Cross Relate Tidal Reconstructed 21cm Signal with Kinematic Sunyaev-Zel'dovich Effect: A New Probe for Missing Baryons at Redshift 1

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(Dated: March 20, 2016)

21cm intensity mapping has emerged as a promising technique to map the large scale structure of the Universe, at redshifts z from 1 to 10. Unfortunately, many of the key cross correlations with photo-z galaxies and the CMB have been thought to be impossible due to foreground contamination for radial modes with small wavenumbers (copied). These modes are usually subtracted in the foreground subtraction process. We recover lost 21cm radial modes via cosmic tidal reconstruction and find more than 60% cross correlation signal at $\ell \lesssim 100$ and even more on larger scales can be recovered from null. The tidal reconstruction method opens up a new set of possiblities to probe our Universe and is extremely valuable not only for 21cm surveys but also CMB and photometric redshift observations.

PACS numbers:

INTRODUCTION

Over past decades, a deficiency of baryons in local universe has been noticed comparing to the baryon density of the early universe , which was fixed by the cosmic microwave background,Big Bang Nucleosynthesis and Lyman-α forest[**?**][**?**][**?**][**?**]. At $z2$ the observed baryons in collapsed objects such as galaxies, galaxy clusters and groups only account for 10% of the predicted amount. More baryons are believe to reside in Warm-Hot Intergalactic Mediums (WHIM) with typical temperature of 10^5 K to 10^7 K[**?**]. Due to low density and relatively low temperature, it is difficult to measure. Over the years, continuous effort has been made to detect this part of the baryons, using absorption lines of hydrogen and metal in different ionizations states(eg, HI, Mg II,Si II, C II, Si III, C III, Si IV, O VI, O VII).[**?**][**?**] However, these detections are usually limited to circumgalactic medium, while at least 25% of the baryons are in more diffused region[**?**]. Moreover, the uncertainty in metalicity would reduce the reliability.

A possibly more promising tool to probe the missing baryon may be the kinetic Sunyaev-Zel'dovich(kSZ) effect[**?**][**?**]. It refers to the secondary temperature anisotropy in CMB caused by radial motions of free electrons. It is promising because: first, it gives an integrated signal coming from all the electrons, so we should in principle be able to find signals of all baryons as long as they have ionized electrons; second, unlike thermal SZ effect, kSZ signal is only related to the density and velocity of the electrons, and is less confined to collapesed objects with higher thermal temperature and electron pressure. Moreover, since the prominent contribution to the velocity field comes from large scale structures, it is less biased towards local high density and therefore serve as better probe for total baryon distribution.

Due to the contamination from primary CMB and residual thermal SZ signal, as well as the loss of redshift information, it is not easy to measure ksz signal by itself. Previous approches tend to cross relate the CMB temperature anisotropy with galaxy surveys. whether using pairwise-momentum estimator[**?**] or velocity-field-reconstruction estimator[**?**][**?**], a common requirement is that they need spectroscopy of galaxies to provide accurate redshift. And this largely limit the volume and redshift range to apply the method. A fairly recent effort try to fix this by using photometries of infrared-selected galaxies, and cross relate them with squared ksz signal. However, since they used projected fields of the galaxies, they lost the information of individual redshift[**?**].

In this paper, we present a new cross relating source—neutral hydrogen density field, that may help probe the baryon content to redshift one in very near future. The field can be obtained from 21cm intensity mapping surveys, a kind of survey that integrate spectrum of diffuse line radiation rather than detect individual objects. It is designed to detect weak, diffuse HI signals, and therefore can be easily extended to probe higher redshift universe. Moreover, the 21cm spectrum contains relatively accurate redshift information, which makes it a good candidate to cross relate with kSZ signals. However, it also has a great drawback. The continuum foregrounds of 21cm measurement could be $10^2 - 10^3$ times brighter than cosmological signal, almost completely bury the information about large scale density field in radial direction, i.e. modes with small $k_\parallel$. On the other hand, the large scale structure make contributions to the distribution of velocity, which make the corelation seem nearly impossible previously.

However, a new method called *cosmic tidal reconstruction* has been developed recently[**?**][**?**], it can reconstruct the large scale density field from the alignment of small scale cosmic structures. Applying it, we will be able to cross correlate the kSZ signal with 21cm density field.

The paper is organized as follows. In section II, we introduce the tidal reconstruction methods, and how to use the reconstructed density field to correlate with the kSZ signal. In section III, we address the simulation setup and results. In section IV, we discuss the error scale and future applications.

ALGORITHM

Cosmic Tidal Reconstruction

The basic idea of cosmic tidal reconstruction is using small scale filamentary structures to solve for the large scale tidal shear and gravitational potential. It is in principle a type of quadratic statistics on local anisotropy.

The basic steps are as follows.

First, we filter for the part of information corresponding to linear small scale structure from the 21cm density field.

To achieve this, (1) Convolve the field with a Gaussian kernal $S(\boldsymbol{k}) = e^{-k^2 R^2/2}$, we take $R = 1.25\ \mathrm{Mpc}/h$ [?][?], and expect it to filter out the nonlinear structures in small scales. (2) Gaussianize the smoothed field, by taking $\delta_g = \ln(1+\delta)$, this is to alleviate the problem that the filter we apply in next step heavily weights the high density region. (3) Convolve with filter $W_i(\boldsymbol{k})$ which filters for the small scale structures, $W_i(\boldsymbol{k}) = (\frac{P(k)f(k)}{P_{tot}^2(k)})^{\frac{1}{2}}\hat{k}_i$, where i corresponds to k_x, k_y directions, $P_{tot} = P + P_{noise}$ is the observed powerspectrum, f is a function related to the redshift and linear growth funcion of the universe, see [?]. [1]

Second, we reconstruct the large scale density field from tidal shear field.

(1) Estimate the tidal shear fields from density variance. To avoid error caused by peculiar velocity, we only consider the shear field in tangental plane (perpendicular to the line of sight). $\gamma_1 = (\delta_g^{w1})^2 - (\delta_g^{w2})^2$, $\gamma_2 = 2\delta_g^{w1}\delta_g^{w2}$. (2) Reconstruct 3D density field from Possion equations.

$$\kappa_{3D}(\boldsymbol{k}) = \frac{2k^2}{3(k_1^2 - k_2^2)^2}[(k_1^2 - k_2^2)\gamma_1(\boldsymbol{k} + 2k_1 k_2 \gamma_2(\boldsymbol{k})] \ . \quad (1)$$

Third, we correct bias and control noise with a Wiener filter.

From Eq.(1) we can infer that the error of $\kappa_{3D}(\boldsymbol{x})$ is $\sigma_{k3d}(\boldsymbol{k}) \propto (\frac{k^2}{k_\perp^2})^2$, where $k_\perp$ refers to modes that are tangental. The anisotropy in $k_\perp$ and $k_\parallel$ is due to the discard of information about radial shear field. To control the large noise corresponds to small k_perp, we apply filter to calculate the clean large scale density field$\hat{\kappa}_c$:

$$\hat{\kappa}_c(\boldsymbol{k}) = \frac{\kappa_{3D}(\boldsymbol{k}}{b(k_\perp, k_\parallel)} W(k_\perp, k_\parallel) \ , \quad (2)$$

[1] The effect of the filter W_i on different scales could be seen in Appendix 1.

where the bias $b = \frac{P_{k3D\delta}}{P_\delta}$, Wiener filter $W = \frac{P_\delta}{P_{k3D}/b^2}$, here and afterwards, we use $\wedge$ to denote recontructed fields.

Velocity Reconstruction and kSZ signals

The temperature fluctuations caused by kSZ effect is:

$$\Theta_{kSZ}(\hat{n}) \equiv \frac{\Delta T_{kSZ}}{T_{CMB}} = -\frac{1}{c}\int d\eta g(\eta)\boldsymbol{p}_\parallel \ , \quad (3)$$

where $\eta(z)$ is the comoving distance at redshift z, $g(\eta) = e^{-\tau} d\tau/d\eta$, τ is the optical depth to Thomson scattering, $\boldsymbol{p}_\parallel = (1+\delta)\boldsymbol{v}_\parallel$, with δ the electron overdensity.

Since direct cross correlations between kSZ signal and density field will vanish due to the cancellation of positive and negative velocity, we first construct a 3D velocity field[?] from the clean large scale density field κ_c.

In linear region, the continuity equation goes like: $\dot{\delta} + \nabla \cdot \boldsymbol{v} = 0$, where $\boldsymbol{v}$ is the peculiar velocity and δ is the matter overdensity. Since the 21cm density field is believed to well trace the dark matter fields in low redshift, we use κ_c here, instead of δ.

Therefore, we get velocity field:

$$\hat{v}_z(\boldsymbol{k}) = iaH\frac{d\ln D}{d\ln a}\kappa(\boldsymbol{k})\frac{k_z}{k^2} \quad (4)$$

where D(a) is the linear growth function.

As we can see, $v_z \propto \frac{k_z}{k^2}$, indicating the most prominent signal comes from small k mode, which corresponds to large scale structure. This partly consolidate our motivation for the tidal reconstruction procedure.

To compare with the original kSZ signal, we calculate the $\hat{\Theta}(\boldsymbol{n})$ using reconstructed velocity field.

However, before apply Eq.(3) we notice that the additional term $\frac{k_z}{k^2}$ in Eq.(4) will strongly amplify the noise in small k modes. Therefore, we apply a Wiener filter similar to Eq.(2) for the velocity field.

Then we use the orignal 21cm density field as δ, and reconstruct the kSZ signal following Eq.(3). We compare it with the original signal directly from simulations.

SIMULATIONS

Simulation Set up

We test the feasibility of the idea with numerical simulations. To quantify how well the algorithm perform, we employ a quantity r to show the tightness of correlation.

$$r \equiv \frac{P_{recon,real}}{\sqrt{P_{recon}P_{real}}} \quad (5)$$

We employ an ensemble of six N-body simulations from the CUBEP^{3}M code [?]. Each simulation includes 2048^3

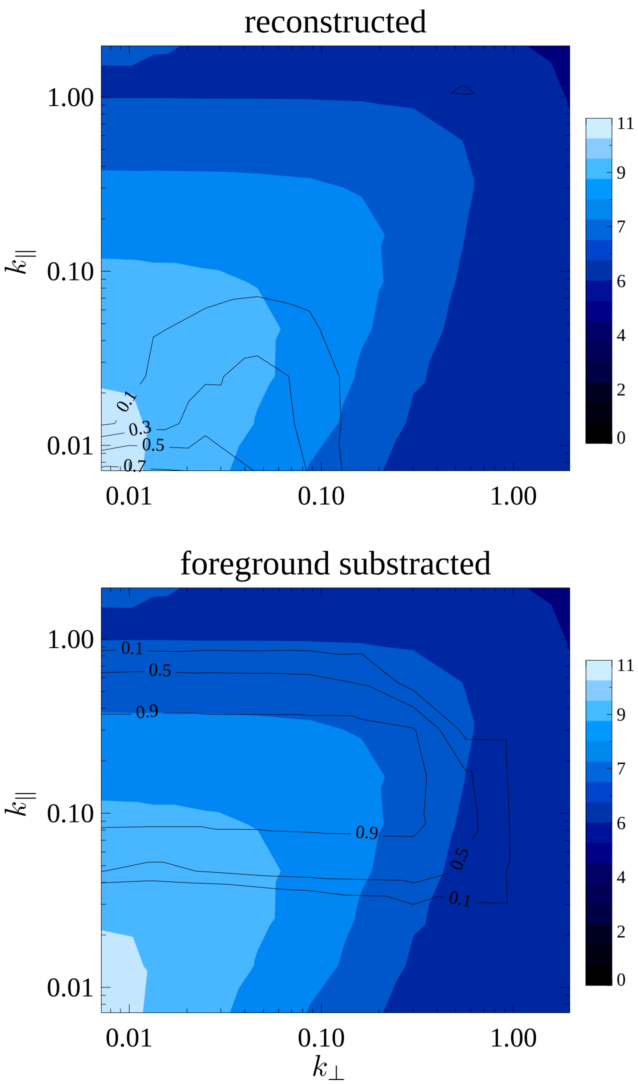

FIG. 1: (Top) the correlation $r(k_\perp, k_\parallel)$ between the real velocity field v_z^{real} and $\hat{v}_z$ from the tidal reconstructed field; (bottom) the correlation r between v_z^{real} and v_z^{fs} from the foreground substracted field. The background color indicating the level of powerspectrum of v_z^{real} in logrithm, $lg(P_{v_z^{real}})$

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particles in a $(1.2\mathrm{Gpc}/h)^3$ box. In the following analysis we use outputs at $z = 1$.

For simplicity, we assume the experimental noise to be zero above a cut off scale and infinity below the cut off scale. This is a reasonable approximation for a filled aperture experiment, which has good brightness sensitivity and an exponetially growing noise at small scales. We choose this scale to be $k_c = 0.5\ h/\mathrm{Mpc}$, which corresponds to $\ell = 1150$ at $z = 1$. This is realistic for the ongoing 21cm experiments like CHIME [**?**][**?**] and Tianlai [**?**][**?**]. copied

To mimic the influence of foreground substraction, we use a high pass filter $W_{fs}(k_\parallel) = 1 - e^{-k_\parallel^2 R_\parallel^2/2}$. We choose $R_\parallel = 15\ \mathrm{Mpc}/h$, which gives $W_{fs} = 0.5$ at $k_\parallel = 0.08\ \mathrm{Mpc}/h$. This corresponds to the condition of current 21cm observations [**?**][**?**].

The observed 21cm field after foreground subtraction is given by

$$\delta_{fs}(\boldsymbol{k}) = \delta(\boldsymbol{k}) W_{fs}(k_\parallel)\Theta(k_c - k), \tag{6}$$

where $\delta(\boldsymbol{k})$ is the density field from simulations, W_{fs} accounts for the effect of foreground subtraction and $\Theta(x)$ is the step function which equals 1 for $x \geq 0$ and otherwise 0. Then we get the reconstructed clean field $\hat{\kappa}_c$ from δ_{fs} via cosmic tidal reconstruction. Using $\hat{\kappa}_c$ we obtain an estimate radial velocity field $\hat{v}_z$ as in Eq.(4). And then we reconstruct the kSZ signal following Eq.(3) and compare it with the kSZ signal from simulations.

results

We demonstrate the correlation effect of the reconstructed kSZ signal in Fig.2. The upper panel shows the powerspectrum of orginal kSZ signal P_{kSZ}, reconstructed kSZ signal from 21cm intensity mapping P_{21cm} and the cross powerspectrum of this two field P_{cross}; and the lower panel demonstrates the correlation r between reconstructed kSZ signal $\hat{\Theta}$ and the orginal kSZ signal Θ. As we can see, we have a stable 0.3 correlation from $l \sim 100$ to $l \sim 2000$, which indicates a detectable signal in real observations.

DISCUSSION

Behavior of the kSZ signal

When to apply Tidal Reconstruction

One of the main concerns about employing Cosmic Tidal Reconstruction is that it may import additional noise.

Now I am going to address under which conditions, the gain of perform tidal reconstruction will far exceeds the loss.

First, let us demonstrate the different information encorporated in the foreground substracted density field and the tidal reconstructed field. To better compare them, we calculate the velocity field directly from the foreground substracted field. In Fig.1, the upper panel shows the correlation $r(k_\perp, k_\parallel)$ between the real velocity field v_z^{real} from simulation and v_z^{fs}; the lower panel shows the correlation r between v_z^{real} and $\hat{v}_z$. The background color indicating the level of powerspectrum of v_z^{real}. As we can see, the tidal reconstruction procedure really retrieve the part of velocity that matters most. Moreover, if we further calculate kSZ signal with the foreground substracted field, its correlation coefficient r with the original signal will be close to 0.

To better understand the reason, let's write Eq.(3) in Fourier space.

$$\Theta(\boldsymbol{k}_\perp) \equiv \Theta(k_x, k_y, 0) = \int d^3k\, \delta(\boldsymbol{k}) v_z(\boldsymbol{k}_\perp - \boldsymbol{k}) \tag{7}$$

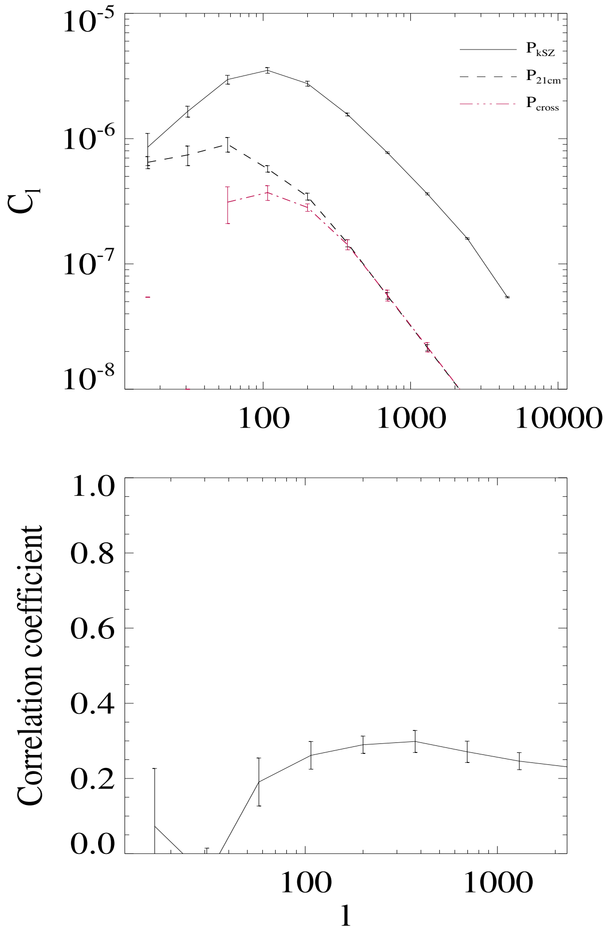

FIG. 2: (Top) the powerspectrum of orginal kSZ signal P_{kSZ}, reconstructed kSZ signal from 21cm intensity mapping P_{21cm} and the cross powerspectrum of this two field P_{cross}; (Bottom) the correlation r between reconstructed kSZ signal $\hat{\Theta}$ and the orginal kSZ signal Θ.

Since $v(\boldsymbol{k}) \propto \delta(\boldsymbol{k})\frac{k_z}{k^2}$, its amplitudes drops much faster than $delta(\boldsymbol{k})$ when k gets larger, therefore could be consider as delta function in original signal when $k_\perp >> 0.01$. However, as the foreground contaminate the large scale signal, we loose the peak in delta function and hence select total different part of the δ in the mock kSZ signal. On the other hand, when we perform the Tidal Reconstruction, we retrieve the modes with small k_z and tolerable $k_\perp$, we partly recover the delta function, and get correlated signal.

The correlation coefficient is not very high, because the drawback that we lost the smallest $k_\perp$ modes. So there is a optimal situation, when we still have the information in k 0.1, then we would be able to retrieve better kSZ signal without tidal reconstruction.

Statistical Noise