RevMexAA (Serie de Conferencias), **35**, 182–187 (2009)

WIDE EXTRAGALACTIC (SUB-)MILLIMETER SURVEYS WITH SCUBA AND AZTEC

I. Aretxaga,[1] D. H. Hughes,[1] and the SHADES and AzTEC/ASTE collaborations

RESUMEN

Presentamos el estado actual del conocimiento sobre la población de galaxias (sub-)milimétricas, derivado de grandes prospecciones del cielo, como SHADES, el censo de medio grado cuadrado de la cámara SCUBA, y el estado de la nueva generación de censos levantados con la cámara AzTEC, que ha cubierto hasta el momento más de dos grados cuadrados del cielo a 1.1 mm.

ABSTRACT

We summarize the present status of our knowledge of the millimeter galaxy population derived from extensive (sub-) millimeter extragalactic surveys like the SCUBA HAlf Degree Survey (SHADES), and the current status of the next generation of surveys traced with the AzTEC camera, that has, so far, surveyed more than 2 degrees at 1.1 mm wavelengths.

Key Words: galaxies: evolution — infrared: galaxies — submillimeter — surveys

1. INTRODUCTION

Observational evidence suggests that much of the on-going star-formation in the universe takes place in a heavily-obscured interstellar medium. Rest-frame far-infrared (FIR) to mm wavelength observations provide a "transparent" view into the cores of star-forming molecular clouds, and therefore these data have the ability to detect violent star formation in dusty and gas-rich galaxies which might be "missed" in surveys conducted at rest-frame optical-UV wavelengths. Furthermore, due to the strong negative k-correction (e.g. Blain et al. 2002), sub-mm and mm wavelength observations are able to trace the evolution of star formation in dusty galaxies throughout a large volume of the high-z universe (in principle, with as much ease at $z > 8$ as at $z \sim 1$). Given this, it is possible to test whether sub-mm galaxies represent the rapid formation of massive elliptical systems in a single violent collapse of material in the highest-density peaks of the underlying large-scale matter distribution, or whether they built over a longer period from the continuous merging of lower-mass systems with much more modest rates of star formation. Eventually, sensitive and high-resolution interferometric imaging surveys with instruments like ALMA will provide a more dramatic and precise description of the manner in which massive galaxies form. In the meantime, however, the source-counts, redshift distribution and large-scale clustering information obtained from the current generation of mm surveys are providing valuable statistical studies that can test competing galaxy formation models.

[1]Instituto Nacional de Astrofísica, Óptica y Electrónica, Apdo. Postal 51 y 216, Puebla, Pue., México (itziar@inaoep.mx).

2. SHADES RESULTS

The SCUBA HAlf Degree Survey (SHADES, Mortier et al. 2005) was originally designed with the aim of characterizing the star-formation history (Hughes et al. 2002) and clustering properties (van Kampen et al. 2005) of the bright-end of the luminous dust-enshrouded high-redshift galaxy population. To achieve these goals SHADES mapped two regions of the sky centered on the Lockman Hole East (LH) and Subaru XMM-Newton Deep Field (SXDF) with the Submillimetre Common-User Bolometer Array (SCUBA, Holland et al. 1999) at the James Clerk Maxwell Telescope (JCMT). With a proposed 1σ sensitivity of 2 mJy at 850μm, the complete survey was predicted to identify a statistically robust sample of ~ 200 galaxies, with sufficient radio to FIR ancillary data to help identify optical/IR counterparts and derive spectroscopic/photometric redshifts. This redshift information is essential for determining the star formation and clustering properties for the whole population of ultraluminous dust-enshrouded galaxies. SCUBA was decommissioned in mid-2005 having covered only $\sim$ 40 per cent of the originally-proposed area. The complete 1800 sq. arcmins SHADES area, as originally designed towards the LH and the SXDF was surveyed at the JCMT in late 2005 to early 2006 at 1.1 mm with the Aztronomical Thermal Emission

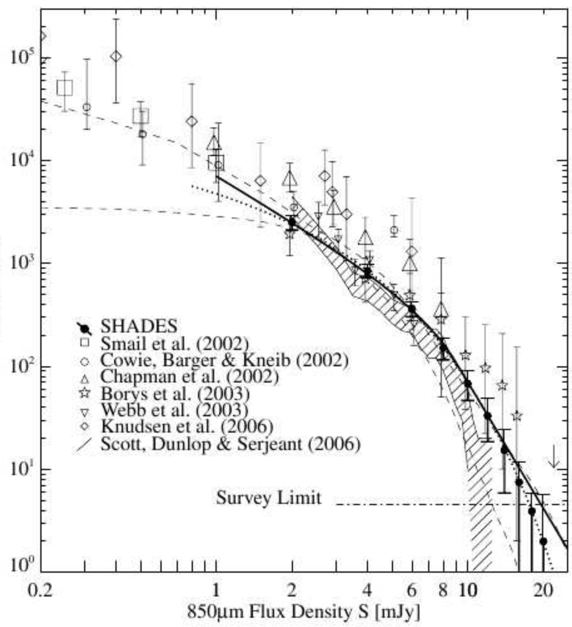

Fig. 1. Number counts derived from SHADES and a comparison with previous smaller-area surveys (taken from Coppin et al. 2006). A broken power-law (solid line) or Schechter function (dotted line) provide good fits to the measured number density of sources.

Camera (AzTEC, Wilson et al. 2008). AzTEC is an instrument ultimately destined for the 50 m Large Millimetre Telescope (LMT, Serrano et al. 2006). The SHADES/AzTEC data is still under analysis.

2.1. *Number counts*

The SCUBA maps cover 720 arcmin^2 with a rms noise level of about 2 mJy at 850μm and have revealed 120 sub-mm galaxies. The SCUBA/SHADES number counts (Coppin et al. 2006; see Figure 1) show, as was known from previous smaller-area surveys (Scott et al. 2002), that significant cosmic evolution is necessary in the sub-mm galaxy (SMG) population if the local 60-μm FIR luminosity function is to be adopted as the local reference to the SMG population. Often, luminosity evolution of the form $(1+z)^3$ up to $z \sim 2$ is invoked. Since precise luminosity functions have not yet been derived it is still unclear if density and/or luminosity evolution dominates. The number counts are better fit with a broken power law or a Schechter function than with a single power law. The SHADES data show that a break is required at ~ 8 mJy at 850μm , although the position of the break is still not well constrained. The 850μm survey complete down to 3 mJy resolves 20–30 per cent of the far-infrared background into point sources.

2.2. *Counterparts to SMGs*

SCUBA is capable of providing only approximate positions for SMGs, given the FWHM 15″ beam resolution at 850μm. To refine positions and find robust multi-wavelength counterparts for large catalogs of sub-mm sources we frequently rely on radio observations. There is a tight correlation between radio-continuum emission, dominated by synchrotron radiation from supernova remnants, and thermal emission from warm dust heated by young stars (Helou et al. 1985). Hence we can use the radio emission as a high-resolution proxy for the rest-frame FIR emission observed in the sub-mm (Ivison et al. 1998). However, since radio observations suffer from a positive k-correction, there is potential for missing the highest-z sources (Aretxaga et al. 2003; Valiante et al. 2007). The SHADES areas have been covered with deep ($S_{1.4\mathrm{GHz}}$ 5–10μJy) Very Large Array (VLA) observations, providing radio-counterparts for 58% of the SHADES sources (Ivison et al. 2007), with an accepted probability of random association between sub-mm and radio objects of $P < 0.05$. Furthermore 17% of these associations are not unique, since one or more possible radio-counterparts exist for a single sub-mm position. Mid-IR imaging with Spitzer has also proved useful for refining lower-z positions (e.g. Egami et al. 2004; Pope et al. 2006), albeit with an uncertain connection to bolometric luminosity. Submillimeter Array (SMA) detections of SMGs, however, indicate that mid-IR observations do not necessarily identify the correct counterparts (Younger et al. 2007).

2.3. *Redshift distribution*

Using these radio observations and other FIR/sub-mm/mm and radio photometry that have been previously acquired in the SHADES fields, photometric redshifts were obtained for 60% of the SHADES sample (Aretxaga et al. 2007). An rms accuracy ranging from $\Delta z \approx 0.3$ to 0.8 is achieved when using the most complete FIR-mm-radio photometry or only 2-band photometric redshift estimates. The redshift distribution of SMGs, for the majority of sources derived from at least two photometric bands, peaks at $z \approx 2.4$ and has a near-Gaussian distribution with 50 per cent (interquartile range) of sources at $z = 1.8$ to 3.1 (see Figure 2). The photometric redshift distribution of the radio-detected SMGs is qualitatively similar to the optical spectroscopic redshift distribution published by Chapman et al. (2003, 2005), who followed-up a sample of SMGs with radio and optical/IR counterparts derived from various surveys. Our calculations do not support the existence of a substantial

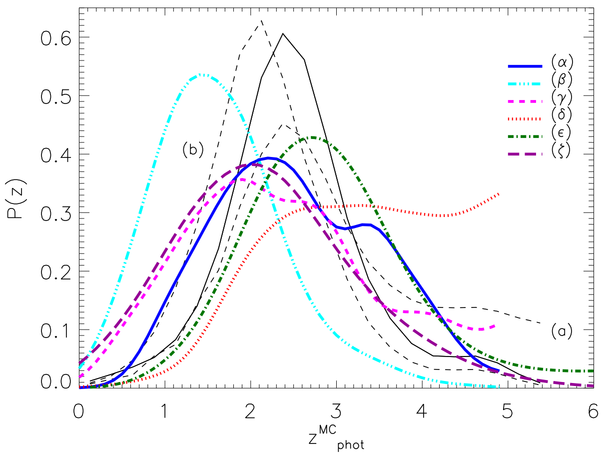

Fig. 2. Probability density of the combined redshift distribution of SHADES galaxies (Aretxaga et al. 2007), in a thin black solid-line for those galaxies with at least 2-band photometry, and thin dashed-lines (a and b) for the combination of these with the rest of sources. These distributions are compared with the redshift distributions for six galaxy formation models (thick lines), convolved with a Gaussian error of width $\sigma_z = 0.4$ to provide representative redshift-uncertainties.

low-redshift ($z < 1.5$) tail within the luminous sub-mm radio-detected population sampled by SHADES. This distribution also suggests that only a modest fraction of SMGs could be hiding in the optical redshift desert at $z \approx 1.5 - 1.8$ during spectroscopic searches for SHADES sources with robust radio counterparts.

We find a statistically-significant difference between the measured redshift distributions in the two SHADES fields; the SXDF peaking at a slightly lower redshift (median $z \approx 2.2$) than the LH (median $z \approx 2.7$). We partly attribute these differences to different noise-properties of the radio observations for the two fields. We demonstrate, however, that there could also be substantial field-to-field variations that are consistent with the measured differences in the redshift distributions ($\delta z \approx 0.25 - 0.55$), and hence, that the incomplete area observed by SHADES with SCUBA, despite being the largest sub-mm survey to date, may still be too small to fully characterize the bright sub-mm galaxy population.

The 42% fraction of SHADES sources with no radio counterparts, only have detections at 850μm, and thus, their redshift distributions are very broad, often only providing lower limits. We incorporate these sources in different ways into the total redshift distribution of the population of SMGs: (a) with equal probability between their calculated lower 90% confidence limits and $z = 5$; and alternatively, (b) between their lower limits and $z = 2$, or only at their lower redshift-limits in the cases that these lie at $z > 2$, in order to compare our findings with an array of models (Figure 2).

2.4. *Comparison to models for galaxy formation and contribution to the density of star formation*

We compare the redshift distribution measured in the SHADES fields with those predicted by an array of galaxy formation models (Figure 2), all of which can reproduce the number counts of Figure 1. A Kolmogorov-Smirnov test suggests that only model (ϵ), a semi-analytical model for the joint formation of QSOs and spheroids (Granato et al. 2004) is close to being formally acceptable, with an 87% probability for the model to agree with the measured probability density distribution that includes SHADES sources with and without radio-detections, according to solution (a) of distributing the sources with no radio counterparts. With only a small shift ($\delta z \sim -0.3$) in the distribution, consistent with SHADES-like area field-to-field variations, model (ϵ) also qualitatively reproduces the photometric-redshift distribution of the radio-detected SHADES galaxies.

If sources detected only at 850μm are also introduced into the redshift probability-density, with other priors than those illustrated here, then the hydrodynamical model of Muanwong et al. (2002) and the phenomenological model of van Kampen et al. (2005) could also be in agreement with the observations (models α and γ) (see Figure 3). These compatible models, which are physically quite distinct, predict different clustering properties for the SHADES galaxies that could allow further discrimination between them (van Kampen et al. 2005).

The co-moving volume of these galaxies, which are derived to have a SFR$\sim 200 - 2000\ M_\odot$ yr^{-1} is 10^{-5} Mpc^{-3}, in good agreement with the local density of first-rank elliptical galaxies.

The bright SHADES galaxies contribute to the SFR density of the Universe with ~ 0.01 to $0.03\ M_\odot$ yr^{-1} Mpc^{-3} in the redshift interval $1 < z < 5$, and reach the levels of the dust-uncorrected Lyman Break Galaxy (LBG) population (Giavalisco et al. 2004). The SFR density of dust-enshrouded starburst galaxies traced by ultraluminous SHADES galaxies, completing the luminosity function to lower luminosity galaxies, is estimated to be a factor of 2 larger. This is still a factor of 1.2 to 2 lower than the optical/UV-selected starburst galaxy samples that include the latest dust-correction estimates

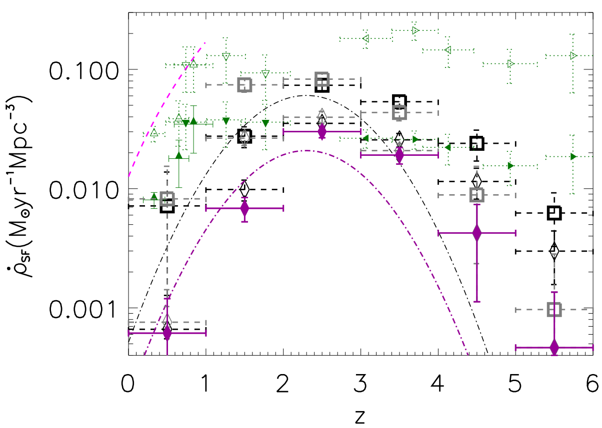

Fig. 3. Evolution of the global star formation rate density (SFRD) for different samples of galaxies (Aretxaga et al. 2007). We show the SFRD for radio-detected SHADES sources (solid diamonds) and for all SHADES galaxies, considering both the radio-detected and radio-undetected sources (open diamonds). The redshift probability distributions for the radio-undetected sources have been assumed to be flat between their lower redshift-limits and $z = 2$ (grey open diamonds) and $z = 5$ (black open diamonds). The redshift error-bars indicate the width of the redshift bins. The error-bars in $\dot{\rho}_{\rm SF}$ are a combination of the uncertainty in the photometry, the recovery of the luminosity of each source due to SED differences, and the uncertainty in redshift that divides the contribution of sources across several redshift bins. The empty-square grey/black symbols represent the SFRD traced by ultraluminous 850μm-selected starbursts, by correcting the SFRDs derived for SHADES galaxies via the completion of the IRAS 60μm luminosity function with pure luminosity evolution up to $z = 2$. The (pink) dashed-line shows the SFRD inferred from 24μm-selected luminous and ultraluminous infrared galaxies (Le Floc'h et al. 2005), which follow a similar luminosity evolution to that presented here for the SHADES galaxies. The (purple) thick dash-dotted line shows the SFRD for the sample of SCUBA galaxies from Chapman et al. (2005). The thin dash-dotted line, which is a factor of ~ 3 higher, is an estimation of the contribution of 850μm-selected galaxies down to the ~ 1 mJy level. The SFRDs for optical/UV-selected starbursts are shown as small triangles, and are taken from several catalogs. The optical/UV data are shown with and without corrections for dust-obscuration as empty and solid triangles respectively, and all data have been homogenized to the same set of parameters and corrected to complete a Schechter luminosity-function (Giavalisco et al. 2004).

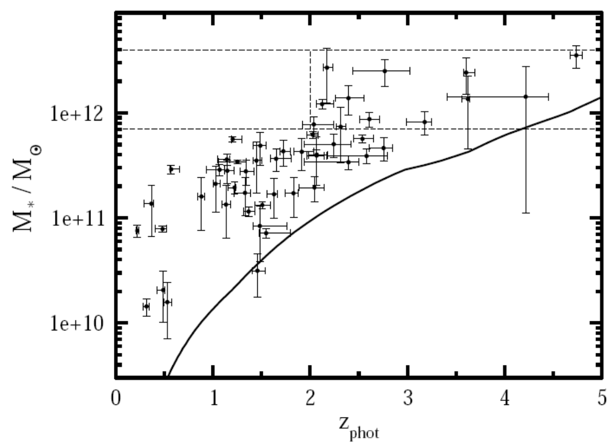

Fig. 4. Mass estimates of SHADES galaxies (from Dye et al. 2008). The solid line marks the survey limit. Notice the lack of objects at $z < 2$, $M > 7 \times 10^{11} M_{\odot}$.

(see Figure 4). The current SHADES survey and complementary multiwavelength data, however, cannot characterize the bulk of the rest-frame FIR emission arising from these lower luminosity galaxies due to a lack of sensitivity and high confusion-limit. A more statistically-complete measurement of the universal history of star-formation from powerful dusty, optically-obscured galaxies awaits the commissioning of future large-aperture single-dish millimetre telescopes. The LMT, for example, will target suitable extragalactic fields that have the necessary multi-wavelength ancillary data. LMT key projects will combine confusion-limited surveys with shallower wide-area surveys to resolve 100% of the mm-wavelength background, detecting 10^5 to 10^7 galaxies.

2.5. *Star formation history of SHADES galaxies*

Using the optical/IR counterparts, derived from radio positions, star formation histories can be determined for each galaxy (Dye et al. 2008). The analysis carried out with the deep photometry in the Lockman Hole, using data at $BRIzK$, 3.6/4.5/5.8/8.0μm, shows that SCUBA sources form a significant fraction of their stars in an early period of star formation and that most of the remainder forms in a shorter more intense burst at the epoch at which it is observed. This is consistent with the findings of Borys et al. (2005) who concluded that the average SCUBA source already has a massive population in place by $z = 2.2$. This trend does not vary significantly with source redshift but the exact ratio of early to late mass is quite sensitive to the way dust extinction is treated in the modeling.

The SED fittings show that the observed bursts of star formation creates 15 to 65% of the total stellar mass of the galaxy. The most recent 5–15% of the average history of SCUBA sources (220 to 660 Myr on average) shows the highest rates of star formation ever experienced by the source. Coupled with the fact that ~ 1 per cent of bright field galaxies selected by $L_\star + 2$ mag $< L(\mathrm{optical}) < L_\star - 1$ mag over the redshift range $0 < z < 3$ appear to be SCUBA galaxies, it can be estimated that 1/5 and 1/15 of these galaxies will at some point in their lifetime experience a similar energetic burst of star formation.

Both in the LH and the SXDF fields (Dye et al. 2008; Clements et al. 2008; see Figure 4) there is a distinct lack of SHADES sources in the redshift interval $0 < z < 2$ with stellar masses $> 7 \times 10^{11}\ M_\odot$, while sources of that mass and above can be found at $2 < z < 5$. This is clear evidence in favour of a downsizing scenario, where star formation shifts to progressively smaller systems as the Universe ages.

3. AZTEC SURVEYS

AzTEC is a mm-wavelength bolometric camera utilizing 144 silicon nitride micromesh detectors, and has been operational since 2005 (Wilson et al. 2008). The first scientific campaign with AzTEC was made at the 15 m JCMT in the winter of 2005–2006. The second and third campaign are being conducted on the Japanese 10 m Atacama Submillimeter Telescope Experiment (ASTE), during June to November in 2007 and 2008. AzTEC on the JCMT and ASTE has a mapping speed which is roughly 20 times faster than SCUBA. Eventually AzTEC will be installed on the LMT providing a further significant increase in mapping speed (a factor of ~ 30), or equivalent to SCUBA-2 on the JCMT.

Collectively, in the 2005–2007 campaign AzTEC mapped about 1 sq. degree of the extragalactic sky to an rms of 0.7 to 1.7 mJy at 1.1 mm (e.g. Scott et al. 2008; Perera et al. 2008) with high uniformity in the noise properties across the fields due to the raster-scan observations mode employed — see Figure 5. Most of the observations were carried out towards blank-fields (GOODS-N, COSMOS, SXDF, LH), but the project also targeted two biased fields towards potential proto-clusters.

3.1. *COSMOS*

Analysis of the 2005–2006 campaign continues, but the AzTEC data towards the COSMOS field, for instance, has already provided robust samples of bright galaxies that have been followed-up with the Sub-Millimeter Array (SMA), in which 100% of the AzTEC sources have been detected by SMA as single sources of size < 12 kpc ($\phi < 1''.2$), $L_{\mathrm{IR}} \sim 3 - 5 \times 10^{13}\ L_\odot$, or SFR $\sim 1000 - 5000 M_\odot\ \mathrm{yr}^{-1}$ (Younger et al. 2007). The sources are all coincident with Spitzer/IRAC detections, but not always with 24μm counterparts, which highlights the problem of possible misidentifications in past surveys that did not benefit from precise sub-mm interferometry to guide counterpart identification (Younger et al. 2007; Yun et al. 2008). All radio-faint AzTEC sources have photometric redshifts which place them at $z > 3$, with physical scales similar to local-ULIRGs, albeit more luminous than their local analogs. A high-z tail for the mm-galaxy population that extends beyond that depicted in Figure 2 is, thus, still a possibility.

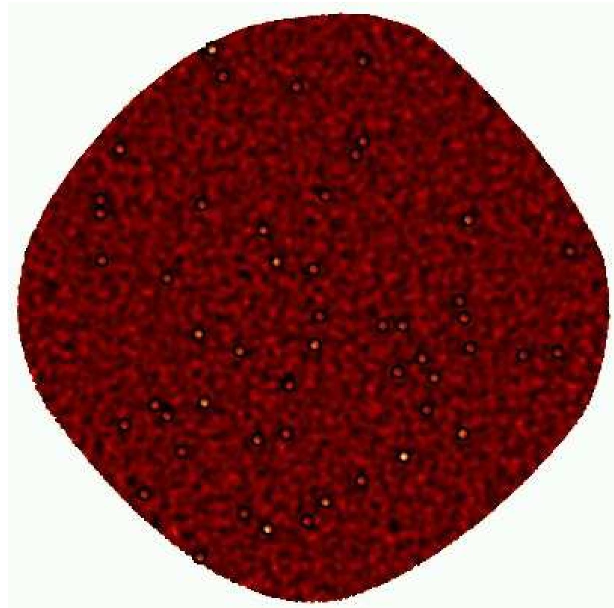

Fig. 5. AzTEC map towards a 0.15 sq. degree portion of the COSMOS field (Scott et al. 2008). The bright mm galaxies detected at S/N$>$ 3.5 are marked with circles.

The portion of the COSMOS field mapped by AzTEC shows a $\sim 3\sigma$ over-density of robust mm-galaxy detections when compared to other blank-fields like SHADES (Austermann et al. 2008). We find that the over-density and spatial correlation to the lower-redshift ($z < 1.1$) optical-IR galaxy density are consistent with lensing of a background mm population by foreground mass structures along the line of sight, most prominently those found at $z \sim 0.6$. The positions of AzTEC sources, however, are only weakly correlated with the weak-lensing maps of COSMOS, suggesting that the dominant sources of correlation are individual galaxies and the more tenuous filamentary structures in the region and not the massive and compact clusters. These results highlight the important roles cosmic variance and large-scale structure can play in the study of mm galaxies, and once again, underlines the fact that the surveys carried out to date are still too small to fully characterize the population. We will need the higher-speed maps of AzTEC on the LMT, or of SCUBA-2 in the JCMT to accomplish this task.

3.2. *ACES*

The strong clustering and bias of elliptical galaxies to over-dense regions in the local Universe suggests that measuring the distribution of massive proto-ellipticals, caught in the act of formation, offers an opportunity to find rapidly evolving proto-clusters. The rapid conversion of molecular gas into stars has been shown to be an extremely luminous, heavily-obscured event in the high-z Universe, providing mm-wavelength instruments with the capability to reveal powerful bursts of activity via continuum and spectral line measurements. During the last 2 years we have been conducting the AzTEC Cluster Evolution Survey (ACES), a 1.1 mm survey of galaxy formation towards > 30 clusters, proto-clusters (traced by other galaxy populations, like LBGs or Lyman-α emitters), and large-scale environments of high-z radio-galaxies (HzRGs) with the AzTEC camera mounted first on the 15 m JCMT, as a pilot project with imaging towards the HzRG 4C41.17, and now on the 10 m ASTE with a larger sample of environments. ACES has been allocated 500 hrs in 2007 and 500 hrs in 2008 to explore the connections between mm galaxies and the cluster/proto-cluster environments.

4C41.17 was selected because of empirical data suggesting it is an extremely massive galaxy that resides in a deep gravitational potential traced by over-densities in different galaxy populations (Stevens et al. 2003). The AzTEC 1.1 mm survey towards 4C41.17, covering 300 sq. arcmin has detected and spatially-resolved a high over-density (factor 5) of the most ultraluminous massive starburst galaxies (with $L_{\rm FIR} > 5 \times 10^{12} L_{\odot}$ or SFR $> 500 M_{\odot}$ yr^{-1}), compared to the surface-density of lower-redshift blank-field sub-mm galaxies. A natural interpretation of the over-density is that they are proto-ellipticals tracing the distribution of massive dark-matter (DM) haloes within a large ($\sim 6 \times 6$ Mpc^2) proto-cluster structure undergoing assembly at $z \sim 3.8$. Proving, however, the physical association of these massive starbursts with the environments of HzRGs, and not with the blank-field population, for which 50% of the population lies at $1.9 < z < 2.9$, remains one of the outstanding problems for galaxy formation in biased regions.

ACES covers 4 bins of redshift space between $0 < z < 5$. In addition to observations of the environments of HzRGs at $z > 1.5$, the selection of lower-redshift massive nearby clusters is based on X-ray brightness, or on their location in the survey-regions of the Atacama Cosmology Telescope (ACT). AzTEC will produce a catalog of $\sim$ 1000 high-z galaxies in the southern hemisphere and equatorial regions, to combine with the deep CMB surveys by ACT (which will identify clusters via the Sunyaev-Zel'dovich effect), and BLAST and ALMA observations.

Apart from the ACES project, AzTEC is also being utilized to map larger blank-field areas, like GOODS-S, South Ecliptic Pole and others, and also has a range of Galactic projects to find proto-planetary disks around young stars.

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