What do we know about HI Cosmic Reionization?
New Constraints from the High-z Lyman-\(\alpha\) Forest

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Outline

1. What do we know about HI Reionization?

2. Reionization and the Thermal State of the Intergalactic Medium

3. Constraining HI Reionization from the $z \sim 5 - 6$ Ly-\(\alpha\) Forest

4. Take Away Messages
Hydrogen Reionization of the Universe: HI $\rightarrow$ HII

TIME

- Big Bang
- Recombination $z = 1100$
- First galaxies and quasars
- HI Reionization $z = 6 - 10$
  - Driven by UV radiation from galaxies and/or quasars
  - Reionization injects heat into the IGM
- Today $z = 0$
Hydrogen Reionization of the Universe: $\text{HI} \rightarrow \text{HII}$

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

\[ \tau \propto n_{\text{HI}} \propto n_H^2 \frac{T^{-0.7}}{\Gamma_{\text{HI}}} \]
Empirical Constraints on HI Reionization: IGM transmission

\[ \tau \propto n_{HI} \propto n_{H}^2 \frac{T^{-0.7}}{\Gamma_{HI}} \]

Hydrogen Neutral Fraction

\[ \langle x_{HI} \rangle (z) \]

Time (Gyr)

\[ z \]

\[ 0 2 4 6 8 10 12 14 16 \]

\[ 10^0 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} \]

\[ 13.8 2.0 1.0 0.5 0.3 \]
Empirical Constraints on HI Reionization: IGM transmission

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

Lyman-\(\alpha\) transmission overly sensitive saturates at \(x_{HI} \sim 10^{-4}\)

McGreer et al. 2015
Danforth et al. 2016
*Bolton et al. 2007
Fan et al. 2006
Bolton et al. 2005
Empirical Constraints on HI Reionization: IGM transmission

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

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Empirical Constraints on HI Reionization: IGM transmission

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Lyman-\( \alpha \) transmission overly sensitive saturates at \( x_{HI} \sim 10^{-4} \)

Ly\( \beta \)  
HST  
\( z_{QSO} = 0.35 \)
Ly\( \alpha \)
VLT  
\( z_{QSO} = 2.89 \)
Keck  
\( z_{QSO} = 6.33 \)

\( \langle x_{HI} \rangle / \langle x \rangle \)

McGreer et al. 2015
Danforth et al. 2016
Bolton et al. 2007
Fan et al. 2006
Bolton et al. 2005

13.8 2.0 1.0 0.5 0.3
Time (Gyr)

0 2 4 6 8 10 12 14 16

\( z \)

\( 10^{-6} \)
\( 10^{-5} \)
\( 10^{-4} \)
\( 10^{-3} \)
\( 10^{-2} \)
\( 10^{-1} \)
\( 10^0 \)

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Empirical Constraints on HI Reionization: IGM transmission

\[ \tau \propto n_{\text{HI}} \propto \frac{n_H^2 T^{-0.7}}{\Gamma_{\text{HI}}} \]

Lyman-\( \alpha \) transmission overly sensitive saturates at \( x_{\text{HI}} \sim 10^{-4} \)
Empirical Constraints on HI Reionization: CMB polarization

Temperature fluctuations in the CMB

CMB photons can interact with electrons through Thomson scattering

⇒ 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.
Empirical Constraints on HI Reionization: CMB polarization

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

HI reionization produces unique signatures on large scales correlations.

Planck has also measured it!!

Quadrupole Anisotropy

Thomson Scattering

Linear Polarization

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Empirical Constraints on HI Reionization: CMB polarization

Thomson Scattering Optical depth:

\[ \tau_e = \int \sigma_T n_e^{-}(z) \, dz; \quad n_e^{-} \propto x_{\text{HII}} n_H \]
Empirical Constraints on HI Reionization: CMB polarization

Thomson Scattering Optical depth:
$$\tau_e = \int \sigma_T n_e(z) dz; \quad n_e \propto x_{HI} n_H$$

$$\tau_e = 0.055 \pm 0.009$$
Empirical Constraints on HI Reionization: CMB polarization

Thomson Scattering Optical depth:

$$\tau_e = \int \sigma_T n_e^- (z) dz; \quad n_e^- \propto x_{HI} n_H$$

$$\langle x_{HI} \rangle_{V(z)}$$

McGreer et al. 2015
Danforth et al. 2016
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Time (Gyr)

13.8 2.0 1.0 0.5 0.3

$10^{-1}$ $10^{-2}$ $10^{-3}$ $10^{-4}$ $10^{-5}$ $10^{-6}$

$10^0$ $10^1$ $10^2$ $10^3$ $10^4$ $10^5$ $10^6$

$0$ $2$ $4$ $6$ $8$ $10$ $12$ $14$ $16$

$z$

$\Delta C_{EE} (\mu K^2)$

$0.4$ $0.2$ $0.0$ $-0.2$ $-0.4$

$0$ $5$ $10$ $15$ $20$ $25$ $30$

$I$
Empirical Constraints on HI Reionization: CMB polarization

Thomson Scattering Optical depth:

\[ \tau_e = \int \sigma_T n_e^-(z) dz; \quad n_e^- \propto x_{\text{HII}} n_H \]
Empirical Constraints on HI Reionization: CMB polarization

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Empirical Constraints on HI Reionization:
CMB polarization

Thomson Scattering Optical depth:
\[ \tau_e = \int \sigma_T n_e^- (z) dz; \quad n_e^- \propto x_{\text{HII}} n_H \]

\[ \langle x_{\text{HI}} \rangle (z) \]

\[ x_{\text{HII}} = 1.0 - x_{\text{HI}} \]
Empirical Constraints on HI Reionization: CMB polarization

Thomson Scattering Optical depth:
\[ \tau_e = \int \sigma_T n_e^-(z) dz; \quad n_e^- \propto x_{\text{HII}} n_H \]

\[ x_{\text{HII}} = 1.0 - x_{\text{HI}} \]
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-$\alpha$ Damping Wing

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

Willott+2011
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 $\langle x_{HII} \rangle$

Davies+2018
Empirical Constraints on HI Reionization: Lyman-\( \alpha \) emitting galaxies

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

\[ -20.25 < M_{\text{UV}} < -18.75 \]
\[ \text{EW}_{\text{Ly}\alpha} > 25 \text{ Å} \]

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 $\sim$ 2 orders of magnitude above expected signal.

Beardsley et al. 2015
(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 $\sim 2$ 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: $z_{\text{reion}} \lesssim 10$
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. $T_{\text{IGM}}$ important for galaxy formation ($M_{\text{halo,min}}$)
The Pressure Smoothing Scale of the IGM

cMpc

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

cMpc

Pressure forces $\rightarrow$ baryon smoother than dark matter

(Kulkarni, JO+2015)
Pressure forces → baryon smoother than dark matter

Jeans sound-crossing time $\lambda_{\text{Jeans}}/c_s \sim t_H$ Hubble time,

IGM pressure scale depends on full thermal history

(Kulkarni, JO+2015)
Microscopic random motions of $T \sim 10^4$ K gas thermal Doppler broadens Ly$\alpha$ 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

- 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 $z_{\text{reion}}$ and heat injection $\Delta T$ treated as phenomenological input
The High-z IGM Retains Thermal Memory of Reionization

2 free parameters: $z_{\text{reion}}$, $\Delta T$

- **Ionization history**: $z_{\text{reion}}$
- **Amount of reionization heat injection**: $\Delta T \leftrightarrow$ spectral slope of reion. sources
The High-z IGM Retains Thermal Memory of Reionization

2 free parameters: $z_{\text{reion}}$, $\Delta T$

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

$z=5.40$
The High-z IGM Retains Thermal Memory of Reionization

2 free parameters: $z_{\text{reion}}$, $\Delta T$

- Ionization history: $z_{\text{reion}}$
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The High-z IGM Retains Thermal Memory of Reionization

2 free parameters: $z_{\text{reion}}$, $\Delta T$

- Ionization history: $z_{\text{reion}}$
- Amount of reionization heat injection: $\Delta T \Leftrightarrow$ spectral slope of reion. sources
- Computational Challenge
The High-z IGM Retains Thermal Memory of Reionization

![Graph showing the thermal memory of reionization at high-z.](image_url)
The High-z IGM Retains Thermal Memory of Reionization
The High-z IGM Retains Thermal Memory of Reionization

![Graph showing thermal memory and reionization parameters](image)
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 et al. 2013 (HIRES and MIKE)
HI Reionization Constraints from $z = 5 - 6$ Lyman-$\alpha$
(Oñorbe+ in prep)

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

- Consistent with Planck $\tau_e$ + ”galaxy driven” reionization ($\Delta T$)
- 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

- Parameterize our ignorance as free parameters: \( M_{\text{halo, min}}, \eta_{\text{ion}}, \text{etc} \)
- Allows to explore parameter space
Simulating Inhomogeneous Reionization in Hydrodynamical Simulations

(Oñorbe+ in prep)

White: Hydrogen Ionized Fraction; Black: Neutral Fraction

Temperature
Simulating Inhomogeneous Reionization in Hydrodynamical Simulations

Flash reionization: all regions reionize at the same time

\[ \langle x_{\text{HII}} \rangle (z) \]

\( z = 7.75 \)

Inhomogeneous reionization: Different regions reionize at different times

\[ \tau \propto n_{\text{HI}} \propto n_{\text{H}}^2 T^{-0.7} \Gamma_{\text{HI}} \]
Simulating Inhomogeneous Reionization in Hydrodynamical Simulations

Flash reionization: all regions reionize at the same time

Inhomogeneous reionization: Different regions reionize at different times

⇒ Temperature fluctuations

\[ \tau \propto n_{\text{HI}} \propto \frac{n_{\text{HI}}^2 T^{-0.7}}{\Gamma_{\text{HI}}} \]
Flash and inhomogeneous model share the same cut-off shape when

\[ z_{\text{rei,flash}} = z_{\text{rei,inhomo}} \implies z_{\text{median,rei,inhomo}} = 8.15^{+0.79}_{-1.05} \]
Simulating Inhomogeneous Reionization in Hydrodynamical Simulations

- Flash and inhomogeneous model share the same cut-off shape when $z_{\text{rei, flash}} = z_{\text{rei, inhom}}^{\text{median}} \Rightarrow z_{\text{rei, inhom}}^{\text{median}} = 8.15^{+0.79}_{-1.05}$
- Temperature fluctuations increase power at $k \lesssim 0.01$
  $\Rightarrow$ Sensitive to $z_{\text{rei}}$, $\Delta z_{\text{rei}}$, $\Delta T$
Flash and inhomogeneous model share the same cut-off shape when
\[ z_{\text{rei, flash}} = z_{\text{rei, inhomogeneous}} \Rightarrow z_{\text{median, inhomogeneous}} = 8.15^{+0.79}_{-1.05} \]

Temperature fluctuations increase power at \( k \lesssim 0.01 \)
\[ \Rightarrow \text{Sensitive to } z_{\text{rei}}, \Delta z_{\text{rei}}, \Delta T \]
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-$\alpha$ 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.