New HI Reionization Constraints from the High-z Lyman-α forest

Jose Oñorbe

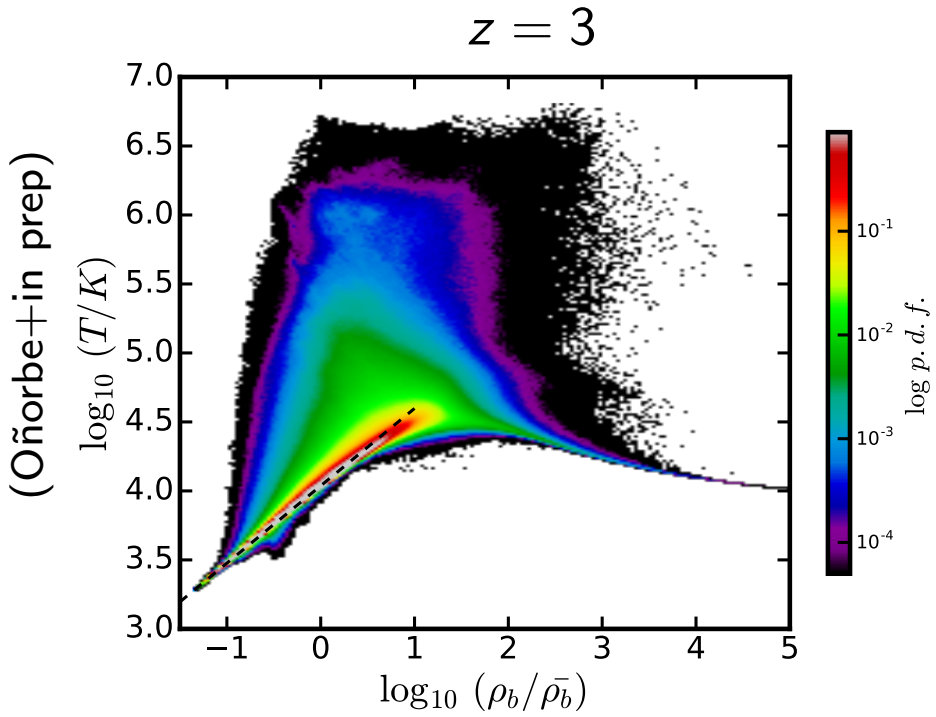
Institute for Astronomy
University of Edinburgh
(onorbe@roe.ac.uk)

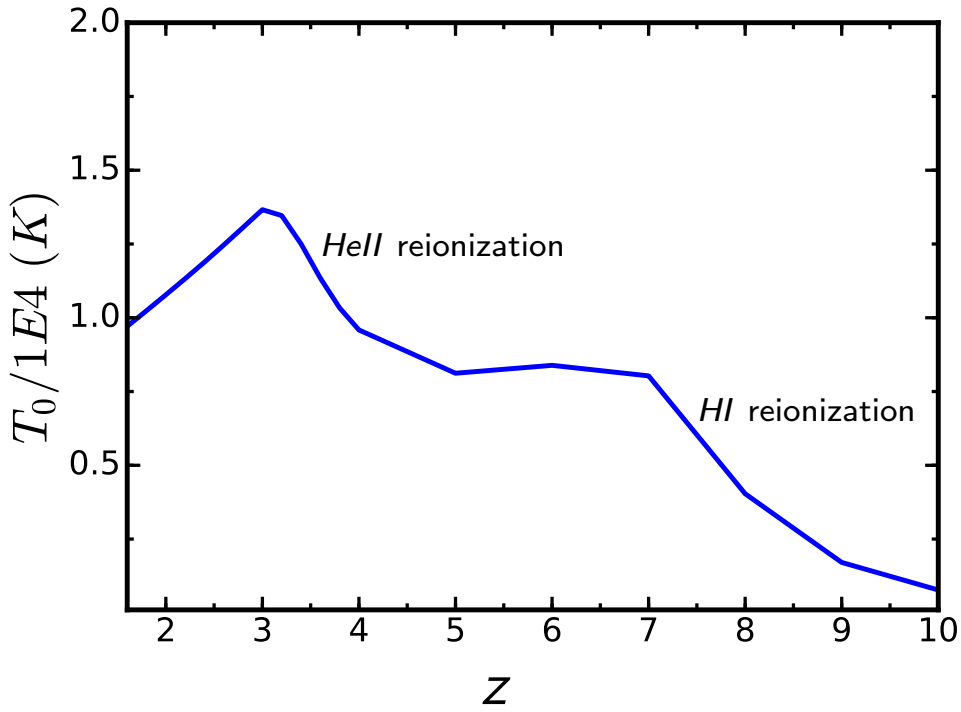
Collaborators: J. Hennawi (UCSB), Z. Lukić (LBNL), F. Davies (UCSB), M. Walther (UCSB) and D. Sorini (MPIA)

Intergalactic Interconnections
July 12th, 2018

Reionization Sets the Thermal State of the IGM

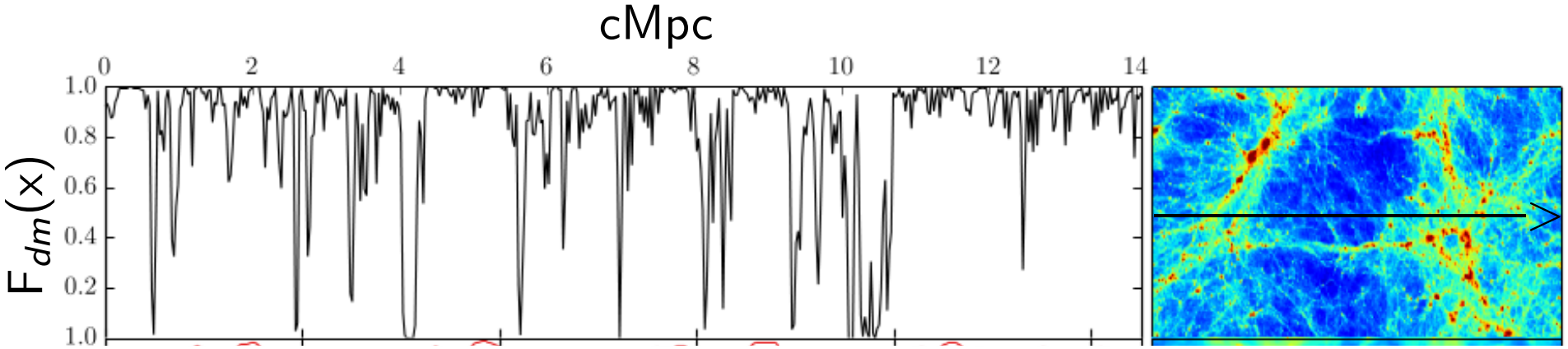
- Balance of photoheating and adiabatic cooling gives a $T - \rho$ relationship: $T(\rho) = T_0(\rho/\bar{\rho})^{\gamma-1}$ (Hui & Gnedin, 1997)





1. Study the reionization history
2. Constrain the thermal injection from ionizing sources
3. $T_{\rm IGM}$ important for galaxy formation ($M_{\rm halo,min}$)

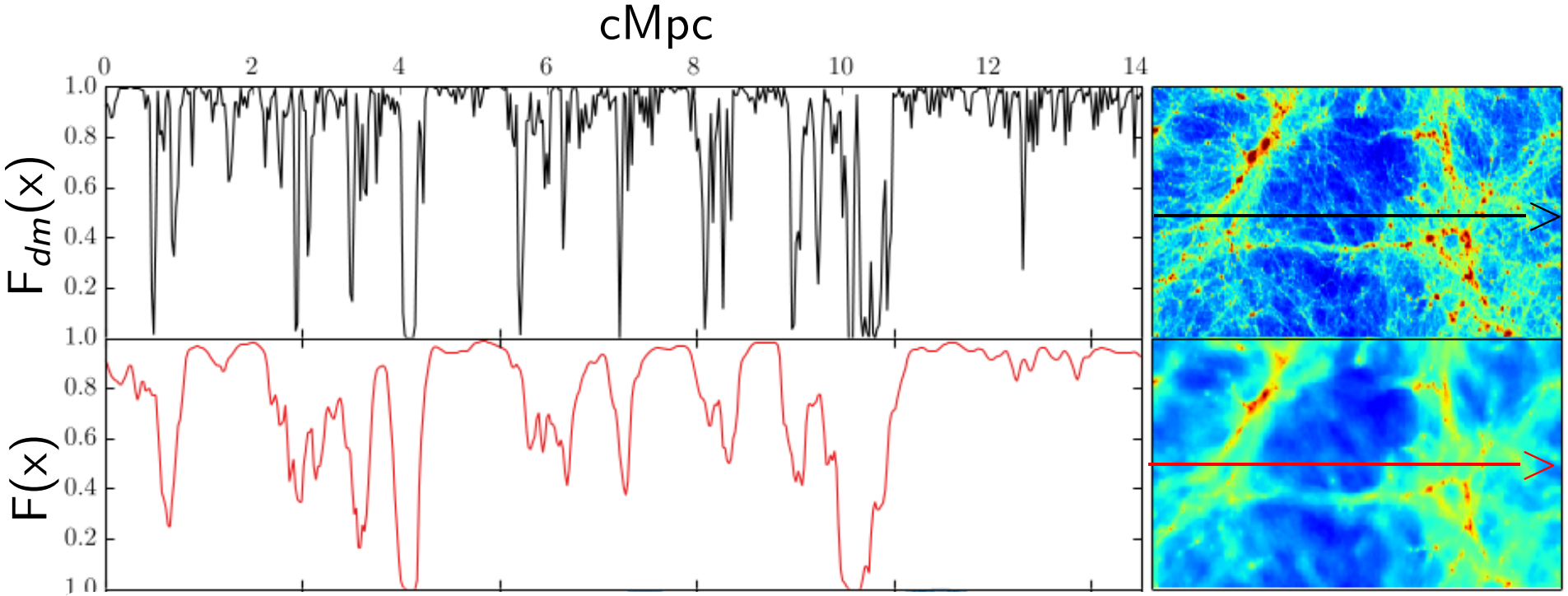
The Pressure Smoothing Scale of the IGM



If we could somehow probe the dark-matter directly
the Ly-α forest would look like this

(Kulkarni,JO+2015)

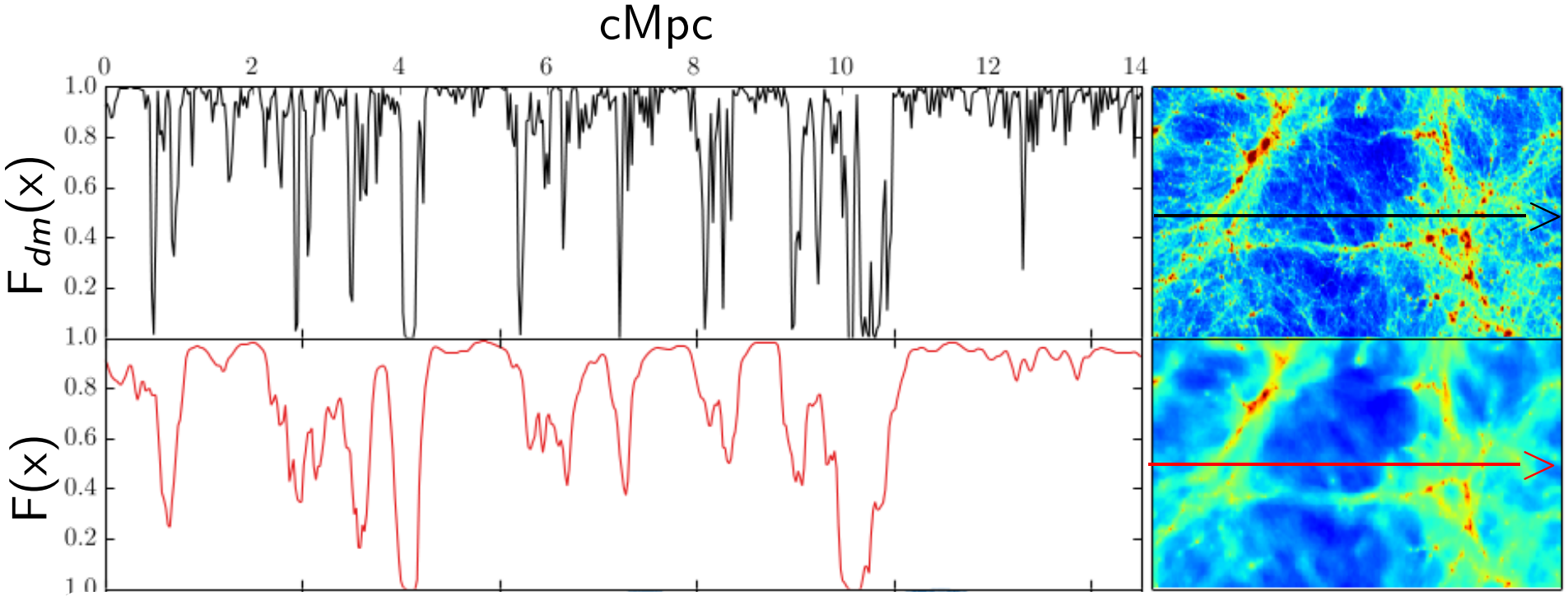
The Pressure Smoothing Scale of the IGM



Pressure forces $\rightarrow$ baryon smoother than dark matter

(Kulkarni,JO+2015)

The Pressure Smoothing Scale of the IGM

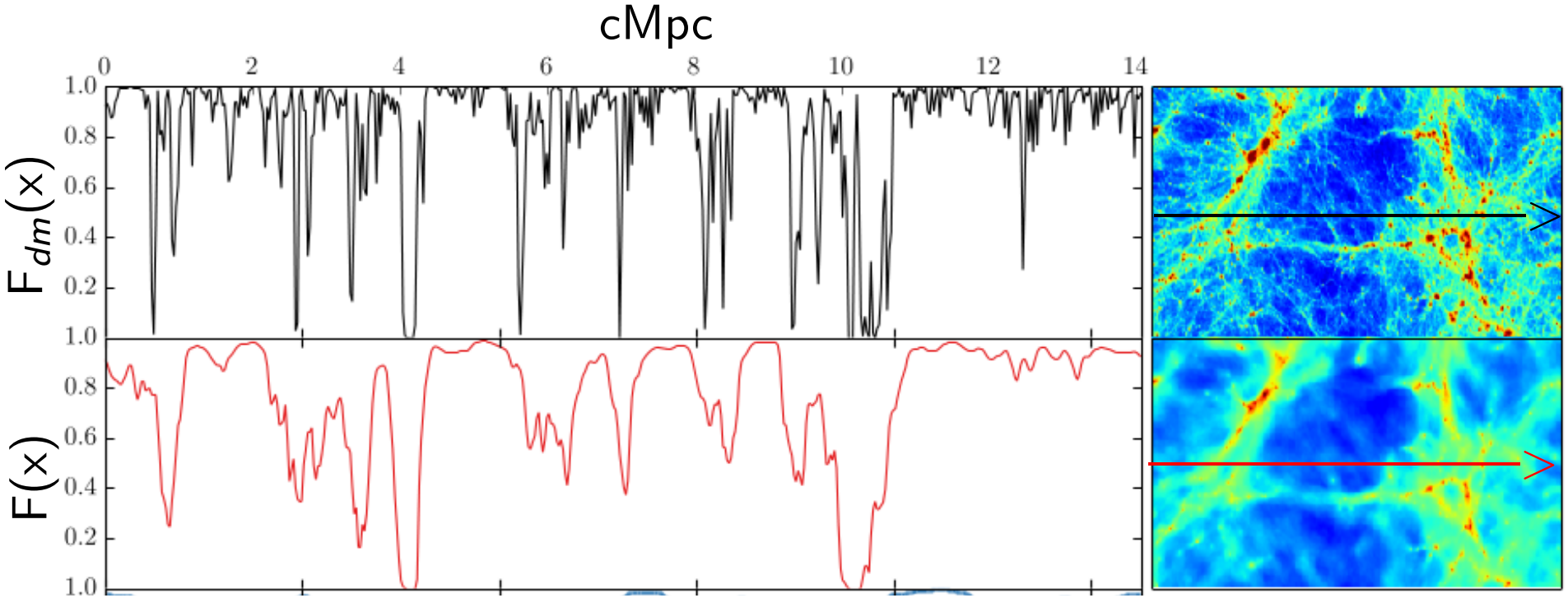


Pressure forces $\rightarrow$ baryon smoother than dark matter

Jeans sound-crossing time $\lambda_{Jeans}/c_s \sim t_H$ Hubble time,
IGM pressure scale depends on full thermal history

(Kulkarni,JO+2015)

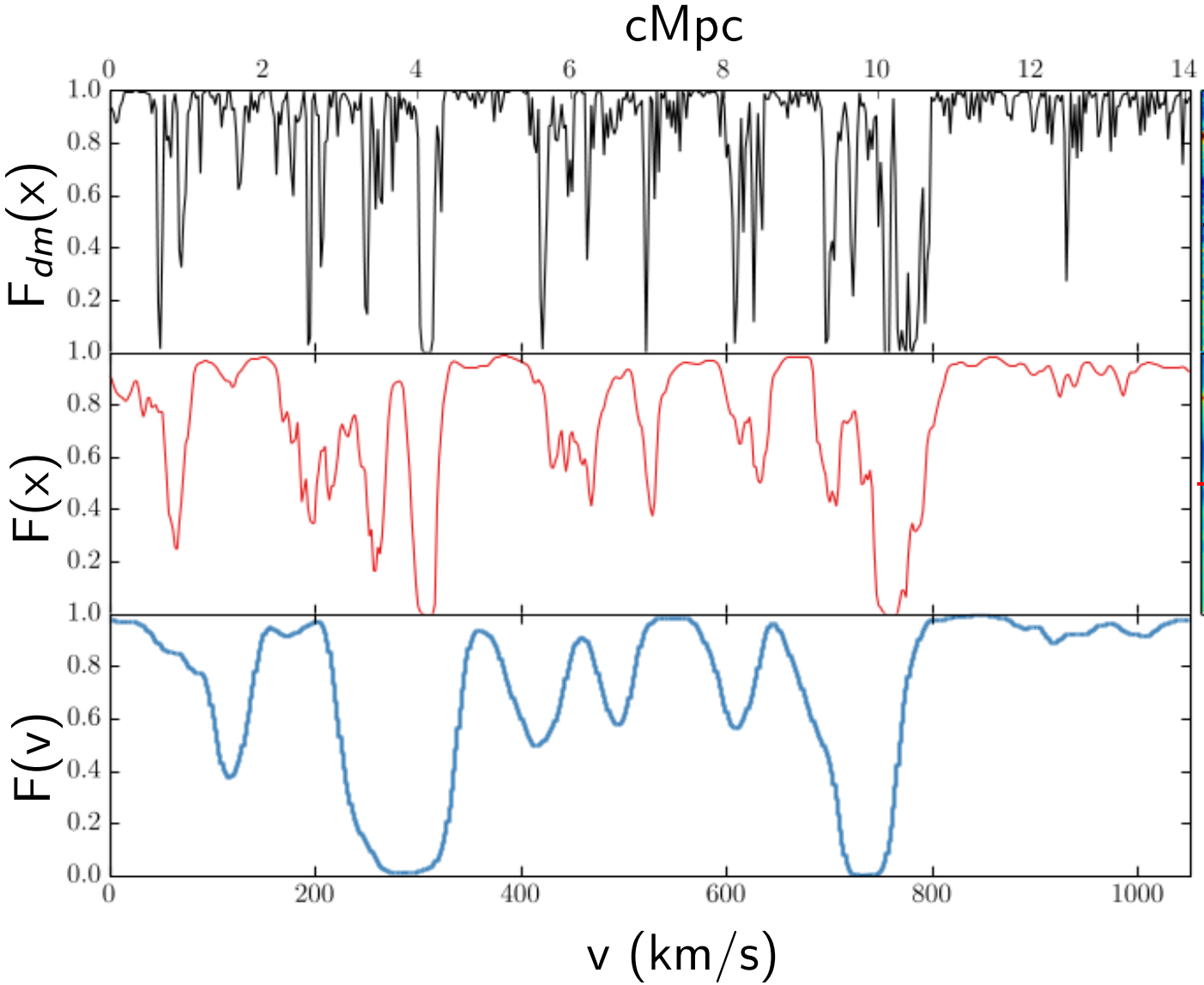
Thermal Doppler Broadening

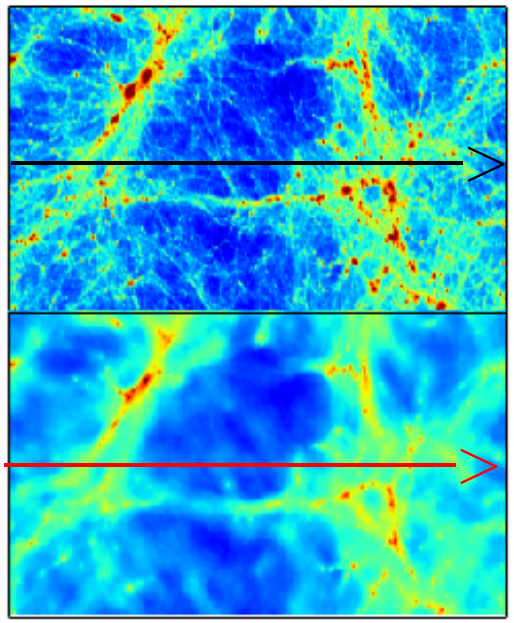


Microscopic random motions of $T \sim 10^4$ K gas thermal Doppler broadens Lyα forest lines

(Kulkarni,JO+2015)

Cosmic Calorimetry with the Ly-α Forest





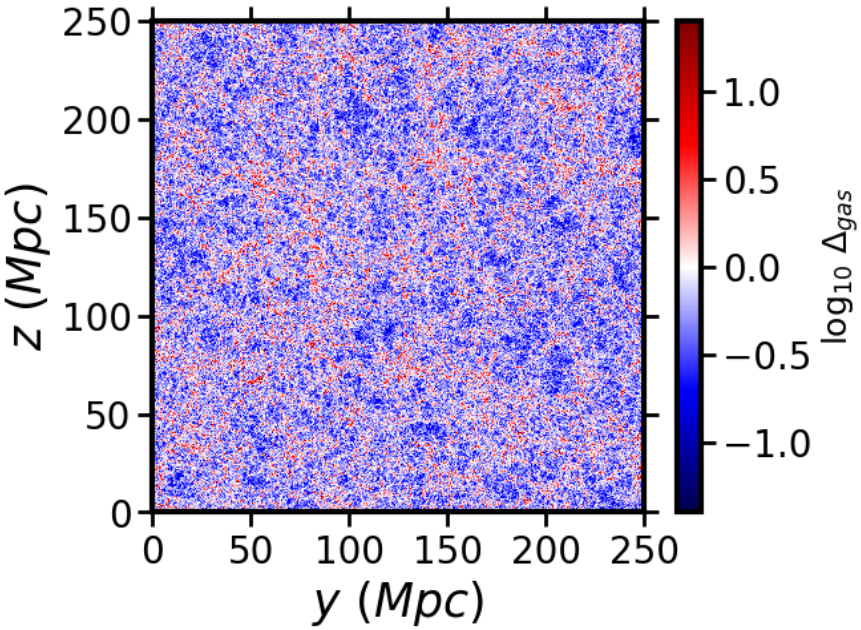
Observed Ly-α forest:
pressure smoothed +
thermally broadened

(Kulkarni,JO+2015)

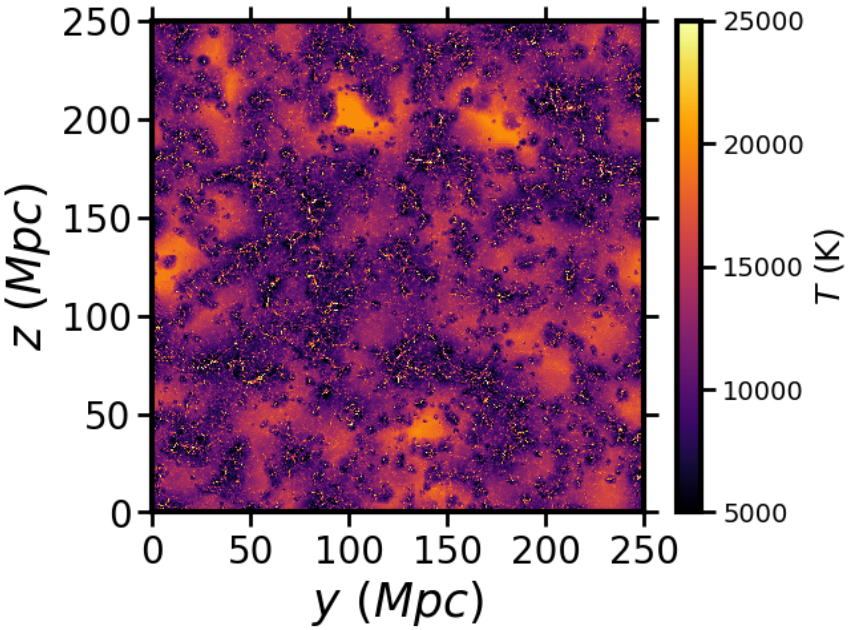
Simulating the Intergalactic Medium

250 Mpc 8192^3 $z = 6$

Density

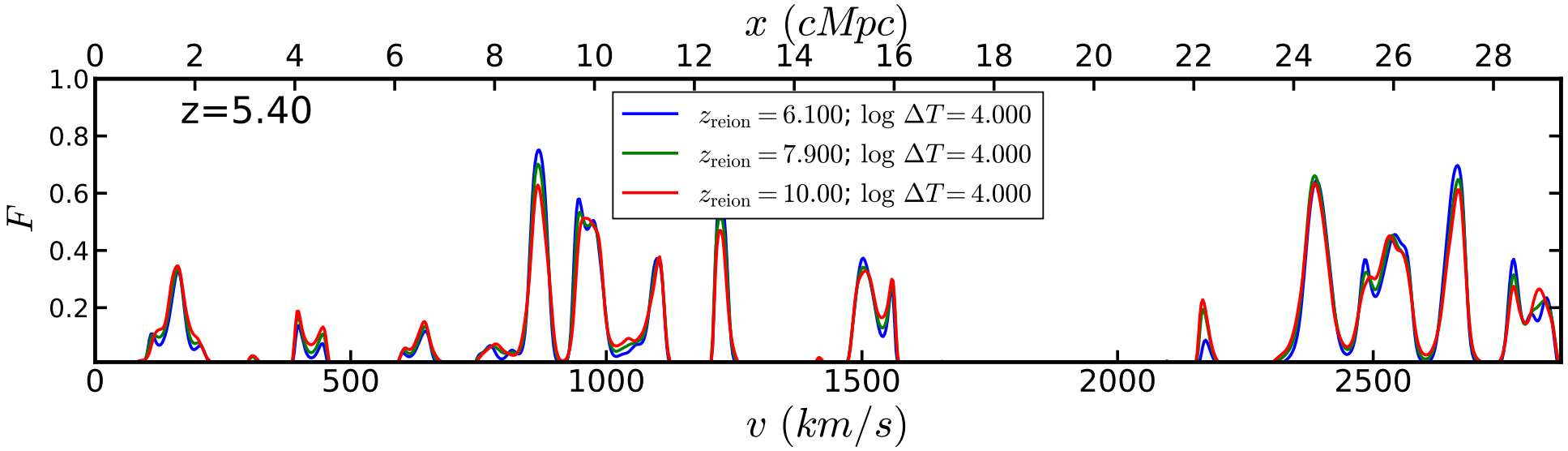


Temperature



- Hydro + gravity, low density, CMB gives initial conditions
- Nyx massively parallel grid hydro code (AImgren+ 2013; Lukic+ 2015).
- Reionization redshift $z_{\rm reion}$ and heat injection $\Delta T_{\rm reion}$ treated as phenomenological input. 2048^3 – 40 Mpc/h

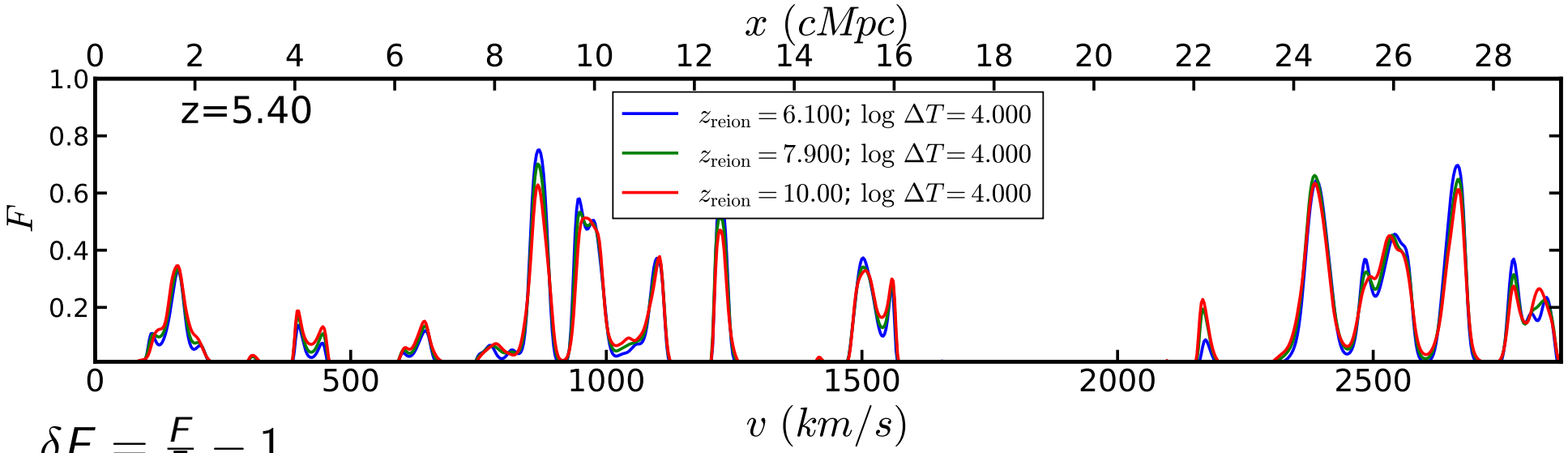
The High-z IGM Retains Thermal Memory of Reionization



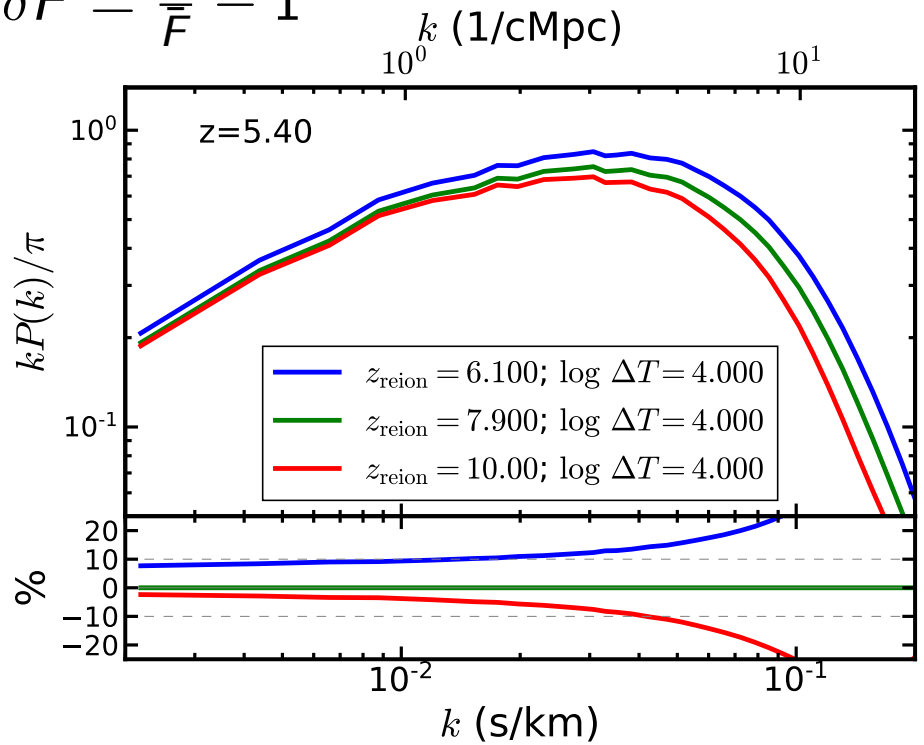
Free parameters: $z_{\rm reion}$, $\Delta T_{\rm reion}$

- Ionization History: $z_{\rm reion}$
- Amount of reionization heat injection: $T_{\rm reion} \Leftrightarrow$ spectral slope of reion. sources

The High-z IGM Retains Thermal Memory of Reionization



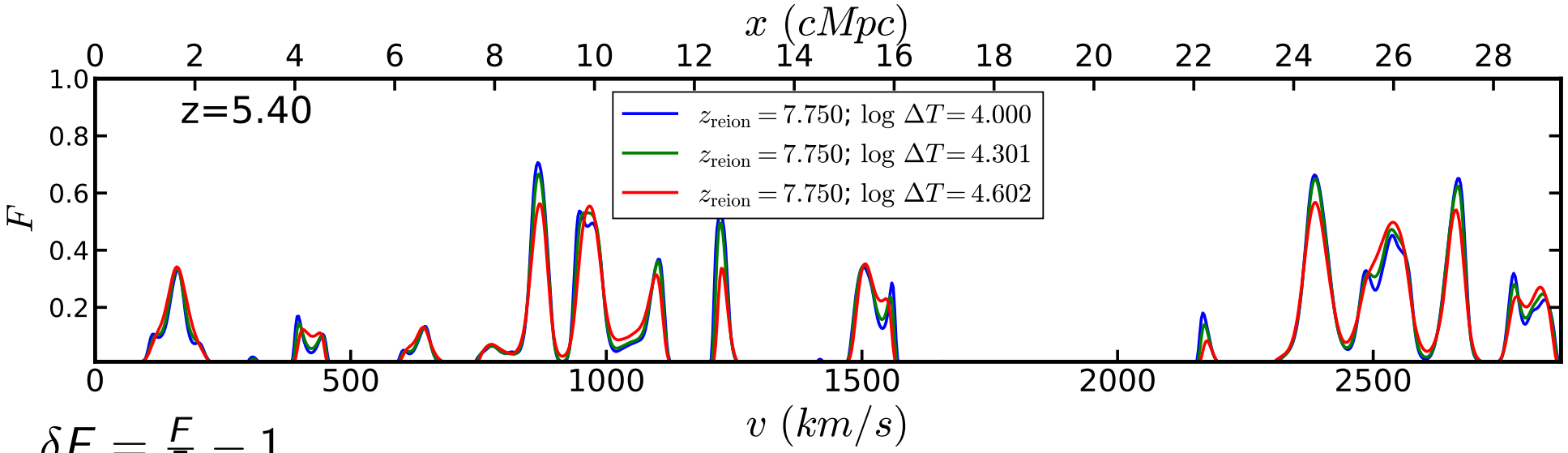
$$\delta F = \frac{F}{\bar{F}} - 1$$



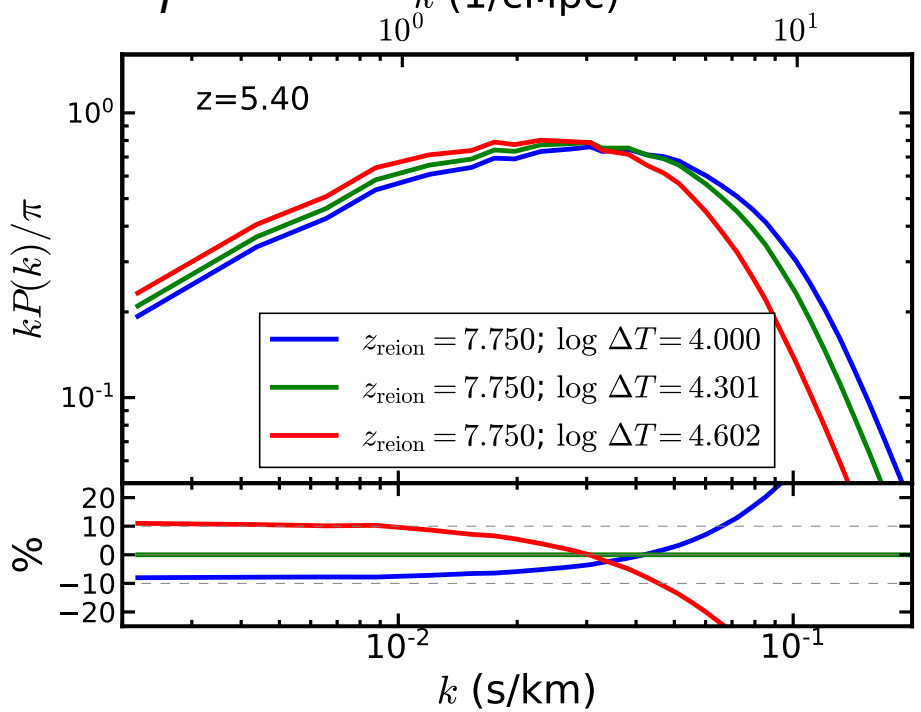
Free parameters: $z_{\rm reion}$, $\Delta T_{\rm reion}$

- Ionization History: $z_{\rm reion}$
- Amount of reionization heat injection: $T_{\rm reion} \Leftrightarrow$ spectral slope of reion. sources

The High-z IGM Retains Thermal Memory of Reionization



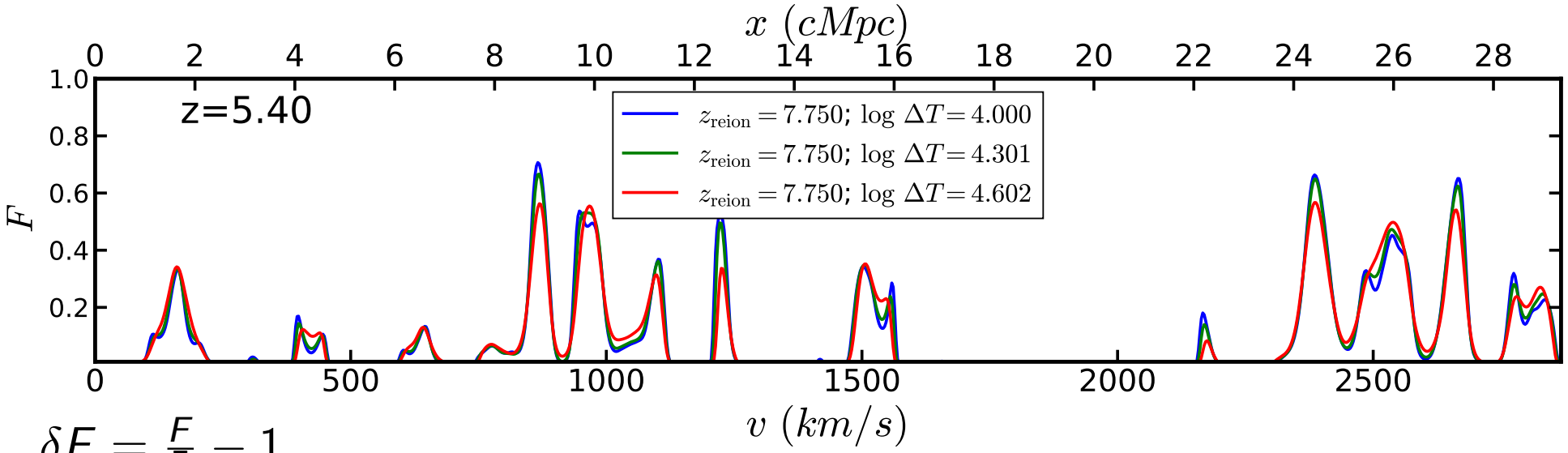
$$\delta F = \frac{F}{\bar{F}} - 1$$



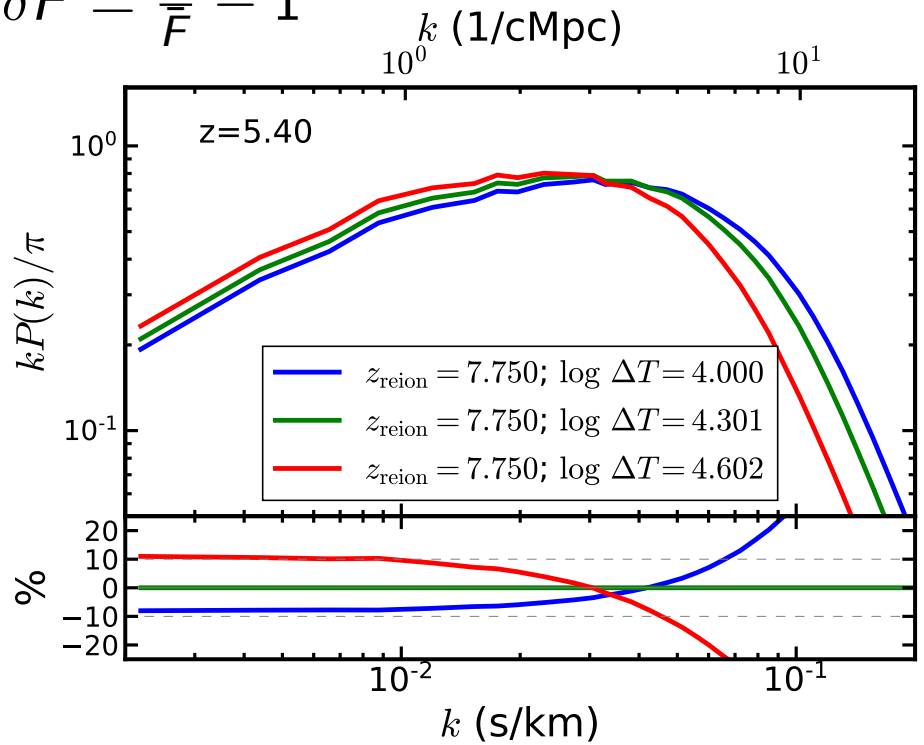
Free parameters: $z_{\rm reion}$, $\Delta T_{\rm reion}$

- Ionization History: $z_{\rm reion}$
- Amount of reionization heat injection: $T_{\rm reion} \Leftrightarrow$ spectral slope of reion. sources

The High-z IGM Retains Thermal Memory of Reionization



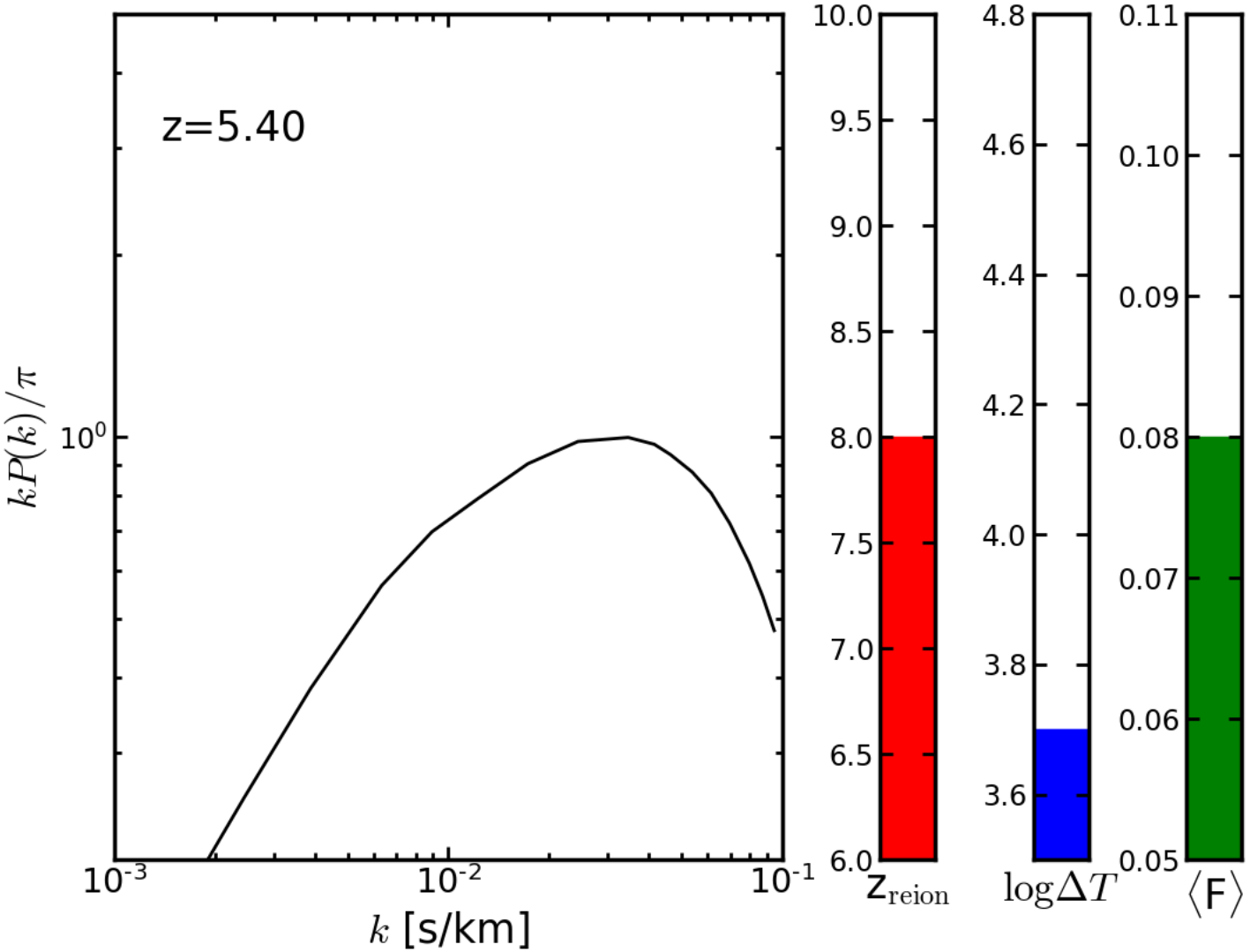
$$\delta F = \frac{F}{\bar{F}} - 1$$



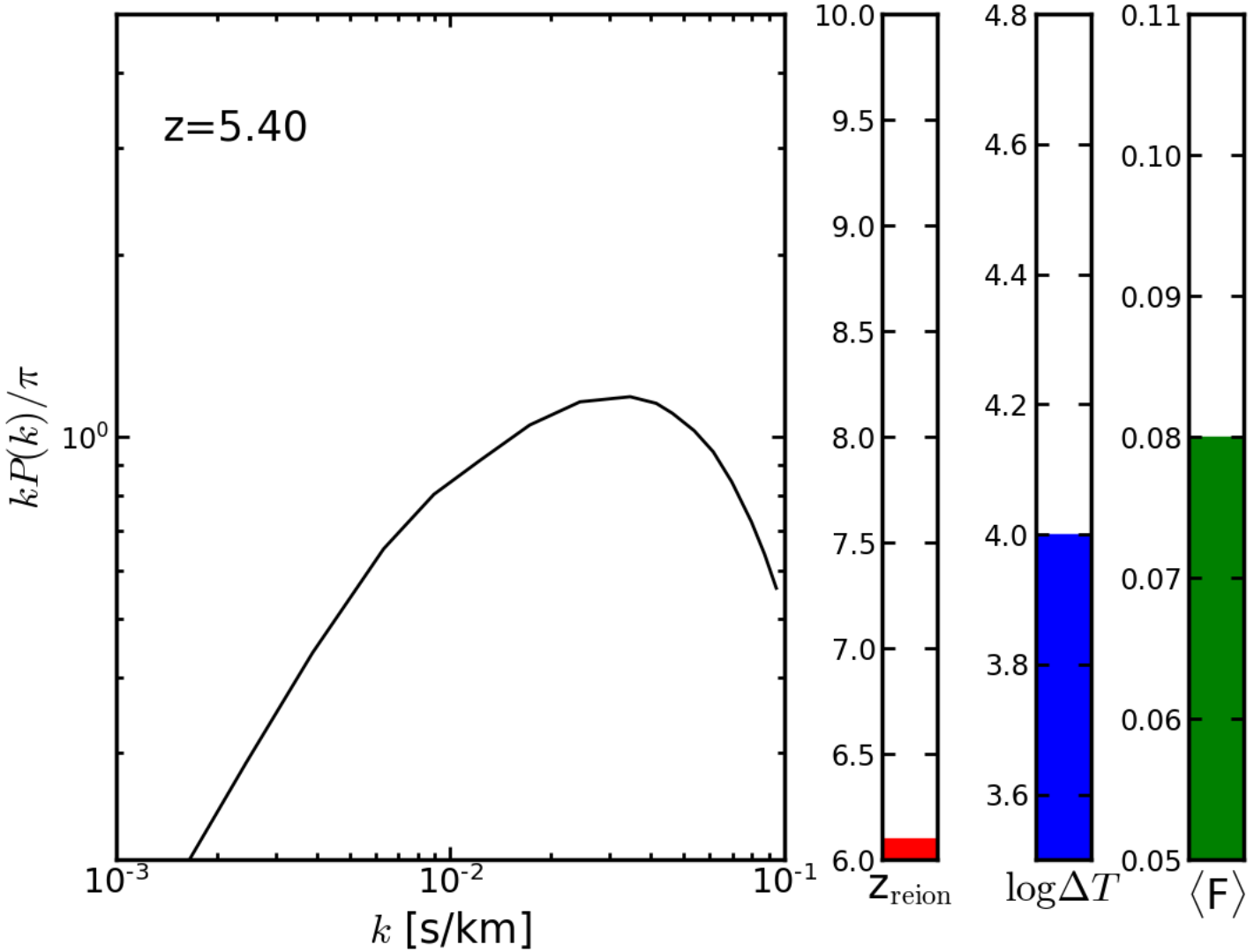
Free parameters: $z_{\rm reion}$, $\Delta T_{\rm reion}$

- Ionization History: $z_{\rm reion}$
- Amount of reionization heat injection: $T_{\rm reion} \Leftrightarrow$ spectral slope of reion. sources
- Computational Challenge

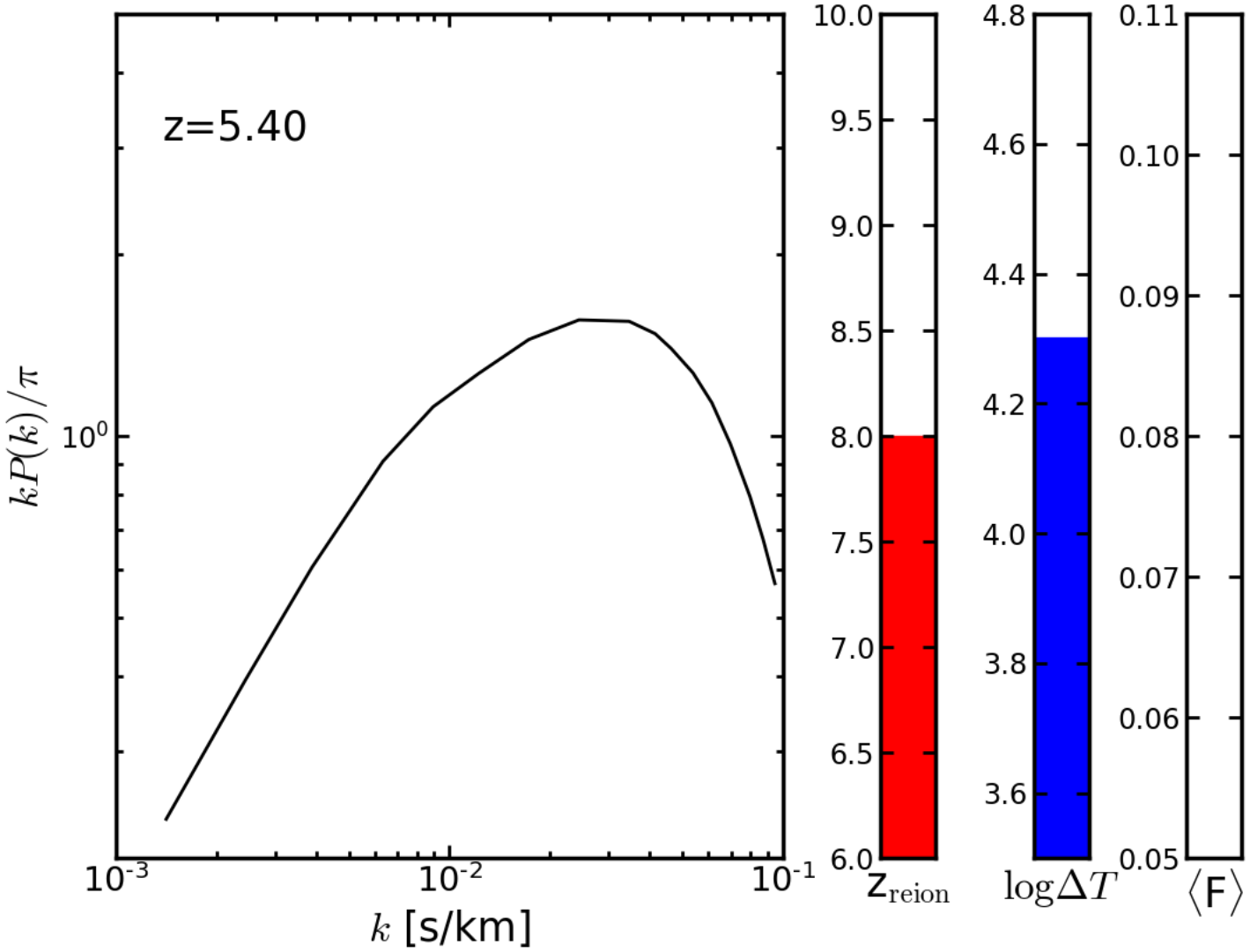
The High-z IGM Retains Thermal Memory of Reionization



The High-z IGM Retains Thermal Memory of Reionization

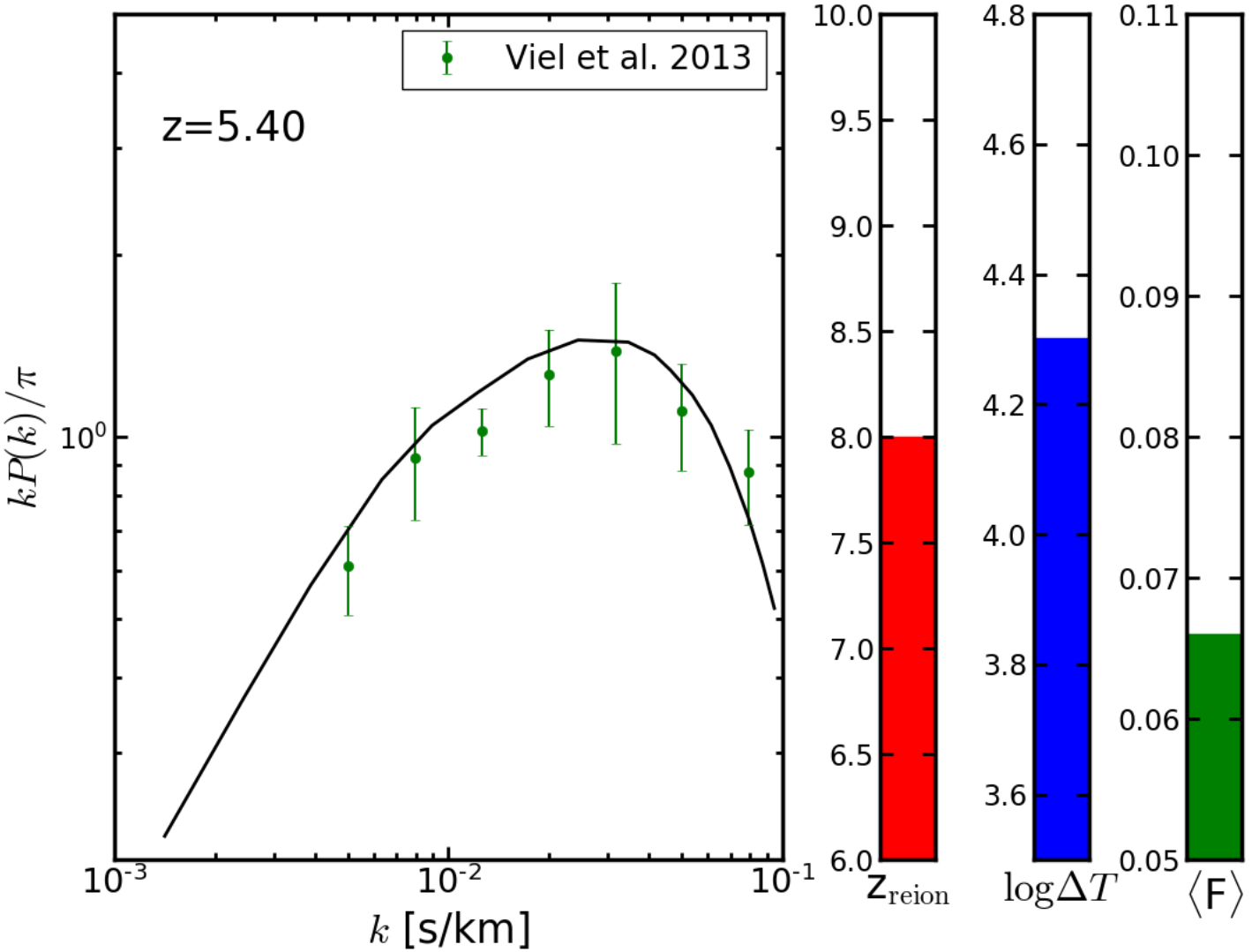


The High-z IGM Retains Thermal Memory of Reionization



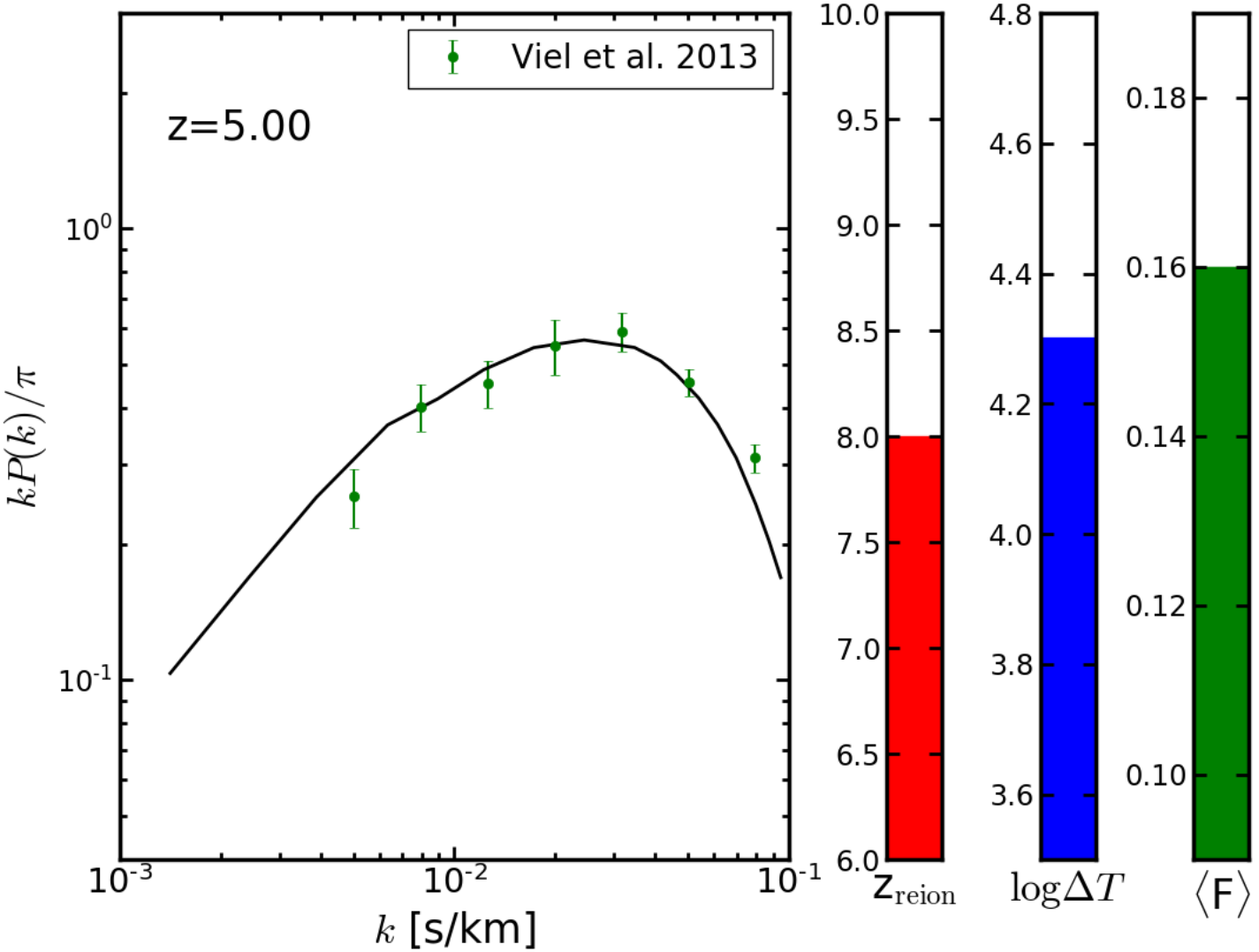
The High-z IGM Retains Thermal Memory of Reionization

High resolution high S/N spectra: Viel at al. 2013 (HIRES and MIKE)



The High-z IGM Retains Thermal Memory of Reionization

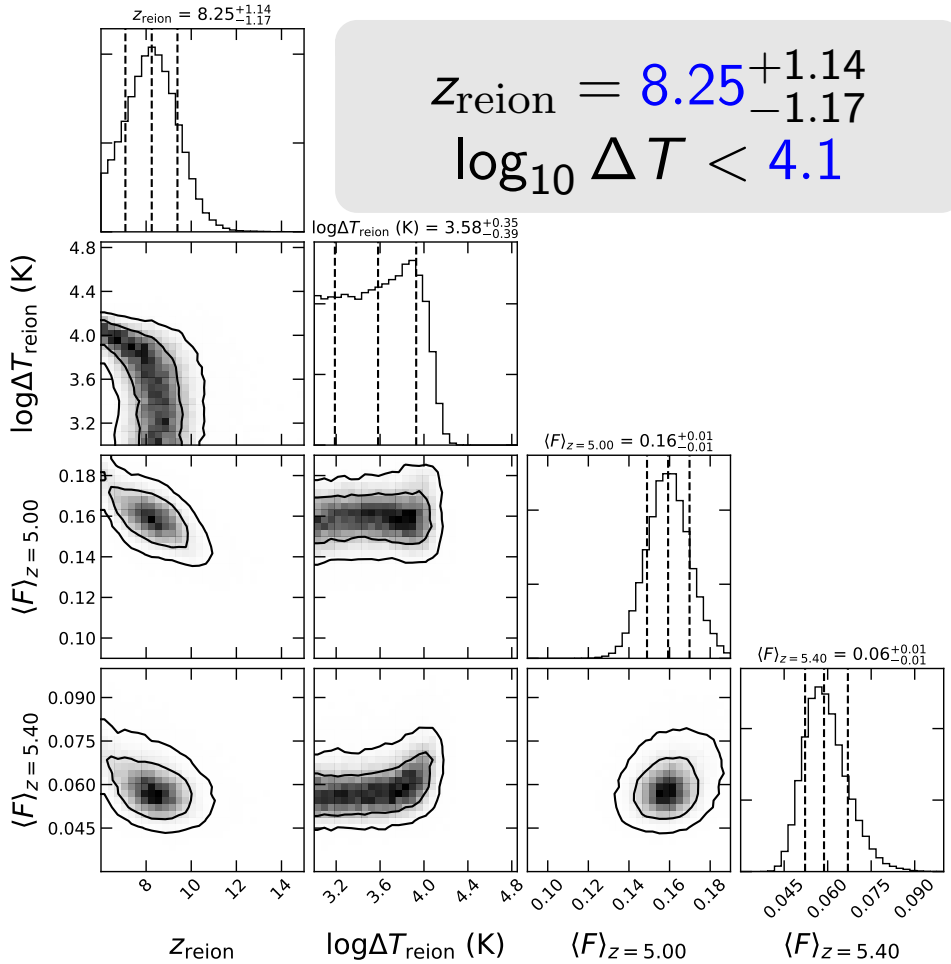
High resolution high S/N spectra: Viel at al. 2013 (HIRES and MIKE)

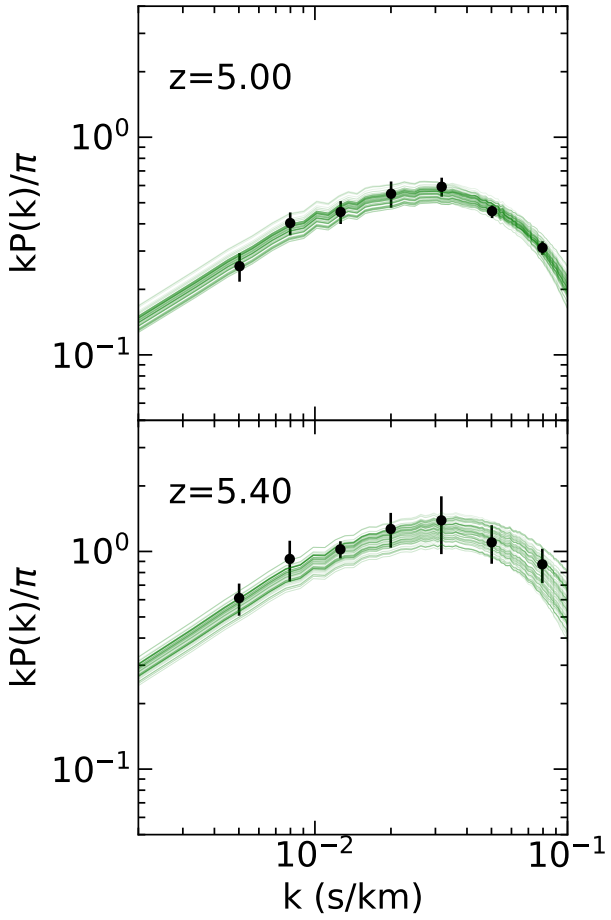


HI Reionization Constraints from $z = 5 - 6$ Lyman-α

(Oñorbe+in prep)

$$z_{\rm reion} = 8.25^{+1.14}_{-1.17}$$
$$\log_{10}\Delta T < 4.1$$





- Consistent with Planck τ_e + "galaxy driven" reionization ($T_{\rm reion}$)
- Measurements based on handful of QSOs, many more exist (Factor > 5 at $z > 6$, Pan-STARRS, DES, etc.)

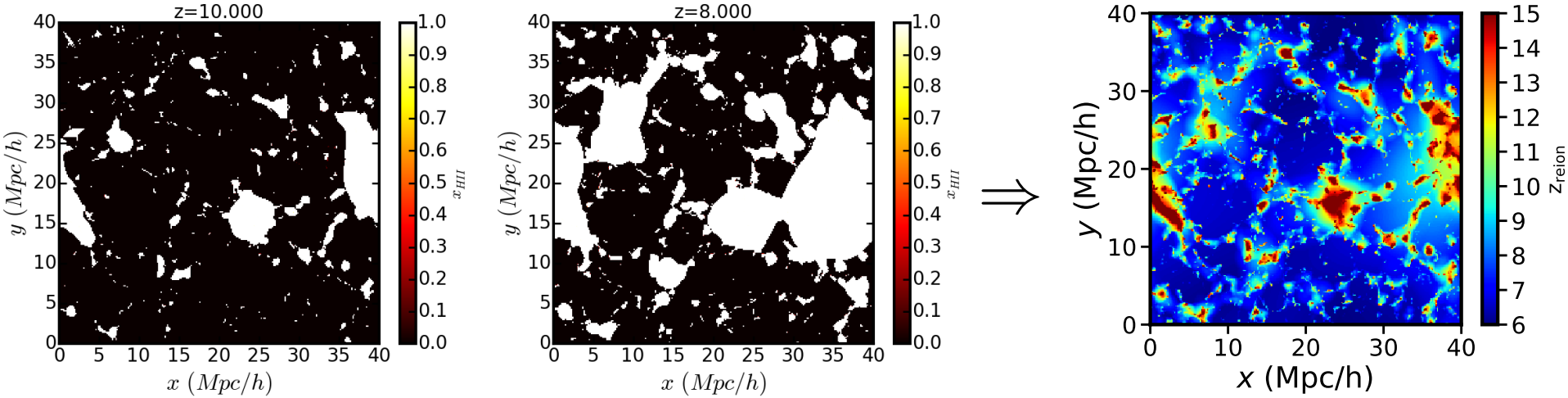
Simulating Inhomogeneous Reionization in Hydrodynamical Simulations

(Oñorbe+ in prep)

Semi-analytic model to generate reionization histories

(e.g. Mesinger+2010, Duffy+2014, Battaglia+2013, Davies+2016)

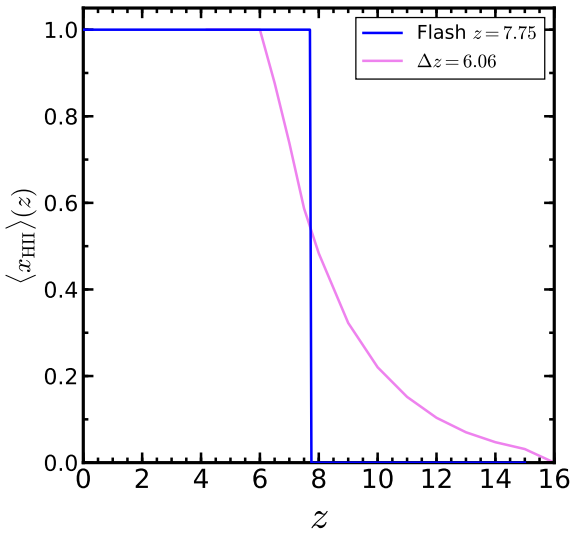
White: Hydrogen Ionized Fraction; Black: Neutral Fraction

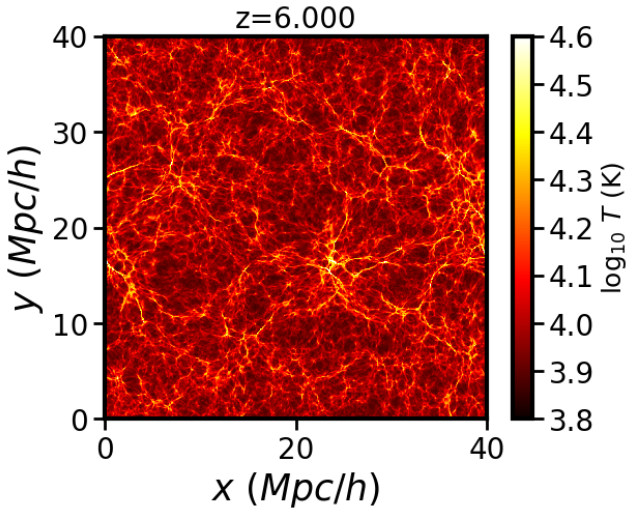


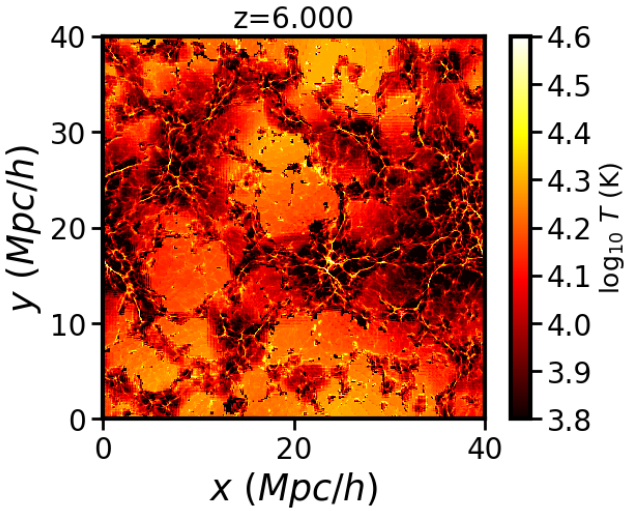
- Parameterize our ignorance as free parameters: $M_{\rm halo,min}$, $\eta_{\rm ion}$, etc
- Allows to explore parameter space

Simulating Inhomogeneous Reionization in Hydrodynamical Simulations

Flash reionization: all regions reionize at the same time







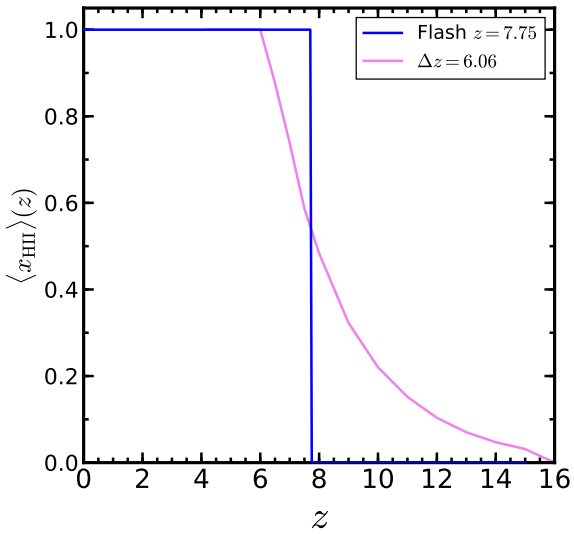
Inhomogeneous reionization: Different regions reionize at different times

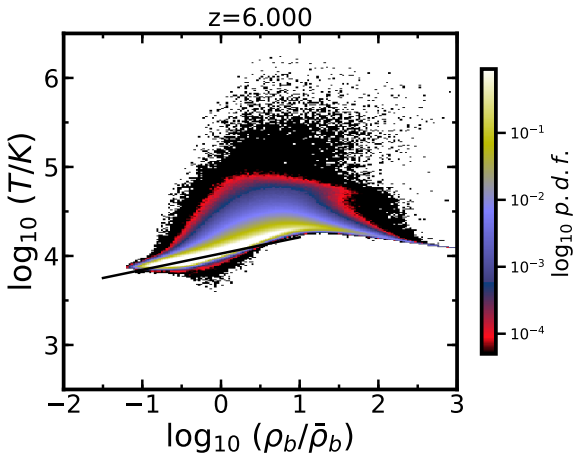
$\Rightarrow$ Temperature fluctuations

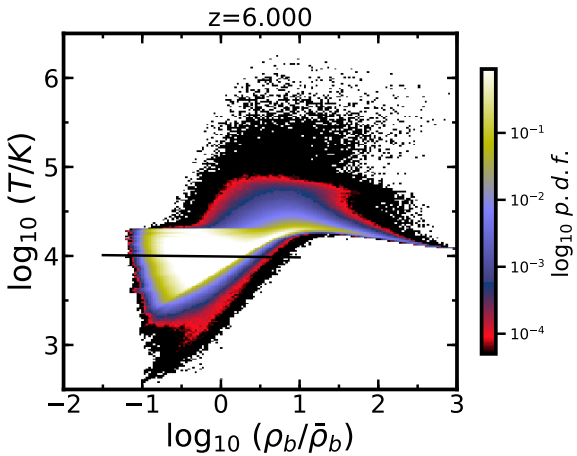
$$\tau \propto n_{HI} \propto \frac{n_H^2 T^{-0.7}}{\Gamma_{HI}}$$

Simulating Inhomogeneous Reionization in Hydrodynamical Simulations

Flash reionization: all regions reionize at the same time





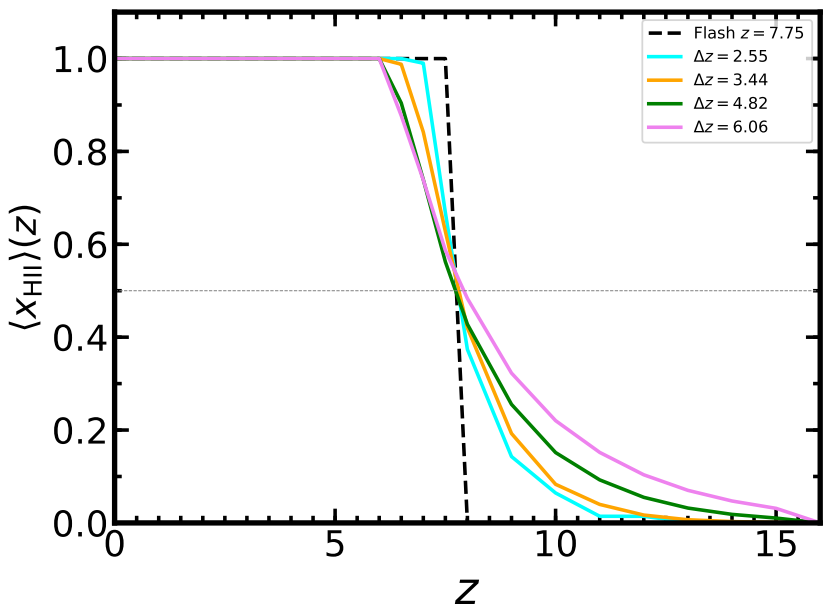


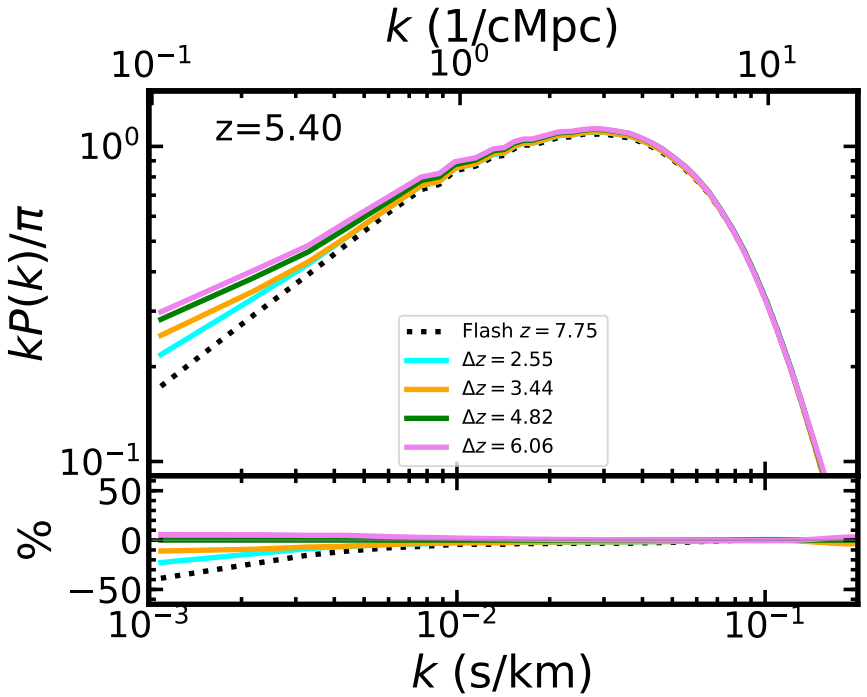
Inhomogeneous reionization: Different regions reionize at different times

$\Rightarrow$ Temperature fluctuations

$$\tau \propto n_{HI} \propto \frac{n_H^2 T^{-0.7}}{\Gamma_{HI}}$$

Simulating Inhomogeneous Reionization in Hydrodynamical Simulations

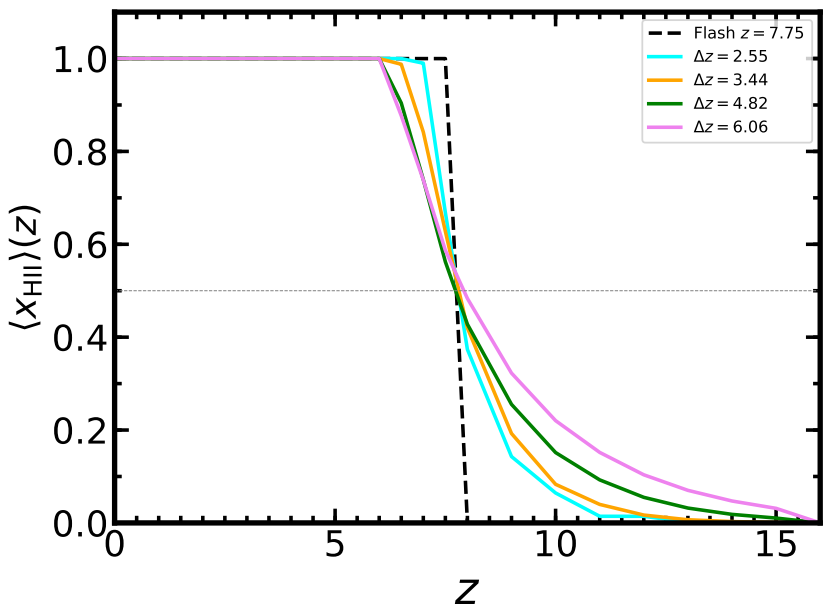


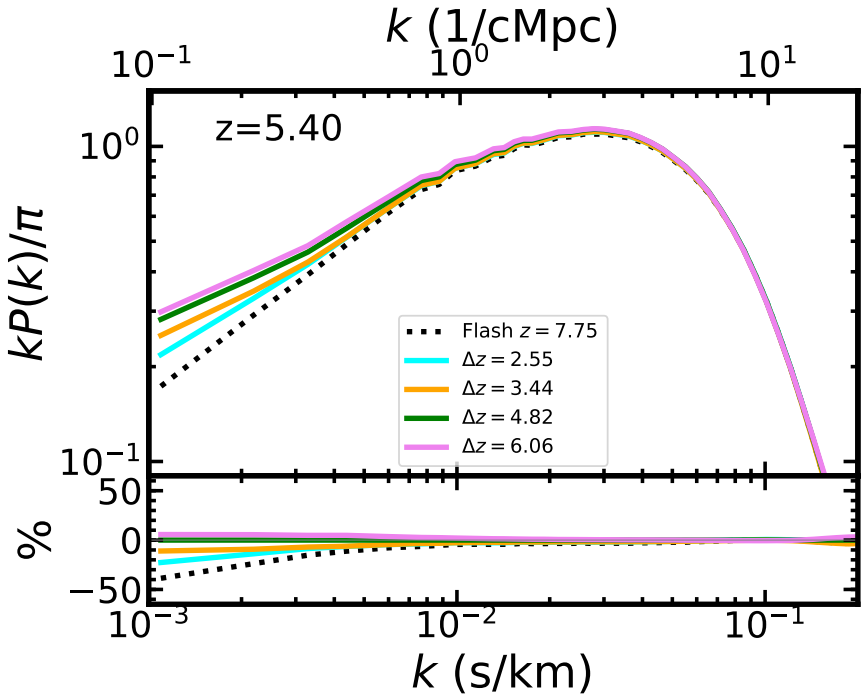


- Flash and inhomogeneous model share the same cut-off shape when

$$z_{\rm reion,flash} = z^{\rm median}_{\rm reion,inhomo} \quad \Rightarrow z^{\rm median}_{\rm reion,inhomo} = 8.25^{+1.14}_{-1.17}$$

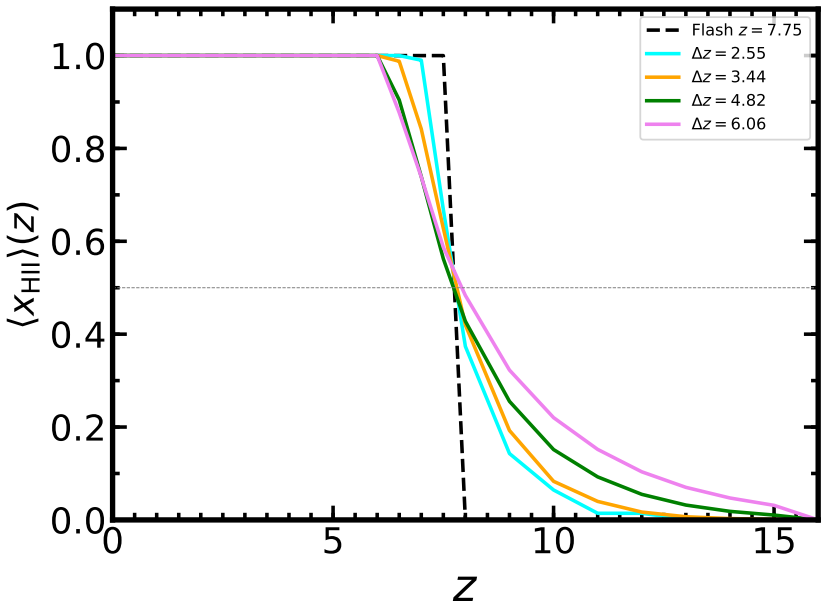
Simulating Inhomogeneous Reionization in Hydrodynamical Simulations

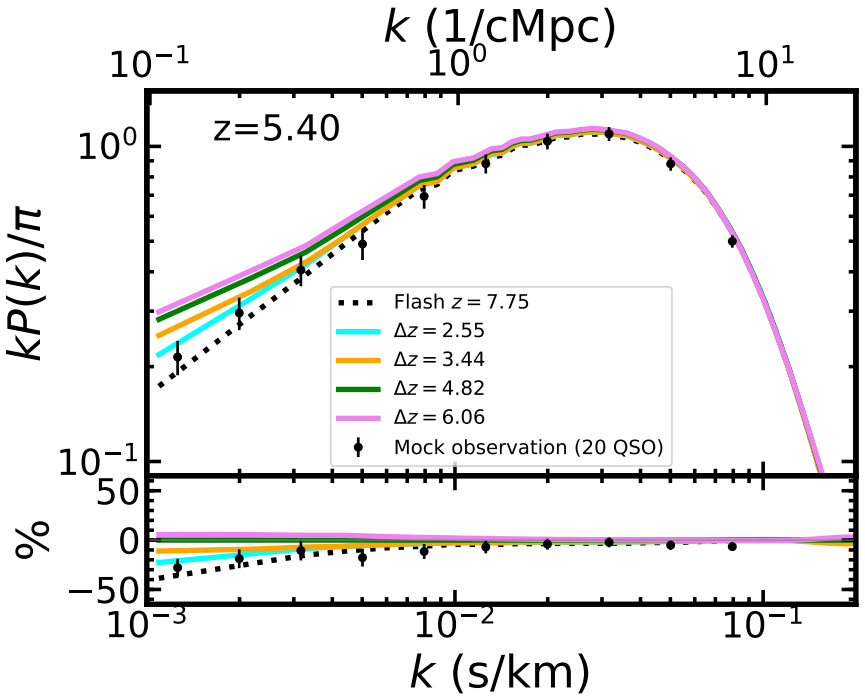




- Flash and inhomogeneous model share the same cut-off shape when $z_{\rm reion,flash} = z^{\rm median}_{\rm reion,inhomo} \Rightarrow z^{\rm median}_{\rm reion,inhomo} = 8.25^{+1.14}_{-1.17}$
- Temperature fluctuations increase power at $k \lesssim 0.01$
  $\Rightarrow$ Sensitive to $z_{\rm reion}$, $\Delta z_{\rm reion}$, $T_{\rm reion}$

Simulating Inhomogeneous Reionization in Hydrodynamical Simulations

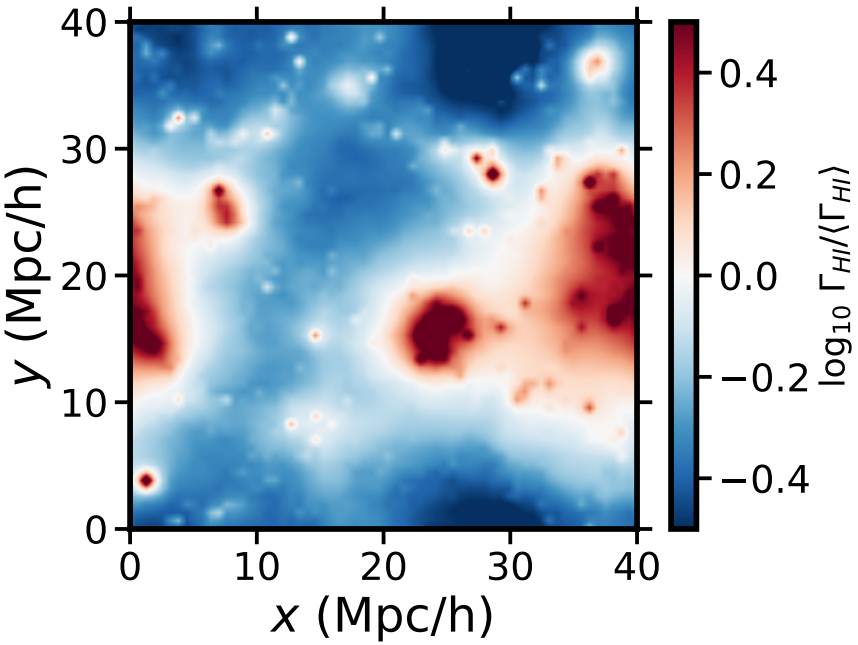


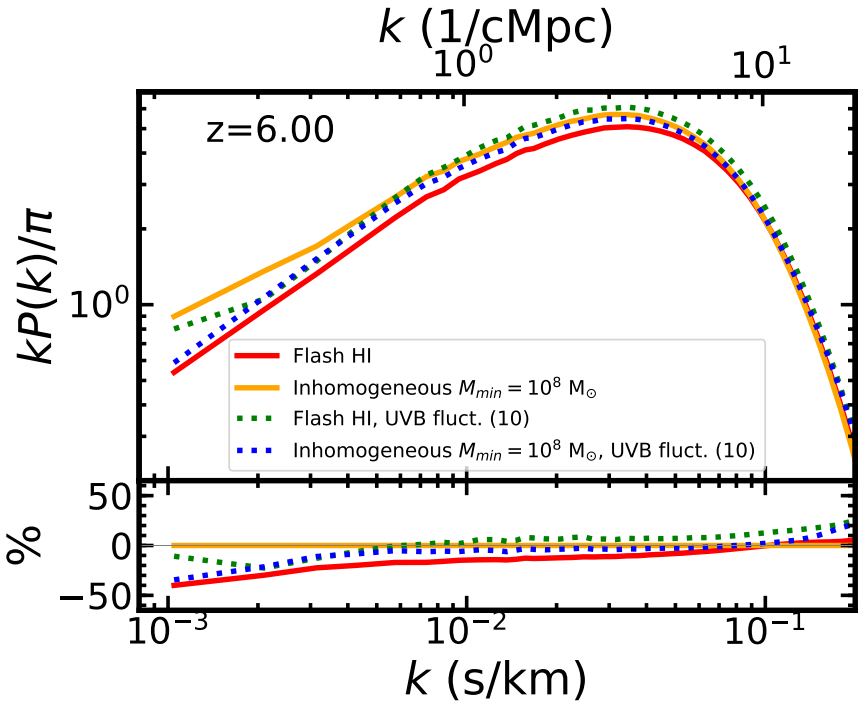


- Flash and inhomogeneous model share the same cut-off shape when $z_{\rm reion,flash} = z^{\rm median}_{\rm reion,inhomo} \Rightarrow z^{\rm median}_{\rm reion,inhomo} = 8.25^{+1.14}_{-1.17}$
- Temperature fluctuations increase power at $k \lesssim 0.01$
  $\Rightarrow$ Sensitive to $z_{\rm reion}$, $\Delta z_{\rm reion}$, $T_{\rm reion}$

Inhomogeneous Reionization: UVB Fluctuations

UV Background is not fully homogeneous at high-z





Take Away Messages

1. Reionization imprints a thermal record on the IGM detectable in the $z \sim 5-6$ Ly-α forest
2. The shape of 1D flux power spectrum at $z \sim 5-6$ depends on the timing of reionization and its associated heat injection
3. Existing high-z QSO samples can provide a new precision probe of reionization