Cross Correlate Tidal Reconstructed 21cm Signal with Kinematic Sunyaev-Zel'dovich Effect: A New Probe for Missing Baryons at $z \sim 1$

We propose a new way to study baryon abundance and distribution in local universe. We cross correlate density field from HI 21cm intensity mapping with temperature anisotropy of Cosmic Microwave Background(CMB) caused by raidal motion of free electrons, eg. kinetic Sunyaev-Zel'dovich (kSZ) effect. We apply Cosmic Tidal Reconstruction to recover the modes lost in 21cm foreground noise, and this promote the appearance of correlation signal.

The method is less biased towards local density contraction, Since kinemic motion is mainly related to large scale structures. Precise redshift information can be obtained from 21cm spectrum. The method could be easily applied to redshift much higher than current spectroscopic galaxy surveys.

We tested the idea using simulations performed on $z = 1$, with realistic foreground noise level. We successfully recover $60\% \sim 70\%$ signal of the 21cm density field at $k \sim 0.01h/Mpc$. We correlate it with kSZ signals using velocity-reconstruction method. We obtain a $r \sim 0.3$ correlation from $l \sim 100 - 2000$, which indicates a detectable signal.

Consider the large volume and high depth of current and future 21cm surveys, our proposal will compensate for the study on relating kSZ signal with spectroscopic or even photometric galaxy surveys.

PACS numbers:

I. INTRODUCTION

While the baryon abundance of early universe is well fixed by the cosmic microwave background (CMB),Big Bang Nucleosynthesis and Lyman-α forest[**?**][**?**][**?**][**?**], a deficiency was noiticed in local universe. At $z \lesssim 2$ the detected baryon content in collapsed objects, eg. 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[**?**], which is too cold and diffuse to be easily detected. Continuous effort has been made to detect this part of the baryons. One common approach is using hydrogen and metal absorption lines(eg, HI, Mg II,Si II, C II, Si III, C III, Si IV, O VI, O VII).[**?**][**?**] However, the lines are usually limited to very close circumgalactic medium, while at least 25% of the baryons are bebieved to reside in more diffused region[**?**]. Moreover, the uncertainty in metalicity would sometimes reduce the reliability.

A promising tool to probe the missing baryon is the kinetic Sunyaev-Zel'dovich(kSZ) effect[**?**][**?**]. It refers to the secondary temperature anisotropy in CMB caused by radial motions of free electrons. Since kSZ signal only relate to electron density and velocity, regardless the temperature and pressure, and velocity field mainly results from large scale structure, the method is less biased towards hot, compact place, and provide more information on the fraction of diffused baryons.

Attractive as it is, due to the contamination from primary CMB and residual thermal SZ signal it is difficult to filter the kSZ signal without other sources. Worse still, the signal itself does not contain redshift information.

To fix this, previous approches usually cross correlate it with galaxy surveys, eg. using pairwise-momentum estimator[**?**] or velocity-field-reconstruction estimator[**?**][**?**]. However since they all require spectroscopy of galaxies to provide accurate redshift, the sky volume and redshift range to apply the method will be very limited. A recent effort try to fix this by using photometries of infrared-selected galaxies. However, since they used projected fields of the galaxies, they could only obtain a rough estimate of a wide redshift bin[**?**].

In this paper, we present a new cross relating source—neutral hydrogen density field, that may help probe the baryon content to $z \sim 1$ in very near future. The field can be obtained from 21cm intensity mapping—surveys that provide integrated signals of diffuse 21cm spectra, rather than detecting individual objects. It is designed to detect weak, diffuse HI signals, and can be easily extended to probe higher redshift universe. Moreover, the 21cm spectrum contains accurate redshift information, which makes it a good candidate to be cross correlated to kSZ signals.

This powerful probe was rarely employed in this topic previously, because the continuum foregrounds in 21cm measurements would bury the distribution of large scale structures in radial direction, i.e. modes with small $k_{\parallel}$. Meanwhile the veocity field is closely related with the large scale structure. It seems that there would be very little correlation between the two signals.

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 scales and future applications.

II. ALGORITHM

A. 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.

(1) Convolve the field with a Gaussian kernal $S(\boldsymbol{k}) = e^{-k^2R^2/2}$, we take $R = 1.25$ 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 allieviate 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, $W_i(\boldsymbol{k}) = (\frac{P(k)f(k)}{P^2_{tot}(k)})^{\frac{1}{2}}\hat{k}_i$, 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.

$$\kappa_{3D}(\boldsymbol{k}) = \frac{2k^2}{3(k_1^2-k_2^2)^2}[(k_1^2-k_2^2)\gamma_1(\boldsymbol{k}+2k_1k_2\gamma_2(\boldsymbol{k})] \ . \quad (1)$$

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$\hat{\kappa}_c$:

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

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.

B. Velocity Reconstruction and kSZ signals

The temperature fluctuations caused by kSZ effect is:

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

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 $\hat{\kappa}_c$.

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

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.

III. SIMULATIONS

A. 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 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

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

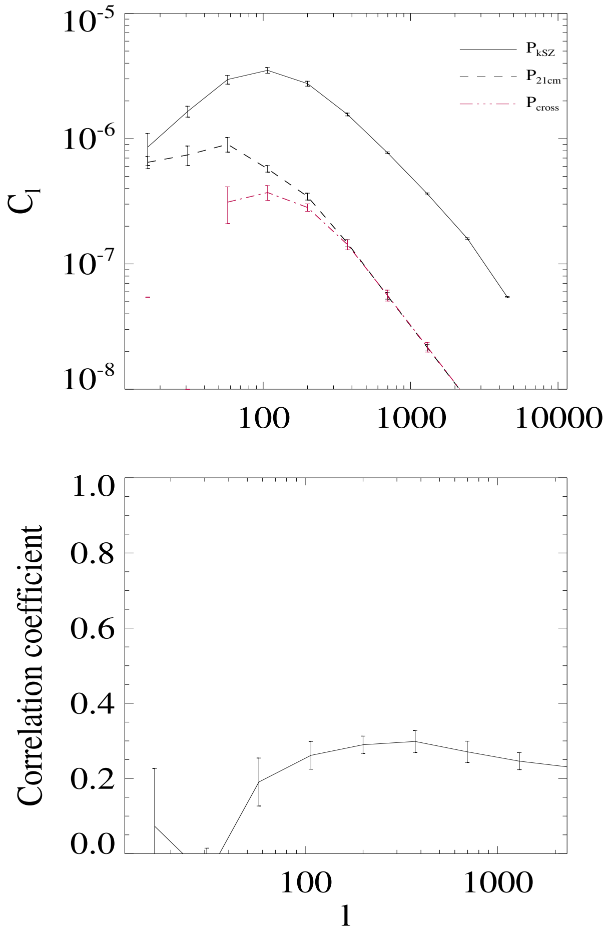

FIG. 1: (Top) the powerspectrum of orginal kSZ signal P_{kSZ}, reconstructed kSZ signal from 21cm intensity mapping P_{21cm} and the cross powerspectrum of this two field P_{cross}; (Bottom) the correlation r between reconstructed kSZ signal $\hat{\Theta}$ and the orginal kSZ signal Θ.

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.

B. Results

We demonstrate the correlation effect of the reconstructed kSZ signal in Fig.1. 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.

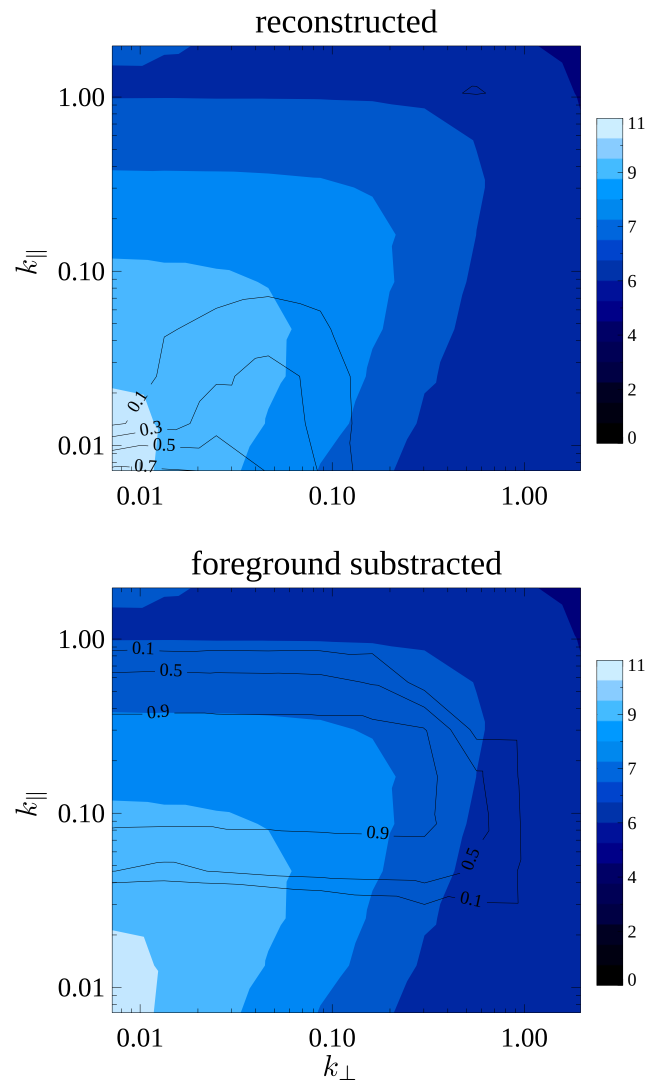

FIG. 2: (Top) Contour shows the correlation $r(k_\perp, k_\parallel)$ between the real velocity field v_z^{real} and $\hat{v}_z$ from the tidal reconstructed field; (Bottom) contour shows the correlation r between v_z^{real} and v_z^{fs} from the foreground substracted field. The background color indicating the level of powerspectrum of v_z^{real} in logrithm, $lg(P_{v_z^{real}})$

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IV. DISCUSSION

A. Why/When Tidal Reconstruction

One of the main concerns about employing Cosmic Tidal Reconstruction is that it will import additional noise. The question is when and why the gain will worth the loss.

To demonstrate the gain and loss, we calculate the velocity field v_{fs} from the foreground substracted field δ_{fs}, following identical procedure. In Fig.2, contours in upper panel show the correlation $r(k_\perp, k_\parallel)$ between the real velocity field v_z^{real} and v_z^{fs}; contours in lower panel show 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, although importing large noise to large k modes, the tidal reconstruction procedure retrieve small k modes that corresponds to larger $|v(k)|$. This part of signals play a more important role in kSZ signals. Moreover, if we calculate kSZ signal with the foreground substracted field, its correlation coefficient r with the original signal will remain 0 until $l \sim 1000$.

To better understand the behavior of kSZ signal, we write Eq.(3) in Fourier space.

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

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. So $\Theta(\boldsymbol{k}_\perp) \sim \delta(\boldsymbol{k}_\perp)$

However, as the foreground contaminate the small k modes, we lose the original peak in $v(k)$ and hence select different part of δ in mock kSZ signal.

On the other hand, when we perform the Tidal Reconstruction, we retrieve the modes with small k_z and tolerable $k_\perp$, which is close to the original peak in $v(k)$ and therefore enable us to get correlated signals.

However, we have to noitice that by performing Tidal Reconstruction, we lost parts of small $k_\parallel$ modes(discussed in [**?**]), which explains why we do not get a better correlation.

Judging from Fig.2 and previous statement, we claim that in an optimal case—the foreground noise is low and removed cleanly —we have at least half density field structure remains at $k \sim 0.02$ Mpc/h, i.e. choose $R_\parallel = 60$ Mpc/h, it is a better choise to apply cross correlation directly using the original field.

In all, the tidal reconstruction method is not designed to help us find the optimal correlation of the two signals, it is more like a safe belt that enable us to find a detectable correlation even when the measurement is not optimal. If you have good 21cm measurements, then perform the cross correlation directly, you will be likely to get good results; however, if measurements do not go well, with the tidal reconstruction, it is still feasible to perform the cross correlation, and get some trial results —that is the value of the method.

B. Statistical Error in Real Surveys

In real surveys, when we calculate the cross angular power spectrum C_l between reconstructed kSZ signals and CMB measurements, we will have to face statistical errors. They can be approximated as:

$$\frac{\Delta C_l}{C_l} \simeq \frac{1}{2rl\Delta l f_{sky}} \sqrt{\frac{C_l^{\mathrm{CMB}} + C_l^{ksz} + C_l^{\mathrm{CMB},N}}{C_{kSZ,\Delta z}(1 + \frac{C_{\hat{\Theta}}^N}{C_{\hat{\Theta}}})}} \quad (8)$$

V. ACKNOWLEDGE