A tale of seven narrow spikes and a long trough: constraining the timing of the percolation of HII bubbles at the tail-end of reionization with ULAS J1120+0641.

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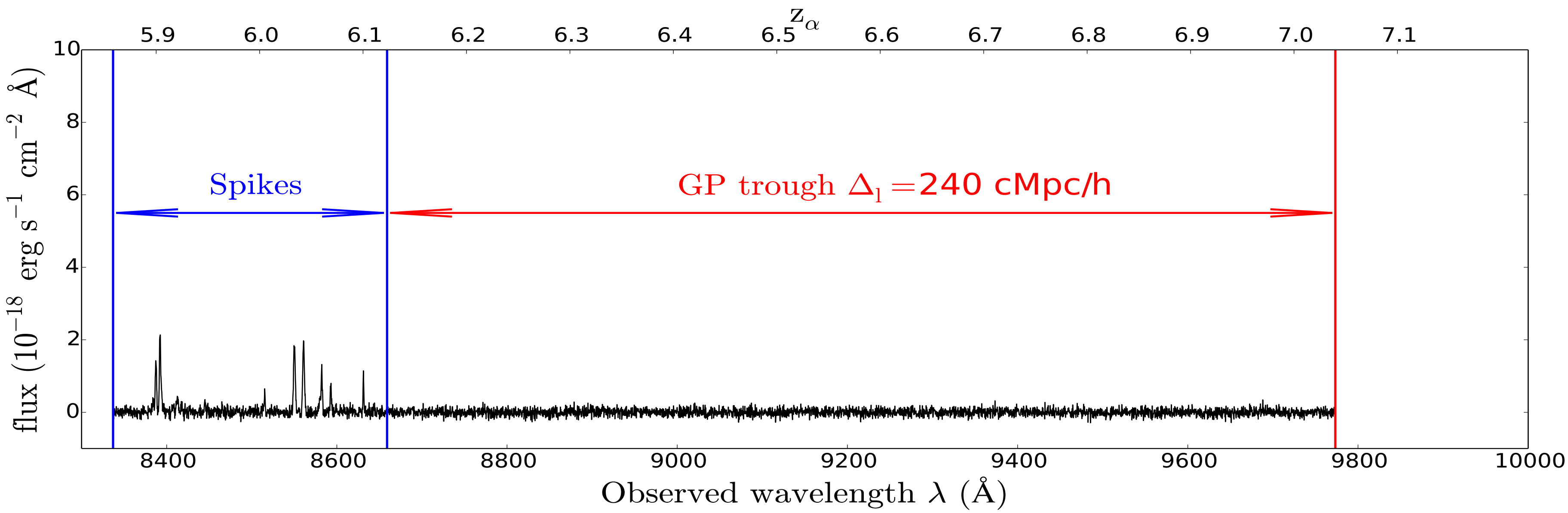

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The high resolution spectrum of ULAS J1120+0641

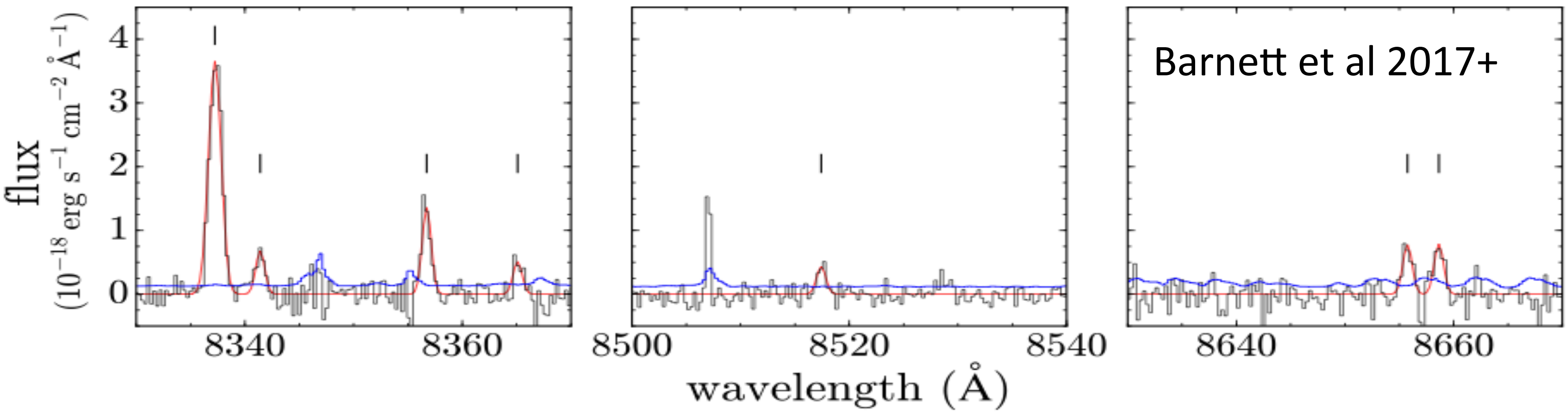


Fig. 5: Significant transmission of flux in the Lyα forest towards ULAS J1120+0641. The unbinned X-shooter spectrum of ULAS J1120+0641 is shown in grey with a pixel size of 10 km s^{-1}. Shown in blue is the 1σ error spectrum, and the derived transmission spectrum is overlaid in red. The seven detections presented in Table 2 are indicated.

- 30 h integration spectrum of ULAS J1120+0641, the high redshift quasar at z=7.084
- Presence of 7 spikes in the redshift range 5.858<=z<=6.122
- Largest Gunn-Peterson trough ever reported (240 cMpc/h) from z=6.122 up to z=7.04 : the near zone of the quasar.

Using radiative transfer simulation to model the observed spectrum

Model name	Box size	Particle number
512-20-good_h (Fiducial)	20	512^3
512-20-good_l (Late)	20	512^3
512-20-early (Early)	20	512^3
512-40 (Low-res)	40	512^3
512-10 (High-res)	10	512^3

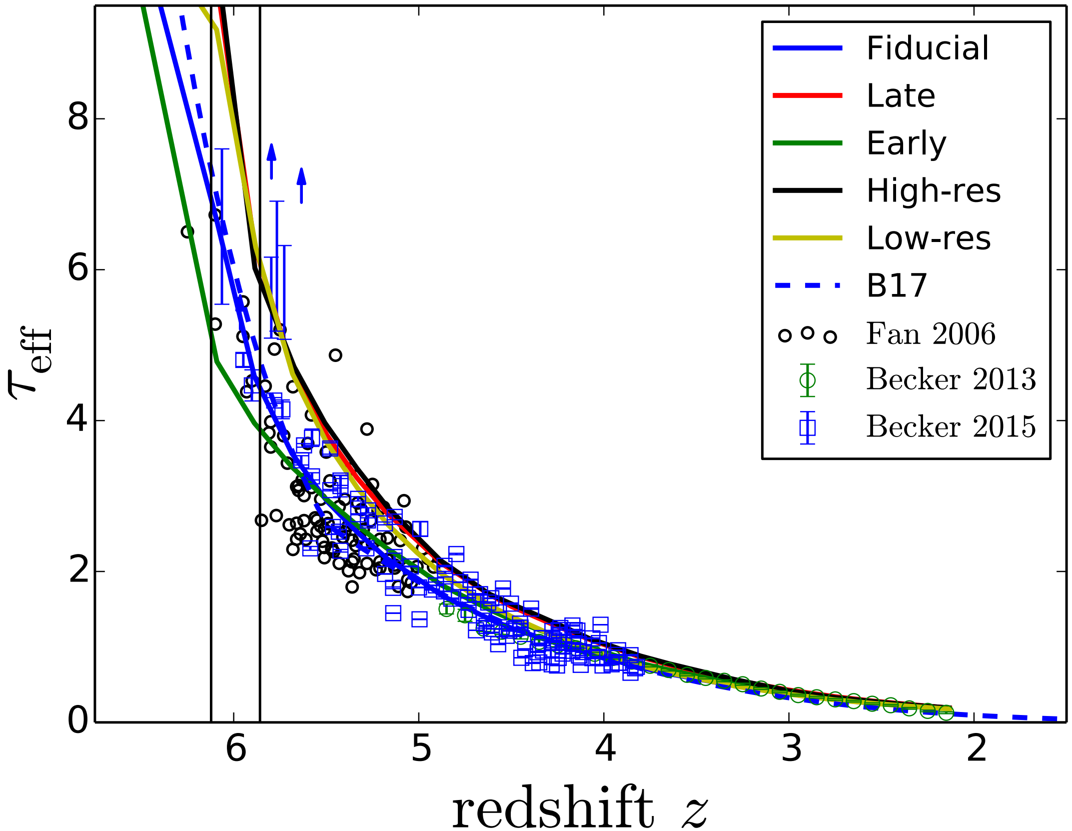
Table 1. Summary of the different simulations studied in this work.

- Five different models from Chardin+2015
- Three 20 cMpc/h boxes with slightly different reionization hisories
- One 40 and one 10 cMpc/h box to test resolution with same reionization history as the Late 20 cMpc/h model
- Post-processed RT simulation with ATON on top of hydro RAMSES simulation
- Calibrated to reproduce well Lyman alpha forest data in the post reionization IGM

The teff evolution in the simulations

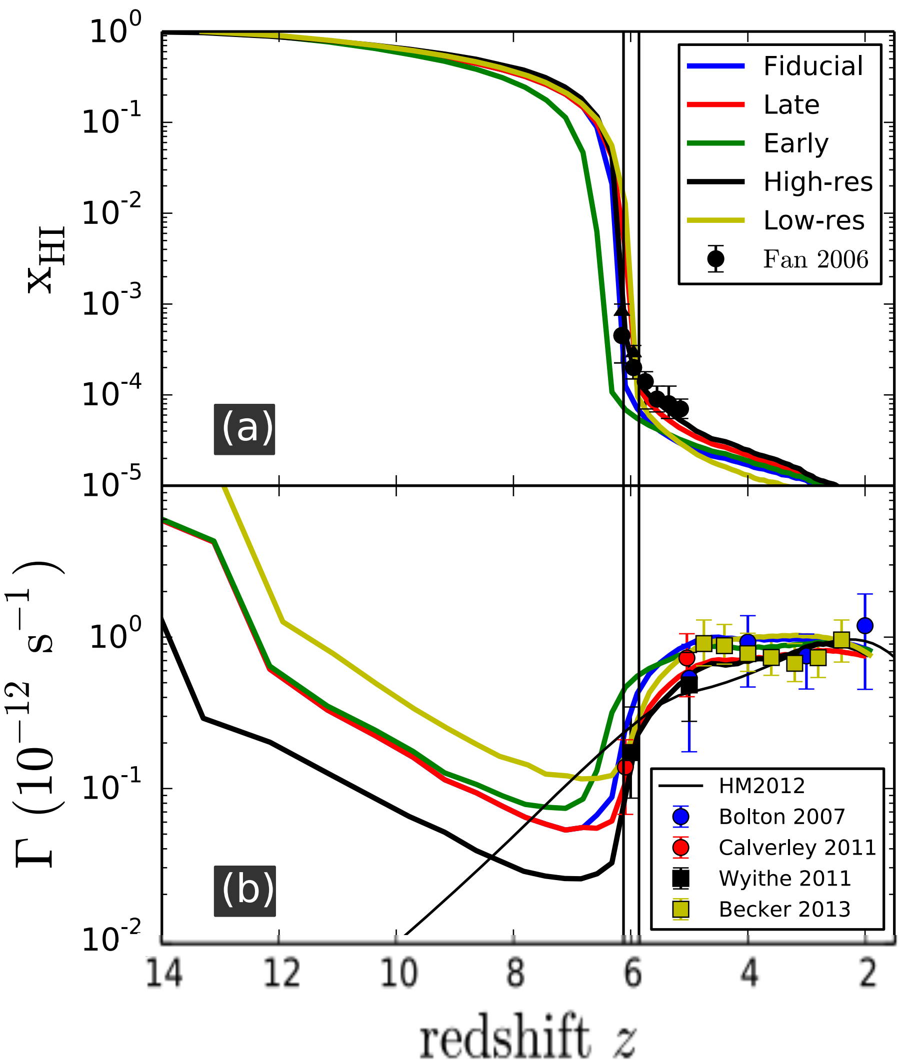
- Evolution of the effective optical depth to Lyman alpha inferred from Barnett et al. 2017 (blue dashed curve)

$$\tau_{GP}^{eff}(z) = \begin{cases} 0.85\left(\frac{1+z}{5}\right)^{4.3} & z \leq 5.5 \\ 2.63\left(\frac{1+z}{6.5}\right)^{11.2} & z > 5.5 \end{cases}$$



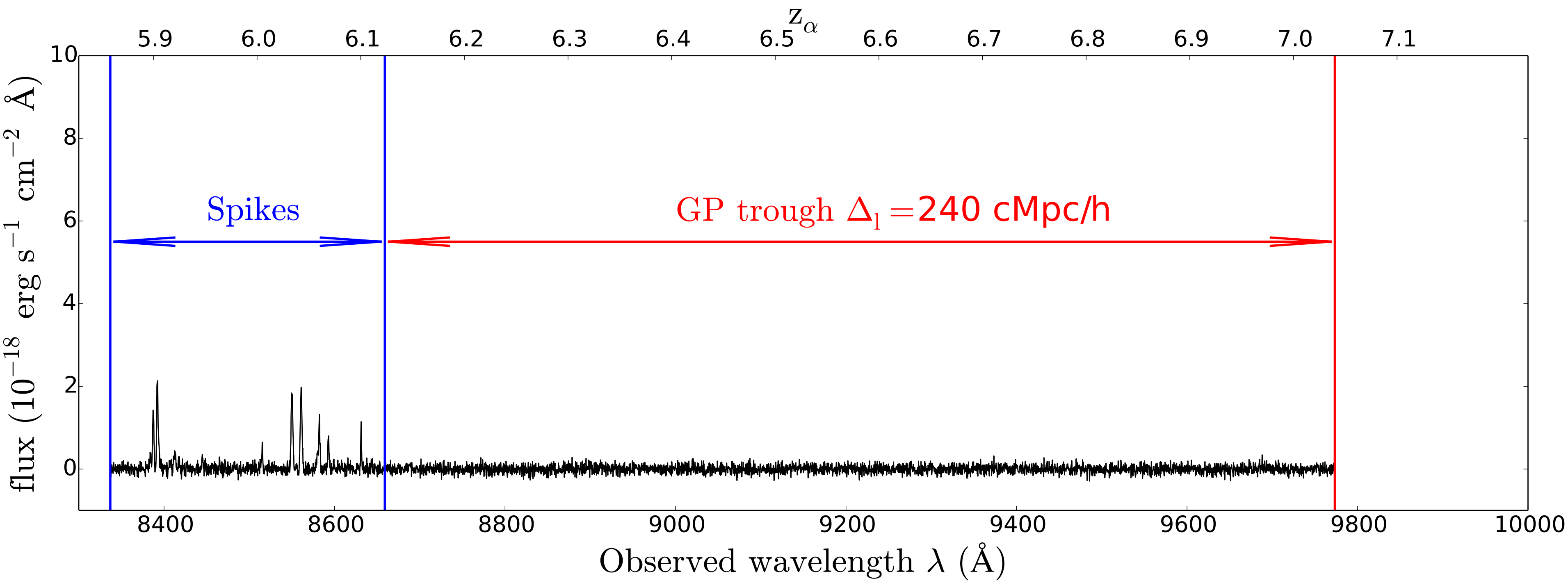
- Fiducial evolution match exactly the Barnett+ power-law
- Other models bracket the inferred evolution from the observations
- Test if we can reproduce the statistic of the observed transmission spikes with the simulations

The reionization histories



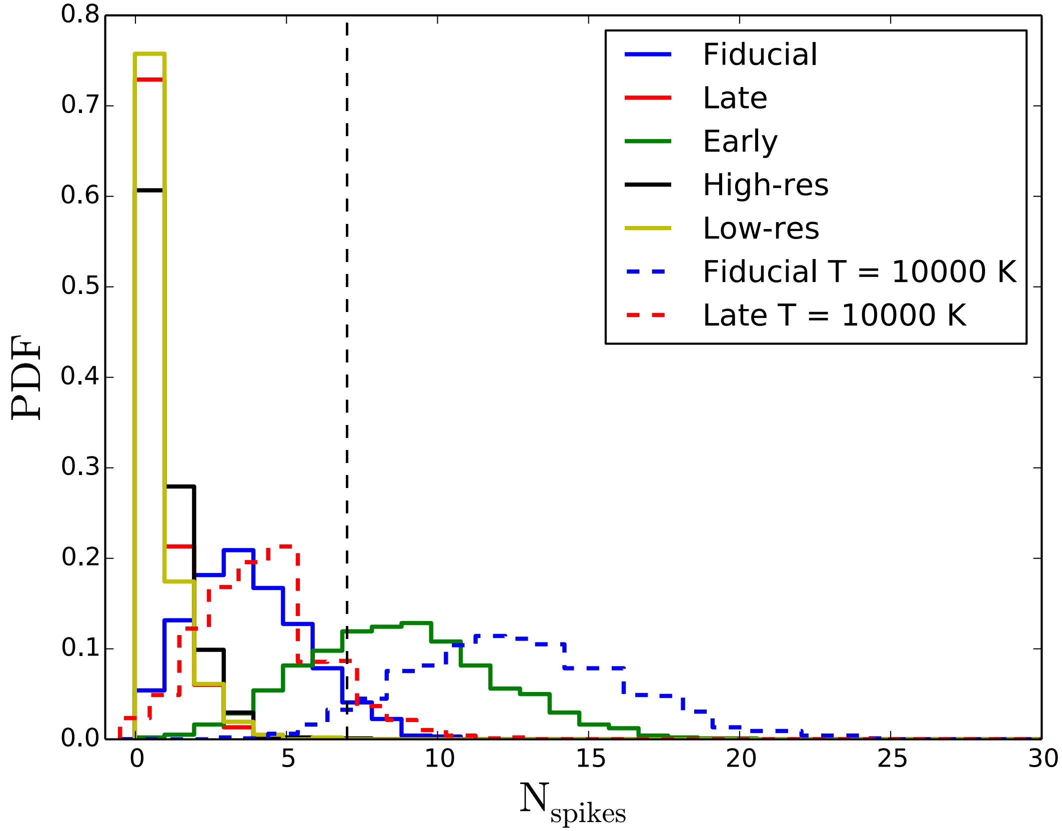
- All models fit well a lot of observational constraints
- Some differences in the redshift range corresponding to the spikes region in the observed spectrum
- Testing how the statistic of spikes vary between the different model could help us to constrain the timing of reionization precisely

Creating mock Lyman alpha forest spectra



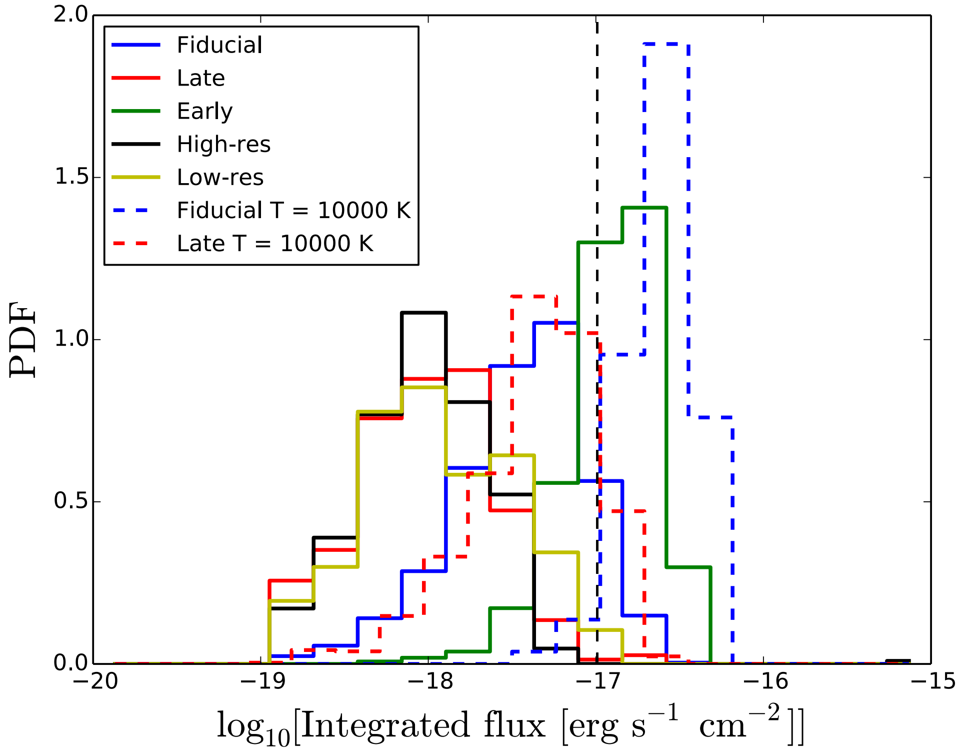
- Stitch line-of-sight from different outputs to cover the observed spectrum wavelength range
- Smooth to instrumental resolution + re-bin to 10 km/s + add random Gaussian noise as in the observed spectrum
- Mock spectra resemble the observed one with transmitted spikes and long trough

Occurrence of transmission spikes



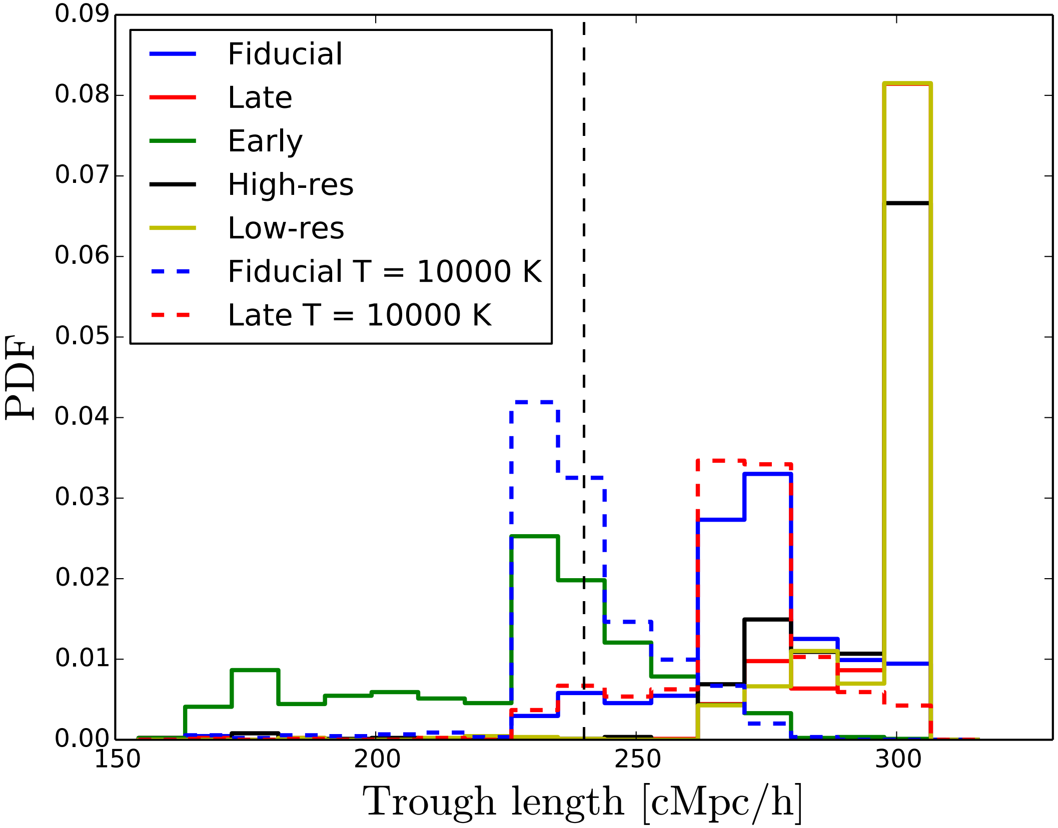
- Early model best match the data
- Fiducial model still consistent
- Late and low/high res model inconsistent
- Changing the IGM temperature can change consequently the results
- Late model could still be consistent with the data

Flux in spikes



- Early model best match the data
- Fiducial model still consistent
- Late and low/high res model inconsistent
- Temperature change the results

GP trough lengths



- Early model best match the data
- Some of the spectra show spikes at higher redshift reducing the length of the trough
- Fiducial model still consistent
- Late low/high res models are not consistent with data
- Increasing temperature in the voids reduces the discrepancies since spikes can be detected at higher redshift

Future works

Simulations

- No QSOs radiation incorporated
- Fluctuation in the photoionization rate will complicate the picture
- Temperature fluctuations would change the results for a given reionization history
- Box size might be too small

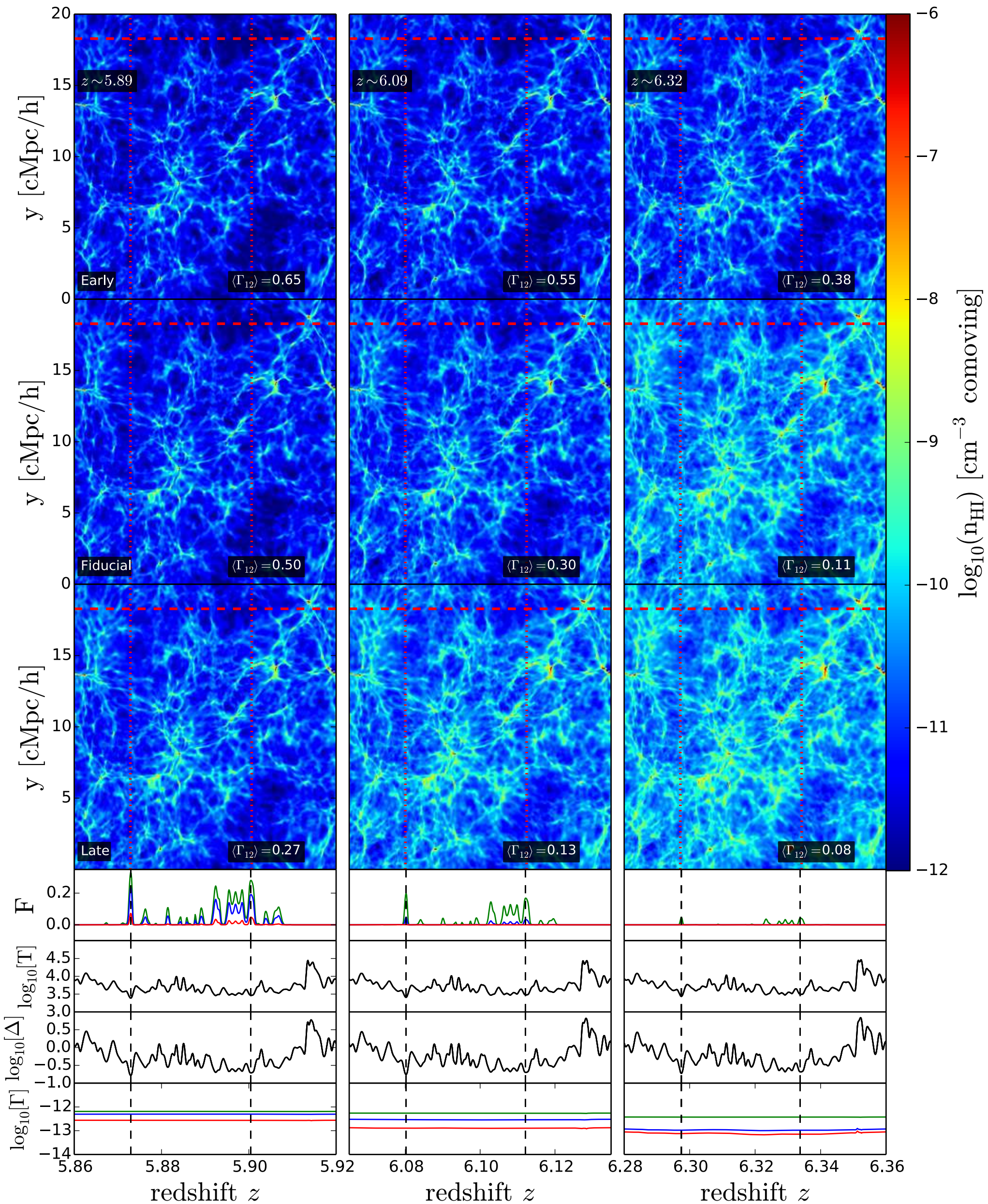
Observations

- Now only ~20 QSOs at z>=6.5
- Only the spectrum shown here has such a high resolution enabling to find rare transmission spikes
- Re-observations of already known QSOs spectra would improve the constrain on the reionization history

Conclusion

- Our models are successful at reproducing the occurrence of spikes, the integrated transmitted flux and the GP trough length as in the observed QSO spectrum
- Our models suggest a somewhat early reionization history
- Higher temperatures in under-dense regions favor later reionization history
- Future observation of high resolution QSO spectra could constrain the ionization state of the IGM up to z=6.1 very precisely

Line-of-sights comparison



- Neutral hydrogen density in the three 20 cMpc/h models
- Transmitted flux in under-dense regions
- Small Γ variations lead to large differences in the transmitted flux
- Spike statistic should be rather different between the models