Constraining the Epoch of Reionization with the Lyman-α Forest and Planck

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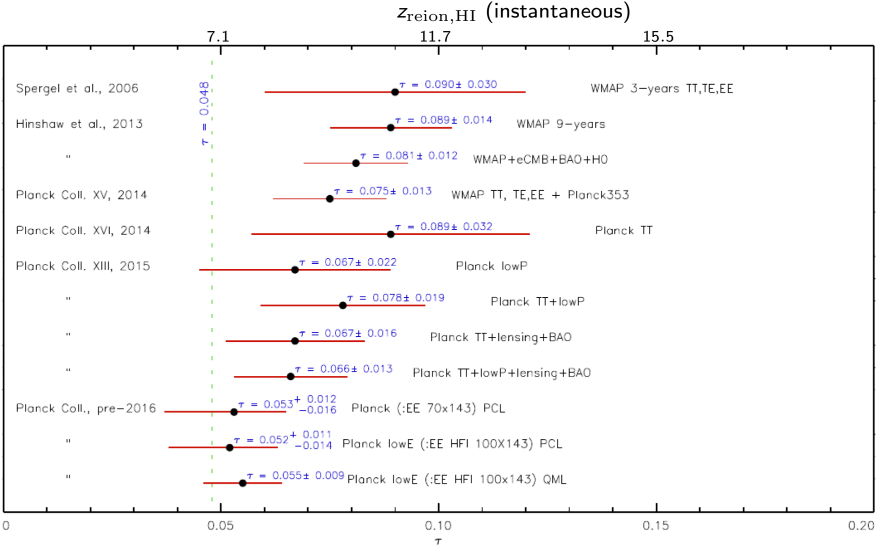
Illuminating the Dark Ages, Heidelberg

The CMB Constraints on Reionization

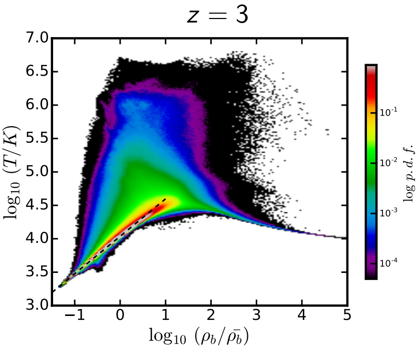


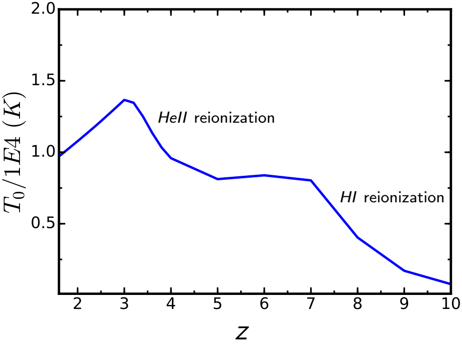
Planck Collaboration (2016a, 2016b)

Reionization Sets Up the Thermal State of the IGM

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

(Oñorbe+in prep)

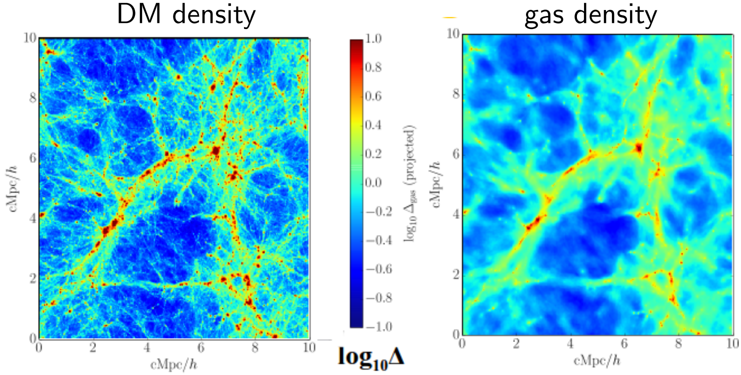




1. Study the reionization history
2. Constrain the thermal injection from ionizing sources
3. $T_{\rm IGM}$ determines galaxy formation ($M_{\rm halo,min}$)

The Thermal History of the Universe: Jeans Scale

Gas pressure can counterbalance gravitational collapse

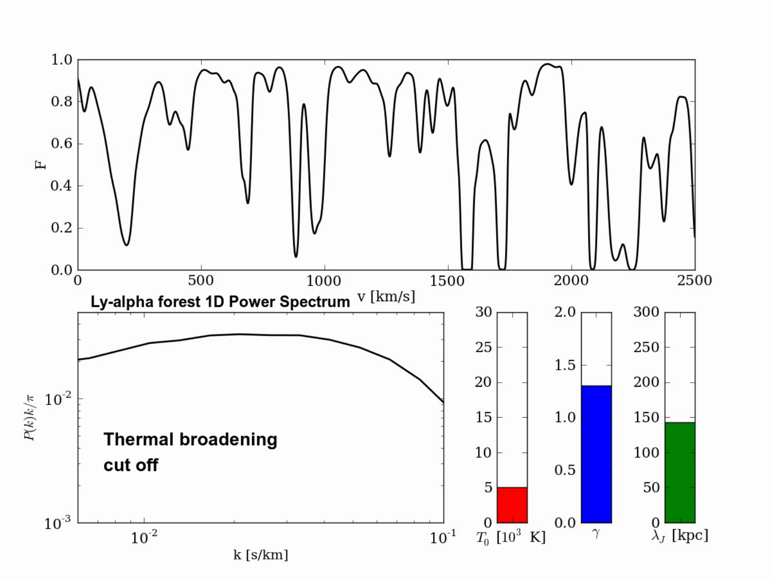


(Kulkarni,Oñorbe+2015)

- Gas traces large-scale distribution of dark matter, but small-scale fluctuations suppressed by pressure: $\lambda_{Jeans} = c_s\sqrt{\pi/G\rho} \sim 200ckpc$
- At IGM densities, the sound crossing time $\lambda_J/c_s \sim t_H$ Hubble time $\rightarrow$ pressure scale depends on the full thermal history: $\lambda \propto \int f(T[z])dz$ (Gnedin & Hui 1998)

Thermal Parameters Affect the Lyman-α Statistics

Credit video: A. Rorai



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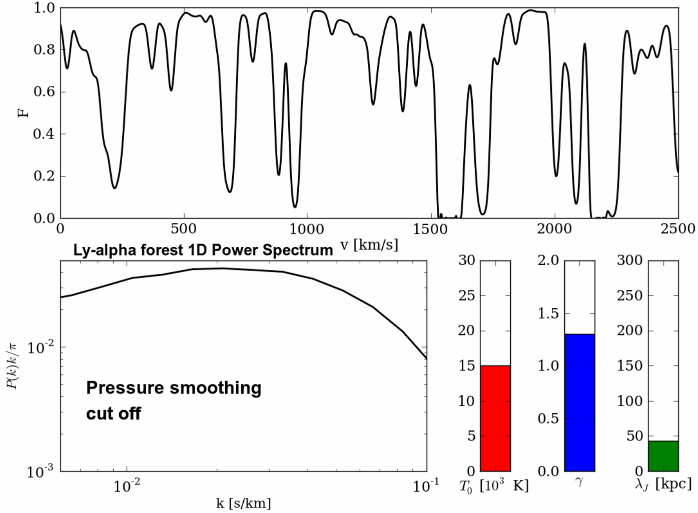
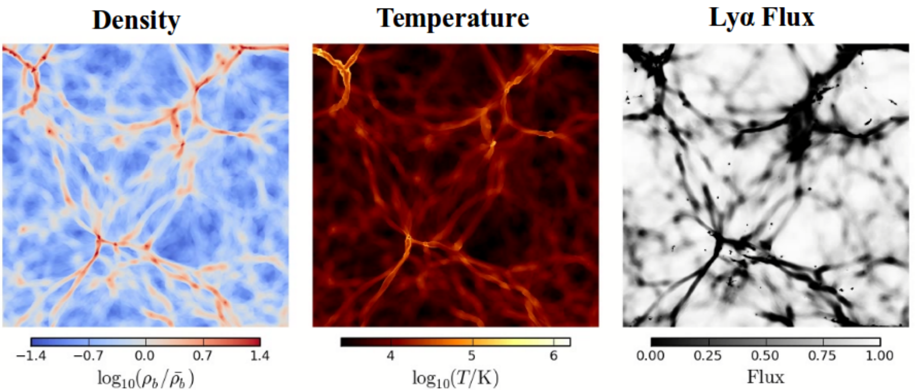
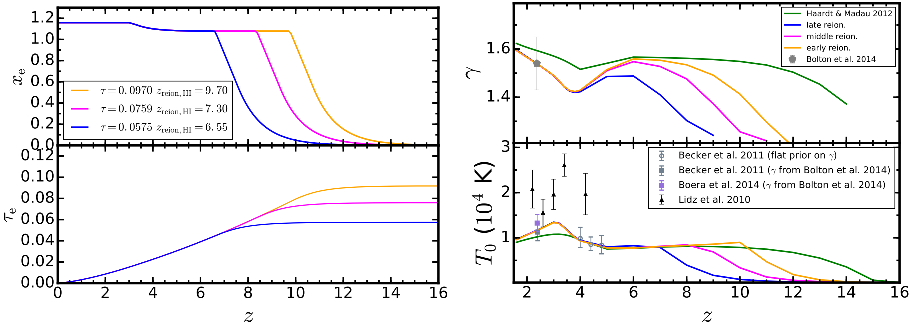


Simulating the Lyman-α Forest



- Low density hydro + gravity, CMB gives initial conditions
- Nyx massively parallel grid hydro code (Almgren+ 2013; Lukic+ 2015). A 2048^3 – 40 Mpc/h run costs $\sim 5 \times 10^5$ cpu-hrs
- Specific model of reionization (UV Background, Haardt & Madau 2012, Faucher-Giguere+2009)

Simulating Self-Consistent Reionization Histories



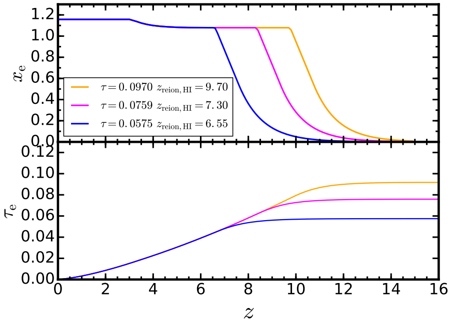
Oñorbe+2016a

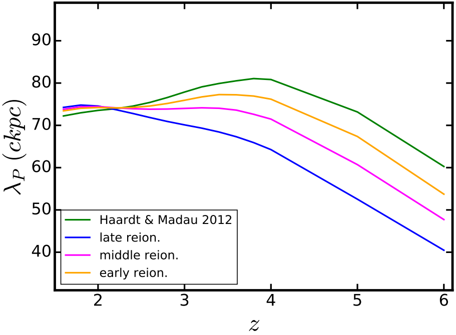
Input free parameters for the reionization model

1) Ionization History: $x_e(z) \sim z_{reion}, \Delta z$
2) Total Heat Injection: ΔT

Tables publicly available for your favorite hydro code

Simulating Self-Consistent Reionization Histories





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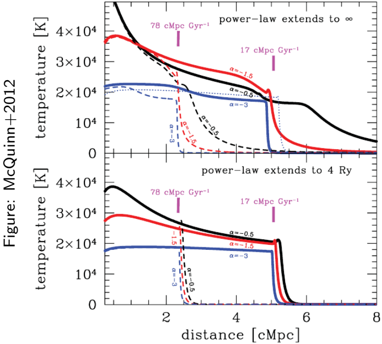
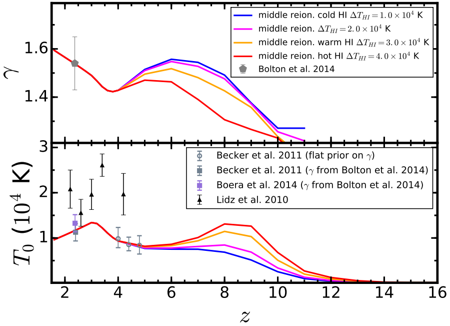




Oñorbe+2016a

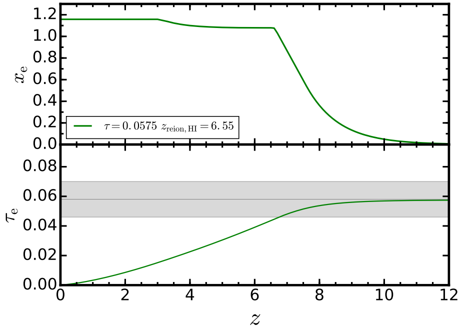
Input free parameters for the reionization model

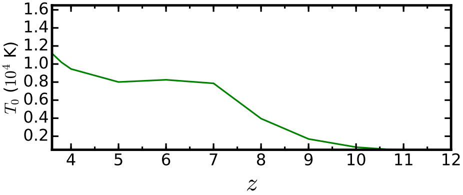
1) Ionization History: $x_e(z) \sim z_{reion}$, Δz
2) Total Heat Injection: $\Delta T \Leftrightarrow$ spectral slope of reion. sources

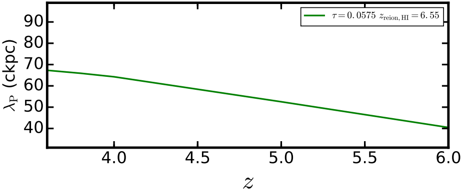
Tables publicly available for your favorite hydro code

New Planck Constraints and Lyman-α Statistics at High-z

(Oñorbe+ in prep)







Planck 2016 τ_e value, $\Delta T_{HI} = 2 \times 10^4$ K

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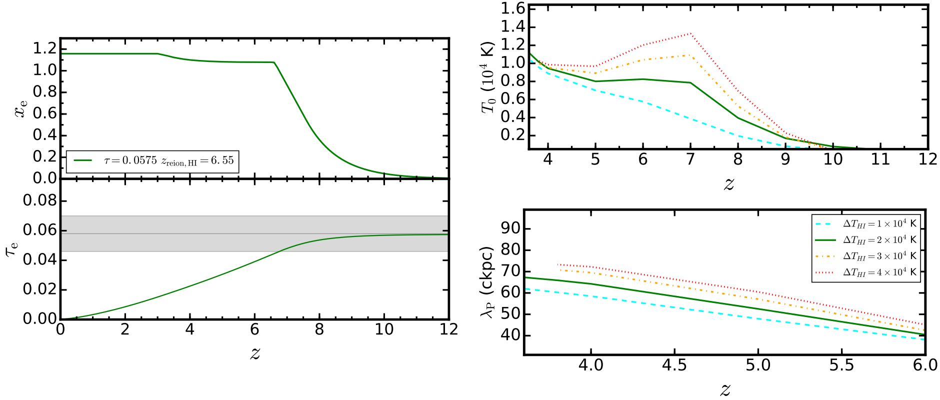

Same ionization history, different heat injection during HI reionization (spectral slope of the sources)

New Planck Constraints and Lyman-α Statistics at High-z

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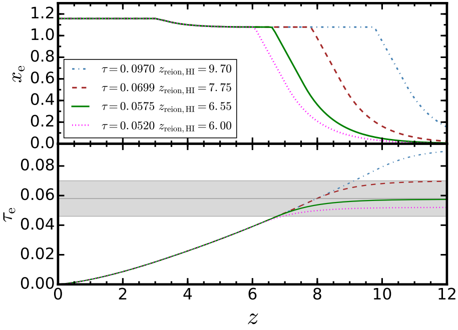
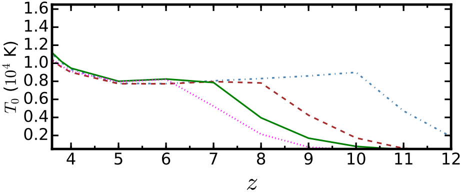
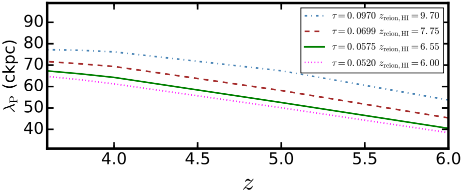


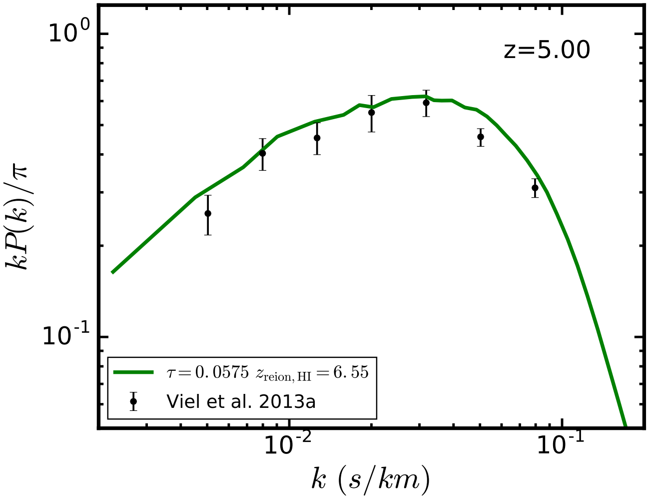




Same HI heat input, different ionization history

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

(Oñorbe+ in prep.) See also F. Nasir+2016 & poster!



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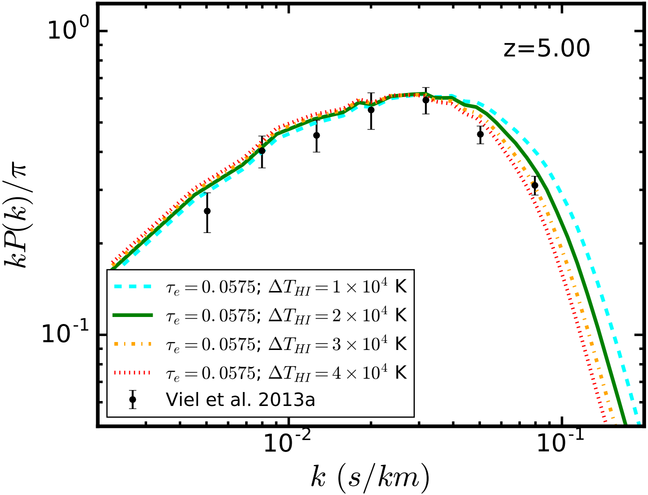
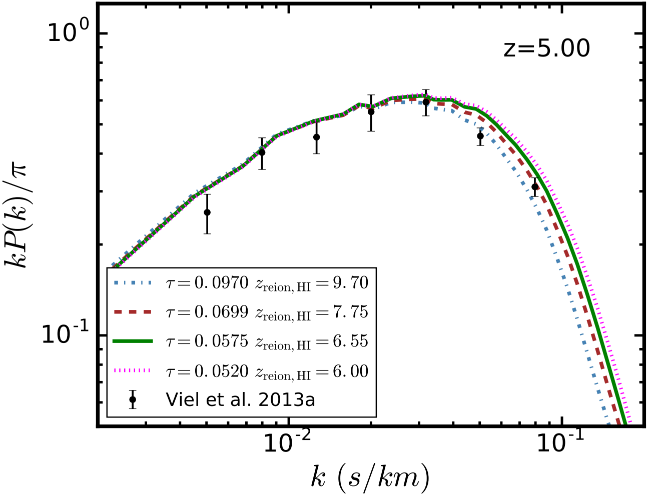


$z = 5$ observations point towards a hotter IGM
(higher heat input during HI reionization)

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

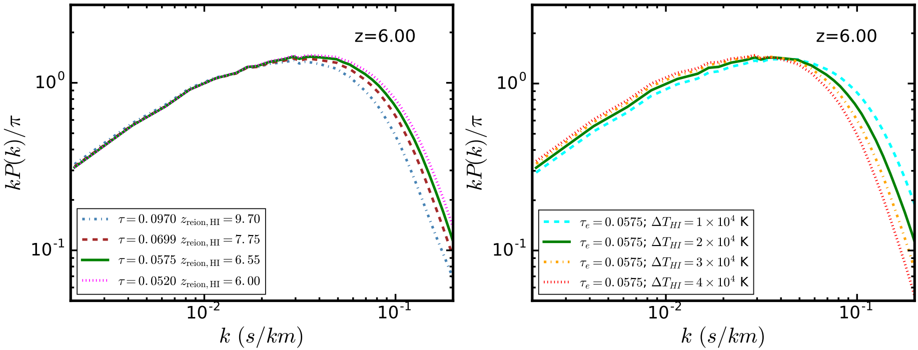
(Oñorbe+ in prep.) See also F. Nasir+2016 & poster!



$z = 5$ observations point towards a hotter IGM or an earlier reionization ($\sim 2\sigma$ from Planck)

At $z \sim 6$ Differences in the IGM Are Bigger

(Oñorbe+ in prep.)

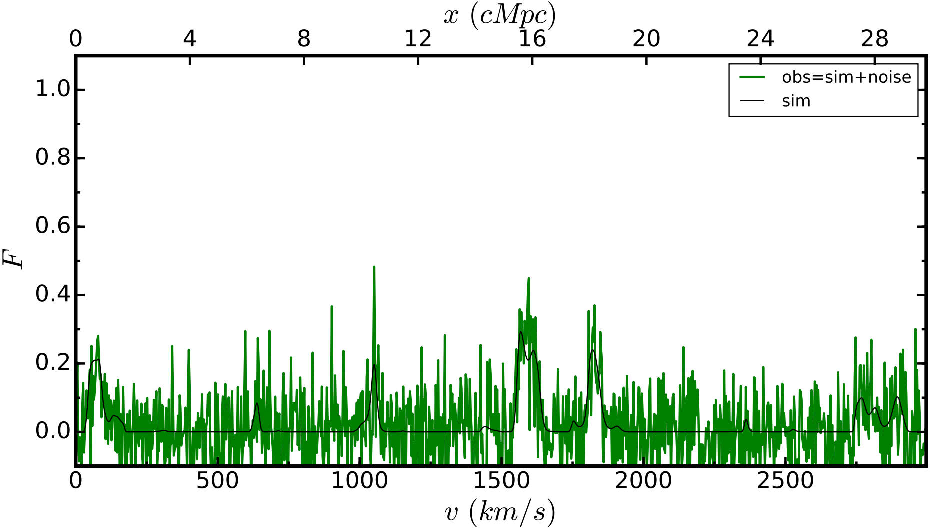


Easier to distinguish between thermal histories

PS1D at $z = 6$

(Oñorbe+ in prep.)

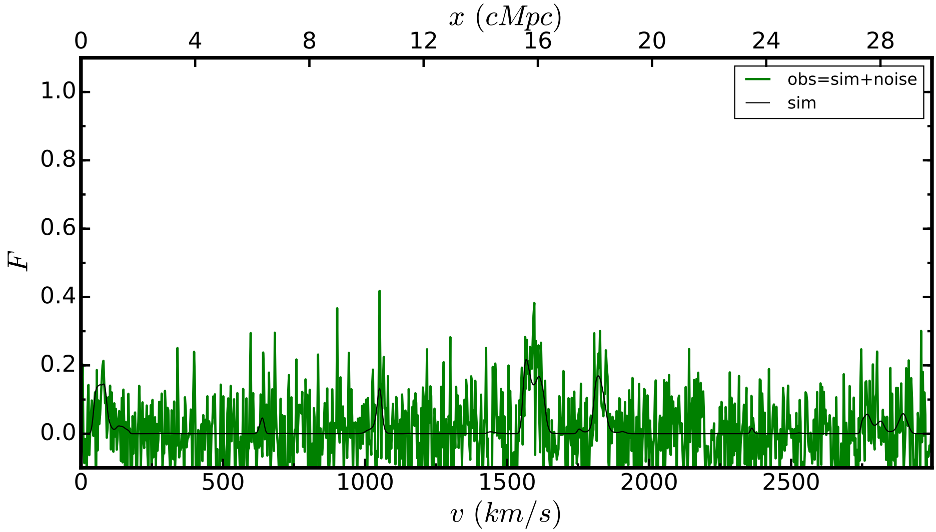
Mock spectra at $z = 6$; S/N= 10/*pixel*; $\langle\tau\rangle = \mathbf{4.0}$



PS1D at $z = 6$

(Oñorbe+ in prep.)

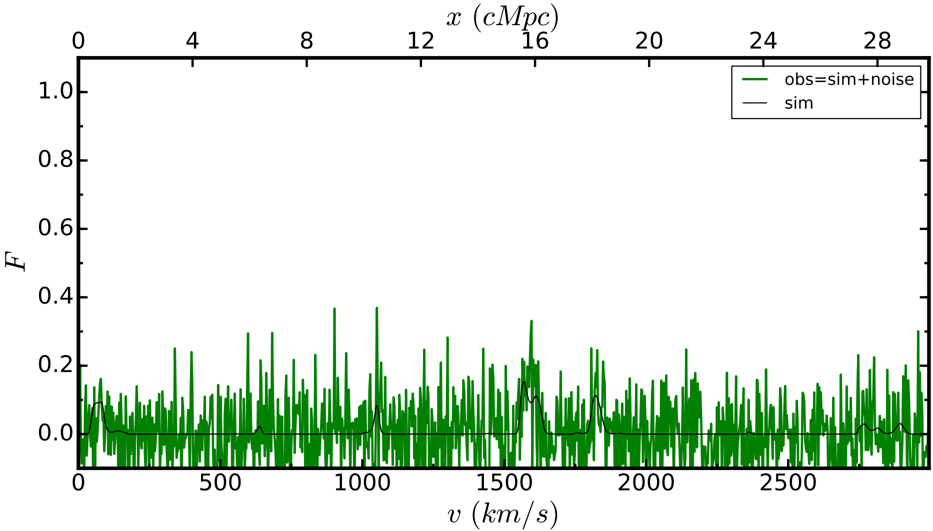
Mock spectra at $z = 6$; S/N= 10/*pixel*; $\langle\tau\rangle = \mathbf{4.5}$



PS1D at $z = 6$

(Oñorbe+ in prep.)

Mock spectra at $z = 6$; S/N= 10/*pixel*; $\langle\tau\rangle = \mathbf{5.0}$



PS1D at $z = 6$

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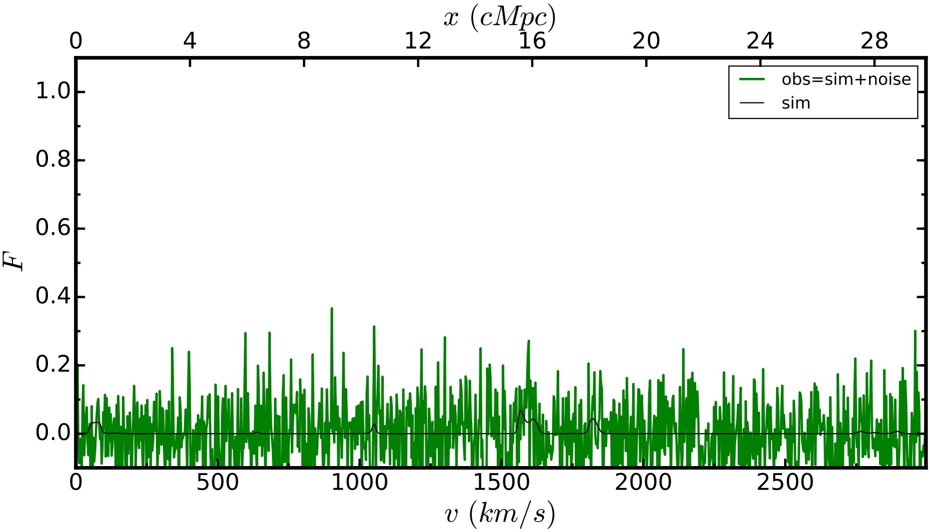
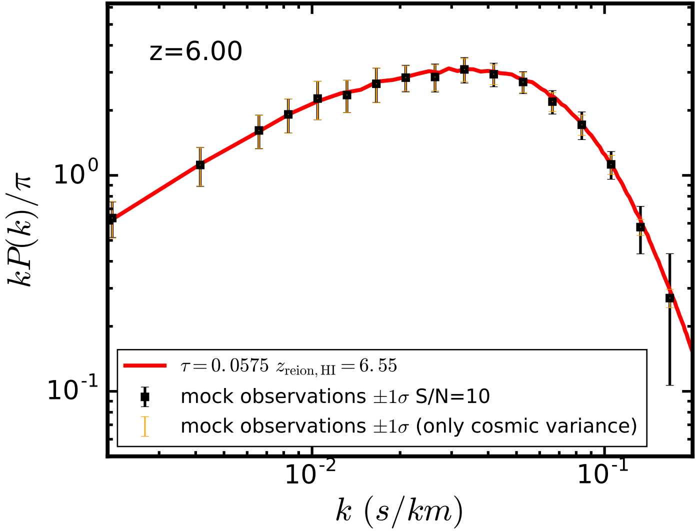
Mock spectra at $z = 6$; S/N= 10/*pixel*; $\langle\tau\rangle = \mathbf{6.0}$



PS1D at $z = 6$

(Oñorbe+ in prep.)

Mock: 20 quasars $\Delta z = 0.2$ each; S/N$=$ 10/pixel; $\langle \tau_{\rm eff,HI} \rangle =$ **4.0**



PS1D at $z = 6$

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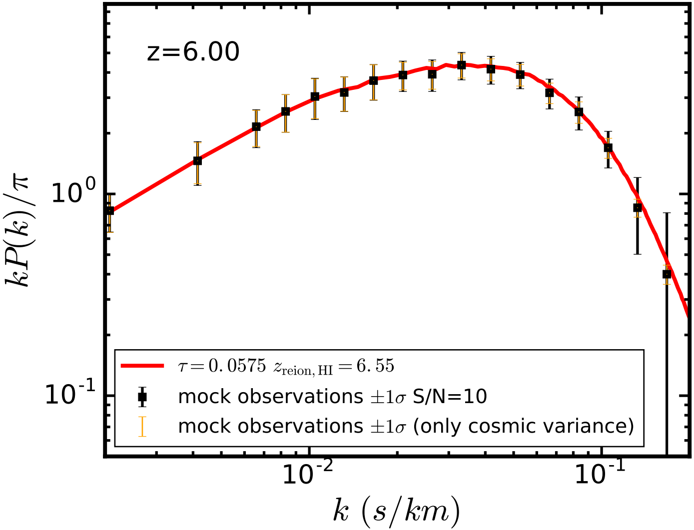
Mock: 20 quasars $\Delta z = 0.2$ each; S/N= 10/pixel; $\langle \tau_{\rm eff,HI} \rangle =$ **4.5**



PS1D at $z = 6$

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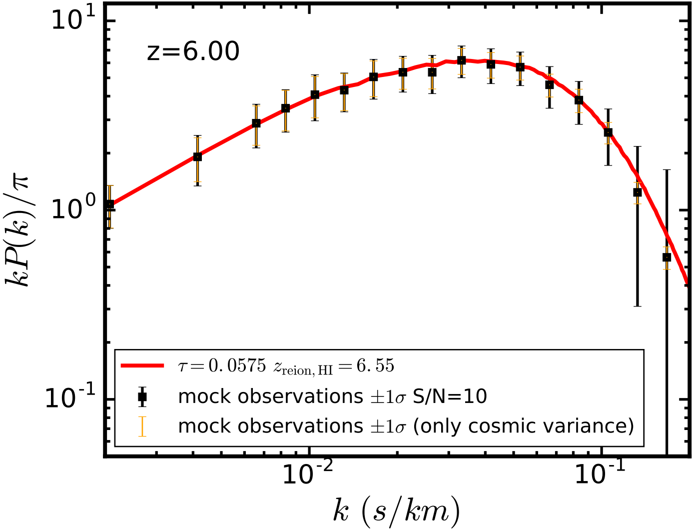
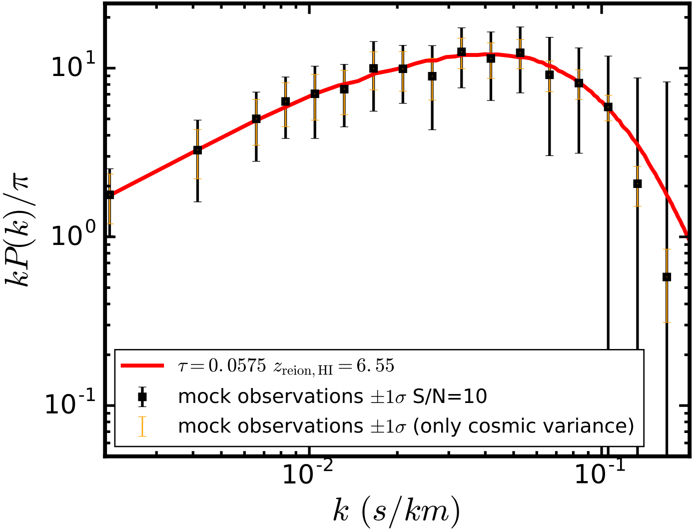
Mock: 20 quasars $\Delta z = 0.2$ each; S/N= 10/pixel; $\langle \tau_{\mathrm{eff,HI}} \rangle = \mathbf{5.0}$



PS1D at $z > 6$?

(Oñorbe+ in prep.)

Mock: 20 quasars $\Delta z = 0.2$ each; S/N= 10/pixel; $\langle \tau_{\mathrm{eff,HI}} \rangle$ = **6.0**



PS1D at $z > 6$?

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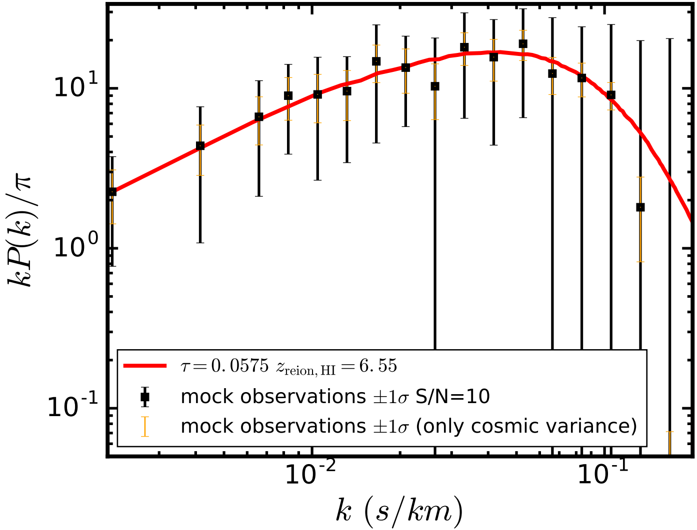
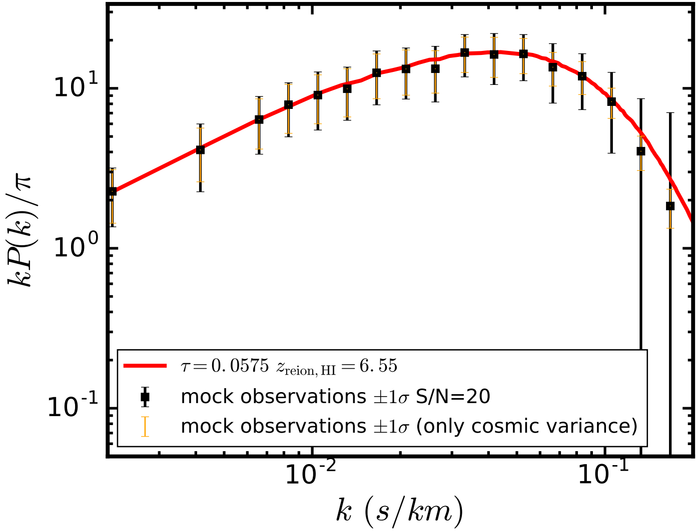


PS1D at $z > 6$?

(Oñorbe+ in prep.)

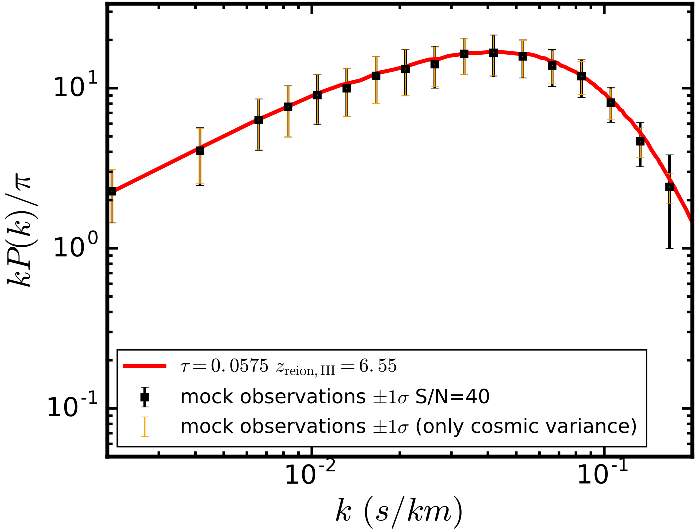
Mock: 20 quasars $\Delta z = 0.2$ each; S/N= **20**/pixel; $\langle \tau_{\mathrm{eff,HI}} \rangle = \mathbf{6.5}$



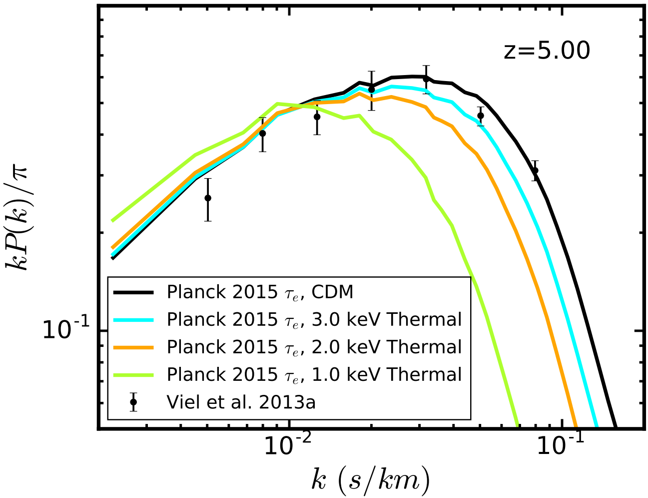
PS1D at $z > 6$?

(Oñorbe+ in prep.)

Mock: 20 quasars $\Delta z = 0.2$ each; S/N= **40**/pixel; $\langle \tau_{\mathrm{eff,HI}} \rangle =$ **6.5**



Degeneracy with Cosmological Parameters



Warm Dark matter degenerated with IGM thermal properties but very different evolution

Take Away Messages

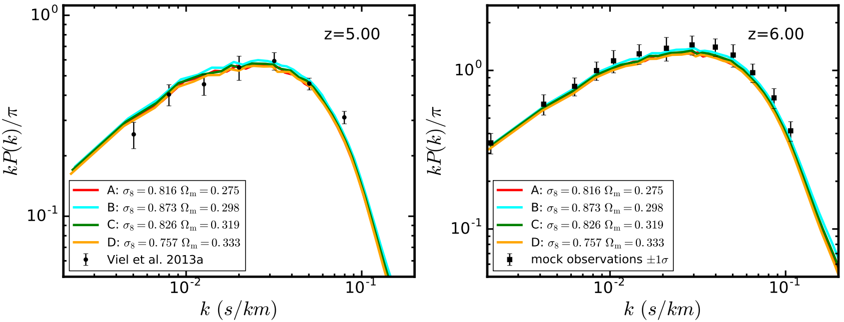
1. The Lyman-α forest at high-z allows us to study the thermal state of the IGM $\Rightarrow$ HI reionization

2. $z = 5$ Lyman-α 1D Power spectrum points towards higher IGM temperatures or higher τ_e values (but 2σ away from Planck constraints).

3. A $z = 6$ measurement is doable using current facilities and will be very helpful to clarify this picture.

4. Lower warm dark matter mass has the same physical effect as a hotter IGM (or earlier reionization) but different redshift evolution.

Degeneracy with Cosmological Parameters



Degeneracy with Warm Dark Matter