# Probing HI evolution during EoR through bispectrum multipoles


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We study the squeezed monopole ($B_0^0$) and quadrupole ($B_2^0$) moments of the 21-cm bispectrum (BS) from EoR simulations. Both $B_0^0$ and $B_2^0$ are positive at the early stage of EoR where the mean neutral hydrogen (HI) density fraction $\bar{x}_{HI} \approx 0.99$. The subsequent evolution of $B_0^0$ and $B_2^0$ at large and intermediate scales ($k = 0.29$ and $0.56\ Mpc^{-1}$, respectively) is punctuated by two sign changes which mark transitions in the HI distribution. The first sign flip where $B_0^0$ becomes negative occurs in the intermediate stages of EoR ($\bar{x}_{HI} > 0.5$), at large scale first followed by the intermediate scale. This marks the emergence of distinct ionized bubbles in the neutral background. $B_2^0$ is relatively less affected by this transition, and it mostly remains positive even when $B_0^0$ becomes negative. The second sign flip, which affects both $B_0^0$ and $B_2^0$, occurs at the late stage of EoR ($\bar{x}_{HI} < 0.5$). This marks a transition in the topology of the HI distribution, after which we have distinct HI islands in an ionized background. This causes $B_0^0$ to become positive. The negative $B_2^0$ is a definite indication that the HI islands survive only in under-dense regions.

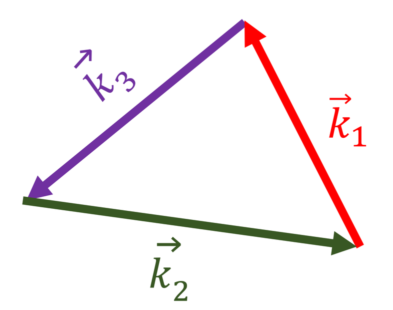

## Bispectrum

$$B(\vec{k}_1, \vec{k}_2, \vec{k}_3) \equiv \langle \Delta(\vec{k}_1)\Delta(\vec{k}_2)\Delta(\vec{k}_3)\rangle$$

Ensemble Average

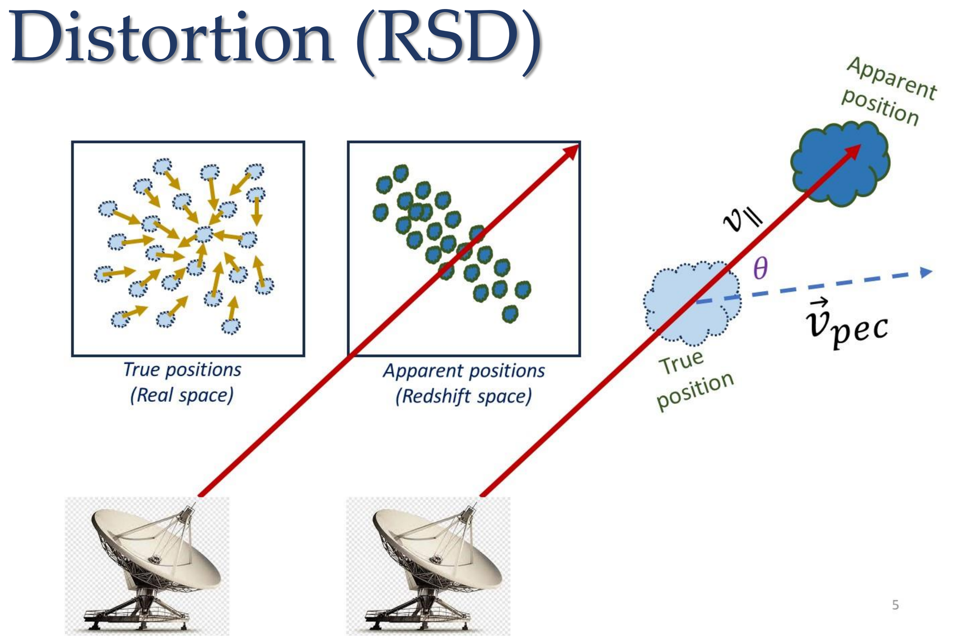
Bispectrum: a measure of non-Gaussianity in fluctuations

Brightness temperature fluctuations in Fourier space




## Redshift Space Distortion (RSD)

- Peculiar velocities introduce anisotropy along line of sight in the observed bispectrum
- Bispectrum is function of shape, size and orientation of triangle wrt LoS




## The effect of RSD on bispectrum can be studied by decomposing it into spherical harmonics

$$B_l^m(k_1, k_2, k_3) = \sqrt{\frac{2l+1}{4\pi}} \int [Y_l^m(\hat{p})]^* \, B^s(\hat{p}, k_1, k_2, k_3)\, d\Omega_{\hat{p}}$$

- $[\Delta_l^s]^3 = \frac{k^6 B_l^0}{(2\pi^2)^2}$
- *$k$ is the largest side of triangle*

## Results

- *No ionization*
  $[\Delta_0^s]_I^3 \approx 0$
- *Matter drives non – Gaussianity*
  $[\Delta_0^s]^3 \approx [\Delta_0^s]_M^3$

*Onset of ionization*

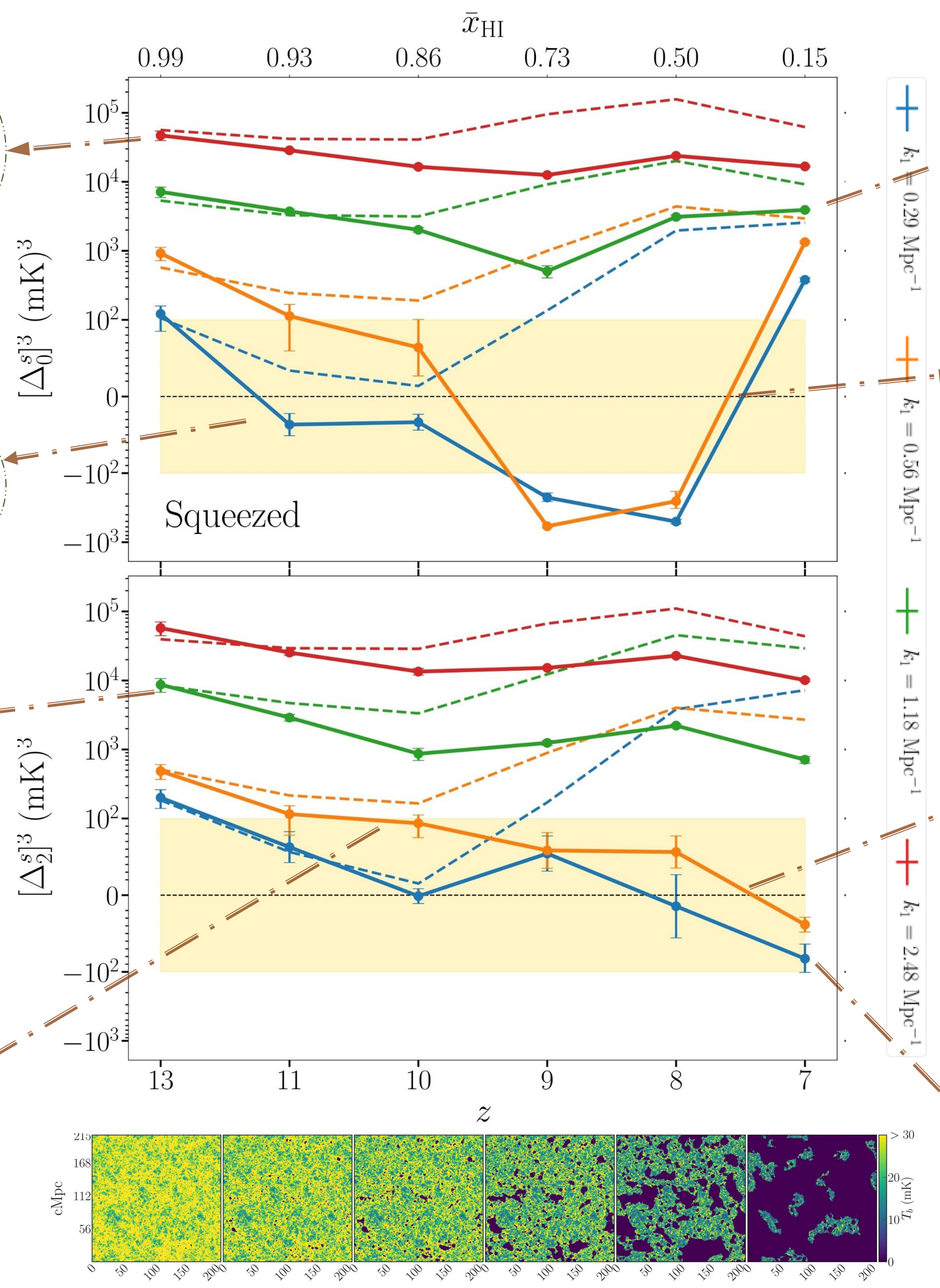
- $[\Delta_0^s]_I^3 < 0$
- $[\Delta_0^s]^3 < [\Delta_0^s]_M^3$

*No ionization*

- $[\Delta_2^s]_{IM}^3 \approx 0$
- $[\Delta_2^s]^3 \approx [\Delta_2^s]_M^3$

*Onset of ionization*

- $[\Delta_2^s]_{IM}^3 < 0$ *but smaller than* $[\Delta_0^s]_I^3$
- $[\Delta_2^s]^3$ *deviates from* $[\Delta_2^s]_M^3$




*End of re – ionization*

- $[\Delta_I^s]^3 > 0$
- $[\Delta_0^s]^3 > 0$

*Transition in topology*

- *HII bubbles embedded in neutral background* ($\bar{x}_{HI} > 0.5$)
  *To*
  *distinct HI islands embedded in ionized regions* ($\bar{x}_{HI} < 0.5$)
- *Field at late stage is negative image of field at early stage*
  $[\Delta_0^s]_I^3 > 0$
- *HI resides in under dense regions. Velocities responsible for RSD & HI are anticorrelated*
  $[\Delta_0^s]_{IM}^3 < 0$

*Model distinction*

- $[\Delta_2^s]_{IM}^3$ *dominates at large scales &* $[\Delta_2^s]^3 < 0$
- $[\Delta_2^s]^3$ *is positive for outside – in model*

## Interpretation

$$[\Delta_0^S]^3 \approx [\Delta_0^S]_M^3 + [\Delta_0^S]_I^3$$

*Non-Gaussianity* = Nonlinear matter distribution + HII bubbles distribution + HI & matter cross-terms

$$[\Delta_2^S]^3 \approx [\Delta_2^S]_M^3 + [\Delta_2^S]_{IM}^3$$

## Discussion

- At early stage, non-Gaussinity is driven by underlying matter.
- Quadrupole has similar magnitude that of monopole
  $[\Delta_2^s]_M^3 \approx [\Delta_0^s]_M^3$
- Sign flips of bispectrum monopole and quadrupole corresponds to phase transitions of HI
- Bispectrum quadrupole can distinguish between inside-out and outside-in reionization models
- The information encoded in higher bispectrum multipoles is subject to further exploration.

**Reference**


- Gill S. S., Pramanick S., Bharadwaj S., Shaw A. K., Majumdar S., 2023, MNRAS , 527, 1135. Arxiv: 2310.15579