Constraining the states of the intergalactic medium during the Epoch of Reionization using 21-cm observations

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TECHNION
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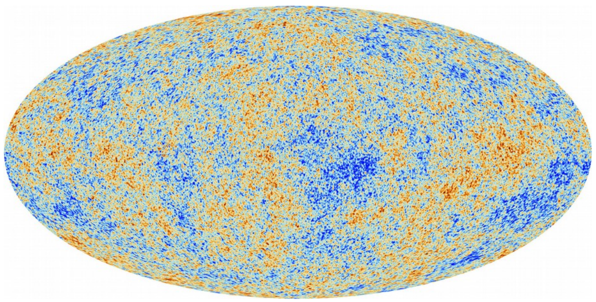
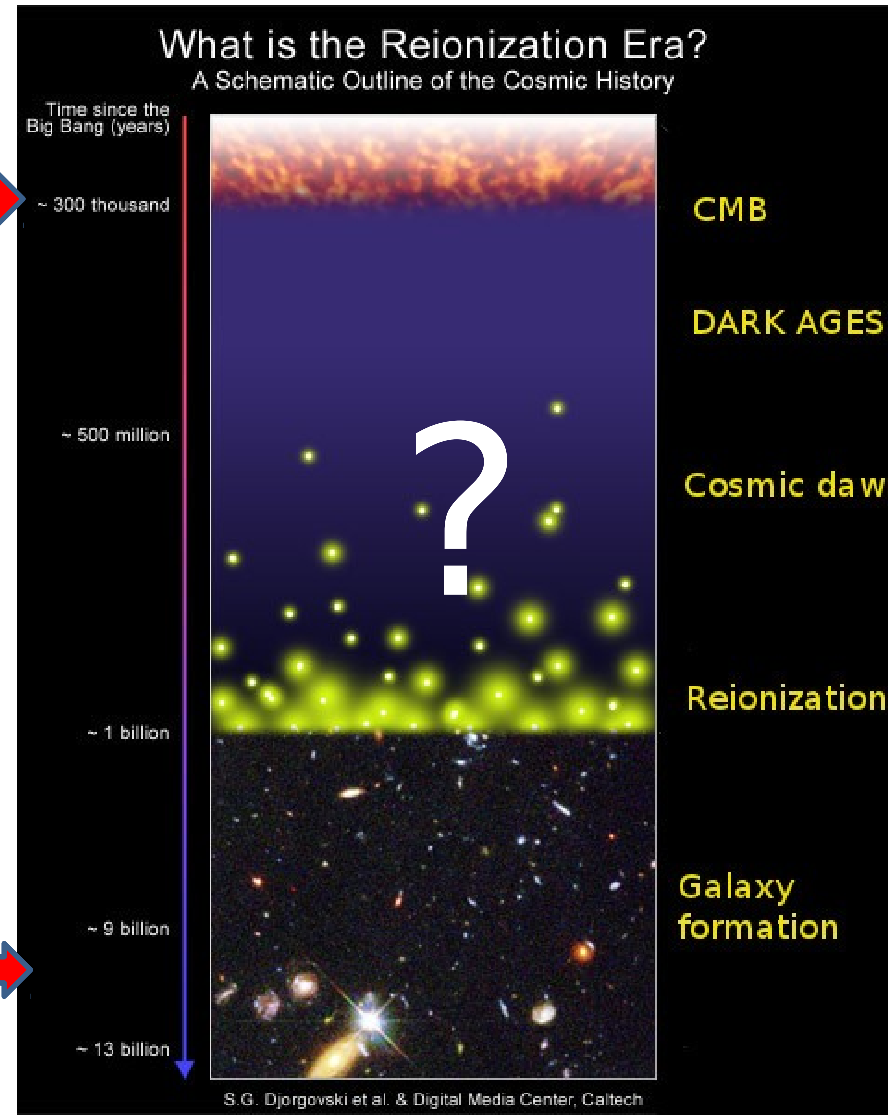
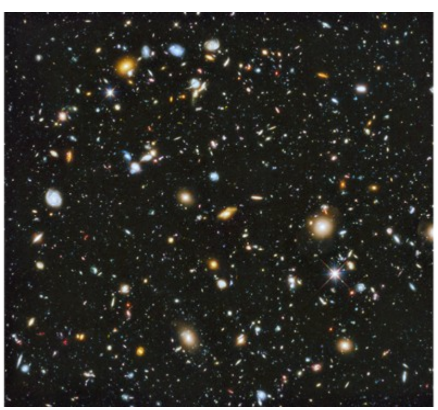
Cosmic History



Cosmic Microwave Background
(Planck)

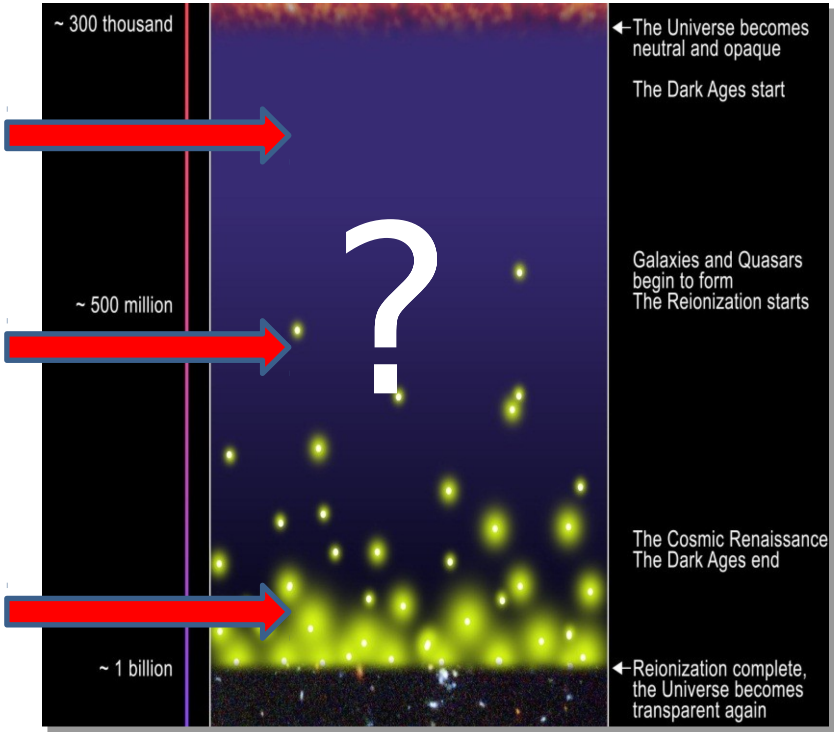


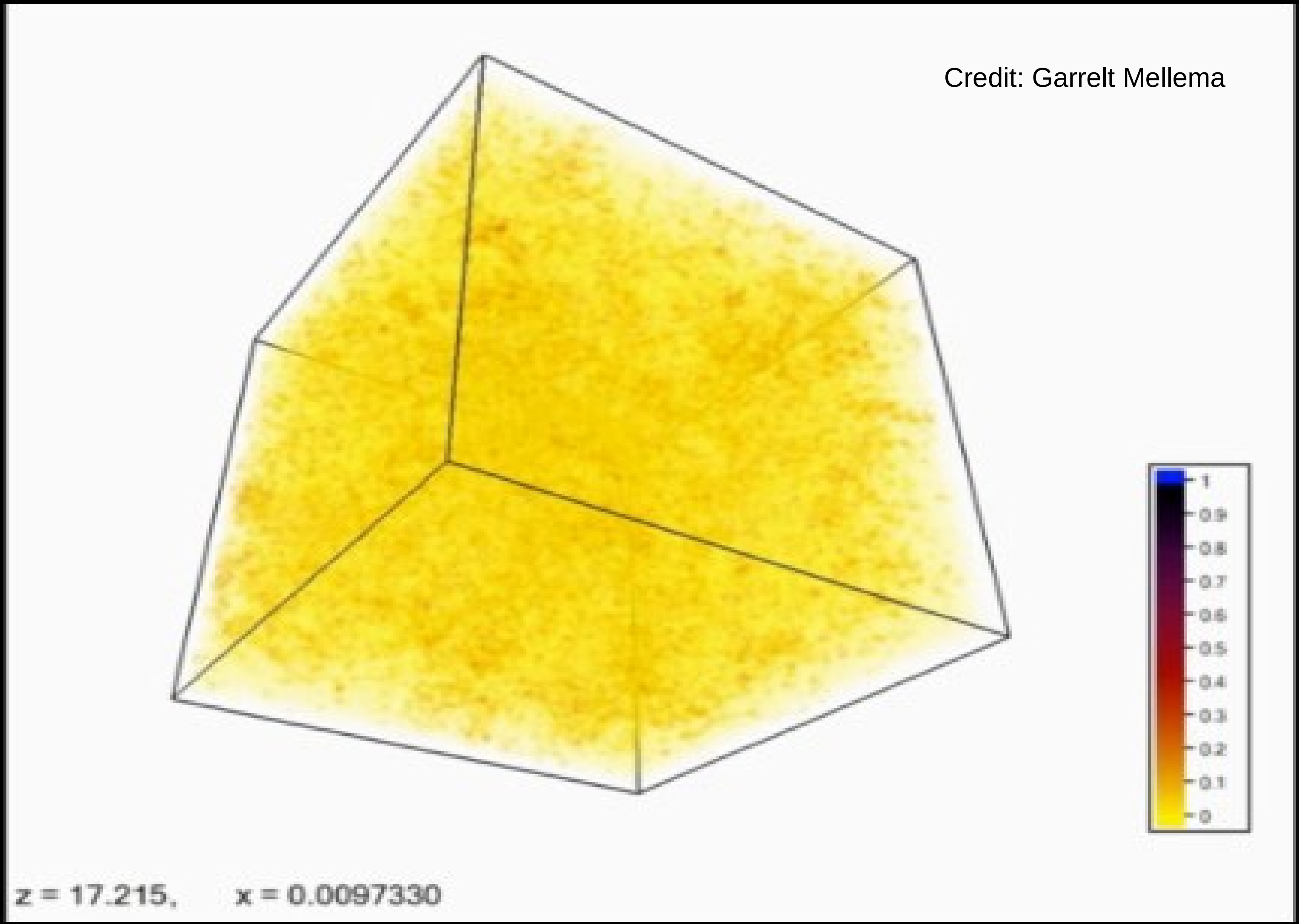


Hubble Ultra Deep Field

Intermediate phases

1. **Dark ages**: no sources of radiation; Universe neutral.
2. **Cosmic Dawn**: first stars & x-ray sources; Universe mostly neutral.
3. **Reionization**: earliest galaxies; neutral hydrogen starts to disappear.

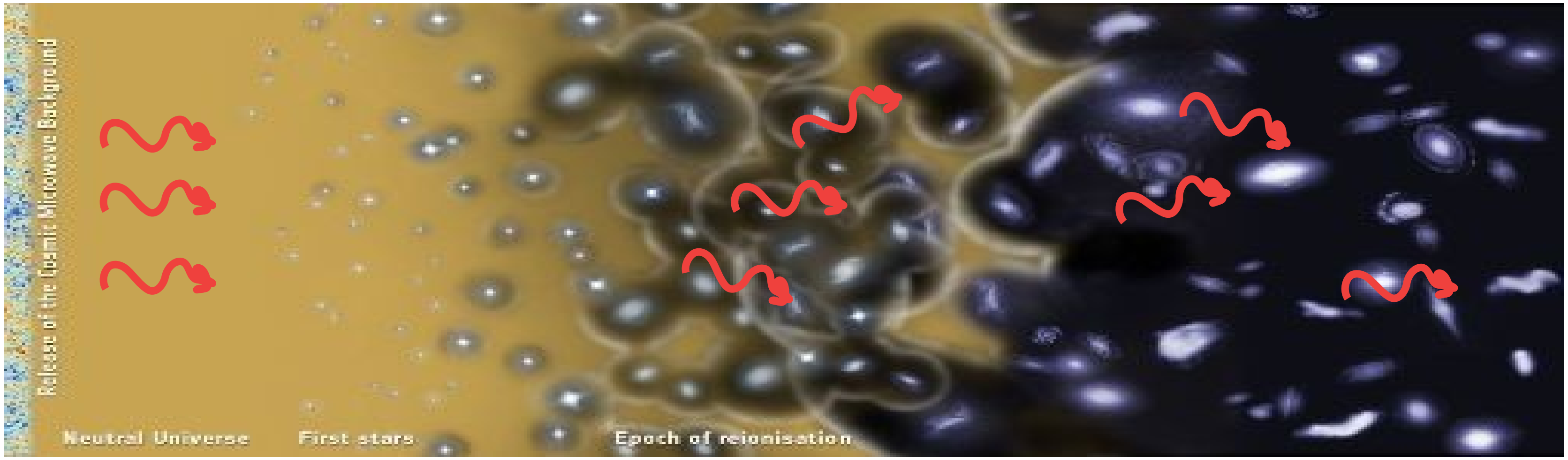


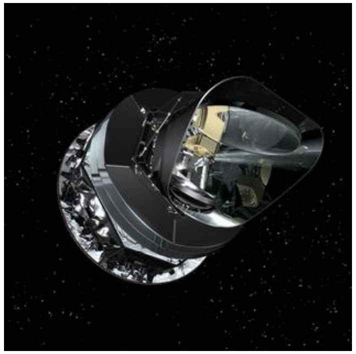

Credit: Garrelt Mellema
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
z = 17.215,   x = 0.0097330

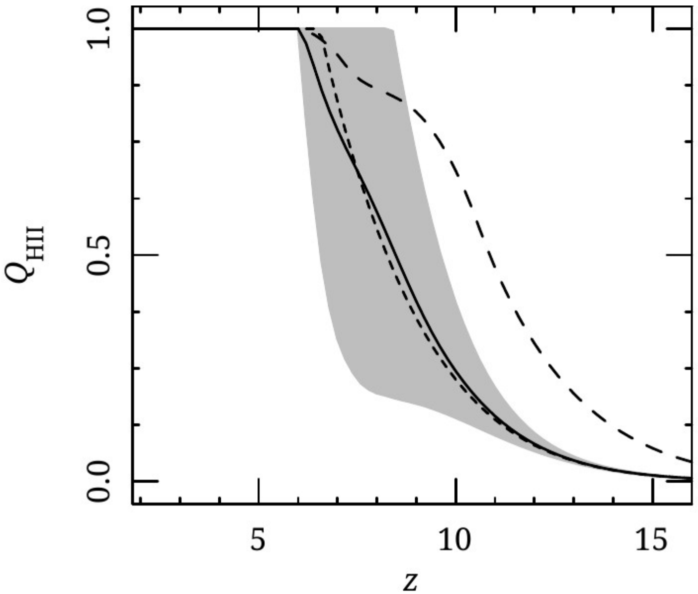
Cosmic Dawn & Epoch of Reionization

- Some of the fundamental questions:
  - When did the first galaxies form?
  - What were their properties? Galaxies, Quasars, High Mass X-ray Binaries?
    - HST, Subaru
    - Future: JWST, E-ELT, Euclid
  - How did the thermal and ionization states of intergalactic medium evolve during CD and EoR?
  - When did reionization occur?
  - Impact of the reionization process on the structure formation ?

Probes of EoR IGM: Integrated CMB constraints

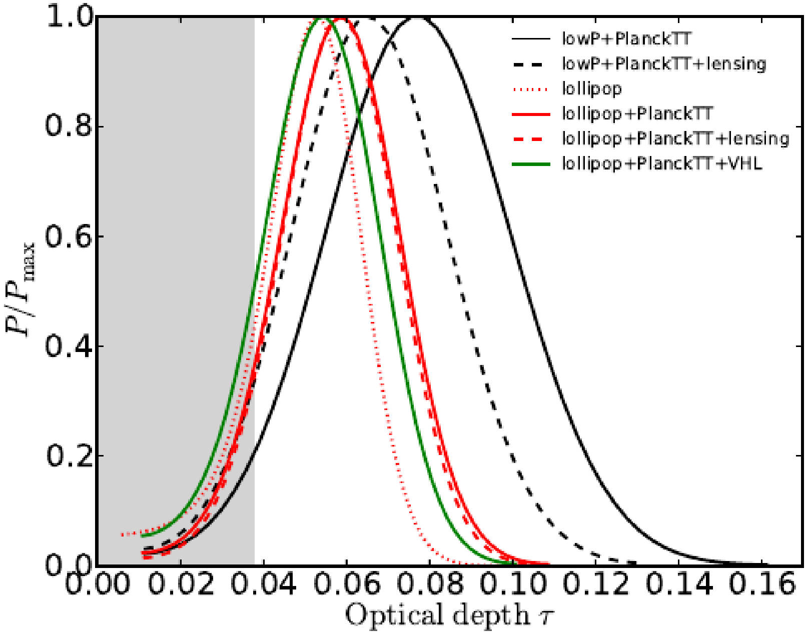






Mitra+2015

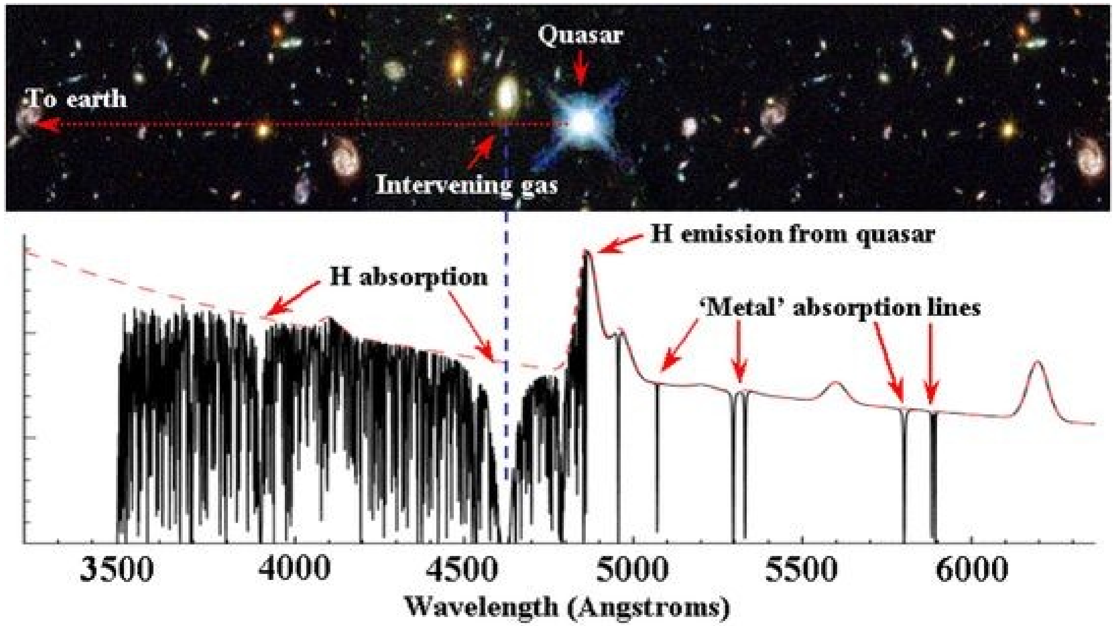
$Z_{\rm reion}$ =8.8±1.2

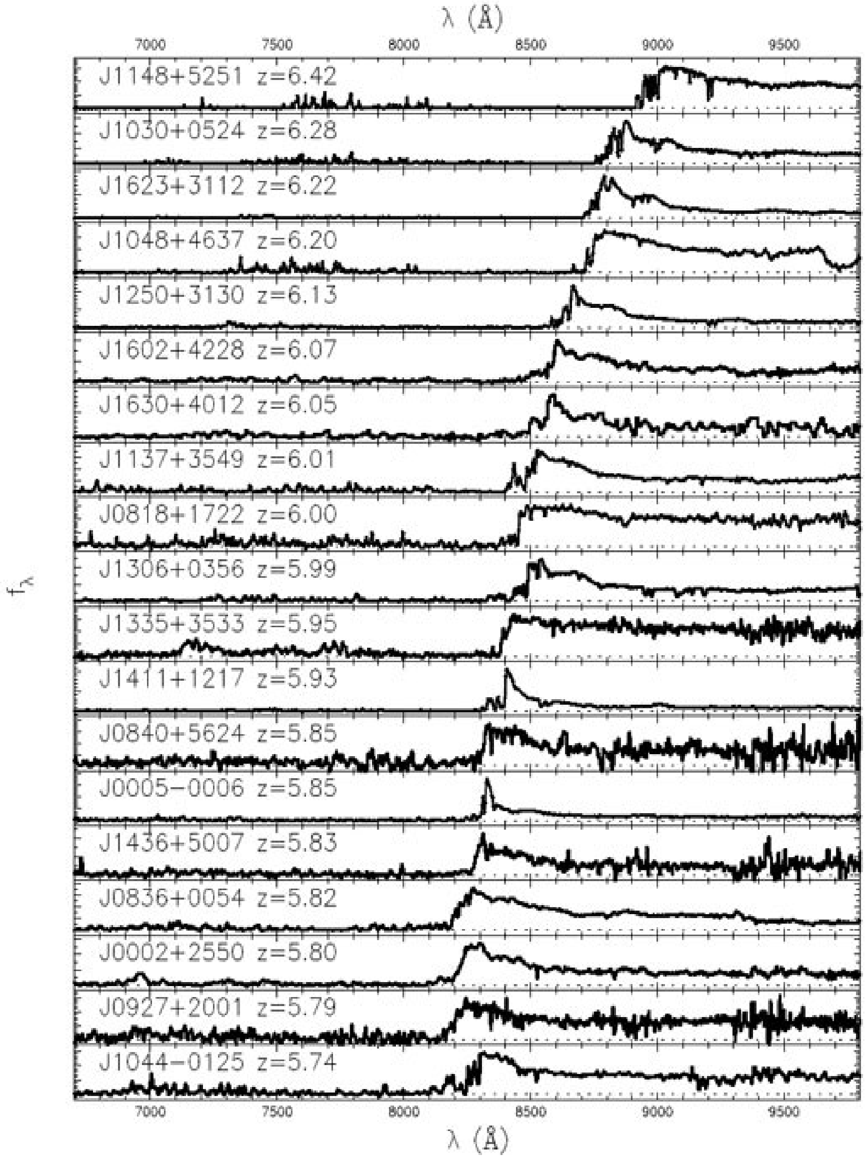


Planck Collaboration

Probes of EoR IGM: Lyα Scattering

Spectroscopy of high-z QSOs, LAEs, GRBs.

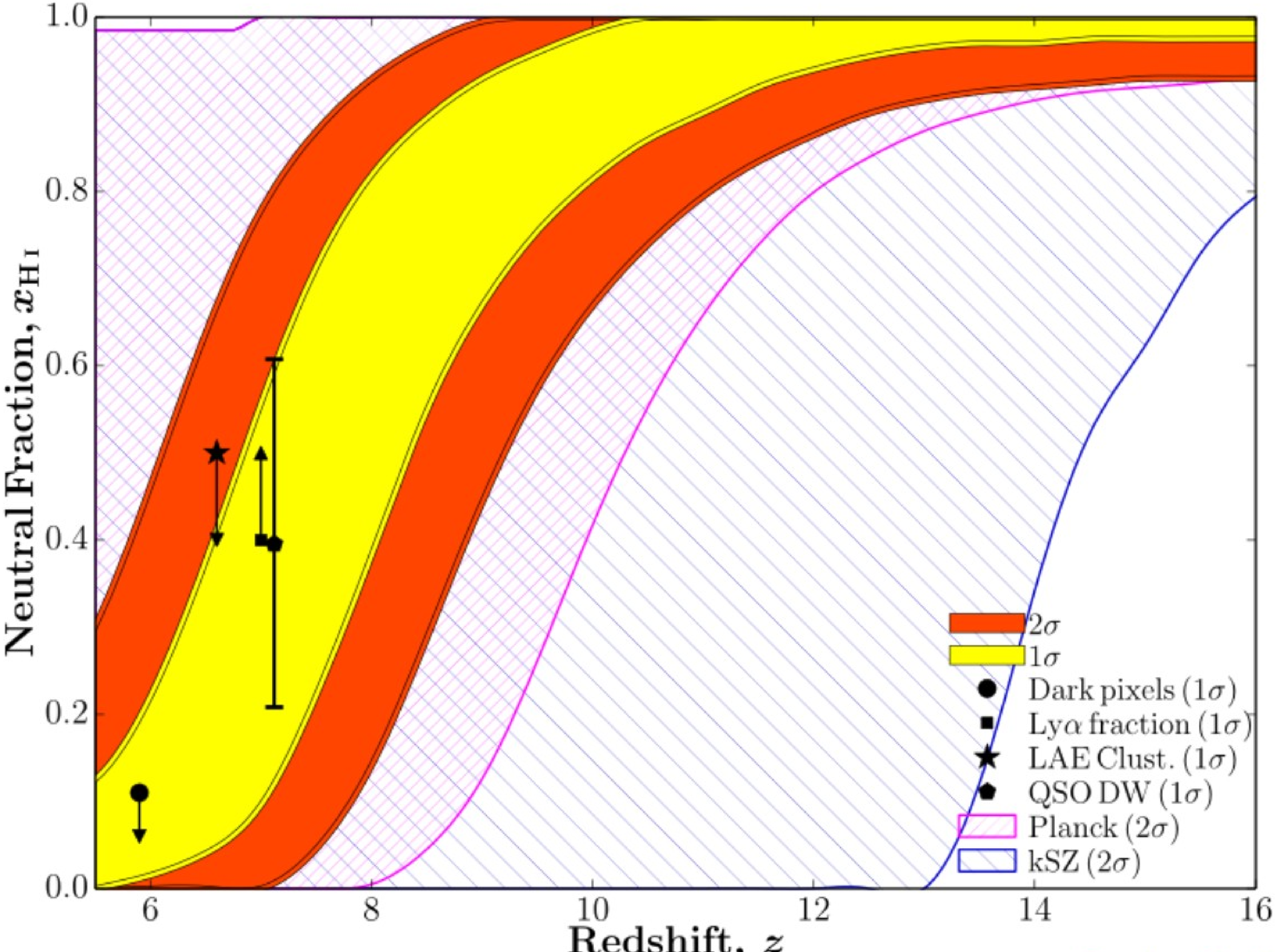




Lyα forest saturates at redshift z>6

Even for neutral fraction X_{HI} ~10^{-4}, no flux

Fan+06



Greig & Mesinger 2017

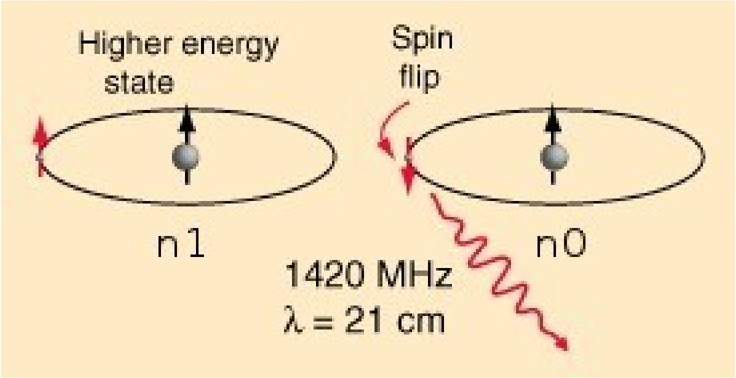
21-cm signal

- Hyperfine transition of neutral hydrogen (HI).
- Spin temperature :

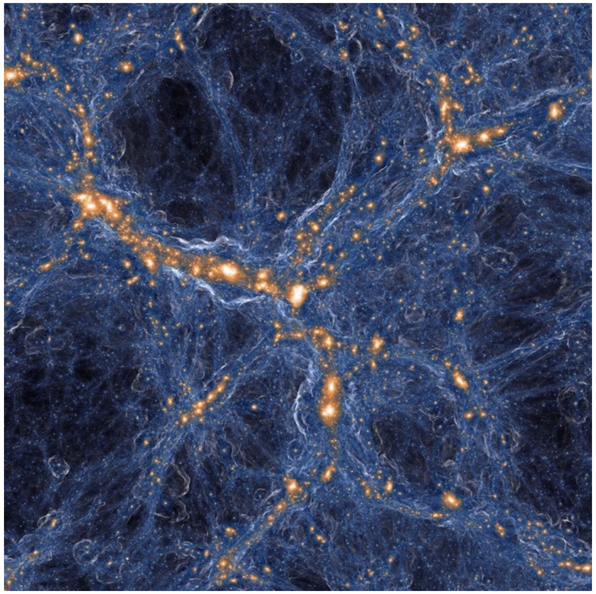
$$n_1/n_0 = 3\exp(-T_\star/T_\mathrm{S})$$

where

$$T_\star \equiv hc/k\lambda_{21\mathrm{cm}} = 0.0628\,\mathrm{K}$$



~100 Mpc



H is the most abundant element of the Universe

- Spin temperature :

$$T_\mathrm{S}^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_\alpha^{-1} + x_c T_\mathrm{K}^{-1}}{1 + x_\alpha + x_c}$$

where,

T_γ = CMB temperature

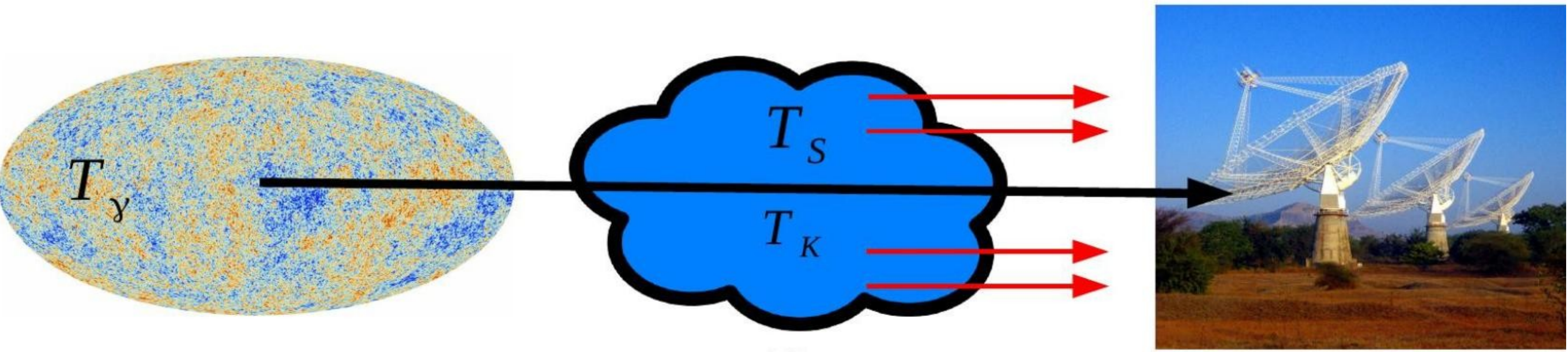
T_K = Gas temperature

T_α = Colour temperature of Lyα radiation field.

x_α = Wouthysen-Field effect coupling coefficient

x_c = Collisional coupling coefficient

21-cm signal from CD & EoR



CMBR

HI

$\nu = 1420\, MHz$

δT_b

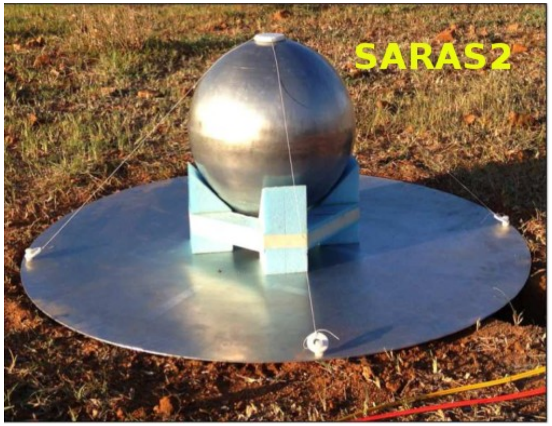
Differential Brightness Temperature

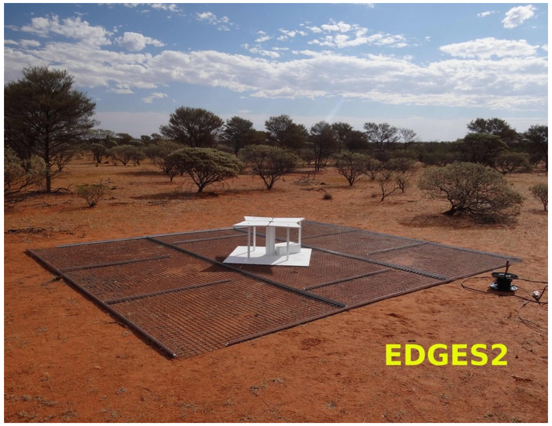
$$\delta T_b = 27\, x_{HI} \left(\frac{T_S - T_\gamma}{T_S}\right) (1+\delta_B) \left(\frac{H}{dv_r/dr + H}\right) \left(\frac{\Omega_B h^2}{0.023}\right) \left(\frac{0.15}{\Omega_m h^2} \frac{1+z}{10}\right)^{1/2} mK$$

Astrophysics

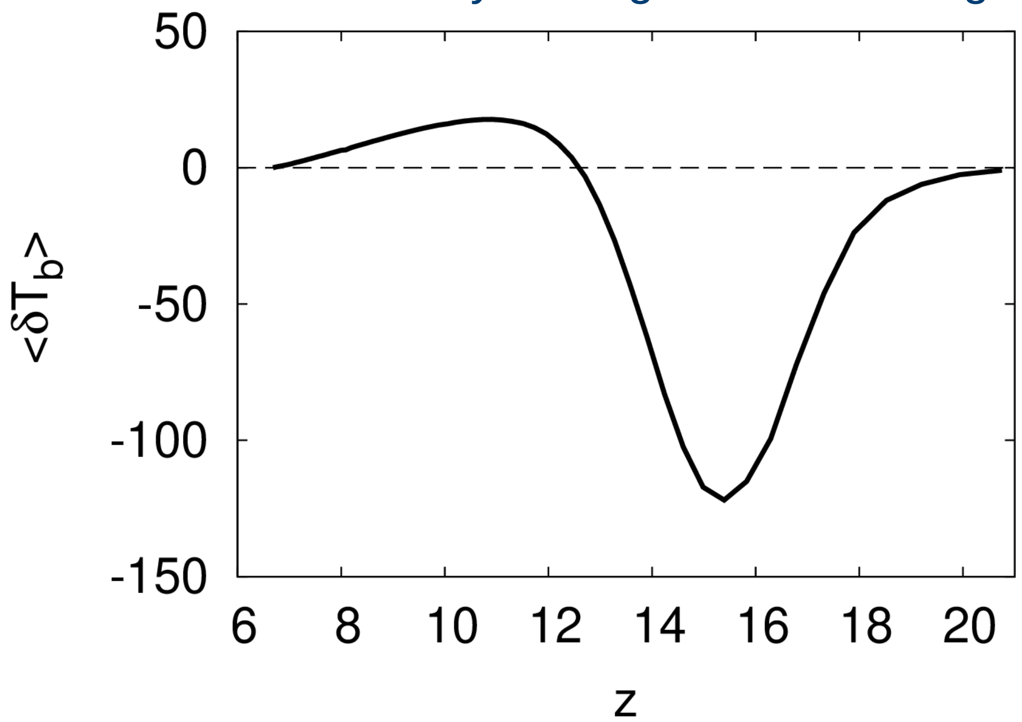
Cosmology

Observations: using single antenna

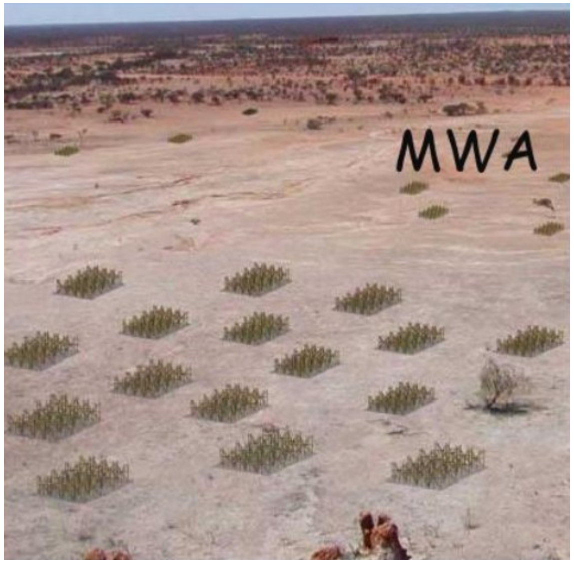




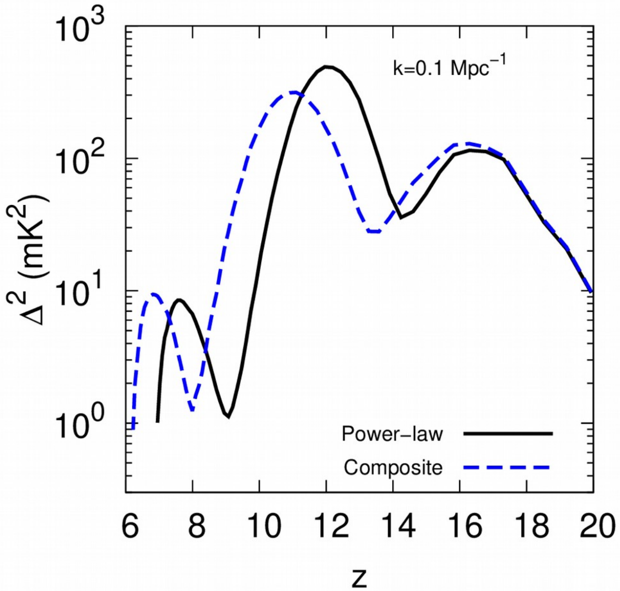
Probes sky averaged HI 21-cm signal

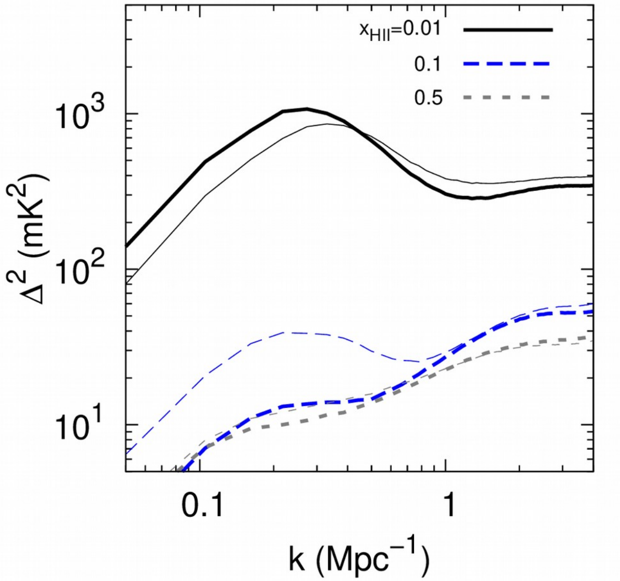


Observations: using radio interferometers



Probes Fluctuations

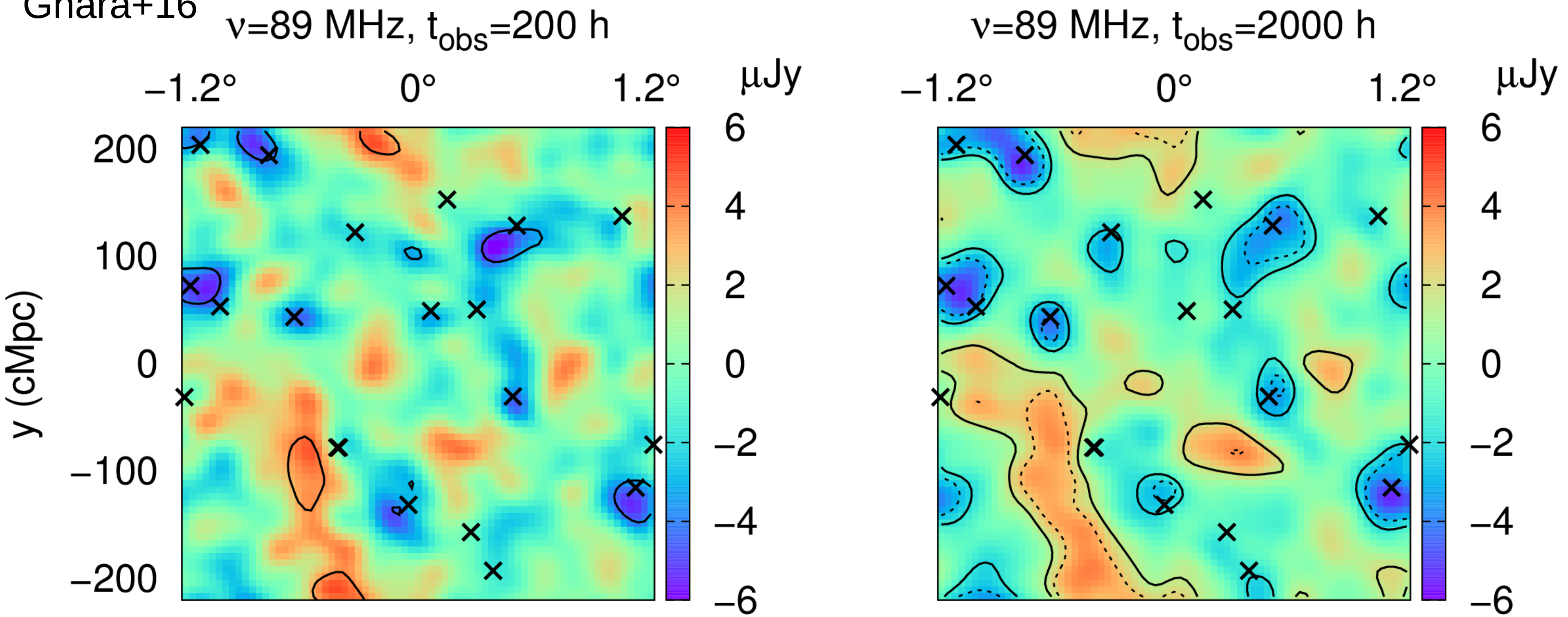




Prospects with SKA

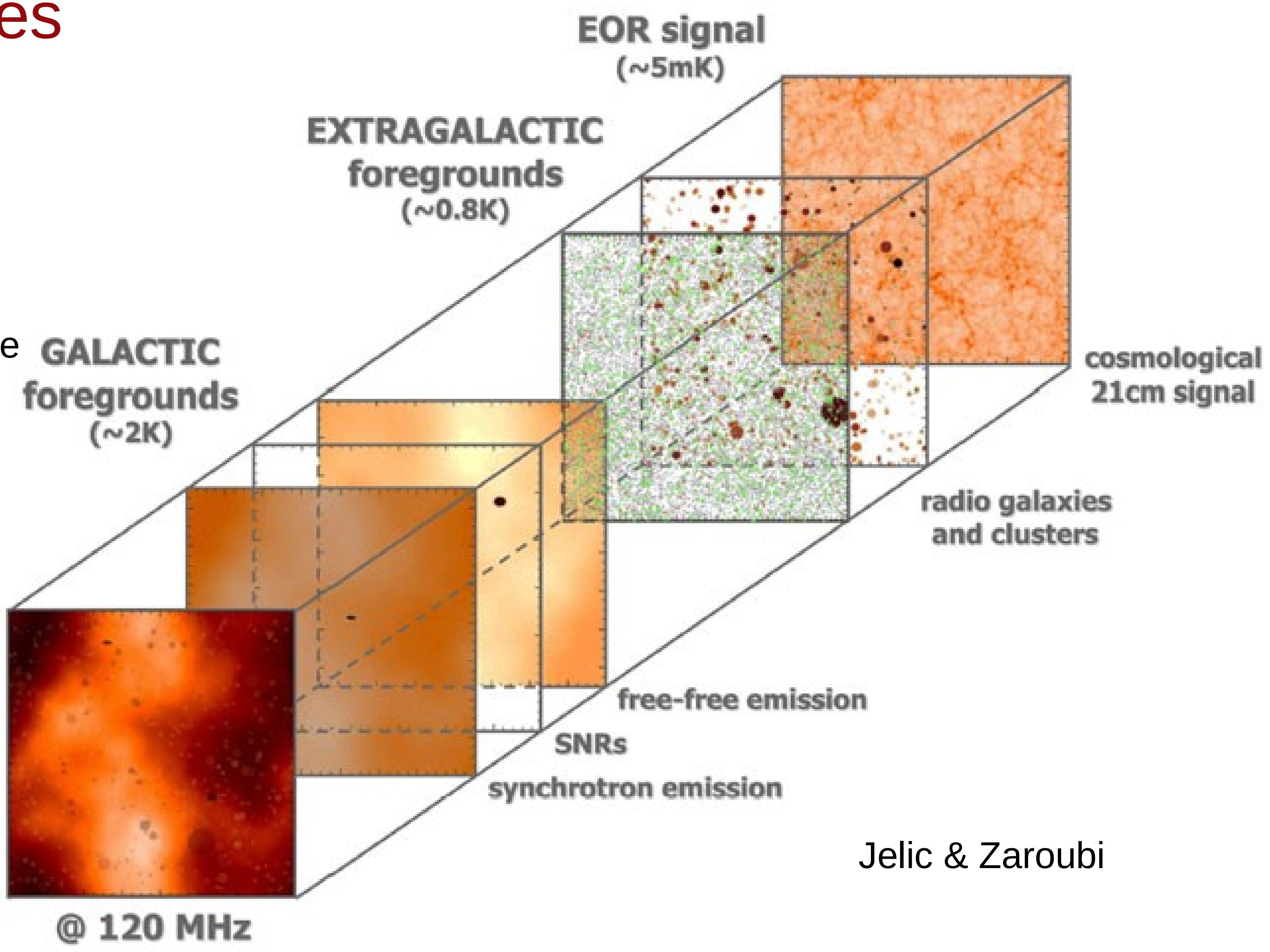
SKA will have the sensitivity
to image the HI 21-cm signal

Ghara+16



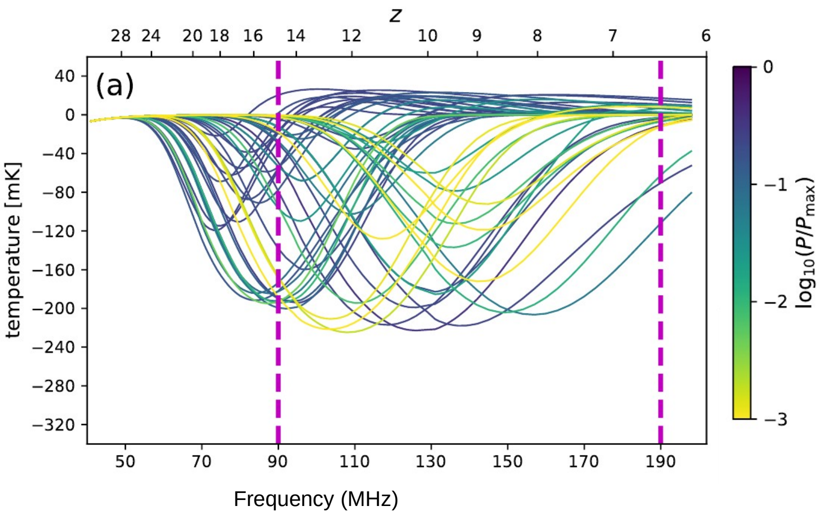
Difficulties

- Foregrounds
- Calibration
- Ionosphere
- Telescope noise
- RFI
- ….

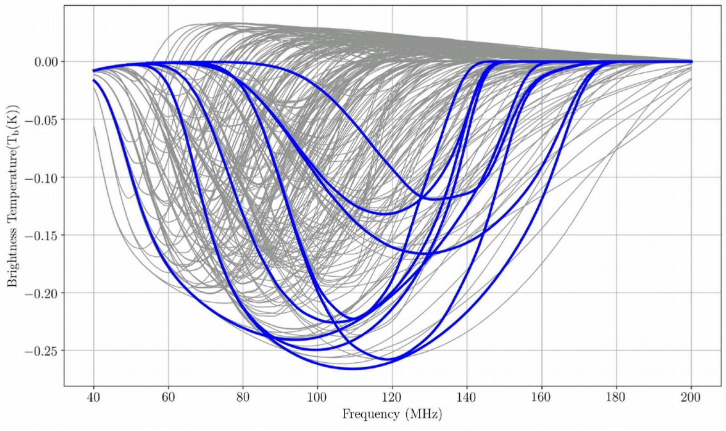


Jelic & Zaroubi

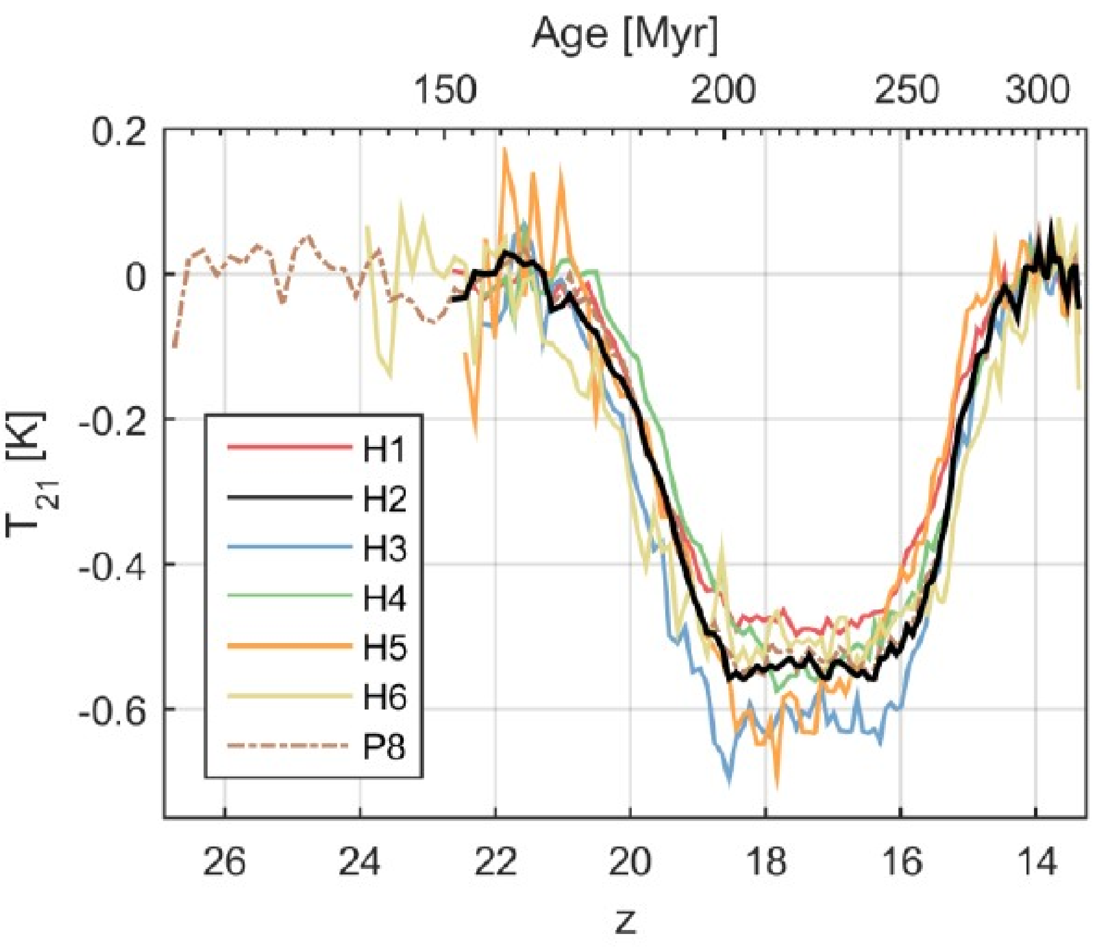
Global 21-cm Signal Measurements



EDGES-High Band, Monsalve+2018



SARAS2, Singh+2017



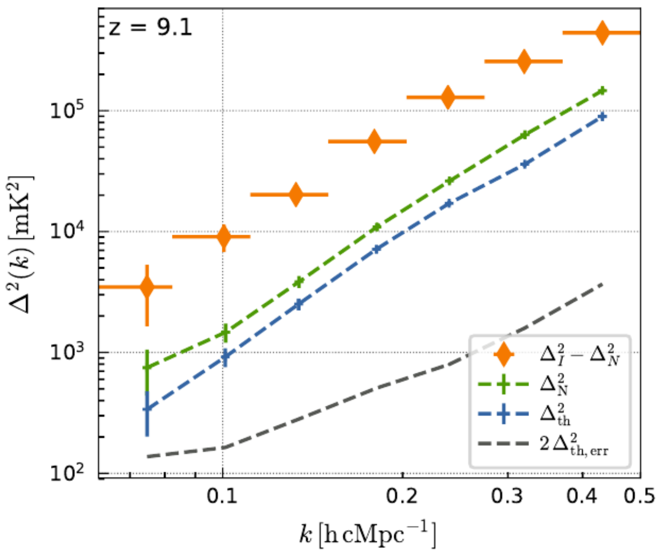
EDGES-low Band, Bowman+2018

Interferometric Measurements

- Dimensionless spherically averaged power spectrum (one of the measured quantities)

$$\Delta^2(k) = \frac{k^3 P(k)}{2\pi^2}$$

- GMRT: 2σ value of (248 mK)^2 for k = 0.5 h/Mpc at z = 8.6 (Paciga+2013).
- PAPER: 2σ value of (300 mK)^2 for k = 0.4 h/Mpc at z = 7.5 (Kolopanis+2019).
- LOFAR: 2σ value of (73 mK)^2 for k = 0.075 h/Mpc at z = 9.1 (Mertens+2020).
- MWA: 2σ value of (43 mK)^2 for k = 0.14 h/Mpc at z = 6.5 (Trott+2020).

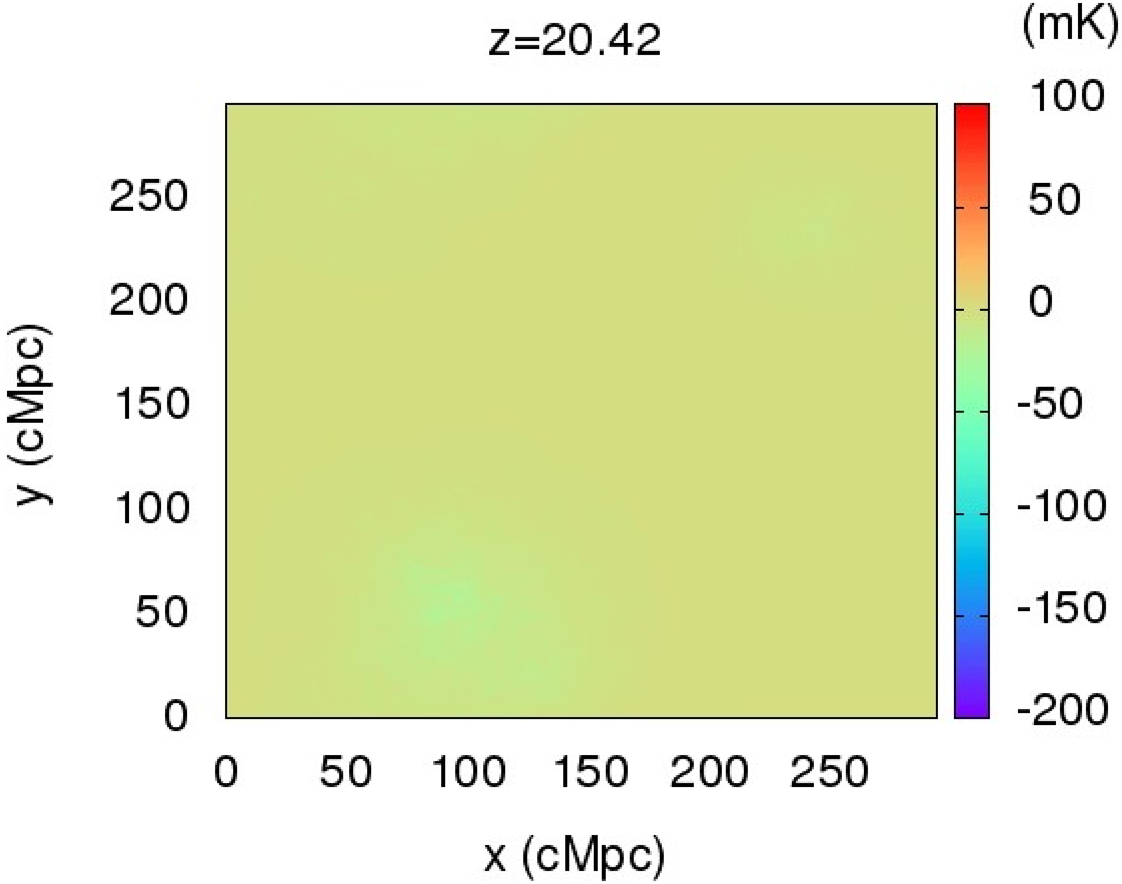


LOFAR, 10 nights observation, Mertens+2020

Modelling of 21-cm signal

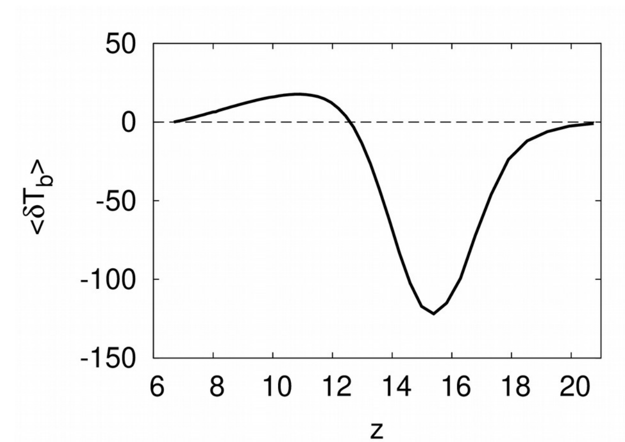
- Extraction of the information about the sources and IGM from the 21-cm observation depends on modelling of the signal.
  - Analytical (e.g., Furlanetto+2004, Paranjape+ 2014)
  - Semi-numerical (Zahn+07, Mesinger+07, Santos+08, Choudhury+09)
  - Numerical with radiative transfer (e.g, Iliev+2006, Mellema+2006, Baek+2009, Thomas+2009, Ghara+2015)
- Model parameters:
  - ζ : ionization efficiency
  - M_{min} : minimum halo mass that host sources of UV radiation
  - $M_{min,X}$: minimum halo mass that host sources of X radiation
  - f_X : X-ray heating efficiency
  - ...

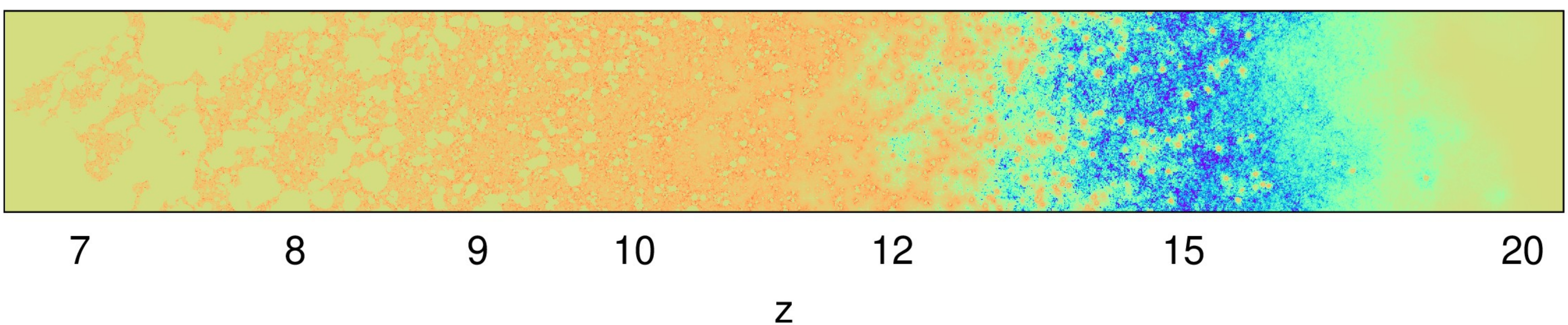
View of Reionization in 21-cm



GRIZZLY
(Ghara+2015)

- Based on 1D radiative transfer.
- Uses outputs from N-body simulations & source spectrum.
- UV, X-ray, Lyα photons





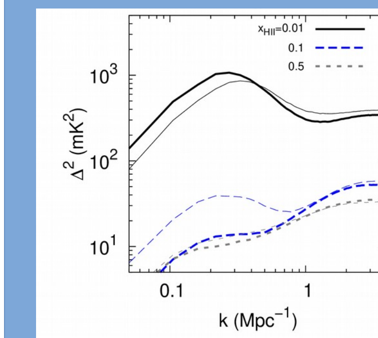
Basics of 21-cm signal modelling framework

Source Parameters
(ζ, M_{min}, M_{minX}, $f_{X,..}$)

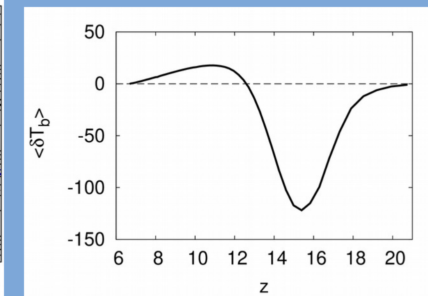
21-cm signal Model
e.g., GRIZZLY
(Cosmology, HMF, feedbacks)

Observables

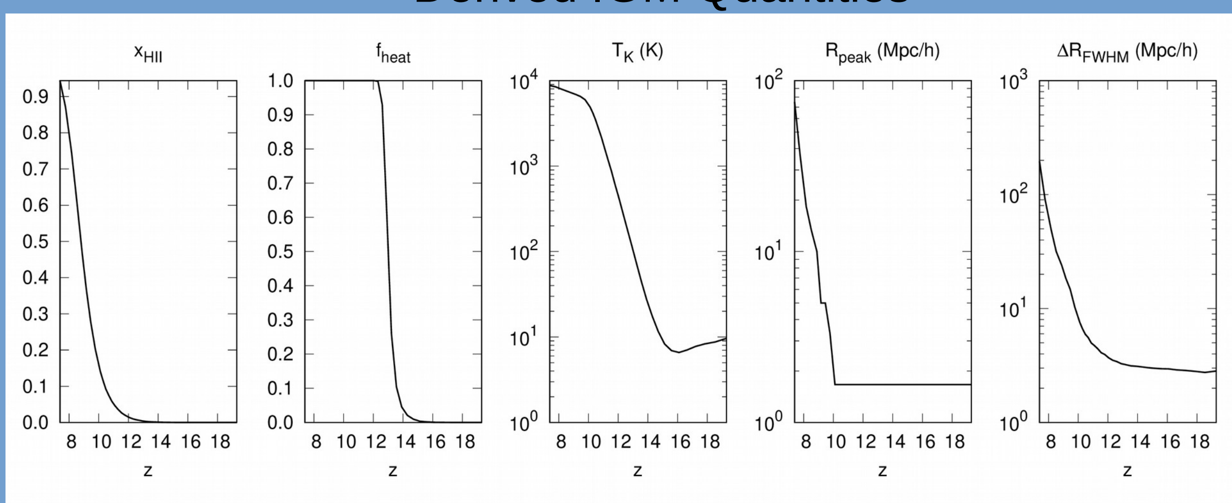
Power spectrum



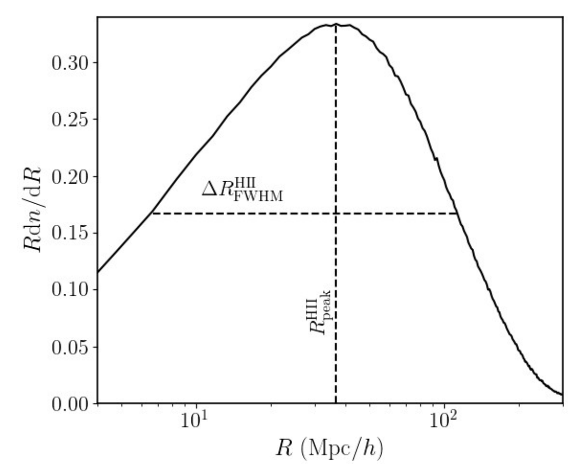
Mean Signal



Derived IGM Quantities

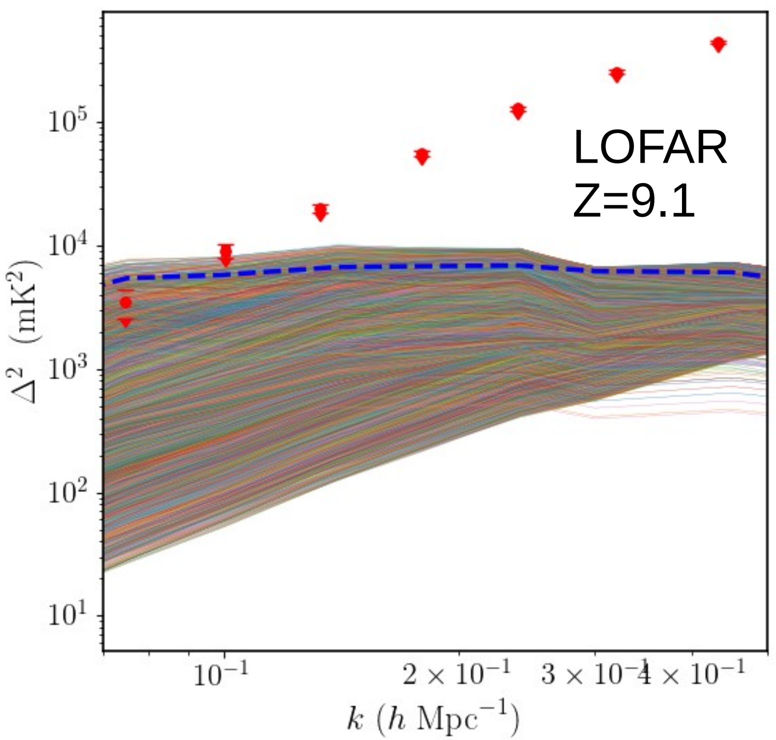


Bubble Size Distribution



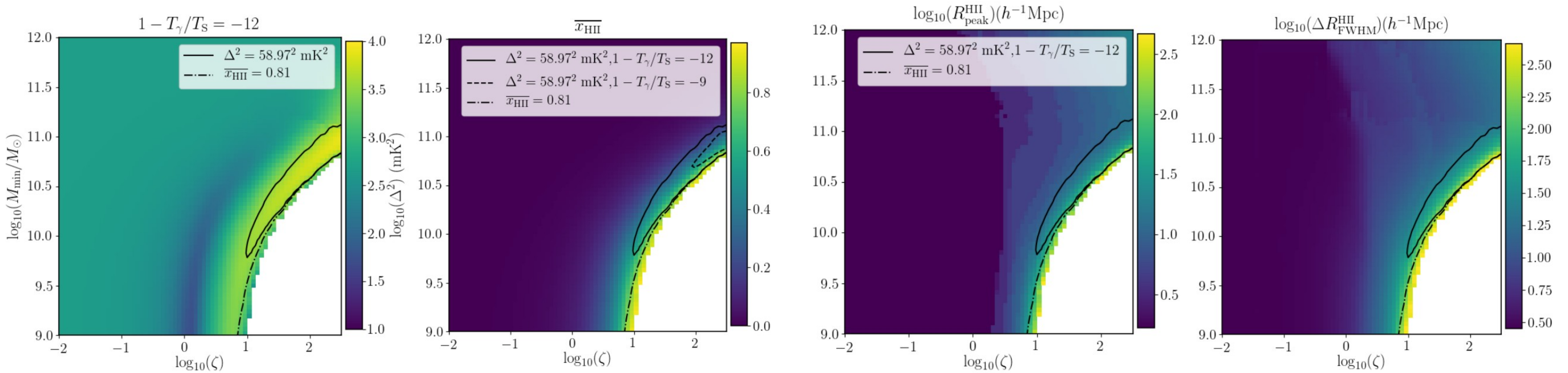
Framework

Ghara+2020



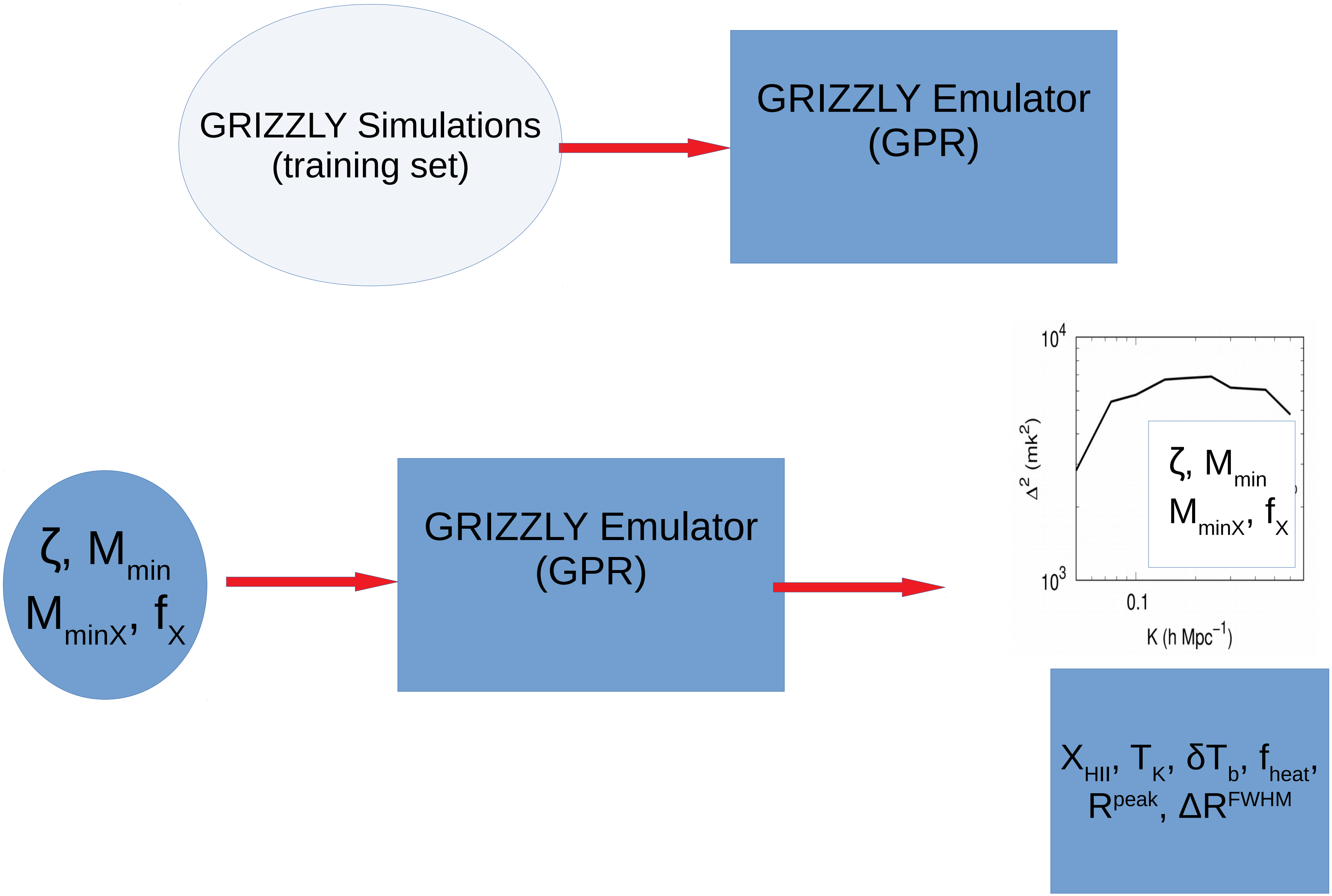
- Step I: run a large number of simulations covering the GRIZZLY source parameter space.

  These will be the training set for building an emulator.



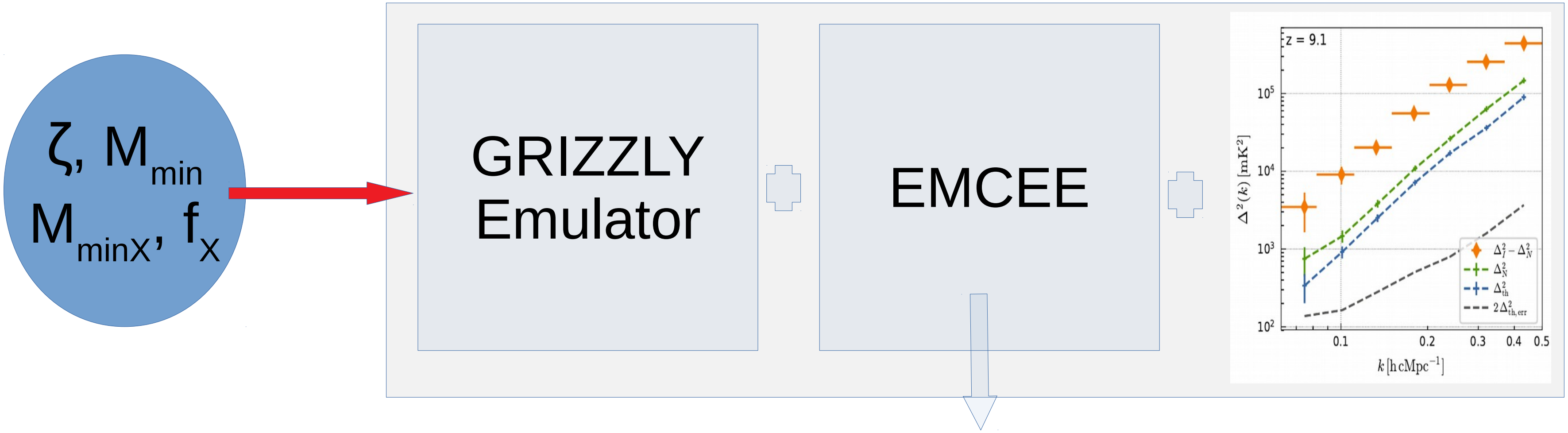
Framework

- Step II: Build an emulator

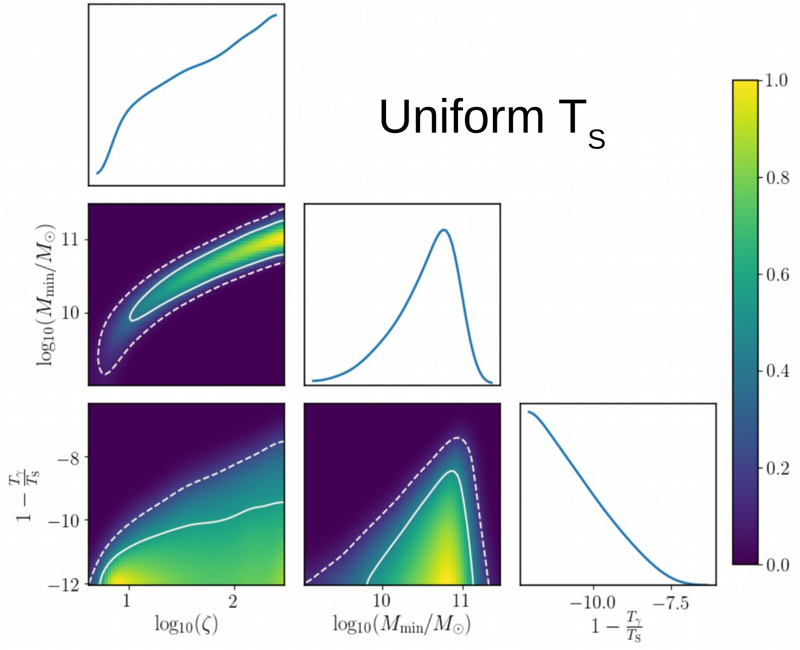


Framework

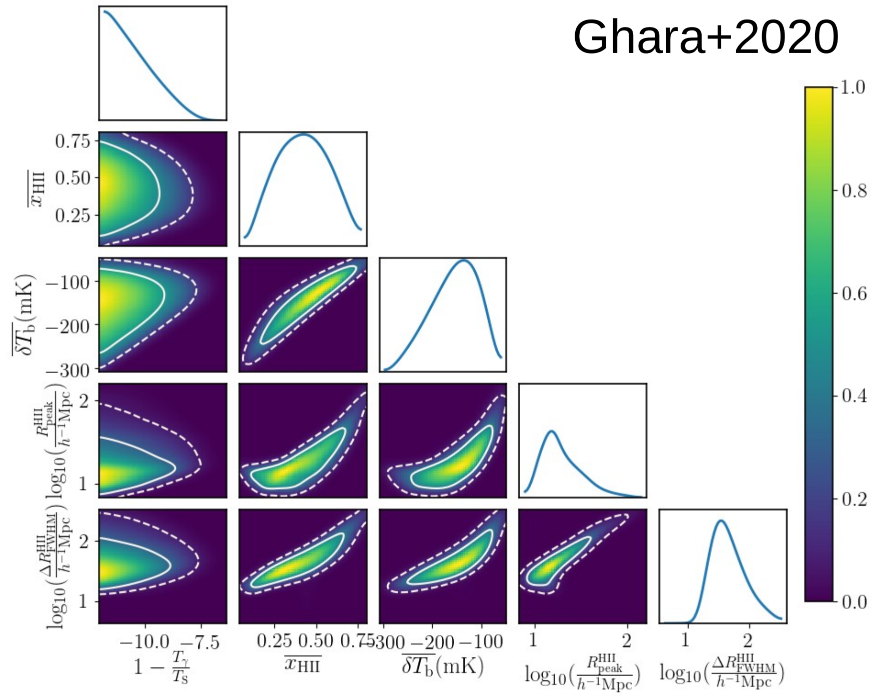
- Step III: explore parameter space, Bayesian inference



Posterior distribution of excluded models



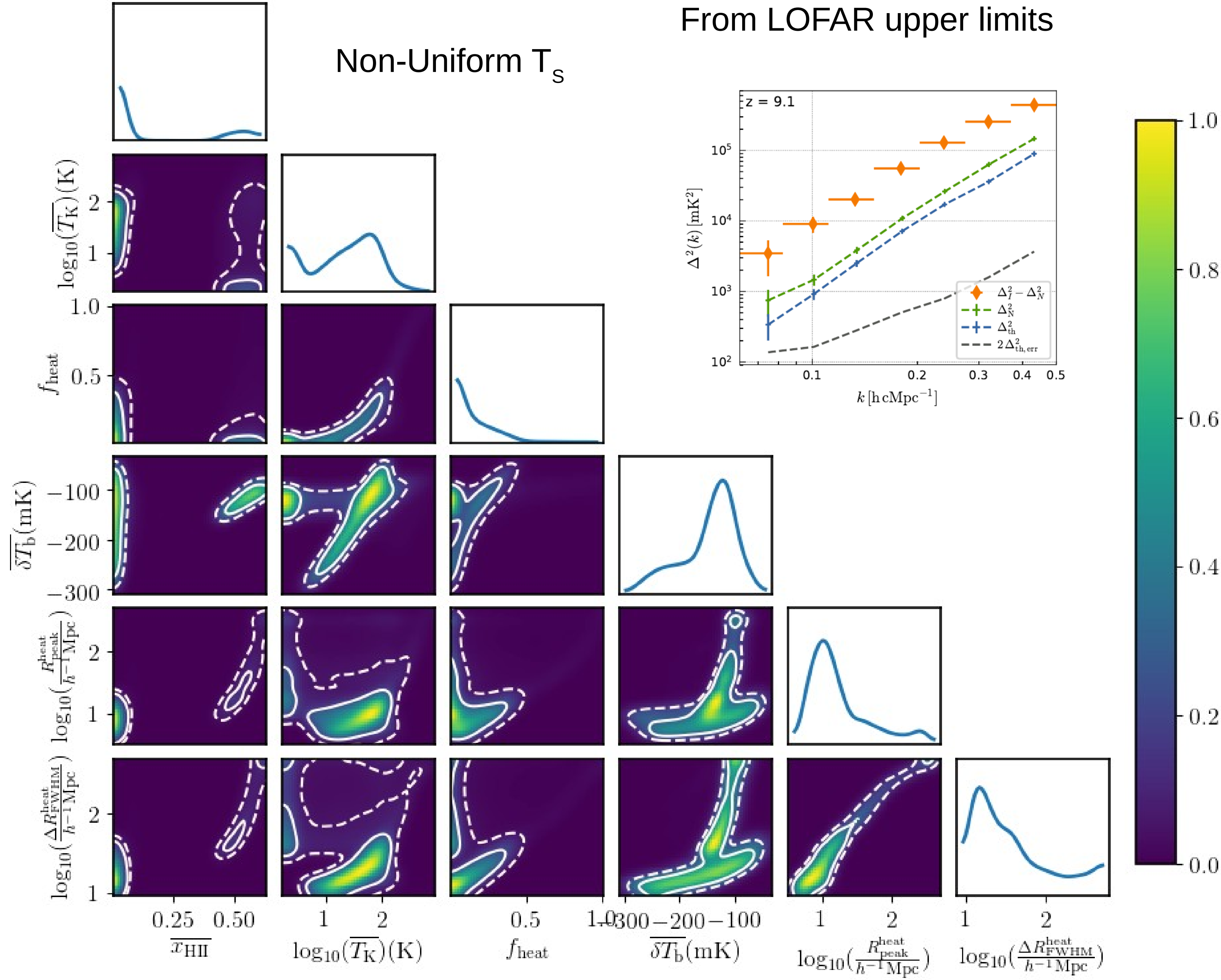
Ghara+2020



Posterior distribution of excluded models

Constraints on IGM at z=9.1
From LOFAR upper limits

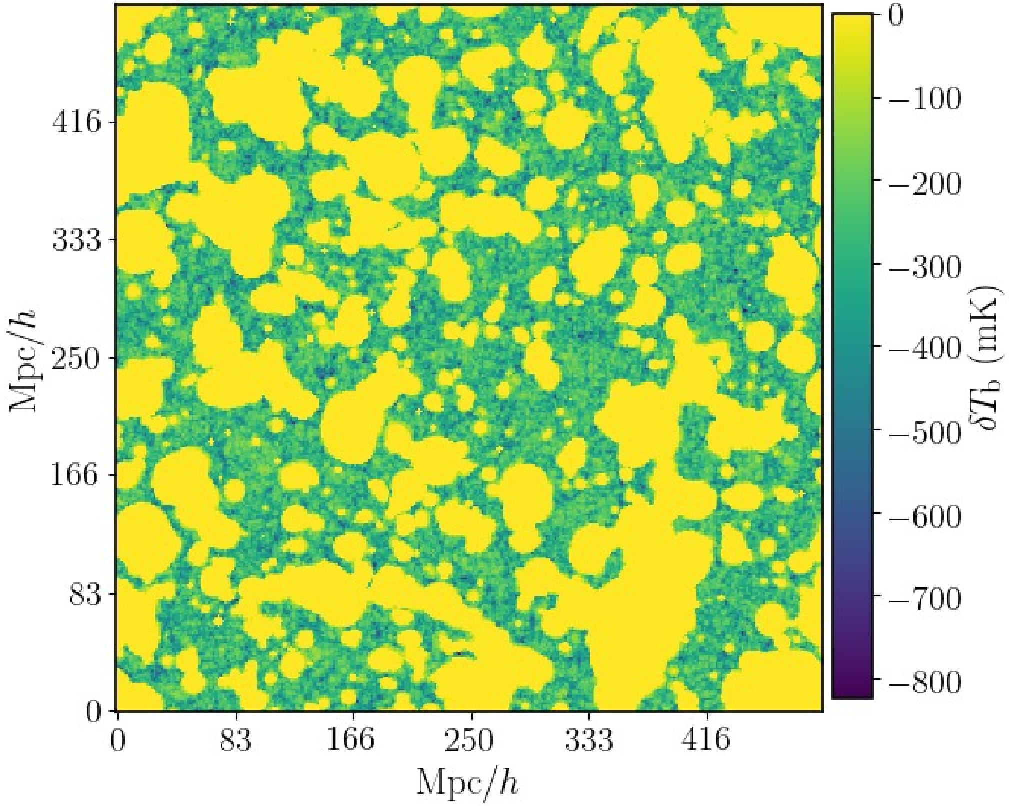
Non-Uniform T_S



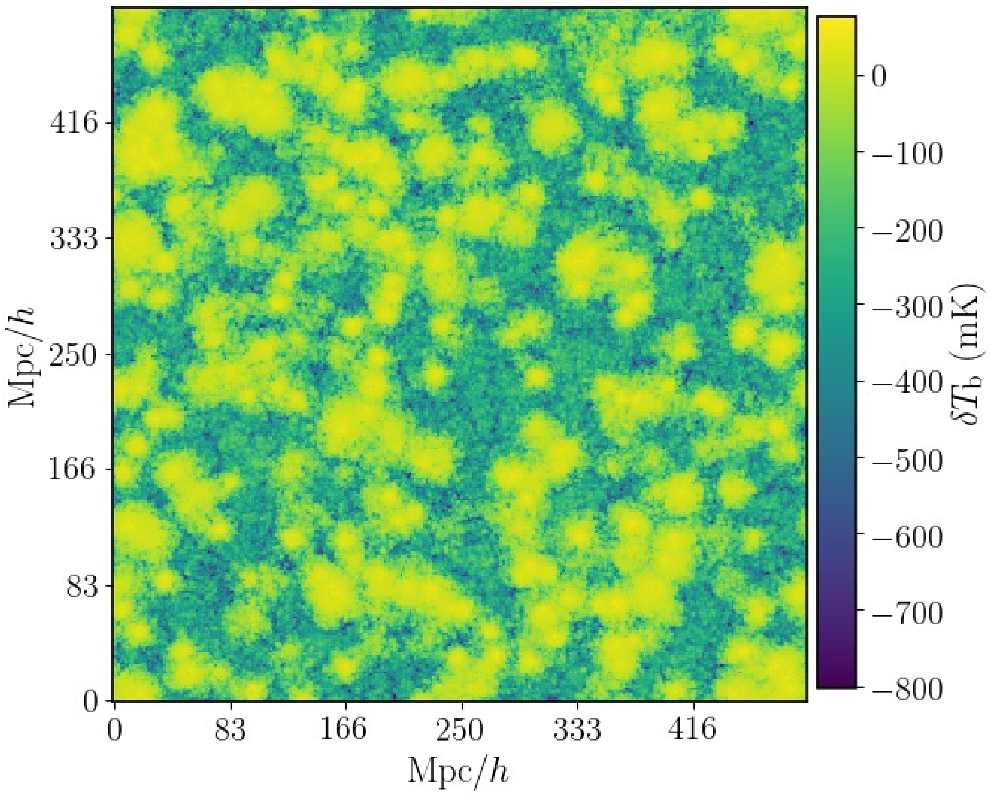
Interpretation

Two scenarios to be ruled out easily

Large-scale fluctuations are driven by fluctuations in ionization fraction

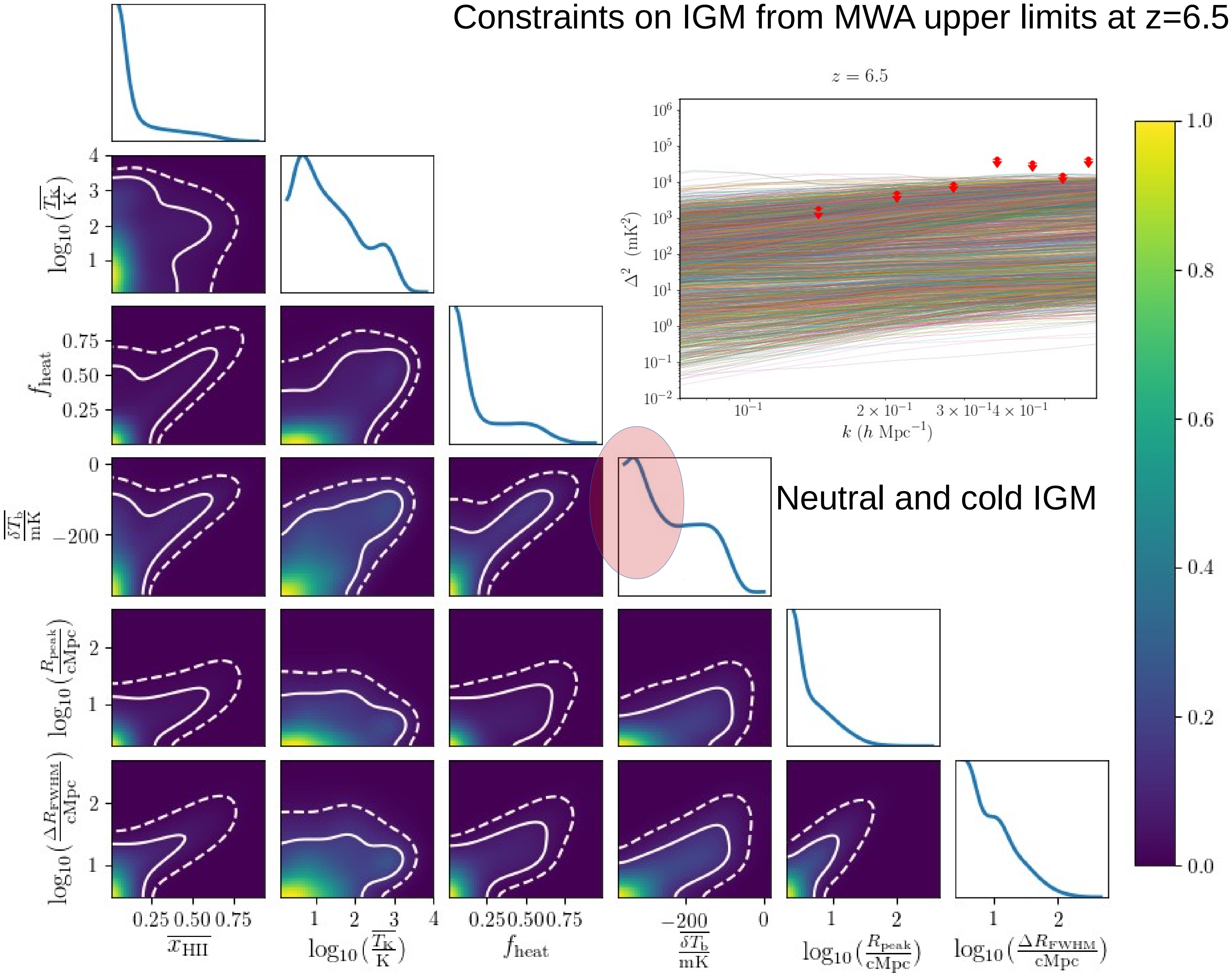


Large-scale fluctuations are driven by fluctuations in spin temeprature



IGM Parameters of non-uniform T_S scenario	Prior	68% credible interval of the excluded models	95% credible interval of the excluded models
$\overline{x_{\rm HII}}$	Flat in [0, 0.81]	[0, 0.06], [0.50, 0.58]	[0, 0.08], [0.45, 0.62]
$\overline{T_{\rm K}}$ (K)	Flat in [2.10, ∞)	[19.23, 115.61], [2.10, 2.32]	[7.41, 158.48], [2.10, 3.55]
$f_{\rm heat}$	–	[0, 0.14]	[0, 0.34]
$\overline{\delta T_{\rm b}}$ (mK)	–	[−154.50, −84.26]	[−234.15, −65.53]
$R_{\rm peak}^{\rm heat}$ (h^{-1}Mpc)	–	[5.32, 17.78]	[3.50, 69.82]
$\Delta R_{\rm FWHM}^{\rm heat}$ (h^{-1}Mpc)	–	[10.47, 38.01]	[0, 113.76]

Constraints on IGM from MWA upper limits at z=6.5

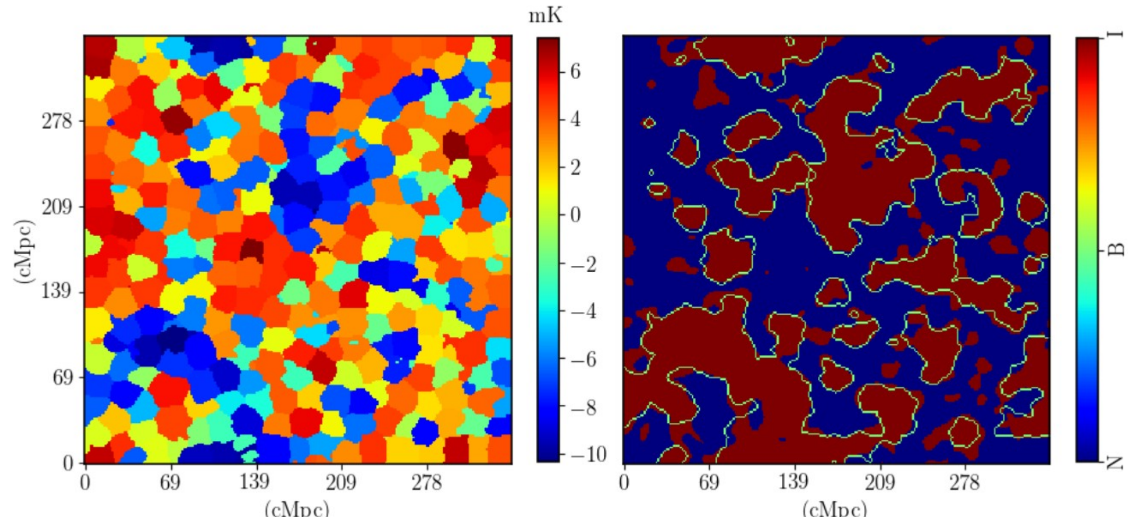


Ghara+2021, will be submitted soon

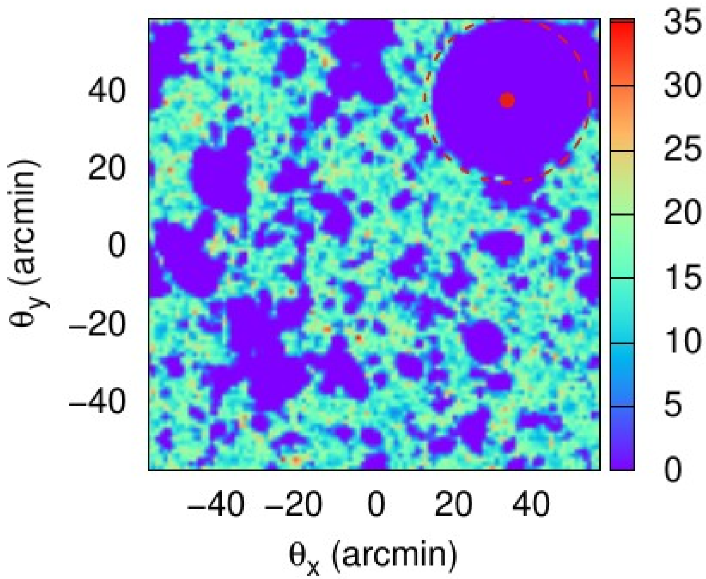
Prospects with SKA

- Direct estimates of Bubble size distribution from 21-cm Images
- Study SKA 21-cm images using morphological descriptors
- SKA observations and Matched filtering technique

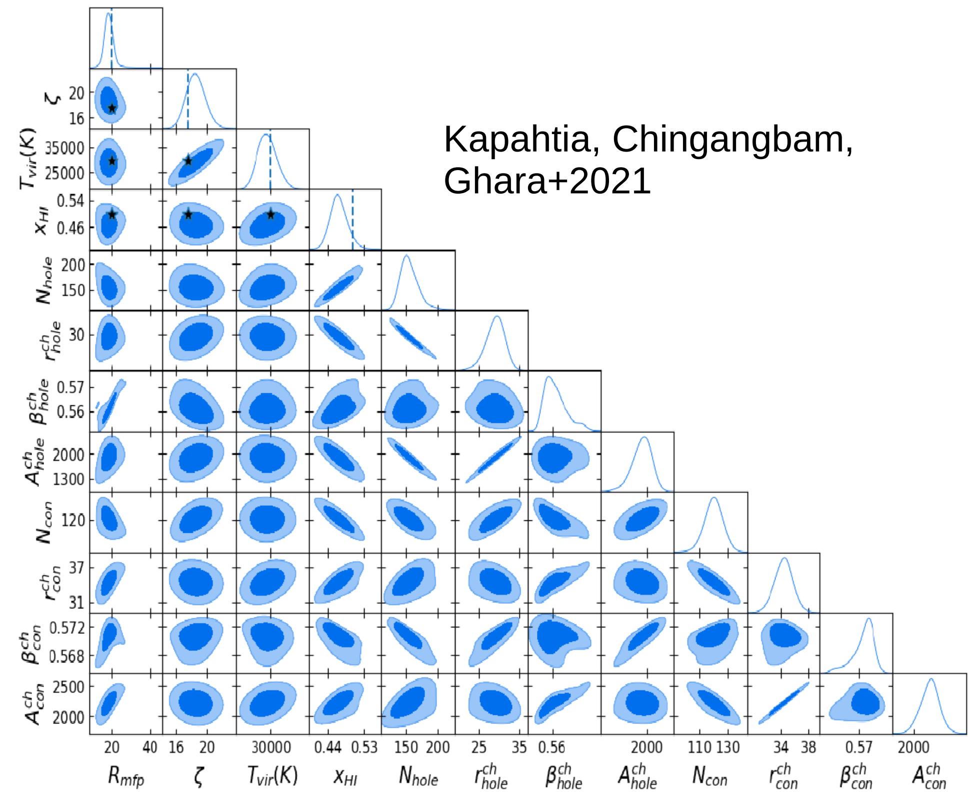
Giri, Mellema & Ghara 2017



Ghara, Choudhury+2020



Kapahtia, Chingangbam, Ghara+2021



Summary

- 21-cm signal observations is a promising probe to constrain the properties of the early sources as well as the states of the IGM during the EoR.
- If the large-scale fluctuations of the signal are driven by T_S fluctuations, an IGM with a volume fraction < 0.34 of heated regions with a temperature larger than CMB, average gas temperature $7 - 160$ K and a distribution of the heated regions with characteristic size 3.5-70 Mpc/h and FWHM of <110 Mpc/h is excluded by LOFAR upper limits at z=9.1 (95% CI).
- Cold neutral IGM at z=6.5 is ruled out by MWA upper limits.
- New stronger upper limits will put stronger constraints on the IGM.