Thermal Energy Census with the Sunyaev–Zel’dovich Effect of DESI Galaxy Clusters/Groups and Its Implication on the Weak-lensing Power Spectrum

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Abstract

We carry out a thermal energy census of hot baryons at $z < 1$, by cross correlating the Planck Modified Internal Linear Combination Algorithm (MILCA) $y$ map with 0.8 million clusters/groups selected from the Yang et al. catalog. The thermal Sunyaev–Zel’dovich effect around these clusters/groups is reliably obtained, which enables us to make our model constraints based on one-halo (1h) and two-halo (2h) contributions, respectively. (1) The total measurement signal-to-noise (S/N) of the one-halo term is 63. We constrain the $Y-M$ relation over the halo mass range of $10^{13} - 10^{15} M_\odot h^{-1}$, and find $Y \propto M^{\alpha}$ with $\alpha = 1.8$ at $z = 0.14$ ($\alpha = 2.1$ at $z = 0.75$). The total thermal energy of gas bound to clusters/groups increases from 0.1 meV cm$^{-3}$ at $z = 0.14$ to 0.22 meV cm$^{-3}$ at $z = 0.75$. (2) The 2h term is used to constrain the bias-weighted electron pressure $\langle b, P_e \rangle$. We find that $\langle b, P_e \rangle$ (in units of meV cm$^{-3}$) increases from 0.24 ± 0.02 at $z = 0.14$ to 0.45 ± 0.02 at $z = 0.75$. These results lead to several implications. (i) The hot gas fraction $f_{\text{gas}}$ in clusters/groups monotonically increase with the halo mass, where $f_{\text{gas}}$ of a $10^{14} M_\odot h^{-1}$ halo is ~50% (25%) of the cosmic mean at $z = 0.14 (0.75)$. (ii) By comparing the 1h and 2h terms, we obtain a tentative constraint on the thermal energy of unbound gas. (iii) The above results lead to significant suppression of the matter and weak-lensing power spectrum at small scales. These implications are important for astrophysics and cosmology, and we will further investigate them with improved data and gas modeling.

Unified Astronomy Thesaurus concepts: Large-scale structure of the universe (902); Cosmology (343); Sunyaev-Zeldovich effect (1654)

1. Introduction

Hot, free electrons in the late universe scatter cosmic microwave background (CMB) photons through inverse Compton scattering and generate the secondary CMB anisotropies. This is the famous thermal Sunyaev–Zel’dovich (tSZ) effect (Sunyaev & Zeldovich 1972; Carlstrom et al. 2002; Kitayama 2014). It induces a temperature fluctuation $\Delta T_{\text{tSZ}}$ with a characteristic spectral dependence $(g(x))$ and amplitude described by the Compton $y$ parameter:

$$\frac{\Delta T_{\text{tSZ}}}{T_{\text{CMB}}} = g(x) y, \quad y = \frac{\sigma_T}{m_e c^2} \int n_e k_B T_{\text{CMB}} d\chi,$$

(1)

where $g(x) = x \coth(x/2) - 4$ and $x \equiv h\nu/k_B T_{\text{CMB}}$.

The tSZ effect contains important information regarding the astrophysics of clusters/groups and cosmology. In the first, the tSZ effect is a direct probe of the cluster pressure profile (Ruppin et al. 2018; Ma et al. 2021; Pandey et al. 2022), baryon abundance (Hernández-Monteagudo et al. 2006; Lim et al. 2018), and distribution (Le Brun et al. 2015; Ma et al. 2015; Amodeo et al. 2021; Kim et al. 2022; Meinke et al. 2021; Kim et al. 2022). Even the baryons in filaments can be inferred by stacking the tSZ maps of cluster pairs (Muñoz & Loeb 2018; de Graaff et al. 2019; Tanimura et al. 2019; Gouin et al. 2022). Also, it can shed light on constraining the strength of supernova and active galactic nuclei (AGN) feedback (Hojjati et al. 2017; Spacek et al. 2018; Tröster et al. 2021; Gatti et al. 2022; Chen et al. 2023). In addition, the cross correlation of the tSZ effect with the galaxy distribution (Zhang & Pen 2001; Hill et al. 2018; Pandey et al. 2020) or a weak-lensing survey (Shao et al. 2011; Hojjati et al. 2015; Gatti et al. 2022; Pandey et al. 2022) can greatly increase the measurement significance of the tSZ effect. This kind of cross correlation has enabled the measurement of the mean bias-weighted pressure $\langle b, P_e \rangle$ as a function of the redshift (Van Waerbeke et al. 2014; Vikram et al. 2017; Chiang et al. 2020; Koukoufilippas et al. 2020; Yan et al. 2021). Furthermore, the tSZ effect can also be used to constrain cosmological parameters such as $\sigma_8$ (Komatsu & Seljak 2002; Zhang et al. 2002; Horowitz & Seljak 2017; Osato et al. 2020), the dark energy properties (Bolliet et al. 2018), and the evolution of $T_{\text{CMB}}$ (Hurier et al. 2014).

Direct measurement of the cluster tSZ effect by Planck, Atacama Cosmology Telescope (ACT), and South Pole Telescope (SPT) is limited to clusters with masses $\gtrsim 2 \times 10^{14} M_\odot h^{-1}$ (Planck Collaboration et al. 2014a; Marriage et al. 2011; Hasselfield et al. 2013; Reichardt et al. 2013; Bleem et al. 2015; Brodwin et al. 2015). As a noticeable fraction of thermal energy comes from less massive clusters/groups, the above measurements are incapable of carrying out a complete thermal energy census of clusters/groups. On the other hand, the cross correlation measurement with galaxies only measures $\langle b, P_e \rangle$ and lacks detailed information on the thermal energy distribution. The recently released group catalog (Yang et al. 2021) provides us with a good opportunity to constrain both the thermal energy and $\langle b, P_e \rangle$ as a function of the halo mass down to $10^{13} M_\odot h^{-1}$.
Based on observations obtained with Planck to $10^{13} M_\odot h^{-1}$. This group catalog contains about a million clusters/groups robustly identified (with richness $\geq 5$) in the $z < 1$ universe. This data set is not only large in cluster number but also has reasonable completeness and redshift/mass estimation. It has enabled us to measure the CMB lensing with $S/N \approx 40$ (Sun et al. 2022), and the kinematic Sunyaev–Zel’dovich (kSZ) effect with $S/N \approx 5$ (Chen et al. 2022b).

Given that cluster/group tSZ effect is significantly stronger than the KSZ effect, we expect high $S/N$ in the tSZ measurement. This measurement will provide valuable information on the thermal energy distribution in the universe and shed light on important astrophysics such as feedback. It can also put a useful constraint on the baryonic effect on weak-lensing cosmology.

This paper is organized as follows. We first introduce the data in Section 2 and then present the method of measuring the tSZ effect in Section 3. The results are shown and analyzed in Section 4. We show the implications of this measurement in Section 5 and finally present our conclusions and discussions in Section 6. We also include an appendix to explain further details and tests. We adopt a flat cosmology with parameters: $h = 0.676$, $\Omega_{dm} h^2 = 0.119$, $\Omega_b h^2 = 0.022$, $\sigma_8 = 0.81$, and $n_s = 0.967$ (Planck Collaboration et al. 2020).

2. Data

2.1. Planck Compton Parameter Map

The Planck collaboration released the full-sky Compton parameter map ($\gamma$ map) of the tSZ effect constructed by two algorithms, Needlet Independent Linear Combination (NILC) and Modified Internal Linear Combination Algorithm (MILCA) (Planck Collaboration et al. 2016). These two methods are both based on the internal linear combination (ILC) method and the known spectrum of the CMB components. The difference is the method to calculate the optimal scale-independent and spatially varying linear weight. The performances of NILC and MILCA do not show distinguishable differences in many studies (Vikram et al. 2017; Koukoufilippas et al. 2020). Besides, a higher noise level is shown in the large-scale NILC map. Therefore, we choose to utilize the MILCA map to measure the $\gamma$ profile of clusters. This map has a circular Gaussian beam of $10''$ and nside $= 2048$ for healpix pixelization resolution (Planck Collaboration et al. 2016).

To reduce the contamination from residual Galactic foregrounds, we apply a combination of Planck Galactic mask with a 40% sky coverage and a point-source mask from the foreground masks used for the Compton parameter analysis provided by Planck.

2.2. DESI Group Catalog

In this work, we use the DESI group catalog obtained by Yang et al. (2021; Y21) from data release 9 (DR9) of the DESI Legacy Imaging survey. This group catalog was constructed using an extended version of the halo-based group finder developed by Yang et al. (2005, 2007), which can simultaneously use photometric or spectroscopic redshifts for galaxies. The biggest advantage of this catalog for our concern is that the global completeness and overall purity of the detected groups is high. The completeness and purity of clusters with masses larger than $10^{14} M_\odot h^{-1}$ are close to one, and the completeness of groups with masses $> 10^{12}$ is from 70% to 80%. It is well-known that most of the thermal energy of the universe resides in these massive clusters. The tSZ effect, which is proportional to the thermal energy of baryons, can be detected with high measurement significance with this catalog, and the large sample size also enables the detection of a thermal contribution from small halos. In addition, this catalog provides a reliable estimation of the cluster redshift and mass. The redshift accuracy for groups with more than 10 members is about 0.008. The dark-matter (DM) halos by definition have overdensities 180 times larger than the mean universe background density. The uncertainty in the halo mass is about 0.2 dex for massive clusters ($> 10^{13.2} M_\odot h^{-1}$) and about 0.40 dex at the low-mass end ($\sim 10^{12} M_\odot h^{-1}$).

When measuring the tSZ effect in this work, we only use clusters with at least five members. Because there are relatively large uncertainties in the mass and redshift estimation for clusters with $N_e < 5$. These uncertainties would bias the measurement in an unexpected way. In addition, clusters with small richness are usually small-mass halos or have a higher probability to be misidentified. Moreover, as we have tested, including them in our measurements would not improve the $S/N$ significantly.

To investigate how the tSZ effect may depend on the cluster mass and redshift, we divide the cluster sample into several redshift and mass bins. First, we separate clusters/groups in our sample into four redshift bins: $0.0 \leq z < 0.2$, $0.2 \leq z < 0.4$, $0.4 \leq z < 0.6$, and $0.6 \leq z < 1$. Then, the binning for the cluster mass is applied so that we can obtain reliable tSZ effect measurements. In total we have 39 cluster/group subsamples for our subsequent study. The details of selecting the clusters/groups in different redshift and halo–mass bins, as well as their numbers, are outlined in the first three columns of Table 1.

3. Method

To obtain a high significance measurement of the tSZ effect, the secondary anisotropy of CMB, we stack the Planck MILCA $\gamma$ map at the position of galaxy clusters. From DESI group catalog DR9, we can obtain the coordinates, i.e., the R.A., decl., and redshift, of clusters. Then the tSZ plane surrounding each cluster would be cut from the MILCA $\gamma$ map with the flat approximation. The length of the plane is set to be $160''$ and divided into $101 \times 101$ grids. The cluster is positioned at the center (origin point) of the plane. The value of a grid point is set to be the value of the pixel in which it is located. Here, we assume the $\gamma$ profile of a cluster is circular symmetric. So the directions of the $x$- and $y$-axes on the stacking plane can be chosen randomly. Finally, the stacked $\gamma$ profile around clusters is

$$\hat{\gamma} (\theta) = \frac{\sum_j w_j y_j (\theta)}{\sum_j w_j},$$

where $j$ represents the $j$th cluster in a sample, and the length of $\theta$ belongs to the $i$th $\theta$ bin. To avoid contamination from the Galactic foreground, we adopt the combination of a 40% Galactic mask and a point-source mask both provided by Planck. The pixel within the masked region has weight $w_j = 0$; otherwise $w_j = 1$. 

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* Based on observations obtained with Planck (http://www.esa.int/Planck), an ESA science mission with instruments and contributions directly funded by ESA Member States, NASA, and Canada.
The stacked y profile $\hat{y}(\theta)$ is the combination of the 1h term, 2h term, and background term coming from residual CMB or other components. Below, we present how we obtain the template of the 1h and 2h terms and how to fit the coefficient of each term.

### 3.1. 1h-term Profile

To model the 1h term of the y profile, we adopt the Komatsu–Seljak (KS) gas density and temperature profiles (Komatsu & Seljak 2001) as the baseline. Note that here we only keep the shapes of the pressure profile fixed as the KS prediction, but treat its amplitude as a free parameter. This parameter is a major indicator of the cluster gas fraction and intracluster gasphysics. Gasphysics may also alter the halo concentration and therefore change the pressure profile. As the Planck angular resolution does not allow us to put a useful constraint on its variation, we will only discuss its impact in Appendix B.

The KS profile assumes that the gas is in hydrostatic equilibrium and the gas density profile tracks the DM profiles in the outer region of a halo. Here, we follow the simplified version in Martizzi et al. (2013) and Mead et al. (2020) with a fixed polytropic index $\Gamma$. The model is briefly described below.
The density profile of gravitationally bound gas is

\[ \rho_{\text{gas}}(M, r) \propto \left( \ln \left( 1 + \frac{r}{r_s} \right) \right)^{\Gamma - 1} \frac{1}{r_s}, \]

where \( \Gamma = 1.17 \), and \( r_s = \frac{c}{r_v} \) is the ratio of the virial radius to the concentration. The concentration–mass relation is

\[ c(M) = 7.85 \left( \frac{\frac{M}{2 \times 10^{12} h^{-1} M_\odot}}{1 + z} \right)^{-0.081} \]

(Duffy et al. 2008). Further analysis may adopt a more accurate \( c-M \) relation such as that of Zhao et al. (2009), in particular at higher redshift. The normalization of the above profile is

\[ f_{\text{gas}}(M)M = \int_0^r 4\pi r^2 \rho_{\text{gas}}(M, r) dr. \]

It is expected that \( f_{\text{gas}} = \Omega_b/\Omega_m \) for sufficiently massive clusters, while feedback will reduce its value. This \( f_{\text{gas}} \) (equivalently the \( A_1 \) fitting parameter, which will be introduced later) is a major parameter that our measurement will constrain.

The temperature profile is fixed by the hydrostatic equilibrium

\[ T_e(M, r) = T_0(M) \frac{1}{r} \left( 1 + \frac{r}{r_s} \right)^{\frac{\Gamma - 1}{1 + \frac{r}{r_s}}}, \]

where \( T_0(M) \) is the virial temperature

\[ \frac{3}{2} k_B T_0(M) = \frac{6 \pi m_p \mu_p}{a e} \frac{G M}{r}. \]

\( m_p \) is the proton mass, \( \mu_p \) is the mean gas particle mass divided by the proton mass, \( r_v \) is the comoving virial radius, and \( a \) is the scale factor. The electron pressure is the product of the density and temperature profile

\[ P_e(M, r) = \frac{\rho_{\text{gas}}(M, r)}{m_p \mu_e} k_B T_e(M, r), \]

where \( \mu_e = 1.17 \) is the mean gas particle mass divided by the proton mass. The 1h-term y profile is the integration of \( P_e(M, r) \) along the line of sight

\[ y(\theta) = \frac{\sigma_T}{m_e c^2} \int \frac{d\chi}{1 + z} P_e(\theta|\chi). \]

The beam size of Planck has also been taken into account and approximated using a Gaussian function \( W(l) = \exp(-l^2/2) \). For the Planck MILCA map, \( \sigma_\text{beam} = \text{FWHM}/2\sqrt{2 \ln 2} = 4' 25 \). Therefore, the final 1h-term profile is

\[ y_1(\theta) = \int \frac{dl}{2\pi} J_0(\theta l) y(l) W(l). \]

\( y(l) \) is the Hankel transformation of \( y(\theta) \)

\[ y(l) = 2 \pi \int J_0(\theta l) y(\theta) d\theta d\theta. \]

In addition, the mis-centering effect in cluster determination causes a similar effect as the beam. So we replace \( \sigma_\text{beam} \) as \( \sigma_\text{eff} = \sqrt{\sigma_\text{beam}^2 + \sigma_\text{mc}^2} \) to take mis-centering into account

\[ \sigma_\text{mc} = \eta_\text{mc} \frac{r_v}{d_c}. \]

where \( r_v \) and \( d_c \) are the virial radius and comoving distance of a cluster, respectively. The default value of \( \eta_\text{mc} \) is set to 0.2. We will discuss how this parameter would influence the results in Appendix C.

### 3.2. 2h-term Profile

The 2h term would also contribute to the stacked y profile \( y(\theta) \). Its profile is

\[ \int B_\xi_{\rho} \frac{\sigma_T \sigma_{\text{ad}}}{m_e c^2} \int \xi_{\rho m}(\theta, r) J_0(r) d\theta dw. \]

Here, we assume that at large scales the gas distribution follows that of DM. The integration of the correlation function is

\[ \int \xi_{\rho m}(r_\perp, r) J_0(r) d\theta \]

\[ = b_\rho \int P_m(k_\perp z) e^{ik_\perp r_{\perp}} \frac{k_{\perp} dk_{\perp}}{(2\pi)^2}, \]

where \( b_\rho \) is the bias of the clusters/groups in consideration, and \( P_m(k, z) \) is the matter power spectrum at redshift \( z \). We estimate \( b_\rho \) from the cluster mass distribution and the bias–mass relation (Sheth et al. 2001). As

\[ \int_0^{2\pi} e^{ik_\perp r_{\perp}} = 2\pi J_0(k_\perp r_{\perp}), \]

the template of 2h-term profile is

\[ y_2(\theta) = b_\rho \int P_m(k_\perp z) e^{-\frac{i^2 k_{\perp} r_{\perp}}{2}} J_0(k_\perp r_{\perp}) \frac{k_{\perp} dk_{\perp}}{2\pi}. \]

Here, we consider the smoothing effect from the beam size of the CMB survey.

### 3.3. Fitting

We assume that the measured stacking tSZ profile contains three components, and the theoretical model is

\[ y^{\text{th}}(\theta) = A_1 y_1(\theta) + A_2 y_2(\theta) + A_3 y_3(\theta), \]

\( A_1 \) is the coefficient of the 1h-term profile within our methodology. Its physical meaning is the ratio of the fraction of gas in a cluster and the mean fraction of baryon in the universe.

\[ A_1 = \frac{f_{\text{gas}}}{\Omega_b/\Omega_m}. \]

This free parameter captures how much baryon matter is blown away by feedback processes. \( A_2 \) is the coefficient of the 2h term

\[ A_2 = \langle b_\rho P_m \rangle. \]

In addition, \( y_3(\theta) = 1 \) represents a scale-independent background term, in order to consider the residuals of other CMB components that could contaminate the MILCA y map.

From Equations (10) and (16), the 1h-term template \( y_1(\theta) \) relies on the mass and redshift distribution of the stacked cluster sample, while the 2h-template \( y_2(\theta) \) only relies on the redshift distribution. It is worth noting that the mass estimated using the DESI group catalog DR9 is higher than the true value.
and the uncertainty is about 0.2–0.4 dex from the high-mass to the low-mass end (as shown in Figure 9 in Yang et al. (2021)). In Appendix A, we discuss how to obtain an unbiased 1h-term estimation.

To obtain the best-fit value of $A_1$, $A_2$, and $A_3$, we minimize the likelihood

$$L \propto \exp\left(-\frac{1}{2} \chi^2\right),$$  \hspace{1cm} (20)

and

$$\chi^2 = \left[\hat{y}(\theta) - \hat{y}^{\text{th}}(\theta)\right]^T C^{-1} \left[\hat{y}(\theta) - \hat{y}^{\text{th}}(\theta)\right].$$  \hspace{1cm} (21)

$C$ is the covariance matrix. We estimate it by Jackknife resampling. The number of the Jackknife sample is set to $N_{\text{JK}} = 100$. The Fisher matrix for free parameters $A_1$, $A_2$, and $A_3$ is

$$\mathbf{F} = \begin{pmatrix} y_1^T C^{-1} y_1 & y_1^T C^{-1} y_2 & y_1^T C^{-1} y_3 \\ y_2^T C^{-1} y_1 & y_2^T C^{-1} y_2 & y_2^T C^{-1} y_3 \\ y_3^T C^{-1} y_1 & y_3^T C^{-1} y_2 & y_3^T C^{-1} y_3 \end{pmatrix},$$  \hspace{1cm} (22)

where

$$y_i = (y_i(\theta_1), y_i(\theta_2), \ldots, y_i(\theta_n))^T.$$  \hspace{1cm} (23)

is the template of the 1h, 2h, or background terms. The best-fitting values of $A_1$, $A_2$, and $A_3$ are the solution of equation

$$\mathbf{F} \begin{pmatrix} A_1 \\ A_2 \\ A_3 \end{pmatrix} = \begin{pmatrix} y_1 C^{-1} \hat{y} \\ y_2 C^{-1} \hat{y} \\ y_3 C^{-1} \hat{y} \end{pmatrix}. \hspace{1cm} (24)$$

The uncertainty in $A_i$ is

$$\sigma_i^2 = (F^{-1})_{ii}.$$  \hspace{1cm} (25)

The S/N of $A_i$ is defined as $A_i/\sigma_i$.

4. Analysis

We measure the stacked tSZ profile from the Planck MILCA map for our 39 DESI cluster/group subsamples. The stacked tSZ profiles as a function of the angular radius are shown in Figure 1. For brevity, we only show the results of $0.4 < z < 0.6$. The results of the other three redshift bins are similar. As expected, the stacked tSZ peaks at the center and decreases with increasing radius. The peak value drops nearly monotonically with decreasing cluster mass. It drops by a factor of 100 from the most massive cluster ($10^{15} M_{\odot} h^{-1}$) to small groups ($\sim 10^{13} M_{\odot} h^{-1}$).

Figure 2 shows the normalized covariance matrix for the most massive bin in $0.4 \leq z < 0.6$. The covariance of other bins is similar. There is large correlation between neighboring bins separated by $\lesssim 5''$. This may be caused by the beam and miscentering effects, which mix the signal at different radius.
largely due to the Planck beam. Near data points are strongly correlated, and the real degree of freedom is larger than 1014.5. The most massive bins of 0.2 < z < 0.4, 0.4 < z < 0.6 are abandoned, and the reason is explained in Appendix A. Over the last decade, quite a lot of SZ-selected samples have been published by Planck (Planck Collaboration et al. 2014b, 2014a, 2015), ACT (Marriage et al. 2011; Hasselfield et al. 2013), SPT (Reichardt et al. 2013; Bleem et al. 2015), and other surveys (Brodwin et al. 2015). Our work probes the Y–M relation down to much lower masses ($10^{13} M_\odot h^{-1}$) than the above samples. In Planck Collaboration et al. (2014b), the Y–M relation can be described by the formula

$$E^{-3/2}(z) \left[ \frac{D_A^2 Y}{A \times 10^{-4} \text{Mpc}^2} \right] = \left( \frac{M}{10^{14} M_\odot h^{-1}} \right)^\alpha, \quad (27)$$

assuming the universe is flat, and $D_A$ is the angular distance.

We fit this formula with the measurements, and the results are shown as the solid lines in Figure 3. Under hydrostatic equilibrium, the slope is $\alpha = 5/3$. In our measurements, the slope $\alpha$ exceeds 1.8 in all redshift bins, indicating that less massive clusters possess less pressure than the hydrostatic equilibrium prediction. This can be explained by two possibilities. First, the baryon fraction is lower in less massive clusters, which is mainly affected by mass determination systematic errors, the redshift evolution is not evident among three other bins. Further measurements are necessary to verify the existence of this redshift evolution.

4.1.2. Thermal Energy Census of Bound Gas

The thermal energy of baryons, although tiny, is an important property of the universe (Zhang et al. 2004; Fukugita & Peebles 2004; Chiang et al. 2020). The tSZ effect is contributed by all thermal energy in the universe. It is known
that most thermal energy resides in the center of massive clusters, which is also observed in IllustrisTNG simulations (Gouin et al. 2022). Thanks to the high completeness of DESI group catalog DR9, which contains almost all massive clusters from \(z = 0\) to \(z = 1\), a census of thermal energy that is bound to halos in the universe can be conducted. The relation between the thermal gas pressure and the electron pressure measured by the tSZ effect is

\[
P_{\text{th}} = \frac{3 + 5X}{2} P_e,
\]

where \(X = 0.76\) is the primordial hydrogen abundance. The profile of \(P_e\) is from Equation (8) and \(f_{\text{gas}}(M)\) is obtained by 1h-term measurements (Section 5.1). With the assumption that baryons are fully ionized, \(P_{\text{th}} = 1.93P_e\), and the thermal energy is

\[
E_{\text{th}} = \frac{3}{2} P_{\text{th}}.
\]

Therefore the total thermal energy density bound to halos is

\[
E = \int \left( \int E_{\text{th}} dV \right) \frac{dn}{d\lg M} d\lg M.
\]

The inner integration represents the total thermal energy in a halo with mass \(M\). \(\frac{dn}{d\lg M}\) is obtained from the mass distribution of the Y21 catalog.

In Figure 4, the dashed lines show the contribution of thermal energy from clusters with different masses. Most of the thermal energy is coming from clusters with masses \(> 10^{13}\) \(M_{\odot}\). Half of the thermal energy is coming from clusters whose masses are above \(10^{14.43}, 10^{14.49}, 10^{14.39}\), and \(10^{14.14} M_{\odot} \, h^{-1}\) in the redshift bins \(0 < z < 0.2, 0.2 < z < 0.4, 0.4 < z < 0.6\), and \(0.6 < z < 1\), respectively. The peak tends to move to lower masses with increasing redshift. The solid lines in the figure show the accumulated thermal energy as a function of the cluster mass. A plateau is reached before \(M = 10^{12} M_{\odot} \, h^{-1}\) in all redshift bins, which means that the thermal energy in clusters/groups with masses smaller than \(10^{12} M_{\odot} \, h^{-1}\) can be ignored. In our measurement, the thermal energy bound to halos is \(0.105 \pm 0.003, 0.174 \pm 0.004, 0.201 \pm 0.007\), and \(0.214 \pm 0.017\) [meV cm\(^{-3}\)] in the redshift bins \(0 < z < 0.2, 0.2 < z < 0.4, 0.4 < z < 0.6\), and \(0.6 < z < 1\), respectively.

\[\langle bP_e \rangle \]

The coefficient of the 2h-term \(A_2\) describes the bias-weighted electron pressure \(\langle bP_e \rangle\). We show \(\langle bP_e \rangle\) for different masses and redshift bins in Figure 5. In the fitting we absorb the galaxy bias \(b_g\) in the 2h-term template and fix its value by a \(b_g-M\) relation model. The values of different mass bins in the same redshift bin are consistent with each other in the 1\(\sigma\) error bar. This reflects the validity of the \(b_g-M\) model. The \(\langle bP_e \rangle\) estimated from all mass bins is

\[
\langle bP_e \rangle = \sum_i \frac{\langle b_P_e \rangle_i}{\sigma_i^2} / \sum_i \frac{1}{\sigma_i^2},
\]

where \(i\) represents different mass bins in the same redshift bin. Its relationship with the redshift is an indicator of the cosmic thermal history.
The measured bias-weighted electron pressure as a function of the redshift is shown in Figure 6. \( \langle b_y P_e \rangle \) increases monotonically with increasing redshift. The redshift interval is \( \Delta z = 0.2 \) in our fiducial measurement. We find that \( \langle b_y P_e \rangle \) increases significantly with \( z \). Therefore we also try a smaller redshift bin size, \( \Delta z = 0.1 \). The uncertainty of each red point is \( \Delta z = 0.1 \), the validity of the \( 1 \) interpretation assumes that feedback would not change the temperature profile. This assumption is valid at the first order in which the temperature is fixed by the gravitational potential. At high order, this interpretation may be inaccurate.

The measured bias-weighted electron pressure as a function of the redshift is shown in Figure 6. \( \langle b_y P_e \rangle \) increases monotonically with increasing redshift. The redshift interval is \( \Delta z = 0.2 \) in our fiducial measurement. We find that \( \langle b_y P_e \rangle \) increases significantly with \( z \). Therefore we also try a smaller redshift bin size, \( \Delta z = 0.1 \). The uncertainty of each red point is

\[
\Delta z = 0.2, \text{this work} \quad \Delta z = 0.1, \text{this work} \quad \text{Yan, 2020} \quad \text{Chiang, 2020} \quad \text{Koukoufilippas, 2020}
\]

The blue and red points are our measurements with \( \Delta z = 0.2 \) and \( \Delta z = 0.1 \). The orange, cyan, and gray points are the measurements from Yan et al. (2021), Chiang et al. (2020), and Koukoufilippas et al. (2020), respectively. All these data points measured by different methods and data sets are consistent.

### Table 2

| Range of \( z \) | \( \bar{z}_{\text{mean}} \) | \( \langle b_y P_e \rangle \ [\text{meV cm}^{-3}] \) |
|-----------------|-----------------|------------------|
| \([0.0, 0.2)\)  | 0.14            | 0.244 \(\pm\) 0.025 |
| \([0.2, 0.4)\)  | 0.31            | 0.267 \(\pm\) 0.013 |
| \([0.4, 0.6)\)  | 0.49            | 0.327 \(\pm\) 0.015 |
| \([0.6, 1.0)\)  | 0.75            | 0.446 \(\pm\) 0.024 |
| \([0.1, 0.2)\)  | 0.15            | 0.200 \(\pm\) 0.024 |
| \([0.2, 0.3)\)  | 0.25            | 0.222 \(\pm\) 0.017 |
| \([0.3, 0.4)\)  | 0.35            | 0.301 \(\pm\) 0.017 |
| \([0.4, 0.5)\)  | 0.45            | 0.302 \(\pm\) 0.018 |
| \([0.5, 0.6)\)  | 0.55            | 0.395 \(\pm\) 0.027 |

The measured bias-weighted electron pressure as a function of the redshift is shown in Figure 6. \( \langle b_y P_e \rangle \) increases monotonically with increasing redshift. The redshift interval is \( \Delta z = 0.2 \) in our fiducial measurement. We find that \( \langle b_y P_e \rangle \) increases significantly with \( z \). Therefore we also try a smaller redshift bin size, \( \Delta z = 0.1 \). The uncertainty of each red point is larger than that of each blue point due to the decreasing number of clusters in a narrow redshift bin. Besides, the measurements of different redshift bin lengths are consistent with each other. The measurements of these redshift bins are summarized in Table 2.

We also show the comparison with other measurements in the literature. Yan et al. (2021) adopts galaxy–tSZ–CMB lensing cross correlation using Planck and Kilo-Degree Survey data (KiDS; Kuijken et al. 2019). Chiang et al. (2020) uses tomographic tSZ measurements from Planck and a spectroscopic galaxy sample from the Sloan Digital Sky Survey (SDSS). Koukoufilippas et al. (2020) uses the same method but a photometric redshift galaxy sample from the Wide-field Infrared Survey Explorer’s SuperCOSMOS public catalog (gray points). In Figure 6, these results from different methods and different data sets are consistent with each other.

### 4.3. Consistency of the 1h and 2h Terms

From the measurement of the 1h term, the electron pressure density profile \( P_e(r) \) of a halo with a given mass and redshift can be inferred. The TSZ 2h term (Section 4.2) measures the mean \( \langle b_y P_e \rangle \) as a function of the redshift. In this subsection, we check the consistency between the 1h- and 2h-term measurements. With the assumption of the halo model, the mean electron pressure that is bound to halos is

\[
\langle P_e \rangle_{\text{bound}} = \int \left( \int P_e dV \right) \frac{dn}{dM} dM,
\]

and

\[
b_y,\text{bound} = \frac{\int b_y \bar{\nabla} \frac{dn}{dM} dM}{\int b_y \frac{dn}{dM} dM}.
\]

We adopt the halo mass function and bias–mass relation from Sheth et al. (2001). Then we estimated the \( \langle b_y P_e \rangle_{\text{bound}} \) from the 1h-term measurement. The comparison with the measurement from the 2h term is shown in Figure 7. \( \langle b_y P_e \rangle \) measured by the 2h halo term is the sum of that of bound and unbound gas

\[
\langle b_y P_e \rangle = \langle b_y P_e \rangle_{\text{bound}} + \langle b_y P_e \rangle_{\text{unbound}}.
\]

Therefore,

\[
\langle b_y P_e \rangle > \langle b_y P_e \rangle_{\text{bound}}.
\]

Equation (36) is the consistency relation that we need to test with both 1h- and 2h-term measurements. Figure 7 shows that this relation is indeed satisfied at all four redshift bins. We will further discuss the difference between \( \langle b_y P_e \rangle \) and \( \langle b_y P_e \rangle_{\text{bound}} \) in Section 5.2.

### 5. Astrophysical and Cosmological Implications

#### 5.1. Baryon Abundance in Clusters

The baryon feedback, such as SNe and AGN, would heat blow the gas out of the halo. The potential suppression of a gas fraction is captured by parameter \( A_1 \). Given the \( A_1 \) measurement in Table 1, we obtain the relationship between \( A_1 \) and the cluster mass \( M_t \) at each redshift. We fit this relation against the
the parameters $\lg M_0$ and $\beta$ are the parameters to fit. In this parameterization, the gas fraction of a cluster with $M = M_0$ is 50% of the cosmic mean.

The fitting results are shown in Figure 8. We discard the two most massive bin of $0.2 < z < 0.4$ and $0.4 < z < 0.6$, because their mass distribution may be modeled inaccurately (Appendix A). The best-fitting values and uncertainties in $\lg M_0$ and $\beta$ are also shown in Figure 8.

The baryon abundance becomes lower as the halo mass decreases in each redshift bin. $M_0$ is $10^{14.12,14.73,14.69,14.93} \pm 0.6 M_h h^{-1}$ at the redshift bins $0 < z < 0.2$, $0.2 < z < 0.4$, $0.4 < z < 0.6$, and $0.6 < z < 1$, respectively. Correspondingly, $\beta = 0.20 \pm 0.14$, $0.47 \pm 0.08$, $0.60 \pm 0.09$, and $0.55 \pm 0.11$. These results imply a strong impact of the feedback on the cluster gas fraction. In addition, we find a slight evolution of the cluster baryon abundance with the redshift. The baryon abundance is higher in low redshift than high redshift in halos with the same mass. We will verify these findings in a future work with the help of hydrodynamical simulations.

In previous works, the halo baryon abundance is usually measured using X-ray observations. Sun et al. (2009) finds a average value $f_{\text{gas}} \sim 0.12$, and the slope of the $f_{\text{gas}} - M_{500}$ relation is $0.135 \pm 0.030$ with large scatter, using 43 nearby galaxy groups with $10^{13} < M_{500} < 10^{14} M_h h^{-1}$, $0.012 < z < 0.12$ based on Chandra archival data. With 49 low-redshift clusters provided by Chandra and ROSAT data, Vikhlinin et al. (2009) finds a linear relation of $f_{\text{gas}}$ and $\lg M_{500}$ with the mass range $M_{500} > 13.7 M_h h^{-1}$. In addition, Gonzalez et al. (2013) finds a $f_{\text{gas}} - M_{500}$ relation $f_{\text{gas}} \propto M_{500}^{0.20 \pm 0.03}$ for 12 galaxy groups/clusters at $z \sim 0.1$ with $10^{14} < M_{500} < 5 \times 10^{14} M_h h^{-1}$ observed by the XMM-Newton X-ray telescope. There is a distinguishable difference in the slope for cluster samples with different mass ranges. Utilizing all the above X-ray measurements, Schneider & Teyssier (2015) parameterize the $f_{\text{gas}} - M_{500}$ relation as Equation (37) with the best-fitting parameters $M_0 = 1.2 \times 10^{14} M_h h^{-1}$ and $\beta = 0.6$. $\beta = 0.6$ is different from our measurement of $\beta = 0.20 \pm 0.14$ in $0 \leq z < 0.2$. This may be caused by the poor description of the measurement by Equation (37) (left panel in Figure 8). Considering the large measurement uncertainty and different mass definition, however, these X-ray measurements are consistent with our results in the lowest redshift bin. Also, Lim et al. (2018) constrain the hot gas fraction using the tSZ effect with the combination of Planck and a group catalog given in Lim et al. (2017) at redshift $z < 0.2$. Although they only adopt low-redshift cluster samples, in the halo mass range $M_{500} > 10^{13.5} M_h h^{-1}$ they find a similar relation to ours.

Recently Chen et al. (2023) constrained the baryonic feedback combining the DES Year-3 small-scale cosmic shear measurement and the baryon correction model, in which the gas fraction has the same parameterization as in Equation (37) (Chen et al. 2023; Schneider & Teyssier 2015; Aricò et al. 2020). The work adopted $\beta = 0.321$, which agrees with our constraint at low redshift. It constrained $\log M_0 = 14.12^{+0.62}_{-0.37}$, which also agrees with our constraint.

In addition, we caution that the above obtained gas fraction in dark-matter halos, $f_{\text{gas}}$, depends on our model assumption of the hydrostatic equilibrium of the gas temperature (e.g., Equation (6)), and in general it can be regarded as the “hot” gas fraction. In case the gas temperature is much lower than the virial temperature of the dark-matter halo, $f_{\text{gas}}$ will be underestimated. Very interestingly, in a recent paper, using the kSZ effect around 40,000 low-redshift groups in the SDSS observation, Lim et al. (2020) claimed the detection of the “missing baryons”. The total kSZ flux within the halos estimated implies that the gas fraction in the halos is about the universal baryon fraction, even in low-mass halos with masses $\sim 10^{12.5} M_h h^{-1}$. It thus indicates that the gas temperature is indeed significantly lower than the halo virial temperature.

5.2. Pressure from Unbound Gas

When the gas is ejected from the halo, its fate is hard to measure and hard to model. The feedback process injects thermal or kinematic energy into the gas. It may lose energy when escaping from the gravitational wall of the halo or still stay hot. Some models treat this gas just as a diffuse background that only contributes to the 2h term. Other models assume that this gas would not be driven too far away from the halo but would reside around the halo, as the so-called circumgalactic medium (CGM) (Tumlinson et al. 2017). Due to the low density of this unbound gas, its measurement is very difficult. On the other hand, detecting such gas would learn valuable information on the feedback process.

As we have simultaneously measured both the total electron pressure $\langle b \cdot P_e \rangle$ from the 2-halo term and $\langle b \cdot P_e \rangle_{\text{bound}}$ of the gas bound to halos from the 1h term, we can directly infer the...
electron pressure contributed by the unbound gas.

\[
\langle b_y P_e \rangle_{\text{unbound}} = \langle b_y P_e \rangle_{\text{bound}}^{2h} - \langle b_y P_e \rangle_{\text{bound}}^{1h}. \tag{38}
\]

\[
\langle b_y P_e \rangle_{\text{bound}}^{2h} = \int \frac{\Omega_b/\Omega_{m} - f_{\text{gas}}}{f_{\text{gas}}} d \langle b_y P_e \rangle_{\text{bound}}^{1h} d \log M. \tag{39}
\]

In scenario 2, we assume that the unbound gas keeps its thermal energy, but it diffuses into a smooth background. Therefore \( b_y = 1 \). In this case,

\[
\langle b_y P_e \rangle_{\text{bound}}^{1h} = \int \frac{\Omega_b/\Omega_{m} - f_{\text{gas}}}{f_{\text{gas}}} d \langle b_y P_e \rangle_{\text{bound}}^{2h} d \log M. \tag{40}
\]

\( b_y P_e \) of these scenarios is summarized in the third and forth columns of Table 3. For \( z > 0.2 \), the predictions of both scenarios are larger than the measurement by a factor of \( \gtrsim 10 \). As in the scenario we have set \( b_y = 1 \) for unbound/ejected gas, it can be inferred that the temperature of the ejected gas would decrease largely when they escape the halo.\(^7\)

### 5.3. Suppression of Weak-lensing Power Spectrum

In this subsection, we show another cosmological implication of tSZ measurement. The probe, weak-lensing, is sensitive to the matter distribution and can constrain the parameters of cosmological models. The underlying matter power spectrum of a cosmology model is usually provided by dark-matter-only simulations with assuming baryon processes do not impact the large-scale structure formation. However, this assumption is no longer valid when \( k \) larger than \( \sim 1h/\text{Mpc} \). The next generation surveys would provide a one-percent-level constraint on weak-lensing measurements on these scales. Therefore, it is important to characterize the influence on the matter power spectrum caused by baryon processing.

\(^7\) The expectations are the low redshift bins of \( 0 \leq z < 0.2 \) and \( 0.1 \leq z < 0.2 \). As there are other potential problems of group identification and determination of group mass and redshifts, we postpone further investigation on their \( b_y P_e \) until the above problems are significantly improved.

Nowadays, a large set of hydrodynamic simulations are used to characterize the suppression of the matter power spectrum caused by baryons and its feedback effects (Sembolini et al. 2011; Chiari et al. 2018; Schneider et al. 2019; Debackere et al. 2020). Harnois-Déras et al. (2015) construct an analytic fitting formula that describes the effect of the baryons on the mass power spectrum based on three scenarios of the OWL simulations. Giri & Schneider (2021) finds that the suppression reaches a maximum of 20–28% at around \( k \sim 7h/\text{Mpc} \) and produces an emulator of baryon effects on the matter power spectrum. van Daalen et al. (2020) utilizes a set of 92 matter power spectra from several hydrodynamic simulations to conduct a detailed investigation of the dependence on different ΛCDM cosmoologies, neutrino masses, subgrid prescriptions, and AGN feedback strengths. They find that the effectiveness of AGN feedback significantly influence the matter power spectrum on scales \( k > 0.1h/\text{Mpc} \). The results of different hydrodynamic simulations are determined by the parameters of baryon feedback processes, such as the strength of the AGN feedback. In this subsection, we provide a constraint on how the baryon effect would suppress the matter power spectrum from tSZ observation.

We utilize the measurement in Section 5.1 and adopt the halo model from Mead et al. (2020). Here is a brief description of the halo model to estimate the lensing statistics. The total power spectrum is the sum of the 1h and 2h terms

\[ P_{2h,\mu\nu}(k) = P_{\text{lin}} \prod_{i=\mu,\nu} \int b(M) W_i(M, z) n(M) dM \quad (41) \]

\[ P_{1h,\mu\nu}(k) = \int W_i(M, z) W_i(M, z) n(M) dM, \quad (42) \]

where \( P_{\text{lin}} \) is the linear matter power spectrum, \( b(M) \) is the linear halo bias, \( n(M) \) is the halo mass function, and \( \mu, \nu \) represent different matter components such as dark matter, bound gas, and unbound gas. For dark matter, we adopt the Navarro–Frenk–White (NFW) profile

\[ \rho_{\text{DM}} \propto \frac{1}{r/r_s(1 + r/r_s)^2} \quad (43) \]

( Navarro et al. 1997). For the gas, we adopt a KS profile (Komatsu & Seljak 2001). The normalization of these profiles is determined by

\[ f\nu(M) = \int_0^\infty 4\pi r^2 \rho_i(M, r) dr. \quad (44) \]

\( f_{\text{dm}} \) equals \( (\Omega_m - \Omega_b)/\Omega_m \). For gas, we set two models to characterize the impact of baryon feedback. For model 1, \( f_{\text{bound}} = \Omega_b/\Omega_m \) and \( f_{\text{unbound}} = 0 \), which is without baryon feedback. For model 2, \( f_{\text{bound}} = f_{\text{gas}} \) measured in Section 5.1 as a function of the mass and redshift and \( f_{\text{unbound}} = \Omega_b/\Omega_m - f_{\text{gas}} \). We adopt the approximation that the unbound gas does not contribute to the 1h term but only to the 2h term as a diffused background.

We show the ratio of the matter power spectrum of model 2 and model 1 in Figure 9. This ratio quantifies the impact of feedback. At \( k = 1h/\text{Mpc} \), the matter spectrum is suppressed by 10% at \( z = 0 \) and increasing to 30% at \( z = 1 \). The suppression at smaller scales is larger.

We also show the suppression on the weak-lensing angular power spectrum, when the source is at \( z_s = 0.5 \) or \( z_s = 1 \) in Figure 10. The suppression is about \( \gtrsim 10\% \) when \( l \gtrsim 1000 \).

### Table 3

| Range of \( z \) | \( \langle b_y P_e \rangle_{\text{unbound}} \) \{meV cm\(^{-3}\)\} | Scenario 1 | Scenario 2 |
|-----------------|-----------------|-------------|-------------|
| (0.1, 0.2)      | 0.065 ± 0.025   | 0.162       | 0.046       |
| (0.2, 0.4)      | 0.014 ± 0.013   | 0.491       | 0.118       |
| (0.4, 0.6)      | 0.011 ± 0.016   | 0.835       | 0.183       |
| (0.6, 1.0)      | 0.065 ± 0.028   | 1.693       | 0.336       |
This suppression is an order of magnitude larger than the precision of the weak-lensing measurement by Stage IV. This indicates that the baryon feedback effect needs to be taken into account in weak-lensing measurement. Otherwise, it would become a serious systematic effect entering cosmology. The 1h-term measurement provides a differential description of the cluster/group thermal energy, while the 2h-term provides an integral constraint on the thermal energy of all hot baryons, bound and unbound. The 1h-term measurements extend the $Y$--$M$ relation by one order of magnitude in the mass range. We further find the sign of departure in the $Y$--$M$ redshift evolution from the prediction of adiabatic gastrophysics. The 2h-term measurements are consistent with previous works but with smaller error bars. The comparison between the 1h and 2h terms provides clues to the unbound gas and the impact of feedback. An important cosmological implication is the significant suppression of the weak-lensing auto-power spectrum, which is $\lesssim 10\%$ at $l \gtrsim 1000$. This confirms that the baryonic effect is a major systematic effect in weak lensing.

Although the total S/N of the tSZ detection exceeds 70, our measurement and theoretical interpretation suffer from a number of uncertainties. It is beyond the scope of this work to fully account for these uncertainties in the analysis, due to complexities in describing them and incapability of constraining them by the data. Instead, we list the major uncertainties and discuss the improvements that will be achieved by upcoming surveys.

1. **Redshift uncertainty.** The redshift of galaxies in the DESI group catalog DR9 is photometric, and its uncertainty is about 0.01($1+z$) (Yang et al. 2021). The uncertainty in the redshift would cause redshift uncertainties of clusters and result in biased templates of 1h and 2h terms, especially in low redshift bins. The ongoing DESI spectroscopic survey will directly provide spectroscopic redshifts for a fraction of member galaxies. For the rest, cross correlation between the groups and spectroscopic galaxies will tightly constrain the mean redshift of group samples and possibly the outlier rate.

2. **Mass uncertainty.** The mass uncertainty for the DESI group catalog DR9 is 0.2 dex at the high-mass end and 0.40 dex at the low-mass end. In Appendix A, we use mock data from the simulation to calibrate the mass of clusters in the catalog. However, the number of halos in the simulation is limited, which would cause uncertainty in the $\lg M_r - \lg M_L$ relation. Furthermore, the halo mass function in the simulation relies on the reference cosmology. This may induce certain model dependence in the measurements. The mass uncertainty can be calibrated against cross correlation with cosmic shear (e.g., the catalog \footnote{https://gaz.sjtu.edu.cn/data/DESI.html} constructed by the Fourier--Quad method (Zhang 2008)) or spectroscopic galaxies.

3. **Halo concentration.** In Section 3, we assume that the concentration of halo is the same as the dark-matter-only situation. However, if a large fraction of baryon is blown away from a halo, the halo would become less compact, corresponding to a smaller concentration. Then the 1h-term profile would be changed. In Appendix B, we test how the change in concentration would influence our
4. Nonthermal pressure and baryon feedback. There are two effects would cause difference between the KS profile and the true one. In the first, nonthermal motion, referred to as ‘turbulence’, inside clusters would provide extra pressure support against gravity (Shaw et al. 2010; Shi & Komatsu 2014; Osato et al. 2018). The nonthermal fraction $f_{\text{nth}} = P_{\text{nth}}/(P_{\text{th}} + P_{\text{nth}})$ monotonically increases with the cluster radius and reaches $\sim 0.4$ when $r = r_{200}$ (Nelson et al. 2014; Shi et al. 2015, 2016). In addition, the baryon feedback would break the hydrodynamic equilibrium and cause departure from the KS profile for a fraction of clusters. The thermal pressure profile has also been measured in some previous works (Arnaud et al. 2010; Tramonte et al. 2023) utilizing generalized the NFW (gNFW) formula. However, they usually use the halo mass definition, $M_{500}$. Transforming the halo mass definition from $M_{500}$ to $M_{\text{vir}}$ is nontrivial, as the baryon processes would alter the NFW mass profile of clusters. Then we will adopt these gNGW profiles in future analysis with a more meticulous calibration. In this work, we set a free parameter $A_1$ to capture the change of profile amplitude. For the shape, the beam size of Planck is so large that the details of profile shape are smoothed greatly. As checked in Appendix B, the change in template would not cause a distinguishable difference of the results.

5. Mis-centering. To account for mis-centering of clusters, we set $\eta_{\text{nc}} = 0.2$ in Equation (12) for our fiducial measurement. In Appendix C, we discuss how parameter $\eta_{\text{nc}}$ would influence the results and find $\eta_{\text{nc}} = 0.2$ is an optimal choice. Further analysis may adopt a more complicated and more realistic description of mis-centering (e.g Yan et al. (2020)). With higher resolution CMB experiments such as ACT, SPT, and CMB-S4, the tSZ data alone will have constraining power for both $c$ and the mis-centering effect.

6. Residual foregrounds in the tSZ map. This work adopts the Planck $y$ map. In the future, we may follow Chiang et al. (2020) to include non-Planck measurements in infrared bands and construct better cleaned $y$-maps.

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Appendix A

Relationship between the True Mass and the Observed Mass

In the DESI group catalog DR9, the assigned halo mass $M_L$ and halo true mass $M_t$ is not a one-to-one relation. In Figure 11, we show the difference $\delta \lg M$ of $\lg M_L$ and $\lg M_t$ and its scatter $\sigma_{\lg M}$. The mean value and the scatter all depend on $\lg M_L$. The amplitude of 1h term is proportional to $M_L^{1/3}$. Thus the uncertainty of 0.2 dex for mass means 2.2 times difference for the 1h-term profile. Therefore it is necessary to calibrate the cluster mass when calculating the 1h-term template. Otherwise the measurement $f_{\text{gas}}$ would be catastrophically biased. We show how to obtain an appropriate 1h-term profile according to the $\lg M_t - \lg M_L$ distribution relation as follows.

Using these mock data, we can obtain the possibility distribution of $\delta \lg M$ in the mass bin $\lg M_1 < \lg M < \lg M_2$. Figure 12 shows the probability density function and CDF of $\delta \lg M$ in four redshift bins. Then the 1h profile of an observed cluster sample is

$$
\gamma_0 = \int_{\lg M_{\text{min}}}^{\lg M_{\text{max}}} \int_{\lg M_{\text{min}}}^{\lg M_{\text{max}}} \int_{\lg M=0}^{\lg M_{\text{max}}} \gamma_0(\lg M_t, \zeta) n(\lg M_t, \zeta) \rho(\delta \lg M = \lg M_t - \lg M_L) d\lg M_t d\lg M_L dz, \quad (A1)
$$

Figure 11. Left: Each blue point represents a halo in the Mock catalog, the x- and y-axis is the assigned mass and the true mass. Red line is $y = x$ and green is the mean $\lg M_t$ as a function of $\lg M_L$. Middle: Mean value of the difference $\delta \lg M$ as a function of $\lg M_L$. Right: Scatter of the difference $\delta \lg M$ as a function of $\lg M_L$. 12
where \( y_\delta(\lg M, z) \) is the \( y \) profile of a halo whose mass and redshift are \( M \) and \( z \); \( n(\lg M, z) \) is the number of clusters in the mass bin \( (\lg M - \frac{\delta \lg M}{2}, \lg M + \frac{\delta \lg M}{2}) \) and redshift bin \( (z - \frac{\delta z}{2}, z + \frac{\delta z}{2}) \); and \( p(\delta \lg M|\lg M_i) \) is the PDF of \( \delta \lg M \) at \( \lg M_i \). When the bin length \( \delta \lg M \) and \( \delta z \) are small enough, Equation (A1) is the unbiased 1h-term template for the cluster sample with \( z_{\text{max}} < z < z_{\text{min}} \) and \( \lg M_{i,\text{max}} < \lg M_i < \lg M_{i,\text{min}} \).

Here we do not consider the uncertainty in the PDF \( p(\delta \lg M|\lg M_i) \). However, the number of halos decreases with the halo mass, so there are only a few massive halos in massive mass bins. This may cause a large uncertainty in the estimate of the mean value of \( \delta \lg M \) and the total PDF at large \( \lg M_i \). In addition, Wang et al. (2022) shows that there is a slight difference between halo masses determined by their ESD model and those provided by Yang et al. (2021) when \( \lg M_i \sim 14.8 \). Therefore we abandon the most massive bin in redshift 0.2 < \( z < 0.4 \) and 0.4 < \( z < 0.6 \), whose \( M_i \geq 10^{14.5} M_\odot h^{-1} \), in fitting relation of \( f_{\text{gas}} \) and halo mass \( M \).

In Section 4.1.1, we obtain a slightly redshift-evolving \( Y-M \) relation. Here, we want to point out that a possible redshift-dependent systematic error in mass estimation may influence this relation. In Wang et al. (2022), Figure 7 shows a redshift evolution of the difference between the cluster mass determined by cosmic shear and that given by the Y21 catalog. However, when modifying the cluster mass with simulations, we do not take the redshift dependence into consideration due to the scarcity of simulation data.

### Appendix B

#### Concentration

In the fiducial measurement, we assume the concentration–mass relation from Duffy et al. (2008) for dark-matter halos. However, the effects from baryons would influence the concentration and the 1h-term profile. In Section 5.1, it has been observed that more than half of the baryons are blown away from the halo with \( M < 10^{15} M_\odot h^{-1} \). Therefore, these halos would become more loose. Following Mead et al. (2020), we adopt the method to modify the concentration for unbound gas

\[
c_{\text{new}}(M) = c(M) \left[ 1 + \eta_c \left( 1 - \frac{\rho_{\text{gas}}}{\Omega_b/\Omega_m} \right) \right],
\]

When \( f_{\text{gas}} = 0 \), \( c_{\text{new}}(M) = c(M) \), as in the fiducial case. When all baryons are blown away from the halo, \( f_{\text{gas}} = 1 \), \( c_{\text{new}}(M) = (1 + \eta_c) c(M) \). The factor \( 1 + \eta_c \) can characterize how the concentration of a halo would change, if it loses all baryons. Here, we compare three situations with \( \eta_c = 0, -0.1, -0.2 \). In Figure 13, we show the comparison of these three situations for four redshift bins. For each redshift bin, the top panel shows the ratio of the fitted \( f_{\text{gas}} \) and the fiducial case. The bottom panel shows the ratio of \( \chi^2_{\text{min}} \) and the fiducial case.

For massive, low-redshift cluster samples, the fitted \( f_{\text{gas}} \) increases with decreasing \( \eta_c \). For other cluster bins, the fitted \( f_{\text{gas}} \) decreases with decreasing \( \eta_c \). Low-mass clusters are more sensitive to the modification of concentration because their baryon abundance is lower. However, the measurement uncertainties of the low-mass cluster sample are also larger.

Fortunately, all differences cannot be distinguished by the 1\( \sigma \) error bar. Therefore, the simple fiducial assumption of concentration would not bias the measurements. On the other hand, this means that our measurement cannot raise a constraint on the halo concentration currently.

With more accurate measurements with the upcoming surveys, the concentration (or the shape of the density profile) may become a nonnegligible ingredient. Fortunately, the shear-group correlation could put a constraint on the halo concentration as a function of the redshift and halo mass (Wang et al. 2022).
Appendix C

Mis-centering

In the DESI group catalog DR9, the position of clusters would have misalignments with the actual minimum gravitational potential points of them. This mis-centering would suppress stacked tSZ profiles. Here, we treat this effect the same way as the beam in the CMB survey when generating 1h- and 2h-term templates. We assume that the amplitude of the mis-centering is proportional to the virial radius of a halo.

\[ \sigma_{\text{mc}} = \eta_{\text{mc}} \frac{r_v}{d_c} \]  

(C1)

In the templates of the 1h and 2h terms, parameter \( \sigma_{\text{beam}} \) is replaced by \( \sigma_{\text{eff}} = \sqrt{\sigma_{\text{beam}}^2 + \sigma_{\text{mc}}^2} \).

In Figure 14, we test how parameter \( \eta_{\text{mc}} \) would influence the measurements. In the top panel of each redshift, it shows the

Figure 13. Coefficient of the 1h term influenced by the concentration model. The three different concentration models are \( \eta_c = 0, -0.1, -0.2 \) represented by red, green, and blue points, respectively. \( \eta_c \) is the parameter that characterizes how the concentration is sensitive to the fraction of baryons in a halo (Equation (B1)). The redshift bin is the label on the top of each panel. The top part of each panel shows \( A_1 \) of each mass bin for the three models. To make the figure more readable, each point is normalized by the \( A_1(\eta_c = 0) \) in the same bin. The bottom part shows \( \chi^2_{\text{min}} \).
We find that \( \eta_{mc} \) indeed has a large influence on the fitting, especially for the low-redshift, massive cluster samples. For small clusters and high-redshift clusters, \( \sigma_{mc} \) is smaller than the beam size \( \sigma_{beam} \), due to the small \( r_c \) or large \( d_c \). In this situation, the fitting is less sensitive to the mis-centering effect. Low-redshift samples suffer from the mis-centering effect more seriously. For most cluster samples with \( 0 \leq z < 0.2 \), when \( \eta_{mc} = 0.2 \), \( \chi^2_{min} \) reaches the minimum point. Therefore, we set \( \eta_{mc} = 0.2 \) in the fiducial measurement.

Appendix D
Low-mass Group Sample
In this suction, we show the tSZ measurement of the group with \( \lg M < 13 \) (\( \lg M < 13.5 \) for \( 0.6 \leq z < 1 \)). An example of \( 0.4 \leq z < 0.6 \) is shown in Figure 15. Results of other redshift bins are shown in Table 4. At these mass ranges, the amplitude...
of the background is comparable to that of the 1h and 2h terms. The amplitude of the 1h term becomes unreasonable. This means the shape of the background plays an important role in the fitting results. The large fluctuations at $\theta > 20^\circ$ may indicate a scale-dependent background. Therefore we do not include these results in the main-body analysis.

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Figure 15. Stacking results of the tSZ measurements as a function of the angular distance to the center of clusters for a sample with $0.4 < z < 0.6$ and $11 < lgM_{t} < 13$. The black dots are the stacking results with error bars estimated by Jackknife resampling. The red, green, and blue lines represent the best-fit 1h, 2h, and the background term. The dotted lines are the sum of these three terms.

### Table 4

| Range of $z$ | Range of $lgM_{t}$ | $N_{\text{cluster}}$ | $lgM_{t}$ | $\delta_{L}$ | $A_{1}$ | $S/N(A_{1})$ | $A_{2}$ | $S/N(A_{2})$ | $A_{3} \times 10^{8}$ | $S/N(A_{3})$ | $\chi_{\text{min}}^{2}$ |
|-------------|-------------------|---------------------|-----------|-------------|--------|-------------|--------|-------------|----------------|-------------|------------------|
| $[0.0, 0.2]$ | $[11, 13]$, 66648 | 12.69 | 1.14 | 2.311 | 3.65 | 0.51 | 10.9 | $-1.36$ | 4.0 | 14.81 |
| $[0.2, 0.4]$ | $[11, 13]$, 102191 | 12.8 | 1.26 | 5.164 | 5.92 | 0.61 | 13.1 | $-0.81$ | 4.9 | 12.866 |
| $[0.4, 0.6]$ | $[11, 13]$, 29076 | 12.86 | 1.4 | 5.09 | 2.7 | 0.59 | 3.9 | 1.22 | 4.2 | 10.013 |
| $[0.6, 1.0]$ | $[13, 13.5]$, 20361 | 13.34 | 2.07 | $-0.309$ | 0.63 | 0.5 | 1.7 | 0.58 | 1.7 | 2.977 |
