The formation of disc galaxies in high resolution moving-mesh cosmological simulations

Federico Marinacci\textsuperscript{1,2}, Rüdiger Pakmor\textsuperscript{1} and Volker Springel\textsuperscript{1,2}

\textsuperscript{1}Heidelberger Institut für Theoretische Studien, Schloss-Wolfsbrunnenweg 35, 69118 Heidelberg, Germany
\textsuperscript{2}Zentrum für Astronomie der Universität Heidelberg, Astronomisches Recheninstitut, Mönchhofstr. 12-14, 69120 Heidelberg, Germany

24 May 2013

ABSTRACT
We present cosmological hydrodynamical simulations of eight Milky Way-sized haloes that have been previously studied with dark matter only in the Aquarius project. For the first time, we employ the moving-mesh code AREPO in zoom simulations combined with a new comprehensive model for galaxy formation physics designed for large cosmological simulations. Our simulations form in most of the eight haloes strongly disc-dominated systems with realistic rotation curves, close to exponential surface density profiles, a stellar-mass to halo-mass ratio that matches expectations from abundance matching techniques, and galaxy sizes and ages consistent with expectations from large galaxy surveys in the local Universe. There is no evidence for any dark matter core formation in our simulations, even so they include repeated baryonic outflows by supernova-driven winds and black hole quasar feedback. The simulations significantly improve upon the results obtained for the same objects in some of the earlier work based on the SPH technique, and also on the results obtained in the recent ‘Aquila’ code comparison project which focused on one of the haloes from our set. For this Aquila object, we carried out a resolution study with our techniques, covering a dynamic range of 64 in mass resolution. Without any change in our feedback parameters, the final galaxy properties are reassuringly similar, in contrast to other modeling techniques used in the field that are inherently resolution dependent. This success in producing realistic disc galaxies is reached without resorting to a high density threshold for star formation, a low star formation efficiency, or early stellar feedback, factors deemed crucial for disc formation by other recent numerical studies.

Key words: methods: numerical – galaxies: formation – galaxies: evolution – galaxies: spiral

1 INTRODUCTION

Forming realistic disc galaxies in self-consistent hydrodynamical simulations of the ΛCDM cosmology has been a nagging problem for more than two decades (after pioneering work by Katz & Gunn 1991). In stark contrast to the successes reached with dark matter only simulations of cosmic large-scale structure (e.g. Davis et al. 1985; Springel et al. 2006) and with semi-analytic galaxy formation models (e.g. Guo et al. 2011), making realistic spiral galaxies on the computer has emerged as an unexpectedly difficult endeavor that has withstood countless attempts at solving it over the years. Instead, the simulated galaxies were often too small due to an angular momentum deficit (e.g. Navarro & Steinmetz 2000), they featured at best anemic discs and almost universally too concentrated and massive bulges (e.g. Scannapieco et al. 2009), their rotation curves had unrealistic shapes (e.g. Hummels & Bryan 2012), and in general they were far too luminous (e.g. Martig et al. 2012) as a result of the “overcooling catastrophe” (Balogh et al. 2001).

Recently, however, the situation has profoundly changed, and there are now several studies that obtained disc galaxies in quite reasonable agreement with key observables (Governato et al. 2010; Agertz et al. 2011; Guedes et al. 2011; Brooks et al. 2011; Stinson et al. 2013; Aumer et al. 2013). In particular, for the first time, we have seen simulations that produce reasonably small bulges and a dominant disc, combined with realistic rotation curves, roughly correct sizes, and low enough stellar masses to be compatible with abundance matching expectations (Stinson et al. 2013; Aumer et al. 2013). This progress raises the question of what cut the Gordian knot that had allowed only incremental advances for many years (Governato et al. 2004, 2007; Robertson et al. 2004; Scannapieco et al. 2008, 2009, 2011; Sales...
et al. 2009, 2010; Stinson et al. 2010; Piontek & Steinmetz 2011).

There are different claims in the literature about the key remedy for the impasse. Some studies have argued that very high numerical resolution is a central and potentially sufficient requirement (e.g. Kaufmann et al. 2007; Governato et al. 2007), whereas other works emphasized that the degree of success critically depends on the modeling of the physics of star formation and feedback (e.g. Okamoto et al. 2005; Scannapieco et al. 2008; Sales et al. 2010). Recently, some authors suggested that a high star formation threshold is a key factor in allowing the successful formation of a late-type spiral galaxy like the Milky Way (Guedes et al. 2011). On the other hand, Agertz et al. (2011) find that a low star-formation efficiency, particularly at high redshift, is important, whereas an opposite conclusion was reached by Sommer-Larsen et al. (2003) and Sales et al. (2010), who favoured a high star formation efficiency instead. Other studies pointed out that additional feedback channels such as cosmic rays (e.g. Uhlig et al. 2012), or stellar evolutionary processes in the form of mass return (Leitner & Kravtsov 2011) need to be considered.

Which of these factors reflects essential physics important for disc formation rather than numerics or the particularities of a specific modelling technique is far from clear. A recurrent theme, though, is that in all the recent successful simulations of disc galaxies a much stronger feedback than employed in previous calculations is invoked. In particular, the advances in reproducing disc galaxies by Stinson et al. (2013) and Aumer et al. (2013) are attributed to ‘early stellar feedback’ introduced by the authors. In the actual numerical implementation of Stinson et al. (2013), this is injecting considerably more energy than from supernovae alone and allows the simulations to finally curtail the overproduction of stars at high redshift that invarably led to an excessively massive central bulge component later on. Whether the adopted subgrid modelling of the physics of radiation pressure of newly born stars is realistic has to be seen, but optimistic assumptions about the efficiency of feedback are needed by all authors to reduce early star formation and delay disc formation to sufficiently late times.

Indeed, perhaps the most general lesson of recent simulation work on galaxy formation is that the importance of feedback for the outcome of hydrodynamical cosmological simulations can hardly be overstated. The Aquila comparison project (Scannapieco et al. 2012) has shown that different numerical codes can give widely different outcomes for the same initial conditions. Even the same code can give substantially different answers if small details in the implementation of feedback and star formation physics are changed. Many feedback implementations in current use are not robust to resolution changes and require ‘returning’ of the free parameters of the model to obtain the same or a similar result when the resolution is changed – if at all possible. The differences can be as extreme as those reported in Okamoto et al. (2005), where a galaxy’s morphology simulated at different resolution varied over the entire range of Hubble types. Part of this sensitivity to small model and simulation details can be attributed to the highly non-linear nature of the feedback loops that need to drastically reduce star formation both in small and large haloes. This is already a significant complication for strong supernova-driven winds but is especially evident for AGN feedback (Springel et al. 2005b). For some periods of time, BHs are expected to grow exponentially, a process that can hugely amplify any tiny numerical differences of the conditions around the BH that set the accretion rate. However, part of the lack of robustness in simulation outcomes certainly also needs to be blamed on numerical models that are essentially ill-posed, in the sense that the feedback prescriptions used are often heuristic, and not derived rigorously as a discretization of some well-defined partial differential equations that approximate the physics. As a result, the response of the models to resolution changes is poorly defined and sometimes not well understood. This often reflects a fuzzy notion of how ‘subgrid’ physics (which invariably plays an important role in this problem) should be treated, or an ignorance of this unavoidable limitation altogether. We argue in this paper that resolution-dependent feedback implementations make it hard to separate physics from numerical effects, and we hence advocate the use of more explicit subgrid models.

Even at the level of the ordinary hydrodynamical equations that describe an ideal gas, simulation results can be strongly affected by the numerical scheme employed for solving hydrodynamics, as emphasized recently (Vogelsberger et al. 2012; Sijacki et al. 2012; Kereš et al. 2012; Torrey et al. 2012). These studies have shown that accuracy differences between smoothed particle hydrodynamics (SPH, as implemented in the GADGET code) and the moving-mesh approach of the AREPO code directly translate into sizable changes of predicted galaxy properties. In fact, there is an artificial numerical quenching of the cooling rate in large haloes in SPH, caused by viscosity and noise effects (Bauer & Springel 2012). The standard formulation of SPH also creates spurious dense gas clumps orbiting in haloes. This greatly modifies how galaxies acquire their gas in large haloes, suppressing the relative importance of hot mode gas accretion in these systems (Nelson et al. 2013).

Unfortunately, the size of these numerical uncertainties is so large that they can mask important physical processes and induce incorrect calibrations of the required feedback strength. It is therefore important to use an as accurate numerical technique for hydrodynamics as is available. Similarly, sensitive dependences on fine details of feedback implementations, especially with respect to numerical resolution, are highly undesirable as this will add to the difficulty of separating physics from numerics, and ultimately compromise the predictive power of the simulations. Hence, we argue that a crucial requirement for the current generation of cosmological simulations of galaxy formation is that their numerical models should be sufficiently well posed to yield results approximately invariant with numerical resolution, at least over a reasonable range where crucial physics remains subgrid and can only be treated in a phenomenological way. To our knowledge, this requirement is not yet fulfilled by the reported successful simulations of disc galaxy formation in the recent literature.

In this paper, we study the problem by applying a newly developed numerical methodology for cosmological galaxy formation to ‘zoom’-simulations of Milky Way-sized galaxies. The objects we study are taken from the Aquarius project (Springel et al. 2008), where they have been examined in great detail with dark matter only simulations. We
added two further haloes to the Aquarius set which were not run at high resolution in the original project but were still part of its target list. This same extended set of Milky Way-sized haloes has been previously studied with hydrodynamics by Scannapieco et al. (2009) using SPH, which hence serves as an interesting comparison for our results. One of the Aquarius haloes, the “Aq-C” system, has been the object selected for the Aquila code comparison project (Scannapieco et al. 2012), yielding another reference for direct comparisons. Finally, a subset of the Aquarius systems has been simulated very recently by Aumer et al. (2013) with an updated SPH code (based on Scannapieco et al. 2009), yielding considerably improved results, in particular with respect to the disc-to-bulge ratio and the total stellar mass.

The novel simulation methodology we apply to all eight haloes consists of our moving-mesh code Arepo (Springel 2010) combined with a comprehensive model for the galaxy formation physics, as described in full detail in Vogelsberger et al. (2013). We also include a resolution study by considering both a higher and a lower resolution run by a factor of 8 in mass around the nominal resolutions of Scannapieco et al. (2009) and Aumer et al. (2013), which is equal to the default resolution that we have picked here. Our primary goal is to investigate whether our new numerical treatments yield reasonable galaxy morphologies and properties in these systems, despite the fact that we do not use a high density threshold for star formation, a low star-formation efficiency, or early stellar feedback – or in other words, some of the ingredients that have been deemed essential by other studies for successfully forming disc galaxies.

This paper is structured as follows. In Section 2, we briefly summarize the numerical methodology used in our moving-mesh simulations, and we detail the simulation set that we examine. In Section 3, we analyze the present-day structures of the galaxies that we obtain in the Aquarius haloes, including an analysis of their gas content. In Section 4 we turn to an analysis of the formation history of the galaxies, both in terms of their stars and their embedded supermassive black holes. A brief analysis of the halo mass structure and the impact of baryonic physics on the dark matter distribution is given in Section 5, followed by results of a resolution study in Section 6. Finally, we discuss our findings and present our conclusions in Section 7.

2 NUMERICAL METHODOLOGY AND SIMULATION SET

2.1 Initial conditions

We use initial conditions from the Aquarius suite of high-resolution dark matter simulations of Milky-Way sized haloes (Springel et al. 2008). The simulated volume is a periodic cube with a side length of 100 \( h^{-1} \) Mpc. The adopted ΛCDM cosmology uses the parameters \( \Omega_m = \Omega_{\Lambda} + \Omega_b = 0.25, \Omega_{\Lambda} = 0.04, \Omega_b = 0.25, \Omega_\Lambda = 0.75, \sigma_8 = 0.9, n_s = 1 \), and a Hubble constant of \( H_0 = 100 h \text{ km s}^{-1} \text{ Mpc}^{-1} \). These cosmological parameters are the same as in the Millennium and Millennium-II simulations (Springel et al. 2005; Boylan-Kolchin et al. 2009). While they are now in tension with the diminished error bars of the latest cosmological constraints from the WMAP and PLANCK satellites, this is of no relevance for the present study. In order to achieve the high resolution needed to resolve the formation of a Milky Way-like galaxy, our initial conditions utilize the “zoom-in technique”, i.e. the Lagrangian region from which the main galaxy forms is sampled with a high number of low mass particles whereas the rest of the simulation volume is filled with progressively higher mass particles whose mass grows with distance from the target galaxy. This saves computational time while still ensuring the correct cosmological tidal field and mass infall rate for the forming target galaxy.

The target galaxies themselves have been selected randomly from a small mass interval around \( 10^{12} \text{ M}_\odot \), applying only a rather mild isolation criterion that excluded objects close to another massive galaxy. Specifically, haloes with mass greater than half that of the candidate object were required to be at least 1.37 Mpc away from the candidate halo at \( z = 0 \). This weak criterion is not very restrictive; it was not met by about 22% of the haloes from the purely mass-selected sample, but it still helps to preferentially select galaxies with quiet merger histories which are expected to be favourable sites for producing late-type galaxies. A detailed analysis of the formation history of the selected haloes and the scatter among the set can be found in Boylan-Kolchin et al. (2010).

We note that recent estimates of the mass of the Galaxy’s dark matter halo range from \( 1 - 3 \times 10^{12} \) (Wilkinson & Evans 1999; Sakamoto et al. 2003; Battaglia et al. 2005; Delhene et al. 2006; Xue et al. 2008; Li & White 2008). In order to alleviate tensions due to the “missing massive satellites problem” pointed out by Boylan-Kolchin et al. (2011, 2012), a recent analysis by Wang et al. (2012) favours masses at the lower end of this interval, at around \( 10^{12} \text{ M}_\odot \), which is also the centre of the narrow mass interval that we study. On the other hand, using the space motion of the Leo I dwarf spheroidal galaxy, Boylan-Kolchin et al. (2012) put a strong lower limit on the Milky Way’s mass, finding a median MW mass of \( 1.6 \times 10^{12} \text{ M}_\odot \), rather similar to several of our candidate systems.

Following the nomenclature used in the Aquarius project, the primary simulations that we carry out are hydrodynamical versions of Aq-A-5, Aq-B-5, Aq-C-5, Aq-D-5, Aq-E-5, Aq-F-5, Aq-G-5, and Aq-H-5. Here the “5” in the name refers to the resolution level, corresponding to a baryonic mass resolution of \( \sim 4.1 \times 10^5 \text{ M}_\odot \), and a dark matter mass resolution of \( \sim 2.2 \times 10^6 \text{ M}_\odot \) (for Aq-C-5). At \( z > 1 \), we keep the gravitational softening length of all mass components in the high-resolution region constant in comoving units, growing the physical gravitational softening length to a maximum of 680 pc, which was then held constant for \( z \leq 1 \). In our resolution study of the Aq-C halo (which is the object studied in the Aquila comparison project), we also consider simulations adopting a baryonic mass resolution of \( 3.2 \times 10^6 \text{ M}_\odot \) with a gravitational softening of 1.36 kpc, as well as \( 5 \times 10^5 \text{ M}_\odot \) with a gravitational softening length of 340 pc, which correspond to mass resolutions a factor of 8 better or worse (equivalent to levels 4 and 6 in the Aquarius project) than our default, respectively. We note that these softening values follow the optimum choices derived by Power et al. (2003). Smaller softening values would lead to significant two-body effects and a spurious heating of the gas, particularly at high redshift, and are hence not well justified.
Table 1. Primary numerical parameters of the simulated haloes at $z = 0$. We list the virial radius defined as a sphere enclosing an overdensity of 200 with respect to the critical density. The further columns give total mass, gas mass, stellar mass and dark matter particle mass inside the virial radius. The corresponding numbers of gaseous cells, star particles, and dark matter particles are given next, followed by the mass and dark matter resolutions in the high-resolution region. Finally, the last column gives the baryon fraction, $f_b \equiv (\Omega_{\text{dm}}/\Omega_b)(M_{\text{gas}} + M_\star + M_{\text{bh}})/M_{\text{dm}}$ relative to the cosmological mean. In all the runs, the gravitational softening has been kept fixed in comoving units at $z \geq 1$ and in physical units ($680 \, \text{pc}$ for level 5 runs) at $0 \leq z < 1$.

2.2 Simulation code

In the following, we briefly describe our simulation code and the most important parameter settings used in this work. In the interest of brevity, we only discuss the most important code characteristics and refer, for further details, to the code paper of arepo (Springel 2010) and the application tests discussed in Vogelsberger et al. (2012) and Sijacki et al. (2012).

The moving-mesh code arepo employs a dynamic Voronoi mesh for a finite-volume discretization of the Euler equations. The fluxes between the individual Voronoi cells are calculated using a second-order Godunov scheme together with an exact Riemann solver. This approach is akin to ordinary grid-based Eulerian schemes for hydrodynamics, except that an unstructured mesh is used that is generated as the Voronoi tessellation of a set of mesh-generating points. In addition, these mesh-generating points may be moved freely, inducing a dynamical and continuous transformation of the mesh without the occurrence of pathological mesh distortions. The most interesting way to exploit this freedom of a dynamic mesh is to move the mesh-generating points with the local flow velocity. In this default mode of operation, a pseudo-Lagrangian method results where the mass per cell is kept approximately constant and a Galilean-invariant numerical method is obtained.

The automatic adaptivity of arepo is thus similar to that of smoothed particle hydrodynamics (SPH), but the mass per cell is not forced to stay strictly constant. Instead, local variations in the gas mass per cell may occur, but in case the mass deviates by more than a factor of two from the target gas mass resolution, we either split the cell into two, or dissolve it (as in Vogelsberger et al. 2012), which is very similar to a Lagrangian refinement criterion in adaptive mesh refinement (AMR) codes. But thanks to the adaptive nature of the dynamic mesh, such refinement and derefinement operations are needed much less frequently. Perhaps the most important advantage of arepo compared to traditional mesh codes with a static mesh is a significant reduction of advection errors, which becomes particularly relevant for highly supersonic motions. Compared to SPH, the most important advantages are the absence of an artificial

1 Omitting the small dark matter only simulations considered in section 5 for the sake of brevity.

2 Following standard procedure, we define the virial mass as the mass contained within a sphere that encloses a mean matter density 200 times the critical density for closure, $\rho_{\text{crit}} = 3H^2(z)/(8\pi G)$.

| Run      | $R_{\text{vir}}$ | $M_{\text{tot}}$ | $M_{\text{gas}}$ | $M_\star$ | $M_{\text{dm}}$ | $N_{\text{cells}}$ | $N_\star$ | $N_{\text{dm}}$ | $m_{\text{gas}}$ | $m_{\text{dm}}$ | $f_b$ |
|----------|-----------------|-----------------|-----------------|-----------|-----------------|-------------------|-----------|----------------|-----------------|-----------------|-------|
| Aq-A-5   | 239.0           | 169.13          | 11.21           | 4.95      | 152.95          | 203822            | 152476    | 579342         | 5.03            | 26.40           | 0.55  |
| Aq-B-5   | 183.0           | 75.93           | 4.08            | 4.88      | 66.97           | 108806            | 234310    | 444557         | 3.35            | 17.59           | 0.70  |
| Aq-C-5   | 234.5           | 159.74          | 7.09            | 7.00      | 145.64          | 163726            | 273124    | 674547         | 4.11            | 21.59           | 0.51  |
| Aq-D-5   | 240.2           | 171.67          | 7.59            | 12.10     | 151.97          | 159591            | 424966    | 657760         | 4.40            | 23.10           | 0.68  |
| Aq-E-5   | 206.3           | 108.74          | 3.58            | 8.75      | 96.39           | 101041            | 431167    | 550757         | 3.33            | 17.50           | 0.67  |
| Aq-F-5   | 209.0           | 113.05          | 6.85            | 8.86      | 95.51           | 331692            | 620784    | 791829         | 2.30            | 12.06           | 0.96  |
| Aq-G-5   | 204.4           | 105.83          | 11.43           | 6.00      | 88.40           | 346061            | 328784    | 708979         | 2.83            | 14.88           | 1.03  |
| Aq-H-5   | 183.1           | 76.06           | 2.95            | 5.01      | 68.10           | 91792             | 273228    | 525235         | 2.96            | 15.56           | 0.61  |
Disc galaxies in moving-mesh cosmological simulations

Figure 1. Projected stellar density for the eight simulated haloes at $z = 0$. The chosen projection box is 50 kpc in all directions and is centred on the halo potential minimum. Edge-on (top portion of each panel) and face-on views (bottom portion of each panel) are displayed. A stellar disc is detectable in all the simulated haloes. The images are obtained by logarithmically mapping the K-, B- and U-band luminosity of the stars to RGB colour channels in order to have a visual impression of the age of the different stellar populations contained in the final galaxy. As a result, very young stars show up blue while older stars appear progressively redder.

viscosity, a reduced sampling noise, a higher accuracy of gradient estimates, and a faster convergence rate in multidimensional flow.

As far as the gravity solver and collisionless dynamics are concerned, AREPO applies the same techniques as the TreePM code GADGET (Springel 2005). This makes the two codes particularly well suited for a code comparison that focuses on an analysis of the differences induced by the hydrodynamic treatment alone, and/or differences due to feedback implementations, as differences originating in the treatment of gravity can be largely excluded. In previous work, we have carried out such comparisons (e.g. Vogelsberger et al. 2012; Sijacki et al. 2012; Scannapieco et al. 2012) for models with identical (minimal) feedback physics. The simulations presented in this paper use a new strong feedback model (see below) and can be directly compared with the GADGET results obtained by Scannapieco et al. (2009) and Aumer et al. (2013) for matching haloes from the Aquarius sample, as well as with the results reported in the Aquila project (Scannapieco et al. 2012) for a multitude of codes and feedback models applied to the Aq-C halo.

2.3 Physical model for galaxy formation

We here employ a novel implementation of the most important physical processes of galaxy formation in AREPO, presented in detail in Vogelsberger et al. (2013). For the sake of brevity, we list here only the most important characteristics and refer to the papers of Vogelsberger et al. (2013) and Torrey et al. (2013) for full details and cosmological tests. The model includes:

(i) Primordial and metal line cooling with self-shielding corrections.

(ii) A simple subresolution model for the interstellar medium (ISM), which pictures the ISM as a two-phase medium that is predominantly composed of cold clouds embedded in a tenuous, supernova-heated phase (Springel & Hernquist 2003).

(iii) Stellar evolution, gas recycling and chemical enrich-
ment. The chemical enrichment follows nine elements (H, He, C, N, O, Ne, Mg, Si, Fe) independently, and tracks the overall metallicity and the total mass return from stars to gas.

(iv) Stellar feedback realized through a kinetic wind scheme in which the wind velocity is scaled with the local halo size (similar to Puchwein & Springel 2013), which in turn is estimated by the dark matter velocity dispersion. The adopted scaling of the mass loading of winds corresponds to energy-driven winds.

(v) A metal loading of outflows that is determined independently of the mass loading of the winds. This is required to simultaneously reproduce the stellar mass content of low mass haloes and their gas oxygen abundances.

(vi) Black hole (BH) seeding, BH accretion and BH merging procedures based on an updated version of the model described in Springel et al. (2005b). The BH growth distinguishes between quasar- and radio-mode feedback. In addition, a novel prescription for radiative feedback from active galactic nuclei is included that modifies the ionization state and hence the cooling rate nearby to an active BH. This implementation assumes an average spectral energy distribution and a luminosity-dependent scaling of obscuration effects.

(vii) A spatially uniform UV background following the model of Faucher-Giguère et al. (2009), which completes H I reionization at a redshift of $z \simeq 6$.

(viii) A new Lagrangian tracer particle formalism introduced by Genel et al. (2013) that follows the flow faithfully with a Monte-Carlo based approach.

We set the free parameters of the model to identical values as identified by Vogelsberger et al. (2013) for their best match model in cosmological simulations of galaxy formation. These fiducial settings produce a good match to the stellar-mass to halo-mass function, the galaxy luminosity functions, the history of the cosmic star formation rate density, and to several other key observables. These parameters hence represent a good candidate for testing the model at higher resolution than possible in simulations of uniformly sampled cosmological volumes. We only deviate from Vogelsberger et al. (2013) with respect to two minor points. As their radio-mode AGN feedback in large haloes is based on the stochastic triggering of hot bubbles in halo atmospheres, numerical convergence with varying resolution can not necessarily be expected for individual objects, but only for the population mean. Because this could spoil our convergence study, we replaced the bubble heating with a much gentler halo heating model where more bubbles of individually much weaker strength are created. We note however that this feedback channel is almost unimportant for our galaxies because of their moderate halo mass. The other small change that we made concerns the galactic winds, which we opted to endow with some amount of thermal energy in order to make them ’hot’ rather than ’cold’ when they are launched. Specifically, we split the total energy of the wind particles equally between kinetic and thermal components. Since all the other wind parameters (in particular the wind velocity and the wind energy flux) are fixed as in Vogelsberger et al. (2013), this reduces the wind mass loading slightly because the wind now also carries away some energy in thermal form. Our tests have shown that providing some amount of thermal energy to galactic winds makes the gas flows in the haloes more regular without changing the stellar mass of the galaxies in any significant way.

3 PRESENT DAY GALAXY STRUCTURE

3.1 Stellar discs

In Figure 1, we show the stellar mass distributions of all of our eight simulated haloes at $z = 0$, both in face-on and edge-on projections. The images were constructed by mapping the K-, B- and U-band luminosities to the red, green and blue channels of a full colour composite image. Young stellar populations hence appear blue, old stellar compo-

![Figure 2. Time evolution of the Aq-G-5 simulation directly before $z = 0$.](image-url)
nents appear red. All images use the same logarithmic mapping of stellar luminosity to image intensity and display the same physical extension of 50 kpc on a side. The face-on orientation used for the projections was defined through the angular momentum of the cold galactic gas. Using instead the major axis of the moment-of-inertia tensor of the stars or the stellar angular momentum vector yields essentially the same directions, and represents an equally well working choice for these galaxies. For definiteness, we define an aligned coordinate system \((x'y'z')\) for each galaxy where the \(z'\)-axis points along the angular momentum of the cold gas, while the \(y'\)-axis points along the intersection of the \(z' = 0\) plane with the \(z = 0\) plane of the simulation’s original coordinate system. This leaves two possible directions for the \(x'\)-axis: we pick the one with the smaller angle between the positive \(x'\) and \(x\) axes.

Clearly evident in Fig. 1 is the pronounced disc morphology of almost all of the systems. The one exception is the galaxy Aq-E-5, which is the reddest among the set. Most of its stars appear to lie in an elongated spheroid that shows substantially flattening. There is also a feeble disc of young stars misaligned with the old flattened stellar distribution. The disc of galaxy Aq-D-5 is dominated by a prominent bar, and also is comparatively red. The other six galaxies feature nicely symmetric, thin and extended discs, with some indication of a red bulge in the centre, which is however not prominent enough to be readily apparent in the edge-on projections. Interestingly, these well-defined discs show blue

### Table 2. Parameters of the surface density profile decomposition. For each run the columns give (from left to right): the logarithm of the central surface density of the disc, the disc scale-length, the logarithm of the bulge surface density at the effective radius, the bulge effective radius (defined as the radius enclosing half of the bulge mass), the Sérsic index of the bulge, the inferred disc mass, the inferred bulge mass, the disc-to-total mass ratio, the total mass of the system as computed by the simulation output, the total mass of the system as derived from the fit, and the quality-of-fit parameter \(Q\).

| Run  | \(\log_{10} \Sigma_d\) \[M_\odot kpc^{-2}\] | \(R_d\) \[kpc\] | \(\log_{10} \Sigma_{eff}\) \[M_\odot kpc^{-2}\] | \(r_{eff}\) \[kpc\] | \(n\) | Disc mass \[10^{10} M_\odot\] | Bulge mass \[10^{10} M_\odot\] | \(D/T\) | Total mass \[10^{10} M_\odot\] | Fit Mass \[10^{10} M_\odot\] | \(Q\) |
|------|--------------------------------|----------------|--------------------------------|----------------|-----|----------------------|----------------------|--------|----------------------|----------------------|-----|
| Aq-A-5 | 7.422 | 7.630 | 9.843 | 3.116 | 1.356 | 0.967 | 3.566 | 0.21 | 4.345 | 4.533 | 0.004 |
| Aq-B-5 | 9.060 | 2.483 | 9.486 | 1.575 | 0.020 | 4.451 | 7.315 | 0.38 | 10.71 | 11.81 | 0.004 |
| Aq-C-5 | 9.000 | 2.107 | 9.952 | 0.435 | 0.596 | 6.072 | 0.409 | 0.91 | 6.600 | 6.680 | 0.050 |
| Aq-D-5 | 8.069 | 7.818 | 9.885 | 3.340 | 0.537 | 4.499 | 7.315 | 0.38 | 10.71 | 11.81 | 0.004 |
| Aq-E-5 | 7.784 | 9.203 | 9.910 | 1.933 | 0.919 | 3.239 | 5.429 | 0.37 | 7.581 | 8.664 | 0.002 |
| Aq-F-5 | 8.633 | 4.157 | 9.896 | 1.923 | 0.331 | 4.662 | 2.685 | 0.63 | 7.150 | 7.347 | 0.019 |
| Aq-G-5 | 8.769 | 3.398 | 9.802 | 0.212 | 0.824 | 4.261 | 0.005 | 1.00 | 4.177 | 4.267 | 0.109 |
| Aq-H-5 | 8.783 | 3.257 | 9.887 | 1.076 | 0.561 | 4.041 | 0.804 | 0.83 | 4.758 | 4.845 | 0.034 |

Figure 3. Stellar surface density profiles of the simulated galaxies, seen face-on. Decompositions of the total profile into an exponential disc and a Sérsic profile are also shown (provided the Sérsic fit is sufficiently well defined.). The fits are carried out up to the vertical dotted line located at 0.1 \(R_{eff}\). The resulting disc scale-length and disc-to-total mass ratio are indicated in each panel. A comprehensive list of the structural parameters derived from the disc-bulge decomposition can be found in Table 2.
Figure 4. Distribution of the mass-weighted stellar circularities $\epsilon$ for the eight Aquarius haloes at $z = 0$. The plots are obtained by considering only stars with $r < 0.1 R_{\text{vir}}$. The solid black lines show the $\epsilon$ distributions obtained by following the definition of Abadi et al. (2003). The distributions are further subdivided into a bulge (red) and a disc (blue) component by mirroring around zero the fraction of stars with negative $\epsilon$ and considering the resulting distribution as making up the bulge. The disc-to-total mass ratios derived from this kinematic decomposition are reported in the legend of each panel in square brackets, while the other values are obtained from the fraction of stars with $r > 0.7$. The thin grey lines show the distribution of stellar circularities if the definition of $\epsilon_V$ adopted in the Aquila project is used. For the Aq-E-5 system, an additional dashed line is shown that gives the distribution of $\epsilon_V$ if the face-on projection is aligned with the disc of young stars forming in this system, which is roughly perpendicular to the rotation direction of the old stars.

outer rings and some spiral features that indicate substantial star formation in these regions. The blue/red appearance of the discs shows a striking resemblance with some observed galaxies, such as NGC 7217 which compares quite nicely with Aq-H-5, for example.

Actually, we have shown the galaxy Aq-G-5 at $z = 0.07$ rather than $z = 0$ in Fig. 1. This is done because Aq-G-5 happens to just undergo an encounter with a massive satellite galaxy at $z = 0$, inducing a significant tidal perturbation that started to deform its disc and created a prominent tidal arm to the North. This is seen explicitly in Figure 2, which displays snapshots of the time evolution of the Aq-G-5 system from $z = 0.1$ to $z = 0$. In order to avoid that our results are distorted by the strong encounter right at $z = 0$, we use the $z = 0.07$ output of Aq-G-5 for all subsequent analysis.

In Figure 3, we show azimuthally averaged face-on stellar surface density profiles of our eight galaxies (black circles). The profiles are obtained by projecting on the $x'y'$ plane (see above) the mass of all stellar particles contained in a box centred on the halo potential minimum, with a total height equal to $0.1 \times R_{\text{vir}}$. Stars are binned in circular annuli in the projection plane, and the total stellar mass of each bin is then divided by its surface area to get the surface density.

Interestingly, most of the galaxies show surface density profiles that present, in their outer parts, the characteristic exponentially declining trend observed in many spiral galaxies. In some of the simulated galaxies a clear central excess can be seen, signifying the presence of a central bulge. To quantify the importance of the two contributions we have carried out two-component fits of the surface density profiles with a Sérsic (1963) profile (red lines) for the central part, and an exponential profile (blue lines) for the outer parts. The fits are performed by first finding the optimal parameters of the exponential profile for all the points with radius greater than a predefined radius $r_{\text{cut}}$. Subsequently, the central residual excess is modelled with the Sérsic profile. We also estimate the quality of the fit as (see Scannapieco et al. 2011)

$$Q = \frac{1}{n} \sum_{k=1}^{n} (\log \Sigma_k - \log \Sigma_{k,\text{fit}})^2,$$

where $n$ is the number of radii at which the surface density $\Sigma_k$ is sampled. Finally, we iterate the procedure above by varying $r_{\text{cut}}$ until a minimum value of $Q$ is reached. The parameters obtained with this minimization procedure are listed in Table 2.

We find that these fits work quite well in most of the cases, and hence yield a tentative estimate of the bulge and disc stellar masses, and of the disc-to-total ratio. These quantities are also reported in Table 2. We note however that such profile fits, which form the basis of photometric determinations of the bulge-disc ratio, are often not sufficiently unique to allow a robust decomposition. In particular, fits with very similar quality parameter $Q$ can be obtained for
quite different values of $r_{\text{cut}}$, and sometimes this affects the structural parameters of the disc and bulge strongly even though the total recovered profile does not show any appreciable difference. This technique is also known to typically overestimate the disc-to-bulge (D/B) mass ratio. The essentially pure discs we obtain for Aq-B, Aq-C and Aq-G therefore need to be taken with a grain of salt.

This is corroborated by a much more reliable kinematic bulge-to-disc decomposition which we consider in Figure 4. Here we follow Abadi et al. (2003) and define for every star with specific angular moment $J_z$ around the symmetry axis (which we take as the $z'$ axis as defined above) a circularity parameter

$$
\epsilon = \frac{J_z}{J(E)},
$$

where $J(E)$ is the maximum specific angular momentum possible at the specific binding energy $E$ of the star. We note that another definition of circularity that is sometimes used in the literature (e.g. Scannapieco et al. 2009, 2012) is to replace $J(E)$ with the angular momentum $r v_c (r)$ of a star in circular motion at the star radial distance $r$, where $v_c (r) = \sqrt{G M(<r)/r}$ is the circular velocity, yielding

$$
\epsilon_V = \frac{J_z}{r v_c (r)}
$$

To allow an easy comparison with both literature conventions, we include results for both definitions in our mass-weighted circularity distributions $f(\epsilon)$. We note that the distributions presented in Fig. 4 are normalized such that $\int f(\epsilon) \, d\epsilon = 1$.

Perfectly cold stellar discs should show up as a narrow distribution around $\epsilon \sim 1$. As we see from Figure 4, there are massive discs in all of our systems, but with varying contributions to the total stellar mass. The best characterised disc – considering both the prominence of the peak at $\epsilon \sim 1$ and the resulting mass fraction – is actually found in halo Aq-C, consistently with the original motivation for picking this halo for the Aquila comparison project, which was simply the desire to select a system that is most likely to make a disc. This has, among other factors, to do with the quiet formation history of Aq-C. Its halo forms comparatively early for systems of this mass (Boylan-Kolchin et al. 2010), thus favouring the unperturbed growth of a nice disc over an extended period of time.

The disc-to-total (D/T) ratios obtained from the kinematic decomposition are included in the individual panels of Figure 4, based on the fraction of stars with $\epsilon > 0.7$ (Aumer et al. 2013, find this measure to be roughly equivalent to the fraction $\epsilon_V > 0.8$). Yet another kinematic measure of the disc fraction is based on the original approach of Abadi et al. (2003), who defined as bulge component twice the fraction of stars with $\epsilon < 0$. This gives the highest kinematic estimates of D/T ratios for the systems and can be seen as a plausible upper limit on the disc fraction. We also include these values in square brackets in the individual panels of Fig. 4. The highest D/T ratios we obtain are about $0.5$ based on the $\epsilon > 0.7$ definition, and even reaching up to $0.8$ when the measure of Abadi et al. (2003) is adopted. Our discs are equally prominent as the best cases in Aumer et al. (2013), but not significantly stronger. They are better defined and feature a higher disc-to-bulge ratio than most of the other successful disc formations in the recent literature, which were in part reporting D/T values based on photometric decompositions. Note that with the latter method, we would conclude to have obtained pure discs in some of the systems.

In Figure 5 we compare the scale-length of our exponential discs, as measured from fits to the surface density profiles (see Table 2), with observational data of the size – luminosity relationship in the B-band. The observational data were taken from the compilation of literature catalogues\(^3\) considered in Graham & Worley (2008), and have been corrected for inclination and dust effects as in Graham & Worley (2008). From the same reference we also plot the best-fitting relation (solid line) and the observed upper boundary to the surface brightness (dotted line).

\(^3\) The references to the catalogues, also given in the legend of Fig. 5, are: Möllenhoff (2004); MacArthur et al. (2003); Graham (2001, 2002).
lenghts and at lower luminosities with respect to the best-fitting relation, although well within the observed scatter of the data. Another simpler measure of the galaxy size is obtained by considering the stellar half-mass radii $R_{\star,50}$. This can be compared with observational data for the $R_{\star,50}$–stellar mass relationship, which is done in Figure 6. We find that the simulated galaxies fall right into the observational distribution of half-light radii at comparable stellar masses found by Shen et al. (2003) for the Sloan Digital Sky Survey (SDSS). We hence conclude that our galaxies have sizes for their luminosities that agree well with the observational data.

In Figure 7 we consider the Tully-Fisher relation (Tully & Fisher 1977) of the simulated galaxies at $z = 0$. We determine the stellar masses associated with each galaxy by simply summing the masses of the stellar particles that lie within 10% of the virial radius of each halo (the centre of the halo coincides with the position of its potential minimum), while for the rotation velocity we take the circular velocity defined as $v_c(r) = \sqrt{GM(<r)/r}$, where $M(<r)$ is the enclosed total mass at the radius $r$. Different choices for the radius at which $v_c$ is measured and adopted as characteristic galaxy velocity are possible, and depending on the detailed shape of $v_c(r)$ (see Fig. 18 and section 5.1 for a more detailed discussion of the rotation curves of the simulated galaxies) somewhat different values of the rotation velocity can be assigned to each galaxy. In what follows, we use for the Tully-Fisher relation the rotation velocity at $R_{\star,50}$, corresponding to the radius within which 80% of the stellar mass is enclosed. At that position the circular velocity of the galaxy has already reached the flat part of the rotation curve. We have investigated the range of systematic uncertainty in assigning a circular velocity to each galaxy by also considering the peak value of the rotation curves, finding no dramatic difference, except for the Aq-E halo, which in this case is pushed slightly above the scatter of the observed Tully-Fisher relation.

In Fig. 7 we include, as grey symbols, a collection of observed galaxies (from Pizagno et al. 2007; Verheijen 2001; Courteau et al. 2007) for which surface photometry and measurements of rotation velocities were available in the literature. This dataset was already analysed by Dutton et al. (2011) and we follow their method to convert galaxy luminosities into (MPA/JHU group) stellar masses, with the appropriate normalization for a Chabrier (2003) IMF. The included best-fitting to the Tully-Fisher relation (long dashed line) is also taken from Dutton et al. (2011). Our simulated galaxies fall comfortably within the observed scatter of the relation.

### 3.2 Gaseous discs

In Figures 8 and 9 we show projections of the gas density and gas velocity fields for all eight simulated galaxies at $z = 0$. For each galaxy, three panels arranged in one row are shown, corresponding to a face-on and two edge-on projec-
Figure 8. Gas distributions at $z = 0$ for the galaxies in haloes Aq-A to Aq-D. Each row of panels shows a face-on (left) and two edge-on (centre and right) views of the projected gas density for the resolution level 5. The chosen projection box is 50 kpc on a side and extends for a total of 10 kpc in the projection direction, centred on the halo potential minimum. The density-weighted gas velocity field is overlapped on the density distribution as arrows with lengths proportional to the gas velocity. The colour hue encodes the density-weighted gas temperature, ranging from blue (cold) to yellow (hot). The velocity vectors are drawn either in blue or yellow according to the local temperature in order to improve visibility. An extended gaseous disc supported by rotation is clearly visible in all cases, and in the edge-on panels, a global outflow motion of low density gas, due to our kinetic wind feedback, can be seen.
Figure 9. The same as Fig. 8, but for haloes Aq-E to Aq-H.
gas fractions along the principal directions defined for the $(x'y'z')$ frame of each galaxy. In each case, the projections show all the gas in a $50 \times 50 \times 10$ kpc box around a galaxy’s centre. To enhance the visibility of the dense gas, the projections are weighted by the local gas density of each cell. The colour map encodes the gas density as image brightness, and the average gas temperature as colour hue. In addition, velocity field vectors are overplotted on a uniform grid of dimension $32 \times 32$. The length of the velocity vectors is proportional to the magnitude of the velocity in the projection plane, and either a blue or yellow colour is used for the arrows depending on the local temperature in order to enhance visual clarity.

The gas velocity fields in the face-on projections show a high degree of regular circular motions, especially in the dense neutral gas phase, which in the denser parts coincides with the star-forming regions. The surface density profiles of the gas are nearly flat, similar to the RAMSES simulations of Agertz et al. (2011). In a few cases, one also sees distortions of the gas disc, as expected based on the stellar distributions. For example, Aq-D-5 shows a bar-like gas distribution and a central density depression that is presumably related to AGN feedback. The lowest gas surface density is seen in Aq-E-5, which appears red in the stellar projections. Apparently, comparatively little star formation is ongoing in this system, but this is still occurring in a disc-like configuration, which is however roughly orthogonally oriented compared to the spin of the old stars. The morphology of the gas discs is quite smooth, in stark contrast to the flocculent gas structures in the SPH simulations of Guedes et al. (2011), and Aumer et al. (2013) that are a result of their delayed cooling and/or early stellar feedback models.

Of particular interest in the gas projections are the edge-on views, which reveal the presence of low-density winds emanating from the star-forming discs. These outflows are a direct consequence of the strong kinetic wind feedback realized in our models. Gas streams onto the discs mostly at large radii and from directions close to the disc plane. However, there are also fountain-like inflows of dense gas scattered over the disc plane. The gas flows in the circumgalactic medium are clearly quite complicated, reflecting the expected complex interactions between the galactic winds, the gaseous halo, and cosmological infall. We note that there is no evidence for a population of small dense gaseous ‘blobs’ in the halo as seen in many SPH calculations (Kaufmann et al. 2006; Guedes et al. 2011).

In Figure 10, we compare the gas fractions of the simulated galaxies at the present day relative to observational data in the $f_{\text{gas}} - M_R$ plane. The gas fractions are defined as

$$f_{\text{gas}} = \frac{M_{\text{gas}}}{M_{\text{gas}} + M_{\text{stars}}},$$

where $M_{\text{gas}}$ and $M_{\text{stars}}$ are the gas and the stellar mass within a radius $r = 0.1 \times R_{\text{vir}}$. Stellar R-band magnitudes follow from the total stellar luminosity within the same radius in that passband$^4$. Again, dust attenuation has not been taken into account. Data points in Fig. 10 have been obtained by cross-correlating two samples of nearby galaxies from Haynes et al. (1999a, b) presenting 21–cm H I observations and I-band photometry, respectively. H I integrated line fluxes are converted into gas masses through the formula (see e.g., Wakker & van Woerden 1991)

$$M_{\text{HI}} = 2.35 \times 10^6 \left(\frac{D}{\text{Mpc}}\right)^2 \left(\frac{S}{\text{Jy km s}^{-1}}\right) M_\odot,$$

where $D$ is the distance to the galaxy and $S$ the integrated H I line flux. The resulting masses are then multiplied by a factor 1.37 to correct for helium abundance. I-band magnitudes are transformed to R-band by assuming an average $(R-I)$ colour of 0.5 as in the original paper by Haynes et al. (1999b). They are also used as an input to compute the observed stellar masses through a linear fit of the simulation results in the $M_{\text{star}} - M_R$ plane. The gas fractions that we measure for the simulations are between 10 – 30%, which is reassuringly high and consistent with the observational data. Strong feedback models often tend to have significant difficulties in retaining a sufficiently large amount of gas available for star formation at late times. Our models do not appear to suffer from this problem. The only exception is the Aq-E halo, which has a gas fraction of $\sim 5\%$. However, this system represents a particular case which is characterized by a rather strong merger event at $z \sim 1$. This triggered significant black hole growth and associated feedback in our simulation, similar to the scenario of merger-induced formation of red ellipticals described in Springel et al. (2005a).

---

$^4$ Actually, in the current implementation of the stellar photometry R-band magnitudes are not available. To compute them we converted SDSS r-band magnitudes by using eq. (A8) in Windhorst et al. (1991).
Figure 11. Time evolution sequence of the formation of the Aq-C-5 galaxy, from $z \sim 10$ to $z = 0$, as labeled. We show all stars in a box of length 50 kpc (physical) on a side, centred on the potential minimum of the main progenitor’s dark matter halo. The $z = 0$ frame has been oriented for a face-on view, and this projection direction is kept in all other panels. Rest-frame stellar luminosities are mapped to image intensity and colour as in Fig. 1.
Figure 12. Time evolution sequence of the formation of the Aq-D-5 galaxy (as in Fig. 11, but for the Aq-D-5 simulation).
4 FORMATION HISTORY

A first qualitative impression of the formation history of our Milky Way-sized galaxies can be obtained from time evolution sequences of the stellar distributions of the simulations. In Figures 11 and 12, we show this for Aq-C-5 and Aq-D-5 in an exemplary fashion. We have selected Aq-C-5 as a prototypical case making a nice disc at $z = 0$ (and because it is of particular interest due to its prior analysis in the Aquila project), and Aq-D-5 to show a partially failed disc, in this case through the formation of a strong bar. All the panels of the evolutionary sequence show the stars in a region of fixed physical size (50 kpc on a side centred on the galaxy’s most massive progenitor), so that the images directly reflect the size evolution. The stars are shown with their luminosities in the rest-frame, with the same mapping to colour and intensity as in Fig. 1. This mapping is kept the same at all redshifts and output times, so that the brightness and colour evolution of the images indicates the variations in the star formation histories of the galaxies displayed at the individual redshifts. In particular, we can directly infer from the images that the heyday of blue disc formation lies in the redshift range $z \sim 0.5 - 1.5$ for our simulations. At higher redshift, the galaxies in our sample tend to be small and blue, whereas they redden progressively towards lower redshifts.

4.1 Star formation history

The realistic gas fractions measured for our galaxies at the present epoch support star formation rates comparable to expectations for late-type galaxies at $z = 0$. This is seen in Figure 13, where we compare the present-day star formation rates of our simulations with observational data as a function of stellar mass. We measure the star formation rate time-averaged over the past 0.5 Gyr by determining the stellar mass younger than 0.5 Gyr in a sphere of radius $0.1 \times R_{\text{vir}}$ centred on the halo’s potential minimum. For measuring the total stellar mass no age cut is applied. Note that this is the same procedure as adopted in the Aquila comparison project (Scannapieco et al. 2012). The background dots in Fig. 13 are a random sub-sample of nearby ($z < 0.1$) galaxies from the SDSS MPA-JHU DR7 release, divided into the so-called “blue cloud” and “red sequence” on the basis of the colour condition (see again Scannapieco et al. 2012)

$$(g - r) = 0.59 + 0.052 \log \left( \frac{M_{\text{star}}}{10^{10} M_{\odot}} \right),$$

with the galaxy symbols coloured accordingly. Only 10% of the total sample is plotted. All the simulated galaxies are actively star-forming and tend to cluster around the current location of the Milky Way in the blue cloud, which is marked by the down-pointing triangle, with properties taken from Leitner & Kravtsov (2011, Table 2). Again, a clear outlier in our galaxy set is the Aq-E halo, which is located in the outskirts of the red sequence. This is not surprising: given the small amount of gas left in the galaxy (see Fig. 10) a low star formation rate is expected. We also include in Fig. 13 the results of the Aquila comparison project at resolution level 5, for all the employed codes and feedback models (grey boxes). Interestingly, these simulations appear to systematically miss the location of the Milky Way and cluster around the dashed line. Those simulations that manage to reduce the star formation rate sufficiently end up being too red, while those with enough current star formation are too massive. This highlights the difficulty to arrive at simulation models that suppress star formation strongly especially at high redshift, but allow a high star formation rate at low redshift. Our new code combined with the implemented feedback physics achieves this considerably better than the models studied in the Aquila project.

In Figure 14, we show plots of the formation history of the stars contained in each galaxy. This is based on the age histogram of stars that end up in the galaxies at the present time (again selected as all the stellar particles in a sphere of radius $0.1 \times R_{\text{vir}}$ centred on the halo potential minimum). Star formation rates (SFRs) are then computed by dividing the stellar mass in each age bin by the width of the bin itself, so that they effectively represent the average SFR over the temporal bin width. Since we model the stellar mass return to the ISM in our simulations, the initial mass of each star particle (i.e., the mass that the particle has when it is created) is employed for the derivation of the SFRs. We used 100 bins of 140 Myr for a total time span of 14 Gyr. We additionally mark the formation rate of stars that have formed in situ in the main progenitor (blue histograms), or have been accreted from substructures (red histograms). The accreted stars are usually a small fraction, amounting to $\lesssim 10\%$ of...
the total stellar mass, with the notable exception of the Aq-F halo for which this fraction increases up to 23%. We also overplot the accretion rate of the central BH (green lines), determined as the average accretion rate between two simulation outputs and rescaled by a factor 1/250 to make it visible in the plots, to compare its formation history to that of stars. The general picture that emerges from this comparison is that of a connection between the two components, which show similar features in their formation histories at roughly the same look-back times. We address this point in more detail in section 4.2.

From the figure it can be seen that star formation histories (SFHs) come in a variety of shapes, that reflect the underlying mass assembly history of the haloes. The general trend is that of a peak of the SFR at early times ($z \sim 3-5$), with typical maximum star formation rates of the order of $20\, M_\odot\, \text{yr}^{-1}$, followed by a decline and a rather constant SFR at $z \gtrsim 1$, with most of our galaxies ending up with star formation rates of $\sim 2-3\, M_\odot\, \text{yr}^{-1}$ at $z = 0$. However, there are many exceptions to this rule, especially in systems where a bar instability. Another interesting case is that of the halo Aq-G, which features unusually little star formation at high redshift, a period of quite low star formation in the redshift interval $1-3$ followed by quite intense star formation from $z = 1$ to the present, and finally a merger even right at the present time that triggers a $z \approx 0$ increase of the star formation rate. This history implies a quite young age of this galaxy.

This expectation is borne out in Figure 15, which compares the mean mass-weighted stellar ages of our galaxies with SDSS data, as a function of stellar mass. Here, the galaxy Aq-G has indeed the youngest stellar population. It also has one of the smallest stellar masses among our set, making it in fact agree rather well with the observational determination of the age – stellar mass relation of late-type galaxies in the SDSS carried out by Gallazzi et al. (2005).

Our other galaxies also agree well with these measurements, but our dynamic range in galaxy mass is too small to say whether we also reproduce the significant decline in age towards smaller stellar masses seen in the observations.

Based on the kinematic disc-to-bulge decomposition carried out in section 3.1, we can also determine the mean stellar ages of these components individually. As expected, the bulge components tend to be old; they have mean mass-weighted ages of $\sim 7-8$ Gyrs, while the stellar disc components are on average younger with mean ages of the order of $\sim 4-5$ Gyrs. Given also the general shape of the star formation history curves, this suggests that bulge formation is associated with the early peak in the SFR while discs are built in a more gradual way at later times, consistent with the inside-out picture of Fall & Efstathiou (1980).
Of particular interest is how the stellar masses compare to the total virial masses of haloes. This is seen in Figure 16, where we compare all of our simulations against the stellar mass – halo mass relation (dotted line) derived by Guo et al. (2010) from abundance matching arguments. The shaded region around the expected relation is determined such that its upper and lower boundaries are at ±0.2 dex from the fiducial values, while the dashed line shows the baryonic content of a halo of a given virial mass if the universal baryon fraction is assumed. For each system, we include the results at a range of output times, from redshift $z = 2$ to $z = 0$, such that a continuous track is formed. As the abundance matching results only weakly depend on redshift (Moster et al. 2010; Behroozi et al. 2010), this then also gives a useful test to see whether our galaxies evolve consistently with this expected relation. We note that extending this test to still higher redshift would require taking into account the residual redshift dependence of the abundance matching results and the different growth histories of our haloes.

Reassuringly, the stellar masses of our systems are indeed small enough to be consistent with abundance matching arguments, although a subset of our galaxies are at the upper end of what is acceptable within the expected scatter. A good match is even obtained for two of the more massive galaxies of the sample, namely Aq-A and Aq-C, which have virial masses of almost $2 \times 10^{12} \, M_\odot$ but still manage to have a sufficiently small stellar mass and to form an extended disc. Matching the stellar mass – halo mass relation has not been achieved in the Aquila comparison project, except for runs G3-TO, G3-CR and R-AGN, which however did not form realistic disc systems with the employed implementations of strong feedback. Also, as pointed out by Guo et al. (2011) and Sawala et al. (2011), previous simulations – even the most successful ones among them – generally failed to match this relation. Only very recently, a few studies (Guedes et al. 2011; Stinson et al. 2013; Aumer et al. 2013) have reported successful simulations of individual galaxies conforming with the stellar mass – halo mass relation. Similar to our work, these successes have ultimately become possible due to an increased feedback strength and a more efficient coupling of the feedback energy to the gas phase. However, we note that most of these works employed halo masses considerably less massive than used here, typically around $\sim 0.7 \times 10^{12} \, M_\odot$. This lower mass makes it easier to suppress star formation. A case in point is provided by the high mass systems in Aumer et al. (2013), which show overly high low-redshift star formation, whereas their lower mass systems do not have this problem. To the best of our knowledge, our runs are the first examples of the successful formation of late-time spirals in haloes in the mass range $1 - 2 \times 10^{12} \, M_\odot$, which is the size of the Milky Way.

4.2 Central black hole growth

In Figure 17, we compare the BH mass growth to the stellar mass growth as a function of look-back time and redshift. The stellar mass growth curves are obtained by summing the masses of all the stellar particles within 10% of the halo virial radius at any given look-back time, while the BH masses are those of the most massive black hole in the halo progenitor again at any given time. For all the haloes the two curves exhibit similar features. Both components show a steady growth over cosmic time, starting with a rapid growth...
rate at high redshift that subsequently flattens at low redshift ($z \lesssim 1$). These similarities in the general behaviour are indicative of a co-evolution between the stellar content of a galaxy and its central BH, consistent with the observed relation between the masses of the two components (e.g. Magorrian et al. 1998; Häring & Rix 2004).

This is not entirely unexpected since the growth of both components relies on the supply of the same fuel (i.e. gas), but it is not immediately obvious why two processes, such as star formation and gas accretion onto a BH, occurring on vastly different physical scales (the star-forming disc and the circum-nuclear regions of a galaxy) should be so tightly related (for a recent review see Kormendy & Ho 2013). In fact, different conjectures have been made about the cause for the observed apparent co-evolution and tight galaxy – BH relations, ranging from feedback-regulated BH growth to statistical averaging as a result of successive mergers. We recall that our simulations are based on a local model for feedback-regulated growth of BHs through gas accretion. This produces a quite close co-evolution of the BH-mass and the stellar mass in galaxies, as seen in Figure 17.

A closer inspection of the figure reveals however a difference in the slope of the evolutionary curves, especially at late times, where the BH mass in the majority of cases grows more slowly than the stellar mass, as can be inferred from the mass ratios between stellar mass and BH mass indicated at selected redshifts in the individual panels. This implies that our simulations typically predict a higher black hole mass to stellar mass ratio at high redshift than seen in the local Universe. There is tentative observational evidence that this may indeed be the case; unusually large BH masses have for example been discovered in galaxies in the local Universe that are structurally similar to galaxies at much earlier times (van den Bosch et al. 2012). Another feature that can be seen in the evolution of the BH masses is the occurrence of merger events. They appear as sudden increases (almost in a step-like fashion) in the mass assembly history of the BHs, caused by brief phases of exponential Eddington-limited BH growth. Similar features are present, but less visible, in the stellar mass evolution curves as well.

All of the BHs in our galaxies end up with relatively high masses around $10^8 M_\odot$, which are however still consistent with the BH mass – stellar mass relation of Häring & Rix (2004). The fact that we get reasonable BH masses together with realistic disc properties in self-consistent cosmological simulations represents an important achievement of our galaxy formation model. This is especially noteworthy as other BH feedback schemes are known to negatively impact galaxy morphologies. For example, in Haas et al. (2012) the gaseous discs in $z = 2$ galaxies were lost once AGN feedback was activated. Similarly, in the Aquila comparison project (Scannapieco et al. 2012), the nice (but overly massive) disc formed by RAMSES was lost once BH feedback was activated.

Figure 17. Evolution of the galaxy's stellar (red lines) and central black hole (black lines) masses, as a function of look-back time and redshift, for the eight Aquarius haloes. The stellar masses are computed as the sum of the mass of each star particle within 10% of the halo virial radius at a given time, while for the black hole we plot for any selected time the most massive black hole present in the halo's redshift ($z < 6$). These similarities in the general behaviour are indicative of a co-evolution between the stellar content of a galaxy and its central BH, consistent with the observed relation between the masses of the two components (e.g. Magorrian et al. 1998; Häring & Rix 2004).
5 HALO MASS STRUCTURE

In this section, we discuss the overall mass structure of our galaxies, as reflected for example in their rotation curves. This is interesting for at least two reasons. On the one hand, the inner shape of the rotation curves is arguably one of the two primary areas where significant “small-scale tensions” between ΛCDM and observational data may be present (the other contentious area is the abundance, central structure, and spatial distribution of satellites, a topic beyond the scope of the present paper). On the other hand, baryonic effects have recently been claimed to substantially affect the central dark matter structure, even in large spiral galaxies (Macciò et al. 2012). The claimed effect of strong, repetitive outflows originating in supernova feedback is that of introducing a dark matter core, thereby overcoming the adiabatic contraction of the halo that is usually expected as result of baryons cooling out in the centre. Given that our galaxies experience strong outflows, including repeated ‘explosive’ ones from strong quasar feedback, it is interesting to check to what extent we can confirm this finding in our simulations.

5.1 Rotation curves

The detailed shape of the rotation curve of a galaxy encodes key information about the mass distribution within the system. For instance, a pronounced peak of the rotation velocity in the innermost regions followed by a rapid decline is indicative of a presence of a massive and compact structure (often associated with a large, dominant stellar bulge in earlier simulation work of galaxy formation, see also Scannapieco et al. 2012), whilst late-type spirals are characterized by an almost flat profile of the rotational velocity which in the outer parts requires dark matter if the ordinary laws of gravity hold.

In Figure 18, we present the rotation curves of our simulated galaxies. Contributions to the total rotation velocity (solid lines) have also been separately computed via \( v_c(r) = \sqrt{GM(<r)/r} \) for the primary mass components that constitute each galaxy: stars (dotted lines), gas (dashed lines) and dark matter (dotted-dashed lines). With the exception of Aq-E, all galaxies have approximately flat rotation curves that show a rapid rise in the centre followed by a slowly declining trend after the maximum velocity has been reached. Baryons (in the form of stars) tend to dominate only in the innermost couple of kpc. However, for systems Aq-D, Aq-E and Aq-F this behaviour extends out to about 10 kpc and is responsible for the appearance of a more pronounced peak in the rotation profiles. These galaxies have the largest central bulges (and also the largest stellar masses), with Aq-E leading the set in this respect. Aq-G has the least massive stellar distribution in the inner parts and is dark matter dominated everywhere except for the innermost kpc.

For what concerns the gas component, its contribution to the rotational velocity is quite sub-dominant but not completely negligible either, since velocities of up to \( \approx 50 \, \text{km s}^{-1} \) are reached. Again, the exception is represented by the gas-poor system Aq-E, where only a maximum velocity of \( \approx 35 \, \text{km s}^{-1} \) is attained. It is also interesting to
Figure 19. Spherically averaged dark matter (grey lines) and hot gas ($T > 3.0 \times 10^5$ K, red lines) density profiles of the eight simulated haloes. The density profiles obtained in the pure dark matter simulations (thin black lines) of the same haloes, rescaled by the factor $1 - \Omega_b/\Omega_m$, are also shown for comparison. The dotted vertical lines indicate the position of the virial radius of each halo. The contraction of the dark matter haloes due to the cooling and the infall of baryons in the central regions can be clearly detected in the majority of the simulated objects, whereas there is no sign of dark matter core formation in any of the galaxies. In the radial range between $\sim 10$ kpc and the virial radius, the hot gas follows to good approximation a power-law profile (dashed lines), $\rho_{\text{hot}}(r) \propto r^\alpha$, with $\alpha$ varying between $-1.35$ to $-2.2$ in the different systems.

5.2 Baryonic physics impact on dark matter

The modification of the dark matter structure of a Milky Way-sized halo due to baryonic effects is an extremely interesting, and so far unsettled question. While dark matter only simulations of Milky Way-sized haloes can be viewed as quite reliable these days, with several groups reaching consistent results independently and with different methods (e.g. Springel et al. 2008; Stadel et al. 2009), the situation with respect to baryons is far less clear. Navarro et al. (1996) were the first to demonstrate with $N$-body simulations that a sudden loss of a large fraction of the baryonic component from a dwarf galaxy halo could imprint a (small) dark matter core. Gnedin & Zhao (2002) however showed that even for assumptions of maximum feedback the central halo cusp could not be destroyed by outflows, with the inner density lowered only by a moderate factor. A similar conclusion was reached by Ogiya & Mori (2011). Mashchenko et al. (2006) argued that a larger impact is possible if there are strong random bulk motions of baryons in dark matter potentials in the early Universe, an idea that has recently gained popularity. Several studies have argued that baryonic effects can induce through this process dark matter cores in dwarf galaxies (Governato et al. 2010; Pontzen & Governato 2012; Governato et al. 2012), or even in large Milky Way size haloes or galaxy clusters (Macciò et al. 2012; Martizzi et al. 2012). However, the recent work by Garrison-Kimmel et al. (2013) questions these results. There is simply not enough energy available in supernovae to achieve the reported dark matter flattenings. Also, cyclic blow outs are not necessarily more effective than a single large burst.

We provide here a simple first analysis of this important issue, which has also significant bearings on dark matter indirect detection in the Galaxy (e.g. Yang et al. 2013). In Figure 19, we show spherically averaged dark matter density profiles for our eight different haloes (grey solid lines). We compare them to corresponding runs carried out with the same initial conditions but using dark matter alone (black thin lines). In these comparison simulations the baryons behave effectively as if they were dark matter as well. To make the comparison of the dark matter profiles more direct, we rescale the measured dark matter density of the latter runs by the factor $1 - \Omega_b/\Omega_m$, where $\Omega_b$ and $\Omega_m$ are the density parameters of baryons and dark matter in our hydrodynamical models, respectively. In this way, any difference in the recovered dark matter density profiles in the two sets of runs can be ascribed to the influence of baryonic physics alone. We see that in all cases the central dark matter density of our simulations that include baryons is increased, showing the expected effect for a mild adiabatic contraction. There is no trace of core formation in our results, despite the fact that
we have substantial early feedback from winds and repeated quasar-driven outflows. These are apparently not sufficiently strong to trigger the alleged process of core formation, a finding consistent with the recent analysis of idealized test simulation by Garrison-Kimmel et al. (2013).

In Fig. 19 we also include measurements of the spherically averaged density profiles of the hot ($T > 3 \times 10^5$ K) gas component in our hydrodynamical simulations. This gas component forms a pressure-supported atmosphere, known as corona, which is nearly in hydrostatic equilibrium with the dark matter potential. The hot corona is rather extended, reaching distances up to the halo virial radius (the vertical dotted lines in the figure) and beyond. The slope of its density profile is in general shallower than that of the dark matter, with a tendency of forming an approximately constant density state in the central regions ($r < \sim 10$ kpc) where the galaxy is located. Compared to the Eris simulation (Guedes et al. 2011), our hot gas profiles have considerably steeper profiles; none is as strongly flattened as Eris, which shows a power-law profile with slope $-1.13$ over a similar radial range as our simulations.

6 RESOLUTION STUDY

It is interesting to examine how robust our results are to changes in numerical resolution when the same halo is simulated at drastically different mass resolution. Experience shows that the high non-linearity of the feedback loops needed to tame star formation in Milky Way-sized haloes make the numerical results often less robust than is desirable when the resolution is changed. The Aquarius systems are ideal for examining this issue as the high-quality of the initial conditions has been validated to high accuracy with dark matter only simulations.

To allow a straightforward comparison with the Aquila code comparison project we focus on the Aq-C system, which we have simulated both at eight times higher (Aq-C-4) and eight times lower (Aq-C-6) mass resolution than used in our default set-up. In Figure 20, we compare the stellar morphology we obtain for these three cases. The images are constructed in the same way as those shown in Fig. 1, and use the same mapping of stellar luminosity to image intensity and colour. We have opted to show the $z = 0.2$ output instead of $z = 0$, because the Aq-C-4 run experiences a close tidal encounter with a massive satellite at around this time, which subsequently affects the ongoing star formation in Aq-C-4 and temporarily restricts it to a narrow inner ring. This changes the appearance of new young blue stars significantly, reducing the good visual correspondence of the systems Aq-C-5 and Aq-C-4 right at the particular output time of $z = 0$, which is a bit misleading given the overall good agreement of the runs. We note that also in the Aquila comparison project, a late time merger in the Aq-C system complicates the comparison of the different simulations as the exact timing and orbit of this incoming substructure depends sensitively on simulation details.

More quantitatively, in Figure 21 we compare several different basic quantities and examine how they compare with each other in our Aq-C-4, Aq-C-5 and Aq-C-6 simulations. We consider the rotation curves, eccentricity distributions, surface mass density profiles, the relation between stellar half mass radius and stellar mass, star formation rate history and black hole growth history. We find that the eccentricity distribution converges particularly well, which is reassuring. This suggests that the overall morphology is quite robustly predicted by our simulation methodology, even at the comparatively low resolution of Aq-C-6. Also, the stellar surface mass density profiles converge quite well, especially between the higher resolution simulations Aq-C-5 and Aq-C-4. The low resolution run shows still a quite similar disc profile, which is however slightly flatter. Similarly, the rotation curves exhibit very similar shape with only small deviations around the bulge and peak regions. Finally, the growth histories of the stars and the galaxy’s supermassive black hole show good overall agreement, with well aligned pat-
Figure 21. Comparison of the results obtained for the Aq-C halo at three different levels of numerical resolution, spanning a dynamic range of 64 in mass: Aq-C-6 (red), Aq-C-5 (green) and Aq-C-4 (blue). The six panels show: the circular velocity profiles (top left), the circularity distributions of stellar orbits (top middle), the stellar surface density profiles (top right), the relation between stellar half mass radius and stellar mass (bottom left), the star formation rate history (bottom middle), and finally, the growth rate of the central supermassive black hole (bottom right). In the comparison of $R_{\star, 50}$ with $M_{\text{stars}}$, we include the simulation results of the Aquila comparison project for the same Aq-C halo, and simulations carried out at different numerical resolution (indicated by squares for level 5 and circles for level 6) but with the same code and physical model are connected by thin lines.

This demonstrates that our simulations reliably and reproducibly track the same formation history of the Aq-C galaxy despite a variation of the mass resolution over a factor of 64, and despite the presence of very strong negative (winds and black hole growth) and positive (enhanced cooling due to metal enrichment) feedback.

The lower left panel in Fig. 21 shows our three different resolution simulations as symbols in the half-mass – stellar-mass plane. The three runs of the Aq-C object are connected by thin lines, forming a small triangle. For comparison, we also include in the figure the results of all the Aq-C simulations carried out in the Aquila comparison project, which employed a large set of other simulation codes and feedback models. In Aquila, the two lower resolutions corresponding to Aq-C-6 and Aq-C-5 were considered, and we include these results as symbols (circles for level 6 and squares for level 5), connecting each pair of runs carried out with the same code by a thin line. Note that the sides of the small triangle we obtained for our AREPO runs are shorter than any of the connecting lines for other codes, highlighting the good convergence properties of our simulation methodology relative to other implementations. Especially the galaxy sizes appear to be more robust in our code than in other implementations of the galaxy formation physics. This good convergence for galaxy sizes can be interpreted as circumstantial evidence that angular momentum conservation, which is not manifest in mesh codes, is sufficiently accurate in our simulations. Interestingly, two simulations from the Aquila project reached almost the same combination of stellar mass and galaxy size as found in our simulations. These are the gadget3 run with black holes (GR-BH) and the ramses run with AGN-feedback (R-AGN), both at resolution level-5. However, these simulations formed a dominant spheroid with at best a feeble disc component. The majority of the Aquila galaxies was however simply too massive, by up to a factor of $\sim 5$, and also too compact given their stellar mass.
7 DISCUSSION

7.1 Comparison with previous studies

Previous studies, in particular the Aquila comparison project (Scannapieco et al. 2012), have shown that the formation of disc galaxies hinges strongly on the relative level of star formation at early and late times. In fact, there is a clear correlation in the sense that the more successful models are those which manage to suppress high-redshift star formation while still allowing efficient star formation at late times. The difference this makes is particularly evident in a comparison of the results of Scannapieco et al. (2009) and Aumer et al. (2013) which partially overlap in the set of objects studied and use largely the same numerical techniques, except that Aumer et al. (2013) invoke an additional strong feedback channel in order to account for ‘early stellar feedback’. The difference in the results they obtain is striking. While in Scannapieco et al. (2009) none of the galaxies contain more than 20 per cent of the total stellar mass in their discs, Aumer et al. (2013) achieve the highest disc-to-bulge ratios reported in the literature thus far, with values for D/T as large as ~ 0.6. This is comparable to what we reach here.

The disc fractions reported by Guedes et al. (2011) and Agertz et al. (2011) are similarly high but are based on photometric decompositions, which is known to produce inflated disc fractions compared to kinematic decompositions (e.g. Scannapieco et al. 2011). We note that the Eris simulation did not include high temperature metal-cooling, an effect that would have significantly boosted cooling, given that outflows are strong in Eris. The galaxy studied by Agertz et al. (2011) has accounted fully for metal-line cooling (as we do) and promptly obtained rotation curves peaks that are too high, indicating still too efficient cooling and a stellar content inconsistent with abundance matching results. A similar, albeit more severe problem is seen in the recent simulations reported by Few et al. (2012) based on the RAMSES code, which feature quite well defined discs but also rotation curves rising to the centre as a result of overly luminous bulges.

It is worth stressing that our simulations study the same initial conditions as in Scannapieco et al. (2009) and (in part) in Aumer et al. (2013), but use a fundamentally different numerical method and a radically different treatment of feedback processes. In particular, we do not invoke early stellar feedback, rather we resort to supernova-driven outflows, modelled as energy-driven winds whose velocity is tied to the characteristic velocity of haloes. The efficiency of this process is assumed to be close to the upper envelope of what is energetically plausible. We do not implement the feedback through a “delayed cooling” approach that has become very popular in recent times in cosmological simulations of galaxy formation (Stinson et al. 2006; Guedes et al. 2011). As has been pointed by Agertz et al. (2012), the present implementations of these schemes appear to considerably exaggerate the impact of the SNII energy input they are meant to mimic. It also needs to be seen whether the optimistic assumptions made about the efficiency of radiative pressure feedback from early stars are plausible. Serious doubts about this seem justified (Krumholz & Thompson 2013).

We note that we do not use the high star formation threshold advocated by Governato et al. (2010) and Guedes et al. (2011). Hence, this is not a unique requirement to form realistic disc galaxies, even though it may still be essential within a certain numerical framework for treating hydrodynamics, star formation and feedback. Our feedback model follows the philosophy of an explicit subgrid model that does not require model adjustments when the numerical resolution is changed. While physical processes that are subgrid (such as the formation of individual stars or the launching of the galactic wind) remain unresolved when the resolution is increased, this approach allows numerically and physically well-posed simulation schemes with results that do not strongly depend on numerical resolution. This is highly desirable to obtain meaningful results in cosmological structure formation, where invariably galaxies of widely different mass form concurrently.

Another interesting point to observe is that the haloes of most of our galaxies are considerably more massive than those of the best successful disc galaxies reported in the literature thus far. When accounting for the different virial mass definition adopted by Eris (which gives ~ 15% higher values than ), in fact all of our haloes are more massive than Eris and the g136 halo of Stinson et al. (2013). It becomes more difficult to control excessive star formation in such larger haloes, and we consider it to be a success of our model that this is possible in haloes above $10^{12} \, M_\odot$. Only Aumer et al. (2013) have reported good discs in such more massive haloes, but their simulations tend to show too high star formation rates at low redshift in the corresponding galaxies, a problem that our simulations do not have, in part due to the inclusion of AGN feedback. Also their high mass galaxies at $z = 0$ appear to be too small, and the trend between stellar mass and size is too flat.

7.2 Conclusions

Our simulations are probably the most successful hydrodynamical simulations of the formation of Milky Way-like galaxies within a full cosmological context published thus far. The models Aq-C and Aq-F are the best Milky Way look-alikes among our set. They feature galaxies with high D/T ratio that form in sufficiently massive dark matter haloes to qualify as Milky Way systems. At the same time, these galaxies have a stellar mass, a current star formation rate, a rotation curve, a size, and a present-day gas fraction in reasonable agreement with properties of the Milky Way. Our models are also the first successful disc formation runs that simultaneously grow a supermassive black hole of reasonable size even though back-reaction on the forming galaxies through strong AGN feedback is included. The final black hole masses we obtain tend to be significantly higher than the mass of Sagittarius A* in the centre of the Milky Way. This could be rectified by assuming a higher coupling efficiency for the BH feedback. The self-regulated nature of the BH growth would then still inject the same energy – and leave the galaxy properties to first order unchanged – but achieve this with a smaller BH mass growth. However, the good match to the BH-mass scaling relations (Häring & Rix 2004) may then be lost.

As shown by Vogelsberger et al. (2013) and Torrey et al. (2013), the simulation methodology used here also produces very promising results for the galaxy population as a whole. This suggests that hydrodynamical studies of galaxy formation in large volumes, and at extremely high resolution in
individual haloes, are finally turning into serious competition for semi-analytic models of galaxy formation in terms of their ability to predict galaxies in reasonable agreement with observational data. The higher physical fidelity of hydrodynamic simulations, especially when it comes to the dynamics of the diffuse gas phase, make them ultimately the superior tool for exploring and understanding galaxy formation physics. We note that our methods also represent a significant advance in computational efficiency compared to previous generations of hydrodynamical galaxy formation simulations, despite the fact that we employ a complicated unstructured moving-mesh code. Our simulation of Aq-C-4 has consumed less than $10^8$ CPU hours on a cluster with Intel Sandy Bridge 2.7 GHz CPUs (2.7 GHz) and 512 MPI tasks, including all group finding and subfind post-processing. Given that this calculation features only a slightly smaller number of resolution elements in the virial radius than Eris, which took 1.5 million CPU hours, this is a quite competitive timing. We also recall the good numerical convergence of our approach, which to our knowledge is presently unmatched by other simulation methodologies in the field.

The near-term future of cosmological hydrodynamic simulations appears truly exciting. There are now several groups and codes that have made great strides towards forming realistic galaxies, both in cosmological simulations like the ones discussed here, and in simulations of isolated galaxies (e.g. Hopkins et al. 2012). This will be of enormous help for advancing our theoretical understanding of galaxy formation and for properly interpreting the wealth of observational data. However, the devil is very much in the details of feedback, and for the time being this remains a major headache which compromises some of the predictive power of simulations. A ‘first principles’ understanding of how galaxies form will ultimately require simulations that fully account for the physics of the ISM and the cosmological context at the same time, a truly formidable task for the future.

ACKNOWLEDGEMENTS

We thank Mark Vogelsberger, Shy Genel, Lars Hernquist, Debora Sijacki, Paul Torrey, Christoph Pfrommer, Christopher Hayward and Ewald Puchwein for useful discussions. F.M. and V.S. acknowledge support by the DFG Research Centre SFB-881 ‘The Milky Way System’ through project F1. This work has also been supported by the European Research Council under ERC-StG grant EXAGAL-308037 and by the Klaus Tschira Foundation.

REFERENCES

Abadi M. G., Navarro J. F., Steinmetz M., Eke V. R., 2003, ApJ, 597, 21
Agertz O., Kravtsov A. V., Leitner S. N., Gnedin N. Y., 2012, ArXiv e-prints, 1210.4957
Agertz O., Teyssier R., Moore B., 2011, MNRAS, 410, 1391
Aumer M., White S., Naab T., Scannapieco C., 2013, ArXiv e-prints, 1304.1559
Balogh M. L., Pearce F. R., Bower R. G., Kay S. T., 2001, MNRAS, 326, 1228
Battaglia G., Helmi A., Morrison H., Harding P., Olszewski E. W., Mateo M., Freeman K. C., Norris J., Shectman S. A., 2005, MNRAS, 364, 433
Bauer A., Springel V., 2012, MNRAS, 423, 2558
Behroozi P. S., Conroy C., Wechsler R. H., 2010, ApJ, 717, 379
Boylan-Kolchin M., Bullock J. S., Kaplinghat M., 2011, MNRAS, 415, L40
Boylan-Kolchin M., Bullock J. S., Kaplinghat M., 2012, MNRAS, 422, 1203
Boylan-Kolchin M., Bullock J. S., Sohn S. T., Besla G., van der Marel R. P., 2012, ArXiv:1210.6046
Boylan-Kolchin M., Springel V., White S. D. M., Jenkins A., 2010, MNRAS, 406, 896
Boylan-Kolchin M., Springel V., White S. D. M., Jenkins A., Lemson G., 2009, MNRAS, 398, 1150
Brooks A. M., Solomon A. R., Governato F., Mc Cleary J., MacArthur L. A., Brook C. B. A., Jonsson P., Quinn T. R., Wadsley J., 2011, ApJ, 728, 51
Chabrier G., 2003, ApJ, 586, L133
Courteau S., Dutton A. A., van den Bosch F. C., MacArthur L. A., Dekel A., McIntosh D. H., Dale D. A., 2007, ApJ, 671, 203
Davis M., Efstathiou G., Frenk C. S., White S. D. M., 1985, ApJ, 292, 371
Dehnen W., McLaughlin D. E., Sachania J., 2006, MNRAS, 369, 1688
Dutton A. A., Conroy C., van den Bosch F. C., Simard L., Mendel J. T., Courteau S., Dekel A., More S., Prada F., 2011, MNRAS, 416, 322
Fall S. M., Efstathiou G., 1980, MNRAS, 193, 189
Faucher-Giguère C.-A., Liedz A., Zaldarriaga M., Hernquist L., 2009, ApJ, 703, 1416
Few C. G., Gibson B. K., Courty S., Michel-Dansac L., Brook C. B., Stinson G. S., 2012, A&A, 547, A63
Gallazzi A., Charlot S., Brinchmann J., White S. D. M., Tremonti C. A., 2005, MNRAS, 362, 41
Garrison-Kimmel S., Rocha M., Boylan-Kolchin M., Bullock J., Lally J., 2013, ArXiv e-prints, 1301.3137
Genel S., Vogelsberger M., Nelson D., Sijacki D., Springel V., Hernquist L., 2013, ArXiv e-prints, 1305.2195
Gnedin O. Y., Zhao H., 2002, MNRAS, 333, 299
Governato F., Brook C., Mayer L., Brooks A., Rhee G., Wadsley J., Jonsson P., Willman B., Stinson G., Quinn T., Majda P., 2010, Nature, 463, 203
Governato F., Mayer L., Wadsley J., Gardner J. P., Willman B., Hayashi E., Quinn T., Stadel J., Lake G., 2004, ApJ, 607, 688
Governato F., Willman B., Mayer L., Brooks A., Stinson G., Valenzuela O., Wadsley J., Quinn T., 2007, MNRAS, 374, 1479
Governato F., Zolotov A., Pontzen A., Christensen C., Oh S. H., Brooks A. M., Quinn T., Shen S., Wadsley J., 2012, MNRAS, 422, 1231
Graham A. W., 2001, AJ, 121, 820
Graham A. W., 2002, MNRAS, 334, 721
Graham A. W., Worley C. E., 2008, MNRAS, 388, 1708
Guedes J., Callegari S., Madau P., Mayer L., 2011, ApJ, 742, 76
Guo Q., White S., Boylan-Kolchin M., De Lucia G., Kauffmann G., Lemson G., Li C., Springel V., Weinmann S., 2011, MNRAS, 413, 101

© 2013 RAS, MNRAS 000, 1–27

Disc galaxies in moving-mesh cosmological simulations 25
van den Bosch R. C. E., Gebhardt K., Gültekin K., van de Ven G., van der Wel A., Walsh J. L., 2012, Nature, 491, 729

Verheijen M. A. W., 2001, ApJ, 563, 694

Vogelsberger M., Genel S., Sijacki D., Torrey P., Springel V., Hernquist L., 2013, submitted to MNRAS, ArXiv e-prints, 1305.2913

Vogelsberger M., Sijacki D., Kereš D., Springel V., Hernquist L., 2012, MNRAS, 425, 3024

Wakker B. P., van Woerden H., 1991, A&A, 250, 509

Wang J., Frenk C. S., Navarro J. F., Gao L., Sawala T., 2012, MNRAS, 424, 2715

Wilkinson M. I., Evans N. W., 1999, MNRAS, 310, 645

Windhorst R. A., Burstein D., Mathis D. F., Neuschaefer L. W., Bertola F., Buson L. M., Koo D. C., Matthews K., Barthel P. D., Chambers K. C., 1991, ApJ, 380, 362

Xue X. X., Rix H. W., Zhao G., Re Fiorentin P., Naab T., Steinmetz M., van den Bosch F. C., Beers T. C., Lee Y. S., Bell E. F., Rockosi C., Yanny B., Newberg H., Wilhelm R., Kang X., Smith M. C., Schneider D. P., 2008, ApJ, 684, 1143

Yang R.-Z., Feng L., Li X., Fan Y.-Z., 2013, ArXiv e-prints, 1304.7986