

2005

# Building Galaxies with Simulations

R Dave

K Finlator

L Hernquist

N Katz

*University of Massachusetts - Amherst*

D Keres

*See next page for additional authors*

Follow this and additional works at: [https://scholarworks.umass.edu/astro\\_faculty\\_pubs](https://scholarworks.umass.edu/astro_faculty_pubs)



Part of the [Astrophysics and Astronomy Commons](#)

---

## Recommended Citation

Dave, R; Finlator, K; Hernquist, L; Katz, N; Keres, D; Papovich, C; and Weinberg, DH, "Building Galaxies with Simulations" (2005). *Astronomy Department Faculty Publication Series*. 1003.

Retrieved from [https://scholarworks.umass.edu/astro\\_faculty\\_pubs/1003](https://scholarworks.umass.edu/astro_faculty_pubs/1003)

This Article is brought to you for free and open access by the Astronomy at ScholarWorks@UMass Amherst. It has been accepted for inclusion in Astronomy Department Faculty Publication Series by an authorized administrator of ScholarWorks@UMass Amherst. For more information, please contact [scholarworks@library.umass.edu](mailto:scholarworks@library.umass.edu).

---

**Authors**

R Dave, K Finlator, L Hernquist, N Katz, D Keres, C Papovich, and DH Weinberg

# Building Galaxies with Simulations

Romeel Davé  
*University of Arizona*

Kristian Finlator  
*University of Arizona*

Lars Hernquist  
*Harvard University*

Neal Katz  
*University of Massachusetts*

Dušan Kereš  
*University of Massachusetts*

Casey Papovich  
*University of Arizona*

David H. Weinberg  
*Ohio State University*

**Abstract.** We present an overview of some of the issues surrounding current models of galaxy formation, highlighting recent insights obtained from cosmological hydrodynamic simulations. Detailed examination of gas accretion processes show a hot mode of gas cooling from near the halo's virial temperature, and a previously underappreciated cold mode where gas flows in along filaments on dynamical timescales, emitting its energy in line radiation. Cold mode dominates in systems with halo masses slightly smaller than the Milky Way and below, and hence dominates the global accretion during the heyday of galaxy formation. This rapid accretion path enables prompt assembly of massive galaxies in the early universe, and results in  $z \sim 4$  galaxy properties in broad agreement with observations, with the most massive galaxies being the most rapid star formers. Massive galaxies today are forming stars at a much reduced rate, a trend called downsizing. The trend of downsizing is naturally reproduced in simulations, owing to a transition from cold mode accretion in the early growth phase to slower hot mode accretion once their halos grow large. However, massive galaxies at the present epoch are still observed to have considerably redder colors than simulations suggest, suggesting that star formation is not sufficiently truncated in models by the transition to hot mode, and that another process not included in current simulations is required to suppress star formation.

## 1 Introduction

Galaxy formation is harder than it looks. The classic papers of the 1970's outlined broad scenarios for how galaxies form in the presence of dark matter halos (e.g. [1]), and together with the advent of hierarchical structure formation, the following conventional wisdom has dominated models for galaxy formation: Galaxies form within biased peaks in large-scale structure, by cooling out from a virial-temperature halo of gas onto a rotationally-supported central disk where stars form. The broad success of this scenario has spawned an increasingly sophisticated industry known as semi-analytic modeling, building on the above framework by introducing and tuning analytic parameters to describe the sundry astrophysical processes that govern the appearance and evolution of galaxies. While promising, various semi-analytic methods have often found non-unique solutions in parameter space that are able to equivalently match available data, resulting in some ambiguity for the predictions of such models. The ultimate goal of galaxy formation theory is to understand the process thoroughly enough that semi-analytic (or equivalently simple and intuitive) models can successfully and uniquely reproduce the broad range of properties that galaxies exhibit across cosmic time. Unfortunately, it appears that our current level of understanding leaves us far from this goal.

To better understand and characterize galaxy formation, it is useful to employ numerical simulations of the growth of structure that dynamically follow the processes required to form baryonic galaxies. Such techniques have been developing at an accelerated pace due to a combination of Moore's Law, algorithmic improvements in modeling complex baryonic physics, and the advent of a standard model of cosmology [2]. Since galaxy formation

connects scales from sub-parsec star formation to megaparsec structure formation, simulations are unrelentingly limited by dynamic range; hence the continuing exponential increase in hardware computing speed have not only enabled more accurate models, but have also spurred greater levels of insight. Modeling baryons better involves both developing more accurate algorithms to follow gas dynamics, as well as understanding how to model all the physical processes that are relevant to galaxy formation; both areas have seen significant progress in recent years. Finally, the concordance cosmology now favored by a variety of observations allows the evolution of large-scale structure and dark matter halos to be specified precisely (or precisely enough), so that efforts in exploring parameter space can now be expended towards constraining more uncertain baryonic processes rather than the underlying cosmology. These improvements together have propelled simulations into becoming an indispensable tool for studying the physics of galaxy formation and interpreting observations of galaxies.

A successful theory of galaxy formation must be able to explain a wide range of multiwavelength observations at a variety of epochs. X-rays observations indicate that galaxies must have a significant impact on their environment, because intracluster gas shows elevated entropy levels and substantial enrichment. Optical surveys such as SDSS and 2dF have mapped the local galaxy distribution in exquisite detail, and deeper probes are now finding substantial populations of galaxies out to  $z \sim 6$ . Near infrared surveys, a focus of this meeting reflecting the recent detector-driven boom in this field, have enabled detailed stellar mass assembly studies out to  $z \sim 3$ , along with searches for galaxies into the reionization epoch. Far infrared studies have also received a large boost from *Spitzer*, revealing the evolution of the dust enshrouded universe. Sub-millimeter bolometers have detected galaxies at a range of redshifts thanks to fortuitous K-corrections, discovering some of the most actively star forming galaxies in the universe. Radio observations are useful for studying molecular gas out to  $z \sim 6$ , and the promise of 21 cm mapping of the high-redshift HI distribution looms on the horizon. Forefront work in many of these areas is represented in these proceedings.

In order to model the formation of all these objects in the correct number and by the correct time, we have at our disposal the following: An understanding of the growth of the dominant mass component in the universe, an empirically tight yet vague understanding of how gas turns into stars from the Kennicutt (1998) relation, and some really big computers. Can we do it? Not surprisingly, the current answer is no, but in this review I hope to give at least a partial view of where we stand in the process.

Galaxy formation can be thought of as having two phases: Gas enters into galaxies from the intergalactic medium (“accretion”), and gas is returned from galaxies, carrying energy and metals, back into the intergalactic medium (“feedback”). Our understanding of both components remains incomplete, significantly more so for the latter. In these proceedings I will discuss recent progress using cosmological hydrodynamic simulations towards understanding how gas gets into galaxies, present some comparisons to observations at high redshifts, mention the origin of galaxy downsizing and implications thereof, and discuss how massive early type galaxies reveal some outstanding issues that simulations must confront in the coming years.

## 2 How Does Gas Get Into Galaxies?

Recent simulations have provided some quantitative insights into the nature of gas accretion onto galaxies at various masses and epochs. The White & Rees [1] scenario for gas accretion onto galaxies is clearly seen to occur in simulations; hot halos form around massive galaxies with central densities sufficiently high that a cooling flow is established. Indeed, later we will discuss the difficulty in preventing such a cooling flow, as appears to be required by observations.

But this form of accretion does not appear to be the whole story, or indeed even the majority of the story. Kereš et al. [3] found that a second mode of gas accretion dominates in halos with masses somewhat smaller than the Milky Way’s and below. To differentiate, they dubbed accretion from cooling of virial temperature gas as “hot mode”, and this alternate mode as “cold mode”. Cold mode occurs when the cooling time in the halo outskirts is sufficiently short that infall becomes regulated instead by the dynamical time. In cold mode, the infalling gas temperature never approaches the virial temperature of the halo, but instead its gravitational potential energy is radiated away as line emission in primordial and (if present) metal atomic cooling lines.

The existence of cold mode accretion is not a new idea. [4] recognized that such a mechanism should exist, and indeed all semi-analytic models contain such a mode that gets activated whenever the cooling time at the virial radius is shorter than the Hubble time (or some other relevant formation timescale). Hydrodynamic simulations have provided additional insights into the quantitative importance of cold mode, in particular demonstrating that owing to processes inherent in a three-dimensional fully dynamical model, cold mode is significantly more important than had been previously realized.

To estimate the quantitative importance of cold mode versus hot mode, one can track the temperature history of each gas particle that ends up as a star in a galaxy, find the maximum temperature achieved, and determined the fraction of mass accreted at a given maximum temperature. Such a plot (from Kereš et al.) is shown in Figure 1, at a range of redshifts. The bimodality of accretion temperatures is evident, particularly at early times ( $z > 2$ ) when the universe is rapidly forming stars. Identifying the lower-temperature hump with cold mode and the higher-temperature one with hot mode, these simulations show a dividing temperature between modes of  $\approx 2.5 \times 10^5$  K. As can be seen, when star formation is most active in the universe at  $z > 2$ , cold mode is actually the dominant mechanism for gas accretion into galaxies.

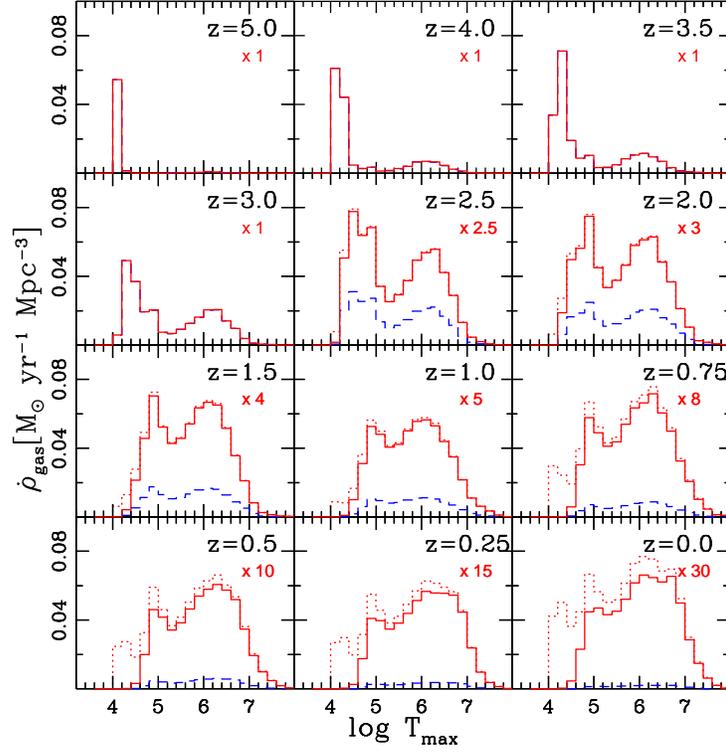


Figure 1: Histograms of maximum gas temperatures achieved by particles that turned into stars by the indicated redshift. The bimodality of hot and cold mode accretion is evident at all redshifts, though stronger at high- $z$ . Cold mode dominates at early times ( $z > 2$ ), when the accretion rates onto galaxies are the highest. From [3].

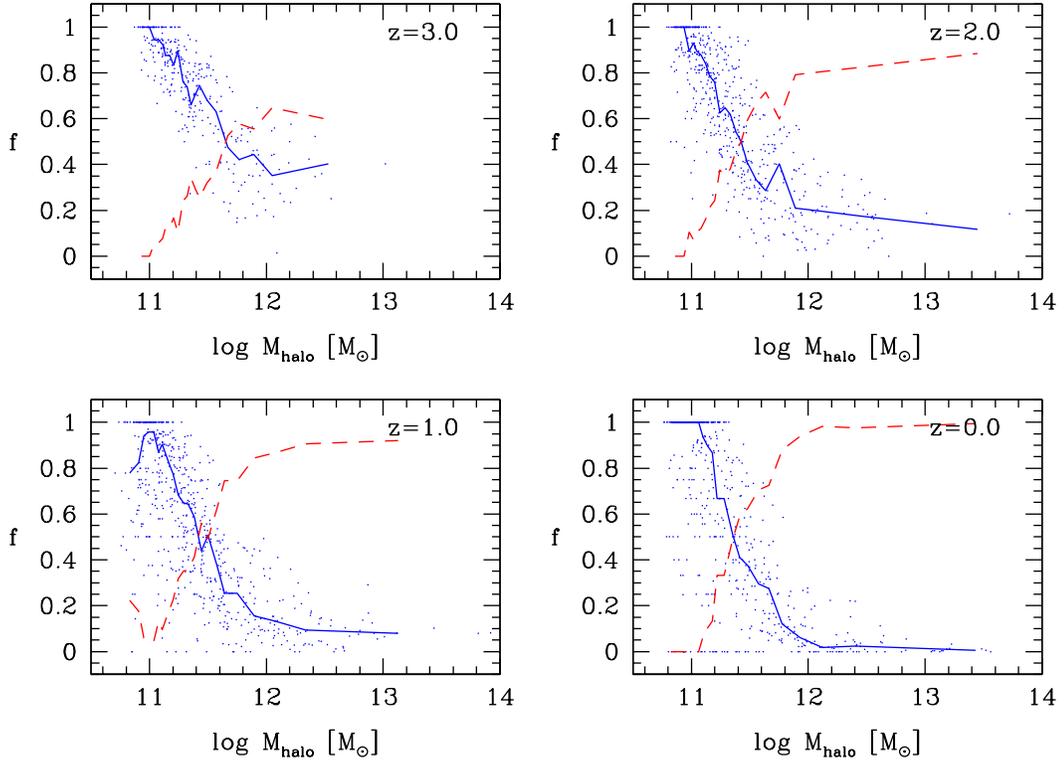


Figure 2: Fraction  $f$  of gas accreted in cold mode for galaxies at various redshifts. Blue line shows the median cold mode fraction, and red line shows the median hot mode fraction. The crossover point is at few times  $10^{11} M_{\odot}$ , basically independent of redshift from  $z = 3 \rightarrow 0$ . From [3].

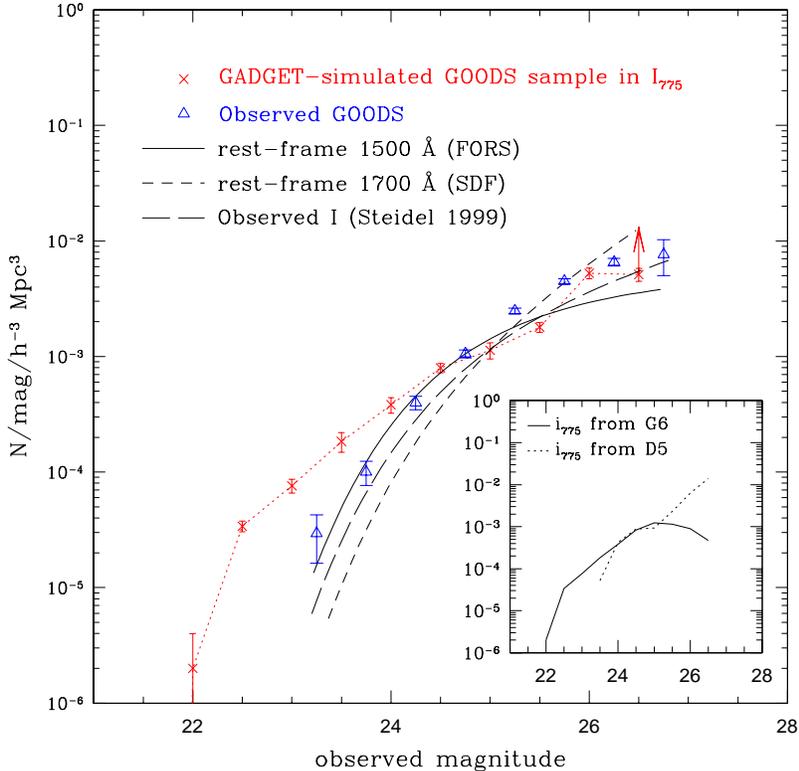


Figure 3: The simulated rest-frame UV LF of B-dropouts compared with several published curves and the GOODS data. Red crosses indicate the simulated LF in observed  $i_{775}$ . The GOODS B-dropout sample is indicated by blue triangles. The simulated LFs are in broad agreement with available constraints, with a possible excess at the bright end. *Inset*: The LFs of the D5 and G6 simulations, which were combined to produce the full curve. From [7].

Insights on the physical mechanism behind cold accretion come from investigating the dependence of the cold mode fraction (i.e. the fraction of star particles whose parent gas particle’s temperature never exceeded  $2.5 \times 10^5$  K) on galaxy and halo mass. The clearest trends occurred with halo mass, in the sense that there appears to be a dividing mass of  $\approx 10^{11.4} M_{\odot}$ , independent of redshift (for  $z < 3$ ), below which accretion is predominantly cold mode, as shown in Figure 2. This value exceeds by a factor of a few the mass threshold obtained by simply equating the cooling time to the Hubble time at the virial radius. An independent investigation by [5] using a one-dimensional galaxy formation model including primordial cooling and cosmological accretion found a threshold for stable accretion shock formation of below  $10^{11} M_{\odot}$ , comparable to the value from a simple virial radius cooling time argument. Hence it is the three-dimensional geometry of infall, particularly enhancement of density along filaments [6], that is responsible for the increased importance of cold mode accretion.

The exact temperature of the division between hot and cold accretion depends on a variety of parameters. The investigations above only included primordial cooling, whereas if metal line cooling is included the dividing mass will presumably rise. The exact value is also sensitive to the ratio of  $\Omega_m/\Omega_b$ , which was assumed to be 7.5 in Kereš et al.; a more canonical concordance value of 6 would likewise result in a higher dividing mass. It is probable therefore that cold mode is even more important overall than suggested in Kereš et al. In any case, more significant than the precise values are the qualitative notions that (1) Cold mode dominates in smaller halos, and hence is more important at earlier epochs; (2) Cold mode dominates in galaxies with masses up to  $M_*$  and higher at redshifts when the universe is most rapidly forming stars; and (3) Cold mode arises from the lack of virial shock pressure support in the presence of radiative cooling.

### 3 An Early Epoch of Star Formation

One consequence of having a rapid mode of accretion being effective at high redshift is that it enables massive galaxies to form their stars quickly in the early universe. Such an early epoch of star formation has been inferred from the observed stellar populations of early type galaxies out to  $z \sim 2$ . The galaxy population in the early universe therefore presents an interesting test of the overall simulation picture of stellar mass assembly and gas accretion in galaxies.

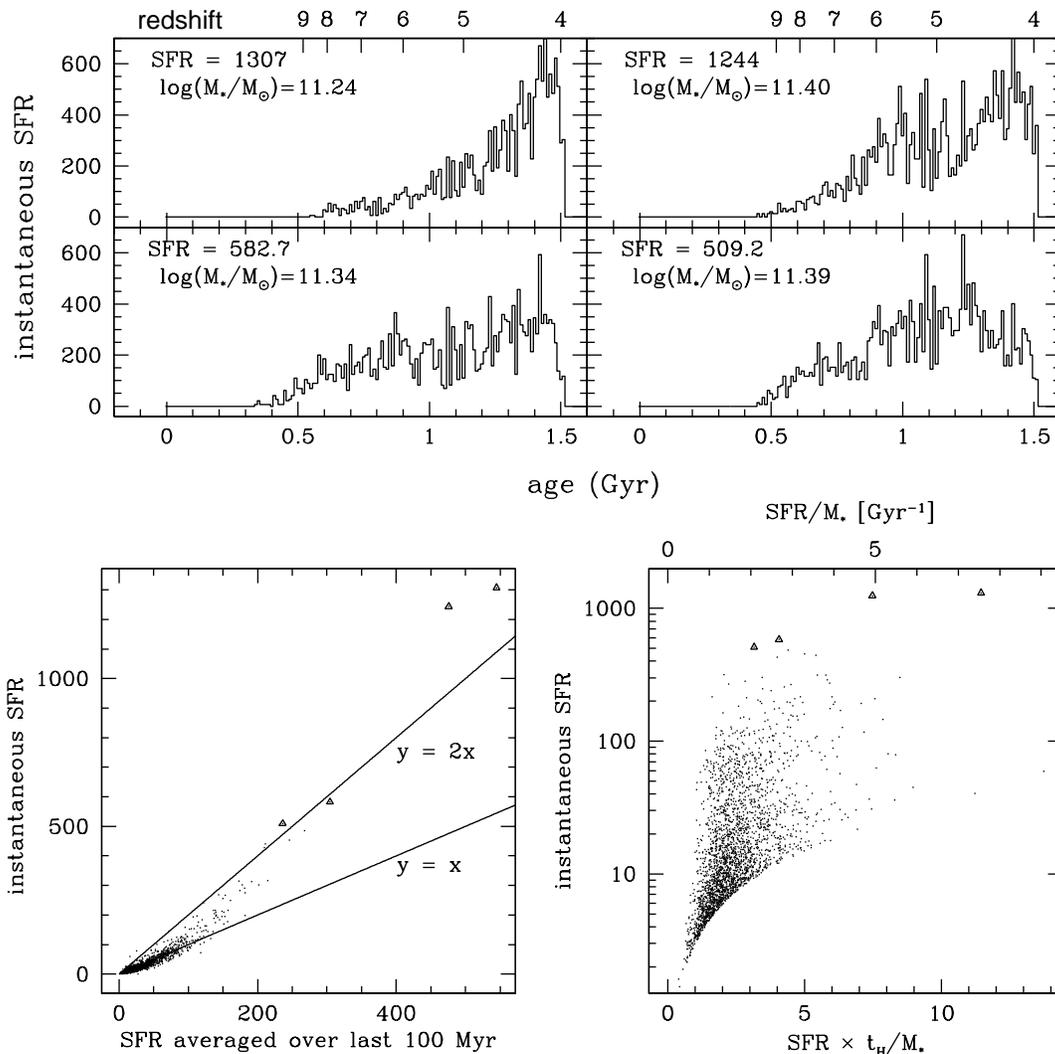


Figure 4: Top panel shows star formation histories of the four most rapidly star forming galaxies in the simulated samples. The instantaneous star formation rates and stellar masses at  $z = 4$  are given in the top left. Bottom left panel shows instantaneous versus time-averaged star formation rate for the GOODS-selected galaxies in the G6 simulation, with the four most rapid star formers marked by triangles. Bottom right panel shows instantaneous star formation rate versus birthrate. Lower envelope arises from our  $10^{9.64} M_{\odot}$  mass resolution cut. These massive, rapid star formers are experiencing at most a mild burst of star formation and may be identifiable as high-redshift submillimeter galaxies. From [7].

To study this, Finlator et al. [7] examined the population of galaxies in Gadget-2 [8] simulations of  $z = 4$  galaxies, as would be seen in the color selected B-dropout sample of the Great Observatories Origins Deep Survey (GOODS). By calculating the photometric properties of galaxies using the star formation histories convolved with the Bruzual & Charlot (2003) population synthesis code, we predicted the luminosity function as would be observed using a Lyman break selection technique at  $z \approx 4$ . We also included dust reddening using a novel prescription calibrated from the local metallicity-extinction relation from SDSS.

The results are shown in Figure 3. The agreement is quite good around  $L_*$ , but it appears the simulations produce too many brighter galaxies. Recent work from the VVDS Survey [9] that does not use color selection suggests that many bright galaxies are missed by the color criteria typically used for Lyman break selection. Hence it remains to be seen if the excess actually indicates a substantial failing of the model, or merely an improper reckoning of selection effects.

Another possibility is that the bright galaxies are actually much dustier than is assumed by the reddening prescription used (so that they would not be seen in UV-selected samples), and in fact that such galaxies should instead be associated with sub-millimeter sources detected by SCUBA. Figure 4 shows the instantaneous star formation rates of these bright galaxies, which in some cases exceeds  $1000 M_{\odot}/\text{yr}$ , similar to that inferred for SCUBA galaxies. The star formation histories of the most rapid star formers are shown in the top panel of Figure 4, and show a time-averaged rate of  $\sim 500 M_{\odot}/\text{yr}$  in the recent past. This means that these galaxies are undergoing only a mild burst of star formation, by a factor of a couple, over their “quiescent” state. This

is shown more clearly the lower left panel of Figure 4, plotting the instantaneous versus time-averaged star formation rates for all galaxies in the G6 run. Visual inspection indicates that these rapid star formers live at the centers of protoclusters, and exhibit a disturbed morphology due to the local high density of galaxies.

Overall, the latest observations of galaxy properties at  $z \sim 4$  are broadly reproduced in simulations. This is reassuring, both because it means that gas accretion processes are probably being modeled in a reasonable manner, and also because it appears that there are no physical processes that are unaccounted for in these models that have a large impact on the galaxy population. As we will see in the next section, this statement is not true at lower redshifts.

## 4 What Stops Gas From Getting Into Galaxies?

While agreement at high redshifts is comforting, it is obtained in part because the data at those epochs is not of the same quality and quantity as is available locally. Galaxy observations in the local universe cover a wide range of objects at a wide range of wavelengths, and there are many outstanding issues that remain to be resolved theoretically. Here we focus on massive early-type systems that should, in principle, be among the easiest and simplest systems to model. As we consider the various observations of massive ellipticals out to  $z \sim 1$ , one common feature unifies these objects: They are virtually all “red and dead”.

This feature is best illustrated by the red sequence in a color-magnitude diagram. The uniformly old stellar populations together with a mass-metallicity correlation produce a tight locus in color-magnitude space in which more luminous galaxies are redder. The tightness of this relation is indicative of the lack of recent star formation. It is this feature that is among the most difficult to understand about galaxy formation.

In simulations, massive galaxies sit at the bottom of large potential wells, where intergalactic gas is constantly infalling. This is the classic scenario for hot mode accretion, where the central gas density is high enough for cooling times to be rapid, resulting in a substantial amount of gas cooling and subsequent star formation. Shutting this gas supply off requires not only tremendous amounts of feedback energy, but also requires that that energy be distributed quasi-spherically among the gas elements in the cooling flow region. What physical process could be responsible for turning off gas accretion in massive galaxies?

The current wisdom is to invoke AGN as the heating mechanism. This idea has a number of positives, in that there is plenty of energy in the central engine, it can be generated with a very small amount of accompanying gas infall or star formation, and there is a tight observed relation between central black hole and bulge masses. Indeed, Kauffmann in these proceedings has assembled a compelling set of observations showing that AGN are responsible for moving galaxies onto the red sequence. Simulations of galaxy mergers with AGN feedback [14] reproduce many observed properties of quasars [15], and succeed in heating gas sufficiently to prevent star formation. All in all, there is accumulating evidence pointing towards AGN shutting off star formation, although much of it remains circumstantial. The main remaining difficulty is trying to understand how energy from the black hole couples to the gas in such a uniform and widespread manner so as to shut off cooling flows.

Whatever the mechanism, it is clear that star formation must be truncated, rapidly and at an early epoch, in massive galaxies. One approach is to identify what physical parameter governs when a galaxy will shut off its accretion. Is it the galaxy mass? Is it hot mode accretion? We can roughly test these ideas by turning off star formation in massive systems by post-processing their simulated star formation histories.

To do so, we take the G6 Gadget-2 simulation of [8] (described in [7]), identify all galaxies at  $z = 0$ , and compute each galaxy’s  $U$  and  $V$  absolute magnitudes. The top panel of Figure 5 shows the resulting simulated color-magnitude diagram. As can be seen, there is no red sequence evident at  $U - V \approx 1.5$  as observed for real galaxies, and more massive galaxies do not become progressively redder. This is because of residual star formation in massive systems due to continued cooling and infall.

We now take each galaxy, track its growth back in time, and eliminate all star formation once its progenitor’s stellar mass exceed  $2 \times 10^{10} M_{\odot}$ . The resulting star formation histories are then used to recompute the CMD, shown in the middle panel of Figure 5. This approach results in a decent looking red sequence (although it does not have the proper slope, but this may be due to metallicity effects not included here). However, it is now missing another important population: Massive blue spiral galaxies, such as our own Milky Way! This simple stellar mass cut apparently truncates star formation in all galaxies, rather than only the early types.

Another idea, suggested by [3] and [13], is that whatever mechanism is responsible for stopping cooling flows preferentially does so by keeping virial temperature gas hot, and not allowing it to cool. Again, we can examine this in our simulation by tracking the temperature history of each particle, and removing all star formation events if the parent gas particle’s temperature had at any time exceeded  $2.5 \times 10^5$  K, i.e. if it is a hot mode accretion event. The resulting CMD is shown in the bottom panel. This scenario is at best only slightly more successful, as once again bright blue galaxies have mostly been eliminated, and larger galaxies are not particularly redder. It seems that while the hot/cold accretion scenario may play some role in the truncation of star formation in massive systems, it does not appear to be the governing factor.

Semi-analytic models of [11] and [12] have had some success producing a red sequence, in the former case by truncating star formation when the bulge mass (not total mass) exceeds a certain value, and in the latter case by shutting off gas accretion onto satellite galaxies and including a “radio mode” of feedback tied to AGN growth. These parameterizations serve as useful guides for constraining the phenomena that may be responsible.

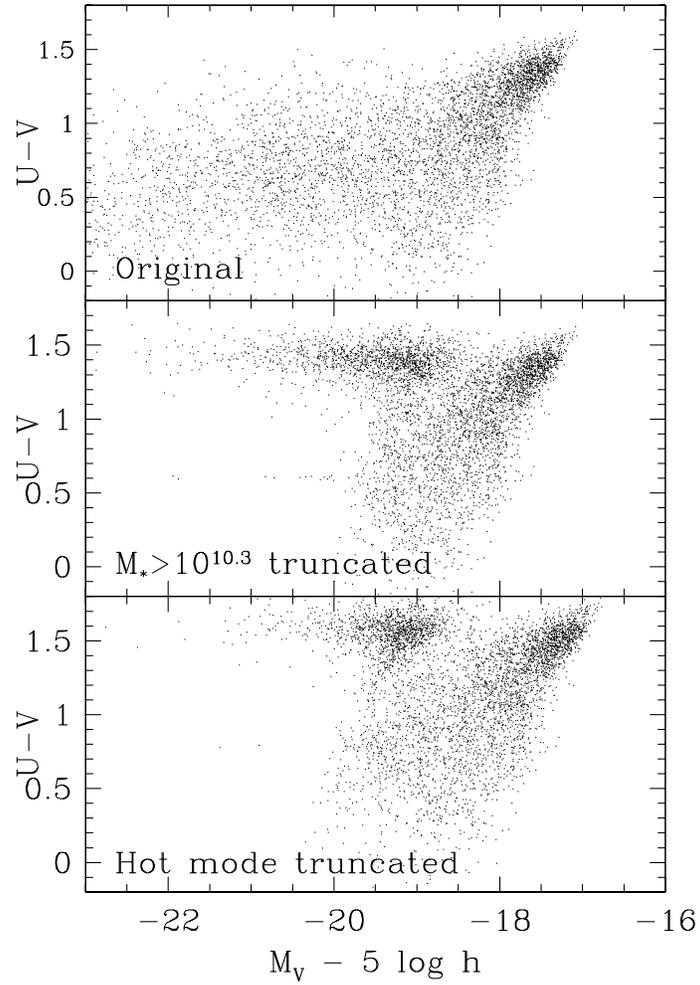


Figure 5:  $U - V$  vs.  $V$  color-magnitude diagrams (CMDs) from the G6 Gadget-2 simulation [7]. Top panel shows the original CMD at  $z = 0$ , obtained by computing magnitudes from the star formation history as given by the original simulation. Middle panel shows the result of modifying the star formation history (post facto) so that all star formation events are removed once the galaxy mass exceeds  $2 \times 10^{10} M_\odot$ ; this moves all massive galaxies onto the red sequence, but unfortunately also removes all large blue galaxies. The bottom panel shows the result on removing all star formation events that occurred due to hot mode accretion; this looks somewhat more promising, although some odd features remain.

## 5 Birthrates and Downsizing

The formation of a red sequence is part of a larger trend in galaxy formation known as downsizing [10]. Downsizing states that massive galaxies form their stars earlier and are comparatively quiescent now, while smaller galaxies have formed (or are forming) most of their stars today. This trend can be summarized using the birthrate parameter, which measures the current star formation rate normalized to the past averaged star formation rate.

To study birthrates, we run a Gadget-2 simulation having  $32h^{-1}\text{Mpc}$  box size,  $2.5h^{-1}\text{kpc}$  softening, and  $2 \times 256^3$  particles, turning off superwind feedback so we can more cleanly study the basic processes of accretion and star formation as a function of galaxy mass. Figure 6 shows the birthrates from this simulation at  $z = 3$ , 2, and 1.5, where the past averaged star formation rate has been computed over a Hubble time. A galaxy with a birthrate parameter of unity, for example, would double its stellar mass in another Hubble time (assuming no merging).

Downsizing reflects the trend that massive galaxies have lower birthrates at the present time than less massive galaxies. Such a trend is evident in the top panel of Figure 6, at every epoch shown. Another way to characterize this plot is to say that the typical mass of actively star forming galaxies (e.g. those with birthrate parameters exceeding unity) reduces with time. Thus the observed trend of downsizing is in accord with predictions of hierarchical galaxy formation models.

The sense of the trend can be easily understood in terms of hot and cold mode accretion: Big galaxies reside in large density fluctuations that collapse first in the early universe, and start forming stars vigorously owing to rapid cold mode accretion. As they grow in size, a virial shock is able to form which slows down the accretion, leading to a higher birthrate in the past than at the present day—i.e., downsizing. Smaller galaxies continue to form stars vigorously even today as they collapse later and continue to be dominated by cold mode accretion. Although the transition from hot mode to cold mode is fairly sharp in halo mass, when viewed as a function of galaxy stellar mass it is much more gradual, which is why no obvious feature exists in the birthrate plot marking the transition between hot and cold mode.

Another statement of downsizing is that the formation time of stars is older in more massive galaxies. The bottom panel of Figure 6 shows a histogram of the median formation time of stars in galaxies subdivided into three mass bins. This plot is made at  $z = 1.5$ , when the universe is 4.2 Gyr old ( $\Omega = 0.3$ ,  $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Lambda\text{CDM}$ ). This shows that large galaxies typically form their stars at earlier times. Here, galaxies with  $M_* \approx 2 \times 10^{11}$  have a median star formation redshift of  $z \approx 4$  (1.5 Gyr), while for galaxies with  $M_* \approx 3 \times 10^9 M_\odot$  it is around  $z \approx 2.5$ . Note that the median star formation time is *inversely* correlated with the median halo formation time, since large halos assemble later in hierarchical models. Hence the “anti-hierarchical” appearance of downsizing is in fact a natural outcome of galaxy assembly within hierarchical structure formation models.

Unfortunately, the qualitative trend of downsizing is only part of the story. Quantitatively, it appears that cosmological simulations cannot self-consistently reproduce the *strength* of downsizing in massive galaxies. While massive galaxies form stars more slowly relative to their stellar mass than smaller ones, they are still forming some stars, whereas observations indicate they don’t form stars at all (though see new GALEX results in these proceedings showing residual star formation in  $\sim 20\%$  of present-day ellipticals). So some physics is still missing.

A topical implication of downsizing is that massive galaxies must grow substantially by so-called dry merging, i.e. mergers of predominantly stellar systems. The argument for this simply goes that if today’s massive systems form their stars early while their masses are still small, then in order to grow into massive systems we see today they must merge with other large systems who must have also formed their stars early. These mergers will then be predominantly stellar. Indeed, there is growing evidence for ubiquitous dry merging locally (see van Dokkum, these proceedings), and out to  $z \sim 0.7$  [16].

In summary, the trend of downsizing is naturally expected in a hierarchical structure formation scenario, arising from the interplay of biased galaxy formation and gas accretion processes. This trend implies that dry merging is an important growth path for massive galaxies. However, the strength of the downsizing in massive galaxies seems to be underestimated in current models, requiring a new form of feedback possibly associated with black hole growth to sufficiently truncate star formation in today’s ellipticals.

## 6 Conclusions

Galaxy formation remains an unsolved problem. Hydrodynamic simulations have enabled many advances in understanding the accretion processes by which galaxies obtain their fuel for growth, including a newfound appreciation for the importance of cold mode accretion. Observations of high-redshift galaxies provide a critical test for models, and current comparisons suggest that simulations are doing a reasonable job producing big galaxies in their youth. A critical test appears to be the formation of red sequence galaxies at low redshifts, something that is currently pointing towards new feedback processes such as AGN heating. The coming years will see continued dramatic advances in observations, and it is incumbent upon theoretical models to keep pace. A solid foundation is in place connecting primordial fluctuations and the objects we see today, but the details remain a work in progress.

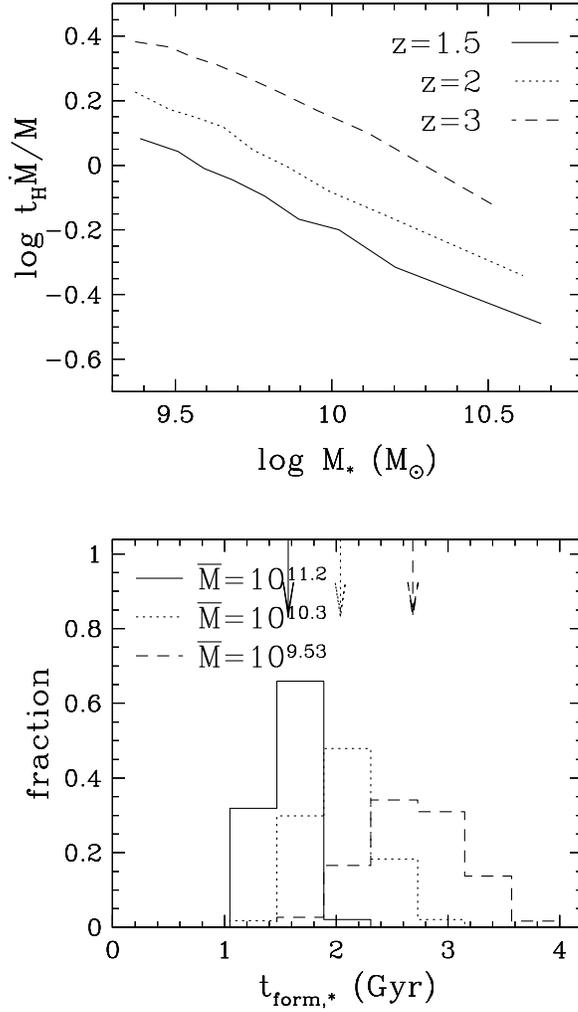


Figure 6: Downsizing in Gadget-2 simulations of galaxy formation with superwinds turned off (cf. [8]). Top panel shows the median birthrate as a function of galaxy stellar mass at  $z = 3, 2,$  and  $1.5$ . The birthrates decrease with time as the global star formation rate decreases. At all epochs shown, massive galaxies are forming stars more slowly relative to their stellar mass, in accord with the downsizing phenomenon. Bottom panel shows a histogram of the median star formation times of galaxies at  $z = 1.5$ , in three galaxy mass bins. Large galaxies form their stars earlier, and therefore have older stellar populations. Hence in hierarchical galaxy formation models, the star formation time and halo formation time are in general inversely correlated. While these qualitative trends of downsizing are in agreement with observations, massive galaxies are still forming stars too rapidly to place them on the red sequence, hence an additional physical process is still required to truncate star formation in these systems.

**Acknowledgements.** We thank V. Le Brun and all the organizers for a fabulous meeting. We also thank V. Springel for providing us with the Gadget-2 code used throughout this work. Some of the simulations presented here were done at the National Center for Supercomputing Applications (NCSA).

## References

- [1] White, S. D. M., & Rees, M. J. 1978, MNRAS, 183, 341
- [2] Springel, D. N. et al. 2003, ApJS, 148, 175
- [3] Kereš, D., Katz, N., Weinberg, D. H., & Davé, R. 2005, MNRAS, 363, 2
- [4] Binney, J. 1977, MNRAS, 215, 483
- [5] Birnboim, Y., Dekel, A. 2003, MNRAS, 345, 349
- [6] Katz, N., Kereš, D., Davé, R., Weinberg, D. H. 2002, in proc. "IGM/Galaxy Connection- The Distribution of Baryons at  $z=0$ ", eds. J. L. Rosenberg & M. E. Putman
- [7] Finlator, K., Davé, R., Papovich, C., & Hernquist, L. 2005, ApJ, submitted
- [8] Springel, V. & Hernquist, L. 2003a, MNRAS 339, 289
- [9] Le Fevre, O., et al. 2005, Nature, 437, 519
- [10] Cowie, L. L., Songaila, A. Hu, E. M., Cohen, J. G. 1996, AJ, 112 839
- [11] Somerville, R., private communication
- [12] Croton, D. J., et al. 2005, MNRAS, submitted
- [13] Dekel, A. & Birnboim, Y. 2004, in The New Cosmology: Conference on Strings and Cosmology, eds. R. E. Allen, D. V. Nanopoulos, & C. N. Pope. AIP conf. proc. v.743, p.162-189
- [14] Di Matteo, T., Springel, V., Hernquist, L. 2005, Nature, 433, 604
- [15] Hopkins, P. F., Hernquist, L., Cox, T. J., Di Matteo, T., Martini, P., Robertson, B., Springel, V. 2005, ApJ, 630, 705
- [16] Bell, E. F. et al. 2005, ApJ, submitted, astro-ph/0506425