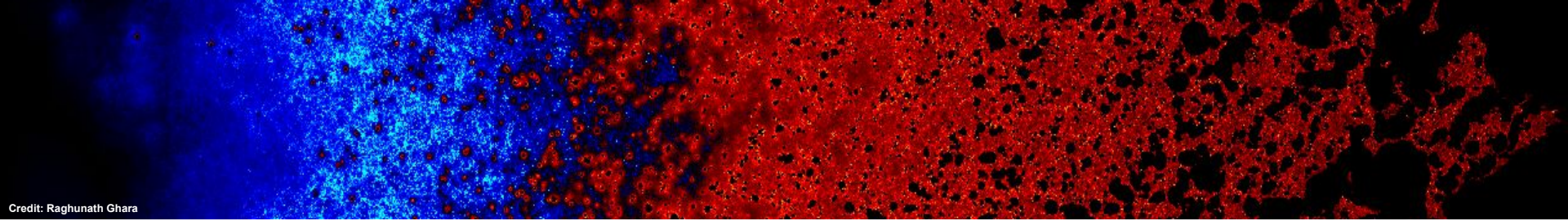
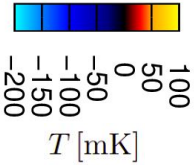




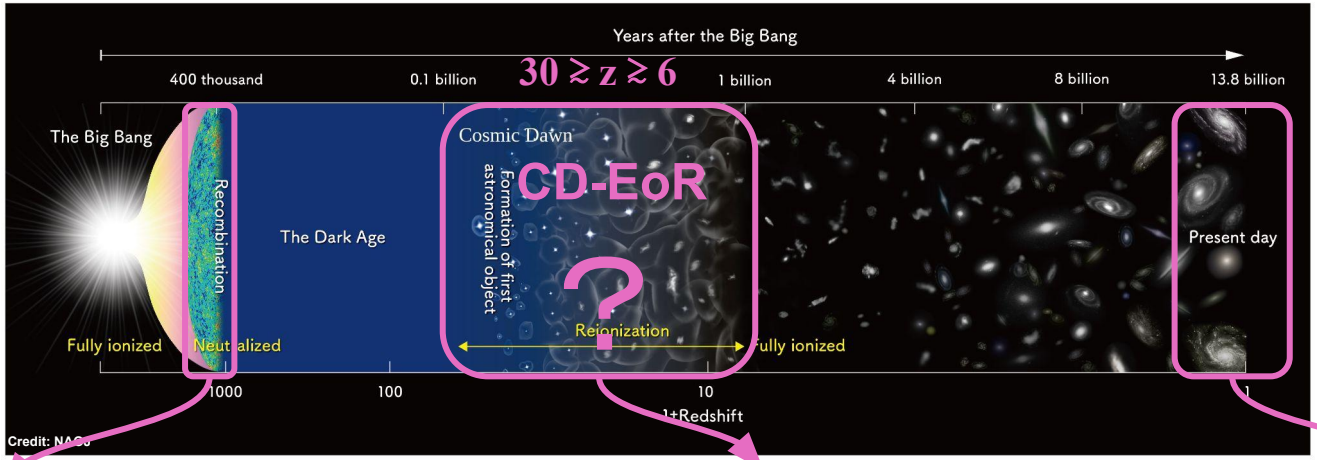
Probing the Cosmic Dawn using the redshifted 21-cm bispectrum

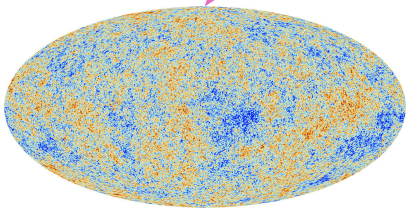
Mohd Kamran

UPPSALA UNIVERSITET

Co-authors: Suman Majumdar (IIT Indore), Raghunath Ghara (Technion Israel), Garrelt Mellema (Stockholm University), Somnath Bharadwaj (IIT KGP), Jonathan R. Pritchard (Imperial College London), Rajesh Mondal (Tel Aviv University), Ilian T. Iliev (University of Sussex)

Cosmic History:
Cosmic Dawn and Epoch of Reionization (CD-EoR)





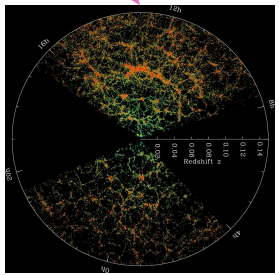
Cosmic Microwave Background (Planck)

INTERMEDIATE PHASES

Cosmic Dawn: First stars and X-ray sources; Neutral Universe.

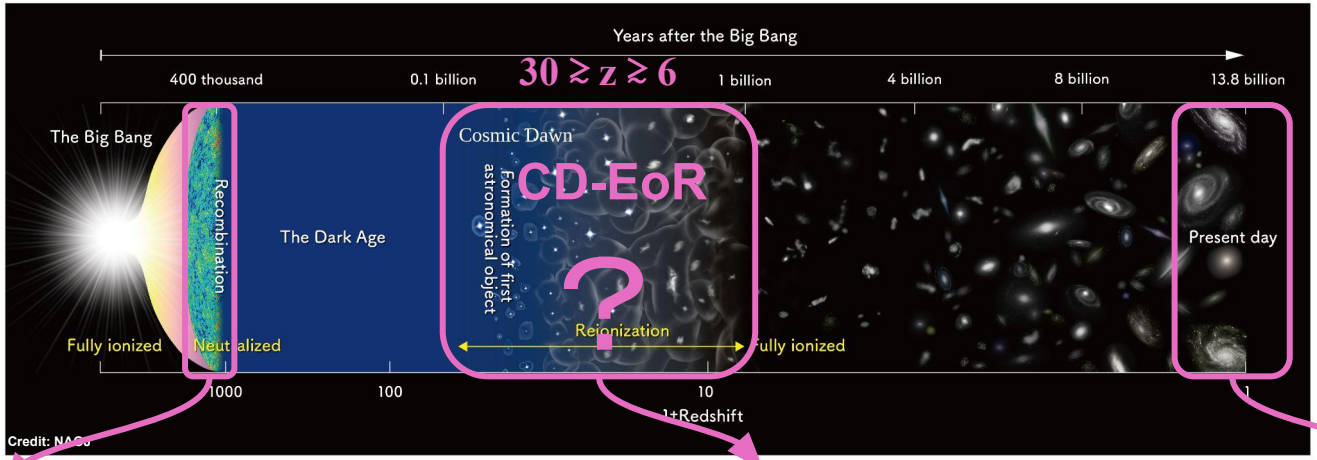
Epoch of Reionization: Earliest galaxies; Neutral hydrogen starts to disappear.

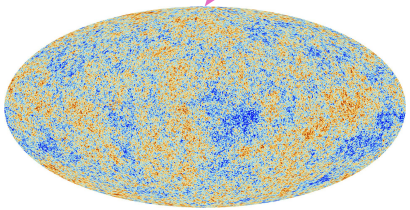
During first Byr



Galaxy Redshift Survey (SDSS)

Cosmic History:
Cosmic Dawn and Epoch of Reionization (CD-EoR)





Cosmic Microwave Background (Planck)

INTERMEDIATE PHASES

Cosmic Dawn: First stars and X-ray sources; Neutral Universe.

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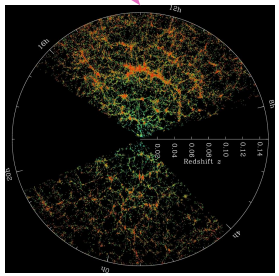
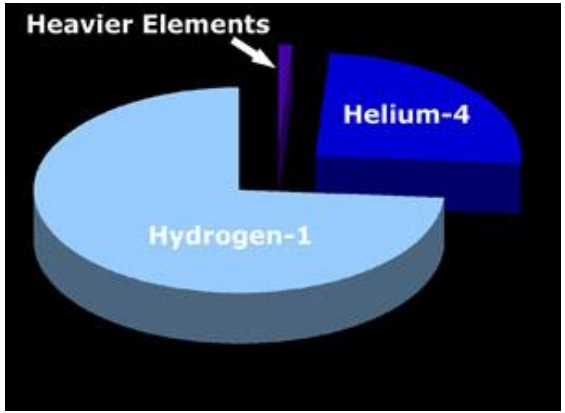
Least Known Chapters
Largely untested by the observations



Galaxy Redshift Survey (SDSS)

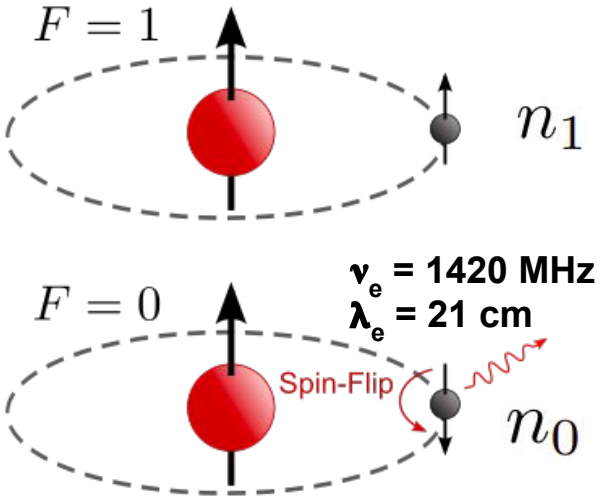
Neutral Hydrogen (HI) is abundant in the IGM:



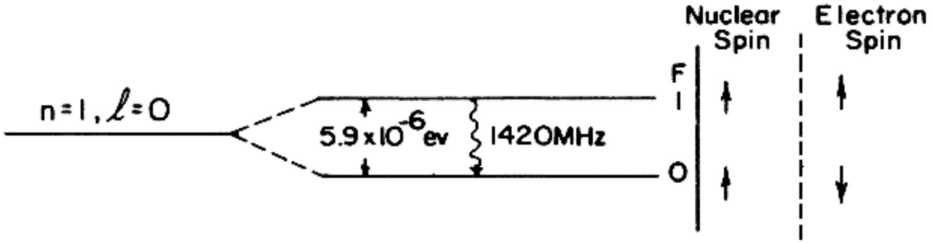
Elemental composition of baryons in the Universe

Source: universeadventure.org

How can we see the hydrogen?
HI 21-cm line



ν_e = 1420 MHz
λ_e = 21 cm



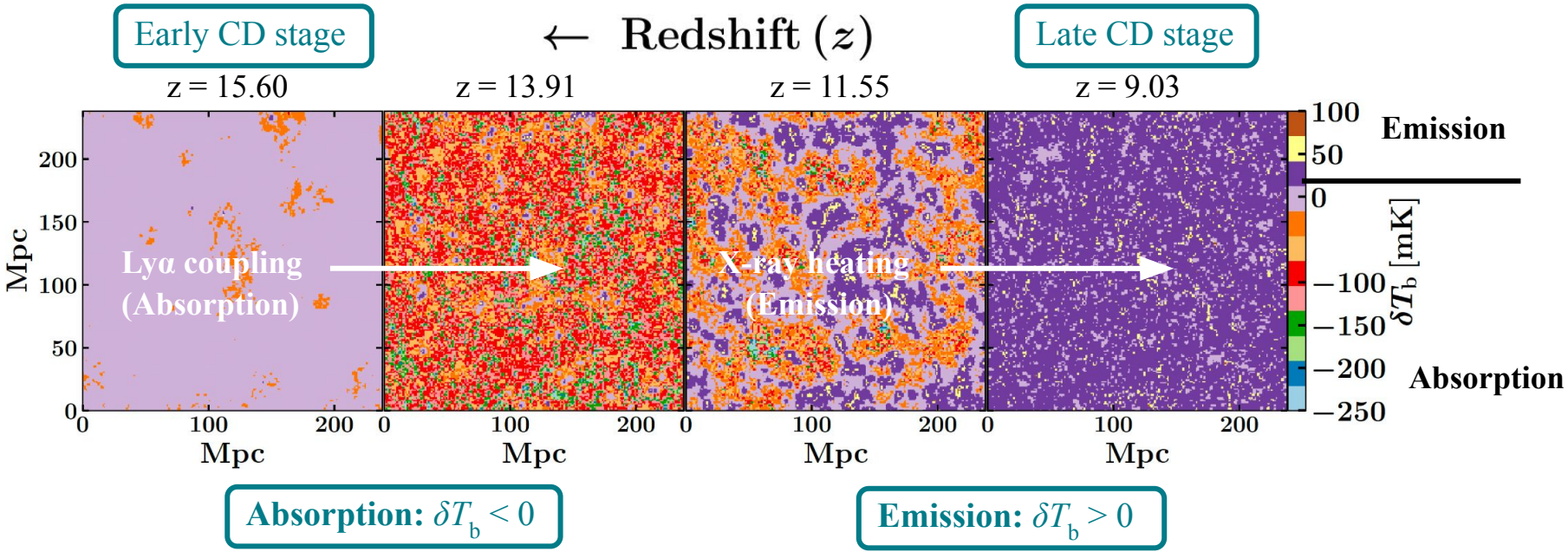
Source: Wikimedia.org

Differential brightness temperature

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

Astrophysics

21-cm fluctuations!



Absorption: $\delta T_{\rm b} < 0$

Emission: $\delta T_{\rm b} > 0$

The non-Gaussianity:

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

Astrophysics

21-cm fluctuations!

Highly non-Gaussian

The non-Gaussianity:

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

Astrophysics

21-cm fluctuations!

Highly non-Gaussian

Non-Gaussianity:

- Intrinsic
- Time-evolving

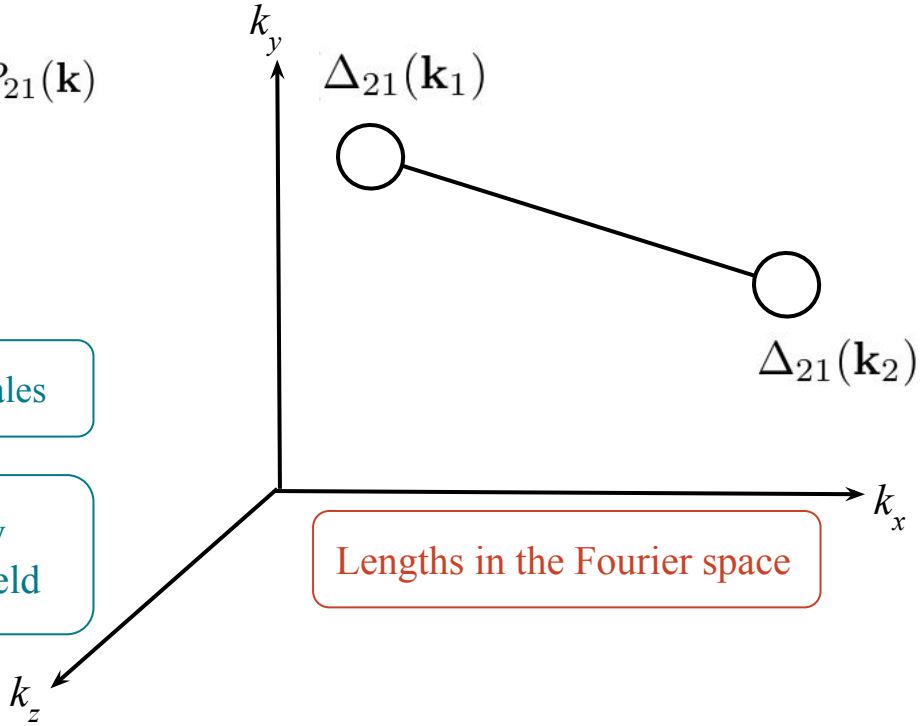
The Power Spectrum:
A conventional statistical measure of the 21-cm signal

$$\langle \Delta_{21}(\mathbf{k}_1)\Delta_{21}(\mathbf{k}_2)\rangle = (2\pi)^3\delta_{\rm D}^3(\mathbf{k}_1-\mathbf{k}_2)\,P_{21}(\mathbf{k})$$

$$\Delta_{21}(\mathbf{k}) \overset{\text{FT}}{\longleftrightarrow} \delta T_{\rm b}(\mathbf{r})$$

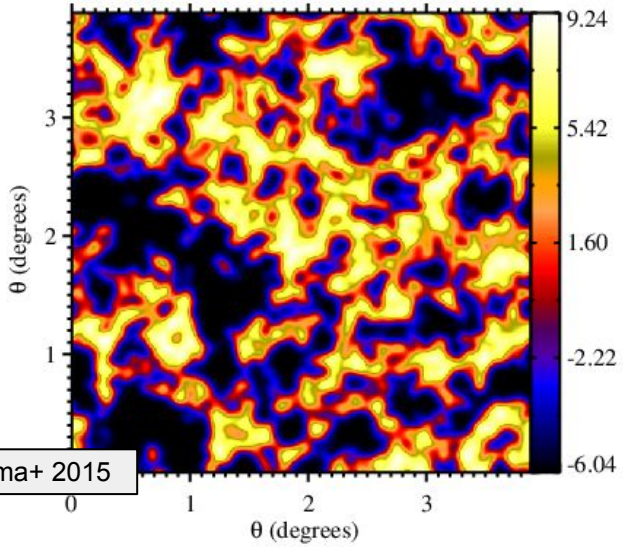
Amplitude of fluctuations at different length scales

Power spectrum describes a field completely only when it is a **pure Gaussian random** field



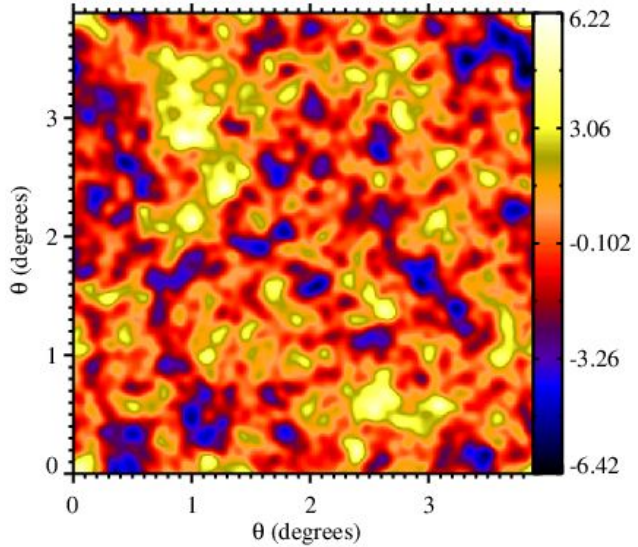
The non-Gaussianity:

Non-Gaussian 21-cm map



Mellema+ 2015

Gaussian fluctuations

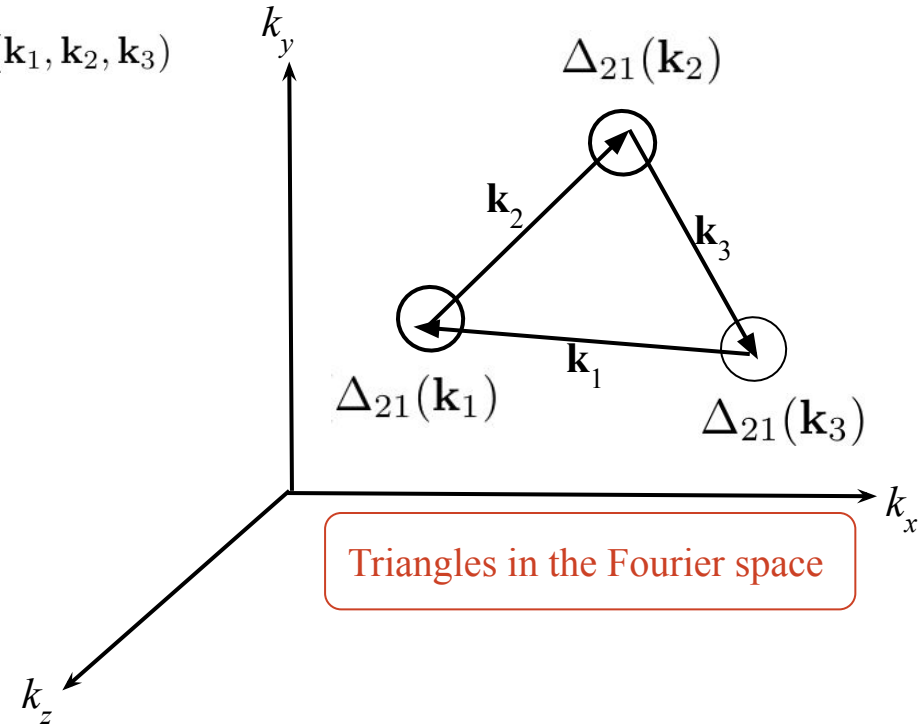


Same power spectrum but different images

The Bispectrum:

$$\langle \Delta_{21}(\mathbf{k}_1)\Delta_{21}(\mathbf{k}_2)\Delta_{21}(\mathbf{k}_3)\rangle = V\delta^{\mathrm{K}}_{\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3,0}\, B_{21}(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3)$$

$$\Delta_{21}(\mathbf{k}) \xleftrightarrow{\text{FT}} \delta T_{\mathrm{b}}(\mathbf{r})$$



Triangles in the Fourier space

The Bispectrum:

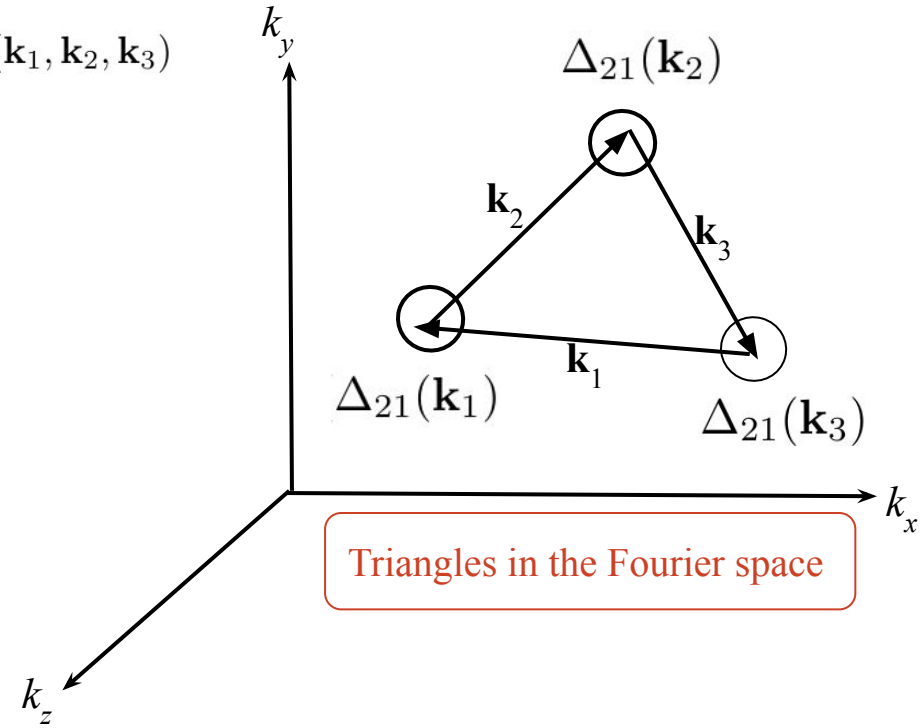
$$\langle \Delta_{21}(\mathbf{k}_1)\Delta_{21}(\mathbf{k}_2)\Delta_{21}(\mathbf{k}_3)\rangle = V\delta^{\mathrm{K}}_{\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3,0}\, B_{21}(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3)$$

$$\Delta_{21}(\mathbf{k}) \overset{\text{FT}}{\longleftrightarrow} \delta T_{\mathrm{b}}(\mathbf{r})$$

- $B_{21} \neq 0$, iff 3 **k** modes in the definition form a closed triangle.

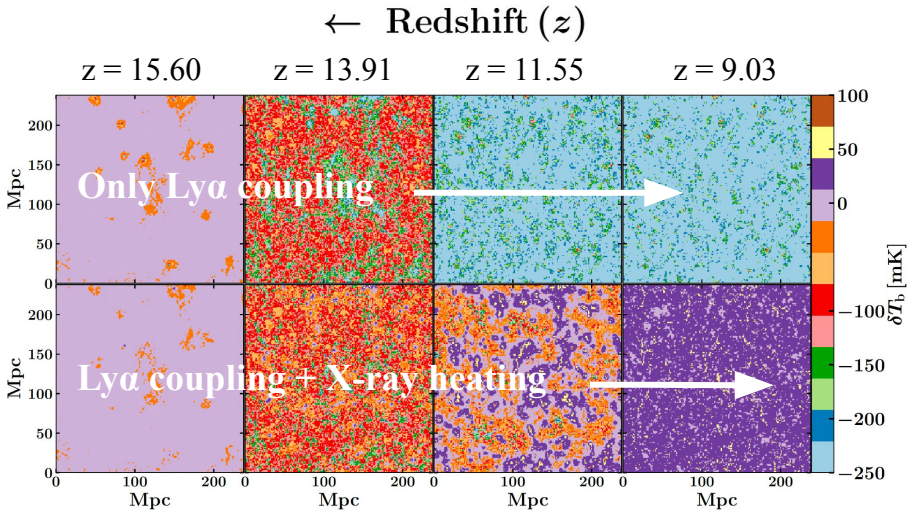
$$\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3 = 0$$

- B_{21} can attain both positive and negative values



Triangles in the Fourier space

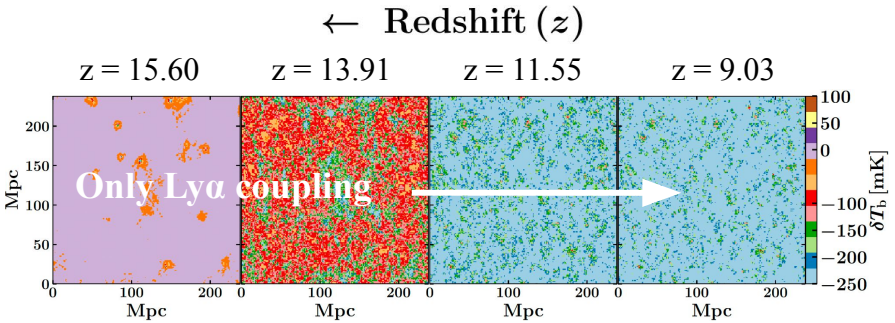
Two simulated CD scenarios:

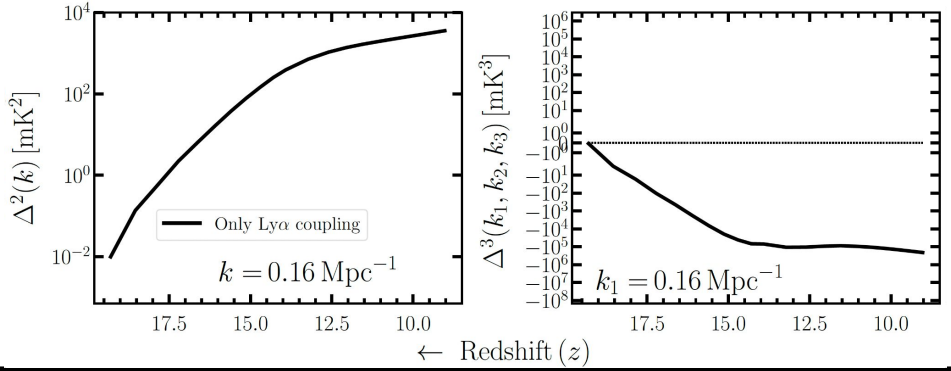


Results from GRIZZLY simulation (Ghara et al. 2015a, 2018)

Results

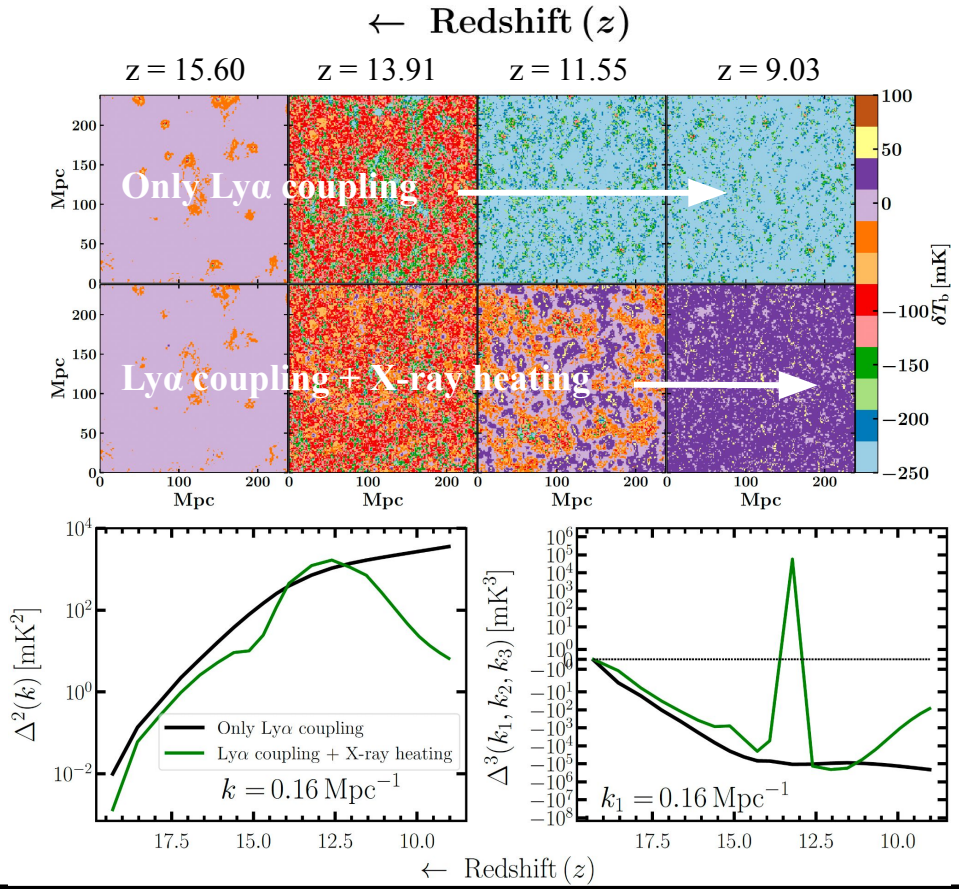
The Bispectrum as a probe of IGM physics:





Kamran+2021b (under review in PRL)

The Bispectrum as a probe of IGM physics:



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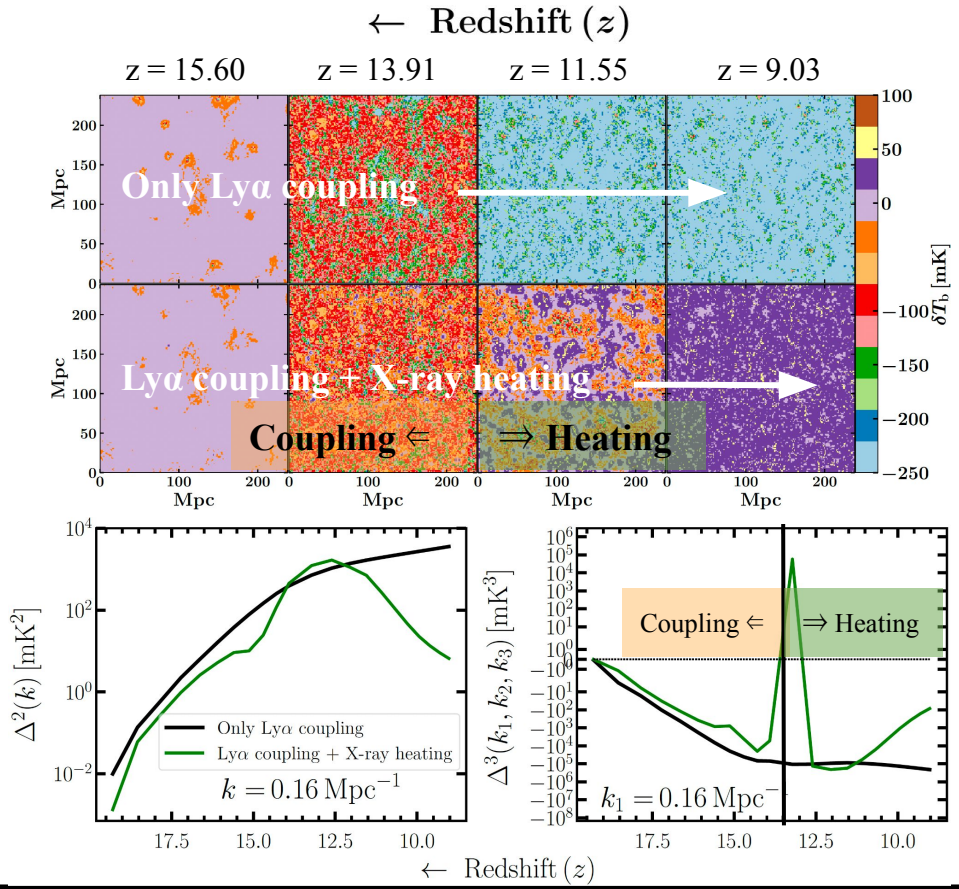

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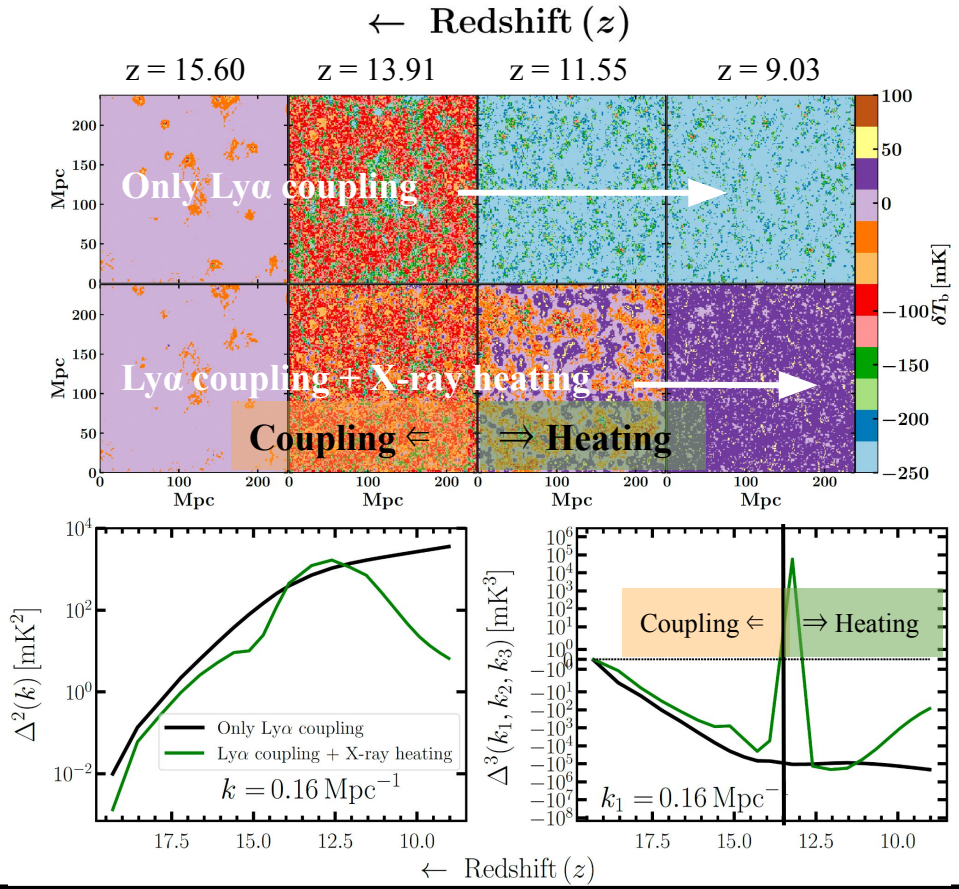


These features can be used as a test of confermative detection of the 21-cm fluctuations in the future SKA observations

Kamran+2021b (under review in PRL)

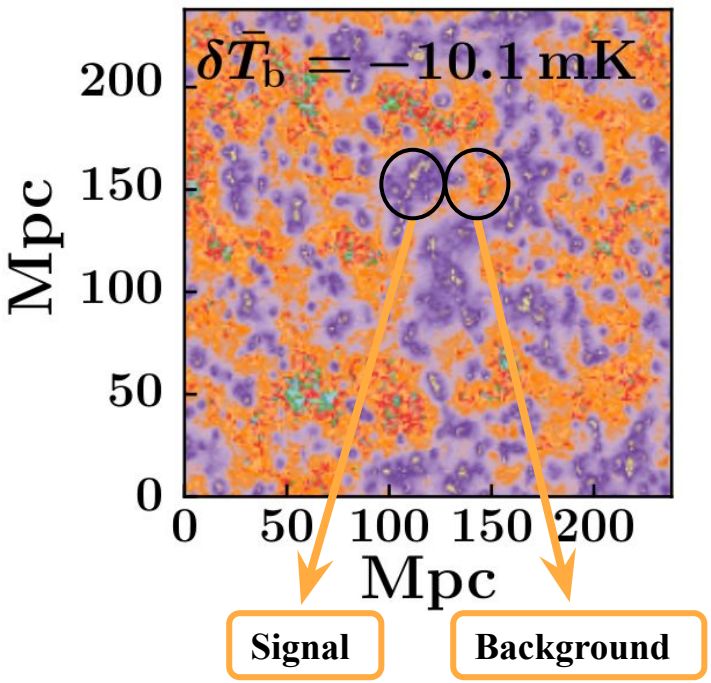
Detectability predictions of the bispectrum using the SKA-Low:

Mondal+Mellema+Kamran et al. 2021

More than a 5σ detection is possible using 1000 hrs of SKA observations of the bispectra for a few special k-triangles

Summary

- CD-EoR 21-cm signal is highly non-Gaussian in nature.
- The bispectrum statistic can potentially capture this time evolving non-Gaussianity.
- The bispectrum being the potential probe of the non-Gaussianity – > can probe the IGM physics that sources the non-Gaussianity in the signal.



Summary

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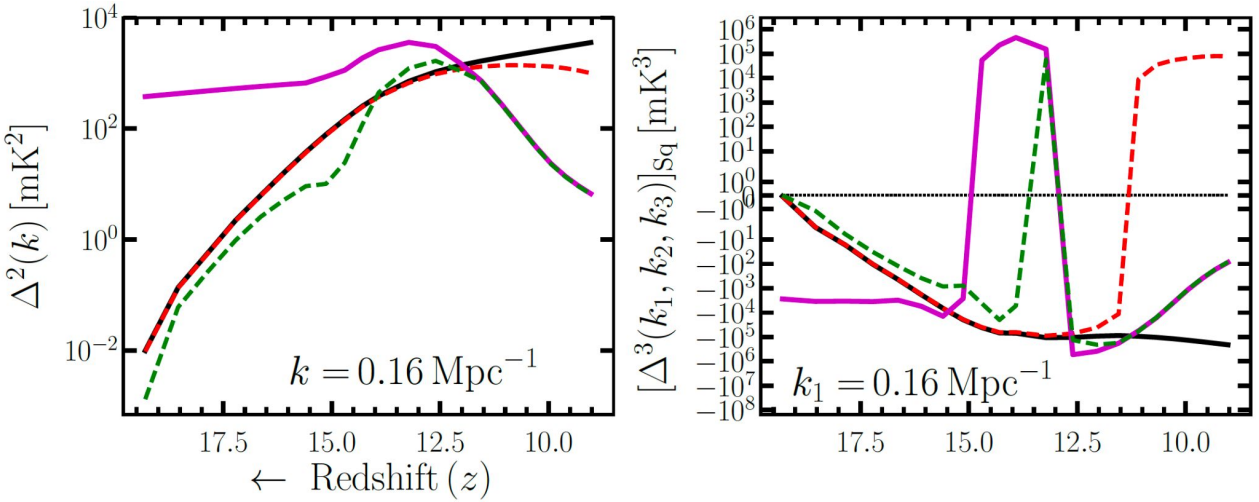
- The bispectrum statistic can potentially capture this time evolving non-Gaussianity.
- The bispectrum being the potential probe of the non-Gaussianity – > can probe the IGM physics that sources the non-Gaussianity in the signal.

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


$\Delta^2(k)\,[\mathrm{mK}^2]$
10^4
10^2
10^0
10^{-2}
$k = 0.16\,\mathrm{Mpc}^{-1}$
17.5
15.0
12.5
10.0
← Redshift (z)
$[\Delta^3(k_1, k_2, k_3)]_{\mathrm{Sq}}\,[\mathrm{mK}^3]$
$k_1 = 0.16\,\mathrm{Mpc}^{-1}$