Testing Reionization with Lyman-α Galaxies

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Drawing on collaborations with

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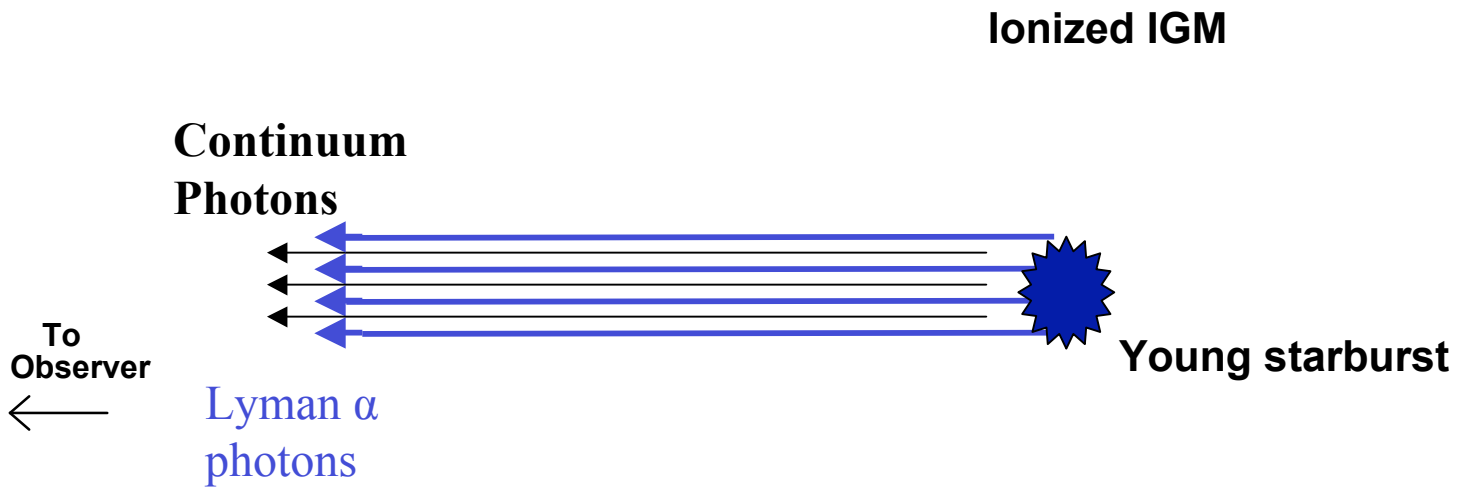
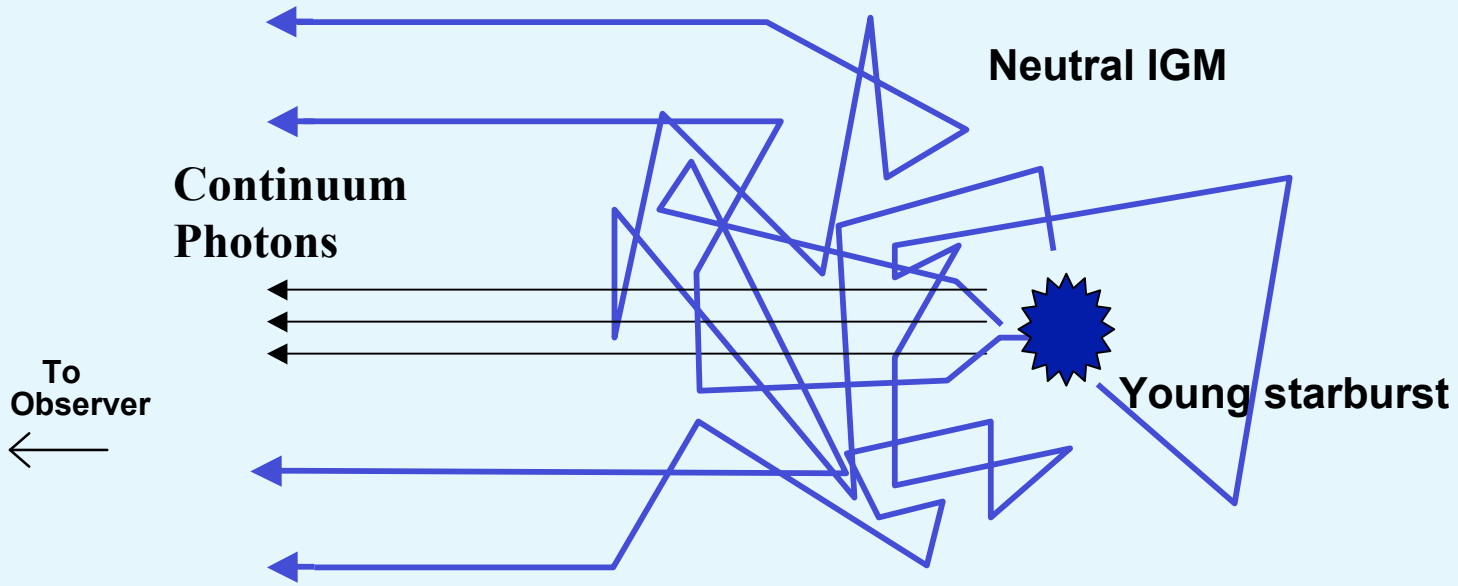
The Lyman-α ReionizationTest

Radiative transfer of Lyman-α and continuum photons in an ionized intergalactic medium.



The Lyman-α Reionization Test

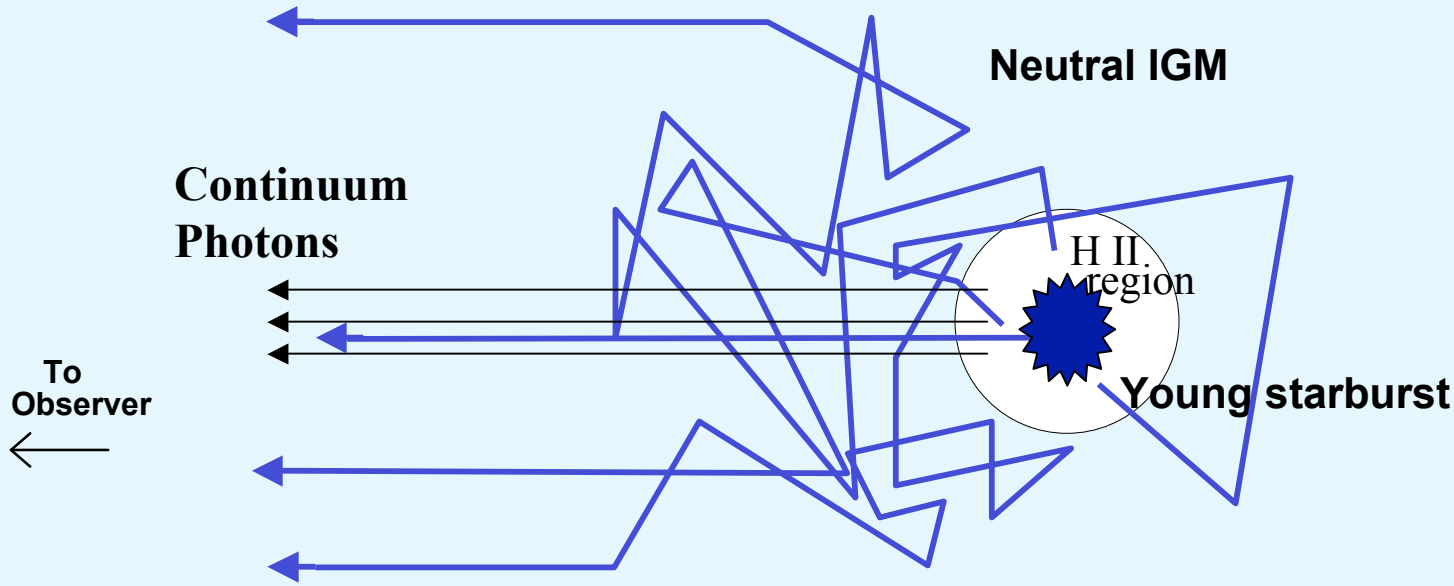
Radiative transfer of Lyman-α and continuum photons in a neutral intergalactic medium.



(Theory: Miralda-Escude 1998; Miralda-Escude & Rees 1998; Haiman & Spaans 1999; Loeb & Rybicki 1999;

Observation: Rhoads & Malhotra 2001, Hu et al 2002, Malhotra & Rhoads 2004, Stern et al 2004, Kashikawa et al 2006, Malhotra & Rhoads 2006…)

The Lyman α Test… Pesky Details!



- Some flux comes through if the starburst is in a substantial HII region (Madau & Rees 1999; Rhoads & Malhotra 2001; Haiman 2002).
- The red wing of the line is less suppressed (Haiman 2002).
- Gas motions alter Ly-α radiative transfer (Santos 2004).

Lyman α Test Details

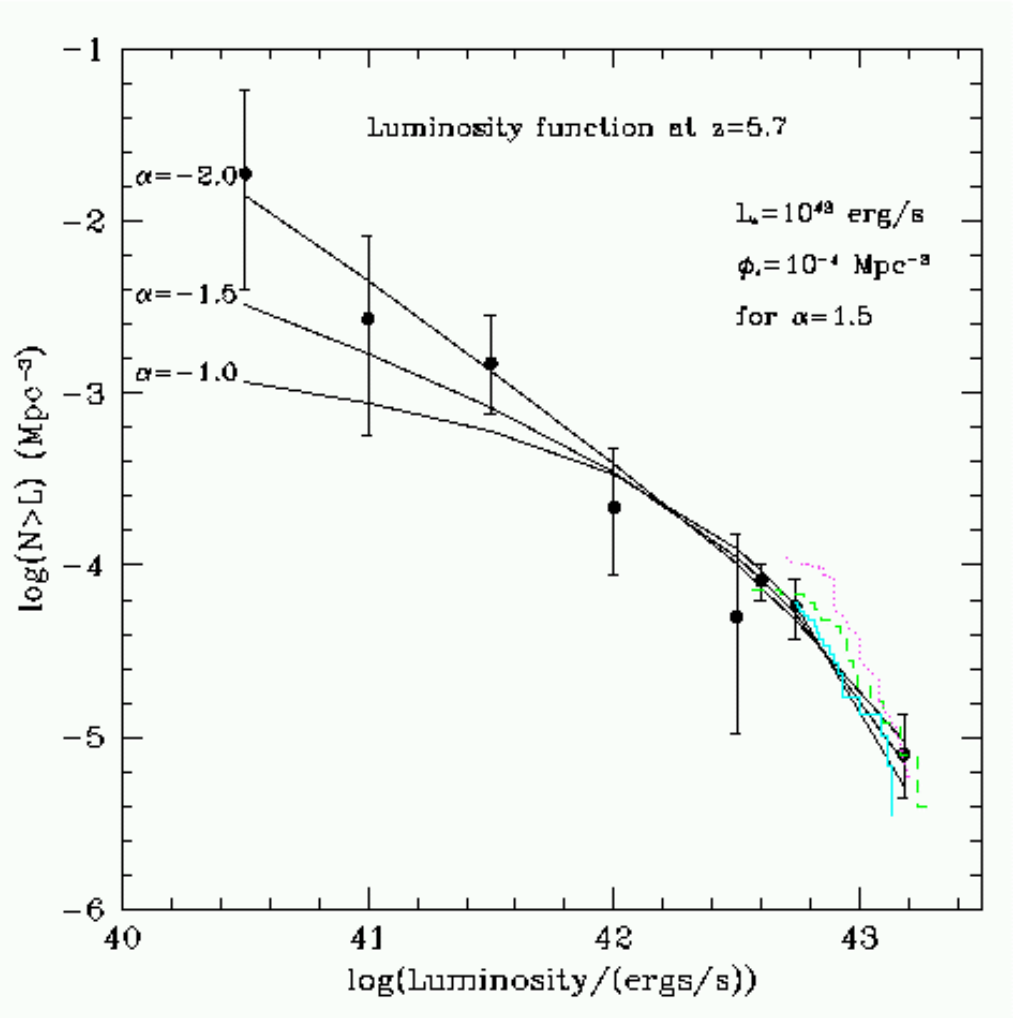
- **Bottom line**: Factors of ~ 3 reduction in Ly-α luminosity are unavoidable in neutral universe. Reduction larger in many models but not all.

➔ ***The observed Ly-α Luminosity Function should change markedly at reionization.***

The Luminosity Function Test

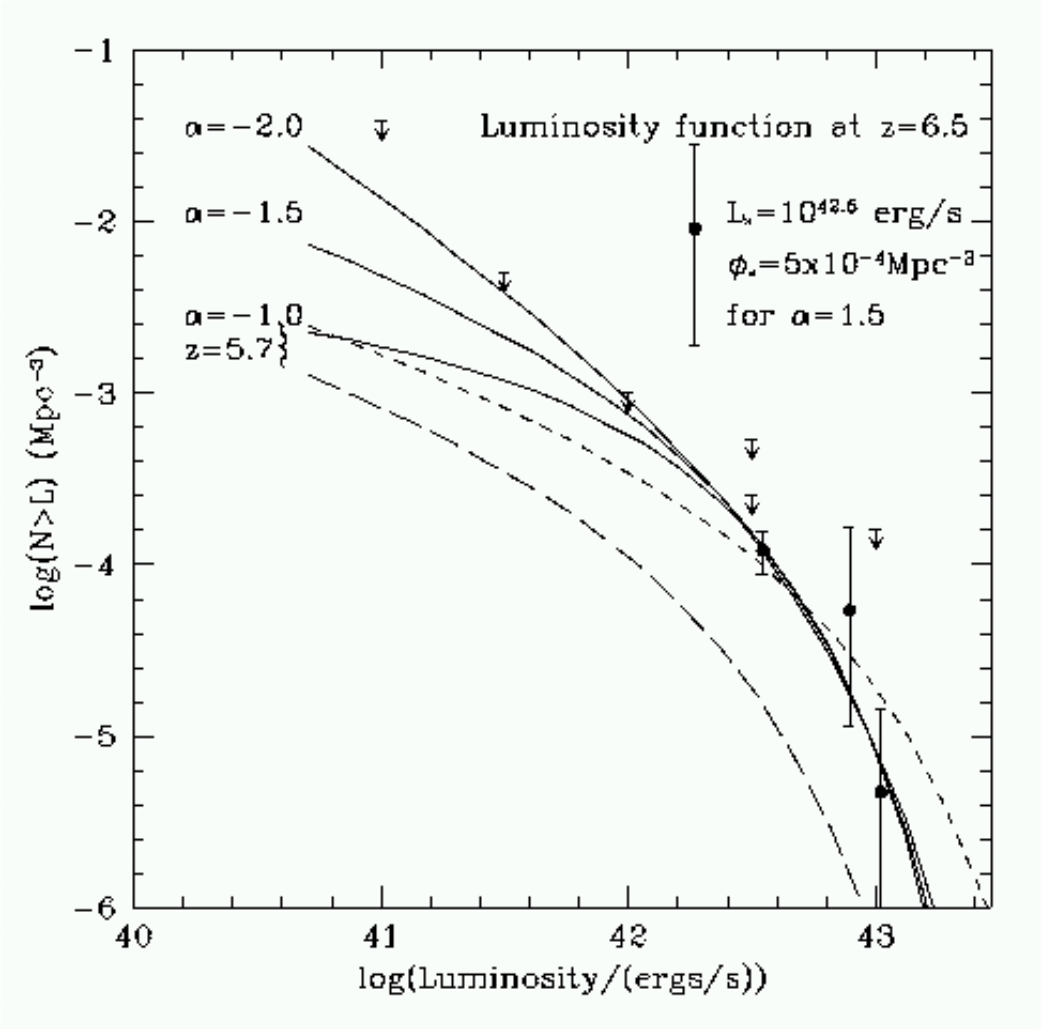
Malhotra & Rhoads 2004, *ApJ Letters* **617**, L5;
See also Stern et al 2005; Haiman & Cen 2005; Kashikawa et al 2006

- We constructed Ly-α luminosity functions at z=5.7 and z=6.5 from a variety of surveys (including work from LALA, Hu et al, Kodaira et al, Taniguchi et al, Santos et al, Ajiki et al, Tran et al, Martin & Sawicki.)
- Schechter function fits, with the faint end slope fixed and the L*, Φ* fitted by grid search.
- z = 5.7 fit for 3 faint end slopes (data: LALA, Santos et al, Hu et al, Ajiki et al.)



Lyman-α Luminosity Functions

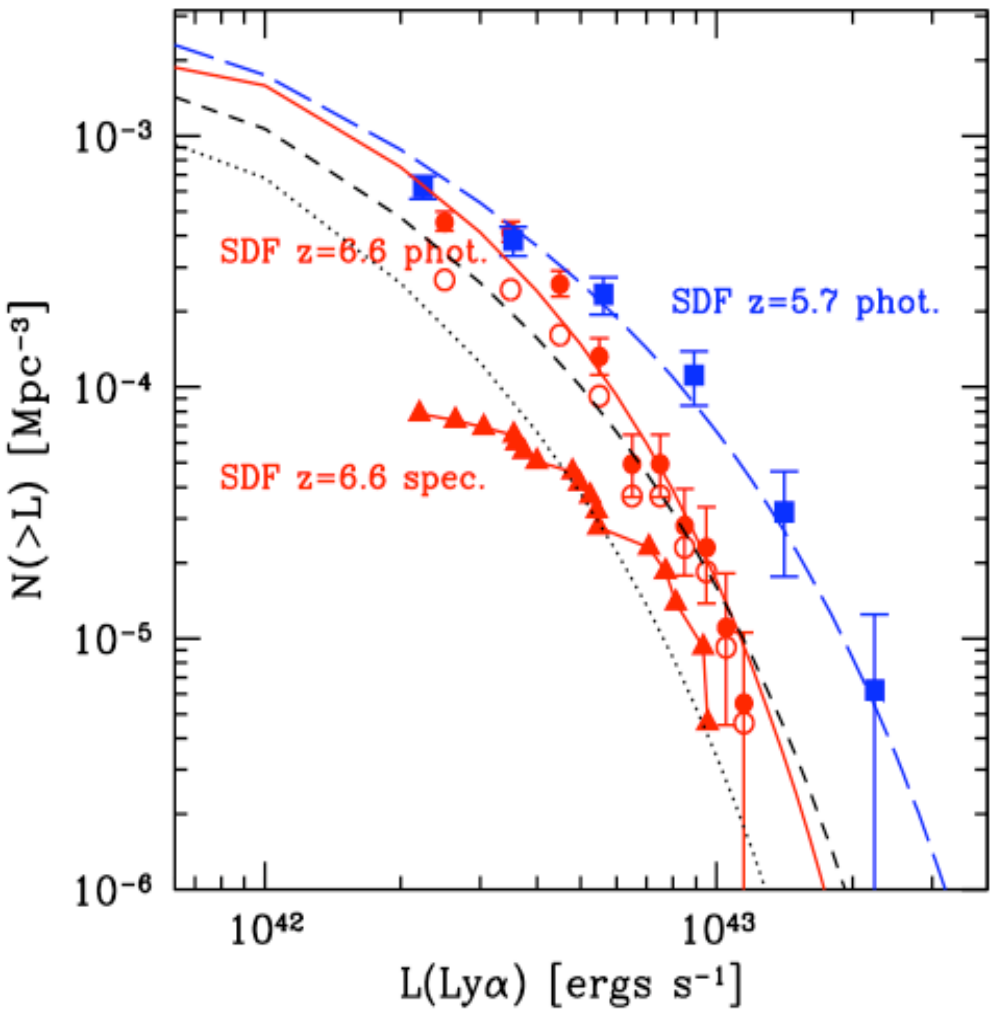
- Luminosity function fits for three faint-end slopes.
- z = 6.5 plot shows two null hypotheses:
  - z = 5.7 LF, or
  - z = 5.7 LF reduced by a factor of 3 in luminosity to approximate IGM absorption.
- ***No evidence for neutral IGM!***



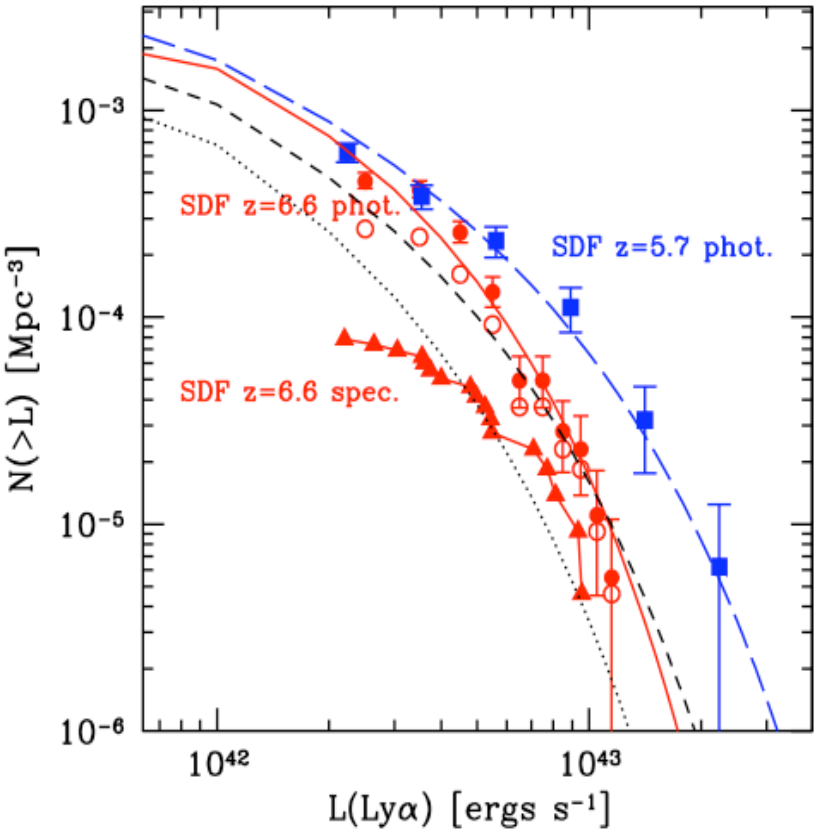
Malhotra & Rhoads 2004, *ApJ Letters* **617**, L5

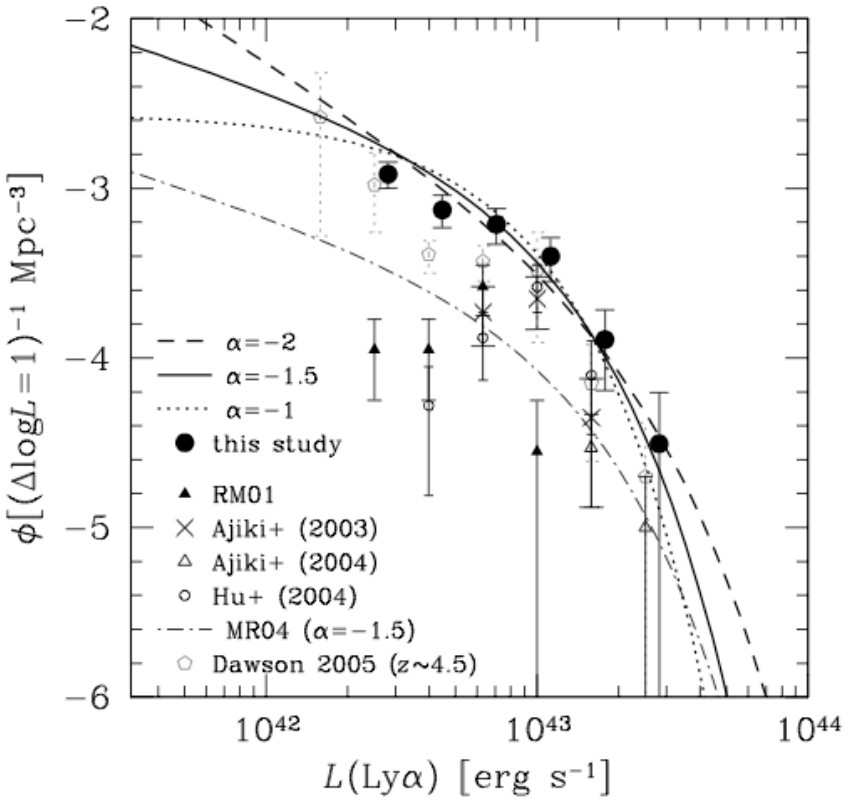
Ly-α Luminosity Functions Revisited

- Shimasaku et al (2006), Kashikawa et al (2006), Ota et al (2008), Ouchi et al (2008) have revisited the LyA luminosity functions at z=5.7, z=6.5 and z=6.9.
- Find apparent bright end evolution. Interpretation:
  - Neutral IGM? But: LF shape change not as expected
  - True LF evolution (Dijkstra et al 2007)?
  - Field to field variations?



Ly-α Luminosity Functions Revisited





The z=5.7 LF from Shimasaku et al is the highest yet observed.

If we compared z=6.5 from K06 to any other z=5.7 LF, the difference would be smaller... Field to field variations?

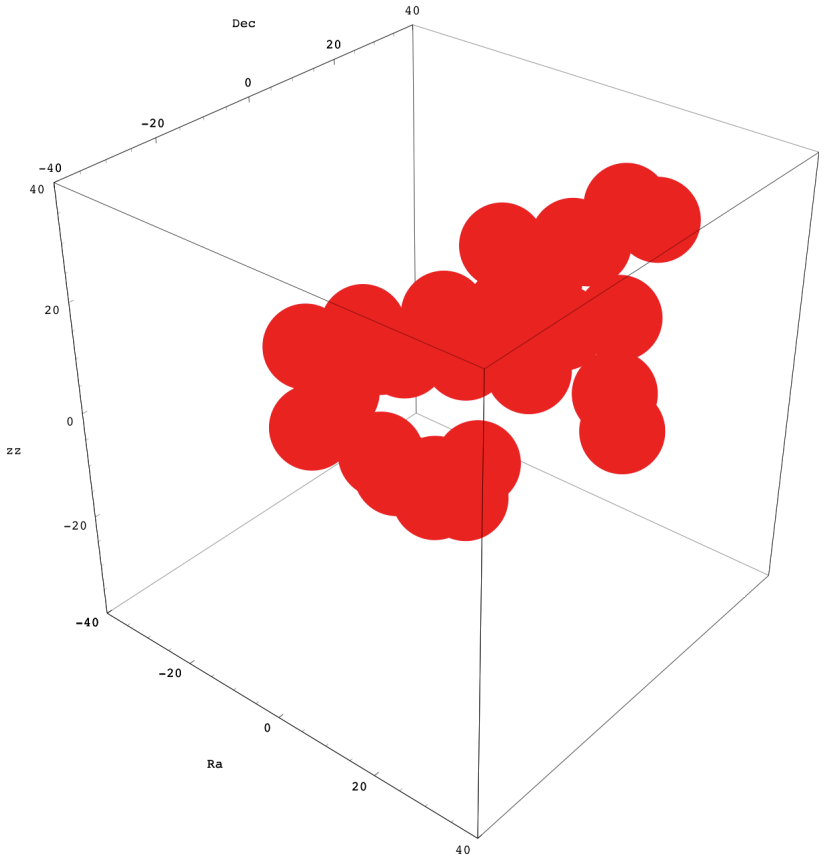
The volume test:

(Malhotra & Rhoads, 2006)

Suppose each Lyman-α emitter is visible because of a local Stromgren sphere, created by neighboring undetected dwarf galaxies, hidden AGNs, decaying dark matter…

- We know the space density of Lyman-α galaxies at z=6.5:

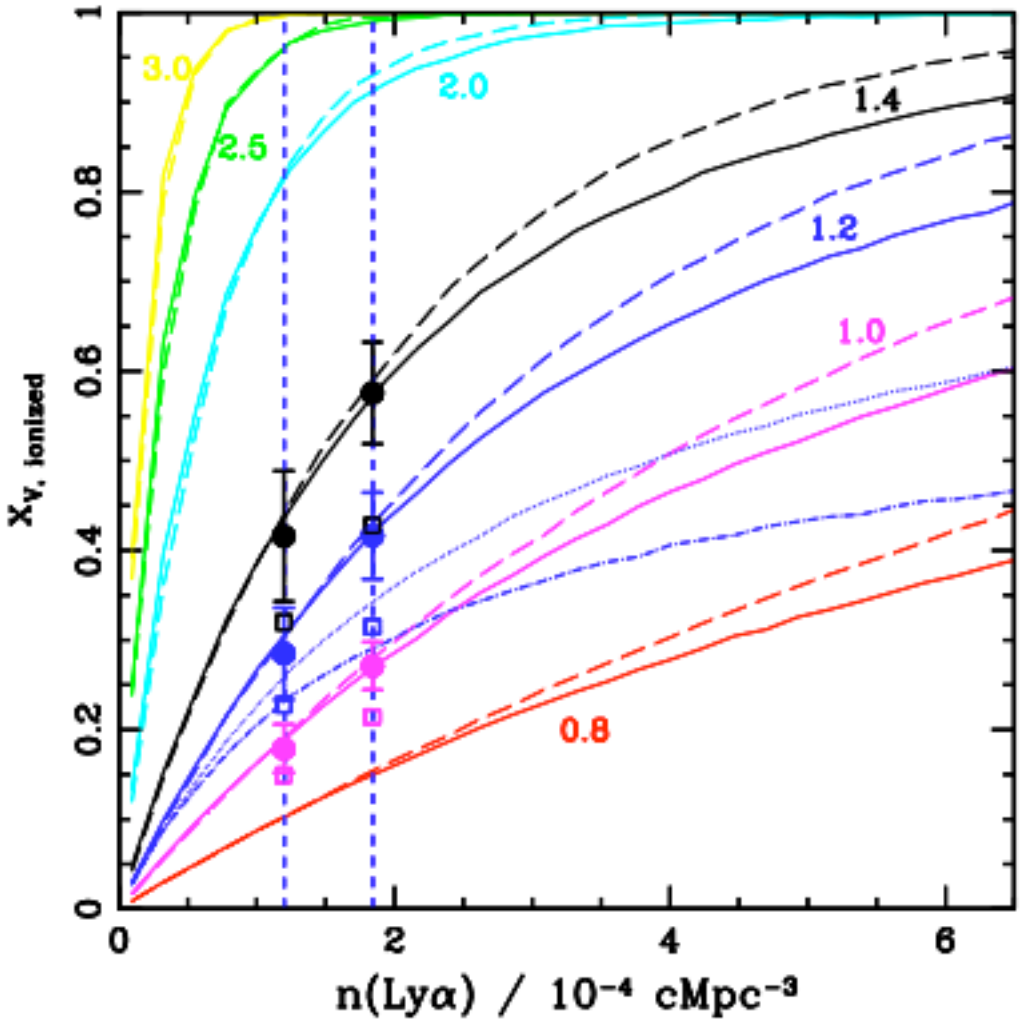
  $n > 1 \times 10^{-4}$ cMpc^{-3} (Taniguchi et al. 2005)
- Place each in the smallest ionized bubble that allows half the line flux to escape
  - $V_{HII} > 4\pi R_{ss}^3 / 3$
- Get a filling factor: $f = n V_{HII}$
- The neutral fraction is then exp(-f), and ionized fraction is then 1 - exp(-f).
- Correlations modify this modestly.
- **Bottom Line: 30% ionized is a conservative lower bound at z=6.5.**



The Volume Test - more details

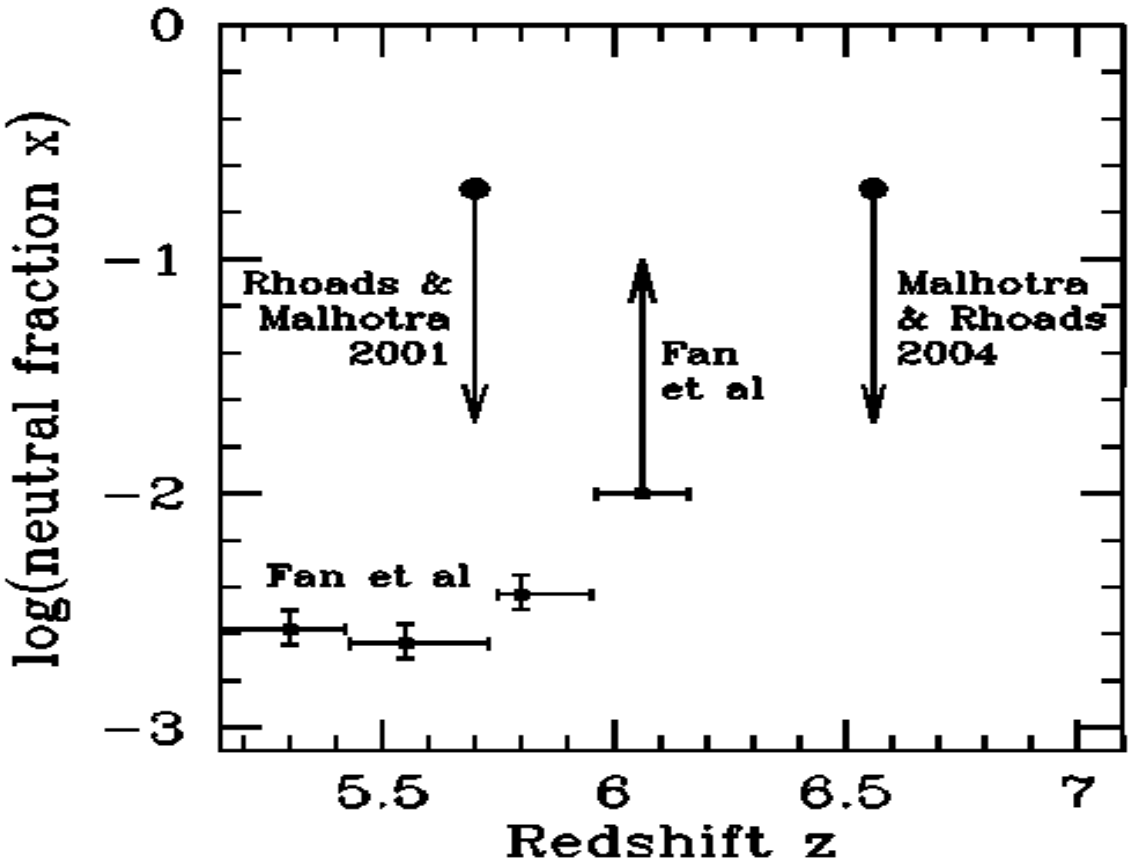
- Bottom line for volume test at z=6.5.
- Each curve color corresponds to a particular ionized bubble radius.
- Each line style to a particular correlation length.
- 30% is a conservative lower bound at z=6.5.

- See Malhotra & Rhoads 2006 for more details… ApJ Letters 647, L95.



Charting Reionization

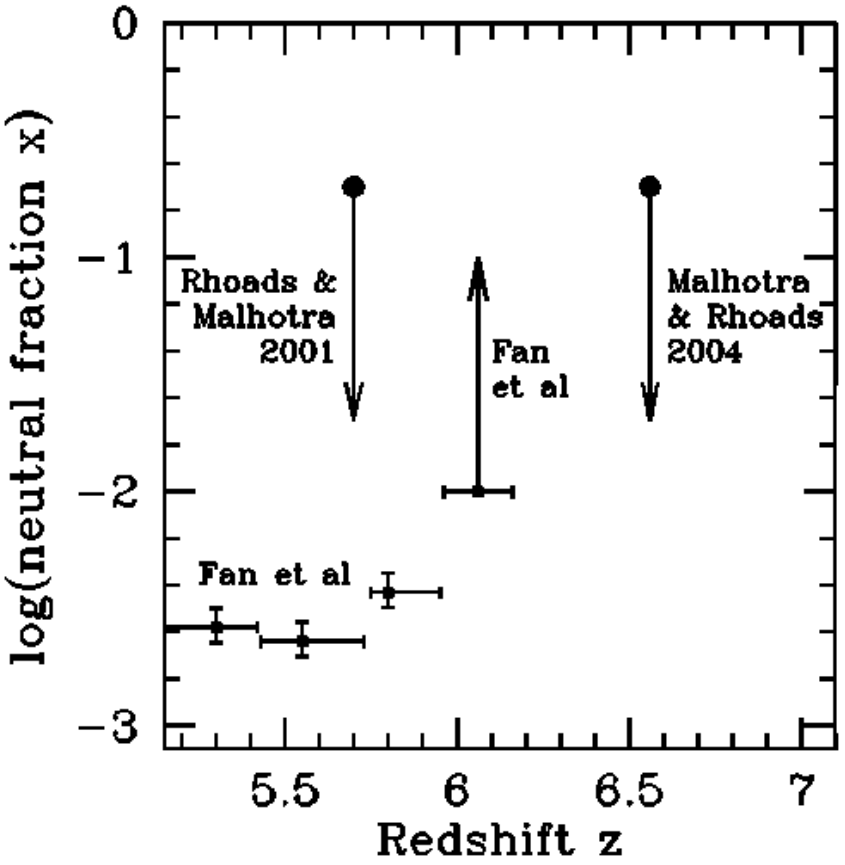
Current evidence: Combine the Lyman α, Gunn-Peterson, and dark gap statistic tests (Fan et al 2006) to study the evolution of the mass averaged neutral fraction, x:

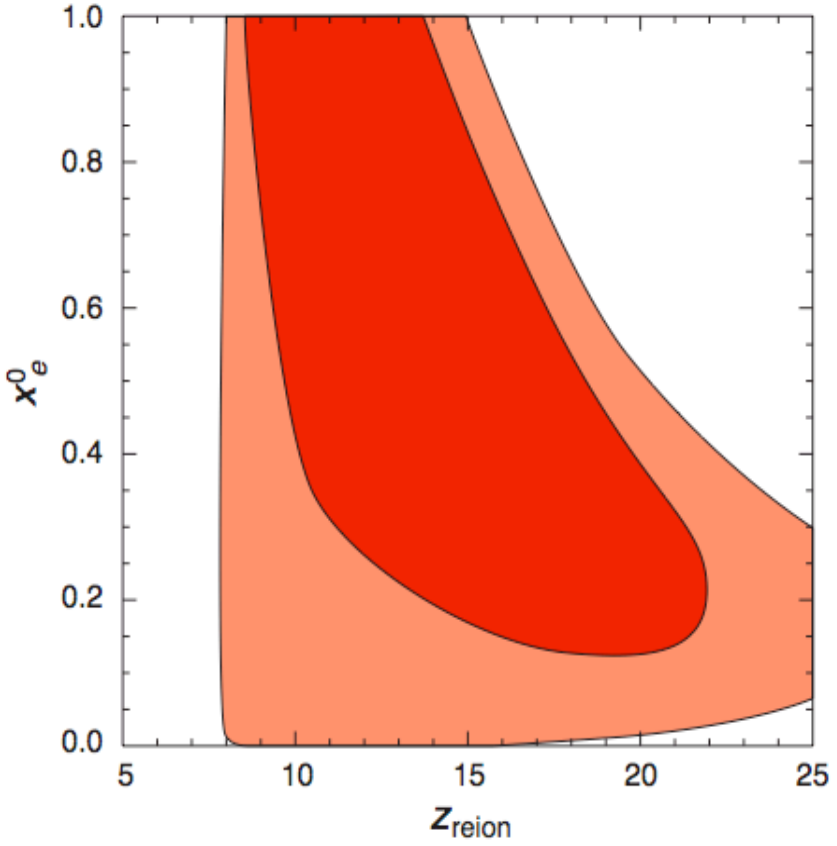


There is no contradiction between the GP effect at z=6.2 and the Ly α at z=6.5.

Charting Reionization

Now add in the WMAP results (fig 3 from Spergel et al 2006). Model constraints for step function reionization: Ionized fraction x^0_e for $7 < z < z_{reion}$; 68% and 95% confidence regions. (The allowed parameter space from 5 year WMAP is smaller than the 3 year WMAP results shown here.)





Extension to redshifts z > 7

- Windows in the atmospheric OH spectrum continue into the J and H bands, though narrower.
- Newest NIR cameras have AΩ sufficient for plausible Ly-α searches.
- Several efforts under way…
  - Horton et al 2004 (DAzLE project): VLT + DAzLE, z ~ 7.7
  - Smith et al (see Barton et al 2004): Gemini + NIRI, z ~ 8.2
  - Willis et al ("ZEN" project): VLT +ISAAC, z ~ 8.8
  - Cuby, Hibon, et al: VLT+ISAAC, z ~ 8.8; CFHT+WIRCAM, z~7.7
  - Nilsson, Fynbo, et al: VISTA + NB, z ~ 8.8
  - Veilleux, Rhoads, Malhotra, et al: KPNO 4m + NEWFIRM, z ~7.7

Spatial Correlations and Reionization

- We can map ionized bubbles by studying the Lyα galaxy distribution.
- Patches of neutral and ionized gas will cause a patchy Lyα galaxy distribution. *This offers another reionization test.*
- Furlanetto et al (2005) explored this test using an analytic model of reionization.
- McQuinn et al (2007, astro-ph/0704.2239) explored it using cosmological simulations.
  - **Comparing to Subaru SDF results, they conclude that a fully ionized universe is favored.**
  - Presently a 2σ result; will improve with larger data sets.

Summary

- Lyman-α galaxies afford a test of reionization that is sensitive to neutral fractions ~ 30 - 50%.
- Three versions of this test have now been applied: Luminosity function comparison (MR04, Stern et al '05, Kashikawa et al '06), the volume test (MR06), and the strength of spatial correlations (McQuinn et al '07).
- ***Lyman α tests generally indicate a universe that was largely ionized by z=6.5***.
- The loopholes are being closed one by one… e.g., faint neighbors are not likely to give us a biased result.
- Extensions to $7 < z < 10$ under way.
- We can *map* bubbles in the IGM using Lyman-α galaxies.

Where to find me later…

ASU Arizona State University

School of Earth and Space Exploration

- A growing concern in Astronomy…
- Astro Faculty: Desch, Hester, Malhotra, Rhoads, Scannapieco, Starrfield, Timmes, Windhorst, Young
- Planetary / solar system: Christiansen, Greeley, Robinson, Wadhwa.
- 25 assorted geologists, 5 engineers.
- Access to Arizona telescope system, with facilities on four mountains in southern Arizona, plus Magellan in Chile.
- (LBT, MMT, Bok, Magellan, Catalina mountains)