Are fossil groups a challenge of the cold dark matter paradigm?

Stefano Zibetti,1⋆ Daniele Pierini2 and Gabriel W. Pratt2

1Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany
2Max-Planck-Institut für extraterrestrische Physik, Postfach 1312, D-85741 Garching bei München, Germany

Accepted 2008 October 15. Received 2008 October 15; in original form 2008 July 15

ABSTRACT

We study six groups and clusters of galaxies suggested in the literature to be ‘fossil’ systems (i.e. to have luminous diffuse X-ray emission and a magnitude gap of at least 2 mag R between the first and the second ranked member within half of the virial radius), each having good quality X-ray data and Sloan Digital Sky Survey (SDSS) spectroscopic or photometric coverage out to the virial radius. The poor cluster AWM 4 is clearly established as a fossil system, and we confirm the fossil nature of four other systems (RX J1331.5+1108, RX J1340.6+4018, RX J1256.0+2556 and RX J1416.4+2315), while the cluster RX J1552.2+2013 is disqualified as fossil system. For all systems, we present the luminosity functions within 0.5 and 1 virial radius that are consistent, within the uncertainties, with the universal luminosity function of clusters. For the five bona fide fossil systems, having a mass range $2 \times 10^{13} - 3 \times 10^{14} M_\odot$, we compute accurate cumulative substructure distribution functions (CSDFs) and compare them with the CSDFs of observed and simulated groups/clusters available in the literature. We demonstrate that the CSDFs of fossil systems are consistent with those of normal observed clusters and do not lack any substructure with respect to simulated galaxy systems in the cosmological Λ cold dark matter (ΛCDM) framework. In particular, this holds for the archetype fossil group RX J1340.6+4018 as well, contrary to earlier claims.

Key words: galaxies: clusters: general – galaxies: evolution – galaxies: formation – galaxies: luminosity function, mass function – cosmology: observations.

1 INTRODUCTION

Early numerical simulations suggested that the most compact galaxy groups could merge to form a single elliptical galaxy (hence a ‘fossil group’) in a few billion years (Barnes 1989). An elliptical galaxy formed by the merger of such a group retains its X-ray emitting halo of hot gas, which is unaffected by merging (Ponman & Bertram 1993). Following this indication, Ponman et al. (1994) discovered the archetype fossil group RX J1340.6+4018.

Vikhlinin et al. (1999) and Jones et al. (2003), on the basis of ROSAT observations, have suggested that fossil groups constitute a considerable population of objects. Their X-ray extent, bolometric X-ray luminosity ($L_{X, bol} > 10^{42} h_{70}^{-2}$ erg s$^{-1}$), dark matter dominated total mass, and mass in the diffuse hot gas component are comparable to those of bright groups and poor clusters of galaxies ($\sim 10^{13} - 10^{14} h_{70}^{-1}$ M$_\odot$). The brightest member of a fossil group has an optical luminosity comparable to that of a cluster cD galaxy (i.e. $M_R < -22.5 + 5 \log h_{70}$) and dominates the galaxy luminosity function (LF) of the system. The observational definition of a fossil system lies in the detection of extended, very luminous X-ray emission from the hot gas of the intracluster medium, and in the existence of an R-band magnitude gap $\Delta m_{12} > 2$ between the brightest and second brightest members within 0.5 $R_{vir}$ (Jones, Ponman & Forbes 2000).

As noted by Vikhlinin et al. (1999), fossil groups may represent the ultimate examples of hydrostatic equilibrium in virialized systems, since they must have been undisturbed for a very long time if they are the result of galaxy merging within a group. High-resolution hydrodynamical cosmological simulations in the Λ cold dark matter (ΛCDM) framework have shown that fossil groups have already assembled half of their final dark matter (DM) mass at redshifts $z \geq 1$, and subsequently they typically grow by minor mergers only, whereas non-fossil systems of similar masses on average form later (D’Onghia et al. 2005). The early assembly of fossil groups leaves sufficient time for objects with luminosities close to the characteristic luminosity (i.e. $L \sim L^*$) to merge into the central galaxy by dynamical friction, producing the magnitude gap which defines a fossil system. In addition, the simulated fossil groups were found to be overluminous in X-rays relative to non-fossil groups of the same optical luminosity, in qualitative agreement with observations (cf. Vikhlinin et al. 1999; Jones et al. 2000). In a recent paper, von Benda-Beckmann et al. (2008) showed that many galaxy groups may undergo a fossil phase in their lives but may not necessarily stay fossil down to $z = 0$, owing to renewed infall of $L \sim L^*$ galaxies from the large-scale environment. Such infall episodes are

E-mail: zibetti@mpia.de

© 2008 The Authors. Journal compilation © 2008 RAS

Downloaded from https://academic.oup.com/mnras/article-abstract/392/2/525/976262 by guest on 16 March 2020
statistically more likely for more massive systems, so that the fraction of quasi-fossil systems (i.e. those with a large luminosity gap between the central galaxy and the most luminous satellite) is lower among clusters than among groups (Milosavljević et al. 2006; Yang, Mo & van den Bosch 2008).

Fossil groups have become a puzzling problem to cosmology since D’Onghia & Lake (2004, hereafter DL04) showed that, with respect to state-of-the-art predictions on the frequency of substructures in CDM haloes (De Lucia et al. 2004), a virialized system like RX J1340.6+4018 lacks galaxies nearly as luminous as the Milky Way. Conversely, the same numerical simulations are able to accurately describe the frequency of substructures in galaxy clusters as massive as Virgo or Coma to well below the circular velocity of a Milky Way-size dark halo (i.e. with $V_{\text{circ}} \leq 220 \text{ km s}^{-1}$). In this respect, fossil groups appeared to exacerbate the so-called ‘small-scale crisis’ of CDM universes (Klypin et al. 1999). In fact, DL04 concluded that the missing substructure problem affects systems up to the scale of groups (typically with $kT_X \lesssim 1 \text{ keV}$). However, this result has been challenged by Sales et al. (2007), who find that the abundance and LF of simulated fossil systems are in reasonable agreement with the few available observational constraints.

Given the great interest of this cosmological issue, some optical studies have aimed at better characterizing the mass and LF of already known fossil systems (e.g. Mendes de Oliveira et al. 2006; Cypriano, Mendes de Oliveira & Sodré 2006) or identifying new ones (e.g. Santos, Mendes de Oliveira & Sodré 2007), although identifying low-mass fossil systems is hampered by the fact that groups are under-represented in existing X-ray catalogues. In spite of the increasing quality of the data and number of candidates, no new cumulative substructure distribution function (CSDF) has so far been produced for a fossil system to compare with that obtained by DL04 for the archetype fossil group RX J1340.6+4018. The determination of the CSDF for fossil systems with a range of masses is the objective of the present study.

In the following, we adopt a ΛCDM cosmological model ($\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$) with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$. This model is consistent with the main Wilkinson Microwave Anisotropy Probe 5 (WMAP5) results (cf. Hinshaw et al. 2008). This work is mainly based on Sloan Digital Sky Survey (SDSS; York et al. 2000) data from the sixth data release (DR6; Adelman-McCarthy et al. 2008, and references therein).

## 2 THE FOSSIL SAMPLE

In this study, we consider five groups and poor clusters of galaxies from the sample of fossil systems originally identified by Ponman et al. (1994) and Jones et al. (2003). In addition, we include the poor cluster AWM 4, whose status as fossil system has been suggested by Lin & Mohr (2004) and is established in this work (see Appendix A1). These six systems were selected to have (i) high-quality X-ray observations, either with Chandra (Weisskopf et al. 2000) or XMM–Newton (Jansen et al. 2001), to allow for a reliable determination of their halo properties (i.e. $R_{200}$, $M_{200}$, $V_{\text{parent}}$), and (ii) to be covered by SDSS photometry and, in the case of AWM 4, by SDSS spectroscopy. This enables us to study membership (via spectroscopic redshifts or combining photometric redshifts and statistical foreground/background subtraction) and photometric properties of members across a wide field, out to the virial radius of a system. Such coverage is mandatory to enable us to compare the observed CSDFs with previous determinations and the output of cosmological simulations in the literature, which are normally computed out to the virial radius of a system (i.e. $R_{200}$).\(^1\) Table 1 lists coordinates and redshifts of the six systems.

### 2.1 X-ray data

The X-ray and derived halo properties are reported in Table 2, along with the references to the works from which these data are taken. For all systems (except AWM 4 and RX J1416.4+2315), $M_{200}$ and $R_{200}$ are computed from the X-ray temperatures published by Khosroshahi, Ponman & Jones (2007) using the scaling relations given by Arnaud, Pointecouteau & Pratt (2005). We adopt their fits to the $M_{300}–T_X$ and $R_{200}–T_X$ relations of the entire sample to derive our fiducial estimates. In our analysis, in Section 3, we consider the effect of estimating mass and radius from fits to both the entire sample of Arnaud et al. (2005), which has a slope of 1.71, and from fits to the hot systems alone ($kT > 3.5 \text{ keV}$), which has a slope of 1.49. The resulting masses are reported in Table 2. Our motivation for this choice of relation is based on the recent results of Sun et al. (2008), who derive the mass temperature scaling relation from 1 to 10 keV using high quality Chandra data of a large sample of groups and clusters. Their $M–T$ relation normalization is similar to that of Arnaud et al. (2005), and they find a slope of 1.67, such that group masses would be 18 per cent higher at 1 keV than that derived from the fit to the full sample of Arnaud et al. (2005). In using both Arnaud et al. relations, we wish to attempt to bracket the most likely value of the $M–T$ normalization in this mass range. We note however that Khosroshahi et al. (2007) suggest that fossil groups may fall low on the $M–T$ relation, although Sun et al. (2008) find no evidence for this with a smaller sample of fossil groups. The extent of the offset found by Khosroshahi et al. appears to be mass dependent and is negligible at higher group temperatures ($kT \gtrsim 2 \text{ keV}$), although it could be up to a factor of 2–3 for the very lowest temperature systems. Deeper X-ray observations of fossil groups have been obtained to help resolve this issue, and will be the subject of a forthcoming paper.

As we show in Section 3, the CSDFs we derive are relatively insensitive to the exact choice of X-ray scaling relation and our conclusions are robust in case fossil groups should indeed fall low on the $M–T$ relation.

For AWM 4 and RX J1416.4+2315, estimates of $M_{200}$ and $R_{200}$ are taken from Gastaldello et al. (2007) and Khosroshahi et al. (2006), respectively, who fitted NFW profiles (Navarro, Frenk & White 1997) to the observed mass density profiles of these two systems. It is worth noting that there is a very good agreement

### Table 1. The sample.

| Denomination | RA (J2000.0) | Dec. (J2000.0) | $z$ |
|--------------|--------------|---------------|-----|
| AWM 4        | 16:04:57.0   | +23:55:14     | 0.0317 |
| RX J1256.0+2556 | 12:56:03.4   | +25:56:48     | 0.2320 |
| RX J1331.5+1108 | 13:31:30.2   | +11:08:04     | 0.0810 |
| RX J1340.6+4018 | 13:40:33.4   | +40:17:48     | 0.1710 |
| RX J1416.4+2315 | 14:16:26.9   | +23:15:32     | 0.1370 |
| RX J1552.2+2013 | 15:52:12.5   | +20:13:32     | 0.1370 |

\(^1\) The CSDF gives the number of subhaloes with circular velocity $V_{\text{circ}}$ larger than a given fraction of the circular velocity of the parent halo $V_{\text{parent}}$.

\(^2\) $R_{200}$ is the radius within which the average density of the system is 200 times the critical density of the Universe. $M_{200}$ is the mass within $R_{200}$.

\(^3\) Throughout the paper, we use $R_{200}$ as a proxy for the virial radius $R_{\text{vir}}$.

---

© 2008 The Authors. Journal compilation © 2008 RAS, MNRAS 392, 525–536
between the estimates given in the two papers referred above and those derived from the scaling relations of Arnaud et al. (2005). From Table 2, one can clearly see that our sample spans a broad range in mass and X-ray temperature, in the regime of groups and poor clusters.

Once \(M_{200}\) and \(R_{200}\) are obtained, the circular velocity of the parent halo of each system is computed:

\[
V_{\text{parent}} = \sqrt{\frac{GM_{200}}{R_{200}}} . \tag{1}
\]

### 2.2 Optical data

With the exception of AWM 4, the nearest cluster at \(z = 0.0317\), the analysis of all systems relies on SDSS photometric data only (including photometric redshifts). Although for some of them spectroscopic redshifts are available through the SDSS or other published catalogues, the lack of completeness or insufficient depth prevents us from using them. The SDSS spectroscopic data, in particular, are limited to 17.77 mag (r band, see Strauss et al. 2002); this translates into absolute magnitude limits ranging from \(-19\) (for RX J1331.5+1108 at \(z = 0.081\)) to \(-22.5\) (for RX J1256.0+2556 at \(z = 0.23\)), thus making the faint end of the LF inaccessible to our analysis. In contrast, assuming a conservative limit of 20.5 mag, the SDSS photometry allows us to probe down to roughly 1 mag fainter than \(L^*\) for all systems. Although one could, in principle, combine the complete information derived from photometric data alone with the spectroscopic measurements for the brightest galaxies or in the regions covered by other surveys, combining different selection functions is an unnecessary complication. In particular, we have checked that for all bright galaxies (\(r < 17.77\) mag) with available spectroscopy the spectroscopic membership coincides with the purely photometric one.

In Appendix A, we comment further on issues specific to individual systems and on their status of fossil. In summary, AWM 4 is established as fossil; RX J1331.5+1108, RX J1340.6+4018 and RX J1416.4+2315 are confirmed fossil systems; observational uncertainties do not allow us to establish RX J1256.0+2556 as a fossil with very high confidence, but we will consider it as a fossil in the following; lastly, RX J1552.2+2013 does not match the magnitude gap requirement and is disqualifed as a fossil system.

### 3 THE CSDF: METHOD

In this section, we describe how the cumulative substructure distribution function is computed for the systems in our sample. As mentioned in Section 1, the CSDF of a galaxy system, \(N(>x) = V_{\text{circ}}(x)\), is defined as the number of members (i.e. substructures of the parent DM halo), other than the brightest member, which are satellites and have circular velocities \(V_{\text{circ}}\) larger than \(x\). Here, \(V_{\text{parent}}\) is the circular velocity of the parent system considered as a whole (defined in equation 1) and \(x < 1\). Theoretically, each galaxy in a group/cluster is associated with a DM subhalo of a given mass \(M_{\text{sub}}\) and radius \(R_{\text{sub}}\) such that the circular velocity is simply defined as \(V_{\text{circ}} = \sqrt{GM_{\text{sub}}/R_{\text{sub}}}\). Observationally, this information is only accessible for few well-studied galaxies. For the galaxies in our systems, circular velocities must be derived from basic observables (luminosity, central velocity dispersion) by means of scaling relations, as we describe in Section 3.1.

The second essential ingredient for computing the CSDF is the method to count galaxies up to a given circular velocity either by means of a complete cluster membership selection based on spectroscopic redshifts or by means of a robust statistical subtraction of the galaxy foreground/background from the counts in the cluster/group region. This is discussed in Section 3.2.

### 3.1 Inferring \(V_{\text{circ}}\)

The structure and luminosity of galaxies are known to be linked to their kinematics via scaling relations. For late-type (spiral) galaxies, the Tully–Fisher (TF) relation (Tully & Fisher 1977) links luminosity and (maximum or asymptotic) circular velocity in the disc, which we assume to coincide with \(V_{\text{circ}}\). For early-type (elliptical) galaxies, the central velocity dispersion \(\sigma_0\) can be inferred either from the luminosity using the Faber–Jackson (FJ) relation (Faber & Jackson 1976) or, when more information about the surface brightness distribution is available, via the Fundamental Plane (FP) relation that connects half light radius, effective surface brightness and central velocity dispersion \(\sigma_0\). Once \(\sigma_0\) is known, the circular velocity can then be inferred. In doing so, one can either assume isothermal dynamics, in which case \(V_{\text{circ}} = \sqrt{\sigma_0/m}\), or adopt empirical scaling relations between the two quantities based on very deep observations of extended rotation curves in early-type galaxies (e.g. Ferrarese 2002; Pizzella et al. 2005). In the following analysis, we adopt the relation given by Pizzella et al. (2005), viz.,

\[
V_{\text{circ}} = (1.32 \pm 0.09)\sigma_0 + (46 \pm 14) \text{[km s}^{-1}] ,
\]

\[\text{This is an approximation that may lead to a systematic overestimate of the true } V_{\text{circ}} \text{ at the subhalo virial radius by some 10 per cent (see Salucci et al. 2007).}\]
as it includes a comprehensive sample of both low and high surface brightness galaxies over the range between ~50 and 350 km s$^{-1}$, and is therefore best suited for an heterogeneous sample like ours. In fact, equation (2) applies to every galaxy, irrespective of its morphological type, provided that the central velocity dispersion is measured.

We note that the analysis presented in this work relies on the reasonable assumption that scaling relations hold everywhere and phenomena like the tidal truncation of subhaloes do not modify them significantly.

In practice, we are faced with very different kinds of data, requiring a diversity of approaches, as we now describe.

3.1.1 $V_{\text{circ}}$ in AWM 4

Most of the galaxies in AWM 4 have a measured velocity dispersion from SDSS spectra. For these galaxies, we first correct the measured value for the standard aperture corresponding to the effective radius $R_{\text{e}25}$, using the recipe given by Jørgensen, Franx & Kjaergaard (1995). Then, we apply the scaling relation of Pizzella et al. (2005) to infer $V_{\text{circ}}$.

In cases where the velocity dispersion is not available, the relatively small distance to this cluster allows a reliable estimate of the structural parameters of the galaxies to be achieved. Hence, we proceed as follows.

(i) First, we select early-type galaxies based on the concentration index $C_i \equiv R_{\text{g}25}/R_{\text{g}0} > 2.5$ as given by the SDSS in $i$ band (as in Bernardi et al. 2003a). For these galaxies, $\sigma_0$ is derived from the $r$-band FP relation of Bernardi et al. (2003c), after applying $k$ and cosmological dimming $[\{z+1\}^5]$ corrections to the effective surface brightness. Thereafter, $\sigma_0$ is converted into $V_{\text{circ}}$ using the Pizzella et al. (2005) relation as detailed above.

(ii) Bright galaxies (rest-frame $M_i < -19$ mag) with $C_i \leq 2.5$ are considered bona fide disc-dominated galaxies and their $V_{\text{circ}}$ is computed via the TF relation. In order to minimize systematic errors, our best estimate of $V_{\text{circ}}$ is given by the mean of the TF estimate of Pizagno et al. (2007), using $i$-band Petrosian magnitudes and of Tully et al. (1998, 1999), using $i$-band 'total' composite model magnitudes converted to $I_C$. In both cases, magnitudes are $k$-corrected and corrected for the inclination-dependent internal extinction using the recipe of Tully et al. (1998). $i$ and $I_C$ bands are explicitly chosen to minimize the amount and uncertainty of this correction (cf e.g. Pierini 1999; Pierini, Gordon & Witt 2003).

(iii) Finally, for galaxies fainter than $M_i = -19$ mag and with $C_i \leq 2.5$, the concentration index is not indicative of the dynamical state (e.g. dwarf elliptical galaxies can be 'hot' systems yet have low concentration). In this case, our best guess $V_{\text{circ}}$ is given by the mean of the estimate from the FP – as in case (i) – and from the TF – as in case (ii).

Statistical errors are computed by summing uncertainties on the measured quantities propagated to $V_{\text{circ}}$ and the typical rms scatter around the scaling relations, in quadrature. In particular, we adopt a scatter of 15 km s$^{-1}$ for $V_{\text{circ}}$ in the Pizzella et al. (2005) relation, 10 per cent rms for $\sigma_0$ from the FP and 15 per cent for $V_{\text{circ}}$ about the TF relation (Pizagno et al. 2007). The effect of random errors on the CSDF are quantified by means of Monte Carlo simulations (see Section 4.2).

Systematic errors may have even greater impact on our conclusions about the CSDFs as they can shift or expand/shrink the real distributions. We consider systematic uncertainties for all adopted scaling relations. In the FP and Pizzella et al. (2005) relation, we use the uncertainties on the fitting parameters given in the reference papers. In particular, for the Pizzella et al. (2005) relation, we account for the covariance between the two fitted coefficients by re-writing the fitting function referred to the mean abscissa of the points and considering only the error on the slope. The covariance terms between the FP parameters can then be safely neglected as fig. 2 of Zibetti et al. (2002) illustrates. For the TF estimates, we adopt half of the range spanned by the two relations of Pizagno et al. (2007) and Tully et al. (1998) as a systematic uncertainty.

The set of all possible systematics and their permutations gives us useful upper and lower limits for the computed CSDFs, as we will show in Fig. 3.

3.1.2 $V_{\text{circ}}$ for RX groups/clusters

For the five RX systems, we rely on photometric data alone to compute $V_{\text{circ}}$ for the reasons outlined in Section 2. In addition, their higher redshift relative to AWM 4 makes use of structural parameters much more uncertain. Moreover, uncertainties on membership determined through statistical methods (see Section 3.2) will completely dominate over the uncertainties brought in by the scaling relations. Therefore, we simplify the procedure described above.

For the RX systems, we determine $V_{\text{circ}}$ (i) either using the TF relation of Pizagno et al. (2007) for the most accurate $r$ band or (ii) by converting $\sigma_0$, inferred from the $r$-band magnitude via the FJ relation of Bernardi et al. (2003b), into $V_{\text{circ}}$ using the Pizzella et al. (2005) relation. The choice between the two is dictated by the colour of the galaxy, according to the well-known colour bimodality (e.g. Baldry et al. 2004). For each cluster/group, we look at the $g-i$ colour distribution of galaxies with a photometric redshift close to the redshift of the system, and determine by eye the cut between blue and red galaxies. The values of $V_{\text{circ}}$ of the former are determined via the TF relation, while for the latter we use the combination of FJ and Pizagella et al. (2005) relations.

All magnitudes we use for the scaling relations are taken from SDSS-DR6 and are corrected for foreground Galactic extinction, redshift ($k$-corrections as given by Csabai et al. 2003) and, for red galaxies only, passive stellar evolution, according to the output of the code of Bruzual & Charlot (2003). We have checked that our results are largely insensitive to the particular choice of colour cut or, alternatively, to a cut in spectral type, as derived from the photometric redshift algorithm (see Csabai et al. 2003, for details).

3.2 Membership and statistical foreground/background subtraction methods

With the exception of AWM 4, for which cluster membership is assigned to individual galaxies via spectroscopic redshifts (see Section A1), member galaxy counts are based on photometric redshifts from the SDSS-DR6 (Csabai et al. 2003) and are obtained after application of statistical foreground/background subtraction methods.

For each system, we define a circle corresponding to the projected $R_{2500}$, centred at the coordinates of the peak of the X-ray emission, and 1000 control fields of the same circular aperture, randomly distributed inside an annulus with inner radius $2R_{2500}$ and outer radius $4 R_{2500}$. The inner radius is chosen to avoid the cluster region, while the outer radius allows us to avoid control field overlapping. We assume each galaxy lies at the redshift of the system in question, and the corresponding property $X$ (e.g. absolute magnitude, velocity...
Are fossil groups a challenge of CDM?

Figure 1. The LF of the six galaxy systems, ordered by ascending circular velocity from left to right and top to bottom. Counts are per bin of magnitude (0.5 mag width). Filled blue histograms and magenta symbols represent the entire area within $R_{200}$, hatched histograms and black symbols represent the area within 0.5$R_{200}$. Error bars are derived via statistical methods (see text for details). The curves represent the analytical LF of Popesso et al. (2005), normalized to the total number of galaxies down to 20 $r$ mag (apparent), with no other adjustable parameter.

5 The distribution computed in this way actually measures the excess of counts in the cluster versus the field. To obtain the true cluster counts, we correct the field counts by subtracting the contribution of the physical space that would be occupied by the cluster. Such a correction is well below the per cent level in all cases.

We then apply a cut in photometric redshift to exclude the largest possible number of contaminants in the fore- and background, but avoiding exclusion of system members. Unfortunately, photometric redshifts are typically affected by significant uncertainties, from 0.03 rms at $r = 16$ mag to 0.08 at $r = 20.5$ mag (Csabai et al. 2003). Therefore, the selected ranges $z_{sys} \pm \Delta z$ need to be quite broad. We optimise the result by adapting the cut widths $\Delta z$ to linearly scale as a function of apparent magnitude, such that $\Delta z(m_r = 14.5) = 0.05$ and $\Delta z(m_r = 20.5) = 0.1$.

This pre-selection in photometric redshift and stellarity index allows us to attain a satisfactory signal to noise (S/N), while leaving us with a clean and unbiased selection. This is confirmed by the stability of our distributions when we adopt less restrictive cuts (at the cost of a degradation in S/N, however). Moreover, as already mentioned in Section 2.2, the memberships of the brightest galaxies based on this photometric method coincide with those resulting from spectroscopic redshifts, whenever these are available. As a key test for our method, we next discuss the LFs for all of our systems.

4 RESULTS

4.1 The luminosity function of fossil systems

Fig. 1 shows the LF of the six galaxy systems. The objects are plotted from left to right and from top to bottom in order of
ascending circular velocity $V_{\text{opt}}$. We examine the LF in two apertures, namely within $R_{200}$ (blue filled histograms and magenta lines) and 0.5 $R_{200}$ (black hatched histograms and black lines). For all systems but AWM 4 error bars show the confidence intervals derived from control field statistics.

The solid curves represent the universal LF of Popesso et al. (2005), normalized to the total number of galaxies down to $r = 20$ mag (apparent). We stress that no other parameter is tuned in order to improve the match between these curves and the measured histogram. Errors are too large to claim any agreement or disagreement with the universal LF for the least massive groups because of the small number statistics and the weak contrast against the background. For the three most massive systems, however, the plots show an almost perfect agreement within the error bars.

The normalization $N$ of the LF\(^7\) scales, as expected, with cluster mass or, equivalently, with X-ray temperature, as we show in Fig. 2. The orthogonal fit to the data points (solid line) gives $N \propto L^1_{X} \pm 0.33$, where the error on the exponent is formally derived under the hypothesis of Gaussian errors. If the assumption is made that the total optical luminosity of the cluster ($r$ band), $L_{\text{opt,r}}$, scales proportionally to $N$, we can compare this result with the finding of Popesso et al. (2004): $L_{\text{opt,r}} \propto L^1_{X}$ (dashed line in Fig. 2). Formally, our relation is significantly (at more than 2$\sigma$) steeper than the one found by Popesso et al. (2004), but consistent with the 3/2 slope expected for self-similar systems. However, our small number statistics and possible systematics hidden behind the assumption $L_{\text{opt,r}} \propto N$ prevent us from drawing any quantitative conclusion.

The LFs within 0.5 $R_{200}$ also confirm the magnitude gaps typical of fossil systems (see Appendix A). This is particularly remarkable as it shows that the photometric redshift pre-selection works very well in the bright regime, and provides very high completeness and low contamination.

Finally, we note that the LF (inside 0.5 $R_{200}$) for RXJ1416.4+2315 and RXJ1552.2+2013 are in very good quantitative agreement with those determined by Cypriano et al. (2006) and Mendes de Oliveira et al. (2006), respectively, based on spectroscopic membership determination. A detailed comparison indicates that the drop of number counts that we observe in RXJ1552.2+2013 at $M_r > -19$ mag is fully consistent with the observations of Mendes de Oliveira et al. (2006), and therefore is most likely real.

In light of the above, we conclude that our statistical method of membership estimation is sufficiently robust and accurate to study the LF, and hence is applicable also to study of the CSDF.

### 4.2 Substructure distribution functions

CSDFs are constructed following different methods for AWM 4 and the five RX systems. In the case of AWM 4, all spectroscopic members are used directly to build the CSDF from their estimated $V_{\text{circ}}/N_{\text{parent}}$. In the case of RX systems, the method described in Section 3.2 is adopted with the property $X$ replaced by $V_{\text{circ}}/N_{\text{parent}}$. The CSDFs obtained in this way, assuming the values of $V_{\text{parent}}$ given in Table 2, are shown as thick blue lines in Fig. 3.

The limiting magnitudes that define the completeness of our sample translate into a very complicated completeness function for $V_{\text{circ}}/N_{\text{parent}}$ because of the different scaling relations adopted. By inverting each scaling relation, we calculate the set of $V_{\text{circ}}$ corresponding to the limiting magnitudes of our samples. The maximum among these values is then our completeness limit for the CSDF. The CSDFs of the RX systems are cut at this limit in Fig. 3. For AWM 4, the entire CSDF is shown, and the completeness limit is marked with a vertical dashed line.

Fig. 3 also shows statistical and systematic uncertainties. Concerning AWM 4, the $V_{\text{circ}}$ of each galaxy has an associated error. To quantify the effect of these uncertainties on the CSDF, we run 10,000 Monte Carlo simulations offsetting each $V_{\text{circ}}$ by a random $\Delta v$ drawn from a Gaussian distribution with the same width as the associated uncertainty. For each realization, the CSDF is computed. The confidence range is determined from the 16th–84th percentile range of $V_{\text{circ}}/V_{\text{parent}}$ at each step of the CSDF, and is shown as the cyan shaded area in Fig. 3. This randomization procedure is undertaken assuming the standard scaling relations. If we now let the parameters of the scaling relations vary within their uncertainties, we obtain the orange and the magenta hatched regions as extreme cases. On the other hand, the X-ray data appear to be good enough to determine $R_{200}$ and $V_{\text{parent}}$ with an accuracy of better than 10 per cent. This implies that galaxy counts would change only slightly, and the CSDF could shift horizontally by 10 per cent at most, which is comparable to or less than the effect of other systematic uncertainties.

For the five RX systems, we consider only uncertainties due to statistical foreground/background subtraction and to the determination of the properties of the parent system. The cyan shaded areas in Fig. 3 show the 16th–84th percentile range of variation due to the statistical uncertainties of background counts. The red thick lines represent the CSDFs that we obtain by adopting the X-ray scaling relations determined from systems with $kT > 3.5$ keV instead of the full range (i.e. the parent system parameters derived from the ‘hot’ scaling relations, see Section 2). The range of variation due to each uncertainty is of the same magnitude at the lower end of

---

\(^6\) Note that the brightest galaxy is not considered as part of the regular LF.

\(^7\) $N$ is the number of galaxies per 0.5 mag at $M_r = -18.0$. 

---

\(^{©}\) 2008 The Authors. Journal compilation © 2008 RAS, MNRAS 392, 525–536
the mass range; at higher masses, uncertainties due to statistical foreground/background subtraction dominate.

We note that the observed $M-T_X$ relations exhibit normalizations which are lower than those produced from simulations by ∼10 per cent, perhaps due to a neglect of non-thermal pressure support (Arnaud, Pointecouteau & Pratt 2005; Vikhlinin et al. 2006; Nagai, Kravtsov & Vikhlinin 2007). Such a systematic effect would lead us to underestimate both $R_{200}$ and $V_{\text{parent}}$ in the calculation of the CSDFs. This would tend to shift all CSDFs slightly down and to the right in Fig. 3. On the other hand, if fossil groups had lower masses for a given $T_X$ as claimed by Khosroshahi et al. (2007), their CSDFs would shift to the right, in the sense of more abundant substructure. This should mainly affect groups with $k_{T_X} \lesssim 2$ k e V, i.e. only RXJ1331.5+1108 and RXJ1340.5+4017 in our sample. It is worth noting, however, that these two groups are those that lie closer to the $M-T_X$ relation of normal groups (see Khosroshahi et al. 2007, their fig. 8). By comparing $R_5$ and $M_3$ at overdensity $\delta = 500$ as given by Khosroshahi et al. (2007) and as estimated from our fiducial scaling relations (Arnaud et al. 2005), we conclude that the CSDFs of RXJ1331.5+1108 and RXJ1340.5+4017 could further shift to higher $V_{\text{circ}}/V_{\text{parent}}$ by 25 and 17 per cent, respectively. Errors in the X-ray temperature itself propagate quite weakly on the CSDF. The effect of under(over)-estimating $T_X$ is to under(over)-estimate both $R_{200}$ and $V_{\text{parent}}$, with the result of decreasing (increasing) the galaxy counts but simultaneously shifting the distribution to the right (left).

5 DISCUSSION

Fig. 3 shows an interesting feature: the CSDFs shift to lower $V_{\text{circ}}/V_{\text{parent}}$ by almost a factor of two as the mass of the system increases. Noticeably, this is in agreement with the statistical behaviour of $V_{\text{circ},2nd}/V_{\text{parent}}$ for the second brightest member of SDSS groups/clusters as a function of mass as presented by Yang et al. (2008). From their figs 6 and 7, we compute that $V_{\text{circ},2nd}/V_{\text{parent}}$ decreases by $\approx 0.24$ dex when $M_{200}$ increases from $2 \times 10^{13}$ to $3 \times 10^{14} M_\odot$, as in our sample. This decrease nicely matches the shift observed in Fig. 3 and does not point to any anomalous behaviour of fossil with respect to non-fossil systems of the same mass.

As a test, following Sales et al. (2007) we compute the magnitude gap between the first and the 10th ranked member $\Delta M_{10}$ of AWM 4, using the spectroscopic membership determinations. With a central galaxy luminosity $L = 2.34 \times 10^{11} L_\odot$ and $\Delta M_{10} = 3.29$ mag, AWM 4 falls in the region covered by the simulations of isolated bright galaxies by Sales et al. (2007, their fig. 3). Once more, this suggests that fossil systems are not anomalous when compared to current ΛCDM simulations.

To better prove this, we compare the CSDFs of the five bona fide fossil systems with those of observed nearby clusters/groups and of simulated systems in the ΛCDM framework. In particular, we refer to the results presented in Desai et al. (2004, their fig. 5). These authors have measured CSDFs for 34 clusters/groups identified in the SDSS, with velocity dispersions ranging from 250 to 1000 km s$^{-1}$. 

© 2008 The Authors. Journal compilation © 2008 RAS, MNRAS 392, 525–536
Desai et al. (2004) also consider 15 simulated groups/clusters in approximately the same velocity dispersion range and measured the corresponding CSDFs. Fig. 4 reproduces their observed (left-hand panel) and simulated CSDFs (right-hand panel) as hatched areas, overlaid on to the CSDFs of our five fossil systems (grey-shaded areas, displaying the range of statistical uncertainties, equivalent to the cyan area in Fig. 3; the thick black lines are the CSDF of AWM 4).

The CSDFs of all fossil systems fall in the range of measured CSDFs for SDSS clusters. In comparison to simulations, the CSDFs of our fossil systems are generally in good agreement, although an excess of substructure is observed at high $V_{\text{circ}}/V_{\text{parent}}$. This discrepancy is seen also between the real and the simulated clusters by Desai et al. (2004). As these authors show (their section 6.4), it most likely results from not properly taking the effects of baryons into account in simulations. What is most interesting to note here, however, is that none of the fossil systems appears to be lacking significant amount of substructure, this result being robust against systematic effects induced by different choices of scaling relations.

In particular, we are unable to reproduce the results of DL04 concerning RX J1340.6+4018: although with large uncertainties, the archetype fossil group does not show any evidence for missing substructure. We note that the entire CSDF of DL04 (their fig. 1) is shifted to a factor of 2 lower velocities with respect to ours. This might result from a different choice of scaling relations, although (as we show for AWM 4) choices within a reasonable range of parameters cannot change the results by such a large amount. Moreover, our photometric data set allows us to apply scaling laws in a very accurate and galaxy-type specific way, as detailed in Section 3.1.2. In contrast to DL04, we also take advantage of a much better and more complete sample selection, based on complete photometric coverage over the entire virialized region of the group, and perform robust statistical foreground/background subtraction. Finally, we have thoroughly investigated all possible sources of uncertainty which could propagate into our determination of the CSDFs of these systems, finding them all to be relatively small.

In conclusion, the present analysis rules out lack of substructure in fossil clusters ($M_{200} \gtrsim 10^{14} M_\odot$), where our two photometrically derived CSDFs are robust and consistent with the CSDF of AWM 4 based on spectroscopy. The same appears to hold for lower mass fossil systems, although with non-negligible uncertainties. Spectroscopic determinations of CSDFs for fossil groups ($M_{200} \approx 10^{13}$–$10^{14} M_\odot$) would greatly help to reach a firm conclusion in this mass range.

6 CONCLUSIONS

We have studied six galaxy groups and clusters suggested in the literature to be fossil systems, and having high quality X-ray and SDSS spectroscopic or photometric information. Among them, we have established AWM 4 as fossil system. We confirm three other systems (RX J1331.5+1108, RX J1340.6+4018 and RX J1416.4+2315) to be fossil. RX J1256.0+2556 has characteristics very close to a genuine fossil system, although observational errors are still too large for a robust classification as fossil. Finally, we demonstrate that RX J1552.2+2013 does not match the magnitude gap requirement to qualify as a fossil.

For each system, we have computed the LFs within 0.5 and 1 virial radius. Although with uncertainties, that are remarkably large for the least massive systems, they are consistent with the universal LF of clusters derived by Popesso et al. (2005).

We have derived detailed CSDFs for the six galaxy groups and clusters. Our motivation was to produce CSDFs for systems with a range of masses in the group and poor cluster regime, for comparison with the original CDSF derived for the archetype fossil system RX J1340.6+4018 by DL04. In fact, these authors claimed a lack
of substructure for RX J1340.6-i-4018, suggesting that the so-called ‘small-scale crisis’ of Milky Way-size haloes (Klypin et al. 1999) exists up to the scale of X-ray bright groups. In addition, we wanted to compare the CSDFs of our fossil systems with results from normal groups and clusters identified in the SDSS (Desai et al. 2004), and in cosmological simulations (Desai et al. 2004; Sales et al. 2007).

Our conclusions are as follows.

(i) The CSDF of AWM 4, based on spectroscopic data, is completely consistent both with Desai et al.’s (2004) data and with simulations. AWM 4 also matches the simulations by Sales et al. (2007) of isolated bright galaxies in terms of central galaxy luminosity versus magnitude gap between the first and the 10th ranked member.

(ii) The photometrically derived CSDFs of the other four bona fide fossil systems are all completely consistent with the CSDF envelope derived from observed normal groups and clusters (Desai et al. 2004). With respect to numerically simulated systems in Desai et al. (2004) none of our fossil systems appears to lack any substructure.

We therefore conclude that no evidence can be provided that the ‘small-scale crisis’ is occurring on the scale of fossil systems. In other words, the presence of a large magnitude gap between the first and second ranked members of a group/cluster does not imply anything special about its substructure, which can be fully accounted for by existing ΛCDM simulations.

Interestingly, we also observe a systematic shift of the CSDFs towards lower $V_{circ}/V_{parent}$ at increasing $V_{parent}$. This can be reproduced using the scaling relations of first and second brightest members versus halo mass derived for a representative sample of groups and clusters by Yang et al. (2008). Once more, this reinforces the idea that fossil systems are not anomalous as far as scaling relations are concerned.

Further deep, wide-field spectroscopic observations of fossil systems are required to confirm the results we have obtained in the present work. This is particularly necessary at the low end of the mass range. On the theoretical side, analyses which mimic observational approaches such as that described here would allow us to compare real data and simulations on an equal footing. This paper is the first in a series which will characterize many of these aspects of fossil groups.

ACKNOWLEDGMENTS

We thank Simon White and Hans-Walter Rix for useful comments. SZ acknowledges the hospitality of the Max-Planck-Institut für extraterrestrische Physik in Garching. DP acknowledges useful discussions with E. D’Onghia and the hospitality of the Institute for Theoretical Physics of the University of Zurich. DP acknowledges support from the German Deutsches Zentrum für Luft- und Raumfahrt, DLR project number 50 OR 0405. GWP acknowledges support from DFG Transregio Programme TR 33.

Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the U.S. Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England. The SDSS Web Site is http://www.sdss.org/.

The SDSS is managed by the Astrophysical Research Consortium for the Participating Institutions. The Participating Institutions are the American Museum of Natural History, Astrophysical Institute Potsdam, University of Basel, University of Cambridge, Case Western Reserve University, University of Chicago, Drexel University, Fermilab, the Institute for Advanced Study, the Japan Participation Group, Johns Hopkins University, the Joint Institute for Nuclear Astrophysics, the Kavli Institute for Particle Astrophysics and Cosmology, the Korean Scientist Group, the Chinese Academy of Sciences (LAMOST), Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPIA), the Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, Ohio State University, University of Pittsburgh, University of Portsmouth, Princeton University, the United States Naval Observatory, and the University of Washington.

This research has made use of the NASA/IPAC Extragalactic Data base (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

REFERENCES

Adelman-McCarthy J. K. et al., 2008, ApJS, 175, 297
Albert C. E., White R. A., Morgan W. W., 1977, ApJ, 211, 309
Arnaud M., Pointecouteau E., Pratt G. W., 2005, A& A, 441, 893
Baldry I. K., Glazebrook K., Brinkmann J., Ivezić Z., Lupton R. H., Nichol R. C., Szalay A. S., 2004, ApJ, 600, 681
Barnes J. E., 1989, Nat., 338, 123
Bernardi M. et al., 2005a, AJ, 125, 1817
Bernardi M. et al., 2005b, AJ, 125, 1849
Bernardi M. et al., 2005c, AJ, 125, 1866
Bernardi M., Hyde J. B., Sheth R. K., Miller C. J., Nichol R. C., 2007, AJ, 134, 1741
Bruzual G., Charlot S., 2003, MNRAS, 344, 1000
Csabai I. et al., 2003, AJ, 125, 580
Cypriano E. S., Mendes de Oliveira C. L., Sodré L. J., 2006, AJ, 132, 514
De Lucia G., Kauffmann G., Springel V., White S. D. M., Lanzoni B., Stoehr F., Tormen G., Yoshida N., 2004, MNRAS, 348, 333
Desai V., Dalcanton J. J., Mayer L., Reed D., Quinn T., Governato F., 2004, MNRAS, 351, 265
de Vaucouleurs G., de Vaucouleurs A., Corwin H. G. Jr, Buta R. J., Paturel G., Fouque P., 1991, Third Reference Catalogue of Bright Galaxies, Vols 1–3, Springer-Verlag, Berlin
D’Onghia E., Lake G., 2004, ApJ, 612, 628 (DL04)
D’Onghia E., Sommer-Larsen J., Romeo A. D., Burkert A., Pedersen K., Portinari L., Rasmussen J., 2005, ApJ, 630, L109
Fabrer S. M., Jackson R. E., 1976, ApJ, 204, 668
Ferrarese L., 2002, ApJ, 578, 90
Gastaldello F., Buote D. A., Humphrey P. J., Zappacosta L., Bullock J. S., Brighenti F., Mathews W. G., 2007, ApJ, 669, 158
Gastaldello F., Buote D. A., Brighenti F., Mathews W. G., 2008, ApJ, 673, L17
Gavazzi G., Zibetti S., Boselli A., Franzetti P., Scdoggio M., Martocci S., 2001, A& A, 372, 29
Hinshaw G. et al., 2008, ApJS, in press (arXiv: 0803.0732)
Jansen F. et al., 2001, A& A, 365, L1
Jarrett T. H., Chester T., Cutri R., Schneider S., Skrutskie M., Huchra J. P., 2000, AJ, 119, 2498
Jeltema T. E., Mulchaey J. S., Lubin L. M., Fassnacht C. D., 2007, ApJ, 658, 865
Jones C., Forman W., 1999, ApJ, 511, 65
Jones L. R., Ponman T. J., Forbes D. A., 2000, MNRAS, 312, 139
Jones L. R., Ponman T. J., Horton A., Babul A., Ebeling H., Burke D. J., 2003, MNRAS, 343, 627
Jørgensen I., Franx M., Kjaergaard P., 1995, MNRAS, 276, 1341
APPENDIX A: NOTES ON INDIVIDUAL OBJECTS

A1 AWM4

AWM4 belongs to a special subset of poor clusters, originally selected in the optical by Morgan, Kayser & White (1975, MKW) and Albert, White & Morgan (1977, AWM) in a search for cD-like galaxies outside rich clusters, where these galaxies had traditionally been found. NGC 6051, $V_0^r = 12.93$ mag (de Vaucouleurs et al. 1991), located at $z = 0.031 755 \pm 0.000 033$ (Wegner et al. 1999), is the cD of AWM4. Koranyi & Geller (2002) subsequently identified 28 members brighter than $R = 15.5$ mag. Most are early-type galaxies, concentrated in the centre and with a smooth Gaussian velocity distribution centred at the velocity of NGC 6051. The velocity dispersion of the system is 440 km s$^{-1}$.

AWM4 first appeared as an extended X-ray source in the catalogue of images of galaxy clusters detected by the Einstein Imaging Proportional Counter (Jones & Forman 1999). No substructure nor a departure from symmetry was found in this X-ray image of AWM4 at a 24 arcsec resolution. This has been confirmed by the latest X-ray observations, with XMM–Newton and at a resolution of 6 arcsec (O’Sullivan et al. 2005), where the X-ray emission is centred on NGC 6051. Despite the presence of a powerful active galactic nucleus (AGN) (see Gastaldello et al. 2008, for a thorough discussion), the relaxed appearance of AWM4 both in optical and X-rays motivated Gastaldello et al. (2007) to include this system in their sample of 16 bright relaxed groups/clusters to which they applied a hydrostatic analysis to measure mass profiles. We use the results of their best fitting NFW profile to characterize the DM halo of AWM4. The resulting total mass, $1.6 \times 10^{14} M_{\odot}$, and X-ray temperature, 2.5 keV, qualify AWM4 as a poor cluster.

Lin & Mohr (2004) first pointed out that AWM4 appears to be a fossil system, since it is X-ray luminous and meets the magnitude-gap criterion in $K_s$ band. Within a half of the projected virial radius from the X-ray centre of AWM2 spectroscopic members have the same $K_s$-band magnitude gap from NGC 6051, of $\Delta m = 2.2$ mag. However, fossil groups were defined using $R$-band photometry (Jones et al. 2003). In the following, we show that the gap is present in $R$ band too. AWM4 is covered by SDSS imaging and spectroscopy out to its virial radius. Only four over 135 spectroscopic targets (see Strauss et al. 2002, for the spectroscopic target selection in the SDSS) do not have a valid redshift measurement down to the limit of $r = 17.77$ mag (corrected for Galactic extinction), corresponding to the absolute magnitude $M_r = -17.91$ mag at the redshift of AWM4 for the average $k$-correction. The spectroscopic completeness reaches 100 per cent at $r = 17.25$ mag; it decreases to 90 per cent between 17.25 and 17.77 mag. This allows us to perform a complete cluster-member identification that is almost a factor of 10 deeper in luminosity than previously done by Koranyi & Geller (2002). Moreover, the superior photometric quality of the SDSS images allows us to establish the status of AWM4 as a fossil system, by safely assuming that the gap in $r$ band is the same as in $R$ band.

We identify as members all galaxies within the projected virial radius with spectroscopic redshift that differs from the velocity of the system by less than 1000 km s$^{-1}$. We find a total of 42 members, 23 within half of the virial radius (including NGC 6051). As SDSS photometry is known to underestimate the luminosity of large galaxies (see, e.g. Bernardi et al. 2007) because of the problematic sky subtraction inherent in the automatic pipeline, we perform our own photometric measurements on the original $r$-band SDSS ‘corrected frames’ for all galaxies within $0.5 R_{200}$, following the same procedure described in Gavazzi et al. (2001). The sky background is measured in empty areas, sufficiently far away from galaxies, after masking stars. Elliptical isophotes are fitted to the images of individual galaxies using the IRAF task ellipse, after carefully masking contaminating sources, in particular the bright star projected on top of NGC 6051. The resulting 1D azimuthally averaged surface density is consistent with the system by less than 1000 km s$^{-1}$.

8 Photometry in the $J$, $H$ and $K_s$ bands, complete down to $K_s = 13.5$, is available from the Two Micron All-Sky Survey extended source catalogue (2MASS; Jarrett et al. 2000).
brightness profiles are fitted with analytical functions (exponential, de Vaucouleurs or combined). Finally, total magnitudes are derived by extrapolating the measured flux to infinity, according to the best-fitting analytic model. As expected, the luminosities of the brightest galaxies are significantly underestimated by the SDSS automatic pipeline. By comparing the so-called ‘model’ magnitudes from the SDSS-DR6 with our own measurements, we find that NGC 6051 is reported 0.67 mag too faint, while other galaxies down to \(\approx 15\) mag are systematically fainter by 0.1–0.2 mag.

Magnitudes for the three brightest members of AWM 4 are reported in Table A1. All magnitudes are corrected for foreground Galactic extinction. Column 4 lists our extrapolated magnitudes, reported along with the statistical uncertainty due to photometric errors and fitting uncertainties, and upper and lower systematic shifts due to background uncertainties. Column 5 contains our magnitude determinations within the isophotal ellipse corresponding to 25 mag arcsec\(^{-2}\). Columns 6 and 7 are the Petrosian and model magnitudes from the SDSS, respectively.

From our extrapolated magnitudes, we conclude that AWM 4 fulfills the requirement of magnitude gap \(\geq 2\) mag in \(r\) band (\(\approx R\) band), with a \(\Delta m_{12} = 2.23 \pm 0.14\) mag. Comparison with the other magnitude determinations and the systematic uncertainty due to the background level also demonstrate how critical the inclusion of the diffuse envelope of the cD is in establishing AWM 4 as a genuine fossil system.

### A2 RX J1256.0+2556
RXJ1256.0+2556 is one of the fossil groups originally included in the sample of Jones et al. (2003). These authors reported that the presence of the magnitude gap within 0.5 \(R_{200}\) critically depends on the exact value of \(R_{vir}\). Although a better determination is now available from Khosroshahi et al. (2007), the uncertainty on the X-ray temperature of this system (2.63 ± 0.12 keV) translates into a large uncertainty on \(R_{200} = 1.03^{+0.08}_{-0.07}\) Mpc = 4.66\(^{+1.09}_{-1.26}\) arcmin. The galaxy [JML2007] J125557.90+255819.6 (whose membership is confirmed by Jeltema et al. 2007) is only 1.2 mag fainter than the brightest member and is located at 1.96 arcmin from the peak of the X-ray emission. All other potential members with distance \(\leq 1.96\) arcmin have a magnitude difference with respect to the cD in excess of 2 mag. The uncertainty on \(R_{200}\) therefore does not allow us to establish whether the \(\geq 2\) mag gap is present or not inside 0.5\(R_{200}\).

Although Jeltema et al. (2007) have conducted a spectroscopic campaign on RX J1256.0+2556, we can not rely on their data to study the CSDF of this system due to the relatively high incompleteness of their survey (45–90 per cent at \(V = 20.5\)) and especially the limited span of their data (the inner 700 kpc, thus only 70 per cent of \(R_{200}\)). On the other hand, SDSS-DR6 only provides sparse spectroscopic redshifts in this region. Therefore, for the following analysis, we will rely on SDSS photometric data alone.

### A3 RX J1331.5+1108
This group has the lowest temperature (0.81 keV) in our sample. From available SDSS spectroscopy and photometry, we find \(\Delta m_{12} = 1.93\) mag (SDSS model magnitudes), with the second brightest member within 0.5\(R_{200}\) (SDSS J133141.49+110644.6) being located at 3.07 arcmin = (0.493 ± 0.013)\(R_{200}\) from the X-ray peak. As for AWM 4, we perform our own photometric analysis and find a gap \(\Delta m_{12} = 2.17\) mag instead. The disagreement with SDSS is possibly generated by sky oversubtraction for the brightest galaxy in the SDSS photometric pipeline. Thus, we confirm this group as a genuine fossil.

### A4 RX J1340.6+4018
This group is the fossil group archetype (Ponman et al. 1994). The magnitude gap is unambiguous here: the second brightest extended object within 0.5 \(R_{200}\) is \(\approx 2.6\) mag fainter than the cD. DL04 based their claim for a substructure crisis in fossil groups scale on data from this object. Contrary to DL04, who approximated the circular velocity of this group with \(V_{circ} = \sqrt{\sigma} \ (\sigma\ being\ the\ 1D\ projected\ velocity\ dispersion)\ of\ the\ group\ reported\ by\ Jones\ et\ al.\ (2000)\), we use more accurate X-ray determinations, but obtain a very similar value, within 30 km s\(^{-1}\).

### A5 RX J1416.4+2515
This system, with its \(M_{200} \approx 3 \times 10^{14}\ M_{\odot}\), is rather a poor cluster than a group. It has recently been studied by Cypriano et al. (2006), who obtained spectroscopic redshift and studied the LF in the inner \(\approx 3\) arcmin (\(\approx 0.35\) \(R_{200}\)). They confirm a magnitude gap of \(\Delta m_{12} = 16.73 - 14.19 = 2.54\) mag in \(i\) band (\(AB\)), which we can safely assume to be close enough to the gap in \(R\) band. Although the region within 0.5 \(R_{200}\) is not completely covered by their survey, we check against SDSS imaging that no brighter member is missed. It is worth noting, once again, that the SDSS magnitude for the cD is severely underestimated by 0.54 mag and therefore would not have allowed a reliable estimation of the magnitude gap to be obtained.

The limited coverage provided by the observations in Cypriano et al. (2006) forces us to rely on SDSS photometry to compute the CSDF.

### A6 RX J1552.2+2013
Similarly to RXJ1416.4+2515, RXJ1552.2+2013 is a poor cluster and has been the target of a spectroscopic campaign aimed at determining membership and LF (Mendes de Oliveira et al. 2006). As in the previous case, the coverage is limited to the inner \(\approx 3\) arcmin (\(\approx 0.4\) \(R_{200}\)). Mendes de Oliveira et al. (2006) report a gap \(\Delta m_{12} \approx 2.2\) mag in \(i\) band (\(AB\); see their fig. 2). However, by inspecting a larger region using SDSS images, at 2.6 arcmin from the X-ray peak we find an elliptical galaxy (SDSS J155201.61+201350.5)
of 16.0 mag, that is only 1.2 mag fainter than the brightest cluster galaxy. This galaxy is missing from the sample of Mendes de Oliveira et al. (2006), likely because it is only partly included in their image (their fig. 1). For this galaxy, SDSS gives a photometric redshift of 0.15, hence fully consistent with the redshift of the cluster. Assuming that this redshift is correct and our determination of $R_{200}$ is correct, even if only within the large uncertainties quoted in Table 2, this cluster does not qualify as fossil.

This paper has been typeset from a TeX/LaTeX file prepared by the author.