Idealized models for galactic disc formation and evolution in ‘realistic’ ΛCDM haloes

Michael Aumer* and Simon D. M. White

Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, 85748 Garching, Germany

Accepted 2012 September 26. Received 2012 August 27; in original form 2012 March 02

ABSTRACT
We study the dynamics of galactic disc formation and evolution in ‘realistic’ Λ cold dark matter haloes with idealized baryonic initial conditions. We add rotating spheres of hot gas at $z = 1.3$ to two fully cosmological dark-matter-only halo (re)simulations. The gas cools according to an artificial and adjustable cooling function to form a rotationally supported galaxy. The simulations evolve in the full cosmological context until $z = 0$. We vary the angular momentum and density profiles of the initial gas sphere, the cooling time and the orientation of the angular momentum vector to study the effects on the formation and evolution of the disc. The final discs show exponential radial and (double)-exponential vertical stellar density profiles, and stellar velocity dispersions that increase with age of the stars, as in real disc galaxies. The slower the cooling/accretion processes, the higher the kinematic disc-to-bulge (D/B) ratio of the resulting system. We find that the initial orientation of the baryonic angular momentum with respect to the halo has a major effect on the resulting D/B. The most stable systems result from orientations parallel to the halo minor axis. Despite the spherical and coherently rotating initial gas distribution, the orientation of the central disc and of the outer gas components, and the relative angle between the components can all change by more than 90° over several billion years. Initial orientations perpendicular to the major axis tend to align with the minor axis during their evolution, but the sign of the spin can have a strong effect. Discs can form from initial conditions oriented parallel to the major axis, but there is often strong misalignment between inner and outer material. The more the orientation of the baryonic angular momentum changes during the evolution, the lower the final D/B. The behaviour varies strongly from halo to halo. Even our very simple initial conditions can lead to strong bars, dominant bulges, massive, misaligned rings and counter-rotating components. We discuss how our results may relate to the failure or success of fully cosmological disc formation simulations.

Key words: galaxies: evolution – galaxies: formation – galaxies: kinematics and dynamics – galaxies: structure – dark matter.

1 INTRODUCTION
The majority of galaxies in the local Universe with masses similar to that of the Milky Way are disc dominated (e.g. Delgado-Serrano et al. 2010). In the standard paradigm, these discs are formed through cooling and condensation of gas within CDM haloes (White & Rees 1978; Fall & Efstathiou 1980). Disk size is a consequence of the angular momentum of the gas, which had previously been acquired through tidal torques from neighbouring structures (e.g. Peebles 1969; White 1984).

Numerical hydrodynamical simulations of this formation scenario have been carried out in great number (e.g. Navarro & White 1994; Navarro & Steinmetz 1997; Abadi et al. 2003; Governato et al. 2007; Scannapieco et al. 2009). Despite recent progress (e.g. Agertz, Teyssier & Moore 2011; Guedes et al. 2011; Sales et al. 2011), these simulations have in general suffered from a range of problems, including angular momentum loss leading to overly small discs (Navarro & Benz 1991), production of overly massive galaxies (Guo et al. 2010), and too much early and too little late star formation (SF; Scannapieco et al. 2009). Even if extended discs form, they are often destroyed by infalling satellites (Toth & Ostriker 1992) or the accretion of misaligned gas (Scannapieco et al. 2009; Sales et al. 2011). Moreover, different numerical schemes can yield very different galaxies for the same initial conditions (Keres et al. 2011; Scannapieco et al. 2012). In particular, the angular momentum content and thus the structure of the discs depend strongly on the numerical method applied (Torrey et al. 2011). Overall, the

*E-mail: maumer@mpa-garching.mpg.de

© 2012 The Authors
Published by Oxford University Press on behalf of the Royal Astronomical Society
galaxy population predicted by cosmological gas dynamical simulations disagrees in major ways with observations. Since detailed population properties are reproduced quite well in the standard Λ cold dark matter (ΛCDM) paradigm by simple semi-analytic simulations (e.g. Guo et al. 2011), it has been argued that the relevant SF and feedback processes are still inadequately represented in hydrodynamical simulations. Such semi-analytic models are however not capable of properly capturing the complex dynamical interactions between gas, stars and dark matter found to be important in the above-mentioned simulations.

In contrast, there is general agreement on the formation and structure of dark matter haloes in ΛCDM (e.g. Springel et al. 2008), and on the observational side, a detailed picture of the structure of disc galaxies has been assembled over the last few decades (see van der Kruit & Freeman 2011 for a recent review). In this study, we therefore study whether the detailed output of simulations of dark matter halo formation and our detailed knowledge of disc galaxies can be brought into agreement if the fully cosmological treatment of baryon physics is replaced by idealized models.

Previous attempts in this direction include the models of Weil, Eke & Efstathiou (1998), who showed that the prevention of radiative gas cooling in cosmological hydrodynamical simulations until \( z = 1 \) allows the formation of a disc galaxy population with realistic angular momentum content. Kaufmann et al. (2006, 2007) simulated disc formation by allowing a rotating gas distribution to cool inside idealized (moshialy) spherical equilibrium haloes. This enabled them to examine numerical effects as well as some physical processes related to disc simulations.

ΛCDM haloes, however, show substructure, are triaxial and are continuously accreting (Frenk et al. 1988). The impact of halo shape is still an open issue. Disc galaxies in cosmological hydrodynamical simulations are typically aligned with the halo minor axis (Bailin et al. 2005). Moreover, it has been argued that the interaction of the forming disc galaxy with the dark matter tends to make the haloes axisymmetric (e.g. Berentzen & Shlosman 2006; Kazantzidis, Abadi & Navarro 2010). Berentzen & Shlosman (2006) introduced a disc galaxy within a cosmological triaxial halo by gradually adding stellar disc particles according to an axisymmetric analytical disc model with growing mass and size, to the simulation. They were then able to analyse the interplay between a galactic disc and a triaxial halo. A similar study was undertaken for the same dark matter haloes we use here by DeBuhr et al. (2012).

For our study, we perform a set of controlled numerical experiments using simplified prescriptions for the physics of gas accretion and SF in order to gain insight into the dynamical processes that affect the formation of galaxy discs within ΛCDM haloes. We use fully cosmological, triaxial haloes as initial conditions, but simulate disc formation and evolution by the cooling of a rotating gas sphere starting at redshift \( z = 1.3 \). Our idealized treatment allows us to study how the formation of a galactic disc is affected by the rapidity of gas cooling, by the angular momentum and mass of the gas and by the orientation of its angular momentum with respect to the principal axes of the dark halo. We compare our results to the direct output of fully cosmological hydrodynamical simulations carried out for the same haloes, so that we can better understand why they fail to produce substantial discs.

In Section 2, we describe the setup and numerical methods of this work. In Section 3, we describe the formation, evolution and structure of one particular disc model. In Section 4, we analyse the dependence of the disc growth on our model parameters. In Section 5, we discuss the influence of initial spin orientation and the stability of the orientation of the resulting discs. In Section 6, we compare our models to the fully cosmological galaxy formation simulations of Scannapieco et al. (2009, CS09 hereafter). Finally, in Section 7, we summarize and conclude.

2 SIMULATION SETUP

To mimic the formation of galactic discs within fully cosmological dark-matter-only simulations of haloes expected to host Milky Way-type galaxies, we make use of the Aquarius simulations (Springel et al. 2008), a suite of high-resolution zoom-in re-simulations of six dark matter haloes. These haloes were chosen from a simulation of a cosmological box with a side-length of 137 Mpc, and were simulated from \( z = 127 \) assuming a ΛCDM universe with the following parameters: \( \Omega_m = 0.75, \Omega_b = 0.25, \Omega_\Lambda = 0.04, \sigma_8 = 0.9 \) and \( H_0 = 73 \text{ km s}^{-1} \text{ Mpc}^{-1} \). For details we refer to Springel et al. (2008).

We select two haloes, named A and C, both at resolution level 5, which corresponds to dark matter particle masses of \( m_{\text{dm}} \approx 3 \times 10^6 M_\odot \) and a gravitational softening length of \( \epsilon_{\text{dm}} = 685 \text{ pc} \). These haloes have (dark matter only) \( z = 0 \) virial masses of \( M_{\text{vir},0} = 1.853 \) and \( 1.793 \times 10^{12} M_\odot \), and have been studied in the fully cosmological galaxy formation simulations of CS09. We selected halo A as it has a very quiescent merger history after redshift \( z \sim 1 \) and has been identified as a prime candidate for hosting a disc galaxy by semi-analytical modelling. However, CS09 did not find a significant disc component in their \( z = 0 \) simulations. Halo C, in contrast, showed the highest (yet still unrealistically low) disc-to-bulge ratio, \( D/B \sim 1/4 \), of all eight haloes studied in this work. Halo C was also studied in the Aquila comparison project (Scannapieco et al. 2012), which compared the results of various cosmological gas-dynamical codes.

For our simulations, we apply the TREESPH code GADGET-3, last described in Springel (2005), an extended version of which was used by CS09.

As initial conditions for our numerical experiments we use the simulation outputs of Springel et al. (2008) at \( z = 1.3 \). We choose this time, as it falls after the epoch of major mergers. Disc galaxies have very likely been in place and continuously forming since before \( z = 1.3 \). For example, age estimates for the solar neighbourhood exceed 10 Gyr (see Aumer & Binney 2009 and references therein), making our choice appear problematic. It has been argued that the ages of thin disc stars are consistent with formation after \( z \sim 1.5 \) (e.g. Reddy, Lambert & Allende Prieto 2006), but it is not clear, if a two-component division of the Milky Way disc into thin and thick components is sensible (e.g. Schönrich & Binney 2009). Our goal is not however to model the entire formation and evolution of disc galaxies, but to study the ability of realistic dark matter haloes with evolving substructure to host thin disc galaxies over cosmological times.

To simulate the formation of a disc galaxy within the dark matter halo, we insert a rotating sphere of gas into the inner halo and evolve the combined system until \( z = 0 \). In our models, the gas component is initially hot (\( T \sim 10^6 \text{ K} \)), with an internal energy structure determined by the assumption of approximate hydrostatic equilibrium (cf. Kaufmann et al. 2006; Aumer et al. 2010). The pressure profile is thus

\[
p(r) = \int_0^r \rho_{\text{gas}} \frac{G M_{\text{gas}}(r)}{r^2} \, dr,
\]

where \( M_{\text{gas}}(r) \) is the spherically averaged mass of dark matter and gas within spherical radius \( r \). The gas sphere has a density profile \( \rho(r) \propto r^{-1} \) (e.g. Navarro & White 1993) and its total mass is \( M_{\text{tot}} = \frac{4}{3} \pi \int_0^\infty \rho(r) r^2 \, dr \).
5.0—7.5 × 10¹⁰ M⊙, in the range of estimated stellar masses for the Milky Way (McMillan 2011) and of galaxy masses expected for this halo mass range by abundance matching techniques (e.g. Guo et al. 2010). We choose this profile as tests of various other profiles yielded undesired artefacts. A Navarro-Frenk-White (NFW)-like profile, as used by Aumer et al. (2010), leads to more dominant dispersion-dominated populations forming from the initially greater central gas mass, which adjusts to the triaxial potential of the central halo before transition to a disc-like configuration. For a constant density sphere, however, the central build-up of baryonic mass is initially too slow, delaying the transition from triaxial to disc-like potential relative to the baryonic mass build-up.

The gas sphere is truncated at radius Rgas = 60–100 kpc. We assume zero pressure outside the gas sphere when determining the pressure profile according to equation (1). This leads to an initial expansion phase for the outermost gas layers due to the finite temperatures assigned to the smoothed particle hydrodynamics (SPH) particles. However, this effect is negligible compared to the adjustment of the initially spherical gas distribution to the triaxial and substructured gravitational potential of the dark halo, which prevents the setup of idealized equilibrium initial conditions. The effects of this adjustment are discussed in Sections 3 and 4. Still, as we also show in these sections, this simple setup is justified by the fact that it leads to disc galaxy models with realistic properties.

We use a baryonic particle mass of mbary ≈ 10⁵ M⊙ and a gravitational softening εgas = 205 pc. Kaufmann et al. (2007) found that the angular momentum content and morphology of forming discs depend on resolution. Our resolution is similar to their highest resolution, for which they found significantly reduced angular momentum losses. In Section 4, we show that angular momentum losses due to lack of resolution are negligible in our simulations. The gas is set to rotate with a rotation velocity profile Vrot(r), which is either constant or changing linearly from central to outer spherical radii r. These profiles yield realistic disc mass profiles as is shown in the following sections. The angular momentum vector of the gas is aligned either with one of the principal axes of the halo or with its angular momentum in order to study how this affects the final orientation of the disc (see Section 5).

To model the cooling of the hot gas into the centre of the halo, we apply a simple parametrized cooling function with

$$ t_{\text{cool}} = t_{\text{cool},0} \left( \frac{\rho}{\rho_{\text{cool},0}} \right)^{-\alpha}, $$

(2)

where the normalization $t_{\text{cool},0}$ determines the rapidity of cooling. We choose $t_{\text{cool},0} = 0.5–2.0$ Gyr for $\rho_{\text{cool},0} = 10^5$ M⊙ kpc⁻³ ≈ 4 × 10⁻³ mH cm⁻³ and $\alpha = 0.56$. These values were chosen to combine a simple dependence of the cooling time on the density with cooling time values which initially are a few times the free fall time $t_{ff}$ at all radii, $t_{\text{cool}}$ increasing with radius, yet the ratio $t_{\text{cool}}/t_{ff}$ decreasing with radius. This enables an initially slow transition of the triaxial dark-matter-dominated centre of the halo to a disc-dominated quasi-axisymmetric system. Ratios of $t_{\text{cool}}/t_{ff}$ as a function of radius for several models with different initial density and cooling time parameters are shown in Fig. 1 to illustrate how these parameters affect the cooling of gas in our models. The initial cooling time profiles are affected by the implications of the non-equilibrium initial conditions as discussed above on dynamical time-scales, and by the cooling of gas and SF on cooling time-scales. In Sections 3 and 4, we show that this cooling time setup produces gas accretion histories appropriate for our models.

A temperature floor $T_{\text{floor}} = 10^3$ K (Kaufmann et al. 2006) is applied to ensure that the forming disc does not fragment into a few massive clumps (Aumer et al. 2010), which would then enhance bulge formation. The high choice of $T_{\text{floor}} = 10^3$ K also prevents dense clumps from forming in the infalling gas via the cooling instability (Kaufmann et al. 2006).

Such a setup clearly ignores evidence from cosmological hydrodynamical simulations that steady, narrow, cold gas streams penetrating the shock-heated atmosphere of massive dark matter haloes are important in feeding gas on to forming galaxies (e.g. Dekel et al. 2009). However, cold streams are only expected to be the dominant accretion mode at $z > 2$ (Faucher-Giguère, Kereš & Ma 2011) and even at these redshifts, there is little direct observational evidence for them (e.g. Steidel et al. 2010). The majority of the stellar mass in the Milky Way disc was formed after $z > 2$ (Aumer & Binney 2009) and it may be argued that the underlying continuous SF since $z \approx 1$ is driven by cooling of hot coronal gas in the wakes of galactic fountain clouds, which transfers gas from the virial-temperature corona to the disc (e.g. Marinacci et al. 2010). Our focus here is not on simulating a realistic assembly process, but rather on using a simplified scheme, which allows important aspects of the underlying dynamics to be clarified.

In our simulations, once the gas has reached the temperature floor and crossed a density threshold $\rho_{0,\text{str}}$, it can form stars with

$$ t_{\text{str}} = t_{\text{str},0} \left( \frac{\rho}{\rho_{0,\text{str}}} \right)^{-\beta}. $$

(3)

We choose $\rho_{0,\text{str}}$ to correspond to a hydrogen number density $n_{\text{H}} = 0.1$ cm⁻³, and we use $\beta = 0.5$ and $t_{\text{str},0} = 10 \times t_{\text{cool}}(\rho_{0,\text{str}})$, as often applied in simulations of this resolution (CS09). Gas particles eligible for SF are stochastically turned into collisionless particles of the same mass (see e.g. Lia, Portinari & Carraro 2002).

In our simulation, the formation of stars is not accompanied by any kind of feedback processes. We have run tests with 50 times higher values of $\rho_{0,\text{str}}$ and/or 10 times lower values of $T_{\text{floor}}$ and did not find any major changes to our results. Both changes tend to produce dynamically hotter stellar discs as a slower cooling floor leads to stronger fragmentation of the disc and thus enhances disc heating by dense substructures. A higher density threshold lowers...
3 QUANTIFYING A DISC MODEL

We start the analysis of our models by discussing in detail one model in halo A, which is named ARef. We choose this model as it produces a system which has certain structural similarities to the Milky Way. The parameters applied are an initial radius of \( R_{\text{gas}} = 60 \text{kpc} \), a total mass of \( M_{\text{gas}} = 5 \times 10^{10} M_{\odot} \), a cooling time which is about twice as long as the free-fall time for the outermost gas (see Fig. 1), a rotational velocity which increases from 120 kms\(^{-1}\) in the centre to 180 kms\(^{-1}\) at \( R_{\text{gas}} \) and an orientation of the baryonic angular momentum vector parallel to that of the dark matter within 300 kpc. This orientation is close to the minor axis of the potential of the inner halo. The dependence of the final disc properties on these initial parameters is discussed in the following section. We split this section into subsections that deal with disc structure, angular momentum loss, kinematics and disc heating.

3.1 Structural evolution

Analysing ARef at \( z = 0 \), 86 percent of the baryonic mass has formed stars and the remaining gas is situated mainly in a thin, extended gas disc (see the top row of Fig. 8). This gas fraction is in reasonable agreement with \( z \sim 0 \) spirals (Evoli et al. 2011). As can be seen in the top-left panel of Fig. 2, the SFR rises steeply to a peak at \( z \sim 1 \) before falling by two orders of magnitude by \( z = 0 \).

In the middle-left panel of Fig. 2 we show the evolution of the stellar surface density profile \( \Sigma(R) \) of model ARef from \( z = 1.1 \) until 0. It can be seen that the first stars form in a concentrated bulge-like structure at \( R < 2 \text{kpc} \). This structure is actually triaxial because the infalling gas adjusts to the potential imposed by the halo. Its surface density only increases by a factor of \( \sim 2 \) by \( z = 0 \). The surface density profile outside the bulge region is already exponential in this early phase. Once most of the baryons have cooled, the infalling gas and the forming stars settle in a well-defined disc, which grows transforming the central potential into an axisymmetric configuration. The disc grows inside-out showing a truncation at a radius \( R_{\text{max}}(z) \) as observed in disc galaxies (van der Kruit & Searle 1981). This is a consequence of high-angular-momentum gas living initially at greater radii, lower densities and thus longer cooling times. Moreover, according to our assumed SF law, SF time-scales are longer at lower surface densities. The break in \( \Sigma(R) \) moves outwards with time to around \( R \sim 19 \text{kpc} \) at \( z = 0 \). There is observational evidence for inside-out formation of real disc galaxies (Wang et al. 2011) and for outward movement of their truncations (Azzollini, Trujillo & Beckman 2008).

Due to the numerically imposed cooling floor \( T_{\text{cool}} \) and the density threshold \( \rho_{\text{thresh}} \), there is an imposed SF threshold surface density \( \Sigma_{\text{thresh}} \). As is shown in the first row of Fig. 8, the gas disc at \( z = 0 \) extends to larger radii, where this threshold is not reached. This also indicates that the truncation of the initial spherical distribution does not play a role here. The extended gas disc is also slightly warped, as in real disc galaxies (Sancisi 1976). The warp is a result of a slight misalignment between the disc and the late-infall gas (see Sections 5 and 7 for a discussion of misalignments).

Exponential disc profiles with central concentrations are common in real galaxies (de Vaucouleurs 1958) and also in simulations (Katz & Gunn 1991), although most simulations significantly overpredict the mass in the central bulge component [CS09, Scannapieco et al. 2010, but see Brook et al. 2012 for simulations of lower mass (nearly) bulge-less discs]. The \( \Sigma(R) \) profile at \( z = 0 \) as displayed in the middle-right panel of Fig. 2 is well-fitted by a profile of the form \( \Sigma_{\text{Sers}} \exp(-\frac{R}{\sigma_R}) + \Sigma_{\text{0.2}} \exp(-\frac{R}{\sigma_{\text{d}}}) \), which combines an exponential disc with a Sersic profile. The Sersic indices found for our disc models are \( n \sim 0.5 - 2.0 \), similar to observed pseudo-bulges. The scalelengths for ARef are \( R_{\text{s}} = 1.0 \text{kpc} \) and \( R_{\text{d}} = 2.9 \text{kpc} \). Calculating a D/B mass ratio from this profile alone yields \( D/B \sim 12 \).

In the bottom-left panel of Fig. 2, we display the vertical stellar density profile \( \rho(z) \) for all stars in model ARef that are located in an annulus of width 1 kpc centred around \( R = 5 \text{kpc} \) at \( z = 0 \). The profile is well fitted by a double exponential with scaleheights 420 and 1300 pc. The vertical profile does not vary significantly within \( R < 10 \text{kpc} \), but at larger radii the disc flares and the scaleheight increases by a factor of \( \sim 2 \) until \( R_{\text{max}} \). Thus, the outer vertical structure of this model is in conflict with observations of constant vertical structure within the exponential disc region (van der Kruit & Searle 1981). In the following section, we will show that this conflict is absent for some of our models. The flaring and the ‘thick’ discs are caused by old stellar material formed in the bulge-formation period around \( z \sim 1 \). From then on the scaleheights first become smaller due to the growth of a young, cold disc before beginning to increase again due to disc heating. This increase is stronger in the inner disc as the outer disc has a younger mass-weighted age. The ARef disc thus has similar structural characteristics to the Milky Way disc (Jurić et al. 2008; McMillan 2011), although its disc is \( \sim 40 \) per cent thicker.

3.2 Angular momentum loss of infalling gas

The radial structure of the disc discussed above is determined by the potential and the angular momentum content of the stellar population. The concentrated peak in \( \Sigma(r) \) produced in the early stages of SF indicates an unexpectedly high amount of low angular momentum material and thus angular momentum losses. We investigate this in Fig. 3, in which we plot the evolution of the total specific angular momentum of populations of baryons initially located in concentric shells of 5 kpc width. The material initially located at \( R < 10 \text{kpc} \) loses \( \gtrsim 99 \) per cent of its angular momentum within the first 500 Myr. The material in the next two shells still loses \( \gtrsim 90 \) per cent, the outermost material \( \sim 50 \) per cent. The strongest losses occur in the phase when the central potential is transformed from a triaxial to a disc-like configuration, in the process of which the bulge forms. Moreover, the losses are subsequently delayed for outer shells, indicating that the angular momentum is lost as the gas cools and moves to the centre.

3.3 Kinematical properties

We move on to analyse the kinematics of ARef. The top-right panel of Fig. 2 depicts the rotation velocity \( V_{\text{rot}} \) and the velocity dispersions \( \sigma_R, \sigma_R, \sigma_\phi \) of the disc stars, and the spherically averaged circular velocity \( V_{\text{circ}}(r) = \sqrt{GM(r)/r} \) profile at \( z = 0 \). \( V_{\text{circ}} \) peaks at \( \sim 250 \text{kms}^{-1} \) at \( R \sim 10 \text{kpc} \) and gently decreases outside. The stellar rotation curve shows a broad peak at \( 7 < 8 \text{kms}^{-1} < 15 \) at \( V_{\text{rot}} \sim 240 \text{kms}^{-1} \). For velocity dispersions, we find a decreasing profile out to \( R \sim 12 \text{kpc} \) and \( \sigma_\phi > \sigma_\phi > \sigma_\phi \) in the rotation-dominated region. The kinematical properties of the ARef disc are thus also similar to, but slightly hotter than the Milky Way disc (Aumer & Binney 2009; Schönrich 2012).

As a tool to quantify D/B ratios, the circularity \( \epsilon = V_{\text{rot}}/V_{\text{rot, max}}(E) \) for a stellar particle at energy \( E \) has been widely
Disc models within $\Lambda CDM$ haloes

Figure 2. Properties of model ARef. Top-left: SFR as a function of redshift $z$. Top-right: stellar kinematics as a function of disc radius $R$ at $z = 0$. Only stars within 500 pc of the mid-plane were taken into account. In purple, we overplot the spherically averaged circular velocity $V_{\text{circ}} = \sqrt{GM(<r)/r}$. Middle-left: the evolution of the surface density profile $\Sigma(R)$ from $z = 1.1$ to 0. Middle-right: surface density profile $\Sigma(R)$ at $z = 0$ fitted with a two-component profile $\Sigma_{0,1} \exp(-\frac{R}{R_d}) + \Sigma_{0,2} \exp(-\frac{R}{R_b})^{0.47}$ with scalelengths $R_d = 2.9$ kpc and $R_b = 1.0$ kpc and $n = 0.47$. Bottom-left: normalized $z = 0$ vertical density profile at $R = 5$ kpc fitted by a double exponential with $h_{\text{thin}} = 420$ pc and $h_{\text{thick}} = 1300$ pc. Bottom-right: circularity distribution for all stars at $z = 0$.

used (Abadi et al. 2003). Particles on a perfect circular orbit have $\epsilon = 1$ and thus a disc will show a peak close to $\epsilon = 1$, whereas a non-rotating bulge will have a peak at $\epsilon = 0$. The bottom-right panel of Fig. 2 depicts the $\epsilon$-histogram for ARef, which shows a distinct peak at $\epsilon = 0.95$ and only a shallow peak at $\epsilon = 0$, corresponding to a $D/B \sim 4$. Thus, the kinematic estimate for $D/B$ is significantly lower than the one from $\Sigma(R)$ fitting, consistent with e.g. the results of Scannapieco et al. (2010) for simulations of disc formation from cosmological initial conditions.

However, this analysis is not capable of distinguishing between old and young stars and is also not good at quantifying how thin and dynamically cold a disc is. In the left-hand panel of Fig. 4, we therefore employ a plot of the rotation-to-dispersion ratio $V_{\text{rot}}/\sigma_z$ as a function of the age of the stars. We define a disc plane perpendicular to the total stellar angular momentum at each output time $t$. $V_{\text{rot}}$ is calculated as the mean tangential velocity and $\sigma_z$ as the rms velocity in the direction of the rotation axis of all stars in a certain age bin. Keep in mind that the Milky Way young thin disc has
evolution of $V_{\text{rot}}/\sigma_z$ over time, we can see that the bulge kinematics do not change from $z = 0.9$ to 0.0, whereas the disc populations show decreasing $V_{\text{rot}}/\sigma_z$ ratios over time, i.e. the disc populations are heated, indicating that at least 1/3 of the stellar particles are born with thin-disc-like kinematics.

### 3.4 Disc heating

In order to analyse disc heating as it occurs in ARef in more detail, we plot the evolution of $\sigma_z$ for several coeval populations through time in the right-hand panel of Fig. 4. The stars that form earliest and most centrally (see the middle-left panel of Fig. 2) show high, almost isotropic velocity dispersion (top-right panel of Fig. 2). These stars are strongly heated within a few $10^8$ yr (black line) or born hot (red line). Within $\sim$1 Gyr after the first SF in the models the initial $\sigma_z$ has already become significantly lower, indicating the transition from bulge to disc formation. Within another $\sim$0.5 Gyr $\sigma_z$ at birth has dropped below 20 km s$^{-1}$. Only the stars that form latest form with a smaller $\sigma_z \sim 10$ km s$^{-1}$. As will be shown below, the high initial velocity dispersions of the first stars in this model are an effect of the structure of the dark halo. Test simulations in spherically symmetric gas physics (House et al. 2011), and the formation of a realistically cold young thin disc population is thus not possible in our current models.

All the disky coeval populations show an increase of $\sigma_z$ over time. Such continuous disc heating has been inferred for solar neighbourhood stars (Holmberg, Nordström & Andersen 2009) and is usually linked with the scattering of stars off disc substructure such as transient spirals and/or giant molecular clouds (Jenkins & Binney 1990). For our models we cannot, however, exclude that this effect

---

**Figure 3.** Angular momentum loss as a function of time for model ARef. The initial gas sphere has been divided into 12 spherical shells of 5 kpc width each. For each shell the absolute of the total angular momentum vector $j_i$ of all particles initially in shell $i$ is calculated at each output.

**Figure 4.** Disc heating in model ARef. Left: the ratio of the rotation velocity of stars to their vertical velocity dispersion $V_{\text{rot}}/\sigma_z$ as a function of the fraction of stellar mass that has formed until the formation time $t_{\text{form}}$ of a star particle relative to the total stellar mass at $z = 0$ for model ARef. The first stars are found at $x$-value 0, the ones formed at $z = 0$ at $x$-value 1. Curves are plotted for redshifts $z = 0.9, 0.6, 0.4, 0.2$ and 0. The endpoints of curves indicate the fraction of stellar mass that has formed up to the time in consideration. We do this for five different redshifts. The black $z = 0$ line shows that $V_{\text{rot}}/\sigma_z$ monotonically decreases with increasing age. Only the youngest stars are compatible with thin disc kinematics. The oldest $\sim 1/5$ are dispersion dominated and correspond to the bulge peak seen in the bottom left-hand panel of Fig. 2. Most of the galaxy thus has thick disc kinematics. Considering the
is partly due to numerical heating (e.g. Steinmetz & White 1997). A closer analysis of the phenomenon over all of our models reveals that the strongest heating always occurs when distinct substructure in the form of a bar or spirals is present. A look at the evolution of \( \sigma_z \) at different disc radii \( R \) over time reveals that due to the combined effect of the heating of coeval populations and the inside-out formation of our models in the inner disc regions, \( \sigma_z \), first drops due to the formation of a thin disc and then increases due to disc heating, whereas at outer radii the formation phase lasts longer and \( \sigma_z \) remains almost constant after an initial drop.

3.5 Summary

In conclusion, our setup is capable of producing disc galaxy models with realistic structural and kinematic properties. Disc formation proceeds inside-out and follows an early bulge-formation episode, during which the central halo potential is transformed into a disc-like configuration. This transformation is connected to angular momentum losses for the infalling gas. Moreover, a thick disc component in the vertical profiles originates from this epoch. We confirm that for a disc/bulge decomposition, a kinematic analysis is superior to a surface density decomposition. However, circularity distributions alone, as often applied, are not ideally suited to distinguish properly between thin and thick disc components, which is why \( \rho_{\text{gas}}/\sigma_z \), ratios should be used in addition. Our model does show a significant thin disc component; however, its \( V_{\text{rot}}/\sigma_z \) is limited to values \( \sim 10 \) compared to 20 for real young thin discs, due to the numerical lower limit we impose on \( \sigma_z \). The disc undergoes secular disc heating and shows a significant decline of zero-age velocity dispersion of stars.

4 HOW TO MAKE BETTER DISCS

In this and the next section, we discuss the dependences of our models on the parameters that define them.

(i) The mass of the model \( M_{\text{gas}} \), the initial radius \( R_{\text{gas}} \) and thus the initial density profile \( \rho(R) \).

(ii) The rapidity of cooling and thus accretion of gas on to the forming galaxy represented by the cooling time normalization \( t_{\text{cool,0}} \).

(iii) The initial angular momentum distribution of the gas represented by the rotation velocity profile \( V_{\text{rot}}(R) \).

(iv) The orientation of the angular momentum vector of the gas (see also the following section).

Our goal is to understand which physical conditions favour thin disc formation in \( \Lambda \)CDM haloes. An overview of our models and their parameters can be found in Table 1. In this section, we will mainly focus on halo A. For the parameters \( M_{\text{gas}} \), \( R_{\text{gas}} \), \( t_{\text{cool,0}} \) and \( V_{\text{rot}}(R) \), we could not find significant halo-to-halo differences. Most differences because of orientations are discussed in Section 5. As in the previous section, we split our analysis into subsections that deal with SF, angular momentum loss, disc structure, kinematics and disc heating.

4.1 Gas infall and star formation

We begin with a discussion of how the model parameters influence the formation histories of our models. The SFRs of the models displayed in Fig. 5 reveal that the process of gas inflow depends mainly on \( t_{\text{cool,0}} \) and the loss of angular momentum, which is put into the initial models via \( V_{\text{rot}}(R) \). Models ARef (black line), ARef+Maj (purple) and AMaj2C (turquoise) share the initial density profile and cooling time. All models show a steep rise followed by a softer decrease in SFR. ARef+Maj and ARef differ only in orientation; consequently, they show qualitatively similar SFRs. ARef+Maj loses a smaller amount of angular momentum (see below), thus forms a more extended structure with lower densities and has longer SF time-scales, a lower peak SFR and a higher late-time SFR. The second peak for ARef+Maj corresponds to SF in a ring structure (see the following section). ARef+Maj and AMaj2C differ only in \( V_{\text{rot}}(R) \) with AMaj2C having significantly less angular momentum, which leads to a much more concentrated object, higher densities, higher cooling rates, higher SFRs, an earlier peak and a steeper decrease in SFR. The same is true for a comparison of AExt1C (red line), AExt (green) and AExtLoAM (blue). They are all more extended with a higher initial gas mass than the models mentioned so far and thus represent a different initial density profile. AExt1C cools four times faster than AExt, and AExtLoAM has three times less angular momentum than AExt. In both cases, this results in a higher and earlier peak in SFR.

Directly connected to the SFR is the remaining gas fraction in the discs. At \( z = 0 \), these are almost independent of cooling time, as the cooling and SF time-scales are small compared to the simulation time and the gas disc outside \( R_{\text{max}} \) contains a negligible amount of mass. Thus, AExt1C and AExt both show a final gas fraction of 18 per cent. Angular momentum variation can significantly alter the mass in the outer gas disc with very long cooling and SF time-scales. Thus, ARef+Maj (36 per cent) and AExt (18 per cent) have much higher gas fractions than AMaj2C (3 per cent) and AExtLoAM (4 per cent). Realistic gas ratios are 5–25 per cent (Evoli et al. 2011), so that only our most extreme models are inconsistent with observations.

4.2 Why does infalling gas lose angular momentum?

As we have shown in Section 3.2, gas in our models loses angular momentum as it falls to the centre. Fig. 6 allows a closer inspection of angular momentum loss in several models. For each model the solid line represents the absolute value of the total specific angular momentum of all baryonic particles, whereas the dashed line represents only the particles that initially live within \( R < 0.2 R_{\text{gas}} \). The left-hand panel focuses on models which differ only in orientation and apart from AMaj2C, share the same density and velocity profiles and cooling times. Apart from ARef-Med and AMaj2C the central parts show higher angular momentum losses. The difference between central and total mass is biggest for model ARef as discussed above. Focusing on total angular momentum losses, the models aligned with the major halo axis (ARef+Maj and AMaj2C) show the lowest losses. They are about 10 per cent at \( t = 8 \) Gyr and subsequently only increase for ARef+Maj which develops strong misalignments between the inner and outer galaxy, leading to higher losses than in AMaj2C, which forms a well-aligned disc. ARef45, which starts with its orientation 45° offset, has lost 40 per cent of its total angular momentum at \( t = 8 \) Gyr. The rest of the models, which all started oriented perpendicularly to the major axis, show losses well in excess of 50 per cent. Only a small part of these losses, perhaps of the order of 10 per cent can be of numerical origin. Kaufmann et al. (2007) reported 10 per cent losses for their highest resolution model in a spherical halo, the resolution of which is similar to our models.

As halo A has an approximately prolate shape (Vera-Ciro et al. 2011), the axis ratio of the halo potential in the plane perpendicular to the major axis is close to 1, i.e. almost axisymmetric, whereas it is \( \sim 0.7 \) if the disc axis is perpendicular to the major axis.
Thus, the formation of a disc in the former case requires a less severe transition of the central halo potential into an oblate, axisymmetric, disc potential, than is the case for the latter models. The strongest angular momentum losses in our models occur in these initial transformation phases. As our spherical initial gas distributions are not in equilibrium with the gravitational potential of the halo, the gas, which is significantly less dense than the dark matter in the region in consideration, adjusts to the triaxial potential in the early phases of our simulations. Due to its rotation the shape of the gas distribution becomes offset from the shape of the potential if the halo symmetry axis and the axis of rotation do not agree. Gravitational torques then lead to the transfer of angular momentum to the halo. This explains the initial loss of angular momentum in all models except those oriented parallel to the major axis, as seen in Fig. 6. The differences in the evolution of models at the same orientation or with orientations perpendicular to major, which all show similar axis ratios of the equipotential ellipses in the plane defined by their initial orientation, appear at later times (after $\sim 0.5–1$ Gyr) and coincide with phases of reorientation of the angular momentum vector (see below).

In Fig. 7, we illustrate this reorientation of the total baryonic angular momentum vector in models ARef-Med, ARef+Med and ARef. Strong reorientation starts to develop after $\sim 0.5–1$ Gyr. At these times, the assembly of baryons in the centre of the halo has led to a transformation of the central halo potential shape, which apparently can induce strong reorientation of the baryonic angular momentum vector. ARef shows the lowest amount of reorientation and has the lowest losses of angular momentum. ARef+Med shows continuous reorientation, whereas ARef+Med settles into a new orientation relatively quickly. Consequently, ARef+Med loses the most angular momentum (see Fig. 6).
Disc models within ΛCDM haloes

Figure 5. SFRs as a function of redshift z for various models.

In the right-hand panel of Fig. 6, we focus on models with the same rotation axis. ARef180, which differs in orientation by 180° from ARef, and loses more angular momentum, as it shows strong reorientation (Fig. 7). However, the losses are smaller than in ARef-Med, showing that angular momentum losses depend not only on reorientation and on the shape of the potential in the disc plane, but also on the complex details of the interaction of hot gas, dark halo and stellar component. AExt1C, which is more extended, more massive and has a higher total angular momentum content, shows a smaller total angular momentum loss. AExt, which differs from AExt1C only by a four times longer cooling time, loses approximately the same amount of angular momentum, but on a longer time-scale, illustrating again that the loss occurs as the gas cools to the centre. AExtLoAM, which has the lowest amount of angular momentum and goes bar unstable (see Fig. 8), shows smaller losses than AExt, which only differs in $V_{\text{rot}}(R)$.

For fixed values of other parameters, shorter cooling time-scales, stronger reorientation and higher initial densities lead to increased angular momentum loss. Higher initial angular momentum also leads to greater fractional losses.

Figure 6. Angular momentum loss for different models. The left-hand panel features different orientations with otherwise constant parameters, whereas the right-hand panel focuses on different representations of physics at the same orientation. The definition of angular momentum loss is the same as in Fig. 3. The solid lines represent all baryonic particles in the simulations, and the dashed lines only the particles that initially reside at $R < 0.2R_{\text{gas}}$.

4.3 Structural properties

We continue with a study of the influence of the model parameters on the structure of the disc models. In Fig. 9, we analyse $\Sigma(r)$ profiles for several models in halo A. Here we focus on the models, which produce the strongest discs. The others are discussed in the following section. Model AExt1C, which has more initial angular momentum, a higher mass and a larger initial radius than ARef (see the bottom-left panel of Fig. 2) produces a more extended disc with a disc scalelength $R_d = 5.3$ kpc and no truncation out to 30 kpc. The four times longer cooling time of AExt mildly extends the scalelength to 6.1 kpc, but produces a truncation around 20 kpc as the outermost material cools too slowly to form stars. The bulge profiles are very similar in the two models, showing that the formation of a centrally concentrated component due to transformation of the central halo potential depends little on cooling time.

Model AExtLoAM goes bar unstable and thus shows a much stronger central component with a longer scalelength (1.2 versus...
Figure 8. Edge-on and face-on surface density projections for stars (left-hand panels) and gas (right-hand panels) at $z = 0$ for models (top to bottom): ARef, CExtCosmo, AExtLoAM, ARef-Min, CExt+AM and C-Maj.
Disc models within $\Lambda$CDM haloes

Figure 9. Radial stellar surface density profiles, $\Sigma(R)$ at $z = 0$ for models CExt+AM, AExt1C, AExt, CExtCosmo, AExtLoAM, C-Maj, AMaj2C and ARef-Min. Overplotted are fits of the type $\Sigma_0,1 \exp(-\frac{R}{R_d}) + \Sigma_{0,2} \exp[-(\frac{R}{R_b})^{1/n}]$. The numbers indicate the scalelengths of the two components.

0.9 kpc). The bulge profile extends to 8 kpc. The profile outside can be approximated by an exponential disc, but clearly shows a ring structure, that is also visible in Fig. 8, in both stars and gas. Pseudo-bulge and ring are results of bar-induced gas flows as discussed e.g. in Athanassoula (1992).

In model AMaj2C there is no severe initial central transformation. The profile can be fitted by a single exponential, that, because of the very low angular momentum losses, has a larger scalelength than ARef (4.5 versus 2.9 kpc) despite the low initial angular momentum content. The low angular momentum also leads to a small truncation radius $R_{\text{max}} \sim 12$ kpc.

The coldest discs form in AExt and CExtCosmo, which share initial density and angular momentum profiles as well as cooling time-scales, and undergo little reorientation. They show small halto-halo differences in terms of $\Sigma(R)$. AExt has a more massive bulge component, a slightly less extended disc ($R_d = 6.1$ versus 7.0 kpc) and a slightly smaller truncation radius. This underlines that the effects of the parameters discussed in this section are very similar in the two cases.

In Fig. 10, we compare vertical profiles of several models at $R = 5$ kpc. In contrast to the double exponential of ARef (see Fig. 2), AExt shows a single exponential profile with a slightly reduced exponential scaleheight $h_z = 400$ pc (compared to 420 pc for ARef).

We also present the profile of CExtCosmo. It has an even thinner disc with $h_z = 330$ pc, consistent with the reduced bulge fraction discussed above. Moreover, the flaring of these discs is significantly reduced compared to ARef. Scaleheights for CExtCosmo are $h_z < 400$ pc at $R < 10$ kpc and $h_z < 550$ pc out to $R \sim 20$ kpc.

The edge-on and face-on surface density projections in gas and stars of Fig. 8 (second row) nicely reveal that CExtCosmo sustains spiral substructure in the stellar and gas discs until $z = 0$, unlike ARef, which at this time has a significantly lower SFR. A comparison to ARef also highlights the less prominent bulge structure and
the lack of an underlying thick component. A longer cooling time and a higher angular momentum content result in a prolonged SF in the disc of CExtCosmo. Together with a small amount of reorientation of the angular momentum vector, this leads to the continuous existence of a relatively thin stellar disc preventing the formation of a thick component.

In comparison to these extended discs the low angular momentum model AExtLoAM, which goes bar unstable, shows a thick vertical profile at \( R = 5 \) kpc (in the bar region), which is fitted neither by an exponential nor isothermal profile. In the edge-on view in the third row of Fig. 8, the peanut shape of the stellar system is clearly visible.

### 4.4 Kinematical properties

The significant parameter dependences found above are also reflected in the stellar kinematics of our models. In terms of the circularity distribution, longer cooling times and the resulting thinner and more extended discs result in a slightly enhanced disc peak and a reduced bulge peak as may be seen by comparing AExt and ARef in Fig. 11. The massive bar in AExtLoAM significantly diminishes the \( \epsilon \sim 1 \) peak and shifts material into a wide, asymmetric distribution at \(-1 < \epsilon < 0.8\).

The parameter dependence of the discs is summarized in the rotation-to-dispersion-ratio plots of Fig. 12. In the upper-panel, we compare models ARef, AExtLoMa and AExt2C. Compared to ARef, AExtLoMa is more extended (\( R_{\text{gas}} = 100 \) versus 60 kpc). This leads to an increase of \( V_{\text{rot}}/\sigma_z \) for all generations of stars, a reduction of the bulge-fraction, but no significant increase in the thin disc population. A lower density, which already results in slower cooling (cf. Fig. 1), thus helps reduce the impact of initial bulge formation. An increase in mass by 50 per cent has little impact as may be seen by comparing AExt2C to AExtLoMa. It leads to more \( z = 0 \) thin disc stars as it increases the surface density and thus prolongs SF in the disc outskirts. Increasing the mass again by

**Figure 11.** Circularity distributions for models ARef, ARef−Min, AExt, AExtLoAM, ARef180 and C−Maj.

**Figure 12.** Rotation-to-dispersion ratio as in Fig. 4, but now for different models at \( z = 0 \). Top: the effect of the initial radius \( R_{\text{gas}} \) and mass \( M_{\text{gas}} \) illustrated by models ARef, AExtLoMa, AExt2C and AExtHiMa. Middle: the effect of the normalization of the cooling time \( t_{\text{cool},0} \) illustrated by models AExt1C, AExt2C and AExt. Bottom: the effect of the angular momentum content/rotation velocity profile \( V_{\text{rot}}(r) \) illustrated by models AExt, AExtMedAM and AExtLoAM.
a factor of 2, as in AExtHiMa, reduces the rotation-to-dispersion ratio significantly. The bulge fraction is reduced due to the longer cooling time applied (see middle panel). The disc goes bar unstable, however, and the bar subsequently heats the disc.

The second panel compares the models AExt1C, AExt2C and AExt and thus reveals the impact of the cooling time. Clearly a longer cooling time leads to an increase of $V_{\text{rot}}/\sigma_z$ for all generations of stars. The increase is especially significant for the old population. AExt only shows $\sim 5$ per cent bulge stars. From Fig. 4 we know that $V_{\text{rot}}/\sigma_z$ decreases due to disc heating as stellar populations age. As we know from Fig. 5 that AExt has a much younger population than AExt1C, the difference for the disc stars can be attributed mainly to the younger ages of the population. $V_{\text{rot}}/\sigma_z$ for the thin disc population is similar for all models, confirming that this is mainly determined by resolution and by the prescriptions for SF and for cooling.

The bottom panel of Fig. 12 concerns the initial angular momentum content of the models. Compared to AExt, $V_{\text{rot}}(R)$ in AExtMedAM has been reduced by 1/3 and by 2/3 in AExtLoAM. Interestingly, AExtMedAM shows a slightly smaller dispersion-dominated component. This indicates that the transfer of angular momentum from baryons to the dark halo plays a crucial role in the initial phase of bulge formation/transformation of the central potential. For the younger population, AExt is colder than AExtMedAM, as it is more extended and thus has longer SF time-scales for the outer populations. AExtLoAM has been discussed above and shown to go massively bar unstable. The consequence is a drastic reduction of $V_{\text{rot}}/\sigma_z$ for all ages.

### 4.5 Disc heating

To illustrate differences in disc heating, we depict in Fig. 13 the evolution of $\sigma_z(t)$ for several coeval populations of stars in models AExtLoAM and CExtCosmo. Compared to model ARef, presented in Fig. 4, they both have lower initial densities and slower cooling times. Like ARef they show continuous disc heating for all populations. Moreover, the oldest populations undergo strong heating in the first several $10^7$ yr, but, unlike ARef, the slower initial transformation of the central potential prevents hot initial dispersions $\sigma_{z,\text{ini}} > 50$ km s$^{-1}$.

The low angular momentum model AExtLoAM shows the strongest heating of old components (to $\sigma_z \sim 120$ km s$^{-1}$) due to the most concentrated surface density profile. At $t \sim 11$ Gyr after the massive bar has developed (cf. Fig. 8), a strong enhancement in the heating of disc populations is visible. In less than a Gyr, $\sigma_z(t)$ increases by about 50 per cent for all populations except the oldest, which are dispersion dominated and are hardly affected by the bar. An inspection of radial velocity dispersion $\sigma_R(t)$ reveals that in-plane heating is already enhanced at $t \sim 9$ Gyr, when the bar starts to form. The bar also increases the birth velocity dispersions of stars by about 50 per cent. The final bar/disc populations are heated more efficiently and are thus significantly hotter than in ARef. Analysing $\sigma_z(t)$ for radial bins shows that the increase occurs at all radii less than $\sim 8$ kpc and also in the central kpc. The stellar populations outside $R \gtrsim 10$ kpc (outside the bar region) are however not affected.

For the disc populations in the high angular momentum model CExtCosmo, $\sigma_z(t)$ behaves as for the corresponding populations in ARef, continuously increasing with the birth dispersions decreasing with time. The initial heating for the oldest populations is however significantly reduced compared to ARef. Consequently, the transition between the oldest and the subsequent populations is not as strong as in the other models. This is reflected by the increase in D/B for disc models with longer assembly time-scales. Still, CExtCosmo and all other disc models show a decrease in the birth velocity dispersions with time. This behaviour is a consequence of the triaxial halo and its substructure, and does not occur in simulations within idealized spherical haloes.

### 4.6 Summary

In this section, we have studied the influence of cooling time-scales, angular momentum content, initial density profile and mass on our models. We show that the formation time-scale increases with increasing cooling time and increasing angular momentum content. The angular momentum loss in our models increases mainly with increasing initial ellipticity of the dark matter potential in the disc plane. If reorientation of the baryonic angular momentum vector occurs in a model, it adds to the loss of angular momentum. A slower formation process and thus a slower transformation of the central potential yields thinner and more dominant final discs, and weakens the formation of prominent bulge and thick disc components. Massive bulges can only be avoided if the initial potential contours in

---

**Figure 13.** Vertical velocity dispersions $\sigma_z(t)$ as a function of time for coeval populations in models AExtLoAM (left) and CExtCosmo (right). See Fig. 4 for an explanation of how these plots are constructed.
the disc plane are almost circular. Double-exponential vertical disc
profiles are suppressed by a slow formation time-scale. All our discs
show continuous secular heating due to (spiral) substructure (e.g.
Jenkins & Binney 1990), so that younger discs are thinner. Disc
heating is strongly enhanced by bars, as was recently also discussed
by Saha, Tseng & Taam (2010). Additionally, heating is strongest
for the old bulge populations and the birth velocity dispersion of
stars in our simulations always decreases with time, which adds to
the age–velocity dispersion relation (see also House et al. 2011).
Higher angular momentum content leads to more extended discs
and larger truncation radii. The latter also increase with faster cool-
ing. Bars form, if, at fixed other parameters, the mass exceeds or the
angular momentum falls below (due to loss or initial lack) a stabil-
ity limit consistent with standard stability criteria for bar formation
(see Binney & Tremaine 2008 Section 6.3). (Pseudo-)Bulges are
enhanced by bar-induced gas inflows.

5 (RE)ORIENTATIONS OF DISCS

So far we have paid relatively little attention to the influence of the
initial orientation of the angular momentum vector of the rotating
gas sphere. We have shown that it plays a crucial role in angular
momentum loss of the infalling gas (Fig. 6). Moreover, Fig. 7 re-
vealed that this orientation is not fixed, rather different models can
undergo very different amount of reorientation. Model ARef and
many others, which we used to study the influence of parameters,
were initially oriented parallel to the angular momentum vector of
the dark matter within 300 kpc. This orientation was chosen as it
yielded the coldest discs in several test simulations and showed an
amount of reorientation that is similar to that of the dark halo itself
from $z = 1.3$ to 0.0. In terms of the principal axes of the triaxial
potential ellipsoid, the orientation of ARef is close to the minor
axis, but produces slightly better results than an exact alignment
with this axis.

HALO A $z = 1.3$ $z = 0.0$

In halo C, this setup failed. The dark matter angular momentum
is poorly aligned with the principal axes, and thus, the plane de-
ned by this orientation contains strong variations of the vertical
gravitational force, preventing quiescent disc formation. However,
orientations close to the minor axis proved to work well, underlin-
ing that the influence of the shape of the halo potential is stronger
than the influence of its angular momentum. This finding is consis-
tent with previous findings that discs in cosmological simulations
preferentially align with the minor axis of the halo (Bailin et al.
2005). In this section, we therefore explore which orientations in
haloes A and C are capable of producing thin discs. We do so in
subsections, first discussing (re)orientations in minor and medium
orientation models and the effects of reorientation on kinematics.
Then, we discuss major/intermediate orientation models, the struc-
ture of peculiar models and how reorientation shapes the potential.

5.1 Models with orientations perpendicular to the major axis

As both haloes are close to prolate at $z = 1.3$, we start by exploring
orientations, which lie in or close to the plane perpendicular to the
major axis of the halo potential. We illustrate the findings for halo
A in Fig. 14, where in the left half we show the initial orientations
of the angular momentum of the gas sphere in the right half we
show the orientations of the angular momentum of all the stars that
have formed by $z = 0$. The coordinate system is fixed and identical
in both halves. Zero degrees is defined by the initial orientation
of ARef and the numbers in brackets beside the model numbers
indicate the angles by which the orientations are offset from the
plane in degrees. Initially all these models are within 12° of this
plane. We show models aligned with the dark angular momentum
within 300 kpc (ARef, AExt), 180° offset from this (ARef180,
AExt180), aligned with the minor axis (ARef+Min, ARef-Min),
with the medium axis (ARef+Med, AExt+Med, ARef-Med, AExt-
Med), and with the final orientation of model ARef (ARefEnd).

Figure 14. Visualization of reorientation in halo A for models with initial orientations (approximately) in the plane perpendicular to the major axis of the halo
potential. On the left are initial orientations at $z = 1.3$ and on the right are mass-weighted mean orientations of the stellar systems at $z = 0$. The coordinate
system is static and was fixed to be perpendicular to the major axis of the halo potential at $z = 1.3$ and to have the initial orientation of model ARef at 0°. The
Greek letters and colours code the models, and the numbers in brackets indicate the angle between the orientation and the plane in degrees. AQg stands for
the orientation of the angular momentum of the gas at $R = 30–100$ kpc at $z = 0$ in the simulation of CS09.
The final orientations of the galaxies in halo A show a clear crowding of models around the minor axis. All models with orientations between ARef+Min and ARef+Med end up within $\sim 20^\circ$ from the reference model ARef and close to the plane perpendicular to the initial potential major axis. Fig. 7 shows a continuous reorientation of a total of $30^\circ$ for ARef. ARef+Med however first turns by $\sim 90^\circ$ before also showing a small, continuous reorientation. Thus, these models all seem to adjust to the 'correct' orientation and then evolve rather quiescently. Models with different parameters sharing the same initial orientation show very similar final orientations as illustrated by models ARef/AExt and ARef+Med/AExt+Med.

All the other models however end up with significantly different orientations, and there is no clear correlation between their initial and final orientation. ARef$180$ seems to end up close to its original orientation; however, it flips by almost $120^\circ$ before slowly returning. If dark matter influenced the evolution only through its global potential, there should be no difference between two orientations differing by $180^\circ$, which is clearly not the case, so halo rotation and transfer of angular momentum between the baryons and the dark matter must play a role in the described processes. Comparing AExt$180$ and ARef$180$, which share initial orientation, we detect a final offset of more than $90^\circ$. A smaller, but significant difference exists also between AExt-Med and ARef-Med. In Fig. 7, one can see that the initial turn of ARef$180$ by $\sim 120^\circ$ is also seen in AExt$180$, where this process takes longer. The model then stabilizes in this orientation. Model ARef-Med, which starts from a medium orientation, shows continual and strong reorientation.

In Fig. 15, we illustrate the situation in halo C. Zero degrees is defined by the initial orientation of CExt+Min, which was aligned with the halo minor axis. CExt-Min is $180^\circ$ offset, CExt-Med and CExt+Med are aligned with the medium axis, and CExtEnd is the final orientation of CExt+Min. CExt+Arb and CExt-Arb result from an error in the setup but are useful for this analysis. AQ marks the orientation of the disc in the cosmological galaxy formation simulations of CS09. Finally, CExtCosmo uses the $\epsilon = 1.3$ cosmological orientation as an initial condition. We see that the cosmological disc is well aligned with the minor axis, around which many models again crowd at $z = 0$, in this case all models with orientations between those of CExt+Arb and CExt+Min in the initial conditions. CExt-Min and CExt+Med indicate that, for halo C, the direction $180^\circ$ offset from the 'best disc' orientation is also a preferred orientation at $z = 0$. Among the models presented, only CExt-Arb ends up in a significantly different orientation.

5.2 How reorientation affects kinematics

In the previous subsection, we have shown that the orientation of the angular momentum of infalling gas can undergo significant changes. In the previous section, we have already shown that this leads to loss of angular momentum. Here, we study the effects of these processes on the kinematics of the models.

In Fig. 16, we show rotation-to-dispersion ratios for the halo A models ending up close to the ARef final orientation (top panel) and for the other models of Fig. 14 (middle panel). In both panels, the models with longer cooling times show higher $\frac{V_{\text{rot}}}{\sigma}$, for the disky populations as was discussed in the previous section. There is, however, a clear dichotomy between the two panels. All models in the upper panel show a monotonic increase in $\frac{V_{\text{rot}}}{\sigma}$ from old to young stars, indicating that these are continuously forming discs. It also shows that ARef has the coldest disc population of the models sharing the same parameters, presumably because it also shows the smallest amount of reorientation. However, ARef+Min and ARef+Med, which start exactly in the plane perpendicular to the major axis show a smaller bulge population than ARef and ARefEnd, which start with a small misalignment to this plane.

The models depicted in the middle panel do not end up close to the preferred disc orientation and all show counter-rotating young populations indicating the infall of gas misaligned with the rotation of the stellar object at late times and none of these objects show thin disc populations of stars.

Circularity distributions for ARef$180$ and ARef-Min are shown in Fig. 11. The compact, barred disc of ARef-Min has lost its $\epsilon \sim 1$ peak and shows a wide, asymmetric distribution peaking at $\epsilon \sim 0.6$. It has a strongly enhanced counter-rotating population compared to ARef. ARef$180$, in contrast, shows only a mildly diminished

![Figure 15](https://academic.oup.com/mnras/article-abstract/428/2/1055/999429)

**Figure 15.** Same as Fig. 14 but for models in halo C. The initial orientation of model CExt+Min is at $0^\circ$. AQ stands for the disc in halo C of CS09.
Figure 16. Rotation-to-dispersion ratios as defined in Fig. 4 but now for models with different orientation. A negative ratio indicates a component that is counter rotating with respect to the total stellar angular momentum. Top panel: models perpendicular to the major axis ending up in ‘disc orientation’ and disc-like rotation: ARef+Med, ARef, ARef+Min, ARefEnd and AExt. Middle panel: models perpendicular to the major axis not showing a continuous disc formation, but all showing significant reorientation and developing counter-rotating components: ARef−Med, ARef180, ARef−Min, AExt−Med and AExt180. Bottom panel: models parallel to the major axis: ARef+Maj, ARef−Maj, AMaj2C, AMaj, AMaj180 and model ARef45.

Figure 17. Vertical velocity dispersions $\sigma_z(R)$ as a function of disc radius $R$ in the models ARef+Med, ARef, ARef180, ARef+Min and ARefEnd.

disc peak compared to ARef, but features a distinct, small counter-rotating disc peak at $\epsilon \sim (−1)$.

In Fig. 17, we analyse the radial profiles of vertical velocity dispersion $\sigma_z(R)$ for several of the models just discussed. Unlike ARef, which shows a realistically declining $\sigma_z(R)$, there are several models showing an outward increase in $\sigma_z(R)$ after a drop at inner radii, most strikingly ARef180. According to Fig. 7, ARef180 shows the strongest reorientation during its evolution and according to Fig. 6 also the strongest losses of angular momentum of all models, whereas ARef shows only weak reorientation. This trend is confirmed by AExt180 and ARef+Med, which are intermediate between ARef and ARef180 in terms of $\sigma_z(R)$ flaring and reorientation. ARef-Med, which shows the strongest angular momentum losses and continuously strong reorientation shows very high $\sigma_z(R)$ at all radii and mild flaring. This also strengthens the conclusion that these two processes lead to high velocity dispersions in the final systems, especially in the outskirts.

In the top panel of Fig. 18, we plot rotation-to-dispersion ratios for all models in halo C that end up with a thin disc population of stars ($V/\sigma_z > 5$ and $V/\sigma_z$ decreasing monotonically with age). CExtEnd and CExtCosmo, the orientations motivated by the cosmological model and the final orientation of CExt+Min, produce the coldest discs. Similarly to AExt in halo A, these models are slightly offset from the minor orientation. CExt+Min, the minor orientation run, still has a better disc than CExt-Min, which starts and ends at an angle of 180°. Unlike in halo A, this orientation still produces a disc. The medium orientation runs CExt-Med and CExt+Med, which also start and end up at an angle of 180° produce slightly worse discs due to the effects of reorientation. CExt+Arb, which starts from an orientation about 120° offset from CExt+Min, also produces a disc in the preferred final direction. CExt-Arb is the only model not following the trend. The orientation changes strongly and the model results in a thick disc surrounded by misaligned components, each resulting from a different formation phase as indicated in the lower panel of Fig. 18.

5.3 Models with major and intermediate initial orientations

Until now, we have focused only on models that start (nearly) perpendicular to the major axis. As already discussed in the previous section, AMaj2C, which starts aligned with the major axis, also produces a relatively small, thin and exponential disc. As can be seen
The system might be classified as a barred, fast rotating 1. In halo C, the situation is similar. C+Maj, which starts in major axis orientation with the same parameters as AMaj, also produces a disc. It also undergoes reorientation away from the major axis and ends up at an angle \( \approx 30^\circ \) from the final orientation of CExt+Min. However, C-Maj, which has an initial gas angular momentum orientation 180° apart from C+Maj and a more extended initial radius and thus higher angular momentum, does not produce a nice disc, showing outer misalignments as in ARef+Maj. This model shows that misalignments are common for initial orientations parallel to the major halo axis, also for medium angular momentum content.

The model CExt+AM is initially aligned with the angular momentum of the halo at \( R < 300 \kpc \), which is at an angle of \( \approx 45^\circ \) to the major axis. This is why the model experiences similar problems to ARef45. The same is true for CExt-AM, which starts at an angle of 180° to CExt+AM.

### 5.4 The structure of peculiar models

Although our models were designed to produce discs, not all of them end up as such, as we have shown above. Here we briefly analyse the structure of three of those models in more detail.

ARef-Min is one of the models, which starts oriented perpendicular to the major axis and show continuous, strong reorientation, which leads to strong angular momentum losses and high velocity dispersion (see the middle panel of Fig. 16). We have included surface density projections of ARef-Min in Fig. 8 (fourth row). Due to the angular momentum losses the resulting disc is compact, barred and thick with an exponential scaleheight of \( h_z = 1.3 \kpc \) (see Fig. 10). Its exponential-like radial profile is very steep with \( R_0 \approx 1.8 \kpc \) as shown in Fig. 9. The galaxy has a high bulge fraction, \( D/B \approx 1 \). Even at \( z = 0 \) the remaining gas is concentrated in the central bulge and does not show a disc structure. Also the stellar disc structure is mostly bar-like and is surrounded by a spheroidal star distribution. Its circularity distribution (Fig. 11) shows a wide, asymmetric peak at \( \epsilon \approx 0.6 \). The system might be classified as a barred, fast rotating early-type galaxy applying a classification scheme as used for the ATLAS3D survey (Emsellem et al. 2011).

CExt+AM represents the models starting with intermediate initial orientations. In the fifth row of Fig. 8, we show its \( z = 0 \) surface density projections. The gas lives in a perfect disc, whereas the stellar disc shows two regions: a dominant bulge-like central structure, which is elongated perpendicular to the gas disc, and outer regions dominated by rings and separated from the centre by a drop in surface density around \( R \approx 9 \kpc \) (see Fig. 9). The vertical profile at \( R = 5 \kpc \) can be fitted by a thick exponential with \( h_z \approx 3.5 \kpc \) (Fig. 10). Fig. 18 reveals several dips and peaks in \( V_{\text{rot}}/\sigma_z \) during the formation of the object indicating several misaligned populations, which prevent the formation of a cold disc. The system bears some resemblance with polar bulge galaxies (see e.g. Corsini et al. 2012).

Models starting in major orientations and developing strong misalignments are represented by C-Maj, the surface density projections of which are shown in the bottom row of Fig. 8. Two stellar components at an angle \( \approx 60^\circ \) are clearly visible. Consequently, the circularity distribution in Fig. 11 shows two distinct peaks at \( \epsilon \approx 0.85 \) and \( \approx 0.25 \). The latter represents the ring which forms at late...
5.5 How reorientation affects the shape of the potential

In the context of the results already presented in this section, the question arises, how the shape of the final gravitational potential differs between models. Clearly, in central regions dominated by a disc, the potential is found to be oblately symmetric. Due to the interaction with the forming disc, the dark matter halo becomes less triaxial, in agreement with the results of Kazantzidis et al. (2010). Moreover, the initial triaxiality of the halo, which in the dark-matter-only simulations shows little reorientation, is still imprinted at outer, halo-dominated radii. Consequently, for models such as AExt or CExtCosmo, the gas angular momentum of which was initially aligned with the minor potential axis, the final disc axis is well aligned with the final minor axis of the potential at all radii. For disc models, which end up in preferred disc orientation, but started with a different initial orientation, such as ARef+Med or CExt+Arb, the situation is similar, yet the potential contours are less flattened, consistent with the fact that these discs are thicker. For models, where the final stellar angular momentum does not align with the preferred disc orientation, such as ARef-Med or CExt-Arb, there is also no alignment between the final potential ellipsoids at inner and outer radii. This is also true for compact disc models, which formed from gas which was initially aligned with the major axis. The discs, which are finally closest to an alignment with the major axis of the outer potential, are AMaj and AMaj2C with an offset angle of $\sim 30^\circ$.

5.6 Summary

In conclusion, we have shown that each of the two haloes we studied shows a preferred orientation for discs, which roughly agrees with the minor axis of the inner halo potential, in agreement with the results of Bailin et al. (2005) for fully cosmological simulations. However, a flip of the initial angular momentum vector by $180^\circ$ produces a slightly worse (halo C) or unsuitable (halo A) orientation for a forming disc. This shows that it is not the shape of the potential alone that determines the preferred orientation. Models with initial non-preferred angular momentum orientations tend to reorient to a preferred axis, producing thickened and flaring discs. In some cases, they fail to settle to a stable orientation and do not end up with significant discs. There is no obvious simple criterion to explain this dichotomy. Models starting with angular momentum parallel to the major halo axis also do not show a stable orientation. They form stable discs only if their angular momentum content is low, so that they rapidly form compact objects, which cannot be destroyed by reorientation, which misaligns inner and outer components. Realistic thin discs with continuously forming populations are thus only possible for initial orientations close to the halo minor axis. Models with initial orientations in between these cases are not capable of producing cold discs. Taking results of the previous sections into account, we have also shown that the orientations of both the central disc and the outer gas can change by more than $90^\circ$, despite the simple and coherent initial distributions of our gas components. This is also true for the angle between the components.

6 COMPARISON TO COSMOLOGICAL SIMULATIONS

Until now, we have shown that, with our method, we are capable of introducing discs into Aquarius haloes A and C. Using the cosmological orientations of the discs at $z = 1.3$ in the simulations of CS09, we showed that for halo C the disc is in the ‘right place’, meaning that our model CExtCosmo, which starts with this orientation, produces a nice disc at $z = 0$. In halo A, the cosmological disc is in the ‘wrong place’, i.e. our model ACosmo, starting in the corresponding orientation, fails to produce a nice disc. We have identified reorientation of the angular momentum of infalling material and the angular momentum losses and misalignments connected to this phenomenon as the key factors in the failure of many of our models to build substantial discs. CS09 also identified misaligned infall of gas as the problem destroying the existing disc structure in their resimulation of halo A.

In this section, we would therefore like to analyse the reorientation of gas in the runs of CS09 and compare them to our own. In these cosmological simulations, the inflow of gas is continuous and more complex than in ours; it is not desirable to define fixed gas populations by their radial position at a certain time. It is more instructive to follow how the angular momentum of gas evolves in fixed radial shells of 10 kpc width as is shown in Fig. 19, where we compare the reorientation in models ACosmo and CExtCosmo to the reorientation in models A and C from CS09.

ACosmo, as depicted in the top-left panel of Fig. 19, shows strong and continuous reorientation for all baryons, gaseous and stellar. Reorientation is slightly delayed for the outer shells compared to the inner, but the resulting misalignments are small compared to the models discussed in the previous section. After $t \sim 9$ Gyr there is no overall detectable misalignment among the initially defined shells, although there is a small counter-rotating component as shown in Fig. 16 originating from temporary misalignments and continuous reorientation. As shown in Fig. 14, ACosmo is $\sim 45^\circ$ offset from the orientation of most of the disc models in halo A at $z = 0$. During its evolution it evolves towards this orientation until $t \sim 11$ Gyr, when it is only $\sim 20^\circ$ offset and then starts to turn away again.

For the fully cosmological model, we start the analysis at $z = 2$ (lower-left panel). The reference orientation is the one of the stars within $R < 10$ kpc at $z = 1.3$, which is the initial orientation of ACosmo. At $z = 2$ the orientation of the stellar angular momentum differs by less than $10^\circ$. Even at $z = 2$ the gas out to $R = 120$ kpc is not well aligned with the galaxy. Until $z \sim 1$ there is a clear misaligning process. From then on, gas in all shells shows an orientation $\sim 150^\circ$ offset from that of the galaxy at $z = 1.3$. The new orientation is also depicted in Fig. 14. It only differs by $\sim 20^\circ$ from the initial orientation of model ARef, which explains why this orientation yielded the best results. The offset is caused by a stronger misalignment with the plane perpendicular to the major axis.

The strong reorientation of the gas is also depicted in fig. 10 of CS09, where the evolution of the angle between the stellar and the gas components within 27 comoving kpc is plotted. The fact that the components become aligned again at $z = 0$ indicates that the inner stellar component reorients to the same direction, but with a delay. Moreover, the central gas components (black lines in Fig. 19) are also offset from the outer gas by up to $\sim 50^\circ$.

The new orientation of the (outer) gas is also within $\sim 20^\circ$ of the orientation of model ACosmo shows at $t \sim 10.5$ Gyr, but at $z = 0$ the orientations differ by $\sim 70^\circ$. This is due to the continual reorientation in model ACosmo. While the reorientation process is qualitatively similar in these models, the final orientation of the
Disc models within ΛCDM haloes

Figure 19. Orientation angle as a function of time for models ACosmo (top-left) and CExtCosmo (top-right). The initial gas sphere has been divided into 12 radial shells of $R_{\text{gas}}/12$ width each. For each shell the angle of the angular momentum vector $j_i(t)$ of all particles initially in shell $i$ to the initial orientation is calculated at each output time $t$. The panels in the bottom row show the spin orientation in the same coordinate system for the gas content of 12 spatially fixed concentric shells of 10 kpc width for the A and C runs of CS09.

The galaxy is also dependent on the details of its assembly, as seen above for non-disc models with identical initial orientation but otherwise different parameters such as ARef180 and AExt180.

For halo C the situation is less complicated. The orientation of the gas in the CS09 model, which was used as an initial condition for our model CExtCosmo at $z = 1.3$, behaves very similarly to CExtCosmo. It shows an overall reorientation by the same amount ($\sim 20^\circ$) and comparatively small misalignments, $<45^\circ$.

In Fig. 20, we compare the orientation of the galaxy (all stars within 10 kpc) in a given model to the orientation of the angular momentum of the dark matter (including subhaloes) within $R$ as a function of radius $R$. Model ARef is initially set up to be aligned with the dark matter within 300 kpc. As can be seen, this orientation is not, however, aligned with the dark matter within 200 kpc, but the stars and dark matter become aligned by $z = 0$ where the alignment is, in fact, better than $30^\circ$ for all radii $R < 500$ kpc.

In the fully cosmological halo A model the galaxy is aligned with the dark matter within $R \sim 100$ kpc at $z = 1.3$, but is strongly misaligned otherwise, especially at $R > 150$ kpc, where the angle reaches $\sim 150^\circ$. At $z = 0$, there is no disc and thus the orientation of the galaxy is not well defined. Considering stars within 10 or 30 kpc yields different results as indicated by the black and blue lines. The stars at $R < 10$ kpc are well aligned with the central dark halo, whereas the stars at $10 < R/kpc < 30$ are not. Both populations are misaligned with the dark matter outside $R \sim 50$ kpc, but the misalignment is significantly smaller for the stars at $10 < R/kpc < 30$.

For halo C the picture is different. Model CExtCosmo is initially misaligned with the dark matter angular momentum by an angle of $\sim 50^\circ$. This hardly changes by $z = 0$, when the inner 100 kpc have become more aligned, but the outer parts remain unchanged. In the fully cosmological run, the situation is strikingly different. In the inner $\sim 50$ kpc, the dark matter both at $z = 1.3$ and 0.0 is strongly misaligned with the galaxy, almost $180^\circ$ near the centre. This explains why there is no clear correlation between dark matter and galaxy angular momenta in our models based on halo C.

In summary, there are no large discrepancies between our models and fully cosmological galaxy formation simulations within the same haloes. In the absence of any destructive events such as major mergers, a disc will survive over cosmological time-scales, if it has formed in the preferred orientation for its halo. As we showed, this orientation does not depend on the potential alone (Section 5), nor is there a clear correlation with the angular momentum of the halo (this section). The orientations of the halo principal axes and the halo spin axis can change with time (see Vera-Ciro et al. 2011 and Bett & Frenk 2012, respectively) and so apparently, can the preferred disc orientation, as is clear from the halo A run of CS09, where a disc is destroyed by inflowing matter oriented in a new preferred direction. Despite this, we were able to find initial gas setups which lead to thin discs in this halo. For halo C there is no such orientation
change and thus both our own and the fully cosmological models produce surviving discs.

7 CONCLUSIONS

We have presented a series of simulations of idealized SPH models for the formation and evolution of galactic discs within fully cosmological ΛCDM haloes. At \( z = 1.3 \) we add rotating spheres of hot gas in approximate hydrostatic equilibrium to two dark matter haloes from the Aquarius project (Springel et al. 2008). A parametrized cooling law and standard prescriptions for SF allow us to study the evolution of the combined baryon-ΛCDM systems until \( z = 0 \). We study models with different orientations and amount of baryonic initial angular momentum, different cooling time-scales and different density profiles. This allows us to determine favourable and non-favourable conditions for the formation and survival of discs.

Clearly, such simulations are not full models for the formation of disc galaxies. However, they allow us to study processes relevant to the formation of discs within triaxial and realistically evolving dark matter haloes, and hence explore the conditions under which massive discs can exist in ΛCDM haloes. This should help us understand the failure or success of various fully cosmological simulations of disc galaxy formation, which still suffer from a multitude of uncertainties (e.g. Governato et al. 2007; CS09; Guedes et al. 2011; Scannapieco et al. 2012). A particular problem may be that these simulations tend to produce overly old stellar populations (see the discussion in Aumer & Binney 2009) and thus to underpredict the stellar mass formed since \( z \sim 1 \), the epoch generally thought to be best suited for disc formation due to the absence of major mergers at such late times. Our models are unable to reproduce full SF histories but yield interesting insights into galaxy formation at relatively recent times.

Our setup has an inherent initial discrepancy between the triaxial, substructured and dynamically growing halo and the rotating quasi-equilibrium gas sphere. This leads to an initial phase, in which the gas adjusts to the potential. Thereafter, it loses angular momentum to the dark matter as it cools to the centre and transforms the total central potential, and thus also the halo, into a more axisymmetric configuration capable of hosting a stable disc. We show that the shorter the time-scale of this transformation, the more destructive the effect on the forming disc, and thus the more dominant the resulting bulge and thick disc components. Haloes are expected to be near prolate after major mergers (e.g. Romano-Díaz et al. 2009) before most of the stellar mass assembles into discs, so this process of bulge formation during halo transformation is not unrealistic. Romano-Díaz et al. also report the initial formation of an asymmetric, bar-unstable disc in their fully cosmological simulations. Only if we align the initial angular momentum of the gas sphere with the major axis of the potential, can we suppress this destructive process. However, the transformation from a prolate potential to an oblate disc potential triggers misalignments between inner and outer baryonic components, which hinders disc survival.
We have shown that our models are capable of producing, and thus that the haloes in consideration are capable of hosting, discs with realistic structural and kinematic properties, which unlike in most cosmological simulations show realistic D/B mass ratios D/B > 4. As has been shown previously (Scannapieco et al. 2010), structural and kinematic decompositions yield strongly differing results, with structural values exceeding kinematic ones by factors of a few. We show that our discs have rotation-to-dispersion ratios $V_{rot}/\sigma_z$ monotonically decreasing with increasing age, which arises from continuous disc heating due to substructures and a monotonic decrease in birth velocity dispersion connected to the transformation of the central potential. Due to limitations in resolution, our simulations are not capable of producing realistic young thin stellar discs with $\sigma_z < 10$ km s$^{-1}$ (see also House et al. 2011), but they agree qualitatively with age–velocity dispersion relations for the solar neighbourhood (Aumer & Binney 2009; Holmberg et al. 2009). Our discs show truncations, which move outwards with time and the radius of which increases with decreasing formation time-scale and increasing angular momentum content.

We find that the slower the formation of a model galaxy, the colder and more dominant the final disc. This is the result of the combined effects of the suppression of bulge formation during potential sphericalization and of continuous disc heating being less efficient for younger populations. Bars develop in our model discs if their surface density is enhanced by a higher total mass or lower total angular momentum. They strongly increase disc heating (see Saha et al. 2010), enhance the bulge fraction and produce prominent ring structures outside the bar regions (see Athanassoula 1992), thus lowering the resulting $V_{rot}/\sigma_z$ by factors of a few.

We show that the most stable, most extended and coldest discs form from a gas angular momentum orientation that is aligned with the minor axis of the inner halo, as had been previously found in cosmological simulations by Bailin et al. (2005). Out of the two such orientations given by the halo (180° apart) one is clearly preferred. For one of our two haloes, the preferred direction is determined by the angular momentum of the outer halo in the initial conditions; by the end of the simulation all regions are (marginally) aligned with the central disc. The counter-rotating orientation is strongly disfavoured and does not produce stable discs. For the second halo, there is no alignment between halo angular momentum and shape. The non-preferred minor axis orientation of the gas angular momentum is the one which makes the larger angle with the halo spin axis. Models with this initial orientation are able to host stable, yet thicker discs. In each halo we find a certain range of initial gas angular momentum orientations perpendicular to the halo major axis, for which a reorientation of the baryonic spin vector to one of the stable orientations occurs with the disc thickening but surviving. Models, where the gas angular momentum is initially aligned with the halo major axis can produce discs, but their orientation is not stable. Intermediate models cannot produce stable discs. Reorientation especially heats the outer, lower surface density parts of discs, where self-gravity is unable to keep the stellar orbits aligned. Compact, high surface density discs are significantly less heated by orientation changes.

As reorientation is common for both halo shapes (Vera-Ciro et al. 2011) and halo angular momenta (Bett & Frenk 2012), the preferred orientation will evolve with time in ΛCDM haloes. This is directly connected to the well-known phenomenon of misaligned matter infall during the assembly of haloes and galaxies (e.g. Quinn & Binney 1992). However, in our models, the initial gas distribution is spherically symmetric and its angular momentum is aligned at all radii. Despite this, the orientations of outer and inner gas and of stellar discs and also the angle between these components change by more than 90° in many cases. Misalignment is thus a consequence of strongly non-linear dynamical interactions in the final stages of galaxy assembly, not just of evolving asymmetries in the cosmological context, which feeds halo growth.

Misaligned components are common in observed galaxies in the form of warps (Sancisi 1976), polar rings (Whitmore et al. 1990), polar bulges (Corsi et al. 2012) or counter-rotating components in early-type galaxies (Krajnović et al. 2008). Misaligned cosmological infall has been identified as a cause for a variety of phenomena, such as the destruction of discs (CS09), the formation of polar discs (Brook et al. 2008) and the excitation of warps (Roškar et al. 2010). Interestingly, all of these phenomena also occur in our models. We qualitatively reproduce the misaligned infall found in the cosmological resimulation of halo A by CS09 starting from a spherical and coherently rotating gas distribution. The torques acting in our simulation must originate in the non-linear structure of the dark halo, suggesting a mechanism different from the conclusions of Roškar et al. (2010) who found negligible influence of the dark halo torques in comparison to anisotropic cosmological infall.

All these processes of misalignment are associated with the loss of angular momentum (see also Roškar et al. 2010) and produce more compact, hotter objects. Thin extended discs can thus only form in stable orientations and thus in haloes for which the preferred disc orientation undergoes little temporal evolution. This conclusion is similar to that of Sales et al. (2011), who found that disc form from the continuous accretion of material with coherently aligned angular momentum orientation and that misaligned accretion of gas tends to produce spheroids. The question arises whether ΛCDM offers enough haloes which fulfil these conditions to explain the observed abundance of disc galaxies in the Universe. Sales et al. (2011) find a significant fraction of such disc-dominated systems in their model sample of galaxies, but the limitations of their simulations do not allow a full comparison with the statistical properties of observed samples. Semi-analytic models of galaxy formation (e.g. Guo et al. 2011) are helpful for studying galaxy populations, but they do not capture the role of misalignments and other dynamical details that, as we have shown, play a major role in galaxy evolution. It would be desirable to add proper treatment of these processes to the models; however, we are not able to offer straightforward prescriptions, as we are not capable of drawing general conclusions from this study of two haloes.

Considering our work and recent improvements in cosmological resimulations of individual galaxies (e.g. Guedes et al. 2011; Brook et al. 2012) realistic ΛCDM haloes appear to be capable of hosting realistic disc galaxies. However, more work is needed to understand whether the population of ΛCDM haloes agrees in detail with the observed population of galaxies.

ACKNOWLEDGMENTS

We are grateful to Jackson DeBuhr, Chung-Pei Ma, Laura Sales and Ralph Schönrich for valuable discussions. We thank Cecilia Scannapieco for kindly providing and discussing her cosmological simulations. MA acknowledges support from the DFG Excellence Cluster ‘Origin and Structure of the Universe’.

REFERENCES

Abadi M. G., Navarro J. F., Steinmetz M., Eke V. R., 2003, ApJ, 597, 21
Agertz O., Teyssier R., Moore B., 2011, MNRAS, 410, 1391
Athanassoula E., 1992, MNRAS, 259, 345

Downloaded from https://academic.oup.com/mnras/article-abstract/428/2/1055/999429 on 27 July 2018
