The Host Galaxies of High-Redshift Quasars

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Abstract

In the early Universe, we observe supermassive black holes with masses of up to $10^9 M_\odot$, accreting at or even above the Eddington limit. These high-redshift quasars are some of the most luminous objects in the Universe, and raise many questions about the formation and growth of the first black holes. Investigating their host galaxies provides a useful probe for understanding these high-redshift quasars. In the local Universe, there are clear correlations between the mass of a supermassive black hole and the properties of its host galaxy, indicating a black hole–galaxy co-evolution. Exploring how these black hole–host relations evolve with redshift can give valuable insights into why these relations exist. Studying the host galaxies of high-redshift quasars thus provides vital insights into the early growth of supermassive black holes and the black hole–galaxy connection. In this thesis I use three techniques to study the host galaxies of high-redshift quasars: the MERAXES semi-analytic model, the BLUE TIDES hydrodynamical simulation, and observations with the Hubble Space Telescope.

MERAXES is a semi-analytic model designed to study galaxy formation and evolution at high redshift. Using this model, I study the sizes, angular momenta and morphologies of high-redshift galaxies. I also use MERAXES to study the evolution of black holes and their host galaxies from high redshift to the present day. The model predicts no significant evolution in the black hole–host mass relations out to high redshift, with the growth of galaxies and black holes tightly related even in the early Universe. I also examine the growth mechanisms of black holes in MERAXES, finding that the majority of black hole growth is caused by internal disc instabilities, and not by galaxy mergers.

I then use the BLUE TIDES cosmological hydrodynamical simulation to investigate the detailed properties of quasar host galaxies at $z = 7$. I find that the hosts of quasars are generally highly star-forming and bulge dominated, and are significantly more compact than the typical high-redshift galaxy. Using BLUE TIDES I make predictions for observations of quasars with the James Webb Space Telescope, finding that detecting quasar hosts at these redshifts may be possible, but will still be challenging with this groundbreaking instrument.

Finally, I use observations from the Hubble Space Telescope to obtain deep upper limits on the rest-frame ultraviolet luminosities of six $z \simeq 6$ quasars. I also detect up to 9 potential companion galaxies surrounding these quasars, which may be interacting with their host galaxies. Observations with the upcoming James Webb Space Telescope are needed to detect quasar host galaxies in the rest-frame ultraviolet and optical for the first time.
Declaration of Authorship

I declare that this thesis titled ‘The Host Galaxies of High-Redshift Quasars’ and the work presented in it are my own. I confirm that:

- The thesis comprises only my original work towards the Doctor of Philosophy except where indicated in the preface;
- Due acknowledgement has been made in the text to all other material used; and
- The thesis is fewer than 100,000 words in length, exclusive of tables, maps, bibliographies and appendices.

Madeline Anne Marshall
Preface

While the majority of the work presented in this thesis is my own, some sections are the result of collaborations. Any work that is not my own is cited appropriately in the text. Additional details are outlined below.

- Chapter 1 presents a review of cosmology, quasars, the host galaxies of high-redshift quasars and astrophysical simulation techniques. This work is entirely my own, and some small portions have been adapted from the four papers outlined below.

- Chapters 2 and 3 present the Meraxes semi-analytic model and predictions of the sizes, angular momenta and morphologies of high-redshift galaxies. These chapters are based closely on the publication:


  I conducted the majority of this work, under the supervision of Stuart Wyithe and Simon Mutch and with suggestions from Yuxiang Qin and Gregory Poole. The updates to the Meraxes code were continued from initial work by Simon Mutch.

- Chapter 4 presents predictions for the evolution of black holes and the black hole–host relations from the Meraxes model. This is based on the publication:


  The description of the black hole growth model in Meraxes in Chapter 2 is also adapted from this publication. I conducted the majority of this work, under the supervision of Stuart Wyithe and Simon Mutch and with suggestions from Yuxiang Qin and Gregory Poole.
• Chapter 5 presents predictions for the host galaxies of $z = 7$ quasars from the BlueTides simulation. This is based on the publication:


I conducted the majority of this work, under the supervision of Stuart Wyithe and in collaboration with the core BlueTides team of Tiziana Di Matteo, Rupert Croft and Yueying Ni. Yueying Ni provided the base code from which the majority of this analysis was adapted, as well as the luminosity function in Figure 5.1, and the merger image shown in Figure 5.20. Stephen Wilkins and Jussi Kuusisto provided assistance with the SynthObs mock imaging software.

• Chapter 6 presents a study of the host galaxies of six $z \simeq 6$ quasars observed with the Hubble Space Telescope. This is based on the publication:


I conducted the majority of this work, under the supervision of Stuart Wyithe and in collaboration with Rogier Windhorst, Seth Cohen, Rolf Jansen and Mira Mechtley, and their extended team. The successful HST proposals were completed by Mira Mechtley, Rogier Windhorst, Seth Cohen, Linhua Jiang, Rolf Jansen, Russell Ryan, Glenn Schneider, Nimish Hathi, William Keel, Anton Koekemoer, Huub Röttgering, Evan Scannapieco, Donald Schneider, Michael Strauss and Haojing Yan. The HST images were processed by Mira Mechtley with assistance from the wider team. Mira Mechtley created the PSFMC software and the code to run this on the HST data and produce the output images. Mira Mechtley and Victoria Jones analysed the images with PSFMC, testing whether the quasar should be modelled with a Sérsic index as well as a point source. The original analysis of NDWFS J1425+3254 was contained in Mechtley (2014). I re-analysed all images with PSFMC, developed the host measurement technique, and performed the full analysis of the hosts and companions, as well as writing the text. Additional co-authors provided comments and suggestions.
Chapter 7 presents a summary. This work is entirely my own, and some small portions been adapted from the four papers outlined above.

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This thesis made use of Python packages and software AstroPy (Astropy Collaboration et al., 2013), AstroDataPy (Qin, 2018), astroRMS (Mechtley, 2011), BigFile (Feng et al., 2017), corner (Foreman-Mackey, 2016), Cosmolopy (Kramer, 2010), DRAGONS (Mutch, 2013), emcee (Foreman-Mackey et al., 2013), FLARE (Wilkins, 2019a), Gaepsi2 (Feng, 2018), Matplotlib (Hunter, 2007), NumPy (van der Walt et al., 2011), Pandas (Pandas Development Team, 2020), Photutils (Bradley et al., 2018), psfMC (Mechtley, 2019), SciPy (Virtanen et al., 2020), Seaborn (Waskom, 2012), Synphot (STScI Development Team, 2018) and SynthObs (Wilkins, 2019b). This thesis also makes use of version 17.00 of Cloudy, last described by Ferland et al. (2017).
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To Rogier Windhorst, Seth Cohen and Rolf Jansen, for inviting me to work with you at Arizona State University only one month into my PhD, and subsequently changing my entire research project, offering me JWST data of two high-redshift quasars. After so many delays on JWST’s launch my project had to change again. However, it’s worked out better than I could have hoped, and this very much is thanks to you.

Thank you also to Tiziana Di Matteo, whose arrival at the University of Melbourne in 2018 provided the piece of the puzzle that this thesis was missing. Collaborating with Tiziana, Rupert Croft and Yueying Ni has been fantastic, and I am very grateful to have had the opportunity to work with you all.

Thank you to the many other collaborators who have contributed to the work in this thesis, those who I’ve befriended at conferences, and those who’ve chatted to me about on my work along the way.

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Last, but certainly not least, to my wonderful family. Thank you to my parents for being extremely supportive and encouraging, and always believing in me. Thank you also for letting me move back home for the last 4 months of my PhD due to the ongoing pandemic, and supporting me through this crazy time. Finally, to Oliver, thank you for going on this journey with me.
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Chapter 1

Introduction

In this chapter, I first introduce the standard ΛCDM cosmological model, including the expansion of the Universe and cosmological distance measures, in Section 1.1. I then introduce black holes and quasars in Section 1.2, before focusing particularly on quasars in the early Universe in Section 1.3. I discuss the first black holes in the Universe, or black hole seeds, and the environments of high-redshift quasars. I then focus on the host galaxies of high-redshift quasars in Section 1.4, discussing their observability in the rest-frame ultraviolet and far-infrared, before reviewing the local correlations between black holes and their hosts, and the current understanding of these relations at higher redshifts. In Section 1.5 I introduce common simulation techniques used to study galaxies and black holes in the Universe on cosmological scales. An outline of this thesis, which studies the host galaxies of high-redshift quasars using these techniques and observations, is given in Section 1.6.

1.1 Cosmology

The Universe began 13.8 billion years ago, and was extremely hot and dense. It rapidly expanded, cooling and forming subatomic particles, which in the first few minutes combined to form atoms—75 per cent neutral hydrogen and 25 per cent helium by mass. 380,000 years later, the Universe had cooled enough for photons to decouple with matter, marking the beginning of the transparent Universe and leaving behind the cosmic microwave background (Penzias & Wilson, 1965). From this point, it took at least another ~ 30 Myr (Naoz et al., 2006; Fialkov et al., 2012) for the atoms in the Universe to collapse under
gravity to form the first light in the Universe, produced by nuclear fusion in the centre of the first stars and protogalaxies, ending the cosmic dark ages. Continued gravitational collapse eventually formed the first galaxies, which began to reionize the neutral Universe, forming the ionized Universe in which we live today.

The Universe can be well described by the 6-parameter ΛCDM (Lambda cold dark matter) model. The ΛCDM model assumes that the Universe is composed of ordinary matter (baryons and electrons) and photons (∼ 5%), neutrinos (∼ 1%), cold dark matter (CDM; ∼ 26%), and dark energy (Λ; ∼ 69%) (e.g. Planck Collaboration, 2016). This model assumes that the Universe can be described by the Friedmann–Lemaître–Robertson–Walker (FLRW) metric (Friedman, 1922; Lemaître, 1933), the solution to the theory of General Relativity (Einstein, 1917) assuming a homogeneous, isotropic, expanding Universe.

Under this model, the expansion rate of the Universe is described by

\[ H(a) \equiv \frac{\dot{a}}{a} = H_0 \sqrt{\Omega_m a^{-3} + \Omega_R a^{-4} + \Omega_\Lambda}. \]  

(1.1)

where \( a(t) \) is the scale factor of the Universe at time \( t \), where \( 0 \leq a \leq 1 \) and \( a = 1 \) today. Here \( \Omega_m, \Omega_R \) and \( \Omega_\Lambda \) are the present-day matter, radiation and dark energy densities, respectively, defined relative to the critical density of the Universe \( \Omega_x \equiv \frac{\rho_x(t=t_0)}{\rho_{\text{crit}}} \), where \( \rho_{\text{crit}} = \frac{3H_0^2}{8\pi G} \) and \( G \) is the gravitational constant. The Hubble constant \( H_0 \) is the expansion rate of the Universe today (Hubble, 1929), measured to be ∼ 70 km/s/Mpc (e.g. Freedman et al., 2001; Beutler et al., 2011; Riess et al., 2011), and \( h = H_0/100 \) km/s/Mpc. Measurements find \( \Omega_R \approx 10^{-4} \), and so neglecting this term, Equation 1.1 can be solved analytically for \( a(t) \), with

\[ a(t) = \left( \frac{\Omega_m}{\Omega_\Lambda} \right)^{1/3} \sinh^{2/3}(t/t_\Lambda) \]  

(1.2)

where \( t_\Lambda \equiv 2/(3H_0\sqrt{\Omega_\Lambda}) \) (see e.g. Frieman et al., 2008; Deruelle & Uzan, 2018).

Due to the expansion of the Universe, light emitted from an object travels through expanding space. This ‘stretches’ the photons, decreasing their frequency from \( f_{\text{emitted}} \) to \( f_{\text{observed}} = a(t_{\text{emitted}})f_{\text{emitted}} \), where \( t_{\text{emitted}} \) is the time at which the light from the object was emitted. As wavelength \( \lambda = c/f \), where \( c \) is the speed of light, this corresponds to an increase in wavelength of \( \lambda_{\text{emitted}} \) to \( \lambda_{\text{observed}} = (1 + z)\lambda_{\text{emitted}} \), where \( z \) is the redshift, related to the scale factor \( a \) by \( a = \frac{1}{1+z} \). The redshift of objects can be measured through
the emission and absorption spectra of their constituent atoms, which have known frequencies. As this can be directly and simply measured, the redshift of an object is commonly used as a measure of time and distance from when the photons were emitted. By assuming a cosmology, redshifts can be used to determine distance measures commonly used in cosmology and throughout this thesis, which are introduced below (see e.g. Hogg, 1999; Schneider, 2006).

Co-moving coordinates are defined on a reference frame which moves with the Hubble flow, or the expansion of the Universe. The co-moving distance between two nearby galaxies is

$$d_C = d_P / a(t_{emitted}) = d_P (1 + z), \quad (1.3)$$

where $d_P$ is the distance between them that would be measured using a ruler, at the time that they are being observed—the ‘proper’ distance. The co-moving distance between two galaxies does not increase with time due to the expansion of the Universe, while their true physical or proper distance does.

The angular diameter distance $d_A$ relates the physical size of an object $D$ to its angular size on the sky $\theta$:

$$d_A = \frac{D}{\theta} = \frac{1}{1 + z} \int_0^z \frac{c}{H(z)} \, dz. \quad (1.4)$$

This peaks at $z \approx 1.7$, and so the angular size of an object with fixed size $D$ will decrease from the local Universe to $\approx 1.7$, and will then increase at larger redshifts.

The luminosity distance $d_L$ relates the observed bolometric flux $F$ of an object to its bolometric luminosity $L$,

$$d_L = \sqrt{\frac{L}{4\pi F}}, \quad (1.5)$$

and is related to the angular diameter distance by $d_L = (1+z)^2 d_A$. The luminosity distance can be used to convert from apparent magnitude $m = -2.5 \log(F/F_0)$, a measure of the observed brightness of the object in a given filter or bandpass, to the absolute magnitude $M$, the apparent magnitude the object would have if it were viewed at a distance of 10 pc:

$$M = m - 5 \log(d_L/10\text{ pc}) - K. \quad (1.6)$$

Here $5 \log(d_L/10\text{ pc})$ is often defined as the distance modulus $DM$ and $K$ is the k-correction, which accounts for sources at different redshifts being sampled at different
rest-frame frequencies (e.g. Oke & Sandage, 1968; Hogg et al., 2002). Often it is simply assumed that \( K = -2.5 \log(1 + z) \), which accounts for the flux per unit wavelength changing with redshift by a factor of \((1 + z)\).

Now that I have introduced these cosmological concepts, I will focus on the most peculiar of objects within this Universe—black holes.

### 1.2 Black holes

Black holes are a singularity in space-time (Penrose, 1965; Hawking, 1967), a location of extreme density from which neither matter nor light can escape. The Schwarzschild radius \( r_s = \frac{2GM}{c^2} \) defines the location of a singularity in the solution to Einstein’s field equations for the gravitational field surrounding a non-rotating, spherically symmetric body of mass \( M \) (Schwarzschild, 1916). This is equivalent to the radius of a spherically symmetric body for which the escape velocity is equal to the speed of light in Newtonian mechanics (Michell, 1784; Laplace, 1796). Any object smaller than the Schwarzschild radius is a black hole, with \( r = r_s \) the event horizon.

Supermassive black holes with masses of \( M_{\text{BH}} \simeq 10^6 \text{–} 10^{10} M_\odot \) are found at the centre of almost every galaxy. Their presence can be inferred from the dynamics of the gas and stars in the centre of the galaxy (e.g. Greenhill et al., 1995; Miyoshi et al., 1995; Ferrarese et al., 1996; van der Marel & van den Bosch, 1998). Some supermassive black holes are active, growing via gas accretion from an extremely hot and luminous accretion disc (e.g. Salpeter, 1964). These active black holes, or active galactic nuclei (AGN), are some of the most luminous objects in the Universe, with emission observed over a vast range of wavelengths. X-rays and gamma-rays are emitted from the inner regions of the nucleus. The thermally-emitting accretion disc produces radiation in the ultraviolet (UV), which is reprocessed by dust in an obscuring region resulting in mid-infrared (IR) radiation. Emission lines from the narrow- and broad-line regions are observable at optical wavelengths, and radio emission is sometimes caused by synchrotron radiation from large-scale radio jets. Quasars are a class of AGN which appear on the sky as very compact sources, or star-like, and hence are also referred to as quasi-stellar objects (QSOs). Their discovery in the radio wavelengths (Schmidt, 1963) lead to the name quasar, which is an abbreviation of sorts
from the phrase ‘quasi-stellar radio sources’ (Chiu, 1964). See, for example, Schneider (2006) and Heckman & Best (2014) for a comprehensive review of AGN and quasars.

1.3 High-redshift quasars

Due to their extreme brightness, quasars can be observed out to very large distances or redshifts. Since the initial discovery of quasars at \( z > 5.7 \) in the Sloan Digital Sky Survey (SDSS, Fan et al., 2000, 2001, 2003, 2004), to date, high-redshift quasars have been observed as far as \( z = 7.5 \) (Bañados et al., 2017), with more than 100 quasars now discovered at redshifts greater than 5.6 (Jiang et al., 2016), when the Universe was \( \lesssim 1 \) Gyr old. These quasars are found to be powered by supermassive black holes with masses of up to a few times \( 10^9 M_\odot \) (Barth et al., 2003; Jiang et al., 2007; Kurk et al., 2007; Rosa et al., 2011), with intense accretion at or even above the Eddington limit (Willott et al., 2010b; Rosa et al., 2011), which prompts investigation on how such massive black holes could have formed in such a small period of time. The space density of typical SDSS quasars \( (M_{UV,AGN} < -26) \) is less than 1 per Gpc\(^3\) at \( z \gtrsim 6 \) (Willott et al., 2010a; Kashikawa et al., 2015; Jiang et al., 2016). Their rarity and extreme properties raise many questions such as ‘Are the biggest black holes found in the rarest, most overdense regions, i.e. the biggest haloes and galaxies (e.g. Springel et al., 2005b; Shen et al., 2007; Fanidakis et al., 2013; Ren et al., 2020)?’ and ‘Is this rapid growth driven by galaxy mergers, with hosts that are highly star forming, or are their host galaxies more discy and quiet (e.g. Mor et al., 2012; Netzer et al., 2014; Trakhtenbrot et al., 2017a)?’ For further discussion see, for example, the recent reviews of Valiante et al. (2017), Mayer & Bonoli (2018), and Inayoshi et al. (2020).

High-redshift quasars are invaluable probes of the early Universe, providing constraints on the Epoch of Reionization (e.g. Fan et al., 2006c; Mortlock et al., 2011; Greig & Mesinger, 2017; Davies et al., 2018; Greig et al., 2019), the relation between the growth of black holes and their host galaxies (e.g. Shields et al., 2006; Wang et al., 2013; Valiante et al., 2014; Schulze & Wisotzki, 2014; Willott et al., 2017), and black hole seed theories (e.g. Mortlock et al., 2011; Volonteri, 2012; Bañados et al., 2017).
1.3.1 Black hole seeds

The formation of the first black holes in the Universe, known as black hole seeds, is yet to be understood. Currently, it is thought that one (or more) of three main mechanisms are the source of black hole seeds: Population III remnants ($M_{\text{seed}} \approx 100M_\odot$; light seeds), collisions of stars and stellar mass black holes in nuclear clusters ($M_{\text{seed}} \approx 10^3 - 10^4M_\odot$; intermediate seeds) or the collapse of a supermassive star ($M_{\text{seed}} \approx 10^4 - 10^6M_\odot$; heavy seeds) (see e.g. Valiante et al., 2017; Inayoshi et al., 2020).

Population III stars are the first stars in the Universe, which formed from primordial, metal-free gas. These stars may have masses of $\sim$ 10s to 100s of solar masses (Hirano et al., 2014), and at the end of their lives at $z \gtrsim 20$ they are likely to collapse into $\sim 10$–$100M_\odot$ black holes (Bond et al., 1984; Madau & Rees, 2001). As these black hole seeds are so light, this mechanism requires sustained extreme black hole growth to form the massive quasars observed at $z \approx 6$–7, which is generally thought to be unlikely (see the review by Inayoshi et al., 2020).

As primordial gas clouds collapse, they may fragment into an ultra-dense cluster of low-mass stars. These stars may then undergo a runaway collapse, merging into a massive star which may then collapse into an intermediate mass black hole, of $M_{\text{BH, seed}} < 10^2$–$10^4M_\odot$ at $z \approx 10$–20 (Omukai et al., 2008; Devecchi & Volonteri, 2009; Tagawa et al., 2020). Alternatively, these stars could individually collapse into $\sim 10M_\odot$ black holes and then merge, building a similarly massive black hole (Tagawa et al., 2016).

One of the most popular theories is the formation of massive $\sim 10^4$–$10^6M_\odot$ black hole seeds via the formation and then collapse of a supermassive star from a primordial gas cloud—‘direct collapse supermassive black holes’ (e.g. Loeb & Rasio, 1994; Begelman et al., 2006; Ferrara et al., 2014). The physical conditions theorised for the formation of supermassive stars are likely quite rare, with the gas having to remain warm ($T \gtrsim 5000$ K) via the suppression of efficient cooling to avoid fragmentation (see e.g. Inayoshi et al., 2020). This requires extremely low metallicity gas, and suppression of molecular hydrogen cooling, potentially via exposure to intense Lyman-Werner radiation (Omukai, 2001; Bromm & Loeb, 2003; Visbal et al., 2014; Latif & Volonteri, 2015). Alternatively, under these rare conditions the cloud may bypass the star formation phase and collapse directly into a black hole (Ryu et al., 2016; Inayoshi et al., 2016). This seed mechanism produces the largest black hole seeds, and so requires the least intense growth to form the massive black holes.
we see at $z \simeq 7$. However, these conditions and thus the resulting black hole seeds are likely to be rare.

Observations of high redshift quasars can help to determine the masses and therefore formation mechanism of black hole seeds. If mass accretes onto the black hole at the Eddington limit, which is the rate beyond which radiation pressure from the black hole would exceed the gravitational force, then it will have a mass of

$$M(t) = M_{\text{seed}} \exp \left( \frac{1 - \epsilon}{\epsilon} \frac{t}{t_{\text{Edd}}} \right)$$

(1.7)

where $t_{\text{Edd}} = 0.45$ Gyr, $\epsilon$ is the radiative efficiency and $t$ is the total growth time of the black hole since the seed of mass $M_{\text{seed}}$ formed.

By measuring the black hole mass of a high-redshift quasar, this equation can be used to estimate the seed mass required for the black hole to form at a given redshift. At low redshifts, black hole masses can be derived from the dynamics of the material surrounding the black hole, using, for example, dynamical modelling or reverberation mapping. However, at higher redshifts where this is not possible, masses must be derived using empirical correlations. For example, the widths of H$\beta$, MgII and CIV emission lines, among others, can be used in combination with continuum luminosities to estimate the black hole mass (see e.g. McLure & Jarvis, 2002; Vestergaard, 2002). However these methods are calibrated using low-redshift measurements, which may cause significant biases when extrapolated to higher redshifts (see e.g. Shen, 2013; Peterson, 2013, for reviews on black hole mass estimates).

Once the quasar’s black hole mass has been estimated, Equation 1.7 can be used to infer black hole seed masses, often assuming constant accretion at some fraction of the Eddington accretion rate. Ikeda et al. (2017) for example, found that for faint $\sim 10^9 M_\odot$ quasars at $z \simeq 5$, if the Eddington rate was constant or proportional to $(1 + z)^2$, the seed black hole masses are estimated as $> 10^5 M_\odot$; however, using more complicated accretion models reduces this to $\gtrsim 10^3 M_\odot$. Mazzucchelli et al. (2017) studied $15 z \gtrsim 6.5$ quasars, and considered different radiative efficiencies ($\epsilon = 0.07$ and 0.1), growth rates ($L_{\text{bol}}/L_{\text{Edd}} = 1$ and 0.39) and seed redshifts ($z = \infty$, 30 and 20). They found that with $\epsilon = 0.07$ and $L_{\text{bol}}/L_{\text{Edd}} = 1$, the seed masses are low enough to be consistent with even Population III remnants. However, higher efficiencies, later seed formation and lower accretion rates
all result in more massive black hole seeds \( (M_{\text{BH}} \approx 10^3 - 10^4 M_\odot) \) being required as the progenitors of these quasars.

Estimates of the black hole seed mass are highly dependent on the accretion model used, and whether or not super-critical Eddington accretion is allowed. Some studies show that super-Eddington accretion is possible. For example, if the infalling gas has low angular momentum, super-Eddington accretion may occur, with an optically thick envelope forming which may obscure the AGN (Begelman & Volonteri, 2016). Levinson & Nakar (2017) posit that the rate at which a black hole can accrete is determined by interactions of winds with the galaxy bulge and not the Eddington rate; however, due to photon trapping, the observed intensity of such a system may not largely exceed the Eddington limit. Using a slim disc model, Volonteri et al. (2015) show that short-lived phases of supercritical accretion are possible with radiation trapping, leading to lower observed luminosities than the Eddington luminosity.

Observations of high-redshift quasars can give insights into the seed mechanisms of black holes, however uncertainties in the measured black hole masses and accretion histories of these objects severely limit the feasibility of this approach. Ideally, we instead require direct measurements of black holes at or below the predicted seed masses at high redshifts. This may begin to be possible with upcoming infrared and X-ray instruments such as the James Webb Space Telescope (JWST) and Lynx, that could potentially detect a \( M_{\text{BH}} \approx 10^5 M_\odot \) black hole at \( z = 10 \), and gravitational wave instruments such as LISA which could detect the merger of \( M_{\text{BH}} \approx 10^4 - 10^7 M_\odot \) to redshifts beyond 20 (Inayoshi et al., 2020). For a detailed discussion of these and other potential observational signatures of black hole seeds, see Inayoshi et al. (2020).

Regardless of the seed mechanism, once these black hole seeds formed, they then grew via accretion and mergers with other black hole seeds to form supermassive black holes in the very early stages of the Universe (as seen in simulations by Li et al., 2008, for example), leading to the quasars that are observed at high redshift. Many studies investigate the environments of high-redshift quasars for clues about the intense growth of these black holes.
1.3.2 Quasar environments

The extreme nature of high-redshift quasars suggests that they may live in exceptional high-density environments. However, observations do not find that quasars generally reside in large-scale high-density regions (e.g. Kim et al., 2009; Bañados et al., 2013; Morselli et al., 2014), challenging our understanding. Theoretically, however, it is kpc-scale interactions that could trigger supermassive black hole growth (e.g., Sanders et al., 1988; Hopkins et al., 2006), despite not universally being observed in lower redshift ($z < 2$) quasar systems. For example, only 25 per cent of moderate-luminosity $z < 0.05$ X-ray AGN have signs of being in mergers (Koss et al., 2010), although the fraction is much higher for luminous AGN (Hong et al., 2015). Cisternas et al. (2010) found that less than 15 per cent of X-ray selected AGN in $z \simeq 0.3$–$1.0$ show signs of being in mergers, with their accretion mostly triggered by some other mechanism. This is also consistent with the findings of Georgakakis et al. (2009) who claim that a large fraction of AGN at $z \simeq 1$ are triggered by processes other than major mergers, as do Villforth et al. (2018) at $z \simeq 0.9$, and Schawinski et al. (2012), Mechtley et al. (2016), Del Moro et al. (2015) and Marian et al. (2019) for AGN at $z \simeq 2$.

Atacama Large Millimeter/sub-millimeter Array (ALMA) observations in the sub-mm have detected companion galaxies around a range of high-redshift quasars at separations of $\sim 8$–$60$ kpc (Wagg et al., 2012; Decarli et al., 2017; Trakhtenbrot et al., 2017a; Trakhtenbrot et al., 2018). For example, Trakhtenbrot et al. (2017a) found companions physically associated with three of six $z \simeq 4.8$ quasars observed with ALMA, at separations of 14–45 kpc, which have been interpreted as major galaxy interactions. In the rest-frame UV, McGreer et al. (2014) also discovered companion galaxies within 12 kpc projected separations of two high-redshift quasars. However, McGreer et al. (2014) reported that bright companions around high-redshift quasars are uncommon, with an incidence of $\lesssim 2/29$ for $\gtrsim 5L^*$ galaxies and $\lesssim 1/6$ for $2 \lesssim L \lesssim 5L^*$ galaxies. Finding quasar companion galaxies is consistent with the scenario that the growth of high-redshift quasars can be triggered by galaxy mergers. These observations suggest that major mergers may be important drivers of rapid black hole growth in the early Universe, and thus probing the local environments of quasars can give important insights into the growth mechanisms of these extreme systems.
1.4 Quasar host galaxies

Alongside their local environment, many studies investigate the host galaxies of these quasars to understand the connection between black hole and galaxy growth in the early Universe (e.g. Shields et al., 2006; Wang et al., 2013; Willott et al., 2017). However, observations of quasar host galaxies are challenging with current facilities (e.g. Bahcall et al., 1994; Disney et al., 1995; Kukula et al., 2001; Hutchings, 2003). These observations are strongly focused in two wavelength ranges where detectability is relatively easy: rest-frame UV emission observed in the near-infrared from $\approx 0.7 - 2.2\mu m$, and rest-frame far-infrared (FIR) emission observed at sub-mm wavelengths. The UV emission traces the bright accretion disc and stellar light from the host galaxy, while the FIR instead predominantly traces cold dust in the host.

1.4.1 Rest-frame ultraviolet observations

The extreme luminosity of quasars in the UV often means that they significantly outshine their host galaxies (e.g., Schmidt, 1963; McLeod & Rieke, 1994; Dunlop et al., 2003; Hutchings, 2003; Floyd et al., 2013). Subtracting the quasar light has resulted in host detections out to $z \approx 2$ (Jahnke et al., 2009; Mechtley et al., 2016), but is yet to be successful for detecting the highest redshift quasars at $z \approx 6$ (Mechtley et al., 2012). The highest redshift at which the UV emission from a quasar host has unambiguously been observed from ground-based telescopes is $z \approx 4$ (McLeod & Bechtold, 2009; Targett et al., 2012).

Galaxies are more compact at higher redshifts, with physical sizes evolving as $R_e \propto (1 + z)^{-m}$, where $m$ is typically measured to be between 1 and 1.5 (e.g. Bouwens et al., 2004; Oesch et al., 2010; Ono et al., 2013; Kawamata et al., 2015; Shibuya et al., 2015; Laporte et al., 2016; Kawamata et al., 2018). This rate of decrease of galaxy sizes toward higher redshifts is stronger than the increase in apparent diameters at $z \gtrsim 2$ due to the cosmic angular size–distance relation (Equation 1.4). Thus, at higher redshifts, the angular size of galaxies becomes small relative to the point spread function (PSF) of current telescopes, and so the bright quasar entirely conceals the host galaxy emission (e.g. Mechtley et al., 2012). Surface brightness dimming also causes the host galaxies and any tidal features to be more difficult to detect at high redshift.
The launch of JWST in the near future will create new possibilities of observing quasar host galaxies in the rest-frame UV. Its improved resolution over the Hubble Space Telescope (HST) may resolve these small host galaxies, and its increased thermal stability will allow for better subtraction of the quasar light. JWST will also open up the possibility of observing the quasar hosts in the rest-frame optical, where the majority of bright galaxy emission lines occur, such as [OIII], [OIII], Hα, Hβ and [SII], and where common stellar mass estimators can be used (e.g. Zibetti et al., 2009; Taylor et al., 2011).

1.4.2 Rest-frame far-infrared observations

The only current detections of high-redshift quasar hosts are instead in the rest-frame FIR, observed in the sub-mm (e.g. Bertoldi et al., 2003b; Walter et al., 2003, 2004; Riechers et al., 2007; Wang et al., 2010, 2011; Venemans et al., 2019), which traces cold dust in the host galaxy.

Observations at sub-mm and mm wavelengths with ALMA and the IRAM Plateau de Bure Interferometer (PdBI), for example, imply a diverse population of quasar hosts, with inferred dynamical masses of $10^{10}$–$10^{11}\,M_\odot$ (Walter et al., 2009; Wang et al., 2013; Venemans et al., 2015, 2017; Willott et al., 2017; Trakhtenbrot et al., 2017a; Izumi et al., 2018, 2019; Pensabene et al., 2020), dust masses of $10^7$–$10^9\,M_\odot$ (Venemans et al., 2015; Izumi et al., 2018), sizes of 1-5 kpc (Wang et al., 2013; Venemans et al., 2015; Willott et al., 2017; Izumi et al., 2019), and a wide range of star-formation rates (SFRs) of 10–2700\,M_\odot/yr (Venemans et al., 2015, 2017; Willott et al., 2017; Trakhtenbrot et al., 2017a; Izumi et al., 2018, 2019; Shao et al., 2019). The hosts are found in a variety of dynamical states, with some having nearby companions which may suggest a merger system (e.g Trakhtenbrot et al., 2017a), while some show signatures of a rotating disc (e.g Willott et al., 2017; Trakhtenbrot et al., 2017a), or even no ordered motion (Venemans, 2017). However, since cold dust may not trace the stellar distribution, there may be significant biases in stellar properties inferred through these observations (e.g Narayanan et al., 2009; Valiante et al., 2014; Lupi et al., 2019).

For these quasars, host masses are often estimated using the widths of observed emission lines, such as the [CII]$_{158\mu m}$ and CO (6–5) lines (e.g. Wang et al., 2013). To determine galaxy dynamical masses from [CII] line observations, it is assumed that the galaxy has a
rotating disc geometry, and so $M_{\text{dyn}}$ is calculated as:

$$M_{\text{dyn}} = 1.16 \times 10^5 \, v_{\text{cir}}^2 \, D \, M_\odot$$

(1.8)

(see e.g. Wang et al., 2013; Willott et al., 2017). Here $D$ is the diameter of the disc in kpc, which Willott et al. (2017) estimate as 1.5 times the deconvolved Gaussian spatial full width at half maximum (FWHM) of the line. The maximum circular velocity of the gas disc $v_{\text{cir}}$ can be estimated as $v_{\text{cir}} = 0.75 \, \text{FWHM}_{[\text{CII}]} / \sin i$, where $i$ is the inclination angle between the disc and the line of sight. If the disc is resolved, $i$ can be determined using the ratio of the minor $a_{\text{min}}$ and major $a_{\text{maj}}$ axes using $i = \cos^{-1}(a_{\text{min}}/a_{\text{maj}})$. Wang et al. (2013) note, however, that due to the large uncertainties in source sizes, these inclination angle assumptions can change the determined measurements by roughly 3 orders of magnitude. For unresolved galaxies, $D$ and $i$ need to be estimated based on observations of other galaxies. Since measuring these properties is difficult and dependent on assumptions about the geometry, there are large uncertainties in any dynamical masses determined at high redshift using this method (see e.g. Valiante et al., 2014). Measurement uncertainties in $M_{\text{dyn}} \sin i$ in Wang et al. (2013) for example, were 10%–40%, and $i$ estimates are very uncertain.

Additional issues can arise when determining the masses of high redshift galaxies since the emitting regions may not trace the overall spatial distribution of the galaxy. For example, Narayanan et al. (2009) show that using CO to estimate the physical conditions of galaxies can lead to overestimates in the dynamical mass of a factor of 1.5–2, while line ratio conversion assumptions can lead to underestimates of the gas mass. Hydrodynamical simulations also show that quasar hosts are compact, with the bulk of the star formation only occurring in the very inner regions, and so observations measuring the dynamical mass will not necessarily trace the galaxy stellar mass (Valiante et al. 2014, see also Lupi et al. 2019). Ideally, host masses would be determined from measurements in the rest-frame optical, where common stellar mass estimators can be used (e.g. Zibetti et al., 2009; Taylor et al., 2011), which may be possible with future telescopes such as JWST. Precise measurements of the masses of high-redshift quasar hosts are important for accurately determining the relations between black holes and their host galaxies in the early Universe.
1.4.3 Black hole–host relations

Extensive research has been undertaken in order to understand the host galaxies of AGN, and how galaxies and supermassive black holes co-evolve (see the review by Heckman & Best, 2014). The majority of these studies have focussed on the low redshift Universe where there is an abundance of high quality spectroscopy from surveys such as the SDSS (Richards et al., 2002), which gives detailed information about the black holes and their host galaxies. These observations find tight correlations between certain properties, such as the black hole and bulge mass, velocity dispersion and luminosity (e.g. Magorrian et al., 1998; Gebhardt et al., 2000; Merritt & Ferrarese, 2001; Tremaine et al., 2002; Marconi & Hunt, 2003; Haring & Rix, 2004; Bentz et al., 2009; Kormendy & Ho, 2013; Reines & Volonteri, 2015; see the review by Heckman & Best, 2014). Häring & Rix (2004) provided an estimate of the relation between $M_{\text{BH}}$ and $M_{\text{bulge}}$ locally, finding that

$$\log(M_{\text{BH}}) = (8.20 \pm 0.10) + (1.12 \pm 0.06) \log(M_{\text{bulge}}/10^{11} M_\odot), \quad (1.9)$$

or that at a bulge mass of $5 \times 10^{10} M_\odot$, the median value of $\log(M_{\text{BH}}/M_{\text{Bulge}})$ is $-2.85 \pm 0.15$ dex. This is consistent with results of Merritt & Ferrarese (2001) with $\log(M_{\text{BH}}/M_{\text{Bulge}}) = -2.9 \pm 0.45$ dex, and of Marconi & Hunt (2003) with $\log(M_{\text{BH}}/M_{\text{Bulge}}) = -2.6$ to $-2.8$, depending on the galaxy sample and method of calculation. These tight correlations suggest a co-evolution between galaxies and supermassive black holes, which may be causal, due to feedback from the AGN (e.g. Silk & Rees, 1998; Di Matteo et al., 2005b; Bower et al., 2006; Cioffi et al., 2010) or the efficiency with which the galaxy can fuel the black hole (e.g. Hopkins & Quataert, 2010; Cen, 2015; Anglés-Alcázar et al., 2017), or coincidental, simply due to mergers causing both black hole and galaxy growth (e.g. Haehnelt & Kauffmann, 2000; Croton, 2006; Peng, 2007; Gaskell, 2011; Jahnke & Macciò, 2011). To understand what drives this black hole–host co-evolution, it is necessary to study how these correlations change with redshift.

At higher redshifts, current observations suggest that black holes are more massive compared to their hosts; on average, $M_{\text{BH}}/M_{\text{Bulge}}$ is larger than the local value by factors of roughly 4 at $z \simeq 2$ (e.g. Peng et al., 2006a,b), or more at $z \simeq 4$–6 (e.g. Wang et al. 2010; Targett et al. 2012; see Kormendy & Ho 2013 for a review). For example, ALMA observations of five $z \simeq 6$ quasar hosts find black hole to dynamical mass ratios of $M_{\text{BH}}/M_{\text{dyn}} \simeq 0.012$–0.030—roughly an order of magnitude higher than the local
value (Wang et al., 2013). Similar studies at $z \simeq 4–7$ (e.g. Maiolino et al., 2007; Riechers et al., 2008; Venemans et al., 2012a) also give estimates for individual quasars of $M_{\text{BH}}/M_{\text{dyn}} \gtrsim 10^{-2}$, which is significantly larger than the local value if dynamical masses and bulge masses are assumed to be roughly equivalent. This suggests a faster evolution of the first supermassive black holes with respect to their host galaxies (Valiante et al., 2014). However, these high-redshift quasar host observations use the dynamical mass as a proxy for stellar mass, which may not be a reliable assumption, as discussed above.

One potential physical explanation for this higher $M_{\text{BH}}/M_{\text{bulge}}$ ratio is that bursts of super-Eddington black hole growth and positive supernova feedback may account for the growth of early supermassive black holes and co-evolution with their hosts. Volonteri et al. (2015) show that in super-critical slim disc models, short-lived phases of supercritical accretion can occur, resulting in $M_{\text{BH}}/M_{\ast} \gg 10^{-3}$ and so $M_{\text{BH}}/M_{\ast} > 10^{-3}$ (the local value). Alternatively, Croton (2006) show that the evolution of the $M_{\text{BH}}-M_{\text{bulge}}$ relation could be driven by the growth of bulges and not black holes, with an increasing contribution of disrupted discs to bulges over time leading to a larger ratio at higher redshifts.

However, the high observed $M_{\text{BH}}/M_{\text{dyn}}$ relation at high redshift could be a result of selection effects (Lauer et al., 2007; Schulze & Wisotzki, 2011, 2014; DeGraf et al., 2015; Willott et al., 2017). Willott et al. (2017) suggest this could be due to the relation having a wide dispersion and only the most massive $z > 6$ black holes being observed. This relates to the Lauer bias (Lauer et al., 2007), which says that since the luminosity function falls off rapidly at high masses, the most massive black holes occur more often as outliers in galaxies of smaller masses than as typical black holes in the most massive galaxies. Indeed, Willott et al. (2017) found that black holes with $M < 10^9 M_{\odot}$ at $z > 6$ fall below the $M_{\text{BH}}-M_{\text{dyn}}$ relation for low redshift galaxies, in contrast to the opposite being true for higher mass black holes. This suggests a $M_{\text{BH}}-M_{\text{dyn}}$ relation with larger scatter at high redshift.

Willott et al. (2017) posit that this is due to merging and AGN feedback tightening the relation over time. Similarly, Schulze & Wisotzki (2014) claim that selection effects are the reason for the observed evolution of the $M_{\text{BH}}-M_{\text{bulge}}$ relation. On applying a fitting method to correct for selection effects, they find no statistical evidence for a cosmological evolution in the $M_{\text{BH}}$-bulge relation (see Figure 4.8).

A lack of evolution in the black hole–host relations is consistent with the findings of cosmological hydrodynamical simulations such as Horizon-AGN (Volonteri et al., 2016),
which observes very little evolution in the $M_{BH} - M_*$ relation from $z = 0$ to 5, and BlueTides (Huang et al., 2018), which finds a $M_{BH} - M_*$ relation at $z = 8$ that is consistent with the local Kormendy & Ho (2013) relation. DeGraf et al. (2015), on the other hand, found that the relation evolves slightly for $z \geq 1$ for the highest mass black holes, with a steeper slope at the high-mass end at higher redshifts, making selection effects important. The more statistical study of Schindler et al. (2016) found that the ratio of the black hole to stellar mass density is constant within the uncertainties from $z = 0$ to 5, with a slight decrease in the ratio at $3 \leq z \leq 5$. This is also consistent with no cosmological evolution in the $M_{BH} - M_*$ relation.

Interpreting observed relations between the properties of black holes and their host galaxies allows us to understand the physics of the formation and co-evolution of these systems. However, at higher redshifts where these objects are much harder to observe, a comprehensive understanding of these relations and therefore the co-evolution of black holes and their hosts is lacking.

While there are significant challenges in determining the properties of black holes and their host galaxies at high redshift, upcoming facilities will provide the next frontier for understanding high-redshift quasars. Infrared surveys with Euclid (Amiaux et al., 2012) and the Nancy Grace Roman Space Telescope (RST; formerly WFIRST Spergel et al., 2015) will significantly increase the known sample of $z \gtrsim 6$ quasars. The improved resolution of the James Webb Space Telescope (JWST; Gardner et al., 2006) may produce the first detections of the stellar component of their host galaxies, which will be invaluable for accurately determining the properties of quasar hosts. Making detailed theoretical predictions for the results of these groundbreaking instruments is thus a current priority.

### 1.5 Theoretical studies

There are two main types of simulations which are used to theoretically study the Universe on cosmological scales—hydrodynamical simulations and semi-analytic models (see e.g. Taylor, 2015; McAlpine, 2018).
1.5.1 Semi-analytic models

Semi-analytic models are suites of analytical prescriptions for the physical processes involved in galaxy formation, based on the properties of the dark matter haloes in which the galaxy resides. These models were traditionally applied to dark matter haloes produced by algorithms based on the Press-Schechter formalism (e.g. White & Frenk, 1991; Bower, 1991; Kauffmann et al., 1993; Kauffmann & White, 1993). In more recent works, the dark matter haloes are produced by an N-body dark-matter only simulation (e.g. Croton et al., 2006; Henriques et al., 2015; Mutch et al., 2016; Croton et al., 2016; Lagos et al., 2018). These N-body simulations generally adopt the standard ΛCDM cosmology, assume cosmological initial conditions for the distribution of dark matter particles, and then model the effect of gravity to determine where dark matter haloes grow and cluster in such a universe (e.g. Springel et al., 2005b; Angulo et al., 2012; Poole et al., 2016).

Semi-analytic models assume that a galaxy resides in the centre of each dark matter halo. They then use the properties of each halo to determine the properties of the galaxy through a range of approximations and assumptions. These models generally include analytical prescriptions which describe the effects of gas cooling from the surrounding environment onto the galaxy, star formation, supernova feedback, black hole growth and AGN feedback, and many other physical processes involved in galaxy evolution (see e.g. Mutch et al., 2016; Croton et al., 2016), which contain a range of free parameters which must be calibrated against observational data. The models then output a range of properties for each galaxy, including the mass of hot gas, cold gas, stars and its central black hole, its star formation rate, size, and morphology at each snapshot of the dark matter simulation.

Semi-analytic models are computationally inexpensive, allowing for extensive tests of various physical models and parameters, which can give important insights into the underlying physics. The N-body simulations are also inexpensive relative to full cosmological hydrodynamical simulations, allowing for large simulation boxes of volumes up to even (4 co-moving Gpc)$^3$ (Angulo et al., 2012). This allows semi-analytic models to make predictions for a large number of galaxies over a wide range of environments. However, these models have a few disadvantages. They do not usually provide information about the distribution of properties in galaxies, instead focusing on galaxy averages (although see
e.g. Stevens et al., 2016, for improvements). They are also highly dependent on the (often simplistic) physical models implemented, their calibration method, and the resulting parameter choices.

1.5.2 Cosmological hydrodynamical simulations

Cosmological hydrodynamical simulations allow for a more physical approach to modelling the Universe. As well as modelling dark matter particles under the effects of gravity, these simulations also include baryons which self-consistently evolve with the dark matter particles according to hydrodynamics. Such simulations generally take one of two approaches to modelling the baryons. In Adaptive Mesh Refinement (AMR; e.g. Teyssier, 2002; Bryan et al., 2014) codes, the computational volume is divided into a grid of evolving cells, across which the baryons flow as a fluid. Smoothed Particle Hydrodynamics (SPH; Gingold & Monaghan, 1977; Monaghan, 1992; Price, 2012) codes are Lagrangian in nature, and instead trace ‘particles’ (large collections of baryons) as they evolve throughout the simulation volume.

Due to the extreme physical scales involved, from large-scale structure at Mpc scales to star formation and black hole growth on sub-pc scales, it is impossible to resolve the scales necessary to truly model the Universe in these simulations. Thus, modelling gas cooling, star formation, black hole formation and growth, and less understood processes such as supernova feedback and AGN feedback, are treated in these simulations using a set of sub-grid models (e.g. Katz et al., 1999; Springel & Hernquist, 2003; Springel et al., 2005a; Di Matteo et al., 2005b; Vogelsberger et al., 2013), which are calibrated against observational data or higher resolution simulations.

While these simulations also rely on approximations to the underlying physics as in semi-analytic models, hydrodynamical simulations give a detailed view of individual galaxies. They are able to make more accurate predictions for the structures of galaxies, including the kinematics and distributions of gas and stars, and include important baryonic effects such as ram pressure stripping. Recent state-of-the-art hydrodynamical simulations such as EAGLE (Schaye et al., 2014; Crain et al., 2015), Illustris and Illustris-TNG (Vogelsberger et al., 2014; Pillepich et al., 2017; Nelson et al., 2019), and Horizon-AGN (Dubois et al., 2014) simulate volumes of $\sim (100 \text{ cMpc})^3$, providing the detailed growth histories of tens of thousands of galaxies in a wide range of environments, throughout the age of the
Universe. These simulations have been extensively used, and have dramatically improved our understanding of galaxy evolution (e.g. Qu et al., 2016; Volonteri et al., 2016; Welker et al., 2016; Muthu-Pakdil et al., 2017; Lagos et al., 2017; Martin et al., 2017; Tacchella et al., 2019; Habouzit et al., 2019a).

Due to the rarity of high-redshift quasars, comprehensive theoretical predictions require high-resolution simulations with large computational volumes. Cosmological hydrodynamical simulations such as Massive Black (Di Matteo et al., 2012), with a volume of \((533/h \, \text{cMpc})^3\), and BLUETIDES (Feng et al., 2015), with a volume of \((400/h \, \text{cMpc})^3\), have pioneered this area. These simulations have been used to investigate the rapid growth of black holes (Di Matteo et al., 2012; DeGraf et al., 2012b; Feng et al., 2014; Di Matteo et al., 2017) and their relationship to their host galaxies (Khandai et al., 2012; DeGraf et al., 2015; Huang et al., 2018), and make predictions for the highest-redshift quasars that are observed (DeGraf et al., 2012a; Tenneti et al., 2018; Ni et al., 2018).

1.6 Thesis outline

In this thesis, I use three techniques to investigate the host galaxies of high-redshift quasars: a semi-analytic model, a cosmological hydrodynamical simulation, and observations.

In Chapter 2 I introduce the MERAXES semi-analytic model (Mutch et al., 2016) and describe improvements I made to the model in order to study the morphology of galaxies. These updates were motivated by the goal of studying the black hole–bulge mass relations, which the model could not previously predict. Chapter 3 focuses on using this updated MERAXES model to study the sizes, angular momenta and morphology of galaxies at high-redshift, taking advantage of these new model updates. In Chapter 4, I then use this MERAXES model to study the evolution of the black hole–host relations from high redshift to the present day. MERAXES is ideal for giving a statistical overview of the galaxy and black hole populations and their evolution, particularly at high redshifts. Its semi-analytic nature allows us to study how various black hole growth model parameters affect the evolution of the scaling relations. However, MERAXES is run on the \((100 \, \text{cMpc})^3\) N-body simulation Tiamat (Poole et al., 2016), which is too small to contain the rare, massive high-redshift quasars that are observed in the Universe. It is also unable to make detailed predictions for individual quasar host galaxies.
In Chapter 5, I use the BlueTides simulation (Feng et al., 2015) to study the host galaxies of $z = 7$ quasars. This massive simulation with a volume of $(400/h \text{ cMpc})^3$ includes the rare quasars that Tiamat misses, and has the ability to resolve galaxies down to a smoothing length of $1.5/h \text{ ckpc}$, however is limited to $z \geq 7$. I use BlueTides to make predictions for the properties of the hosts of observable high-redshift quasars, the black hole–host scaling relations at $z = 7$, and the environments of high-redshift quasars. I also make ‘mock’ images with BlueTides, to make predictions for future JWST quasar observations.

In Chapter 6 I switch focus to observations, presenting an analysis of deep near-infrared HST images of six $z \simeq 6$ quasars. I use a state-of-the-art quasar subtraction technique in an attempt to detect emission from their hosts, and present the most robust upper limits to date on the rest-frame UV brightness of each of the quasar host galaxies. This work significantly increases the sample of high-redshift quasar hosts with deep UV upper limits determined by this method, extending on the previous work of Mechtley et al. (2012) which studied only one quasar. I also use the HST images to study the environments of these $z \simeq 6$ quasars, uncovering nearby galaxies which may be interacting with the hosts and triggering this rapid black hole growth.

Chapter 7 concludes with a summary and a discussion of future avenues for this work.
Chapter 2

The Meraxes Semi-Analytic Model

Meraxes (Mutch et al., 2016) is a semi-analytic galaxy formation model designed to study high-redshift galaxy evolution. Using the properties of dark matter haloes from an N-body simulation, Meraxes analytically models the physics involved in galaxy formation and evolution. In this chapter I give an overview of the Meraxes semi-analytic model and the Tiamat and Tiamat-125-HR N-body simulations, and describe improvements that I made to the model to allow for studies of the sizes, angular momenta and morphologies of galaxies.

2.1 N-body simulations

In this thesis, I apply Meraxes to two collisionless N-body dark matter simulations, Tiamat and Tiamat-125-HR. The Tiamat simulation (Poole et al., 2016, 2017) has a co-moving box size of \((67.8/h \text{ Mpc})^3\), and contains \(2160^3\) particles each of mass \(2.64 \times 10^6/h M_\odot\). Tiamat outputs 164 snapshots from \(z = 35\) to \(z = 1.8\), with a temporal resolution of 11.1 Myr to \(z = 5\), and with the snapshots between \(z = 5\) and \(z = 1.8\) separated equally in units of Hubble time. The high mass and temporal resolution of Tiamat make it an extremely accurate and ideal simulation for studying galaxy evolution at high redshifts. Tiamat is used throughout this thesis unless otherwise specified.

To investigate lower redshifts, I run Meraxes on Tiamat-125-HR (Poole et al., 2017), a low-redshift compliment to Tiamat, with the same cosmology and snapshot cadence extended to \(z = 0\). Tiamat-125-HR has a larger box size of \((125/h \text{ Mpc})^3\) and a lower
mass resolution, with $1080^3$ particles with mass $1.33 \times 10^8 / h M_\odot$, adequate for investigating low-redshift galaxy evolution. For a detailed description of these simulations, see Poole et al. (2016) and Poole et al. (2017).

### 2.2 An overview of Meraxes

Meraxes (Mutch et al., 2016) is a semi-analytic model designed to study galaxy evolution during the Epoch of Reionization. Using the properties of the dark matter haloes from Tiamat and Tiamat-125-HR, Meraxes models the baryonic physics involved in galaxy formation and evolution analytically, including prescriptions for physical processes such as gas cooling, star formation, AGN and supernova feedback, and black hole growth. For full details of the model, see Mutch et al. (2016), and Qin et al. (2017) (hereafter Q17) for the black hole growth prescription.

The original Meraxes model (Mutch et al., 2016) first assumes that each dark matter halo contains a mix of primordial baryons, which are shocked to the virial temperature and added to a reservoir of diffuse hot gas. At each time step of the N-body simulation, Meraxes then assumes that some fraction of this hot gas cools and condenses into the centre of the halo. This cold gas is assumed to settle into a rotationally-supported disc with scale radius $R_s = \lambda R_{\text{vir}} / \sqrt{2}$, where $\lambda$ is the halo spin parameter (Bullock et al. 2001; see Section 2.6).

Meraxes assumes that stars will form if the cold gas disc exceeds a critical surface density (Kauffmann, 1996), which is converted to a critical mass, assuming that the gas is evenly distributed in the disc out to a radius of $3R_s$. When the mass of cold gas in the disc exceeds this critical mass, the star formation rate is given by $\dot{M}_s = \alpha_{\text{SF}} V_{\text{vir}} (M_{\text{cold}} - M_{\text{crit}}) / (3R_s)$, where $\alpha_{\text{SF}}$ is a free parameter of the model (Croton et al., 2006). These stars form a disc with scale radius $R_s$. Meraxes then assumes that some percentage of these stars undergo supernova in future time-steps, injecting energy into the surrounding gas, reheating some cold gas and ejecting some of the hot gas from the system entirely. This supernova feedback regulates the amount of available gas for star formation in future time-steps. Supernovae are also assumed to create metals, enriching the interstellar medium and enhancing the cooling rate of gas onto the galaxy.
Meraxes includes a basic model for gas stripping when haloes infall into more massive systems, assuming that the hot and ejected gas reservoirs are instantly stripped and added to the hot component of the new parent. Meraxes also includes a model for galaxy mergers in merging haloes, using dynamical friction arguments to determine the time it will take for the two galaxies to merge. Meraxes assumes that the merger results in an efficient burst of star formation if the mass ratio of the two merging galaxies is greater than 0.1.

A key goal of Meraxes is to study the reionization of the Universe, linking the evolution of reionization to the galaxy population. Thus, alongside these models for galaxy evolution, Meraxes includes a reionization prescription by embedding the 21cmFAST semi-numerical reionization code (Mesinger et al., 2010). 21cmFAST calculates the local ionizing UV background based on the Meraxes galaxy properties at each time-step, influencing the subsequent galaxy evolution. This is the first semi-analytic model which self-consistently coupled reionization with galaxy evolution, both temporally and spatially.

These analytical prescriptions include a range of free parameters, which are calibrated to reproduce certain observations, such as the evolution of the galaxy stellar mass function, and, for the parameters related to reionization, measurements of the integrated free electron Thomson scattering optical depth (see Sections 2.7, 3.1.1 and 4.1). The model outputs a large set of properties describing each simulated galaxy, such as the mass of hot and cold gas, stars, and the central black hole, its star formation rate, disc size, and type (central or satellite), at each snapshot of the dark matter simulation.

This chapter introduces several extensions I have made to Meraxes: i) I now split galaxies into bulge and disc components, instead of the original disc-only model, ii) I introduce a new mechanism for black hole growth, iii) I use a more physical star formation prescription, iv) I implement a new model for determining galaxy disc sizes, and v) the angular momenta of the gas and stellar discs are now tracked throughout the evolution of the galaxy. These changes are discussed in detail in the following sections.

2.3 Bulge formation and growth

Previously published versions of Meraxes made no attempt to decompose a galaxy into its morphological components, instead assuming that all cold gas and stars in a galaxy
are contained in a disc component. Following previous semi-analytic models (e.g. Croton et al., 2006; De Lucia et al., 2006; Guo et al., 2011; Menci et al., 2014; Tonini et al., 2016), I expand the model to include a second galaxy component—galaxy bulges. These are assumed to contain no gas, and have no angular momentum, for simplicity. My model for bulge growth is analogous to that of Tonini et al. (2016), with bulges growing during galaxy mergers and disc instabilities. Semi-analytic models often assume that bulges can be formed through mergers and disc instabilities, and are able to get good agreement with low-redshift morphological observations (e.g. Guo et al., 2011; Tonini et al., 2016; Izquierdo-Villalba et al., 2019). As in Tonini et al. (2016), I split galaxy bulges into two types—merger-driven and instability-driven. I assume that the instability-driven bulge is disc-like, with a mass distribution that is flattened in the disc direction, whereas the merger-driven bulge is spheroidal. These bulges are somewhat comparable to observed classical and ‘pseudo’ bulges—which are typically built by mergers and disc instabilities, respectively (see e.g. Kormendy & Kennicutt, 2004; Gadotti, 2009)—although they are classified by their observed properties and not their formation mechanism.

For a diagrammatic depiction of the bulge growth model, see figure 1 of Tonini et al. (2016).

### 2.3.1 Galaxy mergers

When two galaxies merge, I first assume that the gas discs of the primary and secondary galaxies add, using the disc addition process described in Section 2.6.

Galaxy mergers can induce an efficient burst of star formation, by causing strong shocks and turbulence which can drive cold gas towards the inner regions of the parent galaxy. I assume that in a merger with merger ratio $\gamma = M_2/M_1 \geq 0.01$ (where $M$ is the total galaxy mass and the subscripts 1 and 2 herein denote the primary and secondary galaxy, respectively) the remnant undergoes a merger-driven starburst. This causes mass $M_{\text{burst}} = 0.57 \gamma^{0.7} M_{\text{cold},1}$ to be converted from cold gas into stars (Somerville et al., 2001; Mutch et al., 2016), where $M_{\text{cold}}$ is the mass of cold gas in the galaxy. Any gas that is not converted into stars during this burst remains in a gas disc, regardless of merger ratio.

To determine where these new stars are added, I consider the morphology of the primary galaxy, as I assume that the dominant dynamical component of the primary galaxy will
regulate where the mass from the satellite will be deposited (see Tonini et al., 2016). If the primary is dominated by a discy component—either the stellar disc, if $M_{*\text{disc,1}}/M_{*\text{,1}} > 0.5$, or the instability-driven bulge, if $M_{*\text{disc,1}}/M_{*\text{,1}} \leq 0.5$ and $M_{\text{MDB,1}}/M_{*\text{,1}} < 0.5$ (where $M_{*\text{disc}}$ is the mass of the stellar disc, $M_{*}$ is the total stellar mass of the galaxy, and $M_{\text{MDB}}$ is the mass of the merger-driven bulge)—the mass deposition is likely to occur in the plane of the disc, and so these stars are added to the instability-driven bulge. Otherwise, the dominant mass component of the primary is the spheroidal merger-driven bulge, and so I assume that the newly formed stars will accumulate in shells around it; stars from the burst are added to the merger-driven bulge.

After the starburst, the black holes of the primary and secondary are combined (‘BH–BH coalescence’). The remnant undergoes merger-driven quasar-mode black hole growth, as described below.

Finally, I consider the addition of the stellar component of the secondary galaxy to the primary. If a galaxy undergoes a major merger, which is defined as a merger with $\gamma > 0.1^1$, all stars and metals from both galaxies are placed into the merger-driven bulge of the remnant—major mergers are assumed to form pure bulge galaxies. In a minor merger ($\gamma \leq 0.1$) where the primary is disc-dominated ($M_{*\text{disc,1}}/M_{*\text{,1}} > 0.5$), I assume that the stars from the secondary are added to the primary’s disc. This causes a gravitational instability such that $M_{*\text{,2}}$ is taken from the disc of the primary and placed into its instability-driven bulge (see Tonini et al., 2016). In a minor merger where the primary is bulge-dominated ($M_{*\text{disc,1}}/M_{*\text{,1}} \leq 0.5$), the secondary’s mass is simply added to the primary’s bulge (either the instability-driven bulge if $M_{\text{MDB,1}}/M_{*\text{,1}} < 0.5$, or the merger-driven bulge otherwise).

### 2.3.2 Disc instabilities

For thin galaxy discs with an exponential surface density (with scale-radius $R_s$) and flat rotation curve (with velocity $V_{\text{disc}}$), a disc is stable if its mass $M_{\text{disc}} < V_{\text{disc}}^2 R_s / G = M_{\text{crit}}$ (Efstathiou et al., 1982; Mo et al., 1998). Thus, I assume that if the galaxy disc accretes enough material such that $M_{\text{disc}} > M_{\text{crit}}$, then it is no longer in dynamical equilibrium and so an amount $M_{\text{unstable}} = M_{\text{disc}} - M_{\text{crit}}$ of this disc mass is unstable. Here, I take $M_{\text{disc}}$ as the combined mass of both gas and stars, and $R_s$ as the mass-weighted scale radius of the

---

1 Mutch et al. (2016) and Q17 define a major merger as one with $\gamma > 0.3$. Here I modify the definition to $\gamma > 0.1$, to produce better agreement between this model and the observed bulge fraction of high-mass galaxies—see Section 3.1.1
stellar and gas discs. I assume that the ratio of unstable stars to gas is equal to their total mass ratio, so \( M_{\text{unstable, } \star} = M_{\text{unstable}} M_{\star \text{ disc}} / M_{\text{disc}} \). To return the disc to equilibrium, I assume that \( M_{\text{unstable, } \star} \) of stars is transferred from the disc to the instability-driven bulge, with their current metallicity.

I then assume that the disc instability can drive black hole growth (as seen in e.g. Fanidakis et al., 2011; Hirschmann et al., 2012; Menci et al., 2014; Croton et al., 2016; Irodotou et al., 2019), as described below.

Any excess gas will migrate towards the denser galaxy centre and form stars. Hence in the model, after this black hole growth, the remainder of the unstable gas is consumed in a 100 per cent efficient starburst, with the stars formed added to the instability-driven bulge.

### 2.4 Black holes

The MERAXES black hole model was introduced in Q17, and is updated here to include instability-driven growth. The model is summarised below, however the interested reader is encouraged to refer to Q17 for the full details.

In MERAXES, black holes are seeded in every newly-formed galaxy, with a seed mass of \( 10^4 M_\odot \). Black holes then grow by accretion of both hot and cold gas, through the radio- and quasar modes, respectively. I also assume that black holes grow in galaxy mergers, with the black holes in each galaxy merging together.

#### 2.4.1 Radio-mode growth

Black holes accrete hot gas from the static hot gas reservoir around the galaxy (of mass \( M_{\text{hot}} \) and density \( \rho_{\text{hot}} \)), at a fraction \( k_h \) of the Bondi-Hoyle accretion rate:

\[
\dot{M}_{\text{Bondi}} = \frac{2.5 \pi G^2 M_{\text{BH}}^2}{c_s^3} \rho_{\text{hot}}. \tag{2.1}
\]

I consider \( k_h \) a free parameter, which adjusts the efficiency of radio-mode black hole growth (Croton et al., 2016). This accretion is limited by the amount of hot gas in the reservoir and the Eddington limit, so the mass available for accretion during a simulation time-step...
of width $\Delta t$ is
\begin{equation}
M_{\text{accretion}} = \min\left(M_{\text{hot}}, M_{\text{Edd}}, k\dot{M}_{\text{Bondi}}\Delta t\right),
\end{equation}
where $M_{\text{Edd}}$ is the mass that would be accreted continually at the Eddington rate over $\Delta t$:
\begin{equation}
M_{\text{Edd}} = M_{\text{BH}}\left[\exp\left(\frac{\Delta t}{\eta t_{\text{Edd}}}\right) - 1\right],
\end{equation}
Here $t_{\text{Edd}} \equiv \frac{\sigma T \epsilon}{4\pi G m_p} \approx 450$ Myr is the Eddington accretion time, $M_{\text{BH}}$ is the black hole mass at the beginning of the time step, and $\sigma_T$ is the Thomson cross-section. A fraction $\eta$ of this accretion mass is radiated away—$L_{\text{AGN}} = \eta M_{\text{accretion}}c^2$—and so during one snapshot, black holes grow through the radio-mode by mass
\begin{equation}
\Delta M_{\text{BH,R}} = (1 - \eta)M_{\text{accretion}}.
\end{equation}

The model includes the effects of radio-mode AGN feedback by assuming that a fraction $\kappa_r$ of the radiated energy is coupled to the surrounding gas, adiabatically heating a mass of
\begin{equation}
M_{\text{heat}} = \frac{\kappa_r L_{\text{AGN}}}{0.5V_{\text{vir}}^2} = \frac{\kappa_r \eta M_{\text{accretion}}c^2}{0.5V_{\text{vir}}^2}.
\end{equation}
This heated gas is subtracted from the cooling flow, regulating the accretion of new gas onto the black hole (see Croton et al., 2006, 2016, Q17). This AGN feedback has no significant effect on the results of Tiamat at $z \geq 2$, suppressing the growth of only the most massive galaxies in Tiamat-125-HR at lower redshifts (see Figure 4.1).

### 2.4.2 Quasar-mode growth

Black holes accrete cold gas from the galaxy (total mass $M_{\text{cold}}$), when triggered by either a galaxy-galaxy merger or a disc instability. Following the prescription of Croton et al. (2016), during such an event, the black hole mass grows by a total of
\begin{equation}
\Delta M_{\text{BH,Q}} = \min\left(M_{\text{cold}}, \frac{k M_{\text{cold}}}{\left(1 + \frac{280}{V_{\text{vir}}^2}\right)^2}\right),
\end{equation}
where $V_{\text{vir}}$ is the virial velocity of the halo and $k$ is a free parameter to adjust the growth efficiency. For merger-triggered growth, $k = k_c \gamma$ where $\gamma$ is the merger ratio and $k_c$ is a constant. For instability driven growth, $k = k_i$. Note that while Croton et al. (2016)
choose to have $k_i = k_c$, I consider $k_c$ and $k_i$ two separate free parameters (see Section 3.1), as it produces a better agreement with the local black hole–bulge mass relation. Physically, I know of no expectation for the two growth modes to have the same black hole growth efficiency due to the different physical processes that drive them. During the quasar mode, black holes are assumed to accrete at the Eddington rate, and thus the mass accreted by the black hole during one simulation snapshot is limited to $M_{\text{Edd}}$, i.e. \( \min (M_{\text{Edd}}, \Delta M_{\text{BH,Q}}) \). This can result in the mass $\Delta M_{\text{BH,Q}}$ being accreted over multiple simulation snapshots (see Q17 for a more detailed discussion).

The model incorporates quasar-mode AGN feedback by considering the energy injected into the gas during a simulation time-step, $\kappa_q \eta \min (M_{\text{Edd}}, \Delta M_{\text{BH,Q}}) c^2$, where $\kappa_q$ is the mass coupling factor. It is assumed that this energy generates a wind that heats the cold disc gas and transfers it to the hot gas reservoir, depleting the supply of cold gas available for the black hole to accrete. If sufficient energy is injected by the quasar, this wind can also eject the hot gas (see Q17).

### 2.4.3 Quasar luminosities

I calculate the bolometric luminosities of each black hole in the model following the Q17 method, which assumes Eddington luminosity for all accreting black holes, and self-consistently calculates the duty cycle. I consider the luminosities from both the quasar- and radio-modes of accretion. As described in Q17, at high-redshifts the contribution from the radio-mode is negligible. At the lowest redshifts ($z \leq 2$), the radio-mode becomes a more significant growth mechanism for the most massive black holes, and so their luminosities are enhanced slightly by the addition of the radio-mode luminosity.

I convert from bolometric to $B$-band luminosities using the Hopkins et al. (2007) bolometric correction, and then assume a continuum slope of $\alpha = 0.44$ to convert to UV luminosities (see Q17 for details). I also account for obscuration due to quasar orientation, by scaling the UV luminosity function by \( 1 - \cos(\theta/2) \), where $\theta$ represents the opening angle of quasar radiation. MERAXES assumes a constant $\theta$, for simplicity, which is a free parameter in the model; this simply adjusts the normalisation of the UV luminosity functions.
2.5 Star formation

I implement a new density-dependent star formation prescription in MERAXES, equivalent to that in Tonini et al. (2016). This uses the mass of cold gas above the critical density for star formation to determine how many stars are formed. To calculate this critical mass from the critical surface density, the original MERAXES star formation prescription, used commonly in other semi-analytic models such as Croton et al. (2006, 2016), assumed that the mass in the gas disc was evenly distributed out to a radius of $3R_{s,g}$, where $R_{s,g}$ is the scale-length of the gas disc. Models such as De Lucia & Helmi (2008), Lagos et al. (2011) and Tonini et al. (2016) improve this by assuming that the gas in the disc is exponentially distributed. This will result in a lower fraction of gas being above the critical density over longer periods of time, reducing the burstiness of the star formation.

The gas surface density threshold for star formation is $\Sigma_{\text{crit}} = 10M_\odot/pc^2$ (Kormendy & Kennicutt, 2004). For gas discs with an exponential surface density profile $\Sigma(r) = \Sigma_0 \exp(-r/R_{s,g})$: $\Sigma_0 = M_{\text{cold}}/(2\pi R_{s,g}^2)$, where the scale radii $R_{s,g}$ are determined as outlined in Section 2.6. The radius at which the surface density drops below this critical value is

$$r_{\text{crit}} = R_{s,g} \ln(\Sigma_0/\Sigma_{\text{crit}}).$$

The total mass of gas inside this radius is

$$M_{\text{crit}} = M_{\text{cold}} \left(1 - \exp\left(-\frac{r_{\text{crit}}}{R_{s,g}}\right) \left(1 + \frac{r_{\text{crit}}}{R_{s,g}}\right)^2\right)$$

and so I assume that this amount of gas is capable of forming stars since it is above the critical density threshold for star formation. New stars form at a rate of $\Sigma_{\text{crit}} = \epsilon M_{\text{crit}}/t_{\text{dyn}} = \epsilon M_{\text{crit}}V_{\text{vir}}/r_{\text{crit}}$, where $t_{\text{dyn}} = r_{\text{crit}}/V_{\text{vir}}$ is the dynamical time of the disc and $\epsilon$ is a free parameter describing the efficiency of star formation. Therefore, over the snapshot time length of $dt$, the total mass of new stars which have formed is

$$\delta M_* = \epsilon M_{\text{crit}}V_{\text{vir}}/r_{\text{crit}} dt.$$  

2.6 Galaxy sizes and angular momenta

2.6.1 Existing models of galaxy sizes

In the hierarchical structure formation scenario, gas cools in the centres of dark matter haloes to form galaxies. The Mo et al. (1998) analytical model of this process predicts
that if galaxies are thin exponential discs with flat rotation curves, and specific angular momentum is conserved, the scale length of a galaxy disc $R_s$ is

$$R_s = \frac{\lambda}{\sqrt{2}} \left( \frac{J_d}{J_H} \frac{M_{\text{vir}}}{M_d} \right) R_{\text{vir}}$$

where $J_d$ is its angular momentum, $M_d$ its mass, $R_{\text{vir}}$, $M_{\text{vir}}$, $J_H$ and $j_H$ are the virial radius, virial mass, and total and specific angular momentum of its dark matter halo, and

$$\lambda = \frac{|j_H|}{(\sqrt{2} R_{\text{vir}} V_{\text{vir}})}$$

is the halo spin parameter (Bullock et al. 2001; see Angel et al. 2016 for an examination at high redshift). Note that this model is an extension of the Fall (1983) model which assumed $R_s = \lambda R_{\text{vir}} / \sqrt{2}$, with $J_d = J_H$ and $M_d = M_{\text{vir}}$.

Semi-analytic models often use the Fall (1983) model and assume $R_s = \lambda R_{\text{vir}} / \sqrt{2}$ to predict the sizes of galaxies within their simulated dark matter haloes (e.g. Croton et al., 2006; Mutch et al., 2016; Liu et al., 2016b). While simplistic, this model has had success in reproducing the size evolution of galaxies from $z \sim 5$–9 (Liu et al., 2016b). More advanced semi-analytic models improve their disc size estimates by explicitly tracking the angular momentum of galaxy discs (e.g. Lagos et al., 2009; Guo et al., 2011; Benson, 2012; Stevens et al., 2016; Tonini et al., 2016; Xie et al., 2017; Zoldan et al., 2019). Under the assumption that galaxy discs have a constant velocity profile and an exponential surface density profile, their specific angular momentum is $j = 2 R_s V$, and so their radii can be estimated as $R_s = j / 2V$. These models generally assume that the velocity of the galaxy disc $V$ is equal to the maximum circular velocity of the surrounding dark matter halo (e.g. Guo et al., 2011; Tonini et al., 2016; Zoldan et al., 2019). Stevens et al. (2016) introduce a more sophisticated semi-analytic model, splitting galaxy discs into a series of constant $j$ annuli, which allows the model to self-consistently evolve the radial and angular momentum structure of galaxy discs. The Stevens et al. (2016) model, alongside hydrodynamical simulations (e.g. Pedrosa & Tissera, 2015; Teklu et al., 2015; Lagos et al., 2017), have made predictions for the redshift evolution of angular momentum, with some finding no or minimal increase of $j$ with decreasing redshifts, while others support the gradual growth of $j$ in galaxies. However, at high redshifts ($z > 2$), no theoretical studies have been compared with the (minimal) observational angular momentum data.
2.6.2 Improvements to the Meraxes size model

The simulated properties of dark matter haloes can jump significantly between adjacent snapshots due to errors in the halo-finding process (e.g. central-satellite switching, ejected cores, and the ‘small halo problem’; for details see Poole et al., 2017). In previous versions of Meraxes (e.g. Mutch et al., 2016; Liu et al., 2016b), the scale radius of the disc $R_s$ is approximated from the radius $R_{\text{vir}}$ and spin $\lambda$ of the host halo—$R_s = R_{\text{vir}} \lambda/\sqrt{2}$—and it is assumed that the rotational velocity of the disc is equal to the maximal circular velocity of the halo. This means that the galaxy properties can also jump significantly between adjacent snapshots due to such errors. Clearly this is unphysical, and decoupling the galaxy properties from the instantaneous halo properties to remove these errors would be ideal. I therefore introduce a new method for determining the scale radius of galaxy discs, in which the disc is evolved incrementally in response to changes that have occurred at each snapshot. In order to do so, I consider any changes to the mass of the disc as a sum (or subtraction) of two discs: the existing disc and a pseudo-disc of material to be added (or removed), and determine the size of the resulting disc using conservation of energy and angular momentum arguments. This requires that I also track the vector angular momentum of both the stellar and cold gas discs. Note that I do not attempt to track the angular momentum of the bulge, and simply assume it to be zero. The method of calculating disc radii and tracking angular momentum is as follows.

I assume that the stellar and gas discs have:

i. Constant velocity profile $V(r) = V$ (i.e. the rotation curve of the disc is flat)

ii. An exponential surface density profile, $\Sigma(r) = (M_{\text{disc}}/2\pi R_s^2) \exp(-r/R_s)$, as in Mo et al. (1998)

The total energy of such a disc is

$$E_{\text{tot}} = -\frac{GM_{\text{disc}}}{R_s^2} \int_0^\infty M(< r) e^{-r/R_s} dr + \frac{1}{2} M_{\text{disc}} V^2. \quad (2.10)$$

For a stellar disc in a galaxy with a bulge, gas disc and surrounding dark matter halo, $M(< r) = M_{\star, \text{disc}}(< r) + M_{\text{cold}}(< r) + M_{\text{halo}}(< r) + M_{\text{bulge}}(< r)$. For discs with exponential surface density profiles, $M_{\text{disc}}(< r) = M_{\text{tot}} (1 - (1 + r/R_s) \exp(-r/R_s))$. Assuming that
both the halo and the bulge are singular isothermal spheres such that $M_{\text{bulge}}(< r) = V_{\text{bulge}}^2 r/G$ and $M_{\text{halo}}(< r) = V_{\text{vir}}^2 r/G$, then:

$$E_{\text{tot}} = -\frac{GM_{\ast,\text{disc}}}{R_{s,\ast}} \left( \frac{M_{s,\text{disc}}}{4} + M_{\text{cold}} \frac{R_{s,\ast}^2}{(R_{s,\ast} + R_{s,g})^2} \right) - M_{s,\text{disc}} V_{\text{vir}}^2 - M_{s,\text{disc}} V_{\text{bulge}}^2 + \frac{1}{2} M_{s,\text{disc}} V^2,$$

where $R_{s,\ast}$ and $R_{s,g}$ are the scale radii of the stellar and gas discs, respectively.

The potential energy from the gas disc and the stellar disc itself are negligible relative to the potential energy from the halo and bulge: neglecting these gives the simplified total energy equation

$$E_{\text{tot}} \simeq -M_{s,\text{disc}} V_{\text{vir}}^2 - M_{s,\text{disc}} V_{\text{bulge}}^2 + \frac{1}{2} M_{s,\text{disc}} V^2.$$

An identical argument applies to the energy of a gas disc.

Now consider the sum (or subtraction) of two such discs, the existing disc and a pseudo-disc of material to be added (or removed). Both discs are assumed to reside at the centre of the same halo, and are associated with the same bulge component. If these discs have masses $M_1$ and $M_2$, scale radii $R_1$ and $R_2$, and velocities $V_1$ and $V_2$, then from conservation of energy, $E_1 + E_2 = E_{\text{new}}$, which leads to, upon cancellation of the potential terms:

$$\frac{1}{2} M_1 V_1^2 + \frac{1}{2} M_2 V_2^2 = \frac{1}{2} (M_1 + M_2) V_{\text{new}}^2.$$

Assuming conservation of angular momentum, $J_1 + J_2 = J_{\text{new}}$, the angular momentum of the combined disc $J_{\text{new}}$ is easily calculated by summing the individual angular momentum vectors of each disc, which are tracked by the model. Under the assumptions $i$ and $ii$, the angular momentum is

$$|J| = \int_0^{\infty} \Sigma(r) 2\pi r^2 V dr$$

$$= \frac{M_{\text{disc}} V}{R_s^2} \int_0^{\infty} e^{(-r/R_s) r^2} dr$$

$$= 2M_{\text{disc}} VR_s.$$
Using conservation of energy and angular momentum (Equations 2.13 and 2.14), the new
disc scale length can be calculated using the galaxy’s existing properties and the properties
of the new material added:

\[
\begin{align*}
V_{\text{new}} &= \sqrt{\frac{M_1 V_{\text{vir}}^2 + M_2 V_{\text{vir}}^2}{M_1 + M_2}} \\
R_{\text{new}} &= \frac{|J_{\text{new}}|}{2V_{\text{new}}(M_1 + M_2)}
\end{align*}
\]  

(2.15)  
(2.16)

This method is applied when the galaxy undergoes several different processes, as follows.

**Gas cooling:** In each dark matter halo MERAXES assumes that there is a hot reservoir
of pristine primordial gas. Some fraction of this gas will then cool and condense into a
gas disc. I assume that the hot halo gas is settled into the dark matter halo such that
\( V_{\text{hot}} = V_{\text{vir}} \) and \( j_{\text{hot}} = j_H \). Then, I assume that when this gas cools on to the galaxy,
it forms in a disc with velocity and specific angular momentum \( V_{\text{cold}} = V_{\text{hot}} = V_{\text{vir}} \) and
\( j_{\text{cold}} = j_{\text{hot}} = j_H \), and thus with scale radius \( R = |j_H|/(2V_{\text{vir}}) \). If the galaxy already
contains some gas, this new gas disc is added to the existing gas disc.

**Star formation:** If the gas disc exceeds some critical density (see Section 2.5), stars
will form. Since these stars are originating in the disc, they are assumed to form in a
stellar disc with \( R = R_{\text{cold}} \), \( V = V_{\text{cold}} \) and \( j = j_{\text{cold}} \). This disc of new stars is added to the
existing stellar disc and subtracted from the existing gas disc (by taking the mass \( M_2 \) to
be negative), and the total angular momentum of these new stars is transferred from the
gas to the stellar disc.

Stars can also form in this model via bursts caused by disc instabilities or mergers. If such
a burst occurs, the model prescribes that new stars, with total mass \( \Delta M_* \), form in the
bulge and not the stellar disc. In this case, the stellar disc is unaffected, while the gas disc
loses some mass \( \Delta M_{\text{cold}} = -\Delta M_* \). I assume that the new stars form with zero angular
momentum, so that the angular momentum of the gas disc is conserved. Assuming that
the velocity of the gas disc remains constant, I use

\[
r_{\text{new}} = \frac{|J_{\text{cold}}|}{2V_{\text{cold}}(M_{\text{cold}} + \Delta M_{\text{cold}})} = \frac{r_{\text{original}}}{1 - \Delta M_*/M_{\text{cold}}}
\]

(2.17)
to update the radius (note that mass is removed from the disc, and so its radius will increase).

**Mergers:** In a minor merger, the stellar and gas discs of the secondary galaxy are added to those of the primary galaxy, using the disc addition process described above.

To determine the angular momentum of the merger remnant, the Tonini et al. (2016) prescription assumes that the gas from the secondary is stripped and settles into the dark matter halo before being accreted by the primary, retaining no ‘memory’ of the disc structure. In such a scenario, the angular momentum of the stripped material will be $J_{\text{stripped}} = M_{\text{sat}} \times j_{\text{FOF group of sat}}$, and so the angular momentum of the merger remnant will be $J_{\text{new}} = J_1 + J_{\text{stripped}} = J_1 + M_{\text{sat}} \times j_{\text{FOF group of sat}}$. Lee et al. (2018) find that the majority of satellite galaxies experience little change to their angular momentum after their infall into a cluster. In contrast to the Tonini et al. (2016) model, I therefore assume that the secondary’s disc retains its angular momentum, instead of being stripped. To determine the angular momentum of the merger remnant, I thus simply add the secondary’s angular momentum, as tracked throughout its history, to that of the primary: $J_{\text{new}} = J_1 + J_2$.

In a major merger, the stellar component of the remnant galaxy is assumed to become purely a bulge, and so the scale length, velocity and angular momentum of the stellar disc are set to zero. I assume that the gas disc remains intact, with the gas discs of both galaxies added together, where they form more stars (see Section 2.3.1).

**Supernovae:** Supernovae convert material from stars into gas. I assume that a factor of $(1 - M_{\text{bulge}}/M_{\ast,\text{total}})$ of the stars going supernova are in the stellar disc. The proportion of stars in the disc and bulge going supernova may be different as they may have stellar populations with different ages; however, I do not expect this to significantly change the galaxy sizes.

For supernovae in the galaxy disc, I assume that the fraction of stars going supernova relative to the number of stars at any radius is constant—the surface density of supernovae and therefore of the gas disc that they form is proportional to the stellar disc surface density. Therefore, I assume that the new gas disc caused by supernovae has the same velocity, specific angular momentum and scale radius $R = |j_\ast|/(2V_\ast)$ as the stellar disc.
This disc of new gas is added to the existing gas disc, and subtracted from the existing stellar disc, with the angular momentum transferred from the stellar disc to the gas disc.

I treat supernovae in the galaxy bulge differently, as I do not model bulge sizes or angular momenta, and therefore do not track the orbital parameters of the bulge stars going supernova or the gas that they eject. To account for this, I assume that the gas from supernovae in the bulge is ejected into the surrounding halo, where it will approach equilibrium with the surrounding dark matter. This gas will settle into a disc with the velocity and specific angular momentum of the host halo, with scale radius \( R = \frac{|j_H|}{2V_{\text{vir}}} \). This disc is added to the existing gas disc, as is the total angular momentum of this new gas. This assumption for the ejected gas from the bulge is motivated by the expectation that the bulge would have some angular momentum. However, note that a more straightforward choice would be to assume that the ejected gas has no angular momentum. I ran Meraxes with this alternative assumption and found no differences in the results, due to the minimal mass ejected by bulge supernovae.

Some cold disc gas is reheated by supernova feedback. This has total angular momentum \( J_{\text{reheat}} = M_{\text{reheat}} j_{\text{cold}} \), which is removed from the gas disc. This angular momentum is effectively given to the hot gas, however I do not track the angular momentum of the hot halo as I assume it is in equilibrium with the dark matter halo. Extending the model to track the hot gas angular momentum, as in the more complex model of Hou et al. (2017), for example, is left for future work.

**Disc instabilities:** When a disc is gravitationally unstable, I assume some stars from the disc are transferred to the bulge. In this scenario, instead of considering the subtraction of a pseudo-disc, I follow the Tonini et al. (2016) prescription. While the angular momentum of the disc is conserved, its mass decreases by \( \Delta M_* \). Assuming that the velocity of the disc remains constant, I use

\[
 r_{\text{new}} = \frac{|J_*|}{2V_*(M_* - \Delta M_*)} = \frac{r_{\text{original}}}{1 - \Delta M_*/M_*} \tag{2.18}
\]

to update the radius, which will increase as the mass decreases.

**AGN feedback:** Quasar mode AGN feedback reheats some of the gas in the disc. I assume that the same fraction of gas gets heated at all locations in the disc, so the scale
length of the reheated gas disc is equal to that of the original disc \((R_1 = R_2)\), and the two discs have the same velocities \((V_1 = V_2)\). In reality, the central AGN would preferentially expel gas from the centre of the galaxy; this simplistic assumption could be improved in future work by following the approach of Stevens et al. (2016), for example.

Under this assumption, since \(j = 2VR\), I am effectively assuming that the specific angular momentum of the disc is conserved during this process. Therefore, I decrease the total angular momentum of the disc by \(m_{\text{reheated}}j\). This disc of reheated gas is subtracted from the existing gas disc, with the mass given to the hot gas reservoir. I ensure that the scale length and velocity are zero if the mass of the disc is zero.

Finally, note that in general, \(J_1\), \(J_2\) and \(J_{\text{new}}\) will not be aligned. I define the new orientation of the disc using the direction of \(J_{\text{new}}\). Consider the projection of \(J_1\) and \(J_2\) on to this direction:

\[
\begin{align*}
J_{1p} &= |J_1| \sin \theta_1 \frac{J_{\text{new}}}{|J_{\text{new}}|} = 2M_1 V_1 R_1 \sin \theta_1 \frac{J_{\text{new}}}{|J_{\text{new}}|} \\
J_{2p} &= |J_2| \sin \theta_2 \frac{J_{\text{new}}}{|J_{\text{new}}|} = 2M_2 V_2 R_2 \sin \theta_2 \frac{J_{\text{new}}}{|J_{\text{new}}|}.
\end{align*}
\]

Now \(J_{\text{new}} = J_1 + J_2\), so \(|J_{\text{new}}| = |J_{1p}| + |J_{2p}|\), that is,

\[
|J_{\text{new}}| = 2M_{\text{new}} V_{\text{new}} R_{\text{new}} = 2M_1 V_1 R_1 \sin \theta_1 + 2M_2 V_2 R_2 \sin \theta_2.
\]

This can be interpreted as summing two discs that are projected on to the new plane, with projected radii \(R_1 \sin \theta_1\) and \(R_2 \sin \theta_2\). Therefore, this method is a simpler version of the Stevens et al. (2016) method of projecting the two discs prior to their addition, which captures the effect of more compact discs.

### 2.7 Using Meraxes: calibration and resolution

The Meraxes semi-analytic model includes a number of free parameters, which need to be calibrated against a range of observations. In Mutch et al. (2016), the model was calibrated to the observed evolution of the galaxy stellar mass function between redshifts 5–7, as this has been shown to provide a tight constraint on both the star formation efficiency and supernova feedback parameters (see e.g. Mutch et al., 2013; Henriques et al., 2013).
Mutch et al. (2016) also calibrated the model to measurements of the integrated free electron Thomson scattering optical depth, and the $z \lesssim 6$ ionizing emissivity, in order to investigate the process of reionization. Qin et al. (2017) introduced new parameters in the black hole growth model, and thus also calibrated against the black hole mass function ($z \lesssim 0.5$) and the quasar luminosity function ($z \sim 6$–$0.6$).

In Chapter 3, I calibrate the free parameters in Meraxes to match the observed stellar mass functions at $z = 0$–$8$ (Figure 3.1), and the black hole–bulge mass relation at $z = 0$ (Figure 3.2). In Chapter 4, I instead calibrate the free parameters in the model to match the observed stellar mass functions at $z = 0$–$8$ (Figure 4.1), the Shankar et al. (2009) and Davis et al. (2014) black hole mass function at $z = 0$ (Figure 4.2), and the quasar X-ray luminosity functions from $z = 5$ to $2$ (Figure 4.3), as I find that this better reproduces the black hole observations. Full details on the calibration are given in these chapters.

Note that I use the same parameter values for both Tiamat and Tiamat-125-HR, and use both simulations to tune the model: Tiamat for matching $z \geq 2$ observations and Tiamat-125-HR for $z < 2$. Figure 2.1 shows the $z = 2$ stellar mass- and black hole mass functions for Meraxes applied to both simulations, as calibrated against the observed stellar mass functions at $z = 0$–$8$, and the black hole–bulge mass relation at $z = 0$, as in Chapter 3. The stellar- and black hole mass functions from the Tiamat and Tiamat-125-HR simulations at $z = 2$ are converged above $M_* = 10^{8.65} M_\odot$ and $M_{BH} = 10^{7.1} M_\odot$, respectively. Below $M_* = 10^{8.6} M_\odot$ the Tiamat-125-HR stellar mass function experiences a slight upturn before a rapid turn-over, diverging from the Tiamat function. A similar divergence is also present in the black hole mass function. These are signatures of the resolution of the simulation. I use these signatures to determine the Tiamat-125-HR simulation resolution at redshifts where Tiamat is unavailable for comparison as follows.

I choose the mass at which the stellar mass function begins to upturn as the stellar mass resolution; at $z = 0$, this corresponds to a mass of $M_* = 10^{8.65} M_\odot$. For the black hole mass function, I take mass resolution as the mass at which the black hole mass function begins to flatten—$M_{BH} = 10^{7.35} M_\odot$ at $z = 0$. I therefore place no significance on the trends observed with Tiamat-125-HR for lower stellar and black hole masses, as these may be affected by resolution effects. These convergence limits are shown on all relevant plots in Chapter 3.

All analysis in Chapters 3 and 4 are conducted using model galaxies with $M_* > 10^7 M_\odot$, the
Chapter 2

Log \( \frac{M}{M_\odot} \)

\[ \log \left( \frac{M}{M_\odot} \right) \]

-5
-4
-3
-2
-1
0
1
\[ \log \left( \frac{M}{M_\odot} \right) \]

-5
-4
-3
-2
-1
0
1
\[ \log \frac{\Phi}{\text{dex}^{-1} \text{Mpc}^{-3}} \]

6 8 10 12

6 8 10

Figure 2.1 The \( z = 2 \) stellar mass and black hole mass functions for MERAXES applied to both Tiamat (black solid) and Tiamat-125-HR (purple dashed).

resolution limit of MERAXES when run on the Tiamat simulation (see Mutch et al., 2016). MERAXES includes a limited prescription for modelling the physics of satellite galaxies, assuming a maximally efficient hot halo stripping scenario and excluding potentially important dynamical effects which could alter satellite sizes or morphologies. To ensure that the conclusions are robust, I therefore only consider galaxies classified as centrals, except in the stellar mass and luminosity functions, which require the full galaxy sample. I leave a detailed exploration of the effect of including satellite galaxies to future work (however see, for example, Zoldan et al., 2018).
Chapter 3

The Sizes, Angular Momenta and Morphologies of High-Redshift Galaxies

Size, angular momentum and morphology are three of the most fundamental galaxy properties, and are integral probes for understanding the structure and growth of galaxies. Observing these properties at high redshifts offers an invaluable insight into galaxy formation and evolution in the early Universe.

The sizes of high-redshift Lyman-break galaxies have been measured using deep Hubble Space Telescope (HST) fields in a number of studies from $z \simeq 6–12$ (e.g. Oesch et al., 2010; Mosleh et al., 2012; Grazian et al., 2012; Ono et al., 2013; Huang et al., 2013; Holwerda et al., 2015; Kawamata et al., 2015; Shibuya et al., 2015; Kawamata et al., 2018). They find sizes consistent with an evolution of the galaxy effective radius $R_e \propto (1 + z)^{-m}$ at fixed luminosity, with measurements of $m$ typically in the range of $1 \lesssim m \lesssim 1.5$.

While observing galaxy morphologies at high-redshift is challenging (see e.g. Abraham, 2001), observations generally find that high-redshift galaxies are more clumpy and irregular than those at low redshift (Abraham, 2001; Papovich et al., 2005; Elmegreen, 2014). Several studies find that there is a larger fraction of spheroids at higher redshifts (e.g. Bundy et al., 2005; Franceschini et al., 2006; Ravindranath et al., 2006; Lotz et al., 2006; Dahlen et al., 2007), although Ravindranath et al. (2006) find that the $z \simeq 2.5–5$ population is not dominated by spheroids but by extended disc-like galaxies and irregulars or merger-like systems.

Unfortunately, there are only a few observational studies of galaxy angular momentum at redshifts $z > 1$ (e.g. Swinbank et al., 2017; Alcorn et al., 2018; Okamura et al., 2018).
since obtaining large spectroscopic samples to measure kinematics and thus specific angular momenta at high redshifts is difficult. Okamura et al. (2018), for example, estimated the specific angular momentum of $z \approx 2, 3 \text{ and } 4$ galaxies from their measured disc sizes, using the analytic model of Mo et al. (1998), and found little redshift evolution of the ratio of stellar to halo specific angular momentum. Because of the difficulty of observing these properties at high redshift, models and simulations play a necessary role for measuring and understanding their evolution in the early Universe.

In this chapter, I study the evolution of galaxy sizes, angular momenta and morphologies, using the new Meraxes model introduced in Chapter 2. This chapter is organised as follows. I calibrate the model and verify its predictions for low redshift sizes, angular momenta and morphologies in Section 3.1. I then make predictions for the high-redshift evolution of galaxy sizes in Section 3.2, angular momenta in Section 3.3 and morphologies in Section 3.4. I conclude in Section 3.5. Throughout this chapter, I adopt the Planck Collaboration (2016) cosmological parameters: $(h, \Omega_m, \Omega_b, \Omega_\Lambda, \sigma_8, n_s) = (0.678, 0.308, 0.0484, 0.692, 0.692, 0.968)$. All magnitudes are presented in the AB system (Oke & Gunn, 1983).

3.1 Model verification

In this section I detail how the free parameters in Meraxes are calibrated for this study, and show that this calibrated model can reproduce a range of observations.

3.1.1 Calibration

The free parameters in Meraxes are tuned to match the observed stellar mass functions at $z = 8-0$ (Figure 3.1), which constrain both the star formation efficiency and supernova feedback parameters, and the $M_{\text{BH}}-M_{\text{bulge}}$ relation at $z = 0$ (Figure 3.2), which calibrates the black hole growth parameters. Note that I use the $M_{\text{BH}}-M_{\text{bulge}}$ relation instead of the black hole mass function as in Q17, as the $M_{\text{BH}}-M_{\text{bulge}}$ relation is a more direct observable than the black hole mass function, and the model now has the capability of modelling bulge masses. I place an emphasis on matching the canonical Kormendy & Ho (2013) observations at high stellar and bulge masses, as this is a widely-used and reliable sample. Note that the model does not reproduce the wide scatter observed by Scott et al.
Figure 3.1 Galaxy stellar mass functions at $z = 8$–0 from the Q17 Meraxes (grey) and the new model (M19, black) applied to Tiamat (solid) and Tiamat-125-HR (dashed), compared to a range of observational data (see legend). Meraxes is calibrated such that these observed stellar mass functions are reproduced. The vertical grey dotted line indicates the stellar mass below which Tiamat and Tiamat-125-HR are not converged, and thus where galaxies from Tiamat-125-HR can be subject to resolution effects (see Section 2.7).

(2013), nor the Reines & Volonteri (2015) population of high stellar mass, low black hole mass galaxies, albeit this sample falls under the resolution limits (see Figure 3.2).

To produce a median bulge fraction that is in better agreement with local observations at the highest stellar masses (see Section 3.1.2.2 and Figure 3.4), I also modify the definition of a major merger to be one with $\gamma > 0.1$, instead of $\gamma > 0.3$ as used in Mutch et al. (2016) and Q17\textsuperscript{1}.

\textsuperscript{1}Semi-analytic models use a range of merger thresholds, such as 0.1 (Henriques et al., 2015), 0.2 (Izquierdo-Villalba et al., 2019), and 1/3 (Guo et al., 2011), and this is often tuned to better reproduce morphologies (e.g. Henriques et al., 2015; Izquierdo-Villalba et al., 2019).
Figure 3.2 **Left panel:** The $z = 0$ black hole–bulge mass relation, and **Right panel:** the $z = 0$ black hole–total stellar mass relation, for the model applied to *Tiamat-125-HR* (blue density plot). Only galaxies classified as centrals are shown. A range of observations are also plotted (*Kormendy & Ho, 2013; Scott et al., 2013; Graham & Scott, 2015; Reines & Volonteri, 2015, see legend*). A best-fitting line for the model galaxies with $M > 10^{9.5} M_\odot$ is also shown (solid line). **MERAXES** is calibrated to fit the canonical *Kormendy & Ho (2013)* observations in the high stellar and bulge mass regime. The grey dotted lines indicate the stellar and black hole masses below which *Tiamat* and *Tiamat-125-HR* are not converged, and thus where galaxy properties from *Tiamat-125-HR* are more uncertain (see Section 2.7).

Table 3.1 Optimal values of **MERAXES** parameters that are either introduced or discussed in Chapter 2, or have different values from those used in Q17 due to the model update and re-calibration I have implemented.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Q17</th>
<th>M19</th>
</tr>
</thead>
<tbody>
<tr>
<td>Star formation efficiency $^a$</td>
<td>0.08</td>
<td>0.03</td>
</tr>
<tr>
<td>Supernova ejection efficiency $^b$</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>Minimum merger ratio for major merger</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>Minimum merger ratio for starburst</td>
<td>0.1</td>
<td>0.01</td>
</tr>
<tr>
<td>Black hole seed mass ($M_\odot$)</td>
<td>$10^4$</td>
<td>$10^4$</td>
</tr>
<tr>
<td>Merger-driven black hole growth efficiency ($k_c$) $^c$</td>
<td>0.05</td>
<td>0.03</td>
</tr>
<tr>
<td>Instability-driven black hole growth efficiency ($k_i$) $^d$</td>
<td>-</td>
<td>0.02</td>
</tr>
<tr>
<td>Radio mode black hole growth efficiency $^e$</td>
<td>0.3</td>
<td>0.003</td>
</tr>
<tr>
<td>Black hole efficiency of converting mass to energy $^f$</td>
<td>0.06</td>
<td>0.2</td>
</tr>
<tr>
<td>Opening angle of AGN radiation $^g$</td>
<td>80$^\circ$</td>
<td>30$^\circ$</td>
</tr>
</tbody>
</table>

$^a$ Mutch et al. (2016) equation 7  
$^b$ Mutch et al. (2016) equation 13. Note that in Mutch et al. (2016) this value was 0.5, as it is now.  
$^c$ Equation 2.6, Q17 equation 19  
$^d$ Equation 2.6  
$^e$ Q17 equation 14  
$^f$ Q17 equation 15  
$^g$ Q17 section 3.3
The parameter values discussed in Chapter 2 and those that differ from the Q17 values are shown in Table 3.1. The only parameters I have introduced with the model updates described in Chapter 2 are the instability-driven black hole growth efficiency, and the efficiency at which mass is converted to luminosity upon accretion by a black hole, $\eta$: $L_{\text{BH}} = \eta \dot{M}_{\text{BH}} c^2$, where $c$ is the speed of light. In previous versions of Meraxes, this value was fixed at 0.06 (Qin et al., 2017). However, I add this free parameter to better model the high-mass end of both the stellar and black hole mass functions, and set it to $\eta = 0.2$ through the parameter tuning (see Croton et al., 2016, for a discussion).

### 3.1.2 Further validation

Once the model has been tuned to reproduce the galaxy stellar mass functions and local black hole–bulge relation, I verify the changes to the model by comparing the output to a range of local observations: the stellar mass–disc size relation, bulge fractions, and angular momentum–mass relations. Additionally, comparison of the high-redshift galaxy UV luminosity functions and the stellar mass–star formation rate relation can be seen in Appendix A.

#### 3.1.2.1 Low-redshift disc size–mass relation

I present the sizes of model galaxies using the physical effective radius, or half-light radius, $R_e$. I estimate this as $R_e = 1.678 R_s$, which is the half-light radius for a disc with an exponential surface density profile and a constant mass-to-light ratio.

Figure 3.3 shows the relation between the stellar disc effective radius and stellar mass at $z = 0$ for Meraxes and a range of observations. The model agrees reasonably well with the Dutton et al. (2011), Lange et al. (2016) and Lapi et al. (2018) observations, with the median matching their relations closely for $10^9 < M_*/M_\odot < 10^{10.5}$. At higher masses, the model median jumps to higher radii, although is still reasonably consistent with the observations. This jump is most likely a result of the lower sample size of high-mass galaxies, due to the limited simulation box size. The observations of Wu (2018) extend to much lower masses; the median of the model is highly consistent with this sample at $M_* < 10^{8.5} M_\odot$, while being slightly higher yet still consistent with the observations at higher masses.
Figure 3.3 The relation between the disc effective radius ($R_e$) and stellar mass ($M_*$) at $z = 0$ for the updated MERAXES (M19, blue density plot). Only galaxies classified as centrals are shown. A range of observations are also plotted (Gadotti, 2009; Dutton et al., 2011; Lange et al., 2016; Wu, 2018; Lapi et al., 2018, see legend). The black squares and errorbars represent the median and 16th and 84th percentile ranges of galaxy disc sizes from the model, in mass bins with width 0.5 dex. The filled regions around the observations represent the 1σ scatter for Dutton et al. (2011) and Lange et al. (2016), and 2σ for Wu (2018). The grey dotted line indicates the stellar mass below which Tiamat and Tiamat-125-HR are not converged, and thus where galaxy properties from Tiamat-125-HR are more uncertain (see Section 2.7).

Dutton et al. (2011), Wu (2018), and Lapi et al. (2018) consider only disc galaxies, while the Lange et al. (2016) and Gadotti (2009) samples have no clear morphology biases. These observations are all selected in the optical/near-infrared, except for the Wu (2018) observations which are HI selected, and are generally volume-limited. Gadotti (2009) note that their sample, however, contains a larger fraction of massive and more concentrated galaxies than a volume-limited sample. In addition, they use circular apertures, as opposed to more accurate elliptical apertures, leading to an underestimation of the sizes of galaxies. Indeed, Figure 3.3 shows that Gadotti (2009) observe smaller disc sizes relative to the other observations and the model for galaxies in $10^{9.5} < M_*/M_\odot < 10^{11}$.

I conclude that the MERAXES model is reproducing reasonable $z = 0$ galaxy sizes, given the dispersion in available observational data.
3.1.2.2 Galaxy morphologies at low redshift

To verify that the bulge model is producing galaxies with reasonable morphologies, I consider the median fraction of stellar mass contained within galaxy bulges as a function of total stellar mass at $z = 0.1$ (Figure 3.4). Note that I chose this redshift instead of $z = 0$ as it is the median redshift of the Thanjavur et al. (2016) observations to which I compare the model, and this allows me to implement a magnitude cut to mimic their selection effects; however, the equivalent plots at $z = 0$ are qualitatively identical.

The model predicts that the majority of stellar mass for low mass galaxies ($M_* \sim 10^9 M_\odot$) is contained in the bulge component, discs contribute a peak of $\sim 60$ per cent of the stellar mass at $M_* \sim 10^{9.5} M_\odot$, and bulges again dominate at larger masses. This dip in the bulge-to-total mass ratio B/T is due to the masses at which the two bulge growth mechanisms are dominant; the merger-driven growth mode peaks for galaxies with $M_* \sim 10^9 M_\odot$, while the instability-driven growth mode peaks at $M_* \sim 10^{11} M_\odot$. This suggests that high-mass galaxy discs are likely to be unstable and thus form bulges, while it is predominantly only less massive galaxies which form their bulges via mergers. I also see a steep increase in the merger-driven bulge fraction for the most massive galaxies, with major mergers forming giant ellipticals. Note that at masses $M_* < 10^{8.65} M_\odot$, where the Tiamat and Tiamat-125-HR simulations are not converged, the bulge fraction drops rapidly—this is most likely a resolution effect.

I compare my results to the SDSS observations of Thanjavur et al. (2016), which are also shown in Figure 3.4. I implement a magnitude cut of $r < 17.77$, to match those observations; this magnitude cut restricts my sample to galaxies with $M_* > 10^{10} M_\odot$. For stellar masses of $\lesssim 10^{11} M_\odot$ the model predicts a bulge fraction in remarkable agreement with the observations, increasing with mass to $\simeq 0.9$ at $M_* \simeq 10^{11.5} M_\odot$. For masses $10^{10} < M_* < 10^{11} M_\odot$, the model overpredicts the total bulge fraction by approximately 10 per cent, although is consistent within the 16th–84th percentile range of simulated galaxy bulge fractions.

I perform an equivalent comparison with the GAMA observations of Moffett et al. (2016) (Figure 3.4). I implement a magnitude cut of $r < 19.8$, to match those observations; this magnitude cut restricts the sample to galaxies with $M_* > 10^9 M_\odot$. For stellar masses of $M_* \gtrsim 10^{11} M_\odot$ and $M_* \lesssim 10^{10} M_\odot$ the model predicts a bulge fraction in good agreement with the observations. For masses $10^{10} < M_*/M_\odot < 10^{11}$, the model overpredicts the
Figure 3.4 The fraction of stellar mass contained in the bulge components of galaxies as a function of total stellar mass at $z = 0.1$. Only model galaxies classified as centrals are shown. Left panel: Purple solid lines show the median galaxy bulge fraction for the entire sample of central galaxies, in mass bins of width 0.2 dex, and the purple shaded regions show the 16th and 84th percentile range. Also shown are the median mass fractions of the instability-driven bulge (orange dashed) and merger-driven bulge (green dot-dashed), alongside their 16th and 84th percentile ranges. For comparison, the predictions of the EAGLE simulation at $z = 0$ (Clauwens et al., 2018) are also shown (grey dotted). Middle panel: Purple solid lines show the median galaxy bulge fraction for the central galaxies with magnitude $r < 17.77$, in mass bins of width 0.2 dex, and the purple shaded regions show the 16th and 84th percentile range. Also shown are the observed $z = 0.1$ SDSS bulge fractions from Thanjavur et al. (2016) binned by stellar mass (grey points and line); these observations have a magnitude limit of $r < 17.77$. Right panel: Purple solid lines show the median galaxy bulge fraction for the central galaxies with magnitude $r < 19.8$, in mass bins of width 0.2 dex, and the purple shaded regions show the 16th and 84th percentile range. Also shown are the observed $0.002 < z < 0.06$ GAMA bulge fractions from Moffett et al. (2016), binned by stellar mass (grey points and errors); these observations have a magnitude limit of $r < 19.8$. In all panels, the grey dotted line indicates the stellar mass below which Tiamat and Tiamat-125-HR are not converged (see Section 2.7).

total bulge fraction by up to 40 per cent. However, note that their analysis does not include pseudobulges—this mass range is precisely where I predict the instability-driven or ‘pseudo’ bulge to dominate, which may explain this discrepancy.

The SDSS and GAMA observations provide the most comprehensive and quantitative comparison, however, other studies have also investigated the bulge fraction as a function of stellar mass. Bundy et al. (2005) predict a similar trend, finding that E/S0 galaxies dominate at higher masses and spirals at lower masses, with the transition at $(2–3) \times 10^{10} M_{\odot}$ at $z \simeq 0.3$. The trend the model predicts for the $B/T$ ratio is qualitatively consistent with observations such as Conselice (2006), who found that the spiral fraction is largest in
galaxies with $10^9 < M_* < 10^{11} M_\odot$, with ellipticals dominant at higher masses and irregular galaxies at lower masses. Simons et al. (2015) find that for $M_*>10^{9.5} M_\odot$, galaxies are mostly rotation dominated and disc-like, while below this mass galaxies can be either rotation-dominated discs or asymmetric or compact galaxies; however, note that they only consider ‘blue’ galaxies, so this comparison is limited. Wheeler et al. (2017) found that the majority of dwarf galaxies with $M_* < 10^8 M_\odot$ are dispersion-supported (i.e. bulgy; due to the resolution limit I cannot make a comparison with this study).

My predictions are in reasonable agreement with those of the Izquierdo-Villalba et al. (2019) semi-analytic model, who find that pseudo-bulges, or those caused by disc instabilities, are typically present in more massive galaxies, peaking at $M_* \simeq 10^{10} M_\odot$, while ellipticals dominate at the highest masses due to major mergers turning the galaxies into pure bulges. The predictions of the model are also qualitatively very similar to those of the EAGLE simulation (Clauwens et al., 2018), whose median B/T ratios as a function of total stellar mass at $z=0$ are overplotted in Figure 3.4. Clauwens et al. (2018) see three phases of galaxy growth, with $10^9 < M_* < 10^{9.5} M_\odot$ galaxies mostly spheroidal, disorganised irregulars, $10^{9.5} < M_* < 10^{11} M_\odot$ galaxies dominated by discs, and galaxies with $M_*>10^{11} M_\odot$ mostly elliptical (Clauwens et al., 2018). While the dip in their B/T is slightly deeper and occurs at $\sim 0.5$ dex higher mass, the predictions are qualitatively similar to those of my model. I can adjust my galaxy morphologies by introducing an additional free parameter in the disc-instability criterion, $\eta$, such that $M_{\text{crit}} = \eta V_{\text{disc}}^2 R_s/G$ (Efstathiou et al., 1982); here $\eta$ is a parameter that determines the importance of the self-gravity of the disc. I find that increasing $\eta$ from its default value of 1 deepens the dip in B/T and shifts it to higher masses, bringing my model to closer agreement with Clauwens et al. (2018). However, I opt not to introduce this as an additional free parameter in the model (as in e.g. Lagos et al., 2018; Izquierdo-Villalba et al., 2019). My results are also consistent with the morphologies predicted by the Illustris hydrodynamical simulation (Snyder et al., 2015), which find at $M_* \simeq 10^{10} M_\odot$ that galaxies are a combination of spirals and composite systems, shifting to ellipticals at higher masses.

My bulge model therefore produces reasonable galaxy morphologies, and bulge and disc masses, given the stellar mass functions and bulge fractions are in agreement with the observations.
3.1.2.3 Angular momentum–mass relations

In this section I investigate the success of the model at reproducing the angular momentum–mass relations observed in local galaxies. I consider only disc-dominated galaxies, with bulge-to-total mass ratio $B/T < 0.3$, in order to compare with observations, which are of predominantly discy galaxies. I continue to restrict the analysis to only model galaxies classified as centrals, with $M_*>10^7M_\odot$. Since I assume that the bulge component has negligible angular momentum relative to the disc, I approximate the total stellar specific angular momentum as $j_*=J_*/M_*=J_*/(M_{\text{disc}}+M_{\text{bulge}})$. I refer to the stellar-disc specific angular momentum as $j_{\text{disc}}=J_{\text{disc}}/M_{\text{disc}}$.

The correlation between stellar specific angular momentum $j_*$ and total stellar mass $M_*$ (commonly referred to as the Fall relation) is claimed to be one of the most fundamental galaxy scaling relations (e.g. Fall & Romanowsky, 2018). The $j_*-M_*$ relation predicted by Meraxes at $z=0$ is shown in Figure 3.5. I also show a range of observations of both the $j_*-M_*$ relation, and of the $j_{\text{disc}}-M_{\text{disc}}$ relation for disc galaxies (Fall & Romanowsky, 2013; Burkert et al., 2016; Harrison et al., 2017; Lapi et al., 2018; Sweet et al., 2018; Posti et al., 2018b; Fall & Romanowsky, 2018)\(^3\), to which the model shows remarkable agreement.

The Posti et al. (2018b) observations extend to low stellar masses, where they find that the $j_*-M_*$ relation remains as a single, unbroken power-law, challenging, for example, the Stevens et al. (2016) galaxy-formation model which predicts a flattening of the relation at low masses ($M_*<10^9M_\odot$). My model shows no significant flattening of the $j_*-M_*$ relation at $M_*<10^9M_\odot$; however, the predictions at these masses are insignificant due to the simulation convergence limits of $M_*=10^{8.65}M_\odot$. The lack of flattening produced by the model is consistent with the Posti et al. (2018b) observations, as well as the Lagos et al. (2017) and Zoldan et al. (2018) models, for example. Posti et al. (2018b) posit that this flattening is due to assuming a constant disc-to-halo specific angular momentum ratio $j_d/j_H$ with mass, since they find that lower mass galaxies require a much smaller $j_d/j_H$.

I make no explicit assumptions regarding the $j_d/j_H$ ratio and its mass dependence; once I assume that $j_{\text{cold}}/j_H=1$ for gas cooling from the halo, the model then self-consistently

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\(^2\)Note that plotting the model $j_{\text{disc}}-M_{\text{disc}}$ relation produces a very similar relation to that in Figure 3.5, as I only select disc-dominated galaxies.

\(^3\)Note that the Fall & Romanowsky (2018) relation is an updated fit to the same data used in Fall & Romanowsky (2013)
Figure 3.5 The relation between total stellar specific angular momentum $j_*$ and total stellar mass $M_*$ for disc-dominated (B/T $< 0.3$), central galaxies at $z = 0$ in Meraxes (blue density plot). The black squares and errorbars represent the median and 16th and 84th percentile ranges of galaxy angular momenta from the model, in mass bins with width 0.5 dex. A range of observational data is also shown (see legend). The grey dotted line indicates the stellar mass below which Tiamat and Tiamat-125-HR are not converged (see Section 2.7).

tracks changes in the angular momentum for each galaxy throughout its history. The relation between $j_*/j_H$ ratio and stellar and halo mass for the galaxies is shown in Figure 3.6.

The angular momentum retention factor, $j/j_H$, encapsulates how much angular momentum from the dark matter halo is retained by the galaxy as it forms and evolves. This can be affected by the many processes that alter the state of the galaxy, such as gas cooling, friction, and feedback processes, each of which has a differing effect on the angular momentum of the galaxy, and which may also have dependencies on the galaxy and halo mass. The $j/j_H$ ratio gives an insight into the overall effect of these processes on a galaxy. Meraxes predicts a decreasing $j_*/j_H$ ratio with decreasing stellar and halo mass, as shown in Figure 3.6. While the model contains galaxies with a wide range of $j_*/j_H$ values, the distribution has a median lower than one, with $j_*/j_H \approx 0.5$ at $M_{\text{vir}} \approx 10^{12} M_\odot$ and $M_* \approx 10^{10} M_\odot$. The model therefore suggests that the majority of galaxies lose angular
Figure 3.6 The relation between the ratio of stellar to halo specific angular momentum $j_*/j_H$ and total stellar mass (left panel) and host halo mass (right panel), for disc-dominated (B/T < 0.3), central galaxies at $z = 0$ in MERAXES (blue density plot). The black squares and errorbars represent the median and 16th and 84th percentile ranges from the model. The Lapi et al. (2018) and Dutton & van den Bosch (2012) observations are also shown (see legend). The grey dotted lines indicate the stellar mass below which Tiamat and Tiamat-125-HR are not converged, and the (100 particle) halo mass resolution limit for Tiamat-125-HR.

momentum as they evolve, since $j_*/j_H < 1$.

My predictions overlap with the confidence intervals of the Lapi et al. (2018) and Dutton & van den Bosch (2012) observations. Lapi et al. (2018) find a decrease in $j_*/j_H$ towards lower stellar masses at $M_* < 10^{10} M_\odot$, consistent with my predictions, but they predict a turn-over at $M_* \simeq 10^{10} M_\odot$ with the ratio decreasing at larger masses. They also predict an increase in $j_*/j_H$ towards lower halo masses for $M_{\text{vir}} > 10^{11.5} M_\odot$, before a turn-over at $M_{\text{vir}} \simeq 10^{11.5} M_\odot$. Dutton & van den Bosch (2012) find that $j_*/j_H$ is roughly constant, with only a slight increase with increasing halo mass (I plot the average $j_*/j_H$ quoted by Dutton & van den Bosch 2012, as they provide no functional fit to this relation). Fall & Romanowsky (2018) find $j_*/j_H \simeq 1$ for disc galaxies and $\simeq 0.1$ for bulges, which are roughly constant over $10^{9.5} \lesssim M_*/M_\odot \lesssim 10^{11.5}$; my predictions for the entire galaxy sample lie between these two values. My results are also consistent with the Burkert et al. (2016) study which found $j_d/j_H = 1.0 \pm 0.6$.

Note that the model of Posti et al. (2018a) predicts that, for a range of observed stellar-to-halo mass relations, to match the $j_* - M_*$ relation late-type galaxies must have $j_*/j_H \simeq 0.3$ at $M_* \simeq 10^{8.5} M_\odot$ or $M_{\text{vir}} \simeq 10^{11} M_\odot$. They find that $j_*/j_H$ should increase slowly with stellar mass, until a turn-over at $M_* \simeq 10^{10.5} M_\odot$, beyond which $j_*/j_H$ steeply decreases.
Figure 3.7 The relation between total stellar specific angular momentum $j_*$ and total stellar mass $M_*$ for central MERAXES galaxies at $z = 0$, coloured by their bulge-to-total mass ratio B/T. The grey dotted line indicates the stellar mass below which Tiamat and Tiamat-125-HR are not converged (see Section 2.7). Also plotted are the observed relations for discs and bulges found by Fall & Romanowsky (2018).

As a function of halo mass, $j_*/j_H$ increases with mass until $M_{\text{vir}} \simeq 10^{12} M_\odot$, above which it shows a clear decrease with increasing mass. The trends that Posti et al. (2018a) find at low halo and stellar masses is consistent with the findings of my simulation, however there are too few galaxies with $M_* > 10^{10.5} M_\odot$ or $M_{\text{vir}} > 10^{12} M_\odot$ to investigate whether I also predict a decrease at these high masses. I make different predictions to previous simulations and semi-analytic models, such as Pedrosa & Tissera (2015), who find roughly no mass dependence of $j_d/j_H$ in their hydrodynamical simulation, as does the Dark SAGE semi-analytic model (Stevens et al., 2016), which predicts $j_*/j_H = 0.4 \pm 0.29$ for spiral galaxies. The FIRE-2 simulation, however, also finds that the ratio of galaxy to halo specific angular momentum increases with stellar mass (El-Badry et al., 2018).

Finally, I consider the morphological dependence of the specific angular momentum–mass relation, as observations suggest that mass, angular momentum and bulge-to-total ratio are strongly correlated (e.g. Romanowsky & Fall, 2012; Fall & Romanowsky, 2013; Obreschkow & Glazebrook, 2014; Sweet et al., 2018), with galaxies with higher B/T having lower specific angular momenta, at a fixed stellar mass (Fall & Romanowsky, 2013; Sweet et al., 2018; Fall & Romanowsky, 2018). The $j_*-M_*$ relation for galaxies in the model, coloured by their bulge-to-total mass ratio B/T, is shown in Figure 3.7. There is a clear trend of
bulge-dominated galaxies lying below the disc-dominated sequence, consistent with the Fall & Romanowsky (2018) observations. This trend arises naturally from my assumption that the bulge component has negligible angular momentum. The Illustris (Genel et al., 2015) and Magneticum Pathfinder (Teklu et al., 2015) simulations also predict a similar correlation between galaxy type and $j_*$, although they do not have visual morphological classifications of their galaxies. The hydrodynamical simulation of Pedrosa & Tissera (2015) also predicts a similar trend, with bulge and disc galaxies showing a relation with the same slopes, with the offset not dependent on the stellar or halo mass.

Overall, the MERAXES model reproduces the local angular momentum–mass scaling relations well.

### 3.2 High-redshift galaxy sizes

In Section 3.1.2 I showed that MERAXES now predicts local galaxy sizes, angular momentum and morphologies that are in great agreement with observations. This is an important test of the galaxy formation and evolution model, and gives confidence in its predictions at higher redshifts. In the following sections, I show the model’s predictions for the high-redshift size–luminosity and size–mass relations, alongside the redshift evolution of the median disc size (for further discussion on these relations see the review by Dayal & Ferrara, 2018).

#### 3.2.1 Size–luminosity relations

I investigate the relationship between the sizes of stellar discs and the UV magnitude of galaxies in the model from $z = 5–10$, as shown in Figure 3.8. Here, the UV magnitude $M_{UV}$ is the dust-extincted luminosity at rest-frame 1600Å, and the radius is the effective radius of the exponential disc, $R_e$. As bulges tend to be smaller than discs, this will lead to an overprediction of the sizes of bulge-dominated galaxies in comparison to the observations. I obtain the UV luminosities of each galaxy following the method described in Liu et al. (2016a). These luminosities are for the entire galaxy; the luminosities will be decomposed into their bulge and disc components in future work.
I find that for all redshifts, brighter galaxies tend to have larger sizes. This is in agreement with the previous Meraxes predictions from Liu et al. (2016b) (hereafter L16), however I see a steeper slope at the brightest magnitudes. For faint galaxies with $M_{UV} > -14.5$ at the highest redshifts, L16 find that the stellar disc radius does not change significantly with luminosity; my model only shows a mild flattening in comparison. This is due to the improvements of the new disc size model. In L16, the galaxy radius was simply related to the halo radius. However, in Meraxes galaxies can only form in haloes above the minimum gas cooling mass; this puts an artificial limit on the minimum size a galaxy could have. By tracing the evolution of disc-sizes more physically, my galaxy sizes do not show this artificial flattening at fainter magnitudes.

For comparison, the Grazian et al. (2012), Ono et al. (2013), Huang et al. (2013), Holwerda et al. (2015) and Kawamata et al. (2018) observations are also shown in Figure 3.8. The model agrees well with the Grazian et al. (2012), Ono et al. (2013), Huang et al. (2013) and Holwerda et al. (2015) observations. At redshifts $z = 6$, 7 and 8, the best-fit relation of Kawamata et al. (2018) agrees well at the brightest magnitudes, but my model shows a flattening in the relation at lower magnitudes that is not seen in those observations. At $z = 9$, Kawamata et al. (2018) find larger sizes than my model and the...
Grazian et al. (2012), Ono et al. (2013) and Holwerda et al. (2015) observations. Note that the Grazian et al. (2012), Huang et al. (2013), Ono et al. (2013), and Kawamata et al. (2018) observations include comprehensive corrections for incompleteness and biases such as cosmological surface-brightness dimming, and hence their results should not be significantly affected by selection effects. However, the Holwerda et al. (2015) observations of very luminous galaxies do not include such corrections.

The size–luminosity relation is commonly described by

\[ R_e = R_0 \left( \frac{L_{UV}}{L_{z=3}^*} \right)^\beta \]

(3.1)

where \( R_0 \) is the effective radius at \( L_{z=3}^* \), and \( \beta \) is the slope. \( L_{z=3}^* \) is the characteristic UV luminosity for \( z \approx 3 \) Lyman-break galaxies, which corresponds to \( M_{1600} = -21.0 \) (Steidel et al., 1999). This relation can be rewritten as

\[ \log R_e = -0.4\beta(M_{UV} + 21) + \log R_0. \]

(3.2)

I fit this relation to the model galaxies with \( M < -18 \) at \( z = 5, 6, 7, 8, 9 \) and \( 10 \), with the best-fitting values for \( R_0 \) and \( \beta \) given in Table 3.2. The slope of the size–luminosity relation \( \beta \) is roughly constant from \( z = 5 \) to \( z = 10 \), while the normalization \( R_0 \) decreases significantly. These slopes are steeper than those predicted by L16, which have a median value of \( \beta \approx 0.25 \) for galaxies with \( M_{UV} < -14.5 \), and increase slightly with redshift.

There is wide scatter in the \( \beta \) values determined through different observations. For example, local observations of spiral galaxies have found \( \beta = 0.253 \pm 0.020 \) (de Jong & Lacey, 2000) and \( \beta = 0.321 \pm 0.010 \) Courteau et al. (2007). At higher redshifts, \( \beta = 0.22 \) for \( z \approx 4 \) and \( \beta = 0.25 \) for \( z \approx 5 \) (Huang et al., 2013), at \( z \approx 7 \) \( \beta = 0.3–0.5 \) (Grazian et al., 2012) or \( \beta = 0.24 \pm 0.06 \) (Holwerda et al., 2015), and Shibuya et al. (2015) find \( \beta = 0.27 \pm 0.01 \) at \( z \approx 0–8 \), with no evolution. My values are broadly consistent with these results.

Analytically, Wyithe & Loeb (2011) predict that for a simple star formation model with no feedback, \( \beta = 1/3 \). For models including supernova feedback \( \beta \) decreases, to 1/4 for a model with supernova wind conserving momentum in their interaction with the galactic gas, or 1/5 if energy is instead conserved (Wyithe & Loeb, 2011). My predictions for \( \beta \) are most consistent with the model with no supernova feedback, \( \beta = 1/3 \). Meraxes includes
Table 3.2 The best fitting parameters for the fits to the size–mass (Equation 3.3) and size–luminosity (Equation 3.2) relations for the model galaxies at $z = 5–10$, where $R_0$ is the normalization, and $b$ and $\beta$ are the slopes of the two relations, respectively. The size–luminosity relation is fit only to galaxies with $M_{UV} < -18$.

<table>
<thead>
<tr>
<th>$z$</th>
<th>$R_0$/kpc</th>
<th>$b$</th>
<th>$L_{UV} (M_{UV} &lt; -18)$</th>
<th>$R_0$/kpc</th>
<th>$\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.841 ± 0.006</td>
<td>0.242 ± 0.002</td>
<td>1.53 ± 0.03</td>
<td>0.32 ± 0.01</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.712 ± 0.008</td>
<td>0.246 ± 0.003</td>
<td>1.14 ± 0.03</td>
<td>0.34 ± 0.01</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.616 ± 0.010</td>
<td>0.253 ± 0.004</td>
<td>0.85 ± 0.02</td>
<td>0.32 ± 0.01</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.545 ± 0.012</td>
<td>0.263 ± 0.006</td>
<td>0.66 ± 0.02</td>
<td>0.33 ± 0.02</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0.467 ± 0.015</td>
<td>0.263 ± 0.008</td>
<td>0.49 ± 0.02</td>
<td>0.32 ± 0.02</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.425 ± 0.016</td>
<td>0.277 ± 0.009</td>
<td>0.43 ± 0.02</td>
<td>0.36 ± 0.02</td>
<td></td>
</tr>
</tbody>
</table>

a supernova feedback model which conserves energy, however, due to the complications of the hierarchical model such a comparison is not straightforward. However, note that including fainter galaxies in the fit reduces $\beta$ to be more consistent with $\beta = 1/5$.

### 3.2.2 Size–mass relations

The relations between the stellar disc effective radius and galaxy stellar mass from $z = 5–10$ are shown in Figure 3.9, for the model galaxies and the Mosleh et al. (2012) and Holwerda et al. (2015) observations. The model shows a clear trend of increasing disc size with increasing stellar mass. The Mosleh et al. (2012) observations match well with the model predictions at $z = 5$ and 7, while being smaller than the median at $z = 6$. The Holwerda et al. (2015) galaxies also match well with my predictions. Note that these observations do not correct for measurement biases, however tests by Mosleh et al. (2012) find that systematic uncertainties on their measured sizes are very small ($< 10\%$). My relations are consistent with the previous MERAXES results of L16, which are also shown in Figure 3.9.

I fit the relation

$$R_e = R_0 \left( \frac{M_\ast}{M_0} \right)^b$$

(3.3)

where $M_0 = 10^9M_\odot$, as in Holwerda et al. (2015), to the model galaxies at $z = 5, 6, 7, 8, 9$ and 10, with the best-fitting values for $R_0$ and $b$ given in Table 3.2. The normalization $R_0$ decreases from $z = 5$ to $z = 10$, while the slope $b$ increases. My values for $b$ are consistent with some of those derived by Holwerda et al. (2015), although their values vary significantly depending on the observations used; they derive $b = 0.14 \pm 0.20$ for
Figure 3.9 The size–mass relations for the central model galaxies at $z = 5–10$ (density plots), alongside the Mosleh et al. (2012) and Holwerda et al. (2015) observations (see legend). The black squares (grey circles) and errorbars represent the median and 16th and 84th percentile ranges of galaxy radii from this Meraxes model (the L16 Meraxes model) in bins with a width of 0.5 log $M_\ast$.

$z = 6$ (from the Mosleh et al. 2012 data), $b = 0.24 \pm 0.08$ and $b = 1.35 \pm 0.34$ for $z = 7$ (from the Grazian et al. 2012 and Ono et al. 2013 data, respectively), and $b = 0.12 \pm 0.06$ at $z = 9–10$ (from the Holwerda et al. 2015 data).

3.2.3 Redshift evolution of disc size

The Meraxes predictions for the redshift evolution of the stellar disc effective radius are shown in Figure 3.10. I split the galaxies into two luminosity bins, $(0.12–0.3) L^*_{z=3}$ and $(0.3–1) L^*_{z=3}$, in order to compare with observations; these luminosity ranges correspond to UV magnitudes $-18.7$ to $-19.7$ and $-19.7$ to $-21.0$, respectively. The observations of Bouwens et al. (2004), Oesch et al. (2010), Ono et al. (2013), Kawamata et al. (2015), Shibuya et al. (2015), Holwerda et al. (2015), Laporte et al. (2016) and Kawamata et al. (2018) are also shown. My predictions are consistent with these observations, but are somewhat steeper.

Note that the Oesch et al. (2010), Ono et al. (2013), Kawamata et al. (2015), and Kawamata et al. (2018) observations include comprehensive corrections for incompleteness and biases such as cosmological surface-brightness dimming, and hence their results should
Figure 3.10 The redshift evolution of the median galaxy effective radius for central galaxies in the luminosity range $(0.3–1)L^*_{z=3}$ (upper panel) and $(0.12–0.3)L^*_{z=3}$ (lower panel). The MERAXES predictions are shown for all central galaxies (solid purple lines), and the predictions by the L16 MERAXES model are also shown (dashed purple lines). For these simulated galaxies I only plot bins that contain 10 or more galaxies. A range of observations and their errors are also shown (see legend), as are the resolution limits for HST, JWST and GMT (black dotted lines).
not be significantly affected by selection effects. Bouwens et al. (2004) and Shibuya et al. (2015), however, find that surface brightness biases have no significant effect on their measured galaxy sizes, and are important only for galaxies close to the magnitude limit. Hence, observations that do not account for this should not significantly underestimate the true galaxy size.

The steepness of the model relative to the observations can be seen in the fitting of the relation with the form \( R_e \propto (1 + z)^{-m} \), the functional form commonly used to describe the size-redshift relation. I obtain this \( m \) by performing non-linear least squares on the sizes of each model galaxy at \( z = 5, 6, 7, 8, 9 \) and 10. I obtain \( m = 1.98 \pm 0.07 \) for galaxies with \((0.3–1)L^*_{z=3}\), with \( R_e(z = 7) = 0.74 \pm 0.01 \), and \( m = 2.15 \pm 0.05 \) for galaxies with \((0.12–0.3)L^*_{z=3}\), with \( R_e(z = 7) = 0.522 \pm 0.006 \). These are within 3\( \sigma \) of the L16 values, of \( m = 2.00 \pm 0.07 \) for galaxies with \((0.3–1)L^*_{z=3}\) and \( m = 2.02 \pm 0.04 \) for galaxies with \((0.12–0.3)L^*_{z=3}\) My predictions are also consistent with the FIRE-2 hydrodynamical simulation (Ma et al., 2018), which predicts \( m = 1–2 \), depending on the fixed mass or luminosity at which the relation is calculated.

Measurements of \( m \) derived from the individual observational data sets shown in Figure 3.10, all predict \( 1 \lesssim m \lesssim 1.5 \) (except for Holwerda et al. (2015), who predict \( m = 0.76 \pm 0.12 \)) My predictions for \( m \) are higher than these values. However, L16 show that a combined fit to these \( z > 5 \) observations produces larger values of \( m \) than the individual analyses, which include \( z < 5 \) data, of \( m = 1.64 \pm 0.30 \) and \( m = 1.82 \pm 0.51 \) for the \((0.3–1)L^*_{z=3}\) and \((0.12–0.3)L^*_{z=3}\) ranges, respectively; these are consistent with my predictions at \( < 2\sigma \). Analytically, models that assume that galaxy size is proportional to \( R_{\text{vir}} \) (e.g. Mo et al., 1998) predict evolution with an index of \( m = 1 \) for fixed halo mass, or \( m = 1.5 \) for fixed circular velocity. However, these are simplistic models that assume no star-formation feedback. Including physical prescriptions for feedback processes alters a model’s predictions for \( m \) (Wyithe & Loeb, 2011).

Figure 3.10 shows the resolution limits of HST, JWST, and the Giant Magellan Telescope (GMT). The resolution of a telescope with mirror diameter \( D_{\text{tel}} \) is

\[
\Delta l = \Delta \Omega d_A = \frac{1.22\lambda}{D_{\text{tel}}} d_A \tag{3.4}
\]

where \( \Delta \Omega \) is the angular resolution determined by the Rayleigh criterion, \( d_A \) is the angular diameter distance, and \( \lambda = 1600(1 + z) \) Å is the observed wavelength of UV photons.
Studies using HST indicate that galaxies can be resolved if $R_e \gtrsim \Delta l/2$ (e.g. Ono et al., 2013; Shibuya et al., 2015) and so I adopt the resolution limit $R_{\text{min}} = \Delta l/2$.

For HST ($D_{\text{tel}} = 2.4\text{m}$), I find that the typical $(0.12-0.3)L_{z=3}^*$ galaxy can be resolved to $z \simeq 8$, and the typical $(0.3-1)L_{z=3}^*$ galaxy to $z \simeq 9$. With its larger mirrors, JWST ($D_{\text{tel}} = 6.5\text{m}$) can resolve the majority of these $(0.12-1)L_{z=3}^*$ galaxies at $z = 10$. The next generation of ground-based telescopes such as the GMT ($D_{\text{tel}} = 25\text{m}$) will be able to resolve at least 98 per cent of all $z = 10$ galaxies.

### 3.3 Redshift evolution of angular momentum

In Section 3.1.2 I showed that MERAXES can reproduce the observed local relations between angular momentum and mass. I now present the model’s predictions for the evolution of these relations with redshift. I restrict the analysis to disc-dominated ($B/T < 0.3$), central galaxies.

The median total stellar specific angular momentum as a function of total stellar mass from $z = 7$ to $z = 2$ is shown in Figure 3.11. The relation evolves to higher values of $j_*$ for lower redshifts, at a fixed stellar mass. From $z = 7$ to $z = 2$, the relation increases by $\sim 0.5$ dex, significant relative to the 16th–84th percentile range for the $z = 2$ relation.

At lower redshifts, observations show a range of results for the evolution of the $j_*-M_*$ relation. For example, Contini et al. (2016) investigated a sample of low-mass star-forming galaxies at $0.2 < z < 1.4$ (median $z \simeq 0.6$) and found them to follow the $z = 0$ relation. The $z = 1$ observations of Marasco et al. (2019) are also consistent with no evolution. Harrison et al. (2017), however, find that star forming galaxies at $z \simeq 0.9$ have $0.2$–$0.3$ dex less angular momentum for a fixed stellar mass compared to $z = 0$ galaxies. Swinbank et al. (2017) study star-forming galaxies in $z = 0.23$–$1.65$ and find that most massive star-forming discs at $z \simeq 0$ must have increased their specific angular momentum by around a factor of 3 since $z \simeq 1$. Alcorn et al. (2018) find a decrease in angular momentum for star-forming galaxies at $2 < z < 2.5$ consistent with Harrison et al. (2017), however they find little to no increase in the $j_*-M_*$ relation if its slope is constrained to $2/3$.

My model is consistent with the predictions of Dark SAGE (Stevens et al., 2016), which investigates redshifts $0 < z < 4.8$ and finds a weak trend for galaxies of fixed mass to have
Figure 3.11 Left panel: The median relation between total stellar specific angular momentum $j_*$ and total stellar mass $M_*$ for disc-dominated (B/T< 0.3), central galaxies at $z = 2$–7 in MERAXES (see legend). Middle and Right panels: The median ratio of stellar to halo specific angular momentum $j_*/j_H$ as a function of total stellar mass and halo mass, for disc-dominated (B/T< 0.3), central galaxies at $z = 2$–7 in MERAXES (see legend). The pink shaded region shows the 16th and 84th percentile range for the $z = 2$ model galaxies. The Okamura et al. (2018) observations are also shown (orange solid line, 1σ errors are shaded).

lower specific angular momentum at higher redshifts. In contrast, the hydrodynamical simulation of Pedrosa & Tissera (2015) finds that the $j_d$–$M_*$ relations are statistically unchanged up to $z \simeq 2$, and their ratio $j_d/j_H \simeq 1$ shows no clear evolution with redshift. Zoldan et al. (2019) also predict with their semi-analytic model that the $j_*–M_*$ relation shows little evolution with redshift to $z \simeq 2$ for star-forming galaxies, however quiescent and early-type galaxies show a moderately decreasing $j_*$ with increasing redshift.

The relations between $j_*/j_H$ and total stellar mass and halo mass at high redshifts are also shown in Figure 3.11. There is an increase in the $j_*/j_H$ ratio with decreasing redshift at constant stellar mass, increasing by around $\sim 0.1$ for $10^{7.5} < M_*/M_\odot < 10^9$ from $z = 7$ to $z = 2$, much less than the scatter in the relation. The $j_*/j_H$-$M_{\text{vir}}$ relation also shows no significant redshift evolution.

Okamura et al. (2018) study the angular momentum of galaxies observed at $z = 2, 3,$ and 4 by using the Mo et al. (1998) analytic model to estimate $j_* \text{ disc}$ from the measured galaxy sizes. They use two methods to estimate the halo masses, finding that $j_* \text{ disc}/j_H = 0.77 \pm 0.06$ from a clustering analysis and $j_* \text{ disc}/j_H = 0.83 \pm 0.13$ from abundance matching, with no strong redshift evolution. They find a weak dependence of $j_* \text{ disc}/j_H$ on $M_{\text{vir}}$, with an increase in $j_* \text{ disc}/j_H$ with decreasing stellar mass. This is in contrast to my predictions.
Note, however, that their halo masses are strongly dependent on the estimation method used, and since they adopt an analytic model to estimate $j_{\ast, \text{disc}}$ instead of measuring it kinematically, there may be uncertainty in this mass trend.

### 3.4 High-redshift galaxy morphologies

In Section 3.1.2 I showed that Meraxes can reasonably reproduce the morphological distribution of observed low-redshift galaxies. Here I show the Meraxes predictions for galaxy morphologies at high-redshift.

Figure 3.12 shows the redshift evolution of the B/T ratio as a function of total stellar mass. As redshift increases, the dip in the B/T ratio becomes shallower and shifts to lower masses. This is a result of an evolution of the masses at which the merger- and instability-driven growth modes are effective. The masses at which the merger-driven mode typically operates shift to lower values at higher redshift, and the steep cut-off between the masses where the instability-driven mode does and does not operate flattens at higher redshifts. This results in an average B/T that is higher at high redshifts, suggesting that high-redshift galaxies are more likely to be bulge-dominated than those at low redshift.

This is consistent with the current observations, which suggest that the spheroidal fraction increases to higher redshifts (e.g. Ravindranath et al., 2006; Lotz et al., 2006; Dahlen et al., 2007; Shibuya et al., 2015). This is supported by the IllustrisTNG hydro simulation (Pillepich et al., 2019). The EAGLE hydro simulation (Trayford et al., 2018) finds that the both the disc and bulge fractions decrease to higher redshifts, with the high-redshift population dominated instead by asymmetric galaxies.

### 3.5 Conclusions

In this chapter I use updates to the semi-analytic model Meraxes introduced in Chapter 2 to investigate the evolution of sizes, angular momenta and morphologies of galaxies to high redshifts. The model is calibrated to the observed stellar mass functions at $z = 8–0$ and the black hole–bulge mass relation at $z = 0$. 
Figure 3.12 The fraction of stellar mass contained in the (combined) bulge components (B/T) of model galaxies as a function of total stellar mass at \( z = 2–7 \). Only galaxies classified as centrals are shown. Purple solid lines show the median galaxy bulge fraction in mass bins of width 0.2 dex, and the purple shaded regions show the 16th and 84th percentile range. Also shown are the median mass fractions of the instability-driven bulge (orange dashed) and merger-driven bulge (green dot-dashed), alongside their 16th and 84th percentile ranges.

At low redshifts, the model reproduces the observed galaxy size–mass relation well. It produces galaxy morphologies that are consistent with observations, with galaxies at \( M_\ast \approx 10^{9.5} M_\odot \) forming their bulges predominantly through galaxy mergers, while disc instabilities dominate for bulge growth in galaxies with \( M_\ast \approx 10^{10}–10^{11.5} M_\odot \), and major mergers form massive ellipticals for galaxies with \( M_\ast > 10^{11.5} M_\odot \). The model predicts a specific angular momentum–mass relation that is consistent with observations, and shows no flattening at low-masses, thus being more consistent with observations than previous semi-analytic models (e.g. Stevens et al., 2016). I find that the specific angular momentum–mass relation depends on galaxy morphology, with bulge dominated galaxies lying below the disc-dominated sequence, consistent with the observed trends. I predict that the ratio between stellar and halo specific angular momentum is typically less than one, suggesting that galaxies lose angular momentum as they evolve, and that it decreases with halo and stellar mass.

At high redshifts, I make the following predictions:

- The size–luminosity relation \( R_e = R_0 (L_{UV}/L_\ast^{z=3})^\beta \) has \( \beta = 0.32 \pm 0.01 \) and \( R_0 = \)
1.53 ± 0.03 kpc at $z = 5$, with the normalisation decreasing at higher redshifts but the slope remaining roughly constant, and is consistent with available high-redshift observations.

- The size–mass relation $R_e = R_0 \left( \frac{M_*}{M_0} \right)^b$ has $b = 0.242 ± 0.002$ and $R_0 = 0.841 ± 0.006$ kpc at $z = 5$, with both slope and normalisation decreasing at higher redshifts, and is reasonably consistent with the available observations.

- The median size of a galaxy disc decreases with redshift as $R_e \propto (1 + z)^{-m}$, where $m = 1.98 ± 0.07$ for galaxies with $(0.3–1)L^{*}_{z=3}$, with $R_e(z = 7) = 0.74 ± 0.01$, and $m = 2.15 ± 0.05$ for galaxies with $(0.12–0.3)L^{*}_{z=3}$, with $R_e(z = 7) = 0.522 ± 0.006$.

- The specific angular momentum–stellar mass relation evolves to higher values of $j_*$ for lower redshifts, at a fixed stellar mass, with an increase of $\sim 0.5$ dex from $z = 7$ to $z = 2$.

- The relations between the ratio of stellar and halo specific angular momentum $j_*/j_H$ to stellar mass and halo mass show no significant redshift evolution.

- Galaxies at high redshifts are predominantly bulge-dominated.

Meraxes can now predict a wide-range of relations that can be observed and tested by the next generation of telescopes, such as JWST. For example, I am now able to make predictions for the high-redshift black hole–bulge relation, which is the topic of the next chapter.
Chapter 4

The High-Redshift Evolution of Black Holes and Their Host Galaxies

In the local Universe there are clear correlations between the properties of a black hole and its host galaxy, one of the best studied being the relation between the black hole mass and the mass of the galaxy’s bulge (Magorrian et al., 1998; Merritt & Ferrarese, 2001; Marconi & Hunt, 2003; Haring & Rix, 2004; Graham, 2012; Graham & Scott, 2015; Kormendy & Ho, 2013; Heckman & Best, 2014). Investigating how these correlations change with redshift can provide important insights into what drives the co-evolution between black holes and their host galaxies. However, it is difficult to measure these relations at high redshift with current observations, with large biases and measurement uncertainties (Lauer et al., 2007; Schulze & Wisotzki, 2011, 2014; Wang et al., 2013; DeGraf et al., 2015; Willott et al., 2017, see Section 1.4.3). Simulations therefore play a vital role in our understanding of their evolution.

Cosmological hydrodynamical simulations such as Horizon-AGN (Volonteri et al., 2016) and BLUETIDES (Huang et al., 2018) find very little evolution in the black hole–stellar mass relation out to $z = 5$ and $z = 8$ respectively. However, DeGraf et al. (2015) instead found that the relation evolves slightly for $z \geq 1$ for the highest mass black holes, with an increasing slope at higher redshifts. The more statistical study of Schindler et al. (2016) found that the ratio of the black hole to stellar mass density is constant within the uncertainties from $z = 0$ to 5, and is consistent with no cosmological evolution in
the $M_{\text{BH}}-M_*$ relation. With its new ability to model bulge masses, the MERAXES semi-analytic model can now be used to provide additional, independent predictions for the high-redshift black hole–host mass relations.

In this chapter I use MERAXES to explore the evolution of the black hole–host relations from high redshift to the present day. The outline of this chapter is as follows. I detail the calibration procedure in Section 4.1. I investigate the redshift evolution of the black hole–host scaling relations in Section 4.2. In Section 4.3 I consider the relative contributions of the different black hole growth modes, and in Section 4.4 I consider the black hole–host scaling relations in galaxies of different morphologies. I conclude in Section 4.5. As in Chapter 3, I adopt the Planck Collaboration (2016) cosmological parameters: $(h, \Omega_m, \Omega_b, \Omega_\Lambda, \sigma_8, n_s) = (0.678, 0.308, 0.0484, 0.692, 0.815, 0.968)$.

### 4.1 Model calibration

In Chapter 3 I calibrated the free parameters in MERAXES to match the observed stellar mass functions at $z = 0$–8 (Figure 3.1), and the black hole–bulge mass relation at $z = 0$ (Figure 3.2). Using this model, I find that the black hole mass function and quasar luminosity functions are much larger than predicted by the observations (Figures 4.2, 4.3 and 4.4). In addition, note that Shankar et al. (2016) find significant selection biases in the black hole–bulge mass relation—a topic of recent debate (see e.g. Kormendy, 2019). Therefore I assume that the Shankar et al. (2009) $z = 0$ black hole mass function is a less biased indicator of the local black hole population, and retune the model here to better reproduce the black hole observations.

I calibrate the free parameters in the model to match the observed stellar mass functions at $z = 0$–8 (Figure 4.1), the Shankar et al. (2009) and Davis et al. (2014) black hole mass function at $z = 0$ (Figure 4.2), and the quasar X-ray luminosity functions from $z = 5$ to 2 (Figure 4.3). The black hole mass functions produced by Tiamat and Tiamat-125-HR are converged at $z = 2$ for black holes with mass $M_{\text{BH}} > 10^{7.1} M_\odot$ (see Figure 4.2 and Section 2.7), with Tiamat producing more low-mass black holes. I therefore focus on matching the observed black hole mass functions at $M_{\text{BH}} > 10^{7.1} M_\odot$. While the Shankar et al. (2009) and Davis et al. (2014) relations are different, particularly at $M_{\text{BH}} \sim 10^{8.5} M_\odot$, they are
Figure 4.1 Galaxy stellar mass functions at $0 < z < 8$ from the best Meraxes model (black) applied to Tiamat (solid) and Tiamat-125-HR (dashed), compared to a range of observational data (see legend). Meraxes is calibrated such that these observed stellar mass functions are reproduced. The vertical grey dotted line indicates the stellar mass below which Tiamat and Tiamat-125-HR are not converged, and thus where galaxies from Tiamat-125-HR can be subject to resolution effects (see Section 2.7). Also shown are the stellar mass functions produced by Meraxes when AGN feedback is switched off (grey dot-dashed). This shows that AGN feedback has no effect on galaxies in Tiamat at $z \geq 2$, but suppresses the growth of the most massive galaxies at lower redshifts as seen in Tiamat-125-HR.

Since Shankar et al. (2016) found that the observed black hole–bulge mass relation is biased to high black hole masses, I also require the model to not over-predict this relation, however I do not otherwise tune to it. The best models produce black hole–host mass relations lower than the observations, consistent with the expectations of Shankar et al. (2009), and have steeper slopes (Figure 4.5).

I find that these calibration criteria are met by a range of free parameter values for the merger-driven black hole growth efficiency, $k_c = 0.005, 0.01, 0.03$ and $0.09$, and the definition of a major merger, $\gamma > 0.1$ and $\gamma > 0.3$ (see Table 4.1). All of these parameter sets produce very similar results, so unless otherwise specified I only show the model results for the $k_c = 0.005$ and $\gamma > 0.1$ case hereafter.
Figure 4.2 Black hole mass functions at $0 < z < 7$ from the best MERAXES model applied to Tiamat (solid) and Tiamat-125-HR (dashed). MERAXES is calibrated to best reproduce the Shankar et al. (2009) and Davis et al. (2014) observed black hole mass functions at $z = 0$, which are also shown (see legend). I also plot the $z = 0$ black hole mass function from the Chapter 3 MERAXES model (M19), showing that this overpredicted the observed black hole mass functions.

As a further check of the black hole population, I plot the black hole accretion rate density as a function of redshift for models with these different merger-driven black hole growth efficiencies (with $\gamma > 0.1$), in Figure 4.6. I find that the models with $k_c = 0.005$ and $k_c = 0.01$ give black hole accretion histories in approximate agreement with the observations (Figure 4.6). The larger values of $k_c$ overproduce measurements of the black hole accretion rate density (e.g. Delvecchio et al., 2014).

Table 4.1 MERAXES black hole growth parameters as used in Chapter 3, and as retuned for this study.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Chapter 3</th>
<th>This Chapter</th>
</tr>
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<tbody>
<tr>
<td>Minimum merger ratio for major merger</td>
<td>0.1</td>
<td>0.1, 0.3</td>
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<tr>
<td>Black hole seed mass ($M_\odot$)</td>
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<td>$10^4$</td>
</tr>
<tr>
<td>Merger-driven black hole growth efficiency $k_c$</td>
<td>0.03</td>
<td>0.005, 0.01, 0.03, 0.09</td>
</tr>
<tr>
<td>Instability-driven black hole growth efficiency $k_i$</td>
<td>0.02</td>
<td>0.005</td>
</tr>
<tr>
<td>Radio mode black hole growth efficiency $k_h$</td>
<td>0.003</td>
<td>0.03</td>
</tr>
<tr>
<td>Black hole efficiency of converting mass to energy $\eta$</td>
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<td>0.06</td>
</tr>
<tr>
<td>Opening angle of AGN radiation $\theta$</td>
<td>$30^\circ$</td>
<td>$70^\circ$</td>
</tr>
</tbody>
</table>

$^a$ Equation 2.6  
$^b$ Equation 2.4  
$^c$ $L_{AGN} = \eta \Delta M_{BH} c^2$, Equation 2.4  
$^d$ Section 2.4.3
4.1.1 Quasar luminosity functions

The quasar X-ray luminosity functions at $z = 5$–0 are shown in Figure 4.3, with X-ray luminosities calculated using the Hopkins et al. (2007) bolometric to X-ray correction. At $z = 2$ the model and the observations agree remarkably well. At $z > 2$ the model over-predicts the observed quasar X-ray luminosity function at intermediate luminosities, by up to $\sim 0.7$ dex at $z = 4$, while at $z < 2$ the model under-predicts the luminosity function at these luminosities. The model shows better agreement with the observations than previous versions of MERAXES (Chapter 3, as seen in Figure 4.3, and Q17; see also...
log\(\frac{M_{\text{bulge}}}{M_\odot}\)  

\(\log\frac{M_{\text{BH}}}{M_\odot}\)  

Kormendy & Ho (2013)  
- Ellipticals  
- Classical Bulges  
Scott et al. (2013)  
Sahu et al. (2019)  
Graham and Scott (2015)  
Reines & Volonteri (2015)  
Davis et al. (2018)  
Tiamat-125-HR (\(M > 10^{9.5} M_\odot\))

<table>
<thead>
<tr>
<th>Number of Galaxies</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
</tr>
<tr>
<td>101</td>
</tr>
<tr>
<td>102</td>
</tr>
</tbody>
</table>

Figure 4.5 **Left panel:** The \(z = 0\) black hole–bulge mass relation, and **Right panel:** the \(z = 0\) black hole–total stellar mass relation, for the best MERAXES model applied to Tiamat-125-HR (blue density plot). Only galaxies classified as centrals are shown. A range of observations are also plotted (Kormendy & Ho, 2013; Scott et al., 2013; Graham & Scott, 2015; Reines & Volonteri, 2015; Davis et al., 2018; Sahu et al., 2019, see legend). A best-fitting line for the model galaxies with \(M > 10^{9.5} M_\odot\) is also shown (solid line).

Amarantidis et al. 2019).

While the observations show a slight increase in the X-ray quasar luminosity functions from \(z = 4\) to 2, the model predicts a slight decrease. In fact, I cannot find a combination of black hole parameters (see Table 4.1) that results in a redshift evolution that matches that of the observed X-ray quasar luminosity function at \(z > 2\). However, the key quantity of black hole accretion rate density is predicted by the model to peak at \(z = 2\) as observed. In addition to published uncertainties in the observations, it may also be the case that at higher redshifts X-ray AGN are more likely to be obscured, which is consistent with evidence from a range of X-ray observations (Treister & Urry, 2006; Vito et al., 2014; Buchner et al., 2015). Thus the inability of the model to match the redshift evolution of the X-ray quasar luminosity function may not represent a significant concern.

The quasar UV luminosity functions at \(z = 5–0\) are shown in Figure 4.4. The opening angle of AGN radiation, \(\theta\), adjusts the normalization of the UV luminosity function. I tune this to match the observations, shown in Figure 4.4, finding a preferred \(\theta\) of 70 degrees, corresponding to an observable fraction of UV quasars of 18 per cent. I find that, as with the X-ray luminosity function, the UV luminosity function decreases from \(z = 5\) to 0, although it agrees well with observations at \(z > 2\). At \(z < 2\), however,
Figure 4.6 The black hole accretion rate density as a function of redshift from MERAXES, and as estimated from the AGN bolometric luminosity function (black points; Delvecchio et al., 2014). I calculate the black hole accretion rate density as the total black hole mass growth in the simulation between adjacent simulation snapshots, divided by the time between snapshots and normalized by the simulation volume. I show four models, with different merger-driven black hole growth efficiencies: $k_c = 0.005$, 0.01, 0.03 and 0.09 (see legend). These parameters were all found during the model tuning to reproduce the observations well.

note that the faint-end of the UV luminosity function becomes flat, and by $z < 1$ there is a significant disagreement with the observations, with the model producing too many luminous quasars. As seen in Figure 4.6, the black hole accretion rate density becomes significantly higher than the observations at $z < 1$, consistent with the quasar luminosities being overestimated at these redshifts. This excess black hole accretion is most likely a result of the model missing important physics required for modelling low-redshift galaxy evolution, particularly in the quenching of massive galaxies, or due to the simplifications assumed in the model such as a constant black hole accretion efficiency. However, as the overall accretion rate density at these redshifts is low, this will not have a significant impact on the black hole mass, an integrated quantity. Thus, while the $z < 1$ black hole accretion rates are overestimated, the black hole mass function (Figure 4.2) and black hole–host mass relations (Figure 4.5) are reliable at low redshifts.
Table 4.2 The fitting coefficients $\alpha$ and $\beta$ (slope and normalization) of Equation 4.1, with the standard deviation of residuals $\epsilon$ at each redshift, for $M = M_*$ and $M = M_{\text{bulge}}$. Also included is the number of galaxies that are used in each fit, $N$. Errors on $\alpha$ and $\beta$ are obtained from the standard deviation of 10000 bootstrap realizations. For $z \geq 2$, fits are from the Tiamat simulation, while the fits at $z < 2$ use Tiamat-125-HR.

<table>
<thead>
<tr>
<th>$z$</th>
<th>$N$</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$\epsilon$</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$\epsilon$</th>
</tr>
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<tbody>
<tr>
<td>0</td>
<td>58997</td>
<td>$1.809 \pm 0.002$</td>
<td>$-11.91 \pm 0.02$</td>
<td>0.36</td>
<td>$1.624 \pm 0.003$</td>
<td>$-9.72 \pm 0.03$</td>
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<tr>
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<td>$-11.90 \pm 0.03$</td>
<td>0.28</td>
<td>$1.563 \pm 0.002$</td>
<td>$-8.86 \pm 0.03$</td>
<td>0.23</td>
</tr>
<tr>
<td>2</td>
<td>7503</td>
<td>$1.485 \pm 0.005$</td>
<td>$-7.98 \pm 0.05$</td>
<td>0.19</td>
<td>$1.380 \pm 0.005$</td>
<td>$-6.77 \pm 0.05$</td>
<td>0.15</td>
</tr>
<tr>
<td>3</td>
<td>4638</td>
<td>$1.432 \pm 0.005$</td>
<td>$-7.33 \pm 0.05$</td>
<td>0.15</td>
<td>$1.377 \pm 0.005$</td>
<td>$-6.69 \pm 0.05$</td>
<td>0.13</td>
</tr>
<tr>
<td>4</td>
<td>2423</td>
<td>$1.392 \pm 0.007$</td>
<td>$-6.88 \pm 0.07$</td>
<td>0.15</td>
<td>$1.359 \pm 0.007$</td>
<td>$-6.48 \pm 0.07$</td>
<td>0.13</td>
</tr>
<tr>
<td>5</td>
<td>917</td>
<td>$1.351 \pm 0.016$</td>
<td>$-6.46 \pm 0.16$</td>
<td>0.18</td>
<td>$1.308 \pm 0.018$</td>
<td>$-5.96 \pm 0.17$</td>
<td>0.17</td>
</tr>
<tr>
<td>6</td>
<td>317</td>
<td>$1.367 \pm 0.030$</td>
<td>$-6.58 \pm 0.30$</td>
<td>0.16</td>
<td>$1.339 \pm 0.027$</td>
<td>$-6.26 \pm 0.27$</td>
<td>0.14</td>
</tr>
</tbody>
</table>

4.2 Redshift evolution of the black hole–bulge and total stellar mass relations

To investigate the redshift evolution of the black hole–bulge and black hole–total stellar mass relations I first perform linear least squares fits to the relations:

$$
\log \left( \frac{M_{\text{BH}}}{M_\odot} \right) = \alpha \log \left( \frac{M}{M_\odot} \right) + \beta,
$$

(4.1)

for $M = M_*$ and $M = M_{\text{bulge}}$, at a range of redshifts. I only include galaxies with $M > 10^{9.5} M_\odot$ in the fits, so that they are not biased by the large number of low-mass galaxies. These relations are shown in Figure 4.7, and Table 4.2 gives the parameters $\alpha$ and $\beta$, alongside the standard deviation of the residuals, $\epsilon$, and number of galaxies in each fit, $N$. Both relations have a slope that decreases and a normalization that increases with redshift from $z = 0$ to 2, with much weaker evolution for $z > 2$. This is not due to the simulation changing at $z = 2$ (see Appendix B). Relative to the scatter in the relations, there is minimal changing in both the black hole–bulge and black hole–total stellar mass relations from $z = 0$ to 6. This lack of evolution in the black hole–host mass relations is consistent with the findings of cosmological hydrodynamical simulations such as Horizon-AGN (Volonteri et al., 2016) and BlueTides (Huang et al., 2018).

I find that the black hole–total stellar mass relation has similar but slightly larger scatter than the black hole–bulge relation, with the scatter in both decreasing with increasing...
redshift. While the black hole mass has a slightly stronger relationship with the bulge stellar mass, the black hole and total stellar mass are still tightly correlated. The scatter in the relations is slightly larger than the 0.28 dex observed by Kormendy & Ho (2013) locally. However, they are very consistent with those from the BlueTides simulation at high redshift ($\simeq 0.15$ dex and $\simeq 0.14$ dex for the black hole–bulge and total stellar mass relations, respectively; Huang et al., 2018). The scatter decreases with increasing stellar mass—including only galaxies with $M_*/M_{\text{bulge}} > (10^{10}, 10^{10.5})$ reduces the scatter to $\epsilon = (0.30, 0.20)$ dex and $\epsilon = (0.23, 0.16)$ dex, for the $z = 0$ black hole–total stellar mass and bulge mass relations, respectively.

Figure 4.8 shows the median $M_{\text{BH}}/M$ as a function of redshift for galaxies with $M_{\text{BH}} > 10^6 M_\odot$, for $M = M_*$ and $M = M_{\text{bulge}}$. The figure shows no statistically-significant evolution in the median $M_{\text{BH}}/M_{\text{bulge}}$ and $M_{\text{BH}}/M_*$ out to $z \simeq 8$. This is consistent with current high-redshift observations; when selection effects are accounted for, the observations at high redshift are consistent with no cosmological evolution in these relations (Schulze & Wisotzki, 2014).

The model predicts no significant evolution in the black hole–host mass relations, with the scatter in the relations decreasing at the highest redshifts. This indicates that there is a
connection between the growth of black holes and their host galaxies. Indeed, the model includes joint triggering of star formation and black hole growth during galaxy mergers, and black hole feedback which regulates star formation, meaning that the co-evolution of black holes and galaxies is implicit in the model. This is not consistent with the scenario proposed by Peng (2007) and Jahnke & Macciò (2011), for example, where the black hole and galaxy growth is uncorrelated and the relationships are generated naturally within a merger driven galaxy evolution framework, due to a central-limit-like tendency.

Figure 4.8 also shows the median $M_{\text{BH}}/M_*$ ratio as a function of redshift with galaxies split
into black hole mass bins. This shows that lower mass black holes have lower $M_{BH}/M_*$ ratios than higher mass black holes. For example, at high redshifts ($z > 2$), the median $M_{BH}/M_*$ ratio for black holes with $10^7 < M_{BH}/M_\odot < 10^8$ is higher than those with $10^6 < M_{BH}/M_\odot < 10^7$ by $\sim 0.25$ dex, with that for black holes with $M_{BH}/M_\odot > 10^8$ being a further $\sim 0.25$ dex higher. This will lead to a notable selection bias, since when observing the most massive black holes, the measured $M_{BH}/M_*$ ratio will be higher than that of the entire population. This is generally expected for any sample selected by black hole mass or luminosity where the scatter in the relation is large (e.g. Lauer et al., 2007).

Finally, note an interesting effect of changing the parameter controlling the black hole efficiency for converting mass to energy, $\eta$ (see Section 2.4). The median black hole–stellar mass ratio for the best model is shown in Figure 4.9, alongside Meraxes run with $\eta = 0.2$ instead of 0.06, with all other parameters unchanged. For $\eta = 0.2$, the median black hole–stellar mass ratio decreases at redshifts $z \gtrsim 6$, instead of remaining constant with redshift as in the $\eta = 0.06$ model. This effect is not seen by adjusting any of the other black hole parameters I tune in the model (Table 4.1). I investigate the cause of this high-redshift decrease in the black hole–host relation by considering the Eddington limit:

$$M_{\text{Edd}} = M_{BH} \left( \exp \left( \frac{\Delta t}{\eta\epsilon_{\text{Edd}}} \right) - 1 \right),$$

(4.2)

the maximal mass by which a black hole with mass $M_{BH}$ can grow in the model between snapshots of width $\Delta t$ (see Equation 2.3). Increasing $\eta$ from 0.06 to 0.2 decreases the Eddington limit. This results in many black holes having Eddington-limited growth at the highest redshifts ($z \gtrsim 6$), which is not the case for the $\eta = 0.06$ model. This causes black holes to grow slower than their host galaxies at high redshifts, resulting in a decreased black hole–stellar mass ratio. Observing the high-redshift black hole–stellar mass relation may therefore probe the Eddington limit and the efficiency of black holes in converting mass to energy.

4.3 Black hole growth mechanisms

I consider the cumulative fraction of black hole mass formed through each of the mechanisms in the model: black hole seeding, merger-driven quasar-mode accretion, instability-driven quasar-mode accretion, radio-mode accretion and black hole–black hole coalescence
Figure 4.9 The ratio of black hole to total stellar mass as a function of redshift for galaxies with $M_{\text{BH}} > 10^6 M_\odot$, for the best model ($\eta = 0.06$) and an otherwise identical model with $\eta = 0.2$. The median ratio is shown with the solid line, and the region between the 16th and 84th percentile range shaded.

in galaxy mergers. These are shown as a function of black hole mass at a range of redshifts in Figure 4.10. On average, instabilities grow the majority of mass in black holes at all redshifts, except for galaxies with $M_{\text{BH}} > 10^9 M_\odot$ at $z \simeq 0$, whose black hole growth becomes dominated by galaxy mergers. Radio-mode growth slowly increases in significance with redshift, yet still has only contributed to a small proportion of the total black hole mass by $z = 0$, except at the highest masses; this is discussed in Q17. Note that I consider growth from disc instabilities that are triggered by earlier galaxy mergers as growth via the instability-driven mode, and do not treat them in a more detailed manner as in Izquierdo-Villalba et al. (2019), for example.

I also consider the instantaneous growth fractions of black hole mass formed through each mechanism as a function of redshift, as shown in Figure 4.11. Here I take the ‘instantaneous’ fraction to be the fraction of growth caused by a mechanism between the specified redshift and the simulation snapshot immediately preceding it. As discussed in Section 4.1.1, the model produces unreliable black hole accretion rates at $z < 1$, and so I only consider these black hole growth rates at $z > 1$. Figure 4.11 shows that the instability-driven growth mode is the dominant growth mechanism, on average, at all redshifts, regardless of black hole mass. The merger-driven quasar mode and black hole–black hole coalescence mode are sub-dominant at all redshifts. The radio-mode grows more mass at low redshift
My finding that mergers are not the dominant mechanism for growing black holes is in agreement with a range of observations. For example, Koss et al. (2010) find that only 25 per cent of local ($z < 0.05$), moderate luminosity X-ray AGN show signs of mergers, although the fraction is much higher for luminous AGN (Hong et al., 2015). From $z \approx 0.3 - 1.0$, Cisternas et al. (2010) find that the vast majority ($> 85$ per cent) of X-ray selected AGN do not show signs of mergers, suggesting that the bulk of their black hole accretion has been triggered by some other mechanism. This is also consistent with the findings of Georgakakis et al. (2009) who claim that a large fraction of AGN at $z \approx 1$ are triggered by processes other than major mergers, as do Villforth et al. (2018) at $z \approx 0.9$, and Schawinski et al. (2012), Mechtley et al. (2016), Del Moro et al. (2015) and Marian et al. (2019) for AGN at $z \approx 2$.

My result that disc instabilities cause the majority of black hole growth is also consistent with predictions from other simulations. In the GALFORM semi-analytic model, Fanidakis et al. (2011) found that the growth of black holes is dominated by accretion due to disc instabilities, with the fraction of mass in black holes produced by disc instabilities more than an order of magnitude larger than that produced by mergers, at all redshifts. Using an
Figure 4.11 The instantaneous fraction of black hole mass formed through each of the growth mechanisms in MERAXES relative to the total black hole mass, as a function of redshift from \( z = 7 \) to 1. I take the ‘instantaneous’ fraction to be the fraction of growth between the specified redshift and the simulation snapshot immediately preceding it. I do not include the seed mechanism, as that ‘growth’ occurs only once for each black hole. The model with merger-driven black hole growth efficiency \( k_c = k_i = 0.005 \) is shown. I do not show the results at \( z < 1 \), as the model produces unreliable black hole accretion rates at such low redshifts (see Figure 4.6 and its discussion).

updated GALFORM model, Griffin et al. (2019) found that accretion of hot gas dominates the growth of black holes at \( z < 2 \), with disc-instabilities dominant at higher redshifts. Hirschmann et al. (2012) found that instability-driven black hole growth was required to reproduce AGN downsizing, and that while major mergers are the dominant trigger for luminous AGN, especially at high redshift, disc instabilities cause the majority of black hole growth in moderately luminous Seyfert galaxies at low redshift. Menci et al. (2014) find that in their semi-analytic model disc instabilities can provide enough black hole accretion to reproduce the observed AGN luminosity functions up to \( z \approx 4.5 \), but are not likely to be dominant for the highest luminosity AGN or at the highest redshifts. In contrast, Shirakata et al. (2018) find that the primary trigger of AGN at \( z \leq 4 \) in their semi-analytic model is mergers, while disc instabilities are essential for fuelling moderate luminosity AGN at higher redshifts. The hydrodynamical simulation Horizon-AGN found that only \( \sim 35 \) per cent of black hole mass in local massive galaxies is directly attributable to mergers, with the majority of black hole growth instead growing via secular processes.
(Martin et al., 2018). The Magneticum Pathfinder Simulation also found that merger events are not the dominant fuelling mechanism for black holes in $z = 0\text{--}2$, with merger fractions less than 20 per cent, except for very luminous quasars at $z \simeq 2$ (Steinborn et al., 2018).

Finally, I comment on the effect of the efficiency parameters for merger-driven and instability-driven black hole growth in the model, $k_c$ and $k_i$ respectively (see Equation 2.6). I find $k_i = 0.005$ from tuning the model, whereas $k_c$ is less constrained, with $k_c = 0.005, 0.01, 0.03$ and $0.09$ producing reasonable model results (although the larger values of $k_c$ produce a black hole growth history that is too large; see Section 4.1 and Figure 4.6). Having a merger growth efficiency that is twice, six times or even 18 times larger than the instability-driven growth efficiency may have an effect on the conclusions outlined above, which use the model $k_c = k_i = 0.005$. I therefore plot the cumulative fraction of black hole mass formed through each of the mechanisms at $z = 2$ for all four models, $k_c = 0.005, 0.01, 0.03$ and $0.09$ (Figure 4.12). I find, as expected, that models with larger $k_c$ result in more merger-driven growth. For $k_c = 0.01$, the instability-driven mode still dominates at $z = 2$, while for $k_c = 0.03$, the merger-driven mode begins to dominate at the highest black hole masses, $M_{BH} \simeq 10^9 M_\odot$. For the model with $k_c = 0.09$, the merger-driven mode contributes even more black hole growth, but is still not the dominant growth mode for $10^6 < M_{BH}/M_\odot < 10^9$ black holes. The Tiamat-125-HR simulation at $z = 0$ shows the same trend, with the merger-driven growth mode becoming more dominant as $k_c$ increases. For the most extreme case of $k_c = 0.09$, the merger-driven mode remains the dominant growth mode for $M_{BH} > 10^9 M_\odot$ black holes, however the instability-driven mode is still the main source of growth for smaller black holes. Thus, while the efficiency parameter for merger-driven growth has some effect on the relative distributions of the instability-driven and merger-driven growth modes, the instability-driven mode is still dominant for the majority of black holes, even if the merger growth efficiency is as much as 18 times larger than the secular growth efficiency.
Figure 4.12 The average fraction of black hole mass formed through each of the growth mechanisms in Meraxes relative to the total black hole mass by $z = 2$, in black hole mass bins of 0.25 dex, for models with different merger-driven black hole growth efficiencies: $k_c = 0.005, 0.01, 0.03$ and 0.09. These parameters were all found during the model tuning to reproduce the observations well, however the larger values of $k_c$ produce a black hole growth history that is larger than observed. Increasing $k_c$ increases the contribution of the merger-driven mode to growing black holes, but the instability-driven mode is still dominant except for at the lowest and highest black hole masses. Note that these are cumulative fractions, and not the fraction of growth produced by each mechanism at $z = 2$.

Figure 4.13 Left panel: the black hole–bulge mass relation, and Right panel: the black hole–total stellar mass relation, for Meraxes galaxies at $z = 0$. Galaxies are split into bulge-dominated galaxies ($B/T > 0.7$; red contours) and disc-dominated galaxies ($B/T < 0.3$; blue contours), with the distribution for all galaxies also shown (grey contours). Contours show regions containing probability distributions of 20, 40, 60 and 80 per cent.
4.4 The morphology dependence of the black hole–host mass relations

A popular explanation for the black hole–host correlations is that major mergers drive the growth of both black holes and bulges (e.g. Haehnelt & Kauffmann, 2000; Croton, 2006). If this were the case, one would expect that black holes would only correlate with galaxy properties directly related to the merger process, such as bulge mass, and not, for example, total stellar mass. Simmons et al. (2017) consider a sample of 101 disc-dominated AGN hosts from the SDSS, which they assume must have a major merger-free history since \( z \approx 2 \). They found that these galaxies lie on the typical \( M_{\text{BH}}-M_* \) relation, but lie offset to the left of the \( M_{\text{BH}}-M_{\text{bulge}} \) relation. This indicates that the substantial and ongoing black hole growth in these merger-free disc galaxies must be due to a process other than major mergers, and that major mergers cannot be the primary mechanism behind the black hole–host correlations.

The \( M_{\text{BH}}-M_* \) and \( M_{\text{BH}}-M_{\text{bulge}} \) relation for disc-dominated and bulge-dominated galaxies at \( z = 0 \) in Meraxes are shown in Figure 4.13. The simulated disc galaxies lie on the \( M_{\text{BH}}-M_* \) relation, but lie offset to the left of the \( M_{\text{BH}}-M_{\text{bulge}} \) relation, as they have small bulges relative to their black hole mass. This is consistent with the Simmons et al. (2017) observations, and the results from the Horizon-AGN hydrodynamical simulation (Martin et al., 2018). However, I see a less significant offset, which occurs at lower black hole masses than Simmons et al. (2017) and Martin et al. (2018), since the black holes in my disc-dominated galaxies are less massive in comparison. Mutlu-Pakdil et al. (2017) also find no dependence of the \( M_{\text{BH}}-M_* \) relation on galaxy type in the Illustris hydrodynamical simulation. Martin et al. (2018) suggest that major mergers therefore cannot be primarily responsible for feeding black holes, otherwise major-merger free disc galaxies should have less massive black holes than are observed and simulated. This is consistent with my finding that the instability-driven mode is the dominant growth mechanism for black holes (see Section 4.3).
4.5 Conclusions

I use the Meraxes semi-analytic model to investigate the evolution of black holes and their relations to their host galaxies. I find the following key predictions of the model:

- There is minimal statistically-significant evolution in the black hole–bulge and black hole–total stellar mass relations out to high redshifts ($z \approx 8$).

- The black hole–total stellar mass relation has similar but slightly larger scatter than the black hole–bulge relation, with the scatter in both decreasing with increasing redshift. This indicates that the growth of galaxies, bulges and black holes are all tightly related, even at the highest redshifts.

- Higher mass black holes have higher black hole–total stellar mass ratios, leading to a significant selection effect in measurements of this ratio when observing only the most massive black holes.

- Instability-driven or secular quasar-mode growth is the dominant growth mechanism for black holes at all redshifts. The contribution from merger-driven quasar-mode growth only becomes significant at low redshift for black holes with $M_{\text{BH}} \gtrsim 10^9 M_\odot$.

- Disc-dominated galaxies lie on the black hole–total stellar mass relation, but lie offset from the black hole–bulge mass relation.

The Meraxes model is limited in making predictions for the highest redshift quasars at $z = 6–7$ due to the simulation box size and resolution. Running Meraxes on larger N-body simulations in the future would allow me to make predictions for these more extreme objects.
Chapter 5

The Host Galaxies of $z = 7$ Quasars: Predictions from the BlueTides Simulation

Upcoming facilities such as JWST (Gardner et al., 2006), Euclid (Amiaux et al., 2012), and RST (Spergel et al., 2015), will bring significant advancements in our understanding of high-redshift quasars, substantially increasing our known sample of $z \gtrsim 6$ quasars, and providing a more detailed view of their host galaxies and environments. Making detailed theoretical predictions for the results of these state-of-the-art instruments is a current priority.

Due to the rarity of high-redshift quasars, with a space density of less than 1 per Gpc$^3$ at $z \gtrsim 6$ (Willott et al., 2010a; Kashikawa et al., 2015; Jiang et al., 2016; Wang et al., 2019), cosmological simulations require very large volumes to make predictions for these objects. The cosmological hydrodynamical simulations Massive Black (Di Matteo et al., 2012), with a volume of $(0.76 \text{ Gpc})^3$, and BlueTides (Feng et al., 2015), with a volume of $(0.57 \text{ Gpc})^3$, have pioneered this area. These simulations have been used to make predictions for observed high-redshift quasars (DeGraf et al., 2012a; Tenneti et al., 2018; Ni et al., 2018), and to investigate the growth of black holes (Di Matteo et al., 2012; DeGraf et al., 2012b; Feng et al., 2014; Di Matteo et al., 2017) and the black hole–host relations in the early Universe (Khandai et al., 2012; DeGraf et al., 2015; Huang et al., 2018).

Previous BlueTides analyses were performed with the phase I simulation, which reached a minimum redshift of $z = 8.0$, and BlueTides-II, the second phase of the simulation which had been run to $z = 7.5$ when last analysed (Tenneti et al., 2018). In this chapter I use the BlueTides-II simulation extended further to $z = 7.0$ to make predictions for
the properties of quasar host galaxies. At \( z = 7.5 \), there is one quasar analogue in the BlueTides simulation, as studied by Tenneti et al. (2018). Extending the simulation from \( z = 7.5 \) to 7.0, a period of only 58 Myr, results in a considerable increase in the number of observable quasar analogues to the order of 100, since this is such an intense growth phase of black holes in the Universe. This statistical sample allows BlueTides to make predictions for the broader quasar population, and not just for individual, extreme systems as was possible previously.

The chapter is outlined as follows. Section 5.1 describes the BlueTides simulation and the post-processing used to obtain mock spectra of the quasars and their host galaxies. Section 5.2 makes predictions for the intrinsic galaxy properties of the hosts of black holes and quasars. I consider observable properties in Section 5.3, making spectra and mock JWST images. In Section 5.4 I examine the black hole–stellar mass relation, showing how observations of these quasars will lead to a biased measurement. The environments of quasars are explored in 5.5, and a summary is given in Section 5.6. The cosmological parameters used throughout this chapter are from the nine-year Wilkinson Microwave Anisotropy Probe (WMAP; Hinshaw et al., 2013): \( \Omega_M = 0.2814, \Omega_\Lambda = 0.7186, \Omega_b = 0.0464, \sigma_8 = 0.820, \eta_s = 0.971 \) and \( h = 0.697 \).

5.1 Simulation

5.1.1 BlueTides

The BlueTides simulation\(^1\) (Feng et al., 2015) is a cosmological hydrodynamical simulation, which uses the Pressure Entropy Smoothed Particle Hydrodynamics (SPH) code MP-Gadget to model the evolution of \( 2 \times 10^3 \) particles in a cosmological box of volume \( (400/h \text{ cMpc})^3 \). The mass resolution of the simulation is \( 1.2 \times 10^7/h \ M_\odot \) for dark matter particles and \( 2.4 \times 10^6/h \ M_\odot \) for gas particles (in the initial condition). Star particles are converted from gas particles with sufficient star formation rates, and each have a stellar mass of \( 6 \times 10^5/h \ M_\odot \). The gravitational softening length of \( \epsilon_{\text{grav}} = 1.5/h \text{ ckpc} \) is the effective spatial resolution. From the initial conditions at \( z = 99 \), BlueTides evolved the box to \( z = 8 \) in phase I (Feng et al., 2015). Phase II of the simulation continued the evolution of the box from \( z = 8 \) to lower redshifts, with the first results from this phase.

\(^1\)http://BlueTides-project.org/
given in Tenneti et al. (2018). Here I focus on the lowest redshift currently reached by phase II, $z = 7.0$. From the simulation, I consider the 108000 most massive haloes, with masses $M_{\text{vir}} > 10^{10.8} M_\odot$, which contain galaxies with $M_\ast > 10^{5.9} M_\odot$ and black holes with $M_{\text{BH}} > 10^{5.8} M_\odot$ (the seed mass).

\texttt{BlueTides} implements a variety of sub-grid physics to model galaxy and black hole formation and their feedback processes. Here some of its basic features are briefly listed, and the reader is referred to the original paper (Feng et al., 2015) for more detailed descriptions. In the \texttt{BlueTides} simulation, gas cooling is performed through both primordial radiative cooling (Katz et al., 1999) and metal line cooling (Vogelsberger et al., 2014). Star formation is based on the multi-phase star formation model originally from Springel & Hernquist (2003) with modifications following Vogelsberger et al. (2013). \texttt{BlueTides} also implements the formation of molecular hydrogen and models its effects on star formation using the prescription from Krumholz & Gnedin (2011), which self-consistently estimates the fraction of molecular hydrogen gas from the baryon column density, which in turn couples the density gradient into the star formation rate. For stellar feedback, \texttt{BlueTides} applies a type-II supernova wind feedback model from Okamoto et al. (2010), assuming wind speeds proportional to the local one-dimensional dark matter velocity dispersion. The large volume of \texttt{BlueTides} also allows the inclusion of a model of ‘patchy reionization’ (Battaglia et al., 2013), yielding a mean reionization redshift $z \simeq 10$, and incorporating the UV background estimated by Faucher-Giguère et al. (2009).

The black hole sub-grid model associated with black hole growth and AGN feedback are the same as in the \texttt{MassiveBlack I & II} simulations, originally developed in Springel et al. (2005a) and Di Matteo et al. (2005a), with modifications consistent with \texttt{ILLUSTRIS}; see DeGraf et al. (2012b) and DeGraf et al. (2015) for full details. Black holes are seeded with a mass of $M_{\text{BH,seed}} = 5 \times 10^5/h M_\odot$ in dark matter haloes above a threshold mass of $M_{\text{BH,seed}} = 5 \times 10^{10}/h M_\odot$. The simulation makes no direct assumption of the black hole formation mechanism, although this mass is most consistent with seed masses predicted by direct collapse scenarios (e.g. Begelman et al., 2006; Shang et al., 2010; Volonteri, 2010; Latif et al., 2013). Black holes grow by merging with other black holes, and via gas accretion at the Bondi-Hoyle accretion rate (Hoyle & Lyttleton, 1939; Bondi & Hoyle, 1944; Bondi, 1952), $\dot{M}_{\text{BH}} = \alpha 4\pi G^2 M_{\text{BH}}^2 \rho_{\text{BH}} (c_s^2 + v^2)^{-3/2}$, where $\rho_{\text{BH}}$ is the local gas density, $c_s$ is the local sound speed, $v$ is the velocity of the black hole relative to the surrounding gas, and $\alpha$ is a dimensionless parameter. Mildly super-Eddington accretion is permitted,
with the accretion rate limited to two times the Eddington limit. In this sub-grid model, 
the black hole mass grows smoothly at this accretion rate. In order to account for the 
discrete nature of gas particles, once a black hole has grown by an amount equivalent to 
the mass of a gas particle, a gas particle is removed and its mass transferred to the black 
hole’s ‘dynamical mass’. This discrete dynamical mass allows the particle dynamics to 
be calculated correctly within the simulation; however, the continuous black hole mass is 
always used in any analyses. Finally, \textsc{BlueTides} assumes that black holes radiate with 
bolometric luminosity $L_{\text{AGN}} = \eta \dot{M}_{\text{BH}} c^2$, with a radiative efficiency $\eta$ of 0.1.

Throughout this work, I generally consider only black holes with $M_{\text{BH}} > 10^{6.5} M_\odot$, in 
order to minimize any possible influence of the seeding prescription on the analysis. I also 
consider only the $z = 7.0$ snapshot. This is in contrast to Tenneti et al. (2018), which 
explored a range of snapshots around $z \simeq 7.5$ in order to find the brightest quasar in the 
simulation, as quasar luminosity varies significantly due to the time-variability of black 
hole accretion. Using only one snapshot is more representative of an observational sample, 
in which galaxies are observed at a random phase in their growth history, and not, for 
example, only when their black hole is at its peak luminosity.

To extract the properties of galaxies from the simulation, a friends-of-friends (FOF) al-
gorithm is run (Davis et al., 1985). The galaxy properties, such as the star formation 
density, stellar mass function and UV luminosity function, have been shown to match 
current observational constraints at $z = 8$, 9 and 10 (Feng et al., 2015; Waters et al., 2016; 
Wilkins et al., 2017).

To determine the stellar mass of the galaxies from the total stellar mass contained in their 
host dark matter haloes, I calculate the galaxy $R_{200}$, the radius containing 200 times the 
critical stellar mass density (the critical density of the Universe multiplied by the baryon 
fraction and star formation efficiency of the simulation). I define the stellar mass of a 
galaxy as the mass contained within $R_{200}$. This generally includes the inner dense core of 
the galaxy and also the more diffuse outer regions, ensuring that the majority of particles 
truly associated with each galaxy are included. For determining the sizes of galaxies, I 
calculate the half-mass radius inside this $R_{200}$, $R_{0.5}$.

The morphology of the galaxy is determined by its bulge-to-total ratio, calculated using 
the bulge-to-disc decomposition method of Scannapieco et al. (2009). The circularity pa-
rameter $\epsilon = j_z / j_{\text{circ}}(r)$ is calculated for each star particle in the galaxy within $R_{200}$, where
\( j_z \) is the projection of the specific angular momentum of the star particle in the direction of the total angular momentum of the galaxy, and \( j_{\text{circ}}(r) \) is the angular momentum expected for a circular orbit at the radius \( r \): \( j_{\text{circ}} = r v_{\text{circ}}(r) = \sqrt{GM(<r)r} \). Star particles with \( \epsilon > 0.7 \) are identified as disc stars, and the bulge-to-total ratio is defined as \( B/T = 1 - f_{\epsilon>0.7} \), where \( f_{\epsilon>0.7} \) is the fraction of disc stars in the galaxy.

5.1.2 Mock spectra

5.1.2.1 Galaxy SEDs

To determine the spectral energy distribution (SED) of a galaxy, a SED from a simple stellar population (SSP) is assigned to each star particle within \( R_{200} \), based on its mass, age and metallicity. This is done using the Binary Population and Spectral Population Synthesis model (BPASS, version 2.2; Stanway & Eldridge, 2018), assuming a modified Salpeter initial mass function with a high-mass cut-off of \( 300M_\odot \). The SED of the galaxy is taken as the sum of the SEDs of each of its star particles. To determine the relative contribution of the stellar and nebular emission, an escape fraction of 0.9 is assumed.

5.1.2.2 Quasar spectra

To assign spectra to each of the quasars, I use the CLOUDY spectral synthesis code (Ferland et al., 2017), as in Tenneti et al. (2018).

The continuum is given by

\[
f_\nu = \nu^{\alpha_{\text{UV}}} \exp \left( -\frac{h\nu}{kT_{\text{BB}}} \right) \exp \left( -\frac{kT_{\text{IR}}}{h\nu} \right) + a\nu^{\alpha_{\text{x}}}
\]

(5.1)

where \( \alpha_{\text{UV}} = -0.5 \), \( \alpha_{\text{x}} = -1 \), \( kT_{\text{IR}} = 0.01\text{Ryd} \), and \( T_{\text{BB}} \) is the temperature of the accretion disc, which is determined by the black hole mass and its accretion rate

\[
T_{\text{BB}} = \left( \frac{3c^6}{8\pi^6\sigma_{\text{SB}}G^2M_{\odot}} \frac{\dot{M}_{\text{BH}}}{M_{\odot}} \right)^{1/4} = 2.24 \times 10^9 \left( \frac{\dot{M}_{\text{BH}}}{M_{\odot}/\text{yr}} \right)^{1/4} \left( \frac{M_{\text{BH}}}{M_{\odot}} \right)^{-1/2} \text{K}.
\]

(5.2)

The normalisation of the continuum is set by the bolometric luminosity of the quasar.
The emission lines are calculated with CLOUDY assuming a hydrogen density of \(10^{10}\) cm\(^{-3}\) at the face of the cloud, which has inner radius \(10^{18}\) cm, and a total hydrogen column density of \(10^{22}\) cm\(^{-2}\).

I also implement Lyman-forest extinction on the redshifted spectra (Madau, 1995; STScI Development Team, 2018) for both the quasars and the host galaxies.

### 5.1.2.3 Dust attenuation and extinction

As in Wilkins et al. (2017), the dust attenuation of BlueTides galaxies is modelled by relating the density of metals along a line of sight to the UV-band dust optical depth \(\tau_{UV}\). For each star particle in the galaxy, \(\tau_{UV,s}\) is calculated as

\[
\tau_{UV,s} = -\kappa \Sigma(x, y, z) \left( \frac{\lambda}{5500\text{Å}} \right)^\gamma. \tag{5.3}
\]

where \(\Sigma(x, y, z) = \int_{z'=0}^{z} \rho_{\text{metal}}(x, y, z') dz'\) is the metal surface density at the position of the star particle, along the z-direction line of sight, and \(\kappa\) and \(\gamma\) are free parameters. Here \(\kappa = 10^{4.6}\) and \(\gamma = -1.0\), which are calibrated against the observed galaxy UV luminosity function at redshift \(z = 7\). The total dust-attenuated galaxy luminosity is the sum of the extincted luminosities of each individual star particle.

The same technique is applied to determine the dust attenuation of the AGN, with the dust optical depth calculated using the metal column density integrated along a line of sight to the quasar:

\[
\tau_{UV,AGN} = \kappa \int \rho_{\text{metal}}(l) dl \left( \frac{\lambda}{5500\text{Å}} \right)^\gamma, \tag{5.4}
\]

with the same value of \(\kappa\) and \(\gamma\) (see also Ni et al., 2020). Dust attenuation of the AGN mainly traces the regions of high gas density near the centre of the galaxy, with the gas metallicity \(Z\) only modulating the dust extinction at a sub-dominant level (see Figure 14 in Ni et al., 2020, for illustration.). Because of the angular variation in the density field surrounding the central black hole, the dust extinction for AGN is sensitive to the choice of line of sight, unlike for galaxies, whose dust attenuation is accumulated over the extended source. For each quasar \(\tau_{UV,AGN}\) is therefore calculated along approximately 1000 lines of sight. See Ni et al. (2020) for full details.
5.2 Properties of black hole host galaxies

5.2.1 Sample selection

The black hole population in BLUETIDES at $z = 7.0$ is presented in Figure 5.1, which shows the distributions of their masses and AGN luminosities, as well as the AGN UV luminosity function. By considering the UV-band dust extinction as described in Section 5.1.2.3 and Ni et al. (2020), BLUETIDES produces a quasar luminosity function that is in good agreement with the high-redshift observations of Jiang et al. (2016) and Wang et al. (2019) — BLUETIDES predicts the expected number density of high-z quasars. The most massive black holes in BLUETIDES at $z = 7$ have masses $M_{BH} \approx 10^{8.5} M_\odot$, and the most luminous AGN have intrinsic bolometric luminosities $L_{bol} \approx 10^{47} \text{erg s}^{-1} \approx 10^{13} L_\odot$, equivalent to those of currently observed high-z quasars.

From this black hole population I select three samples; the most massive black holes, ‘quasars’, and ‘hidden quasars’.

**Massive black hole sample:** I consider the ten most massive black holes at $z = 7$, which have masses $M_{BH} = 10^{8.44} - 10^{8.89} M_\odot$, to be the ‘massive black hole’ sample.

**Quasar sample:** To select ‘quasars’ from the simulation, I consider the galaxy and AGN UV-band absolute magnitudes, as shown in Figure 5.2. I make the simple assumption that every bright ($L_{AGN} > 10^{44} \text{erg s}^{-1}$) black hole with $M_{UV,AGN} < M_{UV,Host}$ would be classified as a quasar, since the AGN outshines the host galaxy. This results in a sample of 205 BLUETIDES quasars, which is only 2.1 per cent of the black holes with $M_{BH} > 10^{6.5} M_\odot$, and 2.6 per cent of black holes with $L_{AGN} > 10^{44} \text{erg s}^{-1}$ (see Figure 5.2). Note that the assumption that $M_{UV,AGN} < M_{UV,Host}$ for a galaxy to be classified as a quasar is not an accurate representation of the true observational quasar selection techniques, and may underestimate the number of galaxies in the sample that would be observed as quasars.

**Hidden quasar sample:** Within the simulation, 70.5 per cent of black holes brighter than the faintest currently-known high-redshift quasar, $m_{UV} = 24.85$ ($L_{AGN} > 10^{45.1} \text{erg s}^{-1}$ at $z = 7$; Matsuoka et al., 2018a), have host luminosities that outshine the AGN. These 488 black holes are experiencing significant black hole growth, with high AGN luminosities, but are simply ‘hidden’ by their luminous host galaxies. I consider all black holes with
Figure 5.1 Left: The distribution of black hole masses and AGN bolometric luminosities for BLUETIDES galaxies at $z = 7$ (blue density plot). The Eddington limit is shown for reference (dashed black line), as well as twice the Eddington limit, which is the upper limit of the black hole accretion rate set in the simulation. The luminosity of the faintest SDSS quasar, the faintest currently-known high-redshift quasar, and the RST detection limit are shown for reference (grey dashed lines). Right: The UV-band luminosity function of AGN at $z = 7$. The black solid line is the dust-extincted quasar luminosity function from BLUETIDES. The brown solid line is the luminosity function including only the AGN that outshine their host galaxies. The grey shaded area gives the error estimate by considering the dust extinction through all lines of sight of the AGN population. The orange solid symbols with error bars show the measured binned quasar luminosity function from Wang et al. (2019) at $z \sim 6.7$. The red dotted line is the $z \sim 6$ fitted quasar luminosity function measured by Jiang et al. (2016). The purple dashed line gives the luminosity function from Matsuoka et al. (2018b), based on the population of $5.7 < z < 6.5$ quasars and extrapolated to $z = 7$.

intrinsic luminosities $L_{\text{AGN}} > 10^{45.1} \text{erg s}^{-1}$ and with $M_{\text{UV,AGN}} > M_{\text{UV,Host}}$ as ‘hidden’ quasars, i.e. those outshined by their host galaxy.

5.2.2 Galaxy properties

I now investigate the properties of the hosts of the most massive black holes and quasars in BLUETIDES at $z = 7$.

Figure 5.3 shows the relation between AGN luminosity and both stellar mass and star formation rate at $z = 7$. The most massive black holes are in massive galaxies with stellar masses $\log(M_*/M_\odot) = 10.80^{+0.20}_{-0.16}$, which have large star formation rates, $513^{+1225}_{-351} M_\odot$/yr.\textsuperscript{2}

\textsuperscript{2}Errors presented in this manner correspond to the 16th and 84th percentiles of the distributions, relative to the median value.
Figure 5.2 The distribution of host and AGN intrinsic UV absolute magnitudes for BlueTides galaxies at $z = 7$ (blue density plot). Quasars (white circles) are classified as those with $M_{UV,AGN} < M_{UV,Host}$, since the AGN outshines the host galaxy. The 10 most massive black holes (black circles) are also shown. The luminosity of the faintest SDSS quasar, the faintest currently-known high-redshift quasar, and the RST detection limit are shown for reference (grey dashed lines).

The quasar hosts also have large but lower stellar masses of $\log(\frac{M_*}{M_\odot}) = 10.25^{+0.40}_{-0.37}$, and lower star formation rates of $191^{+288}_{-120}M_\odot/yr$.

These star formation rates are broadly consistent with those observed in the hosts of luminous high-redshift quasars with the PdBI of $\simeq 1700M_\odot/yr$ (Walter et al., 2009), and with ALMA: 100–1600 $M_\odot/yr$ (Venemans et al., 2015), 200–3500 $M_\odot/yr$ (Trakhtenbrot et al., 2017a), 30–3000 $M_\odot/yr$ (Decarli et al., 2018), 50–2700 $M_\odot/yr$ (Venemans et al., 2018), and $\simeq 2500M_\odot/yr$ (Shao et al., 2019). However, the simulation does not contain quasar hosts with extreme star formation rates of $\gtrsim 1000M_\odot/yr$, as are observed. This is most likely because by $z = 7$ BlueTides has not yet produced a population of extremely luminous quasars, which are those generally found in such extreme hosts. Note, however, that star-formation rates derived from far-infrared observations can have uncertainties of a factor of $\sim 2–3$ (e.g. Venemans et al., 2018). A comparison of BlueTides at lower redshift with more precise star formation rates measured in the rest-frame UV using JWST, for example, would allow for a deeper understanding of quasar host star formation rates.

From Figure 5.3, on average, lower luminosity quasars have less extreme host galaxies, with
Figure 5.3 The relations between AGN luminosity and stellar mass (upper right panel) and star formation rate (lower right panel). The blue density plot shows the distribution for all BLUETIDES galaxies, with the most massive black holes and quasars also plotted (see legend). The left panels show the distributions of the host properties for the most massive black holes (black line), quasars (white line), hidden quasars (salmon line), and for all black holes with $L_{\text{AGN}} > 10^{45.1}\text{erg s}^{-1}$ (blue line). The luminosity of the faintest SDSS quasar, the faintest currently-known high-redshift quasar ($L_{\text{AGN}} = 10^{45.1}\text{erg s}^{-1}$), and the RST detection limit are shown in the right panels for reference (grey dashed lines).
lower masses and star formation rates. The hosts of lower luminosity quasars are indeed observed to have lower star formation rates: $\lesssim 10 \, M_\odot/\text{yr}$ (Willott et al., 2017), 100–500 $M_\odot/\text{yr}$ (Trakhtenbrot et al., 2017a), and 23–40 $M_\odot/\text{yr}$ (Izumi et al., 2018). While the $z = 7$ BLUE-TIDES predictions do not extend to such low star formation rates, by $z \simeq 6$ there could be more scatter in the relation, alongside more ‘quenched’ quasars, where feedback has significantly reduced the star formation in the host galaxy.

Figure 5.3 also shows the one-dimensional distributions of stellar mass and star formation rate for these samples, alongside all black holes brighter than $L_{\text{AGN}} > 10^{45.1}\text{erg s}^{-1}$, and ‘hidden’ quasars. This shows that the most massive black holes live in more massive galaxies, with higher star formation rates, than the total sample of bright black holes ($L_{\text{AGN}} > 10^{45.1}\text{erg s}^{-1}$), which have $\log(M_*/M_\odot) = 10.18^{+0.37}_{-0.32}$ and star formation rates of $170^{+219}_{-98} M_\odot/\text{yr}$. The hidden quasars are hosted by galaxies with $\log(M_*/M_\odot) = 10.16^{+0.34}_{-0.30}$ and star formation rates of $166^{+189}_{-83} M_\odot/\text{yr}$.

At a fixed quasar luminosity, the quasars are hosted by less massive galaxies with lower star formation rates than the hidden quasars. This is expected due to the $M_{\text{UV,AGN}} < M_{\text{UV,Host}}$ selection: the quasar sample contains galaxies with lower $M_{\text{UV,Host}}$ for fixed $M_{\text{UV,AGN}}$, which is produced by having a lower star formation rate. Galaxies with higher star formation rates have higher luminosities which outshine their quasar, resulting in ‘hidden’ quasars of the same quasar luminosity. As stellar mass is an integrated quantity, the selection effect is weakened slightly.

Figure 5.4 shows the relation between AGN luminosity and the ratio of stellar mass contained in a galaxy’s bulge to its total stellar mass ($B/T$). The hosts of the most massive black holes and quasars all show bulge-dominated morphologies, although there is a large tail to lower $B/T$, with $B/T = 0.85^{+0.09}_{-0.10}$, and $0.89^{+0.07}_{-0.11}$ for the two samples respectively. Their morphologies have a similar distribution to that of the total sample of bright black holes ($L_{\text{AGN}} > 10^{45.1}\text{erg s}^{-1}$), with $B/T = 0.85^{+0.09}_{-0.12}$, and hidden quasars, with $B/T = 0.84^{+0.10}_{-0.14}$. The hosts of the most massive black holes and quasars in BLUE-TIDES are generally bulge-dominated, but are not biased in morphology relative to the overall galaxy sample at $z = 7$.

Lupi et al. (2019) performed a high-resolution cosmological zoom-in simulation of a halo containing a black hole with mass $M_{\text{BH}} = 10^{8.9} M_\odot$ at $z = 7$, similar to that of the most massive black hole in BLUE-TIDES. They found its host galaxy to have a mass of
Figure 5.4 The relation between AGN luminosity and the bulge-to-total mass ratio ($B/T$). The blue density plot shows the distribution for all BLueTides galaxies, with the most massive black holes and quasars also plotted (see legend). The left panel shows the distribution of $B/T$ for the most massive black holes (black line), quasars (white line), hidden quasars (salmon line), and all black holes brighter than $L_{\text{AGN}} > 10^{45.1}\text{erg s}^{-1}$ (blue line). The luminosity of the faintest SDSS quasar, the faintest currently-known high-redshift quasar ($L_{\text{AGN}} = 10^{45.1}\text{erg s}^{-1}$), and the RST detection limit are shown in the right panel for reference (grey dashed lines).

$M_\ast \simeq 10^{11} M_\odot$ and a large star formation rate of $\sim 10^{2.5} M_\odot/\text{yr}$ at $z = 7$, equivalent to the most massive and star forming galaxies in BLueTides. Their quasar host is less bulge-dominated than those in the BLueTides quasar sample, with a bulge-to-total mass ratio of $B/T \simeq 0.45$. This is potentially due to the increased resolution of their simulation, which has the ability to better resolve the disc structure. The results of Lupi et al. (2019) are therefore reasonably consistent with the BLueTides simulation, given their sample of only one quasar host.

Figure 5.5 shows the relation between half-mass radius $R_{0.5}$ and stellar mass, halo mass and host UV magnitude. For comparison, a range of observations of $z \simeq 6–7$ Lyman-break galaxies with $M_{\text{UV}} < -20$ are also shown. These observed galaxies have a wide range of sizes, consistent with the sizes of the general BLueTides galaxy sample. The most massive black hole hosts in BLueTides have small radii of $R_{0.5} = 0.41^{+0.18}_{-0.14}$ kpc, and the quasar hosts $R_{0.5} = 0.40^{+0.11}_{-0.09}$ kpc. The total sample of bright black holes ($L_{\text{AGN}} > 10^{45.1}\text{erg s}^{-1}$) have much larger sizes of $R_{0.5} = 0.51^{+0.27}_{-0.21}$ kpc, as do hidden quasars, which
Figure 5.5 The relation between half-mass radius and stellar mass (left), halo mass (centre), and dust-attenuated galaxy UV magnitude (right). The blue density plots show the distribution for all BLUETIDES galaxies, with the most massive black holes and quasars also plotted (see legend). Also shown in the right panel are a range of observations of individual $z \simeq 6-7$ Lyman-break galaxies (Bowler et al., 2016; Kawamata et al., 2018; Bridge et al., 2019), and the size–luminosity relation for Lyman-break galaxies at $z = 7$ derived by Shibuya et al. (2015). Horizontal grey dashed lines show the pixel scales of the JWST NIRCam short-wavelength (SW; 0.6–2.3 µm) and long-wavelength (LW; 2.4–5.0 µm) detectors, of 0′′.031 and 0′′.063 respectively, for reference. The left-most panel shows the distributions of half-mass radius for the most massive black holes (black line), quasars (white line), hidden quasars (salmon line), all black holes brighter than $L_{\text{AGN}} > 10^{45.1}$ erg s$^{-1}$ (blue line) and the total sample of galaxies with $M_* > 10^{9.5} M_\odot$, $M_{\text{Halo}} > 10^{11.3} M_\odot$ and $M_{\text{UV,Host (dust)}} < -20.5$ (green line). These limits are shown in the corresponding panels for reference (green dashed lines).

have $R_{0.5} = 0.56^{+0.30}_{-0.23}$ kpc, and galaxies with similar masses and luminosities ($M_{\text{Halo}} > 10^{11.3} M_\odot$, $M_* > 10^{9.5} M_\odot$, $M_{\text{UV,Host (dust)}} < -20.5$), which have $R_{0.5} = 0.71^{+0.28}_{-0.25}$ kpc. A distinguishing feature of massive black hole and quasar hosts is therefore that they are very compact. This is consistent with the lower redshift conclusions of Bornancini & Lambas (2020), who observe that $1.4 \leq z \leq 2.5$ AGN and quasar hosts are more compact than star-forming galaxies. Silverman et al. (2019) find that $1.2 \leq z \leq 1.7$ AGN hosts have intermediate sizes, between those of star-forming, disc-dominated galaxies, and more compact quiescent, bulge-dominated galaxies.

Observations of high-redshift quasar host galaxies at sub-mm wavelengths generally measure larger extents of their gas and dust distributions than these predictions for the sizes of their stellar distributions. For example, studies of [CII] line emission in $z \gtrsim 6$ quasars using ALMA find radii of 1.7–3.5 kpc (Wang et al., 2013), 2.1–4.0 kpc Venemans et al.
(2015), a median radius of 2.25 kpc (Willott et al., 2017), and for low-luminosity quasars, radii of 2.6–5.2 kpc (Izumi et al., 2018) and 2.1–4.0 kpc (Izumi et al., 2019). In a larger study, Decarli et al. (2018) measured the [CII] emission of a sample of 27 $z > 5.94$ quasars with ALMA, finding radii of 1.2–4.1 kpc. These sizes are much larger than the BlueTides predictions for the stellar distributions of quasar host galaxies, of $R_{0.5} = 0.40^{+0.11}_{-0.09}$ kpc, and even the general galaxy distribution of $R_{0.5} = 0.71^{+0.28}_{-0.25}$ kpc. Note, however, that FIR continuum and [CII] line observations generally find that [CII] emission is more extended than the dust continuum emission (Wang et al., 2013; Venemans et al., 2015; Willott et al., 2017; Izumi et al., 2018, 2019), with in some cases the continuum radius smaller than the [CII] radius by even a factor of $\sim 3$ (Izumi et al., 2019). As the different observations trace different components, this suggests that the gas and dust, and likewise potentially the stars in galaxies, may have different distributions (see also Khandai et al., 2012; Lupi et al., 2019).

Using the FIRE simulation and a radiative transfer code to study galaxies in $1 < z < 5$, Cochrane et al. (2019) find that emission from the stellar component is generally less extended than that of dust continuum emission, cool gas and dust; an example galaxy is quoted as having $R_* \sim 0.8$ kpc, $R_{\text{cool gas}} \sim 2.7$ kpc, and $R_{\text{dust}} \sim 2.4$ kpc. Observations of main-sequence star-forming galaxies at $z \simeq 4–6$ with both ALMA and HST find that the [CII] radii exceed the rest-frame UV radii by factors of $\sim 2–3$, with median sizes $R_{\text{[CII]}} = 2.1 \pm 0.16$ kpc, $R_{F160W} = 0.91 \pm 0.06$ kpc and $R_{F814W} = 0.66 \pm 0.04$ kpc, where $R_{F160W}$ and $R_{F814W}$ are radii measured from the HST F160W and F814W filters, respectively (Fujimoto et al., 2020). Thus, it seems reasonable that while ALMA observations find extended emission in quasar hosts from dust and cold gas, these BlueTides predictions expect the stellar emission to be much more compact. I will use BlueTides to make predictions for the gas and dust properties of quasar hosts and compare these to the stellar properties in future work.

5.3 Quasar observations

In Section 5.2, I considered the properties of the host galaxies of the most massive black holes and intrinsically bright quasars in the BlueTides simulation. I now consider the effects of dust-attenuation and survey magnitude limits to mimic true quasar observations, to make predictions for upcoming observations with JWST.
5.3.1 Observable quasar sample selection

5.3.1.1 Magnitude limits of quasar observations

To select the observable quasar samples, I first consider the magnitude limits of various observational surveys.

The most well-known sample of high-z quasars is that of the Sloan Digital Sky Survey (SDSS; e.g. Fan et al., 2003, 2006b; Jiang et al., 2016). The faintest quasar in this sample is SDSS J0129–0035, with $m_{1450} = 22.8$, or $M_{1450} = -23.89$ at $z = 5.78$ (Wang et al., 2013; Bañados et al., 2016). This is of similar luminosity to the brightest quasars in the BLUETIDES simulation at $z = 7$.

The faintest high-z quasars observed to date are those discovered in the Subaru High-z Exploration of Low-Luminosity Quasars (SHELLQs) project (Matsuoka et al., 2018a), which uses imaging from the Subaru Hyper Suprime-Cam and follow-up spectroscopy using the Gran Telescopio Canarias and the Subaru Telescope. This sample includes $5.7 < z < 6.8$ quasars down to magnitudes of $m_{1450} = 24.85$, or $M_{1450} = -21.93$ (HSC J1423–0018 at $z = 6.13$).

Surveys with upcoming facilities will significantly increase the sample of known high-redshift quasars. The Euclid spacecraft, expected to launch in the latter half of 2022, will perform a wide survey of 15,000 square degrees to a magnitude of 24.0 in the $Y$, $J$ and $H$ bands, and a deep survey of 40 square degrees to a magnitude of 26.0 (Laureijs et al., 2011). The Vera C. Rubin Observatory, previously known as the Large Synoptic Survey Telescope or LSST, will perform a survey over 18,000 square degrees, reaching depths of magnitude 26.2 in the $z$-band and 24.9 in the $y$-band, commencing in 2023 (LSST Science Collaboration et al., 2009). These large surveys will discover a large number of high-redshift quasars, complementing the smaller, existing sample of SHELLQs quasars, which found quasars to a similar depth. The deep Euclid survey will discover even fainter quasars, although its much smaller area will result in a smaller quasar sample.

At the forefront of upcoming high-redshift quasar discovery surveys is the RST High Latitude Survey, which will cover 2,000 square degrees to a magnitude of 26.9 in the $Y$, $J$ and $H$ bands (Spergel et al., 2015). While RST will not launch until at least 2025, potentially beyond the 5-year mission plan of JWST, the large volume and significant
Figure 5.6 The distributions of dust extinction $A = M_{\text{dust}} - M_{\text{intrinsic}}$ applied to galaxies and AGN. The dust extinction for the AGN is taken as that along the line of sight with the least dust-extinction, which is typically the face-on direction, as an optimistic assumption.

depth of this survey will result in the largest sample of faint quasars in the foreseeable future. I assume that there will be some bluer comparison data of significant depth which can be used to select dropouts, so take $m_{1450} = 26.9$ as the faintest $z = 7$ AGN luminosity that could be detected by RST.

5.3.1.2 Observable quasars

In Section 5.2 I selected the quasar sample based on the intrinsic UV-band magnitudes of the black holes and host galaxies (Figure 5.2), with ‘quasars’ defined as black holes which had intrinsic magnitudes brighter than their hosts. Figure 5.6 shows the difference between dust-attenuated and intrinsic magnitudes for both AGN and host galaxies, $A = M_{\text{dust}} - M_{\text{intrinsic}}$, as calculated following the procedures outlined in Section 5.1.2.3. Here, and throughout the remainder of this paper, I take the dust extinction for the AGN as that along the line-of-sight with the minimum $\tau_{\text{UV,AGN}}$, as an optimistic estimate of the AGN dust extinction. This generally corresponds to the face-on direction (see Ni et al., 2020).

Figure 5.6 shows that AGN and host galaxies experience a similar level of dust attenuation in the majority of cases. The AGN population, however, exhibits a small tail in the distribution extending to large $A$. These AGN with extreme dust attenuation are a
mixed population of black holes, with a variety of masses and accretion rates. This extinction results in some of the ‘intrinsic quasars’ having dust-attenuated AGN magnitudes that no longer outshine their host galaxy. It is therefore important when making mock observational samples to select them based on their dust-attenuated magnitudes.

The relation between galaxy and AGN dust-attenuated UV magnitudes for the BLUE-TIDES galaxies is shown in Figure 5.7. Since surveys are limited by apparent and not absolute magnitude, I convert the AGN magnitudes to $m_{UV,AGN}$ using $m - M = DM - 2.5 \log(1 + z) = 46.99$, and overplot the observational selection limits described in 5.3.1.1.

As in Section 5.2, I make the simple assumption that AGN which outshine their host galaxy in the UV-band are classified as ‘quasars’. In contrast to Section 5.2, however, this classification is made using dust-attenuated magnitudes: ‘quasars’ are black holes with
Figure 5.8 The spectra of a quasar and its host galaxy, for the median mass black hole in the most massive black hole sample (far left), and the black hole with the median dust-attenuated luminosity in the SDSS (middle left), currently observable (middle right) and RST (far right) quasar samples. The upper grey curves show the intrinsic quasar spectra, while the lower black curves shows the quasar spectra with the dust extinction law applied. The upper turquoise curves show the intrinsic host galaxy spectra, while the lower turquoise curves show the host galaxy spectra with the dust extinction law applied.

\[ M_{UV,AGN}^{(dust)} < M_{UV,Host}^{(dust)} \]. Using the limiting magnitudes from SDSS, SHELLQs and RST, I define the three observable quasar samples as:

- SDSS quasars: \( M_{UV,AGN}^{(dust)} < M_{UV,Host}^{(dust)} \) and \( m_{UV,AGN}^{(dust)} < 22.8 \)
- Currently observable quasars: \( M_{UV,AGN}^{(dust)} < M_{UV,Host}^{(dust)} \) and \( 22.8 < m_{UV,AGN}^{(dust)} < 24.85 \)
- RST quasars: \( M_{UV,AGN}^{(dust)} < M_{UV,Host}^{(dust)} \) and \( 24.85 < m_{UV,AGN}^{(dust)} < 26.9 \)

The ‘SDSS’, ‘currently observable’ and ‘RST’ quasar samples contain 23, 177 and 498 quasars respectively, which is all black holes in the simulation with \( m_{UV,AGN}^{(dust)} < 22.8 \), 99 per cent of black holes with \( 22.8 < m_{UV,AGN}^{(dust)} < 24.85 \), and 38 per cent of black holes with \( 24.85 < m_{UV,AGN}^{(dust)} < 26.9 \) (see Figure 5.2). Defining the observable quasar samples using the dust attenuated magnitudes therefore selects a different, larger sample of black holes. The spectra of the black holes with the median dust-attenuated AGN luminosity from these three quasar samples are shown in Figure 5.8 as examples, alongside that of the median mass black hole from the most massive black hole sample.
Most Massive

Black Holes

$B/T \simeq 0.65$

$M_{BH} = 3.33 \times 10^8$

$B/T \simeq 0.75$

$M_{BH} = 3.74 \times 10^8$

$B/T \simeq 0.85$

$M_{BH} = 2.93 \times 10^8$

$B/T \simeq 0.95$

$M_{BH} = 2.93 \times 10^8$

Figure 5.9 The stellar mass distribution of four BLuETiDES galaxies from each of the samples: the 10 most massive black holes, SDSS quasars, currently observable quasars, and RST quasars, selected to show a range of morphologies ($B/T \simeq 0.65, 0.75, 0.85$ and $0.95$; left to right shows more disc-like to more bulge-dominated galaxies). The minimum $B/T$ for the most massive black hole sample is $\sim 0.70$ and so only three galaxies from that sample are shown. Each galaxy is viewed face-on, with a field of view of $3 \times 3$ kpc. The colour depicts the age of the stellar population, from bluest ($\leq 20$ Myr) to reddest ($\geq 220$ Myr), with a linear scale.

5.3.2 Images of quasar hosts

To visualize the host galaxies of the most massive black holes and ‘SDSS’, ‘currently observable’ and ‘RST’ quasars, I first make images of their mass distributions using GAEPSI2 (Feng, 2018), a suite of routines for visualizing SPH simulations. I select four galaxies from each sample with a representative range of morphologies ($B/T \simeq 0.65, 0.75, 0.85$ and $0.95$) to image. Note that the minimum $B/T$ for the most massive black hole sample is $\simeq 0.70$ and so only three galaxies from that sample are selected. The mass distributions of these sample galaxies from a face-on and edge-on perspective are shown in Figures 5.9 and 5.10 respectively, with colours depicting stellar age. These images show a variety of sizes, shapes and ages of the black hole and quasar host galaxies.

I also construct a matched sample for comparison with the three representative most massive black hole hosts. These matched galaxies are chosen to have small black holes, $10^{6.5} < M_{BH}/M_\odot < 10^7$, but the most similar stellar mass and $B/T$ to those of the three
Chapter 5

Most Massive
Black Holes

\[ \frac{B}{T} \approx 0.65 \]

\[ M_{BH} = 3.33 \times 10^8 \]

\[ \frac{B}{T} \approx 0.75 \]

\[ M_{BH} = 3.74 \times 10^8 \]

\[ \frac{B}{T} \approx 0.85 \]

\[ M_{BH} = 2.93 \times 10^8 \]

\[ \frac{B}{T} \approx 0.95 \]

Most Massive
Black Holes

SDSS
Quasars

\[ M_{UV, AGN} = -25.3 \]

\[ M_{UV, AGN} = -25.9 \]

\[ M_{UV, AGN} = -26.1 \]

\[ M_{UV, AGN} = -26.0 \]

Currently Observable
Quasars

\[ M_{UV, AGN} = -24.2 \]

\[ M_{UV, AGN} = -23.2 \]

\[ M_{UV, AGN} = -23.1 \]

\[ M_{UV, AGN} = -24.2 \]

RST
Quasars

\[ M_{UV, AGN} = -20.8 \]

\[ M_{UV, AGN} = -22.1 \]

\[ M_{UV, AGN} = -22.1 \]

\[ M_{UV, AGN} = -22.2 \]

Figure 5.10 The stellar mass distribution of four BlueTides galaxies from each of the samples: the 10 most massive black holes, SDSS quasars, currently observable quasars, and RST quasars, selected to show a range of morphologies \((B/T \approx 0.65, 0.75, 0.85 \) and 0.95; left to right shows more disc-like to more bulge-dominated galaxies). The minimum \(B/T\) for the most massive black hole sample is \(\sim 0.70\) and so only three galaxies from that sample are shown. Each galaxy is viewed edge-on, with a field of view of \(3 \times 3\) kpc. The colour depicts the age of the stellar population, from bluest \((\leq 20\) Myr\) to reddest \((\geq 220\) Myr\), with a linear scale.

Figure 5.11 The stellar mass distribution of three BlueTides galaxies from the most massive black hole sample, alongside a matched sample of galaxies with a similar stellar mass and bulge-to-total ratio, but low black hole masses. Each galaxy is viewed face-on, with a field of view of \(3 \times 3\) kpc. The colour depicts the age of the stellar population, from bluest \((\leq 20\) Myr\) to reddest \((\geq 220\) Myr\), with a linear scale.
most massive black hole hosts. Images of these representative most massive black holes and the matched galaxy sample can be seen in Figure 5.11. The galaxies in the matched sample are more diffuse and slightly more extended than the hosts of the most massive black holes. This is consistent with the findings from Figure 5.5, which shows that the hosts of massive black holes are more compact than other galaxies of equivalent stellar mass.

I produce mock JWST images using SYNTHOBS (Wilkins, 2019b), a package for producing synthetic observations from SPH simulations. SYNTHOBS takes the flux of each stellar particle, applies the specified photometric filter, and convolves this emission with the corresponding JWST point-spread function (PSF). I assume that the quasar emission comes from a single point, with the quasar thus appearing as a point source convolved with the PSF in the images. By applying the appropriate smoothing, SYNTHOBS produces a mock image with the pixel scale of the instrument. The effects of noise are included by adding a random background noise map to the SYNTHOBS images, with noise $\sigma$ from the predicted 10$\sigma$ sensitivity of JWST, using a circular photometric aperture 2.5 pixels in radius (STSci, 2017). Dust-attenuation is applied following the methodology described in Section 5.1.2.3, and the minimum AGN dust attenuation of the various sight-lines is used.

Figure 5.12 shows mock JWST imaging in the NIRCam F200W filter of the galaxies hosting the median mass black hole in the most massive black hole sample, and the black hole with the median dust-attenuated luminosity in the SDSS, currently observable and RST quasar samples (i.e. those whose spectra are shown in Figure 5.8). These images show the combined (dust-attenuated) quasar and host emission with varying exposure times: 1ks, 5ks, 10ks, and an image with no noise background for comparison. This shows that deep exposure times of $\gtrsim$ 5ks are required to observe the detailed structure present in the noise-less images, which is likely to be necessary for detecting the underlying host galaxy emission, which generally has low surface brightness and is hidden by the bright quasar emission (see discussion below). I therefore choose to adopt an exposure time of 10ks for the mock images herein. I choose to show the F200W filter as an example, as it has the highest sensitivity of the NIRCam wide-band filters, resulting in the least background noise for a given exposure time.

Mock JWST imaging in the NIRCam F200W filter of the same four sample galaxies, with and without dust attenuation, and with and without the quasar emission, is shown in
Figure 5.12 Simulated face-on images of BlueTides galaxies in the JWST NIRCam F200W filter, showing one galaxy from each black hole sample. The galaxy displayed from the most massive black hole sample has the black hole with the median black hole mass, while the galaxies displayed from the two quasar samples are those with the median AGN luminosity (i.e. the galaxies whose spectra is shown in Figure 5.8). The combined quasar and host galaxy emission including dust-attenuation is shown. In the first three panels from left to right, the images assume an exposure time of 1ks, 5ks, and 10ks, which are predicted to achieve a 10σ detection of 63.4, 18.2 and 13.2 nJy point sources, using a circular photometric aperture 2.5 pixels in radius (STSci, 2017). The right-most panel shows the images with no noise background. The field of view is $10 \times 10$ kpc, or $1''86 \times 1''86$. Note that all panels are shown with the same intensity scale.

Figure 5.13. With a resolution of 0.031 arcseconds, JWST only partially resolves the host galaxies, with diameters of $\sim 0.8$ kpc or $\sim 0.15$ arcseconds at $z = 7$. Their emission is centrally concentrated, and so the hosts appear as a smeared PSF at this resolution. However, as the density of dust is highest in the central regions, the dust attenuated images show more interesting, asymmetrical features.

The limited resolution of these small galaxies makes it difficult to distinguish the host galaxy once the point-source quasar emission is included in the images. For the intrinsic images, the image is broader than the quasar image (i.e. the PSF of the telescope), suggesting that an accurate modelling technique should be able to detect the host emission despite
Figure 5.13 Simulated face-on images of BlueTides galaxies in the JWST NIRCam F200W filter, showing one galaxy from each black hole sample. The galaxy displayed from the most massive black hole sample has the black hole with the median black hole mass, while the galaxies displayed from the three quasar samples are those with the median AGN luminosity (i.e. the galaxies whose spectra is shown in Figure 5.8). The host galaxy emission is shown with and without dust-attenuation in the two left-most panels. The emission from the quasar is shown with and without dust-attenuation in the middle panels, with the combined quasar and host galaxy image shown with and without dust attenuation (applied to both the host and quasar) in the right-most panels. These images assume an exposure time of 10ks, which is predicted to achieve a 10σ detection of 13.2 nJy (AB mag ∼ 28.8) point sources, using a circular photometric aperture 2.5 pixels in radius (STScI, 2017). The field of view is 10 × 10 kpc, or 1″86 × 1″86. Note that all panels are shown with the same intensity scale.

the presence of the quasar. However, including the effect of dust-attenuation makes the host more difficult to distinguish from the quasar, as its emission becomes fainter and less extended, particularly for the sample most massive black hole, SDSS and currently observable quasars. For these three sample black holes, the brightness contrast between the host and quasar is ∼ 1.5 orders of magnitude at the centre, decreasing with distance from the quasar, with the two having similar brightnesses towards the edge of the host galaxy at ∼ 0.5″. The sample RST quasar has a lower contrast between the quasar and host, resulting in the host being more easily visible around the bright, central emission from the quasar. Distinguishing the host galaxy from the quasar emission will therefore
still be challenging with JWST, even with its improved resolution over HST.

While it appears that the host galaxies are more easily detected in the fainter quasar samples, this is an effect of the contrast ratio between the host and quasar, and not the quasar’s total brightness. For the systems chosen from the most massive black hole sample and the SDSS, currently observable and RST quasar samples, the difference in AGN and host magnitude is 3.51, 3.62, 1.74, and 0.37, respectively (see Figure 5.7). Thus, for the sample most massive black hole and SDSS quasar, as the AGN magnitude is much brighter than the host, it completely obscures any host emission. For the sample currently observable quasar, the bright point source still dominates, however the total emission is somewhat broader than the quasar PSF, which may allow for a host detection with an accurate modelling technique. For the sample RST quasar, the lower contrast ratio results in an easily distinguishable host galaxy.

To investigate this effect further, I consider the black hole in each sample which has the lowest contrast ratio between the AGN and host luminosity, $M_{UV, Host(dust)} - M_{UV, AGN(dust)}$ (with $M_{UV, AGN(dust)} < M_{UV, Host(dust)}$). Mock JWST images of these galaxies are shown in Figure 5.14. The host galaxies of these black holes are much easier to distinguish from the quasar point source emission, particularly for those that have the lowest contrast ratios, and for hosts that have more extended emission. Thus, while the host galaxies of quasars will still be difficult to detect with JWST in general, it should be possible to detect the hosts of quasars with low contrast ratios.

Figure 5.15 shows mock JWST images of the currently observable quasar with the median AGN luminosity in all of the NIRCam wide-band filters red-ward of the Lyman-break. Most filters show a combined image that is slightly broader than the quasar PSF, however no filter makes the host clearly more detectable. As the wavelength increases, the resolution of the telescope decreases. Thus, while the contrast ratio of the quasar and its host should be lower at larger wavelengths due to the spectral shapes of quasars and host galaxies (see Figure 5.8), redder NIRCam filters do not particularly make the host more easily distinguishable. The instrument sensitivity increases from the F090W to F200W filters, and then decreases for the higher wavelength filters (STSci, 2017). The highest sensitivity F200W filter results in the clearest image of the quasar system for a given exposure time (here 10 ks), and thus may offer the best results for detecting quasar host galaxies with JWST.
Figure 5.14 Simulated face-on images of BlueTides galaxies in the JWST NIRCam F200W filter, showing the galaxy from each black hole sample that has the lowest contrast ratio between the quasar and the host $M_{\text{UV,Host (dust)}} - M_{\text{UV,AGN (dust)}}$ (with $M_{\text{UV,AGN (dust)}} < M_{\text{UV,Host (dust)}}$). The host galaxy emission is shown in the left-most panels, with the emission from the quasar shown in the middle panels. The combined quasar and host galaxy image is shown the right-most panels. All images include the effect of dust-attenuation. These images assume an exposure time of 10ks, which is predicted to achieve a $10\sigma$ detection of 13.2 nJy (AB mag $\sim 28.8$) point sources, using a circular photometric aperture 2.5 pixels in radius (STSci, 2017). The field of view is $10 \times 10$ kpc, or $1^\prime.86 \times 1^\prime.86$. Note that all panels are shown with the same intensity scale.

These conclusions are based only on examining the resulting images by eye. In future work, I will make more detailed and robust predictions for the detectability of quasar hosts with JWST by running an observational technique used to detect quasar host galaxies (see Chapter 6) on these simulated images.

5.4 Biases in the observed scaling relations

I now consider the $z = 7$ black hole–stellar mass and black hole–bulge mass relations predicted by BlueTides, shown in Figure 5.16. The best-fitting relations for black holes
Figure 5.15 Simulated face-on images of the currently observable quasar with the median AGN luminosity, in the JWST NIRCam wide-band filters red-ward of the $z = 7$ Lyman-break. The host galaxy emission is shown in the top panels, the emission from the quasar in the middle panels, with the combined quasar and host galaxy image shown in the bottom panels. All images include dust extinction of both the quasar and the host galaxy. These images assume an exposure time of 10ks, with $10\sigma$ detection sensitivities as predicted by STSci (2017). The field of view is $12 \times 12$ kpc, or $2''23 \times 2''23$. Note that all panels are shown with the same intensity scale.

with $M_{\text{BH}} > 10^{6.5} M_\odot$ and galaxies with $M_* > 10^{9.7} M_\odot$ are

$$\log(M_{\text{BH}}/M_\odot) = (1.30 \pm 0.02) \log(M_*/M_\odot) - (5.9 \pm 0.2),$$  \hspace{1cm} (5.5)$$

and

$$\log(M_{\text{BH}}/M_\odot) = (1.50 \pm 0.02) \log(M_{\text{Bulge}}/M_\odot) - (7.7 \pm 0.2),$$  \hspace{1cm} (5.6)$$

with errors calculated from 10,000 bootstrap realisations. The standard deviation of the residuals, or scatter, is 0.2 dex for both relations, so the simulation shows no preference for a tighter correlation of black hole mass with either total or bulge stellar mass. Note that these relations are unlikely to be sensitive to the black hole seeding prescription, as only black holes that have grown significantly above the seed mass of $10^{5.8} M_\odot$ are considered.

The BLUETIDES black hole–bulge mass relation at $z = 7$ is steeper than the local relation (Kormendy & Ho, 2013), which is also shown in Figure 5.16. However, the simulations and local observations are reasonably consistent, particularly at the highest masses where the observed relation is best measured. Figure 5.16 also shows a range of observations of $5 \lesssim z \lesssim 7$ quasars, assuming their stellar mass is equal to their measured dynamical
Figure 5.16 The relation between black hole mass and stellar mass (left) and black hole mass and bulge mass (right) for BlueTides galaxies at $z = 7$, and their best-fitting relations as given in Equations 5.5 and 5.6. A range of observations of $5 \lesssim z \lesssim 7$ quasars from the literature are also shown (Willott et al., 2017; Izumi et al., 2018, 2019; Pensabene et al., 2020), assuming their stellar mass is equal to their measured dynamical mass. Also shown is the observed black hole mass–bulge mass relation at $z = 0$ (Kormendy & Ho, 2013), which is also shown in the left (stellar mass) panel for comparison.

mass (Willott et al., 2017; Izumi et al., 2018, 2019; Pensabene et al., 2020). Quasars observed with $M_{\text{BH}} > 10^{8.5} M_{\odot}$ show a wide range of dynamical masses, and generally lie above the local relation. These observed black holes are larger than those present in the BlueTides simulation at $z = 7$, so a comparison cannot be made. Observations of lower-luminosity quasars with $M_{\text{BH}} < 10^{8.5} M_{\odot}$ are consistent with the BlueTides relation.

Figure 5.17 shows the black hole–stellar mass relation for the most massive black holes, SDSS quasars, currently observable quasars, and RST quasars. These all show black hole mass distributions that are skewed to higher masses than the total sample of galaxies with $M_* > 10^{10} M_{\odot}$, as seen in the left panel of Figure 5.17; the hosts of the most massive black holes and quasars have large black hole masses for their stellar mass. To investigate the effect of this bias on the observed black hole–stellar mass relation, fits are made to the SDSS, currently observable and RST quasar samples, constraining the slope to be equal to that of the total sample:

$$\log(M_{\text{BH}}/M_{\odot}) = 1.32\log(M_*/M_{\odot}) + b.$$  (5.7)

where for the full sample $b = -6.06$ (Equation 5.5). The SDSS, currently observable and
Figure 5.17 The relation between black hole mass and stellar mass. The blue density plot shows the distribution for all BlueTides galaxies, while the circles show the most massive black holes, SDSS quasar, currently observable quasar and RST quasar samples (see legend). The solid lines are fits to the total (blue), SDSS quasar (red) currently observable quasar (orange) and RST quasar (yellow) samples, constraining the slope to be the same as that for the total sample (Equation 5.7). The left panel shows the distribution of black hole mass for all galaxies with $M_*>10^{10}M_\odot$ (blue line), most massive black holes (black line), SDSS quasars (red line), currently observable quasars (orange line), and RST quasars (yellow line). $M_*=10^{10}M_\odot$ is shown in the right panel for reference (grey dashed line).

RST quasar samples have a normalization of $b = -5.85, -5.87$ and $-5.90$, respectively, $\sim 0.2$ dex higher than that of the full galaxy sample. Quasar samples are therefore biased samples of the intrinsic black hole–stellar mass relations, consistent with expectations from observations (e.g. Lauer et al., 2007; Salviander et al., 2007; Schulze & Wisotzki, 2014; Willott et al., 2017). The BlueTides simulation provides a calibration of this systematic effect. A similar bias to larger black hole masses is theoretically expected to occur when observing the black hole–velocity dispersion relation (see e.g. Volonteri & Stark, 2011).
5.5 The environments of high-redshift quasars

I now study the environments of high-redshift quasars in the BlueTides simulation, by investigating neighbouring galaxies within 200 kpc that host a black hole. The requirement for a companion to host a black hole is due to no halo sub-finding algorithm being implemented on the simulation; it cannot identify multiple galaxies within an individual dark matter halo, which are precisely the systems of interest. As an approximation, I identify neighbouring galaxies via their black holes, and assign all particles within $R_{0.5}$ of the black hole to that galaxy.

5.5.1 The number of nearby galaxies

I first consider the number of nearby galaxies around each black hole ($M_{BH} > 10^{5.8} M_\odot$). I compare the most massive and quasar samples to the overall sample of black holes with $M_{BH} > 10^{6.5} M_\odot$.

Figure 5.18 shows the average number of neighbours within a given distance, for black holes in the various samples. No companions are detected within 340 kpc, down to the magnitude limit of the faintest SDSS quasar, $M_{UV} = 22.8$. At a deeper magnitude limit of $M_{UV} < 24.85$, the magnitude of the faintest known high-redshift quasar, no black hole samples are predicted to have nearby companions within $\sim 80$ kpc, on average. The average number of companions increases slightly at larger distances for the massive black hole and quasar samples. At distances $\gtrsim 150$ kpc, the most massive black holes have an average of $\sim 1$ companion with $M_{UV} < 24.85$, more than expected for the overall sample. However, this enhancement is not significant given the uncertainties.

Many more companions are observable with RST, with $M_{UV} < 26.9$. The number of companions for each sample increases with distance from the black hole, with the most massive black holes having an average of $\sim 2$ companions within $\sim 100$ kpc, and $\sim 4$ companions within $\sim 300$ kpc. This sample shows the largest number of companions, with the SDSS quasars, currently observable quasars, RST quasars and all black holes having progressively less companion galaxies, with all black holes having $\sim 0.5$ companions within $\sim 100$ kpc, and $\sim 1.5$ companions within $\sim 300$ kpc. A similar enhancement is seen when considering all companion galaxies, with no magnitude cut. On average, the most massive black holes have the most companion galaxies at 50–340 kpc, followed by the
Figure 5.18  

Top row: The average number of companion galaxies around each black hole in the sample, as a function of distance from the black hole. Each panel shows companions brighter than a given magnitude limit. From left to right: companions with $M_{\text{UV}} < 22.8$, i.e. the magnitude of the faintest SDSS quasar; companions with $M_{\text{UV}} < 24.85$, i.e. the magnitude of the faintest currently known quasar; companions observable in RST, with $M_{\text{UV}} < 26.9$; and all companion galaxies. The solid coloured lines show the average number of companions at each magnitude limit, including the effect of dust attenuation, and shaded regions show the $\pm 1\sigma$ range. The dashed coloured lines show the average number of companions that are intrinsically brighter than the magnitude limit (i.e. without the effect of dust attenuation). Vertical grey dashed lines show the ALMA (Trakhtenbrot et al., 2018) and JWST NIRCam fields of view.

Bottom row: The fraction of companions around a black hole that are missed due to dust attenuation, at each magnitude limit. The solid lines show the average fraction, and the shaded regions show the $\pm 1\sigma$ range. The ‘all black hole’ sample refers to black holes with $M_{\text{BH}} > 10^{6.5} M_{\odot}$.

quasar samples from brightest to faintest, with the enhancement above the overall black hole sample largest at larger distances (> 150 kpc). As more neighbouring galaxies are predicted at larger separations (> 50 kpc), the majority of companion galaxies are too distant to be detected in the small field of view of ALMA.

The most massive black holes are more likely to be found in denser environments than the typical $M_{\text{BH}} > 10^{6.5} M_{\odot}$ black hole, with quasars showing a weaker enhancement. However, the increased number of companions found around the most massive black holes and quasars above the general sample is statistically insignificant, with a large variation
seen in the number of galaxies around each black hole. These conclusions are consistent with the more comprehensive analysis of Habouzit et al. (2019b), who investigated black hole environments in the Horizon-AGN simulation at $z \simeq 4$–6. Habouzit et al. (2019b) found that, on average, massive black holes live in regions with more nearby galaxies, with an excess of up to 10 galaxies within 1 cMpc at $z \simeq 4$–5. The enhancement is larger for more massive black holes. Habouzit et al. (2019b) find a diversity in number counts, with some massive black holes having similar numbers of nearby neighbours to the average number counts, consistent with the expectations from BlueTides.

Companion galaxies have been observed near high-redshift quasars, particularly in sub-mm observations (e.g. Wagg et al., 2012; McGreer et al., 2014; Decarli et al., 2017; Willott et al., 2017; Neeleman et al., 2019). In the rest-frame UV/optical, McGreer et al. (2014) detected two companion galaxies, and found that bright companion galaxies within 20 kpc are uncommon, with an incidence of $\lesssim 2/29$ for $\gtrsim 5L^*$ galaxies and $\lesssim 1/6$ for $2 \lesssim L \lesssim 5L^*$ galaxies. In the sub-mm, Trakhtenbrot et al. (2017a) observed six $z \simeq 4.8$ quasars with ALMA and found nearby companions around three of the quasars, at distances of 14–45 kpc. Given that these companions are not detected in the infrared with Spitzer, Trakhtenbrot et al. (2018) conclude that there must be significant dust-attenuation in these galaxies. Decarli et al. (2017) detected four companion galaxies around 4 of 25 $z \gtrsim 6$ quasars with ALMA, and similarly Willott et al. (2017) found one quasar companion in a sample of 5 $z \gtrsim 6$ quasars. Mazzucchelli et al. (2019) took follow-up observations of these companions in the optical/IR, detecting the emission from only one of the companions, finding that the remaining three must be “highly dust-enshrouded”. Willott et al. (2005) also hypothesise that the lack of companions observed in rest-frame UV observations, relative to sub-mm observations, is a result of dust attenuation.

Figure 5.18 considers the effect of dust attenuation on the observed number of companion galaxies, by showing the number of companions that are intrinsically brighter than each magnitude limit, and the fraction of these companions that have dust-attenuated magnitudes fainter than the limit and thus would be ‘missed’ by observations in the rest-frame UV. Almost 100 per cent of companions with $M_{UV} < 22.8$ are missed due to dust attenuation, however the overall number of intrinsic companions is low ($< 1$ within 300 kpc). At a magnitude limit of $M_{UV} < 24.85$, around 50 per cent of the companions of the most massive black holes are missed, while for the other black hole samples this is around 75
per cent. RST, at a depth of $M_{UV} = 26.9$, will be able to detect the majority of intrinsic companions, with less than 10 per cent of companions missed due to dust-attenuation.

Overall, these predictions expect that a large fraction (75% of companions to $M_{UV} < 24.85$) of quasar companions will be ‘missed’ in current rest-frame UV observations due to dust obscuration. These dusty galaxies are likely to be observable in the sub-mm, and so these predictions are consistent with expectations (e.g Willott et al., 2005).

5.5.2 Properties of nearby neighbours

I now investigate the nearest neighbour to each black hole, with distances less than 200 kpc. I find that 90 per cent of the most massive black holes have their nearest neighbour within 200 kpc, compared with 87 per cent of SDSS quasars, 80 per cent of currently observable quasars and 67 per cent of RST quasars. For comparison, 63 per cent of black holes with $M_{BH} > 10^{6.5} M_\odot$ have their nearest neighbour within 200 kpc.

Figure 5.19 shows various properties of the nearest neighbours: their distance, UV magnitude (both with and without dust attenuation), stellar mass and black hole mass, and the differences between these neighbour properties and those of the black hole host. Most of the nearest neighbours lie within 100 kpc or 20 arcseconds of the black hole host galaxy. The vast majority of these neighbours are brighter than $M_{UV} = -20$, so should be readily detectable by RST. Some companions are fainter than the black hole host by up to 5 magnitudes, although most are of similar brightness. The stellar mass and black hole mass distributions of the neighbouring galaxies are consistent between the various black hole samples. However, as the most massive black holes and quasars are hosted by massive galaxies, the mass ratios between the neighbour and the black hole host $M_{*2}/M_{*1}$ are lower. More than 75 per cent of neighbours of quasars, and 90 per cent of neighbours of the most massive black holes, have less than 1/10th of the stellar mass of the black hole host, and so the majority of these would be classified as only minor mergers; this is compared with around 60 per cent of neighbours of all $M_{BH} > 10^{6.5} M_\odot$ black holes. More than 75 per cent of the neighbours of quasars and most massive black holes have black hole mass ratios $M_{BH2}/M_{BH1}$ that are also less than 1/10, compared with 26 per cent of neighbours of all $M_{BH} > 10^{6.5} M_\odot$ black holes.
Figure 5.19 The properties of the nearest neighbour to each black hole in the various samples, that have a distance of less than 200 kpc. The various panels show probability distribution functions for the distance to the nearest neighbour in arcseconds and kpc, the UV magnitude of the neighbouring galaxy (with and without dust-attenuation), the difference between the host and companion’s magnitude, the companion’s stellar and black hole mass, and the stellar and black hole mass ratio of the neighbour’s mass to that of the sample black hole’s host. The ‘all black hole’ sample refers to black holes with $M_{\text{BH}} > 10^{6.5} M_\odot$.

The quasar companions observed by Trakhtenbrot et al. (2017a) have dynamical masses $M_{\text{dyn}} = (2.1 - 10.7) \times 10^{10} M_\star$, relative to $M_{\text{dyn}} = (3.7 - 7.4) \times 10^{10} M_\star$ for the quasar hosts, and so these interactions would be classified as major mergers. The quasar companions found by McGreer et al. (2014) are also likely to be major mergers. These companions are also found at projected distances of 5 and 12 kpc, which, depending on the angle of projection, are much smaller than the average distance of companions in the Blue-Tides simulation, as are the majority of ALMA-discovered companions, due to its small field of view. This may be a result of the companion classification used in the simulation being ineffective at low separations.

One of the most massive black holes which has its nearest neighbour within 200 kpc is examined more closely. This black hole has a mass of $\log(M_{\text{BH}}/M_\odot) = 8.56$, and is hosted by a galaxy of mass $\log(M_\star/M_\odot) = 11.11$. At $z = 7.0$, its dark matter halo contains 5 additional black holes, with masses $\log(M_{\text{BH}}/M_\odot) = (8.20, 7.80, 6.53, 7.06, 5.97)$, in galaxies
Figure 5.20 The host galaxies of two merging black holes from $z = 7.25$ to $z = 7.0$. At $z = 7.3$, the primary black hole (at the centre of the images) has a black hole mass of $\log(M_{\text{BH}}/M_\odot) = 8.25$, while the companion has a mass of $\log(M_{\text{BH}}/M_\odot) = 6.37$ and is at a distance of 82 ckpc or 9.9 kpc from the primary black hole. The black hole which results from this merger is one of the ten most massive black holes in the simulation at $z = 7$, with a mass of $\log(M_{\text{BH}}/M_\odot) = 8.56$, in a galaxy with a stellar mass of $\log(M_*/M_\odot) = 11.11$. Each panel is $120/h$ ckpc per side, showing the stellar density colour coded by the age of star (from blue to red indicating young to old populations respectively).

with stellar masses of $\log(M_*/M_\odot) = (10.54, 10.58, 9.24, 9.66, 8.57)$. Imaging this system at various redshifts shows that this galaxy has been involved in a recent merger between $z = 7.3$ and $z = 7.0$, with the central black hole (of mass $\log(M_{\text{BH}}/M_\odot) = 8.25$ at $z = 7.3$) merging with another black hole of mass $\log(M_{\text{BH}}/M_\odot) = 6.37$ (Figure 5.20).

5.6 Conclusions

In this chapter I use the BLUETides simulation to make predictions for the host galaxies of the most massive black holes and quasars at $z = 7$. The main findings are as follows.

- The 10 most massive black holes are in massive galaxies with stellar masses $\log(M_*/M_\odot) = 10.80^{+0.20}_{-0.16}$, which have large star formation rates, $513^{+1225}_{-361}M_\odot/yr$. Quasar hosts are
less massive, \( \log(M_*/M_\odot) = 10.25^{+0.40}_{-0.37} \) with lower star formation rates, \( 191^{+288}_{-120} M_\odot/\text{yr} \). Lower luminosity quasars are hosted by less extreme host galaxies.

- The hosts of the most massive black holes and quasars in BLUETIDES are generally bulge-dominated, with \( B/T \simeq 0.85 \pm 0.1 \), however their morphologies are not biased relative to the overall \( z = 7 \) galaxy sample.

- The hosts of the most massive black holes and quasars are compact, with half-mass radii of \( R_{0.5} = 0.41^{+0.18}_{-0.14} \) and \( 0.40^{+0.11}_{-0.09} \) kpc respectively, compared to galaxies of similar mass which have \( R_{0.5} = 0.71^{+0.28}_{-0.25} \) kpc.

- Despite its increased resolution over the Hubble Space Telescope, distinguishing the compact host galaxies from the quasar emission will still be challenging with JWST, as shown through the mock images. This will be more successful for galaxies that have the lowest contrast ratio between the host and the AGN.

- The \( z = 7 \) sample has a black hole–stellar mass relation that is steeper than the local Kormendy & Ho (2013) relation, but the two are reasonably consistent, particularly at the highest masses where the observations are most robust. Observations of \( 5 \lesssim z \lesssim 7 \) quasars with \( M_{\text{BH}} < 10^{8.5} M_\odot \) are consistent with the predicted relation.

- Observations of quasars are biased to measure higher black hole–stellar mass relations. The SDSS, currently observable and RST quasar samples have black hole–stellar mass relations 0.2 dex higher than the total galaxy sample, providing an estimate of the systematic offset of quasar observations of the \( M_*/M_{\text{BH}} \) relation from the true population.

- The most massive black holes and quasars have more nearby companions than the typical \( M_{\text{BH}} > 10^{6.5} M_\odot \) black hole. The majority of their nearest neighbours have stellar mass ratios \( M_{\ast2}/M_{\ast1} < 0.1 \) and thus would be classified as minor mergers. A large fraction of these nearby companion galaxies will be missed by rest-frame UV observations due to dust attenuation.
Chapter 6

Limits to Rest-Frame Ultraviolet Emission From Far-Infrared-Luminous $z \approx 6$ Quasar Hosts

Observing quasar host galaxies in the rest-frame UV is extremely challenging, as the intense quasar emission often significantly outshines the light from the host (e.g., Schmidt, 1963; McLeod & Rieke, 1994; Dunlop et al., 2003; Hutchings, 2003; Floyd et al., 2013, see Section 1.4.2). At high redshifts, where the host galaxies are small relative to the resolution of current telescopes, the underlying host emission is completely concealed by the quasar. To date, the rest-frame UV emission of quasar hosts has not been observed at $z \gtrsim 4$ (McLeod & Bechtold, 2009; Targett et al., 2012).

One method used to detect the rest-frame UV emission from quasar hosts is to accurately model the quasar emission and examine the signal in the residual image. In an attempt to detect the underlying UV emission from the host of the redshift $z = 6.42$ quasar SDSS J114816.64+525150.3 (hereafter SDSS J1148+5251), Mechtley et al. (2012) used GALFIT (Peng et al., 2010) to model the quasar contribution to the emission in HST Wide Field Camera 3 (WFC3) images. This quasar model was subtracted to obtain upper limits on the brightness of the host galaxy, of $m_J > 22.8$ and $m_H > 23.0$ mag. To improve this modelling technique, Mechtley (2014) developed a Markov-Chain Monte-Carlo (MCMC) simultaneous fitting software, psfMC$^1$. While this technique allows for host detections at lower redshifts ($z = 2$, Mechtley et al., 2016; Marian et al., 2019), the smaller angular sizes of the hosts at higher redshifts make this significantly more challenging.

$^1$The details of the software implementation are given in Mechtley (2014). The software, documentation, examples, and source code are available at: https://github.com/mmechtley/psfMC
In this chapter, I present deep near-infrared F125W (J) and F160W (H) HST WFC3 images of six $z \simeq 6$ quasars, described in Sections 6.1 and 6.2. In Section 6.3, I describe my efforts to detect rest-frame near-UV emission from the hosts using the psfMC software, and present the most robust upper limits to date on the rest-frame UV brightness of each of the quasar host galaxies in Section 6.4.1. This significantly increases the sample of high-redshift quasar hosts with deep UV upper limits determined by this method, extending on the previous work of Mechtley et al. (2012) which studied only one quasar. The subtraction of the quasar PSF using the psfMC software also allows for an unobscured view of the quasar environment on kpc-scales, uncovering nearby galaxies which may be interacting with the host and triggering this rapid black hole growth, discussed in Section 6.4.2. Discussions and conclusions are presented in Sections 6.5 and 6.6.

Throughout this chapter I adopt a ΛCDM cosmology with $h = 0.67$, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$ (Planck Collaboration et al., 2014). All magnitudes are on the AB system (Oke & Gunn, 1983) and have been corrected for Galactic extinction using the reddening map of Schlegel et al. (1998) as recalibrated by Schlafly & Finkbeiner (2011).

### 6.1 Quasar sample

In this work I study five UV-faint FIR-luminous quasars and one dust-free quasar, all at $z \simeq 6$. The dust-free quasar was observed in a second epoch of the original pilot program, alongside SDSS J1148+5251 (ID 12332, PI: R. Windhorst; see Mechtley et al., 2012), but is previously unpublished. The five UV-faint FIR-luminous quasars were observed in 2013 as part of HST program 12974 (PI: M. Mechtley), which built on the original program. The observations and modelling technique (Sections 6.2–6.3) are identical for all sources. Relevant properties of each of the six targets are summarized in Table 6.1.

#### 6.1.1 UV-faint FIR-luminous quasars

Guided by the initial experience with SDSS J1148+5251 (Mechtley et al., 2012), it was determined that high-redshift quasars with weaker UV emission ($M_{1450\AA} > -26.5$ mag), but secure sub-mm detections, i.e., with large rest-frame FIR to UV flux ratios ($F_{\text{FIR}}/F_{\text{UV}} \gtrsim 100$), are the best candidates for successful detection of host emission.
Table 6.1. Quasars observed with HST

<table>
<thead>
<tr>
<th>Quasar Name</th>
<th>Redshift</th>
<th>$M_{1450}$ (mag)</th>
<th>$L_{\text{FIR}}$ ($10^{12} L_{\odot}$)</th>
<th>$\log(M_{\text{BH}}/M_{\odot})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFHQS J003311.40–012524.9</td>
<td>6.13</td>
<td>−25.14</td>
<td>2.6 ± 0.8</td>
<td>9.52 ± 0.87^a</td>
</tr>
<tr>
<td>SDSS J012958.51–003539.7</td>
<td>5.78</td>
<td>−23.89</td>
<td>5.2 ± 0.9</td>
<td>8.23 ± 0.45^b</td>
</tr>
<tr>
<td>SDSS J020332.39+001229.3</td>
<td>5.72</td>
<td>−26.26</td>
<td>4.4 ± 1.1</td>
<td>10.72 ± 0.26^a</td>
</tr>
<tr>
<td>NDWFS J142516.30+325409.0</td>
<td>5.89</td>
<td>−26.47</td>
<td>5.4 ± 1.2</td>
<td>9.41 ± 0.11^a</td>
</tr>
<tr>
<td>SDSS J205406.42–000514.8</td>
<td>6.04</td>
<td>−26.21</td>
<td>5.5 ± 1.2</td>
<td>8.95 ± 0.47^b</td>
</tr>
<tr>
<td>SDSS J000552.34–000655.8</td>
<td>5.85</td>
<td>−25.73</td>
<td>&lt; 3.4</td>
<td>8.02^c</td>
</tr>
</tbody>
</table>

Note. — Quasar names include the full sexagesimal coordinates. Redshifts and absolute magnitudes are from the same references as Table 7 in Bañados et al. (2016). FIR luminosities are from Wang et al. (2010, 2011). Black hole masses are from a) Shen et al. (2019), b) Wang et al. (2013)/Willott et al. (2015) and c) Trakhtenbrot et al. (2017b), and are calculated using the MgII line where available, else with the CIV line (NDWFS-J1425+3254) or by assuming the black hole is accreting at the Eddington luminosity (SDSS J0129-0035 and SDSS J2054-0005).

The rationale behind this selection is that a high FIR luminosity—and associated high star formation rate—coupled with a lower nuclear UV luminosity results in a less extreme nuclear-to-host contrast ratio, and thus improved detectability of host UV emission. At the time of selection (February 2012), there were only five such $z \simeq 6$ quasars known that met these criteria: CFHQS J0033–0125, SDSS J0129–0035, SDSS J0203+0012, NDWFS J1425+3254, and SDSS J2054–0005 (see Figure 6.1). Note that, while these quasars are UV-‘faint’ relative to the observed high-redshift quasar sample, they are still very luminous in the UV with $−26.5 < M_{1450\AA} < −23.9$ mag.

Although the FIR emission suggests the presence of significant dust in the host galaxies, the quasar discovery spectra (rest-frame UV) do not show anomalous features compared to the rest of the population—i.e. they are otherwise normal $z \simeq 6$ quasars, rather than showing significant spectral reddening or absorption features such as present in the FIRST/2MASS sample at lower redshifts (Urrutia et al., 2008; Glikman et al., 2015). Furthermore, more than $\sim 25\%$ of $z \simeq 6$ quasars have similarly high FIR luminosities (Willott et al., 2007; Wang et al., 2008, 2010, 2011), so these FIR-luminous quasars are broadly representative of a significant sub-population, rather than atypical objects.
Figure 6.1 Selection of UV-faint, FIR-luminous quasars based on absolute magnitude (rest-frame 1450Å) and observed sub-mm to near-infrared flux ratio. The sample of six quasars studied here is denoted by magenta circles, with detections for the five FIR-luminous quasars, and an upper limit for the additional quasar SDSS J0005-0006. Other $z > 5.6$ quasars with sub-mm observations are plotted in grey (Fan et al., 2000, 2001, 2003, 2004, 2006a; Petric et al., 2003; Bertoldi et al., 2003a; Mahabal et al., 2005; Cool et al., 2006; McGreer et al., 2006; Goto, 2006; Venemans et al., 2007, 2013; Wang et al., 2007, 2008, 2011, 2013; Kurk et al., 2007, 2009; Willott et al., 2007, 2010b,a; Jiang et al., 2007, 2008, 2009; Mortlock et al., 2009, 2011; Zeimann et al., 2011; Rosa et al., 2011; De Rosa et al., 2014; Omont et al., 2013; Bañados et al., 2014; Wu et al., 2015).

6.1.2 Dust-free quasar

In addition to the FIR-luminous quasars described above, I also analyze data from the prototype hot-dust-free quasar SDSS J0005–0006 (Fan et al., 2004; Jiang et al., 2010), which also lacks cold dust (Wang et al., 2008). With a lower-luminosity and no evidence for significant dust content, this quasar was selected as a counterpoint to SDSS J1148+5251. This source is representative of a smaller, but still important sub-population. At 5.8 < $z$ < 6.4, Jiang et al. (2010) found two apparently dust-free quasars in a sample of 21 quasars, or $\sim 10\%$ of the population. Leipski et al. (2014) also found that $\sim 15\%$ of their sample of 69 quasars at $z > 5$ are deficient in (but not devoid of) hot dust, and there is evidence of a trend toward higher dust-poor fraction with increasing redshift (Jun & Im, 2013).
6.2 Hubble Space Telescope data and observing strategy

Each of the six quasars was observed with the HST WFC3 infrared channel in the F125W (J-band) and F160W (H-band) filters. The five FIR-luminous quasars were observed for two orbits (4800 s) in each filter, while SDSS J0005–0006 was observed for four orbits (10400 s) in each filter. Windhorst et al. (2011) provides details on the WFC3 IR two-orbit sensitivity.

In addition to the quasar observations, coeval observations of a nearby PSF reference star were completed along with each epoch of quasar imaging. Although the HST PSF is stable compared to ground-based observatories, slight changes in the position of the secondary mirror cause small time-dependent focus variations. These variations are believed to be caused primarily by changes in the spacecraft thermal environment (Bély et al., 1993; Hershey, 1998; Cox & Niemi, 2011). This effect was mitigated by imposing constraints on the PSF star observations, as in the pilot program (Mechtley et al., 2012)—the (non-binary) stars were selected to be within 5° of the quasar, to minimize differences in the solar illumination angle, and the stars were observed in the orbit immediately following the quasar observations, to best match the orbital day/night cycle. The HST flight calendar builders also attempted, where possible, to schedule these quasar and PSF observations immediately after a HST target from a different program in a similar part of the sky as the quasar, so as to further mitigate differences in orbital thermal variations between the first and subsequent orbits on that quasar and PSF target. This special request was possible to schedule for some of the quasars. PSF star exposures were alternated in F125W and F160W to fully sample the focal variation within an orbit (for details, see Mechtley et al., 2012). Additionally, the stars were selected to have (J–H) colours similar to the quasars, since the diffraction-limited PSF also varies with wavelength. In wide filters, redder sources can have a measurably broader PSF than bluer sources.

Four exposures were taken in each orbit of quasar and PSF star observations, using the four-point box sub-pixel dither pattern to improve PSF sampling and assist in the rejection of bad pixels and cosmic rays. Critically-sampled images were reconstructed using ASTRODRIZZLE, following approaches similar to those described in Koekemoer et al. (2002, 2011, 2013), with a linear pixel scale of 0′′.06 (a spatial scale of ~ 0.36 kpc at z ≃ 6) and a pixfrac parameter of 0.8, to reduce correlated noise while maintaining a relatively uniform weighting per-pixel. “ERR” (inverse variance) weighting was used for the final
image combination step. The ERR extensions from the HST exposures were transformed to per-pixel RMS error maps that include all sources of error, including shot noise, and account for correlated noise, as in Casertano et al. (2000) and Dickinson et al. (2004), using ASTRORMS (Mechtley, 2011).

### 6.3 Source modelling and point source subtraction

I performed 2D surface brightness modelling for each quasar using the publicly available MCMC-based software PSFMC (Mechtley, 2014; Mechtley et al., 2016). PSFMC allows the user to model an input image using a combination of point sources and Sérsic profiles (Sérsic, 1963, 1968) with the parameters: sky background; point source magnitude and position; and Sérsic magnitude, position, Sérsic index $n$, effective radius of the major axis $R_e$, ratio between the major and minor axes $b/a$, and position angle. The MCMC process explores a range of model parameters specified by input prior probability distributions, convolving each model with an input PSF and comparing it with the telescope image, to determine the posterior probability distribution of model parameters given the observed data. The software uses the emcee ensemble sampler (Foreman-Mackey et al., 2013), which improves sampling efficiency compared to the pyMC (Patil et al., 2010) version that was used in Mechtley (2014).

For each image of each source, two different models were attempted—one with both a point source and an underlying Sérsic profile, and one with only a point source. The results of the two models were compared both visually and using the Bayesian Information Criterion as a model selection heuristic. In all cases, there was no evidence that the data required the additional Sérsic profile—the seven additional free parameters were primarily fitting noise peaks rather than residual flux from the hosts.

For all further analysis, I model the quasars as pure point sources. I also model any surrounding galaxies within $\sim 3''$ of the quasar with a Sérsic profile\footnote{Two galaxies could not be reasonably fit by one Sérsic profile, so I instead fit them with two Sérsic profiles superimposed, constraining their Sérsic indices such that one represents a disc-like component and the other a more spheroidal component. The properties of both profiles for these galaxies are given in Table 6.3, with their UV magnitude and slope calculated using the combined magnitude of both profiles.}. It should be stressed, however, that if the galaxies are associated with the quasar and undergoing a merger, their rest-frame UV emission need not be distributed in anything like a Sérsic profile. Rather, this approach is simply used to model their flux to avoid over-subtraction. I assume
uniform priors over a reasonable range, for all of the model parameters. For each quasar image, I run the MCMC with 200 chains, and a minimum of 10,000 iterations with the first 5,000 discarded as a burn-in period (systems with more surrounding galaxies required up to twice as many iterations to obtain convergence). To ensure that the model is well-fit to the data, I examine the resulting posterior distributions, altering the allowed parameter range and iteration count until each parameter has converged and the residual flux in the model subtracted image is consistent with random noise.

For the six quasars and their companion galaxies, I create posterior-weighted model images before convolution with the PSF, and after the model has been convolved with the PSF and subtracted from the original image. These weighted images are the (per-pixel) mean of all sample images, with more probable locations in parameter space being more densely populated with samples. The resulting images for the six quasars in the J- and H-bands are shown in Figures 6.2–6.4. The residual images show a central core of flux, which contains some residual flux from the quasar, and may also contain underlying host emission. The
Figure 6.3 Posterior-weighted model images for SDSS J0129–0035, SDSS J0203+0012 and NDWFS J1425+3254. See Figure 6.2 for details.
Figure 6.4 Posterior-weighted model images for SDSS J2054–0005 and SDSS J0005–0006. See Figure 6.2 for details.

regions in the residual images where companion galaxy models have been subtracted purely consists of noise, demonstrating that the psfMC model fits the observations superbly and the observations are noise-limited.

psfMC also outputs the ‘best’ parameter values from the maximum posterior model, alongside their errors. These values for the companion galaxy fits are given in Table 6.3.
Figure 6.5 Residual images showing the central regions of the quasars after PSF subtraction. The deep red and blue regions show pixels with formal $S/N$ with large absolute value, artifacts of the quasar subtraction technique which caused significant pixel-to-pixel variations in the residual flux. The two circles shown in each image have radii of $0'.42$ and $0'.60$, which are used when performing photometry of the underlying quasar host emission.

6.4 Results

6.4.1 Quasar host galaxies

6.4.1.1Magnitude limits

The formal signal-to-noise ratio ($S/N$) of the residual flux in the core of each quasar after PSF-subtraction is presented in Figure 6.5. This central region includes residual flux from the core of the quasar PSF, caused by an imperfect match of profiles of the quasar and empirical PSF used for subtraction, alongside any potential host galaxy flux. While the total flux is subtracted correctly, with a median residual consistent with zero, the pixel-to-pixel variation of the PSFs results in pixels with residual flux that is significantly larger than expected by the noise map, with formal signal-to-noise ratios of up to $|S/N| \simeq 30$. In other words, the subtraction technique produces considerable residuals in the inner region.

Note that significant quasar over- or under-subtraction is unlikely as this would produce negative or positive residuals in the diffraction spikes, respectively, which are not visible.

To estimate the flux of the host without including this contaminated inner region, I instead measure the surface brightness in annuli from 7 to 10 pixels, or $0'.42–0'.60$. I choose an inner radius of 7 pixels, as this is where the pixel-to-pixel variations of the $S/N$ first reach the expected/background level. This approach ignores the central core, while including enough pixels to make a reasonable detection if any flux was present. For all quasars in
Table 6.2. Quasar host galaxy detection limits

<table>
<thead>
<tr>
<th>Quasar Name</th>
<th>SB_J ((0\farcs42-0\farcs60)) 2(\sigma) limit (AB mag/('')^2)</th>
<th>m_J (Sérsic fit) 2(\sigma) limit (AB mag)</th>
<th>SB_H ((0\farcs42-0\farcs60)) 2(\sigma) limit (AB mag/('')^2)</th>
<th>m_H (Sérsic fit) 2(\sigma) limit (AB mag)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFHQS J0033-0125</td>
<td>24.6</td>
<td>22.9</td>
<td>24.4</td>
<td>22.7</td>
</tr>
<tr>
<td>SDSS J0129-0035</td>
<td>24.5</td>
<td>22.8</td>
<td>24.3</td>
<td>22.6</td>
</tr>
<tr>
<td>SDSS J0203+0012</td>
<td>24.4</td>
<td>22.7</td>
<td>24.2</td>
<td>22.4</td>
</tr>
<tr>
<td>NDWFS J1425+3254</td>
<td>24.7</td>
<td>22.9</td>
<td>24.4</td>
<td>22.7</td>
</tr>
<tr>
<td>SDSS J2054-0005</td>
<td>24.6</td>
<td>22.9</td>
<td>24.4</td>
<td>22.7</td>
</tr>
<tr>
<td>SDSS J0005-0006</td>
<td>24.8</td>
<td>23.1</td>
<td>24.6</td>
<td>22.9</td>
</tr>
</tbody>
</table>

Note. — Photometry of the residual image (after PSF subtraction) in the regions surrounding each quasar. The left columns for each filter give the surface brightness in the annulus \(0\farcs42-0\farcs60\) surrounding each quasar, as shown in Figure 6.5. As no significant signal is detected, these are 2\(\sigma\) upper limits calculated from the noise in each image. The right column for each filter gives magnitude limits estimated from these surface brightness limits. These are calculated by considering a range of Sérsic profiles with reasonable \(n\) and \(R_e\) (Shibuya et al., 2015) that are constrained to have the measured surface brightness in \(0\farcs42-0\farcs60\), and determining the most likely magnitude limit using a Monte Carlo approach (see Appendix C).

To obtain the total magnitude limit of a given host, I consider a range of Sérsic profiles, with a distribution of \(n\) and \(R_e\) guided by \(z \simeq 6\) observations (Shibuya et al., 2015), and take a Monte Carlo approach to determine the most likely magnitude limit given the surface brightness limit in the annulus (see Appendix C). The 2\(\sigma\) magnitude limits obtained by this method are given in Table 6.2, with the J- and H-band limits ranging from 22.7–23.1 mag and 22.4–22.9 mag, respectively.

6.4.1.2 Stellar mass limits

Measuring the redshift evolution of the black hole–stellar mass relation is of key importance for understanding the co-evolution of black holes and their host galaxies. Relative to the well-studied and accurately measured local relation (see, e.g., the review of Kormendy & Ho, 2013), at higher redshifts observations suggest that black holes are more massive compared to their hosts. For example, at \(z \simeq 1.5\) Ding et al. (2020) find a black hole–stellar mass ratio that is 2.7 times larger than the local relation, while at \(z \simeq 2\), Peng
et al. (2006b) find a black hole–bulge mass relation 3–6 times larger. At higher redshifts, existing observations of luminous \( z \simeq 6 \) quasars with ALMA generally find black hole to dynamical mass ratios that are significantly larger than the local relation (e.g. Maiolino et al., 2007; Riechers et al., 2008; Venemans et al., 2012b; Wang et al., 2013). However, many studies claim that high observed relations are a result of selection effects, (Lauer et al., 2007; Schulze & Wisotzki, 2011, 2014; DeGraf et al., 2015; Willott et al., 2017; Ding et al., 2020). ALMA observations of lower-luminosity \( z \simeq 6 \) quasars indeed find these to lie on or below the local relation (Willott et al., 2017; Izumi et al., 2018, 2019).

To investigate the black hole–stellar mass relation using these HST observations, I convert the host magnitude limits to limits on stellar mass. I calculate UV slopes \( \beta \) of the hosts by fitting the relation

\[
m = -2.5 \log(\lambda^{\beta+2}) + m_0, \]

equivalent to \( f_\lambda \propto \lambda^\beta \), to the two host magnitude limits \( m_J \) and \( m_H \) at \( \lambda = 1.25 \) and 1.6 \( \mu \)m respectively. Using this relation and the determined \( \beta \) and \( m_0 \), I calculate the UV apparent magnitude limit \( m_{UV} \) as that at rest-frame 1500 Å, or \( \lambda = (1 + z) \times 0.15 \mu \)m. I convert this to an absolute magnitude using

\[
M_{UV} = m_{UV} - DM + 2.5 \log(1 + z) \]

where \( DM \) is the distance modulus.

I adopt the \( z = 6 \) \( M_\star - M_{UV} \) relation derived by Song et al. (2016) using a large sample of galaxies from the Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (CANDELS)/Great Observatories Origins Deep Survey (GOODS) fields and the Hubble Ultra Deep Field (HUDF):

\[
\log(M_\star) = 9.53 \pm 0.02 - (0.50 \pm 0.03) \times (M_{UV} + 21) \tag{6.1}
\]

with a scatter of 0.36 dex. I use a Monte Carlo technique, sampling from a uniform distribution of magnitudes ranging from \( M_{UV} = -20 \) mag to my 2\( \sigma \) upper limit for each quasar host. The lower luminosity limit of \( M_{UV} = -20 \) mag was chosen as this is as faint as high-redshift quasar hosts are expected to be from the BLUETIDES simulation (Feng et al., 2015, see Figure 6.12, Chapter 5). I assign a stellar mass to each sampled magnitude using Equation 6.1, given a normal distribution with \( \sigma = 0.36 \) dex, to determine the resulting probability distribution of stellar masses. These stellar masses are normally-distributed, so I adopt the 2\( \sigma \) upper limit from this relation as my host mass limit. Note that this results in a lower, less pessimistic limit than simply taking the 2\( \sigma \) upper mass limit at the 2\( \sigma \) magnitude limit, which is very conservative.
I present the black hole–stellar mass relation from the stellar mass limits of these $z \simeq 6$ quasar hosts in Figure 6.6. My limits are consistent with the black hole–stellar mass relation from existing sub-mm observations of $z \simeq 6$ quasars, (Willott et al., 2017; Izumi et al., 2018, 2019; Pensabene et al., 2020), which measure the dynamical mass of the host using gas dynamics as probed by the [CII] line, and assume $M_* = M_{\text{dyn}}$. Three of the six observed quasars have dynamical mass measurements (Wang et al., 2010; Pensabene et al., 2020), which are also shown in Figure 6.6. The stellar mass upper limit for SDSS J2054-0005 lies above the measured dynamical mass of $M_{\text{dyn}} = 0.7^{+1.5}_{-0.3} \times 10^{10} M_\odot$ (Pensabene et al., 2020), suggesting that either my limit is significantly larger than the true stellar mass, with much deeper observations required to detect the underlying stellar emission, or the measured dynamical mass underestimates the total mass of the galaxy. The stellar mass upper limit for SDSS J0129-0035 is consistent with the lower dynamical mass limit of $M_{\text{dyn}} > 7.8 \times 10^{10} M_\odot$ (Pensabene et al., 2020). The lower limit on the dynamical mass for NDWFS J1425+3254 of $M_{\text{dyn}} > 1.56 \times 10^{11} M_\odot$ (Wang et al., 2010) is larger than the
stellar mass upper limit, suggesting that we are close to detecting the stellar component of this quasar host galaxy.

The stellar mass limits of five of the six quasars are consistent with the local Kormendy & Ho (2013) $M_\ast - M_{BH}$ relation. SDSS-J0203+0012, however, has a stellar mass of $M_\ast < 1.89 \times 10^{11} M_\odot$, lower than expected by the local relation, given its extremely large black hole mass of $M_{BH} = 5.2 \times 10^{10} M_\odot$ (Table 6.1, Shen et al., 2019). However, note that this black hole mass is determined by the CIV line, as the more robust MgII line is not covered by ground-based observations. SDSS-J0203+0012 is a broad absorption line (BAL) quasar (Mortlock et al., 2009) and so the dynamics probed by the CIV line are likely affected by the outflows. Hence I place no significance on the black hole–stellar mass relation limit for this object.

The $M_\ast - M_{UV}$ relation is derived from observations of UV-selected galaxies, and might not apply if the hosts were dusty star-forming or quiescent galaxies; as these galaxies may be particularly dusty, my mass limits would be underestimates. Mid-infrared observations to allow for detailed spectral energy distribution fitting, using JWST, for example, are necessary to accurately determine the stellar masses of these potentially dusty host galaxies.

### 6.4.2 The prevalence of close, blue neighbours

Figures 6.2–6.4 reveal that all of the six quasars have neighbouring galaxies within the surrounding $\sim 6.5' \times 6.5'$. For SDSS-J0129-0035, NDWFS-J1425+3254 and SDSS-J0005-0006, some companions overlap with the quasar PSF, highlighting the need for the quasar PSF subtraction in order to fully understand the local quasar environment.

The properties of these 20 neighbouring galaxies from the maximum posterior model found by psfMC are listed in Table 6.3. I calculate their UV magnitudes and slopes following the same procedure as for the host galaxies (see Section 6.4.1.2). The magnitudes and colours of these galaxies are displayed in Figure 6.7, along with samples of star-forming galaxies at $z \simeq 6$. Four of these companions have colours/UV-slopes that are too red ($\beta > 0$) or too blue ($\beta < -4$) to be consistent with $z \simeq 6$ galaxies. In addition, seven galaxies are too bright to be likely at this redshift, with magnitudes brighter than $M_{UV} = -22.1$ mag, the magnitude of the brightest spectroscopically-confirmed $z \simeq 6$ galaxy in the sample.
Table 6.3. Properties of galaxies surrounding the quasars

<table>
<thead>
<tr>
<th>Quasar Name</th>
<th>Galaxy</th>
<th>$m_J$ (AB mag)</th>
<th>$m_J - m_H$ (AB mag)</th>
<th>RA</th>
<th>Dec</th>
<th>$d_{\text{projected}}$ (kpc)</th>
<th>Sérsic index $n$</th>
<th>$R_e$ (kpc)</th>
<th>$b/a$</th>
<th>$M_{1200}$ (AB mag)</th>
<th>UV slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFHQS J0033-0125</td>
<td>1†</td>
<td>24.7 ± 0.1</td>
<td>0.1 ± 0.1</td>
<td>03:11:519</td>
<td>-1:25:33.6</td>
<td>17.6 ± 0.1</td>
<td>2.2 ± 0.8</td>
<td>2.9 ± 0.5</td>
<td>0.31 ± 0.08</td>
<td>-22.1 ± 0.2</td>
<td>-1.7 ± 0.6</td>
</tr>
<tr>
<td>SDSS J0129-0035</td>
<td>1*</td>
<td>26.6 ± 0.3</td>
<td>0.8 ± 0.3</td>
<td>1:29:58:088</td>
<td>-0:35:45.3</td>
<td>18.6 ± 0.2</td>
<td>5.5 ± 1.7</td>
<td>1.1 ± 0.4</td>
<td>0.64 ± 0.35</td>
<td>-19.4 ± 0.5</td>
<td>1.5 ± 1.6</td>
</tr>
<tr>
<td></td>
<td>2*</td>
<td>25.9 ± 0.2</td>
<td>-0.7 ± 0.2</td>
<td>1:29:58:179</td>
<td>-0:35:42.2</td>
<td>5.3 ± 0.2</td>
<td>5.2 ± 1.8</td>
<td>1.7 ± 0.4</td>
<td>0.65 ± 0.23</td>
<td>-21.4 ± 0.4</td>
<td>-4.9 ± 1.4</td>
</tr>
<tr>
<td></td>
<td>3*</td>
<td>24.1 ± 0.0</td>
<td>0.1 ± 0.0</td>
<td>1:29:58:114</td>
<td>-0:35:43.8</td>
<td>10.7 ± 0.1</td>
<td>0.5 ± 0.0</td>
<td>1.9 ± 0.1</td>
<td>0.46 ± 0.03</td>
<td>-22.6 ± 0.1</td>
<td>-1.6 ± 0.2</td>
</tr>
<tr>
<td>SDSS J0203+0012</td>
<td>1a*</td>
<td>23.3 ± 0.1</td>
<td>0.1 ± 0.1</td>
<td>2:03:31:865</td>
<td>-1:25:26.0</td>
<td>21.3 ± 0.1</td>
<td>0.5 ± 0.0</td>
<td>1.8 ± 0.0</td>
<td>0.22 ± 0.02</td>
<td>-23.8 ± 0.3</td>
<td>-1.7 ± 1.3</td>
</tr>
<tr>
<td></td>
<td>1b*</td>
<td>24.1 ± 0.1</td>
<td>-0.1 ± 0.3</td>
<td>2:03:31:860</td>
<td>-1:24:29.8</td>
<td>22.1 ± 0.1</td>
<td>2.1 ± 0.7</td>
<td>1.6 ± 0.3</td>
<td>0.76 ± 0.20</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>26.6 ± 0.2</td>
<td>0.2 ± 0.3</td>
<td>2:03:31:883</td>
<td>-1:28:26.1</td>
<td>15.9 ± 0.3</td>
<td>4.2 ± 2.0</td>
<td>1.6 ± 0.4</td>
<td>0.57 ± 0.29</td>
<td>-19.9 ± 0.4</td>
<td>-1.1 ± 1.6</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>26.2 ± 0.3</td>
<td>0.2 ± 0.3</td>
<td>2:03:32:180</td>
<td>-1:25:94.0</td>
<td>16.0 ± 0.2</td>
<td>4.7 ± 1.9</td>
<td>1.8 ± 0.5</td>
<td>0.50 ± 0.31</td>
<td>-20.3 ± 0.5</td>
<td>-1.2 ± 1.6</td>
</tr>
<tr>
<td>NDWFS J1425+3254</td>
<td>1†</td>
<td>24.6 ± 0.1</td>
<td>0.4 ± 0.1</td>
<td>14:25:16:767</td>
<td>32:54:06.9</td>
<td>8.4 ± 0.1</td>
<td>3.6 ± 0.7</td>
<td>2.6 ± 0.4</td>
<td>0.81 ± 0.21</td>
<td>-21.8 ± 0.2</td>
<td>-0.4 ± 0.8</td>
</tr>
<tr>
<td></td>
<td>2*</td>
<td>24.4 ± 0.1</td>
<td>0.1 ± 0.1</td>
<td>14:25:16:733</td>
<td>32:54:05.4</td>
<td>3.4 ± 0.2</td>
<td>0.5 ± 0.0</td>
<td>2.7 ± 0.1</td>
<td>0.94 ± 0.07</td>
<td>-22.3 ± 0.2</td>
<td>-1.6 ± 0.6</td>
</tr>
<tr>
<td>SDSS J2054-0005</td>
<td>1*</td>
<td>23.7 ± 0.1</td>
<td>0.0 ± 0.1</td>
<td>20:54:06:075</td>
<td>-0:05:18.1</td>
<td>12.3 ± 0.1</td>
<td>1.7 ± 0.2</td>
<td>4.2 ± 0.2</td>
<td>0.39 ± 0.04</td>
<td>-23.1 ± 0.1</td>
<td>-2.2 ± 0.4</td>
</tr>
<tr>
<td></td>
<td>2*</td>
<td>24.3 ± 0.1</td>
<td>0.4 ± 0.1</td>
<td>20:54:06:028</td>
<td>-0:05:17.4</td>
<td>15.6 ± 0.1</td>
<td>0.9 ± 0.2</td>
<td>2.2 ± 0.2</td>
<td>0.49 ± 0.05</td>
<td>-22.1 ± 0.1</td>
<td>-0.1 ± 0.4</td>
</tr>
<tr>
<td></td>
<td>3*</td>
<td>23.3 ± 0.0</td>
<td>0.1 ± 0.0</td>
<td>20:54:06:080</td>
<td>-0:05:17.3</td>
<td>11.1 ± 0.0</td>
<td>1.6 ± 0.1</td>
<td>0.7 ± 0.0</td>
<td>0.81 ± 0.03</td>
<td>-23.5 ± 0.0</td>
<td>-1.6 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>4*</td>
<td>24.8 ± 0.2</td>
<td>-0.6 ± 0.1</td>
<td>20:54:05:998</td>
<td>-0:05:15.1</td>
<td>22.7 ± 0.0</td>
<td>5.7 ± 1.0</td>
<td>2.3 ± 0.4</td>
<td>0.41 ± 0.15</td>
<td>-22.5 ± 0.3</td>
<td>-4.6 ± 0.9</td>
</tr>
<tr>
<td></td>
<td>5†</td>
<td>24.9 ± 0.1</td>
<td>0.2 ± 0.1</td>
<td>20:54:06:265</td>
<td>-0:05:19.8</td>
<td>15.7 ± 0.0</td>
<td>7.0 ± 0.8</td>
<td>2.2 ± 0.5</td>
<td>0.63 ± 0.24</td>
<td>-21.7 ± 0.2</td>
<td>-1.1 ± 0.8</td>
</tr>
<tr>
<td></td>
<td>6†</td>
<td>25.1 ± 0.1</td>
<td>0.4 ± 0.1</td>
<td>20:54:06:376</td>
<td>-0:05:19.4</td>
<td>19.4 ± 0.1</td>
<td>4.6 ± 0.8</td>
<td>3.7 ± 0.4</td>
<td>0.72 ± 0.13</td>
<td>-21.4 ± 0.2</td>
<td>-0.2 ± 0.8</td>
</tr>
<tr>
<td></td>
<td>7†</td>
<td>25.3 ± 0.2</td>
<td>0.4 ± 0.2</td>
<td>20:54:06:336</td>
<td>-0:05:18.9</td>
<td>14.8 ± 0.0</td>
<td>5.6 ± 0.9</td>
<td>1.7 ± 0.2</td>
<td>0.55 ± 0.11</td>
<td>-21.1 ± 0.3</td>
<td>-0.2 ± 1.1</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>26.0 ± 0.2</td>
<td>0.4 ± 0.2</td>
<td>20:54:06:334</td>
<td>-0:05:18.9</td>
<td>14.7 ± 0.0</td>
<td>4.8 ± 0.8</td>
<td>2.2 ± 0.4</td>
<td>0.56 ± 0.16</td>
<td>-20.5 ± 0.3</td>
<td>-0.5 ± 1.1</td>
</tr>
<tr>
<td>SDSS J0005-0006</td>
<td>1a*</td>
<td>25.1 ± 0.1</td>
<td>-0.3 ± 0.3</td>
<td>00:52:046</td>
<td>-0:06:59.9</td>
<td>10.8 ± 0.1</td>
<td>0.7 ± 0.2</td>
<td>1.0 ± 0.1</td>
<td>0.85 ± 0.10</td>
<td>-22.1 ± 0.6</td>
<td>-1.8 ± 2.1</td>
</tr>
<tr>
<td></td>
<td>1b*</td>
<td>25.7 ± 0.3</td>
<td>0.5 ± 0.2</td>
<td>00:52:038</td>
<td>-0:06:59.8</td>
<td>9.8 ± 0.2</td>
<td>6.4 ± 1.2</td>
<td>2.0 ± 0.9</td>
<td>0.59 ± 0.45</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>2*</td>
<td>25.7 ± 0.1</td>
<td>0.7 ± 0.4</td>
<td>00:52:217</td>
<td>-0:06:56.5</td>
<td>23.5 ± 0.1</td>
<td>5.7 ± 1.5</td>
<td>2.7 ± 0.6</td>
<td>0.41 ± 0.16</td>
<td>-20.4 ± 0.4</td>
<td>1.0 ± 1.7</td>
</tr>
<tr>
<td></td>
<td>3†</td>
<td>25.4 ± 0.1</td>
<td>0.0 ± 0.2</td>
<td>00:52:032</td>
<td>-0:06:55.6</td>
<td>17.3 ± 0.1</td>
<td>2.1 ± 0.9</td>
<td>2.6 ± 0.5</td>
<td>0.35 ± 0.11</td>
<td>-21.3 ± 0.3</td>
<td>-2.0 ± 0.9</td>
</tr>
</tbody>
</table>

Note. — Properties of the galaxies surrounding each of the quasars, with the central value denoting the maximum posterior model and the error extracted from the MCMC fits. The projected distance between the quasar and galaxy centres is denoted as $d_{\text{projected}}$. Galaxies with an $a/b$ marked next to their identifier (column 2) are those which needed two Sérsic profiles to be fit to match their brightness distribution. The properties for the individual fits are given, but their UV magnitude and slope $\beta$ are calculated by combining both Sérsic magnitudes. Asterisks (*) denote companions with UV magnitudes and/or slopes that make them unlikely to be $z \approx 6$ galaxies, and are instead likely to be foreground interlopers. Daggers (†) denote potential $z \approx 6$ companions with UV magnitudes brighter than $M^*$ at $z = 6$. 

Figure 6.7 Left: \( J - H \) colour vs. J-band magnitude and Right: Rest-frame UV slope \( \beta \) vs. 1500 Å absolute magnitude, measured for each of the galaxies within \( \sim 3'' \) of the six quasars, assuming they are at the same redshift as the quasar. Filled coloured circles show those with colours and magnitudes consistent with \( z \sim 6 \) galaxies, while open coloured circles show candidates which are likely to be foreground interlopers given their colours and magnitudes. The numerical labels correspond to labels in the individual quasar images (Figures 6.2–6.4), and Table 6.3, for ease of comparison. Grey symbols represent spectroscopically-confirmed \( z \sim 6 \) galaxies from Jiang et al. (2013, 2020) and the average relations for dropout-selected Lyman-break galaxies from Bouwens et al. (2012), Dunlop et al. (2012), and Finkelstein et al. (2012) (see legend). The dashed black line shows the value of \( M^* \) (Finkelstein, 2016).

of Finkelstein et al. (2015). The remaining 9 companion galaxies—surrounding five of the six quasars—have UV magnitudes and slopes consistent with those of star-forming galaxies at \( z \sim 6 \). The majority of these are brighter than \( M^* \) (\( -20.79 \) mag at \( z = 6 \), Finkelstein, 2016, see Table 6.3). Unfortunately, existing observations at sub-mm to radio wavelengths do not resolve and/or detect the individual sources (e.g. Wang et al., 2013), so morphological comparisons with existing data are not possible.

These 9 potential companion galaxies are separated from the quasars by 1.4′–3′.2, corresponding to projected distances of 8.4–19.4 kpc. Simulations show that galaxies with companions at similar separations have higher AGN fractions (McAlpine et al., 2020), and also enhanced star formation rates (Patton et al., 2020). This suggests that these companions, if their true 3D distance is of order their projected distance, could be interacting with the quasar host galaxies and may potentially have triggered or enhanced the observed AGN activity. However, tidal features from any such interaction would likely be rendered invisible due to the \( (1 + z)^4 \) surface brightness dimming at \( z \sim 6 \).

I examine the relationship between size, Sérsic index and magnitude for these neighbouring
Figure 6.8 The morphological properties measured for each of the galaxies within 3'' of the 6 quasars. Top row: effective radius $R_e$ vs. J-band magnitude. Bottom row: Sérsic index $n$ vs. J-band magnitude. Filled coloured circles show those with colours and magnitudes consistent with $z \approx 6$ galaxies, while open coloured circles show candidates which are likely to be foreground interlopers given their colours and magnitudes. The numerical labels correspond to labels in the individual quasar images (Figures 6.2–6.4), and Table 6.3, for ease of comparison. Also shown are measurements of galaxy sizes in the CANDELS GOODS-South survey from van der Wel et al. (2012), for comparison. Left panel: van der Wel et al. (2012) galaxies with best estimate redshift $z > 5.5$, and a 95 per cent confidence that $z > 5$. Right panel: Galaxies within 3'' of these $z > 5.5$ galaxies, at any redshift. Grey dots show individual galaxies, and the grey line shows the median in bins of 1 magnitude.

galaxies in Figure 6.8, in comparison to $z \approx 6$ galaxies in the CANDELS GOODS-South sample (van der Wel et al., 2012; Brammer et al., 2012; Skelton et al., 2014; Momcheva et al., 2016). This shows that the companion galaxy sizes are as large as the largest $z \approx 6$ CANDELS field galaxies, but are larger than the median size of $z \approx 6$ field galaxies by an average of $0''.1$. Their Sérsic profiles are as steep as the steepest Sérsic indexes of CANDELS $z \approx 6$ field galaxies, but are larger than the median Sérsic index of $z \approx 6$ field galaxies by an average of $\Delta n = 2$. Thus, the potential quasar companion galaxies have morphological parameters that are consistent with the larger and steeper-Sérsic CANDELS $z \approx 6$ field galaxies. Similar conclusions are made when comparing the potential companion galaxies to neighbours within 3'' of $z \approx 6$ galaxies in the CANDELS GOODS-South sample (Figure 6.8, van der Wel et al., 2012), of which the majority (95%) are foreground objects at $z < 5.5$. The potential companions have sizes and Sérsic indices that are larger than
the median of the neighbours of \( z \approx 6 \) CANDELS galaxies, although their properties are reasonably consistent with the more massive neighbours. Hence, based on their size and Sérsic distributions it cannot be determined whether the observed neighbours are more likely to be \( z \approx 6 \) galaxies than foreground interlopers.

The relationship between size and UV absolute magnitude for these potential companion galaxies is shown in Figure 6.9, assuming they are at the same redshift as the quasar. The objects that have UV magnitudes and slopes consistent with \( z \approx 6 \) galaxies lie on a relatively tight size-luminosity relation. This relation is fairly consistent with, but somewhat higher than, that of \( z \approx 6 \) Lyman-break galaxies measured by Shibuya et al. (2015) (for galaxies with \(-22 \lesssim M_{UV} \lesssim -18\) mag) and Kawamata et al. (2018) (for galaxies with \(-21.5 \lesssim M_{UV} \lesssim -12\) mag), with these objects having larger sizes at the same luminosities.

Note that the measured sizes of galaxies may be affected by systematic differences between these studies. For example, the treatment of the sky background in the fitting can have a significant impact on the resulting Sérsic fit parameters (see, e.g., Guo et al., 2009; Bruce...
et al., 2012). I include the background level as a free parameter in the MCMC-fitting, which can result in larger values of $R_e$ and Sérsic index $n$ than if the background level is fixed (Bruce et al., 2012), potentially contributing to some of the discrepancy between my results and those of Shibuya et al. (2015), who assume a fixed background level. Bruce et al. (2012) show that there is a positive correlation between measured $R_e$ and Sérsic index $n$. Shibuya et al. (2015) assume $n = 1.5$ for Lyman-break galaxies, and Kawamata et al. (2018) fix $n = 1$. As my fitting method finds larger Sérsic indices for the potential $z \simeq 6$ companion galaxies, with a mean of $n = 4.3$, this correlation may explain, at least in part, my larger measured sizes.

Using the number of galaxies observed in HST data of comparable depth (WFC3 ERS2 field, $m_H < 26.5$: Windhorst et al., 2011, see their figure 12), the average number of galaxies observed is $\sim 373,000$ per square degree, or 0.0288 objects per square arcseconds, if galaxies are uniformly distributed on the sky. I thus expect to find on average 7.3 random foreground objects within the six $\sim 6''5 \times 6''5$ quasar images (total area $\approx 250$ square arcseconds; Figures 6.2–6.4), at $z \ll 6$ and unrelated to the quasars. The surface density variations in these numbers due to foreground cosmic variance and photometric zeropoint errors is expected to be $\lesssim 15\%$ in the H-band (see, e.g., figure 3 of Driver et al., 2016), so I would on average expect $\lesssim 8.4$ random foreground objects at $z \ll 6$.

Assuming that the galaxy neighbour distribution follows a Poisson distribution, the probability of observing a total of 20 galaxies within the $\sim 250$ square arcsecond area, $4\sigma$ above the expected value of 8.4 foreground galaxies, is $\lesssim 0.0003$. Hence, given the unlikelihood that so many galaxies would be found by chance, it is probable that some of these objects are physically associated with the quasars. Of the 20 close neighbours, 11 have UV magnitudes and slopes that suggest that they are unlikely to be at $z \simeq 6$. Finding these 11 foreground galaxies is consistent within $1\sigma$ of these Poisson expectations. The remaining 9 neighbours have UV magnitudes and slopes consistent with known $z \simeq 6$ galaxies. I will adopt this number of 9 potential quasar companion galaxies in the discussion below, however note that the true number of $m_J < 26.5$ $z \simeq 6$ companion galaxies in the images could be between 0 and 20, with 9 a more reasonable upper limit on the expected number based on the above arguments.

Figure 6.10 shows the average number of potential $z \simeq 6$ companion galaxies found in the
Figure 6.10 The average number of potential $z \simeq 6$ companion galaxies found within $3''2$ (0.13 cMpc) of the six quasars, compared with expectations for counts of $z = 6$ galaxies in random fields from the Finkelstein et al. (2015) luminosity function, as a function of projected distance from the quasar. I consider a cylindrical volume centred on the quasar with depth $\Delta z = 1$. Errors on the observation show the range of 1–20 true $z \simeq 6$ companions, around my best estimate of 9, where 20 is the total number of objects found within $3''2$ of the six quasars; the lower error is marked with an arrow to account for the (unlikely) limiting case that none of the neighbouring galaxies are true $z \simeq 6$ companions. Also shown are the observations of $z \geq 6$ quasar companions of Decarli et al. (2017), for comparison. I also plot the Finkelstein et al. (2015) luminosity function predictions modified to account for the effect of large-scale clustering. I take two models for the excess in the galaxy number density $\xi(r) = (r_0/r)^\gamma$, with $r_0 = 8.83^{+1.39}_{-1.51}/h$ cMpc and $\gamma = 2.0$ from the quasar–Lyman break galaxy clustering of $z = 4$ galaxies measured by García-Vergara et al. (2017), and $r_0 = 5.3^{+2.3}_{-2.6}/h$ cMpc and $\gamma = 1.6$ from the galaxy–galaxy clustering measurements of $z = 5.9$ $M_{UV} < -19.99$ galaxies (Qiu et al., 2018).

quasar fields, compared to expectations for number counts of $z = 6$ galaxies in random fields (Finkelstein et al., 2015). I see significant excess compared to expectations of random pointings, with an average of $\sim 1.5$ galaxies within 0.13 cMpc of the quasars ($3''2$ at $z = 6$) higher than the expected number of 0.0056 galaxies, corresponding to an overdensity of a factor of $\sim 270$. This large excess is similar to the overdensity found by Decarli et al. (2017, see their figure 3b), who detected 4 companion galaxies in [CII] with ALMA around 4 of 25 $z \gtrsim 6$ quasars.

Decarli et al. (2017) find that their measured overdensity is consistent with measurements of quasar–Lyman break galaxy clustering at $z \simeq 4$ (García-Vergara et al., 2017), when
applied to the [CII] luminosity function. I consider the models of the \( z \simeq 4 \) García-Vergara et al. (2017) quasar–galaxy clustering and the \( z = 5.9 \) galaxy–galaxy clustering of Qiu et al. (2018) to account for this effect, and find that my measurement is consistent with both clustering models applied to the Finkelstein et al. (2015) luminosity function. Thus, as with the Decarli et al. (2017) sample, these observed potential \( z \simeq 6 \) companion counts can be explained by expectations for high-redshift galaxy clustering. Hence, while I find that these quasars are in environments that are more dense than the average field density, with an overdensity of a factor of \( \sim 270 \), they are in similar environments to that expected for a typical luminous \( z \simeq 6 \) field galaxy. In fact, if I have overestimated the number of true companion galaxies at 9, then these quasars may be in somewhat less dense regions than the typical luminous \( z \simeq 6 \) galaxy.

While Decarli et al. (2017) had a secure number of \( z \simeq 6 \) companions from ALMA [CII] redshifts, I present a consistent upper limit from the number of possible \( z \simeq 6 \) companions following the above arguments. Clearly, JWST integral field redshifts, ALMA [CII] redshifts, or VLT MUSE redshifts would be needed to determine the real number of companion galaxies around the quasars, and their overdensity compared to the field at \( z \simeq 6 \).

### 6.4.2.1 Additional observations of NDWFS-J1425+3254

The quasar NDWFS-J1425+3254 shows further evidence for having close companions. The discovery spectrum of Cool et al. (2006) shows a significant absorption feature at roughly 8350 Å, 20 Å red-ward of Lyman-\( \alpha \). This line could potentially be caused by HI absorption from a companion galaxy infalling at 720 km s\(^{-1}\) (Mechtley, 2014). By assuming the system is virialized and that the companion is at a projected distance of 4.8 kpc, Mechtley (2014) find that this corresponds to a dynamical mass of \( \sim 5.8 \times 10^{11} M_\odot \). Using the Song et al. (2016) \( M_\star - M_{UV} \) relation (Equation 6.1), from my detection limits the host of NDWFS-J1425+3254 has a stellar mass of \( M_\star < 2.0 \times 10^{11} M_\odot \), with the two companions having masses of \( \sim 7.8 \times 10^8 M_\odot \) and \( \sim 1.3 \times 10^9 M_\odot \). The properties of the CO (6 – 5) line (Wang et al., 2010) provide independent evidence for a group-like gravitational potential; the line fit gives a FWHM of 690 ± 180 km s\(^{-1}\), and the peak of the emission is redshifted (\( z = 5.89 \)) from the reported Ly\( \alpha \) redshift (\( z = 5.85 \), Cool et al., 2006).
Figure 6.11 Thumbnail images of NDWFS-J1425+3254. From left to right: LBT/LBC $g$-, $r$-, and $i$-bands, and HST WFC3 IR J- and H-bands. The companion galaxies are visible within the green circle of radius $2^\prime 0$ in the point source-subtracted WFC3 IR images. Lyman-$\alpha$ emission from the quasar at $\approx 8330\,\AA$ is captured by the $i$-band image, while Lyman-Werner flux from the quasar is bright enough to be seen in the $r$-band, even in these LBT observations (see the discovery spectrum of Cool et al., 2006). Due to the seeing of the ground-based images, estimated as $\approx 0^\prime 8$–$1^\prime 0$ FWHM, point source subtraction on the $r$-band LBC image produces an inconclusive upper limit for the combined companion galaxy flux.

To further investigate this system, the team obtained observations with the Large Binocular Camera (LBC) on the Large Binocular Telescope (LBT) in the $g$-, $r$-, and $i$-bands (Fig 6.11). No LBC $g$-band flux is detected in a $2^\prime 0$ aperture to a limit of $m_g \gtrsim 28.3$ mag, with Lyman-Werner flux from the quasar detected in the $r$-band at $m_r = 24.7$ mag. Even in decent seeing conditions ($\sim 0^\prime 8$–$1^\prime 0$) the ground-based PSF of the quasar has broad wings that significantly affect the detection limit of close companions out to $2^\prime 0$ or greater (see, e.g., Ashcraft et al., 2018). A best-effort point-source subtraction results in an upper limit of $m_r \gtrsim 25.7$ mag for the more distant of the two companions. The $J$- and $H$-band detections but faint $g$- and $r$-band limits are sufficient to exclude the possibility that these companions are blue foreground galaxies, but not that they could be red luminous galaxies at $z \approx 1.1$. Additional observations are therefore required to confirm that these ‘companion’ galaxies are indeed at $z \approx 6$, and not foreground interlopers.

6.5 Discussion

6.5.1 The dust content of quasar hosts

To understand the magnitude limits and dust properties of the quasar host galaxies, I consider the sample of $z = 7$ quasars in the BlueTides simulation (Feng et al., 2015). BlueTides is a large-scale cosmological hydrodynamical simulation, which models the evolution of $2 \times 7040^3$ particles in a cosmological box of volume $(400/h\,\text{cMpc})^3$ from
initial conditions at $z = 99$ to $z = 7$, the lowest published redshift to date (Chapter 5; Ni et al., 2020). Figure 6.12 presents the relation between galaxy and quasar UV luminosity, for the observations and the BlueTides quasars. Both the intrinsic and dust-attenuated galaxy magnitudes for the BlueTides galaxies are shown, with the dust attenuation of galaxies modelled in BlueTides using the density of metals along a line of sight (see Section 5.1.2.3). From the BlueTides simulation, I find that hosts of $M_{\text{UV}} < -23$ mag quasars at $z = 7$ have between 1.4 to 3.8 mag extinction in the UV, with an average of $A_{\text{UV}} = 2.6$ mag, corresponding to $A_V = 1.0$ (Calzetti et al., 2000).

From Figure 6.12, the majority of intrinsic UV magnitudes for host galaxies of similar luminosity quasars in BlueTides are brighter than my host galaxy upper limits, with only a small percentage consistent with the limits. Given that I make no detections of all six quasar hosts, these upper limits are sufficient to rule out the possibility that the quasars are generally hosted by dust-free galaxies. Instead, my limits favour host galaxies with significant dust-attenuation, consistent with the $\langle A_{\text{UV}} \rangle = 2.6$ mag that is seen for the BlueTides quasar hosts (Figure 6.12, Chapter 5). If the BlueTides sample including dust obscuration is representative of the true $z \approx 6$ quasar population, my upper limits are brighter than the host magnitudes that are expected, and future observations would need to probe at least $\sim 1$ mag fainter to begin to detect the host emission. I will focus on integrating BlueTides with this observational technique to make specific predictions for upcoming JWST observations in future work.

SDSS J0005-0006 was found to be a dust-poor quasar by Jiang et al. (2013), as it was undetected with the Spitzer Space Telescope at 15.6 and 24 $\mu$m. Further observations by Leipski et al. (2014) detected the quasar with Spitzer at these wavelengths, however did not detect emission at $\geq 100 \mu$m with Herschel, and so they also conclude that the quasar is deficient of hot dust compared to the majority of quasars in their sample. Non-detection of the quasar with the Max Planck Millimeter Bolometer Array (MAMBO) at 250 GHz (Wang et al., 2008) results in upper limits of the dust mass of the host of $M_{\text{dust}} < 1.9 \times 10^8 M_\odot$ (Calura et al., 2014). While these observations do not detect significant amounts of dust in this system, it is still possible for some dust to be present, resulting in low-level dust attenuation of the host galaxy. Thus, while my magnitude limit for the host of SDSS J0005-0006 is fainter than the magnitudes expected of quasar hosts with no dust attenuation from the BlueTides simulation, the non-detection of the host can be reasonably explained by some minor dust attenuation in the generally dust-deficient
Figure 6.12 The relation between quasar and host galaxy UV-luminosity for this observed sample (coloured upper limits; see legend) and for the simulated $z=7$ quasars from the BlueTides simulation (grey density plots). The left panel shows the BlueTides host galaxies’ intrinsic UV-luminosities, while the right panel shows them after dust attenuation, which is calculated using the density of gas in the simulation (Section 5.1.2.3; Ni et al., 2020). Diagonal black lines show where the ratio of quasar to host brightness is 1:1, 10:1 and 100:1.

These six quasars were selected in the $z$-band as $i$-band dropouts with rest-frame UV luminosities at $z \simeq 6$ of $-26.5 \lesssim M_{UV} \lesssim -24$ mag (Table 6.1). Hence, their UV accretion discs are still, by selection, remarkably well visible. Five of the $z \simeq 6$ quasars were also selected to have significant FIR emission, and as a consequence the young stellar populations in their host galaxies are not visible in the best high dynamic range J- and H-band images that HST can produce.

I inferred that their host galaxies are likely considerably dusty ($\langle A_{UV} \rangle = 2.6$ mag), yet the embedded quasars are easily detected in the rest-frame UV and thus not significantly obscured (see, e.g., Vito et al., 2019). This must have significant consequences for the geometry of the small and large scale dust distribution. One possible explanation is that the embedded rapidly-accreting supermassive black hole produced a significant outflow that vacated a sufficiently large cone on scales of 10–100 pc—fortuitously aligned in our direction—that the quasar has become clearly visible at rest-frame UV wavelengths, while
the host galaxy is not. Significant outflows have indeed been observed from high-redshift quasars (e.g. Alexander et al., 2010; Nesvadba et al., 2011; Maiolino et al., 2012), and are expected to be able to carve a window for observing the quasar through otherwise high-density gas (Ni et al., 2020). Thus, it seems likely that such outflows are present in these systems. These objects are therefore high priority targets for JWST, which will add 1.6–29 μm wavelength imaging coverage to the 1.2–1.6 μm HST images, and so is expected to much better constrain the dust extinction and geometry that UV images alone cannot capture.

6.5.2 Quasar selection bias

Five $z \approx 6$ quasars for this HST program were selected as those UV-faint quasars with confirmed sub-mm detections, and thus the greatest rest-frame $L_{\text{FIR}}/L_{\text{UV}}$ ratios. This selects host systems with the greatest non-AGN contribution to the FIR flux, with inferred ultraluminous infrared galaxy (ULIRG)-class FIR luminosities ($> 10^{12} L_\odot$) and implied star formation rates of $\approx 500 M_\odot \text{yr}^{-1}$ (Wang et al., 2011). Locally, ULIRGs are gas-rich with high inferred star formation rates, and most are undergoing major mergers or at least strong interactions (e.g. Howell et al., 2010; Kim et al., 2013). This suggests that this sample of $z \approx 6$ quasars are a distinct quasar sub-population, which may be biased towards quasars with nearby interacting galaxies. This potential selection bias may mean that while the six quasars are in environments typical of luminous $z \approx 6$ galaxies, the overall $z \approx 6$ quasar population may reside in somewhat under-dense environments.

However, note that Trakhtenbrot et al. (2018) observed three FIR-bright and three FIR-faint quasars with ALMA, finding spectroscopically confirmed sub-mm companion galaxies interacting with three quasars—one FIR-bright and two FIR-faint. I also find a potential companion around SDSS J0005-0006, which is not detected in the FIR (Wang et al., 2008; Jiang et al., 2013; Leipski et al., 2014). Hence, companion galaxies are not necessarily a feature of only FIR-bright quasars.

This selection bias is also likely to affect the measured black hole–stellar mass relation, as these quasars are not necessarily representative of the overall $z \approx 6$ quasar population. For example, the most highly star-forming quasar host galaxies in BLUETIDES show a significantly steeper black hole–stellar mass relation, with such quasars lying on the main relation for the most massive black holes, and below the relation for lower-mass black
holes. This result suggests that the ULIRG-type hosts, which are also selected to be UV-faint and thus potentially have lower mass black holes, may lie below the black hole–stellar mass relation of the full quasar population.

The bias to selecting ULIRG-class host galaxies may also affect my stellar mass limits, as these galaxies generally lie significantly above the SFR–stellar mass main sequence. Their extreme star-formation rates may indicate the presence of large amounts of dust extinction, as discussed in Section 6.5.1, which could further bias these measurements.

6.5.3 The prevalence of $z \approx 6$ quasars with companions

Companion galaxies have been discovered around a range of high-redshift quasars, with the majority seen only in observations at sub-mm wavelengths (e.g. Wagg et al., 2012; Decarli et al., 2017). For example, Trakhtenbrot et al. (2017a) found companions physically associated with three of six $z \approx 4.8$ quasars observed with ALMA, at separations of 14-45 kpc. Those companions have dynamical masses $M_{\text{dyn}} = (2.1 - 10.7) \times 10^{10} M_\odot$, compared with the quasar hosts which have $M_{\text{dyn}} = (3.7 - 7.4) \times 10^{10} M_\odot$, indicative of major galaxy interactions. These companion galaxies are not detected in Spitzer data, and so Trakhtenbrot et al. (2018) conclude that there must be significant dust-obscuration. This result may explain the lack of companions observed in rest-frame UV observations (e.g. Willott et al., 2005); this is supported by simulations (see Section 5.5.1).

My potential companion galaxies are detected in the rest-frame UV, suggesting that these companions may have less dust attenuation than those observed in the sub-mm. Other studies have also observed companions in the rest-frame UV; for example, McGreer et al. (2014) discovered a companion galaxy around both a $z = 4.9$ and a $z = 6.25$ quasar, at 5 and 12 kpc projected separations. While the companion of the $z = 4.9$ quasar is spectroscopically confirmed, the $z = 6.25$ companion is presumed to be at that redshift based on imaging in two HST filters, as in this study. While identifying these two companions, McGreer et al. (2014) reported that bright companions around high-redshift quasars are uncommon, with an incidence of $\lesssim 2/29$ for $\gtrsim 5L^\ast$ galaxies and $\lesssim 1/6$ for $2 \lesssim L \lesssim 5L^\ast$ galaxies.

Finding quasar companion galaxies is consistent with the scenario that the growth of high-redshift quasars is triggered by galaxy mergers. While simulations predict that galaxy
mergers can fuel quasar activity, it is unclear if these are the dominant cause of high-redshift black hole growth. For example, using the EAGLE simulation, McAlpine et al. (2018) reported that at $z = 0$, $\sim 60\%$ of black holes undergoing a rapid growth phase do so within $\pm 0.5$ dynamical times of a galaxy-galaxy merger, and McAlpine et al. (2020) found an over-abundance of AGN within merging systems relative to control samples of inactive or isolated galaxies. However, while galaxies experiencing mergers have two to three times higher accretion rates than isolated galaxies, the majority of black hole mass growth does not occur during the merger periods (McAlpine et al., 2020). Thus, if the potential companions are confirmed to be associated with the $z \simeq 6$ quasars, this result may be due to the biased sample of FIR-luminous quasars (see discussion in Section 6.5.2) and not necessarily indicative that nearby companions are common around high-redshift quasars.

6.6 Summary

In this chapter, I use HST imaging of five FIR-luminous $z \simeq 6$ quasars, and the hot-dust free quasar SDSS J0005-0006, to search for rest-frame UV emission from their host galaxies. Using the MCMC estimator \texttt{psfMC}, I perform 2D surface brightness modelling for each quasar to model and subtract the quasar point source in order to detect possible underlying host emission.

Only upper limits were found for the quasar host galaxies, of $m_J > 22.7$ and $m_H > 22.4$ mag. These limits are beginning to probe magnitudes expected for high-redshift quasar hosts from the \textsc{BlueTides} simulation, which suggests that the increased resolution and near–mid-infrared spectroscopic capability of JWST should detect host emission in the rest-frame UV/optical for the first time (see also Chapter 5). These host galaxies could be quite dusty, with $\langle A_{UV} \rangle \simeq 2.6$ mag (see Figure 6.12), and thus probing their mid-infrared emission with JWST will be invaluable.

Converting these magnitude limits to stellar mass limits suggests that five of the six quasars could be consistent with the local black hole–stellar mass relation of Kormendy & Ho (2013), and with existing sub-mm observations of $z \simeq 6$ quasar hosts (Willott et al., 2017; Izumi et al., 2018, 2019; Pensabene et al., 2020). SDSS-J0203+0012 has a stellar mass of
\[ \log(M_*/M_\odot) < 11.28 \] and a large black hole mass of \[ \log(M_{BH}/M_\odot) = 10.72, \] which places it above the local relation. However, its black hole mass is likely inaccurate.

I detect up to nine potential \( z \simeq 6 \) companion galaxies surrounding five of the six quasars, with magnitudes and UV spectral slopes consistent with luminous \( z \simeq 6 \) star-forming galaxies. These galaxies lie within 1"-3" of the quasars, or at a projected distance of 8.4–19.4 kpc (if at the same redshift). If their true distance is of order their projected distance, these companions could be interacting with the quasar host galaxies, potentially enhancing their quasar activity (McAlpine et al., 2020; Patton et al., 2020). Finding nine potential \( z \simeq 6 \) companion galaxies is consistent with expectations for large-scale clustering around high-redshift quasars (García-Vergara et al., 2017) and galaxies (Qiu et al., 2018, see Figure 6.10). Hence, I find that these quasars are in environments typical of luminous \( z \simeq 6 \) galaxies.

The existing data cannot rule out the possibility that some of these potential companions are foreground interlopers. Future observations will focus on better constraining the spectral energy distributions of the companions, including deep \( r \)-band imaging to identify low-redshift interlopers, and adaptive optics-corrected K-band imaging to better constrain the rest-frame UV spectral energy distributions. The launch of JWST will allow spectroscopic measurements of the redshifts of these potential companion galaxies, determining whether they are indeed physically associated with the quasars, and perhaps being high-redshift mergers in progress.
Chapter 7

Conclusions and Future Directions

Studying the host galaxies of high-redshift quasars provides vital insights into the early growth of supermassive black holes and the black hole–host galaxy connection, and offers a unique probe into galaxies in the early Universe. Throughout this thesis I have studied the host galaxies of high-redshift quasars using a range of techniques: the MERAXES semi-analytic model, the BLUETIDES hydrodynamical simulation, and observations with the Hubble Space Telescope. In this chapter, I summarise the findings of these studies, and discuss future directions of this work.

7.1 Conclusions

In Chapters 3 and 4 I used the MERAXES semi-analytic model, updated in Chapter 2, to study the evolution of galaxy properties from high-redshift to the present day.

In Chapter 3 I studied the sizes, angular momenta and morphologies of high-redshift galaxies. MERAXES successfully reproduces a range of observations from redshifts $z = 0$–10. I found that in MERAXES the effective radius of a galaxy disc scales with UV luminosity as $R_e \propto L_{UV}^{0.33}$ at $z = 5$–10, and with stellar mass as $R_e \propto M_\star^{0.24}$ at $z = 5$ but with a slope that increases at higher redshifts. The model predicts that the median galaxy size scales with redshift as $R_e \propto (1 + z)^{-m}$, where $m = 1.98 \pm 0.07$ for galaxies with $(0.3–1)L_* z=3$ and $m = 2.15 \pm 0.05$ for galaxies with $(0.12–0.3)L_* z=3$. I found that the ratio between stellar and halo specific angular momentum is typically less than one and decreases with halo and stellar mass. This relation shows no redshift dependence, while the relation between
specific angular momentum and stellar mass decreases by \( \sim 0.5 \) dex from \( z = 7 \) to \( z = 2 \). The model reproduces the distribution of local galaxy morphologies, with bulges formed predominantly through galaxy mergers for low-mass galaxies, disc-instabilities for galaxies with \( M_* \sim 10^{10} - 10^{11.5} M_\odot \), and major mergers for the most massive galaxies. At high redshifts, galaxy morphologies in Meraxes are predominantly bulge-dominated.

In Chapter 4, I used Meraxes to investigate the growth of black holes and their host galaxies from high redshift to the present day. Meraxes finds no significant evolution in the black hole–bulge and black hole–total stellar mass relations out to a redshift of 8. The black hole–total stellar mass relation has similar but slightly larger scatter than the black hole–bulge relation, with the scatter in both decreasing with increasing redshift. In Meraxes the growth of galaxies, bulges and black holes are all tightly related, even at the highest redshifts. I found that black hole growth is dominated by instability-driven or secular quasar-mode growth and not by merger-driven growth at all redshifts. The model also predicts that disc-dominated galaxies lie on the black hole–total stellar mass relation, but lie offset from the black hole–bulge mass relation, in agreement with recent observations and hydrodynamical simulations.

Meraxes is ideal for studying the evolution of galaxies and black holes statistically, particularly at high redshifts, with the high temporal and spatial resolutions of the base Tiamat simulation. Meraxes can also be used to study the impact of various model parameters on the resulting observables, providing useful information about the underlying physics. However, it is unable to make detailed predictions for individual quasar host galaxies. Meraxes is run on the \((67.8/h \text{ cMpc})^3\) N-body simulation Tiamat (Poole et al., 2016), and the larger \((125/h \text{ cMpc})^3\) Tiamat-125-HR simulation (Poole et al., 2017), which has a lower resolution and so is only used for lower-redshift studies. Unfortunately, the volume of Tiamat is too small to contain the rare, massive quasars that are observed in the high-redshift Universe. In the near future Meraxes will be run on upcoming larger-volume Genesis N-body simulations, which will allow Meraxes to make predictions for such quasars.

In Chapter 5 I used the BlueTides cosmological hydrodynamical simulation to study the host galaxies of \( z = 7 \) quasars. The BlueTides volume of \((400/h \text{ cMpc})^3\) contains hundreds of quasars at \( z = 7 \), and can resolve more detailed properties of their host
galaxies. However, BlueTides is limited to $z \geq 7$, and so unlike Meraxes cannot be used to study the evolution of the black hole population to low redshift.

In Chapter 5, I showed that the 10 most massive black holes and the 191 quasars in the BlueTides simulation (with $M_{UV, AGN} < M_{UV, host}$) are hosted by massive galaxies with stellar masses $\log(M_*/M_\odot) = 10.8 \pm 0.2$, and $10.2 \pm 0.4$, which have large star formation rates, of $513^{+1225}_{-351} M_\odot/yr$ and $191^{+288}_{-120} M_\odot/yr$, respectively. The hosts of the most massive black holes and quasars in BlueTides are generally bulge-dominated, with bulge-to-total mass ratio $B/T \simeq 0.85 \pm 0.1$, however their morphologies are not biased relative to the overall $z = 7$ galaxy sample. The hosts of the most massive black holes and quasars are significantly more compact, with half-mass radii $R_{0.5} = 0.41^{+0.18}_{-0.14}$ kpc and $0.40^{+0.11}_{-0.09}$ kpc respectively, relative to galaxies with similar masses, which have $R_{0.5} = 0.71^{+0.28}_{-0.23}$ kpc. I made mock JWST images of these quasars and their host galaxies. Distinguishing the host from the quasar emission will be possible but still challenging with JWST, due to the small sizes of quasar hosts. I also found that quasar samples are biased tracers of the intrinsic black hole–stellar mass relations, following a relation that is 0.2 dex higher than that of the full galaxy sample. Finally, the most massive black holes and quasars are more likely to be found in denser environments than the typical $M_{BH} > 10^{6.5} M_\odot$ black hole, indicating that minor mergers at least play some role in growing black holes in the early Universe.

Finally, in Chapter 6, I used Hubble Space Telescope observations to search for rest-frame UV emission from the host galaxies of five FIR-luminous $z \simeq 6$ quasars and the $z = 5.85$ hot-dust free quasar SDSS J0005-0006. I performed 2D surface brightness modelling for each quasar using a Markov-Chain Monte-Carlo estimator, to simultaneously fit and subtract the quasar point source in order to constrain the underlying host galaxy emission. I measured upper limits for the quasar host galaxies of $m_J > 22.7$ mag and $m_H > 22.4$ mag, corresponding to stellar masses of $M_* < 2 \times 10^{11} M_\odot$. These stellar mass limits are consistent with the local $M_{BH} - M_*$ relation. These flux limits are consistent with those predicted for the UV stellar populations of high-redshift host galaxies from BlueTides, but likely in the presence of significant dust ($\langle A_{UV} \rangle \simeq 2.6$ mag). I also detected a total of up to 9 potential $z \simeq 6$ quasar companion galaxies surrounding five of the six quasars, separated from the quasars by $1''4 - 3''2$, or $8.4 - 19.4$ kpc, which may be interacting with the quasar hosts. These nearby companion galaxies have UV absolute magnitudes of $-22.1$
to $-19.9$ mag, and UV spectral slopes $\beta$ of $-2.0$ to $-0.2$, consistent with luminous star-forming galaxies at $z \approx 6$. These results suggest that the quasars are in dense environments typical of luminous $z \approx 6$ galaxies. However, the possibility that some of these companions are foreground interlopers cannot be ruled out. Infrared observations with JWST will be needed to detect the $z \approx 6$ quasar host galaxies and better constrain their stellar mass and dust content.

### 7.2 Future directions

The launch of JWST in the near future will provide new opportunities for detecting the host galaxies of high redshift quasars. In preparation for this groundbreaking observatory, based on the work presented in this thesis the BLUETIDES simulation can make important predictions and optimisations for these upcoming observations.

#### 7.2.1 Testing the PSF-subtraction technique

In Chapter 5 I used the BLUETIDES simulation to make mock JWST images of quasars and their host galaxies. With these mock images, the quasar subtraction technique used in Chapter 6 can be thoroughly tested. By passing the BLUETIDES mock JWST images through the observational pipeline and comparing the known intrinsic galaxy properties to the resulting measured properties, I can explore the systematic biases and success rates for determining host galaxy properties using this technique. This would also provide useful insights into which quasars should be observed with JWST in order to have the highest chance of detecting the host galaxies, optimising the output of any observing time obtained on this in-demand instrument.

This comparison will also help to determine the best observing strategy for measuring quasar hosts with JWST, by exploring the effectiveness of the technique on images with different photometric filters of the NIRCam and MIRI instruments. In addition, it would be possible to use BLUETIDES to explore different strategies for detecting quasar hosts, for example by measuring the spectra of the combined quasar and host system. The rest-frame optical, redshifted into the infrared for these high-redshift systems, contains bright emission lines that are commonly used in lower redshift observations to measure stellar masses, for example. JWST will allow us to probe these wavelengths in detail for
the first time. BlueTides could even be used to produce mock integral field unit (IFU) spectroscopy, which obtains a spectrum for each image pixel producing a 3D data cube. This would require integration of BlueTides with software designed to make mock IFU data, but could be invaluable for making predictions for upcoming JWST IFU observations.

### 7.2.2 Predictions for sub-mm observations

The BlueTides predictions for quasar hosts in this thesis have focused on their stellar emission. However, the only existing observations of high-redshift quasar hosts are in the rest-frame FIR, observed in the sub-mm (e.g. Bertoldi et al., 2003b; Walter et al., 2003, 2004; Riechers et al., 2007; Wang et al., 2010, 2011), which is sensitive to the emission from cold gas and dust. The distribution of gas in the galaxy may not necessarily trace the stellar distribution, however, leading to significant biases in host stellar properties inferred from these observations (e.g Narayanan et al., 2009; Valiante et al., 2014).

The gas properties of galaxies in BlueTides could be used to make mock sub-mm images which simulate ALMA observations. The typical observational procedures used to measure the dynamical masses and gas properties of these galaxies (e.g. Jahnke et al., 2009; Wang et al., 2013; Willott et al., 2017) could then be applied to these images, which can be compared to the known galaxy properties from the simulation (as in e.g. Lupi et al., 2019). This could help to understand and correct for the biases present in these types of observations, and also determine the types of quasars and host galaxies that will give the least-biased sub-mm detections. This could guide future observational strategies for detecting host galaxies with ALMA, to obtain the most accurate measurements of the black hole–host relations at high redshift.

### 7.2.3 JWST observations

Our team has guaranteed time on JWST to observe two of the quasars studied in Chapter 6, NDWFS J1425+3254 and SDSS J0005-0006, with the NIRSpec IFU instrument. Using the improvements of JWST over HST, I will use the quasar subtraction technique on these observations, hopefully detecting quasar host galaxy emission in the rest-frame UV/optical for the first time. The data will also be used to spectroscopically confirm the redshifts of the companion galaxies of these two quasars. This will confirm whether or not they
are indeed spatially coincident with the quasar, i.e. mergers in progress, and not just foreground interlopers. Witnessing merging galaxies trigger quasar activity at such high redshifts will give valuable insights into black hole and galaxy growth processes.

As well as these planned observations, it will be ideal to obtain further observations of high-redshift quasars with JWST with the aim of detecting their host galaxies, for example of the other 4 quasars in the Chapter 6 sample. These observations would likely be planned based on the results of a deeper analysis with BlueTides and the observational technique, as detailed above, in order to extract the best information about these high-redshift quasar hosts.

It would also be advantageous to observe these quasars with high-resolution ALMA or NOEMA observations, to compare the host properties inferred from the rest-frame UV/optical to those in the rest-frame infrared.

The upcoming launch of JWST will lead to significant improvements in our ability to observe the host galaxies of high redshift quasars. This will allow for a much clearer picture of the black hole–host relations in the early Universe, leading to a deeper understanding of the cause of these correlations and the growth of the first supermassive black holes. We are entering an exciting phase of high-redshift astronomy, with JWST set to address some of the biggest mysteries of the early Universe.
Appendix A

Galaxy UV Luminosities and Star Formation Rates

The galaxy UV luminosity functions at $z = 8–4$ for the new MERAXES model, as calibrated in Chapter 3, are shown in Figure A.1. These agree with those from the Q17 MERAXES model and observations, but diverge slightly at both the bright and faint ends.

The $z = 1.5$ star formation rate–stellar mass relations for the Q17 and new MERAXES models are shown in Figure A.2, alongside observations by Lee et al. (2015), Kurczynski et al. (2016), Santini et al. (2017) and Bisigello et al. (2018). Both the Q17 and new MERAXES models predict a star formation main sequence consistent with the observations, with the new MERAXES showing a relation that extends to lower star formation rates. This is a result of the new star formation prescription (Section 2.5).
Figure A.1 Galaxy luminosity functions at $z = 8$–$4$ from the Q17 MERAXES and the new model (M19; Chapter 3) compared to the observations of Yoshida et al. (2006); van der Burg et al. (2010); Bouwens et al. (2015); Atek et al. (2015) (see legend).

Figure A.2 The relation between star formation rate (SFR) and stellar mass ($M_*$) at $z = 1.5$ for both the Q17 and the updated MERAXES (M19; Chapter 3), alongside observations (Lee et al., 2015; Kurczynski et al., 2016; Santini et al., 2017; Bisigello et al., 2018, see legend). The black squares and errorbars represent the median and 16th and 84th percentile ranges of the models. Only galaxies classified as centrals are shown. The grey dotted line indicates the stellar mass below which Tiamat and Tiamat-125-HR are not converged (see Section 2.7).
Appendix B

Consistency of Tiamat and Tiamat-125-HR

Throughout Chapters 3 and 4, I use the higher resolution *Tiamat* simulation at $z \geq 2$, and *Tiamat-125-HR* for $z < 2$, where *Tiamat* is unavailable. I find that the results discussed in Chapters 3 and 4 are generally consistent between the two simulations at $z \approx 2$, and so in general I am confident that any redshift evolution I find at $z < 2$ is not caused by a change in simulation.

However, one notable result is that the best-fitting black hole–stellar mass relations of Figure 4.7 change rapidly between $z = 2$ (using *Tiamat*) and $z = 1$ (using *Tiamat-125-HR*). To verify that this jump is not purely a result of the simulation change, I show the best-fitting relations from $z = 6–0$ using *Tiamat-125-HR* (Figure B.1). The *Tiamat-125-HR* simulation shows similar results to those found using *Tiamat* at $z \geq 2$ (Figure 4.7), with a slightly milder but still relatively rapid evolution from $z = 2$ to $z = 1$. The qualitative result of the evolution being insignificant relative to the scatter in the relation still holds. Thus, while the change in simulation slightly amplifies the rapid change in the black hole–stellar mass relations from $z = 2$ to $z = 1$, this does not change my conclusions.

I also note that where the black hole mass functions are converged ($M_{BH} > 10^{7.1} M_\odot$), the black hole–stellar mass relations are in good agreement between the two simulations.
Figure B.1 Lines of best-fit to the black hole–bulge mass (left panel) and black hole–total stellar mass (right panel) relations at a range of redshifts, using the Tiamat-125-HR simulation. The blue density plot shows the $z = 0$ distribution. This shows similar results to those found using the Tiamat simulation at $z \geq 2$ (Figure 4.7), with a slightly milder evolution from $z = 2$ to $z = 1$. 
Appendix C

Magnitude Calculation

To convert the surface brightness in the annulus 0′.42–0′.60 to a magnitude, I consider the host galaxy to have a Sérsic profile and to be azimuthally symmetric. The total flux contained within radius $R$ is

$$F(R) = \int_0^R 2\pi r f(r) dr \quad (C.1)$$

where $f(r)$ is the flux per unit physical area at radius $r$. For a Sérsic profile with Sérsic index $n$ and effective radius $R_e$,

$$f(r) = f(R_e) \exp \left( -b_n \left( \frac{r}{R_e} \right)^{1/n} - 1 \right) \quad (C.2)$$

where $b_n$ is defined to satisfy $\Gamma(2n) = 2\gamma(2n, b_n)$, where $\Gamma$ and $\gamma$ are the complete and incomplete gamma functions, $\Gamma(a) = \int_0^\infty t^{a-1} e^{-t} dt$ and $\gamma(a, x) = \int_x^\infty t^{a-1} e^{-t} dt$. Thus, $F(R)$ can be expressed as

$$F(R) = 2\pi R_e^2 f(R_e) \frac{b_n}{n} \gamma(2n, b_n (R/R_e)^{1/n}) \quad (C.3)$$

Given $\Delta F = F(0′.60) - F(0′.42)$ is the flux measured in the annulus, $f(R_e)$ can be calculated from:

$$f(R_e) = \Delta F \left[ 2\pi R_e^2 \frac{b_n}{n} \gamma(2n, x_1) \right]^{-1} \quad (C.4)$$

where $x_1 = b_n(0.60/R_e[\text{arcsec}])^{1/n}$ and $x_2 = b_n(0.42/R_e[\text{arcsec}])^{1/n}$. I thus calculate the flux of the host galaxy as $F(0′.60)$.

I calculate this flux for a range of Sérsic profiles, with $n \in (0.5, 5)$ and $R_e \in (0, 4)$ kpc, ignoring galaxies which have magnitudes brighter than the observed magnitude of the
Guided by the observations of $z \simeq 6$ bright $(1-10L^*_{z=3})$, massive galaxies by Shibuya et al. (2015), I assume probability distribution functions for $n$ and $R_e$, with the combined 2D probability distribution function shown in Figure C.1. I use a Monte Carlo technique to sample from this distribution, and determine the resulting probability distribution function for host galaxy magnitude. I choose the most-likely value from this distribution as the magnitude limit. Note that this is not the magnitude of the most likely $n$-$R_e$ combination, as many less-likely $n$-$R_e$ combinations produce similar magnitudes and make those more likely.
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