The response of dark matter haloes to elliptical galaxy formation: a new test for quenching scenarios.

Aaron A. Dutton\(^*\), Andrea V. Macciò\(^1\), Gregory S. Stinson\(^1\), Thales A. Gutcke\(^1\), Camilla Penzo\(^1\), Tobias Buck\(^1\)

\(^1\)Max-Planck-Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany

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ABSTRACT

We use cosmological hydrodynamical zoom-in simulations with the SPH code GASOLINE of four haloes of mass \(M_{200} \sim 10^{13} M_\odot\) to study the response of the dark matter to elliptical galaxy formation. Our simulations include metallicity dependent gas cooling, star formation, and feedback from massive stars and supernovae, but not active galactic nuclei (AGN). At \(z = 2\) the progenitor galaxies have stellar to halo mass ratios consistent with halo abundance matching, assuming a Salpeter initial mass function. However by \(z = 0\) the standard runs suffer from the well known overcooling problem, overpredicting the stellar masses by a factor of \(\sim 4\). To mimic a suppressive halo quenching scenario, in our forced quenching (FQ) simulations, cooling and star formation are switched off at \(z = 2\). The resulting \(z = 0\) galaxies have stellar masses, sizes and circular velocities close to what is observed. Relative to the control simulations, the dark matter haloes in the FQ simulations have contracted, with central dark matter density slopes \(d \log \rho / d \log r \sim -1.5\), showing that dry merging alone is unable to fully reverse the contraction that occurs at \(z > 2\). Simulations in the literature with AGN feedback however, have found expansion or no net change in the dark matter halo. Thus the response of the dark matter halo to galaxy formation may provide a new test to distinguish between ejective and suppressive quenching mechanisms.

Key words: cosmology: theory – dark matter – galaxies: elliptical and lenticular, cD – galaxies: formation – galaxies: evolution – methods: numerical

1 INTRODUCTION

Dissipationless simulations run in the concordance ΛCDM cosmology make robust predictions for the structure of cold dark matter haloes (e.g., Navarro et al. 1997, 2010; Bullock et al. 2001; Diemand et al. 2007; Macciò et al. 2007; Stadel et al. 2009; Zhao et al. 2009; Klypin et al. 2011; Dutton & Macciò 2014). One of these predictions is that CDM haloes should have “cuspy” central density profiles that scale as \(\rho(r) \propto r^{-\alpha}\) with \(\alpha \approx -1.2\). Observations have yet to unambiguously find these cusps. Furthermore, a variety of studies based on gas dynamics, stellar dynamics and gravitational lensing on scales from dwarf galaxies to galaxy clusters often favor cored (\(\alpha = 0\)) or shallow cusps (i.e., \(\alpha \lesssim 0.5\)) instead (e.g., de Blok et al. 2001; Swaters et al. 2003; Sand et al. 2004; Goerdt et al. 2006; Kuzio de Naray et al. 2008; Walker & Peñarrubia 2011; Oh et al. 2011; Newman et al. 2011; 2013).

This lack of observational evidence for cuspy dark matter density profiles is often used as evidence against the CDM paradigm. However, a major complication in the comparison between observations of dark matter density profiles and those predicted by cosmological N-body simulations is the uncertain impact of baryons. Baryonic processes can both increase and decrease the density profiles of dark matter haloes. This currently prevents the observed structure of dark matter haloes from being used as a robust test of the cold dark matter model. A fully predictive theory for the structure of CDM haloes must take into account the effects of galaxy formation.

If the accretion of baryons onto the central galaxy is smooth and slow then dark matter haloes should contract adiabatically (Blumenthal et al. 1986). This process can increase the density of dark matter haloes by an order of magnitude. Other processes can cause the dark matter halo to expand, such as transfer of energy/angular momentum from baryons to the dark matter via dynamical friction due to minor mergers (El-Zant et al. 2001, 2004; Nipoti et al. 2004; Jardel & Sellwood 2009; Johansson et al. 2009; Lackner & Ostriker 2010; Cole et al. 2011; Laporte & White 2015), or...
galactic bars (Weinberg & Katz 2002; Sellwood (2008), but see McMillan & Dehnen 2005), and rapid mass loss/time variability of the potential due to supernovae (SN) / stellar / active galactic nuclei (AGN) feedback (Navarro et al. 1996; Read & Gilmore 2005; Mashchenko et al. 2006, 2008; Peirani et al. 2008; Governato et al. 2010; Pontzen & Governato 2012; Macciò et al. 2012; Martizzi et al. 2012, 2013). Each of these processes is likely to occur during galaxy formation, but at present it is not clear which process (if any) dominates, and on which galaxy mass scales.

Turning the problem around, if one can observationally measure the halo response, then in the context of ΛCDM, this gives clues to the dominant galaxy formation mechanisms. In particular, as we discuss in this paper, the halo response may provide a test for different galaxy quenching models. While it is known that most of the stars in massive galaxies formed at high redshifts \( z \gtrsim 2 \) (e.g., Thomas et al. 2005), the mechanism(s) responsible for shutting down star formation (quenching), and keeping it off (quiescence) are a subject of much debate. A popular idea is that feed-back of energy from the growth of supermassive black holes (SMBH) ejects cold gas from galaxies and heats the halo gas, preventing it from cooling onto the central galaxy. We refer to this class of models as “AGN quenching”. It is clear there is enough energy released from the AGN to quench star formation, of issue is whether the energy released by the AGN can couple efficiently to the surrounding gas (e.g., Cielo et al. 2014).

An alternative idea is that cooling becomes very inefficient, and effectively shuts down, once the halo mass reaches a critical mass of \( \sim 10^{12} M_\odot \). We refer to this class of models as “halo quenching”. In practice the boundary between these two quenching mechanisms is blurry because AGN can also act as a heat source for the halo gas, although there are non-AGN heating sources such as young and old stellar populations (Kannan et al. 2014, 2015; Conroy et al. 2015). The key difference in these mechanisms is that AGN quenching involves the episodic (and possibly violent) removal of gas from the galaxy center, whereas halo quenching involves the suppression of gas cooling from the halo.

Galaxy formation models implementing both mechanisms can broadly reproduce the colors and mass functions of present day galaxies (e.g., Croton et al. 2006; Cattaneo et al. 2006; Schaye et al. 2015). However, there is at present no clear way to observationally distinguish between these models. The correlation between SMBH mass and galaxy properties is often cited as evidence for a physical link between SMBHs and host galaxies, although (Jahnke & Macciò 2011) showed that such a correlation can naturally arise out of hierarchical merging.

As discussed above, in terms of formation mechanisms, there is one process that makes haloes contract: dissipative gas accretion (Blumenthal et al. 1986), which must occur to form an elliptical galaxy. Two processes have been investigated that make haloes expand: mass outflows driven by AGN feedback (Martizzi et al. 2012); and dynamical friction between baryons and dark matter during the galaxy assembly process (El-Zant et al. 2001). Dry mergers are likely to be more important at late times, while AGN feedback is likely to be more important at early times.

The goal of this study is to determine the impact of dissipationless galaxy assembly on the structure of ΛCDM haloes. In particular, we wish to know whether dry merging can reverse the effects of halo contraction that are expected to occur in the high redshift progenitors. To achieve this we use fully cosmological hydrodynamical simulations of theformation of \( M_{900} \sim 10^{13} M_\odot \) haloes using the smoothed particle hydrodynamics (SPH) code GASOLINE. We use the MiGICC (Stinson et al. 2013) star formation and stellar feedback model which has been shown to produce realistic disk galaxies (Brook et al. 2012) and successfully matches the observed galaxy formation efficiencies across cosmic time in haloes less massive than \( \sim 10^{12} M_\odot \) (Stinson et al. 2013; Wang et al. 2015). Our study improves on previous analytic and N-body calculations (e.g., El-Zant et al. 2001; Lackner & Ostriker 2010) in that our mass assembly histories are fully cosmological, and compared to previous cosmological hydro simulations (e.g., Johansson et al. 2009) our progenitor galaxies have realistic sizes and galaxy formation efficiencies.

This paper is organized as follows: the simulations including sample selection, hydrodynamics, star formation and feedback models are described in 2. Results relating to global parameters such as stellar masses, halo masses, galaxy sizes and circular velocities are presented in 3. The radial mass profiles including the response of the dark matter to galaxy formation are presented in 4. We discuss implications for our results in 5 and give a summary in 6.

### 2 Simulations

The simulations presented here are fully cosmological “zoom-in” simulations of galaxy formation run in a flat ΛCDM cosmology. Cosmological parameters (see Table 1) are based on the Wilkinson Microwave Anisotropy Probe (WMAP) 5th year (Komatsu et al. 2009) and 7th year (Komatsu et al. 2011) results. Haloes are selected from two parent dark matter only simulations run with the pkdgrav tree-code (Stadel 2001): a 90 Mpc box from Macciò et al. (2008) using the WMAP5 cosmology, and a 80 Mpc/h box from Penzo et al. (2014) using the WMAP7 cosmology.

#### 2.1 Sample selection and initial conditions

We select four haloes to re-simulate at higher resolutions. The two selection criteria are (1) a present day halo mass of \( \sim 10^{13} M_\odot \); and (2) no large structures present within three virial radii. Table 2 lists the dark matter and baryon particle masses and force softenings (in comoving kpc). To test for numerical convergence, one of the haloes (halo4) has been

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**Table 1. Cosmological parameters.** Column (1) cosmology ID. Column (2), \( \Omega_m \), present day matter density. Column (3), \( \Omega_\Lambda \), dark energy density. Column (4), \( \Omega_b \), baryon density. Column (5), \( H_0 \), Hubble parameter. Column (6), \( \sigma_8 \), power spectrum normalization. Column (7), n, power spectrum slope.

| Cosmology | \( \Omega_m \) | \( \Omega_\Lambda \) | \( \Omega_b \) | \( H_0 \) | \( \sigma_8 \) | n |
|-----------|--------------|----------------|--------------|-----------|-------------|---|
| WMAP5     | 0.2580       | 0.7420         | 0.0438       | 0.720     | 0.796       | 0.963 |
| WMAP7     | 0.2748       | 0.7252         | 0.0458       | 0.702     | 0.816       | 0.968 |
Table 2. Simulation parameters. Column (1), name of initial conditions. Column (2), $M_{200}$, present day halo mass from adiabatic gas simulation. Column (3), $m_{\text{dark}}$, dark matter particle mass. Column (4), $m_{\text{gas}}$, initial gas particle mass. Column (5), $\epsilon_{\text{dark}}$, dark matter particle force softening in comoving kpc. Column (6), $\epsilon_{\text{gas}}$, gas (and star) particle force softening in comoving kpc. Column (7), $N_{\text{dark}}$, number of high-resolution dark matter particles. Column (8), $N_{\text{gas}}$, initial number of gas particles. Column (9), $n_{\text{th}}$, threshold for star formation. Column (10) name of cosmology – see Table 1. Column (11) symbol used in figures.

| Name    | $\log_{10}M_{200}$ [M$_{\odot}$] | $\log_{10}m_{\text{dark}}$ [M$_{\odot}$] | $\log_{10}m_{\text{gas}}$ [M$_{\odot}$] | $\epsilon_{\text{dark}}$ [kpc] | $\epsilon_{\text{gas}}$ [kpc] | $N_{\text{dark}}$ Million | $N_{\text{gas}}$ Million | $n_{\text{th}}$ | Cosmology | Symbol       |
|---------|---------------------------------|------------------------------------------|----------------------------------------|-------------------------------|-------------------------------|--------------------------|--------------------------|-----------------|------------|--------------|
| halo1   | 13.15                           | 6.91                                     | 6.23                                   | 1.61                          | 1.61                          | 2.49                     | 2.49                     | 9.6             | WMAP5     | triangle     |
| halo2   | 13.19                           | 6.91                                     | 6.23                                   | 1.61                          | 1.61                          | 2.49                     | 2.49                     | 9.6             | WMAP5     | square       |
| halo3   | 13.20                           | 6.91                                     | 6.23                                   | 1.61                          | 1.61                          | 2.49                     | 2.49                     | 9.6             | WMAP5     | pentagon     |
| halo4.0 | 13.36                           | 8.13                                     | 7.43                                   | 4.06                          | 1.81                          | 0.34                     | 0.34                     | 1.16            | WMAP7     | circle       |
| halo4.1 | 13.35                           | 7.23                                     | 6.53                                   | 2.04                          | 0.910                         | 2.68                     | 2.68                     | 1.16            | WMAP7     | circle       |
| halo4.2 | 13.33                           | 6.70                                     | 6.00                                   | 1.36                          | 0.606                         | 9.06                     | 9.06                     | 1.16            | WMAP7     | circle       |
| halo4.3 | 13.42                           | 6.32                                     | 5.63                                   | 1.02                          | 0.455                         | 21.5                     | 21.5                     | 1.16            | WMAP7     | circle       |

run at four different resolution levels, with particle masses varying by a factor of 64, and force softenings by a factor of 4. Note that for halo4 the slightly higher halo mass in the highest resolution run (halo4.3) is due to a merger event that occurs slightly earlier in this simulation compared to the lower resolution runs.

Fig. 1 shows the dark matter mass resolution of our simulations (red filled symbols) compared to a number of state-of-the-art simulations in the literature of comparable mass haloes. We only consider simulations that have been run all the way to redshift $z \simeq 0$. We note that the simulations from Feldmann & Mayer (2015) are higher resolution, with a dark matter particle mass of $7.9 \times 10^5 M_{\odot}$, however, these simulations are only run to $z \simeq 2$, where the halo mass is $\sim 3 \times 10^{12} M_{\odot}$ and thus they do not appear in our comparison.

The highest resolution simulation of a $\sim 10^{13} M_{\odot}$ halo in the literature is from the 25 Mpc box from the EAGLES project (Schaye et al. 2015, open circles). This simulation has a dark matter particle mass of $m_{\text{DM}} = 1.21 \times 10^9 M_{\odot}$ and thus $\sim 7$ million particles for a $\sim 10^{13} M_{\odot}$ halo. Comparable resolution can be obtained with zoom-in simulations with a fraction of the computational cost. The FIRE project (Hopkins et al. 2014, cyan square) includes a simulation with a dark matter particle mass of $m_{\text{DM}} = 2.26 \times 10^8 M_{\odot}$, and roughly 5 million dark matter particles within the virial radius. For comparison our highest resolution runs of halo4 have 3.6 and 10.6 million dark matter particles inside $R_{200}$, and thus are among the highest resolution elliptical galaxy simulations performed to date.

At the fiducial resolution our simulations have $\sim 1.5$ million dark matter particles inside $R_{200}$. This is similar to that of the high resolution halo in Feldmann et al. (2010, blue pentagon), the haloes in Dubois et al. (2013, magenta hexagons), together with the large volume ($\sim 100$ Mpc) simulations by the ILLUSTRIS (Vogelsberger et al. 2014) and EAGLE collaborations (dashed lines). Earlier “zoom-in” simulations from Oser et al. (2010) and Feldmann et al. (2010) have particle masses of $\sim 3.6 \times 10^5 M_{\odot}$, and thus $\sim 300,000$ dark matter particles per halo.

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2.2 Hydrodynamics

Our standard simulations use the same baryonic physics that was used in the MaGICC project (see Stinson et al. 2013), based on the smoothed particle hydrodynamics (SPH) code GASOLINE (Wadsley et al. 2004).

Cooling via hydrogen, helium, and various metal-lines in a uniform ultraviolet ionizing background is included as described in Shen et al. (2010) and was calculated using cloudy (version 07.02; Ferland et al. 1998). These calculations include photo ionization and heating from the Haarrit & Madau (2005) UV background and Compton cooling in the temperature range $10$ to $10^8$ K. In the dense, interstellar medium gas, we do not impose any shielding from the extragalactic UV field as the extragalactic field is a reason-
able approximation in the interstellar medium. Diffusion of metals and thermal energy between particles has been implemented as described in Wadsley et al. (2008).

Stars form from cool dense gas that has reached a temperature of $T < 1.5 \times 10^{5}$K and a density of $n > n_{th}$. For halo1-3 we adopt $n_{th} = 9.6 \text{ cm}^{-3}$ following MaGICC (Stinson et al. 2013). For halo4 we adopt $n_{th} = 1.16 \text{ cm}^{-3}$, which is a conservative estimate of the maximum gas density that can be resolved and is calculated using $n_{th} = 32 (m_{gas}/5)/\epsilon_{gas}$, where $m_{gas}$ is the initial gas particle mass, $m_{gas}/5$ is the minimum gas particle mass, and $\epsilon_{gas}$ is the gas force softening. The factor 32 is the number of SPH smoothing elements. This difference in star formation threshold has no noticeable impact on the structure of the galaxies or dark matter halo. Star formation follows the Kennicutt-Schmidt law with 10 percent efficiency of turning gas into stars during one dynamical time (Stinson et al. 2006). The stellar mass distribution in each star particle follows the Chabrier (2003) stellar initial mass function (IMF).

Massive stars explode as Type II SN and deposit an energy of $E_{SN} = 10^{51}$ erg into the surrounding gas. Cooling for gas particles subject to SN feedback is delayed based on the subgrid approximation of a blast wave as described in Stinson et al. (2006). Furthermore, radiation energy from massive stars is considered since molecular clouds are disrupted before the first SN explosion (which happens after 4 Myr from the formation of the stellar population). We assume that 10 percent of the total radiation energy is coupled with the surrounding gas. The inclusion of this early stellar feedback (ESF) reduces star formation before SN start explodng. Thus, after the ESF heats the gas to $T > 10^{6}$ K, the gas rapidly cools to $10^{4}$ K, which creates a lower density medium than if the gas were allowed to continue cooling until SN exploded. Stinson et al. (2013) and Wang et al. (2015) show how this feedback mechanism limits star formation to the amount prescribed by halo abundance matching (e.g., Behroozi et al. 2013) at all redshifts for haloes of present day virial mass $\sim 10^{10} - 10^{12} M_{\odot}$.

For each initial condition we run three simulations that differ only in their treatment of cooling and star formation.

- **Standard:** cooling, star formation, and stellar feedback at all times following MaGICC (Stinson et al. 2013). Feedback from AGN is not included.
- **Forced Quenching (FQ):** same as standard down to $z \approx 2.1$, after which the simulation is evolved with adiabatic gas until $z = 0$ – i.e., there is no further star formation.
- **No Cooling:** Gas is adiabatic at all times, and thus does not become cool and dense enough to form stars. These simulations act as a control for the effects of galaxy formation (cooling, star formation, and feedback) on the dark halo structure.

The forced quenching simulations act as a limiting case where cooling is shut down and star formation stops rapidly. It allows us to study the effects of dry merging on the structure of the galaxy and dark matter halo with cosmologically consistent initial conditions and merger histories. As we show below this simple prescription allows one to reproduce the stellar mass vs halo mass relation from abundance matching, which is not possible when adopting standard metal line cooling, and no additional heating sources (such as AGN feedback). We note that previous simulations that come close to matching the stellar mass vs halo mass relation without AGN feedback (Oser et al. 2010; Feldmann et al. 2010; Feldmann & Mayer 2015) do so because they adopt primordial metallicity gas in the calculation of the cooling rate. Including realistic halo gas metallicities increases the cooling rate by a factor of $\sim 2 - 3$ (e.g., Dutton & van den Bosch 2012), and thus would result in overcooled...
galaxies. It has been shown that ionizing radiation from young and old stellar populations can significantly reduce cooling rates in $10^{12} M_\odot$ haloes (Kannan et al. 2014). Additionally Conroy et al. (2015) argue that heating provided by the winds of dying low-mass stars is capable of suppressing cooling of hot gas for a Hubble time in halo masses above $\sim 10^{12.5} M_\odot$ at redshifts below $z \sim 2$. Thus, there is motivation for studying the impact of inefficient gas cooling on elliptical galaxy formation.

2.3 Derived galaxy and halo parameters

Haloes in our zoom-in simulations were identified using the MPI+OpenMP hybrid halo finder AHF (Knollmann & Knebe 2009; Gill et al. 2004). AHF locates local over-densities in an adaptively smoothed density field as prospective halo centers. The virial masses of the haloes are defined as the masses within a sphere containing $\Delta = 200$ times the cosmic critical matter density. The virial mass, radius, and circular velocity are denoted $M_{200}$, $R_{200}$, and $V_{200}$. At $z = 0$ there is, by construction, one central halo in the zoom-in region. However, at $z \sim 2$ there are several well resolved progenitor galaxies which we also consider in the global parameter evolution plots.

The mass in stars, $M_{\text{star}}$, is measured within a sphere of radius, $r_{\text{gal}} \equiv 0.2R_{200}$. The stellar half-mass radius, $r_{1/2}$, encloses within a sphere half of the stellar mass within $r_{\text{gal}}$. The half-mass circular velocity is defined as $V_{1/2} = \sqrt{GM(r_{1/2})/r_{1/2}}$, where $M(r_{1/2})$ is the total mass within a sphere of radius $r_{1/2}$. The (mass weighted) slope of the total mass density profile, $\gamma'$, and the “inner” slope of the dark matter density profile, $\alpha$, are measured between 0.01 and 0.02 $R_{200}$. The choice of this scale is motivated by the following: it is used by previous studies (e.g., Di Cintio et al. 2014); it is resolved in our simulations; and it corresponds to the average half-light radii of galaxies (Kravtsov 2013) and is thus observationally accessible.

Images of our simulated galaxies at $z = 0$ are shown in Figs. 2. Each image is 50 kpc on a side and was created using the Monte Carlo radiative transfer code SUNRISE (Jonsson 2006). The image brightness and contrast are scaled using arcsinh as described in Lupton et al. (2004). All simulated galaxies have red colors and elliptical like morphology. Some show signs of recent mergers in the form of shells and streams. The main apparent difference between the standard (upper panels) and forced quenching (lower panels) simulations is a reduction in surface brightness (the same scale is used in all images). As is visible, and we show quantitatively below, the half-light sizes are roughly the same in each type of simulation (standard vs FQ).

3 GLOBAL PROPERTIES

Before we discuss the response of dark matter haloes to galaxy formation in § 4 we present several global properties of our simulated galaxies and compare them to observations. At $z = 2.1$, the standard simulations compare well with observed galaxies. However, once they are evolved to $z = 0$, the standard simulations have too many stars, are too dense, and have mass profiles that are too centrally concentrated. Thus, they are poor candidates for studying halo contraction. In contrast, we show that the forced quenching simulations share many properties with observed galaxies at $z = 0$, so it is more interesting to study them as templates for elliptical galaxy formation.

3.1 Stellar mass vs halo mass

One of the most fundamental properties of a galaxy or dark matter halo is its mass. The relation between the mass in stars, $M_{\text{star}}$, and the virial mass, $M_{200}$, of our simulated galaxies is shown in Fig. 3. Results are shown at redshift $z = 0$ for standard (black open symbols) and forced quenching (red filled symbols) and at $z = 2.1$ (blue open symbols) show the most massive progenitor, while cyan open symbols show other progenitors containing more than 20,000 total particles). The lines show the relations from halo abundance matching from Behroozi et al. (2013), with the shaded region showing the 1σ intrinsic scatter. Two assumptions for the observed stellar masses are shown: A Chabrier (2003) initial mass function (IMF, dashed) as found in the Milky Way; and Chabrier+0.23 dex (solid), which corresponds to a Salpeter (1955) IMF and is likely a better approximation

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Chabrier (dashed) and Salpeter (solid) IMFs. The shaded regions show the black open symbols, and the forced quenching simulations are shown with red filled symbols. At z = 0 the standard simulations are shown with black open symbols, and the forced quenching simulations are shown with red filled symbols. At z = 2.1 the most massive progenitors are shown with blue symbols, and the lower mass progenitors with cyan. The cyan lines show the observed size-mass and velocity-mass relations for star forming galaxies at z = 2.1.

Figure 4. Scaling relations between galaxy size, $r_{1/2}$, circular velocity at the half-mass size $V_{1/2}$, and galaxy stellar masses, $M_{\text{star}}$, at $z = 2.1$ and $z = 0$. The observed relations for quiescent galaxies are shown at $z = 0$ (red/pink) and $z = 2.1$ (blue/grey) for both Chabrier (dashed) and Salpeter (solid) IMFs. The shaded regions show the 1σ scatter. At $z = 0$ the standard simulations are shown with black open symbols, and the forced quenching simulations are shown with red filled symbols. At $z = 2.1$ the most massive progenitors are shown with blue symbols, and the lower mass progenitors with cyan. The cyan lines show the observed size-mass and velocity-mass relations for star forming galaxies at $z = 2.1$.

for the centers of massive elliptical galaxies (e.g., Conroy & van Dokkum 2012; Dutton et al. 2013b).

At redshift $z = 0$ the standard simulations over predict the Chabrier IMF stellar masses by an order of magnitude — this is the classic overcooling problem. Even if one adopts a Salpeter IMF, the stellar masses are still over predicted by a factor of $\sim 4$. Given the 1σ intrinsic scatter in the stellar masses at fixed halo masses is $\sim 0.2$ dex (More et al. 2011; Reddick et al. 2013), real galaxies offset from the median relation by a factor of $\sim 4$ will be extremely rare, if they even exist. Thus there is no escape from the conclusion that these simulations have formed too many stars. At $z = 2.1$, however, the standard simulations have only a factor of $\sim 2$ too many stars compared to a Chabrier IMF. Thus when adopting an observed Salpeter IMF the simulations provide a good match to the halo abundance matching results. Note that while there is a formal inconsistency here between the IMFs used in our simulations (Chabrier) and observation (Salpeter), in practice the feedback efficiency parameters in the simulations can be simply rescaled.

When we disable cooling and force quenching at redshift $z = 2.1$ the resulting stellar masses at $z = 0$ are consistent with halo abundance matching constraints, provided we also adopt a Salpeter-like IMF at $z = 0$. Thus, our simulations show that no new stars are needed to be formed since redshift $z \sim 2$ in haloes of present day mass of $M_{z=200} \sim 10^{13}M_\odot$. This result supports a two phase galaxy formation picture (e.g., Oser et al. 2010). At halo masses below $M_{z=200} \sim 10^{12}M_\odot$ central galaxies form the majority of stars in situ, with the efficiency being regulated by stellar feedback. Above $M_{z=200} \sim 10^{12}M_\odot$ in situ star formation is suppressed, and the growth in stellar mass is dominated by dissipationless mergers.

A consequence of the dissipationless assembly is that whatever IMF characterizes the $z = 0$ galaxies must also describe their most massive progenitors. In our simulations progenitor galaxies with $M_{\text{star}} \gtrsim 10^{10}M_\odot$ at $z = 2.1$ contribute 90% of the present day mass. Since the lower mass progenitors ($M_{\text{star}} \lesssim 10^{10}M_\odot$) don’t contribute significantly to the $z = 0$ central galaxy mass, this self-consistency argument does not constrain their IMF. The stars from the lower mass progenitors preferentially end up at large radii, which would result in a radial IMF gradient if the low mass galaxies have normal IMFs.

3.2 Galaxy sizes and circular velocities

The next global properties we consider are the half-mass size of the stellar mass distribution, $r_{1/2}$, and the circular velocity at $r_{1/2}$. Fig. 4 shows the size-mass (left) and velocity-mass (right) relations at $z \geq 0$ and $z \simeq 2$.

For the size-mass relation we compare to observations from van der Wel et al. (2014) — who measure 2D major axis half-light radii in rest frame V-band light for both quiescent and star forming galaxies. The observed relations for non-star-forming galaxies at $z = 2.1$ and $z = 0$ are shown with blue and red lines, respectively, with the shaded region showing the 1σ intrinsic scatter. As in Fig. 3 the solid lines assume a Salpeter IMF, while the dashed lines assume a Chabrier IMF. At $z = 2.1$ we also show the size-mass relation for star forming galaxies with cyan lines.

In our simulations we measure spherical 3D half-stellar
mass sizes. To correct for projection effects we multiply the observed sizes of ETGs by 4/3. No correction is applied to LTGs as the high disk fractions suggest a minimal difference between projected and spherical aperture sizes. We leave an investigation of projection effects, mass-to-light ratio variations and axis ratios to a future study. The purpose of our current comparison is to determine if the simulated galaxies have reasonable structural properties. The observed relation between 3D half-light size, stellar mass (assuming a Chabrier IMF) and redshift is thus

\[
\frac{R_{1/2}}{[\text{kpc}]} = 5.73 \left( \frac{M_{\text{star}}}{\left[5 \times 10^{10} M_\odot\right]} \right)^{0.75} H(z)^{-1.29}.
\]  

(1)

For the velocity-mass relation we use the \(z = 0\) Faber & Jackson (1976) relation for quiescent galaxies from Gallazzi et al. (2006). We convert velocity dispersions into circular velocity using \(V_{1/2} = 1.5\sigma_e\) (Dutton et al. 2011b; Cappelletti et al. 2013). For the evolution we adopt the scaling of \(\sigma(M_{\text{star}}) \sim (1+z)^{0.44}\) from the observed compilation of Oser et al. (2012). The observed relation between circular velocity, stellar mass (assuming a Chabrier IMF) and redshift is thus

\[
\frac{V_{1/2}}{[\text{km s}^{-1}]} = 220 \left( \frac{M_{\text{star}}}{\left[5 \times 10^{10} M_\odot\right]} \right)^{0.29} (1+z)^{0.44}.
\]  

(2)

For star forming galaxies galaxies at \(z \sim 2\) we use the velocity-mass relation from Dutton et al. (2011a) using data from Cresci et al. (2009).

The most massive galaxies at \(z = 2.1\) in the standard simulations (blue symbols) have half-mass sizes of \(\sim 1 - 2\) kpc and circular velocities of \(\sim 400 - 500\) km s\(^{-1}\), consistent with the size-mass and velocity-mass relations of quiescent galaxies (dark grey shaded regions). The lower mass progenitors (cyan symbols) lie close to the corresponding relations for star forming galaxies (shown with cyan lines). Thus the standard simulations form a realistic population of progenitor galaxies, adding to the successes of MaGICC feedback model (Stinson et al. 2013) in reproducing global scaling relations of spiral galaxies (Brook et al. 2012; Wang et al. 2015).

By \(z = 0\) both the standard and FQ simulations the most massive galaxies have grown substantially in size and mass. The standard simulations (black open symbols) have grown roughly along the \(z = 2.1\) size-mass relation and are thus too dense compared to \(z = 0\) observations. The FQ simulations fall parallel to the observed size-mass relation, being offset on average by factor of \(\sim 1.5\). Observational effects that may contribute to this discrepancy are discussed below. Here we note that numerical resolution may play a role, as the sizes of halo4 have not shown convergence when we increase the mass resolution by a factor of 8 (from level1 to level3). By contrast, stellar masses are stable for simulations with more than a million particles.

The changes since \(z = 2.1\) in the sizes, circular velocities, and stellar masses are more clearly shown in Fig. 5. For both standard and FQ simulations the sizes increase on average by \(\sim 0.6\) dex, albeit with more variation in the FQ simulations. This is interesting given that the mass evolution differs by a factor of \(\sim 4\) between standard and FQ simulations. However, the velocity evolution is different: a decrease of \(\sim -0.1\) dex for the FQ simulations, and an increase of \(\sim 0.15\) dex for the standard simulations.

The dotted lines in Fig. 5 show the changes expected...
for dry major ($R \propto M, V = \text{const}$) and minor mergers ($R \propto M^2, V \propto M^{-1/2}$). (e.g., Bezanson et al. 2009; Hopkins et al. 2010). All but one simulation (halo2, squares) falls within these expected scalings. In halo2 the size increases by a factor of 2.5 with very little increase in stellar mass which points towards an adiabatic expansion scenario.

The solid lines in Fig. 5 show the change in size and velocity-scaling relations between $z = 2.1$ and $z = 0$. For no mass change, sizes need to increase by 0.61 dex and velocities need to decrease by −0.22 dex. If the stellar masses increase, even stronger evolution is required to remain on the size-mass relation. Our FQ simulations have the observed amount of evolution in velocities, but don’t have as much evolution in sizes as observed, they are still too small by a factor of ~1.5. There are several considerations to keep in mind when interpreting the small size:

1) Population growth. If there is substantial growth in the number of quenched galaxies at a given mass, then the scaling relation will be dominated by the new arrivals. Thus earlier quenched galaxies could be significantly offset from the relation without violating the scatter.

2) Progenitor size bias. Star forming galaxies are observed to be larger than quenched galaxies. If the quenching process does not change the galaxy size, then galaxies that are added to the quenched population will have, on average, larger sizes than existing quenched galaxies of the same mass. Thus the earlier quenched galaxies will not need to grow as much in size as the population appears to.

3) M/L variations. In the simulations we are measuring sizes in stellar mass, while observations are for optical stellar light. Galaxies are known to have smaller sizes in longer wavelengths (e.g., van der Wel et al. 2014). For quiescent galaxies the implied conversion from rest frame V-band to K-band (which presumably traces stellar mass) is on average 0.15 dex. Star forming galaxies have stronger gradients at later times, which results in stronger evolution in half-light than half-mass sizes by 0.14 dex. A similar effect for quiescent galaxies would thus explain the entire discrepancy between our simulations and observations. In addition to color gradients, IMF gradients could plausibly make sizes appear larger in light than they are in mass. For example, if the most massive $z = 2.1$ progenitor formed with a uniformly heavy IMF, and then grew by adding galaxies with lighter IMF to the outer parts. We note there are recent observational hints of such radial IMF variations in massive quiescent galaxies (Martín-Navarro et al. 2015).

3.3 Mass density slopes

A further observational test of the realism of the simulated galaxies comes from the slope of the total mass profile, $\gamma'$, which is measured near the galaxy half-light radius. Fig. 6 shows $\gamma'$ vs stellar surface density, $\Sigma_{\text{star}} = M_{\text{star}}/(2\pi R_e^2)$, for our simulations and observations at $z \sim 0$. Points with error bars show observations using strong lensing from the SLACS survey (Auger et al. 2010b), where the stellar density is calculated assuming a Salpeter IMF. In our simulations we measure $\gamma'$ between 1% and 2% of the virial radius, as this corresponds to the typical half-light sizes of quiescent galaxies (Kravtov 2013). The forced quenching simulations (red filled symbols) have $1.8 \lesssim \gamma' \lesssim 2.1$, while the standard simulations (black open symbols) have $2.3 \lesssim \gamma' \lesssim 2.4$. Ob-
served galaxies exist with all such values, though the forced quenching simulations have more typical values, and while the forced quenching simulations fall within the observed distribution of $\gamma'$ and $\Sigma_{\text{star}}$, the standard simulations fall well outside.

It is also possible to measure the mass slope over a longer baseline using the velocities at $r_{1/2}$ and $R_{200}$. Observations using weak gravitational lensing and satellite kinematics find that for massive ellipticals $V_{1/2} \sim V_{200}$ (Dutton et al. 2010). The standard simulations have declining circular velocity profiles with $V_{1/2}/V_{200} \sim 1.6$ to 2.0. The forced quenching simulations have much flatter profiles with $V_{1/2}/V_{200} \sim 0.8$ to 1.0 in agreement with observations.

The slope of the mass profile both locally at $\sim r_{1/2}$ and globally between $r_{1/2}$ and $R_{200}$ further support the conclusion that the FQ simulations have realistic distributions of stars and total matter at small radii, while the standard simulations have too much stellar and total mass at small radii.

### 3.4 Resolution effects on galaxy structure

One of our initial conditions (halo4) has been run at four different resolution levels: level0 is the lowest and level3 is the highest (see Fig. 1 & Table 2). In Figs. 4-7, the galaxy structural parameters for these simulations are shown with larger circles for higher resolution. There is clearly significant variation in the galaxy structural parameters at different resolutions. Here we focus our discussion on the forced quenching simulations at $z = 0$.

The stellar mass increases with resolution by 0.39 dex from lowest to highest. However, most of this difference (0.33 dex) is due to the lowest resolution simulation, which has only $\sim 10^5$ dark matter particles within the virial radius. There is just 0.06 dex difference between level1 and level3. Circular velocity at the half-mass radius, $V_{1/2}$, shows a similar qualitative trend, with higher velocities in higher resolution simulations, but with smaller relative changes. Between the highest three resolution simulations the variation in $V_{1/2}$ is just 2%. Half-mass sizes vary by a factor of $\sim 2$ with no clear trend with resolution. Stellar surface densities show the largest variation with a factor of $\sim 8$ difference. This variation in surface density is clearly visible in the galaxy images shown in Fig. 5. If we remove the lowest resolution simulation the variations in sizes and surface densities are reduced to a factor of $\sim 1.6$ and $\sim 2.0$, respectively.

In summary, for simulations with more than a million particles inside the virial radius the stellar masses and circular velocities are well converged while the half-mass sizes and average stellar surface densities show significant variation.

### 4 DARK HALO RESPONSE TO GALAXY FORMATION

In the previous section we have established how well our various simulations reproduce observed global properties of elliptical galaxies at $z = 0$ and their progenitors at $z \sim 2$. We now turn our attention to the radial distribution of dark matter, and in particular how this responds to the galaxy formation process.
4.1 Circular velocity profiles

Figs. 9-11 show circular velocity profiles, where $V_{\text{circ}} = \sqrt{GM(r)/r}$, for our simulated galaxies at $z = 2.1$ and $z = 0$. Velocity profiles are plotted from $r_{\text{min}}$ to the the virial radius, $R_{200}$. Here $r_{\text{min}}$ is the maximum of the convergence radius as defined by Power et al. (2003) and twice the softening length. The circular velocity at stellar half-mass radius is shown with a different symbol for each halo, following on from previous plots.

When making these velocity profiles we have taken care to ensure that the systems are relaxed. During a merger event the assumption of spherical symmetry breaks down, the center is no longer well defined, and the derived mass profile will have an apparent core in the center. By comparing the mass profiles at different snapshots spaced nearby in time, the presence of mergers is easily detected. We have selected the snapshot closest to $z = 0$ or $z = 2.1$ in which both the galaxy formation and no cooling simulations show no obvious signs of being compromised by mergers.

A comparison of the circular velocities at the virial radius (the last point in the velocity profile) shows that the standard (solid lines, Fig. 10), forced quenching (solid lines, Fig. 11) and no cooling (dashed lines, Figs. 10 & 11) simulations all have the same dark and baryonic masses. Furthermore, this implies that the haloes have been able to retain all of their cosmic share of baryons. In all simulations stars (cyan lines) dominate the baryon budget at small radii, while gas (green lines) becomes as important as the stars at large radii. In the FQ simulations the gas roughly follows the mass...
Figure 13. Change in enclosed dark matter mass due to galaxy formation: with standard physics at $z = 2.1$ (left) at $z = 0$ (middle); and with forced quenching at $z = 0$ (right). Predictions from the adiabatic contraction ("AC") models of Blumenthal et al. (1986, B86) and Gnedin et al. (2004, G04) are shown with green dotted and magenta dot-dashed lines, respectively. At redshift $z = 0$ the contraction in our simulations is substantially weaker than predicted by these models. Upper panels show change with respect to simulations without cooling ("No Cool"), while lower panels show differences with respect to the galaxy formation simulations ("Hydro").

A comparison between the solid and dashed red lines in Figs. 9 - 11 shows that all the dark matter haloes have contracted in response to galaxy formation. The strength of the contraction is more clearly seen in Fig. 12 which shows the ratio of dark matter circular velocities. The numerator is the dark matter circular velocity in the simulations with galaxy formation (i.e., standard/FQ) and the denominator is the dark matter circular velocity in the simulations without galaxy formation (i.e., no cooling). In the standard simulations the velocity ratio is roughly the same at $z = 0$ (black lines) as it is at $z = 2.1$ (blue lines), whereas in the FQ simulations (red lines) the contraction is not as strong.

4.2 Adiabatic contraction formalism

To understand the effect of the baryonic physics on the dark matter density profile, we employ the analytic adiabatic contraction formalism outlined in Blumenthal et al. (1986), and introduced in another context in Barnes & White (1984). The main assumption is that the time scale for galaxy for-
motion is long compared to the orbital time scale of the dark matter particles. With the simplifying assumptions of spherical symmetry and circular dark matter particle orbits, the adiabatic invariant reduces to \( rM(r) = \text{const} \), where \( M(r) \) is the total mass enclosed within radius \( r \).

Thus given a spherically enclosed mass profile from a simulation without gas cooling, \( M_i(r) \), (where the \( i \) refers to initial), we can derive the final dark matter profile, \( M_{\text{fm}}(r) \), once the final baryonic mass profile, \( M_{\text{fb}}(r) \), is specified. The initial total mass profile is split into dark matter \( M_{\text{dm}}(r) \), and baryons \( M_{\text{bar}}(r) \) either explicitly (as in our no cooling simulations) or implicitly assuming \( M_{\text{dm}}(r) = (1 - f_{\text{dm}})M_i(r) \), where \( f_{\text{dm}} \) is the cosmic baryon fraction \((\Omega_b/\Omega_m \sim 0.16)\).

An additional assumption is that the dark matter shells do not cross: \( M_{\text{dm}}(r_i) = M_{\text{dm}}(r_f) \), where \( r_i \) is the “initial” radius of a shell of dark matter, and \( r_f \) is the radius of this shell after the effects of galaxy formation are included. Putting this together yields

\[
\frac{r_i}{r_f} = \frac{M_i(r_i)}{[M_{\text{bar}}(r_i) + M_{\text{dm}}(r_i)]}.
\]  

Thus given \( M_i \) and \( M_{\text{bar}} \), one can solve Eq. 3 for the mapping between \( r_i \) and \( r_f \), and hence derive the final dark matter profile. The appeal of this formalism is that in the adiabatic limit the response of the halo depends only on the final state of the baryons, and is independent of how it was assembled.

Particle orbits in CDM haloes are not circular. To account for this Gnedin et al. (2004) introduced a modified adiabatic invariant: \( rM(r) \), where \( r \) and \( f \) are the current and orbit-averaged particle positions. The orbit average radius can be approximated as: \( \bar{r} \approx R_{\text{vir}}A(r/R_{\text{vir}})^{\nu} \), with \( A \approx 0.85 \) and \( \nu \approx 0.8 \). This modified adiabatic invariant results in slightly weaker contraction.

Fig. 15 shows the change in the dark matter masses profiles in our simulations and that predicted by the adiabatic contraction models of Blumenthal et al. (1986, B86) and Gnedin et al. (2004, G04). At \( z = 2.1 \) (left panel) the G04 model works for radii \( r \gtrsim 5 \) kpc, and the B86 model for \( r \geq 10 \) kpc. At smaller radii the models predict more contraction than seen in our simulations. By \( z = 0 \) (middle and right panel) the over prediction has grown and extends to all radii (less then the virial radius). For example, at 5 kpc the G04 and B86 models over predict the mass by a factor of \( \sim 2 \) and \( \sim 3 \), respectively. These results are qualitatively similar to previous studies on Milky Way mass haloes (Abadi et al. 2010; Pedrosa et al. 2010).

Returning to the halo response formalism, an example of how the radii and masses are calculated in one of our simulations is shown in Fig. 14. The solid lines show the total (black) and dark matter (red) mass profiles for the standard simulation for halo4.2. The dashed lines show the total (black) and dark matter (red) mass profiles for the corresponding simulations with no cooling. The horizontal dotted blue line shows an arbitrary mass, here \( 10^{11}M_\odot \). The radius this intersects the dark matter profile from the standard simulation is termed \( r_1 \) (vertical blue solid line), while the radius this intersects the dark matter profile from the no cooling simulation is termed \( r_1 \) (vertical blue dashed line). The total masses contained within \( r_1 \) and \( r_1 \) are then given by \( M_t \) (horizontal blue solid line) and \( M_i \) (horizontal blue dashed line) respectively.

All simulations show contraction at small radii (see also Figs. 9(11), with the standard simulations at \( z = 0 \) showing a small amount of expansion at large radii, \( r \gtrsim 30 \) kpc, which corresponds to the radius where there is equal baryons and dark matter. The points show the halo response at \( r_i \). The standard simulations at \( z = 2.1 \) and \( z = 0 \) have \( r_1/r_1 \sim 0.5 \), \( \nu \sim 0.1 \) for adiabatic contraction, and the FQ simulations have \( r_1/r_1 \sim 0.8 \) vs \( \nu \sim 0.4 \) for adiabatic contraction.

Overall the halo response does not follow a single track, although interestingly at a given redshift each type of simulation results in a similar halo response. To quantify different halo responses we first consider the equation introduced by Dutton et al. (2007):

\[
r_1/r_1 = (M_t/M_i)^\nu.
\]  

Fig. 14. Example showing how \( r_1/r_1, M_t, M_i \) are calculated in the cumulative mass vs radius plot for simulation Halo4 using standard galaxy formation physics. The horizontal blue dotted line shows an arbitrary mass, here \( 10^{11}M_\odot \). The radius this intersects the dark matter profile from the standard simulation is termed \( r_1 \) (vertical blue solid line), while the radius this intersects the dark matter profile from the no cooling simulation is termed \( r_1 \) (vertical blue dashed line). The total masses contained within \( r_1 \) and \( r_1 \) are then given by \( M_t \) (horizontal blue solid line) and \( M_i \) (horizontal blue dashed line) respectively.
Figure 15. Dark halo response of our simulations: standard $z = 2.1$ (upper left, blue); standard $z = 0$ (upper right, black); forced quenching $z = 0$ (lower right, red); forced quenching $z = 0$ resolution tests with halo4 (lower left, red). The filled points show the halo response at the galaxy half-stellar mass radius (with different simulations represented by different symbols as indicated). The dotted green lines show various halo responses of the form $r_f/r_i = (M_i/M_f)\nu$. Where $\nu = 1$ corresponds to adiabatic contraction, $\nu = 0$ corresponds to no change, and $\nu = 0.5$ and $\nu = 0.25$ correspond to weak contraction. The dot-dashed magenta lines show the halo response model of Abadi et al. (2010, A10).

While the standard simulations at $z = 0$ are approximated by Eq. [3] with $\nu = 0.25$, the standard simulations at $z = 2.1$ and the FQ simulations at $z = 0$ are not well described by this formula. The magenta lines show the formula from Abadi et al. (2010), $r_f/r_i = 1 - 0.3(M_i/M_f - 1)^2$, which approximately describes our forced quenching simulations at $z = 0$ (lower right panel). This similarity may be a coincidence as their simulations are missing important aspects of galaxy formation processes such as star formation and feedback.

The shaded regions in Fig. 15 bracket the halo response shown in the 4 initial conditions. They are given by the following relations, where the uncertainties bracket the range in halo response: standard simulations at $z = 2.1$ (upper left)

$$r_f/r_i = 0.5(0.10^{+0.12}_{-0.12}) + 0.5(0.2^{+0.2}_{-0.1})(M_i/M_f + 0.2^{+0.2}_{-0.1})^2;$$

standard simulations at $z = 0$ (upper right)

$$r_f/r_i = 1.0(0.06^{+0.06}_{-0.06}) - 0.52(M_i/M_f - 1)^2;$$

FQ simulations (lower right)

$$r_f/r_i = 0.75(0.07^{+0.07}_{-0.07}) + 0.25(0.01^{+0.01}_{-0.01})(M_i/M_f)^2;$$

A numerical convergence test is shown in the lower left.
Figure 16. Logarithmic slope of the dark matter density profile, \( \alpha \), measured between 1 and 2\% of the virial radius, \( R_{200} \), vs the ratio between the stellar and virial mass, \( M_{\text{star}}/M_{200} \). Blue symbols show standard simulations of halo4 at \( z = 2.1 \), black symbols show standard simulations at \( z = 0 \), and red symbols show forced quenching simulations at \( z = 0 \). The green dotted lines show \( \alpha \sim -1.2 \) for the control simulations (without cooling). The grey shaded region shows the relation from Tollet et al. (2015, in prep) which was calibrated against haloes of mass \( 10^{10} - 10^{12} M_\odot \).

panel of Fig. 15. This shows the halo response for halo4 run at four different mass (and force) resolution levels (see Table 2). All simulations have similar halo response (especially the highest three resolution simulations), suggesting convergence. The lowest resolution simulation (halo4.0) does not have as much contraction, but follows a similar path in the \( r_t/r_i \) vs \( M_i/M_f \) plane.

4.3 Central dark matter slopes

Another way to express the strength of the contraction of the dark matter halo is the central density slope, \( \alpha \). We measure \( \alpha \) between 0.01 and 0.02\( R_{200} \) which corresponds to \( \sim 5 - 10 R_{200} \). We show this in Fig. 16 for our simulations at \( z = 0 \). Following Di Cintio et al. (2014) we show in Fig. 16 the relation between \( \alpha \) and galaxy formation efficiency, \( M_{\text{star}}/M_{200} \). Our FQ simulations (red points) have \(-1.7 \lesssim \alpha \lesssim -1.4 \), while the standard simulations (black points) have \(-2.0 \lesssim \alpha \lesssim -1.6 \). For reference, the dotted green lines show the no cooling simulations which have \(-1.3 \lesssim \alpha \lesssim -1.1 \), the same values as found in dark matter only simulations.

The solid line and shaded region shows the relation obtained from Tollet et al. (2015, in prep) who used a set of \( \sim 80 \) zoom-in simulations of halo mass \( \sim 10^{10} \) to \( 10^{12} \) from the NIHAO project (Wang et al. 2015). Our standard simulations are close to this relation (both at \( z = 0 \) and \( z = 2.1 \)), but the forced quenching simulations are significantly offset. At a stellar to halo mass ratio of \( M_{\text{star}}/M_{200} \sim 0.01 \) spiral galaxy haloes have large amounts of expansion, whereas our elliptical simulations contract. Thus the inner dark matter density slope is not purely determined by the efficiency of star formation. This difference is a reflection of the different formation channels of spiral vs elliptical galaxies. In spiral galaxies the vast majority of stars form in situ, with the efficiency being regulated by SN feedback which also has strong expansive effects on the halo. In elliptical galaxies, a significant fraction of the stars were formed ex situ, and were assembled with dry mergers which has a milder expansive effect on the halo.

Finally, we note that the form of the halo response in Eqs. (44) which has a constant ratio between initial and final radii at \( r = 0 \), implies that at very small radii the central dark matter slope tends to the dissipationless case. If haloes are described by the Navarro, Frenk & White (1997) formula, then the inner slope would be \(-1 \), however, if the Einasto (1965) profile holds then this implies the centers of dark matter haloes have constant density. Practically speaking, however, the presence of a supersonic black hole may cause a dark matter spike (Gondolo & Silk 1999), rendering these extrapolations a moot point.

4.4 Slow expansion

When we disable gas cooling at \( z = 2.1 \), the gas at small radii heats up and expands to larger radii, see the green lines in Fig. 17. One might worry that this would cause the halo to expand artificially. However, the circular velocity plots in Fig. 9 show that the gas is a sub-dominant component with \( V_{\text{gas}} \sim 0.1 V_{\text{circ}} \), and thus contributes just \( \sim 1\% \) to the enclosed mass at all radii (recall that \( M \propto V^2 \)). Thus in the extreme case that all of the gas is removed instantaneously, the expansion of the dark and stellar mass distributions would be negligible.

Fig. 17 shows the evolution in the mass enclosed within 5 proper kpc for our simulations. The total mass is shown in black, the dark matter in red, the stars in blue and the gas in green. The three line types correspond to the standard (solid), FQ (long-dashed), no cooling (dotted) simulations. Time steps where the halo is clearly undergoing a merger have been removed since it is impossible to determine the central 5 kpc accurately during those time periods.

In the no cooling simulation the dark matter mass is roughly constant at \( \sim 2 - 3 \times 10^{10} M_\odot \) since \( a = 0.15 \) (\( z \sim 5 \)). In the standard simulation the dark halo starts to contract at \( z \sim 5 \), reaches a maximum mass a factor of \( \sim 2.5 \) times that of the no cooling simulation at \( z \sim 2 \), and remains roughly constant to \( z = 0 \). By contrast the stellar mass within 5 kpc continues to increase all the way to \( z = 0 \). In the FQ simulation the stellar mass is roughly constant since \( z = 2.1 \), with a slight reduction due to stellar mass loss, while the dark matter mass slowly decreases since \( z \sim 2 \) by \( \sim 0.2 \) dex. This gradual expansion of the dark matter halo since \( z = 2.1 \) in the forced quenching simulations is further evidence that the expansion is not caused by a single event at \( z = 2.1 \) or later, such as a major merger.

There are two processes that are likely contributing to the smooth expansion: multiple minor mergers (e.g., El-Zant et al. 2001) and adiabatic expansion due to stellar mass loss. In our simulations up to 40\% of the stellar mass, i.e., \( \sim 4 \times 10^{10} M_\odot \), is returned to the ISM. In the standard simu
Figure 17. Mass enclosed within 5 proper kpc vs scale factor for the most massive progenitors in our 4 simulations. The total mass is given by black lines and points, dark matter by red and stars by blue. In the no cooling simulations (crosses, dotted line) the dark matter is in place by $a \sim 0.15$ ($z \sim 5$). In the standard simulations (filled circles, solid lines) the halo contracts, increasing the mass by a factor $\sim 2.5$. The contraction occurs by $z = 2.1$ and remains constant to $z \sim 0$, even though the stellar mass increases by an order of magnitude during this interval. In the forced quenching simulations (open circles, dashed lines) the dark matter within 5 kpc gradually decreases with time due to a combination of stellar mass loss and dry minor merging. We thus conclude that both minor merging and stellar mass loss are responsible for the expansion of the dark matter halo since $z = 2.1$ in our forced quenching simulations.

5 DISCUSSION

For the massive galaxies we simulate in this paper there are three main processes that determine the halo response: dissipative (gas) accretion; dissipationless (dry) merging and gas outflows driven by AGN. In lower mass galaxies SN/stellar winds are the dominant drivers of gas outflows. The first two processes are included in our simulations, while AGN
are not. Dissipative accretion will only cause the halo to contract, while dry merging and AGN feedback can (but will not necessarily) cause halo expansion. These processes are not independent, as for example, stronger dissipation leads to more contraction in the central galaxy, but also denser satellites which can survive to smaller radii, and cause more expansion to the dark matter. Thus, it is not obvious whether more dissipation will always translate into more contraction.

5.1 Does dry merging lead to halo expansion?

In the halo quenching scenario the mass assembly is dominated since $z \sim 2$ by dry mergers. It has been proposed (El-Zant et al. 2001; Luckner & Ostriker 2010) that this will create cores in the dark matter halo. While we do find that dry merging causes haloes to expand relative to the $z \sim 2$ case, the net effect at the halo mass scale we study ($M_{200} \sim 10^{13}M_\odot$) is still contraction: the dark mass within 5 kpc has increased by a factor of $\sim 1.4$. Our simulations show that the contraction effects of dissipation at early times outweigh the expansive effects of dry merging at late times. In contrast to previous studies, our simulations are fully cosmological with realistic progenitor masses and sizes which form realistic elliptical galaxies at $z = 0$. This is important, as the stellar density, orbits, and number of satellite galaxies determines the magnitude of the halo expansion effect.

5.2 What is the halo response due to AGN feedback?

Simulations that incorporate AGN driven feedback can result in halo expansion (e.g., Peirani et al. 2008; Duffy et al. 2010; Martizzi et al. 2012), although others seems to result in no significant change (e.g., Schaller et al. 2015a). Since our forced quenching simulations produce contracted haloes, this difference in halo response suggests a new way to distinguish between suppressive (halo) quenching and effective (AGN) quenching.

It still needs to be determined what simulations with AGN feedback actually predict for halo structure. It is important that the simulations reproduce the global properties of galaxies such as we discuss in §3 since the strength of the feedback will affect both the halo response and the mass and structure of the galaxies. Theoretical models of AGN feedback are often calibrated to match the present day galaxy stellar mass function (e.g., Schaye et al. 2015). A complication to this calibration is that the true stellar masses of galaxies are not known accurately. In the case of the EAGLES simulations (Schaye et al. 2015) the observed stellar mass function used in the calibration was derived assuming a Milky Way IMF. We know from dynamics and lensing studies that a Milky Way IMF requires close to adiabatically contracted dark matter haloes in elliptical galaxies (Auger et al. 2010a; Schulz et al. 2010; Dutton et al. 2011b; 2013b). However, the halos in the EAGLES simulations show almost no change (Schaller et al. 2015a), which points towards an inconsistency between these simulations and observations.

Furthermore, recent evidence points towards non-Milky Way IMFs in massive elliptical galaxies from both dynamical and stellar population modeling approaches (e.g., Auger et al. 2010a; van Dokkum & Conroy 2010; Conroy & van Dokkum 2012; Dutton et al. 2013a; Cappellari et al. 2013; Barnabè et al. 2013; Ferreras et al. 2013; Sonnenfeld et al. 2015). The favored stellar masses are a factor of $\sim 2$ higher than obtained assuming a Milky Way IMF. Thus it would seem necessary for simulations such as EAGLES to be re-calibrated to galaxy mass functions based on heavier IMFs in the most massive galaxies.

The structural properties of galaxies can provide additional constraints for AGN feedback models. In particular the total mass density slopes at $\sim 1\%$ of the virial radius, and the size vs velocity relation are independent of uncertainties in the IMF. At a halo mass of $\sim 3 \times 10^{13}M_\odot$, the total mass density slopes at $1\%$ of the virial radius in the EAGLES simulations are typically shallower than observed (Schaller et al. 2015b), providing further evidence for insufficient dissipation.

Simultaneously reproducing several galaxy structural properties is a non-trivial task. Dubois et al. (2013) present six zoom-in simulations of halo mass $0.4 \sim 8 \times 10^{13}M_\odot$ that include AGN feedback. The simulations broadly reproduce the size vs stellar mass, velocity dispersion vs stellar mass and total mass density slopes at redshift $z \sim 0$. In detail there are some discrepancies that again point towards insufficient dissipation. The total mass density slopes are too shallow, and relative to observed stellar masses derived using a Salpeter IMF the simulated sizes are too large while the velocity dispersions are slightly too small.

5.3 Future directions for halo quenching models

The halo quenching model we implement in this paper could be improved upon in several ways. We turn the gas adiabatic everywhere in the simulation at $z \sim 2$, which corresponds to when the most massive progenitor reaches a halo mass of $\sim 10^{12}M_\odot$. A more realistic scenario would be to only shut off cooling in haloes above $\sim 10^{12}M_\odot$, or some other galaxy property such as stellar density or bulge mass, allowing cooling and star forming in lower mass progenitor galaxies to occur below $z = 2.1$. This additional cooling would presumably result in denser inner galaxies, and more contraction. Another improvement would be to implement photo-ionization from stellar sources (Kannan et al. 2014, 2015) or heating from AGB stars (Conroy et al. 2015) directly into the simulations.

Simulations could be run at different halo masses, e.g., from $\sim 10^{12} \sim 10^{14}M_\odot$ to determine if there is any mass dependence to the halo contraction in halo quenching scenario. In the context of $\Lambda$CDM, more massive haloes have a larger fraction of the stellar mass in the central galaxy assembled through mergers (Behroozi et al. 2013), and thus the expansive effects of dissipationless assembly would be expected to be more important in higher mass haloes. Indeed, at the galaxy cluster scale $M_{200} \sim 10^{15}M_\odot$ Laporte & White (2015) find that dissipationless assembly since $z = 2$ reverses the contraction in the progenitor galaxies resulting in net halo expansion within $\sim 1\%$ of the virial radius by redshift $z = 0$. We note that at a halo mass of $10^{15}M_\odot$ the accreted fraction of stars is already quite high at $\sim 60\%$ (Behroozi et al. 2013), thus any mass dependence is likely to be weak. Furthermore, since the halo and galaxy mass functions are steep, very few quiescent galaxies live in the highest
adiabatic contraction (AC, standard simulations (black) have very low dark matter fractions, (red) are most similar to the weak contraction model. The dark matter fraction on scales of galaxy half-light radii, i.e., An observational test of halo response models is the dark matter fraction with the stellar mass-to-light ratio (e.g., Dutton et al. 2010; Dutton & Treu 2014; Sonnenfeld et al. 2015), although there are some exceptions (Smith et al. 2015). Clearly more work needs to be done to make the distinction more definitive.

5.4 Observations of dark matter fractions

An observational test of halo response models is the dark matter fraction on scales of galaxy half-light radii, i.e., ~5 kpc. Total masses on these scales can be measured reliably using stellar kinematics and/or strong gravitational lensing (e.g., see Courteau et al. 2014 for a review). However, decomposing the total mass into baryons and dark matter is more challenging. Stellar population synthesis models can be used to convert luminosity profiles into stellar mass profiles up to the stellar IMF and systematics uncertain phases in stellar evolution. It is well established observationally that if the IMF is universal, then massive elliptical galaxies have dark matter fractions of \( f_{\text{DM}}(R_c) \sim 0.5 \) and in the context of LCDM, require close to adiabatic halo contraction (Auger et al. 2010; Dutton et al. 2011b, 2013b). In Fig. 18 we show the dark matter fraction within spheres of radius 5 kpc vs the circular velocity at 5 kpc in our simulations (symbols) and compared to observationally constrained models (lines) from Dutton et al. (2013b). This plot is similar to Fig. 21 of Dubois et al. (2013), but we use a fixed physical radius, rather than a relative radius such as the half-light radius to eliminate any differences of scale between the simulations and observations. The forced quenching simulations have dark matter fractions of ~30%, while the standard simulations have ~10%. The lines show models with different assumptions about the halo response parameterized by Eq. 3 from no change (\( \nu = 0 \)) to adiabatic contraction (\( \nu = 1 \)). Models with stronger contraction have correspondingly lower stellar mass to light ratios. At a circular velocity of 300 km s\(^{-1}\) the stellar mass offsets are 0.23, 0.16, and 0.03 dex, where 0.23 corresponds to a Salpeter IMF, and 0.0 to a Chabrier IMF. Note that all models reproduce (by construction) the scaling relations between size, stellar mass, and velocity dispersion.

An accurate measurement of the dark matter within 5 kpc would thus be able to falsify our simulations for elliptical galaxy formation. We note that variety of studies seem to favor models closer to \( \nu = 0 \) and Salpeter IMFs than \( \nu = 1 \) and Chabrier IMFs (Auger et al. 2010a; Dutton et al. 2013b; Dutton & Treu 2014; Sonnenfeld et al. 2015), although there are some exceptions (Smith et al. 2015). Clearly more work needs to be done to make the distinction more definitive.

5.5 Priors on dark matter density slopes

Our results have implications for mass modeling of elliptical galaxies. Observations commonly parameterize the dark matter halo as either a power-law with a free slope, or a double power-law with a free inner slope:

\[
\rho(r)/\rho_0 = (r/r_s)^{-\alpha}(1 + r/r_s)^{-3+\alpha}.
\]

For example, Cappellari et al. (2013) adopt Eq. 8 with a uniform prior on inner slope with limits [0,1.6]. The upper limit is consistent with our forced quenching simulations, but excludes simulations with stronger contraction. Due to the degeneracy between the halo response and dark matter fraction with the stellar mass-to-light ratio (e.g., Dutton et al. 2013b) the choice of prior is important if one wishes to accurately constrain stellar mass-to-light ratios and make inferences on the IMF. Our simulations suggest an upper limit of \( \alpha = 1.6 \) is too restrictive. A more conservative upper limit of \( \alpha = 2 \) allows for the full range of inner slopes found in our simulations.

6 SUMMARY

We use cosmological hydrodynamical simulations with the SPH code GASOLINE to investigate the response of dark matter haloes to the formation of massive elliptical galaxies. We consider 4 initial conditions that grow into haloes of mass \( M_{200} \sim 10^{14} M_\odot \) by the present day. At our standard resolution each simulation has more than 1.5 million dark matter particles within the virial radius at \( z = 0 \) enabling us to resolve the dynamics at 1% of the virial radius. Our highest resolution simulation has 10.6 million dark matter particles within the virial radius at \( z = 0 \), making it one of the highest resolution simulations of elliptical galaxy formation to date. Our standard simulations include metallicity dependent gas cooling, star formation, and stellar feedback.

We summarize our results as follows:

- At redshift \( z = 2.1 \) our standard simulations have stellar to halo mass ratios consistent with halo abundance matching, assuming a Salpeter IMF to derive the stellar

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**Figure 18.** Dark matter fraction vs circular velocity, both measured at 5 kpc. Symbols show our simulations while lines show observed values for different halo response models from Dutton et al. (2013b): no contraction (\( \nu = 0 \)), weak contraction (\( \nu = 0.5 \)) adiabatic contraction (AC, \( \nu = 1 \)). The forced quenching simulations (red) are most similar to the weak contraction model. The standard simulations (black) have very low dark matter fractions, which observationally requires uncontracted halos, but the simulations have contracted indicating an inconsistency.
masses (Fig. 3). Galaxy half-mass sizes and circular velocities are also consistent with observations (Fig. 4).

- At $z = 2.1$ the dark matter haloes have contracted in response to galaxy formation (Figs. 9, 12, 15), but not as strong as predicted by the adiabatic contraction formalism (Blumenthal et al. 1986).

- By $z = 0$ the standard simulations have overcooled, with a factor of $\gtrsim 4$ times too many stars, resulting in circular velocities, stellar densities, and mass density slopes that are too high (Figs. 3, 7).

- We investigate the halo quenching scenario by shutting down cooling and star formation at $z = 2.1$ (when the most massive progenitors have $M_{200} \sim 10^{12} M_\odot$) and evolving the simulation hierarchically to $z = 0$. We refer to these simulations as forced quenching (FQ). The resulting galaxies have many properties consistent with observed elliptical galaxies: $M_{\text{star}} \sim 2 \times 10^{11} M_\odot$, $M_{\text{star}}/M_{200} \sim 0.01$ (Fig. 7), flat circular velocity profiles with mass density slope $\gamma \sim 2$ (Figs. 6 & 11), half-mass sizes of $r_{1/2} \sim 4 - 10$ kpc (Fig. 11), and circular velocities $V_{\text{circ}}(r_{1/2}) \sim 300 - 400$ km s$^{-1}$ (Fig. 4).

- In all the FQ simulations the dark matter haloes contract, although less than in the standard simulations (Fig. 12). The contraction is much weaker than predicted by the adiabatic contraction models of Blumenthal et al. (1986) and Gnedin et al. (2004), but can be described with a simple formula (Eq. 12).

- The dark matter density slopes (at redshift $z = 0$) measured between 1-2% of the virial radius vary from $-1.2 \pm 0.1$ in the control simulations to $-1.53 \pm 0.17$ in the FQ simulations and to $-1.76 \pm 0.17$ in the standard simulations (Fig. 10).

- Dry merging alone is unable to reverse the contractive effects of early dissipation, which must occur to form an elliptical galaxy.

- Simulations in the literature find that AGN feedback can cause halo expansion (e.g., Duffy et al. 2010; Martizzi et al. 2012), and thus there may be qualitatively different halo responses, and dark matter fractions within $\sim 5$ kpc, in the suppressive (halo) quenching and ejective (AGN) quenching scenarios. We note that different halo responses will also require different stellar IMFs in order to be consistent with observed constraints on dark matter fractions (Fig. 13).

While our treatment of the halo quenching process is clearly an oversimplification, we hope that the excellent agreement between the structural properties of our forced quenching simulations with observations motivates further studies of the halo quenching scenario.

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APPENDIX A: GALAXY PARAMETERS

Table A1 lists the parameters of the most massive galaxy in each simulation at redshift $z \sim 2$ and $z \sim 0$. Note that the actual redshifts vary slightly to avoid major mergers that occur at the nominal output redshifts.
Table A1. Galaxy parameters. Column (1) name of the initial conditions – see Table 2 for simulation parameters. Column (2) type of simulation: standard (S) or forced quenching (FQ). Column (3), $z$, redshift of output. Column (4), $M_{200}$, virial mass. Column (5), $M_{\text{star}}$, stellar mass inside 20% of the virial radius. Column (6), $R_{1/2}$, 3D half-mass radius. Column (7), $V_{1/2}$, circular velocity ($V(r) = \sqrt{GM(r)/r}$) at the 3D half-mass radius. Column (8), $V_{200}$, circular velocity at the virial radius. Column (9), $V_{5\text{kpc}}$, circular velocity at 5 kpc. Column (10), $f_{\text{DM}}$, dark matter fraction at 5 kpc. Column (11), $\alpha$, slope of the dark matter density profile measured between 1 and 2% of the virial radius. Column (12), $\gamma'$, slope of the total mass profile measured between 1 and 2% of the virial radius. Column (13), $\Sigma_{\text{star}}$, average surface density of the stars inside the 2D half-stellar mass radius.

| Name   | Type | $z$  | log$_{10} M_{200}$ [M$_\odot$] | log$_{10} M_{\text{star}}$ [M$_\odot$] | $R_{1/2}$ [kpc] | $V_{1/2}$ [km s$^{-1}$] | $V_{200}$ [km s$^{-1}$] | $V_{5\text{kpc}}$ [km s$^{-1}$] | $f_{\text{DM}}$ | $\alpha$ | $\gamma'$ | log$_{10} \Sigma_{\text{star}}$ [M$_\odot$ pc$^{-2}$] |
|--------|------|------|----------------|----------------|-----------------|-----------------|-----------------|-----------------|-----------------|----------------|----------------|----------------|
| halo1 S | 0.12 | 13.14 | 11.80 | 4.28 | 599.3 | 355.5 | 589.5 | 0.146 | -1.88 | 2.37 | 3.99 |
| halo2 S | 0.10 | 13.14 | 11.82 | 4.68 | 580.7 | 353.7 | 577.4 | 0.130 | -1.93 | 2.42 | 3.93 |
| halo3 S | 0.08 | 13.14 | 11.94 | 5.74 | 602.7 | 353.5 | 613.6 | 0.110 | -1.58 | 2.28 | 3.88 |
| halo4.0 S | 0.00 | 13.37 | 12.09 | 4.21 | 825.1 | 414.2 | 798.6 | 0.094 | -1.55 | 2.42 | 4.29 |
| halo4.1 S | 0.12 | 13.33 | 12.09 | 5.08 | 756.7 | 409.6 | 758.6 | 0.108 | -1.61 | 2.36 | 4.13 |
| halo4.2 S | 0.00 | 13.34 | 12.07 | 5.13 | 744.4 | 403.9 | 747.6 | 0.135 | -1.67 | 2.36 | 4.10 |
| halo1 FQ | 0.00 | 13.14 | 11.32 | 6.45 | 343.3 | 348.4 | 326.0 | 0.349 | -1.71 | 1.80 | 3.17 |
| halo2 FQ | 0.14 | 13.13 | 11.00 | 3.59 | 288.2 | 354.2 | 295.3 | 0.344 | -1.63 | 2.10 | 3.36 |
| halo3 FQ | 0.00 | 13.19 | 11.41 | 7.95 | 340.5 | 362.3 | 321.1 | 0.288 | -1.36 | 1.79 | 3.09 |
| halo4.0 FQ | 0.00 | 13.36 | 11.09 | 13.79 | 331.5 | 410.9 | 253.4 | 0.564 | -1.51 | 1.49 | 2.26 |
| halo4.1 FQ | 0.00 | 13.35 | 11.42 | 7.01 | 369.5 | 408.0 | 381.6 | 0.310 | -1.43 | 2.08 | 3.18 |
| halo4.2 FQ | 0.00 | 13.33 | 11.44 | 7.78 | 372.1 | 401.2 | 380.6 | 0.295 | -1.52 | 2.03 | 3.11 |
| halo4.3 FQ | 0.00 | 13.43 | 11.48 | 11.08 | 376.9 | 432.3 | 348.3 | 0.363 | -1.57 | 1.82 | 2.84 |
| halo1 S | 2.22 | 12.15 | 11.01 | 2.06 | 384.7 | 237.0 | 398.0 | 0.390 | -1.20 | 1.21 | 3.83 |
| halo2 S | 2.08 | 12.19 | 10.92 | 1.43 | 404.6 | 240.6 | 373.8 | 0.360 | -1.61 | 1.58 | 4.06 |
| halo3 S | 2.08 | 12.32 | 10.94 | 1.51 | 385.1 | 265.3 | 363.8 | 0.356 | -1.57 | 1.63 | 4.03 |
| halo4.0 S | 2.07 | 12.30 | 10.79 | 2.69 | 320.4 | 259.9 | 343.3 | 0.404 | -1.98 | 0.99 | 3.38 |
| halo4.1 S | 2.07 | 12.25 | 11.14 | 0.96 | 582.2 | 251.2 | 435.0 | 0.354 | -1.86 | 2.31 | 4.62 |
| halo4.2 S | 2.22 | 12.22 | 11.13 | 1.30 | 517.2 | 251.6 | 437.1 | 0.383 | -1.76 | 1.93 | 4.35 |
| halo4.3 S | 2.07 | 12.42 | 11.04 | 1.94 | 410.0 | 286.8 | 401.0 | 0.402 | -1.59 | 1.79 | 3.92 |