A cosmic web filament revealed in Lyman-α emission around a luminous high-redshift quasar

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Simulations of structure formation in the Universe predict that galaxies are embedded in a ‘cosmic web’, where most baryons reside as rarefied and highly ionized gas. This material has been studied for decades in absorption against background sources, but the sparseness of these inherently one-dimensional probes precludes direct constraints on the three-dimensional morphology of the underlying web. Here we report observations of a cosmic web filament in Lyman-α emission, discovered during a survey for cosmic gas fluorescently illuminated by bright quasars at redshift $z \approx 2.3$. With a linear projected size of approximately 460 physical kiloparsecs, the Lyman-α emission surrounding the radio-quiet quasar UM 287 extends well beyond the virial radius of any plausible associated dark-matter halo and therefore traces intergalactic gas. The estimated cold gas mass of the filament from the observed emission—about $10^{12.8} M_\odot$—is more than ten times larger than what is typically found in cosmological simulations, suggesting that a population of intergalactic gas clumps with subkiloparsec sizes may be missing in current numerical models.

A recent pilot survey using a custom-built, narrow-band filter on the Very Large Telescope demonstrated that bright quasars can, like a flashlight, ‘illuminate’ the densest knots in the surrounding cosmic web and boost fluorescent Lyman-α emission to detectable levels. Following the same experiment, we imaged UM 287 on 2012 November 12 and 13 UT with a custom narrow-band filter (NB3985) tuned to Lyman-α at $z = 2.28$ inserted into the camera of the Low Resolution Imaging Spectrometer (LRIS) on the 10-m Keck I telescope (see Extended Data Fig. 1). Figure 1 presents the processed and combined images, centred on UM 287. In the NB3985 image, we identify a very extended nebula originating near the quasar with a projected size of about 1 arcmin. In the broad-band images no extended emission is observed. This requires the narrow-band light to be line-emission, and we identify it as Lyman-α at the redshift of UM 287.

Figure 2 presents the NB3985 image, continuum subtracted using standard techniques (see Methods) and smoothed with a 1-arcsec Gaussian kernel. This image is dominated by the filamentary and asymmetric nebula that has a maximum projected extent of 55 arcsec as defined by the $10^{−18}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ isotropic contour, corresponding to about 460 physical kpc or 1.5 Mpc in co-moving coordinates. Including (excluding) the emission from UM 287 falling within the narrow-band filter, the structure has a total line luminosity $L_{\text{Ly}\alpha} = (1.43 \pm 0.05) \times 10^{45}$ erg s$^{-1}$ ($L_{\text{Ly}\alpha} = (2.2 \pm 0.2) \times 10^{44}$ erg s$^{-1}$).

Although Lyman-α nebulae extending up to about 250 kpc have been previously detected, the UM 287 nebula represents a system that is unique so far: given its size, it extends well beyond any plausible dark-matter halo associated with UM 287 (see below), representing an exceptional example of emitting gas on intergalactic scales.

The largest Lyman-α nebulae previously discovered (see Fig. 3) are associated with the most massive dark-matter haloes present in the high-redshift Universe. High-redshift radio galaxies (HzRGs), inferred to host obscured but luminous active galactic nuclei (AGN), are often surrounded by giant Lyman-α envelopes extending up to about 250 kpc at $z \approx 3$ (ref. 15). Clustering arguments and the observation of large overdensities of Lyman-α galaxies, together with the lack of X-ray detection from a possible intracluster medium, suggest that HzRGs are associated with haloes of $10^{15}$ solar masses $(M_\odot)$. With a virial diameter of about 300 kpc at $z \approx 3$, these haloes are therefore able to contain the largest HzRG Lyman-α nebulae. Blind narrow-band surveys have derived an apparently different population of large nebulae (termed Lyman-α blobs) with sizes extending up to 180 physical kpc at $z \approx 3$ that, in some cases, do not appear to be associated with a particular bright galaxy or AGN. The rarity of these systems may be due not only to its size (about 460 physical kpc) but also to the fact that it is associated with a radio-quiet quasar. Radio-quiet quasars have the smallest host halo mass ($\sim 10^{12.5} M_\odot$) and virial diameter (280 kpc) among previously detected objects and do not have radio-emitting jets that may power Lyman-α emission on large scales. In order for the nebula to be fully contained within the virial radius of a dark-matter halo centred on UM 287, a halo mass would be required that is at least ten times larger than the typical value associated with radio-quiet quasars. This would make the host halo of UM 287 one of the largest known at $z > 2$, a possibility that is excluded by the absence of a significant overdensity of Lyman-α emitters around UM 287 compared to other radio-quiet quasars (see Methods). Differently from any previous detection, the nebula is therefore an image of intergalactic gas at $z > 2$ extending beyond any individual, associated dark-matter halo. The rarity of these systems may be explained by the combination of anisotropic emission from the quasar (typically only about 40% of the solid angle around a bright, high-redshift quasar is unobstructed), the anisotropic distribution of dense filaments and light travel effects that, for quasar ages of less than a few million years, further limit the possible ‘illumination’ volume.

In order to constrain the physical properties of this system, we use a set of Lyman-α radiative transfer calculations combined with adaptive mesh refinement simulation of cosmological structure formation around a dark-matter halo with mass $M_{DM} \approx 10^{12.5} M_\odot$ (see Methods). We consider two possible, extreme scenarios for the Lyman-α emission mechanism of the intergalactic gas associated with the nebula: (1) the gas is highly ionized by the quasar and the Lyman-α emission is mainly produced by hydrogen recombinations; and (2) the gas is mostly neutral and the emission is mainly due to scattering of the Lyman-α and continuum photons produced by the quasar broad line region. The

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models are used to obtain scaling relations between the observable Lyman-α surface brightness from the intergalactic gas surrounding the quasar and the hydrogen column densities (see Extended Data Fig. 3). These scaling relations are consistent with analytical expectations. Note that the estimated column densities for scenario (1) depend on the ionized gas clumping factor ($C = \frac{\langle n_e^2 \rangle}{\langle n_e \rangle^2}$, where $n_e$ is the electron density) below the simulation resolution scale, ranging from about 10 physical kpc for diffuse intergalactic gas to $\sim 160$ physical pc for the densest regions within galaxies.

The results are presented in Fig. 4. The observed Lyman-α emission requires very large column densities of ‘cold’ ($T < 5 \times 10^4$ K) gas, up to $N_{H} < 10^{22}$ cm$^{-2}$. The implied total, cold gas mass ‘illuminated’ by 1.0 $\times$ 10$^{-16}$ 1.8 $\times$ 10$^{-17}$ 3.2 $\times$ 10$^{-18}$ 5.6 $\times$ 10$^{-19}$ 1.0 $\times$ 10$^{-19}$

Figure 2 | Lyman-α image of the UM 287 nebula. We subtracted from the narrow-band image the continuum contribution estimated from the broad-band images (see Methods). The location of UM 287 is labelled with ‘a’. The colour map and the contours indicates, respectively, the Lyman-α (Lyα) surface brightness (upper colour scale) and the signal-to-noise ratio per arcsec$^2$ aperture (lower colour scale). The extended emission spans a projected angular size of $\sim 55$ arcsec ($\sim 285$ physical kpc) measured from the $2\sigma$ ($10^{-18}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$) contours. The object marked with ‘b’ is an optically faint ($g < 23$ AB) quasar at the same redshift as UM 287 (see Extended Data Fig. 2). The nebula appears broadly filamentary and asymmetric, extending mostly on the eastern side of quasar UM 287 up to a projected distance of about 35 arcsec ($\sim 285$ physical kpc) measured from the $2\sigma$ isophotal. The nebula extends towards the southeast in the direction of the optically faint quasar. However, the two quasars do not seem to be directly connected by this structure that continues as a fainter and spatially narrower filament. The large distance between the two quasars and the very broad morphology of the nebula argue against the possibility that it may originate from an interaction between the quasar host galaxies (see Methods).
the quasar is $M_{\text{gas}} \approx 10^{12.0 \pm 0.5} M_{\odot}$ for the 'mostly ionized' case (scenario (1)) assuming $C = 1$ and $M_{\text{gas}} \approx 10^{11.4 \pm 0.6} M_{\odot}$ for the 'mostly neutral' case (scenario (2)). Note that even if we restrict the size measurement of the UM 287 nebula to the $4 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ isophotal to be comparable with the majority of the previous surveys, the measured apparent size of the UM 287 nebula will be reduced only by about 20%.

Figure 3 | Luminosity–size relations for previously detected, bright Lyman-α nebulae and UM 287. The plot includes nebulae surrounding radio galaxies (black circles), radio-loud quasars (blue open squares), radio-quiet quasars (blue filled squares) and Lyman-α ‘blobs’ (green triangles). The reported luminosities include the Lyman-α (L$_{\text{Ly} \alpha}$) emission (within the narrow-band filters) from any sources embedded in the nebula, if present. Excluding the contribution coming directly from the quasar broad line region, the luminosity of the UM 287 nebula corresponds to $L_{\text{Ly} \alpha} = 2.2 \pm 0.2 \times 10^{44}$ erg s$^{-1}$ (about 16% of the total luminosity). Error bars for UM 287 represent the 1σ photometric error including continuum-subtraction (error bar is smaller than 16% of the total luminosity). Error bars for UM 287 represent the 1σ photometric error including continuum-subtraction (error bar is smaller than 16% of the total luminosity). Error bars for UM 287 represent the 1σ photometric error including continuum-subtraction (error bar is smaller than 16% of the total luminosity). Error bars for UM 287 represent the 1σ photometric error including continuum-subtraction (error bar is smaller than 16% of the total luminosity).

The implied column densities and gas masses, in both cases, are at least a factor of ten larger than what is typically observed within cosmological simulations around massive haloes, suggesting that a large number of small clumps within the diffuse intergalactic medium may be missing within current numerical models.

Figure 4 | Inferred hydrogen column densities associated with the UM 287 nebula. We have converted the observed Lyman-α surface brightness into gas column densities $N$ using a set of scaling relations obtained with detailed radiative transfer simulations and consistent with analytical expectations (see Extended Data Fig. 3 and Methods). We have explored two extreme cases: first, the gas is mostly ionized by the quasar radiation ($a$, $N_{\text{H I}}$) and second, the gas is mostly neutral ($b$, $N_{\text{H II}}$). Two circular regions with a diameter of 7 arcsec (~8 times the seeing radius) have been masked at the location of the quasars (black circles). The inferred hydrogen column density in a scale as $C^{-1/2}$, where $C$ is the gas clumping factor on a spatial scale of about 10 physical kpc at moderate overdensities (less than about 40 times the mean density of the Universe at $z = 2.28$). The implied column densities and gas masses, in both cases, are at least a factor of ten larger than what is typically observed within cosmological simulations around massive haloes, suggesting that a large number of small clumps within the diffuse intergalactic medium may be missing within current numerical models.

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How can we explain the large differences between the estimated mass of cold gas in the nebula and the available amount of cold gas predicted by numerical simulations on similar scales? One possibility is to assume that the simulations are not resolving a large population of small, cold gas clumps within the low-density intergalactic medium that are illuminated and ionized by the intense radiation of the quasar. In this case, an extremely high clumping factor, up to $C = 1,000$, on scales below a few kiloparsecs would be required in order to explain the large luminosity of the nebula with the cold gas mass predicted by the simulations. On the other hand, if some physical process that is not fully captured by current grid-based simulations increases the fraction of cold gas around the quasar—for example, a proper treatment of metal mixing—a smaller clumping factor may be required. In the extreme (and rather unrealistic) case that all the hot gas is turned into a cold phase, the required clumping factor would be $C \approx 20$. Even if the gas is not ionized by the quasar (scenario (2) above), the simulations are able to reproduce the observed mass only if a substantial amount of hot gas is converted into a cold phase. Incidentally, this is exactly the same result produced by comparing the properties of Lyman-α absorption systems around a large statistical sample of quasars with simulations. Proper modelling of this gas phase will require a new generation of
numerical models that are able—simultaneously—to spatially resolve these small intergalactic clumps within large simulation boxes, and to treat the multiphase nature of this gas and its interaction with galaxies and quasars.

METHODS SUMMARY

We observed UM 287 for a total of 10 h in a series of dithered, 1.200-s exposures. In parallel, we obtained 10 h of broad-band V images with the LIRIS-red camera and 1 h of B-band imaging. For all observations, we used the D480 dichroic beam splitter. We binned the blue CCDs 2 × 2 to minimize read noise. The images were processed using standard routines within the reduction software IRAF, including bias subtraction, flat fielding and illumination correction. A combination of twilight sky flats and unregistered science frames has been used to produce flat-field images and illumination corrections for each band. We have calibrated the photometry of our images using two spectrophotometric stars (Feige 110 and Feige 34) and the standard star field PG 0231+051. To isolate the emission in the Lyman–α line we estimated and then subtracted the continuum emission from discrete and extended sources contained within the NB3985 filter using a combination of the V band and B band. We derived a relation between the observable Lyman–α emission from diffuse gas illuminated by a quasar and the gas column densities by combining a Lyman–α radiative transfer model with the results of a cosmological hydrodynamical simulation of structure formation at $z = 2.3$ (ref. 5). The cosmological simulation consists of a 40$^3$ co-moving Mpc$^3$ cosmological volume with a 10$^4$ co-moving Mpc$^3$ high-resolution region containing a massive halo compatible with the expected quasar hosts ($M_{\text{halo}} = 10^{12.1} M_\odot$). The equivalent base-grid resolution in the high-resolution region corresponds to a (1.024") grid with a dark-matter particle mass of about 1.8 $\times$ 10$^6$ M$_\odot$. We adaptively refined the grid by a factor of 2, reaching a maximum spatial resolution of about 0.6 co-moving kpc, that is, about 165 proper pc at $z = 2.3$. We have then applied in post processing an ionization and Lyman–α radiative transfer using the RADAMESH adaptive mesh refinement code.

Online Content Any additional Methods, Extended Data display items and Source Data are available in the online version of the paper; references unique to these sections appear only in the online paper.

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Author Contributions S.C. designed the observational survey and the custom-built filter, conducted the observations, led the narrow-band imaging data analysis and interpretation, performed the numerical simulations and led the theoretical interpretation, the writing of the text and the production of the figures. F.A.-B. and J.X.P. assisted with the observations, contributed to data reduction, the text and the figures. In particular, F.A.-B. reduced and calibrated the images, produced the continuum-subtracted image, the catalogues of Lyman–α emitters, and compiled data on all Lyman–α nebulae in the literature. J.X.P. reduced the spectrum of the companion quasar and contributed to the text. J.F.H. and P.M. contributed to the text and assisted with the planning and interpretation of the observations.

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Methods
Observations and data reduction. As part of a continuing programme to search for Lyman-α emission associated with the fluorescence of quasar ionizing radiation, we obtained deep, narrow-band imaging of the field surrounding UM 287, also known as PHL 868 and LBQS 0049+0045. UM 287 was discovered in the University of Michigan emission-line survey, has a measured redshift \( z = 2.277 \pm 0.001 \) based on analysis of [O III] emission lines, and has a bolometric luminosity \( L_{\text{bol}} \approx 10^{43} \) erg s\(^{-1}\) estimated from its 1.450-A rest-frame flux using standard cosmology\(^2\). This places it in the upper quartile of ultraviolet-bright quasars at this redshift. Assuming that the spectral energy distribution follows a power law \( L(\lambda) \propto \lambda^s \) with frequency index \( s = -1.57 \) at energies exceeding 1 eV, we estimate the luminosity of ionizing photons\(^3\) to be \( \Phi = 10^{44.1} \) cm\(^{-2}\) s\(^{-1}\) assuming isotropic emission.

The quasar has no counterpart in the FIRST\(^4\) images at 20 cm (1.4 GHz), and based on the FIRST coverage maps we obtain a 5\% flux limit each \( F_{\text{peak}} \leq 0.376 \) mJy, which, given its large ultraviolet luminosity, classifies this quasar as an ULIRG\(^5\). We selected this source for imaging based solely on its high luminosity, its precisely measured redshift, and its radio-quiet characteristics. We purchased a custom-designed narrow-band filter from Andover Corporation, sized to fit within the grism holder of the Keck/LRIS camera. The filter was tuned to Lyman \( \alpha \) at the source’s systemic redshift and we requested a narrow band-pass (full-width at half-maximum FWHM = 3 nm) that minimized sky background while maximizing throughput. Extended Data Fig. 1 presents the as-measured transmission curve of the NB 3985 filter.

We observed UM 287 on the nights of UT 12–13 November 2013 for a total of 10 h, in a series of dithered, 1,200-s exposures. Conditions were clear, with atmospheric seeing varying from FWHM = 0.6–1. arcsec. In parallel, we obtained 10 h of broadband V images with the LRIS camera and 1 h of B-band imaging. For all observations, we employed the D460 dichroic beam splitter. We binned the blue CCDs 2 \( \times \) 2 to minimize read noise.

All of these data were processed with standard techniques. Bias subtraction was performed using images from the overscan regions of each image. The images had been reduced using standard routines within the reduction software IRAF, including bias subtraction, flat-fielding and illumination correction. A combination of twilight sky flats and unregistered science frames has been used to produce the field images and illumination corrections for each band. Each individual frame has been registered on the SDSS-DR7 catalogue using SExtractor\(^6\).

We have calibrated the photometry of our images in the following manner. First, we observed during the two nights two spectrophotometric stars (Feige 110 and Feige 34) through the narrow-band filter, under clear conditions. For the broadband images, we observed the standard star field PG0231+051.

To compute the zero-point for the narrow-band images, we first measured the number of counts per second of the standard stars Feige 110 and Feige 34. We then compared this measurement with the flux expected, estimated by convolving the spectrum of the standard star with the normalized filter transmission curve (Extended Data Fig. 1). The two measurements agreed to within 0.1 mag. We attribute the difference to small variations in the transparency and adopt an average zero-point of 24.14 mag. The surface brightness limit for our observation in the central region of the image occupied by the nebula is about 5 \( \times \) 10\(^{-17}\) erg s\(^{-1}\) cm\(^{-2}\) arcsec\(^{-2}\) at 1\% confidence level within an aperture of 1 arcsec.

For the broadband images, we compared the number of counts per second of the five stars in the PG0231+051 field with their tabulated \( V \) and \( B \) magnitudes. The derived zero-point for the five stars are consistent with each other within a few percent and we adopt the average values: \( B_{\text{zp}} = 28.40 \) mag and \( V_{\text{zp}} = 28.07 \) mag. As this offset is smaller than the PG0231+051 field, we corrected with a similar airmass of approximately 1.2, which corresponds to the average airmass of our observations, we did not correct the individual images before combination. Moreover, by monitoring unsaturated stars on several exposures, we estimated that the correction would be of the order of a few percent.

Continuum subtraction. To isolate the emission in the Lyman-\( \alpha \) line, we estimated and then subtracted the continuum emission from discrete and extended sources contained within the NB3985 filter. We estimated the continuum using a combination of the V-band and B-band images as follows. First, we smoothed both of the broadband images using a Gaussian kernel of 1 arcsec and set to zero all of the pixels with values less than the measured root-mean-square (1\% level). Additionally, in the V-band we set to zero all of the pixels which have signal above 1\% in the B band, as we prefer to use the latter image when possible given that it lies closer in wavelength to the Lyman-\( \alpha \) line.

After matching the seeing between the narrow-band and the broadband images, the continuum subtraction has been applied using the following formula:

\[
\frac{L_{\text{Ly}\alpha}}{L_{\text{NB\ 3985}}} = a \left( \frac{F_{\text{NB\ 3985}}}{F_{\text{B-band}}} \right) \left( \frac{b}{F_{\text{B-band}}} \right) - b \left( \frac{F_{\text{NB\ 3985}}}{F_{\text{V-band}}} \right) \left( \frac{c}{F_{\text{V-band}}} \right)
\]

where \( L_{\text{Ly}\alpha} \) is the final subtracted image, NB3985 is the smoothed narrow-band image, \( a \) and \( b \) are the smoothed and masked broadband images, and \( T_{\text{NB\ 3985}}, T_{\text{B-band}} \) and \( T_{\text{V-band}} \) are the transmission peak values for NB3985, B-band and V-band filters, respectively. The parameters \( a = 0.85 \) and \( b = 0.65 \) allow a better match to the continuum. Following this procedure, we primarily used the smoothed B-band image to estimate the continuum and we included the V-band to achieve deeper sensitivity and to correct those objects not detected in the B-band image.

Data reduction and analysis for the companion quasar. Upon analysing the continuum-subtracted Lyman-\( \alpha \) image, we identified a compact Lyman-\( \alpha \) excess source at 2.4 arcsec separation from UM 287 (corresponding to about 200 physical kpc), which has a faint counterpart in our LRIS continuum image and is also detected in the SDSS (\( g = 22.8 \pm 0.1 \)). Further exploration of this source reveals it is detected by the FIRST survey (FIRST J005203.26+010108.6) with a flux \( F_{\text{peak}} = 21.38 \) mJy, strongly suggesting that this source is a radio-loud but optically faint quasar. On UT 08 December 2013, we obtained a long-slit spectrum of J005203.26+010108.6 using the Keck/LRIS spectrometer configured with the D560 dichroic, the 600/4000 grism in the LRIS camera, and the 600/10000 grating in the LRIS camera. We oriented the long slit to also cover UM 287.

These data were reduced with the LowRedux (http://www.ucolick.org/~xavier/ LowRedux/index.html) software package using standard techniques. Extended Data Fig. 2 presents the two, optimally extracted spectra from the LRIS camera. One recognizes the broad and bright emission lines characteristic of type I quasars. The redshift estimated from these lines—that has an error of about 800 km s\(^{-1}\) (1\%)—is consistent with the systemic redshift of UM 287, suggesting that UM 287 is actually a member of a binary system with a fainter companion. We emphasize, however, that there is very little (if any) Lyman-\( \alpha \) emission apparent in the narrow-band image that may be associated with J005203.26+010108.6 apart from that produced by its own nuclear activity.

Because of the large distance from UM 287—at least 200 physical kpc and up to 4 physical Mpc considering the 1\% redshift error—and the morphology of the nebula we can exclude the possibility that the UM 287 nebula is the result of tidal interaction due to a merging event between the two quasar hosts. Indeed, such a large separation would imply that any possible encounter between the two quasars is probably a high velocity interaction or an encounter with large impact parameter. We note that it is not impossible but extremely difficult to produce a long and massive tidal tail during a ‘fast’ encounter\(^4\) and the amount of gas stripped by the quasar host galaxies in the best scenario would probably be a very small fraction (<10\%) of its total interstellar medium. Irrespective of the details of the possible interaction between the two quasar host galaxies, any resulting, long tidal tail would be very thin with sizes of the order of few kpc or less\(^8\) whereas the observed nebula has a FWHM thickness of at least 100 physical kpc in its widest dimension.

Galaxy overdensity analysis. We have obtained a sample of 60 Lyman-\( \alpha \) emitter (LAE) candidates above a flux limit of 3 \( \times \) 10\(^{-18}\) erg s\(^{-1}\) cm\(^{-2}\) (2 corresponding to a Lyman-\( \alpha \) luminosity of about 2 \( \times \) 10\(^{42}\) erg s\(^{-1}\) that minimizes sky background while maximizing throughput. The derived zero-point for the narrow-band images is strong evidence against the possibility that the UM 287 nebula may be fully contained by an individual dark-matter halo of mass 10\(^{13.5}\) M\(_{\odot}\), as would be required by its size. Note that the galaxy number density estimate around
UM 287 is a conservative upper limit: if the quasar is illuminating the surrounding volume, we expect a boost in the number of detectable LAE objects due to fluorescence, as demonstrated in our pilot survey\(^1\). Our measurement is also compatible with the number density of LAEs found by other recent, shallower surveys for Lyman-\(\alpha\) emission around eight radio-quiet, bright quasars\(^4\) at \(z \approx 2.7\) that have a host halo mass of \(10^{12.8} M_\odot\) as constrained by the clustering of Lyman break galaxies. These studies found number densities ranging from \(6 \times 10^{-3}\) to \(22 \times 10^{-3}\) moving Mpc\(^{-3}\) around individual quasars above a Lyman-\(\alpha\) luminosity of \(L_{\text{Ly}\alpha} = 5.8 \times 10^{41}\) erg s\(^{-1}\). Combining the 8 fields, the average number density from their survey is \((12.0 \pm 0.4) \times 10^{-3}\) moving Mpc\(^{-3}\).

Using the same luminosity cut, we find a number density of \((12 \pm 2) \times 10^{-3}\) moving Mpc\(^{-3}\), suggesting that the halo mass of UM 287 is indeed within the typical range for the host haloes of radio-quiet quasars.

**Converting the observed Lyman-\(\alpha\) emission to gas column densities.**

We derived a relation between the observable Lyman-\(\alpha\)-emission from diffuse gas illuminated by a quasar and the gas column densities by combining a Lyman-\(\alpha\) radiative transfer model with the results of a cosmological hydrodynamical simulation of structure formation at \(z = 2.3\) (ref. 5). The cosmological simulations have been obtained with the adaptive mesh refinement code RAMSES\(^6\) and consist of a 40\(^3\) moving Mpc\(^3\) cosmological volume with a 10\(^3\) moving Mpc\(^3\) high-resolution region containing a massive halo compatible with the expected quasar hosts, that is, with a dark-matter mass \(M_{\text{DM}} = 10^{12.5} M_\odot\). The equivalent base-grid resolution in the high-resolution region corresponds to a \((1024^3)\) grid with a dark-matter particle mass of about \(1.8 \times 10^9 M_\odot\). We used other additional 6 grid refinement levels, reaching a maximum spatial resolution of about 0.6 co-moving kpc, that is, about 165 physical pc at \(z = 2.3\). Star formation, supernova feedback, and an optically thin ultraviolet background with an on-the-fly self-shielding correction are included using a typical choice of sub-grid parameters for the simulation resolution.\(^7\) We have then applied in post processing an ionization and Lyman-\(\alpha\) radiative transfer using the RADAMESH adaptive mesh refinement code.\(^8\) Ionization, Lyman-\(\alpha\) and non-ionizing continuum radiation from the quasar broad line region is propagated within two symmetric cones that cover half of the solid angle around the quasar. We included light-travel and finite light-speed effects for both ionizing and Lyman-\(\alpha\) radiation transfer and varied the quasar age (from 1 Myr to 10 Myr) and the orientation of the emission cones with respect to the observer line-of-sight and the cosmic web surrounding the simulated halo.

We note that these effects are able to produce asymmetric Lyman-\(\alpha\) nebulae with sizes and morphologies similar to the observations for short quasar ages (<5 Myr).

In order to produce a calibrated relation for scenario 1 as discussed in the main text, we have fixed the quasar ionizing and Lyman-\(\alpha\) luminosity to the observed value and assumed that the ionizing and Lyman-\(\alpha\) emitting cones are coincident. We have then produced mock images with the same angular resolution of the observation that have been convolved with a point spread function (PSF) with 1 arcsec size to simulate atmospheric seeing. A column density map of cold (\(T < 5 \times 10^4\) K) ionized hydrogen was produced from the simulations considering only the gas ‘illuminated’ by the quasar and convolved with the same PSF. We have then cross-correlated the two quantities pixel by pixel and fitted the calibrated relation shown as a solid line in the left panel of Extended Data Fig. 3. This relation is consistent with analytical expectations from highly ionized gas where the Lyman-\(\alpha\) emission is mostly produced by hydrogen recombination with a negligible contribution from collisional excitations and Lyman-\(\alpha\) scattering (or photon-pumping) from the quasar non-ionizing continuum and Lyman-\(\alpha\) radiation.\(^9\) We have repeated the experiment varying the sub-grid clumping factor (\(C\)) below the simulation resolution and found, as expected for highly ionized gas, that the simulated surface brightness scales linearly with \(C\) at a given gas column density.

We have also considered the extreme case in which the simulated gas is only illuminated by non-ionizing radiation from the quasar, and therefore that dense gas in the simulation remains mostly neutral (scenario 2 in the main text) above the self-shielding density to the cosmic ultraviolet background (about 0.01 atoms cm\(^{-3}\)). We obtained and post-processed a mock image as in the previous case and cross-correlated the resulting Lyman-\(\alpha\) surface brightness with the neutral hydrogen column densities (\(N_{\text{HI}}\)). Despite the large scatter, we found a good correlation between these two quantities (right panel of Extended Data Fig. 3) if the surface brightness is normalized by the impact parameter (\(b\)) squared. The relation between the Lyman-\(\alpha\) surface brightness, neutral hydrogen column density and impact parameter is consistent with simple analytical expectations from pure Lyman scattering from the broad line region of the quasar for Lyman-\(\alpha\) optical depth much larger than unity. In this case, the amount of photon-pumping (or, analogously, the equivalent width of the absorbed quasar Lyman-\(\alpha\) and continuum emission) is dominated by the line damping wing and therefore is proportional to \(N_{\text{HI}}^{1/2}\).

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31. McIntosh, D. H., Rieke, M. J., Rix, H.-W., Fritz, C. B. & Weymann, R. J. A statistical study of rest-frame optical emission properties in luminous quasars at \(2.0 < z < 2.5\). *Astrophys. J.* **514**, 40–67 (1999).

32. Planck Collaboration et al. Planck 2013 results. XVI. Cosmological parameters. Preprint at http://arxiv.org/abs/1303.5076 (2013).

33. Telfer, R. C., Zheng, W., Kriss, G. A. & Davidon, A. F. The rest-frame extreme-ultraviolet spectral properties of quasi-stellar objects. *Astrophys. J.* **565**, 773–785 (2002).

34. Hennawi, J. F. et al. Quasars probing quasars. I. Optically thick absorbers near luminous quasars. *Astrophys. J.* **651**, 61–83 (2006).

35. Becker, R. H., White, R. L. & Helfand, D. J. in *Astronomical Data Analysis Software and Systems XII* 744, 110–115 (Astron. Soc. Pacif. Conf. Ser. Vol. 351, 2006).

36. Ivezić, Z. et al. Optical and radio properties of extragalactic sources observed by the FIRST Survey and the Sloan Digital Sky Survey. *Astron. J.* **124**, 2364–2400 (2002).

37. Bertin, E. & Arnouts, S. SExtractor: software for source extraction. *Astron. Astrophys.* **117** (Suppl.), 393–404 (1996).

38. Bertin, E. in *Astronomical Data Analysis Software and Systems XV* (eds Gabriel, C., Arviset, C., Ponz, D. & Enrique, S.) 112–115 (Astron. Soc. Pacif. Conf. Ser. Vol. 351, 2006).

39. Bertin, E. et al. in *Astronomical Data Analysis Software and Systems XI* (eds Bohlelder, D. A., Durand, C. & Handlex, T. H.) 228–237 (Astron. Soc. Pacif. Conf. Ser. Vol. 281, 2002).

40. Laidož, A. U. UBVRI photometric standard stars in the magnitude range 11.5–16.0 around the celestial equator. *Astron. J.* **104**, 340–371 (1992).

41. Barnes, J. E. & Hernquist, L. Dynamics of interacting galaxies. *Annu. Rev. Astron. Astrophys.* **30**, 705–742 (1992).

42. Kurk, J. D. et al. A Search for clusters at high redshift. I. Candidate Lya emitters near 1138-262 at \(z \approx 2.2\). *Astrophys. J.* **358**, L1–L4 (2000).

43. Guaita, L. et al. Lya-emitting galaxies at \(z = 2.1\) in ECDF-S: building blocks of typical present-day galaxies? *Astrophys. J.* **714**, 255–269 (2010).

44. Ciurddi, R. et al. The evolution of Lya-emitting galaxies between \(z = 2.1\) and \(z = 3.1\). *Astrophys. J.* **744**, 110 (2012).

45. Trainor, R. F. & Steidel, C. C. Constraints on hyperluminous QSO lifetimes via fluorescent Lya emitters at \(z \approx 2.7\). *Astrophys. J.* **775**, L3 (2013).

46. Teyssier, R. Cosmological hydrodynamics with adaptive mesh refinement. A new high resolution code called RAMSES. *Astron. Astrophys.* **385**, 337–364 (2002).
Extended Data Figure 1 | Measured transmission curves of the filters used in this study. Solid line, NB3985; dotted lines, B band (left) and V band (right). Bottom axis, observed wavelength; top axis, the rest-frame wavelength for sources at $z = 2.27$. 
Extended Data Figure 2 | Keck/LRIS spectrum of UM 287 and of the faint, radio-loud companion quasar. Black line, spectrum of this companion quasar which is indicated by ‘b’ in Fig. 2 and is separated by about 24 arcsec from UM 287. Blue line, spectrum of UM287. Comparison of the two spectra clearly shows that this companion is a quasar at a redshift similar to that of UM 287.
Extended Data Figure 3 | Pixel-to-pixel correlations for Lyman-α surface brightness for scenarios 1 and 2 in the main text. a, Pixel-to-pixel correlation between simulated Lyman-α surface brightness (SB) divided by the clumping factor ($C$) and corresponding cold ($T < 5 \times 10^4$ K) ionized hydrogen column densities $N_{\text{HII}}$ for scenario 1 (see text for details). The solid line indicates the relation $N_{\text{HII}} = 10^{21} \times (SB)^{1/2} \times C^{-1/2}$ (here SB is in units of $10^{-18}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ and $C$ is dimensionless). b, Pixel-to-pixel correlation between simulated Lyman-α surface brightness (normalized by the quasar impact parameter squared, $b^2$) and corresponding neutral hydrogen column density for scenario 2 (see text for details). The solid line represents the relation $N_{\text{HI}} = 10^{19.1} \times [(SB) / (b/100) \times 100^2 \text{kpc}]^2$ cm$^{-2}$ (here $b$ is in units of kpc).