The most luminous, dusty star-forming galaxies at high redshift discovered by Herschel: the ALMA view

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Abstract

Very high redshift galaxies have been discovered by optical and near-infrared deep surveys. However, they are typically not very massive and present star formation rates up to several hundred solar masses per year (Finkelstein et al. 2013, Nature, 502, 524). The Herschel Multi-tiered Extragalactic Survey (HerMES, Oliver et al. 2012, MNRAS, 424, 1614), the largest project that has being carried out with the Herschel Space Observatory, has discovered massive, maximum-starburst galaxies up to a redshift of 6.34 (Riechers et al. 2013, Nature, 496, 329; Dowell et al. 2014, ApJ, 780, 75). The discovery of these dusty star-forming galaxies (DSFGs) at high-z challenges current theoretical models of galaxy formation. We will describe the method we had developed to find these dusty, massive, star forming galaxies at z > 4 based on Herschel/SPIRE colors and present results from multi-wavelength follow-up observations, including recent ALMA cycle 2 spectroscopy.

1 - Introduction

Before the launch of Herschel, the studied populations of Dusty Star Forming Galaxies (DSFGs), peaking around z = 2 - 3 (e.g., Chapman et al. 2005), have already proven challenging to accommodate in hierarchical structure-formation models (e.g., Baugh et al. 2005). However, even models tuned to match these data predict very few at z > 4 (e.g. theory: Guo et al. 2011; Hayward et al. 2013; phenomenology: Gruppioni et al. 2011; Béthermin et al. 2011, 2012). The fundamental issue is that it is difficult to channel gas efficiently and rapidly enough to the center of massive halos by such an early epoch to fuel such extreme starbursts. Major mergers are known to play an important role in the brightest lower-z DSFGs (e.g., Engel et al. 2010), but their rate is expected to decline rapidly at higher-z. The alternative mechanism, cold-gas accretion and quiescent star formation (e.g., Hayward et al. 2013), is expected to be much too inefficient in the most massive halos due to shock heating of the in-falling gas. Prior to Herschel, this picture could not be tested because only a handful of (largely serendipitously discovered) z > 4 DSFGs were known. By selecting a well-defined population of high-z DSFGs, we have been able to confront predictions with data for the first time. Models and interferometric observations indicate most of these targets are not highly magnified.

2 - Selection of high-redshift HerMES galaxies

We select targets based on their Herschel/SPIRE colors, requiring f (250 μm) < f (350 μm) < f (500 μm); given typical DSFG SEDs, this places them at z > 4. The efficacy of this approach has been confirmed with follow-up spectroscopy.

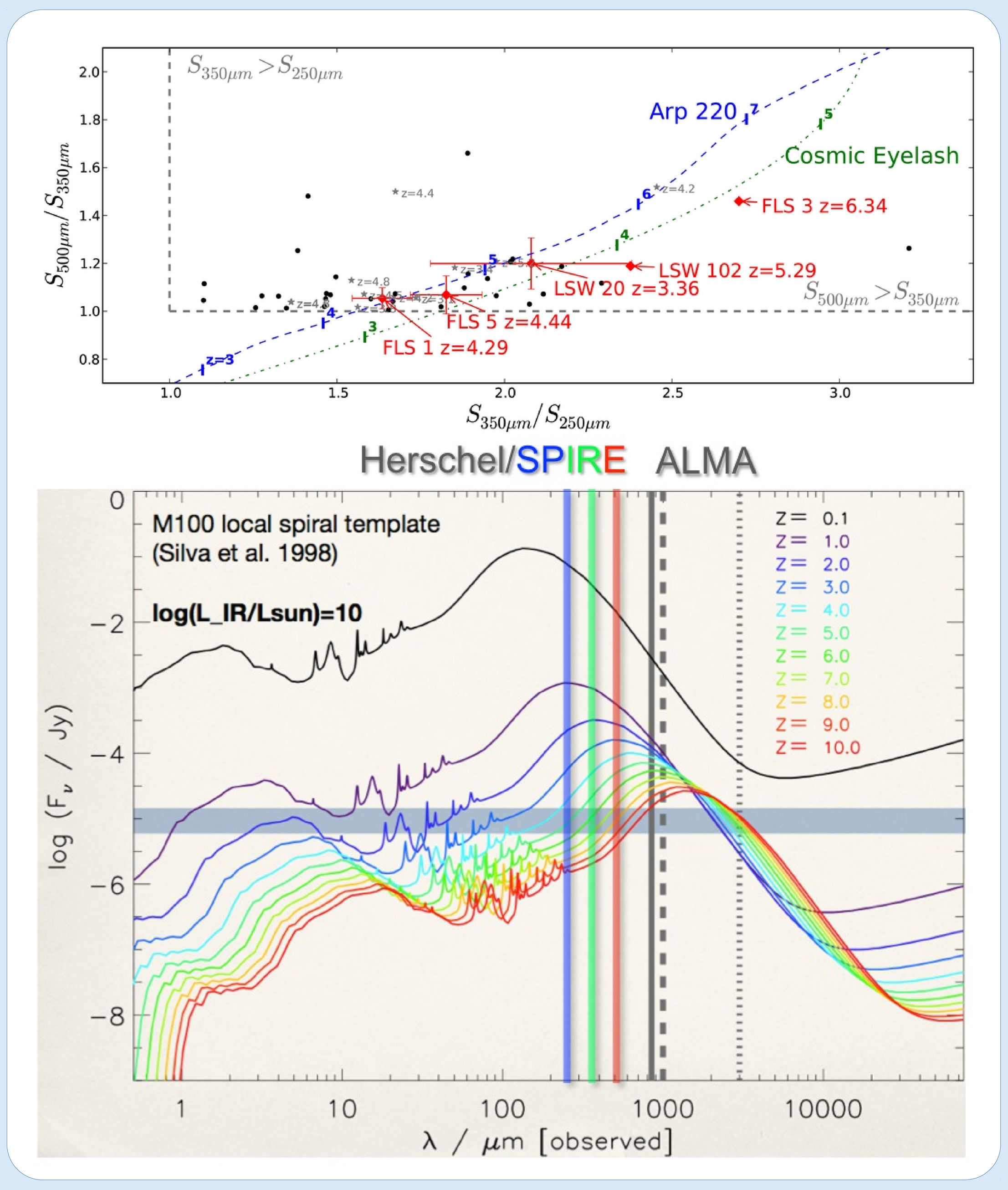

Figure 1. Up: Illustration of where 500 μm-risers lie in the Herschel/SPIRE color ratio plane. The color-color selection used to define the high redshift candidates (grey dashed lines) are shown in comparison with the redshift tracks of the local DSFG Arp220 with tick marks every Δz = 1 from z = 3 – 7 (from Dowell et al. 2014). Down: The peak of the far-IR SED of a dusty galaxy is redshifted to the SPIRE 500 um band and beyond at high redshift.

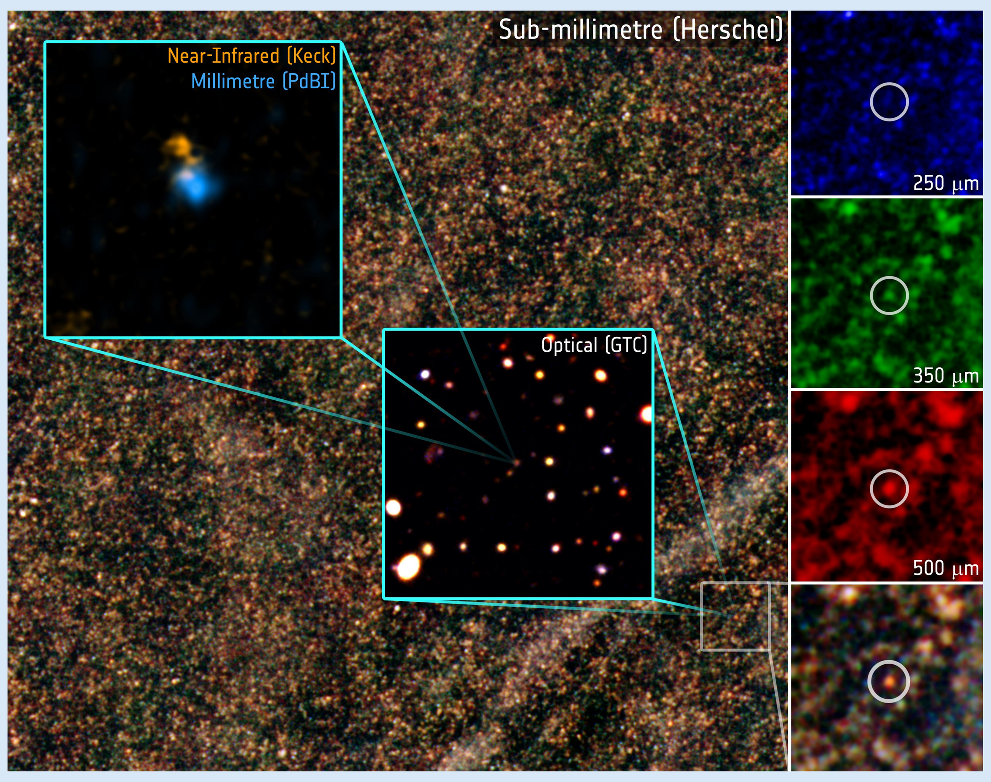

Figure 2. The galaxy HFLS3 appears as a small red dot in the Herschel images (main image, and panels on right). Subsequent observations with ground-based telescopes, ranging from optical to millimeter wavelengths (insets), revealed two galaxies appearing very close together. The two are actually at very different distances, however, and HFLS3 (blue, in millimeter wavelengths) is so far away that we are seeing it as it was when the universe was just 880 million years old (see more details in Riechers et al. 2013, Nature 496, 329).

3 - Identification and CO redshifts; HFLS3, the highest redshift (z=6.34) DSFG

In order to understand this new population of extreme galaxies, we are engaged in an extensive multi-wavelength follow-up program, including sub(mm) interferometry and deep optical and near-infrared imaging. The SPIRE angular resolution is not good enough to identify these galaxies at other wavelengths. So, the first crucial step is to obtain interferometric data at wavelengths close to the peak in the spectral energy distribution, e.g. with the SMA, IRAM PdBI, and ALMA. Redshifts are difficult to measure in the optical or near-infrared. Progress in the determination of CO redshifts has come from interferometers, particularly CARMA and PdBI. A larger sample was observed with ALMA in several cycle 2 programs. One of the highlights of the HerMES program was the discovery of the highest redshift DSFG known (HFLS3, z = 6.34; Riechers et al. 2013). Observations in practically all spectral bands make this galaxy one of the best studied at high redshift. The SFR of HFLS3 (2900 $M_\odot$ yr^{-1}) is about 30-100 times larger than in the z = 7.51 galaxy discovered by Finkelstein et al. (2013).

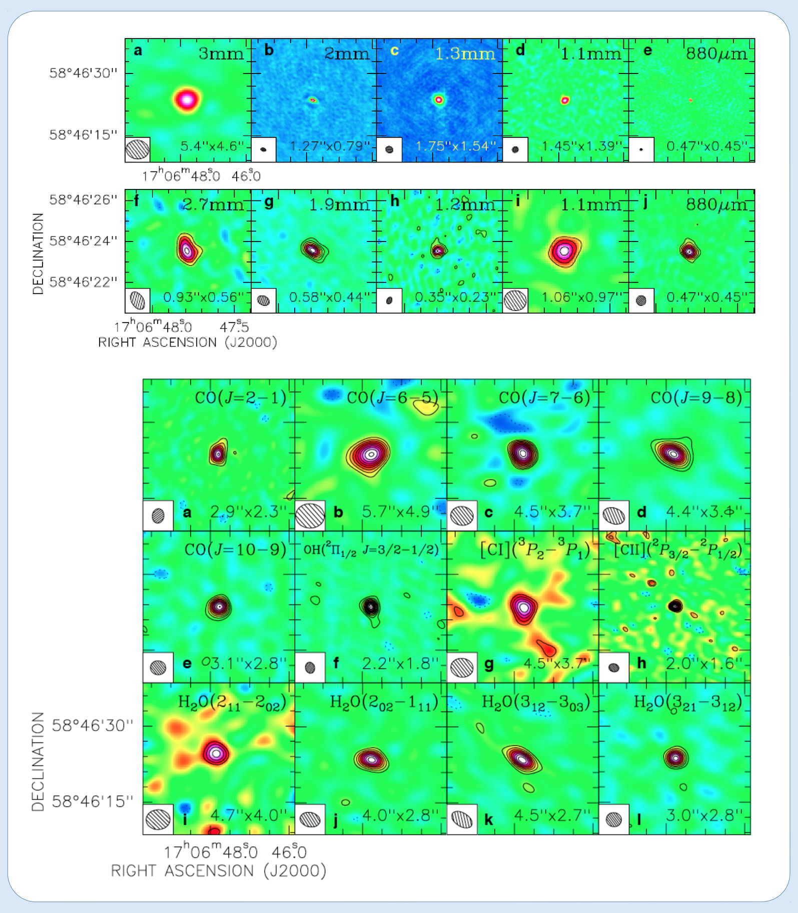

Figure 3. Up: Continuum emission towards HFLS3 in different bands (from CARMA, IRAM PdBI and SMA). Down: Atomic and molecular line emission towards HFLS3 (from CARMA, PdBI, and JVLA) (from Riechers et al 2013).

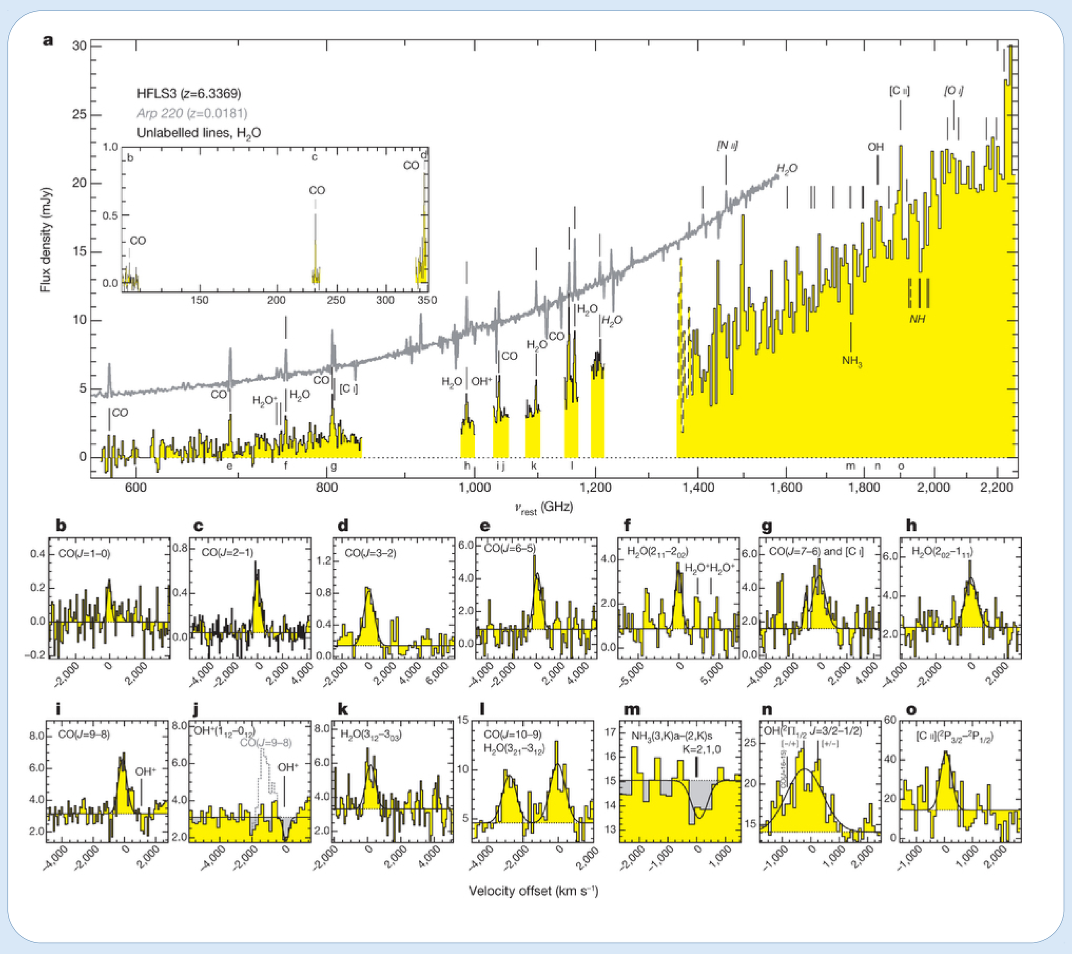

Figure 4. Redshift identification through molecular and atomic spectroscopy of HFLS3 (from Riechers et al. 2013). In the case of HFLS3, a large number of spectroscopic observations were carried out in the observed-frame 0.95 mm to 1.9 cm (rest-frame 130 μm to 2600 μm). For comparison, the Herschel/SPIRE spectrum of the nearby ultra-luminous infrared galaxy Arp220 is overplotted in grey. Most of the bright spectral features detected in Arp220 are also detected in HFLS3.

4 – mm counterparts and ALMA Cycle 2 observations

A large sample of Herschel-SPIRE red sources selected from the HerMES survey have been observed with the SMA (PI: Clements) and with IRAM PdBI (PIs Pérez-Fournon and Bertoldi). In most cases a clear counterpart is detected close to the SPIRE position (see figure 5). The best high-z candidates as well as sources with confirmed CO redshifts > 4 were selected for three successful ALMA Cycle 2 proposals (PIs: Conley, Ivison and Riechers) submitted jointly by the HerMES and Herschel-ATLAS collaborations. One of these programs was carried out to measure the CO redshifts with spectral scans covering the 3mm band, while the other two programs will study the continuum and C+ emission at high spatial resolution. One example of the PdBI 1.3mm counterpart of one of the ALMA targets is shown in figure 5. We also show the spectrum of this source with CO redshift of 5.093 recently measured with ALMA 3mm band spectroscopic observations (PI Alex Conley).

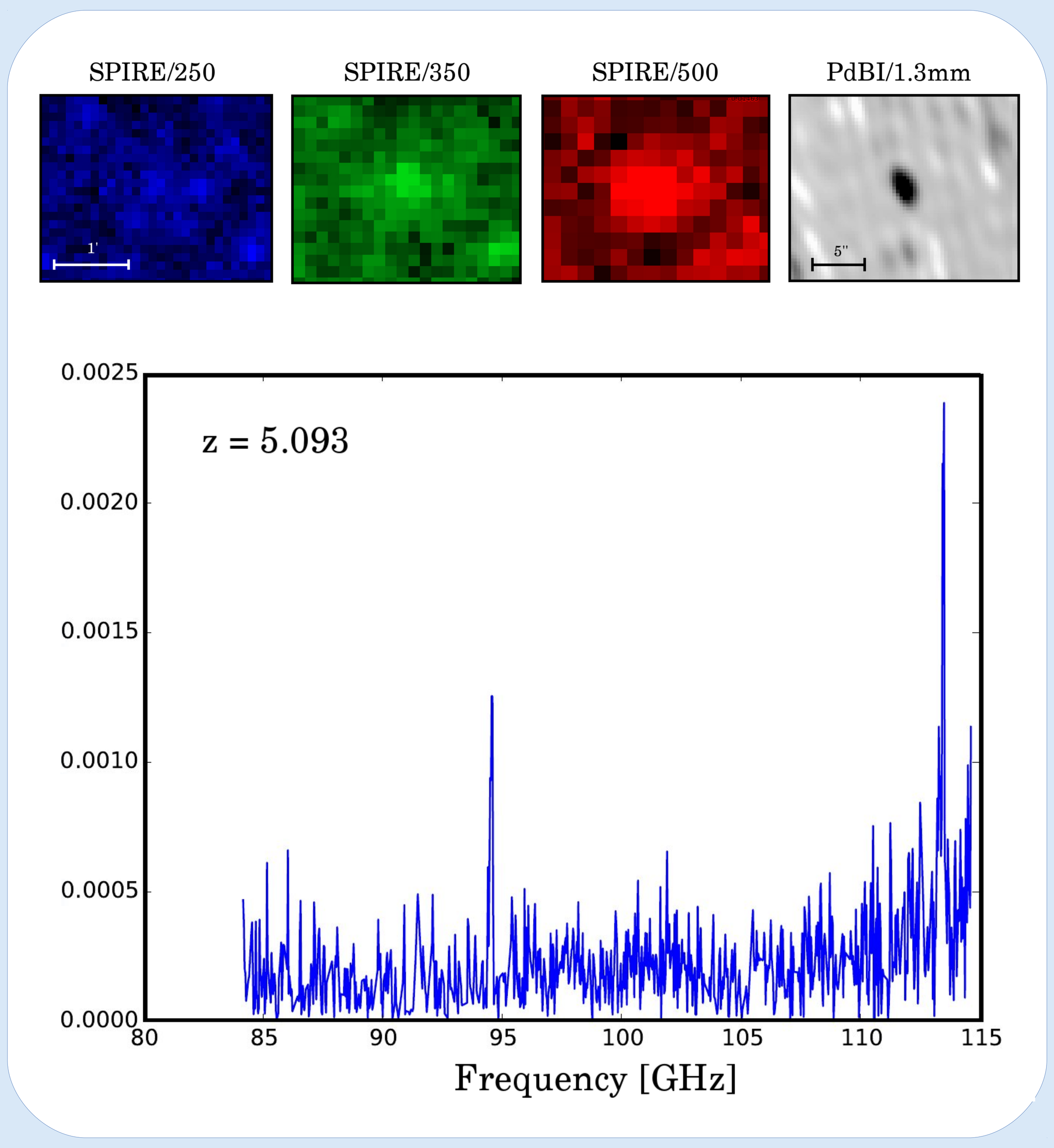

Figure 5. Up: Emission in the SPIRE 250 μm (blue), 350 μm (green) and 500 μm (red) bands and IRAM PdBI 1.3 mm of one of the HerMES red sources. A clear mm counterpart is detected near the SPIRE positions (see the different scale in the SPIRE and PdBI 1.3mm postage stamps). Down: CO redshift of 5.093 recently measured with ALMA 3mm band spectroscopic observations (PI Alex Conley). At this redshift (from CO (5-4) and CO (6-5)), this is one of the highest redshift Herschel-selected galaxies known (Conley et al. 2015, in prep.).

Summary

Quick facts about Herschel-selected high-z DSFGs (see Dowell et al. 2014 and Riechers et al. 2013 for more details):

- Number density of ~ 2 sources deg^{-2}, too small to appear in deep, small area surveys
- This number density if significantly higher than the predictions of existing galaxy population models
- All but one of the sources with confirmed CO redshifts are at z > 4
- Models and interferometric observations indicate most of these targets are not highly magnified
- FIR luminosities > 10^{13} $L_\odot$
- Star Formation Rates of individual galaxies > 1,000 $M_\odot$ yr^{-1} up to ~ 10,000 $M_\odot yr^{-1}$ (the luminosities and SFR values have to be corrected for a small magnification factor)
- Star Formation Rate Density at z ~ 5 of ~ 10^{-3} $M_\odot$ yr^{-1} Mpc^{-3}. This is significantly lower than the total inferred SFRD at these redshifts, but these represent only the tip of the luminosity function

The on-going follow-up programs attempt to study a statistically significant sample of about 100 sources.

References

Baugh et al. 2005, MNRAS, 356, 1191
Béthermin et al. 2011, A&A, 529, A4
Béthermin et al. 2012, ApJ, 757, 23
Bouwens et al. 2007, ApJ, 670, 928
Capozzi et al. 2012, MNRAS, 419, 2821
Chapman et al. 2005, ApJ, 622, 772
Dowell et al. 2014, ApJ, 780, 75
Engel et al. 2010, ApJ, 724, 233
Finkelstein et al. 2013, Nature, 502, 524
Gruppioni et al. 2011, MNRAS 416, 70
Guo et al. 2011, MNRAS 413, 101
Hayward et al. 2013, MNRAS, 428, 2529
Kaviraj et al. 2013, MNRAS, 428, 925
Oliver et al. 2012, MNRAS, 424, 161
Riechers et al. 2013, Nature, 496, 329

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