The *e*-MERGE Survey – (*e*-MERlin Galaxy Evolution Survey)

Coordinators: Tom Muxlow (Manchester, **PI**, Head of Tier 1) [twbm@jb.man.ac.uk]
Ian Smail (Durham, Head of Tier 0) [ian.smail@durham.ac.uk]
Ian McHardy (Southampton, Head of Tier 2) [imh@astro.soton.ac.uk]

Abstract:

We propose an ambitious Legacy survey to exploit *e*-MERLIN's unique combination of sensitivity and spatial resolution to study the formation and evolution of star-forming galaxies and AGN out to redshifts of $z > 5$. These observations will provide a powerful, obscuration-independent tool for measuring the massive star formation and AGN activity in high-redshift galaxies, hence tracing the development of the stellar populations and the black hole growth in the first massive galaxies. With a resolution of 50-200 mas in C- and L-Bands, corresponding to < 0.5-1.5kpc at z > 1, *e*-MERLIN gives us our first truly reliable view of the distribution of star-formation *within* typical galaxies at the epoch where the bulk of the stars in the present-day Universe were being formed. *e*-MERLIN will disentangle the relative contributions of AGN and star-formation, an essential step given the apparently simultaneous growth of the black holes and stellar populations in galaxies. To achieve these goals, we have developed a strategy comprising three nested tiers, which together provide a single, coherent survey addressing fundamental questions about the formation and joint evolution of AGN and galaxies. The completed survey will provide a homogeneous data product with lasting legacy value for the whole astronomical community.

Data working group leads: Steve Rawlings (Oxford, Lead for Simulations area)
Rob Ivision (ROE, Lead for Source Extraction area)
Isabella Prandoni (INAF, Lead for High Frequency Survey area)
Simon Garrington (Manchester, Lead for Data Handling area)

Full list of team members:

Filipe Abdalla (UCL)
Vinod Arumugam (Edinburgh)
Alicia Berciano Alba (Groningen, NL)
Rob Beswick (Manchester)
Marco Bondi (INAF, IT)
Sarah Bridle (UCL)
Benjamin Clement (Marseille, FR)
Juduth Croston (Hertfordshire)
Tom Dwelly (Southampton)
Timothy Garn (Edinburgh)
Jim Geach (Durham)
Loretta Gregorini (INAF, IT)
Eduardo Ibar (Edinburgh)
Rob Ivison (ATC)
Kirsten Knudsen (Bonn, D)
Leon Koopmans (Groningen, NL)
Hideo Matsuhara (ISAS, Japan)
Raffaella Morganti (ASTRON, NL)
Tom Muxlow (Manchester)
Seb Oliver (Sussex)
Paola Parma (INAF, IT)
Miguel Perez-Torres (IAA, ES)
Robert Priddey (Hertforshire)
Johan Richard (Durham)
Isaac Roseboom (Sussex)
Stephen Serjeant (OU)
Chris Simpson (LJMU)
Carlo Stanghellini (INAF, IT)
Toshinobu Takagi (ISAS, Japan)
Takehiko Wada (ISAS, Japan)
Olaf Wucknitz (Bonn, D)
Dave Alexander (Durham)
David Bacon (Portsmouth)
Philip Best (Edinburgh)
Andy Biggs (ATC)
Marica Branchesi (INAF, IT)
Scott Chapman (IoA)
Kristen Coppin (Durham)
Phil Diamond (Manchester)
Mike Garrett (ASTRON, NL)
Simon Garrington (Manchester)
Gabriele Giovannini (INAF, IT)
Ros Hopwood (OU)
Myungshin Im (Seoul Nat. Univ., South Korea)
Matt Jarvis (Hertfordshire)
Jean-Paul Kneib (Marseille, FR)
Yuichi Matsuda (Durham)
Ian McHardy (Southampton)
Angela Mortier (Edinburgh)
Mattia Negrello (OU)
Mat Page (MSSL)
Chris Pearson (RAL)
Isabella Prandoni (INAF, IT)
Steve Rawlings (Oxford)
Anita Richards (Manchester)
Huub Rottgering (Leiden, NL)
Nick Seymour (IPAC, USA)
Ian Smail (Durham)
Mark Swinbank (Durham)
Tiziana Venturi (INAF, IT)
Glen White (OU)
Alessandra Zanichelli (INAF, IT)

1 Science Case:

1.1 Overview: One of the key goals of modern cosmology is to understand the formation and evolution of the *whole* galaxy population. There has been good progress in addressing this problem using optical and near-infrared surveys over the past two decades culminating in the first attempts to determine the integrated star formation history of the Universe (e.g. Lilly et al. 1996; Madau et al. 1996). However, to reliably interpret this evolution we need to break down the integrated history of star formation, and independently track the star formation activity building the stellar mass in the rotationally- and pressure-supported structural components of galaxies (disks and spheroids or bulges), as well as the variation of these processes with redshift, galaxy mass and environment. This separation is essential if fundamental differences exist in the physical processes responsible for the star formation activity which builds disks and spheroids, due to differing timescales, metallicity or density dependence of the modes of star formation. Attempts to do this, using high-resolution (~100-mas) optical imaging from *Hubble Space Telescope (HST)* have suggested that the strong increase seen in the integrated star formation rate in the Universe out to z ~ 1 is driven by increasing activity in disk galaxies (e.g. Lilly et al. 1998). Nevertheless, the presence of significant numbers of blue spheroids suggests that some star formation is occurring in this component (e.g. Menanteau et al. 2001). However, these studies suffer from a major weakness: that they miss the intense star formation activity in the most dust obscured environments within galaxies. There is thus an urgent need to apply a dust-insensitive tracer of star formation to provide *a spatially resolved* view of galaxy formation to identify and so determine which of the myriad of physical processes influencing the evolution of galaxies are critical.

Such an analysis will yield a clear physical understanding of the colour bimodality of the galaxy population (e.g. Baldry et al. 2004), the morphology density relation (Dressler 1980) and the apparent migration of star formation to lower mass galaxies at later times (Cowie et al. 1996). The limited studies currently available hint at the importance of active galactic nuclei (AGN) and the feedback mechanisms driven by such rapidly growing super massive black holes (SMBHs) in defining these empirical trends. Further evidence of the potential importance of accretion driven feedback mechanisms is the apparent relationship between the mass of a SMBH and that of the pressure-supported spheroid hosting it (e.g. Magorrian et al. 1998). This has spurred theoretical efforts to include such processes in galaxy formation theories (e.g. Bower et al. 2006). However, the critical observational work needed to guide and test these theories has only just begun. In particular, we need to understand the physical origin of the difference between the two modes of activity of AGN: the radiatively inefficient ('radio') mode and the radiatively efficient accretion ('quasar') mode typical of optically or X-ray selected AGN. One possible explanation for this difference is that the quasar mode is produced by accretion of cold gas onto the SMBH by galaxy mergers or interactions; whereas the radio mode is triggered by the slow accretion of the hot intergalactic medium gas (Hardcastle et al. 2007). One way to test this scenario is to study the properties and environment of quasar mode and radio mode AGNs. To further test the galaxy formation theories we also need to identify and remove the contribution from obscured accretion activity from bolometric surveys of the evolution of star formation. Then the more challenging next step is to identify and separately trace the total (obscured and unobscured) star formation in the bulges of individual high-redshift galaxies, the related nuclear activity, and any star formation occurring on larger scales within a disk. Only by doing this will we be able to obtain a bolometrically complete census of star formation and the growth of galaxies and their SMBHs.

Radio continuum observations, and the existence of the radio–far-infrared correlation, provide us with the tool we need to resolve and measure the massive star formation in high-redshift galaxies and so track the build up of their stellar populations. To spatially resolve the star formation activity in disks and spheroids we need centimetric radio observations with sub-kpc/kpc spatial resolution at $z>1$, corresponding to 50-100 mas. Moreover, any survey must be deep enough to sample typical galaxies at the epoch of peak activity, $z\sim1$-2, leading to μJy sensitivity limits, and at the same time cover large enough volumes to be free from concerns of sample size and cosmic variance, e.g. 100's of sources across at least degree-scales. The star-formation rate in these galaxies can then be accurately derived from the relation between centimetric radio and far-infrared luminosities, which are tightly correlated over several orders of magnitude (van der Kruit 1973; Condon et al. 1982). Although this correlation is very tight, the physical processes which generate it are poorly understood. Locally, there are claims that certain sub-classes of galaxies deviate from the general trend, such as extremely young (~1 Myr) starburst galaxies that have not had sufficient time to produce the supernovae that ultimately give rise to the radio emission. Moreover, due to larger synchrotron losses, evolving magnetic field and cosmic ray strengths, at high redshift these trends evolve. Nevertheless, using *e*-MERLIN, *Herschel* and SCUBA-2, we can test whether the radio-far-IR correlation varies as function of galaxy morphology, environment, and redshift and so constrain models of the physical processes of star formation and how they differ between clusters and the field. Hence *e*-MERLIN provides the opportunity to supercede current galaxy evolution surveys and so address the crucial question of galaxy formation at the heart of modern cosmology.

Here we propose an ambitious Legacy survey to exploit *e*-MERLIN's unique combination of sensitivity and spatial resolution to study the formation and evolution of star-forming galaxies and AGN out to $z > 5$. This provides a powerful, obscuration-independent tool for measuring the massive star formation in high-redshift galaxies and hence traces the development of the stellar populations in the first massive galaxies. With a resolution of 50-200-mas at C- and L-Band, corresponding to < 0.5-1.5kpc at z > 1, *e*-MERLIN gives us our first truly reliable view of the distribution of star-formation within typical galaxies at the epoch where the bulk of the stars in the present-day Universe were being formed. When these two wavebands are combined to yield spatially-resolved spectral information, *e*-MERLIN will disentangle the relative contributions of AGN and star-formation to the bolometric emission from young galaxies: a crucial tool given the apparently simultaneous growth of the black holes and stellar populations in galaxies. By surveying a wide area this survey will be statistically reliable, with minimal influences from cosmic or sample variance, and its conclusions can then be tested against the detailed star formation histories now being derived from local galaxies from their resolved stellar populations, as well as providing direct constraints on the input physics in cosmological simulations of galaxy evolution. To achieve these goals, we have developed a survey strategy comprising three nested tiers. With 1σ sensitivity limits between 0.1 and 4 μJy/beam at L-Band, 1-15 μJy/beam at C-Band and survey areas from an arcminute to 2 degrees, these three tiers cover a sufficient range in volume and flux to allow us to robustly morphologically and spectrally determine the form and evolution of the radio luminosity function independently for AGN and star forming galaxies out to high redshifts:

Tier 0 exploits the natural magnification provided by gravitational lensing by massive clusters of galaxies to extend the sensitivity of *e*-MERLIN into the nJy regime and its resolution down to sub-kpc scales. Observations through the centres of two cluster lenses will provide a highly amplified, >2-10×, view of an arcminute-sized patch of the high-redshift Universe. This amplification will enable us to detect unresolved sources with intrinsic flux densities of ~300 nJy, giving us a first view of the population in this flux-regime. The legacy of this tier will include guiding the assumptions which are made in planning the deepest observations with SKA. The clusters also provide a unique geometrical route to estimate the redshifts for these individual sources, by interpreting their apparent shapes and multiple images using their highly constrained cluster lens models.

Tier 1 will investigate the very faint radio source population with the deepest *e*-MERLIN pointings, to survey the GOODS-N field at L- and C-Band to depths of 0.5 μJy/beam rms. These radio maps yield morphological and spectral index information on thousands of star-forming galaxies. With an angular resolution of ~200mas the L-Band map will resolve the distribution of star formation within this population and allow us to morphologically trace the total star-formation rate density in the Universe around the critical range z~0.5-3. Deep C-Band imaging at ~50mas resolution will address the role of embedded AGN in controlling star-formation by identifying and separating any weak AGN/jets which may be present and characterizing their role in influencing the star formation activity we see. The legacy value of these sensitive high-resolution radio maps in this region will be immense, as GOODS-N will continue to be one of the most intensely studied regions of the extragalactic sky.

Tier 2 will provide the volume necessary to obtain a representative sample of the brighter and high-redshift radio population. With Tiers 0 and 1, it will ensure a full sampling of the active and star-forming galaxy radio luminosity function out to z~5. Tier 2 will also sample higher density environments, including tens of $> 10^{14} M_o$ clusters out to z~1, to trace the role of environment on the star formation histories and AGN activity in galaxies over the last half of the age of the Universe. To achieve these goals we need to survey approximately 2 degrees^2 spread over six fields (plus the Tier 1 field) at L- and C-Band, to minimise cosmic variance. Each field is 0.25-0.5 degrees^2 in size and have been chosen to provide the greatest wealth of supporting multi-wavelength observations and hence the maximum scientific legacy.

The team supporting this proposal has significant multi-wavelength experience and the project is based upon the established reputation for high-resolution deep radio observations that have been performed by a number of UK-based groups with the existing MERLIN array. This combined survey provides a coherent and statistically reliable tracer of the properties of star forming and AGN systems down to sub-μJy radio flux density limits, while at the same time enabling us to mitigate the effects of cosmic variance.

1.2 Tier 0: *Imaging radio emission from normal galaxies out to redshift 5*

One of the most effective techniques used to understand the formation of the galaxies we see in the local Universe, is to study the properties of faint galaxies at high redshift. Flux-limited galaxy redshift surveys have resulted in considerable progress in understanding the properties of galaxies out to z ~1–1.5 (e.g. Ellis 1997). However, to reach galaxies at even higher redshift other techniques have had to be developed. Of these, currently the most productive uses the signature of the Lyman limit in broad-band optical colours to identify galaxies at $z > 3$–5 (Steidel et al. 1996). The brightest examples of this population can be studied with the most powerful facilities currently available. Unfortunately, it is impossible to derive critical properties such as star formation rates, for the less luminous, but more typical, members of these high-redshift populations. This is especially true of attempts to employ dust-insensitive tracers of star formation such as far-infrared or radio emission – where current facilities have the sensitivity to only detect the brightest and hence most extreme sources at $z > 2$.

To survey the individual star formation properties of typical galaxies in the early Universe in the radio waveband we have to reach into the sub-μJy regime. These very faint sources are expected to be premominantly star-forming systems, with moderate numbers of low luminosity AGN (Jackson 2004). At such faint flux limits the redshift distribution may extend to very high redshift, $z > 5$, providing the opportunity to survey the star formation properties and black hole growth in galaxies in the Epoch of Reionisation, within 1Gyr of the Big Bang.[1]

Such sensitive observations of young galaxies are one of the core science drivers for the SKA. But the goal of this Tier of the Legacy proposal is to ensure that we do not need to wait for SKA to start to investigate the properties of these typical star-forming galaxies and AGN out to z~5. By combining the enhanced sensitivity of *e*-MERLIN and the natural amplification provided by a massive cluster of galaxies, we can survey small regions of the high-redshift sky at sensitivity limits approaching 100 nJy/beam.

When they are viewed through the core of a rich foreground cluster, the images of background galaxies are amplified and distorted, appearing as elongated arcs (Fig. 1). As surface brightness is conserved in lensing, this distortion boosts the apparent flux densities of galaxies which serendipitously fall in a small region of the background sky, by a large amount (> 10×), bringing intrinsically faint galaxies within the reach of detailed investigation. Moreover a much larger number of background galaxies suffer more modest amplifications (> 2×). The serendipitous manner in which clusters amplify background galaxies makes lensing a unique probe of normal galaxies at hitherto unexplored epochs, z > 1–5, and at radio flux density limits below those otherwise achievable (< 1μJy/beam).

The strength of the lensing distortion of a source's image also contains information on the mass distribution in the lensing cluster and the redshift of the source. This degeneracy between source distance and lens mass can be broken by numerical modeling, if the properties of the lens are strongly constrained, and so redshifts for these very faint galaxies can be obtained by inverting the lensing equations. Deep *HST* images have been used to construct precise mass models for a number of lensing clusters – one of the best is Abell 2218 at z = 0.18 (Fig. 1; Kneib et al. 1996). This mass model is sufficiently detailed that redshifts could be predicted for ~100 arclets whose shapes could be measured at 100-mas resolution from the *HST* imaging. Spectroscopy of a subset of these arclets confirmed the reliability of the estimated redshifts (Ebbels et al. 1998). As this is a purely geometric technique, this confirms the reliability of the redshifts for *all* sources with a measurable lensing distortion. Hence we can use the measured shapes of faint radio sources from *e*-MERLIN to determine their redshifts – irrespective of their optical magnitudes.

We are therefore proposing an ambitious project as the deepest Tier of the *e*-MERGE programme: to study the star-formation properties of normal galaxies out to high redshifts (z~5) and to sub-μJy fluxes by using *e*-MERLIN to construct deep maps of two massive lensing clusters. Together the maps of these two clusters will sample a region of the background sky with an area of ~0.5 $arcmin^2$ which is amplified by a factor of A>10, with a typical uncertainty for the most highly amplified sources of ~20%. Assuming current (conservative) radio count models are correct, then we expect to detect over 100 amplified sources, with around 20 sources

---

[1] As a yardstick, we note that a typical luminous infrared galaxy (LIRG) with $L_{FIR} \sim 10^{11} L_o$, equivalent to a SFR ~ 10 M_o/yr, would have a 1.4-GHz flux of 100 nJy at z = 5 (and 30 nJy at $z = 7$). The surface density of sources is expected to be ~ 40 $arcmin^{-2}$ at >100 nJy (Jackson 2004).

amplified from an effective 3-σ limit of 300 nJy at L-Band. 90% of these are predicted to be star-forming galaxies with L_{FIR} ~10^{11} L_o out to z~3-5 and 10% will be FR-I AGN out to z~5. Of course the models could be assuming either too little or too much evolution in the radio population and so these predictions should be treated with caution. Nevertheless, our observations will directly measure the number counts and mix of the radio source population at flux densities well below the detection limit of *e*-MERLIN in blank fields, testing current predictions and thus providing strong constraints on both the faint end of the radio luminosity function at z~1 and the number of bright radio sources at high redshifts, z>3. These measurements are crucial for deriving a reliable integrated star formation density from radio observations. For the most highly magnified sources, our L-Band observations will benefit from the increased linear resolution provided by the lens amplification to identify compact star formation or AGN activity with an effective resolution of ~10 mas – equivalent to just ~100 pc – within a handful of intrinsically faint, high-redshift galaxies to study the physics of star-formation within distant galaxies, e.g. determine limits on the maximum star-formation rate surface density with redshift. This will include mapping the star formation activity within the multiply imaged z=2.5 LIRG behind Abell 2218 (Fig. 1, Kneib et al. 2004, 2005; Garrett et al. 2005). Furthermore, redshift estimates are available from the lens models for any background source in the field with a measurable distortion. Hence, it will be possible to determine the typical redshifts of classes of source only seen in the radio, simply using their apparent shapes in our radio maps. This may include faint radio sources at very high redshifts, with current predictions indicating that 25% of the star forming sources at this depth will be at z>3 (Jackson 2004). Finally, the redshift estimates for the ~100 distant galaxies in our two fields, which correspond to the *e*-MERLIN field of view, makes the mapping of these fields with sub-μJy sensitivity, an extremely efficient probe of the radio-emission from UV-selected galaxies at z ~1–3.

This Tier complements the proposed ultra-deep Tier of this Legacy survey. By using a similar integration time to Tier 1, but taking advantage of strong lensing by massive clusters of galaxies we can probe the counts and properties of a small sample of the radio population up to an order of magnitude fainter in flux at enhanced linear resolution. This should push *e*-MERLIN well into the sub-μJy regime. The small area of the highly amplified region in our cluster lenses is also well matched to the deepest and highest fidelity regions of the *e*-MERLIN + Lovell telescope field of view. The observations will provide legacy value through the multi-wavelength coverage of these regions (e.g. *Spitzer*, *Akari*, *Herschel*, SCUBA-2, *JWST*, etc) – and will simultaneously probe the star forming and AGN populations within the clusters themselves (to search for environmental influences on the morphologies and radio luminosity functions of galaxies, compared to those sources found in the other blank field tiers).

The primary targets are Abell 2218 (16:35+66) and Abell 963 (10:17+39) which have excellent *HST* data, necessary to derive a robust lens model. Although the opportunity for sensitive mapping at low Declination would allow Abell 1689 (13:11–01) and MS0451-03 to be included in the target list.

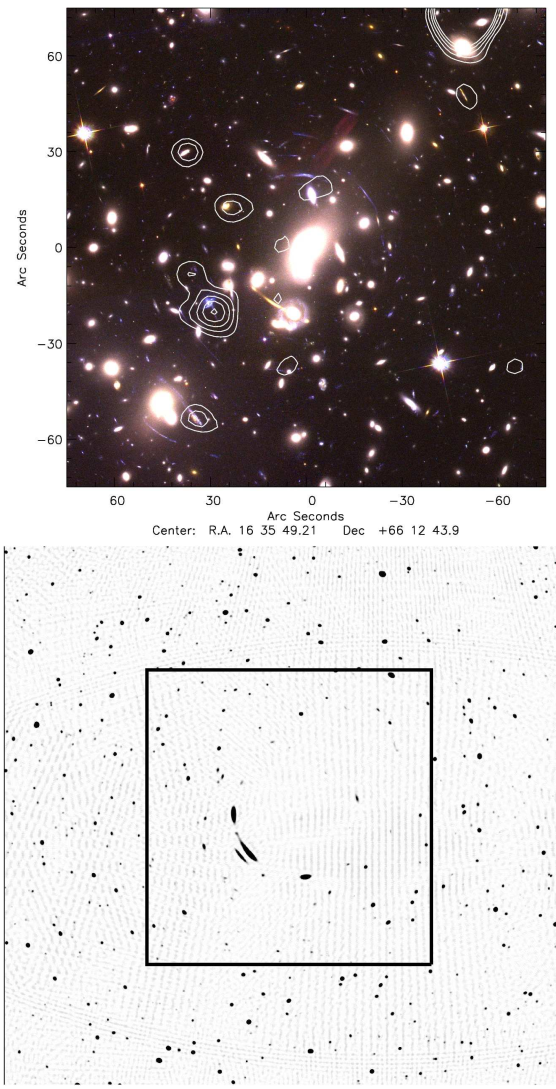

Figure 1. [upper]: The HST ACS true-colour BRI image of the core of Abell 2218. The large number of blue, distorted arcs and arclets arranged tangentially around the central cluster galaxy are images of high-redshift galaxies which have been distorted and magnified by the gravitational lensing effect of the foreground cluster's potential well. As well as boosting sub-μJy sources into the sensitivity range of e-MERLIN, the distortion introduced in the shapes of the sources also contains information on the source redshifts. The overlayed contours show the X-BandVLA observations from Garrett et al. (2005) which detect multiple images of a highly amplified, but optically faint, z=2.5 LIRG lying behind the cluster core. [lower]: A lenstool+SKA simulation of an e-MERLIN observation of Abell 2218 using a population of background sub-μJy sources assuming number counts from Jackson (2004) and scale sizes of 0.1 – 0.5". This shows that we expect to detect a few 10's of sub-μJy radio sources, allowing us to place constraints on the counts down to ~300nJy. The square represents the region shown in the HST image.

1.3 Tier 1: *A very deep directed survey of the* μJy *radio source population*

In this tier of the *e*-MERGE programme we focus on a very deep survey of some of the faintest radio starburst galaxies and AGN systems in the GOODS-N region in a project designed to directly address the following key science drivers and questions:

- To extend the star-formation (SF) density history to redshifts >3 using a single dust-independent star formation tracer and thus trace the evolution of star-formation through cosmic time.
- To study the unobscured SF surface density within these galaxies and thereby understand the evolution of SF thresholds as a function of redshift.
- To determine the contribution of AGN to activity in the distant galaxy population and separate AGN from starbursts by high resolution multi-frequency observations.
- To determine the role of AGN in driving and controlling the SF processes
- To statistically characterize the nature of the sub-μJy radio population – the target objects for the SKA

In an initial radio study of part of GOODS-N, deep radio observations were made with MERLIN and the VLA during 1996 and 1997. Within a 10×10 arcmin field centred on the Hubble Deep Field North, 92 radio sources were detected by the VLA at L-Band above a completeness limit of 40μJy/beam. Combination, high-resolution (200-500 mas) MERLIN+VLA images involving 42 hours of VLA observations and 18 days of MERLIN data were made for small regions around each of the detected sources, as well as other weaker radio sources associated with distant sub-millimetre galaxies (SMGs). The rms noise level in the combination images was ~3.3μJy per 200-mas beam making these images some of the most sensitive yet produced at 1.4-GHz (Muxlow et al. 2005). Many important results have emerged from this study: Primarily, Muxlow et al. (2005) demonstrated that L-Band MERLIN observations could morphologically distinguish AGN from starburst systems and that below a flux density of ~70μJy the radio source population becomes dominated by powerful star-forming galaxies typically at z<1.5 and with star-formation rates of many times those seen in nearby star-forming galaxies like M82. However around 15% of the population lies at higher redshifts, many of which are also identified as sub-mm sources. Some of the most luminous starburst systems also show evidence for powerful embedded AGN although higher angular resolution will be required to characterize the role of such AGN in these morphologically complex systems.

Utilising ancillary data from GOODS-N, radio emission at the level of a few μJy was statistically detected associated with ACS galaxies brighter than a z-band magnitude of 25. These very faint radio sources were identified as extended starburst systems with average properties similar to those star-forming galaxies studied individually by Muxlow et al. (2005), but with an average flux density of just $S_{1.4GHz}$=4μJy, (Muxlow et al. 2007; Beswick et al. 2008). Critically, these MERLIN observations of a sample of luminous z~1.5 galaxies morphologically identified a radio-AGN population which had been misidentified as starbursts at all other wavelengths (Casey et al. 2008). The resolved MERLIN radio morphologies of the similarly luminous z~2 sub-mm galaxies (SMGs) have revolutionized our understanding of this important high-redshift ULIRG population (Chapman et al. 2004; Muxlow et al. 2005, Biggs & Ivison 2008). Two thirds of the SMGs show clearly resolved radio

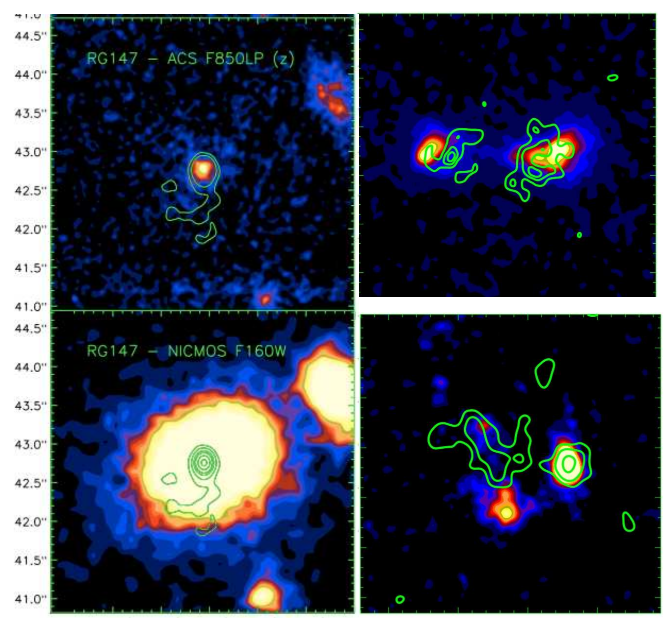

Figure 2: Characterizing the weak z~2 μJy RG and SMG populations (3"x3" boxes, covering roughly 25 kpc regions). [left panels] A z=1.92 radio source thought initially to be a starburst, but revealed exclusively by MERLIN observations to be so compact as to require an AGN to supply the energy. MERLIN 1.4GHz contours show a compact source (<65mas, <400pc at z=1.92) with a jet-like extent to the South. Optical imagery [top] reveals a compact source characterized as a starburst from Keck spectroscopy, while near-IR imagery [bottom] reveals a giant Elliptical galaxy. [right panels] MERLIN contours of Submm-faint [above] and Submm-bright [below] radio sources at z~2, superposed on HST optical imagery, both revealing multiple extended radio morphologies and high degrees of optical obscuration, characteristic of major mergers and high (~1000M_O/yr) star formation rates.

morphologies extending to ~1", and crucially demonstrate that their bolometric output arises in extended, optically faint, dust obscured regions that are forming stars at close to their Eddington limit (see Fig. 2). In conjunction with millimetre interferometry of the molecular gas, the dynamics and star-formation efficiencies (Schmidt Law, e.g. Kennicutt 1998) are being diagnosed for the first time (currently the only population at z>2 where this is possible). Even higher spatial resolution (VLBI) investigations (Garrett et al., 2001, Chi et al., in prep) indicated that some of the brightest examples of the SMG population may contain substantial AGN components, demonstrating the power of high-resolution radio mapping for investigating the origin of the immense luminosities of these galaxies.

e-MERLIN will exceed the depth of the MERLIN map in just 24 hours of on-source integration. Making use of this step-change in sensitivity we propose to individually image the radio source population at flux limits which previously have only been investigated statistically. In a single field, *e*-MERLIN will image ~850 individual starburst and AGN at L-Band with an angular resolution of ~200 mas, complete to ~3μJy (6σ, 0.5μJy rms) in the central 100 arcmins^2 – over an order of magnitude deeper than the original Muxlow et al. (2005) study. In the surrounding 800 square arcmins, *e*-MERLIN will image ~2500 star-forming galaxies and ~1200 AGN brighter than ~6μJy. A complementary deep 1-μJy rms C-Band image of the same central region at ~40mas resolution will map the star-forming regions of several hundred galaxies and will directly detect any embedded compact AGN components. These data will separate and disentangle the AGN/Jet and starburst components of emission and study the role that the AGN play in controlling star-formation via feedback mechanisms on sub-kpc scale sizes out to z>2. The combination of high angular resolution imaging with spectral index information have been identified as the prime requirements for disentangling AGN and starburst systems (e.g. Ivison et al. 2007; Barger et al. 2007; Cowie et al. 2004), and only *e*-MERLIN has the required angular resolution to separate these distinct elements of activity in the very faint radio source population at centimetric wavelengths where such steep-spectrum star-forming galaxies are detectable.

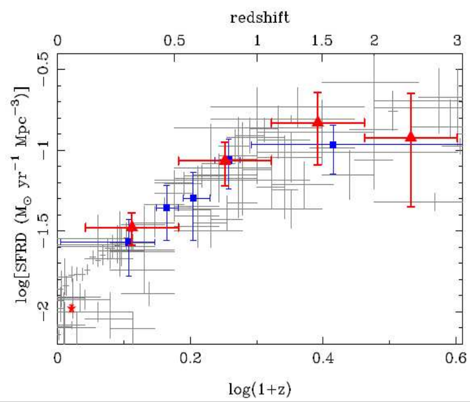

Figure 3: The co-moving star-formation rate density (SFRD) of the Universe as a function of redshift from L-Band radio studies by Seymour et al (2008) [red triangles], Haarsma et al. (2000) [blue triangles], and a selection of other methods (UV, Hα, far-IR etc.) from Hopkins (2004) [gray lines]. After Seymour et al. (2008).

The ultra-deep imaging proposed in this Tier will characterize the nature of the typical star-forming galaxies out to z~1 by imaging thousands of galaxies to ~6μJy (6σ). These key high angular resolution *e*-MERLIN images will provide AGN contamination and obscuration-free star-formation rate estimates for a population complete to between 3-6μJy, and thus enable the evolution of star-formation density to be studied to redshifts in excess of 2. Statistically, this will significantly extend existing studies from current MERLIN and VLA observations – as illustrated in Figure 3 by Seymour et al. (2008) from observations of the 13hr *XMM-Newton*/*Chandra* deep fields and VLA studies by Haarsma et al. (2000). Models of the radio source population (Wilman et al. 2008) indicate that within our survey region there are likely to be of order 600, 700, and 250 star-forming galaxies with L-Band flux densities >6μJy at z=0.5-1, 1-2 and 2-3; an increase by a factor of more than an order of magnitude on current samples (Fig. 3, Seymour et al. 2008). This represents a tightening of the error bars by a factor of around 4 in this vitally important regime around the peak of the star-formation rate density curve. We will be able to image systems with star-formation rates equivalent to Arp 220 at z~1.5, and in addition we will image >100 higher luminosity sources at even larger redshifts, including SMGs which will be revealed by SCUBA-2 surveys (with 450 and 850μm fluxes down to ~2mJy) whose physical nature is still very uncertain. We will push into an entirely new regime of the luminosity function, some the deepest X-ray and *Spitzer* constraints available. The new ultra-deep images of this region will also permit a statistical study of the radio source population down to ~400 nJy at L-Band, to complement the small sample of sources detected individually at this depth in Tier 0. Together, these will characterize the sub-μJy radio source populations, which are the target objects for the SKA.

To conclude, the Tier 1 proposal is to map the GOODS-N field at L-Band with ~200mas resolution to image ~850 starburst galaxies and AGN complete to ~3μJy (6σ) in the central 100 arcmin^2 region and ~1200 AGN and ~2500 star-forming galaxies to ~6μJy in the surrounding 800 arcmin^2. At C-Band a complementary deep image of the same central field at ~40mas resolution will map the star-forming regions of several hundred star-forming galaxies, and by disentangling the AGN and starburst components of emission directly study the role that the AGN plays in controlling star-formation on sub-kpc scale sizes to redshifts in excess of 2.

1.4 Tier 2: *A reliable cosmic census of starburst and AGN populations*

The number counts of radio sources are dominated by AGN at flux densities above ~200μJy, (e.g. Gruppioni et al. 1999; Prandoni et al. 2001; Simpson et al. 2006; Mignano et al. 2008), with star-forming sources increasingly important at lower fluxes (e.g. Muxlow et al. 2005; Biggs & Ivison 2008). However the exact mixture between AGN and star forming galaxies in the population, and its precise variation with flux density (i.e. what constitutes the `bump' in the L-band sub-mJy source counts) is still very much a matter of debate. This uncertainty reflects a fundamental lack of knowledge about the radio luminosity function and its evolution with redshift and environment. The Tier 2 project within *e*-MERGE, in combination with the other tiers, is intended to address this critical issue. To conclusively address the mix of sources contributing to the radio population we are required to distinguish AGN from star formation-dominated sources, both as a class and within individual galaxies; the interaction between AGN and star-formation is one of the major uncertainties in galaxy formation models. Radio morphology, particularly when enhanced by spectral information, although not always unambiguous, is one of the best single AGN/star formation discriminants. For example, steep spectrum radio emission extended on the scale size of a galaxy is almost certainly from a starburst, whilst compact flat-spectrum emission is very probably from an AGN. To take the next step and constrain the evolution of the luminosity functions for these two populations then requires a statistically reliable survey sampling a large volume. Hence *e*-MERLIN's combination of high-resolution and wide-field imaging and broad spectral coverage provides the ideal tool to address this problem. The Tier 2 survey will address the following crucial questions about the high redshift AGN and star-forming galaxy populations:

● *AGN/host galaxy interaction:* Determining how many AGN lie in starburst galaxies, studying the relationship between AGN and star forming galaxies as a function of luminosity, redshift, galaxy mass and morphology. The resultant AGN sample can then be used to identify how low power AGN accrete fuel. There is particular interest in determining whether they accrete fuel and radiate efficiently (`quasar' mode), or inefficiently (`radio' mode). In X-ray binary systems the inefficient accretion (`hard state') is linked to radio and jet production, but radio jets are not associated with the efficient accretion (`soft state'). In AGN the parallels would be low power FRI galaxies (hard state) and radio quiet quasars (soft state), where only faint nuclear sources are seen (Lacy et al. 2001). Using our best estimates of the accretion rate from an X-ray–radio spectral energy distribution, we can then determine which process dominates the faint AGN population and hence the fundamental physics which underpins our theoretical understanding of the effects of AGN on their host galaxies.

● *Obscured AGN activity:* The addition of spatially and spectrally resolved radio classifications to other multi-wavelength data will provide powerful insights into other classes of AGN. For example, Martinez-Sansigre et al. (2005) selected obscured QSOs using a combination of *Spitzer* mid-infrared and radio diagnostics. The improved *e*-MERLIN AGN diagnostics will greatly reduce the contamination of such samples from obscured star forming galaxies, and combined with deep infrared coverage; we can greatly extend their sample: pushing to lower luminosity obscured AGN. By comparing predicted unobscured AGN X-ray fluxes with those measured in the very deep archival *XMM* and *Chandra* observations, we can make a greatly improved estimate of the space density of Compton thick AGN (Martinez-Sansigre et al. 2007; Simpson et al. 2006) and so strongly constrain their contribution to the X-ray background.

● *Clustering:* Such a sample could also be used to study the properties of star forming galaxies, free from contamination by AGN. Locally, star-formation occurs mostly in galaxies in low density environments. Elbaz et al. (2007), using *Spitzer* 24 μm observations, show that the reverse is true at z~1, whereas hierarchical clustering models predict that we should see a reverse only at higher redshifts, z~2. However, AGN emission in the mid-infrared could easily distort these results and so it urgently needs repeating. Radio observations of a sample of star-forming galaxies across a wide range of environments, free from AGN contamination, would be a powerful tool for tracing the influence of environment on the *total* (i.e. unobscured and obscured) star formation rate in galaxies.

● *Downsizing:* In the early Universe, most star-formation appears to have occurred in more massive galaxies whereas, locally, the indications are that lower mass galaxies are the major contributors (e.g. Juneau et al. 2005). With AGN/star-formation discrimination on an individual source basis, redshift estimates for all sources and galaxy masses from rest-frame near-IR luminosities, we will accurately determine the effect of downsizing.

We therefore propose a combination of wide-field L- and C-band observations to provide a survey of medium depth, in 6 areas of the northern sky with outstanding multi-wavelength coverage, chosen to optimize *e*-MERLIN resolution. This project complements the other deeper tiers of the *e*-MERGE survey by providing large numbers of higher luminosity sources. Only with a combination of all three tiers can we achieve the main overall goal of this whole proposal: determining the separate evolution of the star-forming galaxy and AGN populations out to redshift ~5, i.e. beyond the major epoch of star formation. At present the best measurements of the radio LF of star forming galaxies reach barely beyond z~1 (Smolčić et al. 2008). Our L-band observations will be to approximately the same depth (4μJy rms) as the original MERLIN observations of the HDF-N (Muxlow et al 2005), but over a 50× larger area, thus providing a huge improvement in statistical accuracy and in our ability to measure luminosity functions (see Fig. 4). Tier 2 will, in terms of luminosity, provide a link between the low star-formation rate galaxies detected in Tiers 0 and 1 and the very high star formation rate, luminous objects detected by SCUBA-2. The Tier 2 observations proposed here will also fully cover the sub-mJy bump in the L-band counts: the limiting point source flux density is 20μJy (5σ) over an area large enough to contain many sources of >10mJy flux density.

The size of the survey area has been estimated given the science requirement that we should be able to measure the evolution of the star forming and AGN populations out to z~5. We have carried out simulations to determine the optimum observing strategy using the Oxford SKA simulator (Wilman et al. 2008), which includes the effects of clustering. We show the resultant combined Tier 1 and 2 LFs, for the redshift range where star-formation is thought to be near its peak, in Fig. 4. It can clearly be seen how Tier 1 (and 0) constrain the LF below the break, but that Tier 2 is required above the break. From these simulations we conclude that we require an area of approximately 2 degrees^2, observed to an rms sensitivity of 4μJy at L-Band to achieve our science goals. To minimize cosmic variance we subdivide the area into 6 independent fields (and include the Tier 1 field), each well matched to the *e*-MERLIN primary beam. In one of the fields we will extend the coverage to a wider area to allow a search for clustering (see below). We propose to cover the same area at C-band to 15μJy rms, detecting ~1200 steep spectrum sources and ~2000 flat spectrum AGN, many of which will lie in starburst galaxies, allowing the relationship between the AGN and star forming populations to be studied as a function of luminosity and redshift. To measure the spectra of the more extended star forming sources, we will observe these regions with the EVLA at X-band (8-12 GHz), the most sensitive band, where the resolution matches *e*-MERLIN at L-band.

The observations of the chosen fields in other wavebands, particularly very deep mid-infrared observations from *Spitzer* or *AKARI,* which cannot be superseded until the launch of *JWST*, is crucial for a number of reasons. For example, most of the *e*-MERLIN detections will be previously unknown and have no spectroscopic redshifts. Without a redshift one cannot derive a luminosity function. However, archival multi-band optical and near-IR observations exist for all fields, allowing the determination of photometric redshifts to the necessary precision (e.g. Donley et al. 2005; Dwelly et al. 2008). The mid-infrared also provides other AGN/star formation discriminants (e.g. Ivison et al. 2004; Lacy et al. 2004; Stern et al. 2004) of particular value when radio morphology is ambiguous.

We will observe one Tier 2 field over a larger area (Boötes, or UDS, or COSMOS if Chilbolton is available) providing a large enough contiguous area to perform clustering analyses and link the variety of radio source populations to the underlying dark matter halo distribution. Assuming a typical clustering length of massive galaxies of ~8 Mpc for low-luminosity radio sources (e.g. Brand et al. 2003), we require a contiguous area of roughly 0.5 degrees^2 at z~1 to determine the large scale (two-halo) clustering of morphologically separated AGN and star-forming galaxies. From the SKA simulations we expect to measure clustering between z~0.5 and 2, where downsizing is thought to be most prevalent. Furthermore, at z~1 we will carry out this analysis as a function of radio luminosity, allowing us to probe whether lower luminosity star-forming galaxies and AGN reside in dark matter haloes of lower mass. Combining Tiers 1 and 2 we will also be able to measure the clustering on small scales, i.e. active galaxy pairs within the same dark matter halo (one-halo), and so provide information on the merger rate as a function of epoch.

Combined with Tier 0 and 1, the resultant galaxy sample from Tier 2 will allow us to determine the evolution of the AGN activity and star formation rate in the Universe, in an absorption free manner from z~0.1 out to z~5 (c.f. Fig. 3).

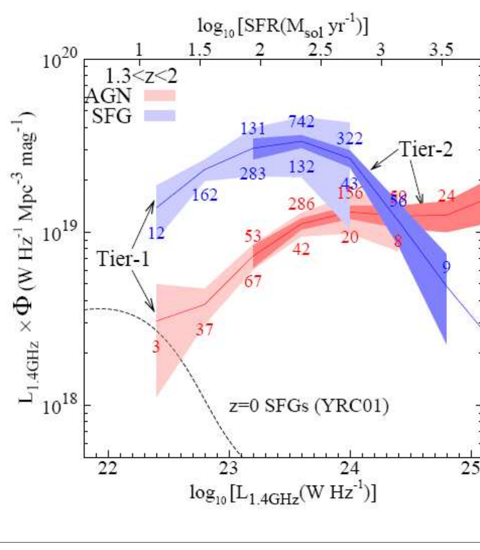

Figure 4: Simulated L-band luminosity density function of SFGs (blue) and AGN (red) expected in the e-MERGE survey, for the range 1.3 < z < 2. Source populations are taken from the models of Wilman et al. (2008). Shaded areas indicate the predicted constraints on the luminosity function from Tier-1 (light shading) and Tier-2 (darker shading), and incorporate a realistic scatter due to cosmic variance. We show the number of sources expected per luminosity bin for each tier. The local luminosity function of SFGs from Yun, Reddy & Condon (2001) is shown as a black line. The conversion from radio luminosity to SFR is from Bell (2003).

2 Related data sets & links with other Legacy programmes:

This programme has strong links with several of the other legacy proposals. In particular, our observations will provide crucial unbiased comparison samples of star forming galaxies and AGN in the field which will act as control samples for studies of the environment of AGN and the influence of environment on galaxy and AGN activity in clusters. Several other proposed *e*-MERLIN legacy programmes directly complement this project, each providing information on galaxies either in denser environments or with greater detail due to their relative proximity. These notably including AGATE (PI: Simpson), e-QUATE (PI:Priddey), LeMMINGs (PI:Beswick), and LIRGI (PI:Conway). All have strong existing scientific and technical links with *e*-MERGE which will be further fostered in order to maximise the scientific output of the legacy programme as a whole, and minimise any duplication of developments.

The *e*-MERGE project is strongly linked with the LOFAR surveys Key Science Project (PI: Rottgering). LOFAR, the Low Frequency Array, will operate at frequencies of 15, 30, 60, 120 and 200 MHz and will provide a goldmine for investigating several fundamental questions in astrophysics, including the formation of massive black holes, galaxies and clusters of galaxies. For a large fraction of the starbursts we can determine radio spectra and investigate whether these spectra are a function of galaxy concentration due to free-free absorption in compact gas rich galaxies. In addition, the spectra might steepen with redshift due to, for example, CMB induced losses.

Our field choices have been dictated by the availability of the highest quality multi-wavelength data:

Tier 0 - for this tier, where amplification by massive, foreground clusters provides unique access to the faintest radio emitters, the choice of target at radio wavelengths would traditionally have been influenced by whether a bright, structurally complex radio galaxy is associated with the central cluster galaxy. This is no longer an important consideration, with the resolution and dynamic range of *e*-MERLIN, so we can simply opt for the clusters with the most accurate mass models (to allow us to reconstruct the source plane), the deepest *Chandra*, *Hubble* and *Spitzer* imaging, and with confusion-limited surveys planned for SCUBA2 (450 and 850 μm) and *Herschel* (PACS and SPIRE) to determine $L_{FIR.}$ We have also taken RA/Dec coverage into consideration, with southerly options, should Chilbolton become available.

Tier 1 - GOODS-N (12:36+62) is the most intensively observed area on the northern sky, and the default choice for the deepest observations with any facility – *e*MERGE's Tier 1, in this case. Many hundreds of *HST* and *Spitzer* orbits have provided unparalleled UV-IR coverage, and it is the target for future *HST*/WFC3 NIR observations. The 2-Ms *Chandra* imaging will be critical for identifying AGN activity. GOODS-N also has the largest investment of deep sub-mm observing with JCMT and IRAM, with a confusion-limited image (σ = 0.5mJy at 450μm) scheduled for the SCUBA-2 Cosmological Legacy Survey. The GOODS-*Herschel* key programme includes observations of the full 150-arcmin^2 field with noise levels well below predicted confusion limits. GOODS-N has the most intensive and densely sampled faint galaxy spectroscopy anywhere. Nearly all data on the GOODS fields come from large public surveys, with several members of the present team involved, and with data products that enjoy massive use by the community.

Tier 2 - for this tier we have chosen the best-known legacy fields in northern sky, having taken RA coverage into consideration. The science goals of this tier rely on the availability of a wide *range* of complementary data. No one field provides all of these data, not even GOODS-N. This has molded our field choices as follows: Lockman/*XMM* (10:53+57) has unsurpassed sensitivity to hard X-rays; Lockman/Owen (10:46+59) is the most radio-friendly area of northern sky; the 13hr *XMM/Chandra* field has good coverage at all wavelengths; AEGIS (14:20+53) has deep wide-field *Chandra/HST* imaging and 14,000 redshifts, and Bootes (14:32+34) is the best northern field with deep optical/IR data covering scales >0.3 deg^2 (to assess clustering); *AKARI* NEP (17:54+67) has unsurpassed photometric redshift leverage in the near/mid-IR. All of these fields have optical/IR imaging of sufficient quality to determine accurate photometric redshifts out to z~2, some have excellent spectroscopic redshift surveys, some have unique X-ray data, several are planned targets for confusion-limited surveys with SCUBA-2 and *Herschel.*

One of our equitorial options, COSMOS (10:00+02) or the UKIDSS Ultra-Deep Field (02:18-05), would take priority over the Bootes field should Chilbolton become available. These fields are the primary legacy fields on scales of ~1 deg^2, with excellent imaging data at all wavelengths (including *HST* for COSMOS), large redshift surveys (zUDS and zCOSMOS) and, of course, being equitorial, they are visible from ALMA and VLT.

3 Technical Justification:

The science goals of the *e*-MERGE survey involve the study of the very weak radio source population and therefore require high sensitivity and wide-field imaging capability. The latter is needed not only to maximise the field of view of study, but to allow the subtraction of confusing sources from the edges of the primary beam of the telescopes whose contribution, if not removed from the data, would prevent the theoretical noise levels from being achieved within the field of view of study. Thus the data must permit imaging beyond the nominal field of view into the primary beam side-lobe structure. These requirements result in very large datasets with long total integrations on source (for ultimate sensitivity) together with narrow channel bandwidths and short data integration times (for wide-field capability). Defined below are the configurations which are needed for the data to realise the ultimate potential of the instrument. Dataset size problems are likely to be mitigated to an extent by averaging after the initial calibration and confusion subtraction stages, though this will require verification with real data.

At L-Band we will utilize the maximum available bandwidth (400-MHz between 1.3- and 1.7-GHz) for the required sensitivity. This will be divided into 16 separate 32-MHz sub-bands each of 256 x 0.125-MHz channels which will allow the required wide-field imaging as well as robustness against RFI which will certainly be present at various levels within the chosen band. This requires one level of correlator recirculation and will produce image smearing of only a few percent at 15 arminutes radius from the pointing centre.

At C-Band we will again utilize the maximum bandwidth available (2048-MHz) over the optical-fibre outstation links. This will be positioned between 4.5- and 6.5-GHz with 16 separate 128-MHz sub-bands each of 256 x 0.25-MHz channels without the need for recirculation. Again this will produce only a few percent image smearing at 5 arcminutes radius from the pointing centre. We have chosen the lower end of the C-Band frequency range so as to maximize the useable field of view and maximize the contribution to the overall sensitivity that is made by the Defford and Lovell *e*-MERLIN antennas whose individual performances degrade toward the upper end of the band.

We wish to incorporate the standard 7-bit data digitization at L-Band and 3-bit digitization at C-Band so as to provide additional linearity overhead for RFI mitigation at L-Band where the interference problems are likely to be worse. We note that the requested configurations require the *e*-MERLIN correlator to be fully operational.

For those tiers requiring extended fields of view, mosaicing is envisaged. Extended mosaics will be assembled in the sky plane from observations at multiple pointing centres. A standard mosaicing pattern will consist of a central field + a hexagonal outer ring of 6 additional pointing centres with the separation between centres of 1.2 primary beam radii. This pattern can be easily extended to cover any extended region. The detailed requirements for each tier are as follows:

Tier 0: We propose two single L-Band pointings will be made with the Lovell telescope centred on each of the primary fields with10 long tracks per field being made. As with the Tier 1 L-Band imaging, there will be a deep inner 10 arcmin, and an outer 30 arcmin region. With close to 18 hours on source per long track, the noise levels in these regions should be close to 1μJy/bm and 2μJy/bm respectively. We anticipate applying for matching L-Band data from EVLA to an equivalent point source sensitivity for the two tier 0 fields, to improve the short-spacing uv-coverage and hence our sensitivity to extended emission in any resolved lensed sources. Total requested time of 20x18= 360 hours.

Tier 1: We propose a single L-Band pointing with a deep central region ~10 arcmin in diameter and a surrounding ~30 arcmin diameter generated from non-Lovell data. At the high Declination of GOODS-N, we can expect around 18 hrs on source long track yielding sensitivities of around 1 and 2 μJy respectively after 20 tracks. Total time requested is 360 hrs. We intend to apply for some additional L-Band data from the EVLA to enhance our sensitivity to extended sources larger than ~4 arcseconds. At C-Band, a 7-pointing mosaic will produce a smooth distribution of sensitivity over about a 6 arcmin diameter central field, with pointing centres separated by 1.2 x a primary beam diameter of 3 arcmin. With a total of 21 full tracks, for this mosaic pattern, each position in the sky in this central 6 arcmin field has ~3 pointing centres each with 3 tracks with Lovell contributing + 12 non-Lovell tracks yielding an expected noise level close to 500nJy/beam. By mosaicing only the central 6 arcmin at Lovell beam separations, the non-Lovell data are virtually on a single pointing which covers the central sensitive 10 arcmin imaged at L-Band. This combines the C- and L-Band imaging well, and the modest amount of mosaicing will assist with the problems of the 25m primary beam effects at 6.5GHz close to the edge of the 10 arcmin field. For the vast majority of the 10 arcmin field, the sensitivity is equivalent to 21 single pointing tracks, yielding an expected noise level of ~700nJy/beam. We thus have 500nJy/bm over the central 6 arcmins and 700nJy/bm over the rest of the 10 arcmin field. Adding additional C-Band EVLA data (6 hours per pointing) to this brings these figures down by a factor~1.5 and adds useful short-spacing *uv*-coverage to help recover the very heavily resolved star-forming radio structures for sizes > 1.2 arcsec at this very high angular resolution of ~40 mas. Assuming 128hrs on source the total requested time at C-Band from 21 long tracks = 378 hours.

Tier 2: We propose to cover a total area of 1.6 deg^2 defined by 8 separate 30arcmin diameter L-Band pointings. Our L-Band survey will consist of one pointing in each of the following well studied Northern legacy fields: Lockman-Hole-*XMM*, Lockman Hole-Owen, 13-hr *XMM/Chandra* deep field, AEGIS, and the *Akari*-NEP field, together with three adjacent pointings (spaced by a primary beam diameter) in the Boötes-NDWFS field. To reach our target on-axis rms of 4µJy/bm we will require an on-source integration of 72 hours per pointing. Allowing for calibration observations, we will therefore require six 18 hr tracks per pointing (assuming an on source time of 12 hrs per track), totalling 864 hrs to cover the full tier-2 survey area. We also note that increased observing efficiency (18 hrs on-source per 24 hr track) may well be possible for our most Northerly (circumpolar) fields.

We propose to mosaic the entire tier-2 L-Band footprint with multiple C-Band pointings, to a flux density limit of 15µJy/bm. A total on source time of ~50 mins per C-Band pointing will be required to reach this sensitivity (using only the 25m antennas). Our simulations have shown that very even coverage can be achieved by mosiaicing each L-Band pointing with a hexagonal arrangement of 37 C-Band pointings spaced by 0.76 times the primary beam diameter (a central pointing surrounded by concentric rings of six, twelve and eighteen pointings). Good *uv*-coverage can be obtained with an observing strategy that involves breaking the observations of each C-band pointing into seven short snapshots, widely spaced in hour angle. We envisage taking a short (7min) scan at each C-Band pointing before moving on to the next pointing via a phase calibrator. Allowing for ~2-3 mins per cycle for slewing/settling, we can reach the desired C-band sensitivity for ~13 C-band pointings per 18 hr track. We would therefore require 23 C-band tracks to cover the full tier-2 L-band footprint, totaling 414 hrs. We will also cover the outer annulus of the tier-1 L-Band survey with a double ring of 30 pointings to a flux density limit of 15µJy/bm, this will require a further two 18hr tracks. Therefore, in total, we request 450hrs for C-Band observations of tier-2.

We will apply for matching (to at least an equivalent point source sensitivity) L-band EVLA data for each tier-2 field, improving both the sensitivity as well as the short-spacing *uv*-coverage. We also note that increased observing efficiency (18 hrs on-source per 24 hr track) may well be possible for our most Northerly (circumpolar) fields.

Table 1 – Resources requested:

Part	Band	# Pointings Area (deg^2)	Rms (µJy)	Mode - *note*[a]	Time (hrs)	R.A./Dec. - *note*[b]	Lovell Telescope
Tier 0	L	2 pt	1.0	WBC	360	10h+39,16h+66	Yes
Tier 1	L	1 pt	0.5	WBC	360	12h+62	Yes
	C	7 pt	1.0	WBC(M)	378		Yes
Tier 2	L	8pt (1.6deg^2)	4.0	WBC(M)	864	10h+59, 10h+59, 12h+62[(C-only)]	No
	C	326pt (1.7deg^2)	15.0	WBC(M)	450	13h+38, 14h+32, 14h+53, 17h+66	No

Notes:
a) We will use Wide-Band Continuum (WBC) observations to mitigate the effects of bandwidth smearing in our fields. Other than the visibility requirements to map the fields given in the table, we do not have any other significant scheduling constraints. Mosaiced fields marked WBC(M)
b) The 1.6deg^2 L-band footprint in tier-2 is defined by eight separate L-band pointings. We propose to place a single pointing in each of the following fields: Lockman Hole-"XMM field", Lockman Hole-"Owen field", 13hr XMM/Chandra field, AEGIS-Extended Groth Strip region (centered to the NE of the field due to the proximity of 3C295), and the AKARI-NEP field. Three adjacent pointings are proposed for the NOAO-wide field survey over Boötes, unless Chilbolton is available when UDS and COSMOS will replace Boötes.

Total time requested (on source): 2412 hrs [Tier 0: 360 hrs; Tier 1: 738 hrs; Tier 2: 1314 hrs]

We expect that there will be an additional overhead of ~20% for standard *e*-MERLIN continuum calibration scans.

4 Pipeline data processing, archiving, and data release policy:

All observations for Tiers 0,1 and 2 will be made in wide-field continuum mode with a set of 16 contiguous sub-bands spanning 2 GHz at C-band and 400 MHz at L-band. Each sub-band will be configured with typically 256 frequency channels and observations will be made with a short integration time (1sec) to allow the full primary beam to be imaged. All observations will be made with frequent calibrator observations, including ~10 mJy sources within ~1 degree observed every few minutes and ~1 Jy sources observed every few hours. The data volume will be up to 40 GB/hr or 1 TB/day (including Chilbolton).

The data will be converted to UV-FITS files (or EVLA/ALMA binary data format with an associated science data model) for processing in AIPS and/or CASA. The main steps in the data processing are envisaged to be as follows:

1: Automated flagging and editing, based on telescope pointing data, T_{sys} measurements, auto-correlation spectra, and automated procedures to recognize discrepant points as a function of time and/or frequency.
2: Initial amplitude calibration using T_{sys} measurements.
3: Further editing of calibrator source scans, based on models of calibrator sources.
4: Amplitude and phase calibration within each sub-band as a function of frequency and time, using bright calibrators.
5: Amplitude and phase calibration as a function of time using the fainter calibrators.
6: Peeling – Iterative location, possible calibration, imaging and removal of confusing sources within each pointing within each sub-band, nested so that Lovell data are ‘peeled’ first.
7: Search for confusing sources using map-and-stack across all sub-bands.
8: Removal of any new confusing sources using simple spectral fit, or multi-frequency deconvolution, incorporating primary-beam effects.
9: Multi-facet imaging of each pointing: map & stack each sub-band.
10: Assess spectral artifacts and noise levels.
11: Refinement of calibration (stage 4) across whole band using in-beam sources (self-calibration – possibly including direction-dependent effects).
12: Polarization calibration within each sub-band using bright calibrators (Direction dependant residual leakage terms may also need to addressed).
13: Final multi-facet/multi-frequency imaging & mosaic.

The final archived data products will include:
1. Cut-out images, with or without Lovell data as appropriate, for all detected sources.
2. VO-compliant servers for image cut-out and stacking analysis at any position.
3. Calibrated UV data for each sub-band with and without confusing sources removed.
4. Proto-type remote imaging server working from UV data.

Each tier will provide resources to process their data. Data from each tier will be made available to all tiers. Initial data reduction will take place in JBCA with the Data Working Groups leading the development of software and scripted procedures which will be exported to other institutes as they and the computer hardware required become available. Several key Co-Is are playing leading roles in other relevant legacy programmes. These links will be used to ensure that any technical developments common to multiple projects draw upon all available expertise and hence minimise any duplication. Once best practice and optimized procedures are established, they will be made available to other legacy programmes and all *e*-MERLIN users.

The data products to be made available to the community as part of this project include source catalogues, atlases of multi-frequency images of all detected sources, final complete images of all the areas surveyed as individual image panels and via cut-out servers and calibrated visibility data sets. We envisage a staged data release, where the early releases may not cover the outer regions of all fields and may not reach the ultimate sensitivity limit. Subsequent data releases will extend to greater depth and area as the processing techniques are refined. We wish to discuss the timing of these data releases, which will very across the tiers, with the LSG but our aim is to start to release data within one year of the completion of the observations for each tier or field. The images and especially the visibility data sets will be large and hence we plan to develop remote access techniques.

5 Management structure and resource plan:

We propose a management structure which includes a clear split in responsibilities between an initial delivery phase and a future exploitation phase. The delivery phase includes the three science tiers and their respective leads, who have the responsibility to plan the relevant observations, and the Data Working Group (DWG), who have the responsibility for the acquisition, reduction, calibration and cataloging of the data. These 7 individuals constitute the Management Group for the delivery phase.

Tier 0 - Ian Smail [Durham]
Tier 1 - Tom Muxlow (PI & Chair of the Management Group) [Manchester]
Tier 2 - Ian McHardy [Southampton]

The Data Working Group:	Source Extraction	- Rob Ivison [ROE]
	Simulations	- Steve Rawlings [Oxford]
	High-frequency Survey	- Isabella Prandoni [INAF]
	Data Handling / Archiving	- Simon Garrington [Manchester]

Simulations: A key goal for deep *e*-MERLIN surveys is to reach as close as possible to thermal Gaussian noise, over a field-of-view limited by the primary beam of the *e*-MERLIN antennas. Achieving this will be a significant step towards the challenging dynamic requirements of SKA and this is one of the areas in which *e*-MERLIN is a pathfinder for SKA. Current versions of the MERLIN pipelines are unlikely to reach this goal, and hence the processing steps outlined in section 4 take account of algorithmic limitations such as the difficulty in standard self-calibration routines of simultaneously correcting for direction-dependent *uv*-plane effects (e.g. ionospheric and tropospheric phase corruptions) and image plane effects (e.g. pointing errors of individual telescopes). We have developed, and parallelised, a simulation tool which uses simulated skies developed through SKADS. This can be straightforwardly used to simulate *e*-MERLIN observations including any expected *uv* - and image-plane effects. This same code can be used as the basis of next-generation self-calibration and mapping routines for *e*-MERLIN. Oxford and Manchester are planning to collaborate on this. We anticipate ~0.7 FTE of effort across the group will be available for this activity, supported by current STFC grants, as well as local expertise, e.g. the Oxford e-Science centre

Source Extraction: We have developed a robust technique to detect and quantify radio emitters in interferometric imaging data. The code produces catalogues, corrected for effects such as bandwidth smearing. It then runs complex simulations to assess completeness and determine accurate source counts. This tool will be developed further for the *e*-MERGE surveys with the aim of producing the equivalent of Sextractor for radio data. In parallel, the other members of *e*-MERGE are developing a Bayesian source-fitting routine. Edinburgh, Manchester and Oxford are planning to collaborate on unifying these source cataloguing approaches in code interfaced to the calibration and mapping routines.

High frequency Surveys: The C-Band data analysis will benefit from targeted effort from our multi-national collaboration, comprising personnel with long-standing experience in VLBI interferometry, deep radio fields and radio mosaics. They will place particular emphasis on the specific demands such as the heavy mosaicing requirements implied by the Tier-2 survey covering 2 deg^2, with the highest resolution imaging. Across the consortium we expect ~2 FTE of effort to focus on this area. We can also count on the valuable capabilities of the IRA computer department that is actively involved in the realization of the eVLBI network. There are planned storage capacities of the order of some 100 Terabytes and adequate computing power, organized in parallel beowulf systems.

Exploitation Phase: The exploitation side will be organized around Science Working Groups (SWGs), these will be both tier-specific and cross-tier, depending upon the appropriate science goals. The intention is that the SWGs will be set up within <6 months after any allocation of time to the programme. This timescale should be sufficient to allow leading members to bid for support from STFC. Membership of the SWGs will be open to all. If considered desirable, the management group will be restructured during the exploitation phase of the project to ensure appropriate representation of the SWGs.

6 Breadth of the project and its requested Legacy status:

The wide area, unbiased nature of the *e*-MERGE Legacy Survey will not only be instrumental in addressing the science goals outlined in this case, but will also be of significant value to the wider astronomical community. Of course, strong arguments can be made for highly targeted research in small chunks of competitive open time. However, the counter argument to these is that with *e*-MERLIN there is an unique opportunity for a truly ground-breaking survey that will be of global significance. We can expect that the most productive and scientifically exciting results will flow from survey work whenever we move into a new region of parameter space. The growing importance of the high-resolution interferometric observations in the millimeter and radio wavebands is well recognized, as a key route to investigate obscured activity and the high redshift universe. eMERLIN offers the opportunity to apply these tools to undertake a single coherent survey with much greater cumulative impact than a myriad of uncoordinated open time proposals.

The enormous legacy value of deep, extragalactic radio surveys targeted within well-studied fields is well proven. For example, the VLA and MERLIN studies of the Hubble Deep Field have had significant impact on studies of high redshift star-forming and sub-mm galaxies. The legacy value of our proposed *e*-MERGE programme should be even greater. *e*-MERLIN is such a uniquely powerful instrument that the co-ordinated approach described here can create a dataset that will revolutionize radio studies of galaxy and AGN evolution, and remain the benchmark in the field for at least the next decade. The detailed morphologies and spectral properties of the faint radio source population as well as their derived clustering and redshift distributions revealed by this survey will play a key role in the development and refinement of galaxy formation models and the interactions between AGN and star formation which will provide the foundation physics to underpin the next generation of cosmological simulations which will be undertaken over the next 10 years.

Strong synergistic links exist with other proposed *e*-MERLIN surveys (such as those targeting clusters or high-redshift AGN), with eMERGE providing a broad view of the radio population as a function of depth and environment against which these narrower and more focused surveys can be compared. Moreover, by targetting this survey programme on the best-studied multiwavelength fields, its long-term legacy value resulting from ever-improving multiwavelength follow-up is assured. Through this e-MERLIN survey, UK astronomers will be in a unique position to exploit the existing and forthcoming public *Herschel*, SCUBA-2, *Spitzer*, *HST*, UKIRT/WFCAM, CFHT, EVLA, LOFAR, *Chandra*, and *XMM* data in these fields to the full. For example, combining LOFAR's spectral information with morphological detail from e-MERLIN we can investigate issues such as whether the radio spectra of starbursts are a function of galaxy concentration due to free absorption in compact, gas-rich galaxies and their variation with redshift due to inverse Compton losses from the CMB. Gemini and Subaru (and VLT for any equatorial fields) follow-up spectroscopy will also inevitably be conducted in these fields over the coming years, allowing the refinement and reanalysis of the e-MERLIN dataset. Finally, the e-MERLIN survey proposed here will also provide the primary source of high-redshift galaxies selected for detailed follow-up with *JWST* (and ALMA for any equatorial fields).

References:

Baldry, I. K., 2004, AIPC, 743, 106.
Beswick, R., et al., 2008, MNRAS, 385, 1143.
Bower, G. C., et al., 2006, MNRAS, 370, 645.
Casey, C. M., et al., 2008, ApJS, 177, 131.
Chi, S., et al., in prep.
Condon, J. J., 1992, A&A, 30, 575.
Cowie, L. L.., et al., 2004, ApJ, 603, 96L.
Dressler, A., 1980, ApJ, 236, 351.
Ebbels, T., et al., 1998, MNRAS, 295, 75.
Ellis, R.S., 1997, ARAA, 35, 389.
Garrett, M.A., et a., 2005, A&A, 431, 21.
Haarsma, D.B., et al., 2000, ApJ, 544, 641.
Ivison, R. J. et al., 2004, ApJS, 154, 124.
Jackson, C., 2004, astroph/0409180.
Kennicutt, R. C., 1998, ApJ, 498, 541.
Kneib, J.-P., et al., 2004, ApJ, 607, 697.
Lacy, M., et al., 2001, ApJ, 551, 17L.
Lilly, S. J., et al., 1996, ApJ, 460, L1.
Madau, P., et al., 1996, MNRAS, 283, 1388.
Martinez-Sansigre, A., et al., 2005, Nature, 436, 666.
Menanteau, F., et al., 2001, MNRAS, 322, 1.
Muxlow, T. W. B., et al., 2005 MNRAS, 358, 1159.
Prandoni, I., et al., 2001, A&A, 369, 787.
Simpson, C., et al., 2006, MNRAS, 372, 741.
Steidel, C.C., et al., 1996, ApJ, 462, L17.
van der Kruit, P. C., 1973, A&A, 29, 263.
Yun, M.S., Reddy, N. A., & Condon, J., 2001, ApJ, 554, 803.
Barger, A., et al., 2007, ApJ, 654, 764.
Biggs, A. D., & Ivison, R. J., 2008, MNRAS,385,893.
Brand, K., et al., 2003, MNRAS, 344, 283.
Chapman, S. C., et al., 2004, ApJ, 611, 732.
Condon, J. J., et al.,1982, ApJ, 252, 102.
Cowie, L. L., 1996, AJ, 112, 839.
Donley, J. L., 2005, ApJ, 634, 169.
Dwelly et al., 2008. IAUS, 245, 415.
Elbaz, D., et al., 2007, A&A, 468, 33.
Garrett, M. A., et al., 2001, A&A, 366, L5.
Gruppioni, C., et al., 1999, MNRAS, 304, 199.
Hardcastle, M. J., et al., 2007, MNRAS, 376, 1849.
Ivison, R. J. et al., 2007, ApJ, 660, L77.
Juneau, S., et al., 2005, ApJ, 619, 135.
Kneib, J.-P., et al., 1996, ApJ, 471, 643.
Kneib, J.-P., et al., 2005, A&A, 434, 819.
Lacy, M., et al., 2004, ApJS, 154, 166.
Lilly, S. J., et al., 1998, ApJ, 500, 75.
Magorrian, J., et al., 1998, AJ, 115, 2285.
Martinez-Sansigre, A., et al., 2007, MNRAS, 379, 6.
Mignano, A., et al., 2008, A&A, 477, 459.
Muxlow, T. W. B., et al., 2007, ASPC 380, 199.
Seymour, N., et al., 2008, MNRAS (In press).
Smolčić, V., et al., 2008, ApJS, 177, 14.
Stern, D., et al., 2004, AAS, 205, 2704.
Wilman, R. J., et al., 2008, MNRAS, 388, 1335.