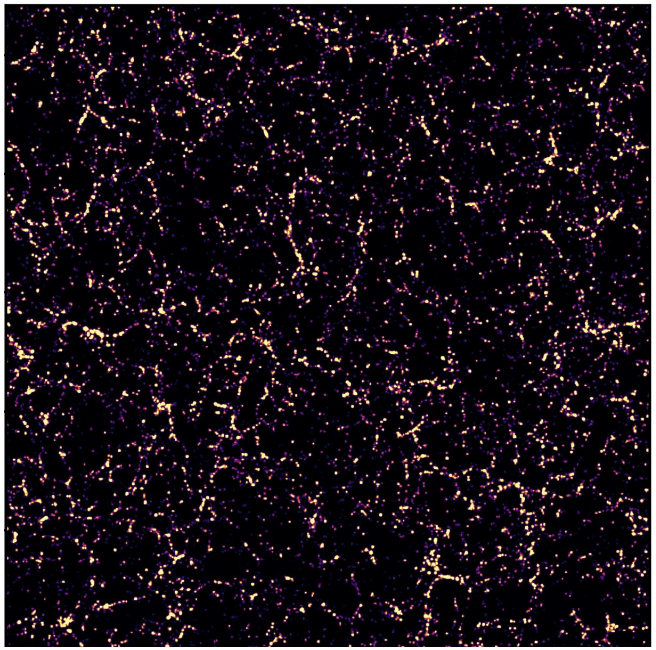
SKAO-Euclid Synergies of post-Reionization Universe: 21cm - galaxy cross bispectrum

Leon Noble
Indian Institute of Technology Indore (IIT Indore)

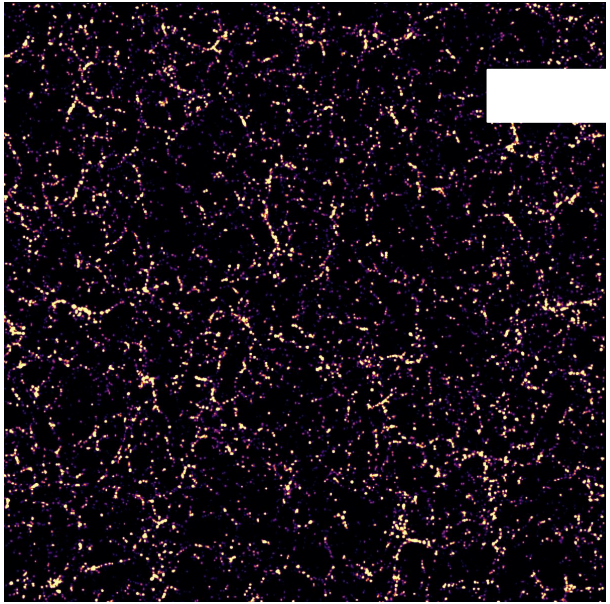
Collaborators: Suman Majumdar (IITI), Matteo Viel (SISSA Trieste), Fabio Fontanot (INAF Trieste), Gabriella De Lucia (INAF Trieste), Marta Spinelli (Observatoire de la Côte d'Azur Nice)

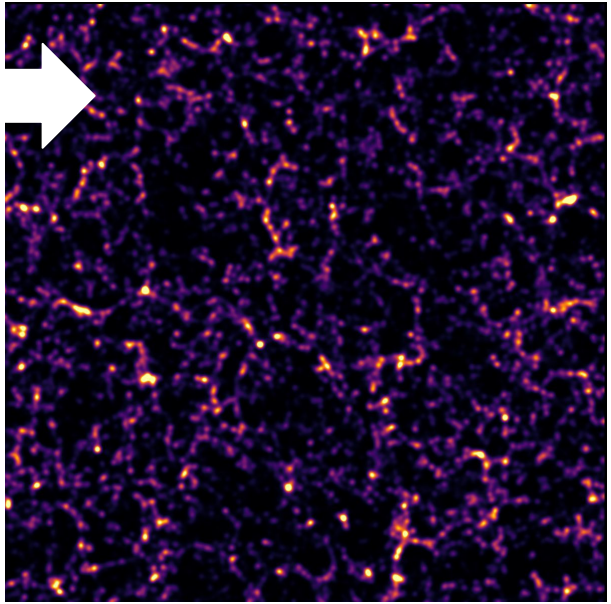
Large Scale Structure with HI Intensity Mapping



Distribution of **neutral Hydrogen (HI)** is biased tracer of **matter clustering**

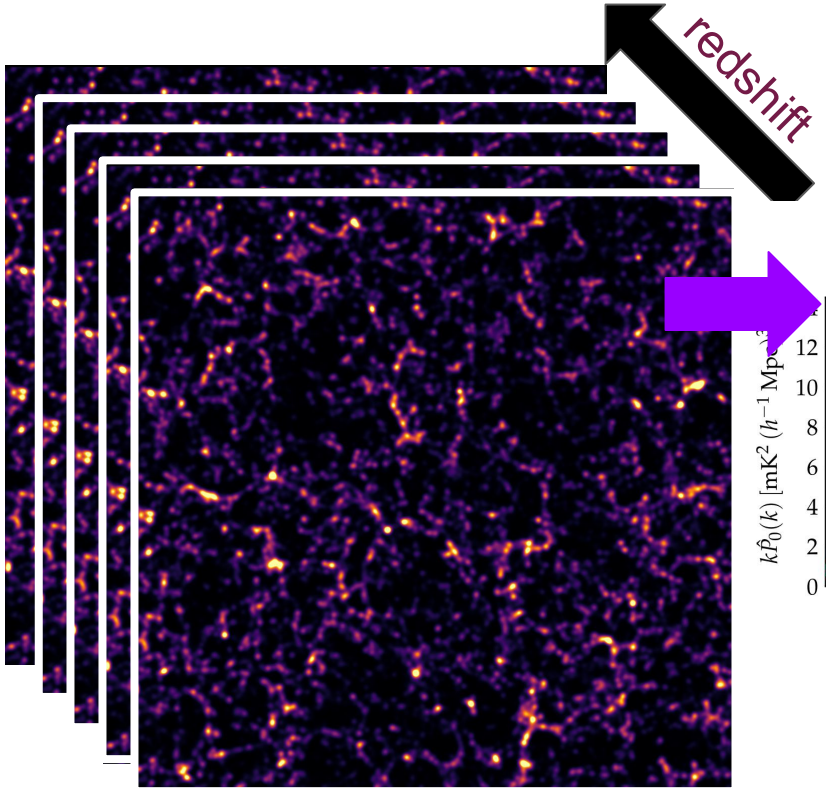
HI Line Intensity Mapping

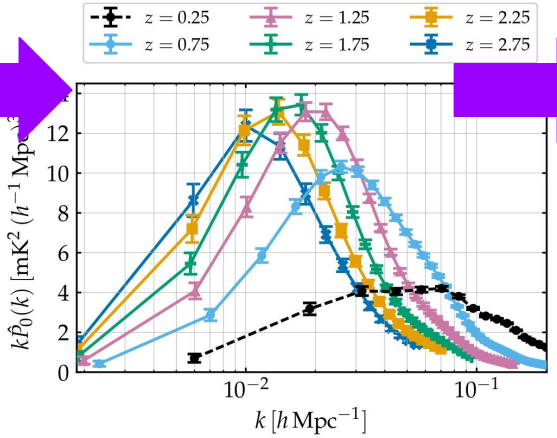


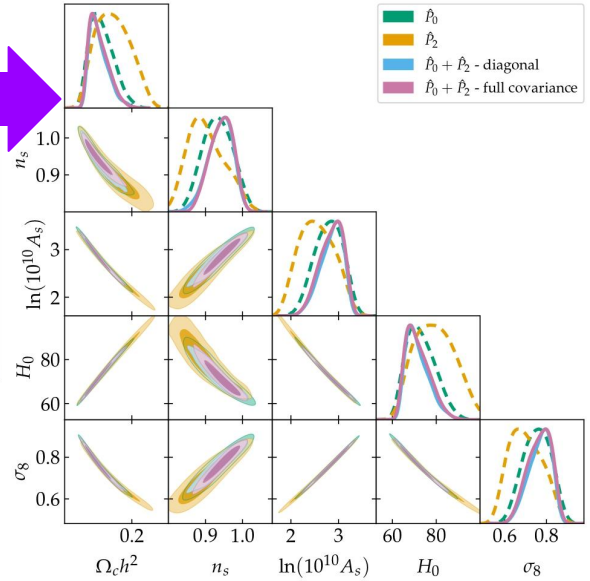


HI LIM with SKA -> key Cosmological probe

Cosmology with HI LIM

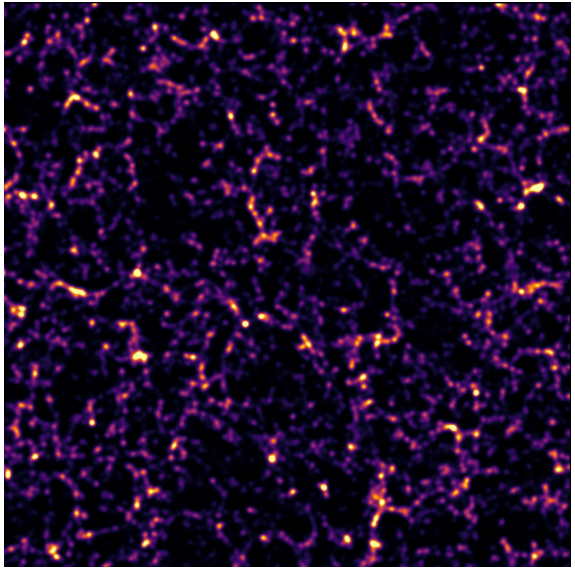






Berti M., Spinelli M., Viel M., 2023, MNRAS, 521, 3221.

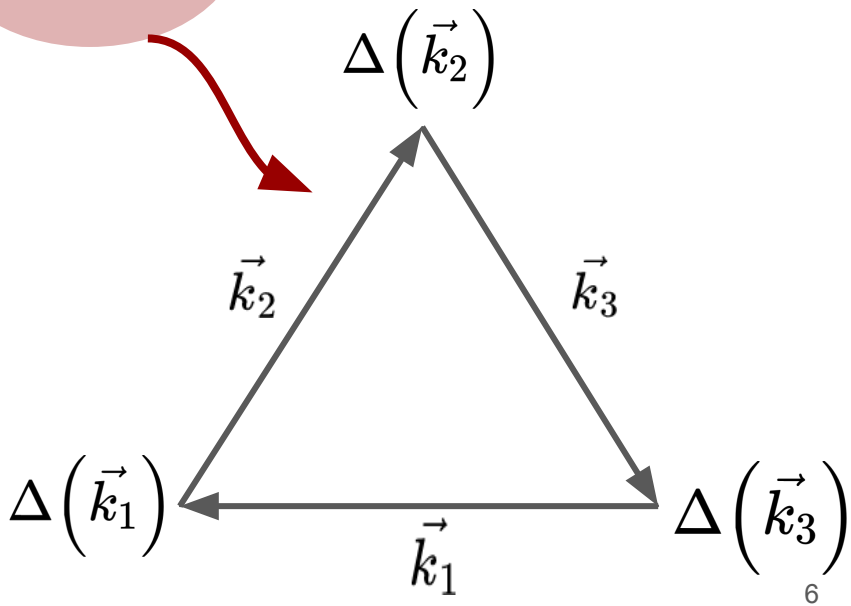
Late Universe is not Gaussian



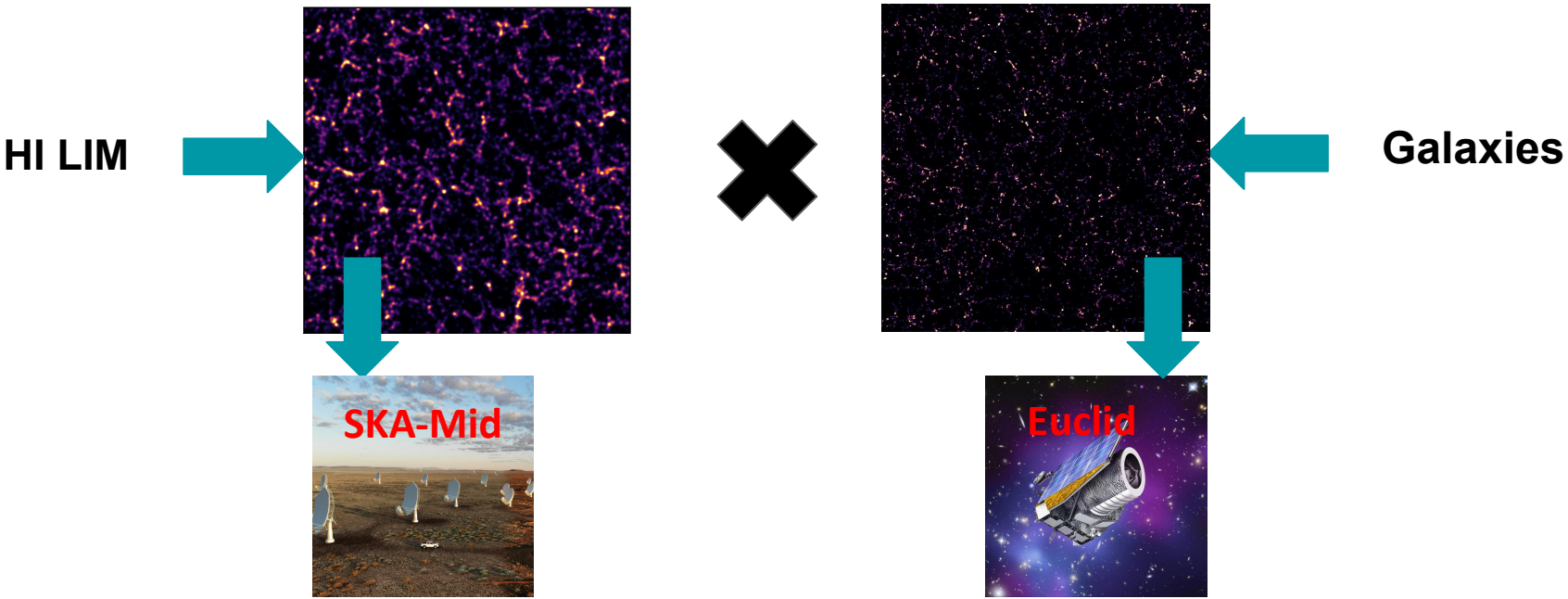
Redshifted **21cm signal** from the post-EoR is **non-Gaussian**
due to non-linear clustering of matter

Non-Gaussian Statistics: Bispectrum

$$< \Delta(\vec{k}_1)\Delta(\vec{k}_2)\Delta(\vec{k}_3) >= V\delta^K_{\vec{k}_1+\vec{k}_2+\vec{k}_3,0} B(\vec{k}_1, \vec{k}_2, \vec{k}_3)$$



21cm-galaxy cross-correlation

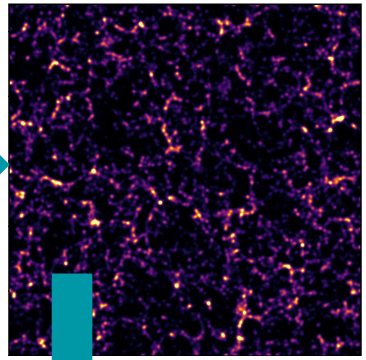


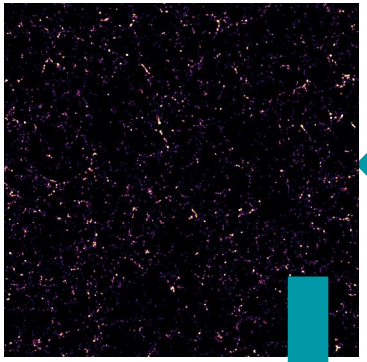
Cross-correlation in the redshift range **0.84 - 1.88**

Cross-correlation might allow us to obtain higher SNR
compared autocorrelation which is severely affected by systematics

21cm-galaxy clustering cross-bispectrum

HI LIM





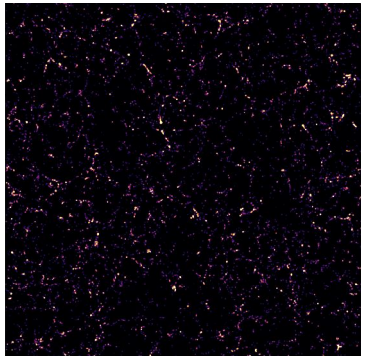
Galaxies

- Test the **detectability** of 21cm-galaxy cross-bispectrum with SKA-Mid and Euclid.
- Does 21cm-galaxy cross-bispectrum put **tighter constraints on Cosmological parameters**?

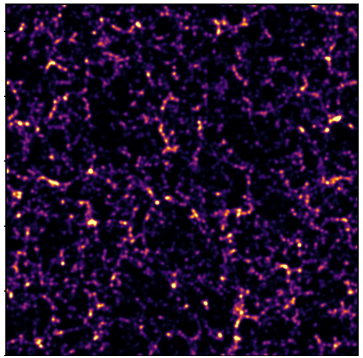
Simulations

P-Millennium
+
GAEA
Semi-analytic galaxy formation model
(Fontanot et al. 2025)

Mock Galaxy Catalogue



HI LIM

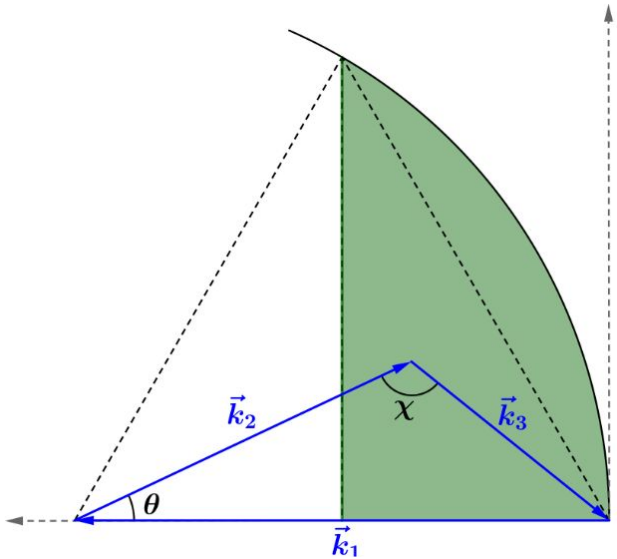


Unique triangles in the Fourier space

$$k_1 \geq k_2 \geq k_3$$

$$0.5 \leq cos(\theta) \leq 1$$

$$0.5 \leq k_2/k_1 \leq 1$$



Bharadwaj S. et al. 2020, MNRAS, 493, 594.
Majumdar S. et al. 2020, MNRAS, 499, 5090.

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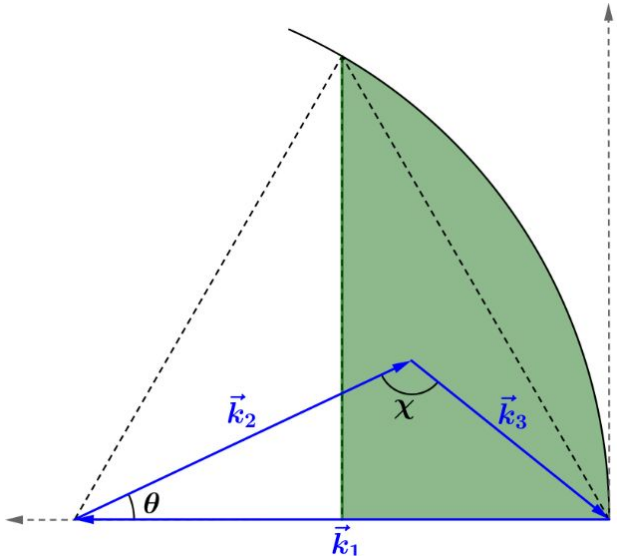
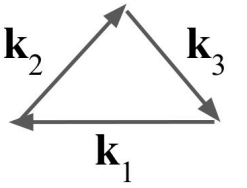
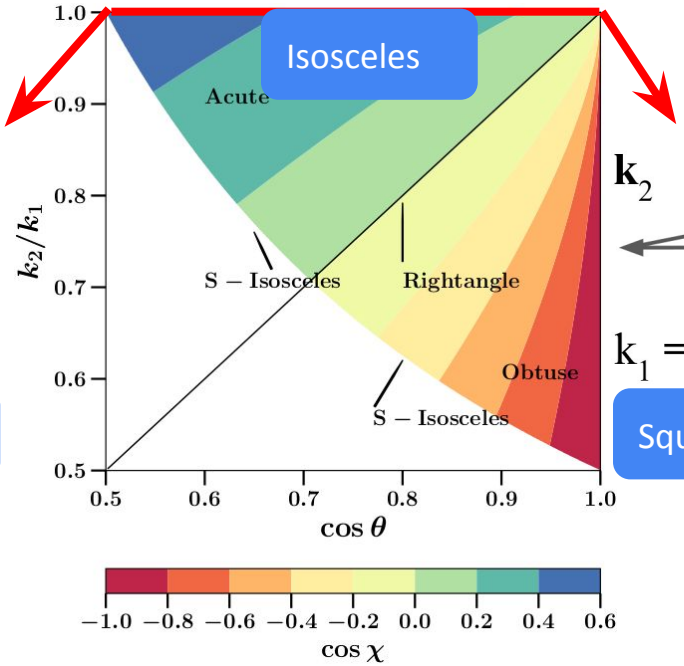
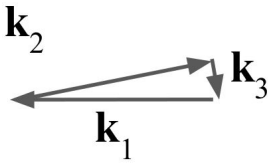




$\mathbf{k}_1 = \mathbf{k}_2 = \mathbf{k}_3$

Equilateral



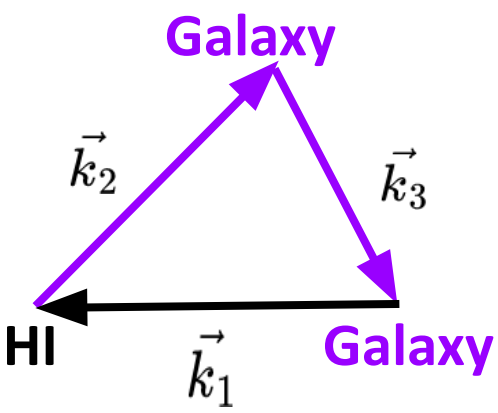


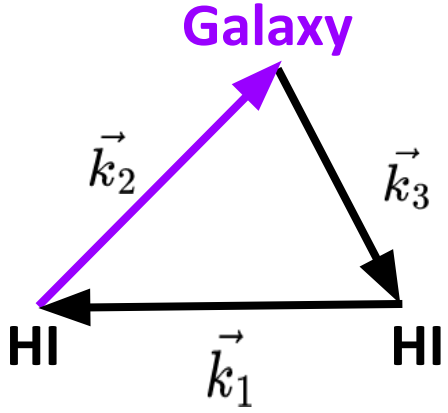
$\mathbf{k}_1 = \mathbf{k}_2,\ \mathbf{k}_3 \rightarrow 0$

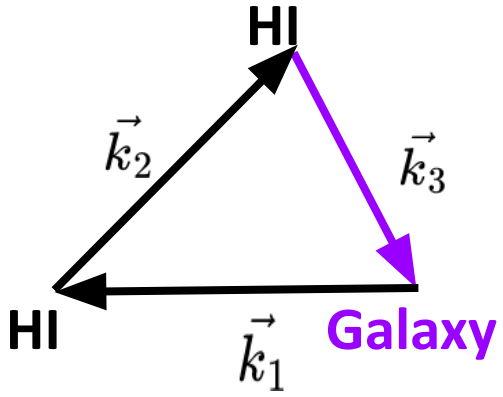
Squeezed-limit

Bharadwaj S. et al. 2020, MNRAS, 493, 594.
Majumdar S. et al. 2020, MNRAS, 499, 5090.

HI LIM-galaxy cross bispectrum



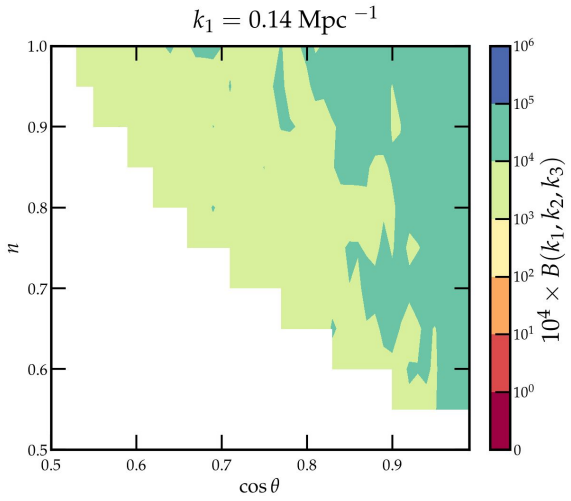




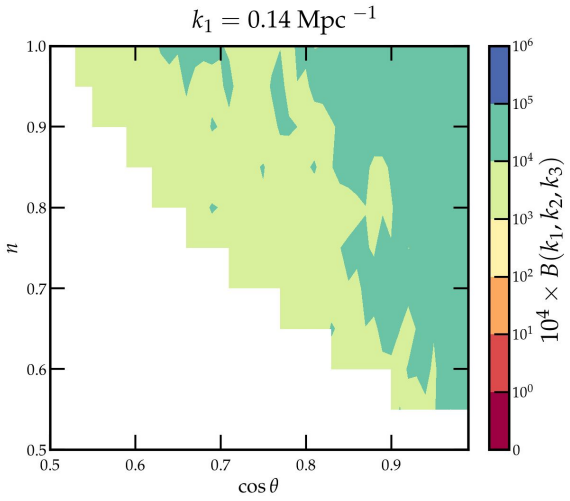
$$< \Delta(\vec{k}_1)\Delta(\vec{k}_2)\Delta(\vec{k}_3) >= V\delta^K_{\vec{k}_1+\vec{k}_2+\vec{k}_3,0} B(\vec{k}_1, \vec{k}_2, \vec{k}_3)$$

A lot to choose from — **triangle shapes, size and cross-combinations….**

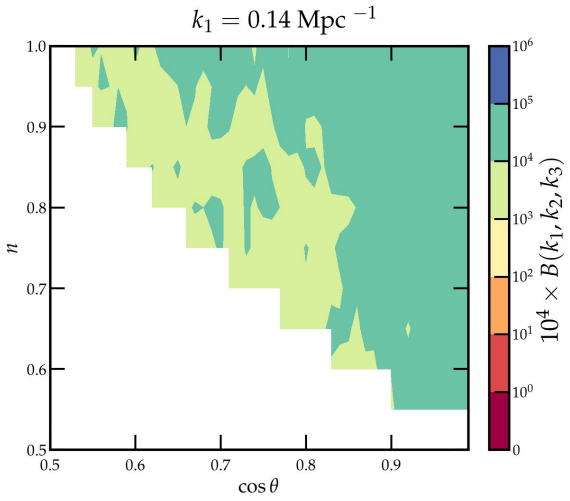
HI LIM-galaxy cross bispectrum



HI-HI-Gal

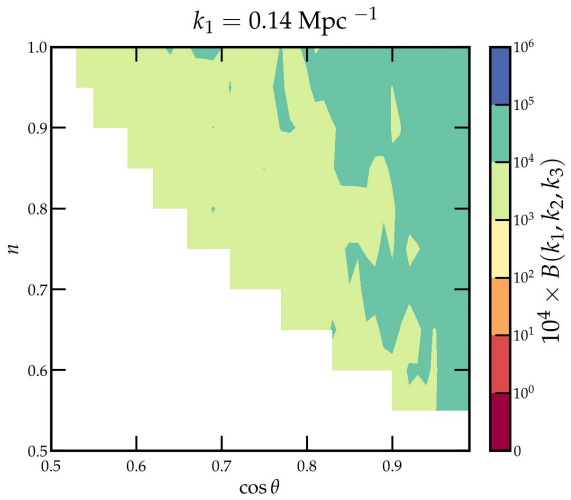


HI- Gal-HI

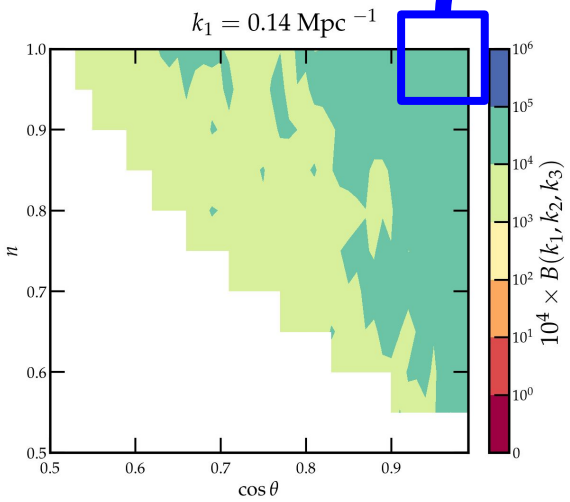


HI-Gal-Gal

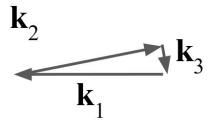
HI LIM-galaxy cross bispectrum

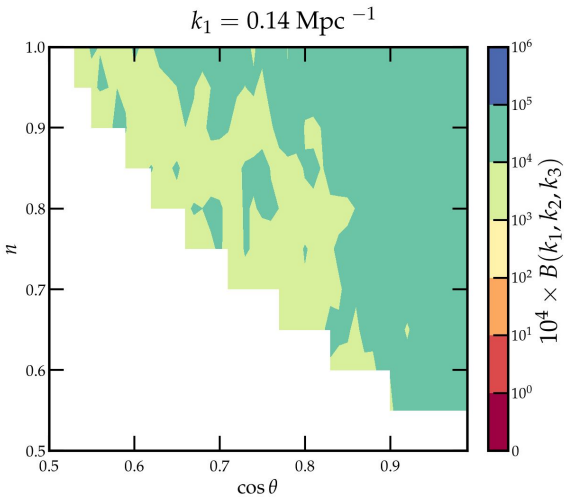


HI-HI-Gal



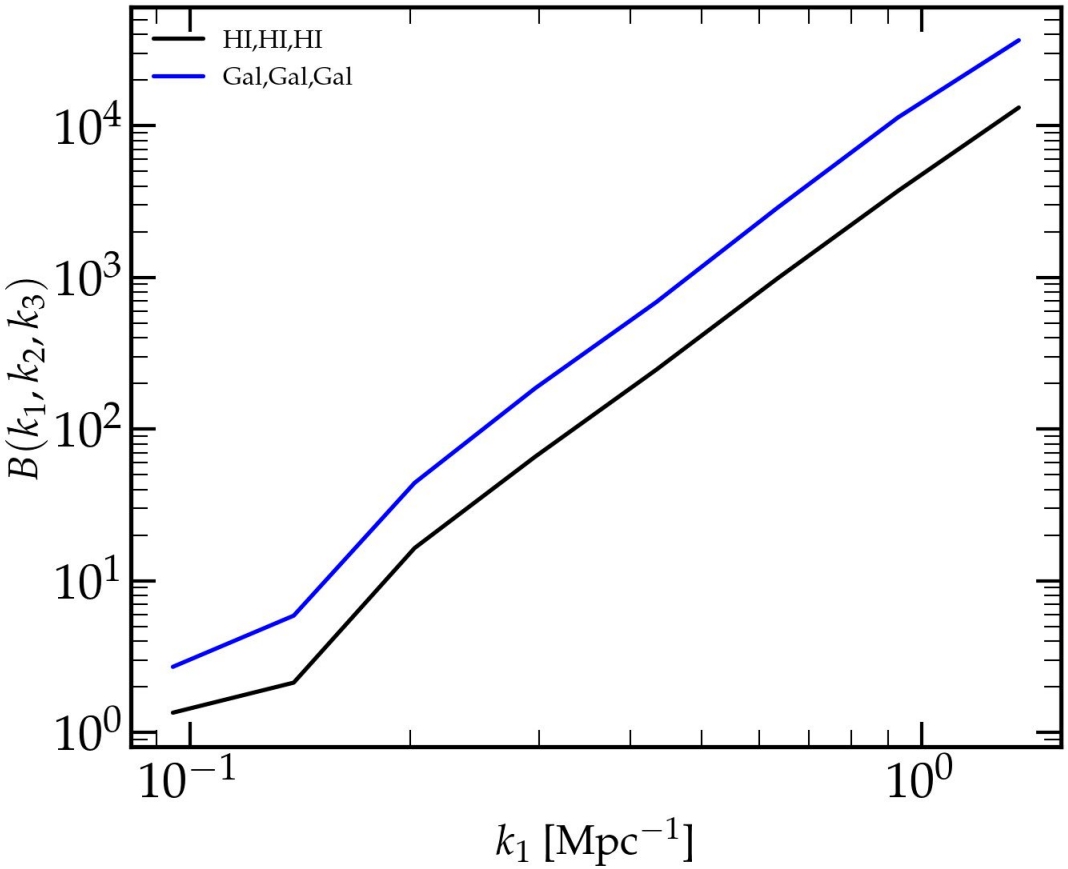
HI- Gal-HI





HI-Gal-Gal

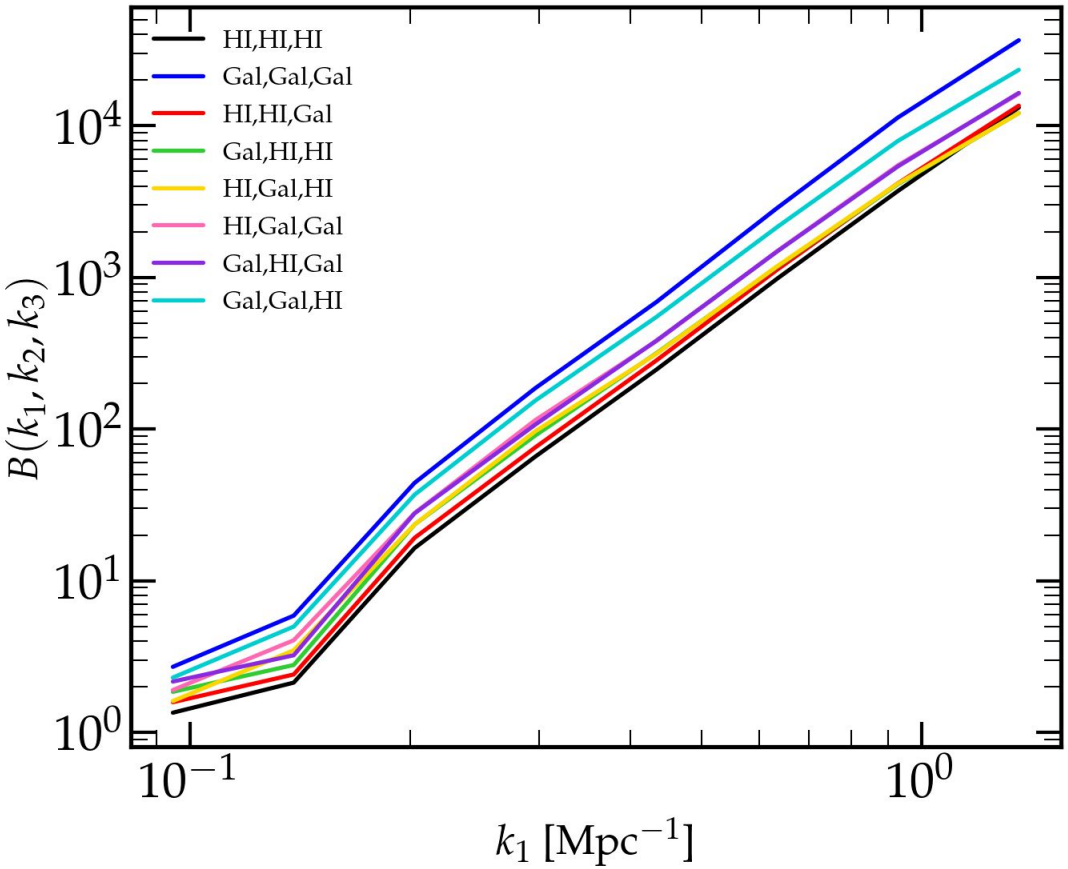
Squeezed-limit bispectrum



Galaxy

HI LIM

Squeezed-limit bispectrum



Galaxy

HI LIM

HI-HI-Gal

Gal-HI- HI

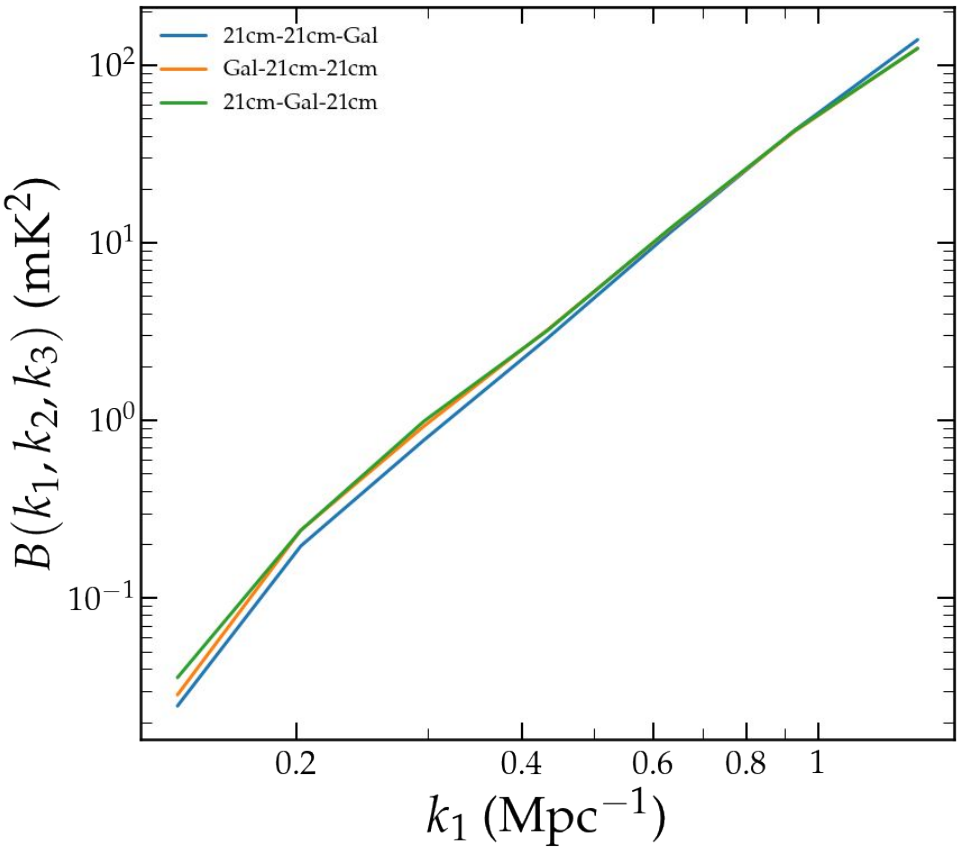
HI-Gal-HI

HI- Gal-Gal

Gal-HI-Gal

Gal-Gal-HI

Squeezed-limit bispectrum

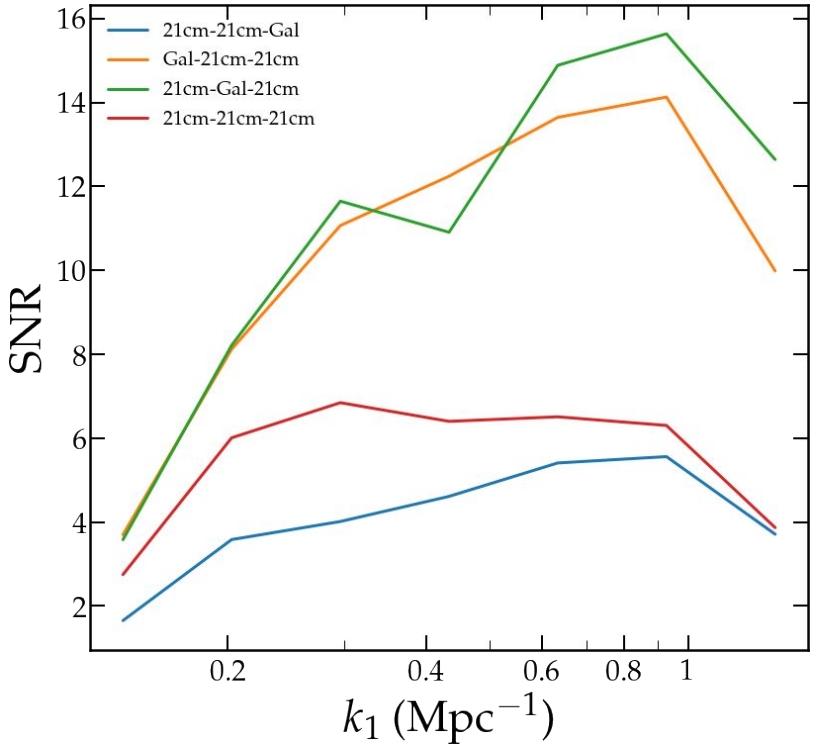


21cm-21cm-Gal

Gal-21cm-Gal

21cm-Gal-21cm

Detectability of cross-bispectrum: Squeezed-limit



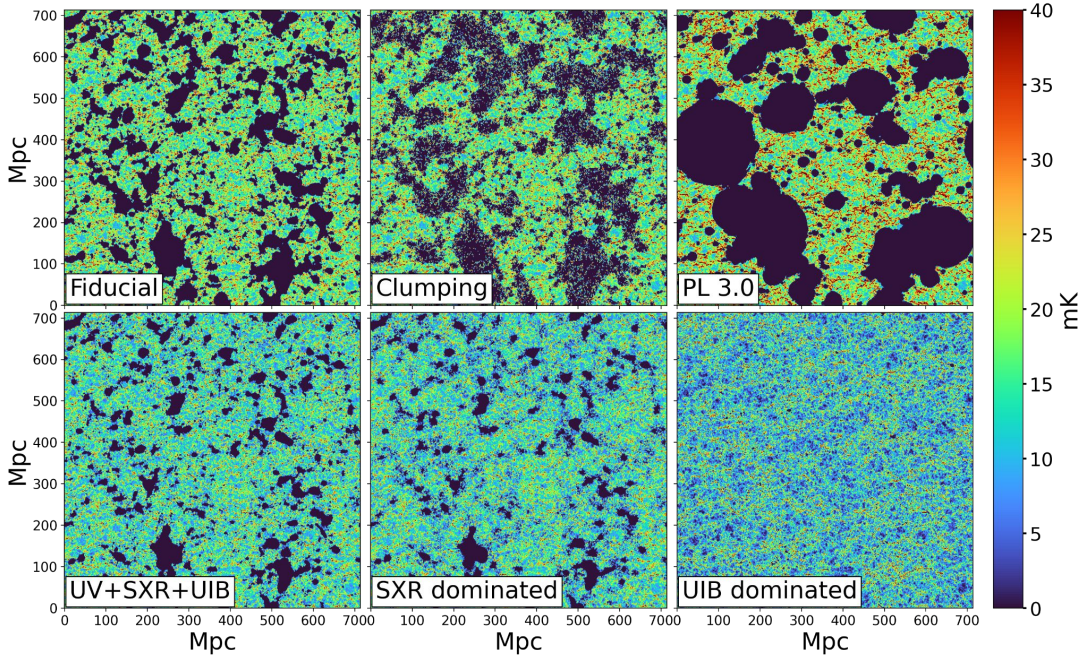
PRELIMINARY

Gal-21cm-Gal

21cm-Gal-21cm

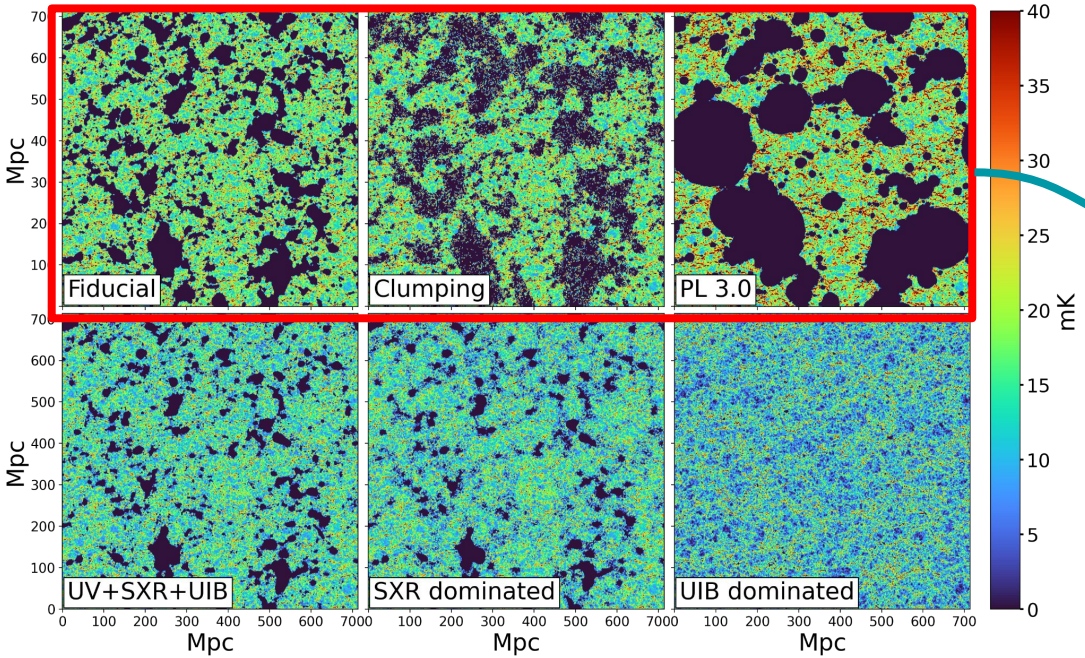
1000 hours of SKA-Mid observations

Impact of the sources of reionization on the 21-cm bispectrum



- Impact of various **reionization morphologies** on the **21-cm bispectrum**
- To what extent the **21-cm bispectrum** can distinguish between different reionization morphologies

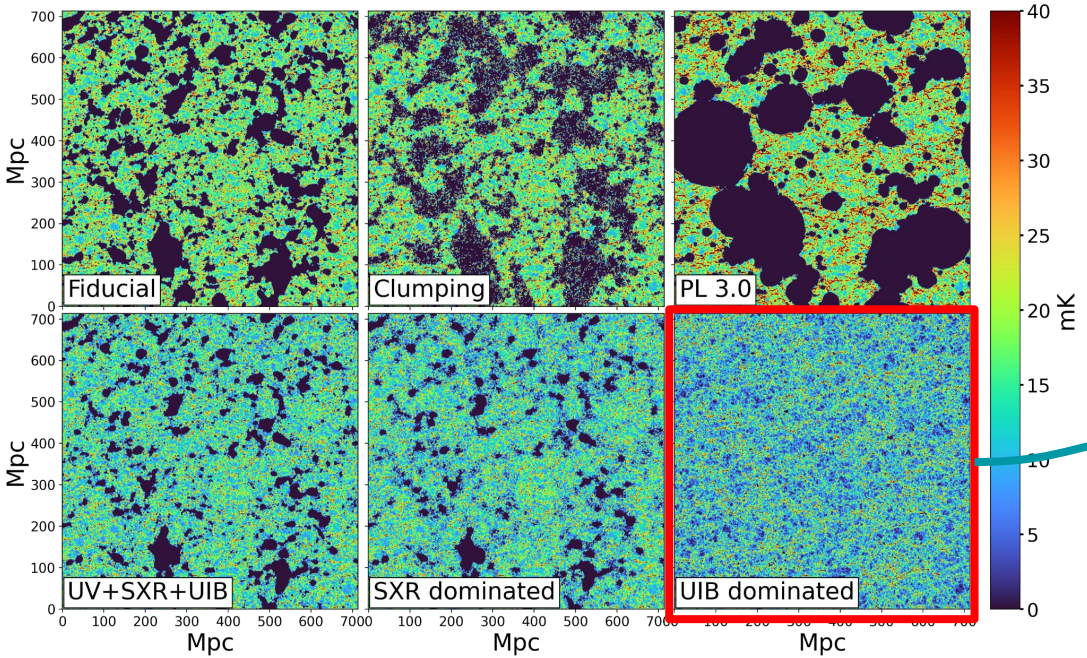
Reionization scenarios



Inside-out reionization scenarios

Noble et al. et al JCAP 10 (2024)003

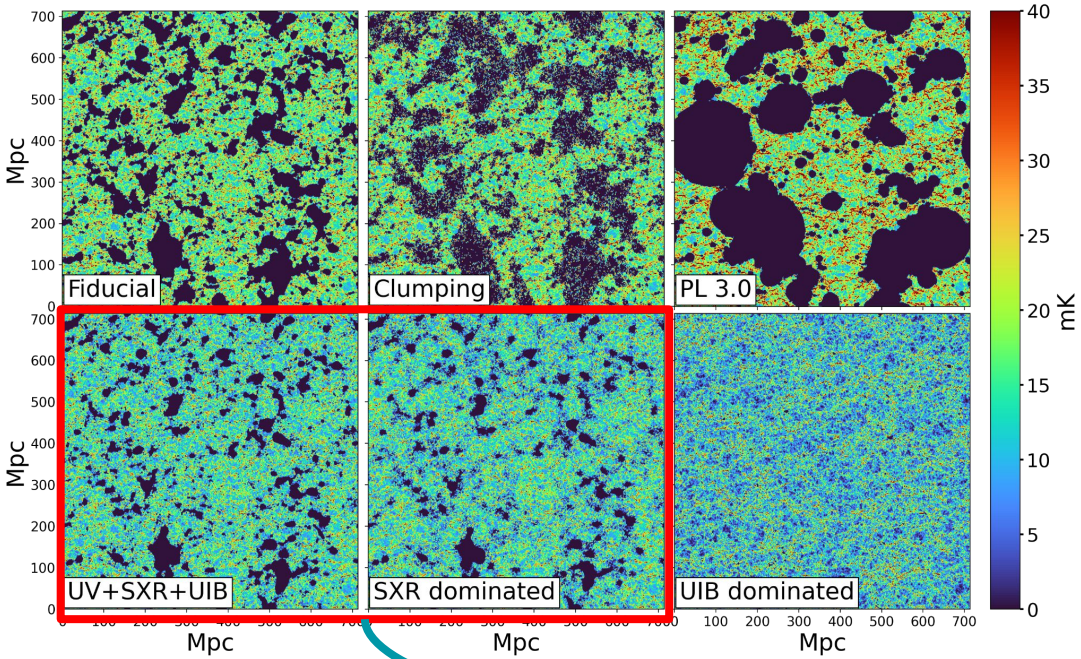
Reionization scenarios



Outside-in reionization scenario

Noble et al. et al JCAP 10 (2024)003

Reionization scenarios

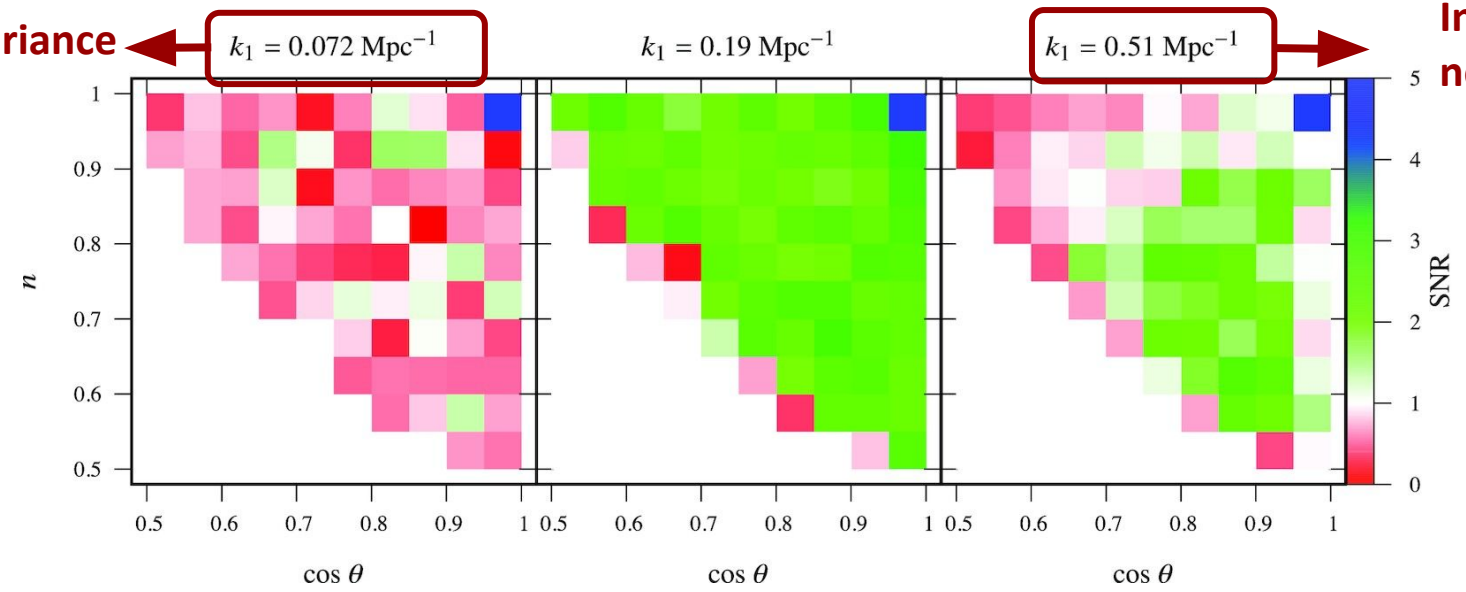


Combination of inside-out and outside-in

Noble et al. et al JCAP 10 (2024)003

Squeezed-limit bispectrum

Cosmic Variance limited

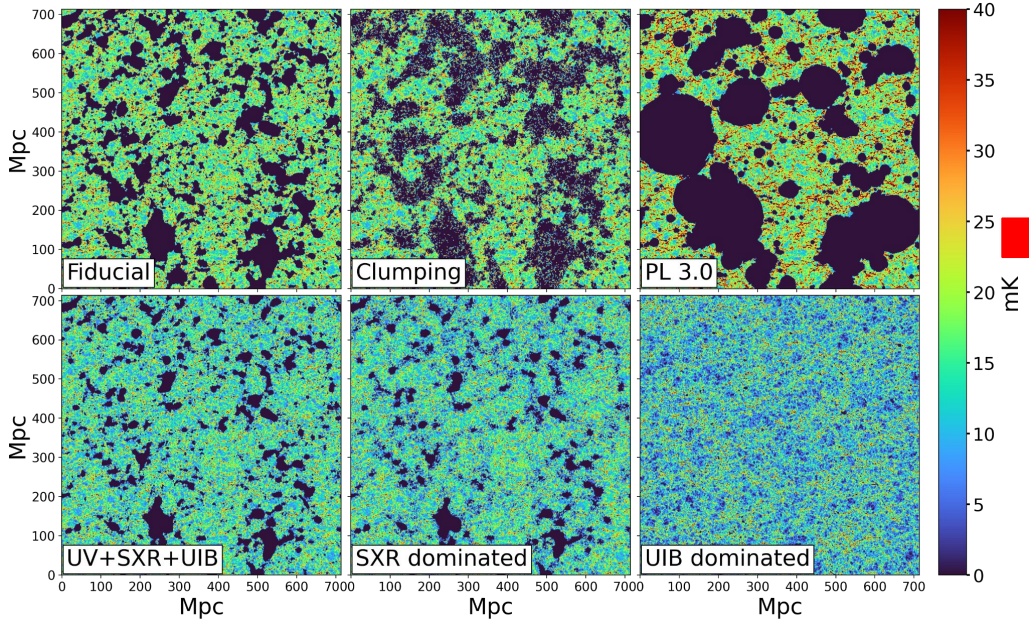


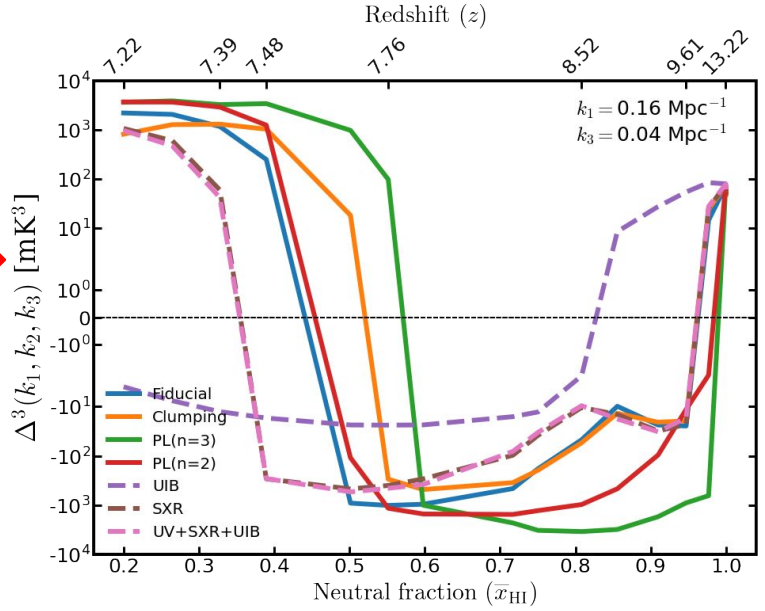
Instrumental noise limited

Highest detection probability by SKA (Mondal R. et al., 2021, MNRAS, 508, 3848.)

We will focus on large scale (k_1 ~ 0.16 Mpc^{-1}) squeezed limit bispectrum

Evolution of squeezed-limit bispectrum





Noble et al. et al JCAP 10 (2024)003

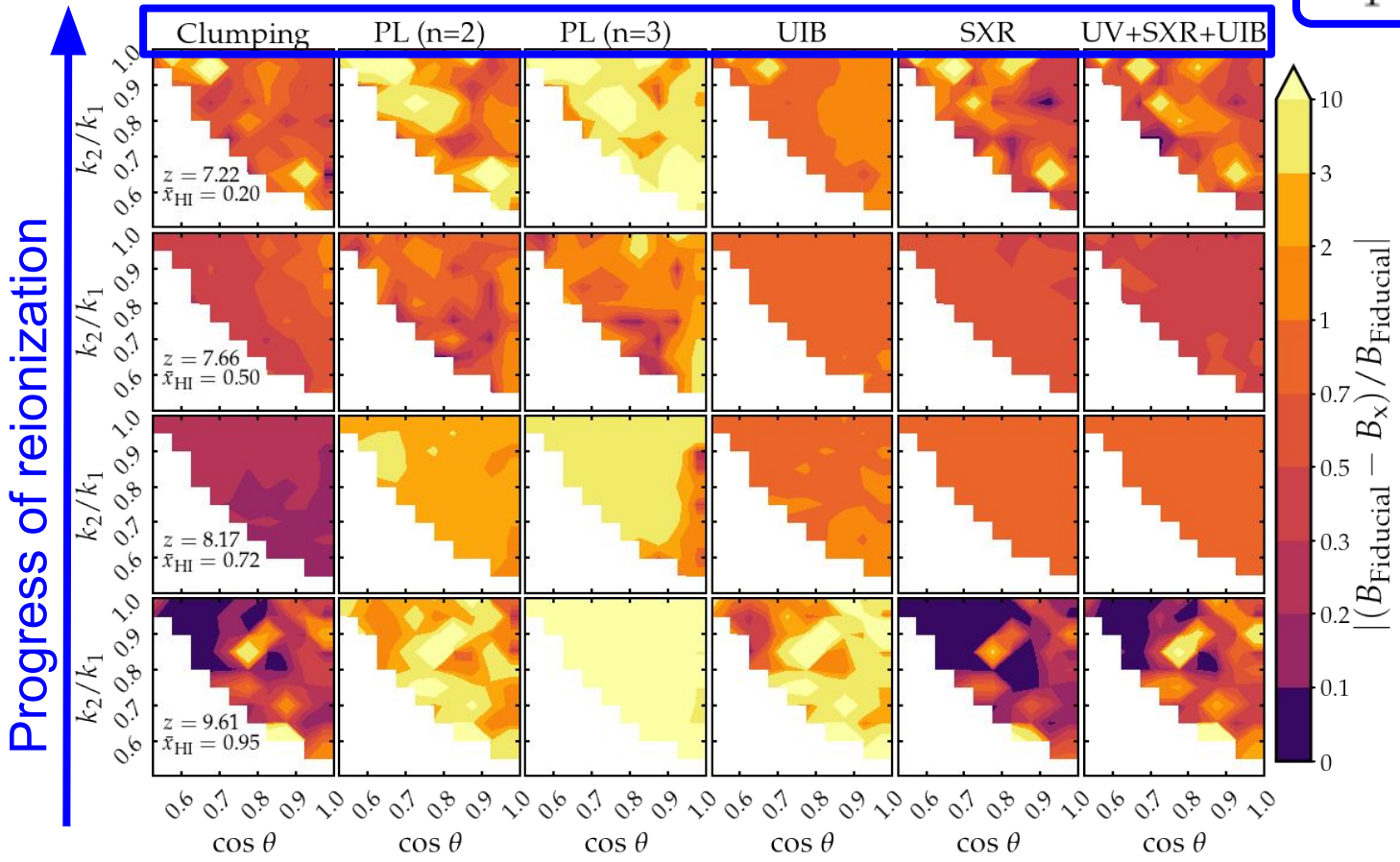
Progress of reionization

Summary

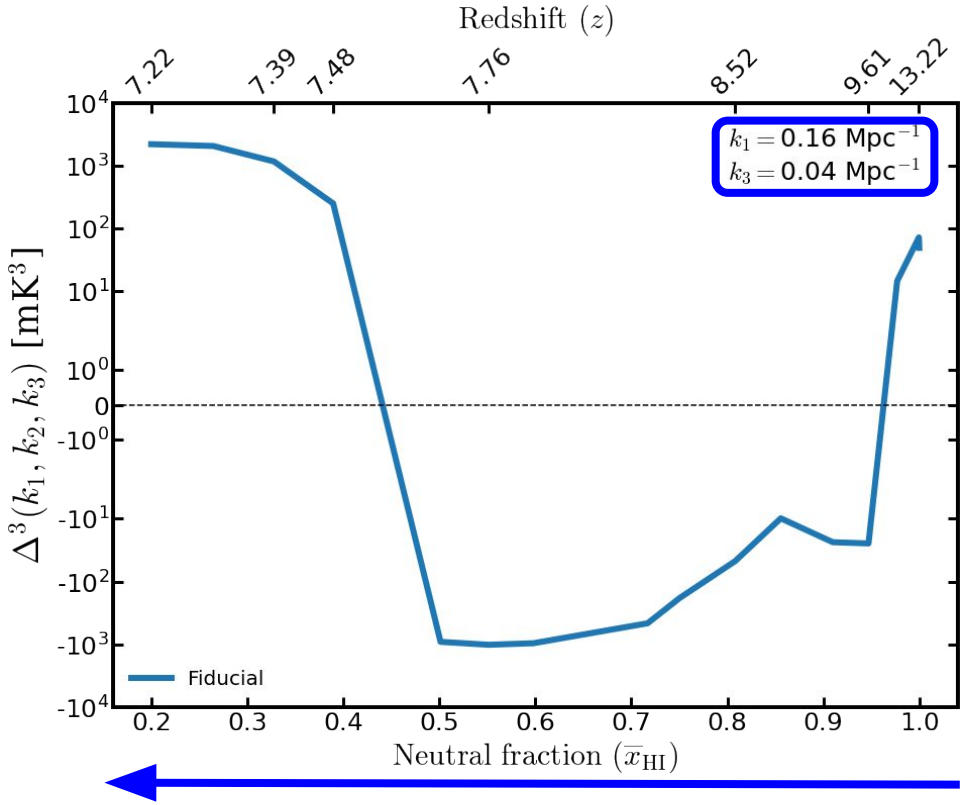
- We are exploring the clustering of matter using 21cm-galaxy cross-bispectrum.
- Our preliminary analysis show higher detectability (SNR) for the 21cm- galaxy cross-bispectrum for squeezed-limit triangles compared to 21cm auto bispectrum.
- We are estimating the detectability of the cross-bispectrum for other shapes of k-triangles.
- EoR 21cm bispectrum can distinguish reionization morphologies.

Magnitude differences in 21-cm bispectrum between different reionization scenarios

$k_1 = 0.16\ \mathrm{Mpc}^{-1}$



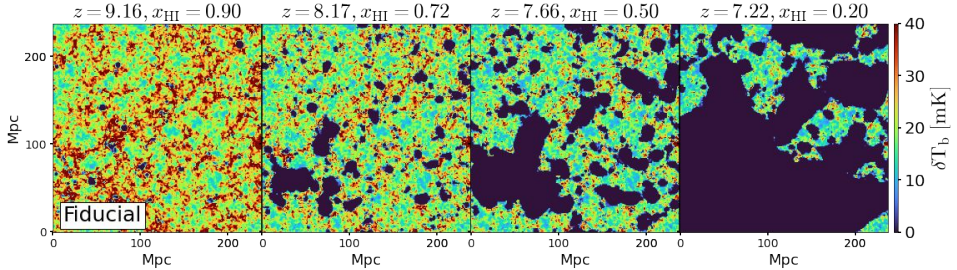
Evolution of squeezed-limit bispectrum



Progress of reionization

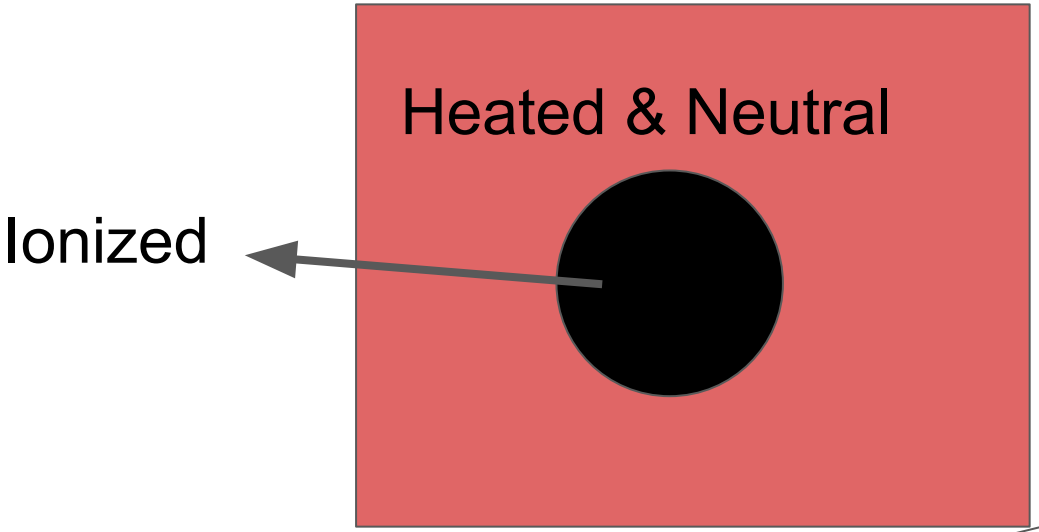
Early stage

Late stage



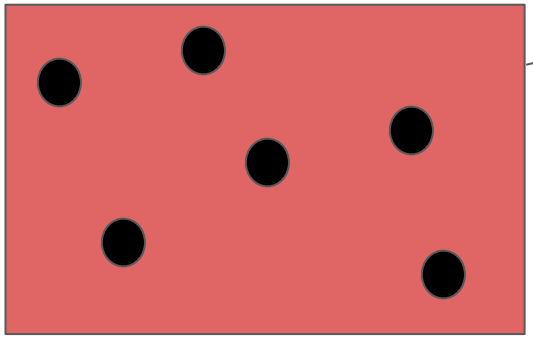
Noble et al. 2024, arXiv: 2406.03118

Interpretation



$$\Delta_{21} \propto -W(kR) \sum \exp\{i\mathbf{k}\cdot\mathbf{r}\}$$

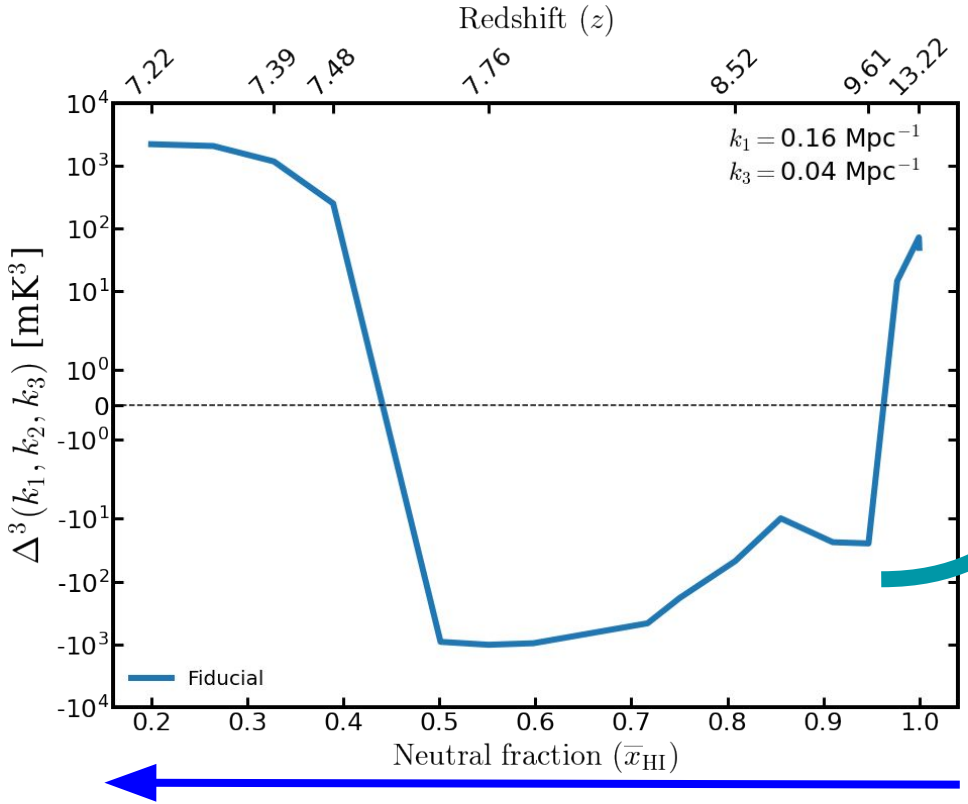
Many non-overlapping ionized regions

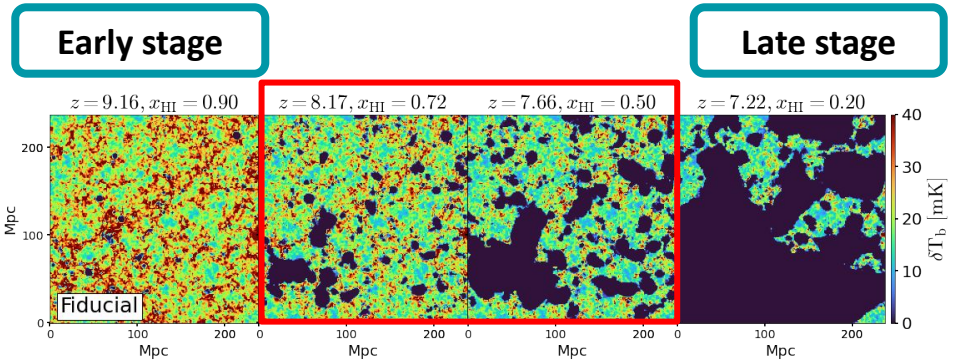


Large scale signal -ve

Bharadwaj & Ali 2004
Bharadwaj & Pandey 2005

Evolution of squeezed-limit bispectrum



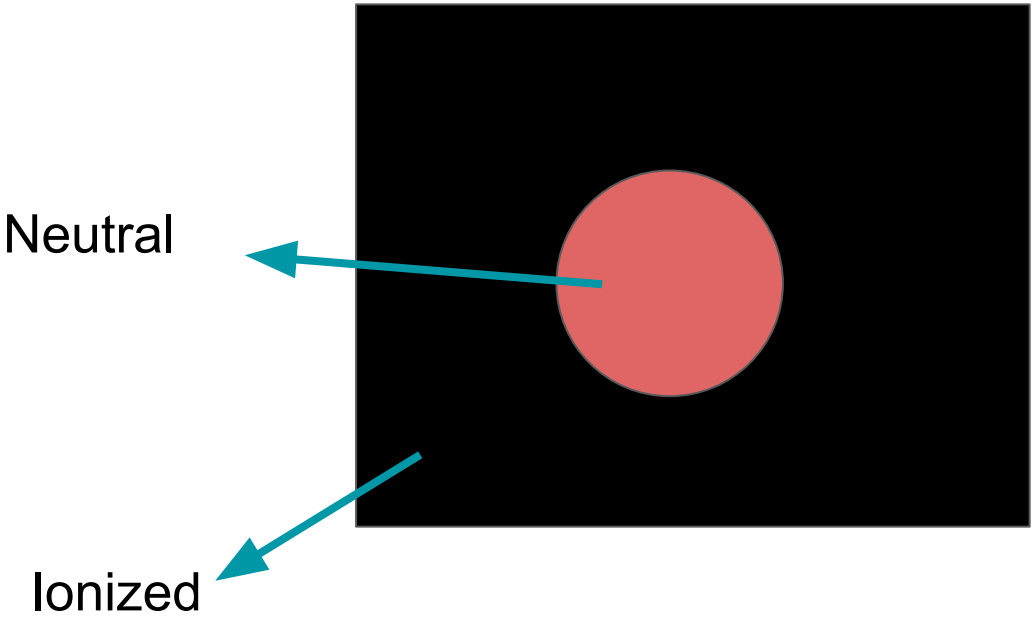


Magnitude of the 21-cm bispectrum increases

Noble et al. 2024, arXiv: 2406.03118

Progress of reionization

Interpretation



$$\Delta_{21} \propto \quad W(kR) \sum \exp\{i\mathbf{k} \cdot \mathbf{r}\}$$

Large scale signal +ve

Bharadwaj & Ali 2004
Bharadwaj & Pandey 2005