A dusty, normal galaxy in the epoch of reionization

Darach Watson1, Lise Christensen1, Kirsten Kraiberg Knudsen2, Johan Richard3, Anna Gallazzi1,4 & Michał Jerzy Michalowski5

Candidates for the modest galaxies that formed most of the stars in the early Universe, at redshifts \( z > 7 \), have been found in large numbers with extremely deep restframe-ultraviolet imaging\(^1\). But it has proved difficult for existing spectrographs to characterize them using their ultraviolet light\(^2–4\). The detailed properties of these galaxies could be measured from dust and cool gas emission at far-infrared wavelengths if the galaxies have become sufficiently enriched in dust and metals. So far, however, the most distant galaxy discovered via its ultraviolet emission and subsequently detected in dust emission is only at \( z = 5.3 \) (ref. 5), and recent results have cast doubt on whether dust and molecules can be found in typical galaxies at \( z = 6–8 \). Here we report thermal dust emission from an archetypal early Universe star-forming galaxy, A1689-zD1. We detect its stellar continuum in spectroscopy and determine its redshift to be \( z = 7.5 \pm 0.2 \) from a spectroscopic detection of the Lyman-\( \alpha \) break. A1689-zD1 is representative of the star-forming population during the epoch of reionization\(^6\), with a total star-formation rate of about 12 solar masses per year. The galaxy is highly evolved: it has a large stellar mass and is heavily enriched in dust, with a dust-to-gas ratio close to that of the Milky Way. Dusty, evolved galaxies are thus present among the fainter star-forming population at \( z > 7 \).

As part of a programme to investigate galaxies at \( z > 7 \) with the X-shooter spectrograph on the Very Large Telescope, we observed the candidate high-redshift galaxy, A1689-zD1, behind the lensing galaxy cluster Abell 1689 (Fig. 1). The source was originally identified\(^5\) as a candidate \( z > 7 \) system from deep imaging with the Hubble and Spitzer space telescopes, with photometry fitting suggesting that it is at \( z = 7.6 \pm 0.4 \). The galaxy is gravitationally magnified by a factor of 9.3 by the galaxy cluster\(^6\). Although it is intrinsically faint, because of the gravitational amplification, it is one of the brightest candidate \( z > 7 \) galaxies known. The X-shooter observations were carried out on several nights between March 2010 and March 2012 with a total time of 16 h on target.

The galaxy continuum is detected and can be seen in the binned spectrum (Fig. 2). The Ly\( \alpha \) cutoff is at 1,035\( \pm 24 \) nm and defines the redshift to be \( z = 7.5 \pm 0.2 \). It is thus one of the most distant galaxies known so far to be confirmed via spectroscopy, and the only galaxy at \( z > 7 \) where the redshift is determined from spectroscopy of its stellar continuum. The spectral slope is blue; using a power-law fit \( F_l \propto \lambda^{-\beta} \), \( \beta = 2.0 \pm 0.1 \), where \( \lambda \) is the wavelength and \( F_l \) is the flux per unit wavelength. The flux break is sharp, and greater than a factor of ten in depth. In addition, no line emission is detected, ruling out a different redshift solution for the galaxy. Line emission is excluded to lensing-corrected...
The redshift \( z = 7.5 \) is determined from the Ly\( \alpha \) break at 1,035 nm. Sky absorption (grey bands) and depths of \( 3 \times 10^{-19} \) erg cm\(^{-2} \) s\(^{-1} \) (3\( \sigma \)) in the absence of sky emission lines, making this by far the deepest intrinsic spectrum published of an object from the epoch of reionization, highlighting the difficulty of obtaining ultraviolet redshifts for objects at this epoch that are not strongly dominated by emission lines. The restframe equivalent width limits are \( 4 \)\( \text{Å} \) for both Ly\( \alpha \) and C\( \text{III} \]\( \lambda 1,909 \)\( \text{Å} \). Our search space for Ly\( \alpha \) is largely free of sky emission lines; they cover 16% of the range.

The lensing-corrected stellar mass of \( 1.7_{-1.0}^{+3.1} \times 10^{9} \) solar masses (that is, \( \log(M_{\star}/M_{\odot}) = 9.23_{-0.15}^{+0.16} \)), with a best-fitting stellar age of 80 million years (that is, \( \log(t(\text{yr})] = 7.91_{-0.23}^{+0.31} \)). The lensing-corrected ultraviolet luminosity is about \( 1.8 \times 10^{10} L_{\odot} \), where \( L_{\odot} \) is the solar luminosity, resulting in a star-formation rate (SFR) estimate of \( 2.7 \pm 0.3 M_{\odot} \) yr\(^{-1} \) based on the ultraviolet emission and uncorrected for dust extinction, for a Chabrier initial mass function\(^{11} \). A1689-zD1 is thus fainter than the turnover luminosity, \( L^{*} \), in the galaxy luminosity function at this redshift, meaning that it is among the faint galaxies that dominate star formation at this epoch\(^{9} \).

Mosaic observations of the lensing cluster were obtained with the Atacama Large Millimetre Array (ALMA) in Cycles 0 and 1 with the receivers tuned to four 3.8 GHz frequency bands between 211 GHz and 241 GHz. A1689-zD1 is located towards the northern edge of the mosaic and is detected at 5.0\( \sigma \) with an observed flux of \( 0.61_{-0.12}^{+0.06} \) mJy in the combined image and at 2.4–3.1\( \sigma \) significance in each of the three individual observations (Fig. 3). A1689-zD1 is located within the primary beam’s full-width at half-maximum (FWHM) of one pointing and the sensitivity (root mean square, rms) around its position is 0.06 mJy per beam, 42% of the sensitivity of the deepest part of the mosaic. The source is the brightest in the mosaic area of 5 square arcminutes. It coincides with the ultraviolet position of A1689-zD1 and is \( 1.5_{-0.9}^{+1.0} \) away from the next-nearest object in the Hubble Space Telescope image, which is not detected in the ALMA map. No line emission is convincingly detected.

![Figure 2](image1.jpg)

**Figure 2** | Spectrum of A1689-zD1. The binned one-dimensional (middle panel) and two-dimensional (upper panel; wavelength versus distance along the slit) spectra are shown, with the 68% confidence uncertainty for the one-dimensional spectrum in the bottom panel. The redshift \( z = 7.5 \) is determined from the Ly\( \alpha \) break at 1,035 nm. Sky absorption (grey bands) and the best-fit SED (blue line) are shown. The Ly\( \alpha \) break is close to the spectrograph’s near-infrared (NIR)/visual (VIS) arm split; however, the break is clearly detected in the NIR arm alone. A nearby galaxy (\( z = 2 \)) visible in the bottom part of the two-dimensional spectrum is detected in both the VIS and the NIR arms.

![Figure 3](image2.jpg)

**Figure 3** | ALMA SNR maps of A1689-zD1. Contours are \( \text{SNR} = 5, 4, 3, 2 \) (black, solid), \(-3, -2 \) (white, dashed). Images and noise maps were primary-beam corrected before making SNR maps. Beam sizes are shown at the bottom left of each panel. Panels are \( 8'' \times 8'' \). The panels show from left to right: the combined data, the two tunings of observation 2011.0.00319.S and observation 2012.1.00261.S. A1689-zD1 is detected from left to right, at 5.0\( \sigma \), 2.4\( \sigma \), 3.1\( \sigma \), and 3.0\( \sigma \). Natural weighting was used and the visibilities were tapered with a 1'' circular Gaussian kernel, resulting in beams of \( 1.36'' \times 1.15'', 1.19'' \times 1.09'', 1.43'' \times 1.12'', 1.43'' \times 1.17'' \) from left to right.
The comparison of the gas mass to stellar mass in this galaxy shows that about 55 ± 25% of the baryonic matter is in the form of gas, indicating that the galaxy has already formed much of its stars and metals. Taken together, these lines of evidence point to a picture of A1689-zD1 consistently forming stars at a moderate rate since \( z \approx 9 \), or possibly having passed through its extreme starburst very rapidly and now being in a declining phase of star formation.

It has been suggested that the decreasing metal contents of high-redshift galaxies will make them challenging to detect at far-infrared wavelengths\(^6,7\). A1689-zD1 is at \( z = 7.5 \) and although it is magnified by a factor of 9.3, it was detected in only brief observations with ALMA. This promises a reasonable detection rate for \( L^\ast \) galaxies in un lensed fields at these redshifts for the full ALMA array, in contrast to the gloomy outlook painted by observations of very-low-metallicity systems\(^8,9\). The precise identification and detailed characterization of the star-forming population of the early Universe should therefore be possible in the far-infrared in the near future and should not be restricted to rare hyper-luminous infrared galaxies.

Table 1 | Comparison of A1689-zD1 to other high-z star-forming galaxies

| Galaxy name | Redshift, \( z \) | Stellar mass, \( M_\ast \) (\( 10^9 M_\odot \)) | SFR, \( \dot{M}_{\ast} \) (\( M_\odot \) yr\(^{-1} \)) | SFR, \( \dot{L}_{\text{TIR}} \) (\( 10^{10} L_\odot \)) | Dust mass, \( M_\text{D} \) (\( 10^{10} M_\odot \)) |
|-------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| HFLS3 (ref. 21) | 6.34 | \( 5.0_{-0.9}^{+0.9} \) | \( 1.3 \pm 0.4^* \) | \( - \) | \( 1.30_{-0.20}^{+0.20} \) |
| HCM6A (ref. 22) | 6.56 | - | \( 9 \pm 2 \) | \( 2 \) | \( <28 \) (ref. 26) |
| Himiko (ref. 8) | 6.50 | 15 ± 2 | \( 30 \pm 2 \) | \( 35 \pm 1 \) | \( <8 \) (ref. 26) |
| A1703-zD1 (ref. 23) | 6.8 | 0.7–1.5 | 7.3 ± 0.3 | \( - \) | \( <16 \) (ref. 26) |
| IOK-1 (ref. 24) | 6.96 | \(<40 \) | \( 23.9 \pm 1.4 \) (ref. 27) | \( 10 \pm 2 \) | \(<10 \) (ref. 28) |
| z8-GND-5296 (ref. 2) | 7.51 | 1.0 ± 0.2 | \( 330 \pm 10 \) | \( - \) | \(<127 \) (ref. 26) |
| HG090423 (ref. 25) | 8.2 | \(<0.05 \) (ref. 29) | \( 0.38 \pm 0.10 \) (ref. 30) | \(<5 \) (ref. 29) | \(<24 \) (ref. 26) |
| A1689-zD1 | 7.5 | 1.7 \( \pm 0.70 \) (ref. 65) | 2.7 ± 0.3 | \(<0.7 \) | \( 3 \pm 2 \) |

\* Derived from the Hubble Space Telescope F160W photometry and corrected for lensing.

\( 95\% \) lower bound only.

\( ^\dagger \) Assuming the same dust parameters assumed for A1689-zD1.

The SFRs are derived from extinction-uncorrected ultraviolet emission, \( L_\text{Ly}\alpha \) emission and far-infrared emission, respectively.

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**METHODS**

All uncertainties quoted are 68% confidence unless stated otherwise.

**Optical spectroscopy.** The X-shooter spectrograph on the Very Large Telescope was used to observe the source A1689-zD1 on the nights 21 March and 18 April 2010, as well as independent of the VIS arm data and present 2, 2 and 3 May 2011 and 17 and 24 March 2012. The observations used a standard dither pattern. Approximately half the exposure time (the 2010 observations) was performed with a fixed slit position, while the rest used the parallactic angle. The slit setups are indicated in Fig. 1. The data were reduced with the ESO X-shooter pipeline version 2.2. The standard calibration routines were used, with the different nod positions employed to subtract the background sky emission. Spectrophotometric standard stars observed on the same night as the galaxy were used for flux calibration. The target was acquired using an offset from a bright nearby star, calculated from the Hubble Space Telescope imaging. Offsets are executed with an accuracy of <0.1′′, that is, the location of the slit is known to better than a pixel. The slit centre position and offsets along the slit were used to shift and co-add the data into a final combined two-dimensional spectrum.

**Spectroscopic redshift.** The spectroscopy rules out a low-redshift solution. We detect no emission lines in the spectrum (see below), but the stellar continuum of the galaxy is detected, allowing us to measure the blue end of the ultraviolet continuum and a sharp break, which cannot be reproduced with dust extinction. Other breaks are excluded by the sharpness and depth of the break in spectroscopy, the blue slope of the ultraviolet continuum, and the deep upper limits in the VIS arm of the spectrum. These data are independent of the original discovery data for the dropout, removing any Eddington-bias-like effect and improving the reliability of the redshift determination.

The SNR per spectral pixel is low. We therefore bin the X-shooter spectra by a large factor in wavelength (see ref. 31 for details). We fit a template spectrum of a 100-million-year-old galaxy to estimate the redshift. This template was shifted to a range of redshifts and corrected for the transmission in the intergalactic medium. The best-fit redshift was found from a χ² minimization. We tested the fit with a variety of bin-sizes: 150, 180, 200, 250 and 400 pixels in the near-infrared. The VIS-spectrum data bin sizes are 1.5 times larger. We extracted the one-dimensional spectrum for each binning and performed 1,000 realizations of the model where we added Gaussian noise corresponding to the uncertainty in each binned pixel. We calculated the uncertainties for the five binning sizes and determined the average 68% confidence level to be z = 7.5 ± 0.2.

To be confident of the location of the spectral break, we also adopt a standard methodology for detecting steps in one-dimensional data: searching for a change in slope in the unbinned cumulative sum (Extended Data Fig. 1). The break at ~1,035 nm is clearly observed only in the data from the NIR arm of the spectrograph. We simulated the data 500 times, using the error spectrum as the standard deviation for the Gaussian random realizations; following the same cumulative sum method and data-cleaning as for the real data, we derived the break position and its uncertainty. This is very close to the analysis of the binned data: z = 7.5 ± 0.2. The fit results and the binned data from the NIR arm are consistent with the five binning sizes and determined the average 68% confidence level to be z = 7.5 ± 0.2.

**Dust mass and temperature.** We show the SFR and dust mass inferred using our fiducial modified blackbody model for various assumed dust temperatures, as used throughout the paper. This corresponds to a detection limit for the nominal Lyα SFR of 0.7 M☉ yr⁻¹ (corrected for lensing). Between the sky lines, the upper limit is <0.09 M☉ yr⁻¹. This implies an effective Lyα escape fraction of either <6% or <0.8% by comparison to the total SFR of 12 M☉ yr⁻¹. The rest-frame Lyα equivalent width is ~<27 Å, or <4 Å between the sky lines. We cannot distinguish between Lyα absorbed by the galaxy interstellar medium, circumgalactic medium or intergalactic medium. However, the dustiness of the galaxy indicates that a substantial fraction of the Lyα may be absorbed in the host.

Similarly, we place a 3σ upper limit of 2 × 10⁻¹⁸ erg cm⁻² s⁻¹ for the lensing uncorrected flux of the CⅢ 1,909 Å emission line, which lies in a region of the spectrum relative to atmospheric effects, corresponding to a restframe equivalent width of <4 Å.

**The ALMA observations and data reduction.** We obtained ALMA mosaic observations for A1689 in Cycle 0 and Cycle 1 as part of the projects 2011.1.00319.S and 2012.1.00261.S. The receivers were tuned to cover 211.06–214.94 GHz, 221.46–225.34 GHz, 227.06–230.94 GHz and 237.46–241.34 GHz; the 2012.1.00261.S data used here cover the first and third frequency setup. The correlator was used in the frequency domain mode with a bandwidth of 1,875 MHz in each spectral window. The projected baselines range between 12 m and 450 m. The quasar 3C 279 was used for bandpass and phase calibration. The distance from 3C 279 to A1689 is 5.9°. Mosaicked images were primary-beam-corrected and the weights of the individual fields were taken into account. Flux calibration was done using Mars and Titan.

Data reduction used the Common Astronomy Software Application (http://casa.nrao.edu/) versions 3.4 and 4.1 for the Cycle 0 and 1 data, respectively. For the Cycle 0 data, additional careful reduction of the observatory–provided preliminary–reduced data was required, including flagging of noisy data as well as producing a frequency-dependent model of 3C 279 to account for the spectral index of the continuum emission through bootstrapping from the flux calibrators. Our results are, however, not more than 1σ different from the preliminary-reduced data.

The data were combined and images using CASA 4.2; when imaging, the calibrated visibilities were naturally weighted (resulting beam size 0.8′ × 1′) and tapered using a two-dimensional Gaussian with 1′ × 1′ to give greater weight to shorter baselines, resulting in a beam-size of 1.36′ × 1.15′. The full mosaic will be presented in a forthcoming paper (K.K. et al., manuscript in preparation). The SNR images are shown in Fig. 3. The flux image for A1689-zD1 is shown in Extended Data Fig. 4.

The most conservative estimate of the astrometric uncertainty is half the beam dimensions, that is, 0.35′ × 0.5′, dominated by residual atmospheric phase effects and the SNR. Together with four other ALMA-detected sources, we found an average offset of 0.4–0.45′ between the ALMA centroids and the Hubble centroids. Part of these offsets is probably contributed by intrinsically different optical and far-infrared morphologies. No noticeable flux is detected from the galaxy 1.5′ from A1689-zD1.

No spectral line is detected towards A1689-zD1 in the ALMA data. Our data cover [CII] 158 μm emission at: z = 6.87–7.00, 7.23–7.37, 7.43–7.58 and 7.84–8.00. This covers ~50% of the 1σ and 2σ ranges allowed by X-shooter. The typical observed luminosity ratio L[CII]/LIR varies between 0.001 and 0.008 (ref. 36). Over the redshift range investigated, we exclude [CII] 158 μm emission at the high end of this ratio (0.0024–5σ for a linewidth of 100 km s⁻¹).

**Code availability.** The data reduction scripts used for the ALMA data are freely available and can be obtained at http://dark.nbi.ku.dk/research/archive.

**Dust mass and temperature.** We derive the far-infrared luminosity (42–122 μm restframe) and dust mass using a single temperature modified blackbody and assuming a typical value for the dust mass absorption coefficient of κ_d = 0.067 × (1+z)^0.15 Hm m² kg⁻¹ at the observed frequency ν = 226 GHz, and β_d = 1.92 (as observed in the high-redshift galaxy HFLS3). Different values for the dust mass absorption coefficient could result in dust masses 0.18 dex (ref. 38). We explore the effect of using more complex full SED models in a section below.

With only one far-infrared flux point it was necessary to assume a value of the dust temperature to recover the dust mass. We assumed 35 K. A lower temperature would increase the inferred dust mass, making the galaxy richer in dust than we infer. The galaxy may not be optically thin to far-infrared radiation; we assume the wavelength of optical depth unity is λ = 200 μm. We apply corrections due to CMB heating and the error induced by the large CMB background subtraction.

We show the SFR and dust mass inferred using our fiducial modified blackbody model for various assumed dust temperatures, β_d and κ_d values in Extended Data Fig. 5.

The constraints induced by the observed correlation between the ultraviolet spectral slope, β_CIV, and the ratio of observed infrared to ultraviolet luminosity, IRX, with the flux uncertainties and β_d slope uncertainties included, are also shown in Extended Data Fig. 5. The dust mass, M_d, for the fiducial model is log(M_d/M☉) = 7.6, with a 2σ lower bound of 7.30, and an upper bound that is not
strongly constrained, but where \(\log(M_\text{IR}(M_\odot)) = 7.9\) implies a dust-to-gas ratio approx-
imately five times that of the Milky Way (see below), and is therefore disfavoured. It has been shown recently that galaxies at high redshift may be preferentially more dusty\(^{34}\). This higher IRX, by 0.3 dex, is quite consistent with A1689-zD1.

**Star formation rate.** We measure the ultraviolet flux \(F_\lambda\) from the Hubble Space Telescope F160W photometric data point. The ultraviolet luminosity is calculated for the best-fit redshift of 7.5 using our standard cosmological parameters\(^{35}\). No dust correction is applied in calculating the ultraviolet SFR. The SFR is derived from the ultraviolet and total infrared (3–100 \(\mu\)m) luminosities\(^{36}\), \(L_{\text{UV}}\) and \(L_{\text{TIR}}\). For the ultraviolet luminosity we find \(L_{\text{UV}} = 1.8 \pm 0.2 \times 10^{40}\) \(\text{erg s}^{-1}\), corre-
spending to a SFR = 2.7 \pm 0.3 M_\odot yr\(^{-1}\). For the total infrared luminosity we obtain \(L_{\text{TIR}} = 6.2 \pm 0.8 \times 10^{12}\) \(\text{erg s}^{-1}\), which is the flux uncertainty only, using our fiducial model, but where the true uncertainty is constrained primarily by the desire to remain consistent within the scatter with the IRX–\(\beta_{\text{UV}}\) relation. These values are consistent with those derived from modelling the SED (see below) and result in a gas conversion, \(X\) of the Schmidt–Kennicutt law, which is a model, but where the true uncertainty is constrained primarily by the desire to remain consistent within the scatter with the IRX–\(\beta_{\text{UV}}\) relation. Therefore, we take this as a conservative estimate of the SFR and note that it may be somewhat higher.

Gas mass and dust-to-gas ratio. We invert the Schmidt–Kennicutt law relating the sur-
f ace density of SFR and gas mass\(^{37}\) to obtain constraints on the gas mass. The dominant uncertainty on this conversion comes from the uncertainty in the slope of the Schmidt–Kennicutt law, which is \(\pm 0.4\) dex scatter—dependence on the surface area of the galaxy is very small \((0.04\text{ dex})\) since it appears in both the SFR and gas mass terms. We here use the relation as originally derived, which reproduces even starburst galaxies quite well, assuming a constant carbon monoxide (CO) to gas conversion, \(X(\text{CO})\)\(^{38}\). Low-metallicity galaxies may have a lower gas mass for a given SFR\(^{39}\), which would only increase the dust-to-gas ratio derived here. The derived gas mass is inversely dependent on the inferred lensing magnification. Since A1689-zD1 is not very close to the critical lines, its lensing amplification is likely to be fairly accurate. A different analysis of the data for the cluster gives a similar magnification of \(6.5 \pm 0.5\) for this source \((M. \text{Limousin, private communication})\), confirming that the lens model contributes only a small additional uncer-
tainty, \(0.025\) dex, for the calculations presented here. The overall uncertainty in the gas mass summed in quadrature is therefore \(0.45\) dex, including the scatter in the Schmidt–Kennicutt relation and the uncertainty on the SFR.

The dust-to-gas ratio we derive for our fiducial model is \(0.017\), with a total uncer-
tainty of \(0.5\) dex under the assumptions outlined above for the derivation of the dust and gas masses. Both values depend on the SFR and this is accounted for in the uncertainty on the ratio. The scatter in the Schmidt–Kennicutt relation and the dust mass systematics dominate the uncertainty.

The age, mass and SED of A1689-zD1. We construct the photometric SED of A1689-zD1 from the Hubble Space Telescope’s ACS camera F775W and F850W, WFC3 camera F105W, F125W, F140W and F160W, and NIC2 camera F110W bands, and the Spitzer Space Telescope’s IRAC camera 3.6 \(\mu\)m and 4.5 \(\mu\)m bands, for 2.5ks each (proposal ID 11802, Principal Investigator: H. Ford). The analysis of the data for the cluster gives a similar magnification of \(6.5 \pm 0.5\) for this source \((M. \text{Limousin, private communication})\), confirming that the lens model contributes only a small additional uncertainty, \(0.025\) dex, for the calculations presented here. The overall uncertainty in the gas mass summed in quadrature is therefore \(0.45\) dex, including the scatter in the Schmidt–Kennicutt relation and the uncertainty on the SFR.

Finally, strong emission lines are not included in the SED modelling. We con-
sider possible contamination by the Balmer \(\text{H}\gamma\) and \(\text{H}\delta\) lines to the 4.5 \(\mu\)m flux. Adopting a SFR of \(12 \text{ M}_\odot\ yr\(^{-1}\) and standard case B Balmer line ratios, we expect the 3.6 \(\mu\)m flux con-
tribution to be at most 7\%. The nebular line contribution to the 4.5 \(\mu\)m flux could amount to 8%–14% (depending on the [O\text{iii}]/H\beta line ratio). By applying these corrections to the observed fluxes, our SED fit would yield a stellar mass 0.06 dex lower and a light-weighted mean age 0.04 dex younger than obtained above. As a final check, we fit self-consistent full ultraviolet to far-infrared SED models using the MAGPHYS\(^{40}\) and GRASIL\(^{41}\) codes. From these fits we derived the fol-
lowing lensing-corrected parameters: SFR = \(10^{10}\) \(\text{M}_\odot\ yr\(^{-1}\)), log\(M_\text{IR}(M_\odot)\) = \(9.3 \pm 0.2\), \(M_\text{gas} = 3 \times 10^{10}\) \(\text{M}_\odot\) (MAGPHYS); SFR = \(9.1 \pm 0.4\) \(\text{M}_\odot\ yr\(^{-1}\)), log\(M_\text{IR}(M_\odot)\) = \(9.4 \pm 0.2\), \(M_\text{gas} = 7 \times 10^{10}\) \(\text{M}_\odot\) (GRASIL). Applying the same order of CMB correction to these fits as to the modified blackbody would increase each parameter by about 30% (that is, +0.12 dex). The fits with these codes are shown in Extended Data Fig. 7.

Following the Bayesian approach developed and extensively applied to lower-
redshift data\(^{42}\), the observed SED is compared to every model SED in the library. This allows us to construct the full probability density function of parameters of interest by weighting each model by its likelihood exp\((-\chi^2/2)\) and marginalizing over the nuisance parameters of the star-formation histories. For completeness we also derive the total (dust-corrected and averaged over the galaxy SFR) \(9.9 \pm 1.1\) \(\text{M}_\odot\ yr\(^{-1}\), and the dust attenuation, \(A_{\text{V,600}} = 1.0 \pm 0.4\) mag, consistent with the values derived elsewhere in the paper. Because of the almost complete absorption of the flux below the Ly\beta line by the intergalactic medium, whether we include the ACS upper limits or not does not change the fit. The best fit to the ultraviolet–optical SED is shown in Extended Data Fig. 6.
**Extended Data Figure 1 | Cumulative sum of the unbinned spectrum.**
The VIS and NIR arms are plotted in blue and red respectively. The best-fitting step function is plotted as a dashed line. The break in the spectrum is clearly detected with the NIR arm only. Gaps in the cumulative spectrum are due to removal of regions affected by strong sky absorption.
**Extended Data Figure 2** | Spectrum obtained only at position angle 64° East of North. The slit consistently covered both the emission from the high redshift galaxy and the galaxy located 2° below it. This spectrum uses approximately half of the total exposure time. The upper panel shows the two-dimensional rectified spectrum, the lower panel the one-dimensional spectrum of the companion. Error bars are 68% confidence. The spectrum of the companion galaxy is recovered through the entire spectral range, including that covered by the transition from the VIS to the NIR data, and shows no indication of the sharp break seen in A1689-zD1.
Extended Data Figure 3 | Probability distribution as a function of redshift for galaxy template fits to the Hubble and Spitzer IRAC photometry data. The probability distribution is based on fitting galaxies using the New-HyperZ code33.
Extended Data Figure 4 | The tapered ALMA flux image at 226 GHz, centred on A1689-zD1; the image is primary-beam-corrected. The depth of the map at the location of A1689-zD1 is 0.12 mJy per beam (42% of the deepest part of the mosaic). The sensitivity decreases towards the edge of the mosaic owing to the overlap of multiple pointings and primary beam correction. The structure north of A1689-zD1 is a probable detection of a different source in the field and will be presented in a forthcoming paper (K.K. et al., manuscript in preparation).
Extended Data Figure 5 | Dust mass and SFR$_{IR}$ from modified blackbody fits. Tracks show how the parameters change with temperature, with different tracks for different opacity wavelengths, $\lambda_0$. Varying $\beta_{IR}$ is shown for $\lambda_0 = 200\mu m$ (black and grey lines). Intrinsic (CMB-corrected) and measured temperatures are indicated for $\lambda_0 = 300\mu m$ (orange line) on the concave and convex sides respectively. A diamond marks our fiducial model: uncorrected $T = 35\, K$, $\lambda_0 = 200\, \mu m$, $\beta_{IR} = 1.92$. Solid-colour regions show <90%, <95%, and <99% confidence intervals due to the $\beta_{UV-IRX}$ relation (including measurement uncertainties, $\beta_{IR} = 1.72-2.12$, and $\lambda_0 < 300\, \mu m$), with solid, dashed, and dot-dashed lines indicating these intervals for the tracks. Dotted lines mark >99%.
Extended Data Figure 6 | Ultraviolet–optical SED for A1689-zD1. Stellar synthesis models from ref. 43 (BC03) are fitted to the photometric data (squares). Error bars are 68% confidence. The best-fitting model is shown in green with the resultant fluxes in the different bands shown as circles. The Very Large Telescope (VLT)/X-shooter spectrum is also plotted (solid histogram) for comparison.
Extended Data Figure 7 | SED of A1689-zD1. Full, self-consistent ultraviolet-to-far-infrared models are fitted to the data using the GRASIL (dashed line) and MAGPHYS (dash-dotted line) codes. The values derived from these models fitted to the photometric data (squares) are largely consistent with those derived from the modified blackbody (solid line) and ultraviolet–optical-only fit, though with an additional contribution from the restframe mid-infrared flux. A CMB correction has not been applied here. Error bars are 68% confidence. Upper limits are 68% confidence for all points except the 8.0-μm band, for which the upper limit is 95% confidence.