The Early Cosmic Web

Stuart Wyithe

with thanks to
Jamie Bolton
Mark Dijkstra

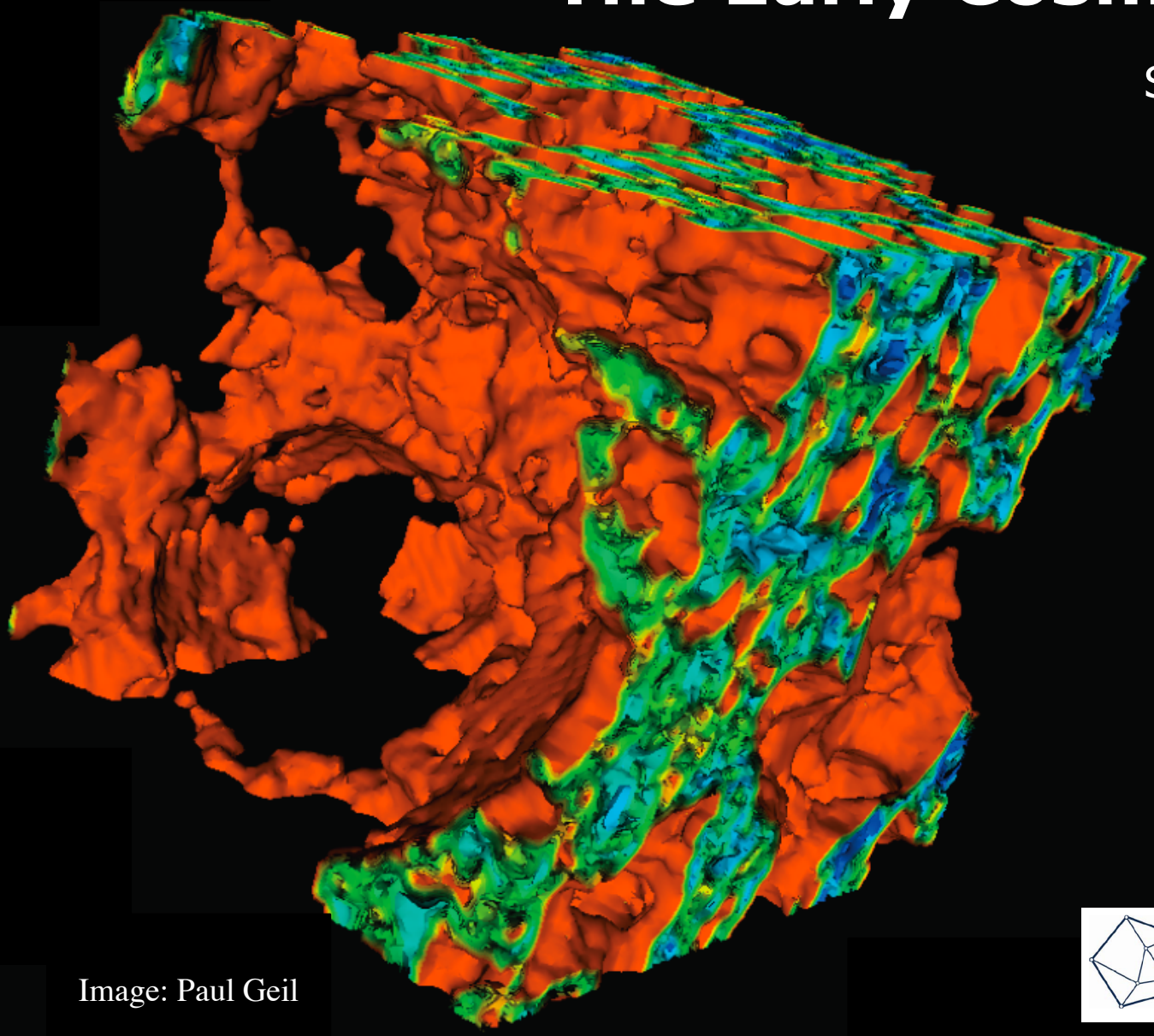

Image: Paul Geil

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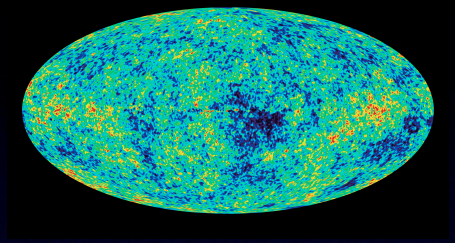
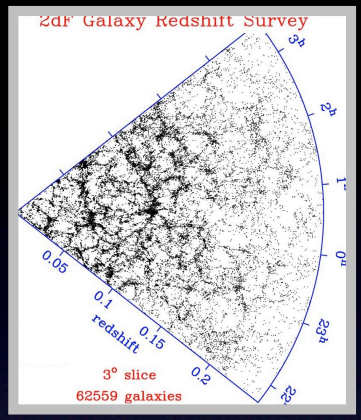
THE UNIVERSITY OF MELBOURNE

Reionization: basic questions





Neutral Gas → **Ionised Gas**

- What were the sources? (stars or quasars)
- When did it occur? (6<z<15)
- What was the topology? (smooth or patchy)
- Where did it start? (outside-in or inside-out)
- Was it regulated by feedback? (radiative or chemical)

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Outline

- Global history of hydrogen reionization
- Ionization structure during reionization
- Constraints from Ly-alpha emitting galaxies
- Constraints from quasar absorption lines
    - ionization fraction
    - IGM temperature

- Future: 21 cm observations (Benedetta Ciardi)

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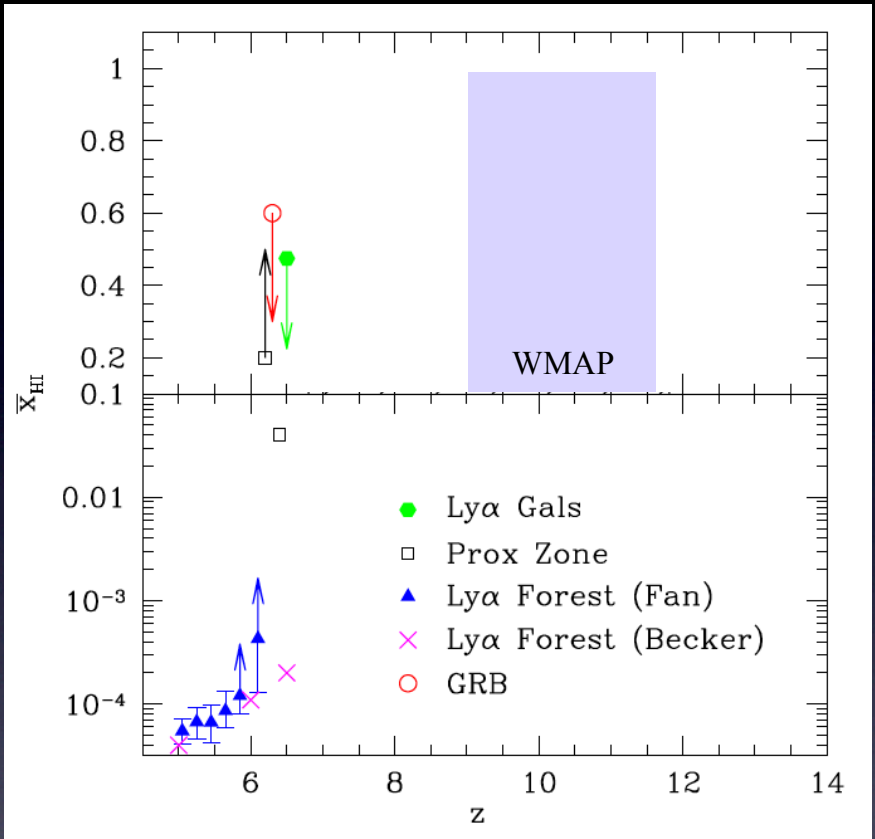
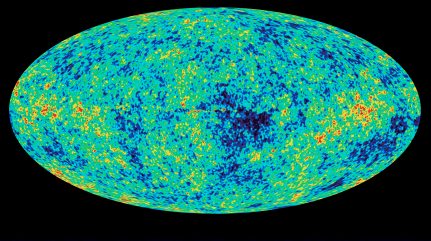
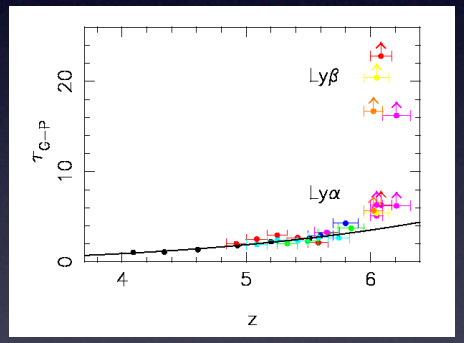
Observational constraints



Furlanetto, Oh & Briggs (2006)



- The optical depth to Thompson scattering measures integrated electron density



- Lyα absorption measures volume averaged neutral density at a particular redshift

- Reionization likely to be completed at z>6, and at z<10

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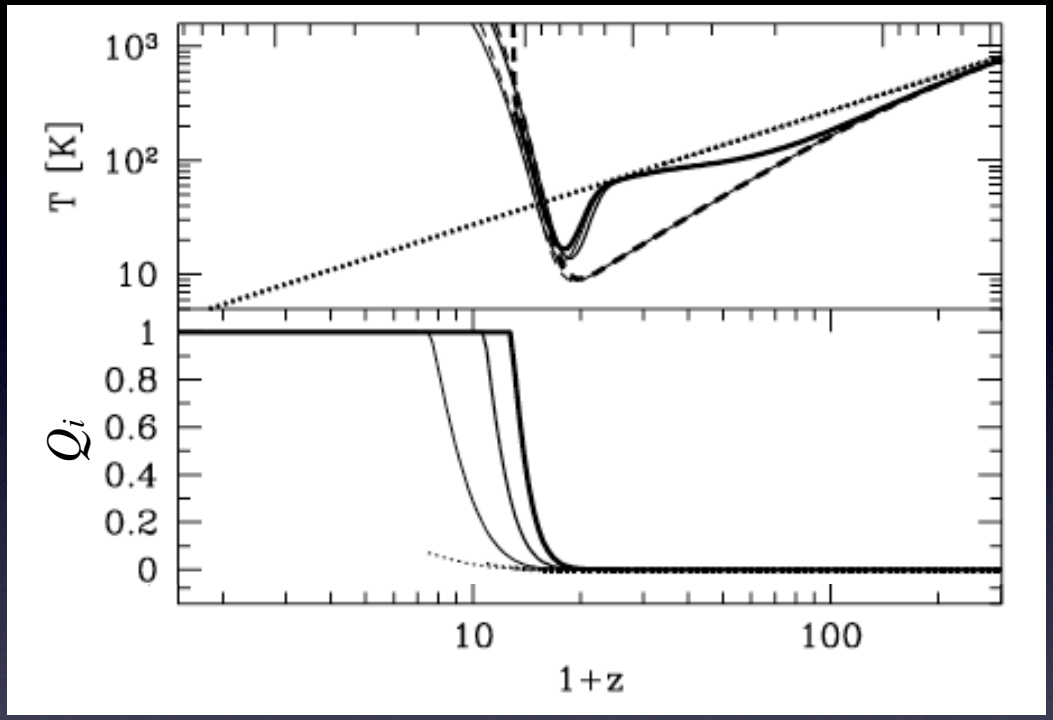
Hydrogen reionization



Pritchard & Loeb (2010)

Ionizations driven by structure formation

Recombinations

$$\frac{dQ_i}{dz} = \frac{1}{n_0}\frac{dn_\gamma}{dz} - \alpha_B \frac{C}{a^3} Q_i n_e \frac{dt}{dz}$$

- High z galaxy-formation heats and reionizes the IGM
- Sensible values for star-formation efficiency, escape fraction etc can reionise hydrogen

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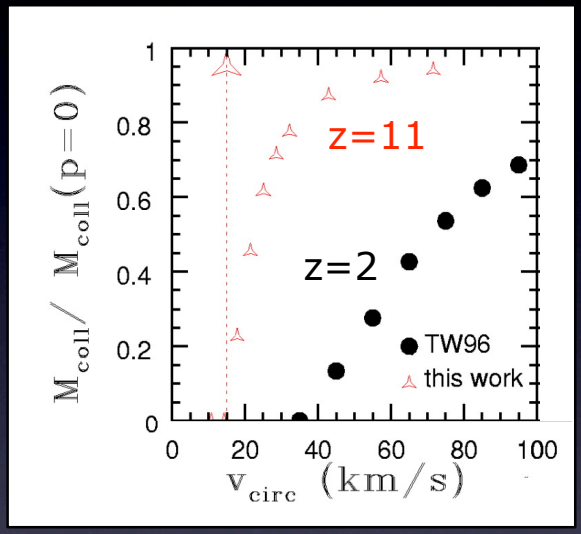
Theory predicts a minimum halo mass for baryonic collapse

- Assume gas settles into hydrostatic equilibrium after collapse into a DM halo from an adiabatically expanding IGM

$$M_{\min} = 5 \times 10^9 \left(\frac{1+z}{10} \right)^{-\frac{3}{2}} M_{solar}$$



Dijkstra et al. (2004)

- A minimum mass is also seen in simulations
- The heating associated with reionization is thought to suppress low mass galaxy formation by raising the Jeans mass above the H-cooling threshold

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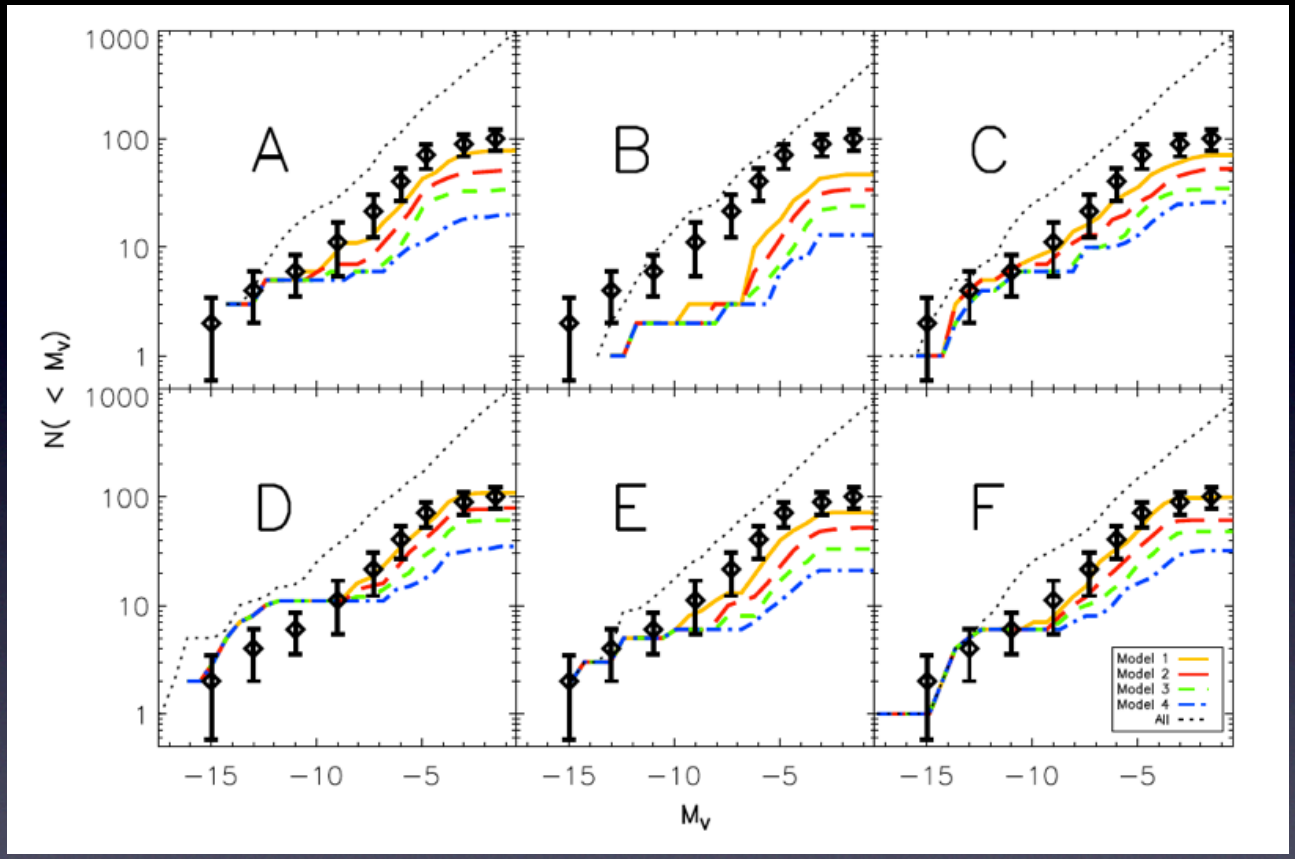
Reionization and missing satellites



Lunnan et al. (2011)

- Reionization impacts the number of satellites observed around Milky-Way like galaxies by preventing their formation at late times

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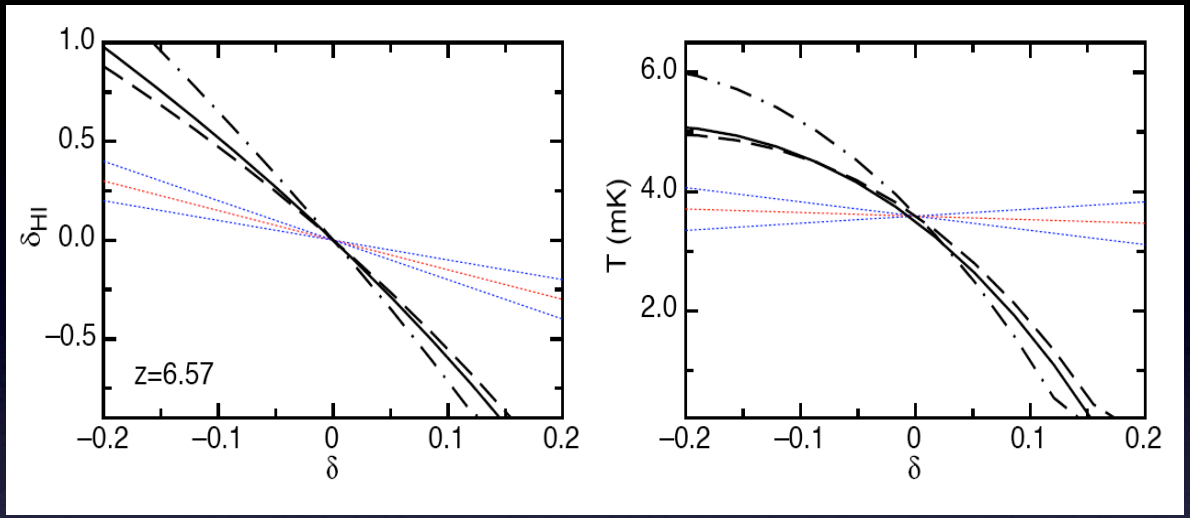
Galaxy bias and patchy reionization



C=2
C=10
C=20

Standard Expression has δ=0 and R=∞.

$$\frac{dQ_{\rm H\ II}}{dt} = \frac{N_{\rm ion}}{0.76}\frac{dF_{\rm col}}{dt} - \alpha_B \frac{C}{a^3}\bar{n}_H^0 Q_{\rm H\ II}$$

$$\begin{aligned}\frac{dQ_{\delta,R}}{dt} &= \frac{N_{\rm ion}}{0.76}\left[Q_{\delta,R}\frac{dF_{\rm col}(\delta,R,z,M_{\rm ion})}{dt}\right. \\ &\left. + (1-Q_{\delta,R})\frac{dF_{\rm col}(\delta,R,z,M_{\rm min})}{dt}\right] \\ &- \alpha_{\rm B} C n_{\rm H}^0 \left(1+\delta\frac{D(z)}{D(z_{\rm obs})}\right)(1+z)^3 Q_{\delta,R},\end{aligned}$$

- Overdense regions of IGM are reionized first

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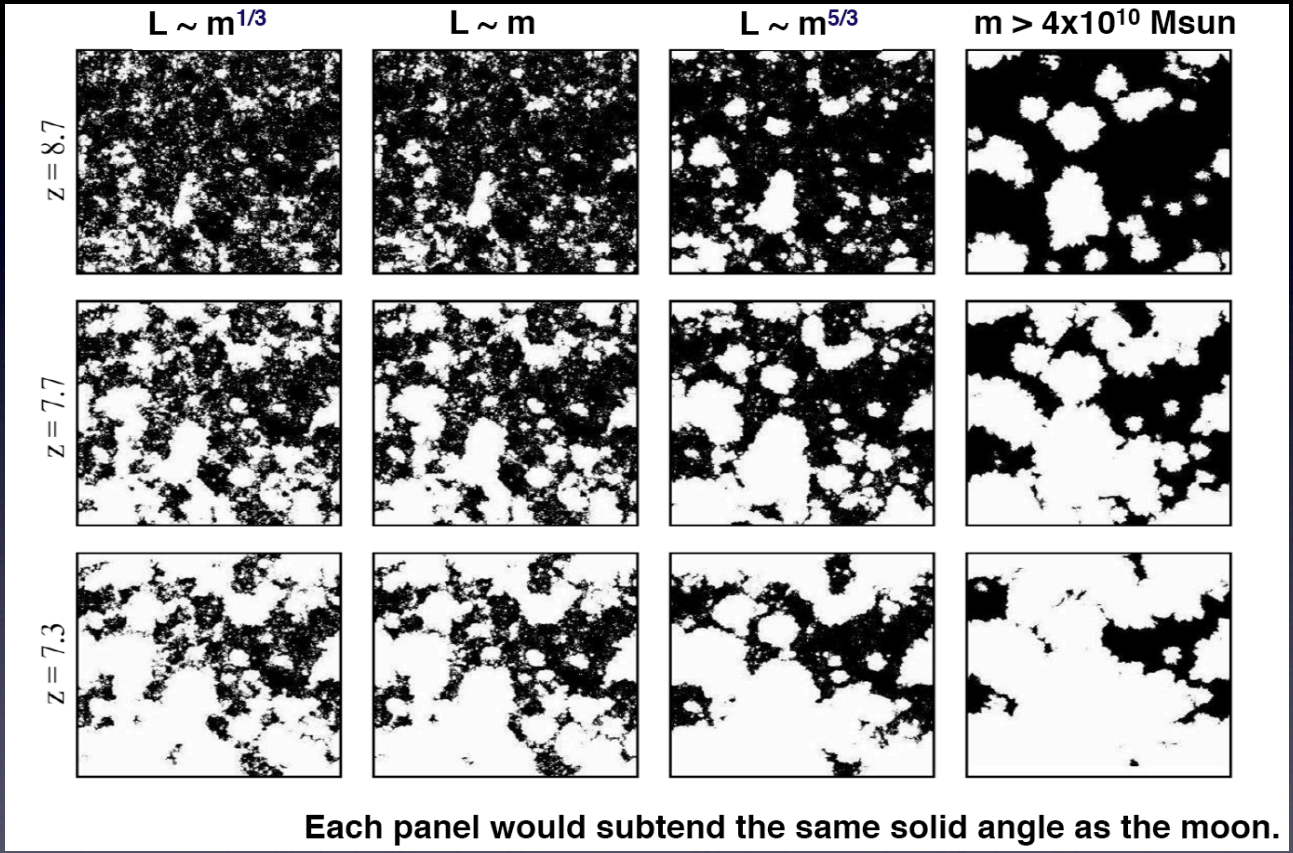
"Structure" of hydrogen reionization is sensitive to the source population



McQuinn et al. (2007)

- Bias drives formation of large HII regions

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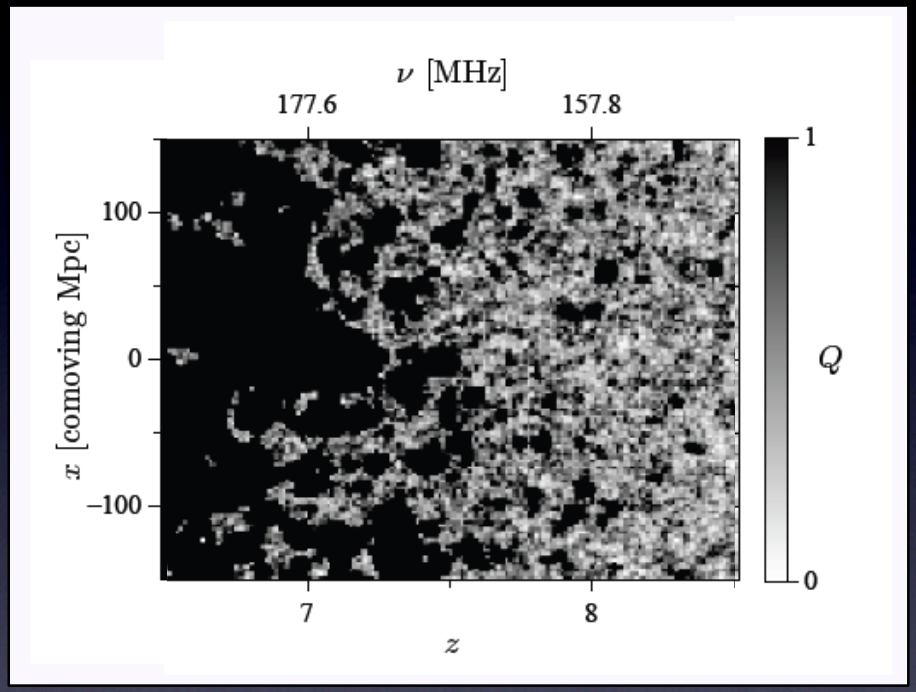
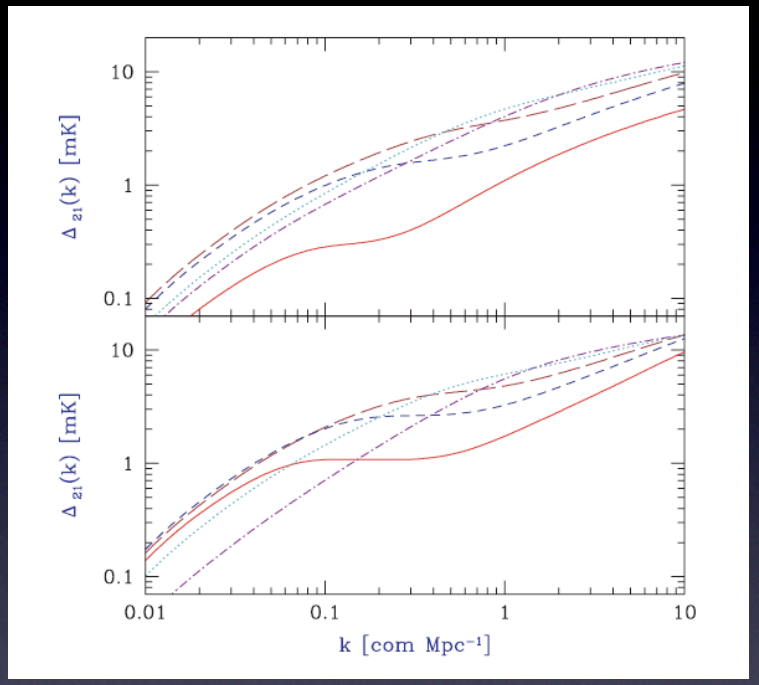
"Structure" of reionization is encoded in the 21cm intensity power-spectrum





Barkana et al. (2007)

- Reionization should leave a distinct mark on the power-spectrum of spatial fluctuations in 21cm emission
- Galaxy evolution drives the shape and amplitude of the 21cm power-spectrum

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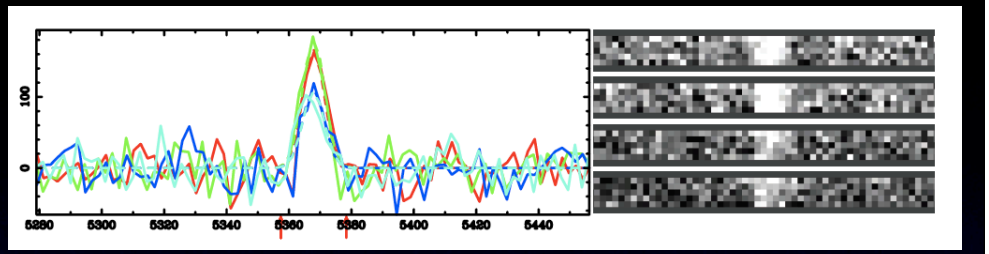
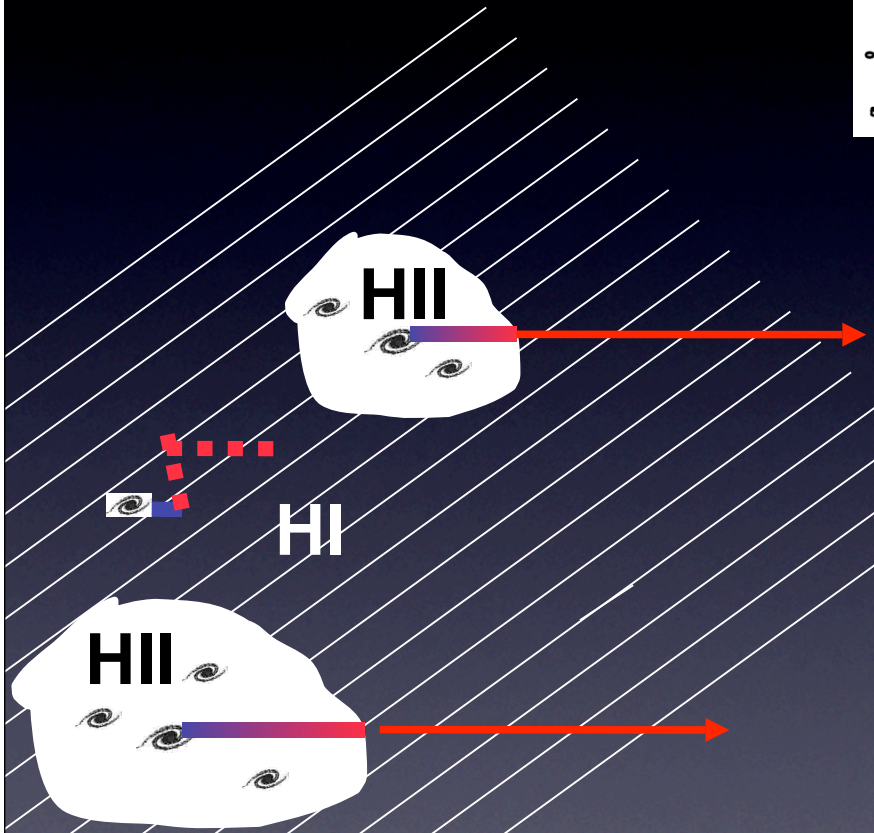
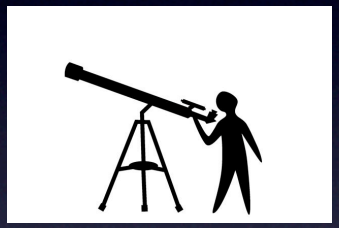
Ly-alpha emitters and reionization







- The IGM absorbs Ly-alpha
- Absorption within HII regions is resonant
- neutral IGM results in a damping wing

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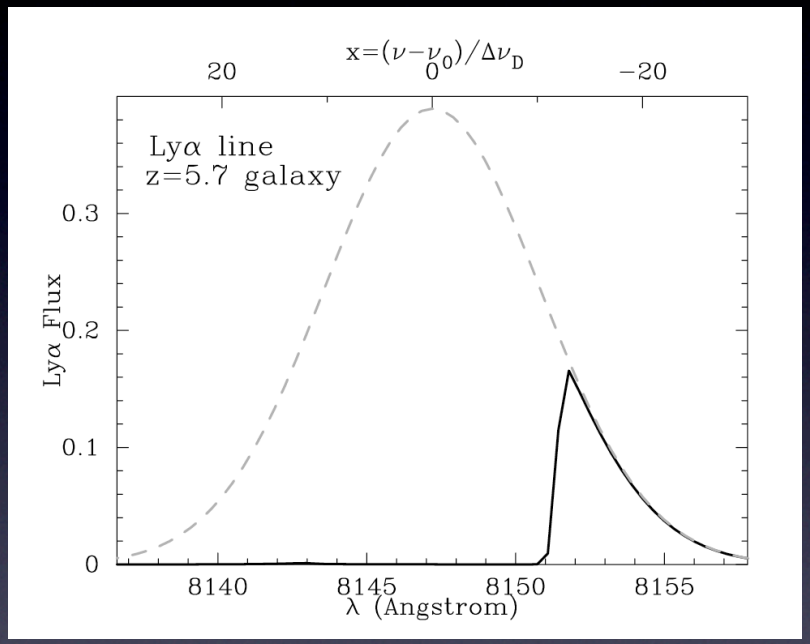
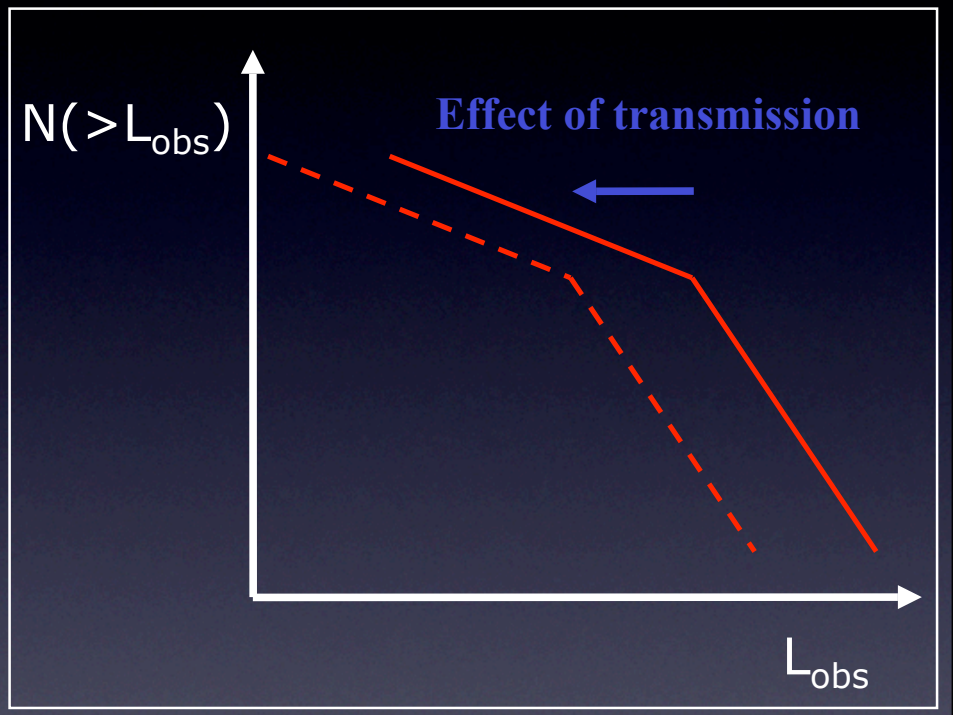
The Ly-alpha line from star-forming galaxies is modified by the IGM

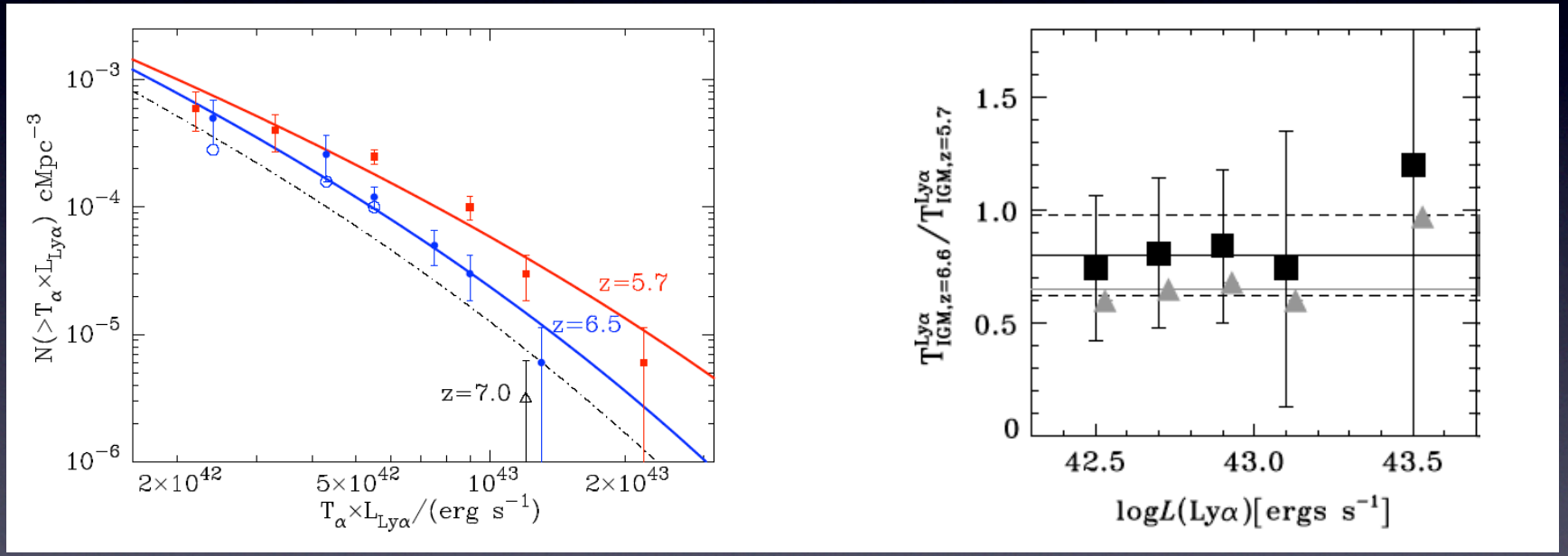


Dijkstra et al. (2007)



- Absorption of the Ly-alpha line reduces the observed number counts of Ly-alpha emitters -> probe of IGM

Evolution of the Ly–alpha luminosity function provides no evidence for reionization at z=6



Shimasaku et al. (2006)
Kashikawa et al. (2006)
Iye et al. (2006)

Dijkstra et al. (2007)
Ouchi et al. (2010)

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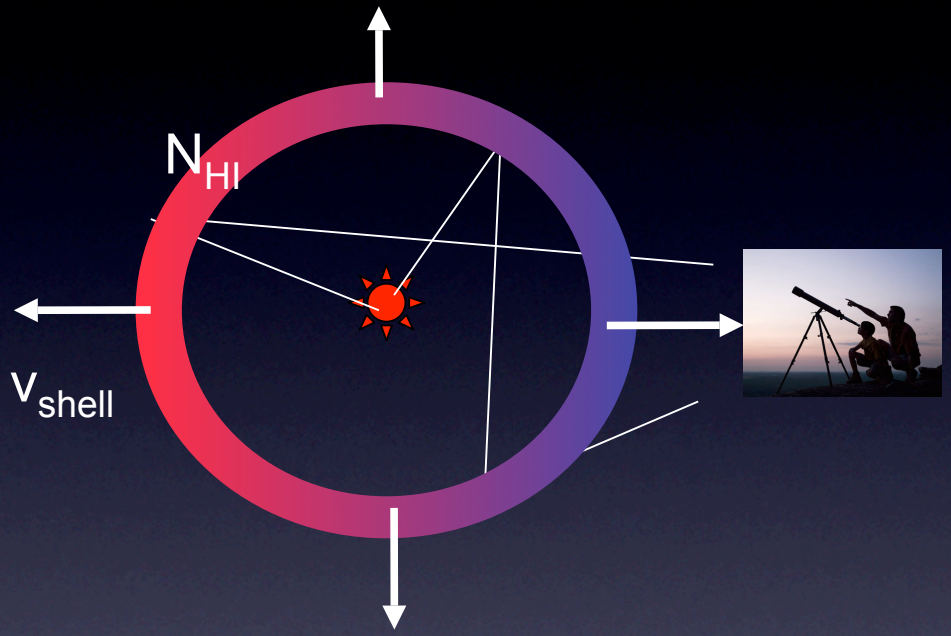
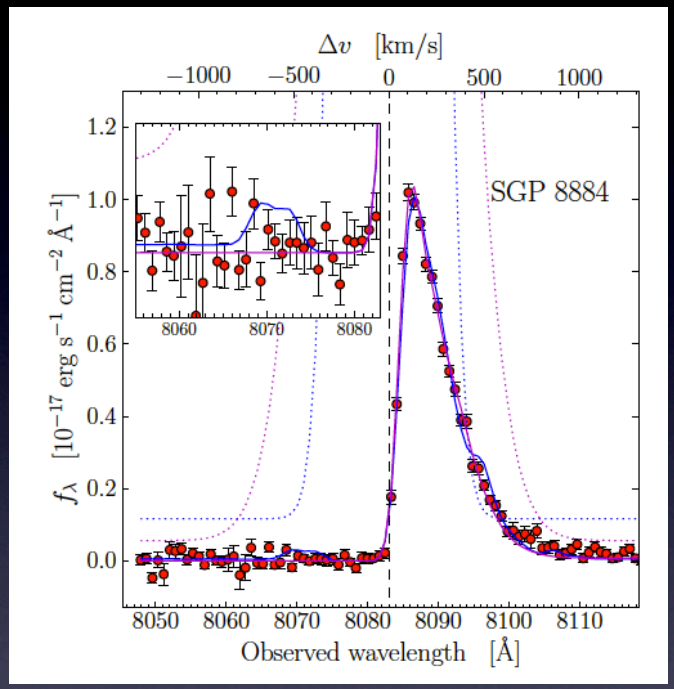
Ly-alpha emitters and reionization





Lidman et al. (2011 sumbitted)

- Observed Ly-alpha line shape can be reproduced using spherical shells of outflowing HI gas (Verhamme et al. 2008)

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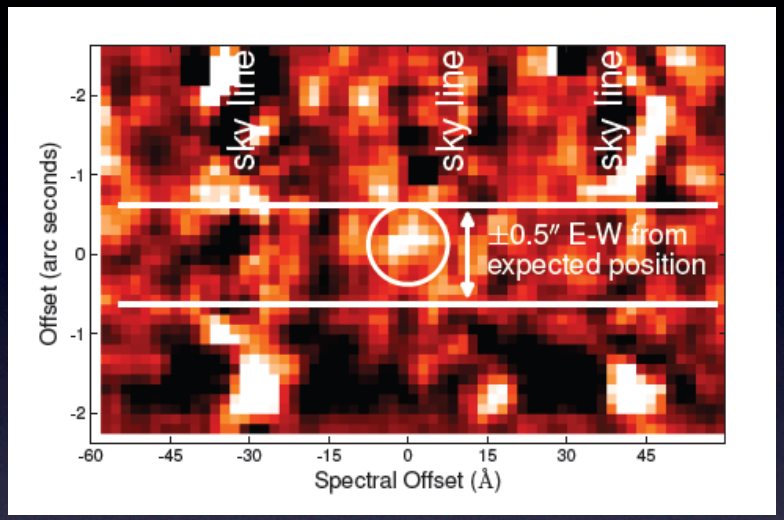
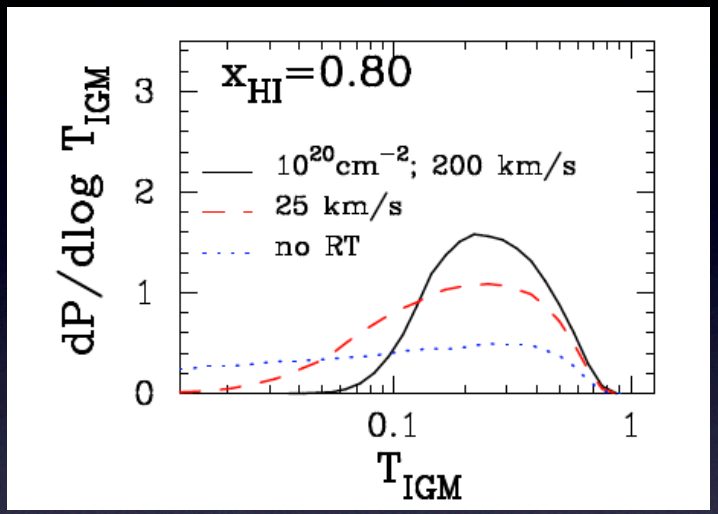


Lenhert et al. (2010)



Dijkstra et al. (2011)

- Lenhert et al. reported detection of Ly-alpha emission from a Y-drop out galaxy at z=8.6, with REW ~ 100 A
- No strong constraint on ionization state of IGM

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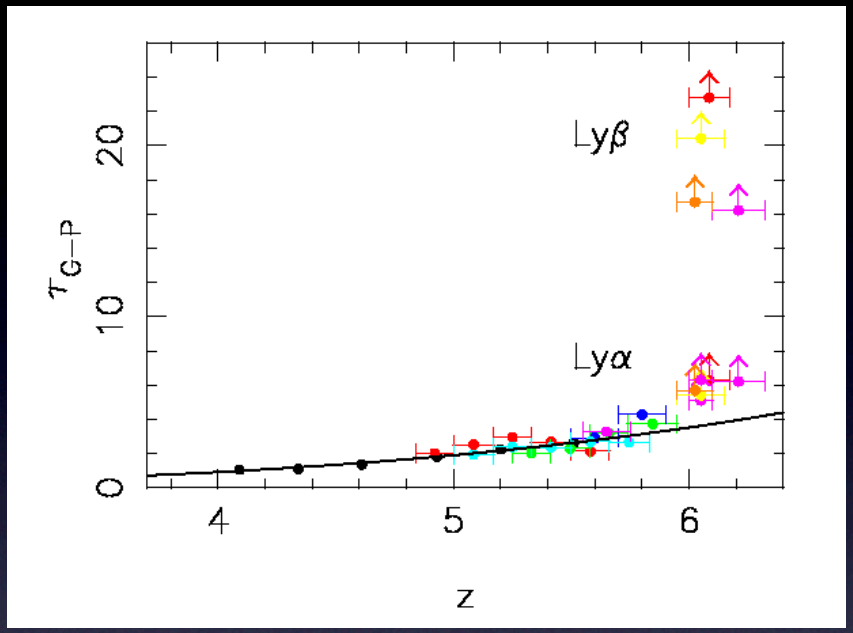
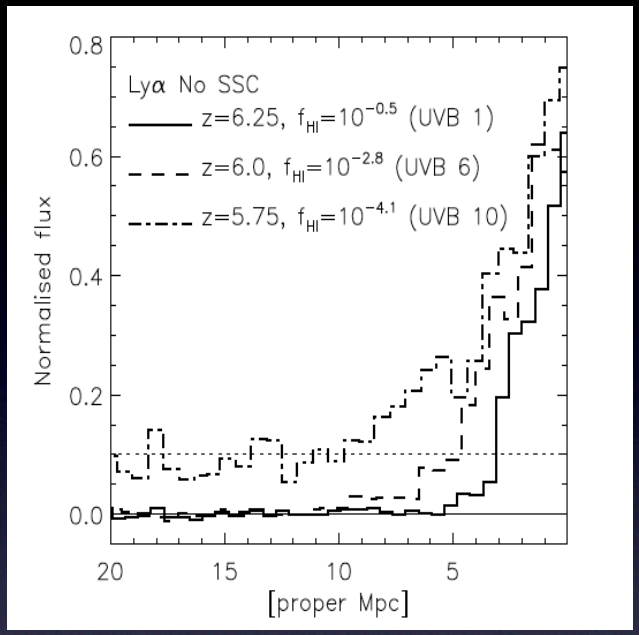
High-z quasar near-zones and the IGM



Fan et al. (2006)



Bolton & Haehnelt. (2007)

- High z quasars show an increasingly thick Ly-alpha forest, including a complete Gunn-Peterson Trough
- The quasars show near-zones of increased transmission
- Can these near-zones put constraint on ionization state of IGM?

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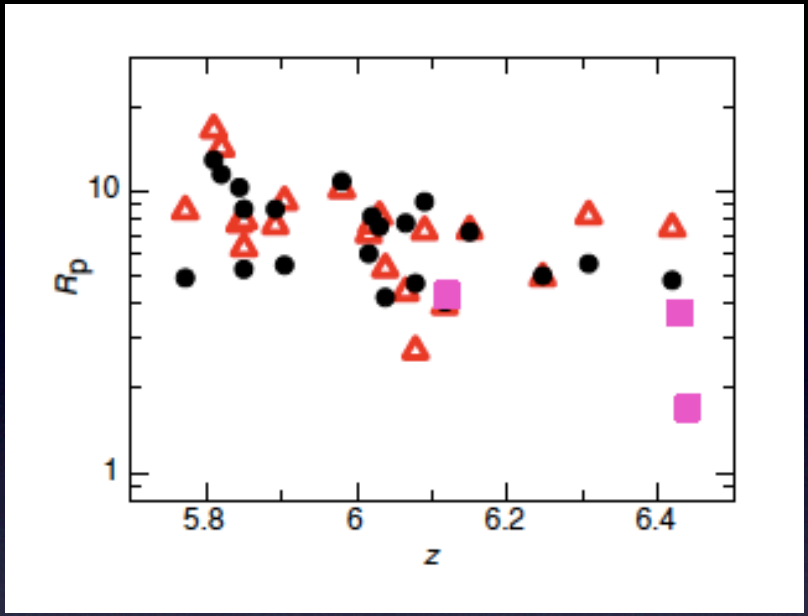
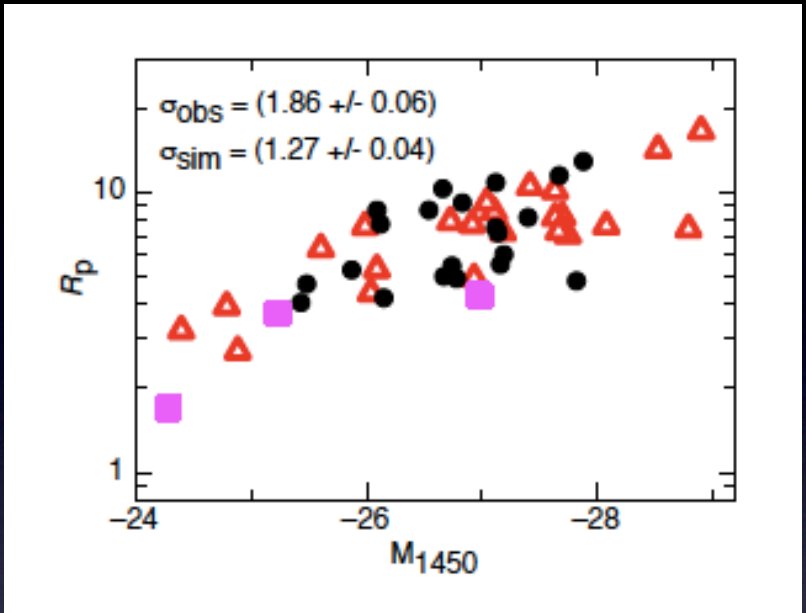
High-z quasar near-zones and the IGM





Carilli et al. (2010)

- The near-zone sizes and redshift evolution are explained by the evolving ionizing background
- The dependence on luminosity is too tight to be explained by HII regions in a partially neutral IGM
- Near-zones imply an ionized IGM at z~6

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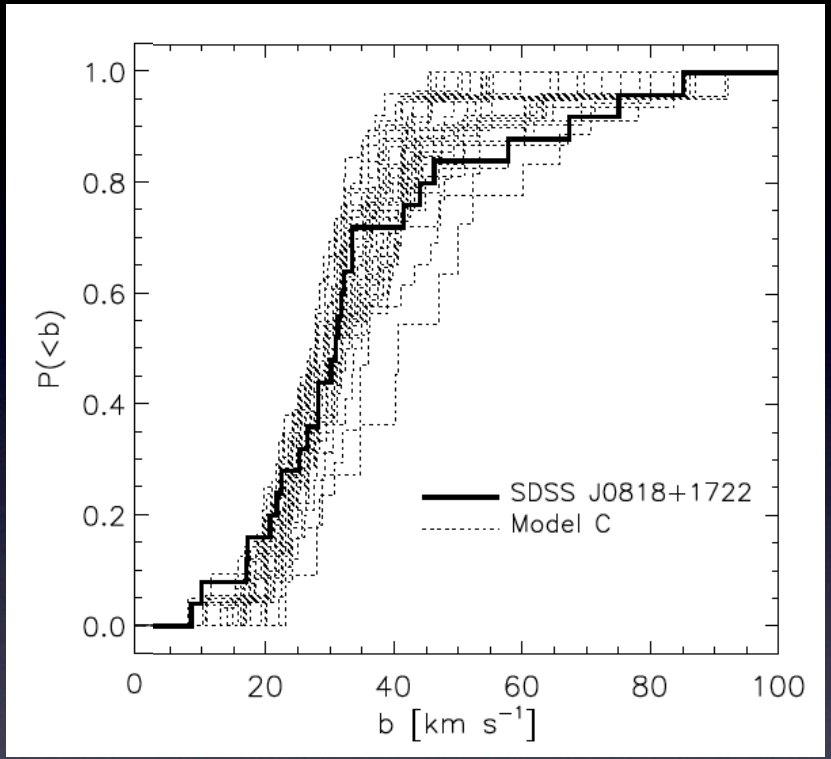
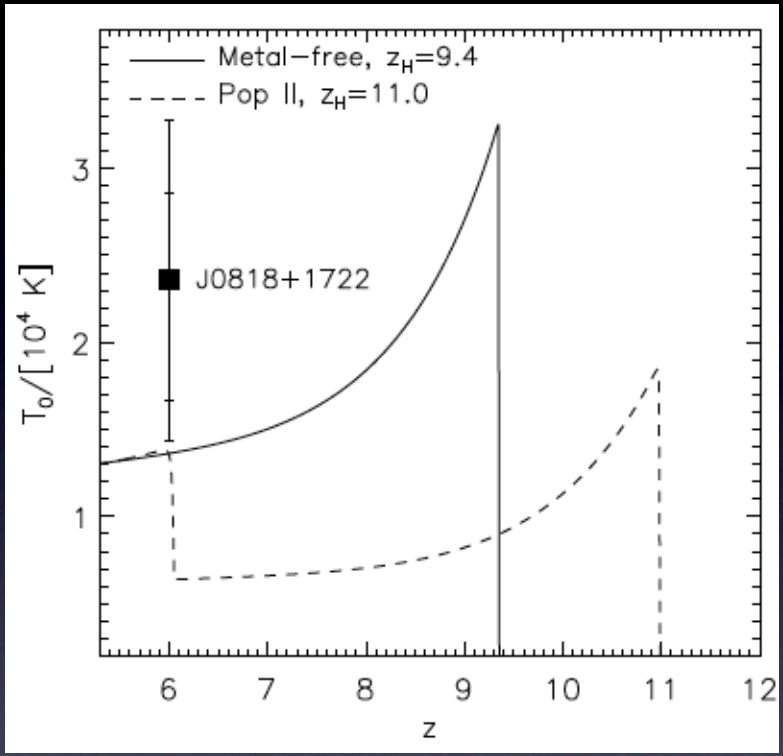
Temperature of the high redshift IGM





Bolton et al. (2010)

- Near-zones provide spectral regions that can be used to probe the temperature of the high redshift IGM
- Gas around SDSS J0818 reionized at z<11

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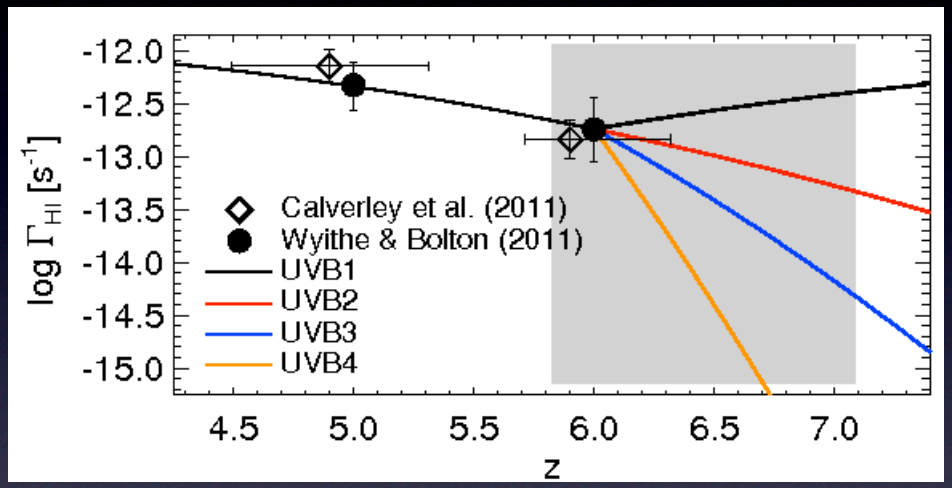
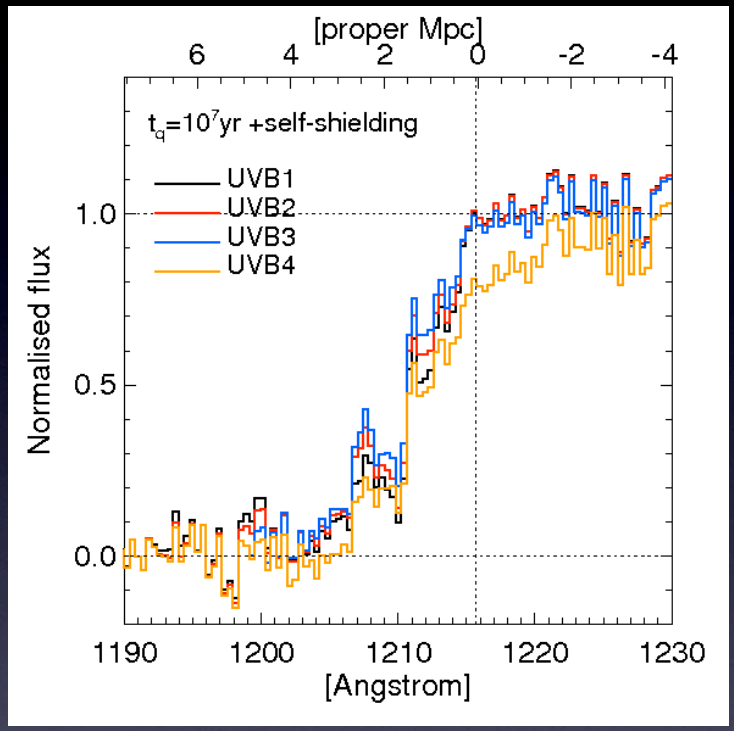
High-z near-zones and the IGM



Bolton et al. (submitted)



- Surveys are now capable of finding quasars at z>7
- Near zones are expected to be smaller, and a damping wing may modify the line

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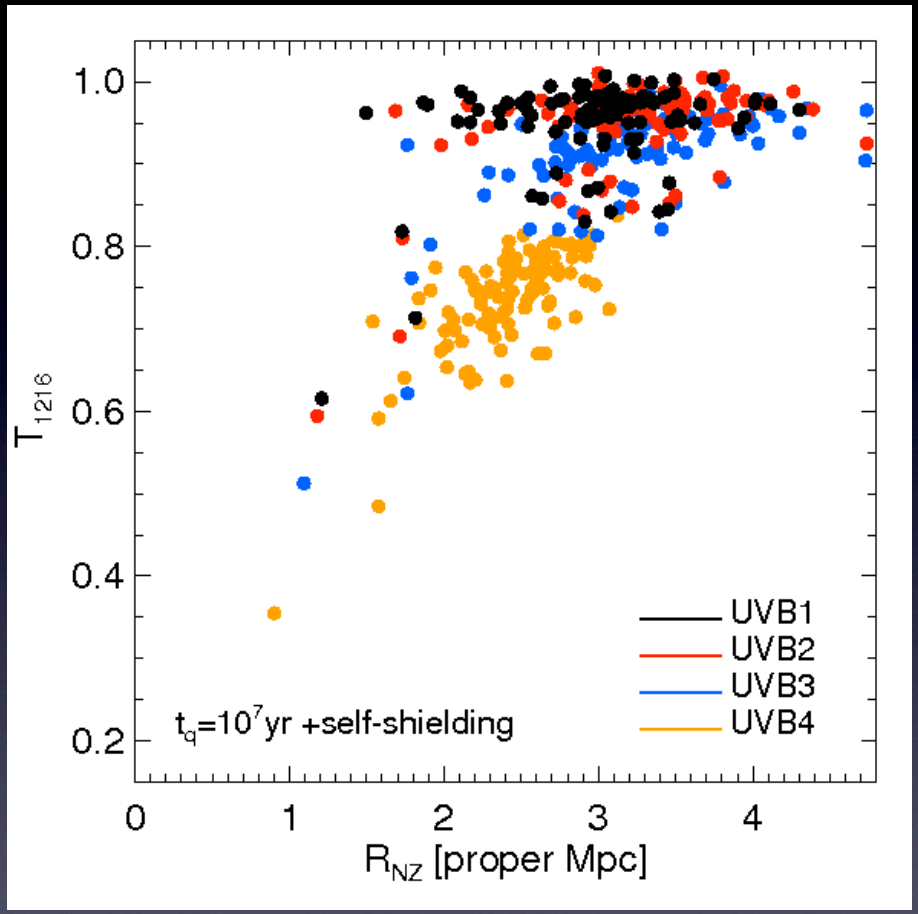
High-z near-zones and the IGM



Bolton et al. (submitted)

- A combination of near-zone size and damping of the Ly-alpha line can probe the ionization state

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Summary

- The reionization of hydrogen represents one of the major milestones in the history of the Universe
- While there is some "theoretical evidence" for aspects of the reionization process, the detailed history remains under-constrained and uncertain
- Observations provide evidence for a reionization that completed at z>6, with most IGM ionized after z~10, but are limited by the large optical depth of Ly-alpha and studies of individual lines of sight
- 21cm studies promise to overcome both these issues

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