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

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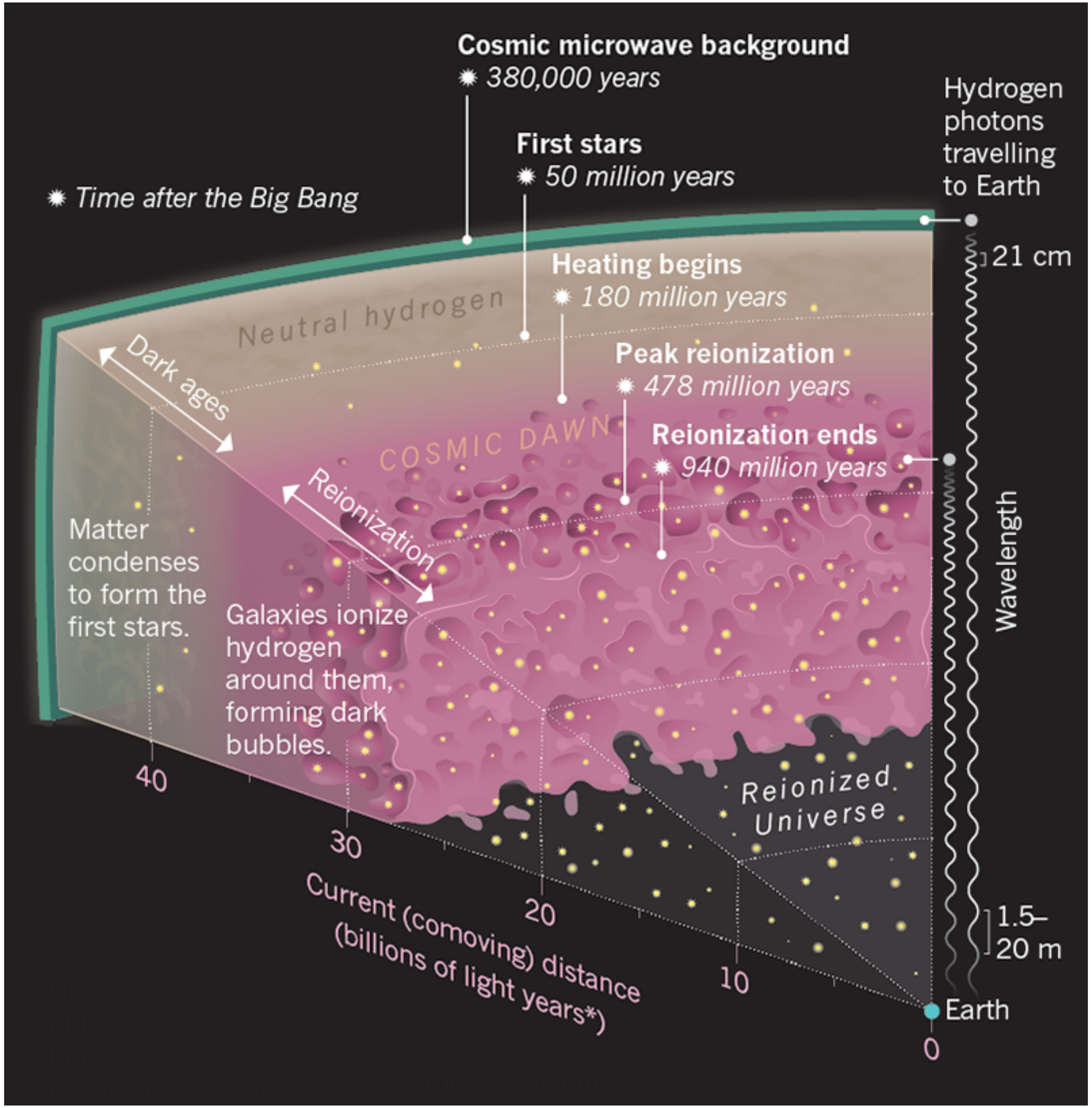

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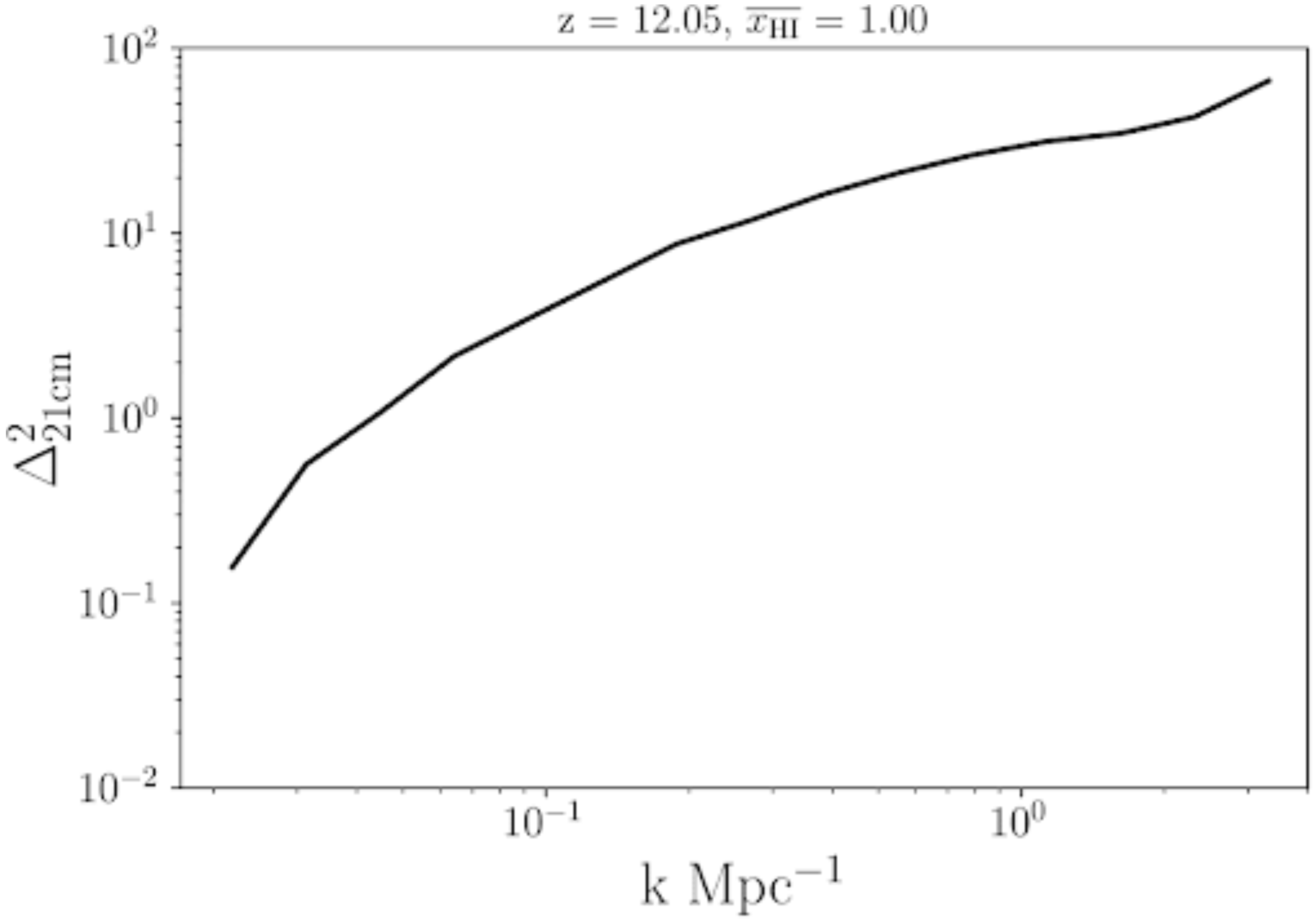
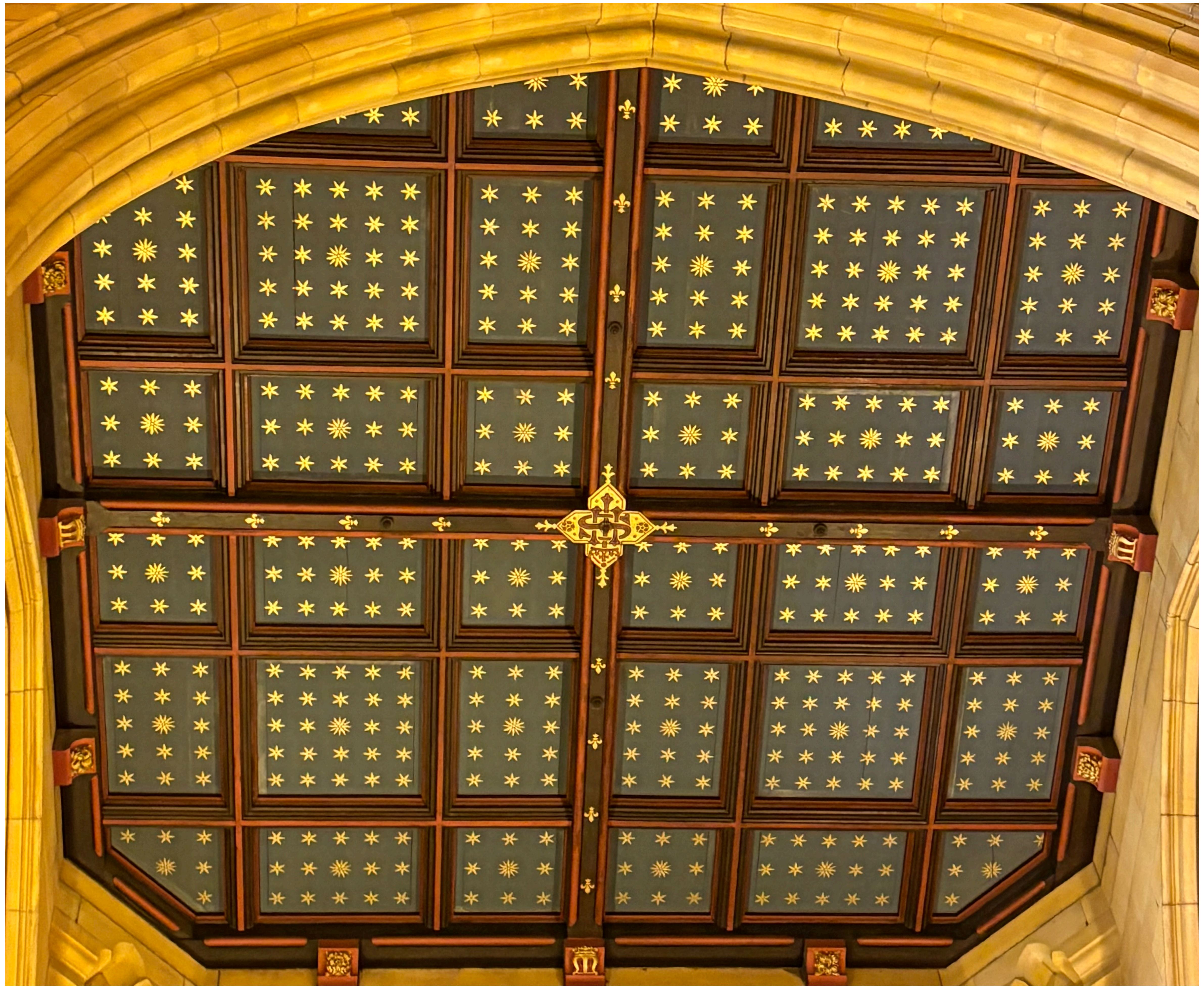
During the cosmic dark ages, the Universe primarily consists of **neutral hydrogen**, which emits radiation via the **21-cm** line (Field et al. 1959).



How do we interpret the 21-cm power spectrum?

Source interpretation

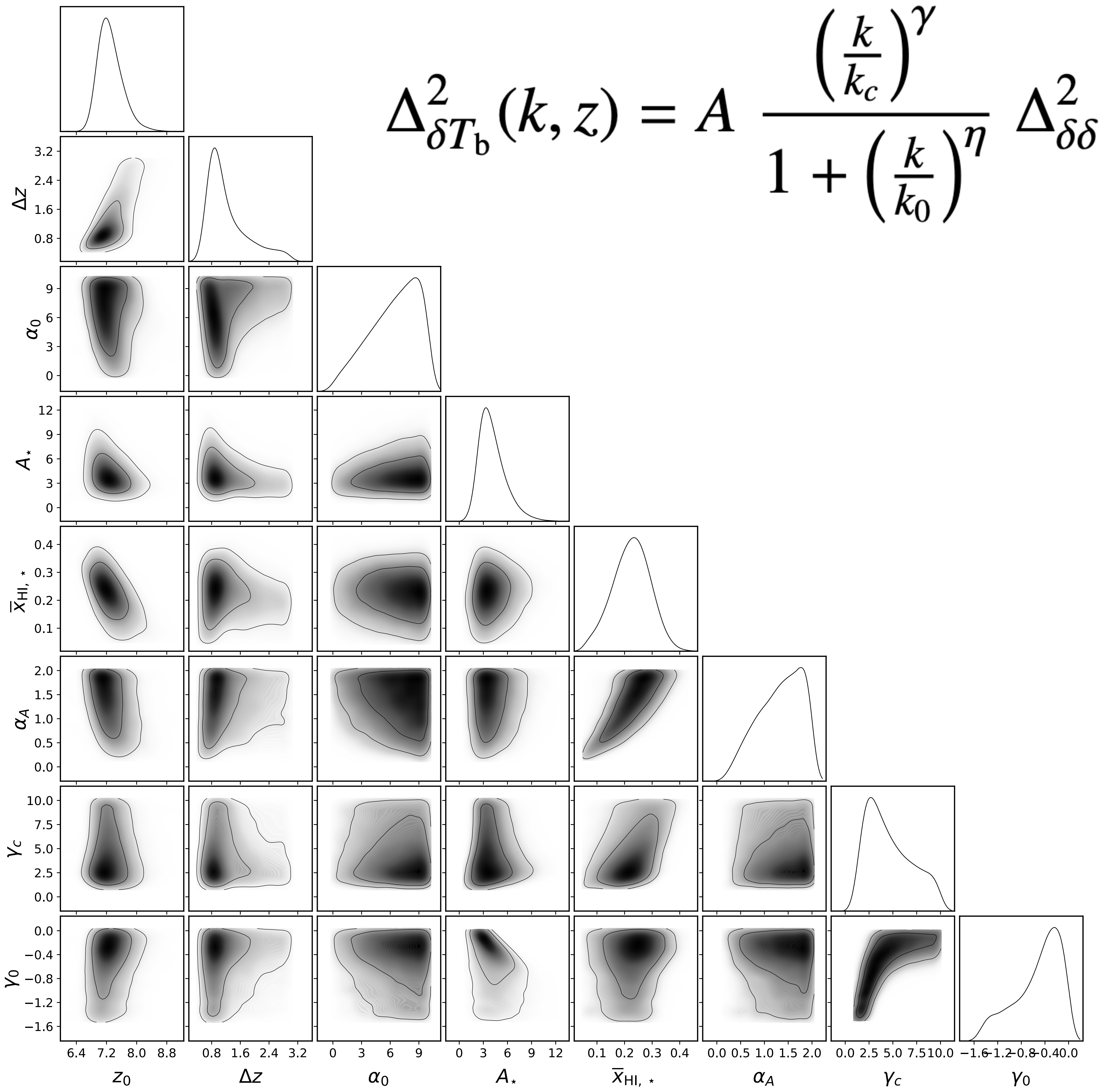
- The sources define the shape and evolution of the 21-cm signal.
- Examples in all interpretation papers (The Hera Collaboration et al. 2022, Mertens et al. 2025, Trott et al. 2025)
- Challenges:
  - Source parametrisation
  - Simulation based



EoR simulation spotted in a cathedral in Sydney?

How do we interpret the 21-cm power spectrum?

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



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?

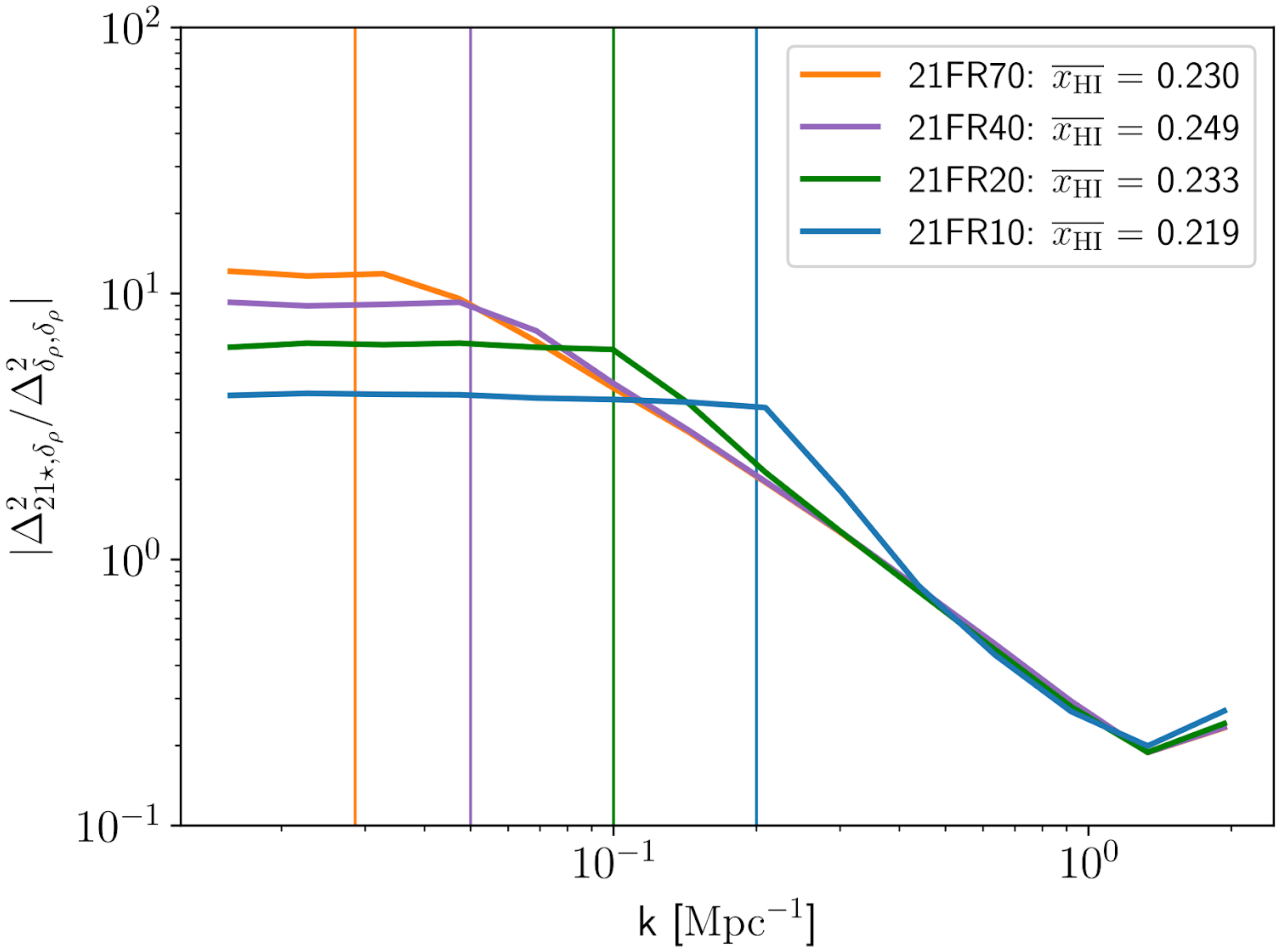
IGM -driven interpretation

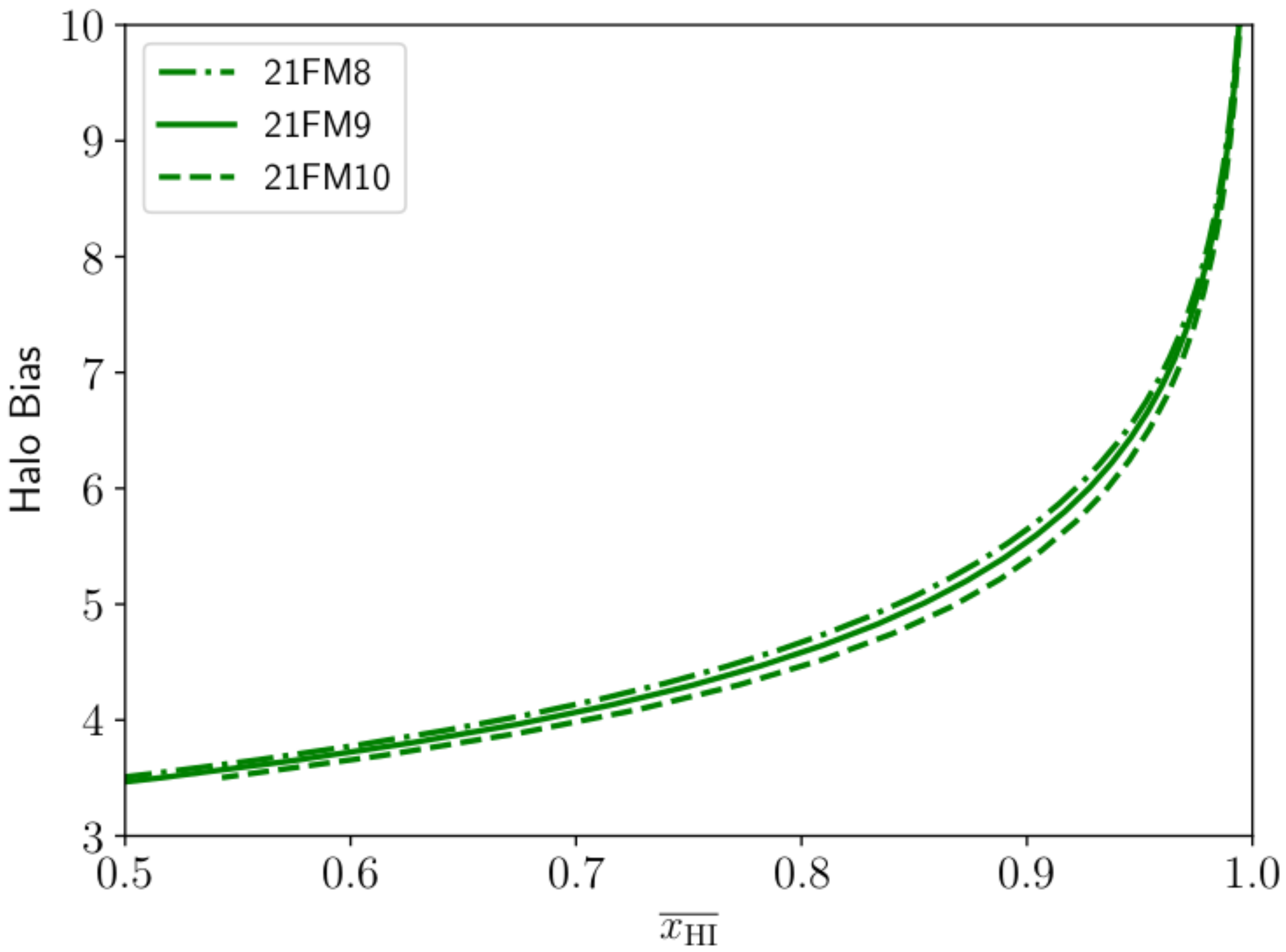
- 21-cm signal is a probe of the state of the IGM.
- Interpret the power spectrum through the properties of the intergalactic medium
- Arrive at a physical driven form which is physically informed and redshift dependent?

Hints of meaning behind the parameters

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

Connection between the shape of the power spectrum and the mean free path of ionising photons as well as the closeting of ionising sources (see also McQuinn et al 2018)





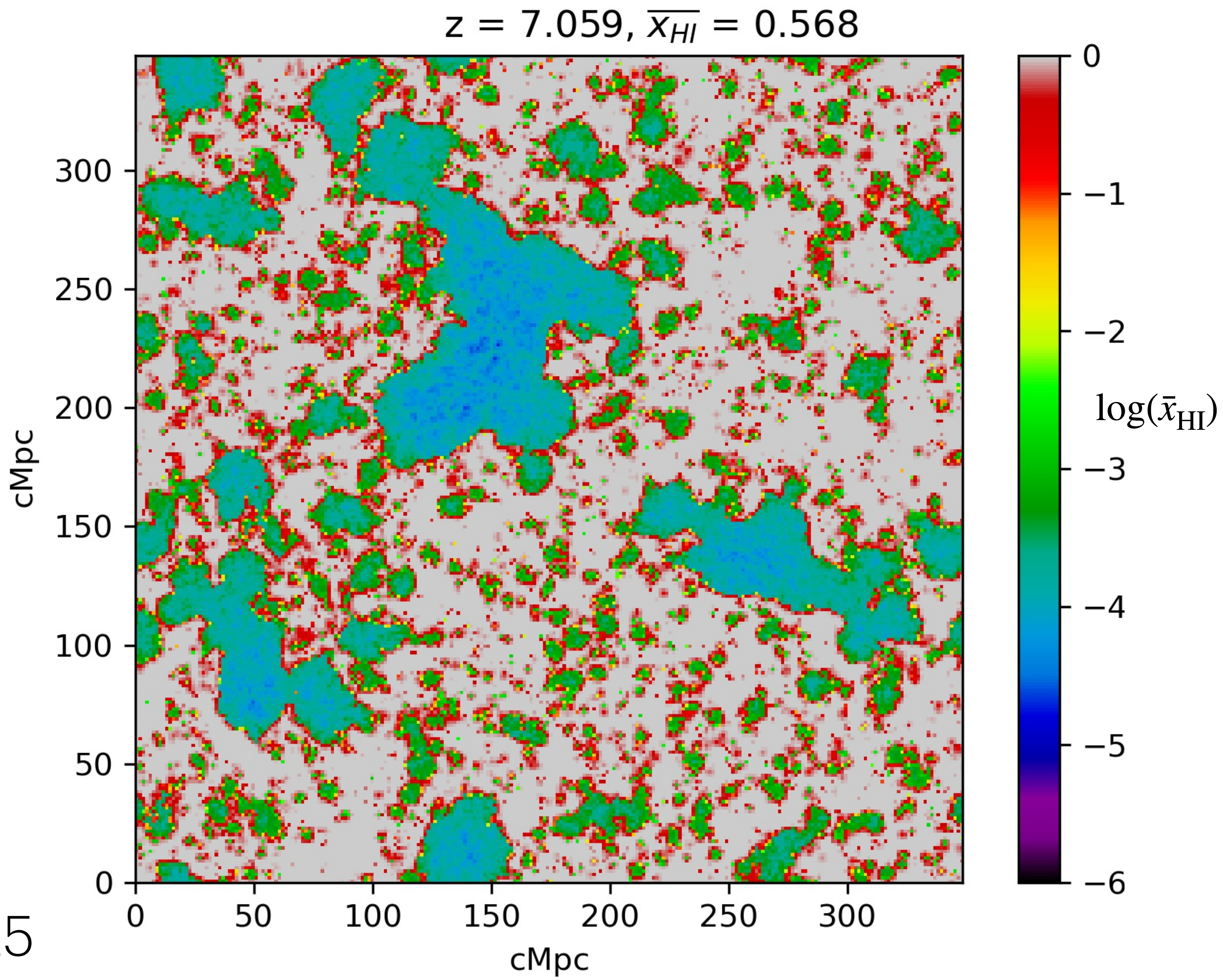
Georgiev et al. 2021

IGM driven parametrisation (Georgiev in prep.)

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

- $\bar{x}_{\rm HI}$: 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.

$$P_{21} = T_0^2 \bar{x}_{\rm HI}^2 \Big(P_{\delta_\rho,\delta_\rho} + P_{\delta_{xHI},\delta_{xHI}} + 2P_{\delta_\rho,\delta_{xHI}} + 2P_{\delta_\rho\delta_{xHI},\delta_{xHI}} + 2P_{\delta_\rho\delta_{xHI},\delta_\rho} + P^2_{\delta_\rho\delta_{xHI},\delta_\rho\delta_{xHI}} \Big)$$



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

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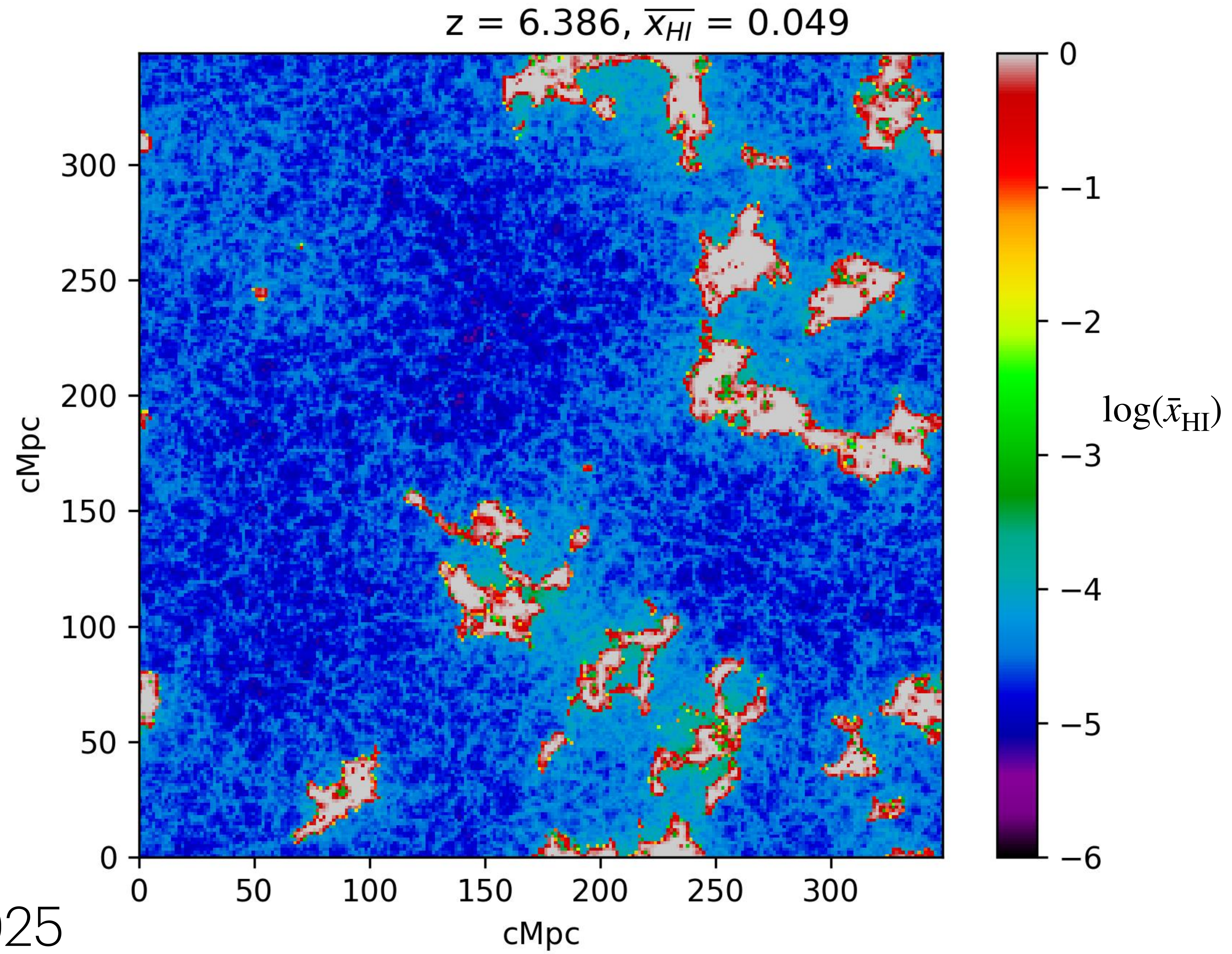

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Asymmetric EoR model from Douspis et al. 2015

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

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

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

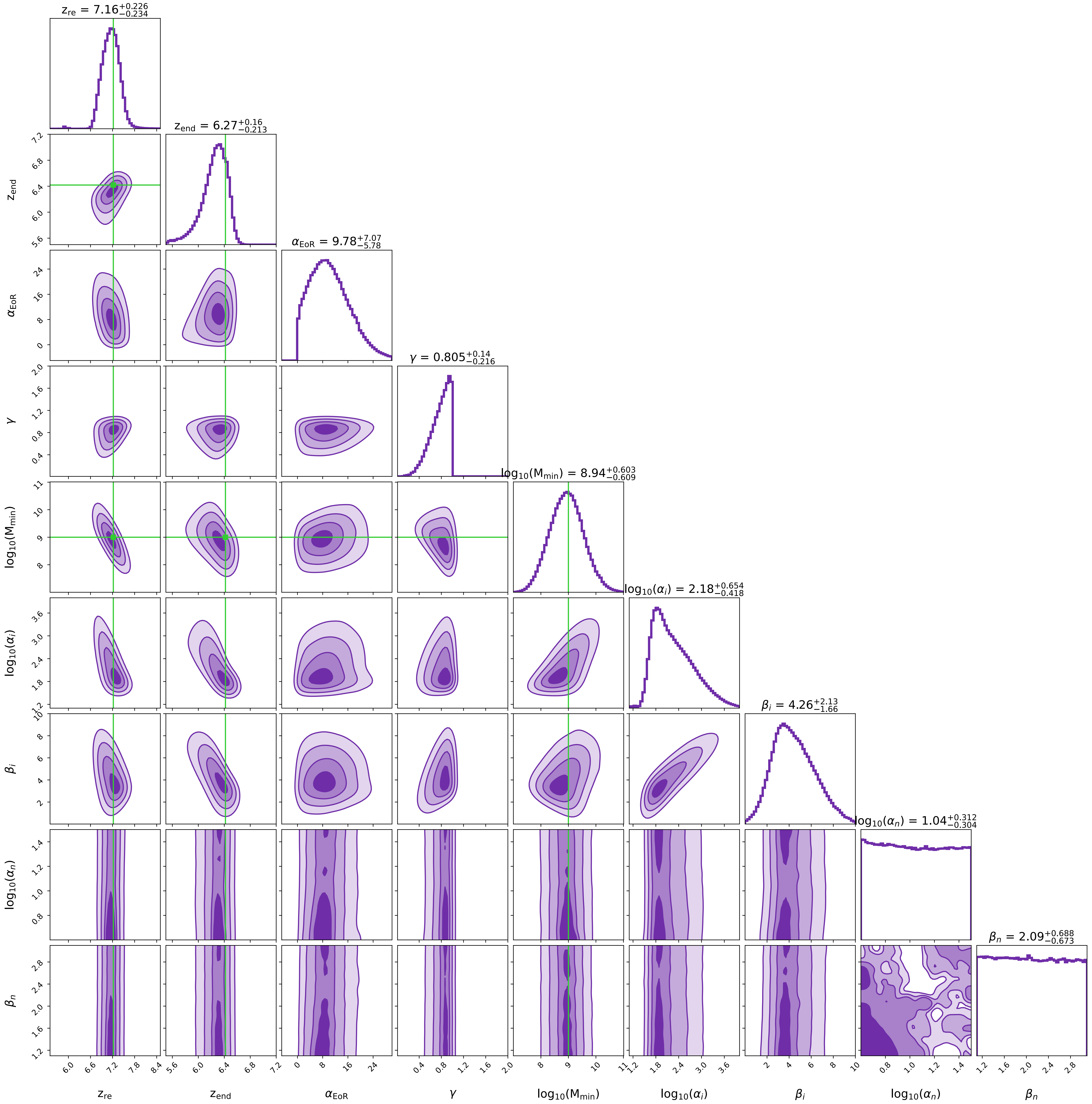
$$\bar{x}_{\rm HIIm} = \bar{x}_{\rm HII}^{\gamma}$$

Bubble parameters (pianissimo):

$$R_i = 10^{\alpha_i} e^{-\beta_i(1-\bar{x}_{\rm HII})}$$

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

Georgiev et al. in prep



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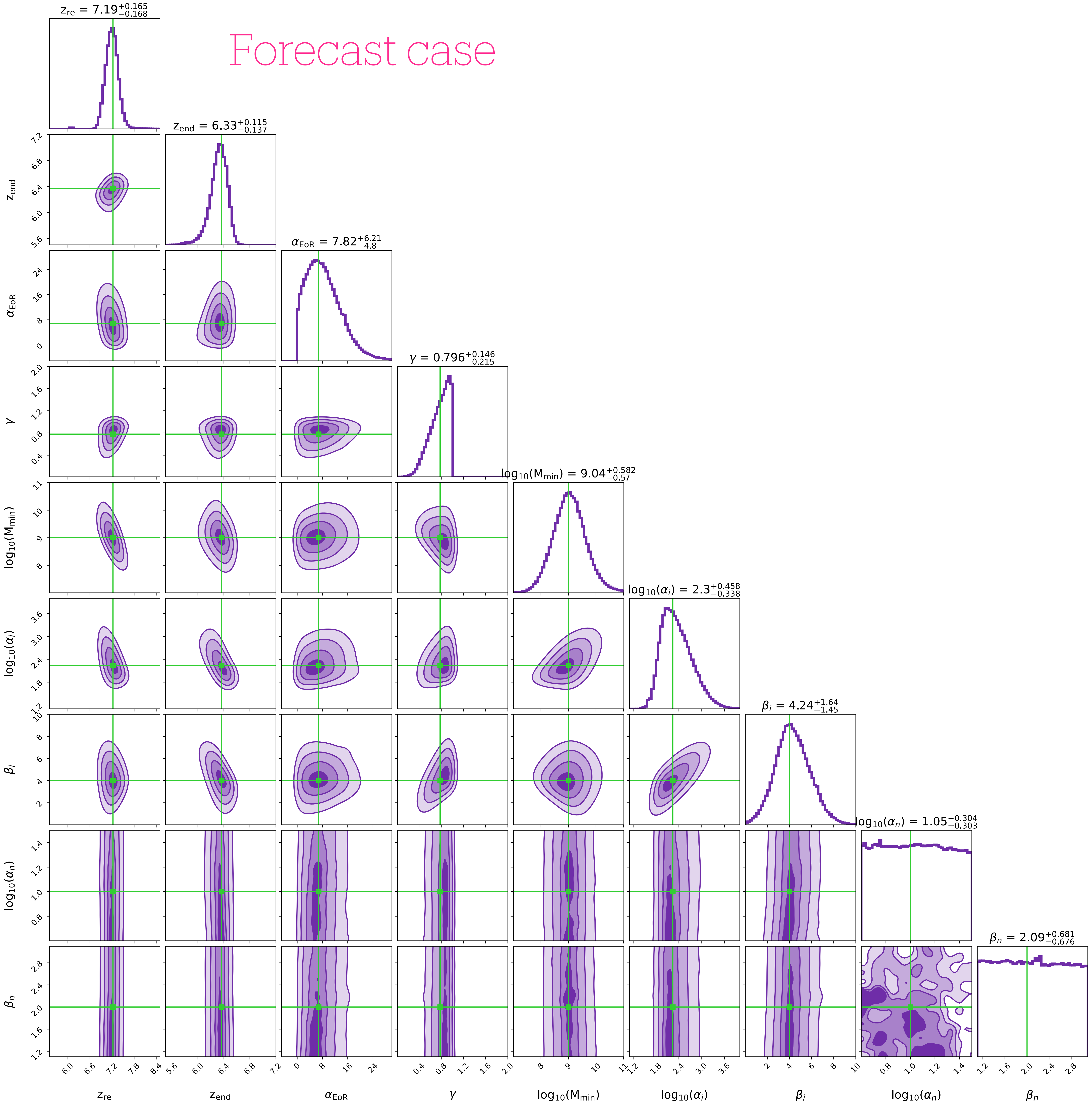
Georgiev et al. in prep

Forecast case



Asymmetric EoR model from Douspis et al. 2015

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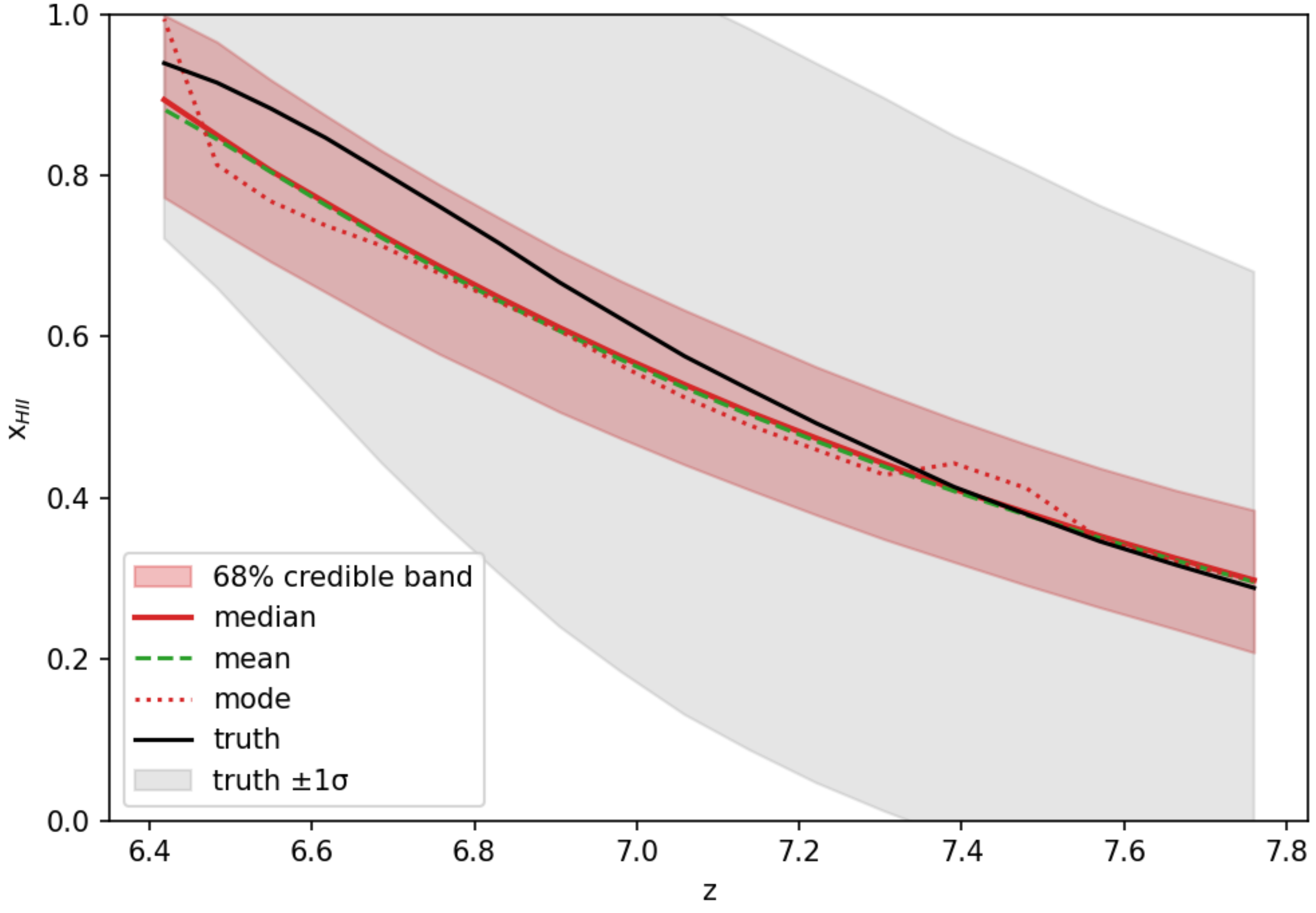
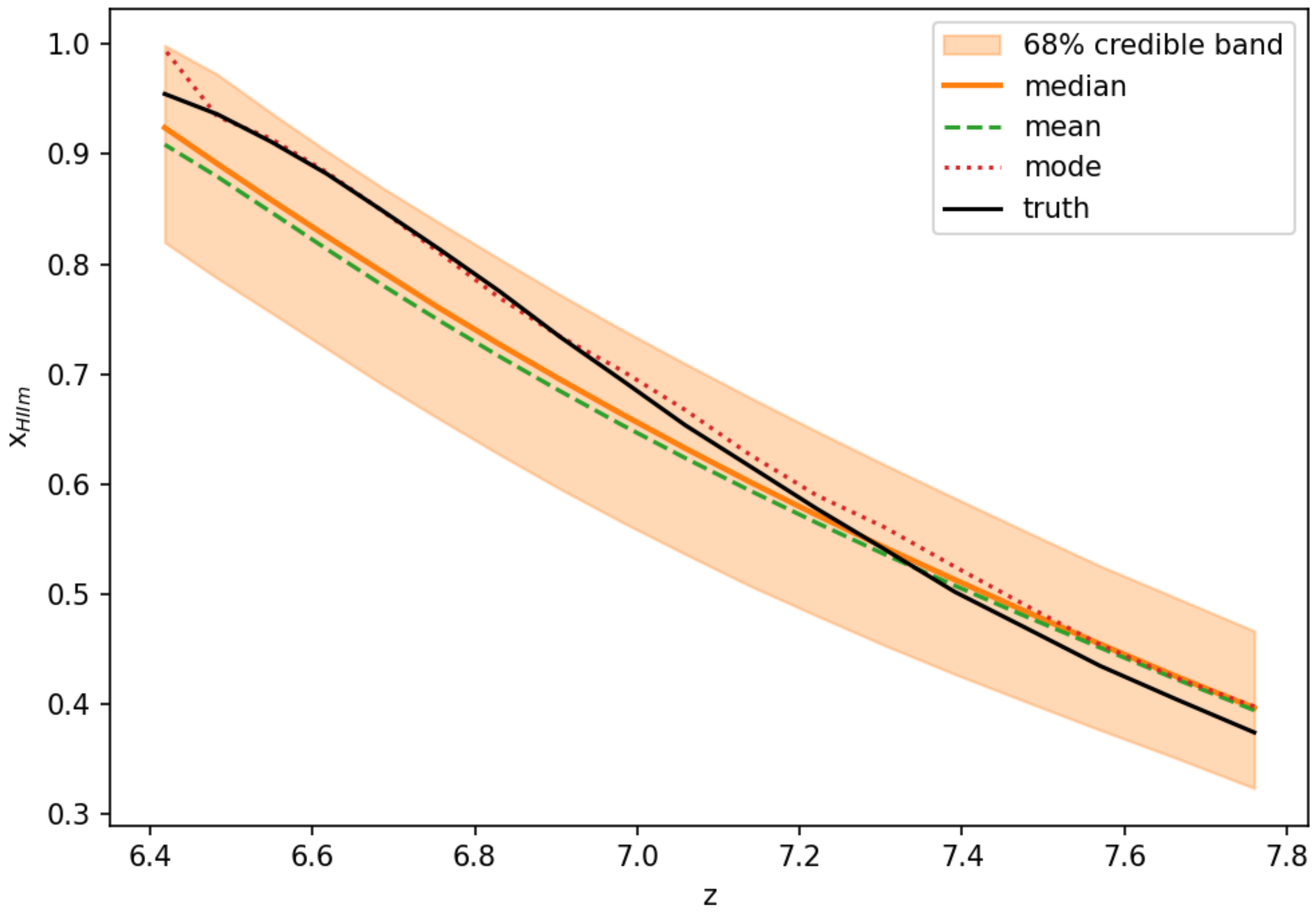
Modelling the EoR history

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



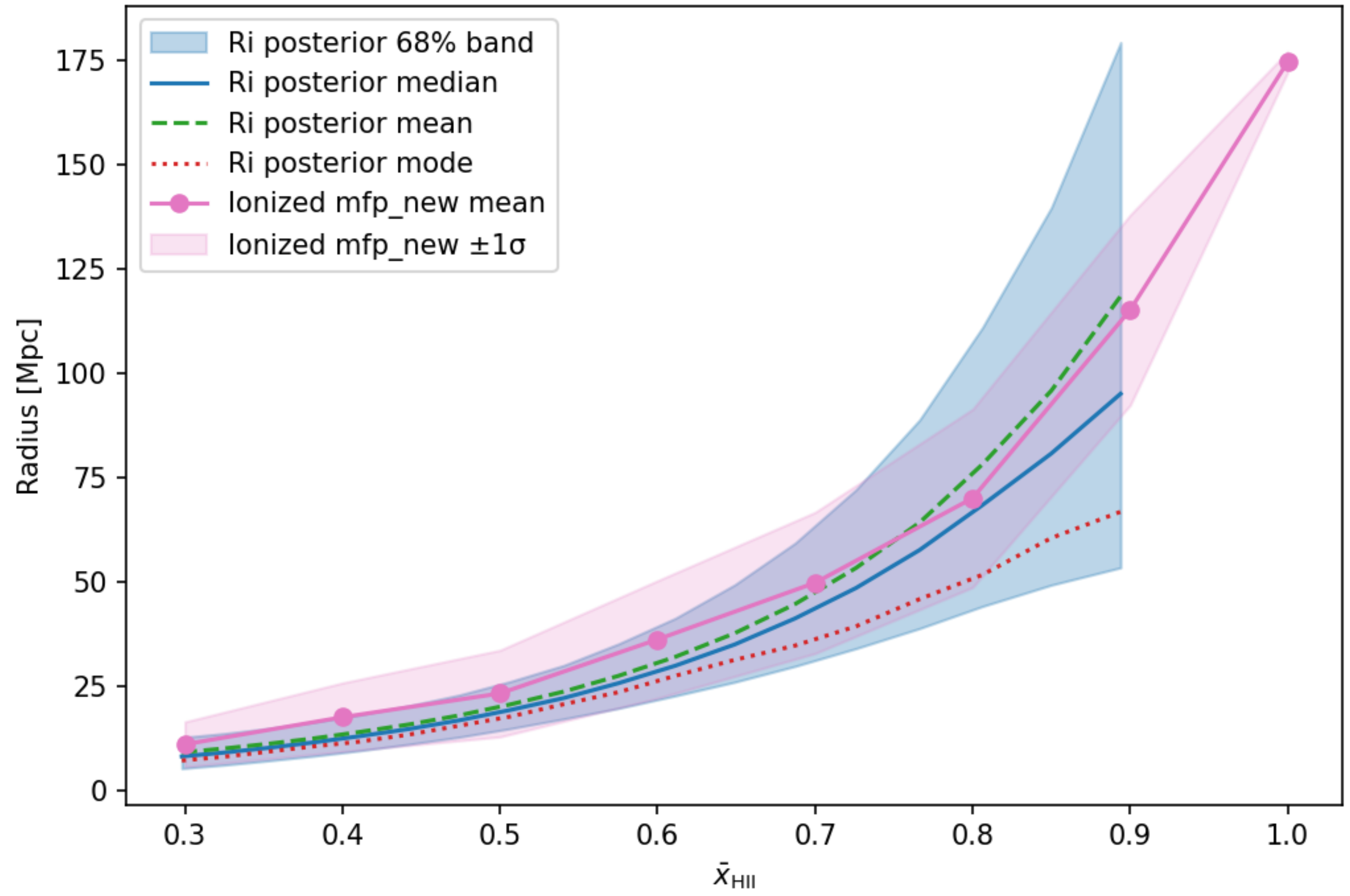


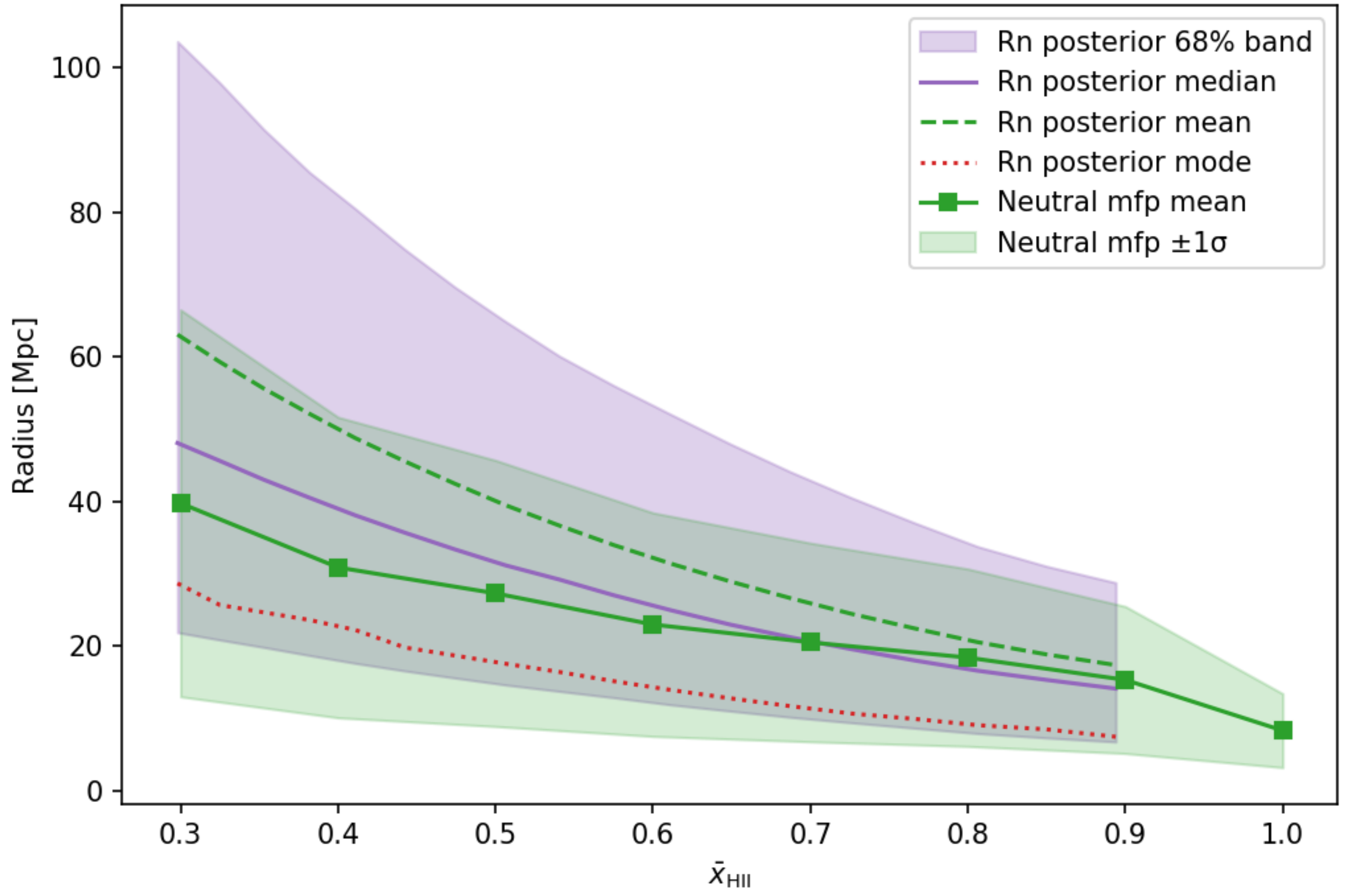
Model behaves well but slightly overestimate at $\bar{x}_{\rm HII}$> 80%. In this regime the EoR history is guided by the mean free path of small-scale absorbers (e.g. Georgiev et al 2025).

Georgiev et al. in prep

Modelling the EoR Topology

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





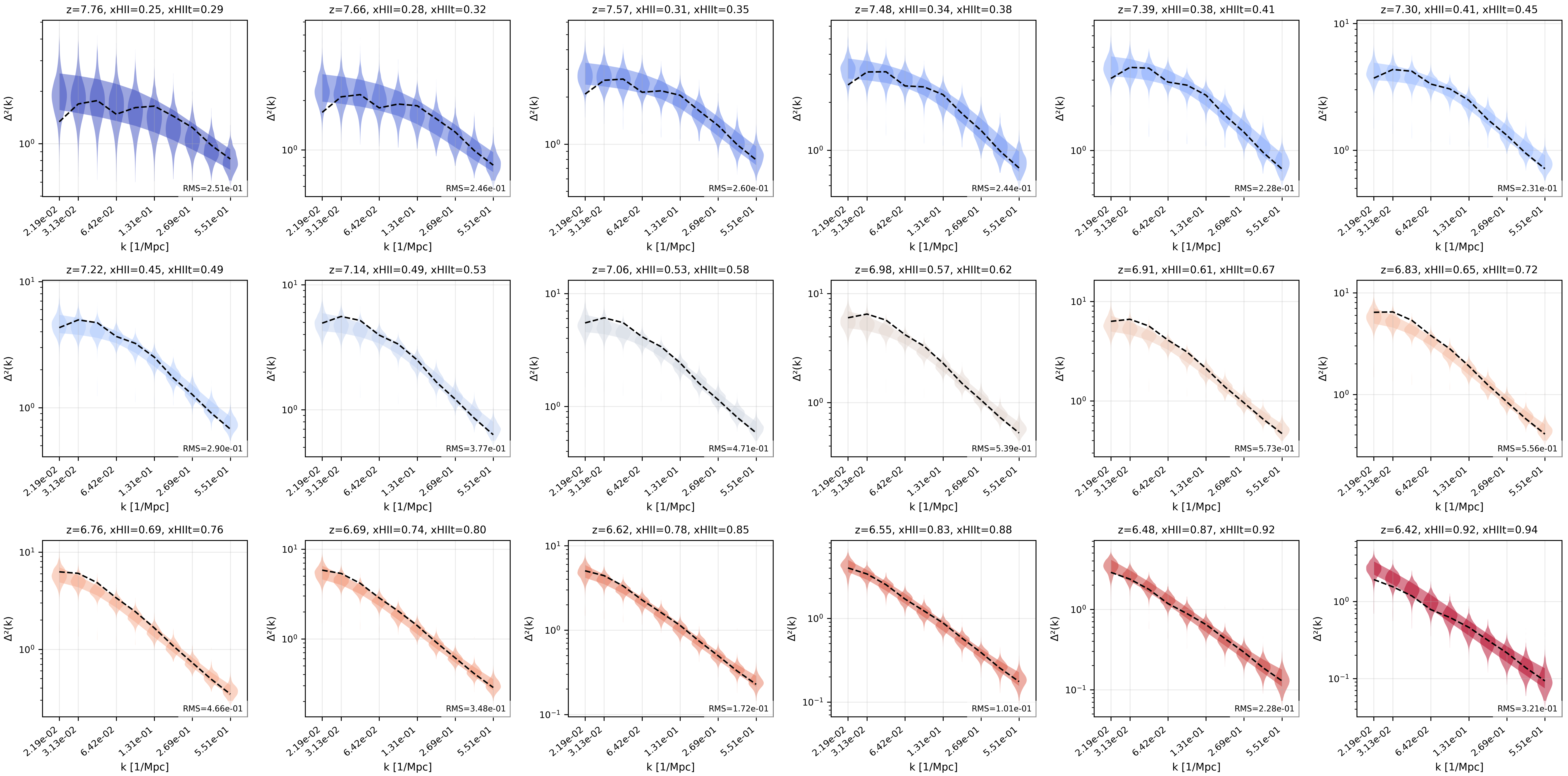
Growth of ionised/neutral regions consistent with methods such as the Bubble Size Mean Free Path Distribution like method from Messenger et al. 2007.

Georgiev et al. in prep

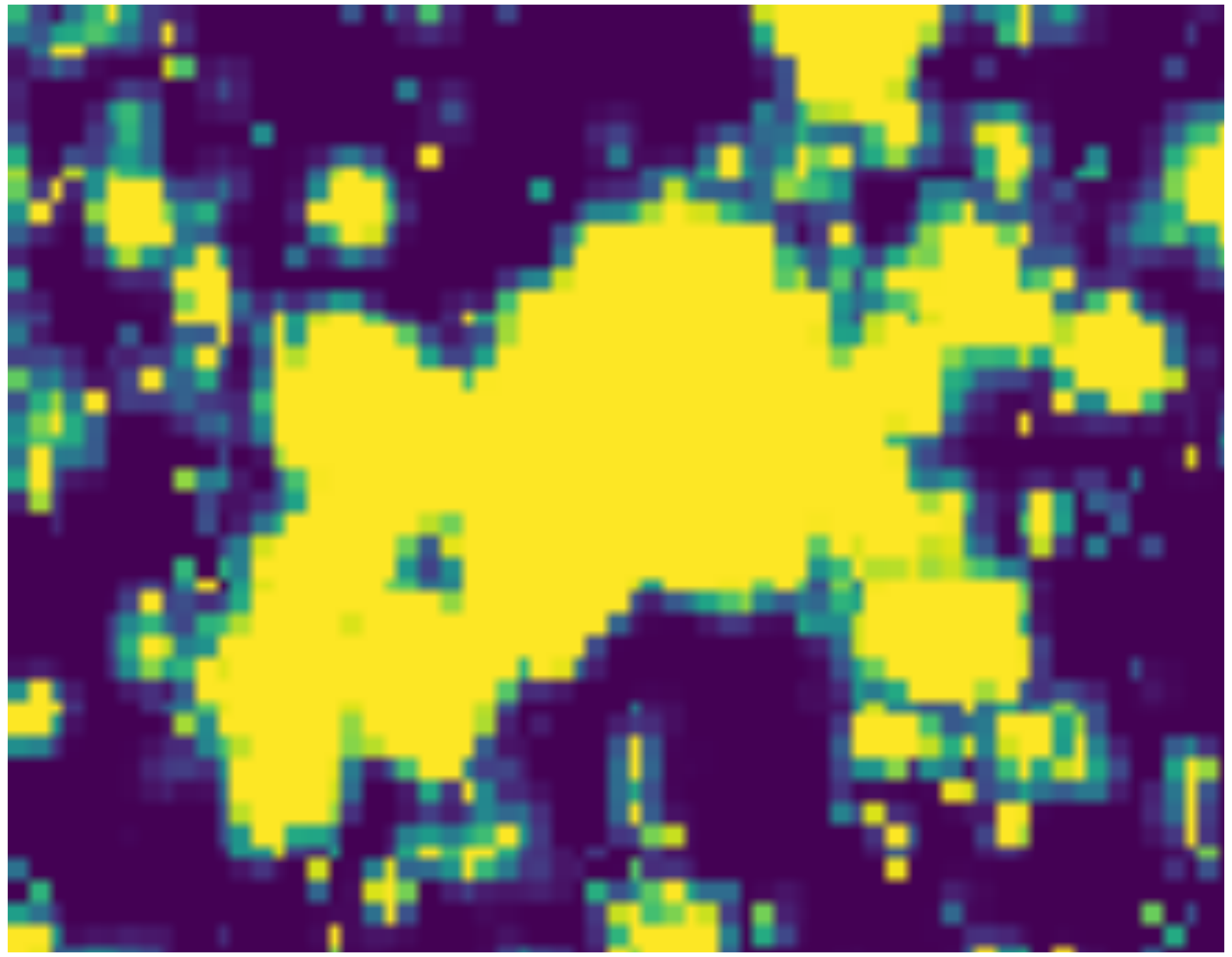
Modelling the EoR Power Spectrum

Georgiev et al. in prep

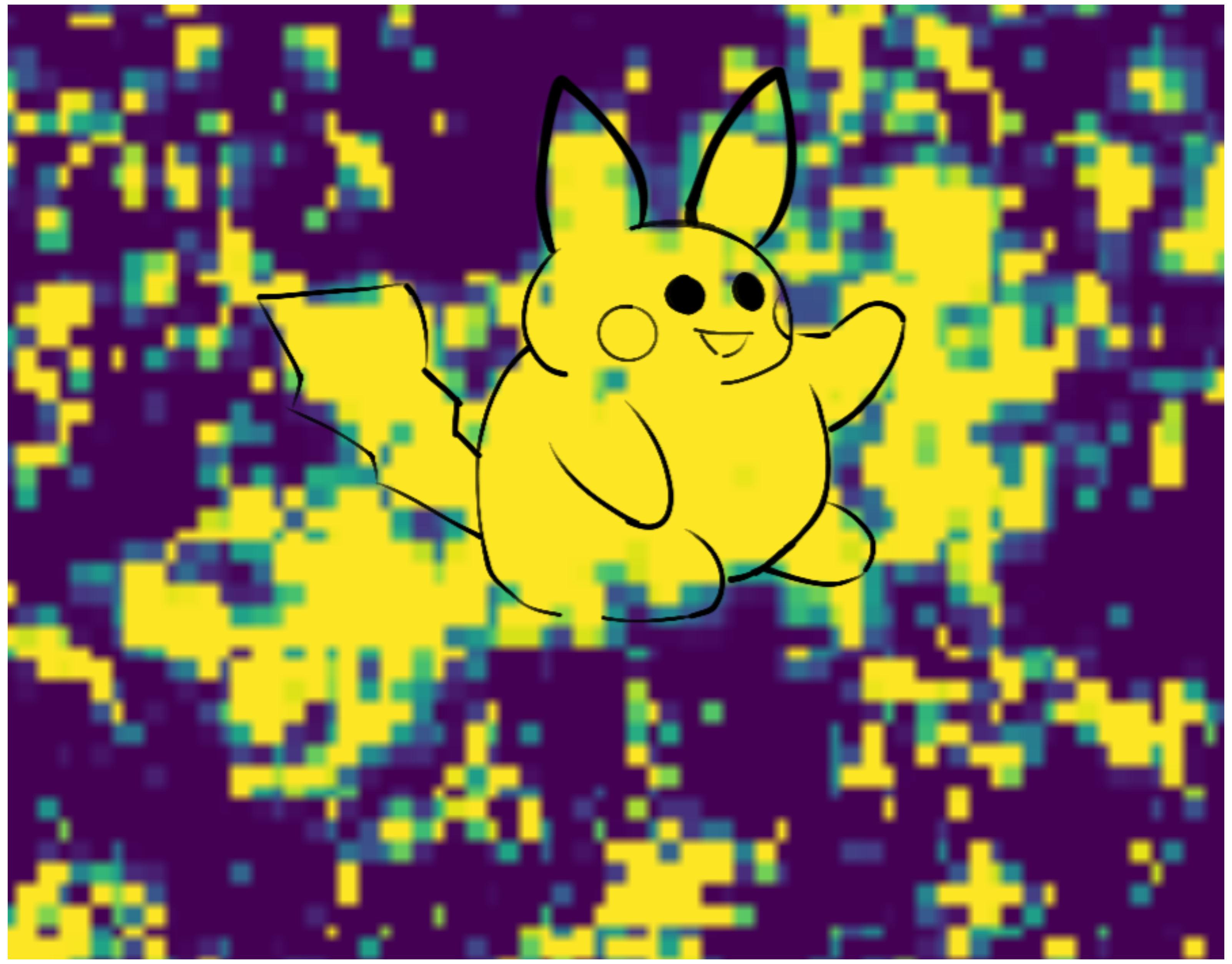
$$P_{21cm}/P_{\delta,\delta}$$



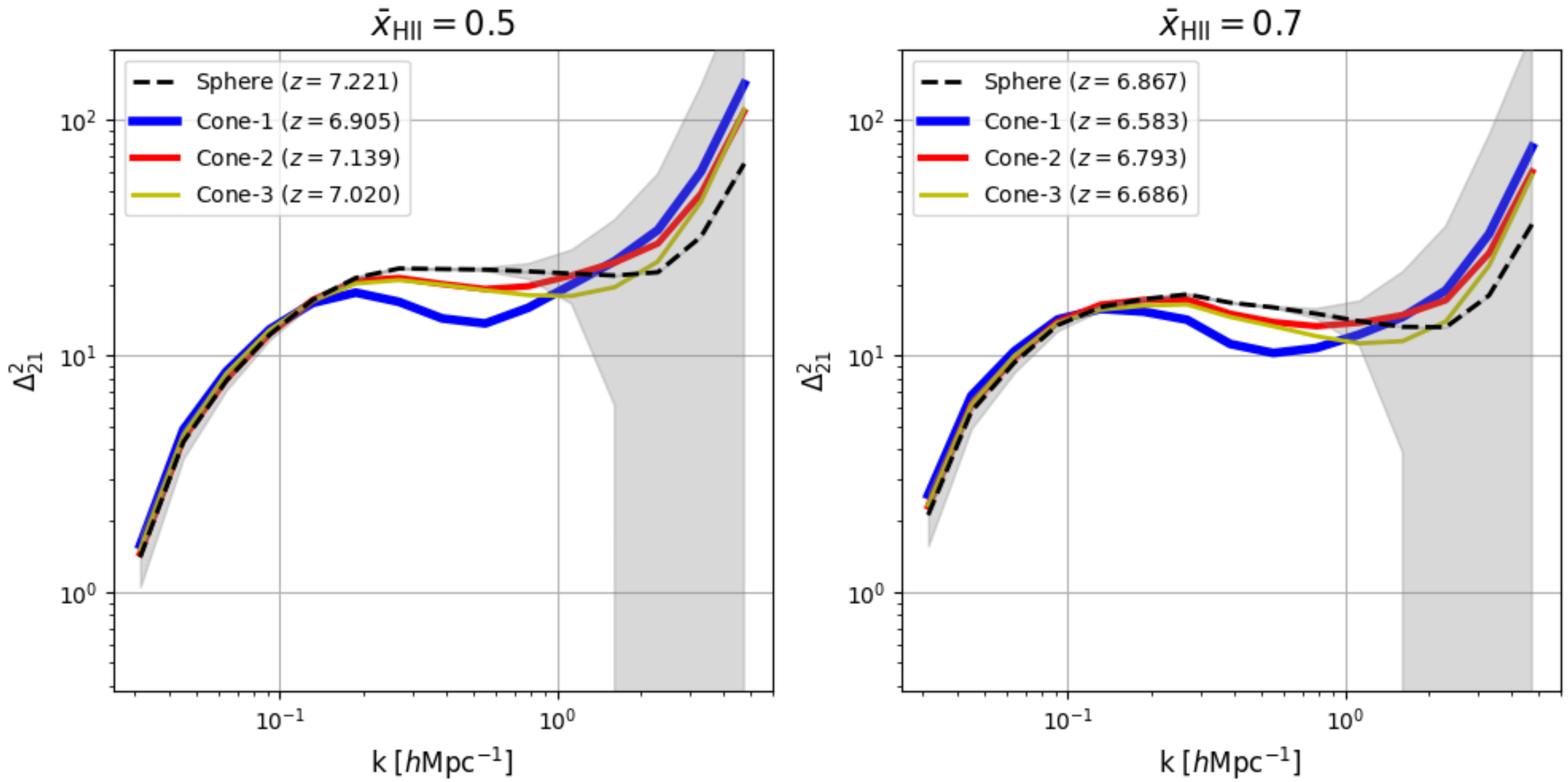
Impact of anisotropic photon emission from sources during the epoch of Reionisation



Sphere case



Cone-1 case



Anisotropic emission from sources suppresses the 21-cm power spectrum by 10 - 40% for k~ (0.1 - 1) hMpc^{-1}

Schwandt, Georgiev et al. 2025

Thank you for your attention!

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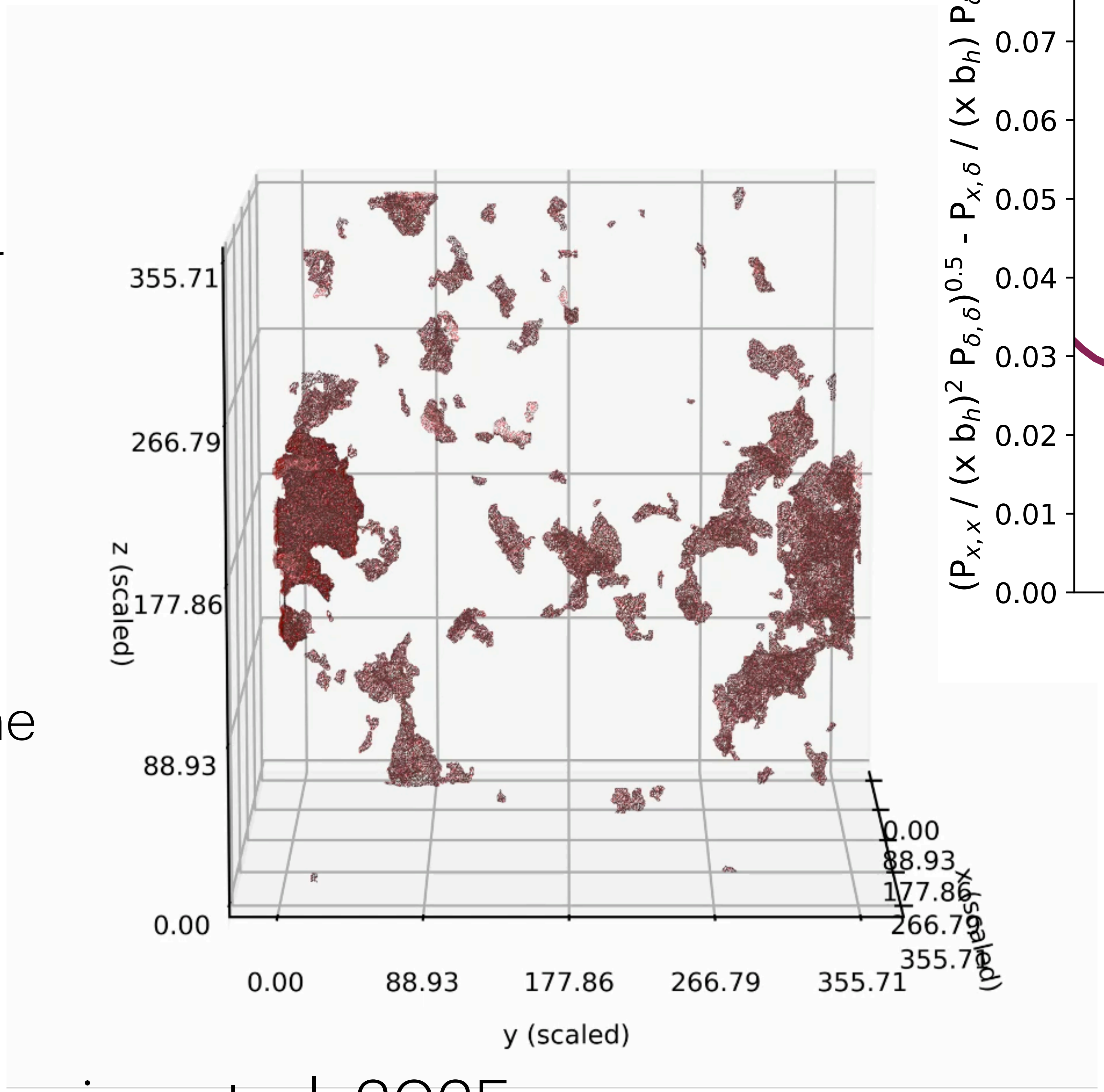

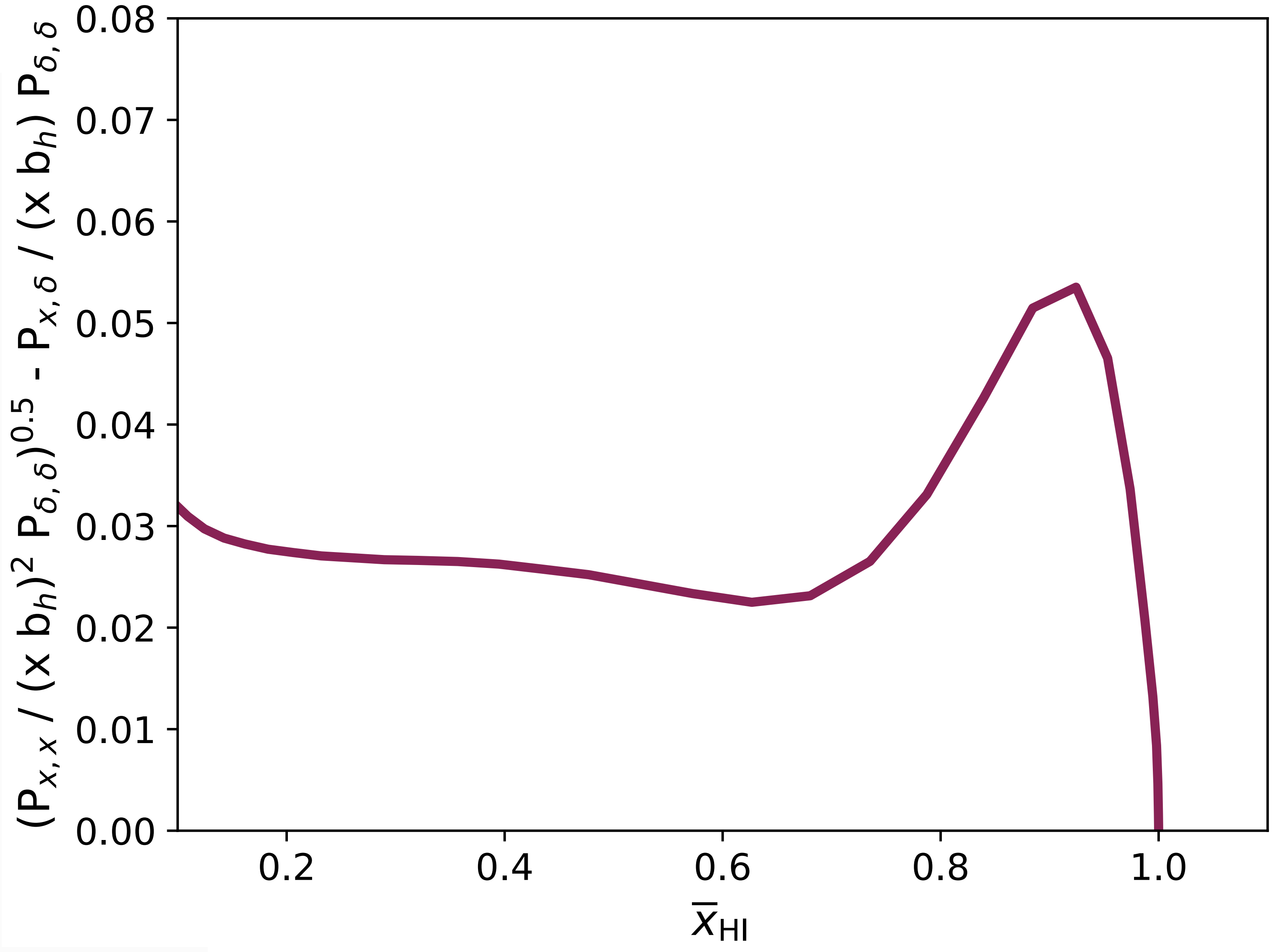

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