SCUBA2 Cosmology Legacy Survey

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Abstract

We propose a major, coherent, cosmological survey with SCUBA2, and present the design of, and scientific case for both a 2-year and an expanded 5-year programme. In developing this programme, we have built on the results of existing SCUBA surveys and associated multi-wavelength follow-up. To further refine the survey design, and in particular to arrive at the optimum values for survey depth and areal coverage, members of our consortium have performed a series of extensive simulations. These simulations have enabled us to quantify i) the survey depth at 850μm required to produce robust, unconfused samples appropriate for clustering analyses, ii) the survey depths at 450 and 850μm required to resolve the majority of the background, iii) the photometric accuracy required to provide useful redshift estimates in conjunction with other multiwavelength information, iv) the necessary detection significance level to achieve the positional accuracy required to yield unambiguous optical/IR identifications, v) the sample size required for the first effective study of the evolution of both sub-mm source clustering, and of the sub-mm luminosity function, vi) the areal coverage and depth required to detect high-redshift clusters, including putative proto-Coma clusters at $z \simeq 2$, vii) the areal coverage required to constrain the number density of the most extreme starburst galaxies, viii) the depth and areal coverage required to explore the connection between obscured star-forming galaxies and other high-redshift galaxy and AGN populations, and ix) the sample sizes, and supporting multi-frequency observations required to perform detailed tests of existing/developing semi-analytic and semi-numerical models of galaxy formation.

The result of this multi-faceted analysis is a simple 2-tier survey proposal, located in a set of well-defined fields with appropriately low far-infrared background, and the extensive multi-frequency supporting data necessary for our analysis. This single co-ordinated survey programme will revolutionize our understanding of sub-mm galaxies, and indeed galaxy formation in general. It will also provide partner-country cosmologists with a uniquely powerful lever for the exploitation of the new and growing range of public survey datasets. Finally, this survey will be of enormous and lasting legacy value, and provide a springboard for future exploitation of ALMA, Herschel, LOFAR, JWST and the SKA.

Co-investigators

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Scientific Justification

The science case for this SCUBA2 Cosmology survey programme is structured as follows. In section 1 we present our proposed 2-yr and 5-yr strategy, and summarize how the many interlocking science drivers have allowed us to converge on a single, coherent, 2-tier survey with tri-national support. Then in sections 2, 3 and 4 we discuss each of the individual science goals in the context of structure formation, cosmic star-formation history, and the detailed modelling of galaxy formation. The feasibility of our objectives, and the required survey parameters are clarified with the results of existing/ongoing surveys and by several new simulations undertaken specifically for the refinement of this proposal.

1 Survey Strategy Summary

The proposed 2-tier survey exploits the sensitivity and mapping speed of SCUBA2 to the full, as well as the new window SCUBA2 effectively provides on the 450μm universe. The survey is targetted on well-studied fields, ensuring our science goals can be met. Our strategy will also place astronomers from the 3 JCMT partner countries in a unique position to exploit future facilities and public datasets. It also guarantees the legacy value of the SCUBA2 survey programme.

2-year plan:

- Map 20 sq. degrees at 850 μm to $\sigma_{850\mu m} = 0.7$ mJy. Survey to be spread between 6 fields; 4 of the SWIRE fields, namely XMM-LSS (8 sq. degrees), Lockman Hole (4 sq. degrees), Chandra-S (2 sq. degrees) and ELAIS N1 (2 sq. degrees) plus the centre of the BOOTES field (2 sq. degrees) and the full COSMOS field (2 sq. degrees).
- Map 0.6 sq. degrees at 450 μm to $\sigma_{450\mu m} = 0.5$ mJy. Survey to be spread between 4 well-studied deep fields – ideally these will be GOODS North (0.05 sq. degrees), GOODS South (0.05 sq. degrees), UDS (central 0.25 sq. degrees), COSMOS (central 0.25 sq. degrees)
- In parallel to the 450μm mapping, obtain ultradeep 850 μm imaging of the same well-studied 0.6 sq. degrees to $\sigma_{850\mu m} = 0.15$ mJy.

5-year plan:

- Map 50 sq. degrees at 850 μm to $\sigma_{850\mu m} = 0.7$ mJy, completing the coverage of the 5 accessible Spitzer SWIRE fields, namely XMM-LSS (10 sq. degrees), Lockman Hole (11 sq. degrees), Chandra-S (8 sq. degrees), ELAIS N1 (10 sq. degrees), and ELAIS N2 (5 sq. degrees) plus an expanded region of the BOOTES field (4 sq. degrees) and the COSMOS field (2 sq. degrees).
- Map 1.5 sq. degrees at 450 μm to $\sigma_{450\mu m} = 0.5$ mJy, completing the coverage of GOODS North (0.05 sq. degrees), GOODS South (0.05 sq. degrees), the UKIDSS UDS (0.7 sq. degrees) and the central region of the COSMOS field (0.7 sq. degrees).
- In parallel to the 450μm mapping, obtain ultradeep 850 μm imaging of the same well-studied 1.5 sq. degrees to $\sigma_{850\mu m} = 0.15$ mJy, completing the deep confusion-limited imaging of the GOODS North, GOODS South, and UKIDSS UDS fields, along with the central 0.7 sq. degrees of the COSMOS field.

1.1 Survey Depth and Area

The choice of survey depth and area has been decided by many factors, all of which have fortunately converged on the common strategy outlined above.

In simple terms the broad 850μm survey can be viewed as obtaining an image as deep as that obtained for the HDF by Hughes et al. (1998, Nature, 394, 241), but over an area comparable to that covered by a sky-survey Schmidt plate. More quantitatively, our adopted r.m.s. depth of $\sigma_{850} = 0.7$ mJy can be justified as follows. First, it will deliver an image in which thermal background noise and extragalactic source confusion noise are comparable. Second, it guarantees 10-σ detections of a source population whose number density is now reasonably well established (Mortier et al. 2005, MNRAS, submitted; Borys et al. 2005, MNRAS, 355, 485). Detections at the 10-σ level are important to i) keep false detections at $< 1\%$ (sections 2.1, 2.3 & 3.3), ii) provide positions accurate to $< 2''$, thus minimizing false identifications (sections 2.2 & 4.1), iii) allowing the determination of sub-mm colours accurate to $\simeq 15\%$, crucial for the construction of meaningful SEDs (sections 2.2 & 3.3), iv) allowing the deconvolution of 850μm detections aided by higher resolution imaging (sections 3.2 & 4.3). Third, it will at the same time deliver a large number of significant detections at the 3–5 mJy level, allowing the first detailed statistical study of this less-extreme component of the sub-mm galaxy population (sections 3.3 & 3.4). Fourth, this depth is required to allow the detection of high-redshift clusters (sections 2.4 & 2.5).

Having decided on depth, the area of the 850μm survey is justified by i) the need to deliver a sample of sufficient size to measure the clustering of the sub-mm population (sections 2.1 & 2.3), ii) the desire to cover sufficient area to detect and study the (rare) progenitors of Coma-class clusters (section 2.4), iii) the desire to explore the bright number counts to determine the prevalence of extreme ($\simeq 30$–50 mJy) starburst galaxies (section 3.1), iv) achieving sufficient coverage of the luminosity-redshift plane to establish the cosmological evolution of the sub-mm luminosity function (section 3.3), v) discovering $\simeq 100$ high-redshift clusters via the S-Z effect (section 2.5). Finally, an upper limit to the sensible area of such a survey is provided by the areal coverage of the Spitzer SWIRE fields (see below).

For the deep survey, the depth requirements are set primarily by the desire to obtain the first confusion-limited imaging at 450μm. This will enable us to resolve the bulk of the extragalactic background light at 450μm, as well as providing precise positions ($\sim 1''$) sufficient to reliably directly identify the counterparts to these sources in other wavebands and assess the size of the submm-emitting regions. In parallel with these observations we will also obtain extremely deep 850μm observations of these fields which will provide both high-quality submm colours for the 450μm sources and information about the very faint 850μm population – although these will be highly confused (see Peacock et al. 2000, MNRAS, 318, 535). A realistic estimate of the final area of our 450μm survey is primarily set by the likely availability of suitable weather conditions. However, the availability of complementary multiwavelength datasets provides a natural upper limit of ~ 2 sq. degrees from the combined area of GOODS-N/S, COSMOS and UKIDSS UDS.

1.2 Survey Fields

The details (position, area, accessibility etc) of the chosen survey fields are given in the technical case. Careful field selection is of key importance because, as has been well-proven, the high-scientific impact of extragalactic sub-mm surveys results from the availability of supporting, multi-frequency datasets of the *necessary depth*. It is also important to minimise galactic cirrus emission, consider accessibility/airmass limitations, and provide sufficient RA spread for the survey programme to be practical. For the 850μm survey the natural fields are the (accessible) Spitzer SWIRE fields, which provide mid and far-infrared imaging of useful depth (covering $\simeq 50$ square degrees). Deciding on these fields now can also ensure that Herschel GTO/Open-time surveys are also targeted on these fields, providing beam matched SED information bridging the gap between 450μm and the Spitzer data. For the deep 450/850 survey, ultradeep near-infrared, optical/HST, X-ray, Spitzer and radio imaging is of key importance, and leads us naturally to the GOODS, COSMOS and UKIDSS UDS fields.

2 Sub-millimetre galaxies and structure formation

In this section we explain how our proposed survey programme will probe sufficiently large volumes, and will yield a sufficiently large robust sample of sources with meaningful redshift information to allow the clustering strength of sub-mm galaxies to be accurately measured, and the link between sub-mm galaxies and dark-matter halos to be established as a function of redshift. We also explain how our survey will allow the detailed study of the high-redshift progenitors of the richest structures seen in the present-day universe (e.g. the Coma cluster), as well as the discovery/study of high-redshift clusters through the Sunyaev-Zeldovich (S-Z) effect.

2.1 Clustering

One of the key aims of the proposed survey programme is to produce a sample of sufficient homogeneity and size to measure the clustering amplitude of the sub-millimetre galaxy population with useful precision. But what is 'useful' precision in this context? To quantify this we have extended the simulations presented by van Kampen et al. (2005, MNRAS, in press, astro-ph/0408552) to encompass the 20 and 50 sq. degree surveys proposed here. We have simulated the constraints that can be expected on the clustering amplitude A_{sky} of the sub-millimetre galaxy population for three alternative/representative models of galaxy evolution (see van Kampen et al. 2005 for details). The results, summarized in Fig.1 show that, even without any redshift information, our proposed surveys will, for the first time, allow A_{sky} to be constrained to sufficient accuracy to differentiate between such models. The crucial impact of the 20 sq. degree survey is clear, as is the added value of the expanded 50 sq. degree survey. Key to this work is the assumption that the surveys will have sufficient depth (i.e. $\sigma_{850} = 0.7$ mJy) to allow the selection of clean samples of sources at the 10σ level (i.e. with negligible contamination by confusion and/or flux boosting of substantially less luminous sources).

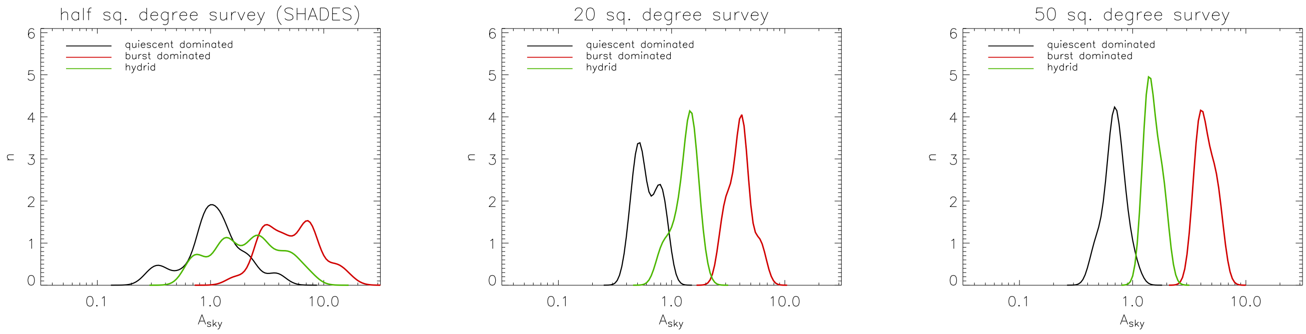

Figure 1: The panels show distributions over predicted clustering amplitudes for the sky-averaged angular correlation function, obtained by fitting this function to 50 mock surveys from a set of simple galaxy-evolution scenarios. The resulting histograms have been smoothed and colour-coded according to the underlying galaxy formation model: the black lines are for a model dominated by quiescent star formation in disks, the red lines represent a starburst-dominated model, whereas the green lines are for a hybrid model in which both star formation modes are important (see van Kampen et al. 2005 for model details). The left-hand panel gives the predictions for the ongoing, 0.5 sq. degree SHADES survey, expected to contain 300 significant sources. The second panel shows the corresponding predictions for the proposed 2-year 20 sq. degree SCUBA2 survey. The diagnostic power of such a survey is clear. The third panel shows the cleanly separated predicted distributions for the 50 sq. degree survey, containing $\simeq 20000$ sources. For all predictions the effects of noise (at the 0.7 mJy level) and the size of the beam have been included, and the sources have been selected at the 10-σ level (i.e. at 7 mJy).

2.2 Redshift information

The high-significance detections which will be obtained through our adopted survey strategy are crucial not just for source reliability, but also for the derivation of complete, unbiased, and unambiguous redshift information. In this context, high-significance detections are value in two ways.

First, the resulting accurate photometry at 850μm and 450μm, when coupled with the depth-matched VLA/Merlin/LOFAR radio, Herschel far-infrared, Spitzer mid-infrared, near-infrared and optical data, will produce accurate SEDs over a long baseline in wavelength. This will allow solid ($\delta z \simeq$ 0.2–0.3) redshift estimates to be obtained for the vast majority of the SCUBA2 sources via a refined version of the SED-fitting developed by various workers (e.g. Aretxaga et al. 2003, MNRAS, 342, 759; Takagi et al. 2005, in prep.). We note that with these long-baseline SEDs, redshift-temperature degeneracies of the type highlighted by Blain et al. (2004, ApJ, 611, 52) should not present a problem.

Second, these high-significance detections will also provide much better astrometry than has generally been achieved in SCUBA surveys. This in turn will produce more robust/unambiguous identifications at other wavelengths, which is both crucial for the construction of *reliable* optical-radio SEDs, and for the provision of solid targets for follow-up optical-infrared spectroscopy. Theoretically, we have shown that optimal source-extraction techniques of the type applied to SCUBA maps by Scott et al. (2002, MNRAS, 331, 817) and Serjeant et al. (2003, MNRAS, 344, 887) should result in 1-D 1-σ uncertainties in source position of $0.6 \times FWHM/SNR$. Recent results from SHADES are consistent with this expectation (Ivison et al. 2005, in prep.). We therefore predict that, with 10-σ detections at 850μm, the 96% confidence search radius for counterparts will be 2.1 arcsec, while at 450μm the 96% search radius will be only 1.1 arcsec. While we expect that many of these high-significance sources will be detected in deep 1.4 GHz VLA maps, it is clear that, for the first time we will not need to rely on deep radio imaging to refine sub-mm positions to the accuracy required to achieve unambiguous identifications. For example to $K \leq 23$ (which encompasses most of the known submm sources) there are roughly 70 objects per sq. arcmin – hence we can reliably identify counterparts to this depth using positional coincidence alone if we have error radii of order 1–2$''$.

In summary, therefore, we can expect to measure spectroscopic redshifts for a substantial fraction of our SCUBA2 sources, information which can in turn be used to refine the redshift estimation techniques which can be applied to essentially every highly-significant source in the survey. As discussed by van Kampen et al. (2005) and Baugh et al. (2005, MNRAS, 356, 1191), this level of redshift information will, in itself, provide an important test of galaxy-formation models. As explained below, it can also be used to determine the redshift evolution of clustering, and hence clarify the role of sub-millimetre galaxies in structure formation, and cosmic star-formation history.

2.3 Locating sub-mm galaxies within ΛCDM structure growth

There are three statistical measures of the sub-mm galaxy population that can be *combined* to place these galaxies directly within the ΛCDM structure-growth framework. They are number counts, the redshift distribution and the clustering strength. In this section we consider what can be learned from these measurements without recourse to galaxy-formation models.

For a population of galaxies in a thin redshift slice, the large-scale clustering of the sources can be matched with a halo mass, or range of halo masses, and the number density then gives the occupation number per halo. An example of such an analysis is presented in Hamana et al. (2004, MNRAS, 347, 813) for the Subaru Deep Field $z = 4$ & $z = 5$ LBGs and LAEs, or for redshift $z \sim 3$ LBGs by Moustakas & Somerville (2002, ApJ, 577, 1) and Bullock et al. (2002, MNRAS, 329, 246). The matching of galaxies to halos using clustering strength is illustrated in Fig. 2, which shows the time evolution of the amplitude of the 2-pt correlation function for different halo masses. It is clear that we require redshift information of the type described above to place each measured clustering amplitude on this plot. The redshift distribution is also required to convert an observed angular clustering measurement to the true 3-D clustering strength. We also wish to consider only high significance sources, as interlopers will also alter the recovered clustering amplitude.

We now use a mock catalogue to demonstrate the potential of our proposed SCUBA-2 survey for such an analysis. The mock survey consists of 10000 sources split over the 6 proposed fields, distributed using the halo model to match a 3D clustering amplitude of $\xi(r) = (r/6.9\mathrm{h}^{-1}\mathrm{Mpc})^{-1.8}$ as found by Blain et al. (2004, ApJ, 611, 725) for radio-selected SCUBA galaxies. A Gaussian redshift distribution is assumed with $\bar{z} = 2.4$ and $\sigma = 0.65$, again matched to the redshift distribution of SCUBA galaxies with reliable IDs (Chapman et al. 2003, Nature, 422, 695). Obviously these clustering strength and redshift distribution measurements need confirmation (e.g. Adelberger 2005, ApJ, in press), but the aim here is simply to demonstrate the potential of our proposed SCUBA2 survey.

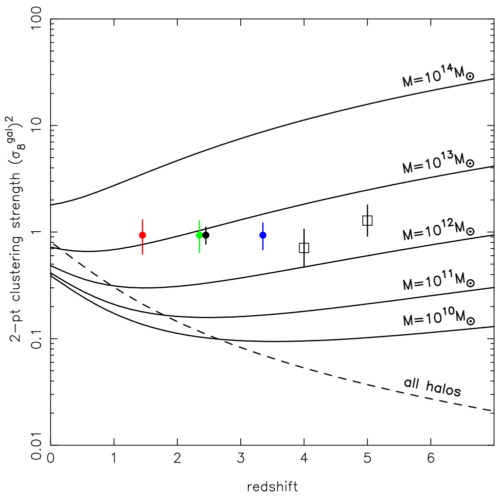

Figure 2: The evolution of the amplitude of the 2-pt statistics – the correlation function and the power spectrum, parameterized by the mean square fluctuations in spheres of radius $8\,h^{-1}\,\mathrm{Mpc}$. The clustering amplitude for halos of different mass in a concordance ΛCDM cosmology (solid lines), and the total matter (dashed line) are compared with the observed clustering strength of the LBGs of Ouchi et al. (2001, ApJ, 558, L83) (open squares) and the expected clustering amplitudes and errors provided by the proposed SCUBA-2 survey (solid symbols – see text for details).

First, we assume that we do not have redshift estimates for each galaxy. Given our adopted redshift distribution, Limber's equation predicts an angular clustering signal with $w(\theta) = (\theta/1.58\mathrm{arcsec})^{-0.8}$. We can clearly detect this level of clustering; the amplitude and expected error are given by the black solid circle in Fig. 2.

Now suppose that we have additional information about the redshift of each galaxy. For simplicity we have assumed Gaussian redshift errors with $\sigma = 0.3$. Splitting into three bins in photometric redshift containing equal numbers of galaxies, our simulations again predict that we will clearly detect the clustering in each of these bins (although there are fewer galaxies, the angular clustering signal is increased because of the narrower redshift range). Converting back to a 3D clustering amplitude, we can then place the recovered clustering strengths on Fig. 2 (coloured circles with expected errors). This analysis will therefore test whether the sub-mm population consists of the same mass object at different redshifts, or instead consists of different phenomena.

To summarise, to statistically place sub-mm galaxies within the ΛCDM structure-growth framework we need a survey of sufficient size to provide a large number of reliable sources to determine the amplitude and shape of the clustering, and with robust redshift information we can start splitting the sample in redshift and learn about the evolution of the population. All of these requirements are met by the survey proposed here.

2.4 Extreme structures

Searching for "proto-clusters" of submm galaxies is a key motivation for panoramic surveys with SCUBA-2 – providing crucial insights into the interplay of galaxies with their environment. If submm galaxies are to be identified with the formation phase of massive ellipticals, then they should trace the highest-density regions in the high-z Universe, which will go on to become the cores of the rich we see today.

In addition to the above-mentioned tentative indications of strong clustering in submm galaxies on $\sim 7h^{-1}$ Mpc scales equivalent to 0.25 degree at $z \sim 2$ (Blain et al. 2004, ApJ, 611, 725), restricted surveys for submm galaxies with SCUBA in proposed high-density environments at $z > 1$ (e.g. around luminous radio galaxies and QSOs) have revealed order-of-magnitude overdensities of sources on arcminute scales (Ivison et al. 2000, ApJ, 542, 27; Stevens et al. 2003, Nature, 425, 264). Such observations provide further support for a connection between sub-mm galaxies and the formation of cluster ellipticals.

The space density of Coma–like clusters at $z \sim 0$ is 6×10^{-9} Mpc^{-3} (those with $L_X \gtrsim 8 \times 10^{44}$ erg s^{-1} or virial masses of $\gtrsim 7 \times 10^{14}$ M$_\odot$). The available volume between $z = 1$ and $z = 3.5$ (the approximate redshift range spanned by the radio-detected submm population brighter than about 5 mJy) is 3×10^7 Mpc^3. Thus we expect to find the high-z progenitor of one Coma–like cluster once in every 5 sq. degrees surveyed on the sky.

Can we hope to detect a proto-cluster as an over-density of submm galaxies? There are $\gtrsim$ 50–100 L^*-or-brighter early-type galaxies within the virial radius of a Coma-like cluster. When these are forming they will be distributed over a 1 sq. degree region (Fig. 3) and assuming for simplicity that they all form within the lifetime of the typical submm-bright phase, then they will produce a $>$ 4-σ overdensity of submm sources projected on the sky when compared to the expected mean counts in a 1-degree aperture ($\sim$ 150 with $>$ 7 mJy). This suggests that it may be possible to even select proto-clusters directly from our submm maps, without information about high-redshift overdensities in our fields from other sources.

Thus, a survey covering $\simeq$ 20–50 square degrees is required to map a statistically-reliable sample of the most massive proto-clusters, as well as a much larger number of less extreme systems.

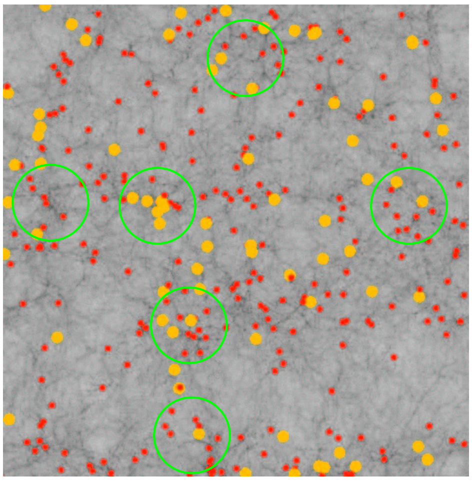

Figure 3: A Λ-CDM model at $z = 2$ with possible sub-mm galaxies highlighted (red $<$ 8mJy, gold $>$ 8mJy) based on the standard GALFORM prescription for identifying sub-mm sources (Baugh et al. 2005, MNRAS, 356, 1191). The field is 200 Mpc on a side at $z = 2$, corresponding to a total area of 42 sq. degrees on the sky. There are 65 $>$ 8 mJy sources in this thin redshift (20 Mpc thick) slice, from a total population of $\sim 10^4$ integrated along the line of sight. The green circles illustrate the radius of a sphere that contains a mass 7×10^{14} M$_\odot$ (Coma–like) before collapse, $\sim$ 16 Mpc or 1 degree diameter on the sky. This should serve as a boundary for any material ending up in a present day cluster of this mass.

2.5 The S-Z effect and high-redshift clusters

The planned 20–50 sq. deg survey at 850μm will provide an important sample of SZ selected clusters at high redshift. The rms flux density sensitivity of this survey, 0.7 mJy, corresponds to an r.m.s. Compton y sensitivity of 1.3×10^{-4} per beam. At such a sensitivity about five clusters per square degree will be detectable in single pixels of a SCUBA-2 map with a significance of 5σ or above (see the simulations of White et al. 2002, ApJ 579, 16; the flux densities in Fig. 4 should be scaled by a factor 12 to obtain 850 μm flux densities, and the predicted cluster numbers have been reduced by a factor 2 to allow for confusion from lensed star-forming galaxies). About double this number of clusters will be detectable with the aid of matched filters. These clusters will be distributed over a wide range of redshifts: the selection function for SCUBA-2 is almost flat for non-evolving clusters. The clusters detected will generally be the most massive objects at any redshift, and so should be readily identifiable on the SCUBA-2 images by their angular extents.

The resulting sample of 100 or more clusters will be almost mass limited if clusters evolve slowly. Heating processes and any redshift of rapid cluster evolution should therefore appear as significant features in the redshift distribution of the detected objects. In particular, the rate of decrease of cluster numbers with increasing redshift is a good measure of the rate of assembly of clusters. Also, since the SZ effects of clusters are a measure of their total thermal energy content in intracluster gas, the distribution of SZ effect flux densities of clusters is an almost model independent measure of the degree of development of cluster gravitational potentials – a fundamental property of developing structure.

The size of the cluster sample will be sufficient to allow an estimate of the evolution of the cluster correlation function with redshift: this is predicted to high accuracy if our cosmological parameters are accurate, and deviations from the expected rate change of the correlation function with redshift are an important consistency check (e.g. Fan & Chiueh 2001, ApJ, 550, 547). The higher sensitivity of the deep 450 μm survey will lead to a higher density of detected clusters: allowing for confusion, we estimate that the deep 450/850μm survey will contain $\simeq$ 25 detectable clusters.

3 Sub-millimetre galaxies and cosmic star-formation history

Here we explain how our proposed programme provides enough dynamic range in luminosity, a sufficient number of sources, adequate redshift information, and the necessary SED information for calculation of bolometric luminosities to allow the cosmological evolution of the sub-mm luminosity function to be delineated. This in turn will allow us to refine the 'Lilly/Madau' diagram, and establish the link between obscured and visible starformation over cosmic history.

3.1 Bright sources – extreme starbursts

At the 10 mJy level, SHADES is confirming cumulative source counts at the level of $\simeq 100$ per sq. degree. However, even after completion of SHADES, the source counts at significantly higher flux densities will remain relatively unconstrained. A SCUBA-2 survey in the 20–50 sq. degree range can address the issue of whether the counts continue as $N(>S) \propto S^{-2}$ at $S_{850} > 10$mJy, or whether there is significant steepening at brighter flux densities, e.g. to $N(>S) \propto S^{-3}$. In the former case, the proposed SCUBA2 survey will contain > 200 sources with $S_{850} > 30$mJy, while in the latter case the simple prediction is only $\simeq 70$ sources. Whatever the outcome, any such rare bright sources will be of great interest for detailed study since, taken at face value, they must be either at relatively low redshift, be significantly boosted by gravitational lensing, or have intrinsic star-formation rates of $\simeq 5000\mathrm{M}_{\odot}\mathrm{yr}^{-1}$.

3.2 Faint sources – resolving the 450μm background

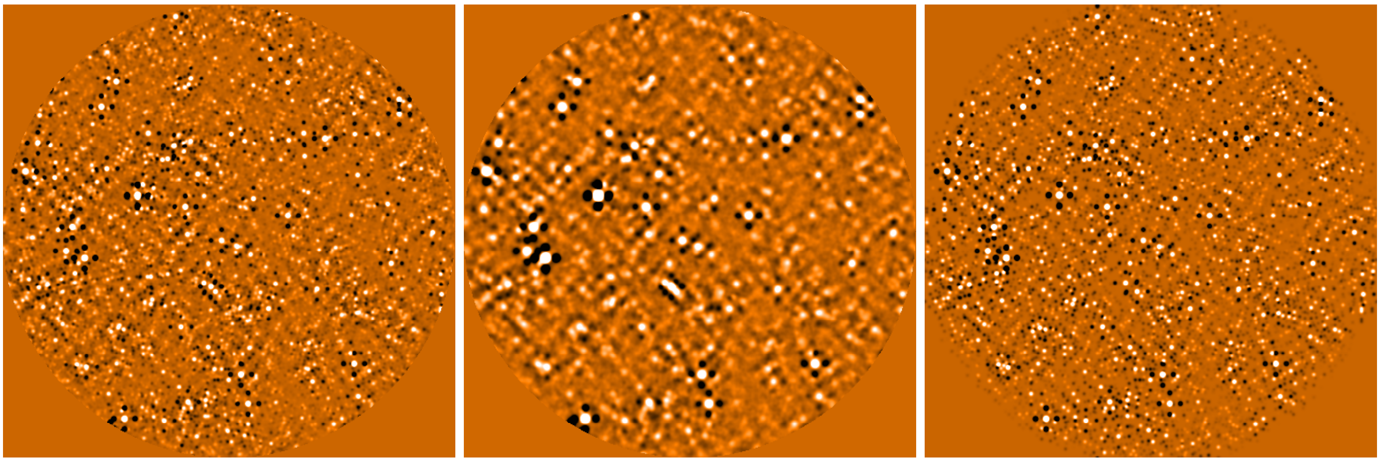

Figure 4: A simulation of the impact of using the deep 450μm survey data to deconvolve the parallel, ultradeep and highly-confused 850μm image ($\sigma_{850} \simeq 0.15$ mJy).The left-hand panel shows a simulated 0.1 sq. degree map, based on current source-count estimates, and including realistic clustering. This is a 'perfect' image, with no noise, and convolved to 450μm resolution (FWHM $\simeq 8$ arcsec). The middle panel predicts how this patch of sky will actually look, when imaged at 850μm with SCUBA2 on the JCMT, assuming background noise $\sigma = 0.15$',mJy. The right-hand panel shows the 'high-resolution' 850μm image which results from de-convolving the central 'real' image with the aid of peak finding algorithms run on the parallel 450μm map (unit scatter in log(S(450)/S(850)), along with $\sigma_{450} = 0.5$ mJy was assumed when constructing the simulated 450μm map from the left-hand panel). The reclaimed image in the right-hand panel compares well with the input shown on the left, and we find that the number counts at 850μm can be reclaimed to $S_{850\mu m} = 0.6$ mJy.

The extra-galactic background in the far-infrared peaks at $\lambda \simeq 200\,\mu$m (Fixen et al. 1998, ApJ, 508, 123). At the moment deep SCUBA surveys at 850μm resolve the bulk of the background at this wavelength (e.g. Blain et al. 1999, ApJ, 512, L87). However, it is clear from the typical 450/850μm ratios of these sources that they probably contribute less than half of the background at 450μm and hence an even lower proportion of the peak of the background. Our proposed deep 450μm survey will allow the detailed study of the source population selected much closer to the background peak than has previously been possible. The sources contributing to the 450μm background are likely to comprise lower-redshift and/or sources with hotter dust temperatures – providing a natural link between the SCUBA population and those uncovered in the mid-infrared by Spitzer. In addition, our target 450μm flux limit corresponds to intrinsic luminosities of the sources roughly $10\times$ fainter than those mapped in the main 850μm survey – with far-infrared luminosities of $< 10^{12}\mathrm{L}_{\odot}$. This population should also overlap with the most active examples of other high-redshift populations, such as UV-selected galaxies and X-ray sources – providing the opportunity to investigate the relationship between many of these (currently independent) populations and bring them into galaxy formation models as a coherent whole.

Moreover, the high angular resolution of the JCMT at 450μm also provides several scientific opportunities – it provides far superior positional accuracy for the counterparts to the submm sources at other wavelengths, it also may allow us to resolve the submm emission from distant sources and test whether for example whether this arises in multiple merging components. As discussed below the superior 450μm beam can be exploited to deconvolve both the 850μm imaging and that from Herschel much closer to the peak of the extragalactic background (likely to fall in the 250μm Herschel band), and hence to quantify the contribution of the 850 and 450μm selected populations to the far-infrared background.

An important and exciting resource which will be obtained in parallel with the deep 450μm survey is ultra-deep 850μm imaging to a (thermal background) noise level $\sigma_{850} \simeq 0.15$ mJy. Of course the measured r.m.s. in this SCUBA2 survey will be substantially larger, because the noise will be completely dominated by source confusion. However, such a completely confusion-limited survey is potentially an extremely rich source of information on the properties of the fainter (i.e. $S_{850} \simeq 1$ mJy) 850-μm source population. In particular, as well as undertaking $P(D)$ analyses (see Hughes et al. 1998, Nature, 394, 241; Peacock et al. 2000, MNRAS, 318, 535) we intend to use the enhanced angular resolution of associated 450μm imaging to help deconvolve the 850μm image, and hence probe the faint 850μm counts. A detailed simulation of the potential power of this type of analysis is shown in Fig. 4. From this simulation we find that the input (i.e. true) 850μm counts can be reproduced down to $S_{850} = 0.6$ mJy. Since this is the source detection level assuming only the thermal noise (i.e. $\sigma \simeq 0.15$ mJy), it is clear that this form of analysis can overcome the (statistical) effects of confusion.

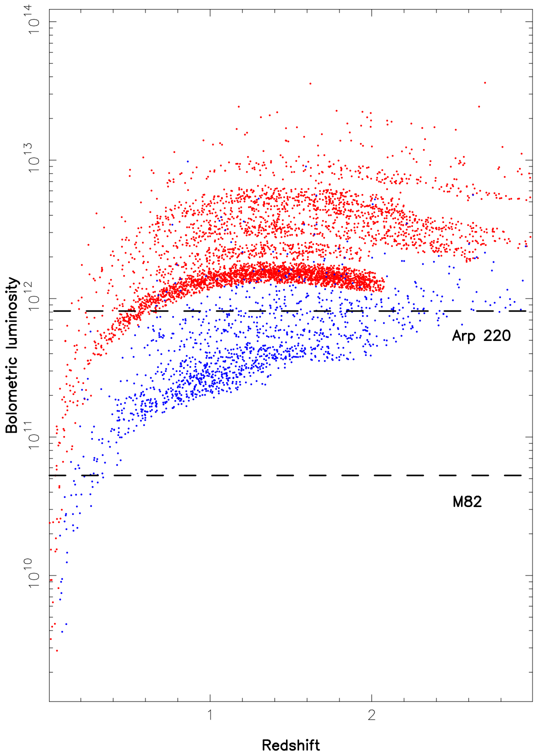

Figure 5: A Monte-Carlo simulation of the coverage of the bolometric luminosity-redshift plane which would be provided by the proposed 2-year survey programme. The simulation adopts a model based on the SCUBA Local Universe and Galaxy Survey (Dunne et al. 2000, MNRAS, 315, 115) and the luminosity-evolution model of Rowan-Robinson (2001, ApJ, 549, 745). The red dots show the sources that will be detected by our 20 sq. degree 850-micron survey; the blue dots the sources that will be detected by the deep 0.6 sq. degree 450-micron survey.

3.3 Evolution of the sub-mm Luminosity Function

Due to i) the large number of robust sources which will be provided by our survey, ii) the dynamic range provided by our two-tier dual-frequency approach, iii) the availability of complete aand unbiased redshift information, and iv) complete SEDs yielding robust bolometric luminosities, it will be possible, for the first time, to derive the cosmological evolution of the sub-mm galaxy luminosity function with useful precision. Fig. 5 shows the coverage of the $L - z$ plane which will result from our proposed survey strategy, allowing the luminosity function to be measured over a range of $50 \rightarrow 100$ in luminosity at every z.

3.4 Cosmic star-formation history

Integration of the evolving luminosity function discussed above will allow us to construct the first robust sub-mm version of the Lilly-Madau plot, with statistical error bars a factor of 10 smaller than can currently be achieved (e.g. Chapman et al. 2005, ApJ, in press), and systematic errors minimized by complete, robust SED information. Moreover, our deep 450/850μm survey will allow us to test the 'obscuration' corrections currently applied to Lyman-break galaxies selected at high redshift, thereby clarifying the relationship between obscured and unobscured star-formation activity over cosmic time. Finally, through comparison with the fossil record of star-formation divided by present-day mass (e.g. Heavens et al. 2004, Nature, 428, 625) we will be able to clarify the the present-day descendents of sub-mm galaxies.

4 Towards a detailed understanding of galaxy formation

In this section we explain how our proposed survey programme allows the exploitation of a wide range of multi-frequency supporting datasets to allow the detailed study of the properties of sub-mm selected galaxies, and hence crucial tests of semi-analytic/numerical models of galaxy formation.

4.1 Stellar masses and evolutionary status

One of the fundamental physical measurements that can be made for high redshift galaxies and one of the more important for placing them into the theoretical context, is the stellar mass. Sub-mm galaxies appear to form through a sequence of mergers (e.g. Conselice et al. 2003, ApJ, 596, L5) and many of the stars may already be in place. The peak emission from an evolved stellar population emerges in the rest-frame H and K bands. For the redshift distribution of the sub-mm population, $z > 1$ (Chapman et al. 2003, Naature, 422, 695; Chapman et al. 2004, ApJ, 614, 671) this translates to $> 3\mu$m, so K-band photometry is contaminated by recent star formation. Instead, *Spitzer* photometry with IRAC (3.6–8μm) and MIPS (24μm) is required to provide a robust estimate of the total stellar mass — a fundamental physical measurement, which allows us to extend the well-known K–z diagram to high redshift in rest-frame K. We can also infer the evolutionary stage of each sub-mm galaxy by comparing the mass of stars already formed, to the visible star-formation rate (from optical-infrared SED fittinng, and to the obscured star-formation rate derived from the sub-mm/far-infrared photometry – a crucial discriminator for the order in which the stars are formed and the galaxies are assembled. This type of study obviously requires high-positional accuracy to identify robust near-infrared and mid-infrared counterparts to sub-mm sources, along with supporting, deep Spitzer IRAC and ground-based K-band imaging.

4.2 Testing semi-analytic models

We will use our observations to confront the latest multiwavelength models of galaxy formation and evolution. In particular, we highlight the membership within our consortium of one of the leading theoretical teams working on semi-analytic models of galaxy formation (Baugh et al. 2005, MNRAS, 356, 1191). This group has devised one of the most advanced models, including detailed modelling of the spectral energy distributions of the model galaxies from the restframe UV to the radio with a self-consistent model for dust production and obscuration. These models also include information from large-scale numerical simulations to derive the merger trees and environments of the model galaxies. Comparisons of models and theoretical predictions for the sub-mm population (Baugh et al. 2005) have shown the power of this population as a strong test of the physics of massive galaxy formation. These comparisons will benefit from the much larger samples, wider range of multiwavelength data and clustering constraints available from our proposed survey.

4.3 Sub-mm source sizes

Experience derived from the SCUBA imaging of bright sources around radio galaxies and quasars (e.g. Stevens et al. 2003, Nature, 425, 264) shows that, with the addition of good radio and 450μm data, it is possible to derive meaningful measurements of the scale-size of the sub-mm emission, and to address the issue of whether the driving starbursts are confined to the nucleus, or extended on scales of several kpc. This survey will contain $\simeq$ 1000 sources with $S_{850} >$ 10mJy, and will thus contain hundreds of sources detected with S/N in excess of 15-20, well suited to such detailed analysis/deconvolution. The added value of the higher resolution provided by the deep 450μm imaging is obvious in this context (Stevens et al. 2004, ApJ, 604, L17). Indeed, it should be possible to test whether the scale-size of starbursts of a given power is a function of redshift.

4.4 The relationship between bulge and black-hole formation

In a survey of this scale, supported by appropriate multi-frequency follow-up one can explore the relationship between AGN activity, black-hole growth, and bulge/spheroid formation and evolution in a quantitative sense with > 100 sources in each $\Delta z = 0.1$ bin. To reproduce the Magorrian relation, each sub-mm galaxy must host a growing black hole (Alexander et al. 2005, Nature, in press). *XMM-Newton* and *Chandra* will uncover some of these, but even *XMM-Newton* will not allow us to detect the most heavily obscured objects ($N_{\rm H} > 10^{23}\,{\rm cm}^{-2}$. However, powerful absorbed AGN frequently have low dust-to-gas ratios (typically 0.01–0.3 Galactic, e.g. Maiolino et al. 2001, A&A, 375, 25) and consequently, buried AGN will be much easier to detect in the mid-IR than in X-rays. *Spitzer* can thus directly detect AGN with column densities up to $10^{24}\,{\rm cm}^{-2}$, with discrimination between starbursts and AGN possible via simple colour-colour diagrams (e.g. Ivison et al. 2004, ApJS, 154, 124).

4.5 The sub-mm : Lyman-break : ERO connection

The depth of the 450μm survey will enable us to study the entire ULIRG population out to redshifts $z \simeq 2$. The star-formation rates probed are a few times the unobscured SFR of the brightest Lyman-break galaxies, and thus we can bridge the gap between obscured and visible star-formation. The surface density of unconfused sub-mm sources detected in the deep 450/850 survey will be $\simeq 1.5$ per sq. arcmin. This is comparable to the surface density of $2.7 < z < 3.4$ Lyman-break galaxies brighter than $R < 25.5$ (Steidel et al. 2004, ApJ, 604, 534). Many of the Lyman-break galaxies should therefore be detectable in the deep SCUBA2 maps if current assumptions about obscured/visible SFR ratios in these sources are correct, and so our observations will provide a direct test of the ratio of obscured to unobscured star formation in such objects. Another important population which may harbour obscured star formation detectable in the deep survey is the class of extremely red galaxies. Even in cases where individual galaxies are not detected by SCUBA2, much information can be gained by statistical approaches such as cross-correlating source lists with the SCUBA2 maps.

5 Technical Case

Survey	Field	RA DEC (J2000)	Depth (mJy)	τ range	2-yr Area (sq. deg.)	2-yr Time (hours)	5-yr Area (sq. deg.)	5-yr Time (hours)
Wide	XMM-LSS	02:21:20 -04:30:00	$\sigma_{850} = 0.7$	0.05-0.10	8	336	10	420
Wide	Chandra-S	03:32:00 -28:16:00	$\sigma_{850} = 0.7$	0.05-0.10	2	84	8	336
Wide	COSMOS	10:00:29 +02:12:00	$\sigma_{850} = 0.7$	0.05-0.10	2	84	2	84
Wide	LOCKMAN	10:45:00 +58:00:00	$\sigma_{850} = 0.7$	0.05-0.10	4	168	11	462
Wide	BOOTES	14:32:06 +34:17:00	$\sigma_{850} = 0.7$	0.05-0.10	2	84	4	168
Wide	ELAIS N1	16:11:00 +55:00:00	$\sigma_{850} = 0.7$	0.05-0.10	2	84	10	420
Wide	ELAIS N2	16:36:48 +41:01:45	$\sigma_{850} = 0.7$	0.05-0.10			5	210
					20	840	50	2100
Deep	UDS	02:18:00 -05:00:00	$\sigma_{450} = 0.5$	< 0.05	0.25	240	0.70	672
Deep	GOODS-S	03:32:28 -27:48:30	$\sigma_{450} = 0.5$	< 0.05	0.05	70	0.05	70
Deep	COSMOS	10:00:29 +02:12:00	$\sigma_{450} = 0.5$	< 0.05	0.25	210	0.70	588
Deep	GOODS-N	12:36:46 +62:13:58	$\sigma_{450} = 0.5$	< 0.05	0.05	60	0.05	60
					0.60	580	1.50	1390

Table 1: Fields, depths, and requested integration times for 2-year and 5-year Cosmology Survey programme

Wide 850 μm survey

The survey would be carried out when the opacity at zenith is in the range $0.05 < \tau_{cso} < 0.10$. Using the sensitivity estimates in the call for proposals we calculate that mapping 1 sq. degree to a depth of $\sigma_{850} = 0.7$ mJy requires a time of 42 hours. Therefore the total time necessary to carry out the 2-year 20 sq. degree survey is 840 hours, while the total for the 5-year 50 sq. degree survey is 2100 hours.

Deep 450 μm survey

The Deep survey strategy is to use the time when the weather conditions are suitable for high-frequency work to map smaller areas to the 450 μm confusion limit. The aim is to achieve 10-σ detections of sources which have a flux density $S_{450\mu m} = 5$ mJy. We propose confining data collection to $\tau_{CSO} \leq 0.05$, and aim to map 0.6 sq. degrees to the required depth over the first two years of the survey, expanding to a total area of 1.5 sq. degrees over 5 years.

The fields for the Deep survey have been selected to maximize the overlap with the deepest data available at other wavelengths. For these reasons, the GOODS-N and GOODS-S fields are included (along with the more easily accessed UKIDSS UDS and HST COSMOS fields) because they have the deepest Spitzer, HST and X-ray imaging over a useful field size. The high- and low-declination of these two targets does increase the amount of time necessary compared to the other two fields. We have considered this issue carefully using weather statistics and an expected plan of observing and the time column in the table reflects the fact that extra time is needed to reach the sensitivity goal.

Using the mapping speeds recommended, the time required to map a 0.05 sq. degree field to $\sigma_{450} = 0.5$ mJy is 42 hours. The standard mapping speeds are based on calculations for an elevation corresponding to 1.1 air masses and $\tau_{CSO} = 0.04$. Since short-wavelength observations are very sensitive to variations in τ, and since some of our deep fields never reach this low an airmass, we have performed a more detailed mapping speed calculation for the short-wavelength fields. We have integrated over source positions above an elevation angle of 30 degrees, and combined the data with inverse variance weighting. Allocations of the numbers of hours listed in Table 1 for each field will result in maps with the required sensitivity, $\sigma_{450} = 0.5$ mJy.

Total time request

Summing the figures given above in Table 1 leads to a total time request of

- 1420 hours with $\tau_{CSO} \leq 0.1$ for the 2-year survey, of which 580 hours require $\tau_{CSO} \leq 0.05$
- 3490 hours with $\tau_{CSO} \leq 0.1$ for the 5-year survey, of which 1390 hours require $\tau_{CSO} \leq 0.05$

6 Legacy and Leverage Value

With the JCMT moving the 12-hour nights from late 2005, the number of hours per year available for 850μm observing with $\tau_{CSO} \leq 0.1$ ($\simeq$ 40% of the time) can be estimated as

293 nights $\times$ 12 hours $\times\ 0.4 = 1406$ hours.

Similarly, the number of hours per year available for 450μm observing with $\tau_{CSO} \leq 0.05$ ($\simeq$ 15% of the time) can be estimated as

293 nights $\times$ 12 hours $\times\ 0.15 = 527$ hours.

Thus, per year, it can be seen that our proposed Cosmology Survey programme is requesting $\simeq 50$% of the likely usable observing time at 850μm, and $\simeq 50$% of the likely usable observing time at 450μm. We view this as very reasonable, given the power, impact, and enormous legacy value of this major, tri-national survey.

The enormous legacy value of deep, extragalactic sub-mm surveys targetted within well-studied fields is well proven. For example, the SCUBA study of the Hubble Deep Field performed by Hughes et al. (1998, Nature, 394, 241) is the 17th most highly-cited paper in astronomy, out of the 250,000 papers published since 1998. Similarly, the 8-mJy SCUBA survey of the Lockman Hole annd ELAIS N2 fields conducted by Scott et al. (2002, MNRAS, 331, 817) is the 24th most highly-cited paper in astronomy, out of the 100,000 papers published in the last 2.5 years.

The legacy value of our proposed SCUBA2 Cosmology survey programme should be even greater. SCUBA2 is such a uniquely powerful instrument that the co-ordinated approach described here can create a dataset that will revolutionize sub-mm cosmology, and remain the benchmark in the field for at least the next decade. The derived clustering, redshift distribution and detailed properties of sub-mm sources as revealed by this survey will play a key role in the development and refinement of galaxy-formation models founded in the largest N-body simulations which will be undertaken over the next 10 years.

By targetting this survey programme on the SWIRE, GOODS, COSMOS, and UKIDSS UDS fields, its long-term legacy value resulting from ever-improving multi-frequency follow-up is assured. Through this SCUBA2 survey, UK, Canadian and Dutch astronomers will be in a unique position to exploit the existing and forthcoming public Spitzer, HST, UKIRT/WFCAM, CFHT, VISTA, VST, VLA, Chandra, and XMM data in these fields to the full. Our consortium is also ideally placed to finalise the design of Herschel Guaranteed Time and Open Time programmes to observe these same fields to useful depth, and bridge the wavelength gap between Spitzer and SCUBA2. VLT, Gemini and Subaru follow-up spectroscopy will also inevitably be conducted in these fields over the coming years, allowing the refinement and reanalysis of the SCUBA2 dataset. Finally, the SCUBA2 survey proposed here will also provide the primary source of high-redshift galaxies selected for detailed follow-up with ALMA and JWST.

7 Management and Resourcing

The survey will be managed by a consortium of scientists formed for that purpose. The duties of the consortium are:

> **to provide scientific oversight** and ensure that the survey's detailed design and implementation meet the scientific goals described in this proposal,
>
> **to staff the telescope** during the course of the survey, and
>
> **to reduce the data** and provide a coherent set of well-documented products, as described below, to an archive centre for prompt public release.

The 'governing council' will be the four signatories of the letter of intent, James Dunlop, Mark Halpern, Ian Smail, and Paul Van Der Werf

Membership in the survey consortium is open to all scientists employed in a JCMT partner country (ie the UK, Canada, the Netherlands plus JAC staff) who agree to help observe and to abide by the consortium's publication policy. It will remain open until actual data collection begins. Exceptions will be decided case by case by the governing council, and the expectation is that new students joining a group and new faculty in a partner country will be welcome.

Each institution is responsible for staffing the telescope for a time proportional its consortium membership, and will choose a representative to liase with the council to manage this duty.

A written **publication policy** will be drafted shortly by the signatories of this proposal. Its main features have already been agreed to.

> The data of this survey, and most data products derived from them, belong to the consortium as a whole for the data collection period plus twelve months, or until publication of results based on the data, whichever is sooner. Thereafter data and products are released to the world. Explicitly, the data from the initial two year survey will be made public on a rapid schedule.
>
> Any member who wishes to write a paper or propose for telescope time based on consortium data must invite other all members of the consortium to join in at the outset. A reasonable effort will be made to avoid duplication of effort and to protect graduate student projects.
>
> Publications (which includes talks) based on proprietary data are publications by the consortium and their contents will be vetted in advance to assure reliability.

Data Archiving The consortium is responsible to provide aid in establishing a high-quality data archive by the end of three years and to assure that it is kept current past the end of the full survey. The archive will include observation log files, calibrated source lists, signal and noise maps, pixel covariance functions and other reduced data. In co-operation with the archive centre, the consortium will also provide the software tools to read all the data products. The preference is to provide source code for as much of the consortium software as is practical. The consortium will make an effort to respond to reasonable requests for additional data products, releasing material through the archive centre rather than individually to the requester.

8 Non-partner country co-Is

There are five scientists who have added essential skills to the survey team and made valuable contributions to the preparation of this proposal.

Colin Borys (CalTech, USA) is a recognized world leader in SCUBA data reduction. He has written independent map making and source extraction pipelines which are in use by the SHADES collaboration, of which he is a member. Through his role as a SHARCII staff scientist he has played an important role in assuring that the team developing the SCUBA2 scanning strategy and data reduction pipeline are aware of lessons learned recently at the CSO. Colin has played a prominent role in the discussions within Canada which helped formulate survey goals.[Colin has accepted a position in Canada before data collection begins.]

Itziar Aretxaga and **David Hughes** (INAOE, Mexico) are highly-respected sub-mm astronomers who have developed a suite of models which allow estimates of galaxy z based on photometric data alone. David has performed some of the most influential measurements made with SCUBA and has taken an active part in developing this survey proposal. In addition, these two scientists are an important part of the effort to build the Large Millimetre-wave Telescope (LMT).

Kirsten Knudsen (MPIFA, Germany) obtained her PhD in 2004 on the thesis 'Deep sub-mm observations of faint dusty galaxies', analysing a large SCUBA survey of gravitationally lensing clusters. She is a recognised expert in sub-mm observations, data reduction and source extraction, and has valuable experience in handling large and complex datasets in a coherent way. Her expertise and effort will be invaluable for the SCUBA2 survey programme.

Eelco van Kampen (Austria) is an astronomer with expertise in the creation of semi-numerical models of galaxy formation. He has been a productive and constructive member of SHADES, producing and analysing synthetic SCUBA maps for a variety of assumed galaxy-formation models. He is also a moderately experienced sub-mm observer. Most recently he performed a series of simulations specifically tailored to determining the size of SCUBA2 survey required to measure the clustering properties of the sub-mm population.

Several Co-investigators have accepted positions at institutions located in partner countries effective July 2005 or sooner and have signed up to this survey as part of their research activity at their future post. They are listed as affiliated with the partner institution. (Examples are Ed Chapin and Catherine Heymans).