Herschel protocluster survey: A search for dusty star-forming galaxies in protoclusters at $z = 2 - 3$

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ABSTRACT
We present a Herschel/SPIRE survey of three protoclusters at $z = 2 - 3$ (2QZCluster, HS1700, SSA22). Based on the SPIRE colours ($S_{350}/S_{250}$ and $S_{500}/S_{350}$) of 250 $\mu$m sources, we selected high redshift dusty star-forming galaxies potentially associated with the protoclusters. In the 2QZCluster field, we found a 4$\sigma$ overdensity of six SPIRE sources around 4.5$'$ ($\sim 2.2$ Mpc) from a density peak of H$\alpha$ emitters at $z = 2.2$. In the HS1700 field, we found a 5$\sigma$ overdensity of eight SPIRE sources around 2.1$'$ ($\sim 1.0$ Mpc) from a density peak of LBGs at $z = 2.3$. We did not find any significant overdensities in SSA22 field, but we found three 500 $\mu$m sources are concentrated 3$'$ ($\sim 1.4$ Mpc) east to the LAE overdensity. If all the SPIRE sources and to investigate what processes enhance the dusty star-formation activity in $z \sim 2 - 3$ protoclusters. Further observations are needed to confirm the redshifts of the SPIRE sources and to investigate what processes enhance the dusty star-formation activity in $z \sim 2 - 3$ protoclusters.

Key words: galaxies: clusters: individual – galaxies: individual – galaxies: formation – galaxies: high-redshift – submillimetre: galaxies – infrared: galaxies

1 INTRODUCTION
The central regions of local clusters are dominated by passive early-type ellipticals and spheroidals, their stellar populations are old, with inferred formation redshifts of $z \gtrsim 2$ (e.g., Ellis et al. 1997). High-redshift dusty star-forming galaxies (DSFGs) are strongly star-forming galaxies ($SFR \gtrsim 100 - 1000$ $M_\odot$ yr$^{-1}$) and have been proposed to the precursors of present-day ellipticals in local clusters (e.g., Lilly et al. 1998; Smail et al. 1998; Lutz et al. 2001; Ivison et al. 2013). Large hydro-dynamical simulations and galaxy formation models predict intense star formation could be detectable as concentrations of DSFGs in $z \gtrsim 2$ protoclusters (e.g., Granato et al. 2015). Indeed, there have been reports of a reversal of the SFR-density relation (e.g., Elbaz et al. 2007;...
Tran et al. 2010), which is increasing SFR with increasing local density at \(z \gtrsim 1\). Protoclusters at \(z \gtrsim 2\) are thus unique laboratories to explore bursting star-formation in a critical epoch of galaxy formation (Casey 2016).

A numbers of studies have confirmed the presence of DSFGs in \(z < 2\) galaxy clusters (e.g., Brodwin et al. 2013; Smail et al. 2014; Ma et al. 2015; Webb et al. 2015), while studies confirming DSFGs at \(z \gtrsim 2\) protoclusters are also progressing (e.g., Tamura et al. 2009; Clements et al. 2014; Umehata et al. 2014, 2015; Casey et al. 2015). Some surveys to search for DSFGs at far-infrared wavelengths have focused on radio galaxy fields (e.g., Stevens et al. 2003; Valtchanov et al. 2013; Rigby et al. 2014; Dannerbauer et al. 2014). Radio galaxies are thought to be tracers of large scale structures, and some fraction of \(z \gtrsim 2\) protoclusters around radio galaxies indeed appear to have experienced bursting dusty star-formation related to DSFGs (e.g., Ivison et al. 2000). However, such regions may be biased by the end to host a currently accreting Super Massive Black Hole (SMBH) and so we also need to explore DSFGs large-scale structures selected by other techniques at \(z \gtrsim 2\) to investigate bursting star-formation more generally. Clements et al. (2014) investigated \(\sim 90\) deg\(^2\) sky observed as part of the HerMES survey with Planck and Herschel to search for clusters undergoing dusty star-formation. They found four candidate clusters, and for all four cases they found evidence of galaxy clusters with red-sequence based on optical/NIR data. The star-formation rate density of these at \(z \gtrsim 2\) are four order of magnitudes higher than the cosmic averaged values. But is this also true for dusty star-formation in known optical/UV-selected galaxy clusters at \(z \gtrsim 2\)?

In this paper, we report a result of observations with the Spectral and Photometric Imaging Receiver (SPIRE; Griffin et al. 2010) on the Herschel Space Observatory (HSO; Pilbratt et al. 2010) for three protoclusters at \(z = 2 - 3\) (2QZCluster, HS1700, and SSA22) at \(z = 2.2, 2.3, 3.1\), respectively. The three protoclusters have filamentary, large scale structures of rest-frame UV to optical selected galaxies. The structure of this paper is following. In §2 we introduce the Herschel/SPIRE observations, the data processing, and our targeted fields. In §3 we present source detection methods, number counts, and SPIRE colour selection. In §4 and §5 we present our results, discussion, and then summarize our main findings. We use the following cosmological parameters: \(\Omega_m = 0.3\), \(\Omega_L = 0.7\), \(h = 0.7\). In this cosmology, the Universe is 2.9, 2.8, and 2 Gyr old and 1.0" corresponds to 8.3, 8.2 and 7.6 kpc in physical length at \(z = 2.2, 2.3\) and 3.1, respectively.

## 2 OBSERVATIONS & TARGET FIELDS

### 2.1 SPIRE OBSERVATIONS

Our Herschel/SPIRE observations were performed as part of the second Open Time (OT2) Herschel programs (PI: Y. Matsuda). We summarize the observations in Table 1. The observations were executed in Large Map mode with a scan rate of 30" s\(^{-1}\), repeated 14 times for each field (\(N_{\text{rep}} = 14\)). The dates of observations are 22 June 2012 (2QZCluster), 4 March 2012 (HS1700), and 10 May 2012 (SSA22). The coverage of the maps are \(\sim 23' \times 23'\) (2QZCluster), \(\sim 22' \times 22'\) (HS1700), and \(\sim 33' \times 33'\) (SSA22) corresponding to \(\sim 40 - 60\) comoving Mpc at the protocluster redshifts, which are sufficient to search for concentration of DSFGs around the density peak of protocluster members. The integration times are 1.8, 1.5 and 3.7 hours for 2QZCluster, HS1700 and SSA22, respectively. Maps were produced with the Herschel Interactive Processing Environment (HIPE, v11.0.0), following the standard data processing and map-making steps with destriping. The full width at half maximum (FWHM) of the SPIRE beam is 18.1", 24.9" and 36.6" at 250, 350, and 500 \(\mu\)m, respectively (Swinyard et al. 2010). The final maps have pixel sizes of 6", 10", and 14" at 250, 350, and 500 \(\mu\)m. We measured the 1\(\sigma\) confusion noise (\(\sigma_{\text{conf}}\)) as map variance of line density within effective area (Table 1), which are slightly higher than the values of blank fields (Nguyen et al. 2010). The instrumental noise measured in our three protoclusters are about one-third of the confusion noise (Table 1).

### 2.2 PROTOCLUSTER TARGETS

**2QZCluster:** This protocluster was originally identified as a concentration of five Quasi Stellar Objects (QSOs) in a \(\sim 1\) degree region at \(z = 2.23\) from the 2dF Quasar Redshift survey (Croton et al. 2001, 2004). Four out of the five QSOs are even more strongly clustered in a \(30 \times 30\) comoving Mpc patch. An Ha narrow-band imaging revealed a filamentary large-scale structure of an over density of 22 HAEmax including the QSOs (Matsuda et al. 2011). Chandra/ACIS-I 100 ks observations of this structure also showed evidence that the Active Galactic Nucleus (AGNs) fraction is a factor of \(\sim 3.5\) higher than blank fields (Lehmer et al. 2013).

**HS1700:** This protocluster was originally discovered as a \(\sim 7\times\) density contrast redshift spike of UV/optical-selected star forming galaxies (BX/BM) within a \(\sim 25\) comoving Mpc region at \(z = 2.30\) (Steidel et al. 2005). A Ly\(\alpha\) narrowband imaging survey revealed a filamentary large-scale structure of six giant Ly\(\alpha\) Blobs (LABs) (Erb, Bogosavljević, & Steidel 2011). Chandra/ACIS-I 200 ks observations of this structure also showed tentative evidence of an enhancement of AGN fraction compared to the field environment (Digby-North et al. 2010).

**SSA22:** This protocluster was originally discovered as a \(\sim 4 \times 6\) density contrast in redshift distribution of Lyman Break Galaxies (LBGs) and Ly\(\alpha\) emitters (LAEs) within a \(\sim 20\) comoving Mpc region at \(z = 3.09\) (Steidel et al. 1998, 2000). A wide-field Ly\(\alpha\) narrowband imaging survey with Subaru Telescope revealed a filamentary large-scale structure of 283 LAEs, extended to at least \(\sim 60\) comoving Mpc (Hayashino et al. 2004). This sample of LAEs includes 35 LABs with sizes of 30–150 kpc scale (Steidel et al. 2000; Matsuda et al. 2004). Chandra/ACIS-I 400 ks observations of this structure showed that the AGN fraction of protocluster members is \(\sim 3\times\) higher than that in the field environment (Lehmer et al. 2009a,b).

**Blank field (COSMOS):** We have chosen well-studied extragalactic field Cosmic Evolution Survey (COSMOS) to use as a blank field, which is observed as a part of Herschel Multi-tiered Extra-galactic survey, HerMES (Oliver et al. 2012). The SPIRE map in COSMOS field is larger and deeper than our observations, so we have reprocessed them by limiting to the same depth using \(N_{\text{rep}} = 14\). Subseq-
Table 1. Summary of our Herschel/SPIRE observations.

| Target       | z         | R.A.       | Dec        | Area          | $t_{int}$ | $S_{250}$ | $S_{350}$ | $S_{500}$ | $\sigma_{conf}$ | $\sigma_{inst}$ |
|--------------|-----------|------------|------------|---------------|-----------|-----------|-----------|-----------|----------------|----------------|
| 2QZCluster   | 2.230 ± 0.016 | 10h03m51s | +00d15m09s | 515 arcmin$^2$ | 1.8       | 6.7       | 7.0       | 7.1       | 2.0–3.9         | 1.6–2.6           |
| HS1700       | 2.300 ± 0.015 | 17h01m15s | +64d14m03s | 497 arcmin$^2$ | 1.5       | 7.3       | 7.4       | 7.5       | 2.0–3.7         | 1.6–2.7           |
| SSA22        | 3.09 ± 0.03   | 22h17m34s | +00d17m01s | 1076 arcmin$^2$ | 3.7       | 7.7       | 7.8       | 8.0       | 1.9–3.2         | 1.6–2.4           |
| COSMOS       | -          | 10h00m37s | +02d11m26s | 3422 arcmin$^2$ | 50.1      | 7.1       | 7.7       | 7.8       | 2.1–2.7         | 1.7–2.0           |

Notes. (a): Redshift range of the member galaxies, based on HAEs for 2QZCluster (Matsuda et al. 2011) and LBGs for HS1700 (Steidel et al. 2005) and SSA22 (Steidel et al. 1998, 2000). (b), (c): The coordinates of the field centre of Herschel/SPIRE observations. (d): The area where the integration time is greater than 30%. For COSMOS field, we used centre of 3422 arcmin$^2$ area. We detected sources within this area. (see also Figure 3). (e): The total integration time. For the survey design of COSMOS field, please see Oliver et al. (2012). (f), (g): The confusion noise and instrumental noise.

Figure 1. Number counts at 250, 350 and 500 μm in the three protoclusters and COSMOS field. We detected S/N > 2 sources in the 250 μm maps and measured the 350 and 500 μm fluxes at the positions of the 250 μm sources. We fitted the data points of COSMOS filed with a bézier curve. The number counts of the SPIRE sources in the protoclusters averaged over their full fields are roughly consistent with those of COSMOS field. The number counts of the SPIRE sources in COSMOS field are also consistent with those of HerMES blank fields (Béthermin et al. 2012), suggesting that COSMOS field can be used as a control field.

3 ANALYSIS

3.1 DETECTION & NUMBER COUNTS

The source detection was conducted on the 250 μm maps, because of the better spatial resolution compared with longer wavelength bands. We cation that 500 μm detection causes a source blending (even 250 μm can deblend these) and large spatial uncertainty. We used the SUSSEXTRACTOR (Smith et al. 2012) for the source detection and photometry. We detected S/N > 2 sources in the maps within the region where the integration time is greater than 30% of the deepest parts (515 arcmin$^2$ for 2QZCluster, 497 arcmin$^2$ for HS1700, 1076 arcmin$^2$ for SSA22, and 3422 arcmin$^2$ for COSMOS field). We measured 350 μm and 500 μm fluxes at the positions of sources detected in the 250 μm maps, then listed these 250 μm sources only if the flux density is above 12 mJy in at least one of the SPIRE bands (See also Table 8–10, and the full tables are avaivable in online). This flux density limit corresponds to ~ 4σ of the instrumental noise and ~ 2σ of the confusion noise in all three bands. For SSA22, we cut out the region shown in Figure 3 due to the high background fluxes from the Galactic cirrus.

We compared these SPIRE number counts with COS- MOS field. We show the raw (i.e., not corrected for the completeness) number counts in Figure 1 (See also Table 5–7). The raw number counts are roughly consistent with COSMOS field data at > 20 mJy bin at 250 and 350 μm. A moderate excess of number counts at $S_{250} > 50$ mJy and $S_{500} > 40$ mJy were found (by a factor of 2–3) in HS1700 and 2QZCluster, although they are within the error bars based on Poisson noise. We also compared number counts in COSMOS field with wider HerMES survey data (Béthermin et al. 2012). The number counts in COSMOS field agree with that of HerMES survey data, suggesting that COSMOS field is suitable as a control field.
3.2 SPIRE COLOUR SELECTION

In order to search for DSFGs possibly associated with the protoclusters, we applied a colour constraint to the SPIRE detected sources. The $S_{350}/S_{250}$ and $S_{500}/S_{350}$ colours were used to select the sources with single grey body SEDs at the protocluster’s redshift ranges, with dust temperatures of $T_d = 30 - 40$ K, and a dust emissivity $\beta = 1.5$. Casey et al. (2012) measured the dust temperatures of SPIRE-selected DSFGs and showed that they are in the range of $T_d = 20 - 60$ K. The dust emissivity index is determined by Hildebrand (1983), and typically $\beta = 1.0 - 2.0$ for DSFGs. Different values of $\beta$ do not significantly affect our conclusion, yielding almost the same temperature and SPIRE colours. We included flux errors of $\pm 20\%$ in estimating the uncertainties in the SPIRE colours. Figure 2 shows $S_{500}/S_{350}$ vs. $S_{350}/S_{250}$ colour-colour diagram of the SPIRE sources in the three protoclusters.

We derived $L_{\text{FIR}}$ ($8 - 1000$ $\mu$m) by fitting single grey body SEDs with $T_d$ a free parameter. From the sources selected based on the SPIRE colours, we further applied a FIR luminosity cut of $L_{\text{FIR}} \geq 5.0 \times 10^{12}$ $L_\odot$ for conservative searching for DSFGs. Thus the lowest flux densities in our samples are (36.0, 30.0, 19.4) mJy for 2QZCluster, (28.8, 26.3, 15.2) mJy for HS1700, and (15.6, 19.2, 12.9) mJy for SSA22 in the SPIRE bands (250, 350, 500) $\mu$m, respectively. We finally obtained a sample of colour-selected bright SPIRE sources with colours consistent with the protocluster redshifts by rejecting $\sim 95\%$ of the 250 $\mu$m sources (thus we select just 12/643 (2\%), 26/579 (5\%), and 55/1253 (4\%) colour-selected bright SPIRE sources in 2QZCluster, SSA22, and HS1700, respectively.)

| Field | Areaa (arcmin$^{-2}$) | Nb (prior) | Nc (catalogued) | Nd (selected) | Nf (arcmin$^{-2}$) | Sigmaf (arcmin$^{-2}$) | Sigmaf (arcmin$^{-2}$) | $\delta^b$ | $\sigma^c$ |
|-------|----------------------|------------|---------------|--------------|-------------------|------------------------|------------------------|----------|---------|
| 2QZCluster | 515             | 643       | 399           | 12           | 6                 | 0.023 ± 0.007          | 0.132 ± 0.054          | 3.0 ± 1.7 | 3.9 ± 2.1 |
| HS1700   | 497             | 579       | 383           | 26           | 8                 | 0.052 ± 0.010          | 0.186 ± 0.066          | 3.7 ± 1.7 | 5.0 ± 2.2 |
| SSA22    | 1076            | 1253      | 772           | 55           | 5                 | 0.051 ± 0.007          | -                      | -        | -       |

**Notes.** (a): The area where the integration time is greater than 30\%. We detected sources within this area. (b): The numbers of S/N (250 $\mu$m) > 2 prior sources. (c): The numbers of catalogued sources which at least one SPIRE band flux is above 12 mJy. (d): The numbers of colour-selected bright SPIRE sources. For SSA22, we excluded the sources in high background fluxes (see Figure 3). (e): The numbers of colour-selected bright SPIRE sources within the overdensities. (f): The surface density of colour-selected bright SPIRE sources. The errors assume Poisson statistics. (g): The surface density of colour-selected bright SPIRE sources in the overdensities, assume an area of the overdensities ($r = 3.8'$ for 2QZCluster, $r = 3.7'$ for HS1700). The errors assume Poisson statistics. (h) - (i): The $\delta$ and $\sigma$ are calculated from $\delta_{pc} = (n_{pc} - n_{ave})/\sigma_{ave}$ and $\sigma_{pc} = (n_{pc} - n_{ave})/\sigma_{ave}$. The errors assume Poisson statistics.

![Figure 2: $S_{500}/S_{350}$ vs $S_{500}/S_{250}$ colour-colour diagram of the 250 $\mu$m sources.](http://mnras.oxfordjournals.org/Downloaded from at University of Durham on June 15, 2016)
Figure 3. Sky distributions of colour-selected bright 250 µm sources (red circles) over-plotted on the SPIRE 250 µm maps. The areas outlined with magenta contour corresponds to the 30% depth coverage. For SSA22, we do not use below the dashed magenta line due to the high background fluxes. The dashed black contours show the density of 19 HAEs and 3 QSOs (Matsuda et al. 2011) for the 2QZCluster, 45 LBGs for HS1700 (Rudie et al. 2012; Steidel et al. 2014), and 742 LAEs for SSA22 (Yamada et al. 2012) respectively. The steps show 1–4σ, 1–4σ, and 3–6σ for 2QZCluster, HS1700, and SSA22 (smoothed with a Gaussian kernel with a FWHM of 6 comoving Mpc). The red contours show 3–4σ, 4–5σ for colour-selected bright SPIRE sources in 2QZCluster and HS1700 with a same Gaussian kernel (1σ is standard deviation of surface density of colour-selected bright SPIRE sources measured in COSMOS field). The large blue circles show the overdensity of colour-selected bright 250 µm sources for 2QZCluster and HS1700, and colour-selected bright 500 µm sources for SSA22 using filtering a radius of 6 comoving Mpc. We find a 4σ and 5σ overdensity in the 2QZCluster and HS1700 fields. We do not find any significant overdensities of 250 µm sources in SSA22, but we found six colour-selected bright 500 µm sources (black squares), and three sources are concentrated 3′ (~1.4 Mpc) east to the LAEs overdensity. The dashed cyan and orange boxes in 2QZCluster show the UKIRT/WFCAM (for HAEs) and Subaru/MOIRCS (for HAAs) coverage. The solid cyan, dashed purple, and orange boxes in HS1700 show the Keck/LRIS (for LAEs and LBGs, respectively) and Palomar/WIRC (for HAEs) coverage. The dashed cyan large circle in SSA22 shows ASTE/AzTEC coverage.
(Upper). The density distributions of the colour-selected bright SPIRE sources in 2QZCluster (left) and HS1700 (right) within an aperture radius of 6 comoving Mpc. 2QZCluster tends to have lower number of colour-selected bright SPIRE sources compared with COSMOS field. This could be explained if there are void-like structures within the survey area although there are also overdense regions. In contrast, HS1700 tends to have higher number of sources. (Lower). Cumulative number of the apertures with a radius of 6 comoving Mpc. We normalized the cumulative number of COSMOS field to the protoclusters.

HS1700 and SSA22). For COSMOS field, we applied the same colour selection as the three protoclusters to obtain a control sample of field galaxies. We have selected 111/4923 (2%), 140/4923 (3%), and 262/4923 (5%) colour-selected bright SPIRE sources in COSMOS field for 2QZCluster, HS1700, and SSA22 (see also Table 2).

4 RESULTS

4.1 SEARCH FOR OVERDENSITIES

We searched for overdensities in an aperture with a radius of 6 comoving Mpc (3.8', 3.7', and 3.2' radius for z = 2.2, 2.3, and 3.1, respectively). This scale corresponds to physical scale of ∼1.5 – 2 Mpc radius for each protocluster redshift, matching the size of the overdensity of DSFGs around radio galaxies (e.g., Rigby et al. 2014; Dannerbauer et al. 2014). We put down a grid of these apertures every 10" for the protoclusters and COSMOS field, and counted the number of colour-selected bright SPIRE sources (L_{SPIRE} > 5.0 \times 10^{12} L^\odot) within each aperture. For SSA22, we excluded a high background region (see in Figure 3).

We found 3.9\sigma and 5.0\sigma overdensities in the 2QZCluster and HS1700 fields respectively, but did not find any significant (> 3\sigma) overdensities in the SSA22 field. We calculated the significance of overdensity, \(\sigma_{pc} = (n_{pc} - n_{ave})/\sigma_{ave}\), where \(n_{pc}\) is the number of colour-selected bright SPIRE sources in overdense region (6 comoving Mpc search radius) of the protocluster fields, \(n_{ave}\) is the average number within a 6 comoving Mpc search radius for COSMOS field, and \(\sigma_{ave}\) is the standard deviation of \(n_{ave}\). We also searched for overdensities of colour-selected bright SPIRE sources in case for 10% and 30% flux error boundaries in Figure 2. The result does not significantly change for 20% and 30% boundaries. We found 30% boundary shows same position of overdensities of colour-selected bright SPIRE sources compared with that of 20% boundary in 2QZCluster and HS1700. We found 10% boundary is not suitable because the number of colour-selected bright SPIRE sources are too small to search for overdensities. In Figure 3, we show the sky distribution of the colour-selected bright SPIRE sources. We also show the density of 19 HAEs and 3 QSOs (Matsuda et al. 2011) for 2QZCluster, 45 LBGs for HS1700 (Rudie et al. 2012; Steidel et al. 2014), and 742 LAEs for SSA22 (Yamada et al. 2012) respectively.

We searched for overdensities of the colour-selected bright SPIRE sources in the COSMOS field in an identical manner as for the protocluster fields. We plot the density distribution of the colour-selected bright SPIRE sources for the 2QZCluster, HS1700 and COSMOS fields in Figure 4. The histogram shows the distribution of the number of colour-selected bright SPIRE sources within a 6 comoving Mpc aperture (normalized by the number of searched apertures). We found that 2QZCluster has a low number of sources. The fraction of the apertures which have no sources is about two times higher compared with COSMOS field. This suggests that there is a void-like distribution while there are also overdensities in 2QZCluster. In contrast, HS1700 tends to have larger number of colour-selected bright SPIRE sources in the search apertures.

We also plot the cumulative number of the cricles in Figure 4. We normalized the cumulative number of COSMOS field to the protoclusters. We found that the normalized cumulative number with > 3.9\sigma overdensities in 2QZCluster field is about two times higher than that in the COSMOS field. There are no overdensities in the COSMOS field which contain eight colour-selected bright SPIRE sources (5.0\sigma) as HS1700. This means that such overdensities are preferentially located in the protoclusters.

4.2 2QZCLUSTER

In the 2QZCluster field, an overdensity of colour-selected bright SPIRE sources were found 4.5' (~2.2 Mpc) west to the HAEs overdensity.

We searched for the counterparts of SPIRE sources with HAEs and QSOs in 2QZCluster, which are summarized by Matsuda et al. (2011), although the SPIRE overdense region did not have Hα image with UKIRT/WFCAM (see Figure 3). In total, 19 HAEs and 3 QSOs are within the 174 arcmin^2 overlap region. We define the following quality criteria based on Downes et al. (1986) for assessing the robustness of identified candidate counterparts. We classify sources with \(p \leq 0.05\) as secure counterparts, and those with \(0.05 < p \leq 0.10\) as tentative counterparts. We calculated the p-value defined by \(p = 1 - \exp(-\pi n^2)\) where \(n\) is the source density, \(\theta\) is the angular offset. We searched for counterparts within 11" radius from the centre of the SPIRE sources.
search radius corresponds to ~40% beam response in 250 μm band.

For the QSOs, 1 optically luminous QSO, which is known as 2QZC-C1-HAE2 (Matsuda et al. 2011), coincides with one of our colour-selected bright SPIRE source 2QZCluster-SPIRE10 (2.7′′ offset). The p-value is lower than 0.01, suggesting a secure counterpart, the probability of chance association of counterparts is lower than 1%. 2QZC1-HAE3 also coincides with our SPIRE source 2QZCluster-SPIRE124 (5.6′′ offset) as a secure counterpart. Such optically luminous FIR bright QSOs are thought to be in a transient phase between DSFGs and QSOs (Simpson et al. 2012). No other HAEs matched with colour-selected bright SPIRE sources. We then repeated this matching using all 250 μm sources, and found five secure HAE counterparts (see Table 11).

We recently conducted Subaru/MOIRCS follow-up NB imaging observations in May 5, 2015 to search for new HAEs as well as counterparts of the SPIRE sources in the SPIRE overdense region (4′ × 7′; dashed orange box in Figure 3). The total exposure time of Ks and NB data is each 1.5 and 2.4 ksec, respectively. The 5σ detection limit of NB < 19.8 (Vega) is almost the same as the previous HAE search depth (NB < 19.9 in Vega) by Matsuda et al. (2011).

We find no new HAE within the area. This may suggest that the area is actually a little under-dense in terms of bright HAE, because Matsuda et al. (2011) claim an average field count of 0.09 per arcmin², which corresponds to two or three HAEs per MOIRCS FOV. Such void structures adjacent to protocluster has been reported previously (e.g., Koyama et al. 2013; Saito et al. 2015).

4.3 HS1700

In HS1700, the overdensity peak of colour-selected bright SPIRE sources coincides with that of the protocluster member galaxies (2.1′ offset, corresponding to ~1.0 Mpc).

We searched for the counterparts of SPIRE sources using UV-selected (BX/BM) star-forming galaxies (LBGs), HAEs, LAEs, and DRGs in the SPIRE overdense region. There are 3010 LBGs within 256 arcmin, 123 LAEs are within 219 arcmin², 83 HAEs and 75 DRGs are within 72 arcmin². The LBG catalogues are from the KBSS (Keck Baryonic Structure Survey; Rutdie et al. 2012; Steidel et al. 2014). HS1700 is one of the fifteen QSO fields intensively studied in KBSS. The Hα and Lyα NB catalogues are from Milan Bogosavljević (Bogosavljević 2010). Individual properties of LBGs, LAEs and observations are described in Shapley et al. (2005), Erb, Bogosavljević & Steidel (2011), Kulas et al. (2013), and Erb et al. (2014). In addition, for the Hα narrow band imaging, we used the Brγ filter (Palomar WIREF, center wavelength 2.17 μm, FWHM=297 Å). The narrow band selection criteria are NB < 20.5 (Vega) and NB − Ks < −0.75. The DRGs have selected with J − K > 2.3 to a limit of Ks = 21 (Vega). We define the quality criteria, and classify sources with p-value described above. We deduced the number density of 45 LBGs which have spectroscopically confirmed redshift in the protocluster (i.e., in the overdensity of z = 2.285 − 2.315) separately from remaining 2965 LBGs outside of overdensity. We searched for counterparts within 11′′ radius from the centre of the SPIRE sources.

We found three colour-selected bright SPIRE sources that have secure counterparts (see Table 12). But one of the LAEs BNB1, the spectrum of this object is extremely odd and that makes difficult to identify the redshift. We identified it as a âÅÎJo-BALÅÎ QSO and it is more likely to have z ~ 2.00, so we do not treat as it is a protocluster member galaxy.

We also found one LAE and LBG are secure, and one DRG and LAE are tentative counterparts of colour-selected faint (i.e., L_{FIR} < 5.0 \times 10^{12} L_{⊙}) SPIRE source. For the SPIRE sources which are not selected with our colour selection, but have at least one SPIRE band above 12 mJy, we found two secure LAEs, three secure HAEs, and one tentative HAE. Thus, we conclude that seven SPIRE sources in the overdensity have secure counterparts of protocluster galaxies (see Table 12).

In order to assess the success rate of the SPIRE colour selection, we compared the matching result for colour-selected bright/faint SPIRE sources and all 250 μm sources lying within overdensity. We assumed that all HAEs and LAEs are associated with the protocluster except for BNB1, although we should note that the HAEs without spectroscopic follow-up are much less likely than spectroscopic confirmed HAEs to be at the cluster redshift. For all secure counterparts, the fractions are 2/7(29%), 1/5(20%), and 4/28(14%), respectively. This suggests that our SPIRE colour selection can select possible protocluster members with three times higher probability compared to not colour-selected sources.

In the HS1700 field, there are several foreground galaxy groups in the field. A z = 0.453 group is very close to the position of HS1700-SPIRE24. Indeed, Peter et al. (2007) found that BX913 is lensed by the group. We calculated a magnification factor by using GLAFIC (Oguri 2010). We used a halo mass of M/h = 1 \times 10^{14} M⊙ (Israel et al. 2014) and a concentration parameter of c=6 (Bhattacharya et al. 2013). We found that the second nearest (1.5′ away from group center) SPIRE source is affected only ~5% magnification, so we conclude that only the HS1700-SPIRE24 could be affected by lensing.

4.4 SSA22

The maximum number of colour-selected bright SPIRE sources found in on 6 comoving Mpc aperture was five, corresponding to a 1.6σ overdensity. This suggests that SSA22 does not have any significant overdensities of colour-selected bright 250 μm sources. But, this could be a problem for SSA22 at z = 3.1 because DSFGs would start to drop out at 250 μm. Here we searched for an overdensity of colour-selected bright 500 μm detected sources with identical colour selection and luminosity cut in §3.2. We found six colour-selected bright 500 μm sources in the SSA22 field, and three sources are concentrated 3′ (~1.4 Mpc) east to the LAEs overdensity (Figure 3). For 350 μm sources, we did not find any significant overdensities as same as 250 μm sources.

We investigated AzTEC 1.1 mm counterparts in Umehata et al. (2014, 2015) for the five colour-selected bright 500 μm sources within ~800 arcmin² overlapped region (Figure 3). We searched for the counterparts within a radius of 14″ (half of AzTEC 1.1 mm FWHM). We found that four colour-selected bright 500 μm sources have
been matched (SSA22-AzTEC1, 2, 5, and 34). Thus \(\sim 80\%\) colour-selected bright 500 \(\mu m\) sources are matched with AzTEC 1.1 mm sources.

5 DISCUSSION & SUMMARY

We searched for DSFGs associated with three protoclusters at \(z = 2 – 3\) (2QZCluster, HS1700, SSA22) using Herschel/SPIRE. In the 2QZCluster and HS1700 field, we found \(4\sigma\) and \(5\sigma\) overdensities of the colour-selected bright SPIRE sources on a scale of 6 comoving Mpc. In the SSA22, we did not find any significant overdensities of 250 \(\mu m\) sources, but we found that three colour-selected bright 500 \(\mu m\) sources are concentrated on a scale of 6 comoving Mpc. The results suggest possible activity associated with enhanced dusty star-formation in protoclusters at \(z \sim 2 – 3\).

We derive the star-formation rate (SFR) density of 2QZ-Cluster, HS1700 and SSA22 to compare with the average value of the Universe. The SFR of DSFGs is often converted from far-infrared luminosity; although the conversion from \(L_{\text{FIR}}\) to SFR is not straightforward and relies on the dust composition and initial mass function (IMF). Most works on the protocluster’s redshifts, and derived \(z\) values at 5

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Table 3. Estimated SFR and assumed volume for Figure 5.

| Field          | \(z\)  | \(\text{SFR}^a\) | \(V^b\) | \(V^c\) | \(\text{SFR}_{\text{min}}^d\) |
|---------------|------|----------|------|------|-----------------|
| All sources   |      | (M\(\odot\) yr\(^{-1}\)) | (Mpc) | (Mpc\(^3\)) | (M\(\odot\) yr\(^{-1}\)) |
| 2QZCluster 2  | 2.230 ± 0.016 | 5000 | 1.0 | 4.2 | 150 |
| HS1700 2      | 2.300 ± 0.015 | 4500 | 1.0 | 4.2 | 280 |
| SSA22 2       | 3.09 ± 0.03  | 7500 | 1.0 | 4.2 | 310 |
| Field corrected values |     |          |      |      |       |
| 2QZCluster    | 2.230 ± 0.016 | 1000 | 1.0 | 4.2 | -    |
| HS1700 2      | 2.300 ± 0.015 | 2000 | 1.0 | 4.2 | -    |
| SSA22 2       | 3.09 ± 0.03  | 4700 | 1.0 | 4.2 | -    |

Notes. (a) Integrated SFR derived from SPIRE sources which are included in column 4 radius. (b) – (c): Used radius and volume to calculate SFR density. (d): Minimum SFR of SPIRE source which is included in integrated SFR.

clusters is consistent with that seen for Planck clumps (Clements et al. 2014). Dannerbauer et al. (2014) presents results based on APEX/LABOCA 870 \(\mu m\) observations around MRC1138–262 at \(z = 2.16\), showing that at least six DSFGs are likely part of the protocluster. The SFR density \(\sim 1500\) M\(\odot\) yr\(^{-1}\) Mpc\(^{-3}\) is similar to Clements et al. (2014) and our protoclusters study. We also plot the error bars in Figure 5. The high end shows the case when including all sources in 1 Mpc radius and the low end shows the case for subtracting field average values. We deduced field values by calculating average number of sources and average luminosity in 1 Mpc radius apertures in the COSMOS field.

In Table 3, we summarized the estimated SFR and assumed volume plotted in Figure 5. We also calculated SFR density in an aperture using a radius of 6 comoving Mpc in the same manner. These radii are 1.9, 1.8 and 1.5 Mpc in physical units for 2QZCluster, HS1700 and SSA22, respectively, and the results do not change compared to the case of 1 Mpc.

What causes the enhanced dusty star-forming activity in our protoclusters? One possible answer to this is galaxies mergers. For instance, Casey et al. (2015) investigated the morphology of the galaxies in a protocluster to search for interaction/merger state by using \(HST\) H-band imaging data. Although the sample size is limited, they found that the fraction of irregular and interacting galaxies among the LBGs and DSFGs is 1.5 times higher in the protocluster than in the field. Webb et al. (2015) suggested that dusty star formation at the center of a \(z = 1.7\) cluster is being driven by galaxy-galaxy interaction, involving a far-infrared luminous Bright Cluster Galaxy (BCG). Because there are strong correlation between the major-merger and the far-infrared luminosity (Kartaltepe et al. 2010, 2012; Engel et al. 2010; Hung et al. 2013), higher major mergers rate in protoclusters could induce dusty star-formation. N-body simulation also predicts that progenitors of cluster and group haloes at \(z > 2\) have \(3 - 5\times\) higher major merger rates than isolated halos (Gottlöber, Klypin, & Kravtsov 2001). The facts that the colour-selected bright SPIRE sources are significantly concentrated in HS1700 and 2QZCluster would support such simultaneously major merging phenomenon. However, further observations are needed to investigate the processes of dusty star-forming activity in these protoclusters.
**Figure 5.** SFR density of clusters, protoclusters and global cosmic SFR densities. The SFR densities of our protoclusters are $10^3$–$10^4$ times higher than the global SFR density (Madau & Dickinson 2014). We show the compilation from Dannerbauer et al. (2014) and data from Clements et al. (2014), which original literature are following; IRAS measurements of Perseus from Meusinger, Brunzendorf, & Krieg (2000), BLAST measurements of A3112 from Braglia et al. (2011), ISO measurements of A1689 from Fadda et al. (2000), and Spitzer measurements of A1758 from Haines et al. (2009), Bullet cluster from Chung et al. (2010), Cl0024+16 and MS0451-03 from Geach et al. (2006). RXJ0057, RXJ0941, RXJ1218, RXJ1249 and RXJ1633 are based on JCMT/SCUBA from Stevens et al. (2010).

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### Table 4. Number of sources which have fluxes above 12 mJy in each bands.

|                  | COSMOS | SSA22 | HS1700 | 2QZCluster |
|------------------|--------|-------|--------|------------|
| 250 µm           | 2552   | 699   | 356    | 365        |
| 350 µm           | 1944   | 529   | 259    | 260        |
| 500 µm           | 961    | 252   | 133    | 116        |

### Table 5. Number counts at 250 µm. The errors take into account the statistical uncertainties, including the Poisson noise.

| Central flux (mJy) | Flux bin (mJy) | SSA22 (dN/dS) [mJy$^{-1}$ deg$^{-2}$] | HS1700 (dN/dS) [mJy$^{-1}$ deg$^{-2}$] | 2QZCluster (dN/dS) [mJy$^{-1}$ deg$^{-2}$] | COSMOS (dN/dS) [mJy$^{-1}$ deg$^{-2}$] |
|--------------------|----------------|---------------------------------------|----------------------------------------|------------------------------------------|-------------------------------------|
| 16.8               | 12.0 – 21.6    | 148.1 ± 7.2                           | 137.2 ± 10.2                           | 157.1 ± 10.7                             | 158.1 ± 4.2                         |
| 23.8               | 21.6 – 26.0    | 70.0 ± 7.3                            | 92.1 ± 12.3                           | 73.0 ± 10.8                              | 87.5 ± 4.6                          |
| 33.6               | 26.0 – 41.2    | 31.5 ± 2.6                            | 37.6 ± 4.2                            | 34.0 ± 4.0                               | 36.4 ± 1.6                          |
| 47.4               | 41.2 – 53.6    | 6.5 ± 1.3                             | 11.7 ± 2.6                            | 7.9 ± 2.1                               | 10.4 ± 0.9                          |
| 67.0               | 53.6 – 80.4    | 1.6 ± 0.5                             | 4.0 ± 1.0                             | 2.3 ± 0.8                               | 2.7 ± 0.3                           |
| 94.6               | 80.4 – 108.8   | 0.12 ± 0.12                           | 0.51 ± 0.36                           | 0.74 ± 0.43                             | 0.74 ± 0.17                         |
| 133.7              | 108.8 – 158.6  | 0.07 ± 0.07                           | 0.15 ± 0.15                           | 0.42 ± 0.24                             | 0.06 ± 0.04                         |
| 188.8              | 158.6 – 219.0  | -                                     | -                                     | -                                       | -                                   |

### Table 6. Number counts at 350 µm. The errors take into account the statistical uncertainties, including the Poisson noise.

| Central flux (mJy) | Flux bin (mJy) | SSA22 (dN/dS) [mJy$^{-1}$ deg$^{-2}$] | HS1700 (dN/dS) [mJy$^{-1}$ deg$^{-2}$] | 2QZCluster (dN/dS) [mJy$^{-1}$ deg$^{-2}$] | COSMOS (dN/dS) [mJy$^{-1}$ deg$^{-2}$] |
|--------------------|----------------|---------------------------------------|----------------------------------------|------------------------------------------|-------------------------------------|
| 16.8               | 12.0 – 21.6    | 113.6 ± 6.3                           | 107.0 ± 9.0                           | 116.4 ± 9.2                             | 127.4 ± 3.7                         |
| 23.8               | 21.6 – 26.0    | 60.1 ± 6.8                            | 69.1 ± 10.7                           | 68.3 ± 10.4                             | 62.2 ± 3.9                          |
| 33.6               | 26.0 – 41.2    | 23.1 ± 2.3                            | 23.8 ± 3.4                            | 18.8 ± 2.9                              | 28.5 ± 1.4                          |
| 47.4               | 41.2 – 53.6    | 3.2 ± 0.9                             | 8.8 ± 2.3                             | 3.4 ± 1.4                               | 5.9 ± 0.7                           |
| 67.0               | 53.6 – 80.4    | 0.9 ± 0.3                             | 2.4 ± 0.8                             | 2.3 ± 0.8                               | 1.5 ± 0.2                           |
| 94.6               | 80.4 – 108.8   | -                                     | -                                     | -                                       | 0.04 ± 0.04                         |
| 133.7              | 108.8 – 158.6  | -                                     | -                                     | 0.14 ± 0.14                             | -                                   |
| 188.8              | 158.6 – 219.0  | -                                     | -                                     | -                                       | -                                   |

### Table 7. Number counts at 500 µm. The errors take into account the statistical uncertainties, including the Poisson noise.

| Central flux (mJy) | Flux bin (mJy) | SSA22 (dN/dS) [mJy$^{-1}$ deg$^{-2}$] | HS1700 (dN/dS) [mJy$^{-1}$ deg$^{-2}$] | 2QZCluster (dN/dS) [mJy$^{-1}$ deg$^{-2}$] | COSMOS (dN/dS) [mJy$^{-1}$ deg$^{-2}$] |
|--------------------|----------------|---------------------------------------|----------------------------------------|------------------------------------------|-------------------------------------|
| 16.8               | 12.0 – 21.6    | 68.3 ± 4.9                            | 70.8 ± 7.3                             | 53.1 ± 6.2                              | 75.2 ± 2.9                          |
| 23.8               | 21.6 – 26.0    | 23.6 ± 4.2                            | 21.4 ± 5.9                             | 39.7 ± 7.9                              | 27.3 ± 2.6                          |
| 33.6               | 26.0 – 41.2    | 3.7 ± 0.9                             | 10.0 ± 2.2                             | 6.4 ± 1.7                               | 9.7 ± 0.8                           |
| 47.4               | 41.2 – 53.6    | 1.3 ± 0.6                             | 2.3 ± 1.2                             | 1.7 ± 1.0                               | 1.6 ± 0.4                           |
| 67.0               | 53.6 – 80.4    | 0.1 ± 0.1                             | 0.27 ± 0.27                           | 0.26 ± 0.26                             | 0.08 ± 0.06                         |
| 94.6               | 80.4 – 108.8   | -                                     | -                                     | -                                       | -                                   |
| 133.7              | 108.8 – 158.6  | -                                     | -                                     | -                                       | -                                   |
| 188.8              | 158.6 – 219.0  | -                                     | -                                     | -                                       | -                                   |
### Table 8. SPIRE sources catalogue of 2QZCluster. The full table is available online.

| ID              | R.A.          | Dec.          | $S_{250}$ (mJy) | $S_{350}$ (mJy) | $S_{500}$ (mJy) |
|-----------------|---------------|---------------|-----------------|-----------------|-----------------|
| 2QZCluster-SPIRE1 | 150.81846968368112 | 0.029424092103377656 | 127.0 ± 2.1 | 54.2 ± 1.9 | 24.6 ± 2.2 |
| 2QZCluster-SPIRE2 | 150.76496504820655 | 0.2250125698209038 | 139.1 ± 2.4 | 117.9 ± 1.8 | 71.4 ± 2.3 |
| 2QZCluster-SPIRE3 | 150.915179065664077 | 0.39098383462920928 | 111.4 ± 2.4 | 55.2 ± 1.8 | 21.2 ± 2.4 |
| 2QZCluster-SPIRE4 | 151.02435668089892 | 0.1260451823404277 | 97.4 ± 2.2 | 54.2 ± 1.8 | 26.5 ± 2.4 |
| 2QZCluster-SPIRE5 | 151.04465762064535 | 0.40739397359634 | 93.6 ± 2.3 | 61.3 ± 1.8 | 24.2 ± 2.2 |
| 2QZCluster-SPIRE6 | 151.07596078745527 | 0.1206691913976963 | 84.1 ± 2.3 | 58.9 ± 1.8 | 31.3 ± 2.3 |
| 2QZCluster-SPIRE7 | 151.11225121980369 | 0.17674219593981788 | 66.1 ± 2.2 | 36.2 ± 2.1 | 13.2 ± 2.1 |
| 2QZCluster-SPIRE8 | 150.7066091151451 | 0.2830585502030584 | 67.4 ± 2.3 | 54.5 ± 1.8 | 18.4 ± 2.2 |
| 2QZCluster-SPIRE9 | 150.94968775985714 | 0.33116978147976 | 64.4 ± 2.2 | 22.2 ± 1.9 | 0.0 ± 2.1 |
| 2QZCluster-SPIRE10 | 150.91631977926385 | 0.3524584795177688 | 60.1 ± 2.1 | 64.7 ± 1.8 | 45.6 ± 2.0 |

### Table 9. SPIRE sources catalogue of HS1700. The full table is available online.

| ID              | R.A.          | Dec.          | $S_{250}$ (mJy) | $S_{350}$ (mJy) | $S_{500}$ (mJy) |
|-----------------|---------------|---------------|-----------------|-----------------|-----------------|
| HS1700-SPIRE1   | 255.53646683056928 | 64.2060083253161 | 422.6 ± 3.1 | 181.4 ± 1.9 | 67.3 ± 2.4 |
| HS1700-SPIRE2   | 255.07096202680116 | 64.3633724187729 | 112.4 ± 2.2 | 49.0 ± 1.9 | 19.5 ± 2.2 |
| HS1700-SPIRE3   | 255.1051146248938 | 64.1466820469269 | 86.2 ± 2.4 | 51.5 ± 2.0 | 21.4 ± 2.1 |
| HS1700-SPIRE4   | 255.15864714103926 | 64.2291613548277 | 85.8 ± 2.5 | 60.5 ± 1.8 | 27.9 ± 2.2 |
| HS1700-SPIRE5   | 254.99347853070503 | 64.26410308634164 | 70.8 ± 2.1 | 76.4 ± 1.7 | 51.2 ± 2.2 |
| HS1700-SPIRE6   | 254.91830411580922 | 64.2174308418698 | 76.7 ± 2.4 | 44.4 ± 1.7 | 17.6 ± 2.3 |
| HS1700-SPIRE7   | 255.22359843297363 | 64.3864521955137 | 65.7 ± 2.2 | 21.3 ± 1.9 | 13.0 ± 2.3 |
| HS1700-SPIRE8   | 254.82938621291324 | 64.1783107895998 | 68.7 ± 2.3 | 59.4 ± 1.7 | 27.6 ± 2.2 |
| HS1700-SPIRE9   | 255.20168775944053 | 64.258505526669 | 66.3 ± 2.2 | 35.3 ± 2.1 | 16.2 ± 2.2 |
| HS1700-SPIRE10  | 255.1823543841818 | 64.0315337252755 | 64.7 ± 2.2 | 64.8 ± 1.9 | 31.2 ± 2.1 |

### Table 10. SPIRE sources catalogue of SSA22. The full table is available online.

| ID              | R.A.          | Dec.          | $S_{250}$ (mJy) | $S_{350}$ (mJy) | $S_{500}$ (mJy) |
|-----------------|---------------|---------------|-----------------|-----------------|-----------------|
| SSA22-SPIRE1    | 334.2644241428561 | 0.676441556203842 | 135.3Å²2.2 | 71.3Å²1.9 | 30.4Å²2.3 |
| SSA22-SPIRE2    | 334.571361684240256 | 0.492191612425483 | 93.3Å²2.2 | 76.7Å²1.7 | 48.7Å²2.3 |
| SSA22-SPIRE3    | 334.3441788443130 | 0.352865223847903 | 79.2Å²2.2 | 34.4Å²1.9 | 10.4Å²2.2 |
| SSA22-SPIRE4    | 334.34457579297244 | 0.607305693911236 | 79.7Å²2.4 | 56.9Å²1.7 | 21.9Å²2.0 |
| SSA22-SPIRE5    | 334.69745115684617 | 0.398386901766686 | 72.9Å²2.2 | 29.8Å²1.9 | 12.8Å²2.1 |
| SSA22-SPIRE6    | 334.392819716858 | 0.304232652494624 | 68.9Å²2.1 | 33.2Å²1.8 | 0.0Å²2.1 |
| SSA22-SPIRE7    | 334.23836274598824 | 0.401941586064945 | 61.8Å²2.1 | 45.8Å²1.8 | 8.8Å²2.1 |
| SSA22-SPIRE8    | 334.55462830631444 | 0.4770183627687165 | 62.9Å²2.1 | 33.3Å²1.8 | 18.3Å²2.0 |
| SSA22-SPIRE9    | 334.384899033597 | 0.291235866249295 | 57.5Å²2.1 | 49.6Å²1.7 | 45.7Å²2.2 |
| SSA22-SPIRE10   | 334.58002216598203 | 0.3500678976437185 | 64.3Å²2.3 | 51.3Å²2.0 | 30.6Å²2.3 |
### Table 11. Matching results for the SPIRE sources which have HAEs counterparts in 2QZCluster.

| ID (SPIRE) | R.A. (J2000) | Dec (J2000) | $S_{250}$ (mJy) | $S_{350}$ (mJy) | $S_{500}$ (mJy) | Counterpart | R.A. (J2000) | Dec (J2000) | Sepa.\(^a\) (arcsec) | p-value\(^b\) | Member\(^c\) |
|------------|--------------|-------------|----------------|----------------|----------------|-------------|--------------|--------------|------------------|--------------|-------------|
| Colour-selected bright SPIRE sources |
| 2QZCluster-SPIRE10 | 150.916320 | 0.352456 | 60.1 ± 2.1 | 64.7 ± 1.8 | 45.6 ± 2.0 | QZC-C1-HAE02(QSO) | 150.915790 | 0.353000 | 2.73 | <0.01 | Secure |

| at least one SPIRE band above 12 mJy sources |
| 2QZCluster-SPIRE124 | 150.965998 | 0.249463 | 21.9 ± 2.2 | 14.2 ± 1.8 | 9.7 ± 2.2 | QZC-C1-HAE03(QSO) | 150.964920 | 0.250583 | 5.60 | <0.01 | Secure |
| 2QZCluster-SPIRE239 | 151.069470 | 0.310488 | 15.4 ± 2.2 | 4.1 ± 1.8 | 6.9 ± 2.3 | QZC-C1-HAE20 | 151.069750 | 0.309167 | 4.86 | <0.01 | Secure |
| 2QZCluster-SPIRE251 | 150.885551 | 0.168325 | 15.5 ± 2.2 | 6.8 ± 2.0 | 3.7 ± 2.3 | QZC-C1-HAE09 | 150.887370 | 0.167917 | 6.71 | <0.01 | Secure |
| 2QZCluster-SPIRE261 | 150.852526 | 0.155903 | 15.8 ± 2.3 | 13.8 ± 1.8 | 12.1 ± 2.2 | QZC-C1-HAE05 | 150.854380 | 0.155694 | 6.72 | <0.01 | Secure |
| 2QZCluster-SPIRE353 | 150.916183 | 0.187292 | 14.4 ± 2.7 | 12.1 ± 1.8 | 3.0 ± 2.1 | QZC-C1-HAE16 | 150.915750 | 0.187722 | 2.20 | <0.01 | Secure |
| 2QZCluster-SPIRE372 | 150.935267 | 0.238716 | 10.2 ± 2.2 | 16.2 ± 1.8 | 14.0 ± 2.1 | QZC-C1-HAE15 | 150.932670 | 0.238944 | 9.39 | 0.01 | Secure |

**Notes.** (a): Separation between SPIRE source and counterparts. (b): p-value based on Downes et al. (1986). (c): We classify sources with $p \leq 0.05$ as secure, and those with $0.05 < p \leq 0.10$ as tentative counterparts.
Table 12. Matching results for the SPIRE sources which have emitter counterparts within overdensity in HS1700.

| ID (SPIRE) | R.A. (J2000) | Dec (J2000) | $S_{250}$ (mJy) | $S_{350}$ (mJy) | $S_{500}$ (mJy) | ID (Count.) | R.A. (J2000) | Dec (J2000) | $z^a$ | Sepa.$^b$ (arcsec) | $p$-value$^c$ | Member$^d$ |
|------------|--------------|-------------|-----------------|-----------------|-----------------|-------------|--------------|-------------|-------|----------------|--------------|----------|
| HS1700-SPIRE21 | 255.3951 | 64.2484 | 52.5 ± 2.2 | 41.2 ± 1.7 | 21.1 ± 2.2 | BNB1 | 255.3953 | 64.2479 | ~2.00$^e$ | 1.63 | < 0.01 | Secure |
| BX980 | 255.3987 | 64.2490 | - | - | - | 6.13 | 0.32 | Not |
| HS1700-SPIRE42 | 255.2428 | 64.2196 | 40.0 ± 2.3 | 46.4 ± 1.8 | 34.3 ± 2.1 | DRG46 | 255.2419 | 64.2195 | - | 1.37 | < 0.01 | Secure |
| HaNB2 | 255.2417 | 64.2196 | - | - | - | 1.75 | < 0.01 | Secure |
| HS1700-SPIRE24 | 255.3349 | 64.2403 | 51.5 ± 2.3 | 63.0 ± 2.0 | 49.3 ± 2.2 | DRG53 | 255.3378 | 64.2395 | ~2.3$^f$ | 5.36 | 0.03 | Secure |
| HaNB10* | 255.3399 | 64.2384 | 2.289(abs) | 10.43 | 0.10 | 0.03 | Secure |
| BX913* | 255.3399 | 64.2385 | 2.291(neb) | 10.29 | 0.05 | Tentative |
| BX928 | 255.3318 | 64.2405 | 2.755(Ly$\alpha$) | 4.92 | 0.22 | Not |

Colour-selected faint SPIRE sources

| ID (SPIRE) | R.A. (J2000) | Dec (J2000) | $S_{250}$ (mJy) | $S_{350}$ (mJy) | $S_{500}$ (mJy) | ID (Count.) | R.A. (J2000) | Dec (J2000) | $z^a$ | Sepa.$^b$ (arcsec) | $p$-value$^c$ | Member$^d$ |
|------------|--------------|-------------|-----------------|-----------------|-----------------|-------------|--------------|-------------|-------|----------------|--------------|----------|
| HS1700-SPIRE321 | 255.2732 | 64.2046 | 13.7 ± 2.4 | 20.2 ± 1.8 | 15.9 ± 2.1 | BNB41* | 255.2688 | 64.2027 | 2.287(abs) | 9.64 | 0.05 | Secure |
| MD109* | 255.2687 | 64.2026 | 2.293(abs,neb) | 10.09 | 0.10 | Tentative |
| DRG38+ | 255.2669 | 64.2032 | 2.286(emi) | 10.98 | 0.05 | Tentative |
| BNB16+ | 255.2670 | 64.2033 | 2.290(emi) | 10.53 | 0.10 | Tentative |

at least one SPIRE band above 12 mJy sources

| ID (SPIRE) | R.A. (J2000) | Dec (J2000) | $S_{250}$ (mJy) | $S_{350}$ (mJy) | $S_{500}$ (mJy) | ID (Count.) | R.A. (J2000) | Dec (J2000) | $z^a$ | Sepa.$^b$ (arcsec) | $p$-value$^c$ | Member$^d$ |
|------------|--------------|-------------|-----------------|-----------------|-----------------|-------------|--------------|-------------|-------|----------------|--------------|----------|
| HS1700-SPIRE70 | 255.2827 | 64.2586 | 31.1 ± 2.2 | 21.4 ± 1.9 | 11.0 ± 2.0 | BNB155 | 255.2811 | 64.2574 | 2.290(Lya) | 5.13 | 0.01 | Secure |
| HaNB27 | 255.2873 | 64.2578 | - | - | - | 7.81 | 0.06 | Tentative |
| HaNB76 | 255.2668 | 64.2469 | 22.7 ± 2.2 | 12.0 ± 1.8 | 1.8 ± 2.2 | HaNB83 | 255.2653 | 64.2487 | - | 6.67 | 0.04 | Secure |
| HaNB45 | 255.3796 | 64.1996 | - | - | - | 3.06 | 0.01 | Secure |
| HaNB45 | 255.3796 | 64.1996 | - | - | - | 5.41 | 0.03 | Secure |

Notes. (a): Redshift information of counterparts. (b): Separation between SPIRE source and counterparts. (c): $p$-value based on Downes et al. (1986). (d): We classify sources with $p \leq 0.05$ as secure, and those with $0.05 < p \leq 0.10$ as tentative counterparts. (e): BNB1 is identified as a $\hat{a}$AJLo-BAL$\hat{a}$AI QSO and therefore it is difficult to measure redshift. (f): Photometric redshift from Chapman et al. (2015).