Thesis cover image!

The forest at EndEoR: The effect of Lyman Limit Systems on the End of Reionisation

Ivelin Georgiev

Collaborators:
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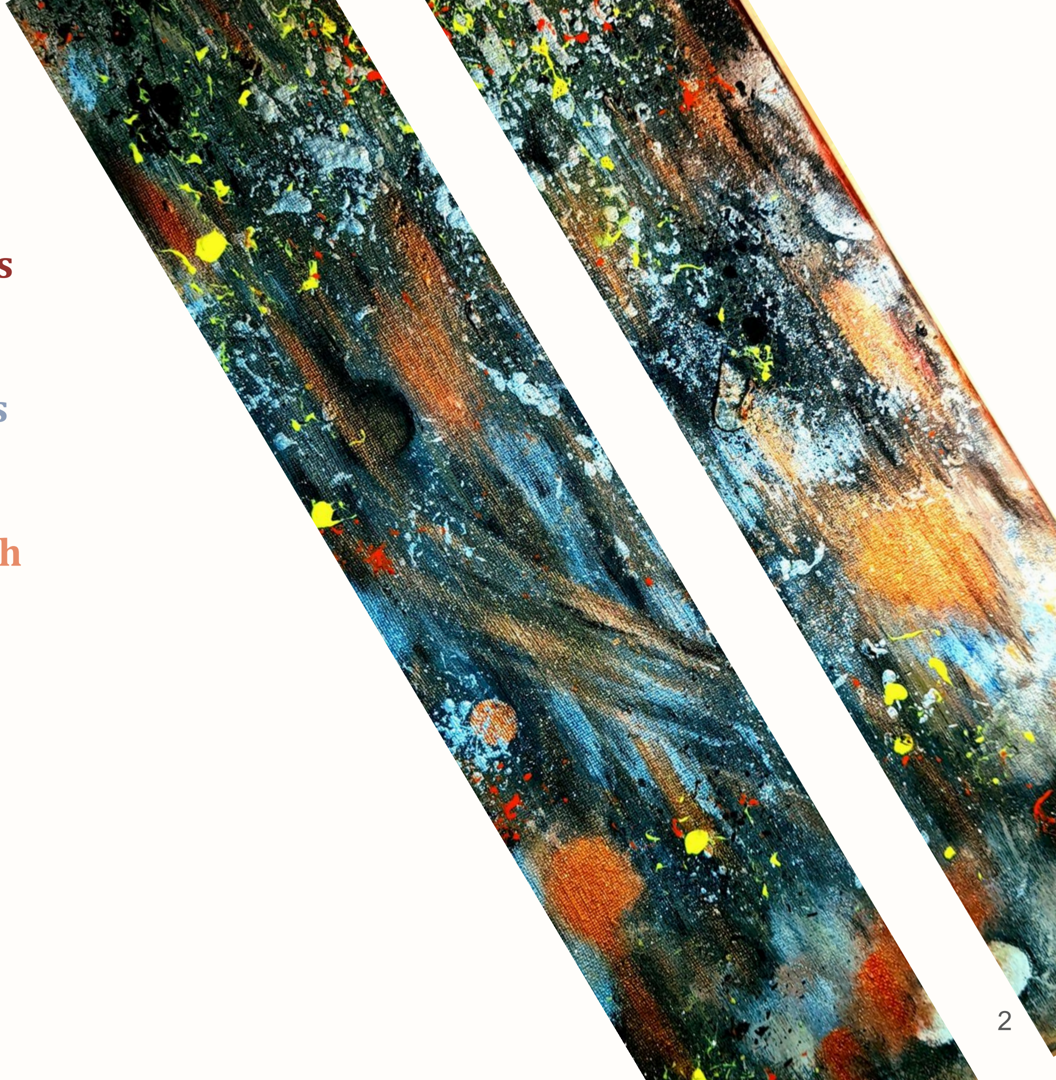
Motivations and Questions

- **How can we better model the final stages of reionization?**

- **What is the role of unresolved absorbers in large-scale simulations?**

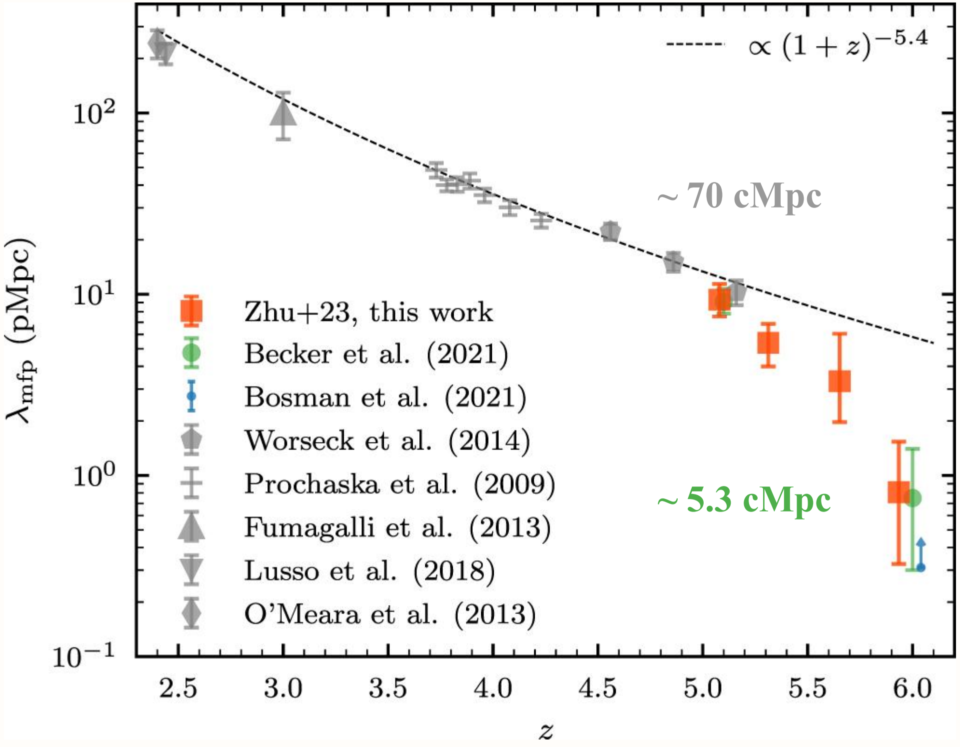
- **Are our large simulations consistent with high-resolution hydrodynamic simulations?**

- **Can we match the observables Quasar data such as the MFP/Γ/xHI etc. ?**



Observations of the Mean Free Path of Ionising photons (MFP)

1 pMpc = 1 / (1+z) cMpc



MFP measurements from the Lyα forest of high-z Quasi-Stellar Objects.

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

What causes this?

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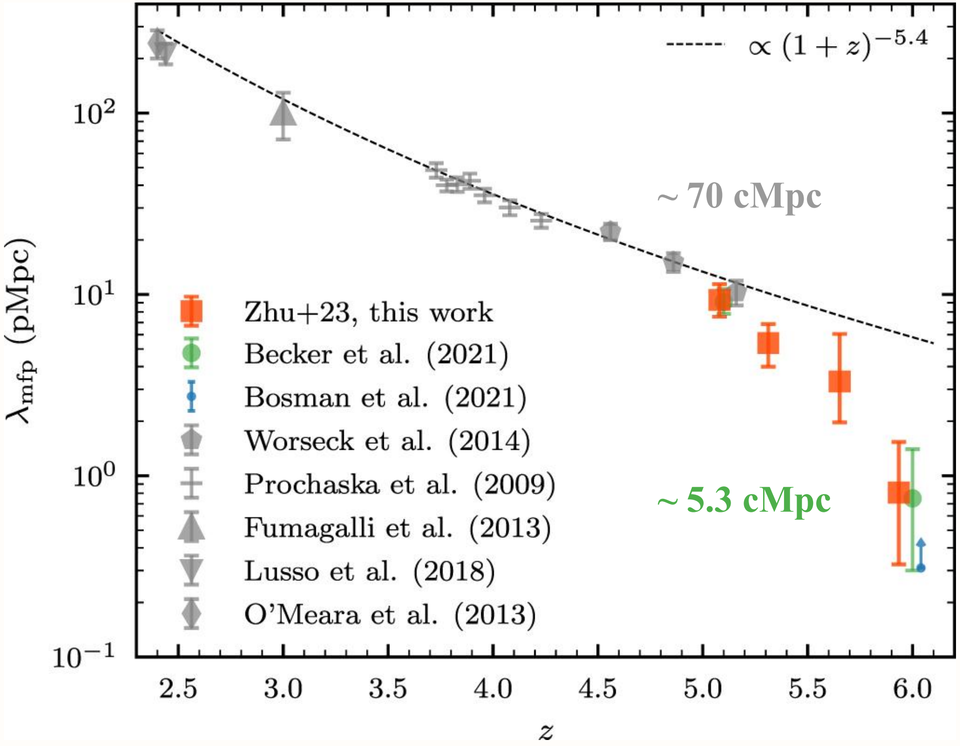

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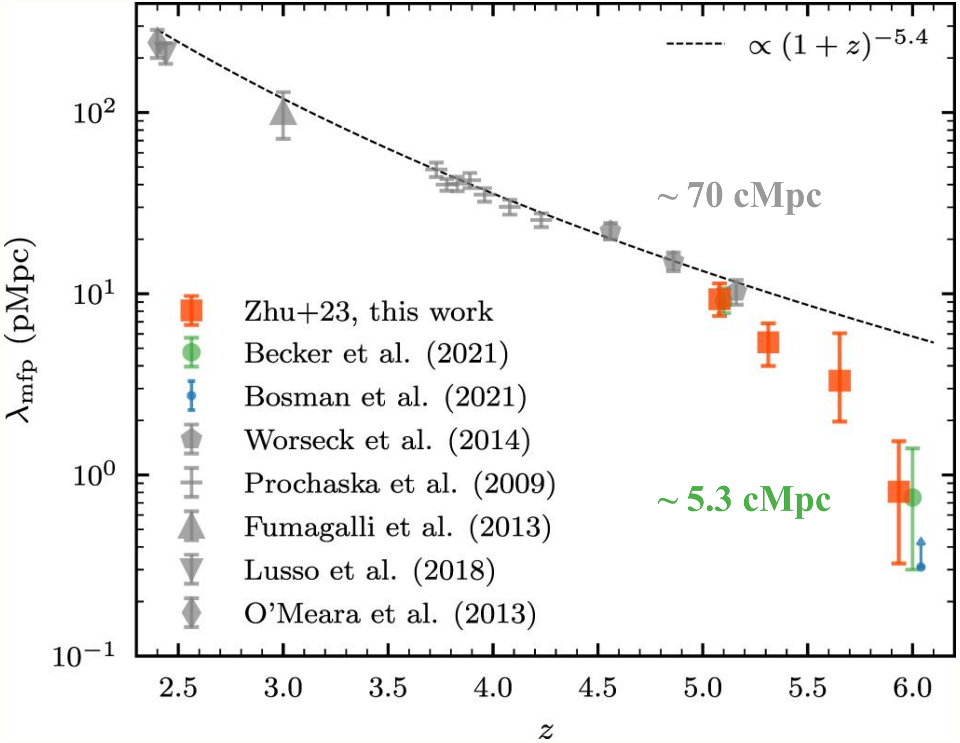

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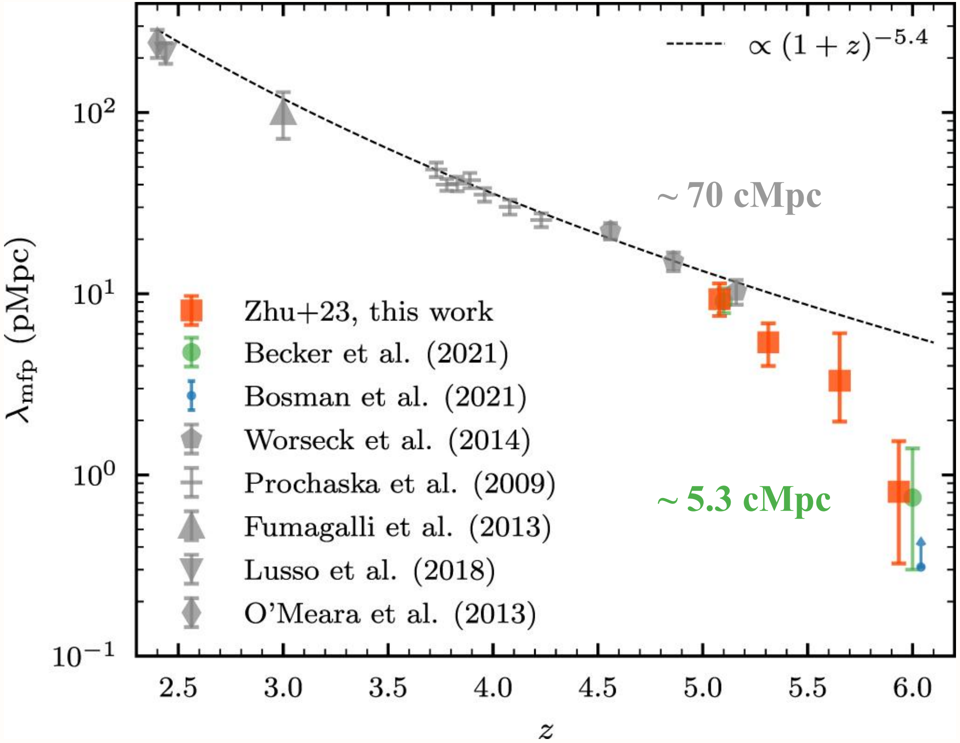

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What causes this?

- Neutral islands?
- Clumping?
- Self-shielded systems?

Ivelin Georgiev Paper: arXiv:2405.04273 Cosmic Dawn at High Latitudes Twitter: reivonization Email: ivelin.georgiev@astro.su.se

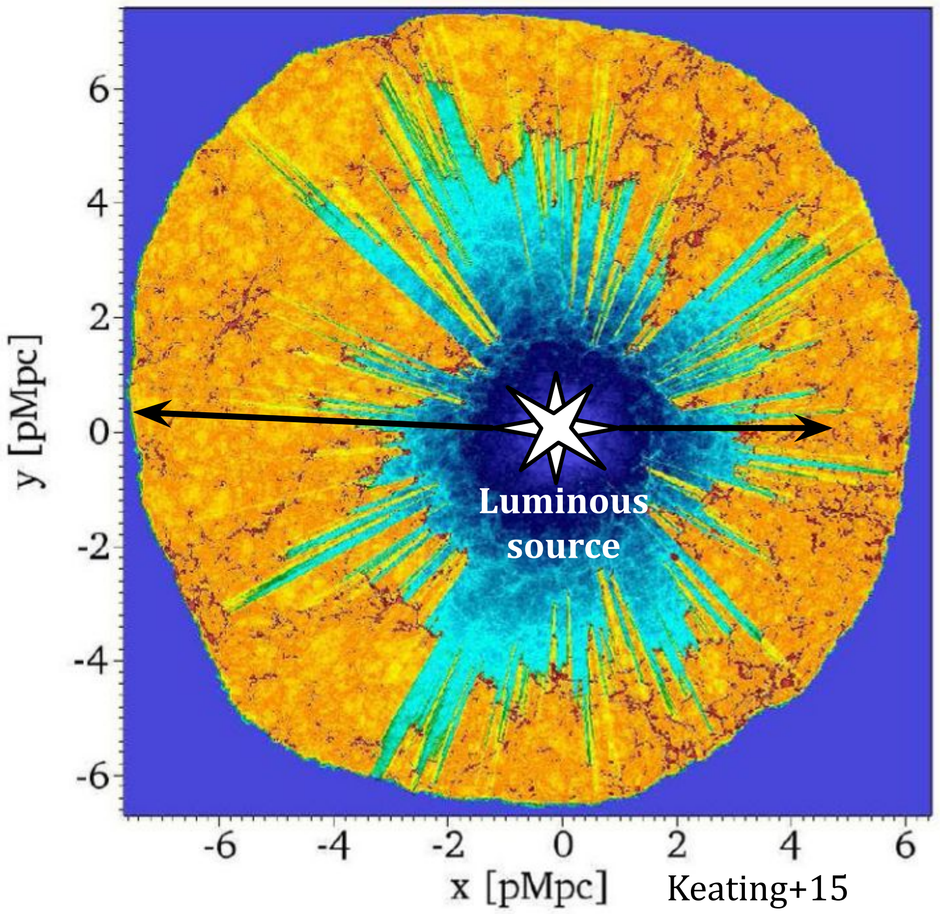
Modelling the MFP Effect is hard and diverse

Mean free path (**MFP**): distance to which an ionising photon travels in the presence of an absorption such that $\sim e^{-\tau}$ for $\tau \approx 1$.

Can be limited by

A. large neutral islands,

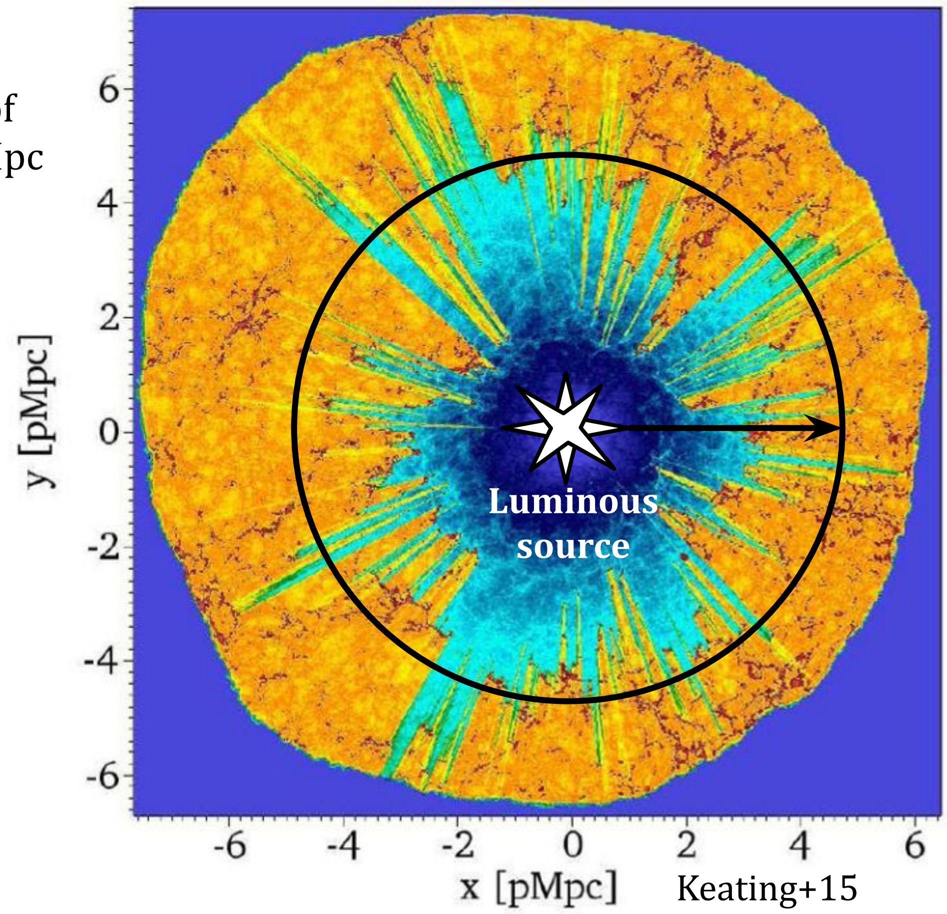
B. absorption due to residual neutral gas in the ionized IGM.



MFP as a hard barrier

Investigate the MFP effect by comparing four sets of **identical** C^2 - Ray simulations of box size $244h^{-1}$cMpc

- **r40**: **hard barrier**
  λ_{mfp} = 40 cMpc (≈ 5.7 pMpc at z = 6),



Keating+15

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MFP induced with the clumping factor

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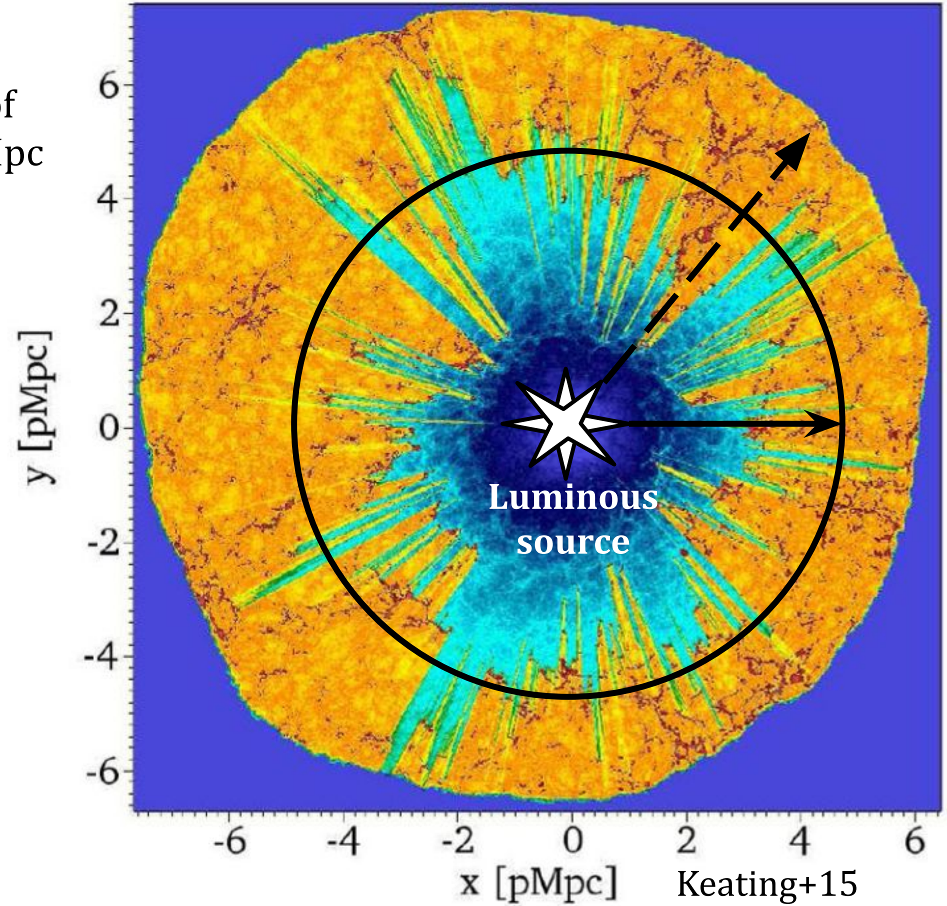
- **C2**: global clumping is doubled
  (ie. higher recombinations rates in ionised regions)



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MFP as a diffuse barrier

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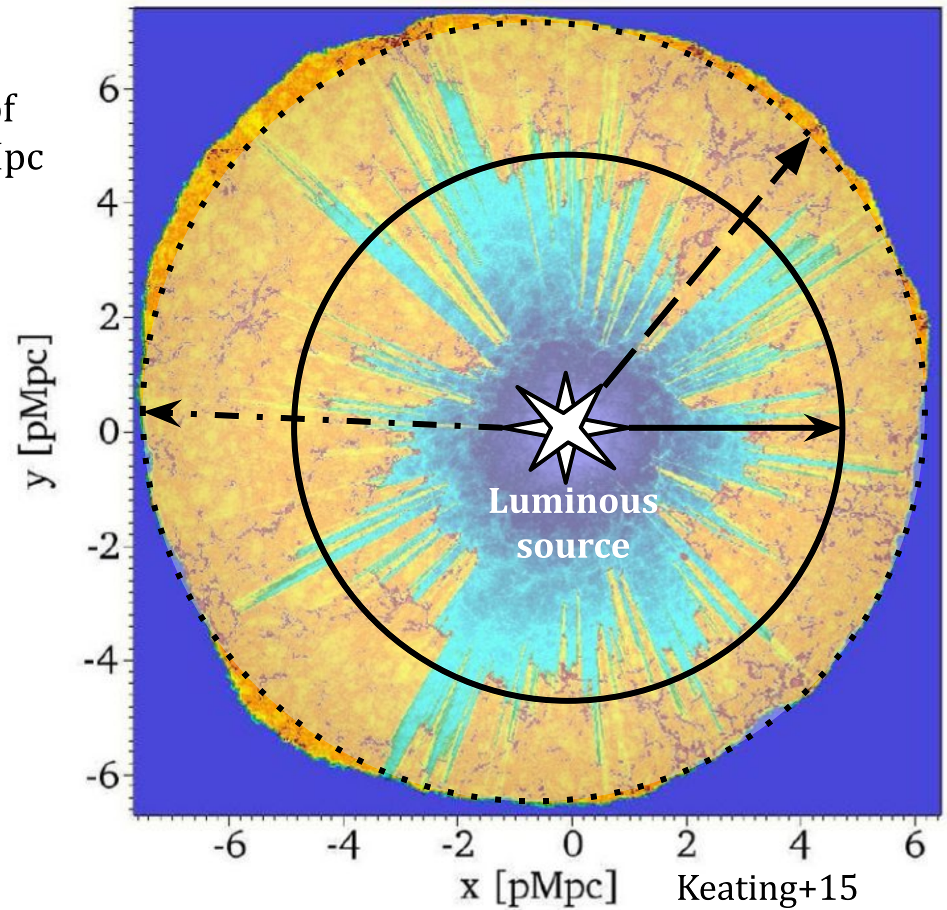
- **eLLS**: **evolving gradual absorption** barrier
  $\tau \approx 1$ at λ_{mfp} from Worseck+14 fit,



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MFP diffuse barrier + halo position

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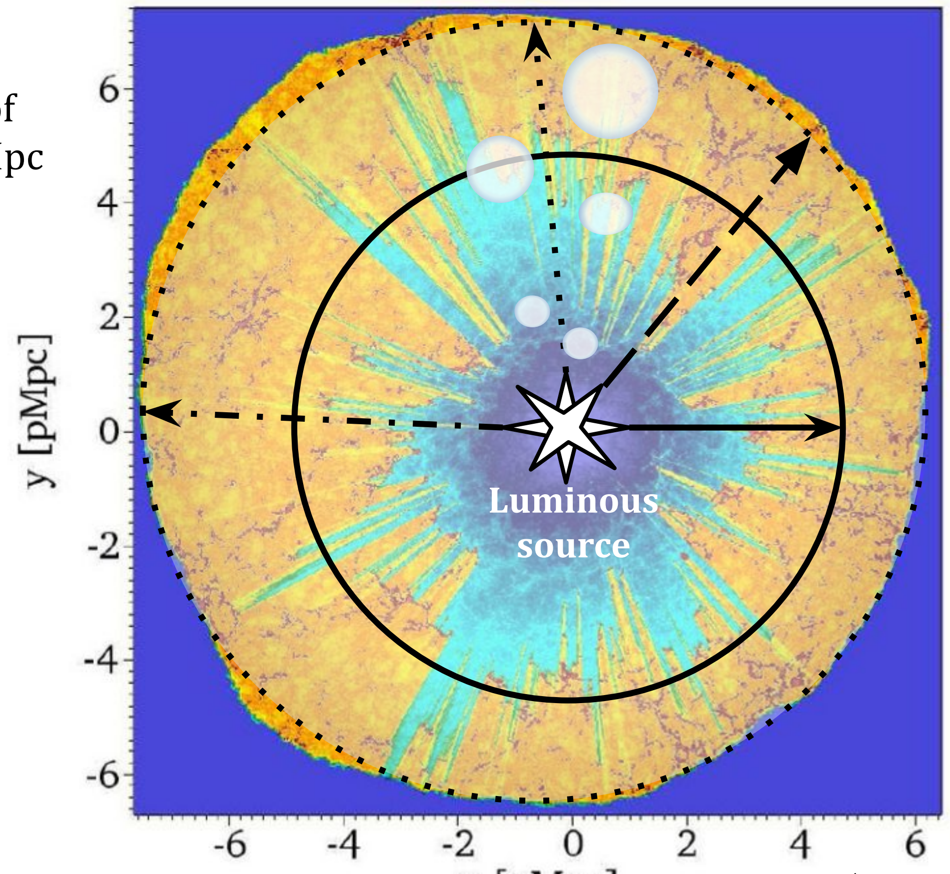
- **pLLS**: as the **eLLS** model + **position dependence.**



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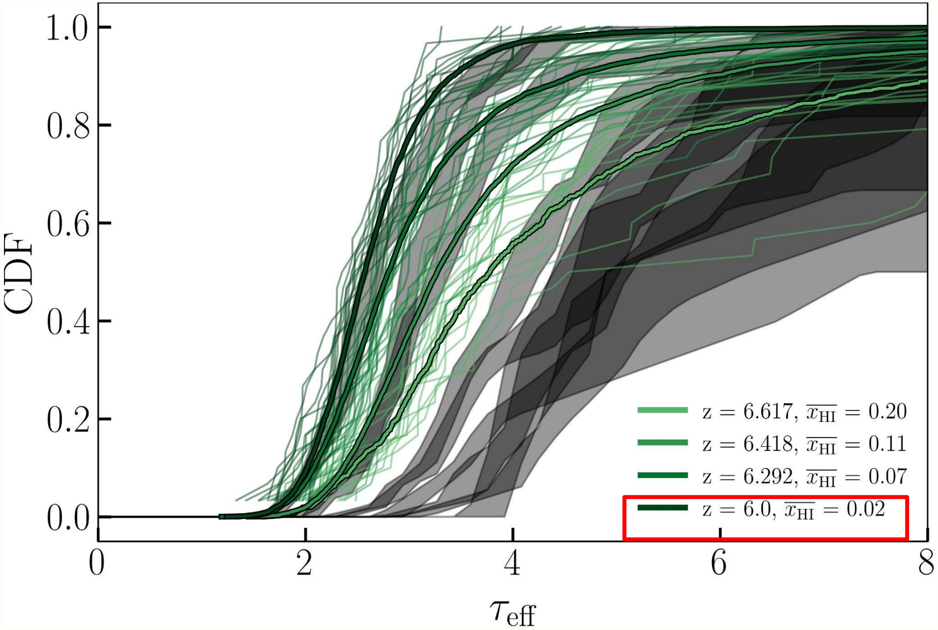
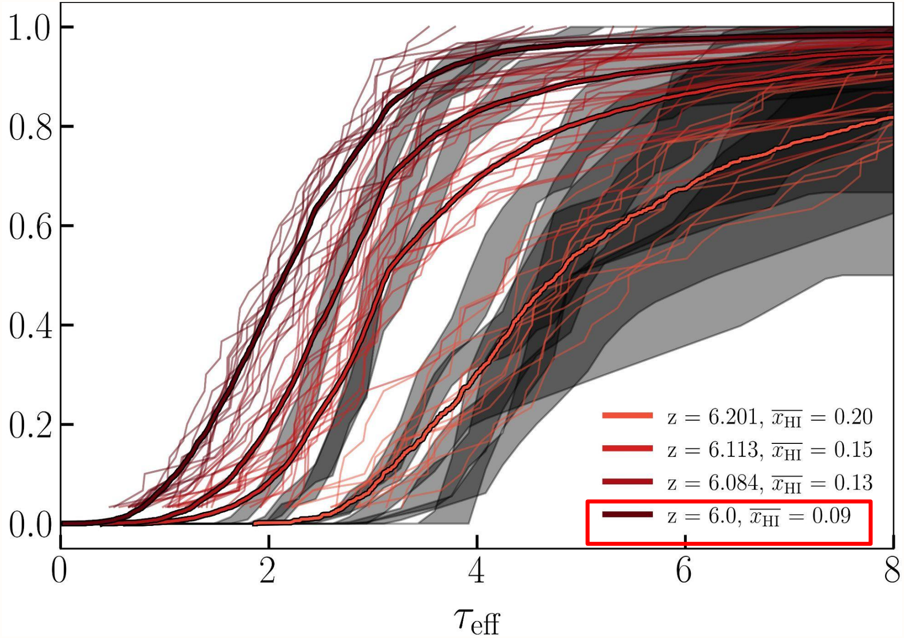
Role of LLS on the Ly-α effective opacity

r40



pLLS

Bosman+22 data in grey



Spatial skewers with lines of sight (30 cMpc long) at the EndEoR (final 20%).
Evolution compared with Lyα transmission reported in Bosman+22.

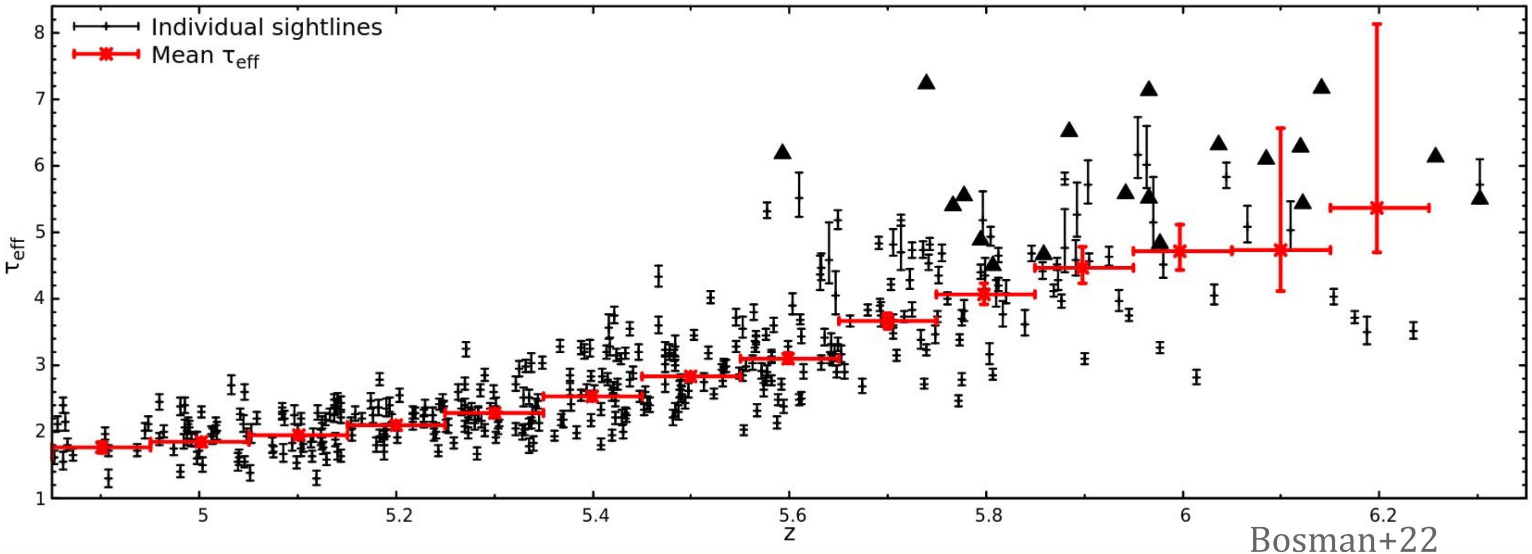
The **r40** model struggles to reproduce the observations, for **pLLS reionization is extended**.

Evolution of the mean Ly-α τ_{eff}

Let's look at the mean Ly-α τ_{eff} and fit the evolution from Bosman+22.

$$\tau_{\rm eff}(1+z) = \tau_0 \left(\frac{1+z}{1+z_0}\right)^{\beta} + C$$

Label	τ_o	β
B22	0.3 ± 0.08	13.7 ± 1.5
r40, hard fixed barrier	2.3 ± 0.1	4.2 ± 0.3
LLS40, soft fixed barrier	2.5 ± 0.1	8.5 ± 0.6
eLLS, soft evolving barrier	2.7 ± 0.1	11.5 ± 0.7
pLLS, density-dependent soft barrier	2.8 ± 0.1	13.3 ± 0.6
C2, global clumping parameter of two	2.5 ± 0.1	10.4 ± 0.8



Bosman+22

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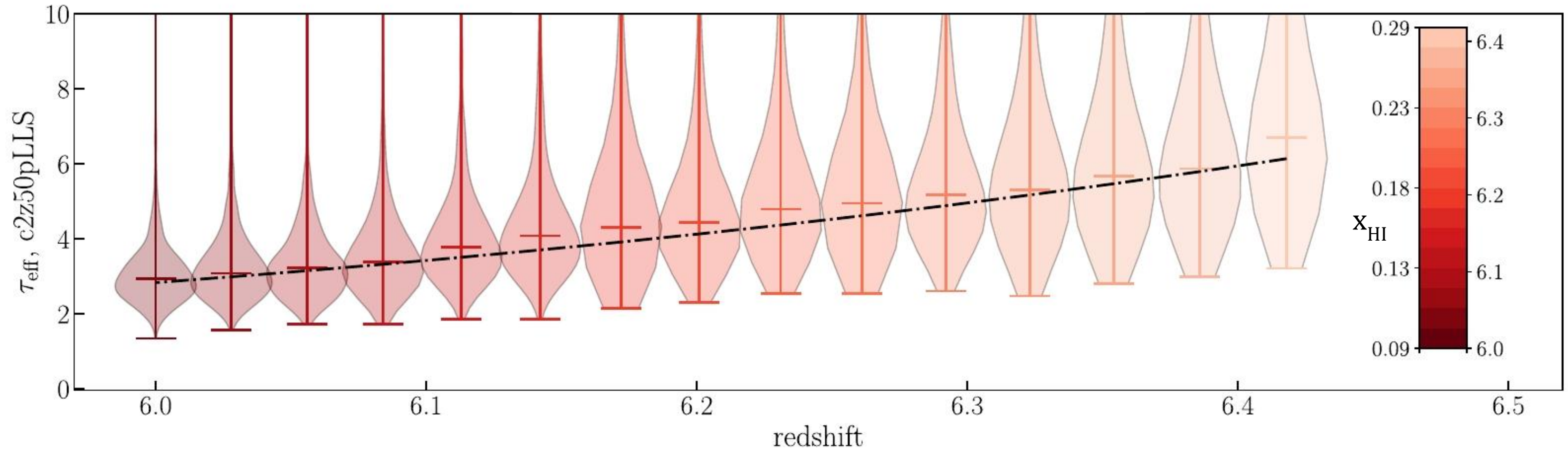

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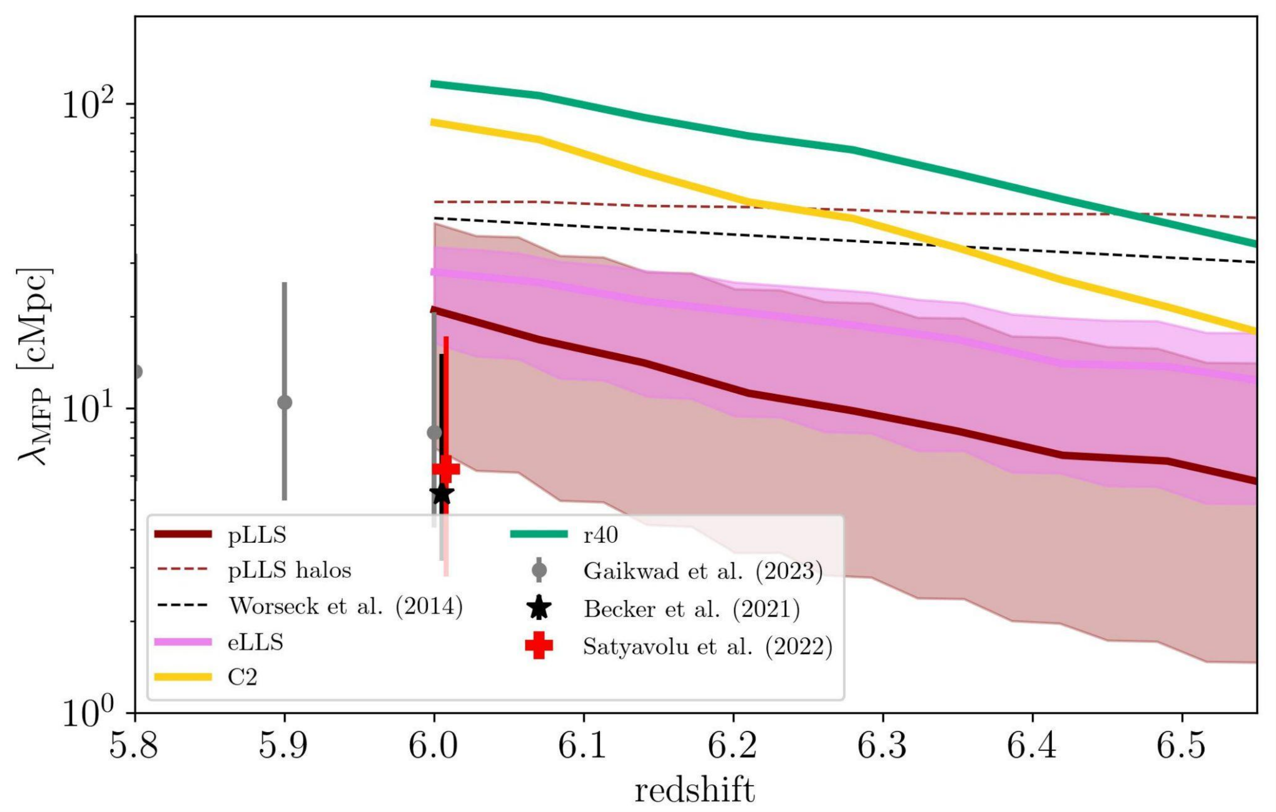
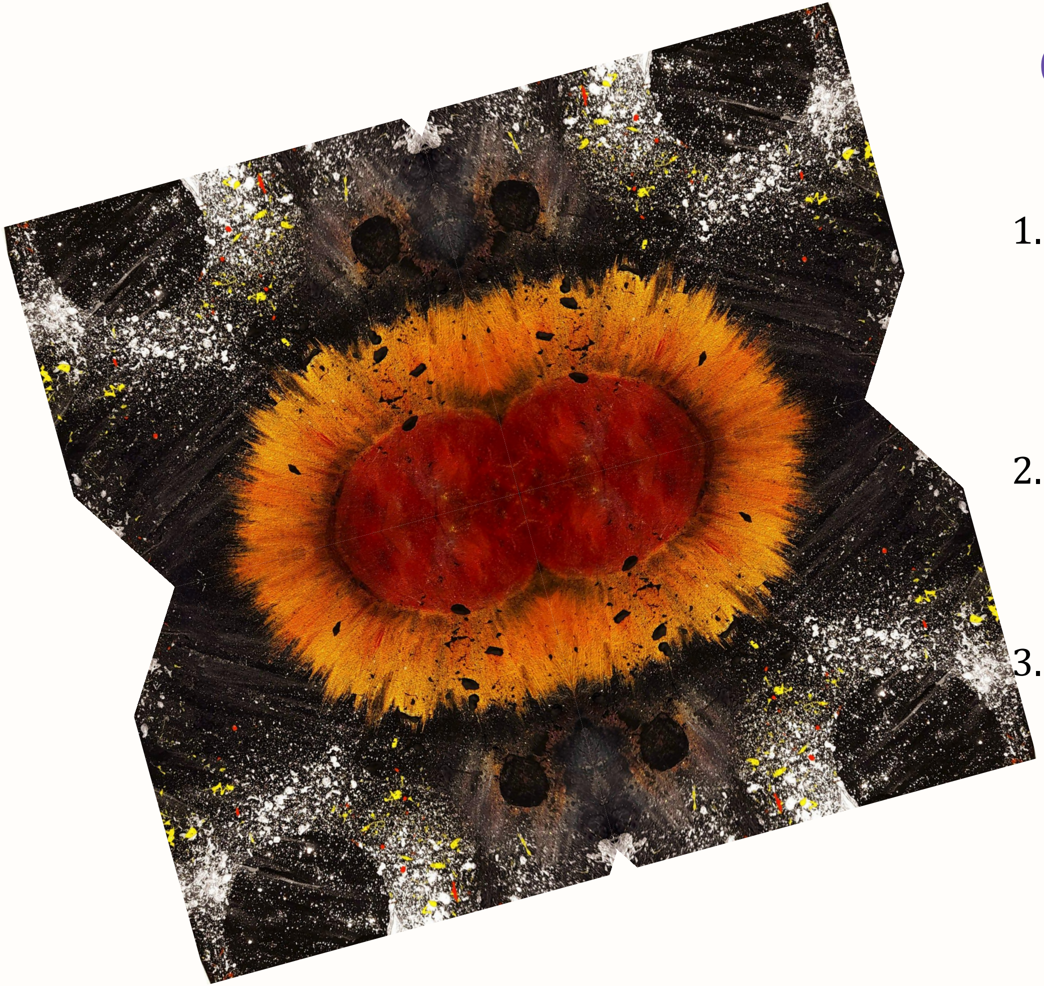
Can we reproduce the mean free path of ionising photons?

More realistic models of small-scale absorbers allows us to reproduce the evolution and amplitude of the the MFP of ionising photons.





Conclusions and Summary

1. The last stages of reionisation are difficult to model but contain a wealth of information and are regulated by the presence of small-scale absorbers such as LLS.

2. Including LLS in our models extends the EoR and helps us reproduce features reported from the Ly-α forest.

3. The position and density of LLS matter for large-scale statistics.

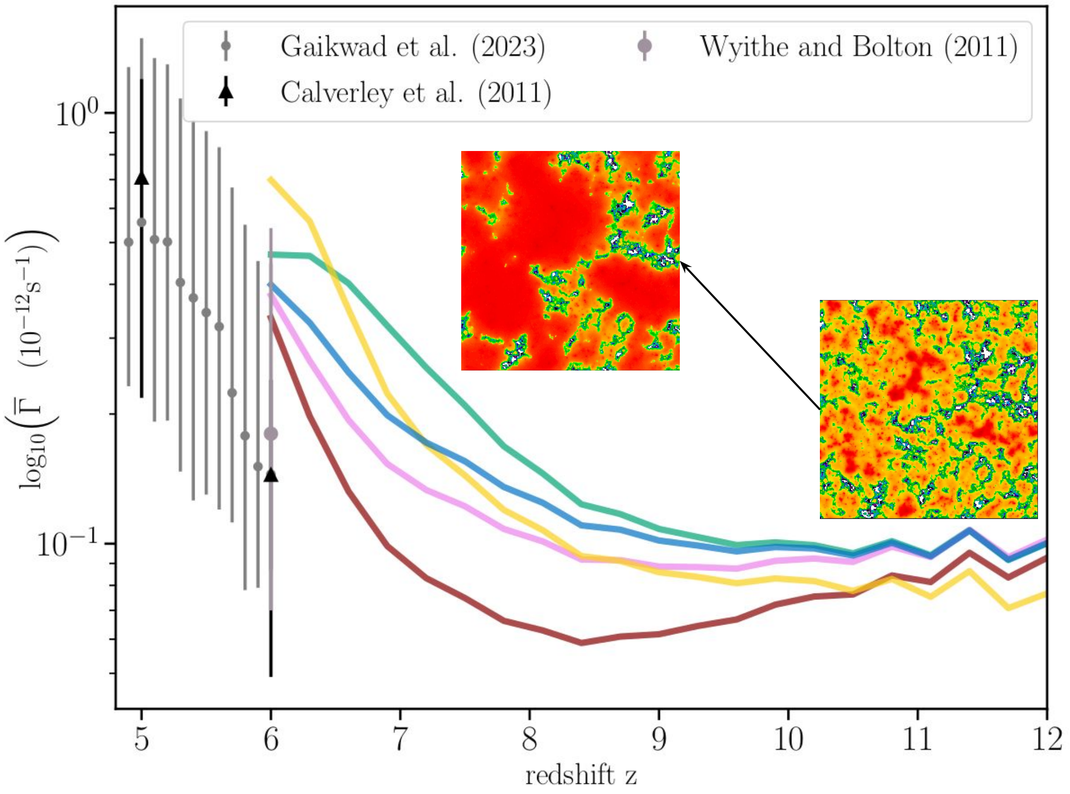
Extra Slides :)

Lyman Limit Systems regulate the UV Background

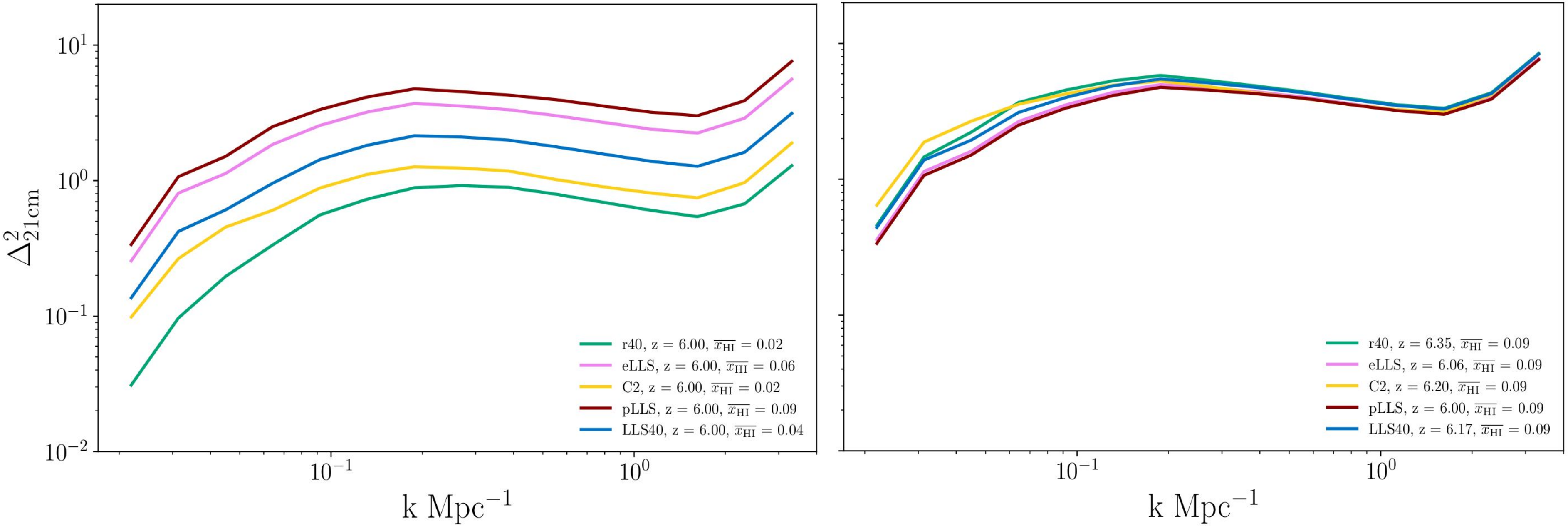
r40 model feature asymptotes.

C2 model overshoot the UVB at z = 6.

eLLS & **pLLS** models agree with high-res hydrodynamic simulations and extend reionisation.



How does this affect the 21-cm power spectrum?



The amplitude of the 21 cm power spectrum is affected by the extension of reionisation.
The implementation of the LLS profoundly dictates the distribution of neutral islands.