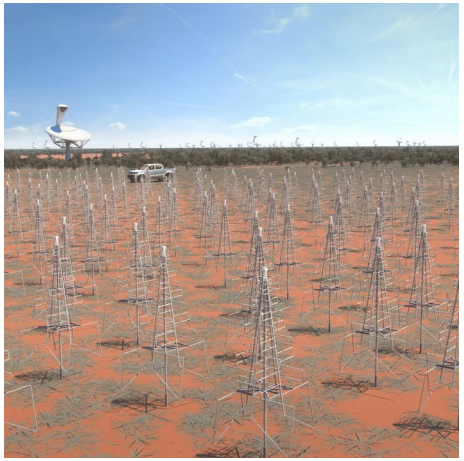
Probing the states of the IGM during the Epoch of Reionization

Raghunath Ghara

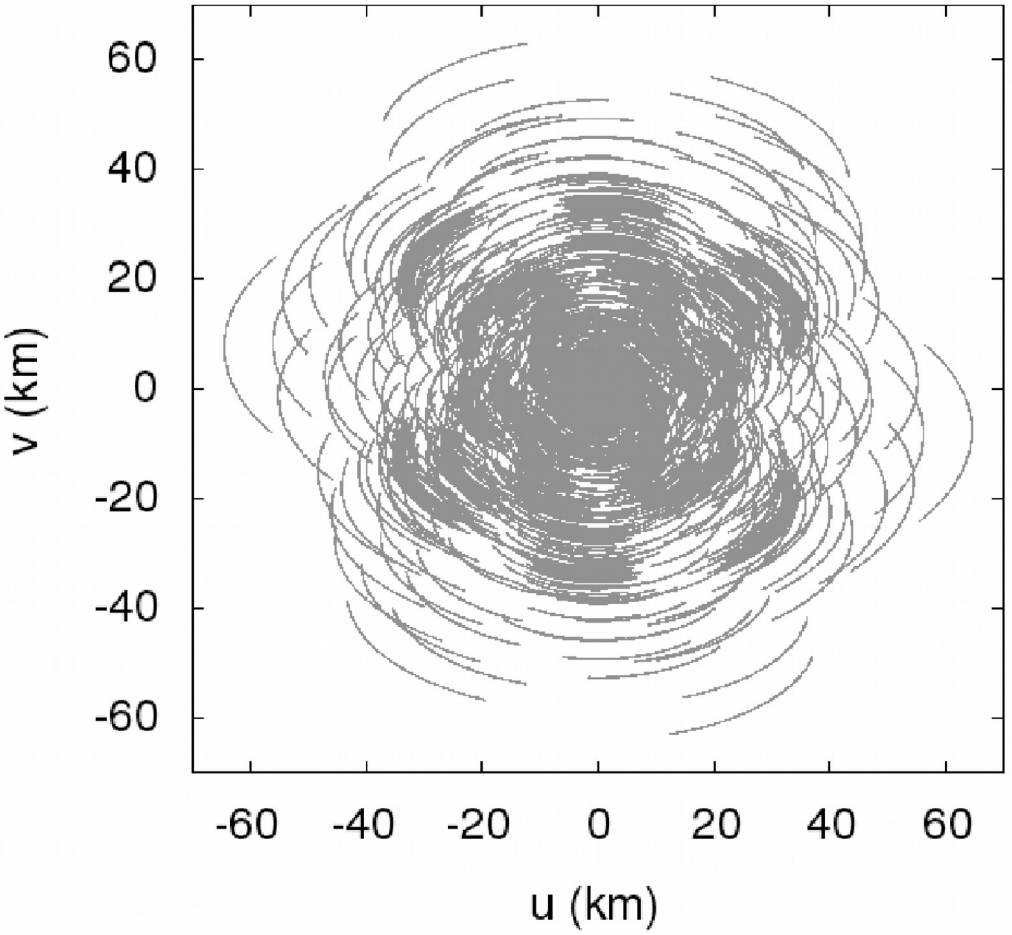
NISER, 21cm Cosmology
Dec, 2023

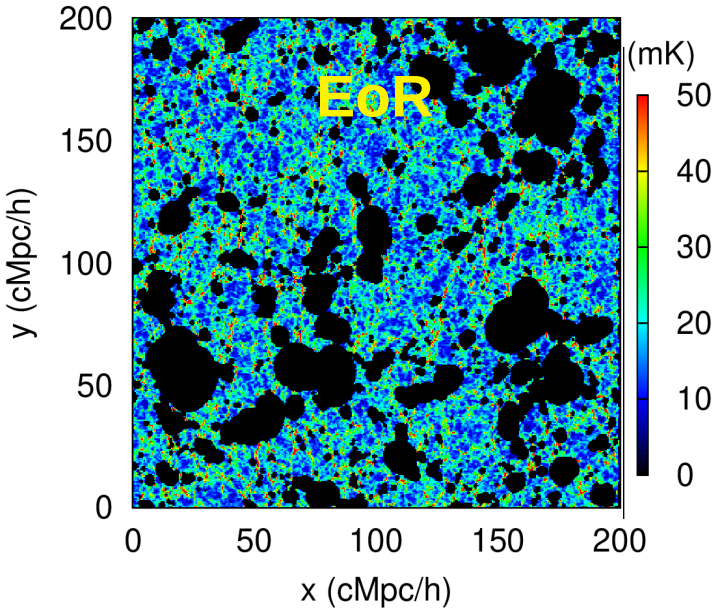
Happening Finally!!

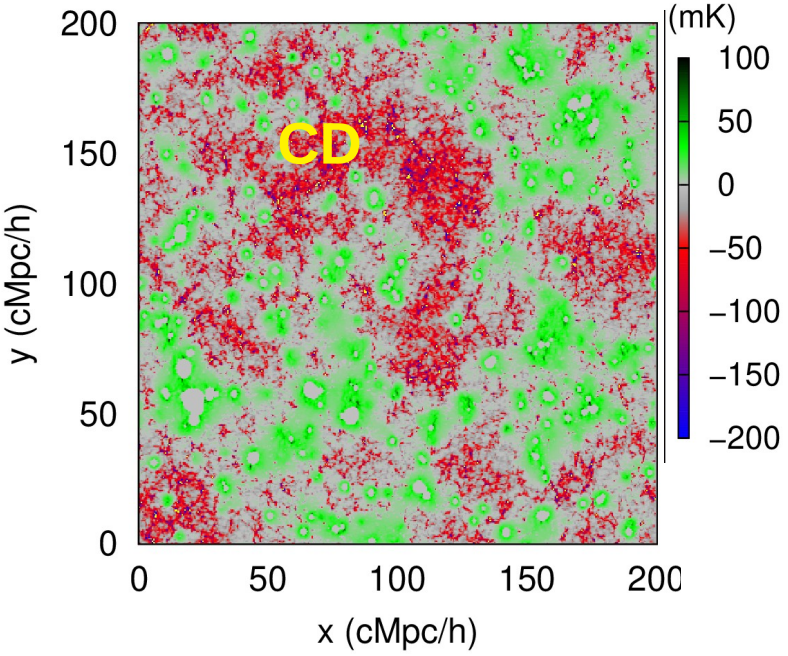


Activity	SKA-LOW		SKA-MID	
	Date	Number of stations	Date	Number of dishes
Start of Construction	Jul 2021		Jul 2021	
Start of major contracts	Aug 2021		Aug 2021	
Finish of Array Assembly 0.5 (AA0.5)	Feb 2024	6	Mar 2024	4
Finish of AA1	Feb 2025	18	Feb 2025	8
Finish of AA2	Feb 2026	64	Dec 2025	64
Finish of AA*	Feb 2027	307	Jun 2026	144
Finish of AA4	Nov 2027	512	Jun 2027	197

SKA will have the sensitivity
to image the HI 21-cm signal

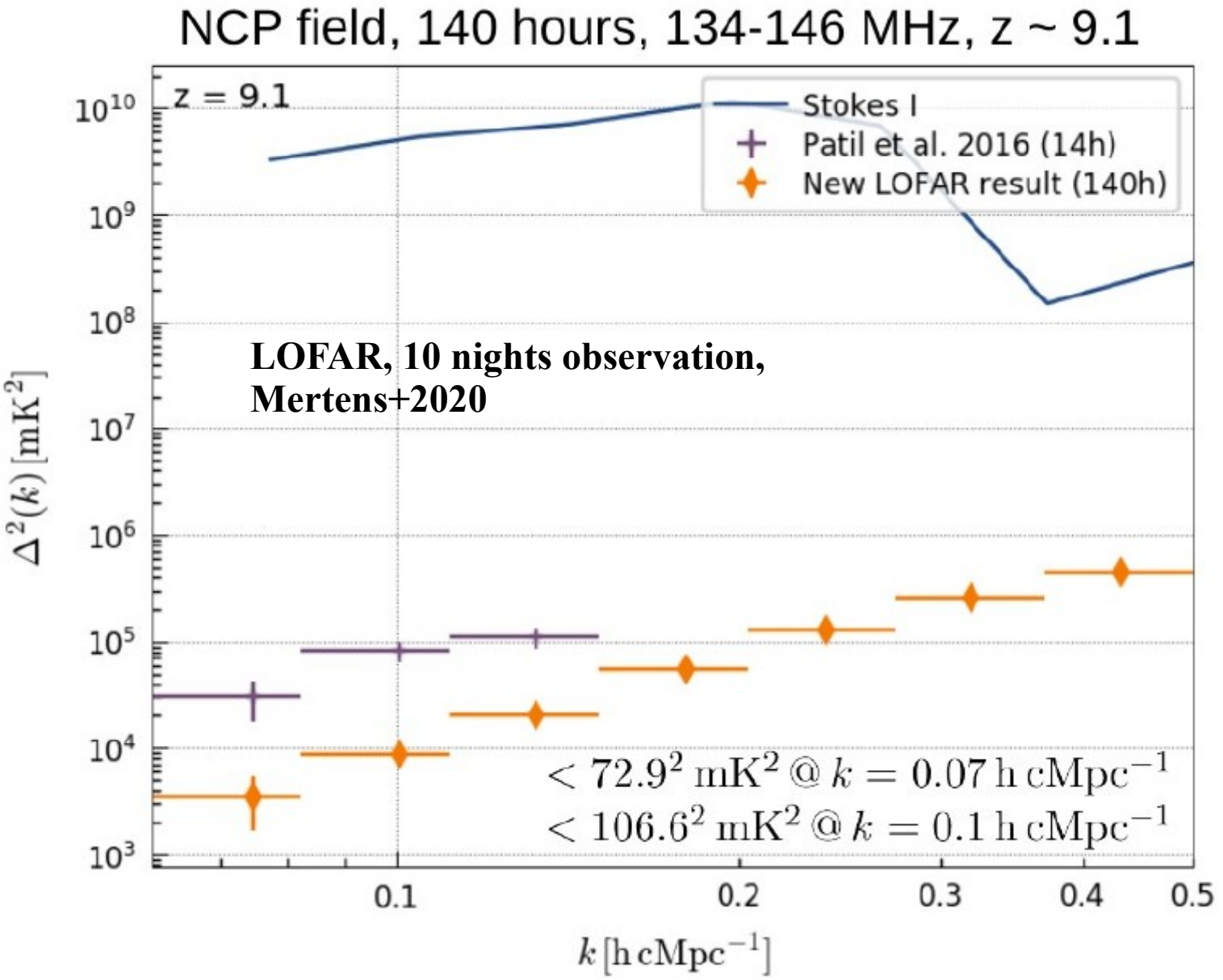




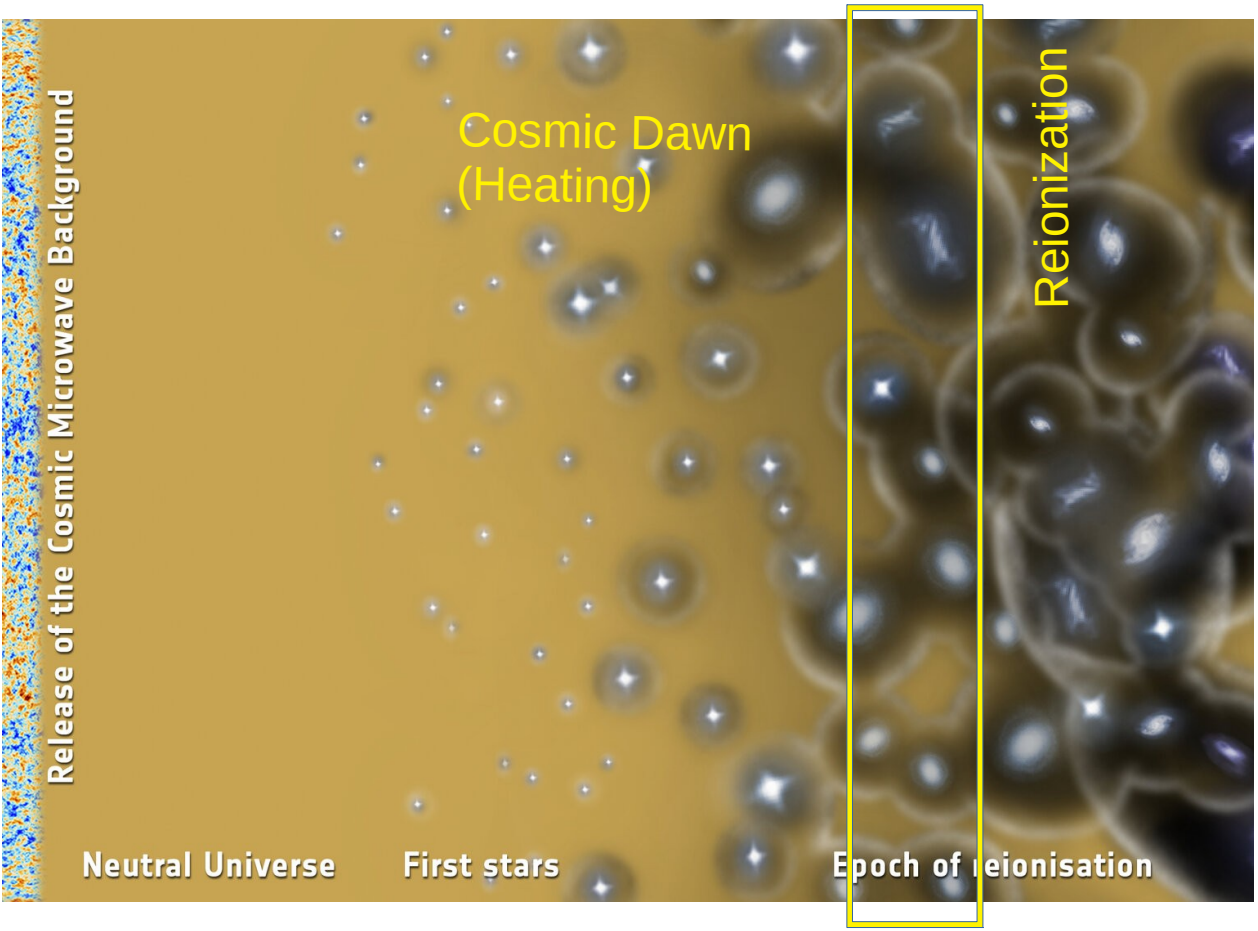


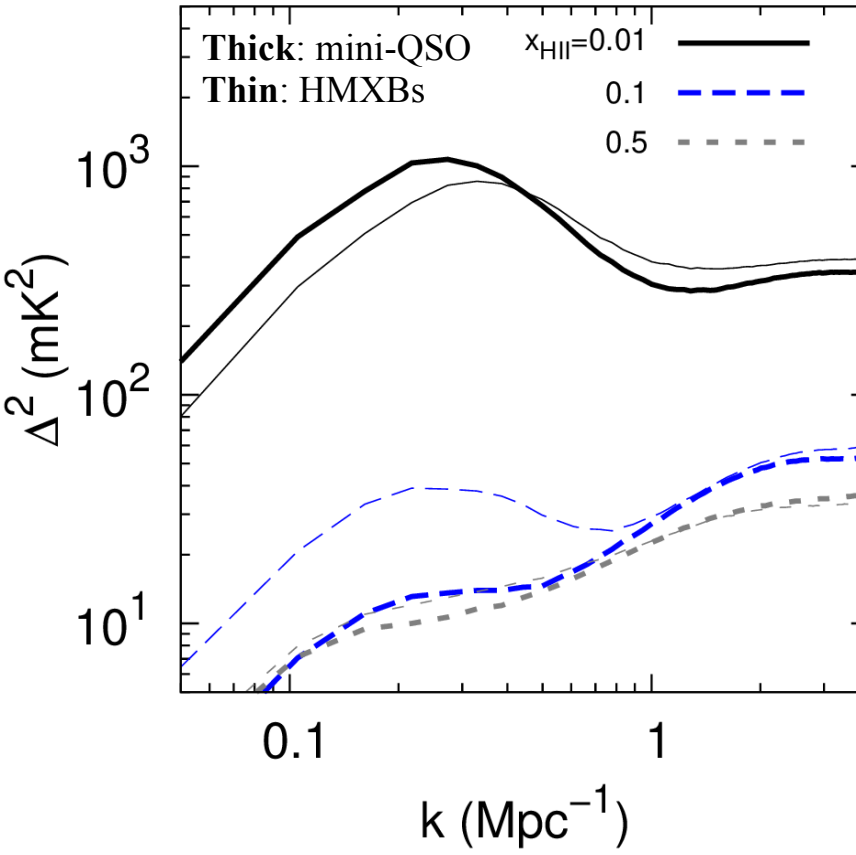
SKA first target: EoR 21-cm signal power spectrum

Perhaps, SKA will also start with a upper limit measurement like LOFAR, HERA, MWA, etc.



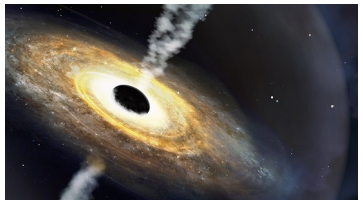
Inference: Source properties





Source properties

- What type of sources?
  - Galaxies, Quasars, HMXBs?
  - UV & X-ray emissivity, etc.
- Population of sources
  - T_{vir}? Or $M_{halo,\ min}$
- PopIII - PopII transition
- Feedbacks
- ….



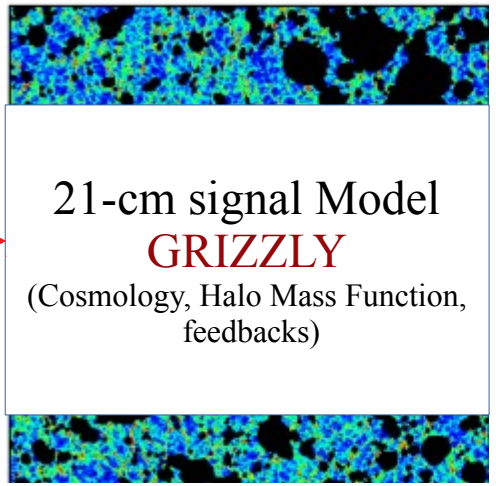
Inference framework

Ghara+2020, MNRAS, 493, 4, 4728
(1st **LOFAR** interpretation paper)
Ghara+2021, MNRAS, 503, 3, 4551
(**MWA** interpretation paper)

Observables

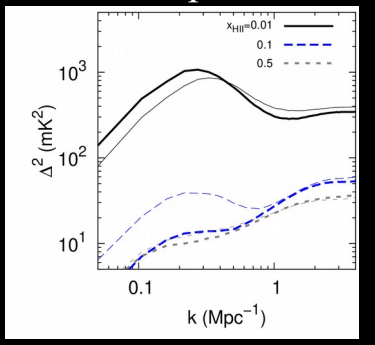
Source Parameters

ζ: Ionization efficiency
M_{min}: Minimum mass of UV Halo
M_{minX}: Minimum mass of X-ray Halo
f_X: X-ray efficiency
α: X-ray Spectral index
……..



21-cm signal Model
GRIZZLY
(Cosmology, Halo Mass Function, feedbacks)

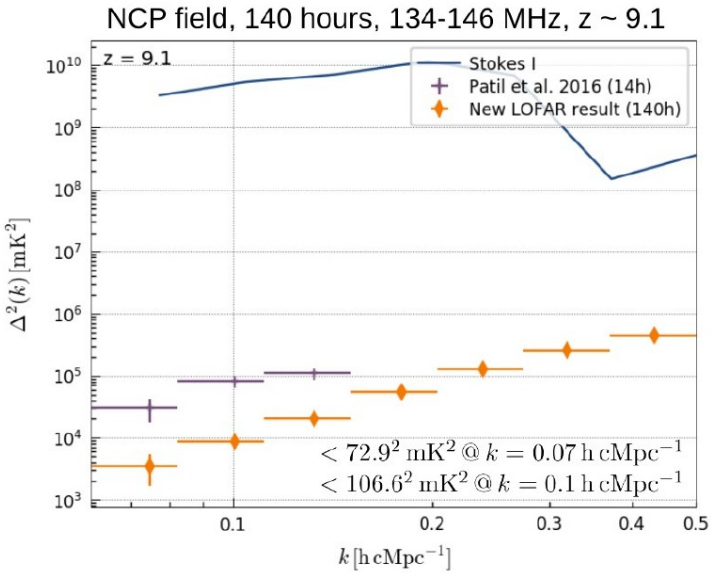
Power spectrum



Likelihood

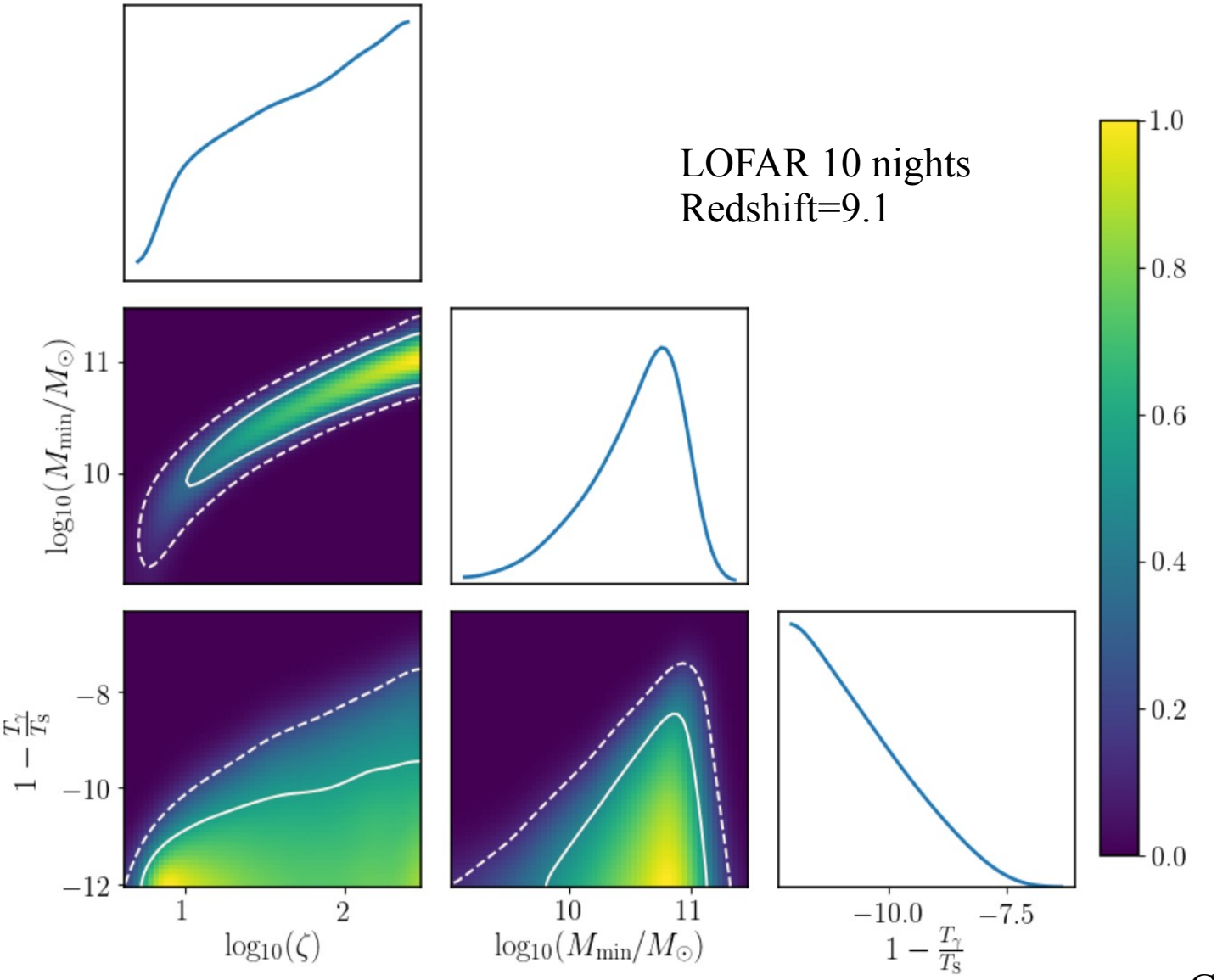
Bayesian inference

MCMC



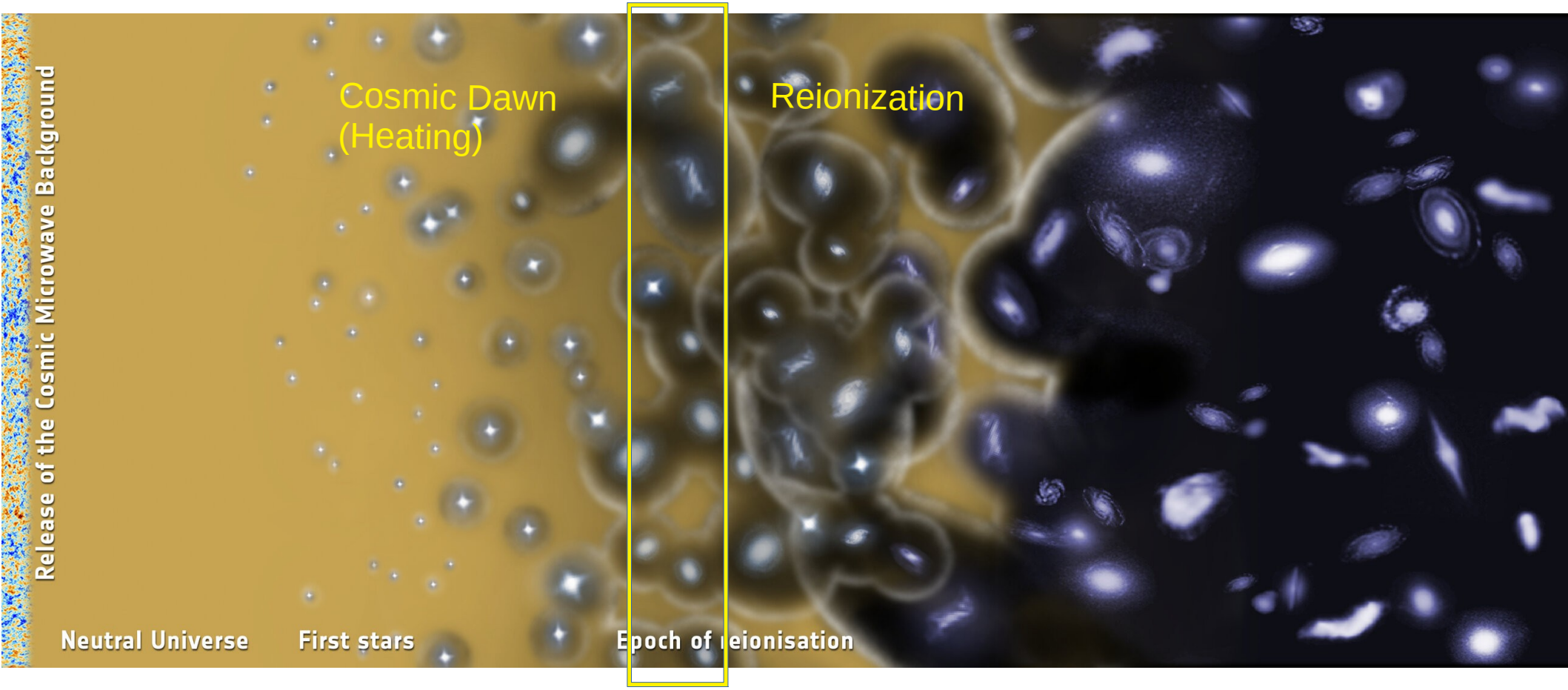
Inference about the EoR sources

- Posterior distribution of **excluded models**, (**Uniform T_s**)



Ghara+2020

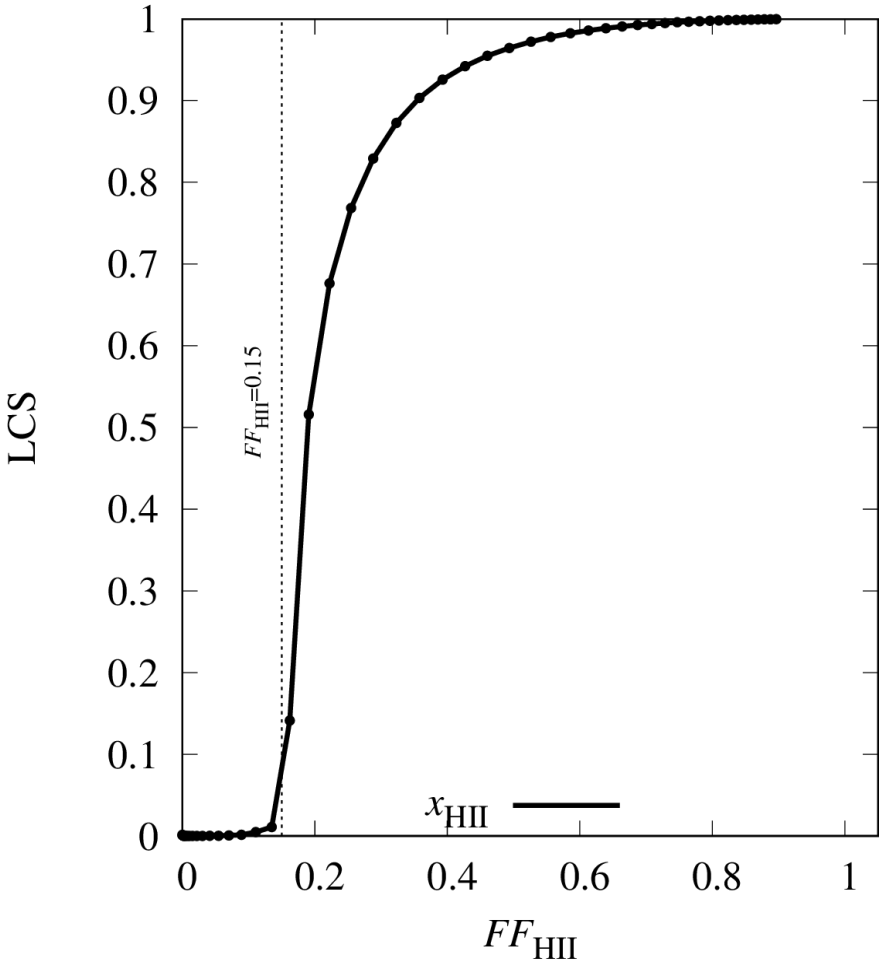
Inference: Properties of the IGM

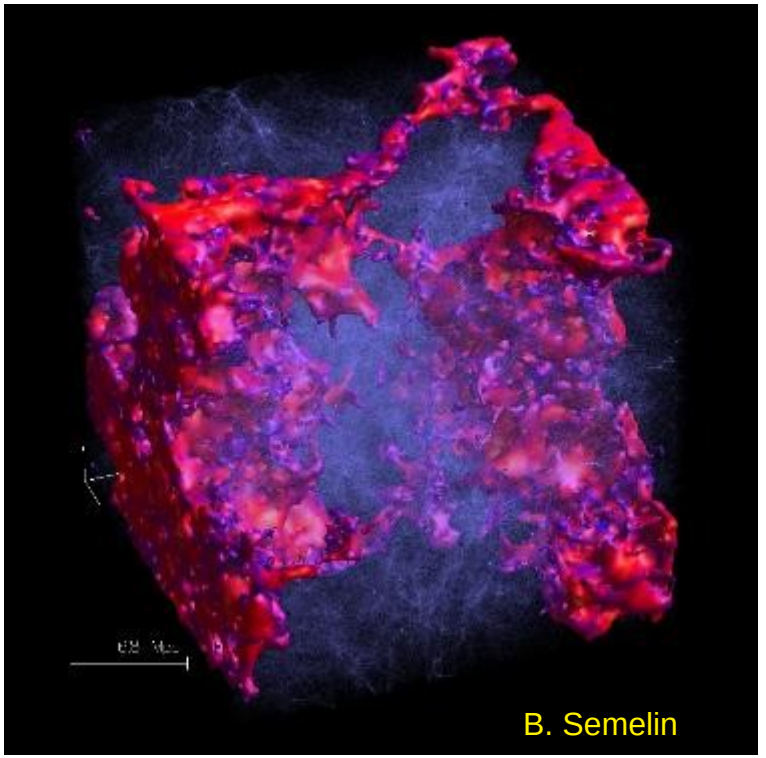


IGM properties

- Fraction of the ionized regions
- Fraction of emission regions
- Mean Gas temperature
- Morphology of the ionized/emission regions
-

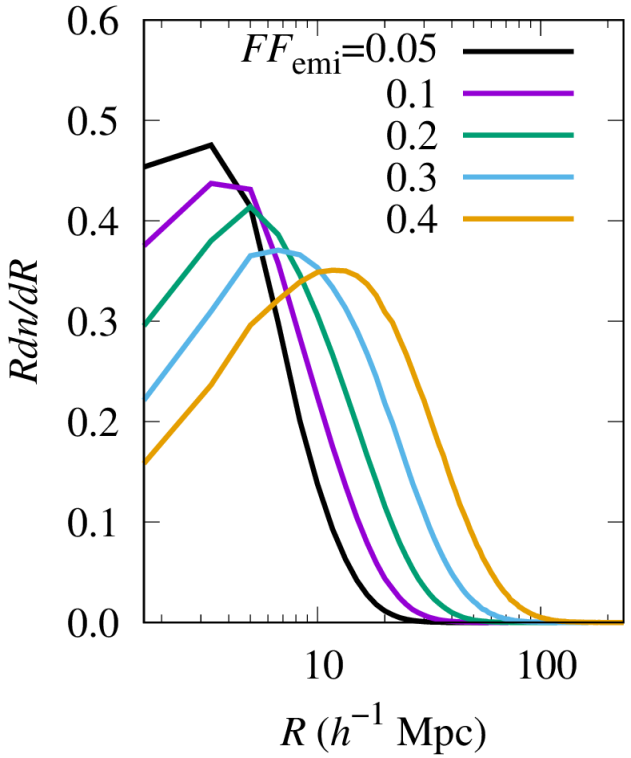
Complex morphology: percolation

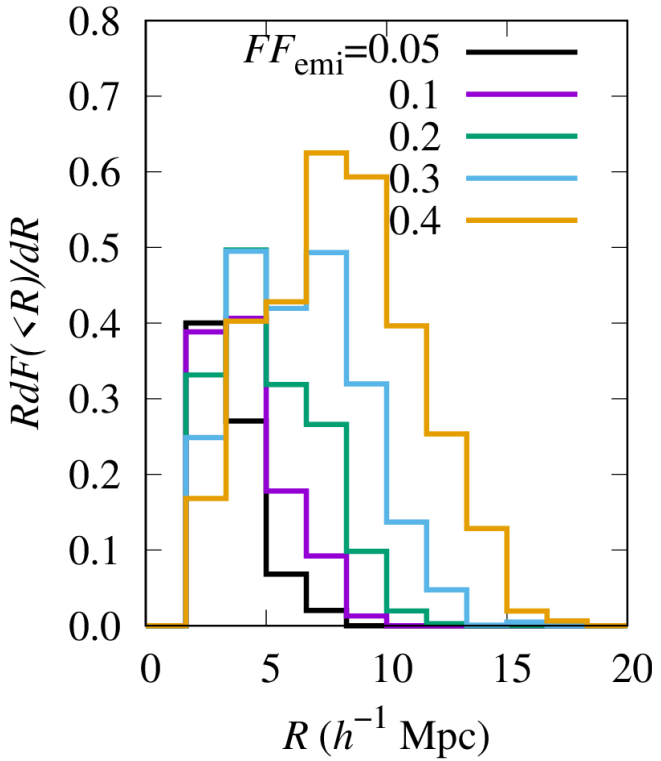


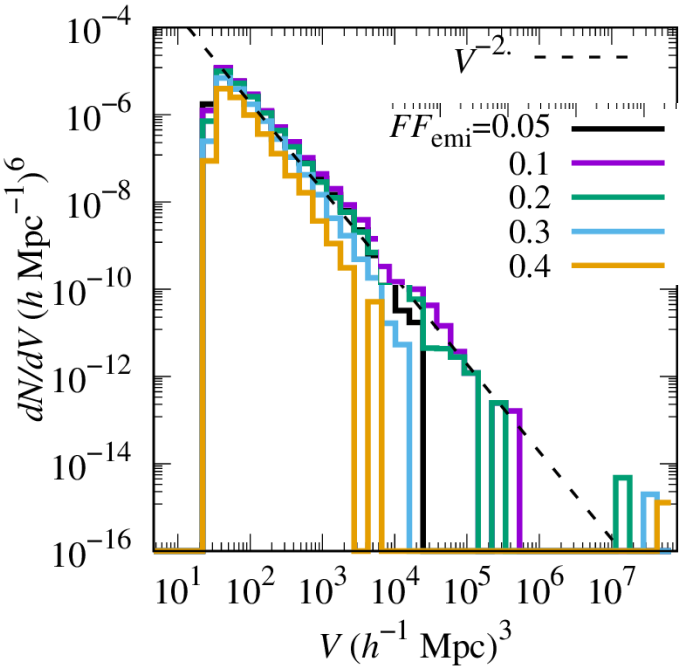


LCS: largest cluster statistics=volume fraction of the largest ionized region

Quantifying morphology







Mean free path method
(Mesinger+2007)
shoots large number of rays around randomly selected points inside the emission (or absorption) regions in random directions and record the lengths of the rays until those reach the edge of the regions.

Granulometry method
(Kakiichi+2017)
based on based Minkowski subtraction and addition steps to estimate the PDFs (applying spherical filters). Sensitive to the smallest dimension of a complex-shaped region.

Friends-of-friends
(Iliev+2006)
considers two neighbouring cells in the binary fields with values larger than 0.5 to be the part of the same region and in the process finds the volume of each region.

IGM inference framework

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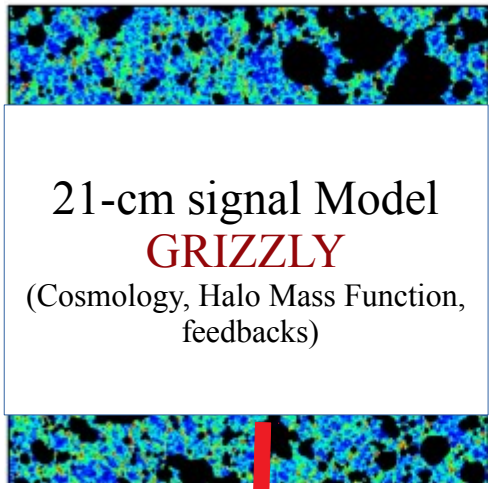

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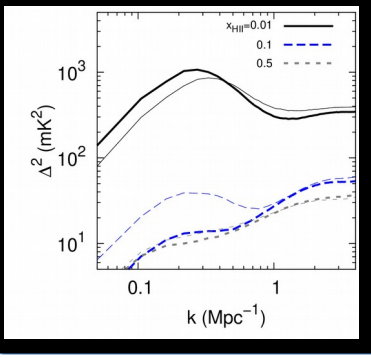
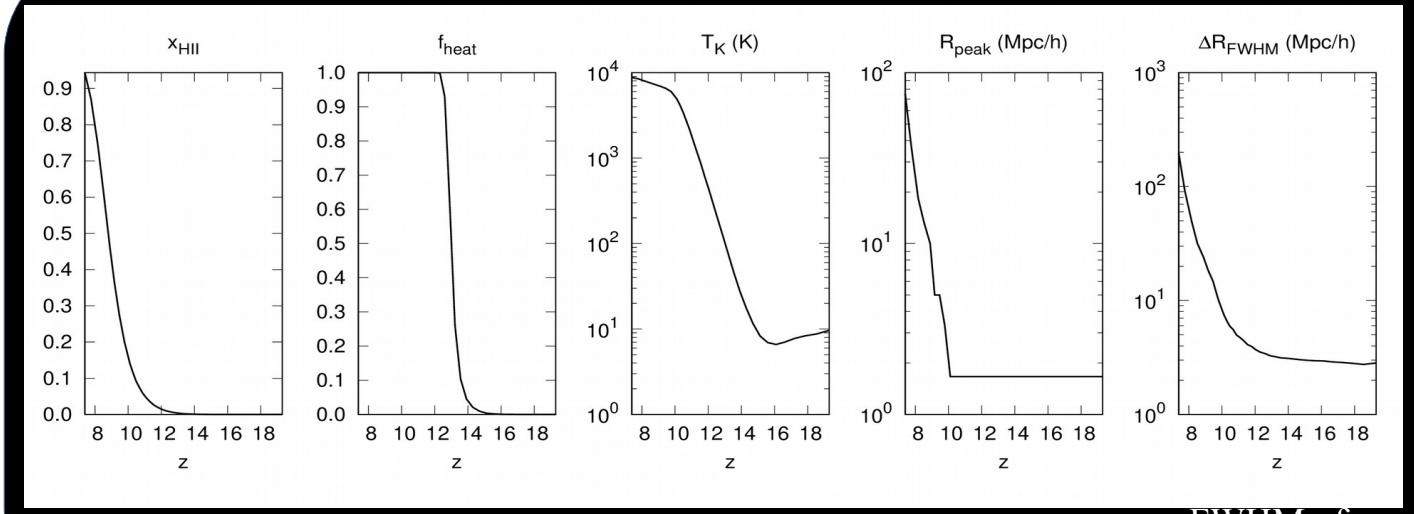
Observables

Power spectrum

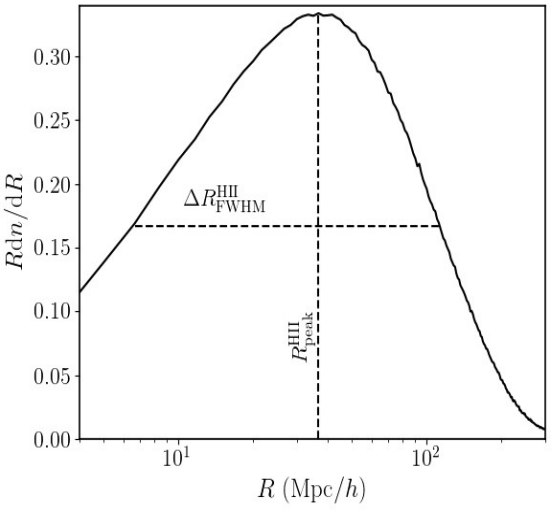


Derived IGM Quantities



Ionization fraction | Heated fraction | Mean gas temperature | Characteristic Size of heated regions | FWHM of bubble size distribution

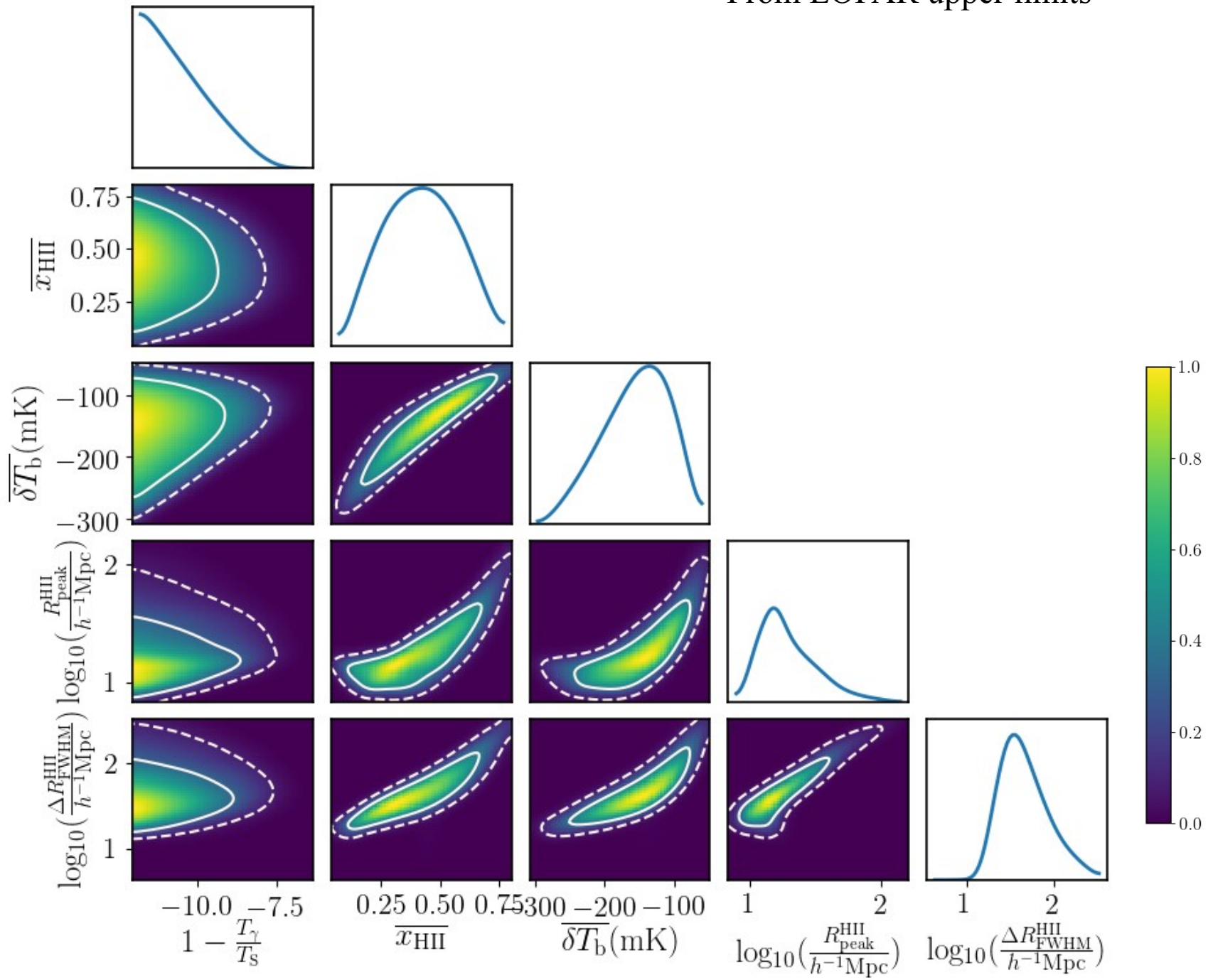
Bubble Size Distribution



Mean free path method

Posterior distribution of **excluded models**

Constraints on IGM at z=9.1
From LOFAR upper limits



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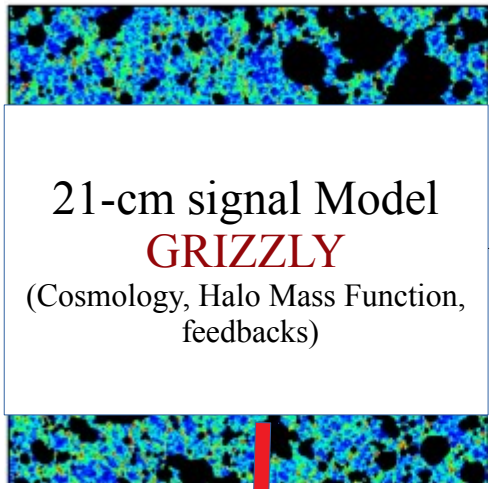

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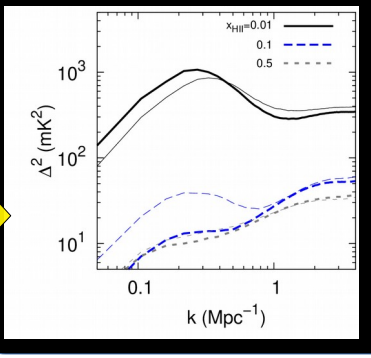

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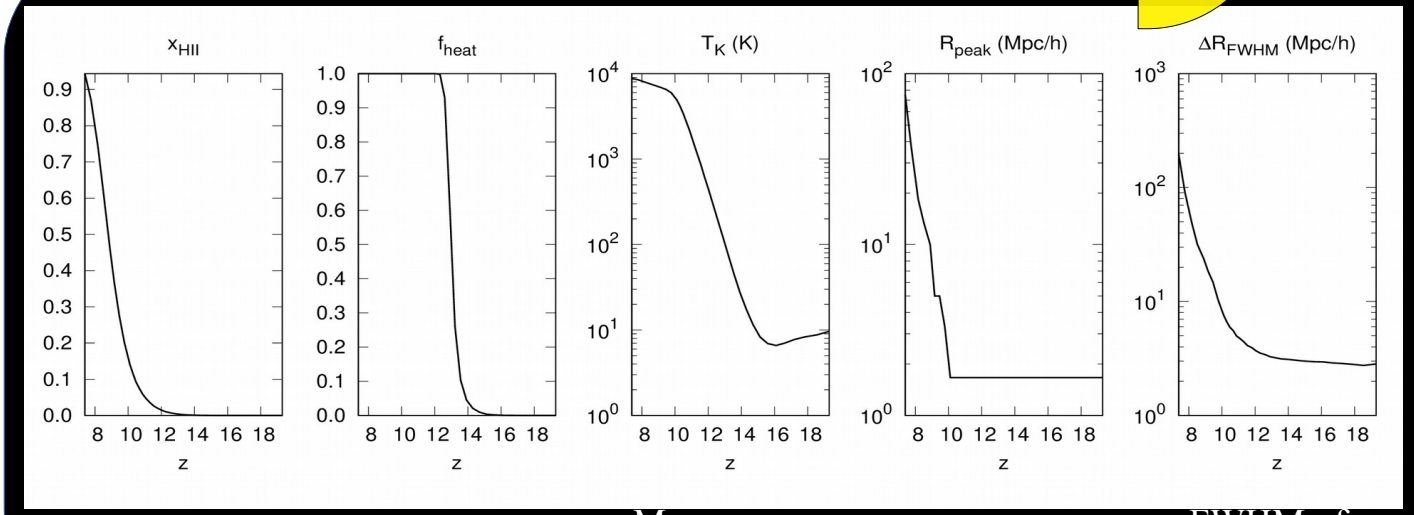

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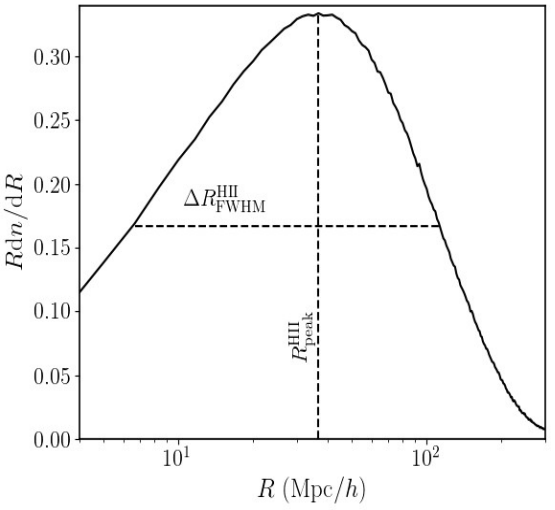
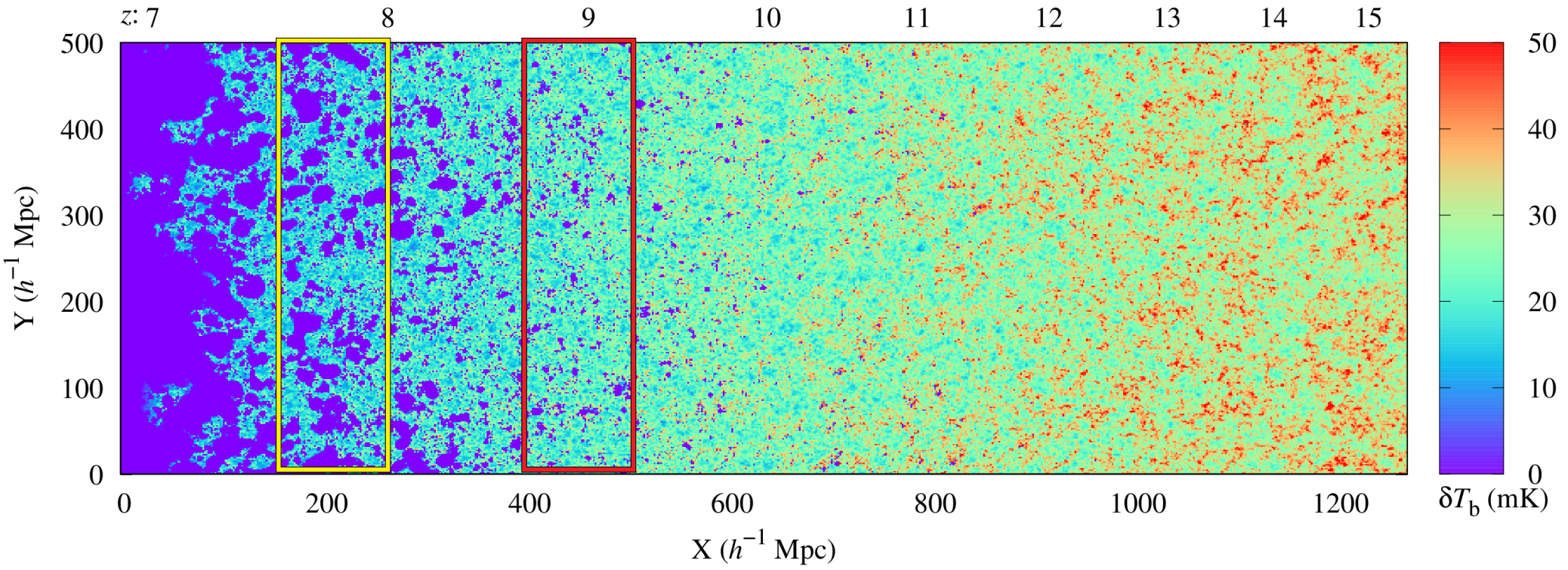
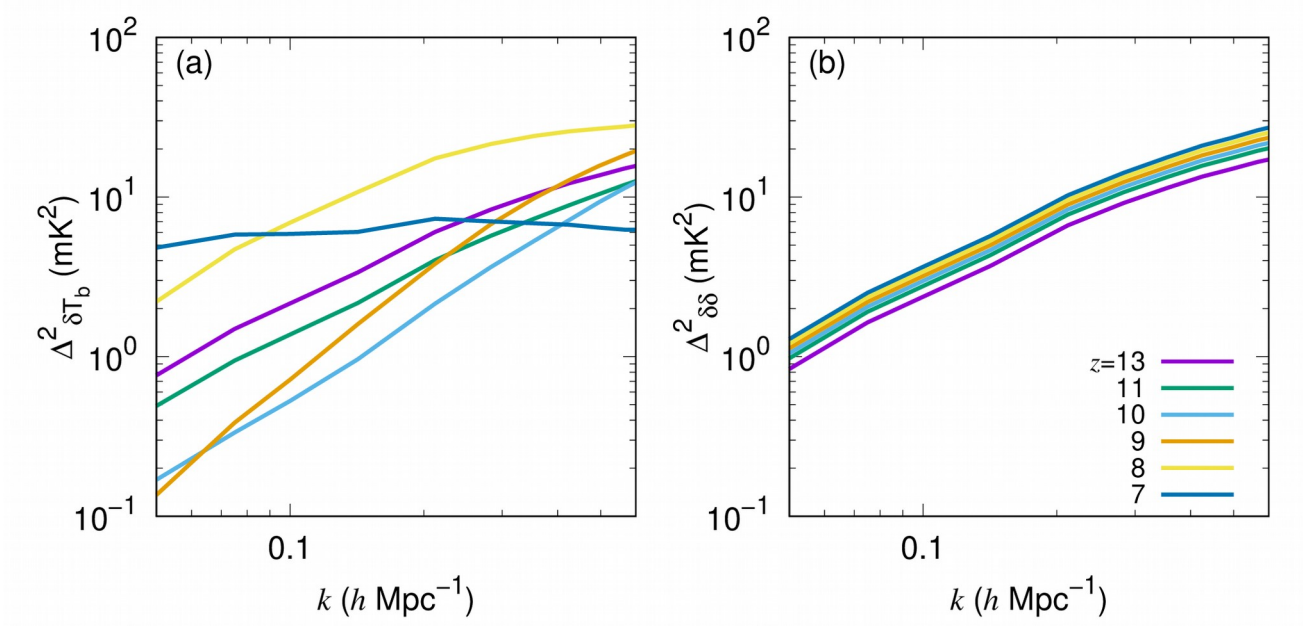


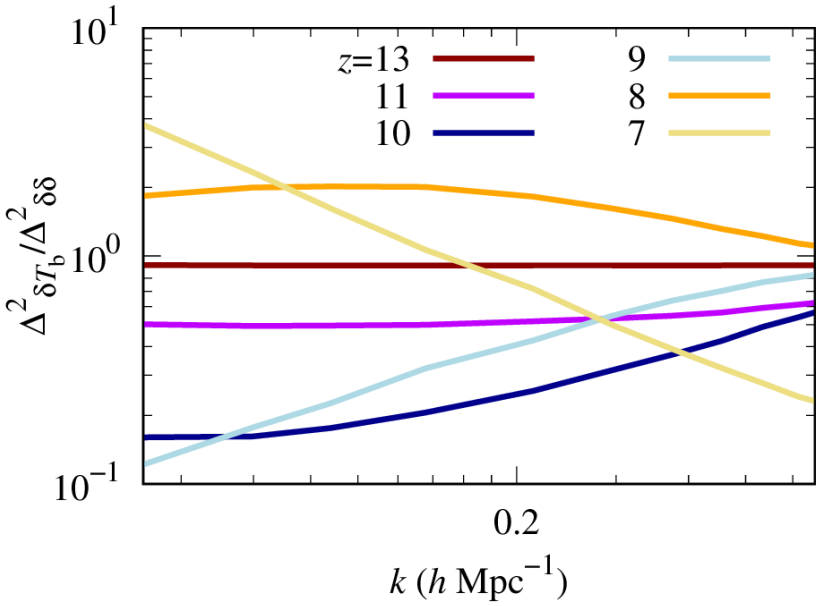
Mean free path method

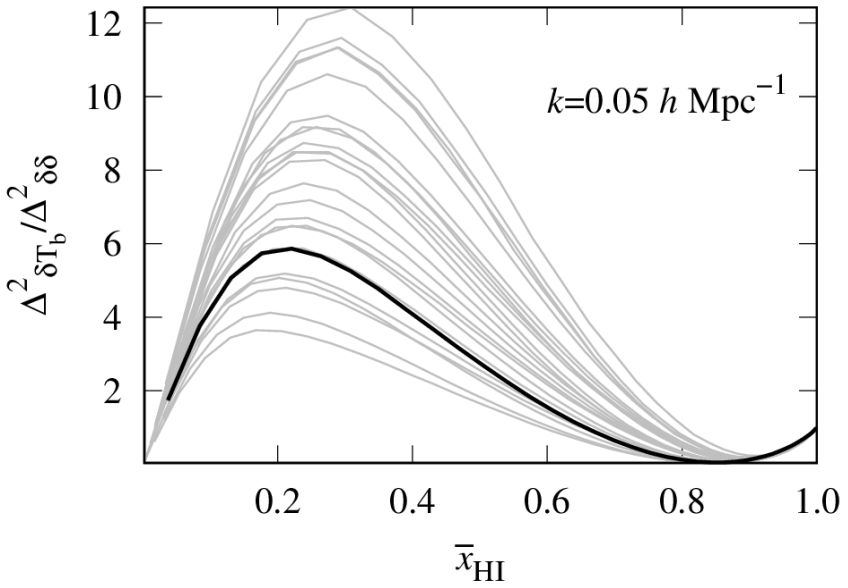
Source free Model for EoR PS





An alternative approach to probe the EoR IGM





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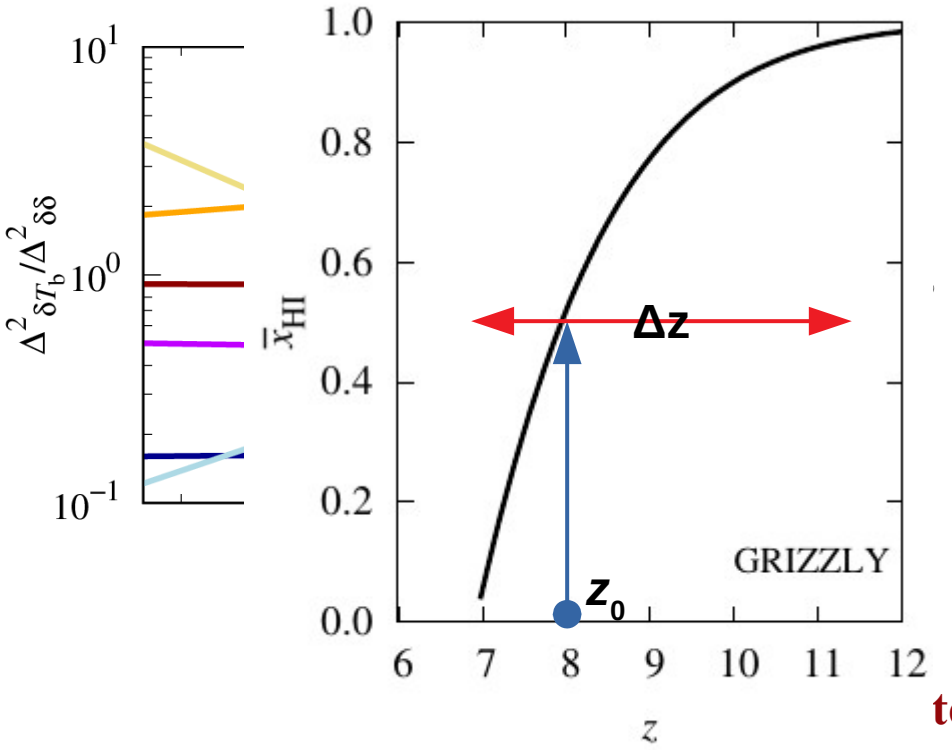
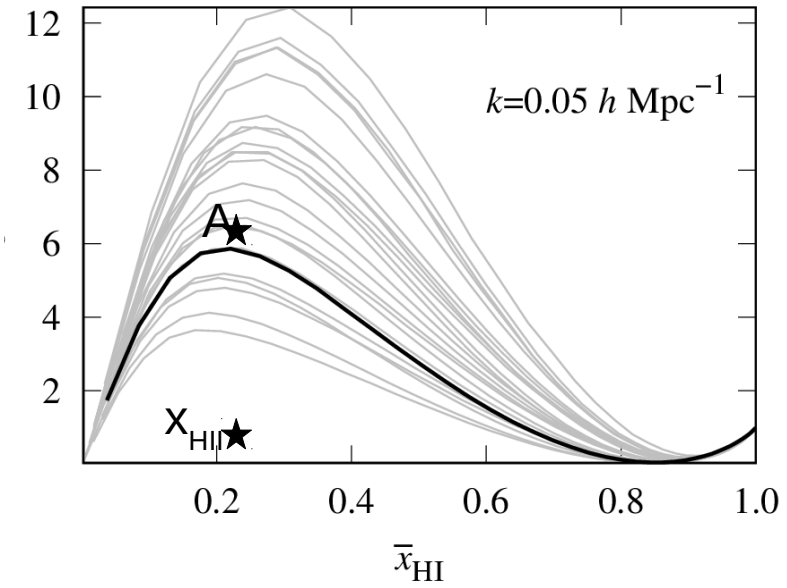


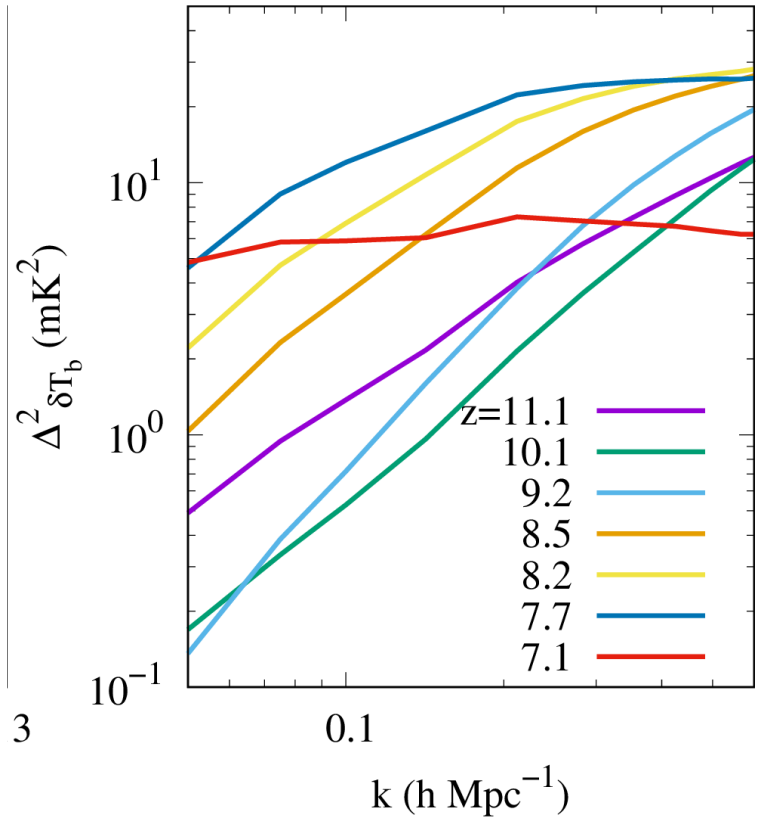


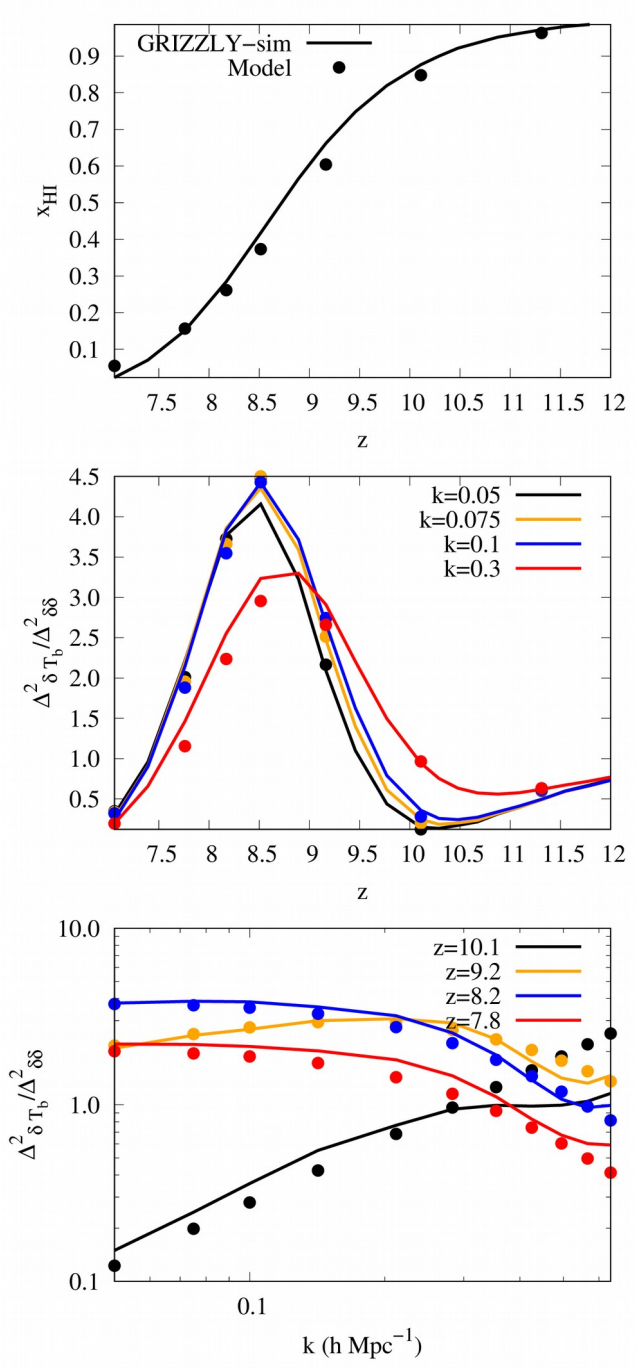
ters (redshift independent)

Parameters	Description
z_0	Redshift corresponds to $\overline{x}_{\rm HI} = 0.5$
Δz	Redshift range of reionization in a $tanh$ reionization model.
α_0	Asymmetry parameter in the redshift evolution of $\overline{x}_{\rm HI}$ around $\overline{x}_{\rm HI} = 0.5$.
$A_\star$	Maximum value of the ratio of $\delta T_{\rm b}$ and density power spectra at $k = 0.05\ h\ {\rm Mpc}^{-1}$.
$\overline{x}_{{\rm HI},\star}$	Mean neutral fraction at the redshift when the ratio of $\delta T_{\rm b}$ and density power spectra $\Delta^2_{\delta T_{\rm b}}/\Delta^2_{\delta\delta}$ at $k = 0.05\ h\ {\rm Mpc}^{-1}$ gets the maxima.
α_A	Power-law index on $\overline{x}_{\rm HI}$ which accounts for the change of $\Delta^2_{\delta T_{\rm b}}/\Delta^2_{\delta\delta}$ as a function of $\overline{x}_{\rm HI}$ at $k = 0.05\ h\ {\rm Mpc}^{-1}$.
γ_c	Account the change in scale-dependence of $\Delta^2_{\delta T_{\rm b}}/\Delta^2_{\delta\delta}$ with $\overline{x}_{\rm HI}$.
γ_0	Account for the all-scale feature of $\Delta^2_{\delta T_{\rm b}}/\Delta^2_{\delta\delta}$ in addition to small-scale feature $1/(1+(k/0.3)^2)$ at stages with $\overline{x}_{\rm HI} \to 0$.

An alternative approach to probe the EoR IGM

Mock measured power spectra

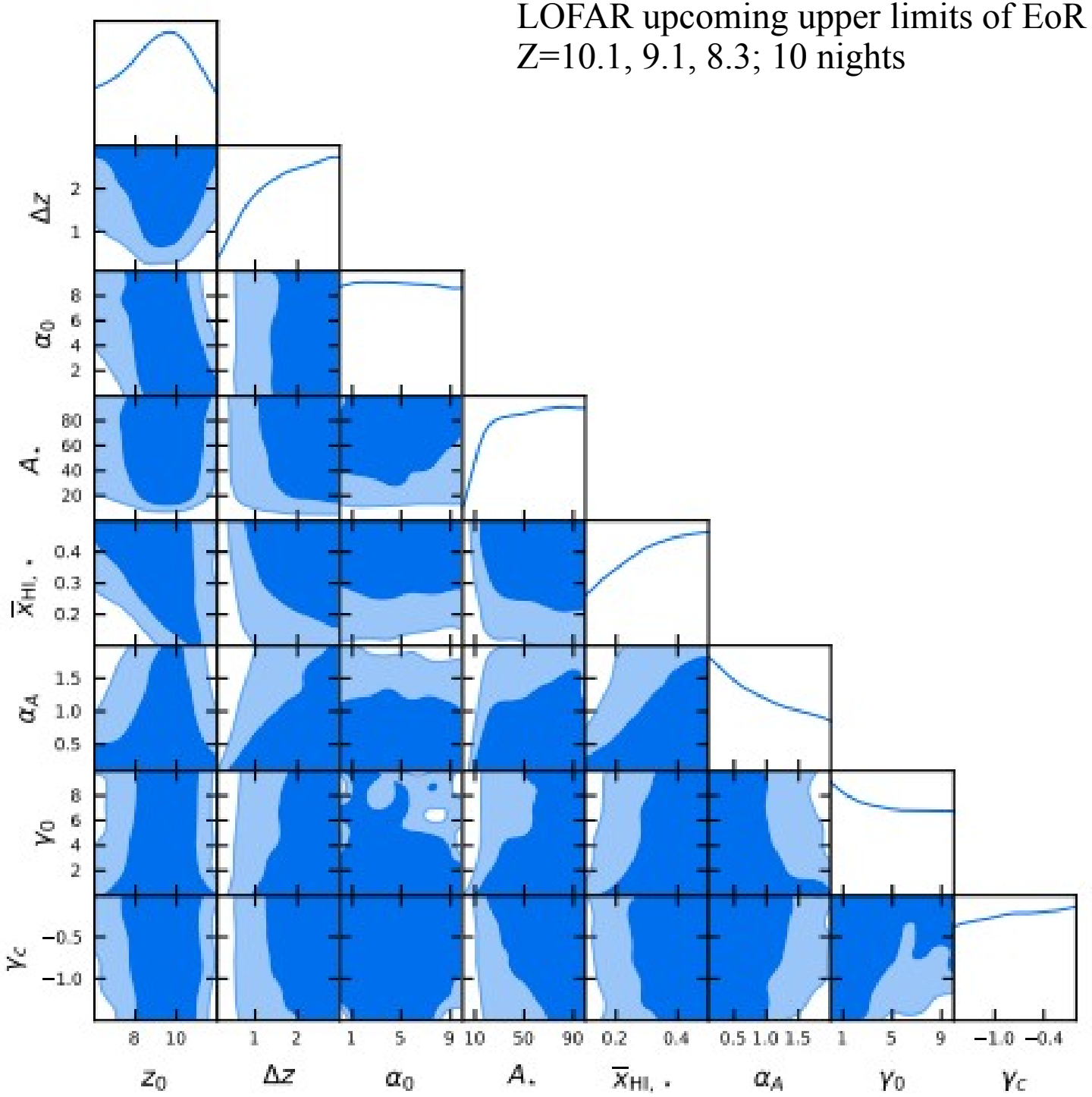




This also works for other simulations

Ghara+ in Prep.

LOFAR upcoming upper limits of EoR 21-cm power spectrum
Z=10.1, 9.1, 8.3; 10 nights



Ghara et al (in preparation)

Summary

- 21-cm signal observations is a promising probe of the first billion years of our Universe.
- Observations with LOFAR/HERA/MWA/.. –towards a detection!.
- Inference: sources properties + IGM properties.
- Current Interferometric upper limits on the 21-cm power spectrum started ruling out scenarios of EoR.
- IGM based theory of 21-cm signal power spectrum?
- SKA+... (the next decade) – exciting time ahead!