Detection of the warm ionized intergalactic medium in the Planck\textsuperscript{1} data using Stack First approach

Baibhav Singari,a Tuhin Ghosh\textsuperscript{a} and Rishi Khatri\textsuperscript{b}

\textsuperscript{a}School of Physical Sciences, National Institute of Science Education and Research, HBNI, Jatni 752050, Odisha, India
\textsuperscript{b}Department of Theoretical Physics, Tata Institute of Fundamental Research, Mumbai 400005, India
E-mail: baibhav.singari@niser.ac.in, tghosh@niser.ac.in, khatri@theory.tifr.res.in

ABSTRACT: We detect the diffuse thermal Sunyaev-Zeldovich (tSZ) effect from the gas filaments between the Luminous Red Galaxy (LRG) pairs using a new approach relying on stacking the individual frequency maps. We apply and demonstrate our method on 88000 LRG pairs in the SDSS DR12 catalogue selected with an improved selection criterion that ensures minimal contamination by the Galactic CO emission as well as the tSZ signal from the clusters of galaxies. We first stack the Planck channel maps and then perform the Internal Linear Combination method to extract the diffuse $y_{\text{tSZ}}$ signal. Our Stack First approach makes the component separation a lot easier as the stacking greatly suppresses the noise and CMB contributions while the dust foreground becomes homogeneous in spectral-domain across the stacked patch. Thus one component, the CMB, is removed while the rest of the foregrounds are made simpler even before component separation algorithm is applied. We obtain the WHIM signal of $y_{\text{WHIM}} = (3.76 \pm 0.44) \times 10^{-8}$ in the gas filaments, accounting for the electron overdensity of $\sim 13$. We estimate the detection significance to be $\approx 8.1\sigma$. This excess $y_{\text{tSZ}}$ signal is tracing the warm-hot intergalactic medium and it could account for most of the missing baryons of the Universe. We show that the Stack First approach is more robust to systematics and produces a cleaner signal compared to the methods relying on stacking the $y$-maps to detect weak tSZ signal currently being used by the cosmology community.

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1 Introduction

According to the standard \(\Lambda\)CDM model of Cosmology, our Universe is composed of approximately 5% baryonic matter with the rest 95% of the total energy density in the form of dark matter and dark energy. The current most precise measurement of the baryonic energy density parameter, \(\Omega_b h^2 = 0.0225 \pm 0.00016\), where \(h = H_0/(100 \text{ km/s/Mpc})\) and \(H_0\) is the Hubble constant, is derived from the cosmic microwave background (CMB) measurements [1] and thus tells us the amount of baryons present at the time of recombination at redshift \(z \approx 1100\) [2, 3]. However, observations of the low redshift Universe show that the baryon fraction today falls below the expected universal value from CMB for almost all regions (except for the massive haloes) [4]. It has been known for sometime now that almost all of the baryons at high redshifts \((z \gtrsim 2)\) are accounted for in the Lyman-\(\alpha\) absorption forest [5]. In contrast, at low redshifts \((z \lesssim 2)\) we see that even after accounting for the baryons in stars, galaxies, Lyman-\(\alpha\) forest gas along with broad Lyman-\(\alpha\) and \(OVI\) absorbers, and hot gas in clusters of galaxies, almost half of the baryons are still missing [6]. This apparent discrepancy between the direct observations spanning the electromagnetic spectrum from radio to X-rays and the predicted baryonic mass in the standard model of cosmology and the galaxy formation theories need to be resolved by locating ‘the missing baryons’.

The gravitational instability of small initial Gaussian density fluctuations results in anisotropic collapse [7, 8] forming sheets (Zeldovich pancakes) and filaments that make up a web like structure,
the cosmic web [9–14]. Galaxies and galaxy clusters, embedded in the knots of the web (also known as dark matter haloes), are therefore connected by large-scale filamentary structures. It has been long known from simulations that a large fraction of the baryons are in the seemingly empty regions of the universe, i.e. outside the gravitationally bound haloes [15]. The haloes are highly overdense regions, but there are regions which are mildly overdense but span a much larger volume. These relatively low density and high volume spanning regions of sheets and filaments could be a rich reservoir of the missing baryons as they go undetected by the conventional methods. The gas in these filaments or the intergalactic medium (IGM) have a density of the order of ten times the mean baryon density and temperatures between $10^5 - 10^7$ K. Hydrodynamical simulations suggest that this warm hot intergalactic medium (WHIM) could contain $30 - 50\%$ of all baryons today [16, 17], even though the filaments occupy only $6\%$ of the total volume [18]. The high ionization degree would have prevented these baryons from being detected in absorption line surveys in the radio and optical bands while the low density and temperature would have prevented them from being detected in either emission lines or in the X-ray surveys targeting thermal X-ray emission, making them an ideal candidate for the *missing baryons*. The efforts for the detection of these missing baryons have been ongoing. Most of the campaigns targeting WHIM have focused on the detection of hot gas using X-rays from individual filaments [19] or from the absorption spectra of quasars [6]. These methods are however able to probe only a part of the phase space of WHIM leaving about $\sim 30\%$ of the baryons still unobserved [6]. Recent observations of OVII absorption lines in the X-ray spectra of a z = 0.48 blazar provide some evidence for a significant fraction of baryons to be present in $\sim 10^6$ K gas at $z \sim 0.4$ [20] leading to the claim by the authors that the missing baryons have been found, albeit in just two systems very close to a single blazar.

The elastic scattering of hot free electrons in the WHIM with the CMB photons boosts the energy of the CMB photons resulting in a characteristic spectral distortion of the CMB, the thermal Sunyaev Zeldovich (tSZ) effect [21]. The tSZ effect provides a way to study WHIM through multifrequency experiments, such as *Planck*, which can separate the tSZ effect from the CMB and foreground emissions [22–24]. The magnitude of tSZ distortion, denoted by $y_{sz}$, is a function of both the gas density and the temperature of the medium [25] and is given by (using *Planck* 2018 cosmological parameters [26] and fully ionized primordial gas)

$$y_{sz} = \int \frac{d\delta}{s} \sigma_T \frac{k_B T_e}{m_e c^2} \approx \frac{r}{\delta} \frac{k_B T_e}{m_e c^2} \approx 7.6 \times 10^{-8} \left( \frac{\delta}{10} \right) \left( \frac{T_e}{10^7 \text{ K}} \right) \left( \frac{r}{10 \text{ Mpc}} \right),$$

(1.1)

where $n_e$ is the free electron number density, $T_e$ is the electron temperature, $\sigma_T$ is the Thomson cross section, $k_B$ is the Boltzmann constant, $m_e$ is the mass of electron, $c$ is the speed of light, the integral is over the line of sight distance, $s$, through the WHIM, $\delta = \rho/\bar{\rho}$ is the overdensity, $\rho$ is the filament baryon density, $\bar{\rho}$ is the average baryon density, $r$ is the length of filament along the line of sight and $\tau_T$ is the Thomson optical depth through the WHIM or the filament along the line of sight. If we take the filament baryon density to be $10\times$ average baryon density ($\delta = 10$), we get an optical depth of $\tau_T \sim 4.5 \times 10^{-6}$/Mpc at $z = 0$. For a temperature of $T_e \sim 10^7$ K, we will get a tSZ signal of $\sim 7.6 \times 10^{-8}$ or a Rayleigh-Jeans temperature decrement of $2y_{sz} \sim 0.1 \mu\text{K}$ after integrating over $r = 10 \text{ Mpc}$ along the line of sight. This signal is much smaller than the noise in the current best CMB experiments, and in particular much smaller compared to the sensitivity of *Planck*. Therefore, it is not possible at present to detect the individual filaments. We can however beat down the noise by stacking hundreds of thousands of filaments, improving the signal to noise ratio, $S/N$, by a factor of hundreds. The $y_{sz}$ signal from the WHIM in the the stacked objects.
would be detectable in the *Planck* data if we can remove the contamination from the CMB as well as Galactic foregrounds with the same accuracy.

The paper is organized as follows. We describe our new approach in Sec. 2. In Sec. 3, we introduce the *Planck* data products and the sky masks used in this paper. Section 4 introduces the main data analysis part of the paper to extract the $y_{sz}$ signal at the location of LRG pairs from the stacked *Planck* maps. The modelling of $y_{sz}$ signal expected from individual halo contribution and its subtraction from the total $y_{sz}$ signal to see the signature of WHIM in the filament region is discussed in Sec. 5. In Sec. 6, we discuss the null test and the error estimate of the excess $y_{sz}$ signal. Finally we present our conclusions in Sec. 9.

2 A new algorithm to detect weak tSZ signals in *Planck* data

The stacking of the tSZ signal in the maps released by the *Planck* collaboration [22] on the positions of known galaxy pairs of massive luminous red galaxy (LRGs) [27, hereafter T19] as well as constant mass (CMASS) galaxy samples [28, hereafter G19] from the Sloan Digital Sky Survey (SDSS) has been attempted previously in an effort to find the missing baryons. In this technique, the selected close galaxy pairs within a certain radial and tangential distance are stacked up coherently in $y_{sz}$ map. Still, there is ambiguity as to what might be the true signal since the stacking is done on preprocessed publicly available *Planck* $y_{sz}$ maps obtained from Needlet Internal Linear Combination (NILC) [29] and Modified Internal Linear Combination Algorithm (MILCA) [30] algorithms. The residual contamination by the other foreground emissions (dust, CO, free-free, synchrotron and...
CMB leakage) after component separation in the $y_{sz}$ maps is much larger compared to the signal we are interested in [24, 31]. Thus, when we stack a large number of galaxy pairs, there will be some cancellation between the positive and negative contamination leaving a net residual systematic which can be either positive or negative. This can be seen in the probability distribution functions (PDFs) of $y_{sz}$ in NILC, MILCA and Linearized Iterative Least-squares (LIL) maps in Fig. 1 for the pixels which lie in-between the galaxies in a galaxy pair. The selection procedure is explained in the next section. We see that there is significant positive as well as negative excess over the Gaussian noise. The negative excess is contamination while the positive excess is contamination + $y_{sz}$ signal. In particular, the contamination signal is more than a factor of 100 larger compared to the $y_{sz}$ signal we are interested in. There is no guarantee that the positive contamination is equal to the negative contamination, and there would be large unknown systematic bias in the $y_{sz}$ signal obtained in this way.

We propose a new method of extracting the $y_{sz}$ signal from the filaments connecting the galaxy pairs. We begin by first stacking the individual Planck frequency maps at the positions of the LRG pairs. We then perform the component separation using Internal Linear Combination (ILC) [32–34] algorithm on the stacked frequency maps to extract out the $y_{sz}$ signal. By doing stacking first and component separation later, we achieve a number of advantages over the conventional method of stacking the $y_{sz}$ map [27, 28]:

1. We suppress the instrumental noise before doing ILC. Thus even the noisy 70 GHz and 100 GHz channel are utilized efficiently. In conventional method, these channels are down-weighted as the ILC tries to strike a compromise between reducing noise and reducing foregrounds in the final map.

2. The Gaussian random CMB fluctuations, uncorrelated with the positions of the galaxies, are suppressed. Thus we have one less component even before we begin the ILC.

3. Since Galactic foregrounds are also uncorrelated with the galaxy positions, by stacking the frequency maps, we are homogenizing the foregrounds in amplitude as well as in spectral shape across our stacked patch. That is, in every pixel in the final stacked map after stacking patches of interest from different parts of the sky, we should expect a sum of foreground contamination from a large number of sources, essentially sampling the whole foreground parameter space. Every pixel should end up with a very similar foreground contribution, effectively summing the complicated foregrounds comprising of many different components varying across the sky to a single foreground component across our patch.

The full power of ILC is therefore concentrated in eliminating the foregrounds, as noise and CMB is eliminated in the pre-ILC stage. The foreground spatial structure is also simplified by stacking the frequency maps. In particular, the dust emission has spectrally smooth behaviour in the stacked frequency images, with negligible variation across the image, as a result of averaging. In our approach, since we are suppressing noise before doing ILC, we can work at higher resolution compared to the conventional method. We will demonstrate this by doing analysis at 8′ resolution although most of our results would be derived at 10′ resolution.

3 Data and masks

3.1 SDSS and Planck data

We use SDSS data release 12 (DR12) with the same criteria as T19 to make a catalog of LRGs with stellar mass $M_\star > 10^{11.3}M_\odot$ [35]. We take the stellar mass estimate based on a principal component analysis method from [36]. Next, we construct a sample of LRG pairs with the radial distance
between the galaxies of a pair \( \leq 6h^{-1}\) Mpc and the tangential distance in the range \( 6 - 10h^{-1}\) Mpc. We adopt a ΛCDM cosmology with \( \Omega_m = 0.3, \Omega_{\Lambda} = 0.7, \) and \( H_0 = 70\text{ km s}^{-1}\text{ Mpc}^{-1} \) for calculation of the comoving distances from the redshift (\( z \)) information. If two or more LRG pairs fall within \( 30' \) in the projected sky coordinates (Galactic latitude and longitude), then we only keep the higher average mass LRG pairs in the sample. We find roughly 161000 LRG pairs satisfying both of the distance criteria in the SDSS DR12 sample. The angular separation between the selected LRG pairs lies between \( 19' \) and \( 203' \).

We will use the Planck 2015 intensity maps from 70 to 857 GHz and IRIS 100 µm (or 3000 GHz) map [37] for our analysis. The temperature data has not changed significantly between 2015 and 2018 releases. We rebeam the Planck HFI maps to a common beam resolution of \( 10' \) full width half maximum (FWHM), taking into account the effective beam function of each map and reduce to a HEALPix resolution of \( N_{\text{side}} = 1024 \) from the original \( N_{\text{side}} = 2048 \) to make computations faster. While smoothing to \( 10' \) beam resolution, we only retain the scales up to \( \ell_{\text{max}} = 4000 \) for Planck HFI channels and \( \ell_{\text{max}} = 2048 \) for Planck 70 GHz LFI channel. As a validation step, we also produce Planck maps at a common beam resolution of \( 8' \) FWHM with \( \ell_{\text{max}} = 3000 \) for Planck HFI channels and keeping 70 GHz LFI channel \( \ell_{\text{max}} = 2048 \).

We will use the MILCA and NILC \( y_{sz} \) maps from the Planck Legacy Archive\(^1\) for comparison. The MILCA \( y_{sz} \) maps were produced using all of the Planck High Frequency Instrument (HFI) intensity maps (100 – 857 GHz). The NILC method uses in addition the Low Frequency Instrument (LFI) data (30 – 70 GHz) at large angular scales (\( \ell < 300 \)). The angular resolution of both of these \( y_{sz} \) maps is \( 10' \) FWHM. We downgrade the original \( y_{sz} \) maps from \( N_{\text{side}} = 2048 \) (pixel size=1.7') to \( N_{\text{side}} = 1024 \) (pixel size=3.4') for computational efficiency.

### 3.2 Sky masks and sample selection

We will use the sky mask obtained in [24, hereafter K86 mask] specifically for the tSZ studies with an unmasked sky fraction \( f_{\text{sky}} = 86\% \) as the baseline. This mask specifically tries to minimize the CO line emission contamination and also covers strong point sources. We will also use the

\(^1\)https://www.cosmos.esa.int/web/planck/pla
Figure 3: The $\chi^2_{\text{CO}-y_{\text{sz}}}$ distribution at the location of LRG pairs. Right panel shows a zoomed-in version. The vertical lines represent different $\chi^2_{\text{CO}-y_{\text{sz}}}$ thresholds used in our stacking analysis.

Figure 4: Left panel: the normalized distribution of the mean mass of the LRG pairs for four different $\chi^2_{\text{CO}-y_{\text{sz}}}$ thresholds. Right panel: the normalized distribution of mean redshift distribution of the LRG pairs as a function of $\chi^2_{\text{CO}-y_{\text{sz}}}$ thresholds.

masks provided by the Planck collaboration, in particular the Galactic + point source mask with $f_{\text{sky}} = 48\%$ (henceforth PL48 mask) to compare with the T19 results.

As we estimated in the last section, we expect the IGM in the filaments between the galaxies to give a very weak tSZ signal, much below the noise level of the Planck for individual objects. Thus, in addition to the regions of strong CO line contamination [24], we also want to avoid the strong tSZ signal coming from much hotter and denser gas in the clusters of galaxies in the foreground or background, i.e. we want to select only those pairs of galaxies for which, in the individual objects, the $y_{\text{sz}}$ signal is undetectable and we are dominated by the instrumental noise. To accomplish this, we use the fact that CO emission is also a weak signal in the Planck data, of similar strength to the $y_{\text{sz}}$ signal but with a different spectrum. We can fit a model consisting of CMB + Dust + tSZ signal to the Planck HFI data as well as a model consisting of CMB + Dust + CO emission, and compare the $\chi^2$ of the two models (which have the same number of parameters). In the regions where CO emission is stronger than the tSZ, we will have smaller $\chi^2$ for the CO model and the difference between the $\chi^2$ for the two models $\chi^2_{\text{CO}-y_{\text{sz}}}$ will be negative. In the opposite case, when we have stronger tSZ signal, $\chi^2_{\text{CO}-y_{\text{sz}}}$ will be positive. We want to avoid both these cases. We want to select
galaxies such that we are noise dominated and unable to distinguish between the two models, i.e. \( \chi^2_{\text{CO-}y_{sz}} \approx 0 \). These model fits were performed in [24] and we will use the \( \chi^2_{\text{CO-}y_{sz}} \) map obtained in [24] to further prune our galaxy sample. For each LRG pair, we attribute a \( \chi^2_{\text{CO-}y_{sz}} \) value by computing the average of the sky pixels that lies within 20\(^\prime\) radius from the centre of LRG location. We have \( \sim 99.6\% \) of our sample with \( |\chi^2_{\text{CO-}y_{sz}}| < 5 \) and \( \sim 96.6\% \) of our sample with a \( |\chi^2_{\text{CO-}y_{sz}}| < 0.5 \). We can thus use aggressive thresholds in \( \chi^2_{\text{CO-}y_{sz}} \), removing the most contaminated galaxy pairs but still loose only a small fraction of the sample.

We first extend the K86 mask by masking the sky pixels where the \( \chi^2_{\text{CO-}y_{sz}} \) values are either highly negative or highly positive, i.e. \( |\chi^2_{\text{CO-}y_{sz}}| > 5 \). This extended K86 mask, hereafter eK86, is shown in Fig. 2. This extension masks the Planck detected 1653 clusters [38], SZ dominated regions and molecular clouds from our concerned sample. If either of the two LRGs of the pair falls in the masked region, then we exclude that LRG pair from our stacking analysis. The PDF of average \( \chi^2_{\text{CO-}y_{sz}} \) for all galaxy pairs in our sample, after applying the eK86 mask, is plotted in Fig. 3. The skewness towards positive values in the distribution of \( \chi^2_{\text{CO-}y_{sz}} \) towards the positive side shows that in the concerned sky regions \( y_{sz} \) signal dominates over the foreground CO emission. To get an even cleaner sample, we further eliminate the galaxies in the tails of the PDF and consider only those LRG pairs for stacking for which \( |\chi^2_{\text{CO-}y_{sz}}| < 0.2 \), marked by vertical lines in Fig. 3. We can get cleaner samples by further reducing the \( \chi^2_{\text{CO-}y_{sz}} \) threshold. Also in order to test that the \( \chi^2_{\text{CO-}y_{sz}} \) threshold does not affect our results, we will consider samples with thresholds of \( |\chi^2_{\text{CO-}y_{sz}}| \leq 0.2, 0.1, 0.07, \) and 0.05 containing 144930, 128528, 113374, and 88001 LRG pairs respectively. We show in Fig. 4 the distributions of mean mass (log(\( M/M_\odot \))) and mean redshift of the LRG pairs for the four \( \chi^2_{\text{CO-}y_{sz}} \) thresholds. We see that the mass and redshift distributions are insensitive to the \( \chi^2_{\text{CO-}y_{sz}} \) thresholds. The \( \chi^2_{\text{CO-}y_{sz}} \) thresholds, therefore, do not introduce any bias in our sample.

4 Stacking analysis

We use the following procedure to stack the Planck sky maps at each frequency. The angular separation between the LRG pairs in our sample spans from 19\(^\prime\) to 203\(^\prime\). We first project a given LRG pair from the spherical coordinates onto a normalized tangent plane centered at the midpoint of the line joining the pair such that one LRG is placed at (-1,0) and the other LRG at (1,0) [39]. We interpolate the tangent plane projections of all the LRG pairs to an equal size grid. For our analysis we project the tangent plane to a grid of 301 × 301 pixels. The angular resolution of each pixel in the grid concerned varies from pair to pair. The two LRGs are always placed 50 pixels apart in the grid, the pixel resolution varies from \( \sim 0.4\) for the pair with least angular separation to \( \sim 4.3\) for the largest. We then stack on the equal sized grids. We interchange the one LRG location from (-1,0) to (1,0) and other vice versa to produce the symmetric stacked signal on both LRG positions. We perform the stacking for the four \( \chi^2_{\text{CO-}y_{sz}} \) selected samples as discussed in the previous section for all of the Planck HFI maps and the 70 GHz LFI map at 8\(^\prime\) and 10\(^\prime\) FWHM resolutions. We note that these are slightly finer compared to the native 70 GHz channel resolution and therefore the noise in 70 GHz maps gets boosted. However, the noise is suppressed again when we stack and we can thus hope that the 70 GHz channel (as well as 100 GHz channel at 8\(^\prime\)) will contribute to the \( y_{sz} \) signal.

We show the stacked Planck frequency maps in Fig. 5. The stacked maps show an increase in foreground contamination as we increase the \( |\chi^2_{\text{CO-}y_{sz}}| \) thresholds from 0.05 to 0.2. We see the unmistakable signatures of the hot gas in the filament region due to the tSZ effect in Fig. 5, i.e. a negative signal at 143 GHz and lower frequencies with respect to the average ambient background around the galaxies and a positive signal for \( \nu > 217 \) GHz. This signature becomes slightly less prominent for higher \( \chi^2_{\text{CO-}y_{sz}} \) thresholds. We will be using our cleanest sample with \( |\chi^2_{\text{CO-}y_{sz}}| < 0.05 \)
for our baseline analysis. The signal at the position of galaxies is dominated by the radio and infrared emission from the galaxies themselves. We expect this galactic contamination to become subdominant as we go away from the centers of the galaxies to the intergalactic medium. We fit the modified blackbody spectrum to every pixel in the stacked image from 217 to 3000 GHz. The dust temperature in the fit is fixed to 18 K. The fitted dust amplitude normalised at 353 GHz has the same morphology as the 353 GHz stacked Planck map. After taking into account the color correction factors due to the Planck bandpasses, the fitted dust spectral indices are close to 1.4 over the entire stacked patch. We can conclude that the dust emission has spectrally smooth behaviour as a result of averaging of dust spectral energy distribution over the different line of sights. We will need to remove the galactic contamination from the LRGs themselves to get an unbiased estimate of the $y_{sz}$ signal from the intergalactic medium.

4.1 Blind component separation

We will use the ILC method [32–34] on the stacked Planck maps to extract the $y_{sz}$ signal. The ILC is a blind component separation method used to extract the signal of interest, whose spectrum is known, from multifrequency observations without assuming anything about the frequency dependence of unwanted foreground contamination. It has been used extensively in the CMB data analysis in the past to extract the CMB signal from multifrequency Wilkinson Microwave Anisotropy Probe (WMAP) sky observations. The ILC method can be applied over distinct regions of the sky in pixel space [34, 40], domains in harmonic space [41], or domains in needlet space [42]. The NILC and MILCA component separation methods used by the Planck collaboration to extract the $y_{sz}$ signal from the multifrequency Planck maps are also based on the ILC method with additional constraints [29, 30].

The ILC is a multifrequency linear filter that minimizes the variance of the reconstructed $y_{sz}$ map. We assume the stacked maps $(x)$ in each Planck channels as a superposition of $y_{sz}$ signal, foreground $(f)$ and noise $(n)$, written as $x_i(p) = a_i y_{sz}(p) + f_i(p) + n_i(p)$, where the index $p$ labels the pixels in the stacked map. The coefficients $a_i$ contain the relative strength of the $y_{sz}$ signal in the different Planck channels. The ILC solution for the $tSZ$ signal, ${\hat y}_{sz}(p)$ is given by

$${\hat y}_{sz}(p) = \sum_{i} w_i x_i(p).$$

The weights, $w_i$, are found by minimizing the variance of ${\hat y}_{sz}(p)$ subjected to the constraint that the $y_{sz}$ signal is preserved, i.e. $\sum_i a_i w_i = 1$ [29, 30].

We use the ILC method in pixel space to reconstruct the stacked $y_{sz}$ signal from the stacked Planck maps. We show the $y_{sz}$ map for our four LRG pair samples with different $\chi^2_{CO-y_{sz}}$ thresholds and using different frequency channel combinations in Fig. 6. We have set the zero level of the map by setting the the background signal for each image, estimated from the average of pixels in the range $-3 < X < 3$ and $-0.05 < Y < 0.05$, to 0.

The ILC ${\hat y}_{sz}$ maps are quite robust w.r.t. to the changing $\chi^2_{CO-y_{sz}}$ thresholds as well as the number of frequency channels. We will use the reconstructed ILC map derived from the frequency range 70–545 GHz for our fiducial analysis. The ILC weights obtained from our analysis with K86 mask and selection criterion $\chi^2_{CO-y_{sz}} \leq 0.05$ are quoted in Table 1 and compared with the ILC weights obtained for unstacked maps. We see from Fig. 6 that removing 70 GHz and/or 545 GHz channels does not make a significant difference, implying that the ILC has converged as far as the number of frequency channels is concerned. The strong signal at the galaxy positions is indicative of residual contamination from the emissions of the stacked galaxies themselves which needs to be estimated and removed.

Since we are doing ILC on a small number of pixels, there maybe ILC bias coming from chance correlations between the noise, $y_{sz}$ signal, and foregrounds [32, 43, 44]. To check for the ILC bias we half the size of the patch around the LRG pairs from $N \times N$ arcmin to $N/2 \times N/2$ arcmin and the number of interpolated pixels from $301 \times 301$ to $151 \times 151$. The results of comparison are shown in Fig. 7. We also do the analysis at original HEALPix resolution of $N_{\text{side}} = 2048$. We see no significant
Figure 5: The stacked Planck maps smoothed at common 10′ FWHM beam resolution for different $\chi^2_{\text{CO-ysz}}$ thresholds: $|\chi^2_{\text{CO-ysz}}| \leq 0.05$ (column 1), $|\chi^2_{\text{CO-ysz}}| \leq 0.07$ (column 2), $|\chi^2_{\text{CO-ysz}}| \leq 0.1$ (column 3), and $|\chi^2_{\text{CO-ysz}}| \leq 0.2$ (column 4). The top to bottom rows represent different Planck channels starting from 70 GHz (top row) to 545 GHz (bottom row). All the Planck maps from 70 to 353 GHz are expressed in $\mu K_{\text{cmb}}$ units and 545 GHz map is in kJy/sr. The zero level of the stacked Planck channels is adjusted such a way that the stacked signal in the range $-3 < X < 3$ and $0.05 < Y < 0.05$ is set to 0.
Figure 6: The stacked ILC $y_{sz}$ signal expressed in units of $10^{-7}$ extracted from the stacked common 10' FWHM beam resolution Planck maps at $N_{\text{side}} = 1024$ for the four different thresholds: $|\chi^2_{\text{CO}-y_{sz}}| \leq 0.05$ (column 1), $|\chi^2_{\text{CO}-y_{sz}}| \leq 0.07$ (column 2), $|\chi^2_{\text{CO}-y_{sz}}| \leq 0.1$ (column 3), and $|\chi^2_{\text{CO}-y_{sz}}| \leq 0.2$ (column 4). The top to bottom rows represent combination of different Planck channels used to extract the stacked ILC $y_{sz}$ signal: 70–353 GHz (row 1), 100–353 GHz (row 2), 70–545 GHz (row 3) and 100–545 GHz (row 4).
4.2 Component separation by parameter fitting

In order to use parameter fitting to do component separation, we need an accurate model. However, stacking on frequency maps mixes different foreground spectra, in particular mixes dust, CO and low frequency emission. It is therefore difficult to come-up with a foreground that will be accurate enough for our purpose. However, we can still use parameter fitting to learn about the foregrounds and check our assumptions. In particular, we want to check whether the foreground shape is really homogenized over our patch by stacking and that any residual foreground contamination is
Table 1: The ILC weights applied to individual Planck stacked maps to reconstruct stacked ILC γ_{sz} signal over different Galactic sky masks used in our analysis. For comparison we also show the weights with the LRGs selected using PL48 mask and using 6 Planck channels. The last column shows the weights when ILC is applied to pixels at the LRG positions in unstacked Planck maps. It is clear that the solution we get for ILC on stacked maps is very different from the one we get for the ILC on unstacked maps.

| Frequency in GHz | Frequency | ILC weights | PL48 mask | Unstacked pixels |
|------------------|-----------|-------------|-----------|-----------------|
| CO − γ_{sz} | |< 0.05 with K86 |          |                |
| 70 | -0.0020 | -0.0164 | -0.0021 |
| 100 | 0.0203 | -0.0955 | -0.0092 |
| 143 | -0.5008 | -0.1628 | -0.3508 |
| 217 | 0.5609 | 0.2382 | 0.3697 |
| 353 | -0.0707 | 0.0119 | -0.0112 |
| 545 | 0.0008 | -0.0024 | -0.0016 |

Figure 8: The stacked γ_{sz} signal (left panel), CO emission (middle panel) and dust amplitude (right panel) obtained from three-component LIL parameter fitting. The zero level of the γ_{sz} map, CO map and the dust amplitude map is adjusted such a way that the stacked signal in the range −3 < X < 3 for 0.05 < Y < 0.05 is set to 0.

morphologically different from the SZ signal we are interested in. We employ LIL parametric fitting algorithm developed in [24, 45]. We fit a simple parametric model consisting of either CMB + dust + tSZ or CMB + dust + CO components to 4 HFI channels from 100 GHz to 353 GHz. We model dust by a modified blackbody spectrum with fixed temperature T_{d} = 18 K and fixed line ratios for CO line contribution in different channels, following [24]. The parameters to fit are CMB temperature, tSZ or CO amplitude, dust amplitude and the dust spectral index.

The results of the parameter fitting exercise are shown in Fig. 8. We recover the γ_{sz} signal with morphology remarkably similar to the ILC method. However, when we fit for CO line emission, we see that there is no correlation with the galaxy positions. In particular, the CO signal is almost uniform over the patch, giving credence to the idea that the foreground spectrum as well as amplitude is homogenized over the patch. In particular, any residual contamination from our own galaxy would be uniform and uncorrelated with the galaxy positions. We therefore do not expect any significant bias due to Galactic foreground residuals while recovering the tSZ signal from the WHIM. We must still account for the residual contamination from the stacked galaxies themselves. This can be seen in the recovered dust amplitude map in Fig. 8. It shows that at the sensitivity we
need, the dust emission from the stacked galaxies is important and would be the main contaminant to the $y_{\text{sz}}$ signal. Luckily, we also see from the dust maps that the morphology is different from the $y_{\text{sz}}$ map. In particular, the dust signal is well approximated by two non-overlapping discs, while the $y_{\text{sz}}$ signal has an excess in the space between the galaxies which is more indicative of a cylindrical filament between the galaxies.

5 Excess signal

We expect two symmetric peaks in the stacked ILC $\hat{y}_{\text{sz}}$ map as we stack the Planck frequency maps twice by interchanging the LRG positions dominated by the dust emission from the galaxies. The middle panel of Fig. 9 shows the profile of the stacked ILC $\hat{y}_{\text{sz}}$ map along Y=0 axis. The stacked ILC $\hat{y}_{\text{sz}}$ signal for our baseline case has the dominant contributions from the individual LRG halo. The circular model for halos is a good approximation since most of our galaxies are unresolved and any non-circular beam effects will get symmetrized when stacking a large number of objects. T19 have shown that other systematic effects are also small. To extract the excess $y_{\text{sz}}$ signal in the filament region connecting the LRG pair, we need to subtract the individual LRG halo contribution. We exclude the central region $-1 < X < 1$ and fit a Gaussian model to the single-halo signal on both the sides [27]. The blue solid line in the middle panel of Fig. 9 is the best-fit Gaussian model to the data, excluding the central LRG region from $-1 < X < 1$. The 2D circular Gaussian model is constructed based on the fit to the data at $Y=0$. The residuals after fitting the best-fit 2D circular Gaussian model along the Y=0 and X=0 are shown in the bottom panel of Fig. 9. The map representation of the same is shown in the top panel of Fig. 9. The amplitude of the excess $y_{\text{sz}}$ signal is $\sim 4 \times 10^{-8}$ in the region $-0.5 < X < 0.5$ at Y=0. The excess $y_{\text{sz}}$ signal peaks in the central filament region between $-0.5 < X < 0.5$ and $-0.5 < Y < 0.5$. The average of the excess $y_{\text{sz}}$ signal in the central filament region is $y_{\text{sz}} = 3.76 \times 10^{-8}$, which is approximately a factor of three higher than the value reported in T19.

We note that our basic selection criteria is same as T19 however we impose additional thresholds to further prune our samples, making our results more robust to accidental contamination by foreground or background clusters. In order to relate the measured $y_{\text{sz}}$ signal to the filament properties, we use the following density profile for the filament similarly to T19,

$$n_e(r, z = 0) = \frac{n_e(r = 0, z = 0)}{\sqrt{1 + (r/r_c)^2}}, \quad (5.1)$$

where $r_c$ is the core radius of the filament and we will take $r_c = 0.5h^{-1}\text{Mpc}$, $r$ denotes the distance from the centre of the filament along the line of sight. The density profile is set to zero at $r > 5r_c$. The electron number density can be derived from the baryon density $\rho_b$ as $n_e(z) = \frac{\bar{n}_e(z)}{\mu_ne/\mu_p}$. We can calculate $\bar{n}_e(z = 0)$, with $\mu_e = 1.14$ being the mean molecular weight per free electron for a hydrogen abundance of 0.76 and $m_p$ being the proton mass. For our assumed cosmology, we find the mean electron density at zero redshift to be $\bar{n}_e(z = 0) = 2.2 \times 10^{-7}\text{cm}^{-3}$. Evidently from the relation of $n_e$ with $\rho_b$, $n_e(z)$ has the same behaviour as $\rho_b(z)$. The evolution of electron number density in the filaments with redshift can be expressed in terms of overdensity ($\delta$) as

$$n_e(r, z) = \delta \frac{\bar{n}_e(z = 0)}{\sqrt{1 + (r/r_c)^2}}(1 + z)^3. \quad (5.2)$$

Assuming a constant electron temperature $T_e$ and a symmetry along the filament axis, we can
express $\Delta y_{sz}$ as a line of sight integration of the filament density profile $(n_e(r,z))$ as,

$$
\Delta y_{sz} = \frac{\sigma_T k_B T_e}{m_e c^2} \int_{-5r_c}^{5r_c} n_e(r,z)dr \\
= \frac{\sigma_T k_B T_e \delta}{m_e c^2} \int_{0}^{5r_c} 2 \frac{\bar{n}_e(z=0)}{\sqrt{1 + (r/r_c)^2}} (1 + z)^3 dr , \quad (5.3)
$$
where $5r_c$ is the cut-off radius of the filaments and $r$ is the parameter for line of sight integration. The mean redshift $'z'$ of each LRG pair in our sample is known, we evolve the mean electron number density to redshift $'z'$ and then perform a numerical integration over $r$ using 5.3. On averaging over all LRG pairs in our fiducial sample, we obtain the average excess $y_{sz}$ signal from the filament for our sample as

$$\Delta y_{sz} = 3.78 \times 10^{-8} \left(\frac{\delta}{13}\right) \left(\frac{T_e}{5 \times 10^6}\right) \left(\frac{r_c}{0.5h^{-1}\text{Mpc}}\right). \quad (5.4)$$

As the WHIM constitutes a major chunk of the matter in the filaments [46], we can assume an average temperature of $5 \times 10^6$ K in order to estimate the density contrast of the filament from the $y_{whim}$ signal. This electron temperature is within the upper bounds obtained from Illustris simulations [46] and in-between the temperatures used by T19 ($T_e = 10^7$ K) and G19 ($T_e = 10^6$ K). Putting the $y_{whim} = 3.76 \times 10^{-8}$, we obtain the mean overdensity in the filament region to be

$$\delta \approx 13 \left(\frac{5 \times 10^6 \text{K}}{T_e}\right) \left(\frac{0.5h^{-1}\text{Mpc}}{r_c}\right) \quad (5.5)$$

Our result is in excellent agreement with expectations of overdensity in filaments ($\sim 10 - 40$) [16] from simulations. We also use different electron density profiles to compute the mean over density in the filament region. For electron density profile $n_e(r) = \text{constant}$ ($r < 2r_c$), the mean overdensity is found to be $\sim 16$. For $n_e(r) = \frac{n_e(0)}{1+(r/r_c)^3}$ ($r < 5r_c$) density profile, the mean overdensity is around 23. Irrespective of the electron density profile, the numbers for the overdensity only change by a factor of 2 and are always within the bounds of the expected WHIM overdensity as suggested by simulations.

6 Estimate of error and significance of detection

In order to obtain the significance of our detection we use the null test and the bootstrap method.

6.1 Null test with misaligned stacking

We use misaligned LRG pairs, i.e. randomly chosen positions for the LRG pairs, to estimate the foreground contamination in the measured $y_{sz}$ signal. We make 100 random realizations of the LRG pair catalogue. In each realization, we shift the Galactic longitude of every LRG pair in the real data by a random amount $\in [5^\circ, 25^\circ]$ either in the positive or negative direction, keeping the Galactic latitude fixed (for example, a pair having central coorindates $[l, b]$ could be shifted to $[l + 20^\circ, b]$). The lower bound in the random shift in longitude makes sure that the filament in the new random location does not overlap the original filament and is sufficiently away from it. We keep the original Galactic latitude so that the Galactic foreground contamination is similar as the original location. If indeed there was some contribution from the Galactic foregrounds, this would be of the similar order of magnitude for the shifted pair, and hence would show up as an excess in the misaligned stack too. We repeat the procedure of component separation with ILC and measure the $y_{whim}$ in each of the 100 random realizations of our fiducial catalogue consisting of 88001 galaxy pairs. The results are shown in Fig. 10. We find the mean and standard deviation of the WHIM signal to be $y_{whim} = (0.19 \pm 0.44) \times 10^{-8}$. We thus find the detected $y_{whim}$ signal to be $8.1\sigma$ away from the mean of random realization, i.e. above the background of $0.19 \times 10^{-8}$ contributed by foreground contamination.

6.2 Bootstrap method

We do an alternate estimate of the errorbar on the reconstructed ILC $y_{sz}$ signal using the bootstrap technique. From our sample of $N_{\text{pairs}} = 88001$, we randomly select galaxy pairs to build a new
Figure 10: The histogram of the excess $y_{sz}$ signal obtained from random 100 misaligned stacking is shown in blue colour and the black line represents the measurement from the actual data. Our measurement of $y_{whim} = 3.76 \times 10^{-8}$ is 8.1σ away from the mean of the misaligned realizations.

sample, allowing each galaxy pair to be sampled more than once, until we again have 88001 galaxy pairs. Because of the random selection, some galaxy pairs would be selected more than once while some would be left out. We thus have a new realization of our galaxy pair catalogue with the same number of pairs as in the original catalogue but each galaxy pair, in general, having a weight different from unity. We make 100 random realizations of our galaxy pair catalogue in this way, and repeat our analysis by stacking, doing ILC component separation and estimating the average $y_{whim}$ signal in the central region $-0.5 < X < 0.5$ and $-0.5 < Y < 0.5$. The standard deviation among the 100 realizations gives us an estimate of the sample variance or the errorbar on the $y_{whim}$ signal. We find the standard deviation for the $y_{whim}$ signal in the region between the LRG pairs, i.e. $-0.5 < X < 0.5$ and $-0.5 < Y < 0.5$, to be $0.44 \times 10^{-8}$, consistent with the misalignment method above.

7 Consistency checks and robustness of the excess $y_{sz}$ signal

We perform a number of tests to check the robustness of our results and to check that the excess $y_{sz}$ signal that we observe is indeed coming from the WHIM between the LRGs.

7.1 Robustness w.r.t. resolution, channel combinations and selection criteria

The WHIM signal is diluted to some extent due to the Planck beam of 10'. T19 have shown with BAHAMAS simulations that there is $\sim 15\%$ dilution in WHIM $y_{sz}$ signal from unsmoothed maps to 10' smoothed maps. As a consistency check, we repeat our analysis with Planck maps rebeamed to 8' resolution. We would expect the smaller beam size to confine the spread of LRG halo contribution to a smaller region and thus reduce any contamination in the filament region. We would also expect a slightly higher signal in the filament region between the LRG pairs. We obtain the mean amplitude of the $y_{whim}$ signal in the filament region to be $4.06 \times 10^{-8}$ at 8' resolution. Thus the dilution in the WHIM signal amplitude is $\sim 7\%$ due to beam smoothing from 8' to 10'.

− 16 −
Figure 11: The comparison of the excess $\hat{y}_{\text{whim}}$ signals along $X=0$ and $Y=0$ after the halo subtraction from individual LRG for different combinations of Planck channels and different beam resolutions.

We present the comparison of the WHIM profiles after halo subtraction for different selection of Planck channels, different $\chi^2_{\text{CO}-y_{\text{whim}}}$ thresholds, and resolutions in Fig. 11. The $y_{\text{whim}}$ signal along $Y=0$ is consistent for different data selection criteria for $\chi^2_{\text{CO}-y_{\text{whim}}} \leq 0.05$. As we see from Fig. 5, $\chi^2_{\text{CO}-y_{\text{whim}}} \leq 0.07$ sample has significantly more contamination than the $\chi^2_{\text{CO}-y_{\text{whim}}} \leq 0.05$ sample. This is also evident in the residual signal in Fig. 11, where we see that there is slightly smaller excess in-between the LRGs and slightly larger excess on the other sides of LRGs at $X, Y < -1$ and $X, Y > 1$.

7.2 Robustness w.r.t choice of point source masks and Galactic masks

We use the point source mask provided by Planck to test the robustness of the signal against contamination from strong radio and infrared point sources. Planck provides individual temperature point source mask for both LFI (30 - 70 GHz) and HFI (100 - 857 GHz) [47]. These are binary masks provided at $N_{\text{side}}=2048$. We downgrade them to $N_{\text{side}} = 1024$ and then select the regions having values $>0.9$ to ensure a sample free from point source contamination. These masks are then combined with the K86 mask. We expect some variation in $y_{\text{whim}}$ and $S/N$ as we are stacking a different number of LRGs with different masks. If there is no contamination then the $y_{\text{whim}}$ signal amplitude along $Y=0$ should remain within the sample variance. Indeed, that is what we observe. We also use the union of individual frequency channel point masks combined with K86 mask as well the point source mask provided by Planck [22] for SZ studies. The results with different masks are presented in Fig. 12. We do not see any significant variation in the signal on using different masks.

We also perform the stacking analysis of the Planck LFI and HFI channels with PL48 mask, which is one of the sky masks recommended by the Planck team for the analysis of tSZ effect. We stack roughly 101000 LRG pairs retained by PL48. The number of LRG pairs allowed by the PL48 mask is roughly the same number as used in our baseline analysis with the threshold criterion $\chi^2_{\text{CO}-y_{\text{whim}}} \leq 0.05$ with K86 mask. The reconstructed stacked ILC $\hat{y}_{\text{whim}}$ map using different combination of Planck channels is presented in Fig. 13. The ILC weights for Planck frequency channels from 70 to 545 GHz for stacking with the PL48 mask are given in Table 1. We perform all the same steps as we have done for the baseline analysis. The average $y_{\text{whim}}$ signal in the central region $-0.5 < X < 0.5$ and $-0.5 < Y < 0.5$ is $(2.4 \pm 0.4) \times 10^{-8}$. The error bar on the measured average $y_{\text{whim}}$ signal is derived from the misalignment technique. If we also combine the PL48 mask with K86 mask along with the threshold criterion $\chi^2_{\text{CO}-y_{\text{whim}}} \leq 0.05$ we retain only $\approx 60000$ LRG pairs, i.e. only $\sim 60\%$ of the sample with just PL48 mask. Thus the LRGs selected by our mask vs the PL48 mask are very different with PL48 mask sample giving a signal that is $\sim 36\%$ smaller. Our
Figure 12: Same as Fig. 11, but for different combinations of Planck point source masks along with K86 mask with threshold criterion $|\chi^2_{\text{CO} - y_{\text{sz}}}| \leq 0.05$ and using 70 – 545 GHz Planck channels at 10′ beam resolution.

Figure 13: The reconstructed ILC $y_{\text{sz}}$ maps using PL48 mask and different combination of Planck channels.

$y_{\text{sz}}$ signal with PL48 mask sample is still much larger compared to the previous studies based on stacking of $y_{\text{sz}}$ maps and is in particular a 6σ detection.

Table 2: The amplitude of the average $y_{\text{whim}}$ signal in the central filament region derived from different combinations of Planck channels in the reconstruct the ILC $y_{\text{sz}}$ map, different $\chi^2_{\text{CO} - y_{\text{sz}}}$ thresholds over K86 and for different FWHMs of the raw Planck maps.

| Channel combinations | $\chi^2_{\text{CO} - y_{\text{sz}}}$ threshold with K86 | FWHM [in arcmin] | $y_{\text{whim}}$ |
|----------------------|------------------------------------------------------|------------------|-----------------|
| 70-545               | 0.05                                                 | 10               | $3.76 \times 10^{-8}$ |
| 100-545              | 0.05                                                 | 10               | $3.76 \times 10^{-8}$ |
| 70-353               | 0.05                                                 | 10               | $4.19 \times 10^{-8}$ |
| 100-353              | 0.05                                                 | 10               | $4.20 \times 10^{-8}$ |
| 70-545               | 0.05                                                 | 8                | $4.07 \times 10^{-8}$ |
| 70-545               | 0.07                                                 | 10               | $3.15 \times 10^{-8}$ |
Figure 14: Same as Fig. 9, but for the stacked ILC $\hat{y}_{sz}$ map using Planck HFI channels 70–545 GHz and PL48 mask.

8 Comparison with stacking of Planck $y_{sz}$ maps

Earlier T19 and G19 have stacked the MILCA and NILC $y_{sz}$ maps at the locations of the LRG pairs. As we argued earlier, the MILCA and NILC $y_{sz}$ maps (or any other full sky tSZ map created from Planck data such as LIL map) have significant contamination (Fig. 1), much higher compared to the signal we are interested in and there is no guarantee that the positive and negative contamination would cancel. As it turns out, there is over-cancellation, resulting in the excess negative contamination decreasing the $y_{sz}$ signal in the WHIM between two LRGs.

In this section we reproduce their results and in particular show that we get results consistent with T19 and G19 when we also stack the $y_{sz}$ maps. We stack on the publicly available MILCA,
NILC and LIL $y_{sz}$ maps at the location of LRG pairs with K86 mask and selection threshold of $|\chi^2_{\text{CO}-y_{sz}}| < 0.05$. The stacking method for $y_{sz}$ maps is identical to the one we used for the Planck frequency channel maps as described in Sect. 4. We estimate the local background signal for each LRG pair in the annular region $9 < r < 10$ ($r^2 = X^2 + Y^2$) and subtract it to get the excess $y_{sz}$ signal above the background. We see two clear peaks at the position of LRG’s along with a bridge connecting the two peaks. The extended $y_{sz}$ signal at the peaks is due to the $y_{sz}$ as well as galactic emission from the two LRGs. After subtracting the LRG halo contribution, we get average $y_{\text{whim}} \sim (1.86 \pm 0.30) \times 10^{-8}$ in the region between the LRGs, i.e. $-0.5 \leq X \leq 0.5$ and $-0.5 \leq Y \leq 0.5$, from the stacked MILCA $y_{sz}$ map. The $1\sigma$ errorbar is derived from the misalignment technique. The result of stacking analysis from MILCA $y_{sz}$ map is shown in Fig. 15. We also use the other two publicly available $y_{sz}$ maps for the stacking analysis. Over the same filament region, we get the average $y_{\text{whim}} \sim 1.88 \times 10^{-8}$ from NILC map and $y_{\text{whim}} \sim 3.47 \times 10^{-8}$ from LIL map. The WHIM signal we get from the stacking of LIL $y_{sz}$ map is close to the one we obtained from our “Stack First” approach.

We also repeat the analysis of T19 by using PL48. The results are presented in Fig. 16. The WHIM $y_{sz}$ signal in the filament region between the LRG pairs is $y_{\text{whim}} = (1.50 \pm 0.22) \times 10^{-8}$, consistent with the value we got above with our custom K86 mask and $\chi^2_{\text{CO}-y_{sz}}$ based selection criteria. Our results are also consistent within $1\sigma$ errorbars to the reported excess $y_{sz}$ signal of $(1.31 \pm 0.24) \times 10^{-8}$ in T19. As argued above, and shown by our results from stacking the individual frequency maps, stacking $y_{sz}$ maps gives biased results due to only partial cancelation of the positive and negative contaminations.

Figure 15: Same as Fig. 9, but for the stacked MILCA $y_{sz}$ map with the threshold criterion $\chi^2_{\text{CO}-y_{sz}} \leq 0.05$ and K86 mask.
Figure 16: Same as Fig. 15, but for the stacked MILCA $y_{hz}$ map and PL48 mask.
9 Conclusion

We have presented a new Stack First approach aimed at detection of weak $y_{\text{sz}}$ signals in stacked objects in the Planck data. The important new ingredient in our recipe is to first stack the individual frequency channel maps and then perform blind component separation. In our approach, the component separation problem that the blind separation algorithm should solve is simpler compared to the common method of first doing component separation and then stacking. This is because the noise as well as the CMB contribution is suppressed due to stacking at random locations and the stacked dust signal becomes spatially uniform in its spectrum. In order to avoid regions with CO contaminations, present in all the Planck HFI channels excluding 143 GHz, as well as strong background and foreground SZ sources, we use an additional mask based on the $\chi^2_{\text{CO}} - y_{\text{sz}}$ thresholds. The $\chi^2_{\text{CO}} - y_{\text{sz}}$ map [24] indicates whether CO emission or $y_{\text{sz}}$ signal fits the Planck data better in addition to the dust and CMB emission. For the weak, noise dominated, sources we are interested in, we should not be able to distinguish between CO and SZ, and thus choose pixels with $\chi^2_{\text{CO}} - y_{\text{sz}}$ close to 0. We restrict our analysis to a limited range of $\chi^2_{\text{CO}} - y_{\text{sz}}$ values, i.e. $|\chi^2_{\text{CO}} - y_{\text{sz}}| \leq 0.05$ to get a cleaner sample of LRG pairs for the stacking analysis. Our approach is different than T19 and G19, as they consider the stacking of the MILCA and NILC $y_{\text{sz}}$ maps at high Galactic latitude without taking into account the residual CO emission and $y_{\text{sz}}$ emission from the background/foreground sources in the $y_{\text{sz}}$ maps. We present our main conclusions below.

- We find the WHIM signal between the LRG pairs to be $y_{\text{whim}} = (3.76 \pm 0.44) \times 10^{-8}$. We have thus detected WHIM at a significance level of $\sim 8.5\sigma$ ignoring systematic contamination and $\sim 8.1\sigma$ taking into account mean systematic bias.

- We find the signal is robust with respect to using different channel combination and masks.

- Our results are consistent with the expectations for the WHIM from hydrodynamic cosmological simulations [16, 17, 46].

- Our WHIM signal is higher compared to the results of T19 and G19. The difference is most likely coming from incomplete cancelation of positive and negative contamination when directly stacking $y_{\text{sz}}$ maps.

- The WHIM (dominant baryonic component in the filaments of the cosmic web), exists in a wide range of temperatures and densities. Assuming an average temperature of $5 \times 10^6$ K indicated by simulations, we find that the overdensity in filaments is $\sim 13$ in agreement with the expectations from simulations of $\sim 10 - 40$ [16].

We therefore conclude that we have detected the missing baryons in the local Universe using the thermal Sunyaev-Zeldovich effect in the Planck data at a significance $> 8\sigma$.

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