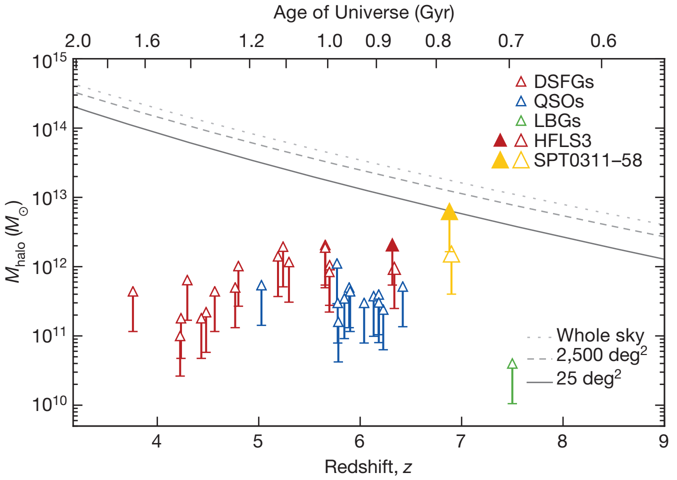

Figure 3 | Halo masses for rare, high-redshift, massive galaxies. The mass of the dark-matter halo (M_{halo}; defined at an density of 200 times the mean density of matter in the Universe) is inferred for galaxies in the first 2 Gyr after the Big Bang (see Methods). These masses present a range of lower limits, from the most conservative assumption (lower bars) that all baryons in the initial halo have been accounted for in the molecular gas mass to the observationally motivated assumption (upper triangles) that the baryonic mass (M_b) in gas is a fixed ratio of the halo mass $M_b/M_{halo} = 0.05$, calibrated through a comparison[3] of simulations and observations spanning $z = 0$–8. The most massive haloes that are expected to be observable[28] within the whole sky (dotted line), within the 2,500-deg^2 area of the South Pole Telescope (SPT) survey (dashed line) and within the subset of that area that is magnified by a factor of two or more (solid line) are also plotted as a function of redshift. As SPT0311−58 E and SPT0311−58 W reside within the same halo, they are combined for this analysis. As in Fig. 2, halo masses are derived for HFLS3 (large red triangles) and SPT0311−58 (large yellow triangles) using only the carbon monoxide luminosity (open symbols) and the more sophisticated dust and carbon monoxide analysis (filled symbols); the pairs of points are slightly offset in redshift for clarity.

a system at this high redshift and in a survey that covered less than 10% of the sky is unprecedented, its existence is not precluded by the current cosmological paradigm.

Online Content Methods, along with any additional 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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1. Springel, V. *et al.* Simulations of the formation, evolution and clustering of galaxies and quasars. *Nature* **435,** 629–636 (2005).
2. Cole, S., Helly, J., Frenk, C. S. & Parkinson, H. The statistical properties of Λ cold dark matter halo formation. *Mon. Not. R. Astron. Soc*. **383,** 546–556 (2008).
3. Behroozi, P. S., Wechsler, R. H. & Conroy, C. The average star formation histories of galaxies in dark matter halos from $z = 0$–8. *Astrophys. J.* **770,** 57 (2013).
4. Riechers, D. A. *et al.* A dust-obscured massive maximum-starburst galaxy at a redshift of 6.34. *Nature* **496,** 329–333 (2013).
5. Vieira, J. D. *et al.* Dusty starburst galaxies in the early Universe as revealed by gravitational lensing. *Nature* **495,** 344–347 (2013).
6. Strandet, M. L. *et al.* ISM properties of a massive dusty star-forming galaxy discovered at $z \sim 7$. *Astrophys. J.* **842,** L15 (2017).
7. Cormier, D. *et al.* The Herschel dwarf galaxy survey. I. Properties of the low-metallicity ISM from PACS spectroscopy. *Astron. Astrophys*. **578,** A53 (2015).
8. Carlstrom, J. E. *et al.* The 10 meter South Pole telescope. *Publ. Astron. Soc. Pacif.* **123,** 568–581 (2011).
9. Mocanu, L. M. *et al.* Extragalactic millimeter-wave point-source catalog, number counts and statistics from 771 deg^2 of the SPT-SZ survey. *Astrophys. J.* **779,** 61 (2013).
10. Planck Collaboration. Planck 2015 results. XIII. Cosmological parameters. Astron. *Astrophys*. **594,** A13 (2016).
11. Casey, C. M., Narayanan, D. & Cooray, A. Dusty star-forming galaxies at high redshift. *Phys. Rep*. **541,** 45–161 (2014).
12. Hezaveh, Y. D. *et al.* Detection of lensing substructure using ALMA observations of the dusty galaxy SDP.81. *Astrophys. J.* **823,** 37 (2016).
13. Mihos, J. C. & Hernquist, L. Gasdynamics and starbursts in major mergers. *Astrophys. J.* **464,** 641–663 (1996).
14. Cooray, A. *et al.* HerMES: the rest-frame UV emission and a lensing model for the $z = 6.34$ luminous dusty starburst galaxy HFLS3. *Astrophys. J.* **790,** 40 (2014).
15. Decarli, R. *et al.* Rapidly star-forming galaxies adjacent to quasars at redshifts exceeding 6. *Nature* **545,** 457–461 (2017).
16. Casey, C. M. *et al.* Near-infrared MOSFIRE spectra of dusty star-forming galaxies at $0.2 < z < 4$. *Astrophys. J.* **840,** 101 (2017).
17. Bouwens, R. J. *et al.* UV luminosity functions at redshifts $z \sim 4$ to $z \sim 10$: 10,000 galaxies from HST legacy fields. *Astrophys. J.* **803,** 34 (2015).
18. Ferkinhoff, C. *et al.* First detection of the [O III] 88 μm line at high redshifts: characterizing the starburst and narrow-line regions in extreme luminosity systems. *Astrophys. J.* **714,** L147–L151 (2010).
19. Brauher, J. R., Dale, D. A. & Helou, G. A compendium of far-infrared line and continuum emission for 227 galaxies observed by the Infrared Space Observatory. *Astrophys. J. Suppl. Ser*. **178,** 280–301 (2008).
20. Inoue, A. K. *et al.* Detection of an oxygen emission line from a high-redshift galaxy in the reionization epoch. *Science* **352,** 1559–1562 (2016).
21. Lebouteiller, V. *et al.* Physical conditions in the gas phases of the giant H II region LMC-N 11 unveiled by Herschel. I. Diffuse [C II] and [O III] emission in LMC-N 11B. *Astron. Astrophys*. **548,** A91 (2012).
22. Díaz-Santos, T. *et al.* Explaining the [C II]157.7 μm deficit in luminous infrared galaxies—first results from a Herschel/PACS study of the GOALS sample. *Astrophys. J.* **774,** 68 (2013).
23. Oteo, I. *et al.* Witnessing the birth of the red sequence: ALMA high-resolution imaging of [C II] and dust in two interacting ultra-red starbursts at $z = 4.425$. *Astrophys. J.* **827,** 34 (2016).
24. Spilker, J. S. *et al.* ALMA imaging and gravitational lens models of South Pole telescope—selected dusty, star-forming galaxies at high redshifts. *Astrophys. J.* **826,** 112 (2016).
25. Bolatto, A. D., Wolfire, M. & Leroy, A. K. The CO-to-H_2 conversion factor. *Annu. Rev. Astron. Astrophys*. **51,** 207–268 (2013).
26. Bothwell, M. S. *et al.* A survey of molecular gas in luminous sub-millimetre galaxies. *Mon. Not. R. Astron. Soc*. **429,** 3047–3067 (2013).
27. Aravena, M. *et al.* A survey of the cold molecular gas in gravitationally lensed star-forming galaxies at $z > 2$. *Mon. Not. R. Astron. Soc*. **457,** 4406–4420 (2016).
28. Harrison, I. & Hotchkiss, S. A consistent approach to falsifying ΛCDM with rare galaxy clusters. *J. Cosmology Astropart. Phys*. **7,** 022 (2013).
29. Weiß, A. *et al.* Highly-excited CO emission in APM 08279+5255 at $z = 3.9$. *Astron. Astrophys*. **467,** 955–969 (2007).

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