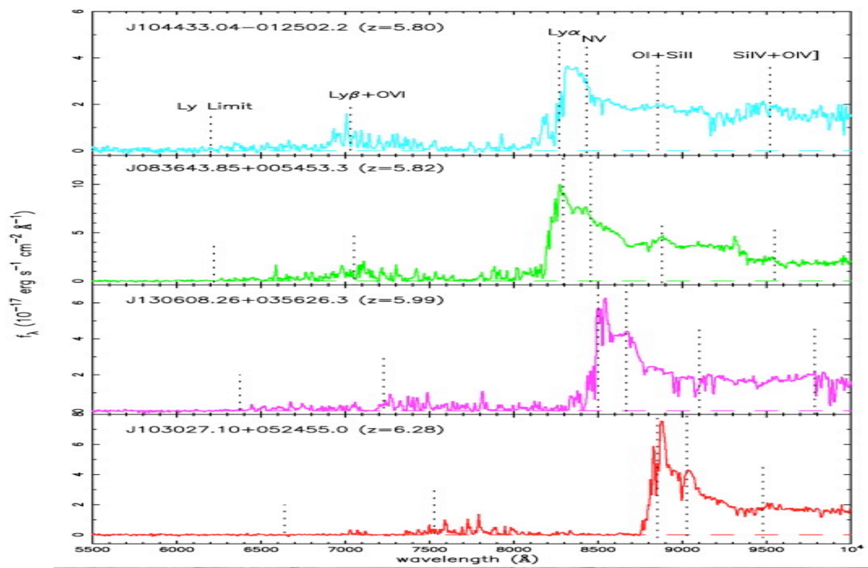
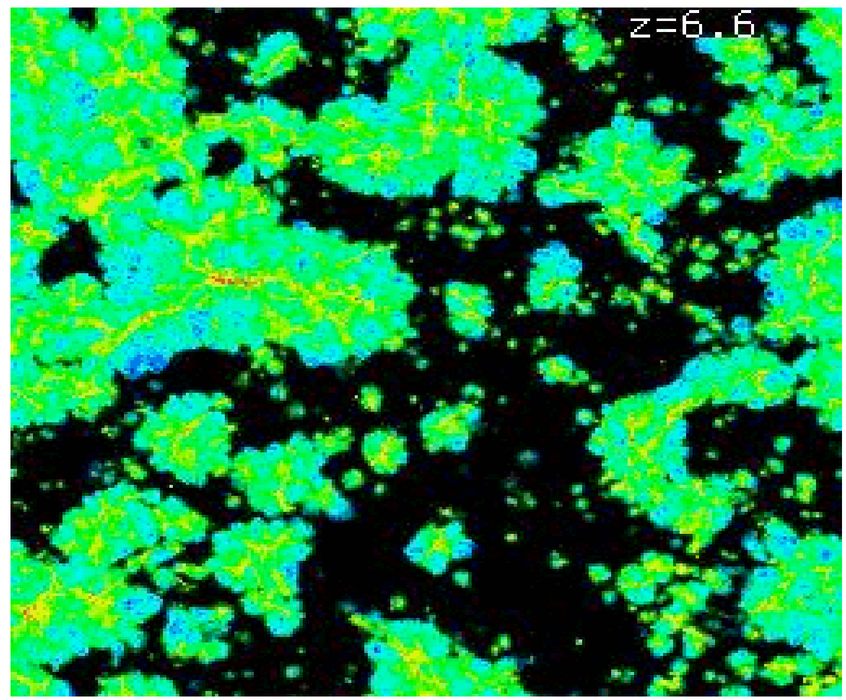
Probing Hydrogen Reionization

Adam Lidz (CfA)
March 5, 2007





Outline

- Reionization -- who cares?
- Observational Status
- Theoretical Modeling
- Quasar Absorption Spectra
- Future: 21 cm Emission from IGM
- Lyman-a Emitters

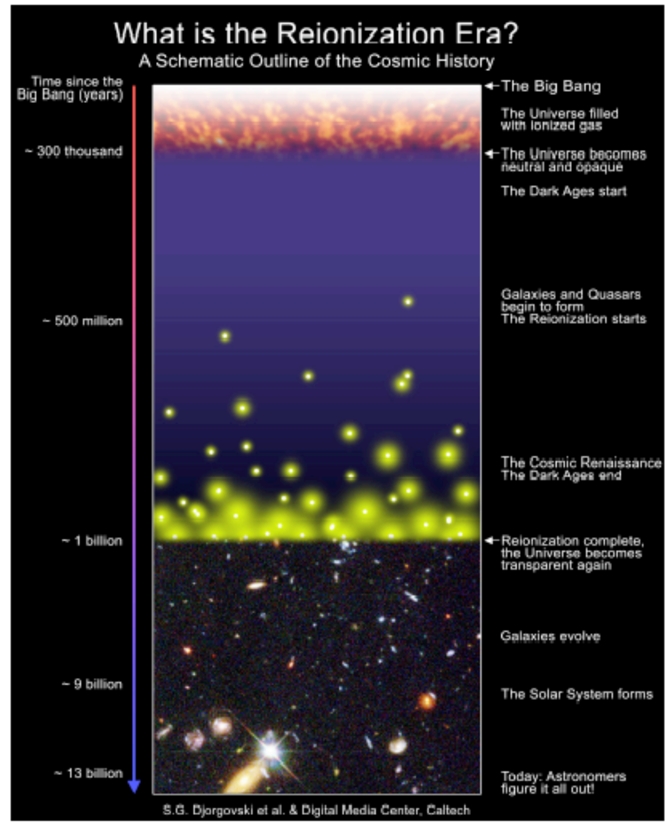
Collaborators

- Suvendra Dutta (CfA)
- Steve Furlanetto (Yale)
- Lars Hernquist (CfA)
- Matt McQuinn (CfA)
- Peng Oh (UC Santa Barbara)
- Oliver Zahn (CfA)
- Matias Zaldarriaga (CfA)

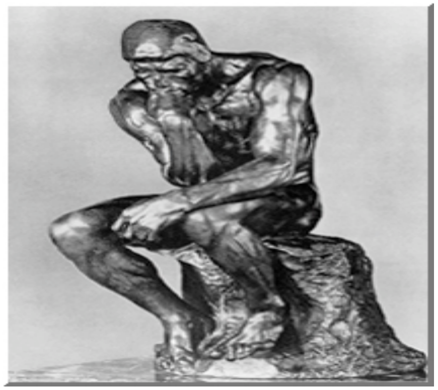
History of the Universe

- CMB gives us detailed info at t~300,000 yrs. Galaxy surveys, quasar spectra tell us about t>~ 1 billion yrs.
- Frontier is 300,000 < t < 1 billion yrs.

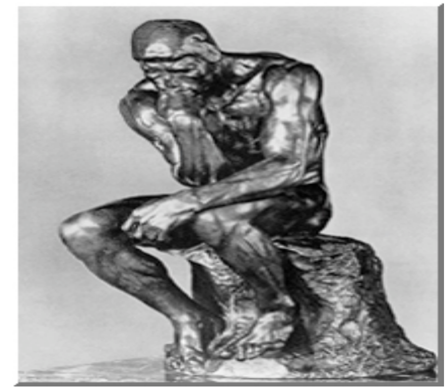
"Particle physics is like playing chess, astrophysics is like mud-wrestling."--?



Djorgovski



Motivating Questions



- When was the Hydrogen reionized, and how extended was the reionization process? When was Helium doubly ionized?

- Who reionized the universe? What do we learn about the very first galaxies, quasars?

- How clumpy was the IGM on small scales during reionization? Was there gas locked up in “mini-halos” (sinks of ionizing photons with T_vir < 10^4 K)?

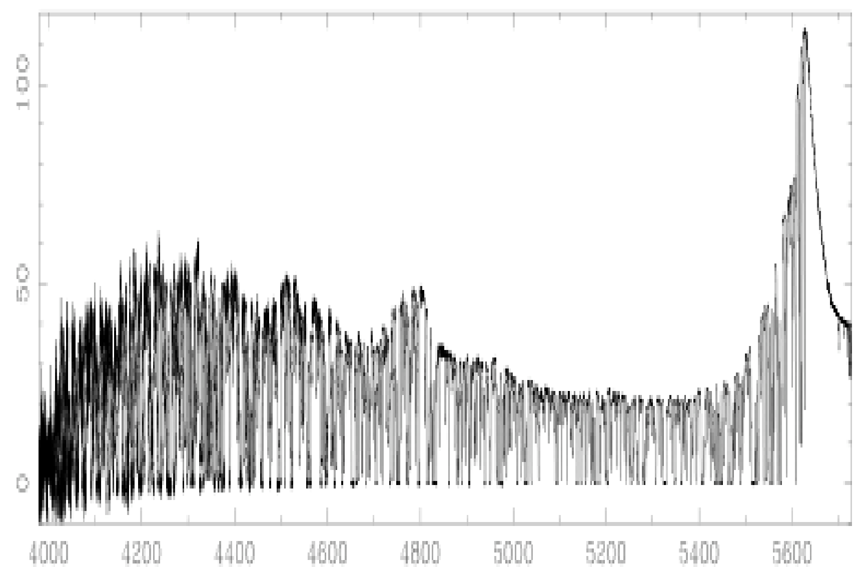
- How large were the ionized HII regions (“bubbles”) at different stages of reionization?

- What was the “adolescence” of our universe like? We don’t know much about t=300,000 - 1 billions years!

The Ly-a Forest at z~3

- Absorption spectra probe line of sight density fluctuations, temperature, and *ionization state.*

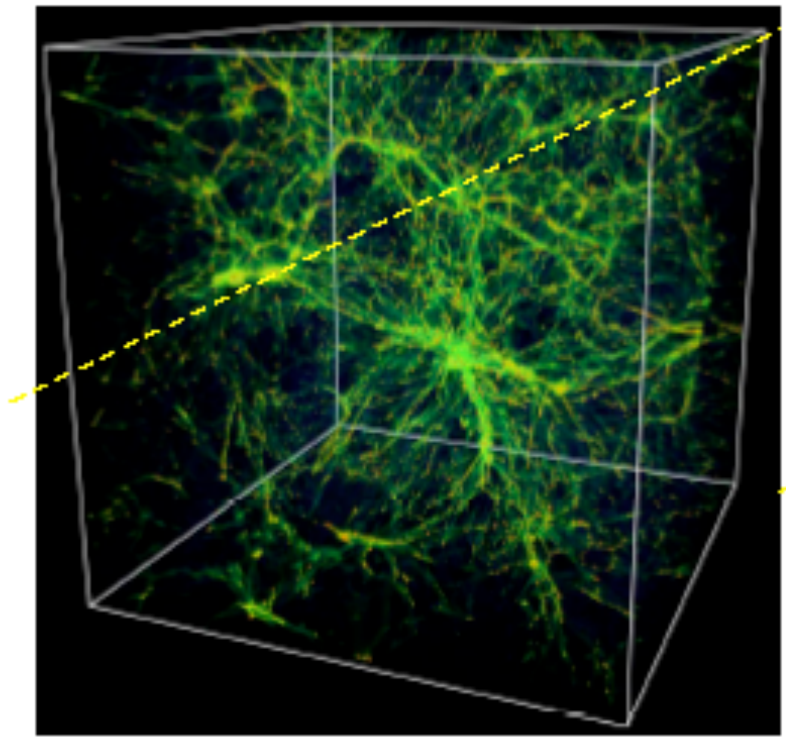
- What happens at progressively higher redshifts?



Rauch & Sargent

Model at z~3 works well!

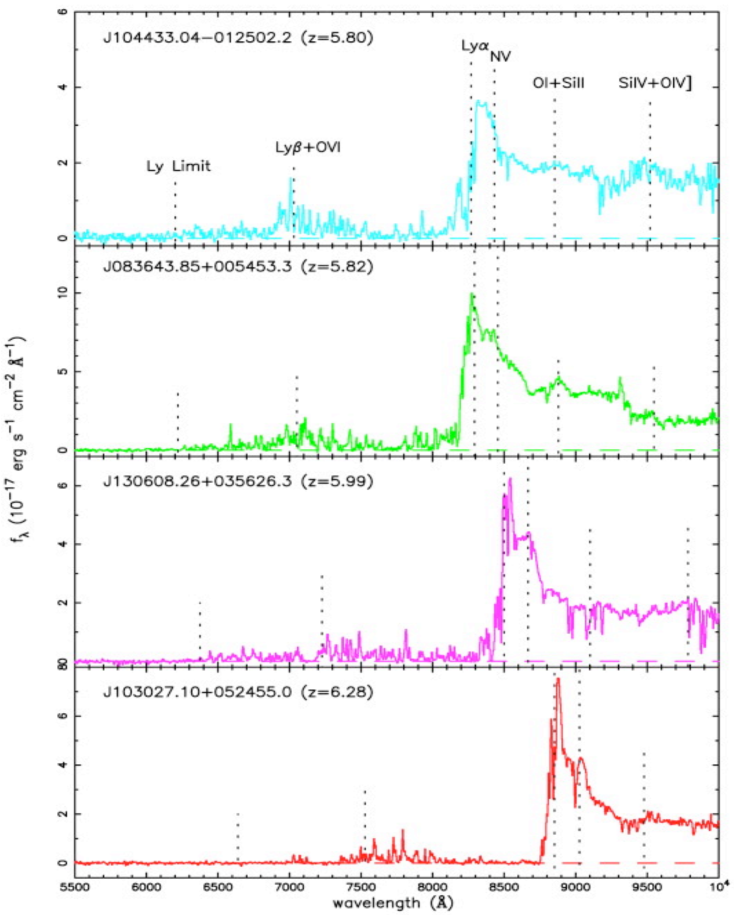
- IGM gas is photoionized by radiation from galaxies and/or quasars (assumed *uniform*)
- Mock quasar spectra from numerical simulations matched observed statistical properties.



R. Cen

The Ly-a Forest at z~6

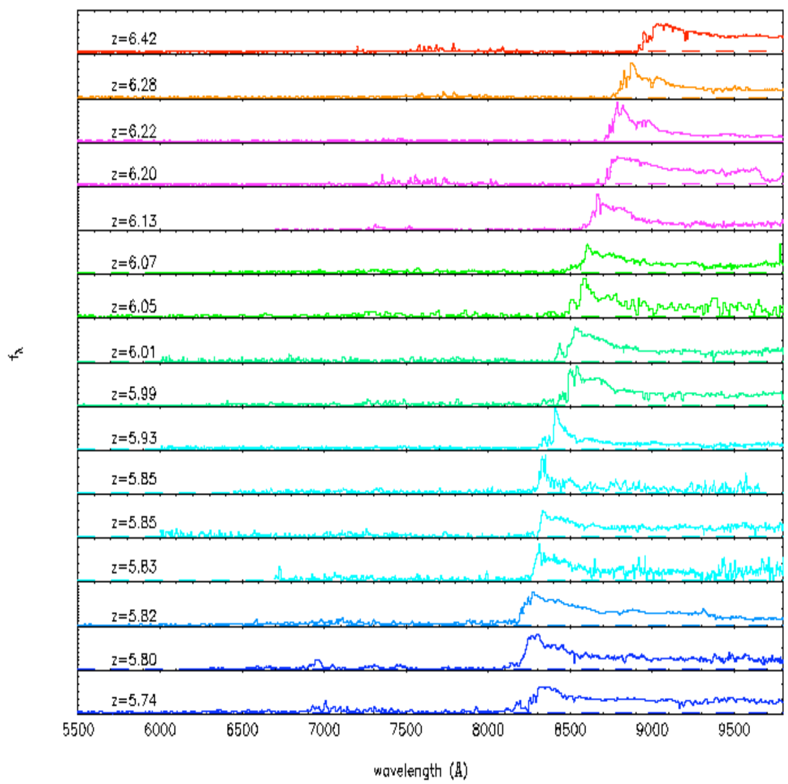
- The forest thickens at high redshift.
- What does this mean for ionization state of gas at z~6?



Becker et al. (2001)

The Ly-a Forest at z~6

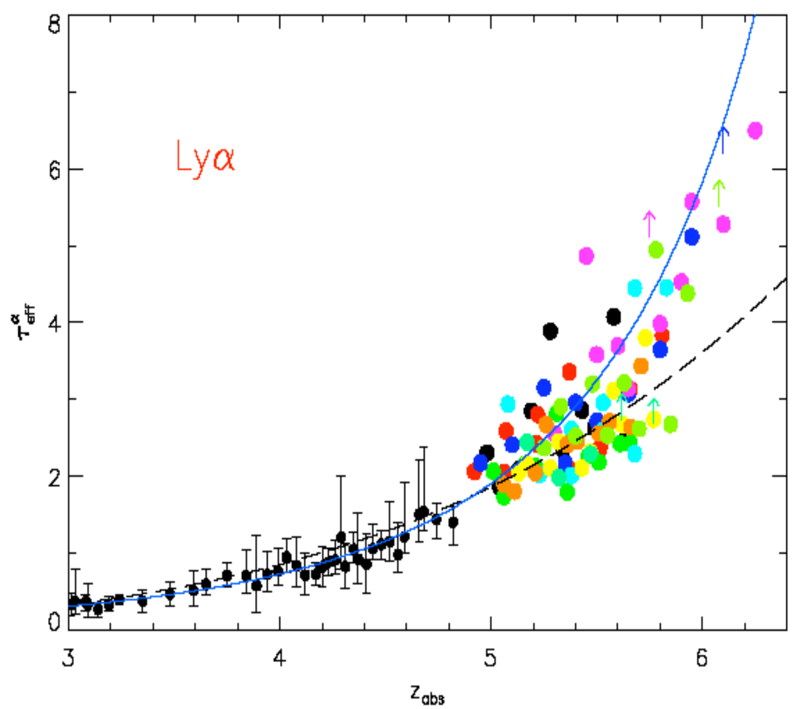
- ~20 quasars at z>~6 now.



Fan et al. 2006

Redshift Evolution

- Absorption in forest increases with redshift.
- Sensitive to the abundance of rare voids in gas density distribution.
- Amount of *scatter* from sightline-to-sightline increases.
- Scatter is substantial even after averaging over ~50 mpc.



Becker et al. 2006

A signature of patchy reionization?

- Scatter interpreted as reionization near z~6.
- Note however aliasing $$P_{\rm 1d}(k_{\|}) = \int_{k_{\|}}^{\infty} \frac{dk}{2\pi} k P_{\rm 3d}(k).$$

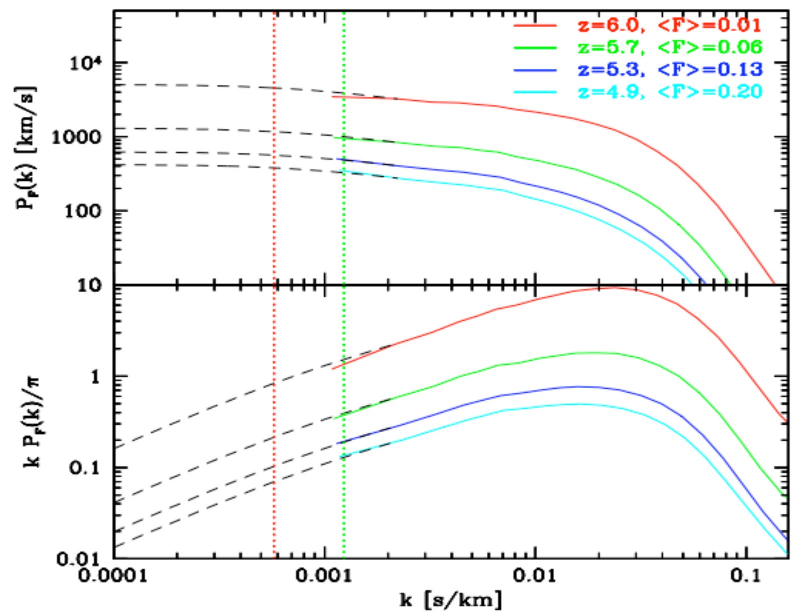
(quasar spectra only provide 1d skewers through IGM --> large fluctuations.)

- Transmission only sensitive to rare voids = highly *biased* tracer.

Lidz, Oh & Furlanetto 2006

Test the null hypothesis!

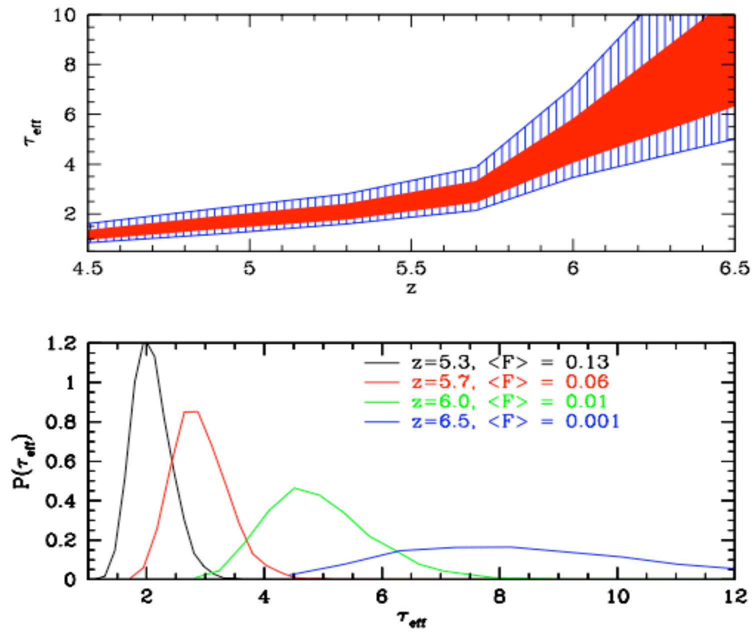
- Is observed scatter in <F> consistent with density fluctuations alone? (I.e., a uniform radiation background?)
- Aliasing, and transmission is increasingly biased towards high redshift.
- Fluctuations are of order ~1 by z~6, L ~ 50 Mpc/h co-moving!



Lidz, Oh, & Furlanetto 2006

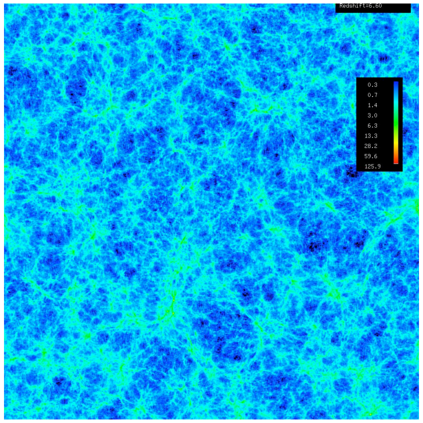
Sightline to Sightline Scatter

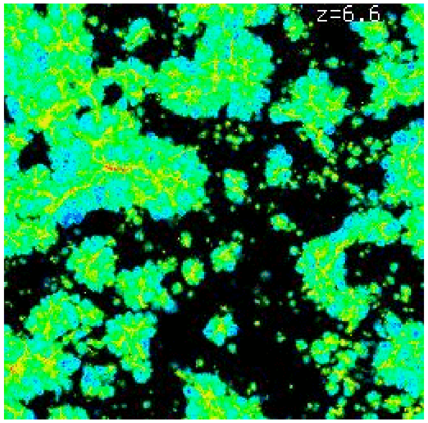
- Observed scatter broadly consistent with density fluctuations alone. Subtle to infer patchy reionization!
- Intrinsic structure and sightline-to-sightline variation in quasar continuum are also likely important.



Lidz, Oh, & Furlanetto 2006

Simulating Hydrogen Reionization





- Require large simulation volume to sample large HII regions
- High mass resolution to resolve sources/sinks of photons. ~ 100 mpc/h box to get 10^8 M_sun requires 3300^3 particles -- 3-4 times larger than Millenium simulation!
- Some treatment of radiative transfer -- 7d problem, want high resolution!

Simulating Hydrogen Reionization

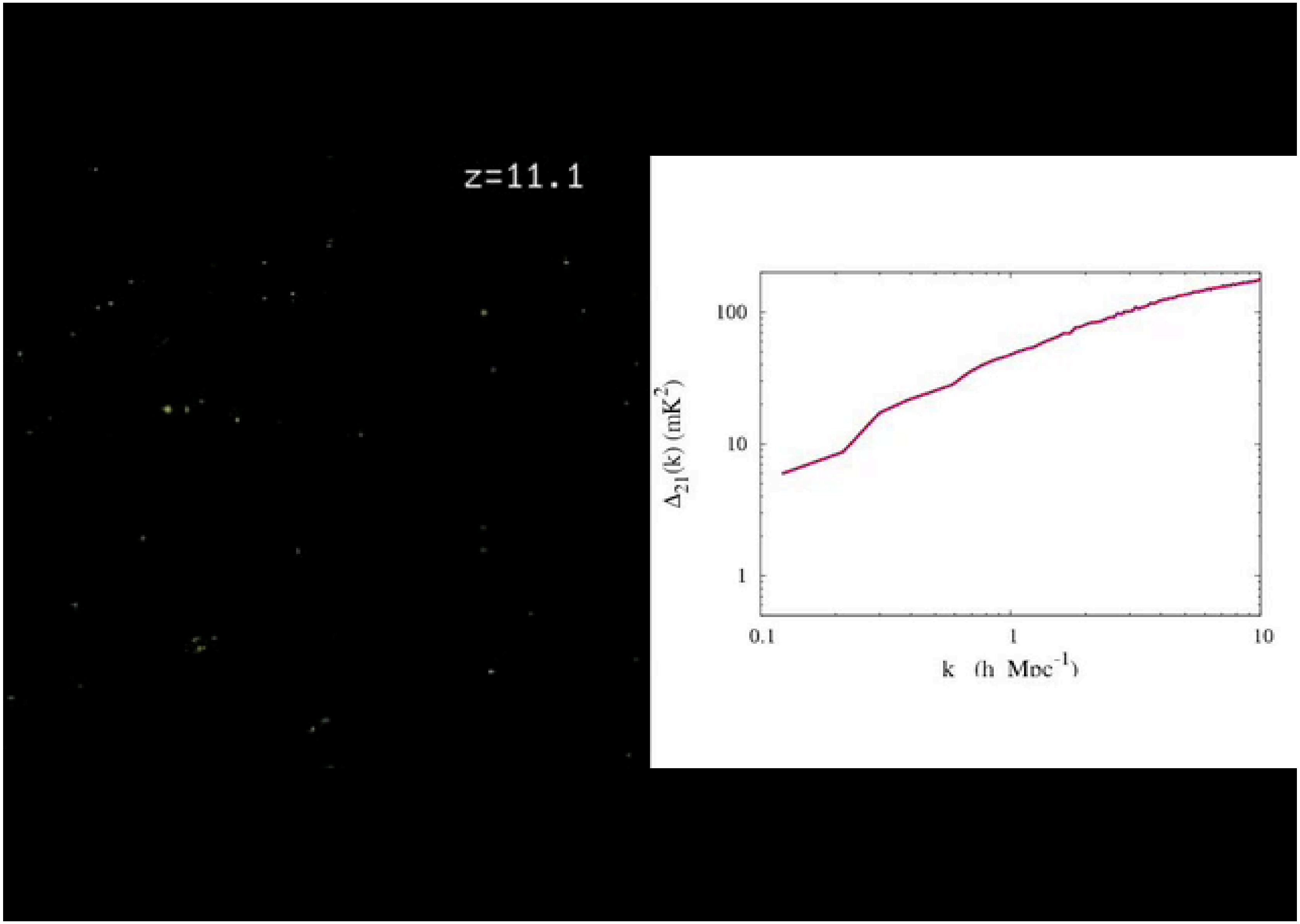
What can we do to make progress? Approximations/Simplifications:

- Treat RT in post-processing. Ok because fronts are mostly super-sonic and move faster than gas can respond.

- Ionization fronts should be pretty sharp due to short mean-free path in neutral IGM. Track position of fronts with jump condition and adaptive ray-casting scheme. Inside fronts adopt ionization equilibrium, uniform temperature.

- Assume gas traces dark matter on scales of interest. Prescriptions for “sub-grid physics”.

- Our current simulation is ~ 65.6 Mpc/h on a side w/ 1024^3 particles, resolving halos down to M_min = 2 10^9 M_sun -- still have several hundred thousand sources near z~6!



M. McQuinn

Semi-Analytic Modeling

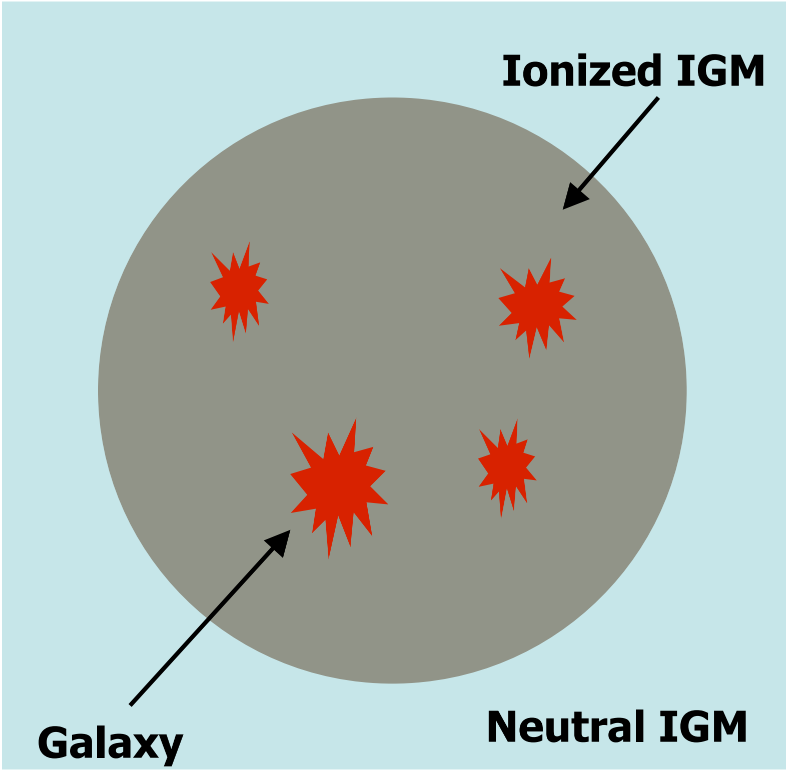
- Simplest variant: assume each galaxy can ionize a mass of $M_{ion} = \xi M_{gal}$
- Region is ionized if

$F_{coll} > \xi^{-1}$

Use extended press-schecter theory to find "mass function" of ionized regions.

Apply in a monte-carlo sense to initial conditions from numerical simulations.

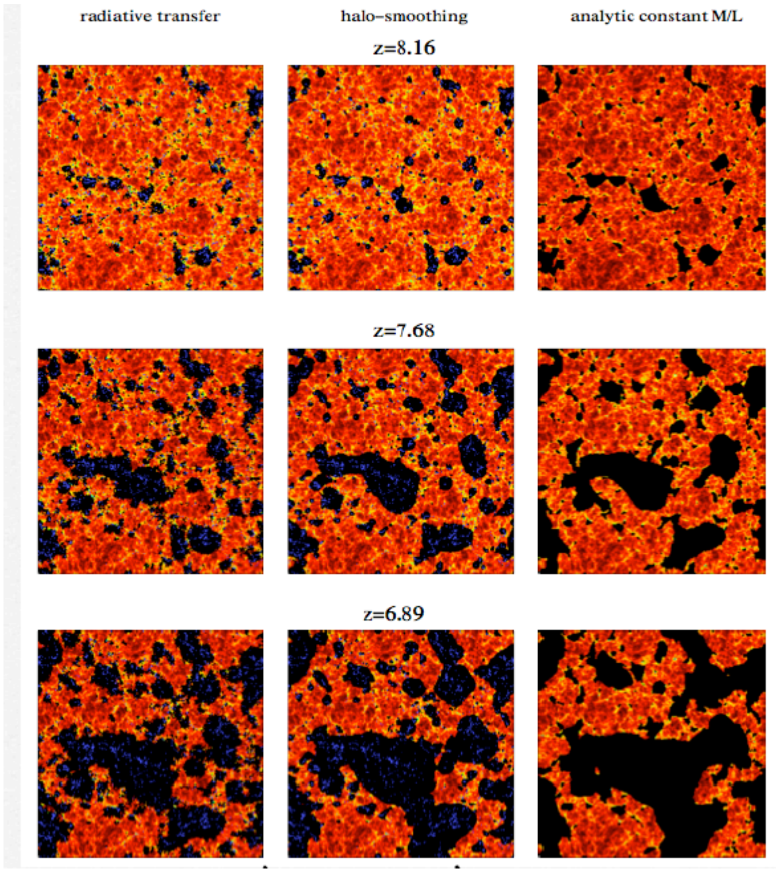
At some level we just need to count photons!



Furlanetto,Zaldarriaga & Hernquist 2004

Large HII regions during reionization

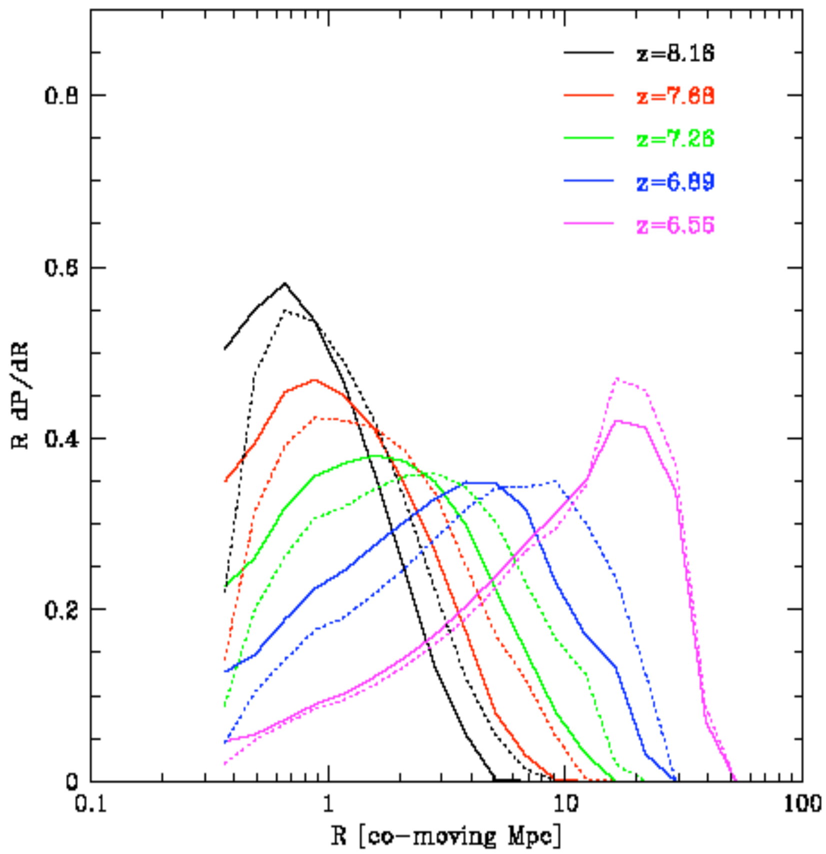
- Semi-analytic models match basic features well.
- Useful for exploring parameter space: 21 cm fast?



Zahn,Lidz et al. 2006

Bubble Size Distribution

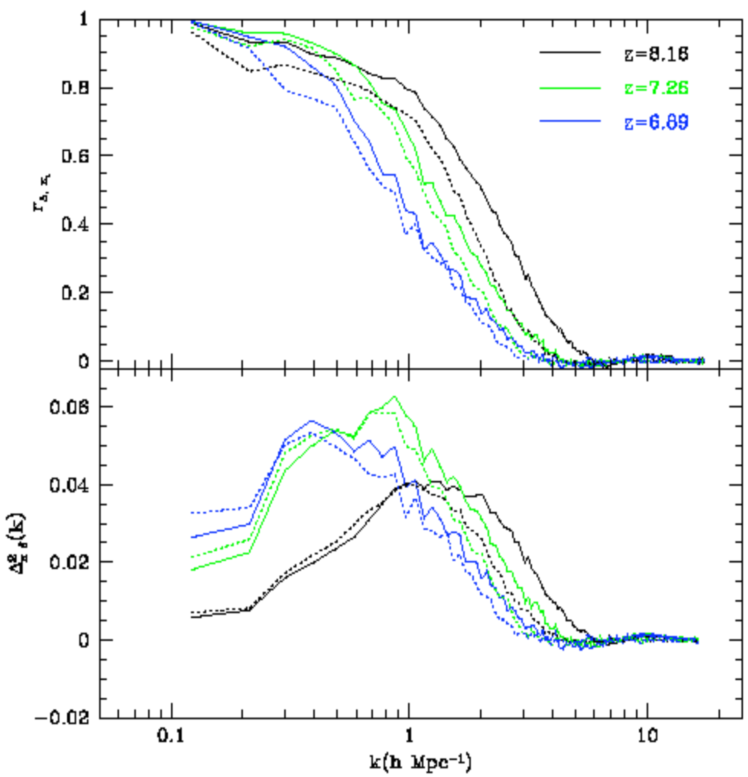
- Fraction of pixels in HII regions of different size.
- HII regions grow quickly around individual sources, overlap and form uber-bubbles.
- <x_i>=0.13,0.22,0.35,0.55, 0.82



Zahn, AL, et al. 2006

Ionized Regions Trace Over-densities

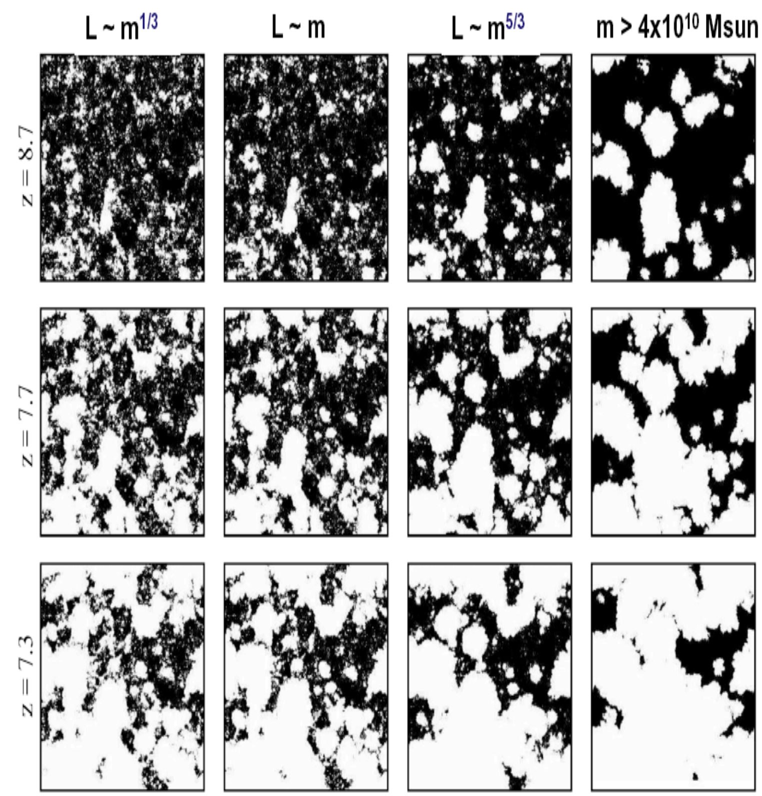
- Galaxy formation happens earlier in large scale over-dense regions. These regions reionize first.
- Ionization and over-density well-correlated on large scales.



Zahn, Lidz et al. 2006

Bubble Sizes and Ionizing Sources

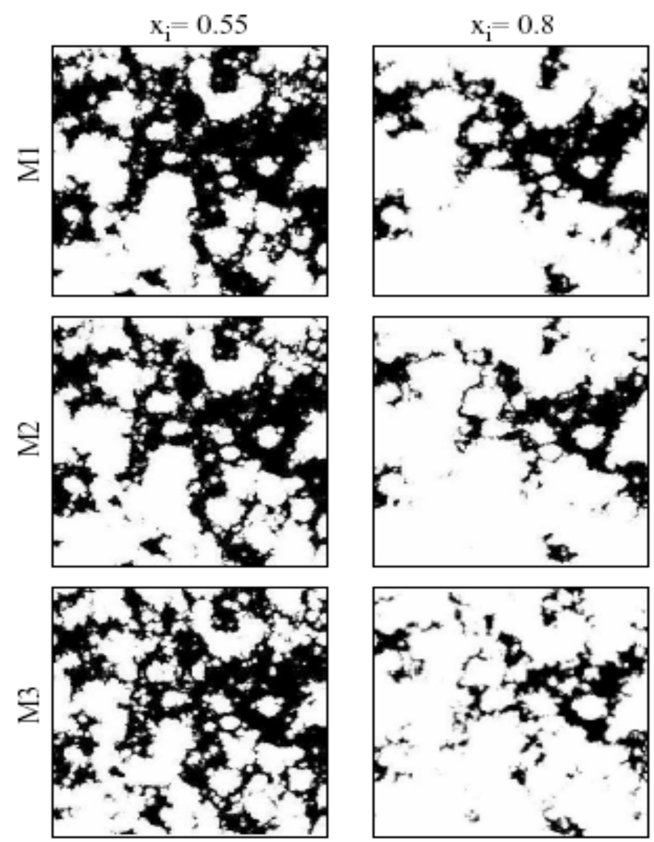
- Size distribution of HII regions at different stages of reionization.
- Depends on whether rare, very efficient or more common sources produce most of the ionizing photons.
- Teach us about *which* sources reionize the IGM!



McQuinn et al. 2006

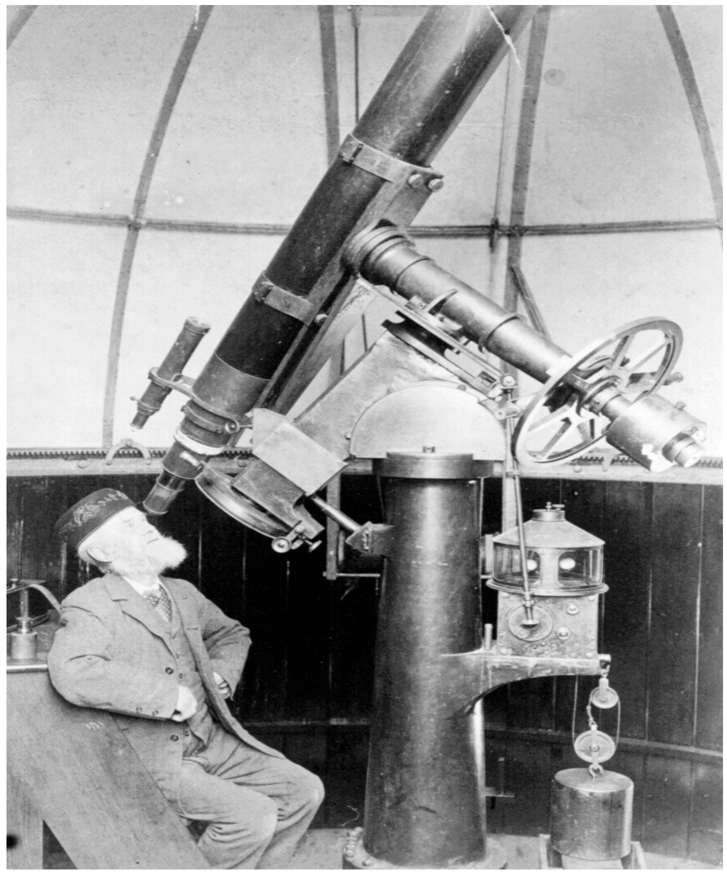
Bubble Sizes and Sinks of Ionizing Photons

- If sinks of ionizing photons (e.g. mini-halos) are abundant, bubbles are a little smaller at a given ionization fraction. (see also Furlanetto & Oh 2005).
- Also important in limiting mean-free path within bubble interiors.



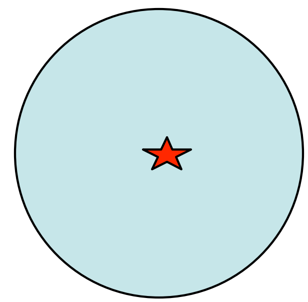
McQuinn et al. 2006

Back to Observations!



Quasar HII regions?

- Imagine quasar point source emitting into uniform IGM with neutral fraction, X_{HI}



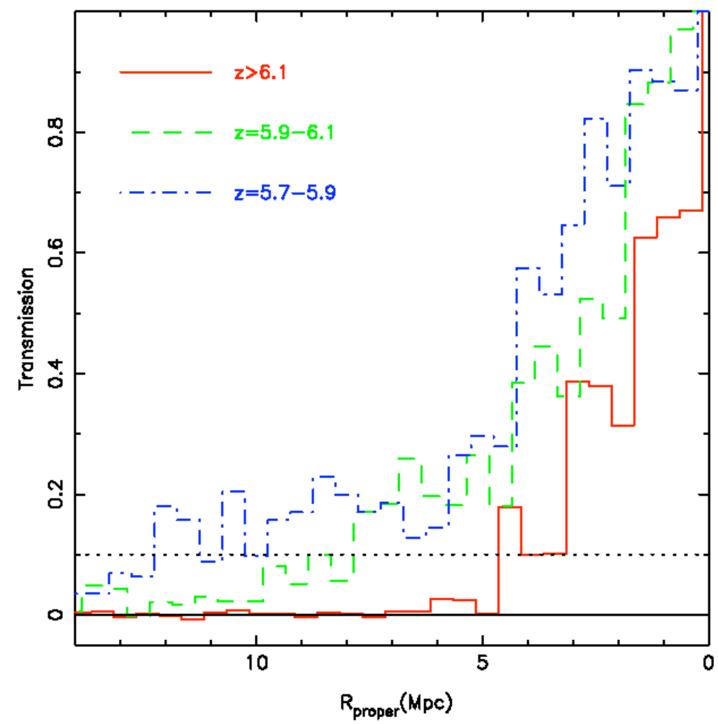
- Expect

$$R = \left[\frac{3\dot{N}t_q}{4\pi n_H X_{\rm HI}}\right]^{1/3}$$

Is IGM very neutral at z~6?

- If observed transmission profile gives R and $t_q \sim 4 \times 10^7$ yrs, then data prefers a highly neutral IGM with X_{HI} >~ 0.25, and higher preferred values.

  (Wyithe & Loeb 2004, Mesinger & Haiman 2004).

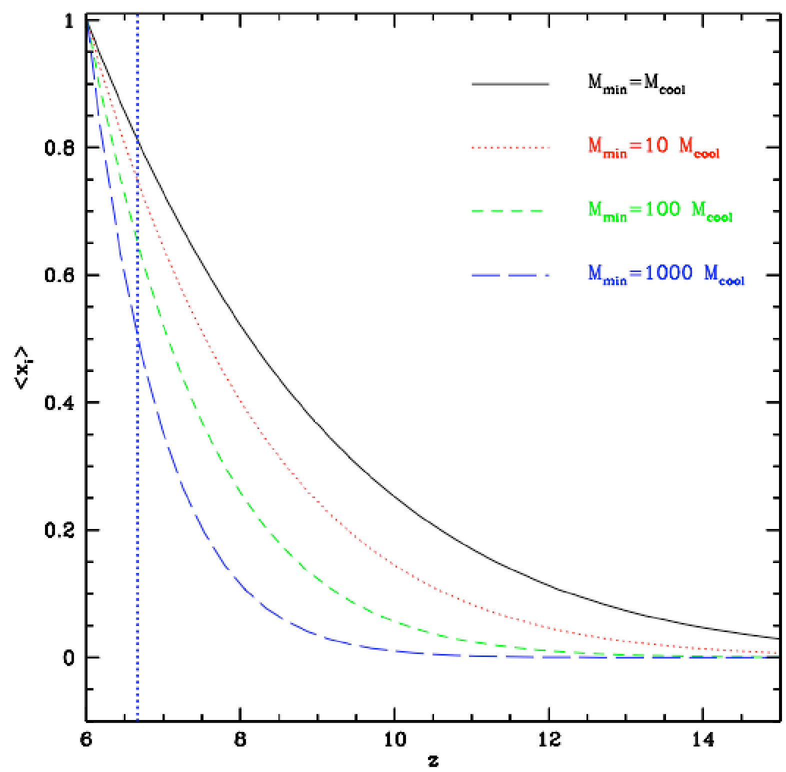


Fan et al. 2006

Reionization is an extended process!

- Even if reionization ends at z~6, process is unlikely fast enough for IGM to be mostly neutral when highest redshift quasars turn on.

- At least 60% of volume should be ionized when quasars turn on and likely more.

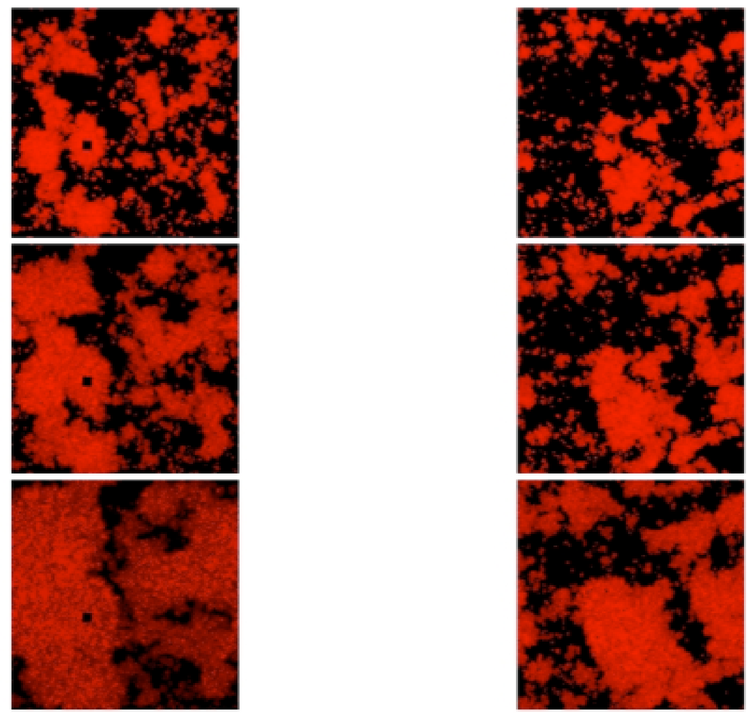


Lidz et al. (in prep)

HII regions around Quasar Progenitors

- Z>~6 quasars are likely born into ionized regions created by galaxies.
- Even when IGM is ~50% neutral, long skewers towards quasars pass entirely through ionized bubbles, even before the quasars turn on.

(see also Yu & Lu 2005).

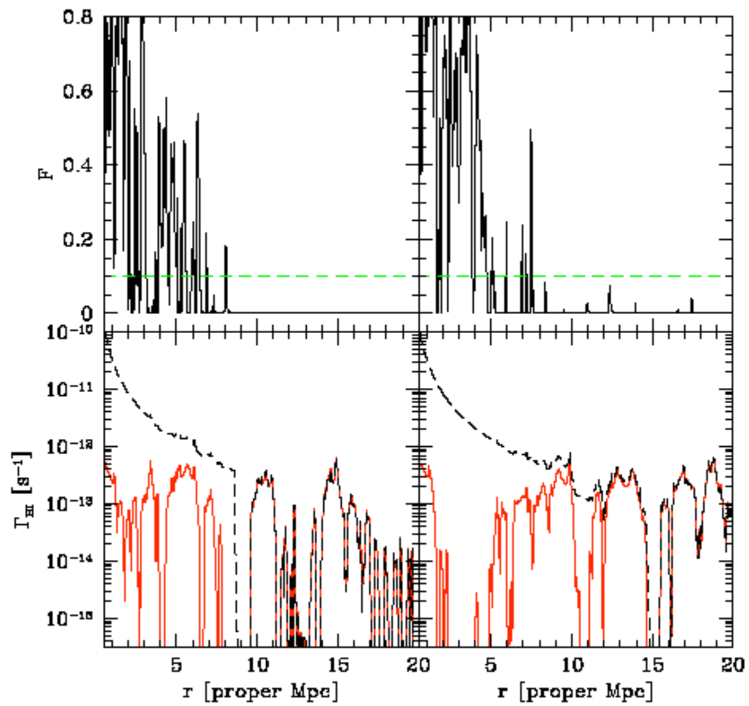


Lidz et al. (in prep)

Quasar Proximity Zones

- Generally difficult to locate extent of quasar ionization fronts with absorption spectra. (Left panel ok, but see right panel…)

- Transmission generally very low at front edge -- usual problem w/ large Ly-a cross section!



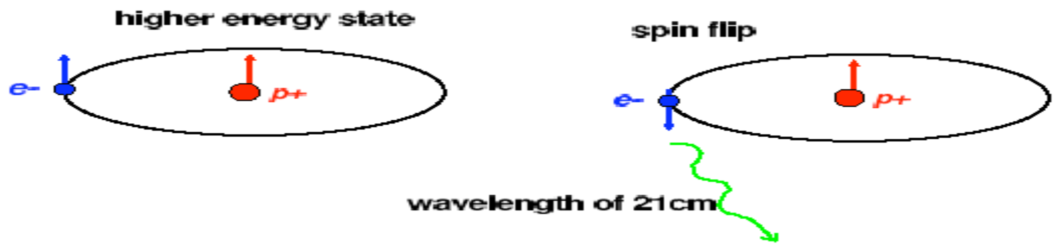
Lidz et al. (in prep)

Quasar Proximity Zones (summary)

- Reionization unlikely fast enough for X_{HI} >~0.50 at quasar turn on.
- Even then, long skewers towards quasar progenitors pass mostly through ionized bubbles.
- Observed transmission may not give us true location of front edge and fraction of volume that is ionized, but reflect last region underdense enough to allow transmission.

We need other probes of reionization!

21cm: why the excitement?



- Spectral line, so can get 3-d information, rather than an integral constraint. Reionization tomography!
- Weak transition, so doesn't suffer (τ~10^{-2}) saturation problems unlike Ly-a
- During reionization, should be able to see neutral IGM in emission against the CMB. The IGM gas is expected to be heated by early X-rays above T_cmb. Excitation temperature coupled to gas temperature by Ly-a photons.

$$\delta T(\nu) \approx 26\, x_H (1+\delta_\rho) \left(\frac{T_S - T_{\rm CMB}}{T_S}\right) \left(\frac{\Omega_b h^2}{0.022}\right) \times \left[\left(\frac{0.15}{\Omega_m h^2}\right)\left(\frac{1+z}{10}\right)\right]^{1/2} {\rm mK}.$$

Foregrounds!

- ~4 orders of magnitude larger than the signal
- Unresolved extragalactic radio sources
- Galactic synchotron, free-free
- Foregrounds expected to be smooth in frequency space, unlike the signal. Remove foreground contamination by cross-correlating maps of different frequency.
- Man-made RFI.
- Many other challenges ahead…ionospheric fluctuations, etc…

21cm Experiments -- Go For It!

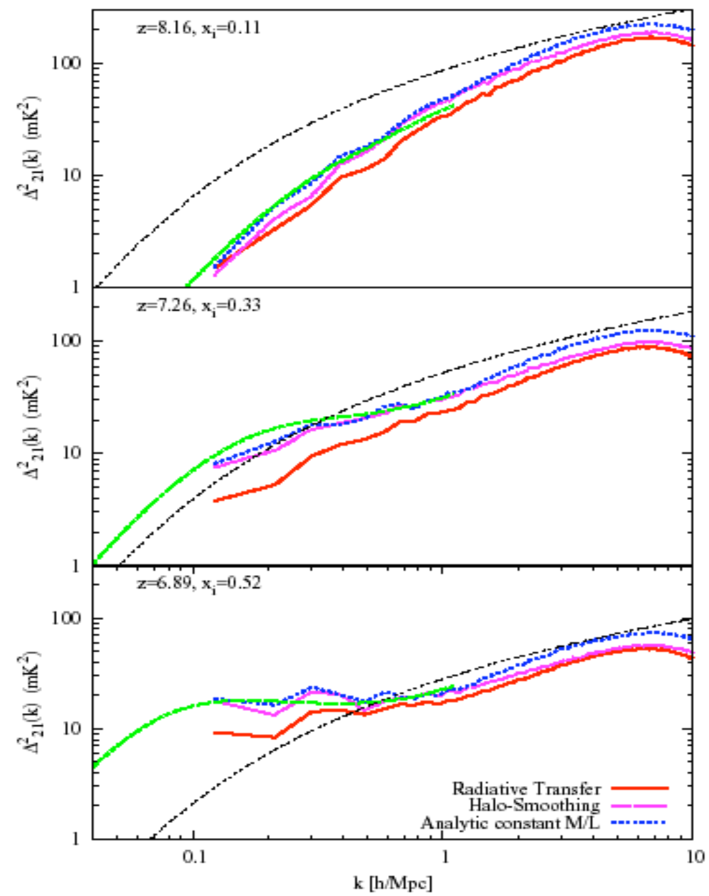
- Several Experiments Underway
- GMRT
- PAPER
- MWA (2008)
- LOFAR (2008)
- SKA (2020?)

- Find a radio-quiet site!

MWA Site
Population = 4

The 21 cm Power Spectrum

- Presence of large HII regions imprints a `knee' in the 21 cm power spectrum.
- First generation surveys have sensitivity to detect this knee, but little `imaging' sensitivity.



Zahn, Lidz et al. 2006

Information Content of 21 cm Power Spectrum

21 cm brightness temp:

$$\delta_T(\vec{x_1}) = T_0 \langle x_H \rangle [1 + \delta_x(\vec{x_1})][1 + \delta_\rho(\vec{x_2})]$$

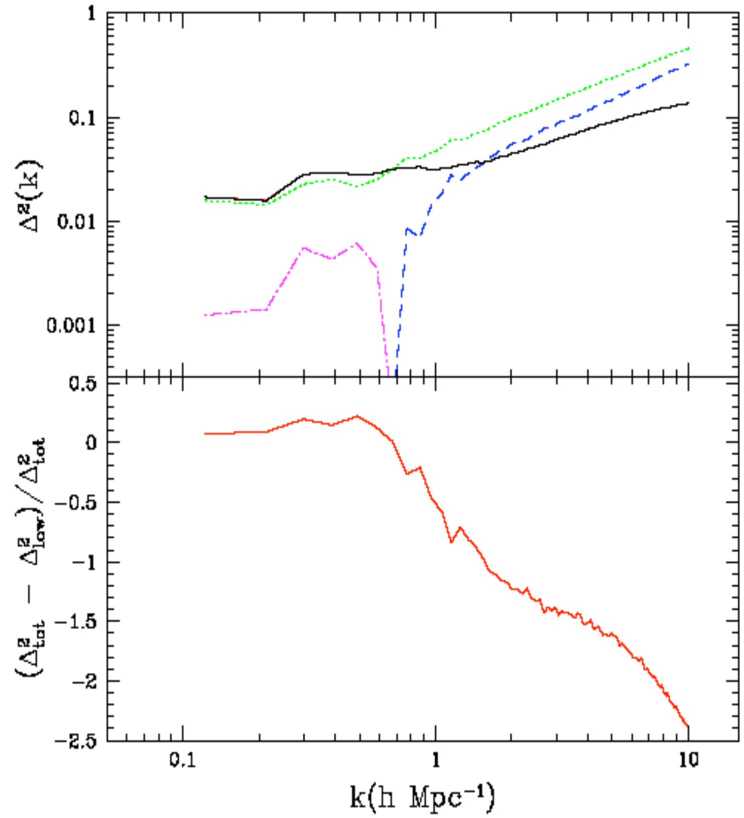
21 cm power spectrum:

$$\begin{aligned}\Delta^2_{21}(k) = T_0^2 \langle x_H \rangle^2 \; [\Delta^2_{\delta_\mathrm{x},\delta_\mathrm{x}}(k) + 2\Delta^2_{\delta_\mathrm{x},\delta_\rho}(k) + \Delta^2_{\delta_\rho,\delta_\rho}(k) \\ + 2\Delta^2_{\delta_\mathrm{x}\delta_\rho,\delta_\mathrm{x}}(k) + 2\Delta^2_{\delta_\mathrm{x}\delta_\rho,\delta_\rho}(k) \\ + \Delta^2_{\delta_\mathrm{x}\delta_\rho,\delta_\mathrm{x}\delta_\rho}(k)] \qquad (3)\end{aligned}$$

$$\Delta^2_{\delta_x \delta_\rho,\delta_\rho}(k) = FFT[\langle < \delta_x(\vec{x_1})\delta_\rho(\vec{x_1})\delta_\rho(\vec{x_2})\rangle]$$

Higher Order, 3-field terms are important!

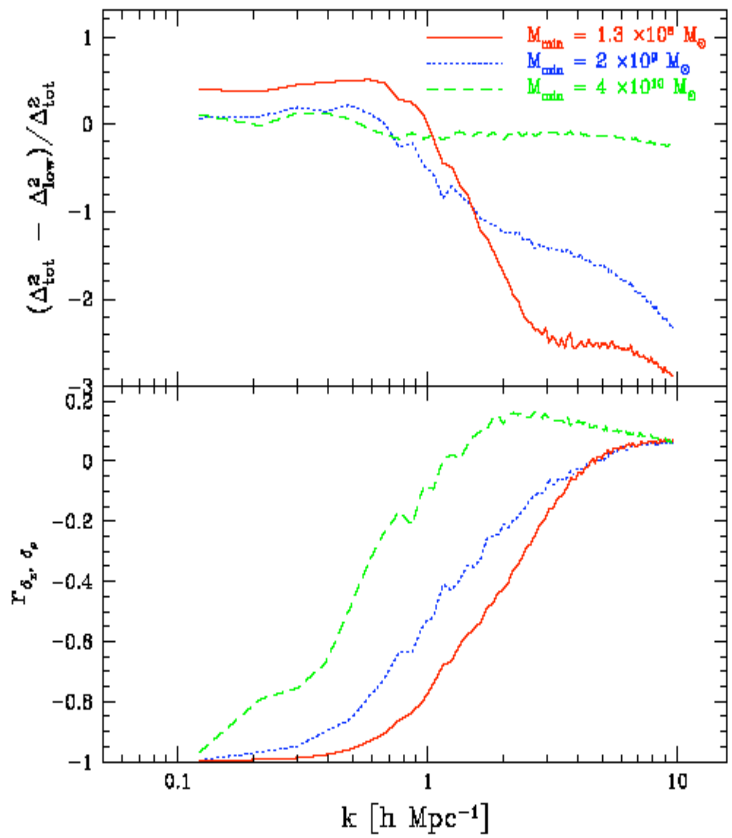
- On small-scales 3-field terms are negative. Factor of ~ 2 difference in signal when <x_H> ~ 0.5!
- At late times, when <x_H> is small, can be important on MWA-scales as well!



Lidz et al. 2006

3-Field Terms mean more info about sources!

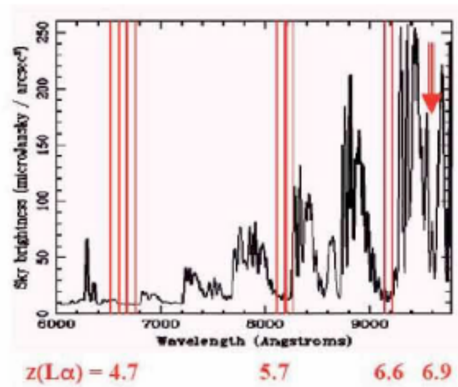
- Importance of 3-field terms depends on how well ionized regions trace overdensities.
- Implies that small-scale 21 cm power spectrum contains more information about ionizing sources than thought previously.

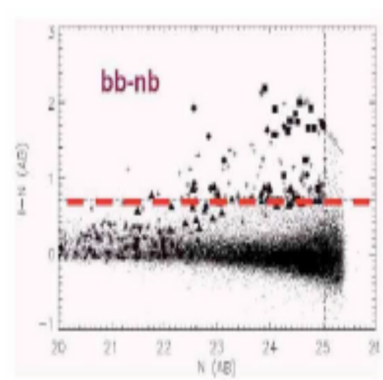


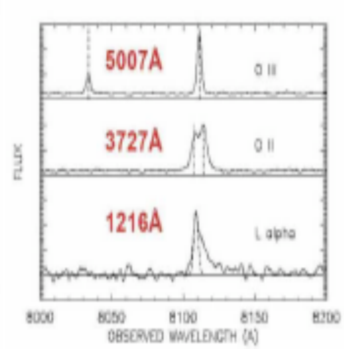
Lidz et al. 2006

Narrow Band Ly-a Galaxy Surveys

- Narrow bands where night sky is not too bad.
- Compare flux in narrow and broad band.
- Spectroscopic follow-up to rule out low-z interlopers.



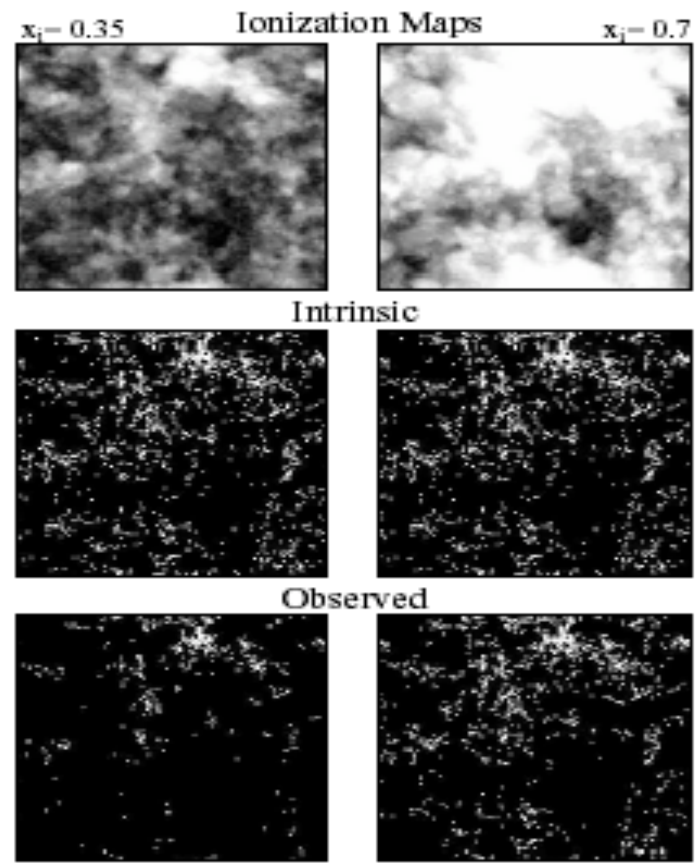




Ellis review, Hu et al. 2004

Ly-a Emitters During Reionization

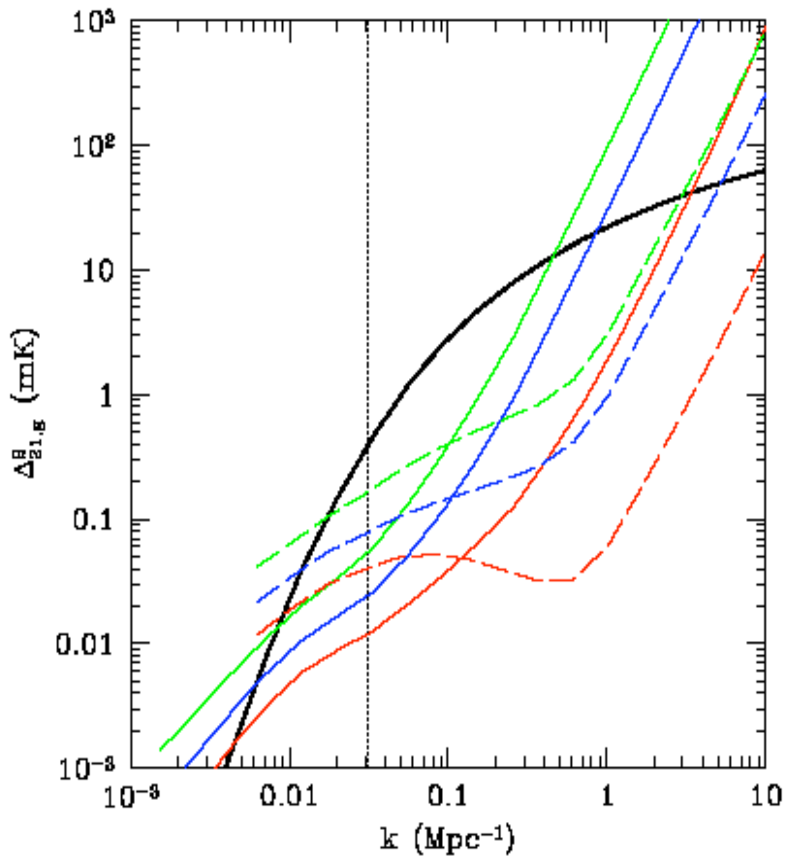
- Only detect Ly-a emitters in large HII bubbles.
- Abundance of emitters if modulated by presence of bubbles: enhances two-point function.
- More robust measure than luminosity function/line-shapes.
- (Furlanetto et al. 2004, McQuinn et al. 2006)



McQuinn et al.2006

21 cm - Galaxy Cross Correlation

- Foreground removal requirements much less stringent!!
- S/N estimate : MWA and futuristic galaxy survey. M_min=10^10, 10^11, 2 10^11 M_sun, comparable field-of-view to MWA.
- Should be detectable with Subaru-like galaxy survey. (Wyithe & Loeb 2006)



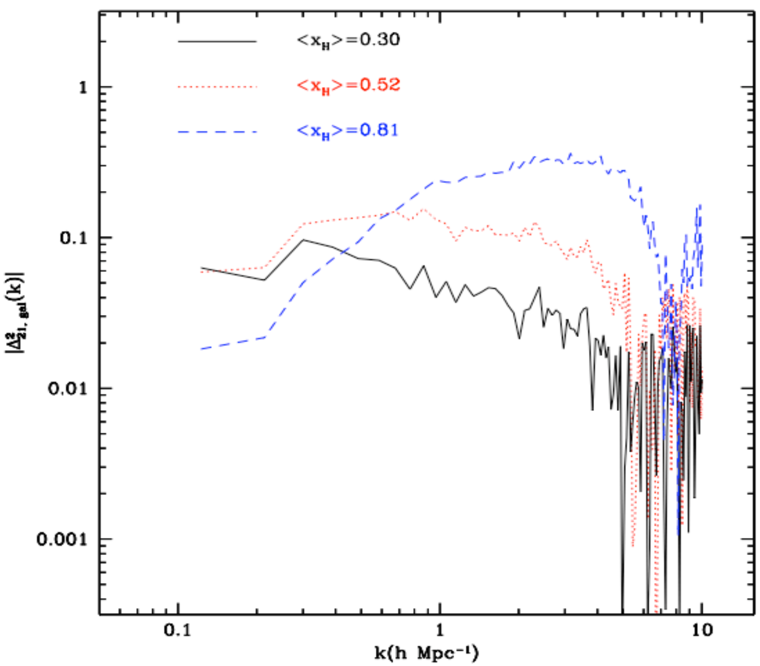
Furlanetto & Lidz (2006)

21 cm - Galaxy Signal

Redshift evolution of signal traces bubble growth

Roughly: 2-fields are anti-correlated with cross-power turning over on scales smaller than bubble-size.

Signal also depends on how well sources trace overdensities.



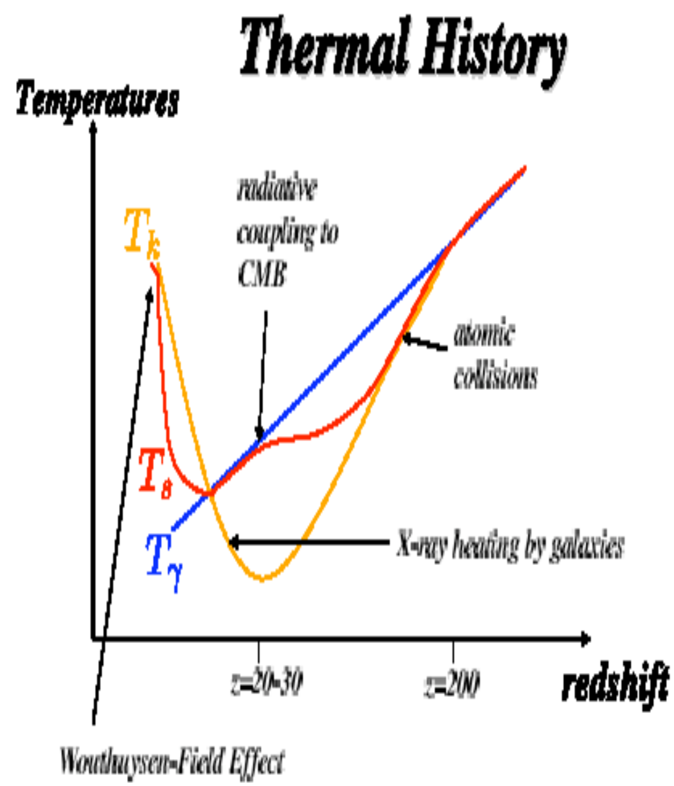
(in prep)

Conclusions

- Present observations of z>~6 IGM are subtle to interpret.
- Theoretical modeling challenging, but simulation efforts (kept in check with semi-analytic models) are underway!
- 21 cm emission from high redshift IGM, and high redshift Ly-a emitter, galaxy surveys will tell us about reionization within a few years.
- Thanks!

21cm Spin Temperature

- After recombination gas temp tracks cmb temp, then dips below it, then is heated by X-rays from first sources before reionization.
- Spin temperature at z>30 tracks gas temperature due to collisions. First galaxies Ly-a photons couple spin temperature to gas temperature at z~20.
- At this stage T_s >> T_cmb, see neutral IGM in emission.



From Avi Loeb