ON THE INTERPLAY BETWEEN STAR FORMATION AND FEEDBACK IN GALAXY FORMATION SIMULATIONS

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ABSTRACT

We investigate the star formation–feedback cycle in cosmological galaxy formation simulations, focusing on the progenitors of Milky Way (MW)-sized galaxies. We find that in order to reproduce key properties of the MW progenitors, such as semi-empirically derived star formation histories (SFHs) and the shape of rotation curves, our implementation of star formation and stellar feedback requires (1) a combination of local early momentum feedback via radiation pressure and stellar winds, and subsequent efficient supernovae feedback, and (2) an efficacy of feedback that results in the self-regulation of the global star formation rate on kiloparsec scales. We show that such feedback-driven self-regulation is achieved globally for a local star formation efficiency per free fall time of $\epsilon_{ff} \approx 10\%$. Although this value is larger than the $\epsilon_{ff} \sim 1\%$ value usually inferred from the Kennicutt–Schmidt (KS) relation, we show that it is consistent with direct observational estimates of $\epsilon_{ff}$ in molecular clouds. Moreover, we show that simulations with local efficiencies of $\epsilon_{ff} \approx 10\%$ reproduce the global observed KS relation. Such simulations also reproduce the cosmic SFH of the MW-sized galaxies and satisfy a number of other observational constraints. Conversely, we find that simulations that priori assume an inefficient mode of star formation, instead of achieving it via stellar feedback regulation, fail to produce sufficiently vigorous outflows and do not reproduce observations. This illustrates the importance of understanding the complex interplay between star formation and feedback, and the detailed processes that contribute to the feedback-regulated formation of galaxies.

Key words: galaxies: evolution – galaxies: formation – galaxies: high-redshift – galaxies: star formation – galaxies: stellar content – methods: numerical

1. INTRODUCTION

The basic scenario of hierarchical galaxy formation (White & Rees 1978; Fall & Efstathiou 1980) has been greatly elaborated and put on a firm footing within the Cold Dark Matter paradigm during the last three decades. Although the $\Lambda$ Cold Dark Matter ($\Lambda$CDM) model has proven 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 large-scale distribution of matter in the universe (Conroy et al. 2006; Springel et al. 2006), many aspects of the theory of galaxy formation are not yet fully understood (see, e.g., Silk & Mamon 2012, for a recent review).

One of the most pressing problems in galaxy formation modeling is understanding why galaxies forming at the centers of dark matter halos are so inefficient in converting their baryons into stars. A number of different methods, such as dark matter halo abundance matching (Conroy & Wechsler 2009; Guo et al. 2010), 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 peak stellar to dark matter mass fractions of $M_*/M_h \approx 3\%–5\%$ on average for $L_*$ galaxies (e.g., Kravtsov et al. 2014), far below the cosmological baryon fraction $\Omega_b/\Omega_m \approx 16\%$ (Planck Collaboration et al. 2014).

The low galactic 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 and the bright end (Silk & Rees 1998; Benson et al. 2003). Modeling these processes in fully cosmological hydrodynamical simulations has proven to be a daunting task due to the multi-scale nature of galaxy formation, where properties of the intergalactic distribution of baryons, on scales $\gtrsim 100$ kpc, are affected by star formation and feedback processes on scales of individual star clusters ($\lesssim 1$ pc).

Although a formal spatial resolution of $\sim 10–100$ pc, comparable to the scale of massive giant molecular clouds (GMCs), is not uncommon in modern cosmological galaxy formation simulations (e.g., Kravtsov 2003; Agertz et al. 2009b; Gnedin & Kravtsov 2010; Hopkins et al. 2014), the relevant star formation and feedback processes remain “subgrid.” In particular, substantial differences in resulting galaxies may arise when different implementations and parameterizations of these processes are used in simulations, even when the same initial conditions are used (Governato et al. 2010; Scannapieco et al. 2012).

Implementations of stellar feedback in galaxy formation simulations have been explored in many studies over the last two decades (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, 2012; 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. 2012; Booth et al. 2013; Stinson et al. 2013; Ceverino et al. 2014; Christensen et al. 2014; Roškar et al. 2014). Nevertheless, we still do not have a full understanding of what processes matter
most for suppressing star formation and driving galactic winds over the vast range of observed galaxy masses.

Recent studies (Leitner 2012; Weinmann et al. 2012; Behroozi et al. 2013; Moster et al. 2013) have shown that not only is galaxy formation an inefficient process, but also that star formation in the progenitors of most galaxies ($L \lesssim L_\star$) is significantly suppressed during the first 3 Gyr of cosmic evolution. van Dokkum et al. (2013) recently reached a similar conclusion by matching cumulative co-moving number densities in the 3D-Hubble Space Telescope and CANDELS Treasury surveys, demonstrating that ~90% of the stellar mass in Milky Way (MW)-mass galaxies formed after $z \sim 2.5$.

Much effort has gone into reproducing the $z = 0$ $M_\star - M_b$ relation over a large range of galaxy masses in simulations with efficient feedback (e.g., Munshi et al. 2013). At the same time, predicting its evolution, and hence reproducing the significant suppression of star formation necessary at $z \gtrsim 2$ has proven more difficult. Brook et al. (2012) and Stinson et al. (2013) discussed the importance of “early feedback” in their smoothed particle hydrodynamics (SPH) simulations, here modeled by assuming that 10% of the bolometric luminosity radiated by young stars get converted into thermal energy. This large energy injection resulted in star formation histories (SFHs) consistent with the data of Moster et al. (2013). Similar results were found by Aumer et al. (2013), who considered a momentum based model of radiation pressure, although with the value of the infrared optical depth of $\tau_{IR} \sim 25$, larger than in the models by Hopkins et al. (2011) and Agertz et al. (2013). Ceverino et al. (2013), Trujillo-Gomez et al. (2015), and Hopkins et al. (2014) also found that radiative feedback, both due to photoionization and radiation pressure, could play an important role in low-mass galaxies (here progenitors of galaxies with $M_\text{vir}(z = 0) \lesssim 10^{12} M_\odot$) at high redshifts, even for more moderate values of photon trapping by dust.

While suppression of star formation in simulations of galaxy formation via strong stellar feedback has been widely explored in the recent literature, freedom in the way in which star formation in the interstellar medium (ISM) is modeled has received less attention. Recent work by Gnedin et al. (2009, see also Gnedin & Kravtsov 2010, 2011; Kuhlen et al. 2012; Christensen et al. 2014) demonstrated how a star formation model based on the local abundance of H$_2$ could explain the observed steepening for $\Sigma_{\text{gas}} < 100 M_\odot pc^{-2}$ in the Kennicutt–Schmidt (KS) relation for $z \approx 3–4$ damped Ly$\alpha$ systems and Lyman Break Galaxies (LBGs). Governato et al. (2010) found that a high threshold for star formation, in conjunction with higher resolution and strong feedback, can lead to more correlated feedback events and a more realistic halo baryon fraction. These results illustrate that it is paramount to explore how parameters of the star formation recipe and feedback implementation affect basic properties of galaxies forming in a given halo.

In this paper we present the results of a systematic study of such dependencies using high-resolution, cosmological simulations of the MW-sized progenitors that include our new model for stellar feedback described in Agertz et al. (2013). We specifically explore how the interplay between various modes of star formation and feedback models affects galactic characteristics at $z \gtrsim 1$. The paper is organized as follows: in Section 2 we outline our numerical method as well as star formation and feedback models. In Section 3 we discuss the empirical constraints on the efficiency of star formation in molecular clouds—one of the most important parameters in our implementation of the star formation-feedback cycle, and show that observations often indicate an efficiency in massive star-forming clouds that is considerably larger than implied by the global normalization of the KS relation. Section 4 describes the initial conditions and the simulation suite. In Section 5 we present our suite of cosmological simulations and demonstrate how two different models of star formation and feedback can match several observational properties of galaxies, including the SFH, the total stellar mass expected from abundance matching, average gas metallicity, and the rotational velocity. In Section 6 we discuss how the degeneracy between the two parameterizations can be broken, and show how only the simulation with efficient stellar feedback together with a high local efficiency of star formation can reproduce all the observed properties of galaxies. Finally, we discuss our results and conclusions in Sections 7 and 8.  

2. NUMERICAL CODE

We carry out cosmological hydro+N-body simulations using the Adaptive Mesh Refinement (AMR) code RAMSES (Teyssier 2002). The fluid dynamics of baryons is calculated using a second-order unsplit Godunov method, while the collisionless dynamics of stellar and dark matter particles is evolved using the particle-mesh technique, with gravitational accelerations computed from the gravitational potential on the mesh. The gravitational potential is calculated by solving the Poisson equation using the multi-grid method (Brandt 1977; Guillet & Teyssier 2011) for all refinement levels. The potential is used to compute accelerations for both the particles and the baryon fluid. The equation of state of the fluid is that of an ideal mono-atomic gas with an adiabatic index $\gamma = 5/3$.

The code achieves high resolution in high density regions using AMR, where the refinement strategy is based on a quasi-Lagrangian approach in which the number of collisionless particles per cell is kept approximately constant. This allows the local force softening to closely match the local mean interparticle separation, which supresses discreteness effects (e.g., Knebe et al. 2000; Romeo et al. 2008). An analogous refinement criterion is also used for the gas.

2.1. Star Formation

We model the local star formation rate (SFR) using the following equation:

$$\dot{\rho}_\star = f_{H_2} \rho_g / t_{\text{SF}},$$

where $f_{H_2}$ is the local mass fraction of molecular hydrogen (H$_2$), $\rho_g$ is the gas density in a cell, and $t_{\text{SF}}$ is the star formation timescale of molecular gas. In Section 2.2 we describe the model we use to calculate $f_{H_2}$. The timescale $t_{\text{SF}}$ is defined by the efficiency of star formation, which, as we show below, is one of the key parameters controlling the basic properties of galaxies forming in a given halo and the efficacy of stellar feedback. Given its importance, we will discuss the empirical constraints and our choices for the value of this parameter in our simulations in Section 3 below.

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Footnote: Feedback that operates at times before the first SNe explosions, i.e., $t \lesssim 4$ Myr, for a coeval stellar population.
To ensure that the number of star particles formed during the course of a simulation is tractable, we sample Equation (1) stochastically at every fine simulation time step $\Delta t$ (see Section 2.3 in Agertz et al. 2013, for details). We also adopt a temperature threshold by only allowing star formation to occur in cells of $T < 10^4$ K, although we find that this threshold has no actual impact on the resulting SFRs.

By adopting the kind of star formation relation in Equation (1), we avoid imposing a fixed, and perhaps arbitrary, star formation density threshold, as is common in the galaxy formation community. We explore the difference between the constant density threshold approach and the molecular hydrogen based star formation model further Appendix. As described in Section 1, relating star formation to the molecular gas is empirically well-motivated, as galactic SFR surface densities correlate 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 kpc scales (Bigiel et al. 2008; Gnedin et al. 2009; Krumholz et al. 2009b).

2.2. Molecular Hydrogen Model

To capture the physics of molecular gas in our simulations, which is a key ingredient in our star formation model (see Section 2.1), we adopt the KMT09 model, which we briefly discuss in this section. Molecular hydrogen forms readily when dust grains are present, but the abundance is very sensitive to the destruction by UV radiation. Krumholz et al. (2008, 2009a) and McKee & Krumholz (2010) developed a model for the abundance of H$_2$ based on radiative transfer calculations of idealized spherical giant molecular–molecular complexes subject to a uniform and isotropic Lyman–Werner (LW) radiation field. When the H$_2$ abundance is calculated assuming formation–dissociation balance, the solution can conveniently be expressed as

$$ f_{H_2} \simeq 1 - \frac{3}{4} \frac{s}{1 + 0.25 s}, \quad \text{(2)} $$

$$ s = \frac{\ln \left( 1 + 0.6 \chi + 0.01 \chi^2 \right)}{0.6 \tau_c}, \quad \text{(3)} $$

$$ \chi = 71 \left( \frac{\sigma_{d,21}}{R_{-16.5}} \right) \frac{G'_0}{n_{H}}, \quad \text{(4)} $$

where $\tau_c$ is the dust optical depth of the cloud, $\sigma_{d,21}$ is the dust cross-section per hydrogen nucleus to radiation at 1000 Å normalized to $10^{-21}$ cm$^2$, and $n_{H}$ is the volume density of hydrogen nuclei in units of cm$^{-3}$. The coefficient $R_{-16.5}$ is the rate for H$_2$ formation on dust grains, normalized to the MW value of $10^{-16.5}$ cm$^3$ s$^{-1}$ (see Wolfire et al. 2008), and $G'_0$ is the ambient UV radiation field intensity, normalized to the Draine (1978) value for the MW. As both $\sigma_d$ and $R$ are linearly proportional to the dust abundance, and hence gas metallicity, their ratio in $\chi$ becomes independent of metallicity.

The equations above can be simplified further by assuming pressure equilibrium between the cold and warm neutral medium (CNM and WNM respectively). Krumholz et al. (2009a) demonstrated that the assumption of pressure balance between the two gas phases causes the minimum CNM density to be linearly proportional to the UV radiation field:

$$ n_{\text{min}} \approx \frac{31}{1 + 3.1 Z_{g}^{0.365}} G'_0. \quad \text{(5)} $$

where $Z_g$ is the gas metallicity in units of solar metallicity, and $Z_{g} = 0.020$. By allowing for the CNM density to be larger than the minimum density by a factor $\phi_{\text{CNM}}$, i.e., $n_{H} = \phi_{\text{CNM}} n_{\text{min}}$, Equation (4) becomes

$$ \chi = 2.3 \left( \frac{\sigma_{d,21}}{R_{-16.5}} \right) \frac{1 + 3.1 Z_{g}^{0.365}}{\phi_{\text{CNM}}}. \quad \text{(6)} $$

As seen in the equation above, the molecular hydrogen mass fraction becomes independent of the local LW intensity. Krumholz & Gnedin (2011) found that the two-phase approximation predicts the H$_2$ abundance accurately compared to full non-equilibrium radiative transfer calculations for $Z_g > 10^{-2} Z_\odot$.

In the remainder of the paper we refer to the above model, including the two-phase CNM-WNM equilibrium assumption, as the KMT09 model. The KMT09 model was adopted in fully cosmological simulations of galaxy formation by Kuhlen et al. (2012, 2013) (see also Tomassetti et al. 2015), who demonstrated how the model led to a strong suppression of star formation in low-mass halos ($M_{\odot} \lesssim 10^{10} M_{\odot}$) at $z > 4$, in agreement with galaxy formation simulations of Gnedin & Kravtsov (2010) which used full non-equilibrium calculations of H$_2$ abundance.

2.3. Feedback

The stellar feedback model adopted in our simulations is described in detail 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 (IMF). Several processes are contributing to stellar feedback, as stars inject energy, momentum, mass, and heavy elements over time via SNI and SNIa explosions, stellar winds, and radiation pressure into the surrounding gas. Hence, at every simulations time step, and for every stellar particle, we account for the following energy, momentum, mass loss, and metal injection rates:

- **Energy:** $\dot{E}_{\text{tot}} = \dot{E}_{\text{SNII}} + \dot{E}_{\text{SNIIa}} + \dot{E}_{\text{wind}}$
- **Momentum:** $\dot{p}_{\text{tot}} = \dot{p}_{\text{SNII}} + \dot{p}_{\text{wind}} + \dot{p}_{\text{rad}}$
- **Massloss:** $\dot{m}_{\text{tot}} = \dot{m}_{\text{SNII}} + \dot{m}_{\text{SNIIa}} + \dot{m}_{\text{wind}} + \dot{m}_{\text{loss}}$
- **Metals:** $\dot{m}_{Z,\text{tot}} = \dot{m}_{Z,\text{SNII}} + \dot{m}_{Z,\text{SNIIa}} + \dot{m}_{Z,\text{wind}} + \dot{m}_{Z,\text{loss}}$. \quad \text{(7)}

Each term in the above equations depends on the stellar age, mass, and gas/stellar metallicity, all accounted for and described in Agertz et al. (2013). Feedback is thus not done instantaneously, but continuously at the appropriate times when the various feedback processes are 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 approximation of the metallicity dependent age-mass relation of Raiteri et al. (1996), obtained as a fit to the results of the Padova stellar evolution models (Alongi et al. 1993; Bressan et al. 1993).
The effect of radiation pressure is modeled as a direct injection of momentum to the cells surrounding newly formed star particles. Here the momentum injection rate from radiation can be written as

\[ \dot{p}_{\text{rad}} = \left( \eta_1 + \eta_2 \tau_{\text{IR}} \right) \frac{L(t)}{c}, \]

where \( \tau_{\text{IR}} \) is the infrared optical depth and \( L(t) \) is the luminosity of the stellar population, here taken from the stellar evolution code STARBURST99 (Leitherer et al. 1999). The first term describes the direct radiation absorption/scattering, and given the large dust and HI opacities in UV present in dense star-forming regions, \( \eta_1 \approx 1 \). The second term describes the momentum transferred by infrared photons re-radiated by dust particles, and scattered multiple times by dust grains before they escape, where \( \eta_2 \) is added to scale the fiducial value of \( \tau_{\text{IR}} \).

Following Agertz et al. (2013), we adopt \( \eta_2 = 2 \). As cosmological simulations cannot resolve the density structure around young massive star clusters on sub-parsec scales, to estimate \( \tau_{\text{IR}} \) we use the empirically motivated subgrid model described in Agertz et al. (2013).

The momentum due to stellar winds, radiation pressure, and SN blastwaves is added to the 26 nearest cells surrounding parent cell of the stellar particle. The thermal energy due to SNe and shocked stellar winds is injected directly into the parent cell.

In most of our simulations 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 previously by Teyssier et al. (2013), 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, or a placeholder for other sources of energy, such as turbulence and cosmic rays (CRs) (Booth et al. 2013).

As described in Section 3.2 of Agertz et al. (2013), at each time step \( \Delta t \) we inject a fraction \( f_{\text{fb}} \) of the calculated feedback energy into a separate energy variable, \( E_{\text{fb}} \), and the remaining energy fraction, \( 1 - f_{\text{fb}} \), is released as thermal energy into the main energy variable. In this work we adopt \( f_{\text{fb}} = 0.5 \). \( E_{\text{fb}} \) has units of energy per unit volume and evolves according to the following equation:

\[ \frac{\partial}{\partial t} (E_{\text{fb}}) + \nabla \cdot (E_{\text{fb}} v_{\text{gas}}) = -P_{\text{fb}} \nabla \cdot v_{\text{gas}} - \frac{E_{\text{fb}}}{t_{\text{dis}}} \]

Note that \( E_{\text{fb}} \) refers to the variable followed by the above equation, not to be confused with \( E_{\text{SNII}} \) which denotes the energy released by Type II SNe. In the momentum equation, the thermal pressure \( P_{\text{therm}} \) is replaced by the total pressure \( P_{\text{tot}} = P_{\text{therm}} + P_{\text{fb}} \), where \( P_{\text{fb}} = (\gamma - 1)E_{\text{fb}} \). To achieve numerical stability, the Courant–Friedrichs–Lewy condition is also updated to account for the sound speed related to the new total pressure when computing the simulations time step \( \Delta t \).

\[ \text{stellar feedback is vigorous, we find that } \Delta t \text{ can be as low as } \sim 500–1000 \text{ yr}. \]

As seen from Equation (9), the feedback energy is thus continuously dissipated over a timescale \( t_{\text{dis}} \), i.e.,

\[ E_{\text{fb}}^f = E_{\text{fb}}^i \exp (-\Delta t/t_{\text{dis}}). \]

We make the assumption that the dissipation timescale is comparable to the decay time of supersonic turbulence, which is of order of the flow crossing time (Ostriker et al. 2001). In all of the simulations presented in this paper, we adopt a fixed \( t_{\text{dis}} = 10 \text{ Myr} \), typical for a few crossing times in massive GMCs (\( t \sim 10–100 \text{ pc} \)), or the vertical crossing time in cold galactic disks, with characteristic velocity dispersions \( \sigma_v \sim 10 \text{ km s}^{-1} \).

Heavy elements (metals) injected by supernovae and winds are advected as a passive scalar and are incorporated self-consistently in the cooling and heating routine. We adopt the tabulated cooling functions of Sutherland & Dopita (1993) for cooling at temperatures \( 10^4–10^8 \text{ K} \), and extend cooling down to \( T = 300 \text{ K} \) using rates from Rosen & Bregman (1995). Heating from the UV background (UVB) radiation is accounted for by using the UVB model of Haardt and Madau (1996), assuming a reionization redshift of \( z = 8.5 \). We follow Agertz et al. (2009b) and adopt an initial metallicity of \( Z = 10^{-3} Z_\odot \) in the high-resolution region (see Section 4) in order to account for enrichment from unresolved Pop III stars (e.g., Wise et al. 2012); their effect needs to be accounted for as it allows for the first molecular hydrogen to be synthesized in high-z galaxy progenitors, hence initiating star formation. Note that the dependence of \( f_{\text{fb}} \) on metallicity at \( Z/Z_\odot \lesssim 10^{-2} \) is not known and is subject to effects such as LW band line overlap (Gnedin & Draine 2014). Thus, our assumption about the metallicity floor is within the uncertainties of the Population III SNe and \( f_{\text{fb}} \) modeling.

3. EFFICIENCY OF STAR FORMATION

The star formation timescale of molecular gas, \( t_{\text{SF}} \), in our adopted star formation relation (Equation (1)) is related to the local efficiency of star formation in a computational cell of a given density. Following Krumholz & Tan 2007, we can write this timescale as \( t_{\text{SF}} = t_{\text{fi}, \text{SF}}/t_{\text{ff}, \text{SF}} \). where \( t_{\text{fi}, \text{SF}} = \sqrt{3\pi/32G\rho_{\text{ff}}} \) is the local free-fall time of the star-forming gas and \( t_{\text{ff}, \text{SF}} \) is the local star formation efficiency free-fall time. As we show below, the basic properties of galaxies forming in a given halo, and the degree to which these properties are affected by stellar feedback, depend sensitively on the value of \( t_{\text{SF}} \) or \( t_{\text{ff}, \text{SF}} \). It is therefore important to discuss the motivation behind particular values of this parameter that we adopt in our simulations.

Star formation overall, and the efficiency with which a given molecular region converts its gas mass into stars, is not yet fully understood theoretically. Nevertheless, useful empirical constraints do exist, and a plethora of theoretical models predicting the star formation efficiency have been developed over the last decade (Padoan et al. 2014).

On global, kiloparsec scales observational measurements show that the gas consumption timescale of molecular gas is \( t_{\text{H}_2, \text{gal}} \approx 2 \text{ Gyrs} \) (Bigiel et al. 2008). If \( \epsilon_{\text{ff}} \) had a universal value in all of the molecular gas, and molecular gas had a common characteristic free-fall time, we would expect a direct relation between the global molecular gas consumption timescale and the local gas consumption time in star-forming clouds, i.e.,

\[ t_{\text{SF}} \approx t_{\text{H}_2, \text{gal}} \text{ and thus } \epsilon_{\text{ff}, \text{SF}} \approx t_{\text{ff}, \text{SF}}/t_{\text{H}_2, \text{gal}}. \]
estimates of the local efficiency, $\epsilon_{\text{ff, GMC}}$, in star-forming clouds indicates that $t_{\text{ff, GMC}}$ is much larger than $t_{\text{ff, SF}}$, and thus a significant fraction of molecular gas is not star-forming, or forms stars with an extremely low efficiency. This is corroborated by measurements of the molecular gas consumption timescale distribution of molecular gas in patches of 12 pc radius in the SMC by Bolatto et al. (2011). The typical consumption timescale for molecular gas is indeed several billion years, and a high star formation efficiency is reached only in a small fraction of molecular patches.

These considerations indicate that the local value of $\epsilon_{\text{ff, SF}}$ in star-forming regions on small scales does not have to correspond to the global value implied by the molecular gas consumption timescale on kiloparsec scales and can be significantly larger. In our study we therefore consider a range of values of $\epsilon_{\text{ff}}$ from 0.01 to 0.1, consistent with the empirical estimates of this efficiency in GMCs shown in Figure 2.

4. INITIAL CONDITIONS AND SIMULATION SUITE

The initial conditions used in this work are identical to those presented in Agertz et al. (2011). In summary, we adopt a WMAP5 (Komatsu et al. 2009) compatible $\Lambda$CDM cosmology with $\Omega_{\Lambda} = 0.73$, $\Omega_m = 0.27$, $\Omega_b = 0.045$, $\sigma_8 = 0.8$, 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 re-simulation 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 a 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 $z = 1$, 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 the 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 $m_{\text{DM}} = 3.2 \times 10^5 M_\odot$, and the adaptive mesh is allowed to refine if a cell contains more than eight dark matter particles, and a similar criterion is employed for the baryonic component. At the maximum level of refinement, the simulations reach a physical resolution of $\Delta x \approx 75$ pc.

4.1. Simulation Suite

The main focus of this work is to investigate the interplay between star formation and feedback. To this end, we carry out a suite of simulations targeting a number of different regimes; (1) no stellar feedback from young stars, (2) all sources of stellar feedback are operating (as discussed in Section 2.3), (3) the impact of neglecting radiative feedback; and (4) the impact of making SN energy feedback less efficient by not tracking it as a separate fluid variable.
For the first two regimes we also study the impact of varying the efficiency of star formation per-free-fall time (see Section 2.1) using simulations with $\epsilon_{ff} = 1\%$ and $10\%$. The lower efficiency is closer to the value derived from the gas consumption timescale in kpc-sized patches of the ISM (see Section 3 above). However, the relevant values of $\epsilon_{ff}$ for GMCs as a function of environment are not fully understood, as we discussed above in Section 3 (see Figure 2). Simulating galaxy formation using a larger efficiency of $\epsilon_{ff} = 10\%$ is thus motivated by GMC observations and allows us to study the ability of stellar feedback to regulate the measured efficiency of globally observed values.

Our fiducial simulations include all feedback processes discussed above, including the second energy variable and star formation efficiency of $\epsilon_{ff} = 10\%$. For the case of $\epsilon_{ff} = 1\%$, we also investigate the effect of increasing the available feedback energy from SNII events, going from the fiducial $E_{SNII} = 10^{51}\text{erg}$ to $5 \times E_{SNII}$. Such an increase could correspond to a somewhat more top heavy IMF.

In the Appendix we compare the results from our simulations with $\text{H}_2$ based star formation with similar simulations in which star formations are assumed to proceed at densities above a fixed density threshold. For the latter simulation we adopt a density threshold of $f_{\text{H}_2} \sim 50\%$ at $Z_e = Z_{\odot}$. We note that this threshold value is lower than the value adopted in the Eris simulation (Guedes et al. 2011), where $n_e = 5 \text{cm}^{-3}$ was used, although close to the $n_e = 20 \text{cm}^{-3}$ adopted for the followup Eris2 simulation.

The entire simulation suite, and the associated star formation and feedback parameters, is summarized in Table 1.

5. RESULTS

In this section we present a detailed analysis of a number of basic galaxy properties at $z \gtrsim 1$, relevant for star-forming MW analogues that ought to be reproduced by simulations of galaxy formation: the SFH, the stellar mass–dark matter halo mass ($M_* - M_h$) relation, the KS ($\Sigma_{\text{gas}} - \Sigma_{\text{SFR}}$) relation, and the stellar mass–gas metallicity ($M_* - Z_{\text{gas}}$) relation. Furthermore, we study the ability of our models to predict rising or flat rotation curves, a key ingredient in explaining the observed Tully–Fisher relation (galaxy luminosity versus disk circular velocity; Tully & Fisher 1977) for extended spiral galaxies (Reyes et al. 2012).

5.1. A Qualitative Comparison

In Figure 3 we show large-scale maps of the gas surface density, mass-weighted temperature, gas metallicity, and stellar surface density, at $z = 3$, for four of our simulations: ALL_Efb_e010, ALL_Efb_e001, ALL_Efb_e001_5ESN, and ALL_e010 (see Table 1). From the first two simulations, which only differ in their choice of star formation efficiency per free fall time, we find a dramatic difference in outflow properties; for $\epsilon_{ff} = 10\%$, galactic winds eject enriched gas from the turbulent galactic disk, while no signs of outflows can be seen when $\epsilon_{ff} = 1\%$. In the latter case, almost all metals are retained in the cold star-forming gas disk, as is the case for simulations neglecting feedback. The stellar distribution in this simulation is also significantly more compact compared to the other runs.

Furthermore, the size of the hot gaseous halo surrounding the main progenitor differs between the simulations; in models with inefficient or no feedback, the hot halo forms via cosmological accretion shocks or shocks generated via rapid gravitational potential fluctuations. At $r \sim 50 \text{kpc}$, which is close to the virial radius at this redshift, the temperature drops off to $T < 10^5 \text{K}$. In contrast, in simulations with strong feedback-driven winds, the gas outflows contribute significantly to pressurizing the hot halo and driving the outer shock. The hot ($T \gtrsim 10^6 \text{K}$) halo in such simulations extends far beyond the virial radius of the main dark matter halo.

Boosting the feedback energy per supernova by a factor of five for the case of $\epsilon_{ff} = 1\%$ radically changes the mode of galaxy formation, and similar metal enriched outflows and turbulent gas disk morphology as for our fiducial simulations is recovered, at least qualitatively. This shows that there is a certain degeneracy between the star formation efficiency and feedback strength, and a quantitative comparison with observations may be necessary to separate the models.

We find that neglecting specific sources of stellar feedback leads to significant differences in galaxy evolution. For example, in the simulation shown in the rightmost column of Figure 3 we do not include the second feedback energy variable, $E_{\text{fb}}$, while keeping the rest of the parameters the same as in our fiducial simulation (the leftmost panel). While metal-rich outflows are still present, the gaseous disk is significantly less turbulent and is more compact, with less neutral gas extending to large distances ($\sim 10 \text{kpc}$ in the fiducial run), as seen in the temperature map. This results in a more massive stellar system, which as we demonstrate below is in tension with semi-empirically derived stellar mass-halo mass relations (Behroozi et al. 2013). A similar conclusion holds for the simulations that neglect radiation pressure.
5.2. Star Formation Histories

Figure 4 shows the SFHs, calculated in bins of \( \Delta t = 100 \text{ Myr} \), for the simulated galaxies compared to the semi-empirically inferred SFH from Behroozi et al. (2013) relevant for a galaxy forming in a \( M_{\text{vir}}(z = 0) = 10^{12} M_\odot \) dark matter halo. Regardless of the choice of star formation efficiency per free fall time, neglecting feedback leads to a dramatic overestimate of the galactic SFR at all redshifts by \( \geq 1 \text{ dex compared to the predictions by Behroozi et al. (2013)} \). This may seem counterintuitive as the lower abundance of \( \text{H}_2 \) in dwarf galaxies at high redshifts is thought to make star formation less efficient. However, as the ISM self-enriches via SNe, and no stellar feedback is present to drive metal-rich winds, a larger fraction of the gas mass rapidly becomes available for star formation due to the effectively lower density threshold via the higher \( f_{\text{ff}} \); see Section 2.2. As mentioned above, this is the case regardless of the adopted value for \( \epsilon_{\text{ff}} \), although the normalization of the relation at \( z > 4 \), and hence how rapidly the galaxy self-enriches, depends on the precise value.

Simply incorporating efficient stellar feedback (Section 2.3) in the KMT09 model does not necessarily overcome this problem. The simulation with \( \epsilon_{\text{ff}} = 1\% \) overpredicts the SFRs by up to a factor of ten and the SFR in this case is not significantly affected by feedback. For star formation to be sufficiently feedback regulated, the local star formation efficiency per free fall time needs to be sufficiently large, here \( \epsilon_{\text{ff}} = 10\% \). Once this is satisfied, the simulations are in excellent agreement with the data of Behroozi et al. (2013).

In a star formation model based on the abundance of \( \text{H}_2 \), such as KMT09, the gas metallicity plays an important role in setting the fraction of gas available for star formation. The local metallicity, in turn, is regulated by the feedback-driven outflows. In our current simulation suite, this only occurs if star formation, and hence feedback, becomes sufficiently spatially and temporally correlated. As we show in Section 5.4, the simulations with efficient wind driving also match the observed evolution of the relation between stellar mass and gas metallicity.

Star formation suppression can also be achieved by increasing the available SN thermal energy budget, here illustrated by employing a boost by a factor of five for the run with \( \epsilon_{\text{ff}} = 1\% \). The resulting SFH agrees almost perfectly with the less energetic, but self-regulated, fiducial simulation at \( z \geq 3 \). As discussed in Section 5.1, this illustrates a certain degeneracy between the details of star formation and feedback prescriptions in such simulations, which needs to be broken by other observables, especially because the feedback boosted simulation severely distorts the gas disk at \( z < 2 \), as seen in Figure 9.

In Figure 4 we also show the impact of neglecting various sources of stellar feedback in our fiducial simulation. By not considering radiation pressure feedback, SFRs increase by a factor of several at all redshifts, as found in Agertz et al. (2013) for isolated disks. Reducing the efficiency of thermal feedback by neglecting the feedback energy variable significantly increases the SFRs at \( z > 4 \), while bringing them into agreement with the Behroozi data at later times. This behavior stems from the inability of radiative feedback to efficiently regulate star formation in low metallicity gas at high redshifts, as photon trapping via dust becomes negligible, whereas this is not the case in the more enriched disk at late times. This collective and highly nonlinear behavior of early radiative feedback and SNe, was recently studied in a fully cosmological setting by Hopkins et al. (2014) who also found that it was necessary to consider these two feedback processes jointly in order to reproduce observationally derived SFHs.

5.3. The Stellar Mass–Halo Mass Relation

In Figure 5 we show the stellar mass fraction \( (M_*/M_z) \) versus halo mass relation for the simulated galaxies. The shaded regions show the inferred 2\( \sigma \) relations for \( z = 3, 2, 1 \), from Behroozi et al. (2013). For consistency with Behroozi
et al. (2013), we use the virial mass definition of Bryan & Norman (1998) to define the halo mass of the progenitor. The $M_\star/M_h$ evolutionary tracks are shown for all simulations at $z \gtrsim 1$, wherever simulation data exists. We note that the $M_\star/M_h$ relation on occasion rapidly evolves vertically, or that $M_h$ even decreases temporarily. This behavior stems from major merger events, which not only boosts star formation, but can complicate measurements of the halo virial mass.

Note that the $M_\star/M_h$ relation and SFHs in the previous section are not independent constraints. Indeed, simulations that also match the inferred SFHs in the previous section are in good agreement with the predicted stellar mass fractions, i.e., runs employing $\epsilon_f = 10\%$ and/or efficient feedback (ALL_Efb_e010 and ALL_Efb_e001_5ESN). Inefficient local star formation ($\epsilon_f = 1\%$) overpredicts the stellar content by an order of magnitude, while in runs in which feedback is neglected the stellar fraction is close to the mean cosmic baryon fraction at all times.

The interplay between radiation pressure and efficient thermal feedback in establishing a realistic stellar mass fraction is illustrated whenever either one of these sources is removed from the feedback budget; the stellar fraction is suppressed to a much greater degree at late times (i.e., more massive dark matter halos) when $E_{fb}$ is neglected, and the opposite is true when radiation pressure is neglected.

Figure 3. Maps of, from top to bottom, gas surface density, mass-weighted temperature, gas metallicity, and stellar surface density for, from left to right, ALL_Efb_e010, ALL_Efb_e001, ALL_Efb_e001_5ESN, and ALL_e010 at $z = 3$. The maps show regions 90 kpc on each side. All simulations, apart from ALL_Efb_e001, show clear signatures of outflows. As discussed in the text, the low input free-fall time efficiency of star formation ($\epsilon_f = 1\%$) does not allow for local feedback to be vigorous enough to generate galactic winds.
5.4. The Mass–Metallicity Relation and Effective Yields

Figure 6 shows the stellar mass–gas metallicity \((M_\ast-Z_{\text{gas}})\) relation for the simulated galaxies at \(z=2-2.5\) and \(z=3-4\). Note that the gas metallicity plotted in the figure is measured for the cold gas component of the galaxies. We compare the simulations with observational data of galaxies at \(z\sim0.07\) (as inferred by Kewley & Ellison 2008), \(z\sim2.2\) (Erb et al. 2006), and \(z\sim3.5\), where a uniform calibration of metallicity indicators was used across all redshifts (Maiolino et al. 2008). In order to compare the data to the observational aperture adopted by Maiolino et al. (2008), we quantify the gas metallicity as the mass-weighted mean metallicity at radii \(r \leq 3\) kpc. The stellar mass is the total stellar mass for \(r \leq 10\) kpc, which safely contains all stellar mass belonging to the central galaxies at all redshifts under investigation. As we only track the average metallicity of the gas in RAMSES, we calculate \(12 + \log(O/H)\) assuming solar mixture and adopt \(12 + \log(O/H)\) for the solar value (Asplund et al. 2009).

From Figure 6 we find that not matching the SFH, \(M_\ast/M_{\text{halo}}\), and KS relations in the previous sections may still allow the galaxy to conform to the observed \(M_\ast-Z_{\text{gas}}\) relation at \(z>2-3\). The fact that the \(M_\ast-Z\) relation is determined primarily by the overall efficiency of galactic star formation, and not necessarily via properties of feedback-driven outflows, has been emphasized before (Brooks et al. 2007; Tassis et al. 2008). The almost 2 dex spread in stellar mass \((8.5 < M_\ast < 10.5)\) in the simulation suite measured at \(z=3-4\) forms a steeper linear relation, \(12 + \log(O/H)=7.5 + \log(M_\ast/10^9 M_\odot)\). Individual simulations, e.g., the favored ALL_Efb_e010 run, trace a more shallow relation over the same redshift range. When \(\epsilon_{\text{fl}}=1\%\) (ALL_Efb_e001), or no feedback is present, star formation is not efficiently regulated, leading to increasing stellar masses and metallicities that eventually causes the galactic average to diverge from the mean relation at lower redshifts. However, as the \(z\sim2-2.5\) data (Erb et al. 2006) form a steeper relation than that at \(z\sim0\), meaning the metallicities at the high stellar mass end show a weaker evolution, these particular simulations are not in strong disagreement with observations below \(z\sim2\).

The fiducial simulation (ALL_Efb_e010) is in excellent agreement with observations at all times. In the case of boosted SNe feedback energy (ALL_Efb_e001), gas metallicities are lower at all redshifts, possibly in tension with observed gas metallicities at \(z\sim2-2.5\), although at the low stellar masses under consideration \((M_\ast\sim3\times10^9 M_\odot)\) the metallicity measurements are only upper limits. At \(z=0\), the fiducial model shows a high central metallicity, but is still in broad agreement with observations, while the boosted feedback energy model is metal deficient and lies close to the high redshift \((z\sim2-2.5)\) relation.

Even though neglecting radiation pressure overestimates stellar masses, see Section 5.3, the enrichment history allows the galaxy to evolve “along” the evolving \(M_\ast-Z_{\text{gas}}\) relation. This is not the case when the second feedback energy variable \(E_{\text{sh}}\) is neglected, as the metal-rich gas disk can be seen to evolve off the observed relation already at \(z\sim4\), illustrating the need in our current models for efficient thermal feedback to regulate the galactic metal content, at least at this specific epoch.

5.4.1. Effective Yields

To better understand the role of metal-rich outflows, we calculate effective yield, defined as

\[
y_{\text{eff}} = \frac{Z_{\text{gas}}}{\ln \left(1/f_{\text{gas}}\right)},
\]

where the shaded regions show, from dark to light gray, the \(z=3, 2, 1\) data from Behroozi et al. (2013) where a uniform calibration of metallicity indicators was used across all redshifts (Maiolino et al. 2008). In order to compare the data to the observational aperture adopted by Maiolino et al. (2008), we quantify the gas metallicity as the mass-weighted mean metallicity at radii \(r \leq 3\) kpc. The stellar mass is the total stellar mass for \(r \leq 10\) kpc, which safely contains all stellar mass belonging to the central galaxies at all redshifts under investigation. As we only track the average metallicity of the gas in RAMSES, we calculate \(12 + \log(O/H)\) assuming solar mixture and adopt \(12 + \log(O/H)\) for the solar value (Asplund et al. 2009).

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\[
y_{\text{eff}} = \frac{Z_{\text{gas}}}{\ln \left(1/f_{\text{gas}}\right)},
\]
where \( f_{\text{gas}} = M_{\text{gas}}/(M_{\text{gas}} + M_*) \) is the fraction of baryons in the gas phase. The effective yield has been widely used as a diagnostic of the evolution of the baryonic component of galaxies, and more specifically as a test of the validity of the closed-box approximation (Pagel & Patchett 1975; Edmunds 1990). Observationally, the effective yield is known to decrease with galactic mass (Tremonti et al. 2004), with a sharp decline around the mass of dwarf galaxies (\( v_{\text{rot}} \lesssim 100 \text{ km s}^{-1} \); Garnett 2002).

Under the closed-box assumption, the effective yield is always equal to the true yield \( \epsilon_{\text{true}} \), typically defined, for a single stellar population, as the mass in newly synthesized metals returned to the ISM normalized to the stellar mass of this population locked up in stellar remnants and long-lived stars, i.e.,

\[
\epsilon_{\text{true,rem}} = \frac{1}{1 - R} \int_0^{100} m \phi(m) dm,
\]

where \( m \) is the stellar mass, \( \phi(m) \) the IMF, \( p_{\text{im}} \) is the instantaneous stellar yield, and \( R \) the mass fraction returned to the ISM. For our feedback prescription we calculate the true yield, \( \epsilon_{\text{true,init}} \), where we consider \( R = 0 \), i.e., the stellar population is assumed to retain all of its initial birth mass.

Following Tassis et al. (2008), we calculate the “observed” effective yield as a function of total baryon mass in our main galaxy using Equation (10), where we consider only the cold gas \( (T \leq 10^3 \text{ K}) \) and the metal content within the stellar extent defined as the radius that includes 90% of the total stellar mass. The result for the entire simulation suite, over the redshift range \( z = 1-7 \), is presented in Figure 7. Our fiducial simulation \( \text{ALL\_Efb\_e010} \) shows a clear plateau toward the true yield for \( M_{\text{bar}} \gtrsim 10^{10} M_\odot \), with lower yields signifying outflows (see also Brooks et al. 2007), as seen in the metal-rich winds in Figure 3. The same is true for the feedback boosted simulations, although the average values for \( M_{\text{bar}} \gtrsim 10^{10} M_\odot \) are lower than for the fiducial case, indicating that outflows are still prominent.

Figure 6. The stellar mass–cold gas metallicity relation at \( z = 3-4 \) (left) and \( z = 2-2.5 \) (right). The upper solid line shows the relation and its dispersion observed at \( z \sim 0.07 \), as inferred by Kewley & Ellison (2008). (Left) Gray symbols show observational data from Maiolino et al. (2008), adopting the same metallicity calibration as Kewley & Ellison (2008), for individual galaxies at \( z \sim 3.5 \) where the lower dashed line is a fit to the data. When star formation is feedback regulated, the simulations conform with the observed \( M_* - Z_{\text{gas}} \) relation. Without any feedback, or in the case of low star formation efficiency \( \text{ALL\_Efb\_e001} \), the galaxy rapidly evolves to a relation more akin to what is observed for \( z \sim 0 \) galaxies. When the available supernovae feedback energy is boosted by a factor of 5, the metal content stays lower than for the other runs (for the same stellar mass). (Right) Gray symbols show observational data from Erb et al. (2006), using the same calibration as the above data sets (see Maiolino et al. 2008), for galaxies at \( z = 2.26 \pm 0.17 \). Simulations without efficient star formation regulation is here no longer in disagreement with the observations, with the different models evolving “along” the relation, making the role of metal-rich outflows in setting the normalization of the \( M_* - Z_{\text{gas}} \) relation less obvious (see also Tassis et al. 2008). The large points show the \( z = 0 \) results for \( \text{ALL\_Efb\_e001\_5ESN} \) and \( \text{ALL\_Efb\_e010} \).
Figure 8. Circular velocities for the entire simulation suite at $z = 4$ (left), $z = 3$ (middle) and $z = 2$ (right). The only two simulations that maintain a rising or flat circular velocity profile are the fiducial simulation ($\text{ALL}_\text{Efb}_\text{e001}$) and the boosted SN feedback run ($\text{ALL}_\text{Efb}_\text{e001}_\text{5ESN}$). As argued in the main text, only these two simulations regulate the star formation rates to reasonable levels while driving galactic winds. When radiation pressure or efficient thermal feedback is removed, the resulting rotation curves remain flat until $z \sim 3$, after which inefficient removal of low angular momentum material leads to a significant upturn in circular velocities in the central parts of the galaxies.

Figure 7 shows that simulations with a low star formation efficiency, $\text{ALL}_\text{Efb}_\text{e001}$ and $\text{NoFB}_\text{e001}$, have effective yields close to the true yield already at early times, although the former simulation is significantly offset at $z \geq 6$ ($\log (M_{\text{gas}}) = 8.5$), indicating that the “observed” effective yield may not solely be explained via galactic winds (Tassis et al. 2008).

A peculiar result is found for the simulation without feedback and $\epsilon_{\text{ff}} = 10\%$ ($\text{NoFB}_\text{e010}$), which is shown for $2.5 < z < 7$. The effective yields lie significantly below all other data for $M_{\text{gas}} \gtrsim 10^{10} M_\odot$, despite having no means of ejecting enriched gas. The reason for this is that, despite being enriched to $Z_{\text{gas}} > Z_\odot$ already at early times, the gas fraction is kept very low due to the short depletion timescale and low effective density threshold for star formation via the KMT09 model. In $\text{ALL}_\text{Efb}_\text{e010}$, $f_{\text{gas}} (r < 10 \text{ kpc}) \sim 65\%$ at $z = 2.5$, compared to $f_{\text{gas}} \sim 9\%$ for $\text{NoFB}_\text{e010}$, which pushes $\gamma_{\text{eff}}$ to lower values in the latter simulation.

5.5. Circular Velocity Profiles

Simulated galaxies have traditionally displayed high central concentrations of baryons, leading to strongly peaked circular velocities toward the galactic center (Navarro & White 1993; Abadi et al. 2003; Okamoto et al. 2005; Piontek & Steinmetz 2009; Scannapieco et al. 2009; Hummels & Bryan 2012). Removal of preferentially low angular momentum gas via stellar feedback can remedy this problem (e.g., Governato et al. 2007; Agertz et al. 2011; Brook et al. 2012; Übler et al. 2014), hence bringing simulated galaxies closer to the observed Tully–Fisher relation (Tully & Fisher 1977; Pizagno 2007).

Figure 8 shows circular velocities of the entire suite of models, adopting the KMT09 model, at $z = 4$, 3, and 2. Strongly peaked circular velocities are found already at $z = 4$ for all models with no feedback, or where the star formation efficiency is too low ($\epsilon_{\text{ff}} = 1\%$) to allow for efficient wind driving. Adapting efficient feedback and efficient local star formation, as in our fiducial run ($\text{ALL}_\text{Efb}_\text{e010}$), as well as boosting the available SN energy ($\text{ALL}_\text{Efb}_\text{e001}_\text{5ESN}$), lead to a rising or flat rotation curve at all times due to efficient removal of low angular momentum gas in feedback driven outflows. Neglecting either radiation pressure or efficient thermal feedback via $E_{\text{fb}}$, results in a massive bulge component at $z \lesssim 2$, demonstrating their important interplay in establishing galactic properties.

6. BREAKING THE DEGENERACY

As we have demonstrated in the previous section, the best matches to observations are found for two of our models: $\text{ALL}_\text{Efb}_\text{e010}$ and $\text{ALL}_\text{Efb}_\text{e001}_\text{5ESN}$. Both models of galaxy formation are able to reproduce global galactic characteristics, despite the significantly different star efficiency values and amount of feedback energy. To break this degeneracy, other properties of simulated galaxies need to be considered. Potentially, this can include a variety of observations, including studies of the circumgalactic medium, absorption line studies of multiphase gas in the galactic halo, detailed properties of the stellar disks etc. For now, we will study the morphological state of the main galaxy progenitor at lower redshifts, properties of galactic winds as well as internal star formation properties, here the $\Sigma_{\text{gas}} - \Sigma_{\text{SFR}}$ (KS) relation.

6.1. Morphology

Figure 9 shows the main galaxy progenitors in $\text{ALL}_\text{Efb}_\text{e010}$ and $\text{ALL}_\text{Efb}_\text{e001}_\text{5ESN}$ at $z = 1$. At this epoch, the fiducial simulation has transitioned into a quiescent state of star formation, with a prominent (turbulent) gaseous disk in place, as well as an emerging stellar disk where stars form in cold clouds in transient spiral arm-like features, as observed e.g., in the Hubble Ultra Deep Field at $1 < z < 2$ (Elmegreen & Elmegreen 2014). This indicates that the disk may have entered an epoch of “disk settling,” as seen in the DEEP2 Survey (Kassin et al. 2012) for galaxies of stellar mass $8 \times 10^7 M_\odot < M_* (M_\odot) < 10.7$ over $0.2 < z < 1.2$. We detect individual hot super bubbles from correlated feedback events in the extended disk, leading to galactic outflows of enriched gas. Most of this enriched gas is found to enter a galactic fountain, rather than large-scale outflows as seen at higher redshifts ($z > 2$). The gas disk metallicity is close to solar.
The differences in galaxy evolution can further be characterized via properties of galaxy winds. In Figure 10, we show the wind mass-loading, defined as $\eta = \dot{m}_{\text{wind}}/\text{SFR}$, and average wind velocity as a function of circular velocity of the galaxy, here simply defined as $v_{\text{circ}}(r = 20 \text{ kpc})$, for ALL_Efb_e001, ALL_Efb_e010, and ALL_Efb_b_e001_5ESN. Each point represents the main progenitor over cosmic time ($1 \lessapprox z \lessapprox 7$).

We compute the radial mass outflow rate in concentric shells via

$$\dot{m} = \sum_{i} m_{i} v_{i,\text{rad}}/\Delta l,$$

where $N_{\text{cell}}$ is the number of cells in a shell, $m_{i}$ and $v_{i,\text{rad}}$ are the mass and radial velocity of the cell, and $\Delta l$ is the shell thickness, here typically in the range 100–200 pc. We only consider gas with radial velocities $v_{\text{rad}} \geq 10 \text{ km s}^{-1}$, i.e., only outflowing gas, and omit all gas belonging to the galactic disk by neglecting gas within a slab of thickness $2 \pm 2$ kpc encompassing the ISM in the disk plane. The outflow rate used to compute the mass-loading is the average rate, i.e., $\dot{m}_{\text{wind}} = \langle \dot{m} \rangle$ for all shells at radial distances 2 kpc $\leq r < 20$ kpc, and the characteristic outflow velocity ($v_{\text{wind}}$) is computed in an analogous fashion.

As seen in Figure 10, the different models give rise to markedly different mass-loading factors. The weak effect of feedback in ALL_Efb_e001 results in $\eta < 1$ at all times, leading to the significant overproduction of stellar mass discussed in Section 5.3. The fiducial model (ALL_Efb_e010) shows large mass-loading factors of the order of $\eta \sim 10$ at low $v_{\text{circ}}$, and hence at early times of galaxy evolution. The mass loading here decreases with increasing galactic mass, as predicted by models based on momentum or energy driven winds; $\dot{m}_{\text{wind}}/\text{SFR} \propto v_{\text{circ}}^{-\alpha}$, where $\alpha \sim 1$–2 (e.g., Oppenheimer and Davé 2006), although our simulated galaxy exhibits a more complex behavior, not described by a single power law. We emphasize that the wind properties shown in these figures have resulted from hydrodynamics of gas flows between the scale of energy and momentum injection, $\sim 50$–100 pc, and the scale of measurement, $\sim 2$–20 kpc, and are therefore predictions of the simulations and not a result of any galactic wind model assumptions (see e.g., Okamoto et al. 2010; Vogelsberger et al. 2013).

Similar to our fiducial model, the ALL_Efb_e001_5ESN run produces large mass-loading factors at low galactic masses, leading to similar SFRs compared to the fiducial model for $z \gtrsim 2$ (see Section 5.2). However, values of $\eta \sim 10$ are present throughout the galactic evolution, even for $v_{\text{circ}} \gtrsim 200 \text{ km s}^{-1}$, hindering the formation of a thin galactic disk.

In the right hand panel of Figure 10 we show the average radial wind velocities as a function of galaxy circular velocity for the three simulations, together with data derived from Na i D absorption measurements from Schwartz & Martin (2004) and Rupke et al. (2005), as well as from Mg II absorption lines from a sample of galaxies at $0.3 < z < 1.4$ (Rubin et al. 2014).
Although the scatter is large, owing to the bursty nature of star formation and feedback, especially at low galaxy masses, it is intriguing that all simulations produce roughly the same wind velocities, close to the circular velocity of the galaxy, in broad agreement with observed outflow velocities. We leave a more detailed investigation of galactic wind properties for future work.

6.3. The \( \Sigma_{\text{gas}} - \Sigma_{\text{SFR}} \) Relation

In Figure 11 we plot the \( \Sigma_{\text{gas}} - \Sigma_{\text{SFR}} \) relation (the KS relation) at \( z = 2-3 \) for the entire simulation suite. We consider only the surface density of cold \( (T < 10^4 \text{ K}) \) atomic and molecular gas, and do not include any contribution from helium.\(^9\) We calculate \( \Sigma_{\text{gas}} \) and \( \Sigma_{\text{SFR}} \) in patches with an area \( A = 750 \times 750 \text{ pc}^2 \) evenly distributed across the simulated disks. We define \( \Sigma_{\text{SFR}} = m_s \tau_s^{-1} A^{-1} \), and consider the total mass of young stars \( m_s \) formed within \( \tau_s = 20 \text{ Myr} \). For each galaxy and redshift we bin the resulting relation for \( \Sigma_{\text{gas}} \) in logarithmic bin sizes of 0.15 dex, and each panel contains measurements of simulations snapshots in the redshift range \( z = 2-3 \) at expansion factor intervals \( \Delta z = 0.01 \).

We compare the simulated relation to the KS relation inferred from observations of \( z \sim 1-3 \) normal star-forming galaxies from Genzel et al. (2010), \( z \sim 3 \) Damped Ly\( \alpha \) Systems (DLAs, Wolfe & Chen 2006), \( z \sim 3 \) low surface brightness emission around (LBGs; Rafelski et al. 2011) as well as the relation of Kennicutt (1998) for \( z \sim 0 \) galaxies. Our simulated galaxy is hosted by a halo of mass \( M_h \sim 10^{11} M_\odot \) at \( z \sim 3 \), consistent recent constraints from the cross-correlation between DLAs, and the Ly\( \alpha \) forest that indicate that most DLAs at \( z \approx 2-3 \) are hosted by relatively massive halos (Font-Ribera et al. 2012). At \( 2 < z < 4 \), DLAs are observed to have a wide distribution of metallicities, \( \log (Z_{\text{gas}}) \sim -2.5 \) to \( -0.5 \), with a peak around \( \log (Z_{\text{gas}}) \sim -1.5 \) (Prochaska et al. 2007). Numerical models by Pontzen et al. (2008) have indicated that the metal-rich DLAs are likely to be associated with halos of mass \( M_h \gtrsim 10^{10} M_\odot \).

The KS relation for the MW progenitor galaxy in the fiducial simulation (ALL\_Efb\_e010) shown in the top left panel of Figure 11 is in agreement with the empirical KS relation for \( \Sigma_{\text{gas}} \gtrsim 100 M_\odot \text{ pc}^{-2} \), and shows a clear drop below this surface density. This transition surface density is related to the physical density at which molecular hydrogen can be synthesized on dust grains (Schaye 2001; Gnedin et al. 2009; Krumholz et al. 2009a; Gnedin & Kravtsov 2010, 2011). The lower star formation efficiency below this transition surface density, where the simulations match the DLA and LBG data, arises from the low gas metallicity, \( Z_g \sim 0.1 - 0.2 Z_\odot \), in the outer disk which in turn results in a low \( f_{\text{ff}} \).

The KS relation in the simulation with \( c_{\text{ff}} = 10\% \) (ALL\_Efb\_e010) is hence in very good agreement with the observed KS relation of both low-\( z \) and high-\( z \) galaxies. Note that simulations with identical ingredients, but with \( c_{\text{ff}} = 1\% \) (ALL\_Efb\_e001), are also consistent with observations at high surface densities, but exhibit a drop in star formation at a somewhat larger gas surface density. The fact that the normalization of the KS relation is similar in simulations with a local efficiency of star formation different by a factor of 10 illustrates that in simulations with efficient feedback and significant outflows, the normalization of the KS relation does not reflect the local star formation efficiency. In this case, the global SFR self-regulates to produce a low overall

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\(^9\) To scale our quoted surface densities to account for helium, multiply them by a factor of 1.36.
Figure 11. The Kennicutt–Schmidt (KS) relation ($\Sigma_{\text{gas}} - \Sigma_{\text{SFR}}$) at $z = 2$–3. The relation from the simulated galaxies (blue crosses) is compared to relations derived from observations: CO data for normal star-forming galaxies at $z \sim 1$–3 (orange hexagons, Genzel et al. 2010), DLAs at $z \sim 3$ (red squares, Wolfe & Chen 2006), and LBGs at $z \sim 3$ (dark green circles, Rafelski et al. 2011). The solid black line represents the average $z = 0$ relation of Kennicutt (1998), i.e., $\Sigma_{\text{SFR}} = 2.5 \times 10^{-4} \Sigma_{\text{gas}}^2$ M$_\odot$ kpc$^{-2}$ yr$^{-1}$. The star formation–feedback interplay establishes a wide array of relations, where the best match to observations is found for the fiducial simulation (ALL _Efb _e010), which predicts the normalization of the KS relation for $\Sigma_{\text{gas}} \gtrsim 10^2$ M$_\odot$ pc$^{-2}$ as well as the truncation at lower surface densities, in agreement with the DLA/LBG observations. See the main text for a discussion of the entire simulation suite.
star formation efficiency (i.e., a long gas consumption timescale).

In contrast, in simulations in which feedback is weak or absent, the normalization of the KS relation is linearly related to the local efficiency. Thus, for example, the normalization in the simulation with $\epsilon_{\text{ff}} = 10\%$, but feedback turned off, is approximately an order of magnitude larger than that in the simulation with $\epsilon_{\text{ff}} = 1\%$ for $\Sigma_{\text{gas}} \gtrsim 100 \, M_\odot \, \text{pc}^{-2}$.

Figure 11 shows that the simulation with $\epsilon_{\text{ff}} = 1\%$ and the SN energy output boosted by a factor of five (ALL_Efb\_e001\_5ESN) has significantly lower normalization of the KS relation compared to our fiducial simulation and in tension with observations. As demonstrated more quantitatively in Section 5.4, this arises due to the very efficient removal of metal-rich gas from the galaxy, leaving the entire disk metal-poor with an outer disk metallicity $Z_\text{e} < 0.1 Z_\odot$. The marked difference between the internal star formation properties of ALL_Efb\_e010 and ALL_Efb\_e001\_5ESN, which both conform to all observed global galactic characteristics, illustrates that it is potentially possible to break the degeneracy between such models by using additional properties and observations.

7. DISCUSSION

7.1. Comparison with Previous Studies

A wide range of numerical studies of galaxy formation focusing on different stellar feedback processes have appeared in the past several years. It is thus useful to discuss how these models differ from, or agree with, the numerical models presented in this work, and why.

Recently, Hopkins et al. (2014) presented a series of high-resolution cosmological zoom-in SPH simulations of galaxy formation run to $z = 0$, spanning halo masses $M_{\text{halo}} \sim 10^{8} - 10^{13} \, M_\odot$. Our results generally agree with those of Hopkins et al., who also find that the star formation efficiency tends to self-regulate in the regime when stellar feedback is efficient. In particular, they found that the observed low normalization of the KS relation was reproduced in their simulations even when a local star formation efficiency as high as $\epsilon_{\text{ff}} = 100\%$ was used. Furthermore, Hopkins et al. (2014) also conclude that both early radiative feedback and subsequent supernova feedback are important. For the latter they use a scheme that captures the momentum generated during the (often unresolved) Sedov–Taylor stage of evolution.

Trujillo-Gomez et al. (2015), and previously Ceverino et al. (2013), presented AMR simulations of galaxy formation at high $z$, in the regime of dwarf galaxies ($M_{\text{halo}}(z = 0) = 3 \times 10^{10} \, M_\odot$) and low-mass spiral galaxies ($M_{\text{halo}}(z = 0) = 2 \times 10^{11} \, M_\odot$). Using an implementation similar to what is presented in this work, the authors demonstrated the importance of considering radiation pressure in galaxy formation simulations. However, at their current resolution (40–80 h$^{-1}$ pc at $z = 0$) the effect of thermal feedback is possibly underestimated, as indicated by the SFHs in Figure 8 in Trujillo-Gomez et al. (2015), where the spiral galaxy’s SFR is overpredicting the rates of Behroozi et al. (2013) by almost a dex at $z = 1.5$. However, the authors compare their simulated galaxy to the data of a galaxy with half the dark matter halo mass. Accounting for this offset brings their model with strong radiative feedback into closer agreement with the semi-empirical expectations (within the 1σ confidence interval; Trujillo-Gomez 2015, private communication).

Using SPH simulations of galaxy formation in halos of masses in the range $M_{\text{halo}} = 10^{11} - 3 \times 10^{12} \, M_\odot$, Aumer et al. (2013) studied the impact of their feedback model based on the multiphase SPH code presented in Scannapieco et al. (2006), with the addition of momentum input from radiation pressure. A good match to global galaxy characteristics at $z = 0$–4, specifically for Milky Way analogues, was recovered if the authors considered a large value of the infrared optical depth, $\tau_{\text{IR}} = 25$, but allowed for more gentle momentum input in low-redshift systems. The authors identified that despite the effort in tuning feedback parameters, the model still over-predicted the mass of stars formed at $z > 4$, and argued that this may be due to inaccurate modeling of star formation at early stages of galaxy formation, or simply due to the specific merger histories of the simulated halos.

Brook et al. (2012) and Stinson et al. (2013) discussed the importance of “early feedback” in their SPH galaxy formation simulations. These authors assume that 10% of the bolometric luminosity radiated by young stars get converted into thermal energy, which significantly affected properties of their simulated galaxies. Although this model differs significantly from our subgrid model of radiation pressure, in which we consider the actual momentum transfer from radiation via local gas/dust UV and IR absorption, the concept of pre-supernovae feedback was shown to have a significant effect on galaxy evolution, in agreement with our conclusions.

All of the above authors have recognized the importance of additional feedback processes in addition to supernovae energy input, in particular momentum injection due to radiative feedback that preconditions star-forming regions before the first supernovae explosion occurs ($t \sim 4 \, \text{Myr}$). This is indeed also the case in our models, where the lack of early momentum based feedback results in SFRs that are a factor of 2 to 10 times higher than the average expected values, see Figure 4.

Recently, Marinacci et al. (2014) presented cosmological simulations, using the Arepo code (Springel 2010), of eight MW-sized halos, previously studied using dark matter only in the Aquarius project (Springel et al. 2008). The simulated galaxies had realistic sizes, rotation curves, and stellar-mass to halo-mass ratios, and the authors noted this was achieved without resorting to factors thought to be crucial for galaxy formation by earlier studies, e.g., a high density threshold for star formation (e.g., Governato et al. 2010), a low star formation efficiency (Agertz et al. 2011), or early stellar feedback (e.g., Brook et al. 2012; Agertz et al. 2013; Hopkins et al. 2014). While the models of Marinacci et al. (2014) demonstrate convincing resolution convergence, as well as encouraging galaxy properties, this neither negates previous work nor comes as a surprise; Marinacci et al. (2014) adopt a stellar feedback approach based on a kinetic wind scheme in which the wind velocity, and mass-loading, is scaled with the local dark matter halo mass (Puchwein & Springel 2013). At the adopted resolution ($\sim 340–680 \, \text{pc force softening}$), a direct modeling of strong feedback tends to affect too much gas due to mixing at the resolution scale, as well as the inability to resolve the multiphase ISM (Roškar et al. 2013). The type of wind scheme adopted by Marinacci et al. (2014) circumvents these problems by essentially postulating the existence of outflows. A natural benefit of this approach is a better resolution convergence on global galactic properties.
7.2. H2-based Star Formation and the Efficiency of Feedback

In this work we have adopted a star formation model based on the local abundance of molecular hydrogen using the formalism presented by Krumholz et al. (2009a). Previous work (Gnedin et al. 2009; Gnedin & Kravtsov 2010, 2011; Kuhlen et al. 2012) have demonstrated how this approach leads to suppressed star formation in the metal-poor environments typical for dwarf galaxies, even resulting in a population of completely dark galaxies situated in dark matter halos of mass $M_{\text{halo}} \lesssim 10^{10} M_\odot$ (Gnedin & Kravtsov 2010; Kuhlen et al. 2013). A relatively unexplored outcome of such a H2-based star formation model is its ability to boost feedback (but see Christensen et al. 2014). In fact, most previous studies completely neglect feedback or included only inefficient thermal feedback from supernovae.

Stellar feedback can be boosted in the H2-based star formation model in several ways. For example, star formation can become more localized because in low-metallicity environments, high gas densities are required for vigorous star formation. This can lead to more correlated energy and momentum injection events. Indeed, this effect was pointed out by Christensen et al. (2014). Furthermore, as the molecular hydrogen fraction, $f_{\text{H}_2}$, is a function of the local dust abundance (and hence gas metallicity), rapid local enrichment of gas from newly formed stars allows for a sudden decrease in the effective star formation threshold, leading to local burst of star formation with associated strongly correlated feedback. As we demonstrate in this study (see Appendix), this changes the nature of the star formation-feedback cycle, resulting in a more efficient suppression of star formation compared to models with fixed star formation density thresholds (here $n = 25 \, \text{cm}^{-3}$). We note that once the numerical resolution is sufficiently high to allow for star formation to robustly occur at densities $n \gg 100 \, \text{cm}^{-3}$, at which gas is expected to be mostly molecular, an explicit subgrid model for $f_{\text{H}_2}$ may have little effect over a fixed high density threshold, as argued by Hopkins et al. (2012).

7.3. Feedback and the Survivability of a Thin Galactic Component

As discussed in the above sections, efficient feedback leading to galactic outflows is a necessary ingredient in order to match a large number of global observables. A caveat to this was raised by Roškar et al. (2013), who demonstrated that while strong feedback can produce stellar masses that conform to semi-empirical $M_*-M_{\text{halo}}$ relations from e.g., Behroozi et al. (2013) and Moster et al. (2013), this had severe consequences on the final galactic disk; no thin stellar disk nor cold gaseous disk survived. In Figure 12 we show the $z = 0$ rotational velocity and velocity dispersions of young and old stars as well as cold gas. Based on the mono-abundance population data by Bovy et al. (2012), Roškar et al. (2013) raised the point that $v_{\text{rot}}/\sigma$, at least for the MW, is $\gtrsim 10$ for young stars (taken to be stars younger than 3 Gyr) at the solar radius, and closer to $\sim 4$ for older stars. Using the same age cut we find that we do not suffer, at least to the same extent, from the problem of Roškar et al. (2013); we clearly see a young thin stellar component with a velocity dispersion at the solar radius close to $\sim 0-20 \, \text{km} \, \text{s}^{-1}$. A cold gaseous disk is present with velocity dispersions to $\sim 10 \, \text{km} \, \text{s}^{-1}$ outside of the bulge ($r \gtrsim 1.5 \, \text{kpc}$), typical of local spiral galaxies (Tamburro et al. 2009; Agertz et al. 2009a). We note that this does not mean we are not suffering from numerical heating due to low resolution, or that the thin disk is the dominant galactic component, only that our approach to feedback and star formation does not necessarily lead to disk destruction as found in Roškar et al. (2013).

7.4. Caveats, Small Scale Issues, and the Next Step

The Efficiency of Star Formation. Although our simulation suite was carried out with relatively high numerical resolution, most key processes related to feedback and star formation remain subgrid, as they operate on $\sim \text{pc}$ scales within GMCs. Given that the true density probability distribution function (PDF) relevant for star formation is not fully resolved in galaxy formation simulations, the adopted star formation efficiencies per free fall time may be modified at a higher resolution. The local gas depletion time is assumed to be $t_{\text{gas}} = t_{\text{ff}}/\epsilon_{\text{ff}}$, and is only modeled, and measured, on large-scales ($\gtrsim 100 \, \text{pc}$), and the adopted value of $\epsilon_{\text{ff}}$ discussed in this work hence only applies on these scales (see Gnedin et al. 2014 for a recent discussion of how $t_{\text{gas}}$ may manifest on different scales).

A number of analytical and numerical studies of star formation in supersonic turbulence, aimed at understanding what sets the star formation efficiency per free-fall time and its evolution in GMCs, have been carried out recently (see e.g., Krumholz & McKee 2005; Hennebelle & Chabrier 2011; Padoan & Nordlund 2011; Vázquez-Semadeni et al. 2011). These studies find that the value of $\epsilon_{\text{ff}}$ depends on detailed properties of star-forming clouds, e.g., the flow Mach number as well as the virial parameter10, $\alpha_{\text{vir}}$ (see review by Padoan et al. 2014), all leading to a time-dependent density PDF where stars form in the high density tail consisting of molecular clumps ($n \sim 10^2-10^4 \, \text{cm}^{-3}$) and cores ($n \gtrsim 10^5 \, \text{cm}^{-3}$). A generic result is that unless star formation is regulated by radiative feedback, protostellar outflows, subsequent supernovae as well as magnetic fields, the resulting efficiency can be significantly larger than the $\epsilon_{\text{ff}} \sim 0.25\%-0.5\%$ deduced from observations on kpc scales (see Section 3), especially for gravitationally bound clouds ($\alpha_{\text{vir}} < 1$).

To some degree, the assumption made in our work regarding feedback regulated star formation is in line with the above results, although we apply the efficiency on much larger, $\sim 100 \, \text{pc}$, scales. More work is definitely necessary in order to “connect the scales,” and future improvements in numerical resolution should allow global characteristics of star-forming regions, such as the virial parameters $\alpha_{\text{vir}}$, to be at least marginally resolved. Padoan et al. (2012) demonstrated (but see González-Samaniego et al. 2014) how the measured star formation efficiency per free-fall time in high resolution simulations of supersonic turbulence could be expressed as a simple law depending only on the cloud free-fall and dynamical time, $\epsilon_{\text{ff}} \propto \exp (-1.6 t_{\text{ff}}/t_{\text{dyn}})$. It remains to be seen whether this kind of assumption propagates to differences in large-scale galactic observables in comparison to the choice of a large uniform $\epsilon_{\text{ff}}$ ($\sim 10\%$) in our work (see also Hopkins et al. 2014).

The Star Formation Recipe. The assumption of an underlying nonlinear star formation law (here $\dot{\rho}_c \propto \rho_{\text{gas}}^\alpha$) may be incorrect. Gnedin et al. (2014) argued that such small scale relation should result in a nonlinear slope in the observed KS relation, which is incompatible with the linear relation observed

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10The ratio of the cloud kinetic energy to gravitational potential energy.
for molecular gas ($\Sigma_{\text{SFR}} \propto \Sigma_{\text{H}_2}$) at $\Sigma_{\text{gas}} \gtrsim 100 M_{\odot} \text{pc}^{-2}$ in the THINGS survey (Bigiel et al. 2008). Although our fiducial model is in good agreement with the observed KS relation at $z \sim 1$–3, it remains to be seen if the same feedback models can regulate star formation at high surface densities to be compatible with local observations of starbursts.

Modeling Thermal Feedback. Our stellar feedback model accounts for radiation pressure, stellar winds, and supernovae Type II and Ia, as well as associated mass loss and metal generation where appropriate (Agertz et al. 2013). While the overall energy and momentum budget has been shown to generate realistic galaxy properties, at least for $z \gtrsim 1$, the detailed role of a separate feedback energy variable remains to be explored. It is clear that storing even a small fraction of SN energy in such variable significantly affects the SFR and efficacy of feedback. It is thus important to understand in detail the physical nature of such extra energy component. As mentioned in Section 2.3, this variable 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. Alternatively, it can be interpreted as crudely modeling kinetic energy stored in unresolved small-scale turbulence or in cosmic rays (CRs). Indeed, Booth et al. 2013 (see also Hanasz et al. 2013; Salem & Bryan 2014) demonstrated that if a modest fraction of the available supernova energy (\sim 10\% of $10^{53}$ erg) is injected as a CR energy density, galactic winds can be driven effectively and can exhibit qualitatively different properties compared to SN-driven winds. In future work we will explore models in which cosmic ray feedback contribution to the stellar feedback budget is modeled explicitly in a fully cosmological setting.

Numerical Resolution and Convergence. We note that the star formation and feedback recipes used in our simulations have been specifically designed to operate on scales of \sim 50–100 pc or below, comparable to the sizes of massive GMCs, as we discuss in detail in our previous paper (Agertz et al. 2013).

We therefore expect them to work best at this particular resolution. In fact, running our fiducial model at $\Delta x \sim 300$ pc resolution produces a different SFH (not presented here), with more stars formed at early times compared to the models presented in this paper. This is not surprising, as at lower resolution, stellar feedback is spread over much more mass, hence achieving lower heating/momentum injection rates, leading to weaker galactic winds.

Of course, it would be desirable for cosmological simulations to be as insensitive to the numerical resolution as possible. However, because the density PDF of the ISM changes with resolution, it is not guaranteed that a specific model of the star formation/feedback cycle is invariant to the gas density PDF change. Simulations where such models are tied to converged quantities, e.g., properties of galactic winds depend on the total mass of the host dark matter halo as in Marinacci et al. (2014) (see also Vogelsberger et al. 2014), are naturally less sensitive to changes in the numerical resolution, as discussed above.

8. CONCLUSIONS

In this paper we have presented a suite of high resolution cosmological zoom-in simulations of galaxy formation, focusing on the formation of a MW-sized galaxy with a halo mass of $M_{\text{200}} \approx 10^{12} M_{\odot}$ at $z = 0$. We have focused on exploring how variations in the modeled star formation and feedback physics affect galaxy evolution and how properties of the simulated MW progenitors compare to modern high-redshift ($z \gtrsim 1$) estimates of global characteristics, such as SFHs, the mass–metallicity relation, the KS relation, and the stellar mass–halo mass relation. Our simulations adopt the feedback model presented recently by Agertz et al. (2013), which accounts for energy and momentum injection via radiation pressure, stellar winds, and Type II and Ia supernovae. Furthermore, star formation is modeled using the local density of molecular gas...
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Gnedin et al. 2009; Krumholz et al. 2009a; Kuhlen et al. 2012).

Perhaps the central result of our study is that in our implementation, feedback becomes efficient in suppressing star formation and driving outflows only if the local star formation efficiency per free fall time is sufficiently large, \( \epsilon_{\text{ ff}} \approx 10\% \) for the density field resolved in the current simulations. Such a large efficiency allows a high degree of temporal and spatial correlation of energy and momentum injection. We show (in Section 3) that such value of the local efficiency is consistent with observational estimates in GMCs. We confirm that in the models with efficient feedback, the star formation efficiency measured on global kiloparsec scales self-regulates to the low value inferred from observations.

The rest of our results can be summarized as follows.

1. At the peak spatial resolution of our simulations, \( \Delta x \sim 75 \) pc, simulated galaxy relations are sensitive not only to the details of stellar feedback processes and their parameters, but also to the underlying star formation model and the adopted efficiency of star formation. This highlights the fact that it is important to model carefully the entire star formation and feedback cycle.

2. If the adopted \( \epsilon_{\text{ ff}} \) is low (here \(~1\%\), relevant for the currently resolved gas density field), hence treating the observed inefficiency of galactic star formation as a model input rather than a prediction from the star formation–feedback cycle, the strength of the feedback must be artificially boosted in order to regulate galaxy masses via galactic outflows. We show that although this can lead to a successful match to the semi-empirical stellar mass–halo mass relation, such simulations may be in tension with the normalization of the KS relation. Furthermore, in agreement with other recent studies (Agerzt et al. 2011; Roškar et al. 2013), we also find that simply boosting feedback with a low \( \epsilon_{\text{ ff}} \), to match global relations, prevents the formation of a well-defined gaseous disk, even at relatively low redshifts (\( z \lesssim 1 \)). The morphology of the gaseous and stellar galactic disks may therefore serve as one of the key additional constraints on the parameters of the star formation–feedback loop.

3. Our simulations indicate a complex interplay between the parameters of star formation and stellar feedback. If the star formation efficiency is sufficiently large to allow for feedback self-regulation, removing key feedback sources, such as radiation pressure or efficient thermal feedback, moves the galaxy off observed scaling relations, but in a complex manner.

4. Encouragingly, we find that our fiducial model provides a good match to all considered observables at different redshifts: semi-empirically derived SFRs, the stellar mass–gas metallicity relation and its evolution, the KS relation, the \( M_* - M_{\text{halo}} \) relation and its evolution, as well as the flat shape of rotation curves, and galaxy morphology. In particular, we show that our fiducial simulation, with feedback sufficient to drive vigorous galactic winds at high-\( z \), is sufficiently gentle to allow for a young thin stellar disk to form by \( z \approx 0 \). The disk has a flat rotation curve, with gas and stellar velocity dispersions consistent with observations of the MW’s at the solar circle.

Our results are encouraging, as they show that a comprehensive model that satisfies a number of non-trivial observational constraints and tests is feasible. In this work we have mostly discussed the \( z \gtrsim 1 \) results for our simulations, as the majority of them were stopped at high redshifts due to the computational expense. A significant fraction of stars in the \( z = 0 \) thin disk is expected to form after \( z \approx 1 \) (van Dokkum et al. 2013), which also appears to be the case in our fiducial model where we see the formation of a well-defined thin stellar disk as soon as the turbulent gas rich disk enters an epoch of “disk settling” (Kassin et al. 2012) at \( z \lesssim 1 \) (see Figures 9, 12 and related text). Building upon the exploratory study presented here, we will in future work (O. Agerzt & A. V. Kravtsov 2015, in preparation) study and contrast galaxy sizes and morphologies at \( z = 0 \) for a subset of the simulated galaxies.

The simulations presented in this paper have been carried out using the Midway cluster at the University of Chicago Research Computing Center. We would like to thank Douglas Rudd for his support in running the simulations. We thank Romain Teyssier, Phil Hopkins, and Dušan Kereš for fruitful discussions. AK would like to thank the Simons foundation and organizers and participants of the Simons symposium on Galactic Super Winds in 2014 March, for stimulating and helpful discussions that aided in the preparation of this paper. A. K. was supported via NSF grant OCI-0904482, by NASA ATP grant NNH12ZDA001N, and by the Kavli Institute for Cosmological Physics at the University of Chicago through grants NSF PHY-0551142 and PHY-1125897, and an endowment from the Kavli Foundation and its founder Fred Kavli.

APPENDIX

IMPACT OF A FIXED DENSITY THRESHOLD FOR STAR FORMATION

The assumed star formation model throughout the work is based on the abundance of molecular hydrogen; see Equation (1). A more common approach in the galaxy formation community is to only allow stars to form above some fixed density threshold \( \rho_* \), i.e.,

\[
\dot{\rho}_* = \frac{\rho}{f_{\text{SF}}} \text{ for } \rho > \rho_*. \tag{A.1}
\]

The appropriate value of this threshold is highly resolution-dependent, as galaxy formation simulations do not yet converge on a density PDF representative of the ISM, and values of this threshold greatly vary in the literature (see discussion in Agerzt et al. 2011). To study the impact of the star formation prescription choice, we adopt the density threshold of \( \rho_* = 25 \text{ cm}^{-3} \), which roughly corresponds to the physical density at which \( f_{\text{H}_2} \sim 50\% \) at \( Z_q = Z_{\odot} \) (Gnedin et al. 2009). Figure A1 shows the dependence of the SFH of the main progenitor on changes of the star formation prescription only, from the molecular based prescription adopted in our study to the fixed density threshold prescription of Equation (A.1). All the other feedback and star formation related settings, e.g., the efficiency per-free-fall, were fixed at their fiducial values. The \( H_2 \) model results in SFRs that are lower by \(~0.5\text{ dex}\) for \( z < 7 \) compared to the traditional
constant density threshold model. The latter disagrees with the Behroozi et al. inference at all redshifts. As shown in the figure, the constant threshold model is in fairly good agreement with the SFH of the Eris simulation (Guedes et al. 2011), which also adopted the constant threshold based star formation model, but with the threshold of $n_s = 5 \text{ cm}^{-3}$. Note that the virial mass of the Eris simulation ($M_{\text{vir}} \approx 7.9 \times 10^{11} M_\odot$) is $\sim 20\%$ lower than the simulated halo in this study.

![Figure A1. Simulated SFHs compared to the Behroozi et al. (2013) data for $M_{\text{vir}} (z = 0) = 10^{12} M_\odot$. Dark- and light-gray shaded areas are one- and two-sigma confidence regions respectively. We adopt bins of size $\Delta z_{\text{bin}} = 100 \text{ Myr}$ for the simulated SFHs. The KMT09 model shows SFHs that are lower by $\sim 0.5 \text{ dex}$ compared to the fixed density threshold model. For comparison we also plot the SFH of the Eris simulation (Guedes et al. 2011).]
