**Super-CLASS: the Super-CLuster Assisted Shear Survey**
**- a weak lensing deep field survey using e-MERLIN**

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**Abstract**

We propose a deep wide-area survey designed to detect the effects of weak lensing in a super-cluster region covering $1.75\,\mathrm{deg}^2$ where there are 5 known clusters. Using a sophisticated mosaicing strategy we expect to achieve an r.m.s of $4\,\mu$Jy in order to reach a source density $\sim 1\,\mathrm{arcmin}^{-2}$. Using standard, and new techniques involving polarization, these data will allow us to probe the dark matter distribution in the region and, by defining a grid of rotation measures, the magnetic field structure. We will propose a program of multi-wavelength observations in order to probe the star-formation and AGN activity in the $\sim 10^4$ sources we expect to detect which will complement the narrower, but deeper e-MERGE survey. The program will involve the development of the polarization, mosaicing and phase referencing capabilities of e-MERLIN and the results will yield information which will guide the design of surveys with the SKA.

**Introduction**

Weak lensing has become recognized as one of the primary cosmological tests since cosmic shear is directly sensitive to the matter/energy content of the Universe and its expansion history (for example, Massey, Kitching & Richard, 2010). It has been used to make maps of the dark matter over small areas of the sky (Gray et al., 2002, Massey et al., 2007) and to constrain cosmological parameters (Fu et al., 2008). The basic idea is to measure the ellipticity, which is typically $\sim 0.3$, of many galaxies and average over them to reduce shot noise in order to deduce the much smaller cosmological signal which produces a change in ellipticity typically $\sim 0.01$. This has been done using observations in optical bands which by virtue of the naturally high source density and resolution are well-suited to this. This started with small areas $\sim 1\,\mathrm{deg}^2$ and now the current state of the art is $\sim 100\,\mathrm{deg}^2$. Future plans are to cover ever increasing areas in order to reduce the sample variance. Ultimately constraints on the dark energy equation of state $\Delta w \sim 0.01$ will be possible with such surveys (for example, *Euclid*) if systematics can be kept under control. However, both instrumental and observational effects (e.g. anisotropic PSFs and atmospheric seeing) and astrophysical contamination (e.g. the degree to which galaxies are *intrinsically* aligned) are serious concerns for future precision weak lensing measurements. Performing lensing measurement in the radio band offers a unique potential for strongly rejecting all of these classes of systematics and providing an independent measurement of the cosmic shear signal.

Cosmic shear on scales of 1 to 4 degrees has been detected in the radio band using data from the FIRST survey (Chang, Refregier & Helfand, 2004). Using the radio has a number of advantages, notably that the telescope beam is much more stable and is essentially unaffected by atmospheric effects at 1.4GHz. However, there are other significant issues inherent to the radio band which have made the optical the waveband of choice. These include the low source density at present flux limits, the limited resolution and relatively small fields of view. This situation is likely to change in the coming years with the advent of the SKA and its progenitors. Hence, detailed measurement of cosmic shear in the radio band is likely to become a significant activity in the coming years.

Of the presently (or very soon to be available) instruments e-MERLIN has a number of advantages for detecting shearing of the sources. Most significant of these is the fact that it has very high resolution ($\approx 0.2\,$arcsec at L-band) making it possible to detect the ellipticity of individual sources since they have similar angular extent to that detected in the optical (Muxlow et al., 2005). We propose an e-MERLIN key project on behalf of JBCA to perform a deep survey of area $\sim 1.75\,\mathrm{deg}^2$ in order to detect cosmic shear over a wide range of scales and in contrast to that which is proposed in other e-MERLIN legacy programs such as e-MERGE and AGATE which are single pointings. Our survey is likely to be similar in many ways to that which will be ultimately done by the SKA, the only difference being the much lower area covered and the somewhat lower source density. Analyzing cosmic shear in such a radio field is a crucial step to be competitive with optical surveys and it will allow the JBCA group with collaborators from the UK and elsewhere, to establish an international leadership position in this important science area. Specifically, it will allow us to develop the bespoke analysis techniques needed to extract the shear signal from interferometer data and understand, on the basis of experience, what is necessary to optimize the extraction of the signal. Moreover, it will allow a test of the idea that one can remove the intrinsic alignment signal using measurement of the polarization position angle (Brown & Battye, 2010).

Such a survey will also yield significant other science, although the choice of field has been selected to optimize the measurement of cosmic shear. The program will detect $\sim 10^4$ sources of which around $\sim 2/3$ are expected to be star-forming galaxies and $\sim 1/3$ jet-powered AGN. This will allow us to probe massive star-formation and AGN galaxies at high-redshift ($z \sim 1$) with the key question being the overall star-formation history of the Universe and how this depends on environment. Importantly the high resolution of e-MERLIN will enable the different populations to be distinguished morphologically. Thus, in addition to their primary science goal of detecting cosmic shear, these e-MERLIN observations will offer the opportunity to obtain an obscuration-free census of star-formation of the Universe out to these high redshifts. Polarization measurements will allow us to measure the polarized source counts at very low flux densities which will be a crucial piece of information in the design of SKA surveys aimed at probing cosmic magnetism and we will able to constrain the magnetic field structure. In addition we would hope to be able to learn more about the correlation between radio and optical axes and about strong gravitational lensing.

As discussed below we have chosen a supercluster region to be the target field. This will increase the shear signal so as to bring it well within detection threshold even under pessimistic assumptions about the source density that we will detect. From the astrophysical point of view this also has a number of advantages chief of which is that there will be a number of different environments which it will probe. In this respect the proposed program is similar to that which has been carried out in the optical on the A901-902 supercluster region using the HST (for example, Gray et al., 2009).

**Scientific objectives**

The main objectives of the survey are listed below.

1. *Detection of cosmic shear in the radio band at high resolution and sensitivity as a test for the SKA/SKA progenitors:* the measurement of cosmic shear in order to constrain cosmological parameters is one of the primary science goals of the SKA. e-MERLIN is the highest resolution of all current radio instruments and hence it should be the best at measuring the ellipticities of the observed galaxies, albeit over a smaller area of sky than instruments such as LOFAR, MeerKAT and ASKAP. We expect to be able to achieve an accurate measurement of the ellipticity for a source density of $\approx 1\text{arcmin}^{-2}$ and dependent on the behaviour of source counts in this presently poorly explored region, we might even achieve $\approx 3\text{arcmin}^{-2}$. Furthermore if we obtain optical data for this field as outlined in subsequent sections, we would be able to pre-select, using photometric redshifts, the galaxies situated at the ideal lensing distance to our targets, hence enhancing the signal-to-noise of our observations. Our main aim will be to test the viability of radio weak lensing which is a science driver for the SKA. We will measure the shear over the area of a field chosen to be a supercluster region. This should allow us to make a map of the dark matter and constrain the power spectrum in the region (although this will not be the underlying power spectrum of the Universe) in a similar way to that done for the COSMOS field in the optical. Ultimately the aim of radio weak lensing is to constrain cosmological parameters, although we do not expect, at this stage, to be competitive in this respect with the very best optical surveys which have surveyed $\sim 100\,\text{deg}^2$ to source densities $20\,\text{arcmin}^{-2}$, albeit with possible systematics.

2. *Use of polarization information to extract the contaminating signal from intrinsic alignment:* Brown and Battye (2010) have developed a novel weak lensing estimator which uses an input estimate for the position angle for each galaxy. If one can obtain an unbiased estimator of the position angle making use of the connection between intrinsic structural position angle and the polarization position angle expected for star-

forming galaxies (Stil et al., 2009) then one can reduce the shot-noise errors and extract the potentially important contamination from intrinsic alignment. We will provide the first test of this technique.

3. *Detailed study of the radio source population at* $\sim 20\mu$Jy*:* Emission in weak radio sources is either jet-powered by an AGN or supernova-powered as a result of recent star-formation. There is huge current interest in the star-formation history of the Universe and how possible feedback from the active nucleus might regulate both star formation and black hole growth. In the proposed survey we will detect both star-forming and jet powered radio galaxies. Most will be in the field but some will be associated with the target supercluster. At a flux density limit of $\sim 20\mu$Jy the majority of the sources in both environments will be star-forming galaxies. To obtain the full star-formation story a multi-tiered approach is required and our proposed survey would bridge the important gap between the ultra-deep surveys, which will be done in the e-MERGE legacy survey, and the detailed study of star-formation in relatively local galaxies, for example, in the LEMMINGS survey. We would expect to find a factor 5–10 more sources than e-MERGE which will allow much stronger statistical inferences to be drawn. By targeting an area centred on a super-cluster we get access to three distinct environments: the field well away from the cluster, the outer parts of the cluster and the dense cluster core. This will also make links with the AGATE legacy survey. Large numbers of jet-powered radio sources should be detected too. The interest there lies in their relationship to the star-forming galaxies and the relative timings of star-formation and AGN activity. Is an outburst of star formation required to fuel the black hole/accretion system or does the latter stimulate the former?

4. *Investigation of the polarization properties of AGN and star-forming galaxies:* There are indications (Taylor et al. 2007, Grant et al. 2010) that the fractional polarization of sources with total intensity flux density $< 10$mJy is substantially larger than at higher flux densities. In fact Subrahmanyan et al. (2010) claim that the fractional polarization increases $\propto S^{-1/2}$ as one goes down from $\approx 10$mJy to 0.5mJy; they measured median fractional polarizations to be $\sim 10\%$ which could be indicative of highly ordered magnetic fields. This is good news for the objective (2) above and would suggest that we could detect $\sim 1000$ galaxies in polarization. The polarization properties of FRI galaxies and star-forming galaxies, which are likely to be the dominant population at these flux densities, are very poorly understood. Our survey will clearly have a significant impact on our understanding of these classes of objects allowing us to model their magnetic field structure. We will be able to make estimates of the polarized source counts at flux density levels which have not been possible so far and this information will have a significant impact on the design of surveys for the Cosmic Magnetism key science project of the SKA.

5. *Cosmic Magnetism in clusters and superclusters:* The prediction of a large-scale cosmic web is one of the defining characteristics of large-scale structure simulations. Detection of the magnetic field within the cosmic web, or placing stringent upper limits on it, will provide powerful observational constraints on the origin of cosmic magnetism. The existence of cluster-wide magnetic fields of a few $\mu$G is well established and evidence for magnetic fields associated with a filamentary cosmic web has also been found in super-clusters (Bagchi et al. 2002). Using the rotation measures of background sources through the large-scale structures of clusters and super-clusters is an excellent method for constraining both the morphology of the magnetic structure and for measuring the strength of magnetic fields within the filamentary web of inter-cluster gas. The frequency coverage of e-MERLIN is ideally suited to the high rotation measure (RM) values expected from clusters and super-clusters (RMs of up to $10^4\,\mathrm{rad\,m^{-2}}$ have been observed in cooling core clusters). This allow us to constrain the magnetic field of the selected region.

6. *Investigation of the alignment properties of radio and optical galaxies:* Battye & Browne (2009) have investigated the correlation between the semi-major/minor axes of the isophotes in the radio and optical using SDSS and FIRST. It was shown that there is an extremely strong correlation between the two semi-major axes for star-forming galaxies and there is also a correlation between the optical semi-major axis and the radio semi-minor axis for passive ellipticals. Patel et al. (2009) were unable to establish this correlation using the MERLIN/VLA and HST observations of the HDF. This maybe due to the relatively small number of objects in that sample, but it could also be due to intrinsic differences between the low-redshift sample from SDSS and FIRST and these much higher redshift objects (though of similar radio luminosity). In addition Patel et al. have suggested that one can combine radio and optical weak lensing estimates of the ellipticity to investigate systematics. Using complementary optical data we will investigate these correlations at high redshift and test for systematics in the ellipticity estimates.

7. *Strong gravitational lensing:* The detection of new strong gravitational lenses will be possible within the survey due to the high resolution. Once found they can be studied in detail and have many uses in measuring mass distributions in distant galaxies, and their statistics as a function of redshift give information about galaxy number density and mass evolution. We would expect to find a few new lenses in the survey and the experience will be an immensely valuable pilot survey for larger-field imaging surveys with lower resolution (e.g. LOFAR, MeerKAT) and will play a significant role in defining the survey strategy for future radio lens surveys, for example, with SKA.

**Survey specifications and predictions of expected survey yield**

The aim will be to achieve an r.m.s. sensitivity level of $4\,\mu\mathrm{Jy\,bm}^{-1}$ over an area of $1.75\,\mathrm{deg}^2$ with a resolution of 0.2 arcsec at L-band. This will use the sophisticated mosaic pattern described later which will use the 6x25 e-MERLIN telescopes plus the Lovell telescope. It is hoped that the Goonhilly telescope will be available in time to enhance the sensitivity, resolution and $u$-$v$ coverage of the survey.

Using the results of the HDF observed by MERLIN and the VLA, there is a source density of $\approx 1\,\mathrm{arcmin}^{-2}$ at $S = 40\,\mu\mathrm{Jy}$ (Muxlow et al.) and this is compatible with the simulations of Wilman et al. (2008) and observations of Biggs and Ivison (2008). The exact threshold necessary for accurate extraction of the ellipticity needs to be investigated. Patel et al. (2009) have made a preliminary investigation, assessing viability of extracting the ellipticity from the HDF. They found that the there was source density of $\approx 0.75\,\mathrm{arcmin}^{-2}$ for which they extracted an accurate ellipticity (their gold sample) and $\approx 3.75\,\mathrm{arcmin}^{-2}$ which may suitable for estimating the ellipticity (their silver sample) - see the discussion in Patel et al. (2009) for the details. We would expect to detect source density of $\approx 1\,\mathrm{arcmin}^{-2}$ at a level of $10\,\sigma$ which should definitely be sufficient for weak lensing studies and under more optimistic assumptions, similar to those of the silver sample in Patel et al. (2009), one might hope to have a source density of $\approx 3\,\mathrm{arcmin}^{-2}$.

We estimate that with these levels of sources we will be able to detect cosmic shear using the standard approach (objective (1)) for an unbiased region at the $\approx 1\,\sigma$ level for a source density of $1\,\mathrm{arcmin}^{-2}$ and $\approx 2\,\sigma$ for $3\,\mathrm{arcmin}^{-2}$. If the sources are $\sim 10\%$ polarized it should be possible to detect it a similar significance using the new method (objective (2)) if the r.m.s. scatter in the difference between intensity and polarization position angles is $\langle\Delta\alpha^2\rangle^{1/2} \approx 7\,\mathrm{deg}$. In order to increase the significance of the detection (and to bring significant extra science in to play) we have decided to observe an overdense supercluster region of the Universe. Experience with the A901/902 region, which was observed in the optical, suggests that this can increase the level of signal by around a factor of 2. Moreover one can ignore the cosmic variance part of the error budget since we are not trying to measure the underlying power spectrum. The use of polarization will be even more interesting in a supercluster region since there is likely to be an identifiable intrinsic alignment signal for the technique to remove.

For more traditional astrophysical applications a source detection significance of $5\sigma$ should be sufficient. Typically this would mean that we would detect more objects than those which can be used for shear analysis. Of these one would expect 2/3 to be star-forming galaxies (normal spiral galaxies plus starbursts such as M82) and 1/3 to be radio AGN (FRI/II). For a detection threshold of $20\,\mu\mathrm{Jy}$ over the $1.75\,\mathrm{deg}^2$, we would expect a source density of somewhere between 2 and $6\,\mathrm{arcmin}^{-2}$. Taking the lower of these two values, conservatively we would to detect more than $10^4$ sources and, further assuming no significant evolution in the relative numbers of star-forming galaxies and AGN, we should detect more than 7000 star-forming galaxies and more than 3000 AGN.

In order to measure rotation measures as high as $10^4\,\mathrm{rad\,m}^{-2}$ we will require $\approx 5$ frequency channels per e-MERLIN 32 MHz sub-band ($\Delta\nu \approx 7\,\mathrm{MHz}$) - NB e-MERLIN has 256 frequency channels per sub-band - and the RM accuracy for a $S/N = 5$ will be $\simeq 17\,\mathrm{rad\,m}^{-2}$, improving linearly with increased signal to noise. If the sources detected in polarization have a number density $\approx 0.1\,\mathrm{arcmin}^{-2}$, then the average source separation will be 3 arcmin and hence a rotation measure grid with this resolution will be possible.

In order to detect a strong gravitational lens, one typically requires around a $20\,\sigma$ detection so that one can detect the multiple components or arc/ring structure reliably (the exact number varies somewhat; for example, equal double lenses can be found in $6\,\sigma$ detections, but very extended sources probably even require a detection of better than $20\,\sigma$). The parent population is thus about 3150 objects ($1800\,\mathrm{deg}^{-2}$ at $80\,\mu\mathrm{Jy\,bm}^{-1}$ x 1.75). The lensing rate obtained in the CLASS survey was about 1 in 600, suggesting about $\sim 5$ lenses should be detected. This will be slightly reduced by the probably lower redshift of the radio source population at these flux density levels, possibly by a factor of 1.5-2, but will be increased again since the survey will be done in an overdense region which will contain a higher proportion of elliptical galaxies that are known to be more likely to be lenses. Given these estimates detecting no strong gravitational lenses would be a surprising result.

### Choice of target field

There were a number of questions to balance in the choice of the field. These include: (i) finding a region with an expected weak lensing signal which is sufficiently large; (ii) is the field at sufficiently high declination so as to allow the ellipticity to be accurately reconstructed from the radio observations and for observations to be easily scheduled; (iii) complementary data in other wavebands already exists. The target we have chosen appears to satisfy the requirements (i) and (ii). Unfortunately, we were unable to find a region which satisfies all three criteria and given that the primary goal of the survey is weak lensing we decided that it was most important to prioritize (i) and (ii). As explained below we will proposed a suite of follow-up observations to provide the multi-wavelength data which will enhance science goals (3) and (4). It is possible that we may choose to change this in light of new information which might come to light before the observations take place. If we were to change the target we would consult the e-MERLIN steering and Legacy program committees to check for possible conflicts with other programs.

In order to search for possible candidate fields we performed an all sky search for clusters in NASA's Extragalactic Database (NED) with declination $> 45°$, $z > 0.15$ and more than 4 references in the literature in order to focus only of actively studied clusters. This list was cross matched against itself using a matching radius of 0.75deg. This process turned up a list of 5 fields which contain more than 3 clusters. The presently chosen target is a region containing 5 Abell clusters at right ascension $\approx 14\,$hours and declination $\approx 68°$ with measured redshifts $\approx 0.2$. All five clusters (A968, A981, A998, A1005, A1006) have been detected by ROSAT with luminosities compatible with them having masses in the range $(1-2)\times 10^{14}M_{\odot}$. It appears to be the best target of the 5 possible fields found in terms of the size and proximity of the clusters. The positions of the clusters are presented in Figure 1 along with a schematic of the proposed field - see below for more details. We expect to be able to detect the weak lensing effect of these clusters and also from some of the large-scale filamentary structure expected to permeate the regions between the clusters.

The angular diameter of the proposed mosaic is 1.5 deg which corresponds to a size of $\approx 15\,$Mpc at $z = 0.2$ and the angular resolution is 0.2 arcsec which is $\approx 1.5\,$kpc. Hence, we will create a map of the cluster region covering $\approx 15\,$Mpc and a resolution $\approx 1.5\,$kpc with $\sim 10^4$ resolution elements across the diameter. The resolution of the rotation measure grid will be $\approx 500\,$kpc and typical scale lengths of the magnetic fields in clusters are expected to be $\sim 1\,$Mpc. Assuming the sources are at $z \approx 1$ the linear resolution used to define the morphology of the sources will be $\approx 0.6\,$kpc.

We have checked that there are no strong radio sources in the region and the surrounding area. The strongest sources within the region are $\sim 100\,$mJy and the nearest strong sources, $\sim 1\,$Jy, are more than 5 deg away. These sources should not have a significant impact on the observations proposed here. In addition we have checked the dust extinction: typically $A_{\rm V} \approx 0.2$ in the region, which is within the range that would allow high fidelity optical observations.

### Technical case

In order achieve a uniform sensitivity over the selected region we will create a mosaic of pointings. This is a standard technique in radio imaging when a large area of sky needs to be mapped. Various mosaicing schemes have been developed, however for simple homogeneous arrays with identical antenna elements the optimum pattern to achieve a smooth and sensitive mosaic is a hexagonal mosaic pattern with a positional step of 0.5 HPBW of the primary beam response. Mosaicing with full e-MERLIN including the 76m Lovell telescope is more complicated since the array is heterogeneous and observations are made with a large fractional bandwidth resulting in significant changes in the primary beam response across the observing band. However significant savings in total observing time can be made when mosaicing since this utilises the large collecting area and sensitivity of the Lovell telescope.

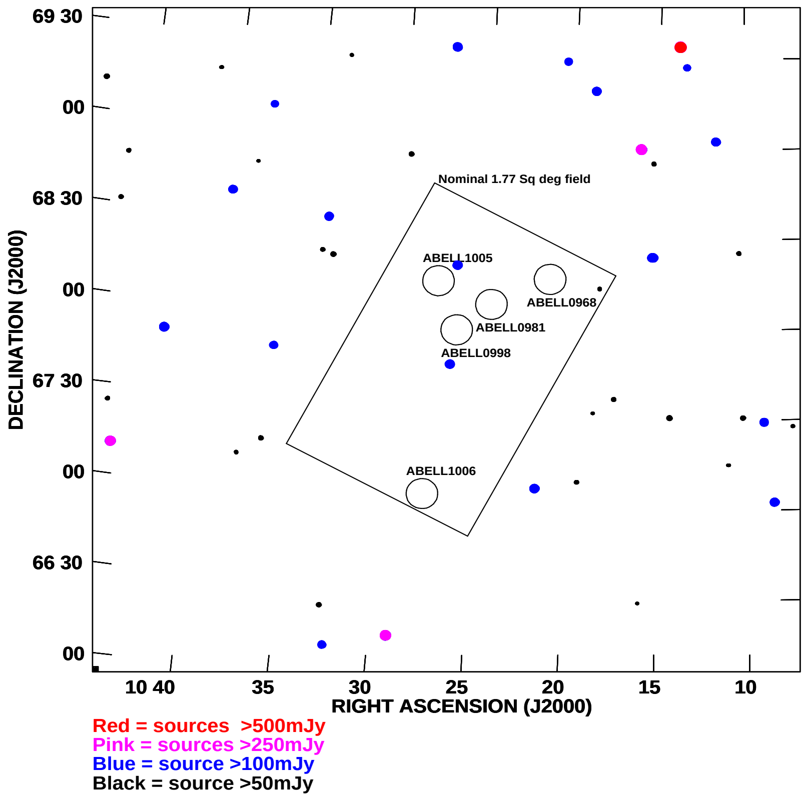


Figure 1: The presently proposed field of observation contains 5 Abell clusters: A968, A981, A998, A1005, A1006 which have $z \approx 0.2$. The box covers the $1.75\,\mathrm{deg}^2$ field which we plan to observe. As explained below we plan a more sophisticated mosaicing strategy, including the Lovell Telescope, which should allow us to achieve a uniform sensitivity across the same region. The coloured dots are the known radio sources from NVSS.

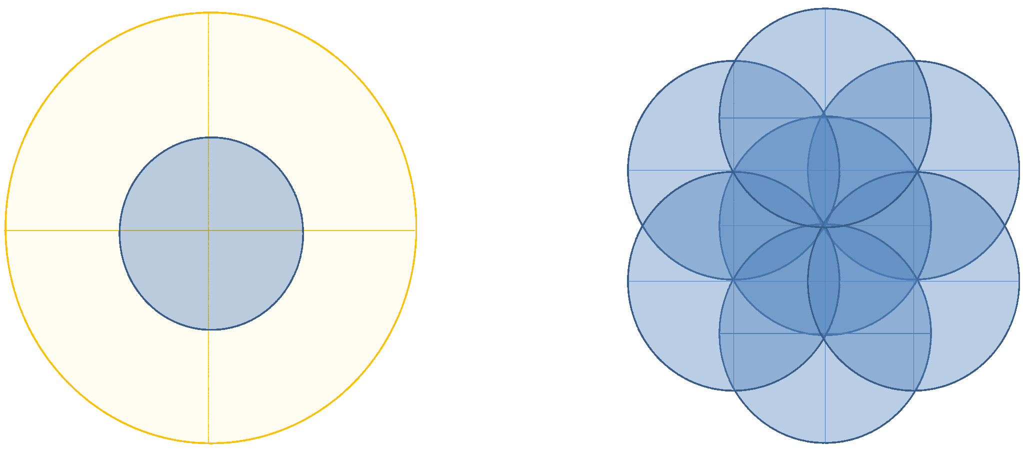

Figure 2: (a) Sensitivity pattern for a single e-MERLIN pointing with an inner sensitive region set by the size of the 76m-25m interferometer beam together with an outer less sensitive annulus set by the size of the 25m-25m interferometer beam. The outer circle is $\approx 30\,$arcmin and the inner is $\approx 11\,$arcmin. (b) A simple hexagonal mosaic based on the central 76m-25m beam size which can be used to image out to the edge of the outer annulus as set by the 25m-25m interferometer beam.

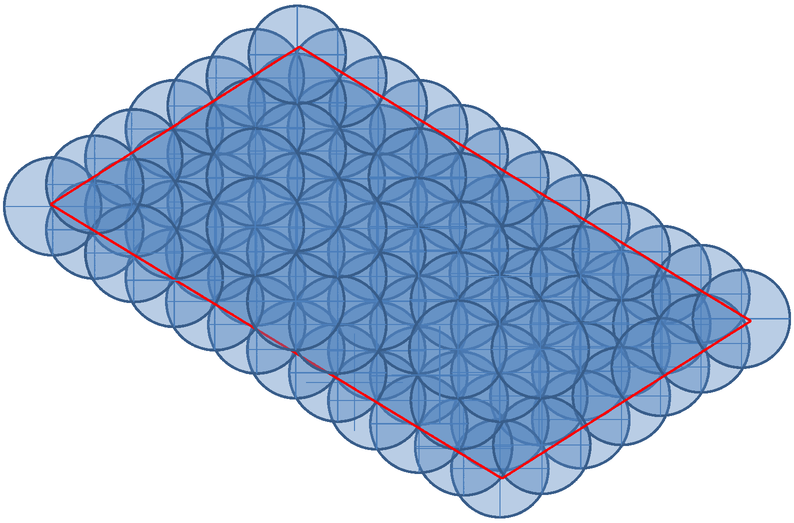

Figure 3: An example extended hexagonal mosaic based on the inner 76m-25m interferometer beam shown in Figures 1 and 2. The central smooth sensitive region in marked by a red border which will be 1.75 $\deg^2$. This region will have a sensitivity of twice that of any single pointing centre and have a total range in sensitivity of only a few percent. A 12x7 (84 pointing centres) mosaic is shown here for illustrative purposes. The Super-CLASS project requires a 16x16 mosaic (256 pointing centres) so as to have a central region of 1.75 square degrees. Variations in the detailed shape of the mosaic pattern can easily be accommodated but care should be taken to ensure that the efficiency (Central region size/total number of pointing centres) is not significantly compromised. For clarity the contributions of the non-Lovell baselines are not shown.

Observations of a single pointing centre with full e-MERLIN including the Lovell telescope result in an inner sensitive region with an outer annulus imaged at a sensitivity about a factor of two lower as illustrated in Figure 2(a). The diameter of the inner region is set by the size of the interferometer beam between the 76m Lovell and the 25m diameter of the other e-MERLIN antennas. In Figure 2(b) a simple hexagonal mosaic based on the central 76m-25m beam size is be used to image out to the edge of the outer annulus as set by the 25m-25m interferometer beam. Extending this mosaicing pattern enables e-MERLIN to produce a smooth sensitive image of a large area of sky. L-band observations with e-MERLIN are from 1380MHz to 1750MHz, and at 1750MHz the 76m-25m beam will have a FWHM diameter of 11.4 arcmin. Using this value for a mosaic rather than a mid-band diameter is relatively conservative, but ensures that the mosaic is fully sampled at all wavelengths and avoids having to utilise data from regions of the primary beam response which are likely to suffer from positional dependent instrumental phase changes. In order to achieve our goals we plan to make a 16x16 e-MERLIN mosaics with a total of 256 pointing centres as shown in Figure 3.

With homogeneous arrays (e.g. VLA, CARMA), the image sensitivity within the central region of a hexagonal mosaic with a 50% beam throw is found to be equivalent to that obtained in $\times 3.5$ the observing time for a single pointing - i.e. just less than a factor of two in sensitivity. For the proposed e-MERLIN mosaic, the combination of contributions from non-Lovell baselines together with the fact that the lower end of the observing band is oversampled by this pattern, means that the factor is closer to 4.5 times the observing time per pointing; conservatively we here assume a factor of 4 which means that the central mosaic is twice as sensitive as any single pointing. With a target rms sensitivity of 4uJy/beam we require that each pointing centre is observed for 2.6 hours (equivalent to 8uJy/beam including phase-referencing overheads). This time must be distributed in hour-angle so as to ensure that each pointing centre has similar spatial frequency coverage. Since standard phase-referencing operations with the Lovell telescope involve a basic 30min. cycle of three 8+2min. scans (two non-Lovell and one Lovell), we propose 6x30min. cycles per pointing centre distributed in hour-angle, resulting in a total of 3 hours per pointing centre. For 256 pointing centres + overheads of 2 hours per day for additional calibration, we request a total of 832 hours.

**Proposed complementary observations**

We will propose an extensive program of observations of the same field across a range of wavebands to complement the e-MERLIN program. Some are absolutely necessary for the viability of the primary cosmological science goals of the survey (science objectives (1) and (2)), for example, the L-band EVLA and optical/NIR photometry, while other data, for example, the FIR/Sub-mm and X-ray/SZ, will enhance the more astrophysical objectives (3-7). Given that the multi-wavelength coverage of the field is, at present, relatively poor when compared to the best studied fields, we would not expect to be awarded time on highly competitive instruments in all wavebands immediately, but would hope that as the high quality of the e-MERLIN data and the strength of the overall program becomes apparent we will find it easier to win time in other wavebands. The short discussions below suggest that the time required to get data in each of the desired wavebands is well within the level of resources routinely awarded to competitive projects on these facilities.

*EVLA at L-band:* The complementarity of e-MERLIN and the VLA in the $u-v$ plane was an important feature of the deep observations of the HDF. In order to improve the sensitivity to the short spacings not available with e-MERLIN we will apply for observations to match the sensitivity of the e-MERLIN survey using the EVLA in A configuration. 10 hours of observing should give an r.m.s. of $4\,\mu$Jy bm$^{-1}$ equivalent to that expected for the e-MERLIN observations over a 30 arcmin field of view. We will apply for $\sim 3$ days of observation of the field at L-band which will allow 7 pointings. This should be seen as a crucial part of the proposed program and should be applied for next time there is an EVLA deadline for A-array observations which is June 1st 2012.

*EVLA at C-band:* The EVLA at 4-6 GHz has comparable resolution (0.35 arcseconds) to e-MERLIN at L-band which will yield spectral index information to aid the separation of starburst and AGN activity. Acquisition of images at comparable depth and resolution to the e-MERLIN observations, but higher frequency, will allow spectral index information to be derived for all but the very faintest sources in the e-MERLIN observations. At C-band, the EVLA can reach about $5\,\mu$Jy bm$^{-1}$ in 1 hour and has a primary beam of about 9 arcminutes. Including some degree of overlap, 100-120 pointings are needed to cover the field. We will therefore apply for 5 days of EVLA observing at C-band, although this has lower priority than the L-band follow-up. Such a survey at matched resolution would allow reliable spectral indices and, for resolved sources, spectral index maps, to be derived for all the sources in the sample. The measurement of polarization at C-band would provide an extra data point for tying down Faraday rotation which could be crucial.

*Optical and NIR photometry:* A critical element of our weak lensing analysis are redshifts for the radio sources identified from our e-MERLIN mosaic. However, the large field of view of the mosaic and the relatively low surface density of the radio sources make classical spectroscopic follow-up of this sample very time consuming, as well as introducing problems due to incompleteness in the redshift desert. Fortunately, the redshift sensitivity of the lensing analysis means that the redshift precision required can be provided by photometric redshifts (which are also likely to be less incomplete). It has been known for over a decade that robust photometric redshifts require both optical and near-infrared broadband photometry over the widest possible wavelength range (Bolzonella et al. 2000). For that reason we intend to obtain both HyperSuprimeCam (the upgrade of the SuprimeCam which should be available in 2012) observations from Subaru of our field in the optical ($ugriz$) and corresponding near-infrared ($JK$) observations using WFCAM on UKIRT. These observations will reach $5\sigma$ limiting magnitudes of AB=26 and 23 in the optical and near-infrared respectively and will provide photometry of the majority of radio sources with sufficient precision, $\sigma_z \sim 0.1$ at $z = 1-3$, to ensure a reliable lensing analysis. The Subaru observations will require $\approx 20$ hrs and the UKIRT observations 48 hrs.

*FIR and Sub-mm imaging:* We intend to exploit the uniquely wide-field coverage of this proposed survey to obtain the first large sample of bright submillimetre galaxies (SMG) with high-resolution radio morphologies, essential to understand the distribution of star formation and AGN activity in this important population (Chapman et al. 2004; Biggs & Ivison 2008). To achieve this we need to obtain complementary submillimetre coverage of this region using *Herschel* and SCUBA-2 to select these luminous starburst–AGN systems.

The survey area is $10\times$ the planned SCUBA-2 coverage of the GOODS-N field which is the target of Tier 1 the e-MERGE legacy survey and is essential to get a statistically significant sample of the brightest

SMGs, $S_{850\mu m} > 10\,\mathrm{mJy}$, which may represent a rare short phase in the life of SMGs or a particularly extreme subset of the population (e.g. Wall et al. 2008). e-MERGE will provide radio morphologies of 30-40 such systems, whereas we will have a sample of 300–400.

The on-sky performance of SCUBA-2 has been demonstrated in "Science Verification" in 2010 and indicates that to survey a 1.75 sq. degree region to $\sigma_{850\mu m} = 1\,\mathrm{mJy}$ will take 36 hrs. This sensitivity limit is sufficient to detect typical submillimetre galaxy (SMG) with $S_{850\mu m} = 5\,\mathrm{mJy}$ at $5\sigma$ (minimising the effects of confusion and flux boosting) and should yield 1000 SMGs over this region, of which around 65% are expected to have radio counterparts above our flux limit.

These observations will be complemented by *Herschel* SPIRE observations at 250, 350 and 500 $\mu$m which probe somewhat lower redshifts and lower luminosities. Observations to the $1\sigma$ sensitivities comparable to the confusion limits at these bands, 6–7 mJy, will require around 10 hrs of on-sky integration and will yield around 800 sources at 250 $\mu$m, 300 are 350 $\mu$m and 50 at 500 $\mu$m down to the $5\sigma$ equivalent flux limits (Clements et al. 2010). These observations will thus trace the luminous and ultraluminous infrared galaxy populations at $z \sim 1$, complementing the SCUBA-2 survey which selects ultraluminous galaxies at $z > 1$–2.

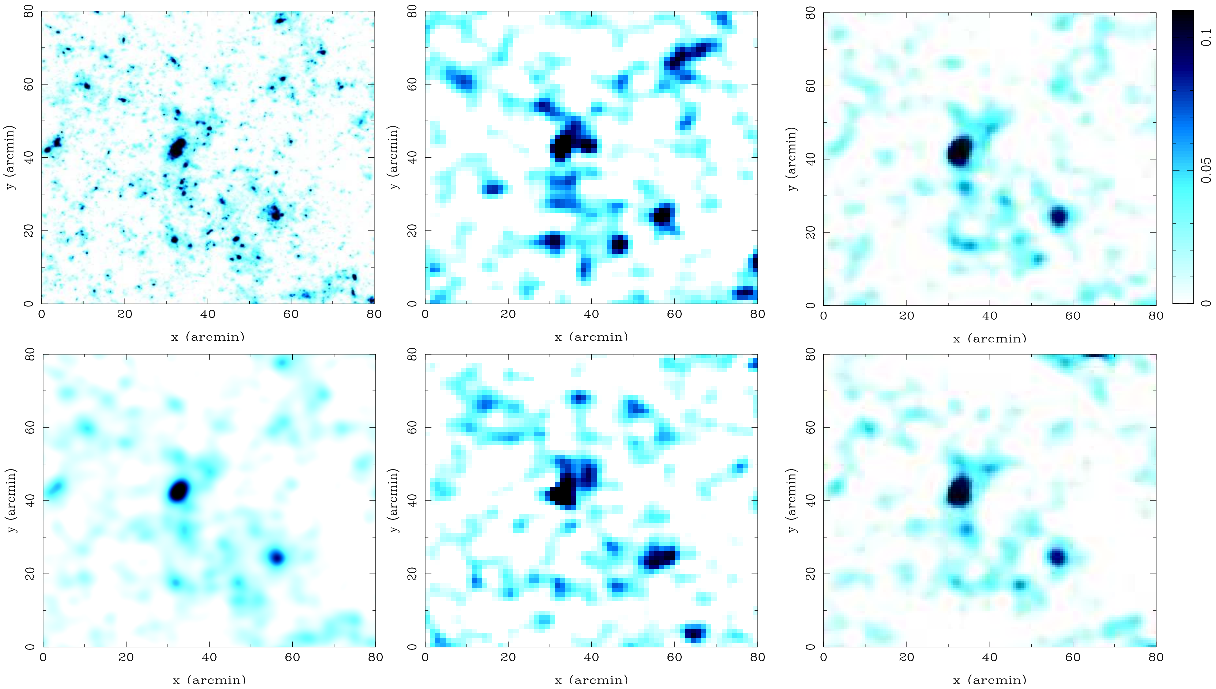


Figure 4: An example reconstruction of the dark matter distribution in a 1.75 deg$^2$ region of the simulations. The input convergence field is shown unaltered in the upper left panel and smoothed with a 2 arcmin Gaussian kernel in the lower left panel. The colour bar denotes the values of the convergence. The simulated reconstruction using total intensity only for observational specifications similar to an e-MERLIN type survey (with $n = 1.5$ arcmin$^{-2}$ and $\langle\epsilon^2\rangle^{1/2} = 0.3$) is shown in the upper central panel. Assuming one third of these galaxies are sufficiently polarized to yield an intrinsic position angle tracer that is unbiased with a scatter of $\langle\Delta\alpha^2\rangle^{1/2} = 7$ deg, the reconstruction obtained using polarization information is shown in the lower central panel. The reconstructions possible with the SKA are shown in the right-hand panels (upper panel — using total intensity only; lower panel — with polarization). For the SKA reconstructions, we have assumed $n = 15$ arcmin$^{-2}$ and that one third of the galaxies are useable in polarization with $\langle\Delta\alpha^2\rangle^{1/2} = 7$ deg.

*Hot gas in clusters:* X-ray and Sunyaev-Zeldovich effect measurements yield information about the state of the hot gas in both the high density clusters and also possibly in the intercluster regions where the Warm-Hot Intergalactic Medium (WHIM) - which may contain a significant fraction of the baryons in the Universe - is postulated to exist. Such measurements are sensitive to the electron density as well as their temperature and these can be combined with weak lensing measurements to model the overall dark matter and gas density profiles, for example, Hurley-Walker et al. (2011), and lend added value to the magnetic fields which can be extracted from rotation measures. We plan to apply for X-ray observations using *XMM* which will build on the available *ROSAT* images - NB A981 is already scheduled for observation with *XMM* as part of the SHARC program - and negotiate access to SZ observations of the field with AMI. This would require a mosaic of $\sim 24$ fields to cover the entire region.

**Simulated reconstruction of weak lensing**

We have performed simulations of the reconstruction of the dark matter distribution which could be achieved using the proposed survey. A more detailed account of these simulations is given in Brown & Battye (2011). The inputs to our simulations are lensing shear and convergence (projected surface mass density) maps obtained by ray-tracing through high-resolution N-body simulations. To mimic the e-MERLIN observations, we sample these shear fields at random galaxy positions assuming a galaxy number density of $1.5\,\mathrm{arcmin}^{-2}$ and an intrinsic dispersion of $\langle\epsilon^2\rangle^{1/2} = 0.3$ in the galaxy ellipticities. We assume that we can detect 10% of the galaxies in polarization. For these, the polarization position angle is simulated as the true intrinsic orientation of the galaxy with an RMS scatter of $\langle\Delta\alpha^2\rangle^{1/2} = 7\,\mathrm{deg}$.

We then apply direct lensing-inversion techniques (see Brown & Battye 2011 for details) to reconstruct the convergence distribution from the simulated noisy observations. An example reconstruction is shown in Figure 4. We find that, for a randomly chosen 1.75 square degree field, the lensing signal can be detected at a significance of $\sim 6.5\sigma$. For a field containing significant structure (such as the one we propose to observe) the detection of a signal is likely to be much more significant. For example, the two largest structures present in the simulation shown in Figure 4 are detected at $\sim 12\sigma$ and $\sim 7\sigma$ using either a standard lensing estimator or the polarization estimator alone. Since the noise is uncorrelated between these two estimators, their combination would reduce the reconstruction noise even further.

One issue which is crucial in the context of an interferometer is the reconstruction of the ellipitcity of the under-sampled beam. We have performed a simulation in Figure 5 which illustrates the level of reconstruction of the position angle which we might expect from the survey. This is very similar to that expected using a circular Gaussian beam which would be the best possible for a given signal to noise.

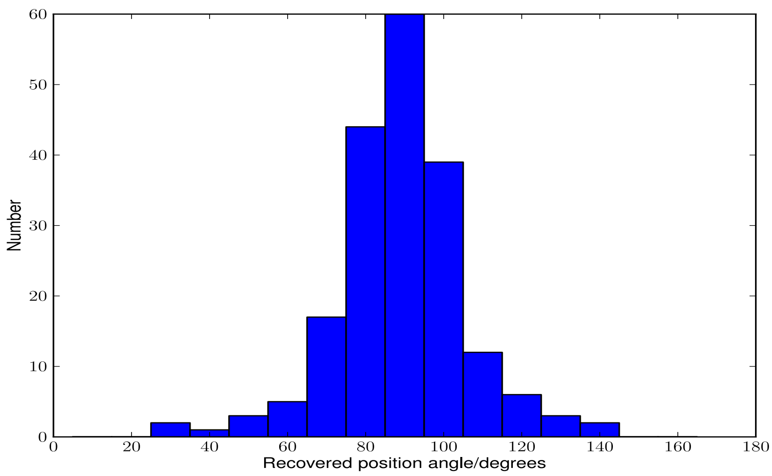


Figure 5: Simulations of e-MERLIN observations of an elliptical (600×250 -mas) Gaussian source, which is likely to be similar in Fourier space to typical star- forming galaxies (which will probably be less elliptical, but on the other hand will have more compact structure than a Gaussian). The source is assumed to be at 68 degrees, has a flux density of $100\mu$Jy, and is observed for a full track. Because of the good u-v coverage of e-MERLIN, such simulations typically approach the quality of results of direct imaging. The histogram shows the recovered position angle of a source, from a combination of e-MERLIN and e-MERLIN/EVLA images, with intrinsic PA 90°. Apart from a few pathologically scattered points, the recovery of the intrinsic PA is good.

**Proposed Manchester PhDs which would use data from this program**

We expect a substantial number of Manchester-based research students will work on the data which will come from this substantial program. Here is a list:

1. Reconstruction and modelling of the dark matter distribution in the vicinity of the A981 supercluster;

2. Using radio polarization as a proxy for intrinsic alignment in weak lensing studies;

3. Radio source population at $10\,\mu$Jy;

4. Polarization properties of the $\mu$Jy radio source population;

5. Alignment properties of star-forming galaxies at high redshift;

6. Prospects for strong gravitational lensing studies of the $\mu$Jy radio source population.

**Management and public data releases**

Richard Battye will be the PI of the project and he will be responsible for the coordination of all the activities related to the project. The data reduction will be lead by Neal Jackson, assisted by Paddy Leahy, Rob Beswick, Simon Garrington, Tom Muxlow, Anita Richards, Ian Browne and Peter Wilkinson. The weak lensing analysis will be formed by a group including Richard Battye, Michael Brown, David Bacon and Filipe Abdalla. Scott Kay will lead the simulations effort.

A number of the the external collaborators have been brought into the project to strengthen expertise in specific areas:

- Steve Rawlings will bring access to the Goonhilly telescope which will enhance the resolution, sensitivity and *u*-*v* coverage of the e-MERLIN survey.

- Bob Nichol and Ian Smail will be responsible for working with the PI to secure the necessary Optical, IR and Sub-mm data which will enhance the capabilities of the survey to probe the nature of the star-formation and AGN activity in high redshift galaxies.

- Steve Myers is a member of staff at the NRAO with a wide range of experience in radio interferometry. He will contirbute to putting the case for VLA time together as well as playing a role in the overal data analysis.

- Filipe Abdalla is playing a leading role in extracting photometric redshifts from optical/IR data as part of the DES and EUCLID consortia. This expertise, along with that of others, will be key in extracting the redshift distribution of the sources needed for the weak lensing and astrophysical analysis.

- Anna Scaife is playing a leading role in the LOFAR cosmic magnetism proposal and, along with Michael Brown, is a key member of the AMI consortium with whom we plan to negotiate access to SZ data for the field we are observing.

We plan to make the raw data available to the community on the e-MERLIN archive 6 months after the last observations take place and publish a catalogue of sources with flux densities $> 200\,\mu$Jy. Our present plan is for the observations to take place during 2012 and 2013 and therefore this would take place in mid-2014. We would hope to publish subsequent higher level data-products, such as thumbnail images of the sources and the full legacy catalogue at 6 months after that. We would expect substantial cross-fertilization with related e-MERLIN legacy programs e-MERGE, LEMMINGS and AGATE given the overlap in terms of personnel, in particular the PIs of e-MERGE tiers 0 and 1, LEMMINGS and AGATE are members of this collaboration.

**Legacy value and impact on e-MERLIN**

The proposed survey is the largest area of deep-field surveys which will be performed by e-MERLIN and the only one *focussed* on weak lensing. It will be similar in many respects to the all-sky surveys which have been proposed for the SKA. Hence, the results will have a significant impact on the planning for the SKA. In addition to a significant catalogue of sources, the key things which we will learn are: (i) the analysis techniques required to extract the weak lensing signal from radio interferometer data; (ii) deep polarized source counts; (iii) the resolution the SKA will need to for a rotation measure survey.

The project will push the envelope of what is technically possible using e-MERLIN. The wide-area and the required polarization performance will require the development of improved techniques to deal with (i) polarization calibration, (ii) mosaicing and (iii) phase referencing. These improvements will have a knock on effect on the other legacy projects and other observations made using e-MERLIN.

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