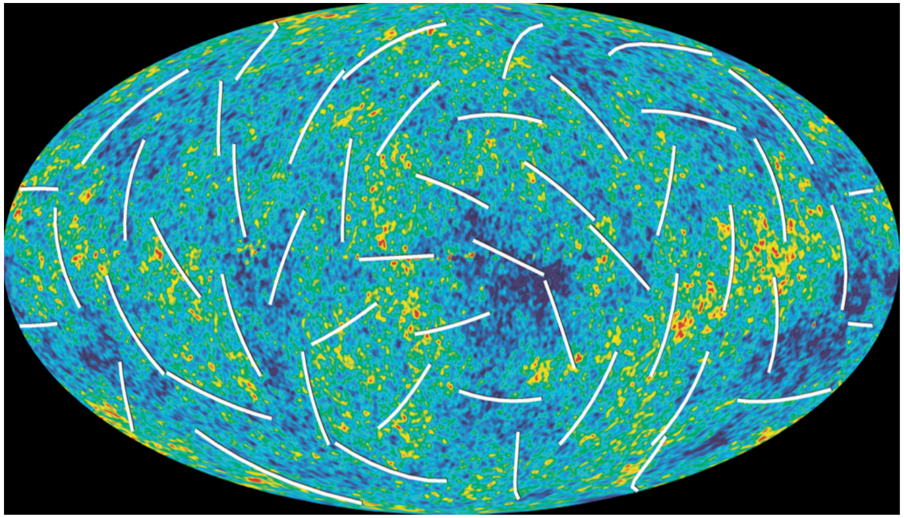
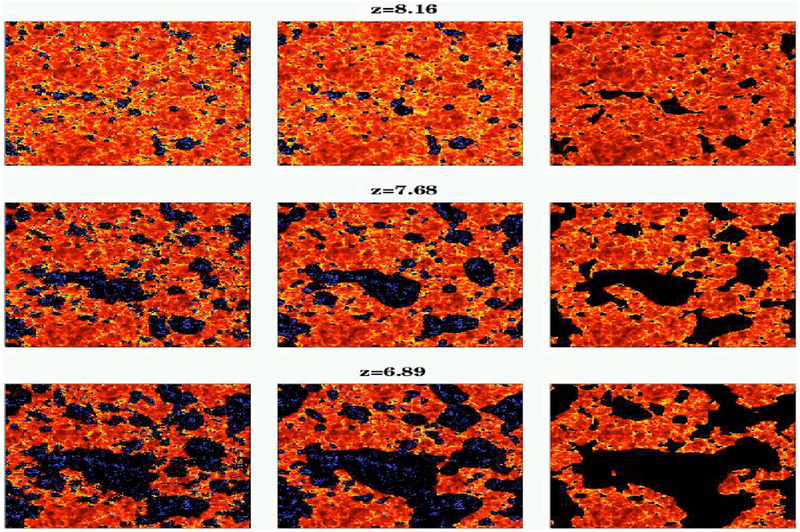
Reionization Science

Adam Lidz (Harvard-CfA)

June 22, 2008

Fermilab, CMBpol Workshop





Two Questions

- What can reionization do for CMBpol?

  How do uncertainties in the reionization history impact cosmological parameter constraints and inflation science?

- What can CMBpol do for reionization?

  What new might we learn about reionization from CMBpol?

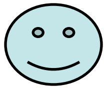
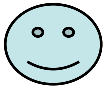
Outline

- What we would like to know about reionization.

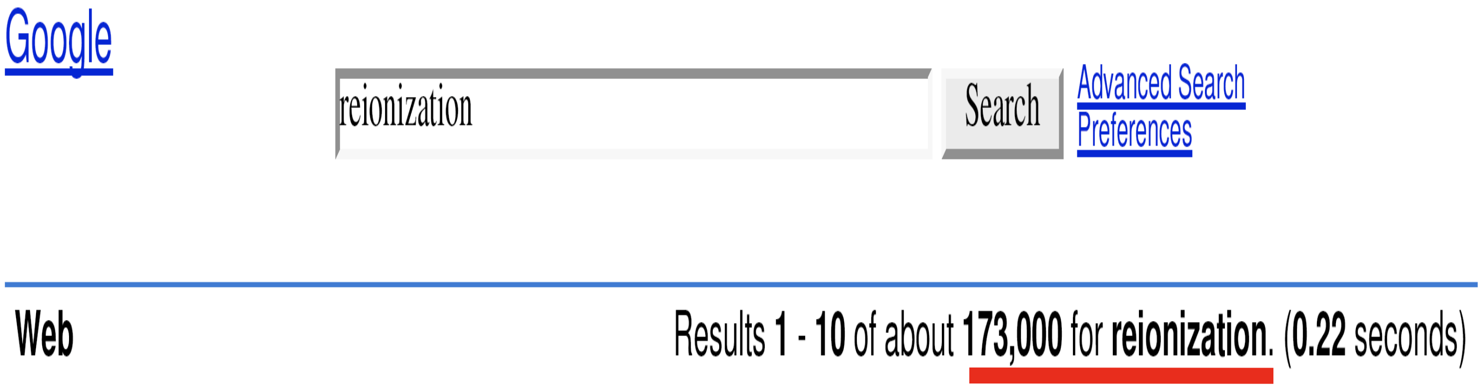
- What we might know in the ~near future.
  a) Quasar Spectra
  b) Lyman-alpha Emitters
  c) GRB optical afterglows
  d) 21 cm Surveys
  e) CMB secondary anisotropies

- How can CMBpol help?

Reionization Collaborators

- Mark Dijkstra (Melbourne/CfA)
- Suvendra Dutta (CfA)
- Claude-Andre Faucher-Giguere (CfA)
- Steve Furlanetto (UCLA)
- Lars Hernquist (CfA)
- Matt McQuinn (CfA) 
- Peng Oh (UC Santa Barbara)
- Oliver Zahn (CfA/Berkeley) 
- Matias Zaldarriaga (CfA)

Lots of Recent Work on Reionization……

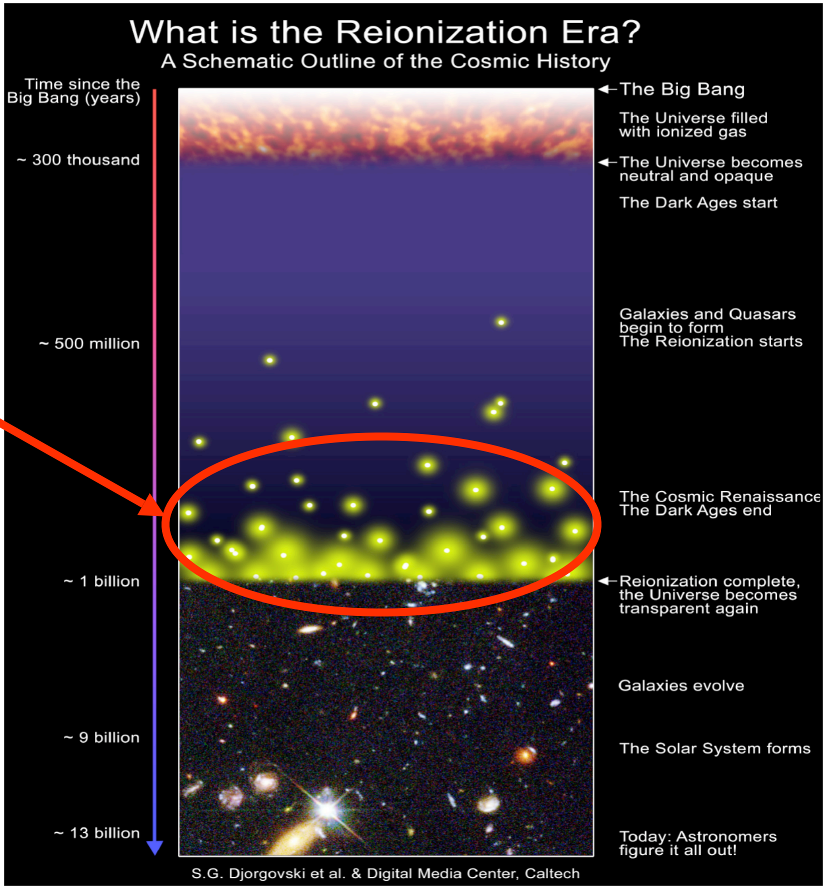


1. Tau from WMAP, SDSS quasar spectra.
2. Semi-analytic/analytic models.
3. Reionization Simulations: Gnedin+, Ciardi+, Iliev+, McQuinn+, Trac & Cen, Altay & Croft

But so far unhealthy ratio of theory papers to data points!!

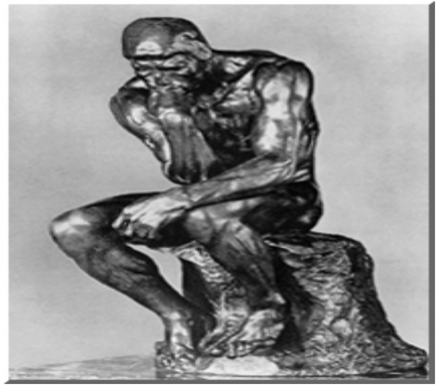
Reionization!

- We detect CMB as gas first becomes neutral.
- Then first sources of light turn on and ionize most of the gas in the universe.
- Key stage in our story of structure formation!
- But when and how?

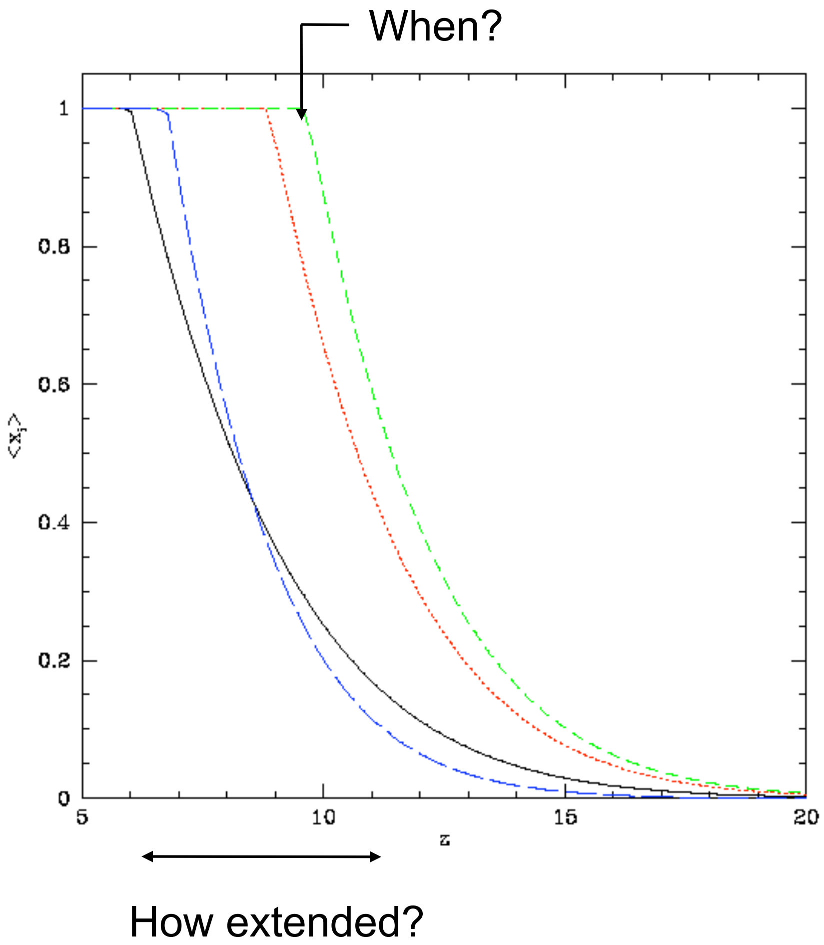


Djorgovski

Motivating Questions

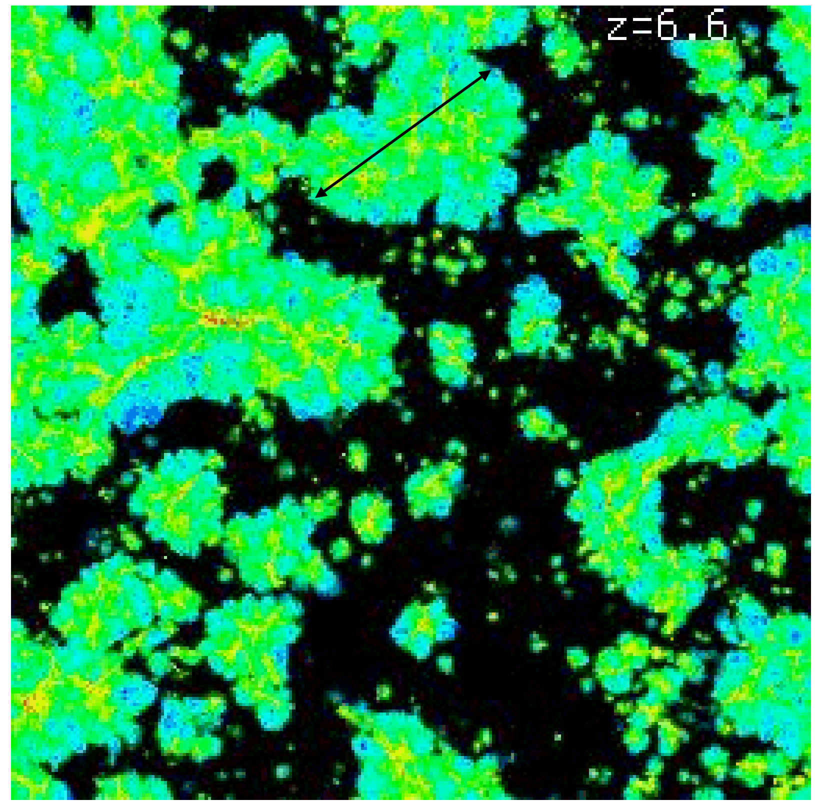


- First sources produce ionizing photons, form ionized “bubbles” which grow and merge.
- When was Hydrogen reionization completed?
- How extended was the reionization process?



Motivating Questions

- Two-phase medium, with neutral regions, and ionized-holes or ‘bubbles’
- What was the topology of reionization like?
- How large were the ionized bubbles at different stages of reionization?



100 Mpc

Motivating Questions

- Who reionized the universe? What were the first sources like?
- Like present day galaxies? Pop III stars? Quasars or mini-quasars?
- Low mass or high mass ?
- Impact of feedback on galaxy formation?

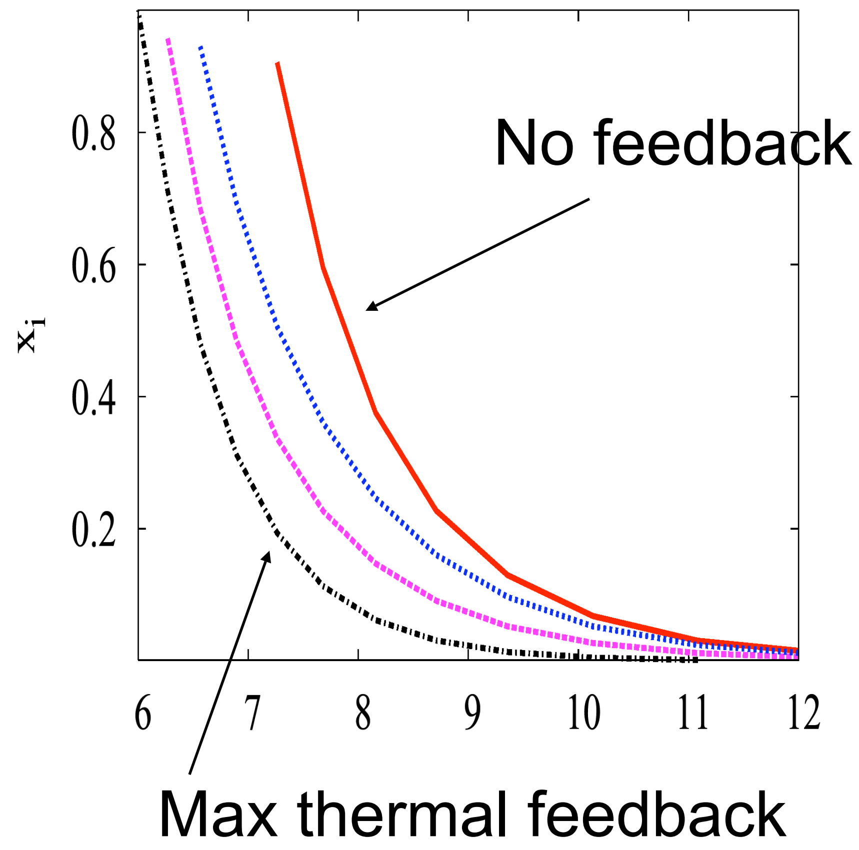
IGM is *laboratory* for learning about first sources…

Abel, Bryan, & Norman 2002

What does <x>(z) tell us?

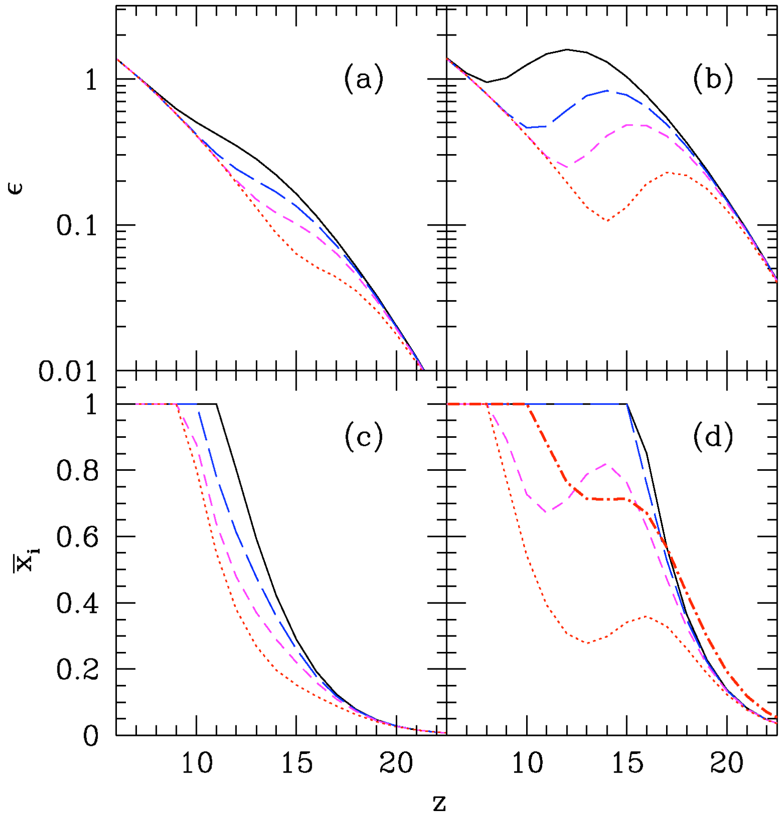
- Efficiency of sources?
- More rapid evolution for efficient, yet massive and rare sources.
- Importance of feedback: how extended?
- Clumpiness of IGM: how many photons per atom are required?

McQuinn, AL, et al. (2007)



<x>(z) (cont.)

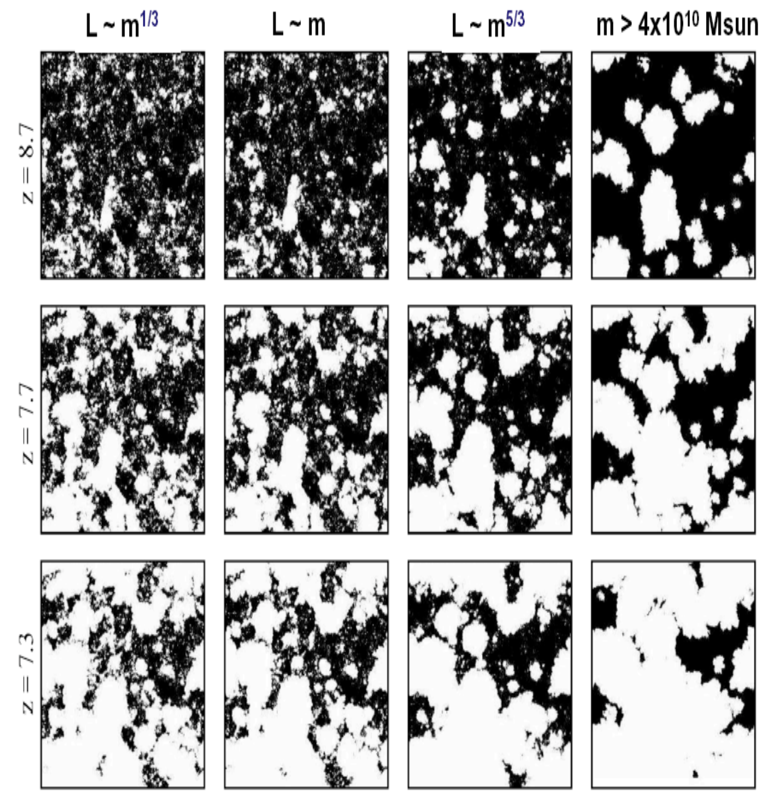
- Very high redshift activity: BEST for CMBpol!!!
- True double reionization unlikely.
- Any evidence for early mode of star formation highly interesting!
- High redshift ionization from annihilating/decaying DM?



Furlanetto & Loeb (2005)

Bubble Sizes and Ionizing Sources

- Bubble sizes at different stages of reionization.
- Depends on whether rare, very efficient or more common sources produce most of the ionizing photons.
- Bubble size depends mostly on clustering strength of source halos.
- Teach us about *which* sources reionize the IGM!



McQuinn,AL, et al. 2006

100 mpc

Recap

- From observations measure or constrain:

  a) <x>(z) -- filling factor of ionized regions. Peng Oh: "Reionization's Madau Plot".

  b) Size distribution of ionized regions. Peng Oh: "Reionization's Mass Function"

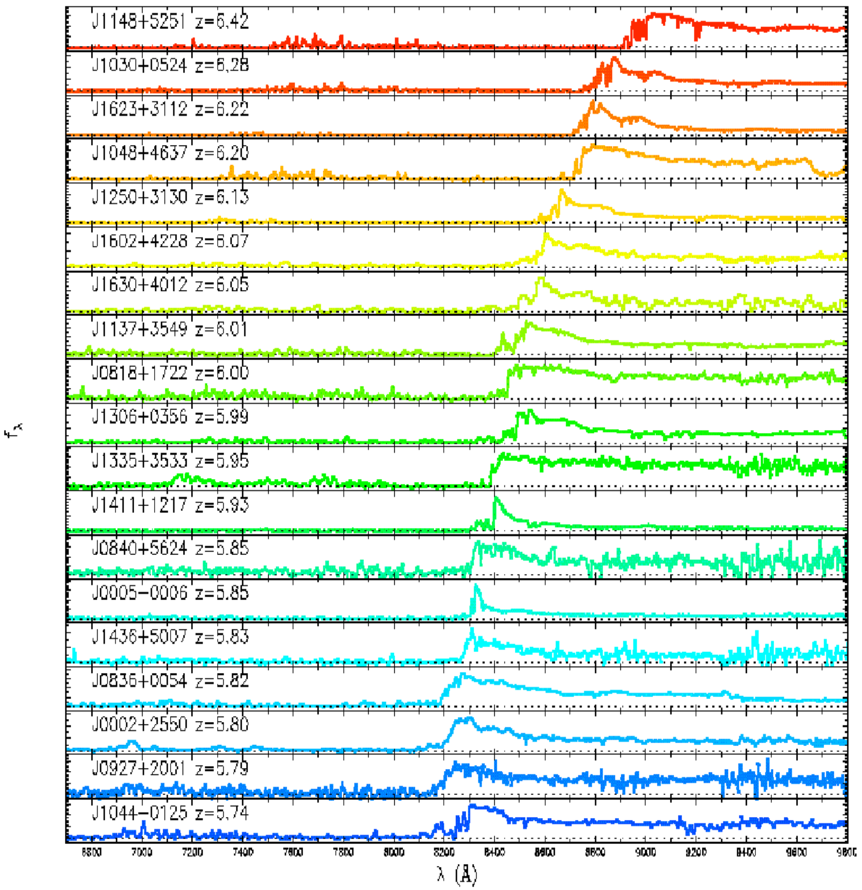
- Use this to determine properties of first sources of light, early structure formation.

- CMBpol may help with a)!

- But will other probes get there first?

The Ly-a Forest at z~6

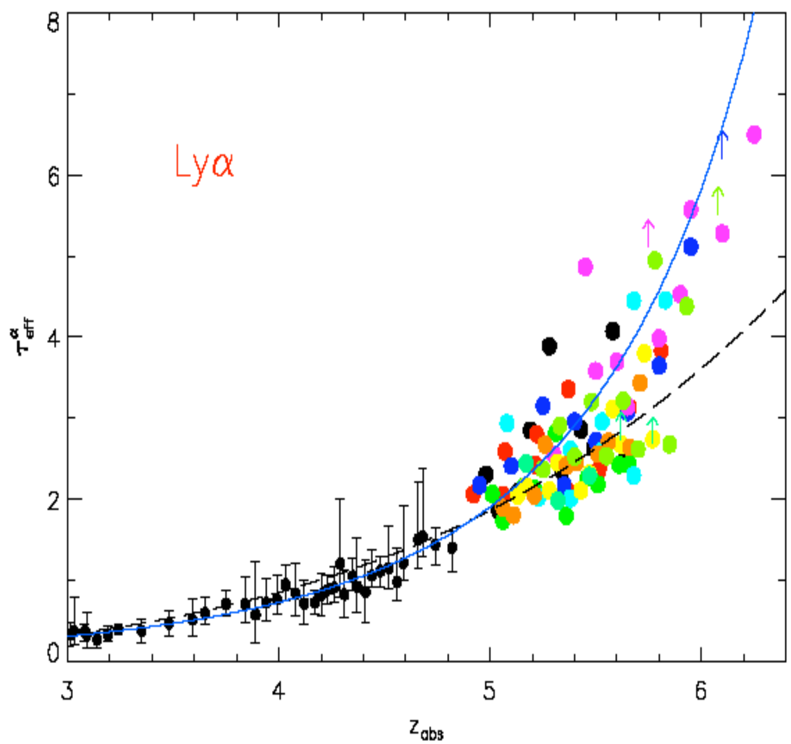
- ~20 quasars at z>~6 now.
- Main question: Are we seeing quasars before reionization completes?
- Is the data consistent with the post-reionization IGM?



Fan et al. 2006

Redshift Evolution

- Absorption in forest increases with redshift.
- Ly-alpha saturates at a neutral fraction of ~10^(-4). Even a highly ionized IGM gives complete absorption at z~6.
- Rapidity of evolution, scatter, quasar proximity zones --> all used to argue reionization is not complete above z>~6, but controversial!



Fan, Becker et al. 2006

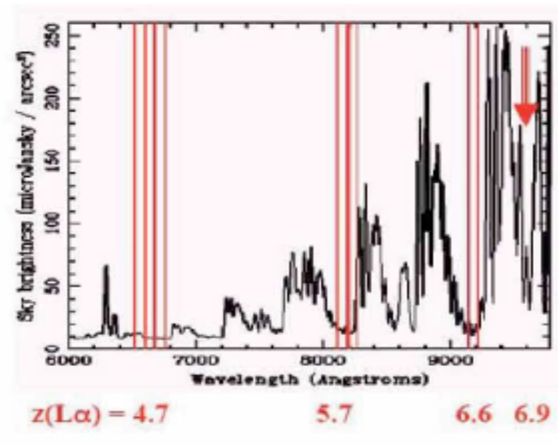
→ e.g. Lidz et al. (2006, 2007)

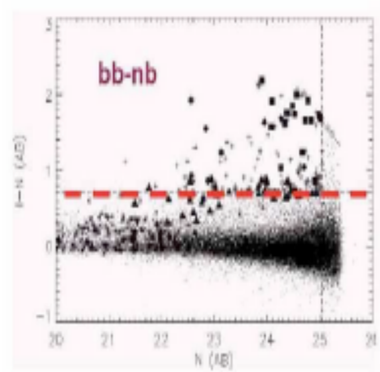
Quasar Spectra Weaknesses

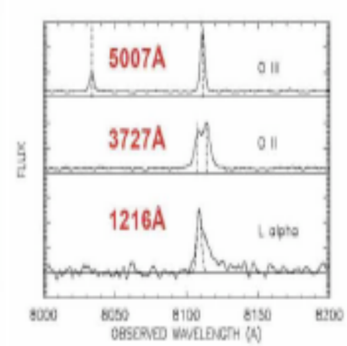
- Transition saturates at X_HI ~ 10^(-4).
- Need bright background quasar, exceedingly rare at high z!
- Unlikely to push this to much higher z in the near future. Expect some z~8 quasars from widefield, deep near IR surveys (e.g. UKIDSS) .

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.
- Hyper-suprime camera on Subaru will push to z~7.3 window soon.







Ellis review, Hu et al. 2004

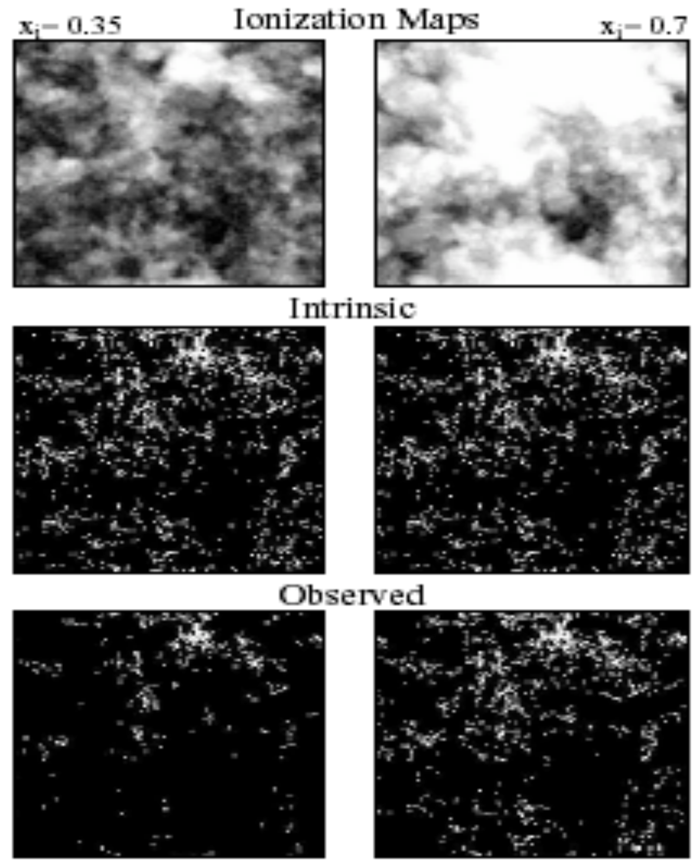
Ly-a Emitters During Reionization

- Only detect Ly-a emitters in large HII bubbles. Damping wing attenuates sources in small bubbles.

- Abundance of emitters is modulated by presence of bubbles: enhances two-point function.

- More robust measure than luminosity function/line-shapes.

- (Miralda-Escude 1998, Furlanetto et al. 2004, McQuinn et al. 2006, 2007)



McQuinn, AL et al. 2006

Ly-a Emitters Weaknesses

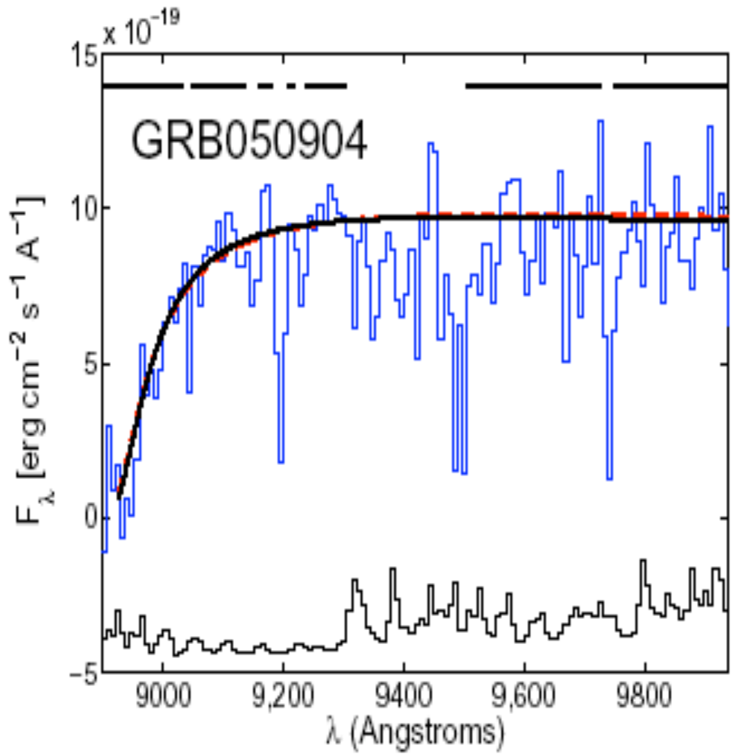
- Abundance modulated by bubbles, but hard to push to z >~ 7.3.

- Modulation/Attenuation strongest in early stages when bubbles are small.

- Ly-a scattering/galactic emission lines are complex: dust, winds, etc…

Probing Reionization with GRB Afterglows

- Have detected afterglows at z~6.3. Might detect one at much higher z, z>10!
- Intrinsic spectrum is simple power-law
- GRB does not ionize its surroundings
- Difficulty: many afterglows have DLAs associated with host. Internal absorption from host galaxy's ISM.

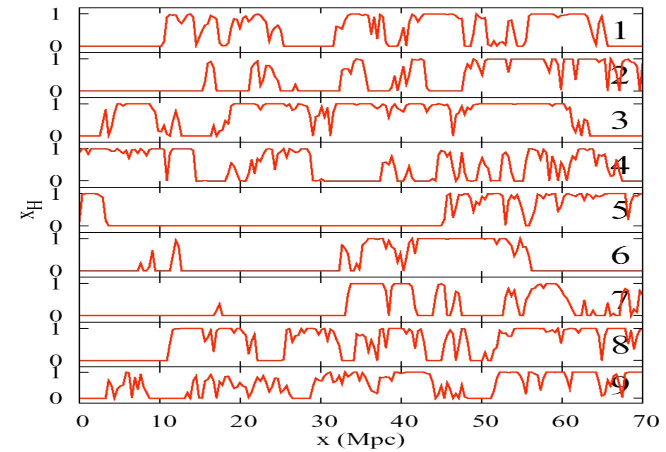


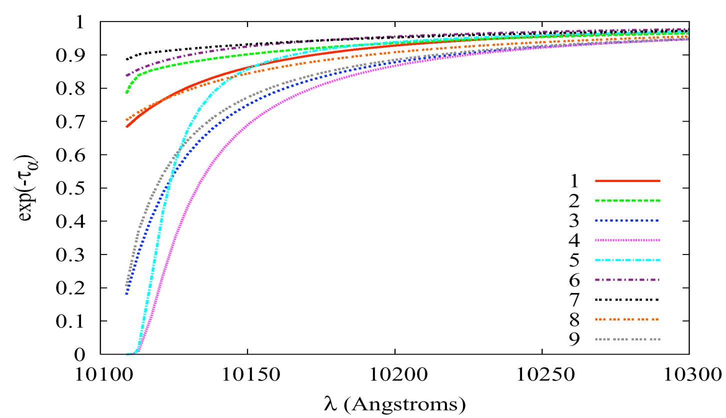
Totani et al. 2006
McQuinn, AL et al. 2007

Sample Variance + Damping-Wing Absorption

- Reionization is inhomogenous --> damping wing absorption varies a lot from sightline-to-sightline.

- Some GRBs will be in big bubbles and see no damping-wing absorption even when x_ion ~ 0.5





McQuinn, AL et al. 2007

Chance of Detecting Partly Neutral IGM with GRB afterglow?

- Say <x>~0.5: want GRB close to bubble edge to detect wing, and only low column DLA in host so that one can distinguish DLA/IGM.

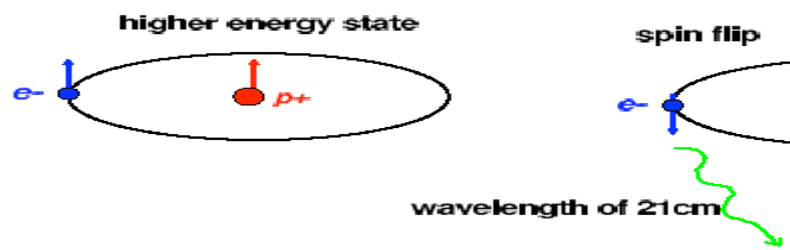
- Estimate with simulated bubbles, distribution of DLAs from afterglows in lower-z observations.

- Detect partly neutral IGM 5-10% of time with current sensitivity. 25-30% with 3 times the current sensitivity --> Catch afterglow early! Requires rapid near-IR followup.

- If lucky, might detect partly neutral IGM, but unlikely to tell us <x>.

McQuinn, AL et al. 2007

21cm: why the excitement?



- Weak transition, so doesn't suffer (τ~10^{-2}) saturation problems.
- Spectral line, so can get 3-d information. Reionization tomography!
- Only known way to probe the "Dark Ages!"

- 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.

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

21cm Experiments -- Go For It!

- 21 CMA
- GMRT
- PAPER
- MWA
- LOFAR
- SKA (2020?)

- Challenges: foregrounds, man-made RFI, freq. dependent beams, etc..

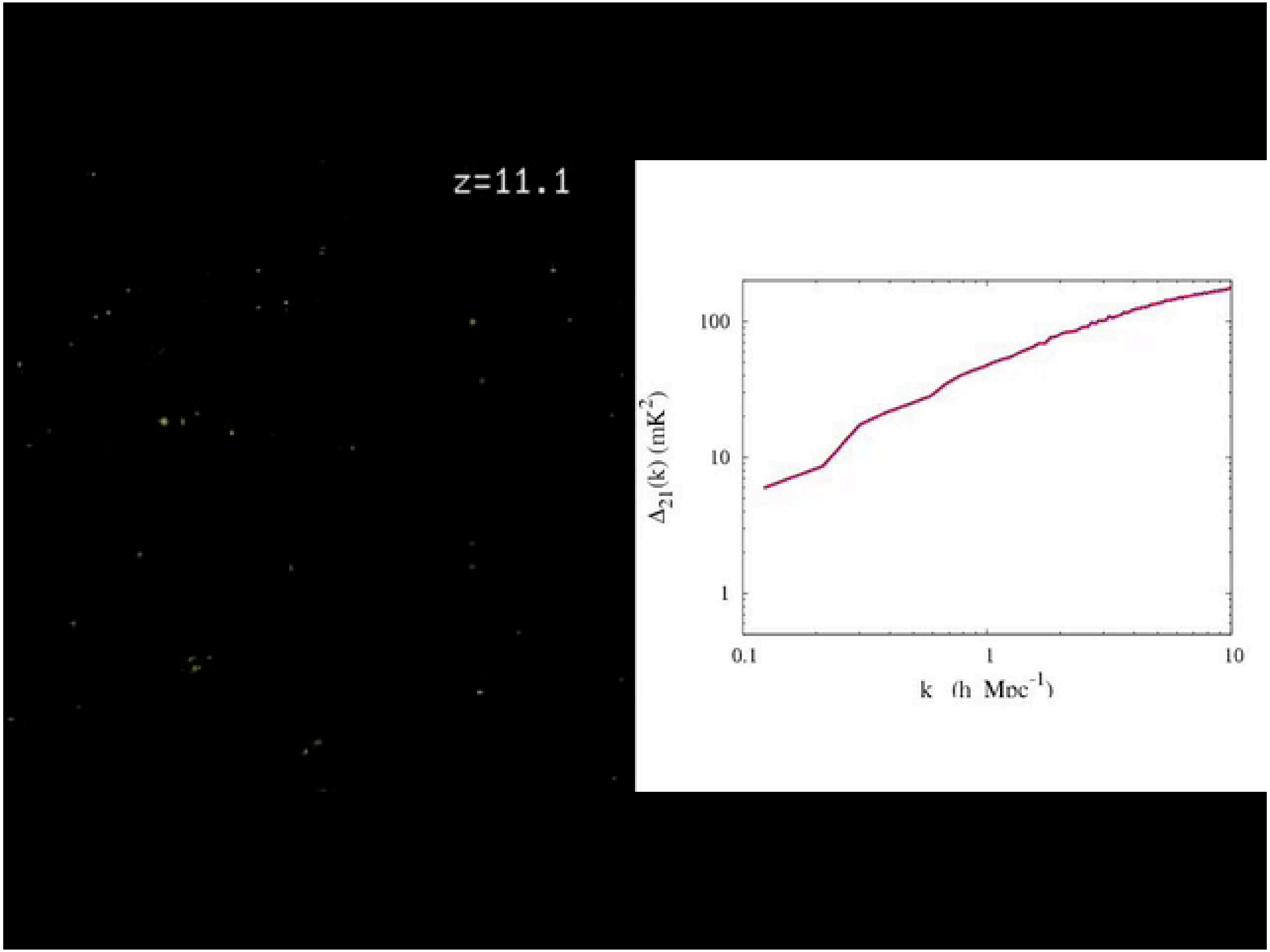
- Find a radio-quiet site!

MWA Site

100 Mpc

M. McQuinn

100 Mpc ~ 1/2 degree on sky



100 Mpc

M. McQuinn

100 Mpc ~ 1/2 degree on sky

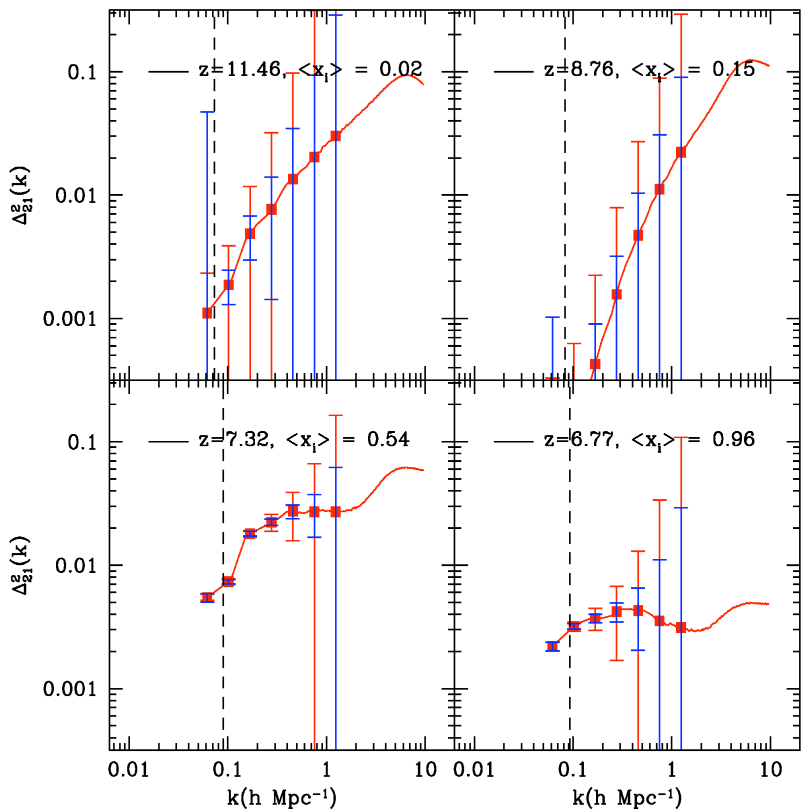
Murchison Widefield Array

- 500 antenna tiles
- Each tile is 16 dipole antennas in 4m x 4m grid.
- 80-300 Mhz
- ~ 800 deg^2 field of view
- 32 Mhz instantaneous bandwidth

Bowman et al. (2007)

MWA Sensitivity

- t_int = 1,000 hrs., B=6 Mhz
- Signal largest when <x>~0.5.
- Sky brightness, detector noise scale like T_sky ~ (1+z)^2.6!
- Hard to detect early reionization activity!
- Instantaneous bandwith: delta_z ~ 2-3.



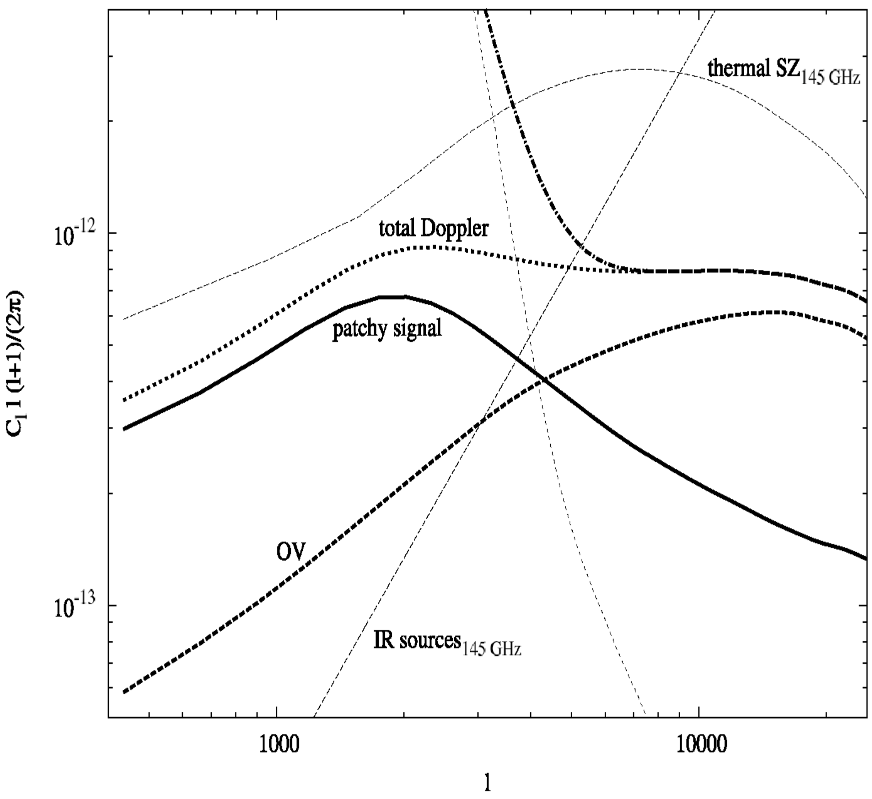
Lidz et al. (2007)

First Generation 21 cm Surveys

- Most direct, but many experimental challenges!
- Inferring <x>(z) from first observations will not be completely straightforward.
- Signal generally largest when <x>~0.5.
- Will not have sensitivity to detect z >~ 10-12 or so IGM.
- First observations over limited delta_z.

Secondary Anisotropies from Reionization

- Patchy reionization produces "Doppler Effect" induced anisotropy.
- Need to separate low redshift (non-linear) Ostriker-Vishniac contribution.
- Point source contamination.

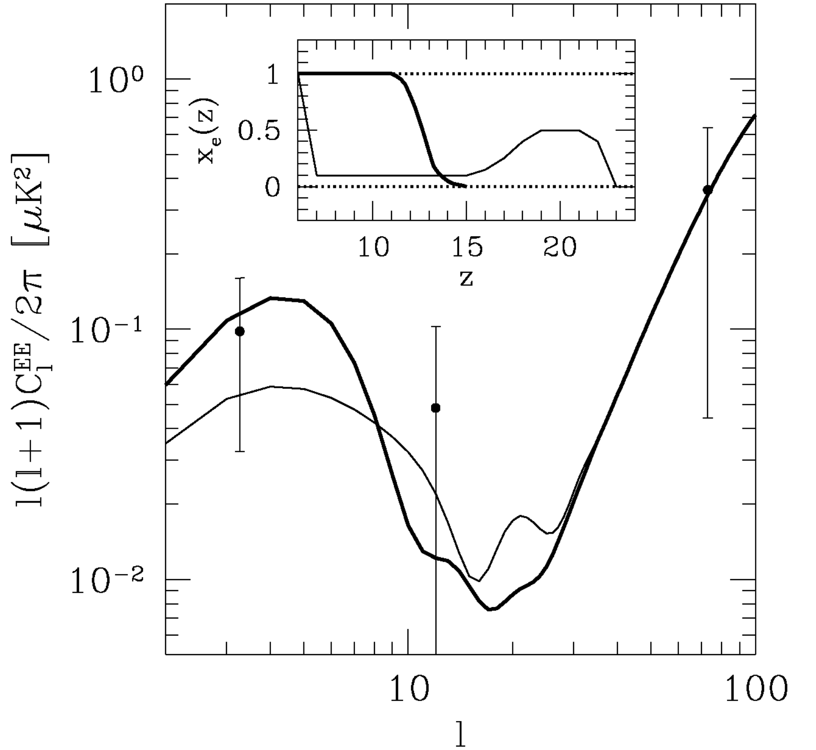


Zahn et al. 2005

CMB Polarization

- l ~ 5-10 for z_r~6-15
- More than just tau!
- Ionization at higher z, more EE power at larger l.

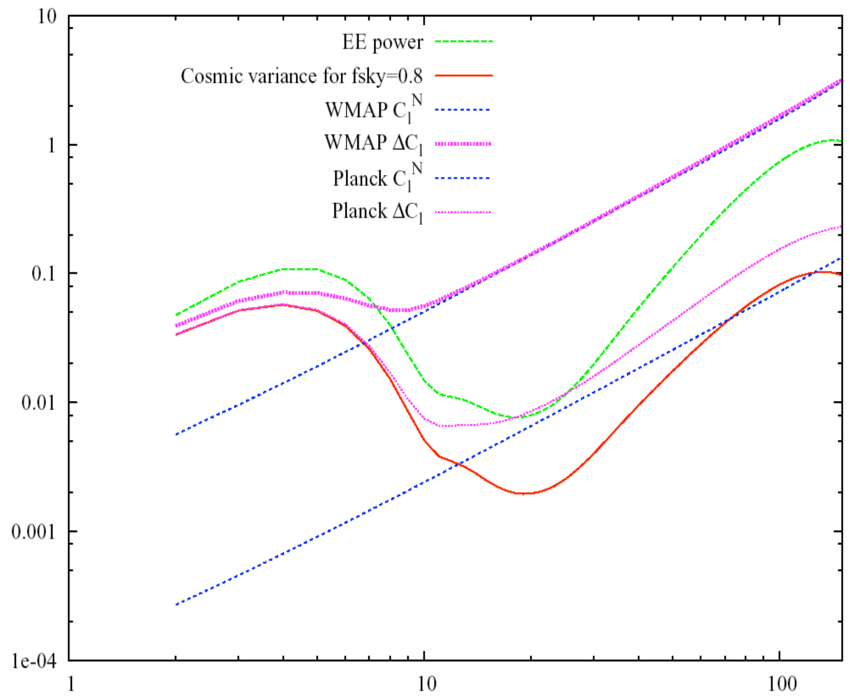
(Kaplinghat et al. 2003, Holder et al. 2003, Mortonson & Hu 2007, Colombo & Pierapoli 2008)



Mortonson & Hu (2007)

CMBpol Role?

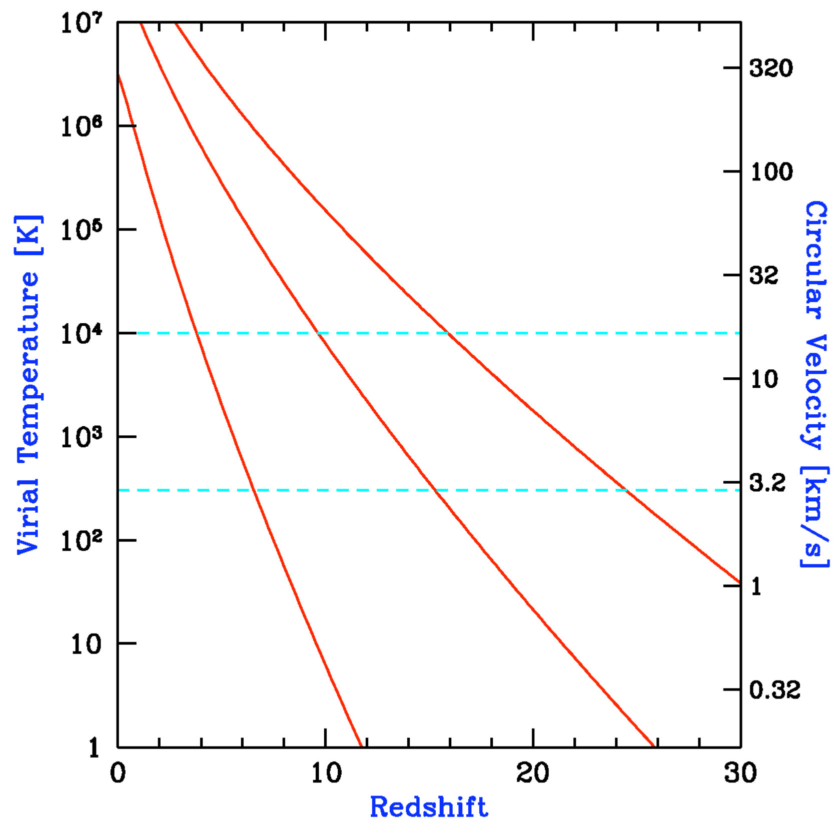
- Planck should be cosmic-variance limited below l<~10 or so.
- CMBpol can help with l~10-40 -- help constrain very early ionization, say z~15-30.
- No other reionization probe will touch this epoch soon!



O. Zahn

Theoretical Expectations?

- Most interesting tau~0.10 case for CMBpol is “double reionization” with early z~20 peak, and rapid end near z~6.
- Extended, but monotonic: less additional info beyond Planck. Quantify?
- This “double reionization” is unlikely, but “There are more things in heaven and earth, Horatio, Than are dreamt of in your philosophy!”



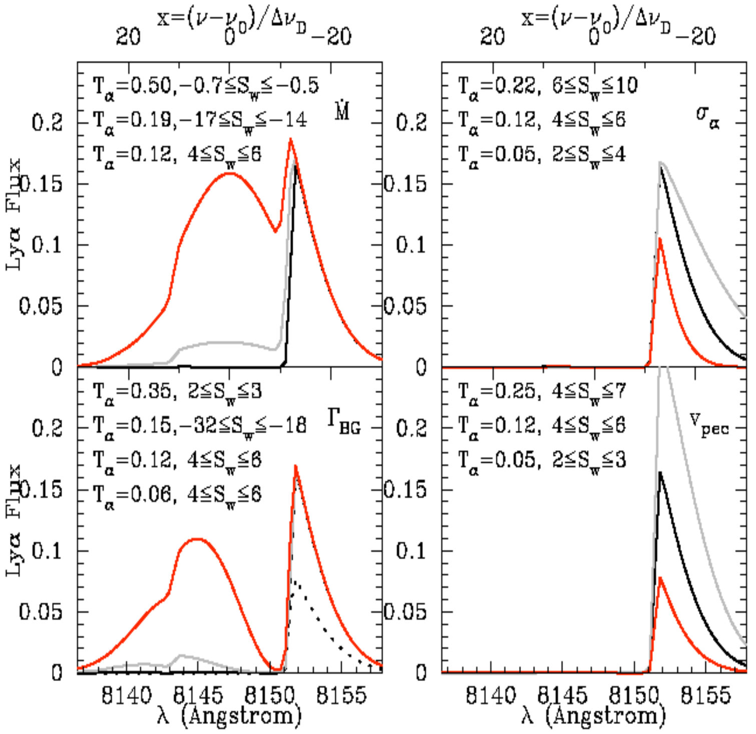
Barkana & Loeb (2001)

Conclusions

- Many upcoming observations/theoretical work!
- We won't know everything that we would like to about reionization from other probes by the time CMBpol flies.
- Might help with $\langle x \rangle(z)$, particularly if there is a very early stage in the reionization history.
- *Complementarity*: other probes will be best at finding neutral gas just above $z > \sim 6$. CMBpol can help constrain earlier phases.

Lyman-a Emission Lines

- Semi-analytic model for shape of high-z Ly-a lines.
- Shape of line depends on SFR, photo-ionizing background, intrinsic width, winds, etc…



Dijkstra, AL et al. 2007