AGATE: Astrophysics of Galaxy Transformation and Evolution

An e-MERLIN Legacy Programme

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Abstract

In the local Universe, some of the most fundamental properties of galaxies are found to be a strong function of environment, such as their morphologies or star-formation histories. Yet it is still unclear whether these trends reflect the initial conditions of galaxy formation (*nature*) or more recent environmental processing of galaxies (*nurture*), and answering this question is essential for unravelling the physics of galaxy formation and evolution. Massive clusters of galaxies represent some of the most extreme environments experienced by galaxies and are therefore ideal laboratories for differentiating the physical processes which can affect and transform the morphologies and star-formation properties of galaxies, efficiently providing large samples of galaxies over a wide range of local environment.

Although most work has focused on the suppression of star-formation activity in galaxies as they become part of the cluster population, recent evidence has increasingly demonstrated that there must also be a period of star-formation *enhancement* to explain the growth of the galactic bulges. This is likely to be accompanied by a period of AGN activity to ensure the central supermassive black hole remains on the $M_{\rm bulge}$:$M_{\rm BH}$ relation. e-MERLIN provides a unique capability to study these processes since (a) it is sensitive to the radio continuum emission produced by both AGN and star-formation activity; (b) it has a sufficiently wide field of view to image a cluster beyond the virial radius and out to where infalling groups lie; and (c) it has the angular resolution required to separate the compact AGN activity from the $\gtrsim$ kpc-scale circumnuclear star formation.

We therefore request 590 hours of e-MERLIN time (not including the Lovell Telescope) to undertake 1.4-GHz continuum mapping observations of six $z \sim 0.5$ rich galaxy clusters which possess a wealth of complementary multi-wavelength data. These systems are some of the most massive clusters known and are therefore excellent laboratories for studying the astrophysical processes which occur in dense environments, as well as being observed at a cosmic epoch when galaxy transformation is occurring. These observations will morphologically and spectrally chart the co-evolution of star formation and AGN activity in cluster galaxies, expected to trace the transformation of bulge-weak, star-forming disc populations into the bulge-strong, passive spheroids which dominate rich cluster populations today.

The extensive multi-wavelength data available for all our cluster fields will ensure prolonged Legacy value for our dataset and complement "blank-field" e-MERLIN surveys.

1 Scientific justification

1.1 Introduction

It has been known for the past several decades that some of the key characteristics of galaxies, such as their morphologies or their star formation histories, vary as a function of environment, e.g., the morphology–density relation (Dressler 1980; Dressler et al. 1997) and the star-formation–density relation (Baldry et al. 2006). This poses a classic question of nature vs nurture – do these trends reflect the initial conditions of galaxy formation (*nature*) or more recent processing of galaxies by environmental factors (*nurture*)? Answering this question is an essential step in unravelling the physics of galaxy formation and evolution.

Observational efforts to answer this question have almost exclusively been focused on studies at optical wavelengths and have led to the current picture where galaxies have their star formation suppressed as they move from the low-density field into higher density environments. However, these studies have two major deficiencies which require us to reassess our current understanding. First, by focusing on the optical properties of galaxies, they miss obscured star formation, which is known to be a major mode of stellar mass growth. Second, they take no account of the central supermassive black holes within the galaxies which it is now believed are a key element in galaxy evolution.

Our aim with this e-MERLIN Legacy Proposal is to eliminate these deficiencies with detailed studies of a representative sample of massive galaxy clusters. We will use the unprecedented combination of angular resolution, field of view, and sensitivity of e-MERLIN, in conjunction with data from other major facilities, to provide a detailed view of *both* star-formation *and* accretion activity, on *sub*galactic scales. This combined dataset will provide a unique view on the physical processes which shape the evolution of galaxies in a range of environments from the cores of rich clusters to the cluster/field interface. Most importantly, we will gain the greatest insight into the physical processes from studying the regions where their effects are greatest even though only a small percentage of all galaxies reside in such regions. It is essential to realise that the dense cluster cores we will be surveying are extremely rare regions of the Universe which will not be sampled in any “blank-field” study and therefore require pointed observations.

We are therefore proposing to undertake an L-band survey of $1.5\,\mathrm{deg}^2$ in the fields of 6 of the most massive and well-studied clusters at $z \sim 0.5$, covering a wide range of substructure. This will provide a complete survey of AGN and star-formation activity across the entire range of environment from the cluster cores to the field, using a combination of morphological and spectral data to classify sources.

1.2 Environmentally-driven galaxy evolution

Since the original identification of the environmental variations in the star formation histories of galaxies, numerous groups have tried to determine the physical process (or processes) responsible for these variations. As massive clusters provide some of the most extreme environments encountered by galaxies, they are a unique laboratory for investigating the interactions between galaxies and their environment, including other galaxies, the hot intracluster gas, and the dark matter which dominates the gravitational potential.

Classical optical studies of clusters – aided by morphological information from sub-arcsecond imaging by *Hubble Space Telescope* – have built up a commonly held view of how galaxies evolve in the cores of typical rich clusters. These environments are dominated by passive, morphologically-classified spheroids at the present-day (including large numbers of S0 galaxies) but, tracing these environments back to $z \sim 0.5$–1 (5–8 Gyrs ago), a striking increase is seen in the fraction of blue, star-forming disk galaxies inhabiting these regions (e.g., Butcher & Oemler 1984; Dressler et al. 1997; Treu et al. 2003). Detailed morphologies from *HST* have shown that this increase in star forming spirals in clusters is matched by an apparent decline in the proportion of lenticular (S0) galaxies in these systems, suggesting that the spiral galaxies are transformed into S0s, but only relatively recently (e.g., Dressler et al. 1997). This increase in the star forming population in clusters as we look back over the past few Gyr parallels that in the surrounding field, suggesting that it results from an increased rate of infall of gas-rich, star-forming disk galaxies as the clusters are being assembled (Bower & Balogh 2004), with subsequent suppression of their star formation to form the passive S0 population seen today.

Several mechanisms have been proposed to explain this suppression. One of the most popular mechanisms is ram-pressure stripping as the galaxy moves through the dense intracluster medium (Quilis et al. 2000). However,

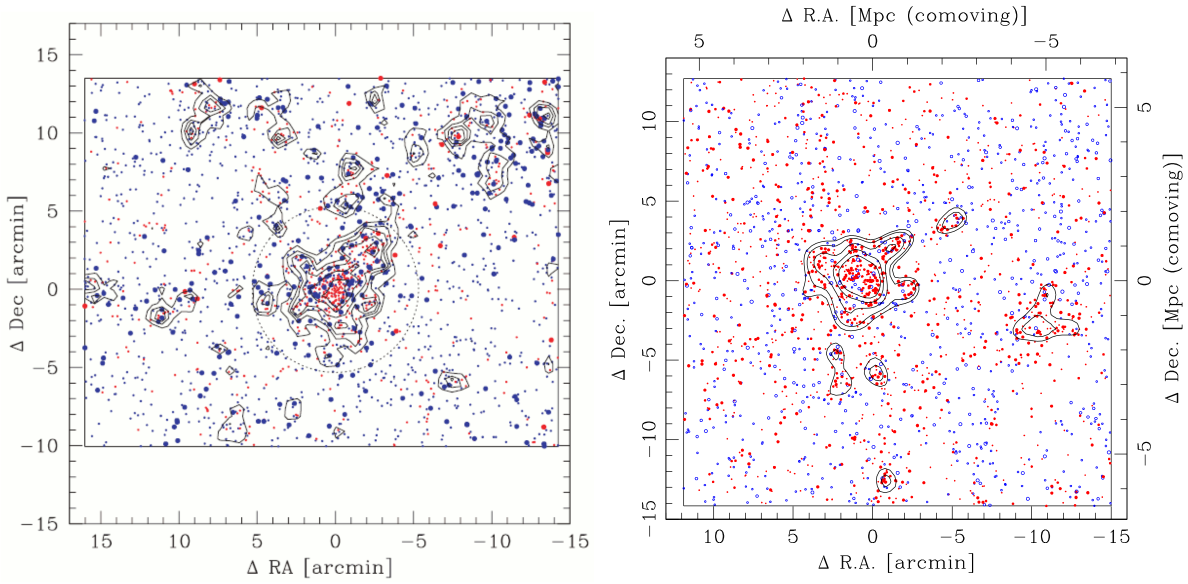


Figure 1: The distribution of photometrically-selected cluster members in our targets Cl 0024+16 (left) and Cl 0939+47 (right), as determined from wide-field Suprime-Cam imaging (Kodama et al. 2001, 2005). Red and blue points indicate red and blue galaxies, separated by a colour cut appropriate for identifying the red sequence at the redshifts of the clusters, and contours trace lines of constant projected galaxy density.

it has also been postulated that the pressure of the ICM can trigger the collapse of molecular clouds and produce an increase in the star formation rate for a period of $\sim 10^7$ yr (Bekki & Couch 2003). The effects of ram-pressure stripping will be most severe in the cores of the most massive clusters since (a) the intracluster medium is denser, and (b) the typical galaxy velocities are larger as a result of the deeper potential well, making the pressure ($\sim \rho v^2$) much larger. These locations therefore make excellent laboratories for studying this process. A related, but distinct and less dramatic, process is known as *strangulation* (Larson et al. 1980), which involves the removal via interaction with the ICM of a galaxy's hot gas halo (as opposed to gas already in the disc) before it can cool onto the disc and form stars.

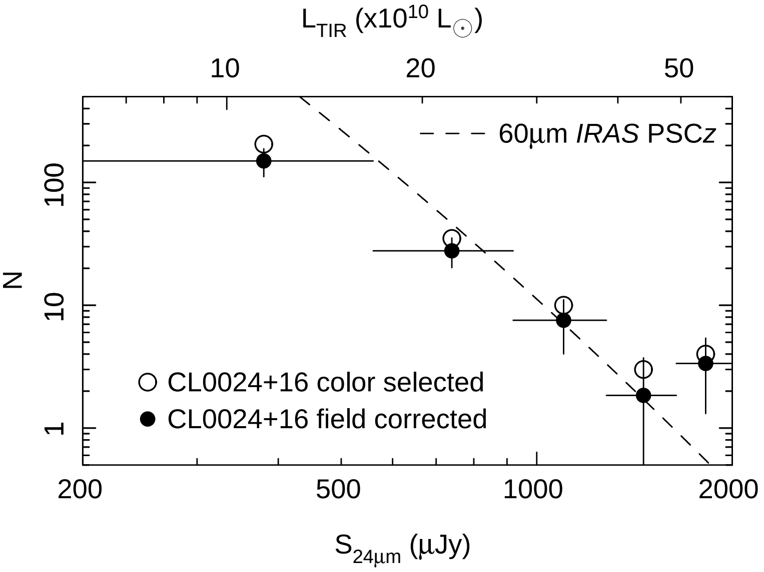
Galaxy *harassment* (Moore et al. 1996, 1999) is a process in which high-speed encounters as galaxies move within the cluster potential affect their evolution. It is most effective in transforming low-mass disc galaxies into spheroids and is expected to produce tidal debris tails within which star formation can occur.

A final factor in explaining the morphology–density relation could be *preprocessing* in the substructure units which coalesce to form clusters in the hierarchical structure formation scenario. Many of the most massive clusters at $z \sim 0.5$ show evidence for substructure and recent growth and so it may be that some of these evolutionary changes are a result of interactions which occur in infalling groups. For example, mergers between galaxies will occur more easily in the dynamically cool environment of a group, than between galaxies within the cluster, which will typically have very high relative velocities. Wide-field imaging with Subaru/Suprime-Cam as part of the PISCES project (Kodama et al., in prep; see also Kodama et al. 2005) has proven very successful at identifying the surrounding large-scale structure and infalling regions (Fig. 1).

Identifying the mechanism(s) responsible for the suppression of star formation requires catching galaxies 'in the act' and this is not as simple as it sounds. High angular resolution is required to map the star formation on subgalactic scales and this favours studies of nearby clusters, but these harbour few star-forming galaxies. Koopmann & Kenney (2004) studied galaxies in the Virgo cluster with Hα imaging and found that half the spiral galaxies showed spatially-truncated emission, while the central regions were relatively unaffected. This led them to favour ram-pressure stripping over strangulation. Thomas (2006; see also Thomas et al. 2008) extended this work to a sample of eight low-redshift ($z \sim 0.02$) clusters and discovered a population of star-forming galaxies with centrally-concentrated Hα emission. Although this was partly due to disc truncation (as found by Koopmann & Kenney) it also required strongly enhanced circumnuclear star formation.

Studies would benefit from being conducted at higher redshift, where the fraction of star-forming galaxies is much larger, but only *HST* can provide the required resolution, and such studies are therefore only sensitive to low-

Figure 2: Mid-infrared luminosity function for Cl 0024+16, using photometrically-selected cluster members, with and without residual field correction. At the redshift of this cluster, a 24 μm flux density of 200 μJy corresponds to a star formation rate of $10 M_\odot$ yr^{-1}. The local *IRAS* 60 μm luminosity function is plotted (with arbitrary normalisation) for reference. This plot shows that our proposed e-MERLIN observations will detect ~ 200 cluster members with the spatial resolution necessary to identify the cause of their activity: AGN or starburst (Reproduced from Geach et al. 2006.)



extinction star-formation regions identified by blue starlight (even Hα imaging is impossible). Moran et al. (2007) suggested, in their study of two moderate-redshift clusters, that a number of processes are at work, starting with preprocessing in the infalling groups, and continuing through harassment to finally gas stripping if the ICM is sufficiently dense. However, their basket of processes only explains the suppression of star formation in the discs of galaxies, and not the physical enhancement of the bulges as galaxies are transformed from spirals to lenticulars (Christlein & Zabludoff 2004).

This problem is undoubtedly linked to one previously identified by Kodama & Smail (2001) which sits uneasily with scenarios (such as that of Bower & Balogh 2004) where the main agent of galaxy transformation is the termination of star formation. Kodama & Smail found that the stellar masses inferred for the S0 galaxies using *HST* are greater than their likely star-forming progenitors in $z \sim 0.5$ clusters requiring significant subsequent star formation, for which there is no evidence in the form of starbursting cluster galaxies. Indeed, the relative paucity of optically-detected starbursts has been used to rule out suppression processes that first produce a strong rise in star formation prior to termination of the star formation (e.g., ram-pressure induced starbursts or mergers, e.g., Poggianti et al. 1999). However, these optical surveys are biased against dusty star formation, and recent radio and mid- infrared surveys, which are much more sensitive to obscured activity, have shown that the starburst activity in $z \sim 0.5$ clusters is much more intense than previously suspected. Hence we must reassess much which has been learnt about the activity and processes in these environments from optical studies.

1.3 The missing cluster starbursts

A population of dusty starburst galaxies in distant clusters was first hinted at by deep radio observations with the VLA (Smail et al. 1999; Owen et al. 2005; Morrison et al. 2003) and through mid-infrared imaging with *ISO* (Duc et al. 2002). However, the advent of *Spitzer* has really opened up this field through the use of panoramic MIPS 24μm imaging as a tool for environmental studies of galaxy evolution (e.g., Geach et al. 2006, 2008; Bai et al. 2007, Marcillac et al. 2007).

In particular, the study of three $z \sim 0.5$ clusters by Geach et al. has uncovered an extensive and previously overlooked starburst population in these systems – which may provide a critical tracer of the environmental processes occurring in high-density regions. Their study covered the central 0.5×0.5 degree of each cluster (~ 10 Mpc diameter) encompassing the whole of the cluster out to the infall radius – essential for an environmental analysis of the active population – and discovered an average of ~ 90 members with inferred bolometric luminosities of $\gtrsim 10^{11} L_\odot$ per cluster (Fig. 2). Strong PAH emission is also seen in the IRS spectroscopy of a subset of these galaxies confirming that the bulk ($> 90\%$) of these galaxies have mid-infrared emission arising from star formation rather than AGN activity. Moreover, the mid-infrared estimated star formation rates (SFRs) are roughly $5\times$ higher than those derived from optical tracers (e.g., Hα), of order 10s of $M_\odot$ yr^{-1}, indicating strong obscuration.

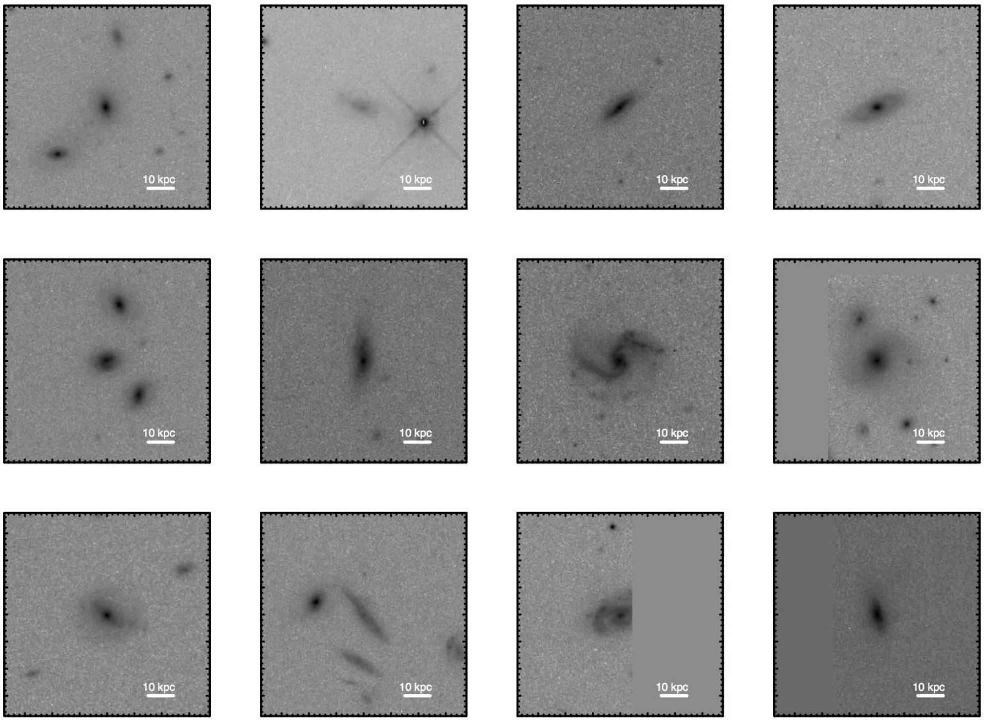


Figure 3: *HST* images of 24 μm-detected sources in Cl 0024+16 (see Fig. 2). Each thumbnail is $8'' \times 8''$ (approximately the MIPS 24 μm beam size). This figure shows the typical morphologies of the active population in this cluster at $0.1''$ resolution – our proposed e-MERLIN observations will yield similar resolution maps showing the distribution of *obscured* activity within these galaxies – critical for distinguishing between physical processes acting upon galaxies in dense environments. (Reproduced from Geach et al., in prep.)

These obscured, star-forming galaxies dominate the star formation activity within rich clusters at $z \sim 0.5$. Thus to understand the star formation cycle of galaxies in these environments we *must* use dust-insensitive tracers of activity – such as radio and mid-infrared surveys – as we cannot hope to reliably correct samples selected using biased optical/near-infrared tracers (e.g., Sato & Martin 2006).

These studies demonstrate that radio and mid-IR observations are an extremely effective tool to locate a missing cluster population of vigorous but obscured starbursts. These dusty starbursts appear to be much more frequent in distant ($z \gg 0.2$) clusters (Geach et al. 2006; Morrison et al. 2003), and they have eluded the traditional optical surveys, leading to an erroneous emphasis on environmental mechanisms which suppress activity in rich clusters (Poggianti et al. 1999). They are an ideal environmental tracer as they provide a highly localised measure of the influence of environment on star formation. Equally, the relatively large number detected, compared to the handful of optically identified starbursts (e.g., Couch & Sharples 1987) means that we can hope for the first time to test the sensitivity of the starburst population to the global cluster properties to investigate their relation to cluster sub-structure and infall, free from shot-noise caused by small number statistics. Previous attempts to correlate star formation activity in clusters with their structural state has used much longer-timescale tracers of star formation (e.g., blue light) which would smooth out the variations arising from recent accretion of detectable substructures leading to ambiguous or null results (e.g., Metevier et al. 2000).

Intriguingly strong variation in the radio source populations has been seen in $z \sim 0.2$ clusters by Rizza et al. (2003). The populations of bright 24 μm members in the clusters studied by Geach et al. (Fig. 3),show a similar large variations between clusters, with many more dusty starbursts detected in Cl 0024+16 and Cl 0939+47 than in MACS 0451$-$03 (only ~8% of the total sample of 24 μm-detected cluster members reside in this cluster, Geach et al. 2006). It is possible that the differences between the clusters' "global" properties are exerting a strong influence on the level of activity within their starburst populations. One scenario is that the hot ICM in the most massive cluster, MS 0451$-$03, is more efficient at stripping cold gas from infalling spirals, thus immediately quenching any starburst populations. The few mid-infrared sources detected in the cluster may represent those with the largest reservoirs of cold gas that have not yet been completely stripped, or are powered by AGN whose fuel comes from regions close to the nucleus. Alternatively, the enhanced level of activity in Cl 0024+16 and Cl 0939+47 could reflect the fact that both of these clusters are characterized by significant sub-structure. This would result in a higher incidence of mergers between galaxies bound in small groups. Thus, these current studies have demonstrated that obscured starbursts are an important and previously unidentified component in distant clusters, but they are unable to distinguish between environmental mechanisms which may be influencing the population as a whole.

Further understanding is hampered by the relatively poor angular resolution of MIPS ($6'' \approx 40\,$kpc), which does not allow the star-forming regions to be localised within each galaxy. This limitation will be removed with our e-MERLIN study, as the extremely tight correlation between the far-infrared and radio luminosities of star-forming regions (Helou, et al. 1985) means that radio emission also traces star formation. This is because the stars which heat the dust explode as supernovae, shocking the interstellar medium and accelerating electrons which then emit synchrotron radiation. As a result, faint radio emission can also be used to trace star formation in galaxies, and at much higher angular resolution than is currently possible in the infrared regime.

This improved angular resolution is required to test the picture proposed by Geach et al. (in prep), who suggest that the mid-infrared spectral properties of their sample of cluster starbursts are best explained by central starbursts. If correct this connects them to a population with rapid bulge growth, thus providing the direct link in the morphological evolution of bulge-weak field spirals into bulge-strong cluster S0s. However, this suggestion needs confirmation by precisely localising the star formation within the galaxies. The $\gtrsim$ kpc size of the active regions where stars are being formed to produce the S0 bulge requires the angular resolution which only e-MERLIN can provide, and enable it to be separated from any $\ll$kpc-scale AGN emission which may also be present.

Our e-MERLIN images will be most powerful when used in concert with the existing archival data from facilities such as *Spitzer*, *HST*, and *Chandra* or *XMM-Newton*, to provide a panchromatic view of the physical processes which dictate galaxy evolution in high-density environments. *HST* imaging (e.g., Dressler et al. 1997) shows the distribution of stars with low foreground extinction but cannot identify regions within a galaxy which might be strongly reddened. We will address this shortcoming with e-MERLIN imaging of a sample of six $z \sim 0.5$ clusters selected to have a narrow range in mass, but a broad range in sub-structure, to distinguish between local and global environmental effects.

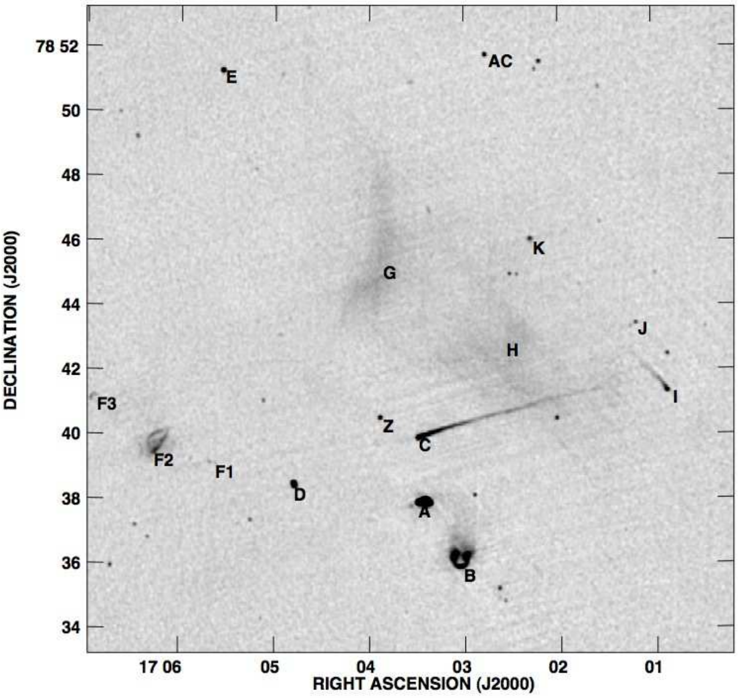
Only e-MERLIN has the capability to unequivocally test whether vigorous, but highly obscured, nuclear starbursts are occurring in large numbers of galaxies in distant clusters. In doing so it will solve the 30-year old puzzle of the Butcher–Oemler effect, by providing a coherent evolutionary scheme linking infalling, star-forming spiral galaxies to the formation of passive S0 galaxies which dominate local clusters. However, if e-MERLIN confirms the presence of circumnuclear starbursts building bulges in the proto-S0 population, then this begs the question of whether there is associated growth of the super massive black holes in these galaxies, to ensure they remain on the spheroid–black hole mass relation. Here again, e-MERLIN is able to provide an important and unique view.

1.4 Accretion activity in clusters

Several recent studies (e.g., Kauffmann et al. 2003) have focused on a link between star formation and AGN activity (accretion onto a supermassive black hole at the centre of a galaxy). These papers have promoted a wider interest in the AGN phenomenon, building upon the discovery of supermassive black holes in the centres of all galaxies (Ferrarese & Merritt 2000; Gebhardt et al. 2000). However, much less effort has been put into understanding how AGN activity, as opposed to star-formation activity, is related to environment, and how these two processes are linked temporally to maintain the tight $M_{\rm bulge}$:$M_{\rm BH}$ relationship across a wide variety of evolutionary processes.

Dressler et al. (1985) found that only 1% of galaxies in ten low-redshift clusters showed spectroscopic evidence of AGN activity, which is much lower than found in the field: a recent review by Ho (2008) indicates that *most* nearby galaxies show such evidence, including 11% of galaxies which possess classical Seyfert spectra. However, as with attempts to quantify the star formation in clusters, optical studies appear not to have provided the complete picture. Recent work (e.g., Martínez-Sansigre et al. 2005) has indicated the existence of a large population of dust-obscured AGN and, just as *Spitzer* has revealed a prodigious amount of obscured star formation in cluster galaxies, so observations with *Chandra* suggest that optical surveys have dramatically underestimated the accretion activity in clusters. Martini et al. (2006, 2007) claim that ~ 5% of galaxies in low-redshift clusters more luminous than $M_R < -20$ host an X-ray-luminous AGN, although this is still lower than is found in the field.

Figure 4: 1.4-GHz VLA image of the core of Abell 2256 ($z = 0.06$). This is very similar, in terms of sensitivity (in luminosity units) and area, to the central $4' \times 4'$ of one of our cluster targets. Note the wide variety of radio source morphologies. The expected increase in cluster activity at $z \sim 0.5$ implies an even higher surface density of cluster radio sources in our images. (Reproduced from Miller, Owen & Hill 2003.)



Two explanations have been advanced to explain this apparent deficit of AGN activity in dense environments. The standard picture for triggering an AGN is the merger of two galaxies (e.g., Barnes & Hernquist 1992) although there is increasing evidence that a close interaction, rather than a major merger, may be a more common trigger at low redshift. Such events are infrequent and short-lived in clusters due to the high velocity dispersion, so any cold gas within the galaxies is unlikely to be driven onto the black hole. The alternative explanation is that any cold gas which could fuel an AGN is removed from the galaxy by the same mechanism (or mechanisms) which curtail star formation. Circumstantial evidence for such a pictures comes from the apparently higher AGN fraction in high-redshift clusters (Eastman et al. 2007), mirroring the Butcher–Oemler effect.

However, because these studies have focused on spectroscopic or X-ray slection, any conclusions drawn from them only apply to so-called *cold mode* accretion, where cold gas is funnelled onto the black hole via an accretion disc. It is this disc which produces the strong ionising radiation field and classical AGN emission-line spectrum. Yet black holes can also accrete via a *hot mode*, which does not progress via a disc and therefore does not produce a rich emission-line spectrum; such objects are seen as radio-loud AGN with luminosities below the Fanaroff & Riley (1974) break. Best et al. (2007) undertook a study of the optical *and* radio properties of galaxies in clusters using the Sloan Digital Sky Survey and found that, within $0.2r_{200}$ of the cluster centre, optical emission-line AGN activity is suppressed, but also discovered that radio-loud AGN activity is enhanced in these regions. They also found that the observed fraction of radio-loud AGNs agrees with expectations from Bondi–Hoyle accretion, suggesting that the excess in the central regions of clusters is caused by an increase in the density of the intracluster medium. It remains unclear whether these objects have had their cold gas reservoirs removed (either by stripping or by having them turned into stars) or whether these reservoirs still exist but have not been perturbed to fuel the black hole. In the latter case, star formation is able to continue and we can look for this by identifying these objects in our e-MERLIN images and looking for warm dust emission from star-forming regions in our MIPS images.

Finally, there remains the possibility that the low AGN fraction found in optical/X-ray surveys is due to a substantial population of Compton-thick sources in clusters, as there is believed to be in the field (e.g., Gilli et al. 2007). As Simpson et al. (2006) note, deep radio surveys are able to identify even the most heavily-absorbed AGN and we will therefore produce the first complete census of AGN activity in clusters.

1.5 The evolution of cluster activity

The projected linear resolution of our e-MERLIN images will be directly comparable with VLA images of lower-redshift clusters. For example, Miller et al. (in prep) recently undertook a 1.4-GHz study of the Coma cluster with $4.4''$ (2.1 kpc) resolution. Given the proximity of Coma, even ground-based images have sub-kpc resolution, and

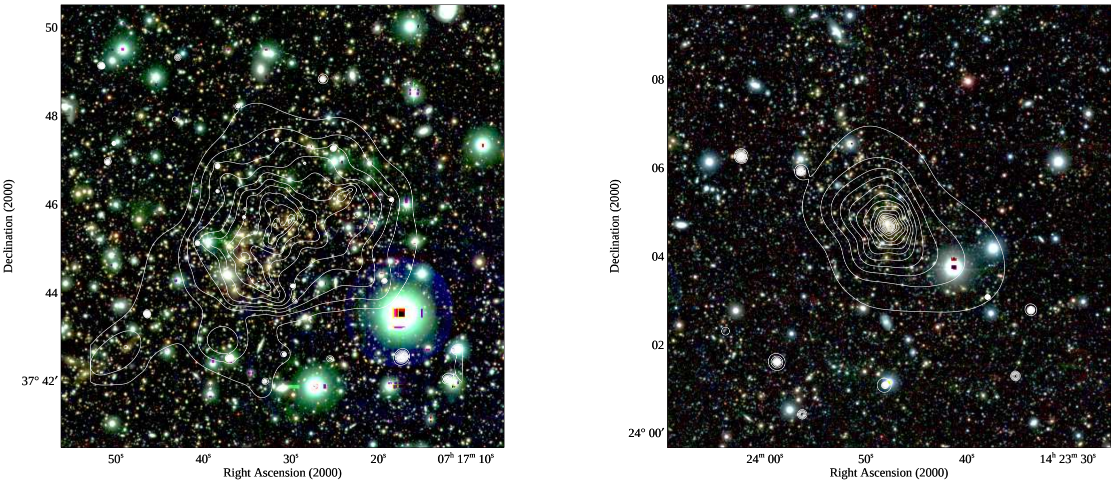


Figure 5: Colour images of two of our targets (0717+37 and 1423+24) with adaptively-smoothed *Chandra* contours overlaid. Note the difference between the merging system 0717+37 (left) and the relaxed cluster 1423+24 (right); note also the AGN detected as point sources in each image.

the *HST* Treasury Project (PI: D. Carter) provides even higher resolution optical images. Miller et al. (2003) have also observed Abell 2256 at slightly lower spatial resolution and their observations reveal a range of radio morphologies (see Fig. 4), as well as identifying an infalling group with higher star-formation activity. By comparing these present-day clusters with our targets (with lookback times of $\sim 5\,$Gyr) we will be able to determine how the galaxies in and around clusters have evolved over the last 40% of the age of the Universe. In particular, this will reveal the importance of preprocessing, which occurs before galaxies encounter the dense cluster ICM.

Finally, our observations will provide a unique perspective on galaxy–ICM interactions since the synchrotron-emitting electrons in radio jets are affected by the pressure of the ICM and reveal the transverse motion of the parent galaxy through their appearance as wide angle tailed sources or head–tail sources (e.g., sources B and C in Fig. 4). The full polarisation information we will obtain will also permit us to estimate the location of radio-emitting galaxies along the line-of-sight through the cluster. We will also have radial velocities from the extensive optical spectroscopy of our clusters, providing complete six-dimensional phase space information for many galaxies and giving a detailed insight into their dynamical histories. This information will reveal whether galaxies are undertaking their first, or a later, orbit through the cluster, and hence tell us the time-scale over which the transformation process occurs.

1.6 Target selection

The processes suggested for galaxy transformation and AGN triggering may occur to some extent in *all* environments, but they can all be most easily identified and studied in the most extreme systems (i.e., massive clusters) which thus provide insights into the evolutionary mechanisms in more typical environments. Moreover, as rich clusters contain hundreds of galaxies it is possible to efficiently survey a wide range of environments in one system to distinguish between the competing global and local environmental processes. However, this requires carefully-planned observations, minimising the variations due to cluster redshift or mass, while at the same time including a full range of cluster properties (e.g., mergers), with diagnostics sensitive to the different mechanisms.

We have assembled a sample of 6 well-studied galaxy clusters at $z \sim 0.5$, all of which possess excellent complementary multi-wavelength data (see next Section), and which span the range of substructure necessary to answer these questions (see Fig. 5). We stress that our aim is not to perform a statistical survey of clusters; anyway, the prevalence of radio-emitting galaxies in clusters at different redshifts does not require the superb angular resolution of e-MERLIN, and will be better undertaken by other instruments, such as LOFAR. Instead, we will use e-MERLIN, in conjunction with the other data, to study in detail the astrophysics of individual galaxies with respect to their relationship to the parent cluster.

As described in the main scientific case, $z \sim 0.5$ is the lowest redshift where the most massive clusters can be found, and also where the Butcher–Oemler effect starts to be observed. It also ensures that a single e-MERLIN field of view subtends a large enough linear size to trace the transition from cluster core to the field.

1.7 Summary

In summary, we will:

- *for the first time*, localise the star formation within galaxies in rich clusters at moderate redshift to independently trace the evolution of the bulge and disk components in these galaxies
- determine the influence of environment on both obscured star formation and AGN activity in infalling galaxies by comparing the morphological and spectral radio properties of our cluster galaxies with field samples
- discover whether the transformation of galaxies from late-type to early-type is accompanied by AGN activity and the influence of this on the star formation within the galaxy
- identify the typical environments associated with star-formation and AGN activity in infalling galaxies and hence distinguish the physical processes which influence the unobscured and obscured star formation and AGN activity within galaxies

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2 Links to other datasets

We have selected a sample of 6 well-studied galaxy clusters at $z \sim 0.5$. Our target list contains three highly disturbed systems (0717+37, 0939+47, 1149+22), two relatively relaxed system (0016+16, 1423+24), and one with an intermediate level of substructure (0024+16), and is thus representative of the full range of morphologies displayed by massive, distant clusters. We can thus test for both global and local environmental influences on obscured star formation and AGN activity within cluster galaxies. All our targets possess excellent complementary multi-wavelength data, with our primary requirements for inclusion being wide-field multicolour optical imaging (to assess likely cluster membership, morphologies, integrated stellar properties, and local galaxy density), MIPS 24 μm imaging (to identify the obscured star-forming population), and X-ray imaging (to trace the ICM properties and AGN population).

0016+16 has been mapped with *Spitzer* MIPS at 24 μm with close to complete coverage of a $\sim 15' \times 30'$ region (Geach et al., in prep). Deep *HST* F606W imaging of the central $6' \times 6'$ is available, with spatially resolved colour information being provided by an additional five WFPC2 pointings in both F555W and F814W (e.g., Smail et al. 1997). The PISCES survey has produced a photometric catalog for ~ 3200 probable cluster galaxies in this region and a recent spectroscopic campaign on Subaru has added to the spectroscopic coverage of this cluster, which currently has 211 confirmed members from 416 redshifts. *XMM* and *Chandra* imaging (21 and 41 ksec, respectively) are also available.

0024+16 has a sparse *HST* F702W mosaic covering a $25' \times 25'$ region (Treu et al. 2003) and was mapped using MIPS at 24 μm (Geach et al. 2006), detecting ~ 150 LIRG cluster members. The full spectroscopic catalogue for the cluster including new Keck observations yields a total of 1121 secure redshifts, of which 435 are members. Approximately 30 ksec each of *XMM* and *Chandra* data exist.

0717+37 is covered in both F555W and F814W by a mosaic of $9' \times 18'$ *HST*/ACS pointings. A MIPS 24 μm mosaic covering this region has been obtained in Cycle 4. 0717+37 is the morphologically most complex cluster in the entire MACS sample (Ebeling et al. 2007) and features several satellite galaxy groups and an extended filament along which matter is funnelled onto the cluster (Ebeling et al. 2004); more than 800 high-quality spectra are available to characterize the galaxies in this field. Strong evidence for a pronounced segregation of gas and dark matter has been found in X-ray and weak-lensing analyses.

0939+47 has a central $9' \times 9'$ WFPC2 F702W mosaic (e.g., Smail et al. 1997) and a $\sim 10'$-long ACS mosaic tracing the most prominent filament out from the cluster core. This cluster was mapped with MIPS by the *Spitzer* GT team, producing a $\sim 15' \times 40'$ map covering the bulk of the cluster (Dressler et al. 2008). Photometric redshifts are available for ~ 2700 probable cluster galaxies across the $30'$ field (Kodama et al. 2001) and there are ~ 330 spectroscopic redshifts in this region, with 200 confirmed cluster members. An *XMM* observation of this cluster also exists and Smail et al. (2002) presented $15' \times 15'$ *JHK* imaging data.

1149+22 is a highly disturbed system which offers an exceptional opportunity to study a wide range of environments in a single target. It possesses *HST*/ACS F555W/F814W imaging of its core and we have been allocated *Spitzer* Cycle 5 time to provide a $25'$ image at 24 μm. There is also a 38 ksec *Chandra* image of the cluster.

1423+24 has two-colour ACS imaging of the cluster core (Stott et al. 2007) and 24 μm MIPS imaging of a $25'$ region is scheduled in Cycle 5. 1423+24 is an apparently fully relaxed system and the most distant massive cooling-core cluster currently known, apparently not having undergone a major merger in several Gyr. This cluster benefits from a very deep *Chandra* exposure.

In addition to the data above, deep wide-field imaging (0.5 degree) in the *UBVRIz'* filters is available for all the clusters from Subaru or CFHT, with near-IR imaging from UKIRT and GALEX near- and far-UV imaging available for several clusters (e.g. 0024+16 in Moran et al. 2007). If this proposal is successful, we will apply for UKIRT/WFCAM time to observe the remaining targets.

As we describe in greater detail in Section 6, the regions of our images which are largely unaffected by the gravitational potential of the target clusters will be suitable for studies of the faint radio source population, providing scientific overlap with Tier 2 of the eMERGE proposal (PI: T. Muxlow).

3 Technical justification

Here is a summary of our 6 cluster targets, indicating the ground-based optical/IR, *HST*, and X-ray data available. All data also possess (or have scheduled) *Spitzer*/MIPS 24 μm observations. We are aware of efforts to upgrade the 25-m dish at Chilbolton and, should this be completed on a favourable time-scale and be shown to produce sufficient image fidelity, we anticipate replacing one of our targets with MS 0451$-$03 ($z = 0.54$), which is one of the best-studied moderate-redshift clusters.

Cluster	z	α (J2000)	δ (J2000)	Ground-based	*HST*	X-ray[†]
0016+16	0.54	00:18:33.2	+16:26:18	*UBVRizJK*	*VI*	XC
0024+16	0.39	00:26:35.7	+17:09:45	*UBVRizJK*,Hα	*R*	XC
0717+37	0.55	07:17:31.8	+37:45:05	*UBVRizJK*	*VI*	C
0939+47	0.41	09:42:59.3	+46:59:30	*BVRIJHK*	*R*	X
1149+22	0.54	11:49:35.1	+22:24:11	*UBVRIz*	*VI*	C
1423+24	0.54	14:23:48.0	+24:04:59	*UBVRIz*	*VI*	C

[†] Indicates whether *XMM-Newton* (X) and/or *Chandra* (C) data exist.

We propose to take single-pointing 1.4-GHz images of our target clusters, using the full 400 MHz bandwidth. This frequency provides the best sensitivity for a given observing time for objects with steep spectral indices (such as star-forming galaxies and AGN). In addition, the primary beam of the e-MERLIN 25-metre dishes at this frequency is well-suited to the sizes of our clusters, corresponding to a transverse dimension of ~ 10 Mpc and thus extending out beyond the infall radius of the clusters. We therefore do not propose to make use of the Lovell Telescope in this project. We will require narrow channel bandwidths and short data integration times to enable wide-field imaging while minimising the effect of bandwidth smearing, as well as reducing the effect of RFI.

Our aim is to reach a limiting (3σ) luminosity of $L_{1.4} = 4 \times 10^{21}\,\mathrm{W\,m^{-2}\,Hz^{-1}}$ in the central regions of the clusters. This is $1 M_\odot\,\mathrm{yr}^{-1}$ in $M > 5 M_\odot$ stars (Condon 1992), or about $10 M_\odot\,\mathrm{yr}^{-1}$ in all stars; it therefore will identify the same population of star-forming galaxies as the *Spitzer* data of Geach et al. (2006; Fig. 2). This is also about half the radio luminosity of NGC 4151, a moderate-luminosity local Seyfert galaxy, and we will therefore be sensitive to most AGN activity, including *all* FR I radio-loud objects. This depth is sufficient to yield radio detections of order 1000 cluster members across the 6 clusters. This sample will then enable us to distinguish global environmental influences, through comparison of the populations between the 6 clusters. We will test for local effects by binning the samples into 5 independent bins, each of ~ 200 sources (i.e., 7% Poisson errors) on the basis of their local galaxy density or ICM density (as derived from the X-ray imaging) and further subdivide the sample based on their radio morphology. Our overall sample size is therefore sufficient to investigate the effects of *local* environment (measured by galaxy density; e.g., Fig. 1) as well as *global* environment (from the range of substructure spanned by our targets).

This translates to required rms sensitivities of 6 μJy (Cl 0024+016, Cl 0939+47) and 3 μJy (other clusters). Based on a sensitivity of 10 μJy beam^{-1} from a full imaging track (without the Lovell Telescope), we estimate ~ 35 hours for each of the two lowest-redshift clusters, and ~ 130 hours for each of the four highest-redshift clusters. Our total time request is therefore **590 hours**. We suggest that the lower-redshift clusters be observed first due to the less stringent noise requirements.

e-MERLIN alone is not sensitive to radio structures on scales $\gtrsim 4''$ at L-band, but this corresponds to a size of ~ 25 kpc, and so larger than any of our cluster galaxies. We will therefore not lose sensitivity to either star formation or AGN activity. Nevertheless, we anticipate applying for EVLA observations to recover larger-scale radio emission (e.g., from relics and/or haloes) and obtain reliable flux measurements of the most extended sources (e.g., FR I radio galaxies). This will enhance the Legacy value of the overall dataset, and improve the overall sensitivity by $\sim 40\%$, but we stress that it is not required to undertake the science goals addressed in this proposal.

4 Pipeline requirements

Our observations will be made in wide-field continuum mode with 16 contiguous sub-bands spanning the full L-band width of 400 MHz. Each sub-band will be configured with 256 frequency channels and we will use an integration time of 1 second to allow the full primary beam to be imaged. We will make frequent observations of calibrators, including several observations of Jansky-level sources within each imaging track.

As with any major new facility, it is impossible to predict where new techniques may be required to optimally reduce the data. We will work closely with the staff at JBCA to learn and implement any such methods. Initial reduction steps are expected to be fairly standard, with automated flagging of the *uv* data, followed by amplitude and phase calibrations based initially on $T_{\rm sys}$ measurements and the observations of the bright calibrators, and then the faint calibration sources.

In order to achieve the required sensitivity, it will be necessary to remove bright confusing sources from the data in an iterative fashion before producing multi-faceted maps within each sub-band and a final map covering the entire L-band.

For each cluster, we will produce a full map (at moderate angular resolution) for the full 400 MHz band, plus at least two broad sub-bands, as there is substantial spectral index information available from the L-band data alone. We will also provide a searchable catalogue incorporating data for all radio-detected sources and all sources with reliable spectroscopic redshifts; these data will be full-resolution e-MERLIN images plus images in other wavebands, and integrated optical/infrared magnitudes. Where *HST* imaging is available, we will also include basic morphological information. Finally, a VO-compliant server capable of producing image cut-outs at any requested position will be maintained.

5 Management Plan

Most of the reduction and analysis will be undertaken at Liverpool John Moores University (led by co-PI Simpson) and Durham University (led by co-PI Smail). These institutions will each bid for 50% PDRA support plus a fraction of staff fEC time to ensure the necessary effort in both data reduction and management and scientific exploitation. These will be in addition to existing resources (e.g., Smith/Stott at LJMU and Geach/Matsuda at Durham) within whose current research parameters this project falls.

LJMU will be responsible for reduction of the e-MERLIN data. The Astrophysics Research Institute at LJMU possesses a modest computing cluster which will be upgraded using RCIF funds and, if this proposal is successful, we will work to install AIPS and/or CASA on it. Simpson is a Co-Investigator of the eMERGE Legacy Proposal (PI Muxlow), which has similar requirements in depth and dynamic range to eMAGE, and he will maintain close links with the Data Working Group of eMERGE (on which Co-Is Jarvis and Rawlings sit) to ensure a free flow of knowledge to maximise the benefit to both projects. The geographical proximity of LJMU to the University of Manchester will also be exploited with the PDRA and Co-PI expected to work closely with members of JBCA to develop optimal processing methods.

Durham will be responsible for collecting the archival complementary multi-wavelength data (much of which already exists in Durham as it was obtained with Smail/Geach/Bower as Co-Is; the remainder will all be public and we have the resources to reduce it) and post-processing them into a suitable state for release with the e-MERLIN data (e.g., Yuichi Matsuda will be starting in October 2008 and his duties include the reduction of Suprime-Cam data over many deep fields). Astrometric registration of the e-MERLIN and *HST* images is essential to properly localise the radio emission within each galaxy and this task will be the responsibility of Durham. Finally, any additional supporting observations which are considered important (e.g., with the EVLA and WFCAM) are also expected to be led from Durham.

The scientific exploitation will be split into three broad areas. The study of the star-forming galaxy population will be led by Smail and Geach, building on their work using *Spitzer* data. The study of the AGN population will be led by Simpson and Rawlings, building on their earlier investigation of the faint radio source population using a combination of radio/optical/X-ray data. Finally, a comparison of the cluster galaxy populations at $z \sim 0.5$ and $z \sim 0$ will be led by Carter and James, exploiting their existing research into local galaxy clusters (e.g., the *HST* Coma Treasury Project).

6 Need for Legacy Status

We are submitting this project as a Legacy Proposal due to the extensive lasting value of the proposed dataset. The scientific justification focuses exclusively on the unique ability of e-MERLIN to address issues of galaxy evolution through studying the radio morphologies of galaxies in and around rich clusters. However, our proposed observations are, of course, deep wide-field radio images of regions with some of the best complementary multi-wavelength data, including large numbers of spectroscopic redshifts (including foreground and background galaxies), which assigns to them the same lasting Legacy value and extensive scientific potential as other comparably deep e-MERLIN images. Although we anticipate ~ 200 radio sources within each cluster, there will be a total of approximately 1000 foreground or (mainly) background sources per field whose properties will largely be unaffected by the presence of the cluster, suffering no, or only very modest, amplification, especially towards the edge of the e-MERLIN field of view. Even though the sensitivity here will be lower than in the centres of our cluster fields, these regions will be available for studies of the $\sim 100\,\mu$Jy radio source population which, as identified by Simpson et al. (2006) and Smolčić et al. (2008), includes substantial numbers of star-forming galaxies, luminous radio-quiet AGN, and low-power FR I radio sources. There is far too little space here to discuss all the scientific questions which can be addressed from studies of these objects, but we briefly note that the star-formation and accretion histories of the Universe can be studied, free from the effects of dust obscuration with the first two sub-populations, while FR I radio sources are important for understanding AGN-driven feedback in massive galaxies.

Of course, some background sources will be lensed by the deep gravitational potential wells of our clusters. Most of our target clusters have strongly lensed features (i.e., multiply imaged sources or giant arcs) which have been identified in the optical (e.g., the giant arc in Cl 0024+16). We therefore anticipate that in the cluster cores the e-MERLIN maps will detect a small number of background radio sources which are being gravitationally lensed and amplified by these massive clusters. This will increase e-MERLIN's already excellent angular resolution by perhaps an additional order of magnitude, allowing us to study distant star-forming galaxies at a resolution of tens of parsecs at both optical and radio wavelengths. The wider influence of the clusters may also be traced through the weak lensing of the background radio population on larger scales.

Finally, we believe that Legacy status will increase our chances of obtaining funding for additional effort required to fulfil the scientific potential of this project. Although we have identified existing resources at LJMU and Durham in the previous section, these are unlikely to be sufficient to produce, for example, a homogeneous VO-compliant dataset, and this will severely impact on the ability of the wider community to make use of our data. Therefore, if the panel recognises the broad scientific benefit of the multi-wavelength dataset we request Legacy status to ensure that we are able to produce data products capable of providing this benefit.