

Large thermal reservoir in nascent intracluster gas at redshift 4.3

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Abstract

Most baryons in present-day galaxy clusters exist as hot gas ($\gtrsim 10^7$ K), forming the intracluster medium (ICM) [1]. Cosmological simulations predict that the mass and temperature of the ICM decline toward earlier times, as intracluster gas in younger clusters is still assembling and being heated [2–4]. To date, hot ICM has been securely detected only in a few systems at or above $z \sim 2$, leaving the timing and mechanism of ICM assembly uncertain [5–7]. Here we report the direct observation of intracluster gas in the protocluster SPT2349–56 with the Atacama Large Millimeter/submillimeter Array (ALMA). SPT2349–56 hosts a large molecular gas reservoir and three radio-loud active galactic nuclei (AGN) within a ~ 100 -kpc region at $z = 4.3$ [8–10]. The measurement implies a thermal energy of $\sim 10^{61}$ erg in the core, about ten times more than gravity alone should produce. Contrary to current theoretical expectations [3, 4, 11], the hot ICM in SPT2349–56 demonstrates that substantial heating can occur very early in

cluster assembly, depositing enough energy to overheat nascent ICM well before mature clusters become common at $z \sim 2$.

The thermal Sunyaev-Zeldovich (tSZ) effect is a redshift independent way to detect hot intracluster gas. It arises when cosmic microwave background (CMB) photons gain energy through interaction with energetic electrons in the hot intracluster medium (ICM), producing a decrement in the CMB at wavelength > 1.4 mm [12, 13].

SPT2349–56 was selected as the brightest protocluster candidate in the 2,500 deg² South Pole Telescope survey [14]. It is a compact, active system at $z = 4.3$ with a dark matter halo of $\sim 10^{13} M_{\odot}$ and a star formation rate (SFR) of $\sim 5,000 M_{\odot} \text{ yr}^{-1}$ within 100 kpc [8, 15]. An extended molecular gas reservoir has been revealed by low-resolution Atacama Compact Array (ACA) observations [10], which may trace the cold component of intracluster gas. At least three radio-loud active galactic nuclei (AGN) and 30 dusty star-forming galaxies (DSFGs) have been spectroscopically confirmed in its core [8, 9, 15, Chapman et al. in prep], providing plausible sources of energy input to any nascent ICM [9, 16–18]. These properties make SPT2349–56 an ideal target for tSZ observations.

We obtained deep 3 mm observations with the Atacama Large Millimeter/submillimeter Array (ALMA) 12-m and ACA 7-m arrays and combined them with archival data. After subtracting the dust continuum emission from DSFGs in the protocluster using a Fourier-space technique (Methods), a strong, extended decrement is present in the core (Fig. 1). The tSZ decrement peaks at 8.4σ in the image and 10.4σ in Fourier space, with an integrated flux density of $-160 \pm 20 \mu\text{Jy}$. We quantify the signal strength by the Compton- y parameter, defined as the fractional energy change of line-of-sight CMB photons, which is proportional to the integrated gas pressure along the line of sight [11, 19, 20]. The corresponding integrated value within the system is further defined as Compton- Y [12]. For SPT2349–56, the detected tSZ decrement corresponds to a Compton- y parameter of $(5.6 \pm 0.8) \times 10^{-6}$, or a Compton- Y parameter of $(2.0 \pm 0.2) \times 10^{-6} \text{ arcmin}^2$.

Because the tSZ effect is directly linked to the number density and temperature of hot electrons in a system, the thermal energy of the ICM can be estimated [21]. From our measured Compton- Y value, we infer a total thermal energy $E_{\text{therm}} \sim 10^{61} \text{ erg}$ (Methods). Historically, assuming shock waves as the primary heating source for a $10^{13} M_{\odot}$ protocluster at $z = 4$, Sunyaev and Zeldovich [11] originally predicted a $\sim 10^6 \text{ K}$ ICM, equivalent to a specific thermal energy of $\sim 10^{14} \text{ erg/g}$. To reproduce the observed decrement in this scenario, a gas mass of $5 \times 10^{13} M_{\odot}$ is required, five times the total mass of the system. Even assuming a fully collapsed system with an abundant ICM [$M_{\text{ICM}}/M_{\text{halo}} \lesssim 6\%$, 9], the expected decrement would be only $Y \lesssim 4 \times 10^{-7} \text{ arcmin}^2$, corresponding to a distortion signal of $\lesssim 30 \mu\text{Jy}$ (Methods). The measured tSZ signal thus exceeds these theoretical expectations by at least a factor of five, suggesting a large thermal energy reservoir in the forming ICM of SPT2349–56.

A useful way to characterize the tSZ excess independent of cosmological redshift evolution is to compare it against the universal relation between cluster mass M and

the Compton- Y parameter [22]. The established ICM is mostly under the hydrostatic equilibrium, which depends on gravity alone and can be described by a self-similar profile [13, 22]. Therefore, the global thermodynamic properties of the ICM can be directly derived from its halo mass and redshift, resulting in a tight correlation between M and Y once the redshift dependence $E(z)^{2/3}$ is factored out [17, 22–26]. Although this relation accurately describes most tSZ-detected systems at $z < 2$ [27, 28], our measured Compton- Y in SPT2349–56 exceeds the relation by a factor of five (Extended Data Fig. 7), which implies that the ICM in some high-redshift systems may not follow the self-similar evolution.

Indeed, because star formation and AGN activities were more intense and the ICM was less evolved at earlier epochs, one expects an increased scatter in the $M - Y$ relation at higher redshifts [3, 4, 17, 29, 30]. To further test this hypothesis, we used the TNG-Cluster simulations, a cosmological simulation suite of 352 zoom-in galaxy clusters, to predict the redshift evolution of the mass-normalized Compton- Y (Supplementary Methods). Fig. 2 shows that the mass-normalized Y from TNG-Cluster follows the self-similar prediction in the past 12 billion years, in line with current observations at low redshift [27, 28, 31], whereas tSZ decrement in less evolved systems are weaker than the simulation prediction [6, 7, 32, 33]. The simulated Y starts falling below the self-similar expectation since $z \gtrsim 4$, suggesting a cooler ICM in protoclusters at these early epochs [4], in contrast to a hotter ICM inferred from our observed tSZ decrement, with a 6.4σ deviation. Although the gas temperature can be high at such an early epoch, the hot-gas fractions of these high-redshift cluster progenitors (Extended Data Fig. 9) remains too small to explain our observed thermal energy excess (Extended Data Fig. 8) [3, 4, 34, 35].

A halo mass three times larger than current observational estimates based on dynamics would be required for SPT2349–56 to match the universal $M - Y$ relation [8, 15]. The inconsistency could be even amplified if one accounts for a steeper $M - Y$ slope and lower hot-gas fraction for high-redshift protoclusters [17, 35]. To explain the measured tSZ strength without invoking an implausibly massive halo, an episode of early ICM “pre-heating” is favored, which is also suggested by the flattened entropy profiles seen in some cluster cores at low redshift [13, 16–18, 25]. While cosmological hydrodynamical simulations reproduce the global cosmic star formation history, they often under-predict the high SFRs of systems like SPT2349–56 [34, 36, 37]. In principle, strong AGN feedback in SPT2349–56 could naturally provide the required energy to the nascent ICM [38–44] (Methods). The elevated ambient gas pressure and density at $z > 4$ confine the ICM and jets, which enhances AGN heating and reduces energy loss to expansion. This confinement allows a large amount of energy stored in the over-pressurized and therefore overheated ICM, producing the strong tSZ decrement seen in SPT2349–56 [17, 18, 30, 45–47].

How common such enormous thermal reservoirs are in nascent ICM at $z \gtrsim 4$ remains unknown. Given that SPT2349–56 is a unique system from a $2,500 \text{ deg}^2$ survey, the observed strong tSZ decrement may simply reflect its own rarity, or may serve as a clue towards a potentially unrecognized but more general short-lived stage of cluster assembly, even if not as extreme as occurring in SPT2349–56 [47]. Notably, the majority of hydrodynamical simulations with state-of-the-art galaxy formation

models have not predicted the extreme heating and over-pressurized hot ICM that we observe in SPT2349–56 [3, 35, 48–51]. This discrepancy could point to the need for more complicated subgrid physics for AGN feedback models at high redshifts in order to match the unanticipated hot and pressurized ICM in nascent clusters [16, 50, 52, 53].

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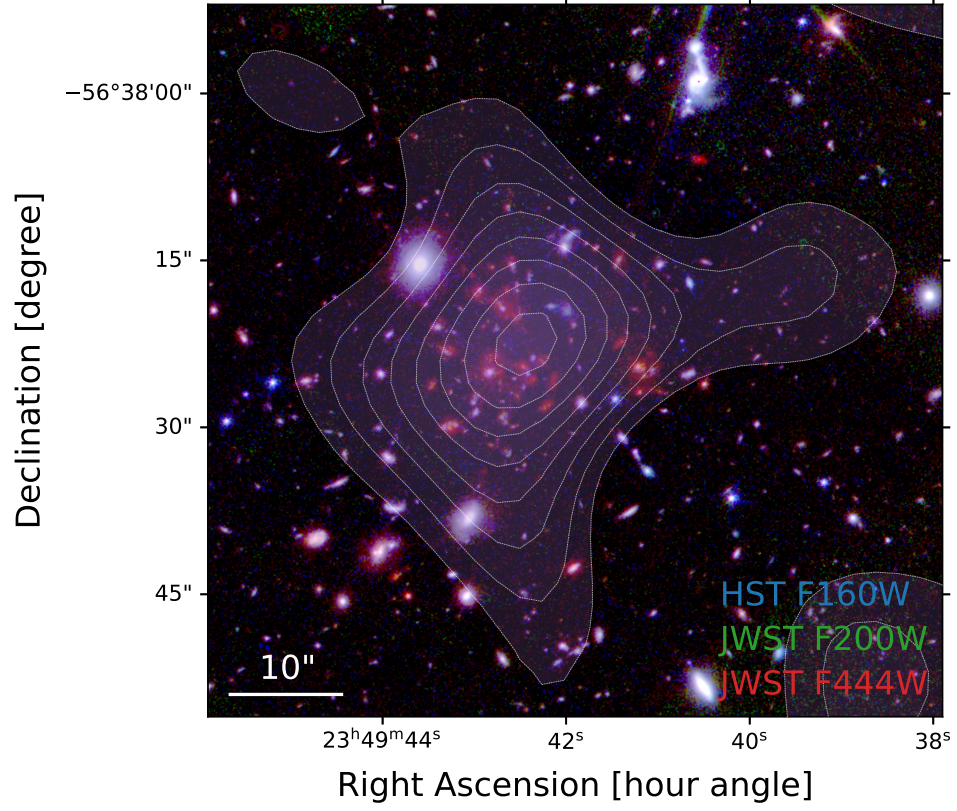


Fig. 1 RGB image of the protocluster SPT2349-56 with tSZ decrement contours. R: JWST F444W band; G: JWST F200W band; B: HST F160W band. The tSZ signal (purple) was obtained after continuum source-subtraction in Fourier space and imaging done with short baselines ($uv < 10k\lambda$). Decrement contours are from -1σ ($8.8\mu\text{Jy}$) to -9σ ($79.2\mu\text{Jy}$) with steps of -1σ . The decrement peak (-8.4σ) is co-spatial with the kinematic center of the protocluster system. The flux density of the tSZ signal is $-160 \pm 20\mu\text{Jy}$ in the image plane.

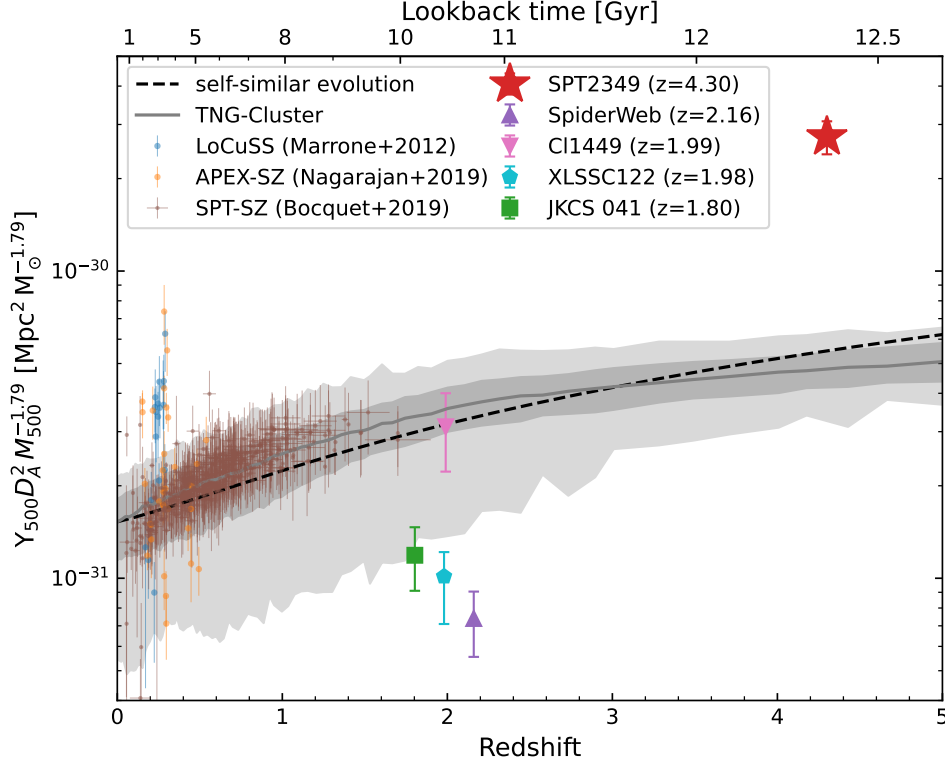


Fig. 2 Redshift evolution of the mass-normalized Compton- Y parameter. The data points contain SPT-SZ [28], APEX-SZ [31], and LoCuSS [27] results, along with high- z systems detected in tSZ [6, 7, 54], including SPT2349–56 at $z = 4.3$, shown as the red star. Errorbar of each data point are the measured uncertainty of the tSZ signal. The self-similar expectation is shown as the dashed line. The solid gray line and shaded region represent the median value, 16% – 84%, and 2% – 98% scatters from the TNG-Cluster simulation, which has been calibrated to the local $M_{500} - Y_{500}$ relation [24]. The tSZ signal in SPT2349–56 lies 6.4σ above the predicted evolutionary tracks, in contrast to more massive systems at later epochs.

Figure legends

Fig. 1 RGB image of the protocluster SPT2349–56 with tSZ decrement contours. R: JWST F444W band; G: JWST F200W band; B: HST F160W band. The tSZ signal (purple) was obtained after continuum source-subtraction in Fourier space and imaging done with short baselines ($uv < 10k\lambda$). Decrement contours are from -1σ ($8.8\mu\text{Jy}$) to -9σ ($79.2\mu\text{Jy}$) with steps of -1σ . The decrement peak (-8.4σ) is co-spatial with the kinematic center of the protocluster system. The flux density of the tSZ signal is $-160 \pm 20\mu\text{Jy}$ in the image plane.

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Methods

Throughout the paper, we used a standard Lambda Cold Dark Matter cosmological model with $H_0 = 67.7 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $\Omega_m = 0.31$ [55], which corresponds to a proper angular scale of 6.9 kpc/arcsec at $z = 4.3$. R_{200} and R_{500} are defined as the radius where the average densities are 200 and 500 times the critical density of the Universe at the source redshift. ρ_{200} , ρ_{500} , M_{200} , M_{500} , Y_{200} , and Y_{500} are the corresponding mean densities, total masses, and Compton- Y parameters within these regions, respectively. We adopted $M_{200} = (9 \pm 5) \times 10^{12} M_\odot$ inferred from the dynamical mass estimate through the velocity dispersion of spectroscopic confirmed protocluster members [15].

Observations

ALMA observations

The ALMA and ACA Band-3 data of SPT2349–56 were obtained under four different programs from the ALMA Science Archive (Cycle 3: 2015.1.01543.T, PI: K. Lacaille; Cycle 5: 2017.1.00273.S, PI: S. Chapman; Cycle 9: 2022.1.00495.S, PI: J. Chen; Cycle 10: 2023.1.00124.S, PI: S. Chapman). The phase centers of these observations are similar except the Cycle 3 program, which is about 10 arcsec to the South of the pointing centers of the other programs. The total on-source exposures are 23.7 and 26.9 hours for ALMA and ACA observations, respectively. The corresponding configurations, data reduction, and tSZ decrement validation are described in Supplementary Methods.

Ancillary data

Hubble Space Telescope (*HST*) F160W (PID: 15701, PI: S. Chapman) and *James Webb Space Telescope* (*JWST*) F200W and F444W (PID: 06669, PI: S. Chapman) images shown in Fig. 1 were retrieved from the Mikulski Archive for Space Telescopes (MAST) server (<https://mast.stsci.edu>). The exposure times of each filter are 8472 s (F160W), 3264 s (F200W), and 3264 s (F444W), respectively. We followed the standard reduction procedure to process the level-1 data through *HST* and *JWST* calibration pipelines (`hstcal/calwf3` and `jwst/calwebb` [56]) within the Space Telescope Environment (`stenv`). We applied an extra de-stripping step for the NIRCам images during the `stage_2` process to mitigate the influence of column stripes. The images were all reprojected and aligned to the F444W band using the python packages `reproject` and `tweakreg`. We produced the RGB image with `astropy` function `make_rgb`, which is presented in Fig. 1 and Extended Data Fig. 1. We also labeled the submillimeter-luminous protocluster galaxies with their alphabetical names in Extended Data Fig. 1. The detailed description of the *JWST* data reduction will be presented in a forthcoming paper.

Photometry measurements of continuum-emitting galaxies

We used the `photutils` package [57] for the photometry measurements of continuum-emitting galaxies from the ‘ALMA high-res’ map. The segmentation map was made using the `detect_sources` function with a 3σ threshold over 10 pixels.

`deblend_sources` (`npixels=5`, `nlevels=32`, `contrast=0.001`) was applied to the segmentation map, which successfully deblended source ‘D’ and ‘E’ (or ID ‘6’ and ‘7’ shown in Extended Data Fig. 2). However, due to the sparse resolution, a few sources remain blended, which were treated as single sources during the measurements.

Subsequently, we made use of the `SourceFinder` function for the source extraction. To avoid noise contamination, we only extracted sources with a peak pixel value $> 4\sigma$. We recorded the flux densities measured from their peak pixels and integrated values within standard kron apertures ($k=1.4$, $R_{\min}=2.5$), with the nearby sources all masked to prevent potential contamination. The aperture photometry uncertainty was estimated by measuring the flux distribution in 10,000 randomly placed apertures of identical shape on the noise map. While the peak pixel can provide a more accurate measurement for unresolved sources, it cannot capture all emission when the source is extended. Therefore, we compared the flux densities obtained from these two methods and adopted the larger one as the ‘best’ flux density (Extended Data Table 1). However, due to the insufficient rms sensitivity and the potential contamination from the tSZ decrement, a few confirmed protocluster members were only marginally detected ($< 4\sigma$). For a conservative assessment of the tSZ signature, we did not include their contribution in the photometry measurement, which could cause a $\lesssim 30\mu\text{Jy}$ underestimation of the total dust continuum within the core.

We also performed the continuum measurements using two independent datasets, the ‘ALMA low-res’ and ‘ACA’ maps, using identical methods. The continuum flux densities in both images are lower than the integrated values from individual galaxies measured from the high-resolution image (see Extended Data Table 1). The fainter emission is contrary to the general expectation from tapering, which usually recovers more extended emission and results in a higher flux density [58, 59]. If the deviations are purely caused by the tSZ contamination, the signal of the tSZ decrement should be at least $131 \pm 32\mu\text{Jy}$. This 4.2σ deficit confirms the reliability of the 2.3σ difference seen in shallower data in previous work, which was speculated to be due to the tSZ contamination by Zhou et al. [10]. Because the tSZ decrement could be more extended than the size defined by continuum emission and the contribution of the faint sources was ignored, the intrinsic strength of the tSZ could be underestimated in this way.

Continuum subtraction and tSZ measurement

To explore the morphology and actual strength of the negative signal free from contamination from dusty galaxies, we further subtracted the known continuum sources in the uv -plane. We used the `CASA` class `componentlist` to construct catalogs of continuum sources as point-like for the ACA and ALMA visibilities, while considering the primary beam attenuation. Next, we Fourier transformed the source list from the image plane to the uv -plane with the `ft` function and recorded the expected visibilities in the model column of each measurement set, which was then subtracted using the `uvsub` command from the calibrated visibilities.

With the continuum-subtracted data, we deconvolved the image created by the visibilities with uv distances $< 10k\lambda$ and generated an initial CLEANed image with the ‘hogbom’ deconvolver down to 4σ without the CLEAN mask. We masked pixels with an absolute value $> 4\sigma$ and expanded to the adjacent $> 2\sigma$ pixels. Then, we used the

multi-scale deconvolver with scales of $[0, 2, 4, 8]$ pixels and further **CLEANed** the data down to 1σ , resulting in an rms sensitivity of $8.8\mu\text{Jy}/\text{beam}$ with a synthesized beam of $13.6'' \times 14.7''$. As shown in Extended Data Fig. 2 and Fig. 3, a strong decrement occurs at the center of the protocluster core [15], with the peak $\Delta(\text{R.A.}, \text{Dec.}) = (-7.2'', 2.1'')$ offset from the radio-loud AGN C.

The curve-of-growth analysis (Extended Data Fig. 4) indicates that the full width at half maximum (FWHM) of the decrement is $\text{FWHM}_{\text{SZ}} \approx 14''$ (100 kpc) with the signal extending out to $R_{\text{SZ}} \approx 20''$ (140 kpc) after correcting for beam broadening. This corresponds to an angular scale of $2R_{\text{SZ}} \sim 40'' \approx 5k\lambda$. Including uncertainties from point-source subtraction and absolute flux calibration, the tSZ decrement is $-100 \pm 15\mu\text{Jy}$ within R_{500} (80 kpc, [9]) and the total signal is $-160 \pm 20\mu\text{Jy}$. After correcting for projection effects [22], we calculated the Compton- Y parameter through the formula [11, 19, 20]

$$\Delta I_\nu = \frac{x^4 e^x}{(e^x - 1)^2} \left(x \frac{e^x + 1}{e^x - 1} - 4 \right) I_0 y = g(x) I_0 y, \quad (1)$$

where the CMB intensity $I_0 = 270.33 \text{ MJy/sr}$, ΔI_ν is the distortion signal in the CMB map (i.e., decrement intensity in the continuum map), and the dimensionless frequency $x = h\nu/kT_{\text{CMB}} = \nu/56.81 \text{ GHz} \approx 1.65$. The Compton- y map is shown in Extended Data Fig. 6. We obtained mean Compton- y parameters of $(10.2 \pm 1.3) \times 10^{-6}$ and $(5.6 \pm 0.8) \times 10^{-6}$ for within R_{500} and within R_{SZ} , respectively. The integrated tSZ signal (Compton- Y) can be calculated as [20]

$$Y_{\text{SZ}} = \int y d\Omega = \frac{1}{g(x)} \frac{1}{I_0} \int \Delta I_\nu d\Omega = \frac{S_\nu}{g(x) I_0}, \quad (2)$$

where Ω is the solid angle of the selected region, and S_ν is the flux density in the same region. This leads to Compton- Y parameters of $Y_{500} = (1.3 \pm 0.2) \times 10^{-6} \text{ arcmin}^2$ and $Y_{\text{total}} = (2.0 \pm 0.2) \times 10^{-6} \text{ arcmin}^2$.

However, considering the large radius of the tSZ decrement, analysis in the uv -plane is needed to evaluate if the signal is limited by insufficient short baselines. We used the **uvplot** package [60] to export all associated data to a single uv table. The corresponding visibilities were then shifted to the position of the decrement peak. Extended Data Fig. 5 shows the visibilities as a function of uv distance, which were averaged over every $3k\lambda$. The uncertainties were estimated through the corresponding weight of each visibility. The positive signal of $\sim 30\mu\text{Jy}$ at $10k\lambda$ is likely from the conservative continuum subtraction strategy, which is consistent with the estimation of the total under-subtraction signal $\sim 30\mu\text{Jy}$. Extended Data Fig. 5 shows that the amplitude of the negative signal profile peaks at the shortest uv distance of $\sim 3k\lambda$ with a large uncertainty, indicating that the current data have less capability in recovering the signal at this scale. This suggests that the signal can approach or even go beyond the MRS and its angular scale should be $\lesssim 6k\lambda$ ($\gtrsim 35''$ or 240 kpc), which is consistent with the analysis conducted in the image plane. Because of the large uncertainty in the shortest uv distance and the primary beam attenuation for such a large scale signal, the intrinsic tSZ signal cannot be directly measured in the uv -plane and a

model-dependent value is out of the scope of this letter, which is planned for a future paper.

Comparison with other tSZ systems

To place our tSZ detection in a broader context, we compiled a sample of systems with tSZ detections, including low-redshift galaxy clusters with weak-lensing mass estimates [27, 28, 31] and high-redshift systems ($z \gtrsim 2$) with tSZ detections [5–7, 33, 54]. Notably, extended X-ray emission has been reported in a few $z > 2$ protoclusters [61–63], which may also indicate hot ICM. Direct tSZ measurements are essential for the confirmation and for a fair comparison.

Since the reported tSZ decrements are derived from different methods and expressed in different units, we adopted a universal pressure profile (‘arnaud10’) to convert all results to the spherical Y_{500} integrated within R_{500} in units of Mpc^2 for consistency [22]. For high-redshift systems, we also used the ‘diemer19’ halo concentration profile to convert the virial masses estimated from velocity dispersions to M_{500} values [64, 65], as most targets lack weak-lensing mass calibration.

The ICM is known to evolve self-similarly with redshift [13, 22, 25]. To compare our detected tSZ signal to the expected $M - Y$ relation, we removed the redshift dependence by factoring out the $E(z)^{2/3}$ scaling for each system. As shown in Extended Data Fig. 7, most low-redshift systems follow the relation $Y_{500} \propto M_{500}^{1.79}$ [24]. However, with the exception of Cl1449, high-redshift systems show a larger scatter and lie below the values predicted by the universal relation, in contrast to the tighter relation at $z \sim 2$ predicted by current simulations [35]. This discrepancy can be explained by the presence of cooler, unvirialized ICM in the early stages of cluster formation [4]. Nevertheless, the tSZ decrement we observed is a factor of five larger than the predicted value, suggesting significantly higher gas pressure in SPT2349–56 at a much earlier epoch.

Thermal energy budget of the nascent ICM

To examine if the decrement can be caused by gravity, we calculated the thermal energy required by the measured tSZ signal and possible gravitational energy of the virialized gas.

We estimated the total thermal energy using the equation [21]

$$E_{\text{therm}} = 2.9 \frac{m_e c^2}{\sigma_T} l_{\text{ang}}^2 \int y d\Omega = 2.9 \times 10^{60} \text{erg} \left(\frac{l_{\text{ang}}}{\text{Gpc}} \right)^2 \frac{Y_{\text{SZ}}}{10^{-6} \text{arcmin}^2}, \quad (3)$$

where the angular diameter distance to the source $l_{\text{ang}} = 1.42 \text{Gpc}$. We obtained a total thermal energy of $E_{\text{therm,total}} = (11.8 \pm 1.2) \times 10^{60} \text{erg}$ and $E_{\text{therm},500} = (7.5 \pm 0.9) \times 10^{60} \text{erg}$ within the R_{500} radius.

To assess if this thermal energy can be matched to the energy of a thermal-equilibrium ICM, we need to explore its constraint on halo mass (M_{200}), ICM temperature (T_{ICM}), and ICM fraction ($f_{\text{ICM}} = M_{\text{ICM}}/M_{200}$). The halo mass M_{200}

can be obtained by

$$M_{200} = \frac{2E_{\text{therm}}\mu m_p}{3f_{\text{ICM}}k_B} \frac{1}{T_{\text{ICM}}}, \quad (4)$$

where the molecular weight $\mu \approx 0.6$, proton mass $m_p \approx 1.67 \times 10^{-24}$ g, and f_{ICM} is the mass ratio between the dark matter halo and the hot ICM. Here we assumed that the thermal energy within R_{200} radius is $E_{\text{therm},200} \approx E_{\text{therm,total}}$. This is a good approximation because $R_{200} = 18.5'' \times (M_{200}/10^{13}M_{\odot})^{1/3}$, which is comparable to the tSZ radius $R_{\text{SZ}} \approx 20''$.

Next, we calculated the gas temperature for a virialized ICM. For simplicity, we used the mean virial temperature $\langle T_{200} \rangle$ within R_{200} given by Voit [13],

$$k_B T_{\text{vir}} \approx k_B \langle T_{200} \rangle = \frac{GM_{200}\mu m_p}{2R_{200}}, \quad (5)$$

where the gravitational constant $G \approx 6.67 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$. The mass M_{200} and radius R_{200} of the halo have the following relation

$$M_{200} = \frac{4}{3}\pi R_{200}^3 \rho_{200}. \quad (6)$$

Combining Eq. 5 and Eq. 6, we can obtain the relation between M_{200} and T_{vir} for a virialized halo

$$M_{200} = \left(\frac{6}{\pi \rho_{200}} \right)^{1/2} \left(\frac{k_B}{G\mu m_p} \right)^{3/2} T_{\text{vir}}^{3/2}. \quad (7)$$

If the system is virialized with a halo mass $M_{200} = (9 \pm 5) \times 10^{12} M_{\odot}$ [15], we can derive a total thermal energy of $(f_{\text{ICM}}/0.02) \times (8.5 \pm 3.2) \times 10^{59}$ erg, which is negligible compared to the ICM thermal energy. Even assuming an extremely abundant ICM $f_{\text{ICM}} = 6\%$ [9], the derived thermal energy is only $(2.6 \pm 1.0) \times 10^{60}$ erg, $\sim 20\%$ of the value inferred by the observed decrement. Under this condition, the estimated thermal energy corresponds to a Compton- Y parameter of $Y = (4.4 \pm 0.4) \times 10^{-7} \text{ arcmin}^2$ or a distortion signal of $34 \pm 4 \mu\text{Jy}$. For a $9 \times 10^{12} M_{\odot}$ halo, it is unlikely that gravity serves as the dominant energy source for the observed tSZ signal.

We then explored the possible halo masses and ICM temperatures allowed by the tSZ decrement. The mass of the hot ICM is limited by the available baryonic budget in the halo. We have a lower limit of the halo mass of

$$M_{200} \geq \frac{1}{f_b - f_{\text{ICM}}}(M_{\text{mol}} + M_*), \quad (8)$$

where f_b is the baryonic fraction of the protocluster. In the following calculation, we used the universal baryonic fraction $f_b = 0.155$. Adopting $\alpha_{\text{CO}} = 4$ would imply a molecular gas mass $M_{\text{mol}} \sim 2 \times 10^{12} M_{\odot}$, about $\sim 20\%$ of $M_{200} \sim 9 \times 10^{12} M_{\odot}$, which already approaches (or even exceeds) the expected baryon budget within R_{200} . To avoid overestimating the cold gas reservoir given the relatively unknown physical conditions and gas excitation, we used $r_{41} = 0.60$ and $\alpha_{\text{CO}} = 1 M_{\odot}/(\text{K km s}^{-1} \text{ pc}^2)$ to calculate the molecular gas mass M_{mol} from the CO(4–3) luminosity of SPT2349–56

[10]. As a result, M_{mol} and M_* of SPT2349–56 are $(4.9 \pm 0.5) \times 10^{11} M_{\odot}$ and $(6.7 \pm 2.3) \times 10^{11} M_{\odot}$, respectively [66].

The parameter space constrained by the measured tSZ decrement and the available baryons is shown in Extended Data Fig. 8. Within the possible M_{ICM} range and without assuming an extreme f_{ICM} , either a more massive virialized halo or a super-virialized ICM gas is necessary to match the observed tSZ decrement.

In the case that the thermal energy is under thermal equilibrium in an extremely massive halo, we can obtain

$$M_{200} \approx (4.4 \pm 0.5) \times 10^{13} M_{\odot} \times \left(\frac{0.02}{f_{\text{ICM}}} \right)^{3/5}. \quad (9)$$

Assuming a regular ICM fraction of $f_{\text{ICM}} \lesssim 0.02$ at $z > 4$, the expected halo mass will be more than five times the halo mass derived from velocity dispersion [15], which is unlikely given the compactness of the system.

Possible energy injection from non-gravitational processes

In addition to energy from gravitational processes, AGN and star-formation activities are likely to provide the additional energy injection needed to explain the large thermal reservoir inferred by the observed tSZ decrement. We note that the photo-ionization would not efficiently heat the hot ionized gas ($> 10^7$ K) as it only becomes significant for cool neutral gas with a temperature of $\sim 10^4$ K. Given that kinetic energy is the dominant source besides gravitational energy for large-scale heating [47], we only consider its contribution to the thermal energy of the nascent ICM in SPT2349–56 for simplicity.

Kinetic-mode AGN feedback

Previous studies indicate that AGN activity is significantly enhanced in SPT2349–56 [9, 67]. At least three protocluster members show strong radio excess, with a total rest-frame 1.4 GHz power of $L_{1.4 \text{ GHz}} = (2.6 \pm 0.1) \times 10^{26} \text{ W/Hz}$ (Chapman et al. in prep), of which one is also luminous in X-rays [67]. From their modest radio luminosities, Chapman et al. [9] speculates that the detected radio AGN can be fueled by hot gas in radio-mode instead of radiative-efficient accretion through recent mergers. Their powerful jets can provide strong kinetic feedback with substantial energy injection on the nascent ICM in the protocluster, analogous to cavity inflation observed in low-redshift clusters, where radio jets inflate overpressurized bubbles that redistribute energy into the ICM.

We used the correlation between the cavity power (P_{cav}) and radio luminosity at 1.4 GHz ($L_{1.4 \text{ GHz}}$) to estimate the kinetic power from radio luminosity alone, which can be described using [68]

$$P_{\text{cav}} = 7 \times 10^{43} \text{ erg/s} \times f_{\text{cav}} \left(\frac{L_{1.4 \text{ GHz}}}{10^{25} \text{ W Hz}^{-1}} \right)^{0.68}, \quad (10)$$

where the enthalpy factor $f_{\text{cav}} = 4$ for relativistic plasma. Shocks induced by the radio jet can cause additional heating, which could imply a higher $f_{\text{cav}} > 4$ [69, 70]. This scaling relation yields a kinetic power of $\dot{E}_{\text{kin,radio}} = (2.6 \pm 0.1) \times 10^{45} \text{ erg/s} \times (f_{\text{cav}}/4)$.

Radiative-mode AGN feedback

On the other hand, the protocluster galaxy ‘A’ is luminous in X-ray with an AGN luminosity of $L_{\text{AGN}} = (1.9 \pm 0.7) \times 10^{47} \text{ erg/s}$ [67], which can also power large-scale outflows through radiation pressure when the outflow exceeds the local escape velocity [43, 47]. We can use the tight correlation between AGN luminosity and outflow rate to estimate the kinetic power from the radiation pressure:

$$\dot{E}_{\text{kin,rad}} = f_{\text{rad}} \times L_{\text{AGN}}, \quad (11)$$

where the coupling efficiency of radiative-mode feedback $f_{\text{rad}} \approx 0.5\%$ [41, 71]. We note that energy can be injected to the forming ICM only when outflows overcome the potential well of the host galaxy. The corresponding escaping power is

$$\dot{E}_{\text{esc,rad}} = f_{\text{esc,rad}} \dot{E}_{\text{kin,rad}} = \left[1 - \left(\frac{v_{\text{esc}}}{v_{\text{out}}} \right)^2 \right] \dot{E}_{\text{kin,rad}}, \quad (12)$$

where $f_{\text{esc,rad}}$ is the escape efficiency for the radiation-driven outflow, $v_{\text{esc}} = \sqrt{2GM/R}$ is the escape velocity from the host galaxy, and v_{out} is the velocity of AGN outflow driven by the radiative feedback. With the assumed AGN-outflow velocity of $v_{\text{out}} \approx 1,000 \text{ km/s}$, estimated dynamical mass $M_{\text{dyn}} \approx 2.7 \times 10^{11} M_{\odot}$, and galaxy radius $R \approx 6 \text{ kpc}$ [15, 72], the escape efficiency is $f_{\text{esc,rad}} \approx 0.6$. The escaping kinetic power from ‘A’ is $\dot{E}_{\text{esc,rad}} = (0.6 \pm 0.2) \times 10^{45} \text{ erg/s} \times (f_{\text{esc,rad}}/0.6) \times (f_{\text{rad}}/0.005)$.

Star formation

We next consider energy injection from star formation activity. The kinetic power from star formation-driven outflows is given by [9, 73]

$$\dot{E}_{\text{esc,SF}} \approx \frac{1}{2} \dot{M}_{\text{out,SF}} v_{\text{out,SF}}^2 f_{\text{esc,SF}}, \quad (13)$$

where $f_{\text{esc,SF}}$ is the escape efficiency of an outflow and the mass outflow rate $\dot{M}_{\text{out,SF}}$ is related to the SFR by the mass-loading factor $\eta = \dot{M}_{\text{out,SF}}/\text{SFR} \approx 1$. Given an SFR of $\sim (5,000 \pm 600) M_{\odot}/\text{yr}$ in the protocluster core [8, 9, 15], the kinetic power from star formation is $\dot{E}_{\text{esc,SF}} = (0.8 \pm 0.1) \times 10^{44} \text{ erg/s} \times (v_{\text{out,SF}}/500 \text{ km s}^{-1})^2 \times (f_{\text{esc,SF}}/0.2)$, which is less than 5% of the kinetic power from AGN feedback. The total stellar mass in the core only requires a star formation episode of $\sim 100 \text{ Myr}$ at the current SFR. We therefore conclude that energy injection from star formation can be safely neglected.

Total energy injection and thermal coupling efficiency

Assuming $f_{\text{cav}} = 4$, $f_{\text{esc,rad}} = 0.6$, and $f_{\text{rad}} = 0.005$, we can estimate the total energy input:

$$\begin{aligned}\Delta E_{\text{inject}} &\approx \dot{E}_{\text{kin,radio}} t_{\text{radio}} + \dot{E}_{\text{esc,rad}} t_{\text{rad}} \\ &= \left[(8.2 \pm 0.3) \times \left(\frac{t_{\text{radio}}}{100 \text{ Myr}} \right) + (1.8 \pm 0.7) \times \left(\frac{t_{\text{rad}}}{100 \text{ Myr}} \right) \right] \times 10^{60} \text{ erg.}\end{aligned}\quad (14)$$

Assuming a characteristic length of ~ 100 kpc and sound speed of $\sim 1,000$ km/s, the relaxation timescale of SPT2349 is ~ 100 Myr, after which earlier heating episodes are partially erased as the gas redistributes toward hydrostatic equilibrium. Adopting $t_{\text{AGN}} = 100$ Myr for AGN activities, we can obtain a total energy injection of $(10.0 \pm 0.8) \times 10^{60}$ erg to be stored in the nascent ICM.

According to thermodynamics and the ideal gas law, the kinetic energy is known to have two effects. The injected energy can lead to a system expansion against the ambient pressure or an increase in the thermal energy of the ICM, which can be expressed as

$$\Delta E_{\text{inject}} \propto \int P dV + \int V dp = \Delta E_{\text{therm}} + W_{\text{expan}} = \frac{\Delta E_{\text{therm}}}{f_{\text{therm}}}, \quad (15)$$

where ΔE_{therm} is the thermal energy change due to the pressure increase, W_{expan} is the expansion work, and the thermal energy coupling efficiency f_{therm} is defined as the fraction of kinetic power increasing the thermal energy instead of the bulk work. Assuming that the halo is virialized with $f_{\text{ICM}} = 0.02$, the thermal energy change is $\Delta E_{\text{therm}} = E_{\text{therm}} - E_{\text{therm,vir}} = (10.9 \pm 1.2) \times 10^{60}$ erg.

With aforementioned assumptions, the overall thermal coupling efficiency is required to be $f_{\text{therm}} \sim 100\%$. In addition to possibly stronger kinetic-mode feedback, reduced system expansion, which suppresses the PdV term, can help drive a relatively high coupling efficiency [38, 40, 43, 74]. Indeed, the ambient gas pressure can be sufficiently high to confine jets in some radio galaxies [45, 75–78]. Because the ICM pressure and density scale with the cosmic critical density, early-time halos naturally provide a high-pressure ambient medium [79]. Under these conditions, limited expansion boosts the fraction of kinetic energy converted into heat, producing a short-lived and large thermal-energy reservoir in the nascent ICM at $z > 4$.

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Declarations

- **Data availability:** The ALMA (2015.1.01543.T; 2017.1.00273.S; 2022.1.00495.S; 2023.1.00124.S) and *HST* data (*HST*-GO-15701) used in this work are publicly available on the ALMA science archive (<https://almascience.nrao.edu/aq/>) and MAST service (<https://mast.stsci.edu>). The *JWST* data were obtained as a part of program *JWST*-GO-06669, which will be accessible after the proprietary period.

- **Code availability:** No custom code central to the conclusions was used. Presented results can be reproduced using the following publicly available packages: `astropy` [80], `astroquery` [81], `CASA` [82], `colossus` [64], `matplotlib` [83], `numpy` [84], `pandas` [85], `photutils` [57], `spectral_cube` [86], `uvplot` [60].
- **Author contribution:** D.Z. reduced and analyzed the data, interpreted the results, produced the figures, and drafted the manuscript. S.C.C. conceived, designed, and supervised the projects. R.G. produced the tSZ model of SPT2349–56 for the ALMA proposal. R.D. and R.G. validated the fidelity of the tSZ decrement. P.A.A. calculated the redshift-evolution of the Compton- Y parameter and hot-gas fraction from TNG-Cluster simulations. S.K. reduced the JWST NIRCам data. All authors contributed substantially to discussing the results and preparing the manuscript.
- **Author information:** The authors declare no competing interests. Correspondence and requests for materials should be addressed to D.Z. (dzhou.astro@gmail.com).

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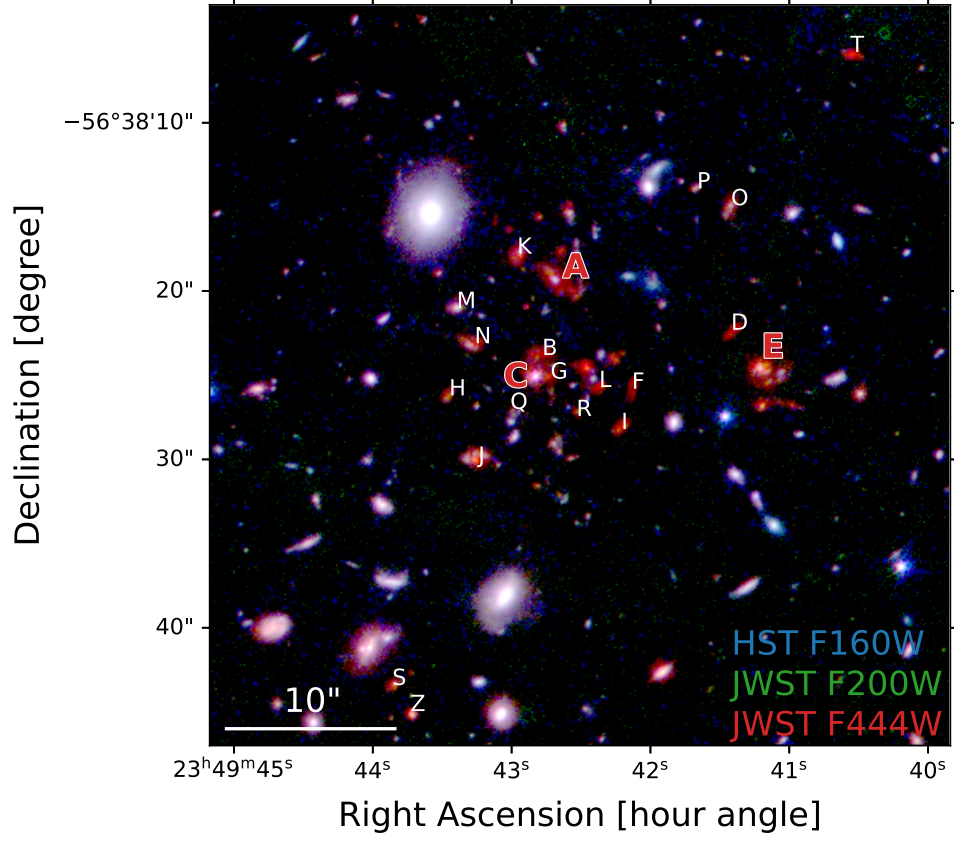
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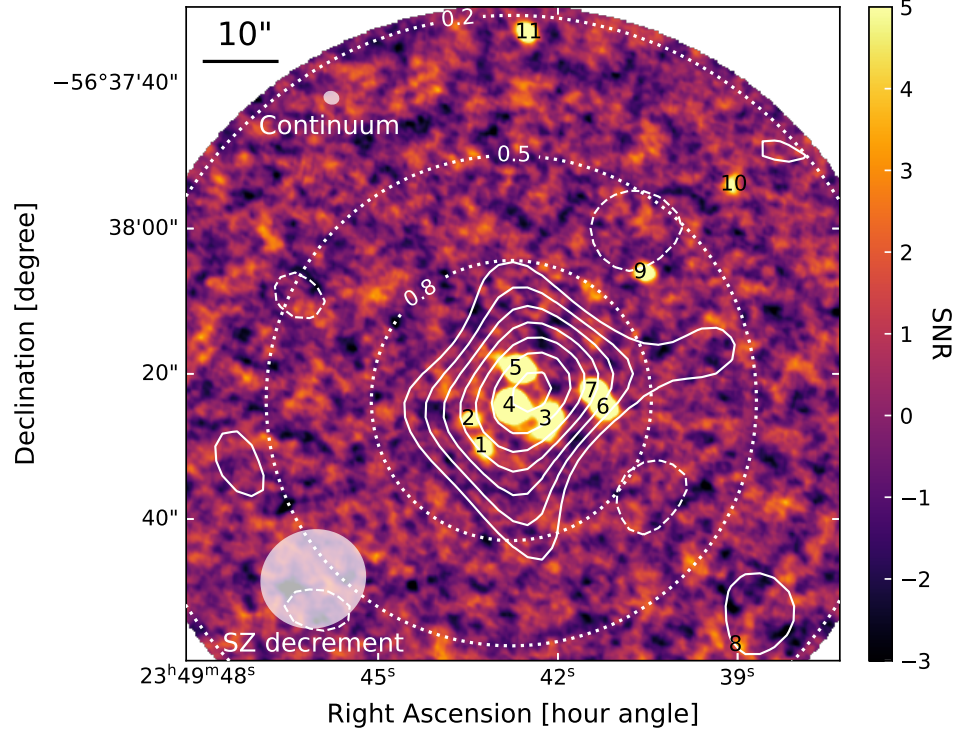
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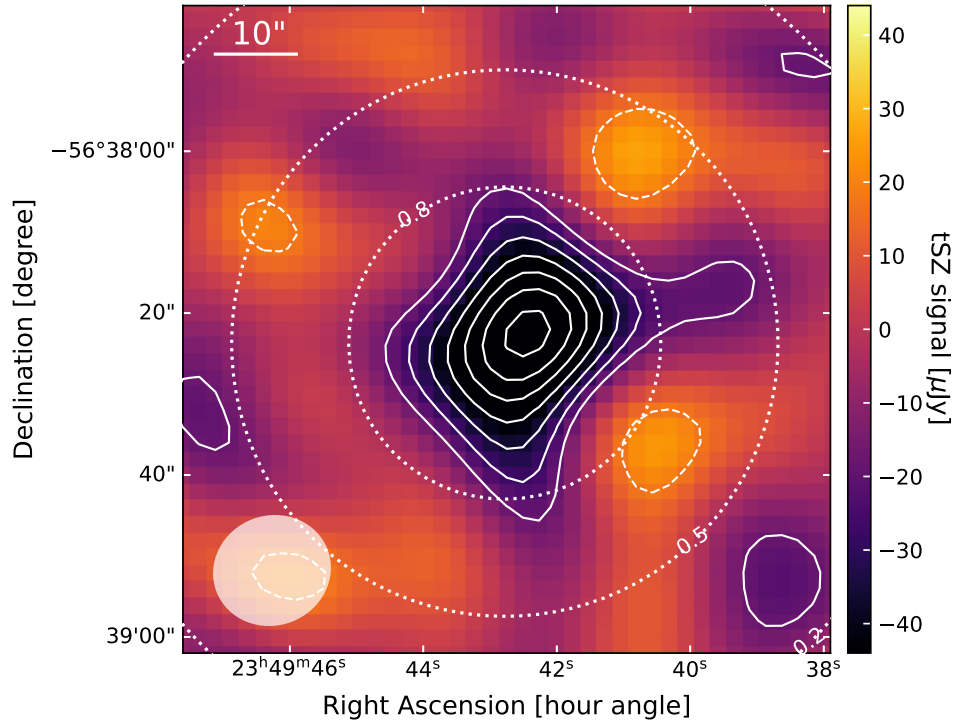
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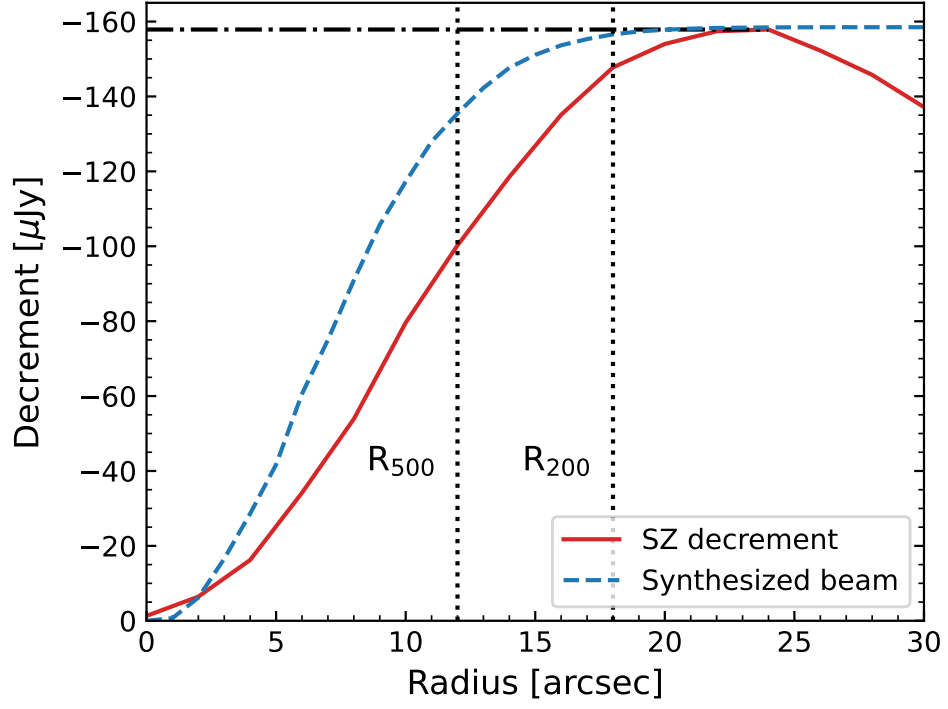
Extended Data Fig. 1 RGB image of the protocluster core. The zoomed-in version of Fig. 1. The positions of submillimeter-luminous protocluster galaxies are indicated by their alphabetical names based on their rank-ordered $850\ \mu\text{m}$ flux densities in Ref.[8]. Three radio-loud AGN (A, C, and E) are highlighted with their names in red. Due to the crowdedness of the protocluster core, labels of faint members with a negligible 3 mm flux density are hidden in this figure for clarity.



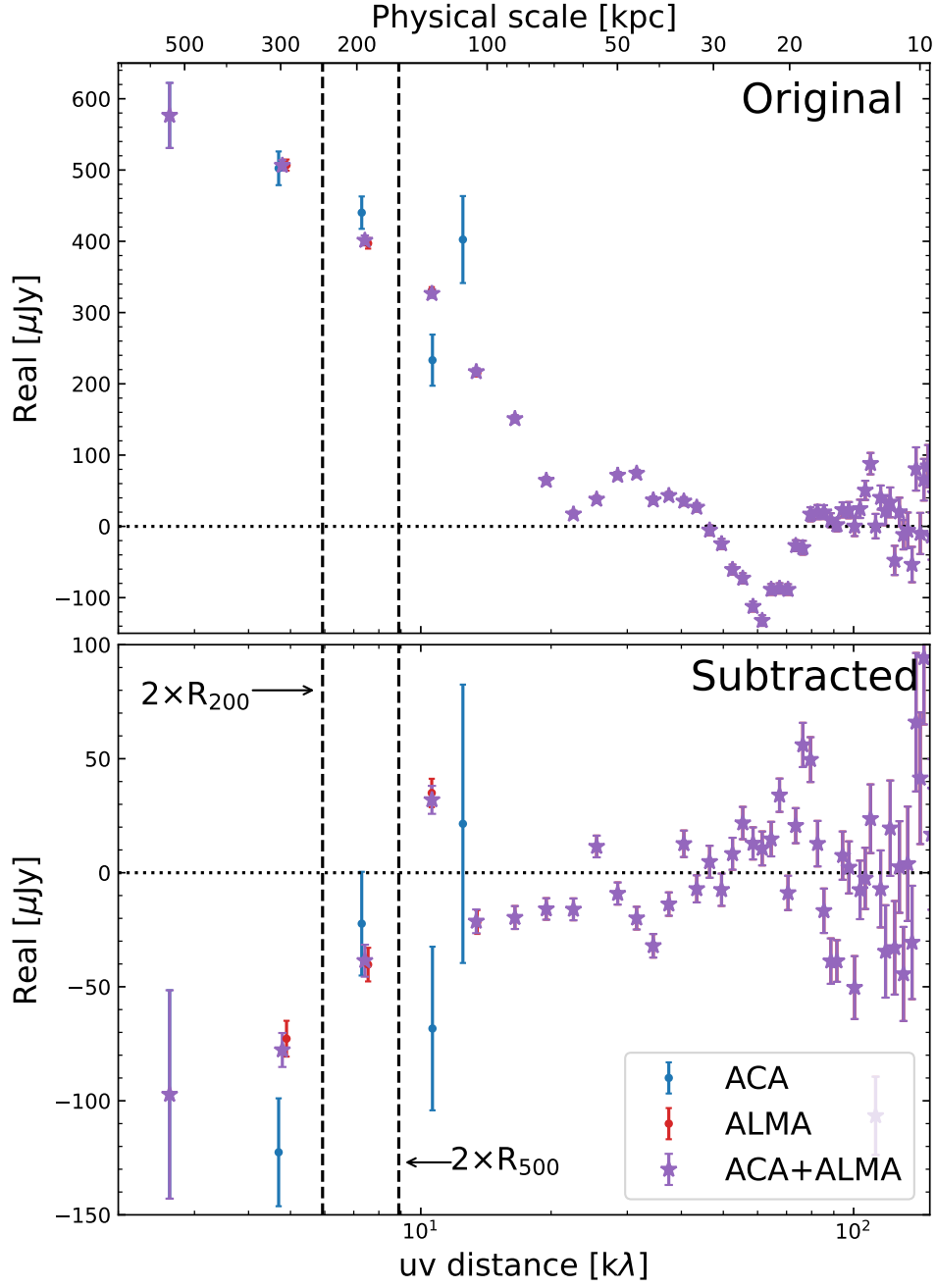
Extended Data Fig. 2 ALMA high-resolution continuum map with the tSZ contours. The solid contours are tSZ signal from -2σ to -8σ with steps of -1σ . The dashed contours indicate regions with values above 2σ . The number labels on sources are IDs from the continuum source catalog in Extended Data Table 1. The primary beam responses are indicated as dotted lines. The synthesized beams of the continuum image ('ALMA high-res') and the SZ decrement ('SZ') are indicated in the upper left and the bottom-left corners, respectively.



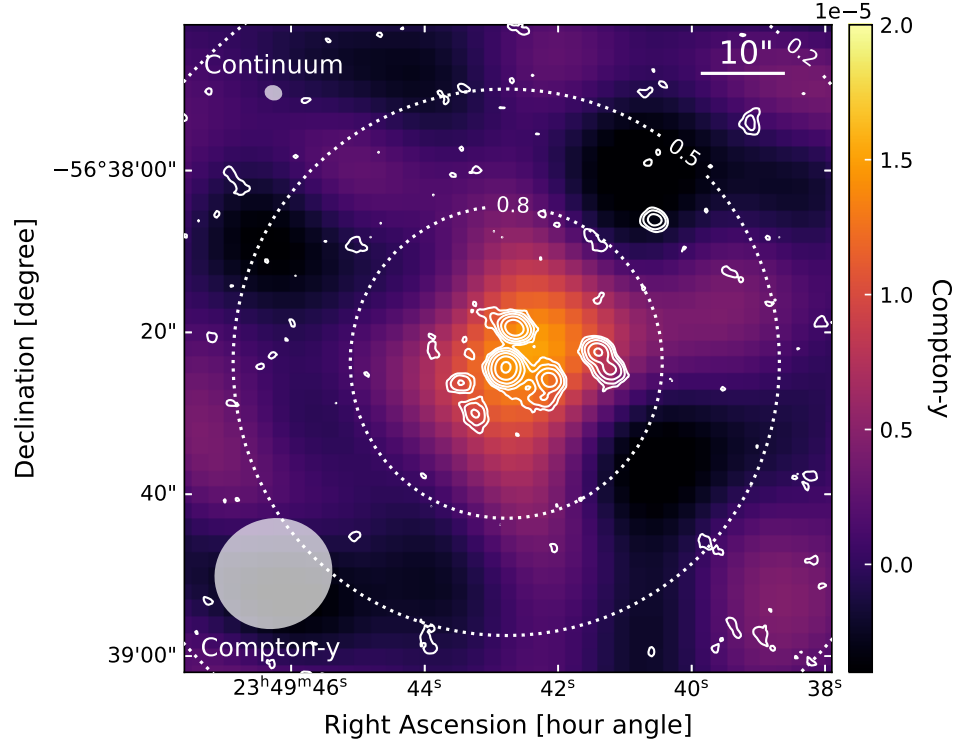
Extended Data Fig. 3 ALMA low-resolution tSZ map. The solid contours are tSZ signal from -2σ to -8σ with steps of -1σ . The dashed contours indicate regions with values above 2σ . The primary beam responses are indicated as dotted lines. The synthesized beams of the SZ decrement is indicated in the bottom-left corners, respectively.



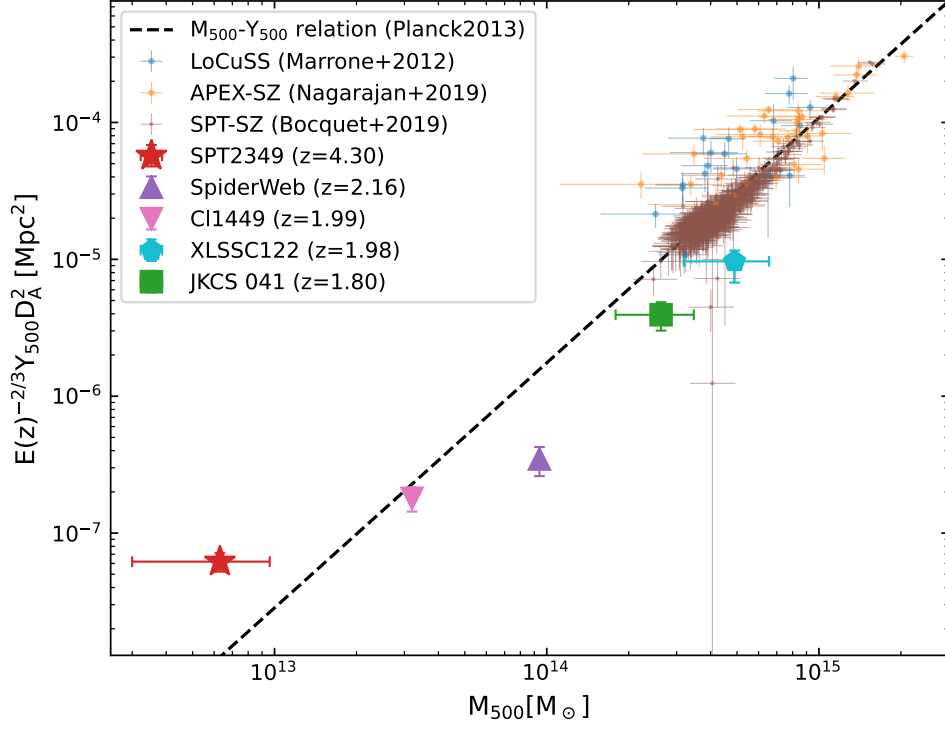
Extended Data Fig. 4 Curve-of-growth analysis for the tSZ decrement. The flux density of the tSZ decrement and the flux-scaled synthesized beam of the ‘SZ’ map are indicated as the red solid and the blue dashed line, respectively. The overdensity radii are also shown as black dotted lines. The decrement turnaround at radii $\gtrsim 25''$ may indicate potential dirty-beam sidelobes from imperfect CLEANing process.



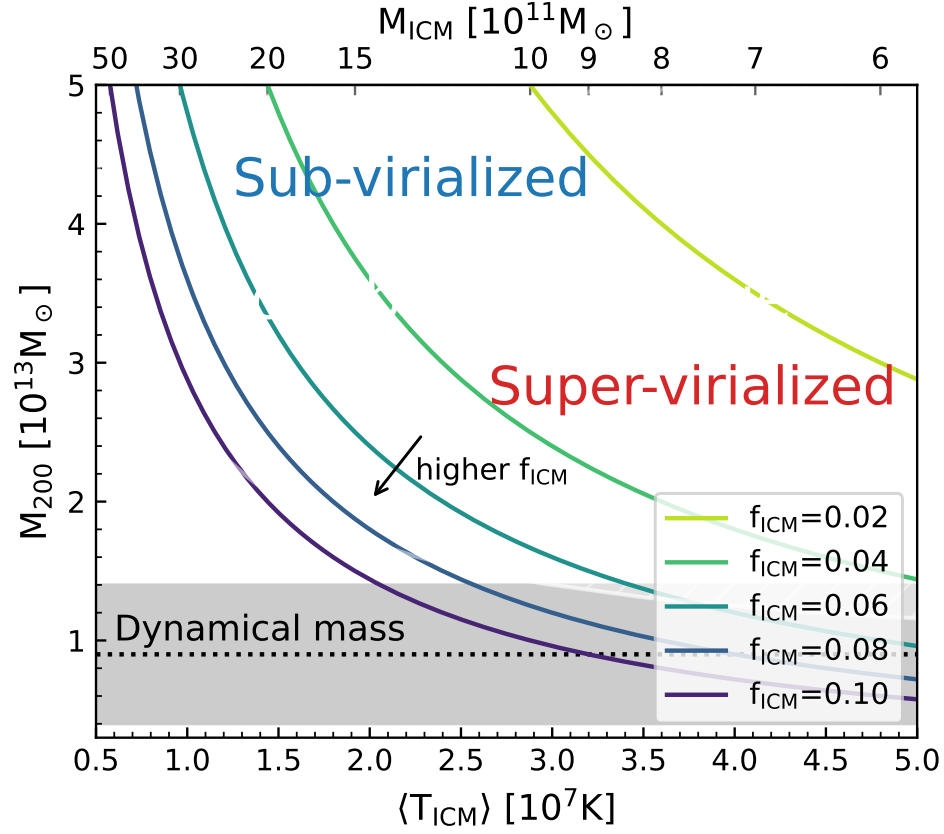
Extended Data Fig. 5 uv profile of the original and continuum subtracted data. The real part of the averaged amplitude measured from the continuum-subtracted measurement sets as a function of uv -distance with uv bins of $3k\lambda$. The errorbars are derived from visibility weightings. The negative signal becomes stronger at a shorter uv distance, suggesting that the tSZ decrement can be limited by the uv -coverage of the ACA and ALMA observations.



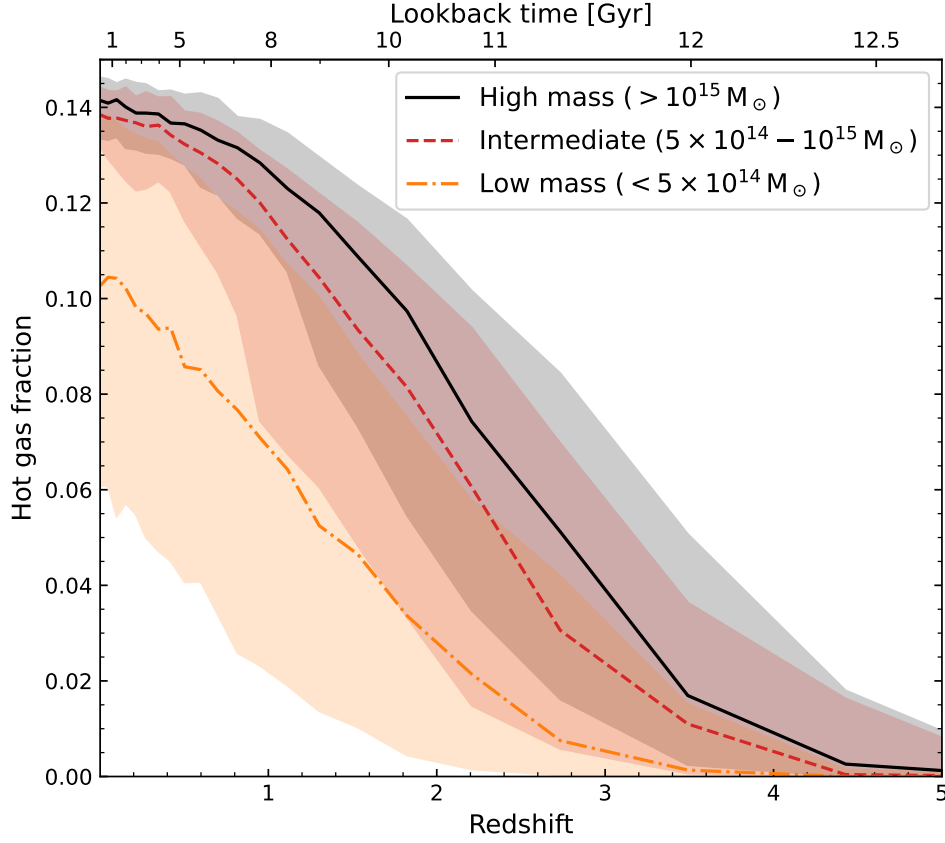
Extended Data Fig. 6 Compton- y map with dust continuum contours. The solid contours are 3 mm continuum emission drawn at $[2.5\sigma, 5\sigma, 10\sigma, 20\sigma, 40\sigma, 80\sigma]$ from the ‘ALMA high-res’ map. The primary beam responses are indicated at dotted lines. The synthesized beams of 3 mm continuum and Compton- y map are indicated in the upper-left and the bottom-left corners.



Extended Data Fig. 7 TSZ signal Y_{500} as a function of halo mass M_{500} within R_{500} . The halo masses M_{500} and Compton- Y Y_{500} are same as in Fig. 2. The self-similar redshift evolution have been taken into account by including a factor of $E(z)^{-2/3}$. The dashed line shows the universal $M_{500} - Y_{500}$ relation reported by Planck Collaboration et al. [24].



Extended Data Fig. 8 Halo mass as a function of ICM temperature. The corresponding ICM mass M_{ICM} is indicated in the top axis. The sub-virialized (blue) and super-virialized (red) regions are separated by the virialized temperature for different M_{200} . The dotted line indicates the dynamical mass of SPT2349–56 [15]. The lighter upper region is the possible M_{ICM} range allowed by the universal baryonic fraction $f_b = 0.155$. Without assuming an extreme ICM fraction f_{ICM} , either a more massive virialized halo or a super-virialized ICM gas is necessary to match the observed tSZ decrement.



Extended Data Fig. 9 Cosmic evolution of the hot gas ($> 10^7$ K) fraction in galaxy clusters. The fraction of hot ICM ($M_{\text{hot ICM},500}/M_{500}$) within r_{500} as a function of redshift obtained from the TNG-Cluster simulation. Based on the total mass M_{200} at $z = 0$, the clusters are placed in three mass bins, high mass ($M_{200} > 10^{15} M_{\odot}$, black solid line), intermediate mass ($5 \times 10^{14} M_{\odot} < M_{200} < 10^{15} M_{\odot}$, red dashed line), and low mass ($M_{200} < 5 \times 10^{14} M_{\odot}$, orange dash-dotted line). The corresponding shaded regions represent the values between the 16th and 84th percentiles in individual mass bins.

Extended Data Table 1 3-mm continuum source catalog.

ID	R.A. hh:mm:ss	Dec. dd:mm:ss	Distance arcsec	S/N	PB	S _{peak} ¹ μJy	S _{kron} ² μJy	S _{best} ³ μJy	Name ⁴
Distance < 15'' (ALMA high-res)									
1	23:49:43.24	-56:38:30.06	9.0	10.7	0.96	23±2	35±6	35±6	J
2	23:49:43.46	-56:38:26.29	7.2	10.1	0.97	22±2	27±5	27±5	H
3	23:49:42.17	-56:38:26.35	6.5	30.8	0.98	66±2	106±6	106±6	F,I,L
4	23:49:42.78	-56:38:24.49	2.5	89.4	1.00	186±2	286±5	286±5	B,C,G
5	23:49:42.67	-56:38:19.37	2.7	75.2	0.99	158±2	185±5	185±5	A, K
6	23:49:41.21	-56:38:24.73	13.0	25.6	0.90	59±2	64±5	64±5	E
7	23:49:41.41	-56:38:22.49	11.1	44.4	0.92	100±2	107±4	107±4	D
Total									
ALMA high-res	...	...	...	...	...	614±6	809±14	809±14	
ALMA low-res	23:49:42.36	-56:38:23.79	3.4	45.0	1.00	502±11	678±29	678±29	
ACA	23:49:42.40	-56:38:24.16	3.2	21.8	1.00	515±24	621±40	621±40	
Distance > 15'' (ALMA high-res)									
8	23:49:38.97	-56:38:57.41	47.2	4.1	0.21	41±10	59±18	59±18	...
9	23:49:40.56	-56:38:06.10	24.1	14.7	0.65	47±3	40±5	47±3	NL1
10	23:49:39.11	-56:37:54.02	41.0	6.6	0.28	49±7	67±18	67±18	...
11	23:49:42.54	-56:37:33.07	49.0	14.0	0.15	197±14	210±23	210±23	N1
Decrement (SZ)	23:49:42.53	-56:38:23.55	2.0	8.4	1.00	-74±9	...	-160 ± 20	

¹Peak flux density of the `photutils` measurement with the primary beam correction.

²Integrated flux density within the kron aperture of the `photutils` measurement with the primary beam correction.

³Best estimate of the source flux density depending on whether the source is resolved in the measurement image.

⁴Names of the corresponding protocluster members (see Extended Data Fig. 1).

Extended Data legends

Extended Data Fig. 1 RGB image of the protocluster core. The zoomed-in version of Fig. 1. The positions of submillimeter-luminous protocluster galaxies are indicated by their alphabetical names based on their rank-ordered $850\ \mu\text{m}$ flux densities in Ref. [8]. Three radio-loud AGN (A, C, and E) are highlighted with their names in red. Due to the crowdedness of the protocluster core, labels of faint members with a negligible 3 mm flux density are hidden in this figure for clarity.

Extended Data Fig. 2 ALMA high-resolution continuum map with the tSZ contours. The solid contours are tSZ signal from -2σ to -8σ with steps of -1σ . The dashed contours indicate regions with values above 2σ . The number labels on sources are IDs from the continuum source catalog in Extended Data Table 1. The primary beam responses are indicated as dotted lines. The synthesized beams of the continuum image (‘ALMA high-res’) and the SZ decrement (‘SZ’) are indicated in the upper left and the bottom-left corners, respectively.

Extended Data Fig. 3 ALMA low-resolution tSZ map. The solid contours are tSZ signal from -2σ to -8σ with steps of -1σ . The dashed contours indicate regions with values above 2σ . The primary beam responses are indicated as dotted lines. The synthesized beams of the SZ decrement is indicated in the bottom-left corners, respectively.

Extended Data Fig. 4 Curve-of-growth analysis for the tSZ decrement. The flux density of the tSZ decrement and the flux-scaled synthesized beam of the ‘SZ’ map are indicated as the red solid and the blue dashed line, respectively. The overdensity radii are also shown as black dotted lines. The decrement turnaround at radii $\gtrsim 25''$ may indicate potential dirty-beam sidelobes from imperfect CLEANing process.

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