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COLD GAS FLOWS AND THE FIRST QUASARS IN COSMOLOGICAL SIMULATIONS

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ABSTRACT

Observations of the most distant bright quasars imply that billion solar mass supermassive black holes (SMBH) have to be assembled within the first eight hundred million years. Under our standard galaxy formation scenario such fast growth implies large gas densities providing sustained accretion at critical or super-critical rates onto an initial black hole seed. It has been a long standing question whether and how such high black hole accretion rates can be achieved and sustained at the centers of early galaxies. Here we use our new *MassiveBlack* cosmological hydrodynamic simulation covering a volume $(0.75\,\mathrm{Gpc})^3$ appropriate for studying the rare first quasars to show that steady high density cold gas flows responsible for assembling the first galaxies produce the high gas densities that lead to sustained critical accretion rates and hence rapid growth commensurate with the existence of $\sim 10^9\,\mathrm{M}_\odot$ black holes as early as $z \sim 7$. We find that under these conditions quasar feedback is not effective at stopping the cold gas from penetrating the central regions and hence cannot quench the accretion until the host galaxy reaches $M_{\rm halo} \gtrsim 10^{12}\,\mathrm{M}_\odot$. This cold-flow driven scenario for the formation of quasars implies that they should be ubiquitous in galaxies in the early universe and that major (proto)galaxy mergers are not a requirement for efficient fuel supply and growth, particularly for the earliest SMBHs.

Subject headings: quasars: general — galaxies: formation — galaxies: active — galaxies: evolution — cosmology: theory — hydrodynamics

1. INTRODUCTION

It is now well established that the properties of supermassive black holes (SMBH) found at the centers of galaxies today are tightly coupled to those of their hosts implying a strong link between black hole and galaxy formation. The strongest direct constraint on the high-redshift evolution of SMBHs comes from the observations of the luminous quasars at $z \sim 6$ in the Sloan Digital Sky Survey (SDSS) (Fan et al. 2006; Jiang et al. 2009) and even more recently at $z = 7$ (Mortlock et al. 2011). Although rare (the comoving space density of $z \sim 6$ quasars is roughly $n \sim$ a few Gpc^{-3}) the inferred hole masses of these quasars are in excess of $10^9\,\mathrm{M}_\odot$ comparable to the masses of the most massive black holes in the Universe today. The origin of these massive black hole seed and the physical conditions that allow early growth to supermassive black holes remain a challenging problem.

In order to have had sufficient time to build up via gas accretion and BH mergers (resulting from the hierarchical merging of their host halos) the first 'seed' black holes must have appeared at early epoch, $z > 10$. The origin and nature of this seed population remain uncertain. Two distinct populations of seed masses, in the range of $100 - 10^5\,\mathrm{M}_\odot$ have been proposed: the small mass seeds are usually thought to be the remnants of the first generation of PopIII stars formed of metal-free gas at $z \sim 20 - 30$ (Bromm et al. 1999; Abel et al. 2000; Nakamura & Umemura 2001; Yoshida et al. 2003; Gao et al. 2006, e.g.), while the large seeds form in direct dynamical collapse in metal-free galaxies (Koushiappas et al. 2004; Begelman et al. 2006, although see also Mayer et al. 2010 for direct collapse into a massive blackhole in metal enriched regime).

Growing the seeds to $10^9\,\mathrm{M}_\odot$ in less than a billion years requires extremely large accretion rates - as mergers between black holes are too rare and too inefficient for significant growth. For a black hole accreting at the critical Eddington accretion rate its luminosity $L_{\rm Edd} = (4\pi G c m_p)/\sigma_T M_{BH} = \eta \dot{M}_{\rm Edd} c^2$ (where G, c, m_p and σ_T are the gravitational constant, speed of light, proton mass and Thomson cross section, and η is the standard accretion efficiency) implies an exponential growth at the characteristic Eddington timescales, $t_{\rm Edd} = 450\eta/(1-\eta)$ Myr, such that $M_{\rm BH} = M_{\rm seed} e^{t/t_{\rm Edd}}$. For a seed mass ranging from $M_{\rm seed} \sim 100 - 10^5\,\mathrm{M}_\odot$ this requires $10 - 17$ e-foldings to reach $M_{\rm BH} \sim 10^9\,\mathrm{M}_\odot$. The crucial question (for any given seed model) is then where (if at all, in which kind of halos) and how (at what gas inflow rates) such vigorous accretion can be sustained at these early times.

As bright quasars are likely to occur in extremely rare high-density peaks in the early universe, large computational volumes are needed to study them. Here we use a new large cosmological Smooth Particle hydrodynamics (SPH) simulation, *Massive Black* (covering a volume of $[0.75\,\mathrm{Gpc}]^3$) with sufficiently high resolution (over 65 billion particles) to be able to include tested prescriptions for star formation, black hole accretion and associated feedback processes to investigate whether and if such objects may be formed within our standard structure formation models. Crucially, our *MassiveBlack* simulation is of sufficiently high-resolution to allow us to follow the mass distribution in the inner regions of galaxies and hence model star formation and black hole growth directly and self-consistently while still evolving a close to Gigaparsec scale region. It therefore provides a unique framework to study the formation of the first quasars.

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2. METHODOLOGY

2.1. *Simulation run: "Massive Black"*

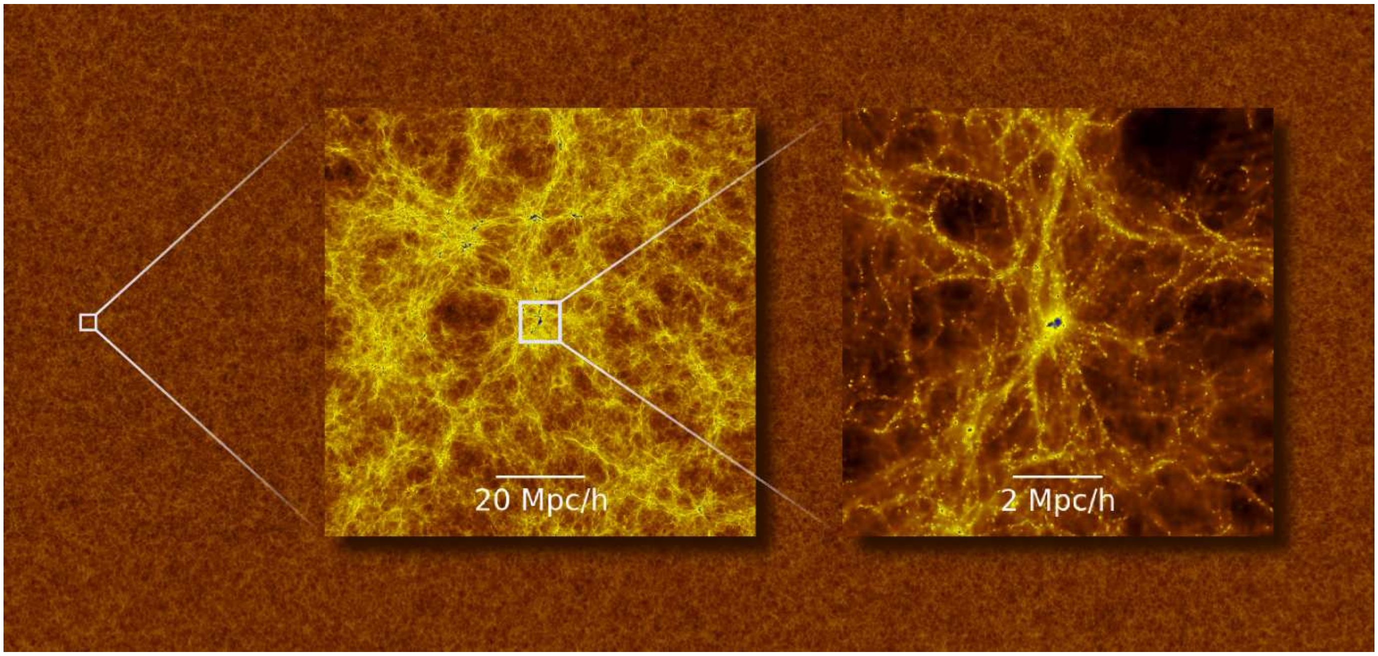

FIG. 1.— The cosmological mass distribution in our the simulation volume at $z = 5$. The projected gas density over the whole volume ('unwrapped' into 2D) is shown in the large scale image. The two overlaid panels show successive zoom-ins by factor of 10, center on the region where the most massive black hole is found.

Our new simulation has been performed with the cosmological TreePM-Smooth Particle Hydrodynamics (SPH) code P-GADGET, a *hybrid* version of the parallel code GADGET2 (Springel 2005) which has been extensively modified and upgraded to run on the new generation of Petaflop scale supercomputers (e.g. machines like the upcoming BlueWaters at NCSA). The major improvement over previous versions of GADGET is in the use of threads in both the gravity and SPH part of the code which allows the effective use of multi core (currently 8-12 cores per node) processors combined with an optimum number of MPI task per node. Here we present initial results from the largest cosmological smooth particle hydrodynamic simulation to date which was run on 10^5 cores corresponding to the entire Cray-XT5 "Kraken" at NICS. The *MassiveBlack* simulation contains $N_{part} = 2 \times 3200^3 = 65.5$ billion particles in a volume of $533\,\mathrm{Mpc}/h$ on a side with a gravitational smoothing length $\epsilon = 5.5\,\mathrm{kpc}/h$ in comoving units). The gas and dark matter particle masses are $m_{\rm g} = 5.7 \times 10^7\,\mathrm{M}_\odot$ and $m_{\rm DM} = 2.8 \times 10^8\,\mathrm{M}_\odot$ respectively. This run contains gravity and hydrodynamics but also extra physics (subgrid modeling) for star formation (Springel & Hernquist 2003), black holes and associated feedback processes. The simulation has currently been run from $z = 159$ to $z = 4.75$ (beyond our original target redshift of $z = 6$). For this massive calculation it is currently prohibitive to push it to $z = 0$ as this would require an unreasonable amount of computational time on the world's current fastest supercomputers. The simulated redshift range probes early structure formation and the emergence of the first galaxies and quasars.

2.2. *Black hole Accretion and Feedback Model*

The prescription for accretion and associated feedback from massive black holes has been developed by Di Matteo et al. (2005); Springel et al. (2005). Detailed studies of this implementation in cosmological simulations and associated predictions (Sijacki et al. 2007; Li et al. 2007; Di Matteo et al. 2008; Croft et al. 2009; Sijacki et al. 2009; Colberg & di Matteo 2008; Degraf et al. 2010, 2011b; Booth & Schaye 2011) have shown that it can reproduce all the basic properties of black hole growth, the observed $M_{BH} - \sigma$, relation (Di Matteo et al. 2008), the quasar luminosity function (Degraf et al. 2010) and its evolution as well as the spatial clustering of quasars (DeGraf et al. 2011c). In a nutshell our black hole accretion and feedback model (Di Matteo et al. 2008) consists of representing black holes by collisionless particles that grow in mass (from an initial seed black hole) by accreting gas in their environments. A fraction of the radiative energy released by the accreted material is assumed to couple thermally to nearby gas and influence its motion and thermodynamic state (typically referred to as BH feedback). Our underlying assumption is that the large-scale feeding of galactic nuclei with gas (which is resolved in our simulations) is ultimately the critical process that determines the growth of massive black holes and the peak of the quasar phase (Di Matteo et al. 2008; Degraf et al. 2010, 2011b). The model, therefore needs to be viewed in the context of cosmological growth of black holes and not detailed accretion physics. While a more detailed treatment of this is certainly desirable and begins to be possible for individual galaxies (Kim et al. 2011; Hopkins & Quataert 2010, e.g.) it is still infeasible for cosmological simulations that seek to follow whole populations of galaxies and their BHs.

We introduce collisionless 'sink' particles in the simulations to model black holes at the centers of forming minihalos. In order to achieve this we keep track of the formation of minihalos by running a friends-of-friends (FOF) group finder on the fly. The group finder is run on sufficiently closely spaced intervals to identify the newly collapsing halos in which we place a black hole seed of fixed mass, $M = 10^5 h^{-1}\,\mathrm{M}_\odot$ (if they do not already contain a BH). In practice most of the halos of this mass and their black holes are formed between $z = 15$ and $z = 30$. The black hole particle then grows in mass via

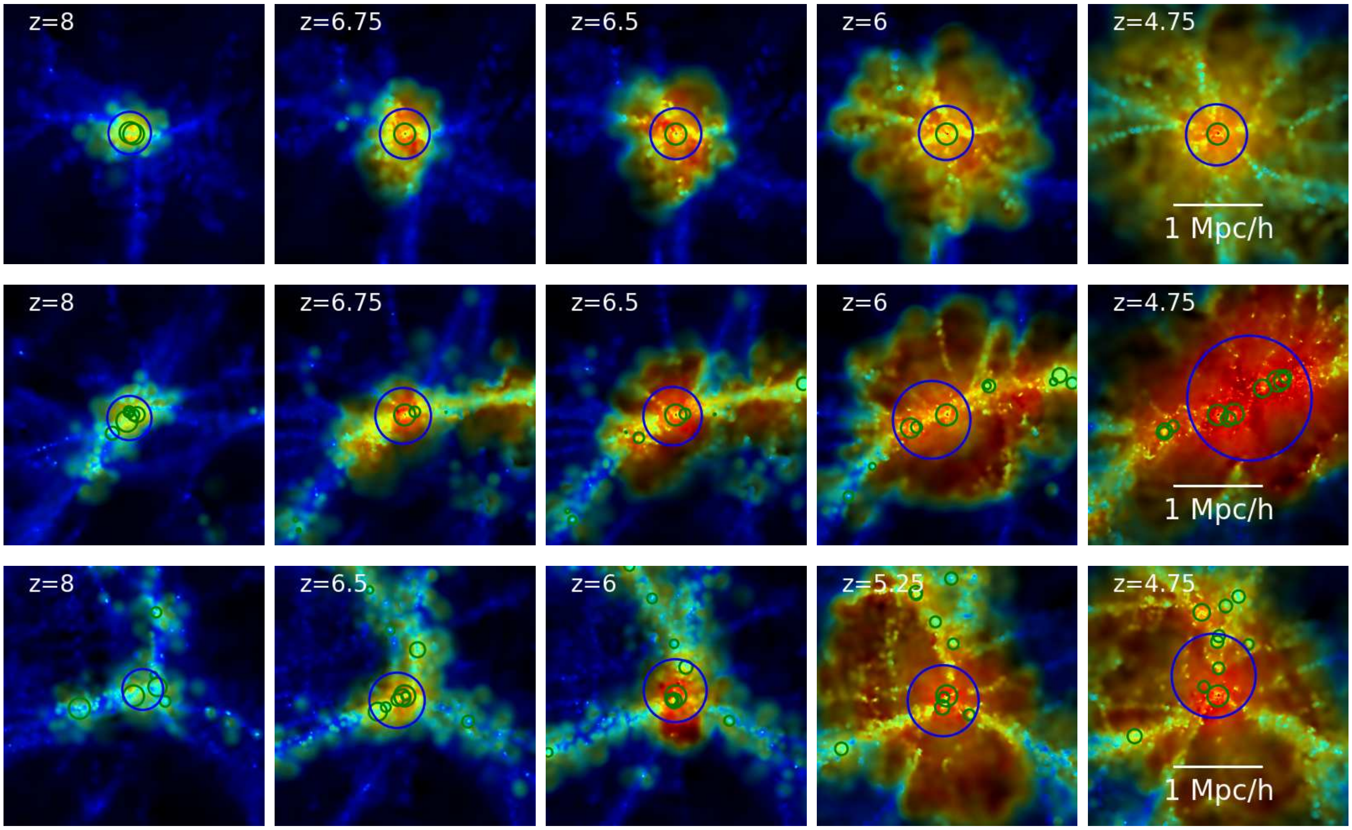

FIG. 2.— Snapshots of the evolution of the cold-flow-fed massive black holes. The images visualise the projected gas distribution color coded by temperature around three example quasars (one in each row) across five different redshifts (labelled on each of the five panels; left to right). The projected density ranges from $\sim 10^{-2}$ to $\sim 10^{2}\,\mathrm{h\,M_\odot\,pc^{-2}}$ and the temperature from $\sim 10^4$ (blue colors) to 10^8 K (red colors). The quasar positions are indicated by the green circles and the virial radius of each halo by the blue circles. The images show the typical structure of cold streams that penetrate the halo all the way into the central regions of galaxies. At first ($z \gtrsim 7.5$) the gas is cold and the black hole is still of relatively low mass, but then below this redshift the black hole growth exponentiates as increasing amounts of cold gas is fed into the central regions. Black hole feedback heats the gas, but does not distrupt the cold streams until $z \lesssim 6$.

accretion of surrounding gas according to $\dot{M}_{\rm BH} = \frac{4\pi G^2 M_{\rm BH}^2 \rho}{(c_s^2+v^2)^{3/2}}$ (where ρ and c_s are the density and sound speed of the hot and cold phase of the ISM gas which when taken into account appropriately as in Pelupessy et al. (2007) - this eliminates the need for a correction factor α previously introduced - and $v_{\rm BH}$ is the velocity of the black hole relative to the gas) and by merging with other black holes. We limit the accretion rate to Eddington (or a few times Eddington). A similar Bondi model has also been used by Johnson & Bromm (2007) to study the growth of the first massive PopII black holes remnants.

The radiated luminosity, $L_{\rm r}$, from the black hole is related to the accretion rate, $\dot{M}_{\rm BH}$ as $L_{\rm r} = \epsilon_{\rm r}\,(\dot{M}_{\rm BH} \times c^2)$, where we take the standard mean value $\epsilon_{\rm r} = 0.1$. Some coupling between the liberated luminosity and the surrounding gas is expected: in the simulation 5% of the luminosity is (isotropically) deposited as thermal energy in the local black hole kernel, providing some form of feedback energy (Di Matteo et al. 2005). This model of AGN feedback as isotropic thermal coupling to the surrounding gas, albeit simple, is a reasonable approximation to any physical mechanism which leads to a shock front which isotropizes and becomes well mixed over physical scales smaller than those relevant in our simulations and on timescales smaller than the dynamical timescales of the halos (Di Matteo et al. 2008; Hopkins et al. 2006). Two black hole particles merge if they come within the spatial resolution (i.e. within the local SPH smoothing length) with relative speed below the local sound speed.

We note that at least two independent groups(Booth & Schaye 2009; Johansson et al. 2008) now have also adopted the same modeling for black hole accretion, feedback and BH mergers in the context of hydrodynamic simulations. These independent works, and in particular, the cosmological simulations by (Booth & Schaye 2009) (part of the OWL program) have allowed to independently explore the parameter space of the reference model of (Di Matteo et al. 2008), as well as variations of our model prescriptions. This large body of already existing work and investigations make this particular model a good choice for more detailed studies of the growth of the first quasars which is the subject we focus on here. In associated publications we show that the *MassiveBlack* quasars are fully consistent with all the fundamental statistical constraints for the observed populations of high redshift quasars, and in particular with the observed luminosity functions of quasars and the high redshift clustering (DeGraf et al. 2011a) and basic properties of quasar hosts (Khandai et al. 2011). To produce the black hole history from the simulation data we rely on SQL databases developed by Lopez et al. (2011).

3. RESULTS

The cosmological gas density distribution in the full volume of the *MassiveBlack* is shown in the large scale image of Figure 1. The large panel shows the whole of the 3D simulation

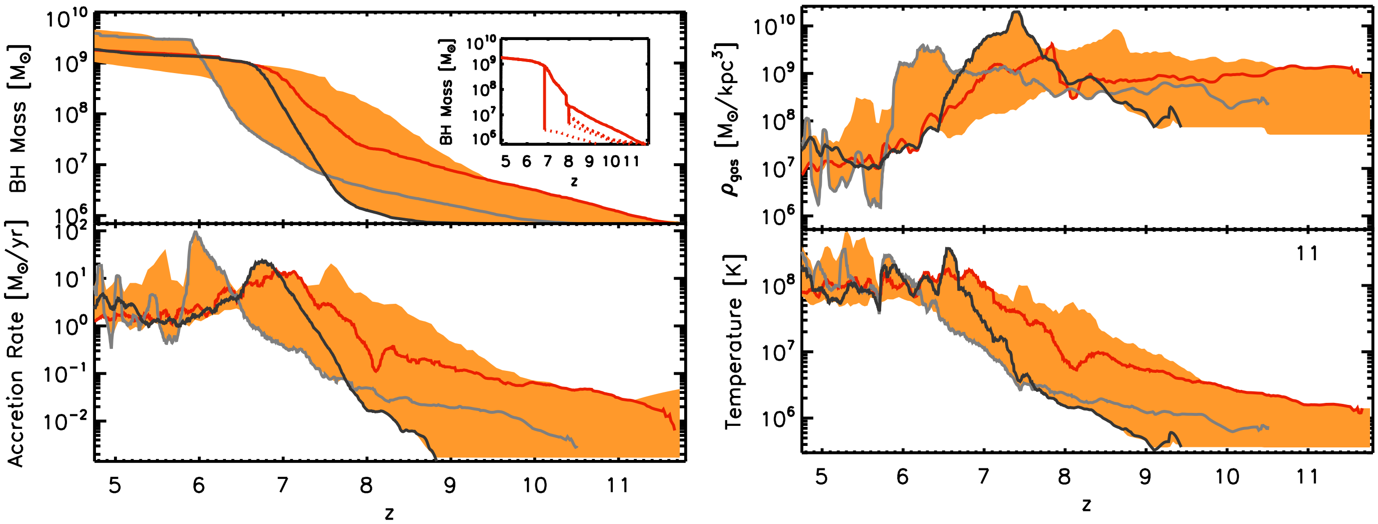

FIG. 3.— The black hole mass and the black hole accretion rate versus redshift are shown in the top and bottom panel on the left. The corresponding gas densities and temperatures of the accreting gas are shown in the top and bottom panels on the right. The lines represent the three black holes shown in Fig. 2 and the shaded orange band indicates the full range of properties encompassed by our most massive black hole sample.

volume "unwrapped" into a 2D image slice (Feng et al. 2011) at $z = 5$. At these large scales the density distribution of the universe appears fairly uniform. The resolution however is sufficiently fine to make it possible to zoom into increasingly smaller regions and search for massive black holes that have experienced significant growth. Superimposed onto the full scale image we show a zoomed region (scale of 100 Mpc h^{-1} and 10 Mpc h^{-1} on a side from left to right, respectively) around one of the largest black holes/quasars at this time. On these scales the images show the typical filaments that compose the cosmic web and in particular how the first massive quasars (the most massive black hole, at the center has a mass $M_{\rm BH} \sim 3 \times 10^9\,{\rm M}_\odot$) form at the same type of intersection/nodes of filaments that are the expected locations of rare (massive) dark matter halos. Remarkably we do find ten black holes in the volume that have grown to about a billion solar masses by $z \sim 6$ or earlier (and many other of smaller masses).

Figure 2 shows the environment and its evolution (five timelapses from about $z \sim 9$ to $z \sim 5$) of three examples from within this sample. Their detailed mass assembly history is shown in Fig. 3. The panels in Figure 2 show the evolution of the gas density color coded by temperature. These objects are found to be continuously fed by intense streams of high density gas (consistent with the cold-accretion picture for the growth of galaxies at intermediate/high redshift by (Dekel & Birnboim 2006, e.g.). During these times Eddington accretion is attained and sustained. By showing the temperature of the gas, the images clearly make visible an expanding 'bubble' (emerging from about $z \sim 6.5 - 7$) of hot gas (red colors) around the central quasars (whose positions are indicated by green circles). This bubble created by the BH feedback is more or less confined within the halo (the virial radius of the halo is shown by the blue circles in Fig. 2) for $z \lesssim 6$. Below this redshift, and rather abruptly, the energy released by the quasars heats and expels the gas as a wind well beyond the halo. Black hole growth has now become self-regulated (see also Figure 3, Eddington rates are reached only sporadically). Although the effects of quasar feedback in our model have been studied in detail previously (Di Matteo et al. 2005, 2008) what is remarkable here is that even though feedback energy consistently heats the gas within and eventually beyond the scale of halos, it does not do much to the streams of in-flowing cold gas. There the gas density is so high (e.g. Fig. 3) that the gas cannot be stopped because, it is too difficult to couple enough feedback energy to it to disrupt the flow. The streams get somewhat (albeit not completely) disrupted only at $z \lesssim 6$. Before this happens billion solar mass black holes are already assembled (see Fig. 3), a process that takes a few hundred million years.

Sustained phases of Eddington accretion onto these black holes start as early as $z \sim 9 - 10$ and go on uninterrupted until $z \sim 6 - 7$, leading to BH masses of the order of $10^9\,{\rm M}_\odot$ in the first massive halos of roughly $M_{\rm halo} \sim 10^{12}\,{\rm M}_\odot$ at $z \sim 6 - 7$ (rare $3 - 4\sigma$ peaks of the density distribution). We have indeed a few objects (the range of the 10 most massive is shown by the orange areas in Fig. 3) that reach these high masses already at $z \sim 7$ consistent with (Mortlock et al. 2011). Interestingly, this process of BH assembly is apparently facilited by the "cold flows" picture of galaxy formation which has revolutionized our understanding of galaxy assembly below the threshold dark matter mass of $M_{\rm halo} \sim 10^{12}\,{\rm M}_\odot$ (Dekel & Birnboim 2006; Dekel et al. 2009; Kereš et al. 2005, 2009). With *MassiveBlack* we are able to trace the formation of the first, rare massive halos, those which are mostly assembled by high density (high redshift) cold streams (Dekel et al. 2009). We find that these same streams easily penetrate all the way into central regions of galaxies even in the presence of strong feedback. We find however that once $M_{\rm halo} \sim 10^{12}\,{\rm M}_\odot$ and halos enter the regime where they are shock-heated (Dekel et al. 2009) the BH growth becomes finally self-regulated (see accretion rate evolution in Fig. 3). The temperature of the accreting gas also is raised well above the virial temperature, $T_{\rm vir} \sim 10^7$ K, rendering some of the gas unbound; Fig. 3). This the point the black hole masses level off at a few $10^9\,{\rm M}_\odot$ (Fig. 3). Even though at $z < 6$ in massive halos the outflows clearly affect the incoming gas it is not clear they fully distrupt the cold flows. According to Dekel & Birnboim (2006, e.g), albeit based on somewhat lower redshift than what we probe, cold streams

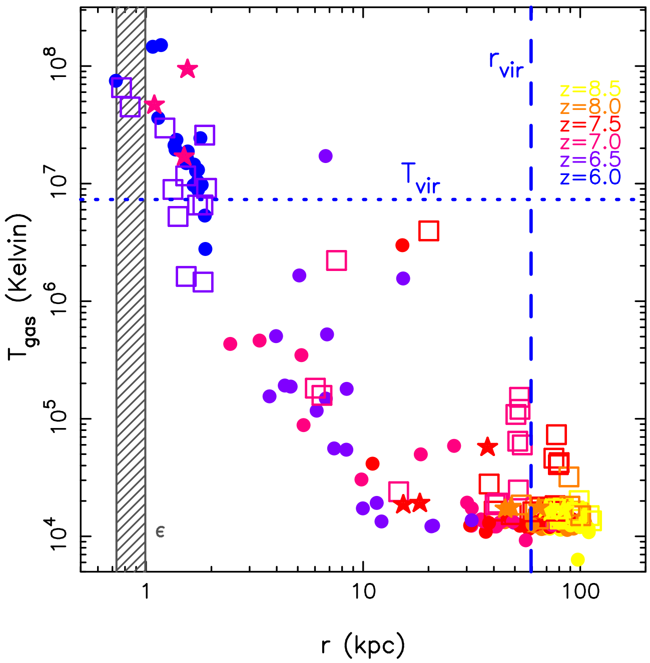

FIG. 4.— The temperature of the gas that is eventually accreted onto the black hole is shown as a function of its position within the host halo (r is plotted in physical units). The plot shows a typical example for one of the host halos in Fig. 3. The points with different symbols representing the groups of 32 nearest neighbours at different redshifts (in the colors indicated by the legend) all traced back to $z = 8.5$. The gray hatched region show the gravitational softening lengths

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should still not be fully distrupted in this rare massive objects even if a dilute hot medium forms. In future work we will address this issue in our simulations in some more details.

We note that the black holes occupying these rare massive halos hardly undergo any mergers, indicative that their hosts are not undergoing major galaxies mergers. In the inset in Fig. 3 we show the histories of all black holes that merge into the main progenitor, which is typical of what we see: a few and typically minor mergers occur. At the redshifts relevant for the first quasars, however, galaxy formation is very different: mergers are still extremely rare events and halos have not yet assembled above their shock heating scale (Dekel et al. 2009), so that quasars are fueled directly by cold streams/flows.

To illustrate directly the origin of the gas fueling the first quasars we track in the simulation the prior history of particles that end up in the vicinity of the black hole, and hence contribute to the accretion. Figure 4 shows one example of the temperature as a function of radius of particles that have participated into the accretion onto the BH between $z = 6$ and $z = 8.5$ (within the smoothing length of the black hole particle). The plot shows that particles always remain cold as they enter the virial radius well into the ten of kpc region in-fact all the way into the region of from which accretion onto the black hole occurs. Here some of the gas is heated, as expected, by BH feedback. The temperature of the gas feeding the black hole is fully commensurate with that of cold flows and always remains below $T_{\rm gas} \sim 10^{5.5-6}$ K just as predicted in galaxy formation Dekel & Birnboim (2006); Kereš et al. (2005). In the shock-heated regime the temperature of the gas would rise to $T_{\rm vir}$ as it enters the halo. However this is not seen.

4. CONCLUSIONS

With our new large cosmological simulation *MassiveBlack* we show that the short timescale associated with infall via cold flows and the short cooling timescales in cold radial streams that penetrate the halo render the flow into the central regions unstoppable by feedback allowing it to easily sustain BH growth at the Eddington rates to build up the required BH masses by $z = 6-7$. One consequence of this scenario is that BH masses at these redshifts are expected to show deviations from the local $M_{BH} - \sigma$ relation. BH masses assembled faster (most growth occurs over few hundred million years) than the stellar spheroid (assembled over Gyrs timescales). Black hole masses larger than that inferred from the local $M_{BH} - \sigma$ relation have infact been suggested for the first quasars. Stream fed accretion will still be relevant over the peak of the quasar phase but mergers (as merger rates peak closer to those redshift) will become an increasingly major player in their growth and formation. We speculate however that most of the growth of a quasar's mass is likely to always occur before the shock heating scale of an halo is reached much like most of its star formation rate (Dekel et al. 2009). We will investigate this further in our large volume in future work. Our scenario is somewhat similar to that proposed by Mayer et al. (2010) or Li et al. (2007) yet, crucially it does not rely on a major merger to induce the strong gas inflows but points to a more common origin for them particularly at these redshifts (which we could find by virtue of having a large volume in our simulation, see also Sijacki et al. (2009) who followed the build-up of a single hihigh-z quasar). As we have shown, relaxing the constraint for massive mergers makes it plausible to attain quite commonly large black hole masses as high as $z = 7$ commensurate with Mortlock et al. (2011).

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REFERENCES

Abel, T., Bryan, G. L., & Norman, M. L. 2000, ApJ, 540, 39
Begelman, M. C., Volonteri, M., & Rees, M. J. 2006, MNRAS, 370, 289
Booth, C. M. & Schaye, J. 2009, MNRAS, 398, 53
—. 2011, MNRAS, 413, 1158
Bromm, V., Coppi, P. S., & Larson, R. B. 1999, ApJ, 527, L5
Colberg, J. M. & di Matteo, T. 2008, MNRAS, 387, 1163
Croft, R. A. C., Di Matteo, T., Springel, V., & Hernquist, L. 2009, MNRAS, 400, 43
DeGraf, C., Di Matteo, T., Khandai, N., Croft, R. A. C., Lopez, J., & Springel, V. 2011a, MNRAS, in preparation

Degraf, C., Di Matteo, T., & Springel, V. 2010, MNRAS, 402, 1927
—. 2011b, MNRAS, 413, 1383
DeGraf, C., Oborski, M., Di Matteo, T., Chatterjee, S., Nagai, D., Zheng, Z., & Richardson, J. 2011c, ArXiv e-prints
Dekel, A. & Birnboim, Y. 2006, MNRAS, 368, 2
Dekel, A., Birnboim, Y., Engel, G., Freundlich, J., Goerdt, T., Mumcuoglu, M., Neistein, E., Pichon, C., Teyssier, R., & Zinger, E. 2009, Nature, 457, 451
Di Matteo, T., Colberg, J., Springel, V., Hernquist, L., & Sijacki, D. 2008, ApJ, 676, 33
Di Matteo, T., Springel, V., & Hernquist, L. 2005, Nature, 433, 604
Fan, X., Strauss, M. A., Becker, R. H., White, R. L., Gunn, J. E., Knapp, G. R., Richards, G. T., Schneider, D. P., Brinkmann, J., & Fukugita, M. 2006, AJ, 132, 117
Feng, Y., Croft, R., Di Matteo, T., Sargent, R., Heckbert, P., & V., S. 2011, ApJS, submitted
Gao, L., Able, T., Frenk, A., A., J., V., S., & N., Y. 2006, MNRAS
Hopkins, P. F., Hernquist, L., Cox, T. J., Di Matteo, T., Robertson, B., & Springel, V. 2006, ApJS, 163, 1
Hopkins, P. F. & Quataert, E. 2010, MNRAS, 407, 1529
Jiang, L., Fan, X., Bian, F., Annis, J., Chiu, K., Jester, S., Lin, H., Lupton, R. H., Richards, G. T., Strauss, M. A., Malanushenko, V., Malanushenko, E., & Schneider, D. P. 2009, AJ, 138, 305
Johansson, P. H., Naab, T., & Burkert, A. 2008, Astronomische Nachrichten, 329, 956
Johnson, J. L. & Bromm, V. 2007, MNRAS, 374, 1557
Kereš, D., Katz, N., Fardal, M., Davé, R., & Weinberg, D. H. 2009, MNRAS, 395, 160
Kereš, D., Katz, N., Weinberg, D. H., & Davé, R. 2005, MNRAS, 363, 2
Khandai, N., Di Matteo, T., Croft, R. A. C., & Springel, V. 2011, MNRAS, in preparation
Kim, J.-h., Wise, J. H., Alvarez, M. A., & Abel, T. 2011, ArXiv e-prints
Koushiappas, S. M., Bullock, J. S., & Dekel, A. 2004, MNRAS, 354, 292
Li, Y., Hernquist, L., Robertson, B., Cox, T. J., Hopkins, P. F., Springel, V., Gao, L., Di Matteo, T., Zentner, A. R., Jenkins, A., & Yoshida, N. 2007, ApJ, 665, 187
Lopez, J., Degraf, C., DiMatteo, T., Fu, B., Fink, E., & Gibson, G. 2011, in Statistical and Scientific Databases Management Conference (SSDBM), Portland, OR
Mayer, L., Kazantzidis, S., Escala, A., & Callegari, S. 2010, Nature, 466, 1082
Mortlock, D. J., Warren, S. J., Venemans, B. P., Patel, M., Hewett, P. C., McMahon, R. G., Simpson, C., Theuns, T., Gonzales-Solares, E. A., Adamson, A., Dye, S., Hambly, N. C., Hirst, P., Irwin, M. J., Kuiper, E., Lawrence, A., & Rottgering, H. J. A. 2011, ArXiv e-prints
Nakamura, F. & Umemura, M. 2001, ApJ, 548, 19
Pelupessy, F. I., Di Matteo, T., & Ciardi, B. 2007, ApJ, 665, 107
Sijacki, D., Springel, V., di Matteo, T., & Hernquist, L. 2007, MNRAS, 380, 877
Sijacki, D., Springel, V., & Haehnelt, M. G. 2009, MNRAS, 400, 100
Springel, V. 2005, MNRAS, 364, 1105
Springel, V., Di Matteo, T., & Hernquist, L. 2005, MNRAS, 361, 776
Springel, V. & Hernquist, L. 2003, MNRAS, 339, 289
Yoshida, N., Sokasian, A., Hernquist, L., & Springel, V. 2003, ApJ, 598, 73