The relationship between substructure in 2D X-ray surface brightness images and weak-lensing mass maps of galaxy clusters: a simulation study

Leila C. Powell,1⋆ Scott T. Kay2 and Arif Babul3

1Oxford Astrophysics, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH
2Jodrell Bank Centre for Astrophysics, Alan Turing Building, The University of Manchester, Manchester M13 9PL
3Department of Physics and Astronomy, University of Victoria, Elliot Building, 3800 Finnerty Road, Victoria, BC, V8P 5C2, Canada

ABSTRACT

Recent X-ray and weak-lensing observations of galaxy clusters have revealed that the hot gas does not always directly trace the dark matter within these systems. Such configurations are extremely interesting. They offer a new vista on to the complex interplay between gravity and baryonic physics, and may even be used as indicators of the clusters’ dynamical state. In this paper, we undertake a study to determine what insight can be reliably gleaned from the comparison of the X-ray and the weak-lensing mass maps of galaxy clusters. We do this by investigating the two-dimensional (2D) substructure within three high-resolution cosmological simulations of galaxy clusters. Our main results focus on non-radiative gas dynamics, but we also consider the effects of radiative cooling at high redshift. For our analysis, we use a novel approach, based on unsharp-masking, to identify substructures in 2D surface mass density and X-ray surface brightness maps. At full resolution (∼15 h−1 kpc), this technique is capable of identifying almost all self-bound dark matter subhaloes with $M > 10^{12} h^{-1} M_\odot$. We also report a correlation between the mass of a subhalo and the area of its corresponding 2D detection; such a correlation, once calibrated, could provide a useful estimator for substructure mass. Comparing our 2D mass and X-ray substructures, we find a surprising number of cases where the matching fails: around one-third of galaxy-sized substructures have no X-ray counterpart. Some interesting cases are also found at larger masses, in particular the cores of merging clusters where the situation can be complex. Finally, we degrade our mass maps to what is currently achievable with weak-lensing observations (∼100 h−1 kpc at $z = 0.2$). While the completeness mass limit increases by around an order of magnitude, a mass–area correlation remains. Our paper clearly demonstrates that the next generation of lensing surveys should start to reveal a wealth of information on cluster substructure.

Key words: gravitational lensing – methods: numerical – X-rays: galaxies: clusters.

1 INTRODUCTION

The advent of the weak-lensing technique has allowed observers to directly probe the distribution of mass in galaxy clusters, rather than simply assuming that light provides an accurate tracer of the underlying dark matter (DM) distribution. This allows us to separate out shortfalls in our understanding of baryonic physics from direct challenges to the cold dark matter (CDM) model, providing an excellent test of the predictions of the CDM paradigm itself and a clearer picture of the influence of the baryonic component.

In recent years, there has been a flurry of papers, with these goals in mind, which compare weak-lensing mass reconstructions to X-ray images of galaxy clusters (e.g. Smail et al. 1997; Machacek et al. 2002; Smith et al. 2005). Some of such observations have highlighted dramatic exceptions to the basic picture that light follows mass, most famously, the bullet cluster (Clowe, Gonzalez & Markevitch 2004) where the main peaks in the X-ray image are offset from those in the weak-lensing mass reconstruction. There have been several follow-up theoretical studies of this unique system (e.g. Takizawa 2006; Springel & Farrar 2007; Mastropietro & Burkert 2008) which conclude that its main features can be reproduced well by idealized, non-radiative merger simulations suggesting the driving factor is ram pressure.

There have also been observations of clusters with features in the weak-lensing map which are absent in the X-ray image. For example, in MS1054-0321 (Jee et al. 2005) and in Abell 1942 (Erben et al. 2000; Gray et al. 2001), for which several theories are put
forward: chance alignments of background galaxies, galaxy clusters that have not yet virialized and so possess little X-ray emitting gas or substructure within the cluster that has somehow been stripped of its gas. Even more puzzling is the recent observation of Abell 520 (Mahdavi et al. 2007), in which an X-ray peak with no corresponding mass concentration and a mass concentration with no galaxies are detected. This is postulated to be a result of either a multiple body interaction or the collision of weakly self-interacting DM during the merger event. Most recent is the observation of another extreme merger event (Bradač et al. 2008), in which two clusters with $M \sim 10^{14} M_\odot$ are both displaced from the single peak in the X-ray emission suggesting that even higher mass substructures could be seen to ‘dark’.

On the galaxy-mass scale, studies of X-ray observations of the hot haloes of elliptical galaxies (Machacek et al. 2006) exhibiting features characteristic of ram pressure stripping were carried out, suggesting we should expect to find galaxy-sized subhaloes that are dark in X-rays. However, a systematic study by Sun et al. (2007) found 60 per cent of galaxies brighter than 2$L_*$ still retained small X-ray coronae, potentially indicating a more complex picture than just hydrodynamics, involving the suppression of heat conduction and viscosity by magnetic fields.

There have been many theoretical studies with the aim of understanding the global properties of purely DM substructure. For example, the systematics (Gao et al. 2004), evolution (Gill et al. 2004; Reed et al. 2005), effects of the parent halo merger history (Taylor & Babul 2004) and spatial distribution (Diemand, Moore & Stadel 2004) of subhalo populations have all been studied in great depth. Attention is now also being paid to the fate of the gas in subhaloes. Hester (2006) incorporated a hot halo component into an analytical model of ram pressure stripping of galaxies in groups and clusters and found that most galaxies were readily stripped of the majority of this. Inspired by the first observations of cold fronts in Chandra data (e.g. Markevitch et al. 2000), some authors invoked separations between the hot gas and DM of either the main cluster (Ascasibar & Markevitch 2006) or a merging subcluster (Takizawa 2005) as a possible mechanism for their production. There were also many other complimentary studies into the fate of gas in subhaloes on the group or cluster mass scale. For example, Bialek, Evrard & Mohr (2002) report the ablation of gas away from the core of a merging subcluster’s DM potential, in a cosmological simulation, resulting in adiabatic cooling, and Heinz et al. (2003) use idealized merger simulations to study this process in more detail. More recently, Poole et al. (2006) performed a suite of idealized cluster mergers and found that gas in both the cores was often disrupted, leading to additional transient structures in the X-ray emitting gas. In order to specifically investigate the fate of hot gas in galaxies orbiting in groups and clusters, McCarthy et al. (2008b) studied a suite of hydrodynamic simulations. They find the majority of the hot gas is stripped within a few Gyr, but that around 30 per cent is retained even after 10 Gyr.

Much of this work on the gaseous component uses simulations of idealized mergers in order to reproduce specific observational features of galaxy cluster substructure. What is required now is a similar treatment to that afforded for DM subhaloes; a systematic study of the statistics of hot gas substructure in fully cosmological simulations. Indeed there have only been two studies of this kind already, Tormen, Moscardini & Yoshida 2004 and Dolag et al. 2009. The former focuses on the time evolution of subhaloes in non-radiative simulations, while the latter examines how the overall distribution of subhalo masses and compositions differs, depending on the physics incorporated. There are two main issues still to address. First, many of the interesting substructures seen in X-ray images of clusters (tidal tails, diffuse gas clouds, etc.) are omitted from simulation studies which simply identify substructure as hot gas bound to subhaloes. Secondly, observationally we can only view the substructure in projection; how does this relate to the substructure in three-dimensions (3D)? Both of these issues can be addressed by undertaking an analysis of galaxy cluster substructure in 2D, allowing projection effects to be quantified without restricting the analysis to the bound components. A comprehensive study in this area will help us to construct a framework within which to interpret the surprising results from comparisons between weak-lensing and X-ray observations, of which there will undoubtedly be many more in the near future.

In this paper, we use high-resolution resimulations of three galaxy clusters to compare the substructure in the hot gas and DM components and examine what factors affect their similarity, or otherwise. We use a technique based on unsharp-masking to identify enhancements to the cluster background in maps of the X-ray surface brightness and total surface mass density, providing us with catalogues of 2D substructures. Our aims are to understand the relationship between 3D DM subhaloes and our 2D total mass substructure catalogues, including the contribution of 3D subhaloes that lie in front of or behind the cluster, yet within the map region. We wish to understand how these 2D mass sources then relate to substructures in the projected X-ray surface brightness, in order that we may place some constraints on the frequency of mismatches between substructure in the hot gas and DM and the mass scales at which these occur. Finally, we investigate how various selection and model parameters influence these two relationships.

This paper is structured as follows. In Section 2, the simulation properties, selection of the cluster sample and generation of the maps are outlined. The detection technique and properties of our 3D subhalo catalogues are included in Section 3, while Section 4 provides the same information for our 2D substructure catalogues. In Section 5, the results of a direct comparison between the 2D mass map substructures and the 3D subhaloes are presented. We investigate the likelihood of finding a 2D X-ray counterpart for each 2D mass substructure in Section 6 and explore the effect that redshift, dynamical state, the inclusion of cooling and observational noise have on this in Section 7. Section 7 also includes several case studies, to illustrate in more detail the fate of a 2D mass substructure’s hot gas component when a 2D X-ray counterpart cannot be found. We provide a short summary of our results at the end of Sections 5, 6 and 7, should the reader wish to skip to the end of these sections. Finally, Section 8 outlines the main conclusions and implications of this work.

2 CLUSTER SIMULATIONS

We use the resimulation technique to study the clusters with high resolution. Three clusters were selected from the larger sample studied by Gao et al. (2004) and resimulated with gas using the publicly available GADGET-2 N-body/smoothed particle hydrodynamics (SPH) code (Springel 2005). A ΛCDM cosmological model was assumed, adopting the following values for key cosmological parameters: $\Omega_m = 0.3$, $\Omega_b = 0.045$, $h = 0.7$, and $\sigma_8 = 0.9$. The DM and gas particle masses in the high-resolution regions were set to $m_{\text{DM}} = 4.3 \times 10^5 h^{-1} M_\odot$ and $m_{\text{gas}} = 7.7 \times 10^4 h^{-1} M_\odot$, respectively, within a comoving box size of 479 $h^{-1}$ Mpc. The simulations were evolved from $z = 36$ to 0, outputting 50 snapshots equally spaced in time. The Plummer gravitational softening length...
was fixed at $\epsilon = 10 \, h^{-1} \, \text{kpc}$ in the comoving frame until $z = 1$, after which its proper length ($\epsilon = 5 \, h^{-1} \, \text{kpc}$) was fixed.

For our main results, we have chosen not to incorporate the complicating effects of non-gravitational physics (particularly radiative cooling and heating from galaxies) for two reasons. First, we wish to investigate any differences between the hot gas and DM in the simplest scenario, i.e. due to ram pressure stripping and viscous heating of the gas. Secondly, a model that successfully reproduces the observed X-ray properties of galaxy clusters in detail does not yet exist, and so only phenomenological heating models tend to be implemented in cluster simulations. Nevertheless, we include a limited analysis of the effects of non-gravitational physics on our results, namely allowing the gas to cool radiatively at high redshift, in Section 7. We defer a study of the additional effects of heating from stars and active galactic nuclei to future work.

2.1 Cluster identification and general properties

To define the properties of each cluster within the simulation data, DM haloes were first identified using a friends-of-friends (FoF) algorithm, where the position of the most bound DM particle was taken as the centre. The spherical overdensity algorithm was then used to grow a sphere around this centre and determine $r_{500}$, the radius containing a total mean density, $\bar{\rho} = 500 \rho_{\text{crit}}(z)$, where $\rho_{\text{crit}}(z)$ is the critical density for a flat universe at redshift, $z$. This radius was chosen as it approximately corresponds to the upper limit of the extent of X-ray observations. The three clusters are labelled as A, B and C, respectively.

At the end of each simulation ($z = 0$), the masses of clusters A, B and C within $r_{500}$ were $M_{500} = [6, 3, 6] \times 10^{14} \, M_{\odot}$, approximately corresponding to $[1.4, 0.7, 1.4] \times 10^{14} \, \text{DM particles}$, respectively. To determine the evolution of each cluster with redshift, candidate progenitors were selected by finding all FoF groups at the previous output, whose centres lie within $0.5 \, r_{500}$ of the present cluster’s centre. We adopt a short (typically $b = 0.05$, but decreasing to $b = 0.025$ for problematic snapshots) FoF linking length to avoid the linking of two merging progenitors in close proximity, which can lead to fluctuations in the centre from output to output. We then select the most massive object as the progenitor, except when there are several candidates with similar mass, in which case we choose the one that is closest (this only occurs for Cluster C). Our choice meant that where Cluster C undergoes an almost equal-mass merger at $z = 0.5$, we did not end up following the most massive object at higher redshift, but tests confirm that this choice has no bearing on our main results.

Fig. 1 (top panels) shows how $M_{500}$ grows with time for each of the three clusters. For convenience, we have used redshift as the time axis; our study is limited to outputs between redshifts 0 and 1. By design, the mass histories vary significantly between the clusters: Cluster A undergoes several major mergers (leading to abrupt jumps in mass) early on, then settles down at $z \sim 0.4$; Cluster B accretes matter over the whole period and Cluster C undergoes two massive mergers (at $z \sim 0.9$ and 0.4, respectively) with relatively quiet stages in between.

2.2 Map making

For our main analysis, we constructed maps of surface mass density (dominated by the DM) and bolometric X-ray surface brightness for each cluster at each redshift. The former quantity is formally related to the volume density ($\rho$) as

$$\Sigma = \int \rho \, dl,$$

while the latter is related to both the electron density and temperature of the intracluster plasma

$$\Sigma_X = \frac{1}{4\pi(1+z)^2} \int n_e^2 \, A(T_e) \, dl,$$

although note that features are primarily due to fluctuations in the density. For the analysis that follows, the explicit redshift dependence of the surface brightness is ignored, and we further assume the ideal conditions of infinite signal-to-noise ratio (except for discreteness noise due to the finite number of particles employed). The conversion from gas to electron density is performed assuming a fully ionized, $Z = 0$ plasma (so $n_e \sim 0.9 \, \rho_{\text{gas}}/m_{\text{H}}$) and the cooling rate is computed using the tables calculated by Sutherland & Dopita (1993) for $Z = 0.3 \, Z_{\odot}$, the typical metallicity of the intracluster medium (ICM).

The estimation procedure followed is similar to that employed by Onuora, Kay & Thomas (2003). Briefly, a cuboid is defined, centred on the cluster, with sides of proper length $2r_{500}$ in the $X$ and $Y$ directions and $8r_{500}$ in the $Z$ direction (to capture material associated with the cluster along the line of sight). Particles that reside within this cuboid are then identified and projected in the $Z$ direction onto a 2D array of 400 $\times$ 400 pixels. The pixel size was chosen to sample length-scales of at least the Plummer softening length (at $z = 0, r_{500} \sim 1 \, h^{-1} \, \text{Mpc}$), so that all real structures were capable of being resolved by the map.

The gas particles are not point-like, but spherical clouds of effective radius, $h$, and shape defined by the (spline) kernel used by the GADGET-2 SPH method (see Springel, Yoshida & White 2001b). Thus, all gas particles were smoothed on to the array using the projected version of the kernel. To reduce the noise in the mass maps, dominated by DM particles, densities and smoothing lengths were adopted in a similar way (defining $h$ such that each DM particle enclosed an additional 31 neighbours) and smoothed using the same kernel as with the gas.

The projected mass density at the centre of each pixel, $R_0$, is therefore

$$\Sigma(R_0) = \frac{1}{A_{\text{pix}}} \sum_{i=1}^{N} m_i \, w(|R_i - R_0|, h_i),$$

where $A_{\text{pix}}$ is the pixel area, the sum runs over all $N$ particles within the cuboid region, $m_i$ is the mass of particle $i$ and $w$ is the projected SPH kernel, suitably normalized to conserve the quantity being smoothed.

The (redshift zero) X-ray surface brightness is estimated using a similar equation

$$\Sigma_X(R_0) = \frac{0.9}{4\pi A_{\text{pix}} m_{\text{H}}} \sum_{i=1}^{N} m_i \, n_e \, A(T_e) \, w(|R_i - R_0|, h_i),$$

where the sum runs over all hot ($T_e > 10^6 \, \text{K}$) gas particles, and we have assumed equivalence between the hot gas and electron temperatures.

The maps are centred for analysis, such that the new centre is set to the brightest pixel in the X-ray surface brightness map, as would generally be the case for observations. The allowed alteration is restricted to ensure that the centre does not ‘jump’ to a bright substructure (this is unrealistic, but possible because of our simple non-radiative model) as this would undermine the effort directed at following the assembling structure.

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Figure 1. Top panels: mass histories, $M_{500}$ versus redshift, for Clusters A (left-hand panel), B (middle panel) and C (right-hand panel). Middle panels: normalized rms centroid displacement, a dimensionless estimator of a cluster’s dynamical state (see the text for details). The horizontal line indicates a value of 10 per cent (which we define as the threshold for a major merger) and filled squares in the top panels show outputs where the estimator exceeds this value. Bottom panels: examples of X-ray surface brightness maps for a cluster with low (0.01; left-hand panel), intermediate (0.1; middle panel) and high (0.2; right-hand panel) values of the rms centroid shift, respectively. Here, contours illustrating equally spaced values of logarithmic surface brightness (white) and surface mass density (black) are overlaid.

The bottom three rows of Fig. 2 illustrate surface mass density (left-hand column) and surface brightness (right-hand column) maps for Clusters A, B and C at $z = 0$. Qualitatively, the strongest features are clearly present in both maps, but there are some differences, notably the lack of some obvious subhaloes in the X-ray maps and extended features in the X-ray maps due to stripped gas. It is also clear that the brightest X-ray substructures tend to be much rounder than in the mass maps, as expected, since the gas traces the potential, which is smoother and more spherical than the density.

2.3 Characterizing dynamical state from the maps

Our first application of the maps is to estimate the dynamical state of the cluster from its visual appearance. We employ the method of O’Hara et al. (2006), also found to provide a reliable indicator of dynamical state by Poole et al. (2006), using idealized simulations of cluster mergers. For this method, the displacement between the X-ray peak and centroid is calculated within circular apertures ranging from $r_{500}$ down to 0.05$r_{500}$ in radius, decreasing by 5 per cent each time, and then the rms value of the displacement is computed, relative to $r_{500}$. We found this technique to be most effective when using heavily smoothed maps to compute the centroid, so adopt the smoothing kernel used in our substructure detection algorithm (described in Section 4), but with $\sigma = 0.1 r_{500}$. The position of the peak is always taken as the centre of the cluster, as defined in the previous section.

The variation of this rms 2D statistic with redshift is shown in the middle panels of Fig. 1. Values above 10 per cent (indicated with a horizontal line) are typically found when a cluster is undergoing a major merger (see e.g. Poole et al. 2006). The redshifts at which this value is exceeded are also indicated with filled symbols in the mass histories (top panels). The bottom panels of the same figure give examples of clusters with low, intermediate and high values of the rms centroid shift, clearly showing an increase in dynamical activity.
3D SUBHALO DETECTION

Although the key objective of our analysis is to study the X-ray and mass maps of the clusters, we can draw important insight from an analysis of the full 3D data. In this section, we identify 3D self-bound DM subhaloes in the map region (a cylinder of radius $r_{500}$ and length 8$r_{500}$, centred on the main cluster) and investigate their global properties. The information we glean from this analysis

Figure 2. Examples of cluster maps. Left-hand column: logarithmic surface mass density maps for, top to bottom, Cluster A cooling run, Clusters A, B and C non-radiative runs at $z = 0$. Right-hand column: the same but for the logarithmic X-ray surface brightness maps.
will help us to interpret our results in Section 6 by allowing us to
distinguish the underlying physical mechanisms from any effects
introduced by our method.

3.1 Detection technique

We use a version of SUBFIND (Springel et al. 2001a) to decompose
FoF groups (identified for this purpose with $b = 0.2$) into 3D self-
bound subhaloes. The modified version, kindly provided by Volker
Springel (see also Dolag et al. 2009), identifies both gas and DM
particles (and star particles when relevant) within each subhalo.
A region larger than the final map region is analysed such that
all subhaloes that contribute significantly to, but may not be fully
within, the map region are included.

We employ a threshold of 100 DM particles, corresponding to
a mass, $M \approx 4 \times 10^{10} h^{-1} M_\odot$, as our minimum resolution limit
for the subhalo catalogues. As we will show, this is significantly
below our 2D completeness limit (determined in Section 5). As our
3D subhalo catalogues will form the basis for comparison with 2D
substructure, we consider not only subhaloes that lie entirely within
the map region, but also those with at least 75 per cent of their mass
along the line of sight (as defined in Section 2), even if their centre
coordinates are outside $r_{500}$ in projection. Note that even if less than
100 per cent of the subhalo’s particles are within the map region,
the whole DM mass of the subhalo is still recorded.

The mass of each subhalo is computed using only the DM parti-
cles, to reduce its dependence on the amount of gas stripping that
has occurred (the mass, $M_{\text{sub}}$, therefore refers to the DM mass of
the subhalo). We take the centre of the subhalo to be the position
of the most bound particle, but also calculate a projected centre,
to facilitate matching with the substructures in the map. This was
determined to be the position of the peak projected number of DM
particles, i.e. the coordinates of the cell containing the most par-
ticles when each subhalo’s DM particles are binned according to
their $X$ and $Y$ coordinates (particles with $Z$ coordinates outside the
map region are excluded).

3.2 Properties of 3D subhaloes

Before we begin discussion of the results in this section, it is im-
portant to note that we always include the main cluster halo in the
subhalo data. This is important to facilitate the comparison to 2D
substructures detected in the maps later on, as the cores of the clus-
ters (see the central mass density peaks clearly evident in the first
column of Fig. 2) are detected in 2D and these cores, therefore, are
detected as 2D substructures in their own right.

In Fig. 3, we show the cumulative subhalo DM mass function for
subhaloes with their most bound particle inside 3D $r_{500}$, down to
our imposed resolution limit of 100 DM particles. The results for
Clusters A (solid), B (dotted) and C (dashed) are shown individually
for $z = 1$ (left-hand panels), 0.5 (middle panels) and 0 (right-hand
panels) in the first row. Note that the main cluster itself is the
most massive subhalo. The total number of resolved subhaloes,
ranging from less than 10 to nearly 60, depends on cluster mass.
For example, Cluster C has significantly fewer subhaloes at $z = 1$
and 0.5 than the other two clusters, but has more at $z = 0$. This
increase reflects Cluster C’s major merger at $z \sim 0.4$, as seen in
Fig. 1. However, when the subhalo masses are scaled to the parent
cluster mass, the scatter between clusters and redshifts is much
smaller, as shown in the second row.

We have also examined how the properties of subhaloes in the
map region vary depending on whether or not they lie within $r_{500}$
in 3D, to assess the impact of subhaloes projected along the line of
sight. It is particularly important that we examine the distribution of
subhaloes, because of the unusual geometry we are using (a cylinder,
rather than a sphere). In the left-hand panel of Fig. 4, we show the

![Figure 3](https://academic.oup.com/mnras/article-abstract/400/2/705/1016362)

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Figure 3. Subhalo mass functions for Cluster A (solid lines), B (dotted lines) and C (dashed lines), at redshifts, $z = 1$ (left-hand panels), $z = 0.5$ (middle panels) and $z = 0$ (right-hand panels). First row: cumulative subhalo (DM) mass functions. Second row: as for first row, but with the subhalo DM masses scaled to $M_{500}$. Data are for subhaloes with their most bound particle within $r_{500}$.
fraction of subhaloes (including the main cluster halo) in the entire map region that lie within \(r_{500}\) (solid) and \(2r_{500}\) (dashed) in 3D for the redshift intervals \(0 \leq z \leq 0.2\) (red lines) and \(0.5 \leq z < 1.0\) (black lines). These redshift intervals were chosen to include an equal number of snapshots (11). Around half of the low-mass subhaloes lie within \(r_{500}\) which is significantly higher than for a uniform distribution, for which we would expect, \(f_{\text{gas}} = 5\pi r_{500}^2/8\pi r_{500}^3 = 1/6\) (indicated by the dot-dashed line). Nearly all subhaloes (80–100 per cent) lie within \(2r_{500}\), suggesting that the contribution to the map from substructure outside the cluster’s virial radius is small. The rise, compared to lower mass bins, in the fraction of subhaloes with \(M_{\text{sub}} > 10^{13} h^{-1} M_\odot\) within \(r_{500}\) is due to the presence of the cluster cores. The cluster cores dominate this bin (in number) and since the map region is centred on them, they are always within \(r_{500}\) by design. At high redshift, the fraction of galaxy-sized \((M_{\text{sub}} < 10^{13} h^{-1} M_\odot)\) subhaloes within \(r_{500}\) is approximately 10 per cent higher than at low redshift. This is likely to be caused by the effects of tidal forces, stripping the DM as the subhalo orbits in the cluster potential. This effect may reduce the likelihood of finding subhaloes which are dark in X-rays in this mass range at low redshift, since they may move to lower DM mass bins (via tidal stripping) shortly after their hot gas is removed.

Given the aims of this investigation, we want to try to place some limits on the fraction of DM substructures without X-ray emission we expect to find. In the middle and right-hand panels of Fig. 4, we now plot the fraction of subhaloes [within \(r_{500}\) (solid) and the full map region (dashed)], with no hot \((T > 10^6 K)\) gas \((f_{\text{gas}} = 0)\) and little hot gas \((f_{\text{gas}} \leq 0.5\Omega_b/\Omega_m)\), respectively. This somewhat arbitrary threshold, \(f_{\text{gas}} \leq 0.5\Omega_b/\Omega_m\), was chosen simply to distinguish hot gas-poor subhaloes from hot gas-rich subhaloes. Note that, by definition, the rest of the subhaloes \((1 - f_{\text{sub}})\) fall into the latter category and have \(f_{\text{gas}} > 0.5\Omega_b/\Omega_m\). The main trend apparent is that the fraction of empty or low-gas subhaloes is higher at lower mass, in agreement with Tormen et al. (2004), who find the survival time of hot gas in subhaloes is a strong increasing function of subhalo mass. Without the added effects of radiative cooling and energy injection from galactic winds, for example, our results already predict that the vast majority of galaxy-sized \((10^{11} \leq M_{\text{sub}}/h^{-1} M_\odot < 10^{13})\) subhaloes are substantially depleted of hot gas, while the opposite is true on group (and cluster) scales. We also find that more subhaloes have no hot gas at low redshift than at high redshift, in agreement with Dolag et al. (2009). We note that the middle panel of Fig. 4 is insensitive to the temperature threshold, since the vast majority of subhaloes with no hot \((T > 10^6 K)\) gas have no gas of any temperature.

The vast difference between the fraction of empty subhaloes in the lowest mass bin and at higher masses (e.g. \(\approx 80\) per cent of subhaloes with \(10^{11} \leq M_{\text{sub}}/h^{-1} M_\odot < 10^{12}\) already gas-free at high redshift, yet still only \(\approx 30\) per cent with \(10^{12} \leq M_{\text{sub}}/h^{-1} M_\odot < 10^{13}\) gas-free at low redshift) is qualitatively in agreement with Tormen et al. (2004), if we assume higher redshift to indicate less time since infall. They find complete removal of hot gas within 1 Gyr (typically massive galaxies) to 3 Gyr (typically groups) of entering the cluster’s virial radius on average. Results from McCarthy et al. (2008b) are in general agreement, but indicate \(\approx 30\) per cent of the hot gas in a halo (typically a massive galaxy) can survive much longer (\(\approx 10\) Gyr); a result shown to improve colours of satellite galaxies in semi-analytic models (Font et al. 2008). We find that the majority of subhaloes with \(M_{\text{sub}} > 10^{12} h^{-1} M_\odot\) always retain some hot gas and indeed at least 20 per cent have \(f_{\text{gas}} > 0.5\Omega_b/\Omega_m\). This shows that our results are compatible with subhaloes retaining some of their original hot gas, although it seems in most cases the majority is removed.

Dolag et al. (2009) find that stripping is very efficient with \(\approx 99\) per cent of all subhaloes in \(r_{500}\) being gas-free at \(z = 0\). Note that this percentage will be dominated by their low-mass subhaloes which are most numerous (and most gas-deficient) and so compares well with the percentage (90 per cent) that we find in our low-mass bin. It remains to be seen how much gas has to be stripped before the likelihood of detecting the substructure in both the total mass and X-ray surface brightness maps is affected.

### 4 2D SUBSTRUCTURE DETECTION

A number of authors have used 2D weak-lensing maps and X-ray images of clusters, both to compare the spatial distribution of hot gas and DM in these objects (e.g. Clowe et al. 2004; Mahdavi et al. 2007; Bradač et al. 2008) and to help infer their dynamical state, by measuring the offset between the centres of these two components (Smith et al. 2005). The scope of the information about the underlying 3D system, which such 2D comparisons could potentially provide, has not yet been explored, and the present study is the first attempt to do this.

The key features of this piece of work are a simple, yet effective, technique for identifying substructure in 2D maps of simulated clusters, in combination with an easy-to-use method for mapping...
2D mass substructures to both 2D X-ray substructures and 3D sub-haloes. First, we analyse our ‘perfect’ observations (i.e. noise-free maps). This allows us to establish how many projected mass and X-ray substructures can, in principle, be uniquely identified despite projection effects and the intensity of the cluster background. This approach also provides insight into the fate of a projected mass substructure’s hot gas when an X-ray counterpart is not found; the maps (unlike 3D data) allow immediate visual follow up and reveal interesting features of the stripping process. We will explore how much of this is observable with current techniques in Section 7.4, by degrading the map resolution and adding noise to both map types.

4.1 Detection technique

The first step towards detection is to enhance the substructure in the maps. For this purpose, we use a method based on the unsharp-masking technique, in order to remove the cluster background. The unsharp-masking technique itself has already been used as a visual aid by highlighting small-scale structure in X-ray images of galaxy clusters, for example Fabian et al. (2003, 2005). The main advantage is that it does not rely on the cluster being circularly symmetric, recovering the distribution of substructure well even in the most complex scenarios (i.e. multiple mergers, as is sometimes the case in our simulations, especially at high redshift).

The first stage of the procedure is to smooth the maps with a preliminary Gaussian filter. This could be used to emulate the point spread function of a real instrument, but here we set the full width half-maximum (FWHM) to simply match the spatial resolution of the simulation, as our results are presented in the limit of no added noise (other than intrinsic discreteness noise due to the finite number of particles employed). Our maps contain a fixed number of pixels (200) across \( r_{500} \), corresponding to a length-scale for each pixel of around \( 5 \, h^{-1} \text{kpc} \) at \( z = 0 \), which is the equivalent Plummer softening length of our simulation (held fixed in proper units over the redshift range of interest here). The minimum length-scale that should be trusted is around three times this, corresponding to the extent at which the gravitational force law becomes perfectly Newtonian in the GADGET-2 code. Furthermore, \( r_{500} \) is smaller at higher redshift, so our pixel scale is also smaller. We therefore set FWHM = \( 15 \, h^{-1} \text{kpc} \) (physical) for all maps studied in this paper. It should also be noted that the maps are generated to be larger in \( X \) and \( Y \) than required, so that the larger maps can be analysed to avoid edge effects in the region of interest. Panels (a) and (e) in Fig. 5 illustrate examples of these pre-smoothed maps.

The second stage is to convolve the pre-smoothed maps again with a broader Gaussian kernel, to create the unsharp-mask image, shown in Fig. 5, panels (b) and (f). Here, we fix \( \sigma_2 \) to be 0.05 \( r_{500} \) (corresponding to an FWHM ranging from approximately 35 to 120 \( h^{-1} \text{kpc} \) over the redshift range), which was deemed to be the most effective value from extensive testing. This twice-smoothed version of the map is then subtracted from the pre-smoothed map, leaving a map showing just the enhancements to the cluster background.

Utilizing the commutative, distributive and associative properties of convolution, it is possible to derive one function that, when convolved with the map image, produces the same result as the series of operations described above. The kernel used to generate the pre-smoothed map approximates the Gaussian function, which is given by

\[
G_{\text{prelim}} = N_1 e^{-\frac{x^2+y^2}{2\sigma_1^2}},
\]

where the normalization,

\[
N_1 = \frac{1}{2\pi\sigma_1^2},
\]

and, in this case,

\[
\sigma_1 = \frac{15 \, h^{-1} \text{kpc}}{\sqrt{8 \ln 2}}
\]

Figure 5. An example of our substructure detection procedure for Cluster C at \( z = 0.162 \). The top row corresponds to the surface mass density maps and the bottom row to the X-ray maps surface brightness maps (see the text for further details).
which is set by the spatial resolution of the simulation. Similarly, the combined operations of pre-smoothing and generating the unsharp-mask image are simply

\[
G_{US} = N_{1,2} e^{-\frac{x^2 + y^2}{2(\sigma_1^2 + \sigma_2^2)}},
\]

where the normalization is now

\[
N_{1,2} = \frac{1}{2\pi(\sigma_1^2 + \sigma_2^2)},
\]

and \(\sigma_2 \approx 0.05r_{500}\). The function representing the entire procedure

\[
F = G_{\text{prelim}} - G_{US},
\]

which is a close approximation to the Mexican-hat function or the matched filter defined by Babul (1990), is shown in Fig. 6.

The sizes of substructures that are detected are dependent on the combination of the standard deviations of the Gaussians used to obtain the final image. We derive an expression that characterizes the width of the kernel and therefore the scale of substructure to which our technique is sensitive. The characteristic width of the function in Fig. 6 can be determined by calculating the radius at which the amplitude of the function is zero. The radius of the zero-points, \(r_0\), is given by

\[
r_0 = \sqrt{2} \left[ \frac{\sigma_1^2 + \sigma_2^2}{\sigma_1^2 / \sigma_2^2} \right] \ln \left( \frac{\sigma_2^2 + \sigma_1^2}{\sigma_1^2 / \sigma_2^2} \right)^{\frac{1}{2}}.
\]

Since \(\sigma_2\) is expressed in units of \(r_{500}\), it has a slight redshift dependency (e.g. for Cluster B, \(r_{500} = 0.34\ h^{-1}\ \text{Mpc}\) at \(z = 1\) and \(0.78\ h^{-1}\ \text{Mpc}\) at \(z = 0\)), meaning that more extended substructures will be detected at lower redshifts. However, the increase in the value of the kernel width is only of the order of 20 per cent of its maximum value over the range of redshifts studied, \(0 \leq z < 1\) (e.g. \(r_0 = 0.014\ h^{-1}\ \text{Mpc}\) for \(z = 1\) and \(0.018\ h^{-1}\ \text{Mpc}\) for \(z = 0\), averaged over the three clusters). We are limited to detect only 2D mass substructures of the order of the size of the kernel and these 2D mass substructures will, of course, be associated with a 3D subhalo mass. Since the typical size of a 3D subhalo above a given mass is larger at lower redshift, due to the decrease in the critical density as the Universe expands, the trend for the kernel to also be larger at lower redshift actually reduces the redshift dependence of the minimum 3D subhalo mass which we can detect in 2D.

In order to pick out the true substructures from other fluctuations, any pixels with values less than \(\mu + X\sigma\) (where \(X\) is an integer, representing our detection threshold, and \(\mu\) and \(\sigma\) are the mean and standard deviations of the residual substructure maps) are discarded. Examples of the resulting maps at this stage of the procedure are shown in Fig. 5, panels (c) and (g). Substructures are then defined similarly to the FoT technique but in 2D, grouping together neighbouring pixels with values greater than the background level. Ellipses are fitted to these pixel groups by finding the eigenvectors (corresponding to the direction of the semimajor and semiminor axes) and the eigenvalues (whose square roots correspond to the magnitude of the semi-axes) of the moment of inertia tensor. This allows us to determine the extent, orientation and circularity of the 2D substructures (see below).

We investigate three values of \(X\) for the projected total mass map: 1, 3 and 5, and evaluate which is most successful when the comparison with the 3D subhalo data is made in Section 5. It was found that the X-ray surface brightness maps respond slightly better to our technique due to the fact the gas distribution is far smoother (because it traces the gravitational potential) and contains fewer small-scale fluctuations, meaning that less stringent cuts are required in order to achieve the same results (upon visual inspection). Therefore, the selection of the parameters used to define the catalogue of X-ray substructures is undertaken separately to that for the mass substructures. We found that \(X = 5\) is too stringent for the X-ray maps, removing substructures that are clearly visible by eye, whereas \(X = 1\) and 3 produce reasonable results for both the X-ray and the mass maps.

### 4.2 Properties of 2D substructures

The total number of substructures detected in the \(1\sigma, 3\sigma\) and \(5\sigma\) total mass catalogues (which consist of 90 maps, i.e. 30 per cluster) is 3224, 1233 and 680, respectively. It is clear from these numbers that, as would be expected, the higher the value of \(X\), the lower the number of detections. There are also considerably fewer X-ray substructures than total mass substructures for the same \(X\) value, with 1169 in the \(1\sigma\) X-ray catalogue and 707 in the \(3\sigma\) X-ray catalogue. This can in part be attributed to the smoother distribution of the hot gas, which responds differently to the unsharp-masking procedure. However, it is also apparent (on visual inspection) that there is simply less inherent structure in the X-ray maps, particularly on small scales.

First, we examine the distribution of total mass (solid) and X-ray surface brightness (dashed) substructure areas, \(A_{sub}\), in the left-hand panel of Fig. 7. \(A_{sub}\) is defined as the number of pixels attributed to the 2D substructure in the unsharp-masked image multiplied by the physical area of the individual pixels. The distributions are very similar, except the X-ray surface brightness distribution peaks at a slightly higher value of \(A_{sub}\), suggesting the X-ray substructures are typically more extended (this is confirmed by visual inspection). There is little dependence on the choice of catalogue here.

We examine the shape of the substructures by plotting the distribution of circularities in the middle panel of Fig. 7 (line styles as before). Here, we define circularity, \(c = (b/a)\), where \(a\) is the major axis and \(b\) the minor axis of the ellipse. This distribution is very stable across the range of catalogues, suggesting that the morphology of the objects we detect changes little between catalogues.

The distribution of mass substructures peaks at \(c \sim 0.75\), due to the triaxial nature of the DM substructure; the gas is slightly rounder
and peaks at $c \sim 0.8$. Knebe et al. (2008) obtain a similar result for their projected sphericity of DM subhaloes, computed from the particles directly. This indicates that our detection method recovers the true 2D shape of the substructures successfully.

The right-hand panel of Fig. 7 shows the distribution of the radial alignment of the 2D substructures with respect to the cluster centre. This is computed by first calculating the angle of inclination between the cluster centre (in 2D) and the centre of the ellipse representing a substructure. The alignment, $\theta$, is then found by subtracting from this the angle of inclination of the semimajor axis of the ellipse. The range of $\theta$ can be reduced to $0^\circ$–$90^\circ$ by treating opposite directions of the semimajor axis vector as equivalent. A mild tendency towards alignment is exhibited by the total mass substructures (solid), however the X-ray substructures (dashed) show no preferred direction. Knebe et al. (2008) perform a similar calculation for their projected DM subhaloes and found a much stronger tendency for alignment than we see here, when they considered all particles associated with the subhalo. However, they investigate the effect of varying the percentage of particles they analyse by limiting the alignment measurement to the inner regions of the subhaloes. The trend for alignment shown in their results weakens as smaller percentages of particles are considered and comes into agreement with observations when analysing the inner 10–20 per cent. Our result is also in much better agreement with theirs for this region. This reflects the fact that our 2D detection technique finds only the cores of the original 3D subhaloes, which is demonstrated by the small scale of the detected 2D substructures. Therefore, we are effectively performing our alignment and circularity analysis on only the innermost particles and so find best agreement with Knebe et al. (2008) when they similarly restrict their analysis.

5 COMPARISON OF 2D MASS SUBSTRUCTURES TO 3D SUBHALOES

In this section, by comparing the 2D total mass substructures (described in Section 4) with 3D self-bound DM subhaloes (described in Section 3), we assess the reliability of our 2D detection method and infer the 3D properties (e.g. subhalo mass) of our 2D substructures. We examine the completeness (with respect to 3D) of our 2D catalogues, as well as the number of individually resolved high-mass objects they contain, in order to select one total mass catalogue that is most suited for the analysis in later sections. Our catalogues contain substructures identified in all three clusters and at all redshifts ($0 \leq z < 1$).

Ideally, we want to be 100 per cent complete down to at least $M_{\text{sub}} \sim 10^{13} h^{-1} M_\odot$, as this is the typical mass scale of substructures detected in current observations of the unusual systems discussed in Section 1. However, high completeness at lower masses would be desirable as smaller subhaloes are the more likely ones to be found stripped of their gas (Tormen et al. 2004). An additional criterion we wish to place on any detections is that, ideally, they are individually resolved (i.e. not confused with another subhalo that is nearby in projection). We also look at the purity of our 2D substructure catalogues by assessing the fraction of 2D substructures which we fail to associate with 3D subhaloes.

5.1 Completeness

First, we determine the completeness of each of our three 2D mass substructure catalogues ($X = 1, 3, 5$). This is done by starting with the 3D subhaloes and looking for 2D counterparts in the mass maps, then examining the resulting matching success (i.e. the fraction of 3D subhaloes for which a 2D counterpart is found) per 3D subhalo mass bin. The criterion for matching the 3D subhaloes to the 2D mass substructures is that the centre of the 3D subhalo must lie within the ellipse that characterizes the 2D substructure (with a ±20 per cent margin for error, which was determined by experiment). As discussed in Section 3, the default 3D centre is taken to be the (projected) position of the most-bound particle in the subhalo, as identified by SUBFIND. This is a robust choice, comparing very well with the peak surface density in the maps in the vast majority of cases. However, during a complicated merger, we found that the most bound particle can occasionally lie outside the cluster core (see Section 7.2), in which case we apply the position of the peak projected DM particle density of the cluster instead.

Multiple 3D subhaloes can be matched to the same substructure in the mass map; we refer to this as a multiple match. However, 2D substructures cannot share a 3D subhalo as our criterion means each subhalo is only ever matched to one 2D substructure. It should also be noted that we start with a limited 3D catalogue containing only those subhaloes whose centres are within the projected $r_{500}$ and match to the complete catalogue of 2D substructures, which extends slightly beyond the projected $r_{500}$ (i.e. outside the map). This simply prevents the failure to match a genuine 2D–3D pair when one substructure’s centre lies slightly outside this boundary.

Fig. 8 illustrates the completeness of our 2D catalogues as a function of subhalo mass (note that the main clusters are included in these data). Specifically, it shows the fraction of all subhaloes in the map region that are detected, including those subhaloes associated with the same 2D substructure, due to source confusion or genuine projection effects (detailed below). In all three catalogues, we clearly associate 2D substructures with all 3D subhaloes...
that have \( M_{\text{sub}} > 10^{13} \, h^{-1} M_\odot \). The 1σ, 3σ and 5σ catalogues are 90 per cent complete per mass bin down to \( 3 \times 10^{11}, 10^{12} \) and \( 3 \times 10^{12} \, h^{-1} M_\odot \), respectively.

The cut-off in completeness, below which our ability to retrieve 3D subhaloes from the projected data decreases sharply with mass, is a result of several limiting factors: the map resolution (effectively set by the pre-smoothing kernel size, \( \sigma_1 \)), the choice of \( \sigma_2 \) and simply the intensity of the cluster background. Low-mass subhaloes have poor contrast against the background since they add little mass in addition to the total mass along the line of sight and so are difficult to distinguish. The mass at which this cut-off occurs is most sensitive to \( \sigma_1 \). As we demonstrate in Section 7.4, when we increase \( \sigma_1 \) by a factor of around 10 (more typical of the resolution of weak-lensing mass reconstructions), the 90 per cent (per mass bin) completeness limit for the 3σ catalogue becomes \( \sim 10^{11} \, h^{-1} M_\odot \) (see Fig. 26).

5.2 Projection and Confusion

Visual inspection of the projected mass maps reveals that two peaks that are very nearby can be detected as one 2D substructure (i.e. confused), if the lower density pixels between them are not removed when pixels \( < \mu + X \sigma \) are discarded. This is not a concern if the mass ratio of the 3D subhaloes that have given rise to the 2D peaks is high (as the inclusion of the less massive object has little effect), or if they are both low-mass subhaloes (\( \sim 10^{11} \, h^{-1} M_\odot \)), below the mass range we are interested in. However if, for example, a subhalo with a mass, \( M_{\text{sub}} \sim 10^{13} \, h^{-1} M_\odot \), and the main cluster core give rise to two adjacent peaks in the map which are confused as one 2D substructure, we limit our opportunities to study the properties of the subhalo in detail. This is particularly important since subhaloes with \( M_{\text{sub}} > 10^{13} \, h^{-1} M_\odot \) are relatively rare. A related effect is that of projection, where two subhaloes that are aligned along the line of sight give rise to only one peak in the projected mass map.

Here, we do not distinguish explicitly between projection and confusion. Instead, we define a detected subhalo as obscured if it is part of a multiple match and is not the most massive subhalo involved; we would not consider such a subhalo to be individually resolved. Fig. 9 shows the fraction of detected subhaloes per mass bin which are obscured. As expected the obscured fraction at the high-mass end is lowest for the 5σ catalogue and highest for the 1σ catalogue, since the former is the most stringent when removing low-density pixels between adjacent substructures, allowing them to be individually resolved. The trend reverses at low mass, however, because the removal of low-density pixels also erases small 2D substructures. Since this is more effective with a larger value of \( \sigma \), the fraction of obscured substructures (detected only because of their association with larger substructures) increases. For the 3σ catalogue, around 70 per cent at \( 10^{11} \, h^{-1} M_\odot \), 5 per cent in the \( 10^{12} - 10^{13} \, h^{-1} M_\odot \) mass range and zero at the high-mass end are obscured. On inspection of the maps, it is apparent that the obscured fraction at mass scales of \( \sim 10^{11} \, h^{-1} M_\odot \) typically occurs in the final stages of a merger and results from confusion when the two objects coalesce.

We adopt the 3σ catalogue from now on as it offers a small reduction in the obscured fraction at high masses while maintaining good completeness above \( M_{\text{sub}} = 10^{12} \, h^{-1} M_\odot \), detecting 98 per cent of all subhaloes above this mass.

5.3 Purity

We now consider the purity of our 3σ catalogue, by undertaking the matching procedure in reverse, i.e. starting with the 2D mass substructures and trying to identify 3D subhalo counterparts for these. The matching success (i.e. the fraction of 2D mass substructures that are successfully matched to a 3D subhalo, in this case) then provides a measure of the purity. This is important as it tells us in which regions of parameter space the raw 2D data could potentially be used directly, without reference to the 3D data for calibration.

Fig. 10 shows the fractional matching success of 2D mass substructures to 3D subhaloes versus the characteristic physical area of the 2D substructure, \( A_{\text{sub}} \).

We achieve very high purity down to \( A_{\text{sub}} \simeq 3 \times 10^{-3} \, h^{-2} \text{Mpc}^2 \), close to the approximate projected area of our combined kernel, \( F(\sigma r_s^2) \simeq 10^{-3} \, h^{-2} \text{Mpc}^2 \); see equations (10) and (11) for definitions of \( F \) and \( r_s \). Reasons for not finding a 3D subhalo to match every 2D substructure are three-fold. First, we have detected a substructure associated with a 3D subhalo with less than 100 DM particles (i.e. our minimum allowed subhalo size). Secondly, the substructure detection is ‘false’, i.e. we have detected a transient enhancement which does not constitute a self-bound subhalo. Or, finally, there is
belong to a subhalo. Effectively, the background halo is the parent halo in which the other subhaloes reside. The background haloes grouped in the top right are the cluster cores themselves, forming a separate population because the 2D detection corresponds to the core only, whereas the mass is that of the entire cluster. The background haloes at lower masses are smaller parent haloes which lie in front of or behind the main clusters. This figure shows that when we are above the completeness limit in terms of associated 3D subhalo DM mass ($M_{\text{sub}} = 10^{12} h^{-1} M_\odot$), most 2D substructures are also in the region where we know our 2D catalogue is pure (i.e. $A_{\text{sub}} > 3 \times 10^{-4} h^{-2} \text{Mpc}^2$); the converse does not hold, however.

For the rest of the substructures, that are not background haloes, we demonstrate a strong correlation between the 3D DM subhalo mass ($M_{\text{sub}}$) and the 2D area ($A_{\text{sub}}$). A least-squares fit to this correlation yields

$$\log \frac{M_{\text{sub}}}{10^{10} h^{-1} M_\odot} = (1.13 \pm 0.04) \log \frac{A_{\text{sub}}}{h^{-2} \text{Mpc}^2} + (5.4 \pm 0.1),$$

(12)

where all points with $A_{\text{sub}} > 3 \times 10^{-4} h^{-2} \text{Mpc}^2$ were considered. Using this correlation, we can select a new threshold of $A_{\text{sub}} = 10^{-3} h^{-2} \text{Mpc}^2$ (corresponding to a mass of $10^{12} h^{-1} M_\odot$) producing a sample of substructures with both high purity and high completeness (we refer to such catalogues as pure).

We can also estimate the intrinsic scatter in this relation using,

$$\sigma_{\log(M_{\text{sub}})} = \sqrt{\frac{1}{N} \sum_i [\log(M_i) - \log(\langle M_i \rangle)]^2},$$

(13)

where $M_i$ is the mass value of each data point and $\log(M_{\text{fit}})$ is the value computed using equation (12) for the corresponding area. We find $\sigma_{\log(M_{\text{sub}})} = 0.35$, which suggests that the typical uncertainty in the DM mass of a subhalo is around a factor of 2. For comparison, the fit was also made using the discarded 1σ and 5σ 2D mass catalogues instead and the intrinsic scatter in the resulting relations was very similar (0.30 and 0.37, respectively) suggesting the quality of the fit is independent of catalogue choice. Furthermore, for a given value of $A_{\text{sub}}$, the maximum variation in the estimated value of $M_{\text{sub}}$ when comparing all three 2D catalogues with each other is approximately a factor of 3, comparable to the error from intrinsic scatter. We also note that the intrinsic scatter is greater at higher redshift, for example it is 0.31 when fitting only to data for $0 \leq z \leq 0.2$ and 0.41 for $0.5 \leq z < 1.0$. Such a correlation, though calibration-dependent, is potentially useful for providing a quick, rough estimate of subhalo DM mass determined from the observed area of a substructure in a weak-lensing map (assuming the substructure is resolved).

### 5.5 Summary

We have matched our 2D total mass substructure catalogues to self-bound 3D subhaloes and have identified the 3σ catalogue as the most suitable for the analysis in future sections. This catalogue is at least 90 per cent complete in all subhalo mass bins above $10^{12} h^{-1} M_\odot$ and pure above a projected area of $3 \times 10^{-4} h^{-2} \text{Mpc}^2$, which is close to the resolution limit of our kernel. We also note a strong correlation between the (observable) area of the 2D substructure and the DM mass of the 3D subhalo. Using this, we derive an area threshold, $10^{-3} h^{-2} \text{Mpc}^2$, above which our substructure catalogues have both high purity and completeness. Projection and confusion effects above the completeness limit are minimal.
6 COMPARISON OF SUBSTRUCTURE IN THE HOT GAS AND DARK MATTER COMPONENTS

We now address the main aim of this paper: comparing the substructure in the X-ray surface brightness and total mass maps. Again, we apply a simple matching technique, this time to our pairs of maps and then attempt to explore the underlying physical mechanisms which govern the resulting matching success, whilst also trying to constrain any potential biases our method may have introduced.

The catalogues of 2D mass substructures and 2D X-ray substructures are compared for each snapshot. The criterion for a match is that there is some overlap of the region enclosed by the ellipse that characterizes the mass substructure and the region enclosed by the ellipse that characterizes the X-ray substructure. In order to keep our method simple, we allow both 2D total mass and 2D X-ray surface brightness substructures to be matched to more than one substructure of the other type, rather than using additional matching criteria to prevent this. We use the term single match to refer to a unique pairing of one mass substructure with one X-ray substructure, and the term multiple match for a mass substructure which has been matched to more than one X-ray substructure or vice versa.

6.1 Direct matching

An important feature of this work is the use of 2D data (maps) so, with this approach in mind, we first undertake the matching with no reference to the 3D subhalo data. This will allow us to confirm how reliable a picture the 2D data alone can provide as we can later compare our results to those which have been calibrated against the 3D subhalo information.

As in Section 5, we undertake the matching procedure in two ways; starting with the 2D total mass substructures and seeking an X-ray counterpart for each and then starting with the 2D X-ray substructures and seeking a mass counterpart for each. Table 1 summarizes the results of these matching processes, where the data for 2D mass substructures come from the former and that for 2D X-ray substructures from the latter. Here, we use the subscripts TM and SB to signify substructures in the total mass and X-ray surface brightness maps, respectively.

First, it is encouraging that the fraction of substructures which are matched to more than one object (f_mismatched) is very low (2–10 per cent) regardless of the choice of 2D X-ray catalogue, or whether only the pure sample of 2D mass substructures is used. High numbers of single matches are preferred as this suggests the effect of confusion is limited and that the number of false matches is low.

The ratios of X-ray to total mass substructures (N_SB/N_TM) show that when using the full 2D mass catalogue, there is always a dearth of X-ray substructures and so, regardless of the criterion employed, there will be unmatched 2D mass substructures. However, when using the pure 2D mass catalogue, there is a factor of ∼2–3 more X-ray substructures. The fraction of total mass substructures that are matched (f_matched) roughly doubles when moving to the pure sample, suggesting that the majority of mass substructures discarded to obtain purity did not have an X-ray counterpart. This could be interpreted in one of the two ways; the discarded 2D mass ‘substructures’ were false detections and so one would not expect to find any corresponding substructure in the X-ray emitting gas, or they were real but may have corresponded to low-mass 3D subhaloes which are less likely to have retained their hot gas. In fact, around 75 per cent of 2D mass substructures below the purity threshold were matched to a 3D subhalo, suggesting it is the latter effect that dominates. Interestingly, when moving from the 1σ to the 3σ X-ray catalogue the fraction of mass substructures matched decreases, but the same quantity for the X-ray increases. Here, the 3σ X-ray catalogue is more pure as a greater fraction of its substructures can be matched to 2D mass substructures; however, the 1σ X-ray catalogue is more complete since a greater absolute number of its substructures are matched to 2D mass. A similar trade-off between purity and completeness was seen when matching 2D mass substructures to 3D mass subhaloes in Section 5. The added complication here, of course, is that unlike the 2D mass substructures and 3D subhaloes, we cannot assume a 1:1 correspondence between the 2D mass and 2D X-ray substructures (in fact the deviation from this is the motivation for this work), so a completeness limit cannot really be established.

Even more surprising than the large fraction of 2D mass substructures with no X-ray counterpart is that a 2D total mass counterpart cannot be found for a high percentage of the 2D X-ray substructures. Even when considering the 3σ X-ray catalogue, which picks out only the most defined 2D substructures in the hot gas, and matching this with the full 3σ 2D mass catalogue, 40 per cent of the X-ray substructures still go unmatched. Investigating the properties of the matched and unmatched substructures should provide insight into this result.

Focusing first on those substructures that are matched, we compare the properties of the 2D matched pairs. Fig. 12 demonstrates the tight correlation between the area of singly matched X-ray (1σ catalogue) and total mass (3σ catalogue) substructures. The best-fitting line for matched pairs from this combination of catalogues, where the 2D mass map substructure is in the pure region (A_H2 > 10^−3 h^−2 Mpc^2), is given by

\[
\log \frac{A_{sub,TM}}{h^{-2} \text{Mpc}^2} = (0.83 \pm 0.04) \log \frac{A_{sub,TM}}{h^{-2} \text{Mpc}^2} - (0.4 \pm 0.1). \tag{14}
\]

Including all multiple matches as well increases the scatter, but the relationship is still clearly evident. Note that the X-ray substructures are slightly larger than the total mass substructures; this is partly due to the use of the 1σ catalogue here, but also due to the extended nature of the hot gas (for comparison, the gradient when using the 3σ X-ray catalogue is 0.91 ± 0.06, still less than 1). The outliers above the line can mostly be attributed to small 2D mass substructures being matched to highly elliptical 2D X-ray substructures, which are usually features near the centre of the main

| X_TM | X_SB | N_SB/N_TM | f_matched | f_mismatched |
|------|------|-----------|------------|-------------|
|      |      |           | TM         | SB          |
| Full 2D mass total substructure catalogue |
| 3    | 1    | 0.95      | 0.43       | 0.45        | 0.06        | 0.07        |
| 3    | 3    | 0.57      | 0.32       | 0.59        | 0.08        | 0.03        |
| Pure 2D mass total substructure catalogue |
| 3    | 1    | 2.83      | 0.77       | 0.30        | 0.10        | 0.04        |
| 3    | 3    | 1.71      | 0.67       | 0.43        | 0.10        | 0.01        |

Top rows: matching between all substructures in the X-ray catalogue, to all those in the total mass catalogue. Bottom rows: direct matching of all substructures in the X-ray catalogue to a pure (A_{sub,TM} > 10^−3 h^−2 Mpc^2) total mass catalogue. Columns: multiple of σ used in indicated catalogue (X), ratio of number of substructures (N_SB/N_TM), fraction of total substructures in the catalogue indicated that are successfully matched (f_matched) and fraction of all matched substructures in the catalogue indicated that are matched more than once (f_mismatched).
cluster corresponding to subhaloes actively undergoing stripping. In many cases, it is impossible to tell whether the match is valid or not, however, the scatter occurs below the threshold area which remarks where our catalogue is pure ($A_{\text{sub,TM}} \sim 10^{-3} h^{-2} \text{Mpc}^2$).

With this in mind, it is unsurprising that some of the scatter here also results from spurious detections, i.e. mass substructures that are later found not to correspond to a subhalo. Scatter below the line seems to arise from two situations: (1) a small gas feature is detected that overlaps with a large mass substructure which has been stripped of its gas, i.e. the two are in chance alignment, and (2) the match appears genuine yet the gas substructure is small, suggesting the outer regions of gas have already been stripped.

Fig. 13 shows the fraction of all 2D total mass substructures matched to X-ray (top) and the fraction of all 2D X-ray substructures matched to total mass (bottom) as a function of substructure area. Above $10^{-3} h^{-2} \text{Mpc}^2$, the matching success is $\geq 50$ per cent per bin for both catalogue types; however, this still suggests a very high number of substructures do not have counterparts in the other map. There are also many large unmatched substructures, for example around 10 per cent of 2D mass substructures in the $-2.25 \leq \log(A_{\text{sub}}/h^{-2} \text{Mpc}^2) \leq -2.0$ range. Using equation (12), we can infer that this corresponds to a mass of approximately $10^{10} h^{-1} \text{M}_\odot$, suggesting these correspond to fairly massive 3D subhaloes. Increasing the radius of the unsharp-masking kernel used to detect the X-ray substructures to twice that of the fiducial kernel (i.e. $0.1r_{500}$), yields a similar matching success. This indicates that the results of the substructure comparison that are shown here do not depend significantly on this aspect of the substructure detection procedure.

It is interesting that there are also a significant number of unmatched X-ray substructures, even at large areas. One would initially assume that once hot gas is separated from its DM subhalo it would disperse and so not be detected as a stand-alone substructure. Large unmatched 2D X-ray substructures were followed up individually by visual inspection of the maps, and it appears that there are three main categories. These are (1) clearly defined substructures which are so displaced that they cannot visually be associated with one particular DM substructure (although there are typically candidates in the vicinity), (2) clearly defined substructures that are slightly offset from a nearby dark matter substructure and (3) detections of gas ‘features’ in the vicinity of the core during merger events – these ‘substructures’ cannot be directly associated with a DM substructure, and it is not necessarily appropriate to do so.

Scenario 1 incorporates the most clear-cut examples of 2D X-ray substructures which are indisputably unmatched, whereas Scenario 2 also includes those whose definition as matched or unmatched is somewhat subjective, as it is clear which mass substructure they belong to even though they are spatially distinct from it (for our purposes, we call these unmatched). An example of the displacement of the X-ray component of a substructure can be seen in Section 7.2 (see Case Study 2, Fig. 19). This example is a simple one, however, because there are often numerous hot gas-deficient mass substructures nearby to confuse matters and make determining from which one the X-ray substructure originated impossible (here we also have the time sequence to help us with this).
Scenario 3 is sensitive to the choice of X-ray catalogue so, treating this type of detection as unwanted, we can conclude that the 1σ catalogue suffers from more false detections (by our definition), which goes part way to explain its lower overall matching success. Scenario 2 can also be sensitive to the catalogue choice, as if the displacement between substructures is small, then the increase in area of a 1σ X-ray detection can be enough to meet the overlap criterion in cases where it was not met for the 3σ X-ray detection. For this reason, we continue to show the main results for matching to both the 1σ and 3σ X-ray catalogues, although it should be noted that this effect does not have a big impact on the matching success. Furthermore, in Section 7, where we simplify the discussion by showing results for only one X-ray catalogue, it is the 1σ that is chosen (despite its more numerous spurious detections) since it provides the most conservative estimate of the number of 2D mass substructures for which an X-ray counterpart cannot be found.

6.2 Matching 2D X-ray substructures to 2D mass substructures with a 3D counterpart

Subhalo mass is expected to be a crucial factor when looking for mismatches between DM and hot gas, as gas stripping procedures have more effect on low-mass subhaloes (Tormen et al. 2004). Here, the 3D subhalo data become an invaluable tool, not only because it effectively calibrates our 2D total mass substructure catalogues but because it allows us to probe the effect of subhalo mass on the success of the matching to the 2D X-ray substructures. We repeat the matching procedure outlined above, but this time only use 2D mass substructures which have successfully been associated with a 3D subhalo in Section 5. It should be noted that, in this section, 2D mass substructure catalogue now refers to the calibrated version of the original catalogue, containing only those 2D mass substructures which have a 3D subhalo counterpart. In the case of 2D mass substructures that have been associated with more than one subhalo (see Section 5), \( M_{\text{sub}} \) refers to the combined DM mass of these subhaloes.

Table 2 shows the overall statistics for matching both the full and pure (i.e. \( A_{\text{sub,TM}} > 10^{-3} \, h^{-2} \, \text{Mpc}^3 \)) catalogues of 2D mass substructures with a 3D subhalo counterpart to the 2D X-ray substructure catalogues. It is worth highlighting here that the results in Tables 1 and 2 are almost identical for the pure 2D mass substructure catalogue because, by definition, the vast majority of 2D mass substructures in the pure sample has a 3D counterpart. Note that the ratios of X-ray substructures to total mass substructures in the first row (full 2D mass catalogue) are larger than the equivalent ratios in Table 1, which does not include any reference to the 3D subhalo data. This difference can be directly attributed to the fact that a 3D subhalo counterpart could not be identified for around 10 per cent of the original 2D mass substructures (in the 3σ catalogue) and so \( N_{\text{TM},\text{Table 2}} / N_{\text{TM},\text{Table 1}} \approx 0.9 \), whereas \( N_{\text{sub}} \) remains the same.

There is a slight improvement in the fraction of 2D mass substructures matched to X-ray after calibrating the mass substructures against the 3D subhalo data (i.e. \( f_{\text{matched,Table 2}} > f_{\text{matched,Table 1}} \)), primarily because this process will have removed any spurious detections from our 2D mass catalogues. These are unlikely to be matched to an X-ray substructure, simply because they are due to discreteness noise in the total mass map or an artefact of the unsharp-masking procedure and, as such, we would not expect these to be correlated with features in the X-ray surface brightness map. The removal of these unmatched mass substructures results in a boost to the overall matching success and slightly reduces the fraction of 2D mass substructures matched more than once (\( f_{\text{multimatched}} \)) to 3σ X-ray substructures. Despite this effect, however, the overall matching success still remains surprisingly low, with a maximum value of 45 per cent, achieved when matching to the 1σ X-ray catalogue.

This overall statistic is dominated by substructures with low associated 3D subhalo masses as these are far more numerous. From Fig. 3 we can estimate that there are approximately three times more subhaloes with \( 10^{11} < M_{\text{sub}}/h^{-1} \, M_{\odot} < 10^{12} \) than subhaloes with \( M_{\text{sub}}/h^{-1} \, M_{\odot} > 10^{12} \) (for subhaloes with their most bound particle within \( r_{\text{sub}} \) only). From the middle panel of Fig. 4, it is apparent that 85–95 per cent of 3D subhaloes in this mass range (and with most bound particle within \( r_{\text{sub}} \)) have no hot gas. With these two results in mind, it is not surprising that the total percentage of 2D mass substructures with 3D subhalo counterparts which also have X-ray counterparts is biased so low. This effect can be further demonstrated by considering the overall matching success to X-ray for the pure 2D mass substructure catalogue (bottom rows, Table 2). This is significantly higher, with a maximum value of 77 per cent (again for the 1σ X-ray catalogue). Here, on removing substructures with \( A_{\text{sub,TM}} < 10^{-3} \, h^{-2} \, \text{Mpc}^2 \) to achieve a pure sample we have, by virtue of the \( M_{\text{sub}} - A_{\text{sub}} \) correlation (equation 12), removed substructures with an associated value of \( M_{\text{sub}} < 10^{12} \, h^{-1} \, M_{\odot} \).

It is clear from the overall matching statistics that the matching success depends heavily on the 3D subhalo mass, so we now examine this dependency in more detail. Fig. 14 shows the success in matching 2D total mass substructures to 2D X-ray substructures as a function of the associated subhalo mass. It should be remembered that \( M_{\text{sub}} \) is the subhalo DM mass, not total mass, and therefore is independent of the amount of gas removal a subhalo may have undergone, other than the secondary effect of the remaining DM being more prone to tidal stripping. We have opted to include only those mass substructures matched to subhaloes above \( M_{\text{sub}} = 10^{12} \, h^{-1} \, M_{\odot} \) (the completeness limit). However, we note that the alternative choice of a sample with \( A_{\text{sub,TM}} > 10^{-3} \, h^{-2} \, \text{Mpc}^2 \) (the purity limit) made little difference to this figure for the mass range shown.

For the 1σ X-ray catalogue, the matching success per mass bin rises gradually with DM subhalo mass: it is >95 per cent for cluster cores (\( M_{\text{sub}} \gtrsim 10^{14} \, h^{-1} \, M_{\odot} \)), >95 per cent for groups (\( M_{\text{sub}} \sim 10^{13} \, h^{-1} \, M_{\odot} \)) and ≈65 per cent for galaxies (\( M_{\text{sub}} \sim 10^{12} \, h^{-1} \, M_{\odot} \)). A similar trend is seen for the 3σ catalogue, except that the success within a given mass bin is around 10–15 per cent lower.
It is expected, based on the trend for \(f_{\text{gas}}\) decreasing with subhalo mass already demonstrated, there would be a cut-off mass below which the fraction of substructures with an X-ray component would fall off sharply from 100 per cent (similar to that seen in Fig. 8 when matching 2D substructures to 3D subhaloes). This feature is present (at \(M_{\text{sub}} \sim 10^{13} h^{-1} M_\odot\)); however, the fall-off is much more gradual and surprisingly the success rate is slightly below 100 per cent even above this value. The position of the cut-off mass and the rate of fall-off thereafter are independent of X-ray catalogue choice, and there is a deviation in the predicted success of only \(\sim 10\) per cent.

In order to link these results to the composition of the underlying 3D subhaloes, we examine the hot (\(T > 10^7\) K) gas fractions, \(f_{\text{gas}}\), of the subhaloes that are matched to the 2D mass substructures. In cases where more than one subhalo is associated with the same 2D mass substructure, we calculate \(f_{\text{gas}}\) for the most massive subhalo (but note that the exclusion of 2D substructures matched to more than one subhalo from the following analysis makes little difference to the results). Fig. 15 shows the average hot gas fraction, \(f_{\text{gas}}\), per mass bin for different samples of 2D mass substructures (binning is identical to that in Fig. 14). Interestingly, the average \(f_{\text{gas}}\) for all 2D mass substructures (dot–dashed) shows the same trend with subhalo mass as the matching success, suggesting that the two are closely linked, as it would have been reasonable to assume.

The solid and dashed lines show the average \(f_{\text{gas}}\) value for 2D mass substructures which are matched to a substructure in the 1σ or 3σ X-ray catalogue, respectively. These values are slightly higher than those for all the substructures (with and without X-ray counterparts) suggesting that only low-mass 3D subhaloes with a higher than average hot gas fraction will be successfully detected in 2D and matched in the X-ray maps. We also examined the minimum \(f_{\text{gas}}\) of a total mass substructure with a 2D X-ray counterpart and the maximum \(f_{\text{gas}}\) of one without a 2D X-ray counterpart, per mass bin, for both X-ray catalogues. These quantities effectively give the hot gas fraction thresholds that define the X-ray substructure catalogues. The minimum \(f_{\text{gas}}\) was catalogue-independent, suggesting the lower detection limit is dominated by another factor, however, the maximum \(f_{\text{gas}}\) was found to be significantly higher for the 3σ catalogue at low masses (compared to the 1σ catalogue and the average value), occasionally by a factor of around 2. Since the average \(f_{\text{gas}}\) of a mass substructure successfully matched to an X-ray substructure is catalogue-independent, yet the maximum \(f_{\text{gas}}\) can be much higher for the 3σ catalogue, this suggests that the difference in numbers of substructures contained in each catalogue is primarily due to hot gas distribution rather than mass. The objects picked up in the 1σ catalogue but not in the 3σ catalogue have \(f_{\text{gas}}\) values higher than the average detected, i.e. if \(f_{\text{gas}}\) is the controlling factor, they should appear in both catalogues. However, if a subhalo had a significant hot gas fraction, but this had been displaced from its centre or the dense core of the hot gas had been disrupted and so the peak in X-ray emission was not so bright, this could explain the same substructure being detected in the 1σ but not the 3σ catalogue (remember the σ values refer to cuts in the residual X-ray surface brightness).

6.3 Summary

We have attempted to match every 2D mass map substructure to a 2D substructure in the corresponding X-ray map and have shown that there are numerous occasions when this is not possible, highlighting differences between substructure in the hot gas and DM components. The frequency of matching failures clearly increases with decreasing subhalo mass: a few per cent of cluster cores (\(M_{\text{sub}} \gtrsim 10^{14} h^{-1} M_\odot\)), \(\gtrsim 5\) per cent of groups (\(M_{\text{sub}} \sim 10^{13} h^{-1} M_\odot\)) and \(\gtrsim 35\) per cent of galaxies (\(M_{\text{sub}} \sim 10^{12} h^{-1} M_\odot\)) do not have X-ray counterparts. Interestingly, we also find that around a half of the X-ray substructures detected do not have counterparts in the mass maps. As more joint weak-lensing and X-ray studies are undertaken, we predict more ‘dark haloes’ will be found, with these discoveries not restricted to rare, merger events involving high-mass subhaloes but occurring frequently on the galaxy-mass scale.

7 Discussion

The benefit of performing a cosmological simulation is that it will best mimic the complicated processes taking place during the formation of real galaxy clusters. However, by the same token, it can...
then be difficult to untangle the influence of one parameter or physical process on the conclusions, from that of another. In this section, we investigate the effects of the main selection parameters (Section 7.1) and the main model parameters (Section 7.3) on Figs. 14. In addition, we define several broad categories for the fate of a mass substructure’s hot gas component, as viewed in 2D. By exploring a case study from each category (Section 7.2), we attempt to illustrate how the overall picture of the correspondence between the total mass and X-ray maps, shown in Fig. 14, is built up. In Section 7.4, we make a preliminary assessment of the potential impact of analysing maps with noise and observationally achievable resolution on our results.

7.1 Selection parameters

Section 6 dealt with all the cluster maps as one data set; however, in reality, there are selection parameters which come in to play when observing clusters. The two most significant are redshift and dynamical state, the effects of which we investigate below.

7.1.1 Variations with redshift

The role of redshift is generally important when examining any class of astrophysical object, as it cannot be assumed that a population will not evolve significantly. In the case of galaxy clusters, our understanding of this factor is particularly significant if they are to become robust probes of the cosmological parameters. In this section, we divide our maps into two samples, \(0 \leq z \leq 0.2\) and \(0.5 \leq z < 1.0\) (chosen to contain an equal number of snapshots; 11), and test if there is any difference in the results.

Fig. 16 shows the fractional success of matching 2D mass substructures, that have been associated with a 3D subhalo, to 2D X-ray substructures versus subhalo mass, split into low- and high-redshift bins. There is a trend for higher matching success between substructures in the total mass and X-ray maps, shown in Fig. 14, is built up.

![Figure 16](https://example.com/figure16.png)

**Figure 16.** Matching success per mass bin of the 3σ 2D mass substructure catalogue to 1σ 2D X-ray substructure catalogues versus subhalo DM mass. Data divided by redshift: \(0 \leq z \leq 0.2\) (dashed) and \(0.5 \leq z < 1.0\) (dot–dashed). Solid line shows combined data from Fig. 14.

7.1.2 Effects of dynamical state

Since major mergers on the cluster mass scale are such energetic events, it would be unsurprising if disturbed clusters exhibited more discrepancies in their hot gas and DM substructure. Indeed, some of the most extreme observational examples are found in highly disturbed clusters, for example the bullet cluster (Clowe et al. 2004) and the ‘cosmic train-wreck’ in Abell 520 (Mahdavi et al. 2007). There is also much debate about the significance of the effect that merger activity has on bulk properties of galaxy clusters potentially making it an important selection effect. Simulations of isolated cluster mergers have suggested that massive, correlated luminosity and temperature boosts are associated with major mergers and that these could cause the masses of high-redshift clusters to be underestimated from both the \(M–T_X\) and the \(M–L_X\) relation (Ricker & Sarazin 2001; Randall, Sarazin & Ricker 2002). It has also been suggested that if this effect is real, such systems would stand out from scaling relations (O’Hara et al. 2006), but in recent high-resolution studies (Poole et al. 2006, 2007, 2008) and cosmological simulations where multiple mergers occur, no such simple correlation between scatter in the \(L_X–T_X\) relation and visible evidence of ongoing major merger activity has been found (e.g. Rowley, Thomas & Kay 2004; Kay et al. 2007).

In order to divide our images into just two subsets (major merger or not), it is necessary to have an additional technique to calibrate the centroid shift variance (described in Section 2.3) and determine which value of this statistic marks the threshold between these two states. Since we are interested in separating out the most extreme merging events, as this should make any trend stand out, we choose a value of the centroid shift variance which singles out the highest peaks in this quantity, which we determine to be 0.1. The sample is then split into two – those snapshots with values above the threshold and those with values below – and this division is confirmed by examination of X-ray surface brightness contour maps (see Fig. 1).

Fig. 17 shows the matching success for the disturbed (dashed) and relaxed (dot–dashed) samples, versus subhalo mass. It is clearly evident that all the matching failures above \(M_{sub} \geq 3 \times 10^{13}\) lie in the disturbed sample, and visual inspection of the maps confirms they are all undergoing significant mergers or collisions. The trend...
is actually reversed for low masses; substructures here have a lower probability of having an X-ray counterpart in relaxed clusters. This can be explained in the same way as the dependency on redshift in this mass range. Substructures in relaxed clusters have been there longer since, by definition, the last merger event was some time ago and therefore have been subject to stripping processes for longer. For comparison with our two redshift samples, we compute the mean redshift of the snapshots in our disturbed and relaxed samples, which we find to be 0.55 and 0.37, respectively. This highlights that there is some degeneracy between the effects of redshift and dynamical state, although these values are much closer than the mean redshifts of our redshift samples (0.72, 0.10; snapshots are equally spaced in time not redshift) and so the fact we get such a dramatic difference suggests looking at redshift alone is not sufficient.

7.2 Detachment of hot gas from dark matter subhaloes

In the previous section, we have investigated the overall probability of finding a 2D X-ray counterpart for the 2D total mass substructures we detected. In order to fully probe all the factors which result in a matching failure in our analysis, a more detailed treatment (e.g. careful tracking of subhaloes between snapshots with higher time resolution or idealized simulations of individual mergers) would be required. Nevertheless, it is very informative to examine some of these matching failures in more detail to gain insight into the variety of scenarios that occur. It is reasonable to assume that ram pressure stripping is the main culprit in the removal of hot gas; however, it is interesting to note that there are several distinct realizations of the outcome of this process in the maps. To illustrate these, we choose a small subset of substructures by visual inspection and follow these up in 2D and 3D. We present these case studies below.

7.2.1 Evidence of partial ram pressure stripping

Although we are primarily concerned with cases in which matching between the 2D total mass and 2D X-ray surface brightness substructures fails, it is interesting to note that we observe the signatures of ram pressure stripping in objects for which the match is still achieved.

Case Study 1. Fig. 18 shows the development of a large tail of hot gas which streams behind the main substructure as it passes near to the cluster centre (its 3D physical displacement in the middle panel is approximately 0.5 r_{500}). The substructure is indicated with an arrow and has \( M_{\text{sub}} \approx 1 \times 10^{12} h^{-1} M_\odot \). Note the temporary decrease in mass (about a factor of 2) in the middle snapshot. This is a well-known issue with SUBFIND, where subhaloes become more difficult to distinguish when in close proximity to the cluster’s centre, due to their low density contrast (Ludlow et al. 2009). In this case, around half of the subhalo’s DM particles in the left-hand image are deemed to belong to the main cluster in the middle image, decreasing to around 20 per cent in the right-hand image, as the subhalo moves away from the core region.

The substructure is clearly visible in both the X-ray image and the mass contours, and is detected and matched in 2D at each time shown, regardless of the choice of the 1σ or 3σ X-ray catalogue. The SUBFIND data reveal that the mass of gas associated with the corresponding subhalo is reduced to 60 per cent of its initial value over the course of this time sequence, however. The subhalo may well be on a highly elongated orbit and may eventually be depleted of enough of its hot gas such that it is no longer detected in the X-ray surface brightness map. As such, it is likely that this represents what is, for many substructures, the first stage in a time sequence that eventually leads to matching failure. However, this stage may not be visible for many substructures, depending on the inclination of the gas tail with respect to the line of sight and the amount of X-ray emission from the stripped gas.

This case study also demonstrates that our detection technique is not too sensitive to the stripping of the outer regions of a substructure’s hot gas and that matching failures therefore represent an extreme depletion or complete removal (or displacement) of the X-ray emitting component.

7.2.2 Matching failure due to complete ram pressure stripping

We now examine the scenario whereby stripping of a substructure’s hot gas results in the DM component turning up as an unmatched total mass substructure. There are two distinct categories here: matching failure due to the spatial displacement of the hot gas component and matching failure due to the hot gas component being erased completely from the X-ray surface brightness map.

Case Study 2. Prokhorov & Durret (2007) produce an analytical model describing the increasing separation between the DM and hot gas components of a substructure moving through the ICM. Indeed this type of displacement, where the hot gas substructure remains intact yet is clearly displaced from the DM, is another reason for

![Figure 18](https://academic.oup.com/mnras/article-abstract/400/2/705/1016362)
matching failures in our analysis. Fig. 19 shows a sequence of maps in which an X-ray counterpart is initially found for a total mass substructure, but then clearly becomes spatially separated to the point where matching fails. It is clear that should this type of displacement occur along the line of sight, we would not be aware of it, however this is not a shortfall of our method; we want to be subject to the same restrictions as observers. In the left-hand panel, the substructure is well matched to its X-ray counterpart (indicated by one arrow only as the contours and surface brightness peak are coincident). In the middle panel, due to the effects of ram pressure, the X-ray component is slightly offset, yet matching is still successful for both the 3σ and 1σ X-ray catalogues. Finally, in the right-hand panel, the progression of the X-ray component has been slowed so much that it is significantly displaced from the total mass substructure and is, therefore, not matched regardless of the choice of X-ray catalogue.

A 3D analysis of this time sequence confirms this picture. The bound gas mass of the corresponding subhalo decreases to almost zero between the left-hand and middle panels of Fig. 19 and the subhalo is completely gas-free by the right-hand panel. We identify, in the right-hand panel, the location of the gas particles which originally belonged to the DM subhalo and confirm that these exist as a clump which is coincident with the substructure in the X-ray surface brightness image.

This separate hot gas component will eventually be completely disrupted, leaving the mass substructure (which will remain intact longer) with no trace of an X-ray counterpart. This situation is seen in the maps fairly frequently and presumably the separation procedure described above is the precursor to this. However, we also encounter an example of more immediate erasing of substructure from the X-ray surface brightness map, which we describe in the next case study.

It should be noted that the survival time of the gaseous component of subhaloes has been shown to be dependent on the numerical techniques employed and the resulting success with which hydrodynamical instabilities that expedite gas stripping are captured. Agertz et al. (2007) show that SPH (with standard artificial viscosity) cannot capture Kelvin–Helmholtz instabilities (KHI) as well as adaptive mesh refinement codes. Indeed, Dolag et al. (2009) demonstrate that using a low-viscosity scheme (less damping of the KHI) in gadget-2 results in smaller gas fractions for subhaloes inside a cluster’s virial radius, suggesting such issues will impact on studies such as this one. More recently, improvements to the SPH methodology have been suggested, which increase its ability to capture KHI (Price 2008; Kawata et al. 2009; Read, Hayfield & Agertz 2009). It is therefore a matter for further investigation, whether the concentrations of stripped subhalo gas which give rise to X-ray surface brightness substructures, as illustrated in this case study, would still occur when the growth of KHI is simulated reliably.

Case Study 3. Fig. 20 shows the encounter of a substructure ($M_{\text{sub}} \approx 10^{13} h^{-1} M_\odot$) with the inner regions of the main cluster at $z \approx 0$. In the left-hand panel, the substructure is detected (and

Figure 19. Sequence showing progressive separation of 2D total mass substructure and its 2D X-ray counterpart for Cluster B at $0.05 < z < 0.01$, which results in a matching failure in the final map of the sequence. Image is composed of the logarithmic X-ray surface brightness map with X-ray surface brightness (white) and surface mass density (black) contours, equally spaced in log, overlaid. $M_{\text{sub}} \approx 2.6 \times 10^{12}, 2.4 \times 10^{12}$ and $3.0 \times 10^{12} h^{-1} M_\odot$, respectively.

Figure 20. Sequence showing stripping of X-ray gas from a substructure in Cluster A for $0.07 \leq z \leq 0$, matching fails in the last image of the sequence. Image and contours as shown in Fig. 19. $M_{\text{sub}} \approx 1.0 \times 10^{13} h^{-1} M_\odot$, undefined (see the text for details) and $4.4 \times 10^{12} h^{-1} M_\odot$, respectively.
clearly visible by eye, indicated with an arrow) in both the total mass and X-ray surface brightness maps, and the matching procedure is successful. In the middle panel, there is a clear double-peaked structure in the centre of the X-ray map, yet this is absent in the total mass contours and the substructure is not detected as a separate object from the cluster core in 2D. SUBFIND individually resolves the subhalo in 3D, albeit with a significantly reduced mass due to the effect discussed in Case Study 1. Therefore, although we have two 3D haloes (the main cluster and the subhalo), their proximity means both are attributed to the same 2DM mass substructure; essentially the resolution limit of our detection procedure has been exceeded here.

In the right-hand panel, the substructure is again detected in the total mass map (its position in the contours is indicated with an arrow) but there is no corresponding detection in this region of the X-ray map. The DM substructure has been completely stripped of its hot gas and is also stripped (tidally) itself; according to SUBFIND, the corresponding subhalo has no bound gas particles in the final panel and the DM mass has been reduced to roughly 40 per cent of its value in the first panel. Indeed the rest of this subhalo’s DM and gas particles are found to belong to the main cluster at the end of this time sequence.

Note, however, the edge-like feature present instead which appears to lag behind the 2DM mass substructure (detections of this are made in both X-ray catalogues but are not matched to the mass substructure as the positions are not coincident). A tail of stripped hot gas is also visible on the right-hand side of this map which resulted from the substructure’s approach and is also apparent in the left-hand and middle panels. A detailed discussion of the gaseous features that can arise during such interactions appears in Poole et al. (2006).

We also note that there are similar scenarios whereby a collision results in the disruption of the X-ray emitting gas, rather than its complete removal as seen here. In these cases, while there is still evidence of gas in the vicinity of the mass map substructure, a defined peak is no longer visible and the detection of an X-ray substructure can then be catalogue-dependent (different catalogues impose different cuts on the residual surface brightness). The issue of catalogue dependence is discussed in the following case study.

If we examine the maps immediately preceding this sequence, we observe the same substructure undergoing stripping of its hot gas on an earlier passage through the cluster’s inner regions, adding weight to our supposition that Case Study 1 may be the precursor to the hot gas being removed completely. In fact, it is plausible that all the case studies may simply be different moments in a sequence where substructures that continue to orbit within the cluster long enough are subject to the stripping of outer regions of hot gas, displacement of remaining hot gas then complete disruption of the hot gas substructure.

Case Study 4. We now examine a scenario in which a close encounter between the main cluster and a subhalo has resulted in the hot gas from one object being removed and assimilated into the main cluster’s ICM. However, in this case the conglomerate hot gas does not correspond spatially with a mass map substructure. This case study highlights how challenging it can be to correctly determine which X-ray substructures are associated with which mass substructures when working in 2D and the limitations of our current detection and matching schemes.

In Fig. 21, we present an image of Cluster A at $z = 1$ (middle panel) which bears similarity, in terms of its configuration, to the recent observation in Bradač et al. (2008). This observation is on a larger scale, however, depicting the merger of two clusters, with nearly equal masses. The left- and right-hand panels show the maps for the snapshot directly before and after, respectively, to provide some insight; however, due to the complexity of the merger, a detailed subhalo merger tree would be required to unravel the full series of events. Here, we focus on the middle panel.

It is clear that the inner region consists of three DM haloes (all detected in 2D by our algorithm) and only two X-ray peaks (also detected). The western X-ray peak is coincident with (and successfully matched to) one of the DM substructures; however, the eastern X-ray peak lies in between the other two substructures. The smaller of these DM substructures ($M_{\text{sub}} \approx 1.6 \times 10^{12} M_{\odot}$) is matched to the eastern X-ray substructure when using either the 1σ or 3σ X-ray catalogue. We can see, however, that this substructure is still offset from the bulk of the hot gas in this region and instead just overlaps with a tail of material extending outwards towards it. Indeed, in 3D this subhalo has a very low gas fraction, suggesting its match with the X-ray substructure is primarily a projection effect. The larger of these DM substructures appears completely devoid of hot gas and is the main cluster as defined by SUBFIND.

![Image of Cluster A undergoing a merger at $z \sim 1$, with the middle panel bearing remarkable similarity to that in Bradač et al. (2008).](https://academic.oup.com/mnras/article-abstract/400/2/705/1016362)

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The displacement of this surface mass density peak from the eastern X-ray surface brightness peak is 90 km s⁻¹ kpc. It is interesting that while the projected mass peak of the main cluster is offset from the bulk of the X-ray emission, its most bound particle actually coincides with the maximum X-ray surface brightness (the white spot in the image). When we use the 1σ X-ray catalogue, the main cluster core is actually matched to a very small, separate X-ray substructure and so does not show up as an unmatched object in these data. This pair would add to the scatter in the area–area correlation plot (Fig. 12) suggesting that, in future work, poor agreement in the area of matched pairs could be used to remove dubious matches.

This case study illustrates that the use of the 3σ X-ray catalogue is the most likely to allow retrieval of all high-mass substructures with no significant hot gas component as these will fail to be matched. The 1σ X-ray catalogue is less stringent and will detect smaller amounts of gas and will also result in the matching of substructures that are slightly offset, since the X-ray substructures in this catalogue are more extended. However, by the same token, it is also more prone to false matches than the 3σ catalogue.

7.3 Gas physics model parameters

Our main results focused on a set of non-radiative clusters, the simplest model for the ICM within a cosmological context. It is well known, however, that additional physical processes must operate in clusters; scaling relations such as the X-ray luminosity–temperature relation are different to what is expected from the so-called self-similar model (e.g. Kaiser 1991). The most favoured explanation for the altered similarity of clusters is that the ICM has undergone an intense, and perhaps extended, period of heating due to galactic outflows (from stars and active galactic nuclei). Radiative cooling also plays a role, selectively removing the low-entropy gas, although is completely reliant on subsequent heating to avoid a cooling catastrophe (e.g. Babul et al. 2002; McCarthy et al. 2004, 2008a).

Investigating the full effects of cooling and heating is beyond the scope of this paper, but we have performed a preliminary investigation on the effects of cooling on our results. To avoid over-cooling the gas and motivated by the observations that stellar populations in clusters are old (e.g. Thomas et al. 2005), we only allow the gas to cool radiatively at early times, until a reasonable fraction of gas has cooled and formed stars. We adopted the same procedure as outlined in Kay et al. (2004), assuming a metal-free gas (Z = 0). The simulation of Cluster A was repeated and cooling was switched on until z = 5, when around 10 per cent of the gas in the high-resolution region had formed stars, in agreement with near-infrared observations, which suggest that the stellar mass, as a percentage of the ICM gas mass, is around 10 per cent on average (e.g. Lin, Mohr & Stanford 2003; Balogh et al. 2001; Cole et al. 2001). The cooled fraction in the cluster, within r₅₀₀, at z = 0 is about 20 per cent, slightly higher than observed by Lin et al. (2003).

We use observed Lₓ–M₅₀₀ and Lₓ–Tₓ relations (Pratt et al. 2009) in order to compare the simulated X-ray luminosity (Lₓ, sim) of Cluster A at z = 0 with that expected from observations (Lₓ, obs) based on both its M₅₀₀ value and its spectroscopic-like temperature, Tₓ(d) (Mazzotta et al. 2004). Table 3 summarizes these properties, including the values for the other clusters as a point of comparison. The non-radiative version of Cluster A has a similar X-ray luminosity to that observed based on its mass, but a much higher luminosity than observed (Lₓ, sim/Lₓ, obs ≈ 5) based on Tₓ(d). Similarly, Clusters B and C also exhibit X-ray luminosities close to those observed for their masses at z = 0, yet are very overluminous for their temperatures. Assuming the observed mass determinations are accurate, then the main difference is that the simulated Tₓ(d) is too low in the non-radiative model due to the presence of too much cold gas (see Kay et al. 2008). Turning on high-redshift cooling in Cluster A preferentially removes this cool gas, bringing down the luminosity (Lₓ, sim/Lₓ, obs ≈ 0.6, based on mass) but increasing Tₓ such that Lₓ, sim/Lₓ, obs ≈ 1.6, based on temperature. So, overall, the cooling model is closer to the observed (best-fit) Lₓ − Tₓ plane. In future, we will also consider the additional effects of heating from supernovae and active galactic nuclei. It will be interesting to see how the competing effects of cooling and heating affect the structure of the subhaloes.

The cluster identification procedure is the same as described in Section 2, except that in order to ensure we follow the same object in all resimulations of the same cluster, the list of cluster candidates in the cooling run is searched for the best match to the selected object in the non-radiative run. In Fig. 2, the surface mass density (left-hand column) and X-ray surface brightness (right-hand column) maps for the cooling run (first row) and non-radiative run (second row) of Cluster A at z = 0 can be compared. Qualitatively, the two sets of maps appear similar, suggesting that cooling at high redshift does not strongly affect our main results.

We can once again examine the properties of our 3D subhalo sample, to see the role cooling has played. Fig. 22 shows the z = 0
subhalo DM mass function for the cooling (solid line) and non-radiative (dashed line) runs of Cluster A. The DM mass functions agree well, although it is apparent that there are more low DM mass subhaloes (a similar effect is also seen at \( z = 0.5 \) and 1), suggesting that the central condensation of the baryons deepens the potential wells and reduces the amount of disruption of the DM.

We examine the effect of cooling on the hot gas within the 3D subhaloes, by computing the average hot (\( T > 10^7 \) K) gas fractions within each mass bin. The results are shown in Fig. 23, for the non-radiative (dashed) and cooling (solid) versions of Cluster A (expressed in units of the global value, \( \Omega_b/\Omega_m = 0.15 \)). In the non-radiative cluster, the hot gas fraction increases with subhalo mass, reflecting the increasing ability of the subhaloes to retain their hot gas as their potential wells deepen (note the main haloes are also shown). In the cooling run, the same trend is seen, but the gas fraction is lower at all masses (compared to the non-radiative run). As a result of their shallower potential, ram pressure stripping of hot gas is most effective in the low-mass (\( \sim 10^{12} h^{-1} M_\odot \)) subhaloes, as indicated by their very low average gas fractions (\( \approx 0.2 \)) in both runs. It is at this mass range, however, that cooling is also most effective because these objects form at high redshift and have short cooling times. We see the result of this effect when comparing the average subhalo total baryon fractions in the two runs; the cooling cluster has around 40 per cent more baryons at \( M_{\text{sub}} \sim 10^{12} h^{-1} M_\odot \), yet the total baryon fractions agree well between the runs at higher masses.

The procedure to detect 2D substructures in maps of X-ray surface brightness and total mass density (described in Section 4) is applied, with identical parameters, to the cooling run of Cluster A. As could be expected from the discussion of the 3D subhalo data for this run, more 2D total mass substructures are found; the 3D mass catalogue contains 611 substructures compared with 473 in the non-radiative run of the same cluster. The number of substructures in both runs. It is at this mass range, however, that cooling is also most effective because these objects form at high redshift and have short cooling times. We see the result of this effect when comparing the average subhalo total baryon fractions in the two runs; the cooling cluster has around 40 per cent more baryons at \( M_{\text{sub}} \sim 10^{12} h^{-1} M_\odot \), yet the total baryon fractions agree well between the runs at higher masses.

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As described in Section 4.1, the 2D mass substructure catalogue contains only those substructures that were successfully identified with a 3D subhalo. Fig. 24 shows the matching success to X-ray for total mass substructures. Surprisingly, the results for the cooling run (solid line) match those for the non-radiative run (dashed line) very closely. In particular, although Fig. 23 shows subhaloes of all masses are more depleted of hot gas in the cooling run, this does not seem to translate into a significant decrease in the likelihood of finding a 2D X-ray counterpart for 2D mass substructures, except for \( M_{\text{sub}} \sim 10^{12} h^{-1} M_\odot \). Overall, it seems that the introduction of high-redshift cooling does not affect the main results and therefore that our non-radiative results are not too sensitive to the gas physics model employed (although further investigation into the effects of cooling plus feedback would be desirable).

### 7.4 Towards realistic observations

The main results of this paper have focused on ‘perfect’ observations. Although a detailed analysis of all the potential observational and instrumental effects is beyond the scope of this paper, we now consider the impact on our results of using an observationally achievable map resolution and including basic noise in the maps. We defer a more detailed treatment of noise and instrumental effects to future work. This analysis is undertaken on the non-radiative simulations as this provides us with a larger sample of clusters, and we have shown that the impact of high-redshift cooling is minimal.

#### 7.4.1 Introducing noise and degrading the resolution

For the purposes of adding noise and adopting a realistic resolution, we opt to place the clusters at \( z = 0.2 \) as this is both the redshift at which our X-ray map resolution can be achieved by *XMM* and is also a redshift representative of recent observations [the bullet cluster is at \( z \approx 0.3 \) (Clowe et al. 2004) and Abell 520 is at \( z \approx 0.2 \) (Mahdavi et al. 2007)].

As described in Section 4.1, maps of both types were first smoothed with a Gaussian kernel with FWHM = 15 h^{-1} kpc equal to the spatial resolution of the simulations. While this resolution is
potentially achievable in X-ray observations, it is necessary for us to increase the smoothing slightly (to FWHM = 25 h^{-1} kpc) in the presence of noise, but note that this resolution is still much higher than currently achievable with weak-lensing analyses. In this case, the resolution that can be obtained is dependent on the number density of background galaxies: for ground-based data, this angular resolution is typically 1 arcmin, yet for space-based data this can be improved to around 45 arcsec (see e.g. Heymans et al. 2008). To investigate the impact of this decreased resolution, we now adopt a preliminary Gaussian kernel with FWHM = 100 h^{-1} kpc when analysing the projected mass maps (corresponding to approximately 45 arcsec angular resolution at z = 0.2) and increase σ_{2} accordingly.

We add Poisson noise to the X-ray maps by making the crude approximation that the photon number is proportional to the X-ray surface brightness. We find that 10^7 photons (corresponding roughly to an exposure of 20 ks) allow us to recover the majority of substructures that were detected in the absence of noise. We add Gaussian noise to the mass maps with zero mean and with a variance determined by van Waerbeke (2000). The latter is given by

$$\Delta M^2 = 4\sigma^4 \left( \frac{\sigma^2}{4\pi\sigma n_g} \right) \Sigma_{\text{crit}}^2$$

$$\left[ 1 - \exp \left( -\frac{2\sigma^2}{2\sigma^2} - \sqrt{\frac{\pi}{2}} a \sigma \text{erf} \left( \frac{a}{\sqrt{2}\sigma} \right) \right) \right]^2$$

for a pixel of size a in a weak-lensing mass reconstruction and is due to the intrinsic ellipticities (with rms, σ_{2}) of background galaxies with an average density of n_{g}. Σ_{crit}, the critical surface density for lensing to occur, is given by

$$\Sigma_{\text{crit}} = \frac{c^2}{4\pi G} \frac{D_{\text{os}}}{D_{\text{ol}} D_{\text{ls}}},$$

where D_{ls} is the angular diameter distance between the observer and the lens, D_{ol} is that between the observer and the galaxies and D_{ls} is that between the lens and the galaxies. Note that we fix the redshift of the lens to be z = 0.2, as outlined above. We use typical values of n_{ls} = 100 galaxies arcmin^{-2} (for space-based data) and σ_{2} = 0.3 (e.g. Starck, Pires & Réfrégier 2006), and assume that the galaxy ellipticities were smoothed with a Gaussian of standard deviation σ = a prior to reconstruction, as in Puchwein & Bartelmann (2007).

We note that the pre-smooth damps the noise a little, but our aim in this preliminary investigation into the impact of noise is simply to make an estimate of the noise level.

Fig. 25 illustrates how the original maps (left-hand column) are affected by the smoothing and addition of noise (right-hand column). While some small substructures are still visible in the X-ray map (albeit made less distinct by the noise), all but the largest substructure have been erased from the mass map.

### 7.4.2 The impact of noise and resolution

We now review our main findings in order to make a preliminary assessment of how they are affected by noise and degraded map resolution.

First, we re-evaluate the relationship between the 2D mass map substructures and the underlying distribution of 3D subhaloes. The impact of just degrading the map resolution is significant and reduces the number of subhaloes detected above 10^{12} h^{-1} M_{\odot} to around 60 per cent of its value in the original maps. When noise is also included, there are further detection failures, most frequently below 5 × 10^{12} h^{-1} M_{\odot}, which reduce the total number of detections above 10^{12} h^{-1} M_{\odot} by an additional 5 per cent.

![Figure 25](https://academic.oup.com/mnras/article-abstract/400/2/705/1016362)

**Figure 25.** Images of Cluster A at z ≈ 0. First row: projected mass map with resolution of 15 h^{-1} kpc (left-hand panel) and mass map with Gaussian noise and resolution degraded to 100 h^{-1} kpc (right-hand panel). Second row: X-ray surface brightness image with resolution of 15 h^{-1} kpc (left-hand panel) and X-ray surface brightness image with 25 h^{-1} kpc resolution and the Poisson noise (right-hand panel). Note that the noisy X-ray image would typically be more heavily smoothed for presentation purposes (see the text for details of the noise models). This snapshot is featured in Case Study 3, Fig. 20.

![Figure 26](https://academic.oup.com/mnras/article-abstract/400/2/705/1016362)

**Figure 26.** Fractional matching success per mass bin of 3D subhaloes to 2D substructures in the noisy, degraded resolution mass maps (solid) and the original mass maps (dotted) as a function of subhalo DM mass for the 3σ 2D catalogue. Bins are equally spaced in log(M_{sub}).

Fig. 26 compares the completeness of the 3σ 2D mass substructure catalogue obtained from the degraded resolution, noisy maps (solid line) with that obtained from our high-resolution, noise-free maps (dotted line, taken from Fig. 8). We can see that the mass threshold for 90 per cent completeness (per mass bin) is now around an order of magnitude higher. For the 3σ catalogue, 90 per cent completeness is now achieved only above 10^{13} h^{-1} M_{\odot} and a factor of ≈8 fewer substructures are detected in total (159 cf. 1233).
Despite the impact of noise, a correlation between the area of the 2D substructure, $A_{\text{sub}}$, and the DM mass of its 3D subhalo, $M_{\text{sub}}$, is still evident in Fig. 27. The reduction in the number of detections (immediately apparent in Fig. 27) translates into higher 1σ errors on the best-fitting line. The purity of the 3σ substructure catalogue is very high (only 1 per cent are false detections), so we do not define a purity threshold here, but simply include all substructures in the fit.

The normalization and slope are now $4.7 \pm 0.2$ and $0.9 \pm 0.1$, respectively. The change in the former is most significant and can be attributed to the use of a larger kernel, resulting in a given 2D substructure having a larger area than before.

We also re-examine the likelihood of finding an X-ray counterpart for all 2D mass map substructures in the 3σ catalogue (the results for our fiducial data set are presented in Fig. 14). Above $10^{14} h^{-1} M_\odot$ (our completeness limit) we now find X-ray counterparts in the 1σ catalogue for all of the 2D mass map substructures. The purity of the 3σ X-ray catalogue, however, we fail to find matches for a few high-mass mass map substructures. The difference between the two X-ray catalogues here arises in situations where there is hot gas in the vicinity of the mass substructure, but it has been disrupted and so does not have a defined peak; the 1σ catalogue detects this whereas the 3σ does not.

The other scenarios in which we no longer find matching failures (but did previously) is an effect of the reduced mass map resolution. At low subhalo masses, we are now unable to resolve the 2D mass map substructure. At high masses, matching failures typically occurred in complex merging cores which now, in some cases, cannot be individually resolved. This can result in two merging cores being detected as one extended mass substructure, facilitating matching with an X-ray substructure. This is an issue that requires further investigation. The current criterion for a match is any degree of overlap between the mass and X-ray substructure. Since substructures in the realistic mass map have a much greater spatial extent due to the lower resolution, they could be associated with an X-ray substructure which is significantly offset from the mass peak. A more detailed follow-up of X-ray-mass matches in the context of more realistic maps would be an interesting extension to the current work.

While we have shown that only a few discrepancies between substructure in the X-ray and the mass maps could be observed currently, our fiducial results show there is an abundance of these to be uncovered. A detailed substructure comparison, such as the one undertaken here, will yield a wealth of interesting results when predicted improvements in lensing mass map resolution are achieved. For example, a resolution of $10 h^{-1} $kpc is forecast by Coe (2009) based on a novel strong lensing analysis technique.

### 7.5 Summary of discussion

In this section, we have discussed in detail the reasons for failing to find an X-ray counterpart for all of our 2D mass substructures. We have demonstrated two distinct scenarios that give rise to a 2D total mass substructure not being matched to a 2D X-ray surface brightness substructure: spatial separation of the X-ray component and destruction (or disruption) of the X-ray component. We have also highlighted the dependence of the matching procedure on the choice of X-ray catalogue.

We have examined how several factors affect the likelihood of finding X-ray counterparts for substructures in the total mass maps. The inclusion of high-redshift cooling in the simulations does not have a dramatic effect on the correspondence between X-ray and total mass. We show that there is a higher probability of finding an X-ray counterpart at high redshift, which can be attributed to a shorter time-scale on which ram pressure stripping could occur. By dividing our sample based on dynamical state, we find that subhaloes with $M_{\text{sub}} > 3 \times 10^{13} h^{-1} M_\odot$ only lack an X-ray counterpart when the cluster is highly disturbed (in agreement with recent observations); however, relaxed clusters exhibit many deviations from the basic picture that light traces mass at lower subhalo masses. Joint weak-lensing and X-ray analyses of relaxed systems are therefore also valuable and will yield much information about the physics of the ICM.

A review of our main results in the presence of observational noise and degraded resolution reveals that many of these interesting mismatch scenarios are not currently observable, yet predicted improvements in lensing mass map resolution suggest that these will be revealed in the coming decade, unveiling frequent deviations from the simple assumption that light traces mass.

### 8 CONCLUSIONS

In this paper, we have used resimulations of three non-radiative galaxy clusters in order to investigate the discrepancies between substructure in the hot gas and DM components, evident from recent comparisons of X-ray and weak-lensing observations. We developed a simple technique to detect 2D substructures in simulated surface mass density and X-ray surface brightness maps of the clusters, without any reliance on circular symmetry or dynamical state. The resulting catalogues of 2D mass and 2D X-ray substructures were matched, and we investigated how the success of this matching procedure varied with redshift, dynamical state and choice of gas physics employed. By utilizing information about the underlying 3D subhalo distribution (obtained with SUBFIND), we have assigned subhaloes to the 2D mass substructures, allowing us to characterize the efficiency of our 2D substructure detection technique and reveal the effect of subhalo mass on the 2D mass to 2D X-ray substructure matching success.
Our main results can be summarized as follows.

(i) Having undertaken a thorough assessment of the properties of the 2D substructure catalogue resulting from our novel detection procedure, we have ensured that any selection effects or biases the technique may have introduced are understood. By attempting to match all 2D substructures detected in the surface mass density map with the 3D subhaloes (identified with SUBFIND), we have concluded that our 2D substructure catalogue is 90 per cent complete per mass bin (98 per cent overall) down to a 3D subhalo DM mass of $\sim 10^{12} h^{-1} M_\odot$ and 100 per cent complete down to a DM mass of $10^{13} h^{-1} M_\odot$. We are confident therefore that, in the 3D subhalo mass range currently probed by weak lensing, the 2D substructure catalogues provide an accurate representation of the true 3D picture. We also establish that the 2D mass substructure catalogue is pure and complete for $A_{\text{sub, TM}} > 10^{-3} h^{-1} \text{Mpc}$, i.e. all 2D mass substructures with areas above this limit are successfully matched to a 3D subhalo and are, therefore, genuine. This purity threshold should allow the same detection procedure to be reliably applied to other simulated surface mass density maps in future, without the need for 3D subhalo data with which to compare.

(ii) We present a correlation between $A_{\text{sub, TM}}$, the area of a 2D mass substructure, and $M_{\text{sub}}$, the DM mass of the 3D subhalo to which it is matched. The correlation is still apparent upon the introduction of basic observational noise, suggesting it could provide a quick estimate of the mass of a subhalo responsible for a peak in a weak-lensing mass reconstruction, after accurate calibration. A measurement of the intrinsic scatter suggests such an estimate would be out by a factor of $\sim 2$.

(iii) The results of the matching between 2D mass substructures and 2D X-ray substructures are surprising. We do not find X-ray counterparts for 23–33 per cent (depending on the choice of X-ray catalogue) of all 2D mass substructures in the pure catalogue. Below $M_{\text{sub}} \sim 10^{12} h^{-1} M_\odot$, the matching success per mass bin begins to decrease significantly with decreasing subhalo mass. For the 1σ X-ray catalogue, a few per cent of cluster cores, 5 per cent of group-size 2D mass substructures and 35 per cent of galaxy-size 2D mass substructures are not associated with a 2D X-ray substructure. The reasons for a matching failure are (1) displacement of hot gas, where the X-ray substructure is intact yet spatially distinct from the DM, (2) depletion of hot gas, where so much gas has been stripped that detection of the 2D X-ray substructure fails, or (3) complete disruption of the hot gas, where all hot gas appears to have been removed such that no 2D X-ray substructure is evident, even on visual inspection. We have conducted a detailed follow-up of examples of these scenarios with a set of case studies.

(iv) The dynamical state of the clusters (characterized by measuring the centroid shift variance in the X-ray surface brightness maps), is found to play a role in determining the fraction of 2D mass substructures without X-ray counterparts. Substructures with $M_{\text{sub}} > 3 \times 10^{12} h^{-1} M_\odot$ without an X-ray counterpart are restricted to the disturbed sample, suggesting major merger events are the cause. Substructures below this mass are less likely to have X-ray counterparts in relaxed systems, suggesting ram pressure stripping plays an important role on this scale; by definition, a long time has elapsed since the last merger, so these substructures have had most time to experience its effects. Similarly, the low-redshift sample ($0 \leq z \leq 0.2$) contains more 2D mass substructures, in this mass range, that are unmatched to X-ray substructures than the high-redshift sample ($0.5 \leq z < 1$).

(v) The inclusion of high-redshift (until $z \simeq 5$) cooling has only a mild impact on our results. It has little effect on the matching success between 2D mass substructures and 2D X-ray substructures for $M_{\text{sub}} > 3 \times 10^{12} h^{-1} M_\odot$, but reduces it, compared to the non-radiative case, below this due to the reduction of hot gas in these objects.

(vi) We have demonstrated that our simple 2D detection technique is still successful when noise which approximates that in real observations is added to the maps and the map resolution is degraded. As could be expected, the subhalo mass at which high completeness is achieved for the mass substructure catalogues is around an order of magnitude higher than in the fiducial set of maps. We have shown that this increase means many of the interesting mismatches which occur at lower mass scales cannot currently be observed. If the resolution of lensing mass maps can be improved by a factor of 10, to $\sim 10 h^{-1} \text{kpc}$, we predict that many more discrepancies between the hot gas and DM components of clusters will be observed and that these will not be restricted to rare, extreme merger events such as the bullet cluster. Such an improvement, while dramatic, has been predicted for the coming decade, and authors are already developing new observational analysis techniques to allow this, such that comparisons in the spirit of the present work can be undertaken (Coe 2009). These future observations will provide a wealth of information about the physics of the ICM, the dynamical state of galaxy clusters and will allow us to probe the properties of the DM substructure directly.

In future work, we will assess the impact of introducing heating processes, for example, from galactic winds and the effects of active galactic nuclei into the resimulations, as well as the effect of including more realistic noise in the maps.

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