LETTER TO THE EDITOR

A lensed protocluster candidate at $z = 7.66$ identified in JWST observations of the galaxy cluster SMACS0723–7327

N. Laporte$^{1,2,3}$, A. Zitrin$^3$, H. Dole$^4$, G. Roberts-Borsani$^5$, L. J. Furtak$^3$, and C. Witten$^6$

1 Kavli Institute for Cosmology, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK
e-mail: n1408@cam.ac.uk
2 Cavendish Laboratory, University of Cambridge, 19 JJ Thomson Avenue, Cambridge CB3 0HE, UK
3 Physics Department, Ben-Gurion University of the Negev, PO Box 653, Be’er-Sheva 8410501, Israel
4 Université Paris-Saclay, CNRS, Institut d’Astrophysique Spatiale, 91405 Orsay, France
5 Department of Physics and Astronomy, University of California, Los Angeles, 430 Portola Plaza, Los Angeles, CA 90095, USA
6 Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK

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ABSTRACT

Context. According to the current paradigm of galaxy formation, the first galaxies likely formed within large dark matter haloes. The fragmentation of these massive haloes led to the formation of galaxy protoclusters, which are usually composed of one to a few bright objects, surrounded by numerous fainter (and less massive) galaxies. These early structures could have played a major role in reionising the neutral hydrogen within the first billion years of the Universe, especially if their number density is significant.

Aims. Taking advantage of the unprecedented sensitivity reached by the James Webb Space Telescope (JWST), galaxy protoclusters can now be identified and studied in increasing numbers beyond $z \geq 6$. Characterising their contribution to the UV photon budget could supply new insights into the reionisation process.

Methods. We analysed the first JWST dataset behind SMACS0723–7327 to search for protoclusters at $z \geq 6$, combining the available spectroscopic and photometric data. We then compared our findings with semi-analytical models and simulations.

Results. In addition to two bright galaxies ($\geq$26.5 AB in $F277W$), separated by $\sim$11″ and spectroscopically confirmed at $z_{\text{spec}} = 7.66$, we identify six additional galaxies with similar colours within a $\theta \sim 20′′$ radius (corresponding to $R \sim 60–90$ kpc in the source plane). Using several methods, we estimate the mass of the dark matter halo of this protocluster as $\sim 3.3 \times 10^{11} M_{\odot}$, accounting for magnification, consistent with various predictions. The physical properties of all protocluster members are also in excellent agreement with what has been previously found at lower redshifts: star formation main sequence and protocluster size. This detection adds to just a few protoclusters currently known in the first billion years of the universe. These $z \geq 7$ galaxy protoclusters may play an important role in cosmic reionisation.

Key words. galaxies: formation – galaxies: distances and redshifts – galaxies: groups: general

1. Introduction

Understanding the formation and evolution of the first population of galaxies a few million years after the Big Bang is one of the most active topics of current extragalactic astronomy. For decades, instruments have been built to push our observational limits ever further. The current most distant and detailed picture of the Universe, the cosmic microwave background (CMB), was obtained by the Planck mission (Planck Collaboration VI 2020). It shows that 380 000 years after the Big Bang, the matter density in the Universe was already inhomogeneously distributed, suggesting that small amplitude density fluctuations were taking place in the early phase of the Universe. These fluctuations grew and eventually the denser regions collapsed to form the first bound objects (Bromm & Yoshida 2011). Moreover, the first dark matter haloes underwent a process of fragmentation, suggesting that the most massive galaxies may have formed in overdense regions known as protoclusters (Genel et al. 2010). Recent N-body simulations and semi-analytic models demonstrate that the first protoclusters may have contributed up to $\sim 50\%$ of the Cosmic Star Formation Rate Density at $z \sim 10$ (Chiang et al. 2017). Therefore, determining the number density of $z \geq 6$ protoclusters could supply new insights into the reionisation process.

A natural method of identifying protoclusters at $z \geq 6$ is to search for overdensities of photometrically selected dropout galaxies at similar high redshifts. For example, using Hubble Frontier Fields data (Lotz et al. 2017), Zheng et al. (2014) identified a likely protocluster of several galaxies at $z \sim 8$, one of which was later targeted and found to show UV and far-IR emission lines placing it at $z = 8.38$ (Laporte et al. 2017). Searching for galaxies with Lyman-α emission at similar redshifts is another successful route to identifying early protoclusters. Since the neutral hydrogen surrounding galaxies at $z \geq 6$ makes the detectability of this line very low at high redshift (De Barros et al. 2017), a Ly detection from a galaxy at $z \geq 6$ suggests that the galaxy is found in a rather large ionised bubble, a result of either high-ionising power of the galaxy itself or the cumulative contribution of several objects at the same redshift (Roberts-Borsani et al. 2022b). Using the Hubble Space Telescope (HST) and deep spectroscopic follow-up campaigns, several groups have identified large ionised bubbles up

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to \( z \sim 6.68 \) (e.g., Castellano et al. 2016; 2022; Tilvi et al. 2020; Leonova et al. 2022; Larson et al. 2022) with the detection of \( \text{Ly}-\alpha \) in bright galaxies. However, the sensitivity of HST is not sufficient to search for much fainter objects in the local environment of these bright galaxies.

The successful launch of the JWST on December 25, 2021, from Europe’s Spaceport in French Guyana has opened a new window for the study of protoclusters. Its unprecedented sensitivity will allow the community to identify and spectroscopically confirm not only bright galaxies, but also fainter galaxies at similar redshifts. On July 12, 2022, the first images and spectra obtained by \( \text{Webb} \) were released, and preliminary analyses show that galaxies had already formed at \( z \geq 12 \) (e.g., Finkelstein et al. 2022; Naidu et al. 2022b; Donnan et al. 2022) reinforcing the idea that a protocluster of galaxies may already be in place at \( z \geq 10 \).

In this paper we analyse the first dataset released by the JWST behind the lensing cluster SMACS0723—7327 to search for protoclusters at \( z \geq 6 \). In Sect. 2 we describe our method, which led to the identification of a protocluster at \( z = 7.66 \) using NIRSpec, NIRISS, and NIRCam data. Then we determine the physical properties of protocluster members as well as the global properties of the protocluster (Sect. 3). Finally, in Sect. 4 we discuss the implication of our findings on the reionisation process.

Throughout this paper we assume a standard \( \Lambda \text{CDM} \) cosmology with parameters from Planck Collaboration VI (2020).

All magnitudes are in the AB system (Oke & Gunn 1983).

### 2. Search for protocluster behind SMACS0723

The first JWST dataset included NIRCam images in F090W, F150W, F200W, F277W, F356W, and F444W filters; MIRI images in F770W, F1000W, F1500W, and F1800W filters; NIRSpec spectra in F170LP and F190LP; and NIRISS spectra obtained with F115W and F200W filters. We first looked at the NIRSpec spectra whose integration time is 2.45 h in each filter. We used the publicly available level 2 data, and visually inspected the 1D spectra using \texttt{Javaiz}\(^1\). The spectroscopic redshift was obtained by fitting a list of nebular lines to the brightest detected lines. Two objects among the 35 observed have a similar redshift of \( z = 7.665 \) and \( z = 7.659 \) (hereafter SMACS0723_PC_6 and SMACS0723_PC_7) and show several UV lines, such as \([\text{OIII}]\lambda4959, 5007 \) and \([\text{OII}]\lambda3727, 3729 \) (Fig. 1). Our redshift measurements are consistent with the values previously measured by other groups (e.g., Curti et al. 2022; Carnall et al. 2022; Atek et al. 2022; Katz et al. 2022; Trussler et al. 2022).

Theoretical studies demonstrate that at \( z \sim 7 \) the size of a protocluster is below 10 comoving Mpc, corresponding to \( \sim 1 \) physical Mpc (Chiang et al. 2017). However, the protocluster core, where the large majority of galaxies are expected, is much smaller. For example, Capak et al. (2011) identified a protocluster at \( z = 5.3 \), with a protocluster core size of 0.14 physical Mpc. While it appears complicated to entirely cover a protocluster at such high redshift with the first JWST dataset, one can easily search for a protocluster core. In the following, we describe how we searched for galaxies with similar colours in a \( 40'' \times 40'' \) box centred on the two galaxies identified at \( z = 7.66 \). Moreover, to increase the number of constraints on the SED, we combined JWST/NIRCam and MIRI data with HST/ACS and WFC3 data.

To define the colour–colour criteria needed to select galaxies at \( z \sim 7.66 \), we used \texttt{BAGPIPES} (Carnall et al. 2018)

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We combined these criteria with non-detection criteria (\(<2\sigma\)) in HST/ACS filters F435W, F606W, and F814W and detection criteria (\(>5\sigma\)) in F150W, F160W, and F200W. Colours are measured on point spread function (psf)-matched images degraded to the seeing of F200W (0.07''\(^2\)), whereas non-detection criteria are measured on original images. We identified six more objects in a \( 40'' \times 40'' \) box (Fig. 3). The photometry of all candidates is reported in Table A.1.

The SMACS0723 ERO dataset also includes NIRISS direct imaging and wide-field slitless spectroscopy (WFSS) in the F115W and F200W filters, which affords sufficient wavelength coverage to observe \( \text{Ly}\alpha \) at \( z > 7.2 \) or, for example, \( \text{H}\beta, \text{OIII}\lambda4507, \) and \( \text{Hr} \) for \( z \sim 2-3 \) galaxies. We reduced and analysed the dataset as described by Roberts-Borsani et al. (2022a), ensuring the modellng and subtrac-

With these numbers in hand we can estimate the overdensity parameter defined in Morselli et al. (2014) as

\[
\delta = \frac{\rho}{\rho_0} - 1,
\]

where \( \rho \) is the number of objects identified and \( \rho_0 \) the number of objects expected from the shape of the UV luminosity function (LF) in our search box. To obtain the latest value, it is necessary to first estimate the surface explored by our survey by masking all bright objects (stars and obvious low-z galaxies) and by correcting each pixel by the magnification by the foreground galaxy cluster SMACS0723—7327. The \( z \sim 8 \) UV LF published in Bouwens et al. (2022) is defined between \( z = 7.5 \) and \( z = 8.5 \), and we therefore estimate from the previous effective surface the volume explored within our search box. We find an overdensity parameter of \( \delta = 4.0^{+2.4}_{-1.8} \). This value is comparable to that computed for protoclusters identified at similar redshift, for example \( \delta = 5.11^{+1.06}_{-0.70} \) for LAGERzODI at \( z = 6.9 \).
3. Physical properties of the protocluster

One of the key parameters that must be determined to characterise a protocluster is its total dark matter halo mass. Several methods have recently been used in the literature to probe the total halo mass of confirmed protoclusters. In the following we apply some of these methods to demonstrate that this structure is a convincing protocluster at $z = 7.66$.

Before estimating the total halo mass, the stellar mass of each candidate protocluster member needs to be estimated (e.g., Long et al. 2020). We use BAGPIPES (Carnall et al. 2018) and assume several SFHs: constant, burst, delayed, and a combination of a young burst and a constant. We allow a redshift range of $z \in [0.0;10.0]$, a stellar mass ranging from $\log M_* \in [6.0;12.0]$, and a reddening range of $A_v \in [0.0;2.0]$. The best SED fit is defined as the fit reducing the Bayesian information criterion (BIC; see Laporte et al. 2021 for more details); the results of this fitting are presented in Table 1. The photometric redshift of the six dropouts identified near the two spectroscopically confirmed galaxies is consistent with these galaxies being at $z = 7.66$ (Fig. 4, right). We apply the same method to obtain the photometric redshift of all objects in the NIRCam field of view. The distribution in redshift of objects in our search box compared to the distribution in the entire field of view suggests a small excess of objects at $z \geq 7$, consistent with the presence of an overdensity in this region (Fig. 4, left). As expected in a protocluster environment (e.g., Muldrew et al. 2015; Lim et al. 2021; Araya-Araya et al. 2021; Gouin et al. 2022), two members are more massive than the others, namely SMACS0723_PC_6 and SMACS0723_PC_7, with a stellar mass $\sim 10^9 M_\odot$.

Figure 5 shows the position of the eight galaxies in our sample on a $M_\star$ vs. Star-Formation Rate (SFR) diagram compared with previous findings at $z \geq 7$ (Leethochawalit et al. 2022; Topping et al. 2022). It confirms that all these sources have properties consistent with what is expected in terms of the star

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{One-dimensional NIRSpec spectra of the two galaxies with identical redshift of $z = 7.66$. The detected lines are shown with blue dashed lines. A spurious line is seen on the spectrum of SMACS0723_PC_6 at 3.31 $\mu$m and has been flagged in this figure. Uncertainties on each spectrum are plotted in grey.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig2.png}
\caption{Colour–colour plot used to select galaxies with colour similar to the two galaxies spectroscopically confirmed. The stars show the positions of the eight objects identified in a 40″×40″ region. The red dots show the positions of the two spectroscopically confirmed galaxies. Lower limits are computed assuming the 2σ depth of the $F900W$ image.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig3.png}
\caption{Colour image ($F900W$, blue; $F150W$, green; $F200W$, red) of SMACS0723. The white square displays the protocluster members search box (40″×40″), the red circles show the position of the two spectroscopically confirmed galaxies at $z = 7.66$ and the green circles are at the position of the six other protocluster members candidates identified in this study.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig4.png}
\caption{One-dimensional NIRSpec spectra of the two galaxies with identical redshift of $z = 7.66$. The detected lines are shown with blue dashed lines. A spurious line is seen on the spectrum of SMACS0723_PC_6 at 3.31 $\mu$m and has been flagged in this figure. Uncertainties on each spectrum are plotted in grey.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig5.png}
\caption{Colour image ($F900W$, blue; $F150W$, green; $F200W$, red) of SMACS0723. The white square displays the protocluster members search box (40″×40″), the red circles show the position of the two spectroscopically confirmed galaxies at $z = 7.66$ and the green circles are at the position of the six other protocluster members candidates identified in this study.}
\end{figure}
confirms that the two spectroscopically confirmed galaxies are over, no candidate has a stellar mass higher than PC_7, which density as large as in the protocluster candidate region. More-
discussed here), but no other region in the field shows an over-
tion criteria (including the eight protocluster member candidates
z note that the projected distance between the protocluster core
of the 40′′ box is 0.38 Mpc, suggesting that some of these
PC_6* 110.844634 −73.435054 7.665 8.59 +0.21 −0.20 3.55 +0.14 −0.10 0.15 +0.07 −0.03 1.68 [1.38–1.78]
PC_7* 110.834062 −73.434509 7.659 8.95 +0.04 −0.04 15.06 ±0.19 1.02 +0.03 −0.03 1.68 [1.41–1.79]
PC_8 110.835151 −73.429499 7.33 +0.09 −0.08 2.61 +0.16 −0.10 0.54 +0.04 −0.06 1.50 [1.29–1.57]

Notes. All the values are not corrected for the best-fit magnification. The last column shows the magnification factor estimated by the lens model presented in Pascale et al. (2022), assuming a redshift of z = 7.66 for all objects. * spectroscopically confirmed at z = 7.66. Spectroscopic redshift are indicated in italics.

formation main sequence currently known at z ≥ 7. We also
expand our search over the entire NIRCam field of view to iden-
tify other z ~ 7.66 objects. Twenty-six objects follow our selec-
tion criteria (including the eight protocluster member candidates
discussed here), but no other region in the field shows an over-
density as large as in the protocluster candidate region. More-
over, no candidate has a stellar mass higher than PC_7, which
confirms that the two spectroscopically confirmed galaxies are
the most massive z = 7.66 galaxies in this field of view. We
also note that the projected distance between the protocluster core
discussed in this paper and the closest z ~ 7.66 galaxy outside
of the 40′′ box is 0.38 Mpc, suggesting that some of these
galaxies may also be related to the protocluster.

The individual halo mass can be estimated from the stellar
mass of each galaxy using the Behroozi et al. (2013) relation-
ship. The halo masses of the eight galaxies range from 2×10^{10} to
6×10^{11} M_⊙, corrected for magnification, with a total protoclus-
ter halo mass of M_h = 3.34 +0.59 −0.50×10^{11} M_⊙. Another method of
estimating the halo mass of a protocluster is to sum all stel-
lar masses (M_{\text{halo}} = 1.46 +0.62 −0.50×10^{11} M_⊙) corrected for
magnification and to convert into halo mass using the baryonic-to-dark
matter fraction measured by Planck Collaboration VI (2020). Following
this method we estimate a total halo mass of 6.52 +2.82 −1.22×10^{11} M_⊙. Finally, we can also determine the halo mass
of the most massive galaxy in our sample from its stellar mass,

Table 1. Physical properties computed with BAGPIPES of the protocluster member candidates identified behind SMACS0723.

| ID  | RA   | Dec  | z_{phot} | log M_⋆ | SFR   | Ál  | μ  |
|-----|------|------|----------|---------|-------|-----|----|
| PC_1| 110.823826 | −73.437880 | 6.68 +0.04 −0.06 | 7.79 +0.20 −0.13 | 3.37 +0.45 −0.18 | 0.35 +0.30 −0.23 | 1.90 [1.49–2.06] |
| PC_2| 110.820512 | −73.436305 | 7.69 +1.88 −0.85 | 8.19 +0.26 −0.31 | 1.71 +0.88 −0.77 | 0.11 +0.11 −0.07 | 1.79 [1.44–1.92] |
| PC_3| 110.845907 | −73.435998 | 7.76 +1.19 −1.02 | 7.96 +0.32 −0.36 | 0.72 +0.31 −0.25 | 0.12 +0.15 −0.12 | 1.73 [1.41–1.83] |
| PC_4| 110.846149 | −73.435474 | 7.20 +0.55 −0.45 | 8.57 +0.22 −0.26 | 3.25 +1.09 −0.83 | 0.33 +0.14 −0.16 | 1.70 [1.39–1.80] |
| PC_5| 110.847412 | −73.435129 | 8.19 +0.83 −0.57 | 8.50 +0.20 −0.23 | 3.23 +1.18 −1.17 | 0.19 +0.12 −0.11 | 1.68 [1.54–1.77] |
| PC_6*| 110.844634 | −73.435054 | 7.665 8.59 +0.19 −0.21 | 3.55 +1.14 −1.08 | 0.15 +0.07 −0.03 | 1.68 [1.38–1.78] |
| PC_7*| 110.834062 | −73.434509 | 7.659 8.95 +0.04 −0.04 | 15.06 ±0.19 1.02 +0.03 −0.03 | 1.68 [1.41–1.79] |
| PC_8| 110.835151 | −73.429499 | 7.33 +0.09 −0.08 | 8.26 +0.16 −0.08 | 2.61 +0.16 −0.10 | 0.54 +0.04 −0.06 | 1.50 [1.29–1.57] |

In an independent analysis, we use the observed stellar-to-
halo mass ratios measured by Shuntov et al. (2022) with the
COSMOS2020 catalogue, which represents the most complete
deep galaxy catalogue to date (Weaver et al. 2022), to compute
an additional measurement of the halo mass of our protoclus-
ter candidate. We fit the redshift-evolution of the Shuntov et al.
(2022) stellar-to-halo mass ratio and extrapolate it out to the
redshift of our cluster (z_{spec} = 7.66) using a Markov chain
Monte Carlo (MCMC) analysis to rigorously propagate the
uncertainties. The resulting halo masses of the eight cluster member
galaxies range from 2×10^{10} to 1×10^{11} M_⊙, which broadly agrees
with the range found using the Behroozi et al. (2013) relation
above. Summing over these halo masses, we find a total halo mass
of M_h = 2.07±1.51×10^{11} M_⊙, which is higher than our
previous estimates but agrees within the uncertainties (1σ). We
note that with this conversion the halo mass of the most massive

Fig. 4. Photometric redshift in SMACS0723 Left: distribution of the detected objects as a function of redshift in the entire field of view (blue) and in the 40″×40″ box around the two spectroscopically confirmed galaxies at z = 7.66. The histograms are normalised to 1. A small excess of z ≥ 7 sources is observed in the protocluster region compared to the entire field of view. Right: redshift probability distribution for the six protocluster member candidates identified in this study. The distribution is compatible with a spectroscopic redshift of z = 7.66 (vertical dashed red line).

Fig. 5. Star formation main sequence for the eight galaxies studied in this paper (blue dots) compared with previously published z ≥ 7 sources for which stellar masses are available (green, Leethochawalit et al. 2022; grey, Topping et al. 2022). The dashed line shows the parametrisation found by Leethochawalit et al. (2022).
Fig. 6. Evolution of protocluster halo mass as a function of redshift. The grey shaded region displays the expected halo mass evolution of a Coma-like cluster (from Chiang et al. 2013) assuming a smooth evolution above $z \geq 7$. The dashed line shows the typical threshold mass for a stable shock in a spherical infall, below which the flows are predominantly cold and above which a shock-heated medium is present (from Dekel & Birnboim 2006). Overplotted are the halo mass of recently studied protoclusters at $z \geq 2$ from Polletta et al. (2021), Casey et al. (2021), Champagne et al. (2021), Wang et al. (2016), McConachie et al. (2022), Toshikawa et al. (2018), Long et al. (2020), Calvi et al. (2021), Chanchaiworawit et al. (2019), and Harikane et al. (2019). Our halo mass estimate (red dot, the sum of halo masses of individual members) is fully consistent with that expected for a Coma-like cluster. The pink point shows the total halo mass without accounting for magnification (shifted to slightly lower redshift for purposes of clarity).

4. Implications for cosmic reionisation

The transmission and escape of Lyman-α and Lyman continuum photons through the intergalactic medium around a galaxy depends exponentially on the optical depth (Furlanetto et al. 2004; Miralda-Escudé et al. 2000). This means that even small amounts of neutral hydrogen will absorb potentially ionising photons. As a result, smaller and fainter galaxies can only very locally ionise their surroundings, if at all. This leads to a strong bias towards detecting Lyman-α from brighter and more massive galaxies in the reionisation era (e.g., Stark et al. 2011) since typically only these galaxies radiate strongly enough to ionise the surrounding hydrogen and create a sufficiently large bubble to allow these photons to escape (e.g., Leenova et al. 2022; Larson et al. 2022). Hence, smaller galaxies located close to these more massive and brighter galaxies are effectively in an ionised bubble, and their UV photons can travel large distances to help reionise the Universe (photons that would otherwise be absorbed in the local vicinity of the galaxies). Therefore, protoclusters may play a significant and important role in the reionisation process.

Chiang et al. (2017) demonstrated, using $N$-body simulations and semi-analytical models that protoclusters could have contributed up to $\sim 50\%$ of the cosmic star formation rate density at $z = 10$. They also show that a protocluster core at $z = 7.66$ can itself represent $\sim 10\%$ of the total ionising budget. Furthermore, Ma et al. (2021) analyse in their simulations a protocluster with a halo mass similar to the protocluster we report in this Letter ($M_h \sim 10^{11} M_\odot$), and conclude that the escape fraction for this type of protocluster could reach $f_{\text{esc}} \sim 20\%$, a golden number to explain the end of the reionisation process by $z \sim 6$.

Moreover, the latest constraints on the shape of the UV luminosity function at $z \geq 6$ show that the number density of galaxies within the first billion years of the Universe is $\leq 10^{-6}$ Mpc$^{-3}$ (e.g., Bouwens et al. 2022; Finkelstein & Ryan 2015), which is similar to the number density of rich clusters at $z = 0$ ($\geq 10^{15} M_\odot$; e.g., Wen et al. 2010). This could suggest that the brightest $z \geq 6$ galaxies detected in deep HST surveys may lie in overdense regions with the vast majority of sources well below the detection limit of Hubble. If this is the case, and assuming that each $z \geq 6$ protocluster has an escape fraction of $\sim 20\%$, as suggested by simulations, it could open a new route to solve the UV photon deficit observed during the reionisation process.

Figure 6 demonstrates that SMACS0723_PC could be seen as the progenitor of a Coma-like cluster ($M_h \geq 10^{13} M_\odot$) and illustrates the importance of studying galaxy protoclusters from cosmic dawn to cosmic noon (e.g., in this $M_h-z$ plane). Previous telescopes were only able to detect the brightest members of such structures. Even if recent HST studies start to see overdensities near extremely bright objects at $z \geq 7$ (e.g., Leonova et al. 2022; Castellano et al. 2022), the density of protoclusters within the first billion years of the Universe is totally unknown. The identification of a protocluster candidate at $z = 7.66$ in less than 15 h with JWST is encouraging. Wider and deeper data are now needed to determine how many bright $z \geq 7$ sources lie in overdense regions, which could give new insights into the cosmic reionisation.

5. Summary

In this Letter we report the detection of a protocluster candidate at $z = 7.66$ behind the lensing cluster SMACS0723−7327 observed with the James Webb Space Telescope. In addition to the spectroscopic confirmation of two $z = 7.66$ sources, we...
identified six more galaxies with similar colours, whose SED fitting suggests that they may lie at the same redshift, and with physical properties comparable to galaxies at the same redshift. Assuming they are all part of the same structure, we estimate an overdensity parameter \( \delta \approx 4 \times 10^2 \), consistent with previous values found for other protoclusters at \( z \geq 6 \). Based on several methods, we estimate the total dark matter halo mass of this protocluster candidate to be \( M_\text{bh} = 3.6 \times 10^{11} M_\odot \). This value agrees perfectly with what is expected for progenitors of a Coma-like cluster. Furthermore, the star formation main sequence at \( z \geq 7 \) and the estimated size are in line with expectations.

Simulations predict that protoclusters may have played an important role in the cosmic reionisation, with up to a 50% contribution to the cosmic star formation rate density. They also suggest that protoclusters with the dark matter halo mass of SMACS0723_PC could have an escape fraction as high as 20%. The main unknown parameter is their number density. However, the number density of bright galaxies at \( z \geq 6 \) is of the same order of magnitude as the number density of rich clusters at \( z \approx 0 \), suggesting that they may be linked. If this is confirmed with the detection of protocluster candidates among many bright galaxies at \( z \geq 6 \) with the JWST, and given the efficiency at which these early structures ionise the neutral hydrogen, it could give new insight into the reionisation process.

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References

Araya-Araya, P., Vicentín, M. C., Sodrè, L. Jr., Overzier, R. A., & Cuevas, H. 2021, MNRAS, 504, 5054
Atek, H., Shuntov, M., Furtak, L.J., et al. 2022, MNRAS, submitted [arXiv:2207.12338]
Behroozi, P. S., Wechsler, R. H., & Conroy, C. 2013, ApJ, 770, 57
Bouwens, R. J., Illingworth, G. D., Ellis, R. S., Oesch, P. A., & Stefanon, M. 2022, A&AS, submitted [arXiv:2205.11526]
Bromm, V., & Yoshida, N. 2011, ARA&A, 49, 373
Calvi, R., Dannerbauer, H., Arrabal Haro, P., et al. 2021, MNRAS, 502, 4558
Calzetti, D., Armus, L., Bohlin, R. C., et al. 2000, ApJ, 533, 682
Capak, P. L., Riechers, D., Scoville, N. Z., et al. 2011, Nature, 470, 233
Carnall, A. C., McLure, R. J., Dunlop, J. S., & Davé, R. 2018, MNRAS, 480, 4379
Carnall, A. C., Begley, R., McLeod, D. J., et al. 2022, MNRAS, submitted [arXiv:2207.12572]

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Appendix A: Photometry of the protocluster members candidates

Table A.1. Photometry of the selected protocluster member candidates.

| ID     | F435W | F606W | F814W | F909W | F105W | F125W | F140W | F150W | F160W | F200W | F277W | F356W | F444W |
|--------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| PC_1   | > 27.72 | > 27.84 | > 26.80 | 29.22 ± 0.47 | > 27.63 | > 27.49 | > 27.77 | 27.71 ± 0.13 | > 27.40 | 27.67 ± 0.11 | 27.80 ± 0.24 | 28.19 ± 0.33 | 28.37 ± 0.56 |
| PC_2   | > 27.72 | > 28.47 | > 27.55 | > 29.93 | > 27.51 | > 28.06 | > 27.10 | 28.47 ± 0.15 | > 28.00 | 28.76 ± 0.18 | 29.19 ± 0.48 | 28.71 ± 0.31 | 29.33 ± 0.72 |
| PC_3   | > 27.67 | > 28.21 | > 27.68 | > 29.69 | > 27.38 | 27.78 ± 0.54 | 27.00 ± 0.25 | 27.38 ± 0.07 | 26.85 ± 0.25 | 27.19 ± 0.05 | 27.22 ± 0.14 | 27.16 ± 0.12 | 27.48 ± 0.23 |
| PC_4   | > 27.59 | > 27.99 | > 27.47 | > 29.65 | 27.56 ± 0.51 | > 26.77 | 26.94 ± 0.28 | 27.19 ± 0.06 | 27.08 ± 0.31 | 27.05 ± 0.05 | 27.30 ± 0.18 | 27.28 ± 0.14 | 27.28 ± 0.18 |
| PC_5   | > 27.76 | > 28.31 | > 27.63 | 28.21 ± 0.13 | 27.34 ± 0.37 | > 25.89 | 26.70 ± 0.20 | 26.57 ± 0.03 | 26.53 ± 0.18 | 26.58 ± 0.03 | 26.61 ± 0.08 | 26.75 ± 0.07 | 26.79 ± 0.11 |
| PC_6   | > 27.66 | > 28.23 | > 27.72 | > 29.73 | 27.46 ± 0.43 | 26.20 ± 0.43 | 26.26 ± 0.14 | 26.02 ± 0.02 | 26.04 ± 0.12 | 25.84 ± 0.02 | 25.74 ± 0.04 | 25.49 ± 0.03 | 24.60 ± 0.02 |
| PC_7   | > 27.76 | > 28.07 | > 27.69 | > 29.83 | 26.95 ± 0.33 | 27.06 ± 0.24 | 26.54 ± 0.35 | 26.82 ± 0.04 | 26.78 ± 0.20 | 26.92 ± 0.04 | 26.87 ± 0.07 | 26.85 ± 0.07 | 26.09 ± 0.05 |
| PC_8   | > 27.70 | > 28.22 | > 27.65 | > 28.23 | OOF | OOF | OOF | OOF | OOF | OOF | OOF | OOF | OOF |

Notes. 2σ non-detections are measured at the position of the candidate in a 0.3” radius aperture. Object PC_8 is not covered by current HST data, and is marked as out of the field (OOF).