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A protocluster traced by LAEs at z ∼ 4.5 in the COSMOS field

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Abstract. In this work, we use the submm source J1000+0234, representative of a population of dusty and distant starburst galaxies expected to inhabit peaks of matter density, as a target for a potential protocluster region. We use combined wide-band and narrow-band optical photometry to identify Lyα emitters (LAEs) within a 21cMpc radius from the submm source J1000+0234, at $z = 4.54 \pm 0.03$, to identify typical star-forming galaxies that may trace the underlying structure containing our target source. In comparison with the LAE density in the field, our results point to a mean LAE number overdensity of $\bar{\delta} = 3$, spanning a region of $\sim (25\,\mathrm{cMpc})^3$, probably evolving into a moderate-mass cluster $(3 - 10 \times 10^{14}\ \mathrm{M}_\odot)$ at $z \sim 0$. This structure likely forms an extension at $z \sim 4.5$, a few comoving Mpc away from the recently identified Taralay protocluster. This work supports the idea that submm sources, although offset from the major overdensity peaks, serve as traces of moderately massive, potentially infalling structures.

Resumo. Neste trabalho, utilizamos a fonte submilimétrica J1000+0234, representativa de uma população de galáxias starburst empoeiradas e distantes, como alvo de uma potencial região de protoaglomerado. Utilizamos fotometria óptica de banda larga e banda estreita combinadas para identificar emissores de Lyα (LAEs) dentro de um raio de 21 cMpc em torno da fonte submilimétrica J1000+0234, em $z = 4.54 \pm 0.03$, com o objetivo de identificar galáxias típicas em formação estelar que traçam a estrutura subjacente que contém nossa fonte-alvo. Em comparação com a densidade de LAEs no campo, nossos resultados apontam para uma sobredensidade média no número de LAEs de $\bar{\delta} = 3$, abrangendo uma região de $\sim (25\,\mathrm{cMpc})^3$, que provavelmente evoluirá para um aglomerado de massa moderada $(3 - 10 \times 10^{14}\ \mathrm{M}_\odot)$ em $z \sim 0$. Essa estrutura forma uma extensão em $z \sim 4.5$, a alguns megaparsecs comóveis do recentemente identificado protoaglomerado Taralay. Este trabalho sustenta a cenário em que fontes submilimétricas, embora deslocadas dos principais picos de sobredensidade, atuam como traçadoras de estruturas moderadamente massivas e potencialmente em processo de colapso em uma estrutura maior.

Keywords. Galaxies: clusters: general – Galaxies: high-redshift – Galaxies: photometry – Submillimeter: galaxies

1. Introduction

Large-scale structure in the Universe arises from anisotropic gravitational collapse driven by dark matter, giving rise to the cosmic web. Galaxy clusters, the densest structures in the local Universe, form at the nodes of this web through a hierarchical sequence of mergers and accretion of minor systems. The precursors of clusters, known as protoclusters, are sparse and unbound structures at high redshift and provide a key laboratory for studying how environmental processes progressively shape galaxy properties.

Identifying protoclusters at high redshift is observationally challenging due to their large spatial extent and low density contrast relative to the field, which demand wide-field and deep observations. An effective way to overcome these difficulties is to use tracers that pinpoint regions likely to host protoclusters. These objects include radio galaxies, QSOs, Lyα blobs, and submillimeter galaxies (SMGs), which have been successfully employed to target overdense environments at early cosmic times (e.g., Calvi 2023). SMGs are massive, dust-obscured, intensely star-forming systems that are expected to reside in density peaks and to represent progenitors of massive elliptical galaxies (e.g. Gomez-Guijarro 2018), although recent studies indicate that they may occupy a wide range of environments, from protoclusters to more typical field regions (e.g., Cornish 2024).

Lyα emitters (LAEs) offer a complementary and powerful probe of large-scale structure at high redshift. These young, low-mass, and relatively dust-free galaxies exhibit low bias and are therefore used for mapping overdensities over large cosmological volumes (e.g., Ramakrishnan 2024). In this work, we investigate the environment of the submillimeter source J1000+0234 at $z = 4.54$ in the COSMOS field. Using narrow-band imaging, we identify LAE candidates within a narrow redshift slice centered on the SMG and calculate the overdensity relative to the field. By comparing the measured overdensities and spatial extents with predictions from cosmological simulations, we evaluate whether the overdense regions are consistent with the progenitors of galaxy groups or clusters by $z = 0$.

1.1. Lyα Emitter Candidate Selection

We identify Lyα emitter (LAE) candidates using a narrow-band (NB) excess technique, comparing the NB flux to the underlying continuum estimated from the overlapping broad-band r^+ filter. Sources exhibiting a significant NB flux excess are interpreted as potential emission-line galaxies.

The candidate selection, Figure 1, is based on two main criteria: (i) a rest-frame equivalent width $\mathrm{EW}_0 \gtrsim 25$ Å. This threshold is adopted in Lα luminosity function studies (e.g, Ouchi 2020). This equivalent width cut translates into a color threshold of $r^+ - \mathrm{NB} \gtrsim 1.13$; (ii) a narrow-band excess three times greater than the photometric uncertainties, $r^+ - \mathrm{NB} > 3\sigma$, where σ is the combined photometric uncertainty of the broad- and narrow-band images. See Rubet (2025) for details.

To further reduce contamination, we crossmatch these sources with the COSMOS2020 catalog and select objects with photometric redshifts consistent with the Lyα redshift range probed by the NB filter ($4.51 \lesssim z \lesssim 4.57$), accounting for photometric redshift uncertainties. A visual inspection of image cutouts is then performed to exclude artifacts and spurious detections, resulting in a final sample of 76 robust LAE candidates. Of these, 54 have photometric redshifts consistent with $z \sim 4.54$, while 22 lack counterparts in the COSMOS2020 catalog. Seven

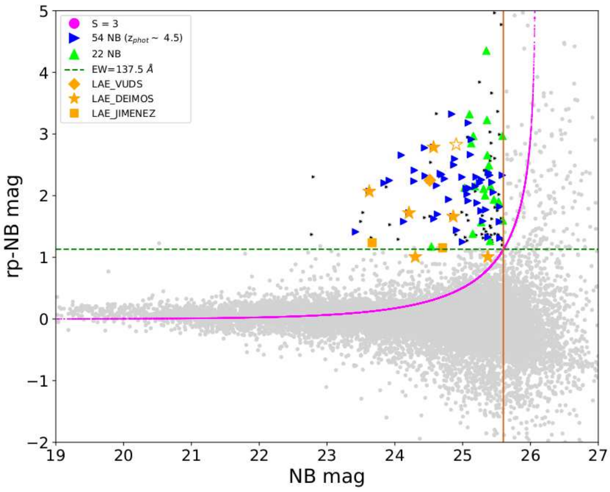

Figure 1. LAE candidates with known and unknown photometric redshifts are shown as blue and green triangles, respectively. Spectroscopically confirmed LAEs are shown as orange symbols. The LAE candidate selection is based on the following criteria: $EW_0 > 137.5$ Å (horizontal green line), color excess $> 3\sigma$ (magenta curve), and the 60% completeness limit, $mag_{NB} < 25.6$ (vertical brown line).

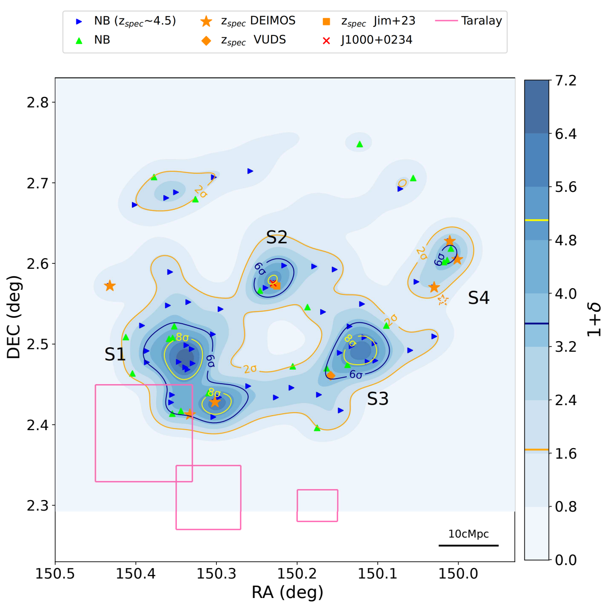

Figure 2. LAE density normalized by the field LAE density. The position of J1000+0234 is marked by the red cross at the center. Overdensities are highlighted by 2σ and 6σ contours. The location of the Taralay protocluster is shown by pink squares.

of these candidates are genuine LAEs identified in spectroscopic catalogs from the literature — the VIMOS Ultra-Deep Survey (Le Fèvre 2015a) and the DEIMOS 10k Spectroscopic Survey (Hasinger 2018) — and in MUSE detections from Jiménez-Andrade (2023).

2. Large-scale Overdensity Traced by LAEs

The identification and characterization of overdense regions rely on the LAE numerical overdensity, defined as the volume density contrast relative to the field:

$$\delta = \frac{n - n'}{n'}, \tag{1}$$

where n is the volumetric number density of LAEs within a given region and n' is the corresponding LAE number density in the field. We derive the field LAE density by integrating the Lyα luminosity function at $z = 4.5$. The luminosity function parameters at $z = 4.5$ are obtained by interpolation of the luminosity function parameters for $z = 3.7$ and $z = 5.7$, described in Ouchi et al.(2020). Because the detection efficiency decreases toward fainter luminosities, the integration is convolved with a completeness function that accounts for the fraction of recovered sources as a function of luminosity:

$$\bar{n} = \int \Phi(L)\, f(L)\, dL, \tag{2}$$

where $\Phi(L)$ is the Lyα luminosity function, $f(L)$ represents the narrow-band completeness.

Using this LAE field number density, we construct a normalized density map from the spatial distribution of LAE candidates through Gaussian kernel density estimation. This method uses a kernel size of 25 cMpc, chosen to match the typical spatial extent of protoclusters at $z \sim 4.5$, to transform the discrete galaxy positions into a smooth density field. We correct for low-redshift interlopers by randomly excluding 46% of the sources without photometric redshifts, based on the interloper fraction inferred from matches with the COSMOS2020 catalog. The final overdensity map, Figure 2, is composed of the mean value at each position from 300 independent realizations of the LAE density field. This map reveals four statistically significant structures — S1, S2, S3, and S4. Among them, S1 is the largest and most extreme, reaching a peak overdensity of $\delta = 5$ and spanning an area of $(27 \times 20)\,\mathrm{cMpc}^2$ out to its 2σ contours.

2.1. Comparison with Simulations

Considering the dimensions described by Muldrew (2015), the extent of the region formed by S1, S2, and S3 — enclosed by a 2σ overdensity contour — corresponds to the scale of a high-mass cluster progenitor, potentially reaching $M > 10^{15}\,M_\odot$ by $z = 0$. Alternatively, following Chiang (2013), regions S1 and S3, which exhibit the highest overdensities, with mean values of $\bar{\delta} = 3$ within $(25\,\mathrm{cMpc})^3$ (S1) and $\bar{\delta} = 3.8$ within $(15.7\,\mathrm{cMpc})^3$ (S3), are consistent with moderate- and low-mass cluster progenitors, with expected descendant masses of $(3\text{–}10) \times 10^{14}\,M_\odot$ and $(1\text{–}3) \times 10^{14}\,M_\odot$, respectively. In contrast, regions S2 — which hosts the target J1000+0234 — and S4 show lower overdensities, with $\bar{\delta} = 2.9$ and 2, respectively, both within volumes of $(15\,\mathrm{cMpc})^3$, consistent with progenitors of galaxy groups. The overdensity peak lies only ~ 10 cMpc from the Taralay protocluster, suggesting that we are observing ongoing large-scale structure assembly. These results support the idea that submillimeter sources, even when offset from the main overdensity peaks, trace moderately overdense and potentially infalling protocluster environments.

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