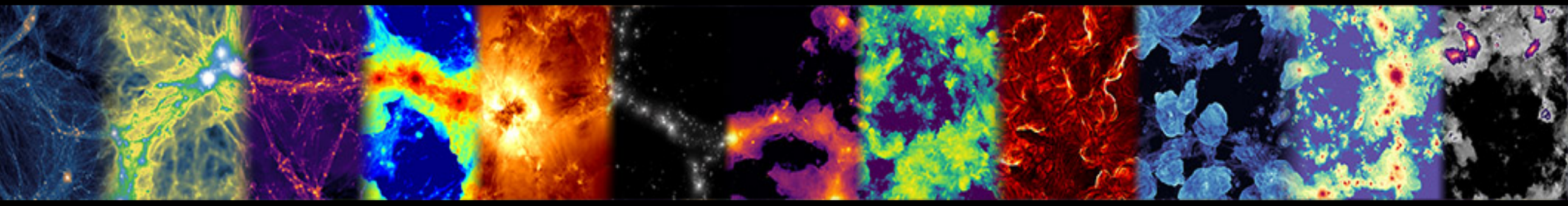
Constraining the Post-EoR HIHM Relation using 21 cm Power Spectrum and Bispectrum



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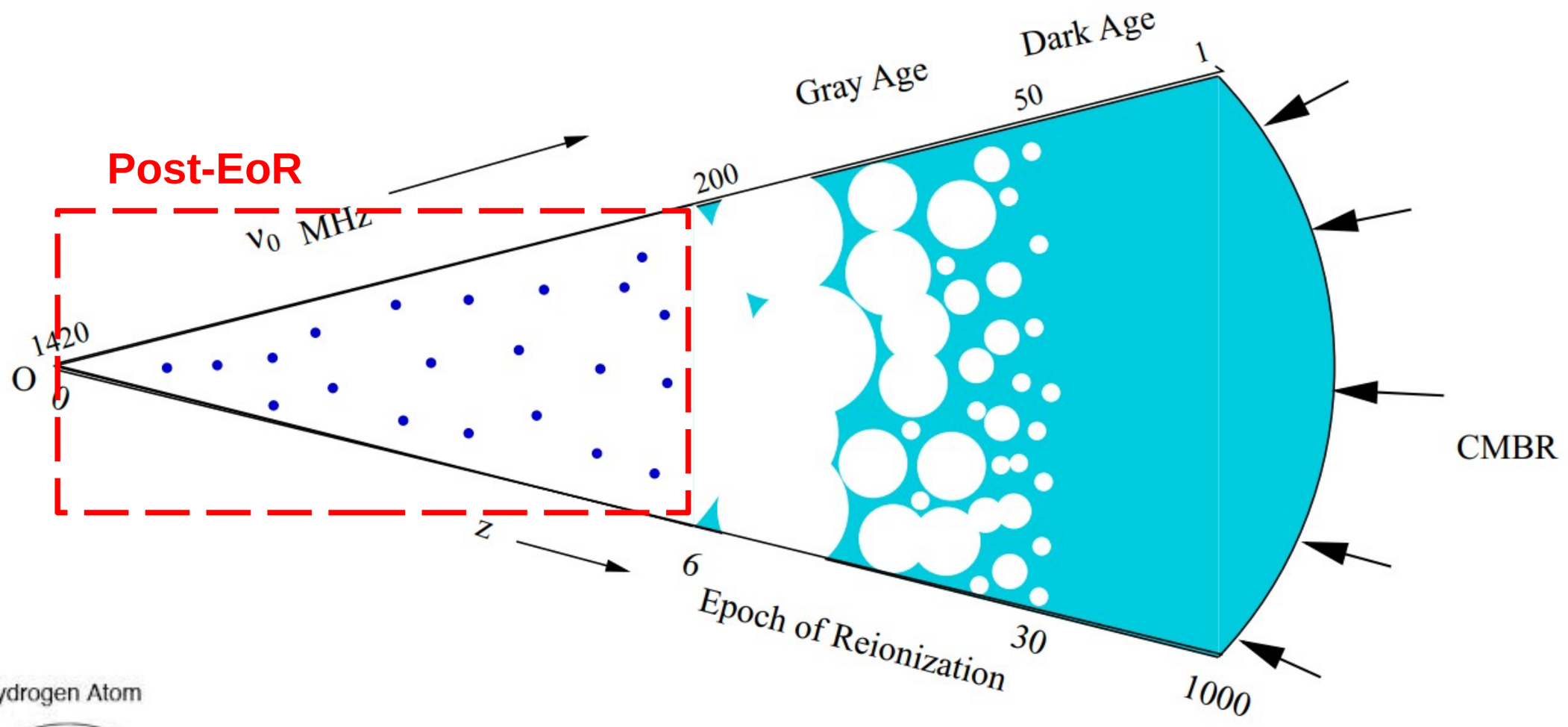
@ SKA Cosmology SWG Meeting, Görlitz, Germany

18th June 2025

Cosmic History through HI



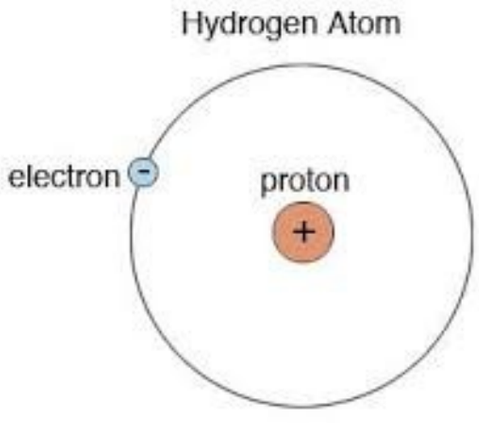
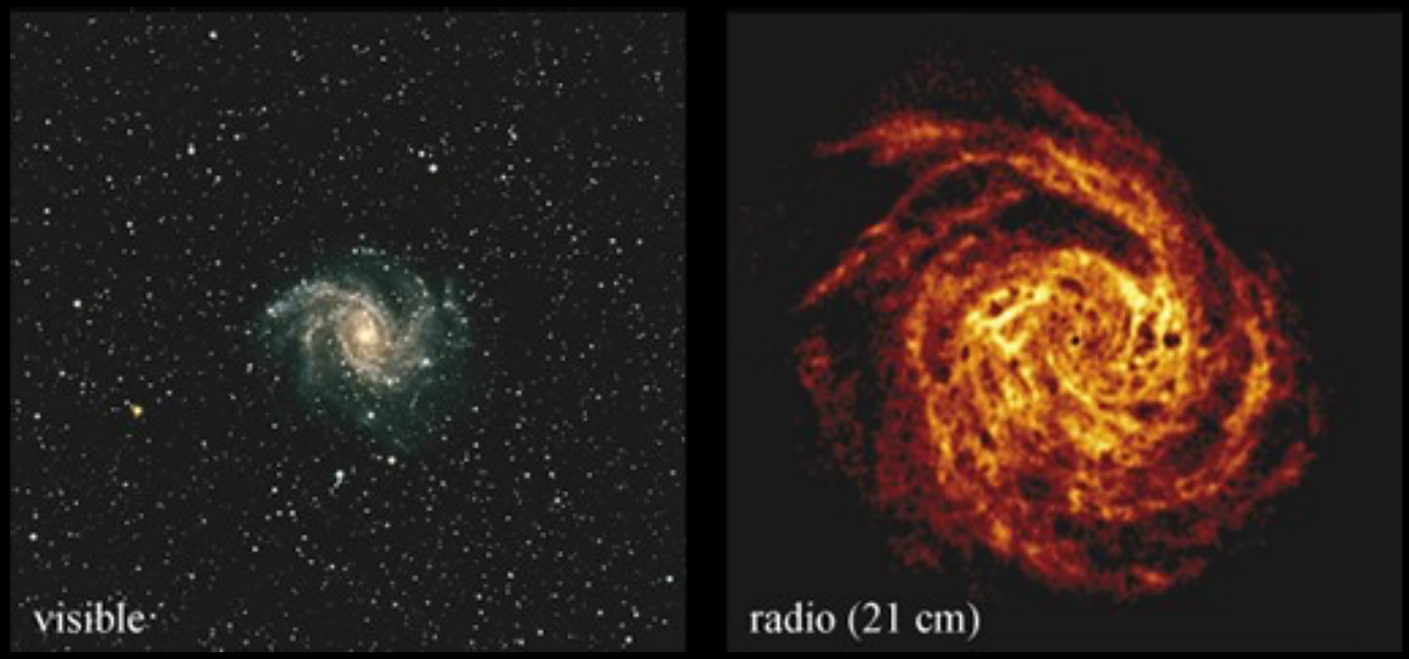


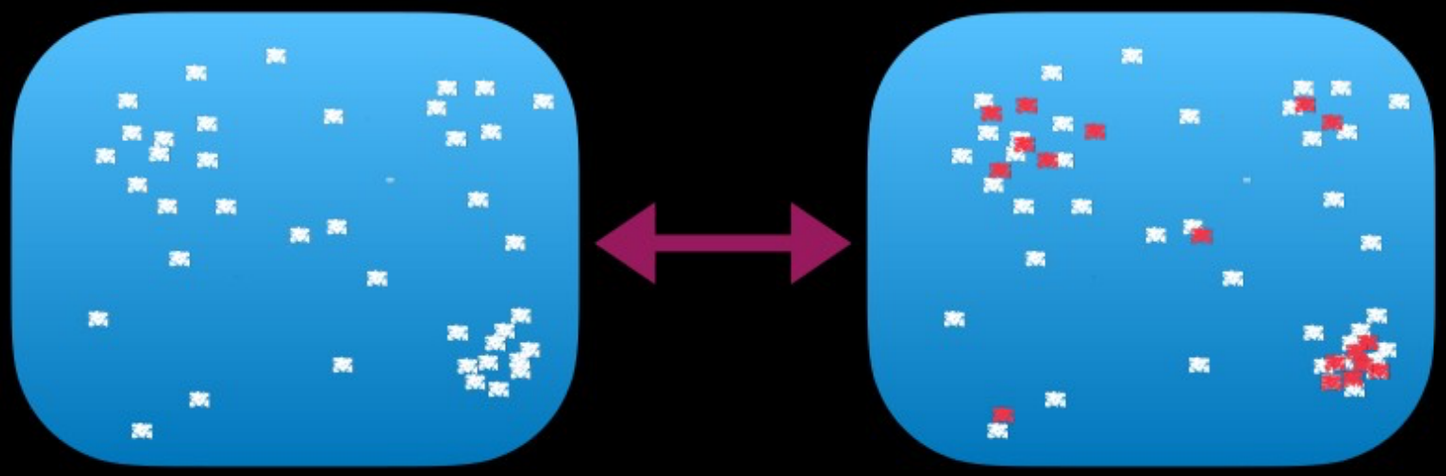
Image credit: Bharadwaj & Ali (2005)

HI in Post-reionization universe

HI found only in dense clumps of matter
Galaxies & DM halos

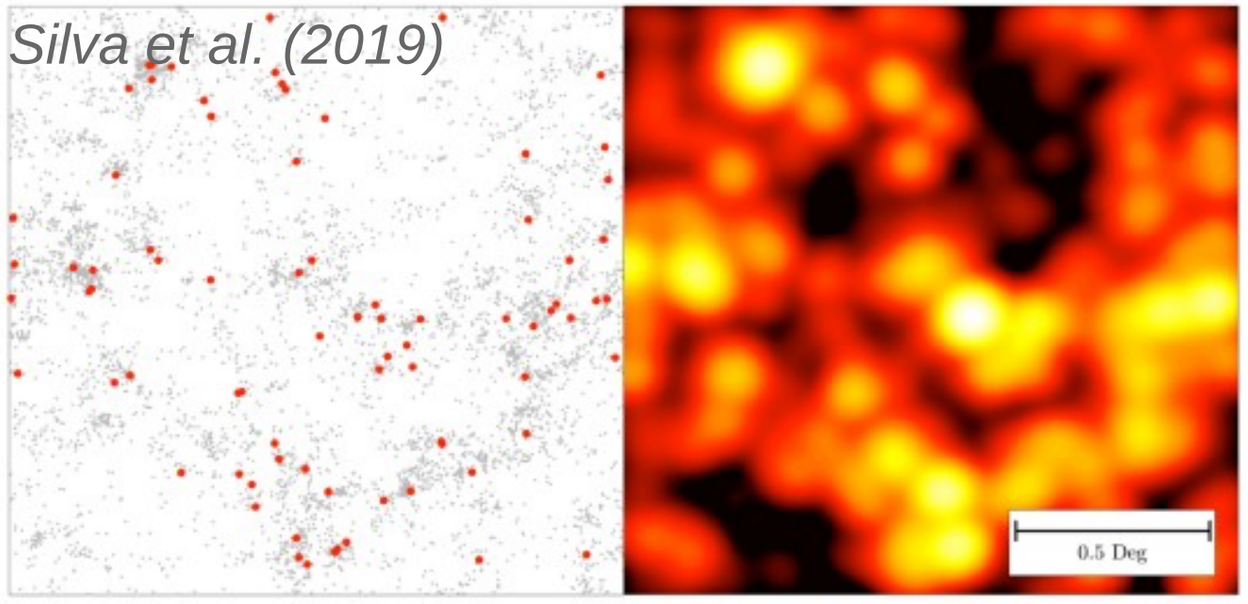


NGC 6946 (Hubble & WSRT)



HI is a **biased tracer** of the matter density

21 cm Line Intensity Mapping

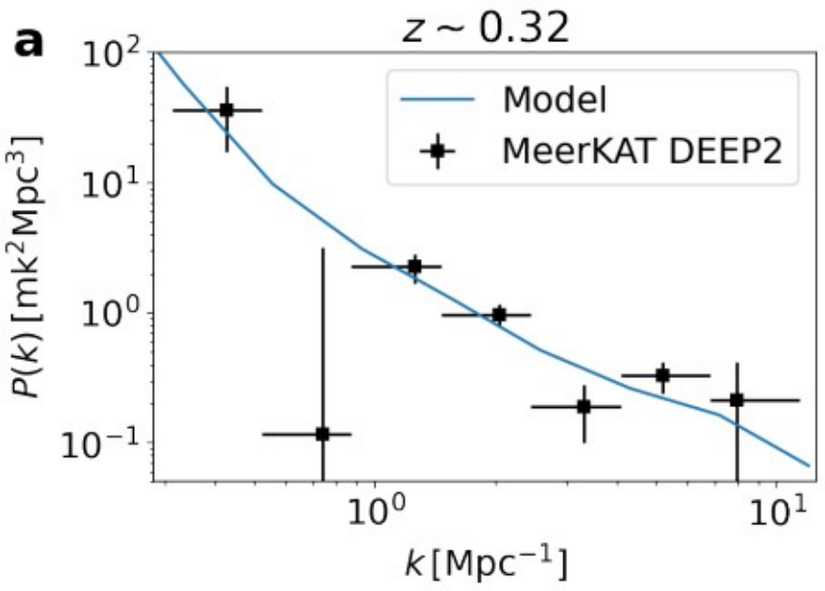


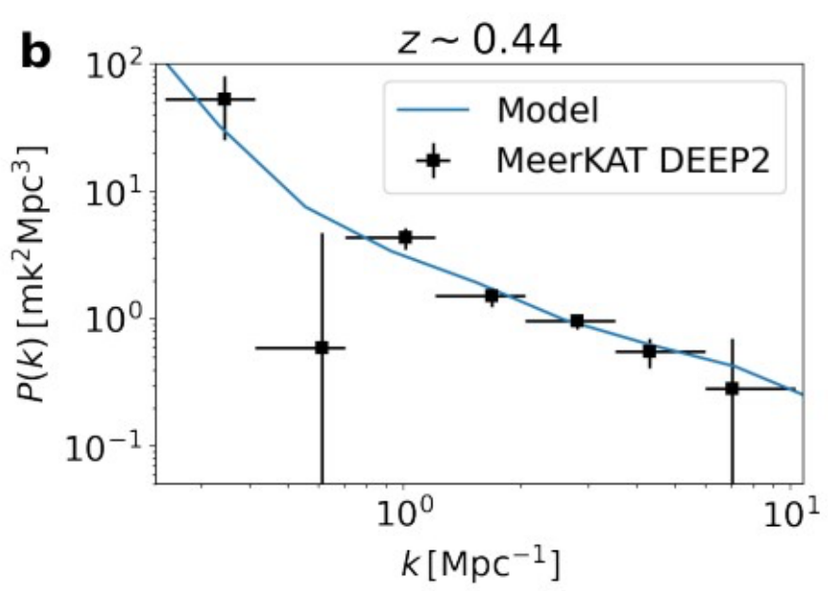
Large Scale Structure + Distribution of HI within galaxies

Cosmological Parameters

Galaxy Formation Physics

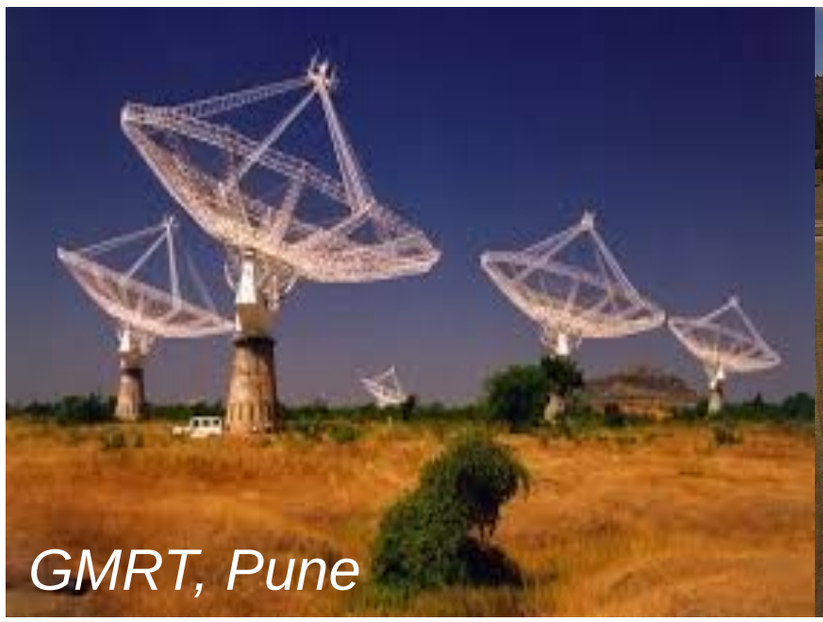
Measuring the fluctuations in the diffused background by the combined emission from all sources !!





NEW ERA OF 21-cm COSMOLOGY

First detection of autocorrelation Power Spectrum by
Paul et al. (2023) using MeerKAT Telescope in South Africa



Simulating Post-EoR HI distribution

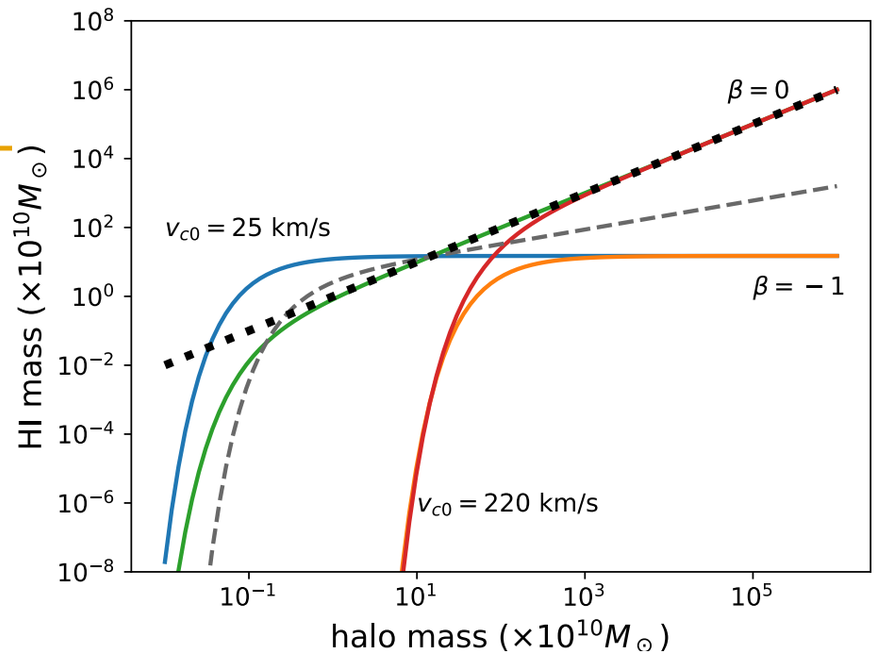
Simulating Post-EoR HI distribution

N-body Simulation → Halo Finding FoF algorithm → **HIHM relation Populating the halos**

$$M_{\rm HI} = \alpha f_{H,c} M_h \left(\frac{M_h}{10^{11} h^{-1} M_\odot} \right)^{\beta} \exp\left[-\frac{M_{\rm cut}}{M_h} \right]$$

$$M_{\rm cut} = 10^{10} M_\odot \left[\frac{v_{c0}}{60\ {\rm km/s}} \right]^3 \left(\frac{1+z}{4} \right)^{-\frac{3}{2}}$$

Parameters : α, β, v_{c0}

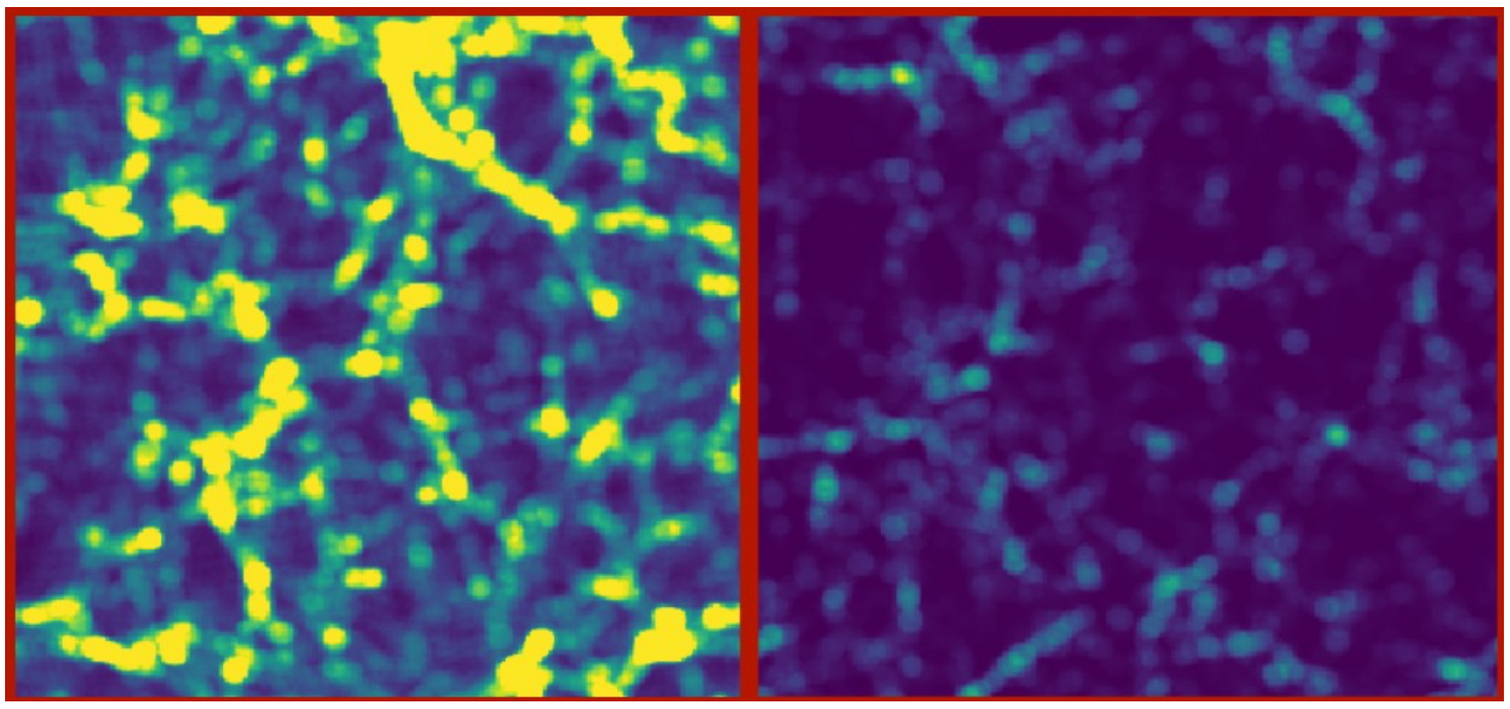


Padmanabhan et al. (2016, 2017)

21 cm Brightness Temperature

Dark Matter Simulation → **Halo Finding** → **HIHM model**

δ δ_{HI}



Measured by Radio Telescopes!

δT_b

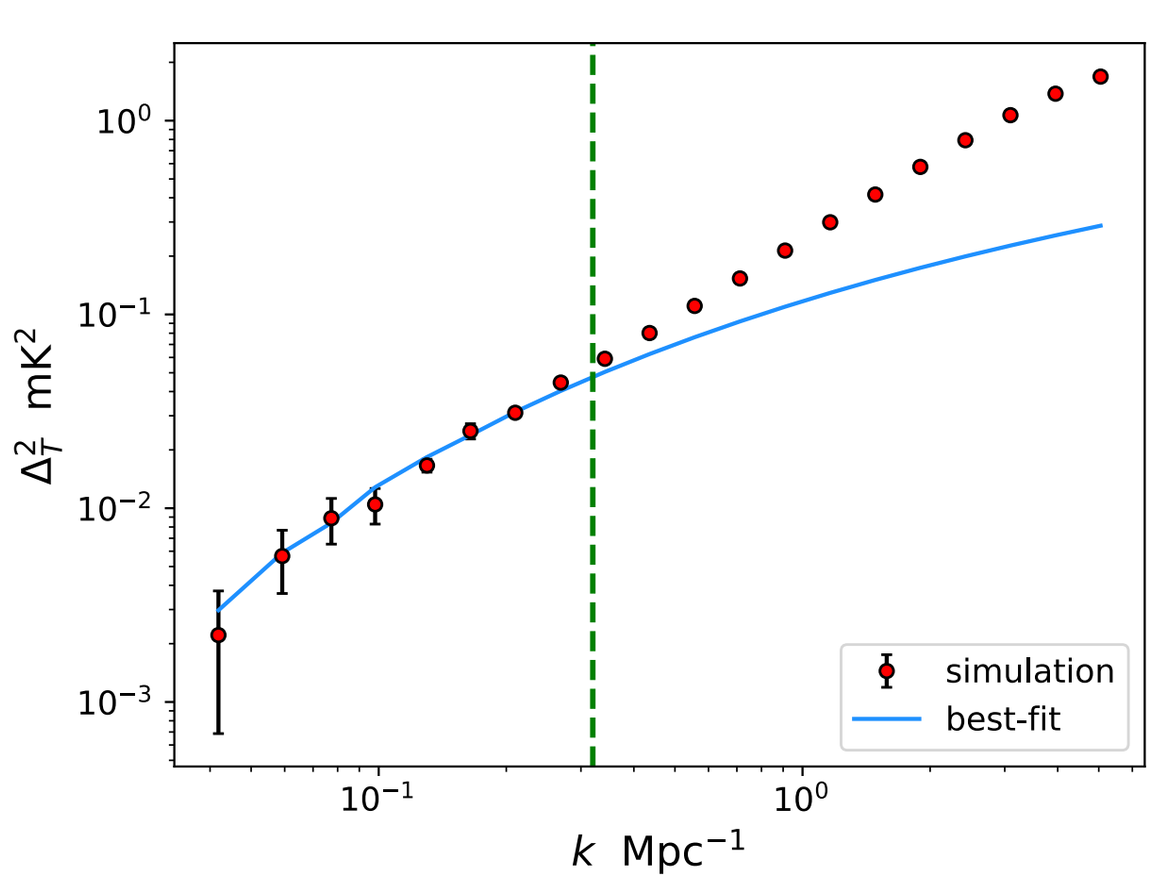
$$\delta T_b(\mathbf{x}, z) = \bar{T}(z)\,\frac{\rho_{\rm HI}(\mathbf{x})}{\bar{\rho}_{\rm H}}$$

Bharadwaj & Ali (2005)

Power Spectrum

Fourier transform of brightness temperature

$$P_{\rm T}(k) = V^{-1}\delta_D(\vec{k_1}+\vec{k_2}) < \delta T_b(\vec{k_1})\delta T_b(\vec{k_2}) >$$

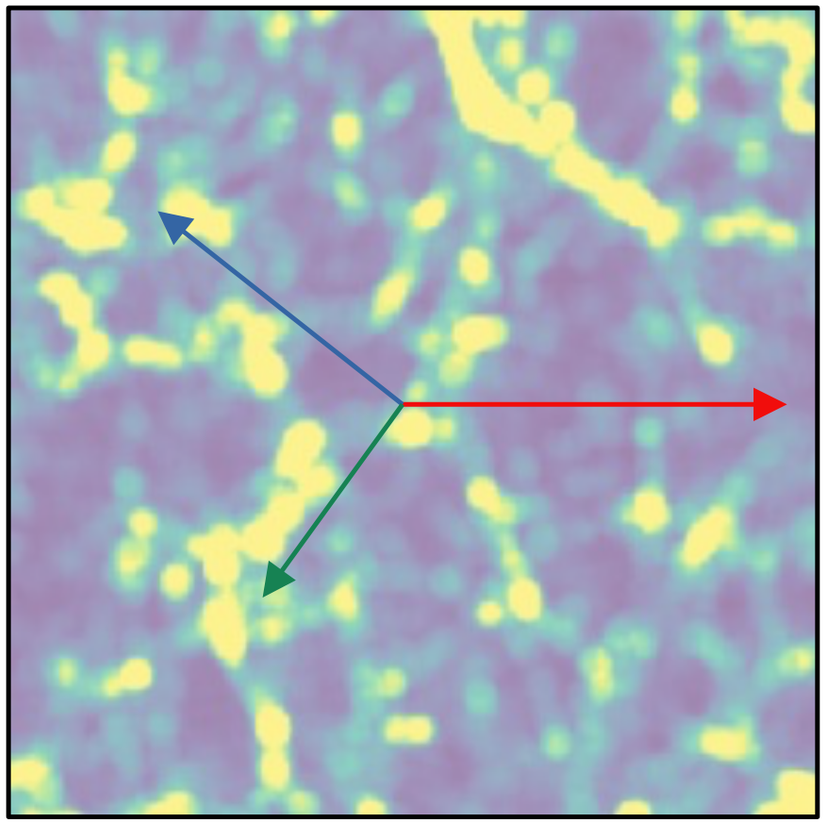


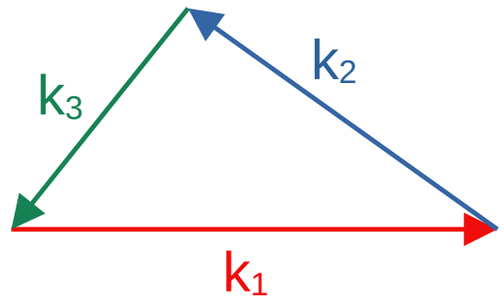
Fourier conjugate of ***2-pt correlation*** *functions !*

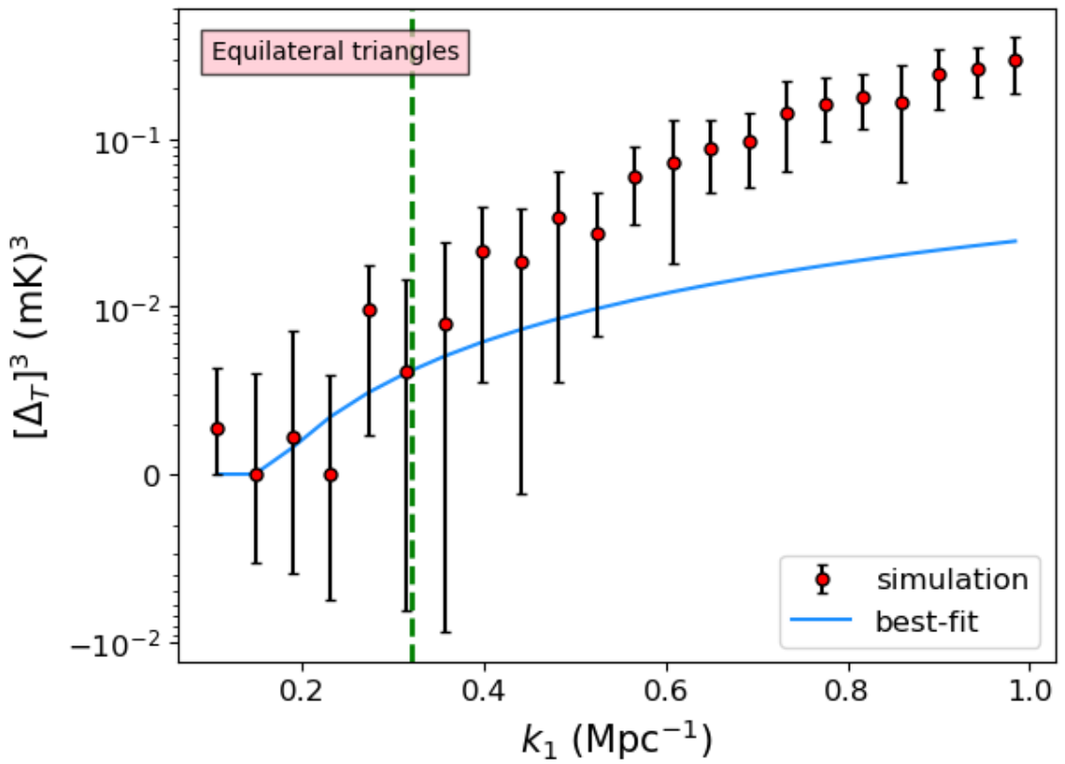
Bispectrum

*Fourier conjugate of **3-pt correlation** functions !*

$$B_{\rm T}(\vec{k_1},\vec{k_2},\vec{k_3}) = V^{-1}\delta_D(\vec{k_1}+\vec{k_2}+\vec{k_3}) < \delta T_b(\vec{k_1})\delta T_b(\vec{k_2})\delta T_b(\vec{k_3}) >$$

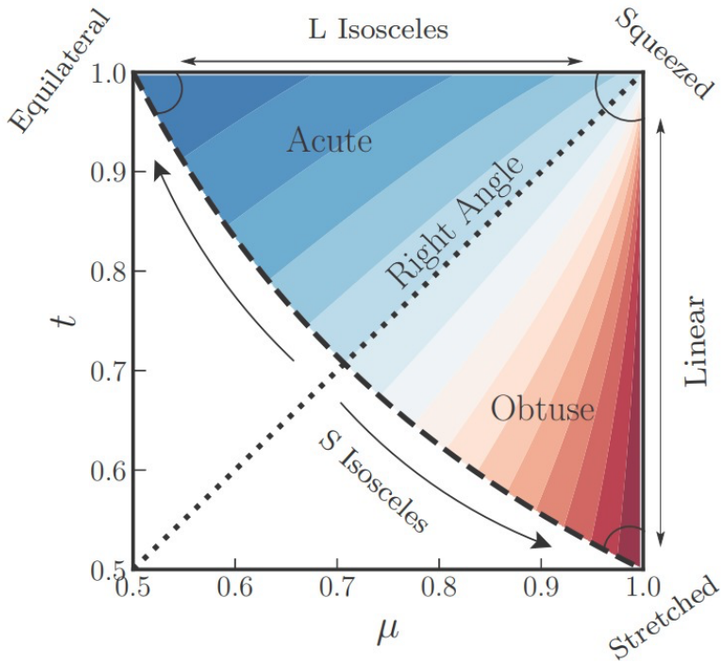






$$\mu = \cos\theta = -\frac{\vec{k_1}\cdot\vec{k_2}}{k_1 k_2}$$

$$t = \frac{k_2}{k_1}$$



Bharadwaj et al. (2020)

Large-Scale HI Bias

HI is a biased tracer of the matter density

$$\delta_{\mathrm{HI}} = b_1 \delta + \frac{b_2}{2} \delta^2$$

Linear Bias

Quadratic Bias

Modelling the Statistics

Power Spectrum

$$P_{\rm T}(k) = \left(\frac{4\bar{T}}{3\Omega_b}\right)^2 [\Omega_{\rm HI} b_1]^2 P(k)$$

Bispectrum

$$B_{\rm T}(k_1, k_2, k_3) = 2\left(\frac{4\bar{T}}{3\Omega_b}\right)^3 [\Omega_{\rm HI} b_1]^3 \left(F(\mathbf{k_1}, \mathbf{k_2}) + \frac{\gamma}{2}\right) P(k_1) P(k_2)$$

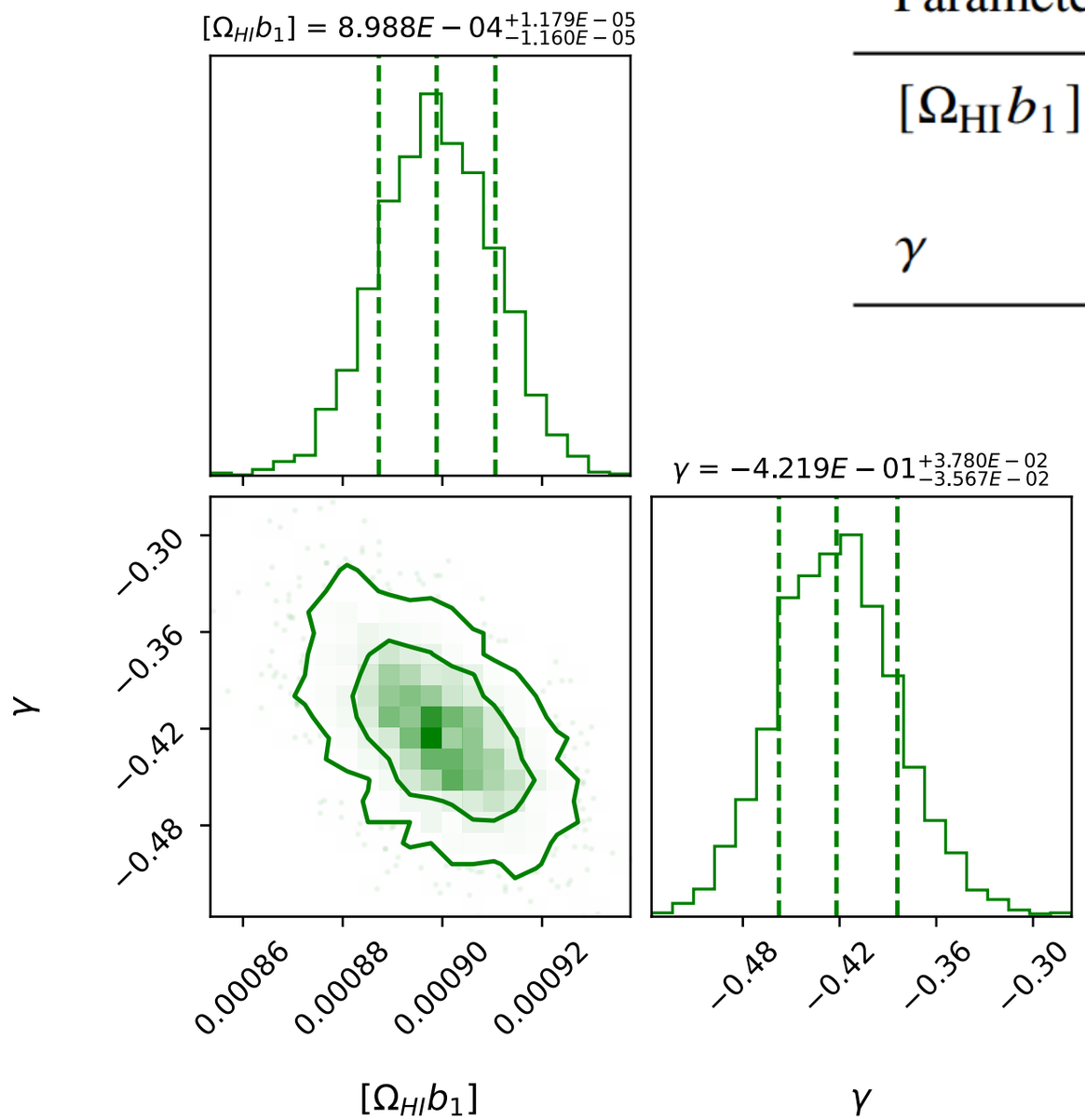
+ cyc..

Unknown Parameters →

$$[\Omega_{\rm HI} b_1]$$

$$\gamma = \frac{b_2}{b_1}$$

Estimating Bias : MCMC



Parameter	Prior	Best-fit
$[\Omega_{\rm HI} b_1]$	$[0, 1]$	$8.988^{+0.117}_{-0.116} \times 10^{-4}$
γ	$[-1, 1]$	$-4.219^{+0.378}_{-0.357} \times 10^{-1}$

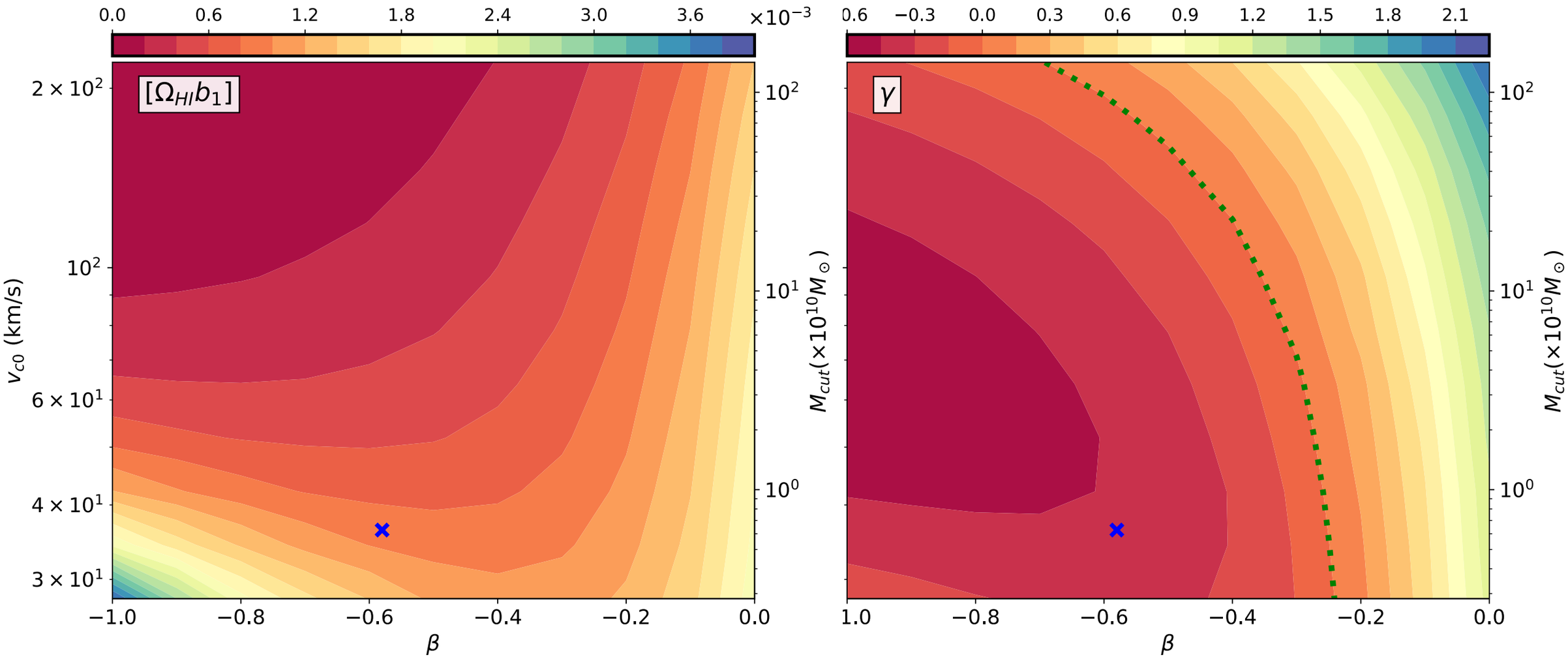
Negative Quadratic Bias !!

Fiducial HIHM Parameters

α = 0.09
β = -0.58
$\mathbf{v}_{c0}$ = 36.3 km/s

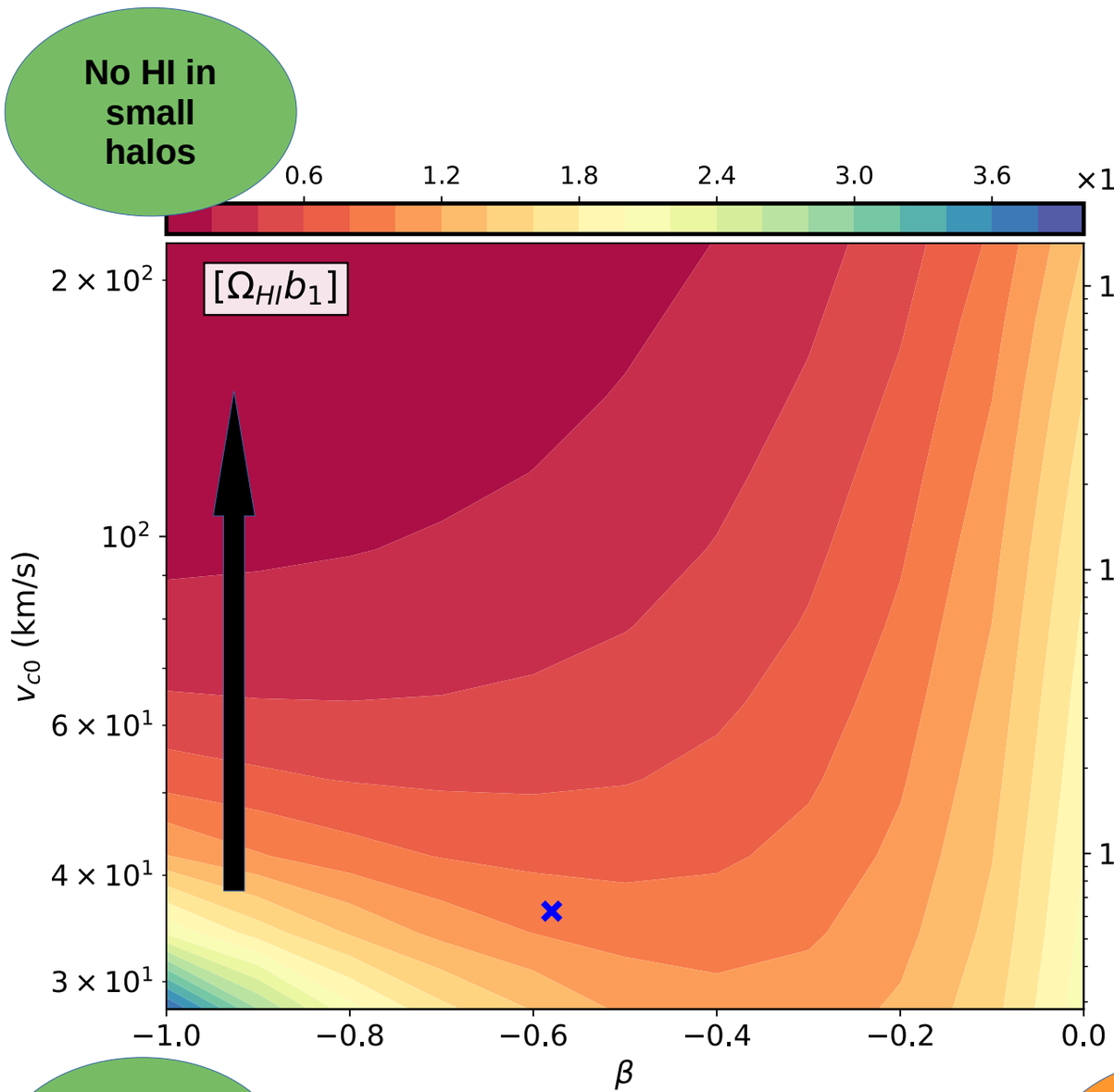
$$k_{ul} = 0.32\ \mathrm{Mpc}^{-1}$$

Bias for different HIHM Parameters

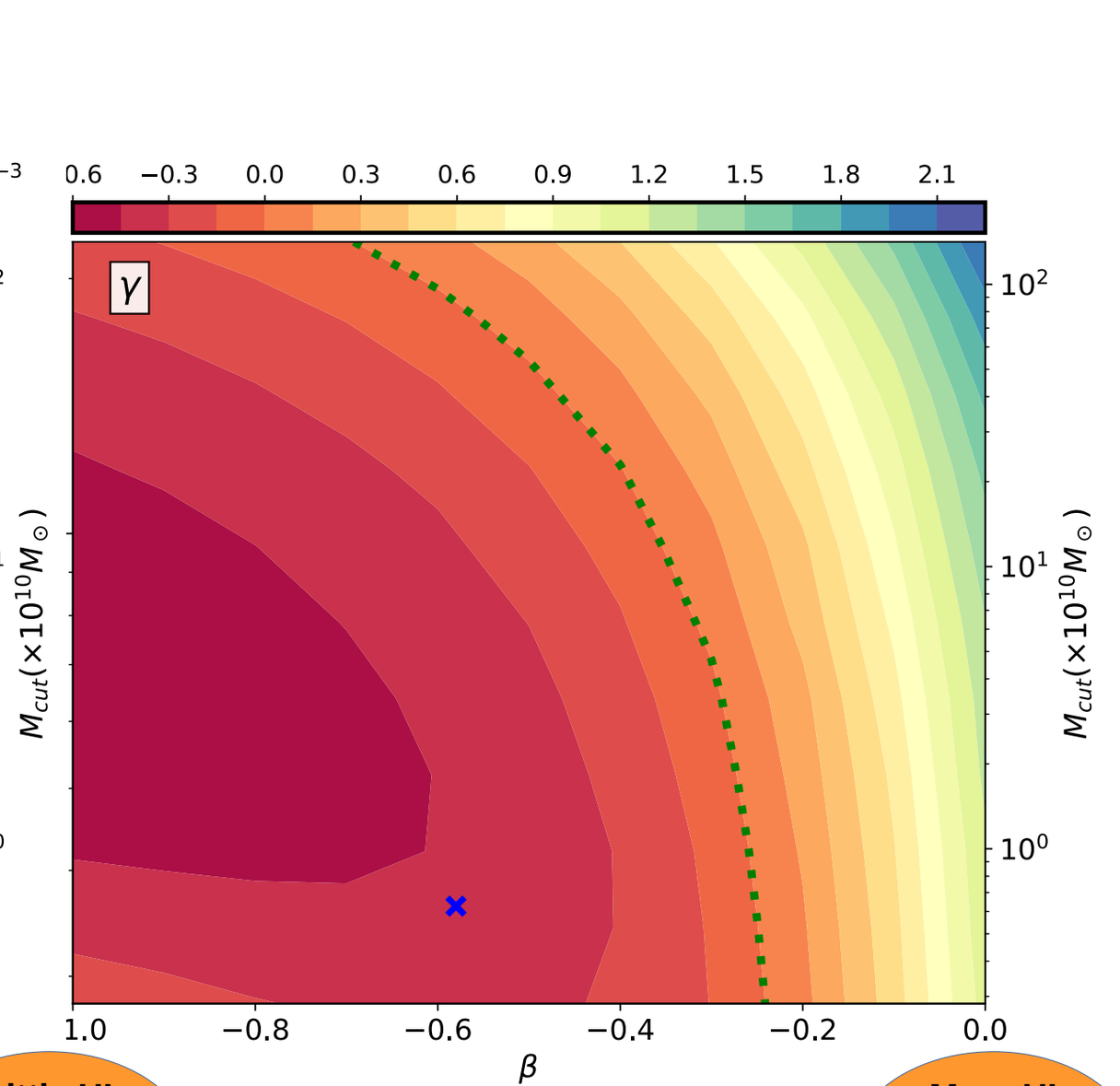


Bias for different HIHM Parameters

No HI in small halos



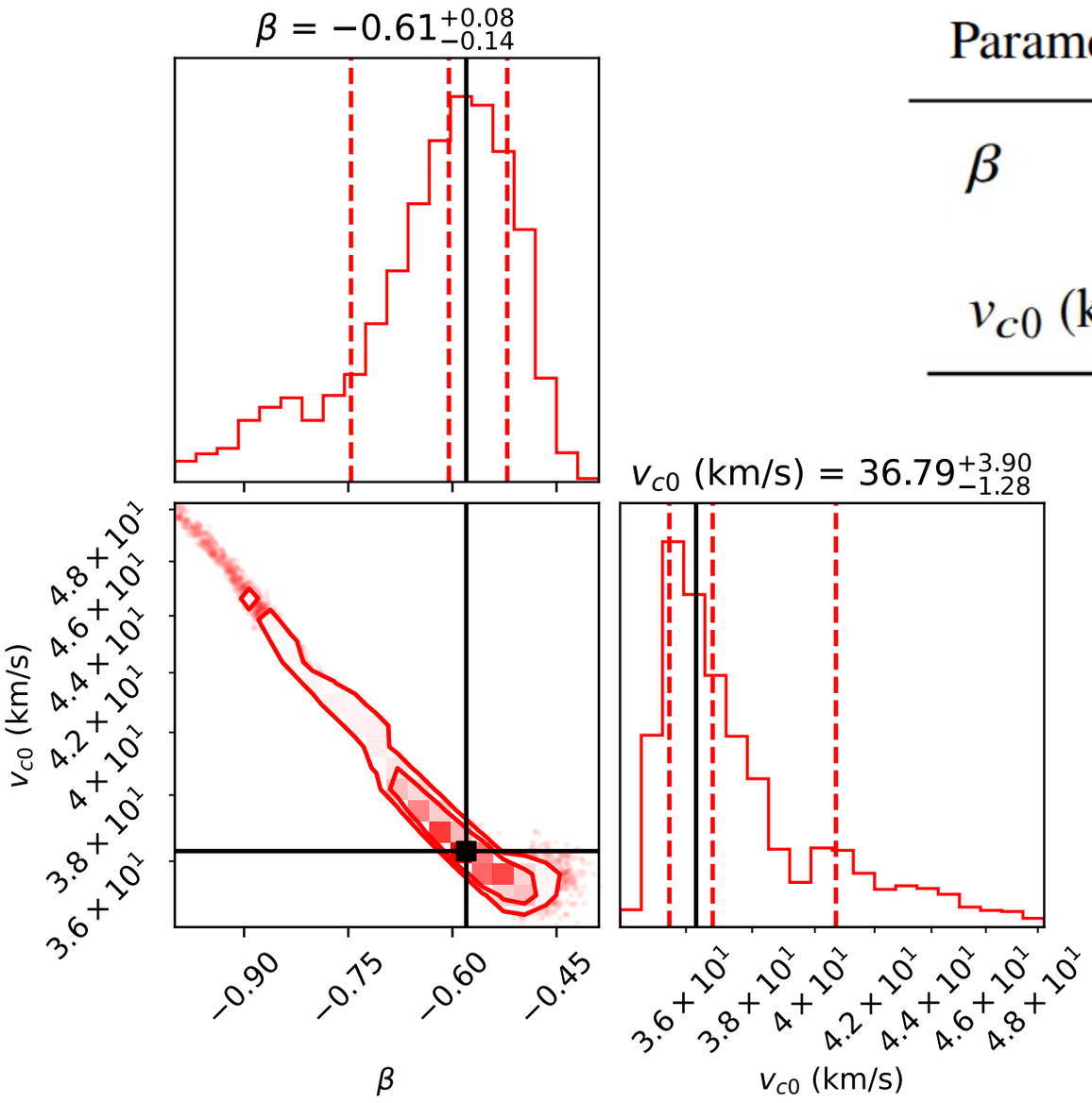
More HI in small halos



Little HI in massive halos

More HI in massive halos

Estimating HIHM Parameters : MCMC



$k_{ul} = 0.32\ \mathrm{Mpc}^{-1}$

Parameter	Prior	Best-fit
β	$[-1, 0]$	$-0.61^{+0.08}_{-0.14}$
v_{c0} (km/s)	$[25, 220]$	$36.79^{+3.90}_{-1.28}$

True values

β = -0.58
v_{c0} = 36.3 km/s

True values lies within 1σ confidence

Result : Given the observations of 21 cm Power Spectrum & Bispectrum on large-scales, we can estimate the post-EoR HIHM parameters !!

Summary and Conclusions

- The statistics of the Neutral hydrogen distribution can be studied using the 21 cm Intensity Mapping Technique.

- On large-scales, the cosmological HI distribution can be modelled using a linear and quadratic bias estimated using the Power Spectrum & Bispectrum.

- The bias values are highly dependent on the parameters of the HIHM model and we can constrain these parameters using bias information.

- True values of the parameters lie within 1σ of our estimate!

- We are now in process of appling this technique to the 21 cm observations in Redshift-space.

THANK YOU