What do we know about HI Cosmic Reionization? New Constraints from the High-z Lyman-α Forest

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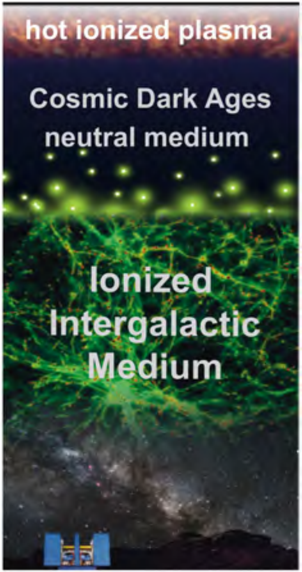
APEC Seminar IPMU
May 31th, 2018

Outline

Hydrogen Reionization of the Universe: HI $\rightarrow$ HII



TIME

$\Leftarrow$Big Bang

$\Leftarrow$Recombination $z = 1100$

- First galaxies and quasars

$\Leftarrow$HI Reionization $z = 6 - 10$

- Driven by UV radiation from galaxies and/or quasars
- Reionization injects heat into the IGM

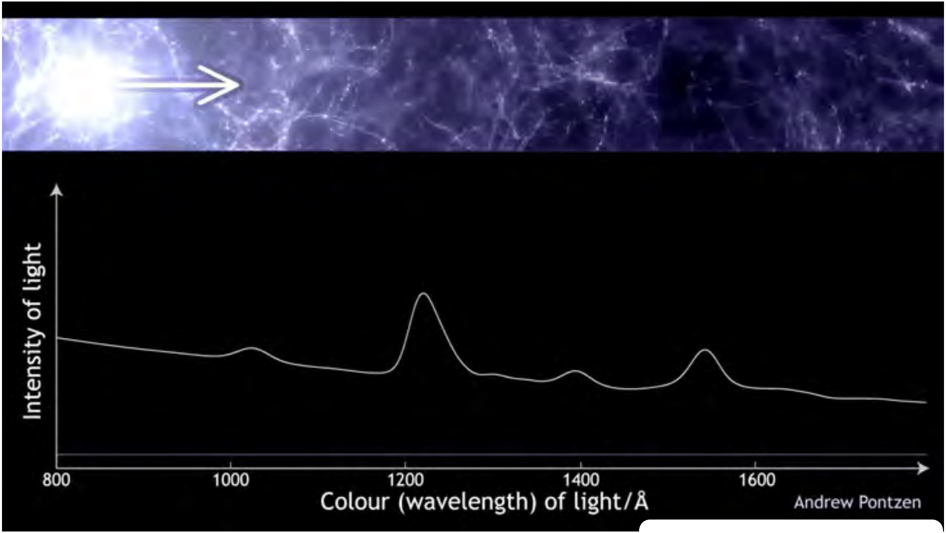
$\Leftarrow$Today $z = 0$

Hydrogen Reionization of the Universe: HI → HII

Credit: M. Alvarez, R. Kaehler, and T. Abel

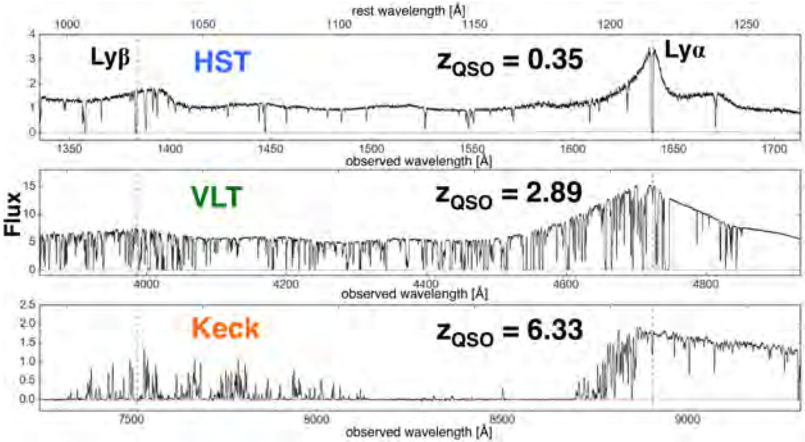
Empirical Constraints on HI Reionization: IGM transmission

The Lyman-α Forest



Credit: A. Pontzen (UCL)

Empirical Constraints on HI Reionization: IGM transmission



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

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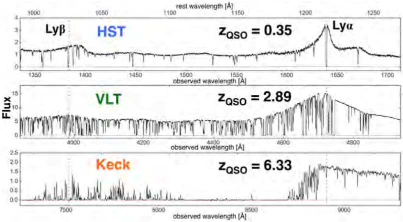

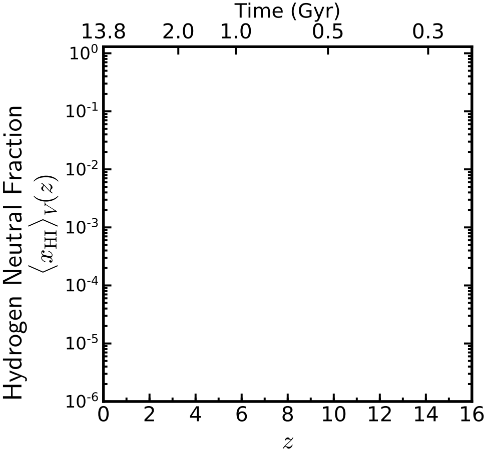

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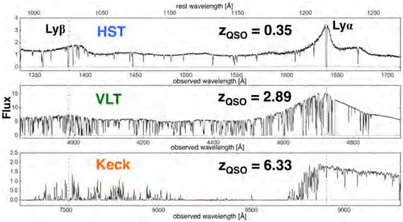
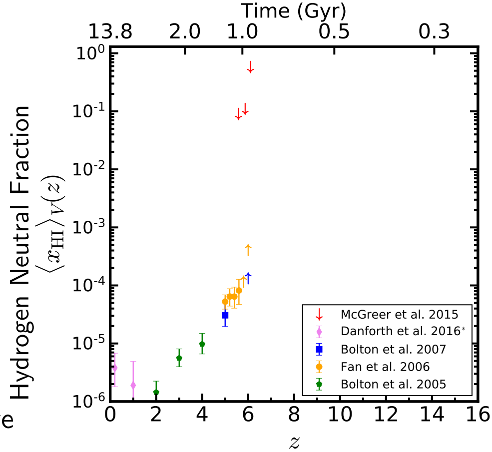


Lyman-α transmission overly sensitive saturates at $x_{HI} \sim 10^{-4}$



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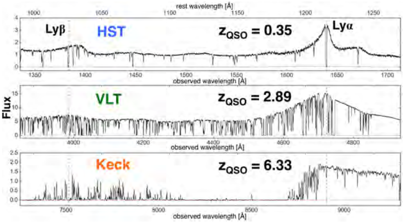

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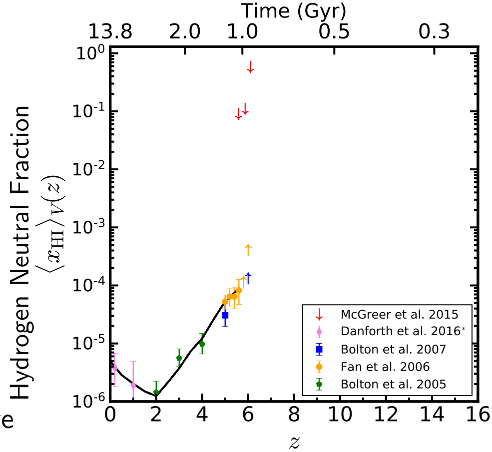

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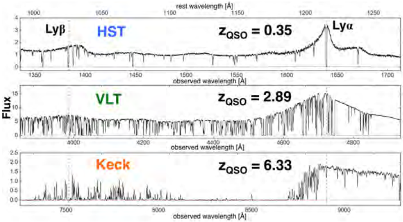

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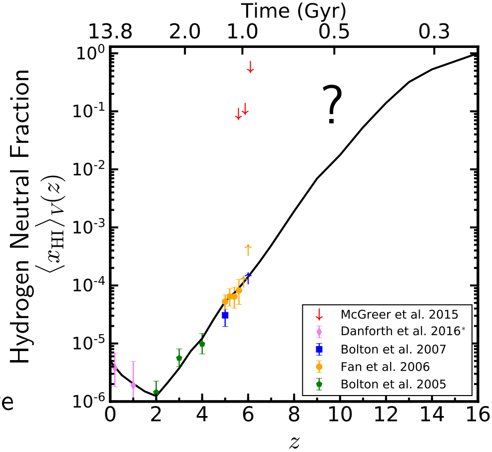

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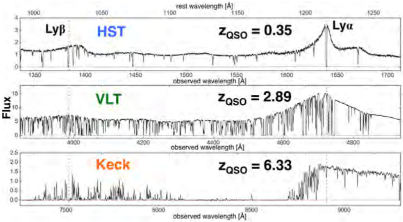

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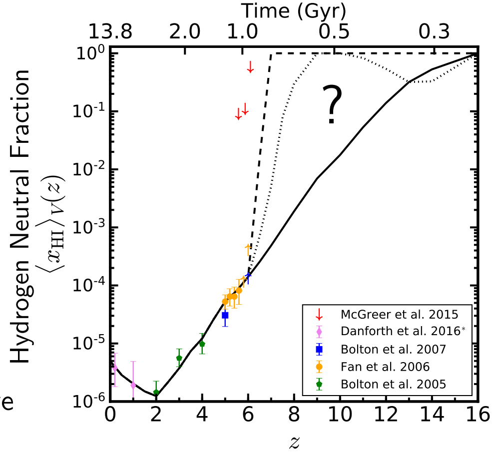
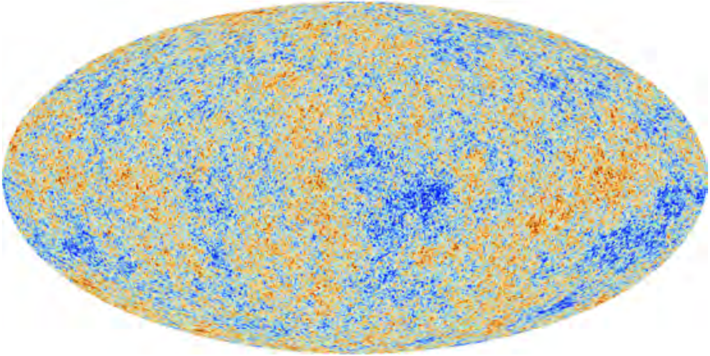


Empirical Constraints on HI Reionization: CMB polarization

Temperature fluctuations in the CMB

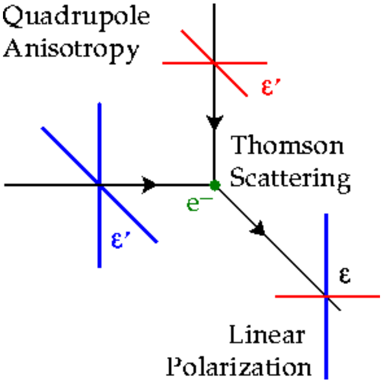


Planck Collaboration

CMB photons can interact with electrons trough Thomson scattering
$\Rightarrow$ CMB anisotropies depend on $n_{e^-}(z)$

Empirical Constraints on HI Reionization: CMB polarization

But Thomson scattering also introduces polarization *slightly* changing the original state of CMB photons



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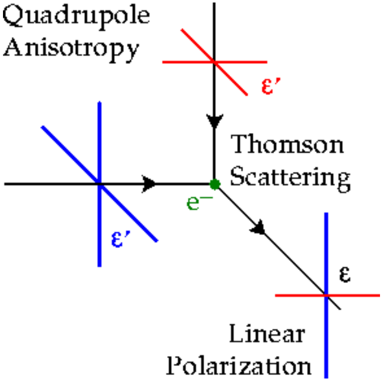
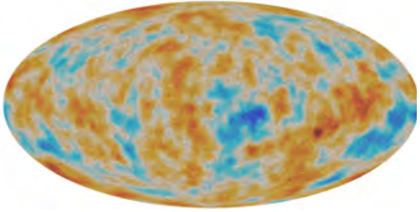


Planck has also measured it!!



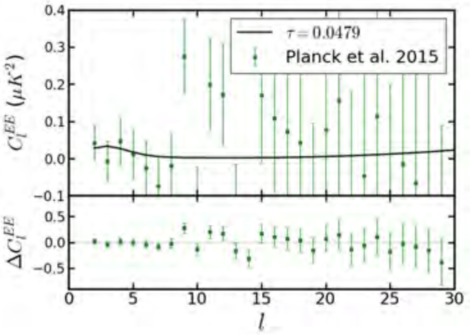
Planck Collaboration

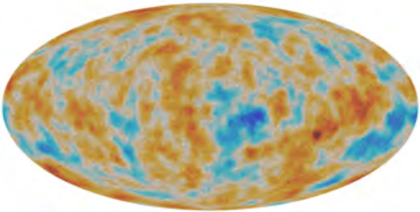
HI reionization produces unique signatures on large scales correlations

Empirical Constraints on HI Reionization: CMB polarization

Thomson Scattering Optical depth:

$\tau_e = \int \sigma_{\rm T} n_{e^-}(z) dz$; $n_{e^-} \propto x_{HII} n_H$





Planck Collaboration

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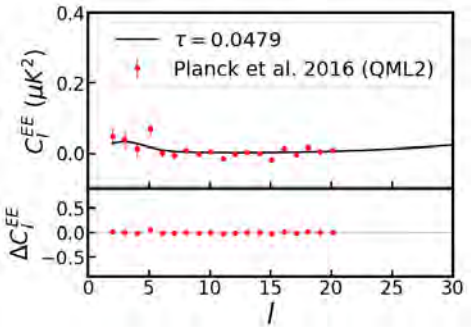

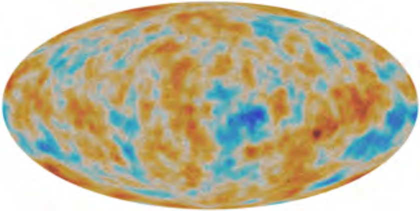

Planck Collaboration

$\tau_e = 0.055 \pm 0.009$

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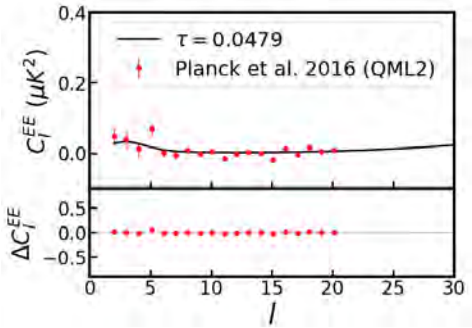

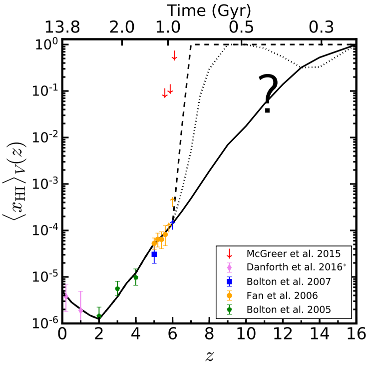

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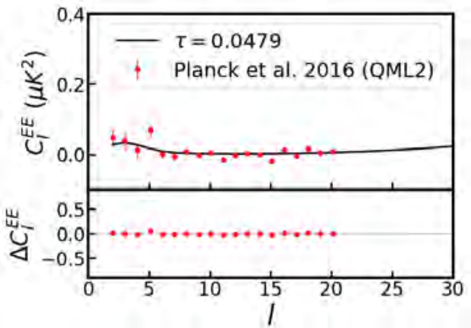

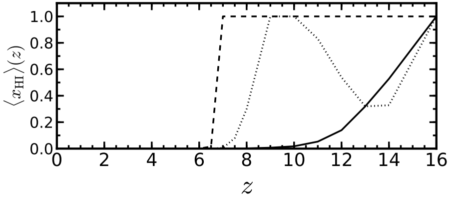

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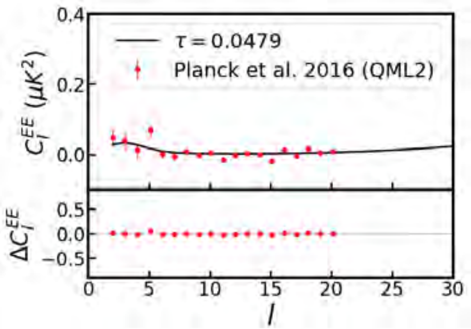
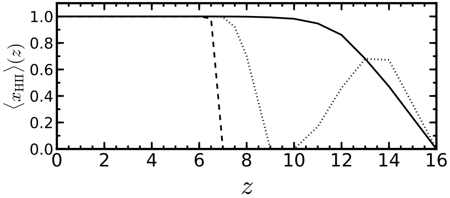


$$x_{HII} = 1.0 - x_{HI}$$



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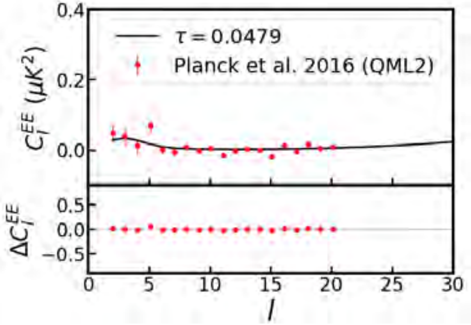

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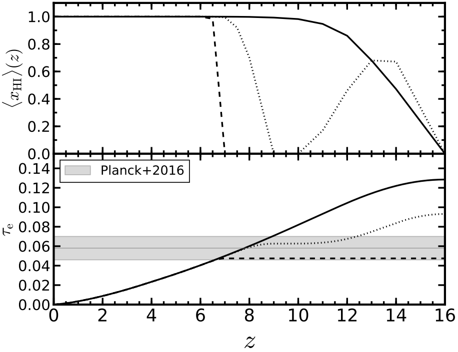

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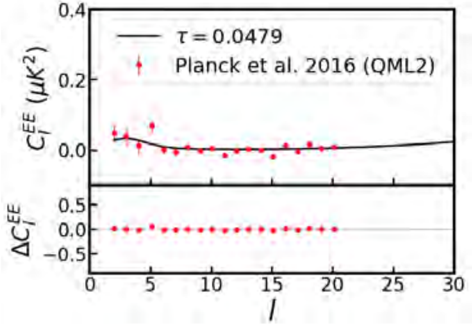

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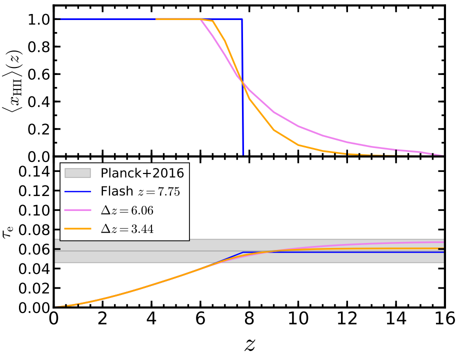
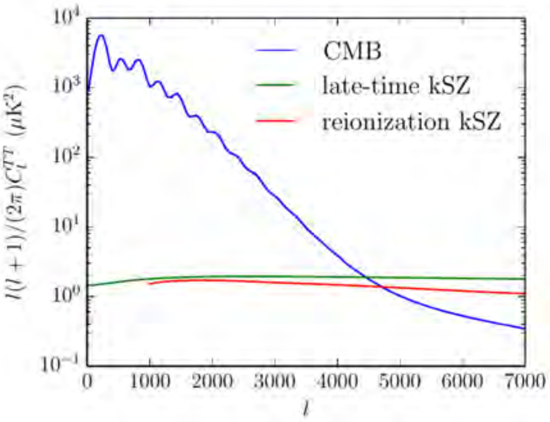


Empirical Constraints on HI Reionization: Kinetic Sunyaev-Zel´dovich effect

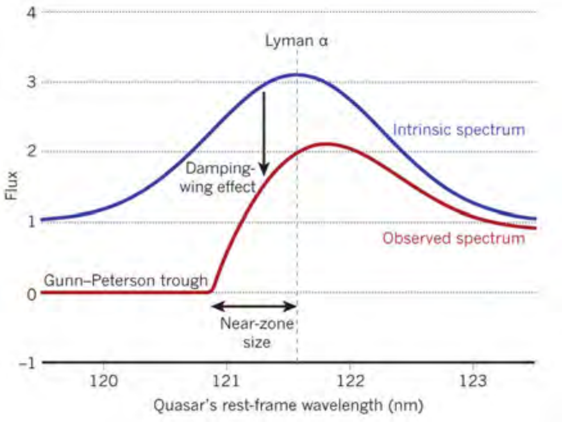
- Doppler scattering off relative motions of ionized structures
- Signal in temperature fluctuations at very high modes
- Need to remove post reionization signal
- $\Delta z < 5.4$ 95% (George+2015, SPT)



Smith+2017

Empirical Constraints on HI Reionization: $z > 6$ Lyman-α Damping Wing

- High-z Lyman-α emitters: Gamma-ray burst, QSO.
- Scattering from the intergalactic medium redward of source-frame
- Need to know intrinsic Lyman-α profile. Degenerate with quasar lifetime.
- Constrain $\langle x_{HII} \rangle$



Willott+2011

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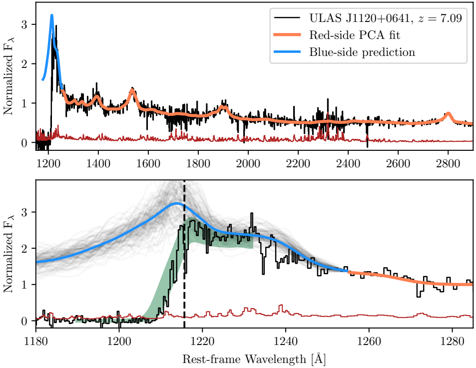
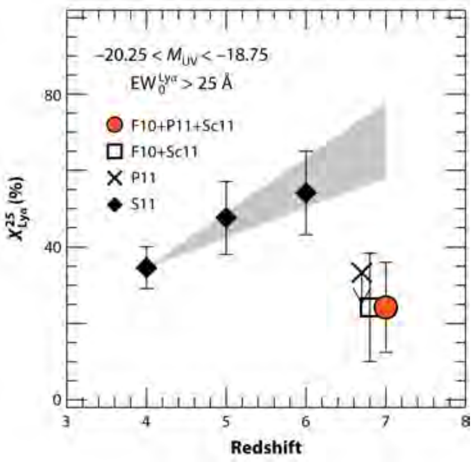


Davies+2018

Empirical Constraints on HI Reionization: Lyman-α emitting galaxies

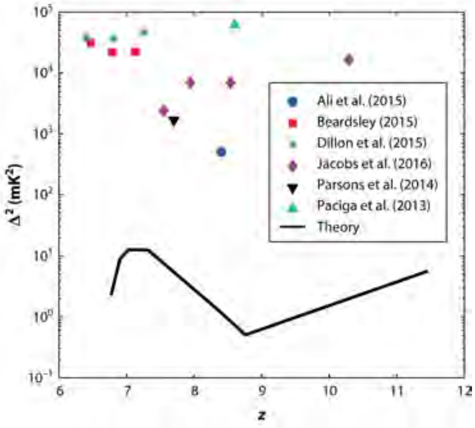
- Reduced abundance of Lyman-α selected galaxies $z > 6$ perhaps due to increased IGM absorption
- Degenerate with intrinsic absorption of the galaxy (H2 regions, CGM)
- Constrain $\langle x_{HII} \rangle$



Ono+2012

(Future?) Empirical Constraints on HI Reionization: Redshifted 21 cm radiation

- Hyperfine transition of atomic neutral hydrogen (spin flip)
- Great constraining power: redshift, duration, morphology, etc.
- Current constraints ~ 2 orders of magnitude above expected signal.



Beardsley+2015

(Future?) Empirical Constraints on HI Reionization: Redshifted 21 cm radiation

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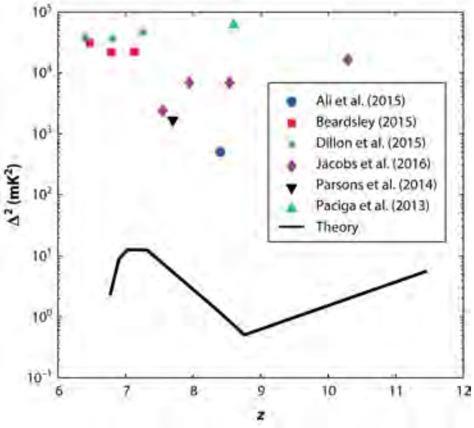
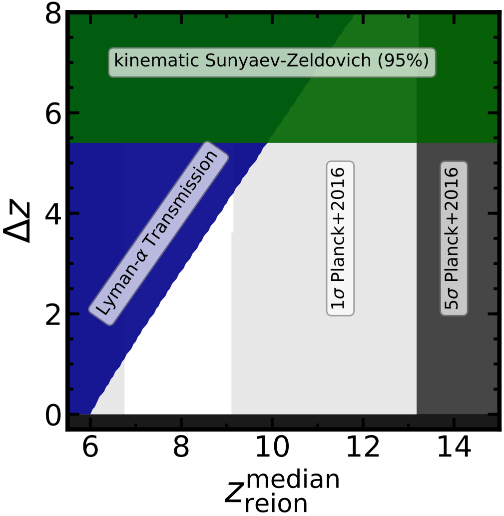
- Great constraining power: redshift, duration, morphology, etc.
- Current constraints ~ 2 orders of magnitude above expected signal.
- First detection by EDGES coll.!? $z \sim 17$



Beardsley+2015

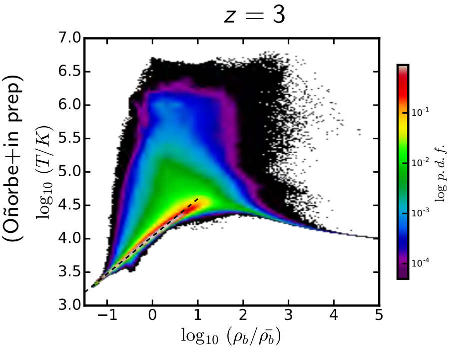
What Do We Know About HI Reionization?

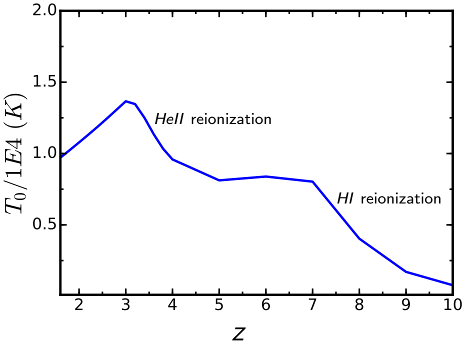
- IGM Transmission: HI reionization must be finished by $z = 6$
- CMB polarization: $z_{\rm reion} \lesssim 10$



Reionization Sets the Thermal State of the IGM

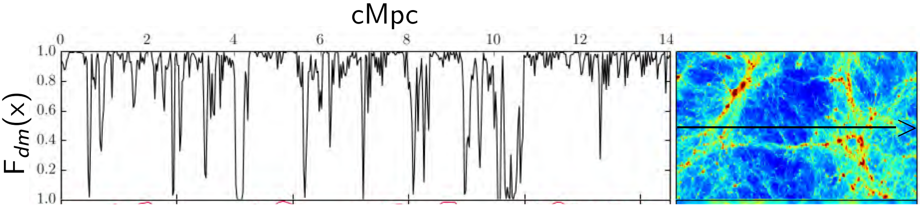
- Balance of photoheating and adiabatic cooling gives a $T-\rho$ relationship: $T(\rho) = T_0(\rho/\bar{\rho})^{\gamma-1}$ (Hui & Gnedin, 1997)





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

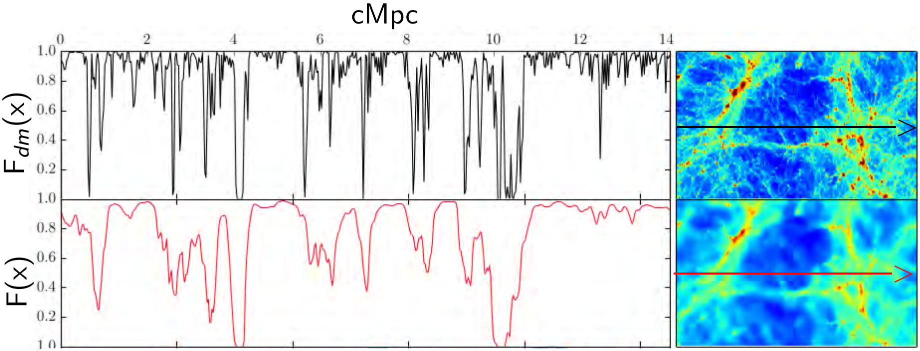
The Pressure Smoothing Scale of the IGM



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)

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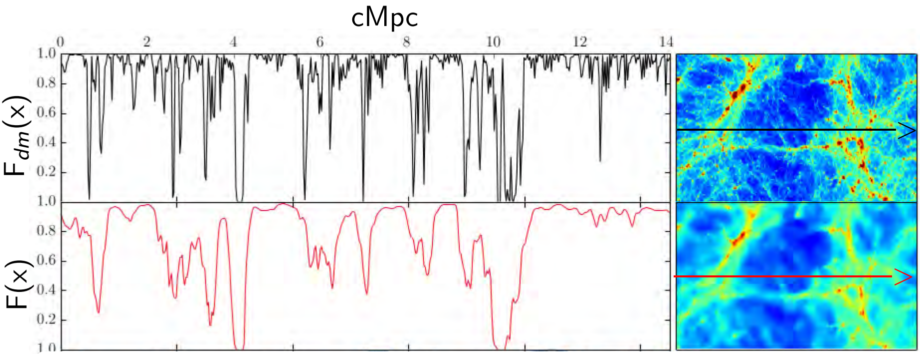
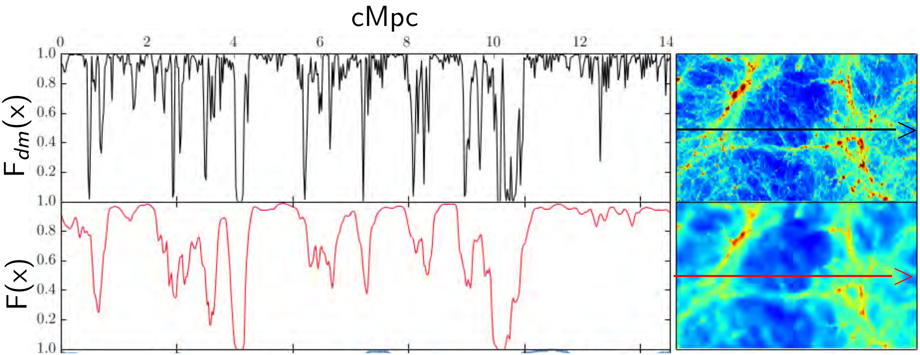


Pressure forces $\rightarrow$ baryon smoother than dark matter

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

(Kulkarni,JO+2015)

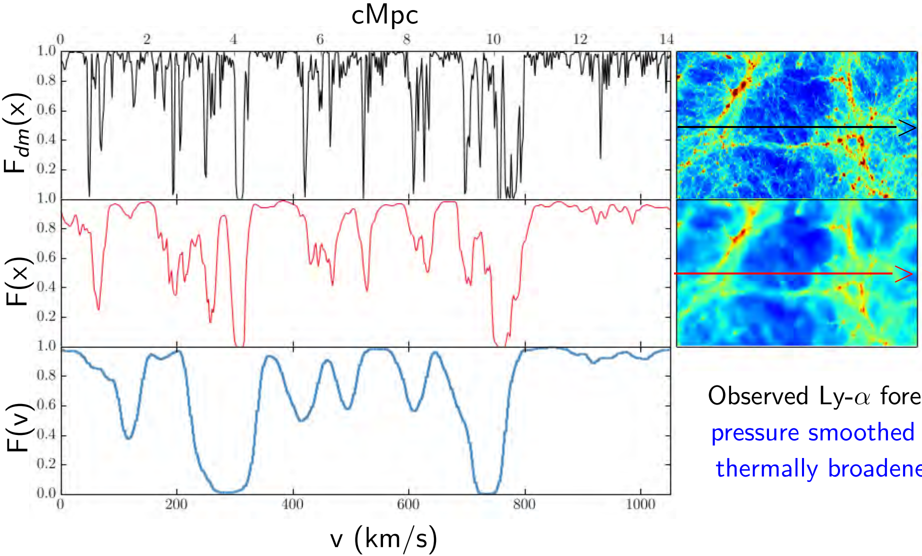
Thermal Doppler Broadening



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

(Kulkarni,JO+2015)

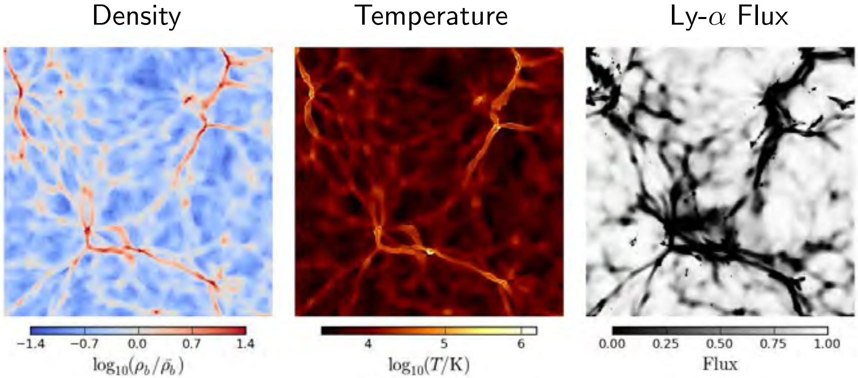
Cosmic Calorimetry with the Ly-α Forest



Observed Ly-α forest:
pressure smoothed +
thermally broadened

(Kulkarni,JO+2015)

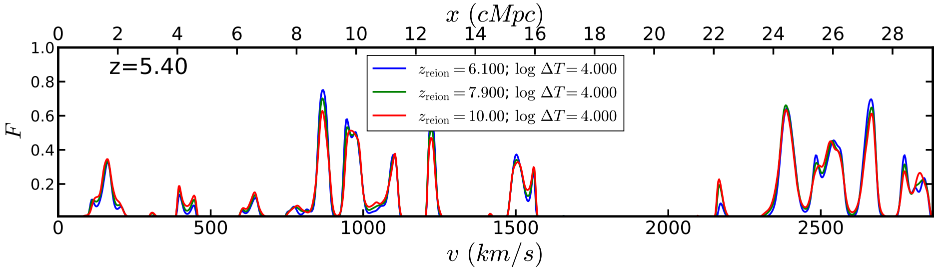
Simulating the Intergalactic Medium



Credit:Lukic

- Hydro + gravity, low density, CMB gives initial conditions
- Nyx massively parallel grid hydro code (Almgren+ 2013; Lukic+ 2015). A 2048^3 – 40 Mpc/h run costs $\sim 3 \times 10^5$ cpu-hrs
- Reionization redshift $z_{\rm reion}$ and heat injection ΔT treated as phenomenological input

The High-z IGM Retains Thermal Memory of Reionization



2 free parameters: $z_{\rm reion}$, ΔT

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

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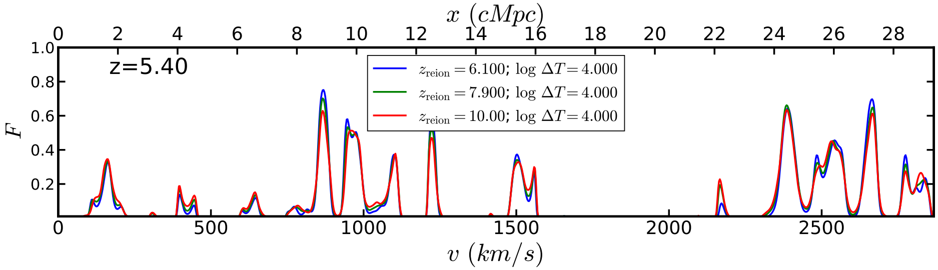

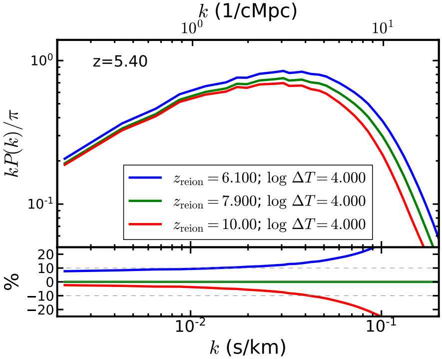

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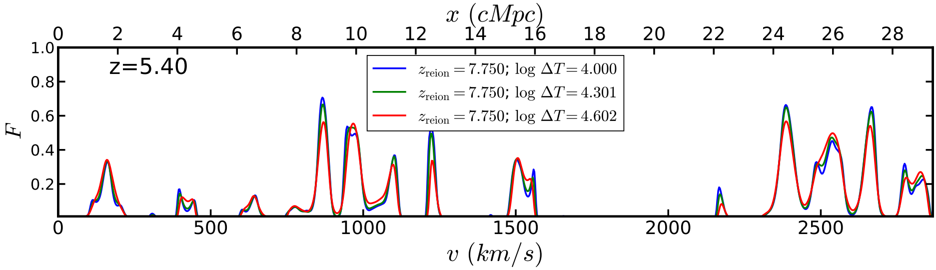

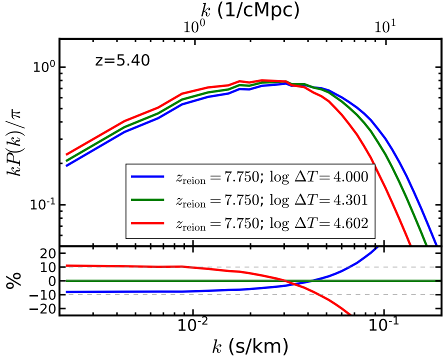

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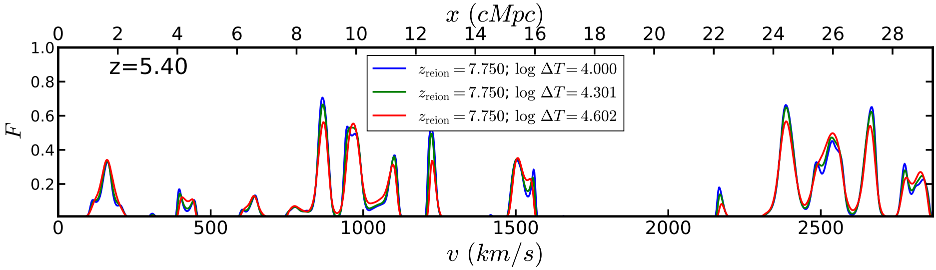
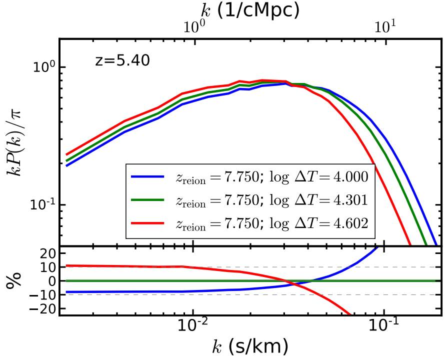
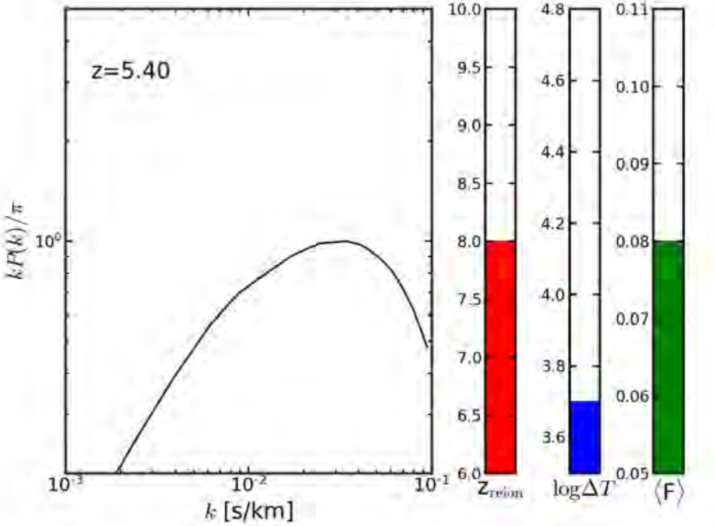




2 free parameters: $z_{\rm reion}$, ΔT

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

The High-z IGM Retains Thermal Memory of Reionization



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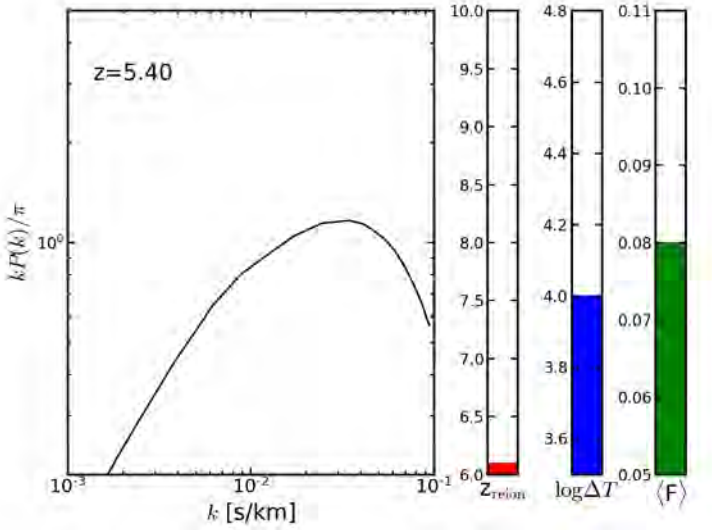

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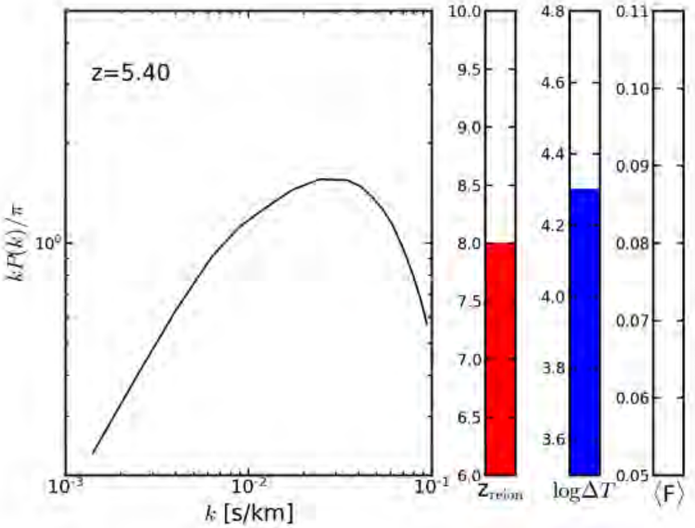
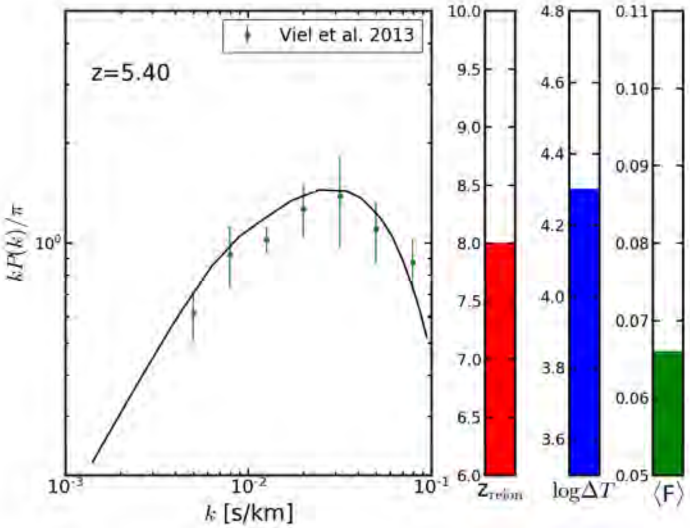


The High-z IGM Retains Thermal Memory of Reionization

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



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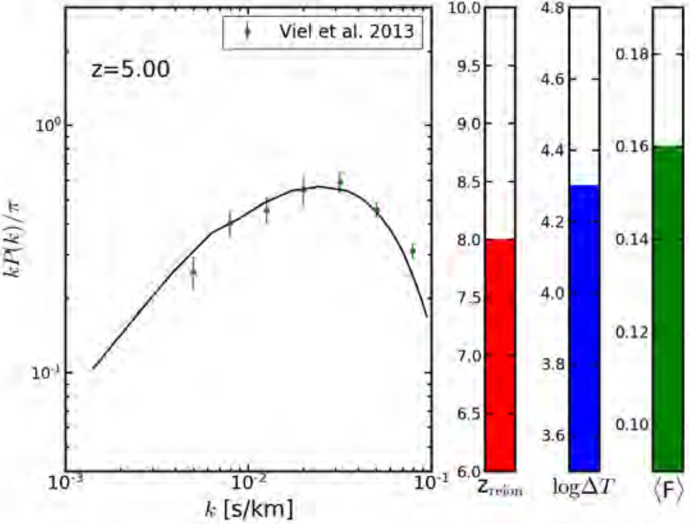
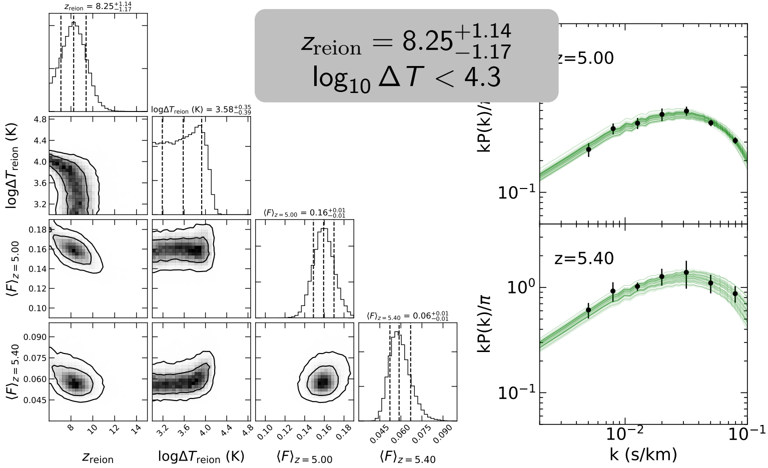


HI Reionization Constraints from $z = 5 - 6$ Lyman-α

(Oñorbe+in prep)

$$z_{\rm reion} = 8.25^{+1.14}_{-1.17}$$
$$\log_{10} \Delta T < 4.3$$



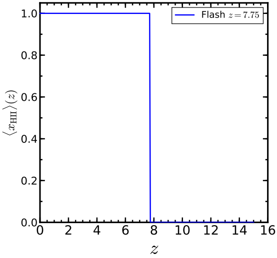
- Consistent with Planck τ_e + "galaxy driven" reionization (ΔT)
- Measurements based on handful of QSOs, many more exist

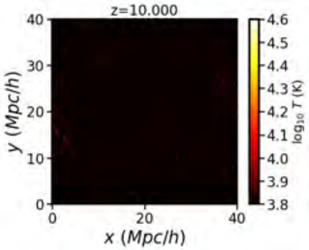
(Factor > 5 at $z > 6$, Pan-STARRS, DECaLS, SHELLQs, etc.)

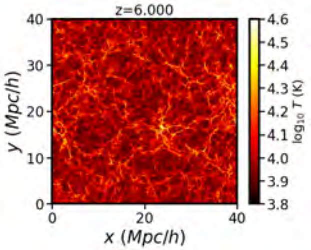
Simulating Inhomogeneous Reionization in Hydrodynamical Simulations

(Oñorbe+ in prep)

Flash reionization: all regions reionize at the same time







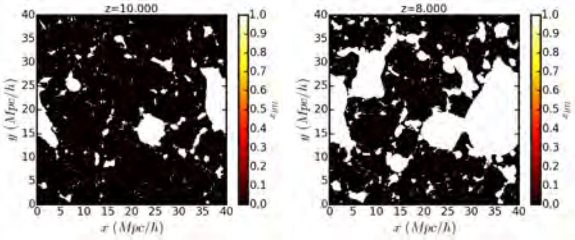
Simulating Inhomogeneous Reionization in Hydrodynamical Simulations

(Oñorbe+ in prep)

Semi-analytic model to generate reionization histories

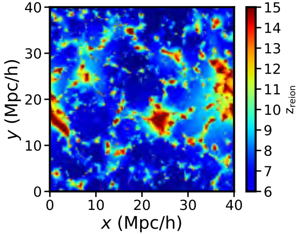
(e.g. Mesinger+2010, Battaglia+2013, Davies+2016)

White: Hydrogen Ionized Fraction; Black: Neutral Fraction



$\Rightarrow$

Reionization Field



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

Simulating Inhomogeneous Reionization in Hydrodynamical Simulations

(Oñorbe+ in prep)

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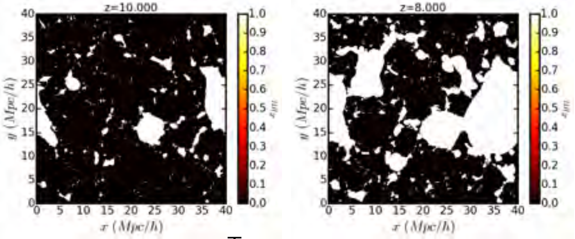
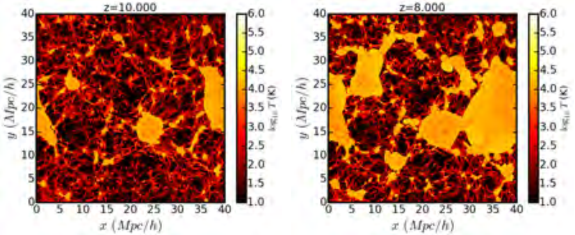
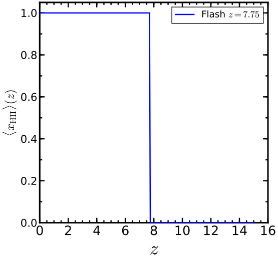


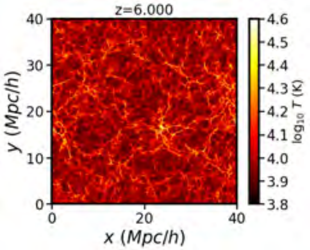
Temperature



Simulating Inhomogeneous Reionization in Hydrodynamical Simulations

Flash reionization: all regions reionize at the same time





Simulating Inhomogeneous Reionization in Hydrodynamical Simulations

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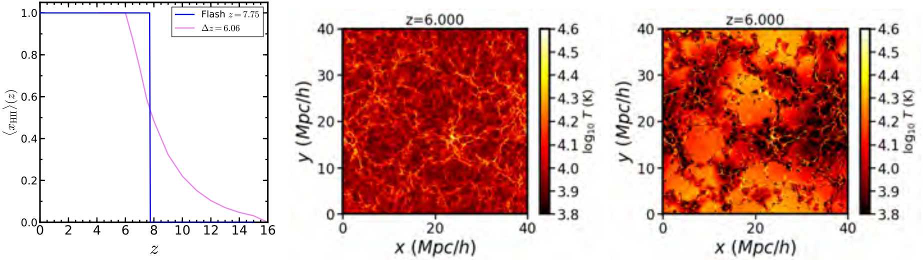
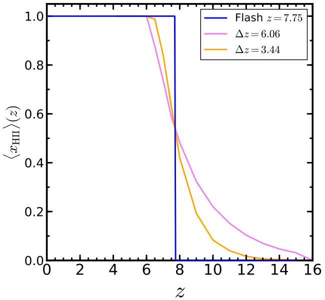


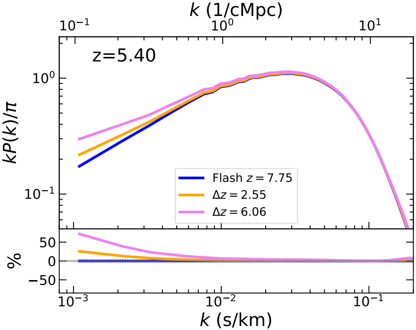
Inhomogeneous reionization: Different regions reionize at different times

$\Rightarrow$ Temperature fluctuations

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

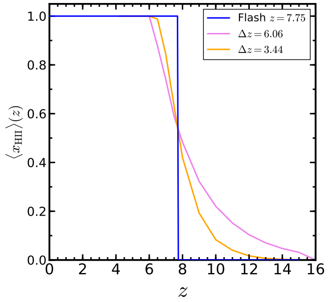
Simulating Inhomogeneous Reionization in Hydrodynamical Simulations

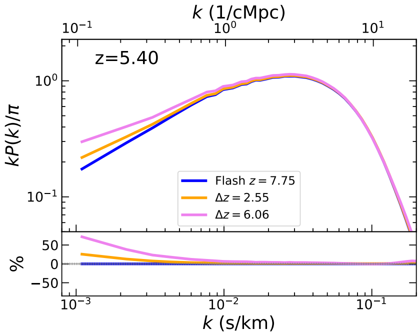




- Flash and inhomogeneous model share the same cut-off shape when $z_{\rm rei,flash} = z^{\rm median}_{\rm rei,inhomo} \quad \Rightarrow z^{\rm median}_{\rm rei,inhomo} = 8.15^{+0.79}_{-1.05}$

Simulating Inhomogeneous Reionization in Hydrodynamical Simulations





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- Temperature fluctuations increase power at $k \lesssim 0.01$
  $\Rightarrow$ Sensitive to $z_{\rm rei}$, $\Delta z_{\rm rei}$, ΔT

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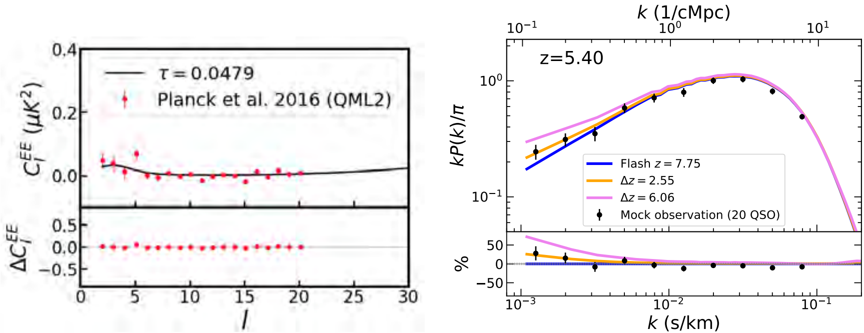

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Take Away Messages

1. From IGM transmission measurements we know that HI reionization must be finished by $z = 6$ and CMB polarization constrain the full reionization history, favoring $z \lesssim 10$ scenarios.

2. Reionization imprints a thermal record on the IGM detectable in the $z \sim 5 - 6$ Ly-α forest

3. The shape of 1D flux power spectrum at $z \sim 5 - 6$ depends on the timing of reionization and its associated heat injection

4. Existing high-z QSO samples can provide a new precision probe of reionization