THE IMPACT OF STELLAR FEEDBACK ON THE STRUCTURE, SIZE, AND MORPHOLOGY OF GALAXIES IN MILKY-WAY-SIZED DARK MATTER HALOS

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ABSTRACT

We use cosmological zoom-in simulations of galaxy formation in a Milky-Way-sized halo started from identical initial conditions to investigate the evolution of galaxy sizes, baryon fractions, morphologies, and angular momenta in runs with different parameters of the star formation–feedback cycle. Our fiducial model with a high local star formation efficiency, which results in efficient feedback, produces a realistic late-type galaxy that matches the evolution of basic properties of late-type galaxies: stellar mass, disk size, morphology dominated by a kinematically cold disk, stellar and gas surface density profiles, and specific angular momentum. We argue that feedback’s role in this success is twofold: (1) removal of low angular momentum gas, and (2) maintaining a low disk-to-halo mass fraction, which suppresses disk instabilities that lead to angular momentum redistribution and a central concentration of baryons. However, our model with a low local star formation efficiency, but large energy input per supernova, chosen to produce a galaxy with a similar star formation history as our fiducial model, leads to a highly irregular galaxy with no kinematically cold component, overly extended stellar distribution, and low angular momentum. This indicates that only when feedback is allowed to become vigorous via locally efficient star formation in dense cold gas do resulting galaxy sizes, gas/stellar surface density profiles, and stellar disk angular momenta agree with observed $z = 0$ galaxies.

Key words: galaxies: evolution – galaxies: formation – galaxies: ISM – galaxies: star formation – galaxies: structure – methods: numerical

1. INTRODUCTION

The cold dark matter scenario, with a low mean matter density and a cosmological constant ($\Lambda$CDM), has proven to be broadly successful in explaining and predicting a variety of observations, such as the cosmic microwave background temperature anisotropies (e.g., Komatsu et al. 2011; Hinshaw et al. 2013; Planck Collaboration et al. 2014), the evolution of cluster abundance (Vikhlinin et al. 2009), and the large-scale distribution of matter in the universe (Conroy et al. 2006; Springel et al. 2006). Nevertheless, although the basic framework of galaxy formation within the CDM scenario (White & Rees 1978; Fall & Efstathiou 1980) is widely accepted, many aspects of the theory of galaxy formation are not yet fully understood (for a recent review, see Silk & Mamon 2012).

One of the most salient issues in galaxy formation modeling is understanding why galaxy formation is such an inefficient process, i.e., what controls the low fraction of cosmic baryons that end up as stars in the centers of dark matter halos. A number of different methods, such as dark matter halo abundance matching (Tasitsiomi et al. 2004; Vale & Ostriker 2004, 2006; Conroy et al. 2006; Conroy & Wechsler 2009; Guo et al. 2010; Moster et al. 2010; Behroozi et al. 2013), satellite kinematics (Klypin & Prada 2009; More et al. 2011), and weak lensing (Mandelbaum et al. 2006) (see Kravtsov et al. 2014, for a comprehensive discussion), point toward stellar to dark matter mass fractions of $M_*/M_h \approx 3\%–5\%$ on average for $L_*$ galaxies and even smaller fractions for galaxies of smaller and larger mass. The fraction of baryons that ends up in observed galaxies is thus well below the cosmological baryon fraction of $\Omega_b/\Omega_m \approx 16\%$ (Planck Collaboration et al. 2015).

Such low baryon fractions are believed to be due to galactic winds driven by stellar feedback at the faint end of the stellar mass function (Dekel & Silk 1986; Efstathiou 2000) and by the active galactic nuclei (AGNs) at the bright end (Silk & Rees 1998; Benson et al. 2003). Over the past two decades there has been an intense effort to incorporate and model these processes in cosmological simulations of galaxy formation (e.g., Katz 1992; Navarro & White 1993; Katz et al. 1996; Thacker & Couchman 2001; Stinson et al. 2006; Governato et al. 2007; Scannapieco et al. 2008; Colín et al. 2010; Agertz et al. 2011, 2013; Avila-Reese et al. 2011; Guedes et al. 2011; Hopkins et al. 2011; Brook et al. 2012b; Scannapieco et al. 2012; Aumer et al. 2013; Booth et al. 2013; Ceverino et al. 2014; Christensen et al. 2014b; Keller et al. 2014; Roškar et al. 2014; Kimm et al. 2015; Murante et al. 2015). However, these processes have proven to be challenging to model, and results are generally mixed. In particular, until recently simulations generally produced galaxies with larger than observed baryonic masses and had difficulties in producing galaxies with realistic bulge-to-disk ratios (although see Governato et al. 2010; Guedes et al. 2011).

Recent work (e.g., Stinson et al. 2013a; Hopkins et al. 2014; Agertz & Kravtsov 2015) has demonstrated the importance of stellar feedback in predicting not only the $z = 0$ stellar mass–halo mass relation but also its evolution, in particular during early stages of galaxy evolution ($z \gtrsim 2$). Furthermore, in our previous study (Agertz & Kravtsov 2015) we have shown that the interplay between star formation and stellar feedback is complex, and multiple ways exist for simulations to reproduce
global galaxy observables, such as stellar masses, flat rotation curves, etc. However, internal characteristics of galaxies, such as the \( \Sigma_{\text{SFR}}-\Sigma_{\text{gas}} \) (Kennicutt–Schmidt) relation and the existence of thin galactic disks, are not reproduced by all models.

As modeling of star formation and stellar feedback in galaxy formation simulations improves, it is important to consider, and test against, a large set of galaxy properties. In particular, it is widely recognized that in addition to basic properties of galaxies, such as stellar mass and morphology, galaxy size and angular momentum play important roles in our understanding of galaxy formation.

In CDM models, angular momentum in galaxies is thought to originate during the initial phase of density perturbation growth, as collapsing peaks are tidally torqued by neighboring overdensities (Hoyle 1951; Peebles 1969; Doroshkevich 1970; White 1984). Angular momentum of dark halos is often expressed as a dimensionless spin parameter \( \lambda = j/\sqrt{2} R_{\text{vir}} V_{\text{vir}} \) (as defined by Bullock et al. 2001), which characterizes the specific angular momentum in units of the angular momentum that would be required for rotational support near the virial radius. Here \( R_{\text{vir}} \) and \( V_{\text{vir}} \) are the virial radius and virial velocity of the halo, and \( j \) is the specific angular momentum inside \( R_{\text{vir}} \).

In classical theories of disk galaxy formation (Fall & Efstatiiho 1980; Ryden & Gunn 1987; Dalcanton et al. 1997; Mo et al. 1998), gas acquires the same specific angular momentum as the host dark matter halo, with only a fraction of it lost during gas condensation onto the halo center. The remaining angular momentum sets the disk size, and the fraction of the angular momentum that is ultimately retained is connected to galaxy morphology and the Hubble sequence (Fall 1983; Fall & Romanowsky 2013).

While the spin parameter of the dark matter within the virial radius of halos is found to have a lognormal distribution with a median \( \lambda \approx 0.04 \) and rms variance of \( \sigma_{\text{ln}} \lambda \approx 0.55 \), regardless of halo mass and cosmic time (e.g., Bullock et al. 2001; Viti et al. 2002; Bett et al. 2010), recent studies have shown that accreted matter, dark matter, and gas, upon entry of the virial radius, feature a higher spin than the halo’s average (e.g., Kimm et al. 2011; Pichon et al. 2011; Codis et al. 2012; Danovich et al. 2012, 2015; Tillison et al. 2012; Stewart et al. 2013; Übler et al. 2014). In particular, Danovich et al. (2015) have recently used a set of zoom-in adaptive mesh refinement (AMR) simulations of galaxy formation at high redshifts (\( z \gtrsim 1-2 \)) to show that \( \lambda \) of the cold gas when crossing the virial radius grows with time (see also Pichon et al. 2011).

Despite the large angular momentum content of accreted gas, numerical simulations of galaxy formation have long suffered from the “angular momentum catastrophe” (Navarro & White 1994; Navarro & Steinmetz 2000), whereby galaxies forming in the centers of dark matter halos are dominated by large bulges with a significantly lower specific angular momentum content than their host halos. In the past several years, galaxy formation simulations showed that this problem can be solved, or at least alleviated, by efficient stellar feedback (Scannapieco et al. 2008; Zavala et al. 2008; Sales et al. 2010). For example, Brook et al. (2011; see also Brook et al. 2012a; Christensen et al. 2014a; Übler et al. 2014) found that supernova (SN) feedback can selectively remove low angular momentum gas via outflows, leading to disk formation. More recently, Genel et al. (2015) used the Illustris simulation suite to show that stellar and AGN feedback, tuned to reproduce the observed \( z = 0 \) stellar mass function, can produce a realistic distribution of specific angular momentum of galaxies.

Despite the complexities of angular momentum evolution due to gas dynamics and effects of feedback outlined above, Kravtsov (2013) showed that observed galaxy sizes and radial surface density profiles of baryons are strongly correlated with properties of their parent halo, and that sizes of both late-type disks and early-type spheroids appear to be set by the specific angular momentum proportional to that acquired by the dark matter halo. Subsequent studies at higher redshifts show that this finding holds for star-forming galaxies from \( z \sim 8 \) to \( z \sim 0 \) (e.g., Shibuya et al. 2015, and references therein). This suggests that the angular momentum distribution in galaxy disks is quite similar to the predictions of the classical disk formation models (e.g., Mo et al. 1998).

There are a number of outstanding issues related to effects of stellar feedback in setting galaxy size and angular momentum. First, while feedback can prevent the loss of angular momentum content of galaxies, or remove the lowest angular momentum gas, hence promoting the formation of disk-dominated galaxies, it is not completely clear why the baryons remaining after feedback-driven outflows retain the angular momentum proportional to the average angular momentum of the halo. Second, as emphasized by Roškar et al. (2014), while strong feedback may help in explaining low baryon fractions, excessively violent energy and momentum input can lead to overheating of gaseous disks, which leads to much thicker disk galaxies than are observed. At the very least, new feedback schemes, as they are developed and introduced, need to be tested against these basic empirical features of galaxy evolution.

In this work we use a suite of cosmological simulations of a Milky Way (MW) mass halo started from the same initial conditions, but run with different parameters for star formation and stellar feedback (presented in Agertz & Kravtsov 2015), to study the evolution of galaxy sizes, morphologies, and angular momenta. Our goal is to (1) understand how different assumptions about the efficiency of star formation and stellar feedback affect the evolution of these fundamental properties of galaxies and (2) compare these results to a variety of observed galaxy properties.

We describe our cosmological simulations of galaxy formation in Section 2, present our results and compare them to observational data in Section 3, discuss our findings and compare to previous studies on this subject in Section 4, and summarize our results and conclusions in Section 5.

## 2. GALAXY FORMATION SIMULATIONS

### 2.1. Star Formation

We carry out cosmological hydro+N-body zoom-in simulations of MW-mass galaxies using the AMR code RAMSES (Teyssier 2002). All simulations, as well as the star formation and feedback physics adopted, are presented in detail in Agertz et al. (2013) and Agertz & Kravtsov (2015). Briefly, we adopt a local star formation rate using the following equation:

\[
\dot{\rho}_s = f_{\text{H}_2} \epsilon_{\text{ff}} \rho_b \frac{\dot{\rho}_b}{t_{\text{ff}}},
\]

where \( f_{\text{H}_2} \) is the local mass fraction of molecular hydrogen (\( \text{H}_2 \)), \( \rho_b \) is the gas density in a cell, \( t_{\text{ff}} = \sqrt{3\pi/32G\dot{\rho}_b} \) is the
local free-fall time of the gas, and $\epsilon_{\text{ff}}$ is the star formation efficiency per free-fall time. We adopt the model developed by Krumholz et al. (2008, 2009a) and McKee & Krumholz (2010), hereafter the KMT09 model, for the abundance of H$_2$ based on radiative transfer calculations of idealized spherical giant atomic–molecular complexes subject to a uniform and isotropic Lyman–Werner (LW) radiation field. Relating star formation to the molecular gas is well motivated empirically, as galactic star formation rate surface density correlates well with the surface density of molecular gas, independent of metallicity, and poorly or not at all with the surface density of atomic gas measured on kiloparsec scales (Bigiel et al. 2008; Gnedin et al. 2009; Krumholz et al. 2009b).

We adopt star formation efficiencies per free-fall time in the range of $\epsilon_{\text{ff}} \sim 0.01$–0.1, motivated by observations of local giant molecular clouds (GMCs; Lada et al. 2010; Murray 2011; Evans et al. 2014). As demonstrated by Agertz & Kravtsov (2015), even large local values of $\epsilon_{\text{ff}}$ (~0.1) can reproduce the low global star formation efficiency inferred from the Kennicutt–Schmidt relation (e.g., Bigiel et al. 2008) due to self-regulating effects of stellar feedback (see also Hopkins et al. 2011, 2014) as discussed in the next section.

### 2.2. Stellar Feedback

We adopt the stellar feedback model described in Agertz et al. (2013). Briefly, each formed stellar particle is treated as a single-age stellar population with a Chabrier (2003) initial mass function. We account for injection of energy, momentum, mass, and heavy elements over time via Type II SN (SN II) and Type Ia SN (SN Ia) explosions, stellar winds, and radiation pressure (allowing for both single-scattering and multiple-scattering events on dust) on the surrounding gas. Each mechanism depends on the stellar age, mass, and gas/stellar metallicity, calibrated on the stellar evolution code STAR-BURST99 (Leitherer et al. 1999). Feedback is done continuously at the appropriate times when each feedback process is known to operate, taking into account the lifetime of stars of different masses in a stellar population. To track the lifetimes of stars within the population, we adopt the metallicity-dependent age–mass relation of Raiteri et al. (1996).

Momentum from stellar winds, radiation pressure, and SN blastwaves is added to the 26 nearest cells surrounding a parent cell of the stellar particle. Thermal energy from shocked SNe and stellar wind ejecta is injected directly into the parent cell. We explore the concept of retaining some fraction of the thermal feedback energy in a separate gas energy variable over longer times than expected purely from the local gas cooling timescale. This approach was discussed by Agertz et al. (2013) and Teyssier et al. (2013) (for our choice of parameters, see Agertz & Kravtsov 2015) and can be viewed as accounting for the effective pressure from a multiphase medium, where local unresolved pockets of hot gas exert work on the surrounding cold phase (see recent work on superbubbles by Keller et al. 2014), or a placeholder for other sources of energy, such as turbulence and cosmic rays (Booth et al. 2013).

In Agertz et al. (2013) we demonstrated effects of this particular stellar feedback implementation on scales ranging from individual computational cells to star-forming clouds, as well as on galactic scales. “Early” pre-SN feedback due to radiation pressure and stellar winds acts to clear out star-forming regions, leading to more vigorous heating by SNe, with gas temperatures often reaching $T > 10^6$ K before the first SN events take place ($t \sim 4$ Myr). For higher local star formation efficiencies, gas clearing is more rapid, and the greater number of SNe can sustain hot bubbles for longer, allowing for it to expand and for the gas to escape the dense regions of the interstellar medium (ISM). This is not the case when star formation is slow; as shown in Agertz & Kravtsov (2015), models with too inefficient local star formation fail to produce outflows due to the lack of runaway heating.

We note, however, that at a sufficiently high numerical resolution, simulations will resolve dense gas with free-fall times so short that even at low $\epsilon_{\text{ff}}$ the local star formation rate will be high enough (see Equation (1), where $\rho_i \propto r_i^{-2}$) for feedback to disperse star-forming gas efficiently (e.g., Hopkins et al. 2011). At the spatial resolution of most current cosmological simulations a high value of $\epsilon_{\text{ff}}$ (1%) allows for feedback to be able to regulate the rate of star formation for longer free-fall times.

Heavy elements (metals) injected by SNe and winds are advected as a passive scalar and are incorporated self-consistently in the cooling and heating routine. The code accounts for metallicity-dependent cooling by using tabulated cooling functions of Sutherland & Dopita (1993) for gas temperatures $10^4$–$10^6$ K, and rates from Rosen & Bregman (1995) for cooling down to lower temperatures. Heating from the UV background (UVB) radiation is accounted for by using the UVB model of Haardt & Madau (1996), assuming a reionization redshift of $z = 8.5$. We follow Agertz et al. (2009) and adopt an initial metallicity of $Z = 10^{-3} Z_\odot$ in the high-resolution zoom-in region in order to account for enrichment from unresolved Population III star formation (e.g., Wise et al. 2012).

### 2.3. Simulation Suite

We adopt a WMAP5 (Komatsu et al. 2009) compatible ΛCDM cosmology with $\Omega_m = 0.73$, $\Omega_b = 0.27$, $\Omega_{\Lambda} = 0.045$, $\sigma_8 = 0.8$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$. A pure dark matter simulation was performed using a simulation cube of size $L_{\text{box}} = 179$ Mpc. At $z = 0$, a halo of mass $M_{200c} \approx 9.7 \times 10^{11}$ $M_\odot$ was selected for resimulation at high resolution and traced back to the initial redshift of $z = 133$. Here $M_{200c}$ is defined as the mass enclosed within a sphere with mean density 200 times the critical density at the redshift of analysis. The corresponding radius is $r_{200c} = 205$ kpc. The mass within the radius enclosing overdensity of 200 times the mean density is $M_{200m} = 1.25 \times 10^{12}$ $M_\odot$ and $r_{200m} = 340$ kpc. When baryons are included in the simulations, the final total halo mass remains approximately the same.

The selected halo does not experience any major merger after $z \approx 1.5$, potentially favoring the formation of an extended late-type galaxy. A nested hierarchy of initial conditions for the dark matter and baryons was generated using the GRAFIC++ code, where we allow for the high-resolution particles to extend to three virial radii from the center of the halo at $z = 0$. This avoids mixing of dark matter particles with different masses in the inner parts of the domain. The dark matter particle mass in the high-resolution region is $m_{DM} = 3.2 \times 10^5$ $M_\odot$, and the adaptive mesh is allowed to refine if a cell contains more than eight dark matter particles. A similar criterion is employed for the baryonic component, where the maximum refinement level

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6 http://grafic.sourceforge.net/
Myrdis = 1 = 5 cm$^3$ = 2

Simulation Description

| Simulation       | Description                                      |
|------------------|--------------------------------------------------|
| ALL_Efb_e001     | All feedback, $\epsilon_f = 1\%$              |
| ALL_Efb_e001_5ESN| All feedback, $\epsilon_f = 1\%$, $E_{SN,II} = 5 \times 10^{51}$ erg |
| ALL_Efb_e010     | All feedback, $\epsilon_f = 10\%$             |

Note. All simulations adopt the KMT09 model (see main text) and second feedback energy variable $E_f$ with $f_{db} = 0.5$ and $t_{db} = 10$ Myr. All simulations reach an average cell size of $\Delta x = 75$ pc.

is set to allow for a mean constant physical resolution of $\Delta x \sim 75$ pc, but the maximal resolution varies between 50 and 100 pc. The maximum level of resolution occurs for gas densities $n \gtrsim 5$ cm$^{-3}$, although this resolution level is typically present throughout the galaxies due to the presence of stars and dark matter particles, which trigger cell refinement.

In this work we focus on three zoom-in simulations from the suite presented in Agertz & Kravtsov (2015). All models adopt the same feedback and star formation implementation, but with different parameters, and are picked to represent three different galaxy formation scenarios: (1) overcooling due to inefficient feedback (ALL_Efb_e001), (2) efficient feedback via boosted SN feedback (ALL_Efb_e001_5ESN), and (3) efficient feedback via efficient star formation (ALL_Efb_e010).

In ALL_Efb_e001 the efficiency of star formation is $\epsilon_f = 1\%$. Agertz & Kravtsov (2015) demonstrated how this resulted in inefficient feedback incapable of driving global galactic outflows. This inability leads to overproduction of stars at high redshifts, in strong tension with semi-empirically derived star formation histories (e.g., Behroozi et al. 2013; Moster et al. 2013). This run forms a very dense and rapidly rotating central concentration (see Section 3.5 and Figure 8 below), which makes the simulation computationally extensive. Given that the galaxy it produces was clearly unrealistic, this simulation was run only to $z = 1.5$.

For ALL_Efb_e001_5ESN the overcooling problem was resolved by boosting the released energy per SN by a factor of five. This led to a good match to many considered observables at $z \gtrsim 1-2$: semi-empirically derived star formation histories, the stellar mass–gas metallicity relation and evolution, the stellar mass–halo mass ($M_* - M_{200}$) relation and its evolution, and flat shapes of rotation curves. However, the normalization of the Kennicutt–Schmidt relation was in tension with high-redshift data, and the vigorous galactic outflows ended up preventing the formation of a cold galactic disk at any redshift, as we show below.

ALL_Efb_e010 explores a scenario where vigorous galactic outflows are generated not by artificially boosting the available stellar feedback momentum or energy budget, but by adopting a higher local star formation efficiency per free-fall time, here $\epsilon_f = 10\%$, in agreement with observed values in massive GMCs (e.g., Lada et al. 2010; Murray 2011; Evans et al. 2014), which leads to more correlated stellar feedback events. This resulted in galactic properties that match well with all considered observables at $z \gtrsim 1$, while producing galactic wind mass loading factors that decrease with increasing dark matter halo masses, leading to an epoch of disk formation at $z \lesssim 1$. In this work we continue the analysis down to $z = 0$.

The simulations used in this study and their star formation and feedback parameters are summarized in Table 1.

3. RESULTS

3.1. Morphology

Figure 1 shows mock composite $g$, $r$, $i$-filter face-on and edge-on images of the galaxies in the three simulations at their respective final redshifts. As we noted in the previous section, the simulation with low star formation efficiency (ALL_Efb_e001, bottom row) was not evolved to $z = 0$ due to the high computational expense, as the galaxy suffered from the classical overcooling problem (see Section 3.2) and was stopped at $z = 1.5$.

While the acquisition of galactic angular momentum and diversity of galaxy morphologies ultimately are linked to
properties of cosmological flows and the halo merger history (see discussion in Section 1), we here find that despite identical initial conditions, the resulting galactic morphologies are strikingly different due to relatively small changes in parameters related to small-scale star formation and feedback.\(^3\)

Overcooling in the ALL\(_{\text{Efb,e001}}\) run (bottom row) produces a very massive galaxy and compact morphology with no clear signature of an extended stellar disk at any time. This morphology is in stark contrast with the well-defined galactic disk formed in the fiducial model (ALL\(_{\text{Efb,e010}}\), top row), which features both a thick and thin stellar disk component at \(z = 0\). The vertical velocity dispersion of the young (\(t_s < 3\) Gyr) thin disk is \(\sigma_z \approx 10\ \text{km s}^{-1}\) (for a full analysis, see Agertz & Kravtsov 2015), and \(\sim 60–70\ \text{km s}^{-1}\) for the old thick disk, compatible with what is observed in the MW (e.g., Bovy et al. 2012). This result is very encouraging, indicating that models with efficient stellar feedback can be compatible with the formation of dynamically cold stellar disks, in contrast to previous models where only thick disks were produced at \(z = 0\) (e.g., Stinson et al. 2013b; Roškar et al. 2014); see Section 4.2 for further discussion. We note that this does not mean that the models do not suffer from disk heating due to limited numerical resolution, or that the thin disk is the dominant galactic component, only that our approach to feedback and star formation allows for the coexistence of a thin and a thick disk.

The model with low star formation efficiency, but boosted energy release per SN (ALL\(_{\text{Efb,e001}_5\text{ESN}}\)), fails to form a cold thin disk, with star formation occurring in an extended and highly turbulent gaseous system. The overall morphology is irregular, with large gaseous clumps and irregular dark dust lanes.

### 3.2. Baryon Fractions

Figure 2 shows the stellar mass fraction of the central galaxies in the three runs, expressed in units of the cosmic baryon fraction, as a function of dark matter halo virial mass for the three models. We compare the simulation data to results from semi-empirical constraints based on the abundance matching approach (Behroozi et al. 2013; Kravtsov et al. 2014), as well as inferences from weak-lensing studies of late- and early-type systems (Mandelbaum et al. 2006; Hudson et al. 2015) and estimates using satellite kinematics (More et al. 2011).

The \(z = 0\) \(M_h\)–\(M_{200}\) we are comparing to was derived by Kravtsov et al. (2014; see this paper for further details) using the stellar mass function measurement by Bernardi et al. (2013), where galaxy luminosity measurements were improved by fitting Sérsic profiles and extrapolating to infinity. Tollet et al. (2016) show that this relation is in very good agreement with simulations of galaxy formation with efficient feedback. This agreement indicates that any baryonic effects on this relation of the kind discussed by Sawala et al. (2013) are small at the galaxy mass scale we are considering.

Figure 2 shows that the fiducial and the boosted feedback runs conform to the \(z = 0\) stellar mass—halo mass relation and its inferred evolution. This is consistent with results of Munshi et al. (2013), who found that proper modeling of star formation in high-density regions and high efficiency of feedback are key to successfully reproducing the \(M_h\)–\(M_{200}\) relation indicated by observations. As already discussed in Agertz & Kravtsov (2015), these models achieve this in very different ways, leading to dramatic differences in the resulting galaxy morphologies (Figure 1). The run with low local star formation efficiency is inconsistent with high-redshift data and is marginally consistent with the expected scatter of stellar fractions at \(z = 0\), although note that the final data point is at \(z = 1.5\).

### 3.3. Size Evolution in Simulations and Comparison with Observations

Figure 3 shows evolution of the stellar mass–half-mass radius (\(M_*–r_{1/2}\)) relation for galaxies in our three runs against the observed relation at \(z = 0\) (see Kravtsov 2013 for details about the observational sample and the method used to estimate \(r_{1/2}\)). The low-efficiency star formation run evolves off the mean relation at early times, and at the last available data point (\(z = 1.5\)) the galaxy is extremely compact with \(r_{1/2} \lesssim 0.5\) kpc. We note that a significant fraction of galaxies at \(1–3\) kpc are in fact compact ellipticals (van Dokkum et al. 2008, 2014; Newman et al. 2010) with \(r_{1/2} < 1\) kpc (Carollo et al. 2013). However, such galaxies are believed to be progenitors of today’s massive elliptical galaxies that evolve at low \(z\) primarily due to mass accretion via minor mergers (e.g., Hopkins et al. 2009). Compact ellipticals are mostly quenched at low \(z\), as characterized by their specific star formation rates. With an SFR \(\sim 20\ M_\odot\ \text{yr}^{-1}\) at \(z = 1.5\), the overcooling model is far from being quenched, and while it could be identified as a
“blue nugget” (progenitors of compact ellipticals; see, e.g., Barro et al. 2013; Dekel & Burkert 2014) and join the population of early-type galaxies at $z=0$ by quenching and late-time expansion (Whitaker et al. 2012), its already significant stellar mass fraction makes it a rather unlikely candidate for a realistic galaxy.

In contrast, the boosted feedback run ALL_Efb_e001_5ESN, in which the resulting galaxy lacks a cold disk component, is very extended, with $r_{1/2} > 10$ kpc at $z=0$. This is $\sim 2$--3 times greater than the observed average $r_{1/2}$. Interestingly, extended spheroidal systems with exponential surface brightness profiles do exist in the nearby universe (van Dokkum et al. 2015). However, such galaxies are rather rare and cannot be considered to be the typical outcome of galaxy formation in a $\sim 10^{12}$ $M_\odot$ halo.

Figure 3 also shows that the galaxy forming in the fiducial run matches the $z=0$ observations at all times. Prior to the last major merger at $z \sim 1.8$, when $M_* \approx 10^{10}$ $M_\odot$, $r_{1/2}$ is roughly constant at $\sim 1$--2 kpc. After this point the galaxy enters an epoch of disk formation and grows rapidly in size, with $r_{1/2} \sim 3$--4 kpc at $z=0$, close to the estimated value for the MW (Bovy & Rix 2013). More precisely, starting from $M_* \approx 10^{10}$ $M_\odot$ at $z \sim 1.8$, our fiducial model grows by a factor of $\sim 1.75$ in $r_{1/2}$ while growing by a factor of 6 in mass until $z=0$, indicating $r_{1/2} \propto M_*^{0.3}$. This is in excellent agreement with the results of van Dokkum et al. (2013) and Patel et al. (2013), who studied the structural evolution of MW-mass progenitors back to $z \sim 2.5$ using the 3D-HST and CANDELS Treasury surveys. Here the half-light radii of star-forming galaxies in their sample were found to scale as $r_{1/2} \propto M_*^{0.29\pm0.08}$.

These results illustrate that while the galactic environment, via mergers, alignment of accretion, etc., must play a role for the resulting galaxy size and morphology (especially in explaining the origin of early-type galaxies; e.g., Hopkins et al. 2010), internal small-scale feedback processes, as well as our limited theoretical understanding of how these should be accounted for over cosmic time, impact, and possibly even dictate, the Hubble sequence of late-type galaxies. We discuss this further in Section 4.

The left panel of Figure 4 shows the evolution of galaxies in the three runs in the plane of half-mass radius, $r_{1/2}$, versus the radius, $R_{200}$, enclosing the density contrast of 200 relative to the critical density of the universe. Simulation results are shown against a collection of $z \approx 0$ observed galaxies (see caption for the data sources), for which $R_{200}$ was estimated from the halo mass obtained by abundance matching. As shown by Kravtsov (2013), this relation is on average close to linear, $r_{1/2} \approx 0.015 R_{200}$, which is shown by the long gray dashed line along with the $2\sigma$ scatter, as expected if galaxy sizes were set by the specific angular momentum of baryons shared with the dark matter halo (i.e., $r_{1/2} \propto \lambda R_{200}$). A similar relation has since been observed over a wide range of redshifts (e.g., Shibuya et al. 2015).

The figure shows that in the weak feedback simulation the galaxy maintains a compact distribution of stars with half-mass radius staying constant at $r_{1/2} \sim 0.3$--0.5 kpc. The fiducial and ALL_Efb_e001_5ESN simulations, however, evolve approximately along the linear relation, albeit with significant fluctuations, especially during early stages of evolution (smaller sizes). As discussed above, the galaxy in the ALL_Efb_e001_5ESN run has a size that is too large for a typical halo expected to host its galaxy at $z=0$. Such galaxies are quite rare in the observed samples. The fiducial run is close to the $z=0$ data inferred for observed galaxies during the late stages of evolution. At high $z$, the ratio $r_{1/2}/R_{200}$ is about twice larger than at low $z$, a behavior that is consistent with the average behavior of observed galaxies reported by Shibuya et al. (2015). Such evolution may be partly due to the physical evolution of the disk size, but could also arise because the disk size is set during the fast mass growth regime of halo evolution, after which a large fraction of the $M_{200}$ growth is not a real physical growth but rather an increase in mass due to pseudo-evolution (Diemer et al. 2013), and is hence not accompanied by the proportional growth of stellar $r_{1/2}$.

To illustrate the latter point, the right panel of Figure 4 shows a somewhat different representation of the evolution. Here the curves representing tracks of simulated galaxies are unchanged from the left panel. The observed $z=0$ sample, however, is corrected for possible pseudo-evolution (PE) of the halo mass. Many indications exist that the inner regions of halos change little from $z \sim 1$--2 until the present (Cuesta et al. 2008; Diemer et al. 2013; More et al. 2015). Thus, the evolution of $M_{200}$ and $R_{200}$ at these redshifts may be simply due to the changing critical density of the universe, to which they are tied by definition, and not the real physical growth. In the extreme scenario, one can imagine that the halos grow only by...
pseudo-evolution since its formation time, which we can operationally define as the time when the halo had a concentration of $c_{\text{form}} = 3$ (Wechsler et al. 2002; Zhao et al. 2009). Thus, in the right panel we correct the virial radii as $R_{200} = c_{\text{form}} R_{200}/\bar{c} (M_{200}, z = 0)$, where $\bar{c} (M_{200}, z = 0)$ is the average concentration of halos of mass $M_{200}$ at $z = 0$, which we calculated using an accurate concentration model by Diemer & Kravtsov (2015) calibrated on a large suite of simulations.

If galaxy halos do exhibit significant pseudo-evolution, the disk sizes were set at higher $z$, and thus they should be compared to the PE-corrected $R_{200}$ values. In other words, in such cases it should be more appropriate to compare the higher-$z$ portion of the galaxy tracks with the data with the PE-corrected virial radii. The right panel of Figure 4 indeed shows that the early stages of galaxy evolution, and hence lower progenitor stellar masses and halo virial radii, track the PE-corrected data points. At late stages they evolve close to the $z \approx 0$ data. This evolution qualitatively and quantitatively tracks the evolution derived for observed galaxies across a wide range of redshifts by Shibuya et al. (2015), who find that star-forming galaxies have $r_{1/2}/R_{200} \approx 0.015-0.02$ at $z \lesssim 2$, increasing somewhat to $r_{1/2}/R_{200} \approx 0.03-0.04$ at larger redshifts.

Overall, these results indicate that in the fiducial and ALL_Efb_e001_5ESN simulations, the angular momentum of the disk is approximately linearly proportional to the specific angular momentum of the halo, and galaxies thus evolve along the $r_{1/2} \propto R_{200}$ track. Similar results were recently reported by Pedrosa & Tissera (2015), who found that galaxies in a large simulated sample followed a linear $R_{200} \propto r_{1/2}$ relation in simulation with efficient feedback, but disk and spheroidal galaxies followed relations with different constants of proportionality.

### 3.4. Surface Density Profiles

Figure 5 shows the stellar and neutral gas surface density profiles for the simulated galaxies in the fiducial and ALL_Efb_e001_5ESN simulations—the two simulations that were evolved to $z = 0$—along with the profiles of late-type galaxies from the THINGS sample (Leroy et al. 2008) in the stellar mass range $M_* \approx 3-10 \times 10^8 M_\odot$ and the MW (Dame 1993; McMillan 2011). In the observed galaxies the gas surface density includes atomic and molecular gas corrected for helium mass fractions, while in the simulations the gas mass includes all of the cold gas of $T < 10^4$ K.

The figure shows that the fiducial simulation reproduces a stellar surface density profile in good agreement with late-type galaxies of this mass range, albeit with a slightly larger bulge component than typical in the observed sample. In contrast, the surface density profile in the ALL_Efb_e001_5ESN simulation is very different from all of the observed THINGS galaxies in this stellar mass range; the $\Sigma_* (R)$ profile is close to exponential,
Figure 5. Comparison of the surface density profiles of stars (left) and cold gas (right) in the simulated galaxies in the fiducial and ALL Efbb e001 5ESN simulations along with the profiles of late-type galaxies from the THINGS sample (Leroy et al. 2008) in the stellar mass range $M_* \approx (3 - 10) \times 10^{10} M_\odot$ and the Milky Way, using a combination of the thin and thick stellar disks with parameters given in Table 2 of McMillan (1993) for $\Sigma_{\text{gas}}$. In observed galaxies the gas surface density includes atomic and molecular gas corrected for helium mass fraction, while in simulations the gas mass includes all of the cold gas of $T < 10^4$ K.

but as discussed above, the scale length is considerably larger than what is observed for most disk galaxies. Thus, it is a counterpart to the rare low surface brightness galaxies, with number densities roughly two orders of magnitude smaller than the number density of typical $L_e$ galaxies, of which some feature very extended exponential disks (e.g., McGaugh & Bothun 1994). Such galaxies are thus unlikely to form in a single random realization of an MW-sized halo.

The $\Sigma_{\text{gas}}(r)$ profile of the fiducial simulation does not match the profile of the MW, which is observed to be considerably more gas poor. However, its shape matches the overall shape of the gas surface density profiles in this mass range, with a somewhat higher normalization than most THINGS galaxies, a notion we return to in Section 4. The $\Sigma_{\text{gas}}(r)$ profile in the ALL Efbb e001 5ESN simulation has an even higher normalization, possibly due to the overall lower star formation rate in comparison to the fiducial simulation at low redshifts, $0.5 \lesssim z \lesssim 2$ (Agertz & Kravtsov 2015), leading to more gas being retained.

Finally, we note that the gas surface density profiles in both simulations exhibit more fluctuations than $\Sigma_*(R)$, with fluctuation strengths comparable to those in the observational data, due to the presence of spiral arms and other inhomogeneities in the gas distribution. Although the distribution of young stars exhibits similar fluctuations, the stellar mass distribution is considerably smoother, which is reflected in the smoother $\Sigma_*(R)$ profile.

### 3.5. Evolution and Scaling of Angular Momentum

Figure 6 shows the evolution of stellar and cold gas ($T < 10^4$ K) specific angular momentum\(^8\) of the central

\[^8\] The specific angular momentum is computed as $j = \sum_i m_i \mathbf{r}_i \times \mathbf{v}_i / \sum_i m_i$, where summation is performed over all $i$ cells of cold gas or all star particles, and $\mathbf{r}$ and $\mathbf{v}$ are position and velocity relative to the galaxy’s center of mass.
galactic winds (see also Übler et al. 2014). In addition, the baryon-rich central galaxy is likely to experience disk instabilities that funnel gas toward the center, lowering its angular momentum content and decreasing $r_{1/2}$. We discuss this issue in more detail in Section 4.1.

Rather surprisingly, the boosted feedback model fails to produce a galaxy rich in angular momentum, with $j_*$ $\sim$ 100–500 km s$^{-1}$ kpc, with large scatter, despite the large physical extent as characterized by $r_{1/2}$. The interaction between feedback and specific stellar angular momentum is here more complex, with the strong feedback leading to a more spheroidal distribution of stars with angular momenta of individual orbits partially canceling each other.

These results imply that strong feedback is not a panacea against the angular momentum catastrophe, as different models of the star formation–feedback cycle can give almost identical results in terms of global quantities ($M_*$, SFR, $v_{circ}$), but differ significantly in other, more detailed observables (Agertz & Kravtsov 2015). In Section 4.2 we discuss feedback implementations further and compare our results to recent studies on the angular momentum content of simulated galaxies.

We find that the specific angular momentum of the cold gas component ($j_{\text{gas}}$) is always greater than that of the stars. This is not surprising as stars form in the dense inner regions of the gaseous disk, and the precise value for the simulated stellar angular momentum is sensitive to numerically resolving star formation at large galactic radii. The cold gas extends much farther than the optical radius (see Figure 5), in agreement with observations (e.g., Kravtsov 2013), and in the fiducial model, $j_{\text{gas}}$ $\sim$ 2000 km s$^{-1}$ kpc, a value compatible with observed $j_*$ in late-type spirals of Sc–Sd type.

With weak stellar feedback, $j_{\text{gas}}$ reaches $\sim$1000 km s$^{-1}$ kpc at $z$ $\sim$ 1.5, 10 times higher than the corresponding $j_*$. In the boosted feedback case, $j_{\text{gas}}$ $\sim$ 500 km s$^{-1}$ kpc after the last major merger (i.e., for $M_* > 10^{10} M_\odot$), which is smaller than $j_{\text{gas}}$ in the fiducial model by a factor of a few. This offset may stem from how outflows are driven in this particular model, as too strong feedback may eject both angular-momentum-poor (e.g., Brook et al. 2011; Übler et al. 2014) and angular-momentum-rich gas, hence destroying the cold ISM of the galaxy; by artificially boosting the available energy per SN, gas even associated with regions of low $\Sigma_{\text{SFR}}$, which otherwise would not necessarily be as affected by feedback, can be ejected from the galaxy.

4. DISCUSSION

The results presented in the previous section clearly show that the morphology of a galaxy forming in a given dark matter halo sensitively depends on the parameters of star formation and feedback. This conclusion is in agreement with a number of other recent studies, as we discuss below in Section 4.2.

In this and previous work (Agertz & Kravtsov 2015), we have demonstrated how models achieving efficient feedback produce galaxies in good agreement with observations. It is worth re-emphasizing that the adopted input value for the local star formation efficiency per free-fall time used in the fiducial model ($\epsilon_{\text{ff}} = 10\%$) is somewhat larger than estimated from observations of star-forming clouds ($\epsilon_{\text{ff}} \sim 1\%$; e.g., Krumholz & Tan 2007) and on galactic scales (Bigiel et al. 2008). However, as we discussed in Section 2.1, $\epsilon_{\text{ff}}$ in GMCs is observed to feature large scatter ($\sim$0.1%–10%; e.g., Lada et al. 2010; Murray 2011; see also Figure 2 in Agertz & Kravtsov 2015). The large scatter is also predicted by galaxy simulations with star formation implementations where the local $\epsilon_{\text{ff}}$ is controlled by the local gas density and the level of turbulence (Semenov et al. 2015). The scatter may also be due to different observed evolutionary stages of the clouds (Feldmann & Gnedin 2011). Furthermore, efficient star formation, with $\epsilon_{\text{ff}} \gg 1\%$, is expected on theoretical grounds in supersonically turbulent flows inside of bound GMCs (e.g., Padoan & Nordlund 2011). Finally, one could argue that if feedback is efficient in dispersing star-forming clouds, the estimates of the star formation efficiency on large scales may be low even if the local $\epsilon_{\text{ff}}$ is high (e.g., Governato et al. 2010;
Hopkins et al. 2011, 2014; Agertz et al. 2013; Agertz & Kravtsov 2015).

Although the role of feedback in setting galaxy morphology and basic properties, such as stellar mass and size, is widely acknowledged, the exact mechanisms by which feedback affects galaxy properties are not yet fully understood. Our results can be used to clarify some aspects of this question, as we discuss next.

4.1. Disk Instabilities, Bulge Formation, and Stellar Feedback

It is widely accepted that stellar and AGN feedback plays a key role in removing low angular momentum gas that is expected in the central regions of galaxies, even if there is no redistribution of angular momentum during galaxy formation (e.g., Bullock et al. 2001; van den Bosch 2001; van den Bosch et al. 2001). However, the role of feedback is likely to be more multifaceted. Even if cosmologically accreted gas has initially no low angular momentum component, redistribution of angular momentum due to disk instabilities can quickly create such a component (e.g., Kormendy & Kennicutt 2004; Bournaud et al. 2007; Weinberg & Katz 2007; Elmegreen et al. 2008). If star formation proceeds in this low angular momentum gas, this results in a more massive central bulge and possibly a spheroid-dominated galaxy. If, on the other hand, stellar feedback removes most of the gas before it is turned into stars, the remaining disk may have a much smaller stellar mass than in observed galaxies. The role of feedback should thus be to remove low angular momentum gas efficiently but still reproduce observed disk masses. As we argue below, such self-regulating behavior can probably be understood by considering overall disk stability.

Disk stability is affected by a number of factors (e.g., Jog & Solomon 1984; Romeo 1992; Christodoulou et al. 1995; Rafikov 2001; Romeo et al. 2010; Agertz et al. 2015), but a key factor controlling the overall global stability is the fraction of the potential contributed by the disk relative to the spheroidal/halo component (Efstathiou et al. 1982). This dependence was realized by Ostriker & Peebles (1973), who used it to argue that the existence of dynamically cold galactic disks requires the existence of massive spheroidal halos around them.

Efstathiou et al. (1982) used N-body simulations to show that for exponential disks embedded in spherical halos the onset of the bar instability can be characterized by the criterion

\[ \epsilon_m \equiv \frac{V_{\text{max}}}{\sqrt{GM_{\text{disk}}/R_d}} \lesssim 1.1, \]

where \( V_{\text{max}} \) is the maximum rotational velocity, \( M_{\text{disk}} \) is the mass of the disk, and \( R_d \) is the disk’s exponential scale length. Due to its simplicity, this is a widely used criterion of instability in semianalytical models of galaxy formation (e.g., Mo et al. 1998; De Lucia et al. 2011; Guo et al. 2011).

Mo et al. (1998) used a detailed disk formation model to show that the criterion in Equation (2) implies disk instability when the disk baryon mass relative to the total halo mass, \( m_d \equiv M_d / M_{200} \), is greater than the disk spin parameter \( \lambda_d \): \( m_d \gtrsim \lambda_d \). If the disk has a specific angular momentum similar to that of the dark matter halo, its spin parameter is expected to have a lognormal distribution with the median of \( \lambda \approx 0.04 \)

with a fractional scatter of \( \sigma_{\ln \lambda} \approx 0.55 \), regardless of halo mass and cosmic time (e.g., Bullock et al. 2001; Vitvitska et al. 2002; Bett et al. 2010). This result implies that when galaxy growth increases the disk mass beyond this limit, strong disk instabilities will set in.

The subsequent evolution will depend on the efficiency of feedback; if feedback removes the low angular momentum gas resulting from mass redistribution in the unstable disk and lowers the disk mass below the critical limit, the galaxy may maintain a disk mass fraction close to, or below, the critical instability threshold. If feedback is inefficient, the galaxy will form a massive central spheroidal component.

These different scenarios are indeed realized in our runs with different star formation and feedback parameters. In Figure 7 we plot the disk baryon fractions (stellar + cold gas) for the three simulated galaxies as a function of redshift, with the gray band roughly indicating a possible transition into a disk-unstable regime and hence bar formation, assuming \( \lambda = j/\sqrt{2R_{200}V_{200}} = 0.044 \), which we measure for our halo at \( z = 0 \). Note that the mass fraction includes all of the mass in the galaxy, while the stability criterion formally should include only the disk mass. We do not attempt to separate disk and spheroidal components and simply examine the total mass of the galaxy. The rationale is that if the entire mass of the galaxy was in a cold disk, the figure would show us the regime in which the disk is expected to be unstable.

The run with low efficiency of star formation does not have sufficiently strong feedback and produces a compact galaxy with \( \sim 80\% \) of the cosmic baryon fraction in the disk at all times. The feedback in the ALL_Efb_e001_5ESN run, however, does drive strong outflows at \( z \gtrsim 1 \) and maintains disk masses right around the critical instability threshold from \( z \sim 5 \) to \( z = 0 \). The feedback in the fiducial run is even stronger at high \( z \), which keeps the disk mass well below the instability threshold until the last major merger at \( z \sim 1.8 \). At lower \( z \), outflows become less prominent (Agertz & Kravtsov 2015;
Muratov et al. (2015) and the disk mass fraction reaches $m_d \equiv M_{\text{disk}}/M_{200} \approx 0.07$ (or $\approx 0.4-0.5$ in units of $\Omega_b/\Omega_m$).

This could indicate that the fiducial model is susceptible to $m = 2$ disk instabilities at late times, which are responsible for growth of its bulge.

Indeed, this is consistent with the evolution of the mass distribution as traced by the circular velocity profile, $v(r)$, in Figure 8, which shows $v(r)$ for all three runs at different $z$ for only the baryons in the disk and all matter separately. At $z = 3$, ALL_Efb_e001_5ESN and the fiducial runs both have disk masses below the critical instability threshold and correspondingly have circular velocity profiles without a central “spike,” which is very pronounced in the profile for the weak feedback run. At $z = 0$, on the other hand, the $v(r)$ profile for the fiducial model features a modest peak at $r \lesssim 1$ kpc, consistent with late evolution of this disk above the critical threshold, whereas the circular velocity in the ALL_Efb_e001_5ESN run, in which the galaxy mass never gets significantly larger than the threshold, maintains a slowly rising $v(r)$ profile without a central concentration. This figure thus indicates that the development of central concentrations in galaxies is related to the development of disk instabilities when the central disk mass exceeds the approximate threshold in Equation (2) above.

This sheds light on the long-standing issue of “spiky” circular velocity profiles in simulations (e.g., Mayer et al. 2008, and references therein): our results indicate that prevalent central spikes in $v(r)$ profiles, even at the highest $z$, are due to the inability of a given feedback prescription of keeping the disk mass around or below the instability threshold. At the same time, our results show that preventing the formation of a central concentration does not necessarily result in the formation of a disk-dominated galaxy. The galaxy that forms in our ALL_Efb_e001_5ESN run has maintained low disk mass and has an exponential surface density profile, but features an irregular morphology and a size that is larger than expected for a galaxy of such stellar mass. This is because stellar feedback in this model continues to strongly “stir” the gas in the disk and disrupts the galaxy’s ISM with outflows and fountains down to $z = 0$. The ISM in this run is thus perpetually in a perturbed state, which prevents the formation of a well-defined cold disk component (Roškar et al. 2014).

The above analysis illustrates the dual effect of stellar feedback: it both removes the low angular momentum gas and regulates disk stability. Late-type $L \sim L_*$ galaxies, i.e., galaxies with low bulge-to-disk ratios or lack of bulges altogether, are predominately low-mass galaxies ($M_\star \lesssim (1-5) \times 10^{10} M_\odot$; Nair & Abraham 2010), and feedback effects should here delicately balance between driving ISM turbulence and outflows, as well as allowing thin disks to form. Such galaxies likely form in halos of masses $\sim 10^{11-10^{12}} M_\odot$ (Behroozi et al. 2013; Kravtsov et al. 2014).

Van Dokkum et al. (2013) studied the structural evolution of MW-mass progenitors back to $z \sim 2.5$ by matching cumulative comoving number densities in the 3D-HST and CANDELS Treasury surveys. The surface brightness profiles were found to be well represented by Sérsic profiles with average indices evolving from $n \sim 1$ (exponential) to $n \sim 3$ (more centrally concentrated) from $z \sim 2.5$ to $z \sim 0$, with $\sim 1$ dex associated increase in average stellar masses and a factor of $\sim 2$ increase in galaxy sizes. These observational trends are close to the evolution found in our fiducial galaxy simulation for $z \lesssim 2$, which develops a more centrally concentrated mass profile at late times via global disk instabilities, with roughly an Sa–Sb $z = 0$ Hubble type.

At lower stellar masses ($M_\star \lesssim 10^{10} M_\odot$), the stellar fraction $M_\star/M_{200}$ decreases rapidly (see Figure 2), meaning that these galaxies are more stable against global disk instabilities, making them less likely to feature massive bulges. Indeed, bulgeless disks are observed to be more abundant at these masses (Nair & Abraham 2010).

### 4.2. Comparison with Previous Studies

A number of recent studies have emphasized the utmost importance of stellar feedback in shaping basic properties and morphologies of galaxies. Following initial findings of Navarro & White (1994), Navarro & Steinmetz (2000) and Abadi et al. (2003) confirmed the fact that when gas is not removed by winds, or when galaxies are allowed to form stars at a high rate during early epochs of evolution, the resulting $z = 0$ galaxies are too compact and have specific angular momentum that is too low compared to observations of late-type galaxies.

Efficient feedback prevents baryons from condensing and accumulating in dense central “blobs” and delays star formation until lower redshifts when the gas is able to settle into a gaseous disk without significant loss of angular momentum (Maller & Dekel 2002). In particular, Zavala et al. (2008; see also Sales et al. 2010; Pedrosa et al. 2014;
Genel et al. (2015) have pointed out that agreement with observations requires that baryons that end up in late-type galaxies have specific angular momentum comparable to that acquired via gravitational torques by their host dark matter halos, as envisioned in the classical analytic models of disk formation (Fall & Efstathiou 1980; Dalcanton et al. 1997; Mo et al. 1998; although see Dutton & van den Bosch 2012, who concluded that observed angular momenta of disk galaxies are somewhat lower than expected for their DM halos). The same conclusion can be reached by comparing sizes of galaxies to the expectations of such analytic models (see Kravtsov 2013).

The importance of efficient feedback in setting galaxy angular momentum, size, and morphology was confirmed by a number of recent studies (Sales et al. 2010; Brook et al. 2011; Scannapieco et al. 2012; Aumer et al. 2013, 2014; Christensen et al. 2014a, 2014b; Übler et al. 2014; Genel et al. 2015; Murante et al. 2015). Thus, the role of feedback and the importance of proper modeling of the star formation–feedback loop are now firmly established. The exact mechanisms by which feedback affects galaxy properties are nevertheless still a subject of debate.

One possible effect of feedback is to self-regulate star formation, making it inefficient and keeping galaxies gas rich. Disks in gas-rich galaxies are much more resilient during mergers, and a thin disk can reform even after major mergers (Robertson et al. 2006). This effect is likely significant at high redshifts when the age of the universe is comparable to or smaller than the typical gas consumption timescale in galaxies. However, by itself self-regulation cannot result in formation of realistic disks as the accumulating gas eventually turns into stars, and without gas removal via winds, galactic stellar masses will end up too high to be compatible with observations.

Zavala et al. (2008) and Scannapieco et al. (2008) argued that the role of feedback was primarily to prevent gas condensation into dense clumps in low-mass dark matter halos and to delay gas accretion onto disks until later epochs, as argued by Maller & Dekel (2002). Brook et al. (2011) and, more recently, Übler et al. (2014) additionally argued that stellar feedback can promote disk formation by preferentially ejecting low angular momentum gas at early times ($z \gtrsim 1$), which can accumulate due to disk instabilities or angular momentum loss in mergers.

Genel et al. (2015) also emphasized the importance of stellar-feedback-driven winds with large mass loading factors for the formation of angular-momentum-rich disks. They concluded, however, that AGN feedback via radio bubbles in their implementation leads to a net loss of angular momentum, concluding that AGN feedback may help explain the low angular momentum of spheroidal stellar systems. Overall, Genel et al. (2015) concluded, as did other recent simulation studies by Aumer et al. (2013) and Fiaccon et al. (2015), that the diverse galaxy morphologies observed in the Illustris simulation did depend on the merger history of galaxies (as argued since the earliest galaxy formation simulations; Navarro & Benz 1991). Both disk and spheroidal galaxies in their simulations had similar specific angular momenta at high $z$ comparable to that of their dark matter halos. Spheroidal galaxies, however, lost a significant fraction of their angular momentum in major mergers. Sales et al. (2012), however, argued that alignment of angular momentum of accreting gas was a more important factor in setting galaxy morphologies than the merger history. In reality, it is likely that both mergers and angular momentum alignment of accreting gas affect galaxy morphology and structure (see, e.g., Aumer et al. 2014).

Our conclusions on the high importance of stellar feedback in setting properties of galaxies are in broad agreement with results of the studies discussed above. Our study has contributed to our continuing quest to understand effects of feedback in several ways. First, our simulations implement a number of state-of-the-art prescriptions for star formation and stellar feedback, such as molecular-hydrogen-based star formation and an implementation of both “early” (pre-SN) and SN momentum and energy injections. Most importantly, our simulations reach a resolution of $\sim 50–100$ pc in the ISM, allowing for the implementation of star formation and feedback prescriptions to operate on these scales, hence more closely resolving the internal processes that shape galaxies structurally.

Large-scale galactic winds then emerge (if they do) self-consistently due to coherent effects of local feedback from multiple star formation sites. This is in contrast to many recent studies, in which large-scale winds are launched explicitly as part of the overall feedback prescription, often accompanied by turning off the interactions between the wind and the galaxy’s ISM and circumgalactic gas. For example, at $z = 0$, gravitational forces in the Illustris simulation analyzed by Genel et al. (2015) are softened on scales of $\sim 710$ pc, compared to $\sim 75$ pc in our current work. A similar difference in resolution exists with the EAGLE and the Magneticum Pathfinder simulations (Schaye et al. 2015; Teklu et al. 2015). The flip side, however, is that the computational expense demanded by such high resolution allowed us to simulate only a handful of galaxy models.

Our results indicate that in addition to the role of feedback in ejecting low angular momentum gas pointed out in previous studies, feedback may also play a role in limiting disk mass, thereby suppressing disk instabilities and preventing associated loss of angular momentum in the first place.

At the same time, our results show that efficient feedback that suppresses galaxy mass to the observed levels or below is no guarantee of forming a galaxy with realistic properties. Thus, feedback in our ALL_Efb_e001_5ESN run maintains a low star formation rate and stellar mass, but the galaxy that forms is highly irregular and has a size that is too large compared to observed galaxies. This is reminiscent of the recent results of Roškar et al. (2014), who demonstrated that the excessively violent energy and momentum input can lead to overheating of gaseous disks, even as the overcooling problem is alleviated (see also Stinson et al. 2013b). This overheating then produces disk galaxies that are much thicker than observed. Although gas stirring by feedback may actually play a role in setting the disk thickness (Bird et al. 2013), these results illustrate that stirring effects should be limited in order not to thicken the disk excessively.

Overall, our results show that basic properties of galaxies forming in a given halo are highly sensitive to the implementation and parameters of star formation and stellar feedback, consistent with findings of Okamoto et al. (2005) and Scannapieco et al. (2012). This inherent sensitivity to details of the star formation–feedback loop indicates that specific results, for a particular set of prescriptions, should be viewed with healthy skepticism, regardless of how well they reproduce a particular set of observations.
Our results published in a companion paper (Liang et al. 2016), in which we compared properties of circumgalactic gas in our simulations to observations, also highlight this point. Although our fiducial run does result in many realistic galaxy features, including stellar mass, morphology, disk-to-bulge ratio, rotation curve shape, disk thickness, etc., it fails spectacularly in reproducing observed properties of circumgalactic gas around galaxies of similar mass. In particular, its gaseous halo is too hot and is almost devoid of any extended warm gas component, the existence of which is revealed by ubiquitous absorption lines of low-ionization energy ions, such as Mg II.

The model with boosted energy per SN (ALL_EF-5ESN) produces a circumgalactic medium closer to observations due to its continuing large-scale outflows to low z, but fails to produce a realistic galaxy. The discrepancy with observed circumgalactic medium (CGM) properties may be due, in part, to low spatial numerical resolution in galactic halo regions (Muzahid 2014; Crighton et al. 2015) or missing physical processes, such as cosmic rays (Enßlin et al. 2007; Booth et al. 2013; Salem & Bryan 2014). For example, if some of the warm absorbers form via thermal instabilities, the relevant scales would be on the order of parsecs. Thus, the current difficulties in matching results of quasar absorption studies should not be taken as a strong indication against a given feedback model. Nevertheless, these discrepancies highlight the fact that a comparison with CGM properties may provide additional constraints and illustrates the importance in comparing galaxy formation models to a wide range of galaxy properties (see also Brook et al. 2012b).

Another potential issue is the missing satellites problem (Klypin et al. 1999; Moore et al. 1999)—the significant discrepancy between the predicted mass function of dark matter satellites and observed stellar mass function of galaxy satellites (see also Kravtsov 2010, for a review). Reproducing the observed stellar mass function of satellites of MW-mass halos has thus become a benchmark for galaxy formation models, with many encouraging results in the recent literature (e.g., Zolotov et al. 2012; Sawala et al. 2016). In our simulations almost no satellite dark matter halos within the virial radius of the main galaxy at $z = 0$ contain stars. This issue stems from the low fraction of molecular hydrogen in the metal-poor gas ($Z \sim 10^{-3} - 10^{-2} Z_\odot$) residing in those halos, leading to a very high effective density threshold for star formation ($n \gtrsim 10^3 \text{cm}^{-3}$; see Section 2.1). The problem is exacerbated by the fact that the structure of dwarf galaxies is poorly resolved, and any conclusions regarding the baryonic content and the density distribution in these low-mass systems are therefore far from robust.

Finally, our results show that changes of parameters related to the star formation and stellar feedback prescriptions can result in variations of galaxy size, $r_{1/2}$, by more than an order of magnitude, while the final specific angular momentum varies only by a factor of two. Therefore, while size evolution as a function of galactic mass is a useful and stringent constraint on galaxy formation models (van Dokkum et al. 2013; Aumer et al. 2014), a comparison to both galaxy sizes and angular momenta is warranted, as they provide complementary information.

5. conclusions

In this study we use cosmological zoom-in simulations of galaxy formation in an MW-sized halo to investigate the evolution of galaxy sizes, morphologies, and angular momenta in models with different parameters of the star formation—feedback loop. In particular, we focus on three runs selected from a larger set of seven runs reported in Agertz & Kravtsov (2015), which employ the model for star formation and feedback described in detail in Agertz et al. (2013).

In these three runs the star formation and feedback prescriptions are kept the same, but the local star formation efficiency per free-fall time is varied by a factor of 10, from $\epsilon_{ff} = 0.1$ in the fiducial run, motivated by observations of massive GMCs (Lada et al. 2010; Murray 2011; Evans et al. 2014), to $\epsilon_{ff} = 0.01$, matching values observed on galactic scales (Bigiel et al. 2008), in the two low star formation efficiency runs. One of the $\epsilon_{ff} = 0.01$ runs has otherwise identical parameters to the fiducial run, while in the other the energy released by SNe is increased by a factor of five relative to the fiducial value of $10^{51}$ erg. Our main results and conclusions can be summarized as follows.

1. One of the runs—the fiducial run with the star formation efficiency of $\epsilon_{ff} = 0.1$—generates vigorous large-scale feedback-driven outflows during early stages of galaxy evolution and reproduces the basic properties of observed late-type galaxies: morphology dominated by a kinematically cold disk, size of the stellar distribution, and specific angular momentum. In addition, the stellar and cold gas surface density profiles in this model are in good agreement with profiles of late-type galaxies from the THINGS sample (Leroy et al. 2008).

2. The stellar half-mass radius in the fiducial simulation evolves approximately along the observed $z = 0$ $r_{1/2}-M_*$ relation and agrees well with the $r_{1/2}-M_*$ evolution for MW-like progenitors traced back to $z \sim 2.5$ by van Dokkum et al. (2013) and Patel et al. (2013). It also roughly follows the approximately linear $r_{1/2}/R_{200c}$-relation (Kravtsov 2013), especially if we correct for effects of pseudo-evolution on the halo mass and virial radius. The evolution along the observed $r_{1/2}/R_{200c}$-relation indicates that the specific angular momentum of the galaxy in this simulation is roughly comparable to, or somewhat smaller than, the angular momentum of the dark matter halo throughout galaxy evolution.

3. Our results indicate that in the fiducial model, feedback-driven outflows delay the bulk of star formation to $z \lesssim 2$. After the last major merger, the galaxy enters an epoch of disk formation, with significant growth due to accretion from the hot gaseous halo. Here the specific angular momentum of the stars ($j_*)$ increases by an order of magnitude toward values compatible for galaxies of roughly Sa–Sab Hubble type.

4. Although the implementation of star formation and feedback in the run with inefficient local star formation ($\epsilon_{ff} = 0.01$) is identical, large-scale outflows are absent, indicating that energy and momentum injection is too weak. The resulting galaxy suffers from the well-known overcooling and angular momentum problem and does not resemble a realistic galaxy. We thus confirm
conclusions of many previous studies that efficient feedback is critical to produce realistic late-type galaxies.

5. Our results indicate that one of the roles of stellar feedback is to maintain stellar mass–halo mass fractions near or below the critical threshold for global disk instabilities. We argue (see Section 4.1) that the failure of many previous simulations in predicting the existence of late-type galaxies, with moderate or low bulge-to-disk ratios, in large part is related to the failure of maintaining the mass of the gaseous disk below such a threshold, which leads to strong bars and spiral instabilities that efficiently channel gas toward the central regions.

6. At the same time, we show that feedback can be too efficient and prevents the formation of a dominant, kinematically cold disk component. The run with \( \varepsilon_{\text{fil}} = 0.01 \), but boosted energy per SN, produces a diffuse irregular galaxy with a size much larger than a typical galaxy of that stellar mass, but with a rather low angular momentum. The galaxy in this run deviates from the observed \( M_*-r_{1/2} \) relation, which illustrates that increasingly abundant observations of the evolution of galaxy sizes will be a useful and stringent constraint on galaxy formation physics (see also Brooks et al. 2011; Aumer et al. 2014).

7. Although the galaxy produced in the fiducial run is far more realistic than the galaxy produced in the run with \( \varepsilon_{\text{fil}} = 0.01 \), but boosted energy per SN, our recent comparison of properties of circumgalactic gas in these simulations to observations presented in Liang et al. (2016) shows that the fiducial run fails to reproduce the observed CGM properties, while the run with boosted \( E_{\text{SN}} \), leading to an unrealistic galaxy, is a much closer match to the observations. This illustrates the importance of testing star formation and feedback prescriptions on the full array of available data.

Overall, the fact that the three runs in our study, differing by only a modest variation of star formation physics parameters, produce galaxies of very different size, angular momentum, and morphology within the same dark matter halo demonstrates the high sensitivity of the resulting galaxy properties to realizations of the star formation–feedback cycle (see also Okamoto et al. 2005; Scannapieco et al. 2012).

Although this sensitivity may appear to make the challenge of understanding galaxy formation daunting, we believe that there is a reasonable hope of success. First, galaxy properties in high-resolution simulations with efficient stellar feedback tend to self-regulate at the values close to observed properties of galaxies (e.g., Hopkins et al. 2011, 2014). Our results indicate this indirectly, as a galaxy with realistic properties emerges using a well-motivated set of key parameters (i.e., the fiducial run) that allows for regulation, whereas if the sensitivity to parameters was high and random, finding the region of parameter space that produces a set of realistic properties would be quite difficult. Furthermore, from the differences between our fiducial and boosted SN energy runs we can conclude that energy and momentum injection has to be concentrated in regions of high star formation efficiency in order to lead to galactic-scale outflows and realistic galaxy properties, not spread throughout the disk (see also Governato et al. 2010).

At the same time, we see that some properties, such as the circumgalactic medium or disk thickness, are sensitive to details of the star formation–feedback loop implementation and are likely even more demanding to capture in terms of numerical resolution (House et al. 2011; Crighton et al. 2015). Therefore, a careful evaluation and further development of such prescriptions warrant further attention and work.

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