# 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 effectively promote the apprearance 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 $k \sim 0.01 h/Mpc$ after tidal reconstruction. 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-$\alpha$ forest [1][2][3][4], 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 [5], 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) [6][7]. 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 [8]. 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 [9][10]. It refers to the secondary temperature anisotropy in CMB caused by radial motions of free electrons. Since kSZ signal only correlates 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 [11] or velocity-field-reconstruction estimator [12][13]. 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 [14].

In this paper, we present a new cross relating source—neutral hydrogen density field, that makes it feasible to 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 harnessed in this topic previously, because the continuum foregrounds in 21cm measurements is typically $10^2 - 10^3$ times brighter than cosmological signals, almost completely 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, which makes the correlation difficult to see.

Fortunately, a new method called *cosmic tidal reconstruction* has been developed recently [15][16]. 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 present the complete procedure and simulation results: In II A, we introduce the tidal reconstruction method; in II B, we address how to use reconstructed field to cross correlate with kSZ signal. in II C, we describe simulation set up and demonstrate results. In section III, we explain the necessity of applying tidal reconstruction, presenting correlation results with non-tidal-reconstructed fields. In section IV, we estimates the statistical errors for real surveys. In section V, we give conclusions and discuss future applications.

## II. COMPLETE PROCEDURE AND SIMULATION RESULTS

### A. Cosmic Tidal Reconstruction

Motivation: recover large scale information of 21cm density field, which is contaminated in foreground emission.

Main idea: using small scale filamentary structures to solve for the large scale tidal shear and gravitational potential.

Method: quadratic statistics on local anisotropy.

Detailed 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 $S(\boldsymbol{k}) = e^{-k^2 R^2/2}$, we take $R = 1.25$ Mpc/$h$ [15][16], 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, $W_i(\boldsymbol{k}) = (\frac{P(k)f(k)}{P_{tot}^2(k)})^{\frac{1}{2}}\hat{k}_i$, 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 [16]. [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 $k_p erp$, 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

Due to the cancellation of positive and negative velocity, direct cross correlation between kSZ signal and density field

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

will vanish. Therefore, we first estimate the peculiar velocity from the 3D density field, then construct the 2D map of kSZ signal, finally correlate it with the real kSZ signal [12].

Detailed steps are as follows.

(1) Estimate the velocity field.

In linear region, the continuity equation goes like: $\dot{\delta} + \nabla \cdot \boldsymbol{v} = 0$, where $\boldsymbol{v}$ is the peculiar velocity and $\delta$ is the matter overdensity.

Therefore, we obtain an estimator of velocity distribution:

$$\hat{v}_z(\boldsymbol{k}) = iaH\frac{d\ln D}{d\ln a}\delta(\boldsymbol{k})\frac{k_z}{k^2} \quad (3)$$

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 further verify our motivation for tidal reconstruction procedure.

(2) suppress the noise in velocity field with a new Wiener filter.

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

(3) calculate the 2D kSZ map.

The CMB temperature fluctuations caused by kSZ effect is:

$$\Theta_{kSZ}(\hat{n}) \equiv \frac{\Delta T_{kSZ}}{T_{\mathrm{CMB}}} = -\frac{1}{c}\int d\eta g(\eta)\boldsymbol{p}_\parallel , \quad (4)$$

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

We assume that $g(\eta)$ doesn't change significally in one redshift bin, and integrate $\boldsymbol{p}_\parallel$ along radial axis to get $\hat{\Theta}_{kSZ}$

### C. 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 [17]. 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 $k_c = 0.5$ $h$/Mpc, which corresponds to $\ell = 1150$ at $z = 1$. This is realistic for the ongoing 21cm experiments like CHIME [18][19] and Tianlai [20][21]. 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 = $
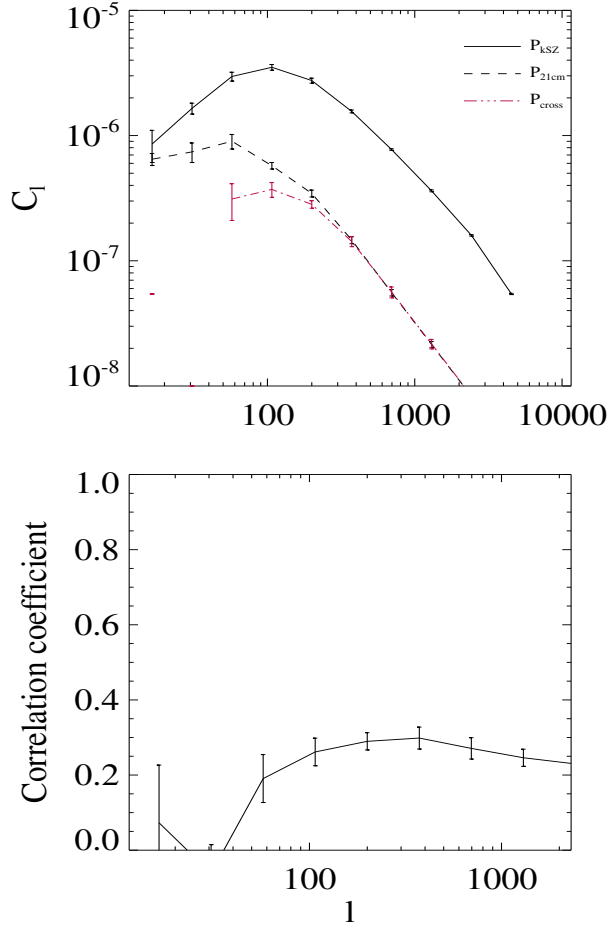
FIG. 1: (Top) the powerspectrum of orginal kSZ signal $P_{kSZ}$, reconstructed kSZ signal from 21cm intensity mapping $P_{21cm}$ and the cross powerspectrum of this two field $P_{cross}$; (Bottom) the correlation r between reconstructed kSZ signal $\hat{\Theta}$ and the orginal kSZ signal $\Theta$.

15 Mpc/$h$, which gives $W_{fs} = 0.5$ at $k_{\parallel} = 0.08$ Mpc/$h$. This corresponds to the condition of current 21cm observations [22][23].

The observed 21cm field after foreground subtraction is given by

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

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 $\delta_{fs}$ via cosmic tidal reconstruction. Using $\hat{\kappa}_c$ we obtain an estimate radial velocity field $\hat{v}_z$ as in Eq.(3). And then we reconstruct the kSZ signal following Eq.(4) and compare it with the kSZ signal from simulations.

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
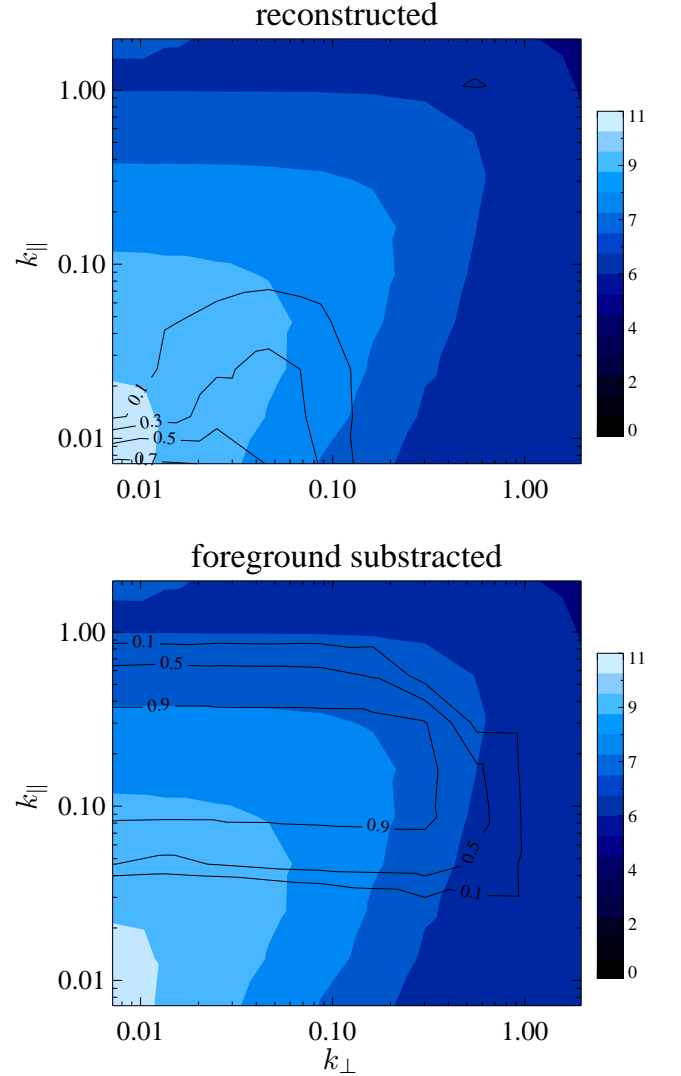


FIG. 2: (Top) Contour shows the correlation $r(k_{\perp}, k_{\parallel})$ between the real velocity field $v_z^{real}$ and $\hat{v}_z$ from the tidal reconstructed field; (Bottom) contour shows the correlation r between $v_z^{real}$ and $v_z^{fs}$ from the foreground substracted field. The background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

## III. 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 $\delta_{fs}$, 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 be-

tween $v_z^{real}$ 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.(4) in Fourier space.

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

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 $\delta$ 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 [16]), 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.

## IV. 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:

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

## V. CONCLUSION AND FUTURE APPLICATION

## VI. ACKNOWLEDGE

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