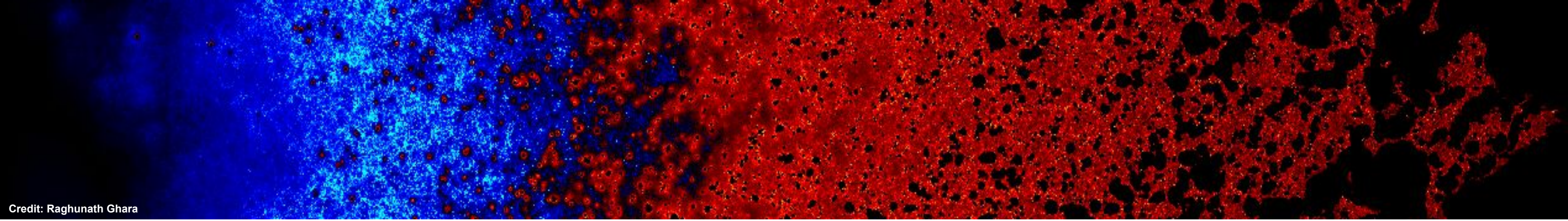
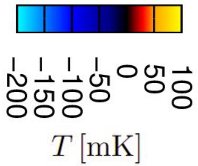




Probing the Cosmic Dawn using the redshifted 21-cm Bispectrum

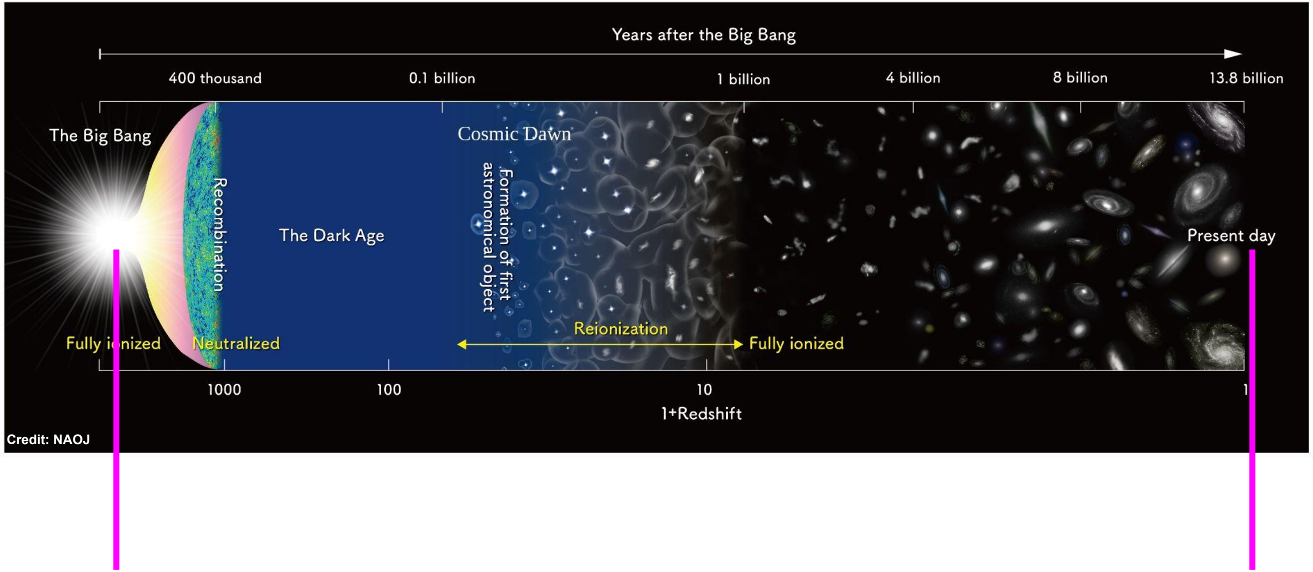
Mohd Kamran

UPPSALA UNIVERSITET

Collaborators: Suman Majumdar (IIT Indore), Raghunath Ghara (Technion), 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)

Motivation: 21-cm cosmology

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



$t_{age} = 0$

$z \sim \infty$

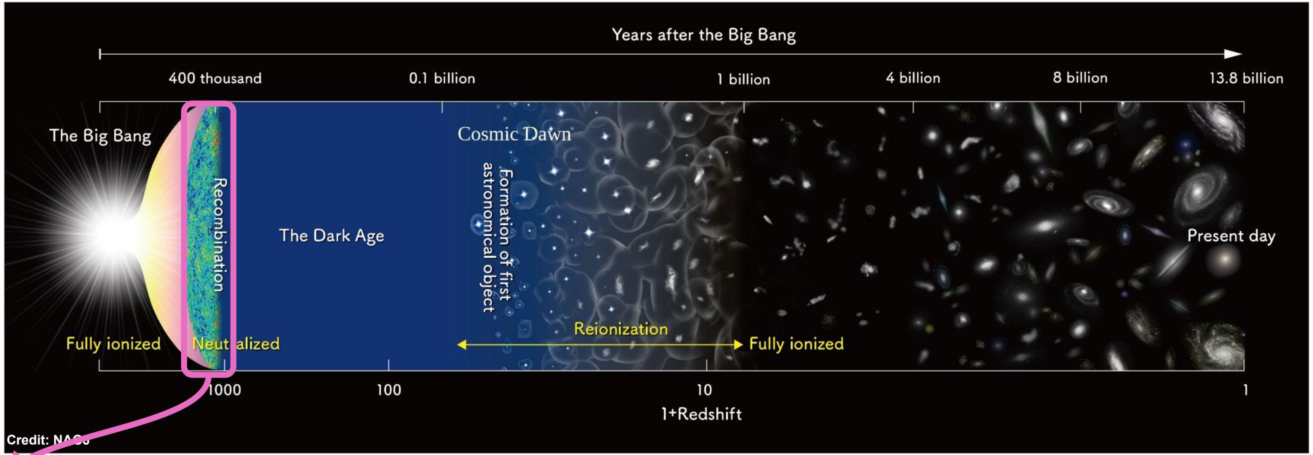
$t_{age} \rightarrow$ Age of the Universe

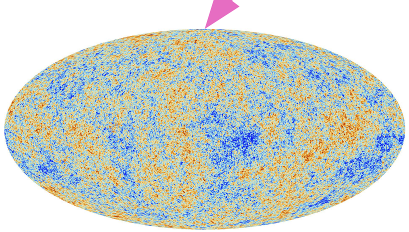
$z \rightarrow$ redshift

$t_{age} \sim 13.8$ Byr

$z = 0$

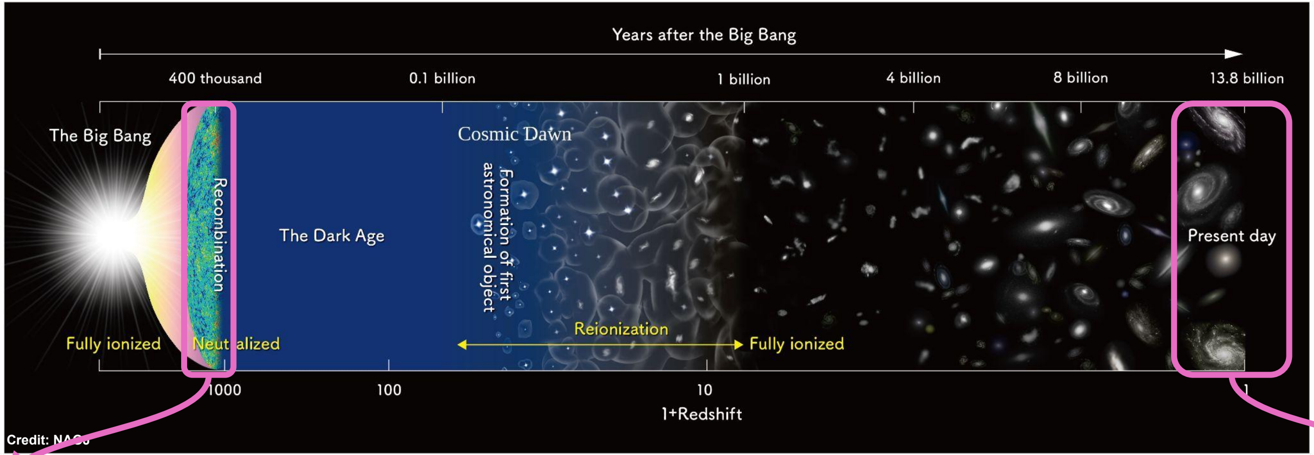
Cosmic History:
Cosmic Dawn and Epoch of Reionization (CD-EoR)

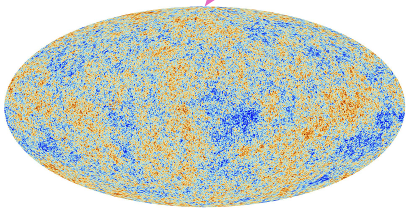




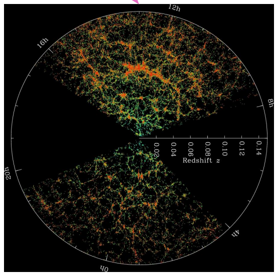
Cosmic Microwave Background (Planck)

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



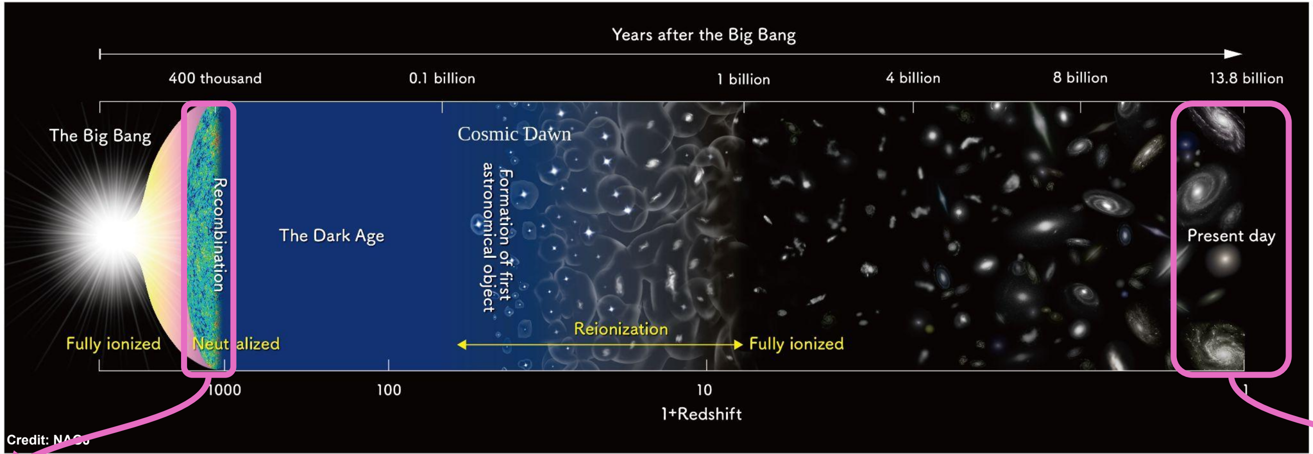


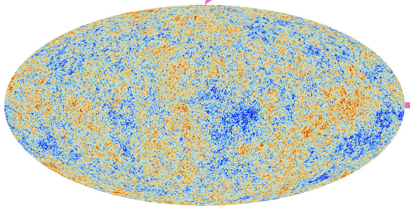
Cosmic Microwave Background (Planck)



Galaxy Redshift Survey (SDSS)

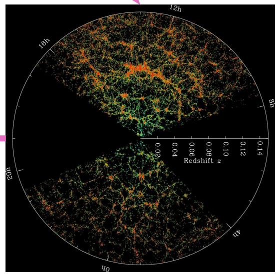
Cosmic History:
Cosmic Dawn and Epoch of Reionization (CD-EoR)





Cosmic Microwave Background (Planck)

Provide clear pictures of the **LSS**



Galaxy Redshift Survey (SDSS)

Cosmic History:
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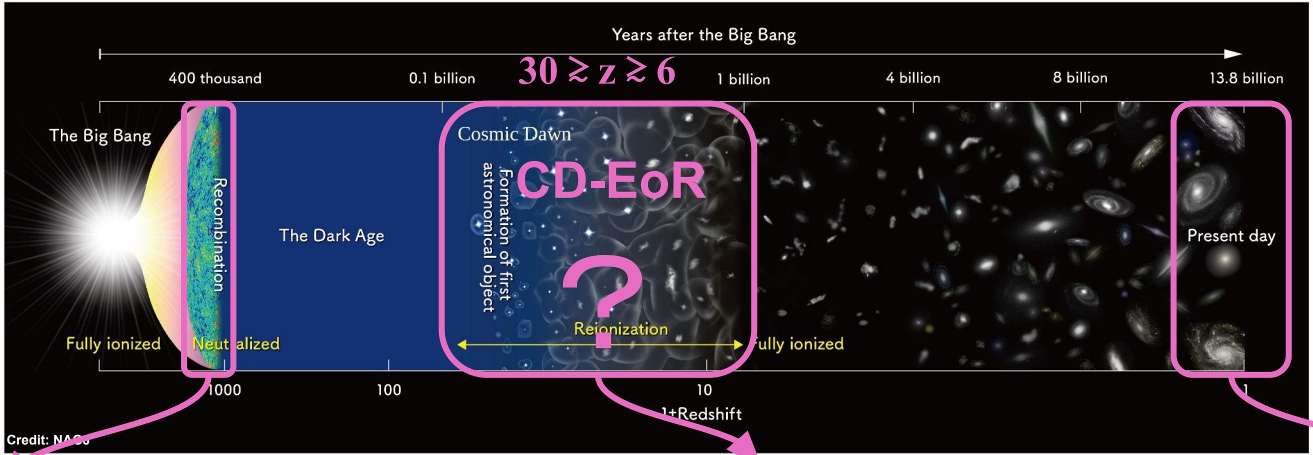
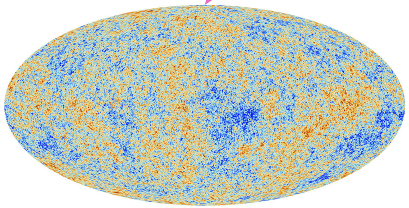




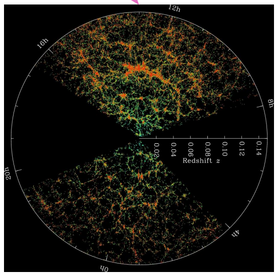
Cosmic Microwave Background (Planck)

INTERMEDIATE PHASES

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

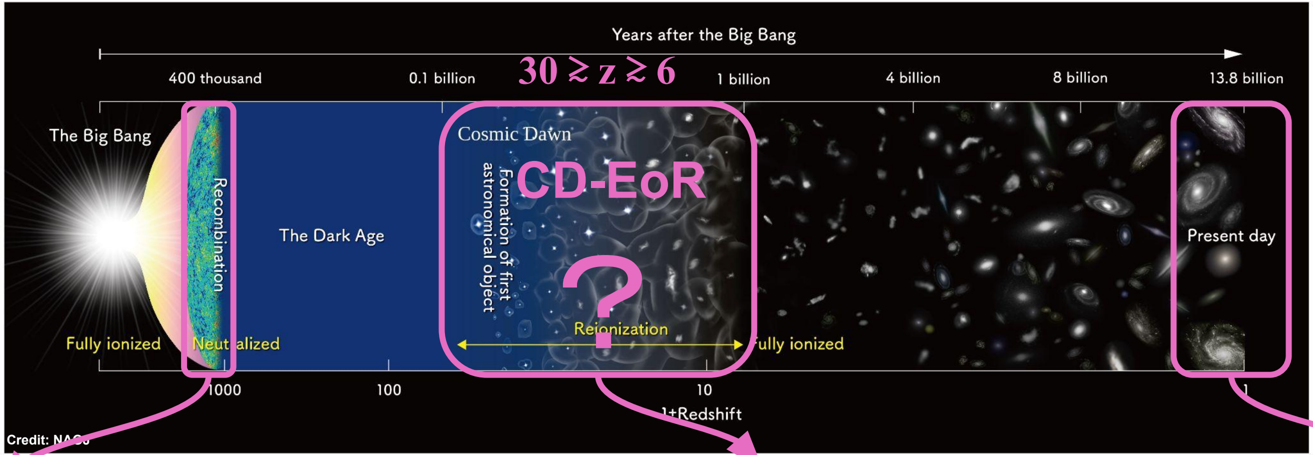
Epoch of Reionization: Earliest galaxies; Neutral hydrogen starts to disappear.

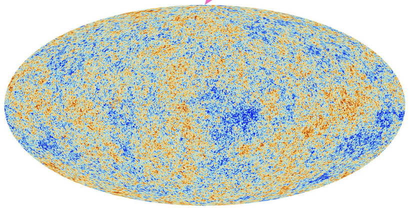
During first Byr



Galaxy Redshift Survey (SDSS)

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





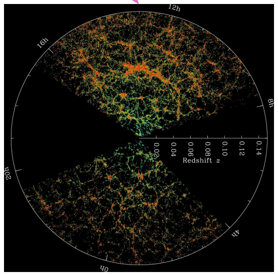
Cosmic Microwave Background (Planck)

INTERMEDIATE PHASES

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

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

Least Known Chapters
Largely untested by the observations



Galaxy Redshift Survey (SDSS)

Fundamental Issues?
Milestones of the CD-EoR

The study of the CD-EoR is crucial as it includes a number of major cosmic milestones, such as:

- Formation and evolution of first luminous sources (stars, galaxies, quasars, etc) during this period.

  Star-forming galaxies: Major sources of **Lyα photons (coupling)** + **UV photons (ionization)**.

  Quasars and HMXBs: Major sources of **X-ray photons (heating)**.

- Astrophysical impacts of these sources on the IGM.
- Topology of the heated and ionized regions formed in the IGM by these sources.

Fundamental Issues?
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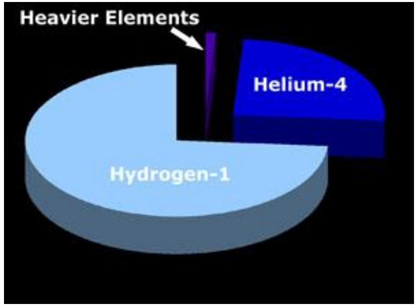
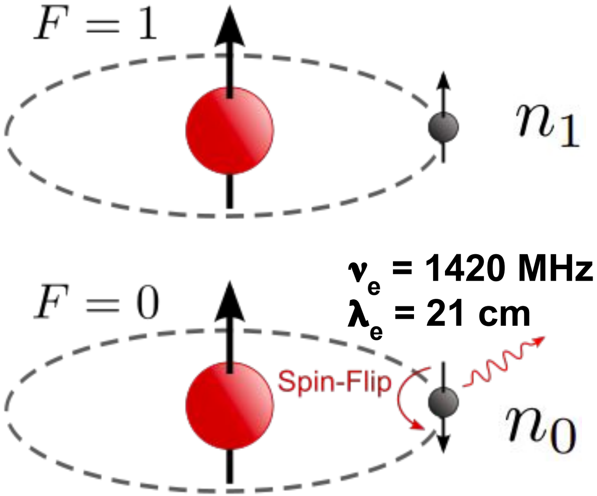


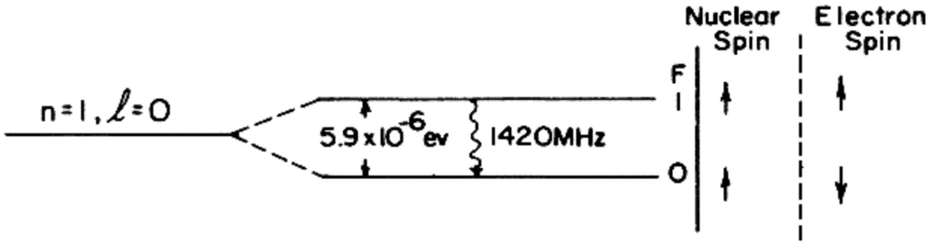
Elemental composition of baryons in the Universe

Source: universeadventure.org

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

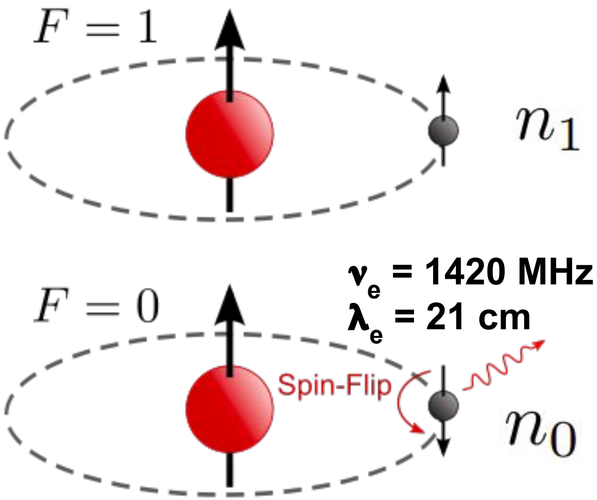


ν_e = 1420 MHz
λ_e = 21 cm



Source: Wikimedia.org

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



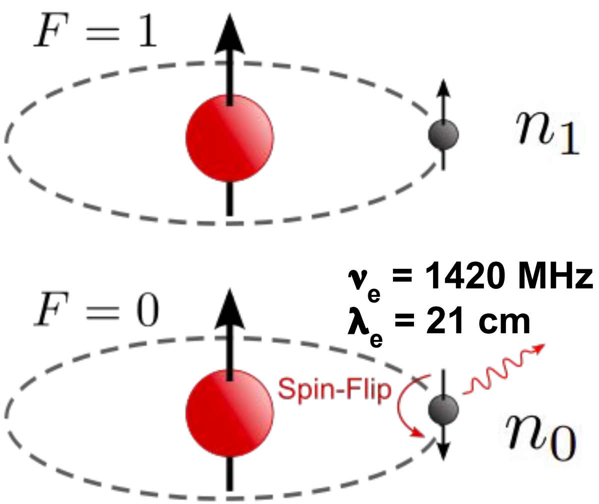
ν_e = 1420 MHz
λ_e = 21 cm

- **Spin Temperature (T_S):** Important at **Cosmic Dawn**

$$\frac{n_1}{n_0} = 3\exp\left(\frac{-0.068\,\mathrm{K}}{T_\mathrm{S}}\right)$$

Source: Wikimedia.org

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



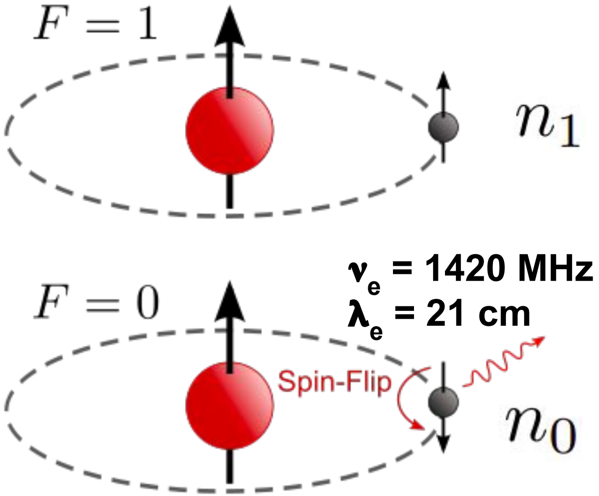
Source: Wikimedia.org

- **Spin Temperature (T_S):** Important at **Cosmic Dawn**

$$\frac{n_1}{n_0} = 3\exp\left(\frac{-0.068\,\mathrm{K}}{T_S}\right)$$

This ratio controls the intensity of the 21-cm radiation from the diffused HI in the IGM.

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



Source: Wikimedia.org

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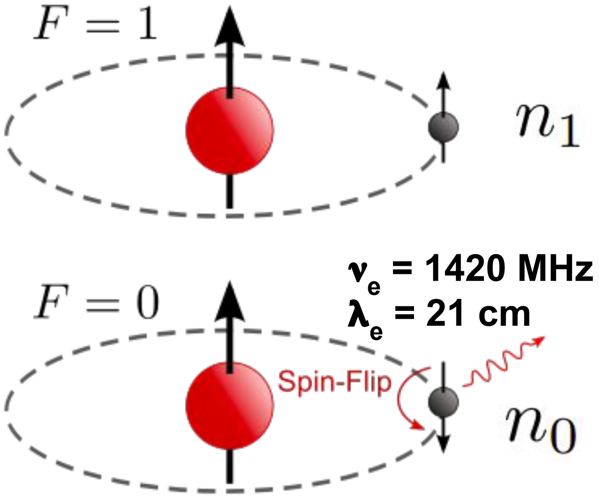
$$\frac{n_1}{n_0} = 3\exp\left(\frac{-0.068\,\mathrm{K}}{T_S}\right)$$

This ratio controls the intensity of the 21-cm radiation from the diffused HI in the IGM.

The T_S thus corresponds to the intensity of this radiation.

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



ν_e = 1420 MHz
λ_e = 21 cm

Source: Wikimedia.org

➢ **Spin Temperature (T_S):** Important at **Cosmic Dawn**

$$\frac{n_1}{n_0} = 3\exp\left(\frac{-0.068\,\mathrm{K}}{T_S}\right)$$

Impact of the first light sources on the T_S

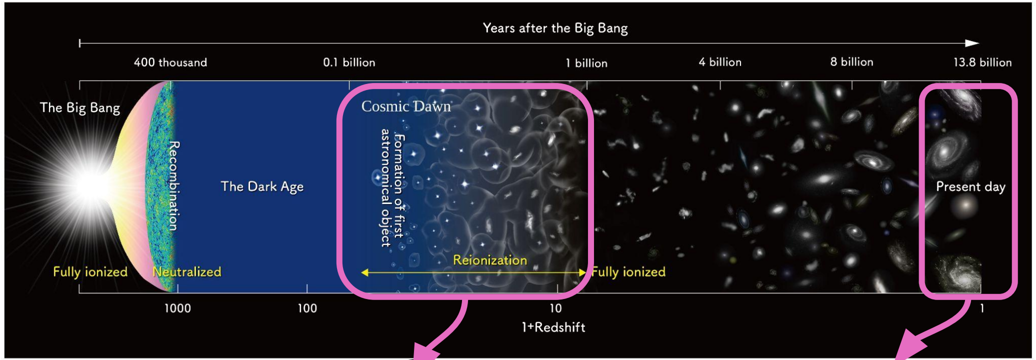
$$T_S(\mathbf{r}, z) = \frac{T_{\mathrm{CMB}}(z) + x_\alpha(\mathbf{r}, z) T_g(\mathbf{r}, z)}{1 + x_\alpha(\mathbf{r}, z)}$$

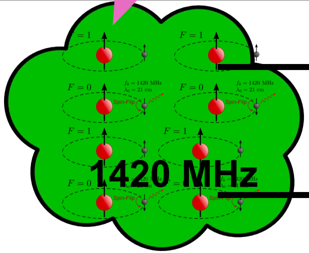
IGM Processes: Dominant during **Cosmic Dawn**

Lyα coupling $\Rightarrow$ $x_\alpha(\mathbf{r}, z)$

X-ray heating $\Rightarrow$ $T_g(\mathbf{r}, z)$

Redshifted 21-cm line





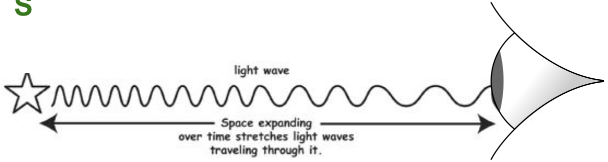
T_S

Carries the information about the IGM when it was emitted.

ν_o = 1420 MHz/(1+z)

Very feeble!

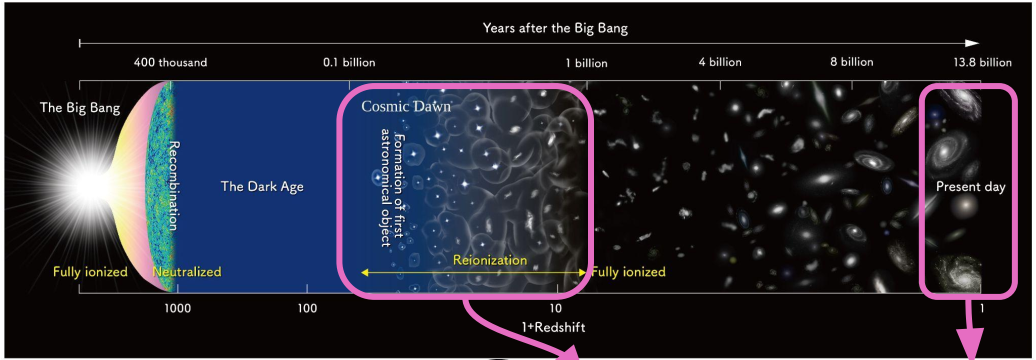
Source



Observer

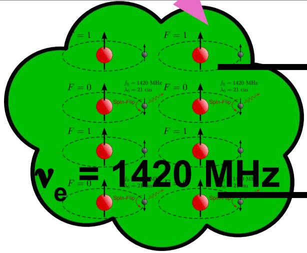
21-cm observable

Differential brightness temperature



Simplistic picture-I:

No Background

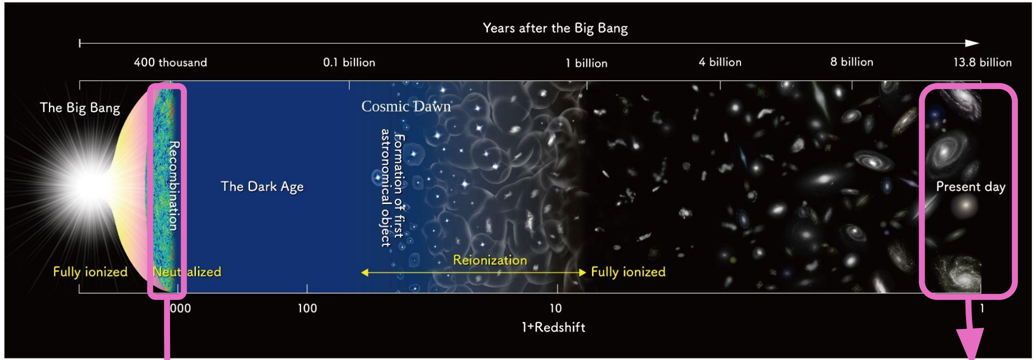


T_S

δT_b

$$\delta T_{\rm b} \propto T_{\rm S}$$

Differential brightness temperature



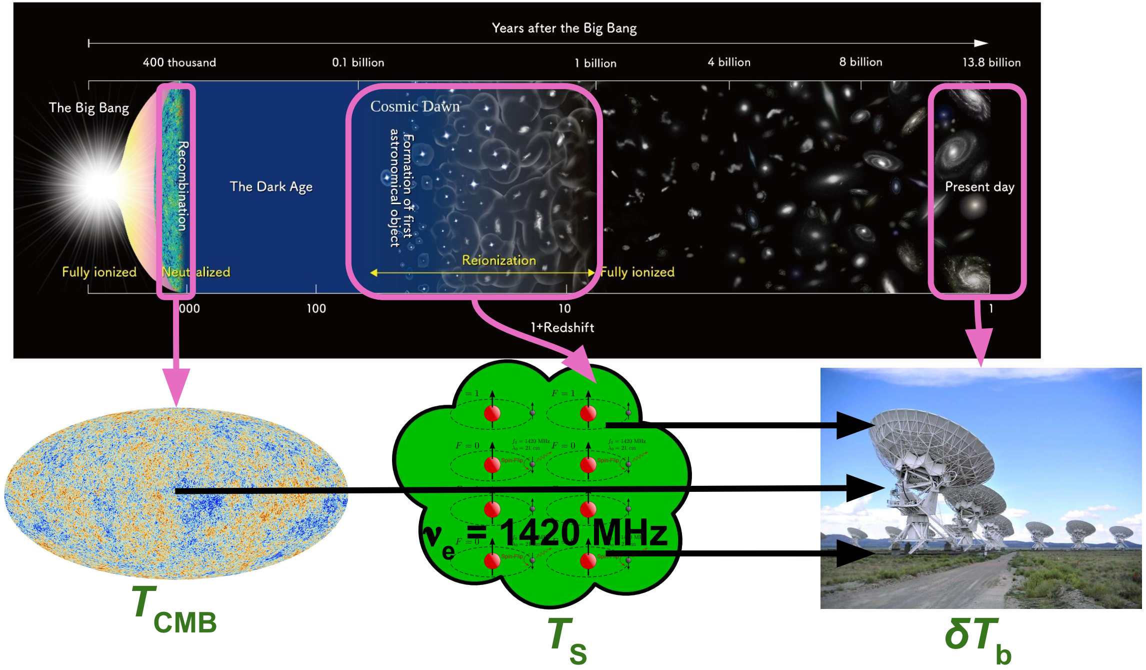
Simplistic picture-II:

T_{CMB} δT_b

$$\delta T_{\rm b} = T_{\rm CMB}$$

Differential brightness temperature

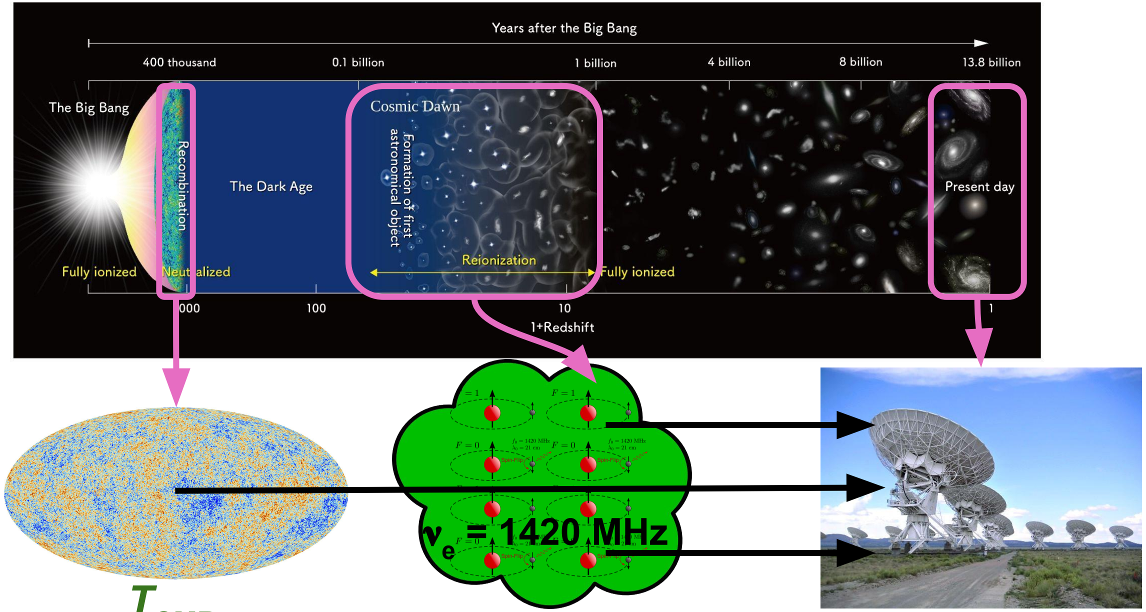
Realistic picture:



$$\delta T_{\rm b}(\mathbf{r}, z) = \frac{T_{\rm S} - T_{\rm CMB}}{1+z}(1 - e^{-\tau})$$

Differential brightness temperature

Realistic picture:



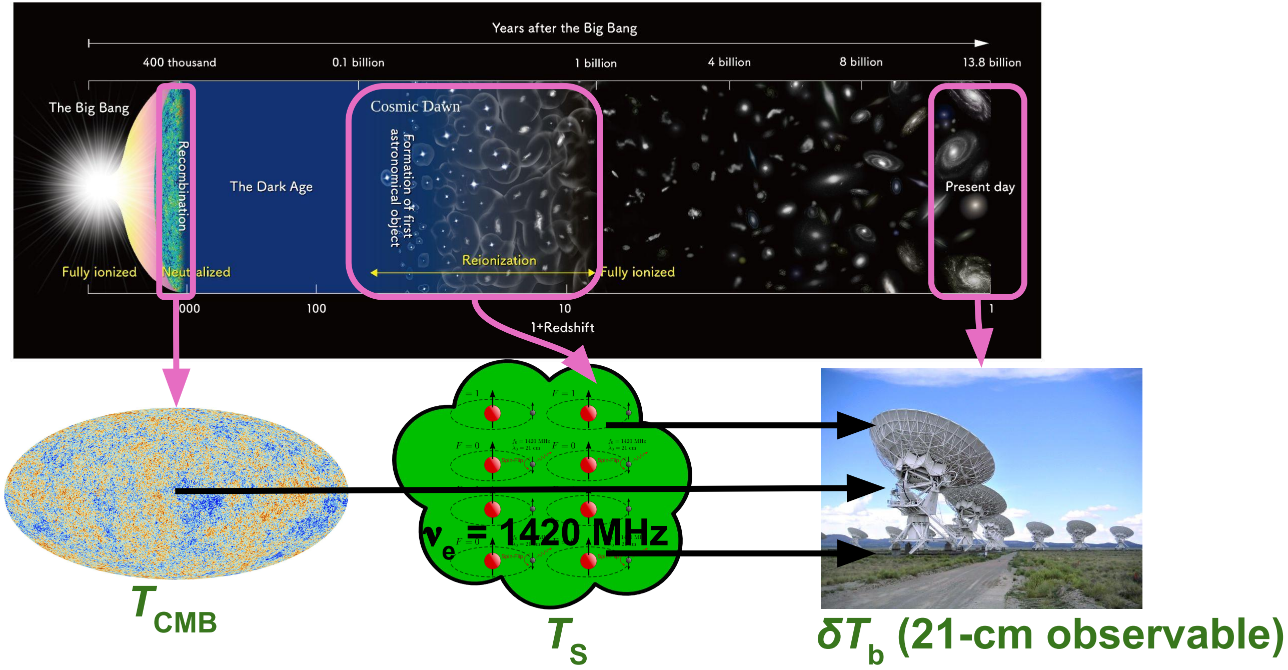
Final expression:

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

21-cm fluctuations!

Differential brightness temperature

Realistic picture:



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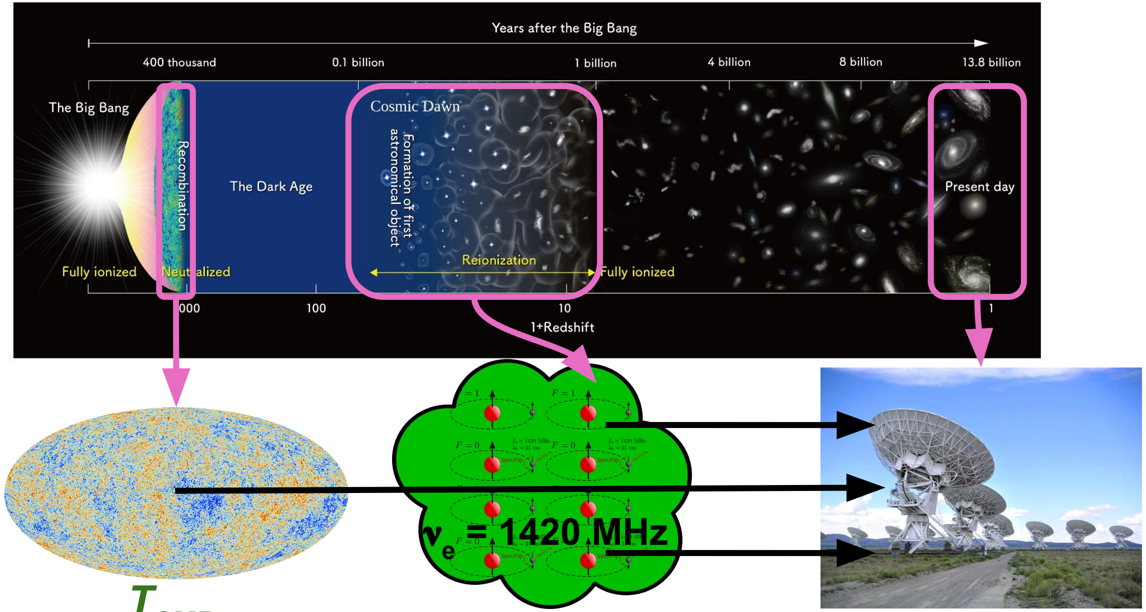
21-cm fluctuations!

Absorption ($\delta T_{\rm b} < 0$): $T_{\rm CMB} > T_{\rm S}$

Emission ($\delta T_{\rm b} > 0$): $T_{\rm CMB} < T_{\rm S}$

Differential brightness temperature

Realistic picture:



T_{CMB}

T_S

δT_b (21-cm observable)

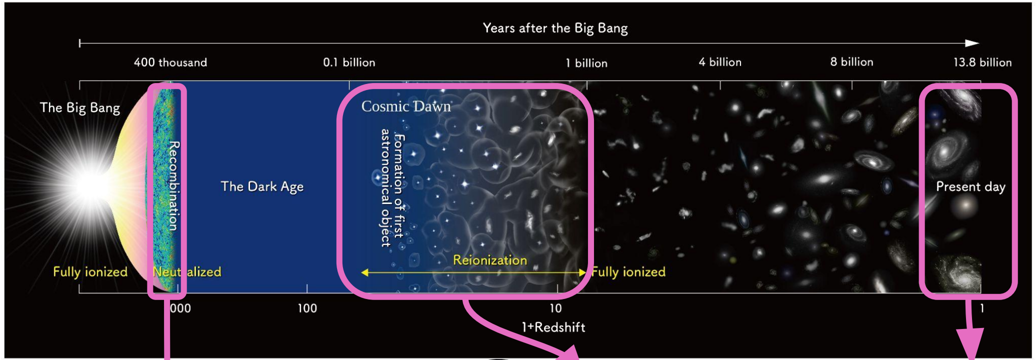
Final expression:

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

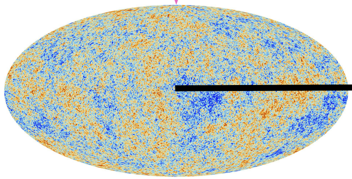
Astrophysics

21-cm fluctuations!

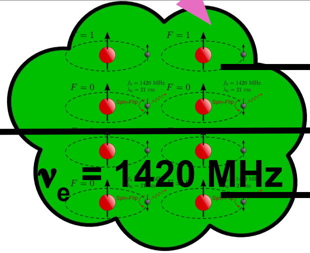
Differential brightness temperature



Realistic picture:



$T_{\rm CMB}$



$T_{\rm S}$

$\delta T_{\rm b}$ (21-cm observable)

Final expression:

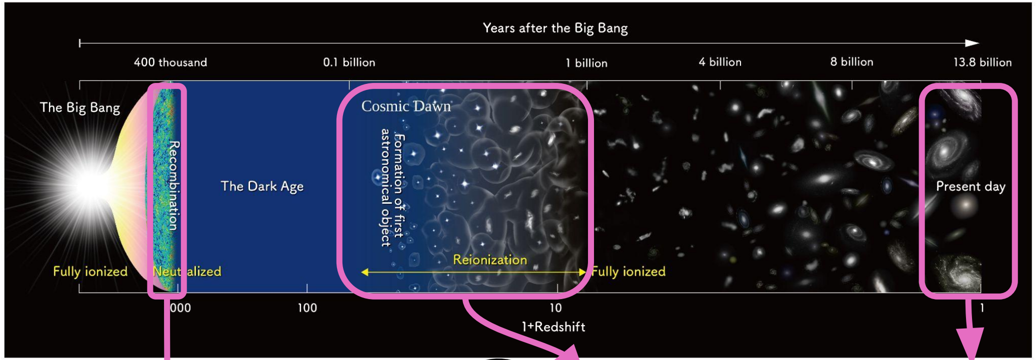
$$\delta T_{\rm b}(\mathbf{r}, z) = 27 x_{\rm HI}(\mathbf{r}, z)\left(1 - \frac{T_{\rm CMB}(z)}{T_{\rm S}(\mathbf{r}, z)}\right)(1+\delta_{\rm b}(\mathbf{r}, z))\left(\frac{\Omega_{\rm b} h^2}{0.023}\right)\left(\frac{0.15}{\Omega_{\rm m} h^2}\frac{1+z}{10}\right)^{1/2} \rm mK$$

21-cm fluctuations!

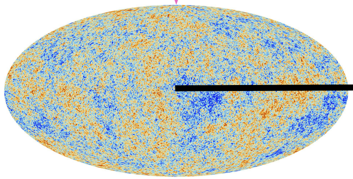
Astrophysics

During CD: Lyα coupling + X-ray heating

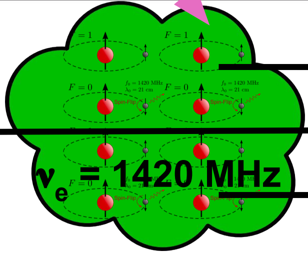
Differential brightness temperature



Realistic picture:



$T_{\rm CMB}$



$T_{\rm S}$

$\delta T_{\rm b}$ (21-cm observable)

Final expression: **During EoR:** Photo-ionization

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

21-cm fluctuations!

Astrophysics

During CD: Lyα coupling + X-ray heating

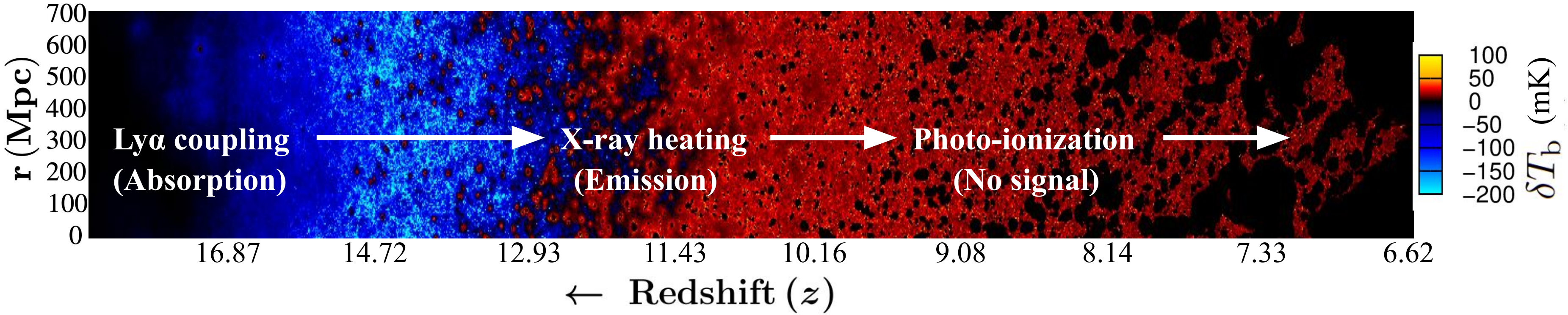
21-cm fluctuations depend on position and time

Differential brightness temperature

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

Astrophysics

21-cm fluctuations!



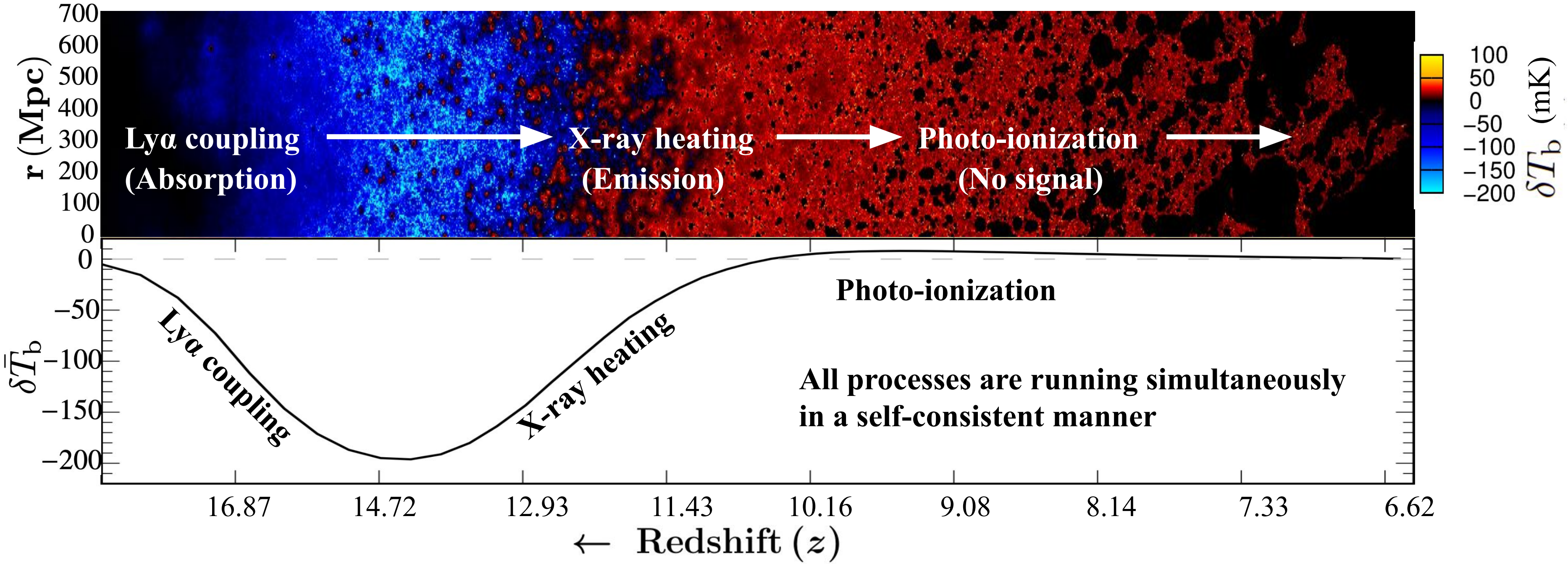
1. Depend on the locations of the sources in the IGM.
2. The radiations from these sources that lead to a number of astrophysical processes, also progress with time.

Differential brightness temperature

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

Astrophysics

21-cm fluctuations!

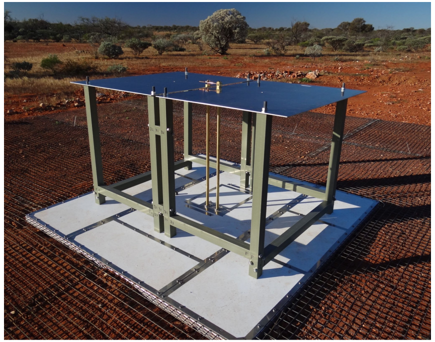


Two broad classes of the 21-cm observations

Detection of the global 21-cm signal (?):

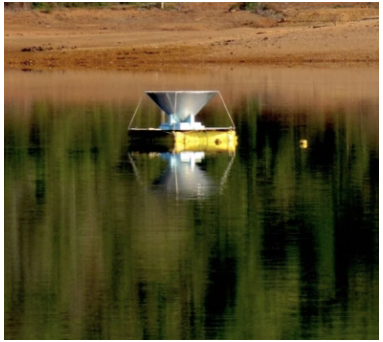
EDGES

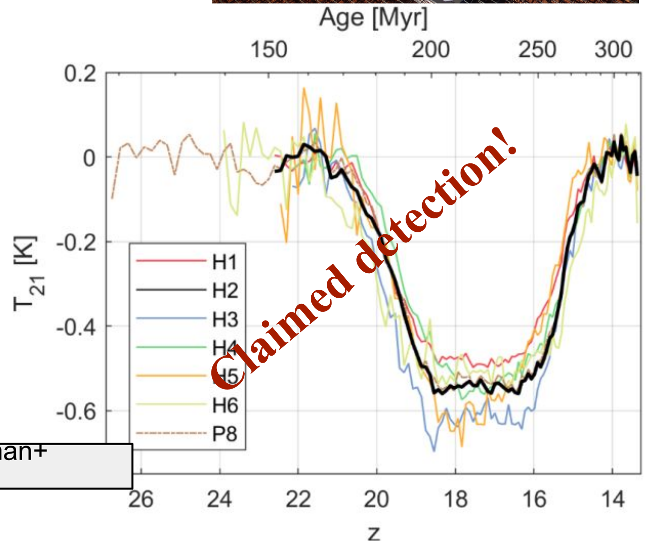
Western Australia



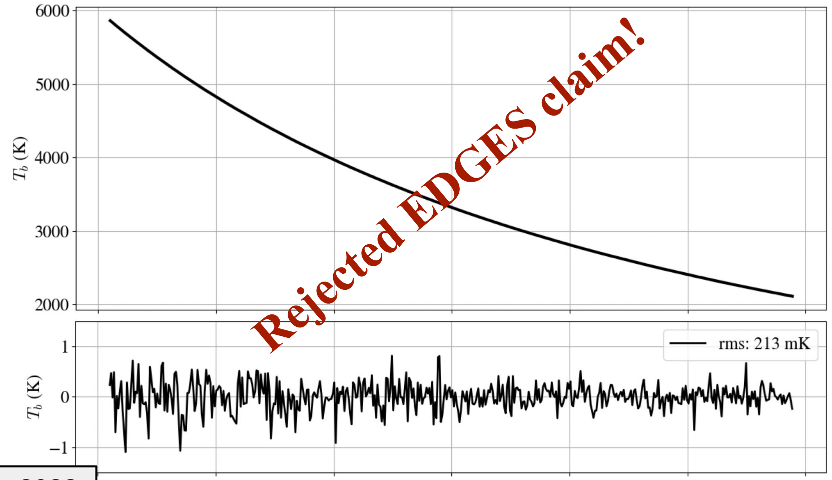
SARAS3

India





Bowman+ 2018



Singh+ 2022

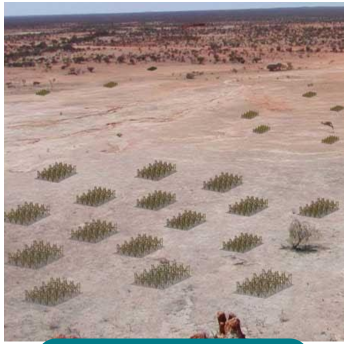
Detection of the fluctuating 21-cm signal (?):

GMRT

India

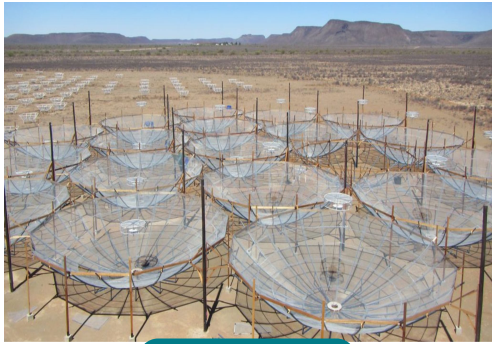
LOFAR

Netherland



MWA

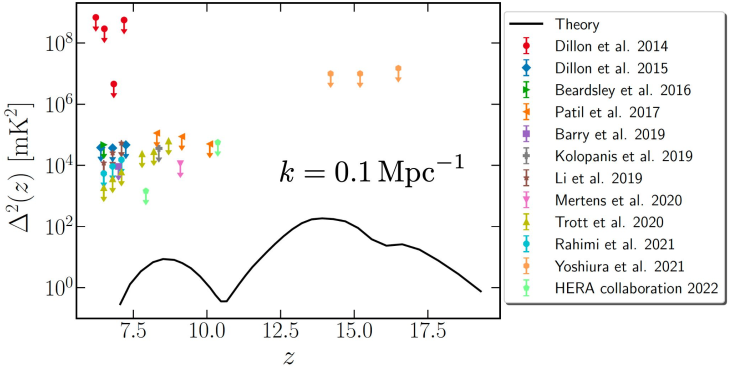
Western Australia



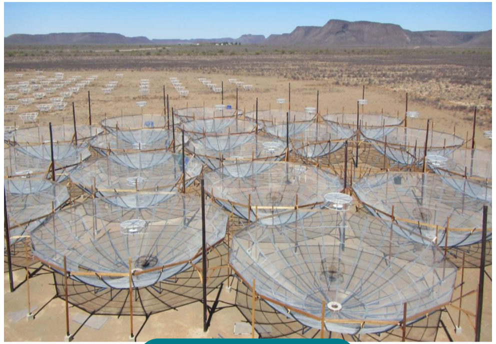
HERA

South Africa

Large-scale 21-cm power spectrum upper-limits



Detection of the fluctuating 21-cm signal (?):



Unable to make the CD-EoR 21-cm maps

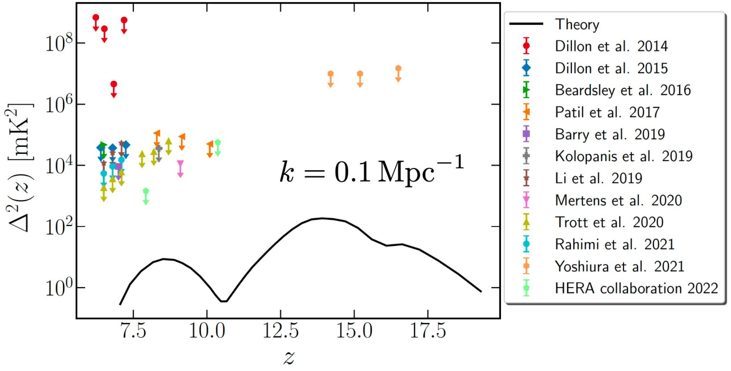
GMRT
India

LOFAR
Netherland

MWA
Western Australia

HERA
South Africa

Large-scale 21-cm power spectrum upper-limits

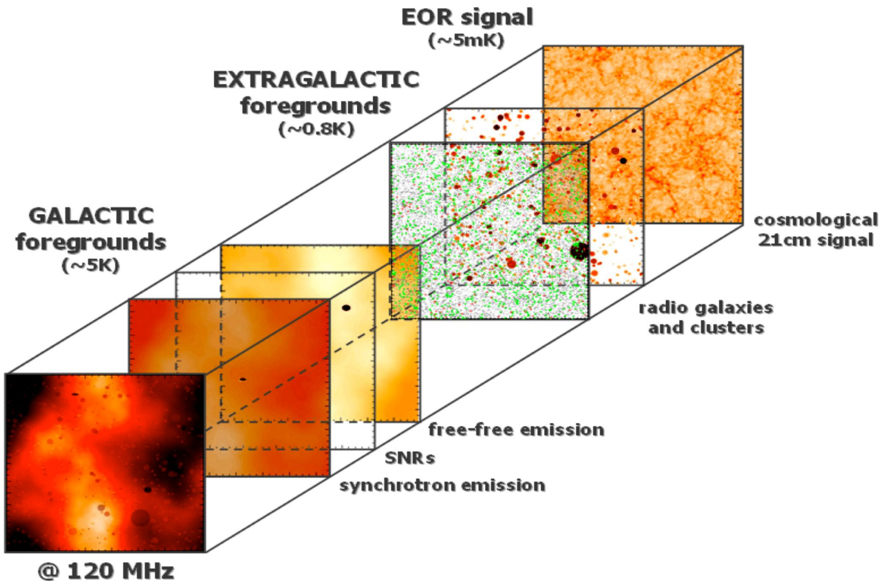


Challenges:

1. **The redshifted 21-cm signal is very feeble.**

2. **Observational obstacles- Contaminates the 21-cm signal**

Foregrounds: Major components –
i) Galactic Synchrotron Radiation
ii) Extra Galactic Point Sources
These are several orders of magnitude larger than the signal and are expected to be smooth in frequency therefore can be removed/avoided in principle.



Credit: Chapman+Jelic+ 2019

Challenges:

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Foregrounds: Major components –
i) Galactic Synchrotron Radiation
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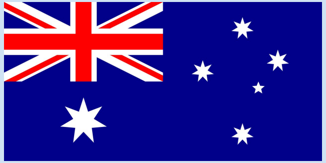
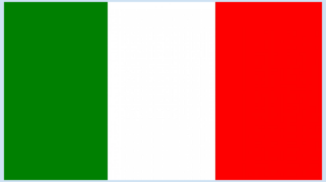
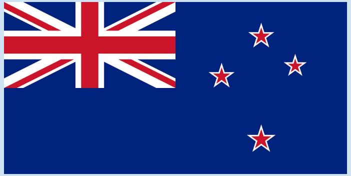
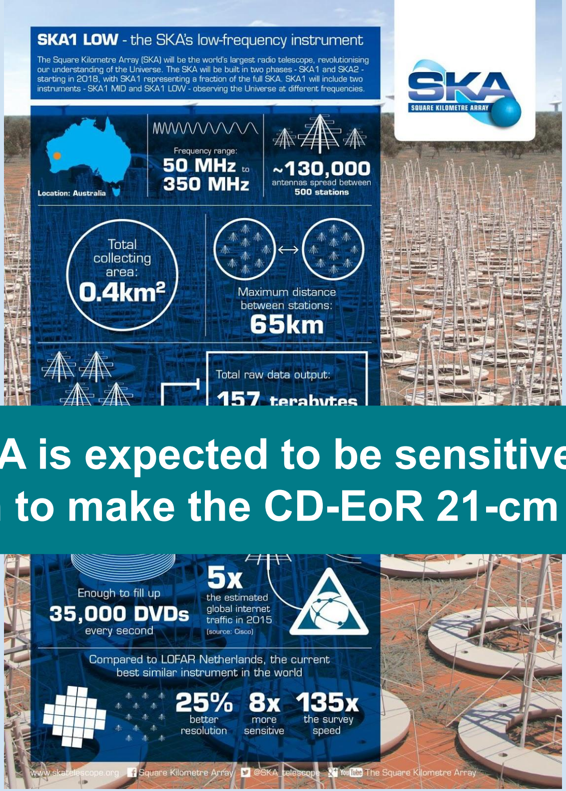
System Noise: Possibly Gaussian Random; can be suppressed below signal for long integration time.

RFI: Radio frequency interference produced by humans.

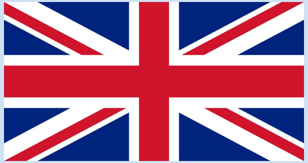
Ionospheric Effect: Turbulence in the ionosphere refracts low frequency radio waves and distorts the apparent magnitude and location of the signal. In principle, this can be corrected for large baselines and wide field of view. However, in practice it is an extremely difficult problem to solve.

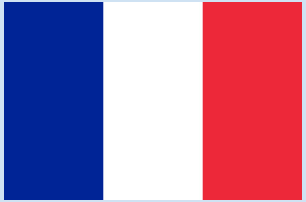





The SKA is expected to be sensitive enough to make the CD-EoR 21-cm maps.





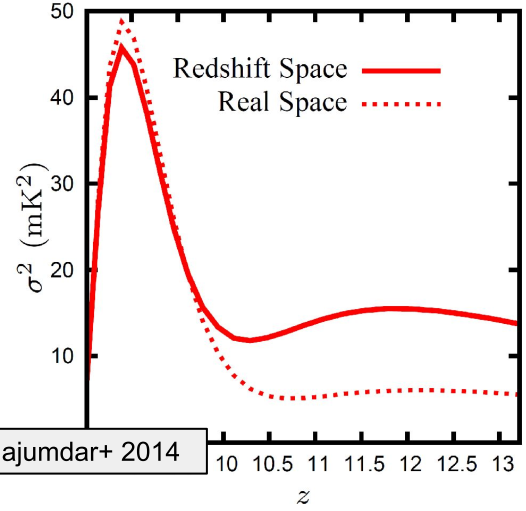
Until the **imaging** is possible, the first generations telescopes have been trying to detect the fluctuations in this signal using **Fourier statistics**

How to quantify and interpret the signal?

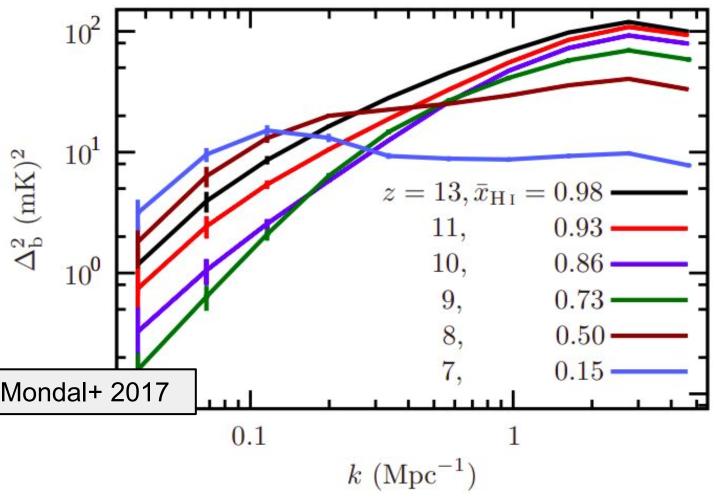
Variance

High SNR

Power Spectrum



Majumdar+ 2014



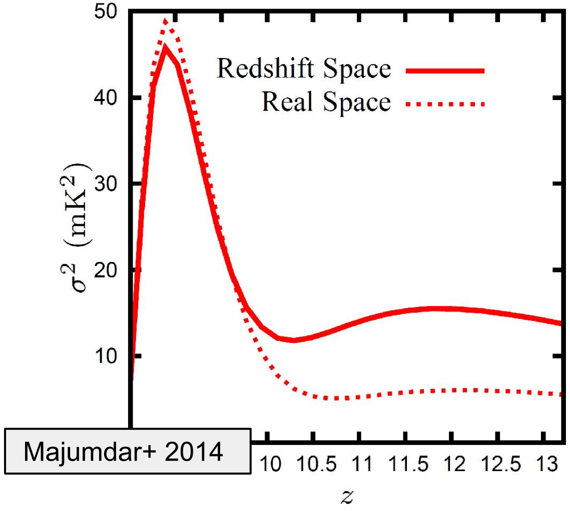
Mondal+ 2017

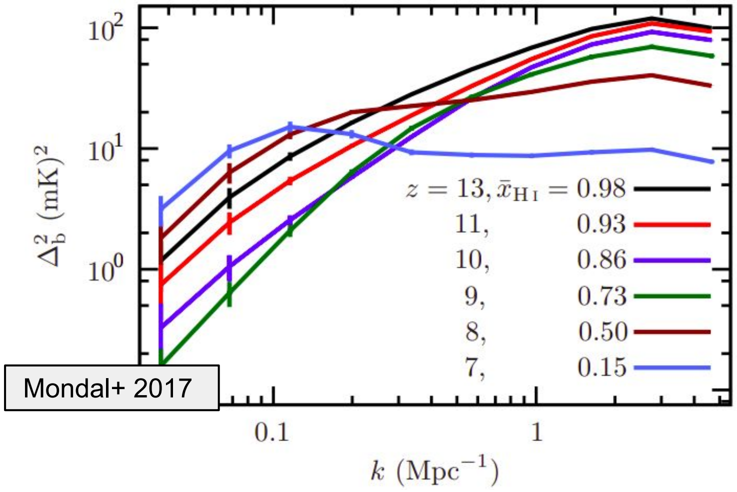
How to quantify and interpret the signal?

Variance

High SNR

Power Spectrum





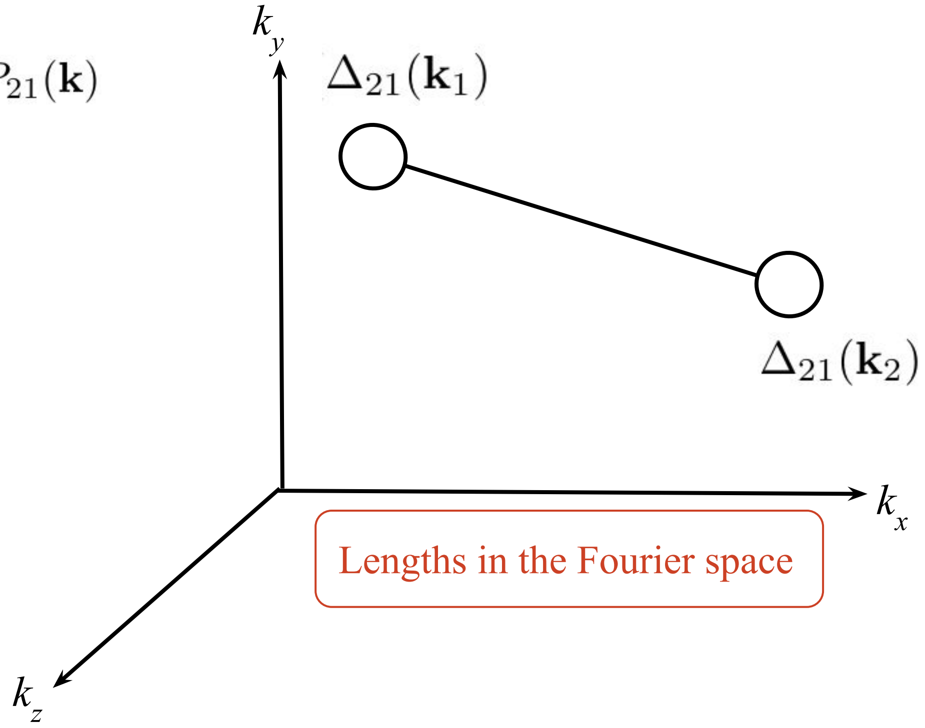
Amplitude of fluctuations at a single length scale

Amplitude of fluctuations at different length scales

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

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

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



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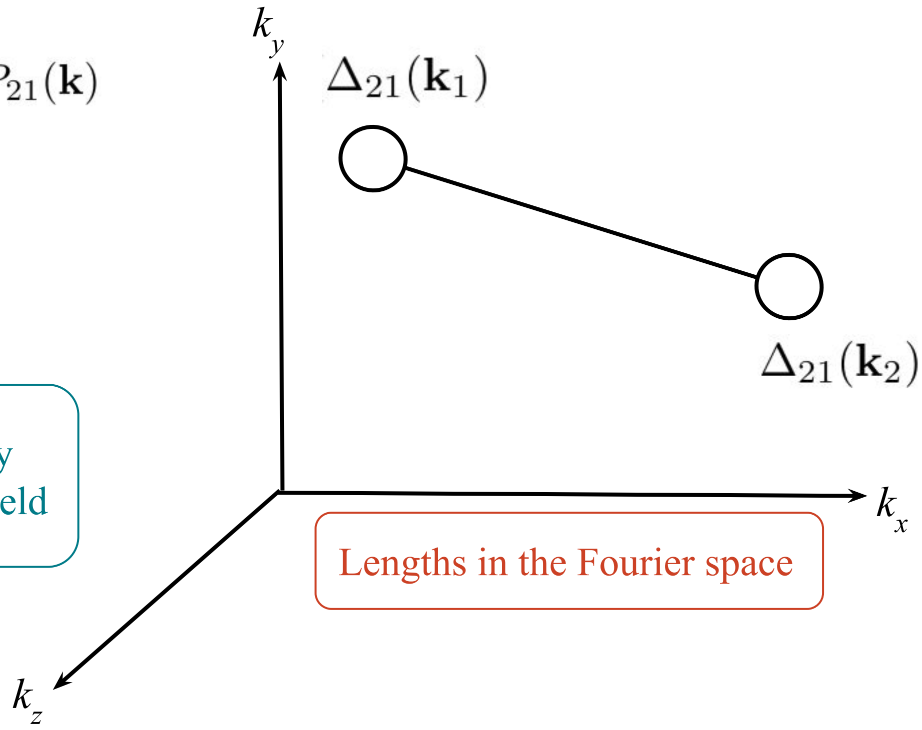
$$\Delta_{21}(\mathbf{k}) \overset{\text{FT}}{\longleftrightarrow} \delta T_{\rm b}(\mathbf{r})$$

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



Lengths in the Fourier space

The spatial and temporal fluctuations of the CD-EoR 21-cm signal are 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

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Non-Gaussianity:

- **Intrinsic**

The radiating sources are distributed at non-random (biased) locations.

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Astrophysics

21-cm fluctuations!

Highly non-Gaussian

Non-Gaussianity:

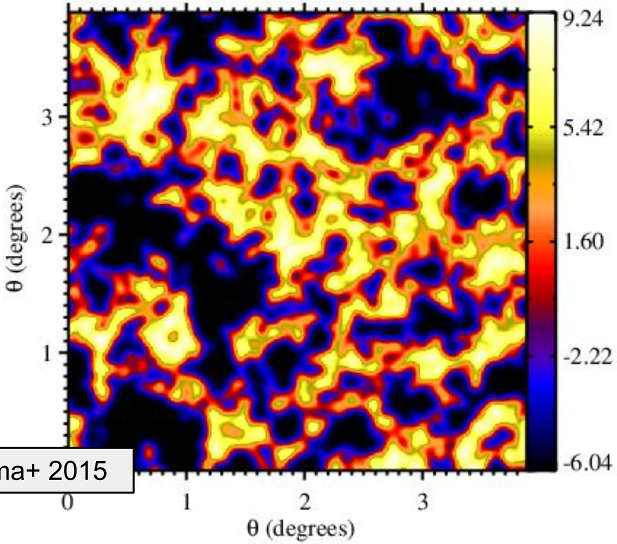
- **Intrinsic**
- **Time-evolving**

The radiating sources are distributed at non-random (biased) locations.

The physical processes in the IGM, controlled by these sources, also progress with time.

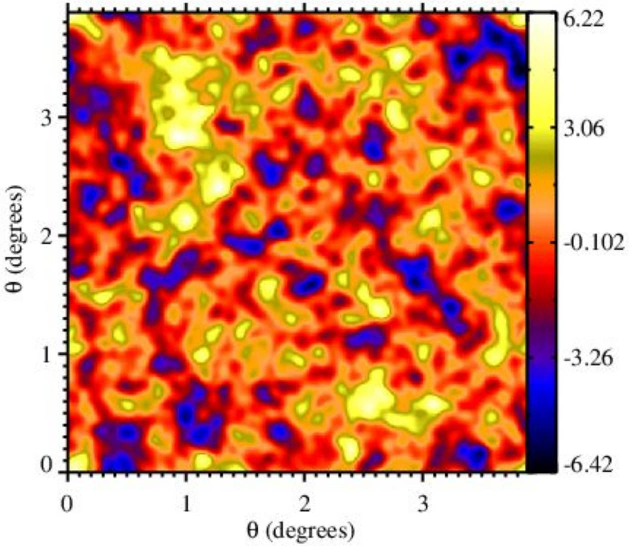
The non-Gaussianity:

Non-Gaussian 21-cm map



Mellema+ 2015

Gaussian fluctuations



Same power spectrum but different images

The Bispectrum:

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

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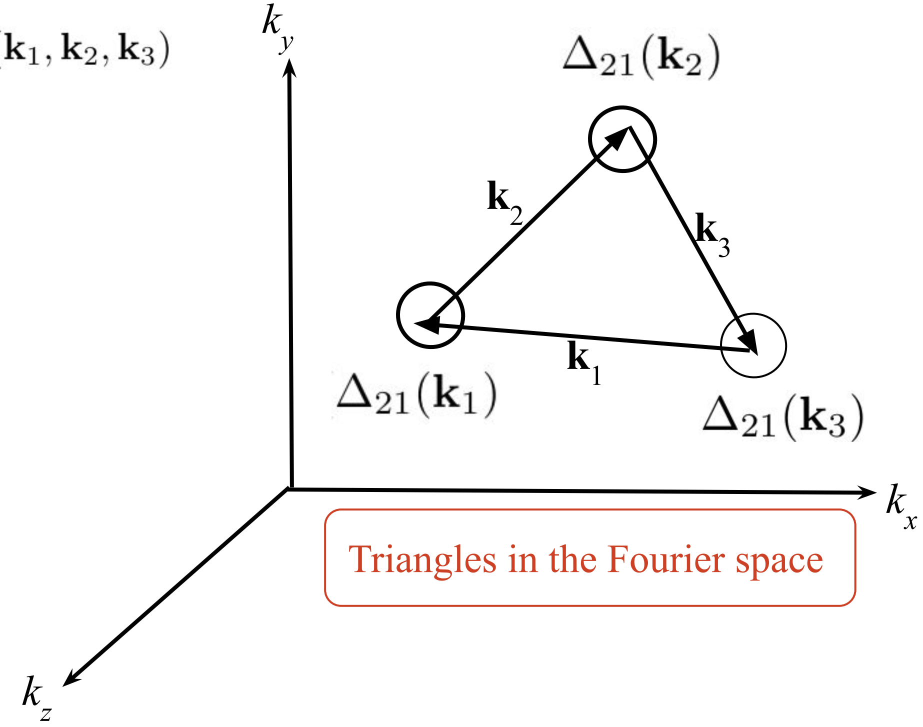

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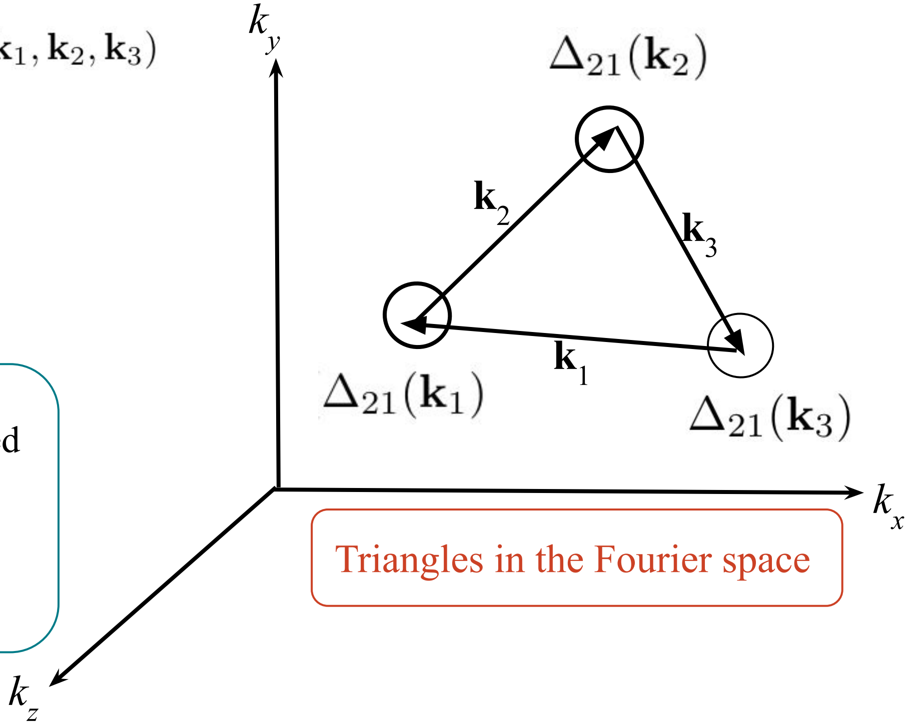
$$\Delta_{21}(\mathbf{k}) \xleftrightarrow{\text{FT}} \delta T_{\mathrm{b}}(\mathbf{r})$$

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

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



Triangles in the Fourier space

SKA-like telescopes are expected to detect the CD-EoR 21-cm bispectrum

Mondal+**Kamran** et al.2021 ; Tiwari+**Kamran** et al. 2022; Watkinson+ 2022

Motivation to study the bispectrum

- Promising probe of the fundamental issues related to the CD-EoR.
- Contains way more information as compared to the power spectrum.

$P_{21} \rightarrow$ Always +ve.

$B_{21} \rightarrow$ +ve or -ve $\Rightarrow$ Additional feature.

- Can potentially capture the non-Gaussianity.

Previous works

1. **Bharadwaj+ 2005**

2. **Majumdar+ 2018**

   (also Yoshiura+ 2015,
   Hutter+ 2019,
   Watkinson+ 2019)

Previous works

1. **Bharadwaj+ 2005** — Based on the **analytical models** of the signal

2. **Majumdar+ 2018** — Based on the **simulations** of the signal

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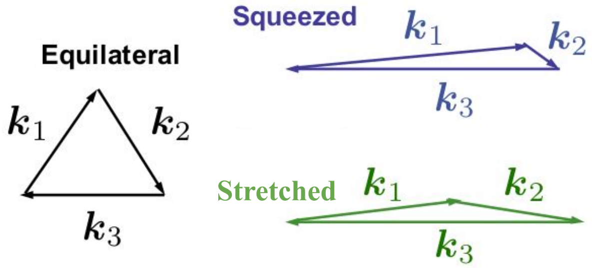
In all previous works:

- **no LoS anisotropy** was considered
- only **a few specific shape of k-triangles** were considered

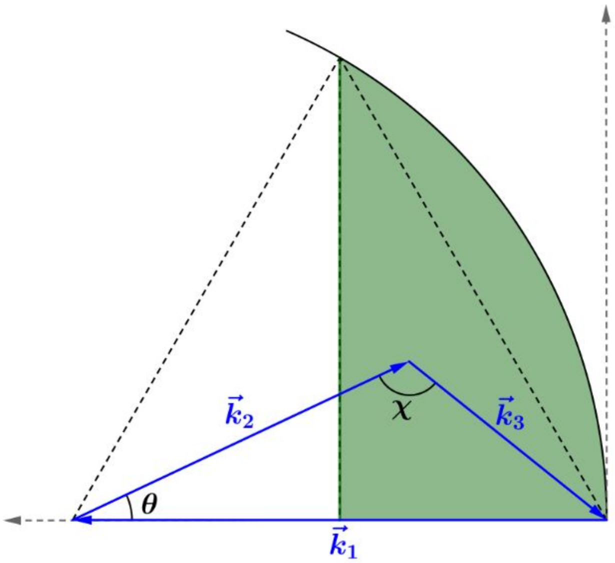


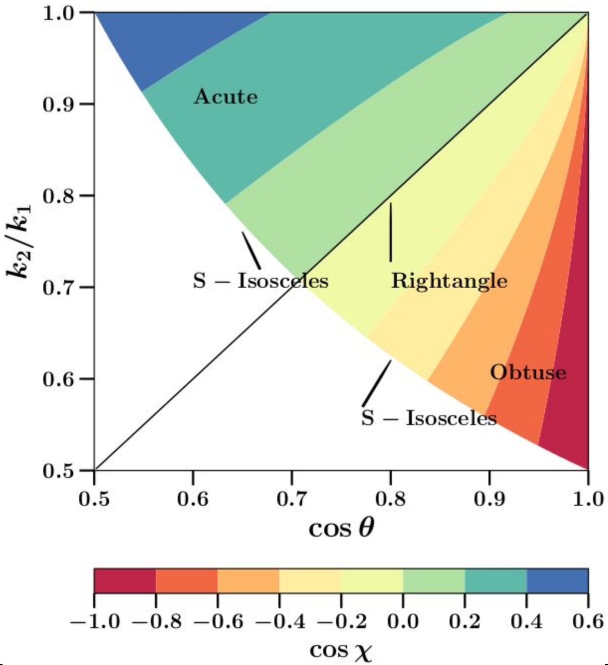
Our contributions

Unique triangles in the Fourier space:

In **Kamran**+ 2021a; Majumdar,**Kamran**+ 2020, for the first time in the literature:

Developed a **comprehensive and correct interpretation** of the CD-EoR 21-cm signal using **bispectra for triangles of all possible unique shapes**.





Bharadwaj+ 2020

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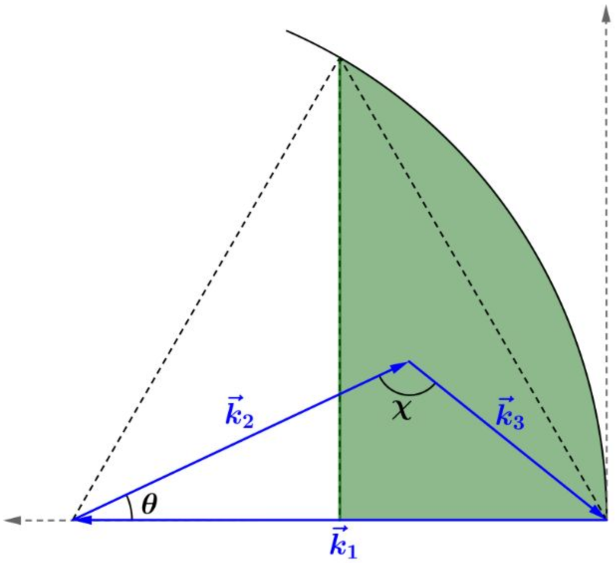
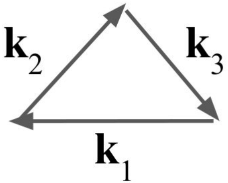
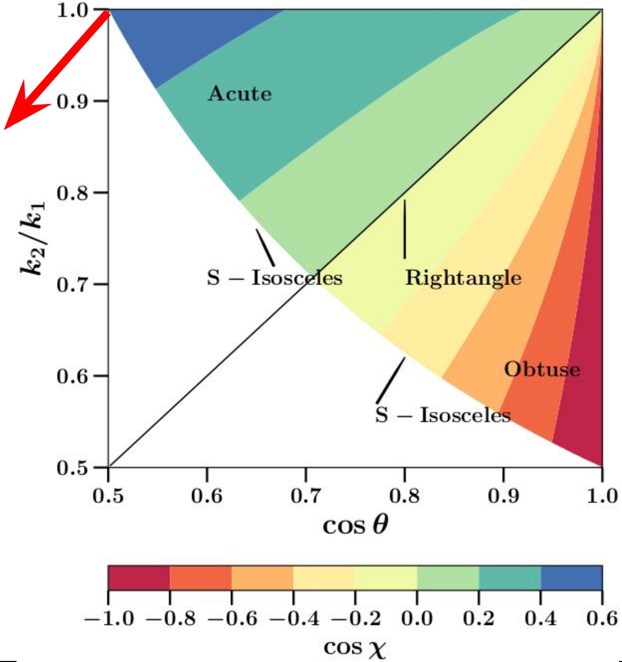




$k_1 = k_2 = k_3$

Equilateral



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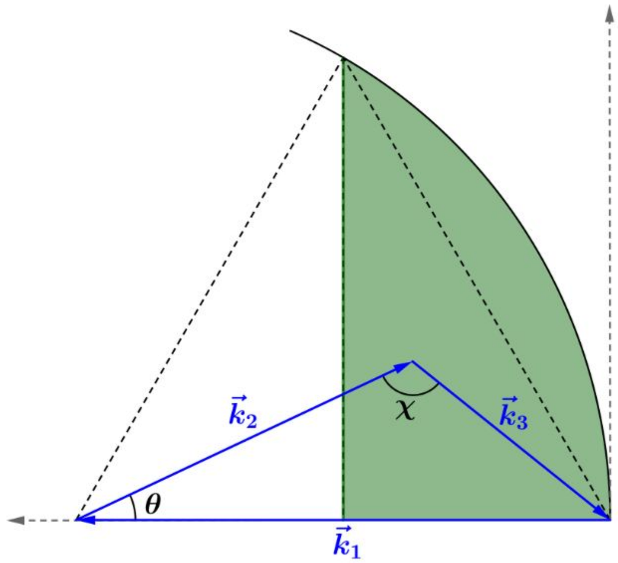

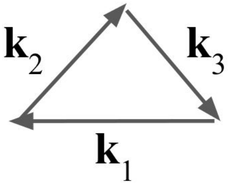

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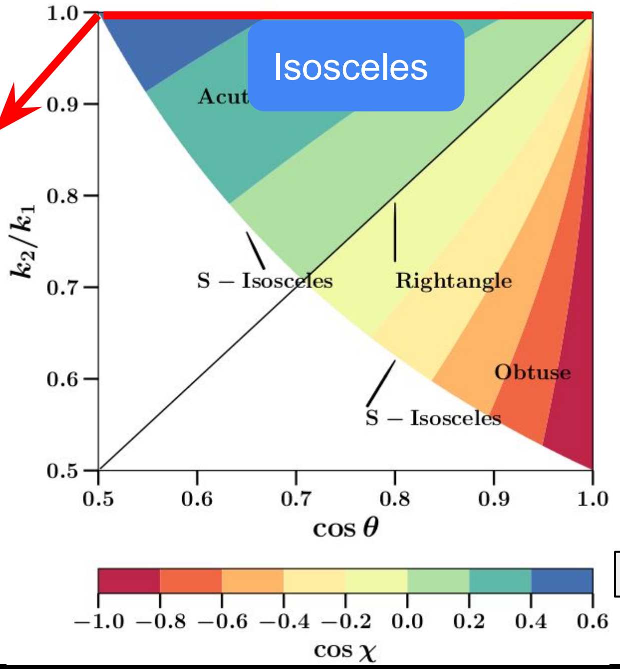

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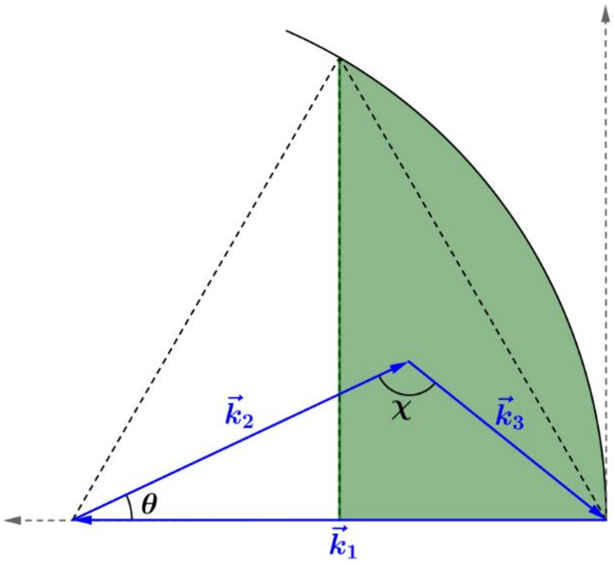
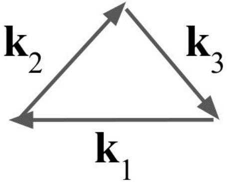
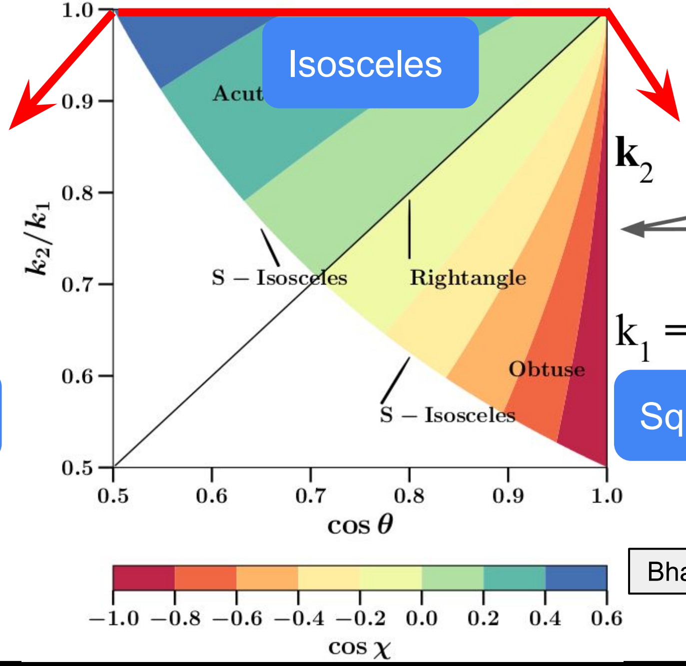
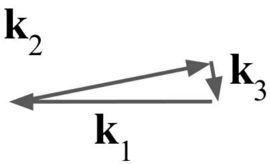




$k_1 = k_2 = k_3$

Equilateral





$k_1 = k_2$, $k_3 \rightarrow 0$

Squeezed

Bharadwaj+ 2020

Simulations

➢ **Dark matter N-body simulation** → To generate dark matter distributions and DM halos.

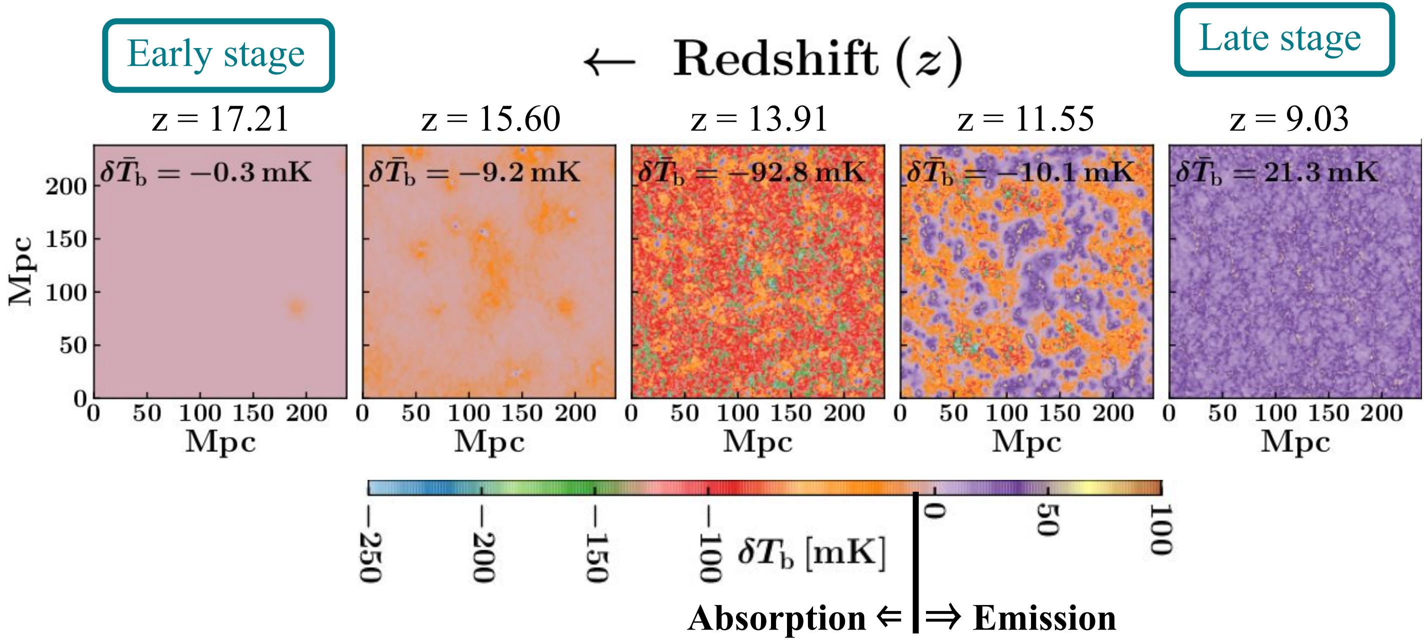
J. Harnois-Déraps+ 2013; Mondal+ 2015

↓

➢ **Sem-num or radiative transfer simulations** → To generate CD-EoR 21-cm maps.

Majumdar+ 2014; Mondal+ 2017; Ghara+ 2015a, 2018

Simulations



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

Bispectrum estimation

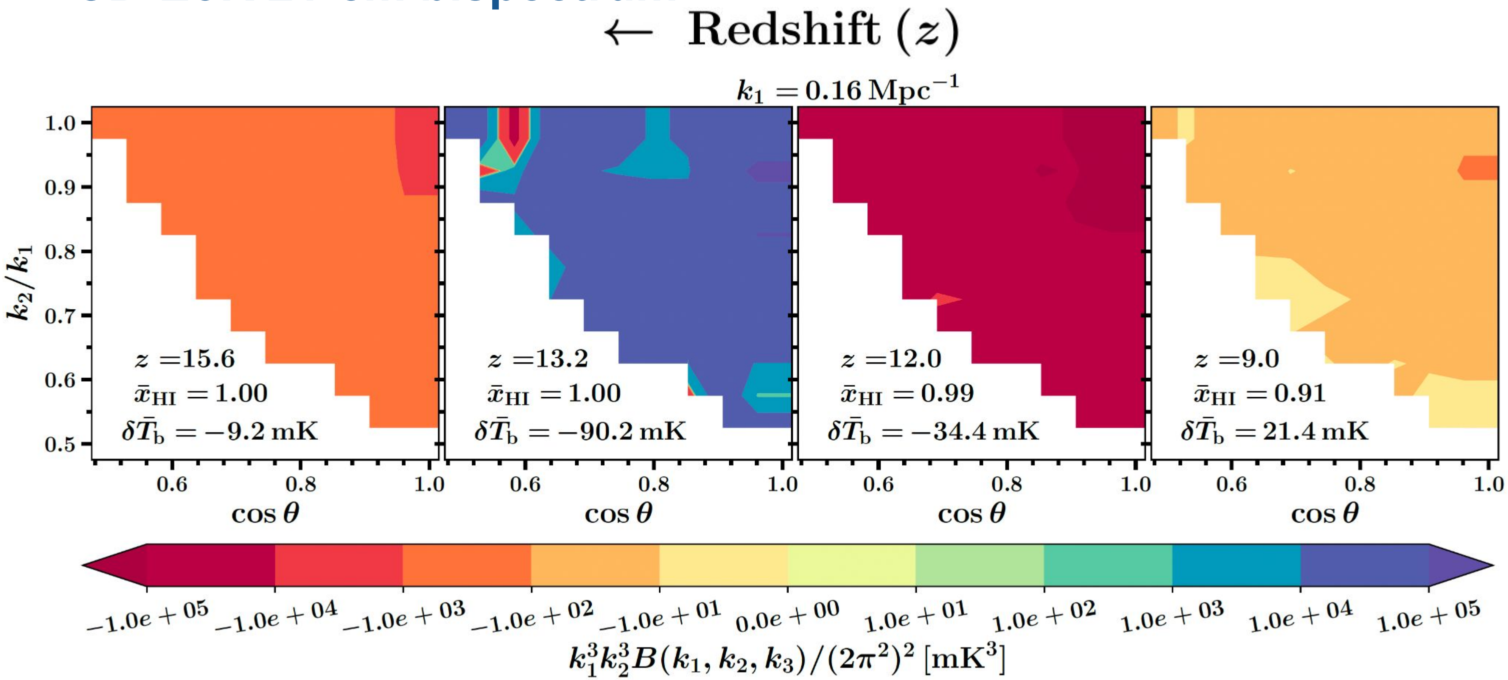
Bispectrum estimator:

$$\hat{B}_i(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3) = \frac{1}{N_{\rm tri} V} \sum_{[\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3=0]\in i} \Delta_{21}(\mathbf{k}_1)\Delta_{21}(\mathbf{k}_2)\Delta_{21}(\mathbf{k}_3)$$

- $\Delta_{21}(\mathbf{k})$ ⟷ (FT) $\delta T_{\rm b}(\mathbf{r})$
- Ntri – > Number of triangles in i^{th} triangle configuration bin while satisfying condition $\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3 = 0$
- V – > Observational volume.

Results

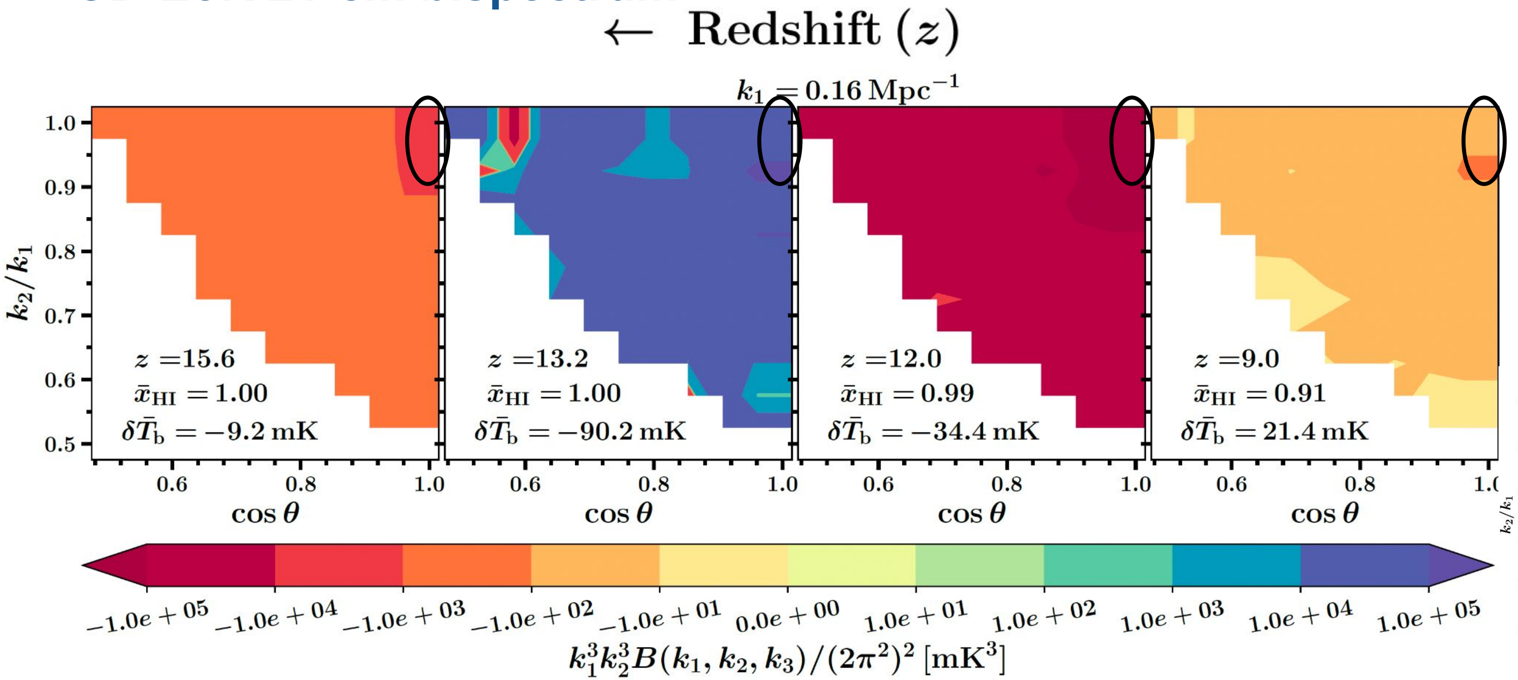
CD-EoR 21-cm bispectrum



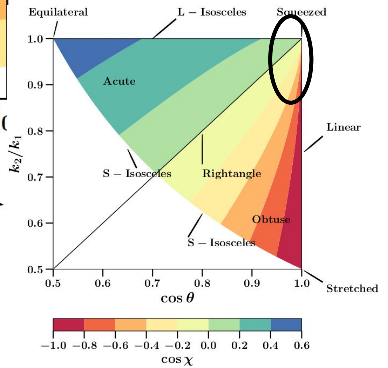
Non-zero bispectra ⇒ high non-Gaussianity

Kamran+2021a, Majumdar+**Kamran** et al. 2020

CD-EoR 21-cm bispectrum



Squeezed



squeezed limit triangle bispectra attain **maximum magnitude**

Largest detection probability by the future **SKA observations**

Kamran+2021a, Majumdar+**Kamran** et al. 2020

Detectability of the EoR 21-cm bispectrum

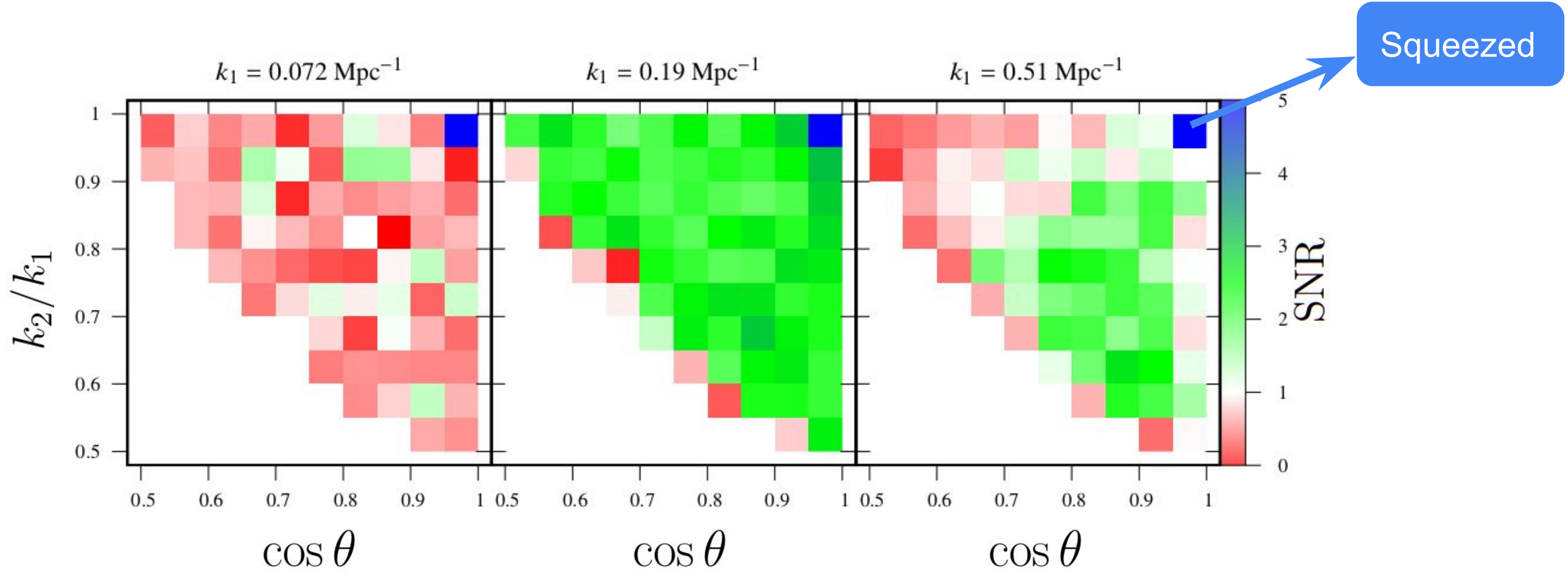


Figure – The SNR for detecting the SABS for all unique triangle configurations for $t_{\rm obs}$ = 1024 hrs for three different triangle sizes.

Squeezed limit triangles are able to achieve a more than 5σ significance over a wide range of scales, $k_1 \lesssim 0.8$ Mpc^{-1} ⇒ will be the most measurable and hence useful.

Mondal+**Kamran** et al. 2021

Squeezed-limit bispectrum as a probe of IGM physics during CD
Different CD scenarios

Processes \ Scenarios	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

Kamran+2021b (under review in PRL)

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↓

Simplistic scenarios

↓

Only a single physical process dominates the 21-cm fluctuations

Kamran+2021b (under review in PRL)

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Simplistic scenarios (Model-a_0, Model-a, Model-b) → Only a single physical process dominates the 21-cm fluctuations

Realistic scenario (Model-c) → All three physical processes dictate the 21-cm fluctuations self-consistently

Kamran+2021b (under review in PRL)

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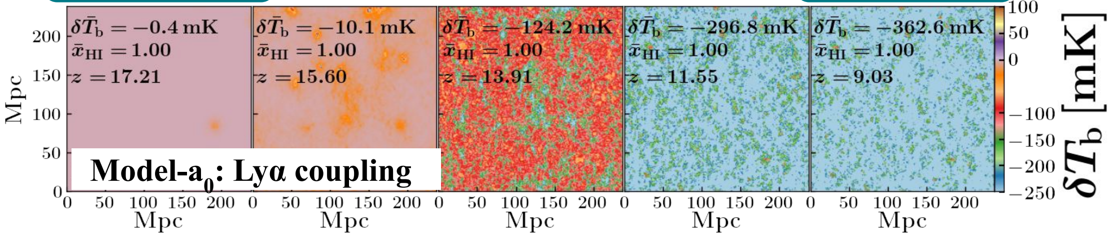
Realistic scenario (Model-c) → All three physical processes dictate the 21-cm fluctuations self-consistently

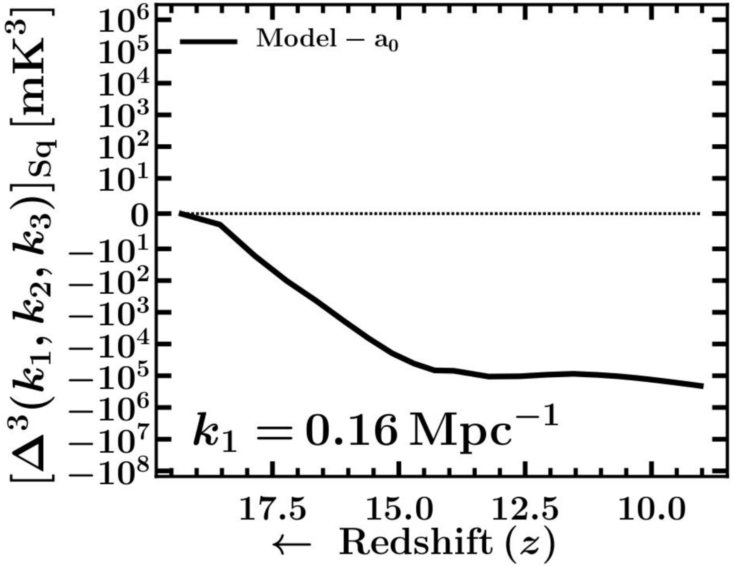
Importance of first three scenarios: Used to identify the unique signature of each IGM processes on the 21-cm bispectrum ⇒ Helps in explaining the bispectrum from Model-c, the most realistic scenario.

Squeezed-limit bispectrum as a probe of IGM physics during CD

Early stage ← Redshift (z) Late stage



Squeezed-limit bispectrum

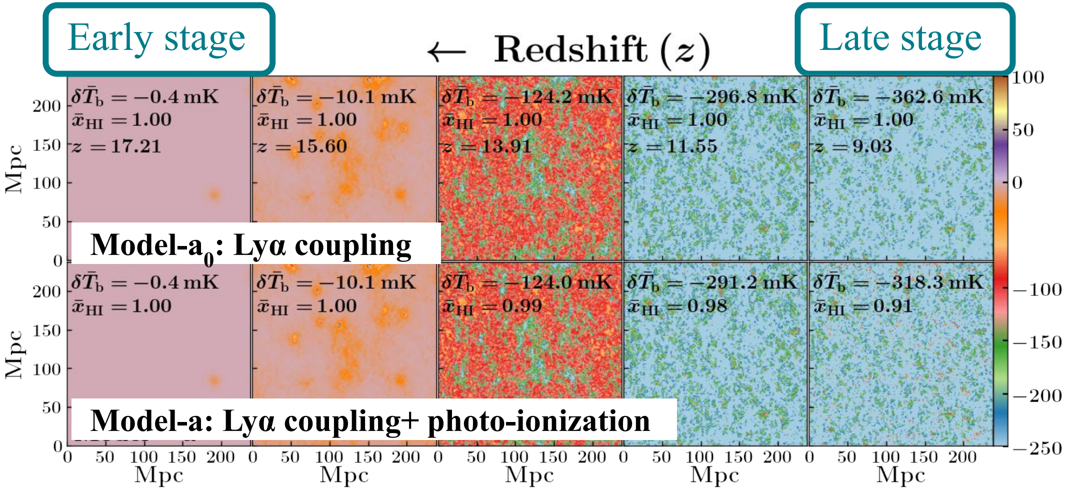


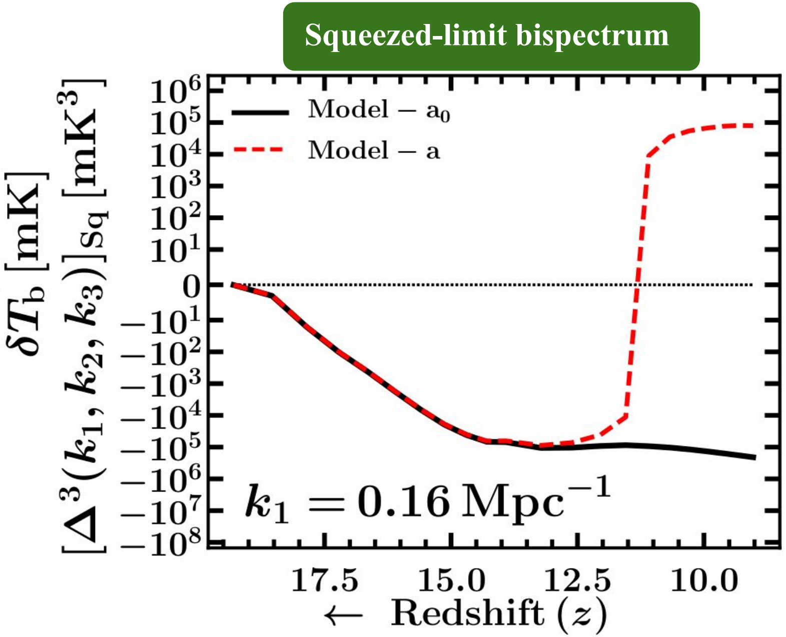
Magnitude: Monotonically increasing

Sign: Negative during entirety of CD

Kamran+2021b (under review in PRL)

Squeezed-limit bispectrum as a probe of IGM physics during CD

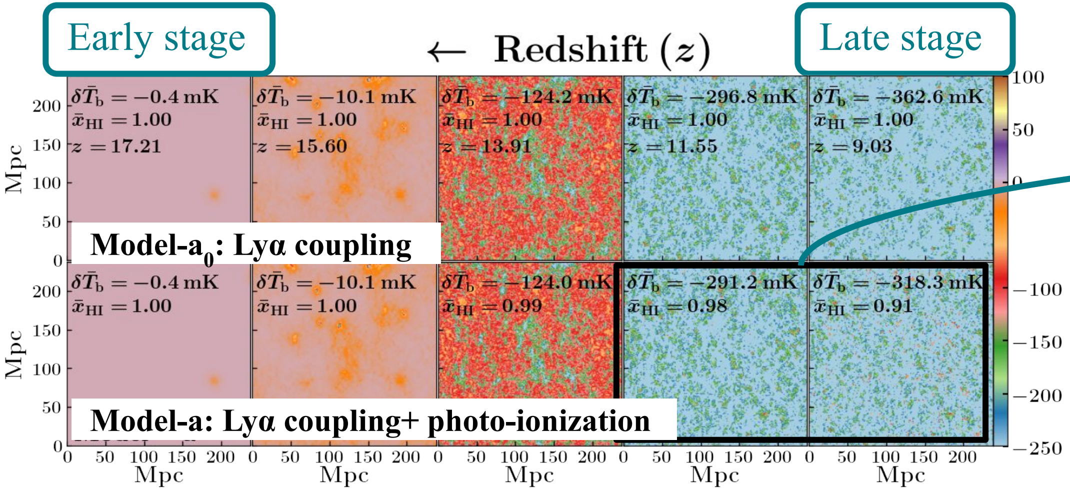


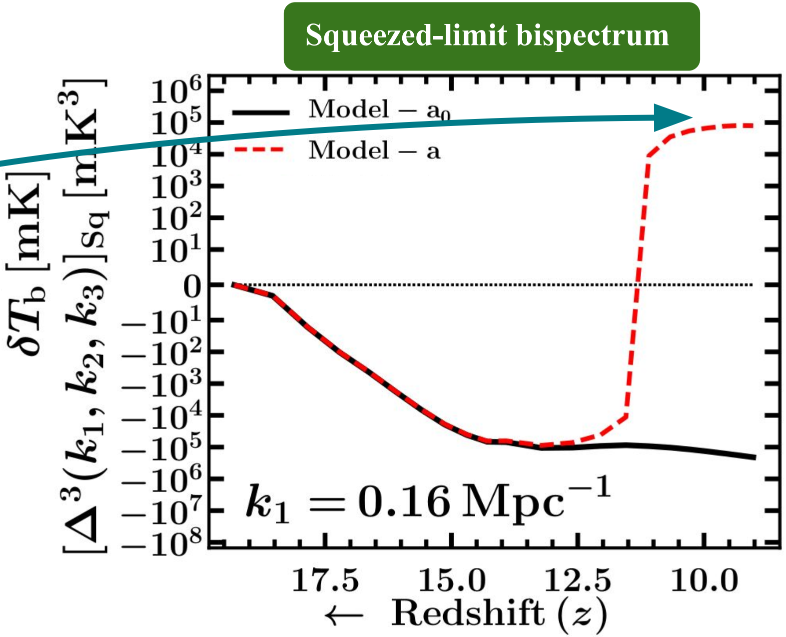


Bispectrum for Model-a agrees well with Model-a_0 until z ~ 13

Kamran+2021b (under review in PRL)

Squeezed-limit bispectrum as a probe of IGM physics during CD





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

At z < 13, sign reversal.

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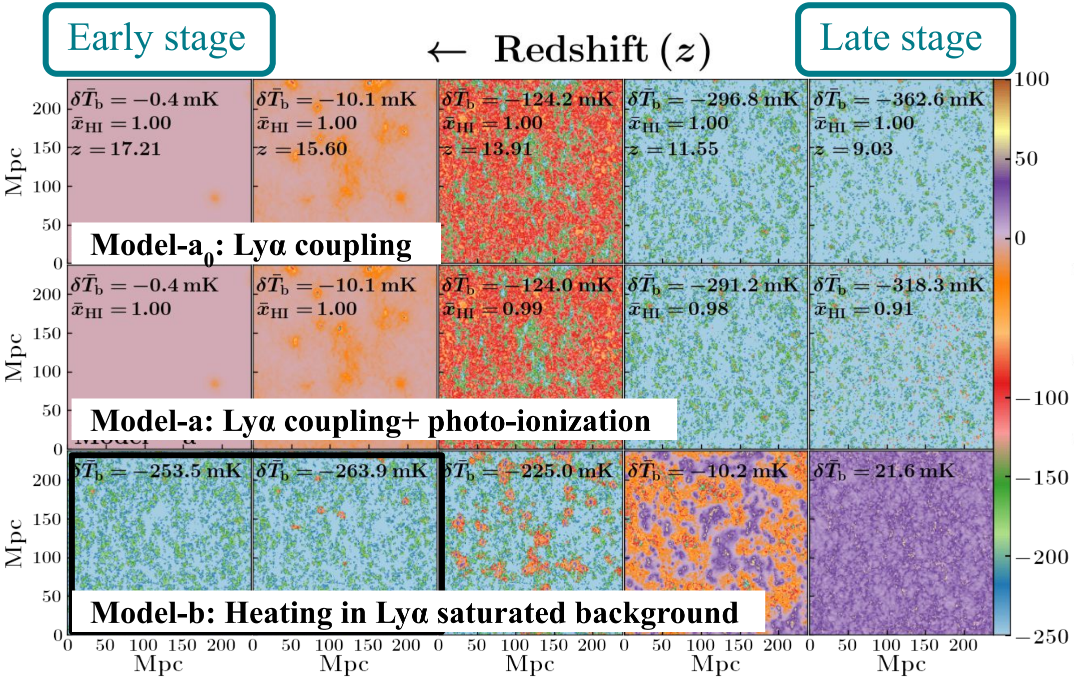

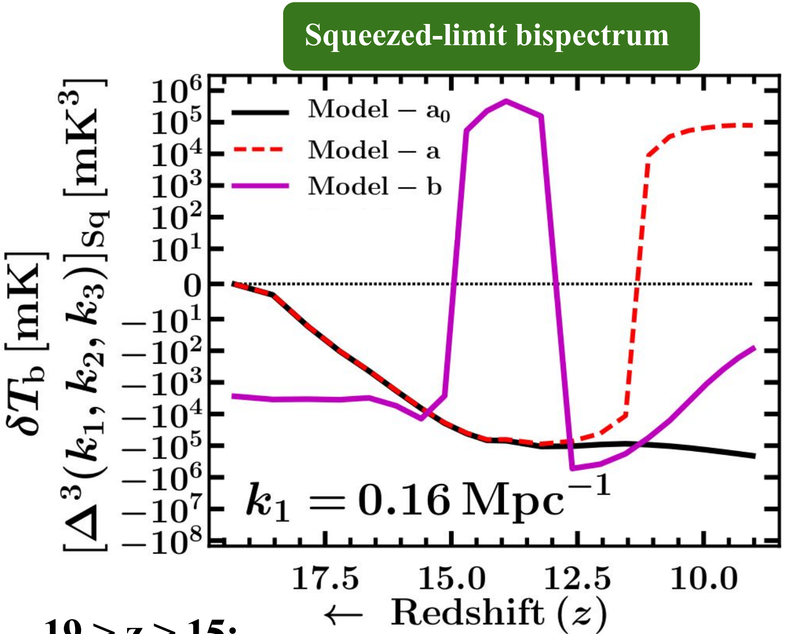

19 > z > 15:

Large magnitude due to already saturated Lyα background.

Sign negative as signal is in absorption

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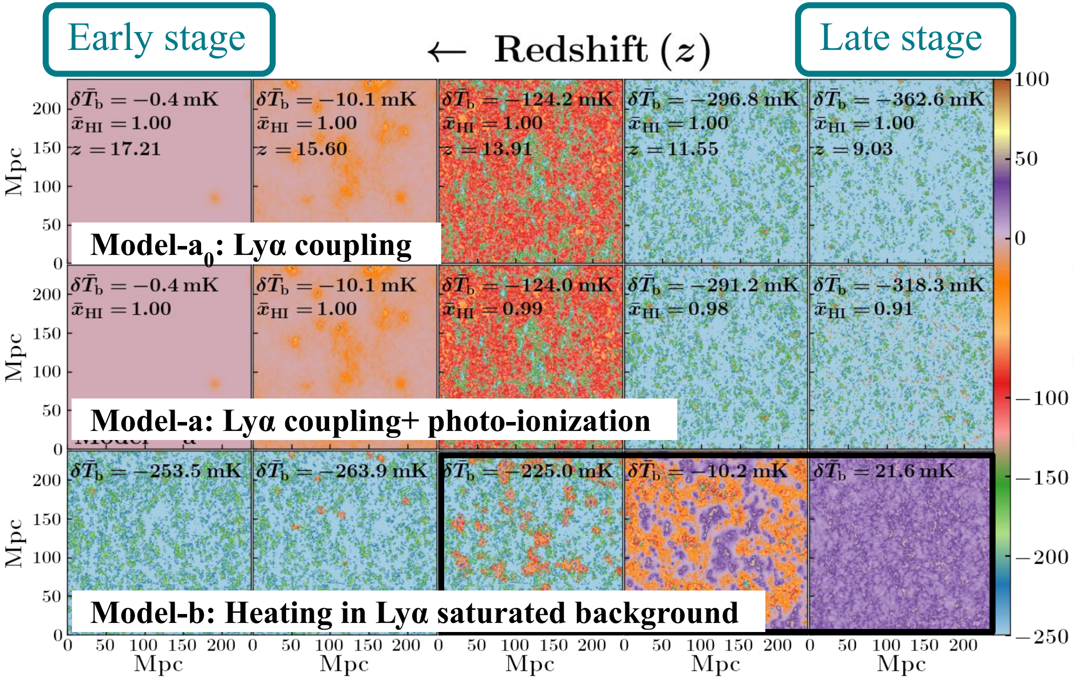
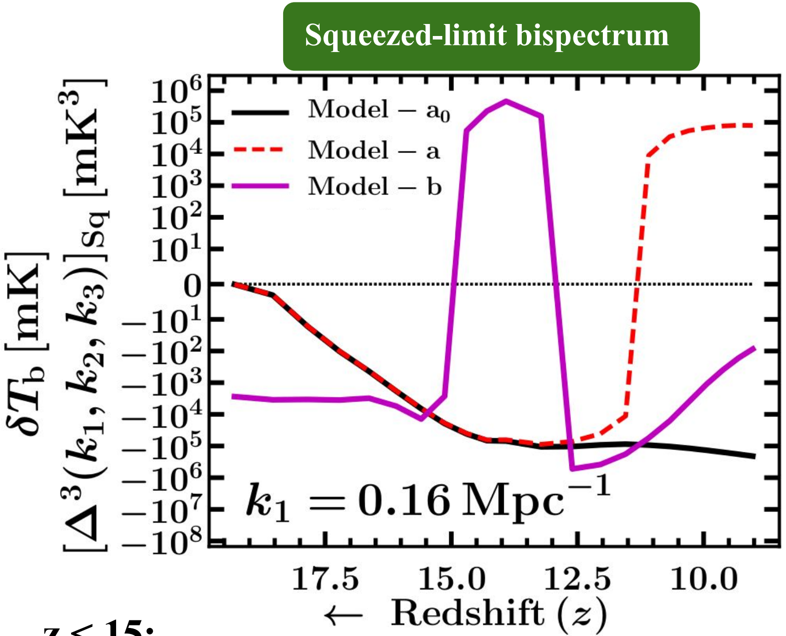


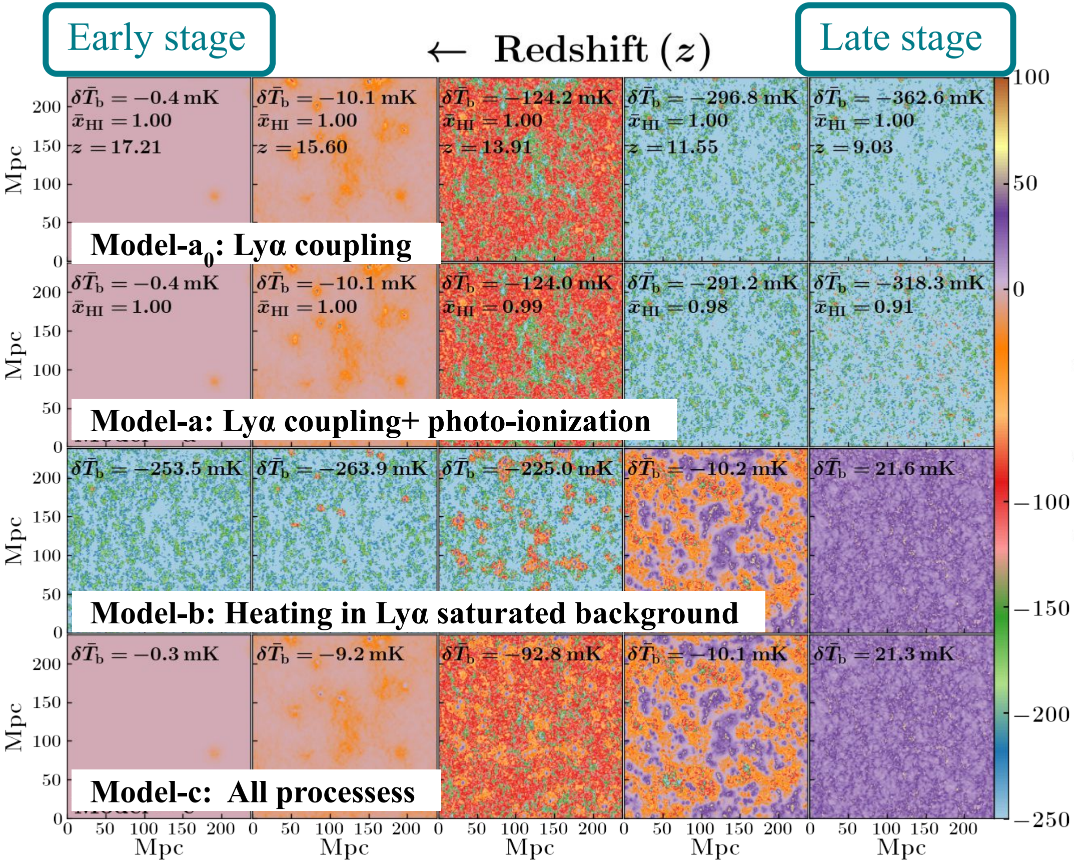


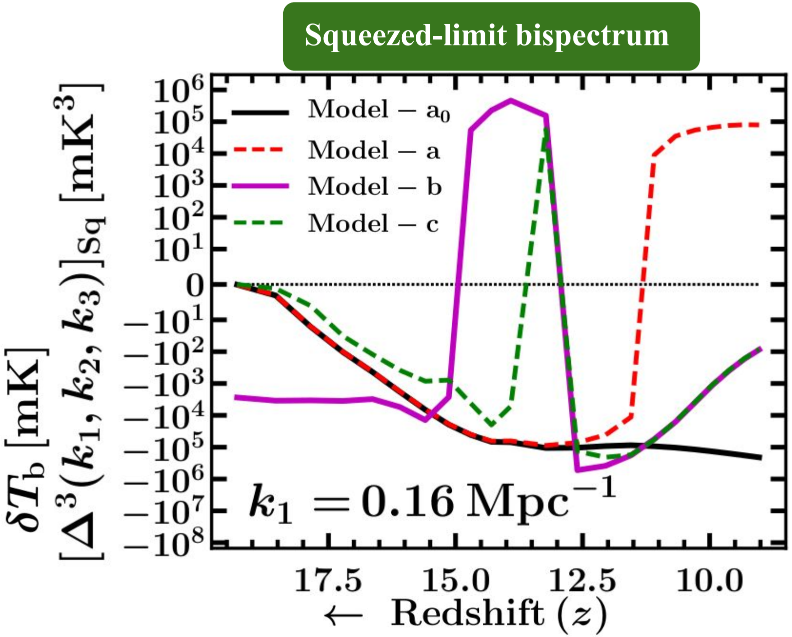
z < 15:

Double sign change due to heating

Kamran+2021b (under review in PRL)

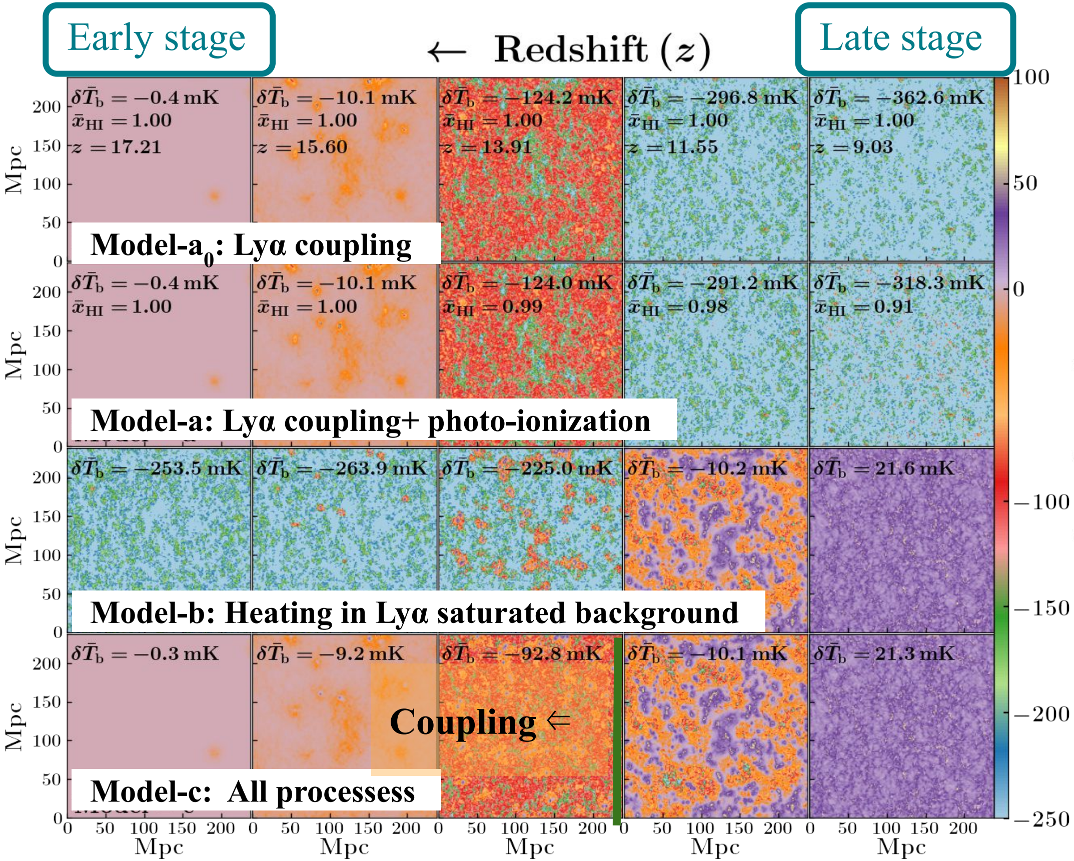
Squeezed-limit bispectrum as a probe of IGM physics during CD

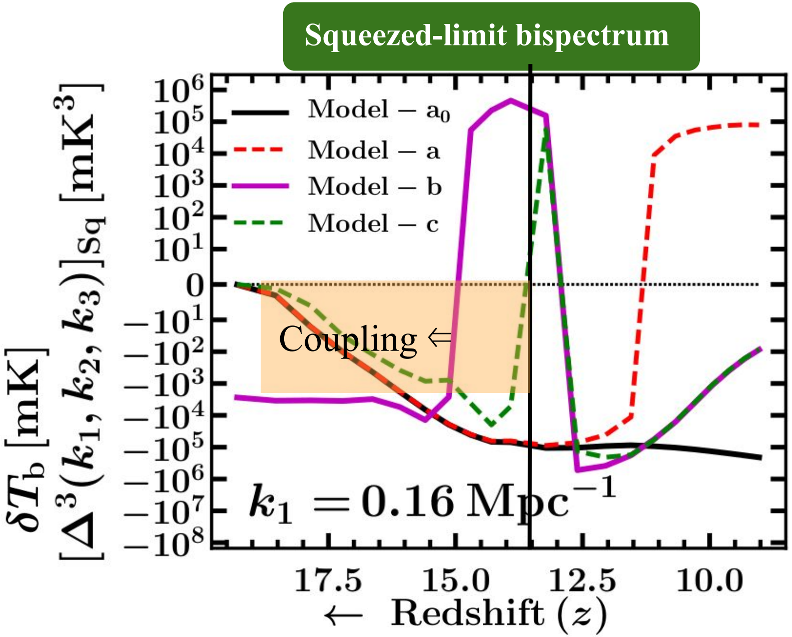




Kamran+2021b (under review in PRL)

Squeezed-limit bispectrum as a probe of IGM physics during CD

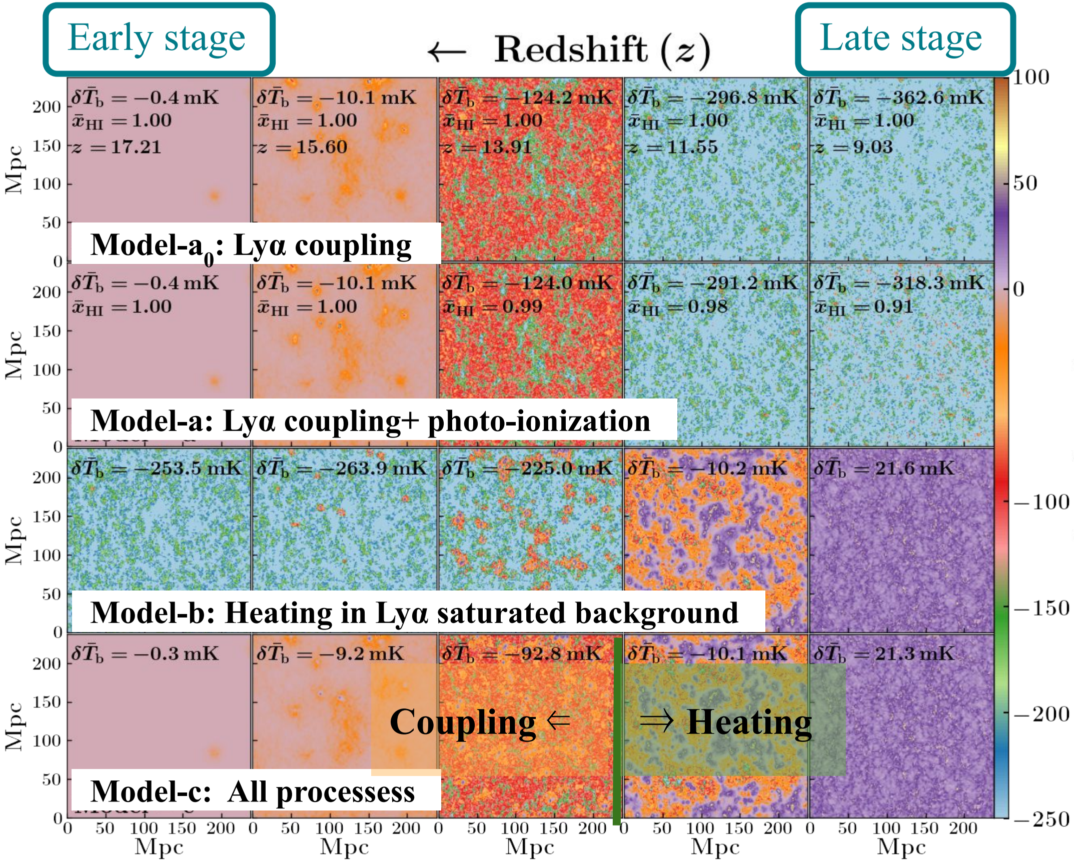


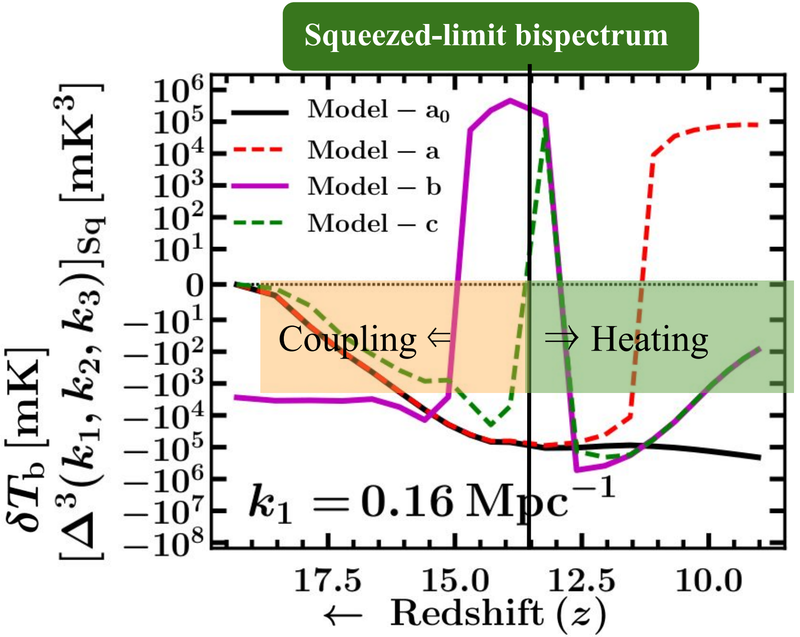


Initially Model-c follows Models-a$_0$ and a
⇒ Lyα coupling dominating until z ~ 14

Kamran+2021b (under review in PRL)

Squeezed-limit bispectrum as a probe of IGM physics during CD

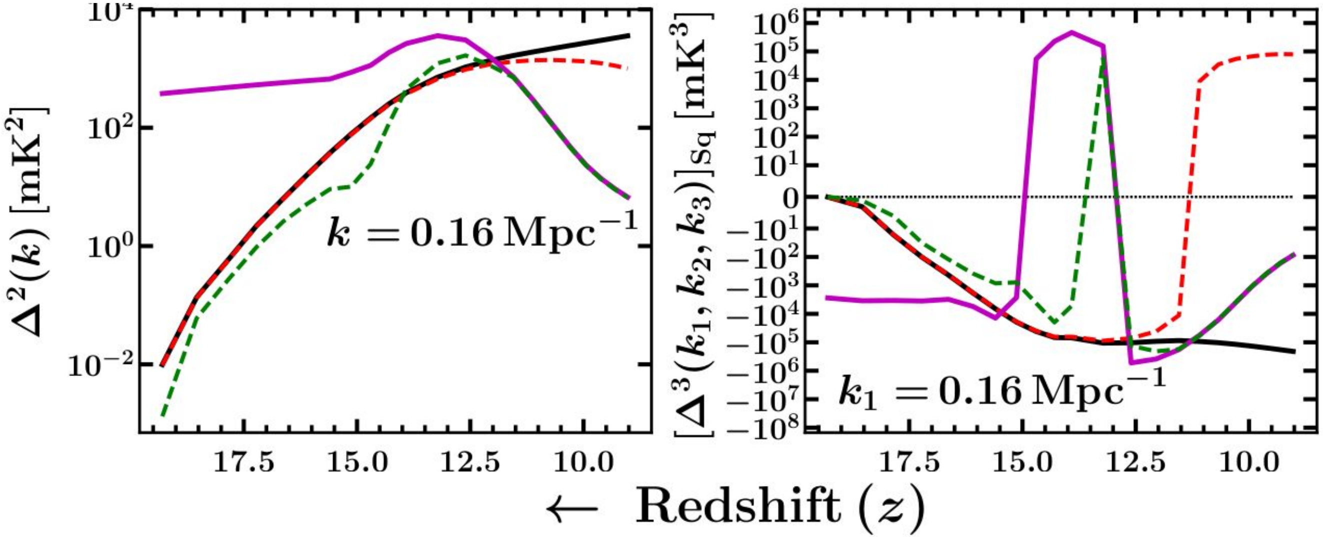




Initially Model-c follows Models-a_0 and a ⇒ Lyα coupling dominating until z ~ 14

At z < 14 Model-c follows Model-b ⇒ X-ray heating dominating

Power spectrum vs bispectrum



Bispectrum via its sign and sign changes can conclusively tell 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.

Kamran+2021b (under review in PRL)

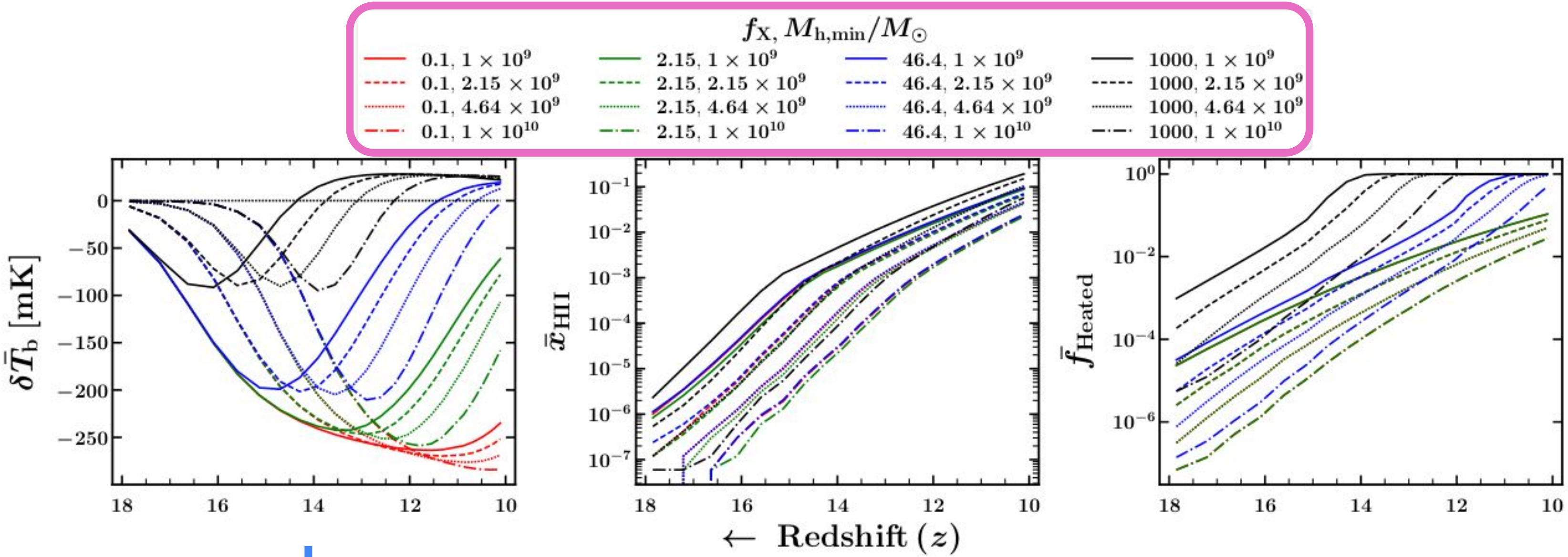
Impact of the CD source parameters on the 21-cm bispectrum

Source Properties

f_X	0.1	2.15	46.4	1000
$M_{h,Min}$ ($10^9\ M_\odot$)	1.0	2.15	4.64	10.0

Kamran+2022

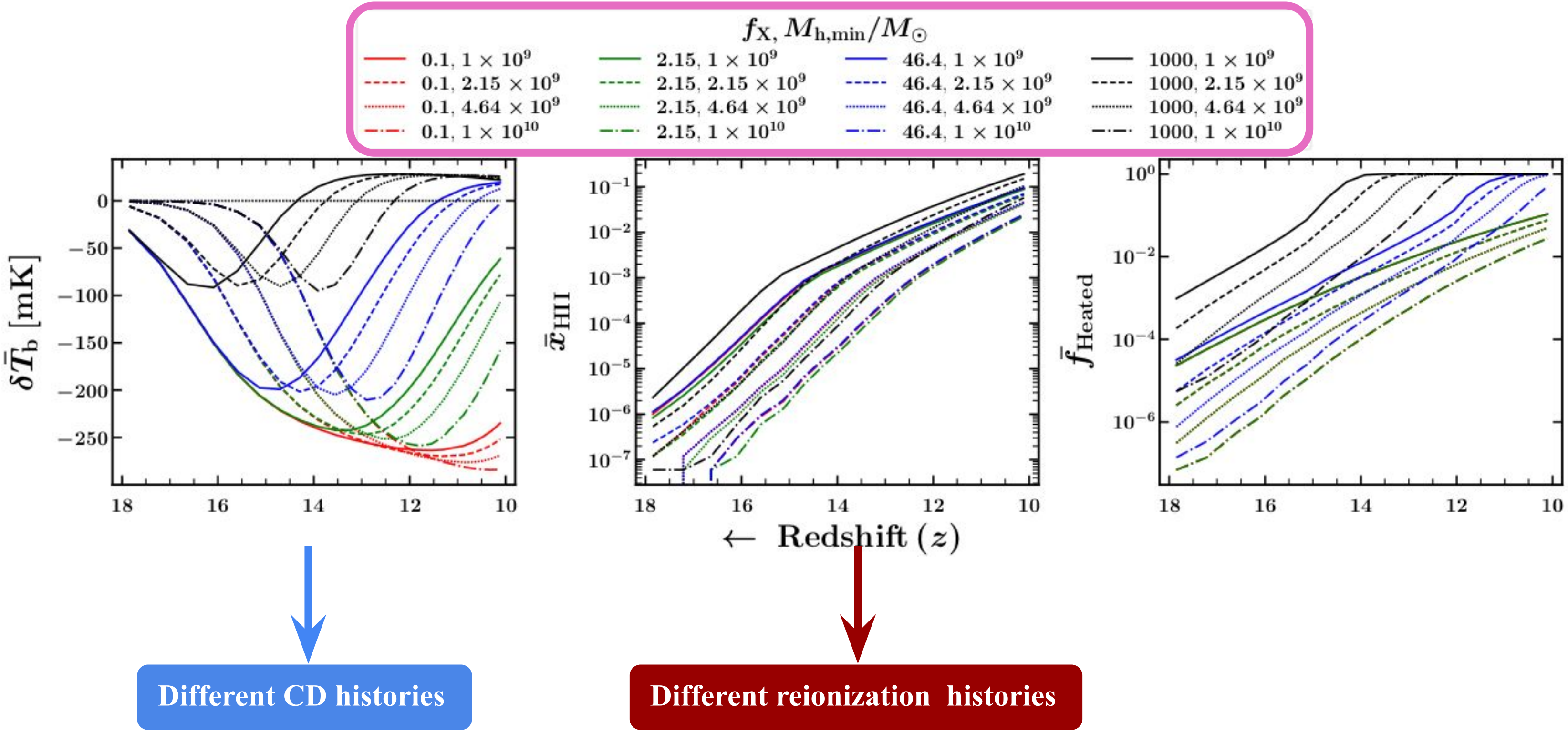
Impact of the CD source parameters on the 21-cm bispectrum



Different CD histories

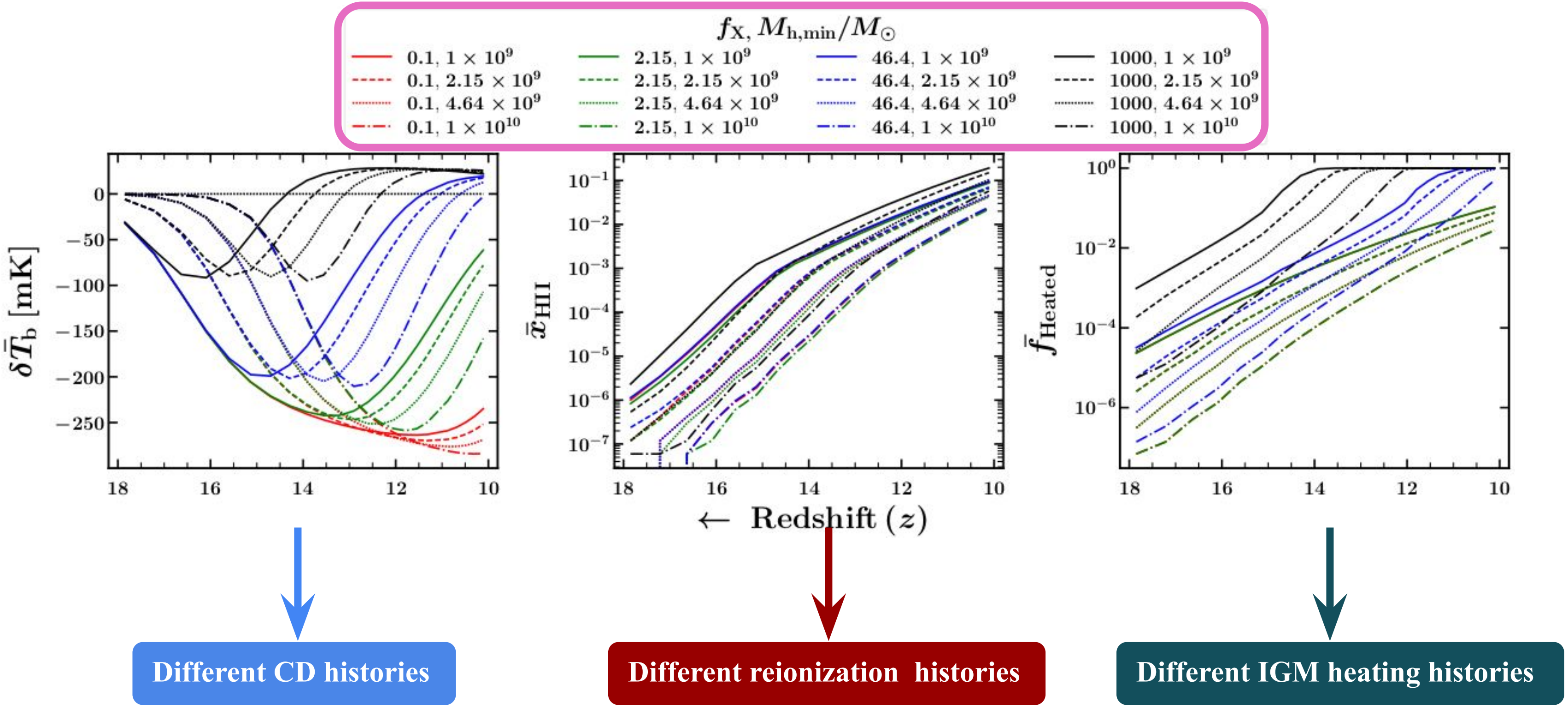
Kamran+2022

Impact of the CD source parameters on the 21-cm bispectrum



Kamran+2022

Impact of the CD source parameters on the 21-cm bispectrum



Kamran+2022

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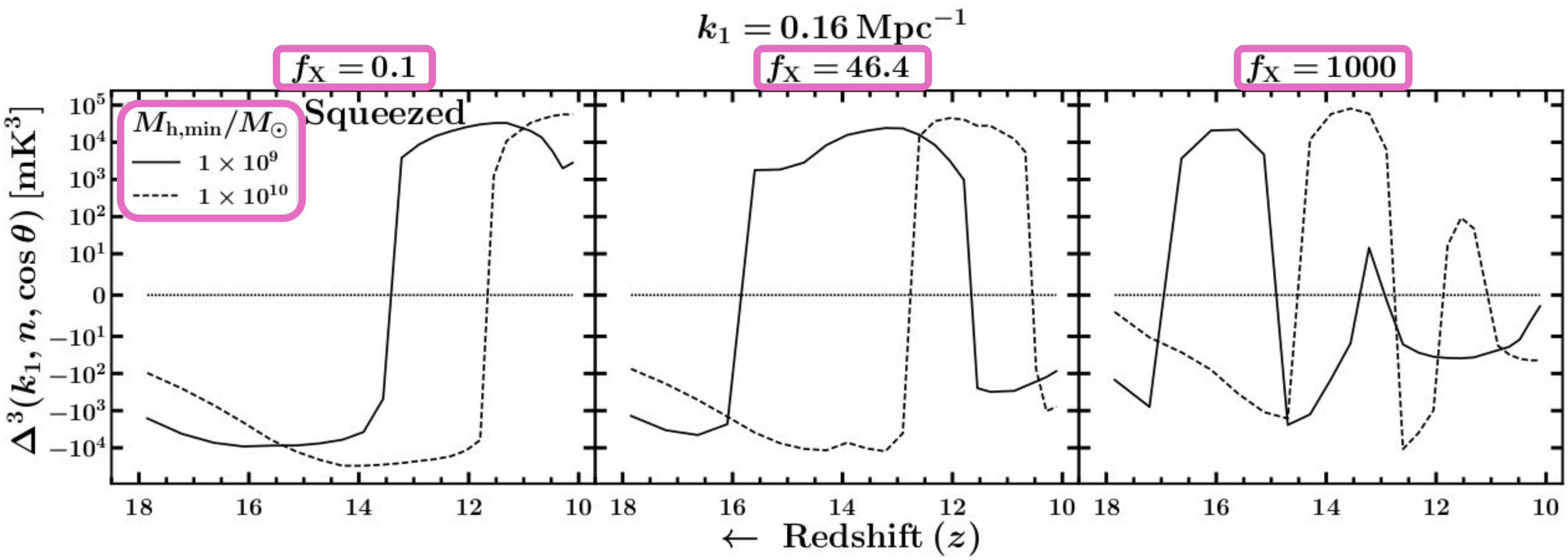
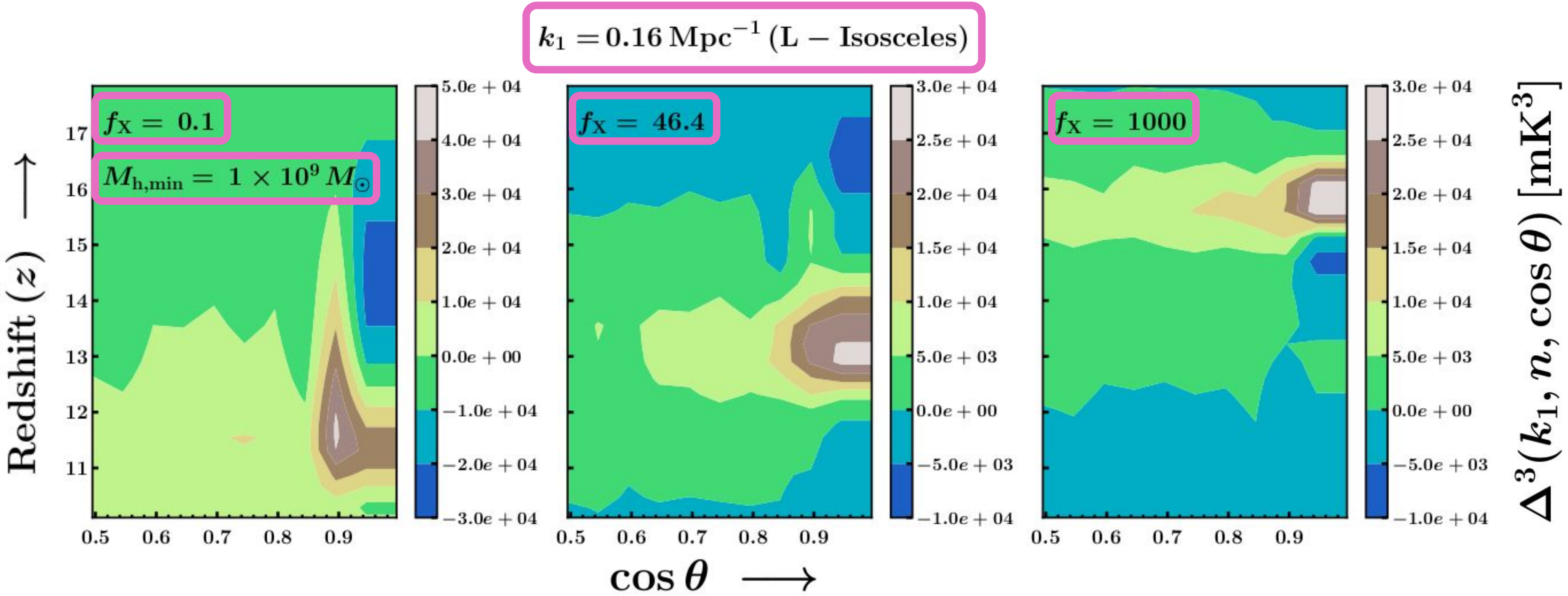


Kamran+2022

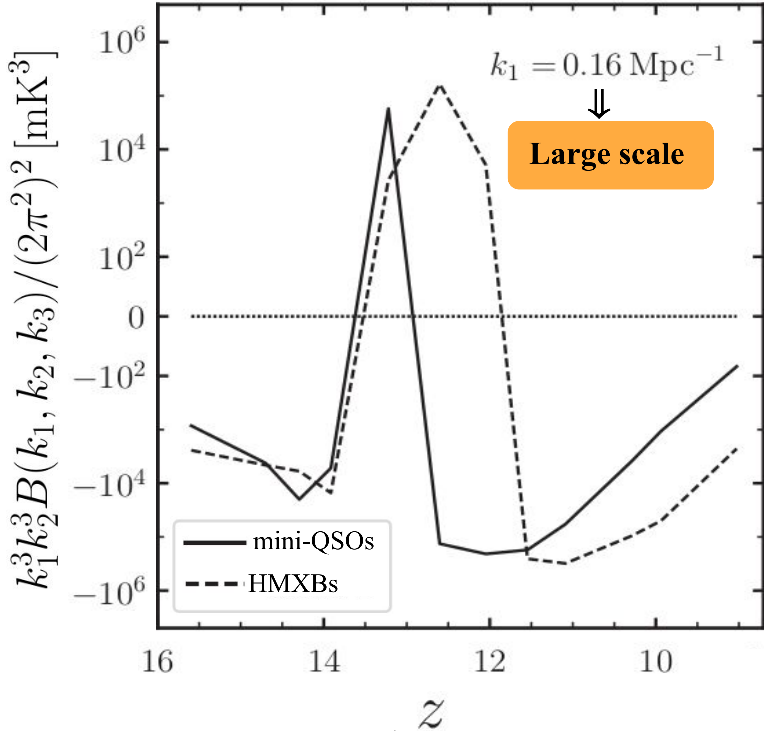
Impact of the CD source parameters on the 21-cm bispectrum



Kamran+2022

Impact of different first sources (mini-QSOs, HMHBs)

Squeezed-limit bispectrum



Decreasing →

Realistic simulations of the CD

+

21-cm bispectrum

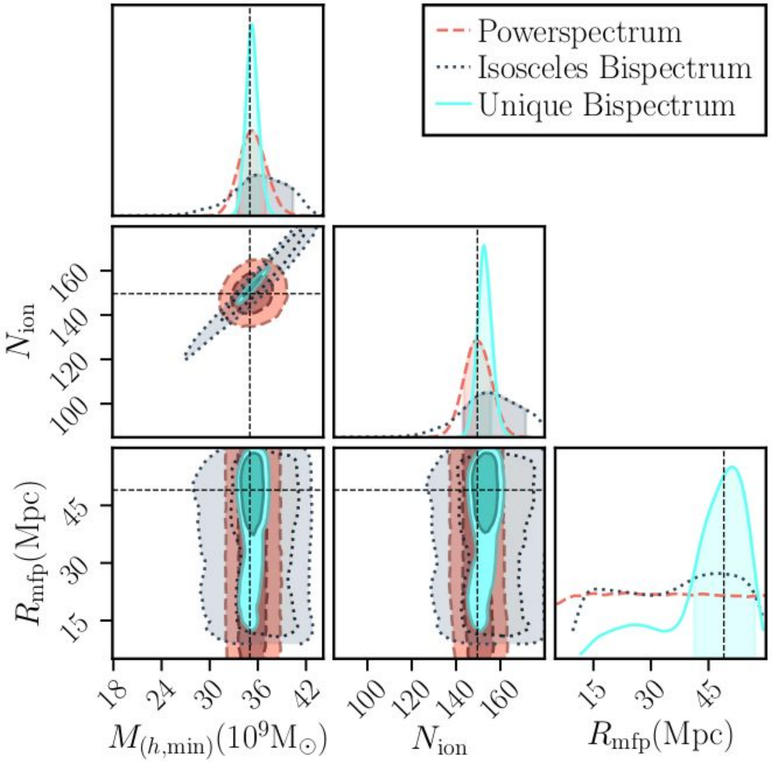
Bispectrum magnitude and sign follow a generic trend e.g. **double sign change**.

Bispectrum is way more sensitive to the CD-EoR parameters than the power spectrum

Kamran+2021a

Parameter inference

EoR parameter estimation using the 21-cm bispectrum



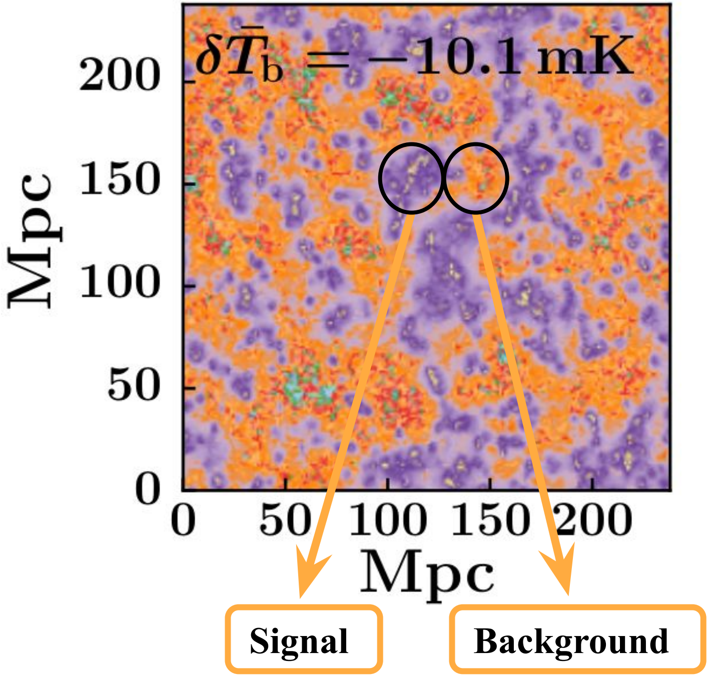
The unique *k*-triangle bispectra provides tighter constraints on the EoR source parameter compared to when the same is done by using the bispectra for only a particular set of *k*-triangle and as well as the power spectrum.

Tiwari+**Kamran** et al. 2022

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.
- The various luminous sources which lead the IGM physics can be distinguished by the bispectrum.

Summary



- ➢ CD-EoR 21-cm signal is highly non-Gaussian in nature.
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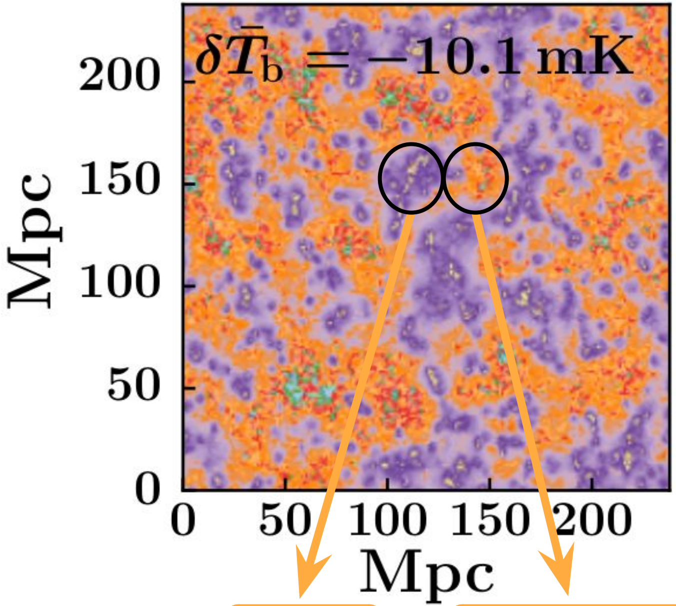
- ➢ The bispectrum being the potential probe of the non-Gaussianity – > can probe the IGM physics that sources the non-Gaussianity in the signal.
- ➢ The various luminous sources which lead the IGM physics can be distinguished by the bispectrum.

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



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.

➢ The various luminous sources which lead the IGM physics can be distinguished by the bispectrum.

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 and shape of the bispectrum works as a smoking gun for the dominant physical processes in the IGM.

What next?

1. To probe dominant IGM processes during EoR using the 21-cm bispectrum.

   ↓

   This can be further used to constrain the properties of ionizing sources during this era

2. To explore the possibility of using the 21-cm bispectrum to constrain the CD model parameters using SKA.

3. To predict the detectability of the CD 21-cm bispectrum using the realistic simulations with the **telescope response**, **foreground**, **noise** etc.

4. To quantify the LoS anisotropies in the 21-cm bispectrum with the higher order multipoles ➔ can provide better insights into the IGM physics.

5. 21-cm + galaxies (CII, OIII, Lyα) cross bispectrum ➔ will open a new avenue to get better insights into the IGM physics ➔ will be able to put tighter constraints on the model parameters

SKA SDC3: Inference

Extraction of reionization parameters (SWG contacts: Mesinger & Mellema)

Target Participants: SWGs like CD/EoR.

Input Data: EoR PS + noise and residual foreground contamination

Challenge will be based on:

a) ability to extract the IGM and source properties

Verification of the results from participants

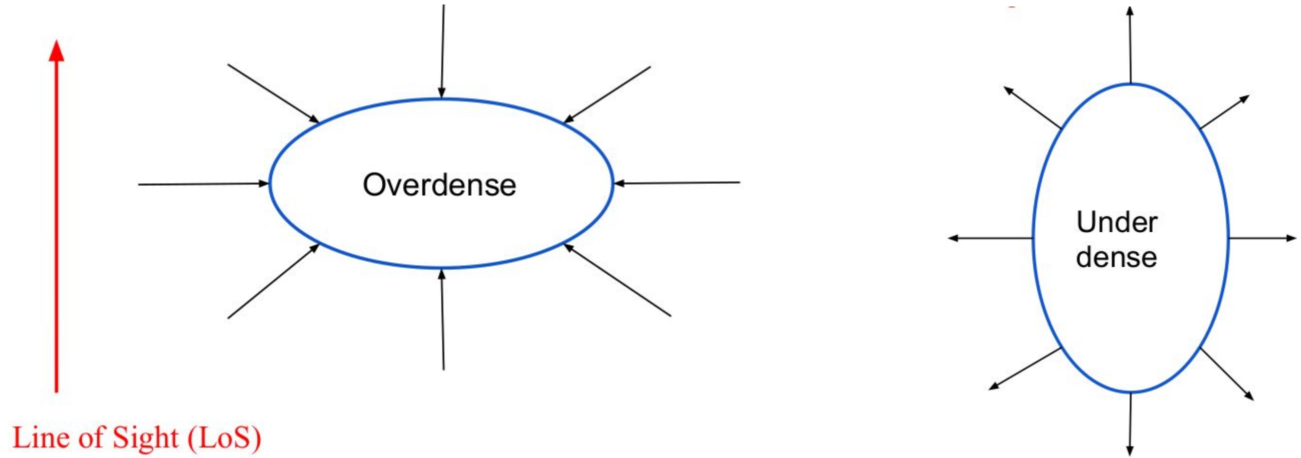
Comparison with the input EoR history **(ionization fraction)**

Slide credit: Anna Bonaldi

21-cm bispectrum from the CD-EoR

Impact of the Line of Sight effects

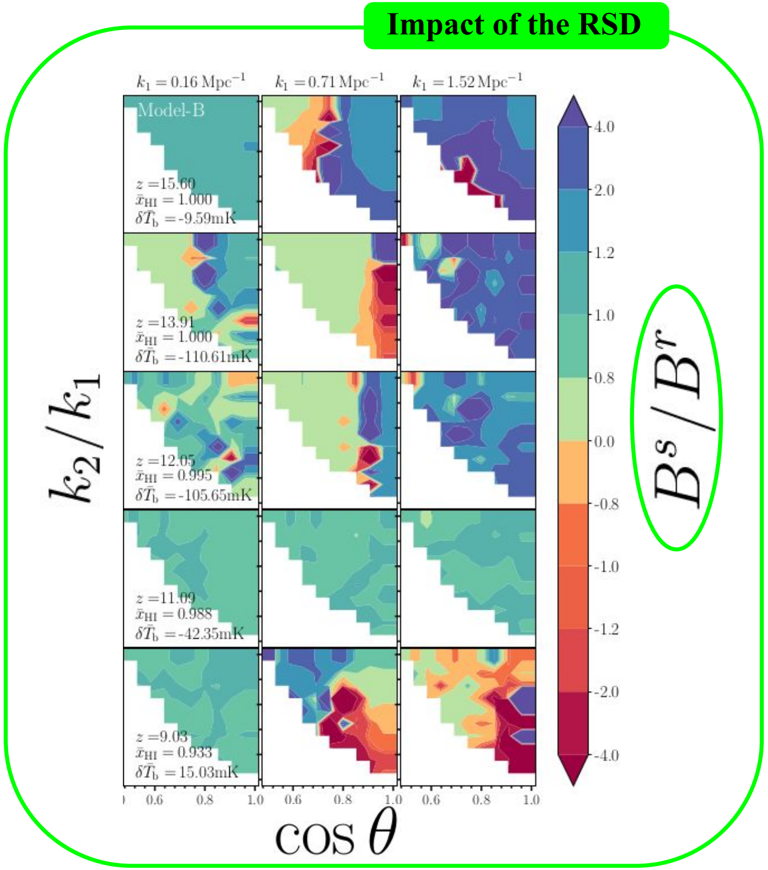
1. **Redshift Space Distortions (RSD):** Signal distortion along the LoS of an observer due to the gas peculiar velocities.

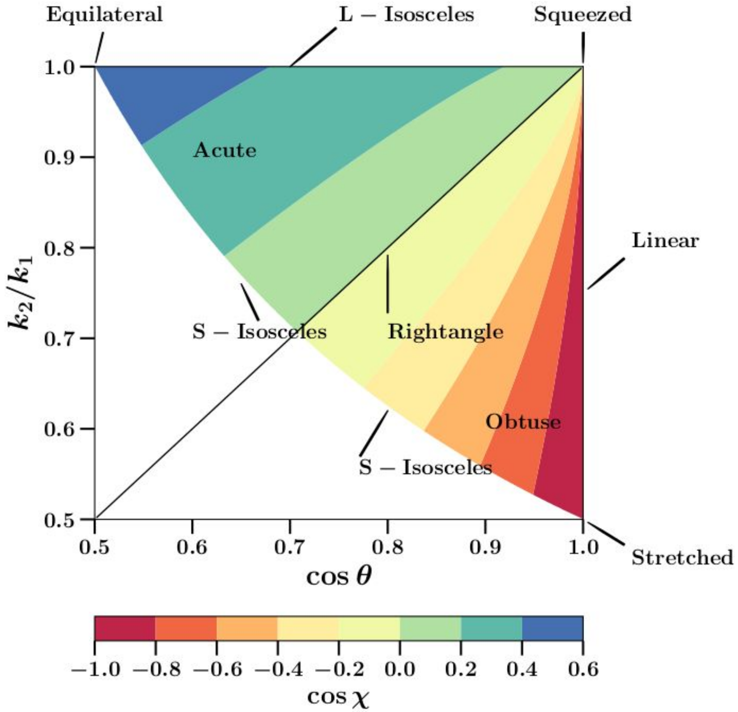


2. **Light Cone (LC) effect :** Signal distortion along the LoS of an observer due to the finite travel time of the signal.

Essential to consider for correctly interpreting the observed signal statistics.

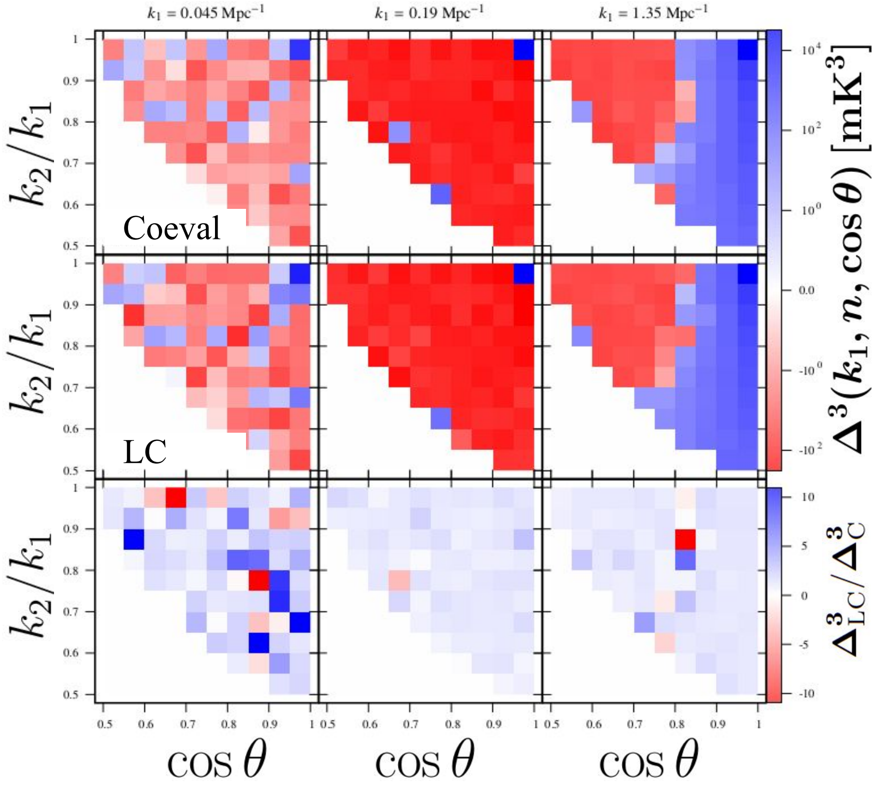
Impact of the RSD effect





Impact is significant on magnitude (>20%) and sign of the bispectrum

Impact of the Light Cone effect



The impact of LC effect is largest for large scale observations.

RSD+LC ⇒ Important to consider for interpreting the observed signal statistics correctly.

Mondal+**Kamran** et al. 2021

Backup Slides

$$f_X = \frac{\int_{100\ \mathrm{eV}}^{10\ \mathrm{keV}} I(E)dE}{\int_{10.2\ \mathrm{eV}}^{100\ \mathrm{eV}} I(E)dE}$$

$$I_q(E) = A\ E^{-\alpha}$$