# A Particular Appetite: Cosmological Hydrodynamic Simulations of Preferential Accretion in the Supermassive Black Holes of Milky Way Size Galaxies

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**ABSTRACT**

[IAU Abstract as Placeholder] Using cosmological hydrodynamic simulations of Milky Way-type Galaxies, we explore the effect of accreted gas as feeding mechanisms for supermassive black holes. By examining two of these galaxies with differing merger histories, one characterized by several major mergers and the other with a quiescent history, we can examine the importance of merger history on black hole accretion. This study is an extension of Bellovary et. al. 2013, which did a similar study analyzing the accretion of high mass, high redshift galaxies and their central black holes. Bellovary found that the gas accreted by the central black holes was proportional to that accreted by the host galaxy. Contrary to the previous study's results, we've found that while a galaxy with a quiescent history will still have a black hole mirroring the accretion of its host, a galaxy with an active merger history has a central black hole that is preferentially fueled by gas accreted through mergers. We look to the the angular momentum of the accreted gas in these Milky Way analogs to develop a clearer picture of the mechanisms best fueling their central SMBHs.

*Subject headings:* Black hole physics – Galaxies: spiral – Galaxies: kinematics and dynamics – Methods: Numerical – Others?

## 1. Introduction

Supermassive black holes (SMBHs) are thought to exist in almost all massive galaxies. These black holes become active galactic nuclei (AGN) during periods of high accretion and wane in periods of quiescence. (Volonteri 12) The galaxy's size, metallicity, and other environmental effects may help to influence the growth of the black hole residing at its center; however, little is known about the relationship between these SMBHs and their much larger host galaxies, as well as how they grow and evolve together.

*In following P: M-bulge mass, M-bulge luminosity. [Ho review?]

The M$-\sigma$ relation, which relates the SMBH's mass and the velocity dispersion of the host galaxy's central stellar population, gives some insight into the complex interplay between these objects. **?** A prominent trend appears, as SMBHs tend to scale with their spheroidal center of their host galaxies, i.e. less massive SMBH residing in galaxies with less disperse bulges, and more massive SMBH living in galaxies with larger velocity dispersions in their bulges. The tightness of the relation is significant and can be seen over several orders of magnitudes in velocity dispersion and black holes mass. (Two in sigma, 4 in mass) Increased scatter exists in the region of very high mass galaxies and among the low mass galaxies. However, scatter in less massive galaxies may imply that there are several channels of black hole growth at play in the low mass end of the relation. One standard explanation for the M$-\sigma$ relation lies in galaxy mergers, which build up galaxies, feed SMBHs, and assemble bulges. These large, active mergers are thought to create feedback from the SMBH which affects the overarching structure of the galaxy.

Major mergers between massive galaxies are thought to be efficient fueling mechanisms for bright AGN. The large influx of material due to tidal torques from the merger collects into pockets of gas and dust which cause bursts of star formation and helps funnel gas directly into the center where the SMBH resides. (Hopkins 04,Richards 06, Reddy 08) Additionally, the most massive, highest-luminosity AGN (i.e. quasars) tend to reside in incredibly luminous infrared galaxies where star formation is abundant, signifying that major mergers may have recently occurred. Distorted morphologies are often characteristics of quasar hosts, and companions can also be present around quasars, both of which are evidence that strengthen the possibility of a recent merger having affected their lifetimes.

In many less massive AGN, however, there is a clear lack of distorted morphologies, close neighbors, and/or other obvious merger evidence. Ryan 2007 (Seyfert 1, smaller than MWG),Hicks 2013 (Seyfert and quiescent galaxies) It is also important to note that many of these AGN exist in spiral galaxies, which are unlikely to have been recently disturbed by major mergers. **(Schawinski 2011)** Nevertheless, some evidence suggest (Governato 2009) some disturbed galaxies may reform a disk quickly, even if their history is characterized by many mergers. More recently, Triester (2012) has suggested that only the highest luminosity AGN require fueling via major mergers, an effect which seems to scale with luminosity rather than redshift. They found that 90% of AGN across all redshifts are fueled by various other mechanisms which may include minor mergers, flybys, and smooth accretion, whereby gas is directly accreted via large filaments from the ambient intergalactic medium. Secular processes, including bar formation and disk instabilities, may also be prominent forms of accretion for these SMBHs.

Smooth accretion, via filamentary inflows, seems a likely candidate for fueling these undisturbed galaxies. The cold flow filaments that feed these galaxies are dependent on the galaxy's mass. Smoothly accreted gas will fuel through cold flow filaments until the galaxy halo reaches a mass near $10^{11} M_{\odot}$. Once the galaxy is greater than this mass threshold, the gas will reach the virial radius of the halo and the rapid increase in temperature within the radius causes the gas to shocked as its temperature quickly increases. Fueling mechanisms are seen to vary across galaxies of different masses based on the diversity of their history and appearance, such as through the major and minor mergers and secular processes described above. Here, we will discuss the fueling mechanisms which also vary between galaxies of similar mass due to different merger and formation histories.

In this paper, we discuss the gas accretion history within two galaxy simulations that appear similar at z = 0 but have very different merger histories. Our "active" galaxy, h258, has a history characterized by many major mergers, while our "quiet" galaxy, h277, has a quiescent history dominated by cold flow accretion and few minor mergers. These galaxies look quite similar at z=0, and have many of the same properties as the Milky Way including $M_{vir}$ (mass within the virial radius), stellar mass, and $v_{circ}$ (circular velocity). However, without a deeper examination, we might not realize they have such varying merger histories. Milky Way-type galaxies host SMBHs on the order of $10^6$ M, which are likely the most common type of massive black hole, yet little is known about them or how they may grow. By examining the feeding mechanisms of these galaxies, as well as what type of gas feeds their central SMBHs, we will be able to compare the accretion rates between h258 and h277 to determine which accretion methods dominate within the central regions of these Milky Way-size galaxies.

Bellovary et. al. (2013) **?** compared simulations of three high mass, high redshift galaxies and found that while mergers and smooth accretion both build up galaxies, no particular method was more adept at feeding the SMBH at their centers. Using a similar method as Bellovary et. al. (2013), this work compares the fueling mechanisms between two MW mass galaxies and the accretion affecting each of their SMBHs. We will compare the BH fractions and halo fractions between and within the galaxies to look for clues about SMBH preferential feeding within these MW-size galaxies and how their histories lead to galaxies with such similar structure.

## 2. Simulation Parameters

I still need to write this. GOOOOOOOO Nicole!
Possibly describe low rez sims here too?
Description of higher resolution simulations
- Better Time Resolution: Accretion Times

The cosmological simulations have been run using the smoothed particle hydrodynamics (SPH) N-body tree code Gasoline (**Stadel 2001; Wadsley 2004**). (**?**) Prescriptions for star formation, supernova feedback (**Stinson 2006**), metal diffusion (**Shen 2010**), and MBH formation, feedback, and accretion (**Bellovary 2010**) are included within Gasoline. Each simulations assumes a WMAP cosmological model (Spergel 2007), Kroupa initial mass function (Kroupa 2001), and a uniformly distributed ultraviolet background (Haardt & Madau 1996). Gasoline simulated galaxies are shown to lie conform with the observed Tully-Fisher relation (Governato 2009), the size-luminosity relation (Brooks 2011), and the mass-metallicity relation (Brooks 2007), in addition to having realistic matter distributions and baryon fractions (Governato 2010; Guedes 2011). Primordial cooling and a low-temperature extension to the cooling curve is used to trace metals (Bromm2001). Gas is allowed to reach a minimum temperature of 100 K, though cooling via molecular hydrogen or metals is not included. The aforementioned works have previously demonstrated that realistic galaxy models can be obtained without the use of these advanced features. (Christensen2012, in addition). Though these previous works have not included AGN feedback or its effects, for small to moderate mass galaxies (like those of previous and current studies) our research shows their central supermassive black holes have little affect on the global properties of their hosts and only directly impacts the central region of their galaxy. Therefore, we are confident these simulations are in good accordance with the broad range of properties in current galaxy observations.

## 3. Reduction Method

In this analysis, we use the method utilized in Brooks et. al. (2009) to trace gas particles from their origin, through their journey into the galaxy, and determine their position within the SMBH or its host. Brooks et. al. (2009) studied the accretion of gas by galaxies in cosmological simulations with a focus on gaseous and stellar buildup of their disks. We use this method to trace the gas particles from their initial location to their moment of halo entry and, for some of the particles, into the SMBH.

As we discussed in the introduction, there are a variety of fueling mechanisms thought to grow SMBH. Even among galaxies of similar mass, different evolutionary pathways and merger histories can lead to different mechanisms of SMBH accretion. Gas particles are initially traced prior to their accretion onto the main halo to determine whether they occupied a different halo at their formation. The particles are then classified by their method of entrance into the primary halo. If the gas particles existed in the primary halo at the first time step (z=4 in this study), they are classified as "early" gas. The final fraction of "early" gas in the galaxy at z=0 is less than four percent for both h258 and h277, a negligible amount. Gas that belonged to a different halo than the primary prior to accretion is classified as "clumpy" and enters the primary halo through mergers.

The Amiga Halo Finder identifies all of the galaxies in the simulations by identifying the virial radii of the halos based on an overdensity using the criterion for a flat universe. (Bellovary 2013) We select the primary halo by determining the most massive galaxy at z=0 and locating the central SMBH. We then trace the SMBH back through time, determining its host halo in each snapshot. Gas particles that are part of merger events are traced back through every merger they've encountered–within their merger trees–to determine their origin and which other halos each gas particles previously inhabited (Too anthropomorphic?).

All other gas is classified as entering the halo via "smooth" accretion, and is then subdivided into two categories: "cold" and "shocked." In the cases where a shock does not develop, cold gas will usually flow into the halo via large-scale, dark matter filaments. (Bellovary 2013) It's possible for the filaments to also be dense enough to pierce an already developed shock allowing for cold gas to funnel into the central region of the galaxy where it can accrete onto the SMBH without being heated to the virial temperature.

Gas particles that undergo smooth accretion, may shock when entering the virial radius of the galaxy, depending on the mass of the galaxy. If the galaxy halo is around or greater than $10^{11}$ $M_{\odot}$, the gas will shock. The galaxies in this study reach final masses on the order of $10^{12}$ $M_{\odot}$, therefore, shocked gas begins to enter the galaxy by the later timesteps of our simulation when it has reached this critical mass.

Shocked gas is defined as gas reaching virial temperature as it enters the primary halo.

Therefore, we determine shocked particles through an increase in entropy and temperature using the following criteria:

$$T_{shock} \geq 3/8T_{vir} \tag{1}$$

where $T_{vir}$ is the virial temperature of the halo and $T_{shock}$ is the temperature of the gas particle, and

$$\Delta S \geq S_{shock} - S_0 \tag{2}$$

where $S_0$ is the initial entropy of the gas particle and

$$S_{shock} = log_{10}[3/8T_{vir}^{1.5}/4\rho_0] \tag{3}$$

where $\rho_0$ is the gas density prior to experiencing the shock.

Gas entering the halo via smooth accretion, whether cold or shocked, is traced to 0.1 $R_{vir}$ from the galaxy, a distance after which the thermal status of the particle can no longer be confidently tracked, as supernova feedback can mimic virial shocking. Gas particles that reach this distance with the above increased in entropy and density are considered shocked particles, while all others are categorized as cold. (”See Brooks et. al. 2009 for complete details about shock physics.”)

Once all the gas particles have been individually categorized, we can use these labels to determine the methods of accretion onto these Milky Way-size galaxies. With the information about which particles are accreting onto the SMBH (from the gas reservoir of particles that have been accreted by the galaxy), we can better compare the methods feeding both the galaxy and its SMBH. We can then determine whether there exists a method more efficiently building up these kinds of galaxies and their SMBH..

## 4. Results

Comment on previous lower rez study finding similar results

• h258 found preference from SMBH to accrete gained through mergers

• This is contrary to previous results of **?**

• In previous study, there was SLIGHT preference for gas of a lower angular momentum to enter the SMBH

• By examining the angular momentum of the gas accreted onto the SMBH at the moment it enters the halo, we were able to determine that a significant preference exists for gas with lower angular momentum to enter the SMBH. The gas attained through mergers tends to enter the halo with a lower angular momentum; this may explain the SMBH's preference for merger gas.

Contrary, low rez h277: • h277, however, found no preference for the SMBH to prefer any one kind of gas in its accretion.

• Like the SMBH in the previous study, the same fraction of gas entering the halo would then be accreted onto the SMBH. (The gas enters a sort of reservoir and enters the SMBH somewhat uniformly.)

• As these SMBHs are similar in size and appearance at z=0, this indicates that the varying histories of these simulations plays a role in the evolution of these galaxies and their central SMBH.

(Assuming high rez finds same preferential accretion?)

• Just as we found in the lower resolution simulation (Can I reference my AAS/IAU posters here?), the high resolution sees a distinct preference for accreting gas that has been gained through the many mergers in its history.

- (MAYBE. We don't know if this is true yet.)

## 5. Conclusion

This is a conclusion. La la la.

Thank you to the Fisk-Vanderbilt Masters-to-PhD Bridge program for their continued funding and support. [GET GRANT NUMBER]

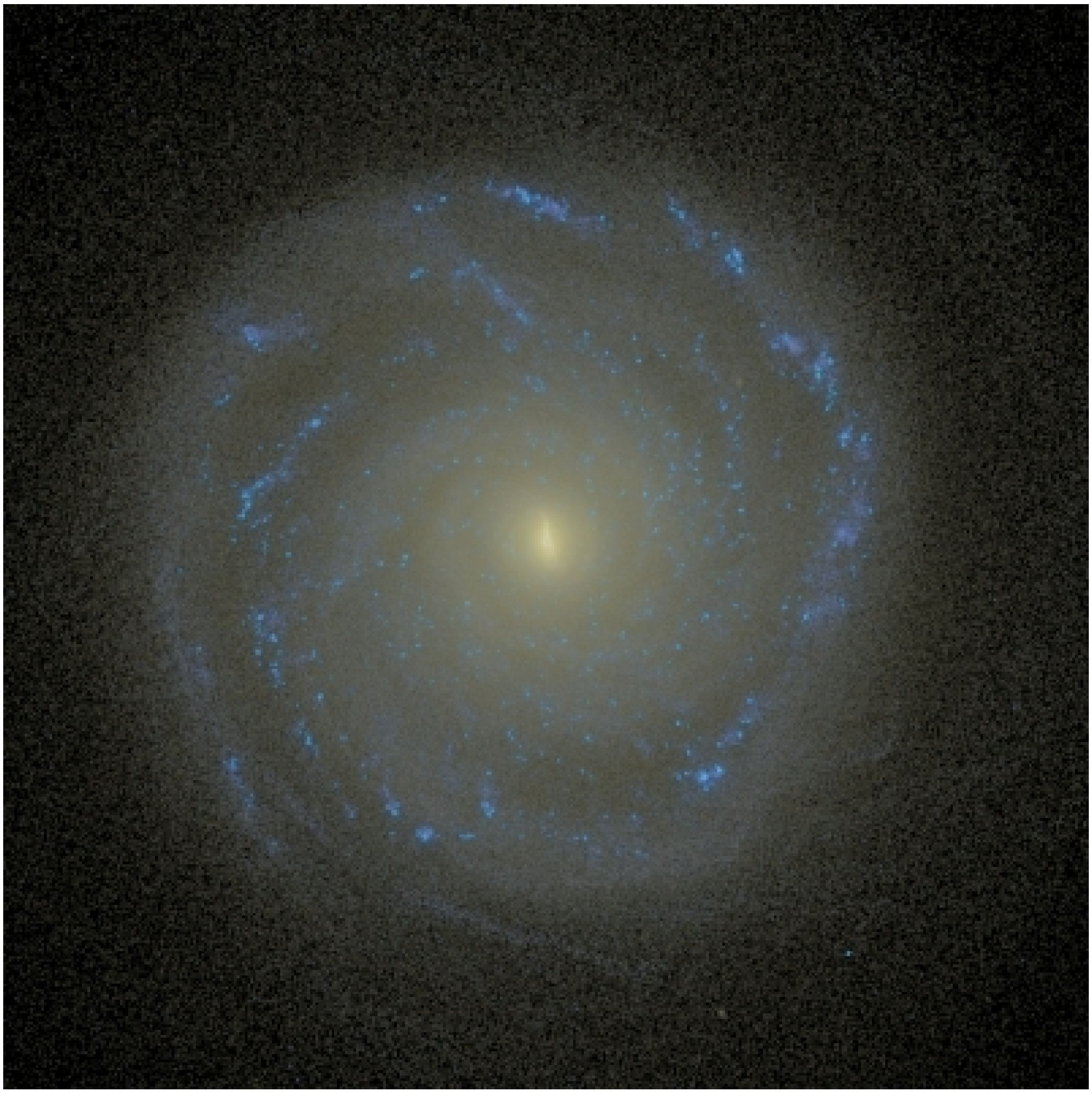


Fig. 1.— Face-on and edge-on Sunrise images of our GASOLINE galaxy, h258, which has an active, merger-rich history.

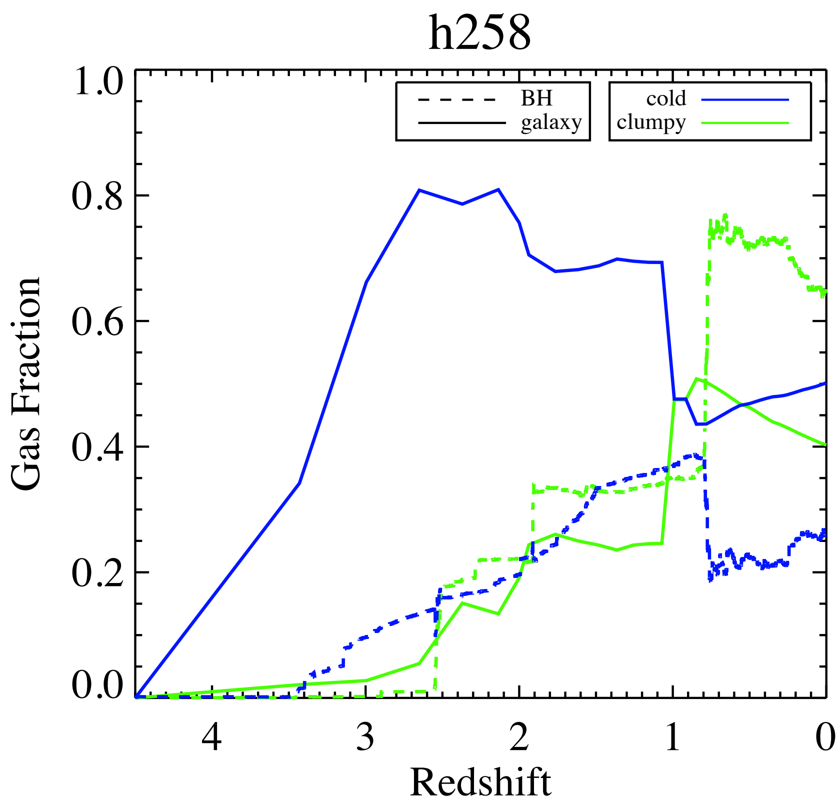



Fig. 2.— Gas fraction across redshift for galaxy (solid lines) and central BH (dashed lines). Green lines signify gas fractions accreted via mergers and blue lines designate gas accreted via cold flow.

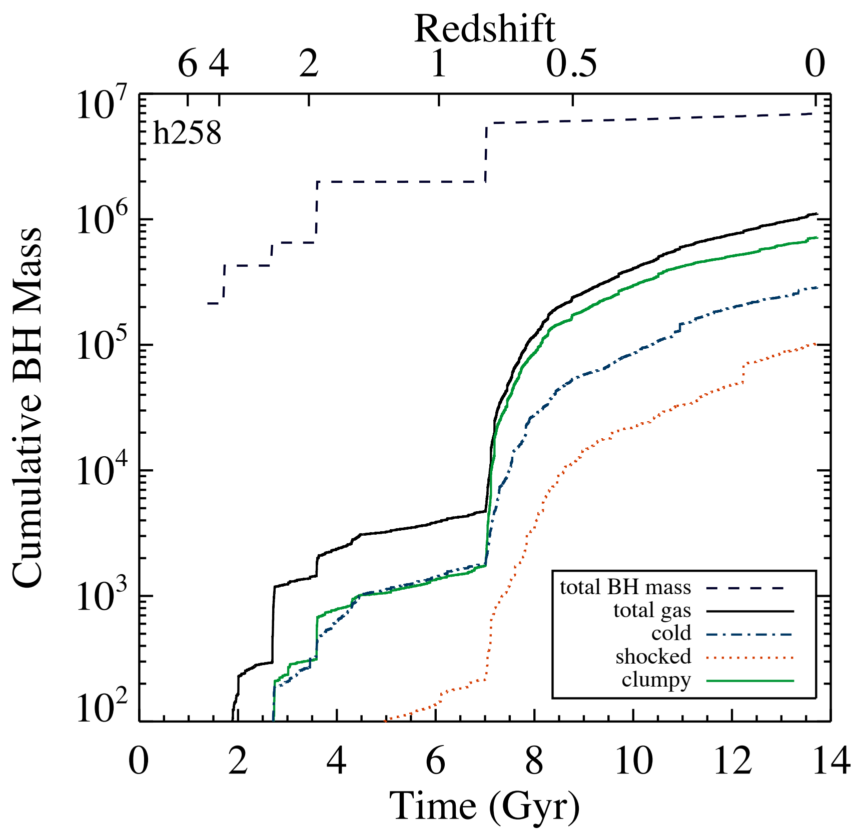
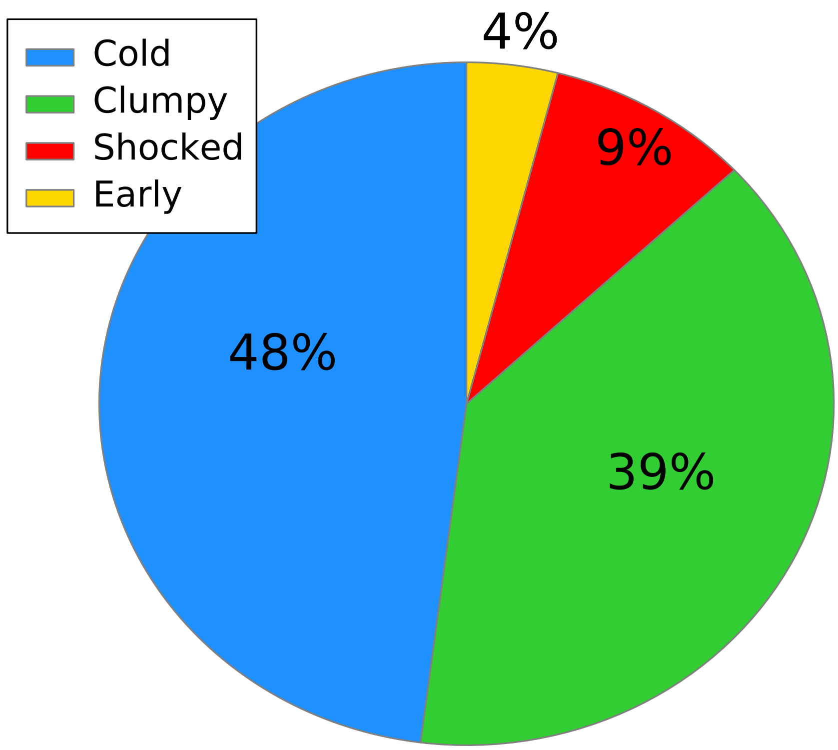
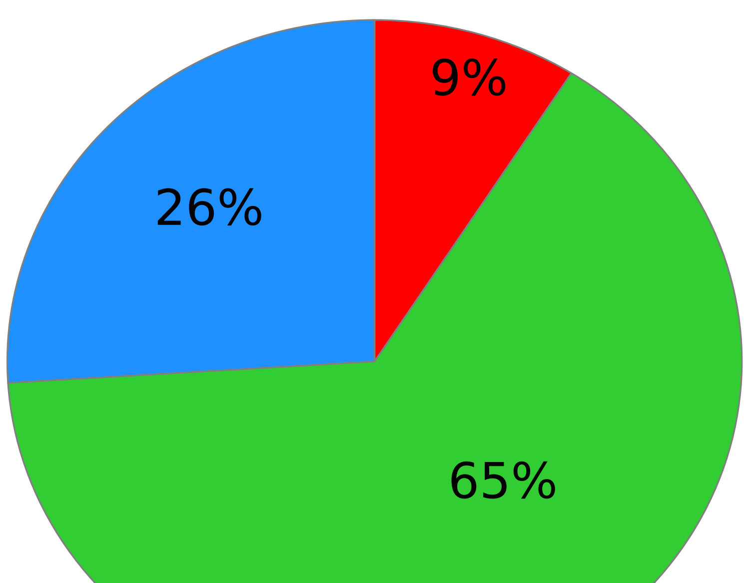



Fig. 3.— The central BHs cumulative mass as a function of time and redshift. The black dashed line indicates the total cumulative BH mass. The black solid line indicates the total gas mass. The blue dot-dashed line indicates the gas mass accreted via cold flows. The green solid line indicates the gas mass accreted through mergers. The red dashed line indicates




h258 Galaxy Gas Fractions



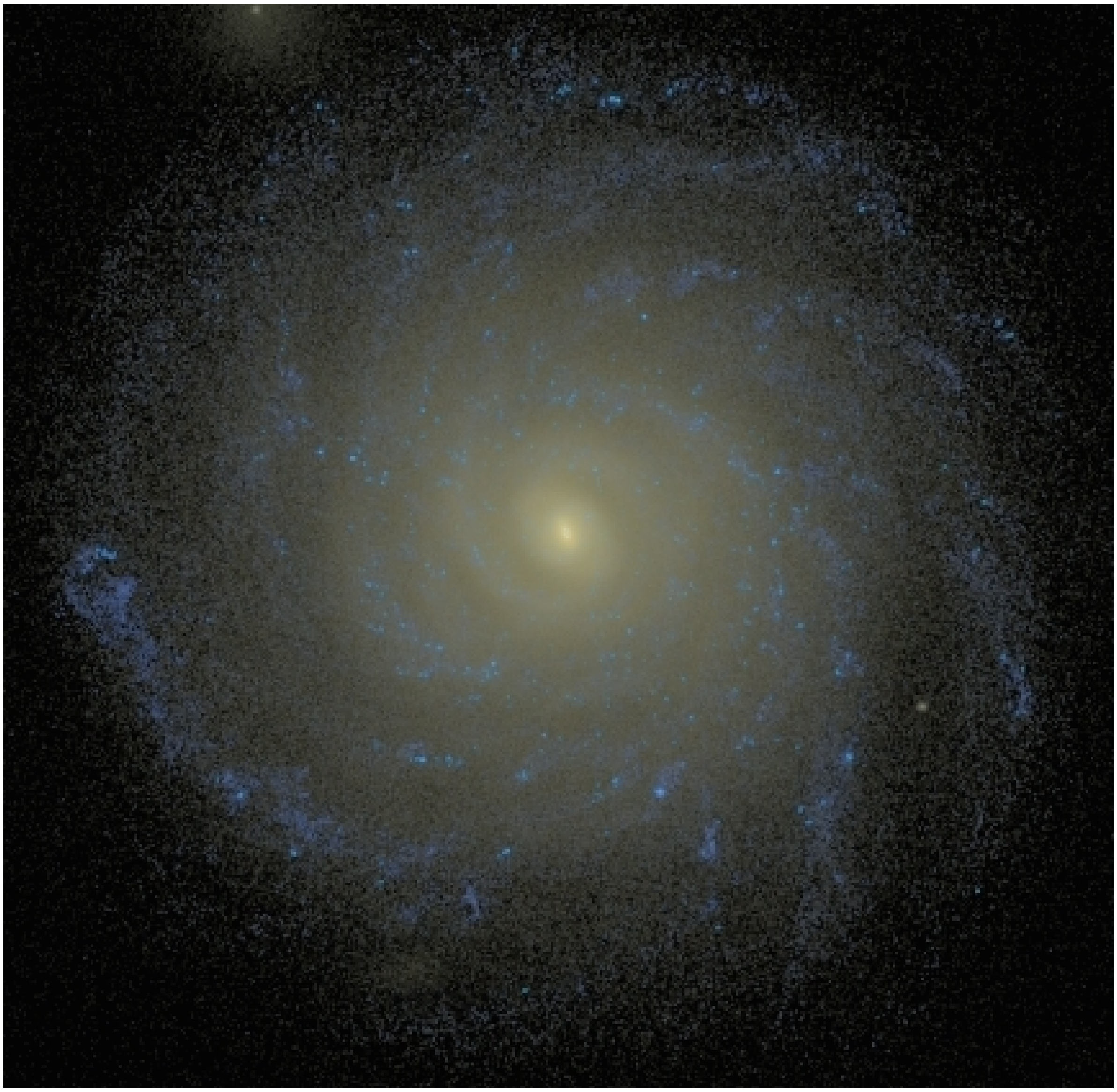


Fig. 5.— Face-on and edge-on Sunrise images of our GASOLINE galaxy, h258, which has an active, merger-rich history.

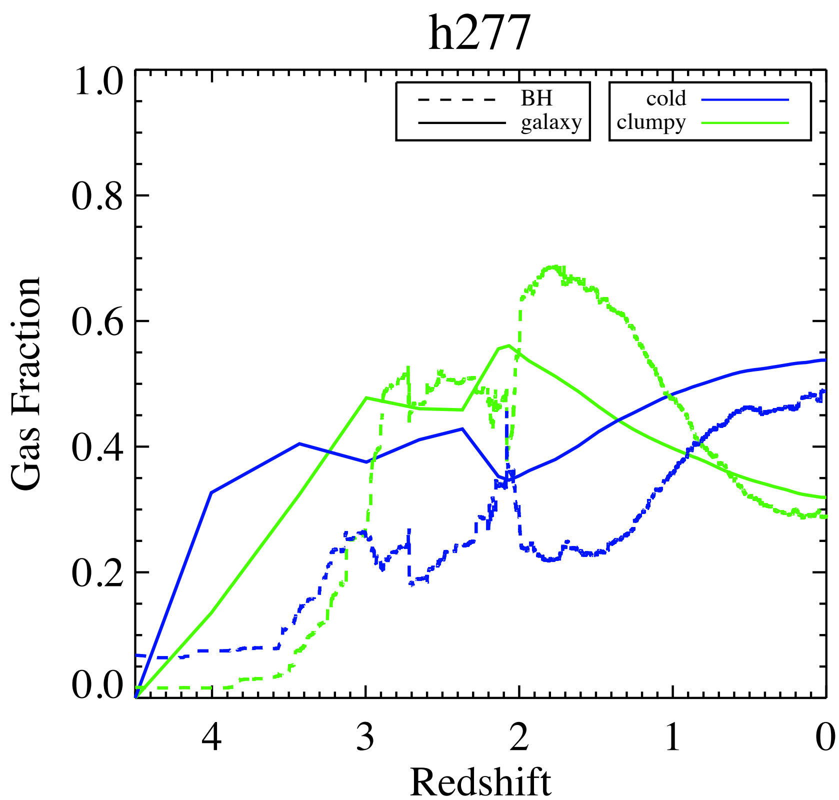
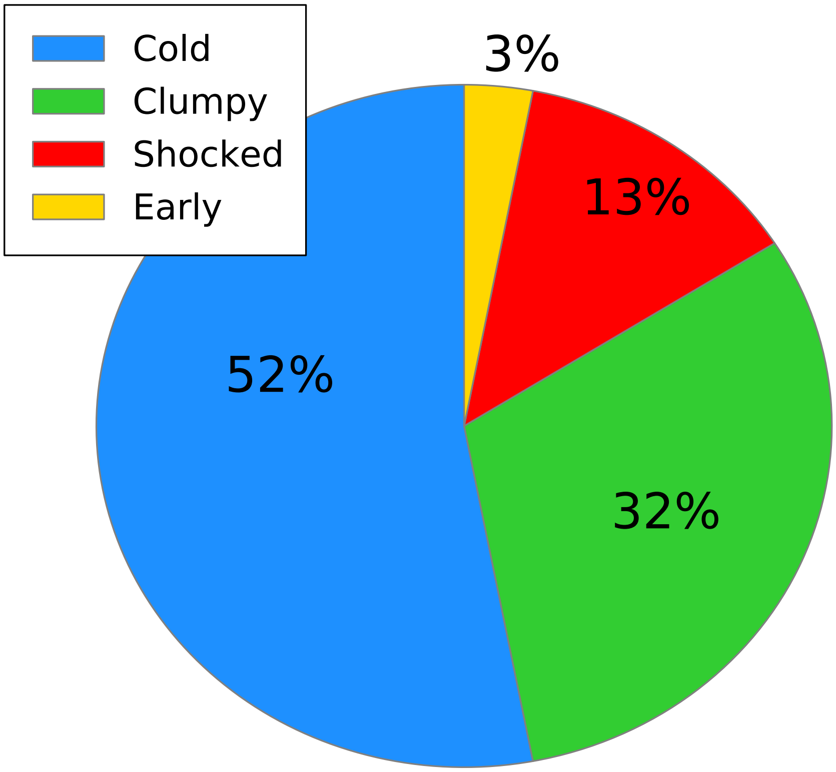
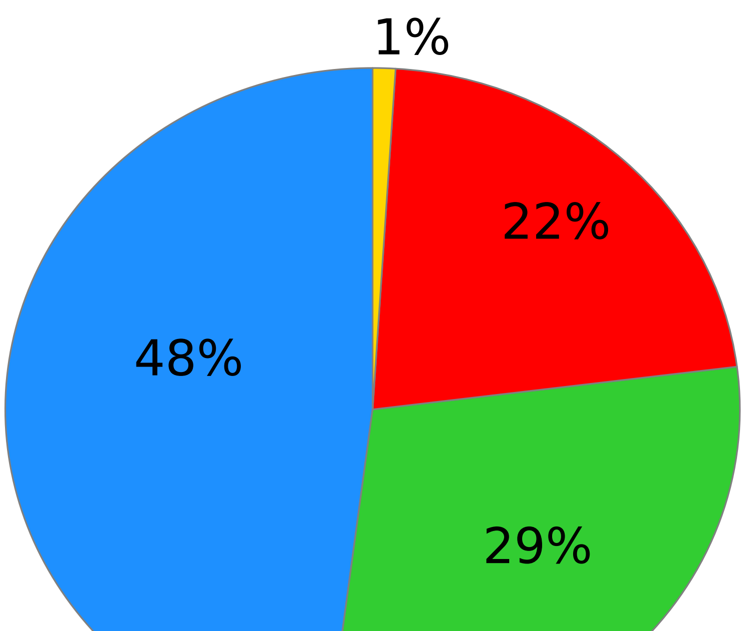



Fig. 6.— Gas fraction across redshift for galaxy (solid lines) and central BH (dashed lines). Green lines signify gas fractions accreted via mergers and blue lines designate gas accreted via cold flow.




h277 Galaxy Gas Fractions



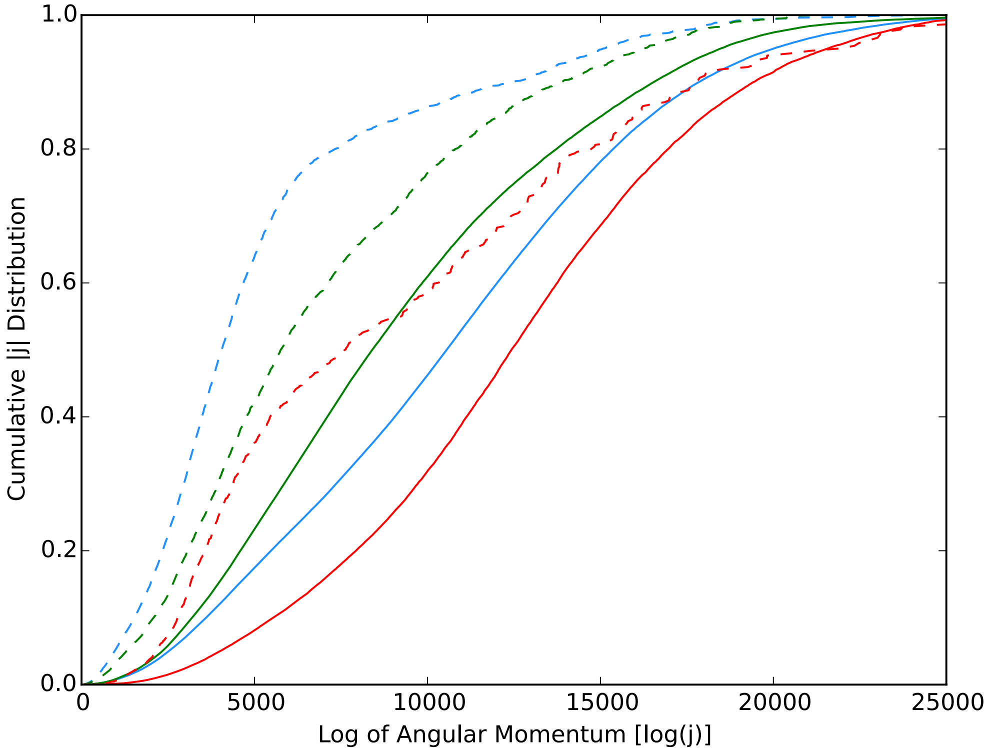



Fig. 8.— Cumulative distribution of angular momentum of the gas particles as they accrete onto the main halo (solid lines) and central black hole (dashed lines).