'Emulator is all you need' for the Reionization Inference with SKA-Low

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IIT INDORE

The Non-Gaussian Universe,
June 16-19, 2026, FORTH, Iraklio


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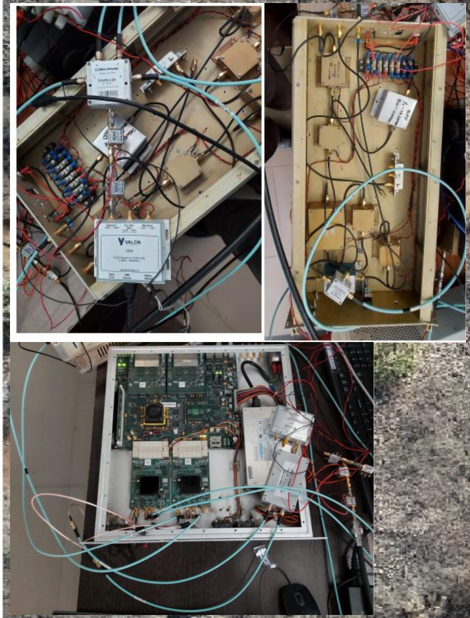
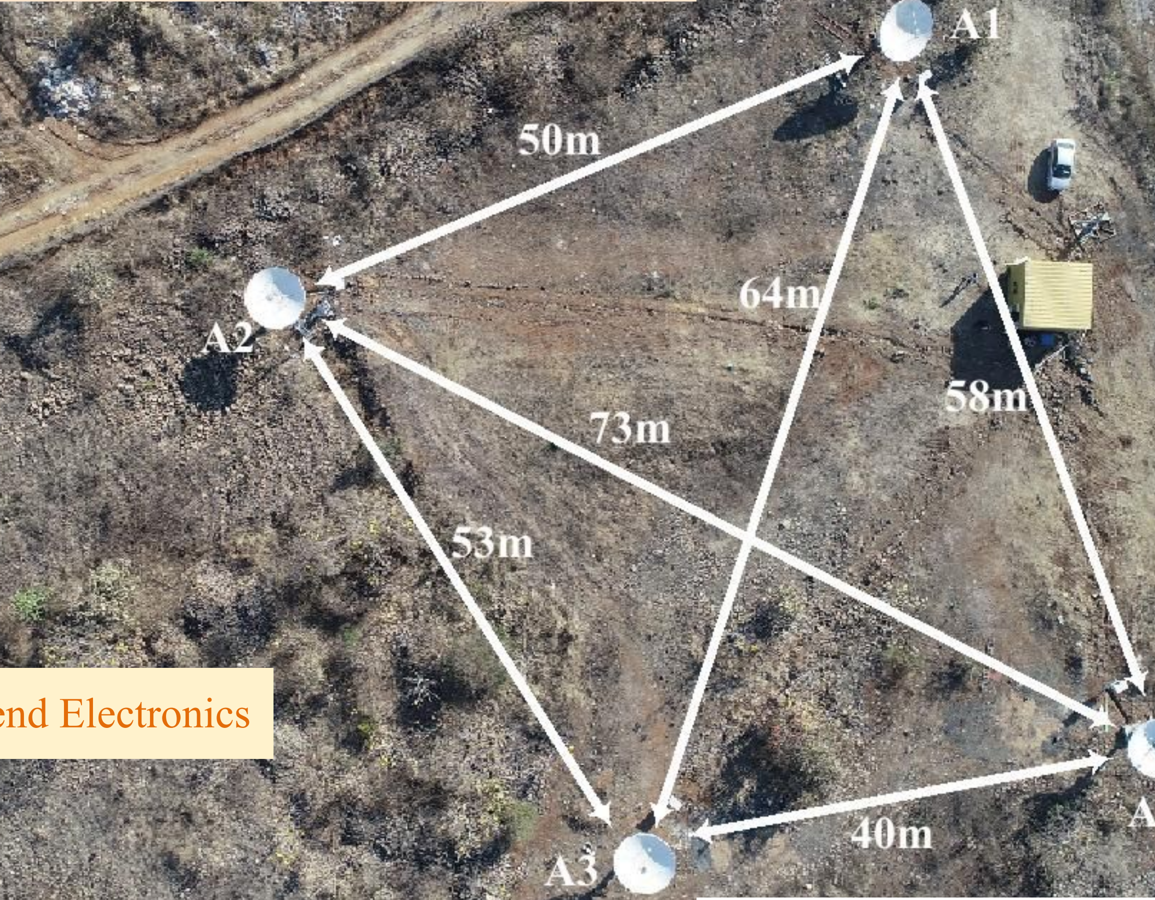
IIT Indore Radio Interferometer (IIRI)

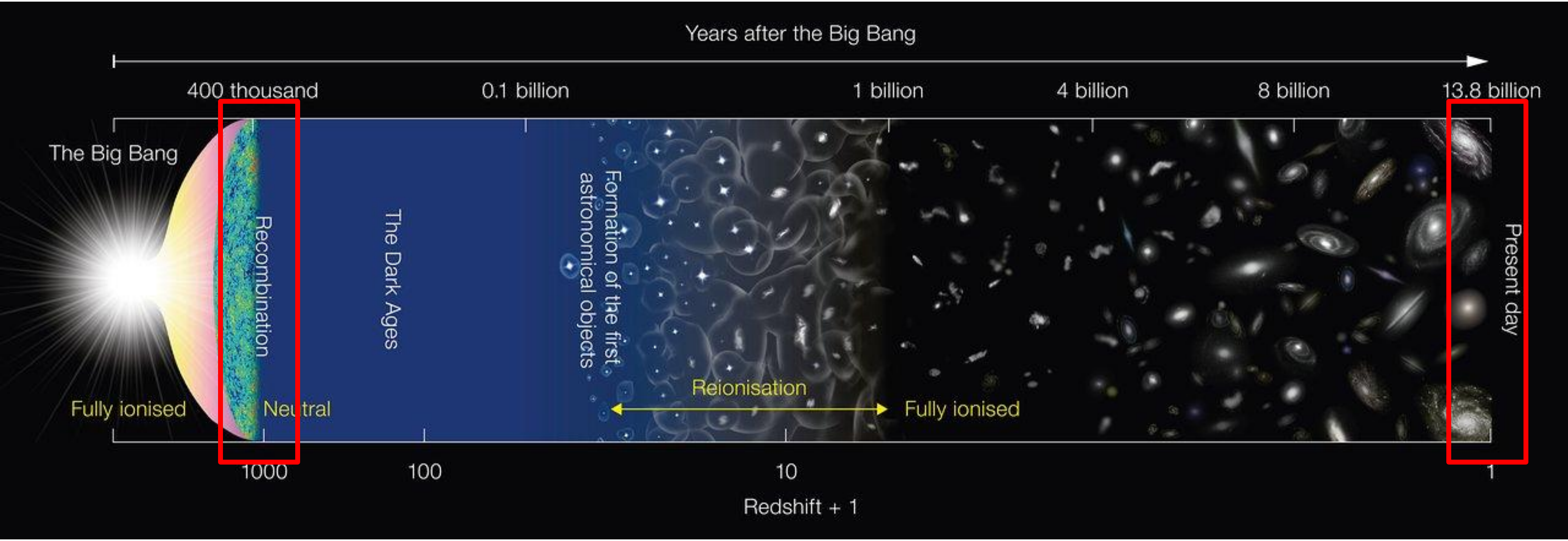


Analog and Digital Backend Electronics



Dishes of IIRI

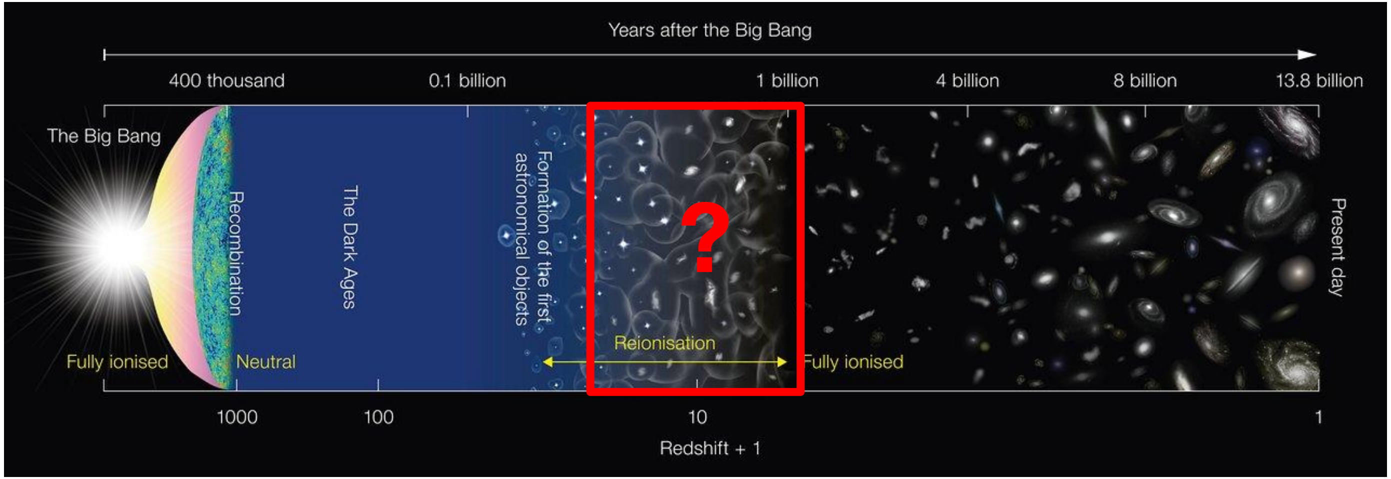
Assembled @ IITI through a DST-SERB grant



How much do we know?

Credit: NAOJ

Epoch of Reionization (EoR)

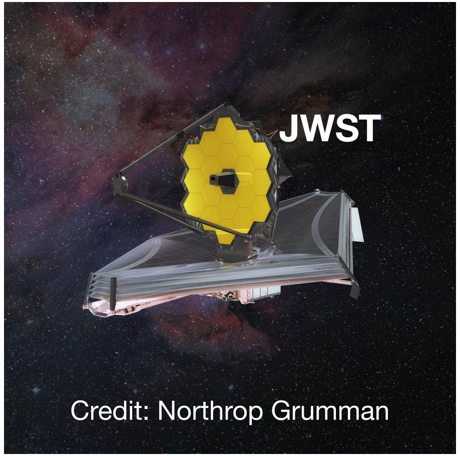


Credit: NAOJ

- First luminous sources (galaxies) were formed
- Ionizing radiation from the luminous sources reionized the neutral IGM

How to probe the EoR universe?

Probing the EoR: galaxies

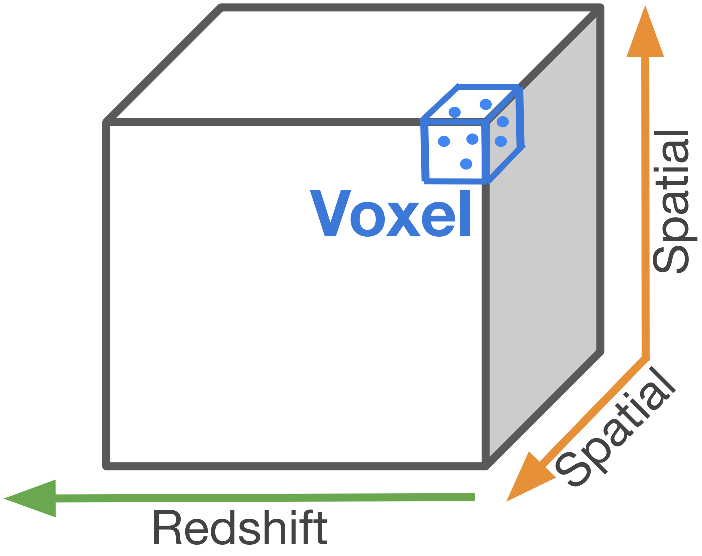


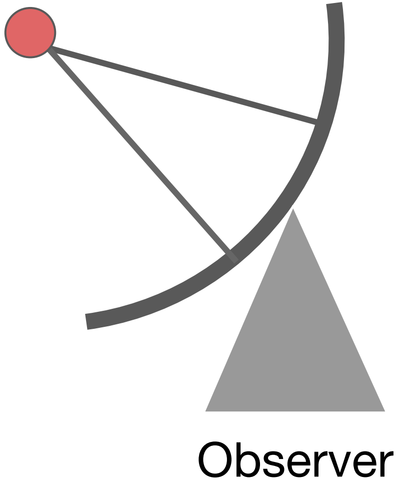
Challenges!

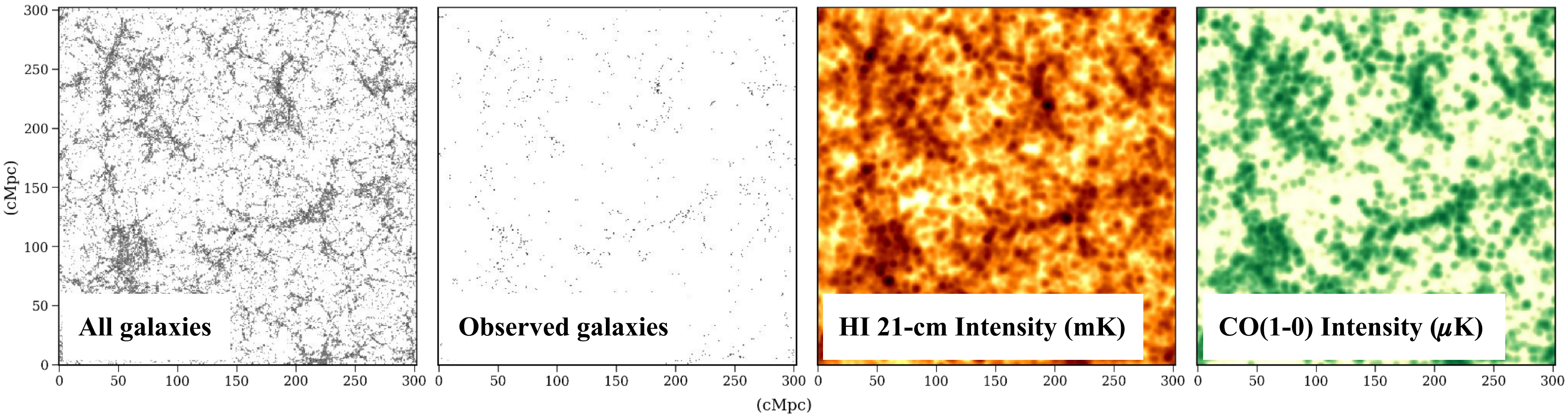
- Demanding sensitivity limits and angular resolutions
- Expensive to operate, therefore it becomes impractical to map large galaxy samples at very high redshifts (z>6)

Line-intensity mapping (LIM)

LIM can probe the large-scale structures by detecting the integrated flux of numerous sources from a comparatively small region (Voxel)







Inference on clustering and morphology biased towards the brightest galaxies

Line Intensity Maps include contributions from faint sources

Line Intensity Mapping

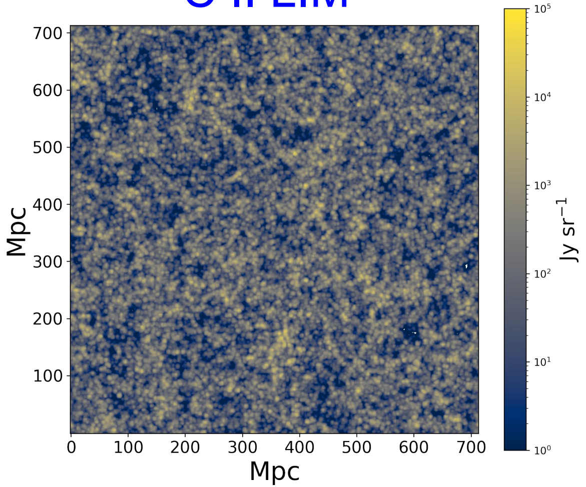
- Maps line emission at a specific observed frequency with low spatial resolution
- Does not resolve individual sources
- Redshift information can be used for tomography

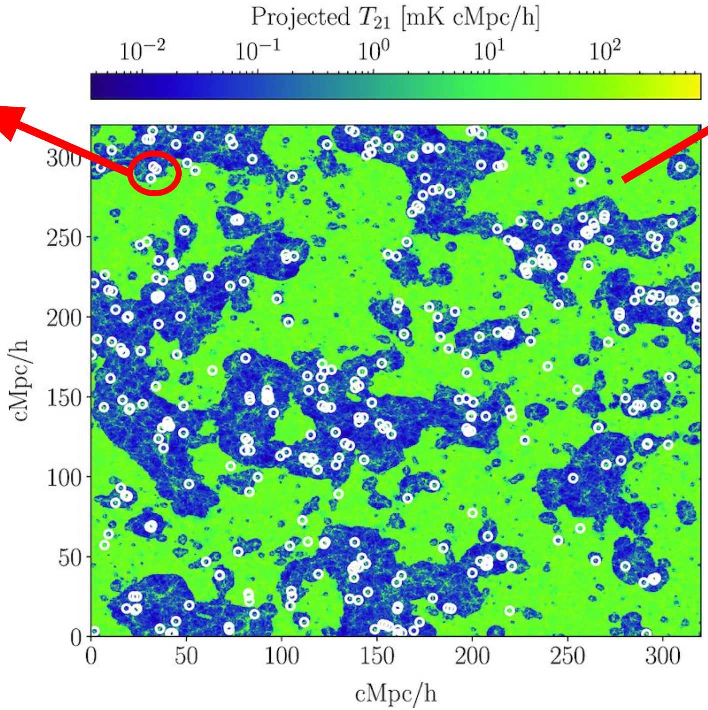
LIM at the EoR

Observing the luminous sources

CII, CO, OII, OIII

C II LIM

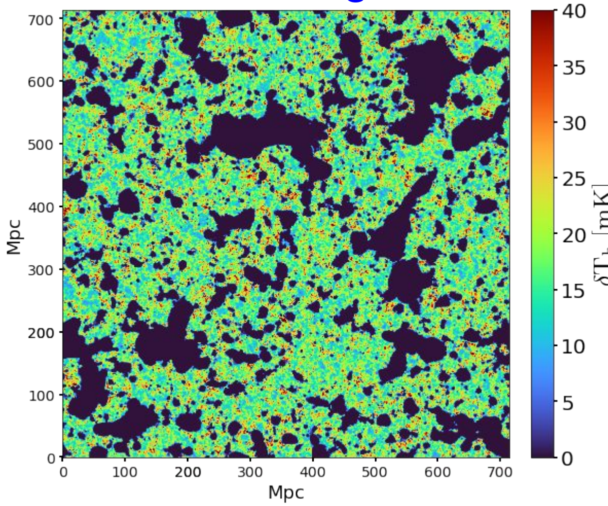




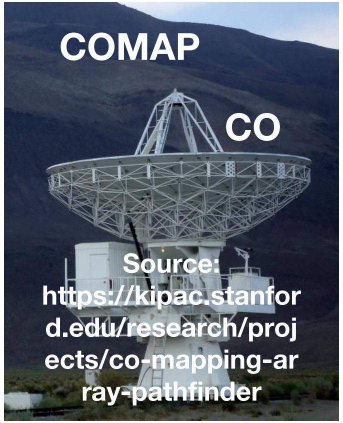
Observing the intergalactic medium

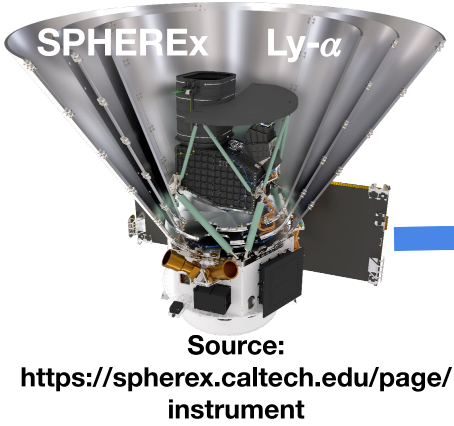
21-cm, Lyα

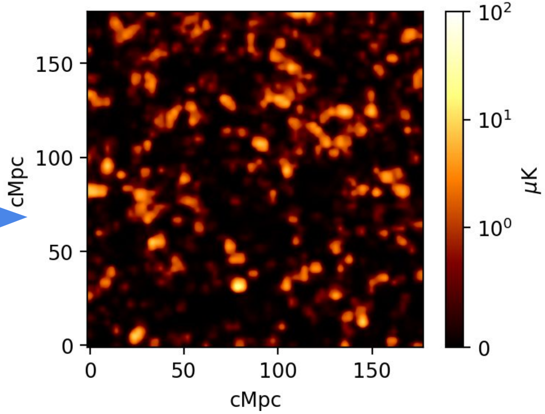
21-cm signal

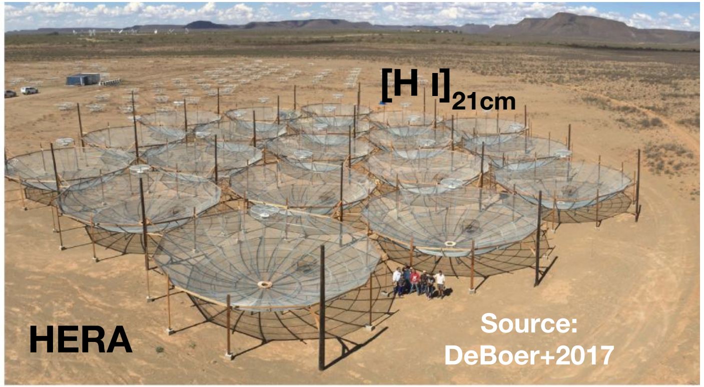


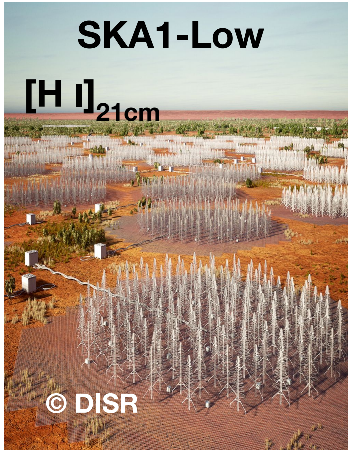
Probing the EoR with Intensity Mapping: galaxies and IGM

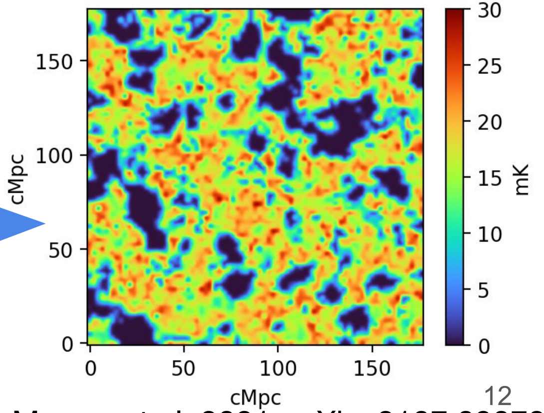




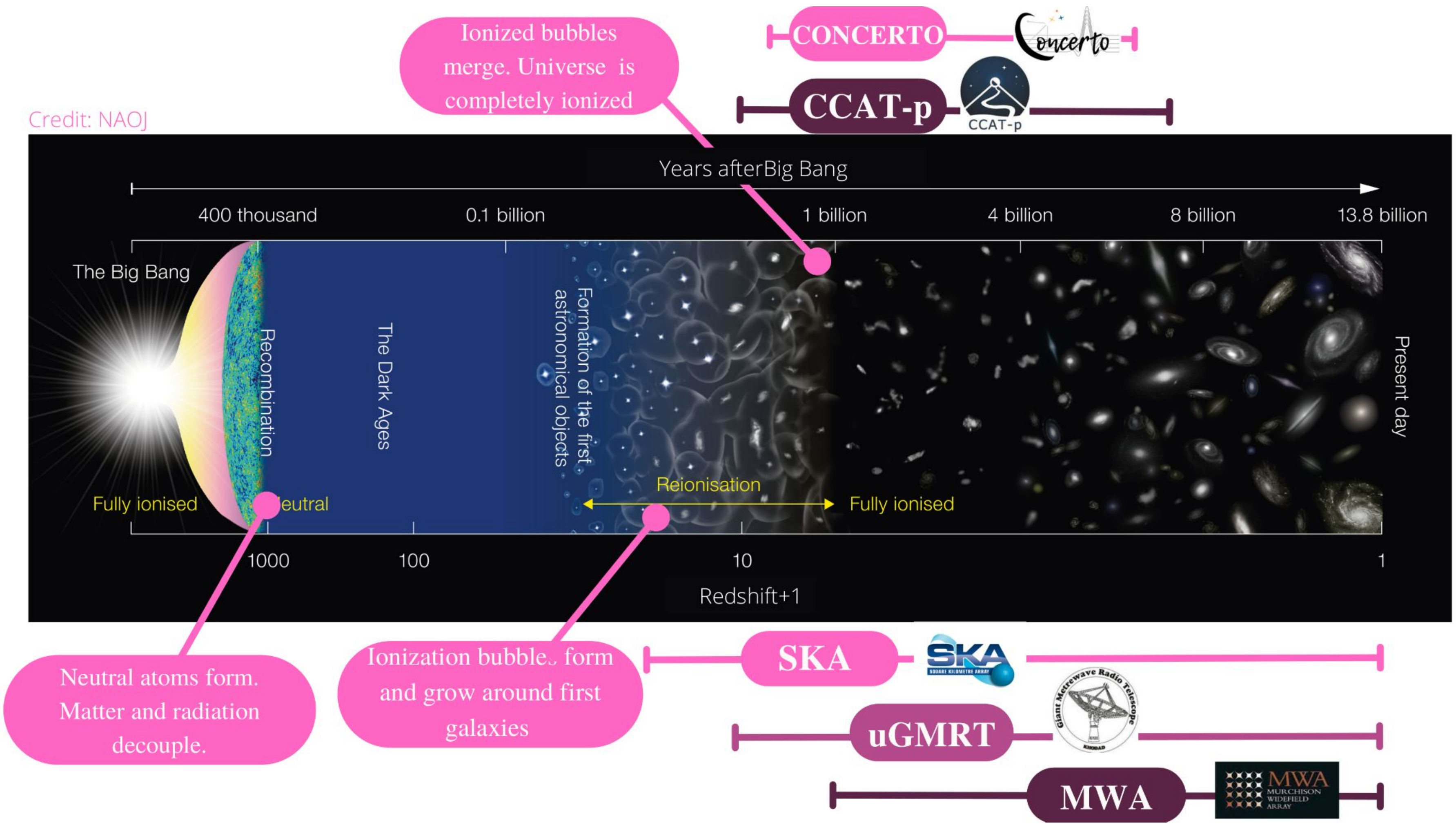






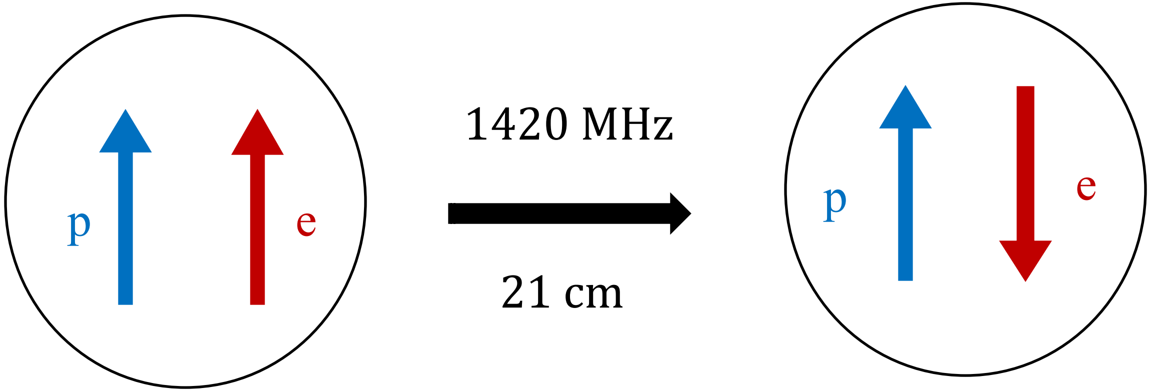


Murmu et al. 2021, arXiv: 2107.09072


Credit: NAOJ
CONCERTO
CCAT-p
Ionized bubbles merge. Universe is completely ionized
Years afterBig Bang
400 thousand
0.1 billion
1 billion
4 billion
8 billion
13.8 billion
The Big Bang
Recombination
The Dark Ages
Formation of the first astronomical objects
Present day
Fully ionised
Reionisation
Fully ionised
1000
100
10
1
Redshift+1
SKA
uGMRT
MWA
Neutral atoms form. Matter and radiation decouple.
and grow around first galaxies

Observing the Hydrogen (HI)

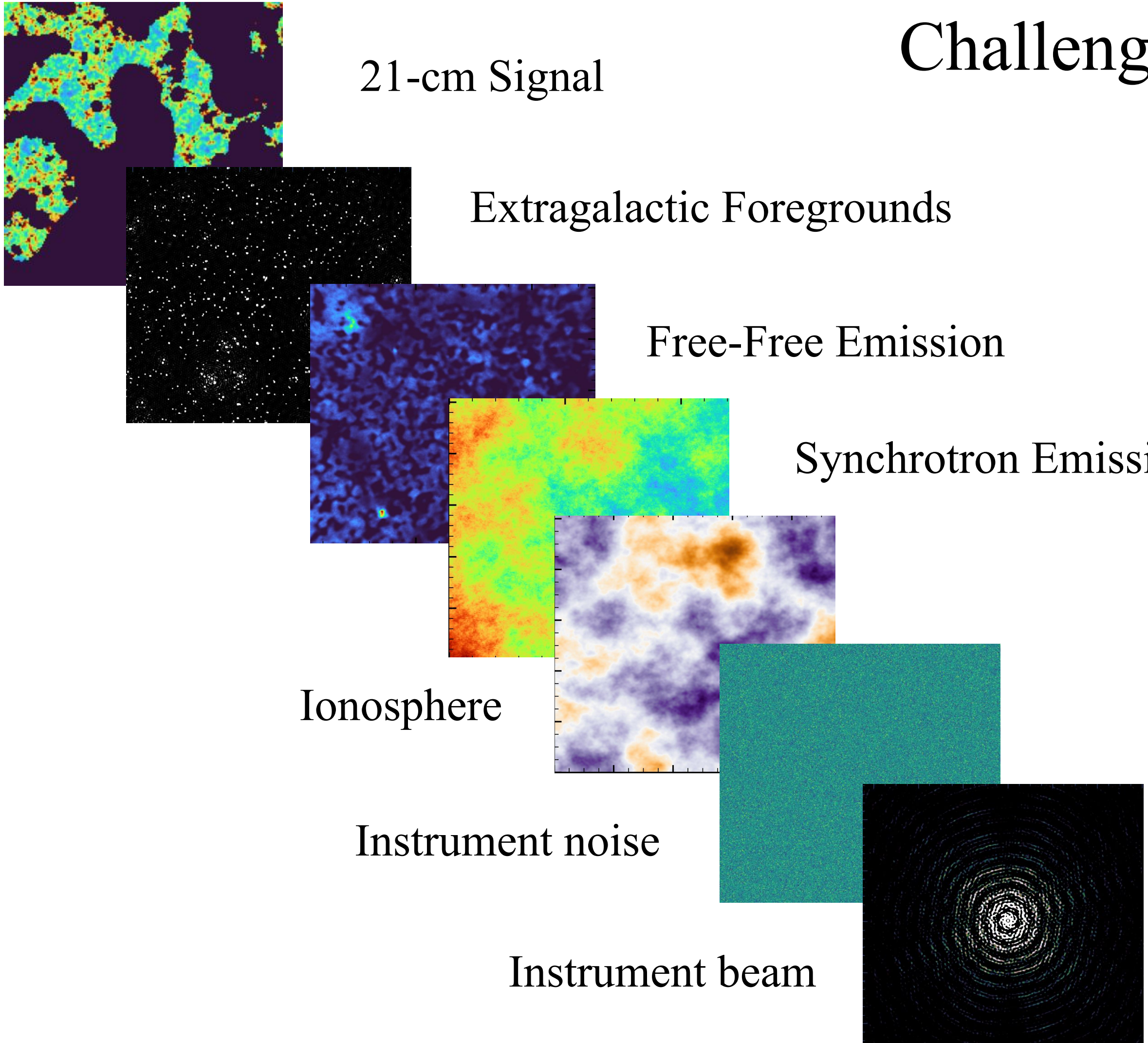
21-cm Line



$$\nu_o = 1420\ \text{MHz}/(1+z)$$

$$\lambda_o = 21\ (1+z)\ \text{cm}$$

Challenges


21-cm Signal
Extragalactic Foregrounds
Free-Free Emission
Synchrotron Emission
Ionosphere
Instrument noise
Instrument beam

Challenges

System Noise: Possibly Gaussian Random; can be suppressed below signal for long integration time.

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

Ionosphere: 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.

How to quantify the signal?

Basic observable in radio interferometry is Visibility
Visibility ≡ Fourier transform of the sky brightness temperature

⬇

Power spectrum: $\langle \tilde{T}_{\rm b}(k_1)\, \tilde{T}_{\rm b}(k_2) \rangle = \delta_{k_1+k_2,0} V\, P(k_1)$

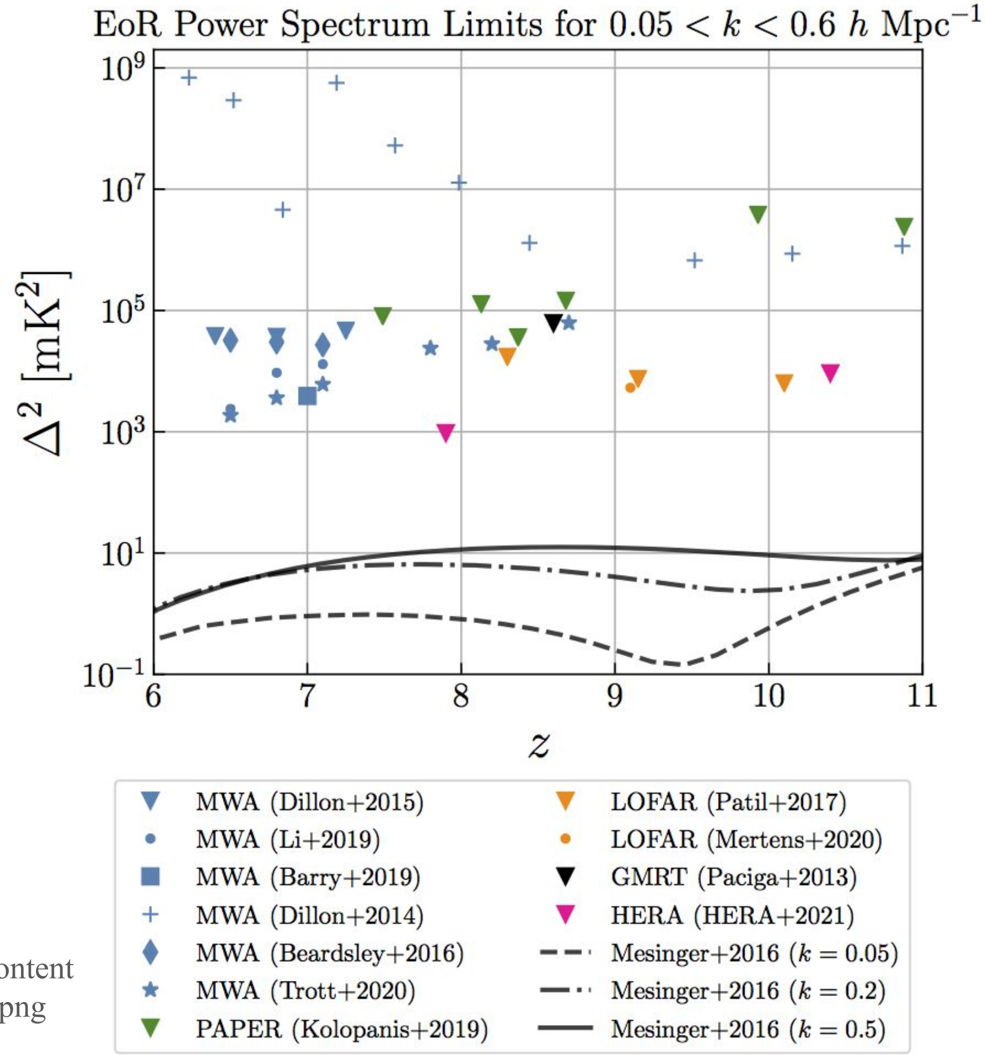
‖

where $k = 2\pi/L$

Amplitude of fluctuations
at different length scales

Bharadwaj et al. 2000
(astro-ph/0003200)

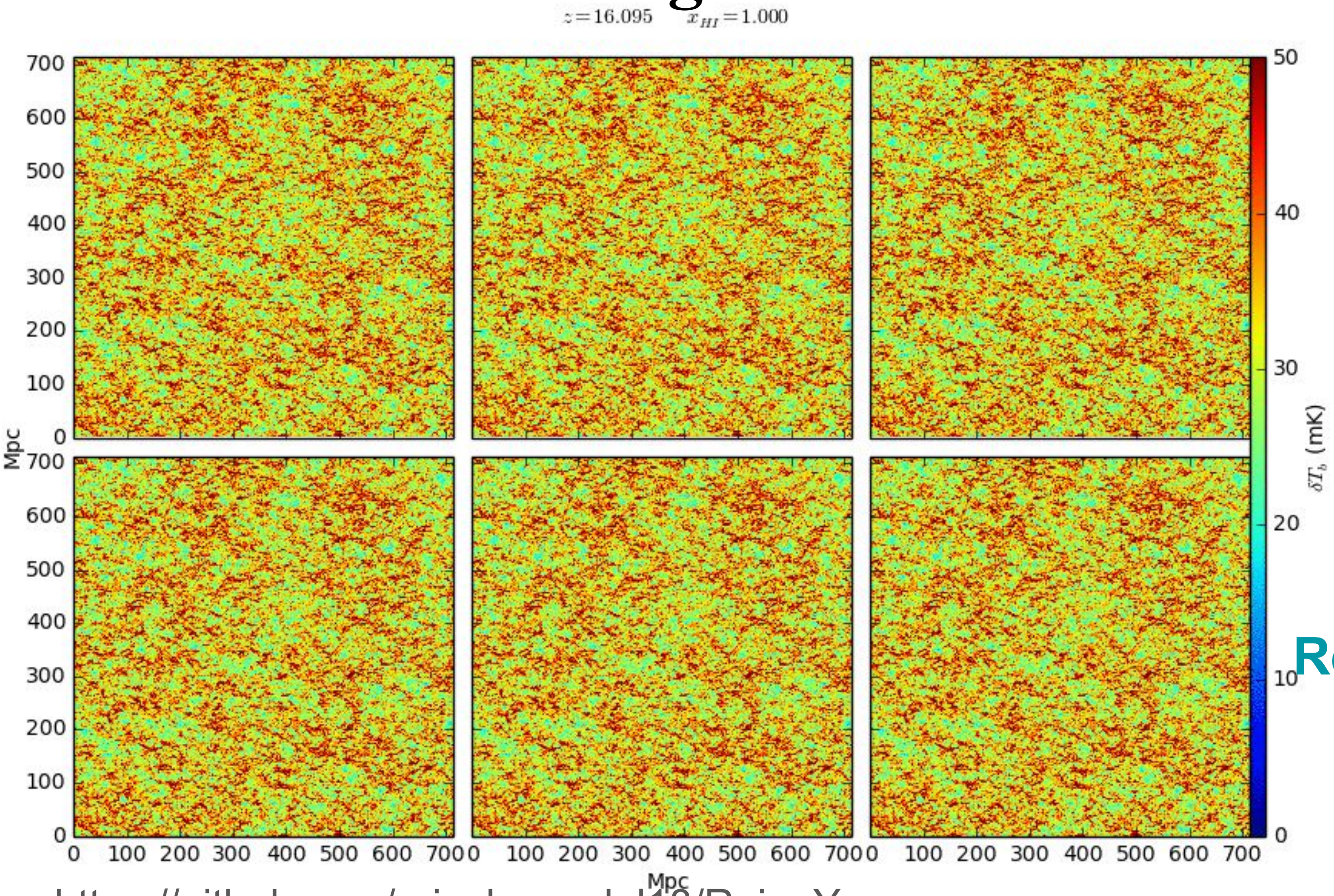
**Radio interferometers are not sensitive to the mean of the signal as signal at $k = 0$ is not recorded.



Where do we stand?

Source: https://reionization.org/wp-content/uploads/2021/08/eor_limits.png

How does the signal look like?



ReionYuga

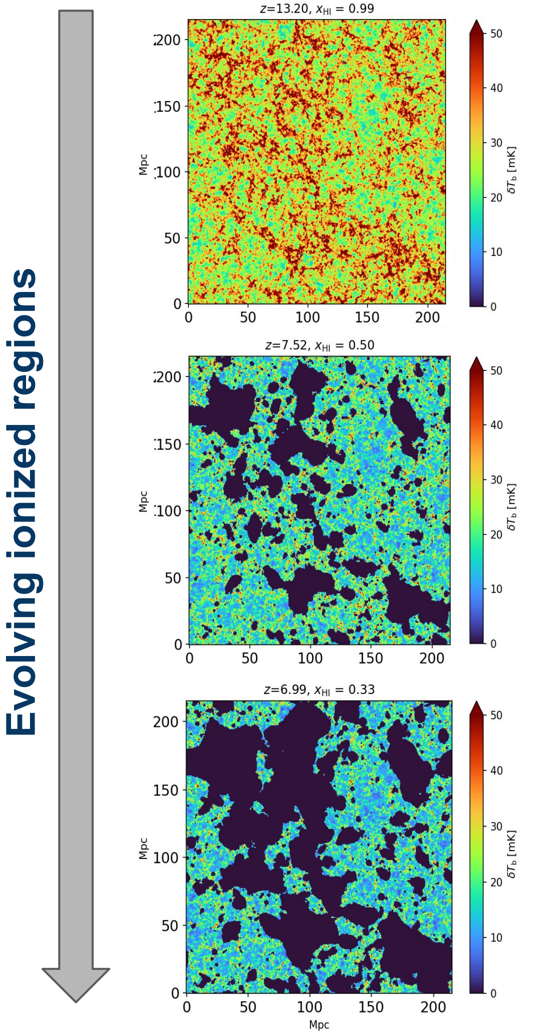
https://github.com/rajeshmondal18/ReionYuga

Non-Gaussian EoR 21-cm Signal

- 21-cm signal from EoR is highly **non-Gaussian**.

  > ➢ Intrinsic: Underlying matter distribution
  >
  > ➢ Evolving: Distribution & growth of ionized regions

- We need higher order signal statistic to quantify this non-Gaussianity



Various ways of quantifying non-Gaussianity (in the context of EoR 21-cm signal)

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

- Position dependent power spectrum → Giri et al 2019 etc

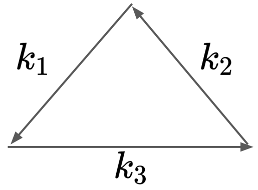
- Wavelet Scattering Transforms → Greig et al 2022, Hoti et al 2024 etc

- 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

Bispectrum as a summary statistic

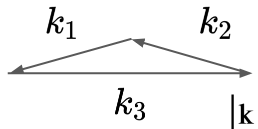
Bispectrum

- Fourier equivalent to three point correlation function.
- It quantifies the correlation between different Fourier modes.



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

$$\langle \Delta_b(k_1)\Delta_b(k_2)\Delta_b(k_3)\rangle = V\delta^K_{(k_1+k_2+k_3,0)} B_b(k_1,k_2,k_3)$$

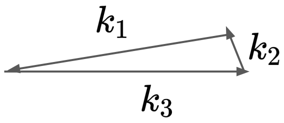


$|\mathbf{k}_1| = |\mathbf{k}_2| = |\mathbf{k}_3|/2$

Stretched

- Normalised Bispectrum

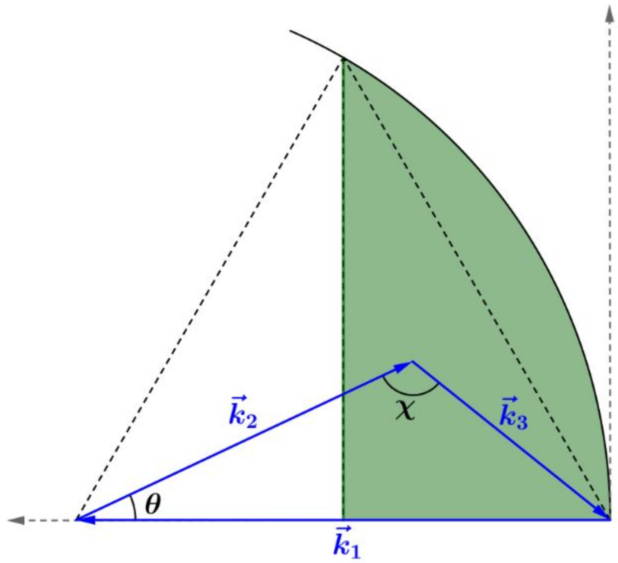
$$\Delta^3(k_1,k_2,k_3) = \frac{k_1^3 k_2^3}{(2\pi^2)^2} B(k_1,k_2,k_3)$$

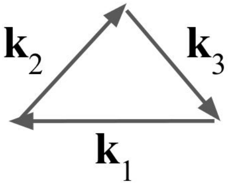


Squeezed Limit $|\mathbf{k}_1| \approx |\mathbf{k}_3|, |\mathbf{k}_2| \to 0$

Majumdar et al. 2018, MNRAS, 476, 4007

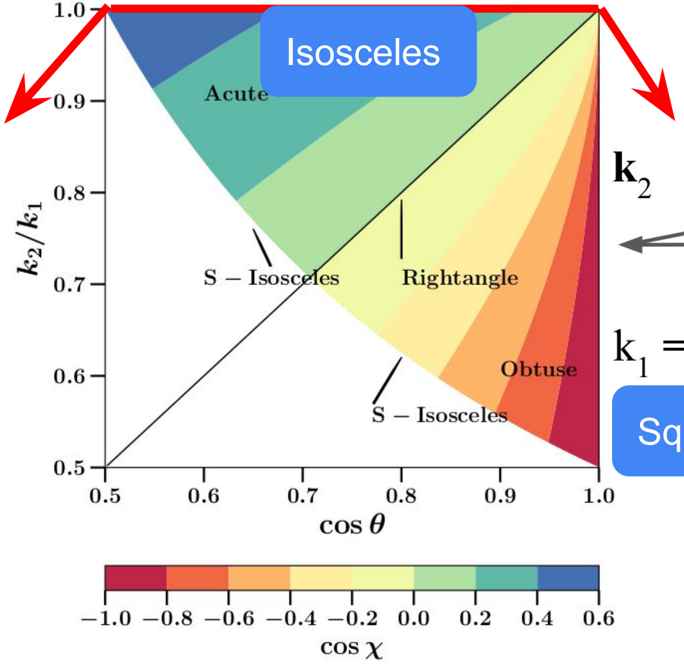
Unique triangles in the Fourier space

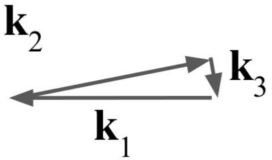




$k_1 = k_2 = k_3$

Equilateral





$k_1 = k_2,\ k_3 \rightarrow 0$

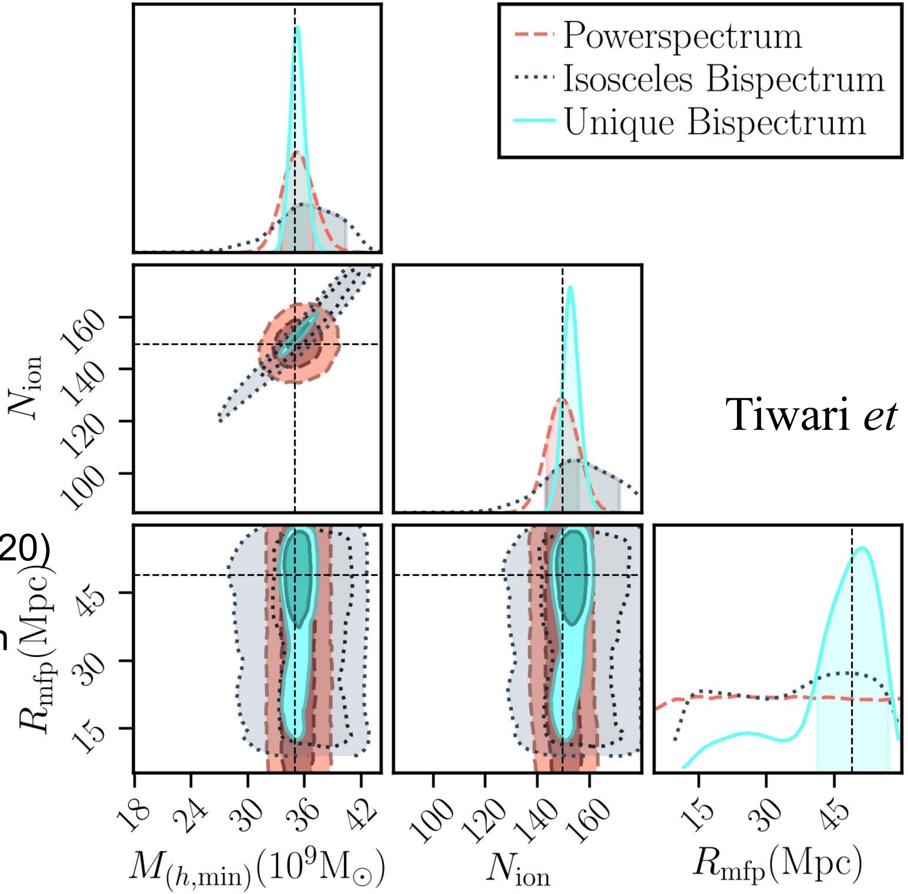
Squeezed

Bharadwaj et al 2020, Majumdar et al 2020

Bispectrum provides better constraints on EoR parameters

Himanshu Tiwari

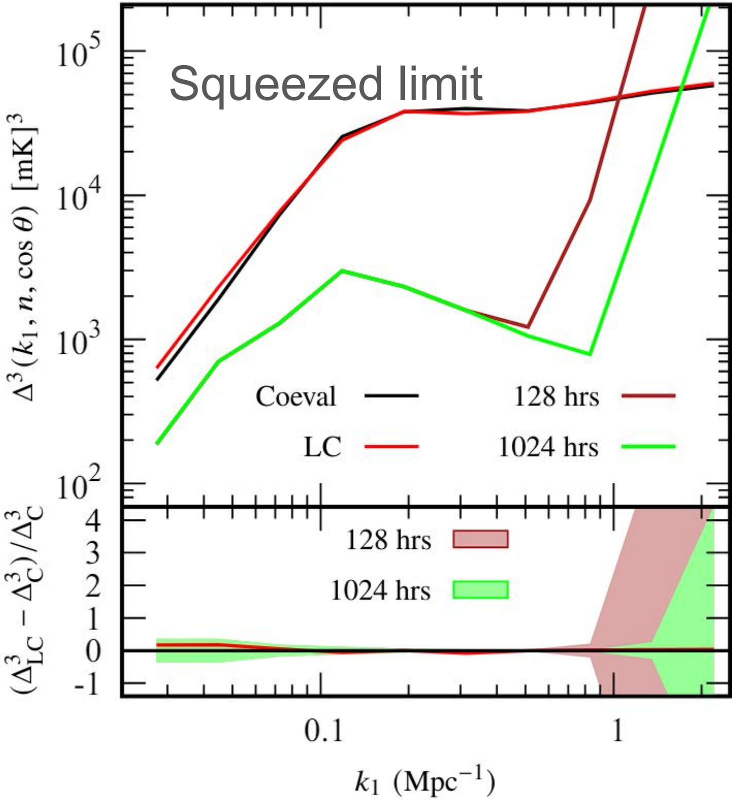
MSc Astronomy IITI (2018-20)
PhD at Curtin Univ. (2024)
Data Scientist at NRI, Perth



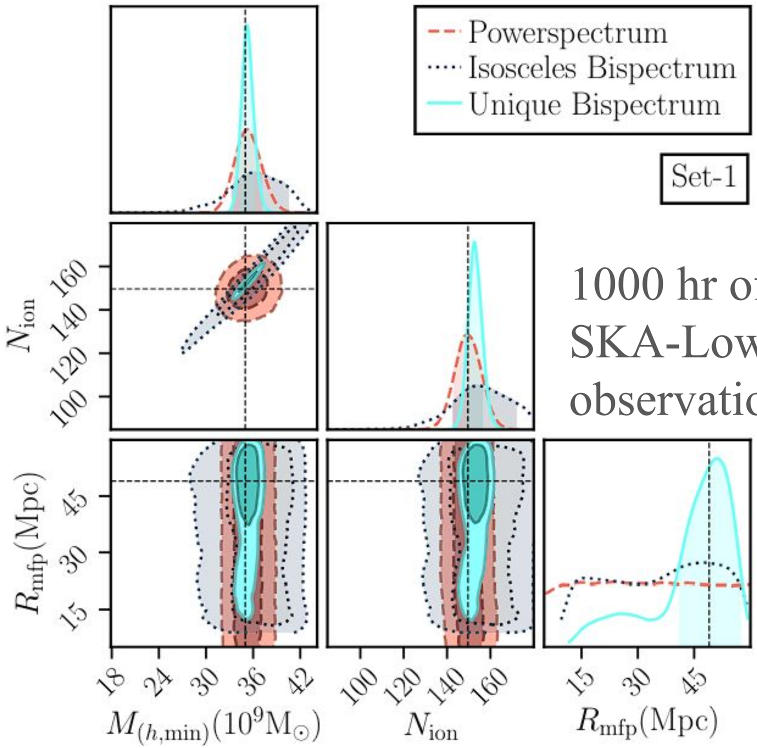
Tiwari *et al* JCAP 04(2022)045

1000 hr of SKA-Low observations

Detectability of the bispectrum with SKA-Low



Mondal, …SM et al 2021 (arXiv:2107.02668)



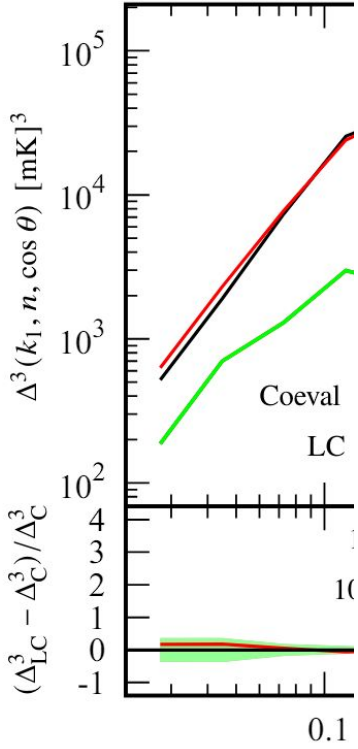
1000 hr of SKA-Low observations

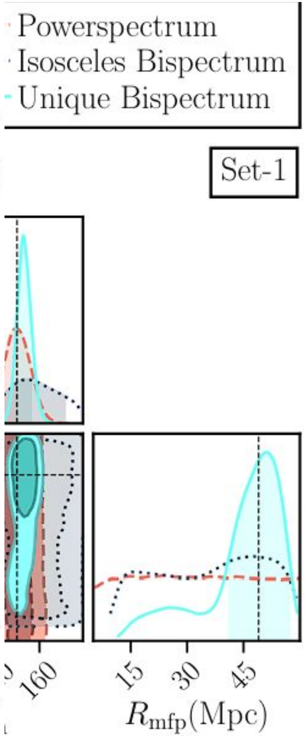
Tiwari, SM et al 2022(arXiv:2108.07279)

Detectabi … with SKA

Trott, …SM et al 2019

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

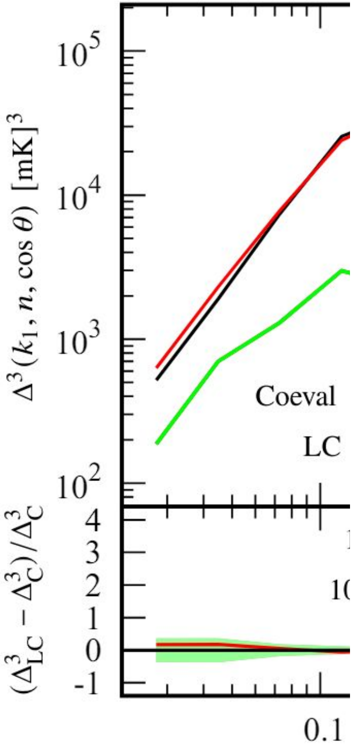


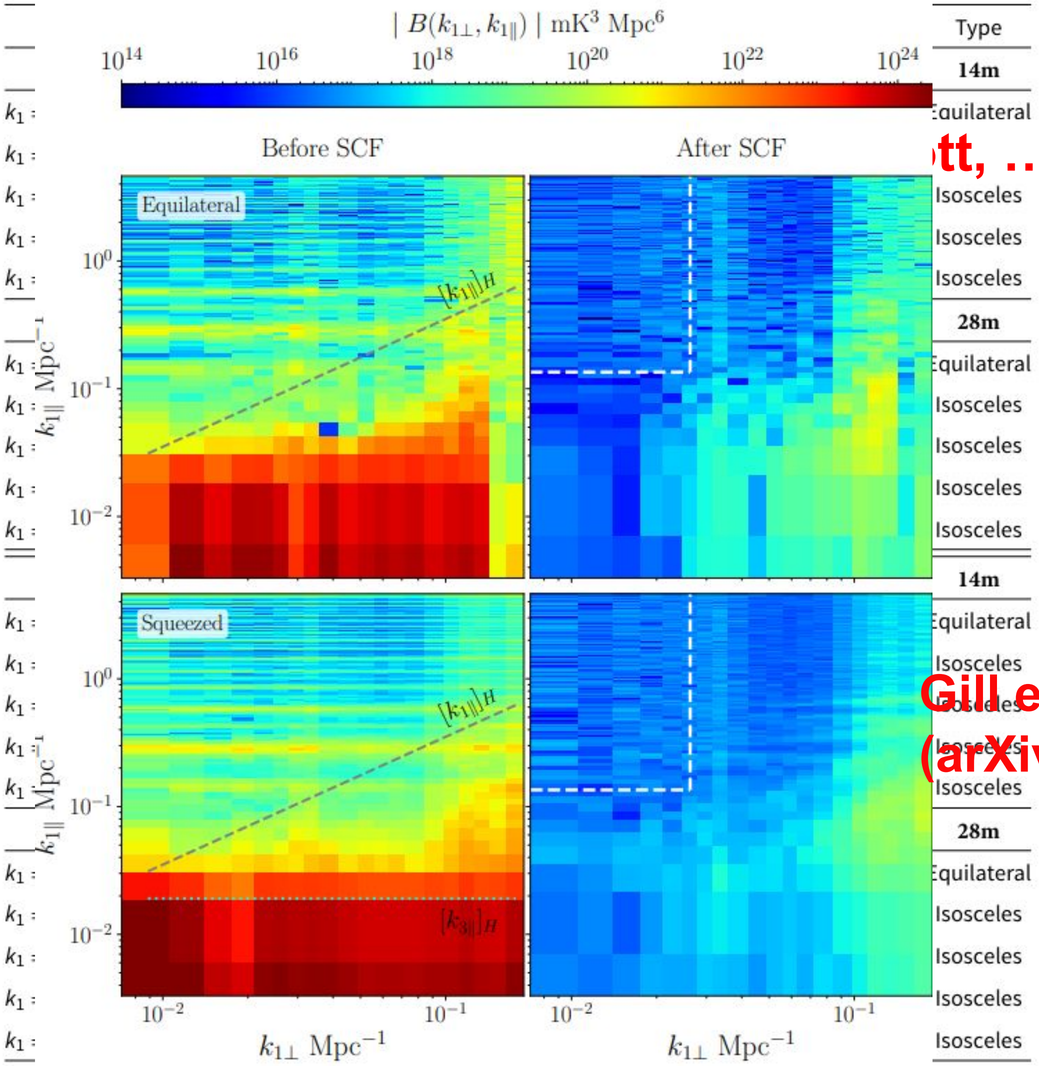


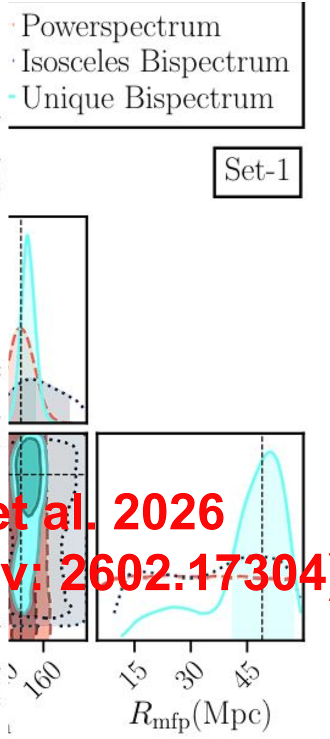
Mondal, …SM … al 2022

Detectabi … with SKA

…tt, …SM et al 2019





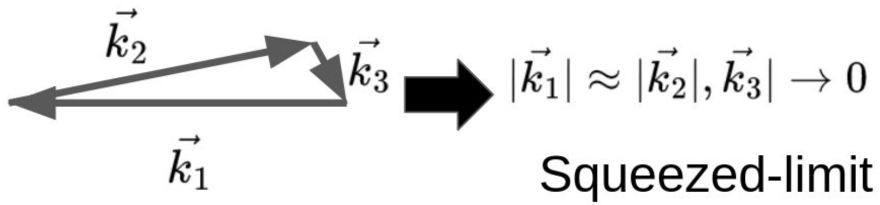


Gill et al. 2026 (arXiv: 2602.17304)

Mondal, …SM

al 2022

Squeezed-limit bispectrum



- **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, Gill et al. 2026**).**

- **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.

Mohammad Kamran

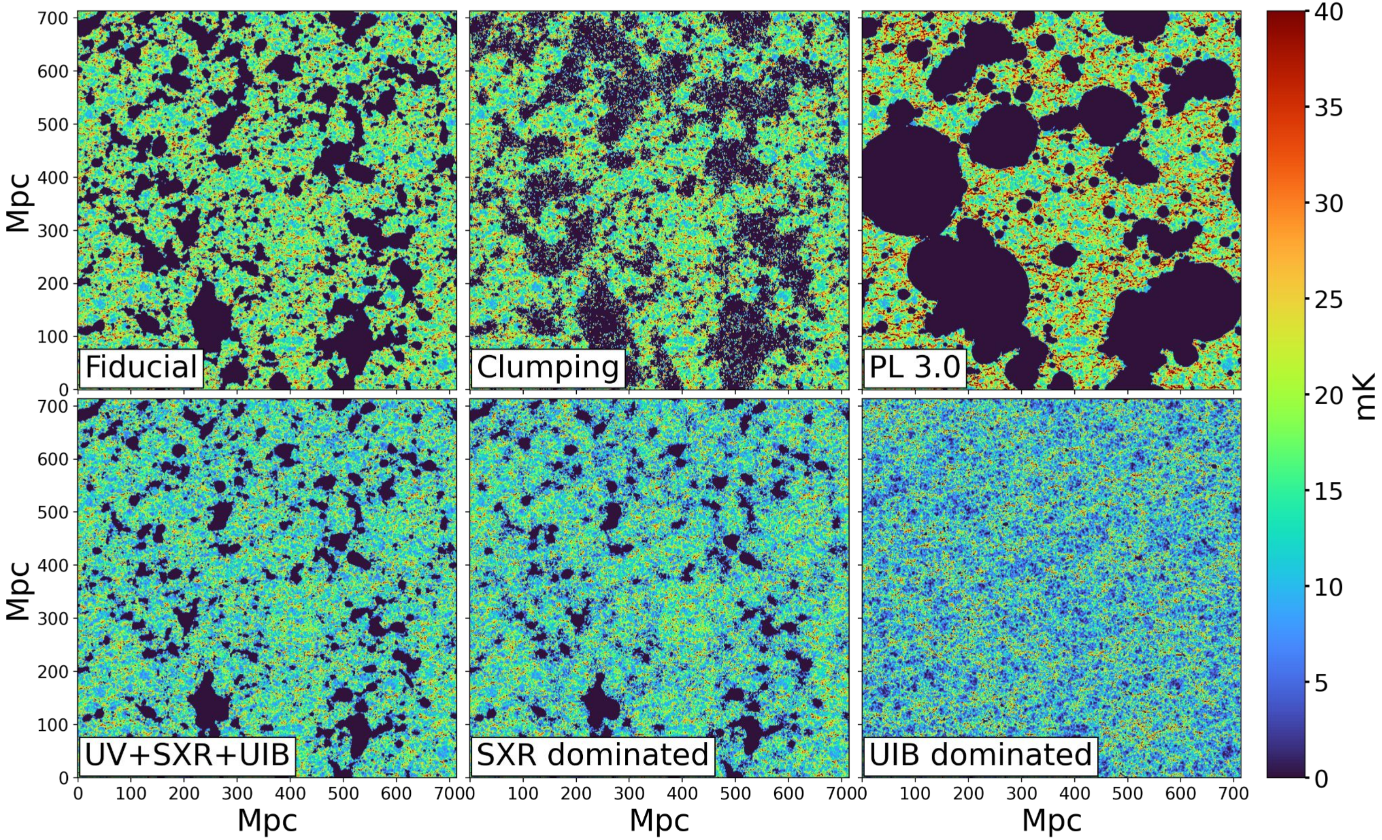
Postdoc at Trieste Observatory (2026 - Till date)
Postdoc at Uppsala University (2022 - 25)
PhD from IIT Indore (2022)

Leon Noble

PhD at IIT Indore (2022 - ongoing)

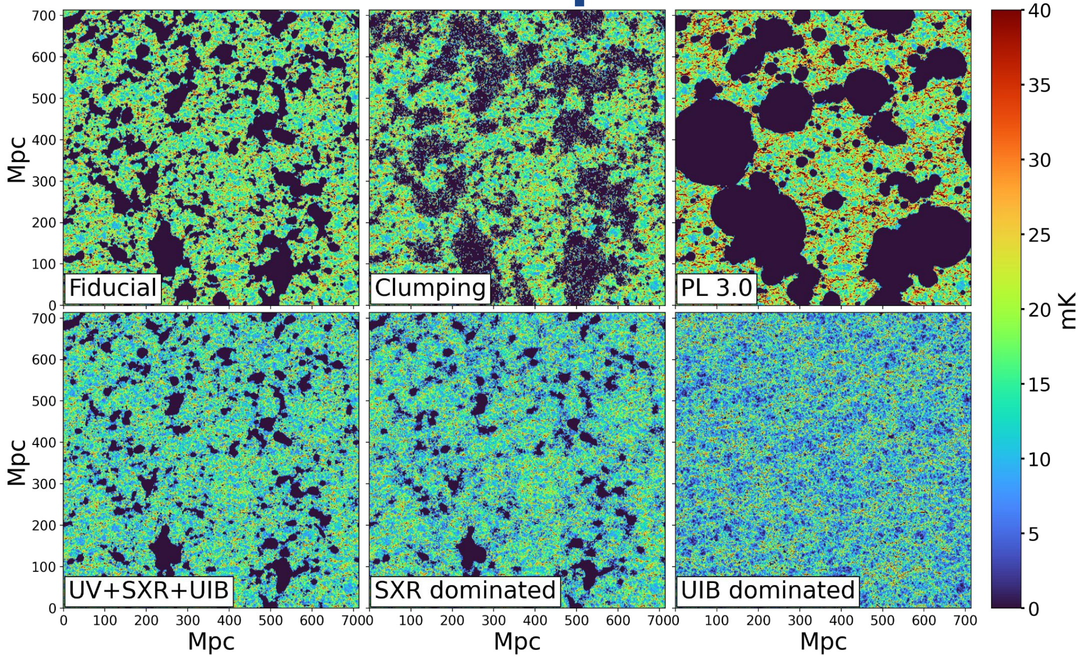
Collaborators: Suman Majumdar (IITI), Chandra Shekhar Murmu (Open University of Israel), Raghunath Ghara (IIT Kharagpur), Garrelt Mellema (Stockholm University), Ilian T. Iliev (University of Sussex) & Jonathan R. Pritchard (MPIfR, Bonn).

Impact of the sources of reionization on 21-cm signal



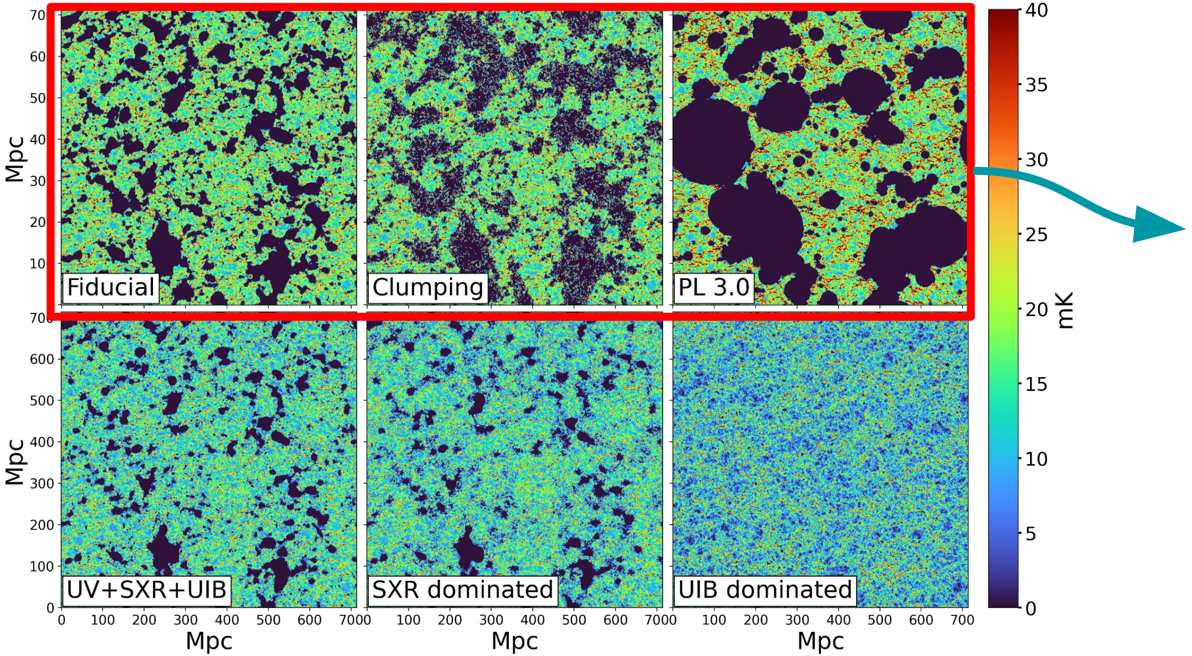
Choudhury et al 2009;
Watkinson et al. 2014;
Majumdar et al. 2016;
Eide et al. 2018;
Hutter et al. 2019;
Watkinson et al. 2021
Pathak et al. 2022;
Raste et al 2024;
Schaeffer et al 2024,……
and many more

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**

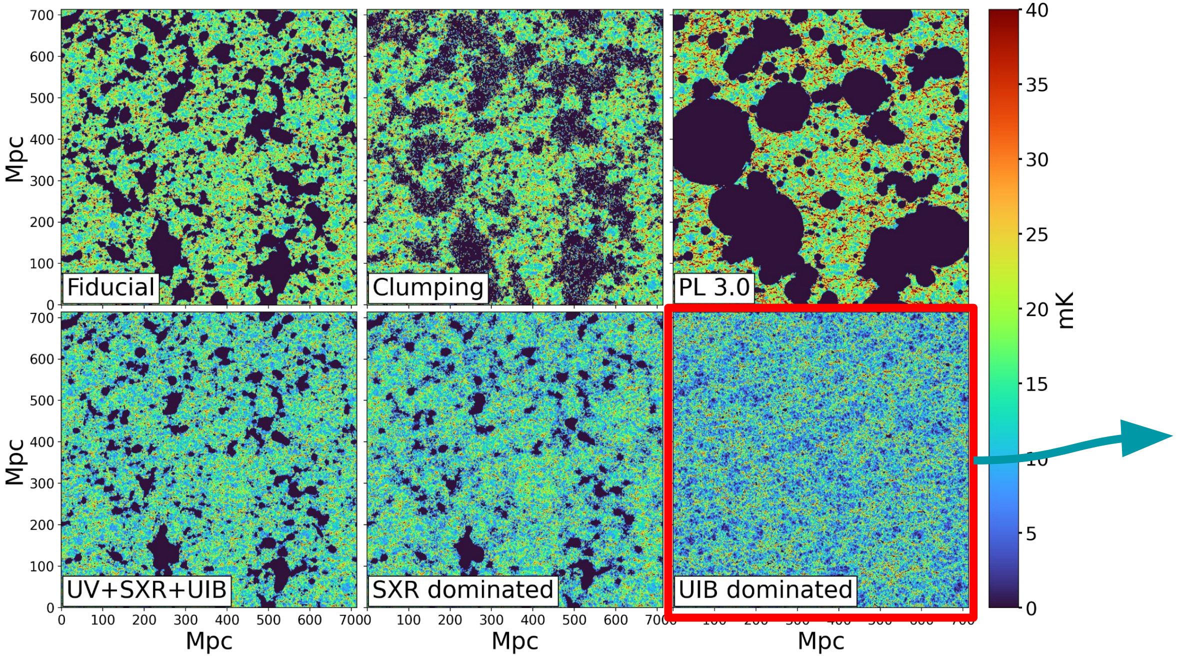
Reionization scenarios



Inside-out reionization scenarios

Noble, SM et al. 2024, arXiv: 2406.03118

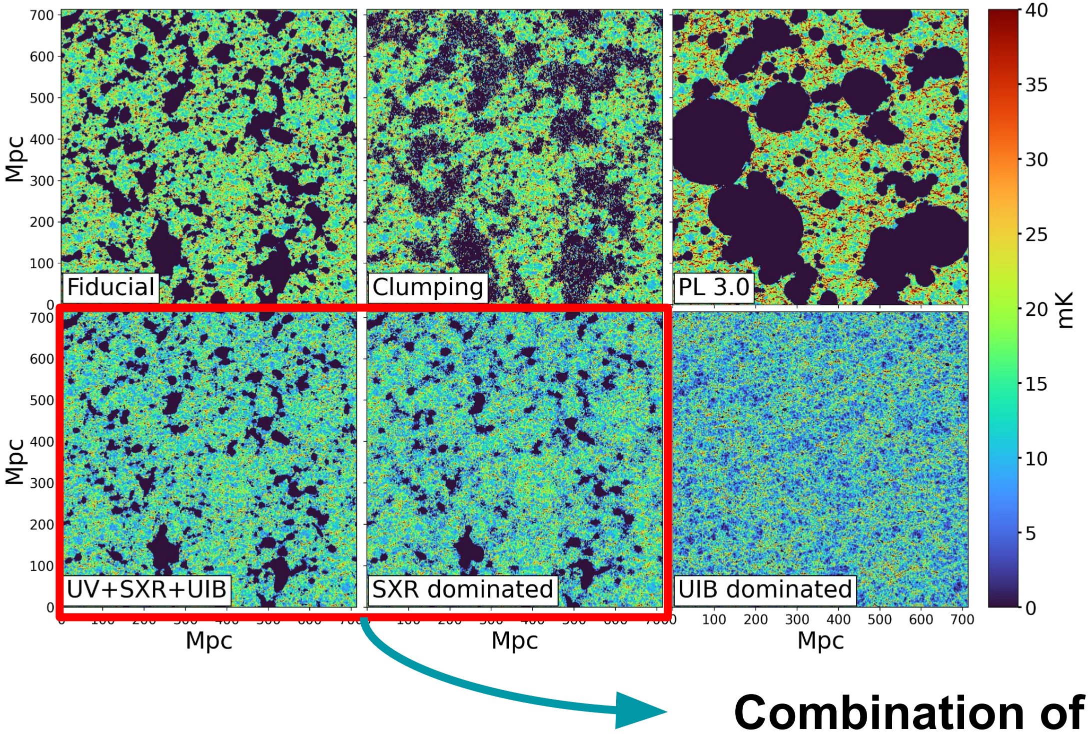
Reionization scenarios



Outside-in reionization scenario

Noble, SM et al. 2024, arXiv: 2406.03118

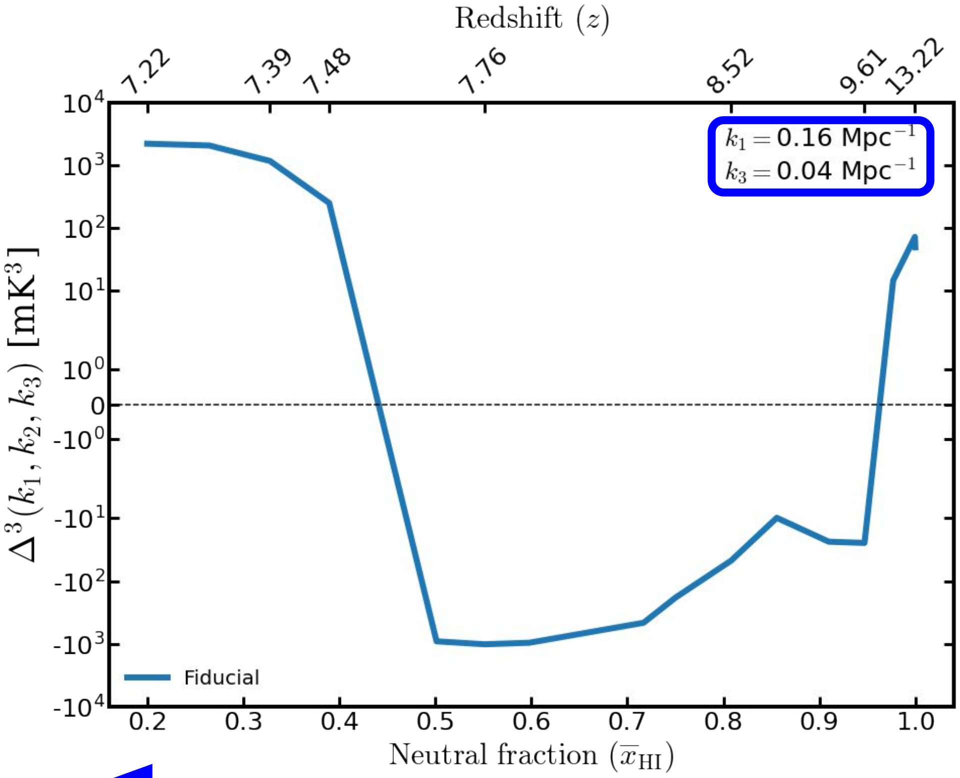
Reionization scenarios



Combination of inside-out and outside-in

Noble, SM et al. 2024, arXiv: 2406.03118

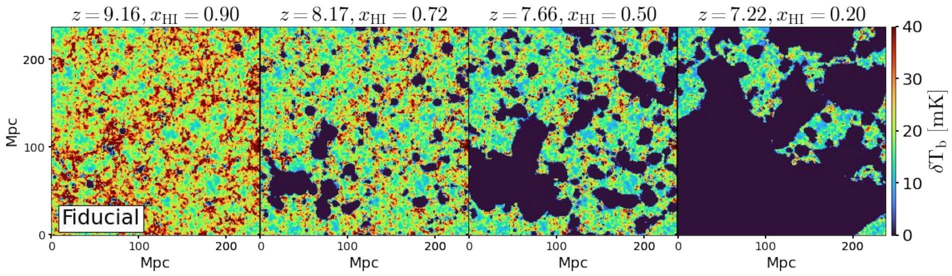
Evolution of squeezed-limit bispectrum



Progress of reionization

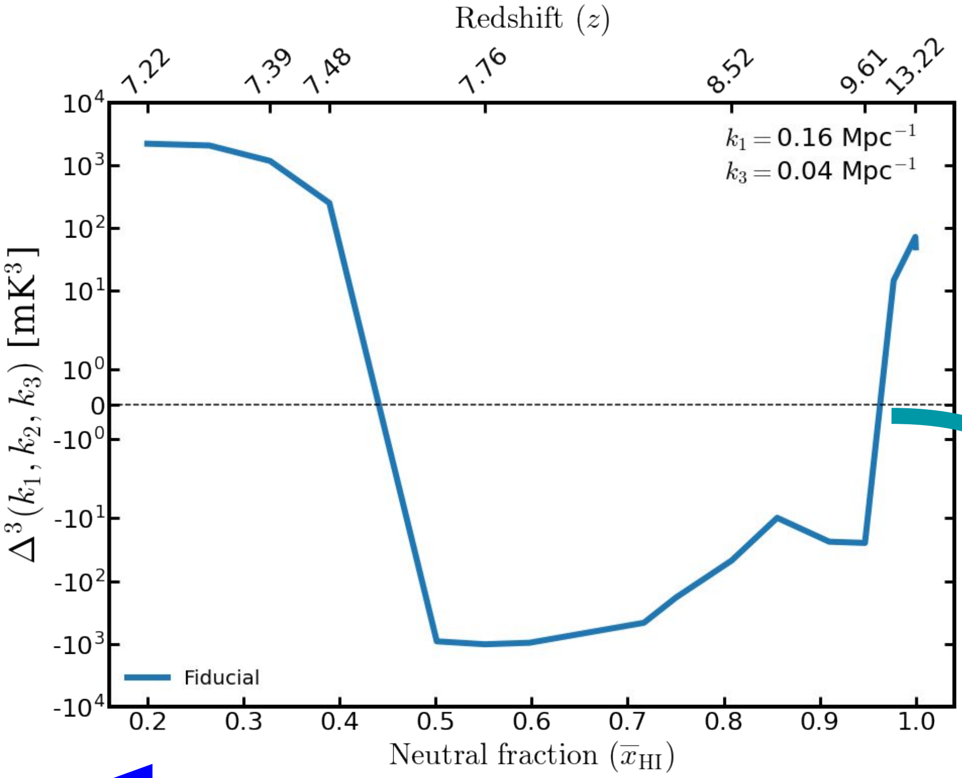
Early stage

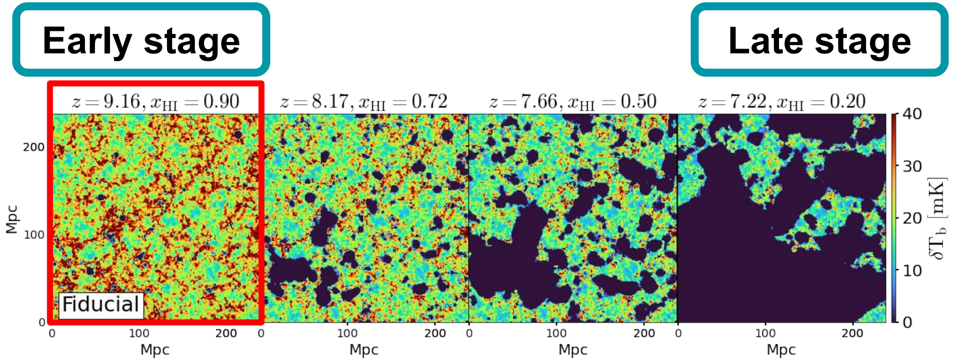
Late stage



Noble, SM et al. 2024, arXiv: 2406.03118

Evolution of squeezed-limit bispectrum



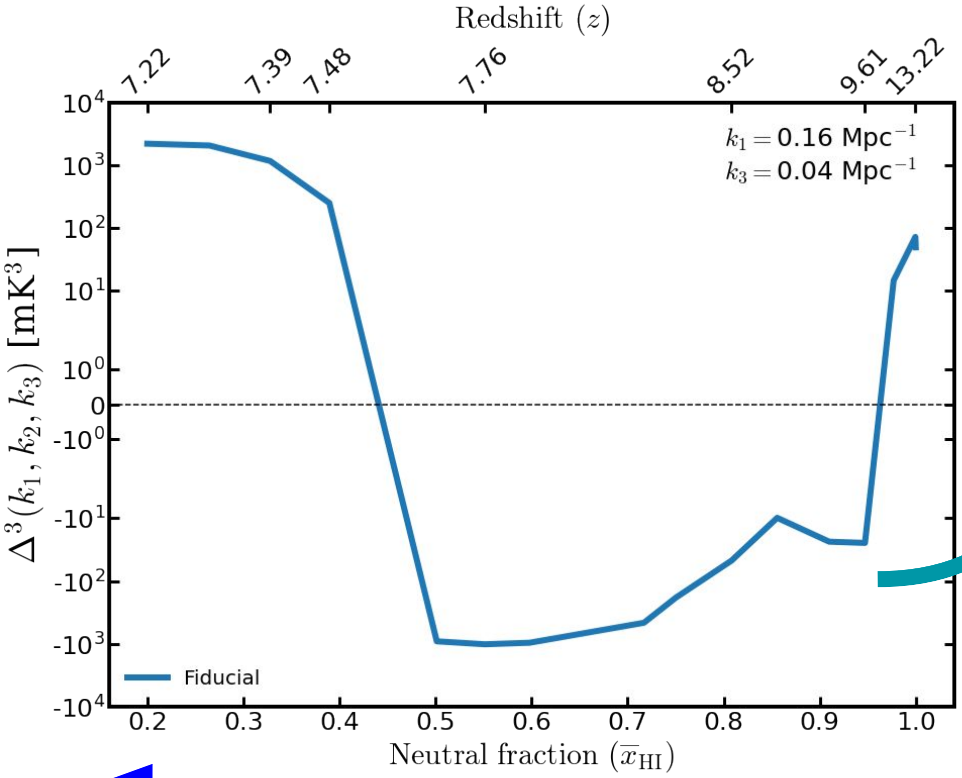


Change in the sign of the bispectrum

Noble, SM et al. 2024, arXiv: 2406.03118

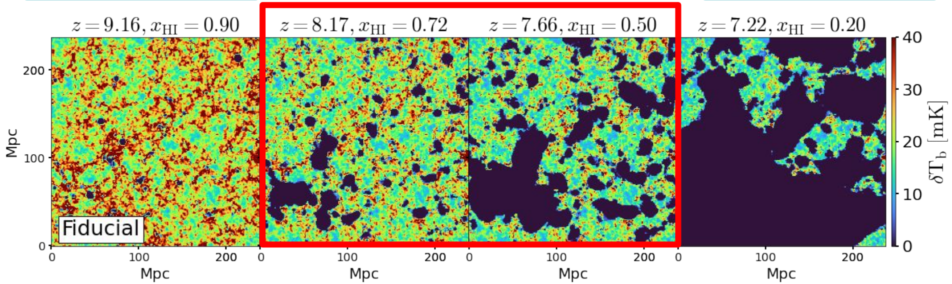
Progress of reionization

Evolution of squeezed-limit bispectrum



Early stage

Late stage

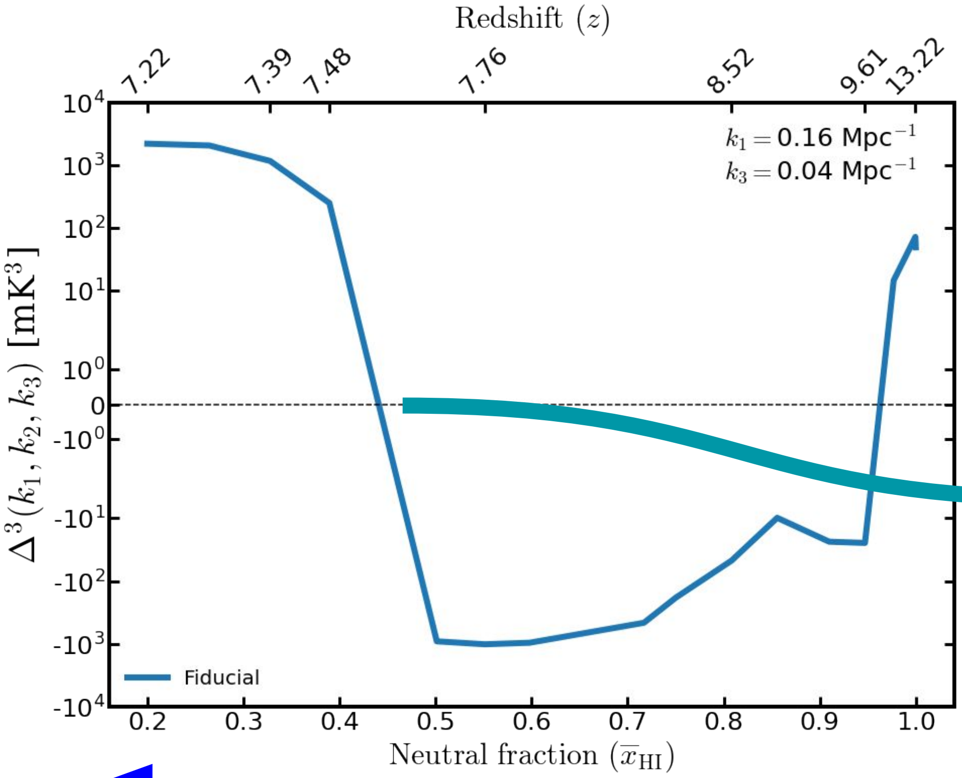


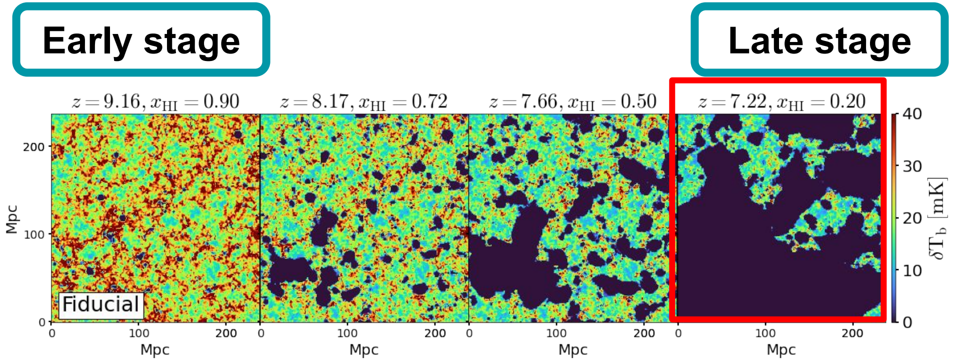
Magnitude of the 21-cm bispectrum increases

Progress of reionization

Noble, SM et al. 2024, arXiv: 2406.03118

Evolution of squeezed-limit bispectrum



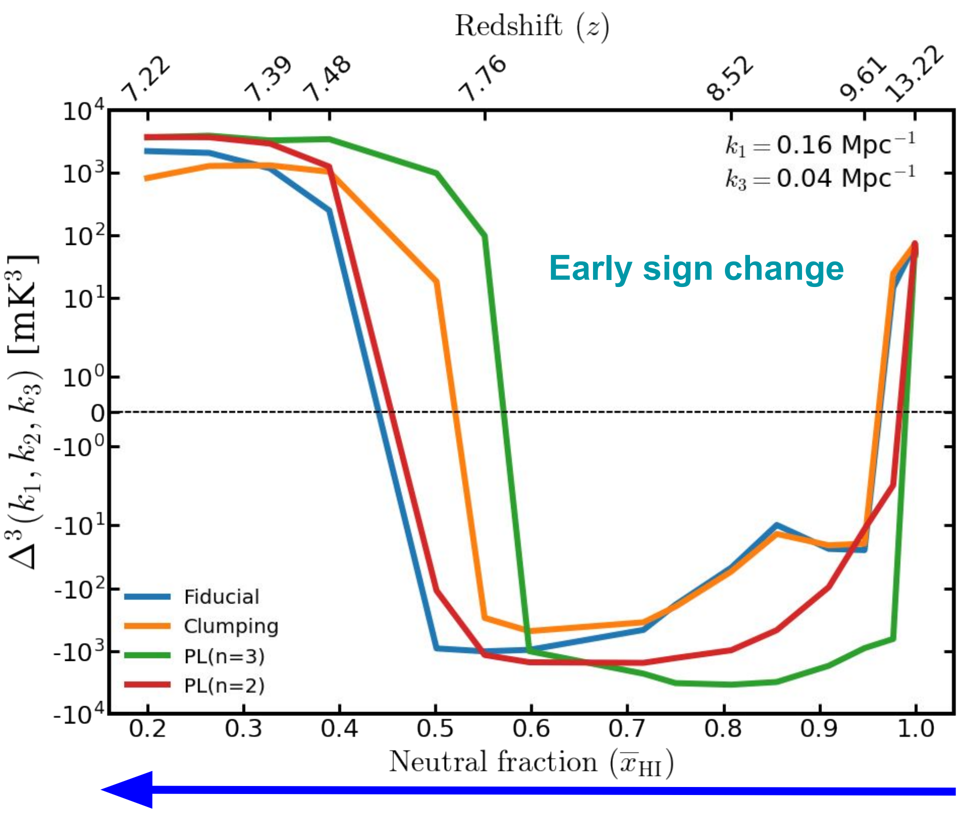


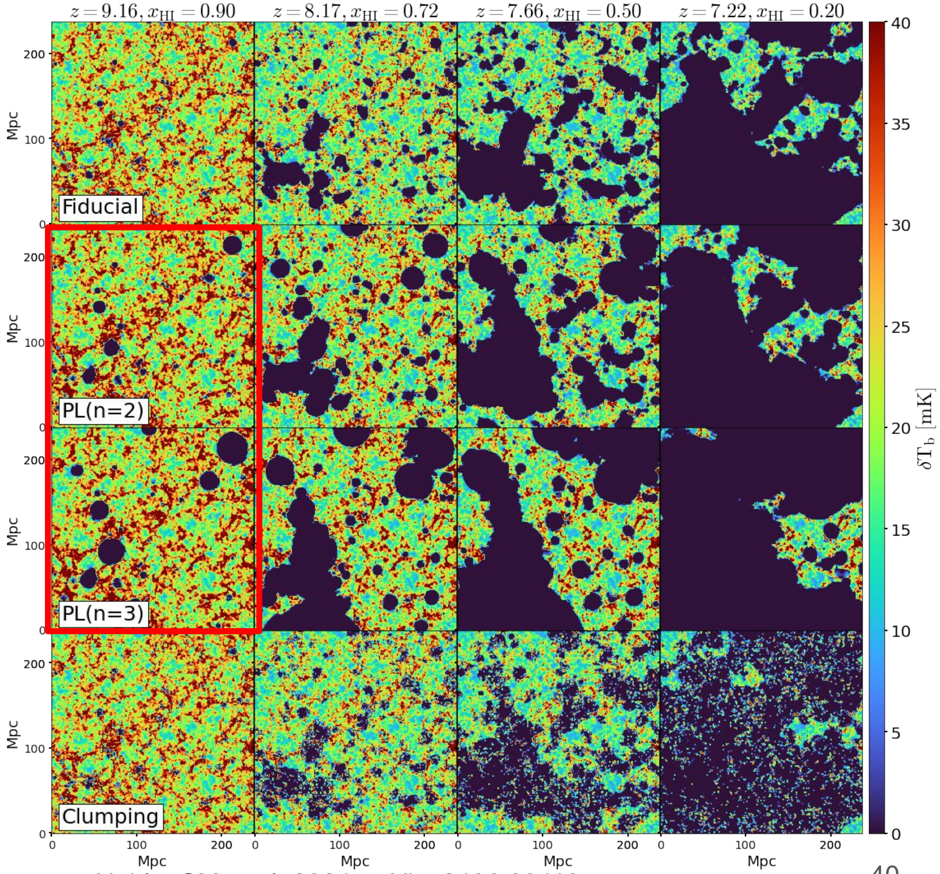
Second sign change in the 21-cm bispectrum

Progress of reionization

Noble, SM et al. 2024, arXiv: 2406.03118

Evolution of squeezed-limit bispectrum: Inside-out scenarios

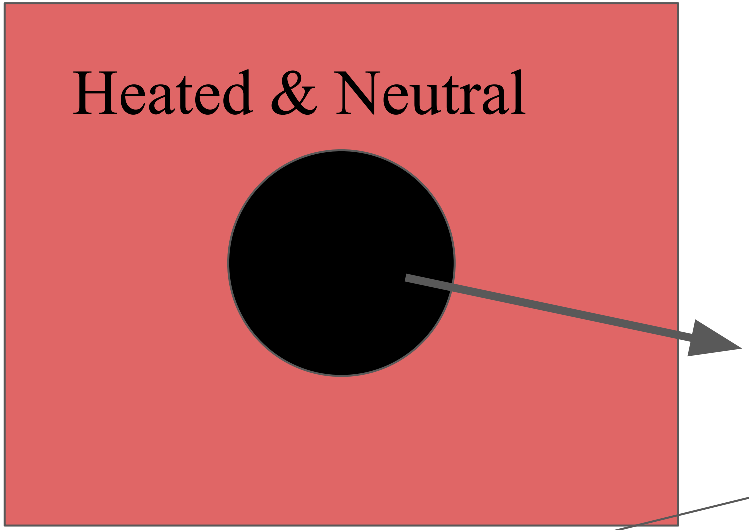




Progress of reionization

Noble, SM et al. 2024, arXiv: 2406.03118

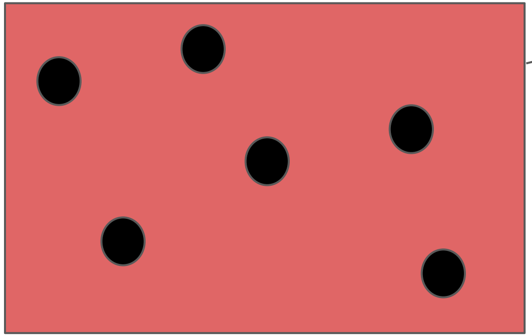
Interpretation



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

Ionized

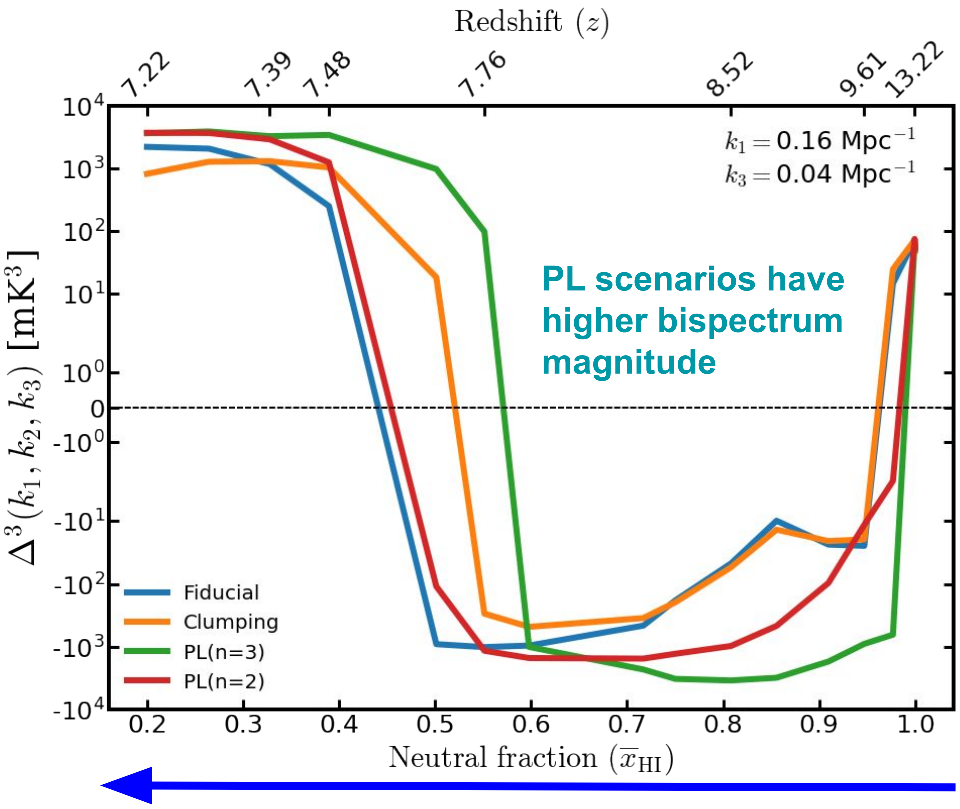
Many non-overlapping ionized regions



Large scale signal -ve

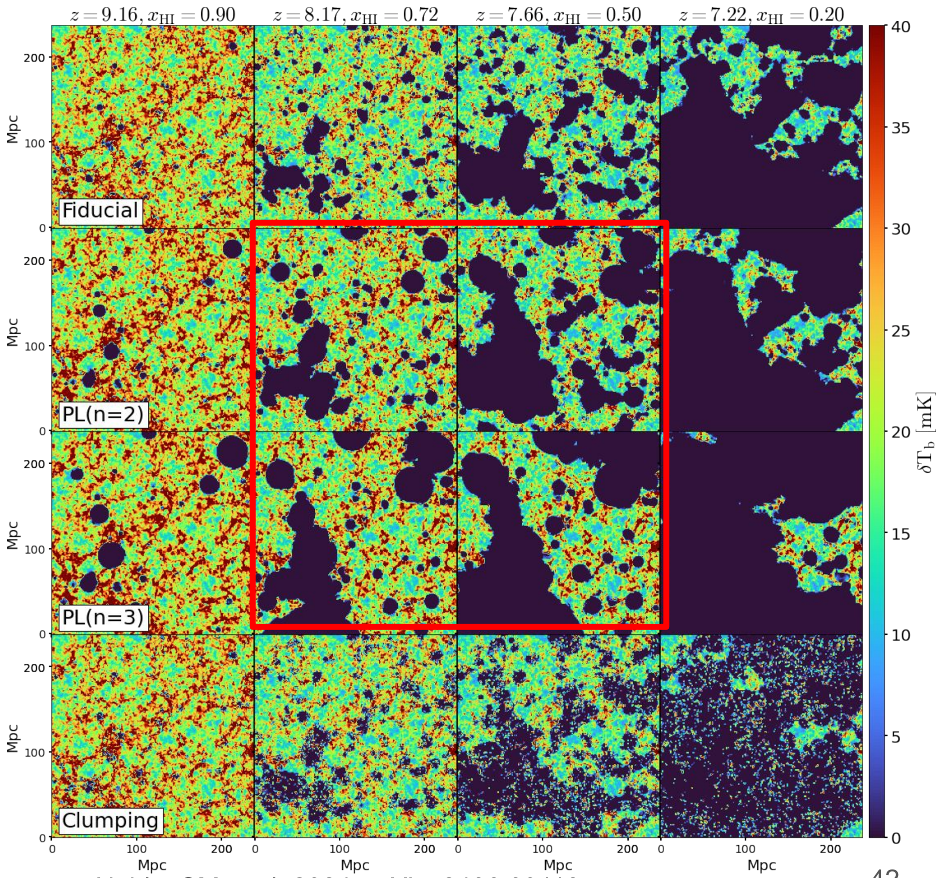
Bharadwaj & Ali 2004
Bharadwaj & Pandey 2005

Evolution of squeezed-limit bispectrum: Inside-out scenarios



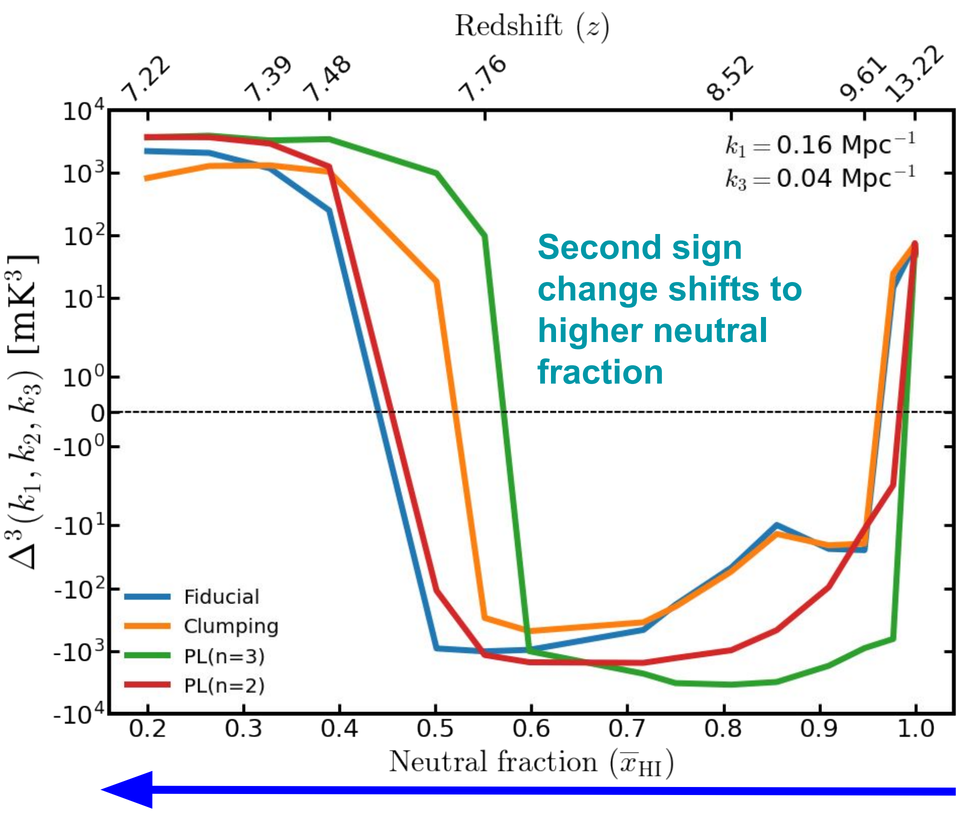
PL scenarios have higher bispectrum magnitude

Progress of reionization

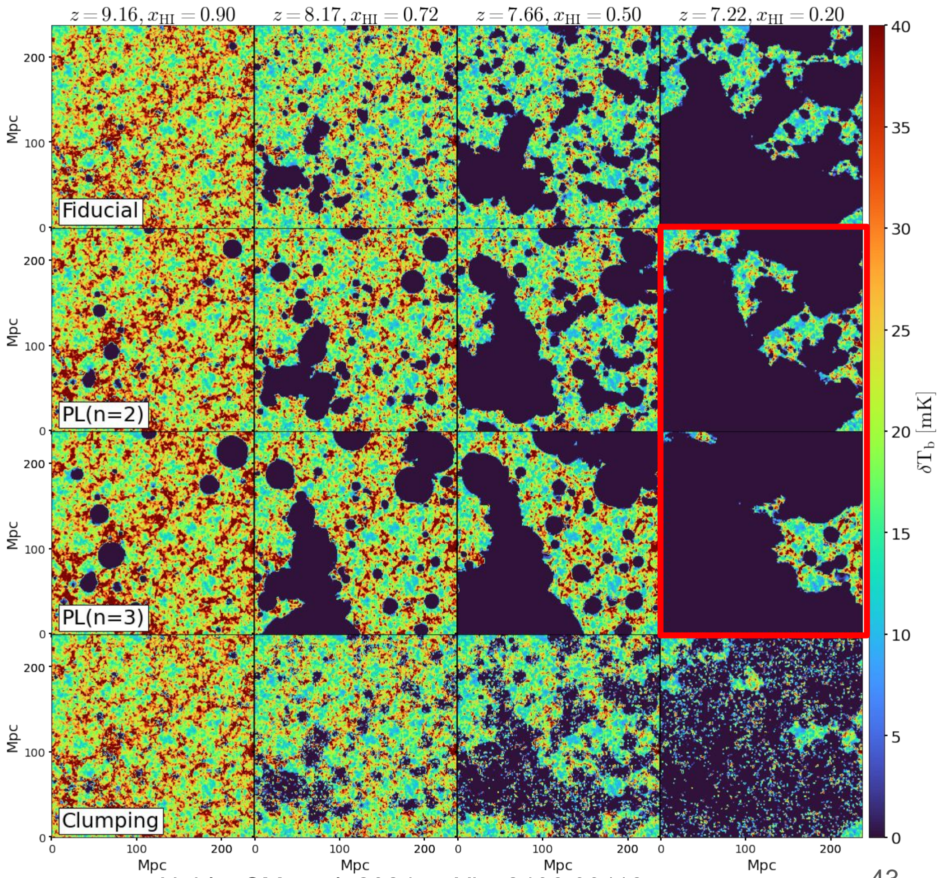


Noble, SM et al. 2024, arXiv: 2406.03118

Evolution of squeezed-limit bispectrum: Inside-out scenarios



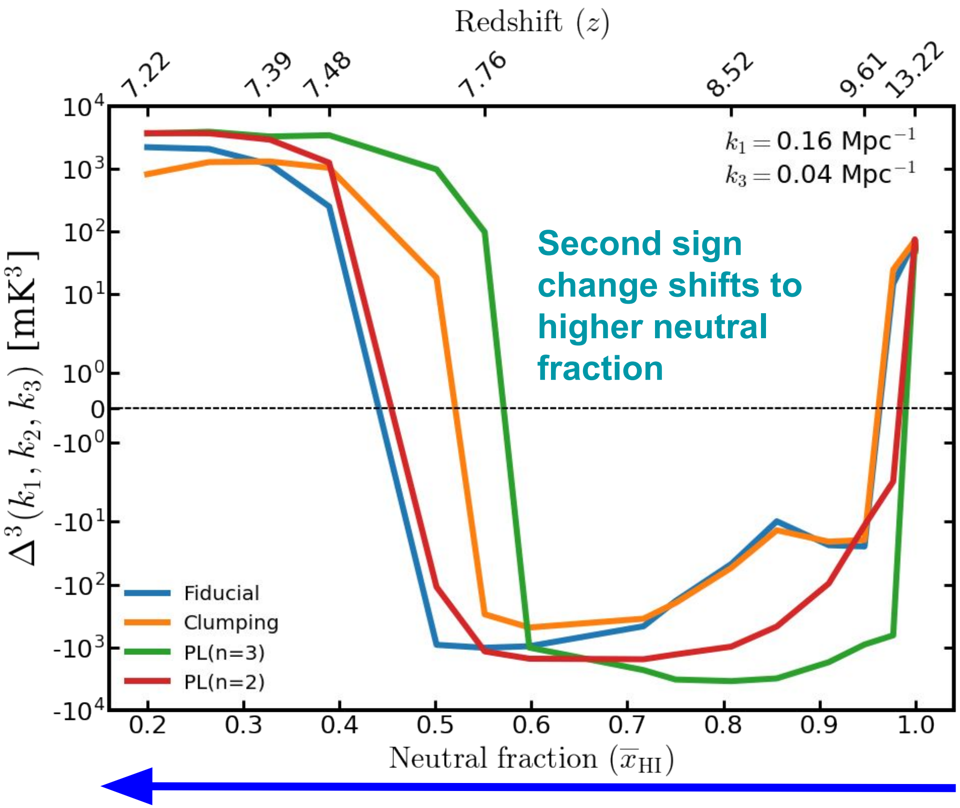
Second sign change shifts to higher neutral fraction

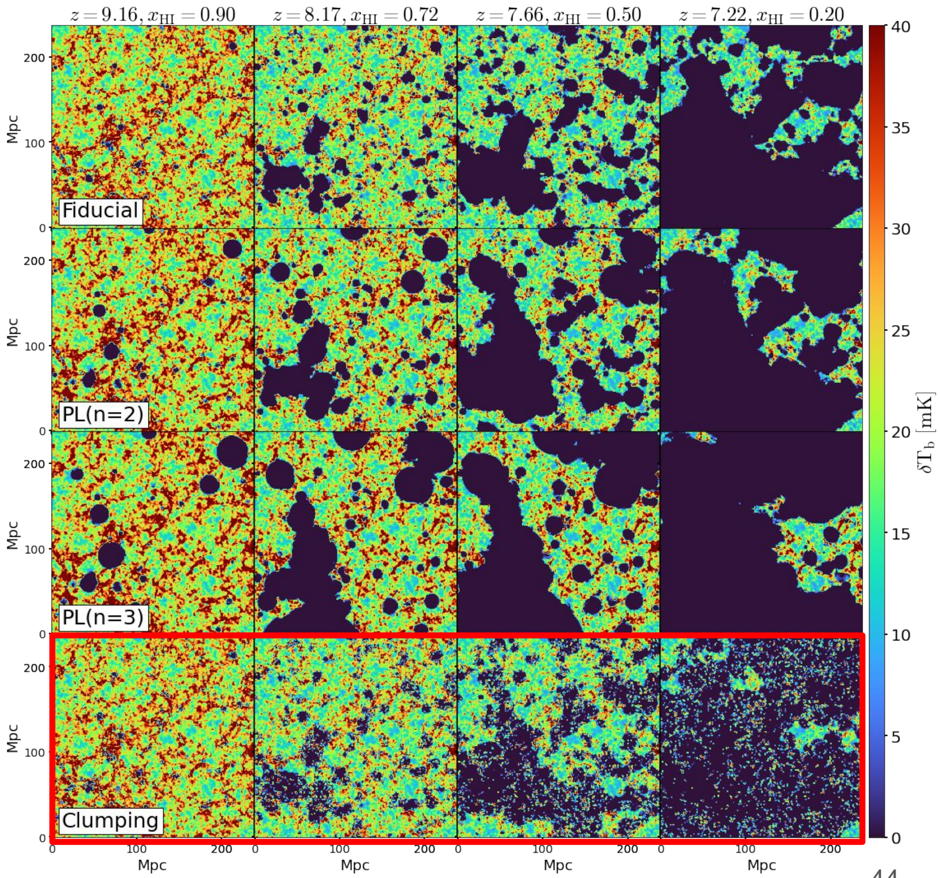


Progress of reionization

Noble, SM et al. 2024, arXiv: 2406.03118

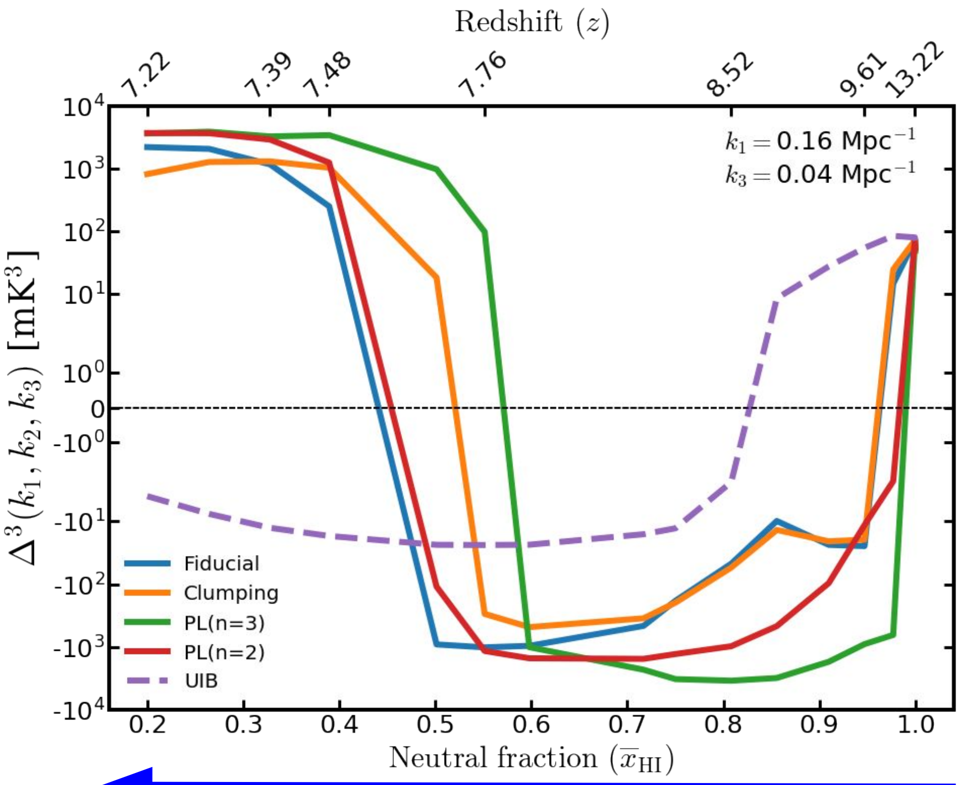
Evolution of squeezed-limit bispectrum: Inside-out scenarios

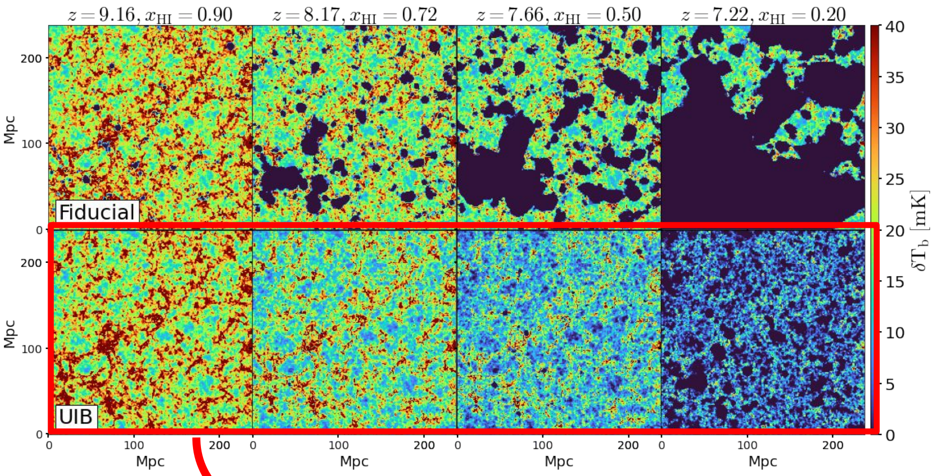




Progress of reionization

Evolution of squeezed-limit bispectrum: Outside-in scenario



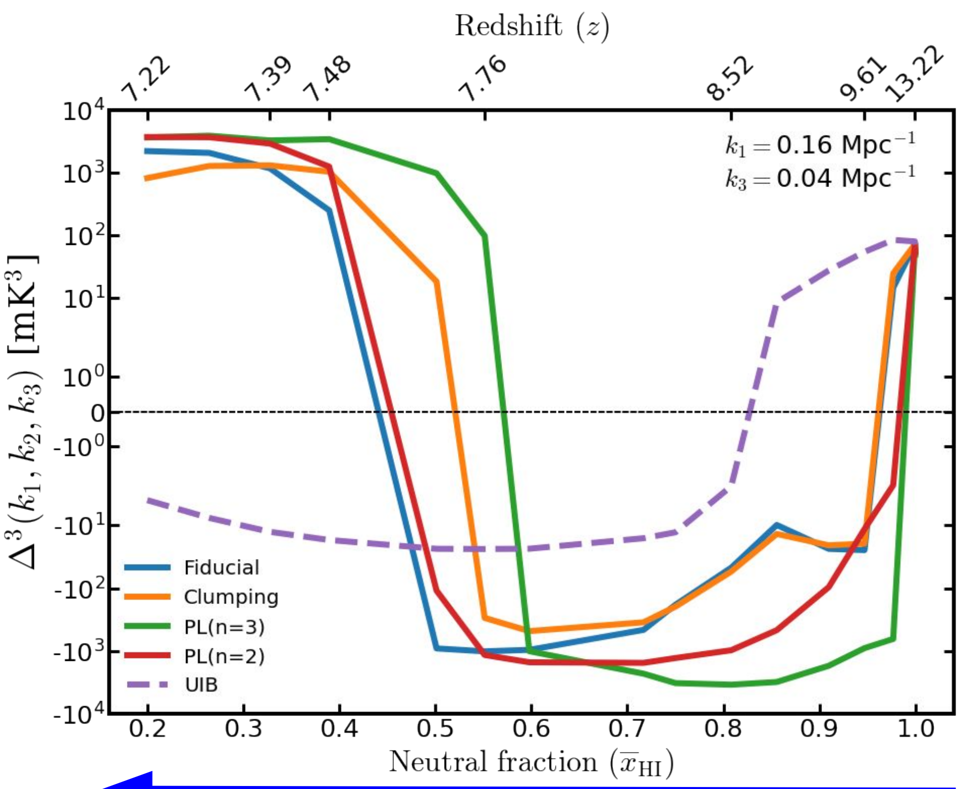


Progress of reionization

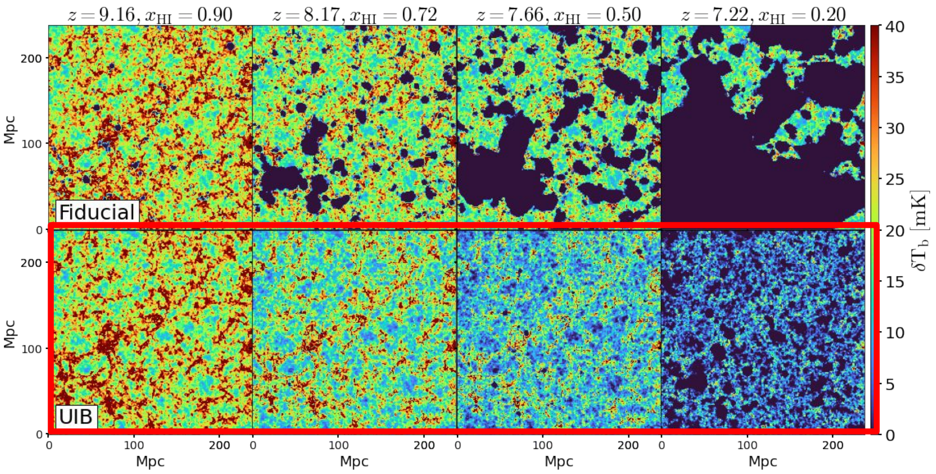
Outside-in reionization scenario

Noble, SM et al. 2024, arXiv: 2406.03118

Evolution of squeezed-limit bispectrum: Outside-in scenario



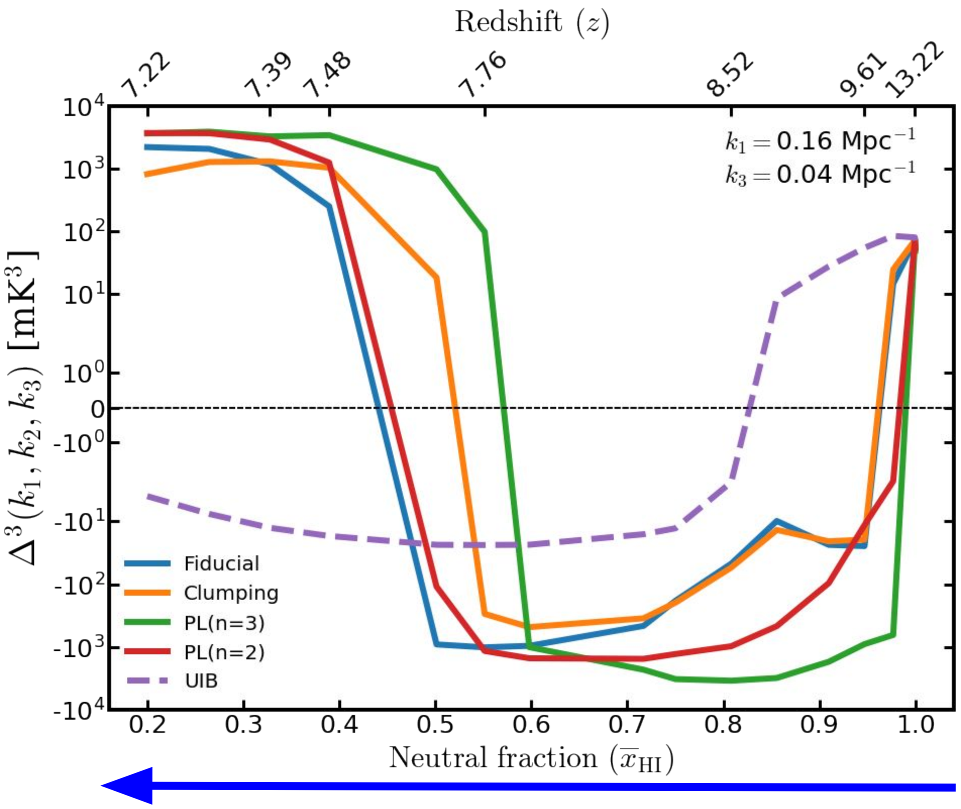
Progress of reionization

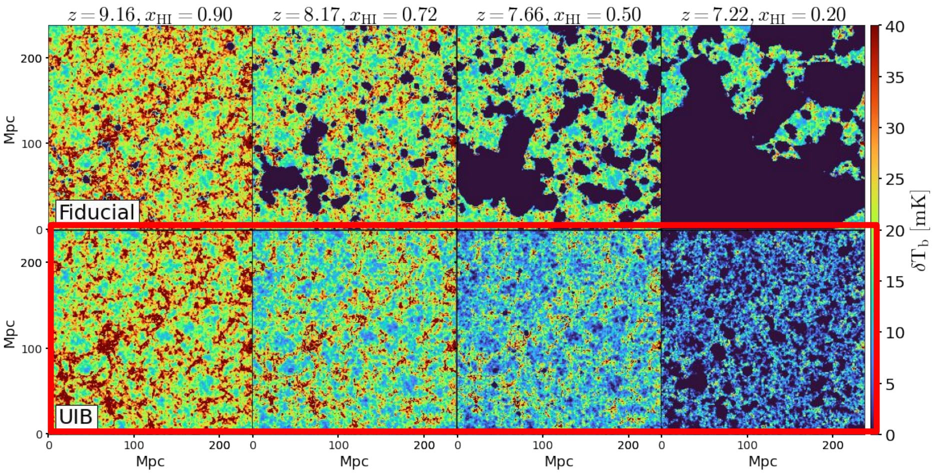


- **First change in the sign of bispectrum happens at a later stage of reionization**
- **Magnitude of the bispectrum is lower than inside-out scenarios**

Noble, SM et al. 2024, arXiv: 2406.03118

Evolution of squeezed-limit bispectrum: Outside-in scenario

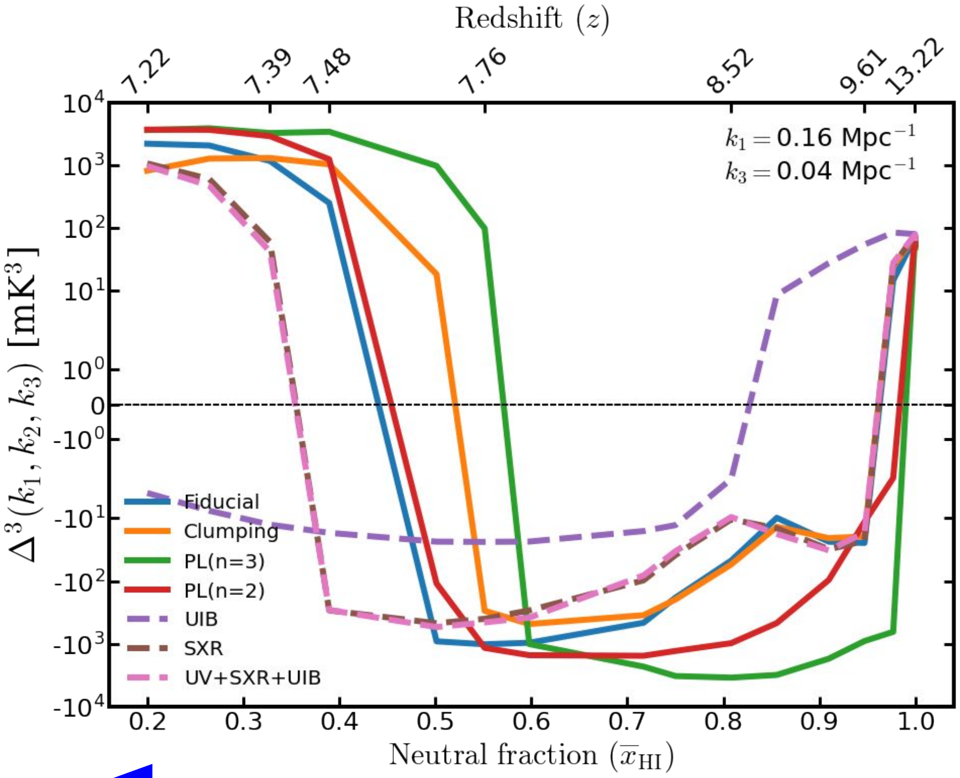


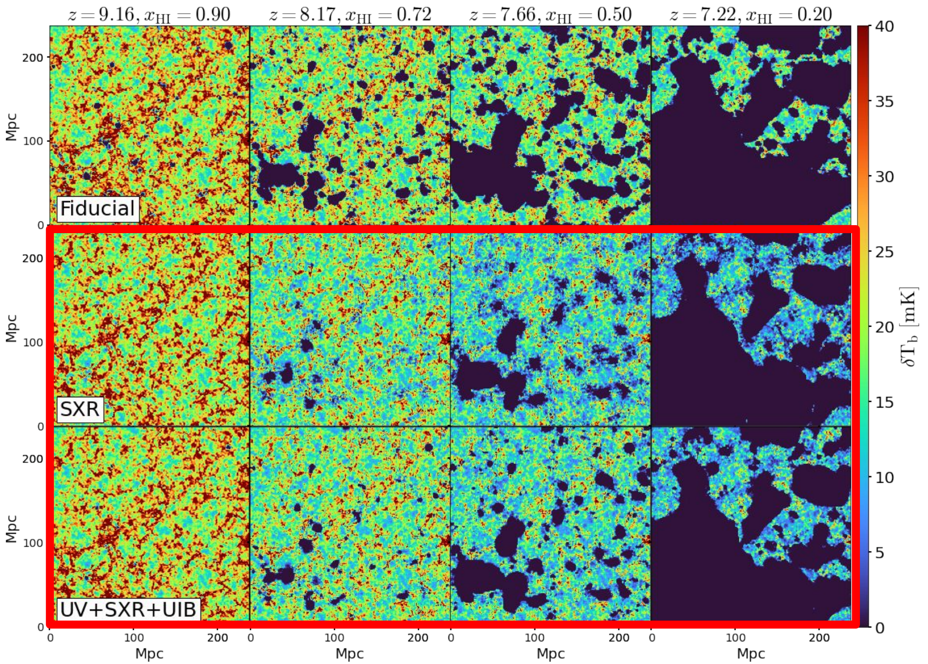


Progress of reionization

- 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



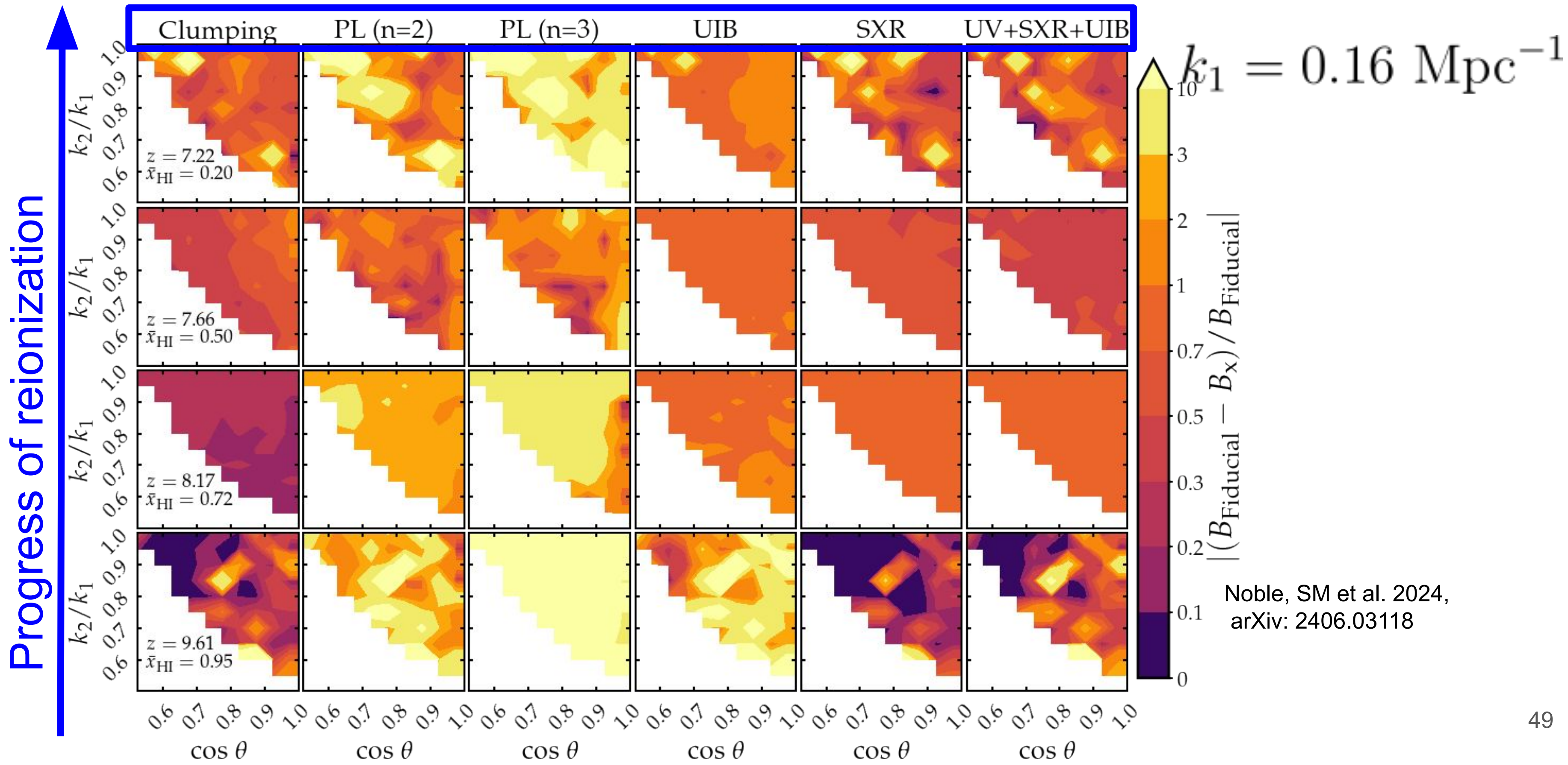


Progress of reionization

Second sign change shifts to lower neutral fraction

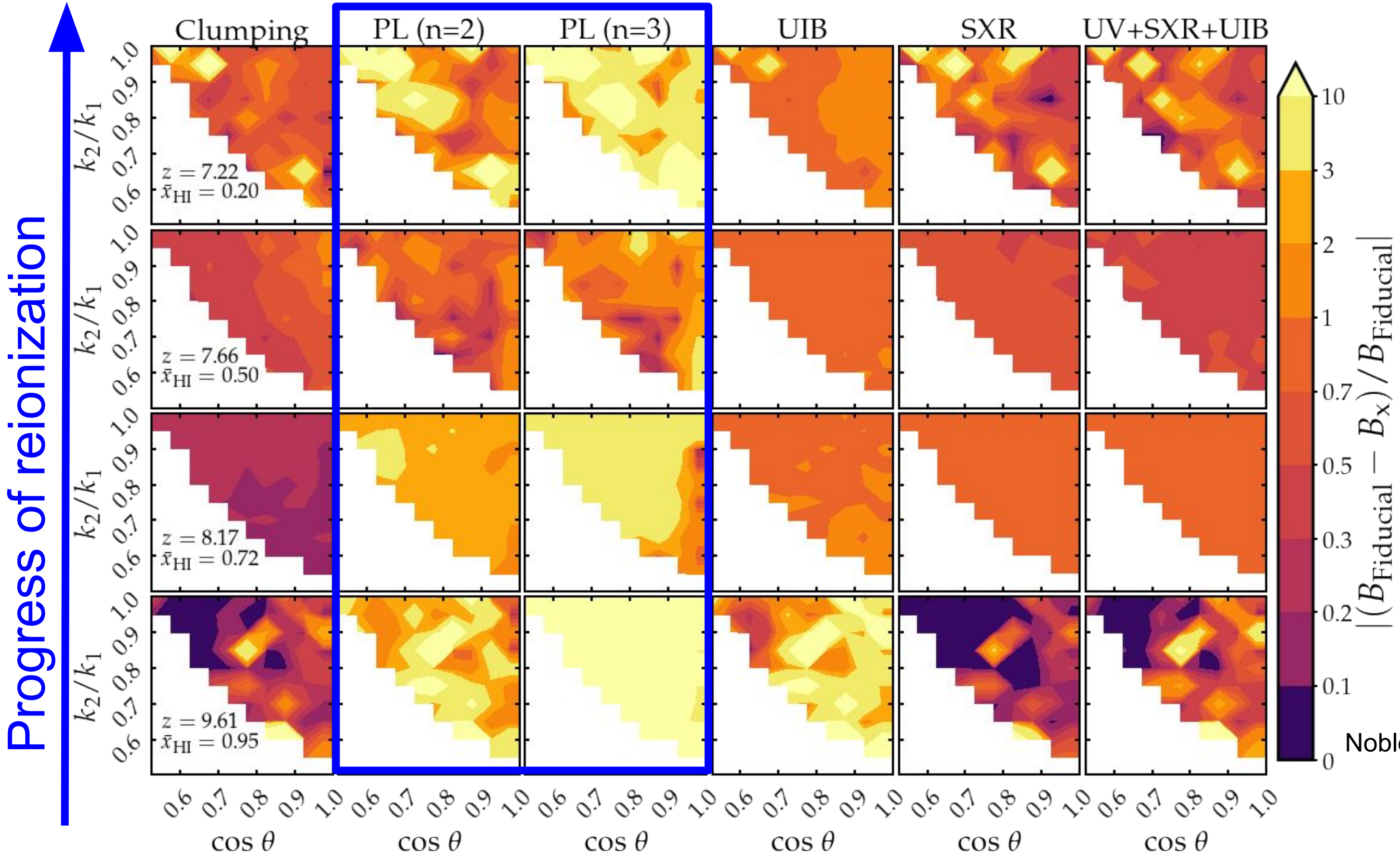
Noble, SM et al. 2024, arXiv: 2406.03118

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



Noble, SM et al. 2024, arXiv: 2406.03118

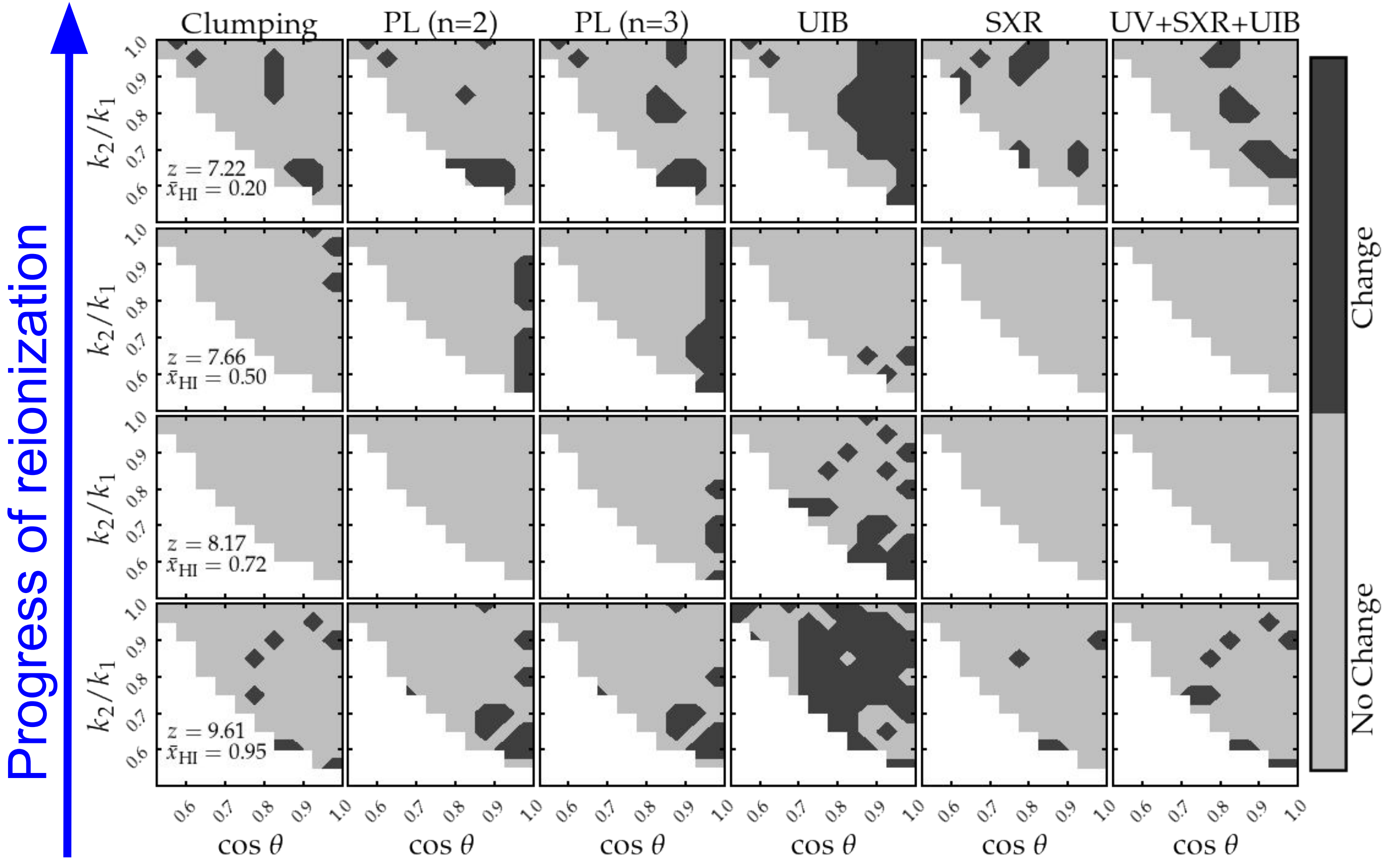
Magnitude differences in 21-cm bispectrum between different reionization scenarios w. r. t. Fiducial



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

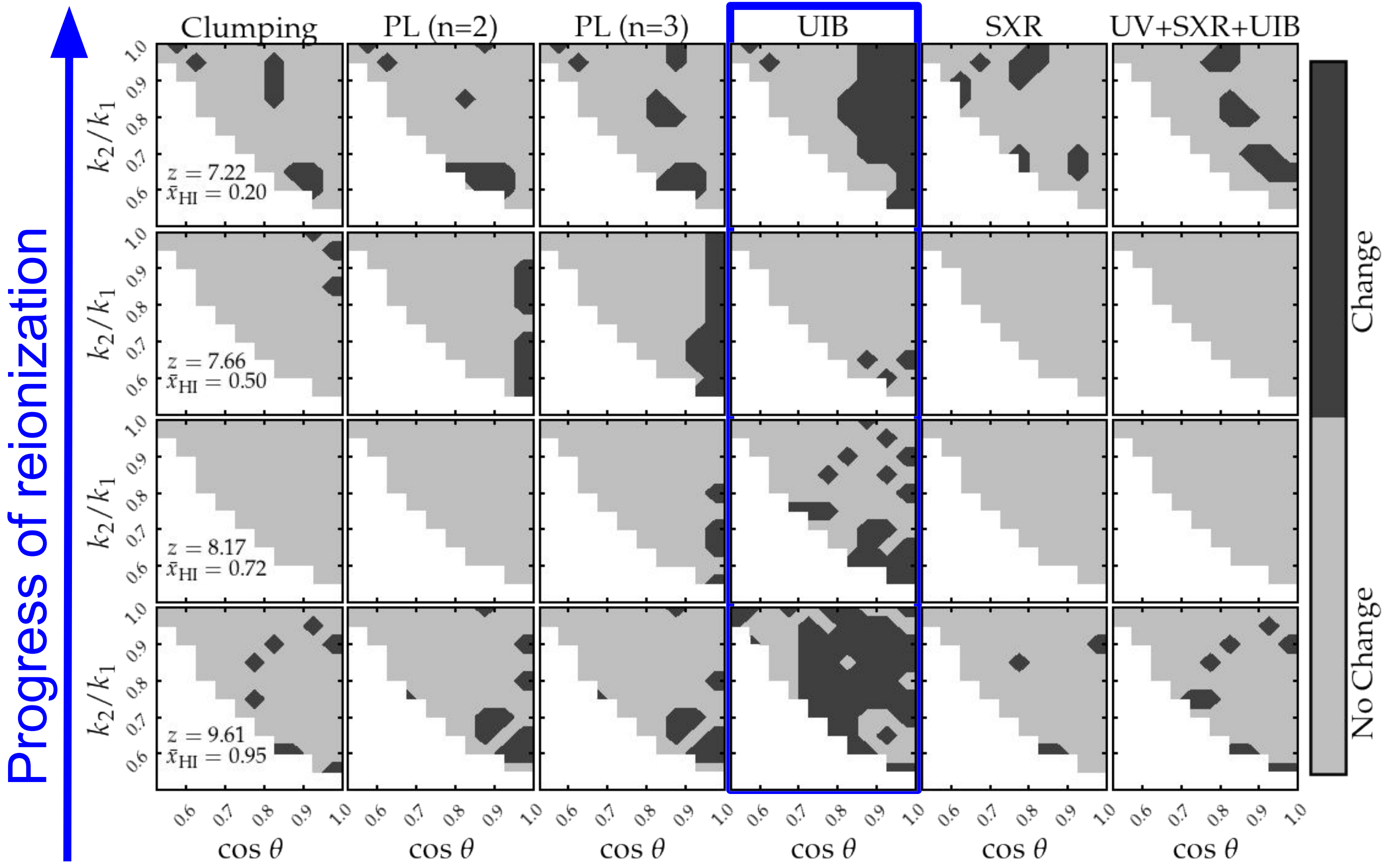
Noble et al. 2024, arXiv: 2406.03118

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



Noble et al. 2024, arXiv: 2406.03118

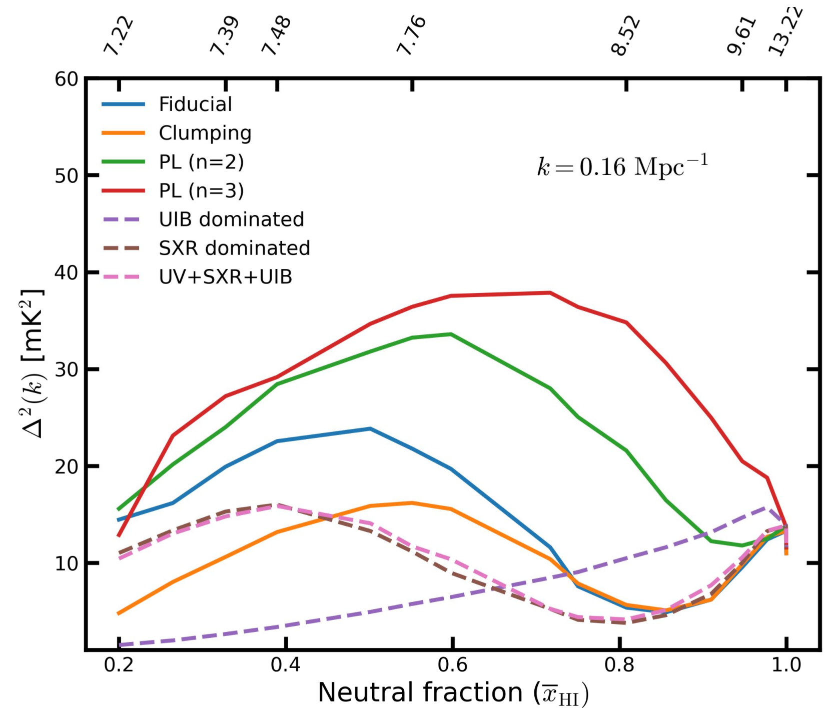
Sign differences in 21-cm bispectrum between different reionization scenarios w. r. t. Fiducial



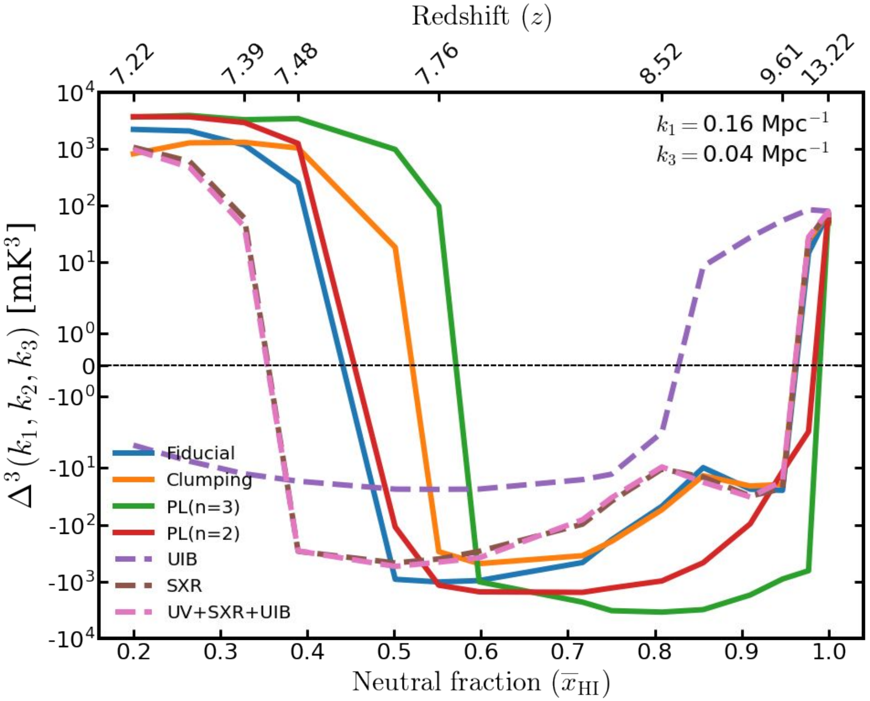
Change is highest in UIB scenario

Noble et al. 2024, arXiv: 2406.03118

Power spectrum vs bispectrum

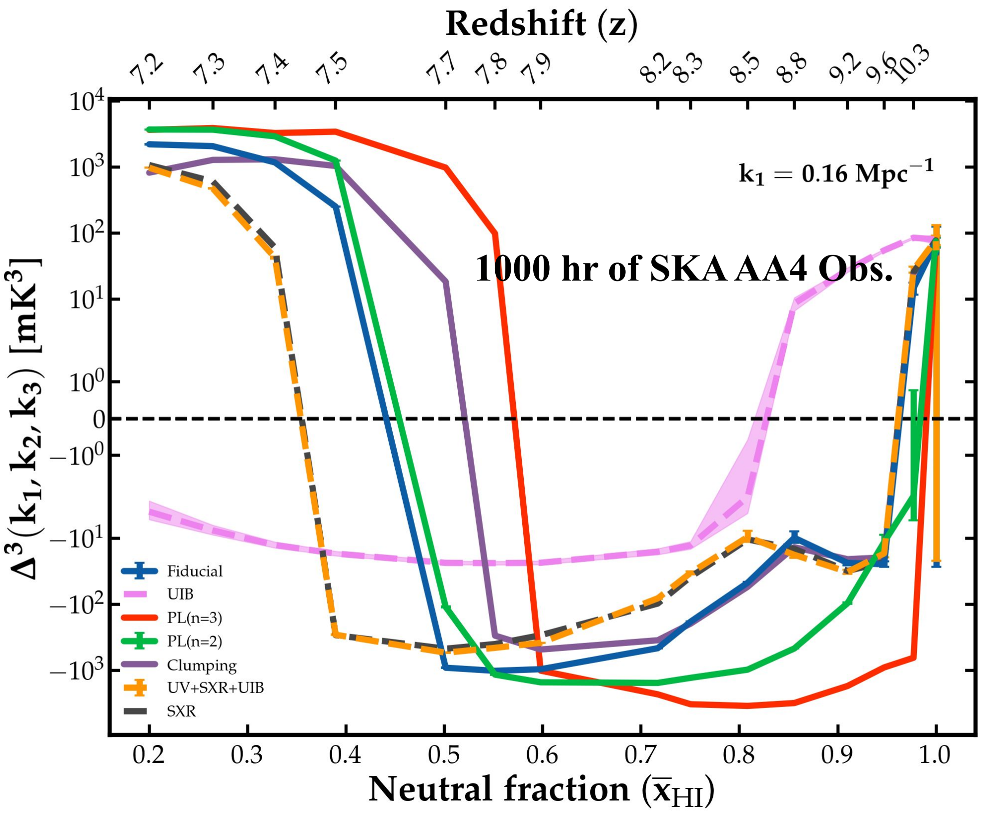


Majumdar et al. 2016, arXiv: 1509.07518



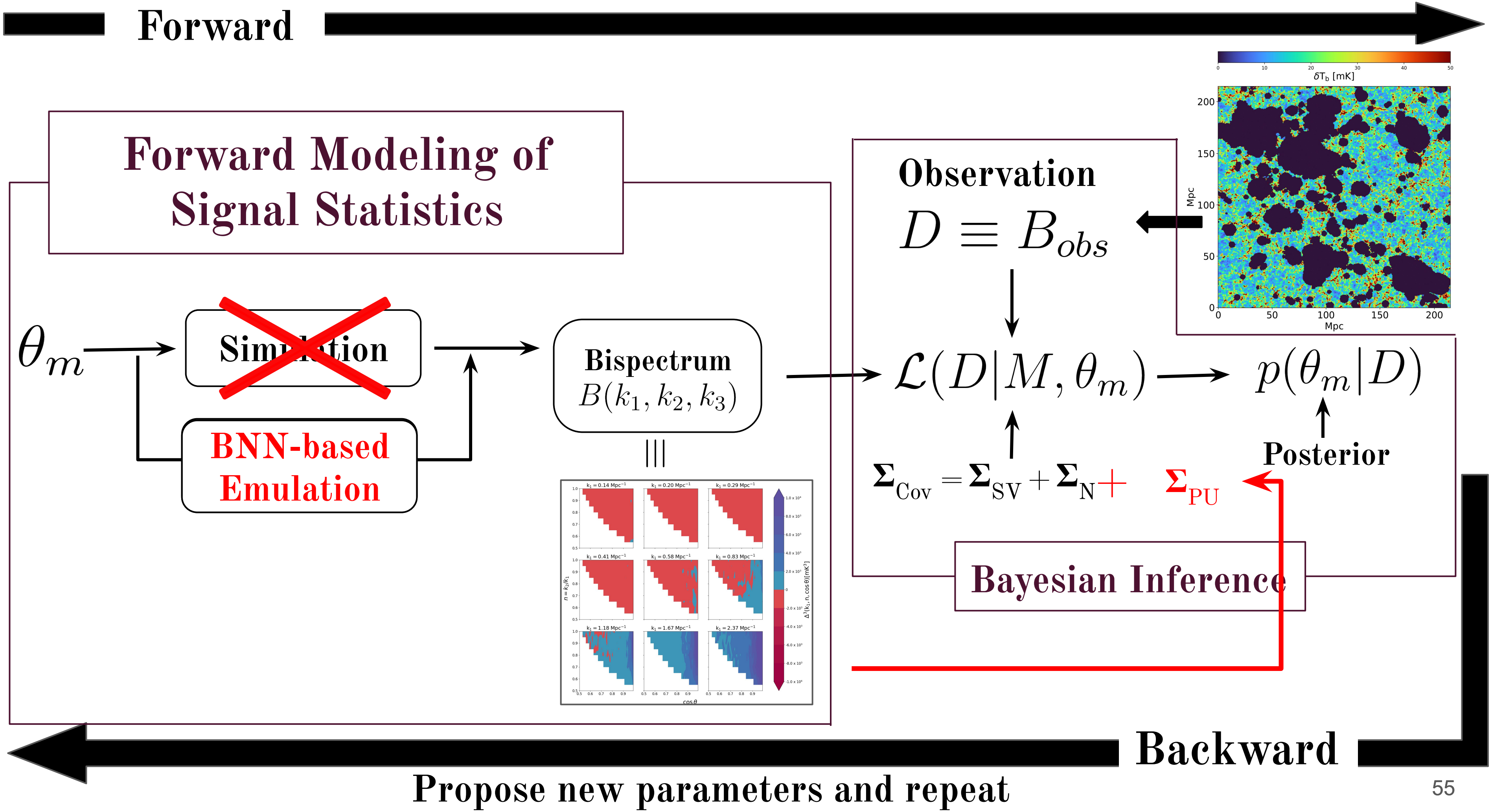
Noble,.., SM,.. et al. 2024, arXiv: 2406.03118

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., JCAP, 2024, arXiv: 2406.03118



Forward
Forward Modeling of Signal Statistics
θ_m
Simulation
BNN-based Emulation
Bispectrum
$B(k_1, k_2, k_3)$
Observation
$D \equiv B_{obs}$
$\mathcal{L}(D|M, \theta_m)$
$p(\theta_m|D)$
Posterior
$\mathbf{\Sigma}_{\rm Cov} = \mathbf{\Sigma}_{\rm SV} + \mathbf{\Sigma}_{\rm N} + \mathbf{\Sigma}_{\rm PU}$
Bayesian Inference
Backward
Propose new parameters and repeat
δT_b [mK]
Mpc

GOAL:

Given a dataset: **D** = $\{x_i, y_i\}$, we want a **complex**, **non-linear** parametric function (aka a Neural Net) y ≡ **f**(x;w), which describes the **D** best.

So, we want to know the network parameters (OR as we call them: "**Weights**")

PROBLEM:

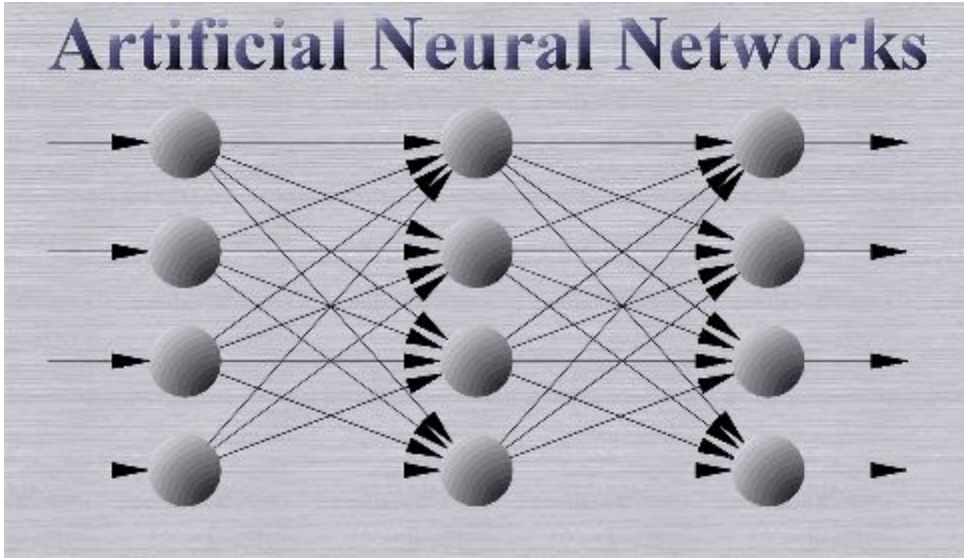
How to get ws, so that the network output y(x) is optimised for the input-output pairs of **D** and make prediction .

Neural networks

– Complex arrangement of neurons
– Can "approximate" any function specially for **complex**, **non-linear** data
– Trained from data by Minimising the Loss function
  - With (form of) stochastic gradient descent
  - Efficient with "automatic differentiation"
  - And backpropagation

Fundamental Architecture of ANNs

Input layer ✚ Hidden layer(s) ✚ Output layer

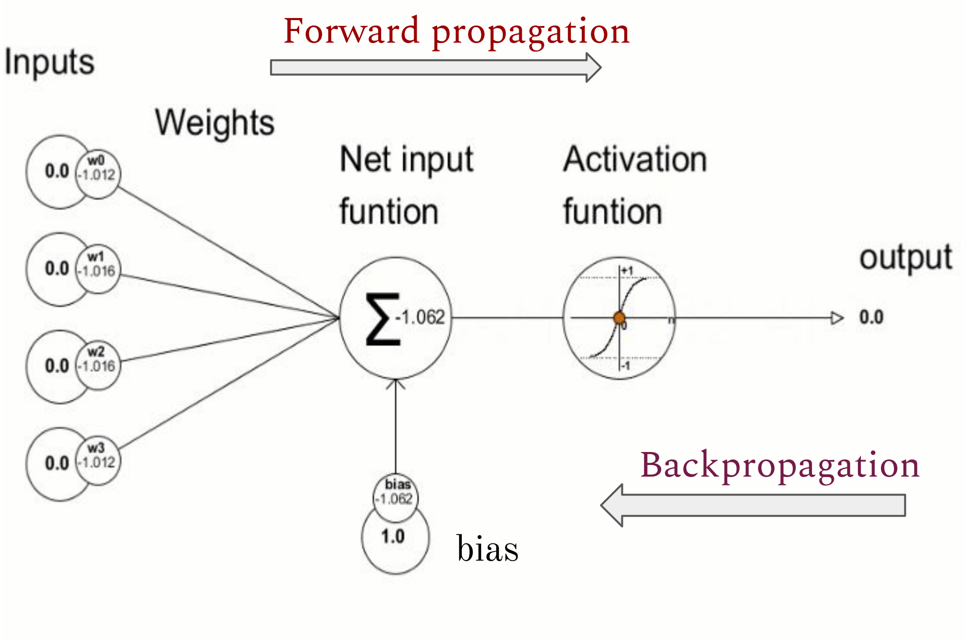


Animation credit : [UNSW]

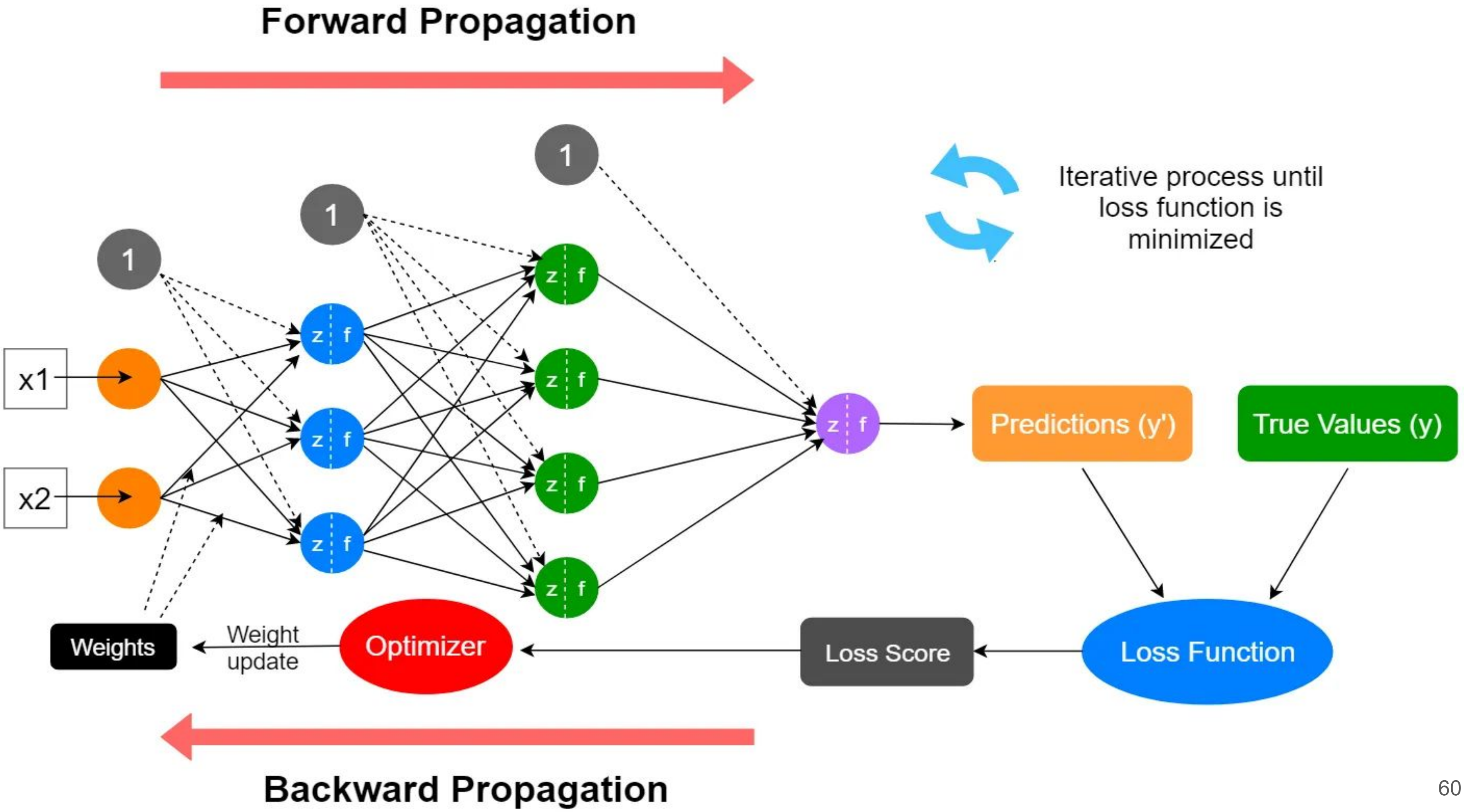
Single Neuron

The fundamental unit of an ANN

This is how information flows through a neuron



Animation credit : [Prabhakar]


Forward Propagation
Iterative process until loss function is minimized
1
1
1
x1
x2
z f
z f
z f
z f
z f
z f
z f
z f
Predictions (y')
True Values (y)
Weights
Weight update
Optimizer
Loss Score
Loss Function
Backward Propagation

Backpropagation

➡ Propagation of errors in backward direction using Gradient Descent

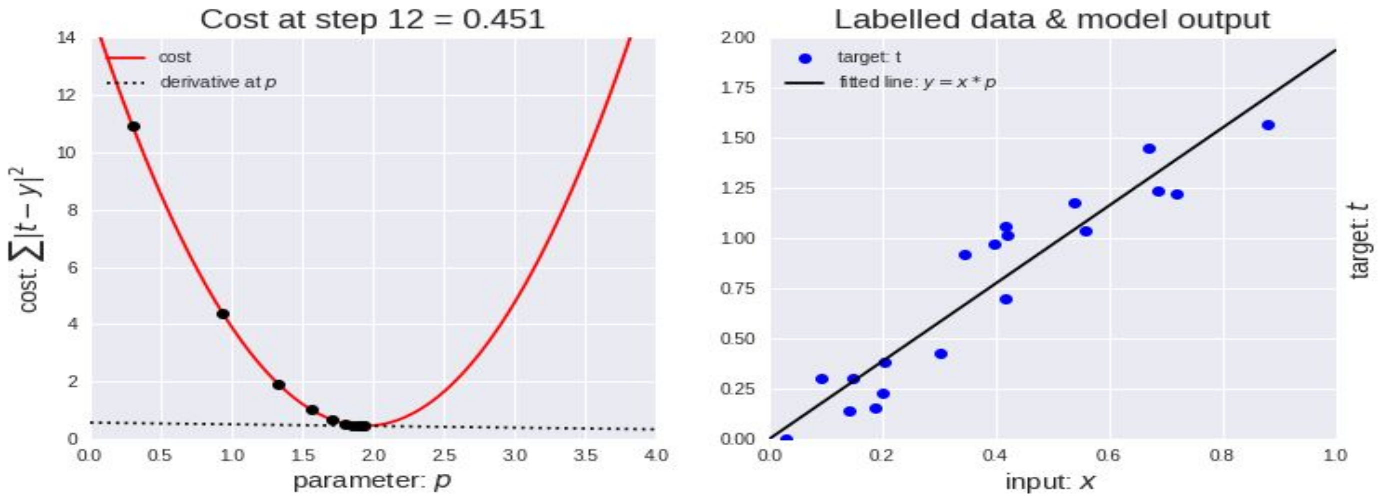
Loss/cost function

$$J = \frac{1}{m}\sum_{i=1}^{m}(y_{true}^{(i)} - y_{pred}^{(i)})^2$$

weight and bias updation during training

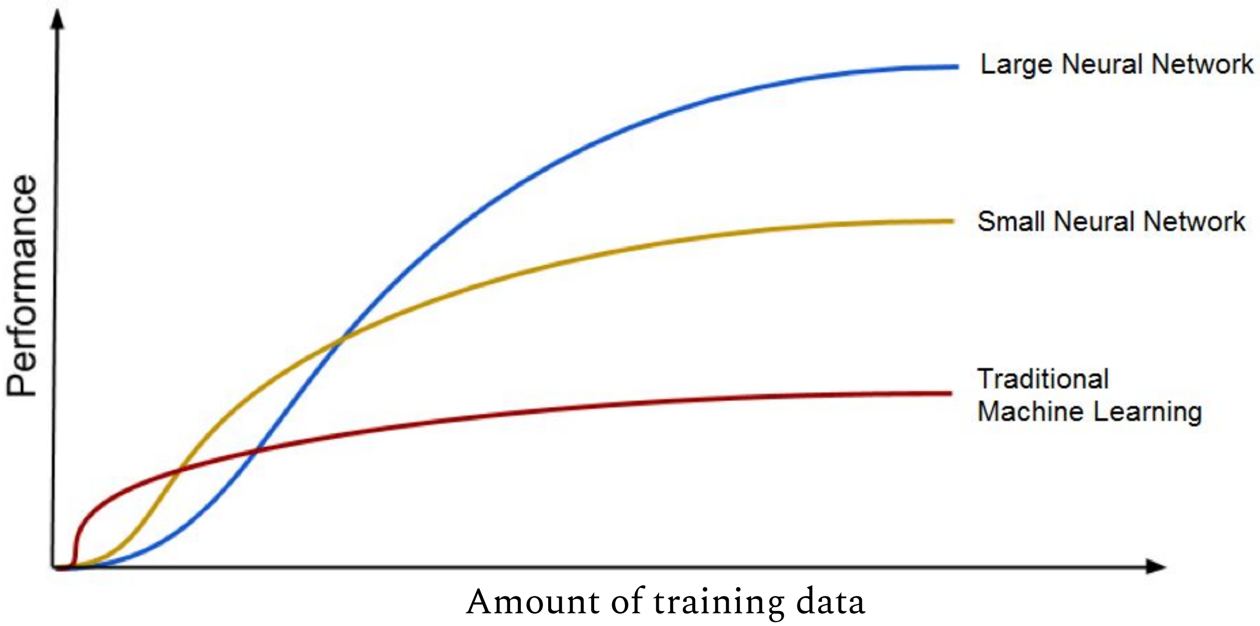
$$w_{t+1} = w_t - \alpha\frac{\partial J}{\partial w_t}$$

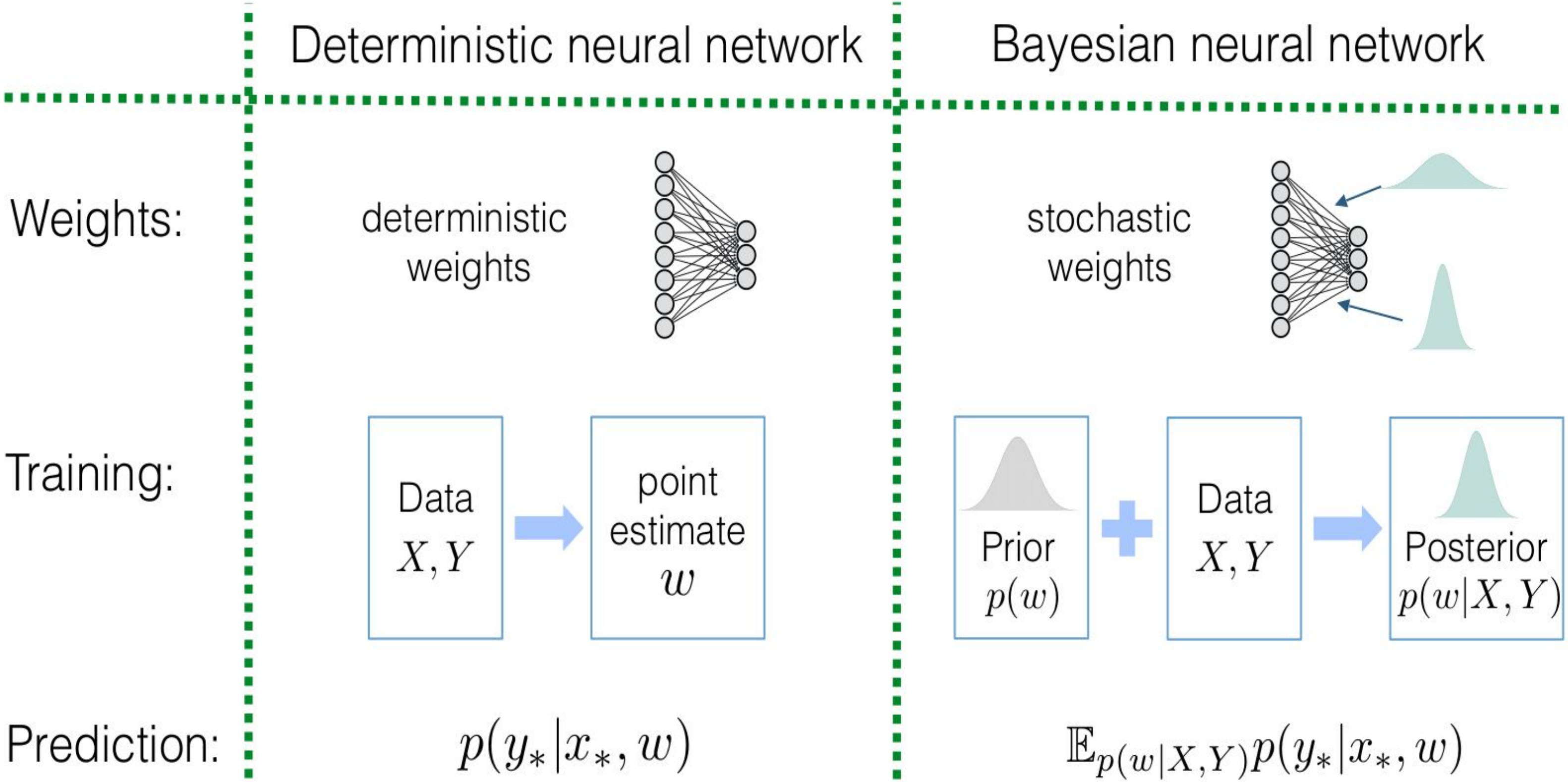
$$b_{t+1} = b_t - \alpha\frac{\partial J}{\partial b_t}$$



Credit: Nishant Garg

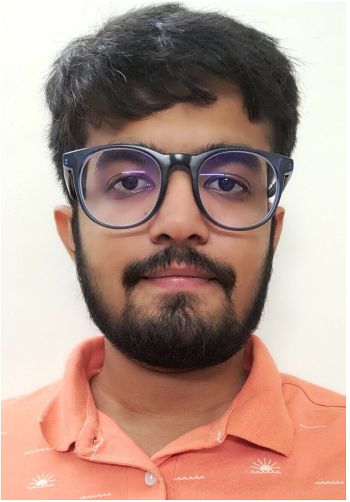
Performance of ANNs with amount of data





Credit: Nadezhda Chirkova

Prasad Rajesh Posture
MSc Astronomy IITI (2023-25)



Yashrajsinh Mahida
PhD IITI (2023-ongoing)

Sanjay Kumar Yadav
MSc Astronomy IITI (2022-24)

Collaborators: Suman Majumdar, Leon Noble, Chandra Shekhar Murmu, Saswata Dasgupta, Sohini Dutta, Himanshu Tiwari, Abinash Kumar Shaw

Generating 21-cm Bispectrum Training Dataset

21-cm Brightness Temperature Map for given set of Parameters

Reionization Parameters:

$M_{(halo,min)}$ = Minimum halo mass that can host the ionizing sources

N_{ion} = Dimensionless parameter which relates the host halos and ionizing photons produced by them.

R_{mfp} = The mean free path of the ionizing photons.

7203 parameter combinations, of which 80% for training 20% for validations

Reionization Code: https://github.com/rajeshmondal18/ReionYuga
Ref: Choudhury et al. 2009,
Majumdar et al. 2014,
Mondal et al. 2017,

Generating 21-cm Bispectrum Training Dataset

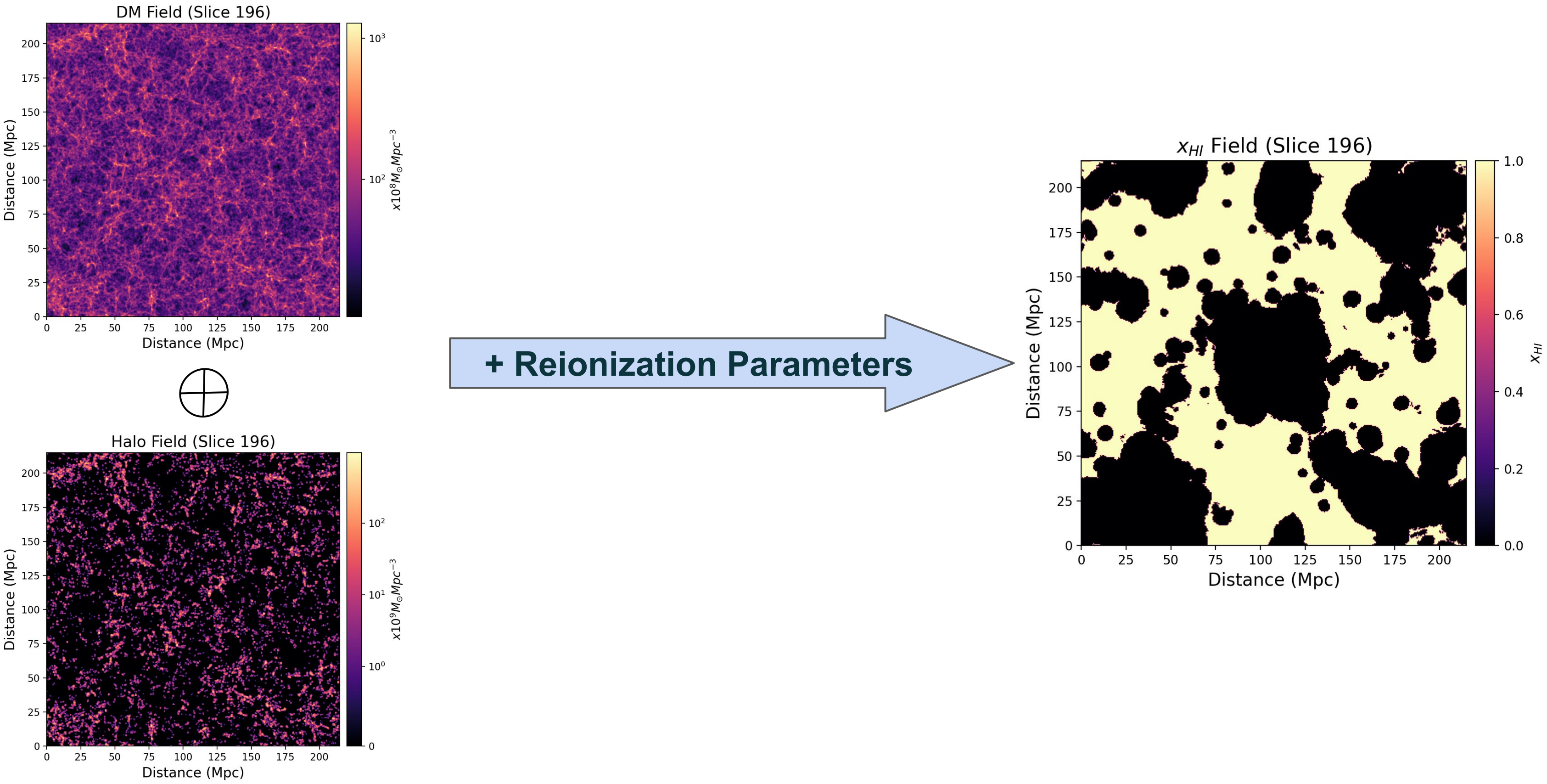
21-cm Brightness Temperature Map for given set of Parameters

Large scale semi-numerical simulations for 21-cm LIM signals from EoR: ReionYuga.

PM N-body dark matter field → FoF halo field → Excursion set formalism to identify cells as ionized or neutral, for a given set of reionization parameters → convert it to brightness temperature maps.

7203 parameter combinations, of which 80% for training 20% for validations.

Reionization Simulation: https://github.com/rajeshmondal18/ReionYuga
Choudhury et al. 2009, Majumdar et al. 2014, Mondal et al. 2017,


DM Field (Slice 196)
Distance (Mpc)
$x10^8 M_\odot Mpc^{-3}$
Halo Field (Slice 196)
$x10^9 M_\odot Mpc^{-3}$
+ Reionization Parameters
x_{HI} Field (Slice 196)
x_{HI}

Emulator Architectures and Performance

ANN Emulator Architecture

First Four k1 bins

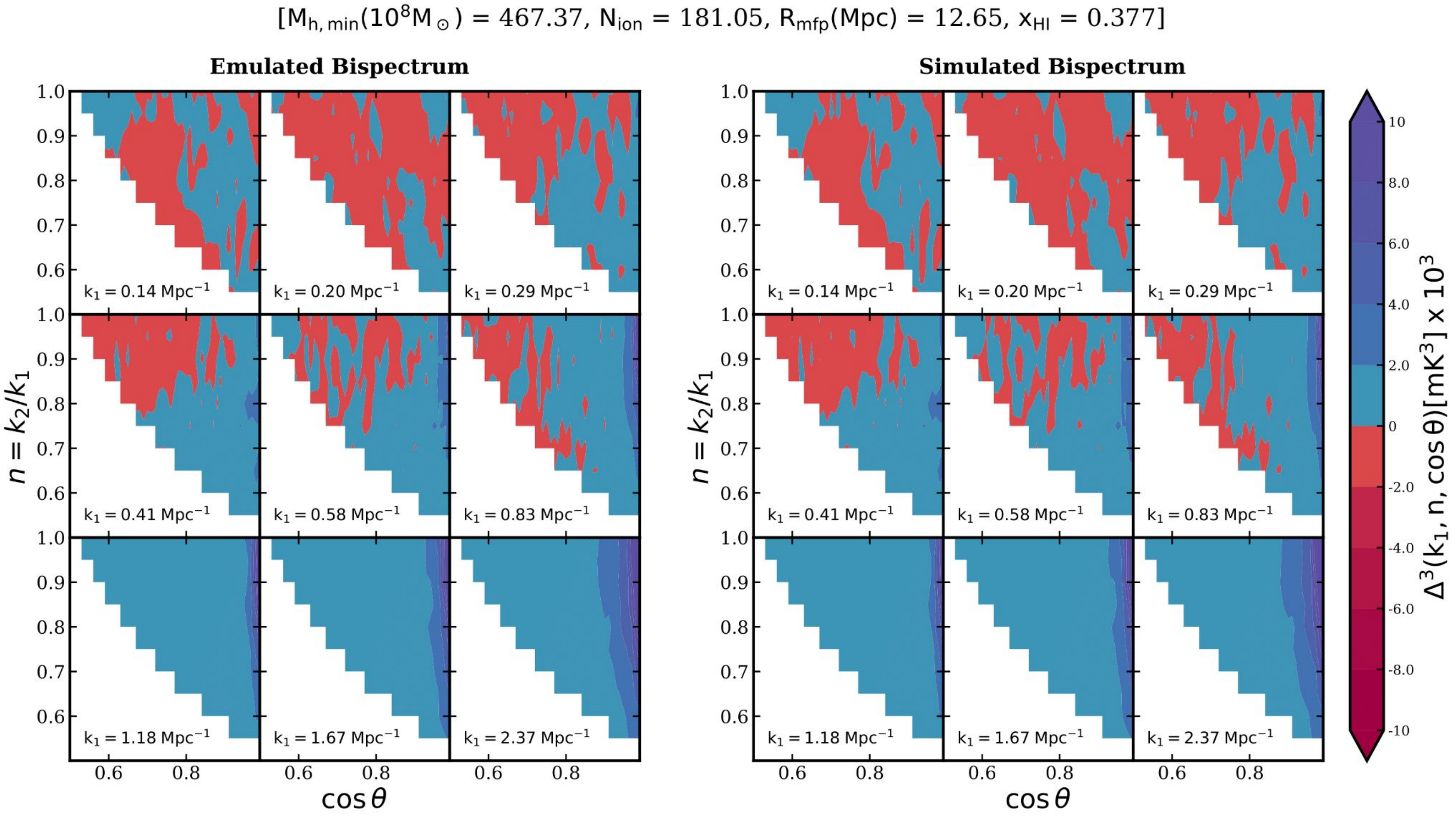
Layers	Nodes	Activation Function
Input Layer	3	
Hidden Layer 1	2255	ReLU
Hidden Layer 2	1524	ReLU
Hidden Layer 3	1008	ReLU
Output Layer 1 [For Magnitude]	328	
Output Layer 2 [For Sign]	328	

Loss Function = MSE (Mean Squared Error)

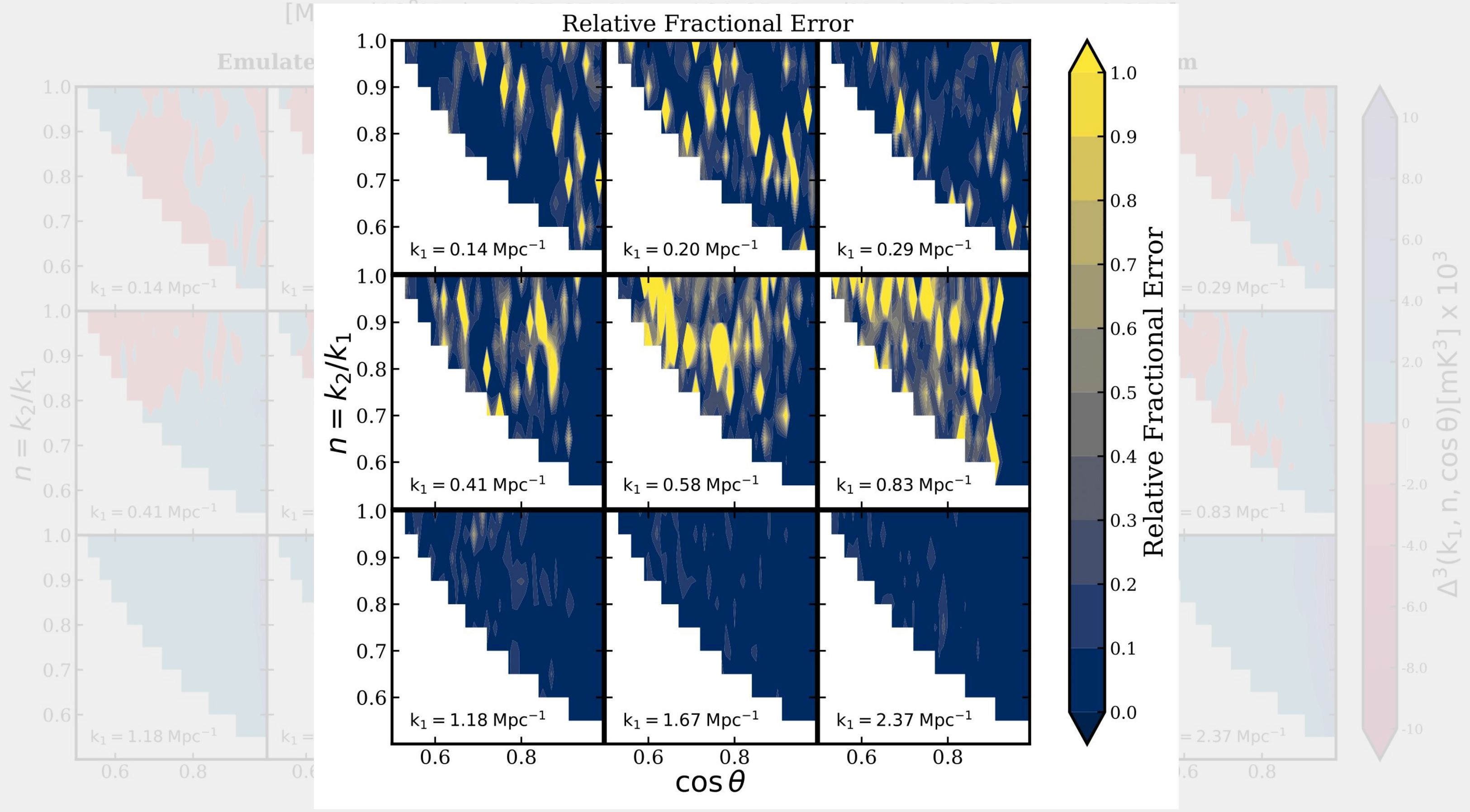
Remaining Five k1 bins

Layers	Nodes	Activation Function
Input Layer	3	
Hidden Layer 1	2255	ReLU
Hidden Layer 2	1524	ReLU
Hidden Layer 3	1008	ReLU
Hidden Layer 4	956	
Output Layer 1 [For Magnitude]	328	
Output Layer 2 [For Sign]	328	

Bispectrum Prediction using ANN



Bispectrum Prediction using ANN



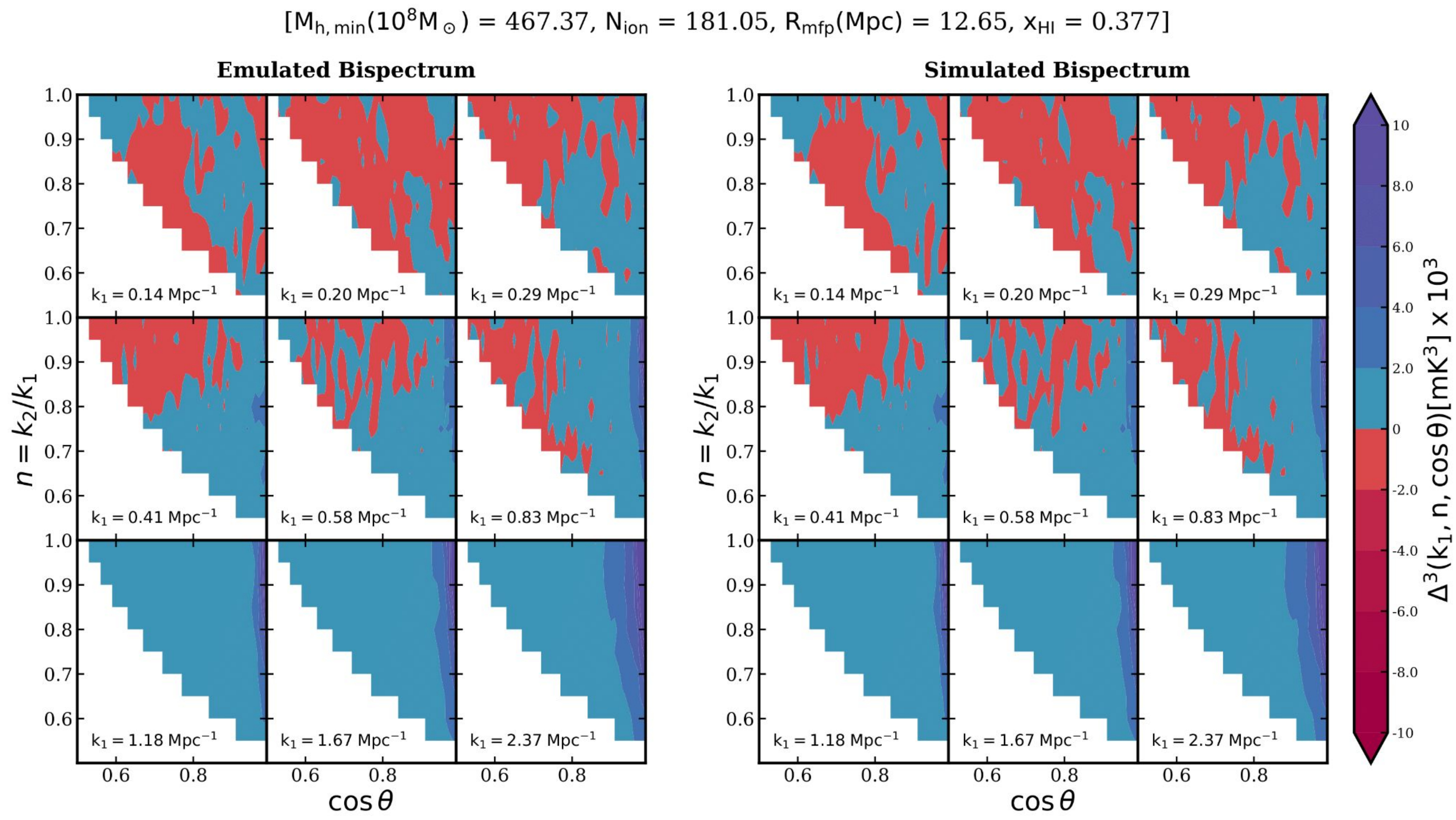
BNN Emulator Architecture

<u>For All k1 bins</u>

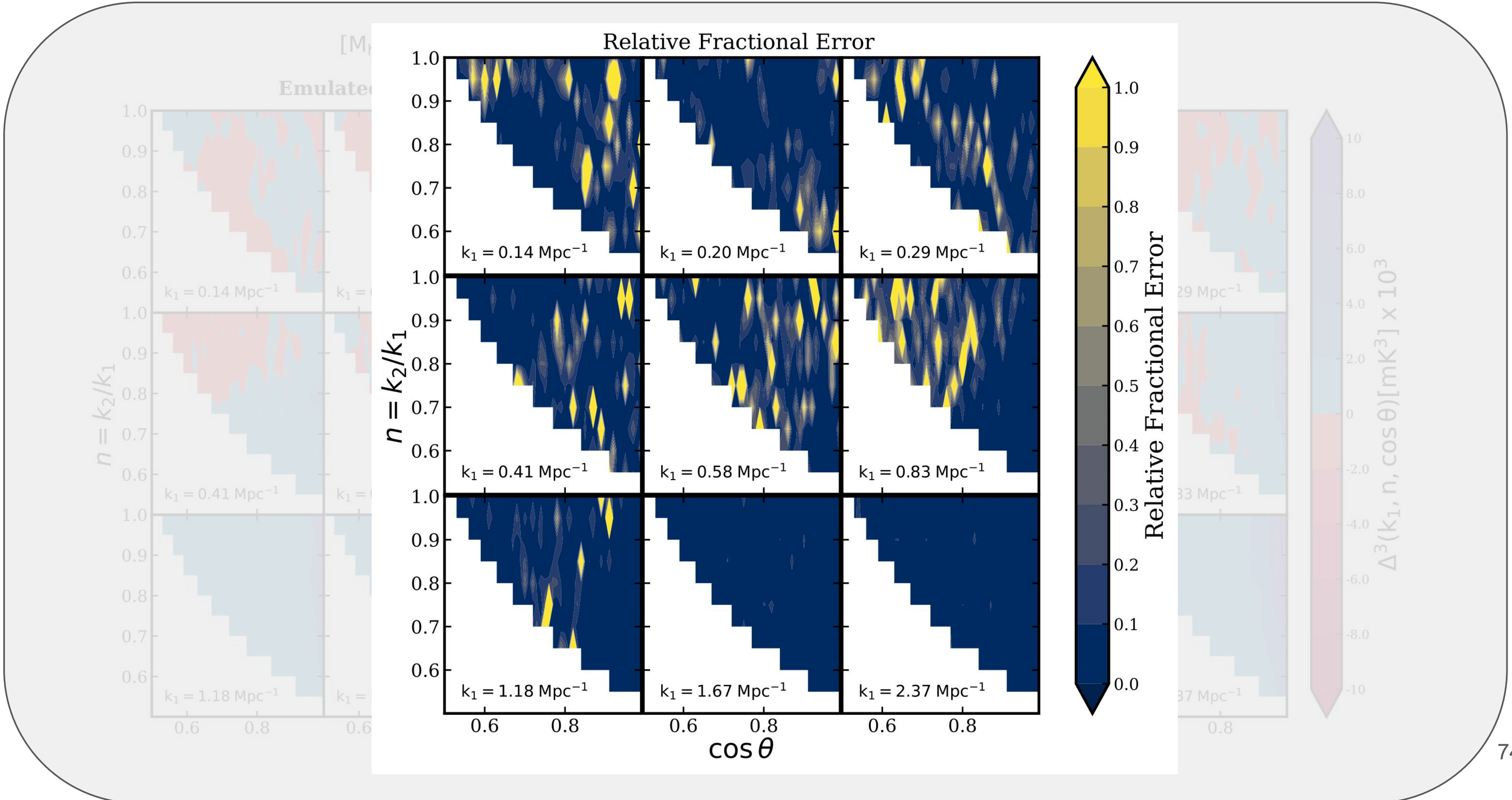
Layers	**Nodes**	**Activation Function**
Input Layer	3	
Hidden Layer 1	128	ELU
Hidden Layer 2	256	ELU
Hidden Layer 3	512	ELU
Output Layer	328	

- Prior distribution of weights & biases $\Rightarrow$ Gaussian
- Likelihood function $\Rightarrow$ Multivariate Gaussian

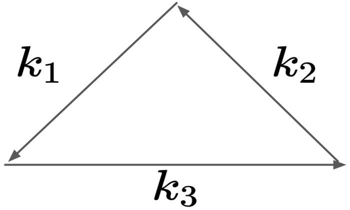
Bispectrum Prediction using BNN



Bispectrum Prediction using BNN

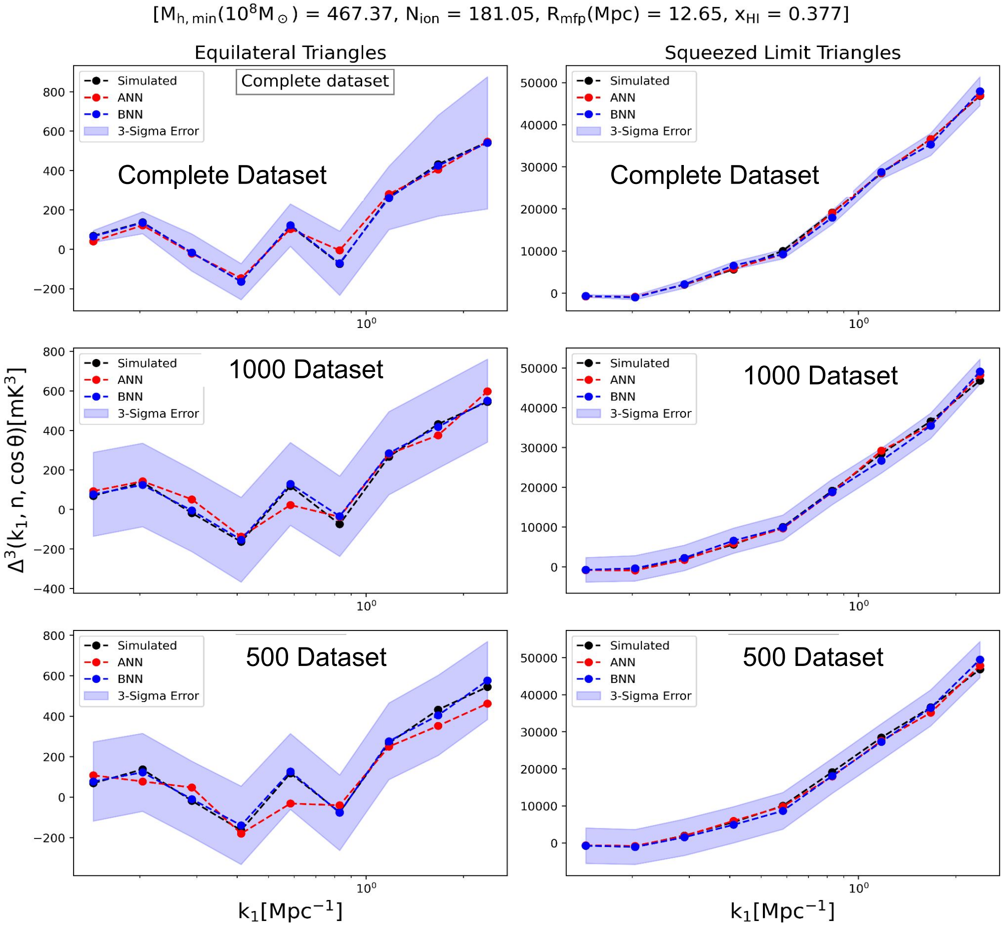


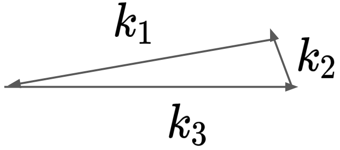
Prediction Comparison



Equilateral

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



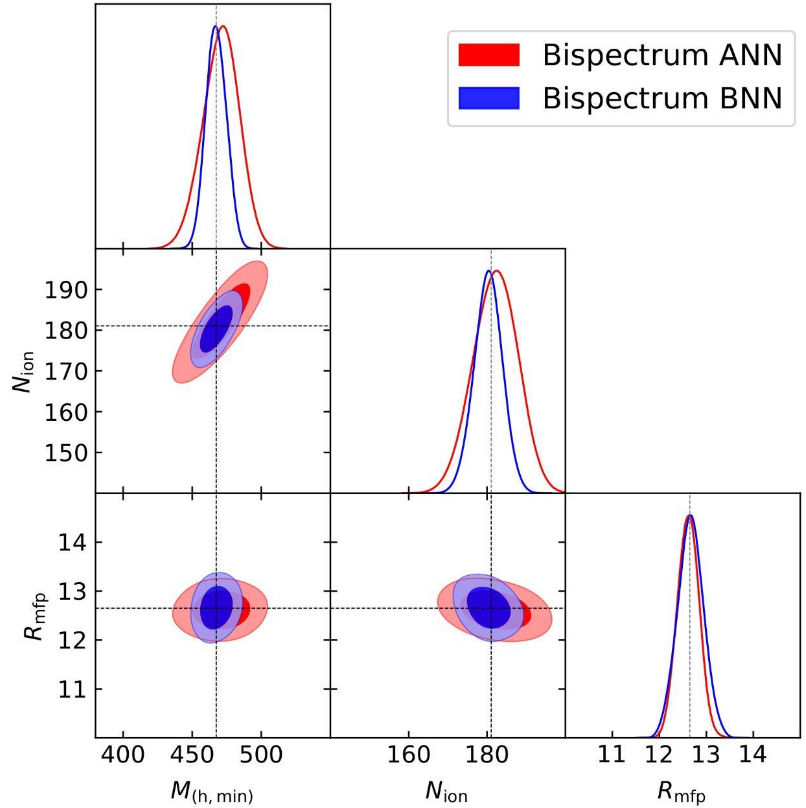


Squeezed Limit

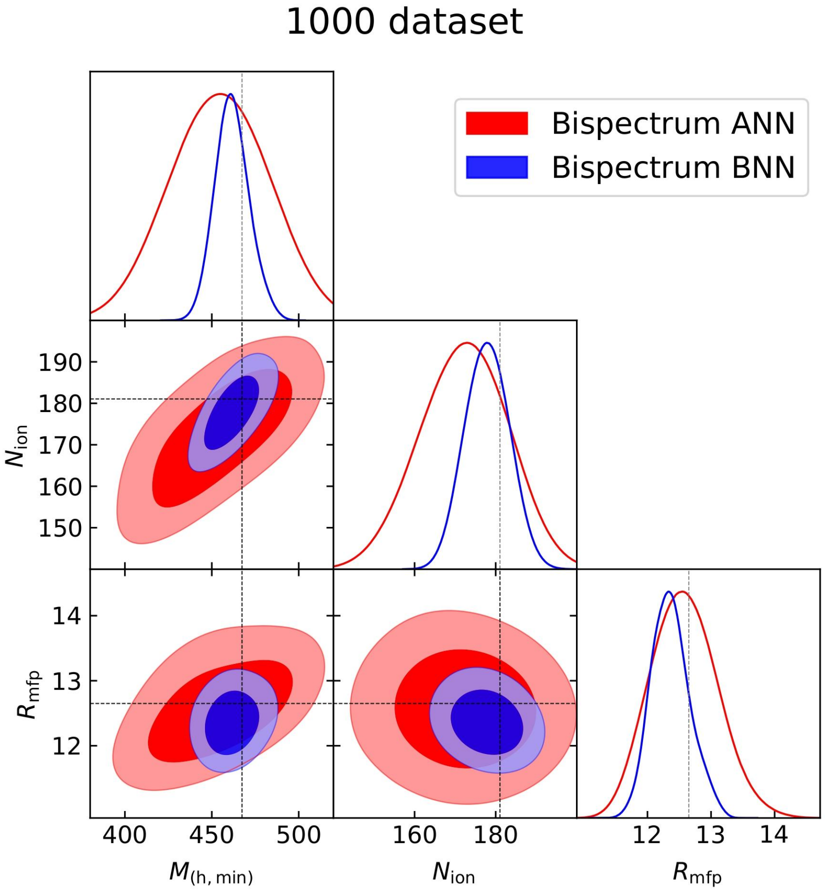
$$|\mathbf{k}_1| \approx |\mathbf{k}_3|, |\mathbf{k}_2| \to 0$$

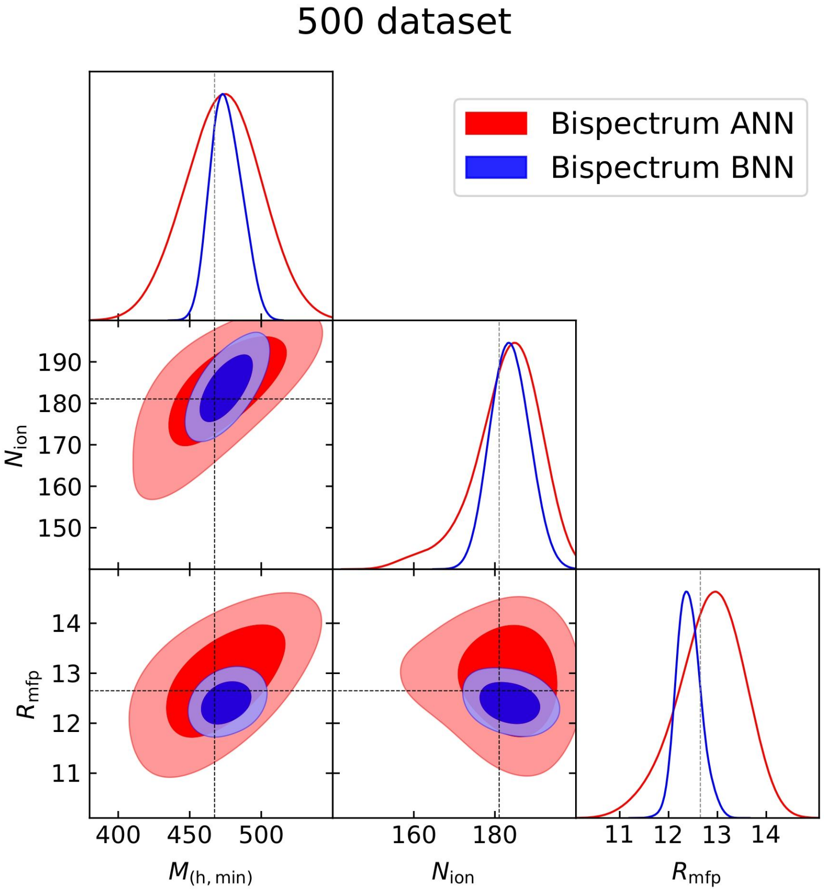
Parameter Estimation: (ANN vs BNN)

$[M_{h,min}(10^8 M_\odot) = 467.37,\ N_{ion} = 181.05,\ R_{mfp}(Mpc) = 12.65,\ \bar{x}_{HI} = 0.377]$



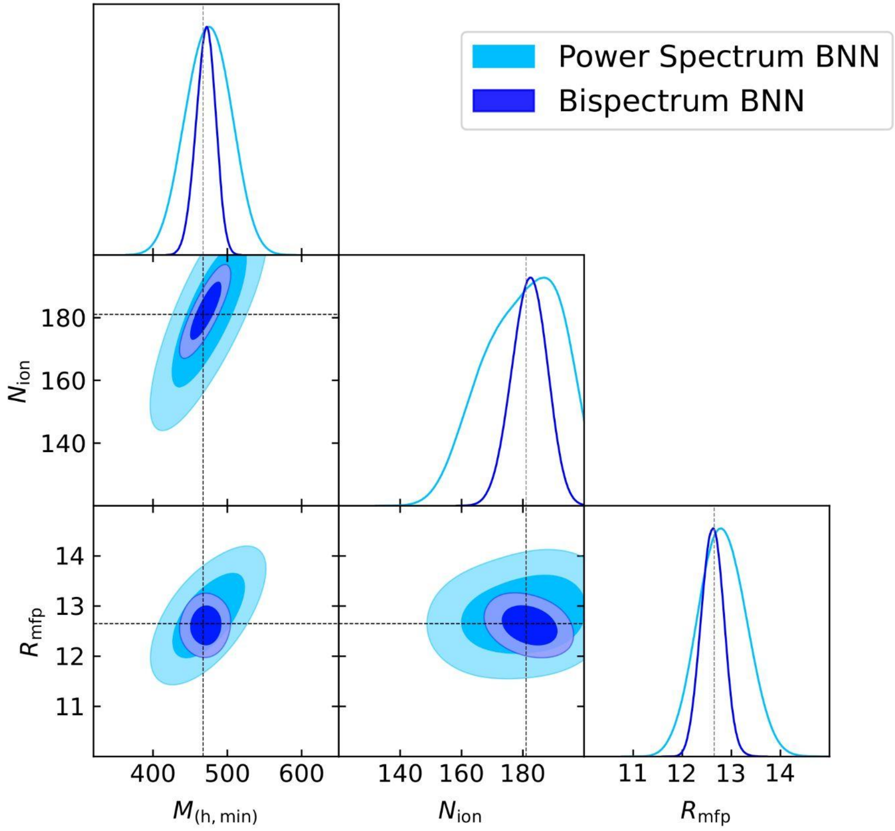
Parameter Estimation: (ANN vs BNN)



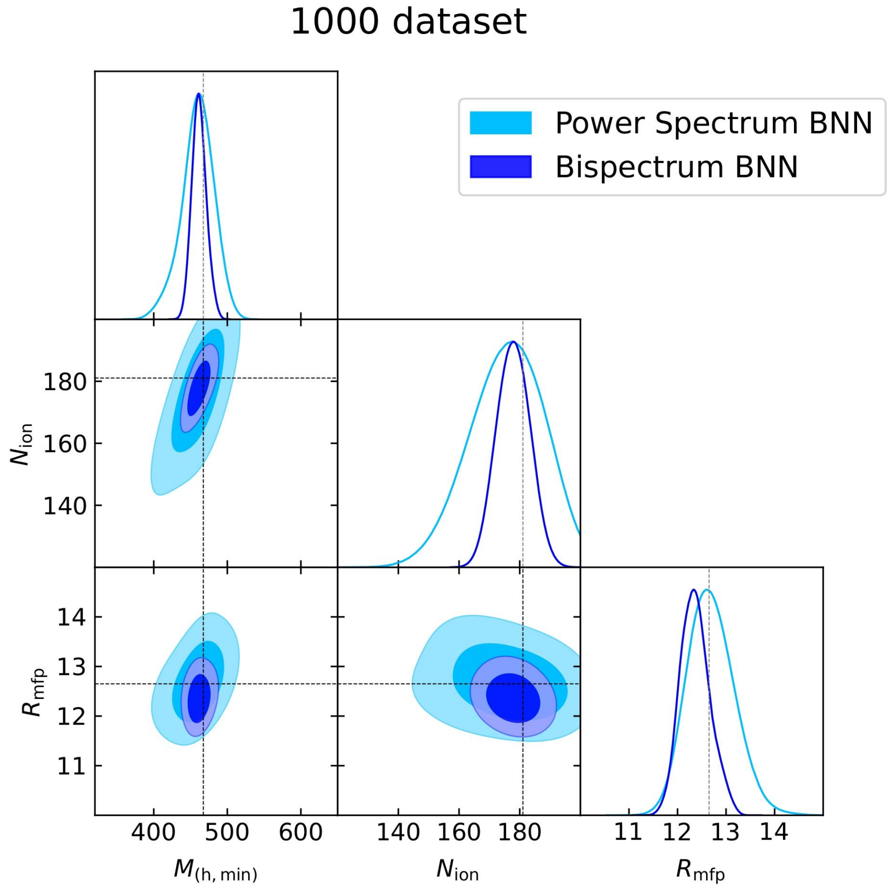


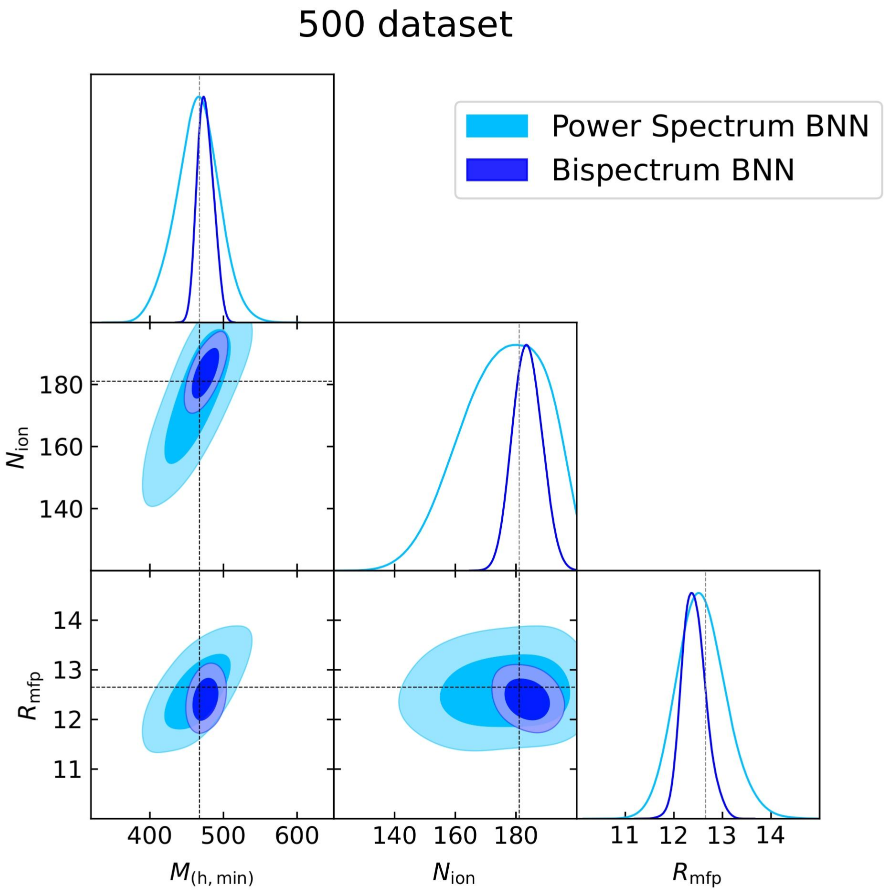
Parameter Estimation: (Power spectrum vs Bispectrum)

$[M_{h,min}(10^8 M_\odot) = 467.37,\ N_{ion} = 181.05,\ R_{mfp}(Mpc) = 12.65,\ \bar{x}_{HI} = 0.377]$



Parameter Estimation: (Power spectrum vs Bispectrum)





From ANN to BNN: Inferring reionization parameters using uncertainty-aware emulators of 21-cm summaries

Authors: Yashrajsinh Mahida, Sanjay Kumar Yadav, Suman Majumdar, Leon Noble, Chandra Shekhar Murmu, Saswata Dasgupta, Sohini Dutta, Himanshu Tiwari, Abinash Kumar Shaw

JCAP 12 (2025) 055
arXiv: 2508.13261

Summary: II

- 21-cm signal is highly non-Gaussian. So, **we use bispectrum** for the parameter estimation

- **ANNs** provide only point value prediction.
  They **cannot quantify the uncertainties** in their prediction.

- We use **BNNs**, which provide the posterior distribution of predicted signal. They **are better at quantifying the model uncertainty.**

- We show that **BNNs give better and robust estimation** of the EoR 21-cm bispectrum compared to ANNs.

However

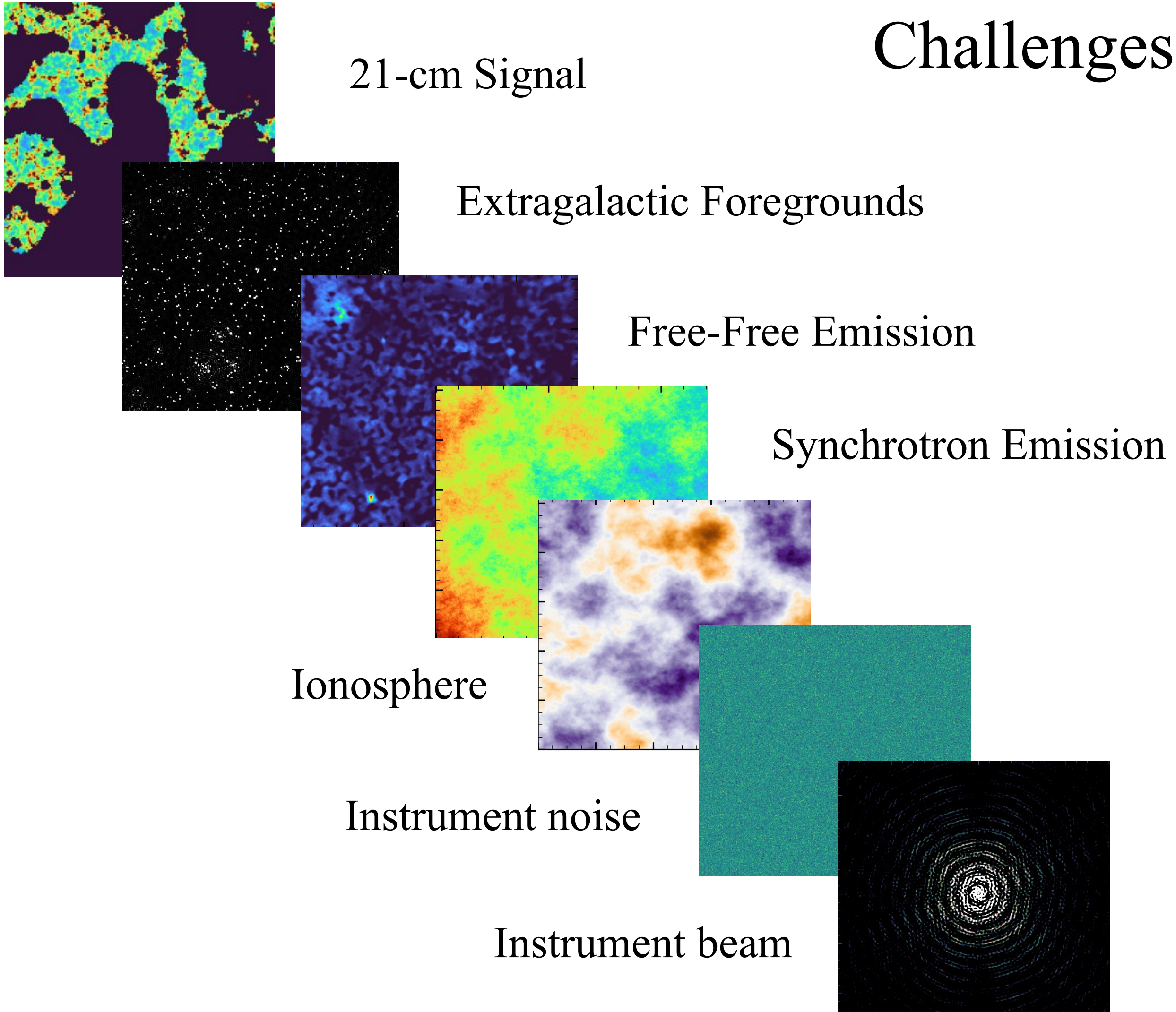
- Even Higher-order statistics (e.g. Bispectrum) cannot describe the non-Gaussian EoR 21-cm field completely. It does not contain the phase information.

- We need all N-point statistics to fully describe the field.

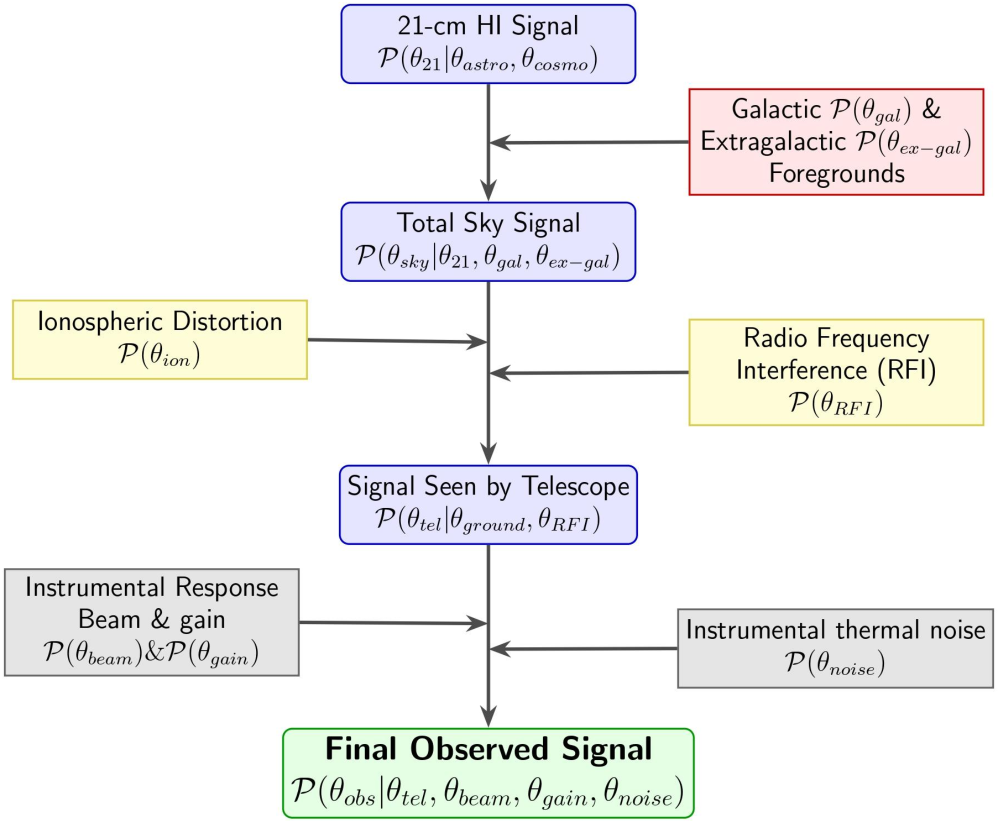
We can use the observable Fields directly

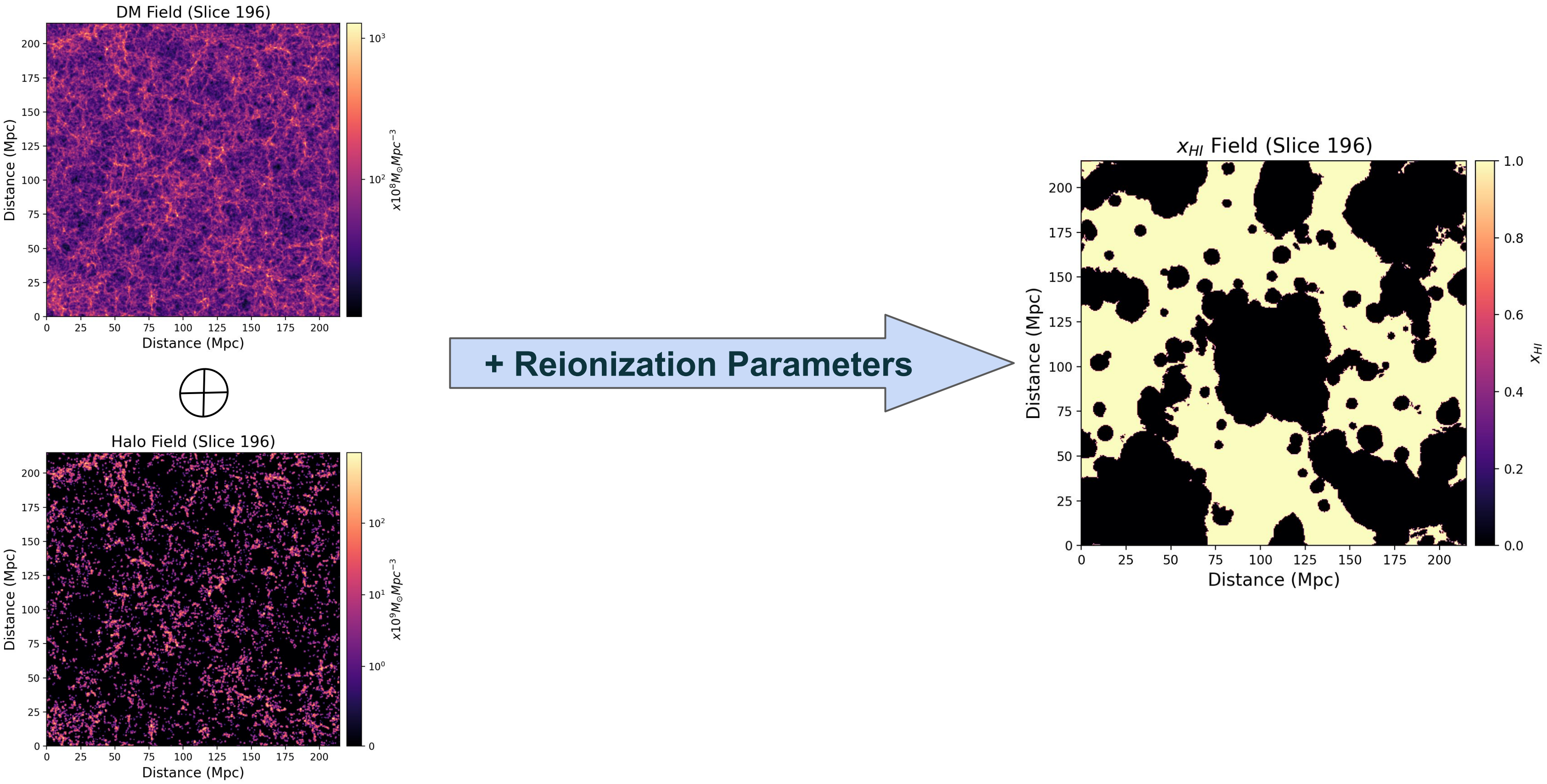
Towards Field-Level Inference of Reionization Parameters

Challenges


21-cm Signal
Extragalactic Foregrounds
Free-Free Emission
Synchrotron Emission
Ionosphere
Instrument noise
Instrument beam

Hierarchical Forward Modeling of Signal



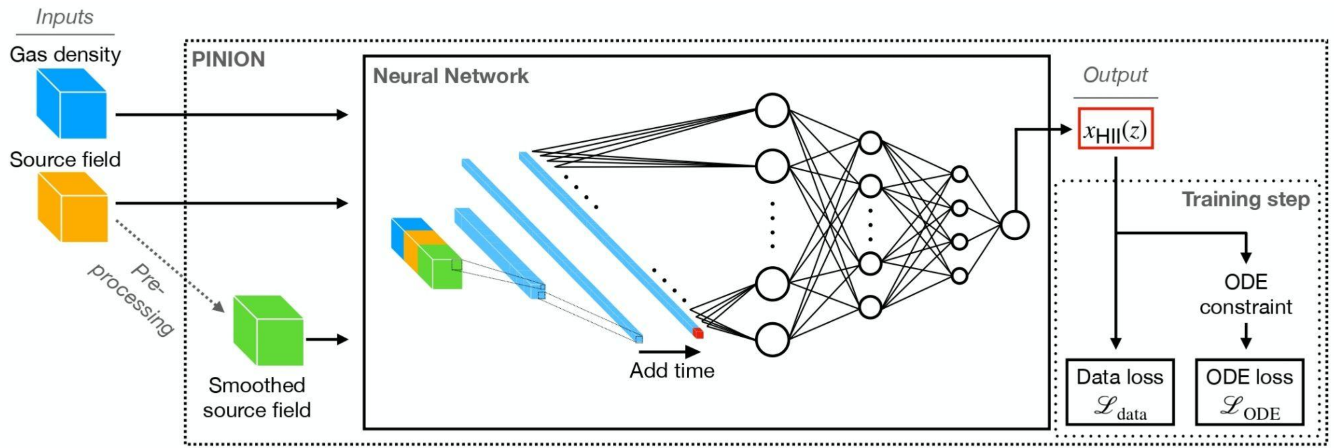


DM Field (Slice 196)
Distance (Mpc)
$x10^8 M_\odot Mpc^{-3}$
Halo Field (Slice 196)
$x10^9 M_\odot Mpc^{-3}$
+ Reionization Parameters
x_{HI} Field (Slice 196)
x_{HI}

Previous Field Emulation Efforts

Use of CNN for Emulation & Its Drawbacks

PINION Architecture



Korber et al., 2023, MNRAS, 521(1), arxiv:2208.13803

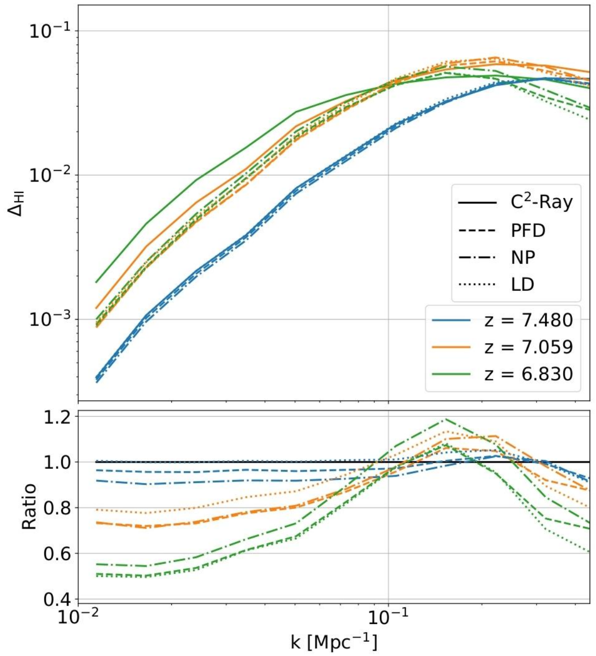
$$\lambda_{\nu HI}(z) \approx \frac{c}{H(z)} \times 0.1 \left(\frac{1+z}{4}\right)^{-2.55}$$

Choudhury et al., 2009, arXiv, arxiv:0904.4596

Use of CNN for Emulation & Its Drawbacks

Drawbacks of PINION

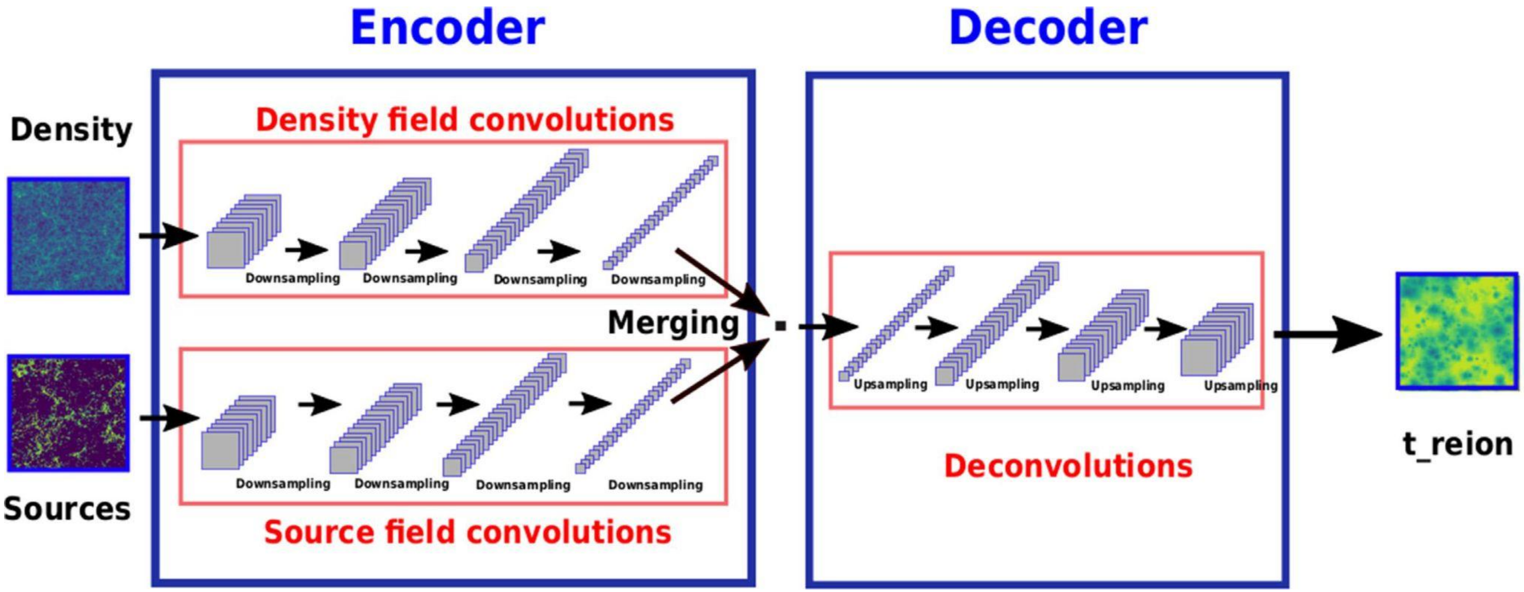
- ❖ An arbitrary smoothing of the input fields have been done which is not well motivated.
- ❖ Takes subvolume of size 7^3 instead of entire cube to predict the ionized fraction on a single grid point.
- ❖ Underpredicts the large scale variations of the signal at the late stages of the EoR.



Korber et al., 2023, MNRAS, 521(1), arxiv:2208.13803

Use of CNN for Emulation & Its Drawbacks

CRADLE Architecture

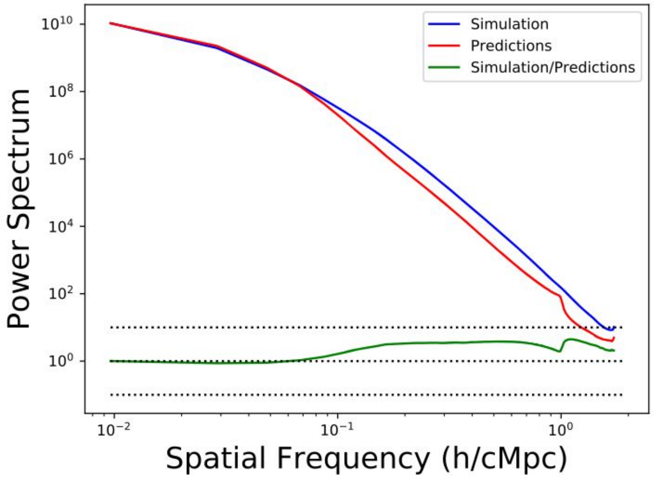


Chardin et al., 2019, MNRAS, 490(1), arxiv:2110.08037

Use of CNN for Emulation & Its Drawbacks

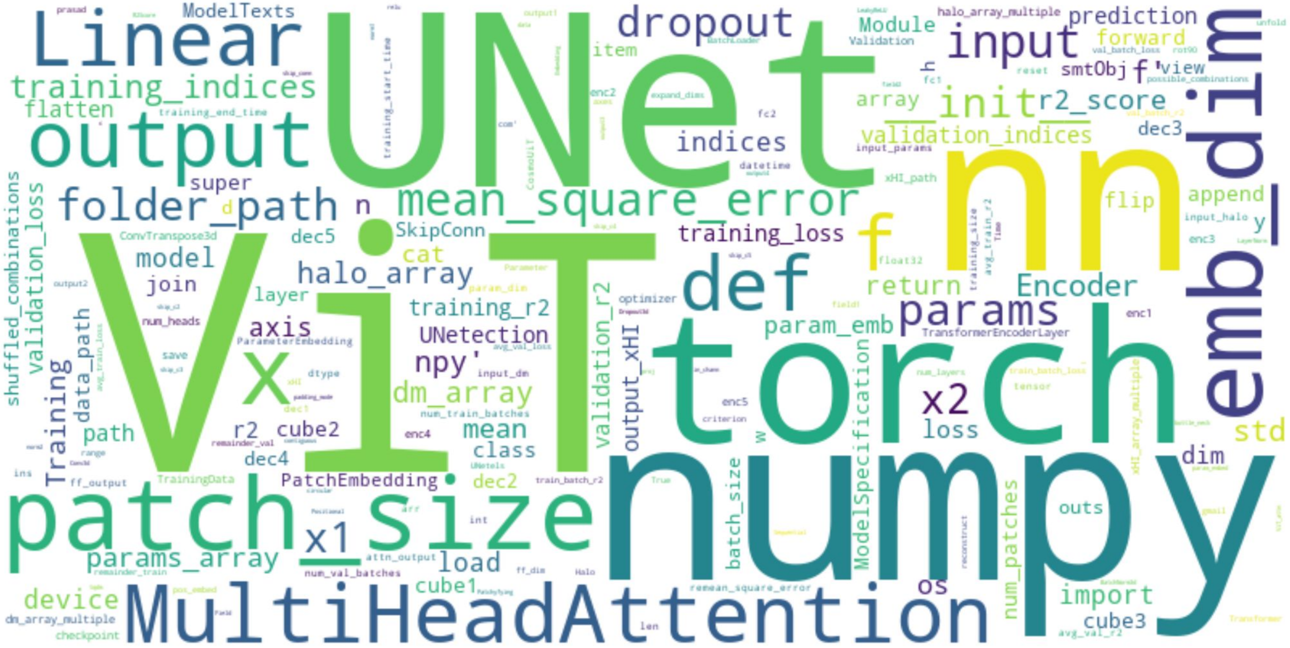
Drawbacks of CRADLE

- ❖ 3D cube is broken into 2D slices which are treated as independent inputs.
- ❖ Influence of sources across the slices are not considered.
- ❖ Smoothing with Gaussian kernel of size 3.75 cMpch^{-1} is done.
- ❖ Underpredicts small scale variations due to smoothing of inputs.

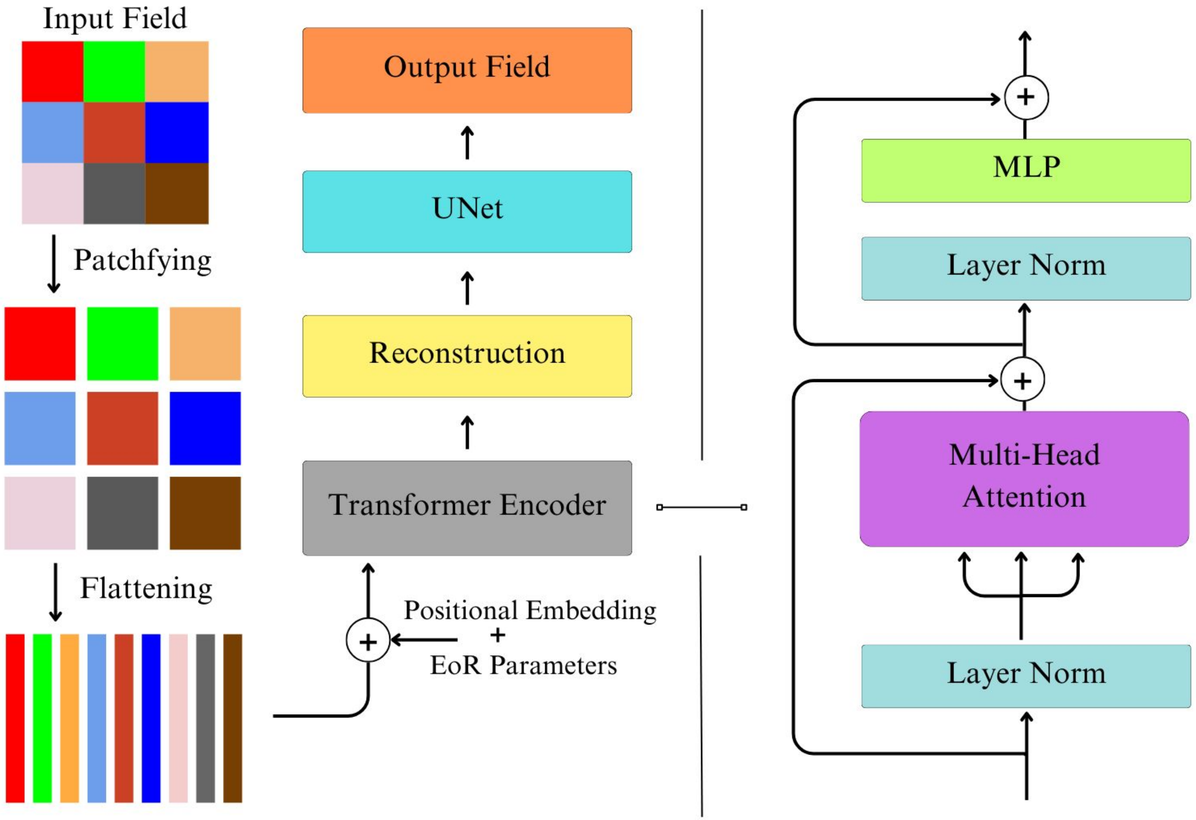


Chardin et al., 2019, MNRAS, 490(1), arxiv:2110.08037

Architectural Strategies

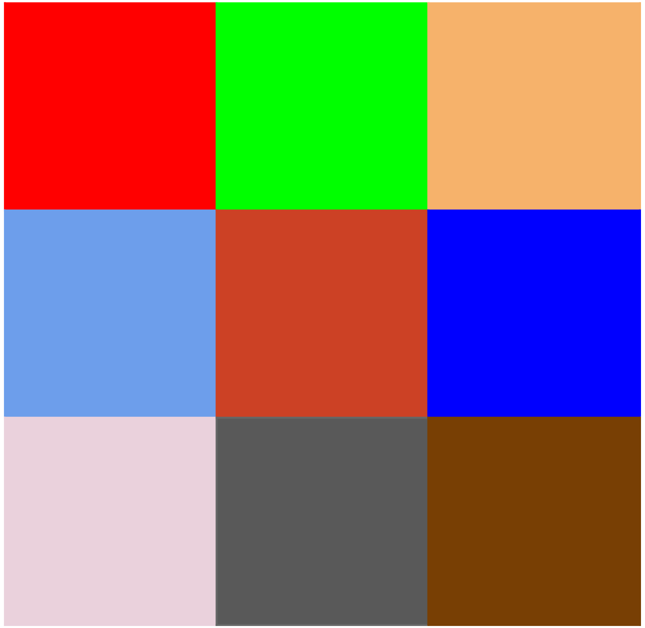


UNet integrated Vision Transformer (CosmoUiT)

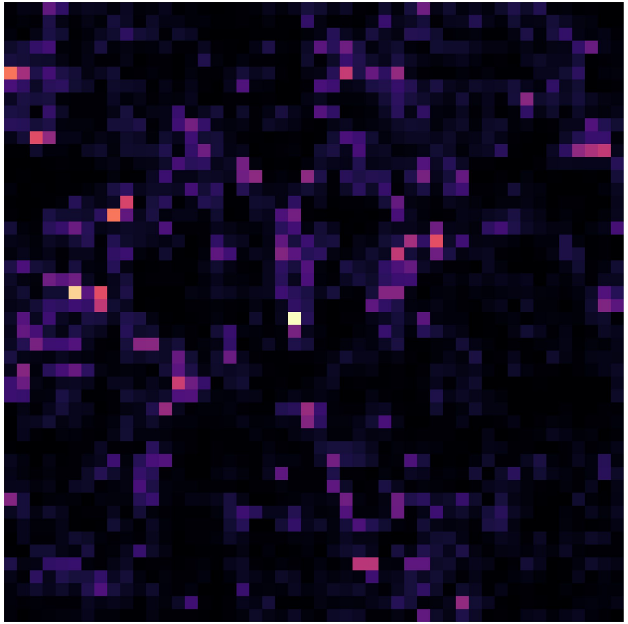


Input Field

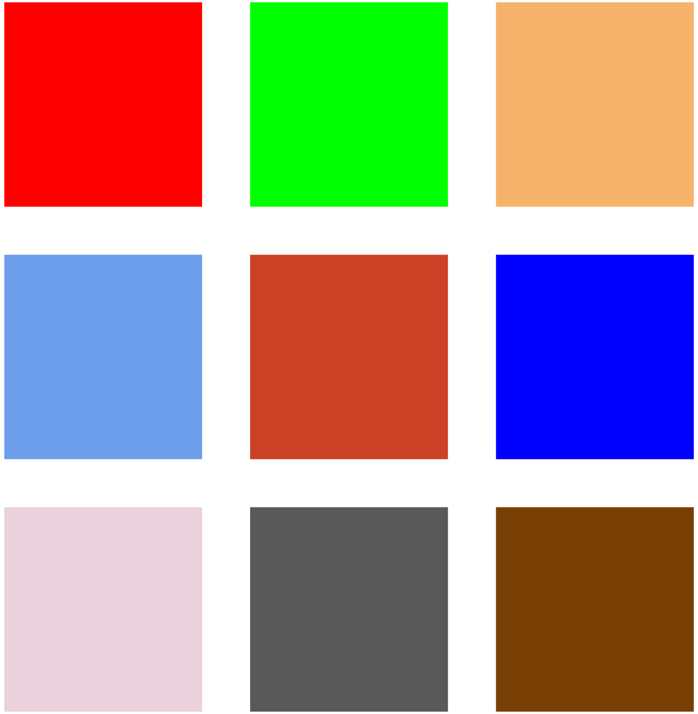
Toy Field

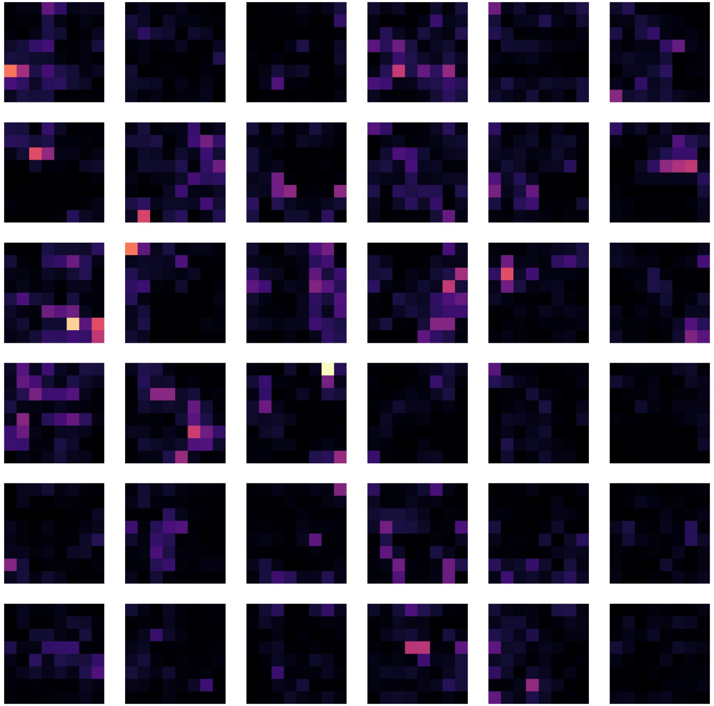


Halo Field

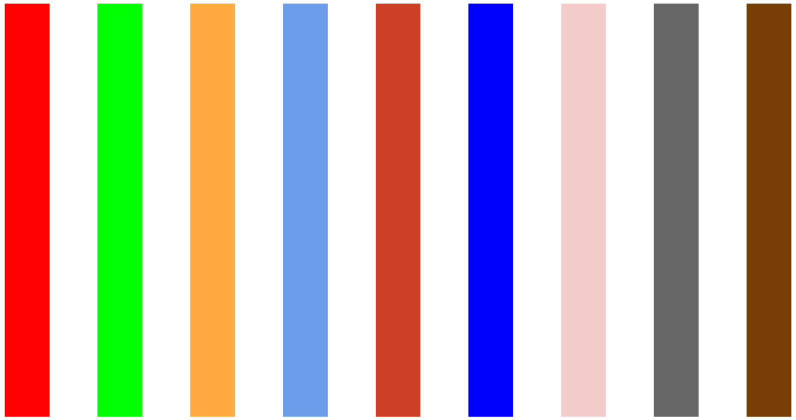


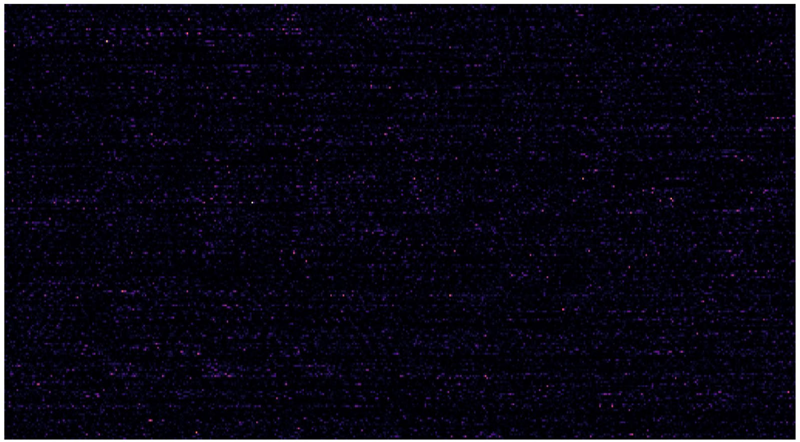
Patchfying



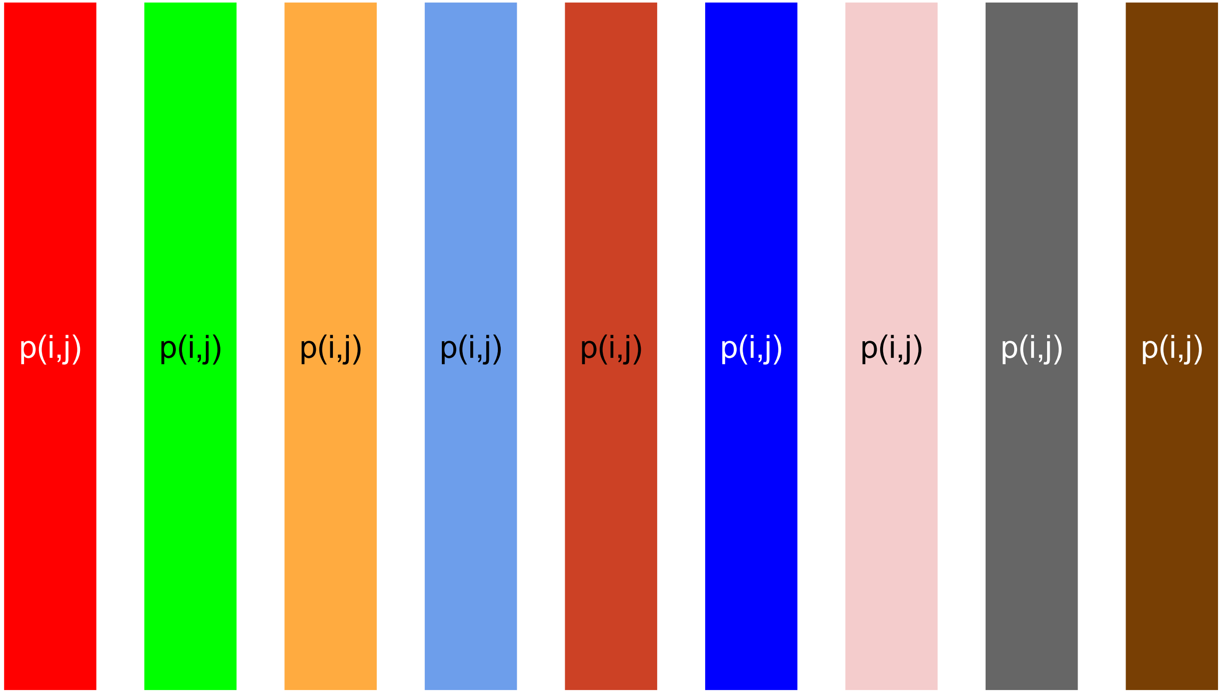


Flattening

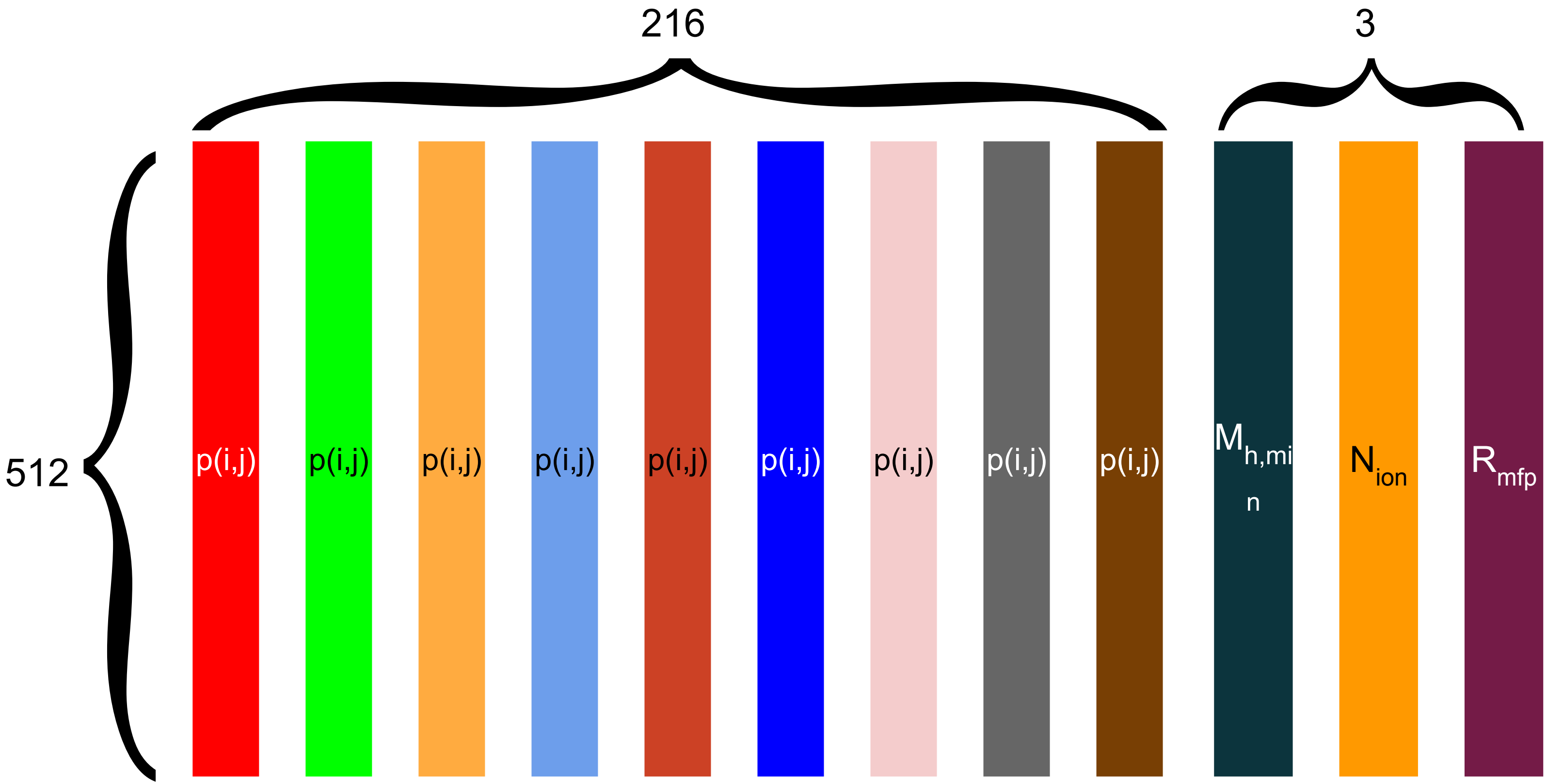




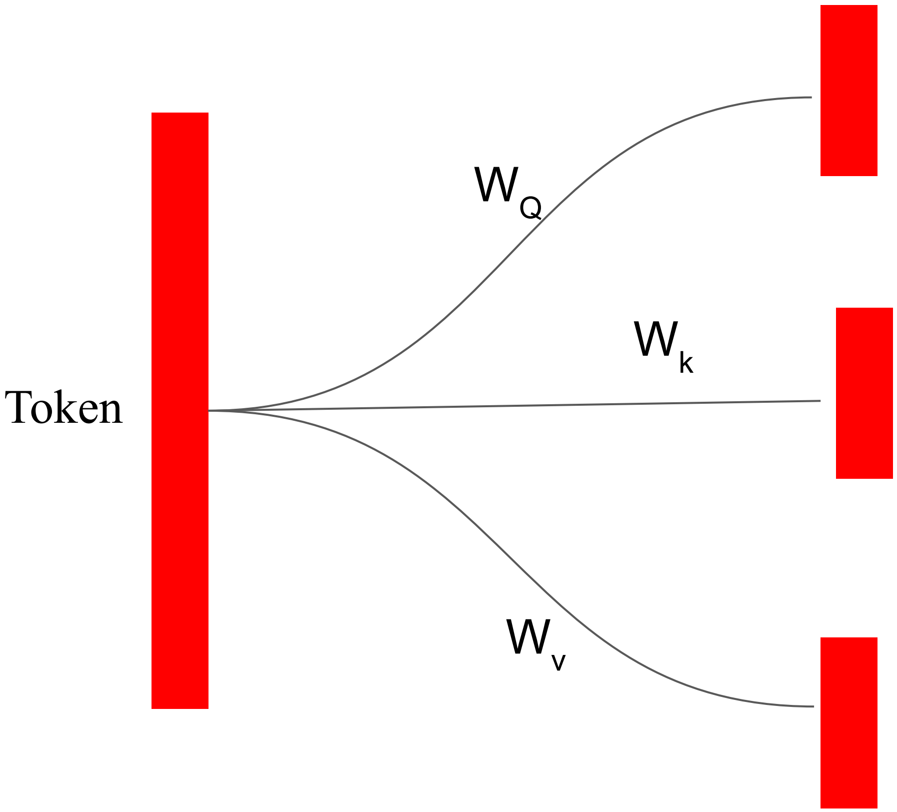
Positional Embedding



Integrating EoR Parameters



Query, Key and Value through Linear Projection

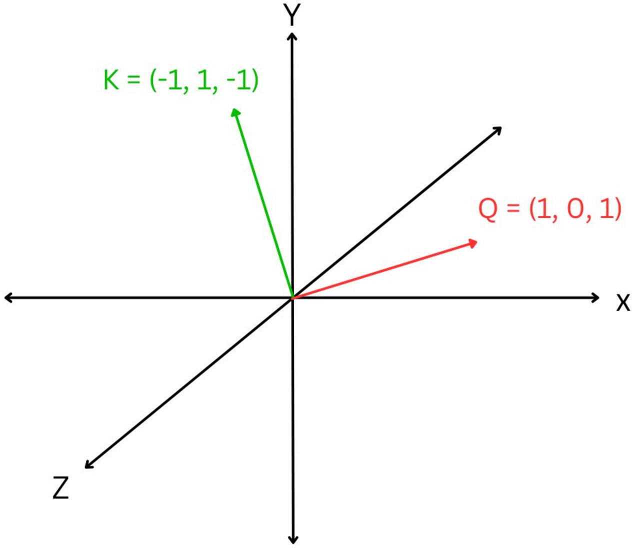


Query
What do I need to know about the other patches to understand this region better?

Key
What each patch can "offer" to help other patches understand their context.

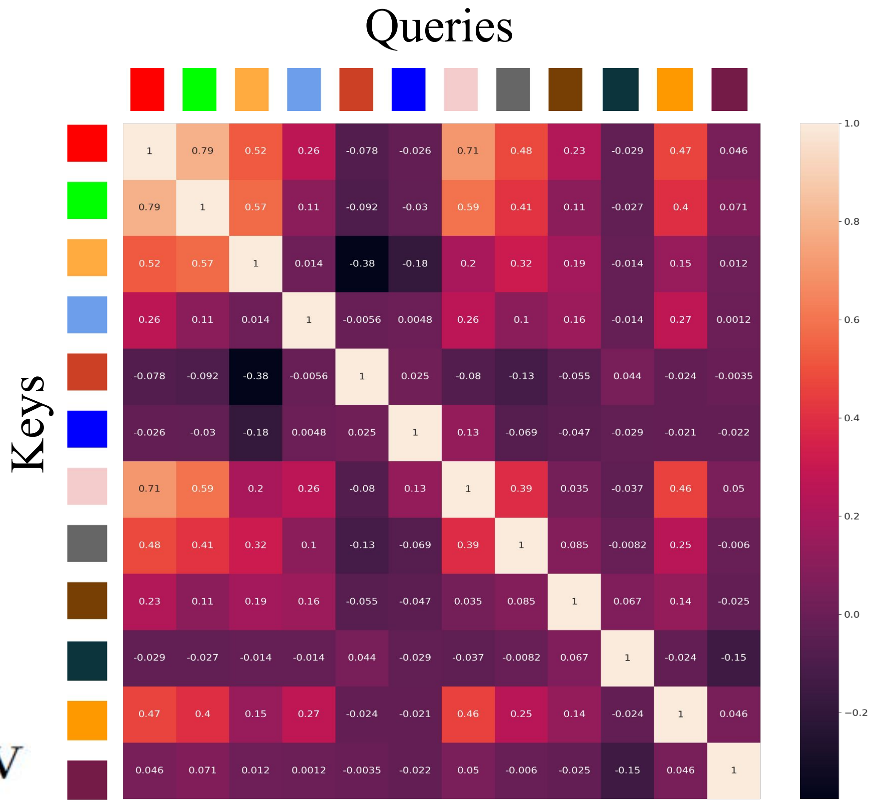
Value
Information from a patch that can be shared when a query finds it relevant.

Attention Score

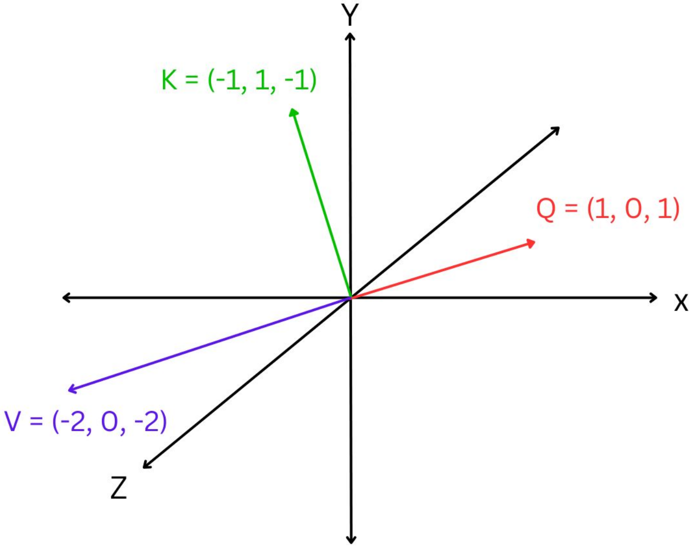


$$\text{Attention}(\mathbf{Q},\mathbf{K},\mathbf{V}) = \text{softmax}\left(\frac{\mathbf{Q}\mathbf{K}^T}{\sqrt{D_H}}\right)\mathbf{V}$$

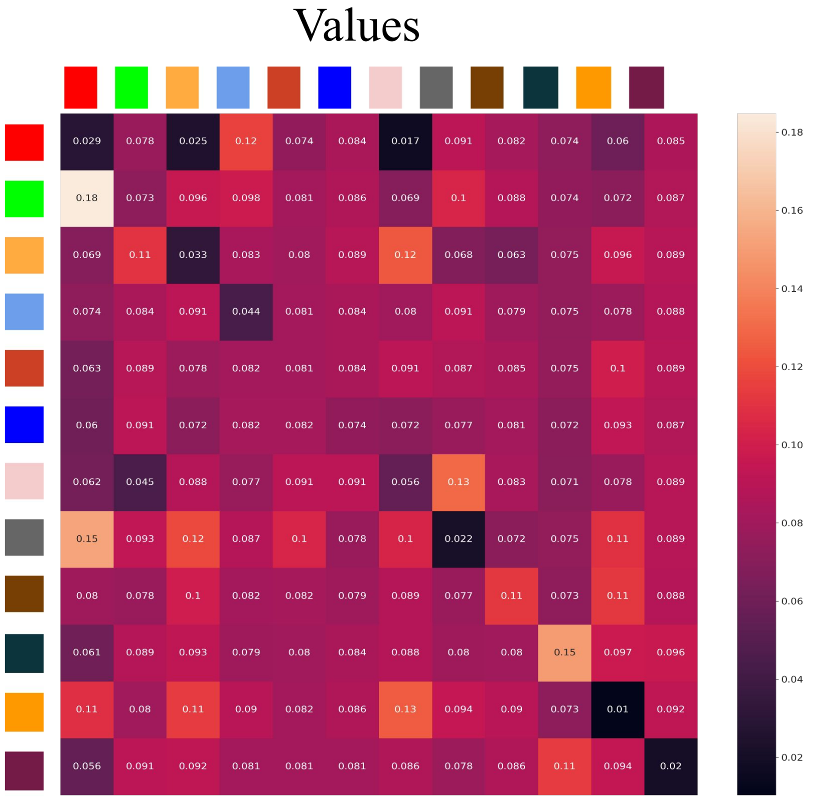
Dot Product



Attention Score

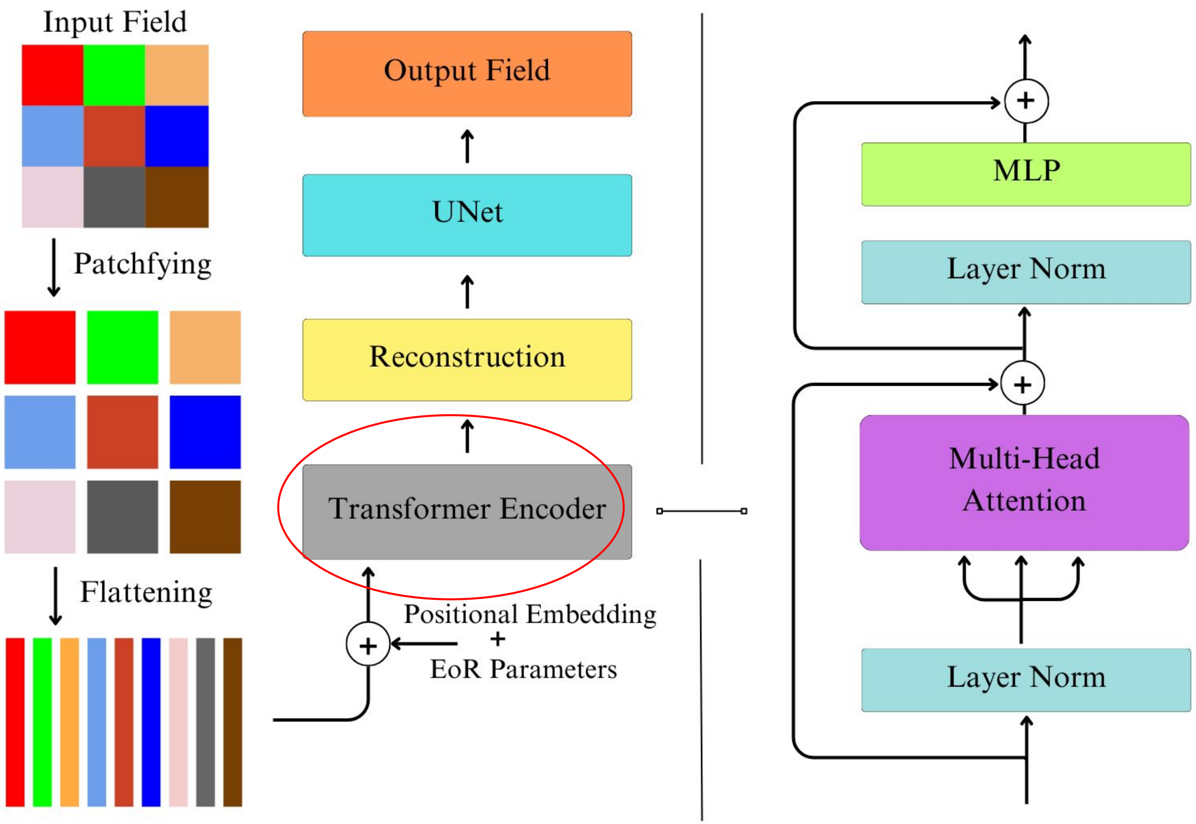


Attention Score

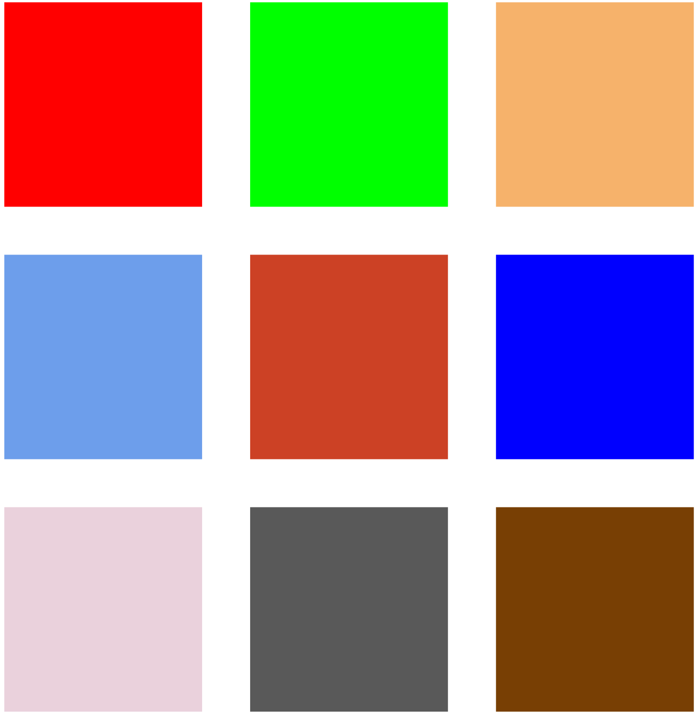


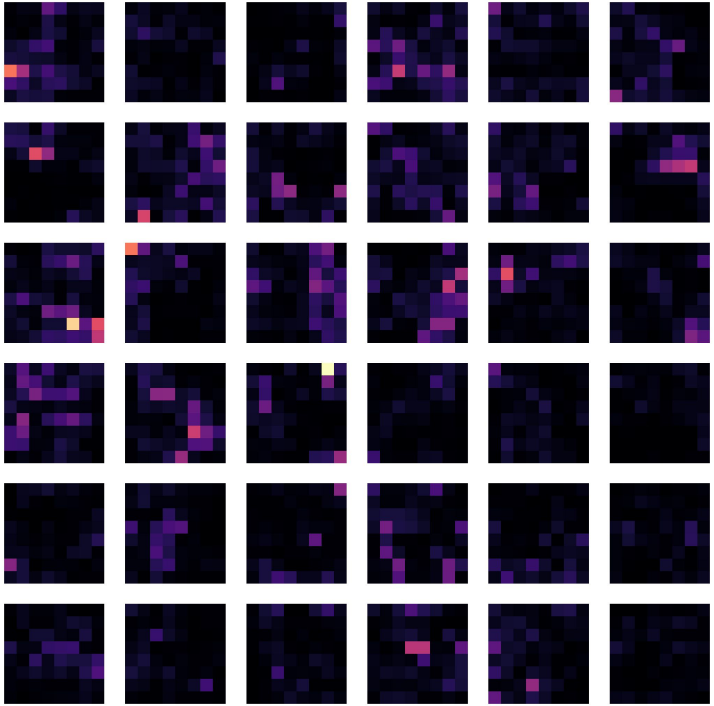
$$\text{Attention}(\mathbf{Q},\mathbf{K},\mathbf{V}) = \text{softmax}\left(\frac{\mathbf{Q}\mathbf{K}^T}{\sqrt{D_H}}\right)\mathbf{V}$$

UNet integrated Vision Transformer (CosmoUiT)

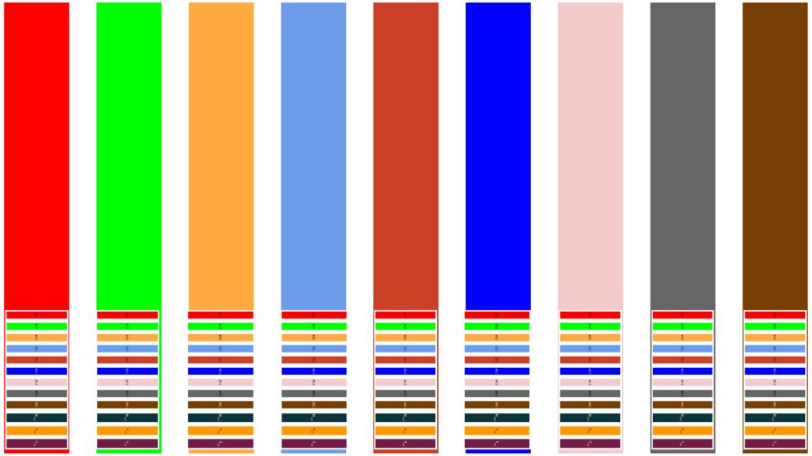


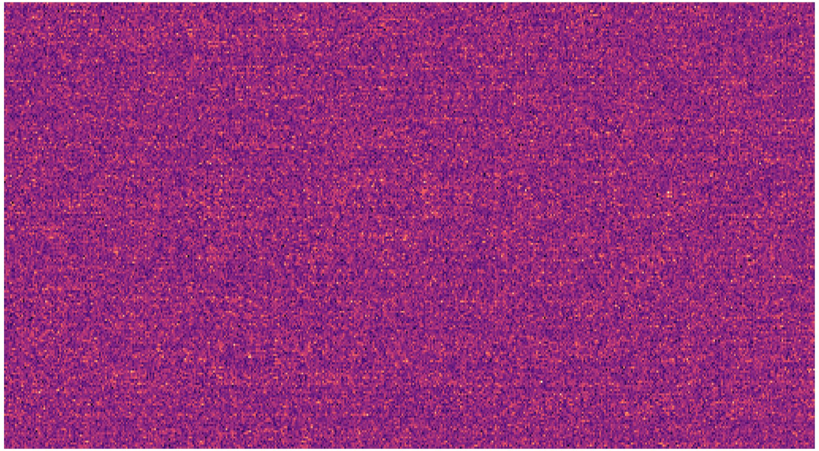
Patchified Field



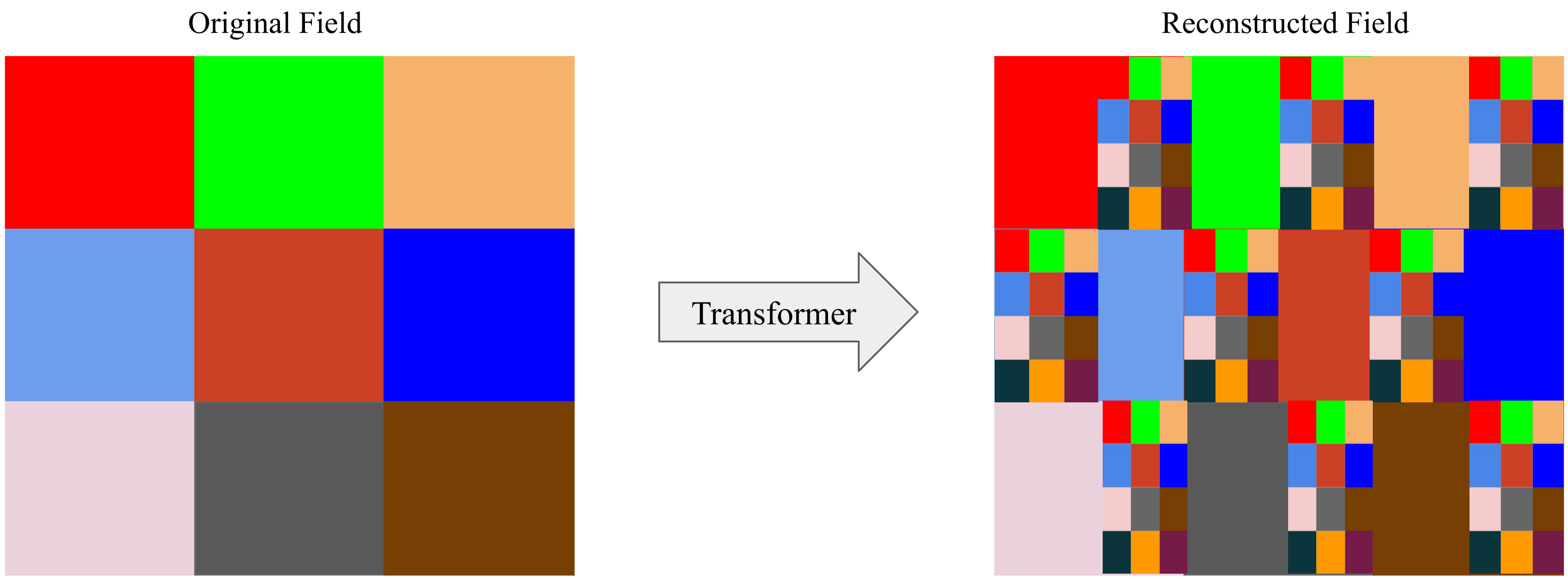


Transformer Output

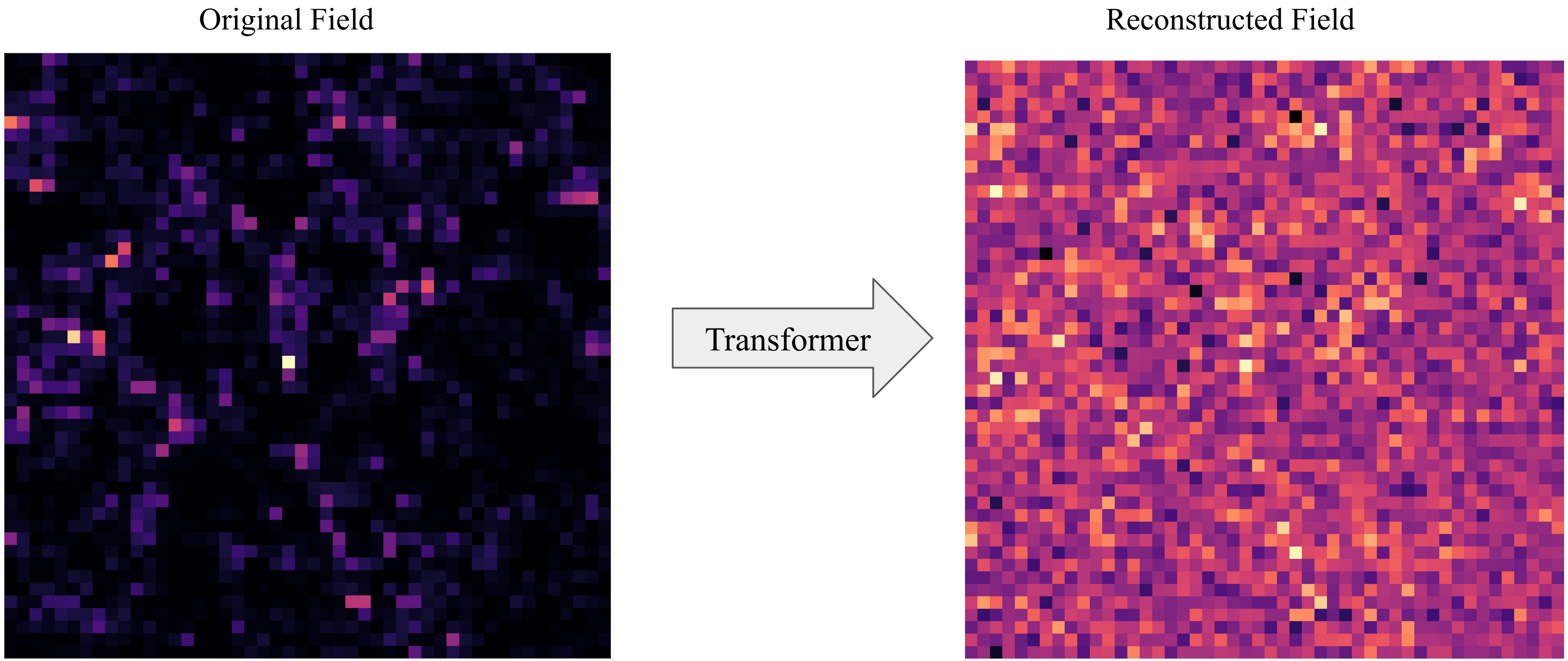




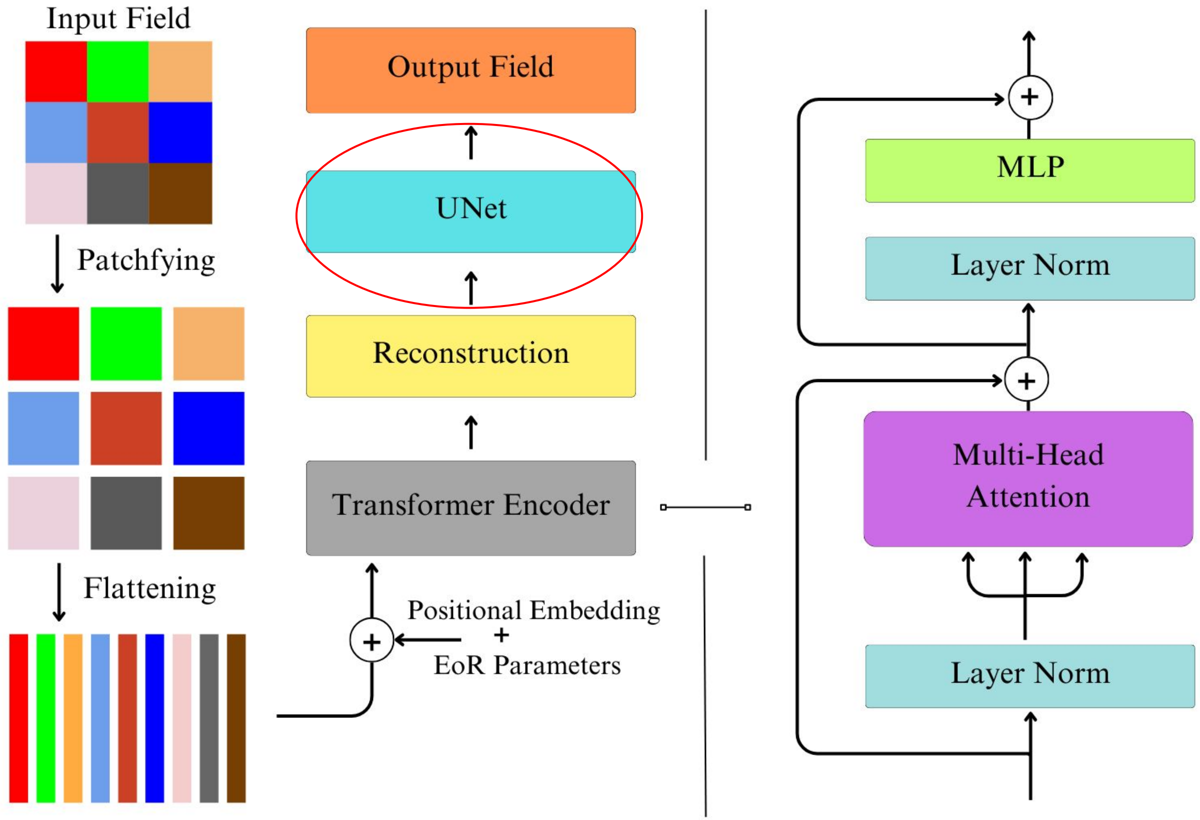
Reconstructed Field



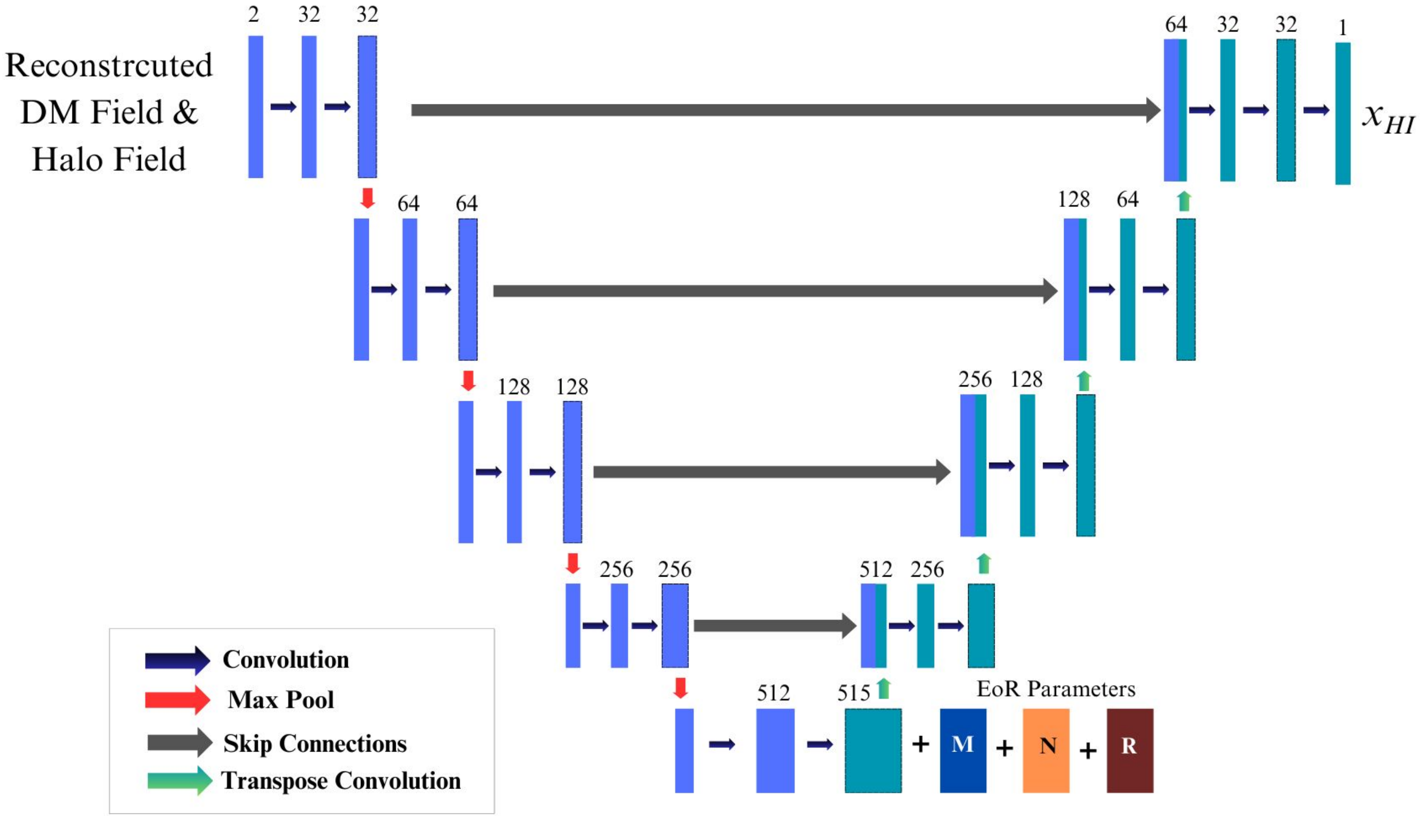
Reconstructed Field



UNet integrated Vision Transformer (CosmoUiT)



UNet Architecture



UNet Architecture

Training Data Set : `CosmoUiT`

Reionization Simulation: ReionYuga https://github.com/rajeshmondal18/ReionYuga

Simulated 21-cm fields within a box of 384 Mpc for following parameters:

- ❖ **Minimum Halo Mass,** $\boldsymbol{M_{h,min}}$ $: 10 \times 10^8\ M_\odot \le M_{h,min} \le 800 \times 10^8\ M_\odot$
- ❖ **Ionizing Photon Emitting Efficiency,** $\boldsymbol{N_{ion}}$ $: 10 < N_{ion} < 200$
- ❖ **Maximal Distance travelled by Ionizing Photons,** $\boldsymbol{R_{mfp}}$ $: 1.12 \le R_{mfp} \le 40.32$ Mpc

7203 parameter combinations, of which 80% for training 20% for validations

GPU Specifications: `CosmoUiT`

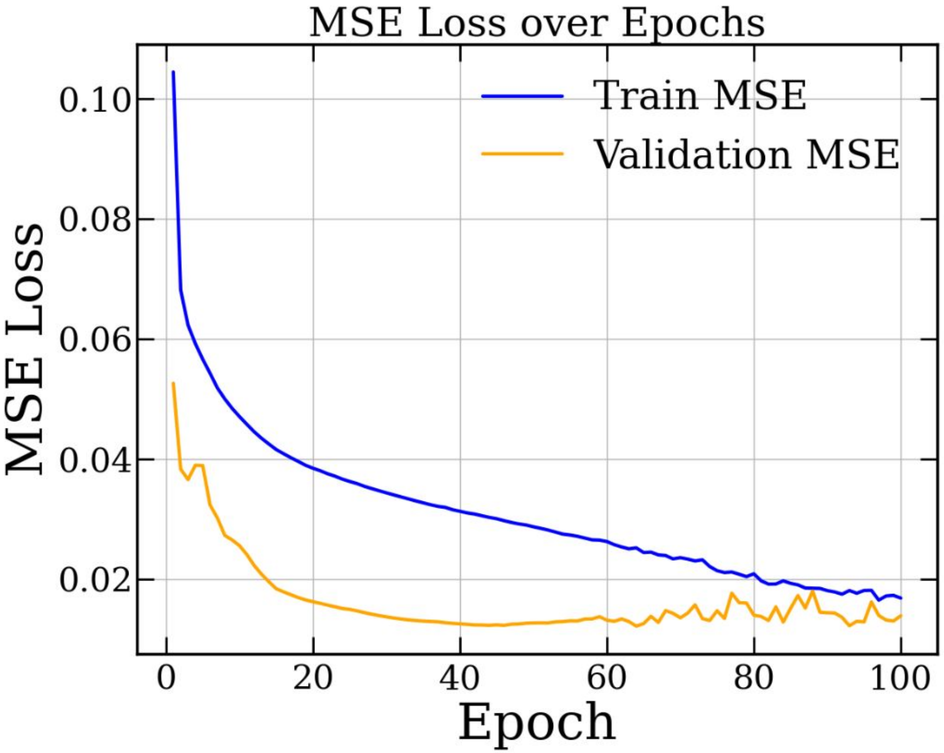
Device Name: NVIDIA A100-SXM4-40GB

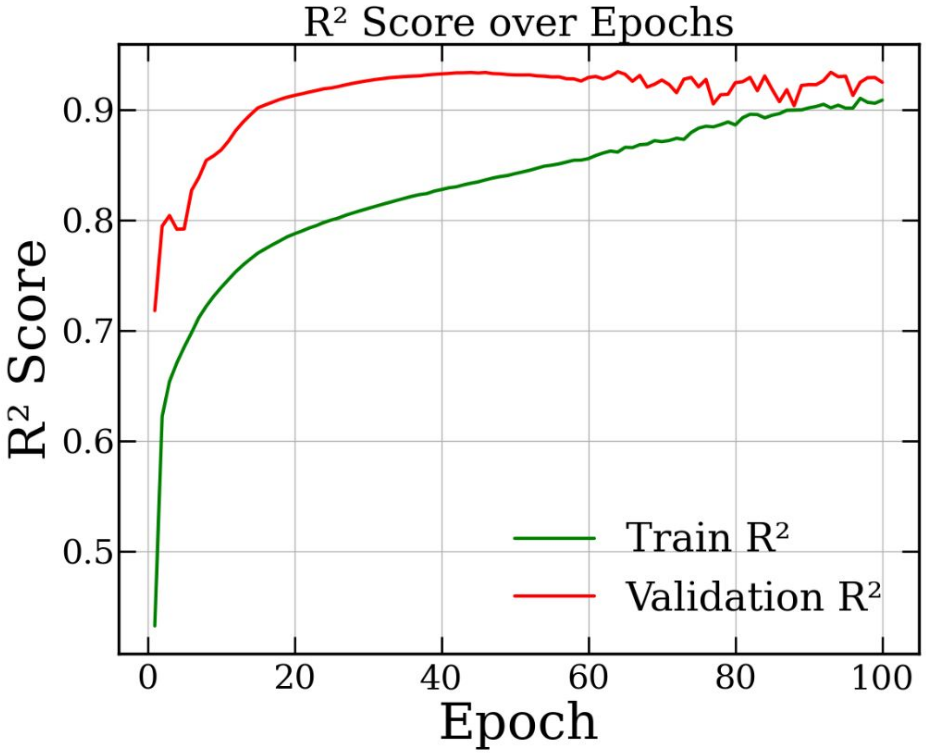
Total Memory Used: 30 GB

Batch size: 16

Training Time: 100 hrs for 100 epochs

Loss and R^2 for CosmoUiT





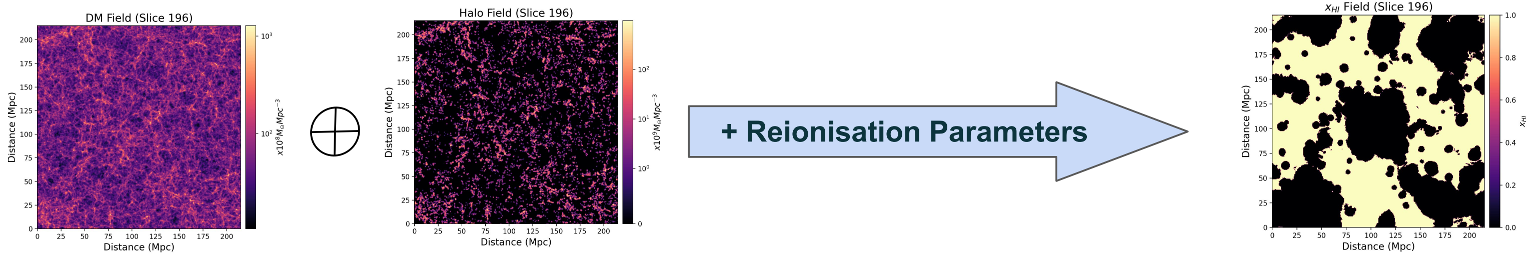
Validation Loss: 0.01385
Training Loss: 0.01678

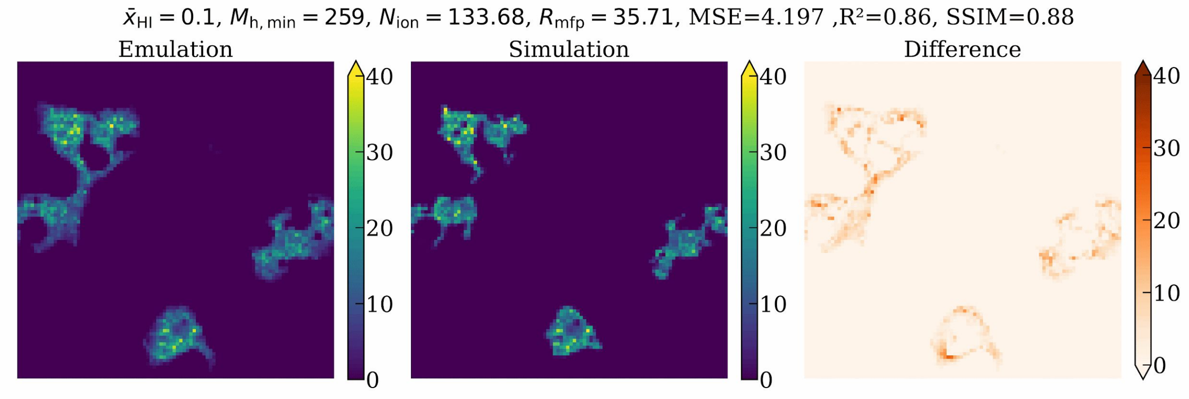
Validation R^2: 0.925
Training R^2: 0.9091

CosmoUiT: Field-Level Emulator (3D Coeval Cubes)

Dark Matter Density field

Halo Density field

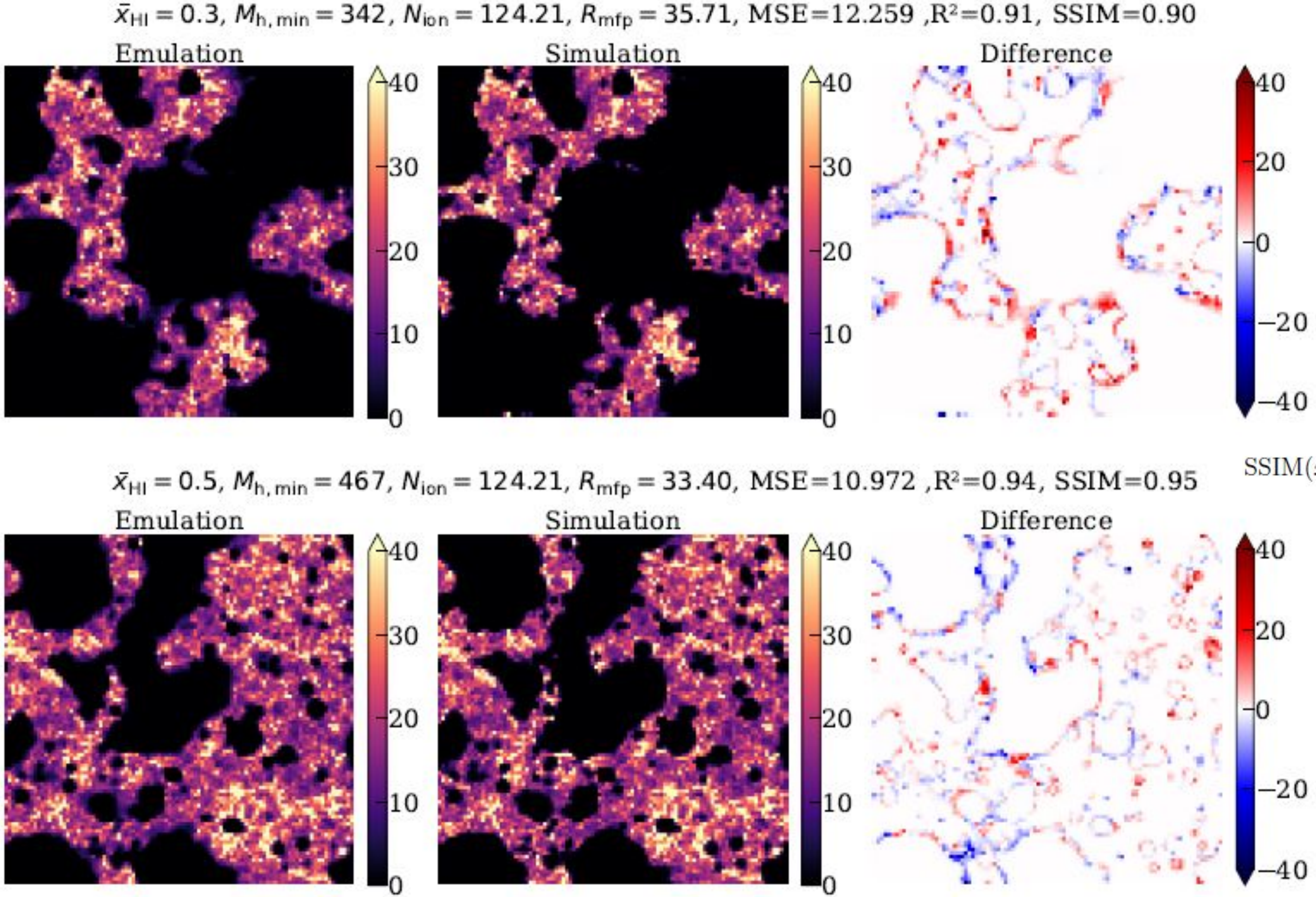




Posture, Mahida et al. 2026 (JCAP)

(arXiv: 2510.01121)

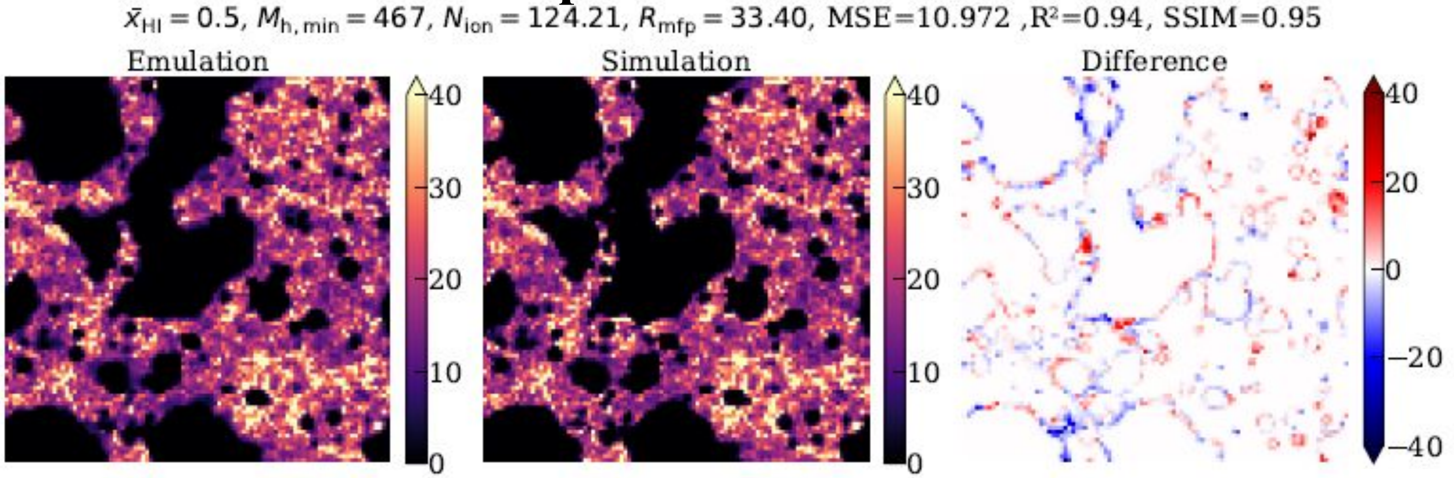
Emulated 21-cm Maps



SSIM ~ 1
=> High structural similarity

$$\mathrm{SSIM}(x,y) = \frac{(2\mu_x\mu_y + C_1)(2\sigma_{xy} + C_2)}{(\mu_x^2 + \mu_y^2 + C_1)(\sigma_x^2 + \sigma_y^2 + C_2)}$$

Emulated 21-cm Maps



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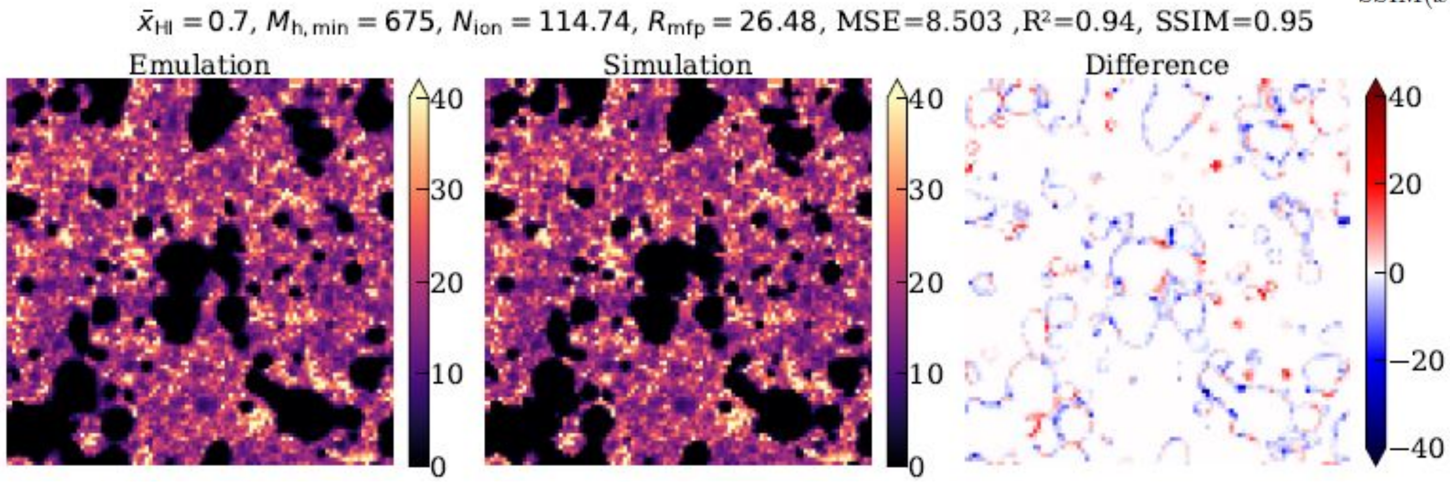
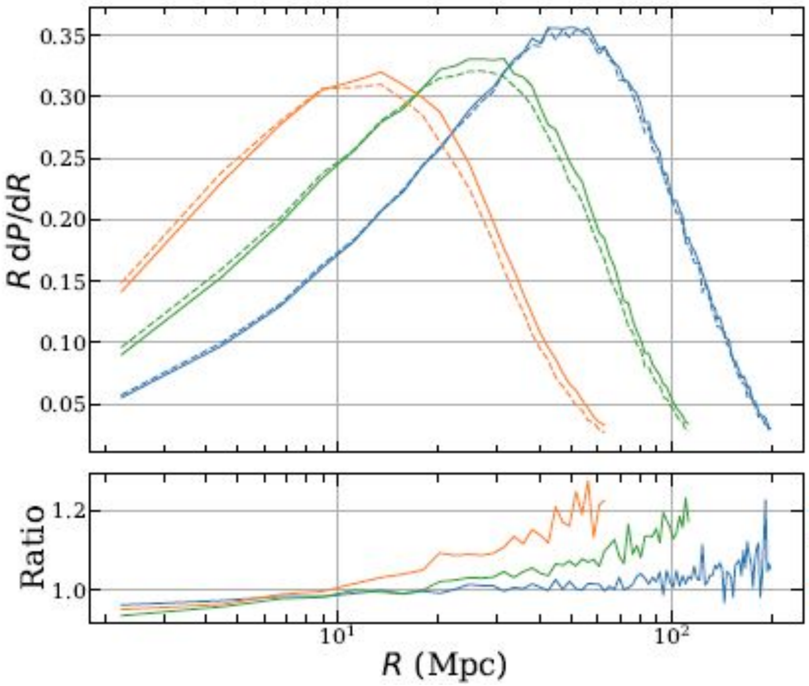
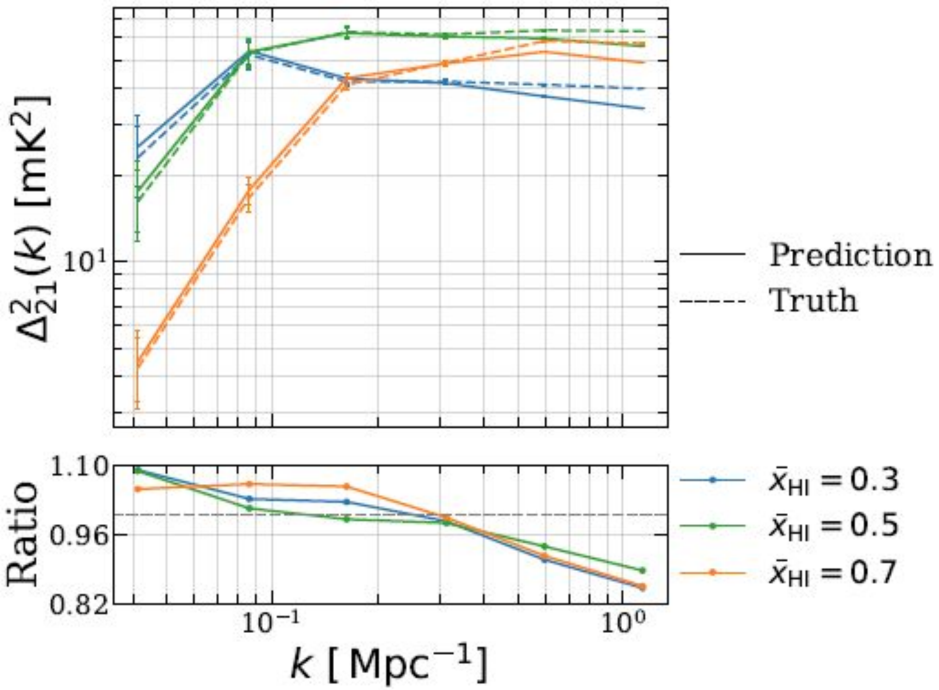
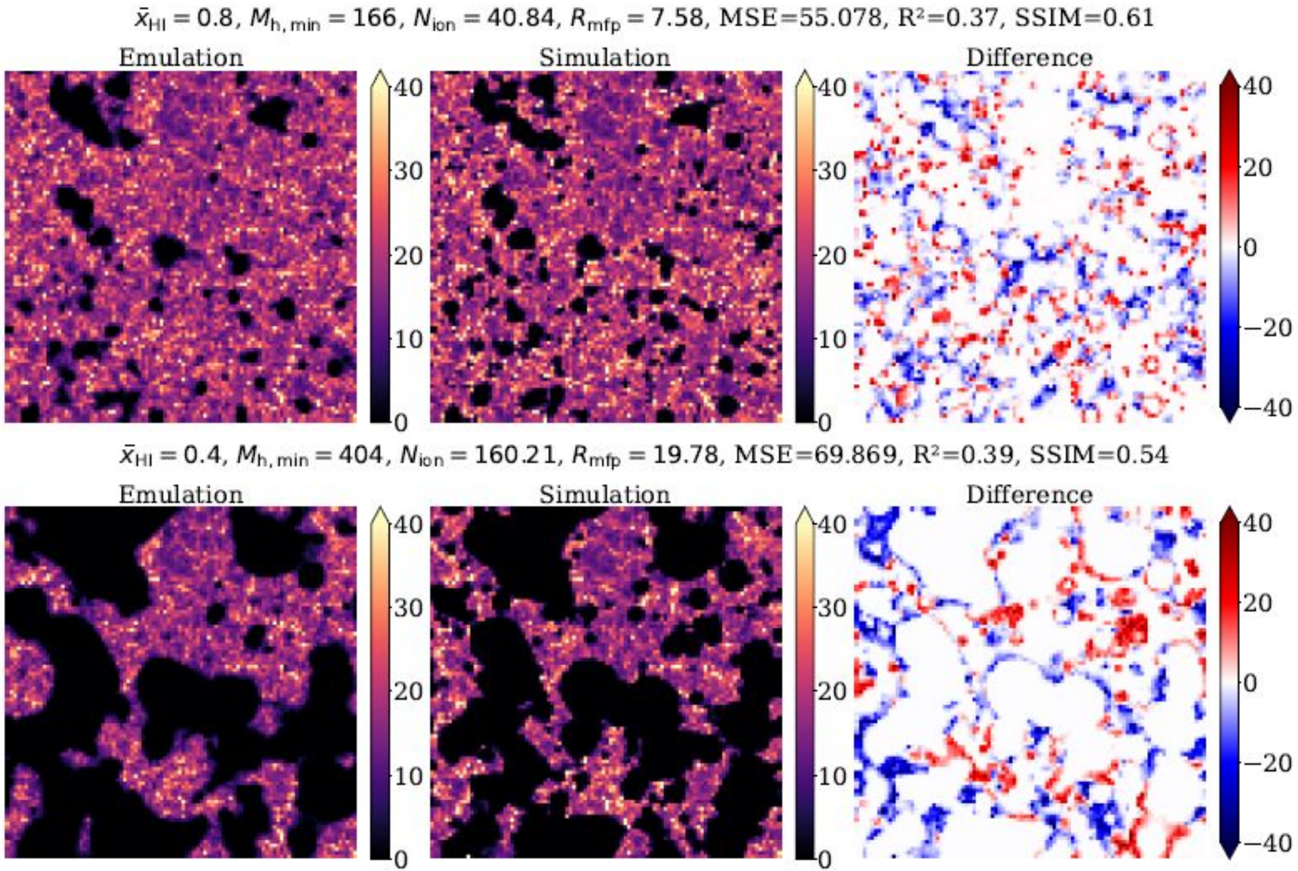


HII Region Size Distribution and Power Spectrum





Generalization for Different Dark Matter and Halo Fields



Summary: III

- `CosmoUiT` can predict the 3D 21-cm field for given input reionization parameters, dark matter and halo fields.

- Transformers can capture the large-scale effects and UNet captures the small scale effects of the reionization.

- `CosmoUiT` as a hybrid architecture effectively predicts both large and small scale features of the ionisation field.

- `CosmoUiT` works considerably well for the out of domain input fields.

Further Development

- Upgrade `CosmoUiT` to predict the entire lightcones of the 21-cm field for given input reionization parameters.

- Train `CosmoUiT` for other simulations; both semi-numerical and radiative transfer.

- Make it more robust by training it for a large ensemble of Nbody realizations.

CosmoUiT: A Vision Transformer-UNet Hybrid fo Fast and Accurate Emulation of 21-cm Maps from the Epoch of Reionization

Authors: Prasad Rajesh Posture, Yashrajsinh Mahida, Suman Majumdar, Leon Noble

Posture, Mahida et al.
2026 (JCAP)
(arXiv: 2510.01121)