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nIFTy Galaxy Cluster simulations VI: The gaseous outskirts of galaxy clusters

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ABSTRACT

Galaxy cluster outskirts provide an intriguing testbed for theories of cosmic structure formation and galaxy formation, marking the transition from the mildly non-linear cosmic web to the highly non-linear, virialised, cluster environment. It is here that cluster environment begins to influence the gaseous content of galaxies, and here we expect to find shocks in the intra-cluster medium (ICM) associated with infalling galaxy groups and gas accretion from the cosmic web. Using a suite of cosmological hydrodynamical zoom simulations of a single galaxy cluster from the nIFTy comparison project, we investigate what current state-of-the-art astrophysics codes predict for ICM structure, kinematics, and thermodynamics in cluster outskirts. These include non-radiative simulations, which probe differences in schemes for solving the equations of hydrodynamics, and full physics simulations, which probe differences in galaxy formation modeling. Our analysis reveals that the ICM in cluster outskirts is relatively insensitive to both choice of code and galaxy formation prescription. Spherically averaged gas density profiles follow the underlying dark matter, scaled by the cosmic baryon fraction, while temperature and velocity profiles show signatures of strong shocks, short-lived interior to the virial radius and longer-lived at larger radii. These shocks can be understood as the combined response to infalling gas accreted along filaments, which we demonstrate by reconstructing the local cosmic web, and along the orbits of accreted substructures. Our results make clear that cluster outskirts are shaped by large-scale gravitational dynamics and strong, inefficiently radiating, shocks.

Key words: methods: numerical – galaxies: clusters: general – galaxies: formation – galaxies: evolution – cosmology: theory

1 INTRODUCTION

Galaxy clusters are the most massive virialised objects in the Universe, and are widely used as a powerful test for theories of dark

matter, dark energy, and galaxy formation, and for estimation of cosmological parameters (e.g. Kravtsov & Borgani 2012; Mantz et al. 2014; Cataneo et al. 2015; Mantz et al. 2016; Morandi & Sun 2016; Sartoris et al. 2016). They are also striking signposts of the cosmic web, anchoring the large-scale network of filaments, sheets, and voids (e.g. Vazza et al. 2011; Durret et al. 2016). This cosmic

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web manifests itself in the spatial and kinematical distribution of cluster galaxies (e.g. Knebe et al. 2004; Bailin & Steinmetz 2005; Pimblet 2005; Hao et al. 2011; Song & Lee 2012; Tempel et al. 2015), but its imprint is also evident from the presence of shocks in the intra-cluster medium (ICM), especially at large cluster-centric radius (e.g. Tozzi et al. 2000; Ryu et al. 2003; Vazza et al. 2011). As gas falls onto the cluster from the warm ($T \lesssim 10^4$ K) diffuse intergalactic medium (IGM), it is accelerated to peculiar velocities of order $\sim 1000 \text{ km s}^{-1}$ and produces strong shocks that give rise to various forms of non-thermal emission, ranging from high energy X-rays and γ -rays (e.g. Keshet et al. 2003, 2004; Zandanel et al. 2014), to radio continuum emission in the form of synchrotron radiation as electrons spiral along magnetic fields (Hoeft et al. 2008; Vazza, Brunetti, & Gheller 2009).

This has led to considerable interest in the utility of the outskirts of galaxy clusters as a probe of the “Warm-Hot Intergalactic Medium” (hereafter, WHIM), which cosmological hydrodynamical simulations predict should trace the cosmic web as a hot ($10^5 - 10^7$ K), diffuse plasma that constitutes about 50 per cent of the cosmic baryon budget (e.g. Cen & Ostriker 1999; Davé et al. 2001). Their low densities imply that these baryons will be challenging to detect. Nevertheless, the presence of the WHIM is hinted at by soft X-ray excesses in the outskirts of Coma (e.g. Finoguenov et al. 2003), in filaments connecting Abell 222 and Abell 223 (e.g. Werner et al. 2008), and in X-ray emission in the vicinity of Abell 1750 (Eckert et al. 2015) and the merging Abell 1750 (Bulbul et al. 2016); by an excess of diffuse, low surface brightness radio continuum emission around 11 X-ray bright Abell clusters (Farnsworth et al. 2013); and, statistically, by measurements of Lyman- α and OVI absorption along a QSO sightline intersecting several massive galaxy cluster pairs (Tejos et al. 2016), and measurements of the thermal Sunyaev-Zel’dovich effect from gas filaments (Tanimura et al. 2017; de Graaff et al. 2017).

Efforts to initially detect and subsequently map the WHIM, especially in the outskirts of galaxy clusters, will intensify in coming years, with the advent of next generation galaxy surveys with the Square Kilometre Array in the radio continuum tracing synchrotron emission (e.g. Brown 2011; Giovannini et al. 2015; Vazza et al. 2015), and X-Ray Imaging and Spectroscopy Mission (XRISM) (e.g. Tashiro et al. 2018) and ATHENA (e.g. Nandra et al. 2013) in X-ray. For this reason, it is timely to assess predictions for the gaseous outskirts of galaxy clusters in the current generation of state-of-the-art cosmological hydrodynamical simulations predict. As already noted, cosmological hydrodynamical simulations have played a pivotal role in guiding our understanding of what the properties of the WHIM are likely to be (e.g. Cen & Ostriker 1999; Davé et al. 2001) and how it might be detected observationally (e.g. Bertone et al. 2010a,b; Araya-Melo et al. 2012; Tepper-García et al. 2012). More broadly, they will provide the theoretical framework for interpreting the astrophysical implications of future observations. It is therefore important to understand how robust simulation predictions are - how sensitive are they to the algorithms used, and to the assumptions underpinning how galaxies form and evolve?

In this paper, we address these important questions by using a cosmological zoom simulation of a massive galaxy cluster run with a range of state-of-the-art astrophysical codes, spanning mesh- and SPH-based schemes, as part of the nIFTy galaxy cluster comparison (see Sembolini et al. 2016a, and subsequent papers). We investigate how the spatial, kinematical, and thermodynamical properties of the cluster are influenced by the approach to solving the equations of hydrodynamics, as well as the assumed galaxy formation prescription. Previous papers in this series (e.g. Sembolini et al. 2016a;

Cui et al. 2016; Sembolini et al. 2016b) have already demonstrated that there are significant differences between code predictions in the inner parts of clusters, reflecting in part the choice of hydrodynamics solver but also, importantly, the choice of galaxy formation prescription. However, we expect the outskirts of galaxy clusters to differ markedly from their cores, with lower gas and galaxy densities, and cooling times that are comparable to the Hubble time. As much is hinted at in some of the results of Cui et al. (2016), but we study cluster outskirts in much greater detail, combining spherically averaged radial gas profiles with analysis characterising cluster substructure and the larger-scale cosmic web. We include codes that are representative of the different schemes for solving the equations of hydrodynamics (mesh, “classic”, and “modern” SPH) and we combine results from both non-radiative and full physics runs, with and without AGN.

The structure of this paper is as follows. In §2, we describe briefly the simulations we have used, including how they were set up and their bulk properties at $z=0$. In §3, we present our main results – spherically averaged radial profiles of gas density, temperature, and kinematics, and the evidence for accretion shocks; the origin of these accretion shocks, as traced by the cluster’s assembly history, the dynamics of massive gas-rich substructures, and the cosmic web; and likely emission in X-ray and radio continuum. Finally, we summarise our results in §4 and comment on how these results can be used to support observational campaigns to detect the WHIM.

2 THE DATA

2.1 The simulations

Our analysis focuses on a suite of cosmological hydrodynamical zoom simulations of a single galaxy cluster – cluster 19, drawn from the *MUSIC*¹ suite (Sembolini et al. 2013; Biffi et al. 2014; Sembolini et al. 2014) and identified originally in the *MultiDark*² 2048³ particle parent cosmological N -body simulation (Prada et al. 2012). The simulations assume cosmological of $\Omega_m=0.27$ for the total matter density; $\Omega_b=0.0469$ for the baryon density; $\Omega_\Lambda=0.73$ for the dark energy density; a power spectrum normalisation of $\sigma_8=0.82$; a primordial spectral index of $n=0.95$; and a dimensionless Hubble parameter of $h=0.7$, all in accord with the WMAP7+BAO+SNI dataset of Komatsu et al. (2011).

Initial conditions for all of the *MUSIC* clusters were generated using the approach of Klypin et al. (2001), which can be summarised as follows;

- (i) All particles within a sphere of radius $6h^{-1}\text{Mpc}$ at $z=0$ centred on the cluster in the parent *MultiDark* simulation are found in the low-resolution 256³ particle version of the parent.
- (ii) These particles are mapped back to the parent’s initial conditions to identify the Lagrangian region from which they originated, from which a mask is created.
- (iii) The initial conditions of the parent simulation are regenerated on a finer mesh of size 4096³, a factor of 8 increase in mass resolution relative to the parent simulation.
- (iv) The mask is then applied to the 4096³ particle dataset, such that particles within the masked region are retained and those outside of the mask are binned to produce coarser mass resolution tidal

¹ <http://music.ft.uam.es/>

² www.cosmosim.org

particles, equivalent to the low-resolution 256^3 version of the parent.

The result is a set of initial conditions in which particles in the high resolution patch have a mass resolution a factor of 8 higher than in the parent run, corresponding to dark matter and gas particle masses of $m_{\text{DM}} = 9.01 \times 10^8 h^{-1} M_{\odot}$ and $m_{\text{gas}} = 1.9 \times 10^8 h^{-1} M_{\odot}$ respectively. In this paper, we use only codes that have used the same aligned parameters (see the Table 4 in Sembolini et al. 2016a) to re-simulate the selected cluster; a summary of the galaxy formation prescriptions adopted in these codes is given in the Appendix.

2.2 Halo finding

We have used the phase-space halo-finder VELOCIRAPTOR³ (Elahi et al., In Preparation) to identify the main cluster and its substructure. VELOCIRAPTOR identifies particle groups using a 3 dimensional friends-of-friends (FOF) algorithm and then refines each 3D-FOF group using a FOF algorithm applied to the full 6 dimensional phase-space. This 6D-FOF group catalogue is cleaned to correct for sets of halos that are combined artificially into a more massive system, arising from spurious bridges of particles between halos that occur during the early stages of mergers; this is done using the velocity dispersions of the 3D-FOF groups. Each 6D-FOF halo is then decomposed into a smooth background and its substructures by applying the phase-space FOF algorithm recursively, locating sets of particles that are dynamically distinct from the background. This approach is capable of finding both subhaloes and streams associated with tidally disrupted systems (Elahi et al. 2013).

The cluster that we consider in this paper (labelled ‘19’) has been studied extensively as part of the nIFTy galaxy cluster comparison (see Sembolini et al. 2016a,b; Elahi et al. 2016; Cui et al. 2016; Arthur et al. 2017). We follow the convention of defining cluster mass as M_{200} , the mass enclosed within a spherical region of radius R_{200} encompassing an overdensity of 200 times the critical density ρ_{crit} at the given redshift z , i.e.

$$M_{200} = \frac{4\pi}{3} 200 \rho_{\text{crit}} R_{200}^3. \quad (1)$$

Using the G3-MUSIC Full Physics run as our fiducial, we measure at $z=0$ values of $M_{200}=1.107 \times 10^{15} h^{-1} M_{\odot}$ and $R_{200}=1.682 h^{-1} \text{Mpc}$, as well as a gas fraction $f_{\text{g}} = M_{\text{gas}}/M_{200}=0.1629$ and 3D gas and dark matter velocity dispersions of $\sigma_{3\text{D}}^{\text{g}}=950 \text{ km/s}$ and $\sigma_{3\text{D}}^{\text{d}}=1960 \text{ km/s}$. Following previous studies (e.g. Thomas et al. 1998; Power et al. 2012), we use the centre-of-mass offset to quantify the cluster’s dynamical state. We define this as $\Delta R = (\bar{R}_{\text{cen}} - \bar{R}_{\text{cm}})/R_{200}$, where $\bar{R}_{\text{cm}}$ is the centre of mass of material within R_{200} and $\bar{R}_{\text{cen}}$ corresponds approximately to the centre of the densest substructure within R_{200} as calculated via the iterative method of Power et al. (2003). The measured value of $\Delta R=0.04$ indicates that the cluster is relatively dynamically relaxed, which is consistent with the visual impression.

3 RESULTS

We now investigate the thermodynamical properties of the ICM in the outskirts of the cluster at $z=0$, and estimate the degree of varia-

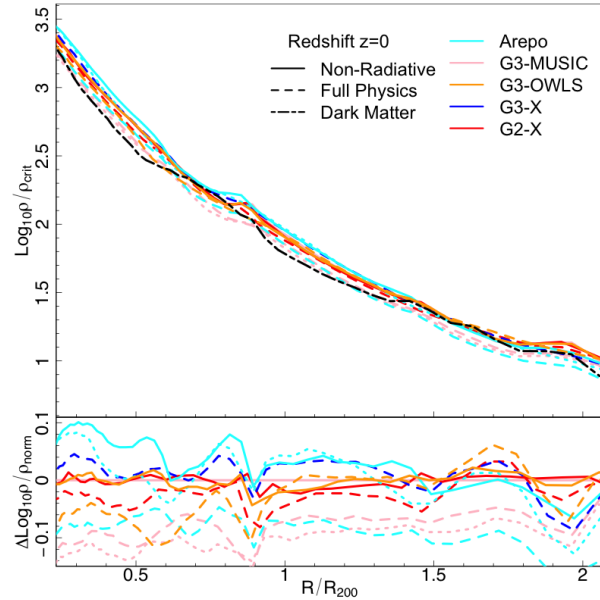


Figure 1. Spherically averaged gas density profiles at $z=0$. In the upper panel, we show the spherically averaged gas density profiles measured in the non-radiative runs (solid curves) and full physics runs (dashed curves). Here radii are normalised to the value of R_{200} in the G3-MUSIC non-radiative run; densities are in units of ρ_{crit} at $z=0$, $2.7755 \times 10^{11} h^2 M_{\odot} \text{Mpc}^{-3}$. The heavy dotted-dashed curve is the dark matter density profile (as found in the dark matter only G3-MUSIC reference run) scaled by the cosmic baryon density, $\Omega_{\text{bar}}/\Omega_{\text{m}}$. In the lower panel, we show the residuals of each of these profiles with respect to our G3-MUSIC non-radiative reference run.

tion between different astrophysical codes and different galaxy formation prescriptions in § 3.1. In particular, we focus on the spherically averaged gas density, temperature, and radial velocity profiles at $0.3 \leq R/R_{200} \leq 2$, and investigate in detail the relationship between structures evident in these profiles, which we interpret as arising from shocks, and the orbital motions of substructures (§ 3.2) and accretion from the cosmic web (§ 3.3). Our reference simulation is the non-radiative G3-MUSIC run, and residuals (when shown) are with respect to this run. All figures include data from both non-radiative and full physics simulations, unless otherwise stated.

3.1 Spherically averaged profiles

We begin our analysis by inspecting the spherically averaged gas density, temperature, and radial velocity profiles at $z=0$ at $0.3 \leq R/R_{200} \leq 2$. In Figure 1, we show gas density profiles measured in the non-radiative (solid curves) and full physics (long dashed curves) simulations in our sample; all radii are normalised to R_{200} , the value in the fiducial G3-MUSIC non-radiative run, while densities are expressed in units of ρ_{crit} , the critical density at $z=0$. For reference, we overlay the density profile of the dark matter only version of the cluster (dotted-dashed curve), scaled by the universal baryon fraction, $\Omega_{\text{bar}}/\Omega_{\text{m}}$. The lower panel shows residuals with respect to the non-radiative G3-MUSIC reference run.

There are a couple of points worthy of note in this figure. First, there is good agreement between the different sets of runs – the difference is no greater than 0.1 dex ($\sim 25\%$) over the radial range we consider, as indicated by the residuals. There is slightly greater variation between the full physics runs than between the non-radiative runs, but these differences tend to be systematic. Second, the scaled

³ VELOCIRAPTOR derives from STRUCTURE FINDER (see Elahi, Thacker, & Widrow 2011) and can be downloaded from <https://github.com/pelahi/VELOCIRaptor-STF.git>.

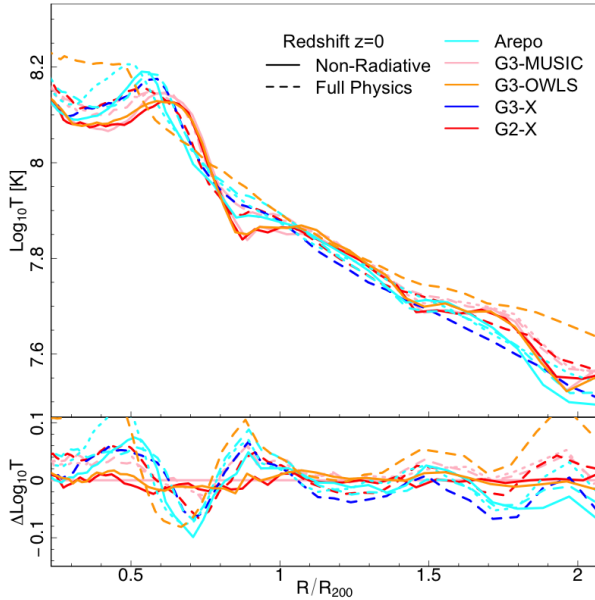


Figure 2. Spherically averaged gas temperature profiles at $z=0$. In the upper panel, we show the spherically averaged gas density profiles measured in the non-radiative runs (solid curves) and full physics runs (dashed curves). Radii are again normalised to R_{200} . In the lower panel, we show the residuals of each of these profiles with respect to the G3-MUSIC non-radiative run.

dark matter density profile provides a good approximation to both the amplitude and shape of the gas density profiles, which is consistent with the findings of earlier hydrodynamical simulations (e.g. Lewis et al. 2000; Pearce et al. 2000) and the assumptions of analytical modeling (e.g. Makino et al. 1998; Komatsu & Seljak 2001).

In Figure 2, we show the corresponding $z=0$ spherically averaged gas temperature profiles (in the upper panel) and their residuals with respect to the non-radiative G3-MUSIC run (in the lower panel). As before, we include both non-radiative and full-physics runs plotted over the range $0.3 \leq R/R_{200} \leq 2$; we plot radii in units of R_{200} but temperature in K. Here we see a pronounced enhancement in temperature, which peaks at $\sim 0.5 - 0.6 R_{200}$, although the precise location and shape of the bump varies between runs; we see also a feature at $\sim 2 - 3 R_{200}$.

We have used snapshots finely spaced over the redshift range $z=0.5$ to $z=0$ to verify that these temperature enhancements within R_{200} occur frequently during the cluster’s assembly; they are transient features whose position moves to smaller radii over a dynamical time, which we speculate is associated with the motions of substructures. In contrast, the feature at $\sim 2 - 3 R_{200}$ identified at $z=0$ varies in amplitude but has remained at approximately $\sim 2 - 3 R_{200}$ since $z=0.5$; we speculate that this is associated with gas inflow and substructure motion in the cosmic web (see, for example, Burns et al. 2010).

In Figure 3, we examine the radial velocity profile of gas within the cluster, reasoning that features in the temperature profile are a response to gravitational and hydrodynamical influences. Here we show the variation of spherically averaged radial velocity of gas with radius, with radii normalised to R_{200} while radial velocities are in units of km/s; $v_{\text{rad}} < 0$ (> 0) implies inflow (outflow). For a system in hydrodynamic equilibrium, we would expect $\langle v_{\text{rad}} \rangle \simeq 0$, but instead we see a pronounced dip to $\sim -500 \text{ km s}^{-1}$ at $\sim 0.9 R_{200}$, before a sharp rise to $\sim 400 \text{ km s}^{-1}$ peaking at

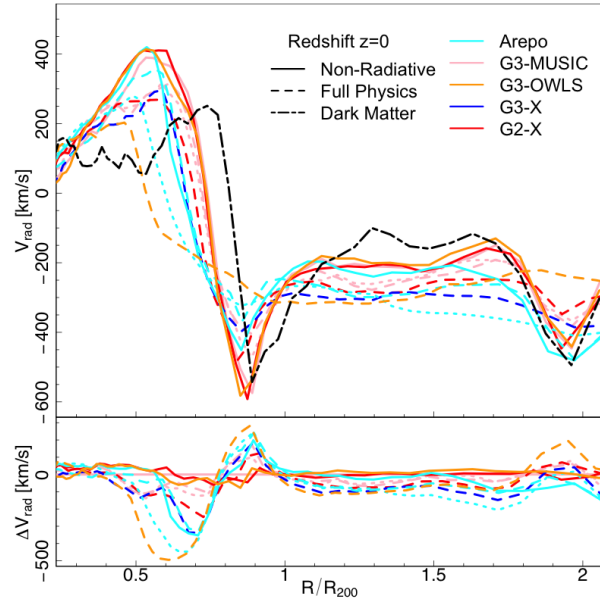


Figure 3. Spherically averaged radial velocity profiles at $z=0$. In the upper panel, we show the spherically averaged radial velocity profiles measured in the non-radiative runs (solid curves) and full physics runs (dashed curves). Velocities are expressed in units of km/s, while we normalise radii by R_{200} as before. The heavy dotted-dashed curve is the dark matter radial velocity profile as found in the G3-MUSIC non-radiative run. In the lower panel, we show the residuals of each of these profiles with respect to the G3-MUSIC non-radiative run again.

$\sim 0.5 - 0.6 R_{200}$. There is appreciable variation between the runs, but the trend is systematic.

Interestingly, we see a feature in the dark matter radial velocity (heavy dotted-dashed curve), similar to the feature evident in the gas radial velocity, albeit smaller in amplitude and displaced outwards in radius. Taken together, the enhancement in gas temperature within R_{200} ; the appearance of such enhancements during the cluster’s assembly history and their transience; and the – apparently – related features in the gas and dark matter radial velocity profiles, all point towards a common origin, which we associate with the passage of a massive substructure through the cluster. There is observational evidence to support that infalling galaxies and groups onto clusters can generate termination shocks, as the work of Brown et al. (2011) on infalling galaxies in the Coma cluster has revealed.

In the following subsections, we explore whether or not these features in the spherically averaged temperature and velocity profiles can be attributed to the motions of substructures; the physical nature of these substructures; and how the cosmic web within which the cluster resides might be imprinted on its thermodynamical structure.

3.2 Impact of Accretion and Mergers

We now investigate the relationship between the features evident in the spherically averaged gas temperature profile and radial velocity profiles of gas and dark matter, and the dynamics of the substructure population within the cluster.

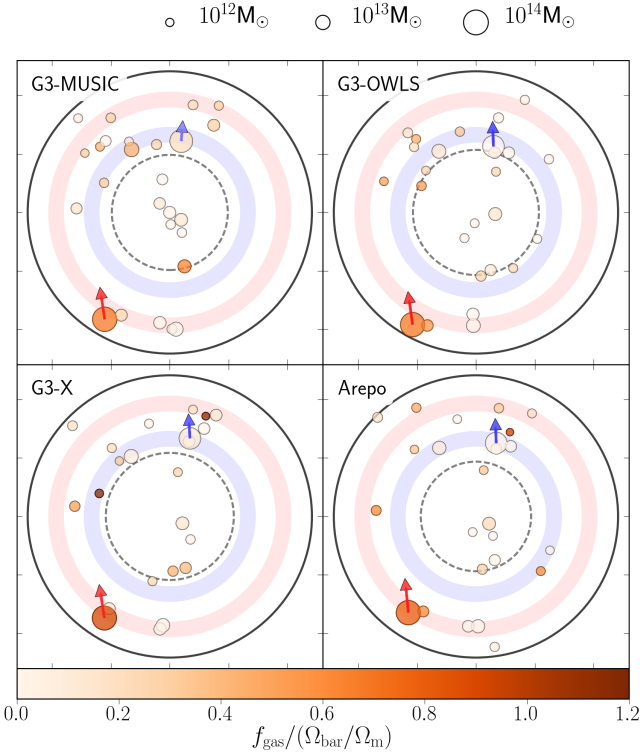


Figure 4. Projected spatial distribution of haloes within $1.25R_{200}$ of the cluster. We include only those haloes with masses $\geq 10^{12}h^{-1}M_{\odot}$. Symbol size and colour scale with mass and gas fraction, with lighter hues indicating gas paucity and dark hues indicating gas richness. The virial radius R_{200} is represented by the solid circle, the radius at which the underlying cluster halo circular velocity profile reaches its maximum by the dashed circle, while the shaded regions indicate the inner and outer boundaries of the temperature and radial velocity profile features.

3.2.1 Subhalo population in general

In Figure 4 we show the projected spatial distribution of haloes of mass $M_{200} \geq 10^{12}h^{-1}M_{\odot}$ and within $1.25R_{200}$ of the cluster's centre in the full-physics simulations. Symbol size is proportional to halo mass, while symbol colour indicates gas fraction. The solid outermost circle represents the cluster's radius R_{200} , while the dashed circle indicates the position of the peak of the circular velocity profile. The shaded regions mark the outer and inner bounds of the features identified in the temperature and radial velocity profiles (i.e. Figures 2 and 3) respectively. We consider a representative sample of the runs, spanning codes employing classic (G3-OWLS, G3-MUSIC) and modern SPH (G3-X), as well as moving meshes (Arepo); and spanning galaxy formation prescriptions, where the fundamental difference is between runs with AGN feedback (G3-OWLS, G3-X, and Arepo) and without AGN (G3-MUSIC).

The most striking feature of Figure 4 is the presence of two distinct massive subhaloes whose radial distances coincide with features in the gas radial velocity profile. Their trajectories are also consistent with the trends we see in the radial velocity profiles - the outer, gas-rich subhalo is infalling with a velocity ~ -1700 km/s, whereas the inner, gas-poor subhalo is moving outwards with a velocity ~ 1500 km/s - although their velocities are much higher than the spherically averaged velocities at these radii, and supersonic. Their velocity vectors are relatively well aligned, with an angle between them of $\sim 20^\circ$, and their direction of motion aligns with the

orientation of the large-scale filaments within which the cluster is embedded (see further discussion in § 3.3).

We have verified that these results do not depend on our choice of run by also checking the non-radiative and dark matter only versions of these simulations⁴; we do this by cross matching the halos identified in the full physics run with those in the non-radiative and dark matter only runs, and confirm excellent agreement between the spatial and kinematic distributions. Differences that we note in the dark matter only run - that the counterpart to the outgoing halo is at a slightly larger cluster-centric distance than in the full physics and non-radiative runs - can be readily understood as a consequence of the change in bound mass arising from the stripping of its gas content.

In Figure 5, we look in detail at how the infalling group, highlighted in Figure 4, influences the intra-cluster medium. Recall that this infalling group is gas-rich ($f_g \sim 0.7 - 0.9\Omega_b/\Omega_m$), and it has a large radial velocity (~ 1700 km/s) relative to the cluster; this velocity is significantly larger than the motions of cluster particles in the same region - for dark matter, $\langle v_r \rangle \sim -150$ km/s with dispersions of ~ 1000 km/s; for gas $\langle v_r \rangle \sim -250$ km/s, with dispersions of ~ 600 km/s. We plot the projected gas distribution, weighted by temperature, in a region $2.1h^{-1}$ Mpc wide and $1.1h^{-1}$ Mpc thick, centred on and in the orbital plane of the group. Contours indicate dark matter, gas, and stellar density associated with the group, while arrows show the direction to the cluster centre ($\vec{x}_C$) and the direction of motion of the group relative to the cluster centre ($\vec{v}_C$).

Figure 5 reveals that the infalling subhalo drives a shock into the intra-cluster medium - there is evidence for shocked gas in advance of the group and trailing gas in its wake in all of the runs. The temperature enhancement associated with the shock is more pronounced in the direction of the cluster centre, towards which the density gradient is higher, than in the direction of motion. Code-to-code variations are evident in the structure of the ICM - the classic SPH codes (G3-MUSIC, G3-OWLS) show more small-scale variations than either the modern SPH codes (G3-X) or the moving-mesh code (Arepo), and the differences are particularly striking when one compares G3-MUSIC, which contains several cool, dense knots within this region (lower left), with G3-X, where such knots are absent. These small-scale variations are especially pronounced in the non-radiative runs (not shown here), and are consistent with previous studies (see, for example, Figure 12 in Power et al. 2014).

That a fast-moving, infalling, gas-rich group might generate a shock in the ICM is not surprising; but what is the influence of the gas-poor group moving outwards? At $z=0$, it is moving with a radial velocity of ~ 1500 km/s; however, its position and velocity *do not* correspond to the inner feature seen in the temperature and radial velocity profiles - its radial velocity is too high, and it is at too great a clustercentric radius. By tracking its orbit to earlier times, we can say that it had a mass on infall of $\sim 6 \times 10^{13} M_{\odot}$ and it was gas-rich. At its pericentric passage of $\sim 0.15 R_{200}$, it deposited a gas mass of $\sim 8 \times 10^{12} M_{\odot}$ in ~ 50 Myrs as it moved at speeds of ~ 2750 km/s, and led to its baryon fraction plummeting from $\gtrsim 0.5\Omega_b/\Omega_m$ to $\ll \Omega_b/\Omega_m$. It is this stripping event and the gas associated with it that produces the shock at $\sim 0.5 - 0.6R_{200}$.

To illustrate these observations, in Figure 6 we show the projected radial velocities and temperatures (upper and lower panels

⁴ See also Fig.1 (DM) and Fig.5 (gas) in Sembolini et al. (2016a) for a visualisation of the non-radiative runs as well as Figs.4 & 6 in Sembolini et al. (2016b) for the counterparts in the full physics runs.

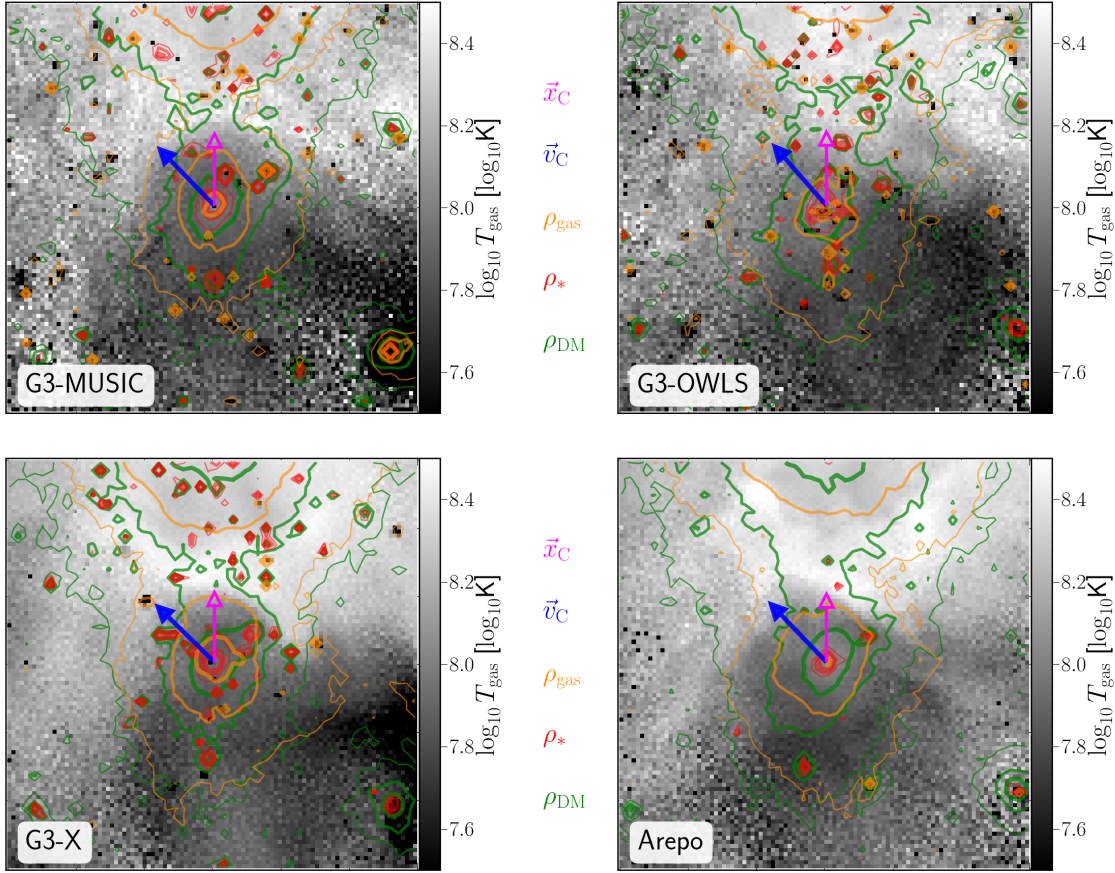


Figure 5. Infalling group shock in a subset of the full physics runs; from top right to bottom left, G3-MUSIC, G3-OWLS, G3-X, and Arepo. Here we zoom in on a region $2.1h^{-1}\text{Mpc}$ wide and $1.1h^{-1}\text{Mpc}$ thick, centred on and in the orbital plane of the galaxy group that generates the shock that gives rise to the feature in the temperature profile at $0.9R_{200}$. We show the mean logarithmic temperature distribution along the line of sight in this slab in grayscale, where each pixel is 20 kpc in size. We show also contour maps of the average dark matter density in green; the average gas density in orange; and the average stellar density in red. The galaxy group’s direction of motion relative to the cluster’s centre-of-mass is shown by a blue arrow, while the direction towards the cluster centre is shown by a magenta arrow.

respectively) of gas in the vicinity of the inner temperature enhancement (left panels), and gas stripped from the outward moving group (right panels). To show the generality of our results and the consistency between code behaviour, we consider two representative cases - G3-OWLS at the top, and Arepo at the bottom. Inspection of the left panels makes clear an arc of shock heated gas, both trailing the outwardly moving group and colliding with infalling gas; the right panels reveal that the shocked cluster gas is propelled outwards by the cold, dense, fast moving gas stripped from the outwardly moving cluster. The fastest outwardly moving portion of this stripped gas is spatially coincident the inner edge of the shock, pushing material in front of it, and it is this outwardly moving wake that shock heats when it encounters infalling gas.

3.3 Influence of the Cosmic Web

The previous discussion has focused on shock structures that are evident in the gas temperature profile within R_{200} , which we have shown are a direct consequence of the passage of two massive groups through the ICM. We noted that the orbits of these groups showed evidence for a preferential direction, which we interpreted as a signature for infall along filaments. We also see evidence for

a shock at $\sim 2R_{200}$ in both a temperature enhancement and a dip in the radial velocity profile, which is roughly where we expect to see the signature of the accretion shock of gas from filaments. We now make the relationship to the cosmic web explicit by using DisPerSe (cf. Sousbie 2011) to characterise filamentary structure in the vicinity of the cluster.

As applied to our simulation data, DisPerSe computes a discrete density field from a Delaunay tessellation of particles and identifies filaments as ridges connecting maxima through saddle points in the underlying density field. The result is a “skeleton” of the density field, consisting of a fully connected network of segments, which can be smoothed (by pairwise averaging of neighbouring segments) to focus on a given spatial scale⁵. Here we com-

⁵ We note that the skeleton can be smoothed on a given spatial scale, or it can be filtered on a *persistence* threshold. Here the concept of persistence characterises the robustness of the topology (i.e. number of holes, tunnels, threads, etc.) of the density field above a given excursion threshold, which can be interpreted as a measure of the significance of topological features, similar to the signal-to-noise ratio in observations. Note that persistence only characterizes robustness of pairs of critical points (such as maximum-saddle point height). We can however also derive a continuous robustness ratio that directly relates to the contrast of filaments (arcs between the crit-

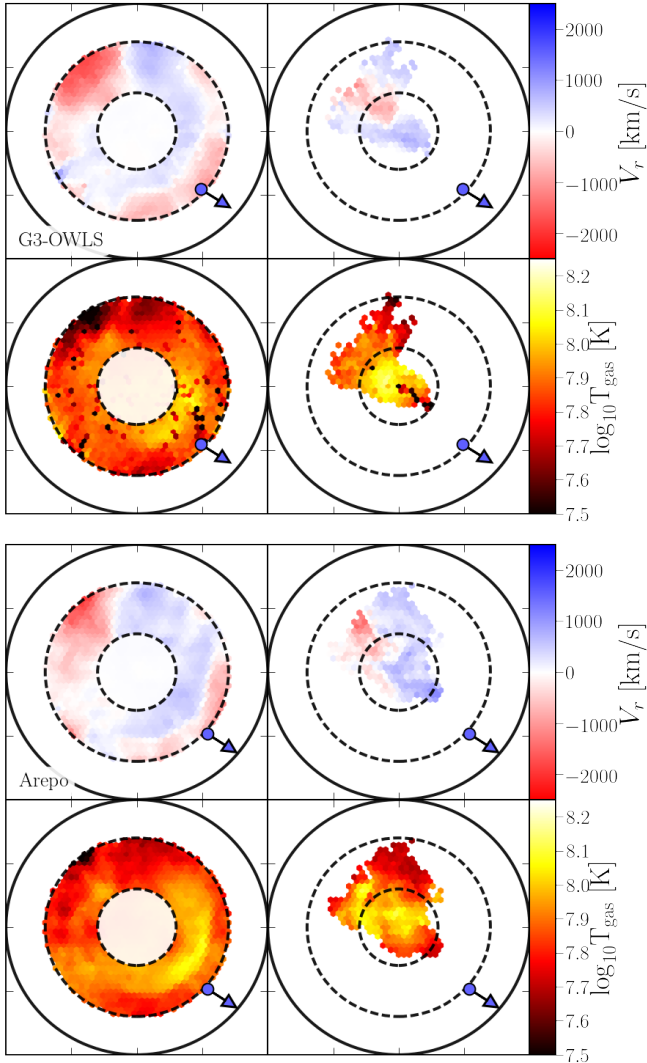


Figure 6. Gas properties around the inner shock in the G3-OWLS and Arepo full physics runs (upper and lower panels, respectively). We show, in projection, the mean radial velocity (upper panels) and temperature (lower panels) of gas in a shell around the shock feature (left panels) and the gas stripped from the outward going group (right panels) in the Arepo full physics run. We show also the position of the outward moving group and its direction of motion, with the point and arrow colour coded according to its radial velocity. The outer solid circle is at R_{200} , while the inner/dashed circles are at $0.4/0.8R_{200}$ and encompass the inner shock. For clarity, we do not include gas interior to the shell in projection.

pute the skeleton using both dark matter and gas in cubes of size 4 and $20 h^{-1}$ Mpc on a side, centered on the location of the maximum density of the cluster.

Figure 7 gives a visual impression of the cosmic web in which the cluster is embedded. Solid red lines show a $3h^{-1}$ Mpc wide slice of the network of filaments with a persistence threshold $c=0.01$ in a $20 h^{-1}$ Mpc cube smoothed onto a 128^3 mesh, consecutively trimmed of arcs with robustness smaller than the mean

ical points) relative to their background (Sousbie 2011). This allows us to distinguish between strong sustained filaments connecting high contrast nodes (high persistence level, high robustness ratio) and fainter, possibly more transient, features (low persistence level, low robustness ratio).

plus 1 standard deviation and smoothed over a $3h^{-1}$ Mpc spatial scale. While these results are calculated for the gas, we note that we recover a very similar skeleton on large scales using the dark matter density. Dashed circles indicate the locations of the features in the radial velocity profiles, while the solid circles correspond to the gas-poor outwardly moving group (lower in x - y , left in y - z) and gas-rich infalling group respectively.

Figure 7 makes clear the trajectories of both groups along the filaments. It also highlights that the feature at $\sim 2 R_{200}$ in the radial velocity profile corresponds to the merging of several smaller filaments along the direction of the most robust one. We note that the location of this feature should be long-lived, whereas the shocks associated with the infall of galaxies and groups within R_{200} should be short-lived and dynamic.

4 SUMMARY

The outskirts of galaxy clusters provide a compelling testbed for current theories of galaxy formation and the growth of large-scale structure. They mark both the transition between the mildly non-linear cosmic web and the highly non-linear virialised cluster centre, and the region where the hot, comparatively dense intra-cluster medium begins to influence the gaseous content of infalling galaxies. We have examined the results of a sample of cosmological hydrodynamical zoom simulation of a single galaxy cluster, run as part of the nIFTy comparison programme (see Sembolini et al. 2016a,b), to study how the predicted thermodynamical properties at $z=0$ of gas density and temperature in cluster outskirts ($0.3 \lesssim R/R_{200} \lesssim 2-3$) are affected by the choice of astrophysical code and the adopted galaxy formation model. The suite of state-of-the-art codes considered in this study includes both mesh- and particle-based approaches, ranging from Arepo to various forms of “classic” and “modern” smoothed particle hydrodynamics (SPH), as implemented in GADGET2 and GADGET3, and the astrophysical models spanned minimal non-radiative runs to full physics runs incorporating radiative cooling, star formation, black hole growth, and stellar and AGN feedback.

Our analysis of the spherically averaged gas density, temperature, and radial velocity profiles revealed very good agreement between different codes and different galaxy formation models at radii $\gtrsim 0.3 R_{200}$. We find that the gas density profile can be reasonably well approximated by the dark matter density profile, scaled by the universal baryon fraction (i.e. Ω_b/Ω_m). However, features evident in the gas temperature and radial velocity profile suggested the presence of shocks both within R_{200} , which we interpreted as the signature of infalling substructures, and at $\sim 2-3 R_{200}$, which we interpret as the imprint of shocked gas accreting from the cosmic web. This interpretation was consistent with analysis of the assembly history of the cluster, which shows that features in the temperature profile associated with shocks within R_{200} are dynamic and short-lived, while those at larger radii are comparatively long-lived.

Using the VELOCraptor halo-finder (Elahi et al., In Prep), we traced the origin of the shocks within R_{200} to two massive substructures - one gas-rich and infalling on a preferentially radial orbit with a relative speed of -1700 km/s, producing the clear signature of a shock in the direction of its motion; the other gas-poor, moving outwards with a velocity of 1500 km/s, and gravitationally influencing gas in its vicinity. Using DisPerSe (cf. Sousbie 2011), we constructed and classified the cosmic web in the vicinity of the cluster, from which we demonstrated that the cluster accretes from two dominant filaments, and showed that a network of filaments

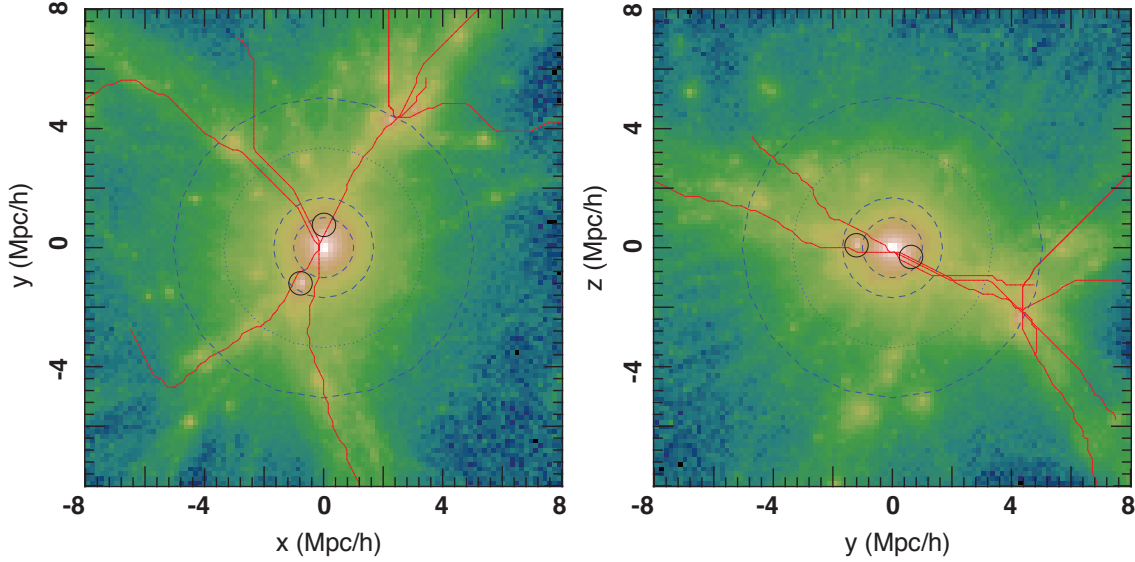


Figure 7. Large-scale cosmic web connectivity in G3-OWLS. Projected gas density centred on the cluster within a $3 R_{200}$ thick slice in the x - y (left panel) and y - z (right panel) planes, colour-coded by the logarithm of the density. As described in the text, the solid red lines show the network of filaments recovered by DisPerSe (cf. Sousbie 2011) while the dashed circles indicate the locations of features evident in the spherically averaged radial velocity profiles, and solid circles correspond to the two massive groups investigated in the previous subsection.

combine at $\sim 2 - 3R_{200}$ to give rise to strong shocks. Interestingly, the trajectories followed by the substructures that give rise to the shock within R_{200} are fixed by the filaments from which they were accreted, suggesting a way to reconstruct orbits of massive substructures from observational data (e.g. X-rays and radio synchrotron emission).

Taken together, these results show that the bulk properties of the intra-cluster medium at large cluster-centric distances are shaped predominantly by the large-scale gravitational field and the physics of strong, inefficiently radiating, shocks. This suggests that we can, for example, gain useful insights into the thermodynamical structure of cluster outskirts from relatively inexpensive non-radiative cosmological hydrodynamical simulations of large volumes. Such an approach could provide the skeletal theoretical framework needed to interpret observations of the WHIM, noting that, in detail, the observable signatures of the WHIM will be influenced by galactic feedback and chemical enrichment (e.g. metal lines will govern X-ray emission). Combined with semi-analytical models of galaxy formation, it should be possible to make predictions for next generation galaxy surveys with the Square Kilometre Array in the radio continuum, tracing synchrotron emission (e.g. Giovannini et al. 2015; Vazza et al. 2015), and eRosita (e.g. Merloni et al. 2012), X-Ray Imaging and Spectroscopy Mission (XRISM) (e.g. Tashiro et al. 2018), and ATHENA (e.g. Nandra et al. 2013) in X-ray, thereby extending the kind of modelling carried out in previous studies (e.g. Keshet et al. 2004; Zandanel et al. 2014).

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The authors contributed to this paper in the following ways: CP,

PJE, & CW formed the core team that organized and analyzed the data, made the plots and wrote the paper. AK, FRP, GY & CP organized the nIFTy workshop at which this program was initiated. GY supplied the initial conditions. STK, AMB, IGMCC, GY, GM, & EP performed the simulations using their codes. All authors read and commented on the paper.

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adopted galaxy formation prescription is described in detail in Pike et al. (2014), but it can summarised as follows; radiative cooling follows the Thomas & Couchman (1992) prescription; stars form following Schaye & Dalla Vecchia (2008) at a rate fixed by the Schmidt-Kennicutt relation (Kennicutt 1998), and produce feedback using a prompt thermal Type II supernova model; and the modelling of AGN feeding and feedback is based on Booth & Schaye (2009).

G3-MUSIC (Yepes)

G3-MUSIC is built on GADGET3, which derives from the public version of the GADGET2 code of Springel (2005), with improvements in time-stepping and domain decomposition. It employs the entropy-conserving formulation of SPH described in Springel & Hernquist (2002), with a spline kernel (Monaghan & Lattanzio 1985) and artificial viscosity as modelled in Monaghan (1997). It uses the standard Springel & Hernquist (2003) scheme, without AGN, in the full physics run.

G3-OWLS (McCarthy, Schaye)

G3-OWLS is built on GADGET3 and employs the standard entropy-conserving SPH scheme of Springel & Hernquist (2002) with a cubic spline kernel of 48 neighbours. The galaxy formation prescription used in the full physics run is presented in extensive detail in Schaye & Dalla Vecchia (2008), Dalla Vecchia & Schaye (2008), Wiersma et al. (2009a), Booth & Schaye (2009), Wiersma et al. (2009b), Schaye et al. (2010), and encompasses modelling of radiative cooling, star formation, stellar evolution, stellar feedback, and AGN feeding.

G3-X (Murante, Borgani, Beck)

G3-X is built on GADGET3 and developed by (Beck et al. 2016) to include a Wendland C^4 kernel with 200 neighbours (cf. Dehnen & Aly 2012), artificial conductivity to promote fluid mixing following Price (2008) and Tricco & Price (2013), but with an additional limiter for gravitationally induced pressure gradients. The full physics run adopts the cooling prescription of Wiersma et al. (2009a); heating via a uniform UV background Haardt & Madau (2001); star formation and chemical evolution as in Tornatore et al. (2007); stellar feedback in the form of supernovae as in Springel & Hernquist (2003); and AGN feedback as in Steinborn et al. (2015).

APPENDIX A: SIMULATION CODES

Arepo (Puchwein)

The basic Arepo code (cf. Springel 2010) utilises a TreePM gravity solver and a finite-volume Godunov scheme on an unstructured moving Voronoi to solve the equations of hydrodynamics. Two galaxy formation prescriptions are used in the full physics runs; the first (Arepo-IL) is used in the *Illustris Simulation*, includes AGN feeding and feedback, and is described in Vogelsberger et al. (2013, 2014). The second (Arepo-SH) uses the standard Springel & Hernquist (2003) scheme, without AGN, and matches that used in G3-MUSIC.

G2-X (Kay)

G2-X is built on the public version of GADGET2 (Springel 2005), using the standard cubic spline kernel with 50 neighbours. The