21cm Intensity Mapping + kSZ Effect: a Handy Probe for Larger Scale, Wider Redshift Baryon Distributions

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(Dated: December 26, 2016)

The prominent defficiency of baryons in observations at $z \lesssim 2$ ([relative to extrapolation from Big Bang Nucleosynthesis?]) and its poorly understood relationship with stellar feedback and the local conditions of the intergalactic medium stand in the way of understanding the evolution of structure in the universe. [Best to use active sentences.] The kinematic Sunyaev-Zel'dovich (kSZ) distortion of the Cosmic Microwave Background (CMB) has been proposed as a method for measuring these diffuse 'missing baryons' directly, on large-scales. However, the faintness and lack of redshift information of the method limit its usefulness, suggesting cross-correlation with another probe. Previous proposals require the combination of spectroscopic galaxy surveys with new generation ground based CMB experiments to obtain convincing signal-to-noise (S/N). This induces constraints on redshift depth and sky coverage, and limit the study to scales larger than $\ell < 2000$. [Do you need to discuss the exact scales in the abstract? It doesn't seem to help your argument.] In this paper, the new possibility of cross-correlating kSZ with the neutral hydrogen (HI) density from 21 cm intensity mapping is discussed. [Using what technique: theory, N-Body, ...?] Ongoing experiments, such as CHIME, will, in next few years, measure the HI distribution at $z \lesssim 2.5$ over large fractions of the sky. These experiments will be sensitive to structure evolution at $\ell \sim 1000 - 2000$, the scale of clusters and filaments. [Again is this necessary in the abstract? Also ℓ of 1000 seems very high, do you mean ℓ of 100?] The greatest challenge for our method is the loss of large-scale 21 cm modes due to the combined effects of foreground filtering and spatial loss of interferometers [What does this mean? If you mean that telescopes have a finite field of view, and so do not measure the whole sky, then I would call it that: finite field of view. If you mean that interferometers are not sensitive to the small modes within their field of view, than my feeling is that this is not correct. Telescopes like CHIME should be sensitive to all modes up to their angular resolution.] We alleviate this problem by applying non-linear tidal reconstruction to recover the long-wavelength modes. A minimum S/N of 15 for both redshifts 1 and 2 could be reached with a cross-correlation of CHIME and Planck. Interferometers with longer baselines, such as HIRAX, will produce S/N reaching ~ 50 at redshift 2.

PACS numbers:

I. INTRODUCTION

For $z \lesssim 2$, a large fraction of the predicted baryon content is missing in observations. The majority of these baryons are believed to reside in the warm-hot intergalactic medium (WHIM), with typical temperatures of 10^5 K to 10^7 K [1, 2]. Its high temperature and associated low density impose difficulties for direct detection. Furthermore, the uncertainty in the spatial distribution of its ionization state, metalicity, and pressure lead to confusion in interpreting signals from absroption lines and soft X-rays. There is therefore an urgency for probes that not only trace the majority of the missing baryons, but also can be interpreted model-independently.

Among proposed probes, the kinematic Sunyaev-Zel'dovich (kSZ) effect [3–5] is a promising one. The kSZ effect results from Compton scattering of Cosmic Microwave Background (CMB) photons off of free electrons. The radial velocity of the electrons provides a Doppler shift to the photons causing a secondary anisotropy in CMB temperature. It is an ideal probe to tackle the missing baryon problem: First, it recieves a contribution from all the free electrons, and hence contains information from $\gtrsim 90\%$ of baryons which are in ionized states. [Do you mean its sensitive to 90% of the ionized photons or that the ionization fraction is 90% at the redshifts we are interested in?] Second, the signal is mainly influenced by the electron density and radial velocity, regardless of the temperature, pressure, and metalicity, so no extra assumptions are needed to estimate the baryon abundance. Third, the dominant piece of the peculiar velocity signal comes fromt the large-scale structure, and therefore the signal is less biased by the local environment, and more indicative of the diffuse distribution.

Attractive as it is, two drawbacks largely reduce the feasibility of harnessing the kSZ signal. First, the signal is weak compared to the primary CMB anisotropies and hence suffers seriously from contaminations from the primary, instrumental noise, the thermal SZ effect, CMB lensing, etc . . . Second, it is an integrated effect along the line of sight and does not contain redshift information.

Cross correlation of the kSZ signal with another tracer, which has both large-scale structure and redshift information, provides a straight-forward mitigation of these disadvantages. Previous work has proposed optical spectroscopic surveys as an ideal tool [6–8]. However, the lack of prominent spectral lines at redshift $1.4-2.5$ makes it difficult to consistently measure evolution from $z=2$ to $z=0$. Moreover, the difficult technical specifications required for source detection, especially at high redshift, largely constrain the sky coverage and limit such surveys to relatively small angular scales, where the power from the primary CMB is low. Methods which relax requirements on density fields [not sure what you mean here], such as cross-correlation of photo-z galaxies with kSZ [9, 10], depend on models of velocity fields and demand next generation CMB facilities, such as ACTpol, CMB-S4, to achieve convincing S/N.

In this paper, the new possibility of cross-correlating the neutral hydrogen (HI) density field from 21 cm intensity mapping (IM) experiments with the kSZ signal is discussed. [Using what methods: theoretical, N-Body, . . . ?] The redshifted 21 cm line provides accurate redshift information, which will soon be available at $z \lesssim 2$. Intensity mapping surveys, rather than distinguishing individual galaxies, integrate [Many intensity mapping surveys integrate, while one intensity mapping survey integrates. I know this is confusing, but sorry that's how English works.] all signals in a pixel, enabling them quickly scan large areas of the sky. In the following few years, there will be several full-sky experiments producing data at redshifts $\lesssim 2.5$ [11–13].

Promising as it seems, the loss of large-scale modes in IM surveys will complicate the cross-correlation of the IM field with large-scale signals. The main challenge comes from the bright astrophysical foregrounds, which contaminate small $k_\parallel$ modes. Besides, the low resolution of IM surveys [as compared to galaxy surveys [?]] and spatial loss from inteferometers [again not sure what this means] will [reduce the S/N of the cross-correlation with the kSZ, in particular [?]]. Fig.1 shows [an illustration] of the modes of the matter density field which can be observed by [a CHIME-like] survey. A mode counting comparison with the kSZ signal (shown in Fig.2) reveals that the deficiency of $\ell < 100$ modes for constructing velocity fields is identified as the main obstacle. [the main obstacle to what? constructing velocity fields?] Therefore, in this work, we make use of an algorithm which uses non-linear tidal distortions on small scales to reconstruct the large-scale field [14, 15]. With it, velocity fields can be well reproduced. Convolving v_z with large ℓ density fields, we could at most assemble resolvable kSZ signals. [I'm not sure what you mean here. Do you mean that the method allows you to maximize the cross-correlation with kSZ?] This procedure is depicted at the bottom of Fig. 1. Final correlation is presented against different conditions. [What do you mean here? Be more specific. What conditions are being varried? Do you mean something like: Finally, we discuss the effect on the cross-correlation of varying various survey-related parameters such as . . . ?]

The paper is organized as follows: Section II introduces the method we use to cross-correlate density fields with the kSZ signal (similarly to [7]); Section III discusses the realities of 21cm IM surveys and properties of the observed fields; Section IV clarifies the important scales of the density and velocity fields in relation to the kSZ signal; Section IV describes the non-linear tidal reconstruction method for the missing large-scale modes in the IM fields; Section V presents our analytical and numerical results, while in Section VI we summarize our S/N calculations; We conclude in Section VII.

II. CROSS-CORRELATION OF DENSITY FIELDS WITH KSZ

The CMB temperature fluctuation caused by the kSZ effect is simply a line-of-sight integral of the free electron momentum field:

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

where $\eta(z)$ is the comoving distance, $g(\eta)=e^{-\tau}d\tau/d\eta$ is the visibility function, τ is the optical depth to Thomson scattering, $p_\parallel = (1+\delta_e)v_\parallel$ is the momentum field parallel to the line of sight, and $\delta_e = (\rho-\bar\rho)/\bar\rho$ is the free electron overdensity, with $\bar\rho$ denoting the average density. It is assumed that electron overdensity δ_e is closely related to baryon overdensity at $z<2$, therefore we simply use δ to denote both hereafter.

The direct correlation between kSZ and density fields vanishes due to the cancellation of positive and negative velocities. To at most retrieve the correlation, [not sure what you mean by 'to at most', how about: To produce a quantity which can correlate non-trivially,] we first reconstruct the peculiar velocity fields v_z, using the linearized continuity equation:

$$v_z(\boldsymbol{k}) = iaHf\delta(\boldsymbol{k})\frac{k_z}{k^2} \tag{2}$$

where a is the scale factor, $f=d\ln D/d\ln a$, $D(a)$ is the linear growth function, H is the Hubble parameter. [z is redshift or the third direction?]

We then reconstruct a 2D kSZ field with v_z and δ following Eq (1) [Out of curiosity, why not construct a kSZ field in each redshift bin?], and quantify the tightness of correlation between reconstructed kSZ and real kSZ with a correlation coefficient r:

$$r \equiv \frac{P_{\rm recon,real}}{\sqrt{P_{\rm recon}P_{\rm real}}} \tag{3}$$

where $P_{\rm recon,real}$ is the cross power spectrum.

III. CHALLENGES FOR 21 CM INTENSITY MAPPING

Ideally, the velocity reconstruction method discussed in the previous section should retrieve a $> 90\%$ cross-correlation with the real kSZ signal [7]. However, realistic 21 cm IM experiments can only detect density fluctuations at certain scales, as illustrated in Fig.1. Three main factors lead to the loss of modes. [Use enumerate environment for lists:]

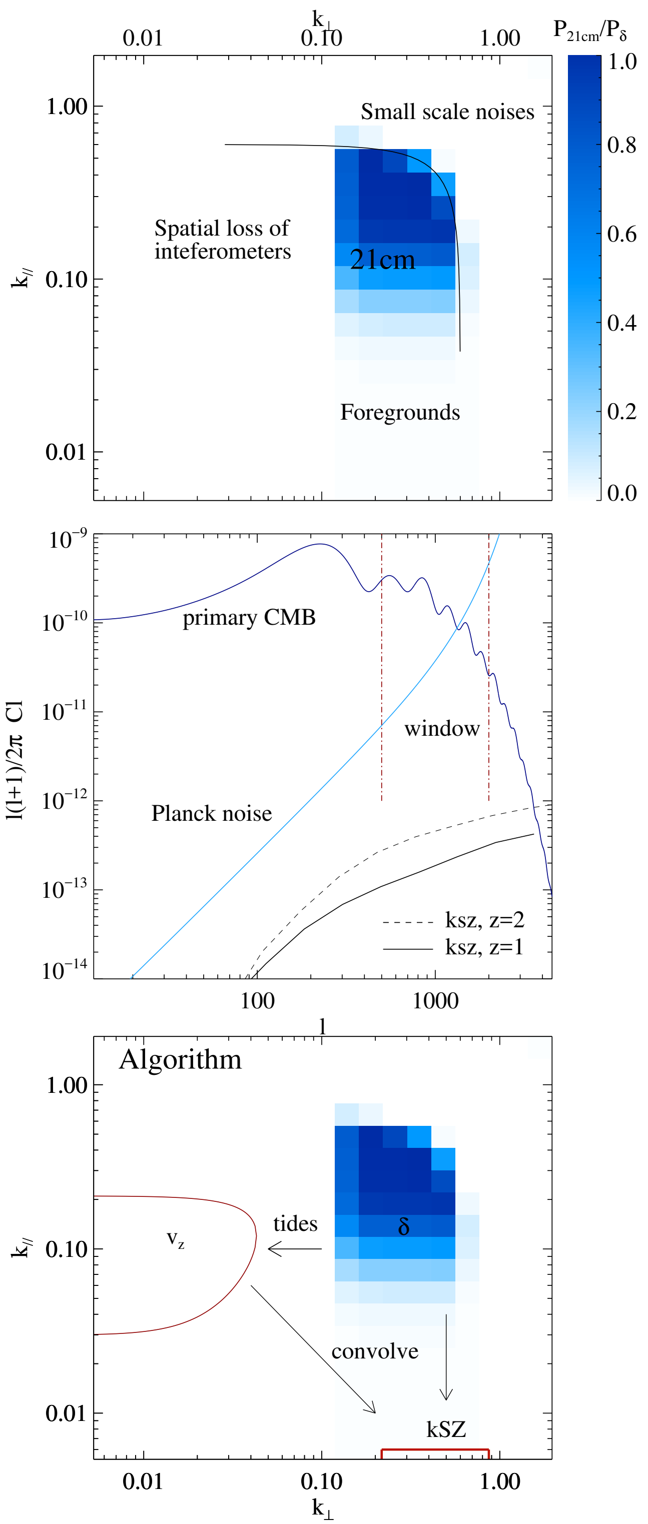

FIG. 1: (Top) Theoretical prediction for the two-dimensional power spectrum of 21 cm fluctuations at $z = 1$ observed by CHIME, assuming high foregrounds ($R_{\|} = 15$ h/Mpc) [Reference the section where this is explained]. (Middle) Window for kSZ measurements based on Planck 217 GHz band noise. The kSZ signal is calculated in 1.2 Gpc boxes. (Bottom) The kSZ signal comes from the cross talk of $v_z(\ell_{\rm low})$ with $\delta(\ell_{\rm high})$, at scales $\ell_{\rm high} - \ell_{\rm low} \sim 1000 - 2000$. Since large scale modes are lost in $\delta_{21\rm cm}$, we first reconstruct them with tidal reconstruction. [I think you are off by an order of magnitude in your wedge. See figure 9 in https://arxiv.org/pdf/1401.2095v1.pdf] [Also, I don't quite understand this schematic. If there is no overlap in $(k_{\|}, k_{\perp})$ the cross-correlation should be zero? Also if v_z large-scale but

1. The angular resolution of the telescope:

   In comparison to galaxy surveys, IM surveys sacrifice angular resolution in exchange for sky coverage and survey speed. The effect of this finite angular resolution on S/N of the cross-correlation can be roughly taken in to account with a Heaviside Function in $k_{\perp}$ space, $H(k_{\rm max} - k)$.

2. Foreground noise level:

   Foregrounds from Galactic emission, extragalactic radio sources and Radio recombination lines, together with the noise of the telescope could be three orders brighter than the targeted signal [16, 17]. The process of foreground removal, which takes advantage of the low spectral degrees of freedom of the forgegrounds [18], requires the removal of the corresponding large-scale structure in the radial direction, as well. To imitate the loss, we apply a high pass filter $W(k_{\|}) = 1 - e^{-k_{\|}^2 R_{\|}^2/2}$.

3. The shortest baseline of inteferometers:

   Current 21cm IM experiments are all carried on inteferometers. To avoid disturbance, two beams of a interferometer cannot be placed infinitely close. The shortest baseline length decides the largest angular scale it could probe. Structures with angular scale greater than a threshold of $\ell_{\rm min}$ will be lost in the 21 cm data when cross-correlating signals from distinct antennas with some minimum spacing. We again use a Heaviside function to mimick this effect. [I've already mentioned before that I don't agree with this point. CHIME is sensitive to the $\ell = 0$ mode even without auto-correlations. You lose it with forgeground filtering only.]

[In Fig. 1 Small scale noises $\rightarrow$ Small scale noise. But actually I think you should not have this there, since the noise curve is part of the Planck data, not the 21 cm data, which you can assume to be confusion limited. The real limit on the largest $k_{\|}$ for a radio telescope is the size of its frequency bins (spectral resolution).] Therefore, a realistic 21 cm density contrast will appear as

$$\delta_{\rm IM}(\boldsymbol{k}) = \delta(\boldsymbol{k}) H(k_{\rm max} - k) W(k_{\|}) H(\ell - \ell_{\rm min}). \qquad (4)$$

[Maybe say "where $k = \ell/\chi$".] Table.I lists several repre- sentive values for the different parameters introduced above, based on previous observations and predictions. Fig. 1 is an illustration of the relevant scales for the various observables, corresponding to $R_{\|} = 15$ Mpc/h, $k_{\rm max} = 0.6$ h/Mpc at $z = 1$. With this 21 cm IM field, we construct a momentum field $p_{\|}$ following Eq.(1). As demonstrated in Fig.2, it does not cover the modes necessary for a cross-correlation with kSZ.

Actually, directly using $\delta_{\rm IM}$ with any combination of the parameters above to yields a correlation coeffcient $r < 0.2$ with observable kSZ signals [do you mean from current (i.e. Planck) data?].

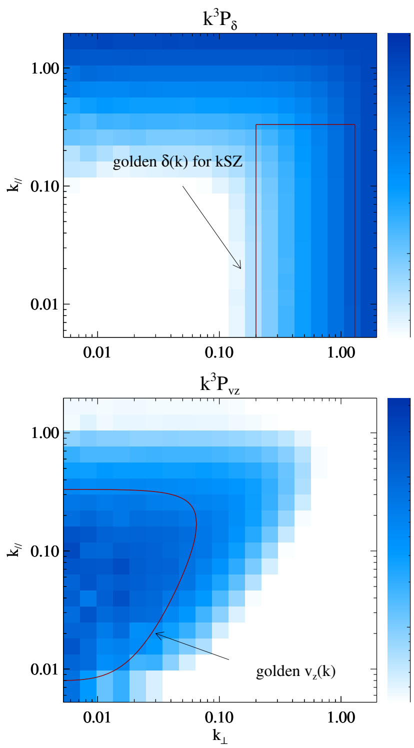

FIG. 2: The variances $2\pi^2\Delta^2 \equiv k^3P$ indicate how Fourier modes of different scales contribute to real space fields, i.e. $\delta(\boldsymbol{x})$ and $v_z(\boldsymbol{x})$. Golden modes [what are golden modes?] for kSZ at $\ell \sim 500-3000$ are marked out.

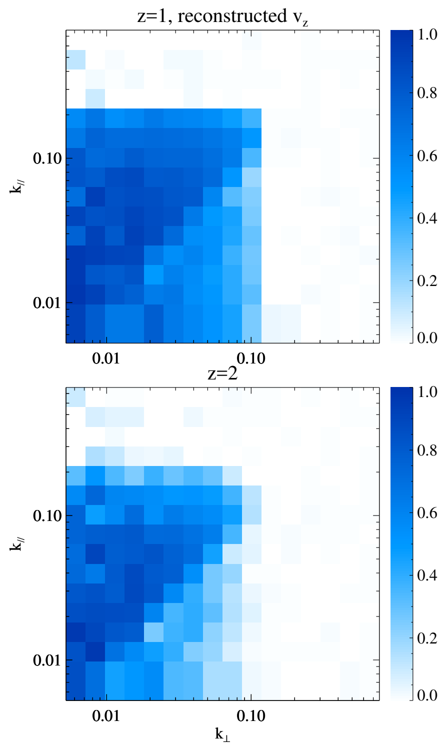

FIG. 3: The correlation coefficient between the reconstructed v_z and actual v_z, assuming a [longest?] baseline of 100 m. Foregrounds seriously contaminate k_z below ~ 0.08 h/Mpc and ~ 0.12 h/Mpc at $z=1$ & 2, respectively [Have you shown this somewhere or referenced?].

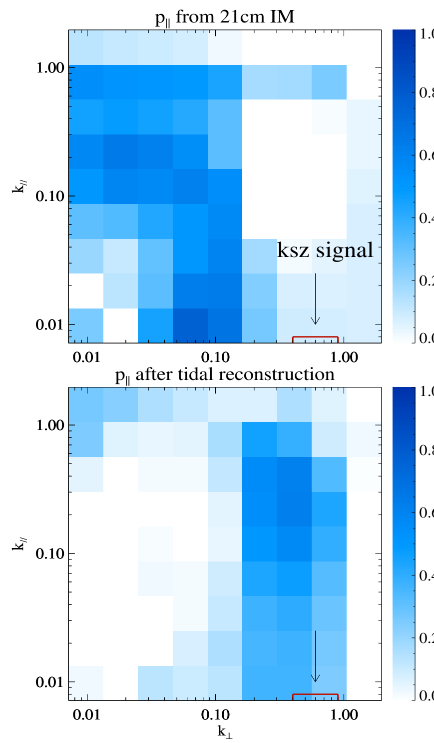

FIG. 4: The correlation coefficient for $p_{||} = (1+\delta)v_z$ before and after tidal reconstruction [between what and what?]. The kSZ signal is roughly $p_{||}$ integrated over line of sight, corresponding to $k_z = 0$ modes. [Titles should say correlation coefficient of . . . or have no title.]

	z=1		z=2	
	high foreground	low foreground	high foreground	low foreground
$R_{\parallel}$ Mpc/h [a]	15	60	10	40
	CHIME	HIRAX	CHIME	HIRAX
$k_{\max}$ h/Mpc [b]	0.6	1.2	0.4	0.8
$\ell_{\min}$ [c]	300			

[a]Foreground: smear $k_z \lesssim 0.08, 0.02, 0.12, 0.03$ h/Mpc respectively. Parameters based on [19–21]

[b]Small scale noise: based on CHIME[11] and HIRAX[13] with 100 m and 200 m longest baseline respectively.

[c]Spatial loss of inteferomenter: assuming shortest baseline of 20 m.

TABLE I: Parameters related to resolvable modes in 21cm IM

IV. IMPORTANT SCALES FOR KSZ SIGNALS

To understand which $\boldsymbol{k}$ of δ are most necessary in reconstructing the kSZ signal, the first step is to clarify which angular scale of the kSZ we are interested in. As demonstrated in Fig.1, the kSZ effect is too faint to be distinguished until the primary CMB starts to fade away, at roughly $\ell > 500$. It is possible to select a frequency band where the thermal SZ signal is negligible, then the dominant factor at high ℓ will be the CMB instrumental noise. With existing Planck [22] data at 217 GHz, $\ell \sim 500-3000$ will be the visible window for kSZ signal. The window could be extended to higher frequency with ACTpol and CMB-S4. [Which window? Because of what effects? Did you show this?]

The next step is to understand what role each scale plays in contributing to the kSZ signal at $\ell \sim 500-3000$. If we write Eq.(1) in Fourier space, and given that $g(\eta)$ varies slowly, we see that $\Theta(\boldsymbol{\ell})$ is propotional to the $k_z = 0$ mode of the momentum field, as marked in Fig.2,

$$\begin{aligned}\Theta(\boldsymbol{\ell}) &\propto p_{||}(k_x\chi, k_y\chi, 0) \\ &\propto \int d^3k'\, \delta(\boldsymbol{\ell}/\chi - \boldsymbol{k}'_\perp, k'_{||}) v_z(\boldsymbol{k}'). \end{aligned} \tag{5}$$

[eqnarray is depricated. Use the align environment instead.] The convolution of δ and v_z indicates the signal comes from the cross talk of $\boldsymbol{\ell}/\chi - \boldsymbol{k}'_\perp$ and $\boldsymbol{k}_\perp$, with a sum over all k'.

Since $v_z \propto k_z/k^3$, its power drops fast at small scales. [compared to?] If we boldly analogize [approximate?] v_z as a Dirac delta function $\delta^D(\boldsymbol{k}')$, $\Theta(\boldsymbol{\ell})$ will reduce to an integral over $\delta(\boldsymbol{\ell}/\chi, 0)v_z(0,0)$, with integration over the other k' being negligible due to the faintness of $v_z(k' \neq 0)$. In reality, where $v_z(\boldsymbol{k})$ is not as sharp as a Dirac delta, the peak will be closer to $(k_\perp, k_\parallel)$=(0.01,0.1) h/Mpc rather than (0,0). We then see that most of the kSZ signal is generated by the cross talk between the part of $v_z(\boldsymbol{k})$ with k in a small ball surrounding (0.01,0.1) h/Mpc and the part of $\delta(k)$ with k close to $\delta(\boldsymbol{\ell}/\chi, 0.1)$ h/Mpc. This is demonstrated in Fig.2. Comparing it with Fig.1, we notice that while the essential modes [what do you mean by the essential modes?] for δ are partly resolved, the large scale information dominating v_z is almost completely filtered out of the 21 cm IM field. Therefore, to retrieve the cross-correlation between kSZ and 21cm IM fields we must first reconstruct the large-scale v_z modes.

V. COSMIC TIDAL RECONSTRUCTION

Until now only linear theory has been considered in the reconstruction. However, to extract the lost large-scale information, we need to consider couplings between different scales which arise in non-linear perturbation theory. While there are a great variety of nonlinear effects, identifying a single one will help conduct clean reconstruction. [Not sure what you mean by "clean".] Here, we present the algorithm we use to solve for the large-scale structure, based on tidal couplings [14, 15].

The evolution of small-scale structure is modulated by large-scale tidal forces. Consider only the anisotropic influence from tidal force, the generated distortions on matter power spectrum will be

$$\delta P(\boldsymbol{k},\tau)|_{t_{ij}} = \hat{k}^i \hat{k}^j t_{ij}^{(0)} P_{1s}(k,\tau) f(k,\tau), \tag{6}$$

where $P_{1s}(k,\tau)$ is the linear power spectrum, $f(k) = 2\alpha(\tau) - \beta(\tau) d\ln P/d\ln k$ is the tidal coupling function, with α and β parameters related to the linear growth funcion [15]. For example, $(\alpha, \beta) = (0.6, 1.3)$ and $(0.4, 0.9)$ for $z = 1$ and $z = 2$, respectively. t_{ij} is the tidal force tensor, which is symmetric and traceless and hence can be decomposed into five components

$$t_{ij} = \begin{pmatrix} \gamma_1 - \gamma_z & \gamma_2 & \gamma_x \\ \gamma_2 & -\gamma_1 - \gamma_z & \gamma_y \\ \gamma_x & \gamma_y & 2\gamma_z \end{pmatrix}. \tag{7}$$

Therefore, from the spatial dependence of the distortions $\delta P(\boldsymbol{k},\tau)$, we can solve for different components of t_{ij}. The tidal forces are related to second derivative of large scale gravitational potential Φ_L,

$$t_{ij} = \partial_i \partial_j \Phi_L - \nabla^2 \Phi_L \delta_{ij}/3/, \tag{8}$$

where δ_{ij} is the Kronecker delta function.

Different components of t_{ij} are related to different k modes of the large-scale density contrast $\kappa_{3\mathrm{D}}$.

$$\kappa_{3\mathrm{D}} \sim \nabla^2 \Phi_L = \frac{3}{2} \nabla^{-2} \partial_i \partial_j t_{ij} \tag{9}$$

[Why are you using the $\sim$ operator here?] We note that $f(k,\tau)$ increases with k at the scales we are interested in, indicating

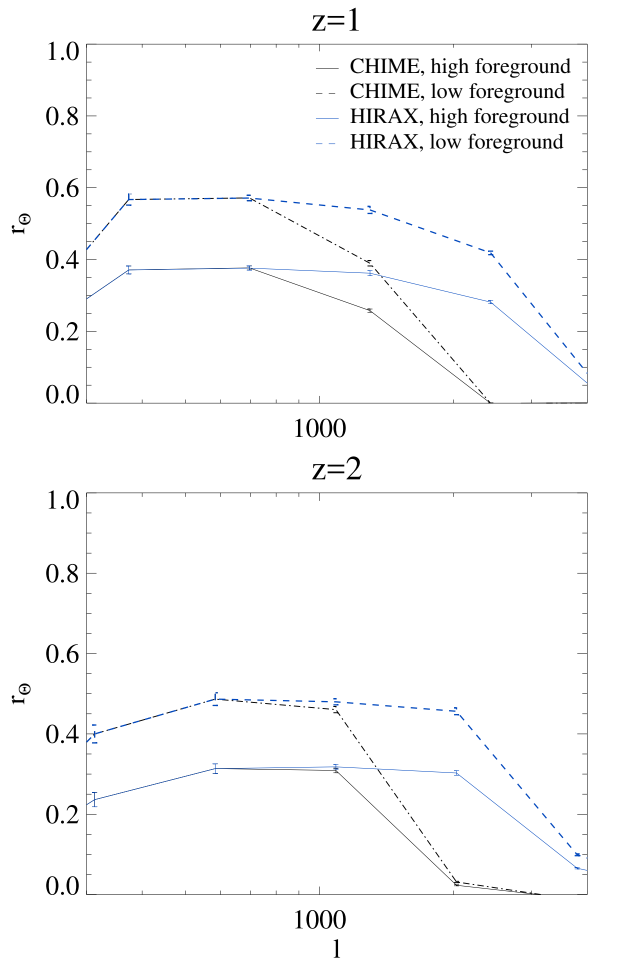

FIG. 5: The correlation coefficient r between real kSZ P_{real} and 21cm IM reconstructed kSZ P_{recon}. [Maybe P is not necessary here, just reference the equation where you define r? Also, maybe add something like: Forecasts for two different telescopes and levels of mode loss due to foreground filtering are calculated at $z = 1$ (above) and $z = 2$ (below).]

the distortions are more manifest on small scales. This explains [reinforces?] the feasibility of using observable high k modes of the 21 cm IM field to extract low k modes.

VI. SIMULATIONS AND RESULTS

To test the algorithm, we performed six N-body simulations, using the CUBEP^{3}M code [23], each evolving 1024^3 particles in a $(1.2\mathrm{Gpc}/h)^3$ box. Simulation parameters are set as: Hubble parameter $h = 0.678$, baryon density $\Omega_b = 0.049$, dark matter density $\Omega_c = 0.259$, amplitude of primordial curvature power spectrum $A_s = 2.139 \times 10^{-9}$ at $k_0 = 0.05\ \mathrm{Mpc}^{-1}$ and scalar spectral index $n_s = 0.968$.

The simulated density and velocity fields at $z = 1$ and 2 are output and used to generate the real kSZ signal. To avoid manipulating noise [not sure what this means], we perform tidal reconstruction on our most conservative estimates, namely

$R_{\parallel} = 15$ Mpc/h, $k_{\max} = 0.6$ h/Mpc, $\ell_{\min} = 200$ for $z = 1$, and $R_{\parallel} = 10$ Mpc/h, $k_{\max} = 0.4$ h/Mpc, $\ell_{\min} = 200$ for $z = 2$. Refer to Table.I, the top of Fig.1 and Chapter III [Section?] for descriptions of the parameters.

The results for the cross-correlation between reconstructed v_z, using the tidal reconstruction method on our simulated data, and the actual v_z, that is output by the simulation, are demonstrated in Fig.3. Important modes for velocity fields (within red line of Fig.2, lower label) are well reproduced by the reconstruction and produce a cross-correlation coefficient greater than 0.7.

We then proceed to a reconstructed kSZ signal by combining the reconstructed velocity field with density fields which have been appropriately treated by instrumental effects, as discussed in Section III. Their correlation coefficients with the exact kSZ are shown in Fig.5. Even with an identical tidal reconstructed velocity field, better foreground removal techniques can improve the correlation coefficient by 0.2. Of course better foreground removal will also provide more modes on which the tidal reconstruction can act. Also, greater angular resolution of telescope will improve the reconstruction at high ℓ, consistent with the previous analysis [of Section . . .]. [There are many reconstructions running around, maybe try to use some different terminology.][Its not super clear to me which fields are reconstructed, I think what you do is reconstruct large-scale modes of the density field and then use linear theory to turn this in to the velocity field?]

VII. STATISTICAL ERROR AND S/N

In this Section, we consider our ability to distinguish the kSZ effect from the primary CMB and instrumental noise. We estimate the signal-to-noise for the kSZ effect as:

$$\frac{S}{N} = \frac{C_\ell}{\Delta C_\ell} \tag{10}$$
$$\simeq r\sqrt{(2\ell+1)\Delta l f_{\rm sky}}\sqrt{\frac{C_\ell^{\rm kSZ,\Delta z}}{C_\ell^{\rm CMB} + C_\ell^{\rm kSZ} + C_\ell^{{\rm CMB},N}}},$$

[Use align.] [Why are you using an approx. equal to? What are the assumptions that go into this estimate for S/N?] where $C_\ell^{\rm CMB}$ is the angular power spectrum of primary CMB, $C_\ell^{\rm CMB,N}$ is the contribution to the covariance from instrumental noise, $C_\ell^{\rm kSZ,\Delta z}$ is the kSZ signal from within a certain redshift bin, r is the correlation coefficient defined in Eq.(3), and $f_{\rm sky}$ is the percent of sky area covered by both the CMB and 21 cm IM surveys.

In our case, $C_\ell^{\rm CMB}$ is calculated using CAMB [24]. $C_\ell^{\rm CMB,N}$ is estimated with Planck data [22] at 217GHz, with sensitivity per beam solid angle given by $\sigma_{p,T} = 8.7\mu K_{\rm CMB}$ and an effective beam full-width-half-maximum of $\theta_{\rm FWHM} \sim 5'$. We choose $f_{\rm sky} = 0.8$ according to the reported 21 cm IM survey area [reference?]. $C_\ell^{\rm kSZ,\Delta z}$ is calculated within two bins of size 1200 Mpc/h, centered at redshift 1 & 2, respectively. [Its not clear to me where the 21 cm IM comes in to the above.]

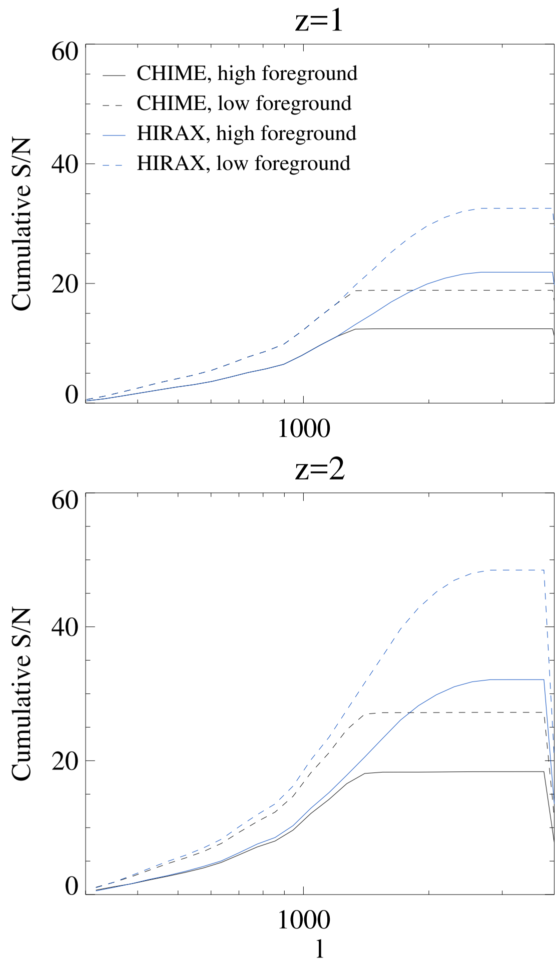

FIG. 6: Cumulative S/N, assuming Planck noise at 217 GHz, $f_{sky} = 0.8$.

The cumulative S/N [calculated using Eq. (10)] is shown in Fig.6. The low correlation [Do you mean the lower power from the less structure growth?] at $z = 2$ is compensated by the high electron density, and the overall S/N should well reach 50 with HIRAX. With Planck noise levels, the resolution of HIRAX already covers the most important ℓ.

VIII. CONCLUSION

In this paper, we have discussed a method for of cross-correlating the kSZ signal with 21 cm intensity mapping, a probe which is directly sensitive to the large-scale distribution of baryons. All of the calculations presented here are based on ongoing experiment conditions and realistic noise levels. A holographic method for cross-correlation is applied. [This is the first time you ever mention this. What does this mean?] We have employed a method for reconstructing the large-scale modes, which typically will be lost to forgeground cleaning in realistic 21 cm IM surveys, which exploits the non-linear tidal coupling between scales. Our method, therefore, is essentially studying the four-point correlation function $< \delta\,\delta\,\delta\,T >$. This is easily understood since the local modulation of the power spectrum $< \delta_s\delta_s >$ is used to reconstruct large-scale modes δ_L and hence v_z, the two of which are then convolved $< \delta_s v_z >$ to mimic the kSZ signal. [Is the conclusion the best place to introduce this new discussion?]

With existing Planck data, it is reasonable to expect a S/N of at least ~ 15 at redshift 2 with data from CHIME, and HIRAX will yield 50 S/N. [The improvement is due to mainly to the increased small-scale resolution provided by longer baselines?] The main obstacle for optimal correlation is the lack of low k_z, high $k_\perp$ data due to foregrounds. This leads to information waste in the reconstructed velocity field. [What information is wasted?] However, data from weak lensing, [or/and?] photo-z galaxy surveys, which contain only large-scale structure in the z direction, could be use to compensate this effect.

This method presented here is promising for due to its feasibility with near-term data and model independence. CHIME has begun collecting data [not actually true, only the Pathfinder has collected data], and construction for HIRAX is under way. [Given the reported experiment timelines?] It is reasonable to expect our method to be testable within the next five years. Moreover, the method does not rely on assumptions about velocity fields or the conditions of the interstellar medium, and therefore the results can be more easily understood. [In comparison to what?] We expect our method to be useful tool for studying the baryon distribution up to redshift 2 or higher. Furthermore, the unique property of 21 cm IM of having both large sky coverage and accurate redshift information offers extra information into the diffuse baryonic structure at angular scales of $\ell \sim 1000 - 2000$, larger scales than probed by all the other similar methods proposed. This will foster understanding of stellar feedback at the scale of galaxy clusters and filaments and therefore the evolution of the large-scale structure.

IX. ACKNOWLEDGEMENTS

We acknowledge discussions Wenkai Hu, Tianxiang Mao and Jiawei Shao. The simulations were performed on the BGQ supercomputer at the SciNet HPC Consortium. SciNet is funded by: the Canada Foundation for Innovation under the auspices of Compute Canada; the Government of Ontario; the Ontario Research Fund – Research Excellence; and the University of Toronto. Research at the Perimeter Institute is supported by the Government of Canada through Industry Canada and by the Province of Ontario through the Ministry of Research & Innovation. The Dunlap Institute is funded through an endowment established by the David Dunlap family and the University of Toronto.

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