ABSTRACT

While the Lyman $\alpha$ (Ly $\alpha$) emission line serves as an important tool in the study of galaxies at $z \lesssim 6$, finding Ly $\alpha$ emitters (LAE) at significantly higher redshifts has been more challenging, probably because of the increasing neutrality of the intergalactic medium above $z \sim 6$. Galaxies with extremely high rest-frame Ly $\alpha$ equivalent widths, EW(Ly $\alpha$) $\gtrsim 150$ Å, at $z > 6$, are good candidates for Ly $\alpha$ follow-up observations, and can stand out in multiband imaging surveys because of their unusual colours. We have conducted a photometric search for such objects in the Cluster Lensing And Supernova survey with Hubble (CLASH), and report here the identification of three likely gravitationally lensed images of a single LAE candidate at $z \sim 6.3$, behind the galaxy cluster Abell 2261 ($z = 0.225$). In the process, we also measured with Keck/Multi-Object Spectrometer For Infra-Red Exploration the first spectroscopic redshift of a multiply imaged galaxy behind Abell 2261, at $z = 3.337$. This allows us to calibrate the lensing model, which, in turn, is used to study the properties of the candidate LAE. Population III galaxy spectral energy distribution model fits to the CLASH broad-band photometry of the possible LAE provide a slightly better fit than Population I/II models. The best-fitting model suggests intrinsic EW(Ly $\alpha$) $\approx 160$ Å after absorption in the interstellar and intergalactic medium. Future spectroscopic observations will examine this prediction as well as shed more light on the morphology of this object, which indicates that it may be a merger of two smaller galaxies.

Key words: gravitational lensing: strong – stars: Population III – galaxies: clusters: individual: Abell 2261 – galaxies: high-redshift – cosmology: observations – dark ages, reionization, first stars.

1 INTRODUCTION

Cluster lensing is a powerful tool for detecting and studying astronomical objects in the distant Universe (see Kneib & Natarajan 2011, for a recent review) and has the potential to bring otherwise undetectable objects within the reach of existing or upcoming telescopes (e.g. Ellis et al. 2001; Kneib et al. 2004; Zackrisson et al. 2010, 2012; Vanzella et al. 2012; Rydberg et al. 2013; Bouwens et al. 2014; Bradley et al. 2014; Whalen et al. 2014; Zitrin et al. 2014; Atek et al. 2015).

For galaxies at redshifts $z \gtrsim 5$, the Ly $\alpha$ line is one of the few emission lines currently available for the spectroscopic confirmation of photometric candidates (although other alternatives exist; see, for example, Inoue et al. 2014, 2016; Stark et al. 2014; Zitrin et al. 2015b; Pentericci et al. 2016). However, LAEs are rare in the reionization era (e.g. Hayes et al. 2011), possibly because of the increasingly neutral intergalactic medium at this epoch (for a recent review, see Dijkstra 2014). Until recently, no secure Ly $\alpha$ detections existed above $z \sim 7.5$ (Schenker et al. 2012; Finkelstein et al. 2013), but lately, more than a handful of spectroscopic detections have been...
reported at $z \geq 7.5$ (e.g. Ono et al. 2012; Finkelstein et al. 2013; Oesch et al. 2015; Watson et al. 2015; Zitrin et al. 2015c; Song et al. 2016; Knudsen et al. 2017), with the highest redshift LAE currently known at $z = 8.68$ (Zitrin et al. 2015c) and the earliest Lyman break galaxy, whose break was verified further by *Hubble Space Telescope (HST)* grism, at $z = 11.1$ (Oesch et al. 2016).

At somewhat lower redshifts, a fraction of LAEs exhibit very high Ly $\alpha$ equivalent widths (extreme LAEs, with EW(Ly $\alpha$) $\gtrsim 150$ Å; e.g. Malhotra & Rhoads 2002; Kashikawa et al. 2011). They are intriguing because they could, in principle, host populations of metal-free (Pop III) stars (e.g. Schaerer 2002; Raiter, Schaerer & Fosbury 2010). Other explanations for these extreme LAEs include gas cooling (Dijkstra 2009), directional EW(Ly $\alpha$) boosting (Gronke & Dijkstra 2014), accreting black holes (Haiman & Rees 2001) and stochastic sampling of the stellar initial mass function (Forer-Romero & Dijkstra 2013). Kashikawa et al. (2012) present an LAE with an observed EW(Ly $\alpha$) of 436$^{+122}_{-110}$ Å at $z = 6.538$. The Ly $\alpha$ line is spectroscopically measured and the continuum is detected in their deep $z$-band image. In Sobral et al. (2015), two objects, CR7 and MASOSA, were presented, both with EW(Ly $\alpha$) $\gtrsim 200$ Å at $z_{spec} = 6.604$ and 6.541, respectively. To our knowledge, the Kashikawa et al. (2012) object and CR7 are the first extreme LAEs detected above $z \sim 6.5$. Sobral et al. (2015) conclude that CR7 is best explained by one population of mostly Pop III stars and two populations of Pop II/III stars (metallicity $Z > 0$). However, Pallottini et al. (2015) as well as Agarwal et al. (2016) and Hartwig et al. (2016) argue that the observations are better explained by a direct collapse black hole accreting primordial gas, a possibility also briefly discussed in Sobral et al. (2015). Bowler et al. (2016) object to both interpretations, claiming that deeper observations in *Spitzer Space Telescope* (Spitzer) 3.6 and 4.5 micron bands indicate strong [O $\text{iii}$] emission. They suggest two alternative interpretations, either a type II AGN or a low-metallicity starburst.

A plausible triple galaxy merger at $z = 6.595$, dubbed ‘Himiko’, was presented in Ouchi et al. (2009, 2013). Although not an extreme LAE, it has strong Ly $\alpha$ emission with EW(Ly $\alpha$) $= 78^{+13}_{-8}$ Å. Its Ly $\alpha$ halo was detected with a narrow-band filter and appears as a ‘blob’ covering all three galaxies. The authors use ALMA to observe the [C $\text{ii}$] line as it is a tracer of star-forming regions and could potentially reveal kinematics of the merger. However, no line was observed, suggesting that Himiko is a metal-poor object. Huang et al. (2016) present a triply imaged galaxy behind the galaxy cluster MACS 2129. Like Himiko, it has similarly strong Ly $\alpha$ emission with EW(Ly $\alpha$) $= 74 \pm 15$ Å and a spectroscopic redshift of 6.85.

In Zackrisson et al. (2011a), we argue that extreme LAEs could, in principle, be identified from *HST* broad-band data even at redshifts up to $z \sim 8$—9 because of their unusual colours. The key point is that the relevant emission lines are so prominent that the broad-band to which the line is redshifted would appear significantly brighter because of the additional flux from the line. Since we know (in part from spectral energy distribution or SED models) that which lines are typically stronger in star-forming young galaxies, we can anticipate the effect of brightening on the broad-band photometry at a given redshift. This selection technique is similar in nature to that recently adopted by Smit et al. (2014, 2015) and Roberts-Borsani et al. (2016) to successfully search for $z \sim 6$–8 galaxies with strong rest-frame optical emission lines. For example, all four objects at $z > 7$ predicted by Roberts-Borsani et al. (2016) to be prominent emission-line galaxies from their unusual broad-band colours were later found to exhibit Ly $\alpha$ in follow-up observations (Oesch et al. 2015; Stark et al. 2015b; Zitrin et al. 2015c; Roberts-Borsani et al. 2016).

The Cluster Lensing And Supernova survey with Hubble (CLASH) survey (Postman et al. 2012) has now produced an extensive broad-band data set for the identification of lensed galaxy candidates at high redshifts (e.g. Zheng et al. 2012; Coe et al. 2013; Bradley et al. 2014; Vanzella et al. 2014). In a companion paper (Rydberg et al. 2015), we presented a search for Pop III LAE candidates at $z \gtrsim 6$ in CLASH, which resulted in two singly imaged candidates with best-fitting redshifts at $z \approx 8$. These candidates – if confirmed spectroscopically – might like the aforementioned Roberts–Borsani object be the highest redshift extreme LAEs detected so far.

Here we examine a possible multiply lensed object behind the galaxy cluster Abell 2261 observed with CLASH. We use a lens model for Abell 2261, which we revise here following the first spectroscopic measurement of a multiply imaged galaxy behind this cluster. The aim is to establish the object as a viable candidate to be a triple-lensed LAE.

Throughout this paper, we assume a ΛCDM Universe with cosmological parameters $H_0 = 67.3$, $\Omega_M = 0.308$ and $\Omega_\Lambda = 0.692$ based on *Planck*, WP (Wilkinson Microwave Anisotropy Probe) polarization), highL (high-resolution cosmic microwave background) and baryon acoustic oscillation data (*Planck* Collaboration et al. 2014). In Section 2, we review the available CLASH, *Spitzer Satellite* and spectroscopic data sets, and in Section 3, we discuss the stellar population models applied in our study. The gravitational lens model we construct is described in Section 4. The analysis of the LAE is presented in Section 5, and we conclude in Section 6.

## 2 OBSERVATIONS

### 2.1 Imaging

CLASH has deep *HST* imaging data for 25 galaxy clusters, including Abell 2261. The observations of Abell 2261 ($z = 0.255$) cover $2000–17 000$ Å in 16 filters from the UV to the near-infrared. A photometric catalogue for Abell 2261, generated with *SExtractor* (Bertin & Arnouts 1996), was made publicly available as a high-end CLASH product (Postman et al. 2012). *SExtractor* was run in dual-image mode with a detection image created through a weighted sum of the IR images. The detection image was specifically created this way to be sensitive to red objects, such as high-redshift galaxies (Postman et al. 2012). Position, aperture and photometry were then determined in the detection image. The result for Abell 2261 was a photometric catalogue containing 2127 potential objects, with data in all 16 filters. The ID numbers for the images of the LAE candidate we use in this study are from this catalogue.

Abell 2261 has also been imaged by *Spitzer*. We use the publicly available1 images from the Infrared Array Camera (Fazio et al. 2004) 3.6-, 4.5-, 5.8- and 8.0-mm filters. The 3.6- and 4.5-mm filters reach $\sim 23$ AB magnitudes, while the 5.8- and 8.0-mm filters reaches only $\sim 20$ AB magnitudes. These approximate limits are deduced from 5σ detections in the official *Spitzer* CLASH catalogues. The two shorter wavelength filters go deep enough to constrain dust attenuation and age; see Section 5.

### 2.2 Spectroscopy

Spectroscopic observations of Abell 2261 were carried out with the Multi-Object Spectrometer For Infra-Red Exploration (MOSFIRE; http://sha.ipac.caltech.edu/applications/Spitzer/SHA/)
McLean et al. (2012) on the Keck 1 telescope, as part of a search for UV metal lines in z \sim 7–8 lensed objects (described in Zitrin et al. 2015b). Abell 2261 was observed on 2014 September 16 for 2.2 h in the H band in sets of 120-s exposures. An AB dither pattern of \pm 1.25 arcsec along the slit was used and the typical seeing was \sim 0.6 arcsec. All spectroscopic data were reduced with the public MOSFIRE pipeline. For each reduced slit (biased, flat-fielded and combined), the 1D spectrum was then extracted with an 11 pixel boxcar (~1 arcsec) centred on the target. The 1\sigma error was extracted with the same procedure, in quadrature.

The H-band (14 500–17 770 Å) mask included a slit placed on multiple image 4a at (17:22:28.56, +32:08:07.92), using the ID given in Coe et al. (2012). The image was identified initially by the method of Zitrin et al. (2009), which is also the one used here for lens modelling. Coe et al. (2012) obtained a photometric redshift of 3.48 \pm 0.03 for this galaxy, and the lens models presented therein similarly predict z \sim 3.3. Our spectroscopic observations, shown in Fig. 1, indicate a redshift of z = 3.377 based on the [O ii] (3727, 3729 Å) doublet and the [N iii] (3869 Å) line, in good agreement with the photometric and initial lens model prediction. This redshift measurement is important, and will allow us to recalculate, for the first time, the lens model of Abell 2261. The H-band observations also covered one of the objects presented in this paper,\(^2\) although no lines were detected.

We have also examined J-band (11 500–13 520 Å) observations covering two of the objects presented here.\(^3\) They were carried out on 2015 June 10 and 11, for a total of 2.9 h. No significant lines were detected.

Detections of metal lines in the H or J band could have ruled out the possibility of the galaxy being metal-free. The J-band observations also weaken the plausibility of the object being a low-redshift galaxy; see Section 5.

3 SPECTRAL ENERGY DISTRIBUTION MODELS

To derive various physical properties and the redshifts of galaxies, model spectra are usually fitted to the photometric data. The models can be either synthetic spectra, empirical spectra or a mix of the two.

\(^2\) Later dubbed Abell 2261-1366.
\(^3\) Abell 2261-9000 and Abell 2261-14000.

\begin{table}
\centering
\caption{The Yggdrasil model’s parameters.}
\begin{tabular}{ll}
\hline
Parameter & Range \\
\hline
Age & \textgreater 1 Myr \\
Covering factor (f_{\text{cov}}) & 0.0–1.0 \\
Initial mass function (IMF) & M_{\text{typ}} \sim 1.0, 10, 100 M\odot \\
Lyman \alpha escape fraction (f_{\text{Ly}\alpha}) & 0–0.5 \\
Metallicity & 0–1.0 Z\odot \\
Starburst duration (SD) & 0–100 Myr \\
\hline
\end{tabular}
\end{table}

We consider here four different grids of spectra to fit to the observed data.

3.1 Yggdrasil

The Yggdrasil population synthesis model is described in detail in Zackrisson et al. (2011b), so only a brief summary is given here. The Yggdrasil model adopted in this paper features the parameters listed in Table 1, described in more detail in Rydberg et al. (2015); see also Sections 3.1.1 and 3.1.2 for f_{\text{Ly}\alpha} and the initial mass function (IMF). The model is applied in two grids: one Pop III galaxy grid (Z = 0) and one grid with Z \geq 0. The purpose is to compare the quality of fit to the two different grids to investigate whether the observations correspond to a Pop III galaxy or a galaxy containing metals.

3.1.1 The Lyman \alpha line

In Yggdrasil models with nebular emission (i.e. f_{\text{cov}} > 0), significant intrinsic Ly \alpha emission is produced. However, the Ly \alpha line is highly resonant and prone to scatter in neutral hydrogen. The parameter f_{\text{Ly}\alpha} represents the fraction of Ly \alpha photons escaping absorption by dust and scattering out of the line of sight in both the interstellar medium (ISM) and the intergalactic medium (IGM). The equivalent widths (EW) used throughout the paper are rest-frame EWs compensated by f_{\text{Ly}\alpha}, so cosmological expansion has not been taken into account.

The Gunn–Peterson trough (Gunn & Peterson 1965) is approximated by setting the flux below the Ly \alpha wavelength (\lambda_{\text{Ly}\alpha} = 1216 Å) to zero for all model spectra at z > 6. At z < 6, we simulate the fractional absorption by neutral hydrogen clouds through use of the model by Madau (1995).
3.1.2 Initial mass function

It is worth noting that in recent studies of the Milky Way halo stellar populations (Carollo et al. 2014; and references therein), alternative IMFs were considered to take into account the properties of the inner and outer halo populations (Carollo et al. 2007, 2010) and their building blocks.

Carollo et al. (2014) analysed the distribution of two main classes of carbon-enhanced metal-poor stars (CEMP-s and CEMP-no; Beers & Christlieb 2005) in the two halo components. They found that the outer halo possesses a much larger fraction of CEMP-no stars, while the inner halo has a fraction of CEMP-s, which is twice the fraction of CEMP-no. These two CEMP classes had different progenitors: intermediate-mass stars (1.3–3.5 M⊙) for the CEMP-s, and massive progenitors (10–60 M⊙) for the CEMP-no. Because of such distinct chemical signatures, Carollo et al. (2014) argued that it is likely that the outer halo dwarf galaxy progenitors possessed a flatter IMF with a slope $\alpha = -1.5$. In contrast, the inner dwarf galaxy progenitors had a standard IMF with slope $\alpha = -2.35$ (assuming a Salpeter power law).

Population synthesis models that employ the alternative IMFs derived from Milky Way halo studies could impact the mass estimate and the results of our fits, and will be considered in future papers.

3.2 Gissel

This is a grid of synthetic spectra from Bruzual & Charlot (2003). Gissel contains models with different metallicities (but not zero metallicities, i.e. no Pop III stars), ages and extinction. These models do not contain nebular emission. To account for dust attenuation, we use three different attenuation curves (Seaton 1979; Prevot et al. 1984; Calzetti et al. 2000).

3.3 CWK, Kinney

The CWK, Kinney grid (Coleman, Wu & Weedman 1980; Kinney et al. 1996; Arnouts et al. 1999) builds partly on empirical spectra. The base are UV observations of nearby galaxies that are then extrapolated with the Gissel code. Starburst galaxies with emission lines are included. In Section 3.2, we use three different attenuation curves (Seaton 1979; Prevot et al. 1984; Calzetti et al. 2000) to simulate dust attenuation.

4 LENS MODEL

Since our LAE images are lensed by a cluster, we use a lens model to derive their magnification and determine if the images are of the same source. The spectroscopic measurement discussed in Section 2.2 provides the first redshift for a multiply imaged galaxy behind the cluster and thus allows us to calibrate and refine an existing lens model for this cluster (Zitrin et al. 2015a). The original model is available from the Mikulski Archive for Space Telescopes as a high-end CLASH science product (Postman et al. 2012). We use the light-traces-mass (LTM) approach by Broadhurst et al. (2005) and Zitrin et al. (2009, 2015a).

The basic LTM model is constructed from two mass components. The first mass component corresponds to the contribution of cluster galaxies and the second one is the contribution by dark matter (DM). We start by identifying cluster-member galaxies by following the red sequence in a colour–magnitude diagram. Each galaxy is assigned a power-law mass density distribution that is projected two-dimensionally and scaled by its luminosity. The superposition map of the contributions from all cluster galaxies is then smoothed with a 2D Gaussian kernel to obtain the smooth, light-tracing-mass DM component. The two components are then summed with relative weights and supplemented by a two-parameter external shear. This basic model has six free parameters: the exponent of the galaxy power law, which is the same for all galaxies, the width of the Gaussian kernel, the relative galaxy-to-DM weight, the direction and amplitude of the external shear, and the overall normalization of the model.

The best-fitting parameter values are derived through a several-thousand long Markov chain Monte Carlo (MCMC), using $\chi^2$ criteria for the reproduced positions of multiple images. Here we generally rely on the list of multiple images presented in (Zitrin et al. 2015a, see also Cole et al. 2012), but use only as constraints the four most secure systems, fixing the redshifts of systems 4 and 5 to the redshift we measure here for image 4a. Most systems lack spectroscopic redshifts, which means that they can be freely optimized by the model around their photometric redshift value. To allow for further flexibility in the reproduction of images, we also allow for the mass and ellipticity of the brightest cluster galaxy to be freely optimized in the minimization procedure.

We use a $\chi^2$ multiple-image positional error of 0.5 arcsec for the minimization, and errors are extracted using 50 realizations of the MCMC model. Note that in Zitrin et al. (2015a), we quantified that the error maps with this positional uncertainty are likely underestimated, and we combine this positional uncertainty with the systematic uncertainty thus estimated by taking the square root of the squared sum. The systematic uncertainty was found to be more representative of shifts caused by random structure along the line of sight (Host 2012) and better encompasses the differences between lens modelling techniques.

We use this model to help us better understand if these are counter-images of the same source, which were not used as constraints. The final model has an image reproduction rms of 0.60 arcsec.

5 RESULTS

Our LAE candidate was identified when searching for Pop III galaxies in the CLASH data. The method, described in more detail in Rydberg et al. (2015), uses $\chi^2$ and cross-validation (see Singh 1981) to fit the observational data to the four model grids (Section 3). The $\chi^2$-fitting was carried out with the publicly available LEPHARE code (Ilbert et al. 2006), while cross-validation was done with a program we developed, which was called OBSERVATIONAL DATA SCANNER. The two methods produce very similar results. The CLASH data set was then scanned for objects with good quality of fits to Pop III model galaxies. The fits should also, preferably, be significantly better than 5 to the redshift we measure here for image 4a. Most systems lack spectroscopic redshifts, which means that they can be freely optimized by the model around their photometric redshift value. To allow for further flexibility in the reproduction of images, we also allow for the mass and ellipticity of the brightest cluster galaxy to be freely optimized in the minimization procedure.

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We use this model to help us better understand if these are counter-images of the same source, which were not used as constraints. The final model has an image reproduction rms of 0.60 arcsec.

5.1 Abell 2261-910 and Abell 2261-911

In the Pop III galaxy search, Abell 2261-910 (previously published in Bradley et al. 2014) was initially flagged as a potential Pop III candidate, although its multiply lensed nature was not suspected at the time (Rydberg 2014). Although it was later found not to be a convincing Pop III galaxy candidate because the quality of the fit for Yggdrasil Z > 0 models was considered to be comparable, its multiply lensed nature was revealed in the analysis. In the region containing Abell 2261-910, a nearby object Abell 2261-911 was identified at a similar redshift and may be a part of the same system,
substructure of the same galaxy or a member of an interacting galaxy pair. Because of their proximity, Abell 2261-910 and Abell 2261-911 will be hereafter treated as substructures of a single object, Abell 2261-9000. Therefore, the fluxes in each filter were added and new magnitudes were calculated. This method might differ in the flux an independent measurement would pick up since the aperture would differ. Abell 2261-9000 has 5σ detections in F850LP and all IR filters, except for a 10σ detection in F110W.

Using the redshifts implied from Yggdrasil fits and the lensing model (Section 4), the expected positions of counter-images for Abell 2261-9000 were then derived. The four positions within the Abell 2261 cluster and the magnification map of the cluster are shown in Fig. 2. The coordinates of the other three areas were used to search for counter-images. All objects within 4 arcsec of the predicted counter-image were considered.

5.2 Abell 2261-1467 and Abell 2261-1468

In the area predicted to contain a counter-image marked by blue in Fig. 2, the official catalogues contained eight objects. Of these, all but two either had redshifts that were too low or were too faint (the detections were all below 5σ), and none had morphologies corresponding to Abell 2261-910/Abell 2261-911. The remaining two, Abell 2261-1467 and Abell 2261-1468, of which the former has been published in Bradley et al. (2014), are close enough to the predicted location to be the counter-image of Abell 2261-9000, including the binary substructure. The images are 1.7 and 0.9 arcsec for Abell 2261-1467 and Abell 2261-1468, respectively, from the predicted location. For the same reason as for the Abell 2261-9000 system, Abell 2261-1467 and Abell 2261-1468 are treated as a single object – hereafter Abell 2261-14000. Like Abell 2261-9000, Abell 2261-14000 has 5σ detections in F850LP as well as all IR filters, even 10σ in F105W, F110W and F140W.

5.3 Abell 2261-1366

In the official catalogues, seven objects exist within 4.0 arcsec (within the purple circle in Fig. 2) of the second counter-image’s predicted position. One of them is a star covering a large fraction of the area where the counter-image is predicted. One is another fainter star, and four are either too faint or do not have matching morphologies, photometric redshifts and/or colours. The last object, Abell 2261-1366 (previously published in Bradley et al. 2014), found 3.2 arcsec from the position of the predicted counter-image, does correspond sufficiently well to Abell 2261-9000 and Abell 2261-14000 to be reliably considered as a counter-image.

Abell 2261-1366 appears as an extended arc parallel to the critical curve (compare Fig. 3 to Fig. 2) in the IR filters except F105W (and to some extent in F850LP) where substructure can be discerned. Abell 2261-1366 has 5σ detections in all IR filters, except for a 10σ detection in F110W. As opposed to Abell 2261-9000 and Abell 2261-14000, Abell 2261-1366 is not detected in F850LP; the difference is discussed in Section 5.7. This non-detection means that the SED fitting uses five filters instead of six, and the image being slightly fainter is the plausible reason for its higher photometric redshift of 6.8 and a generally lower quality of fit compared to Abell 2261-9000 and Abell 2261-14000.
The blue part also connects the substructure, implying that it could be a Lyα halo. Abell 2261-1366 is polluted by a nearby star, which makes the thumbnail background bright. Column 2–8: In the black and white thumbnails, the colours are inverted. Each column represents one of the seven filters with wavelengths relevant for $z > 6$ objects. The Lyα-break is evident between the filters F814W and F850LP for Abell 2261-9000 and Abell 2261-1366. For all three objects, hints of flux can be discerned in F814W, which could be spurious detections or a smaller fraction of the spectrum visible in the filter. There are some substructures for Abell 2261-9000 and Abell 2261-14000 (each was originally identified as two objects) in the form of two detected objects, each in F125W, F140W and F160W, marked by the red circles. In the shorter wavelength filters, the objects look more like extended arcs. For Abell 2261-1366, the substructure is not as clearly identifiable but can be seen in F105W and to some extent in F850LP, and it resembles an arc in the other IR filters. The uppermost third object seen in Abell 2261-9000 was identified as a low-redshift interloper, a conclusion strengthened by the fact that only two objects are observed in Abell 2261-14000. In the filters F105W, F110W and F140W, for Abell 2261-9000, an object can also be seen in the lower part of the thumbnails. However, it is significantly fainter than the other objects, and its data and model fits do not correspond well to the other objects, so we discard it as a part of Abell 2261-9000. Comparing the extended arcs/substructures of the objects to Fig. 2, they can be seen to be parallel to the critical curve. This implies that the gravitational lensing could be the source of the extension/increase in the separation of the substructure.

Its higher photometric redshift does not make it incompatible as a counter-image since its quality of fit is almost as good at the photometric redshifts corresponding to Abell 2261-9000 and Abell 2261-14000. The most plausible alternative explanation to Abell 2261-1366 being a counter-image would be that the brightest star, which obstructs a circular area $r \sim 1$ arcsec, hides the counter-image.

5.4 The third predicted counter-image

The grey circle in Fig. 2 marks the third predicted counter-image. The official catalogues contain nine objects within 4 arcsec of the predicted counter-image. Four of the objects are so faint ($S/N < 5$ in all filters) as to be flagged as spurious detections in the official catalogues. Three objects are stars and the last two objects have a too low photometric redshift. Since the predicted magnifications, $\mu \sim 2.5$, in the region are lower than for the other regions, the counter-image is expected to be fainter. The magnitudes of the fainter objects, $m_{AB} \sim 28.5$, are barely consistent with those of the other counter-images when considering the magnification including errors.

There are two possibilities for the counter-image: either it is one of the fainter objects and the magnification is significantly different from the calculated one (but still barely within the error bars) or it is behind one of the foreground stars. Since their morphology does not correspond to that of either Abell 2261-9000, Abell 2261-14000 or Abell 2261-1366 (as there are no two faint objects close by), we will not consider the fainter objects further.

5.5 Joint analysis of the three counter-images

In addition to examining each image individually and comparing them, we analyse them as one object. We sum the fluxes of all three of them in each filter, henceforth called Abell 2261-stacked. Abell 2261-stacked is constructed directly from observed values. We have also de-lensed the observations before stacking them which yields nearly identical results. One drawback of this approach is that the fitting might be dominated by one image, especially if it is significantly brighter. This means the fit might be good for only one image. However, our three counter-images have roughly similar magnifications and magnitudes. Table 2 lists the coordinates of the objects (including the stacked object) and their AB-magnitudes in the seven longest wavelength CLASH filters. It also contains the redshift, metallicity, the $\chi^2$ value of the fit and the model-implied rest-frame EW(Lyα) corrected for ISM/IGM absorption using $f_{15\mu}$. The magnification estimated with the gravitational lens model is also included (Section 5.7). Fig. 3 shows thumbnail images of the objects.

The $P(z)$ and $P(f_{15\mu})$ quantities, i.e. the photometric-redshift distribution and the photometric-$f_{15\mu}$ distribution, are calculated using the cross-validation technique described in Rydberg et al. (2015). For each $z$ or $f_{15\mu}$, the model (for the considered grid) with the highest cross-validation value (i.e. quality of fit) is selected. A good quality of fit for a certain grid thus means that there is at least one model in the grid that fits the observations well. The cross-validation value is normalized to the interval [0, 1] (where 1 implies that each data point is perfectly reproduced by the model), and is used as a proxy for a probability distribution.

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**Figure 3.** $3.3$ arcsec × $3.3$ arcsec thumbnail images of the counter-images. First column: multicolour thumbnails of the three counter-images (blue: F850LP; green: F125W; F160W: red). Abell 2261-14000s thumbnail image’s blue part is brighter and also larger compared to Abell 2261-9000 and Abell 2261-1366. The blue part also connects the substructure, implying that it could be a Lyα halo. Abell 2261-1366 is polluted by a nearby star, which makes the thumbnail background bright. Column 2–8: In the black and white thumbnails, the colours are inverted. Each column represents one of the seven filters with wavelengths relevant for $z > 6$ objects. The Lyα-break is evident between the filters F814W and F850LP for Abell 2261-9000 and Abell 2261-14000 but not as clearly for Abell 2261-1366. For all three objects, hints of flux can be discerned in F814W, which could be spurious detections or a smaller fraction of the spectrum visible in the filter. There are some substructures for Abell 2261-9000 and Abell 2261-14000 (each was originally identified as two objects) in the form of two detected objects, each in F125W, F140W and F160W, marked by the red circles. In the shorter wavelength filters, the objects look more like extended arcs. For Abell 2261-1366, the substructure is not as clearly identifiable but can be seen in F105W and to some extent in F850LP, and it resembles an arc in the other IR filters. The uppermost third object seen in Abell 2261-9000 was identified as a low-redshift interloper, a conclusion strengthened by the fact that only two objects are observed in Abell 2261-14000. In the filters F105W, F110W and F140W, for Abell 2261-9000, an object can also be seen in the lower part of the thumbnails. However, it is significantly fainter than the other objects, and its data and model fits do not correspond well to the other objects, so we discard it as a part of Abell 2261-9000. Comparing the extended arcs/substructures of the objects to Fig. 2, they can be seen to be parallel to the critical curve. This implies that the gravitational lensing could be the source of the extension/increase in the separation of the substructure.
In Fig. 4, each row corresponds to one of the three objects Abell 2261-9000, Abell 2261-14000 and Abell 2261-1366, as well as the stacked version, Abell 2261-stacked. The observational data and spectrum of the best-fitting model for each grid are listed in the first column, while the second column shows the $p(z)$ from different model grids.

### Table 2. Coordinates, photometric AB-magnitudes, redshifts, metallicities, reduced $\chi^2$'s of the best-fitting model (as a familiar measure of the quality of fit) and model-implied rest-frame EWs for Ly $\alpha$ corrected for ISM/IGM absorption using $f_{32}$. $\mu_z = 6.3$ is the magnification corresponding to the Abell 2261-stacked redshift of 6.3.

<table>
<thead>
<tr>
<th>Object</th>
<th>Abell 2261-9000</th>
<th>Abell 2261-14000</th>
<th>Abell 2261-1366</th>
<th>Abell 2261-stacked</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right Ascension</td>
<td>$17^h22^m25.13^s$</td>
<td>$17^h22^m28.48^s$</td>
<td>$17^h22^m25.85^s$</td>
<td>–</td>
</tr>
<tr>
<td>Declination</td>
<td>$32^\circ08'03.9''$</td>
<td>$32^\circ07'33.7''$</td>
<td>$32^\circ07'39.8''$</td>
<td>–</td>
</tr>
<tr>
<td>$F814W$</td>
<td>27.92 ± 0.43</td>
<td>26.68 ± 0.20</td>
<td>27.75 ± 0.37</td>
<td>26.11 ± 0.18</td>
</tr>
<tr>
<td>$F850LP$</td>
<td>25.93 ± 0.17</td>
<td>24.78 ± 0.12</td>
<td>27.63 ± 0.68</td>
<td>24.40 ± 0.10</td>
</tr>
<tr>
<td>$F105W$</td>
<td>26.17 ± 0.12</td>
<td>25.71 ± 0.10</td>
<td>26.2 ± 0.12</td>
<td>24.80 ± 0.06</td>
</tr>
<tr>
<td>$F110W$</td>
<td>26.04 ± 0.08</td>
<td>25.89 ± 0.08</td>
<td>25.99 ± 0.08</td>
<td>24.78 ± 0.05</td>
</tr>
<tr>
<td>$F125W$</td>
<td>26.27 ± 0.14</td>
<td>25.83 ± 0.11</td>
<td>26.58 ± 0.19</td>
<td>24.99 ± 0.08</td>
</tr>
<tr>
<td>$F140W$</td>
<td>26.28 ± 0.11</td>
<td>25.87 ± 0.10</td>
<td>26.34 ± 0.13</td>
<td>24.95 ± 0.07</td>
</tr>
<tr>
<td>$F160W$</td>
<td>26.37 ± 0.13</td>
<td>25.99 ± 0.11</td>
<td>26.29 ± 0.13</td>
<td>25.01 ± 0.07</td>
</tr>
<tr>
<td>$z$</td>
<td>6.4</td>
<td>6.2</td>
<td>6.8</td>
<td>6.3</td>
</tr>
<tr>
<td>$Z$</td>
<td>0</td>
<td>0</td>
<td>0.02 $Z_\odot$</td>
<td>0</td>
</tr>
<tr>
<td>$\chi^2$</td>
<td>0.85</td>
<td>1.74</td>
<td>2.76</td>
<td>1.37</td>
</tr>
<tr>
<td>EW(Ly $\alpha$)</td>
<td>210 Å</td>
<td>330 Å</td>
<td>200 Å</td>
<td>160 Å</td>
</tr>
<tr>
<td>$\mu_z = 6.3$</td>
<td>$4.3_{-1.2}^{+1.6}$</td>
<td>$3.7_{-1.3}^{+1.3}$</td>
<td>$5.5_{-2.3}^{+4.1}$</td>
<td>–</td>
</tr>
</tbody>
</table>

As a first step, we analyse Abell 2261-stacked (Section 5.5). We find a best fit at $z = 6.3$, with good quality fits extending from $z_L \approx 5.6$ to $z_U \approx 6.5$ and EW(Ly $\alpha$) $\approx 160$ Å. The most plausible redshift is 6.3 for the Yggdrasil $Z > 0$ grid as well with essentially equally good fits. Hence, there are alternatives to the Pop III interpretation of the object. The Gissel and CWL, Kinney grids are not considered further because their $p(z)$ are significantly lower than those of the Yggdrasil grids. Fig. 5 contains the quality of fits dependence on $f_{32}$ for Abell 2261-stacked at $z = 6.3$. It is evident that both Yggdrasil grids have a strong dependence on $f_{32}$.

Fig. 6 compares the magnitudes of the three counter-images after de-lensing them using our magnification estimates. We see that Abell 2261-14000 is approximately 1.0 mag brighter (a factor of 2.5) than Abell 2261-9000 and Abell 2261-1366 after de-lensing. But the errors in the magnification estimates, which are systematic across the filters, are large and the discrepancies are within the errors. The observations in $F850LP$, however, have too large a difference to be explained by magnification errors. Also, when comparing the colours in Fig. 6, the observations in the IR filters are consistent with an SED with a declining slope, while only the $F850LP$ observation for Abell 2261-9000 is consistent with this SED. The $F850LP$ magnitudes of Abell 2261-14000 and Abell 2261-1366 are much brighter and fainter, respectively. This poses a challenge for the interpretation but it could possibly be explained by an extended Ly $\alpha$ halo around the galaxy. The sensitivity of the detector could be such that the halo is only detected if the object is bright enough, and would hence contribute a disproportionate amount of flux if the object is brighter. The flux is consistent with this scenario because it is significantly higher in the brightest image Abell 2261-14000, compared to Abell 2261-9000 and Abell 2261-1366. The reason Abell 2261-1366 differs from Abell 2261-9000 could be that Abell 2261-1366 is contaminated by light from the nearby star, rendering the halo indistinguishable from the illumination provided by the star.

### 5.6 Constraints from non-HST observations

To rule out old and/or dusty objects, data from four Spitzer filters were examined (Section 2.1). Visual inspection yielded no detections in these filters. This strengthens the case for the high-redshift solutions since low-redshift dusty ($E(B-V) \gtrsim 0.3$, when dust attenuation is implemented on Yggdrasil models) objects would be visible in the Spitzer 3.6- and/or 4.5-mm filters. For objects at the same $z$ as the photometric redshift of our object, both extremely dusty objects and old galaxies would be visible and thus are ruled out.

Extremely strong optical emission lines (such as [O II] lines) from low-redshift objects can affect broad-band photometry SED fitting and mimic a high-redshift Ly $\alpha$ line (Huang et al. 2015). But since there is continuum data for this candidate at longer wavelengths and it registers as a non-detection at wavelengths shorter than the Ly $\alpha$-break, it is likely not due to a strong non-Ly $\alpha$ emission line from a faint object. Huang et al. (2015) has conducted a search for extremely strong emission-line galaxies of this type in CLASH and our candidate is not among those they identified, further strengthening the conclusion that our results are not due to strong optical emission lines. Furthermore, our spectroscopic observations, which show no prominent detections in the J band (Section 2.2), disfavour strong [O II] or [O III] from objects at $z \sim 2.1–4.8$.

### 5.7 Counter-image comparison

When considering different images as counter-images of the same object, the images have to be consistent with regard to redshift as well as morphology and fluxes (including magnification).

$^4 E(B-V)$ measures the change of the $B-V$ colour due to dust attenuation. The value of $E(B-V)$ is usually between 0 and 1.
produce a merger. The lowest stellar mass suggested by our models for this structure is \( \sim 10^6 M_\odot \). If 15 per cent of the halo mass is baryonic and all the baryons reside in stars (in reality, only a small fraction do, which would imply an even more massive halo), the halo would be \( \sim 7 \times 10^6 M_\odot \). We take the virialized mass of the structure to be \( M_{200} \), the mass enclosed by the radius at which the density is 200 times the critical density, which also corresponds to the virialized radius \( R_{200} \). For \( M_{200} \sim 7 \times 10^6 M_\odot \), \( R_{200} = 800 \) pc.

Since we assume the minimum mass for the DM halo, this is the lower limit to its virialized radius.

The angular distances between the centres of substructure in the three images (0.60 arcsec for Abell 2261-9000, 0.87 arcsec for Abell 2261-14000 and 1.2 arcsec for Abell 2261-1366), which correspond to de-lensed separations of \( \gtrsim 370 \) pc at \( z = 6.3 \). Since the distance between the substructures along the line of sight is unknown, this should be taken as a lower limit. Comparing this to the
We have discovered a likely multiply lensed LAE candidate with three counter-images, Abell 2261-9000, Abell 2261-14000 and Abell 2261-1366, with magnifications $\mu = 4.3^{+1.6}_{-1.7}$, $3.7^{+1.3}_{-1.4}$ and $5.5^{+2.4}_{-2.3}$, respectively. Another image is predicted but is not detected. In the process of locating the counter-images, we measured the first spectroscopic redshift ($z = 3.377$) of a multiply imaged galaxy behind Abell 2261, which was used to calibrate the lensing model. Using this in combination with the photometric redshifts of our three images, we conclude that it is likely that the three images are of the same object. The LAE was initially considered to be a Pop III galaxy candidate but competitive fits with non-zero metallicity models indicate that other interpretations are equally likely. By combining these fits using Yggdrasil models, a redshift estimate of 6.3 was obtained for the galaxy. This redshift estimate is dependent on the assumption of strong Ly $\alpha$ emission. Future observations targeting Ly $\alpha$ in these objects will soon be able to test these predictions.

In two of the counter-images, substructure appearing as two objects in the same orientation expected from the lens model were found in the filters with the longest wavelengths. The substructure could also be discerned in the third image, even though it was not separable into two objects. They could be star-forming regions belonging to the same galaxy or two interacting galaxies. SED fitting of models to photometry implies extreme Ly $\alpha$ emission, with EW(Ly $\alpha$) $\sim 160$ Å. We also find that the angular distance between its substructures is not too large for them to be a single virialized structure or a merger between two small galaxies. The kinematics of the structures could not be constrained with current observations but might be with additional surveys. Follow-up observations could target any of the lines: [C ii] (Knudsen et al. 2016), [O iii] (Inoue et al. 2016), [C iv] (Stark et al. 2015b) and/or C iii] (Stark et al. 2015a). Given a detection, splitting in the observed line would indicate large relative velocities that may indicate a recent merger.

If confirmed through spectroscopy, this galaxy would join a rising number of LAEs now being discovered at $z > 6$. Similar objects at higher redshifts may be the birthplaces of direct collapse black holes, the likely precursors of the most massive black holes at $z > 6$ (Mortlock et al. 2011; Wu et al. 2015). Others, as may be true of CR7, may harbour Pop III stars. CLASH, Frontier Fields and future surveys of cluster lenses may reveal these objects and yield clues to the origins of the first stars and supermassive black holes in the Universe.

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