METHODS

ALMA millimetre and submillimetre interferometry. We acquired four observations of SPT0311−58 with ALMA in four receiver bands (B3, B6, B7 and B8, covering 84–432 GHz) under projects 2015.1.00504.S and 2016.1.01293.S. A summary of these observations, including dates, calibration sources, integration times, atmospheric opacity, noise levels and resolution, is provided in Extended Data Table 1. Salient details are provided below for each observation.

The redshift of SPT0311−58 and the 3-mm continuum flux density were determined from an 84.2–114.9-GHz spectrum assembled from five separate tunings in ALMA band 3 under ALMA Cycle 3 project 2015.1.00504.S. The observing strategy has been used to discover the redshifts of more than 50 SPT dusty sources, and further details on the redshift coverage are provided in previous works[30,31]. Data were taken on 2015 December 28 and 2016 January 2 in ALMA configuration C36-1 (baseline lengths of 15–310 m) using 34 and 41 antennas, respectively. The resulting image has a resolution of 3.3″ × 3.5″, although there is spatial information on finer scales that allows us to estimate flux densities separately for the E and W sources, which are separated by about 2″. Further details of the analysis are provided elsewhere[6].

ALMA observed SPT0311−58 a second time under project 2015.1.00504.S in band 7 (LO = 343.48 GHz) to produce a continuum image suitable for gravitational lens modelling. Similar observations were used to produce lens models of SPT sources in previous cycles[24,32]. The observations were performed with 41 antennas in the C40-4 configuration, providing 15–770-m baselines. The resulting image has an angular resolution of 0.3″ × 0.5″, although, because it lacks any spectral lines, it was found to be insufficient to provide an unambiguous determination of the lensing configuration.

The ALMA Cycle 4 project 2016.1.01293.S was intended to follow up on the discovery of this very distant source through spectroscopic observations. The 158-μm line of [C II] was observed on 2016 November 3 in ALMA configuration C40-5, which provided baseline lengths of 18–1,120 m. This provides the primary imaging for this work, because it yielded an extremely sensitive detection of the [C II] line and continuum structure at high resolution.

A final observation was obtained in ALMA band 8 (LO = 423.63 GHz), in configuration C40-4 (baselines 15–920 m). The observations were repeated in four segments to yield the required integration time. The resulting data have 0.2″ × 0.3″ resolution. These data provide a final spatially resolved continuum observation, at 90-μm rest-frame wavelength, along with spectroscopic images of the 88-μm line of [O III]. The ALMA continuum images are shown in Extended Data Fig. 1.

Spitzer infrared imaging. Infrared observations of SPT0311−58 were acquired with the Infrared Array Camera (IRAC) instrument[33] on the Spitzer Space Telescope as a part of Cycle 24 Hubble Space Telescope (HST) programme 14740. The observations consisted of 95 dithered 100-s exposures on-source in both operable IRAC arrays at 3.6 μm and 4.5 μm. A large dither throw was used. The dataset thus has sufficiently high redundancy to support our standard reduction procedure, which involves constructing an object-masked median stack of all 95 exposures in each band and then subtracting the median stack from the raw frames to compensate for bad pixels not automatically masked by the pipeline and to remove gradients in the background. After these initial preparatory steps, the background-subtracted exposures were combined in the standard way[34] with IRACproc[35] and MOPEX to create mosaics with 0.6″ pixels. The mosaics achieved an effective total integration time of about 9,000 s after masking cosmic rays and other artefacts. Two flanking fields were covered to the same depth but separately, each in one IRAC passband.

Photometry was performed on the mosaics using Source Extractor[36] in dual-image mode after trimming to exclude the flanking fields and unexposed areas. The lens galaxy associated with SPT0311−58 was well detected with no evidence for saturation or even nonlinear detector behaviour. During this process background and object images were generated and inspected to verify that Source Extractor performed as expected and generated valid photometry.

HST imaging. SPT0311−58 was observed for five orbits of HST imaging with ACS and WFC3/IR in Cycle 24 (PID 14740) to determine the morphology of the foreground lens and to better constrain the spectral energy distribution (SED) of both the lens and source. All observations were acquired on 2017 April 30. The ACS imaging consists of a single orbit divided between the F606W and F775W filters. Exposure times are 844 s and 1.5 ks, respectively. Four orbits of WFC3/IR observing was split evenly between the F125W and F160W filters. Although the nominal exposure times are 5.6 ks, a subset of the data in both filters was compromised by substantial contamination from scattered earthlight. We reprocessed the imaging to remove contaminated data, resulting in final exposure times of 4.9 ks in each band.

Gemini optical and infrared imaging and spectroscopy. With the Gemini Multi-Object Spectrograph[37] (GMOS) of Gemini-South, we obtained deep i and z images of SPT0311−58 (PID GS-2015B-Q-51) on 2016 January 29 and 31. The instrument consists of three 2,048 × 4,176 pixel CCDs, separated by two 6.46″ (80 pixel) gaps, with a scale of 0.0807″ per pixel. The field of view of the GMOS camera is 5.5′ × 5.5′. Our images were taken under photometric conditions and using a 2 × 2 binning, which gives a scale of 0.161″ per pixel. The total integration times were 3,600 s for the i band and 6,600 s for the z band, with average seeing conditions of 1.3″ and 1.0″ in the i and z bands, respectively. The resulting 5σ point source depths were $i_{AB} = 25.2$ and $z_{AB} = 25.0$.

SPT0311−58 was observed using the Facility Near-Infrared Wide-Field Imager and Multi-Object Spectrograph for Gemini (FLAMINGOS-2)[38] at the Gemini-South Observatory on the nights of UT 2016 September 23 and 2017 February 06, under PID GS-2016B-Q-68. The instrument was used in imaging mode, with 0.181″ pixels, and yielded an unvignetted circular field of view of approximately 5.5′ diameter. Our observing sequence for the survey consisted of a randomly ordered dither pattern, with 15″ offsets about the pointing centre. This pattern was repeated until the required total exposure time was achieved. The individual K_s-band exposure time was set at 15 s in the first observation and 10 s in the second observation, yielding a typical background sky level in the K_s band of 10,000–12,000 counts (detector nonlinearity can be corrected to better than 1% up to 45,000 counts). These counts ensure that 2MASS stars with $K_s > 13$ do not saturate and can be used for photometric calibration. The data were reduced using the Python-based FLAMINGOS-2 Data Pipeline, FATBOY[39,40]. In brief, a calibration dark was subtracted from the dataset, a flat field image and a bad pixel map were created, and the flat field was divided through the data. Sky subtraction was performed to remove small-scale structure, with a subsequent low-order correction for the large-scale structure. Finally, the data were aligned and stacked. The seeing conditions averaged 0.7″ in the final image comprising 44 min of integration, reaching $K_{s,AB} = 23.6$ at 5σ.

Spectroscopy was obtained with the GMOS-S instrument on the nights of UT 2016 February 1 and 2 (PID GS-2016B-Q-68) using the 1″-wide long slit at a position angle −10° east of north and the instrument configured with the R400 grating and 2 × 2 detector binning. For a source that fills the 1″ slit this set-up results in a spectral resolution of about 7 Å. The observations were spectrally dithered, using two central wavelength settings (8,300 Å and 8,400 Å) to cover the chip gaps. The data comprise a series of individual 900-s exposures, dithering the source spatially between two positions ('A' and 'B') along the slit in an ABBA pattern, repeated four times, two at each central wavelength setting. The total integration time is 4 h. A bright foreground object was positioned along the slit midway between the acquisition star and SPT0311−58, providing an additional reference point for locating traces along the slit.

The spectra were reduced, beginning with bias subtraction and bad pixel masking using the IRAF GMOS package provided by Gemini. The individual chips were combined into a single mosaic for each exposure and the mosaicked frames were then sky-subtracted by differencing neighbouring A–B exposure pairs; this method resulted in nearly Poisson noise, even under the numerous bright sky lines. A flat-field slit illumination correction was applied and a wavelength calibration derived for each mosaic. The two-dimensional spectrum was created by median-combining the individual exposure frames.

The spectrum shows a faint continuum beginning above 9,000 Å at the location of SPT0311−58. A one-dimensional extraction of the faint trace yields no reliable redshift measurement, but is consistent with the redshifted 4,000-Å break that is expected for the foreground galaxy at $z \approx 1.4$. Calibrated against the nearby $R = 16.4$ star spectrum we find no flux at the expected location of Lyα redshifted to $z = 6.900$ (about 9,600 Å) down to a 3σ flux limit of 3.0×10^{-17} erg s^{-1} cm^{-2} for a emission line 500 km s^{-1} wide.

Image de-blending. At the position of SPT0311−58, our optical and infrared images (Extended Data Fig. 2) show a prominent lower-redshift galaxy that is responsible for lensing the W source, and the HST images, which have the highest resolution, show direct stellar emission from the E source (Extended Data Fig. 3). To extract reliable photometry for SPT0311−58 E, particularly in the low-resolution Spitzer images that cover the rest-frame optical, and to search for emission from the W source underneath the lens galaxy, we must model and remove the lens emission. We follow procedures similar to those used previously[41], using the HST/WFC3 images as the source of the lens galaxy model to de-blend the IRAC image. The foreground lens can be fitted with a single Sérsic profile with an index $n = 1.77$. As seen in Extended Data Fig. 4, there is no clear rest-frame ultraviolet emission from SPT0311−58 W in the HST bands after removal of the lens model. To remove the lens from the IRAC image, the WFC3 model is convolved with the IRAC point spread function and then subtracted from the 3.6-μm and 4.5-μm images. Residual emission is seen near the positions of the E and W sources. Unfortunately, because SPT0311−58 W lies right on top of the lens, the residuals are extremely susceptible to image de-convolution errors and we do not believe