A Planck-selected dusty proto-cluster at $z=2.16$ associated with a strong over-density of massive Hα emitting galaxies

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ABSTRACT
We discovered an over-density of Hα-emitting galaxies associated with a Planck compact source in the COSMOS field (PHZ G237.0+42.5) through narrow-band imaging observations with Subaru/MOIRCS. This Planck-selected dusty proto-cluster at $z = 2.16$ has 38 Hα emitters including six spectroscopically confirmed galaxies in the observed MOIRCS 4′×7′ field (corresponding to ~2.0×3.5 Mpc$^2$). We find that massive Hα emitters with log($M_*/M_\odot$)>10.5 are strongly clustered in the core of the proto-cluster (within ~300-kpc from the density peak of the Hα emitters). Most of the Hα emitters in this proto-cluster lie along the star-forming main sequence using Hα-based SFR estimates, whilst the cluster total SFR derived by integrating the Hα-based SFRs is an order of magnitude smaller than those estimated from Planck/Herschel FIR photometry. Our results suggest that Hα is a good observable for detecting moderately star-forming galaxies and tracing the large-scale environment in and around high-$z$ dusty proto-clusters, but there is a possibility that a large fraction of star formation could be obscured by dust and undetected in Hα observations.

Key words: galaxies: clusters: general — galaxies: evolution — galaxies: star formation.

1 INTRODUCTION
Within the framework of hierarchical growth of large-scale structures of the Universe, galaxy clusters evolve at intersections of the cosmic web across cosmic time (e.g. Overzier 2016). Galaxy clusters in the local Universe are dominated by red (quiescent) galaxies with old stellar population, and they are believed to be formed in the early universe at $z \gg 1$ accompanying intense starbursts (e.g. Bower, Lucey & Ellis 1992). Young forming clusters are predicted to be observed as strong overdensities of dusty starbursts (Casey 2016; Chiang et al. 2017), and therefore it is vital to find such star-bursting proto-clusters at high redshifts and investigate how the properties of galaxies in today’s clusters were put in place. A growing number of studies have identified such star-forming (or potentially starbursting) proto-cluster candidates in the early universe with various techniques (e.g. Hayashi et al. 2012; Dannerbauer, et al. 2014; Wang et al. 2016; Oteo, et al. 2018; Strazzullo et al. 2018; Lacaille et al. 2019).

A unique approach to detect such short-lived (hence rare) dusty objects at high-$z$ is to use FIR-(sub-)millimeter surveys covering a wide area of the sky. A good example of such dust-selected, highly star-forming systems is the proto-cluster identified around SPTz2349–56, the brightest unlensed source from the 2,500-deg$^2$ South Pole Telescope (SPT) survey (Miller et al. 2018; Hill et al. 2020), where a large number of sub-millimeter galaxies (SMGs) at $z = 4.3$ are clustered within a compact region and its total cluster star formation rate (SFR) is estimated to be $\sim 10^4 M_\odot$/$\text{yr}$.

Planck is a very powerful facility for selecting high-$z$ proto-clusters of dusty sources, taking advantage of its all-sky coverage in sub-millimeter (Planck Collaboration 2015; Clements et al. 2014; Flores-Cacho et al. 2016; Greenslade et al. 2018; Cheng et al. 2019; Kubo et al. 2019). Using the Planck high-$z$ source candidates (PHz) catalogue (Planck Collaboration 2016), in combination with Herschel photometry (HerMES; Oliver et al. 2012), we inves-
tigate the region around a Planck source (PHz G237.0+42.5) lying in the COSMOS field. Within this Planck source, there are several Herschel FIR sources as well as an over-density of X-ray sources. Medium-resolution spectroscopy from follow-up NIR LUCI/LBT observations and optical VIMOS/VLT spectra from the zCOSMOS survey (Lilly et al. 2007) reveal a redshift spike at $z = 2.16$. Narrow-band Hα imaging observations are shown to be successful in detecting high-$z$ star-forming galaxies within a narrow redshift slice for general fields (e.g. Geach et al. 2008; Sobral et al. 2013; Tadaki et al. 2013) and for (proto-)cluster environments (e.g. Koyama et al. 2013; Hayashi et al. 2016; Darvish et al. 2020).

In this Letter, we present Hα imaging observations of the PHz G237 field with Subaru/MOIRCS using a narrow-band filter (NB2071), which is perfectly matched to the Hα lines from the redshift of this structure ($z = 2.16$). Narrow-band Hα imaging observations are shown to be successful in detecting high-$z$ star-forming galaxies within a narrow redshift slice for general fields (e.g. Geach et al. 2008; Sobral et al. 2013; Tadaki et al. 2013) and for (proto-)cluster environments (e.g. Koyama et al. 2013; Hayashi et al. 2016; Darvish et al. 2020). This study presents the first attempt to perform Hα imaging observations towards a Planck-selected proto-cluster—-with the aim to reveal the structures traced by typical SF galaxies, and to study the nature of member galaxies residing in the dust-selected proto-cluster at the peak epoch of galaxy formation. Throughout this Letter, we adopt the standard cosmology with H$_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

## 2 OBSERVATIONS AND Hα Emitter Selection

We carried out MOIRCS/Subaru observations of the PHz G237 field using NB2071 filter ($\lambda_c = 2.068$ $\mu$m, $\Delta \lambda = 0.027$ $\mu$m; corresponding to the Hα line at $z = 2.13$–2.17) on December 21, 2018. The observations were executed in service mode (S18B-206S, PI: Y. Koyama) under very good seeing conditions (FWHM = 0.4″) to create a NB-selected source catalogue. We here applied –0.08-mag offset to the $K_s$-band magnitudes to account for the colour term, and we also applied a small offset (+0.03-mag) in the NB photometry to set $K_s$–NB = 0 (median) at the bright end. We define 53 sources which satisfy $K_s$–NB > 0.25 and $K_s$–NB > 2.5 as NB emitters (black squares in Fig. 1), where $\Sigma$ represents the colour excess in $K_s$–NB (e.g. Bunker et al. 1995). We note that all the NB emitters identified here are also detected at $\gtrsim$3$\sigma$ levels in the ULTRA-VISTA K$-\beta$-band data.

To select Hα emitters (HAEs) at $z = 2.16$ and remove contaminant emitters, we use the information of spec-$z$ (photo-$z$) and $B$-$K$ colours. We first select 6 emitters with $2.150 < z_{\text{spec}} < 2.164$ (Polletta et al. in prep.) as spec-$z$ HAEs. For those without spec-$z$ information, we select HAEs using the photo-$z$ (with $1.8 < z_{\text{photo}} < 2.4$) determined by template fitting in the COSMOS2015 catalogue. In addition, we select NB emitters satisfying $B$-$K$ criteria (Fig. 1), regardless of their photo-$z$. Amongst the 53 NB emitters, we select 6 galaxies as spec-$z$ HAEs, 25 galaxies as photo-$z$ HAEs (5 of which are spec-$z$ HAEs), and 12 galaxies as $B$-$K$ HAEs. While the $B$-$K$ selection is designed to select galaxies at $1.4 < z_{\text{spec}} < 2.5$ (Daddi et al. 2004), this simple colour selection combined with the NB excess allows us to efficiently select Hα emitters at $z > 2$ (see e.g. Koyama et al. 2013; Shimakawa et al. 2018); as can be seen in the $B$-$K$ diagram in Fig. 1, our HAE selection is basically unchanged even if we do not use spec-$z$ or photo-$z$ information. We note that two NB emitters which are not detected at $B$- and/or $z'$-band are not shown in the $B$-$K$ diagram in Fig. 1, but we keep these sources as HAEs in this study as the lower limits of their $z$–$K_s$ colours still satisfy $B$-$K$ selection. In summary, we selected 38 HAEs in total in the observed PHz G237 field.

Figure 1. $K_s$–NB2071 colours plotted against NB2071 magnitudes for all objects detected in our MOIRCS field (grey dots). The vertical and slanted dashed lines indicate 5$\sigma$ and 3$\sigma$ detection limit in NB2071 and $K_s$, respectively. The solid-line curves indicate $\pm$2.5$\sigma$ excess for $K_s$–NB colour.

Our conclusions are not changed even if we use $\text{mag}_{\text{auto}}$ as total fluxes, except that a few emitters selected here do not satisfy the criterion of $K_s$–NB > 0.25 in the case we directly use $\text{mag}_{\text{aper}}$ to define NB excess.
3 RESULTS AND DISCUSSION

3.1 Massive Hα emitters are strongly clustered in the Planck-selected proto-cluster core

We show in Fig. 2 the 2-D distribution of the HAEs (squares), photometrically selected potential cluster members (1.8≤z-photo≤2.4; black circles), and all the NB-detected objects (grey circles) in the PHZ G237 field. Objects with “S” marks are spectroscopic members, six of which are Hα emitters. We compute the local number density at a given point by applying gaussian smoothing (σ=300 kpc) for each HAE and by combining the tails of those gaussian wings. We determine (R.A., Dec.=(10:01:53.67, +02:19:38.9) as the HAE density peak, and the yellow contours in Fig. 2 represent 1.5, 2.0, 2.5, 3.0-σ above the median of the density distribution.

In Fig. 2, HAE symbols are colour coded based on their $M_\star$; i.e. redder colours indicate higher $M_\star$. Stellar masses of HAEs are derived by fitting the SEDs (uBVrizJHK and IRAC ch1 and ch2 photometry from COSMOS), using the FAST code (Kriek et al. 2009). We here assume the fixed redshift (z=2.16), the Bruzual & Charlot (2003) stellar population synthesis model, the Calzetti et al. (2000) dust attenuation law, and the Chabrier (2003) IMF. We also assume exponentially declining SFRs (SFR$_\infty$ exp(−t/τ)) with reasonable parameter ranges for τ, age, metallicity, and $A_V$. The choice for these parameters does not significantly affect the stellar mass estimates and does not affect our conclusions.

It is evident from Fig. 2 that massive HAEs (with log($M_\star/M_\odot$)≥10.5) are strongly clustered around the density peak, and that many of these HAEs are not present in the outer regions. A similar trend was reported for other proto-clusters (e.g. Hatch et al. 2011; Matsuda et al. 2011; Koyama et al. 2013), suggesting an accelerated galaxy growth in dense environments in the early universe. We note that many of these massive HAEs residing in the proto-cluster environment are individually detected at Spitzer/MIPS 24μm image (as shown with green circles in Fig. 2). It is therefore unlikely that these massive HAEs are quiescent galaxies. Their stellar masses are already comparable to the present-day massive cluster galaxies, but they are still actively forming stars (see also Sec. 3.2).

It should also be noted that two of the massive HAEs near the density peak are X-ray sources (see “x” marks in Fig. 2), suggesting Hα emission of these two galaxies may be contributed by AGNs. The stellar masses of these X-ray HAEs may be overestimated, but their stellar masses would still be higher than the median $M_\star$ of our HAE sample, even if we consider a significant fraction of their $M_\star$ estimates are contributed by AGNs (see Sec. 3.2).

3.2 Most Hα emitters in the Planck proto-cluster are typical star-forming galaxies on the main sequence

We derive the Hα+[Nii] line fluxes ($F_{\text{Hα}+[Nii]}$), continuum flux density ($f_c$), and the rest-frame equivalent widths (EW$_\text{rest}$) of HAEs from the $K_s$-band and NB2071 photometry in the same way as Koyama et al. (2013). We estimate the contribution of [Nii] lines ([Nii]/Hα ratio) and Hα dust attenuation (A$_{\text{Hα}}$) using the empirical calibrations established for local SF galaxies; we use [Nii]/Hα–EW$_\text{rest}$(Hα) relation presented by Sobral et al. (2012), and the A$_{\text{Hα}}$–M$_\star$–EW$_\text{rest}$(Hα) relation from Koyama et al. (2015) 2. We then convert the Hα luminosity to SFR$_\text{Hα}$ using the Kennicutt (1998) relation by taking into account the IMF difference.

In Fig. 3, we show the SFR–$M_\star$ diagram for the HAEs in the PHZ G237 field (coloured symbols). In this plot, the colour coding indicates the distance from the HAE density peak; the redder colour symbols tend to be skewed to the massive end; this is a confirmation of our finding in Section 3.1 that massive HAEs are clustered in the high-density environment. We also plot in Fig. 3 the Hα emitters in the Spiderweb proto-cluster at the same redshift (z=2.16) selected using the same NB filter and the same instrument (Shimakawa et al. 2018; see also Koyama et al. 2013). For HAEs with log($M_\star/M_\odot$)>9.5, we find that the fraction of massive HAEs (with log($M_\star/M_\odot$)>10.5) is consistent between PHZ G237 (26±12%) and Spiderweb (30±9%).

2 We confirmed that our conclusions are unchanged even if we use the $A_V$ derived from SED fitting to predict A$_{\text{Hα}}$ (assuming the Calzetti et al. (2000) curve and $E(B-V)_{\text{gas}}/E(B-V)_{\text{Hα}}=0.44$). We find that the average dust-corrected SFRs could be higher by a factor of ~1.8x in this case, but we caution that there is a large uncertainties in $E(B-V)_{\text{gas}}/E(B-V)_{\text{Hα}}$ ratio (which can be 0.44–1.0; see e.g. Koyama et al. 2019).
the PHz G237 proto-cluster field are broadly consistent with those in the Spiderweb proto-cluster and in the general field at similar redshifts, suggesting similar mass growth rates in all environments at a given stellar mass, consistent with our previous studies (e.g. Koyama et al. 2013).

The two X-ray detected HAEs are shown with "X" marks in Fig. 3. If we remove these two AGN candidates, most of the massive HAEs in the proto-cluster core (≤500-kpc from the density peak) tend to be located below the SFMS. This result may suggest a decline of specific SFRs in dense environments, but we must wait future spectroscopic observations because accurate dust attenuation correction is critical to reliably measure the SFRs of such massive SF galaxies at high-z. In fact, there are two 24µm-detected HAEs located significantly below the SFMS in Fig. 3, but their SFRs derived from 24µm photometry (using the SED templates presented by Wuyts et al. 2008) turn out to be ~0.6–0.7 dex higher than what we expected from the dust-corrected Hα line. Unfortunately, the IR-based SFRs are not available for other MIPS-undetected HAEs (and SFRs from 24µm alone also suffer from large uncertainties). In any case, we need spectroscopic follow-up observations to accurately measure the dust attenuation effects, to discuss the exact locations of proto-cluster HAEs with respect to the SFMS.

3.3 Cluster total SFR from Hα and IR

In Fig. 4, we show the cumulative SFR distribution from the HAE density peak (out to 1-Mpc). The black and grey lines represent the results when we use dust-corrected and dust-uncorrected Hα SFRs, respectively. For both black and grey lines, the solid lines show the results for all HAEs, while the dashed lines show the results when we remove two X-ray AGNs. We also show in Fig. 4 the cluster-integrated SFRs measured with various approaches. The blue hatched region shows the integrated dust-corrected SFR Hα for all HAEs within the MOIRCS FoV (the width of the hatched region indicates the results with/without AGNs). The orange shaded region shows the integrated SFR (MIR) of the 24µm-detected HAEs. It seems that the total dust-corrected SFR Hα are consistent with 24µm-based SFRs, but we caution that the total MIPS SFR is computed only for 10 HAEs which are individually detected at 24µm, and thus can be regarded as the lower limit for the cluster total SFR.

Figure 3. SFR-Mα diagram for the Hα emitters identified in the PHz G237 proto-cluster field (square symbols). In this plot, the colour coding indicates the distance from the HAE density peak. The large black circles show MIPS24µm-detected HAEs, and the "x" marks indicate X-ray detected sources. For comparison, we also show HAEs in the Spiderweb proto-cluster at the same redshift from Shimakawa et al. (2018), and the dot-dashed line indicates the SFR-Mα relation for HAEs in field environment at z ~ 2 (Oteo et al. 2015). For comparison, we also show the SFMS at z ~ 2 defined by Speagle et al. (2014) and Whitaker et al. (2014).

4 SUMMARY

With our Subaru/MOIRCS NB Hα imaging observations towards a Planck compact source lying in the COSMOS field (PHz G237.0+42.5), we reported the discovery of a dusty proto-cluster at z = 2.16 associated with an over-density of massive Hα-emitting galaxies. We identified 38 HAEs at z = 2.16 within the observed 4′×2′ FoV, out of which 6 galaxies are spectroscopically confirmed. We find that HAEs residing in the proto-cluster core region (located within ~300-kpc from the HAE density peak) are significantly more massive than those located in the outer regions; massive HAEs (with log(Mα/M⊙) > 10.5) are strongly clustered in the HAE density peak. While these massive HAEs tend to be located below the SFMS (as long as we rely on the Hα-based SFRs), it is likely that most of the Hα emitters in this Planck proto-cluster are typical star-forming galaxies at z ~ 2 located on the SFMS. However, we suggest that the cluster total SFR derived by integrating the Hα-based SFRs of all Hα emitters could be an order of magnitude smaller than those predicted from Planck/Herschel/FIR photometry. Our results suggest that Hα is a good indicator for detecting moderately star-forming galaxies and tracing the large-scale environment in and around high-z dusty clusters, but there remains a possibility that a significant amount of star formation is obscured by dust and unseen by Hα observations.
Figure 4. Cluster-integrated (cumulative) SFRs for HAEs in the Phz G237 proto-cluster field plotted against the distance from the HAE density peak. The black/grey lines show the results for the Hα-based SFRs with/without dust attenuation correction. In both cases, solid lines are the results for all HAEs, while the dashed lines are the results for non-AGN HAEs by removing two X-ray sources. We also show the cluster total SFRs measured from various methods. The blue hatched area shows the total dust-corrected SFR(α) for all 38 HAEs within MOIRCS FoV, while the orange shaded region shows the sum of the IR-derived SFRs for 24μm-detected HAEs in the same FoV (the widths of the stripes indicate the results with/without the AGN effects). We also show the FIR-derived total SFR measured from Planck sub-millimeter flux (red shaded region) and from FIR sources with red Herschel colours located within the MOIRCS FoV (green shaded region).

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DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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