Mapping the timing and morphology of the epoch of reionization with Lyman alpha

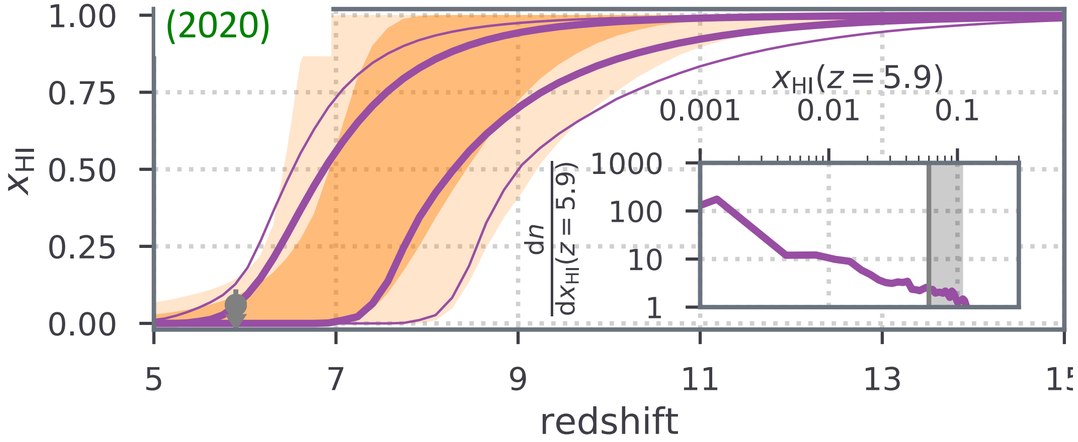
Andrei Mesinger

SCUOLA NORMALE SUPERIORE

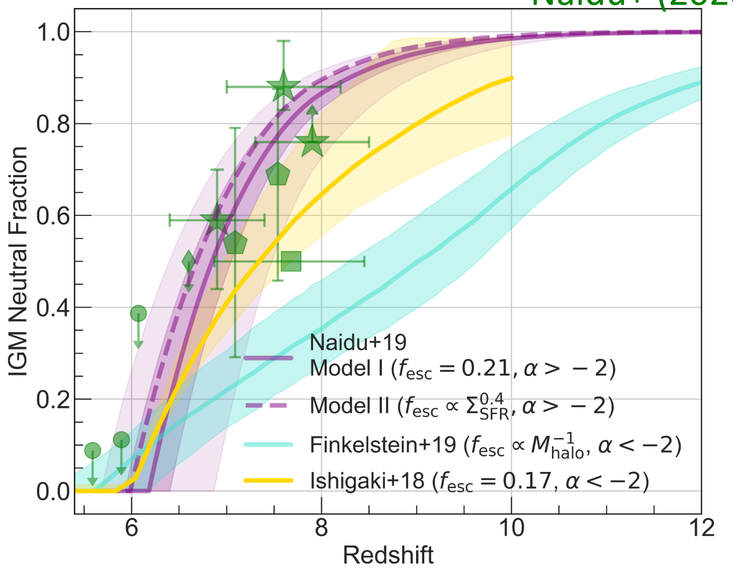
European Research Council

Until recently, the timing of the EoR was fairly uncertain…

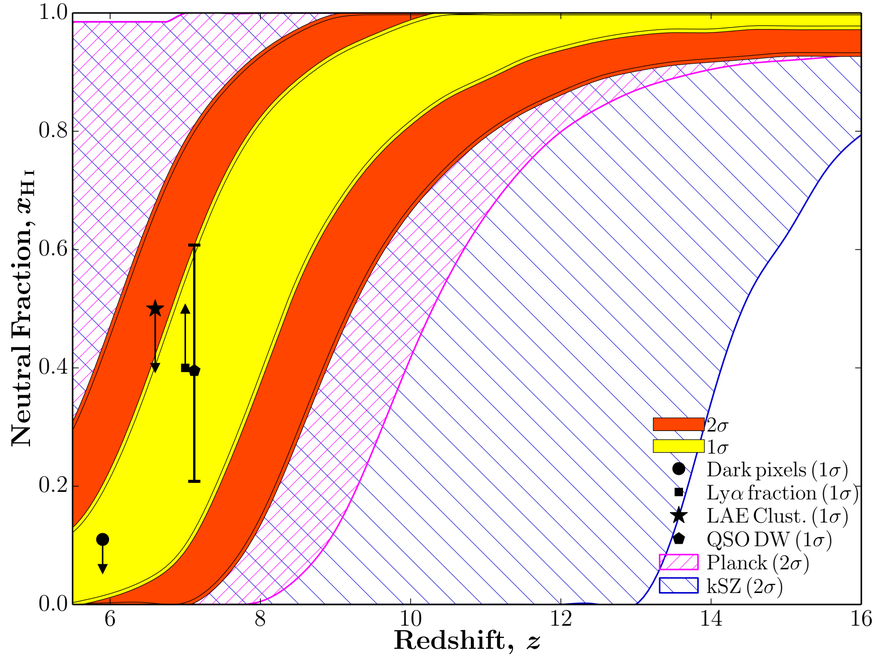
Qin+ (2020)



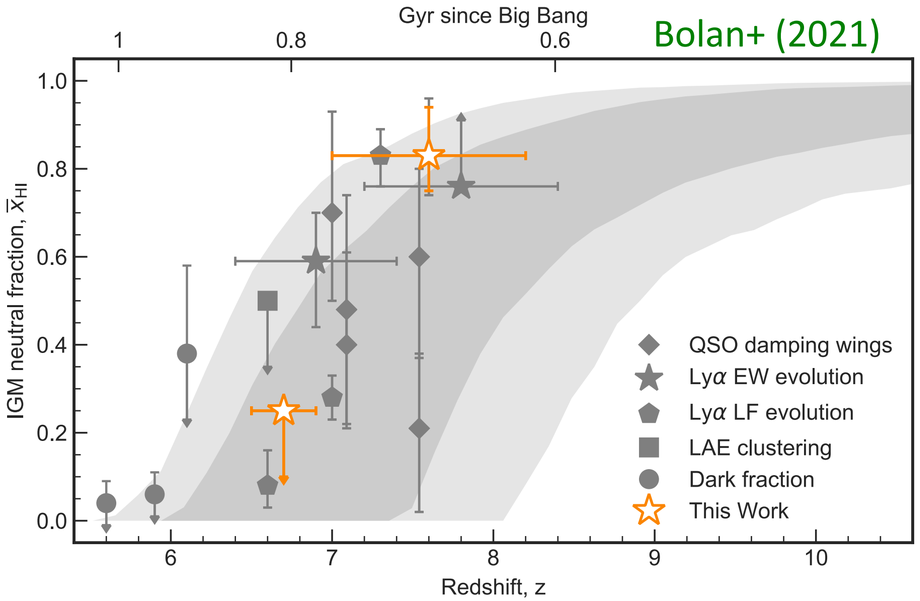
Naidu+ (2020)



Greig & AM (2017)

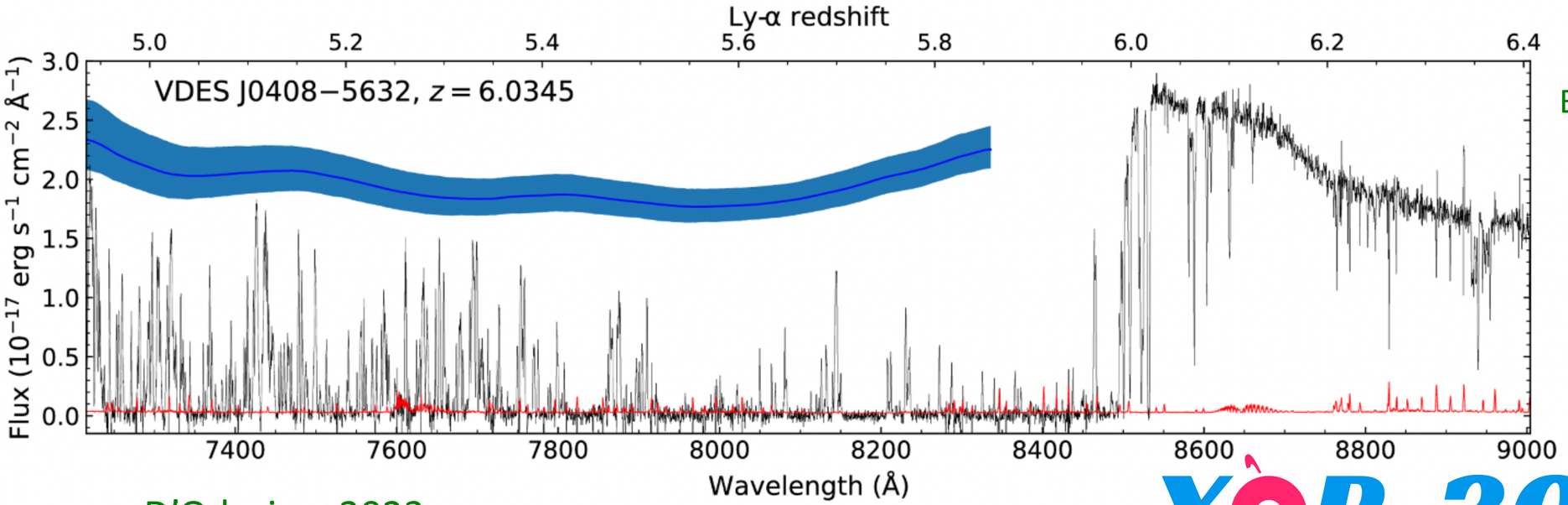


Bolan+ (2021)



Game changer: XQR-30

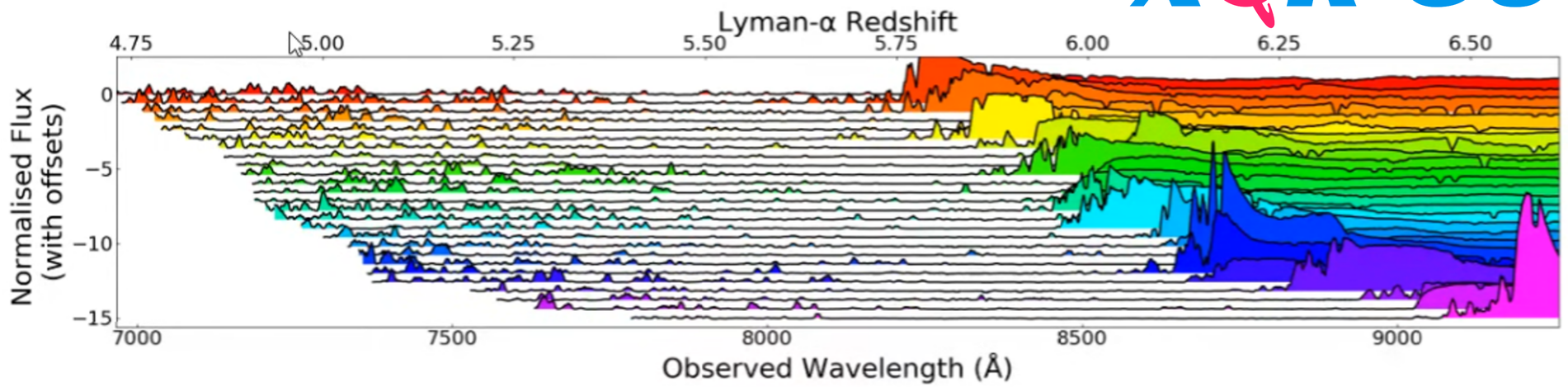
super high-quality QSO spectra at z=5.8-6.6 using X-Shooter on VLT



Bosman+2022

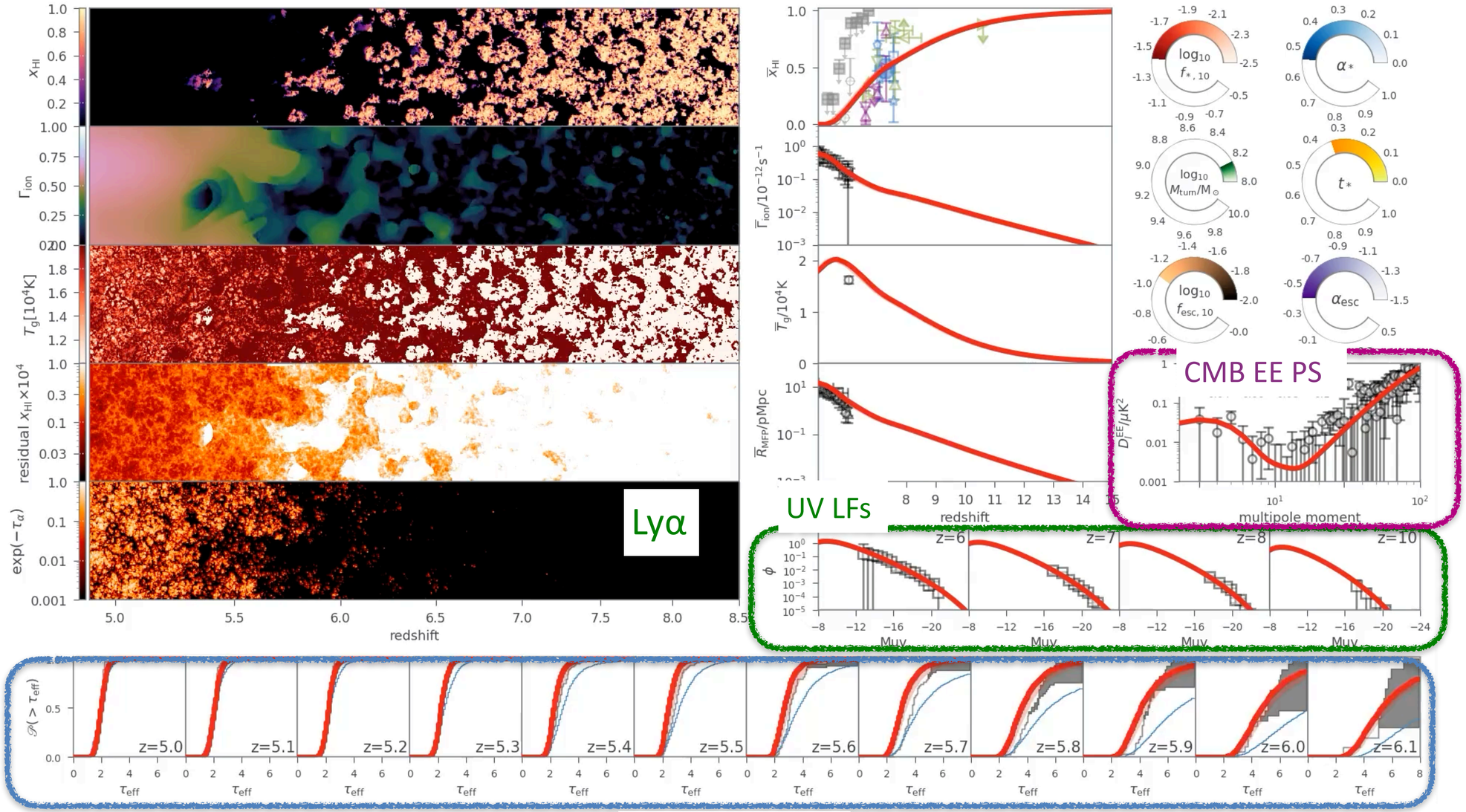
D'Odorico+2023

XQR-30



total sample >40 spectra probing forest at 5<z<6.4

Forward modeling: Lyα forest + UV LFs + CMB τ



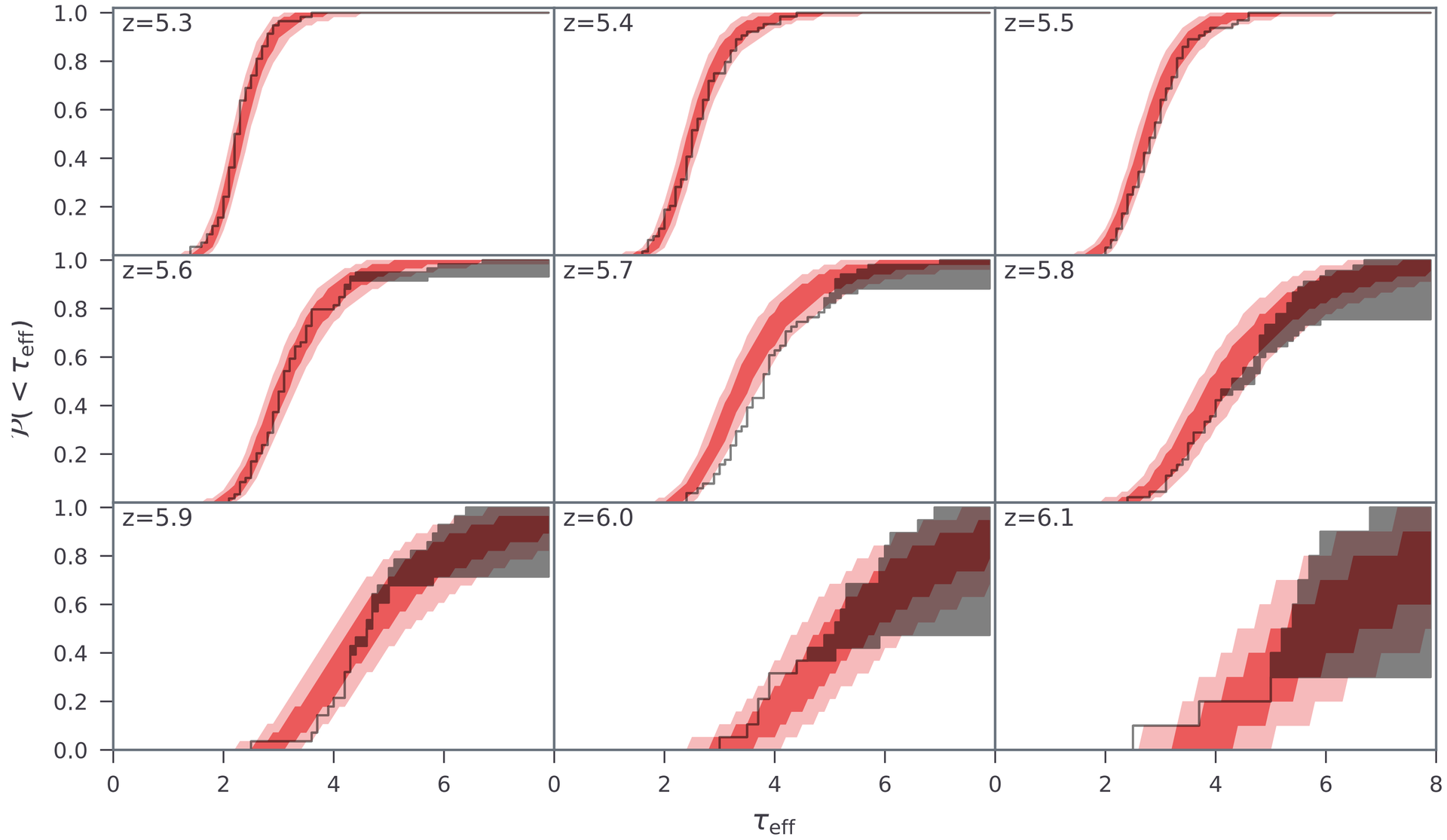
Lyα opacity CDF

Qin, AM+, in prep

Movie credit: Y. Qin

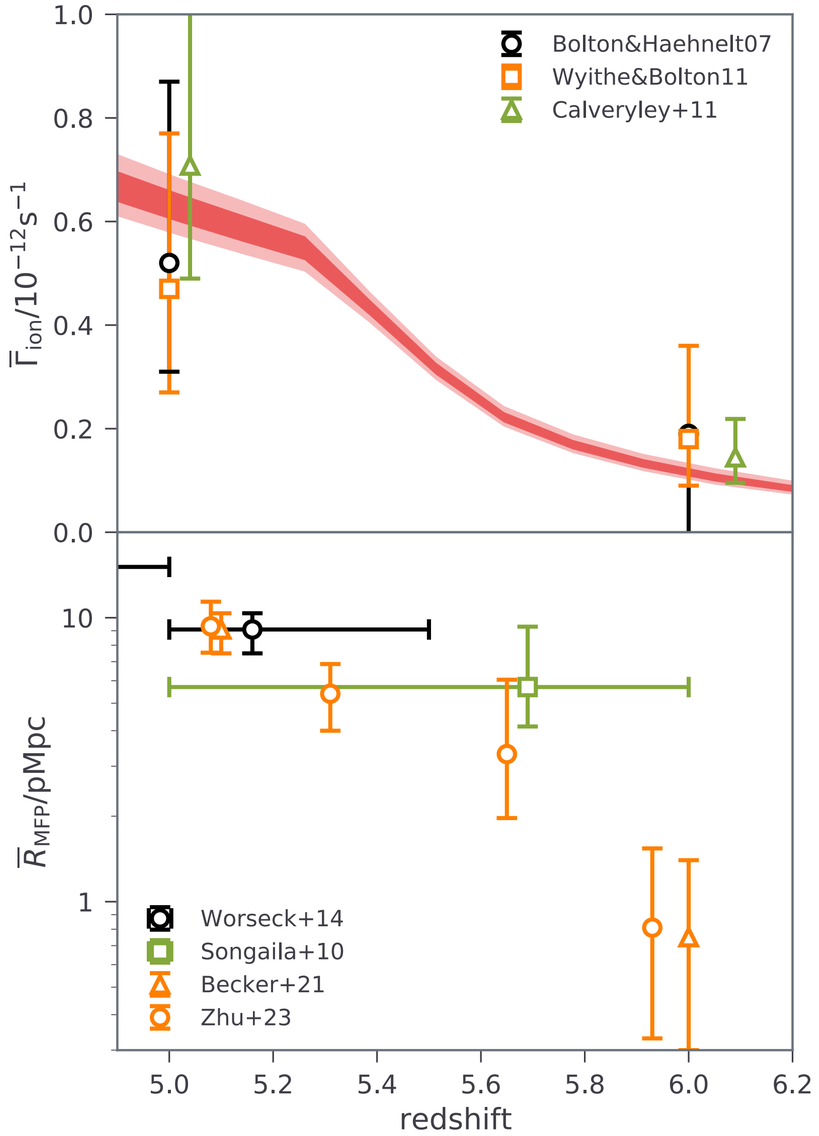
Forest τ_{eff} distributions

Qin, AM+ in prep



Joint fit over all redshift bins! No recalibration at each redshift, hyperparameters, removing mean flux, ad-hoc tuning / effective parameters, artificially scaling mfp or emissivity vs z, etc.

Average IGM properties

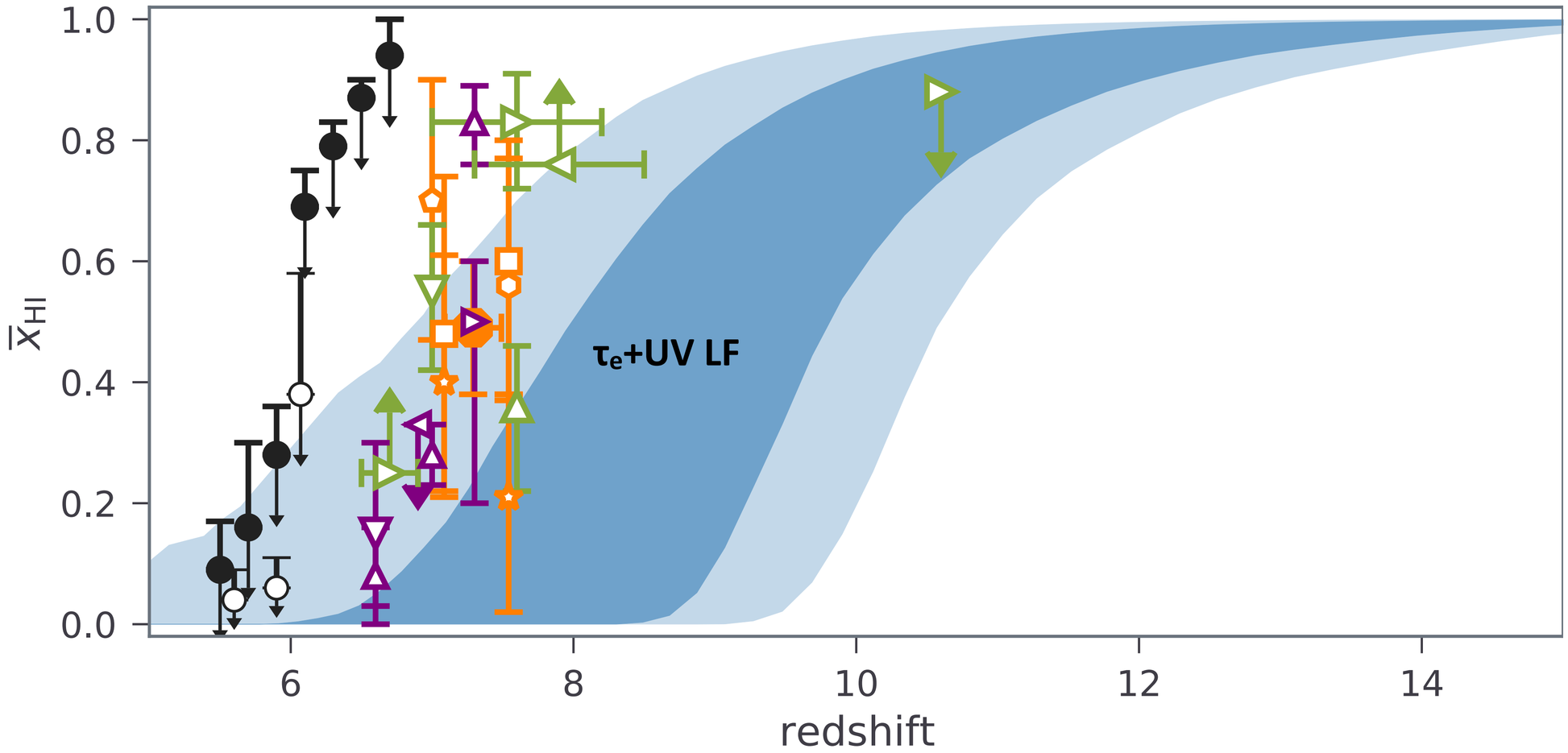


Qin, AM+ in prep

Consistent with data and IGM-parameter studies

None of these data points are used in the likelihood!

Inferred EoR history



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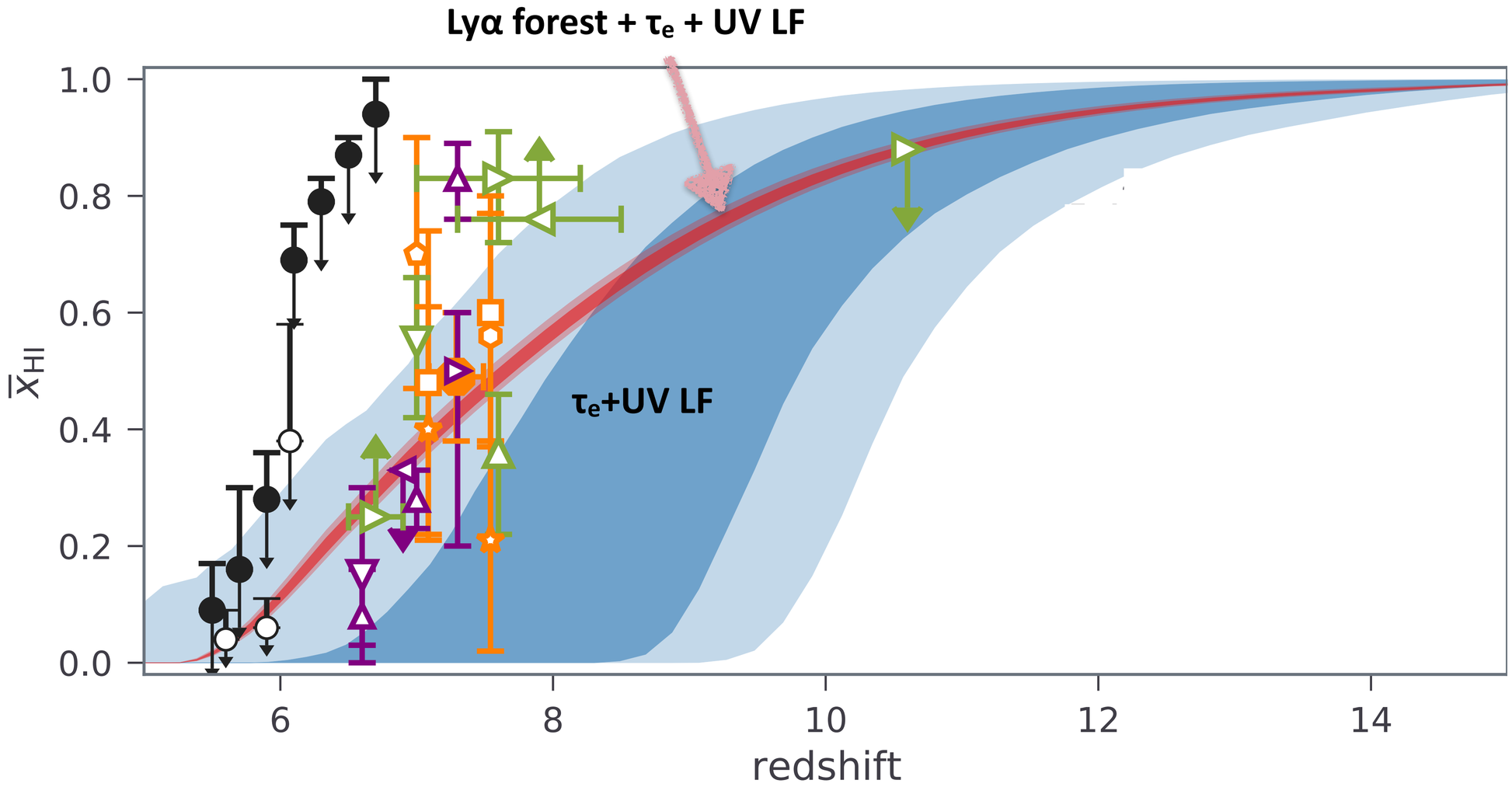

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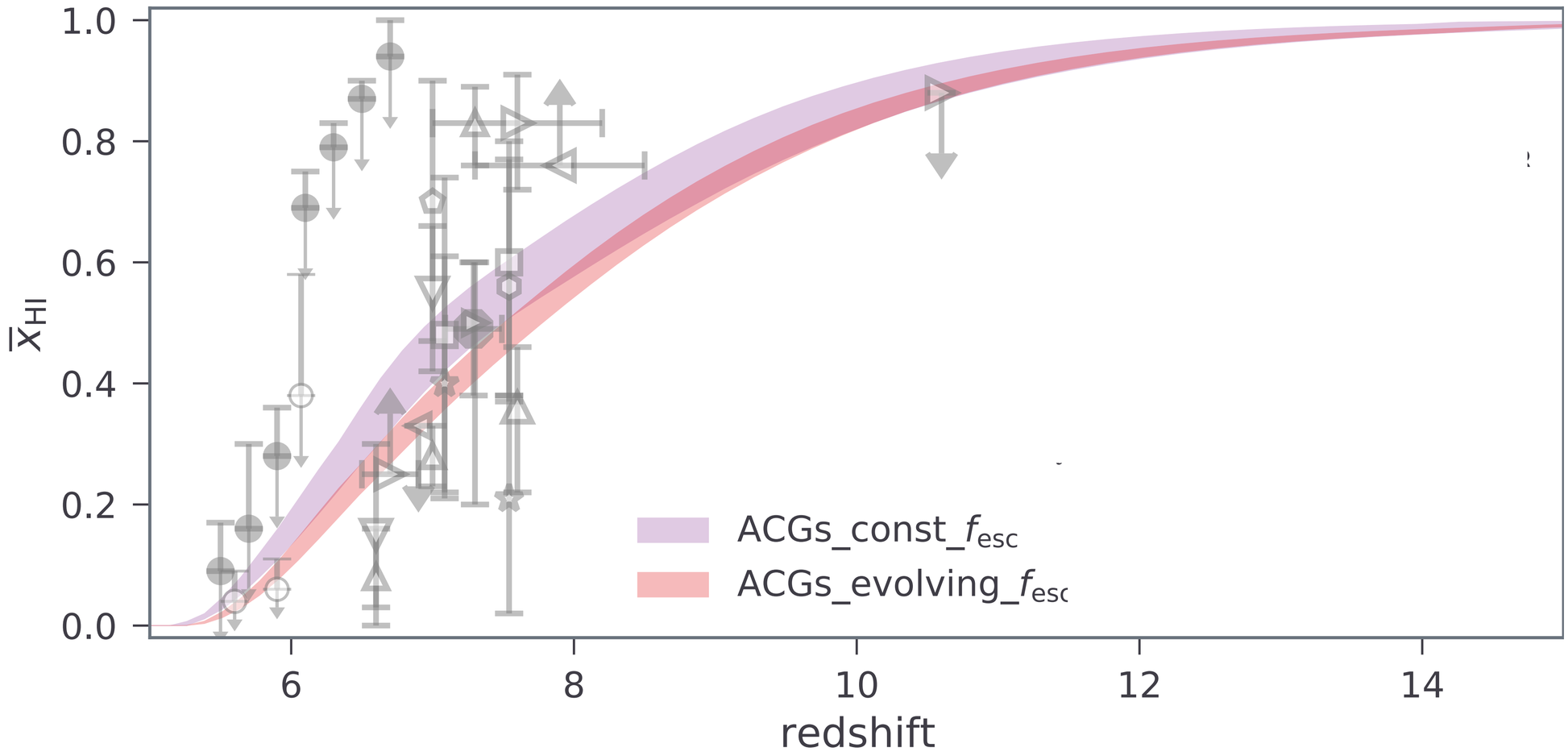

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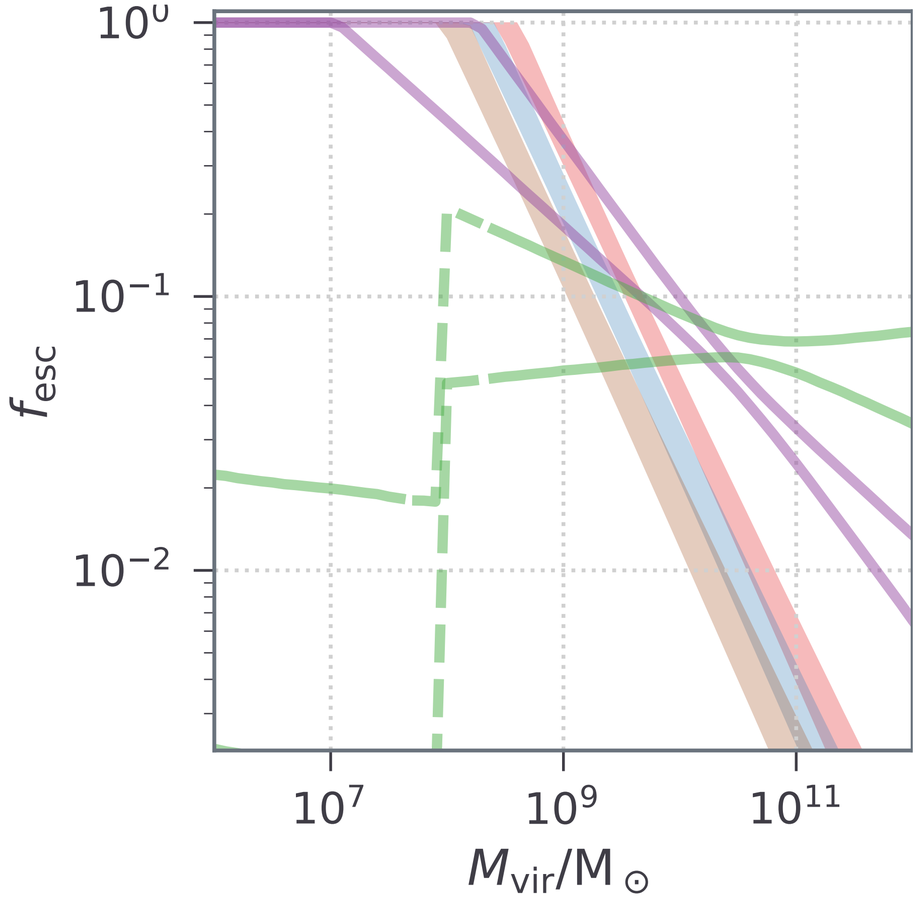
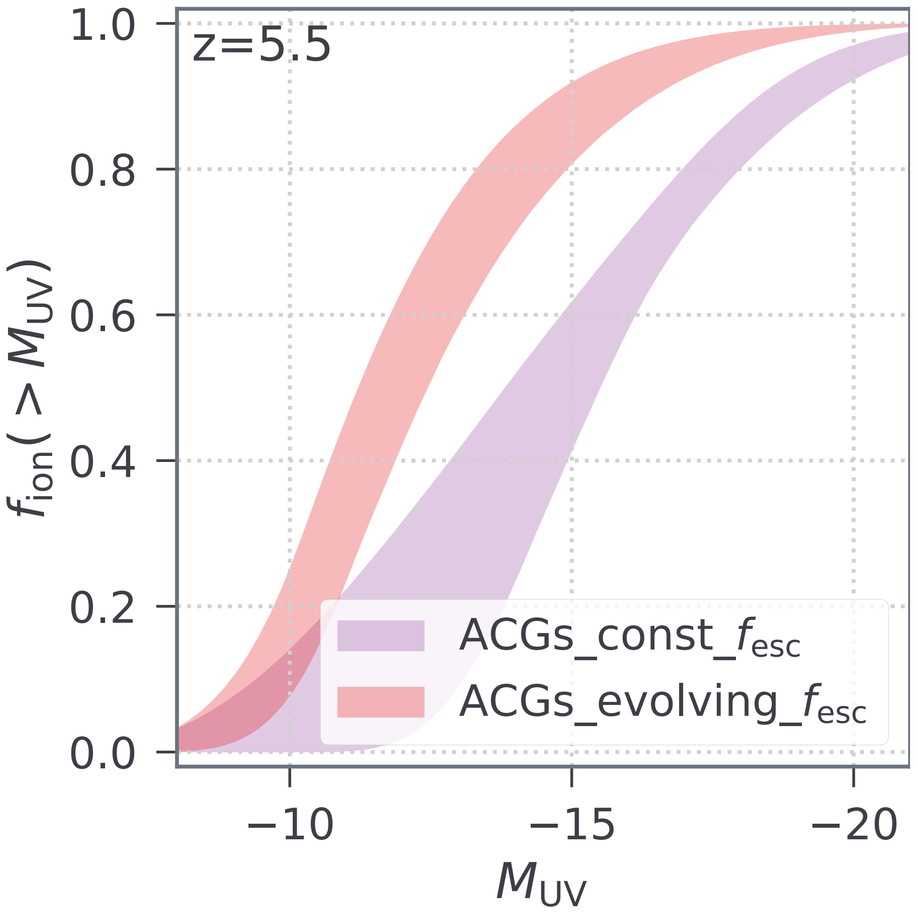
Qin, AM+ in prep

Which galaxies reionize the Universe?

Qin, AM+ in prep



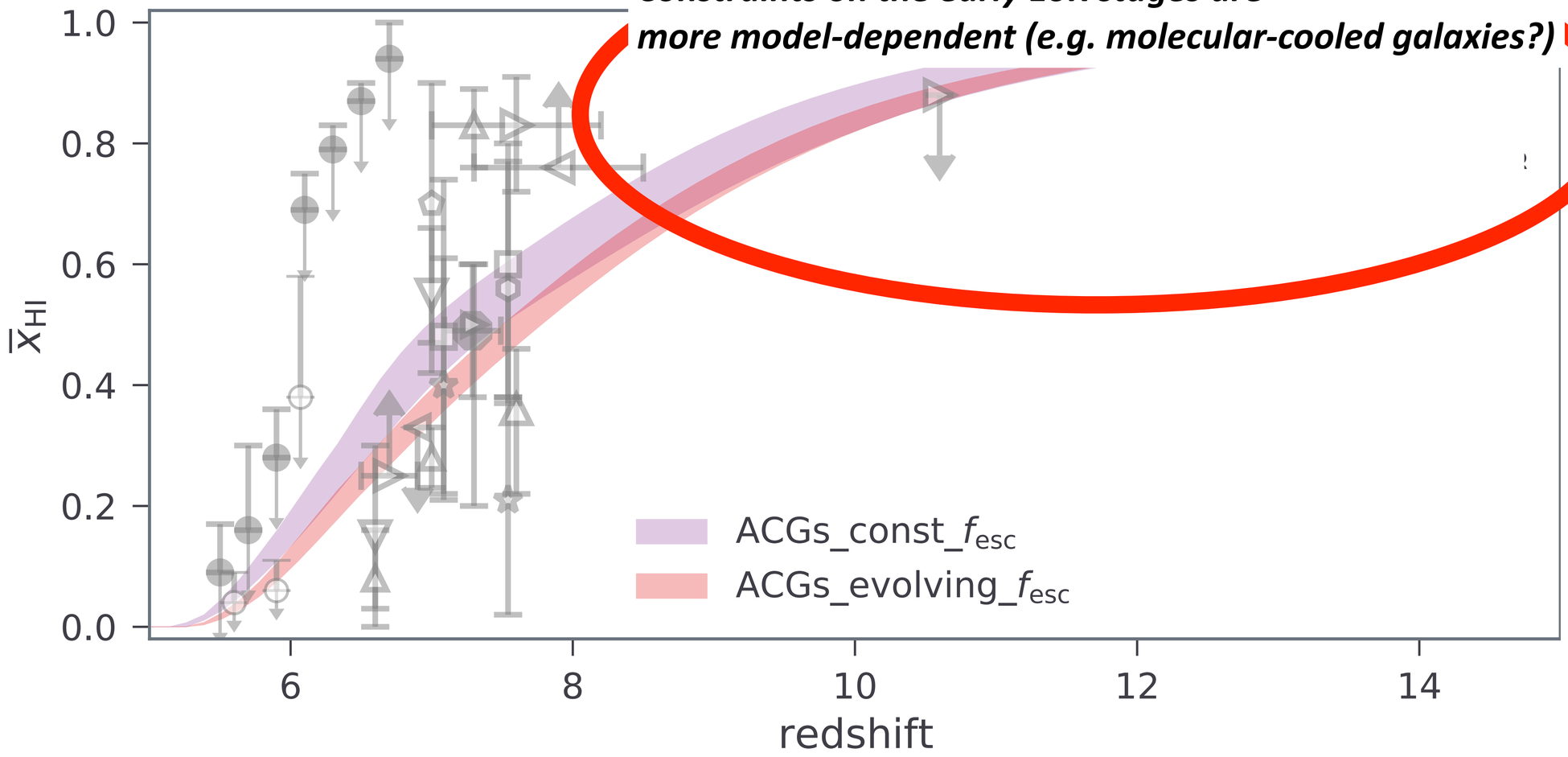


all models agree that the escape fraction has to **decrease with mass**

ΔMuv ~ 2-3 model-to-model scatter in inferred galaxy contribution to EoR

Inferred EoR history

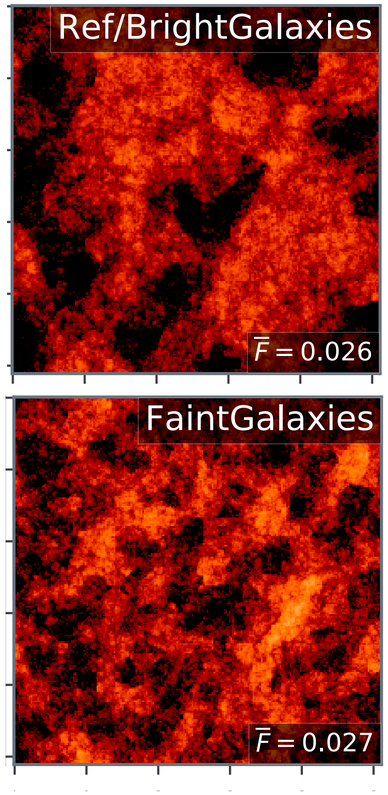
Constraints on the early EoR stages are more model-dependent (e.g. molecular-cooled galaxies?)



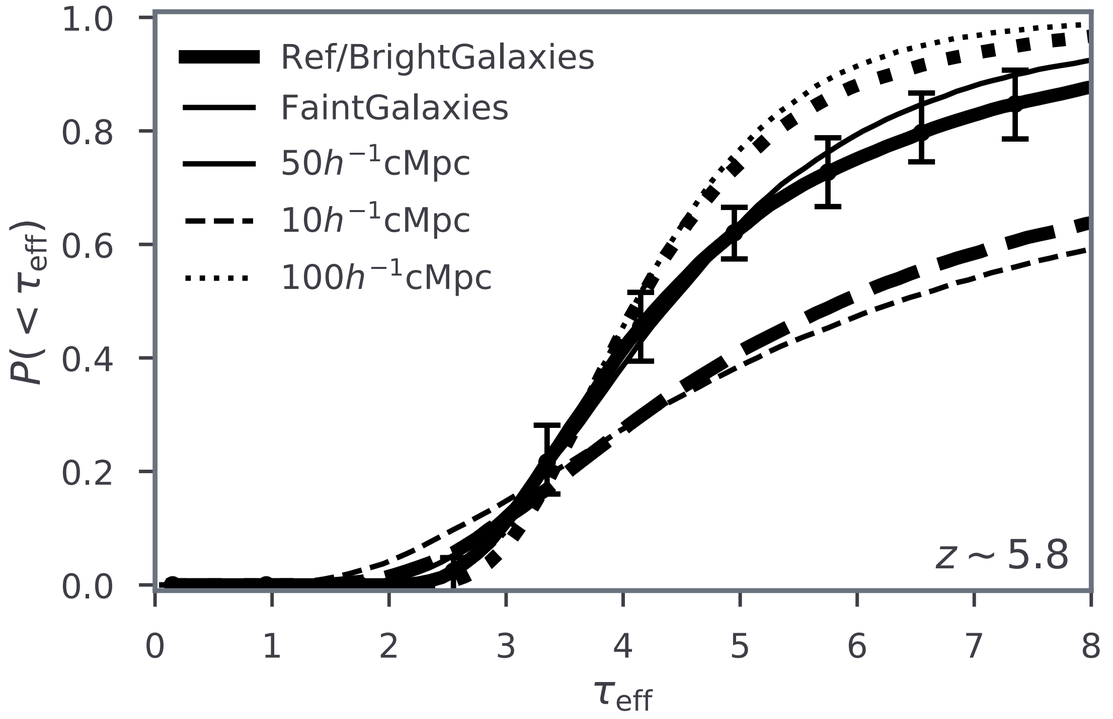
None of these data points are used in the likelihood!

Qin, AM+ in prep

Unfortunately, the Lyα forest does not have the dynamic range to probe EoR morphology

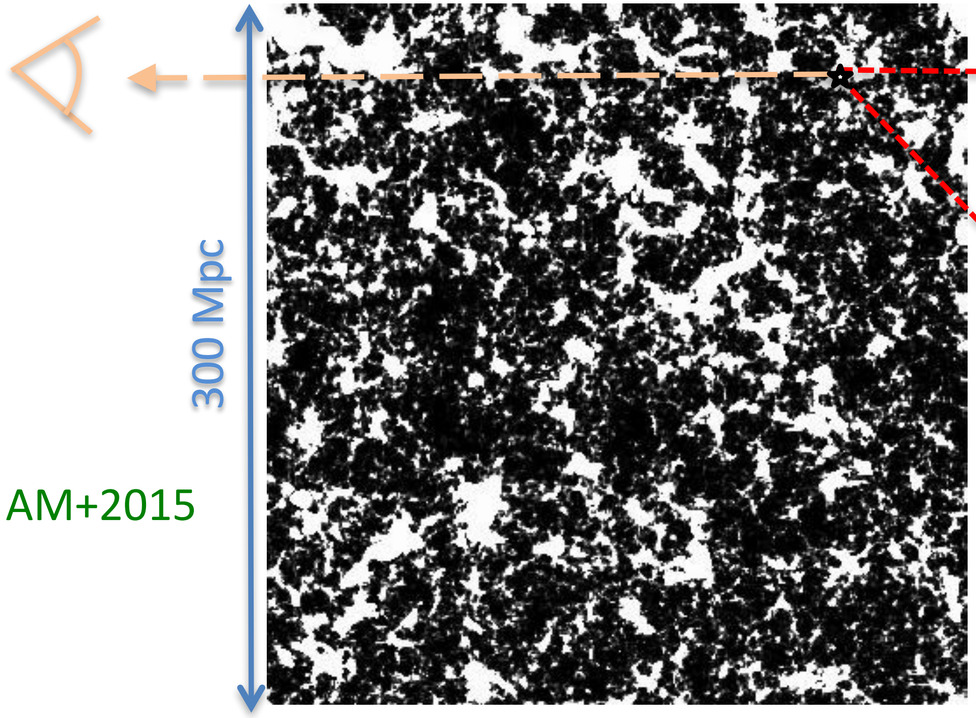


Qin+2021

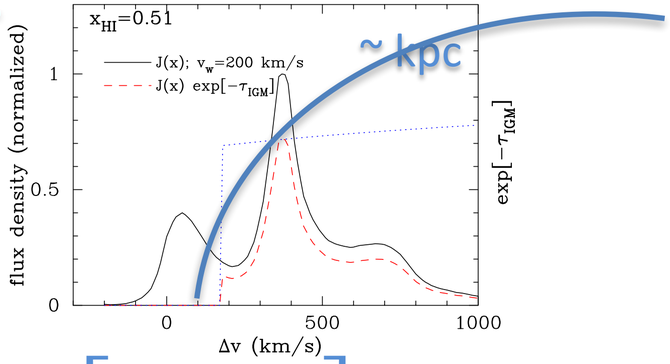


We need other probes to understand morphology…

Lyman alpha from galaxies is a great tool to study EoR topology NOW



AM+2015



$\exp[-\tau_{reion}]$

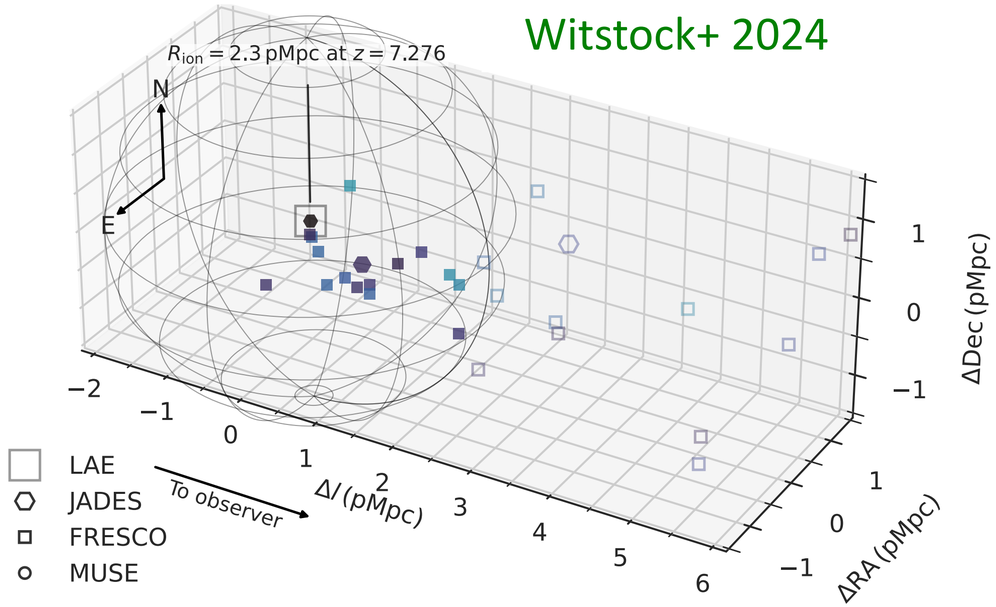
during reionization, cosmic HI patches absorb Lyα photons in the damping wing of the line

Ionization morphology allows us to:

- confirm **which galaxies drive reionization**
- connect the **growth of individual cosmic HII regions to the properties of galaxies** inside them
- connect the JWST-detectable galaxies to the **thousands of surrounding galaxies too faint to detect**

Exciting recent observations of galaxy groups

e.g. Tilvi+20; Endsley & Stark 22; Jung+22; Saxena+23; Whitler+23; Hayes & Scarlatta 23; Umeda+23; Witstock+24



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but…

Analysis of surrounding HII morphology is very approximate / qualitative…

- typically observed galaxies are treated **individually?!?** (*HII regions come from the cumulative radiation of* ***thousands of fainter galaxies***)
- assume **uniform reionization?!?** (*reionization is patchy -> **scatter and bias** e.g.* AM & Furlanetto 08)
- ignores or simplifies many sources of **stochasticity** when assuming **intrinsic emission?!? (e.g. see Ivan's talk)**

New frameworks for studying EoR topology using galaxy “groups”

in collaboration with **Ivan Nikolić** (SNS), **Ting-Yi Lu** (DAWN), Charlotte Mason (DAWN)

Inferring bubbles around galaxies

GOAL: Infer the position and size of an HII region, given galaxy observations

$$P(\mathcal{O}, R_b \,|\, \mathbf{x}^i, f_\alpha^i(\lambda), M_{\rm uv}^i, z)$$

Nikolić, AM+ in prep

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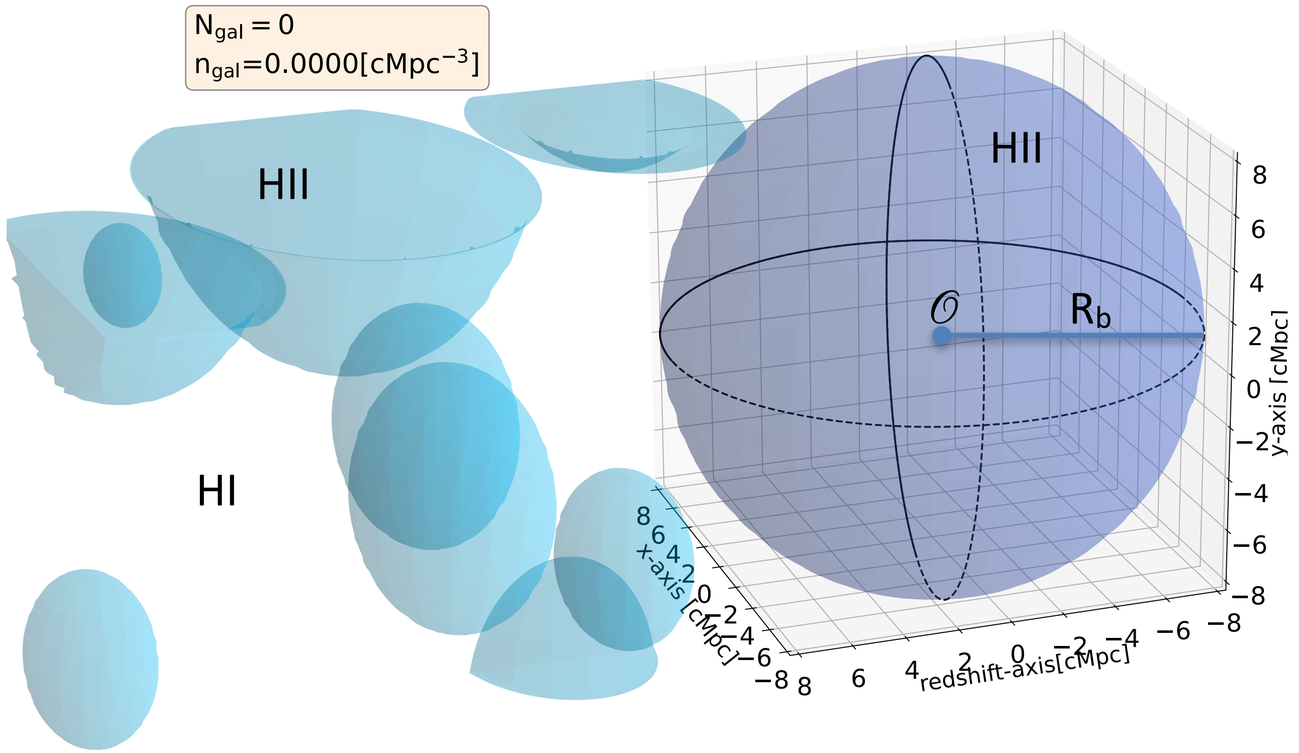
$$P(\mathcal{O}, R_b \,|\, \mathbf{x}^i, f_\alpha^i(\lambda), M_{\rm uv}^i, z)$$

Forward model sources of stochasticity:

- global neutral fraction
- surrounding patchy EoR topology
- galaxy location
- Muv
- Lyα intrinsic flux (Δv, EW)
- NIRSpec noise

Nikolić, AM+ in prep

Inferring individual bubbles around galaxy groups



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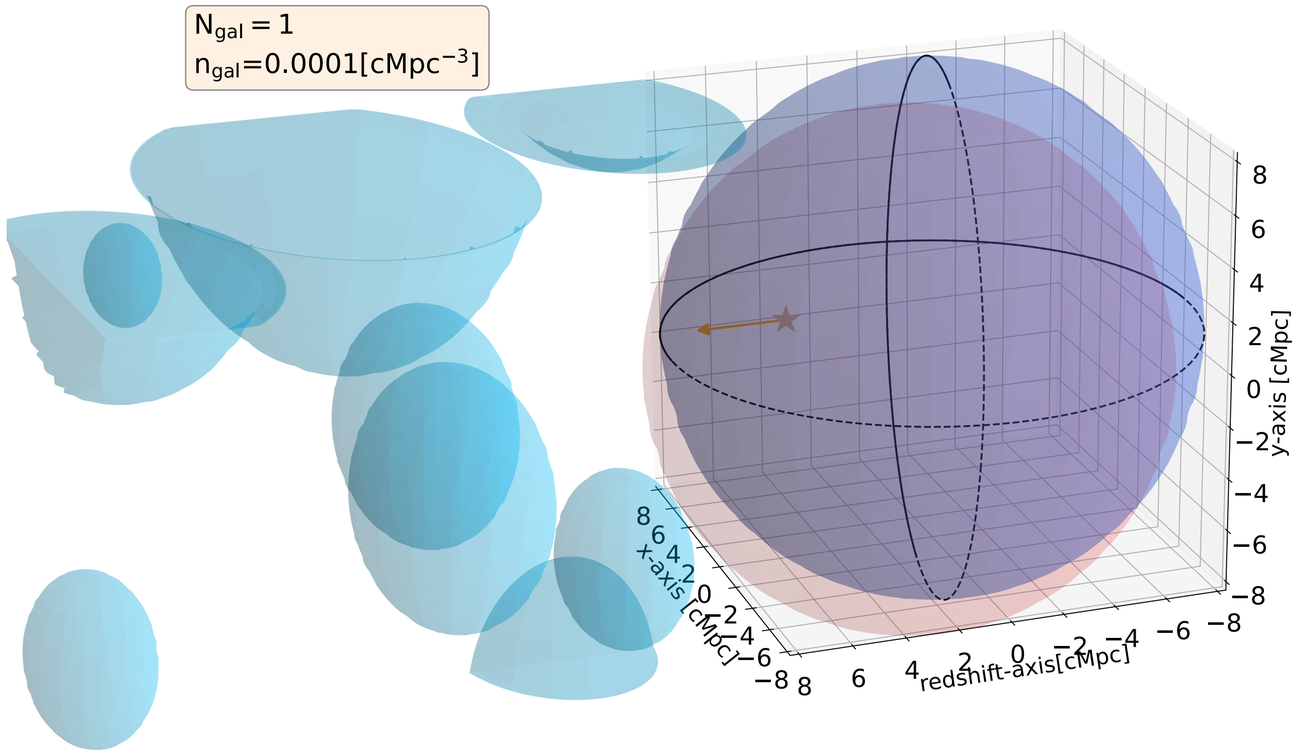

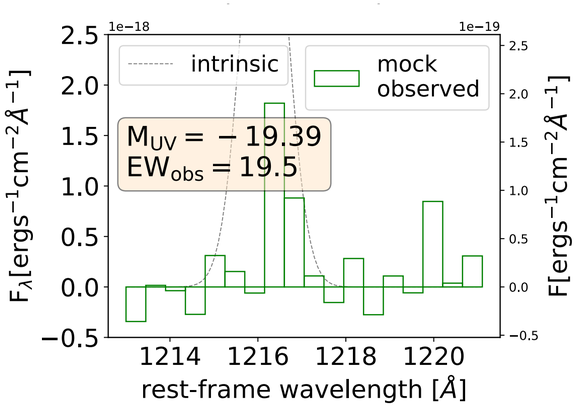

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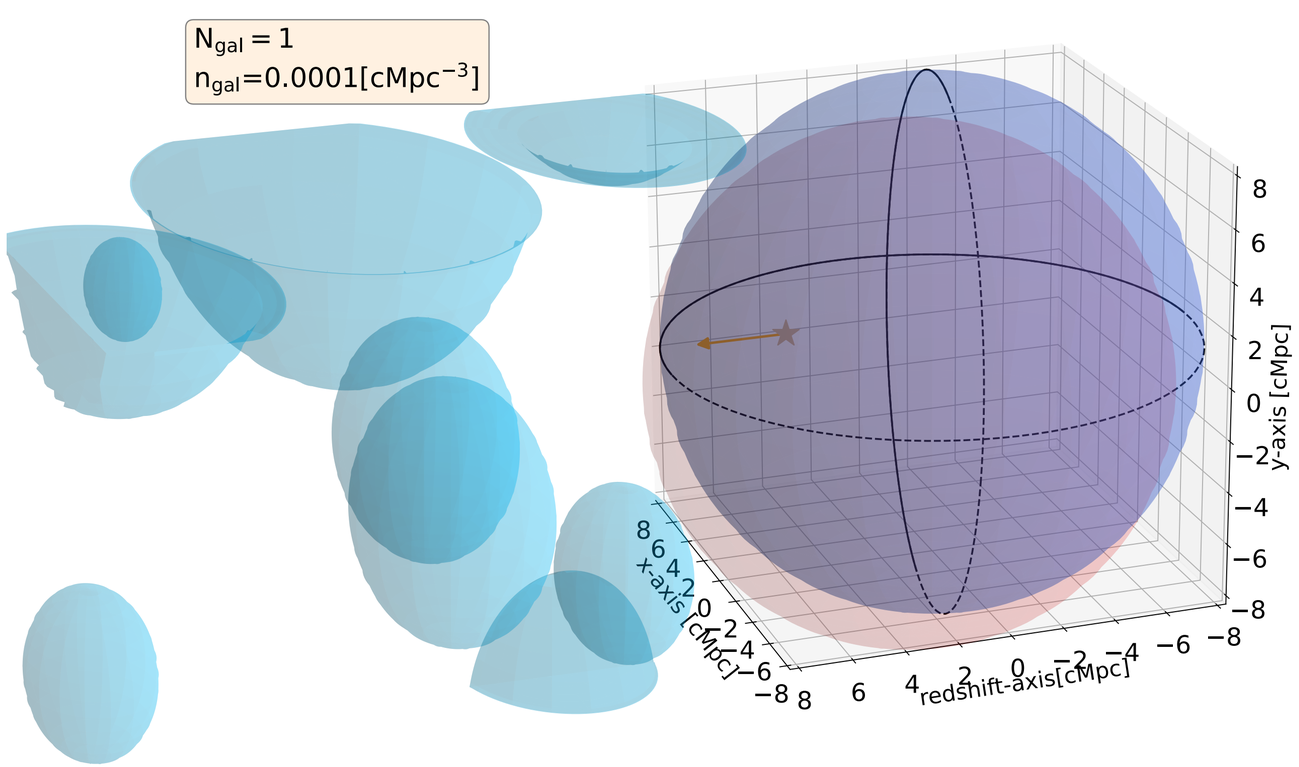

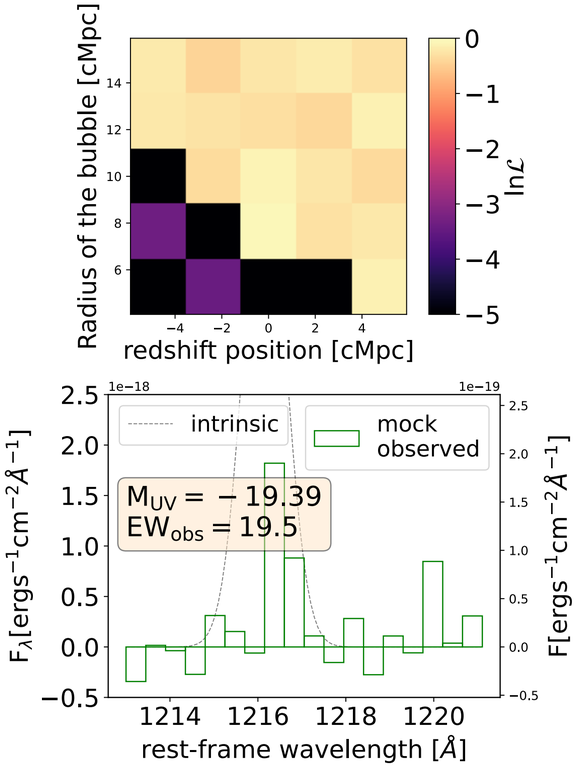

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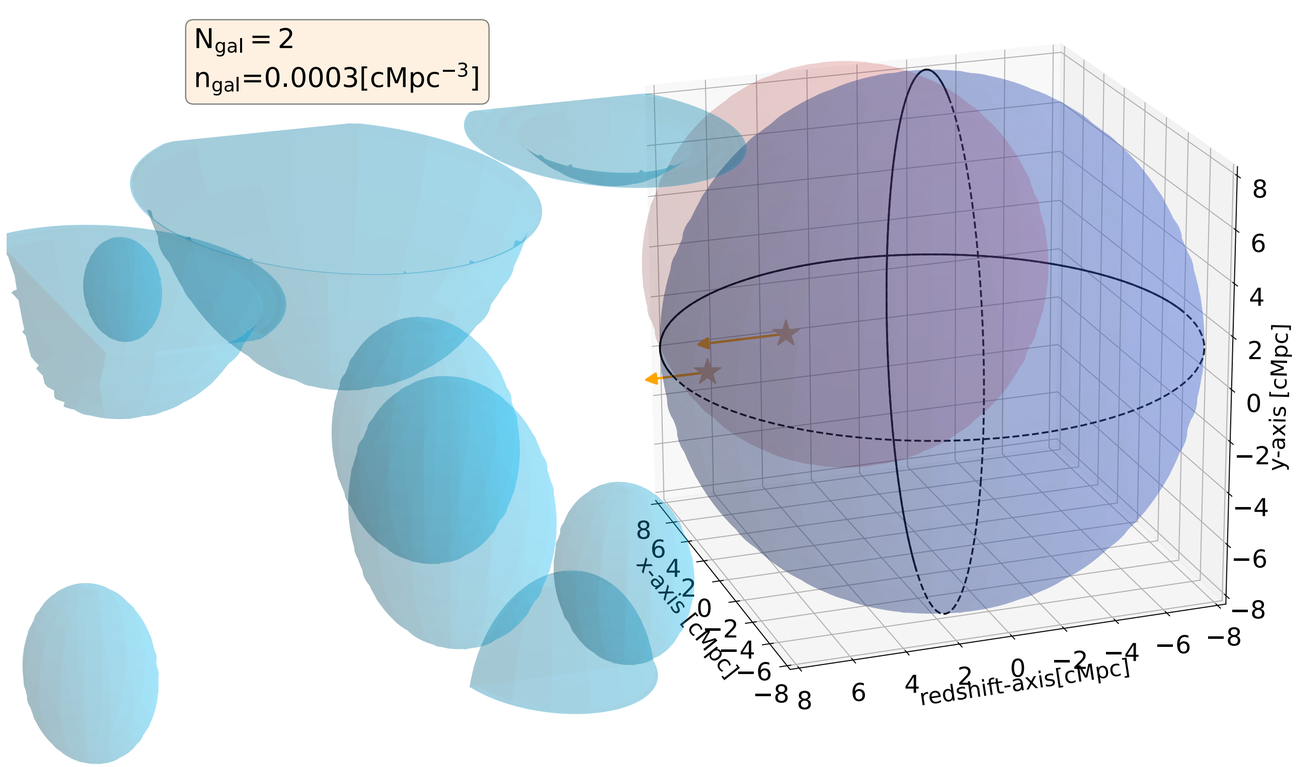

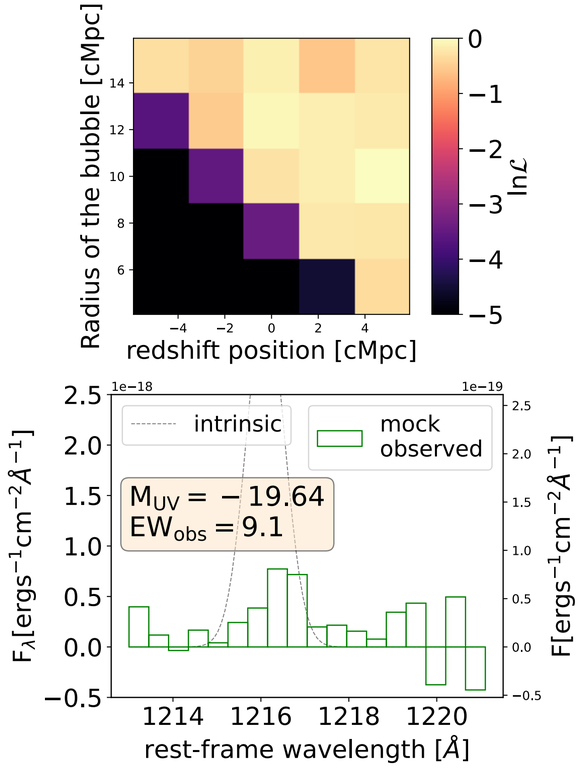

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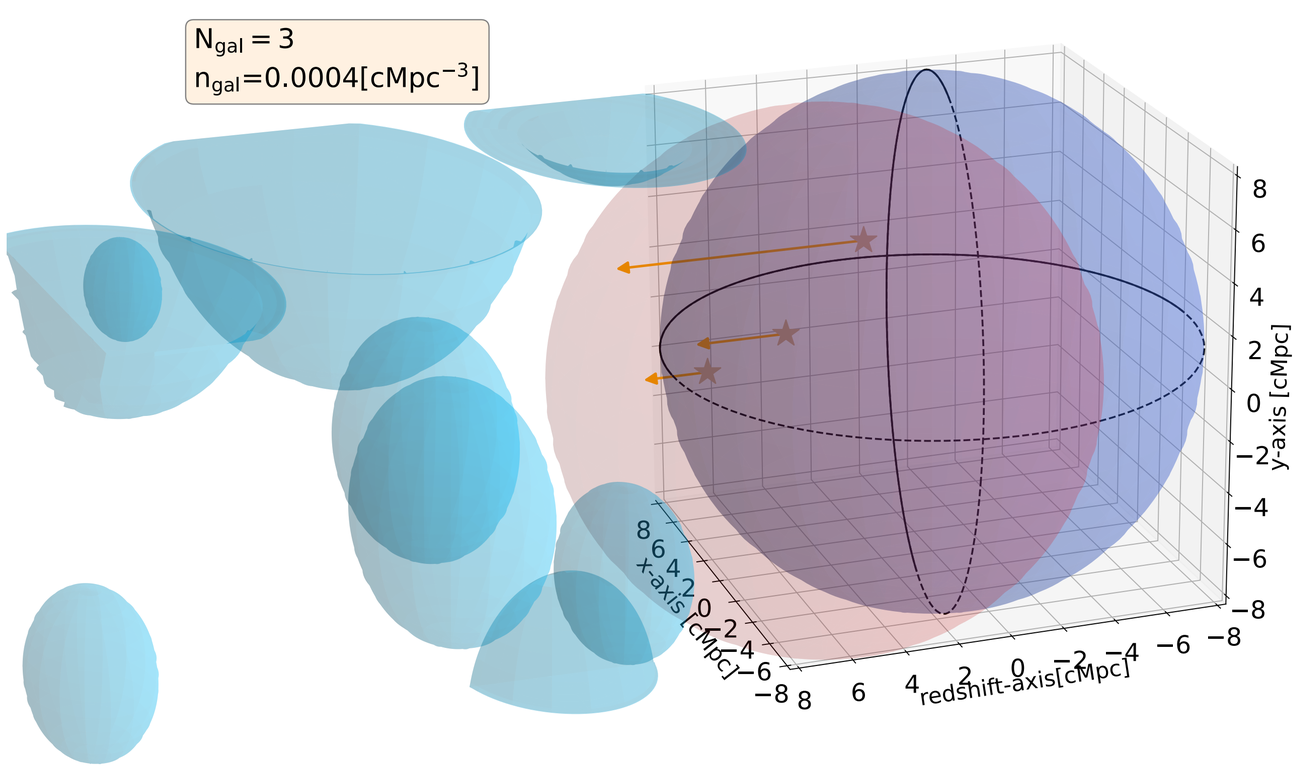

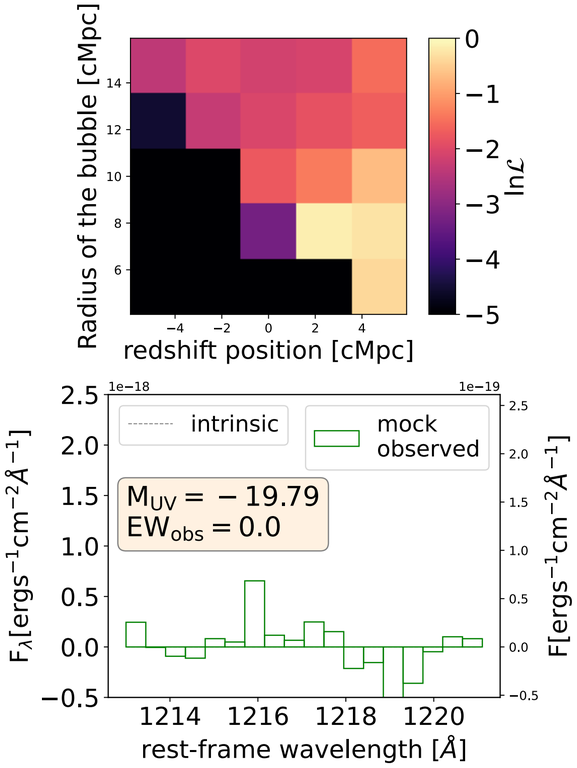

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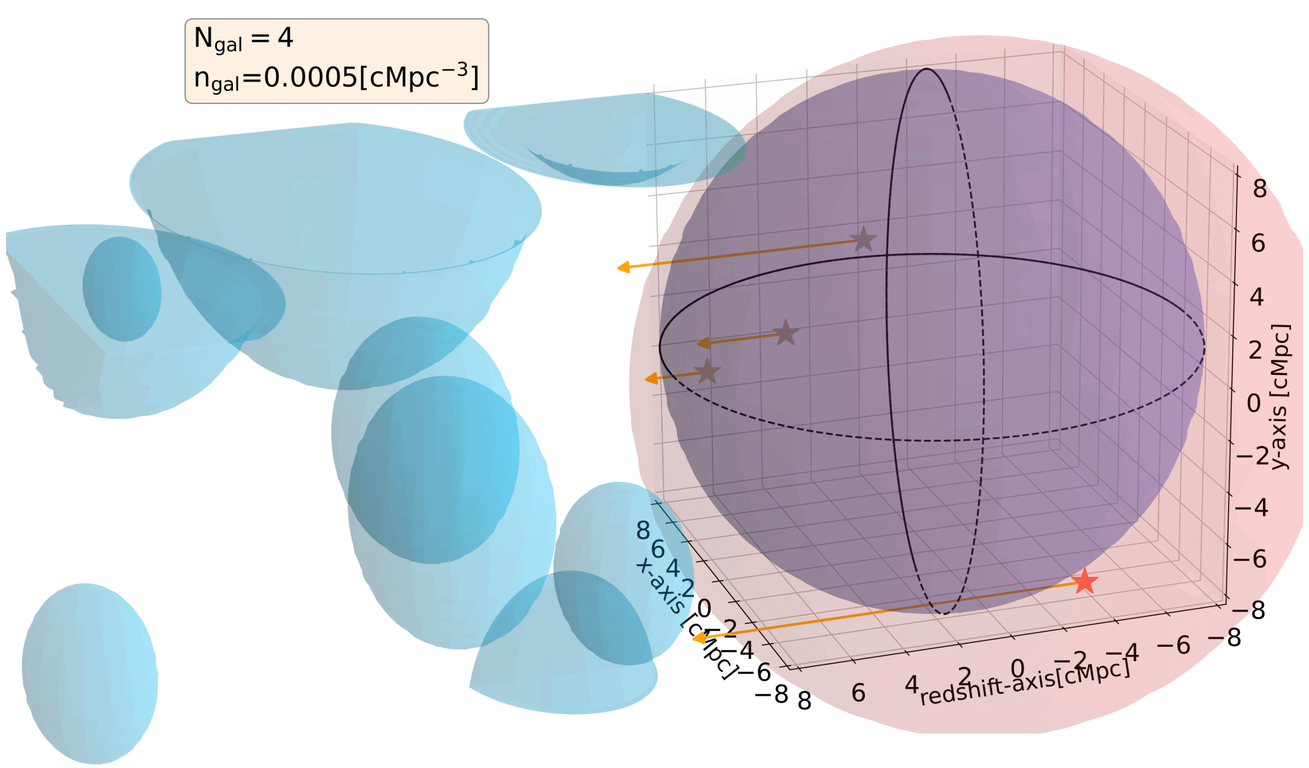
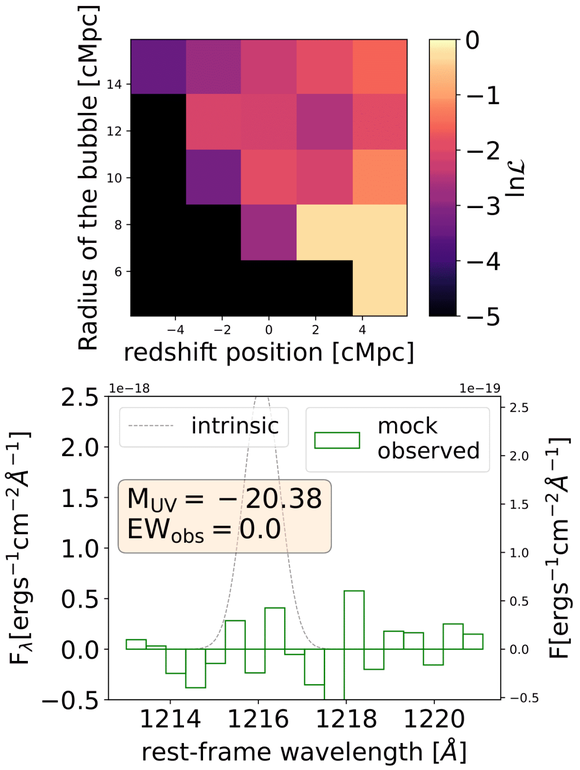
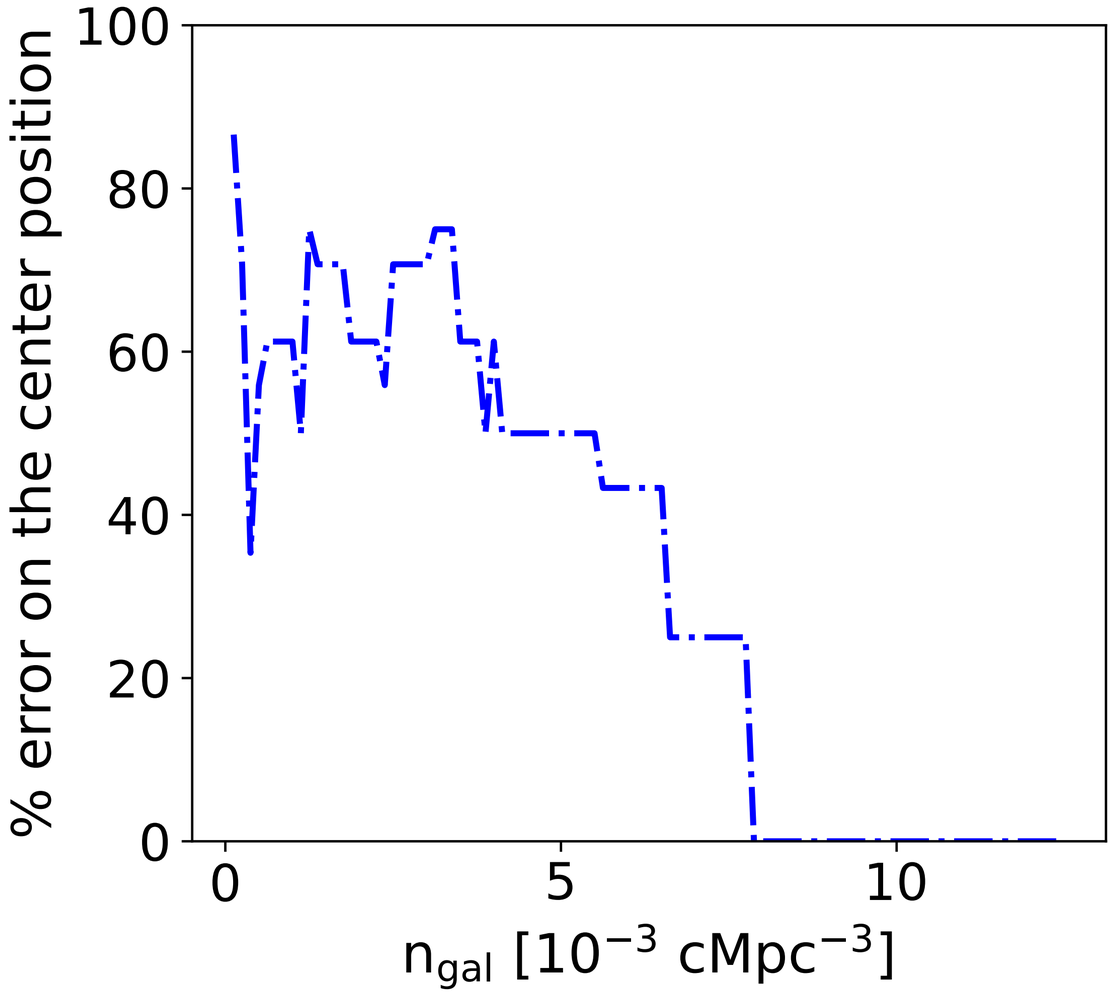


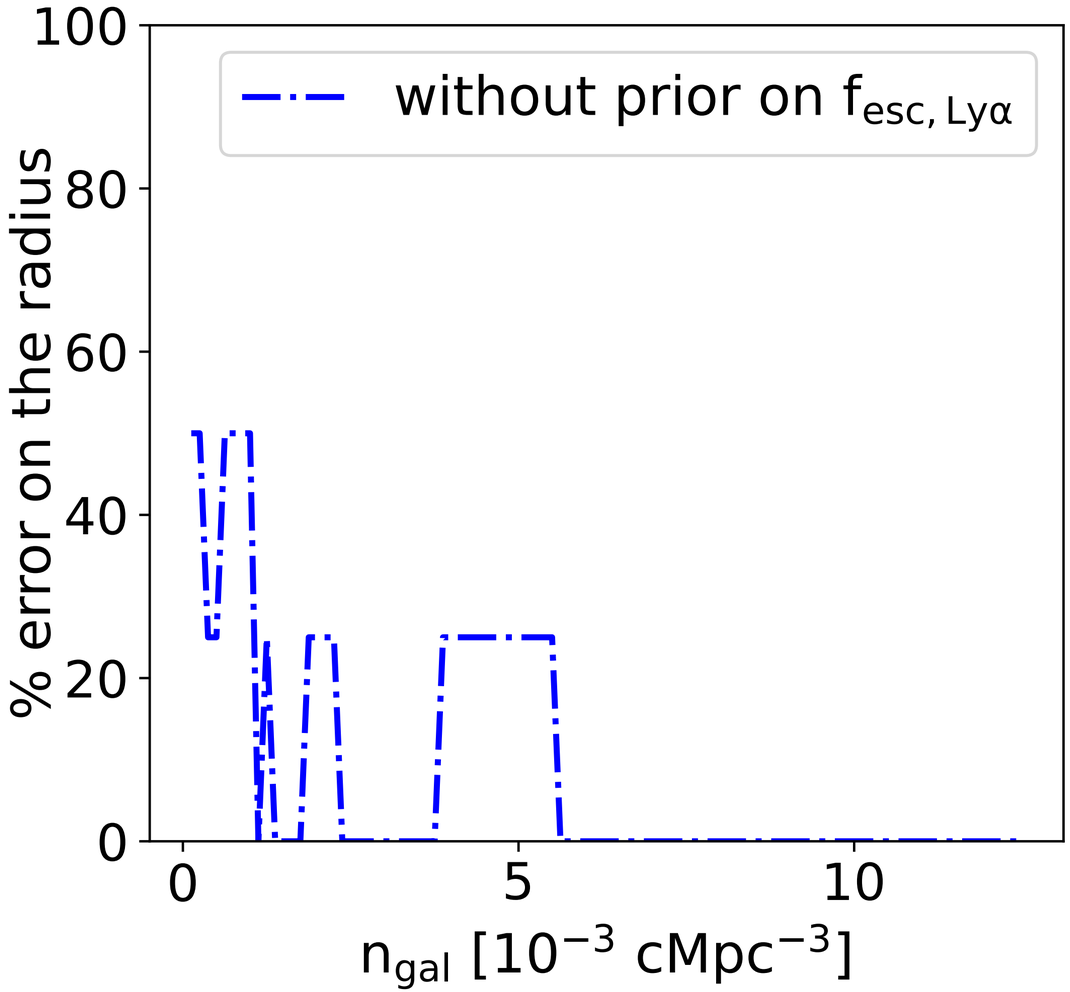


Nikolić, AM+ in prep

How many galaxies are needed?

$R_{fid} = 10$cMpc, $\langle x_H \rangle = 0.8$, z=7.5





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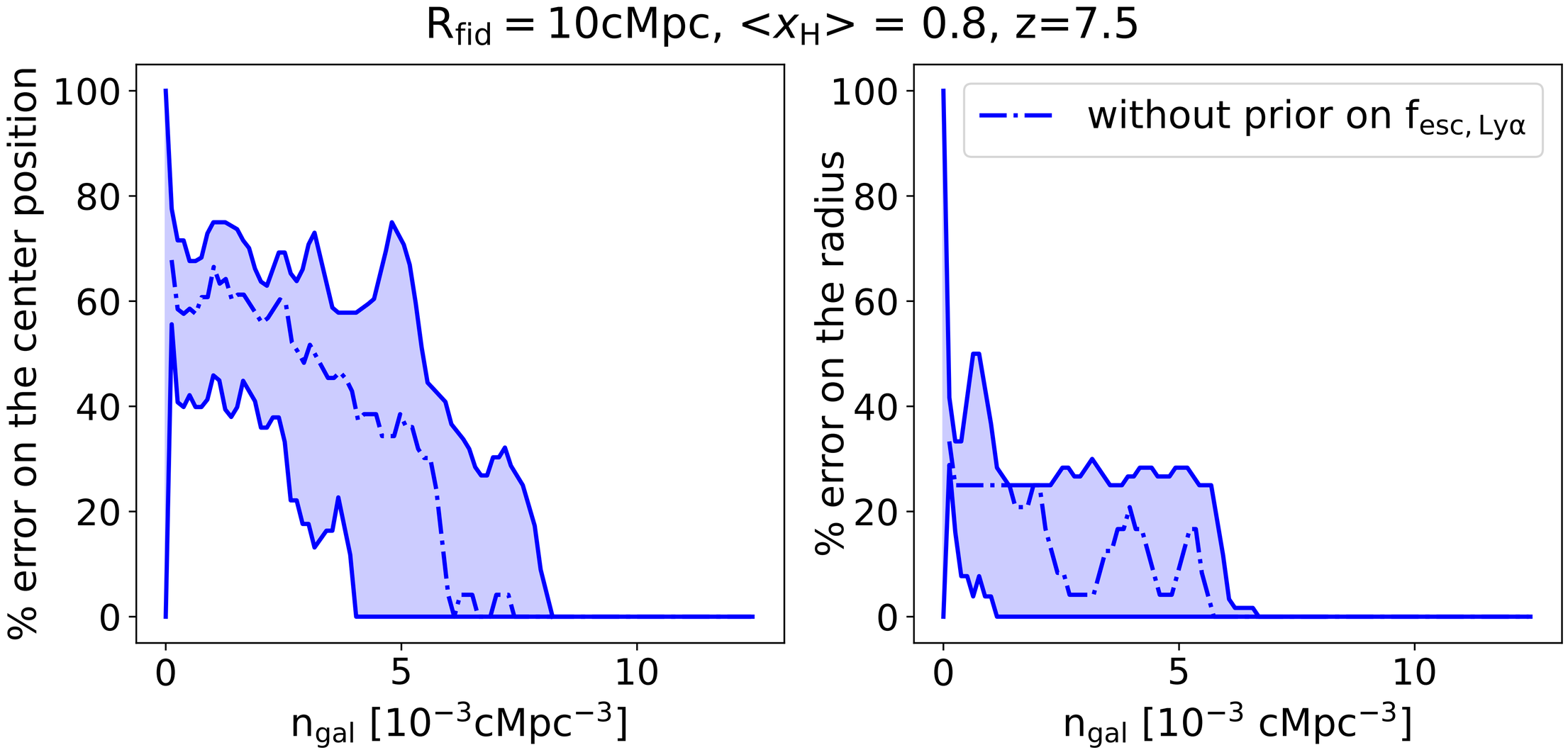

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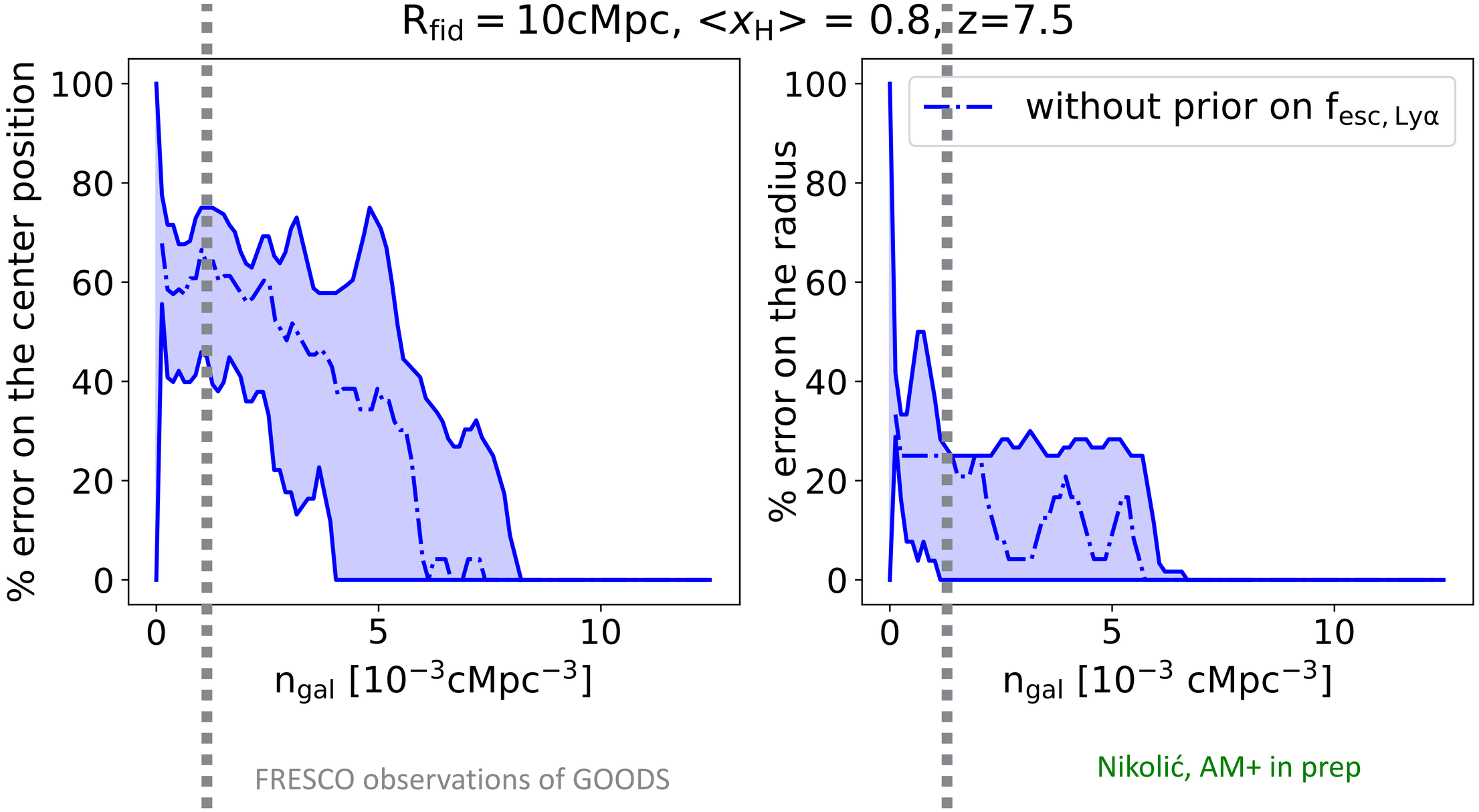

FRESCO observations of GOODS

Nikolić, AM+ in prep

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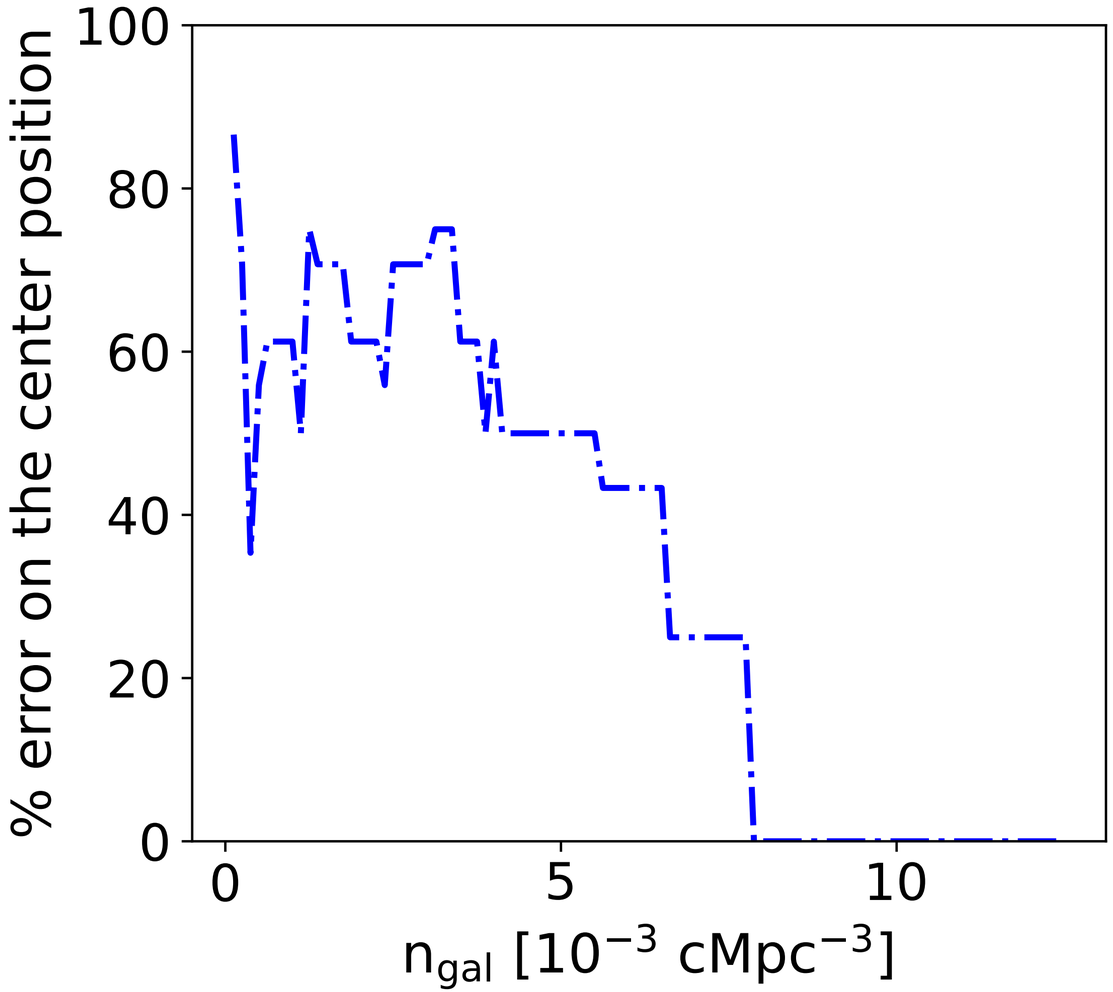

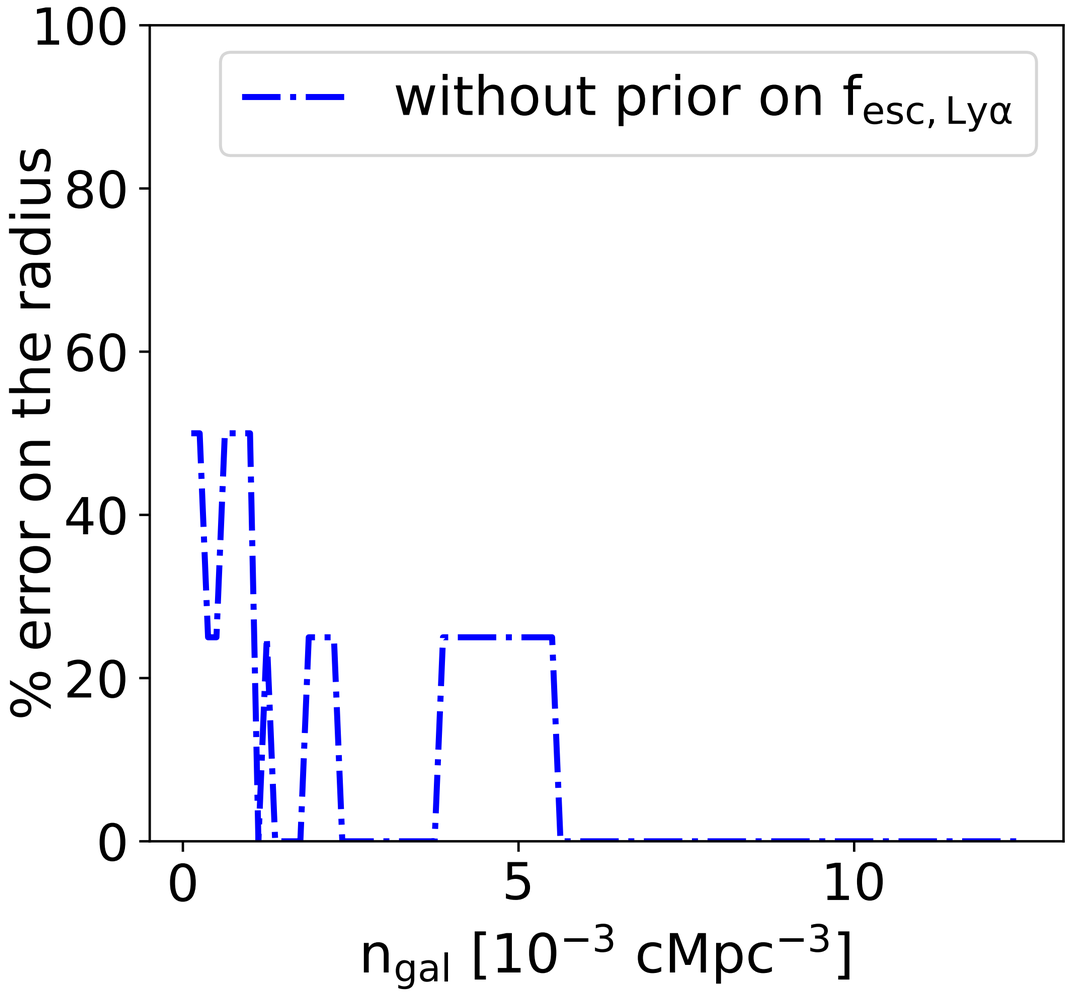

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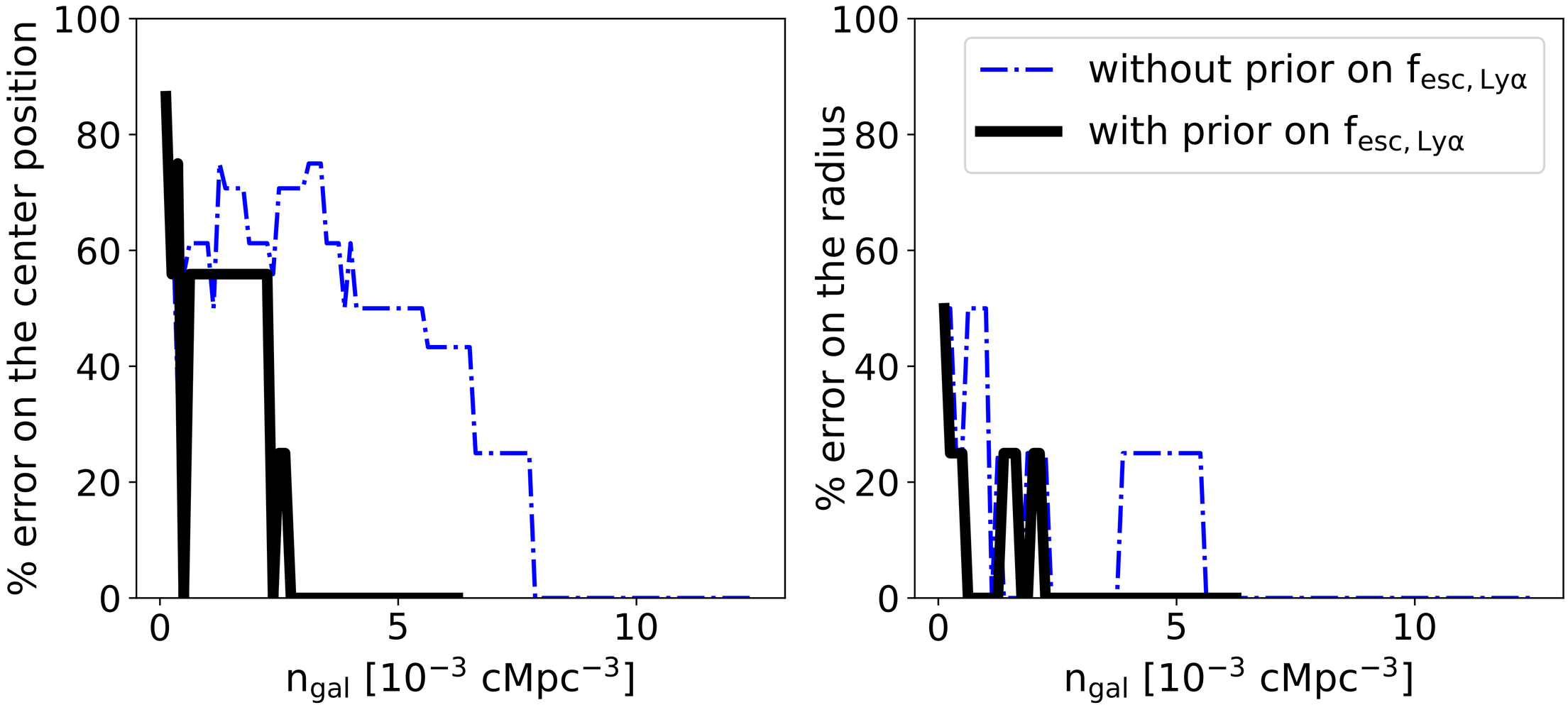

Nikolić, AM+ in prep

Conclusions

- We are finally nailing down the timing of (the second half of) reionization, largely thanks to high quality Lyα forest data:
  (i) **ends at z~5.4 with midpoint at z ~ 7 - 7.5**
  (ii) reionization is **driven by faint galaxies**, with >50% of the ionizing photons sourced by M_{uv} > -12 — -15 galaxies

- Lyα from galaxies can **map** local reionization topology during early EoR allowing us to connect **galaxy properties to local HII** environment
  (i) **Bayesian inference of HII bubbles is possible with ~6×10^{-3} galaxies cMpc^{-3}**
  (ii) including a prior on the intrinsic spectrum ($f_{esc}\alpha$) can lower requirement to **~3×10^{-3} galaxies cMpc^{-3}**
  (iii) asymmetry of large-scale Lyα EW maps can find edges of bubbles (**stay tuned for Ting-Yi's talk**)