/1538-4365/acd556

Natarajan, P., Pacucci, F., Ferrara, A., et al. 2017, ApJ, 838, 117, doi: 10.3847/1538-4357/aa6330

Natarajan, P., Pacucci, F., Ricarte, A., et al. 2023, arXiv e-prints, arXiv:2308.02654, doi: 10.48550/arXiv.2308.02654

Nelson, D., Pillepich, A., Springel, V., et al. 2018, MNRAS, 475, 624, doi: 10.1093/mnras/stx3040

Pacucci, F., & Loeb, A. 2022, MNRAS, 509, 1885, doi: 10.1093/mnras/stab3071

Pacucci, F., Nguyen, B., Carniani, S., Maiolino, R., & Fan, X. 2023, ApJL, 957, L3, doi: 10.3847/2041-8213/ad0158

Peng, C. Y., Impey, C. D., Rix, H.-W., et al. 2006, ApJ, 649, 616, doi: 10.1086/506266

Piotrowska, J. M., Bluck, A. F. L., Maiolino, R., & Peng, Y. 2022, MNRAS, 512, 1052, doi: 10.1093/mnras/stab3673

Planck Collaboration, Aghanim, N., Akrami, Y., et al. 2020, A&A, 641, A6, doi: 10.1051/0004-6361/201833910

Rees, M. J., & Ostriker, J. P. 1977, MNRAS, 179, 541, doi: 10.1093/mnras/179.4.541

Reines, A. E., & Volonteri, M. 2015, ApJ, 813, doi: 10.1088/0004-637X/813/2/82

Robertson, B., Hernquist, L., Cox, T. J., et al. 2006, ApJ, 641, 90, doi: 10.1086/500348

Robinson, D., Avestruz, C., & Gnedin, N. Y. 2022, ApJ, 936, 50, doi: 10.3847/1538-4357/ac85e1

Schaye, J., Crain, R. A., Bower, R. G., et al. 2015, MNRAS, 446, 521, doi: 10.1093/mnras/stu2058

Schutte, Z., & Reines, A. E. 2022, Nature, 601, 329, doi: 10.1038/s41586-021-04215-6

Scoggins, M. T., Haiman, Z., & Wise, J. H. 2023, MNRAS, 519, 2155, doi: 10.1093/mnras/stac3715

Sijacki, D., Vogelsberger, M., Genel, S., et al. 2015, MNRAS, 452, 575, doi: 10.1093/mnras/stv1340

Silk, J., & Rees, M. J. 1998, A&A, 331, L1, doi: 10.48550/arXiv.astro-ph/9801013

Stone, M. A., Lyu, J., Rieke, G. H., Alberts, S., & Hainline, K. N. 2023, arXiv e-prints, arXiv:2310.18395, doi: 10.48550/arXiv.2310.18395

Terrazas, B. A., Bell, E. F., Pillepich, A., et al. 2020, MNRAS, 493, 1888, doi: 10.1093/mnras/staa374

Trakhtenbrot, B., & Netzer, H. 2010, MNRAS, 406, L35, doi: 10.1111/j.1745-3933.2010.00876.x

Übler, H., Maiolino, R., Curtis-Lake, E., et al. 2023, A&A, 677, A145, doi: 10.1051/0004-6361/202346137

Visbal, E., & Haiman, Z. 2018, ApJL, 865, L9, doi: 10.3847/2041-8213/aadf3a

Vogelsberger, M., Genel, S., Springel, V., et al. 2014, Nature, 509, 177, doi: 10.1038/nature13316

Wang, F., Yang, J., Fan, X., et al. 2021, ApJL, 907, L1, doi: 10.3847/2041-8213/abd8c6

Weinberger, R., Springel, V., Hernquist, L., et al. 2017, MNRAS, 465, 3291, doi: 10.1093/mnras/stw2944

White, R. L., Becker, R. H., Fan, X., & Strauss, M. A. 2003, AJ, 126, 1, doi: 10.1086/375547

Wyithe, J. S. B., & Loeb, A. 2003, ApJ, 595, 614, doi: 10.1086/377475

Yue, M., Eilers, A.-C., Simcoe, R. A., et al. 2023, arXiv e-prints, arXiv:2309.04614, doi: 10.48550/arXiv.2309.04614