Impact of the Mean Free Path effect on the Large Scale 21-cm Power Spectrum from Reionization

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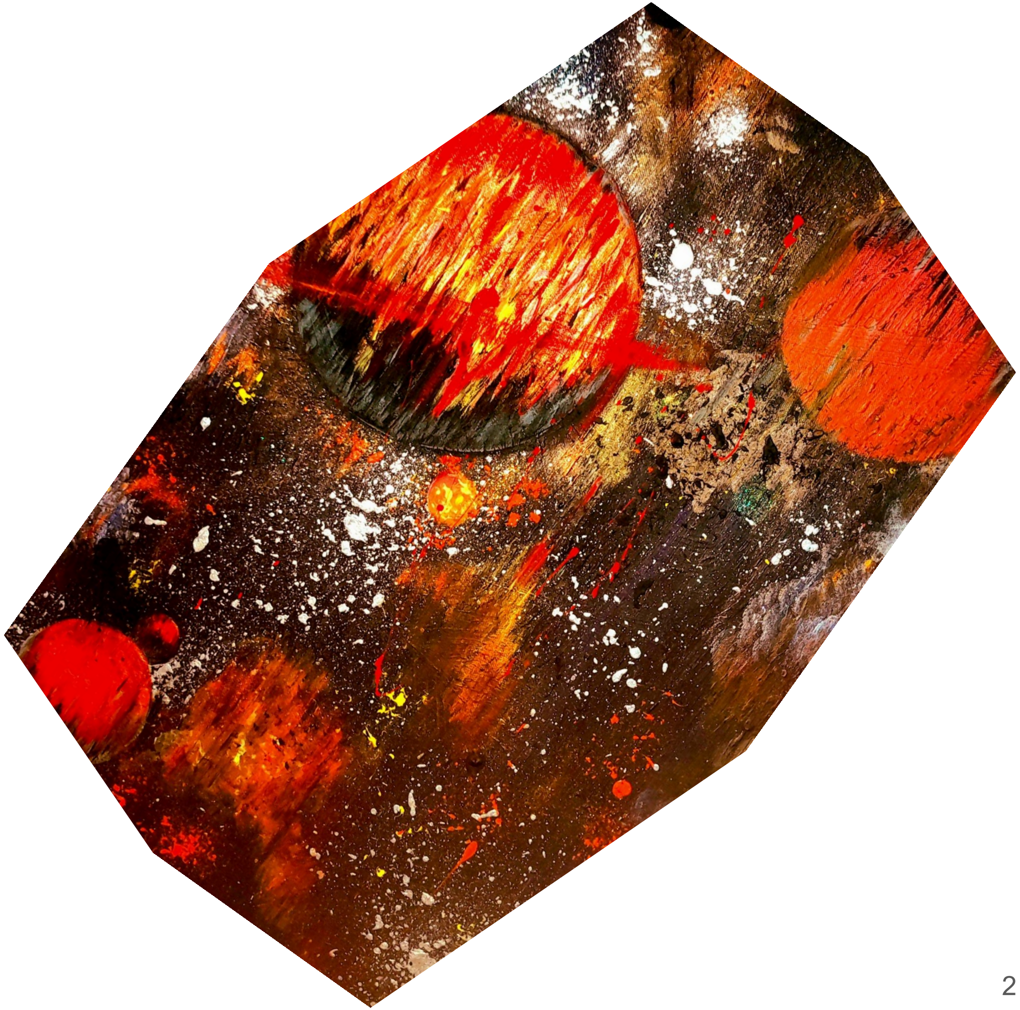
Content and Overview

1. Decomposition of the 21-cm power spectrum in terms of density (δ_ρ) and neutral fraction (δ_{xHI}) fields.

2. Mean free path of ionising photons during reionization (in simulations).

3. Impact of mean free path on shape of the 21-cm power spectrum.



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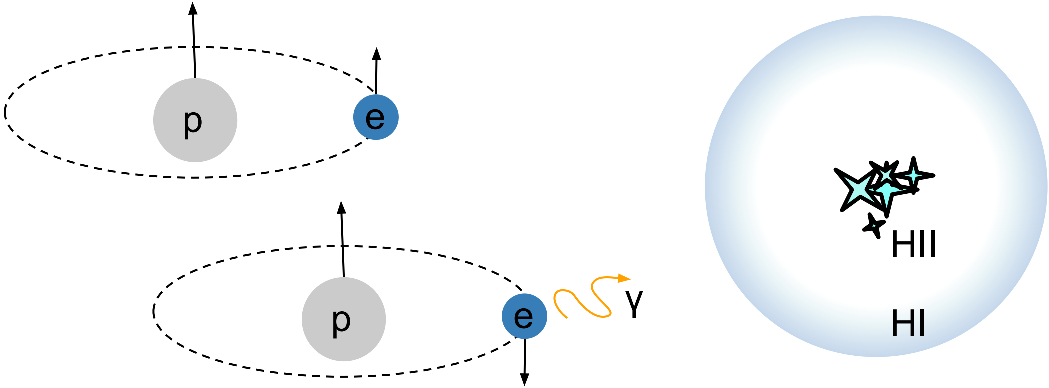
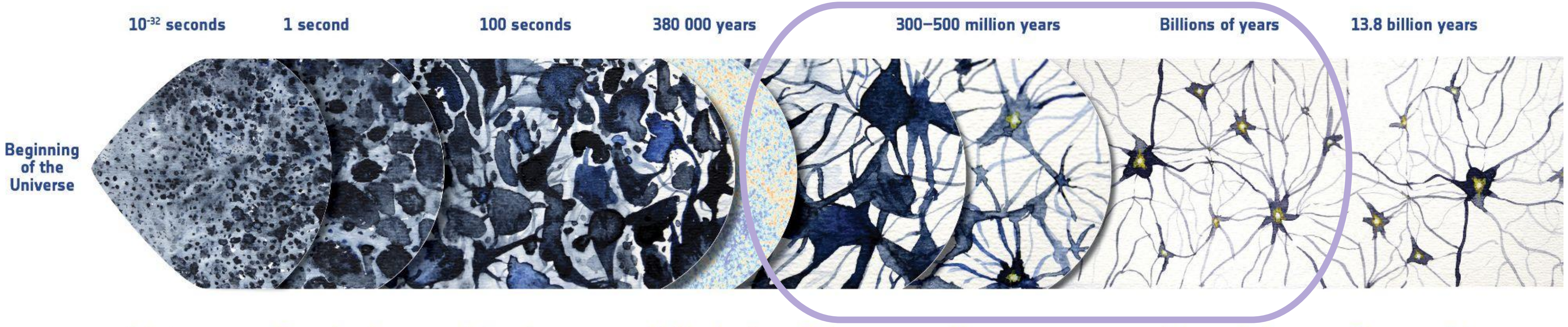
Epoch of Reionization

The Epoch of Reionisation (EoR) spans **astrophysical** & **cosmological scales.** The 21-cm signal contains **ionisation** and **density** information.





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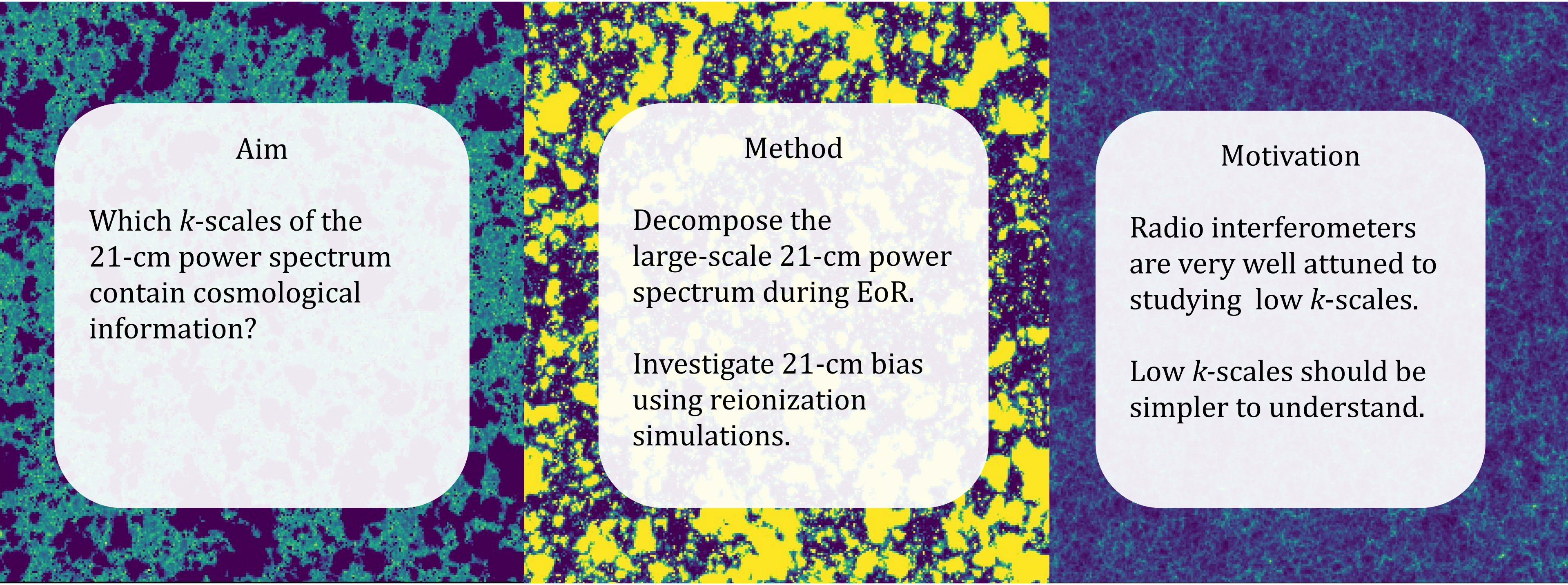
Project Aims and Motivations



Aim

Which *k*-scales of the 21-cm power spectrum contain cosmological information?

Method

Decompose the large-scale 21-cm power spectrum during EoR.

Investigate 21-cm bias using reionization simulations.

Motivation

Radio interferometers are very well attuned to studying low *k*-scales.

Low *k*-scales should be simpler to understand.

Decomposing the 21-cm Power Spectrum

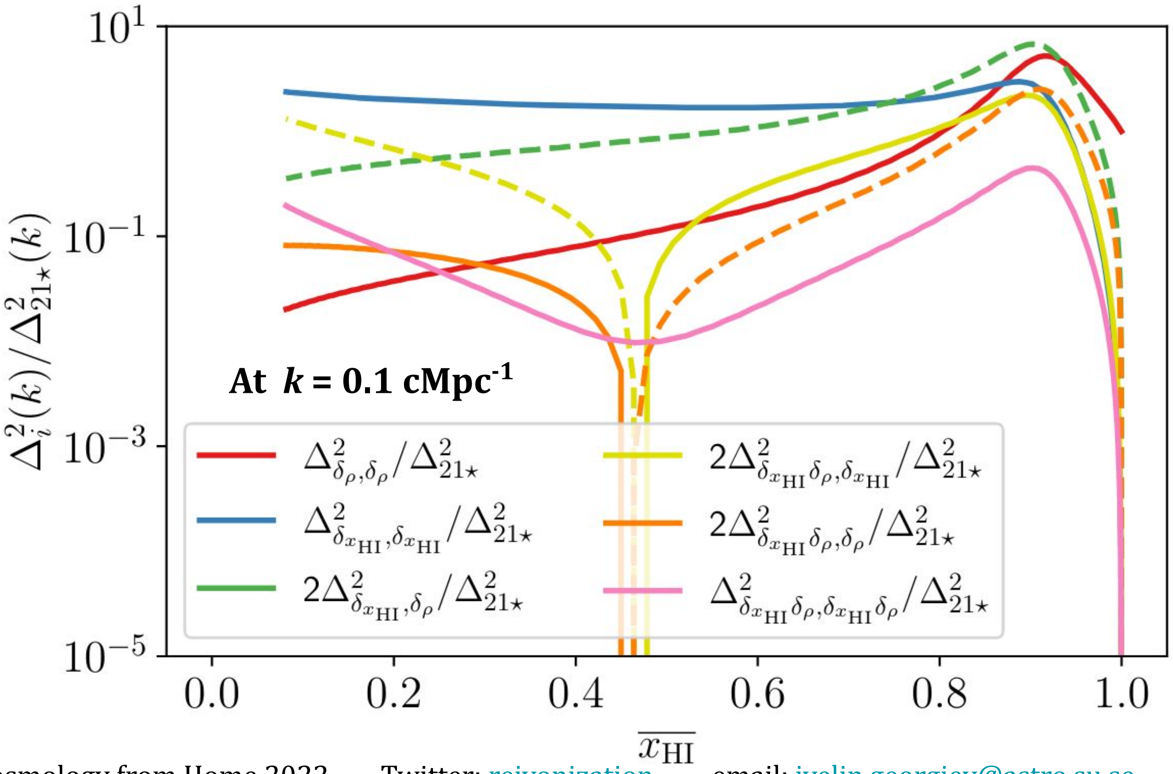
$$\Delta^2_{21cm}(k) = T_0^2 \langle x_{\rm HI} \rangle^2 \left(\Delta^2_{\delta_\rho,\delta_\rho}(k) + \Delta^2_{\delta_{x_{\rm HI}},\delta_{x_{\rm HI}}} + 2\Delta^2_{\delta_\rho,\delta_{x_{\rm HI}}} + 2\Delta^2_{\delta_\rho\delta_{x_{\rm HI}},\delta_{x_{\rm HI}}} + 2\Delta^2_{\delta_\rho\delta_{x_{\rm HI}},\delta_\rho} + \Delta^2_{\delta_\rho\delta_{x_{\rm HI}},\delta_\rho\delta_{x_{\rm HI}}} \right)$$

(Lidz et al. 2007)

— Positive contributions
- - Negative contributions

$\delta T_b = T_0 \langle x_{\rm HI} \rangle (1 + \delta_\rho)(1 + \delta_{x\rm HI})$

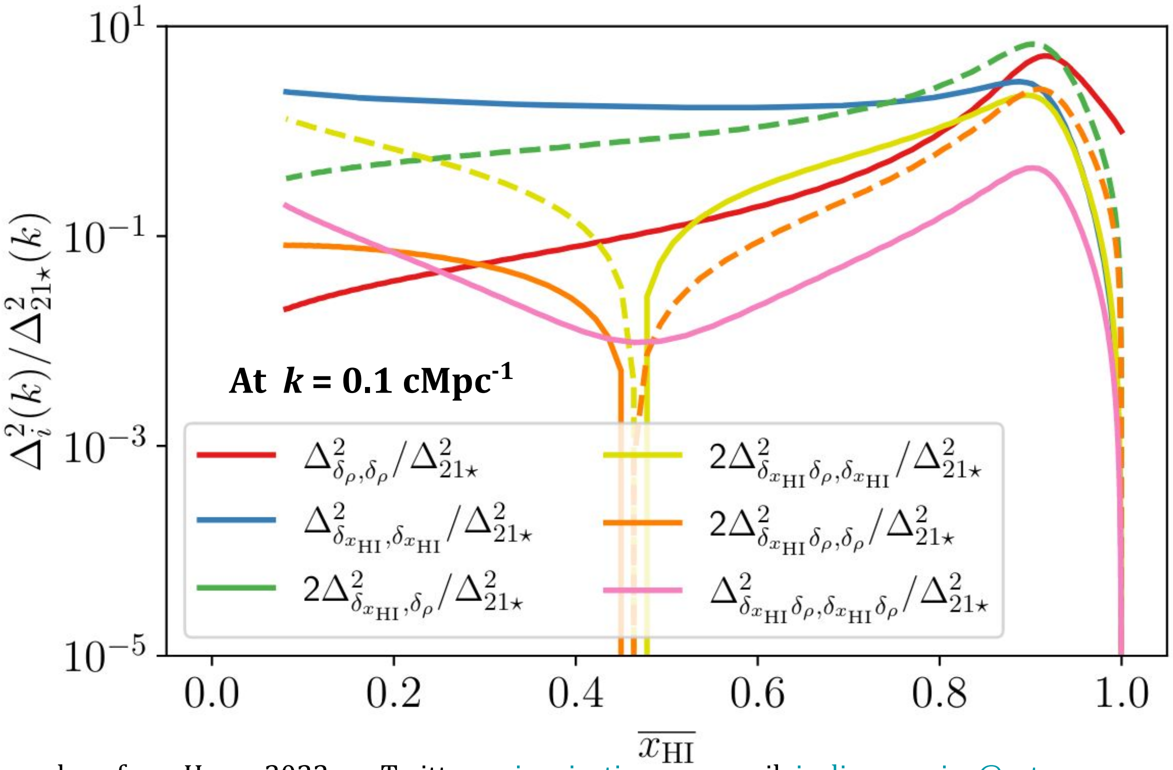
Large scales defined as
$k < 0.3$ cMpc^{-1}.



$$\Delta^2_{21cm}(k) = T_0^2 \langle x_{\rm HI}\rangle^2 \left(\Delta^2_{\delta_\rho,\delta_\rho}(k) + \Delta^2_{\delta_{x_{\rm HI}},\delta_{x_{\rm HI}}} + 2\Delta^2_{\delta_\rho,\delta_{x_{\rm HI}}} + 2\Delta^2_{\delta_\rho\delta_{x_{\rm HI}},\delta_{x_{\rm HI}}} + 2\Delta^2_{\delta_\rho\delta_{x_{\rm HI}},\delta_\rho} + \Delta^2_{\delta_\rho\delta_{x_{\rm HI}},\delta_\rho\delta_{x_{\rm HI}}}\right)$$

Before 10% ionisation,
Δ^2_{21cm} is determined by $\Delta^2_{\delta\rho,\delta\rho}$.

Afterwards,
Δ^2_{21cm} is determined by $\Delta^2_{\delta xHI,\delta xHI}$.



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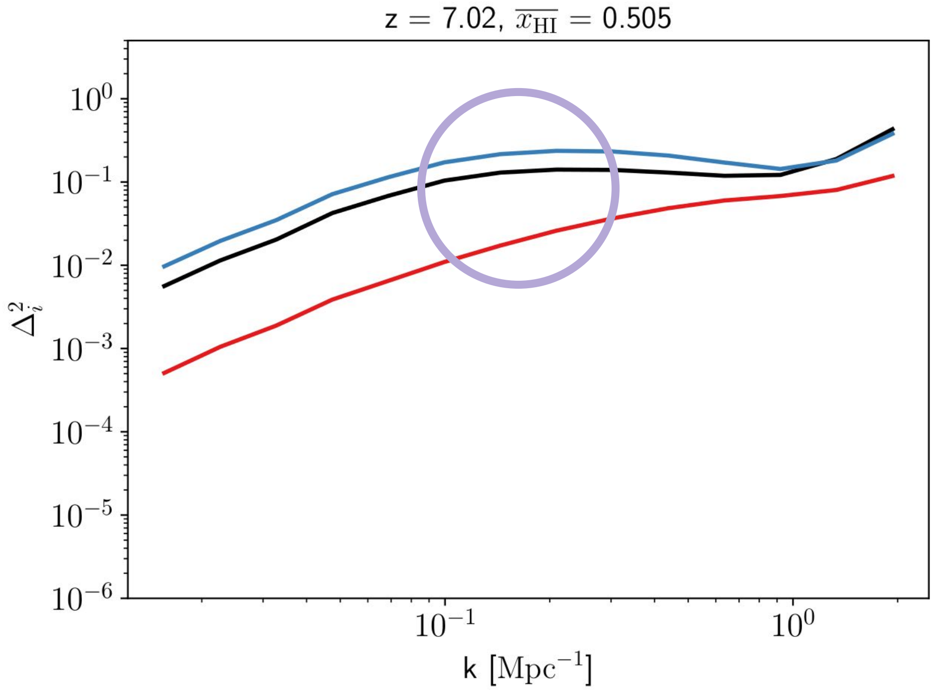
Features of the 21-cm Power Spectrum

$$\Delta^2_{21cm}(k) = T_0^2 \langle x_{\rm HI} \rangle^2 \left(\Delta^2_{\delta_\rho,\delta_\rho}(k) + \Delta^2_{\delta_{x_{\rm HI}},\delta_{x_{\rm HI}}} + 2\Delta^2_{\delta_\rho,\delta_{x_{\rm HI}}} + 2\Delta^2_{\delta_\rho\delta_{x_{\rm HI}},\delta_{x_{\rm HI}}} + 2\Delta^2_{\delta_\rho\delta_{x_{\rm HI}},\delta_\rho} + \Delta^2_{\delta_\rho\delta_{x_{\rm HI}},\delta_\rho\delta_{x_{\rm HI}}} \right)$$

The characteristic "**feature**" of the spectrum marks a transition point between astrophysical and cosmological scales.

Is its position connected to the Mean Free Path of ionising photons (**MFP**) (e.g. Pober et al. 2014)?



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Paths of Ionising Photons

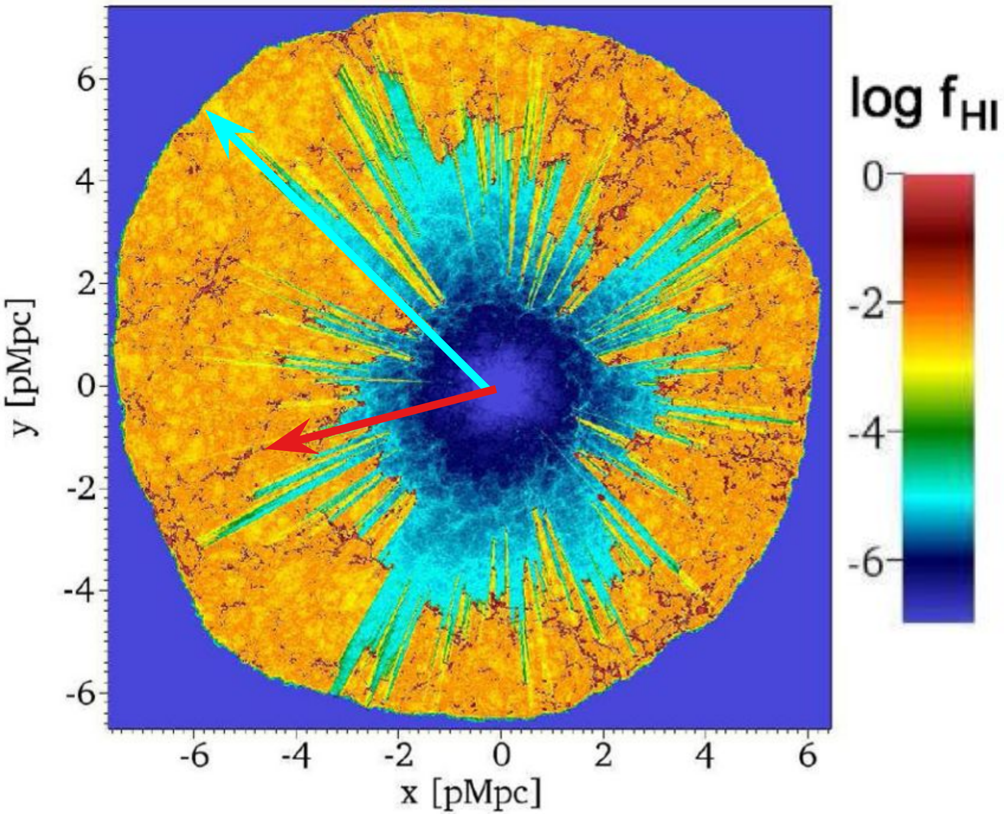
Mean free path (**MFP**): average distance an ionizing photon travels through the IGM.

Can be limited by

A. large neutral islands

B. absorption due to residual neutral gas in the ionized IGM.

MFP due to B. often implemented in coarse EoR simulations as a hard barrier through which no ionising photon can cross (e.g. R_{max} in 21cmFAST).



(Keating et al. 2015)

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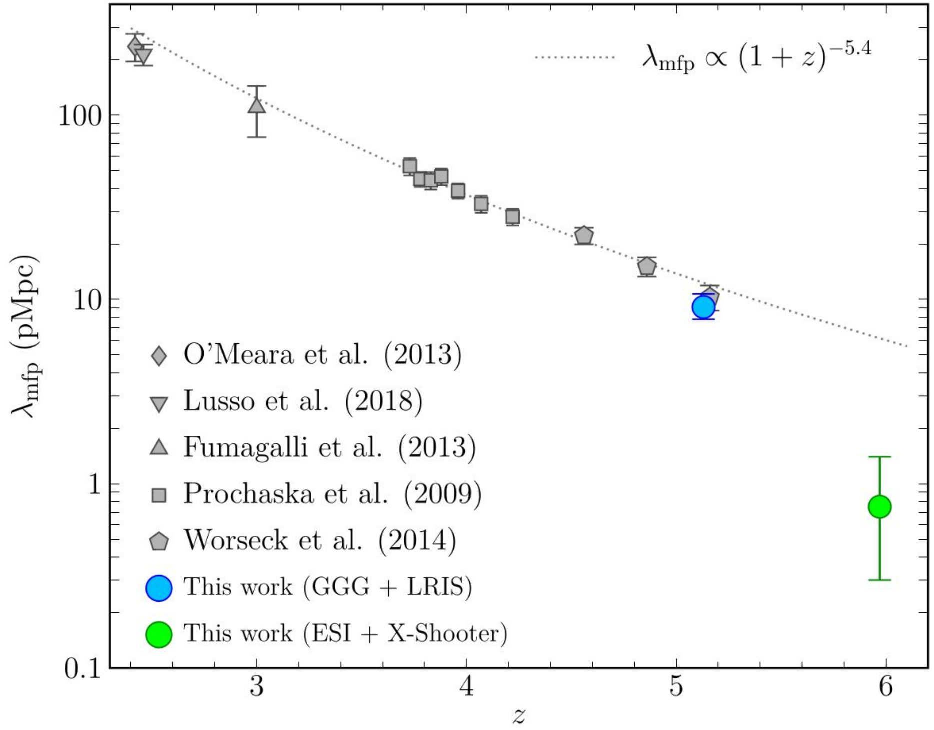
Observations of the Mean Free Path of Ionising photons



(Becker et al. 2021)

Mean Free Path measurements from the Lyα forest of high-z Quasi-Stellar Objects (QSOs).

Well-measured for z= 3 - 5, increasingly challenging to measure as we approach reionization.

1 pMpc = 1 / (1+z) cMpc

Modelling the MFP Effect (B)

Investigate the mfp effect by comparing two sets of two C^2 - Ray simulations of box size 714 cMpc, $M_{min} = 10^9\ M_\odot$

- - - Hard cubic barriers

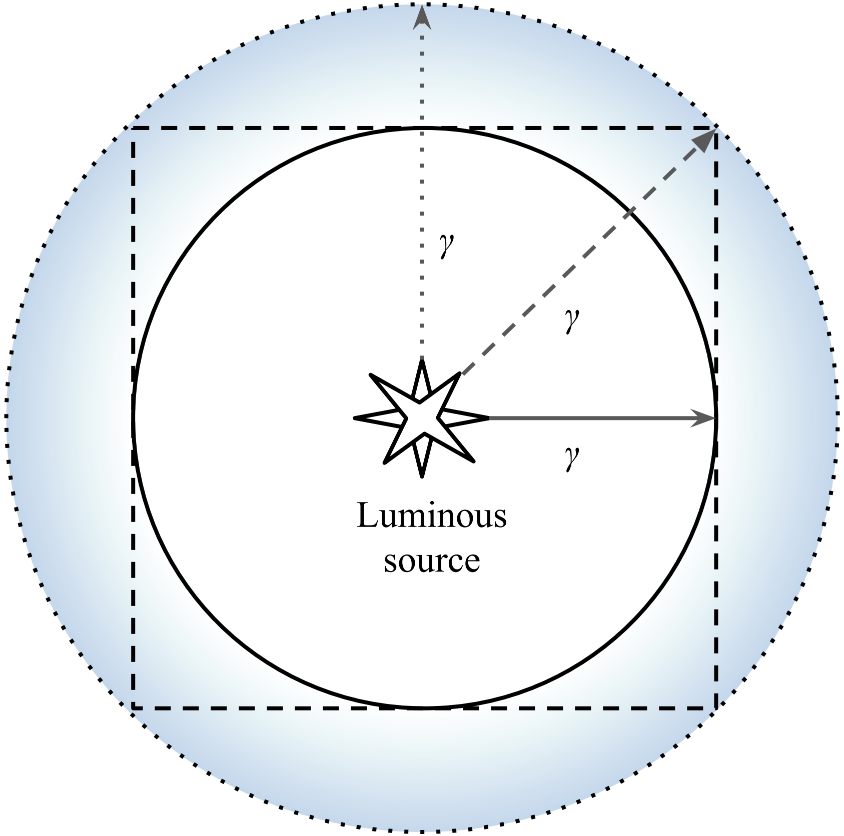
C2λ19 : λ_{mfp} = 19 cMpc (≈ 2.7 pMpc at z = 6)

C2λ70 : λ_{mfp} = 70 cMpc (≈ 10 pMpc at z = 6)

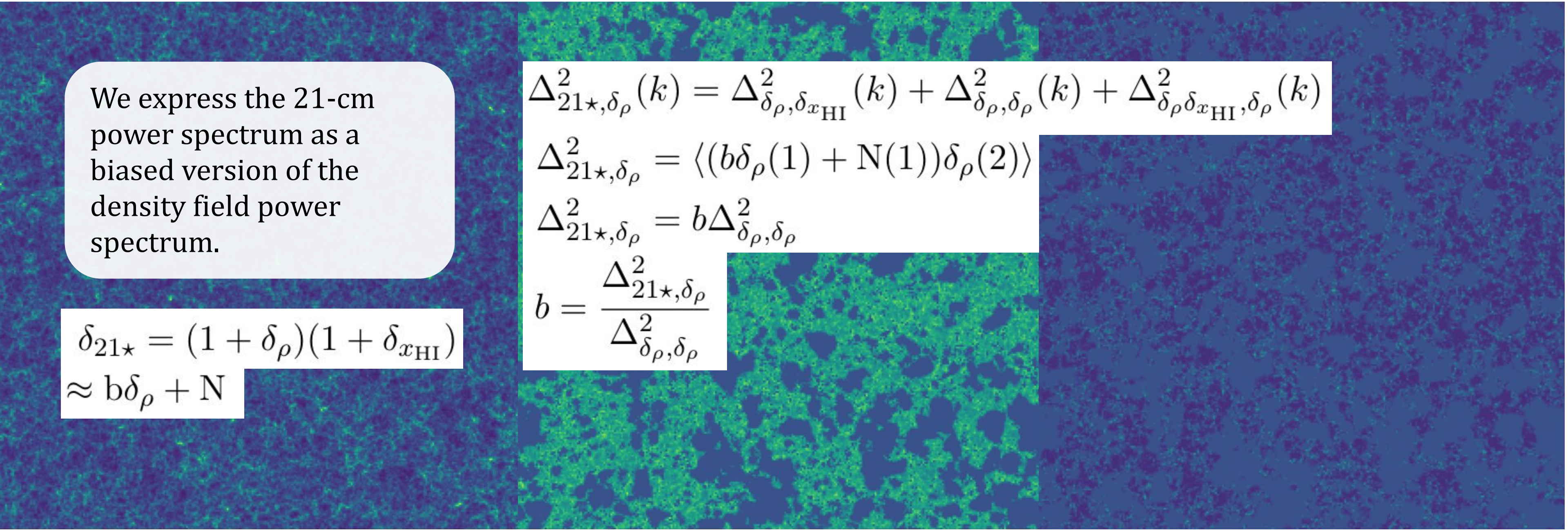
For a fixed λ_{mfp} = 10 cMpc (≈ 1.4 pMpc at z = 6)

— **C2RMAX10** : Hard spherical barrier

· · · · **C2LLS10** : Gradual absorption barrier such that at $\tau \approx 1$ at λ_{mfp}



Constructing a Bias Parameter



We express the 21-cm power spectrum as a biased version of the density field power spectrum.

$$\delta_{21\star} = (1+\delta_\rho)(1+\delta_{x_{\mathrm{HI}}}) \approx \mathrm{b}\delta_\rho + \mathrm{N}$$

$$\Delta^2_{21\star,\delta_\rho}(k) = \Delta^2_{\delta_\rho,\delta_{x_{\mathrm{HI}}}}(k) + \Delta^2_{\delta_\rho,\delta_\rho}(k) + \Delta^2_{\delta_\rho\delta_{x_{\mathrm{HI}}},\delta_\rho}(k)$$

$$\Delta^2_{21\star,\delta_\rho} = \langle(b\delta_\rho(1) + \mathrm{N}(1))\delta_\rho(2)\rangle$$

$$\Delta^2_{21\star,\delta_\rho} = b\Delta^2_{\delta_\rho,\delta_\rho}$$

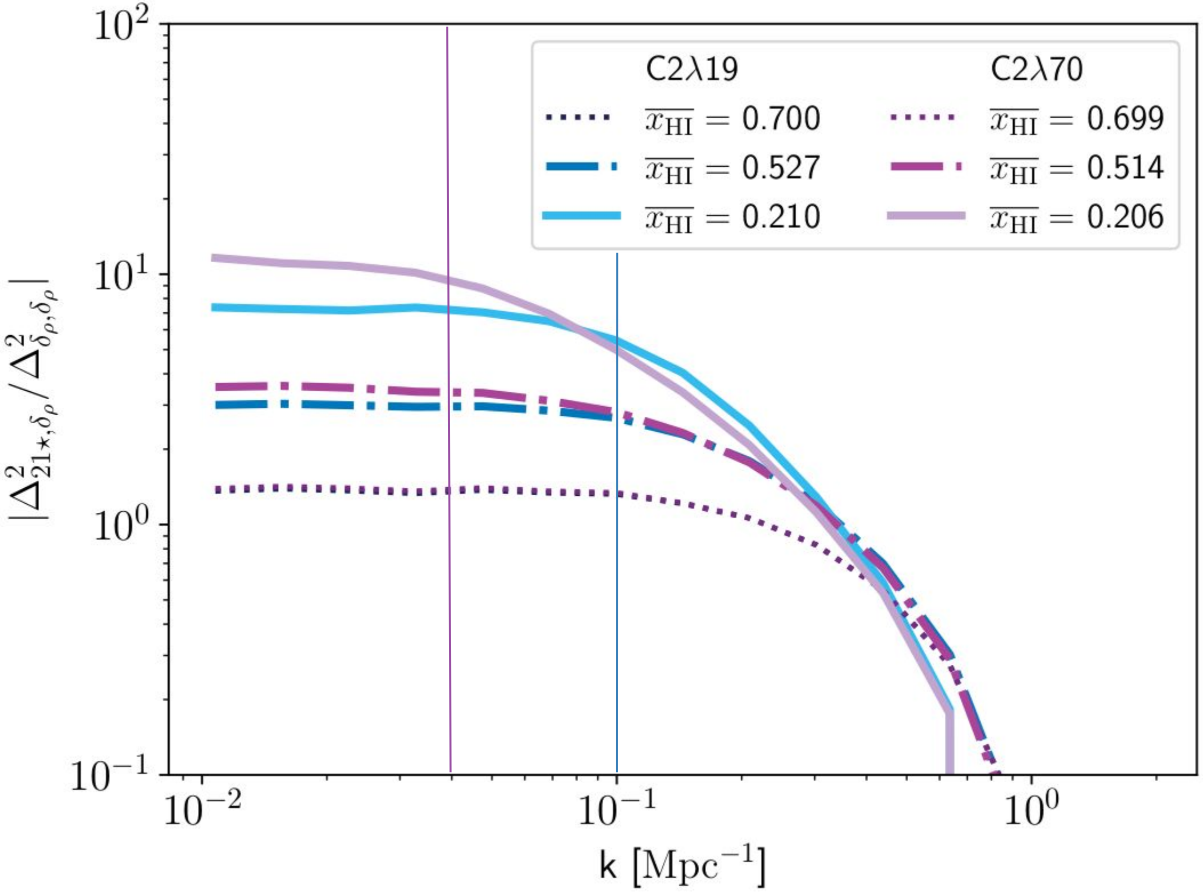
$$b = \frac{\Delta^2_{21\star,\delta_\rho}}{\Delta^2_{\delta_\rho,\delta_\rho}}$$

Impact of different values for MFP

At large scales the 21-cm power spectra becomes a biased version of the density power spectra.

Transition point depends on value of true MFP (A or B): $k \approx 2.0/\lambda_{\mathrm{mfp}}$

Result confirmed with 21cmFAST models.



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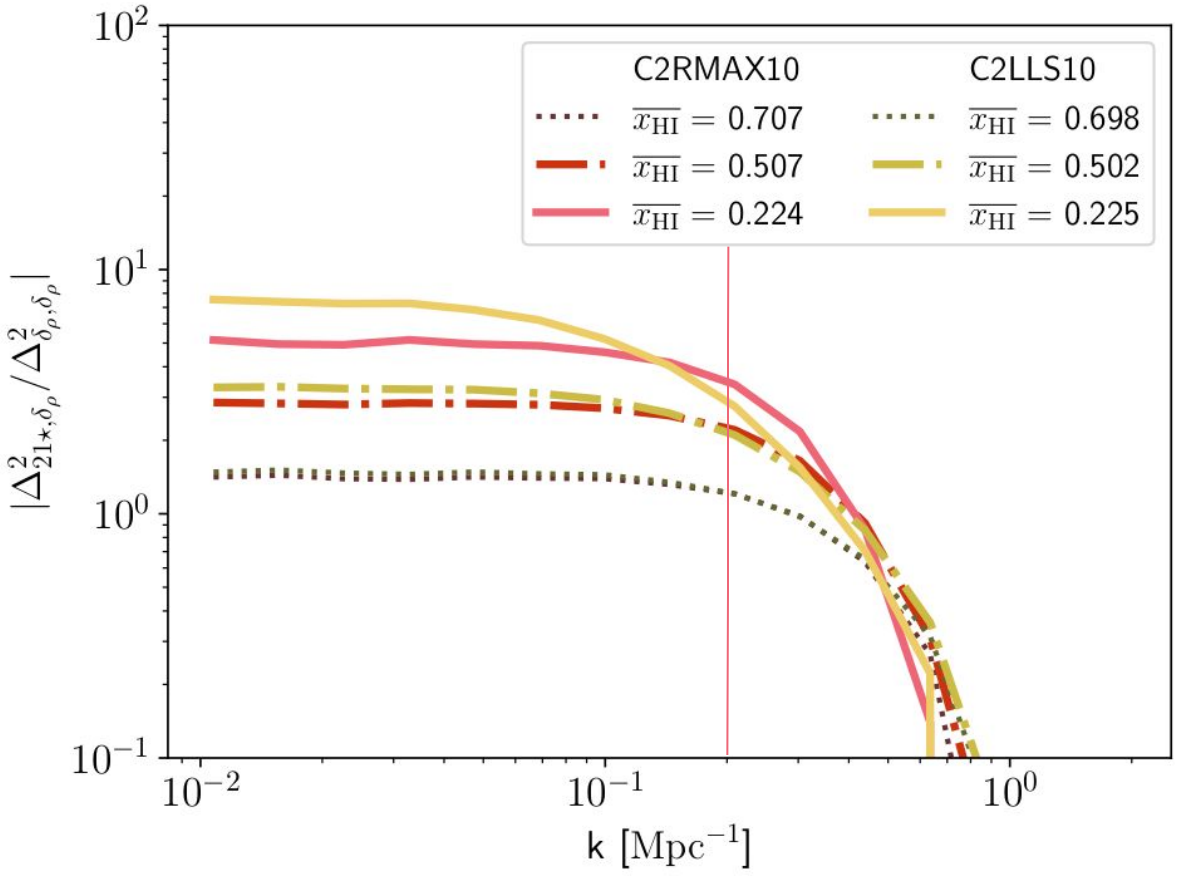
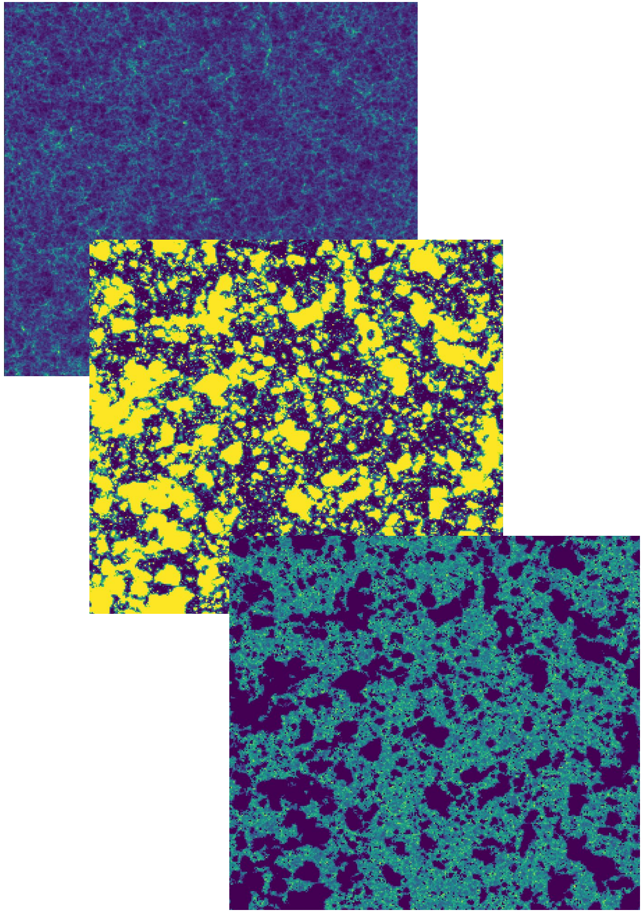
Different Implementations of the MFP Effect (B)

Hard barrier: **C2RMAX10**
Gradual absorption: **C2LLS10**

The method of implementing the MFP effect (B) in the simulation has a profound effect on the bias.

More gradual transition to linear bias regime in case of gradual absorption.





Conclusion and Summary

- After ~10% ionisation, Δ^2_{21cm} follows $\Delta^2_{\delta xHI, \delta xHI}$ which beyond a transition scale is a biased version of $\Delta^2_{\delta\rho, \delta\rho}$.

- The transition point is related to the MFP value (A or B): $k \approx 2.0 / \lambda_{mfp}$

  However the shape of the transition depends on how the MFP effect (B) is modelled in EoR simulations.

- Becker et al. (2021) find $\lambda_{mfp} = 5.3$ cMpc at $z = 6$ from QSO spectra. This MFP value would imply that on scales $\boldsymbol{k < 0.38}$ **cMpc^{-1}** the 21-cm power spectrum would follow the cosmological matter power spectrum.

Thank you for your attention!

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