MAMMOTH: Confirmation of Two Massive Galaxy Overdensities at $z = 2.24$ with Hα Emitters

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ABSTRACT
Massive galaxy overdensities at the peak epoch of cosmic star formation provide ideal testbeds for the formation theories of galaxies and large-scale structure. We report the confirmation of two massive galaxy overdensities at $z = 2.24$, BOSS1244 and BOSS1542, selected from the MAMMOTH project using Lyα absorption from the intergalactic medium over the scales of 15–30 $h^{-1}$Mpc imprinted on the quasar spectra. We use Hα emitters (HAEs) as the density tracer and identify them using deep narrow-band Hα S1 and broadband $K_s$ imaging data obtained with CFHT/WIRCam. In total, 244 and 223 line emitters are detected in these two fields, and 196 ± 2 and 175 ± 2 are expected to be HAEs with an Hα flux of $> 2.5 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ (corresponding to an SFR of $> 1.5 \times 10^{-3}$ M$_\odot$ yr$^{-1}$). The detection rate of HAE candidates suggests an overdensity factor of $\delta_{\text{gal}} = 5.6 \pm 0.3$ and $4.9 \pm 0.3$ over the volume of $54 \times 32 \times 32$ cMpc$^3$. The overdensity factor increases 2–3 times when focusing on the high-density regions of scales 10 – 15 cMpc. Interestingly, the HAE density maps reveal that BOSS1244 contains a dominant structure, while BOSS1542 manifests as a giant filamentary structure. We measure the Hα luminosity functions (HLF), finding that BOSS1244’s HLF is nearly identical to that of the general field at the same epoch, while BOSS1542 shows an excess of HAEs with high Hα luminosity, indicating the presence of enhanced star formation or AGN activity. We conclude that the two massive MAMMOTH overdensities are undergoing a rapid galaxy mass assembly.

Key words: galaxies: clusters: individual – galaxies: high-redshift – galaxies: star formation – quasars: absorption lines

1 INTRODUCTION

Understanding the formation of galaxy clusters is a central task in modern astrophysics (Berrier et al. 2009; Allen, Evrard & Mantz 2011). While the standard ΛCDM model is successful at reproducing the dark matter-driven perspective of cluster formation (e.g., the abundance and clustering properties), the physical processes that regulate the mass assembly of cluster member galaxies and influence the baryons within a cluster through feedback remain to be fully understood (Kravtsov & Borgani 2012; Schaye et al. 2015). Compared with the general field, galaxy clusters contain more massive galaxies and amplify details of these baryonic processes, including gas cooling, star formation, stellar feedback, black hole activity, galaxy merging and environmental effects, thus making them unique testbeds for theoretical models of galaxy formation (Overzier 2016).

It has long been known that the dense environment of galaxy clusters dramatically affect galaxy properties. The massive early-type galaxies in the clusters tend to form at earlier epochs, indicating that their progenitors would be actively star-forming galaxies (SFGs) in galaxy protoclusters at $z \gtrsim 2 – 3$ (Thomas et al. 2005). Indeed, cluster galaxies have lower star formation rates (SFRs) than field galaxies in the local universe (e.g., Dressler 1984; Kauffmann et al. 2004; Blanton & Moustakas 2009; von der Linden et al. 2010; Owers et al. 2019), while this trend is found to be reversed at $z > 1$ (Elbaz et al. 2007; Tanaka et al. 2010; Koyama et al. 2013; Dannerbauer et al. 2014; Tran et al. 2015; Umehata et al. 2015; Hayashi et al. 2016; Shimakawa et al. 2018a). A

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higher fraction of active galactic nuclei (AGNs) was reported in some \( z \sim 1 - 3 \) protoclusters compared with the general field at the same epoch, indicating an enhanced growth of supermassive black holes (SMBHs) in the high-density environment (Lehmer et al. 2009; Digby-North et al. 2010; Martini et al. 2013; Krishnan et al. 2017). Similarly, the fraction of galaxy mergers (Hine et al. 2016; Watson et al. 2019) and galaxy gas fraction (Noble et al. 2017; Coogan et al. 2018) are likely to be higher in \( z > 2 \) protoclusters, although the fraction of massive gas-rich SFGs in the central regions of protoclusters depends on their evolutionary stage (Casey et al. 2015; Wang et al. 2018; Shimakawa et al. 2018a; Zavala et al. 2019). Nevertheless, how these distant SFGs evolve into the local massive galaxies in different cluster environments is still not yet clear (e.g., De Lucia & Blaizot 2007; Lidman et al. 2012; Contini et al. 2016; Casey 2016; Shimakawa et al. 2018b). In particular, where and how different environmental interactions play roles in shaping galaxy properties remain open questions. Galaxy protoclusters at the peak epoch of cosmic star formation and black hole growth (\( z \sim 2 - 3 \); Madau & Dickinson 2014) provide a useful probe of the rapid mass assembly of galaxies in relation to structure formation (Bond, Kofman & Pogosyan 1996; Boylan-Kolchin et al. 2009; Bridwin et al. 2013; Chiang et al. 2017). Investigating massive protoclusters and the properties of their member galaxies at this peak epoch will provide key constraints on the environmental dependence of the galaxy evolution and black hole growth.

A protocluster refers to an unvirialized structure of all the dark matter and baryons that will assemble into a present-day galaxy cluster. Galaxy protoclusters at \( z > 2 \) are expected to have an average overdensity of \( \rho / \bar{\rho} \approx 2 \) over a scale of \( \gtrsim 20 h^{-1} \text{Mpc} (\sim \text{Mpc}) \) (Mulderw, Hatch & Cooke 2015; Lovell, Thomas & Wilkins 2018). In practice, one can identify galaxy overdensities of a given scale at high \( z \) but whether they are protoclusters depends on the scale and their surrounding gravitational environments. Generally, massive overdensities over large scales of \( \gtrsim 10 - 30 h^{-1} \text{cMpc} \) are naturally represent protoclusters while small-scale overdensities may be either the progenitors of local groups or part of the protoclusters. Yet, a number of \( z > 2 \) protoclusters have been spectroscopically identified. However, few of them were initially identified as massive overdensities at a scale of \( \gtrsim 20 h^{-1} \text{cMpc} \). These protoclusters were selected by various means and thus often biased by selection effects (e.g., Shi et al. 2019). Deep cosmic surveys are used to detect protoclusters at high \( z \) (e.g., Lemaux et al. 2014; Cucciati et al. 2014; Yuan et al. 2014; Tran et al. 2015; Chiang et al. 2015; Wang et al. 2016; Toshikawa et al. 2016). Rare massive sources, e.g., quasars or bright radio galaxies, usually reside in dense environments and can also be used as protocluster indicators (Venemans et al. 2007; Hayashi et al. 2012; Ounoue et al. 2018). Surveys for galaxy clusters relying on either the Sunyaev-Zel’dovich (SZ) effects (Bleem et al. 2015) or excess of red-sequence galaxies (Gilbank et al. 2011; Strazzullo et al. 2016) are biased to pick up relaxed ones mostly at \( z < 1.5 \), containing hot gas and/or a large fraction of quenched massive galaxies. The sample of confirmed protoclusters at \( z = 2 - 4 \) selected by these approaches are incomplete and difficult for statistical comparisons with hierarchical models of structure formation (Chiang, Overzier & Gebhardt 2013). Moreover, the evolution of the most massive haloes at high \( z \) are essentially determined by the surrounding density field on large scales of \( \gtrsim 10 h^{-1} \text{cMpc} \) (Angulo et al. 2012). The identified protoclusters at small scales might not necessarily evolve into the present-day massive clusters.

Lya forest optical depth is predicted to be strongly correlated with dark matter overdensity at scales of \( \gtrsim 3 h^{-1} \text{cMpc} \) and the correlation peaks at \( 10 - 30 h^{-1} \text{cMpc} \) (e.g., Kollmeier et al. 2003). Cai et al. (2016) demonstrated with simulations that the intergalactic medium (IGM) traces the underlying dark matter density field, and the strongest IGM Lya absorptions mostly trace massive overdensities at the scale of \( 15 h^{-1} \text{cMpc} \). Based on this correlation, a novel approach (MAMMOTH: Mapping the Most Massive Overdensities Through Hydrogen) has been developed for identifying such mass/galaxy overdensities at \( z = 2 - 3 \), traced by groups of Coherently Strong Lya Absorption (CoSLA) imprinted on the spectra of a number of background quasars (Cai et al. 2016). This method is inherently less biased than many other techniques because the H I density is closely correlated with matter density over large scales. It also covers a much larger survey volume, when using the large quasar absorption line database from spectroscopic surveys such as SDSS and BOSS. This technique has been successfully confirmed with the discovery of the BOSS1441 protocluster at \( z = 2.32 \) using the early data release of SDSS-III (Cai et al. 2017). The spectroscopic database from SDSS-III allow us to search for more massive overdensities of scales of \( 10 - 30 h^{-1} \text{cMpc} \) over dramatically larger volumes.

We aim to construct a statistical sample of MAMMOTH overdensities and fully quantify and characterize their member galaxies. We use a pre-existing narrowband filter \( H_2 S1 \) to detect HAEs at \( z = 2.24 \), which resulted in the selection of two \( z = 2.24 \) overdensities traced by extreme groups of IGM Lya absorption systems from SDSS-III quasar spectra. In this work, we present the results of confirmation of the two massive overdensities with \( H_\alpha \) emitters. A detailed analysis of member \( H_\alpha \) emission-line galaxies will be presented in a subsequent paper (Shi, D. D. et al. in prep). The selection of a sample of MAMMOTH overdensities and implications to the formation of cosmic structures will be given in Cai Z. et al. (in prep).

In Section 2, we introduce how the two targets are selected. Section 3 presents the near-infrared imaging observations and data reduction. Our results are given in Section 4. We discuss and summarize our results in Section 5. A standard CDM cosmology with \( H_0=70 \text{km}^{-1} \text{Mpc}^{-1}. \Omega_M=0.7 \) and \( \Omega_{\Lambda}=0.3 \) and a Kroupa (2001) Initial Mass Function (IMF) are adopted throughout the paper. All magnitudes are referred to the AB system unless mentioned otherwise.

2 SELECTION OF TWO \( z = 2.24 \) MAMMOTH TARGETS

Our goal is to confirm the massive overdensity candidates from MAMMOTH using \( H_\alpha \) emission-line objects at \( z = 2.246 \pm 0.021 \) selected from narrow-band \( H_2 S1 \) (\( \Delta \lambda = 2.130 \mu m, \Delta I = 0.0293 \mu m \)) and broad-band \( K_s \) filters on CFHT/WIRCam. The MAMMOTH overdensities are selected using the IGM Lya forest absorption systems from the SDSS-III (Alam et al. 2015) over a sky coverage of
10,000 deg$^2$. To match the H$_2$S1 filter, only the deep IGM absorption with the redshift range of $z = 2.246 \pm 0.021$ are used.

Following Cai et al. (2016), the deep Ly$\alpha$ absorbers are selected by selecting regions where the effective optical depth ($\tau_{\text{eff}}$) over 15 h$^{-1}$ Mpc ($\sim 15 \AA$) is 4x higher than the mean optical depth at $z = 2.2$. Using the selection criteria described in detail in Cai et al. (in prep), we removed the contaminant DLAs which also causing large EW absorption based on the Ly$\alpha$ absorption profiles. We then select the fields with the highest density of deep IGM absorption. From the complete SDSS-III quasar database, we identified two target fields, BOSS1244 and BOSS1542, suitable for observing in the Spring-Summer semester. The two fields have groups of IGM strong absorption systems comparable to those in the BOSS1441 field (Cai et al. 2017) and also contain several quasi-stellar objects (QSOs; i.e., quasars) at the same redshift. Figure 1 and Figure 2 present the effective optical depth $\tau_{\text{eff}}$ along the line of sight derived from strong Ly$\alpha$ absorption lines by absorbers at $z = 2.24$ imprinted on quasar spectra in the two selected fields. These absorbers probed by background quasars spread over a scale of 15 h$^{-1}$ Mpc.

3 OBSERVATIONS AND DATA REDUCTION

We used WIRCam on board the Canada-France-Hawaii Telescope (CFHT) to obtain deep near-infrared (NIR) imaging of the two MAMMOTH fields in both the narrow H$_2$S1 ($\lambda_c = 2.130 \mu m$, $\Delta \lambda = 0.0293 \mu m$) and broad $K_s$ ($\lambda_c = 2.146 \mu m$, $\Delta \lambda = 0.3250 \mu m$) filters (PI: FX An). The observations were carried out with the regular QSO mode under a median seeing of 0.65 – 0.7. WIRCam has a field of view of 20$\times$20', covered by four 2048$\times$2048 HAWAIIR2-RG detectors with a pixel scale of 0.73 pixel$^{-1}$. The gaps between detectors are 45'''. The observations were dithered to cover gaps between detectors and correct for bad pixels. We centered the FOV of WIRCam at the centers of BOSS1244 (R.A.=12:43:55.49, Dec.=$+35:59:37.4$) and BOSS1542 (R.A.=15:42:19.24, Dec.=$+38:54:14.1$) for the epoch of J2000.0. The total integration times are 7.18 and 4.96 hours for the H$_2$S1 and $K_s$ observations in BOSS1244, and 7.275 and 5.17 hours for the H$_2$S1 and $K_s$ observations in BOSS1542, respectively. Each exposure takes 190 s for the H$_2$S1 filter (194 s in BOSS1542) and 20 seconds for the $K_s$ filter. Accounting for the overall overhead time (10% exposure), the total observing time is 7.50 hours for each of the two bands in BOSS1244, and 7.65 hours for H$_2$S1 and 7.75 hours for $K_s$ in BOSS1542. In total 30.40 hours of telescope time were used in our observing program of two MAMMOTH fields.

The data reduction was carried out following An et al. (2014). The reduced H$_2$S1 and $K_s$ images were calibrated in astrometry using compact sources from SDSS. In total ~700 SDSS compact sources with $12.0 < z[\text{mag}] < 20.5$ in the BOSS1244 field and 1,985 compact sources with $12.0 < z[\text{mag}] < 20.5$ in the BOSS1542 field are used for astrometric calibration, giving an astrometric accuracy of $\sim 0.1$ cent. Co-adding 136/893 and 135/930 frame H$_2$S1/$K_s$ science images produced the final science images and the exposure time maps in BOSS1244 and BOSS1542, respectively. The point sources from 2MASS catalog are used to perform photometric calibration. In total 186 and 283 point sources with 12.6 $< K_s[\text{mag}] < 15.5$ in the two fields are selected for photometric calibration. An empirical point spread function (PSF) is built from these stars and used to derive aperture correction. The photometric calibration reaches an accuracy of 1% for the selected stars in our mosaic H$_2$S1 and $K_s$ images.

All final science images of the two MAMMOTH fields show a similar Point Spread Function (PSF) with Full Width at Half Maximum (FWHM) of 0.78$\pm$0.01. Figure 3 and Figure 4 present the H$_2$S1 and $K_s$ science images and corresponding exposure maps for BOSS1244 and BOSS1542, respectively. The effective area with a total integration time of $> 0.5 \times$ maximum is 417 and 436 arcmin$^2$ for H$_2$S1 and $K_s$ in BOSS1244, and 399 and 444 arcmin$^2$ for H$_2$S1 and $K_s$ in BOSS1542, respectively. The image depth (5$\sigma$, AB for point sources) within the effective area is estimated through random photometry on blank background using an aperture
of 2′′ diameter, giving $H_2S1 = 22.58$ mag and $K_s = 23.29$ mag for BOSS1244 and $H_2S1 = 22.67$ mag and $K_s = 23.23$ mag for BOSS1542.

4 RESULTS

4.1 Identifying emission-line objects

We select emission-line objects through narrow $H_2S1 +$ broad $K_s$ imaging with CFHT/WIRCam in two $20′ × 20′$ fields of MAMMOTH overdensities. The software SExtractor (Bertin & Arnouts 1996) is used for source detection and flux measurement in the $H_2S1$ image. A secure source detection is based on at least five contiguous pixels that contain fluxes above three times the background noise ($≥ 3\sigma$). The exposure map is used as the weight image to suppress false sources in the low signal-to-noise (S/N) area. The exposure map is used as the weight image to suppress false sources in the low signal-to-noise (S/N) area. The $H_2S1$ and $K_s$ images are aligned into the same frame. Photometry is carried out using SExtractor under the “dual-image” mode, in which the flux of a source in the $K_s$ image is measured over the same area as in the $H_2S1$ image. We limit source detection in the area with a 5σ depth down to $H_2S1 = 22.58$ mag for BOSS1244 and $H_2S1 = 22.67$ mag for BOSS1542. The same detection area in $K_s$ reaches a depth of $K_s = 23.29$ mag and $23.23$ mag, respectively. In total, 6,253 and 8,012 sources are securely detected with an S/N ratio of $3+\Sigma$ and $25+\Sigma$ respectively. The presence of a strong emission line induces a flux excess in the narrow band relative to the broad band. We use $K_s - H_2S1$ to select emission-line objects as

$$K_s - H_2S1 > -2.5 \log(1 - \frac{\sigma_{H_2S1}^2 + \sigma_{K_s}^2}{f_{H_2S1}}),$$  \tag{1}$$

where $\Sigma$ is the significant factor, $\sigma_{H_2S1}$ and $\sigma_{K_s}$ are $H_2S1$ and $K_s$ background noises. Here $H_2S1$-band flux is defined as $f_{H_2S1} = 0.3631 \times 10^{0.4(H_2S1)}$. The background noises and $f_{H_2S1}$ are given in units of $\mu$Jy. Figure 5 shows the color $K_s - H_2S1$ as a function of $H_2S1$ magnitude for sources detected in BOSS1244 and BOSS1542. We adopt $\Sigma > 3$ to identify emission-line objects. The strength of an emission line is quantified by the rest-frame equivalent width (EW). Here a cut of $EW > 45$ Å is adopted to minimize false excess caused by the photon noises of bright objects. This cut corresponds to $K_s - H_2S1 > 0.39$ mag. A lower EW cut (e.g., $EW > 30$ Å) will increase only a few more candidates and thus have marginal effect on our results.

From Figure 5, 251 and 230 emission-line candidates are selected with $\Sigma > 3$, $EW > 45$ Å and $H_2S1 < 22.5$ mag in BOSS1244 and BOSS1542, respectively. We visually examined these candidates and removed 7/7 of the 251/230 false sources in the two fields. They are either spikes of bright stars or contaminations. In the end, 244 and 223 emission-line objects are identified in BOSS1244 and BOSS1542, respectively. Among these emission-line objects, five in BOSS1244 and three in BOSS1542 are spectroscopically confirmed as QSOs at $z ∼ 2.24$ in SDSS.

The emission lines in the $H_2S1$ filter may be Hα at $z = 2.24$, Paα at $z = 0.14$, [Fe II] at $z = 0.30$, Paβ at $z = 0.66$, [S III] at $z = 1.23/1.35$ and [O III] at $z = 3.25$. By limiting the $H_2S1$ and $K_s$ data from An et al. (2014) to the depths of our observations, we estimate that about 78 emitters would be detected over 383 arcmin$^2$ of the Extended Chandra Deep Field South (ECDFS). Of these emitters, 36–40 per cent are HAEs (Hayes, Schaerer & Östlin 2010; Lee et al. 2012; An et al. 2014), suggesting a number density of $31 – 34$ over 417 arcmin$^2$ for HAEs in the general field. The numbers of emitters we detect in the two MAMMOTH fields are much higher, undoubtably contributed by an excess of HAEs at $z ∼ 2.24$. This is strongly supported by the fact that a group of CoSLAs at $z ∼ 2.24$, as a convincing tracer of overdensities, are probed by the background quasars, as well as the fact that these spectroscopically-identified QSOs are also detected as the emitters at the same redshift (i.e., $z = 2.24$).
Moreover, the possibility that the excess of emitters is associated with other redshift slices is negligible. We point out that the volume is too small to contain a significant number of Paα emitters at $z = 0.14$ or [Fe ii] emitters at $z = 0.30$. The strong [S ii] emission lines are usually powered by shock waves in the post-starburst phase (An et al. 2013). As we will show later, the excess is contributed by an overdensity of $\delta_{\text{gal}} > 5$, where $\delta_{\text{gal}} = (\Sigma - \Sigma_{\text{field}})/\Sigma_{\text{field}}$. It is hard to believe that a large number of SFGs in such massive overdensities at $z = 1.23/1.35$ could turn them into the post-starburst phase in a locked step. The excess of emitters is unlikely associated with overdensities at $z \approx 3.25$ traced by [O iii] emitters because no $z \approx 3.25$ CoSLAs are found from the spectra of the background quasars. We caution that the weak overdensities at $z = 1.23/1.35$ or $z = 3.25$, if exist, might still contaminate the identification of substructures in the HAE-traced overdensities at $z = 2.24$ unless these emitters are identified with spectroscopic redshifts.

We aim to estimate the total number of HAEs detected in our fields. It is clear that the detection rate of HAEs is sensitive to the image depths and cosmic variance. The datasets in ECDFS suggest 78 emitters (33 HAEs and 45 non-HAEs) to be detected over 383 arcmin$^2$ using our selection criteria. We remind that this likely overestimates the emitter detection rate because the detection completeness is higher in the deeper ECDFS observations. Instead, we adopt 78 emitters detected over the survey area of 417 arcmin$^2$ in BOSS1244, giving a detection rate of 0.187 per arcmin$^2$. We adopt 36 – 40 percent of the emitters as HAEs (Hayes, Schaerer & Östlin 2010; Lee et al. 2012; An et al. 2014), giving a detection rate of 0.071±0.004 per arcmin$^2$ for HAEs at $z = 2.24$ and 0.116±0.004 per arcmin$^2$ for non-HAEs. We obtain 48±2 non-HAEs and 30±2 HAEs over the same area in the general field. We use these two numbers for both of our two fields and ignore the variation in survey area. Of 244/223 emission-line objects, we estimate the number of HAEs at $z = 2.24$ to be $196\pm2/175\pm2$ in BOSS1244/BOSS1542, yielding an overdensity factor $\delta_{\text{gal}} = 5.6 \pm 0.3$ for BOSS1244 and $4.9 \pm 0.3$ for BOSS1542. Here the errors account only for the variation in the fraction of HAEs in the general field. The uncertainty in the detection rate of emitters is mostly driven by the cosmic variance and not counted here. We notice that there are only 21/28 objects in the low-density regions of BOSS1244/BOSS1542, giving an emitter detection rate of 0.124/0.135 per arcmin$^2$ (see next section for more details) slightly lower than the adopted value (0.187 per arcmin$^2$). This hints that the cosmic variance may induce an uncertainty up to 50 per cent. Since the fraction of HAEs in the low-density regions is unknown, we choose ECDFS as a representative for the general field. We point out that decreasing the detection rate for the general field will increase the overdensity factors that we estimated, and further strengthen our conclusions. When focusing on the high-density regions (see Figure 6), the overdensity factor increases by 2–3 times.

The redshift slice of $z = 2.246 \pm 0.021$ over 20 × 20 arcmin$^2$ corresponds to a co-moving box of 54.3×32.0×32.0 (=55,603) $h^{-3}$ cMpc$^3$, equal to a cube of 38.2 $h^{-1}$ cMpc each side. The overdensity factor of $\delta_{\text{gal}} \sim 5–6$ over such a large scale displays the overdensities in our two target fields as most massive ones at the epoch of $z \sim 2–3$ (Cai et al. 2016). We thus conclude that the large excess of HAEs confirms BOSS1244 and BOSS1542 as massive overdensities at $z = 2.24$. The confirmation validates the effectiveness of the MAMMOTH technique in identifying the massive overdensities of scales 15 – 30 $h^{-1}$ Mpc at $z \sim 2–3$. We note that the redshift slice is given by the width of the $H_{2}S1$ filter that corresponds to a line-of-sight distance of 54.3 cMpc at $z = 2.24$. This scale should be sufficiently large for the detection of the progenitor of local clusters like the Coma (Chiang, Overzier & Gebhardt 2013), although there is still possibility that some galaxies of the overdensities might spread out of the redshift slice (e.g., a protocluster across ~ 60 cMpc in the
SSA22 field; Matsuda et al. 2005) possibly partially due to the Fingers of God effect caused by the peculiar velocities of galaxies. A complete census of these massive overdensities will require spectroscopic surveys of galaxies over a larger sky coverage and wider range in redshift to map the kinematics of the overdensities and their surrounding density fields.

4.2 Density maps of Hα emitters

We estimate that 196 of 244 (80 per cent) and 175 of 223 (78 per cent) emission-line objects are HAEs at $z = 2.24$ that belong to the massive overdensity BOSS1244 and BOSS1542, respectively. The non-HAEs are located at foreground or background of the $z = 2.24$ slice. In the ECDFS field, non-HAEs consist of 42 per cent foreground and 58 per cent background emitters (i.e., [O III] emitters at $z = 3.25$), when limiting the detection to the depths of the BOSS1244 observations. One can expect that these non-HAEs spread randomly over the observed area. We thus use all emitters to build the density map and the presence of non-HAEs can be seen as a flat density layer in a statistical manner. We adopt the number density of 0.116 per arcmin$^2$ for non-HAEs and of 0.071 per arcmin$^2$ for $z = 2.24$ HAEs in the general field. We note, however, that galaxies reside in the cosmic web, we can not exclude the possibility that the foreground or background non-HAEs might associate with some structures and contaminate the density maps of HAEs at $z = 2.24$.

We identified the emission-line objects in the high-$S/N$ regions, corresponding to an area of $20' \times 20'$ in each field. We treat each object equally and use the projected number density of all emitters to trace the projected matter density. The detection area is divided into a grid of cells with $1'/2 \times 1'/2$ each, and the number of emitters in each cell region is then counted to generate a density map. A Gaussian kernel of $\sigma=1'$ (1.6 cMpc at $z = 2.246$) is utilized to convolve the density map. Contours of density maps are drawn at the levels of 4, 8, 12, 16, 20 and 24 $\times$ the number density of HAEs of the general field (0.071 per arcmin$^2$) plus the number density of non-HAEs (0.116 per arcmin$^2$). Figure 6 shows the spatial distributions of emission-line objects in two MAMMOTH fields, over plotted with the density maps. The contours in two density maps are given in identical levels in order to compare these two fields. Out of the first contour level lines, there are only 21/28 objects in BOSS1244/BOSS1542. We adopt the contour lines at the level of 5.2 $\times$ 0.071 per arcmin$^2$ (the dotted lines in Figure 6) as the boundaries of the dense regions to ensure that the outskirts contain $\sim$40 objects sufficient for a meaningful statistics and avoid serious contamination from the dense regions at the same time. In BOSS1244, the dense regions include two parts: left density and right density (i.e., the elongated structure). In BOSS1542, HAEs form a giant filamentary structure. We split the dense regions into two roughly equal parts via a horizontal line at Dec = 38.92: top density and bottom density. Figure 7 shows the cumulative curves of line fluxes in different parts of the two MAMMOTH fields. Here five QSOs in BOSS1244 and three QSOs in BOSS1542 are excluded. For comparison, we present the cumulative curves for the HAEs at $z = 2.24$ and non-HAEs (i.e., foreground emitters) in ECDFS from An et al. (2014). These emitters are selected at the same detection depths as our BOSS1244 observations.

It is clear from Figure 6 that the density maps traced by HAEs reveals sub-structures of the two massive overdensities. BOSS1244 exhibits two components within the observed area — a low-density component connected to an elongated high-density component of a scale of 25$x10'$cMpc. The high-density component spreads over an area of 103 arcmin$^2$ within the first contour level and reaches an overdensity factor of $\delta_{gal} \sim 15$, and even $\sim 24$ in the central $4' \times 6'$ region. The massive overdensities of $\delta_{gal} > 6$ traced by star-forming galaxies over (15 cMpc)$^2$ are predicted by simulations exclusively to be proto-clusters, i.e., the progenitors of massive galaxy clusters of $> 10^{15} M_\odot$ (e.g., Coma cluster) in the local universe (Chiang, Overzier & Gebhardt 2013). One caveat is that the elongated structure in BOSS1244 might be extended or divided into multiple components along line of sight over 54.3 cMpc. Even if we divide the overdensity factor $\delta_{gal} \sim 15$ by three to match the volume of (15 cMpc)$^3$, the divided structures would be still sufficiently massive and overdense to form massive clusters.

In contrast, BOSS1542 can be seen as a large-scale filamentary structure with multiple relatively dense clumps. The density and size of these clumps are significantly smaller than the dominant component of BOSS1244. The total length of the structure along the filament reaches 50 cMpc. This structure covers an area of 192 arcmin$^2$ ($\sim 32 \times 15$ cMpc at $z = 2.246$) and yields $\delta_{gal} \sim 10$ within the first contour level shown in Figure 6. The bottom part at Dec. $< 38.88$ spread over 72 arcmin$^2$ ($\sim 12 \times 15$ cMpc at $z = 2.246$) and have a mean $\delta_{gal} \sim 11$. We suspect that at least part of the filamentary structure could eventually condense into one massive galaxy cluster as revealed by simulations (e.g., Chiang, Overzier & Gebhardt 2013). Spectroscopic observations can map kinematics of member galaxies and quantitatively determine if different components in these overdensities could merge into one mature cluster of galaxies. We will carry out a detailed analysis of dynamics and masses for the two HAE-traced overdensities using spectroscopic data in a companion work (Shi D. D. et al., in prep).

We notice that the density maps of our two HAE-traced structures might be contaminated by the foreground or background emitters that are probably associated with overdensities. We examine the possibility by comparing the line flux distributions of those emitters in dense regions and outskirts. Out of the first contour level lines, there are only 21/28 objects in BOSS1244/BOSS1542. We adopt the contour lines at the level of 5.2 $\times$ 0.071 per arcmin$^2$ (the dotted lines in Figure 6) as the boundaries of the dense regions to ensure that the outskirts contain $\sim 40$ objects sufficient for a meaningful statistics and avoid serious contamination from the dense regions at the same time. In BOSS1244, the dense regions include two parts: left density and right density (i.e., the elongated structure). In BOSS1542, HAEs form a giant filamentary structure. We split the dense regions into two roughly equal parts via a horizontal line at Dec = 38.92: top density and bottom density. Figure 7 shows the cumulative curves of line fluxes in different parts of the two MAMMOTH fields. Here five QSOs in BOSS1244 and three QSOs in BOSS1542 are excluded. For comparison, we present the cumulative curves for the HAEs at $z = 2.24$ and non-HAEs (i.e., foreground emitters) in ECDFS from An et al. (2014). These emitters are selected at the same detection depths as our BOSS1244 observations.

It is clear from Figure 7 that in ECDFS the observed line fluxes of the HAEs at $z = 2.24$ are systematically higher by 0.1 dex than those of the non-HAEs. We note that the 45 non-HAEs include 26 [O III] emitters at $z = 3.25$ that appear globally fainter than HAEs at $z = 2.24$. In BOSS1244, the right density (i.e., the elongated dominant structure in Figure 6) contains emitters with line fluxes relatively higher than the emitters in the outskirts; the left density shows a cumulative curve similar to that of the outskirts. It is worth noting that the left density made of 68 objects are an extended and weak concentration, and the right density host
Figure 6. Density maps of HAE candidates in BOSS1244 (left) and BOSS1542 (right). Black circles represent the selected emission-line candidates. A Gaussian kernel of $\sigma = 1'$ (1.6 cMpc at $z = 2.246$) is adopted to smooth the density maps and draw the contours in the same linear scale. The contour levels refer to $[4, 8, 12, 16, 20, 24] \times$ the number density of HAEs in the general field (0.071 per arcmin$^2$). The dotted lines mark the contour level of $5.2 \times 0.071$ per arcmin$^2$ used as the boundaries between the outskirts and dense regions. A group of Coherently Strong Ly$\alpha$ Absorption (CoSLA, green diamonds) and QSOs (blue stars) at $z \approx 2.24$ are marked. Green numbers mark CoSLAs shown in Figure 1 and 2. Black crosses pinpoint the emitters with highest line fluxes ($\log L_{\text{H}\alpha} > 43.4$). The HAE-traced density maps uncover that the two massive overdensities have different structures: BOSS1244 is dominated by an elongated high-density structure, and BOSS1542 appears to be a large-scale filamentary structure.

Figure 7. Cumulative fraction of the observed line fluxes in different parts of BOSS1244 (left) and BOSS1542 (right). The description of these parts are given in the text. The numbers of line emitters in these parts are presented. The line emitters in the ECDFS field from An et al. (2014) are taken as the representative of the general field at $z = 2.24$. Here the detection in ECDFS is limited to the same depths of the $H_2$S1 and $K_s$ observations in BOSS1244. The cumulative curves of H$\alpha$ emitters (black) and of non-H$\alpha$ emitters (gray) in ECDFS are shifted by $-0.5$ dex for clarity. We can see that the line fluxes of H$\alpha$ emitters are relatively higher (by $\sim 0.1$ dex) than those of non-H$\alpha$ emitters in ECDFS. In BOSS1244 and BOSS1542, the emitters in the high-density regions also have emission lines relatively brighter than the emitters in the outskirts. We note that a correction of $[\text{N} \text{II}]/$H$\alpha = 0.117$ is needed to obtain H$\alpha$. The flux of H$\alpha$ at $z = 2.24$ can be converted to luminosity by adding 58.58 dex and extinction correction for $A(\text{H}\alpha) = 1$ mag will increase the luminosity by 0.4 dex.
all emitters with log f_{\text{line}} > -15.6. In BOSS1542, the line fluxes of the emitters in both the top and bottom density are statistically higher by typically ~0.1 dex in comparison with those of the emitters in the outskirts; the top density contains more objects with high line fluxes. We can conclude that the emitters in the high-density regions have line fluxes globally higher than the emitters in the outskirts of the two MAMMOTH overdensities, following the difference of the line flux distributions between HAEs and non-HAEs in ECDFS.

Moreover, the cumulative distribution of line fluxes of the emitters in the outskirts appears analogous to that of the non-HAEs in ECDFS. We use Kolmogorov–Smirnov (K–S) test to quantify the probability that two samples are drawn from the same population. It measures the significance level of consistency of two cumulative distributions. The p-value of K–S test is 0.59, 0.06 and 0.001 when comparing the non-HAEs in ECDFS with the emitters in the outskirts, left-density and right-density regions of BOSS1244, and 0.38, 1.45×10^{-5} and 5.40×10^{-5} with these in the outskirts, top-density and bottom-density regions of BOSS1542, respectively. Similarly, K–S test yields 0.26, 0.96 and 0.97 for the HAEs in ECDFS in comparison with the three emitter samples in BOSS1244, and 0.19, 0.22 and 0.24 with the three emitter samples in BOSS1542, respectively. These results show that the emitters in the outskirts of two MAMMOTH overdensities satisfy the line flux distribution of the non-HAEs in ECDFS at a high significance level, and their line flux distribution inevitably differs from that of the HAEs. On the other hand, the emitters in the high-density regions exhibit similar line flux distribution to the HAEs in ECDFS. The consistency is weaker for BOSS1542 because this giant filamentary structure contains more emitters with high line fluxes. These results support our conclusion that the high-density structures are dominated by Hα emitters at z = 2.24 and unlikely significantly contaminated by foreground emitters. Again, spectroscopic observations will play a key role in characterizing these density substructures.

The large-scale overdensities found at z > 2 often exhibit filamentary structures or multiple components. The z = 3.1 overdensity in the SSA22 field consists of three extended filamentary structures (Matsuda et al. 2005; Yamada et al. 2012); Lee et al. (2014) reported a structure over 50 Mpc containing multiple protoclusters at z = 3.78 in the Boötes field and these protoclusters are connected with filamentary structures; a multi-component proto-supercluster at z = 2.45 has been found in the COSMOS field, expanding over > 60 Mpc in all three dimensions (Cucciati et al. 2018); the massive protocluster at z = 3.13 in the D1 field of the CFHT Legacy Survey (CFHTLS) also exhibits multiple density components traced by LAEs and LBGs (Toshikawa et al. 2016; Shi et al. 2019). The first overdensity discovered using the MAMMOTH technique, BOSS1411at z = 2.32, is an elongated large-scale structure of LAEs on a scale of 15 Mpc (Cai et al. 2017). Traced mostly by LAEs or LBGs, these large-scale structures represent the extremely massive overdensities at z ~ 2–4. In simulations large-scale overdensities of multiple components at z > 2 are found to be very rare, being solely the progenitors of massive structures of ~10^{15} M_\odot (Topping et al. 2018).

### 4.3 Hα luminosity function

It is essential to derive the luminosity function (LF) of the intrinsic Hα luminosity that can be used as an SFR indicator of a galaxy. This will allow us to make a direct comparison of our overdensities with the general field and examine the distribution of star formation in member galaxies of the overdensities. Below we describe the procedure for building the Hα LF. This is done in the same way for both BOSS1244 and BOSS1542.

#### 4.3.1 Estimate of Hα luminosities

We calculate Hα+[N II] flux density (erg s^{-1} cm^{-2}) from the narrowband excess K_s - H2S1 and K_s total magnitude using the formula

$$ F = \Delta H2S1 \times \frac{f_{H2S1}}{1 - \Delta H2S1/\Delta K_s} $$

where \( f_{H2S1} \) and \( f_{K_s} \) refer to flux densities given in the units of erg s^{-1} cm^{-2} Å^{-1} in the H2S1 and K_s bands with band widths \( \Delta H2S1 = 203 \) Å and \( \Delta K_s = 3250 \) Å, respectively. Following An et al. (2014), we use [N II]/Hα=0.117 to subtract the contribution of [N II]\( \lambda \lambda 6548, 6583 \) and obtain the observed Hα line flux. The selection cut \( EW > 45 \) Å (i.e., \( K_s - H2S1 > 0.39 \text{mag} \)) together with the 5σ depths of \( H2S1 = 22.6 \text{mag} \) and \( K_s = 23.3 \text{mag} \) (BOSS1244) determines an Hα flux detection limit of \( > 2.5 \times 10^{-17} \text{erg s}^{-1} \text{cm}^{-2} \). We adopt \( D = 17,892 \text{kMpc} \) as the luminosity distance to \( z = 2.246 \) to convert the Hα line flux into the observed Hα luminosity for all Hα emitters. Following Sobral et al. (2013) a constant extinction correction A(Hα)=1 mag is applied to obtain the intrinsic Hα luminosity, which is used to construct the Hα luminosity function.

We derive SFR from the intrinsic Hα luminosity following log(SFR/M_\odot yr^{-1})=log(L_{Halpha}) – 41.27 given in Kennicutt & Evans (2012). The Hα flux detection limit corresponds to an SFR of 5.1 M_\odot yr^{-1}.

#### 4.3.2 The intrinsic EW distribution

Next step is to derive the completeness across the intrinsic Hα luminosity through fully accounting for detection limits and photometric selection. As shown in Figure 5, our sample selection is done with the \( K_s - H2S1 \) (i.e., an EW) together with source magnitudes in the two bands. We realize that HAEs of a given Hα luminosity can be bright with low EWs or faint with large EWs. We thus need to know the intrinsic EW distribution and quantify the noise effects on our sample selection. A log-normal distribution of EW is adopted for the observed Hα+[N II] fluxes of our sample HAEs, we use a method based on a maximum likelihood algorithm (see An et al. 2014, for more details). We generate log-normal EW distributions having the mean log(EW_{rest}) ranging between 1.8 and 2.3 and the dispersion \( \sigma = \log(EW_{rest}/\AA) \) ranging between 0.15 and 0.65 with a step of 0.1 dex for both parameters. We assume that Hα+[N II] flux is uncorrelated with its EW. This allows us
to produce $H_2 S1$ and $K_s$ magnitudes by randomly assigning EWs that obey a given distribution to the observed $H\alpha + \text{[N} \text{ii]}$ fluxes. Accounting for the background noises from our $H_2 S1$ and $K_s$ images, we apply the $H_2 S1 - K_s$ selection criteria to the simulated galaxies. For each of input intrinsic EW distributions, the ‘observed’ EW distribution is modeled to match our $H_2 S1$ and $K_s$ observations. We determine the intrinsic EW distribution best matching the observed EW distribution of our sample HAEs from the modeled EW distributions using the least-square method. The best-fitting EW distribution is described by a mean $\log(\text{EW}_{\text{rest}}) = 2.00$ and a dispersion $\sigma(\log(\text{EW}_{\text{rest}}/\AA)) = 0.35$.

4.3.3 Deriving the detection completeness

We use the Monte Carlo simulation method to generate mock catalogs of $H\alpha$ emission-line galaxies satisfying a given $H\alpha$ LF at $z = 2.24$. The mock catalogs are used to derive the detection completeness after accounting for the noises and detection limits in our $H_2 S1$ and $K_s$ observations. We adopt the Schechter function with $L_{H\alpha}^* = 10^{32.88}$, $\alpha = -1.60$, and $\log \phi^* = -1.79$ from Sobral et al. (2013) as the intrinsic $H\alpha$ LF for our two overdensities. An et al. (2014) pointed out that the $H\alpha$ LF has a shallower faint-end slope ($\alpha = -1.36$) and mirrors the stellar mass function of SFGs at the same redshift. They derived extinction correction for individual HAEs and recovered some heavily-attenuated HAEs that appear to be less luminous from the observed $H\alpha$ luminosity. However, we are currently unable to derive extinction for individual $H\alpha$ emitters because of the lack of multi-wavelength observations. In Sobral et al. (2013) a constant correction $A(H\alpha) = 1$ mag was applied for all $H\alpha$ galaxies. We adopt their $H\alpha$ LF and extinction correction in our analysis.

The $H_2 S1$ filter centers at $\lambda_c = 2.130 \mu m$ with an effective width of $\Delta \lambda = 0.0293 \mu m$, and probes $H\alpha$ in a redshift bin of $2.225 < z < 2.267$. We use this redshift bin to compute the effective volume for our sample. The extended wing of the filter transmission curve may allow brighter emission-line objects to be detectable than the faint ones. We thus simulate HAEs over $2.20 < z < 2.29$ in order to estimate the contribution of the HAEs out of the redshift bin $2.225 < z < 2.267$. The redshift span of $2.20 < z < 2.29$ is divided into 30 bins. In each redshift bin, one million mock galaxies are generated to have $H\alpha$ luminosities spreading into 500 bins between $40 < \log(L_{H\alpha})/\text{erg} \text{s}^{-1} < 50$ and following the given LF. There are typically ~2000 simulated galaxies in each bin. A flux ratio of $[\text{N} \text{ii}]/H\alpha = 0.117$ is adopted to account for the contribution of $[\text{N} \text{ii}]$ to $H\alpha$. These mock galaxies’ $H\alpha$ lines are simulated with a Gaussian profile of $\sigma = 200 \text{km} \text{s}^{-1}$ at given redshifts, and convolved with the $H_2 S1$ filter transmission curve to yield the observed $H\alpha + [\text{N} \text{ii}]$ fluxes for the mock galaxies.

Similarly, we randomly assign EWs obeying the best-fitting EW distribution to the simulated galaxies of given $H\alpha + [\text{N} \text{ii}]$ fluxes and determine their $H_2 S1$ and $K_s$ magnitudes after including photon noise and sky background noises from the corresponding images. Applying the same selection criteria as presented in Figure 5, we derive the fraction of the selected mock galaxies in all intrinsic $H\alpha$ luminosity bins. Then we obtain the completeness function, as shown Figure 8. As one can see that the completeness declines rapidly at $\log(L_{H\alpha})/\text{erg} \text{s}^{-1} < 42.8$. Here the volume correction and completeness estimate are based on the redshift bin $2.225 < z < 2.267$, and the final completeness curve accounts for all major effects involved in our observations and selection. Note that the completeness curve is insensitive to the input Schechter function in our simulations and thus the determination of the intrinsic $H\alpha$ LF in our two overdensities is little affected by the input function in deriving detection completeness.

4.3.4 Determining $H\alpha$ luminosity function

As shown in Section 4.1, We estimated $48 \pm 2$ non-HAEs for both of our two emitter samples and derived that $196 \pm 2$ of 244 (80 per cent) and $175 \pm 2$ of 223 (78 per cent) emission-
line objects are HAEs at $2.225 < z < 2.267$ belonged to the massive overdensity BOSS1244 and BOSS1542, respectively. Of these objects, five QSOs in BOSS1244 and three QSOs in BOSS1542 are excluded. With current data and observations, we are unable to recognize non-HAEs from the HAEs. We subtract the non-HAEs in a statistic way when constructing $\text{H}\alpha$ LF. It has been shown that the line flux distribution of the emitters in the outskirts of the two overdensities differs from that of the emitters in the dense regions, following the difference between the non-HAEs and HAEs in ECDFS. It is reasonable to draw that the outskirts contain more non-HAEs and the high-density regions are dominated by HAEs. Still, the outskirts contain a fraction of HAEs partially contributed by the dense structures, although the outskirts hold the information of true non-HAEs in the target fields. In practice, we remove 48 emitters following the line flux distribution of the non-HAEs in ECDFS (see Figure 7) from our samples and use the rest 143 objects in BOSS1244 and 124 objects in BOSS1542 to derive the $\text{H}\alpha$ LF. The difference of the line flux distribution between the non-HAEs in ECDFS and the outskirts of the two overdensities does not cause noticeable changes to the line flux distribution of the rest objects. We point out that non-HAEs represent only $\sim 20$ per cent of the total emitters in the two overdensity fields. The uncertainty in estimating the number of the non-HAEs should have no significant effect on our results of the $\text{H}\alpha$ LFs. The observed line fluxes of these non-HAEs tend to be relatively fainter and the vast majority ($\sim 85$ per cent) of them have line fluxes of $\log(f_{\text{line}}) < -15.9$. The error in correction for non-HAEs influences the faint end of the intrinsic $\text{H}\alpha$ LF at $\log L_{\text{H}\alpha} < 43.05$.

Our sample HAEs spread in $2.225 < z < 2.267$ over an area of 417 and 399 arcmin$^2$, giving a volume of 58,154 and 55,644 h$^{-3}$ Mpc$^3$ in BOSS1244 and BOSS1542, respectively. We divide the sample HAEs into six $\text{H}\alpha$ luminosity bins over $42.6 < \log(L_{\text{H}\alpha}) < 43.8$. We calculate the volume density of HAEs at given bins after correcting for the completeness, and obtain our $\text{H}\alpha$ LF data points. The Poisson noise is adopted as their errors. A Schechter function (Schechter 1976) shown below is used to fit the data points:

$$\Phi(\log L) \, d(\log L) = \ln(10) \, \Phi^* \, 10^{(\alpha+1)(\log L - \log L^*)} \, \exp[-10^{(\log L - \log L^*)}] \, d(\log L),$$

(3)

where $L^*$ refers to the characteristic luminosity, $\Phi^*$ is the characteristic density and $\alpha$ represents the power-law index of the faint end. The $\chi^2$ minimization method is utilized to determine the best-fitting parameters, giving $\log L^* = 42.91$, $\Phi^* = 0.0078$ and $\alpha = -1.60$ for BOSS1244, and $\log L^* = 43.13$, $\Phi^* = 0.0032$ and $\alpha = -1.68$ for BOSS1542.

We show the $\text{H}\alpha$ LFs of our two overdensities at $z = 2.24$ in Figure 9. The $\text{H}\alpha$ LF at $z = 2.23$ of the general field from Sobral et al. (2013) is also included for comparison. Note that our $\text{H}\alpha$ LFs of BOSS1244 and BOSS1542 are scaled down by a best-matched factor of 6.3 and 5.6, respectively, consistent with $1 + \delta_{\text{gal}} = 6.6 \pm 0.3$ and $5.9 \pm 0.3$ within the uncertainties. It is clear that the $\text{H}\alpha$ LF of BOSS1244 agrees well with that of the general field, while the $\text{H}\alpha$ LF of BOSS1542 exhibits a prominent excess at the high end. As can be seen from Figure 9, this excess is not due to an underestimate of the overdensity factor because the two data points at $\log(L_{\text{H}\alpha}) < 43$ are already below the $\text{H}\alpha$ LF of the general field. There are 10 and 14 objects with $\log L_{\text{H}\alpha} > 43.4$, accounting for 5 per cent and 8 per cent of HAEs in BOSS1244 and BOSS1542, respectively. Only two objects have $\text{H}\alpha$ with $\log L_{\text{H}\alpha} > 43.6$ in each of the two overdensities. These objects make the two data points at $\log L_{\text{H}\alpha} > 43.4$, and thus are critical to the high end of the $\text{H}\alpha$ LF. Compared with 10 objects (5 per cent of the total) in BOSS1244, the high-end of BOSS1542 consists of 14 objects (8 per cent of the total), showing an excess of 50 per cent for $\log L_{\text{H}\alpha} > 43.4$ at a 2$\sigma$ confidence.

We caution that our samples of HAEs possibly contain
AGNs that are less luminous than quasars but significantly contribute to the Hα luminosity and thus increase the high end of the Hα LF of SFGs that we want to obtain. Based on the 4 Ms Chandra X-ray observations, An et al. (2014) identified three X-ray-detected AGNs among 56 HAEs in the ECDFS field, being exclusively brightest HAEs with log(L_{Hα}) > 43.5. This suggests an AGN fraction of 9 per cent in the field when limiting HAEs to our detection depths. The fraction of AGNs in high-z protoclusters reported in previous studies is typically several per cent but with large scatter, depending on the evolutionary stage, total mass and gas fraction of the protoclusters (e.g., Macuga et al. 2019). The two bins at the high end of Hα LF contain 5/8 per cent of HAEs in BOSS1244/BOSS1542, comparable to the reported AGN fractions in the protoclusters. We caution that the two luminosity bins at log(L_{Hα}) > 43.4 in our Hα LF might be seriously contaminated by AGNs. We lack the X-ray observations to detect AGNs and get rid of them from our samples of HAEs.

5 CONCLUSIONS

We used the WIRCam instrument mounted on CFHT to carry out deep NIR imaging observations through narrow H$_{α}$ S1 and broad K$_{S}$ filters for identifying Hα emission-line galaxies at z = 2.246±0.021 in two 20′×20′ fields, BOSS1244 and BOSS1542, where massive MAMMOTH overdensities are indicated by most extreme groups of IGM Lyα absorption systems at z = 2.24 over a scale of ~20 h$^{-1}$ cMpc imprinted on the available SDSS-III spectra. The two overdensity candidates represent the extremely massive ones selected over a sky coverage of 10,000 deg$^2$.

There are 244/223 emission-line objects selected with rest-frame EW > 45 Å and H$_{α}$ S1 < 22.5 mag over an effective area of 417/399 arcmin$^2$ to the 5σ depths of H$_{α}$ S1 = 22.58/22.67 mag and K$_{S}$ = 23.29/23.23 mag in BOSS1244 and BOSS1542, respectively. Of them, 196 ± 2 (80 per cent) and 175 ± 2 (78 per cent) are estimated to be Hα emitters at z = 2.24 in the two overdensities, in comparison with 36 – 40% of emission-line objects to be HAEs in the general field. We estimate the global overdensity factor of HAEs to be δ$_{gal}$ = 5.6 ± 0.3 and 4.9 ± 0.3 in a volume of 54 × 32 × 32 h$^{-1}$ cMpc$^3$ for the BOSS1244 and BOSS1542, respectively. The overdensity factor would increase 2 – 3 times if focusing on the high-density regions with a scale of 10 – 15 cMpc. The striking excess of HAEs is convincing evidence that the two overdensities are very massive structures at z = 2.

The HAE density maps reveal that the two overdense structures span over 30 h$^{-1}$ cMpc with distinct morphologies. BOSS1244 contains two components: one low-density component connected to the other elongated high-density component. The high-density substructure has δ$_{gal}$ = 15. If confirmed to be one physical structure, it would collapse into a present-day massive cluster, as suggested by simulations. In contrast, BOSS1542 manifests as a large-scale filamentary structure.

We subtract the contribution of possible non-HAEs from our sample of HAE candidates in a statistic manner and construct Hα luminosity functions for our two overdensities. We find that the Hα luminosity functions are well fit with a Schechter function. After correcting for the overdensity factor, BOSS1244’s Hα LF agrees well with that of the general field at the same epoch from Sobral et al. (2013). The Hα LF of BOSS1542, however, shows an excess of HAEs at the high-luminosity end at a 2σ confidence. Interestingly, these HAEs with log(L_{Hα}) > 43.4 are mostly located at the intermediate-density regions other than the density peak area. These suggest that star formation is not seriously influenced by the extremely dense environment in BOSS1244, and even plausibly enhanced in BOSS1542, although our data are unable to probe AGNs and quiescent member galaxies. Taken together with the unbound structures, we infer that the two z = 2.24 massive overdensities were undergoing a rapid assembly.

Our results denote that the two massive overdensities at z = 2.24 are extremely interesting targets to 1) investigate the environment dependence of galaxy evolution; 2) address the environmental mechanisms for triggering quasar activities and address the coevolution between SMBHs and galaxies; and 3) provide constraints on hierarchical structure formation models and standard cosmological model. We will address these issues in upcoming works.

DATA AVAILABILITY

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

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REFERENCES

Alam S. et al., 2015, ApJS, 219, 12
Allen S. W., Evrard A. E., Mantz A. B. 2011, ARA&A, 49, 409
An F. X., Zheng X. Z., Meng Y., Chen Y., Wen Z., Lü G., 2013, SCPMA, 56, 2226
An F. X. et al., 2014, ApJ, 784, 152
