The Galaxy Disk in Cosmological Context
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Mergers and Disk Survival in ΛCDM

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Abstract. Disk galaxies are common in our universe and this is a source of concern for hierarchical formation models like ΛCDM. Here we investigate this issue as motivated by raw merger statistics derived for galaxy-size dark matter halos from ΛCDM simulations. Our analysis shows that a majority ($\sim 70\%$) of galaxy halos with $M_0 = 10^{12} M_\odot$ at $z = 0$ should have accreted at least one object with mass $m > 10^{11} M_\odot \simeq 3\, M_{\rm disk}$ over the last 10 Gyr. Mergers involving larger objects $m \gtrsim 3 \times 10^{11} M_\odot$ should have been very rare for Milky-Way size halos today, and this pinpoints $m/M \sim 0.1$ mass-ratio mergers as the most worrying ones for the survival of thin galactic disks. Motivated by these results, we use use high-resolution, dissipationless N-body simulations to study the response of stellar Milky-Way type disks to these common mergers and show that thin disks do not survive the bombardment. The remnant galaxies are roughly three times as thick and twice as kinematically hot as the observed thin disk of the Milky Way. Finally, we evaluate the suggestion that disks may be preserved if the mergers involve gas-rich progenitors. Using empirical measures to assign stellar masses and gas masses to dark matter halos as a function of redshift, we show that the vast majority of large mergers experienced by $10^{12} M_\odot$ halos should be gas-rich ($f_{gas} > 0.5$), suggesting that this is a potentially viable solution to the disk formation conundrum. Moreover, gas-rich mergers should become increasingly rare in more massive halos $> 10^{12.5} M_\odot$, and this suggest that merger gas fractions may play an important role in establishing morphological trends with galaxy luminosity.

Keywords. Cosmology: theory – galaxies: formation – galaxies: evolution

1. Introduction

Roughly 70% of Milky-Way size dark matter halos are believed to host late-type, disk-dominated galaxies (Weinmann *et al.* 2006, van den Bosch *et al.* 2007, Ilbert *et al.* 2006, Choi *et al.* 2007). Conventional wisdom dictates that disk galaxies result from fairly quiescent formation histories, and this has raised concerns about disk formation within hierarchical Cold Dark Matter-based cosmologies (Toth & Ostriker 1992; Wyse 2001; Kormendy *et al.* 2005). Recent evidence for the existence of a sizeable population of cold, rotationally supported disk galaxies at $z \sim 1.6$ ($\sigma/V \sim 0.2$; Wright *et al.* 2008) is particularly striking, given that the fraction of galaxies with recent mergers is expected to be significantly higher at that time (Stewart *et al.* 2008b).

Unfortunately, a real evaluation of the severity of the problem is limited by both theoretical and observational concerns. Theoretically, the process of disk galaxy formation remains very poorly understood in ΛCDM. Though the first-order models envisioned by Mestel (1963), Fall & Efstathiou (1980), Mo, Mao & White (1998) and others provide useful theoretical guides, the formation of disks via a quiescent acquisition of mass is likely not the only channel. Over the last several years, cosmological hydrodynamic simulations have begun to produce galaxies that resemble realistic disk-dominated systems, and in most cases, early mergers have played a role in the disk's formation (Abadi *et al.* 2003; Brook *et al.* 2004; Robertson *et al.* 2005; Governato *et al.* 2007). In particular, the early disks in the simulations of Brook *et al.* (2004) and Robertson *et al.* (2005) originated in gas-rich mergers. Robertson *et al.* (2006) used a suite of focused simulations to show that mergers with gas-fractions larger than $\sim 50\%$ tend to result in disk-dominated remnants and Hopkins *et al.* (2008) used a larger sample of merger simulations to reach a similar conclusion. Two cautionary notes are in order. First, these results are all subject to the uncertain assumptions associated with modeling 'subgrid' physics in the simulations (ISM pressure, star formation, feedback, etc.). Second, the merger-remnant disks in these simulations tend to be hotter and thicker than the *thin* disk of the Milky Way (Brook *et al.* 2004). Robertson & Bullock (2008) showed that gas-rich merger remnants are a much closer match to the high-dispersion, rapidly rotating disk galaxies observed by integral field spectroscopy at $z \sim 2$ (Förster Schreiber *et al.* 2006; Genzel *et al.* 2006). Gas-rich mergers as an explanation for these high-redshfit disks is further motivated by the expectation that gas fractions should be higher at early times (e.g. Erb *et al.* 2006).

Observationally, the best quantified thin disk is that of the Milky Way. The thin disk of the Milky Way has a scale height $z_d \simeq 350$ pc (see Jurić *et al.* 2008 and references therein), a fairly cold stellar velocity dispersion, $\sigma \simeq 40$ km s^{-1}, and contains stars that are as old as 10 Gyr (Nordström *et al.* 2004). It remains to be determined whether the Milky Way's thin disk is typical of spiral galaxies. This is a vital question. Unfortunately, scale height measurements for a statistical sample of external galaxies remain hindered by the presence of absorbing dust lanes in the disk plane for $\sim L_*$ galaxies (e.g. Yoachim & Dalcanton 2006).

Given the uncertainties associated with the formation of disk galaxies, we might make progress by asking a few focused, conservative questions. First, what is the predicted mass range and frequency of large mergers in galaxy-size halos? Second, can a thin stellar disk survive common mergers, and if not, what does this teach us about disk galaxy formation and/or cosmology? The figures presented below are taken from work described by Stewart *et al.* (2008a) on halo merger histories, Purcell, Kazantzidis, and Bullock (2008) on stellar disk destruction, and from Stewart *et al.* (2009, in preparation) on the expected gas fractions of mergers. The simulations in Purcell *et al.* (2008) were motivated by a program developed in Kazantzidis *et al.* (2008), which aims to understand the morphological response of disk galaxies to cosmologically-motivated accretion histories.

2. Merger Histories from Cosmological Simulations

As described in Stewart *et al.* (2008a), our merger trees are derived from an 80 h^{-1} Mpc box ΛCDM simulation. We concentrate specifically on thousands of Milky Way-sized systems, $M_0 \simeq 10^{12} M_\odot$ at $z = 0$. We categorize the accretion of objects as small as $m \simeq 10^{10} h^{-1} M_\odot$ and focus on the infall statistics into main progenitors of $z = 0$ halos as a function of lookback time.

Figure 1 shows a merger tree for a halo of mass $M_0 = 10^{12.5} h^{-1} M_\odot$ at $z = 0$. Time runs from top to bottom and the corresponding redshift for each timestep is shown to the left of each tree. The radii of the circles are proportional to the halo radius $R \sim M^{1/3}$, while the lines show the descendent–progenitor relationship. The color and type of the connecting lines indicate whether the progenitor halo is a field halo (solid black) or a subhalo (dashed red). The most massive progenitor at each timestep — the main progenitor — is plotted in bold down the middle. Once a halo falls within the radius of another halo, it becomes a subhalo and its line-type changes from black solid to red dashed. Figure 1 shows a fairly typical merger history, with a merger of mass $m \simeq 0.1 M_0$ at $z \simeq 0.51$. The merger ratio at the time of the merger was $m/M_z \simeq 0.5$. Note that this large merger does not survive for long as a resolved subhalo — it quickly loses most of its mass via interactions with the center of the halo, which presumably would host a central galaxy.

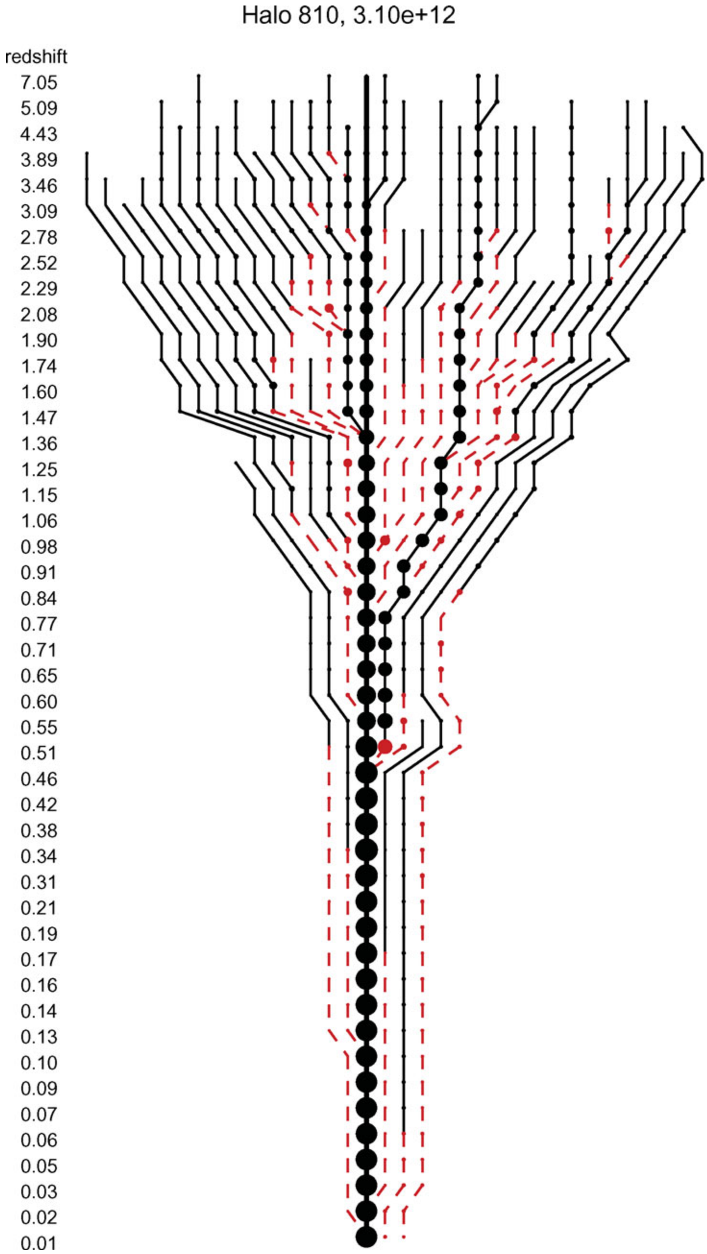

Figure 1. Sample merger tree for a dark matter halo with $z = 0$ mass $M_0 \simeq 3 \times 10^{12} h^{-1} M_\odot$ from Stewart *et al.* (2008a). Time progresses downward, with the redshift z printed on the left hand side. The bold, vertical line at the center corresponds to the main progenitor, with filled circles proportional to the radius of each halo. The minimum mass halo shown in this diagram has $m = 10^{9.9} h^{-1} M_\odot$. Solid (black) and dashed (red) lines and circles correspond to isolated field halos, or subhalos, respectively. The dashed (red) lines that do not merge with main progenitor represent surviving subhalos at $z = 0$. Note that the halo shown here has a fairly typical merger history, and experiences a merger of mass $m \simeq 0.1 M_0 \simeq 0.5 M_z$ at $z = 0.51$.

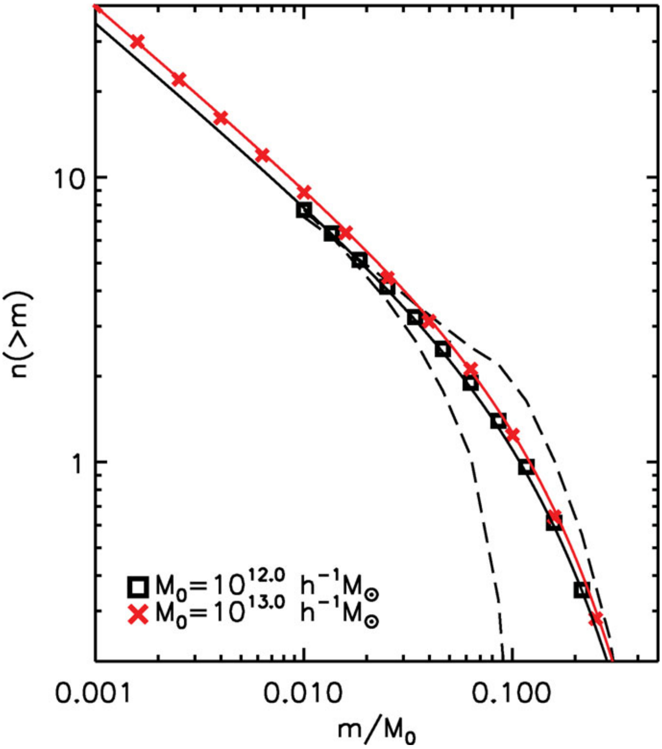

Figure 2. Cumulative mass function of accreted halos from Stewart *et al.* (2008a). The masses of accreted objects have been normalized by the host halo mass at $z = 0$ and the cumulative count is integrated over the main progenitor's formation history. The (black) squares show the average for $10^{12} h^{-1} M_{\odot}$ halos; (red) crosses show the average for $10^{13} h^{-1} M_{\odot}$ halos. Lines through the data points show analytic fits provided in Stewart *et al.* (2008a). The upper/lower dashed lines indicate the $\sim 25\%/20\%$ of halos in the $10^{12} h^{-1} M_{\odot}$ sample that have experienced exactly two/zero $m \geqslant 0.1 M_0$ merger events. Approximately 45% of halos have exactly one $m \geqslant 0.1 M_0$ merger event; these systems have mass accretion functions that resemble very closely the average.

Among the most basic questions concerns the mass spectrum of accreted objects. The solid line in Figure 2 shows the average cumulative number of objects of mass greater than m accreted over a halo's history. Two halo mass bins are shown. We see that, on average, the total mass spectrum of accreted objects (integrated over time) is approximately self-similar in $z = 0$ host mass M_0. Milky Way-sized halos with $M_0 \simeq 10^{12} M_{\odot}$ typically experience ~ 1 merger with objects larger than $m = 0.1 M_0 \simeq 10^{11} M_{\odot}$, and approximately 7 mergers with objects larger than $m = 0.01 M_0 \simeq 10^{10} M_{\odot}$ over their histories. Mergers involving objects larger than $m = 0.2 M_0 \simeq 2 \times 10^{11} M_{\odot}$ should be extremely rare.

Figure 3 shows a particularly important statistical summary for the question of morphological fractions. Specifically we show the fraction of galaxy-sized halos (a bin centered on $M_0 = 10^{12} h^{-1} M_{\odot}$) that have experienced *at least one* "large" merger within the last t Gyr. The different line types correspond to different absolute mass cuts on the accreted halo, from $m > 0.05\, M_0$ to $m > 0.4\, M_0$. The lines flatten at high z because the halo main progenitor masses, M_z, become smaller than the mass threshold on m. We find that while fewer than $\sim 10\%$ of Milky Way-sized halos have *ever* experienced a merger with an object large enough to host a sizeable disk galaxy, ($m > 0.4\, M_0 \simeq 4 \times 10^{11} M_{\odot}$), an

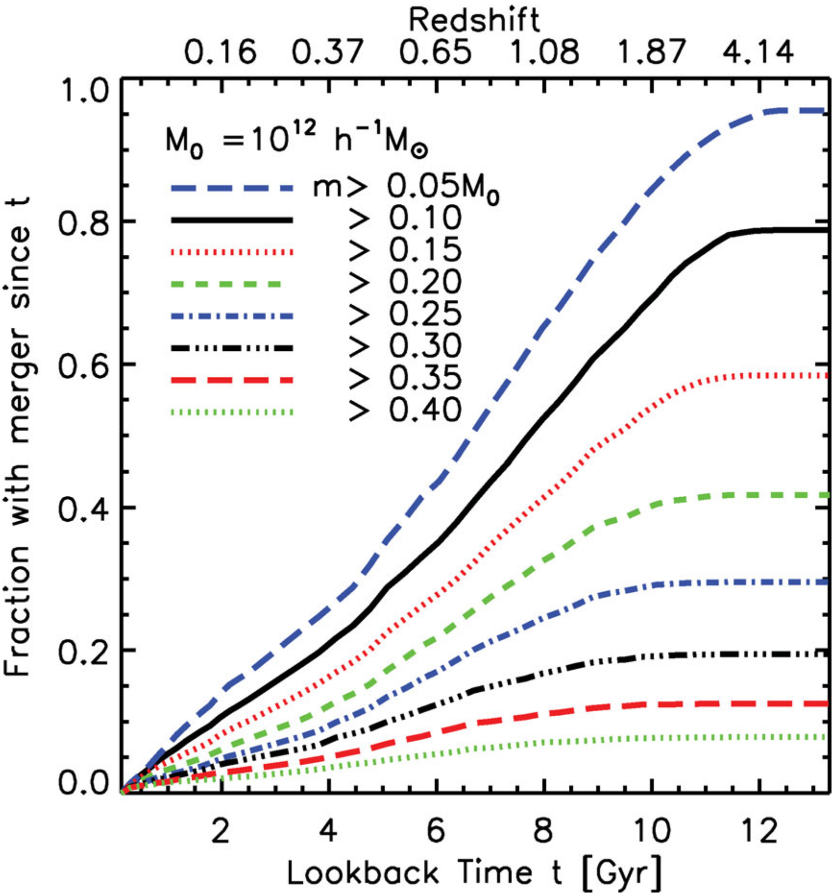

Figure 3. Merger fractions from Stewart *et al.* (2008a). The lines show the fraction of galaxy–sized halos, $M_0 = 10^{12}h^{-1}M_\odot$, that have experienced at least one merger larger than a given mass threshold, m/M_0, since look-back time t.

overwhelming majority (∼ 95%) have accreted an object more massive than the Milky Way's disk ($m > 0.05M_0 \simeq 5 \times 10^{10}M_\odot$). Approximately 70% of halos have accreted an object larger than $m/M_0 = 0.1$ in the last 10 Gyr. We emphasize that the ratios presented here are relative to the *final* halo mass (m/M_0) not the ratio of the masses just before the merger occurred (m/M_z). As presented, the ratios are quite conservative because halos grow with time $M_z < M_0$ and $m/M_z > m/M_0$. We find that typically, for the mergers we record here, $m/M_z \simeq 2m/M_0$ (Stewart *et al.* 2008a) and that makes the implications for disk survival all the more worrying.

3. Targeted Simulations

Recently, Kazantzidis *et al.* (2008) have investigated the response of galactic disks subject to a ΛCDM-motivated satellite accretion histories and showed that the thin disk component survives, though it is strongly perturbed by the violent gravitational encounters with halo substructure (see also Kazantzidis *et al.*, this proceeding). However, these authors focused on subhalos with masses in the range $0.01M_0 \lesssim m \lesssim 0.05M_0$, ignoring the most massive accretion events expected over a galaxy's lifetime. Here, we report on the results of Purcell *et al.* (2008) that expand upon this initiative by investigating the

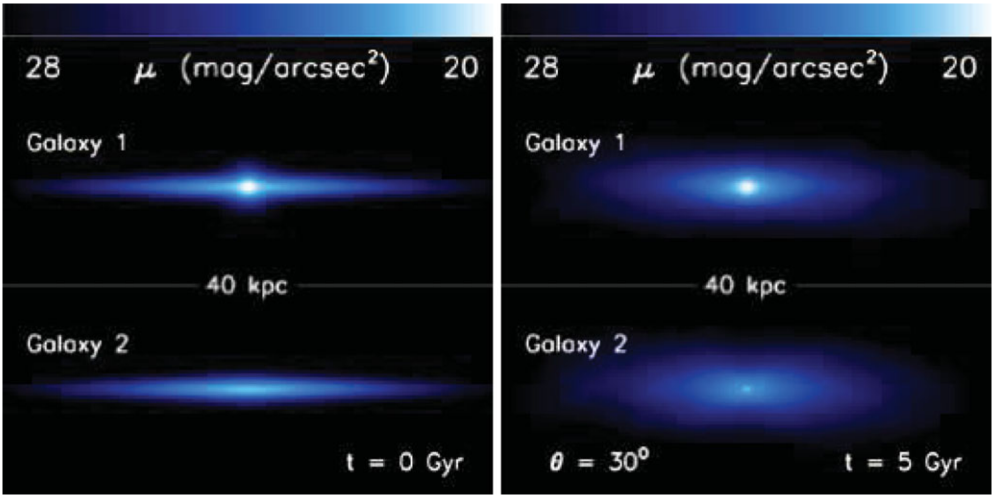

Figure 4. Edge-on surface brightness maps for primary galaxies 1 (upper panels; disk/bulge) and 2 (lower panels; disk only). Initial models ($t = 0$ Gyr) are shown in the left panel, while the final results ($t = 5$ Gyr) for satellite-infall orbital inclination of $\theta = 30°$ appears on the right panel. The associated simulations are discussed in Purcell *et al.* (2008).

evolution of galactic disk morphology and kinematics during merger events with mass ratio $m/M_0 = 0.1$.

As described in more detail in Purcell *et al.* (2008), our simulations are performed using the parallel-tree dissipationless code PKDGRAV (Stadel 2001). The host halo, disk, and infalling satellites were simulated with 4×10^6, 10^6 and 10^6 particles, respectively. The primary Milky-Way-analogue system drawn from the set of self-consistent equilibrium models that best fit Galactic observational parameters as produced by Widrow *et al.* (2008), with a host halo mass of $M_0 = 10^{12} M_\odot$ and a disk mass $M_{\rm disk} = 3.6 \times 10^{10} M_\odot$. We initialize a satellite galaxy with a stellar mass of $2 \times 10^9 M_\odot$ embedded within a dark matter halo of virial mass $m \simeq 0.1 M_{\rm host} = 10^{11} M_\odot$. In the left panel of Figure 4, we show the edge-on surface brightness map for both primary galaxy models, one with a central bulge and one without.

We explore a range of initial orbital parameters assigned to the merging satellite galaxy, motivated by cosmological investigations of substructure mergers (Khochfar & Burkert 2006; Benson 2005). We choose an array of orbital inclination angles ($\theta = 0°, 30°, 60°, \text{and } 90°$) in order to assess the consequence of this parameter on the evolution and final state of the galactic disk in each case. All simulations are allowed to evolve for a total of 5 Gyr, after which time the subhalo has fully coalesced into the center of the host halo and the stellar disk has relaxed into stability, although there are certainly remnant features in the outer disk and halo that will continue to phase-mix and virialize on a much longer timescale; however, our investigations indicate that the disk-heating process has reached a quasi-steady state by this point in the merger's evolution. The morphological thickening of the initial disk after one typical merger is shown in right panels of Figure 4.

Figure 5 provides a direct comparison of all of our merger remnants to observed properties of the Milky Way. The left panel shows the remnant disk scale heights (derived using two-component fits for a thin and thick disk) alongside the values obtained by Juric *et al.* (2008). While the thin-disk scale height (z_{thin}) of our initial model agrees well with the Galactic benchmark of $z_{thin} \simeq 0.3$ kpc, the final systems all have thin-disk

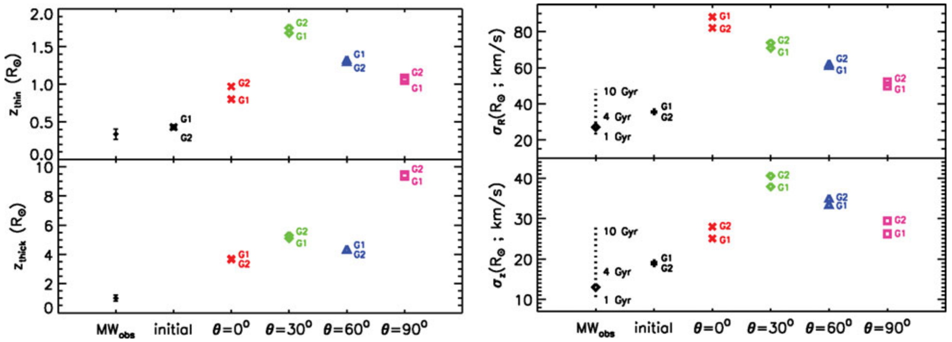

Figure 5. *Left.* The thin- and thick-disk scale heights in the final state for each of our simulated galaxies from Purcell *et al.* (2008), compared to the values derived for the Milky Way. The two panels show the result of a two-component sech^2 fit, with the upper (lower) panel describing the thin (thick) disk's scale height. *Right.* The radial and vertical components of velocity dispersion σ_R and σ_z at the solar neighborhood ($R = 8$ kpc) of our simulated disks, compared to the local values obtained by the Geneva-Copenhagen survey. In each coordinate, the observational spread is marked by a *dotted line* and the dispersion of the sample's median-age stars ($t \sim 2 - 3$ Gyr) is denoted by a *diamond*.

components with z_{thin} larger by a factor of $\sim 3 - 5$. The right panel shows remnant disk velocity dispersions (radial and vertical) as measured in disk planes around $R = 8$ kpc compared to the velocity ellipsoid observed in the solar neighborhood (Nordström *et al.* 2004). Following the simulated 1:10 merger, all three components of velocity dispersion are substantially enhanced. None of the remnants are as cold as the Milky Way disk. Note that while the $\theta = 0°$ in-plane accretion produces the least vertical thickening, it produces a huge amount of radial heating, and leaves the remnant disk much hotter than that of the Milky Way. Our conclusion that cosmologically-motivated 1:10 mergers destroy thin stellar disks.

4. Gas-rich Mergers

As discussed in the introduction, the presence of a stabilizing gas component in merger progenitors can potentially alleviate the thin disk disruption we have described. In order to address whether it is plausible that gas-rich mergers occur frequently enough to alleviate the problem, we employ a semi-empirical approach. Specifically, we assign stellar masses and gas masses to halos at each of our merger tree timesteps using empirical relations and then explore the baryonic content of the mergers that occur. For stellar masses, we use the empirical mapping between halo mass and stellar mass advocated by Conryoy & Wechsler (2008). For gas masses we use observational relations between stellar mass and gas mass (Kannappan 2004; McGaugh 2005; Erb *et al.* 2006). The important qualitative trend is that small halos tend to host galaxies with high gas fractions and that gas fractions are inferred to increase in galaxies of a fixed stellar mass at high redshift.

Figure 6 presents an intriguing result from this exploration. The solid black line shows the fraction of halos that have had a merger larger than $m/M_z = 0.3$ since $z = 2$ as a function of the $z = 0$ host mass. (Note that here the merger ratio is the ratio of masses just prior to the merger). We see that a fairly high fraction ($\sim 60\%$) of Milky-Way size halos have experienced a major merger in the last ~ 10 Gyr. Consider, however, the (blue) dotted line, which restricts the merger count to galaxies where *both* of the progenitors are *gas rich* with $f_{\rm gas} = M_{gas}/(M_{gas} + M_*) > 0.5$. We see that the vast majority of the most

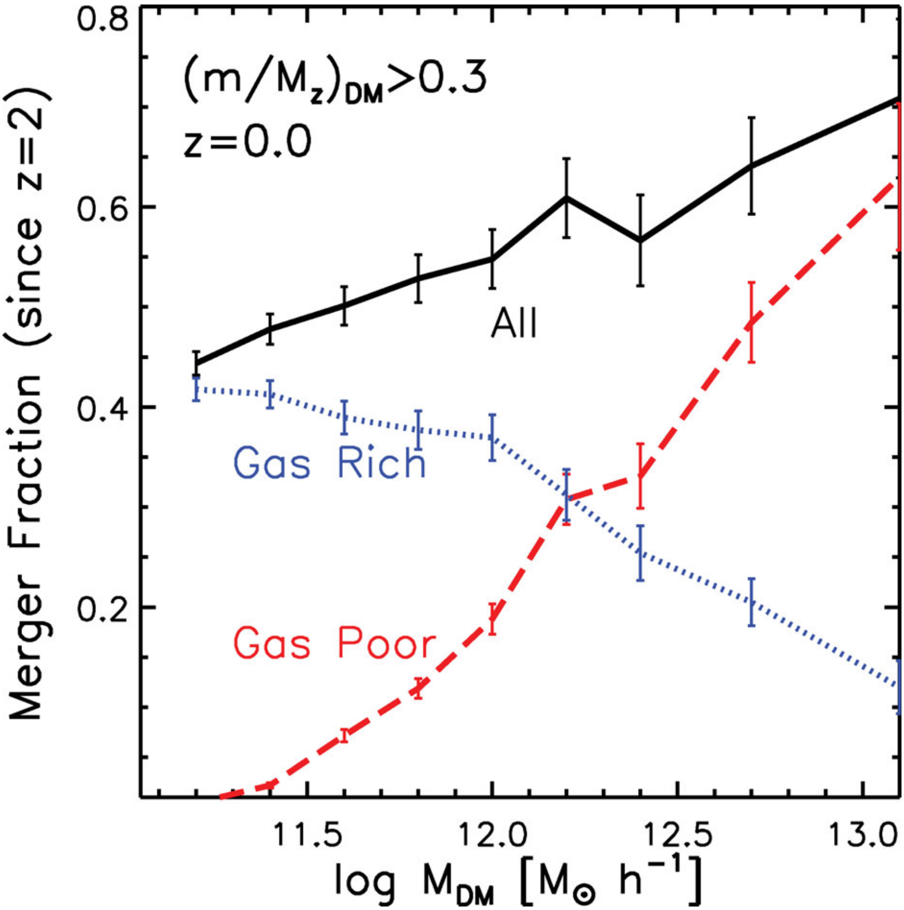

Figure 6. Fraction of dark matter halos of a given mass that have experienced at least one major merger ($m/M_z > 0.3$) since $z = 2$. The solid (black) line is the total DM merger fraction, while the dotted (blue) line *only* includes gas rich major mergers (see text for details), and the dashed (red) line only includes gas poor major mergers. Error bars are Poisson based on number of host halos and the total number of mergers. The figure is modified from Stewart *et al.* (2009, in preparation).

worrying mergers in Milky-Way size halos should have been very gas rich, and that gas-rich major merger become more common in smaller halos. The (red) dashed line shows the fraction mergers that are made up of more gas poor progenitors with $f_{\rm gas} < 0.5$. Not only do these trends provide a possible solution to disk survivability, but they may also provide an interesting clue to the origin of the mass–morphology relation. While dark matter halo merger histories alone show a very weak trend with halo mass, the baryonic content of the mergers should vary significantly with halo mass (and by extension, galaxy luminosity). More massive halos are more likely to experience large, gas-poor mergers, and we expect this to result in a higher fraction of spheroid-dominated galaxies.

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Participants merging and surviving at the Town Hall reception.

55 years of Galaxy symposia: Jan Palouš, Adriaan Blaauw and Bruce Elemgreen at Carlsberg.
Aage Bohr in the background.
Photo: Bruce Elmegreen.