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Ultrasound Black Holes Formed by Triple Quasar Mergers at $z \sim 2$

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Abstract

The origin of rare and elusive ultramassive black holes (UMBHs; with $M_{\text{BH}} > 10^{10} M_\odot$) is an open question. Using the large volume cosmological hydrodynamic simulation ASTRID, we report on the formation of an extremely massive UMBH with $M_{\text{BH}} \sim 10^{11} M_\odot$ at $z \sim 2$. The UMBH is assembled as a result of two successive mergers of massive galaxies each with stellar mass $M_* > 3 \times 10^{11} M_\odot$, that also produces a bright, rare triple quasar system powered by three $\sim 10^9 M_\odot$ black holes. The second merger of supermassive black holes (SMBHs) follows the first after 150 Myr. The merger events lead to sustained Eddington accretion onto the central SMBH, forming a UMBH in the center of a massive compact stellar core with $M_* > 2 \times 10^{12} M_\odot$. The strong feedback of the UMBH quenches the surrounding star formation to $< 10 M_\odot \text{yr}^{-1}$ in the inner 50 $h^{-1}$ kpc region. There are two more UMBHs with $M_{\text{BH}} > 5 \times 10^9 M_\odot$ at $z > 2$ in ASTRID that are also produced by major mergers of galaxies, and their progenitors can be observed as quasar triplets of lower luminosity. The rarely observed quasar multiples can be the cradle of UMBHs at high redshift, and likely end up in the center of the most massive clusters.

Unified Astronomy Thesaurus concepts: Hydrodynamical simulations (767); Supermassive black holes (1663)

1. Introduction

Probing the most massive end of the supermassive black holes (SMBHs) and their relation with host galaxy properties is crucial for us to reach a comprehensive understanding of how they grow and coevolve with cosmic structures like galaxies, galaxy groups, and even clusters of galaxies. Over the last decade, observations of the local universe have established the existence of a few ultramassive black holes (UMBHs; with $M_{\text{BH}} > 10^{10} M_\odot$) in some bright cluster galaxies (e.g., see McConnell et al. 2011; Hlavacek-Larrondo et al. 2012). The current most massive black hole with direct dynamical mass measurement is $M_{\text{BH}} \sim 4 \times 10^{10} M_\odot$ (Mehrgan et al. 2019) at the center of Holm15A, the central galaxy of Abell 85. Indirect mass measurements of high redshift quasars suggest the existence of UMBHs with $M_{\text{BH}} > 6 \times 10^{10} M_\odot$ (e.g., TON618, Shemmer et al. 2004). Given the difficulties and uncertainties lying in the mass measurement of SMBHs (e.g., see Kelly & Merloni 2012; Peterson 2014, for a review), it still remains unclear whether there exist or can exist UMBHs with a larger mass. Some theoretical studies suggest that there is an upper limit for black hole mass in the $M_{\text{BH,max}} = 5 \times 10^{10} - 2 \times 10^{11} M_\odot$ regime, above which they cannot grow through luminous accretion of gas (Natarajan & Treister 2009; King 2016).

It has been suggested that UMBHs could be remnants of extremely luminous quasars seen at higher redshift and hence may form around the peak of the quasar phase at $z \sim 2$. Many observational studies suggest that galaxy mergers can play an important role in the triggering of active galactic nuclei (AGN) activity and growth of SMBHs (see, e.g., Ramos Almeida et al. 2011; Weston et al. 2017; Donley et al. 2018; Gao et al. 2020). Cosmic noon features the peak of quasar and star formation activity (Richards et al. 2006; Madau & Dickinson 2014), as well as a specific galaxy merger rate (Duncan et al. 2019). Major mergers of gas-rich galaxies at this epoch can fuel quasars and give rise to the most extreme black hole growth and assembly.

The existence of multiple simultaneously active SMBHs, in galaxy mergers represents a key observational test (e.g., Bennert et al. 2008) for understanding the processes regulating quasar activity and the growth of SMBHs. Extreme examples of these are the rare quasar multiples, that are rather challenging to detect due to their rarity, the required angular resolution, incompleteness, interlopers of lensed pairs, etc. There are, however, two observations of (luminous) quasar triplets that have been reported so far, QQJ1432-0106 at $z = 2.1$ observed by Djorgovski et al. (2007), and QQ J1519 + 0627 at $z = 1.5$ reported by Farina et al. (2013). The two quasar triplets are observed on galactic scales with separations around tens to hundreds of pkpc at $z \sim 2$. Based on the velocity differences in the triplet, those authors propose that the three quasars are “caught in the act” and form a physical structure of mass $10^{13} M_\odot$. Based on the rarity of this event and the mass of the remnant galaxy and black hole, such a triple quasar system may thus be an ideal candidate for a progenitor of a UMBH in a central cluster galaxy today.

The rare quasar multiples and their mergers are difficult to model in cosmological simulations due to the limited volume. In this work, we inspect the formation of rare UMBHs predicted by the ASTRID simulation at $z \geq 2$ and investigate their origin. ASTRID is a recently developed large volume, high-resolution cosmological hydrodynamic simulation (Bird et al. 2022; Ni et al. 2022). Its large volume of $(250 h^{-1} \text{Mpc})^3$ (the greatest volume for a galaxy formation simulation to date) allows a systematic study of the rare quasar and galaxy population at cosmic noon, and can probe the most extreme events such as multiple major mergers of massive galaxies and systems of quasar multiples.

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The paper is organized as follows. We briefly introduce the ASTRID simulation in Section 2. In Section 3, we give ASTRID predictions for the statistics of the dual and triple quasars with galactic separations. We describe in detail how the merger of the brightest triple quasar system forms a UMBH with mass $M_{\text{BH}} > 10^{11} M_\odot$ and explore the various host galaxy properties. We discuss the result in Section 4 and conclude in Section 5.

2. Simulation

The ASTRID simulation is a cosmological hydrodynamical simulation performed using a new version of the smoothed particle hydrodynamics code MP-Gadget. The simulation evolved a cube of 250 $h^{-1}$ Mpc per side with $2 \times 5500^3$ initial tracer particles of dark matter and baryons, and has currently reached $z=2$. It is the largest cosmological simulation of galaxy formation to date that covers the epoch of cosmic noon.

ASTRID achieves a dark matter particle mass resolution of $M_{\text{DM}} = 6.7 \times 10^6 h^{-1} M_\odot$ and $M_{\text{gas}} = 1.3 \times 10^6 h^{-1} M_\odot$ in the initial conditions. The gravitational softening length is $\epsilon_g = 1.5 h^{-1}$ kpc for both dark matter (DM) and gas particles. The simulation implements a variety of subgrid models for physics governing the formation of galaxies and SMBHs and their associated supernova and AGN feedback, inhomogeneous hydrogen and helium reionization, and the effect of massive neutrinos. We refer the readers to the introductory papers by Bird et al. (2022) and Ni et al. (2022) for detailed descriptions of physical models used in the simulation.

We briefly summarize the models for SMBH applied in ASTRID as follows. The black holes are seeded in halos with $M_{\text{halo}} > 5 \times 10^9 h^{-1} M_\odot$ and $M_{\text{gas}} > 2 \times 10^9 h^{-1} M_\odot$. Seed masses are stochastically drawn from a power-law probability distribution, with a mass between $3 \times 10^5 h^{-1} M_\odot$ and $3 \times 10^8 h^{-1} M_\odot$ and power-law index $n = -1$. The gas accretion rate onto the black hole is estimated via a Bondi–Hoyle–Lyttleton-like prescription (Di Matteo et al. 2005). We allow for short periods of super-Eddington accretion in the simulation but limit the accretion rate to two times the Eddington accretion rate. The black hole radius with a bolometric luminosity $L_{\text{bol}}$ proportional to the accretion rate $M_\dot{\epsilon}$, with a mass-to-energy conversion efficiency $\eta = 0.1$ in an accretion disk according to Shakura & Sunyaev (1973); 5% of the radiated energy is coupled to the surrounding gas as the AGN feedback. Dynamics of the black holes are modeled with a newly developed (subgrid) dynamical friction (Tremmel et al. 2015; Chen et al. 2022) to replace the original implementation that directly repositioned the black holes (BHS) to the local minimum potential. This model gives well-defined black hole trajectories and velocities and therefore provides a more physical treatment of the mergers of black holes. Two black holes can merge if their separation is within two times the gravitational softening length $2 \epsilon_g$; once their kinetic energy is dissipated by dynamical friction and they are gravitationally bound.

Galaxies in the simulation are identified through SUBFIND (Springel et al. 2001) in a postprocessed manner. At $z=2$, ASTRID contains a statistical sample of very massive galaxies and bright quasars, with about $3 \times 10^3$ galaxies having $M_\star > 10^{11} M_\odot$ and 13 galaxies having $M_\star > 10^{12} M_\odot$. It produces 709 black holes with $M_{\text{BH}} > 10^9 M_\odot$, three of which have $M_{\text{BH}} > 5 \times 10^{10} M_\odot$, with the most massive one having reached $10^{11} M_\odot$. The large volume of ASTRID provides us with an ideal suite to study the galaxy and quasar population at cosmic noon.

3. Results

3.1. Quasar Multiples at the Bright End of the Quasar Population

We start with a brief overview of the quasar population predicted by ASTRID, focusing on the bright quasars that can be probed by observations of dual and triple quasar systems. Figure 1 shows the quasar population with luminosity threshold $L_{\text{bol}} > 10^{45.5} \text{ erg s}^{-1}$ (commensurate with observations of, e.g., Shen et al. 2022): ASTRID has a sample of 700–800 quasars, in broad agreement with the observational estimate of Shen et al. (2020) over the full redshift range. Given the transitory nature of the active quasar phase, we calculate the number density of dual and triple quasars in a time-averaged manner (as shown by the orange and pink lines). Only ~1% and 0.02% of quasars are in the dual and triple quasar systems, respectively, with separation from $5 < r < 200 h^{-1}$ kpc (corresponding to angular separation $\delta = 0.3 – 10^\circ$ at $z \sim 2$). Thereby, based on time-averaged estimation, ASTRID predicts dual quasar fraction $f_{\text{QQ}} \sim 1 \times 10^{-2}$ and triple quasar fraction $f_{\text{QQQ}} \sim 2 \times 10^{-3}$ among quasars with $L_{\text{bol}} > 10^{45.5} \text{ erg s}^{-1}$ at $z = 2 \sim 3$.

With the large volume of ASTRID, we are able to find a handful of rare quasar triplets at $z \sim 2$. In the redshift range of $z > 2$, there exist five such systems in ASTRID that contain three quasars that meet the luminosity and distance criteria at a given time, and two of those triplet systems only last for a short period of time with $t_{\text{QQQ}} < 50$ Myr. In the entire simulation, there is only one triplet in which all three quasars have $L_{\text{bol}} > 10^{46} \text{ erg s}^{-1}$. Remarkably, we find that this system is the progenitor of the $10^{11} M_\odot$ black hole, the most extreme UMBH formed in the simulation. We focus on this brightest quasar
triplet and show how the two subsequent mergers of the quasar host galaxies allow the mass assembly of this extreme UMBH.

3.2. Massive Mergers and Triple Quasars

The triple quasar system is formed at the early stages of a merger of three massive galaxies, each hosting strongly accreting SMBHs. The first merger (merger 1) is closely followed by a second one (merger 2).

Table 1 summarizes the properties of the galaxies and black holes taking part in this event. The system is hosted by one of the largest halos in the simulation, with mass $M_{\text{halo}} \sim 6 - 9 \times 10^{13} M_{\odot}$. In the initial phase of the interaction, the three host galaxies all have a stellar mass of a few $10^{11} M_{\odot}$. The system starts from a stage of quasar triplet at $z \sim 2.7$, with each quasar having $L_{\text{bol}} \sim 10^{46} \text{ erg s}^{-1}$, and the associated three SMBHs (with masses ranging from 0.5 to 3 $10^8 M_{\odot}$) residing in their respective host galaxies. This stage is followed by two subsequent mergers of galaxies and the SMBHs, leaving the final remnant massive galaxy hosting a UMBH of mass $M_{\text{BH}} \sim 10^{11} M_{\odot}$ after the second merger at $z \sim 2.3$.

To illustrate those stages, Figure 2 shows the triple quasars together with their respective host galaxies and snapshots over the dynamical evolution of this system. The evolution of the black hole masses, luminosities, as well as the gas distribution, are illustrated by snapshots at $z = 2.7$.

Table 1: Host Information for the Triple Quasar System from $z = 2.7$ to $z = 2.0$; $M_{\text{halo}}$ is the Halo Mass of the Friend-of-friend (FOF) Group

| Redshift | $M_{\text{BH}}$ ($M_{\odot}$) | $L_{\text{bol}}$ (ergs$^{-1}$) | $M_*$ ($M_{\odot}$) | $M_{\text{halo}}$ ($M_{\odot}$) |
|----------|-------------------------------|-------------------------------|-------------------|-------------------|
| $z = 2.7$ | $(3.0 e 9, 8.3 e 8, 5.2 e 8)$ | $[2.6 e 46, 1.7 e 46, 9.6 e 45]$ | $[4.6 e 11, 5.5 e 11, 3.2 e 11]$ | $6.3 e 13$ |
| Before merger 1 | $z = 2.5$ | $(4.3 e 9, 2.3 e 9, 1.6 e 9)$ | $[1.0 e 47, 1.6 e 46, 5.0 e 46]$ | $[9.8 e 11, 4.7 e 11, 3.6 e 11]$ | $7.8 e 13$ |
| After merger 1 | $z = 2.4$ | $(9.4 e 9, 2.7 e 9)$ | $[1.2 e 47, 1.8 e 46]$ | $[1.6 e 12, 5.0 e 11]$ | $9.0 e 13$ |
| After merger 2 | $z = 2.3$ | $(7.2 e 10)$ | $[4.4 e 48]$ | $[2.5 e 12]$ | $9.4 e 13$ |
| $z = 2.0$ | $(1.8 e 11)$ | $[1.9 e 45]$ | $[2.3 e 12]$ | $1.1 e 14$ |

For the first and second merger are 11 Myr and 36 Myr, respectively. The time taken between pairing and merger for these two black holes is short compared to the overall $t_{\text{elapse}}$ distribution for all black hole merger events in ASTRID, which peaks at $t_{\text{elapse}} \sim 200$ Myr (see Ni et al. 2022). The short merger elapse time is a result of the high stellar density surrounding the black holes and associated effective dynamical friction in these environments that quickly dissipates the kinetic energy of the black holes.

At around $z = 2.3$, just after the final black hole merger, we have the most luminous quasar in the entire simulation, with $L_{\text{bol}} > 10^{48} \text{ erg s}^{-1}$ (Figure 3). This critical accretion phase with sustained Eddington rate grows the black hole mass by about tenfold, and is induced by the major merger of the host galaxy. During this most active accretion phase, the central black hole is however surrounded by high density gas with line-of-sight column density ranging from $N_H = 5 \times 10^{23} \sim 10^{25}$ cm$^{-2}$ (with median value $N_H = 10^{25}$ cm$^{-2}$) that heavily obscures most of the sight lines to the quasar. More than 30% of the line sight will get Compton thick obscuration with $N_H > 1.5 \times 10^{24}$ cm$^{-2}$. The close-to-Eddington phase lasts for about 140 Myr and is finally quenched by powerful AGN feedback. At $z < 2.23$ (96 Myr after the second merger event), powerful gas outflow driven by the AGN feedback clears out the dense gas in its surroundings and quenches the active accretion. The luminosity of the UMBH decreases to $10^{46} \text{ erg s}^{-1}$ and the corresponding Eddington ratio falls into the $\lambda_{\text{Edd}} < 10^{-5}$ regime.

3.3. The Remnant Host Galaxy of a Triple Quasar and Newly Formed UMBH

Figure 4 shows the $M_{\text{BH}} - M_*$ and SFR - $M_*$ relations for all the $M_* > 10^8 M_{\odot}$ galaxies in ASTRID at $z=2$ and highlights the triple merger system and its evolution from $z = 2.7$ to $z = 2.0$, in these two planes. Insets to Figure 4 illustrate the evolution of the BH1 host galaxy and the star formation environment in its surroundings.

The overall $M_* - M_{\text{BH}}$ relation in ASTRID shows broad agreement compared to the scaling relation fit to observations of the local AGN population. Massive galaxies with $M_* > 3 \times 10^{11} M_{\odot}$ typically host BHs with $M_{\text{BH}} \geq 5 \times 10^8 M_{\odot}$. The host galaxies of the triple quasars at $z \geq 2.5$ have $M_{\text{BH}} - M_*$ values comparable to (albeit slightly lower than) the overall distribution. All three systems are rich in gas and have high star formation rates $>5 \times 10^2 M_\odot$ yr$^{-1}$ at $z = 2.7$. At $z = 2.5$ when the first two galaxies (hosts of BH1 and BH2) begin their encounter and merge with each other, the central massive galaxy experiences a starburst with star formation rate $>5 \times 10^2 M_\odot$ yr$^{-1}$, which quickly builds up the stellar mass of the remnant. As illustrated by the inset panel, the BH1 host galaxy at $z = 2.5$ exhibits a disturbed morphology.
during the merger process. At z = 2.3, the merger of the second system is responsible for the assembly of the most massive galaxy in the simulation with $M_\ast > 2 \times 10^{12} M_\odot$ and also leads to the most massive black hole with $M_{\text{BH}} \sim 10^9 M_\odot$. The resultant $M_{\text{BH}}$ and $M_\ast$ values for this system sit on the extrapolation of the scaling relation from Reines & Volonteri (2015). The remnant galaxy at $z = 2.0$ has a stellar mass of $M_\ast = 2.3 \times 10^{12} M_\odot$, with half mass–radius $r_{1/2} = 3$ pkpc, in agreement with the observations of $z > 2$ massive galaxies finding that their morphologies are usually compact (e.g., Papovich et al. 2005).

In Figure 4 we show the total star formation rate as a function of stellar mass for the whole population of galaxies in the simulation. We follow the evolution of the star formation rate of the triple system and show in the inset images the star-forming gas surrounding BH1 before and after the merger. Here we see how the starburst in the early stages of the galaxy merger produces a large star formation rate in the center of the galaxy. The powerful AGN feedback is able to blow the star-forming gas out of the galaxy (see also Ni et al. 2018, on quasar outflow), suppressing star formation in the central regions of the remnant host galaxy. At this point, all of the remaining star formation (still of the order of $100 M_\odot \text{yr}^{-1}$) occurs in dense clouds on the outskirts of the galaxy (as shown by the image at $z \sim 2$). The star formation rate in the innermost $50 \ h^{-1}$ kpc region from the central black hole is $\sim 10 M_\odot \text{yr}^{-1}$. The remnant of this triple quasar system is reminiscent of the observation of the large clouds of gas surrounding the quasar in the TON 618 system. The Atacama Large Millimeter/submillimeter Array has recently confirmed that the host galaxy of this system is surrounded by an enormous Ly$\alpha$ blob (LAB) with inferred molecular gas content sufficient to provide $\sim 50 - 100 M_\odot/\text{yr}$ at hundreds of kiloparsecs from the quasar itself (Li et al. 2021). In the simulation, the star-forming gas pushed out by the quasar outflow, and the remnant $z \sim 2$ UMBH appears consistent with the observed environment for a candidate UMBH in TON 618 (Li et al. 2021). This supports a scenario in which the formation of a UMBH involves a strong quasar phase (major triple merger) hosted by a strongly quenched host galaxy with associated molecular gas outflow and extended LAB system at $z \sim 2$.

4. Discussion

The most massive UMBH with $M_{\text{BH}} = 1.8 \times 10^{11} M_\odot$ at $z = 2$ in ASTRID is close to the theoretical estimate of the black hole mass upper limit, which is in the mass regime of $5 \times 10^{10} \sim 2.7 \times 10^{11} M_\odot$ (King 2016). At $z = 2$, there are two other UMBHs with $M_{\text{BH}} > 5 \times 10^{10} M_\odot$ in ASTRID, with the second most massive black hole having mass $M_{\text{BH}} = 6.4 \times 10^{10} M_\odot$. We trace their evolution history and find that they have both experienced two massive black hole mergers involving $M_{\text{BH}} \sim 10^9 M_\odot$ black holes following the merger of their host galaxies. Resembling the $10^{11} M_\odot$ UMBH, the other systems gained the majority of their black hole mass through active gas accretion induced by mergers of galaxies.
Figure 3. Detailed evolution of each of the three quasars. The blue line represents the BH1, the central black hole in Figure 2. The red (orange) line in the first panel gives the 3D distance between BH2 (BH3) and BH1. The horizontal dashed line marks 2r_s as the gravitational softening when the black hole merger occurs in the simulation. The two insets zoom into the dashed rectangles to better show the evolution before the SMBH mergers. The second to the fourth panels show the evolution of black hole mass, bolometric luminosity, and the Eddington ratio, respectively. The bottom panel shows the gas column density N_H surrounding each black hole. We calculate N_H by integrating the neutral hydrogen number density along different lines of sights toward the central BHs and show the median N_H among all sight lines. The vertical dashed lines in each panel mark the time of SMBH mergers.

(with smaller stellar mass). Their progenitors are seen to be quasar triplets with lower luminosities of L_{bol} \sim 10^{45} \text{ erg s}^{-1}.

However, a caveat is that the UMBH mass seen in ASTRID is not a prescription for a new upper limit for the black hole mass, as cosmological simulations cannot directly resolve the physical processes of black hole accretion below kiloparsec scales. The growth or accretion state of black holes (and therefore the final black hole mass) might vary depending on specific prescriptions for the black hole subgrid model that links the thermal state of gas on kiloparsec scales to activity on unresolved scales. In this work, we stress that the most massive UMBHs in the simulation are formed through multiple mergers of SMBHs residing in massive, gas-rich galaxies around cosmic noon, and that the progenitor systems can be observed as quasar triplets. We expect that variations in the black hole subgrid model should not qualitatively change this conclusion.

Given the unprecedented large volume of ASTRID, this may be the first time that such an extreme merger of three M_e > 3 \times 10^{11} M_\odot galaxies at z \sim 2 has been directly modeled in a uniform volume cosmological hydrodynamic simulation of sufficient resolution. We have established that a 10^{11} M_\odot UMBH might form in such an extreme event. The resultant M_{BH} - M_\ast relation lies on (or slightly above) the extrapolation of the M_{BH} - M_\ast fit based on local AGN observations. The UMBH resides at the center of a M_h = 10^{14} M_\odot halo at z = 2. The number density of such massive halos is \phi \sim 10^{-6} \text{ cMpc}^{-3}, as rare as the massive clusters in the local universe with M_h \sim 2 \times 10^{15} M_\odot. This implies that M_{BH} > 10^{11} M_\odot UMBHs may reside in the massive clusters in the local universe and have assembled their mass at cosmic noon through frequent mergers of massive galaxies.

5. Conclusion

ASTRID is the first cosmological hydrodynamic simulation with a volume large enough to cover a handful of the rare most massive M_\ast > 10^{12} M_\odot galaxies and M_e \sim 10^{13} M_\odot halos at the z \sim 2 epoch known as cosmic noon. It models black hole growth and coevolution with galaxies using a set of subgrid physical models that are in broad agreement with various observational constraints, such as galaxy populations, quasar luminosity functions, M_{BH} - M_\ast relations, etc. We find that ultramassive black holes with extreme masses of M_{BH} \gtrsim 5 \times 10^{10} M_\odot can be formed in the rare events that are multiple massive galaxy mergers happening around z \sim 2, the epoch when both star formation and AGN reach their peak activity.

We investigate the population of dual and triple quasars with a luminosity threshold L_{bol} > 10^{45.5} \text{ erg s}^{-1}. For a given quasar at z = 2−3, the probability of finding another (dual) or two other (triple) quasars within a galactic separation of 5 h^{-1} \text{kpc} < r < 200 h^{-1} \text{kpc} (0.25−3 z \sim 2) is on order of f_{QQ} \sim 1 \times 10^{-2} and f_{QQQ} \sim 2 \times 10^{-4}.

We showed the formation of a UMBH with M_{BH} \sim 10^{11} M_\odot at z = 2.3, produced by the merger of a bright triplet quasar system with members having L_{bol} > 10^{46} \text{ erg s}^{-1} and residing in massive galaxies with M_e > 3 \times 10^{11} M_\odot. The subsequent massive galaxy merger triggered active star formation with SFR \sim 5 \times 10^3 M_\odot yr^{-1} and close-to-Eddington accretion of the central 10^{10} M_\odot black hole for about 140 Myr, leading to an extreme quasar luminosity of L_{bol} > 10^{46} \text{ erg s}^{-1} (comparable to the most luminous quasar ever observed). The merger formed a massive compact galaxy with M_e > 2 \times 10^{12} M_\odot.

Powerful feedback from the UMBH quenched the star formation in the surroundings to \sim 10 M_\odot yr^{-1} in the innermost 50 h^{-1} \text{kpc} region. For massive galaxies with M_e > 10^{12} M_\odot, ASTRID predicts M_{BH} - M_\ast on the extrapolation of the scaling relation fit to the observations of local AGN, showing that they can host UMBHs with M_{BH} > 5 \times 10^{10} M_\odot through major galaxy mergers that induce the most active black hole growth.
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**Data Availability**

The code to reproduce the simulation is available at https://github.com/MP-Gadget/MP-Gadget, and continues to be developed. Part of the Astrid snapshots are available at https://astrid-portal.psc.edu/.

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**Figure 4.** Relation between the stellar mass of galaxies with (i) mass of the most massive black hole in that galaxy (left panel) and (ii) star formation rate of the galaxy (right panel). The blue background shows the 2D histogram for all the galaxy populations at z = 2 in the Astrid simulation. The gray dashed line and brown dotted line give the observational fitting of $M_{BH}-M_*$ from Kormendy & Ho (2013) and Reines & Volonteri (2015) based on $z \sim 0$ AGN observations. The orange data points give 2 < z < 4 quasars collected from Kormendy & Ho (2013). The circles mark the evolution of the triple quasar system from z = 2.7 to z = 2.0. Insets in the left panel illustrate the morphology of the BH1 host galaxy (in the face-on direction) at z = 2.5 and z = 2.0 in the 20 h^{-1} kpc region. Insets in the right panel illustrate the gas density field colored by the star formation rate (with red color indicating high star formation rate) in the 300 h^{-1} kpc region centered at BH1.