Redshifted 21-cm bispectrum from CD-EoR: Impact of Source Model and IGM Physics

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arXiv: 2207.09128

Leon Noble

PhD candidate at IIT Indore

arXiv: 2406.03118

How we can see the IGM during EoR

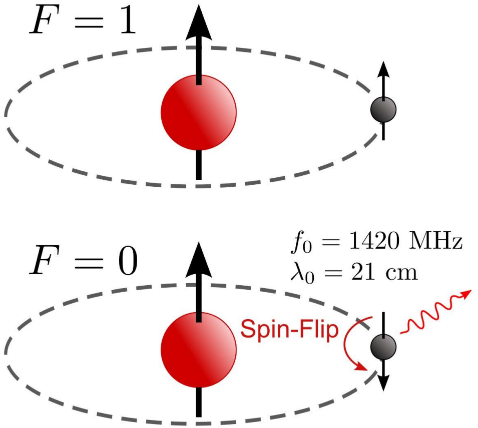
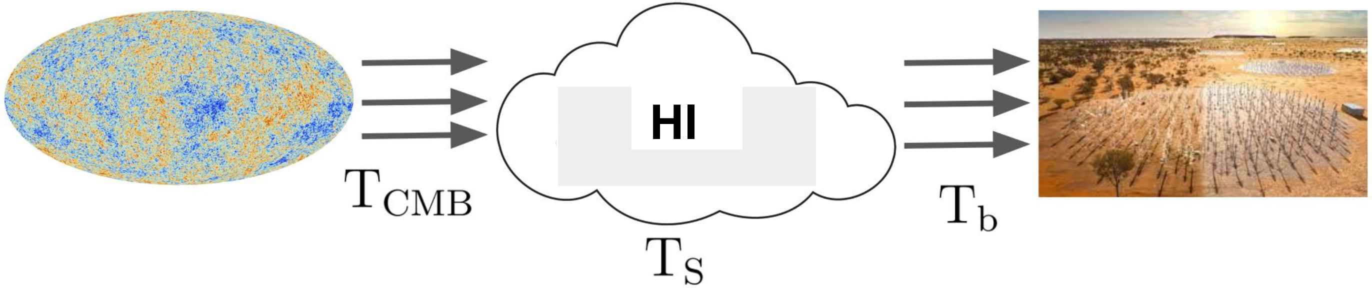


Image credit: Tiltec of Wikipedia

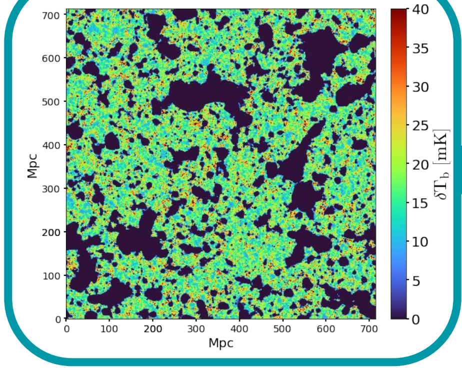


$$\delta T_b = T_b(\mathbf{r}, z) - T_{CMB}(z)$$

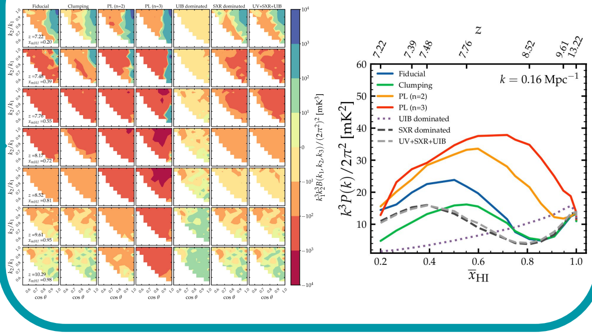
21-cm differential brightness temperature

How to interpret the observations?

Simulations

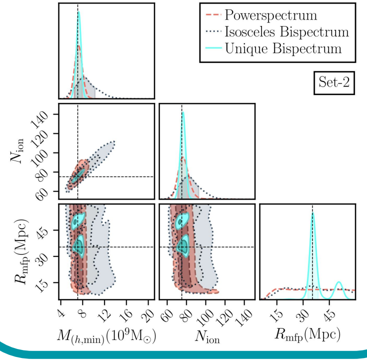


Summary statistics



Bayesian

Parameter estimation



Observations

Summary statistics

Observable summary statistics

21-cm Power spectrum

$$< \Delta(\vec{k}_1)\Delta^*(\vec{k}_2) >= V\delta_D^3(\vec{k}_1 - \vec{k}_2)P(k)$$

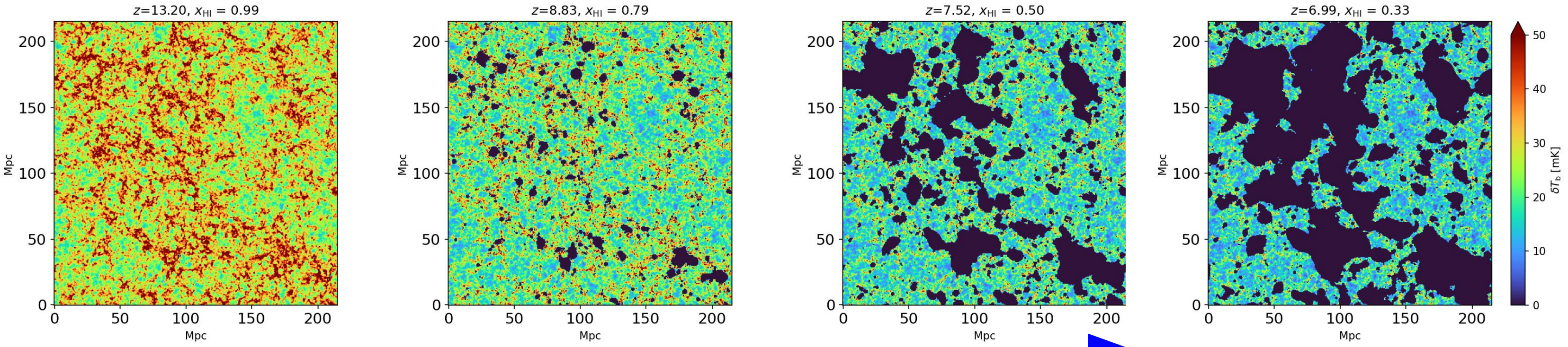
$$\Delta(\vec{k}) \xrightarrow{\mathcal{FT}} \delta T_b$$

Power spectrum can completely characterize the statistical properties of a signal i.e. Gaussian in nature.

IGM 21-cm signal from EoR is highly non-Gaussian

Intrinsic → **The sources of radiation are distributed at non-random (biased) locations**

Time-evolving → **The physical processes in the IGM, controlled by these sources, also progress with time**



Progress of reionization

Various ways of quantifying non-Gaussianity

- One point statistics → Skewness, Kurtosis → Watkinson et al 2014 etc

- Position dependent power spectrum → Giri et al 2019 etc

- Wavelet Scattering Transforms → Greig et al 2022, Hoti et al 2024 etc

- Different image based statistics →
  Bubble Size Distribution, Minkowski functionals,
  Largest Cluster Statistics →
  Iliev et al 2005, 2007, Friedrich et al. 2010, Kakiichi et al. 2017,
  Giri et al. 2017, 2018, Pathak et al 2022, Dasgupta et al 2023 etc

21-cm bispectrum

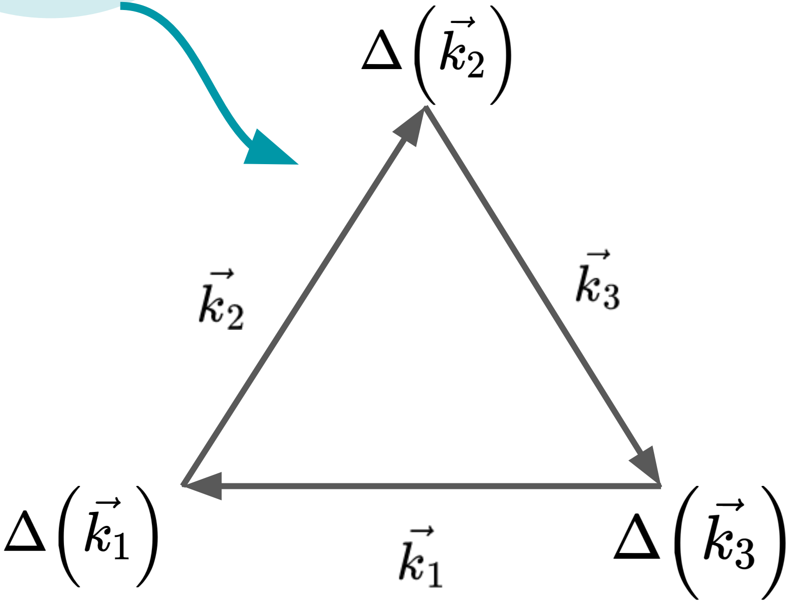
$$< \Delta(\vec{k}_1)\Delta(\vec{k}_2)\Delta(\vec{k}_3) > = V\delta^K_{\vec{k}_1+\vec{k}_2+\vec{k}_3,0} B(\vec{k}_1, \vec{k}_2, \vec{k}_3)$$

$$\Delta(\vec{k}) \xrightarrow{\mathcal{FT}} \delta T_b$$

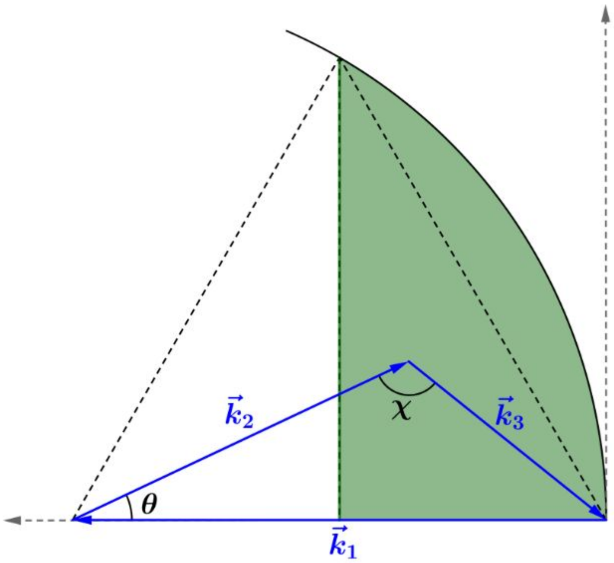
21-cm bispectrum

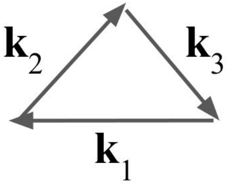
$$< \Delta(\vec{k}_1)\Delta(\vec{k}_2)\Delta(\vec{k}_3) > = V\delta^K_{\vec{k}_1+\vec{k}_2+\vec{k}_3,0} B(\vec{k}_1,\vec{k}_2,\vec{k}_3)$$

$$\Delta(\vec{k}) \xrightarrow{\mathcal{FT}} \delta T_b$$



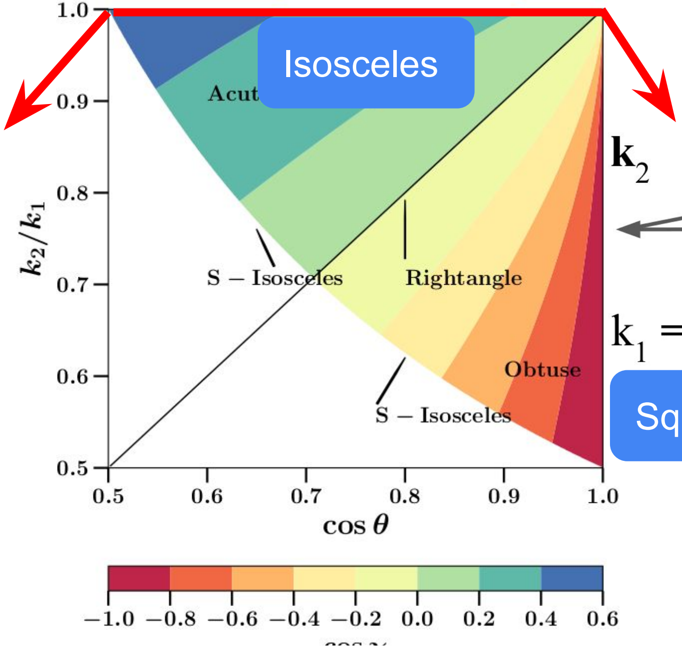
Unique triangles in the Fourier space



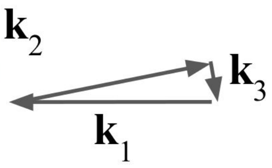


$k_1 = k_2 = k_3$

Equilateral



Isosceles

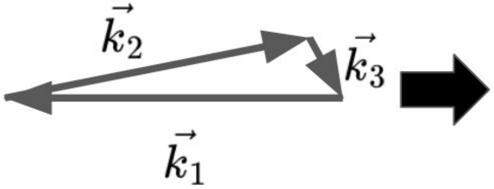


$k_1 = k_2,\ k_3 \rightarrow 0$

Squeezed

Bharadwaj et al 2020, Majumdar et al 2020, Kamran et al 2020, 2021

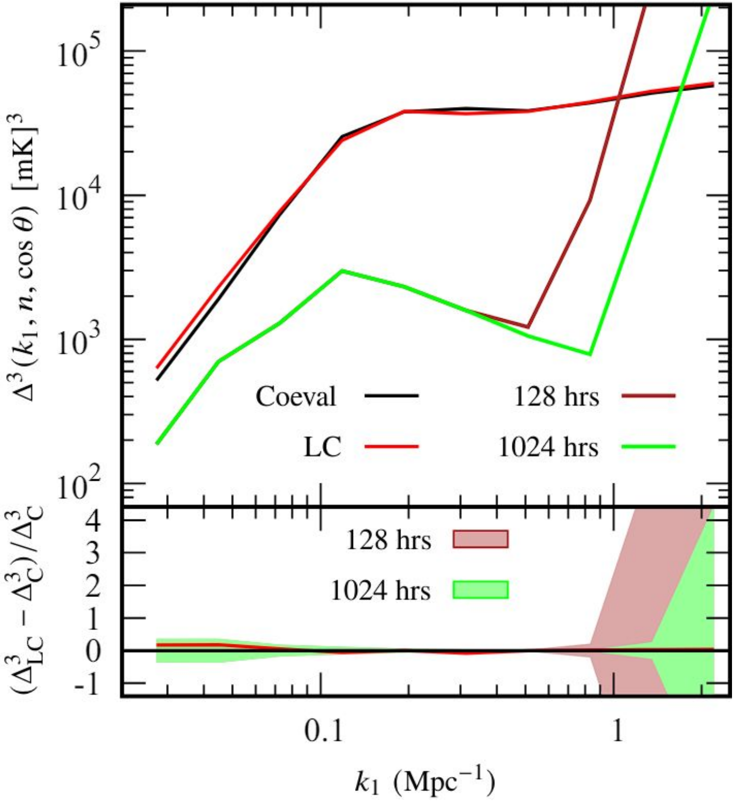
Squeezed-limit bispectrum



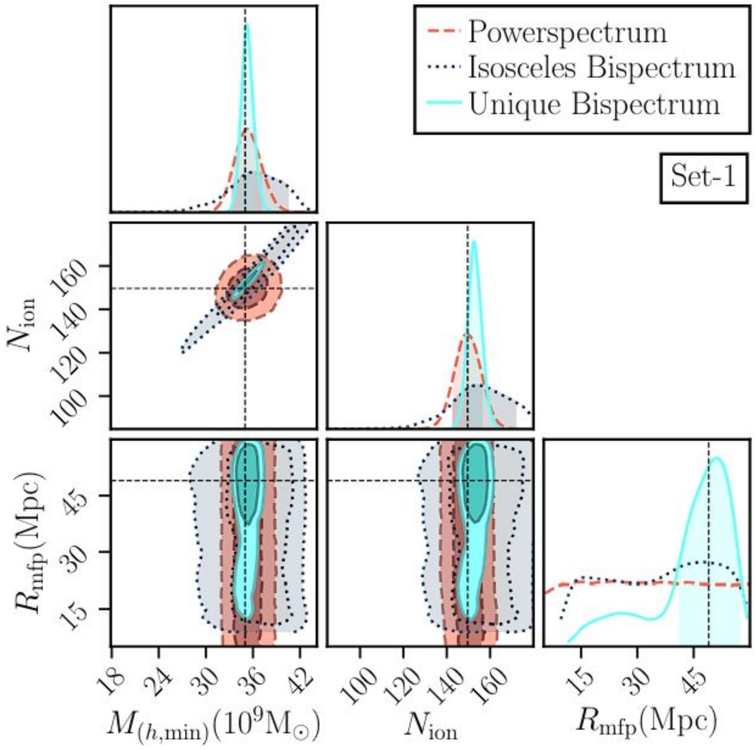
$$|\vec{k}_1| \approx |\vec{k}_2|, \vec{k}_3| \to 0$$

Squeezed-limit

Detectability of the squeezed-limit bispectrum with SKA

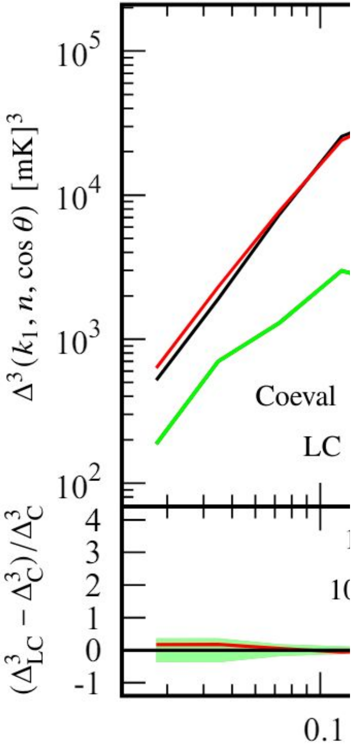


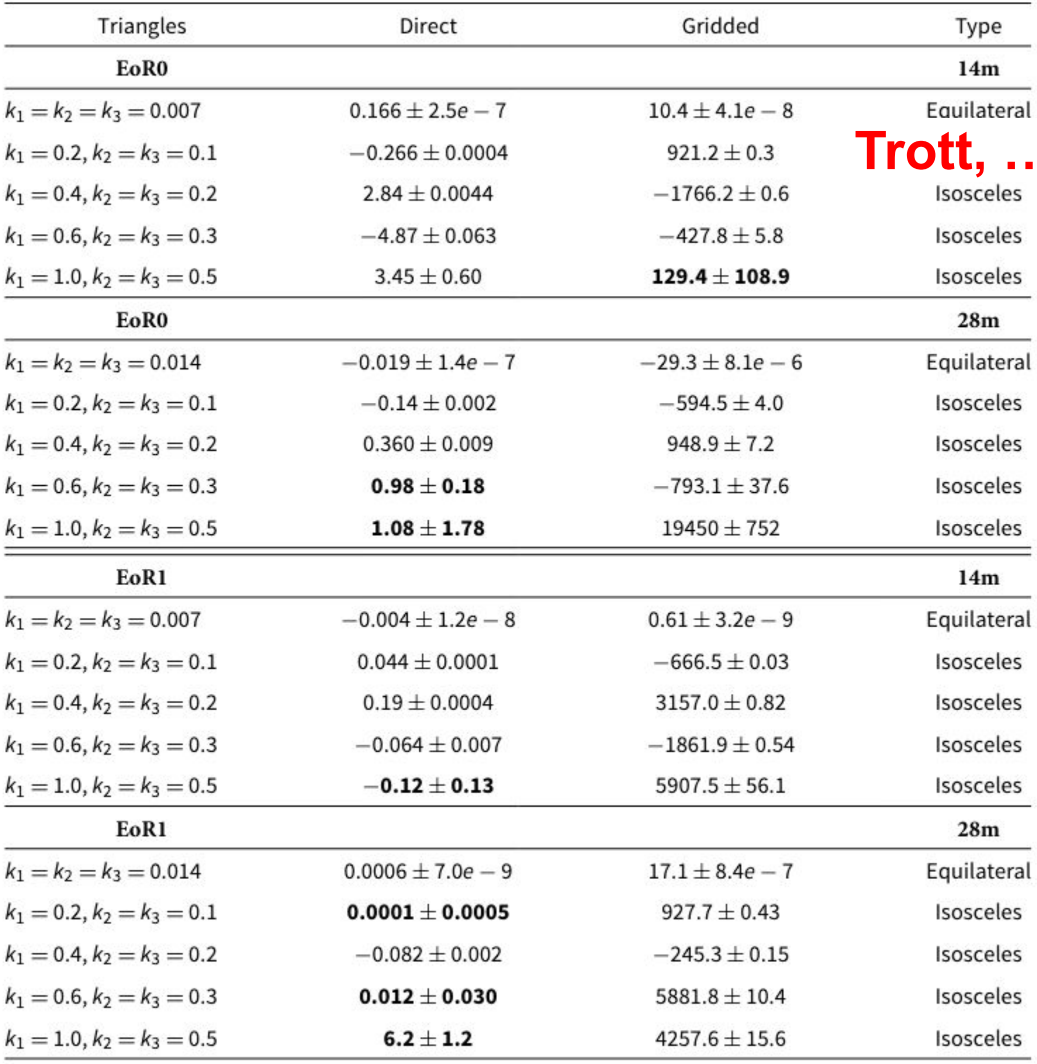
Mondal, …SM et al 2021



Tiwari, SM et al 2022

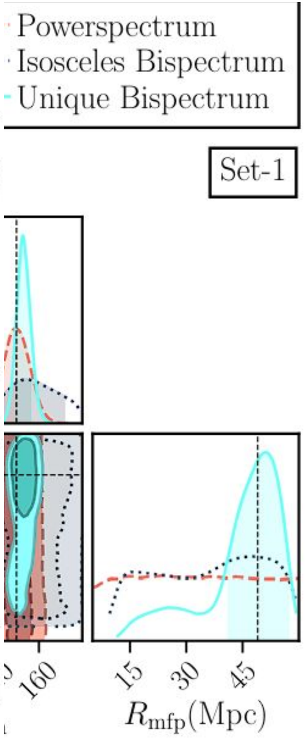
Detectabi with SKA





Triangles	Direct	Gridded	Type
EoR0			**14m**
$k_1 = k_2 = k_3 = 0.007$	$0.166 \pm 2.5e-7$	$10.4 \pm 4.1e-8$	Equilateral
$k_1 = 0.2, k_2 = k_3 = 0.1$	-0.266 ± 0.0004	921.2 ± 0.3	Isosceles
$k_1 = 0.4, k_2 = k_3 = 0.2$	2.84 ± 0.0044	-1766.2 ± 0.6	Isosceles
$k_1 = 0.6, k_2 = k_3 = 0.3$	-4.87 ± 0.063	-427.8 ± 5.8	Isosceles
$k_1 = 1.0, k_2 = k_3 = 0.5$	3.45 ± 0.60	$\mathbf{129.4 \pm 108.9}$	Isosceles
EoR0			**28m**
$k_1 = k_2 = k_3 = 0.014$	$-0.019 \pm 1.4e-7$	$-29.3 \pm 8.1e-6$	Equilateral
$k_1 = 0.2, k_2 = k_3 = 0.1$	-0.14 ± 0.002	-594.5 ± 4.0	Isosceles
$k_1 = 0.4, k_2 = k_3 = 0.2$	0.360 ± 0.009	948.9 ± 7.2	Isosceles
$k_1 = 0.6, k_2 = k_3 = 0.3$	$\mathbf{0.98 \pm 0.18}$	-793.1 ± 37.6	Isosceles
$k_1 = 1.0, k_2 = k_3 = 0.5$	$\mathbf{1.08 \pm 1.78}$	19450 ± 752	Isosceles
EoR1			**14m**
$k_1 = k_2 = k_3 = 0.007$	$-0.004 \pm 1.2e-8$	$0.61 \pm 3.2e-9$	Equilateral
$k_1 = 0.2, k_2 = k_3 = 0.1$	0.044 ± 0.0001	-666.5 ± 0.03	Isosceles
$k_1 = 0.4, k_2 = k_3 = 0.2$	0.19 ± 0.0004	3157.0 ± 0.82	Isosceles
$k_1 = 0.6, k_2 = k_3 = 0.3$	-0.064 ± 0.007	-1861.9 ± 0.54	Isosceles
$k_1 = 1.0, k_2 = k_3 = 0.5$	$\mathbf{-0.12 \pm 0.13}$	5907.5 ± 56.1	Isosceles
EoR1			**28m**
$k_1 = k_2 = k_3 = 0.014$	$0.0006 \pm 7.0e-9$	$17.1 \pm 8.4e-7$	Equilateral
$k_1 = 0.2, k_2 = k_3 = 0.1$	$\mathbf{0.0001 \pm 0.0005}$	927.7 ± 0.43	Isosceles
$k_1 = 0.4, k_2 = k_3 = 0.2$	-0.082 ± 0.002	-245.3 ± 0.15	Isosceles
$k_1 = 0.6, k_2 = k_3 = 0.3$	$\mathbf{0.012 \pm 0.030}$	5881.8 ± 10.4	Isosceles
$k_1 = 1.0, k_2 = k_3 = 0.5$	$\mathbf{6.2 \pm 1.2}$	4257.6 ± 15.6	Isosceles

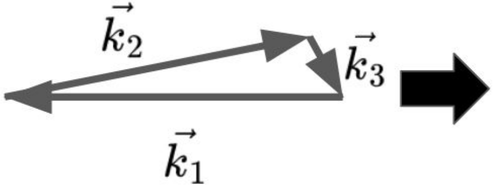
Trott, …SM et al 2019



Mondal, …SM

al 2022

Squeezed-limit bispectrum



$|\vec{k}_1| \approx |\vec{k}_2|, \vec{k}_3| \rightarrow 0$

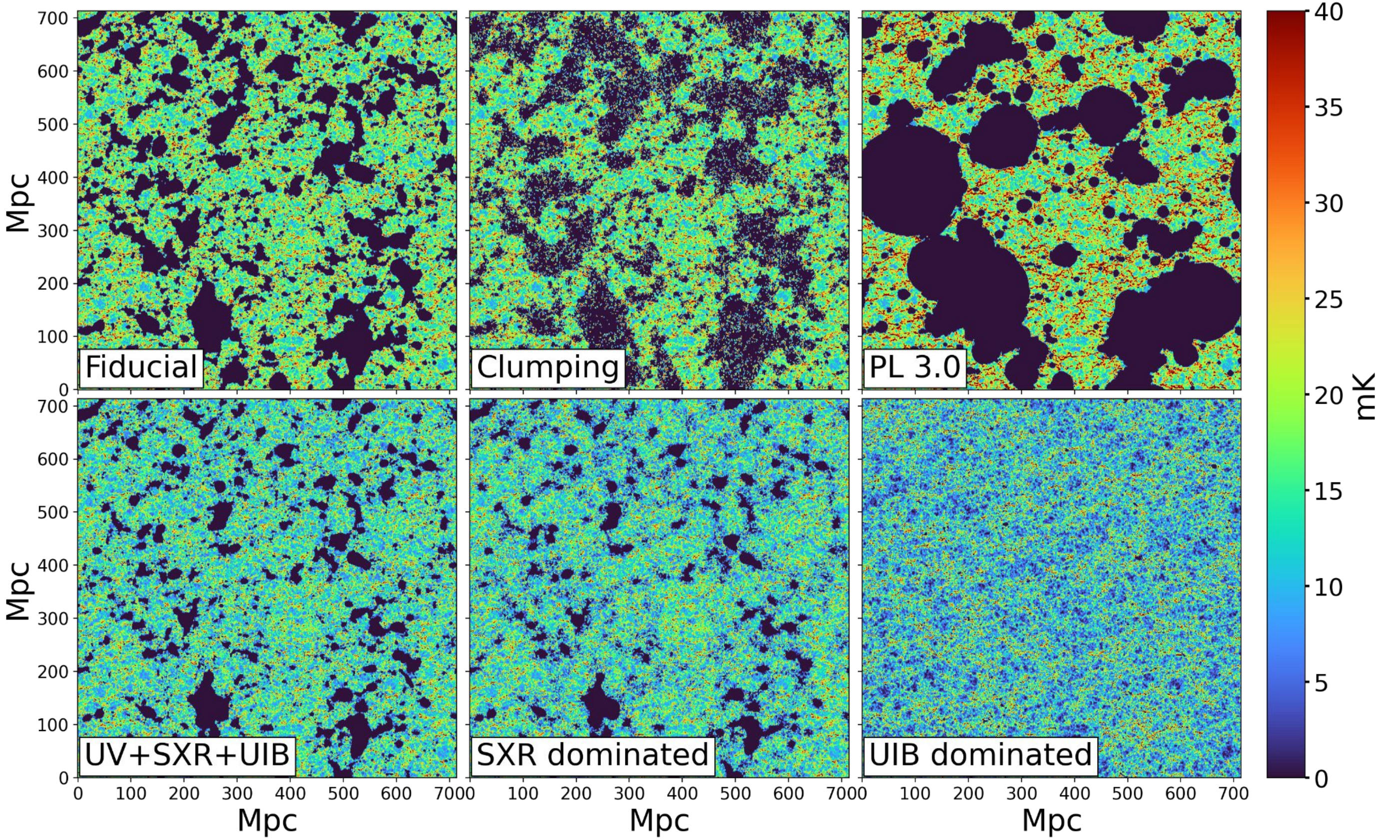
Squeezed-limit

- **Among all possible unique k-triangles, squeezed-limit triangle bispectrum has maximum magnitude**
  (Majumdar et al. 2018, 2020; Hutter et al. 2019, Watkinson et al 2021, Kamran, SM et al. 2021, 2022, Tiwari, SM et al. 2022, Gill, SM et al. 2023, Raste et al. 2024**).**
- **Highest detection probability by SKA**
  (Mondal, SM et al. 2021, Tiwari, SM, et al. 2022**).**

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

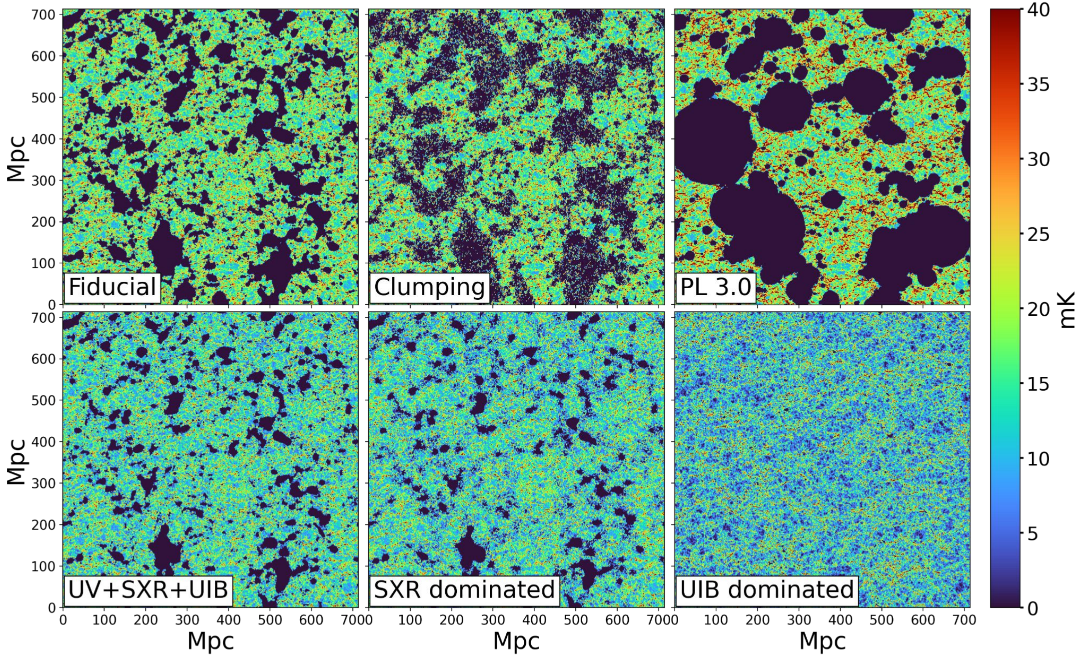
Epoch of Reionization 21-cm bispectrum

Impact of the sources of reionization on 21-cm signal



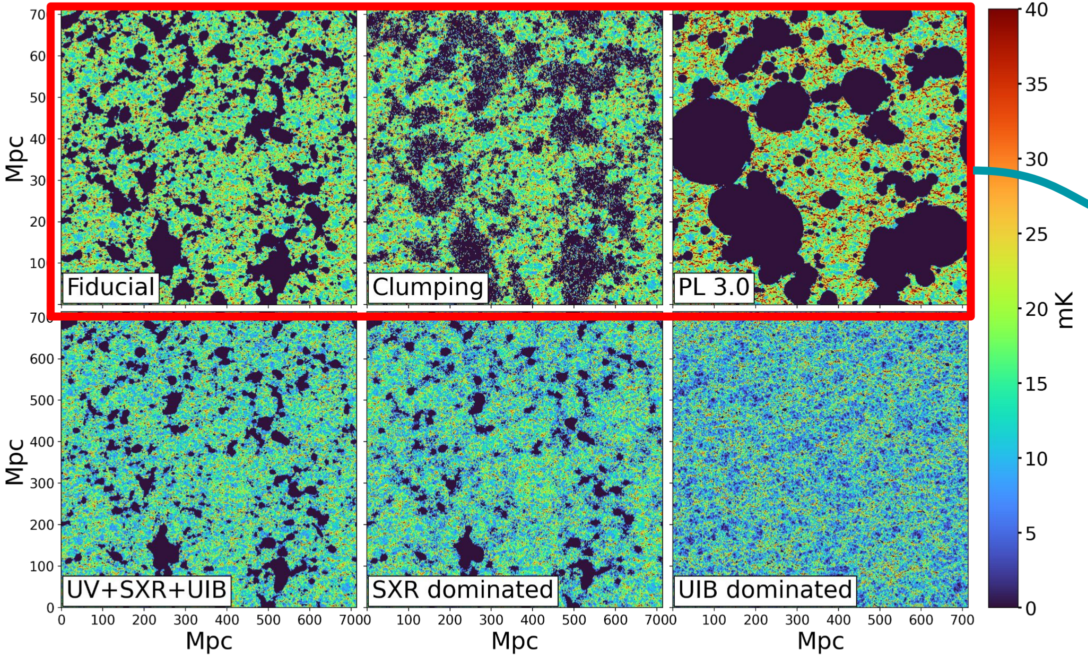
Choudhury et al 2009;
Watkinson et al. 2014;
Majumdar et al. 2016;
Eide et al. 2018;
Hutter et al. 2019;
Watkinson et al. 2021
Pathak et al. 2022;
Raste et al 2024;
Schaeffer et al 2024,……
and many more

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**

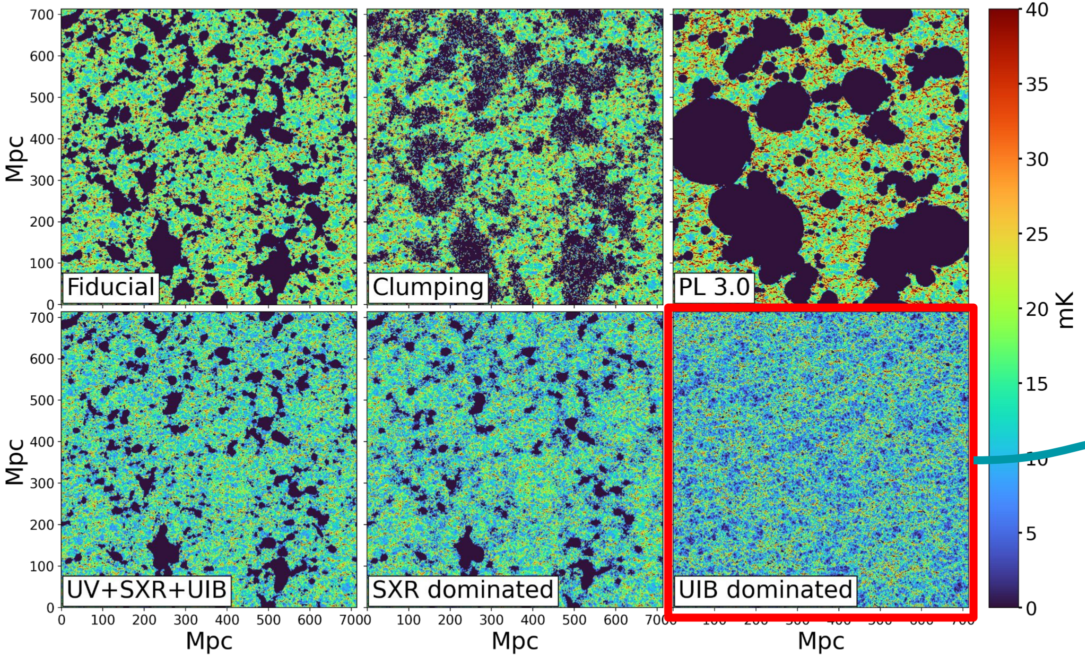
Reionization scenarios



Inside-out reionization scenarios

Noble, SM et al. 2024, arXiv: 2406.03118

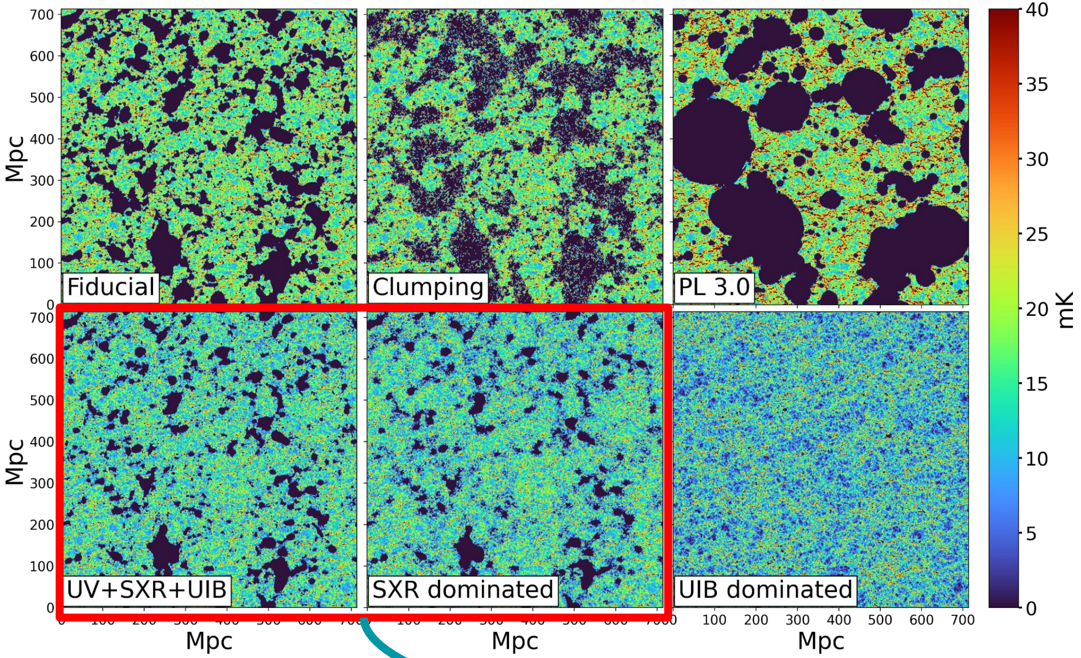
Reionization scenarios



Outside-in reionization scenario

Noble, SM et al. 2024, arXiv: 2406.03118

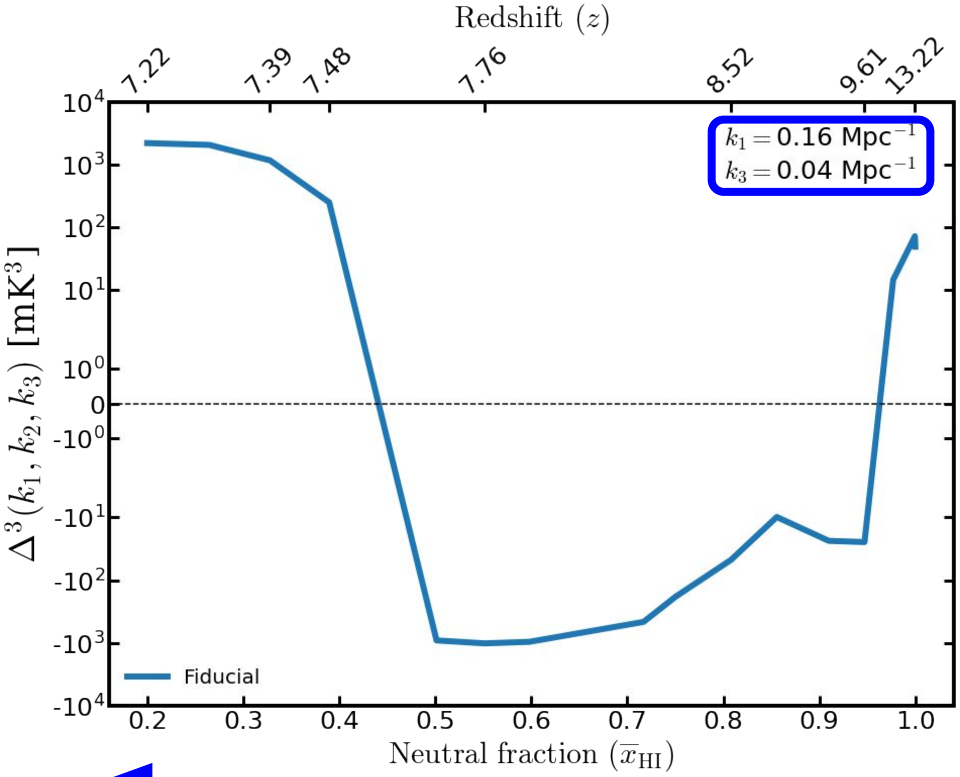
Reionization scenarios



Combination of inside-out and outside-in

Noble, SM et al. 2024, arXiv: 2406.03118

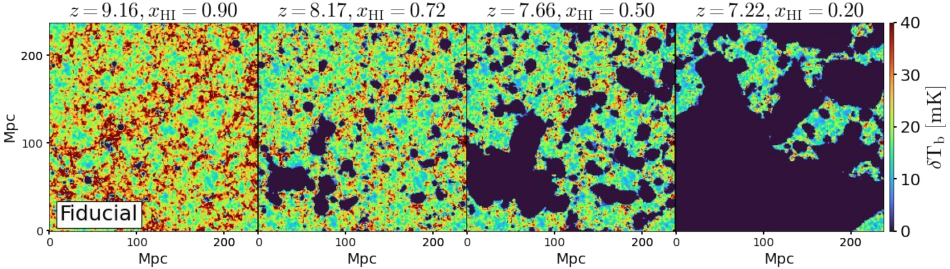
Evolution of squeezed-limit bispectrum



Progress of reionization

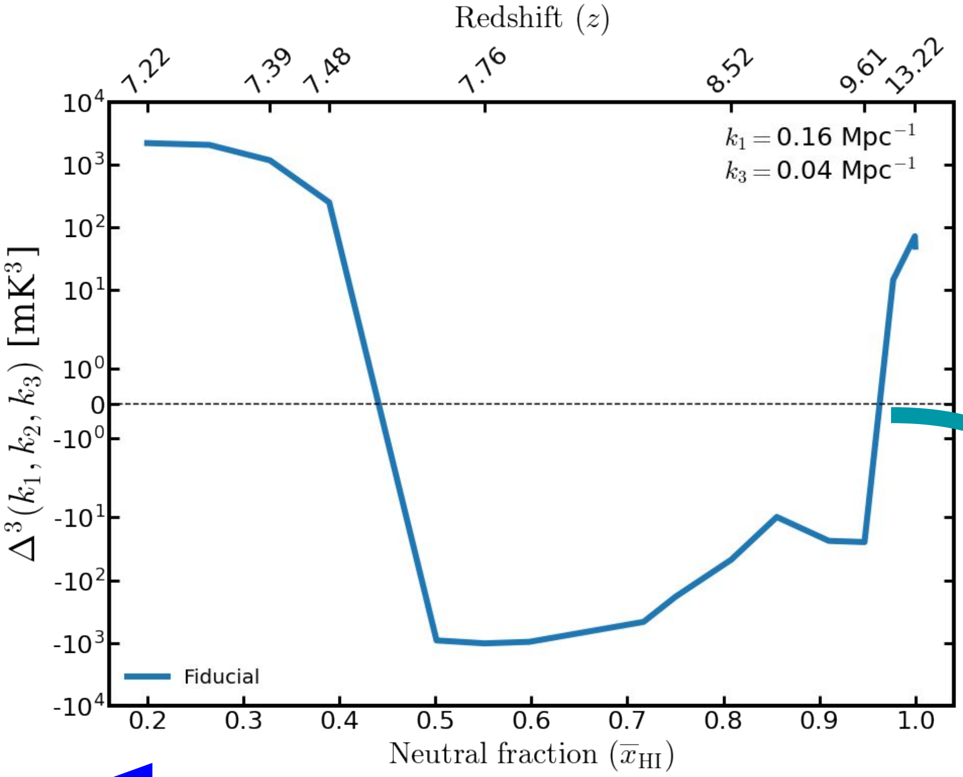
Early stage

Late stage



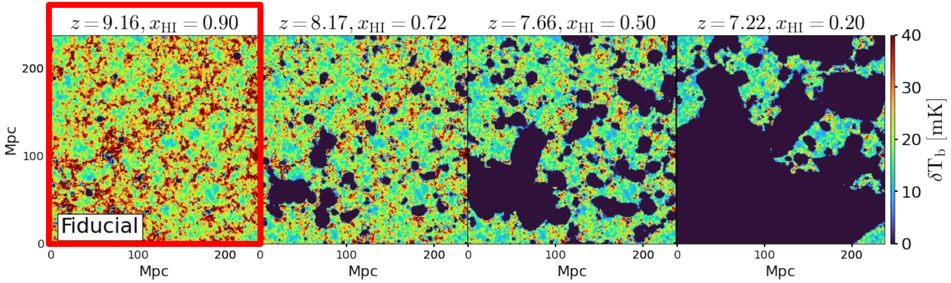
Noble, SM et al. 2024, arXiv: 2406.03118

Evolution of squeezed-limit bispectrum



Early stage

Late stage

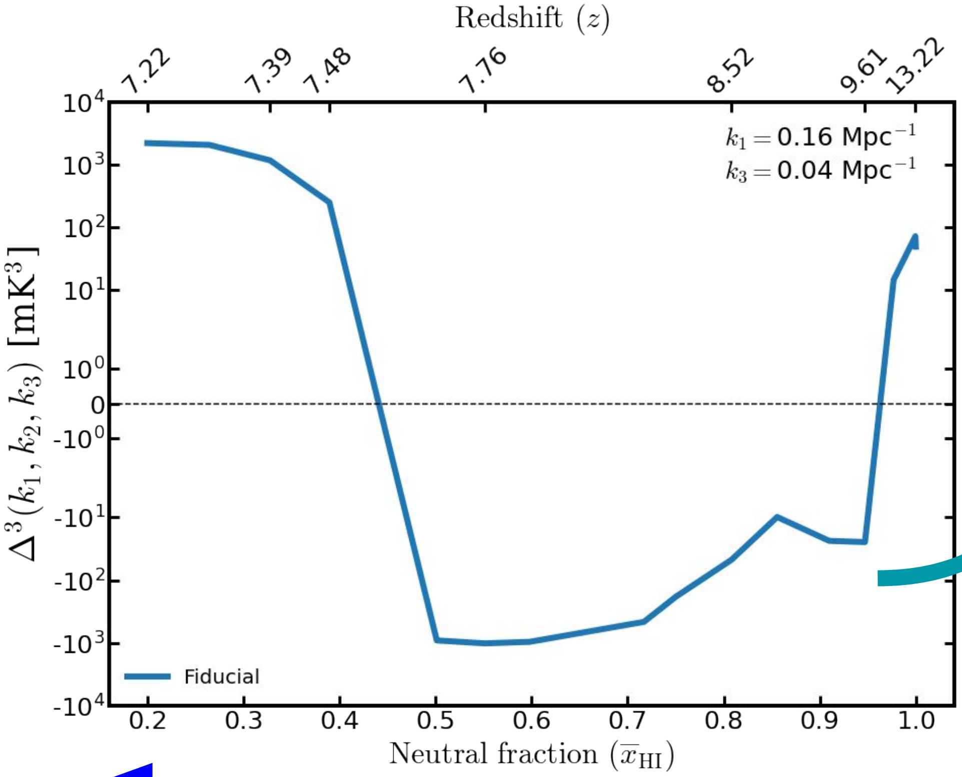


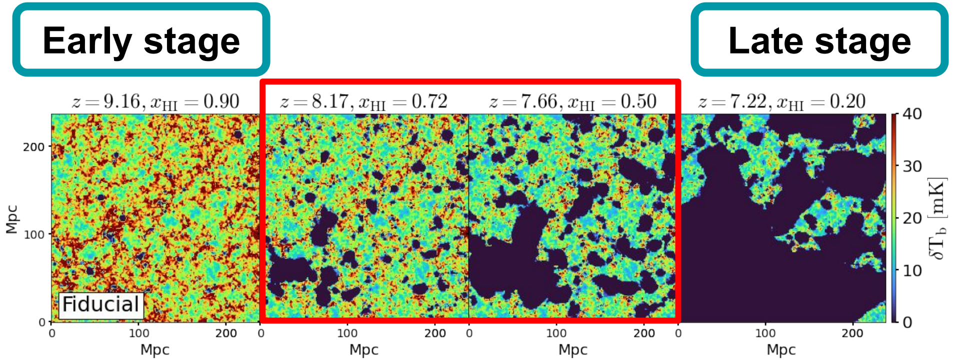
Change in the sign of the bispectrum

Noble, SM et al. 2024, arXiv: 2406.03118

Progress of reionization

Evolution of squeezed-limit bispectrum



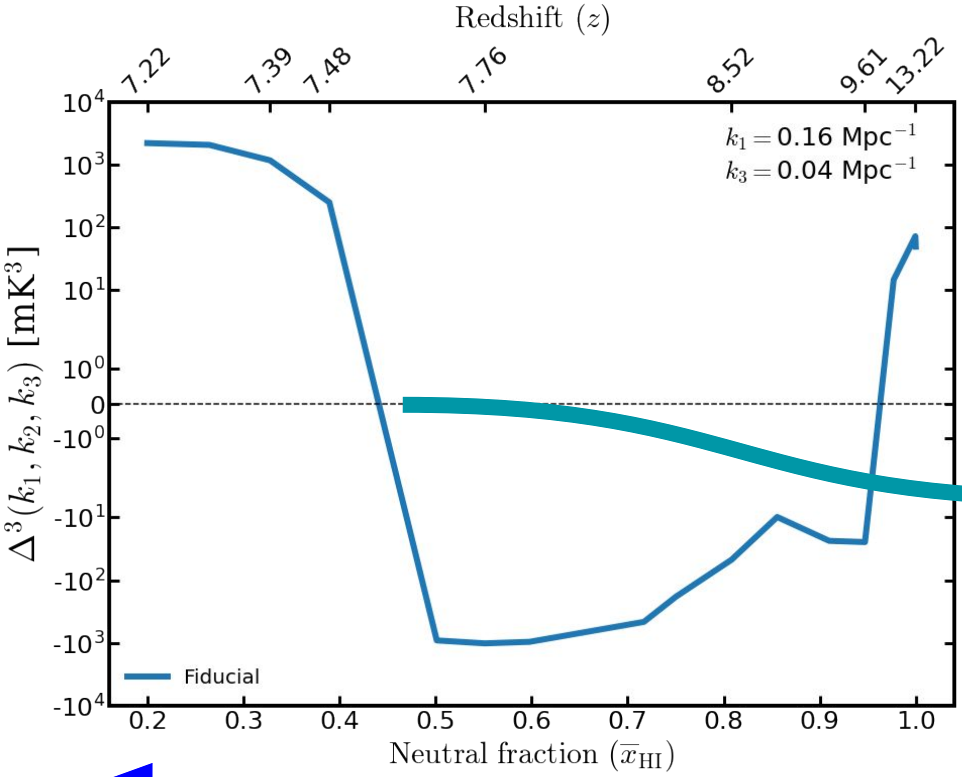


Magnitude of the 21-cm bispectrum increases

Noble, SM et al. 2024, arXiv: 2406.03118

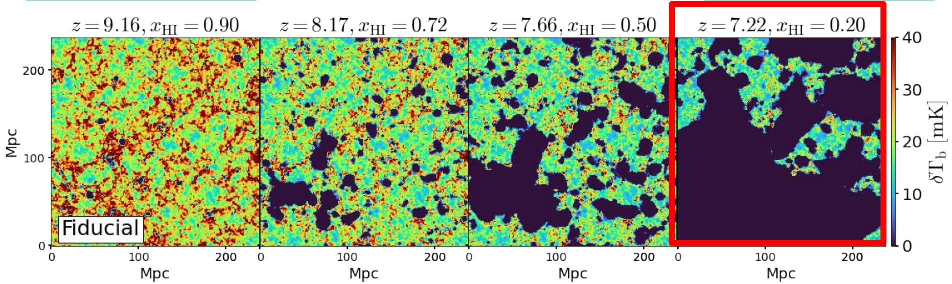
Progress of reionization

Evolution of squeezed-limit bispectrum



Early stage

Late stage

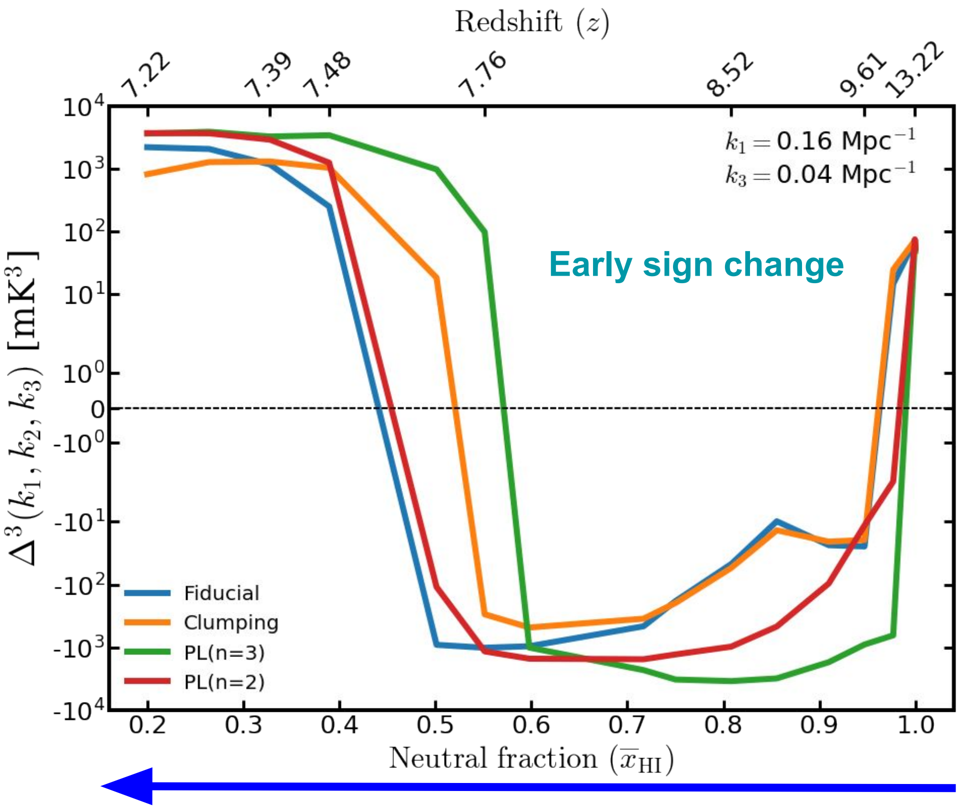


Second sign change in the 21-cm bispectrum

Progress of reionization

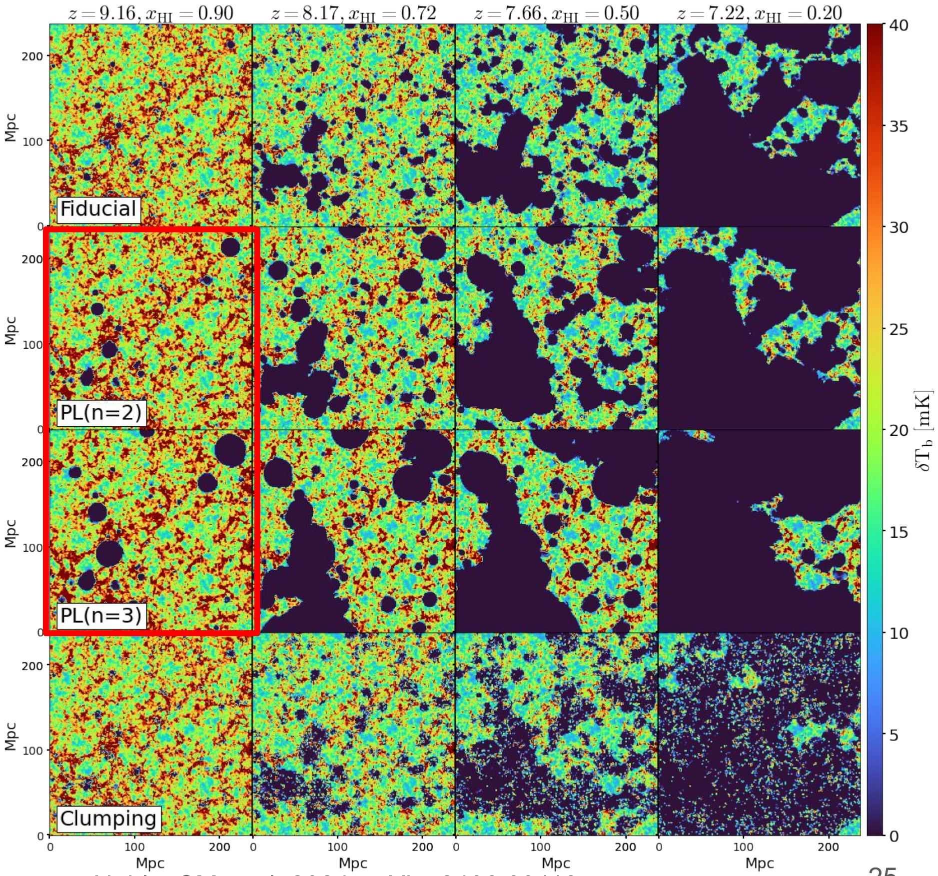
Noble, SM et al. 2024, arXiv: 2406.03118

Evolution of squeezed-limit bispectrum: Inside-out scenarios



Early sign change

Progress of reionization



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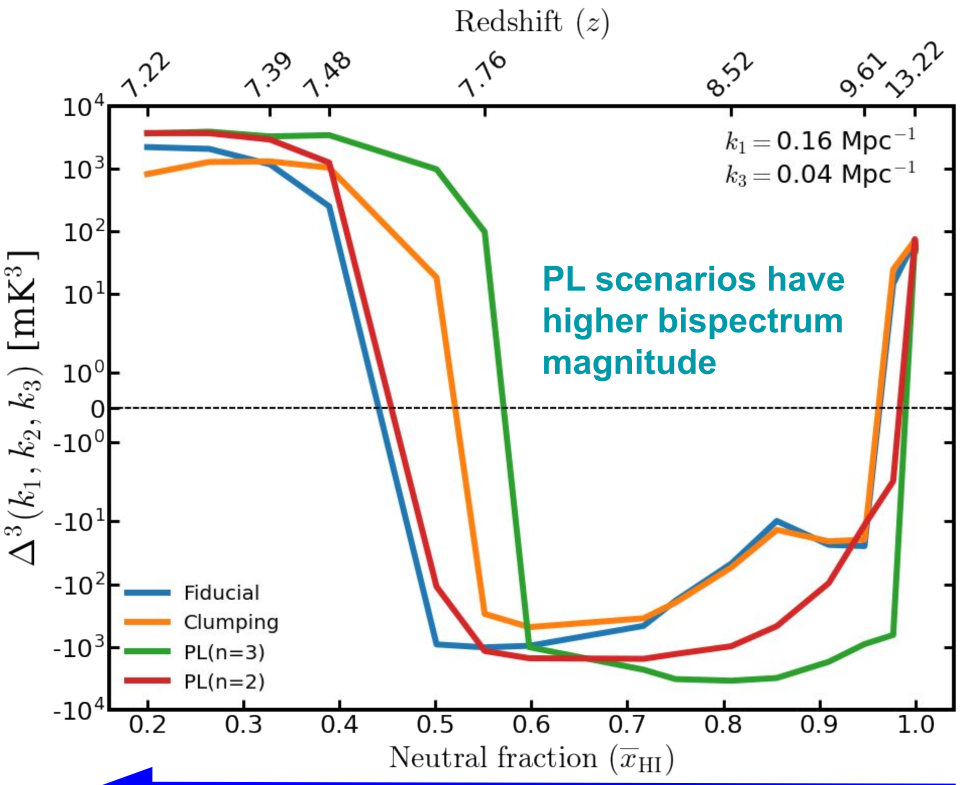
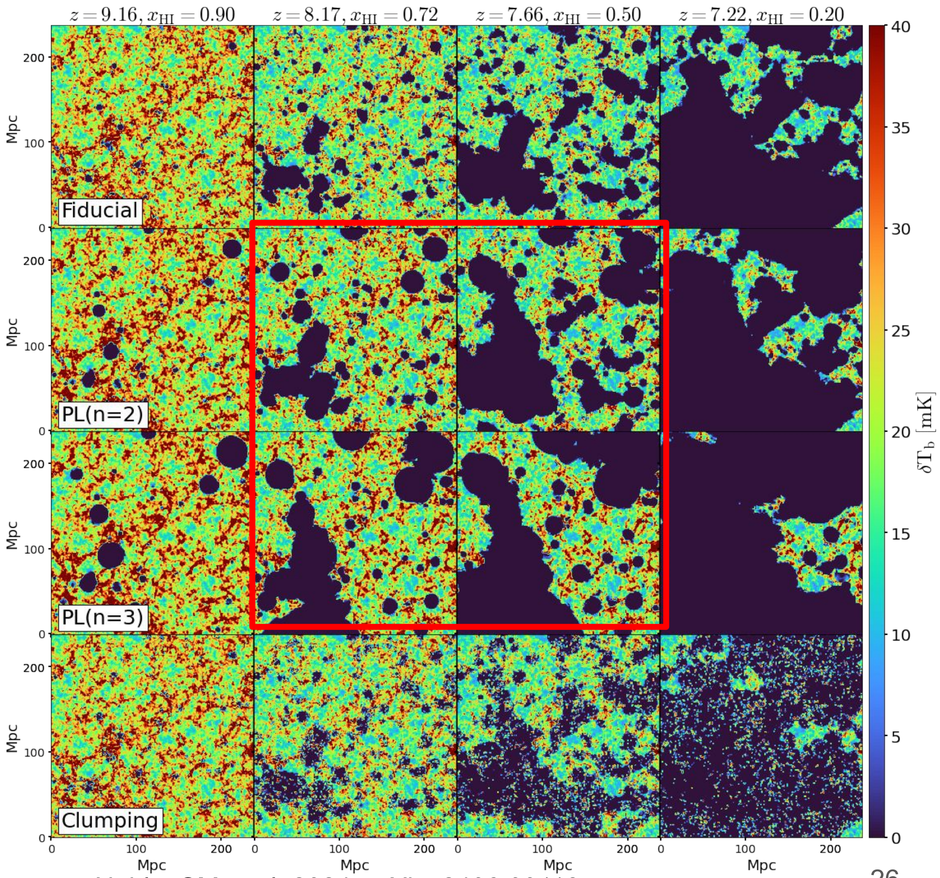
Evolution of squeezed-limit bispectrum: Inside-out scenarios



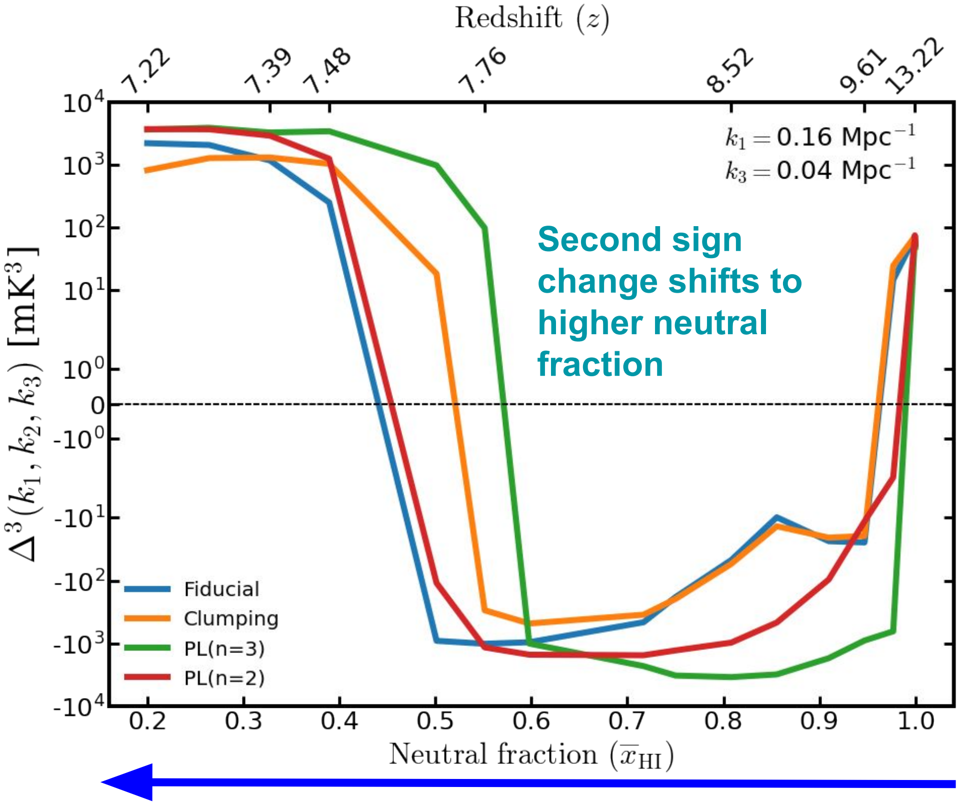
PL scenarios have higher bispectrum magnitude

Progress of reionization



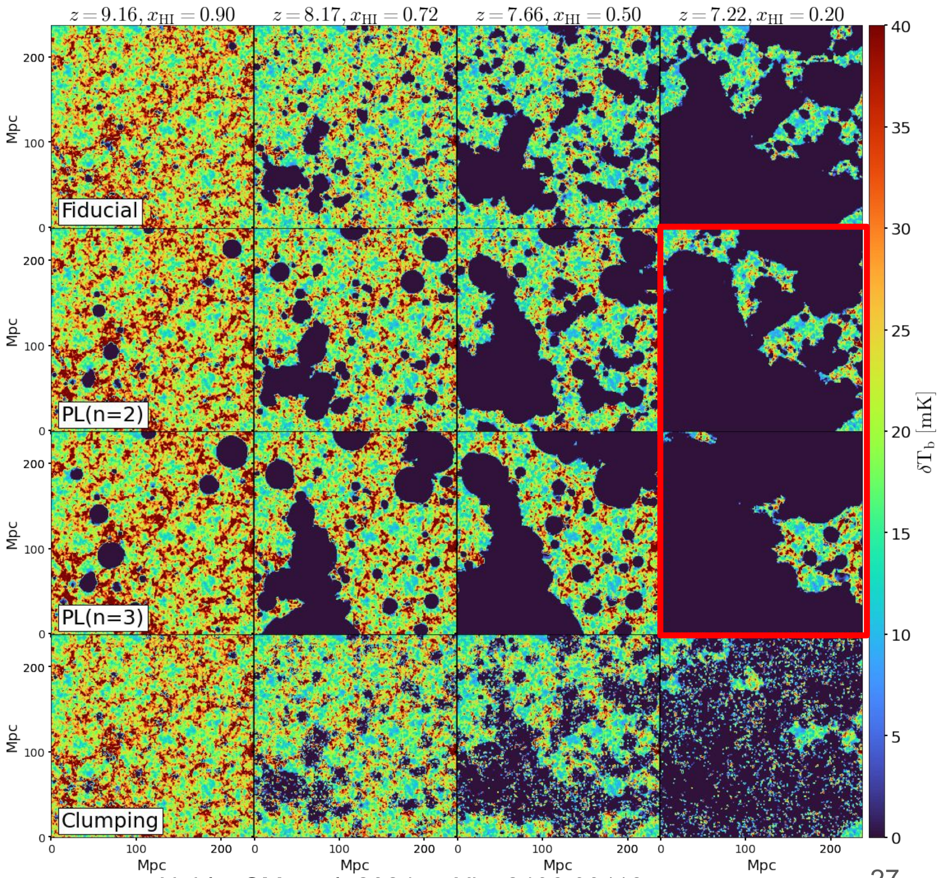
Noble, SM et al. 2024, arXiv: 2406.03118

Evolution of squeezed-limit bispectrum: Inside-out scenarios



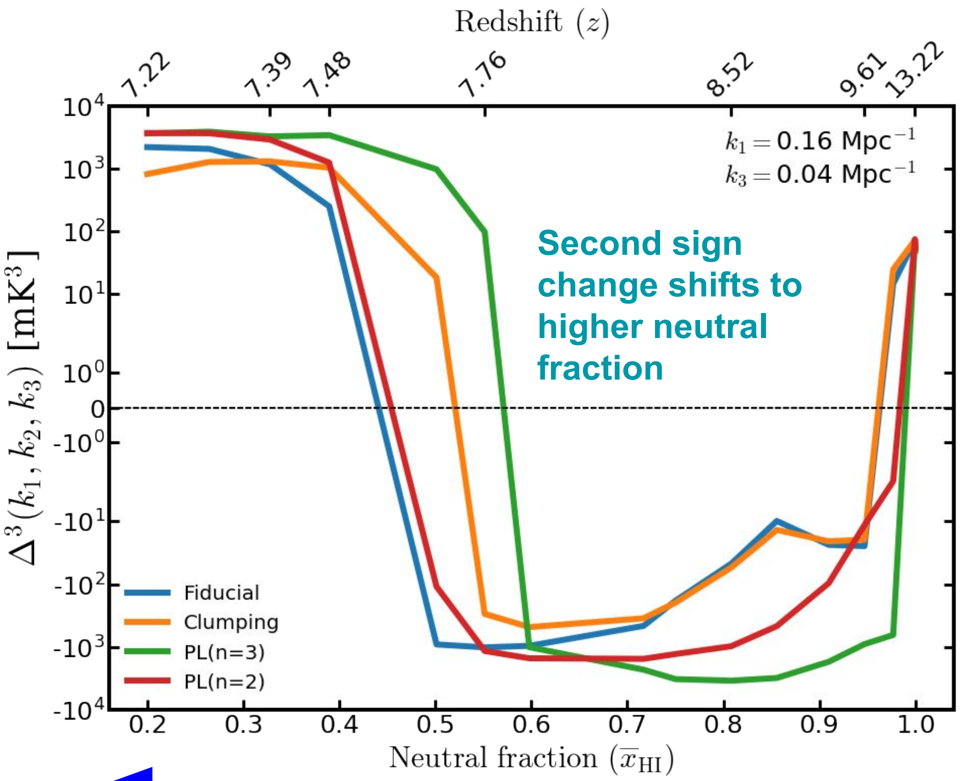
Second sign change shifts to higher neutral fraction

Progress of reionization

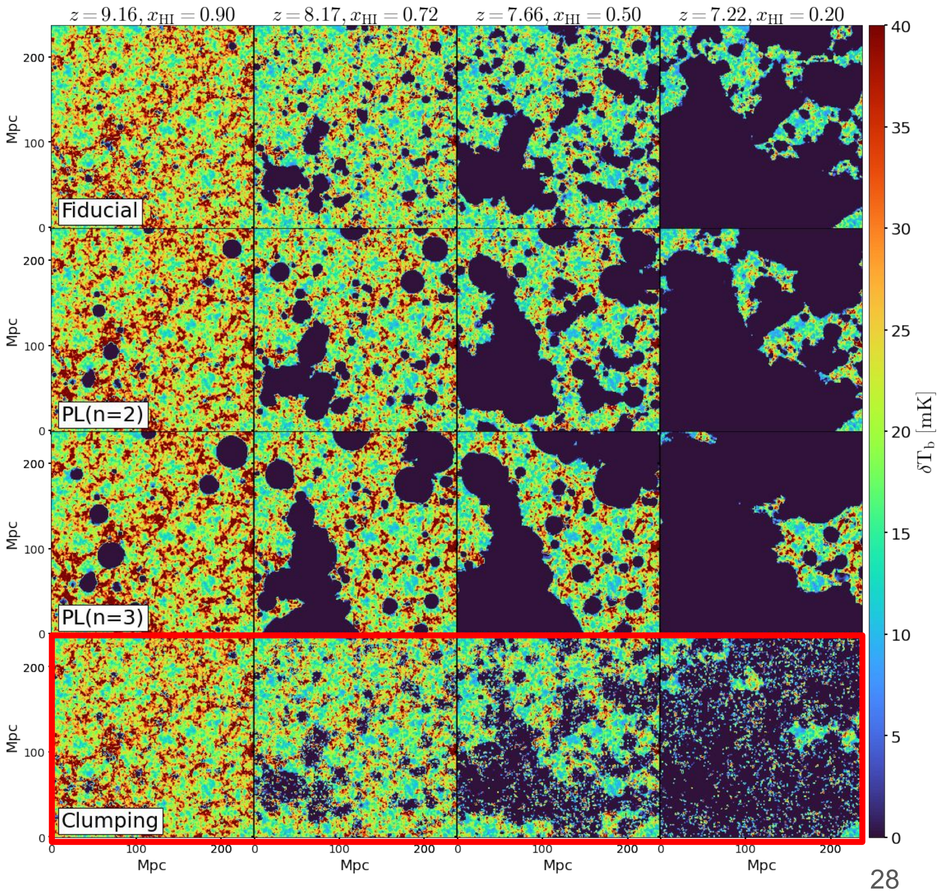


Noble, SM et al. 2024, arXiv: 2406.03118

Evolution of squeezed-limit bispectrum: Inside-out scenarios

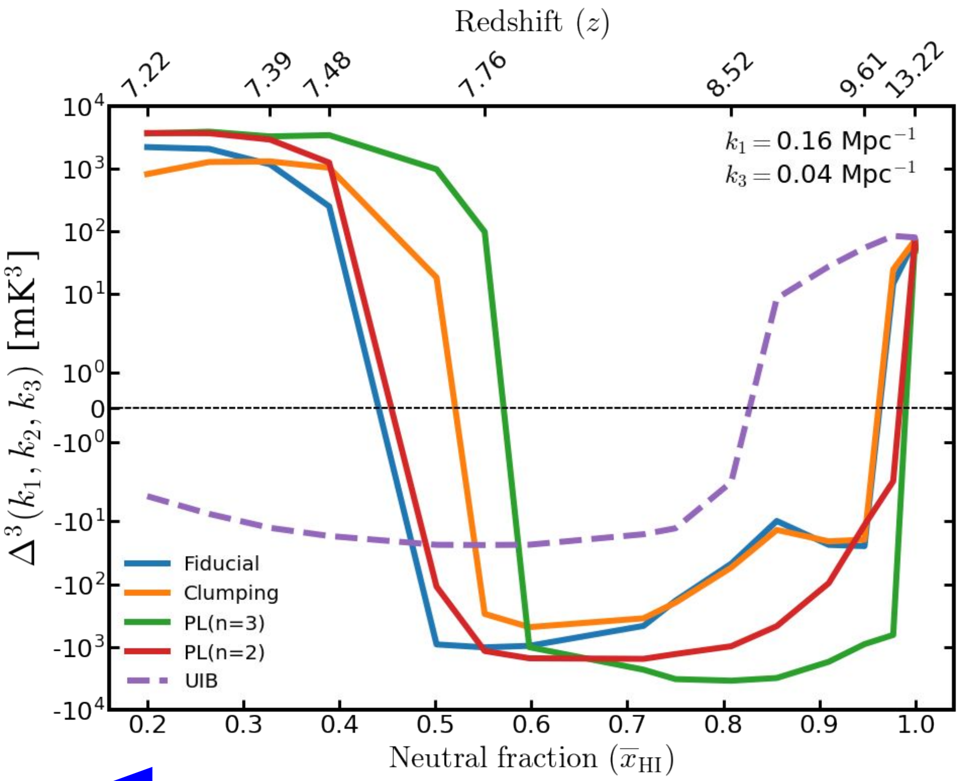


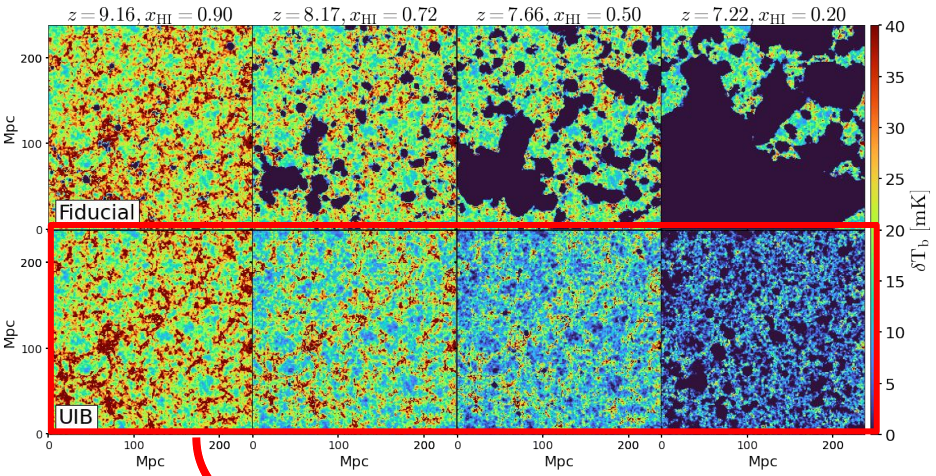
Second sign change shifts to higher neutral fraction



Progress of reionization

Evolution of squeezed-limit bispectrum: Outside-in scenario



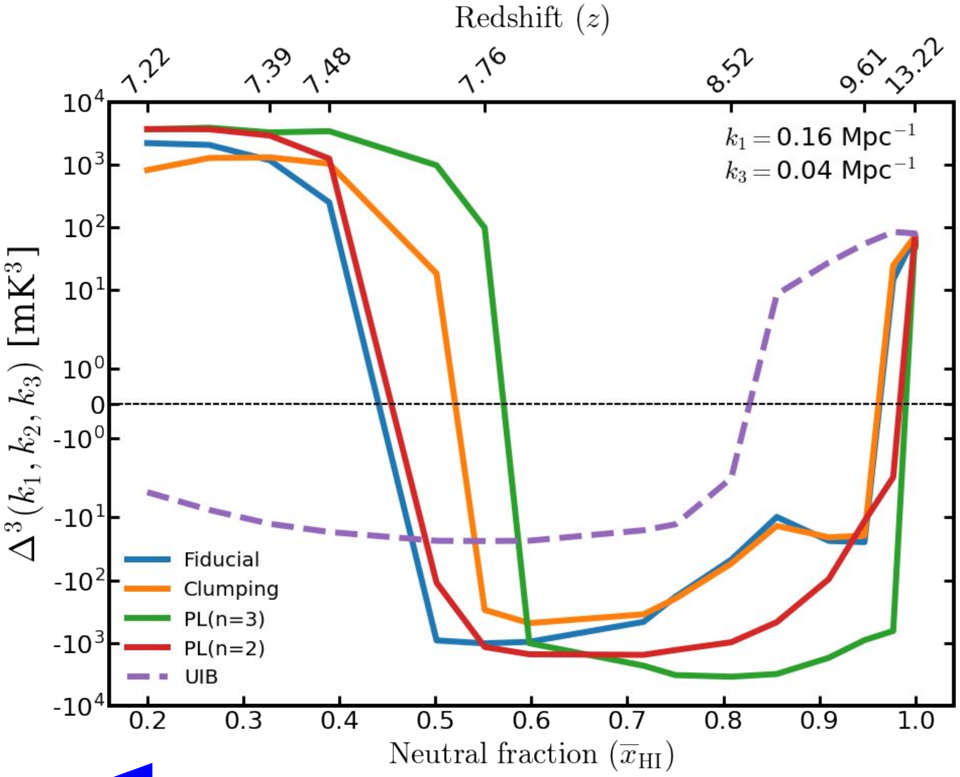


Outside-in reionization scenario

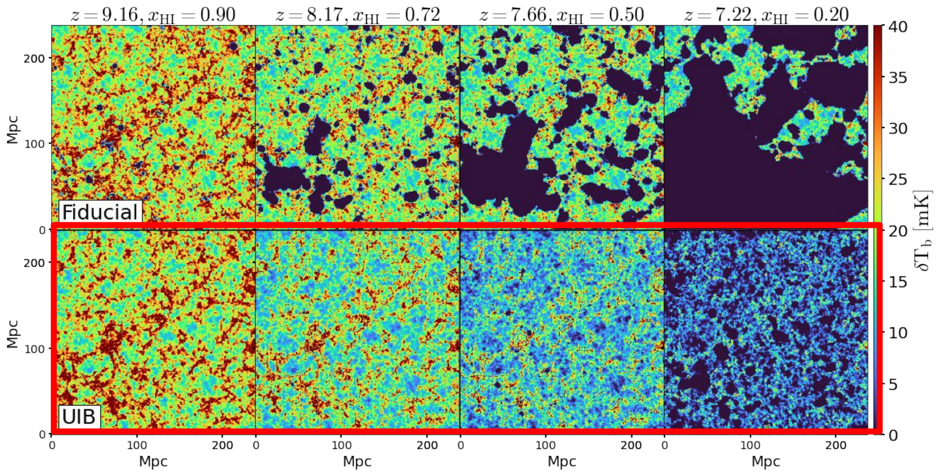
Noble, SM et al. 2024, arXiv: 2406.03118

Progress of reionization

Evolution of squeezed-limit bispectrum: Outside-in scenario



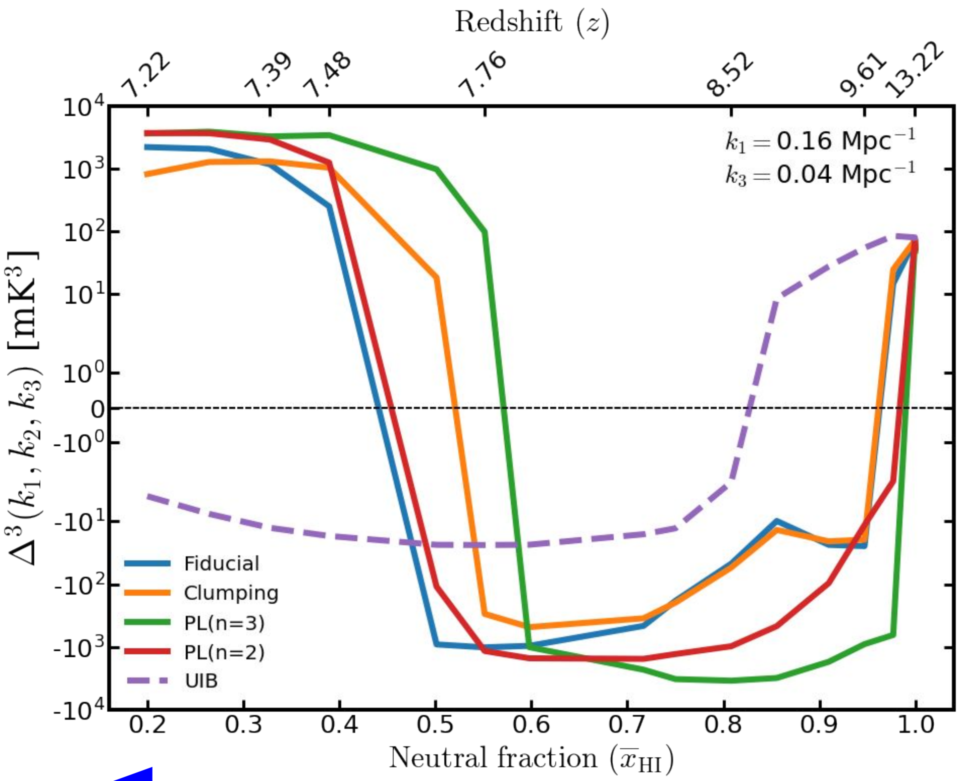
Progress of reionization



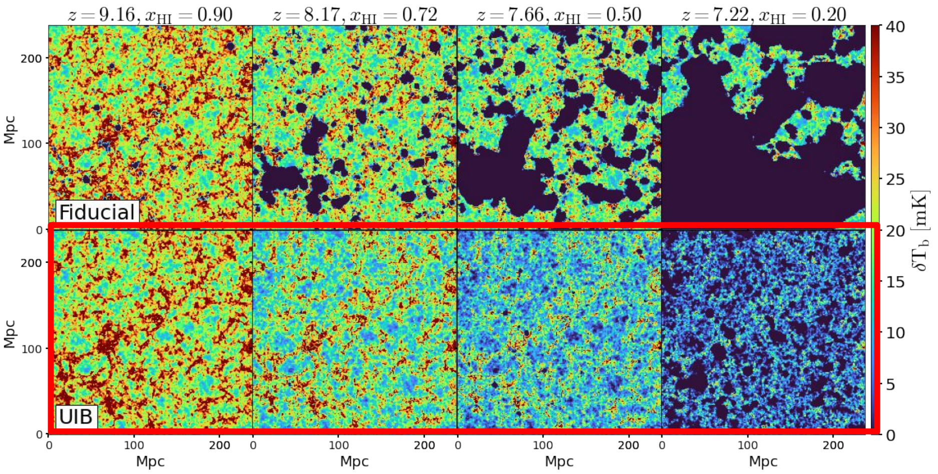
- **First change in the sign of bispectrum happens at a later stage of reionization**
- **Magnitude of the bispectrum is lower than inside-out scenarios**

Noble, SM et al. 2024, arXiv: 2406.03118

Evolution of squeezed-limit bispectrum: Outside-in scenario

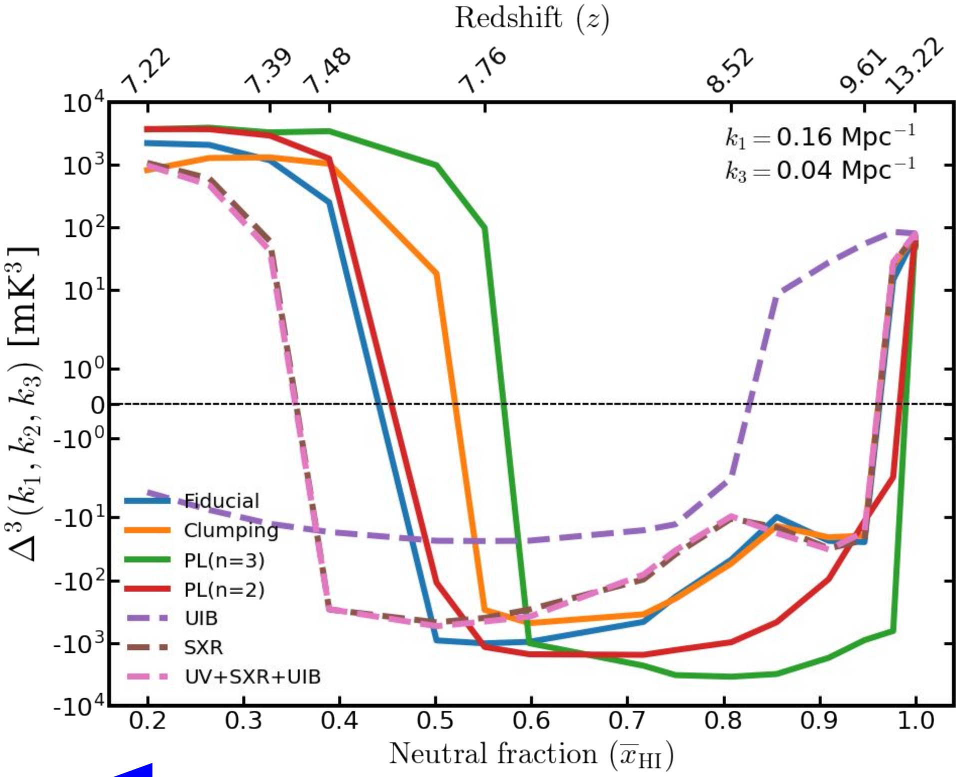


Progress of reionization

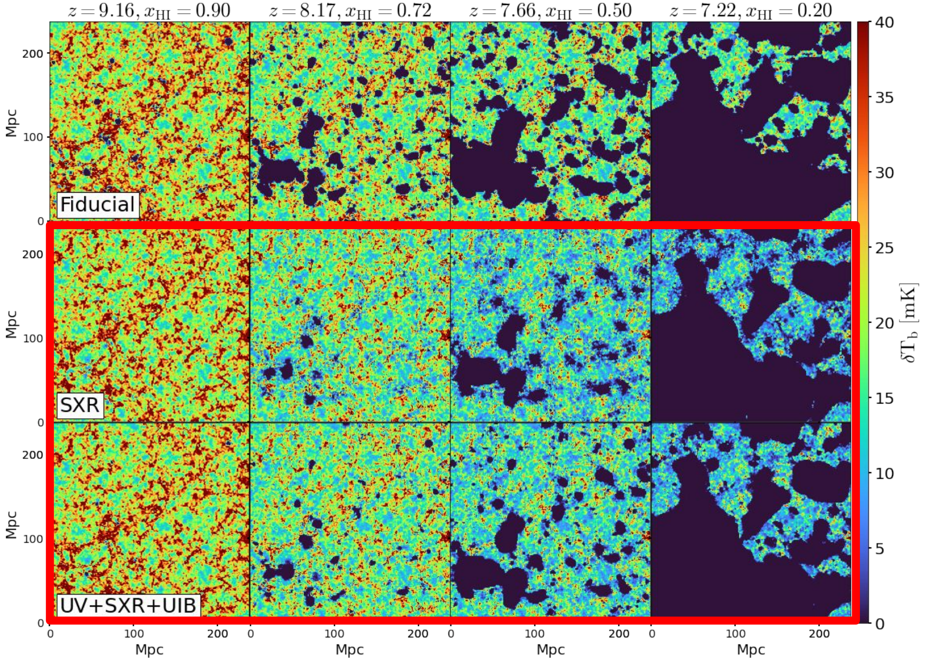


- **First change in the sign of bispectrum happens at a late stage of reionization**
- **Magnitude of the bispectrum is lower than inside-out scenarios**
- **No change in the sign of bispectrum at late stage of reionization**

Evolution of squeezed-limit bispectrum: Combination of inside-out and outside-in



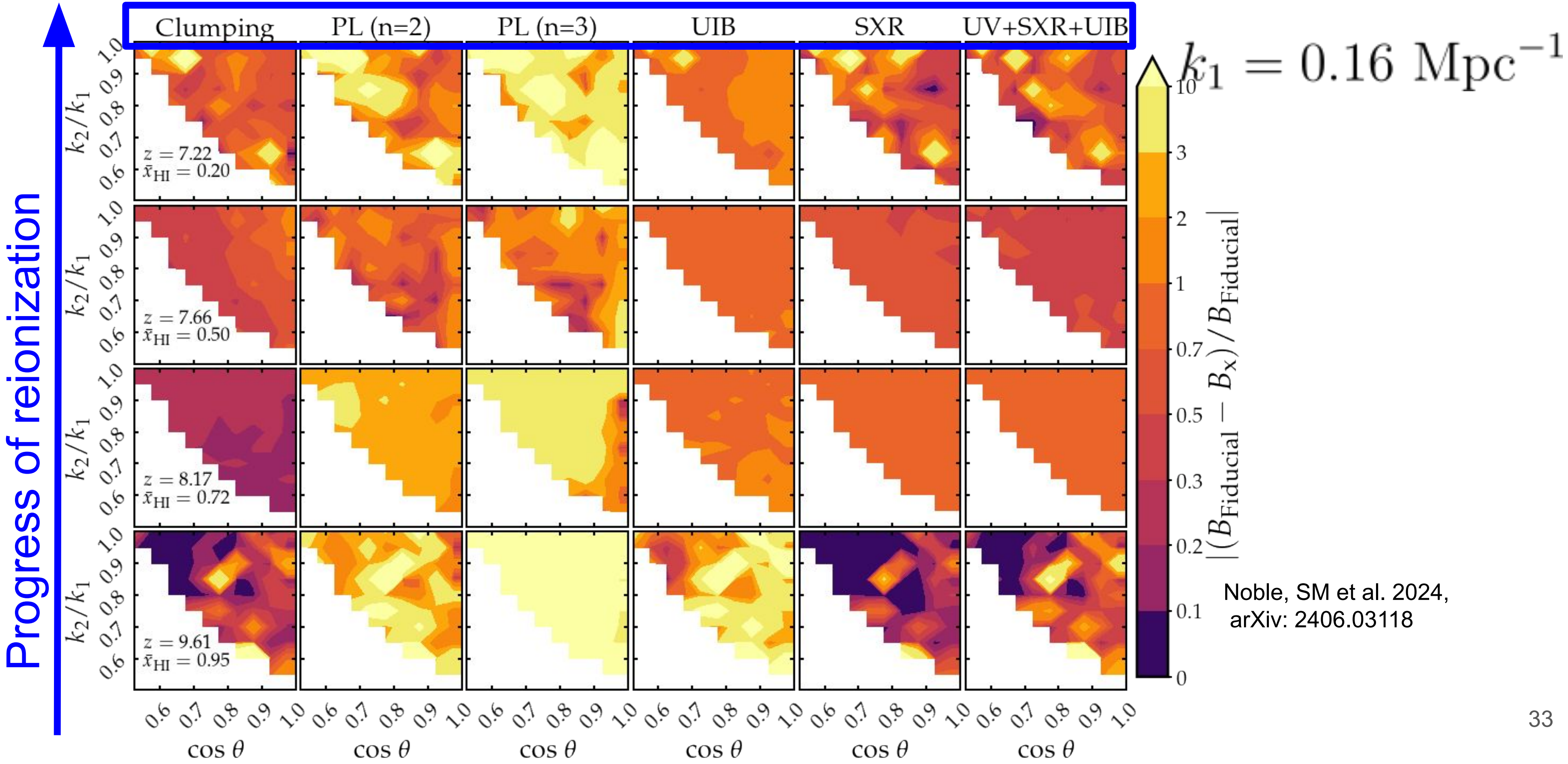
Progress of reionization



Second sign change shifts to lower neutral fraction

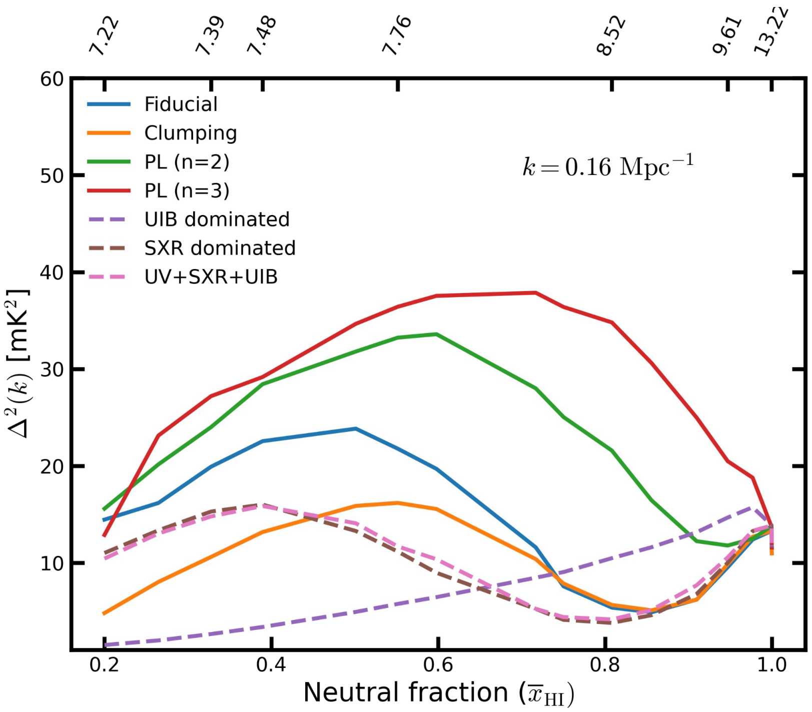
Noble, SM et al. 2024, arXiv: 2406.03118

Magnitude differences in 21-cm bispectrum between different reionization scenarios w. r. t. Fiducial

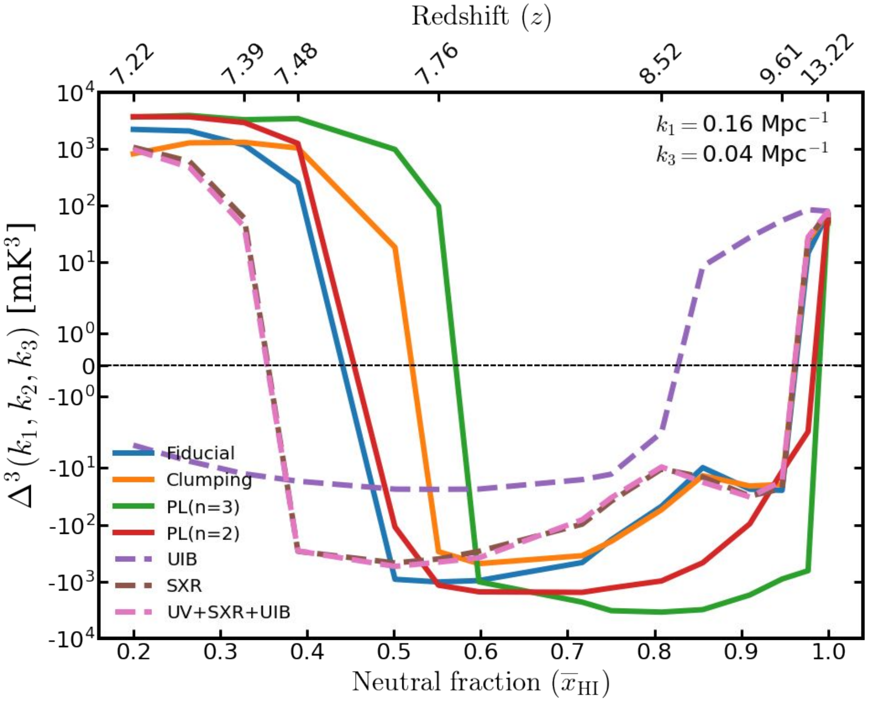


Noble, SM et al. 2024,
arXiv: 2406.03118

Power spectrum vs bispectrum

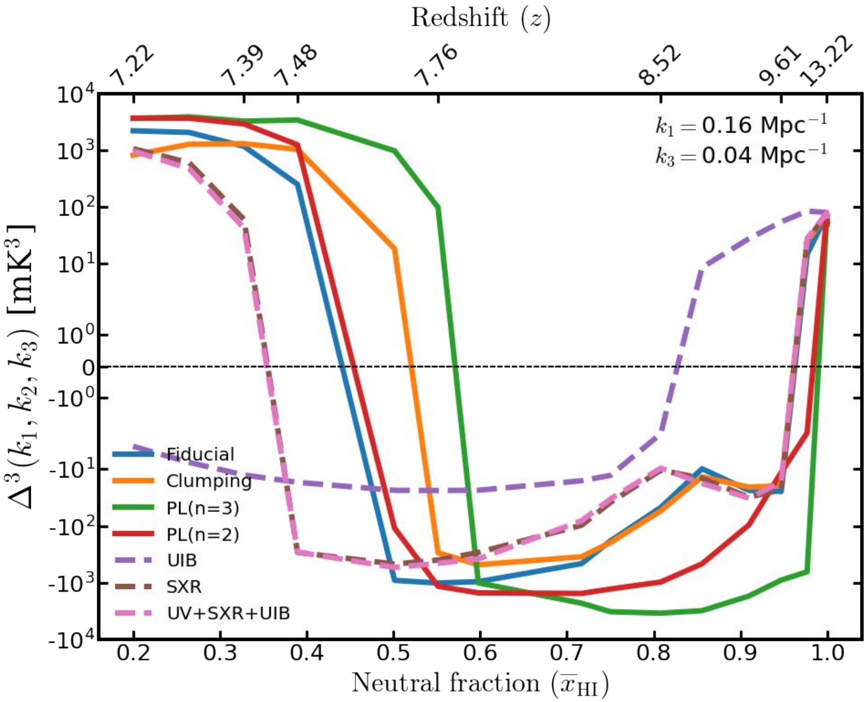


Majumdar et al. 2016, arXiv: 1509.07518



Noble,.., SM,.. et al. 2024, arXiv: 2406.03118

Summary I



- ➢ **21-cm bispectrum can capture the time evolving non-Gaussianity in different reionization scenarios.**
- ➢ **It can distinguish between different reionization scenarios.**
- ➢ **It can distinguish reionization scenarios better than the 21-cm power spectrum thanks to its sign and sequence of sign changes.**

Noble,.., SM et al. 2024, arXiv: 2406.03118

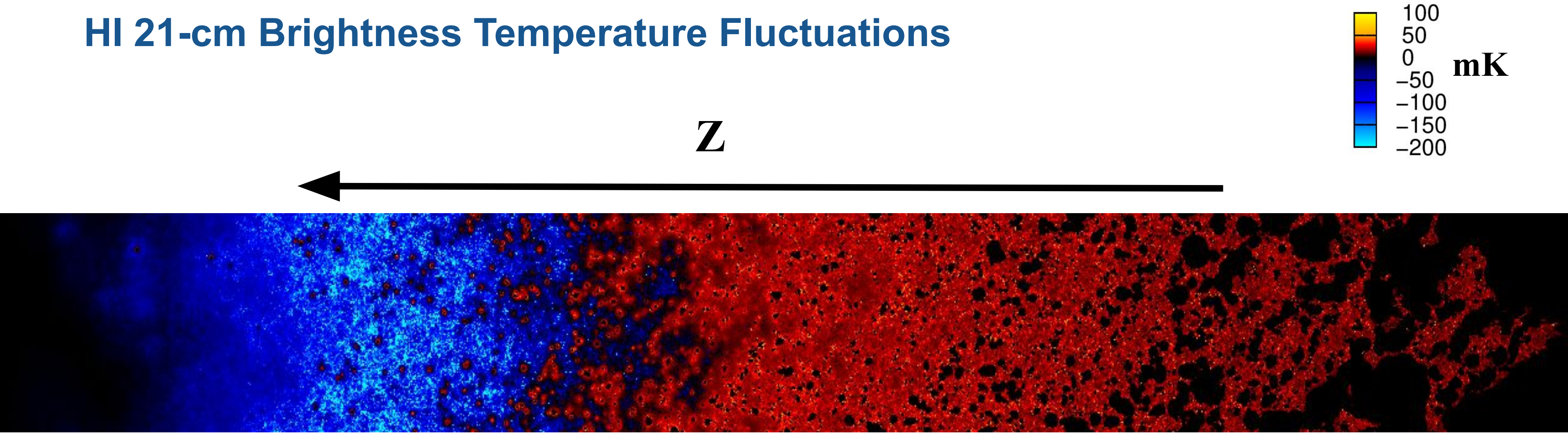
Cosmic Dawn 21-cm bispectrum

To identify which IGM process is dominating at what cosmic time (during CD) using the 21-cm bispectrum

↓

Disentangling the Lyα coupling and X-ray heating

HI 21-cm Brightness Temperature Fluctuations



$$\delta T_{\rm b}(\mathbf{r},z) = 27\,x_{\rm HI}(\mathbf{r},z)\left(1-\frac{T_{\rm CMB}(z)}{T_{\rm S}(\mathbf{r},z)}\right)(1+\delta_{\rm b}(\mathbf{r},z))\left(\frac{\Omega_{\rm b}h^2}{0.023}\right)\left(\frac{0.15}{\Omega_{\rm m}h^2}\frac{1+z}{10}\right)^{1/2}\,\mathrm{mK}$$

IGM physics makes the spatial and temporal fluctuations of the CD-EoR 21-cm signal

highly non-Gaussian!

Image Credit: Raghunath Ghara

Simulations

- **Dark matter N-body simulation** → To generate dark matter distributions.

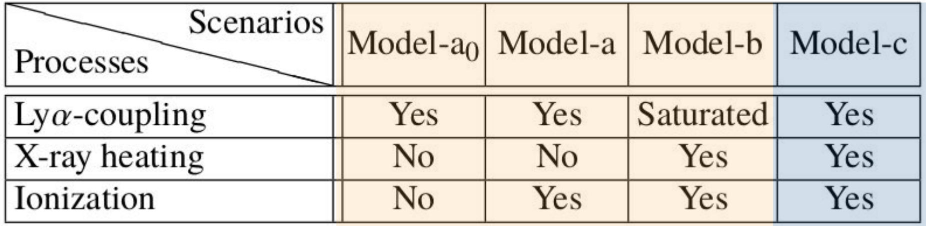
  J. Harnois-Déraps+ 2013

- **Radiative transfer simulation** → GRIZZLY → To generate CD 21-cm maps.

  Ghara+ 2015, 2018

Raghunath Ghara
Postdoc at the University of Pennsylvania

Simulations
Different CD scenarios



Scenarios / Processes	Model-a_0	Model-a	Model-b	Model-c
Lyα-coupling	Yes	Yes	Saturated	Yes
X-ray heating	No	No	Yes	Yes
Ionization	No	Yes	Yes	Yes

Simplistic scenarios

Only one single physical process dominates the 21-cm fluctuations

Realistic scenario

All three physical processes incorporated self-consistently

Importance of first three scenarios:

Used to identify the unique signature of each IGM process on the 21-cm bispectrum

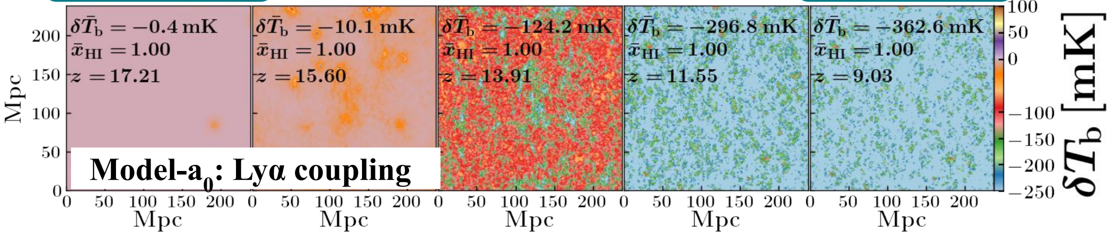
⇒ Helps in explaining the bispectrum from Model-c, the most realistic scenario.

21-cm bispectrum as a probe of IGM physics during CD

Early stage

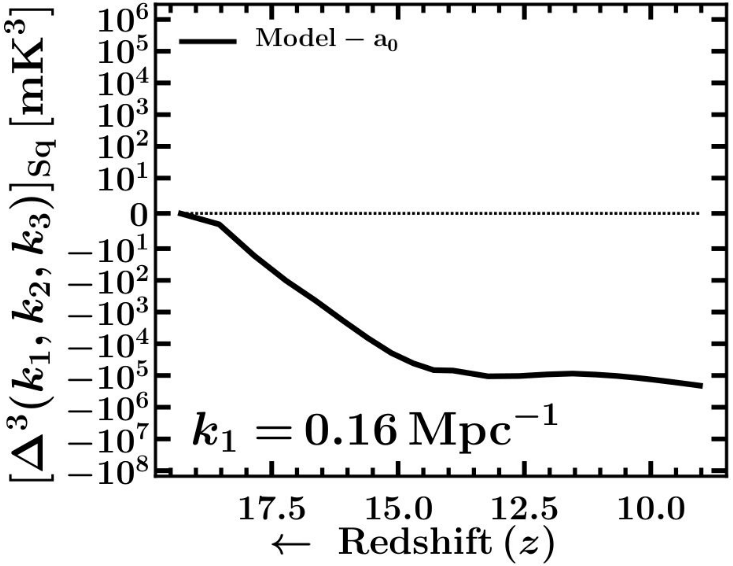
← Redshift (z)

Late stage



Model-a_0: Lyα coupling

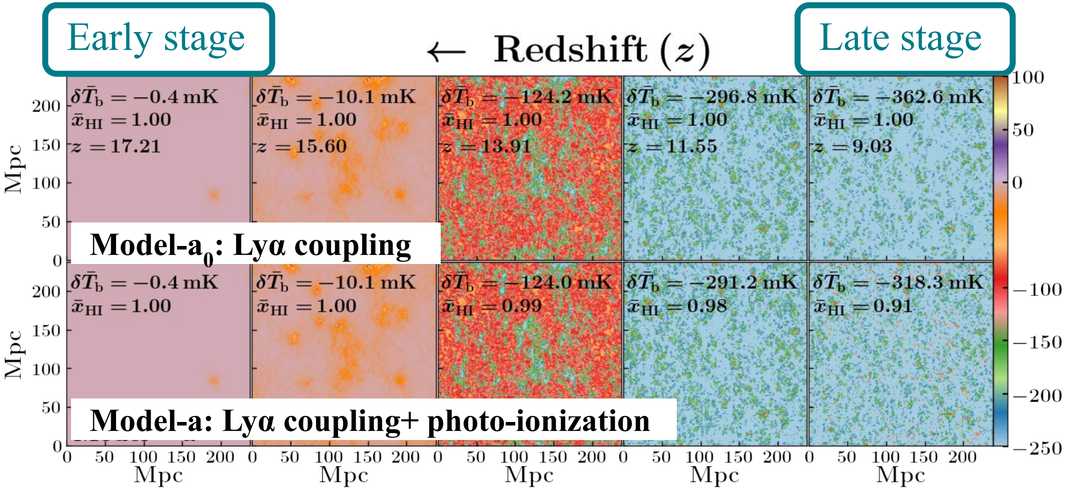
Squeezed-limit bispectrum



Magnitude: Monotonically increasing

Sign: Negative during the entire CD

21-cm bispectrum as a probe of IGM physics during CD



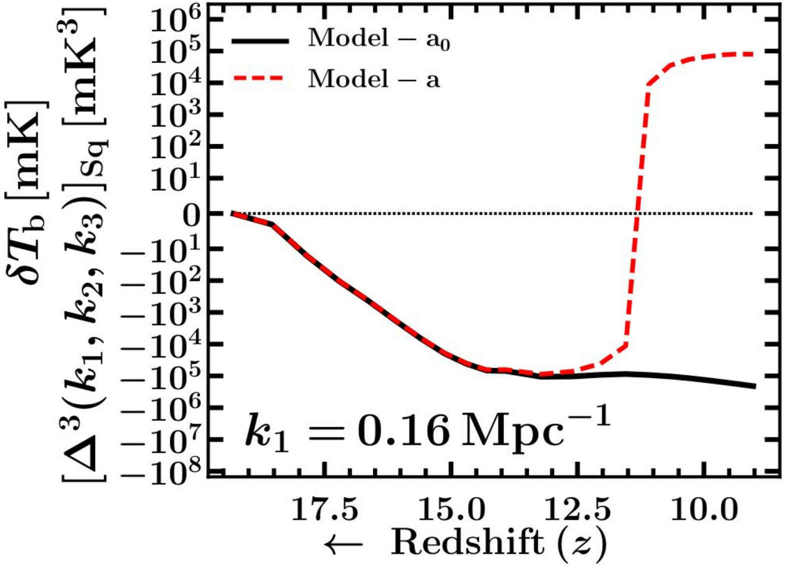
Early stage

Late stage

Model-a$_0$: Lyα coupling

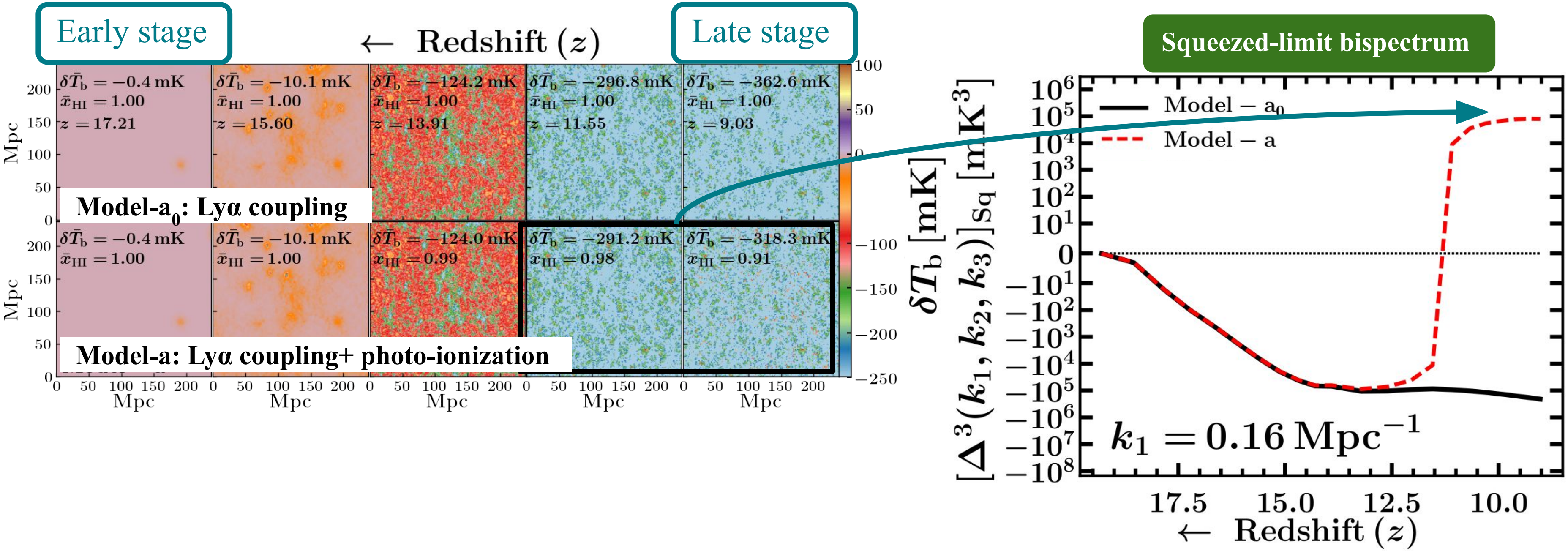
Model-a: Lyα coupling+ photo-ionization

Squeezed-limit bispectrum



Bispectrum for Model-a agrees well with Model-a$_0$ until z ~ 13

21-cm bispectrum as a probe of IGM physics during CD



Early stage

Late stage

Model-a_0: Lyα coupling

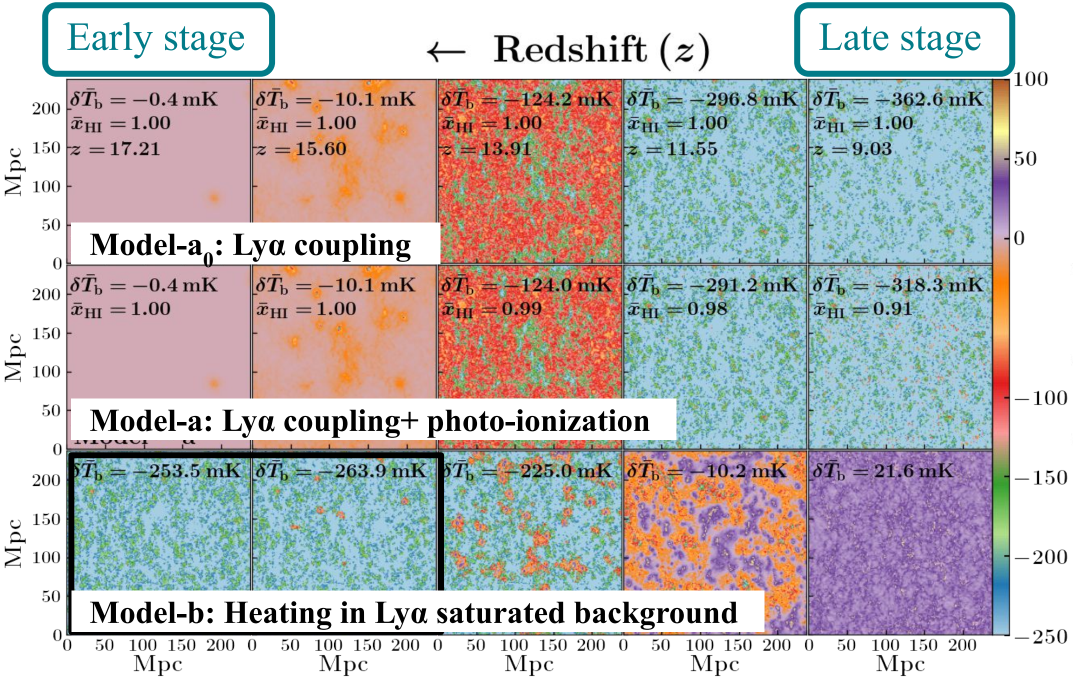
Model-a: Lyα coupling+ photo-ionization

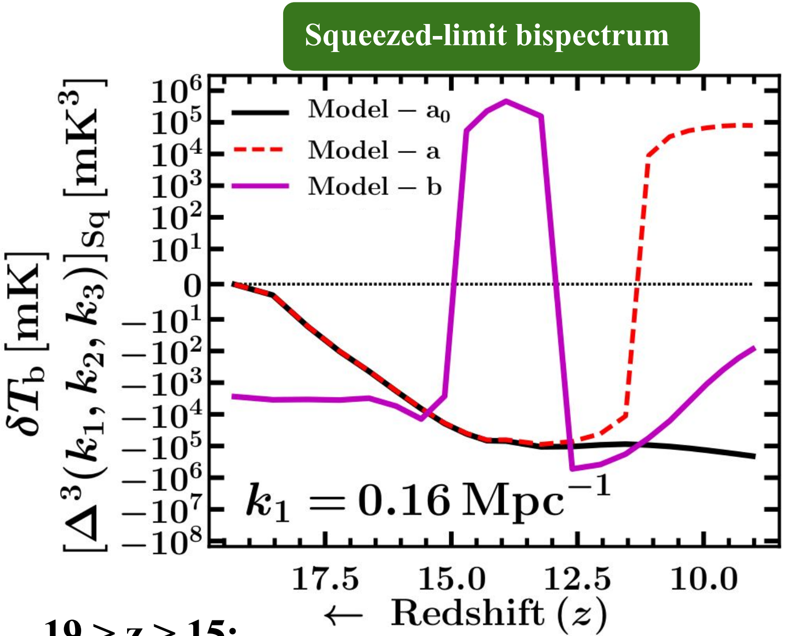
Squeezed-limit bispectrum

Bispectrum for Model-a agrees well with Model-a_0 until $z \sim 13$

At $z < 13$, sign reversal.

21-cm bispectrum as a probe of IGM physics during CD





19 > z > 15:

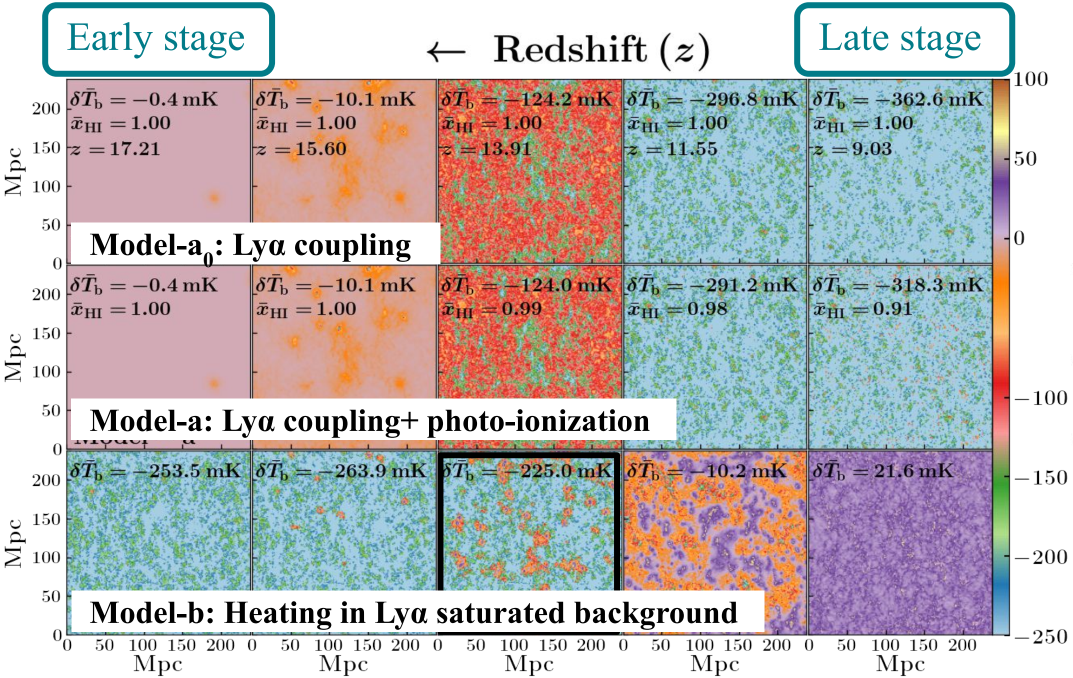
Large magnitude due to already saturated Lyα background.

Sign is negative as the signal is in absorption.

21-cm bispectrum as a probe of IGM physics during CD

Early stage

Late stage

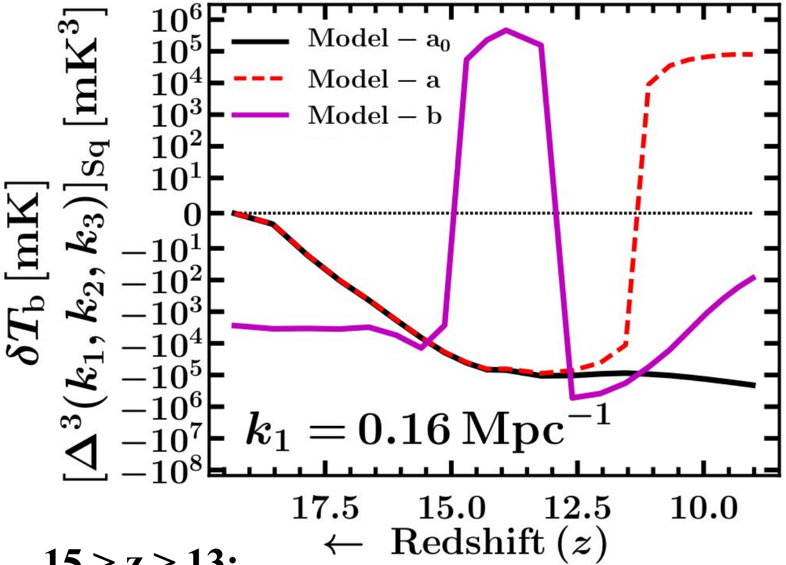


Model-a$_0$: Lyα coupling

Model-a: Lyα coupling+ photo-ionization

Model-b: Heating in Lyα saturated background

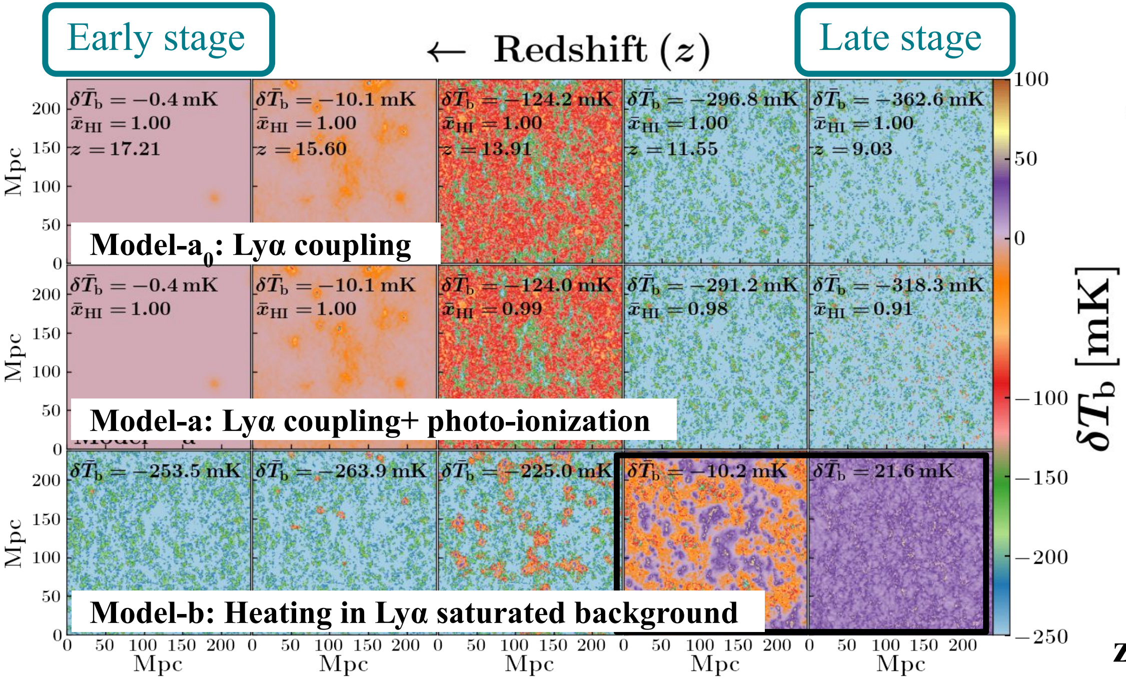
Squeezed-limit bispectrum

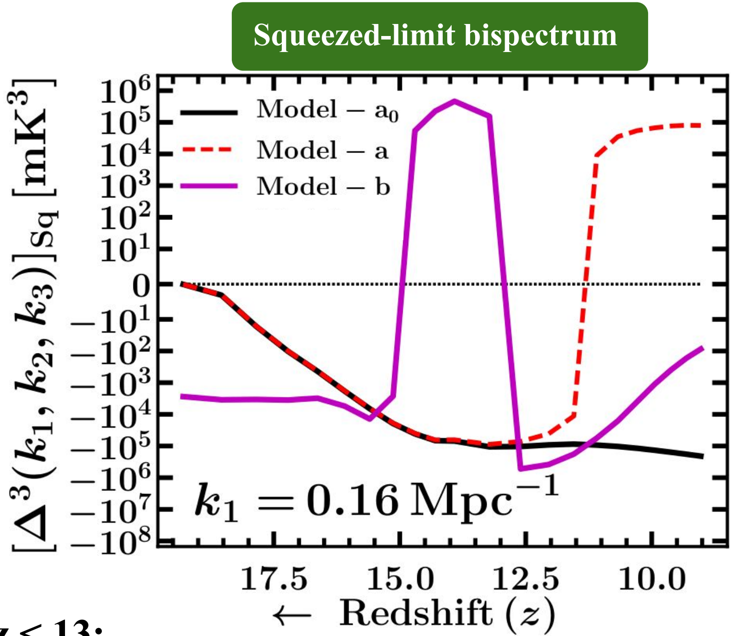


15 > z > 13:

Positive bispectrum due to heating

21-cm bispectrum as a probe of IGM physics during CD





z < 13:

Further heating ⇒ percolation ⇒ a single large connected cluster of heated regions.

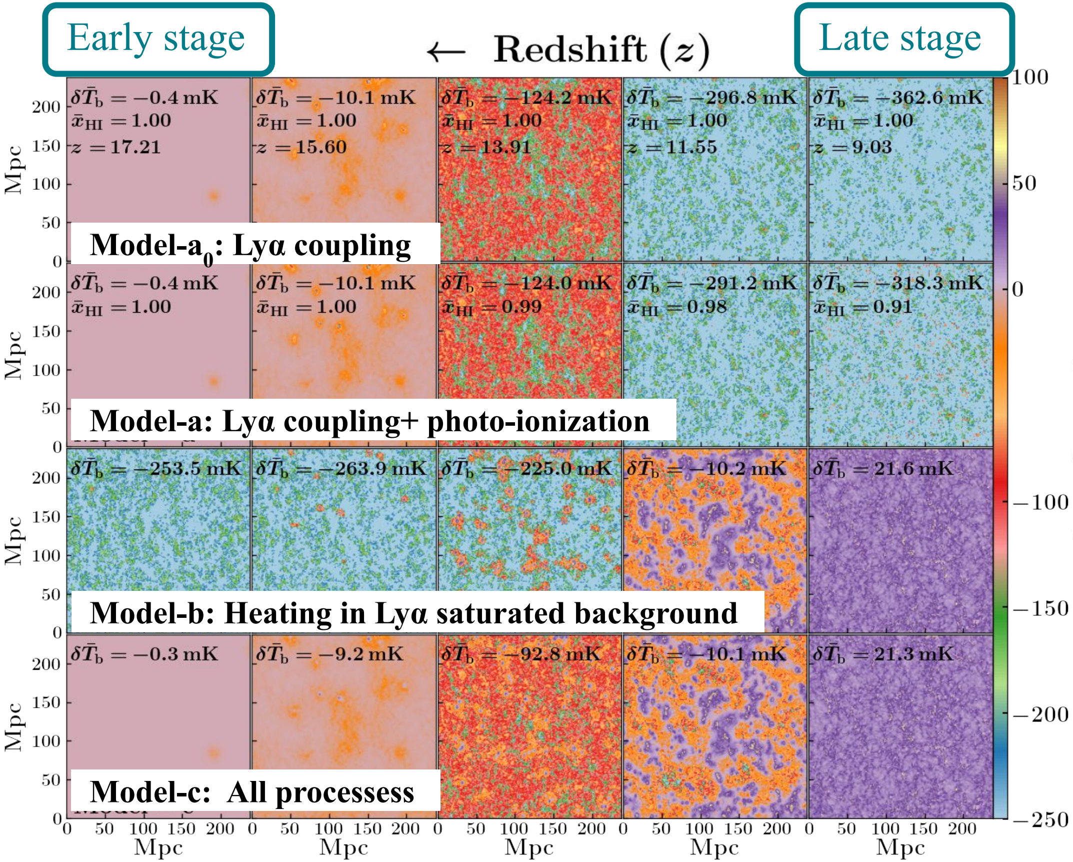
⇓

Negative bispectrum as signal fluctuations are dominated by the leftover absorption regions in a heated background.

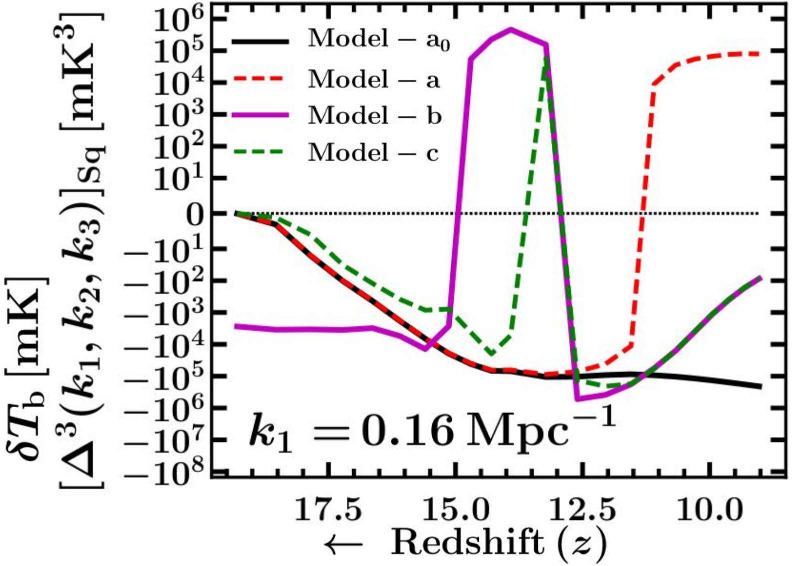
21-cm bispectrum as a probe of IGM physics during CD

Early stage

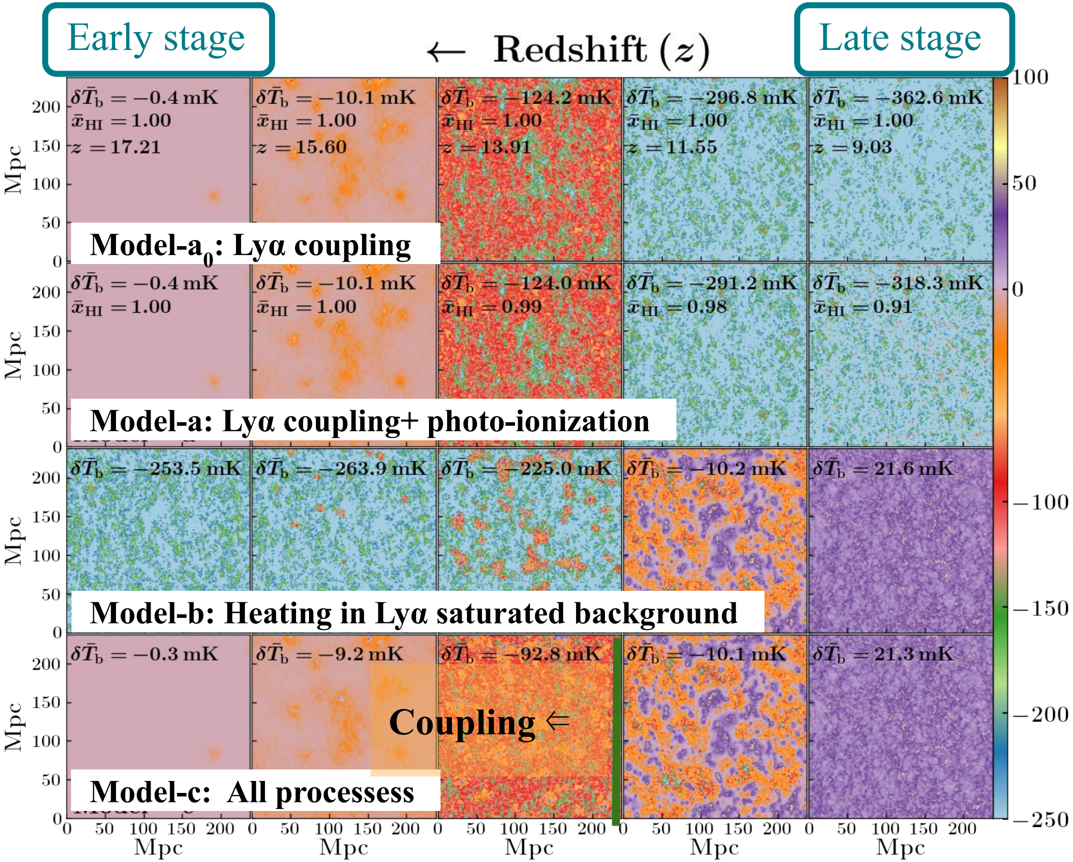
Late stage

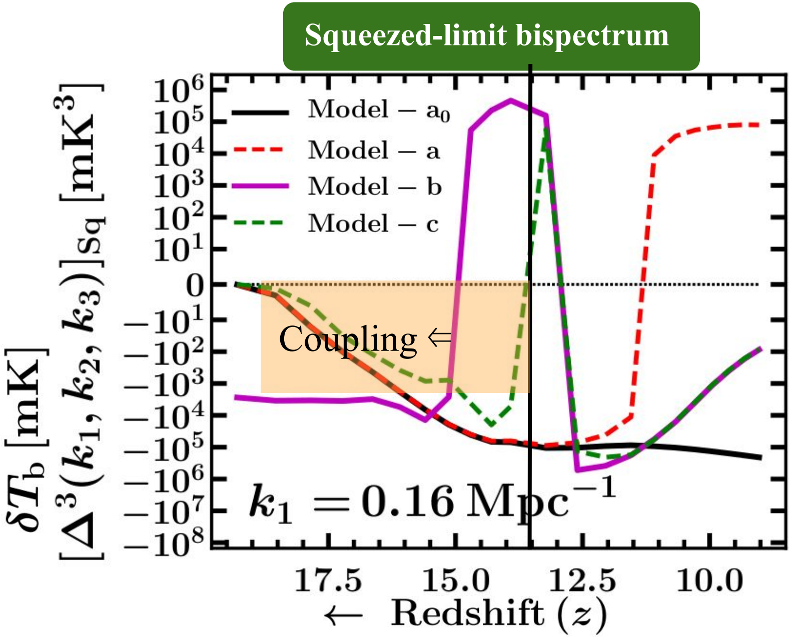


Squeezed-limit bispectrum



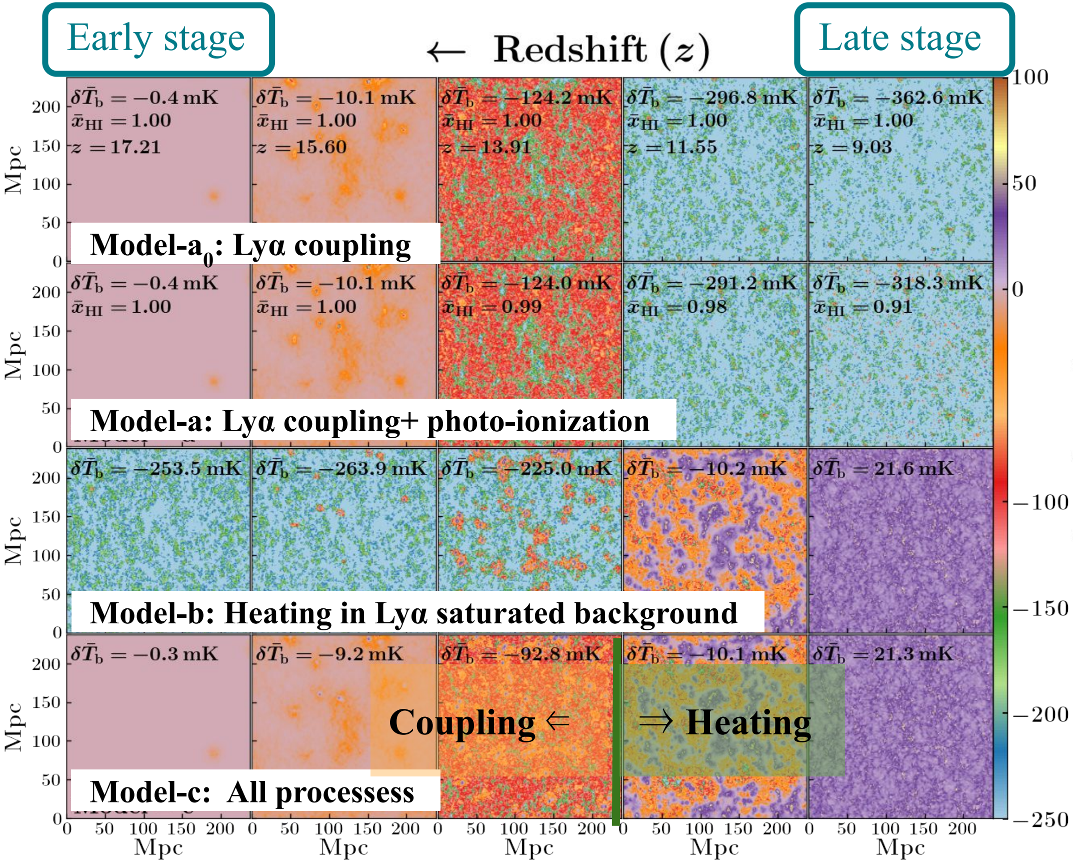
21-cm bispectrum as a probe of IGM physics during CD





Initially Model-c follows Models-a_0 and a ⇒ Lyα coupling dominates until z ~ 14

21-cm bispectrum as a probe of IGM physics during CD


Early stage

Late stage

Model-a_0: Lyα coupling

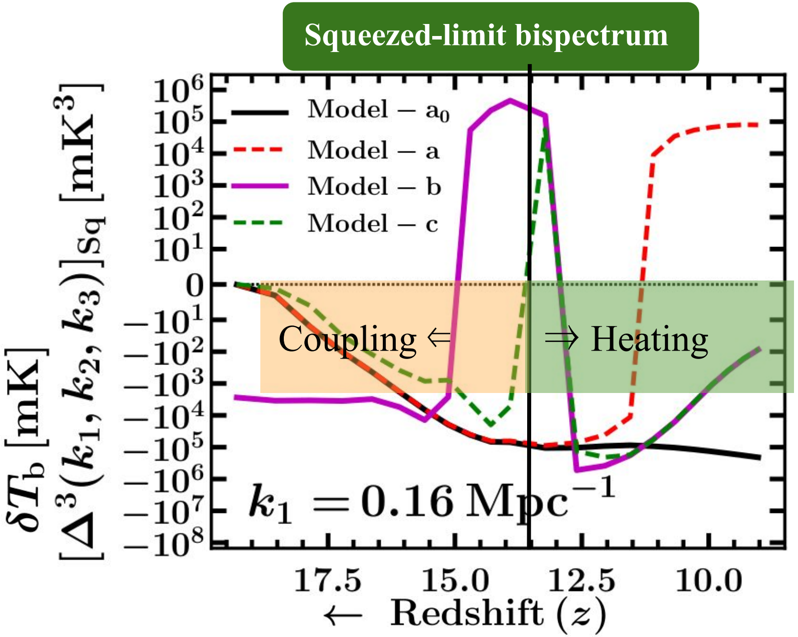
Model-a: Lyα coupling+ photo-ionization

Model-b: Heating in Lyα saturated background

Model-c: All processess

Coupling ⇐

⇒ Heating


Squeezed-limit bispectrum

Coupling ⇐

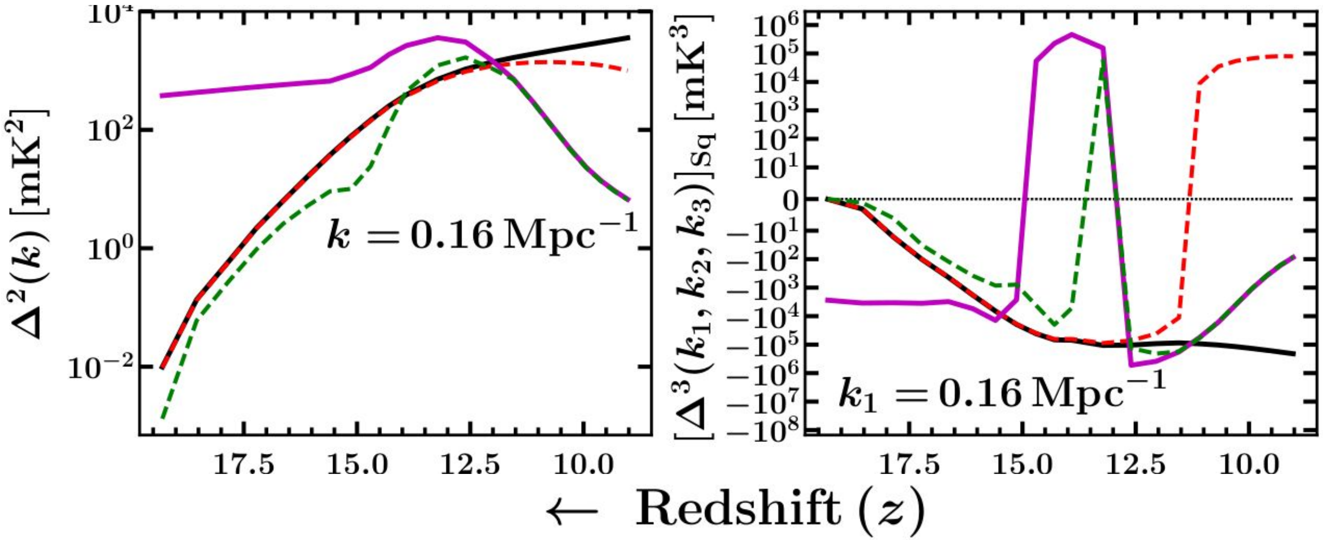
⇒ Heating

Initially Model-c follows Models-a_0 and a ⇒ Lyα coupling dominates until z ~ 14

For z < 14 Model-c follows Model-b ⇒ X-ray heating dominates

Kamran,.., SM et al 2022, arXiv: 2207.09128

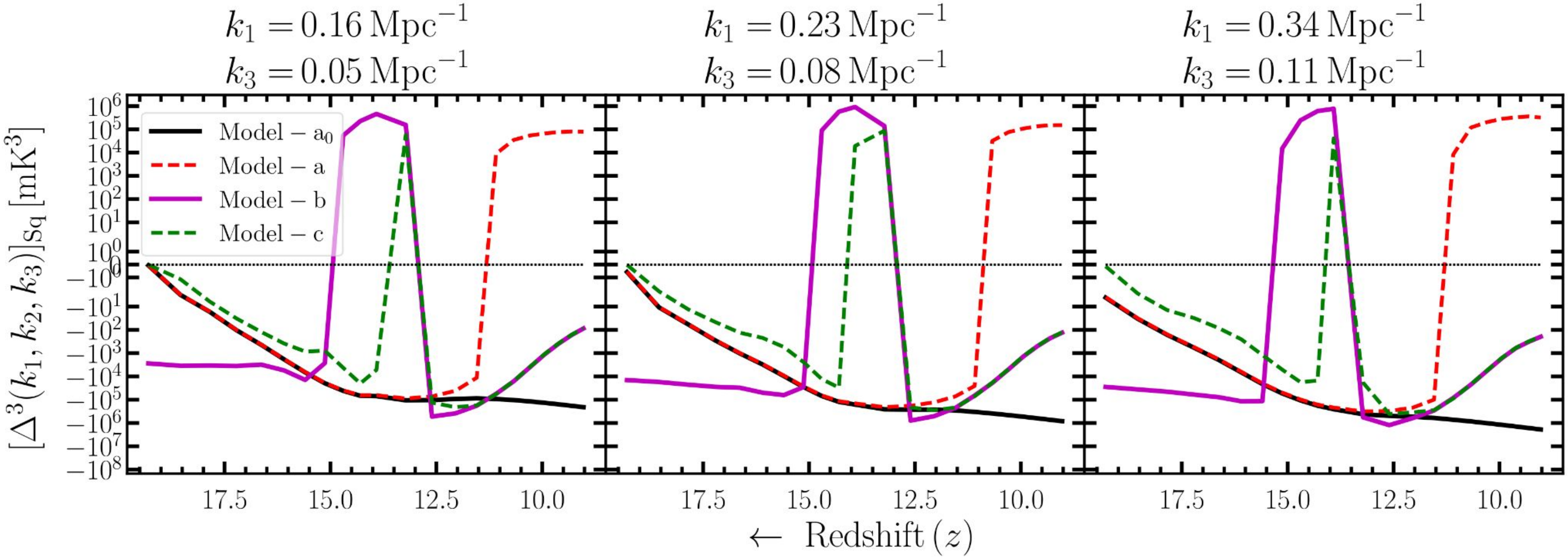
Power spectrum vs bispectrum



Bispectrum via its sign and sign changes can conclusively tells us which IGM process dominates the 21-cm fluctuations at what cosmic time.

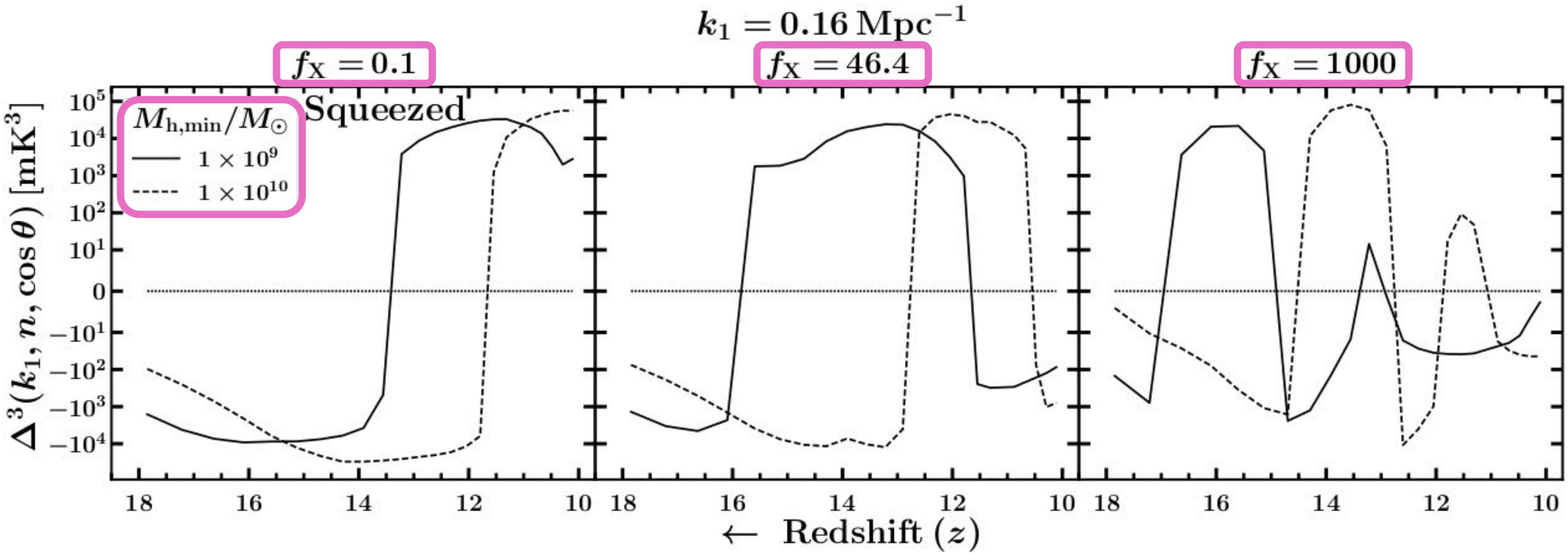
Power spectrum ⇒ always +ve ⇒ it is difficult to unequivocally identify these transitions on the basis of the power spectrum alone.

Robustness of the bispectrum



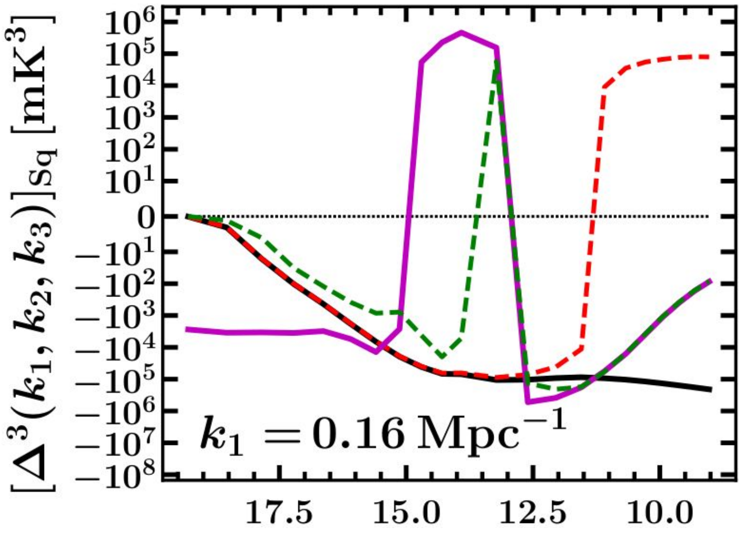
Kamran,.., SM et al 2022, arXiv: 2207.09128

Impact of different source models



Kamran,.., SM et al 2022, arXiv: 2207.09128

Summary II



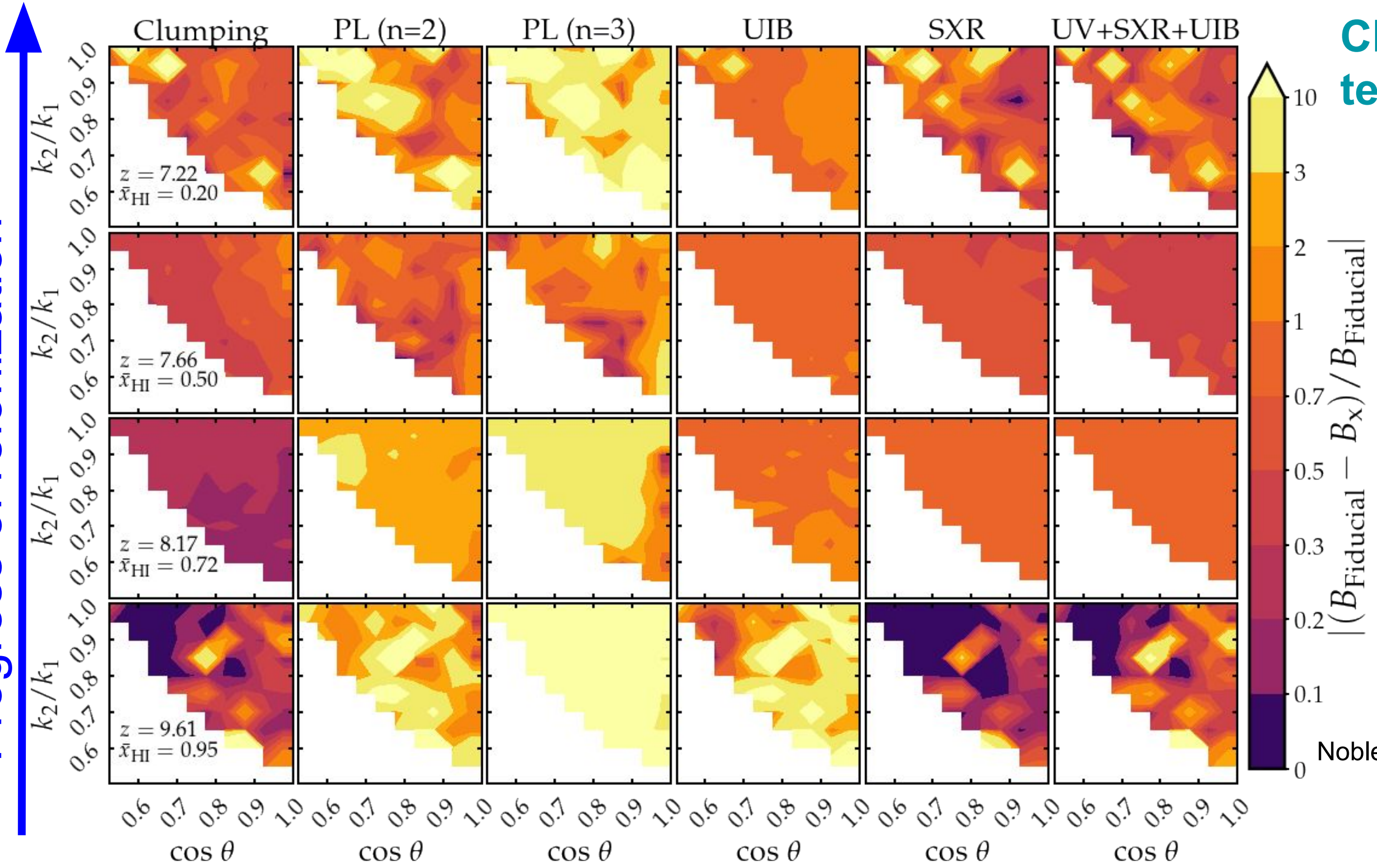
- ➢ CD 21-cm signal is highly non-Gaussian which the bispectrum statistic can potentially capture.
- ➢ The bispectrum can probe the IGM physics that sources the non-Gaussianity in the signal.
- ➢ The bispectrum features can be used as a confirmative test for the 21-cm observations using the next-generation telescopes such as SKA.

The sign of the bispectrum can tell us the relative contrast of the fluctuations in the 21-cm signal with respect to its background.

The sign, shape and the sequence of sign change in the bispectrum works as a smoking gun for the dominant physical processes in the IGM.

Magnitude differences in 21-cm bispectrum between different reionization scenarios w. r. t. Fiducial

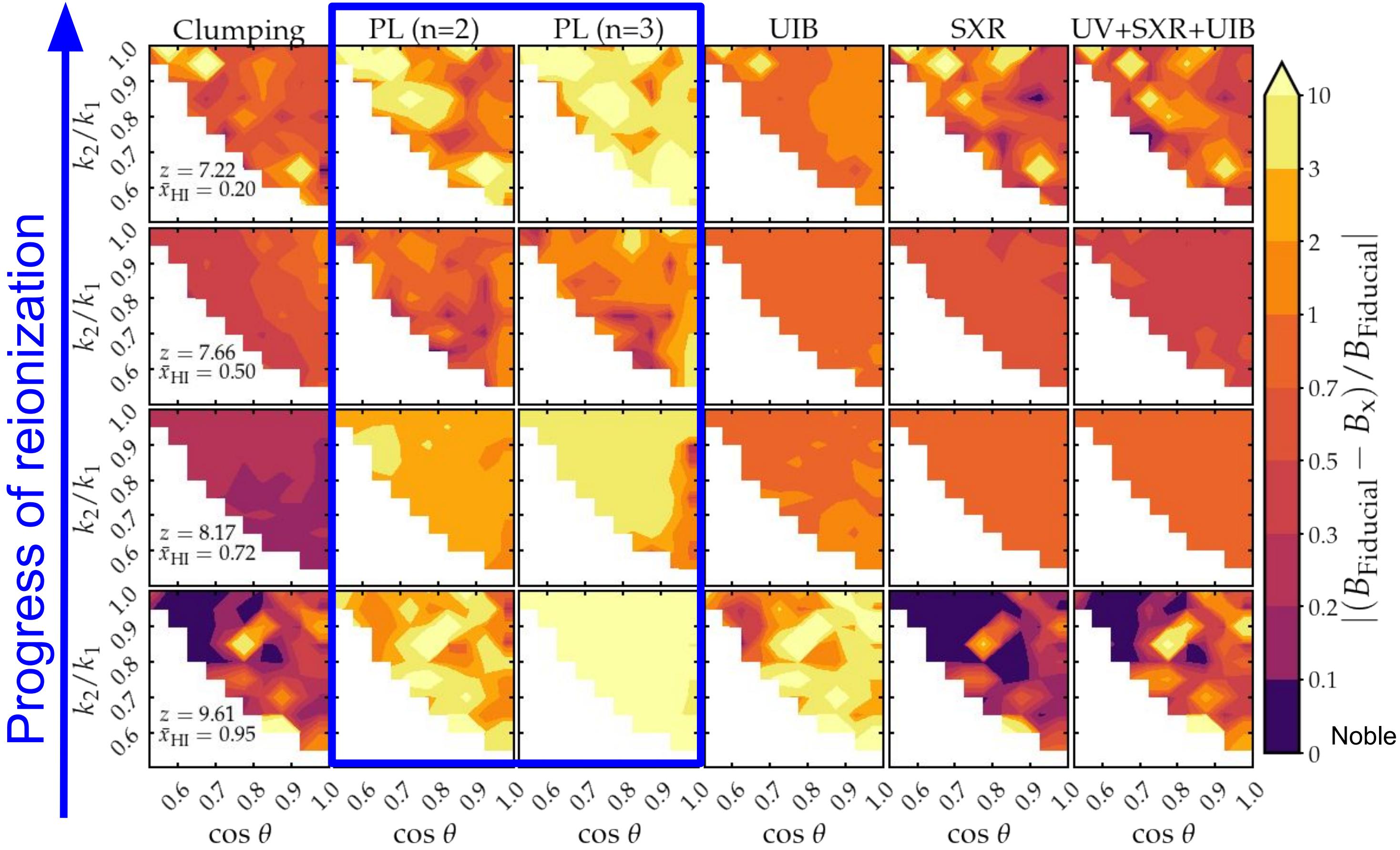
Progress of reionization



Change is more than ten percentage

Noble et al. 2024, arXiv: 2406.03118

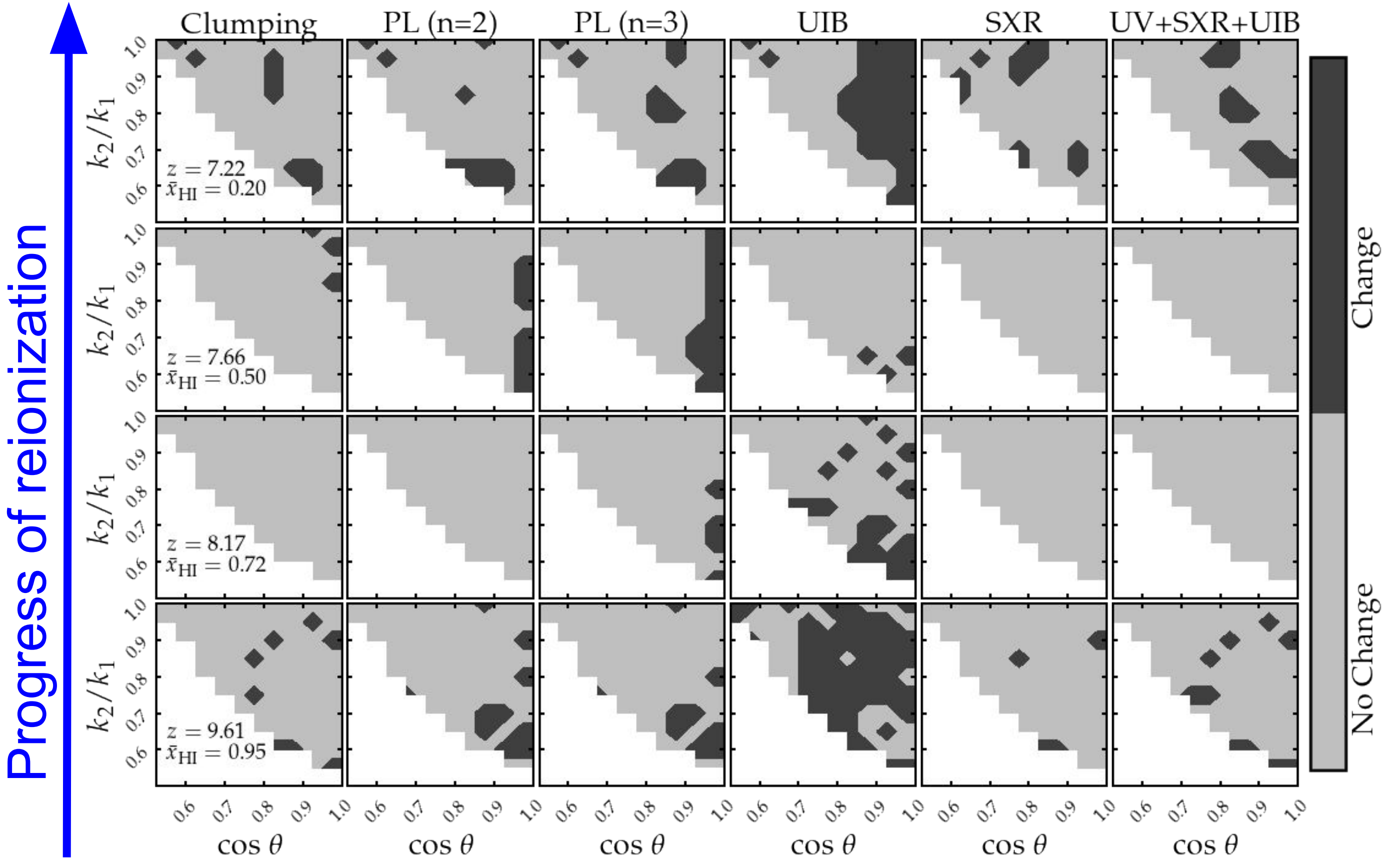
Magnitude differences in 21-cm bispectrum between different reionization scenarios w. r. t. Fiducial



Change is higher than 1000% during early and late stages of reionization in PL scenarios

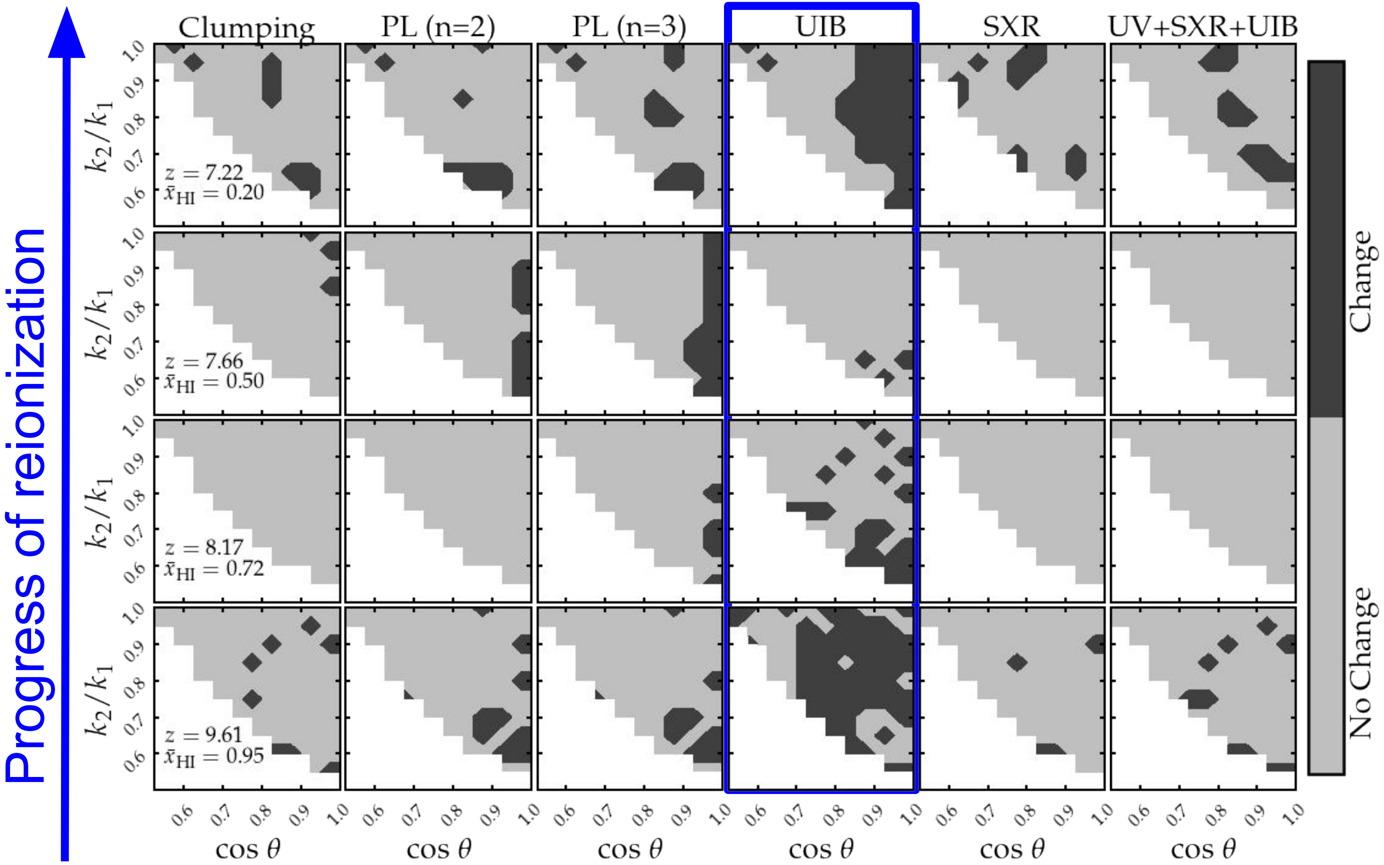
Noble et al. 2024, arXiv: 2406.03118

Sign differences in 21-cm bispectrum between different reionization scenarios w. r. t. Fiducial



Noble et al. 2024, arXiv: 2406.03118

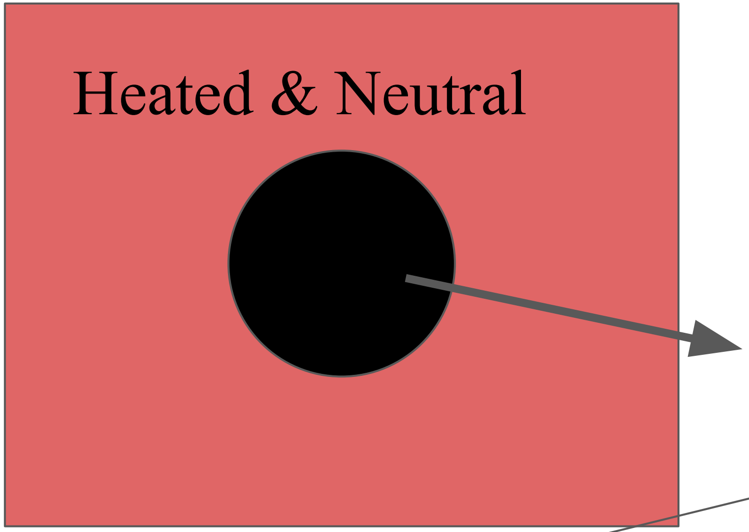
Sign differences in 21-cm bispectrum between different reionization scenarios w. r. t. Fiducial



Change is highest in UIB scenario

Noble et al. 2024, arXiv: 2406.03118

Interpretation

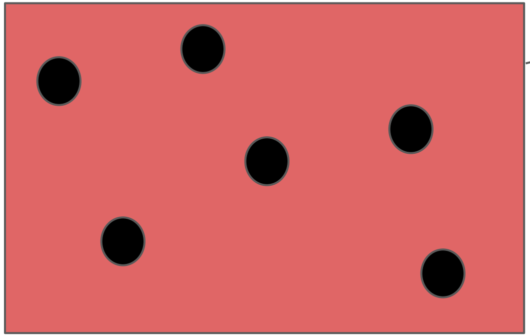


Heated & Neutral

Ionized

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

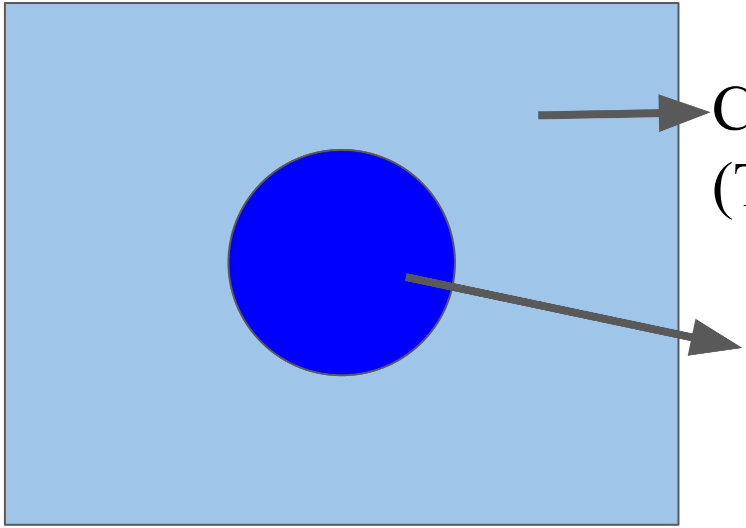
Many non-overlapping ionized regions



Large scale signal -ve

Bharadwaj & Ali 2004
Bharadwaj & Pandey 2005

Interpretation



Cold, Lyα uncoupled & Neutral

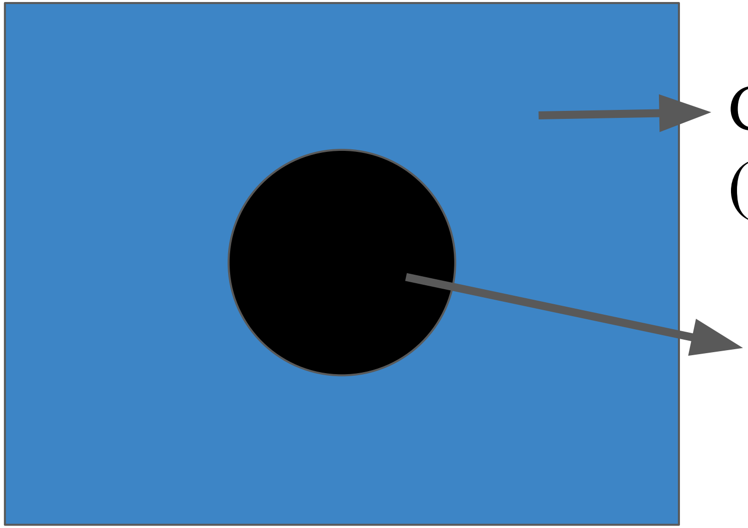
($T_S \sim T_{CMB}$)

Lyα coupled

Strong -ve signal in a weak -ve background

Large scale signal -ve

Interpretation



Cold, Lyα coupled & Neutral

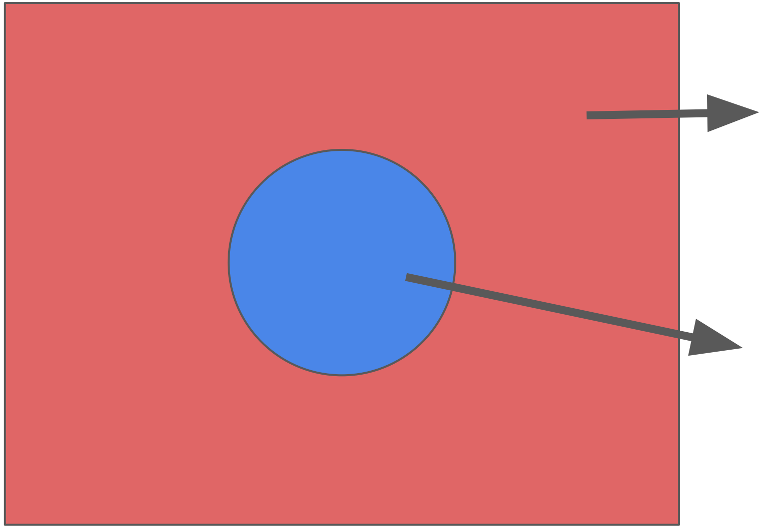
($T_S < T_{CMB}$)

Ionized

zero signal in a -ve background

Large scale signal +ve

Interpretation



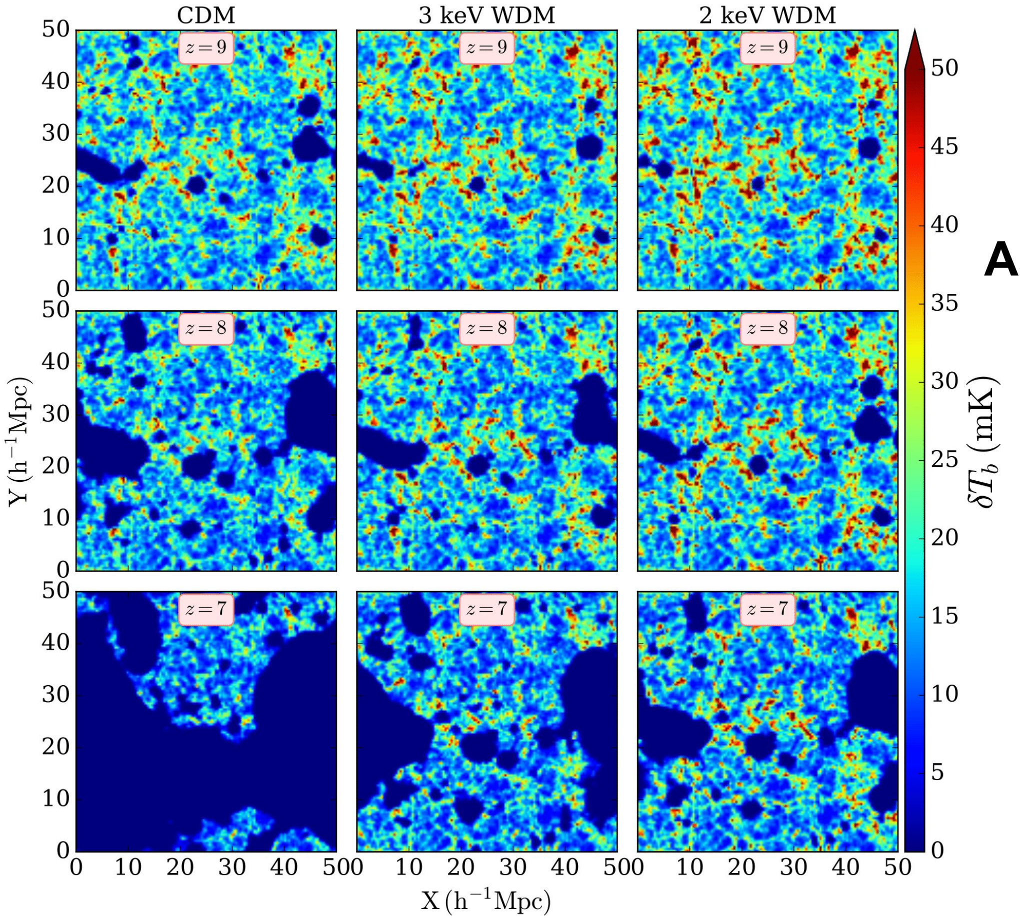
Heated & Neutral
($T_S > T_{CMB}$)

Lyα coupled

-ve signal in a +ve background

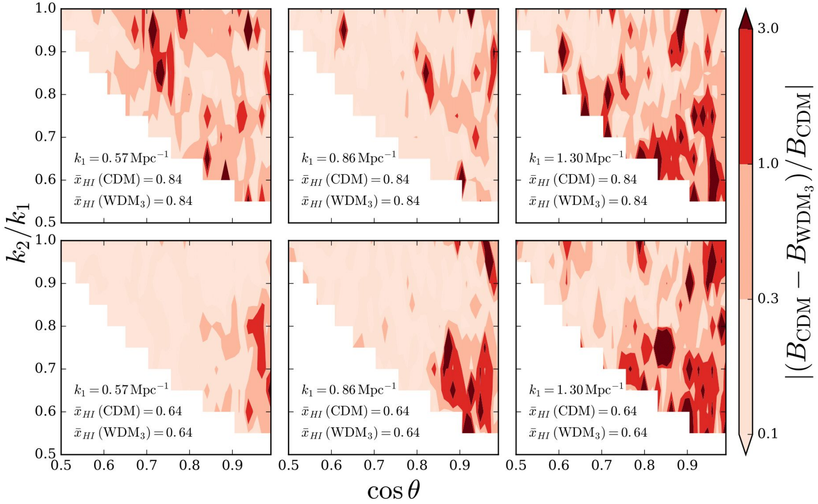
Large scale signal -ve

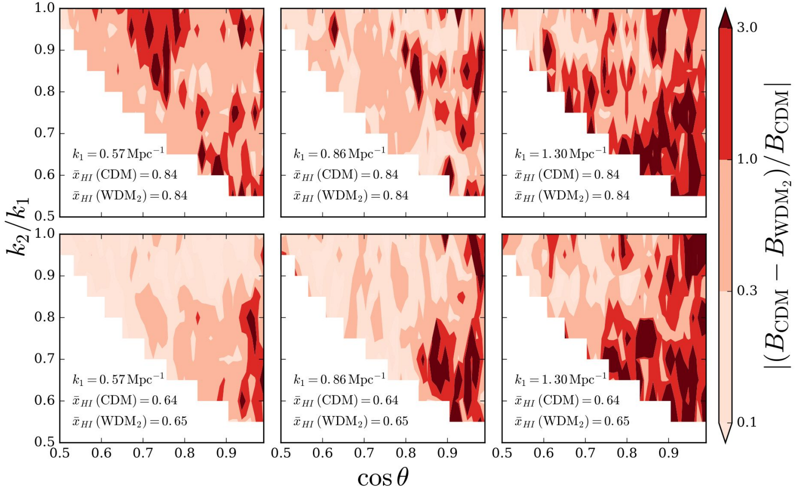
Impact of dark matter models on 21-cm signal bispectrum



Astrophysical parameters remain fixed

Saxena et al. 2020, MNRAS, 497, 2941





Relative differences between the 21-cm bispectra for WDM and CDM models varies between 10% − 300% for all unique k-triangles

Saxena et al. 2020, MNRAS, 497, 2941