21cm line Bispectrum as method to probe Cosmic Dawn and epoch of Reionization

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SKA-JP Square Kilometre Array Japanese Consortium

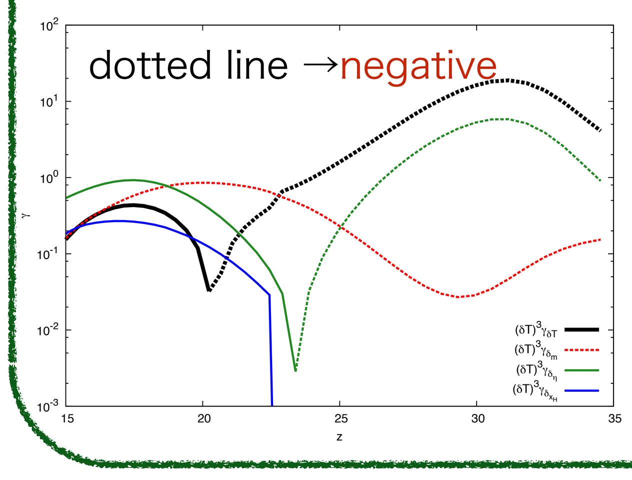
Abstract

Redshifted 21cm signal is a promising tool to investigate the state of intergalactic medium (IGM) in the Cosmic Dawn (CD) and Epoch of Reionization(EoR). In our previous work (Shimabukuro et al 2015), we studied the variance and skewness of the 21cm fluctuations to give a clear interpretation of the 21cm power spectrum and found that skewness is a good indicator of the epoch when X-ray heating becomes effective. Thus, the non-Gaussian feature of the spatial distribution of the 21cm signal is expected to be useful to investigate the astrophysical effects in the CD and EoR. In this paper, in order to investigate such a non-Gaussian feature in more detail, we focus on the bispectrum of the 21cm signal. It is expected that the 21cm brightness temperature bispectrum is produced by non-gaussianity due to the various astrophysical effects such as the Wouthysen-Field (WF) effect, X-ray heating and reionization. We study the various properties of 21cm bispectrum such as scale dependence, shape dependence and redshift evolution. And also we study the contribution from each component of 21cm bispectrum. We find that the contribution from each component has characteristic scale-dependent feature. In particular, we find that the bulk of the 21cm bispectrum at z~=20 comes from the matter fluctuations, while in other epochs it is mainly determined by the spin and/or neutral fraction fluctuations and it is expected that we could obtain more detailed information on the IGM in the CD and EoR by using the 21cm bispectrum in the future experiments, combined with the power spectrum and skewness.

Introduction

In our previous work (Shimabukuro et al,2015), we gave an interpretation to the time evolution of the 21cm power spectrum and we find that the size of skewness is sensitive to the epoch when X-ray heating becomes effective and other work also show the impact of spin temperature fluctuations on the skewness(Watkinson & Pritchard, 2015). Herein we extend these works by considering the bispectrum to investigate the dependence of the skewness on scale because skewness is an integral of the bispectrum with respect to the wavenumber. On thee other hand, the bispectrum itself is powerful tool to investigate the Non Gaussianity in brightness temperature field caused by non linear structure formation at CD and EoR.

It is easier to observe skewness reconstructed from bispectrum(visibility) than from image map directly.



skewness

$$\gamma_{\delta T_b} = (\overline{\delta T_b})^3[\gamma_{\delta_m} + \gamma_{\delta_\eta} + \gamma_{\delta_{x_H}} + \langle \delta_m \delta_\eta \delta_{x_H} \rangle + 3(\langle \delta_m^2 \delta_\eta \rangle + \langle \delta_m^2 \delta_{x_H} \rangle + \langle \delta_\eta^2 \delta_{x_H} \rangle + \langle \delta_m \delta_\eta^2 \rangle + \langle \delta_m \delta_{x_H}^2 \rangle + \langle \delta_\eta \delta_{x_H}^2 \rangle) + O(\delta^4)].$$

S/N~8 at z=20 with SKA2

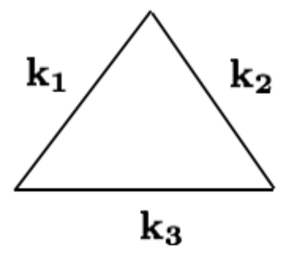
Formalism and set up

Definition of Bispectrum

$$\langle \delta T_b(\mathbf{k}_1)\delta T_b(\mathbf{k}_2)\delta T_b(\mathbf{k}_3)\rangle = \delta(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)B(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3)$$

○equilateral type

$$|\mathbf{k}_1| = |\mathbf{k}_2| = |\mathbf{k}_3| = k$$



○squeezed type

$$|\mathbf{k}_1| = |\mathbf{k}_2| = k, |\mathbf{k}_3| = k_c \quad (k > k_c)$$

○folded type

$$k_1 + k_2 - k_3 = 0$$

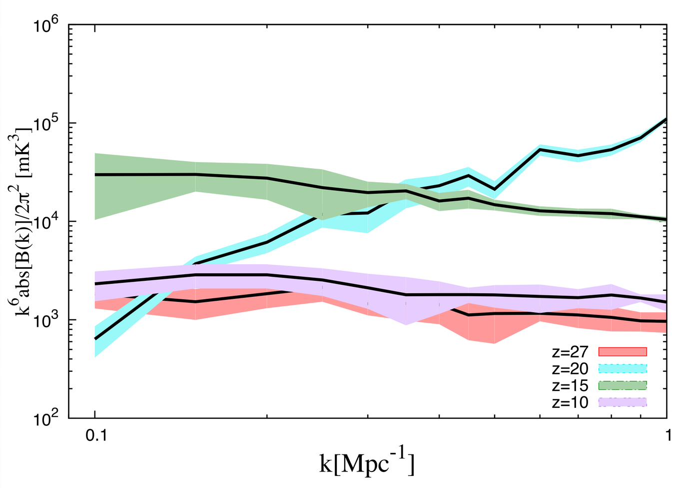
· We use 21cmFAST(Mesinger et al 2010) to calculate brightness temperature field (200Mpc^3, 300^3 grid)

In our study, we actually plot

$$B_{21} = |\langle \delta T_b(\mathbf{k}_1)\delta T_b(\mathbf{k}_2)\delta T_b(\mathbf{k}_3)\rangle|$$

Scale-dependence of 21cm bispectrum

First, in order to see the scale dependence of 21cm bispectrum, we focus on the equilateral shape. We plot the equilateral type bispectrum as a function of wave number k at z=10, 15, 20, 27 with 1sigma sample variance.

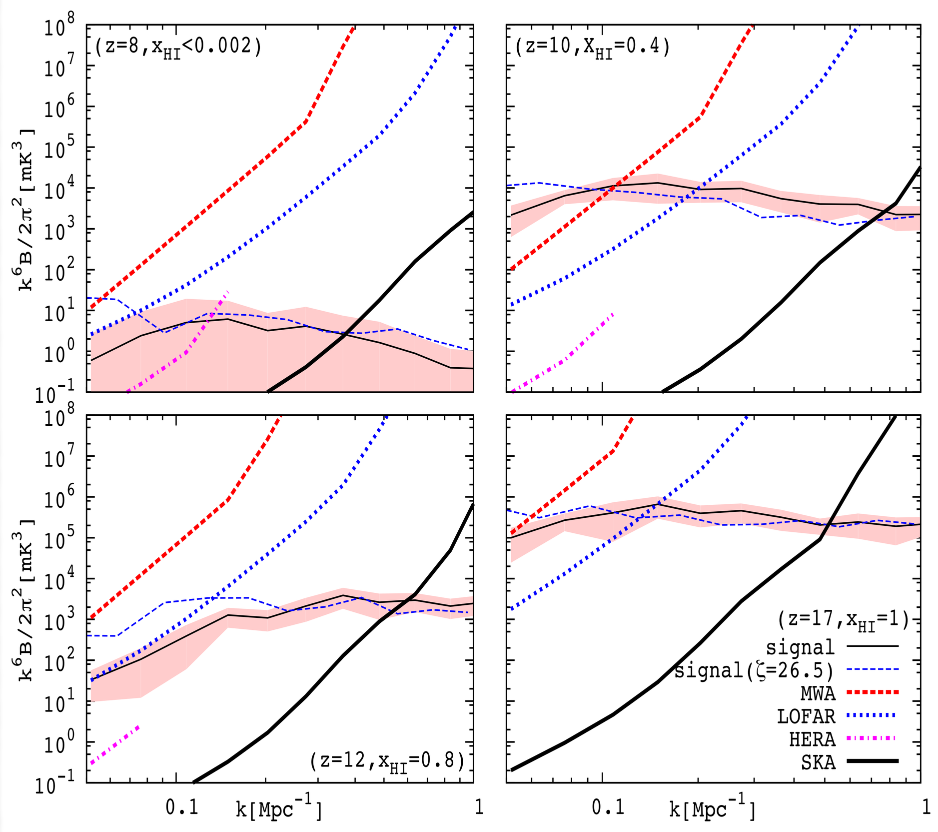


z=10 is a typical redshift during EoR and z=15, 20 are expected to be transition time from CD to EoR, while z=27 is a typical time during CD.

We can find that, except for the case with z=20, the normalized bispectrum is almost scale invariant for the equilateral type shape. On the other hand, for z=20, the normalised bispectrum has a scale dependence as ∝ k^{2}. Such difference is expected to depend on what component gives a dominant contribution to the 21cm bispectrum.

At z=20, matter component is dominant contribution to 21cm bispectrum. Although spin temperature or neutral fraction components are dominant component at other redshifts. Therefore we expect that 21cm bispectrum at z=20 traces the matter bispectrum and it causes scale dependency.

Detectability of 21cm bispectrum



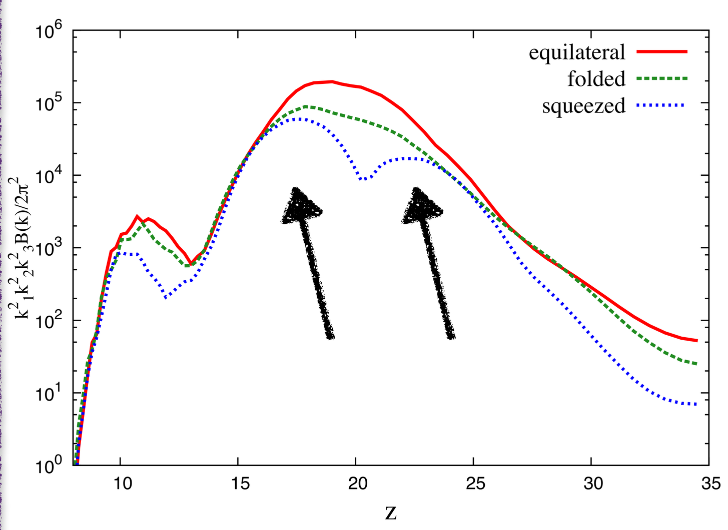
We also discuss the detectability of bispectrum in our previous work. We estimated the signal to noise ratio of bispectrum for some observations (SKA, MWA, HERA, LOFAR).

We found that the SKA1 has enough sensitivity for k<0.3Mpc^{-1} for both equilateral and isosceles triangles at z=8-17.

MWA and LOFAR also have potential to observe bispectrum at large scale.

Redshift-dependence of 21cm bispectrum

Next, we consider redshift evolution of 21cm bispectrum. In this figure, we show the bispectra as function of redshift for several configurations.



We can see two peaks located at around z=20 and 12 for equilateral, folded and squeezed types. These peaks also can be seen in the case of power spectrum with k~1.0Mpc^{-1}.

On the other hand, in case with the squeezed shape, three peaks appear at around z=23, 17 and z=12. This feature is similar to that of the power spectrum with k~0.1Mpc^{-1}

The squeezed type 21cm bispectrum is expected to be described in terms of not only the bispectrum with larger two wave numbers but also that with smaller one.

$k_a = k_b = k_c = 1.0\mathrm{Mpc}^{-1}$ **equilateral**

$k_a = k_b = 1.0\mathrm{Mpc}^{-1}, k_c = 2.0\mathrm{Mpc}^{-1}$ **folded**

$k_a = k_b = 1.0\mathrm{Mpc}^{-1}, k_c = 0.1\mathrm{Mpc}^{-1}$ **squeezed**

Therefore, it would have the information about the correlation between the long and short wave length modes in Fourier space or local non-linearity in the real space.

Decomposition of 21cm bispectrum

At last, we decompose 21cm bispectrum into each component, matter fluctuation, spin temperature fluctuation and neutral fraction fluctuation.

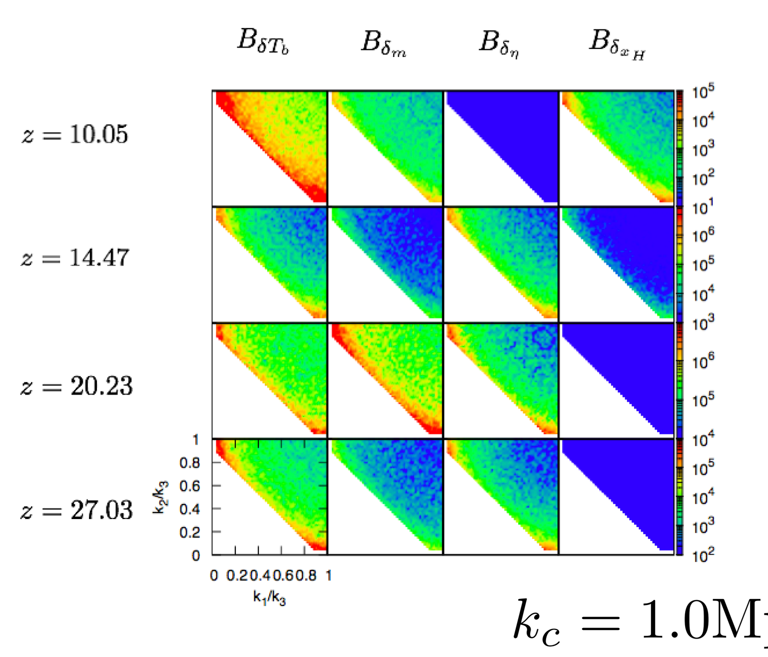
$$B_{\delta T_b} = (\overline{\delta T}_b)^3[B_{\delta_m\delta_m\delta_m} + B_{\delta_{x_H}\delta_{x_H}\delta_{x_H}} + B_{\delta_\eta\delta_\eta\delta_\eta} + (\text{cross correlation terms}) + (\text{higher order terms})].$$

We plot the 21cm bispectrum and auto correlation terms of each component bispectrum in wave number plain with fixing k_{c}=1.0, 0.4 Mpc^{-1}. Note that we do not use the normalized bispectrum but the unnormalized bispectrum.

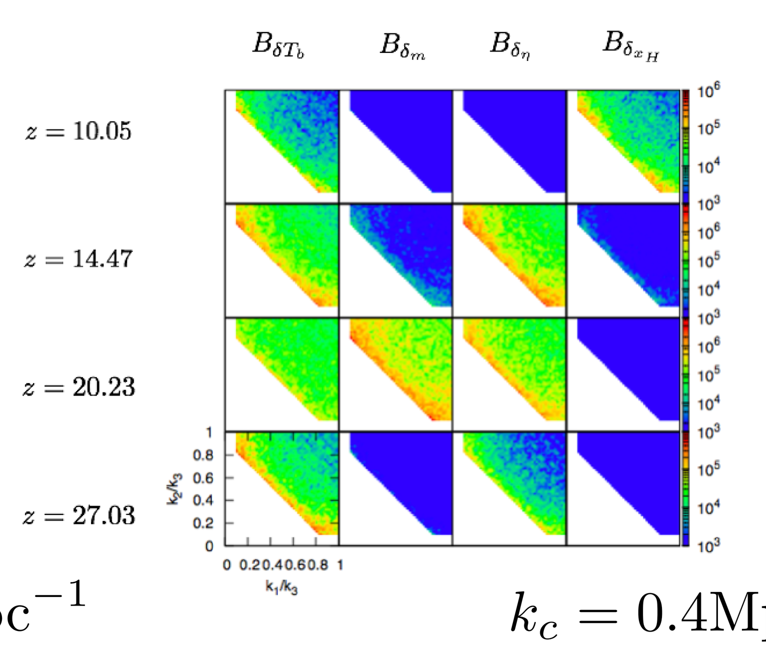
From this figure, we can see what configuration of triangle and component of the bispectra are strong.

For example, for k_{c}=1.0Mpc^{-1} at z=10 when EoR has proceeded to some extent(x_{i}=0.77), the total bispectrum is strong at folded and squeezed types. The contribution from neutral hydrogen fraction fluctuations is dominant at these configurations. At z=14 and z=27, dominant contribution is from spin temperature fluctuation. Although at z=20, both squeezed and folded type of the total bispectrum are strong and both spin temperature and matter fluctuations are dominant.

For k_{c}=0.4 Mpc^{-1}, compared with the case of k_{c}=1.0Mpc^{-1}, contributions form both matter and spin temperature are significant at z=20 and neutral hydrogen fraction at z=10 is clear.



$k_c = 1.0\mathrm{Mpc}^{-1}$



$k_c = 0.4\mathrm{Mpc}^{-1}$

Summary

In this paper, we investigate the 21cm bispectrum of brightness temperature. Especially, we show the scale dependency, redshift evolution of 21cm bispectrum.

We also show the scale and configuration dependences of the component of 21cm bispectrum and find that there are typical component and configurations at each redshift.

One of the applications of bispectrum is to combine with power spectrum to determine EoR parameters and subtract information about CD and EoR from observations.