

Detection of the Pairwise Kinematic Sunyaev-Zel'dovich Effect and Pairwise Velocity with DESI DR1 Galaxies and ACT DR6 and *Planck* CMB data

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We present a 9.3σ detection of the pairwise kinematic Sunyaev-Zel’dovich (kSZ) effect by combining a sample of 913,286 Luminous Red Galaxies (LRGs) from the Dark Energy Spectroscopic Instrument Data Release 1 (DESI DR1) catalog and co-added Atacama Cosmology Telescope (ACT DR6) and *Planck* cosmic microwave background (CMB) temperature maps. This represents the highest-significance pairwise kSZ measurement to date. The analysis uses three ACT CMB temperature maps: co-added 150 GHz, total frequency maps, and a component separated Internal Linear Combination (ILC) map, all of which cover 19,000 square degrees of the sky from Advanced ACTPol observations conducted between 2017 and 2022. Comparison of the results of these three maps serves as a consistency check for potential foreground contamination that may depend on the observation frequency. An estimate of the best-fit mass-averaged optical depth is obtained by comparing the pairwise kSZ curve with the linear theory prediction of the pairwise velocity under the best-fit *Planck* cosmology and is compared with predictions from simulations. This estimate serves as a reference point for future comparisons with thermal SZ-derived optical depth measurements for the same DESI cluster samples, which will be presented in a companion paper. Finally, we employ a machine learning approach, trained on simulations to estimate the optical depth for 456,803 DESI LRG-identified clusters within the simulated mass range ($\gtrsim 10^{13} M_\odot$). These are combined with the measured kSZ signal to infer the individual cluster peculiar velocities, providing the opportunity to constrain the behavior of gravity and the dark sector over a range of cosmic scales and epochs.

I. INTRODUCTION

The kinetic Sunyaev-Zel’dovich (kSZ) effect, which arises from the line-of-sight peculiar motion of free electrons in galaxy clusters relative to the Cosmic Microwave Background (CMB) rest frame, serves as a powerful probe of cosmological structure formation and the large-scale velocity field of the Universe [1, 2]. The detection of the kSZ effect also provides an independent probe of large-scale structure to redshift-space distortions (RSD) [3–7] and weak gravitational lensing [8–12]. In contrast with the thermal Sunyaev-Zel’dovich (tSZ) effect, which originates from inverse Compton scattering of CMB photons by hot electrons in clusters, the kSZ effect directly traces the peculiar velocities of galaxy clusters and groups. This complements alternative methods with analyses sensitive to galaxy bias and nonlinear clustering and weak lensing requiring precise shape measurements of background galaxies, making it an valuable tool for studying cosmological structures and offering an independent avenue for testing models of modified gravity and alternative dark energy models [13–17].

The pairwise kSZ statistic, which measures the average relative momentum of galaxy or cluster pairs, has emerged as a effective approach to detect the kSZ signal [18]. Using the large-scale coherence of velocity fields, this method suppresses uncorrelated noise and significantly enhances detection sensitivity compared to single-object velocity measurements. Through statistical analysis of cluster or galaxy pairs, it becomes possible to probe cosmic velocity fields and constrain key cosmological parameters, including the amplitude of matter fluctuations, the growth rate of structure, neutrino masses, and the nature of dark energy [19–24].

Luminous Red Galaxies (LRGs) are an important and useful tool for many scientific studies. Since the most luminous galaxies within clusters are typically red and bright [25–28], the main scientific goal of the LRG sample is to identify and trace clusters of galaxies to study large-scale structure [29, 30]. The first detections of the pairwise kSZ effect were obtained by combining Atacama Cosmology Telescope (ACT) data with LRG samples from the Sloan Digital Sky Survey (SDSS), providing the first observational evidence of the kSZ signal and marking a key milestone in cosmology [31]. This measurement demonstrated the feasibility of using the pairwise kSZ signal as a robust cosmological probe, motivating subsequent analyses with increasingly sophisticated techniques and larger datasets. Building on this foundation, later studies have extracted the signal with higher precision by combining improved galaxy catalogs from BOSS, DES, and DESI with later CMB maps from ACT and *Planck*, leading to higher sensitivity measurements and opening the door to cosmological constraints [32–38].

The Dark Energy Spectroscopic Instrument (DESI) survey [39] is a next-generation galaxy redshift survey designed to map the large-scale structure of the Universe with unprecedented precision. DESI provides high-precision spectroscopic redshifts for tens of millions of galaxies, quasars, and other cosmological tracers across a wide redshift range. Meanwhile, ACT Data Release 6 (DR6) delivers the deepest ground-based CMB maps to date, with improved sensitivity, wide sky coverage, and broad frequency coverage [40]. Coupled with the DESI Data Release 1 (DR1) galaxy catalog, which contains precise spectroscopic redshifts for millions of galaxies, this analysis significantly improves the sensitivity of the LRG kSZ measurements.

In this work, we exploit the synergy between ACT DR6 maps and the DESI DR1 galaxy catalog to perform a comprehensive analysis of the pairwise kSZ signal. Our goal is to sensitively measure the pairwise kSZ effect and address the limitations of previous LRG studies. In addition, we incorporate machine learning methods to directly infer individual cluster optical depths and peculiar velocities, thereby enabling more robust pairwise velocity estimates.

The structure of this paper is as follows. Section II describes the datasets used in our analysis, focusing on the characteristics of ACT DR6 and DESI DR1. Section III introduces the methodology and statistical tools. Section IV presents the main results, and Section V summarizes the key findings and discusses the prospects for future improvements and analyses.

II. DATA

A. ACT DR6 data

The Atacama Cosmology Telescope (ACT) was a ground-based millimeter-wavelength telescope that was designed to map the CMB with high angular resolution and sensitivity, allowing detailed measurements of temperature and polarization anisotropies across a wide range of angular scales [41, 42]. The resulting dataset enabled high-precision studies of CMB power spectra, gravitational lensing of the CMB, and the SZ effect from massive galaxy clusters, providing independent constraints on the standard cosmological model and the history of structure formation in the Universe [43]. This analysis uses three CMB temperature maps from ACT Data Release 6 (DR6) [44]. The maps are derived from data collected between 2017 and 2022 and are combined with *Planck* data [45], covering a sky area of 19,000 square degrees.

The “f150” map is a combined frequency-specific map centered at 150 GHz (124–172 GHz). The “ftot” map is an optimally inverse-noise-weighted combination of observations at 98, 150, and 220 GHz, designed to maximize the signal-to-noise ratio for CMB anisotropies. Finally, we use the DR6 CMB internal linear combination (“ILC”) map [46], which integrates multi-frequency data from ACT and complementary information from *Planck*, spanning frequencies from 30 GHz to 545 GHz.

In addition to the CMB ILC temperature maps, we also use the DR6 Compton-y ILC map [47], which provides a measurement of the thermal tSZ effect across the sky. In this case, the ILC technique isolates the tSZ signal through linearly combining maps at different frequencies in a way that minimizes contamination from other astrophysical foregrounds and instrumental noise, while preserving the unique spectral signature of the tSZ effect. ACT DR6 CMB gravitational lensing convergence maps, covering the same sky area as the three CMB temperature maps described above, are also used in this work [48, 49]. These trace the projected total matter density along the line of sight, reconstructed from the subtle distortions imprinted on the CMB by intervening large-scale structures. These maps are not used directly in the pairwise kSZ–estimator analysis, but instead are employed to train the

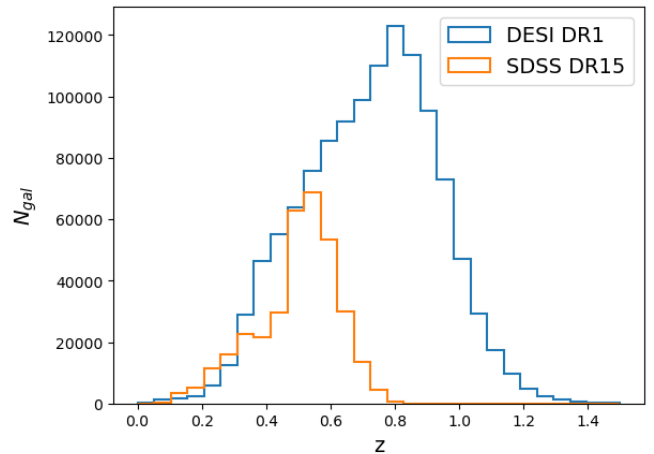


FIG. 1. The redshift distribution, showing the number of LRGs, N_{gal} , in the sample from DESI DR1 [blue] analyzed in this work and, as a reference, from SDSS DR15 [orange] studied previously in [35].

models used to infer the optical depth.

B. DESI DR1 data

The Dark Energy Spectroscopic Instrument (DESI) is conducting a spectroscopic survey designed to investigate the nature of dark energy by mapping the three-dimensional distribution of over 40 million galaxies and quasars [39, 50, 51] with precise redshift measurements, and is expected to reach a total of over 60 million targets. The resulting large-scale structure data will allow for high-precision studies of baryon acoustic oscillations and redshift-space distortions, providing critical constraints on cosmological models and the expansion history of the Universe [52, 53]. Following the DESI Survey Validation phase [54], the Early Data Release (EDR) [55] and the First Data Release (DR1) [56] were completed.

We use the Luminous Red Galaxies (LRGs) sample [57–59] from DR1. Our spectroscopic LRG sample is selected following the DESI Key-Project (KP) [60]. The selection provides 2,388,542 galaxies with luminosities derived from the absolute magnitudes listed in the DESI Value Added Catalog (VAC) [61] that is constructed by jointly fitting DESI’s observed-frame optical spectra and broadband photometry with physically motivated stellar population synthesis and emission-line templates to derive galaxy physical properties. Within the sample, 1,689,748 galaxies overlap with the ACT DR6 f150 map. Following [35], we performed an inverse white noise variance cut at a level of $45 \mu K$ per pixel to the overlapping sample, which removes 69,406 galaxies. Galactic plane masking was then applied using the mask that is used in generating the 2015 *Planck* Compton-y map [62] to minimize contamination from the Milky Way. A conservative 50% mask was chosen to exclude sources located near the Galactic plane, which led to the removal of 392,003 additional sources. We use a 50% cut, consistent with the criterion adopted in previous work [35]. Using a larger cut such

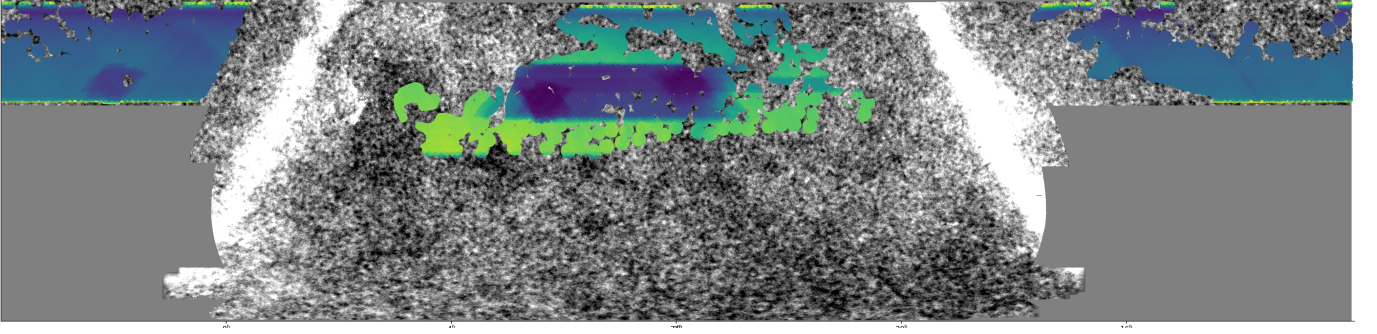


FIG. 2. ACT DR6 and DESI sky coverage. Background shows the ACT DR6 150GHz map. Shaded colored region shows the selected DESI region footprint, and color shows the average noise level in the ACT 150 GHz map. Gaps in coverage result of combining the DESI footprint with the point source, and galactic mask as described in Section II.

Bin Label	Luminosity cut ($10^{10}L_{\odot}$)	Mass cut M_{vir} ($10^{13}M_{\odot}$)	f150 & ftot		ILC	ILC ($z < 0.8$)
			N_{gal}	$\langle z \rangle$	N_{gal}	N_{gal}
L36	$L > 3.6$	$M > 0.38$	957,095	0.76	913,286	512,437
L48	$L > 4.8$	$M > 0.63$	718,542	0.78	685,766	364,878
L60	$L > 6.0$	$M > 0.96$	478,585	0.81	456,803	219,341
L79	$L > 7.9$	$M > 1.65$	239,567	0.85	228,650	92,729
L98	$L > 9.8$	$M > 2.59$	119,353	0.88	114,024	40,387
L36D	$3.6 < L < 4.8$	$0.38 < M < 0.63$	238,553	0.71	227,520	147,559
L48D	$4.8 < L < 6.0$	$0.63 < M < 0.96$	239,957	0.73	228,963	145,537
L60D	$6.0 < L < 7.9$	$0.96 < M < 1.65$	239,018	0.77	228,153	126,612
L79D	$7.9 < L < 9.8$	$1.65 < M < 2.59$	120,214	0.81	114,626	52,342

TABLE I. Overview of the nine luminosity-selected samples used in this study (5 cumulative and 4 disjoint), along with the corresponding bin labels referenced throughout the paper. For each sample we list the host halo mass range (M_{vir}), the number of galaxies (N_{gal}), and the average redshift ($\langle z \rangle$). The number of galaxies for both ILC and ILC ($z < 0.8$) samples are also listed.

as 70% would significantly reduce the number of objects for analysis. We finally mask point sources using the point source and cluster catalog used in the ACT DR6 map production process. Following [63], a 15 mJy point source mask at $10'$ radius was used in the Deep 56 (D56) region [64], a 680 sq. deg. deep sky patch from the ACT surveys, while a 100 mJy mask at $5'$ radius was applied in the rest of the areas. The point source mask removes 7,071 sources from the sample. Using the same point source and cluster catalog and following [65], we also mask out LRGs that are close to massive tSZ clusters as very massive clusters can dominate and skew the measurements. The final catalog selection, after applying all masks, contains 1,197,347 galaxies. The redshift distribution of this sample is shown in Fig. 1 and in Fig. 2 we present the overlap between our selected sample and the ACT DR6 f150 CMB map. In Fig. 1, we also show the redshift distribution of the LRGs sample previously studied in [35] for comparison. The DESI DR1 sample, extending from $0 < z < 1.5$, with a peak around $z = 0.8$, probes deeper into the Universe relative to SDSS DR15, which was confined to lower redshifts, covering $0 < z < 0.8$ and peaking at $z = 0.55$. Most pairwise kSZ analyses to date (e.g., [31, 32, 34, 35, 37]) have focused on SDSS galaxy cluster samples at relatively low redshifts,

$z < 0.8$. With its extensive sky coverage, high target density, and precise redshift measurements, DESI enables the systematic identification and study of tracer galaxies and galaxy clusters to significantly higher redshifts, extending well beyond $z > 1$. In this work, in addition to studying the full dataset, we will also perform an analysis of the $z < 0.8$ subsample on the ILC map to ensure continuity with previous studies.

We divide the sample by luminosity using the 20th, 40th, 60th, and 80th percentiles, corresponding to luminosities $L(10^{10}L_{\odot}) = 3.6, 4.8, 6.0$ and 7.9 , referred to as L36, L48, L60, L79 respectively. We also consider the equivalent discrete bins and additionally include a sample with a luminosity cut of $9.8 \times 10^{10}L_{\odot}$, enabling a continuous comparison with the sample defined in [35]. The properties of the samples in each luminosity-selected bin are outlined in Table I, which includes luminosity-inferred mass ranges, the number of galaxies, and the average redshift and luminosities of each bin. We notice that the ILC map has a slightly different footprint from the f150 and ftot maps near the edges. Therefore, we exclude some objects in the ILC sample that lie close to the apodized map boundaries. The mass estimates are derived following the approach described in [63]: stellar masses are first computed from galaxy luminosities using the mass-to-light ratio

[66–68], and halo masses are then inferred via the stellar–halo mass relation [69]. Our primary analysis uses the L36 sample of 957,095 galaxies. Note, by comparison, that the previous analysis in [35, 63] considered 343,647 galaxies with the low-est luminosity cut of $4.3 \times 10^{10} L_\odot$.

III. METHODS

A. Secondary Anisotropies

The kSZ effect arises from inverse Compton scattering of CMB photons off electrons moving with bulk velocities, imprinting anisotropies proportional to the line-of-sight momentum of the ionized gas, and is given by:

$$\frac{\Delta T_{\text{kSZ}}}{T_{\text{CMB}}} = -\frac{\sigma_T}{c} \int n_e (\mathbf{v} \cdot \hat{\mathbf{n}}) dl, \quad (1)$$

where σ_T is the Thomson cross-section, n_e is the electron number density, $\mathbf{v}$ is the peculiar velocity of the electrons, and $\hat{\mathbf{n}}$ is the line-of-sight unit vector.

In contrast, the tSZ effect originates from inverse Compton scattering of CMB photons by hot electrons within galaxy clusters, altering the CMB’s spectral energy distribution. The resulting temperature change is given by:

$$\frac{\Delta T_{\text{tSZ}}}{T_{\text{CMB}}} = f(\nu)y, \quad (2)$$

and

$$y = \frac{\sigma_T k_B}{m_e c^2} \int n_e T_e dl, \quad (3)$$

where $f(\nu) = x \coth(x/2) - 4$, $x = \frac{h\nu}{k_B T_0}$, y is the Compton parameter, T_e is the electron temperature, m_e is the electron mass, and k_B is Boltzmann’s constant.

Gravitational lensing of CMB photons by intervening structures distorts the observed anisotropies through lensing convergence κ , defined as:

$$\kappa(\hat{\mathbf{n}}) = \frac{3H_0^2 \Omega_m}{2c^2} \int_0^{\chi_*} d\chi \frac{\chi(\chi_* - \chi)}{\chi_*} \frac{\delta(\chi \hat{\mathbf{n}}, z)}{a(\chi)}, \quad (4)$$

where H_0 is the Hubble constant, ω_m is the matter density parameter, χ is the comoving radial distance, χ_* is the comoving radial distance to the last scattering surface, δ is the density contrast, and $a(\chi)$ is the scale factor. This formalism is applied in Sec. IV B.

We measure the kSZ and tSZ signal using aperture photometry (AP). The method involves computing the temperature decrement in a central aperture and subtracting the average temperature in a surrounding annulus of equal area. The aperture photometry estimate of the signal at the location of a galaxy cluster is given by:

$$T_{\text{AP}} = \frac{1}{N_{\text{ap}}} \sum_{i \in \text{ap}} T_i - \frac{1}{N_{\text{ann}}} \sum_{j \in \text{ann}} T_j, \quad (5)$$

where T_i are the temperature values of the pixels within the aperture, T_j are the temperature values of the pixels in the annulus, and N_{ap} and N_{ann} are the number of pixels in the aperture and annulus, respectively.

For the kSZ temperature, following [31, 32, 35], we use an aperture size equal to $2.1'$, which is also a good fit for our sample, and subtract a redshift smoothed temperature, $\bar{T}_{\text{AP}}$, to the AP measurement T_{AP} . The aim is to eliminate possible contamination that could imitate a pairwise signal when comparing aperture temperatures of objects at different redshifts, and it is given by:

$$\bar{T}_{\text{AP}}(z_i) = \frac{\sum_j T_{\text{AP}}(z_j) \exp\left(-\frac{(z_i - z_j)^2}{2\sigma_z^2}\right)}{\sum_j \exp\left(-\frac{(z_i - z_j)^2}{2\sigma_z^2}\right)}, \quad (6)$$

where we use $\sigma_z = 0.01$ as in [32, 35].

As discussed in [70], aperture photometry can suffer systematic signal attenuation, particularly when signals of interest extend into the background annulus. Since the annulus is typically used to estimate and subtract the local background, any genuine signal present in this region is mistakenly removed, leading to an underestimation of the true source amplitude. Following the method described in [70], we also calculate the AP correction factor, A_{AP} , to account for the signal attenuation introduced by background subtraction. Applying A_{AP} , we can recover an unbiased measurement of the kSZ signal from the central disk, mitigating the biases that arise from the overlap of extended kSZ signal profiles with the annulus.

B. Pairwise statistic

The pairwise velocity statistic is a fundamental tool for probing the large-scale dynamics of cosmic structure. Defined as the mean relative velocity between pairs of galaxies (clusters) as a function of their comoving separation, the pairwise velocity is given by:

$$\hat{\mathbf{V}}(r) = -\frac{\sum_{i < j} (v_i - v_j) c_{ij}}{\sum_{i < j} c_{ij}^2}, \quad (7)$$

where r is the comoving separation between two objects and v is the line-of-sight velocity of a cluster. The geometric weight c_{ij} projects the velocity difference along the line of sight and is formulated as follows:

$$c_{ij} = \hat{\mathbf{r}}_{ij} \cdot \frac{\hat{\mathbf{r}}_i + \hat{\mathbf{r}}_j}{2} = \frac{(r_i - r_j)(1 + \cos \alpha)}{2 \sqrt{r_i^2 + r_j^2 - 2r_i r_j \cos \alpha}}, \quad (8)$$

where $\hat{\mathbf{r}}_i$ and $\hat{\mathbf{r}}_j$ are unit vectors in the direction of objects i and j , r_i and r_j are their comoving distances, and $\cos \alpha = \hat{\mathbf{r}}_i \cdot \hat{\mathbf{r}}_j$ defines the angle between the two lines of sight. The vector $\hat{\mathbf{r}}_{ij}$ denotes the unit separation vector between the pair.

In practice, this velocity signal is often inferred from the kSZ effect. The pairwise kSZ momentum estimator is given by:

$$\hat{\mathbf{p}}_{\text{kSZ}}(r, z_i) = -\frac{\sum_{i < j} (\Delta T_{\text{kSZ}, i} - \Delta T_{\text{kSZ}, j}) c_{ij}}{\sum_{i < j} c_{ij}^2}, \quad (9)$$

where $\Delta T_{\text{kSZ},i}$ is the observed temperature fluctuation at object i due to the kSZ effect, computed as $T_{AP} - \bar{T}_{AP}$. The sums in Eqs. 9, 6, 5 are implemented in the pipeline described in Ref. [71].

In accordance with [35], our analysis is conducted using radial separation bins (e.g. used in Fig.3 and 4), starting with evenly spaced intervals of 10 Mpc centered between 5 and 145 Mpc. In addition, we include four broader, non-uniform bins centered at 175, 225, 282.5, and 355 Mpc.

We also model a theoretical prediction for the observed pairwise velocity using linear theory [72] and the best-fit *Planck* cosmological parameters [73]. Following [23, 24], it is calculated as

$$V(r, z) = -\frac{2}{3} \frac{f(z)H(z)r}{1+z} \frac{\bar{\xi}_h(r, z)}{1 + \xi_h(r, z)}, \quad (10)$$

where $f(z)$ denotes the linear growth rate and $H(z)$ is the Hubble parameter. The functions ξ_h and $\bar{\xi}_h$ represent the 2-point halo correlation function and its volume-averaged form, respectively [20, 72]:

$$\xi_h(r, z) = \frac{1}{2\pi^2} \int dk k^2 j_0(kr) P(k, z) b_h^{(2)}(k), \quad (11)$$

$$\bar{\xi}_h(r, z) = \frac{3}{r^3} \int_0^r dr' r'^2 \xi(r', z) b_h^{(1)}(k). \quad (12)$$

Here, $P(k, z)$ is the linear matter power spectrum and $j_0(x) = \sin(x)/x$ is the zeroth-order spherical Bessel function. The quantity $b_h^{(q)}$ denotes the q -th order mass-averaged halo bias moment, defined as:

$$b_h^{(q)}(z) = \frac{\int_{M_{\min}}^{M_{\max}} dM M n(M, z) b^q(M) W^2[kR(M, z)]}{\int_{M_{\min}}^{M_{\max}} dM M n(M, z) W^2[kR(M, z)]}, \quad (13)$$

where $n(M, z)$ is the number density of halos of mass M , based on the halo mass function from [74]. The top-hat window function is:

$$W(x) = 3 \frac{\sin x - x \cos x}{x^3}.$$

The characteristic scale of a halo with mass M is:

$$R(M, z) = \left[\frac{3M}{4\pi\bar{\rho}(z)} \right]^{1/3},$$

with $\bar{\rho}(z)$ being the average matter density of the Universe. This scale represents the physical size of a dark matter halo of mass M at a given redshift z .

C. Mass-averaged optical depth estimate

The theoretical expression for the observed pairwise kSZ momentum is given by

$$\hat{\mathbf{p}}_{\text{th}}(r, z) = -\frac{T_{\text{CMB}}}{c} \bar{\tau} \hat{\mathbf{V}}(r, z), \quad (14)$$

where $\bar{\tau}$ denotes the effective mass-averaged optical depth across the cluster samples and z is the mean redshift. We compare the theoretical predictions for the pairwise velocity with our measurements of the pairwise kSZ momentum. Since the derived $\bar{\tau}$ values are computed by dividing by the theoretical pairwise velocity, they are contingent on the accuracy of the theoretical pairwise velocity values. We omit two bins with $r < 20$ Mpc as nonlinear velocity effects, not accounted for in the linear theoretical model for $\hat{\mathbf{V}}$ described in (10), become significant at these scales. We use the chi-squared statistic to evaluate the likelihood of effective mass-weighted optical depth $\bar{\tau}$,

$$\chi^2(\bar{\tau}) = \sum_{ij} \Delta \hat{\mathbf{p}}_i(\bar{\tau}) \hat{\mathbf{C}}_{ij}^{-1} \Delta \hat{\mathbf{p}}_j(\bar{\tau}), \quad (15)$$

where $\Delta \hat{\mathbf{p}}_i(\bar{\tau}) = \hat{\mathbf{p}}_{i,\text{th}}(\bar{\tau}) - \hat{\mathbf{p}}_{i,\text{obs}}$, with $\hat{\mathbf{p}}_{i,\text{th}}(\bar{\tau})$ representing the theoretical kSZ pairwise momentum prediction at cluster separation r_i for a given average optical depth $\bar{\tau}$, and $\hat{\mathbf{p}}_{i,\text{obs}}$ being the observed value. $\hat{\mathbf{C}}_{ij}^{-1}$ is the inverse of the covariance, where the covariance matrix $\hat{\mathbf{C}}_{ij}$ is estimated by bootstrap analysis with 1000 iterations following the methods outlined in Ref. [35].

The best-fit value is obtained at $\chi_{\min}^2$, and we compute the Probability-To-Exceed (PTE), which quantifies the probability of obtaining a larger chi-squared value:

$$\text{PTE} = \int_{\chi_{\min}^2}^{\infty} \chi_m^2(x) dx, \quad (16)$$

where χ_m^2 is the chi-squared distribution with m degrees of freedom.

In accordance with [35], the signal-to-noise ratio (SNR) is calculated assuming the signal is given by the best-fit theoretical model:

$$\text{SNR}(\bar{\tau}) = \sqrt{\sum_{ij} \hat{\mathbf{p}}_{i,\text{th}}(\bar{\tau}) \hat{\mathbf{C}}_{ij}^{-1} \hat{\mathbf{p}}_{j,\text{th}}(\bar{\tau})}. \quad (17)$$

It is important to note that we use aperture photometry to measure the kSZ temperature. Consequently, the pairwise kSZ curves calculated from T_{AP} will also be attenuated, as discussed in Sec. III A. Therefore, the best-fit optical depth derived using the method described in this section will also be attenuated and is denoted as $\bar{\tau}_{AP}$.

D. Peculiar velocity estimation

In addition to the effective mass-averaged optical depth, we also estimate the kSZ-weighted optical depth for each individual galaxy cluster using the machine learning method developed in [75] (for more details, please refer to the paper). The machine learning model uses a Gradient Boosted Decision Trees (GBDT) algorithm to make prediction. GBDT is an ensemble learning method that builds a sequence of decision trees, where each new tree corrects the errors of the previous trees, improving accuracy by iteratively minimizing

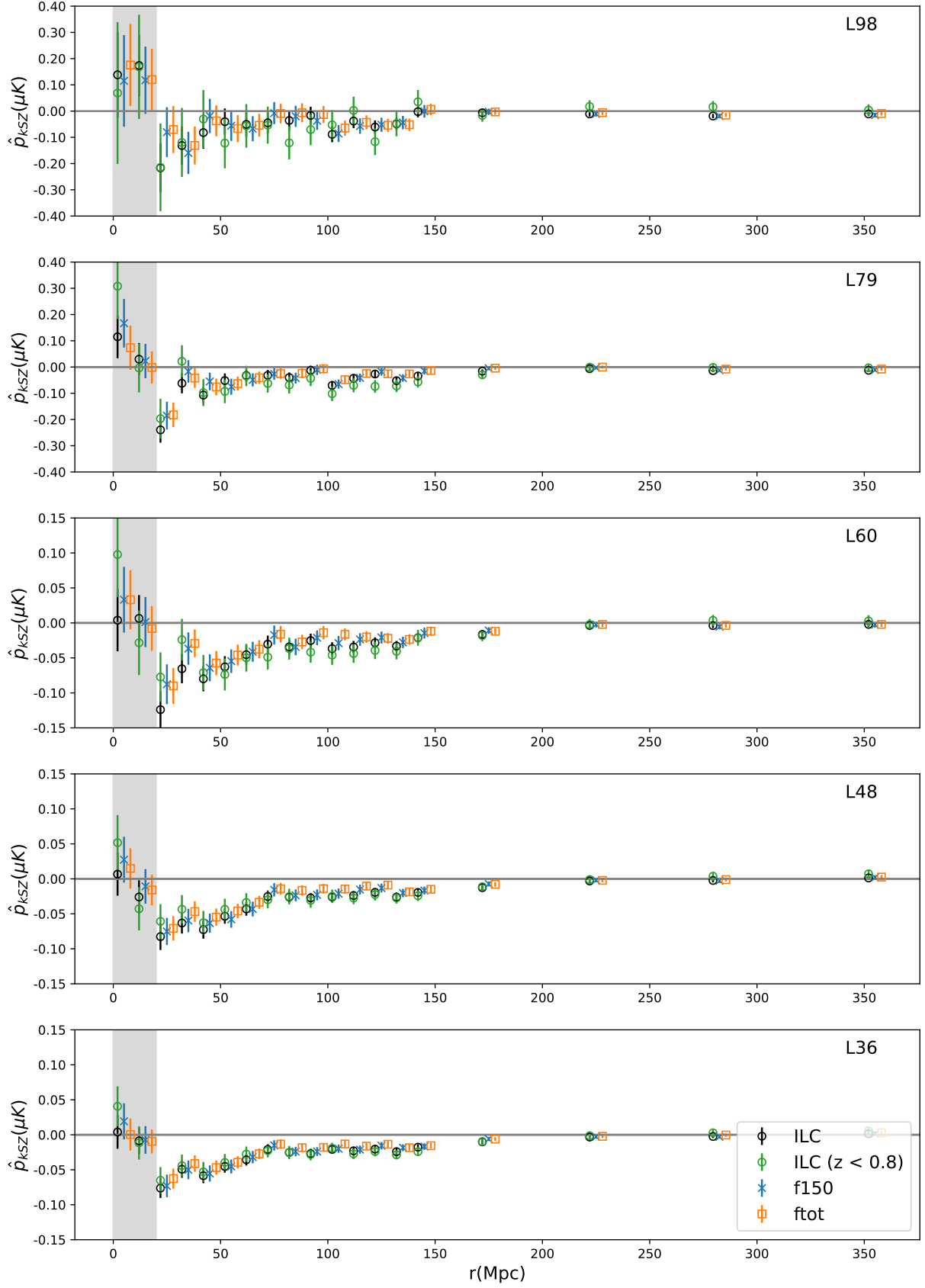


FIG. 3. Measured pairwise kSZ momentum curves for the ILC [black circle], $z < 0.8$ ILC subsample [green], f150 [blue cross], and ftot [orange square] maps, based on sources in nine luminosity-selected galaxy tracer samples. From top to bottom, these samples are: L36, L48, L60, L79, and L98. Two different vertical scales are used, scaled to their respective amplitudes. 1σ uncertainty error bars obtained through bootstrap analysis are also presented. In this study, we concentrate on scales $r > 20$ Mpc, and consequently shade the region corresponding to $r < 20$ Mpc.

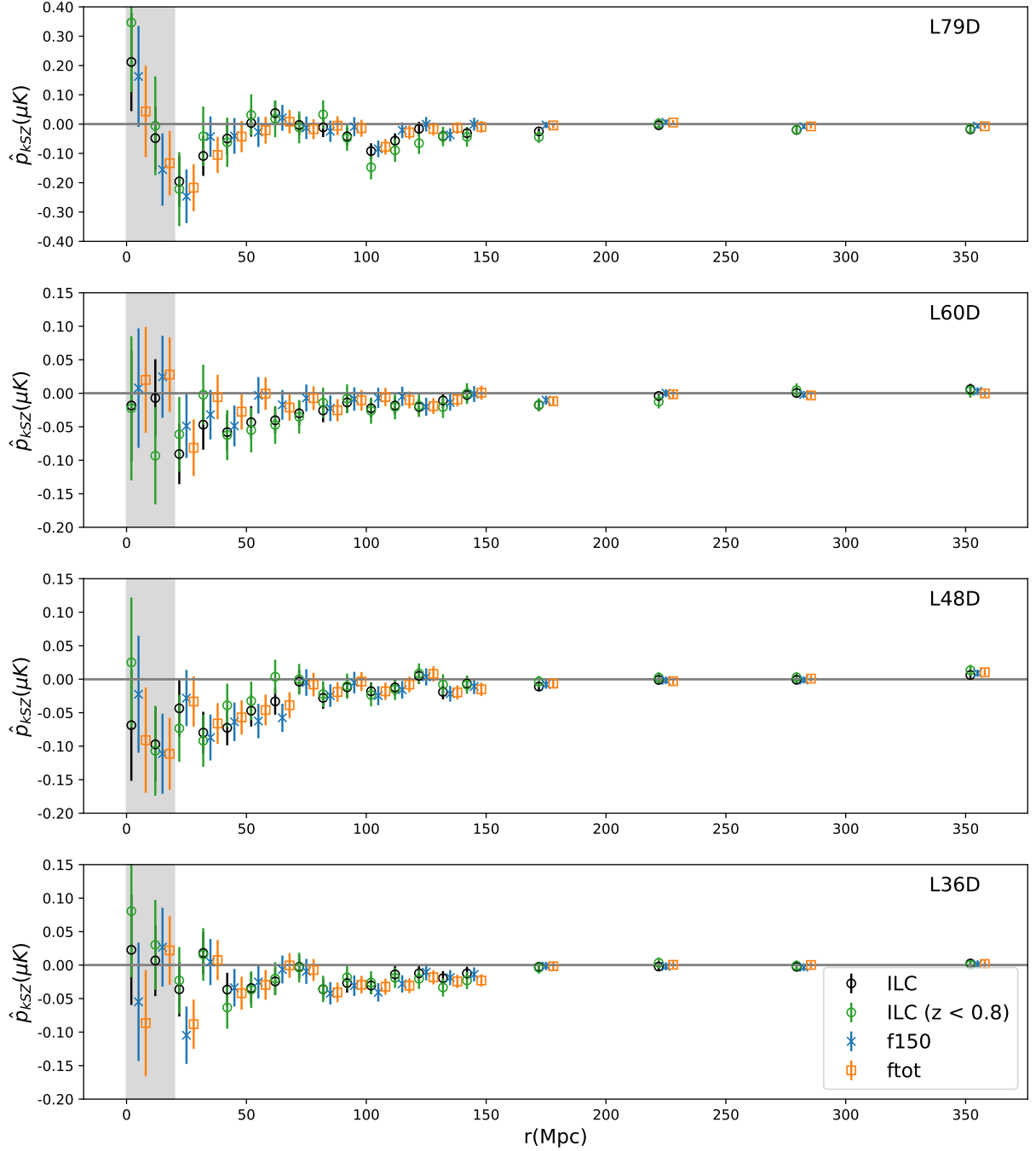


FIG. 4. Same as Fig. 3, but for disjoint luminosity samples: L36D, L48D, L60D, and L79D. Two different vertical scales are used, scaled to their respective amplitudes.

errors using gradient-based methods. The model is trained on the Simons Observatory Forecast simulation [76], which delivers a comprehensive suite of simulated kSZ, tSZ, and lensing convergence maps, together with an associated halo catalog. The method, as described in [75], uses a combination of model features measured from tSZ, using aperture photometry (in contrast to analyses in which the cluster tSZ signals are stacked), the lensing convergence, extracted via

a machine-learning-based filtering model, and cluster mass achieved from the catalog to estimate the optical depth for the cluster independently.

This kSZ-weighted optical depth estimate is then used to combine with the kSZ temperature to estimate the peculiar velocity of each individual galaxy via

$$v_{\text{pred}} = -\frac{c}{\tau_{\text{pred}}} \cdot \frac{T_{AP}}{T_{CMB}}. \quad (18)$$

Tracer sample	ftot				f150				ILC				ILC ($z < 0.8$)			
	$\bar{\tau}_{AP} (\times 10^{-4})$	$\chi^2_{\min}$	PTE	SNR	$\bar{\tau}_{AP} (\times 10^{-4})$	$\chi^2_{\min}$	PTE	SNR	$\bar{\tau}_{AP} (\times 10^{-4})$	$\chi^2_{\min}$	PTE	SNR	$\bar{\tau}_{AP} (\times 10^{-4})$	$\chi^2_{\min}$	PTE	SNR
L36	0.36 ± 0.05	18	0.33	7.2	0.42 ± 0.06	18	0.29	7.5	0.46 ± 0.05	18	0.33	9.3	0.41 ± 0.07	19	0.26	5.9
L48	0.37 ± 0.06	15	0.51	6.8	0.43 ± 0.06	16	0.45	7.1	0.51 ± 0.06	13	0.70	9.2	0.43 ± 0.08	12	0.75	5.3
L60	0.39 ± 0.07	15	0.50	5.7	0.44 ± 0.08	15	0.53	5.3	0.54 ± 0.07	16	0.47	8.1	0.54 ± 0.11	15	0.54	4.9
L79	0.43 ± 0.10	20	0.22	4.2	0.49 ± 0.11	29	0.05	4.1	0.58 ± 0.10	25	0.05	5.4	0.72 ± 0.19	23	0.14	3.9
L98	0.45 ± 0.16	15	0.55	2.8	0.55 ± 0.18	15	0.50	3.1	0.62 ± 0.16	15	0.56	3.9	0.72 ± 0.32	13	0.70	2.3
L36D	0.36 ± 0.10	21	0.17	3.6	0.36 ± 0.12	16	0.45	3.1	0.27 ± 0.11	12	0.74	2.5	0.28 ± 0.13	13	0.68	2.1
L48D	0.36 ± 0.10	18	0.35	3.7	0.43 ± 0.11	17	0.40	4.0	0.41 ± 0.10	13	0.68	4.1	0.35 ± 0.13	12	0.76	2.6
L60D	0.23 ± 0.10	10	0.88	2.3	0.25 ± 0.11	7	0.98	2.3	0.45 ± 0.11	10	0.90	4.2	0.38 ± 0.14	10	0.91	2.7
L79D	0.36 ± 0.16	17	0.39	2.2	0.34 ± 0.18	19	0.27	1.8	0.51 ± 0.17	25	0.07	3.2	0.54 ± 0.26	24	0.10	2.2

TABLE II. Summary of the best-fit $\bar{\tau}_{AP}$ values and associated 1σ uncertainties for the DR6 ftot [left], f150 [center], ILC and ILC ($z < 0.8$) maps [right], based on nine luminosity-selected galaxy tracer samples. The fitted values are obtained by comparing the observed pairwise kSZ curves with the theoretical pairwise velocity derived from the best-fit *Planck* cosmology. The uncertainties are estimated using the bootstrap method. The corresponding χ^2 values (for 17 degrees of freedom), signal-to-noise ratio (SNR), and probability to exceed (PTE) are also listed for each case.

Then, we use these derived velocities and (7) to reconstruct the pairwise velocity statistic. Similar to the pairwise kSZ curves discussed above, the velocity is derived from T_{AP} . Consequently, the corresponding pairwise velocity is attenuated by a factor of A_{AP} as discussed in Sec. III A.

IV. RESULTS

A. Pairwise kSZ momentum and mass-averaged optical depth measurements

In Fig. 3 and 4, we present the pairwise kSZ momentum curves derived from the ftot, f150, and ILC maps with 1σ uncertainties derived from bootstrap analyses. For the L36, L48, L60, L79, and L98 samples, we find that the peak amplitude of the pairwise kSZ curves increases as the average luminosity of the sample increases, consistent with the expectation that the clusters formed in more massive halos possess greater optical depths and larger gravitational potentials and therefore larger pairwise velocities. On scales $r > 20\text{Mpc}$, velocity correlations are theoretically predicted to be linear [31, 32, 35, 77–79], and the negative pairwise signal is interpreted as evidence of gravitational infall between pairs of galaxy clusters as they are drawn toward one another due to their mutual gravitational attraction. As the physical separation between the cluster pairs increases, the strength of the gravitational interaction decreases, resulting in a weaker infall signal. For the discrete luminosity samples L36D, L48D, L60D, and L79D, we find that the kSZ signal becomes less significant as both average mass and sample size decrease.

For each luminosity-selected sample, the corresponding pairwise kSZ curves derived from the three complementary maps (i.e., ftot, f150, and ILC) show agreement within the 1σ uncertainty. This consistency suggests that the results are resistant to substantial and unique sources of contamination arising from foreground emissions that vary with frequency. In other words, even though each map employs observations

in different effective frequencies, the agreement among the kSZ signal measurements implies that no single map is disproportionately affected by foreground interference, thereby affirming the reliability of the findings. These findings also extend to the low redshift sample (i.e., $z < 0.8$), and we also observe a good agreement with the full sample results within 1σ uncertainty, with no significant difference between the full and low redshift samples.

The pairwise kSZ signal is detected with high significance using the ILC map, with the SNR relative to the null signal varying based on the galaxy sample selection. We find that the detection significance improves as the sample size increases. The SNR increases from 5.6σ for the L98 sample to 8.4σ for L79, 8.9σ for L60, and 9.9σ for L48, ultimately peaking at 10.2σ for the L36 sample. In the meantime, at roughly fixed sample size, as the sample luminosity increases the SNR for the corresponding discrete sample also increases ranging from 4.5σ for L36D, up to 5.1σ for L48D, 5.3σ for L60D, and 6.0σ for L79D.

Using Eq. (14), we estimate the effective mass-averaged optical depth, $\bar{\tau}_{AP}$, by comparing the measured pairwise kSZ momentum curves for $r > 20\text{Mpc}$ to the theoretical linear prediction given in (10). For each of the pairwise kSZ curves shown above, we summarize the best-fit mass-averaged optical depth constraints in Table II. The ILC map consistently gives the best detection of the mass-average optical depth over different luminosity bins compared with the other two maps. The best measured detection of mass-averaged optical depth is obtained with the ILC map L36 sample, yielding $\text{SNR} = 9.3$ with $\chi^2 = 18$ for 17 degrees of freedom. This measurement achieves a 72% improvement in SNR compared with our previous work [35], which used the ACT DR5 150 GHz CMB map and the SDSS DR15 LRG sample. The improvement is primarily driven by the increased sample size obtained from using the LRG sample from the DESI spectroscopic galaxy survey. The L48 sample achieves a comparable, but slightly lower, SNR of 9.2, but with a better $\chi^2 = 13$. The SNR increases as signal uncertainties decrease, primarily driven by

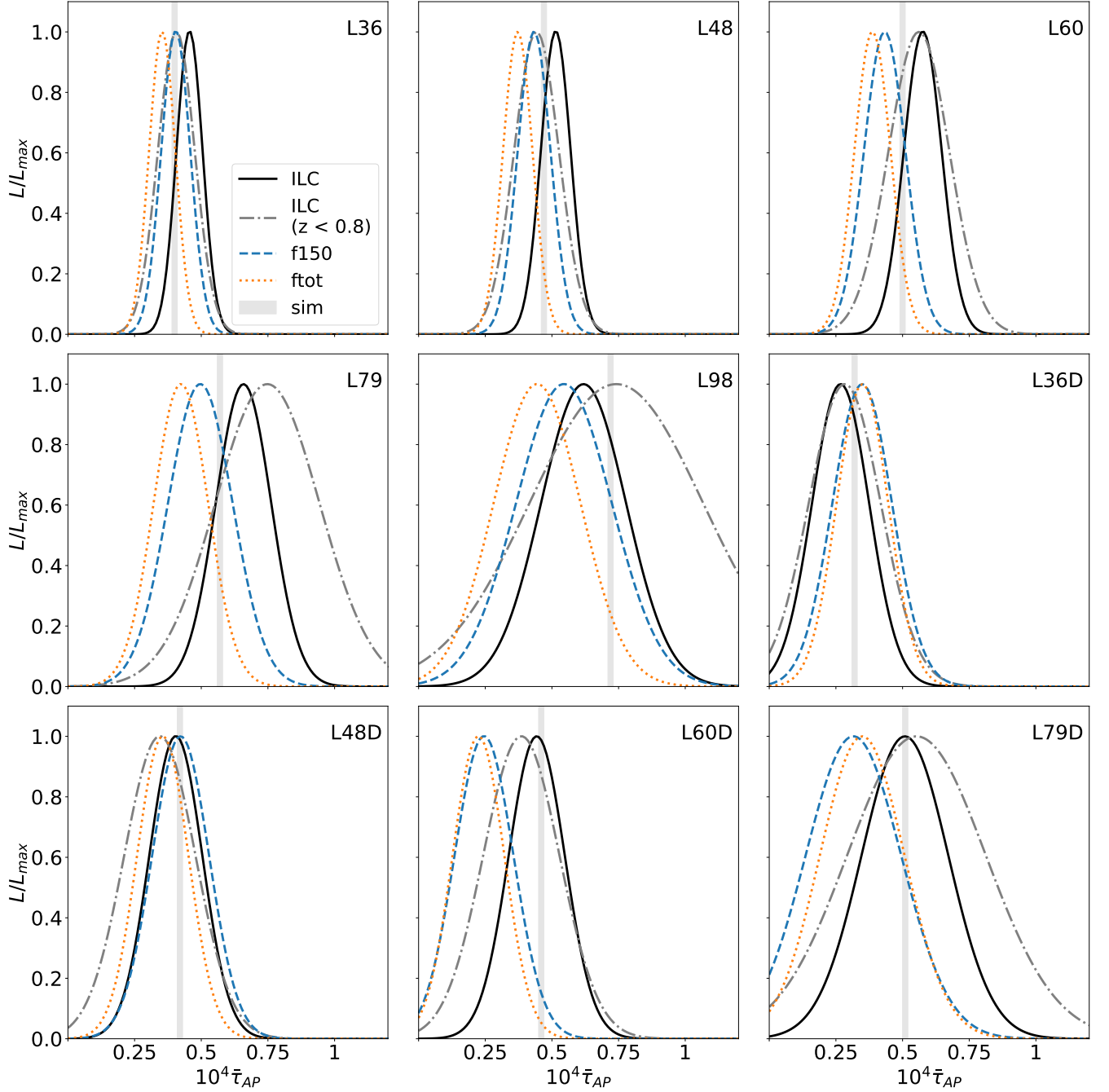


FIG. 5. The normalized likelihoods, $L \propto \exp(-\chi^2)$, for the fitted values of $\bar{\tau}$ using the DR6 ILC [black solid] and its corresponding low redshift subsample [grey dash-dotted], f150 [blue dashed], and ftot [orange dotted] maps, computed for each of the nine luminosity-based tracer samples. The optical depth derived from the simulations is also presented for reference.

the increasing number of galaxies in the luminosity bin. The results demonstrate that the signal is not reliant on the smallest mass halo bin, but that bin does modestly improve the results through reducing statistical errors by increasing the sample size while contributing a smaller amplitude to the pairwise momentum signal.

In Fig. 5, we present the likelihood distributions of the fitted mass-averaged optical depth for each of the pairwise kSZ

curves. The best-fit values are consistent across all three maps, indicating robustness in the measurement. As the sample size increases, the constraints on the optical depth become progressively tighter as progressively lower luminosity thresholds are applied. We also find that in most cases the best-fit mass-averaged optical depths are consistent between the low-redshift sample ($z < 0.8$) and the full sample, indicating that the inclusion of high redshift objects does not affect the mea-

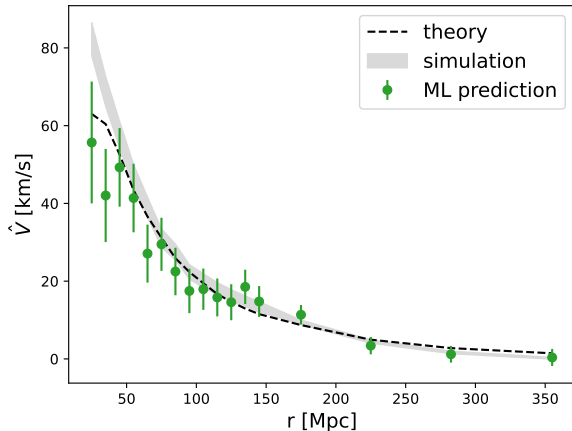


FIG. 6. The pairwise velocity statistics and their 1σ uncertainties [green circle] for the L60 sample. The results are derived using ILC kSZ temperature measurements and optical depths predicted via the GBDT machine learning algorithm, based on data combining tSZ, κ , and M_{vir} information for each cluster [75]. The predicted linear pairwise velocity for the best-fit cosmology based on *Planck* data is also presented for comparison [black dashed line]. We also present the pairwise velocity derived from the simulation for reference [grey shaded region].

measurements significantly. Similar observation is also reported in [34] and the authors discussed that a weak optical depth redshift evolution should be expected. In the figure, we also show the optical depth for each cluster sample, derived from a simulation [80]. This simulation-based optical depth corresponds to the best-fit value obtained by comparing the pairwise kSZ curves with the pairwise velocities measured from the simulated halo catalog and the simulated kSZ map. We are also using aperture photometry to measure the kSZ temperature from the simulated kSZ maps, and thus, the derived optical depth is $\bar{\tau}_{AP}$. We find that the simulation-derived optical depth agrees well with the ILC results, is slightly larger than the 150 GHz results, but remains well within the 1σ uncertainty. This value serves only as a reference and as a cross-check of the robustness of our ACT $\times$ DESI pairwise kSZ-derived optical depth. A more detailed study of the ACT $\times$ DESI tSZ-derived optical depth will be presented in a forthcoming companion paper. In Appendix A, we also conduct a null test to support the significance of our measurements.

B. Pairwise velocity inference

Using the machine learning method developed in [75], we performed a high-fidelity measurement of the peculiar velocity by estimating the optical depth for each individual galaxy cluster within our L60 sample. We focus specifically on the L60 sample, as its mass range is commensurate with that of the halos in the simulations used to train the machine learning model, ensuring that our measurements closely mirror the conditions under which the model was developed. This min-

imizes potential biases and allows for a more reliable and accurate application of the model to our observational data.

We employed a multi-probe methodology, extracting synergistic information from different observational tracers of large-scale structure. We extract the features for the machine learning model from the tSZ Compton- y map and the lensing convergence κ map, and use virial mass estimates to infer the optical depth.

The machine learning algorithm was trained to learn the complex, non-linear relationship between these observables and the underlying gas properties, ultimately yielding a high-fidelity estimate of the optical depth for each individual cluster. Combining these machine learning predicted optical depth estimates with the kSZ temperature measurements, we then derive the peculiar velocities of individual clusters using (18). Using (7), we calculate the pairwise velocity from the derived individual galaxy velocities and we estimate the uncertainties with the bootstrap analysis.

The results are presented in Fig. 6, along with the linear theoretical prediction based on the best-fit *Planck* cosmology. In the figure, we also present the pairwise velocity derived from the simulation for a sample similar to the L60. As discussed in Sec. III A, we apply a correction factor $A_{AP} = 2.73$ to account for the signal attenuation introduced by the aperture photometry measurement [70]. We find that the reconstructed pairwise velocity agrees well with the theoretical prediction based on the *Planck* best-fit cosmology for $r > 20$ Mpc, achieving an SNR of 8.5, $\chi^2 = 10$, and PTE = 0.92 for 17 degrees of freedom with 456,803 galaxies. This provides roughly a two-fold improvement in SNR compared to the ACT DR5 $\times$ SDSS DR15 analysis reported in [75], which obtained an SNR of 4.5 using 117,384 LRGs. We find that the observed pairwise velocity is consistent with both the linear prediction and the simulation within 1σ uncertainty for scales above 40 Mpc.

V. CONCLUSION

In this work, we present a comprehensive analysis of pairwise kSZ curves, using three distinct maps derived from the ACT DR6 data products. Our analysis is based on the f150 and fitot ACT-*Planck* co-added maps, which combine data from both observatories to enhance signal-to-noise ratio, and the component-separated ILC map, which effectively isolates the CMB signal from foreground contaminants. These three maps serve as a robust check on our results, mitigating potential systematic effects inherent to any single data processing pipeline.

We use the LRGs from the DESI DR1 catalog as tracers of the galaxy clusters. We have conducted careful selection of the galaxy (cluster) samples based on their luminosity, a key physical property that correlates with the mass of the host halo while masking out objects located near the galactic plane, close to point sources and massive tSZ clusters, as well as those with high white noise variance in the map. We have divided the DESI catalog into nine distinct luminosity bins. The lowest luminosity cut applied in this study is $L > 3.6 \times 10^{10} L_{\odot}$. Our careful selection and binning strategy allows us to inves-

tigate the dependence of the kSZ signal on cluster properties and to compare our findings with theoretical predictions for the pairwise velocity of the large-scale structure.

Using uncertainties estimated from the bootstrap analysis, we derive the mass-averaged optical depth by comparing the observed pairwise kSZ momentum with the theoretical pairwise velocity assuming the best-fit *Planck* cosmology for each sample. Among all the galaxy tracer samples, the highest-significance detection of the pairwise kSZ signal was achieved with the L36 sample using ILC map, which is composed of 913,286 luminous red galaxies. This sample yielded a 9.3σ detection, providing a highly significant measurement of the kSZ effect, representing a 72% increase in the SNR compared with our previous work, which used the ACT DR5 150 GHz CMB map and the SDSS DR15 LRG sample. This represents the highest-significance pairwise kSZ measurement to date, and this high significance underscores the statistical power of our large galaxy catalog. Furthermore, we have obtained consistent measurements of the optical depth when using the co-added f150 and fitot maps, as well as the component-separated ILC map. The fact that our results are consistent across these three independent frequency analyses is a validation of our measurement pipeline. It suggests that potential foregrounds or systematic effects that might vary with frequency do not bias our results, confirming the robustness of our findings. In addition, we also find good agreement between the results obtained from the full sample and those from the low-redshift subsample.

To further validate the robustness of our kSZ measurements and its derived fitted mass-averaged optical depth, we performed a simple cross-check by estimating the optical depth from the simulation for each sample. This estimation was also derived by comparing the pairwise kSZ curves with the pairwise velocities measured from the simulation. This simulation-derived optical depth serves as an independent reference point for comparison with our primary kSZ-derived results. We found that the optical depth estimated from this simple method agrees well with the ACT $\times$ DESI optical depth inferred from our pairwise kSZ measurements, particularly those derived from both the 150 GHz and the ILC maps. The consistency of these values, well within the 1σ uncertainty, provides strong support for the reliability of our kSZ-based methodology and the derived mass-averaged optical depth values. We emphasize that a more detailed study of the tSZ-based estimation will be presented in a future companion paper.

Finally, we implemented a machine learning model to estimate the optical depth for each individual galaxy in our sample, moving beyond the mass-averaged values. The model was trained on a rich set of features, including tSZ measurements, lensing convergence κ , and cluster mass estimates. By combining these estimated individual optical depths with the measured kSZ signal, we were able to infer the peculiar velocity of each cluster. From these individual velocities, we then computed the pairwise velocity statistic, which probes the dynamics of the large-scale structure. Analyzing the substantial L60 sub-sample, of 456,803 galaxies, we achieved a significant 8.5σ detection of the pairwise velocity. The mea-

sured pairwise velocity is found to be in excellent agreement with the linear theoretical predictions derived from the best-fit *Planck* cosmology, and consistent with the simulation predictions at scales above 40 Mpc.

This comprehensive analysis, which has successfully demonstrated a robust pipeline for measuring the pairwise kSZ effect, establishes a strong foundation for future studies leveraging ACT data with forthcoming DESI data releases. The next generation of cosmic microwave background (CMB) experiments and large-scale structure surveys will further enhance the potential of kSZ science. Upcoming CMB observatories, such as the Simons Observatory [76] and CCAT [81], are designed to deliver high-resolution, low-noise CMB maps over unprecedentedly large areas of the sky. These maps will be essential for resolving the faint kSZ signal with high fidelity. Concurrently, a new wave of large-scale structure surveys, including DESI DR2, Euclid [82], and Roman [83], along with the Rubin telescope [84] will provide complementary optical and infrared datasets with exquisite photometric and spectroscopic coverage. The combination of these efforts will enable cross-correlation studies with unparalleled statistical power, pushing kSZ measurements beyond their current limits. This will make the kSZ effect, and its inferences about the cosmic velocity fields, a competitive and independent probe of cosmology, providing crucial insights into the nature of dark energy and the validity of General Relativity on cosmological scales.

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The authors are honored to be permitted to conduct scientific research on I’oligam Du’ag (Kitt Peak), a mountain with particular significance to the Tohono O’odham Nation.

DATA AVAILABILITY

The data corresponding to the figures in this paper are available at <https://doi.org/10.5281/zenodo.17373480>.

A detailed description of the pipeline used for aperture photometry and pairwise computation can be found in [71].

Appendix A: Null test

To ensure the robustness and validity of our pairwise kSZ measurements, we conducted a null test. The null test serves as a critical verification step, assessing the possibility of systematic errors or biases inherent in the dataset or the analysis methodology.

In practice, the null test involves randomly shuffling galaxy positions while preserving their redshift distribution. Through this randomized procedure, we generate synthetic galaxy catalogs that maintain the statistical characteristics of the original dataset but lack genuine physical correlations between galaxy pairs.

Applying the pairwise kSZ estimator to randomized datasets is expected to yield no significant signal, thereby es-

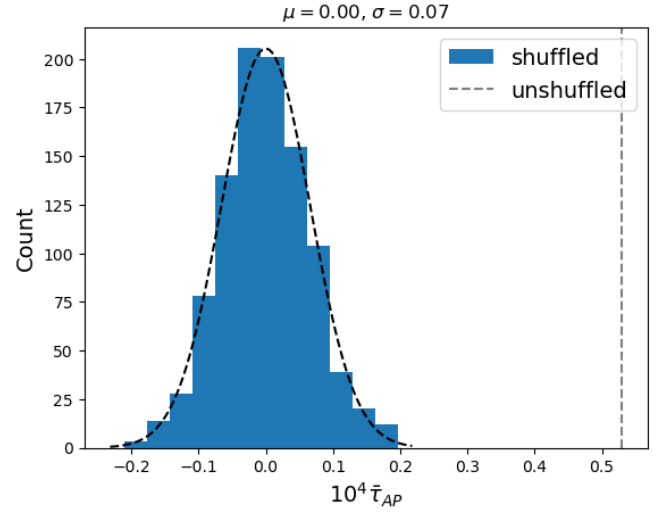


FIG. 7. Histogram of the best-fit $\bar{\tau}$ values from 1,000 null-test realizations for the L60 sample, compared with the theoretical pairwise velocity prediction derived from the best-fit *Planck* cosmology. The black curve represents the fitted normal distribution, with mean zero and a standard deviation of 0.07. The best-fit $\bar{\tau}$ value of the unshuffled result for the L60 sample is shown as the vertical dashed line.

tablishing a baseline for the absence of physical correlations. The results of this null test conducted on the L60 sample using the ILC map are shown in Figure 7, where the best-fit $\bar{\tau}$ values derived from the pairwise kSZ signal measured from 1,000 shuffled realizations clusters tightly revolve around zero, consistent with expectations. The fitted optical depth $\bar{\tau}$ also follows a Gaussian distribution with mean zero. This validates the $\sim 6\sigma$ significance of the unshuffled result shown as the vertical dashed line in the figure.

The consistency of our null test results with zero velocity confirms that our pairwise kSZ measurements are free from significant systematic biases. Any observed deviations from zero in the actual data can therefore be confidently interpreted as genuine physical signals indicative of coherent galaxy motions rather than artifacts from observational or analytical procedures.

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