Section VII

The Big Picture: Large-Scale Effects of Feedback on Galaxies and Their Environment

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Co-Evolution of Central Black Holes and Galaxies
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Black Hole Feeding and Feedback in the Context of Galaxy Formation

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Abstract. I describe ways in which state-of-the-art cosmological simulations are modeling the growth and evolution of supermassive black holes (feeding), and the impact of the energy that they release on galaxies and their surroundings (feedback). I then discuss how this new picture of interconnected co-evolution of galaxies and black holes provides plausible explanations for several of the mysteries that have long vexed theorists studying galaxy formation within the hierarchical cold dark matter paradigm.

Keywords. galaxies: formation, galaxies: evolution, black hole physics, cosmology: theory

1. Introduction

For many years, the communities studying "normal" galaxies and those studying black holes (BHs) and their manifestations (quasars, AGN, etc.) attended different meetings and did not talk to one another much. These days, it is clear that we cannot possibly understand one population without understanding the other, and that the formation of galaxies and black holes is inextricably linked. Questions still remain, however, about exactly how galaxies and black holes "communicate," and whether galaxies dictate black hole properties, black holes dictate galaxy properties, or a combination of the two.

I will focus here on "three mysteries," three problems for which the picture of galaxy black hole co-evolution may provide plausible explanations:

• **The critical mass scale for galaxy formation:** There seems to be a critical stellar mass for galaxies ($\sim 3 \times 10^{10} M_{\odot}$), above which galaxy formation is suppressed (as seen in the sharp decline in the number density of galaxies above this mass). Moreover, galaxies below the critical mass tend to be star forming and have disk-dominated morphologies, while galaxies above this mass tend to be "quenched" (have little or no recent star formation) and have spheroid-dominated morphologies (Kauffmann *et al.* 2003). There are suggestions that this critical mass scale has decreased over cosmic time, resulting in a shift in the objects that dominate star-formation activity from massive to low mass galaxies, sometimes called "downsizing" (see Fontanot *et al.* 2009 and references therein). *What is the significance of this special mass scale, and what physical processes are responsible for this transformation? Why does the critical mass depend on redshift in this manner?*

• **Cooling flows and excess entropy in galaxy clusters:** Based on the temperature and density of the hot gas contained in groups and clusters (which we know from X-ray observations), the cooling times in these objects should be relatively short, $\lesssim 1$ Gyr, in many objects (Fabian 1994). However, we do not observe the large quantities of cold gas or stars that should result from this cooling (this is sometimes termed the "overcooling problem"), nor do we observe the spectral lines associated with cooling from about a third of the virial temperature to lower temperatures (Peterson & Fabian 2006). Furthermore, the observed scaling relations between X-ray temperature and luminosity

(L_X–T_X) deviate from the expectations for purely gravitational heating, implying the need for non-gravitational heating. This is often cast in terms of a requirement for additional entropy in lower-mass clusters and groups (Lloyd-Davies *et al.* 2000). *What process is responsible for preventing cooling and raising the entropy in groups and clusters? Can it be the same process responsible for the "critical mass scale" discussed above?*

• **The origin of BH-galaxy scaling relations:** There is a surprisingly tight observed relationship between black hole mass and galaxy properties, such as spheroid mass or velocity dispersion (Ferrarese & Merritt 2000; Gebhardt *et al.* 2000; Häring & Rix 2004), and some have claimed that there is an observed "black hole fundamental plane" relation between black hole mass and galaxy effective radius, dynamical mass, and velocity dispersion (Hopkins *et al.* 2007c; Marconi & Hunt 2003). It is not yet clear which of these relationships are the most fundamental. There are claims that the relationship between galaxy mass and black hole mass may be evolving with cosmic time (Peng *et al.* 2006; Salviander *et al.* 2007; Woo *et al.* 2008), but these remain controversial. *Do black holes determine the masses of their host galaxies, or vice versa, or is the process of galaxy and black hole formation self-regulated? What would this imply about the redshift evolution of the black hole-galaxy relationship?*

2. The Formation of Galaxies and Black Holes in the ΛCDM Paradigm

In the cold dark matter (CDM) paradigm, galaxies form at the sites where tiny primordial overdensities have grown through gravitational instability to the point where they separate from the Hubble expansion, become gravitationally bound, and collapse and virialize to form a dark matter halo. Both semi-analytic models (SAMs) and numerical hydrodynamic simulations of galaxy formation track this growth of structure in the dominant dark matter component, cooling of gas within dark matter halos by atomic radiation, conversion of cold gas to stars via empirical recipes, and the deposition of energy and heavy elements in the ISM by massive stars and supernova explosions (see Baugh 2006 for a recent review).

2.1. *Modes of Black Hole Growth and AGN Feedback*

Within this well-established picture, many groups are now investigating how black holes form and grow, and how the energy released during their active phase may impact the process of galaxy formation ("AGN feedback"). Here, it is perhaps necessary to take a brief taxonomic detour to clarify just what is meant by "AGN feedback" (for more details, see the contributions by Heckman, King, and Fabian in these proceedings). Two different "modes" of AGN feedback have been identified, corresponding to objects with very different observational signatures, and to different physical mechanisms. Classical optically or X-ray luminous QSOs, which emit most of their energy as radiation, are implicated in what is variously called the "bright mode" or "quasar mode." These objects are accreting rapidly, at near their Eddington rate. Their radiation can couple to the gas and dust in the interstellar medium, driving winds that may shut down further accretion onto the black hole or even drive material out of the galaxy, thereby quenching star formation (SF).

The other mode is associated with objects that typically look like normal massive ellipticals in the optical, but have powerful jets and/or hotspots seen in the radio — hence the usual moniker "radio mode." These objects have low accretion rates and are radiatively inefficient. However, the jets are very efficient at heating the hot gas surrounding galaxies in groups or clusters. There is direct observational evidence for this in the form of bubbles of hot relativistic plasma seen in the X-ray (see Fabian's paper in these proceedings, or the review by McNamara & Nulson 2007). One can estimate how much work must have been done to inflate these bubbles, and thereby obtain at least a lower limit on the jet power (Allen *et al.* 2006; Rafferty *et al.* 2006). By combining these with a proxy for black hole mass such as the galaxy velocity dispersion, we can derive the jet power as a function of black hole mass. This method can currently only be applied to very nearby clusters, so the available sample is small, but it appears that the jet power is a steep function of BH mass. Best *et al.* (2006) and Pasquali *et al.* (2009) have also investigated the fraction of optically identified Sloan Digital Sky Survey galaxies that have low-power radio "loud" counterparts, and find that more massive galaxies are much more likely to be radio loud.

2.2. *Insights from Numerical Simulations*

Any attempt to study the impact of AGN feedback on galaxies in a cosmological context faces a fundamental difficulty — we would require 8–9 orders of magnitude in dynamic range to model accretion onto nuclear supermassive black holes (sub-pc scales), the processes associated with radiative and kinetic feedback from black holes (hundreds of pc to kpc scales), star formation and supernova feedback (pc to kpc scales), galaxy mergers and gas accretion (tens of kpc to Mpc scales), large-scale clustering of galaxies (tens of Mpc) and finally, the Gpc scales needed to study the demographics of luminous quasars. Therefore, a "brute force" numerical approach is not feasible. Perhaps the most effective approach is to carry out specialized high-resolution simulations of individual systems, such as galaxy mergers or galaxy clusters (e.g., Springel *et al.* 2005b; Di Matteo *et al.* 2005; Sijacki *et al.* 2007; Johansson *et al.* 2009), attempt to distill out the relevant physical recipes, and incorporate these self-consistently in a cosmological context either using a semi-analytic model (e.g., Somerville *et al.* 2008, hereafter S08) or an empirical "halo occupation distribution (HOD)" model (Hopkins *et al.* 2008a; Hopkins *et al.* 2008b). Alternatively, it is also possible to implement "sub-grid" recipes within cosmological hydrodynamic simulations (e.g., Di Matteo *et al.* 2007; Booth & Schaye 2009).

The new physics that is now being included in the "unified" models include the formation of seed BH and BH accretion (in two modes, as discussed above, the bright and radio mode), AGN-driven winds, and heating by radio jets. As the field is still relatively new, different groups have included different subsets of these physical processes. For example, many SAMs (e.g., Croton *et al.* 2006; Bower *et al.* 2006) do not include AGN driven winds, while many hydro simulations that purport to include "AGN feedback" do not manifestly include the radio mode (e.g., Springel *et al.* 2005b; Booth & Schaye 2009; Johansson *et al.* 2009). Furthermore, there are still a number of physical processes that may well be important but which have not been included in cosmological models. One example is the formation and destruction of molecular hydrogen, which could be connected either to "positive" feedback via jet-induced star formation (see, e.g., Elbaz in these proceedings), or to negative feedback via destruction of the molecular clouds that host star formation (Hopkins & Elvis 2010; Schawinski *et al.* 2009). Other examples are the physics of accretion disks, conduction (Voit *et al.* 2008), and magnetic fields (Vernaleo & Reynolds 2009).

Putting these aside for the moment, I will summarize some insights gained from extensive studies of hydrodynamic + N-body simulations of galaxy mergers carried out by Cox *et al.* (2006) and Robertson *et al.* (2006b), using methodology developed by Springel *et al.* (2005b) and Di Matteo *et al.* (2005). These simulations are not done in a cosmological context, but consist of two isolated galaxies, each with its own dark matter halo, that are set on a collision course with one another. The great majority of these

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simulations have been of initially disk-dominated galaxies and equal-mass mergers. A seed black hole is placed within each galaxy at the beginning of the simulation, and a simple sub-resolution recipe for accretion onto the central black hole is implemented (using the Bondi–Hoyle–Lyttleton approximation). A small fraction of the radiated luminosity associated with this accretion is deposited isotropically as thermal energy within the region around the black hole.

These experiments have yielded a number of interesting and hopefully qualitatively robust results. First, independent of black hole growth and feedback, we have gained important insights into the origin of the structural properties of spheroids. It has been well established for decades now that near-equal mass mergers between disks lead to spheroidal remnants (Toomre & Toomre 1972; Barnes 1992; Hernquist 1992). Several studies have recently shown that the size and structure of these spheroidal remnants depends quite sensitively on the initial gas fraction in the progenitors (Dekel & Cox 2006; Cox *et al.* 2006; Robertson *et al.* 2006b). This is easy to understand: in a purely collisionless system, energy is conserved so the size of the remnant is nearly the same as the size of the progenitors. However, gas can dissipate energy, and the more energy is lost, the more compact the remnant. Therefore, more gas-rich progenitors produce spheroids with smaller radii and larger velocity dispersions at a given stellar mass. It has been suggested that this could partially explain the origin of the "tilt" in the fundamental plane for elliptical galaxies (Robertson *et al.* 2006b).

It is also well-known that major mergers drive strong inflows of gas into the nucleus, leading to a central starburst that contributes to the spheroidal remnant (e.g., Hernquist 1989; Barnes & Hernquist 1996; Mihos & Hernquist 1994). Hopkins *et al.* (2009) find, however, that the primary driver of these inflows is not the direct torques from the merger, but rather the lag between the stellar bar and the gaseous bar. This implies that in progenitor disks with very high gas fractions (and hence low stellar density), there is less efficient transfer of angular momentum and therefore a larger fraction of material remains in an extended disk. Indeed, major mergers between very high gas fraction disks can even produce disk-dominated remnants (Robertson *et al.* 2006a).

These simulations also yielded the following results related to BH growth and AGN feedback in mergers:

• Energy feedback from the accreting BH leads to self-regulated BH growth, and reproduces the observed $M_{\rm BH}$–$M_{\rm gal}$ scaling relations (Di Matteo *et al.* 2005). The fraction of the AGN radiation that is coupled with the gas determines the normalization of the relation.

• The AGN drives a large-scale wind that removes nearly all of the residual gas from the galaxy, rapidly quenching star formation and leaving merger remnants that are "red and dead" (Springel *et al.* 2005a).

• The simulations predict a characteristic functional form for the QSO light curve (near-Eddington accretion during the active merger phase, followed by a power-law decline as the "blow-out" phase associated with the AGN-driven wind kicks in), and luminosity (or initial BH mass) dependent QSO lifetimes (Hopkins *et al.* 2005b, 2006a).

Taken together, all of this implies that mergers involving progenitors with higher gas fractions will leave behind remnants with a larger BH–spheroid mass ratio. This follows because, as noted above, higher gas fraction in the progenitors leads to more compact remnants. In the simulations, the BH grows until the energy being deposited in the gas in the vicinity of the BH is sufficient to halt further accretion. In this growth phase, the luminosity is roughly Eddington, thus proportional to the mass of the BH, and the amount of energy needed to halt the accretion is greater for a deeper potential well. The net effect is that the BH grows until it reaches a critical mass, where that critical mass relative to the spheroid mass is a function of the initial gas fraction (Hopkins *et al.* 2007a; Hopkins *et al.* 2009). This leads to the prediction that if the gas fraction in galaxies was higher in the past, as expected, then BHs should have been larger relative to their spheroids in the past.

A second implication is that low-mass galaxies, which tend to have higher gas fractions at all redshifts, are inefficient relative to higher-mass galaxies at forming spheroids, and are more likely to remain disk-dominated despite having suffered major mergers. As it is the spheroid potential well that regulates BH growth, BHs also will not grow as large in these low-mass galaxies. As shown by Hopkins *et al.* (2009), when implemented in a cosmological model (either HOD or SAM), this leads to good agreement with the observed mass functions of bulge and disk-dominated galaxies, and cures the overproduction of low-mass spheroids seen in previous models that did not include the gas-fraction dependence.

I now turn to a different topic, one that has been elucidated by 3-D cosmological hydrodynamic simulations as well as 1-D Lagrangian simulations. This work (Birnboim & Dekel 2003; Kereš *et al.* 2005; Kereš *et al.* 2009) shows that cosmological gas accretion can occur in two "modes." In "hot-mode" accretion, gas is shock heated to near the virial temperature ($T_{\rm vir} > 5 \times 10^5$ K for large halos) as the potential of the dark matter halo collapses, and then cools; in "cold-mode" accretion, the gas is never shock heated, but remains at the temperature of the IGM ($\sim 10^4$ K) as it falls in, generally along dense filaments. The conditions for hot versus cold accretion are determined by the ratio of the cooling time and the free fall time, and this leads to a relatively sharp mass division between halos with primarily hot versus primarily cold accretion at a critical mass of a few times 10^{11}–10^{12} $M_\odot$ at $z = 0$ (Kereš *et al.* 2005; Kereš *et al.* 2009). In many cases, however, a hot halo and cold streams can co-exist, and both cold and hot-mode accretion occur simultaneously (Kereš *et al.* 2005; Ocvirk *et al.* 2007). Because the background density of the universe was higher at high redshift, and accretion was more filamentary, this critical mass decreased over time, and may have been about an order of magnitude higher at $z \sim 4$ than it is today (Ocvirk *et al.* 2007; Dekel *et al.* 2009). If we now consider heating by giant radio jets, it seems likely that a quasi-hydrostatic halo of hot, relatively low-density gas must be present in order for the jets to form, and that accretion via the cold dense streams is likely to be fairly impervious to this heating. This implies that radio mode heating is probably less important in low-mass halos and at high redshift (Cattaneo *et al.* 2006).

2.3. *AGN Feedback in Semi-Analytic Models*

Including this radio mode feedback into semi-analytic models has been instrumental in improving the models' agreement with a broad variety of observations that had proved problematic before (e.g., Croton *et al.* 2006; Bower *et al.* 2006; Menci *et al.* 2006; Kang *et al.* 2006; Monaco *et al.* 2007; Somerville *et al.* 2008). For example, the models now do a good job of reproducing local stellar mass functions and luminosity functions, and also do fairly well at reproducing stellar mass densities and specific star formation rates (SFRs) for massive galaxies at high redshift (Fontanot *et al.* 2009). Massive galaxies are active at high redshift, and become "quenched" at around $z \sim 2$ to 1.5, in agreement with observations, and the distribution of galaxy colors and specific SFRs at low redshift ($z < 1$) is bimodal. There are still discrepancies related to low-mass galaxies, but these are unlikely to be related to AGN feedback (Fontanot *et al.* 2009). It is also interesting that although different groups have added black hole growth and AGN feedback in rather different ways, the predictions for *global galaxy properties* such as stellar masses and specific SFRs as a function of redshift are remarkably similar across different groups (Fontanot *et al.* 2009; Kimm *et al.* 2009). Furthermore, Bower *et al.* (2008) show that

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including radio-mode heating could simultaneously reproduce the observed X-ray temperature versus X-ray luminosity scaling relations and hot gas fractions for groups and clusters as well as galaxy properties.

2.4. *Confronting Observational Signposts of Black Hole Activity*

Although there have been many studies testing how well the new models with AGN feedback reproduce various *galaxy* properties, there has been less attention to what seems a crucial question: is the BH activity that we are invoking to solve our problems with galaxies consistent with observations of active BHs?

We noted above that the bubbles of hot gas observed in the X-ray can be used to estimate how much energy is being deposited by radio-mode heating in nearby groups and clusters. S08 address the question: how does the amount of heating required to reproduce galaxy properties in the models compare with these constraints? Figure 11 of S08 shows the jet power (or rate of energy input into the hot gas) as a function of the black hole mass. This figure shows that (1) the models predict a trend between black hole mass and heating rate that is very similar to that observed and (2) the heating rates required in the models lie below the upper envelope of the observational estimates. Since the estimates include only the heat associated with the bubbles, and there is also expected to be significant heating by weak shocks and sound waves, this result is encouraging.

Figure 1 shows the total luminosity density produced by bright-mode AGN as a function of redshift. Observational estimates from Hopkins *et al.* (2007b) are compared with theoretical predictions from several different models (Somerville *et al.* 2008; Croton *et al.* 2006; Bower *et al.* 2006; Malbon *et al.* 2007). The Croton *et al.* models are based on the Munich Millennium models, and the Bower *et al.* and Malbon *et al.* models are different variants of the Durham GALFORM models. Two different versions of the S08 models are shown: one containing the standard assumption that spheroids are always formed in major mergers, and the other with the gas fraction dependent recipe for spheroid formation described by Hopkins *et al.* (2009), based on the numerical merger simulations described above. In the latter model, low-mass galaxies tend to be more gas rich, and so (for reasons discussed earlier) spheroid formation and black hole formation are suppressed at early times. As noted above, all of these models produce very similar predictions with regard to the *galaxy* population at all redshifts. However, one can see that the global black hole accretion rate (BHAR) in these models is quite different. This is a result of adopting different approaches for modelling when and how black holes grow, and what regulates their growth. For example, in the S08 models *all* bright-mode BH growth is triggered by mergers, while in the GALFORM models, most bright-mode BH growth is due to disk instabilities. The Croton *et al.* (2006) model is in between, with comparable contributions from merger-triggered growth and disk instabilities. All of the models normalize their BH accretion recipes to reproduce the observed relationship between BH mass and bulge mass at $z = 0$. The gas-fraction based recipe for spheroid growth and accompanying BH accretion implies that the S08 models predict that BHs were larger with respect to their spheroids in the past. The Croton *et al.* (2006) model also predicts that BHs were more massive in the past relative to their spheroids, as discussed by Croton (2006), while the Malbon *et al.* (2007) models predict almost no evolution in BH mass at a given spheroid mass (see Figure 15 of Malbon et al. 2007). These are examples of ways that future observations may be able to discrimate between different approaches and ultimately provide insight into the physical processes governing BH feeding and feedback.

2.5. *Co-Evolution of SF and BH Activity*

Figure 2 shows the global SFR density and the SFR due to merger-driven starbursts in the (updated) S08 models, compared with the BHAR scaled by a factor of 2000. The BHAR due to merger-driven (bright-mode) accretion and radio-mode accretion are shown separately. Merger-driven BH accretion dominates the growth of BH mass over most of cosmic history, with radio-mode accretion becoming important only at very late times. The SFR due to merger-triggered bursts is also shown. At early times, BH accretion is suppressed relative to SF because the BH growth is Eddington limited and many galaxies are experiencing BH accretion for the first time. Thus, in our models, the increase in the BHAR from high redshift until the peak is due to the Eddington limit and the build-up of massive BHs, while the decline at late times is due to fuel depletion and AGN feedback. Furthermore, the *total* SFR and the BHAR trace each other very closely at $z \lesssim 3$, in spite of the fact that *all* BH growth in this model is associated with mergers (either merging of pre-existing BH or merger-driven accretion). We also see that the contribution to the SFR density from merger-driven starbursts in this model is quite small ($\lesssim 10\%$), in agreement with observations (Robaina *et al.* 2009); most of the star formation takes place in isolated disks.

As shown recently by Zheng *et al.* (2009), the observed global SFR and BHAR do in fact trace each other remarkably closely at $z \lesssim 3$, and are offset by a "magic factor" of 2000, which is what one would expect if BH and galaxies always grew in mass in direct proportion to one another and this proportionality factor remained constant with time. However, this simple picture of co-evolution would imply a relationship between BH mass and galaxy *total stellar mass*, while what we observe is a relationship between BH mass and *spheroid* mass. Furthermore, most star-formation activity (at least at $z \lesssim 1$) occurs in disk-dominated galaxies, while most BH activity (in terms of the growth of BH mass) occurs in spheroid-dominated galaxies. Zheng *et al.* (2009) posed the question: why is it that SF and BH accretion appear to trace each other so closely, while these two kinds of activity seem to occur predominantly in different kinds of objects and hence are presumably triggered or regulated by different processes?

We can try to obtain some insight into this from the models, which show the same apparently paradoxical behavior. Recall that following a merger, the BH is allowed to accrete and grow until it reaches a critical mass. This critical mass is the mass at which the energy being radiated by the BH is sufficient to halt further accretion onto itself, and it depends on the potential well in which the BH is sitting. Thus, the ratio between BH mass and spheroid mass in these models is effectively set by the strength of the coupling between the BH radiation and the gas in the interstellar medium of the galaxy. We treat this coupling factor as a free parameter, which we set in order to reproduce the observed ratio of BH mass to bulge mass in nearby galaxies. The stars from disrupted disks following mergers dominate the potential well of the bulge, which in turn determines how large the BH can grow. The bulk of these stars were formed not in the merger itself, but while their galaxies were living normal lives as isolated disks. This explains the link between the global SFR and the BHAR and resolves the apparent paradox.

3. Conclusions

In conclusion, I return to the "three mysteries" posed in the introduction, and summarize how the new picture of AGN feeding and feedback within the hierarchical paradigm for galaxy formation provides some plausible answers to these questions.

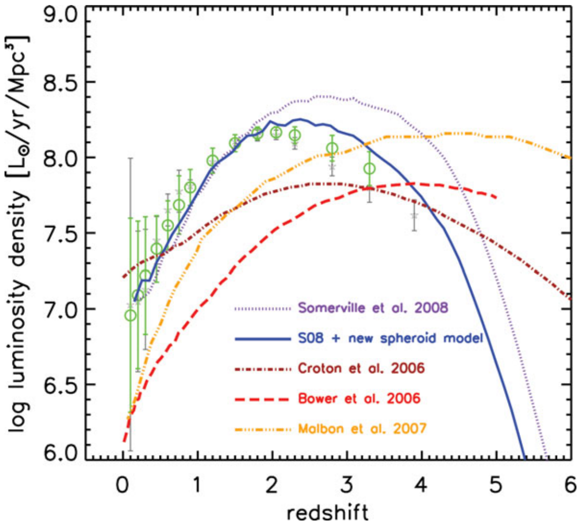

Figure 1. The global bolometric luminosity density of quasars and AGN as a function of redshift. Symbols show observational estimates from Hopkins *et al.* (2007). Lines show predictions from different models, as labeled on the plot and discussed in the text.

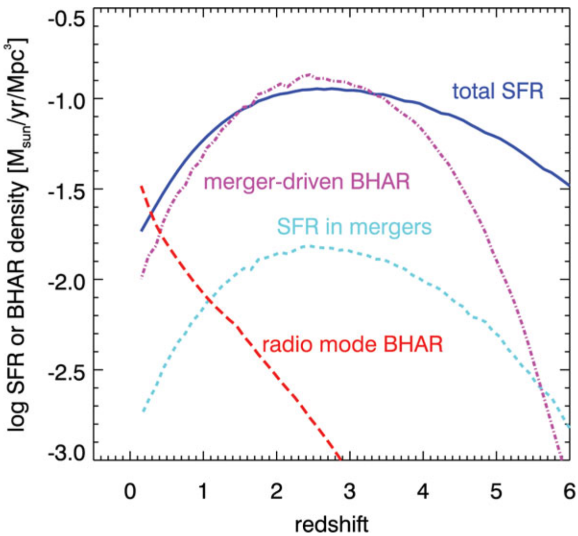

Figure 2. The history of star formation and BH accretion in the semi-analytic model of Somerville *et al.* (2008). The solid line shows the total SFR and the short-dashed line shows the SFR associated with merger-triggered bursts. The dot-dashed line shows the bright-mode BHAR, and the long-dashed line shows the BHAR associated with the radio mode, both scaled up by a factor of 2000.

Q.: Why is there a critical mass for galaxy formation, and why was it larger in the past?

A.: AGN feedback is more effective in massive galaxies because (1) they have lower gas fractions, and are therefore more efficient at forming spheroids and massive BHs and (2) gas is accreted primarily in the "hot mode," which is susceptible to heating by radio jets. The critical *halo* mass, separating halos that are accreting via hot versus cold mode,

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decreases with time. Therefore, star formation is more easily quenched after a halo has exceeded the critical mass.

Q.: What about the cluster cooling flow and entropy problems?

A.: Heating by radio jets raises the entropy of the intracluster medium and quenches cooling flows.

Q.: What is the origin of BH-galaxy scaling relations?

A.: The gravitational and gas physics of mergers set the depth of the potential well in which BH grow. Self-regulated feedback processes (such as radiation pressure driven outflows) determine how much mass the BH can accrete.

Although this picture seems plausible, even promising, there are still many aspects that need to be tested and many details that need to be refined. In particular, the physical recipes describing BH accretion, and the physics of the coupling of energy produced by BH with galaxies and their surroundings, remain schematic at best in the current models. However, meetings like this one, which brought together scientists studying BH feeding and feedback both theoretically and observationally, and across a broad range of scales, will surely help us to make progress.

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