Galaxies in 3D across the Universe
Proceedings IAU Symposium No. 309, 2014
B. L. Ziegler, F. Combes, H. Dannerbauer, M. Verdugo, eds.

doi:10.1017/S174392131400982X

An Excess of Dusty Starbursts at $z = 2.2$

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Abstract. Searching for massive, dusty starbursts offers the great opportunity to trace galaxy overdensities and thus the cosmic web in the distant universe. I will present our APEX-LABOCA 870 μm imaging of the protocluster field of the radio galaxy MRC1138−262 — the so-called Spiderweb Galaxy — at z = 2.16, uncovering a large number of so-called submm galaxies (SMGs). The number counts already indicate an excess of SMGs compared to blank fields. Based on an exquisite multi-wavelength dataset, I will show that a large fraction of these massive, dusty starbursts are physically associated with the protocluster at z = 2.16. Finally, I will discuss both the properties of this starburst overdensity and their individual members.

Keywords. galaxies: individual: MRC1138−262 — galaxies: clusters: individual: MRC1138−262 — galaxies: high redshift — cosmology: observations — Infrared: galaxies — submillimeter: galaxies

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1. Motivation

Understanding when and how did present-day galaxy cluster form at high redshifts have been the science driver for the extensive search, especially at optical and near-infrared wavelengths, for protoclusters of galaxies in the distant universe in the past decade. Powerful high-redshift radio galaxies (HzRG; see for more details the review by Miley & De Breuck 2008) are considered to be the most promising signposts of massive clusters in formation. The VLT survey of Lyα emitters (LAEs), Hα emitters (HAEs), Lyman Break Galaxies and Extremely Red Objects in seven fields containing radio galaxies at redshifts up to 5.2 provided in almost all cases evidence for galaxy overdensities associated with the central galaxy (e.g., Kurk *et al.* 2000, 2004ab; Pentericci *et al.* 2000; Venemans *et al.* 2007; Overzier *et al.* 2006; Miley *et al.* 2004).

2. Dusty Star Forming Galaxies

However, we note that these optical/NIR techniques mainly trace (rather low-mass) galaxies with unobscured star formation, making up only 50% of the cosmic star formation activity (Dole *et al.* 2006). In the last decade (sub)millimeter surveys have revolutionized our understanding of the formation and evolution of galaxies, by revealing an unexpected population of high-redshift, dust-obscured galaxies which are forming stars at a tremendous rate. Submm galaxies (SMGs; see the review by Blain *et al.* 2002), first discovered by Smail *et al.*, (1997), have intense star formation, with rates of a few hundred to several thousands solar masses per year. These dusty starbursts are massive (e.g., Genzel *et al.* 2003; Greve *et al.* 2005), most probably the precursors of present-day ellipticals (e.g., Ivison *et al.* 2013) and excellent tracers of mass density peaks and thus of protoclusters. Studying SMGs offer us an unique opportunity to explore episodes of bursting star formation in a critical epoch of galaxy formation.

3. Galaxy Clusters

From the collapse of the first highest density peaks of matter density fluctuations (after inflation) arose galaxy clusters. These are the nodes of the cosmic web, formed by the inhomogeneously assembled mass along filaments. As the first structures to be collapsed, galaxy clusters have to be seen as the earliest starting fingerprint of galaxy formation and evolution. These structures grew hierarchically through the merging and accretion of smaller units of galaxy halos. These high density regions provide a remarkable environment for investigating the physical processes responsible for the triggering and suppression of star formation and AGN activity. Enhanced star formation activity is observed in large scale structures beyond $z = 1.5$ (Hilton *et al.* 2010; Tran *et al.* 2010). We now know that the wide spread star formation activity (both in the cluster center and the outer parts) is the by-product of the build up of distant clusters whereas local clusters devoid star formation in their centers (e.g., Koyama *et al.* 2010). To summarize, there is strong evidence for star formation being triggered in galaxies that fall into the cluster potential and are affected by the cluster environment, although the details of the physical process are not yet clear. But did this also happen to the most massive galaxies in todays clusters which formed rapidly in the early universe?

A prominent feature of colour-magnitude diagrams of (local) clusters is the red-sequence. Red-sequence galaxies are dominating the core of galaxy clusters and are massive, passively evolving, early-type galaxies. The red-sequence is found in clusters up to $z = 1.5$ (e.g., Rosati *et al.* 2009; Santos *et al.* 2011), and its tightness suggests that they are formed in a short time scale beyond $z = 2$. When and how the progenitors of the red-sequence are formed in clusters is one of the most hotly debated topic. Scenarios for their ancestors include in situ formation or accretion/falling into the cluster potential. SMGs with short time scales of building up the bulk of their stellar mass are promising candidates for being the ancestors of red sequence galaxies.

The limited mapping speed in the (sub)mm wavelength regime (between 870 m and 1.2 mm) does not allow to scan extremely large blank fields in order to find systematically overdensities of SMGs. Only a handful of serendipitous discoveries of single SMGs physically associated to galaxy overdensities traced at other wavelengths (*et al.* Capak *et al.* 2011; Daddi *et al.* 2009; Riechers *et al.* 2010; Walter *et al.* 2012) are known. At larger mm-wavelengths large/all sky surveys such as with the South Pole Telescope or the Planck satellite discover clumps which could be high-z clusters but due to the coarse spatial resolution of these telescopes individual cluster members cannot be detected (see e.g. Clements *et al.* 2014). Targeting a few protocluster fields, and finding overdensities of SMGs in comparison to random fields (e.g., Stevens *et al.* 2003, 2010; De Breuck *et al.* 2004; Greve *et al.* 2007) beyond $z = 1.5$ has already demonstrated the huge potential of submm observations to trace large scale structures. However, in none of these cases the obligatory and time consuming identification work was properly done for the individual sources and presumably cluster members.

These first results imply that a complete census of the cluster members is only possible if source populations selected both from the optical/near-infrared and far-infrared/submm are considered. E.g. the so-called Lyα emitters and Hα emitters are expected to be relatively low, medium mass objects with SFRs between few to hundred solar masses per year whereas dusty starbursts are massive and intense star forming galaxies. Follow-up with Herschel of so-called Planck-clumps (high-z cluster candidates) finds star formation rate densities based on the FIR orders of magnitude higher than in the field (Clements *et al.* 2014) and thus demonstrated the importance of searching for dusty starbursts in known cluster fields selected from optical/near-infrared wavelengths.

4. MRC1138−262

In order to verify the hypothesis that SMGs enable us to reveal overdensities of massive galaxies with intense on-going star formation, we observed the field of a protocluster at $z = 2.16$ with APEX-LABOCA at 870 μm (Dannerbauer *et al.* 2014). This protocluster associated with the high-redshift radio galaxy MRC1138−262 at $z = 2.16$, the so-called Spiderweb Galaxy, is one of the best studied fields so far. Lyα and Hα imaging/spectroscopy of this field reveal an excess of LAEs and HAEs compared to blank fields (Kurk *et al.*, 2000; Pentericci *et al.*, 2000; Kurk *et al.*, 2004a,b; Hatch *et al.*, 2011). The spatial distribution of LAEs and HAEs provides strong evidence that the central galaxy lies in a forming cluster (Pentericci *et al.* 2000; Kurk *et al.* 2000, 2004ab). Two attempts to search for submillimeter overdensities in this field are known. Using SCUBA, Stevens *et al.* (2003) report the (tentative) excess of SMGs, and spatial extension of the submillimeter emission of the HzRG MRC1138−262. However, I note that the field of view of SCUBA has only a diameter of 2 arcmin (~1 Mpc at $z = 2.16$), and thus the reported SMG excess is based on very small numbers. Rigby *et al.* (2014) present Herschel SPIRE observations of a large field (~400 arcmin^2), centered on the HzRG. They report an excess of SPIRE 500 μm sources but found no filamentary structure in the far-infrared as seen in the rest-frame optical (Kurk *et al.* 2004a; Koyama *et al.* 2013). However, in both cases no counterpart identification was attempted for the individual sources. In addition, Valtchanov *et al.* (2013) report the serendipitous discovery of an overdensity of SPIRE sources 7 armin south of the protocluster. Based on the modified blackbody derived redshift distribution, incorporating the color information as well as the SED shape, they conclude that the majority of the 250 μm sources in the overdensity are likely to be at a similar redshift. With the available scarce multi-wavelength data they cannot exclude the attractive possibility that the overdensity is within the same structure as the Spiderweb at $z = 2.2$.

With our 40 hours APEX LABOCA observations, we extended drastically previous SCUBA observations by Stevens *et al.* (2003) focusing on the HzRG and the surrounding region of 2 arcmin diameter. We detected a large number (16) of SMGs down to a 3σ peak flux of 3mJy/beam (Fig, 1), roughly up to a factor four more than expected from the blank field surveys at 870 μmm as e.g. LESS, the LABOCA survey of the Extended Chandra Deep Field South (ECDFS) at these wavelengths (e.g., Weiss *et al.* 2009). This excess is consistent with an excess of Herschel SPIRE 500 μm sources in the same field of the radio galaxy reported by Rigby *et al.* (2014). Based on an exquisite multi-wavelength database, including VLA 1.4 GHz radio and infrared observations, we investigate whether these sources are members of the protocluster structure at $z \approx 2.2$.

Using Herschel PACS+SPIRE and Spitzer MIPS photometry, we derive reliable far-infrared photometric redshifts for all sources. Our VLT ISAAC and SINFONI near-infrared spectra confirm that four of these SMGs have redshifts of $z \approx 2.2$ (Kurk *et al.* in prep.) with consistent FIR-photo-z. We also present evidence that another SMG in this field, earlier detected at 850 μm, has a counterpart exhibiting Hα (HAE229) and CO(1-0) emission at $z = 2.15$ (Emonts *et al.* 2013; Dannerbauer *et al.* in prep.). Including the radio galaxy and two SMGs with FIR-photometric redshifts at z = 2.2, we conclude that at least eight submm sources are part of the protocluster at $z = 2.16$ associated with the radio galaxy MRC1138−262 (see Fig. 1 and 2). Strikingly, these eight sources are concentrated within a region of 2 Mpc (the typical size of clusters in the local universe) and are distributed within the filaments traced by the Hα emitters at $z \approx 2.2$. Thus, as predicted by theories (e.g., De Lucia *et al.* 2004), massive dusty starbursts are indeed tracing the cosmic web. Their location within the filamentary structure would support

https://doi.org/10.1017/S174392131400982X Published online by Cambridge University Press

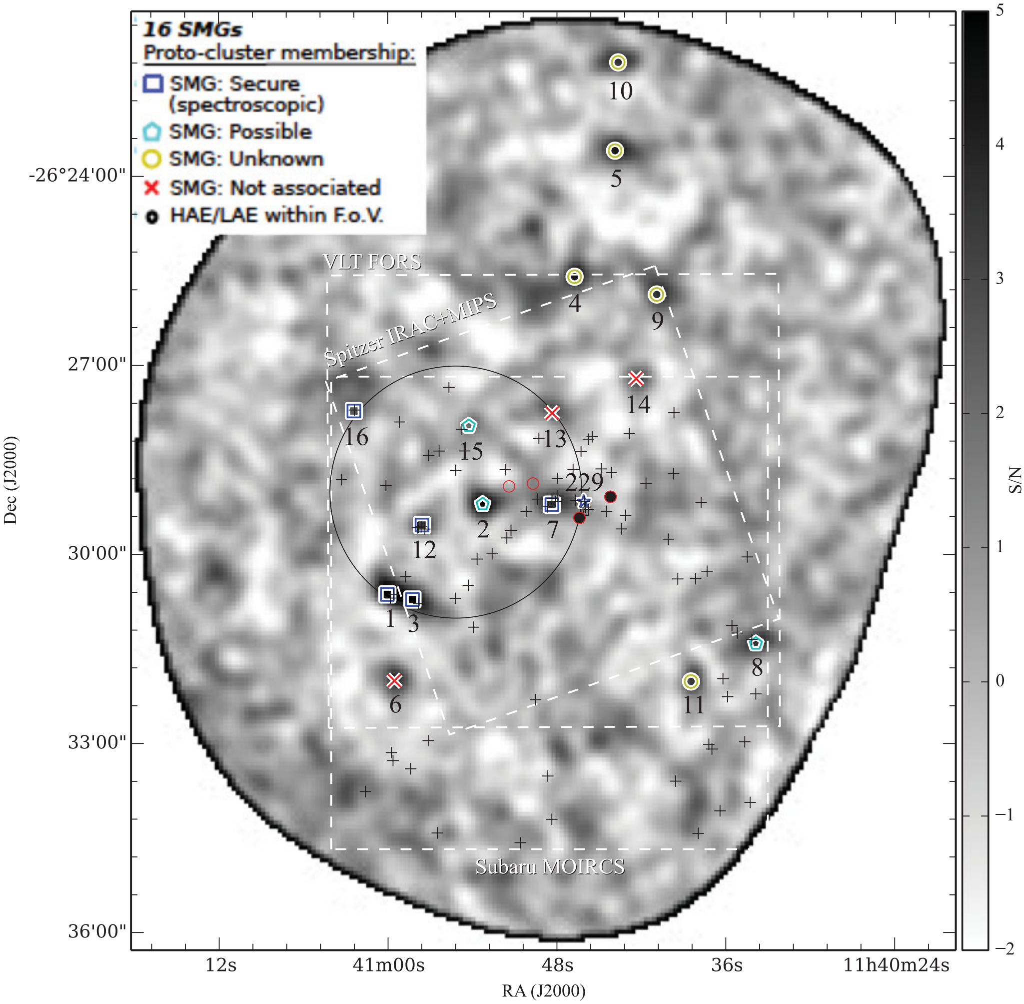

Figure 1. We show the location of 16 SMGs extracted from our LABOCA map of the field of MRC1138 on top of the LABOCA signal-to-noise map (courtesy from Dannerbauer *et al.* 2014). The large circle (solid line) has a diameter of $\sim 240''$ (corresponding to a physical size of 2 Mpc) and shows the region where all seven SMGs with $z = 2.2$ are located. The SMG overdensity is a factor four higher than compared to blank fields (Weiss *et al.* 2009).

the picture that these dusty starbursts are falling into the cluster (center). We even detected SMGs separated between 5 to 10 Mpc from the HzRG, the cluster center, which could trace a further filament (see Fig. 1) but with the current data their membership cannot be verified.

For the 2 Mpc central region, the excess of SMGs is a factor of four higher than the well-known structure of six SMGs at z = 1.99 in GOODS-N distributed over 7x7 Mpc^2 (Blain *et al.* 2004; Chapman *et al.* 2009). Blain *et al.* (2004) report an association of five sources in the HDF-North. All five SMGs have spectroscopically measured redshifts of z = 1.99 (see also Chapman *et al.* 2009). This is the largest blank field association known so far. Chapman *et al.* (2009) report an apparently less significant overdensity of UV-selected galaxies at the same redshift and region of the sky. The protocluster MRC1138−262 at $z = 2.2$ is securely traced by galaxy populations probing different mass

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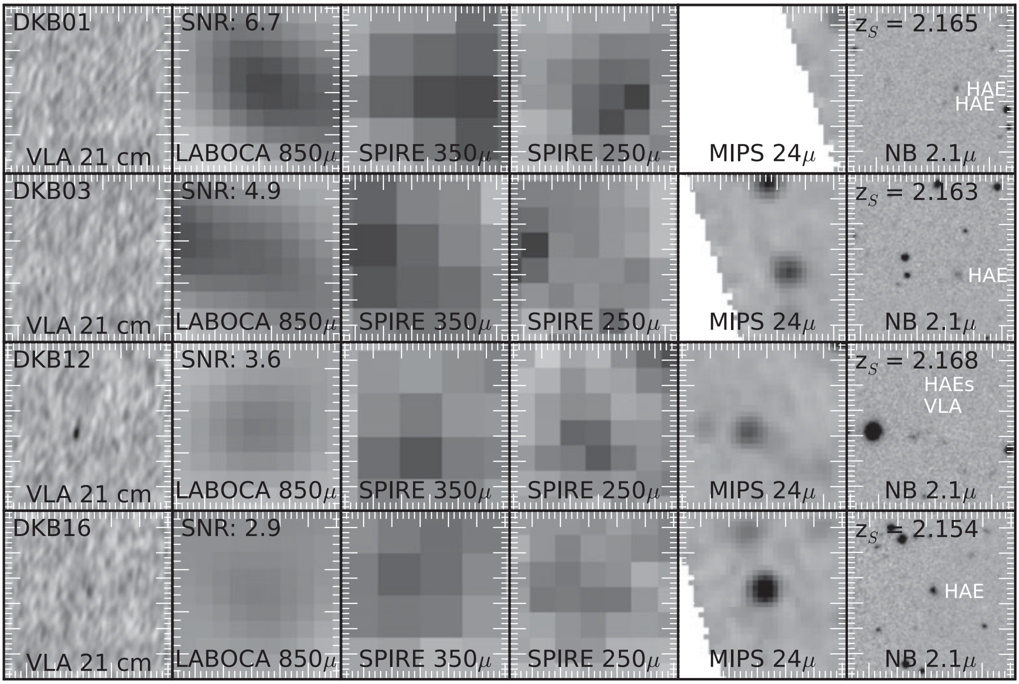

Figure 2. VLA 1.4 GHz image, LABOCA 870 μm, SPIRE 350 μm, SPIRE 250 μm, MIPS 24 μm and MOIRCS Hα images of LABOCA sources. The large white circles represent the size of the LABOCA beam ($\sim$11$''$ diameter). Small white circles are VLA and/or HAE sources.

ranges, star formation and degree of obscuration including LAEs, HAEs and SMGs. The data excludes the cluster membership for three SMGs. For the remaining six SMGs we do not have enough data to make a robust judgement on their membership. We measure a star formation rate density SFRD $\sim$ 1500 M$_\odot$ yr^{-1} Mpc^{-3}, four magnitudes higher compared to the global SFRD at this redshift in the field, similar to results obtained by Clements *et al.* (2014) and thus demonstrating the importance of searching for dusty starbursts in known cluster fields selected from optical/near-infrared wavelengths.

5. Conclusions

Our results demonstrate that submillimeter observations enable us to reveal overdensities of massive, dusty starbursts and is key to complete our census of protocluster member populations. We conclude that systematic and detailed investigations of (proto)clusters in the early universe at submillimeter wavelengths are feasible. Finally, future sensitive subarcsecond resolution observations with mm-interferometers such as ALMA will allow us to complete the characterization of the 16 SMGs discovered by LABOCA.

Acknowledgements

I would like to thank all the scientists coming to our symposium, thus making through their participation this event happening.

https://doi.org/10.1017/S174392131400982X Published online by Cambridge University Press

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