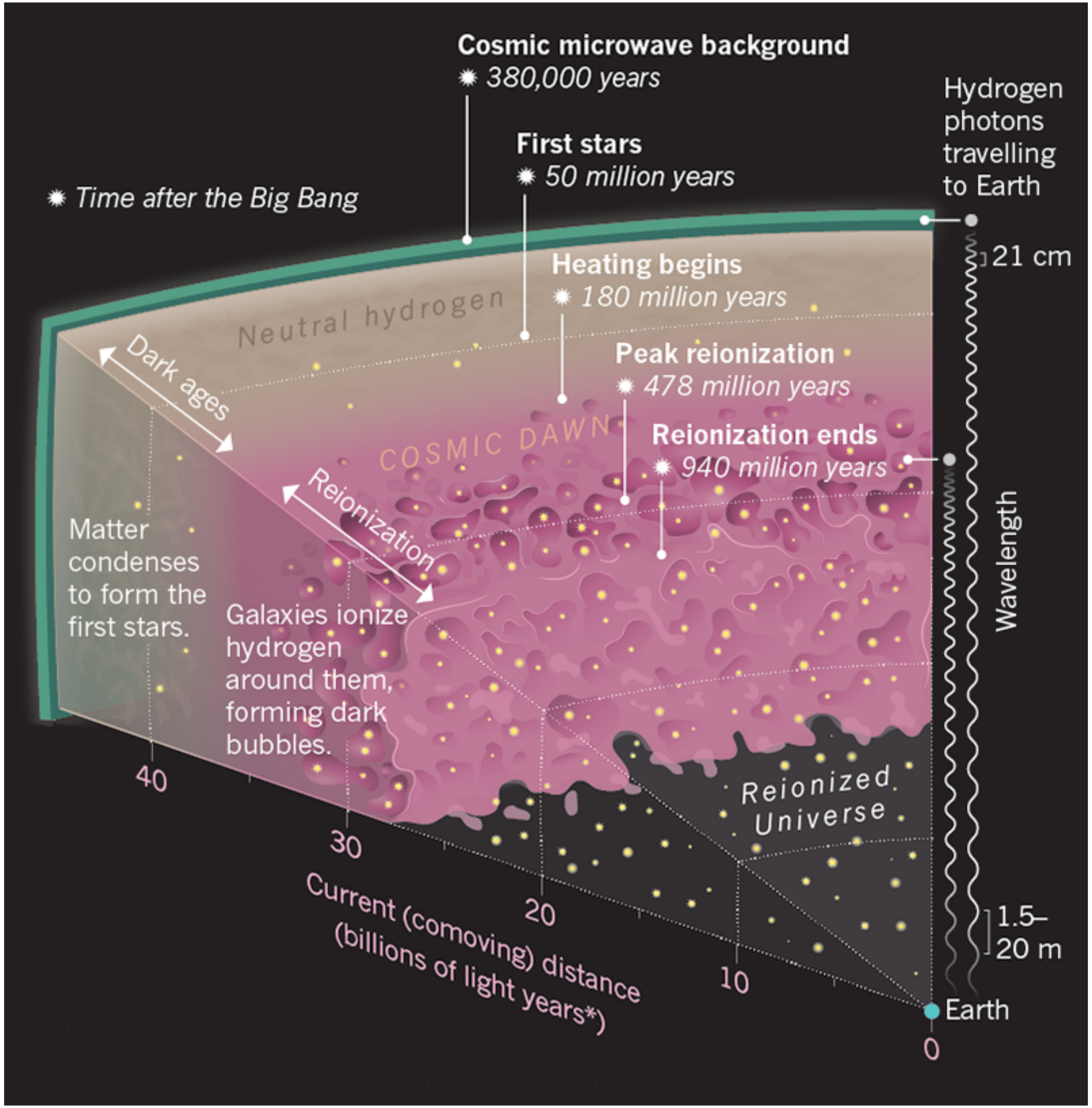
Physical interpretation of the IGM parameters of the 21-cm power spectrum from cosmic reionization

Ivelin Georgiev



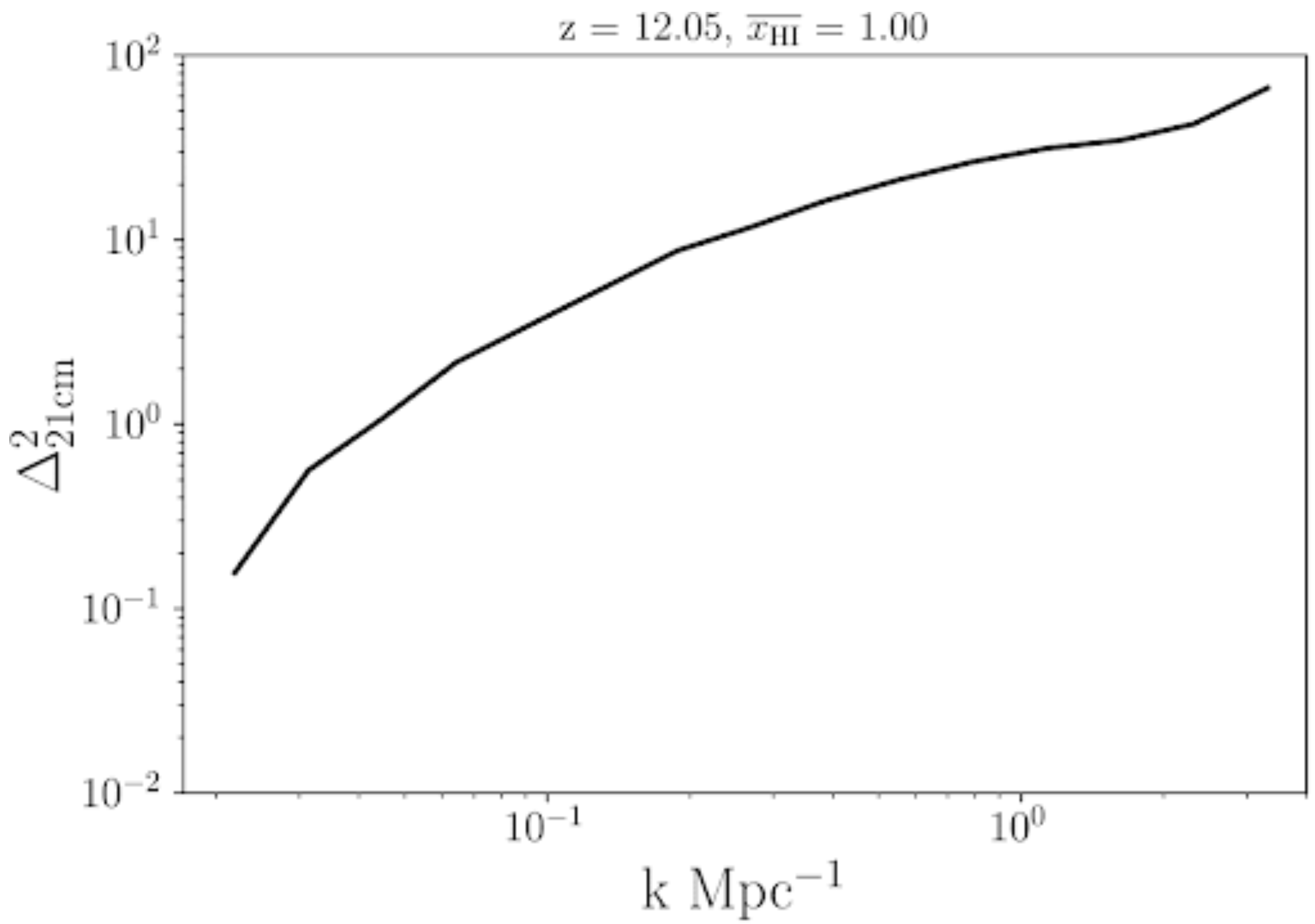
nature.com

During the cosmic dark ages, the Universe primarily consists of **neutral hydrogen**, which emits radiation via the **21-cm** line (Field et al. 1959).

$$\delta T_{\rm b}(\mathbf{r}, z) = T_0(\mathbf{r}, z)\bar{x}_{\rm H\ I}(1+\delta_{\rm H_I}(\mathbf{r}))(1+\delta_\rho(\mathbf{r}))$$

$$\langle G(\mathbf{k}), G^\star(\mathbf{k}')\rangle = (2\pi)^3\delta_D(\mathbf{k}-\mathbf{k}')P_{g,g}(\mathbf{k})$$

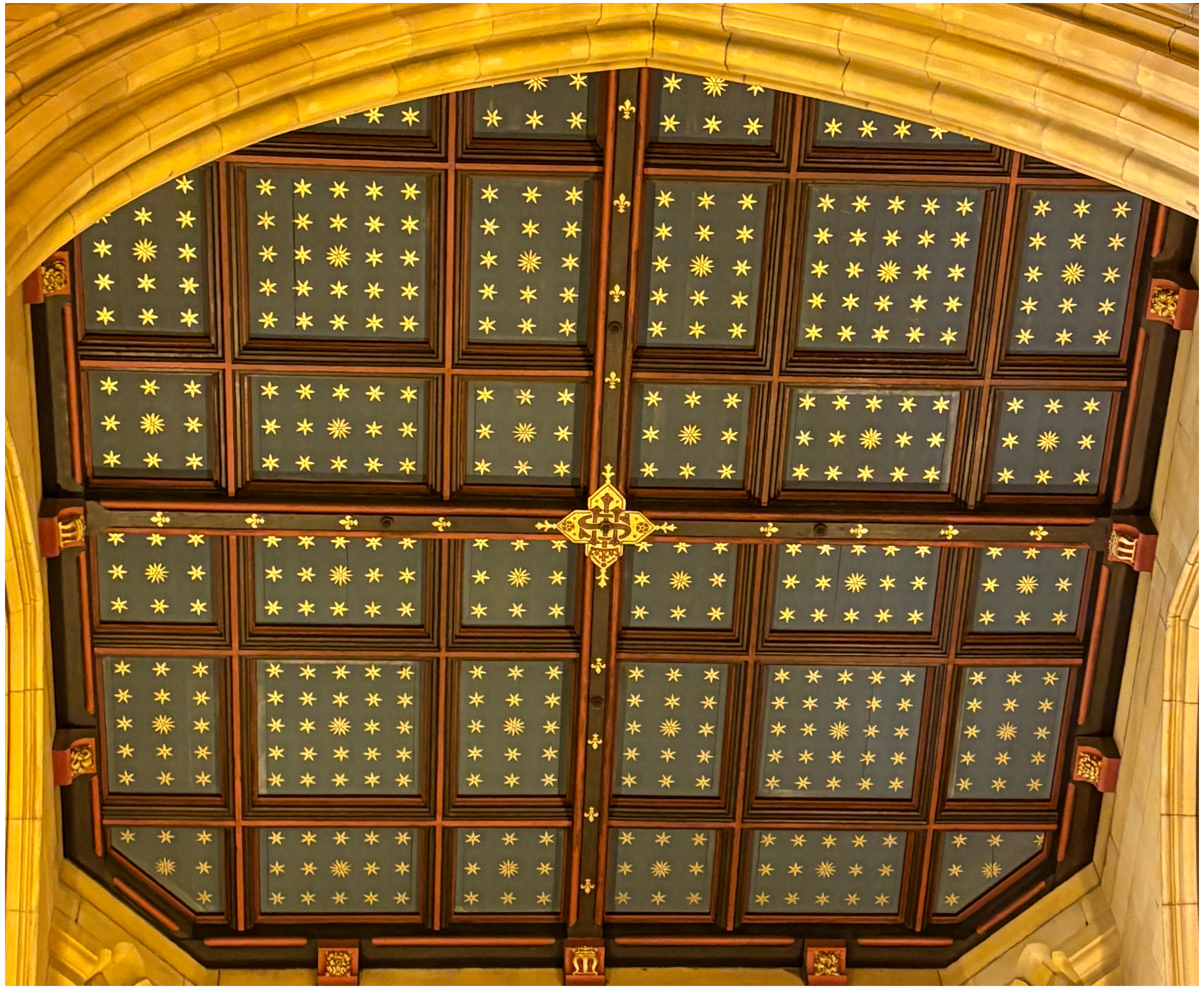
$$\Delta^2_{21cm}(k) = \frac{k^3 P_{\delta_{T_b},\delta_{T_b}}}{2\pi^2}$$



How do we interpret the 21-cm power spectrum?

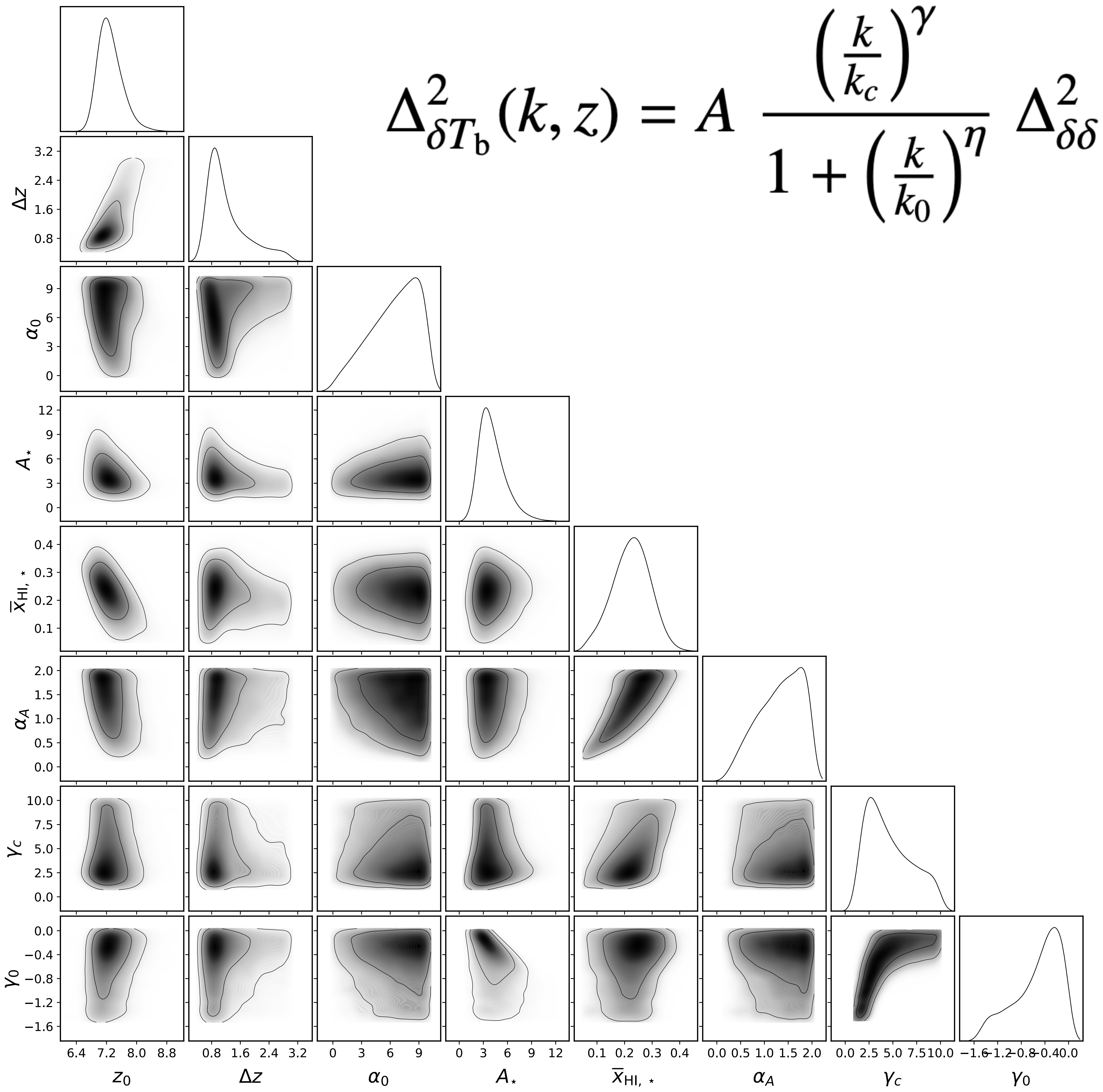
Source interpretation

- The sources define the shape and evolution of the 21-cm signal.
- Examples in all interpretation papers (The Hera Collaboration et al. 2022, Mertens et al. 2025, Trott et al. 2025)
- Challenges:
  - Source parametrisation
  - Simulation based



EoR simulation spotted in a cathedral in Sydney?

How do we interpret the 21-cm power spectrum?



$$\Delta^2_{\delta T_{\rm b}}(k,z) = A \, \frac{\left(\frac{k}{k_c}\right)^{\gamma}}{1+\left(\frac{k}{k_0}\right)^{\eta}} \, \Delta^2_{\delta\delta}(k,z)$$

Ghara et al. 2024

Phenomenological interpretation

- Fit the features of the 21 cm power spectrum
- Example in Ghara et al. (2020) for single redshift (z=9.1), see also Mirocha et al. (2022).
- Challenges:
  - Choice of priors?
  - **How to handle multi-redshift data?**

How do we interpret the 21-cm power spectrum?

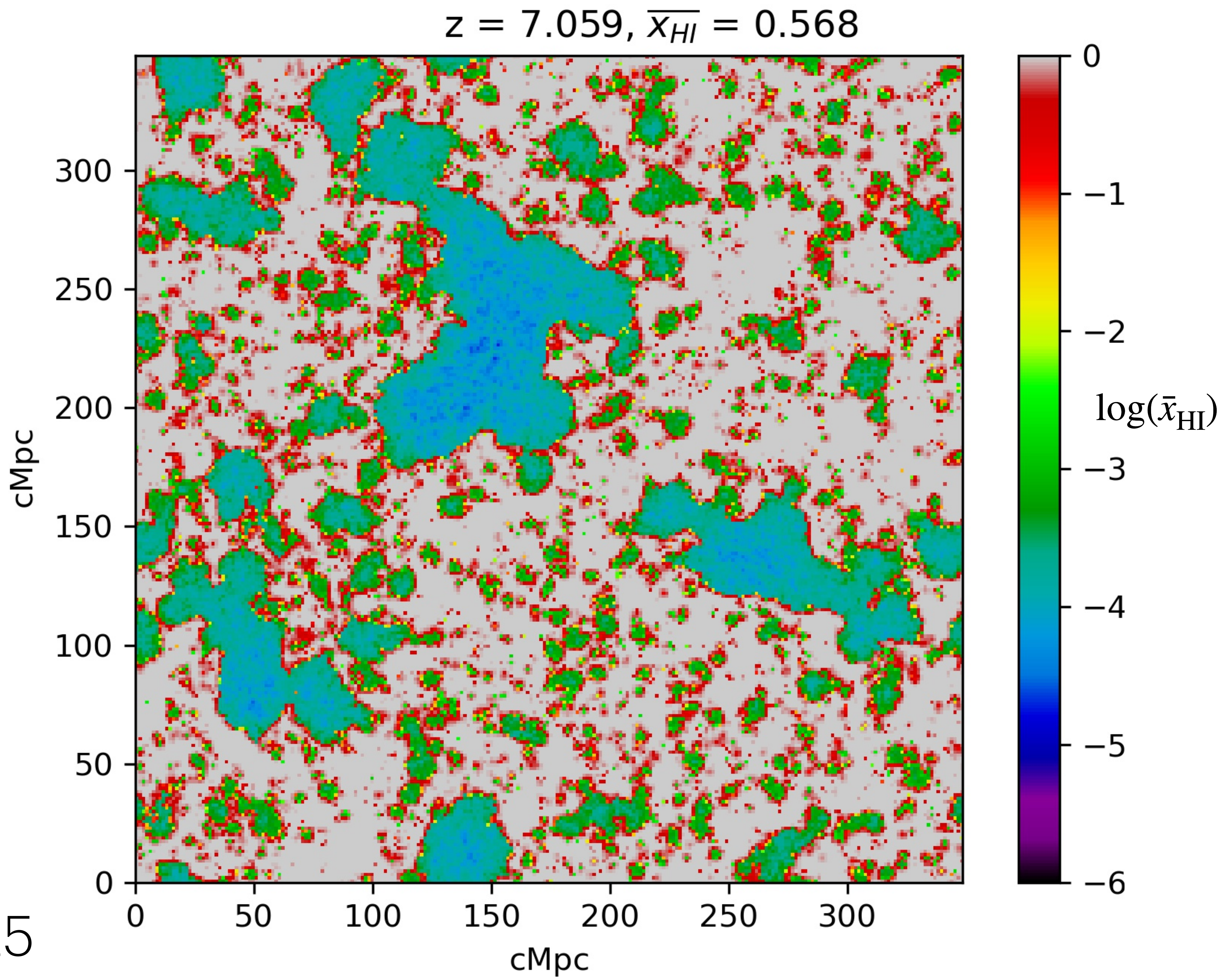
IGM -driven interpretation

- 21-cm signal is a probe of the state of the IGM.
- Interpret the power spectrum through the properties of the intergalactic medium
- Arrive at a physical driven form which is physically informed and redshift dependent?

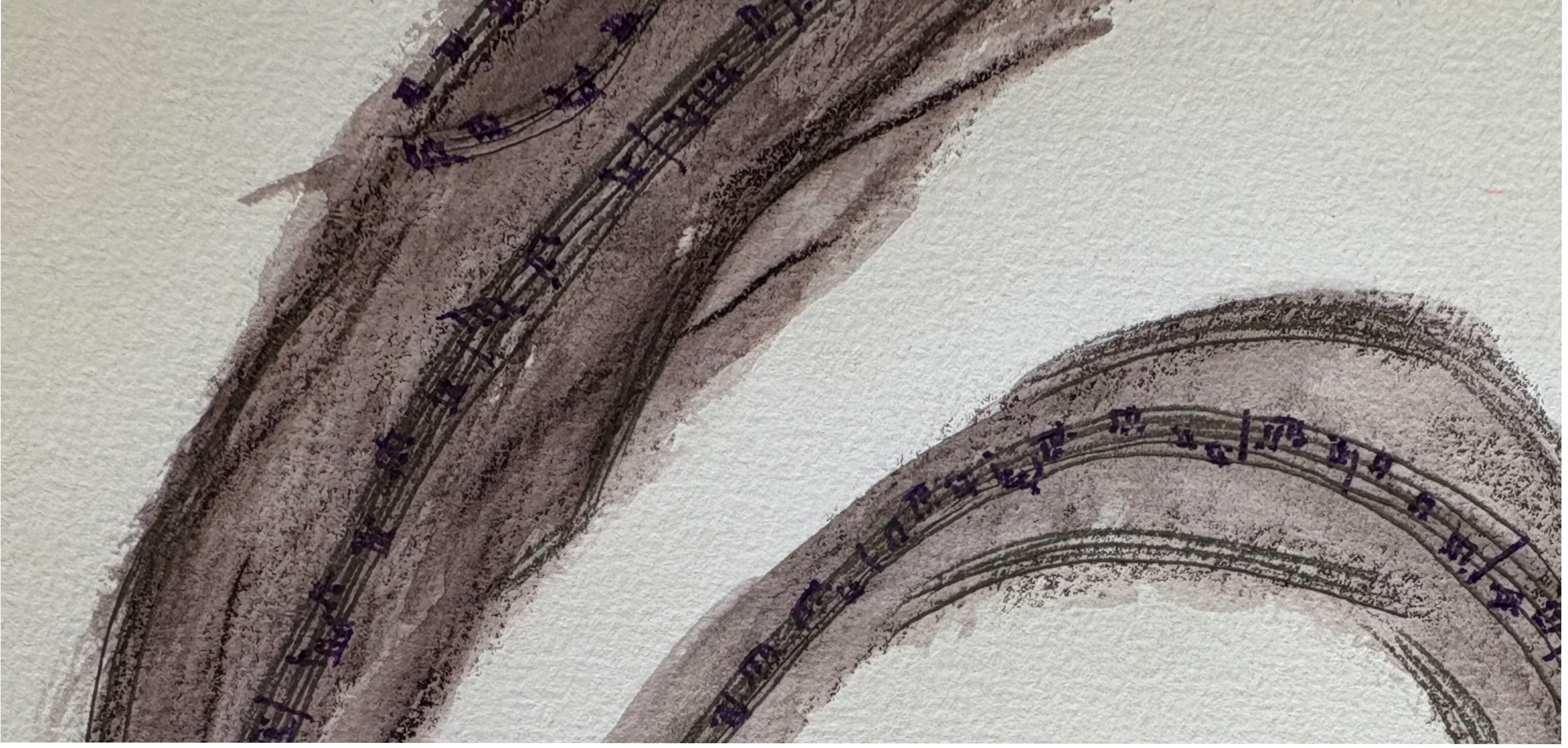
IGM driven parametrisation (Georgiev in prep.)

$$P_{21cm} = T_0^2 \bar{x}_{\rm HI}^2 \left(\frac{(1 + b_i(f+1))^2}{\sqrt{1 + (kR_i)^2}} + \frac{1}{1 + (kR_n)^4} \right) P_{\delta,\delta}$$

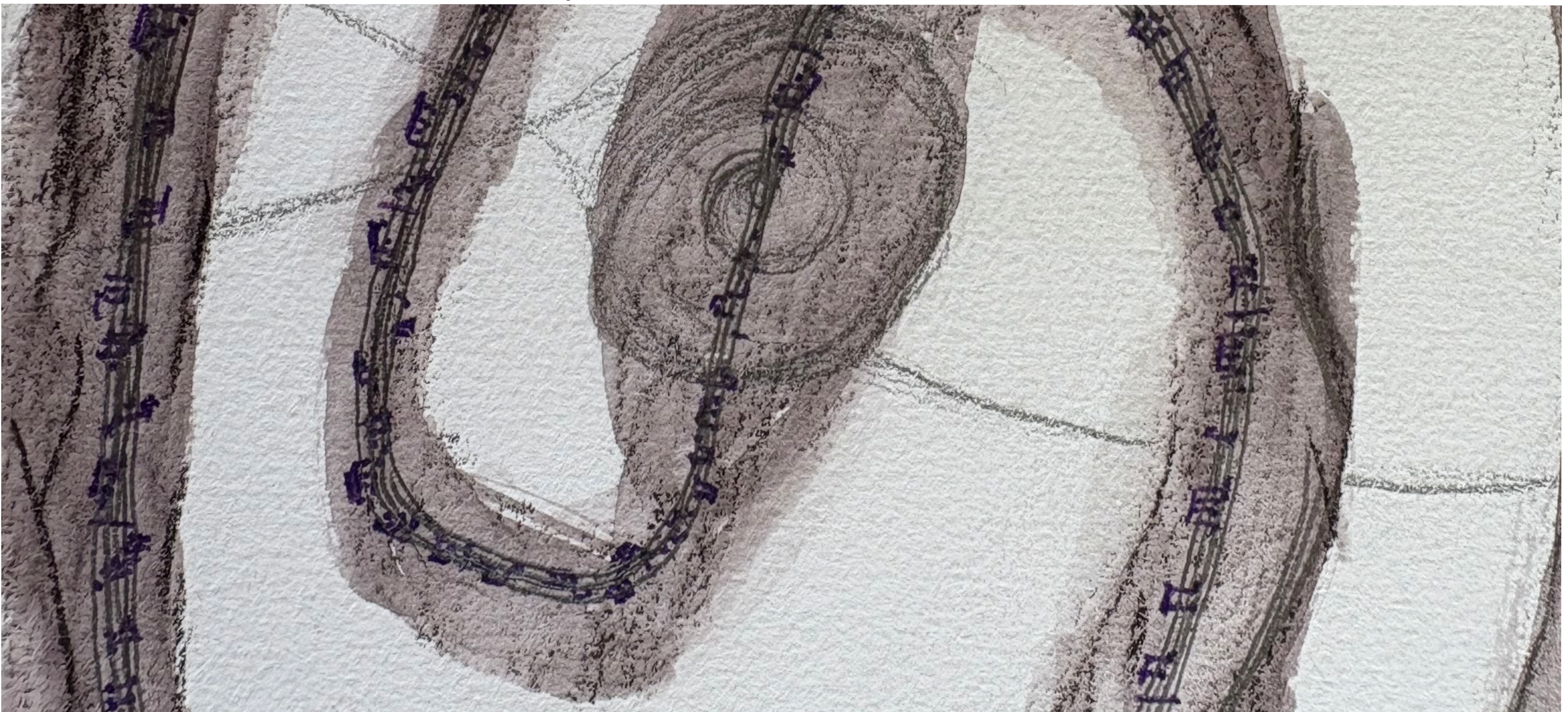
- $\bar{x}_{\rm HI}$: neutral fraction
- b_s : Source biasing + mode coupling, linked to clustering and the halo bias, less important after the midpoint.
- R_i & R_n : "Effective" sizes.
- $f(\bar{x}_{\rm HII}, \bar{x}_{\rm HIIm})$: Large-scale coupling between the ionisation and density fields.



Tested on C²-Ray on simulations from Georgiev et al. 2025



$$P_{21cm} = T_0^2 \bar{x}_{\rm HI}^2 \left(\frac{(1 + b_i(f+1))^2}{\sqrt{1+(kR_i)^2}} + \frac{1}{(1+(kR_n)^4} \right) P_{\delta,\delta}$$



Asymmetric EoR model from Douspis et al. 2015

$$\bar{x}_{\rm HII} = \begin{cases} 0, & z \geq z_{\rm early}, \\ 1, & z \leq z_{\rm re} - dz, \\ \left[\frac{|z_{\rm re} - z|}{dz} \right]^{\alpha_{\rm EoR}}, & \text{otherwise}. \end{cases}$$

Cluster and Correlation parameters (e.g. Tinker et al 2010):

$$b_h(M_{\rm min})$$

$$\bar{x}_{\rm HIIm} = \bar{x}_{\rm HII}^{\gamma}$$

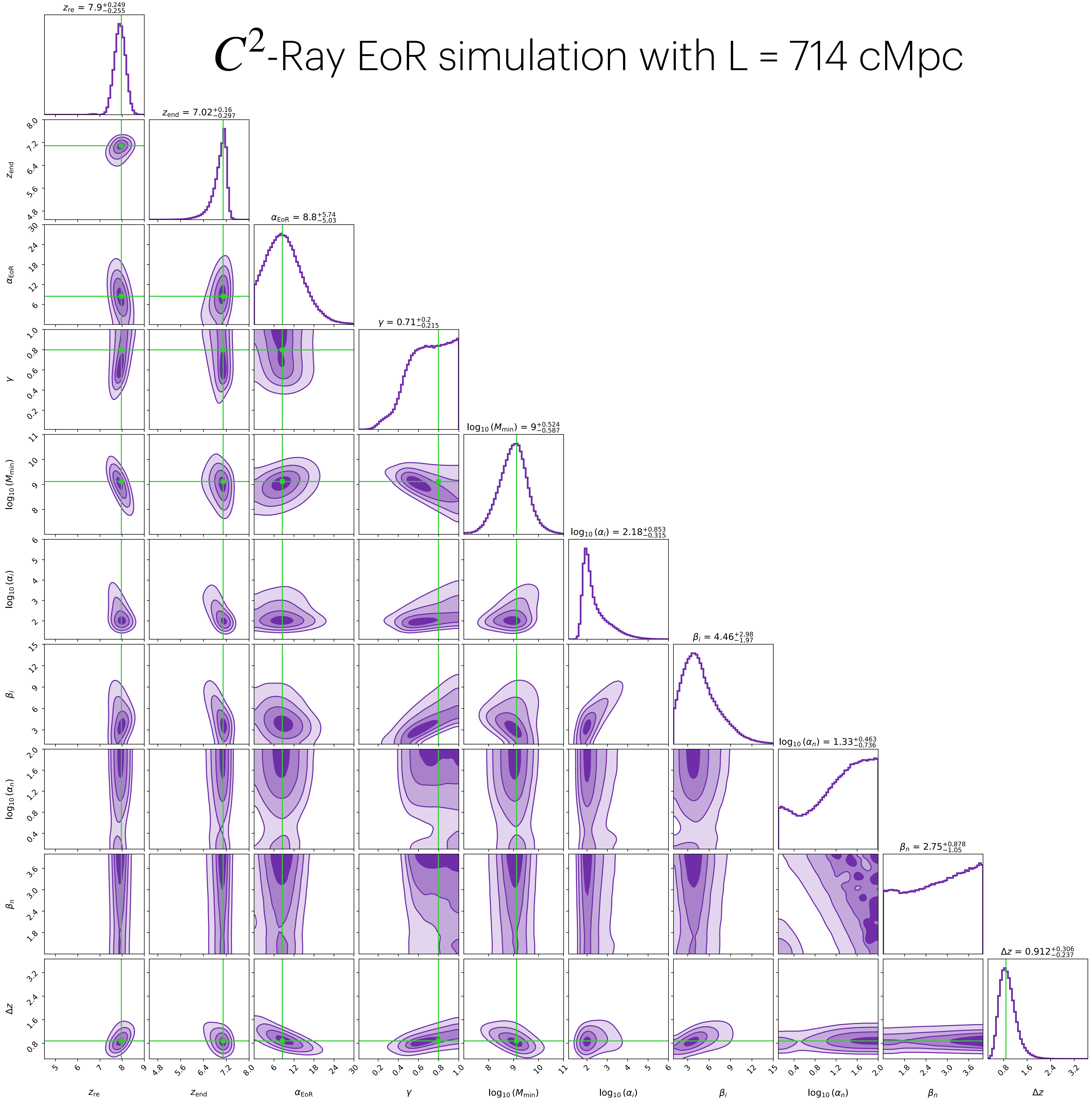
Bubble parameters (pianissimo):

$$R_i = 10^{\alpha_i} \exp\left[-\beta_i \left(\frac{1-\bar{x}_{HII}}{1-x_0} - 1 \right) \right]$$

$$R_n = 10^{\alpha_n} \, \bar{x}_{\rm HI}^{\beta_n}$$

Georgiev et al. in prep

C^2-Ray EoR simulation with L = 714 cMpc



Asymmetric EoR model from Douspis et al. 2015

$$\bar{x}_{\rm HII} = \begin{cases} 0, & z \geq z_{\rm early}, \\ 1, & z \leq z_{\rm re} - dz, \\ \left[\dfrac{|z_{\rm re} - z|}{dz}\right]^{\alpha_{\rm EoR}}, & \text{otherwise}. \end{cases}$$

Cluster and Correlation parameters:

$$b_h(M_{\rm min})$$

$$\bar{x}_{\rm HIIm} = \bar{x}_{\rm HII}^{\gamma}$$

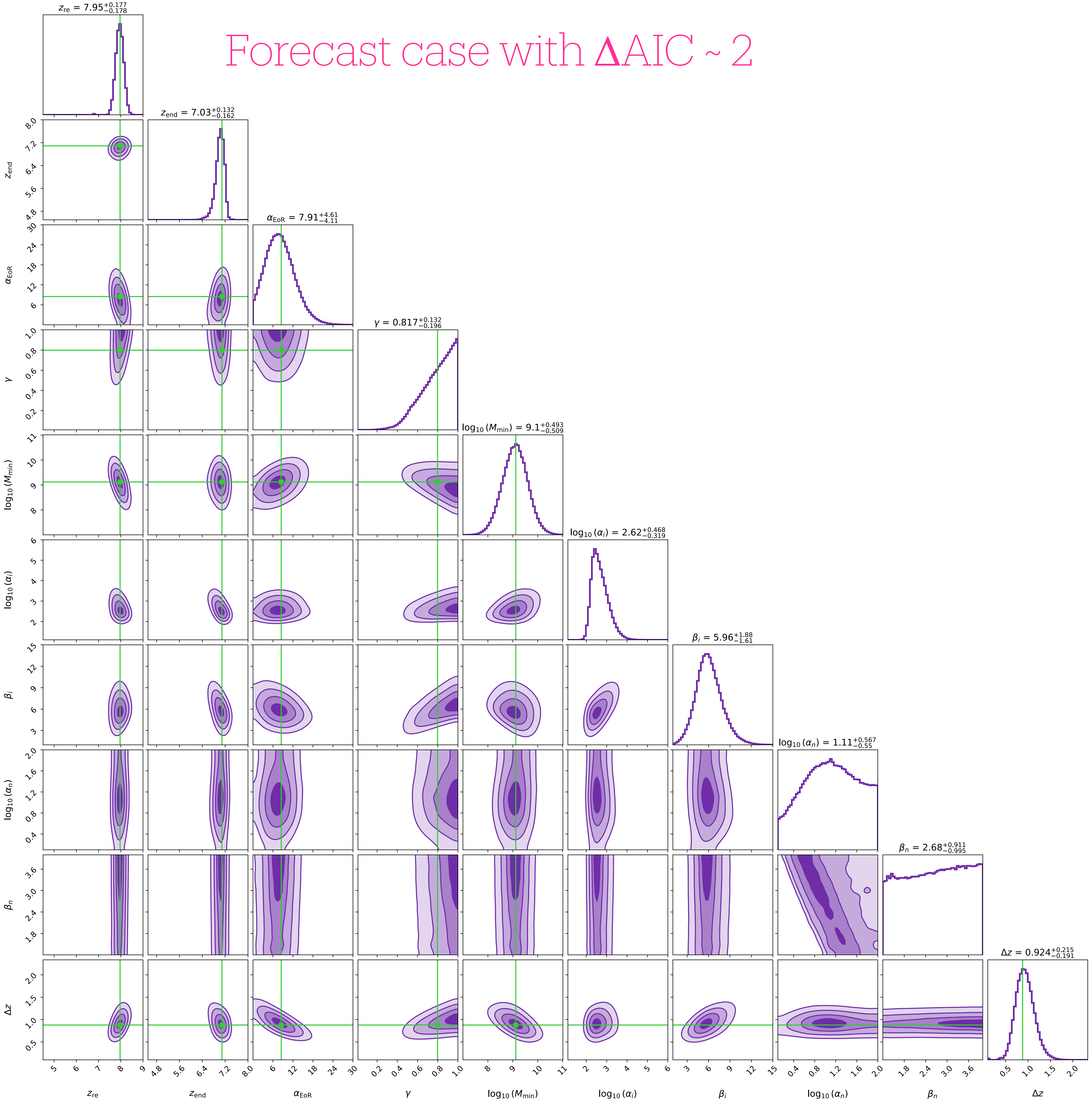
Bubble parameters
(tuned to late EoR observables):

$$R_i = 10^{\alpha_i} \exp\left[-\beta_i\left(\frac{1-\bar{x}_{HII}}{1-x_0} - 1\right)\right]$$

$$R_n = 10^{\alpha_n}(1-\bar{x}_{\rm HII})^{\beta_n}$$

Georgiev et al. in prep

Forecast case with ΔAIC ~ 2



Asymmetric EoR model from Douspis et al. 2015

$$\bar{x}_{\rm HII} = \begin{cases} 0, & z \geq z_{\rm early}, \\ 1, & z \leq z_{\rm re} - dz, \\ \left[\dfrac{|z_{\rm re} - z|}{dz}\right]^{\alpha_{\rm EoR}}, & \text{otherwise}. \end{cases}$$

Cluster and Correlation parameters:

$$b_h(M_{\rm min})$$

$$\bar{x}_{\rm HIIm} = \bar{x}_{\rm HII}^{\gamma}$$

Bubble parameters
(tuned to late EoR observables):

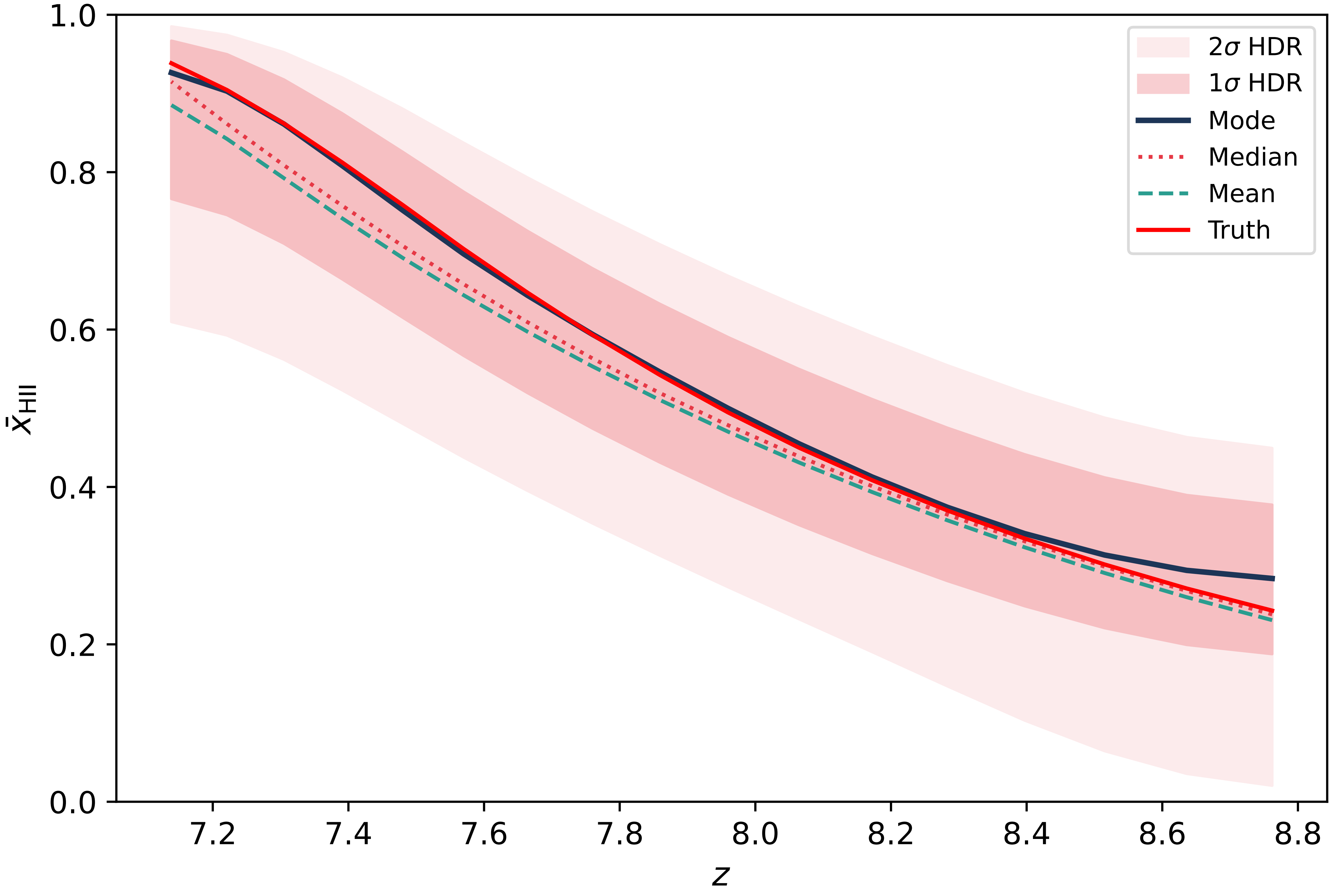
$$R_i = 10^{\alpha_i} \exp\left[-\beta_i\left(\frac{1-\bar{x}_{HII}}{1-x_0} - 1\right)\right]$$

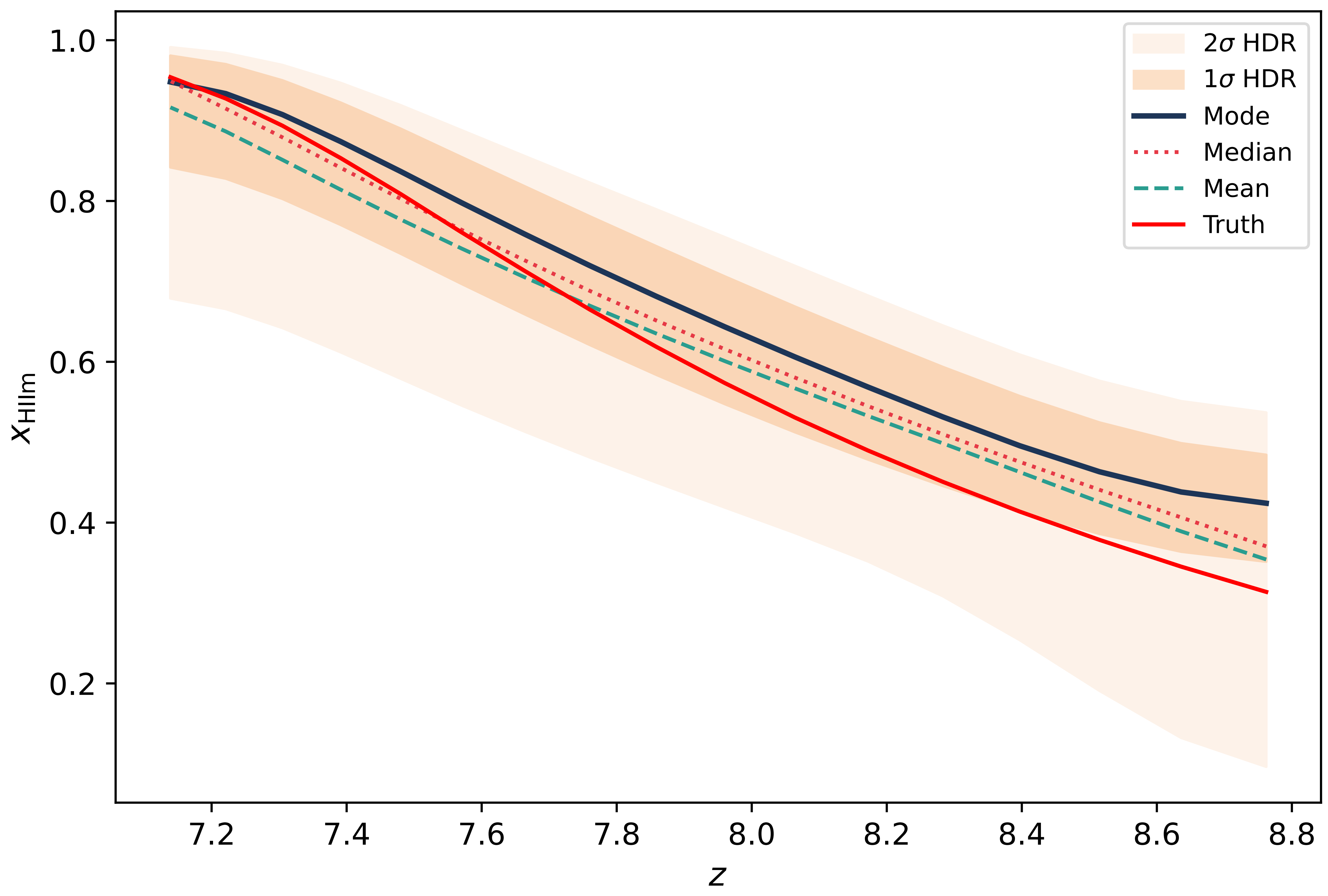
$$R_n = 10^{\alpha_n}(1-\bar{x}_{\rm HII})^{\beta_n}$$

Georgiev et al. in prep

Modelling the EoR history

$$P_{21cm} = T_0^2 \bar{x}_{\rm HI}^2 \left(\frac{(1 + b_i(f+1))^2}{\sqrt{1+(kR_i)^2}} + \frac{1}{1+(kR_n)^4} \right) P_{\delta,\delta}$$



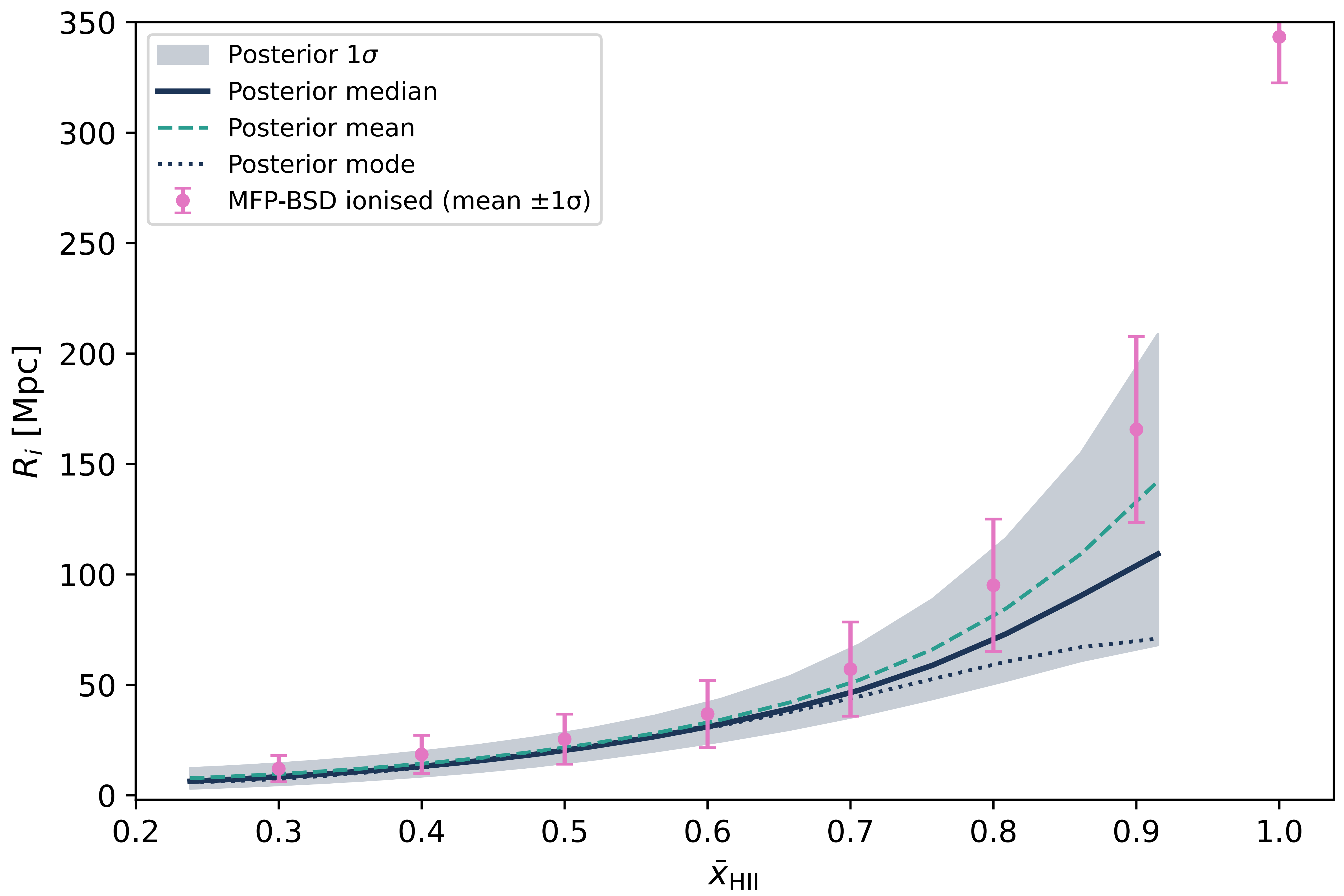


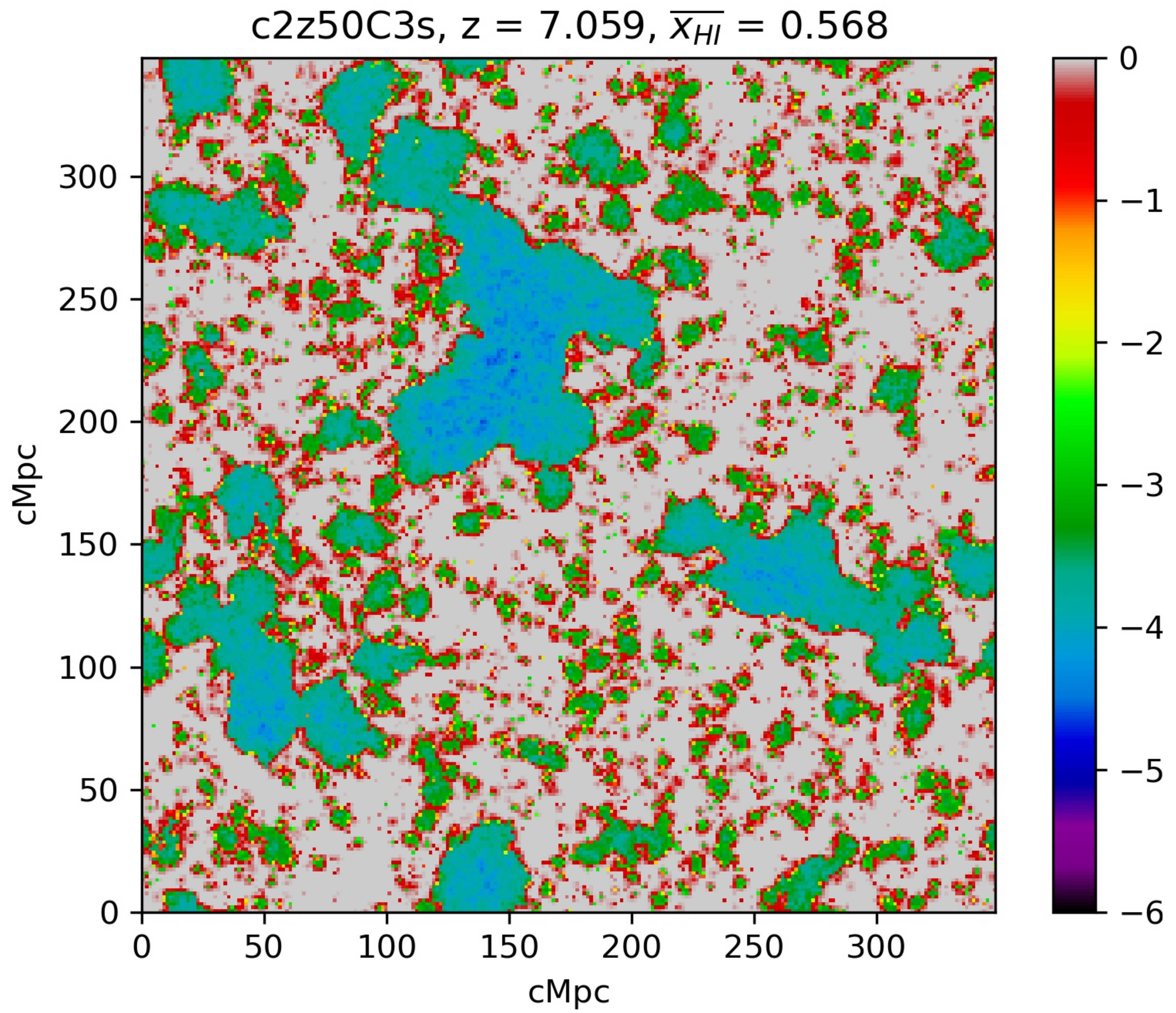
Model behaves well but slightly overestimate at $\bar{x}_{\rm HII}$> 80%. In this regime the EoR history is guided by the mean free path of small-scale absorbers (e.g. Georgiev et al 2025).

Georgiev et al. in prep

Modelling the EoR Topology

$$P_{21cm} = T_0^2 \bar{x}_{\rm HI}^2 \left(\frac{(1+b_i(f+1))^2}{\sqrt{1+(kR_i)^2}} + \frac{1}{1+(kR_n)^4} \right) P_{\delta,\delta}$$



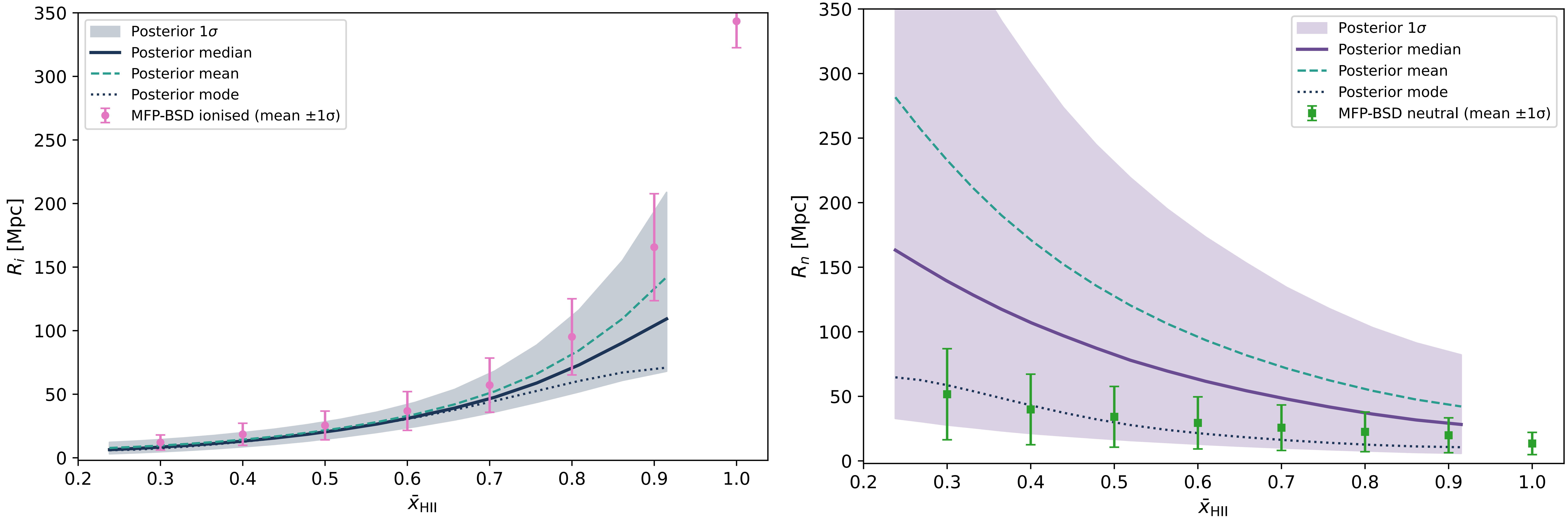


Growth of ionised/neutral regions consistent with methods such as the Bubble Size Mean Free Path Distribution like method from Messenger et al. 2007.

Georgiev et al. in prep

Modelling the EoR Topology

$$P_{21cm} = T_0^2 \bar{x}_{\mathrm{HI}}^2 \left(\frac{(1 + b_i(f+1))^2}{\sqrt{1 + (kR_i)^2}} + \frac{1}{1 + (kR_n)^4} \right) P_{\delta,\delta}$$

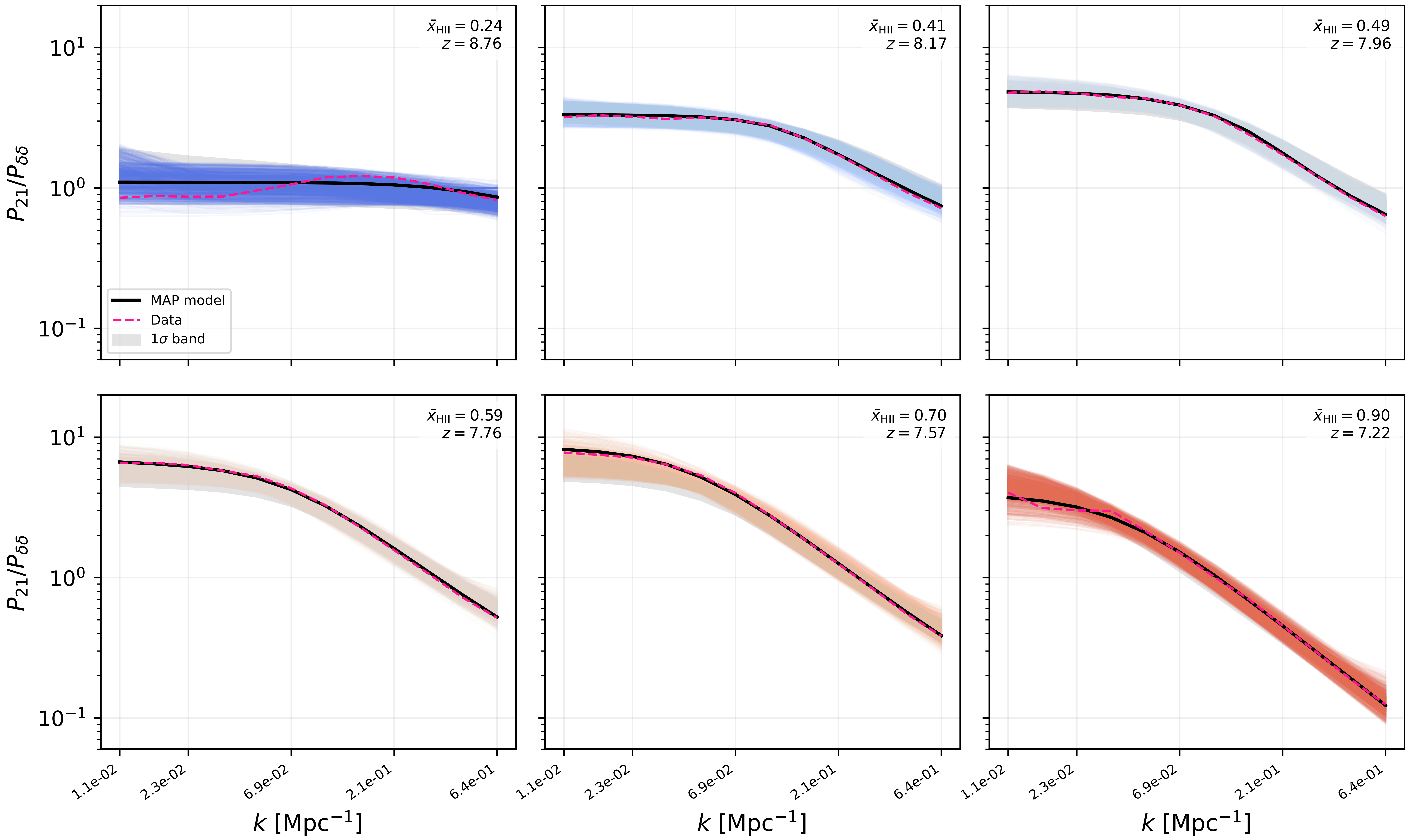


Growth of ionised/neutral regions consistent with methods such as the Bubble Size Mean Free Path Distribution like method from Messenger et al. 2007.

Georgiev et al. in prep

Modelling the EoR Power Spectrum

$$\frac{P_{21cm}}{P_{\delta,\delta}} = T_0^2 \bar{x}_{\rm HI}^2 \left(\frac{(1 + b_i(f+1))^2}{\sqrt{1 + (kR_i)^2}} + \frac{1}{1 + (kR_n)^4} \right)$$



Georgiev et al. in prep

Thank you for your attention!