JWST UNCOVER: A triply imaged faint quasar candidate at $z_{\text{phot}} \simeq 7.7$

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ABSTRACT

Recent JWST/NIRcam imaging taken for the ultra-deep UNCOVER program reveal a very red, triply imaged, compact dropout object at $z_{\text{phot}} \simeq 7.66$ which is prominently lensed by the galaxy cluster Abell 2744 ($z_d = 0.308$). All three images are very compact, i.e. unresolved, with an inferred de-lensed size upper limit of $r_e \lesssim 30 \text{pc}$. The observed F444W magnitude of the three images is $m \sim 25 - 26 \text{AB}$ and its absolute UV magnitude is $M_{\text{UV},1450} = -21.38 \pm 0.09$, after correcting for magnification. Based on its compact, point-like appearance, its positions in color-color and $M_{\text{UV}}$-size diagrams and a spectral energy distribution (SED) analysis, we tentatively conclude that this object is most probably a faint quasar or an extreme emission line object whose nebular emission is boosted by an active galactic nucleus (AGN). We also briefly discuss whether this can originate from other exotic compact objects such as e.g. a cluster of Population III or supermassive stars. Although populations of red galaxies at similar photometric redshifts have been detected with JWST, this object is unique in that its high-redshift nature is corroborated geometrically by lensing, that it is unresolved despite being magnified – and thus intrinsically more compact, and that it occupies notably
distinct and unoccupied regions in both the \( M_{UV} \)-size and color-color space. The planned UNCOVER JWST/NIRSpec observations will allow a more detailed analysis of this object.

**Keywords:** Quasars; High-redshift quasars; High-redshift galaxies; gravitational lensing; Strong; Reionization

1. INTRODUCTION

Quasars, or quasi-stellar objects, are extremely luminous objects powered by supermassive black holes (SMBH), typically situated in the center of a galaxy. Accretion onto the SMBH transfers a large amount of potential energy from the in-falling matter, and kinetic energy due to friction, into thermal energy, which results in very high luminosities (typical bolometric luminosities of \( L_{\text{bol}} \sim 10^{44} - 10^{48} \text{ erg s}^{-1} \); see e.g. Shen et al. 2020).

While quasars are known in relatively large numbers throughout the Universe and especially out to \( z \sim 6 \) (e.g. Bañados et al. 2016), only several quasars are known at high-redshifts \( z \gtrsim 7 \), albeit with increasing numbers (e.g. Bañados et al. 2018; Wang et al. 2018; Yang et al. 2021). Nevertheless, the formation and evolution of these high-redshift SMBHs, observed when the Universe was just a few hundred Myr old, is poorly understood, as the accretion rate onto them, or alternatively their initial masses, seem largely prohibited by common formation scenarios (e.g. Volonteri 2012; Fan et al. 2019, and references therein; though see also Trakhtenbrot et al. 2017). Moreover, while the quasar luminosity function (LF) implies a larger abundance of fainter objects (i.e. faint end slopes of \( \sim 1.2 - 1.6 \); e.g. Glikman et al. 2011; Niida et al. 2020) similar to the galaxy LF, faint quasars with \( M_{UV} \gtrsim -22 \) seem to be rare in observations. Recent work, e.g. Volonteri et al. 2022, also suggests that only active galactic nuclei (AGN) which are excessively massive relative to their host galaxies, accreting at high Eddington rates, would be detectable with JWST at high redshift, potentially shedding light on early black-hole growth.

The last decade has seen many hundreds of high-redshift objects detected with the Hubble Space Telescope (HST) and with several ground-based surveys such as UltraVISTA (McCracken et al. 2012) or LAGER (Zheng et al. 2017), for example. It has by now become well established that the universe was reionized in the first billion years, i.e. by redshift \( z \sim 5.5 - 6 \) (e.g. Fan et al. 2006; Stark et al. 2010; Pentericci et al. 2011; Robertson et al. 2015; Planck Collaboration et al. 2015; Bosman et al. 2022). However, it is not yet clear if early galaxies supply sufficient ionizing radiation to account for reionization or if a major contribution from quasars or other exotic sources (e.g. supermassive stars, X-ray binaries, etc.) is needed. The shape of the galaxy ultra-violet (UV) LF at high redshifts implies that most of the ionizing radiation originated from the more abundant population of faint galaxies (e.g. Atek et al. 2015a), but these have been largely beyond the reach of HST. It is also not clear if the LF already shows a turnover at HST depth, even in the deepest fields imaged while exploiting lensing magnification (e.g. Atek et al. 2015b; Bouwens et al. 2017), although a tentative turnover may have been detected (Bouwens et al. 2022b; Atek et al. 2018). One of the main goals of the JWST, launched one year ago, is to study the first stars and galaxies. In combination with the power of gravitational lensing, we will indeed be able to address some of these key questions, as can already be implied by the first six months of JWST operations (e.g. Adams et al. 2023; Bouwens et al. 2022a; Atek et al. 2022; Furtak et al. 2022a; Castellano et al. 2022; Donnan et al. 2022; Finkelstein et al. 2022; Morishita et al. 2022).

Another crucial ingredient to understanding the epoch of cosmic reionization (EoR) is the spectrum of high redshift galaxies. Some of the highest-redshifts objects spectroscopically confirmed from the ground (Oesch et al. 2015; Zitrin et al. 2015; Roberts-Borsani et al. 2015; Stark et al. 2017) seem to show hints for a harder UV spectrum than expected from typical stellar populations (Stark et al. 2014, 2015), indicating possible AGN activity. Population III (Pop. III) star contribution, or other hard ionizing photon sources (e.g. Mainali et al. 2017; Laporte et al. 2017; Matthee et al. 2020). Observations with the JWST have already supplied unprecedented rest-frame UV and optical spectra for some very high-redshift galaxies (Roberts-Borsani et al. 2022; Williams et al. 2022; Curtis-Lake et al. 2022) and might indeed supply new insight soon. In addition, objects that potentially bridge the typical high-redshift galaxy and AGN populations were also recently reported. Fujimoto et al. (2022) found a dusty \( M_{UV,1450} \sim -23.2 \) compact object bridging galaxies and quasars in the EoR. Its SED was distinct from typical high-redshift galaxies but could be well explained by the combination of a dusty star-forming galaxy (DSFG) SED and that of a quasar (see also Matthee 2021; Cui et al. 2021 for discussion of AGN and high-redshift

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The Fujimoto et al. (2022) galaxy is faint in X-rays, indicating the emergence of a uniquely UV-compact star-forming region or a Compton-thick super-Eddington black hole accretion disk at the dusty starburst core. Additionally, Endsley et al. (2022b) reported a heavily-obscured hyper-luminous AGN at $z = 6.85$ that was originally identified as very dusty Lyman-break $z \simeq 7$ galaxy with strong far-infrared and radio emission (Endsley et al. 2022c). As another example, Onoue et al. (2022) have recently detected a faint Lyman-break $z \simeq 7$ galaxy at $z \sim 5$ in the JWST Cosmic Evolution Early Release Science Survey program (CEERS; Finkelstein et al. 2022; Bagley et al. 2022), based on its compact shape and red spectrum which can be attributed to the redshifted rest-frame optical H$\beta$ and [O III] and H$\alpha$ emission lines.

In this work, we highlight the discovery a very compact high-redshift ($z \gtrsim 7$) object that is triply imaged by the galaxy cluster Abell 2744 ($z_d = 0.308$) in recent JWST imaging. Two of the multiple images of this system were originally found by Atek et al. (2014) in Hubble Frontier Fields (HFF; Lotz et al. 2017) data. The new JWST imaging now allows us to secure the third counter image and hint at the peculiar nature of this object: they accentuate the compact, potentially point-source like nature of the source, and reveal a spectral energy distribution (SED) with very red shape towards the longer wavelengths. The size, appearance, luminosity density, and SED-fits of this object thus suggest that it is not a typical high-redshift galaxy. Rather, its properties suggest a faint high-redshift quasar, an object in transition between a normal high-redshift galaxy and an AGN-dominated one, or potentially another exotic compact object such as a clump of Pop. III or supermassive stars, which we briefly consider here as well. We present here the source and its measured properties, and briefly discuss the various options for their origin.

This paper is organized as follows: In §2 we describe the data used in this work. In §3 we report the discovery of the object and discuss its physical properties. The work is concluded in §4. Throughout this paper, we use a standard flat $\Lambda$CDM cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_{\Lambda} = 0.7$, and $\Omega_m = 0.3$. Magnitudes quoted are in the AB system (Oke & Gunn 1983) and all quoted uncertainties represent 1$\sigma$ ranges unless stated otherwise.

2. DATA

The main data set used in this work are the recent observations taken with the Near Infrared Camera (NIRCam; Rieke et al. 2005) aboard JWST, carried out in the framework of the Ultra-deep NIRSpec and NIRCam Observations before the Epoch of Reionization (UNCOVER) program (Program ID: GO 02561; PIs: I. Labbée & R. Bezanson; Bezanson et al. 2022). The JWST UNCOVER program was designed to observe the SL galaxy cluster Abell 2744 (A2744 hereafter) with NIRCam to unprecedented depths $\sim 29.5 - 30$ AB (reaching about $\sim 32$ AB once the lensing magnification is accounted for) in the F115W, F150W, F200W, F277W, F356W, F410M and F444W bands and over a large area of $\sim 45$ arcmin$^2$ around the cluster. The UNCOVER program also includes spectroscopic follow-up observations with JWST’s Near Infrared Spectrograph (NIRSpec; Jakobsen et al. 2022) which are scheduled for July 2023. The data were reduced using the Grism redshift and line analysis software for space-based spectroscopy (grizli) program1 (Brammer et al., in prep.). A photometric catalog of objects is also generated in the UNCOVER program and is released with its data products (Weaver et al., in prep.; see also Bezanson et al. 2022). The catalog includes also photometric redshift estimates for each identified object and lists the lensing magnifications from the UNCOVER lensing model (Furtak et al. 2022b) which is described in more detail in section 3.3.

A2744 has also recently been observed in two other JWST programs: The early release (ERS) survey GLASS-JWST (Program ID: ERS 1324; PI: T. Treu; Treu et al. 2022), and a director’s discretionary time (DTT) program targeting a lensed supernova (Program ID: DD 2756; PI: P. Kelly). The NIRCam imaging from these programs is also included in the UNCOVER mosaics used in this work. In addition, the cluster will be observed with NIRCam again as part of the JWST guaranteed time observation (GTO) program Prime Extragalactic Areas for Reionization and Lensing Science (PEARLS; Program ID: GTO 1176; PI: R. Windhorst Windhorst et al. 2023). Note that the GLASS-JWST program also obtained Near-Infrared Imager and Slitless Spectrograph (NIRISS; Doyon et al. 2012) spectroscopy of the cluster core covering wavelengths $\lambda \sim 1.1 - 2.2$ $\mu$m.

Ancillary data for A2744 include deep ($\sim 29$ AB) HST imaging, taken in various program and most prominently the HFF and HST grism spectroscopy from Grism Lens-Amplified Survey from Space survey (GLASS; PI: T. Treu Treu et al. 2015). We also note that spectroscopy with the Multi-Unit Spectroscopic Explorer (MUSE; Bacon et al. 2010) on ESO’s Very Large Telescope (VLT) were used to measure the redshift for many multiply imaged galaxies in the cluster (Mahler

1 https://github.com/gbrammer/grizli
Figure 1. JWST/NIRCam composite-color image of Abell 2744 together with the critical curves from our SL model for sources at \( z_s = 1.69 \) (blue) and \( z_s = 7.5 \) (red). The notable three point-like red multiple images in cyan squares are the images (and zoomed-in versions) of the quasar candidate reported here at a redshift of \( z_{\text{phot}} \approx 7.7 \). We refer to these as QSO1A, B and C. For comparison, we also show the three images (JD1A, B and candidate C image) of the Zitrin et al. (2014) \( z \approx 9.76 \) object recently confirmed in Roberts-Borsani et al. (2022) with JWST spectroscopy, in orange squares. All squares in the figure encompass about \( 2.4'' \times 2.4'' \), and a \( 20'' \) bar is given in the bottom left corner. Note that despite being at a lower redshift than JD, the faint quasar candidate is significantly redder. Also, the images of JD1 show significant structure, whereas the images of the red quasar candidate are point-like, implying a very compact de-magnified size of \( r_e < 30 \text{ pc} \), at most. The SED of the red object is shown in Fig. 4.
et al. 2018; Bergamini et al. 2022). Finally, A2744 is also part of the ALMA Frontier Fields survey with the Atacama Large Millimeter/sub-millimeter Array (ALMA) (González-López et al. 2017; Kohno 2019; Sun et al. 2022), the band 6 ($\lambda \sim 1.1$ mm) imaging of which are also used in this work.

3. A TRIPLY IMAGED COMPACT OBJECT AT $z_{\text{phot}} \approx 7.7$

We construct a composite-color image from the UNCOVER NIRCam mosaics including the previous programs mentioned in section 2. Three distinct red point-like objects stand out in the central core of the cluster (see Fig. 1). These follow the lensing symmetry observed for other lensed systems and our lens model from Fur tik et al. (2022b) indeed predicts these to be counter images of the same object at a high redshift, namely $z_{\text{model}} \gtrsim 7$ (but see 3.3 for more details). Two of the images reported here were in fact already designated as high-redshift $z \sim 7 - 8$ candidates by Atek et al. (2014, 2015c) in the HFF data. The recent JWST data now not only allow us to detect the third counter image but also reveal the peculiar properties on this source. We will now review the observed and physical properties of the red object and discuss its possible origins in the following.

3.1. Photometry

We use the photometry of the three images as measured in the UNCOVER catalog (v0.3.1a; Weaver et al. in prep.). The objects are detected in UNCOVER mosaics corrected for intra-cluster light (ICL) with the python implementation of SExtractor (SEP; Bertin & Arnouts 1996; Barbary 2016, 2018). We refer the reader to Weaver et al. (in prep.) for the details of object detection and flux extraction and show the resulting fluxes of the three images of our object in Tab. 1. We note that in particular image B seems to be heavily contaminated with light from the from a nearby cluster galaxy and possibly the ICL.

The UNCOVER catalog also contains a first photometric redshift estimate of $z_{\text{phot}} = 7.188^{+0.006}_{-0.042}$ computed with EAZY (Brammer et al. 2008). This agrees with the high-redshift geometric estimate from our lens model (see section 3.3). We note however that EAZY does not yield a good fit for this object ($\chi^2 = 462$). This is due to the extremely red colors that this object has in the JWST filters (see section 3.2) which cannot be properly reproduced with the standard template set used with EAZY for the UNCOVER catalogs and hints at its peculiar nature. Note that AGN templates are not included in this EAZY run.

Figure 2. Upper panel: Our red compact object in the different JWST/NIRCam bands taken with UNCOVER. The upper left panel shows a stack of the HFF ACS which shows a clear non-detection. Each square is 1.2" x 1.2". We show here the data for the first multiple image (image QSO1A). Bottom panel: Color-color diagram of our object (star) and typical NIRCam-detected $z \sim 7 - 8$ galaxies in the CEERS field (Endsley et al. 2022a). The source presented in this work is redder by about a magnitude compared to the reddest of the Endsley et al. (2022a) sources, which hints at heavy emission line activity due to an AGN component, or a very strong and dusty rest-frame optical continuum.

While this object is covered by the GLASS-JWST NIRISS (see section 2), we do not find any of the three images to be detected spectroscopically. This is not surprising however since the three images are relatively faint ($\sim 28$ magnitudes) in the $\lambda \sim 1.1 - 2.2 \mu$m range covered with NIRISS and thus beyond the detection limit. The strong emission in the redder bands F356W, F410M and F444W (down to $\sim 25$ magnitudes) will however be picked up in the planned UNCOVER JWST/NIRSpec observations.

3.2. Colors
This object appears to be very red, with NIRCam colors $F200W-F277W=0.15 \pm 0.08$, $F277W-F356W=1.80 \pm 0.10$, $F277W-F410W=2.37 \pm 0.05$ $F277W-F444W=2.63 \pm 0.10$, $F356W-F410W=0.57 \pm 0.10$ and $F356W-F444W=0.83 \pm 0.08$. At $z \sim 7.5-8$ the Hβ and [O III] lines are shifted into the F410M- and F444W-bands, whereas the [O II] doublet is shifted into the F356W-band. Indeed, these lines have been observed to be sufficiently strong to modify and boost the broadband colors of galaxies. In fact, these lines have also been used as indicators for possible Lyman-α emitters (LAEs) in the epoch of reionization (e.g. Labbé et al. 2013; Smit et al. 2015; Roberts-Borsani et al. 2015; Stark et al. 2017). However, the NIRCam colors that we find here seem to be much redder than expected for typical early galaxies at $z \sim 7-8$. In Fig. 2 we show color-color diagrams demonstrating that our red object is indeed extreme: it clearly falls outside the region in which typical galaxies found at similar redshifts with JWST reside (Endsley et al. 2022a) and in the direction which suggests higher emission lines, dust extinction, and/or a strong Balmer break. For comparison, Endsley et al. (2022a) have found that one red galaxy in their $z \sim 7-8$ sample (Fig. 14 in Endsley et al. 2022a, see also Labbe et al. 2022) is better explained by a combination of a galaxy with an AGN, resulting in an [O III]$+[\text{H} \beta$ equivalent width (EW) of over 5000 Å. Our object has even more extreme colors and can thus be expected to either have even stronger emission lines, which suggests an AGN component, or an extremely red and dusty rest-frame optical continuum. Both scenarios will be further discussed in the following sections.

While throughout our main candidate engine for the underlying emission is an accretion disk around a massive black hole, we also briefly consider other possible candidates here. The first generations of stars to have formed in the Universe, often referred to as Pop. III stars, are expected to have been very poor in metals, massive ($>10 M_\odot$), energetic, and short lived (e.g. Zackrisson et al. 2011, and references therein) and may have contributed significantly to the cosmic reionization. Supermassive stars, with masses above $10^4 M_\odot$, are a population of stars put forward to explain chemical abundances in globular clusters (e.g. Gieles et al. 2018; Martins et al. 2020, and references therein). Given that they should reside in star clusters and are expected to have a non-typical spectral shape compared to ‘regular’ stars, such as strong Balmer emission lines (as well as other emission or absorption properties that depend on temperature), we briefly consider them here as well. The red colors that we measure, which could also be indicative of strong nebular emission lines as mentioned above, are in disagreement with the colors expected for Pop. III galaxies (see Zackrisson et al. 2011). In addition, Pop. III stars are expected to show strong Balmer lines but only weak lines of heavier elements such as [O III], which would be in tension with the extremely high [O III]$+[\text{H} \beta$ EW we find below (section 3.7). The UV continuum slope expected for Pop. III galaxies is also significantly bluer than our measurements (section 3.4). Nevertheless, the colors could possibly fit the predicted colors of supermassive stars (e.g. see Fig. 15 in Martins et al. 2020). These should therefore possibly be considered as a viable candidate population that drives very red colors of our object as well. We however defer a detailed analysis of these more exotic options to future work.

### 3.3. Lensing magnifications and geometric redshift

| ID     | R.A.   | Dec.  | F435W | F606W | F814W | F105W | F115W | F125W | F140W | F150W |
|--------|--------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| QSO1A  | 3.5798295 | -30.4015694 | <4     | <2    | <2    | 16 ± 2 | 22 ± 2 | 23 ± 3 | 26 ± 3 | 24 ± 2 |
| QSO1B  | 3.5835374 | -30.3966757 | <4     | 28 ± 5 | 62 ± 5 | 149 ± 4 | 158 ± 4 | 168 ± 7 | 173 ± 8 | 195 ± 4 |
| QSO1C  | 3.5972019 | -30.3943298 | <4     | <2    | 5 ± 2  | 12 ± 2 | 13 ± 2 | 10 ± 3 | 12 ± 4 | 14 ± 2 |

Table 1. Photometry of the three multiple images of the red compact object.

Note—Fluxes are in nJy from the deep HST/Advanced Camera for Surveys (ACS), HST/Wide-Field Camera Three (WFC3) and JWST/NIRCam imaging taken from the UNCOVER photometric catalog v9.3.1 (Weaver et al. in prep.). For each of the three images we also indicate the catalog ID number in parentheses. For bands in which the images are not detected, we list the 1σ upper-limit. Note that the central image, #2, is heavily contaminated by light of nearby cluster galaxies and ICL. The magnifications are computed from our UNCOVER-based SL model of A2744 published in Furtak et al. (2022b).
To estimate the de-lensed properties of the object presented here as well as to corroborate the photometric redshift estimates, we use an updated fully parametric SL model of A2744 that we recently constructed in the framework of the UNCOVER program (Furtak et al. 2022b, see also Roberts-Borsani et al. 2022). The model uses a long list of spectroscopically confirmed multiply imaged systems (e.g., Mahler et al. 2018; Bergamini et al. 2022) and additional photometric systems that we identified in the new UNCOVER data, in particular in the northern sub-clusters. Note that this sub-structure only has a minor effect on the SL properties in the main cluster core though where the object studied in this work is situated. For the model, cluster galaxies are modeled as double pseudo elliptical mass profiles (dPIEs; see Keeton 2001; Elíasdóttir et al. 2007) and five dark matter (DM) halos are used, each modeled as a pseudo isothermal elliptical profile (PIED; e.g. Keeton 2001). The final model used in this work reproduces the > 60 multiple image systems which span a wide redshift range from $z \sim 1.7$ to $z \sim 10$ very well with a lens plane RMS of 0.66″. Full details of the model are given in Furtak et al. (2022b). The critical curves from the model for various redshifts can be seen in Fig. 1.

We use this SL model to derive magnification estimates for the three lensed images. We obtain magnifications of $\mu = 7.5 \pm 0.4$, $\mu = 8.4 \pm 0.8$ and $\mu = 4.0 \pm 0.1$ for the images A, B, and C, respectively assuming a source redshift of $z_s \sim 7.5$. These are in broad agreement with the flux ratios that we measure for the three objects (see Tab. 1).

We can also use the SL model to examine the redshift of the source, due to the nesting effect in which the lensing critical curves grow for higher source redshifts. However, as the angular diameter distance ratio saturates for high-redshift sources, a concrete redshift estimate is not easy to obtain, but a lower limit can be placed. In particular, our model from Furtak et al. (2022b) strongly suggests that the object lies at $z > 7$ and in fact pushes to even higher redshifts around $z \sim 10 - 11$ (although these higher redshifts are ruled out by the photometry). To further examine this we therefore generate a suite of different models spanning a larger range of input configurations (i.e. number of DM halos, number of freely weighted massive cluster galaxies, number of photometric multiply imaged systems and multiple image configurations). These models explicitly include the red object system with a free redshift to be optimized and also two new dropout systems at $z_{\text{phot}} \simeq 4.9$ and $z_{\text{phot}} \simeq 6.9$ identified in the UNCOVER data close to the images of the red object. The various resulting models span a range of best-fit redshift estimates for the red object system, with the lowest-redshift ones being $z \gtrsim 5.5$. A similar constraint can in fact be also obtained model-independently from the geometry of multiple image systems near the red object: Systems up to $z \sim 5$ are seen as expected at somewhat smaller angles than the red object, implying that the red object system should lie at a higher redshift.

3.4. UV luminosity and continuum slope

We fit the UV continuum of our object with $F_{\lambda} \propto \lambda^\beta$ and find a UV-slope of $\beta_{\text{UV}} = -1.6 \pm 0.2$. Extrapolating the fitted continuum to 1450 Å, we measure a relatively bright UV luminosity of $M_{\text{UV},1450} = -21.38 \pm 0.09$ (lensing corrected). Given this high UV luminosity and the UV-slope $\beta_{\text{UV}} < -1$, the scenario of very large dust attenuation mentioned in section 3.2 becomes unlikely. This means that the red colors of our object are most likely driven by emission lines or optical continuum emission and not dust.

For comparison, the UV-slope of our object is bluer than a red quasar, such as the $z \sim 7$ object found by Fujimoto et al. (2022), but of the same order as typical high-redshift galaxies and quasars with similar absolute UV luminosities (Bouwens et al. 2014). It is however notably redder than typical early galaxies recently found in JWST observations (e.g. Atek et al. 2022; Adams et al. 2023; Castellano et al. 2022; Cullen et al. 2022; Furtak et al. 2022a, see also discussion in Endsley et al. 2022a). This also includes a population of galaxies at high redshifts with blue UV-slopes but red rest-frame optical colors (Labbe et al. 2022; Finkelstein et al. 2022) which seem to indicate that massive galaxies have started forming early on. Some of the objects in this sample show red colors especially in the long-wavelength (LW) channel (e.g. F277W–F444W $\sim$2), somewhat similar to our object (see section 3.2). However, as we show in sections 3.5 and 3.6, our object is distinct with respect to both typical blue high-redshift galaxies, and this population of red galaxies, in terms of size and UV luminosity density.

3.5. Size

We verify that the source is indeed an unresolved point source with a dedicated GALFIT (Peng et al. 2010) analysis in all available filters. From the GALFIT measurement, we obtain an observed effective radius of $r_e \simeq 1.3$ pixels (with a pixel scale of 0.04″/pixel) in the short-wavelength (SW) bands for both of the images that are not heavily affected by a nearby cluster galaxy light (i.e images A and C, see Fig. 1 and section 3.1), and $r_e < 1$ pixel in the LW bands. Taking the magnification into account, this translates into a source radius upper...
limit of $r_e \lesssim 100$ pc. Moreover, we note that both image A and image C have a very similar effective radius fit of $r_e \approx 1.3$ pixels. However, by the magnification ratio, we would expect image A to have a 40% larger radius if the images were are even marginally resolved. This suggests that indeed, the object is an unresolved point source.

Given the point-like nature of the source, assuming a point-spread-function (PSF) with a full-width half maximum (FWHM) of 0.03″ for the shortest-wavelength filter and taking the magnification into account, we place an upper-limit of FWHM $\lesssim 60$ pc on the source. The relation between the FWHM and effective radius is not straightforward and depends on the light profile shape of the source (Voigt & Bridle 2010; Ryon et al. 2017). For simplicity, we here assume the effective radius $r_e$ to be half of the FWHM. Note that this is somewhat conservative, e.g. for an exponential disk $r_e \approx \frac{\text{FWHM}}{2.44}$ (Murphy et al. 2017). We thus obtain an upper limit on the source size of $r_e \lesssim 30$ pc.

This limits the possible nature of our source even further, by ruling out a possibly evolved galaxy in which the red colors would originate from stellar continuum. Among the remaining scenarios is an extremely bright star-forming clump on the upper size end. These are however usually close to a host galaxy which is clearly not observed here. Indeed, the sizes of lensed high-redshift galaxies measured with HST imply very small $r_e \sim 100$ pc scale upper limits (e.g. Coe et al. 2013; Zitrin et al. 2014; Bouwens et al. 2017; Kawamata et al. 2018). The scenario in which only a bright clump from a distant galaxy is seen, i.e. the host galaxy is below the detection limit, therefore need to be considered. Observations of high-redshift galaxies with JWST have however already revealed them to show sub-structures consistent with multiple star-forming clumps, as in the multiplet imaged $z \sim 10$ object in A2744 (Zitrin et al. 2014; Roberts-Borsani et al. 2022) shown in Fig. 1 or in the $z \sim 11$ object recently observed by Hsiao et al. (2022). With the JWST UNCOVER data, which are much deeper than other JWST images so far, and despite the relatively high lensing magnification (see Tab. 1), we do not find however any hint of an underlying more extended structure to our object. This implies that the measured luminosity may indeed arrive from a single central source with a size on the scale of at most several tens of pc.

3.6. Luminosity density

In Fig. 3, we put the UV luminosity measured in section 3.4 in relation to our source-size upper limit measured in section 3.5. The red compact object studied here seems to have a significantly higher luminosity density than typical galaxies both at high and low redshifts:

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Figure3}
\caption{Size-UV luminosity diagram. Our red compact object is shown as the purple star. For comparison we also show typical compact UV-emitting galaxies at both low redshifts (from Barro et al. 2014; blue dots), and high redshifts (from Bowler et al. 2017; black dots). We also show red galaxies recently detected with JWST in the CEERS field by both Labbe et al. (2022) and Finkelstein et al. (2022). Our red object is more compact by about an order of magnitude compared to the smallest of these galaxies. Also shown (green) is an obscured quasar, or a hybrid galaxy-AGN candidate, GNz7q, recently detected by Fujimoto et al. (2022).}
\end{figure}

It is smaller by over an order of magnitude than the smallest of galaxies. This implies that it may indeed be too bright for its size to be explained by typical stars alone. Bearing in mind that the object is not a transient source (for example, it was already detected in the HFF), only few possible scenarios remain. The main engine driving the observed luminosity and colors could possibly be a faint quasar, i.e. a bright AGN outshining its host galaxy, such as in e.g. Fujimoto et al. (2022) or one of the objects in Eudsey et al. (2022a), or possibly a compact clump of Pop. III or supermassive stars (although the object does not seem to show colors blue enough to support the former, as discussed in section 3.2). While the current data set in absence of spectroscopy does not allow a robust discussion of the possible scenarios, we nevertheless perform an SED-fitting analysis in section 3.7, showing that the AGN scenario is plausible. A more detailed source analysis is deferred to future work when the planned UNCOVER JWST/NIRSpec observations are available (scheduled for July 2023; Bezanson et al. 2022).

3.7. SED fitting
In order to further investigate the origin of our object’s observed properties and to constrain its parameters, we perform an SED-fit to the de-magnified photometry of the first image (see Tab. 1) with the Bayesian Analysis of GaLaxy sEds tool (BEAGLE; Chevallard & Charlot 2016). Following Endsley et al. (2022a), we run two SED-fits with BEAGLE: one with a ‘classical’ star-forming high-redshift galaxy with a constant star-formation history (SFH) and the other with a combination of a star-forming galaxy with an AGN. The former uses the standard Gutkin et al. (2016) set of BEAGLE templates which combine the latest version of the Bruzual & Charlot (2003) stellar population models with Cloudy (Ferland et al. 2013) photoionization models to account for nebular emission. The latter uses the new type II AGN templates developed for BEAGLE by E. Curtis-Lake (Vidal-García et al. 2022) to add AGN emission to the galaxy templates. Both SED-fits assume a Chabrier initial stellar mass function (IMF) (Chabrier 2003) and an SMC dust attenuation law (Pei 1992) and account for intergalactic medium (IGM) attenuation using the Inoue et al. (2014) IGM models.

We show the best-fitting SEDs for both runs in Fig. 4. Both fits consistently find a very well constrained photometric redshift of $z_{\text{phot}} \simeq 7.66$, i.e. somewhat higher than the EAZY-derived redshift from the UNCOVER catalog (see section 3.1). Both BEAGLE fits seem to much better reproduce the observed photometry ($\chi^2 = 136$ and $\chi^2 = 79$ for the galaxy and galaxy+AGN fit respectively, as opposed to the $\chi^2 \sim 460$ from EAZY). Among the two BEAGLE fits, the hybrid galaxy and AGN fit seems to yield the better fit to the photometry. The classical galaxy fit requires a high stellar mass ($\log(M_*/M_\odot) = 8.99^{+0.04}_{-0.03}$) and low stellar age ($\log(t_{\text{age}}/\text{yr}) = 7.010^{+0.001}_{-0.001}$) to reproduce the red colors with mostly continuum emission. The hybrid galaxy+AGN fit on the other hand yields a somewhat lower stellar mass ($\log(M_*/M_\odot) = 8.1^{+0.2}_{-0.3}$) and higher stellar age estimate for the galaxy component ($\log(t_{\text{age}}/\text{yr}) = 8.3^{+0.3}_{-0.3}$), but reproduces the red color in the LW filters with extremely strong nebular emission originating from the AGN component (EW$_{[\text{O III}]+\beta} = 9137^{+1459}_{-1320}$ Å). We also note that the best-fitting galaxy SED (black line in the left-hand panel of Fig. 4) has a distinctly blue UV-slope whereas our photometry clearly shows a redder slope ($\beta_{\text{UV}} \simeq -1.6$; see section 3.4) as can be seen from the blue points in Fig. 4. That being said, it is important to note that in this particular SED-fit, the extremely strong rest-frame optical [O III] and H$\beta$ lines fall exactly onto the edge of the F410M and

Figure 4. Maximum-a-posteriori (MAP) SEDs fitted with BEAGLE (black). The de-magnified photometry of image A is shown in blue, and the best-fitting model fluxes in each band are shown in red. Left: SED-fit with a constant SFH star-forming galaxy. Right: SED-fit with a hybrid combination of a star-forming galaxy with a type II AGN component, similar to Endsley et al. (2022a). We decompose the best-fitting SED (black) into its two components, the galaxy SED (purple) and the AGN emission (orange). Both fits consistently find our object to lie at a redshift of $z_{\text{phot}} \simeq 7.7$. The galaxy+AGN fit seems to better reproduce the observed red colors (see section 3.2) and red UV-slope (see section 3.4) thanks to the strong nebular emission of the AGN component. This is also consistent with the very compact nature of our source as described in sections 3.5 and 3.6.
F444W bands which is also the reason for the seemingly very precise photometric redshift estimate (see Fig. 4). This is due to the fact that the LW bands have a much lower signal-to-noise than the other filters (see Tab. 1) and therefore dominate the fit. For that reason, even though the AGN component yields the better $\chi^2$, we at this stage cannot definitely rule out the compact galaxy or star-cluster scenario.

In addition, we run an independent galaxy SED-fit with prospector (Johnson et al. 2021) in order to complement the BEAGLE fits presented above. We in particular use prospector-α which models a non-parametric SFH and assumes a continuity prior to ensure smooth transitions between time bins (Leja et al. 2017, 2019). We additionally include two priors on the stellar mass and the SFH from Wang et al. (in prep.). The stellar mass prior is constructed from the observed mass functions in Leja et al. 2020 and the dynamic SFH prior is a simple phenomenological description reflecting the consistent observational finding that massive galaxies form much earlier than low-mass galaxies (Cowie et al. 1996; Thomas et al. 2005). The prospector fit finds a best-fitting photometric redshift $z_{\text{phot}} = 7.6^{+0.5}_{-0.2}$ which agrees well with the two BEAGLE fits. It further finds a very large stellar mass (log($M_*/M_\odot$) = 10.57$^{+0.07}_{-0.08}$) and a relatively old age of $t_{\text{age}} = 230^{+130}_{-210}$ Myr. Similarly to the constant SFH galaxy fit with BEAGLE, this is due to the fact that prospector in this case also fits the extremely red colors of our object with stellar continuum and thus requires a very large stellar mass. Such a large galaxy is however unlikely given the extremely compact nature of our source of $r_e \lesssim 30$ pc (see section 3.5). The emission line scenario, which requires an AGN component in order to reproduce the red colors in the rest-frame optical bands as discussed above, is therefore the most likely four our source.

Given these SED-fitting results and the other properties described in the previous sections, in particular the UV-density (section 3.6), we tentatively conclude that this triply imaged red compact object is possibly a faint quasar at $z_{\text{phot}} \simeq 7.7$. This however cannot definitely be determined with the present data and will require spectroscopy. A further investigation of this scenario will be possible once the UNCOVER NIRSpec observations become available. Given the phenomenal strength required in the rest-frame optical emission lines to make-up the red colors of this object, they should be easily detectable with JWST/NIRSpec if present. Note that if confirmed with spectroscopy, this would make our object comparable in distance to the highest-redshift quasar known to date (Wang et al. 2021) and add to the small number of quasars that are known to be multiply imaged by galaxy clusters (e.g. Inada et al. 2003; Sharon et al. 2017). It will also constitute one of the faintest quasars ever detected.

4. CONCLUSIONS

We present a unique, extremely red and compact object at $z_{\text{phot}} \simeq 7.66$ which is triply imaged by the SL galaxy cluster Abell 2744. The object was detected in recent deep multi-band JWST/NIRCam imaging taken for the UNCOVER program and its high-redshift nature is independently supported geometrically by the gravitational lensing (with a lower limit of $z \gtrsim 5.5$).

Thanks to the lensing magnification, we can limit its size at $z \simeq 7.7$ to $r_e \lesssim 30$ pc, suggesting it to be extremely compact. We in addition measure a rather red UV continuum slope of $\beta_{\text{UV}} = -1.6 \pm 0.3$ and a relatively bright UV luminosity of $M_{\text{UV,1450}} = -21.38 \pm 0.09$. Our object resides in significantly different locations on both color-color and $M_{\text{UV}}$-size diagrams than the regions typically occupied by star-forming galaxies or the red high-redshift galaxy populations recently revealed with the JWST. Its compact size, extremely red color indicative of extreme emission lines, and its luminosity density suggest that the emission is likely assisted – or perhaps dominated – by an AGN component, which is also tentatively further supported by a detailed SED-fitting analysis: Using the BEAGLE tool with its newly developed AGN templates, we fit a joint galaxy+AGN model to the photometry of our object and obtain a stellar mass of $M_* \simeq 10^{8.1} M_\odot$ and an age of about 200 Myr. In order to explain the excessively red colors of the object, extreme nebular emission lines are required, reaching [O III]+Hβ EWs of over 9000 Å. This fit seems to be preferable over a fit to a typical high-redshift galaxy, although both fits do not match the observed photometry very well.

Other than an AGN, we also briefly discuss other candidate engines such as a compact clump of Pop. III or supermassive stars. The predicted colors of Pop. III stars however do not seem to agree with the observed colors and strong emission lines needed to explain them, whereas the predicted color of supermassive star populations would agree with the observations and could therefore perhaps be considered an alternative scenario to the AGN. Spectroscopic observations planned for next year with JWST/NIRSpec will be crucial in examining the extreme emission line predictions made here and shed light on the true nature of this source. If confirmed as an AGN at $z = 7.7$, this object would be one of the most distant and faintest quasars observed to date, and add to the short list of known multiply imaged quasars.
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This research made use of Astropy, a community-developed core Python package for Astronomy (Astropy Collaboration et al. 2013; Price-Whelan et al. 2018) as well as the packages NumPy (van der Walt et al. 2011), SciPy (Virtanen et al. 2020), Matplotlib (Hunter 2007) and the MAAT Astronomy and Astrophysics tools for MATLAB (Ofek 2014).

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