A shot in the Dark (Ages): a faint galaxy at $z = 9.76$ confirmed with JWST

Guido Roberts-Borsani$^{*,1}$, Tommaso Treu$^1$, Wenlei Chen$^2$, Takahiro Morishita$^3$, Eros Vanzella$^4$, Adi Zitrin$^5$, Pietro Bergamini$^{4,6}$, Marco Castellano$^7$, Adriano Fontana$^7$, Claudio Grillo$^{6,8}$, Patrick L. Kelly$^2$, Emiliano Merlin$^7$, Diego Paris$^7$, Piero Rosati$^{4,9}$, Ana Acebron$^{6,8}$, Andrea Bonchi$^{7,10}$, Kit Boyett$^{11,12}$, Maruša Bradač$^{13,14}$, Tom Broadhurst$^{15,16,17}$, Antonello Calabró$^7$, Jose M. Diego$^{18}$, Alan Dressler$^{19}$, Lukas J. Furtak$^5$, Alexei V. Filippenko$^{20}$, Karl Glazebrook$^{21}$, Anton M. Koekemoer$^{22}$, Nicha Leethochawalit$^{23}$, Matthew A. Malkan$^1$, Charlotte Mason$^{24,25}$, Amata Mercurio$^{26,27}$, Benjamin Metha$^{1,28,29}$, Themiya Nanayakkara$^{21}$, Laura Pentericci$^7$, Justin Pierel$^{22}$, Steven Rieck$^2$, Namrata Roy$^{30}$, Paola Santini$^7$, Victoria Strait$^{24,25}$, Robert Strausbaugh$^{31}$, Michele Trenti$^{28,29}$, Benedetta Vulcani$^{32}$, Lifan Wang$^{33}$, Xin Wang$^{34,35}$, Rogier Windhorst$^{36}$, and Lilan Yang$^{37}$

$^1$Department of Physics and Astronomy, University of California, Los Angeles, CA 90095, USA

$^2$School of Physics and Astronomy, University of Minnesota, 116 Church Street SE, Minneapolis, MN 55455, USA

$^3$Infrared Processing and Analysis Center, Caltech, 1200 E. California Blvd., Pasadena, CA 91125, USA

$^4$INAF - OAS, Osservatorio di Astrofisica e Scienza dello Spazio di Bologna, via Gobetti 93/3, I-40129 Bologna, Italy

$^5$Physics Department, Ben-Gurion University of the Negev, P.O. Box 653, Be’er-Sheva 84105, Israel

$^6$Dipartimento di Fisica, Università degli Studi di Milano, Via Celoria 16, I-20133 Milano, Italy
7 INAF Osservatorio Astronomico di Roma, Via Frascati 33, 00078 Monteporzio Catone, Rome, Italy

8 INAF - IASF Milano, via A. Corti 12, I-20133 Milano, Italy

9 Dipartimento di Fisica e Scienze della Terra, á degli Studi di Ferrara, Via Saragat 1, I-44122 Ferrara, Italy

10 ASI-Space Science Data Center, Via del Politecnico, I-00133 Roma, Italy

11 School of Physics, University of Melbourne, Parkville 3010, VIC, Australia

12 ARC Centre of Excellence for All Sky Astrophysics in 3 Dimensions (ASTRO 3D), Australia

13 University of Ljubljana, Department of Mathematics and Physics, Jadranska ulica 19, SI-1000 Ljubljana, Slovenia

14 Department of Physics and Astronomy, University of California Davis, 1 Shields Avenue, Davis, CA 95616, USA

15 Department of Theoretical Physics, University of the Basque Country UPV/EHU, Bilbao, Spain

16 Donostia International Physics Center (DIPC), 20018 Donostia, Spain

17 IKERBASQUE, Basque Foundation for Science, Bilbao, Spain

18 Instituto de Física de Cantabria (CSIC-UC). Avda. Los Castros s/n. 39005 Santander, Spain

19 The Observatories, The Carnegie Institution for Science, 813 Santa Barbara St., Pasadena, CA 91101, USA

20 Department of Astronomy, University of California, Berkeley, CA 94720-3411, USA

21 Centre for Astrophysics and Supercomputing, Swinburne University of Technology, PO Box 218, Hawthorn, VIC 3122, Australia
22 Space Telescope Science Institute, 3700 San Martin Dr., Baltimore, MD 21218, USA

23 National Astronomical Research Institute of Thailand (NARIT), Mae Rim, Chiang Mai, 50180, Thailand

24 Cosmic Dawn Center (DAWN)

25 Niels Bohr Institute, University of Copenhagen, Jagtvej 128, 2200 København N, Denmark

26 Dipartimento di Fisica “E.R. Caianiello”, Università degli Studi di Salerno, Via Giovanni Paolo II 132, I-84084 Fisciano (SA), Italy

27 INAF-Osservatorio Astronomico di Capodimonte, Via Moiariello 16, 80131 Napoli, Italy

28 School of Physics, University of Melbourne, Parkville 3010, VIC, Australia

29 ARC Centre of Excellence for All-Sky Astrophysics in 3-Dimensions (ASTRO 3D), Australia

30 Center for Astrophysical Sciences, Department of Physics & Astronomy, Johns Hopkins University, Baltimore, MD 21218, USA

31 Minnesota Institute For Astrophysics, University of Minnesota, 106 Pleasant St SE, Minneapolis, MN 55455, USA

32 INAF Osservatorio Astronomico di Padova, vicolo dell’Osservatorio 5, 35122 Padova, Italy

33 Mitchell Institute for Fundamental Physics & Astronomy, Texas A&M University, Department of Physics and Astronomy, 4242 TAMU, College Station, TX 77843, USA

34 School of Astronomy and Space Science, University of Chinese Academy of Sciences (UCAS), Beijing 100049, China

35 National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, China

36 School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287-1404, USA
The appearance of galaxies over the first billion years after the Big Bang is believed to be responsible for the last dramatic change in the state of the Universe. Ultraviolet photons from galaxies within this time period - the Epoch of Reionization - ionized intergalactic Hydrogen, rendering the Universe transparent to UV radiation and ending the so-called cosmic Dark Ages, sometime after redshift \( z \sim 8 \). The majority of ionizing photons in the first few hundred Myrs of cosmic history are thought to derive from galaxies significantly fainter than the characteristic luminosity \( L^* \). These faint galaxies are thought to be surrounded by sufficient neutral gas to prevent the escape of the Lyman-\( \alpha \) photons that would allow confirmation with current observatories. Here we demonstrate the power of the recently commissioned James Webb Space Telescope to transform our understanding of the sources of reionization, by reporting the first spectroscopic confirmation of a very low luminosity (\( \sim 0.05L^* \)) galaxy at \( z = 9.76 \), observed 480 Myr after the Big Bang, via the detection of the Lyman-break and redward continuum with the NIRSpec and NIRCam instruments. The galaxy JD1\(^3\) is gravitationally magnified by a factor of \( \mu \sim 13 \) by the foreground cluster A2744. The power of JWST and lensing allows us to peer deeper than ever before into the cosmic Dark Ages, revealing the compact (\( \sim 150 \) pc) and complex morphology and physical properties of an ultrafaint galaxy (\( M_{UV} = -17.45 \)).

We conducted James Webb Space Telescope (JWST) observations with NIRCam imaging and NIRSpec prism spectroscopy (DDT 2756; PI Chen) of the galaxy JD1, previously identi-
fied as a triply-imaged galaxy candidate at $z \sim 10$ based on its photometric colors and lensing configuration\textsuperscript{3}. Residing behind the Abell 2744 galaxy cluster, the source is gravitationally lensed and displays three images, of which two bright components (A and B) reside to the North of the main galaxy cluster and a fainter component (C) to the South.

Our observations targeted the two brightest components with NIRCam imaging on 20th October 2022, while NIRSpec prism spectroscopy targeted one of those two components (component B\textsuperscript{1}) on 23rd October 2022. An RGB image using the resulting NIRCam data is shown in Figure 1, where we highlight a portion of the cluster field (including the positions of the A and B lensed images of JD1), with an inset plot focused on the spectroscopic target (henceforth JD1). The two components have approximately the same observed brightness ($F200W=27.26\pm0.23$ AB and $27.43\pm0.20$ AB, corresponding to $30.06\pm0.23$ AB and $30.14\pm0.20$ AB, respectively, after correcting for lensing magnification) as expected for two images straddling the critical line.

The multi-band NIRCam photometry ($F115W$, $F150W$, $F200W$, $F277W$, $F356W$, $F444W$) alone confirms JD1 as a $z \sim 10$ photometric candidate. The colors of JD1 are consistent with the Lyman break being located between the $F115W$ and $F150W$ filter, in which all the photons more energetic than rest-frame Lyman-$\alpha$ have been absorbed and scattered by intervening intergalactic hydrogen. The galaxy is detected at high significance at all wavelengths redward of Lyman-$\alpha$ (i.e., $F200W$, $F277W$, $F356W$, $F444W$ filters). Combining the NIRCam data with deep *Hubble Space Telescope* (*HST*) Frontier Field photometry (including WFC3/F160W, WFC3/F140W, WFC3/F125W filters) \textsuperscript{5}.

\textsuperscript{1}Spectral overlap prevented us from observing both.
WFC3/F125W, WFC3/F105W, ACS/F814W) from [3]³, a fit to the spectral energy distribution (SED) with the photometric redshift-fitting code, EAzY ⁴, yields a precise photometric redshift $z = 9.70^{+0.13}_{-0.13}$ (consistent with the geometric redshift from lens models ³,⁵). The results of the fit, along with postage stamps of the NIRCam images, are shown in the top panel of Figure 2, and include a forced fit of a $z < 4$ interloper, for comparison. We find a $z \sim 10$ solution is clearly favored, with a well-defined $P(z)$ governed by a dominant peak at $z_{\text{phot}} = 9.70$ and a much smaller peak at $z_{\text{phot}} = 2.34$, the latter of which is statistically rejected due to its increased $\chi^2$ statistic ($\chi^2 = 8.8$ and $\chi^2 = 25.9$ for the high-$z$ and low-$z$ fits, respectively). We note that the low redshift solution is also ruled out by the positions and comparable fluxes of the multiple images: for a $z \sim 10$ solution both images are expected to be similar to each other in offsets relative to the critical magnification line, and thus to have comparable fluxes. This is not the case for a $z = 2.34$ solution, which would place the critical lie far closer to the B component. (Figure 1). A comparison of the constraining power of NIRCam and HST data is shown in Extended Data Figure 1.

The NIRSpec spectrum of the galaxy (bottom panel of Figure 2), spanning a wavelength range $\lambda_{\text{obs}} \simeq 0.6 - 5.3\mu\text{m}$, provides the third and conclusive piece of evidence for the redshift identification. A clear continuum break is apparent at $\sim 1.3\mu\text{m}$ and continued continuum emission redward of the break. No prominent emission lines are seen. Identifying the break as the Lyman break, a fit to the spectrum (overplotted in Figure 2b as an orange line) places the galaxy at a spectroscopic redshift of $z_{\text{spec}} = 9.756^{+0.017}_{-0.007}$ (see the Methods section for details), in excellent agreement with the photometric redshift estimated above, and deep into the heart of the cosmic Dark Ages, when the universe was mostly filled with neutral hydrogen⁶. While the break
alone does not completely preclude a $z \sim 2$ solution deriving from a prominent (rest-frame) 4000 Å/Balmer break from mature stellar populations, such a solution is ruled out given that is crucially unable to reproduce the sharp break in the spectrum, and of course would be inconsistent with the photometry and lensing data discussed above.

The absence of strong Lyman-α highlights the likely consequence of damping-wing scattering of the line by a highly neutral medium, indicating this galaxy does not reside in a massive, ionized bubble - unlike some marked examples of especially luminous and extreme objects which may have carved out large bubbles themselves $^7$-$^{11}$ - and illustrating the novel capabilities and power of JWST to detect sources deep in the reionization era via their continuum emission (e.g., $^{12}$). Adopting the upper limit on flux at the expected position of Lyman-α, the binned wavelength resolution, and the best-fit continuum, we set a $2\sigma$ upper limit on the rest-frame equivalent width ($\text{EW}_0$) of 27 Å.

For a $z \sim 9.70$ solution, the $\text{[O\,\text{II}]\lambda\lambda 3726,3729}$ Å emission line doublet is also covered by the spectrum at $\sim 4$ μm and thus in our observed wavelength range. No clear line ($\text{EW}_0 < 40$ Å rest frame at $2\sigma$) is seen at that location, however this is unsurprising given the reduced sensitivity of the spectrum at the red end, and the relatively low spectral resolution. As an illustration, we overplot the expected spectra from the best-fit EAzy solutions (which include prominent emission lines) by injecting these into the JWST Exposure Time Calculator (ETC) and, adopting our DDT observational setup, smooth the resulting spectra in the same fashion as the NIRSpec spectrum of JD1. The results are overplotted in Figure 2b and demonstrates that the non-detection of the
[O II] line from our spectrum does not exclude its presence for EW consistent with the SED fitting. Although there is some hint of possible emission at the expected location, we conservatively only quote an upper limit (see above). Extending the EW limits to the rest of the spectrum blueward of 4 µm (where the spectrum is most reliable), we find a range of upper limits (2σ) EW = 11 − 65 Å, respectively for 1-4 µm.

The combination of lensing magnification and JWST’s extraordinary angular resolution results in an effective resolution of ~80 pc in the galaxy source plane, allowing us to characterize the morphology of JD1. For this purpose, we use the NIRISS images through filter taken as part of the GLASS-ERS program, which deliver the best depth, sampling, and angular resolution for this object (Figure 3). JD1 comprises two components: a knot that likely dominates the signal in the prism spectrum, and an extended component. The knot can be modelled with a pure point spread function (PSF) (model A) or a Sersic (model B). The extended component is well described by a Sersic model. The two models A and B yield fits of similar quality, and the difference is not significant for our interpretation. The effective radius of the extended component is 6.5 pixels, i.e. ~200 mas, and highly elongated (b/a=0.2), consistent with high tangential magnification due to lensing. Correcting for lensing magnification the half light radius of the source is still a very compact ~150 pc (c.f. 14). In sum, JD1 has complex morphology consisting of a compact knot, and an extended source. The complex morphology is observed also in the NIRCAM bands out to ~ 5 µm (Figure 2).

Finally, we infer global galaxy properties based on detailed SED fitting of the source, incor-
porating all of the spectroscopic and photometric constraints. Correcting for a fiducial magnification factor of \( \mu = 13.1^{+0.7}_{-0.7} \) (see Methods section), the best-fit model paints a picture of a young (\( \sim 30 \) Myrs), star-forming (log SFR/M\(_\ast\) yr\(^{-1}\) = −8.38) and low stellar mass (log \( M_\ast/M_\odot = 7.48 \)) galaxy that is dust-poor (\( A_V = 0.20 \) mag) and sub-solar in metallicity (log \( Z_\ast/Z_\odot = -0.23 \)). The inferred UV slope of the spectrum (\( \beta = -1.90 \)) is blue and supports such a hypothesis, where the galaxy is dominated by a young, star-forming system that is beginning its chemical enrichment journey. The absolute UV magnitude of the system, \( M_{UV} = -17.44 \) mag, classifies the galaxy as a sub-\( L^\ast \) (\( \sim 0.05 L^\ast \), adopting \( M_{UV} = -20.6 \) mag\(^{15,16} \)) system and, given its extreme distance, ranks it as the faintest known source at comparable redshifts (c.f. \(^{11,17} \); see Figure 4). As such, the galaxy represents a “typical” low-luminosity system close to the Dark Ages, the likes of which are thought to provide the bulk of the UV photons required to reionize the Universe \(^{1,2} \). We list the best-fit properties and uncertainties in Extended Data Table 2.

Gravitational lensing plays a crucial role in the detection, confirmation, and analysis of this galaxy. First, the galaxy is magnified by a factor \( \mu \sim 13^5 \), which allows such an intrinsically faint system to be detected in imaging and spectroscopy. Second, in addition to the spectroscopy, the geometry of the multiple images allows us to exclude a low redshift solution\(^ {3,5} \) in a robust and consistent fashion through its “geometric” redshift, owing to the dependence of the critical lines on the distance to the source (see Figure 1). Third, the lensing magnification enables a unique study of its properties from the spectro-photometry and the characterization of its morphology, as discussed above.

9
Combining the spectroscopic confirmation of JD1 with the magnification offered by gravitational lensing affords a unique and unprecedented insight into the physics of an ultra-faint galaxy in the heart of the Dark Ages. Here we have shown a first glimpse at this unique window with JWST, highlighting exactly what the observatory was built for. The unveiling of entire populations of faint galaxies and their physical properties through unbiased measurements now represents the logical next step and a significant leap in our ability to characterize the sources that likely reionized the Universe.

Figure 1 | False-color NIRCam image of the Abell 2744 cluster (B=F115W+F150W, G=F200W+F277W, R=F356W+F444W), along with critical curves of formally infinite magnification from two lensing models
(Ref. 5 and an update to Ref. 3 discussed in the methods section; blue and cyan curves respectively). The A and B multiple images of the $z = 9.76$ galaxy are highlighted by red circles. The inset represents a zoom-in on the brightest component (JD1), with the $0.2 \times 1.2$ NIRSpec slit (constructed using three MSA shutters) used for prism spectroscopy in our DDT program. Critical lines for a source at $z \sim 10$, the redshift indicated by the lens model, the photometry, and the spectroscopy, are in excellent mutual agreement – highlighting the robustness of the lens model – and fall between the two images consistent with their very similar brightness. In order to show the power of lensing to constrain the redshift of the source, we also show in orange line the critical line for a source at $z = 2.34$. If JD1 were at this lower redshift the image positions and fluxes would be inconsistent with the measurements.
Figure 2 | The SED and NIRSpec spectrum of JD1. (a) NIRCam postage stamp images (top panels) for each of the NIRCam bands used in this study, along with their extracted photometry (orange points, including HST photometry), and the best-fit SED (bottom panel, blue curve and diamonds) derived with
EAzY. A forced low redshift fit is also shown (grey curve and diamonds) and is disfavored. An inset plot highlights the $P(z)$ of the fit across the entire allowed redshift range. (b) The 2D (top) and 1D (bottom) NIRSpec prism spectrum of JD1. The optimally-extracted 1D spectrum is shown in purple curves and fill, with associated flux uncertainties (purple dashes) and a best-fit model in orange. The combined NIRCam and HST photometry are marked as blue points and we also show the EAzY SED fits in dashed blue ($z = 9.70$ solution) and dashed gray ($z = 2.34$ solution). The sharp clear break in the spectrum strongly disfavors the low redshift solution, for illustration. The 2D spectrum is smoothed by a Gaussian kernel ($\sigma = 0.25$ pixels) while all 1D spectra are binned by a factor of $5 \times$ compared to the native NIRSpec prism resolution, for illustration.
Figure 3 | Morphology of JD1 from *JWST*-NIRISS imaging. From the left to right: the galaxy system (marked by the red line) is shown in the NIRISS F150W image followed by the two models and their residuals described in the Methods section. The final stamp is a NIRISS RGB image.
Figure 4 | Spectroscopically-confirmed sources and their absolute magnitudes. A compilation of sources in the literature\textsuperscript{7–12,17–23} with spectroscopic redshifts (from NIR observations of Lyman-α or the Lyman break, or sub-mm observations of FIR lines such as [O\textsc{iii}] 88 microns) and their associated $M_{\text{UV}}$ values (grey squares), compared to JD1 (orange star). For consistency, all literature $M_{\text{UV}}$ values are calculated using the sources’ $H_{\text{160}}$–band photometry, their spectroscopic redshifts, and assuming a UV slope $\beta = -2$. JD1 is by far the lowest luminosity source (by $\sim 1.5$ mag) at comparable redshifts.
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Author Contributions  GRB led the NIRSPEC data reduction and analysis with input from several coauthors. GRB and TT wrote the paper, and developed the main interpretation of the results. AF, MC, EM,
and DP reduced the NIRCam images and provided the photometry. TM performed the spectral-fitting and derived the physical parameters.

AA, CG, PB, PR developed and updated the reference lens model providing predictions on lensed quantities. AM contributed to the construction of the photometric and spectroscopic catalogs for the lens model.

AZ and LF constructed the new lens model and wrote the accompanying text. TN, KG, and WC assisted with NIRSPEC data reduction and performed quality checks on the 1D and 2D spectra. EV and PR performed the analysis of the source morphology. All authors discussed the results and commented on the manuscript.

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Methods

Cosmological model. The cosmological parameters adopted in this paper are $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$. All magnitudes are quoted in the AB system$^{24}$.

JWST/NIRCam data reduction and photometry. We reduce all broad-band NIRCam images (F115W, F150W, F200W, F277W, F356W, and F444W) adopting the procedures and methods outlined by Merlin et al. (2022)$^{25}$ - we refer the reader to that paper for full details but provide a summary here. We use the public STScI pipeline (v11.16.14) with the latest set of reference files and zeropoints (CRDS_CTX=jwst_1007.pmap), and begin the data reduction with the calwebb_detector1 and calwebb_image2 routines on the uncalibrated raw images to apply flat-field and dark current corrections, as well as obtain data quality flags that denote bad pixels or detector level defects. Using a combination of the resulting pixel masks and a customized version of the SExtractor code$^{26}$, additional custom procedures are made to the images to correct for persisting $1/f$ noise, “snowballs”, and stray light. Single exposure images are then stacked in mosaics and re-binned on a common pixel grid using SWARP$^{27}$. The images are aligned to Gaia DR3 data with the code SCAMP$^{28}$, using pre-existing catalogs of Magellan data. The average difference between the two astrometric solutions is of $\sim 1$ mas, with NMAD $\sim 15$ mas.

The detection image of the galaxy is the co-added F444W image, and extraction of the fluxes is performed in the same manner as in the paper by Merlin et al.$^{25}$ In short, we use the code A-PHOT$^{29}$ to measure the fluxes within fixed circular apertures with diameter $2 \times$ FWHM of the F444W image ($0.28''$), on PSF-matched images; these fluxes provide robust colors, which are used...
to scale the total F444W flux (estimated with a Kron elliptical aperture) obtaining total fluxes in all bands. Since the object is located nearby a bright source, it is likely to be contaminated by the neighbour’s light; we therefore applied a local background subtraction module. We find good consistency comparing the total F150W flux with the flux given by Zitrin et al. (2014)\(^3\) for WFC3 F160W. The resulting photometry and coordinates of each of the components are listed in Extended Data Table 1.

**JWST/NIRSpec observations, data reduction and spectral extraction.** JD1 is composed of three image components, two of which (components A and B in the North; see Figure 1) reside sufficiently close to each other to cause spectral overlap and a third which, while residing on the South side of the foreground cluster, appears far fainter than its counterparts. As such, we target the brightest of the three images, component B. The observations were carried on 23 October 2022 with low-resolution \(R = \lambda/\Delta\lambda \simeq 50 - 350\) prism spectroscopy, adopting a three-shutter slitlet (approximately \(0.''2 \times 1.''2\)) in the Micro-Shutter Array (MSA) and nodding pattern over a total exposure time of \(\sim 1.23\) hrs. The position of the slits relative to the galaxy are shown in the inset image in Figure 1. The observations were carried out over two different pointings but with identical setups and position angles. The resulting exposures of the two pointings were reduced using the same version and reference files as used for the NIRCam data reduction, beginning first with the `calwebb_detector1` on the raw exposures before running the `calwebb_spec2` and `calwebb_spec3` routines to make flat-field corrections and subtract background contributions using the three shutter exposures as science and background exposures. The resulting 2D flat-fielded, background-subtracted, and calibrated (wavelength and flux) spectra are then visually
inspected by two authors (GRB and WC). The 2D spectrum cutouts for JD1 were then used to ex-
tract a 1D spectrum. Rather than use a simple boxcar, we utilize an optimal-extraction procedure
following the method outlined by Horne at al. (1986)\textsuperscript{30}, which constructs an inverse variance-
weighted extraction kernel based on the spatial profile of the spectrum (allowing the FWHM to
evolve as a function of wavelength to account for the varying PSF along the large wavelength
range probed) to optimally extract the spectrum. The routine is run on the 2D flux image as well
as the variance image (squaring the weighting factor) to extract the spectrum and 1σ uncertainties
presented in the bottom panel of Figure 2. The wavelength range covers $\lambda_{\text{obs}} = 0.6 - 5.3 \mu m$ which,
for a $z \sim 10$ object includes the entire rest-frame UV spectrum.

**Photometric redshift estimates.** We employ the photometric redshift code, \textit{EAzY}, to determine
a precise photometric redshift derived from both NIRCam and \textit{HST} photometry from Zitrin et
al. (2014)\textsuperscript{3}. The \textit{HST} filters employed (in addition to our NIRCam data set) are WFC3/F160W,
WFC3/F140W, WFC3/F125W, WFC3/F105W, ACS/F814W. Although deep \textit{Spitzer}/IRAC data
also exist over the Abell 2744 cluster, the relatively poor spatial resolution makes photometry
close to the cluster center uncertain and prone to contamination. As such, we opt not to use those
here. We adopt the default set of galaxy SED templates (v1.3), which include SEDs of dusty,
$z \sim 2$ star-forming galaxies, as well as templates with strong emission lines. We allow a redshift
range of $z = 0 - 15$ and fit all templates independently. All other default settings are adopted. We
run the code on the photometry described above, in addition to two other iterations, one with \textit{HST}
photometry only and one with NIRCam photometry only in order to assess the constraining power
of each data set in deriving a reliable photometric redshift. The resulting $P(z)$’s from each of the
Strong lensing models. In order to check the robustness of our results with respect to the lens model, we utilize two lens models, described below. One is the recently published model by Bergamini et al. (2022), and the second is a major update of the Zitrin et al. (2014) model. The two models are based on a large number of observational constraints and represent the state of the art. They give mutually consistent results, so our conclusions are independent on the choice of lens model. When necessary, we use the Bergamini et al. (2022) magnification, but all the inferred numbers would be the same within the uncertainties for the other model.

In the first model, detailed by Ref. 5, the cluster total mass distribution is reconstructed using the positions of 90 multiple images from 30 different point-like sources, with spectroscopic redshifts between 1.69 and 5.73. Internal velocity dispersion measurements of 85 cluster galaxies are exploited to calibrate the subhalo mass component, which includes 225 cluster galaxies. For this work, we enhance this model by including three additional photometric strongly lensed sources identified with the recently acquired JWST/NIRISS data with a total of 8 multiple images, including two (A and B) of JD1. A uniform prior on the value of the redshift of JD1, between 8 and 12, is adopted. We also update the positions of all the mass components and multiple images in the lens model, adopting the new JWST astrometric grid. The total root mean square (rms) separation between the observed and model-predicted positions is 0.37 arcsec (the same as in the original model 5). To estimate the median magnification values and the confidence level intervals, we extract 500 random sets of parameter values from the final MCMC chain, which has a total of $2.5 \times 10^6$ samples. The predicted magnification values, with their $1\sigma$ confidence level statistical
uncertainties, are $\mu_A = 12.0^{+1.0}_{-0.9}$ and $\mu_B = 13.1^{+0.7}_{-0.7}$ for the multiple images A and B, respectively. The magnification ratio is in excellent agreement with the photometric measurements of images A and B. The redshift value of JD1 predicted by this strong lensing model is $z_{lens} > 8.6$ at the 95% confidence level, thereby fully consistent with the spectroscopic and photometric redshifts of image B.

The second lens model we use here is an update to the model for Abell 2744 presented by Zitrin et al. (2014)³, revisited here as follows. As input we start with the lists of cluster members, and multiple image systems from Bergamini et al. (2022)⁵, which are based on recent spectroscopic MUSE measurements. Following Bergamini et al, external mass clumps around the main central cluster core are also included in this update. However, we limit the external clump positions to places where strong lensing supports them, i.e., we identify a few potential multiply imaged systems in the northern part of the cluster, and use them to improve the model of the part where only weak lensing measurements have been available before. Furthermore, since our goal here is to estimate properties of the high-redshift source images, we also include images A and B as constraints, whereas we do not include image C, which is outside of the NIRCAM field of view.

We build our updated model with a revised, analytic version of the parametric method used by Zitrin et al. (2015)³¹ to model the CLASH sample. The main update is that the new version is not coupled to a specific grid resolution, and thus can achieve more accurate results. Similar to other parametric methods, the model assumes two main components: a superposition of all clusters members, parametrized each here as double Pseudo Isothermal Elliptical (dPIE) density profiles, based on common scaling relations ³²; and a dark matter component consisting of larger scale
halos, parametrized here as Pseudo Isothermal Elliptical Mass Distributions (PIEMD). In addition, the model can accommodate external shear, if warranted by the data.

In addition to the mass associated to the luminous galaxies, we distribute five dark matter halos: two halos are centered on the two central bright galaxies, but their central position is free to move; the other three are fixed to the three bright galaxies in the northern part of the field, about 2.5 arcminutes northwest of the main clump, seen in extended images of the field (e.g. 33).

Following common practice, we adopt a scaling relation to connect the galaxies to their dark matter halos. We leave as free parameters the velocity dispersion and cut-off radius of a typical $L^*$ galaxy, as well as the exponents of the relations themselves. For all dark matter halos, the velocity dispersion, core radius, ellipticity and position angle are free to be optimized. We also leave free the velocity dispersion of six bright galaxies in the central part, as well as the ellipticity parameters of the BCG.

The minimisation is done in the source plane, via a MCMC procedure. We obtain a \( \text{rms} \) value of \( \sim 0.6 \) arcseconds. We obtain magnification estimates of \( 10.7 \pm 0.6, 11.9 \pm 0.8, \) and \( 3.1 \pm 0.2 \) for images A, B, and C, respectively, consistent with the ones obtained by Bergamini et al. (2022)\(^5\). Further details of the model will be given by Furtak et al. (in preparation).

**Spectro-photometric modelling and analyses.** We conduct a spectral energy distribution (SED) fitting analysis by using a publicly available code, \textit{gsf}, which allows us to fit both photometric and spectroscopic data simultaneously\(^34\). The code generates model templates by using \textit{fsp} \(^35\) with the IMF set to the parameters of Chabrier (2003)\(^36\). We assume an SMC dust attenuation
The spectral templates are matched to the resolution of the observed spectrum, \( R \sim 100 \), for spectral data while broadband data points are fitted with the model photometry after convolving the templates by the corresponding filters.

We adopt a non-parametric form for star formation histories (SFHs), by following the recipe presented in \(^{34}\). For the redshift of JD1, we generate multiple templates of different ages, \([1, 3, 10, 30, 100, 300]\) Myrs. An emission line component of ionization parameters \( \log U \in [-3 : 0] \), also generated by fsps, is added by the amount of an amplitude parameter. Dust attenuation, metallicity of the stellar templates, and redshift are set as free parameters during the fit. In sum, we have 6+2+1+1+1=11 free parameters. The posterior distribution of the parameters is sampled by using emcee \(^{38}\) for \( 10^5 \) iterations with the number of walkers set to 100. The final posterior is collected after excluding the first half of the realisations (known as burn-in). The physical parameters quoted in the main text are the 50th percentile of the posterior distribution, along with the 16th to 84th percentile uncertainty ranges. Star-formation rate is calculated by averaging the last 100 Myr of the posterior star formation history.

**Source morphology.** JD1 shows a clear elongated shape along the magnification stretch with an off-centered nucleated emission. The morphology of the source is analysed by exploiting JWST/NIRISS imaging \(^{12,13}\) which is deeper than the NIRCam data presented here and provides an higher SNR in the system. As performed in \(^{39}\) we run GALFIT \(^{40}\) to reproduce the observed JD1 image in the NRISS/F150W band. This band offers the sharpest PSF while probing pure stellar continuum not affected by Lyman-\( \alpha \) emission (if any) and the attenuation from the intergalactic medium. The underlying extended component is modeled by adopting a Gaussian light
profile, effective radius of 6.5 pixels, a position angle of 45 deg and an axis ration (b/a) of 0.2. The nucleated emission was modeled adopting pure PSF and Sersic models. Both approaches provide equivalent results. In particular, Figure 4 shows the JWST/NIRISS input image, the models and the residuals. Very similar results are obtained adopting Gaussian (n=0.5), exponential (n=1) or n=4 indexes, both for the nucleated (when applying a Sersic model) and the extended component. Specifically, the compact knot represents an upper limit on the radius which can be associated to the Half Width at Half Maximum of the fitted PSF ($\approx 40$ milli-arcsec - in the observed plane - in the F150W). The extended component is less constrained at this stage, however an effective radius of 0.2” (observed) with a reasonable 50% uncertainty is extracted. After de-lensing along the magnification stretch, such angular scales translate to an upper limit of 30 pc for the compact object and of the order of $150 \pm 70$ pc for the extended one. However, it is worth stressing that the size of the elongated component can be underestimated because of the faintness of the system.
Extended Data Figure 1 | The $P(z)$ of JD1 from EA$z\bar{Y}$ fits to a variety of photometry. Each $P(z)$ is constructed via EA$z\bar{Y}$ modelling of three sets of photometric data points. Blue adopts HST photometry only\(^3\), orange adopts NIRCam photometry only, and red illustrates results for the combined data set. The HST photometry provides excellent constraining power blueward of the $J$-band, but lacks the wavelength coverage in the IR that NIRCam provides to exclude low-$z$ interlopers. As such, even using NIRCam data alone provides far better constraints for $z > 9$ selections. NB: The photo-$z$ estimated by Zitrin et al. (2014) also incorporates Spitzer/IRAC photometry, not used here.
| Property                      | Value               |
|-------------------------------|---------------------|
| RA (J2000) [deg]              | 3.5950107           |
| Dec (J2000) [deg]             | -30.4007302         |
| \( \mu \)                    | \( 13.1^{+0.6}_{-0.7} \) |
| F115W [AB]                    | 30.00\( \pm \) 3.40 |
| F150W [AB]                    | 27.35\( \pm \) 0.27 |
| F200W [AB]                    | 27.26\( \pm \) 0.23 |
| F277W [AB]                    | 27.36\( \pm \) 0.18 |
| F356W [AB]                    | 27.34\( \pm \) 0.15 |
| F444W [AB]                    | 27.06\( \pm \) 0.01 |
| \( z_{EAzY} \)               | \( 9.70^{+0.13}_{-0.13} \) |

Extended Data Table 1 | A summary of the NIRCam photometry and redshift of JD1. All fluxes are *uncorrected* for magnification. The fiducial magnification factor is from Bergamini et al. (2022)\(^5\).
| Property       | Value                   |
|----------------|-------------------------|
| $z_{\text{spec}}$ | $9.756_{-0.007}^{+0.017}$ |
| $\log M_\ast [M_\odot]$ | $7.50_{-0.15}^{+0.33}$ |
| $\log Z_\ast [Z_\odot]$ | $-0.23_{-0.10}^{+0.08}$ |
| $\log T_\ast [\text{Gyr}]$ | $-1.37_{-0.55}^{+0.56}$ |
| $A_v [\text{mag}]$ | $0.20_{-0.07}^{+0.06}$ |
| $\log SFR [M_\ast/\text{yr}]$ | $-0.88_{-0.08}^{+0.12}$ |
| $\beta_{\text{UV}}$ | $-1.90_{-0.01}^{+0.02}$ |
| $M_{\text{UV}}$ | $-17.45_{-0.02}^{+0.04}$ |

Extended Data Table 2 | A summary of the best-fit global properties of JD1 from the SED analysis presented in the Methods section. All values are corrected for magnification where needed.
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