The effects of cosmic rays on the formation of Milky Way-like galaxies in a cosmological context

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Abstract

We investigate the impact of cosmic rays (CR) and different modes of CR transport on the properties of Milky Way-like galaxies in cosmological magneto-hydrodynamical simulations in the context of the AURIGA project. We systematically study how advection, anisotropic diffusion and additional Alfvén-wave cooling affect the galactic disk and the circum-galactic medium (CGM). Global properties such as stellar mass and star formation rate vary little between simulations with and without various CR transport physics, whereas structural properties such as disk sizes, CGM densities or temperatures can be strongly affected. In our simulations, CRs affect the accretion of gas onto galaxies by modifying the CGM flow structure. This alters the angular momentum distribution which manifests itself as a difference in stellar and gaseous disk size. The strength of this effect depends on the CR transport model: CR advection results in the most compact disks while the Alfvén-wave model resembles more the AURIGA model. The advection and diffusion models exhibit large ($r \sim 50$ kpc) CR pressure-dominated gas haloes causing a smoother and partly cooler CGM. The additional CR pressure smoothes small-scale density peaks and compensates for the missing thermal pressure support at lower CGM temperatures. In contrast, the Alfvén-wave model is only CR pressure dominated at the disk-halo interface and only in this model the gamma-ray emission from hadronic interactions agrees with observations. In contrast to previous findings, we conclude that details of CR transport are critical for accurately predicting the impact of CR feedback on galaxy formation.

Key words: MHD - cosmic rays - galaxies: formation - galaxies: evolution - galaxies: structure - methods: numerical

1 INTRODUCTION

The formation of galaxies is a multi-scale, multi-physics problem and understanding the details of the physical processes involved is one of the most challenging problems in theoretical astrophysics. Cosmological simulations and semi-analytic studies have demonstrated that feedback from stellar winds and radiation fields, supernovae, and active galactic nuclei (AGNs) are key processes in shaping the structure of galaxies (e.g. Brook et al. 2012; Stinson et al. 2013; Puchwein & Springel 2013; Marinacci et al. 2014; Vogelsberger et al. 2014; Henriques et al. 2015; Schaye et al. 2015; Dubois et al. 2016; Kaviraj et al. 2017; Pillepich et al. 2018; Hopkins et al. 2018). These processes effectively drive galactic winds, move gas and metals out of galaxies into the intergalactic medium, regulate the star formation rate (SFR) down to the observed low rates or completely quench it in elliptical galaxies, and balance radiative cooling in the centers of galaxy clusters (Kravtsov & Borgani 2012; Battaglia et al. 2012a,b, 2013; McCarthy et al. 2014, 2017; Dolag et al. 2016; Weinberger et al. 2017).

While the latest galaxy formation models are quite successful in reproducing key observables of realistic galaxies (e.g. Wang et al. 2015; Sawala et al. 2016; Grand et al. 2017; Hopkins et al. 2018; Buck et al. 2019a), most feedback prescriptions are modelled empirically, calibrated against observed scaling relations which limits the predictive power of the corresponding calculations. In particular, resolution requirements of hydrodynamical simulations of galaxy formation made it necessary to implement feedback relatively coarsely: simulations base their feedback prescriptions on explicit sub-grid formulations which model the unresolved, multi-
phase structure of the interstellar medium (ISM) (Springel & Hernquist 2003; Schaye & Dalla Vecchia 2008). The details of the driving mechanisms behind galactic winds and outflows are still unknown and implementations remain phenomenological (Oppenheimer & Davé 2006). On larger scales, feedback from AGNs has been invoked in order to balance star formation in galaxy clusters. Here, accretion rates onto the black hole are estimated by the Bondi prescription and feedback energy is injected in form of pure thermal energy (Di Matteo et al. 2005; Springel et al. 2005) or they involve chaotic cold accretion (Gaspari et al. 2013) or AGN feedback might be modelled slightly more complex (Weinberger et al. 2017; Davé et al. 2019).

Another obvious source of galactic feedback might be due to the energy and momentum deposition of the ultraviolet radiation of the stars. Radiation pressure acting on dust grains and the atomic lines in dense gas has been argued to transfer enough momentum to the gas in order to exceed the escape velocity and drive winds (Murray et al. 2005; Thompson et al. 2005). However, direct radiation-hydrodynamical simulations in simplified set-ups (Krumholz & Thompson 2012) or in isolated galaxy simulations (Rosdahl et al. 2015) do not produce strong radiation pressure driven winds, suggesting that radiation feedback is less effective and more gentle than widely assumed (but see also Emerick et al. 2018).

On the other hand, cosmological simulations often neglect feedback from relativistic particles, so-called cosmic rays (CRs), which provide another source of non-thermal feedback. Such a particle population can be created by diffusive shock acceleration at expanding supernova remnants (e.g. Blandford & Eichler 1987; Jubelgas et al. 2008) or in AGN-powered jets (e.g. Sijacki et al. 2008; Ehler et al. 2018). CRs and magnetic fields are observed to be in pressure equilibrium with the turbulence in the mid-plane of the Milky Way (Boulares & Cox 1990) and the pressure forces of the CRs might be able to accelerate the ISM and drive powerful galactic outflows as suggested by a number of theoretical works (Ipavich 1975; Breitschwerdt et al. 1991, 2002; Zirakashvili et al. 1996; Ptuskin et al. 1997; Socrates et al. 2008; Everett et al. 2008; Samui et al. 2010; Dorfi & Breitschwerdt 2012) and local three-dimensional (3D) simulations of the ISM (Hanasz et al. 2013; Girichidis et al. 2016; Simpson et al. 2016).

In comparison to other feedback mechanisms, CRs have a number of advantageous properties: (i) the CR pressure drops less quickly upon adiabatic expansion than the thermal pressure due to their softer equation of state \( (P_{\text{CR}} \propto \rho_{\text{CR}}^{3/4} \) with \( \gamma_{\text{CR}} = 4/3 \), (ii) CR cooling is generally less efficient than the radiative cooling of a thermal plasma (Enßlin et al. 2007) and thus acts on longer time-scales compared to thermal energy, (iii) the non-thermal energy of CRs is not detectable through thermal observables or X-ray emissions, therefore the (temporary) storage of feedback energy in CRs also avoids problems with the overproduction of these observables (iv) they can maintain the outflows in a warm halo and CRs do not couple to the thermal gas via particle-particle collisions but via particle-wave interactions as fast streaming CRs along the magnetic field resonantly excite Alfvén waves. CRs are then able to scatter off of these waves which isotropise their distribution function in the wave frame, thus transferring energy and momentum to the thermal plasma and exerting a pressure onto the gas. Thereby, CRs not only impart momentum to the ISM at the launching sites but continuously re-power winds via thermal and dynamic coupling of plasma and CRs.

As a result CRs might explain the observed low SFRs in giant elliptical galaxies located at the centers of galaxy groups and clusters. In the absence of any heating processes, the hot gaseous atmosphere of these objects is expected to efficiently cool and form stars at very high rates (up to a few hundred \( M_\odot/\text{yr} \), e.g. Peterson & Fabian 2006). However, observed SFRs are much below these expected rates which is why AGN feedback has been invoked to balance radiative cooling. While theoretical considerations have shown that AGN feedback energies are sufficient, the exact coupling mechanism is still under debate (McNamara & Nulsen 2007). While several physical processes have been proposed to mediate the heating (amongst others the dissipation of turbulent energy powered by the AGN, Zhuravleva et al. 2014) a promising alternative is given by CRs. A net outward flux of streaming CRs can resonantly excite Alfvén waves that experience non-linear Landau damping or decay via a cascading process as a result of strong external turbulence and eventually dissipate locally (Loewenstein et al. 1991; Guo & Oh 2008; Enßlin et al. 2011; Pfrommer 2013; Wiener et al. 2013; Jacob & Pfrommer 2017a; Ruszkowski et al. 2017b; Ehler et al. 2018).

By now there are several (magneto-)hydrodynamics (MHD) simulation codes capable of solving the details of the CR proton acceleration and transport in galaxies and galaxy clusters: the Eulerian mesh codes cosmocmr (Miniati et al. 2001), Zeus-3d (Hanasz & Lesch 2003), the smoothed particle hydrodynamics code gadget-2 (Pfrommer et al. 2006; Enßlin et al. 2007; Jubelgas et al. 2008), the adaptive mesh refinement codes RAMSES (Booth et al. 2013; Dubois et al. 2016), enzo (Salem & Bryan 2014), flash (Girichidis et al. 2016), and Pluto (Mignone et al. 2018), the moving-mesh code arepo (Pakmor et al. 2016b; Pfrommer et al. 2017a) and the mesh-free Lagrangian finite mass code gizmo (Chan et al. 2019). Here, we use the arepo code (Springel 2010; Pakmor et al. 2016a) combined with the numerical implementations of CR physics (Pfrommer et al. 2017a; Pakmor et al. 2016b) to simulate the formation of Milky Way (MW) like galaxies in a cosmological context.

This paper is organized as follows: In Section 2 we describe the simulation setup and the different implementations of CR treatment. In Section 3 we study the central stellar and gaseous disks focussing on the differences and similarities in properties across various CR physics variants. We further investigate here the accretion of gas onto the main galaxy and the successive build-up of angular momentum. In Section 4 we turn to analyse the effects of CRs on the properties and structure of the CGM. We finish our analysis in Section 5 by comparing a direct observable, namely the gamma-ray luminosity of the simulated galaxies, to observations. In Section 6 we conclude this paper with a discussion, compare our results to previous work, and summarize our results in Section 7.

2 COSMOLOGICAL SIMULATIONS

For this work we simulate the formation of two MW-like disk galaxies from cosmological initial conditions taken from the AUGA project (Grand et al. 2017, 2019). Simulations are performed with the second-order accurate, adaptive moving-mesh
The AURIGA model includes primordial and metal-line cooling with self-shielding corrections and the spatially uniform UV background model of Faucher-Giguère et al. (2009) is included (for more details see Vogelsberger et al. 2013). The interstellar medium (ISM) is modelled with an effective equation of state (Springel & Hernquist 2003) and star-forming gas is treated as a two phase medium. Star formation occurs in thermally unstable gas for densities higher than a threshold density of \( n_{th} = 0.13 \text{ cm}^{-3} \) in a stochastic manner where the probability scales exponentially with time in units of the star formation timescale \( t_{sf} = 2.2 \text{ Gyr} \) in the AURIGA model.

Each star particle in this model represents a single stellar population (SSP) characterised by age and metallicity assuming a constant adiabatic index of 4/3 in a two-fluid approximation (Pfrommer et al. 2017a). CRs are generated at core-collapse supernovae remnants by instantaneously injecting all CR energy produced by the star particle into its surroundings immediately after birth. The energy efficiency of the injection is set to \( \epsilon_{inj} = 0.1 \). Following Pfrommer et al. (2017a), we assume an equilibrium momentum distribution for the CRs to model their cooling via Coulomb and hadronic interaction with the ambient gas.

To bracket the uncertainties of CR transport, we simulate three different models with different variants of CR physics (similar to Wiener et al. 2017) and one model without CRs. To explain the differences of our CR models, we briefly review the main aspects of CR hydrodynamics. While individual CRs move close to the speed of light, frequent resonant CR interactions with Alfvén waves causes their distribution function to (nearly) isotropise in the frame of the Alfvén waves such that the CR energy is transported as a superposition of CR advection with the gas, anisotropic streaming with Alfvén waves along the magnetic field and diffusion with respect to the wave frame so that the time evolution equation of the CR energy density \( \epsilon_{cr} \) in the one-moment formulation of CR transport reads as follows:

\[
\frac{\partial \epsilon_{cr}}{\partial t} + \nabla \cdot \left[ \epsilon_{cr} \mathbf{v} + (\epsilon_{cr} + P_{cr}) \mathbf{u}_{ad} - \epsilon_{b} (\mathbf{b} \cdot \nabla \epsilon_{cr}) \right] = - P_{cr} \nabla \cdot \mathbf{u}_{ad} - P_{cr} \nabla \cdot \mathbf{u}_{ad} + \epsilon_{cr} \nabla \times \mathbf{b} + \nabla \cdot \mathbf{U}_{ad} + \nabla \cdot \mathbf{U}_{cr},
\]

Here, \( \mathbf{v} \) denotes the gas velocity, \( \mathbf{v}_{ad} = \mathbf{B} / \sqrt{4 \pi \rho} \) is the Alfvén velocity, \( \mathbf{B} \) is the magnetic field, \( \rho \) is the gas mass density, \( \mathbf{u}_{ad} \) is the CR advection velocity, and \( \mathbf{u}_{cr} \) is the CR streaming velocity.

\[
\mathbf{u}_{ad} = -\epsilon_{ad} \mathbf{b} \frac{\mathbf{B} \cdot \nabla \epsilon_{cr}}{\sqrt{4 \pi \rho} |\mathbf{B}||\nabla \epsilon_{cr}|},
\]

implying that the CR streaming velocity is oriented along magnetic fields lines down the CR pressure gradient with a velocity that corresponds in magnitude to \( \mathbf{u}_{ad} \). The CR pressure, \( \epsilon_{b} \), is the kinetic energy density of relativistic charged particles.
The plot dimensions are 50 kpc × 50 kpc, panel we note structural properties of the stellar disk resulting from a surface density fit of a combined exponential plus Sérsic (1963) profile (see Fig. A1). Younger (older) star particles are therefore represented by bluer (redder) colours. In each face-on projection, the blue colour channels, in logarithmic intervals, respectively. 

Figure 1. Face-on and edge-on projected stellar density at z = 0 for the eight simulations. The upper panel shows the galaxy Au6 and the lower panel shows AuL8. From left to right we show the four different variants of physics: (i) the fiducial AURIGA simulations without CRs, (ii) the simulations with CR advection and anisotropic CR diffusion and Alfvén cooling/heating enabled, (iii) the CR anisotropic diffusion and CR advection simulations, and (iv) the pure CR advection simulations. The images are synthesized from a projection of the K-, B- and U-band luminosity of stars, which are shown by the red, green and blue colour channels, in logarithmic intervals, respectively. Younger (older) star particles are therefore represented by bluer (redder) colours. In each face-on panel we note structural properties of the stellar disk resulting from a surface density fit of a combined exponential plus Sérsic (1963) profile (see Fig. A1). The plot dimensions are 50 kpc × 50 kpc and 50 kpc × 25 kpc, respectively.

energy-weighted spatial CR diffusion coefficient, \( b = B / |\mathbf{B}| \) is the unit vector along the local magnetic field, and \( \Lambda_{\text{cr}} \) and \( \Gamma_{\text{cr}} \) are non-adiabatic CR losses and sources.

Note that CR streaming and diffusion are both anisotropic transport processes along the mean magnetic field and oriented down the CR gradient. While the streaming term advects CRs with the frame of Alfvén waves and maintains CR gradients, diffusion is a dispersive process (owing to the second gradient in the bracket of Eq. (1)) so that the CR gradient weakens over time, implying that the streaming and diffusion fluxes cannot be the same at all times (Wiener et al. 2017). Most importantly, CR diffusion exactly conserves CR energy while CR streaming drains CR energy at a rate \( \kappa_{\text{adiab}} \) due to the excitation of resonant Alfvén waves.

In all of our models we omit the CR streaming term on the left-hand side of Eqn. (1), which can be most accurately solved with the two-moment method of CR transport (Jiang & Oh 2018; Thomas & Pfrommer 2019). In all three CR models, we account for CR advection and adiabatic changes of the CR energy. Our models are defined as follows:

(i) **noCR**: fiducial AURIGA galaxy formation model without CRs.

(ii) **CRadv**: CR advection model where CRs are only advected with the gas.

(iii) **CRdiff**: CR diffusion model where CRs are advected with the gas but are further allowed to anisotropically diffuse relative to the rest frame of the gas with a diffusion coefficient of \( k_{\text{diff}} \sim 10^{28} \text{ cm}^2 \text{ s}^{-1} \) along the magnetic field and no diffusion perpendicular to it (Pakmor et al. 2016b).

(iv) **CRdiffalven**: anisotropic CR diffusion model with the additional inclusion of the Alfvén-wave cooling term that arises due to the energy transfer from CRs to Alfvén waves that are self-excited through the resonant CR streaming instability (Kulsrud & Pearce 1969).

While CR diffusion is thought to describe the transport of high-energy CRs above \( \sim 200 \text{ GeV} \), at lower energies the transport transitions to mainly CR streaming with self-generated Alfvén waves (Evoli et al. 2018), although the role of scattering in external turbulence is not yet settled (Zweibel 2017). While the process of CR diffusion conserves CR energy, additionally accounting for the Alfvén-wave cooling term emulates and approximates CR streaming. While this approximation is justified in cases for which the diffusion and streaming fluxes match each other, solutions will necessarily deviate if this condition is not fulfilled (Wiener et al. 2017).
Future work is needed to clarify how the explicit inclusion of CR streaming in the presence of different wave damping processes changes the picture presented in this work.

3 GALAXY DISK PROPERTIES

3.1 Stellar disk

In Fig. 1 we present face-on and edge-on projections of all eight simulations at $z = 0$ where the upper panels show the four different simulations of the Au6 halo and lower panels of AuL8. The images are a composition of the K-, B- and U-band luminosities (mapped to the red, green and blue colour channels), which indicate the distribution of younger (bluer colours) and older (redder colours) star particles, respectively. All simulations reveal a star-forming disk component with additional clear non-axisymmetric structures such as bars and spiral arms. For the fiducial noCR and the CRdiffalfven model the stellar disk is radically extended and thin. In contrast to that, the CRdiff and CRadv models result in more compact stellar disks further indicated by the lower ratio of D/T between the stellar disk mass (D) and the total stellar mass of the galaxy (T) shown in the lower right corner of each panel. Nevertheless, from the edge-on view these simulations are still identifiable as disk galaxies.

Despite the obvious differences in morphology, the total stellar mass in each model is almost the same as shown by Fig. 2. Here, we investigate the star formation history (SFH) and the stellar mass-halo mass relation (right panel) for the AURIGA haloes. We show the SFHs for galaxy Au6 (left panel) and for AuL8 (middle panel), respectively. In the right panel, we show the final stellar mass of our simulations at $z = 0$ vs their final halo mass. In each panel we compare the SFH/stellar masses of the four different physics variants, the fiducial AURIGA model shown in black, the cosmic ray advection run in blue, the run with additional anisotropic CR diffusion in purple and the run which additionally accounts for CR Alfvén wave cooling in red. In the right panel, the light blue line shows the abundance matching result taken from Moster et al. (2013) while the gray dotted line shows the cosmic baryon fraction.

We further examined the total amount of gas as well as the cold gas mass and found that both quantities do not change much across the different physics variants. We conclude that in our simulations structural disk properties can be significantly changed by CRs, global stellar properties, however, are robust across different CR physics variants and are not much affected by CRs.

3.2 Gas disk

The differences in stellar morphology are mainly a result of differences in the gaseous properties of the central galaxies. Figure 3 shows face-on and edge-on projections of the gas surface density (upper panels), the magnetic field strength (middle panels) and the ratio of CR-to-thermal pressure (lower panels) of the central gaseous disk of Au6. From left to right we show the noCR, the CRdiffalfven, the CRdiff and the CRadv run. Figure 4 complements this by showing the radial profiles in cylindrical bins of radial width 1 kpc and height 2 kpc centered on the disk mid-plane for both galaxies Au6 (upper panels) and AuL8 (lower panels).

Comparing the surface density maps of the four different physics variants we find that the CR runs show a more centrally concentrated, thicker gas disk with slightly higher surface densities within the disk region. This is further highlighted by the larger central densities in the left panels of Fig. 4. Furthermore, from Fig. 3 we see how the CR pressure smoothes out density features in the disk, particularly in the CRadv and CRdiff runs; the CRdiffalfven run most closely resembles the fiducial AURIGA run. The CRadv run exhibits the most compact, thick and smooth gas disk where the additional CR pressure stabilizes and smooths the gas. The lower panels of Fig. 3 and the right-hand panels of Fig. 4 show that in all three CR models the thermal pressure in the gas disk is sub-dominant in comparison to the CR pressure. This effect is most prominent in the CRadv and CRdiff runs where CRs can only cool adiabatically via Coulomb and hadronic interactions. This results in CR-to-thermal pressure ratios of $P_{\text{cr}}/P_{\text{th}} = X_{\text{cr}} \gtrsim 10$ in the disk region.
Figure 3. From top to bottom we show the gas surface density, the magnetic field strength and the CR-to-thermal pressure ratio for the gas disk of the different physics variants (left to right) in the Au6 simulation in face-on and edge-on projections. The projection depth is 25 kpc.
Figure 4. Radial profiles of gas density, magnetic field strength and CR-to-thermal pressure ratio (left to right) in cylindrical shells of height $|z| < 1$ kpc and width $\Delta r_{xy} = 1$ kpc. The upper panels show results for the model galaxy Au6 and lower panels for AuL8. Different physics variants are shown with differently colored lines. The fiducial AURIGA run is shown with a black line, the Alfvén run in red, the CR diffusion run in magenta and the CR advection run in blue.

We observe slightly higher CR-to-thermal pressure ratios in the CRdiff compared to the CRadv run. At first, this result might be surprising because the CRs in the diffusion run are able to diffuse out of the disk into the halo. The reason for this is as follows: if $|\nabla (P_{\text{th}} + P_{\text{gyr}})| > |\nabla \Phi|$ (where $P_{\text{th}}$ is the thermal pressure and $\Phi$ is the gravitational potential), then the composite of CRs and thermal gas adiabatically expands and as a result the CR pressure will exceed the thermal pressure because of its softer equation of state: the CR pressure decreases at a slower rate in comparison to the thermal pressure. As the CRs diffuse above and below the galaxy midplane, they push gas out of the disk (via their gradient pressure force), thus lowering the gas density in the disk (see left panels of Fig. B1). Because the temperature in the star forming regions is set by the effective equation of state, the thermal pressure in the CRdiff model is lower (see right most panels of Fig. B1), and hence the ratio of $P_{\text{cr}}/P_{\text{th}} = X_{\text{cr}}$ is larger in this model.

In the CRdiffalfven run on the other hand, the CRs are allowed to diffuse and to cool via the Alfvén wave cooling mechanism and thus their stabilizing pressure is much dominant compared to the CRadv run. Here we find typical values of $X_{\text{cr}}$ ranging from unity to three within the central $5 - 10$ kpc of the disk (see Fig. 4). This allows for a shallower radial density profile within the disk that is then able to grow larger stellar disks. We caution that some of the drastic differences of the density profiles between the different variants of CR physics may be due to cosmic variance and the different accretion histories. In particular the differing density profiles in Au6 (Fig. 4) are reduced in AuL8 where the CRdiffalfven run’s density profile follows much more closely the fiducial AURIGA run.

The middle panel of Fig. 3 shows the magnetic field strength which looks very similar in the disk for all CR runs but varies drastically from the fiducial AURIGA runs which show a much smoother, ordered magnetic field. All runs show a magnetic field strength of $\sim 1 - 10 \mu G$ in the disk except for the very central regions (see e.g. middle panels of Fig. 4). In detail, the CR runs show a more structured magnetic field which follows closely the structure of the gas disk because the CRs act as a local feedback source while in the noCR run the wind feedback is non local. Thus, CRs are able to inject turbulence in the gas disk, imprinting more small scale structure onto the magnetic field. This feature is absent in the noCR runs and thus the magnetic field appears much more ordered. However, the halo magnetic field looks very different between the three CR runs. Interestingly, the vertical magnetic field extending into the halo in the CRdiff and CRadv is larger compared to the CRdiffalfven and AURIGA runs. Thus, we conclude that CR dynamics alters the dynamo process in comparison to pure MHD simulations and the higher density features in the CR runs lead to a more structured magnetic field in the gas disk (see also middle panels of Fig. 4). We note that different variants of CR transport seem not to affect the disk magnetic field much.
At a lookback time of 6 Gyr this galaxy undergoes a merger which

Figure C1.

entire distribution of gas angular momentum, as can be verified in

Figure 5.

3.3 Gas accretion onto the disk

We have seen that the inclusion of CRs lead to more compact stel-
lar and gaseous disks. In this section, we investigate the evolution of
the angular momentum of gas that ends up in stars in the cen-
tral galaxy at present-day. In practice, we make use of Lagrangian
“tracer particles” (Genel et al. 2013; Grand et al. 2019) to follow
the motion of resolution elements over time. At the beginning of
each simulation, each gas cell in the high-resolution region is as-
signed a tracer particle with a unique ID. A tracer particle in any
given cell moves to a neighbouring cell with a probability propor-
tional to the outward mass flux across a cell face. Usually, a tracer
particle has the highest probability to remain in the same cell, be-
cause the moving-mesh nature of AREPO means that cells follow
the bulk gas flow as closely as possible.

Following the median angular momentum of gas which is in
stars at redshift \( z = 0 \) back in time (Fig. 5) we find that CRs sup-
press the acquisition of angular momentum after the time of disk
formation \( t_{\text{lookback}} \sim 5 - 8 \) Gyr. The suppression is strongest for the
CRadv and CRdiff runs while the CRdiffalfven run more closely
follows the fiducial runs. At present-day, the CR simulations have
acquired a factor of \( \sim 2 - 5 \) times less specific angular momentum
which manifests itself in more compact disks. For AuL8, the differ-
ces between the noCR run and the CR runs are smaller and the
CRdiffalfven run matches the angular momentum of the noCR run.
At a lookback time of 6 Gyr this galaxy undergoes a merger which
masks most of the differences in angular momentum distribution
between the different physics runs. The evolution of the median an-
gular momentum is indeed representative of the evolution of the
entire distribution of gas angular momentum, as can be verified in
Fig. C1.

The angular momentum acquisition of the galaxy is most effi-
cient if the accreted gas from large scales is undisturbed and flows
to the central gas disk. When a large gas disk is first forming in the
fiducial AURIGA model the wind feedback model develops out-
flows perpendicular to the stellar/gas disk (e.g. left panel in Fig. 6),
which is an emergent phenomenon that is the result of the outflow
taking the path of least resistance away from the galaxy (Grand
et al. 2019). As we have discussed earlier (Fig. 3), in the CR runs
the additional CR pressure support inflates the gas disk and thus
enhances the gas density above and below the disk. The gas mor-
phology in these runs is thus less disky and the particular imple-
mentation of the wind model results in more spherically symmetric
flows that are less coherent in the perpendicular direction of the
disk as we exemplify in Fig. 6. This figure shows the gas flow pat-
tern in form of stream lines at redshift \( z = 0.3 \) (corresponding to a
lookback time of \( \sim 3.5 \) Gyr).

In order to compare the wind properties to the dominant pres-
sure forces and assess whether CRs change the hydrodynamic halo
properties, we overlay the streamlines of Fig. 6 on a colour map
that shows the pressure ratio \( (P_{\text{cr}} + P_{\text{th}})/P_{\text{in}} \), where \( P_{\text{in}} = \rho v^2 \)
is the radial kinetic flux term in the Euler equation. This can be seen
by looking at the momentum equation of an ideal fluid in the presence
of CRs, which reads as follows:

\[
\frac{\partial \rho v}{\partial t} + \nabla \cdot (\rho v v + P I - BB^T) = -\rho \nabla \Phi,
\]

where \( P = P_{\text{cr}} + P_{\text{th}} + P_{\text{in}} \) and 1 is the unit rank-two tensor. Con-
verting this equation to spherical coordinates and neglecting the
pressure and tension term of subdominant magnetic fields, the ra-
dial momentum flux density is given by \( \rho v^2 + P_{\text{cr}} + P_{\text{th}} \) (Mihalas
& Mihalas 1984). Figure 6 shows that the divergence in the stream
lines \( (\nabla \cdot v < 0) \) corresponds to a shock where kinetic energy is
converted into thermal energy.

The noCR simulation in Fig. 6 shows coherent outflows along the
direction of the spin axis of the disk, which enable flow chan-
nels to open up in the perpendicular direction along which low-
metallicity gas can be coherently accreted to the central disk (Pak-
mor et al. in prep.). Whereas the gas flow in the CRdiffalfven run
more closely resembles the flow pattern of the fiducial AURIGA
model, the direction of the outflows is less ordered and not always
perpendicular to the disk. The CRdiff and CRadv runs on the other
hand show more spherical, slower outflows which shock the inflow-
gas at a distance of \( r \sim 100 - 200 \) kpc, shutting off the coherent
gas inflows to the central galaxy. Therefore, these models exhibit
a more quiescent, hydrostatic atmosphere in the halo in compari-
son to the former two models as can be see from the larger ratios
of \( (P_{\text{cr}} + P_{\text{th}})/P_{\text{in}} \), (yellow colors in Fig. 6). We verified that this
result remains qualitatively similar over the entire redshift range
\( 0 \leq z \leq 1 \) and we quantified the hydrodynamic effect of CRs on
the gas flow with the distribution of radial inflow and outflow velocities
in Fig. 7.

The simulations with CRs show narrower radial velocity dis-
tributions indicating reduced inflow and outflow velocities. This is
the result of the process described above: the more elliptical and
vertically expanded ISM in the CR runs precludes a geometrically
preferred path of least resistance and slows down the outflows in all
directions. Hence there are no coherent outflows forming along the
spin axis in the CR simulations. Because there are low-velocity out-
flows present in nearly all directions in these CR runs, this shocks the
accreting gas and precludes the formation of most inflow channels
that deliver gas from larger distances to the star forming disk.
The suppression of the inflow velocities is strongest for the CRdiff
run because here CRs impact a larger region compared to the other
runs. Interestingly, in the CRdiffalfven simulation we observe re-
duced infall velocities but similar or even larger outflow velocities
in comparison to the fiducial AURIGA model due to the additional
CR pressure-driven winds.

The immediate manifestation of this process is the suppres-
sion of the accretion of gas from larger distances in the CR runs
as displayed in Fig. 8. In this figure we show the distribution of
radial distances at a lookback time of 5 Gyr of the gas which is at
present-day converted into stars of the stellar disk. In the fiducial
AURIGA runs gas is accreted from farther away in comparison to
the CR counterpart simulations. This is the result of the modified
gas accretion pattern on large scales mediated by the effects of the
CRs on the structure of the gaseous disk on smaller scales.

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In summary, in the fiducial AURIGA and the CRdiffalven simulations gas accretes relatively unimpeded from large distances whereas in the CRadv and CRdiff simulations the more spherically symmetric outflows and the CR pressurised gaseous haloes are able to hold up the gas.

4 CIRCUM-GALACTIC MEDIUM

We now turn to analyse the effects of CRs on the CGM properties in the different physics variants. In particular, we focus on how CRs shape the gas density distribution and impact the gas temperature profile of CGM gas by providing additional support pressure which manifests itself in high ratios of CR pressure to thermal pressure. To this extent we show in Fig. 9 from top to bottom maps of the gas surface density, the gas temperature, the ratio of CR pressure to thermal pressure and the value of CR pressure for galaxy Au6. The orientation is chosen such that the gas disk is seen edge-on and the projection depth is the same as the horizontal/vertical extend (200 kpc). For a more quantitative comparison we accompany the maps by profiles of the same quantities for both galaxies in Fig. 10 as indicated by the panels’ titles. For the CGM properties we have chosen logarithmically spaced spherical shells and averaged profiles over the last ten simulation outputs (~ 1 Gyr). Color-coding of the different physics variants is the same as in previous figures.

Looking at the first row of Fig. 9 and comparing the four different physics variants, we find that the CGM gas surface density in the CR runs outside the disk region (R > 50 kpc) is slightly higher in comparison to the fiducial AURIGA model. Most strikingly, the CGM gas density is significantly more spherical within
Figure 9. Maps of CGM properties for the four different physics runs of halo Au6 as indicated in each panel. From top to bottom we show the gas surface density, the gas temperature, the CR-to-thermal pressure ratio and the CR pressure. The orientation of each panel is chosen to view the central disk edge-on and the projection depth of each panel is equal to its width, 200 kpc. Note the smooth gas distribution in the CR runs owing to the additional pressure of the CRs, which however differs considerably for our different variants of CR transport.

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50 kpc in the CRdiff and CRadv runs compared to the fiducial AURIGA and the CRdiffalfven runs. Additionally, the CGM gas density is smoother in the CR runs in comparison to the noCR run. In the next subsections we address these morphological differences and highlight how CRs cause these changes of the CGM structure by investigating each model separately.

4.1 AURIGA – no cosmic rays

The baseline model for our comparison is the fiducial AURIGA model which has a highly structured CGM with cool, high density patches coexisting next to hot low density regions (left panels in Fig. 9, see also van de Voort et al. 2019). The clumpy CGM morphology is further reflected in a broad gas density distribution with tails to large gas densities as shown in Fig. 11. Here we show the density distribution of all four runs in two different concentric shells of width 50 kpc as indicated by the panel titles. The left two panels show galaxy Au6, the right two AuL8.

4.2 Cosmic ray advection

The most simple approximation for CR transport physics is the advection of CRs, which neglects all active CR transport processes. Therefore, all CRs in the CGM have been transported there by outflows. In the CRadv run the CGM is significantly more spherical within 50 kpc, smoother and of slightly lower temperature (right panel of Fig. 9) when compared to the fiducial AURIGA run owing to the additional CR pressure. Especially far away from the disk at $R \sim 50$ kpc the density is slightly enhanced in comparison to the fiducial run. The inclusion of CRs leads to cooler gas temperatures even at distances of $R \sim 100$ kpc where CR pressure is approximately in equilibrium with the thermal pressure. The additional CR pressure smoothes out almost all small-scale high density peaks in the CGM gas which quantitatively leads to a narrower gas density distribution in Fig. 11.

4.3 Cosmic ray diffusion

Allowing for CR anisotropic diffusion alters the properties of the CGM dramatically but with similarities to the CRAdv run. We find that the CGM gas density is even more spherical within 50 kpc compared to the CRAdv run, highly CR pressure dominated and of much cooler temperatures. In this run, CRs are allowed to diffuse and thus are able to affect the CGM at larger distances from the disk, thus the CR pressure dominated halo is larger in size compared to the CRAdv run. Furthermore, the CR pressure contribution is higher compared to the CRAdv run (see also discussion in Sections 3.2 and 6.1) leading to an even smoother CGM (see narrow gas distribution in Fig. 11 for this run). The additional CR pressure which in this run dominates the CGM out to radii of $R \sim (50 - 100)$ kpc supports the gas against gravitational collapse in the absence of thermal pressure support and thus explains the low CGM temperatures which coincide with the regions where CR pressure dominates. Figure 10 shows that in a region of $R < 50$ kpc the CR pressure is a factor of $\sim 10$ larger than the thermal pressure.
4.4 Cosmic ray diffusion with Alfvén wave cooling

The CRdiffalfven model in turn reveals a CGM morphology similar to the fiducial AURIGA model (although with noticeable differences) and shows clear differences in comparison to the CRdiff and CRadv run. In comparison to the AURIGArun (CR runs) the CGM features smoother (more structured) density peaks and the central CGM appears disky. Again, the additional CR pressure explains the smoother gas density compared to the AURIGA model while the Alfvén cooling explains the weaker damping compared to the CRdiff and CRadv runs. Therefore in Fig. 11, the gas density distribution of the CRdiffalfven run lies between the AURIGA model and the other two CR models.

In comparison to the CRdiff run the CGM is much hotter and shows even less cold regions compared to the fiducial run. In fact, the profiles (middle panels in Fig. 10) show that Au6 has a hotter CGM in the CRdiffalfven run compared to the AURIGA run. AuL8 on the other hand shows a similar CGM temperature. The slightly enhanced CGM temperature in Au6 is presumably due to the additional Alfvén heating of the CRs and the fact that Au6 had a recent burst of SF injecting CRs into the CGM. This burst is not present in AuL8. From the lower panels in Fig. 9 we can further...
see that the CR pressure dominates the central regions (except for the disk) while for most of the CGM gas the CR pressure is in equilibrium with the thermal pressure (see also right panels in Fig. 10). This is different to the other CR runs and a manifestation of the Alfvén wave cooling in which the CRs lose an e-folding of their initial energy as they diffuse a scale height into the CGM.

4.5 CGM pressure support

In Fig. 12 we compare in detail the different pressure components (upper panels) and their contribution to the total pressure (lower panels) in the CGM. We compare magnetic pressure (orange), “kinetic pressure” (red), thermal pressure (blue) and CR pressure (green) to the total pressure (black) in spherical shells as we have explained for Fig. 10. From left to right we show the fiducial AU-RIGA noCR, the CRdiffAlfven, the CRdiff and the CRadv runs.

In the region influenced by accretion onto the disk as well as the disk itself (within a few tens of kpc) the gas is rotationally supported (i.e., has a dominating kinetic pressure) in all runs while the other pressure components, i.e. thermal, magnetic and CR pressure, are roughly in equipartitioning each about ~ 10% to the total pressure. In the outskirts at radii larger than $R > 20$ kpc we find that all the runs become increasingly thermal pressure dominated except for the CRdiff run where CR pressure dominates and the thermal pressure becomes negligible. Only close to the virial radius the thermal pressure becomes important again which was already noted by the huge CR pressure dominated halo in Fig. 9. This confirms our previous findings that the cool region in the CGM at these radii is entirely CR pressure dominated.

4.6 Temperature-density relation

Our findings for the structure and morphology of the CGM are summarized in Fig. 13 showing the temperature-density distribution of the CGM gas in the radial range $50 < R < 200$ kpc. While at first glance differences between the fiducial run and the CR runs are small, one notices that the hot phase in the CR runs tends to inhabit regions of lower temperature. In more detail, we find that the CRdiffAlfven runs show a larger spread in temperature at any density compared to the noCR run which shows the importance of CR Alfvén heating. This figure further shows that for the CRdiff run gas at $\rho \sim (10^{-4} - 10^{-3})$ cm$^{-3}$ piles up at a temperature of $T \sim 10^{4.5}$ K. We interpret this as the CR pressure keeping this gas from falling onto the main galaxy. Finally, we find that in the CRadv run the CR pressure causes a different slope of the $\rho - T$ relation for the non-stellar gas at $T \sim 10^4$ K due to the CR pressure support at the disk-halo interface.

Thus, CRs do not only affect the properties of the gas disk as we have seen in Fig. 3 but also the gas morphology of the CGM even at large distances close to the virial radius of the halo. The analysis in this section reinforces the need to better understand the physics of CR transport, as we have shown here that different variants of approximating it have a strong impact on the stellar structure and especially the properties of the CGM.

5 FAR-INFRARED–GAMMA-RAY RELATION

Finally, after establishing the differences and similarities between the three variants of CR transport in our simulations we connect our results to the most directly observable CR proton properties of galaxies, namely hadronic gamma-ray emission that arises from inelastic collisions of CRs with the ambient ISM. To this end we compare in Fig. 14 the gamma-ray luminosities in the Fermi band (0.1 – 1000 GeV) to the SFR for all the main disk galaxies (big black bordered symbols) in comparison to observational data as indicated in the caption. Additionally, we also show gamma-ray luminosities for the dwarf galaxies within the zoom region (small colored dots). Note that these dwarfs are not satellite galaxies as they are not part of the main halo but proxies of field dwarfs in the Local Volume.

The total far-infrared (FIR) luminosity ($8 - 1000 \mu$m) is a well-established tracer of the SFR of spiral galaxies (Kennicutt 1998a) with a conversion rate (Kennicutt 1998b)

$$\frac{SFR}{M_\odot \text{yr}^{-1}} = 1.7 \times 10^4 \frac{L_{8-1000 \mu m}}{L_\odot}$$

(4)

This SFR-FIR conversion assumes that thermal dust emission is a calorimetric measure of the radiation of young stars, and the factor $c = 0.79$ derives from the Chabrier (2003) IMF (Crain et al. 2010). While this conversion is reliable at $L_{8-1000 \mu m} > 10^9 L_\odot$, it becomes progressively worse at smaller FIR luminosities due to the lower metallicity and dust content, which implies a low optical depth to IR photons and invalidates the calorimetric assumption (Bell 2003). We refer the reader to Pfrommer et al. (2017b) for more details on the FIR-to-SFR conversion and to Pfrommer & Enßlin (2004) for the computation of the gamma-ray emission resulting from hadronic proton interactions with the ambient ISM.
We find that at the MW mass scale or vice-versa at a FIR luminosity of \( \sim 5 \times 10^{10} \, L_\odot \) the three CR models predict very different gamma-ray luminosities. Whereas the CRdiffalfven runs are in good agreement with the observational data, especially for NGC253 and M82, the other two models lie above the best fit observational relation of Rojas-Bravo & Araya (2016) and are barely consistent with upper limits from Fermi-LAT (gray open symbols). This is interesting as the same physical models for CR transport and the excitation of CR driven instabilities. There are contrasted with gamma-ray detections from star-forming galaxies (thick symbols) and dwarf galaxies (thin symbols). Upper limits on the observable gamma-ray emission by Fermi-LAT (open gray symbols; Rojas-Bravo & Araya 2016) are compared with gamma-ray detections from star-forming galaxies only (solid black) and with AGN emission (filled gray); data are taken from Ackermann et al. (2012), except for NGC 2146 (Tang et al. 2014) and Arp 220 (Griffin et al. 2016; Peng et al. 2016). Note that only the CRdiffalfven runs fall on the best-fit observational FIR gamma-ray correlation (orange).

Figure 14. Correlation of the gamma-ray luminosity \( (L_{\gamma, 1-100 \, \text{GeV}}) \) with the SFR and with the FIR luminosity \( (L_{\text{FIR}}) \) of star-forming galaxies. We compare our six simulated CR models (differently coloured and symbols de- lineate Au6 and AuL8 haloes) and plot central galaxies (thick symbols) and dwarf galaxies (thin symbols). Upper limits on the observable gamma-ray emission by Fermi-LAT (open gray symbols; Rojas-Bravo & Araya 2016) are contrasted with gamma-ray detections from star-forming galaxies only (solid black) and with AGN emission (filled gray); data are taken from Ackermann et al. (2012), except for NGC 2146 (Tang et al. 2014) and Arp 220 (Griffin et al. 2016; Peng et al. 2016). Note that only the CRdiffalfven runs fall on the best-fit observational FIR gamma-ray correlation (orange).

6 DISCUSSION

6.1 Implications for CR transport in galaxies and the CGM

These analyses of CR feedback have several important implications for CR transport and the excitation of CR driven instabilities. There is evidence that CRs escaping from the disk into the halo excite the streaming instability (Kulsrud & Pearce 1969; Evoli et al. 2018), which limits the drift speed to that of the Alfvén frame, which is \( \sim 30 \, \text{km} \, \text{s}^{-1} \) at the disk-halo interface and increases to \( \sim 300 \, \text{km} \, \text{s}^{-1} \) at the virial radius. This coincides with the diffusion velocity \( v_{\text{diff}} \) up to the injection scale of turbulence \( L_{\text{inh}} \), where \( v_{\text{diff}} = 3 \times 10^8 \, \text{cm} \, \text{s}^{-1} \) is the CR diffusion coefficient and \( L_{\text{inh}} \) is the CR gradient length, justifying our choice of the CR diffusion coefficient.

The CR pressure in the CRdiff model dominates over the thermal pressure at large radii \( r \geq 60 \, \text{kpc} \). In such a quasi-hydrostatic atmosphere the CGM necessarily attains a comparably smooth distribution. By contrast, the CR pressure distribution reflects the dominating modes of transport and cooling processes. Advection of CRs with the galactic outflows along streamlines implies a highly structured CR distribution (Fig. 9). Turbulent mixing in the halo (Pakmor et al. in prep.) causes a smoother CR distribution, in particular at large radii \( r \geq 50 \, \text{kpc} \).

Additionally including CR diffusion smooths the CR distribution considerably as a result of two effects: (i) CR diffusion on cosmological timescales results in a root mean square displacement of 25 kpc \( \sqrt{\tau_{\text{inh}}} \) along the magnetic field lines and (ii) perpendicular transport is achieved through field line wandering. Assuming that the velocity differences between neighboring points follow a Gaussian distribution, we obtain explosive Richardson diffusion with a displacement \( \langle x^2 \rangle \propto t^3 \) up to the injection scale of turbulence (and standard diffusion above this scale), which smoothes the CR distribution in the CGM considerably (Fig. 9).

Most surprisingly, by additionally accounting for CR Alfvén wave losses, the CR pressure distribution becomes highly structured. As CRs diffuse a scale height, they loose an e-folding of their
initial energy. This distance can be substantially increased if CRs are predominantly advected with the gas. As their diffusive transport reaches the effective scale height, they cool quickly and subsequent turbulent mixing is greatly suppressed. Hence they should trace out individual streamlines of the gas in their pressure as well as in the CR-to-thermal pressure ratio (see Fig. 9).

We have seen in Fig. 12 that the CR and magnetic pressures vary by four orders of magnitude but trace each other within a factor of five out to the virial radius. This remarkable finding has severe consequences for the existence of current driven CR instabilities. The condition for exciting the hybrid, non-resonant CR instability is \( \epsilon_\parallel / \epsilon_\perp \geq 2 \epsilon_\parallel / \epsilon_\parallel \) (Bell 2004), where \( \epsilon_\parallel \) is the drift speed of CRs that is close to the Alfvén speed as explained above. Because our CR and magnetic energy densities closely trace each other, the Bell instability is not excited and hence, no additional growth of the magnetic field is expected from this plasma effect. This also implies that the adopted diffusion coefficient remains valid and is not lowered to the classical Bohm limit due to strong Bell fluctuations, which would scatter CRs off magnetic irregularities at every gyro orbit. This fast CR scattering would manifest itself as a much reduced CR diffusion coefficient by about seven orders of magnitudes, which would effectively imply a transition to the CRadv model.

6.2 Comparison to previous work

6.2.1 Effects on the central galaxy

In this study we found that CRs have little effect on global galaxy properties such as stellar mass and SFR. All our galaxies exhibit a rotationally supported gas disk dominated by the kinetic pressure (\( R \geq 75 \) kpc). The CRdiff run additionally shows a transition region at the disk CGM interface (20 < \( R < 75 \) kpc) where CRs dominate the pressure budget. On the other hand, in the CRadv run this transition region shows an equilibrium of CR pressure with the thermal and the kinetic pressure. This agrees qualitatively with the recent findings of Hopkins et al. (2019) despite the large differences in the diffusion coefficients used (this work: \( \kappa_\parallel = 1 \times 10^{28} \) cm\(^2\) s\(^{-1}\) vs. “best-fit” \( \kappa_\parallel = 3 \times 10^{28} \) cm\(^2\) s\(^{-1}\) in FIRE). In fact, we believe that the choice of such a large diffusion coefficient in the FIRE simulations is predicated upon the particular ISM model in combination with their inability to accurately follow CR transport in the multi-phase ISM, which requires modelling the appropriate wave damping terms in the different phases of the ISM as we will lay out below. Note that our choice for \( \kappa_\parallel \) is justified by CR propagation studies (Kissmann 2014; Jöhnnesson et al. 2016; Evoli et al. 2017) and in line with other simulation analyses of galaxies forming in a cosmological environment (e.g. Salem et al. 2016, who follow the hydodynamics equations without magnetic fields and use an isotropic diffusion coefficient of \( \kappa_{\mathrm{iso}} = 3 \times 10^{28} \) cm\(^2\) s\(^{-1}\) equivalent to \( \kappa_\parallel = 1 \times 10^{28} \) cm\(^2\) s\(^{-1}\) for turbulent magnetic fields). A diffusion coefficient for CRs in the Galactic disk can be estimated from CR propagation models and observations (Strong & Moskalenko 1998; Ptuskin et al. 2006; Ackermann et al. 2012; Tabatabaei et al. 2013). In the Galactic halo CRs have a scale height of \( \sim 3 \) kpc and their residency time in the thick disk is inferred to be \( \tau \sim 3 \times 10^3 \) yr as obtained from measurements of the ratio of secondary-to-primary CR nuclei (Lipari 2014). Thus the diffusion coefficient is given by \( \kappa_{\mathrm{iso}} \sim H^2/(3\tau) \sim 3 \times 10^{28} \) cm\(^2\) s\(^{-1}\) which is a factor of 30 smaller than the assumptions made in the FIRE simulations. The reason why the FIRE simulations need to adopt such high diffusion coefficients follows from the different assumptions made for the star forming gaseous phase. In the AURIGA model the star forming phase is governed by an equation of state (Springel & Hernquist 2003) resulting in a relatively smooth gas distribution where stars form at gas densities of \( n_{\mathrm{th}} \geq 0.13 \) cm\(^{-3}\).

On the other hand, in the FIRE simulations the star formation threshold is chosen to be orders of magnitude higher (\( n_{\mathrm{th}} \approx 100 \) or \( n_{\mathrm{th}} \approx 1000 \) cm\(^{-3}\) depending on the resolution level, Hopkins et al. 2018, table 3) which in turn results in very dense star forming regions where the gas is allowed to cool down to temperatures of \( \sim 10 \) K.\(^1\) Thus, in order for the CRs to escape these dense star forming regions without loosing all their energy caloritically and overproducing the hadronic gamma-ray luminosity in MW-like galaxies, the diffusive escape time, \( \tau_{\mathrm{diff}} \), has to be much shorter than the hadronic loss time, \( \tau_{\mathrm{rad}} \). Adopting typical sizes of star forming regions of \( L = 200 \) pc and typical densities of \( n = 300 \) cm\(^{-3}\) (Hopkins et al. 2018), we obtain \( \tau_{\mathrm{diff}} \approx L^2/k_{\parallel} \approx 40 \) kyr/\( k_{29.5} \) (where \( k_{29.5} = 3 \times 10^{28} \) cm\(^2\) s\(^{-1}\) which is indeed a factor of two shorter than \( \tau_{\mathrm{rad}} \approx 1/(\nu_{\gamma}\sigma_{\mathrm{p}}) \approx 80 \) kyr.

Physically, ion-neutral damping would strongly damp the self-excited Alfvén waves so that CRs become weakly coupled to the largely neutral gas and could escape almost ballistically at their intrinsic speed of light from these regions (Wiener et al. 2017). Once they enter the warm-hot phase of the ISM, they couple again to the gas (because of the weaker wave damping processes such as nonlinear Landau damping) so that they are transported at the Alfvén wave speed, which corresponds to an escape distance. The reason for this is not entirely clear but the very different feedback implementations and resolution effects might certainly play a role. These earlier results analysed simulations of worse resolution compared to the ones used here. Furthermore, the fiducial model used in that study results in a very compact stellar disk of unrealistic size. In contrast to this, the AURIGA-CR models start out from galactic disks of realistic size and mass because the wind feedback of the AURIGA moCR runs was tuned to reproduce MW-like galaxies. We discuss the uncertainties of the wind model in more detail in the next section.

Our results are in stark contrast to the results from Salem et al. (2014) where the stellar disk grows in size when CRs are considered. The reason for this is not entirely clear but the very different feedback implementations and resolution effects might certainly play a role. These earlier results analysed simulations of worse resolution compared to the ones used here. Furthermore, the fiducial model used in that study results in a very compact stellar disk of unrealistic size. In contrast to this, the AURIGA-CR models start out from galactic disks of realistic size and mass because the wind feedback of the AURIGA noCR runs was tuned to reproduce MW-like galaxies. We discuss the uncertainties of the wind model in more detail in the next section.

\(^1\) For such a star forming gas the Jeans mass is \( \simeq 3 M_\odot \), which would need to be resolved by \( \approx 64 \) mass resolution elements to obtain a converged answer (Truelove et al. 1997). However, the adopted target gas mass in the FIRE simulations is \( \approx 5 \times 10^5 M_\odot \), implying that star forming regions in the FIRE setup may suffer from insufficient resolution and may be subject to numerical fragmentation.
6.2.2 Effects on the circum-galactic medium

The most noticeable effect of CRs in the AURIGA simulations is on the structure and morphology of the CGM. Whereas the overall baryonic mass in the CGM is not drastically effected (see density profiles in Fig. 10), the additional CR pressure affects the small scale density and temperature distribution of the CGM. In particular our CRdiff model has a smoother and cooler CGM which is maintained by the additional CR pressure which smoothes out small-scale high density clumps in the CGM and supports the gas at lower temperatures against gravity. These findings are qualitatively similar to earlier results presented in the literature (e.g. Salem et al. 2014, 2016; Chen et al. 2016).

The findings that the CGM becomes smoother and slightly cooler when diffusing CRs are included is consistent with the results of small scale ISM simulations of the galactic disk using stratified boxes (Girichidis et al. 2016, 2018; Simpson et al. 2016). In particular, Girichidis et al. (2018) finds that the CR pressure inside the disk (z ≤ 1 kpc) is largely in equilibrium with the thermal pressure as is the case for all our CR runs (compare Fig. 3). At distances larger than that (z ≥ 1 kpc), the CR pressure starts to dominate over the thermal pressure with values of $P_{\text{cr}}/P_{\text{th}} = 10 – 100$ in good agreement with our results. Thus, despite the approximations of our ISM model and the comparatively lower resolution results on the scales studied here, the simulations appear to be converged.

By contrast, our CRdiffAlfven model shows a warmer CGM in comparison to the model without CRs (noCR) and in strong contrast to earlier work presented in the literature (e.g. Salem et al. 2014, 2016; Chen et al. 2016). As explained above, the reason is the additional CR Alfvén wave cooling term that emulates CR energy losses as they are resonantly exciting Alfvén waves which scatter their pitch angles (angle between their momentum and mean magnetic field vectors). This causes them to isotropise in the Alfvén wave frame and to stream with the Alfvén velocity along the local direction of the magnetic fields (Wiener et al. 2017). Whereas this approximation is justified as long as CR streaming and diffusion fluxes match each other, this cannot be guaranteed at all times due to the dispersive mathematical nature of the diffusion operator. Clearly more work is needed to confirm this finding and to better understand the final state of the CGM in the presence of streaming CRs. On the contrary, recent results by the FIRE simulations suggest that CRs are able to reduce the CGM temperature from $\sim 10^5$ K to $\sim 10^4$ K (see figure 7 in Ji et al. 2019) by providing enough pressure support. Our simulations do not support such a drastic change in CGM temperature as we have shown in Fig. 13. In fact, a complete suppression of the hot phase as in the FIRE model has a smoother and cooler CGM which is maintained by the additional CR pressure and thus the Alfvén waves which scatter their pitch angles (angle between their momentum and mean magnetic field vectors). This causes them to isotropise in the Alfvén wave frame and to stream with the Alfvén velocity along the local direction of the magnetic fields (Wiener et al. 2017). Whereas this approximation is justified as long as CR streaming and diffusion fluxes match each other, this cannot be guaranteed at all times due to the dispersive mathematical nature of the diffusion operator. Clearly more work is needed to confirm this finding and to better understand the final state of the CGM in the presence of streaming CRs. On the contrary, recent results by the FIRE simulations suggest that CRs are able to reduce the CGM temperature from $\sim 10^5$ K to $\sim 10^4$ K (see figure 7 in Ji et al. 2019) by providing enough pressure support. Our simulations do not support such a drastic change in CGM temperature as we have shown in Fig. 13. In fact, a complete suppression of the hot phase as in the FIRE simulations is at odds with X-ray observations of the MW hot halo ( $\sim 10^6$ K, Fang et al. 2013).

The most likely reason for this is the implementation of feedback in FIRE, which is very explosive and could cause a quenching of their magnetic dynamo. This yields to saturation at a low level with a magnetic energy density that is a factor of 100 below our results. Note that our magnetic field distribution matches Faraday rotation measure data of the MW and external galaxies (Pakmor et al. 2018). The lower magnetic field strength causes the Alfvén speed $v_{\text{A}} = B/\sqrt{4\pi\rho}$ to be ten times smaller and hence, also reduces the CR Alfvén wave cooling rate, $|\mathbf{B} \times \nabla P_{\text{Alfven}}|$ by the same factor. Hence, the FIRE runs represent an extreme version of our CRdiff model, in which the CR Alfvén wave cooling is nearly absent.

6.3 Modelling uncertainties

The results obtained in this paper are subject to a number of physical modelling uncertainties which we discuss below.

6.3.1 The AURIGA feedback model

In this study CRs are modelled on top of the AURIGA galaxy formation model which has been calibrated to reproduce MW-like galaxies without the inclusion of CRs. We have kept any “free” parameter in the sub-grid model as in the AURIGA model and added the CR physics on top of this. Therefore, the comparably small impact of CR physics on global galaxy properties such as the total stellar mass or SFR (as opposed to previous findings where CRs showed strong impacts) might be due to the already efficient feedback implementation of the AURIGA model without CRs. Here, the biggest uncertainty is the effect of the wind model coupled with the CR feedback. In the AURIGA model the details of the wind model are calibrated to reproduce observed galaxy properties without out the additional effects of CRs. In this study, we add CR feedback on top of the already calibrated feedback model of AURIGA without re-tuning any parameters. Whereas this strategy allows us to cleanly single out the effects of CRs, one could imagine that the calibrated AURIGA model might already account for some of the effects CRs might have on galaxy formation. Therefore, the exact choice of parameters for the wind model in combination with the effects of CRs might change the amount of angular momentum losses as observed in our study. There might exist a different combination of wind model parameters and CR feedback model in which the CGM flow is less affected by the CRs and thus the angular momentum losses are reduced. However, the cause of the different angular momentum build-up in the three CRs variants is the modified morphology of the disk halo interface and we expect the basic effects to be robust. Nevertheless, unless the parameters of the wind model are derived from either observations or theoretical considerations the wind model presents a considerable systematic uncertainty.

6.3.2 The ISM model

Our simulations adopt a pressurised ISM which even in the stellar disk is relatively smooth without high density, low temperature peaks (e.g. Marinacci et al. 2019, Figs. 9 and 10). Transforming to a multi-phase ISM will effect how CRs escape dense star forming regions and thus how they impact the dynamics of the ISM. Most importantly, recent modeling of CR data suggests that CRs below 200 GeV that carry most of the CR pressure are streaming with the Alfvén velocity and are diffusively transported at higher energies (Evoli et al. 2018). Hence, we need to model CR streaming in the self-confinement picture where CRs resonantly excite Alfvén waves to accurately model their transport in galaxies and the CGM using the two-moment method (Thomas & Pfrommer 2019). Following the evolution equation of small-scale resonant Alfvén wave energies provides a means to self-consistently model CR diffusion in the Alfvén wave frame. This will enable us to simultaneously account for the weaker coupling of CRs in the cold phase ($T < 10^4$ K) due to increased ion-neutral damping and the stronger dynamical coupling in the warm-hot phases due to the prevalent non-linear Landau damping (e.g. McKenzie & Bond 1983) and turbulent damping processes (e.g. Farmer & Goldreich 2004; Yan & Lazarian 2004).
6.3.3 The CR transport models

Another fundamental uncertainty is given by the details of the CR transport physics and its numerical implementation. To explore the influence of CR transport on galaxy formation we decided to adopt three different variants of CR transport and focused our analysis on the question of how each variant impacts the stellar and gaseous properties. These models result in qualitatively similar global trends, but show that structural properties differ between each of the CR variants. As expected, our CRdiffalfven model that emulates CR streaming gave the most realistic results in terms of stellar and gaseous disk properties as well as for the CGM. In particular, the resulting gamma-ray emission (see Fig. 14) appeared to be an important discriminant of the studied CR models.

6.3.4 Cosmological variance of accretion histories

In this study we have focused on analysing the effects of CR physics in cosmological simulations. Additionally to the different CR transport physics the two galaxies in these kind of simulations are further affected by the different accretion histories. For example, AuL8 undergoes a major merger at a lookback time of \( \sim 6 \) Gyr whereas Au6 has a very quiet merger history at low redshift. Thus, there are natural differences in the evolution and properties between the two haloes complicating the separation of the effects of CRs and cosmological accretion history. On the other hand, CRs do not only affect the main galaxy but also the merging satellites and thus a complete picture of their effects can only be gained by studying a large cosmological volume, which samples the complete galaxy population.

6.3.5 Numerical resolution study

Convergence of galaxy properties across different levels of numerical resolution is difficult to achieve in galaxy formation simulations and poses an additional challenge in understanding the physics of galaxy formation. Ideally, the outcome of a simulation should only depend on the modelled physics and not on numerical resolution. In section 6 of Grand et al. (2017) it has been shown that our baseline model, the AURIGA model without CRs, is numerically well converged. We have run additional 8 simulations with a factor of 8 and 16 lower in mass resolution in order to test the numerical robustness of our results. While we detail the resolution dependence of our results in Appendix D, here we summarise the main results: stellar and halo masses of the central galaxies are well converged across different resolution levels (see Table D1) and we have verified that all our results and conclusions do not depend on resolution. Especially our main findings are numerically converged: those include the more compact stellar disks (see Fig. D2 in the Appendix) mediated by the modified accretion flow in the CR runs as well as the gas disks inflated by CR pressure and the smoother CGM in the CRadv and CRdiff models in comparison to the other two models (cf. Fig. D1 and the upper row of Fig. 9). Thus, our simulations are well suited to study the effects of CRs in cosmological simulations as the evolution of the galaxies only depends on our physical modelling and not on numerical resolution.

7 CONCLUSIONS

In this work we set out to study the effects of CRs on the formation of MW-like galaxies in a cosmological context. To this extend we have performed eight magnetohydrodynamical simulations in the context of the AURIGA project (Grand et al. 2017) with three different models of varying complexity for the physics of CR transport. All simulations are performed with the second-order accurate moving mesh code Arepo (Springel 2010; Pakmor et al. 2016a) for magnetohydrodynamics. The galaxy formation model includes detailed models for gas cooling and heating, star formation as well as stellar and AGN feedback. Additionally, the simulations include the following CR physics: the simplest model advects CRs with the gas flow (CRadv), a more complex variant additionally follows the anisotropic diffusion of CRs parallel to the magnetic field (CRdiff) while in the most complex model CRs are further allowed to cool via the excitation of Alfvén waves (CRdiffalfven), attempting to emulate the transport process of self-confined CR streaming.

We have studied in detail the properties of the central galaxy and the CGM and compared model predictions from the CR runs to the fiducial AURIGA model. Bulk galaxy properties are only weakly affected by CRs, whereas the morphology and angular momentum distribution of our galaxies as well as the properties of the CGM are sensitive to the details of the CR physics implementation. Our conclusions are summarized as follows:

- Galaxy properties like the total stellar mass, SFR or gas mass are largely unaffected by CRs and stable across different physics variants. While previous works have found that CRs are able to suppress star formation in isolated galaxy simulations, our cosmological simulations show that the SFR is largely unaffected by CR feedback (see Fig. 2). Note that this could be partially due to the already efficient feedback in AURIGA, which can in principle mask some of the feedback effects CRs would otherwise have.
- Comparing structural parameters of the galaxies such as disk sizes, disk-to-total stellar mass ratios or gas disk morphology we find strong differences between the simulations that include CRs and the fiducial AURIGA model. The CRadv and CRdiff models result in more compact, bulge dominated disks which show thicker and smoother gas disks, in which the vertical force balance is dominated by the CR pressure (see e.g., Figs. 1 and 3). A similar reduction of stellar disk size is also found by the FIRE group in their simulations including CR feedback. In contrast, the stellar and gaseous disks in the CRdiffalfven model have disk sizes which lie between the fiducial results and the more extreme CR models (e.g., the left panel of Fig. 4). We find that the magnetic field strength and morphology is similar in all our runs with a value of the order of \( \sim 10\mu G \) Pakmor et al. (1) that is consistent with MW observations, see 2018) so that our magnetic energy density is roughly 100 times larger than those obtained with the FIRE simulations (e.g. Figs. 3 and 19 of Hopkins et al. 2019).
- The interplay of CRs and the wind feedback model strongly affects the gas flow patterns in the CGM (Figs. 6 and 7). The more compact, bulge dominated disks in the CR simulations cause the outflows to become more spherically symmetric in comparison to the fiducial AURIGA run (Fig. 6) and thus alter the angular momentum acquisition in the cosmological runs. In this way the action of CR feedback in the star forming disk changes the outflow geometry and suppresses the baryonic accretion of high angular momentum gas, especially at late cosmic times (Fig. 5). As a consequence, the gas disks in the CR runs are smaller in size as is highlighted in the left panels of Fig. 4.
- On larger scales, CRs strongly affect the properties of the CGM. The advection and diffusion models exhibit a smoother and partly cooler CGM (Figs. 9 and 10) where the additional CR pressure is able to stabilise the CGM against gravitational collapse com-
pensating for the missing thermal pressure support at lower CGM temperatures. These runs therefore show large ($R \sim 50$ kpc) CR pressure contributions in the haloes. In contrast, the Alfvén wave model is only CR pressure dominated at the disk-halo interface and the CRs come into equilibrium with the thermal pressure as they are advected into the halo along stream lines of the galactic winds (see also Fig. 12). As CRs are actively transported across an effective scale height, they quickly cool, which greatly suppresses further turbulent mixing and causes a highly structured CR pressure distribution in the CGM (Fig. 9). This in turn causes a structured density and temperature distribution in the CGM, which maintains large volumes at thermally unstable temperatures of $10^{5} K$ (Fig. 13) which is warmer than the cool ($\sim 10^{3} - 10^{5} K$) CGM gas found in the CR FIRE simulations (see Fig. 7 in Ji et al. 2019).

- The magnetic and CR pressures trace each other within a factor of five out to the virial radius (Fig. 12). This implies that there is not enough free energy available to drive the hybrid, non-resonant CR instability (Bell 2004), which would require the CR-to-magnetic energy ratio to be larger than $2c/\nu_{B} \sim 10^{3}$...$10^{6}$ where $\nu_{B}$ is the drift speed of CRs that is close to the Alfvén speed. Excitation of the Bell instability would imply fast CR scattering, a much reduced CR diffusion coefficient by about seven orders of magnitudes and effectively transition to the CRadv model.

- There are active ongoing efforts in developing efficient and accurate CR magneto-hydrodynamical schemes (Jiang & Oh 2018; Thomas & Pfrommer 2019) to compute the CR feedback effects in cosmological simulations. To this end, direct observables are invaluable in constraining effective CR transport models, provided the approximations used for CR transport and the ISM are consensurate and not inconsistent. In Fig. 14 we compare the gamma-ray luminosity from hadronic CR interactions with the ISM of our models to observations of local galaxies. We find that the CRdiff/adv model agrees well with observed relations whereas the CRdiff and CRadv produce higher gamma-ray luminosities at the MW mass scale compared to observations. Our comparison here presents a first step towards understanding the effects of CRs on cosmological galaxy formation, but further work in this direction is needed to constrain valid CR transport coefficient and prevailing transport processes.

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Cosmic rays in cosmological simulations

In Fig. A1 we show azimuthally averaged surface density fits to the stellar disk of the eight simulations at redshift $z = 0$. Surface density profiles are created for all the stellar mass within ±5 kpc of the mid plane in the vertical direction. The profiles are simultaneously fit with a Sérsic (1963) (red dashed curve) and exponential (blue curve) profile using a non-linear least squares method. Resulting fit values for the disk scale length, $R_d$, the bulge effective radius, $R_{\text{eff}}$ and the bulge Sérsic index, $n$, are given in each panel. This figure shows that the CRadv and CRdiff runs result in more compact bulge dominated galaxies whereas the CRdiffallven runs result in a disk dominated galaxy more similar to the fiducial AURIGA run. From the fits we derive disk-to-total mass ratios (D/T) which are given in Table 1 in the main text.

APPENDIX A: SURFACE DENSITY FITS

Table 1 in the main text.
APPENDIX B: VERTICAL PROFILES

We have created vertical profiles similar to the radial profiles shown in Fig. 4 for the gas density, the magnetic field strength, the CR pressure and the gas thermal pressure in the central galaxy. We select all Voronoi cells in a cylinder of radius $r = 30$ kpc and height $z = \pm 10$ kpc and show the data in $30$ bins linearly spaced in $z$.

APPENDIX C: ANGULAR MOMENTUM DISTRIBUTION

Figure C1 shows the distribution of gas angular momentum at 8 different points in time for the tracer particles ending up in stars at present-day. This highlights how the angular momentum of the accreted gas changes over time for the different CR runs compared to the noCR run. Upper panels show galaxy Au6 and lower panels AuL8, respectively. At early cosmic times ($t_{\text{lookback}} \gtrsim 12$ Gyr, yellow colors) all simulations show a symmetric distribution of specific angular momenta around $l_\parallel = 0$ kpc km s$^{-1}$. Then, at lookback times of about 8 Gyr (greenish colours) all runs have accreted gas with higher angular momentum of values $l_\parallel \sim 1.5 \times 10^3$ kpc km s$^{-1}$. The noCR and the CRdiffalfven runs keep acquiring high angular momentum gas also at low redshift (smaller lookback times, blue colours) whereas the angular momentum gain in the CRdiff and CRadv runs is suppressed. Thus, at redshift zero, the angular momentum distribution in the latter cases peaks around $l_\parallel \sim 1 \times 10^3$ kpc km s$^{-1}$ and at $l_\parallel \gtrsim 2 \times 10^3$ kpc km s$^{-1}$ in the former cases (see vertical thin lines).

APPENDIX D: RESOLUTION STUDY

Our study shows that CRs strongly affect the CGM and the gaseous and stellar properties of the galactic disks. In combination with the model for the wind feedback, this results in a more hydrostatic gas halo and a modification of the gas accretion onto the central galaxy.

Table D1. Virial mass, $M_{200}$ and stellar mass, $M_{\text{star}}$ for the main galaxy across three different resolution levels for all four models.

| Resolution Level | noCR | CRdiffalfven | CRdiff | CRadv |
|------------------|------|--------------|--------|-------|
| level 4          |      |              |        |       |
| $M_{200} \times 10^{12} M_\odot$ | 1.02 | 1.06 | 1.07 | 1.09 |
| $M_{\text{star}} \times 10^{10} M_\odot$ | 4.36 | 5.54 | 5.81 | 6.19 |
| level 5          |      |              |        |       |
| $M_{200} \times 10^{12} M_\odot$ | 1.03 | 1.02 | 1.07 | 1.06 |
| $M_{\text{star}} \times 10^{10} M_\odot$ | 4.24 | 4.19 | 5.87 | 5.80 |
| level 6          |      |              |        |       |
| $M_{200} \times 10^{12} M_\odot$ | 0.94 | 0.99 | 1.00 | 1.03 |
| $M_{\text{star}} \times 10^{10} M_\odot$ | 3.78 | 2.84 | 3.44 | 3.71 |

This effect is already present at resolution levels 5 and 6 (at a factor of 8 and 16 lower in mass resolution) and does not change at our fiducial resolution at level 4.

We would like to emphasize that we do not change any subgrid parameters for the ISM, wind feedback and CR physics when we change the numerical resolution. Hence, we do not expect to resolve new physics with increasing resolution but we aim at better resolving the poorly resolved regions at the disk-halo interface and the gas accretion and flow pattern in the CGM (i.e., we study convergence of our numerical model). For example, Fig. D1 shows the gas surface density maps of the four models at resolution level 5. These are the same panels as in the upper row of Fig. 9 in the main text. The more compact and inflated gas disks in the vertical direction as well as the smoother CGM in the CRadv simulations are clearly visible. We find that at lower resolution (i.e., at resolution levels 5 and 6) this leads to the same hydrostatic CGM properties we have found for our fiducial resolution (level 4) in Sections 3 and 4.

We further quantify the effects of resolution on the properties of the central galaxy such as the size and morphology of the stellar and gaseous disk. To this extent we compare in Fig. D2 radial pro-

Figure A1. Face-on stellar surface density profiles for all simulations at $z = 0$ (black dots). The four models of Au6 are shown in the upper row, AuL8 in the bottom row. The profiles are simultaneously fit with a Sérsic (1963) (red dashed curve) and exponential (blue curve) profile. The total fitted profile is indicated by the black curve. Resulting fit values for the disk scale length, $R_d$, the bulge effective radius, $R_{\text{eff}}$ and the bulge Sérsic index, $n$, are given in each panel. The CRdiff and CRadv models of AuL8 are well fitted by a pure Sérsic profile.
files of the stellar surface density (upper panels), the gas mass density (middle panels) and the ratio of CR-to-thermal pressure (bottom panels) for all three resolution levels. Stellar and gaseous disk properties are in general well converged across all resolution levels. However, we note some differences of the central stellar and gas density in the lowest resolution simulations (level 6) for the CRadv and CRdiff models. For the fiducial AU-RIGA model, on the other hand, we see that the radial density profiles of the lowest resolution simulations results are slightly steeper. In the CRdiffalfven model the stellar surface density profile is remarkably similar across all resolution levels while the gas density profiles of level 5 and 6 slightly differ from the highest resolution level. However, we note that these differences at various resolution levels are smaller than the differences found between the two haloes studied in the main text. This argues that cosmic variance causes larger differences and that our models are sufficiently nu-
Figure D1. Gas surface density maps of Au6 level 5 for all four models as indicated in the panels. Orientation and projection depth are as in Fig. 9.

Figure D2. Comparison of the profiles of stellar surface density (upper panels), gas density (middle panels) and the CR-to-thermal pressure ratio (bottom panels) of the galaxy Au6 at three different resolution levels (as indicated in the figure legends).
merically converged, not only for global quantities but also for all radial profiles of interest.

Most importantly for our study is that the implementation of CR physics is converged across different resolution levels. In the bottom panel of Fig. D2 we compare the ratio of CR-to-thermal pressure across the three resolution levels and find overall good agreement between the results. The biggest differences appear for the CRadv run where the $X_{\text{cr}}$ values at large radii are higher for level 5 and level 6 in comparison to the fiducial level 4 run.

To conclude, we find that the simulations presented here show good numerical convergence of stellar, gaseous and CR properties across three levels of resolution. This suggests that our models are well posed to study the effects of CRs on the evolution of MW-like galaxies because the simulation properties solely depend on physical parameters and not on numerical resolution.