Understanding 21 cm power spectrum with 1-point statistics

based on
Shimabukuro et al astro-ph/1412.3332

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Outline

- Introduction
- Evolution of 21cm power spectrum
- One-point statistics of spin temperature & brightness temperature
- Summary
Introduction
Introduction

○ z > 30 • • Dark age
Star formation has not started yet.

○ 15 < z < 30 • • Cosmic dawn
After the star formation, astrophysical effects become effective.

○ 7 < z < 15 • • Epoch of Reionization (EoR)
Hydrogen is ionized by UV photon emitted from stars, galaxies
Introduction

- 21 cm line radiation: Hydrogen emits the radiation due to the hyper fine structure.

Spin temperature

\[
\frac{n_1}{n_0} = 3 \exp \left( - \frac{h\nu_{21}}{kT_S} \right)
\]

Interaction with
- CMB
- Ly-alpha photon
- IGM
Introduction

Thermal history

\[ T_{S}^{-1} = \frac{T_{\text{CMB}}^{-1} + x_{\alpha}T_{\alpha}^{-1} + x_{K}T_{K}^{-1}}{1 + x_{\alpha} + x_{K}} \]

Wouthuysen-Field (WF) effect

Spin temperature couples to IGM kinetic temperature due to the Ly-alpha photon from stars.

Mesinger et al 2010
Introduction

Thermal history

○ Brightness temperature

\[
\delta T_b(\nu) = \frac{T_S - T_\gamma}{1 + z} \left(1 - e^{-\tau_{\nu_0}}\right)
\]

\[
\sim 27 x_H(1 + \delta_m) \left(\frac{H}{d\nu_r/\bar{d}r + H}\right) \left(1 - \frac{T_\gamma}{T_S}\right) \left(1 + z \frac{0.15}{10 \Omega_m h^2}\right)^{1/2} \left(\frac{\Omega_b h^2}{0.023}\right)[\text{mK}].
\]

red: astrophysics, blue: cosmology

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See talk Vedantham

Pritchard & Loeb, 2011
Observation

- The observation of 21cm line is a promising tool to know information of EoR. (When does it start? How long?)

- Precursor/pathfinder (MWA, LOFAR, PAPER)

- SKA

- Precursor/pathfinder → to study statistical property of 21cm signal → Power spectrum

\[ \langle \delta(k)\delta^*(k') \rangle = (2\pi)^3 \delta(k + k') P(k) \]
Power spectrum

Mesinger et al 2013  \( k = 0.1 \text{Mpc}^{-1} \)

Power spectrum for EoR history and sensitivity.

It would be possible to detect 21cm power spectrum for some EoR history models at lower redshift by path finder (MWA, LOFAR).

SKA can detect 21cm power spectrum for any model at higher redshift!
Power spectrum

Mesinger et al 2013 \( k=0.1 \text{Mpc}^{-1} \)

We would like to give the insight of the physical interpretation of these peaks.

→ Consider decomposition of power spectrum and 1pt statistics
Evolution of 21cm power spectrum
Method

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

  - Zel’dovich approximation for calculation of matter density field
    +
  - Use analytic model for evolution of ionized field and heating process

- Free parameter → ionizing efficiency, the number of photon emitted from stars, the number of X-ray photon
Decomposition of 21cm power spectrum

Decomposition of 21cm power spectrum into each component

brightness temperature $\rightarrow$ (average) + (fluctuation)

$$\delta T_b = (\delta T_b)(1 + \delta_m)(1 + \delta_{x_H})(1 + \delta_\eta)$$

$\eta = 1 - T_\gamma/T_S$

calculate each power spectrum

$$\langle \delta_m(k)\delta_m(k') \rangle = (2\pi)^3\delta(k + k')P_m(k).$$

$$\langle \delta_{x_H}(k)\delta_{x_H}(k') \rangle = (2\pi)^3\delta(k + k')P_{x_H}(k).$$

$$\langle \delta_\eta(k)\delta_\eta(k') \rangle = (2\pi)^3\delta(k + k')P_\eta(k).$$
Decomposed 21cm power spectrum

- Three peaks are appeared.
- The component $x_{\{H\}}$ produces a peak at EoR.
- The component $\eta$ produces two peaks.
- The matter component also contributes to power spectrum.
Decomposed 21cm power spectrum

At EoR, the fluctuation of $X_{\{H\}}$ is dominant. $\eta$ fluctuation is effective before EoR →WF effect, X-ray heating

We focus on $\eta$ to understand the 2 peaks.
One-point statistics
Evolution of $\eta$

We focus on the region where the matter density is large. Objects tend to be formed and drive astrophysical effects earlier than other low density regions. Around the objects, WF effect is caused by UV photons first and X-ray heating is effective later.
Distribution of $\eta$

- Tail corresponds to the region where objects are formed.
- Higher redshift $\rightarrow$ tail toward low $\eta$. (WF effect)
- Lower redshift $\rightarrow$ tail toward high $\eta$. (X-ray heating)
- Transition of tail $\rightarrow$ nearly gaussian distribution and small width. (X-ray heating begins effective.)
Variance and skewness

\( \sigma^2 = \frac{1}{N} \sum_{i=1}^{N} [X - \bar{X}]^2 \)

\( \gamma = \frac{1}{N\sigma^3} \sum_{i=1}^{N} [X - \bar{X}]^3 \)

left side tail → negative
right side tail → positive

\( \langle \delta_m \delta_\eta \rangle \)

\( \gamma/\sigma^3 \)

negative
Variance and skewness of brightness temperature

We actually observe brightness temperature variance

\[
\sigma_{\delta T} = (\overline{\delta T})^2 \left[ \sigma_{\delta m} + \sigma_{\delta H} + \sigma_{\delta xH} + \langle \delta_m \delta_H \rangle + \langle \delta_m \delta_{xH} \rangle + \langle \delta_H \delta_{xH} \rangle + O(\delta^3) \right].
\]

skewness

\[
\gamma_{\delta T} = (\overline{\delta T})^3 \left[ \gamma_{\delta m} + \gamma_{\delta H} + \gamma_{\delta xH} + \langle \delta_m \delta_H \delta_{xH} \rangle + 3(\langle \delta_m^2 \delta_H \rangle + \langle \delta_m^2 \delta_{xH} \rangle + \langle \delta_H^2 \delta_{xH} \rangle + \langle \delta_m \delta_H^2 \rangle + \langle \delta_m \delta_{xH}^2 \rangle + \langle \delta_H \delta_{xH}^2 \rangle) + O(\delta^4) \right].
\]

Plot the auto correlation term of variance & skewness
○ The change of sign at skewness is different between $\eta$ and $\delta T$ → due to the matter fluctuation. But basic physical interpretation is same.
○ The contribution of neutral hydrogen fluctuation in skewness is more effective than it in variance.
Summary

- We study the physical interpretation of 21cm power spectrum by 1pt statistics

- We decompose 21cm power spectrum into each component and confirm that the $\eta$ is effective before EoR.

- Variance and skewness become good indicator for WF effect and X-ray heating.

- We need to evaluate higher order term $\rightarrow$ bispectrum (Shimabukuro et al in prep)
21cm Bispectrum

We calculated 21cm power spectrum and its component, however, the physical interpretation is difficult...