

# Testing Reionization with Lyman- $\alpha$ Galaxies

James E. Rhoads

(Arizona State University)

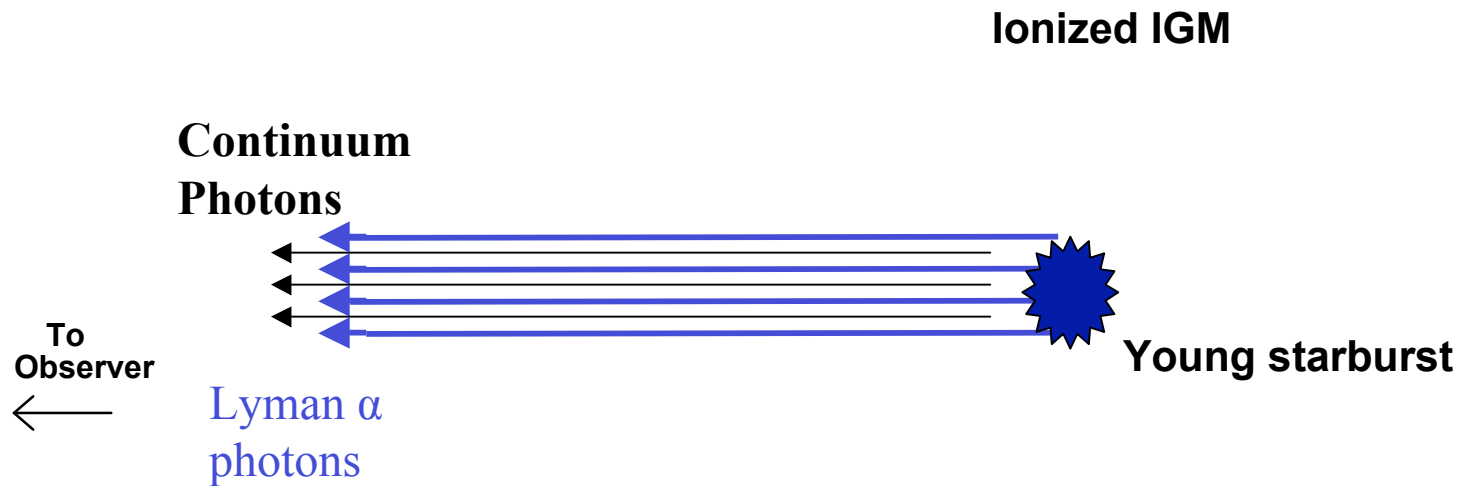
*Paris, 8 July 2008*

Drawing on collaborations with  
Sangeeta Malhotra, Junxian Wang,  
Steve Dawson, Arjun Dey, Steven Finkelstein, Buell  
Jannuzi, Katarina Kovac, Hy Spinrad, Dan Stern, Chun  
Xu, V. S. Tilvi, Ilian Iliev, Garrelt Mellema, Evan  
Scannapieco, and Sylvain Veilleux, and others.



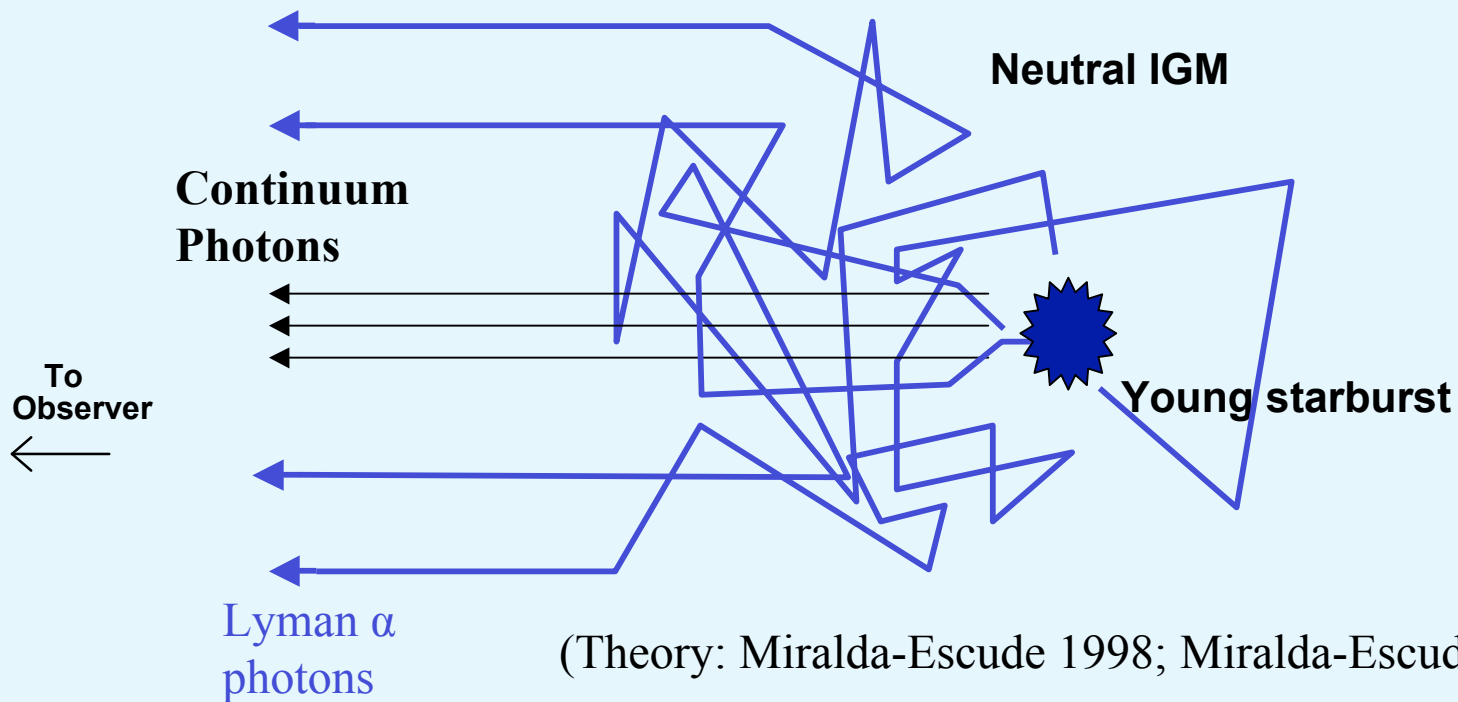
# The Lyman- $\alpha$ Reionization Test

Radiative transfer of Lyman- $\alpha$  and continuum photons in an ionized intergalactic medium.



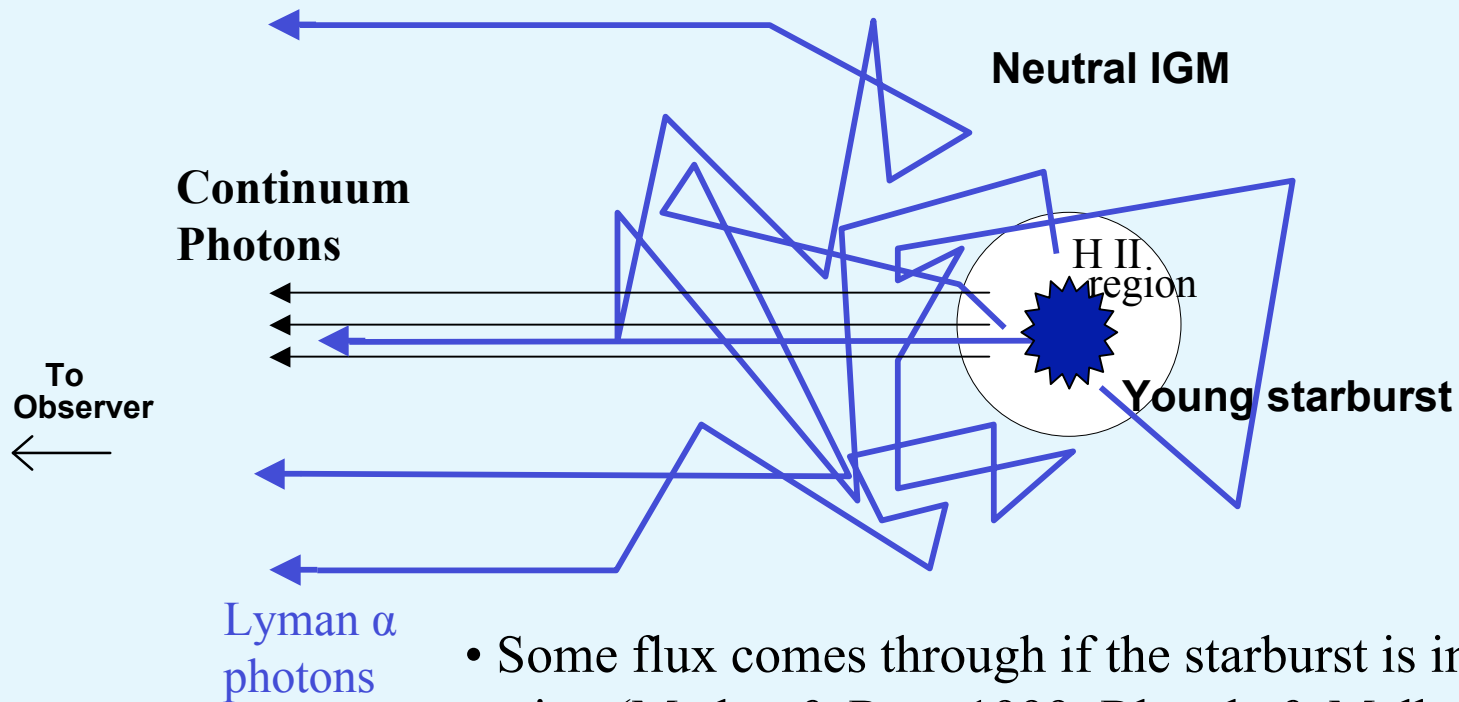
# The Lyman- $\alpha$ Reionization Test

Radiative transfer of Lyman- $\alpha$  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 $\alpha$ 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- $\alpha$  radiative transfer (Santos 2004).

# Lyman $\alpha$ Test Details

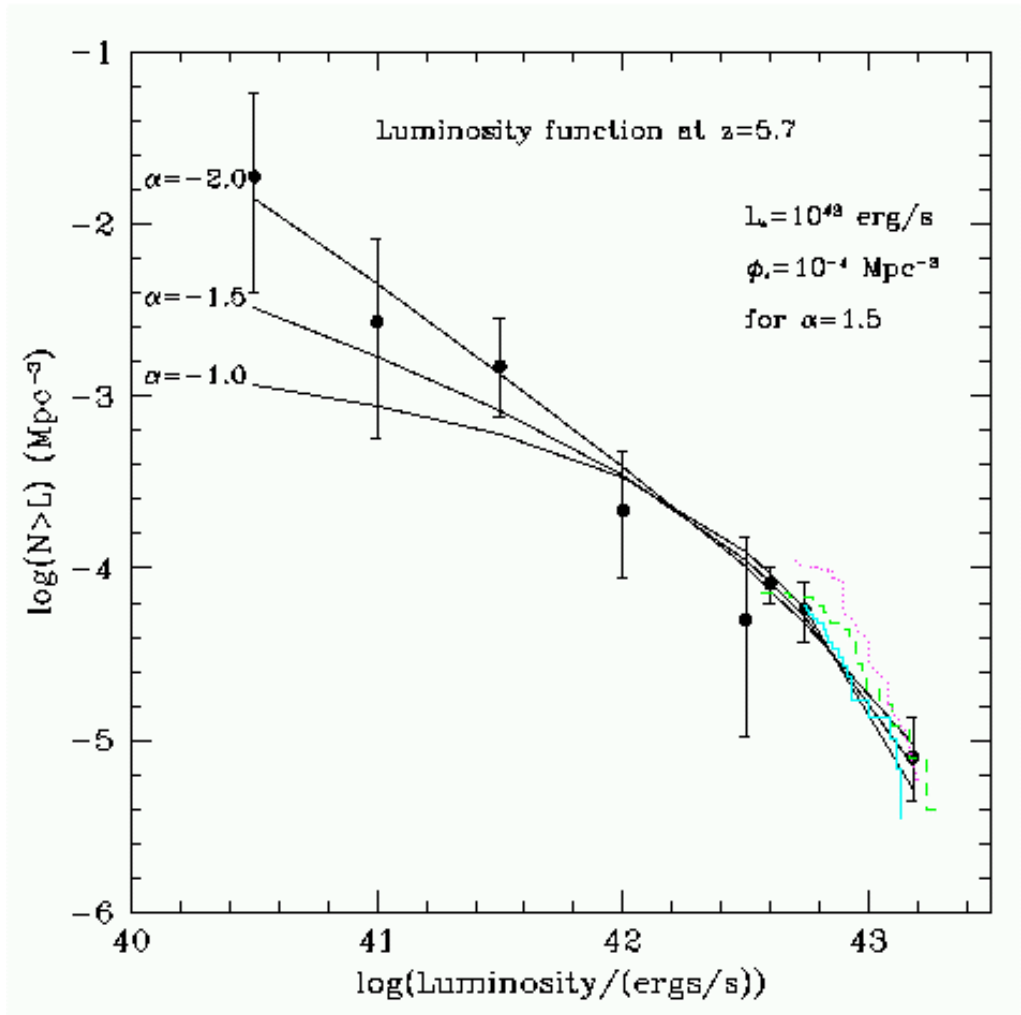
- **Bottom line:** Factors of  $\sim 3$  reduction in Ly- $\alpha$  luminosity are unavoidable in neutral universe. Reduction larger in many models but not all.  
**→ *The observed Ly- $\alpha$  Luminosity Function should change markedly at reionization.***

# The Luminosity Function Test

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

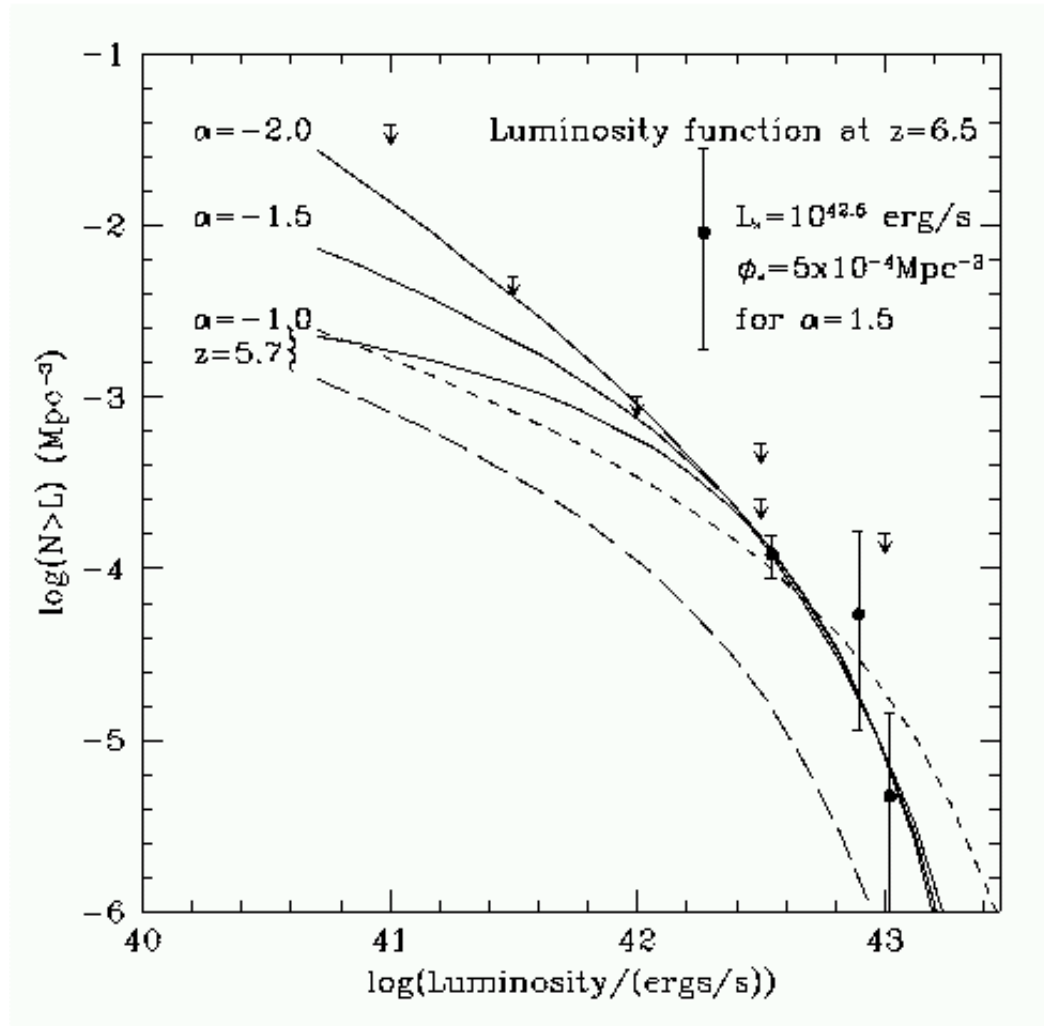
See also Stern et al 2005; Haiman & Cen 2005; Kashikawa et al 2006

- We constructed Ly- $\alpha$  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  $L^*$ ,  $\Phi^*$  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- $\alpha$ Luminosity Functions

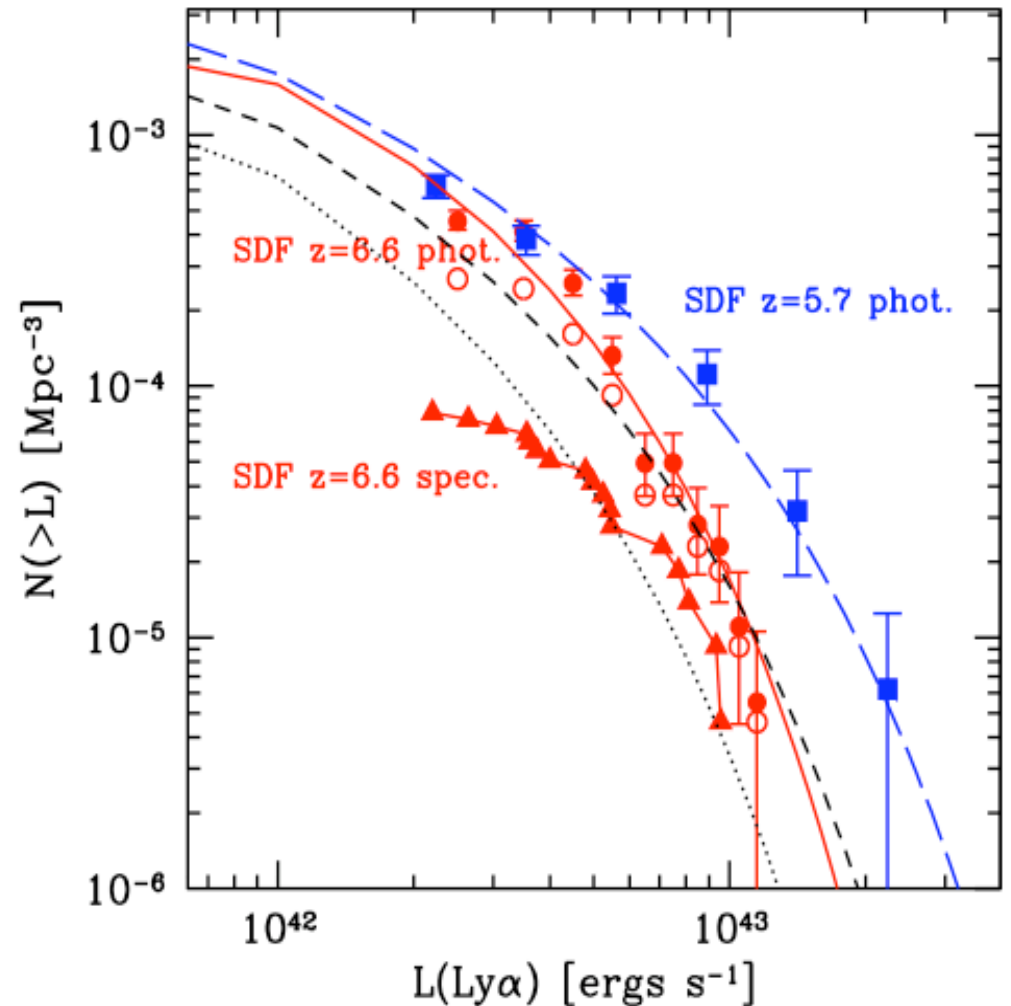
- Luminosity function fits for three faint-end slopes.
- $z = 6.5$  plot shows two null hypotheses:
  - $z = 5.7$  LF, or
  - $z = 5.7$  LF reduced by a factor of 3 in luminosity to approximate IGM absorption.
- ***No evidence for neutral IGM!***



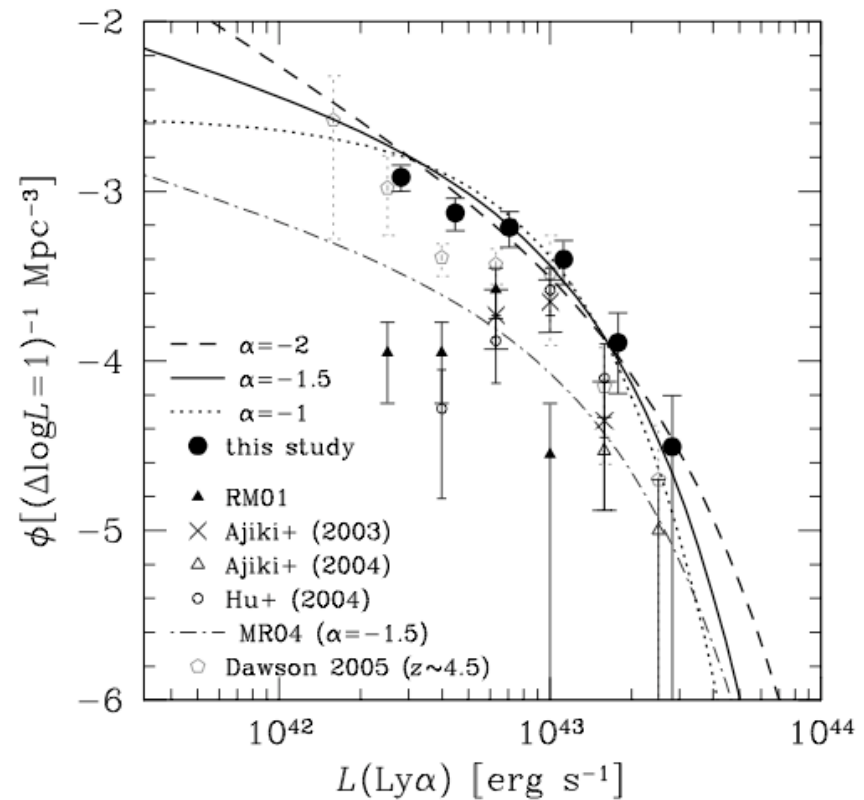
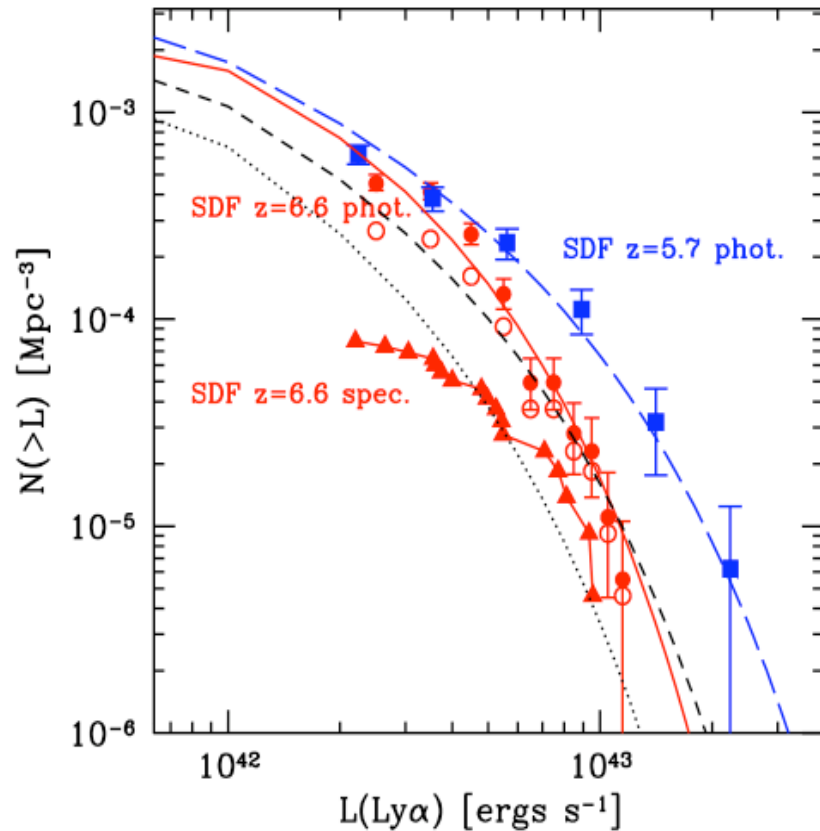
Malhotra & Rhoads 2004, *ApJ Letters* **617**, L5

# Ly- $\alpha$ 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- $\alpha$ Luminosity Functions Revisited



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

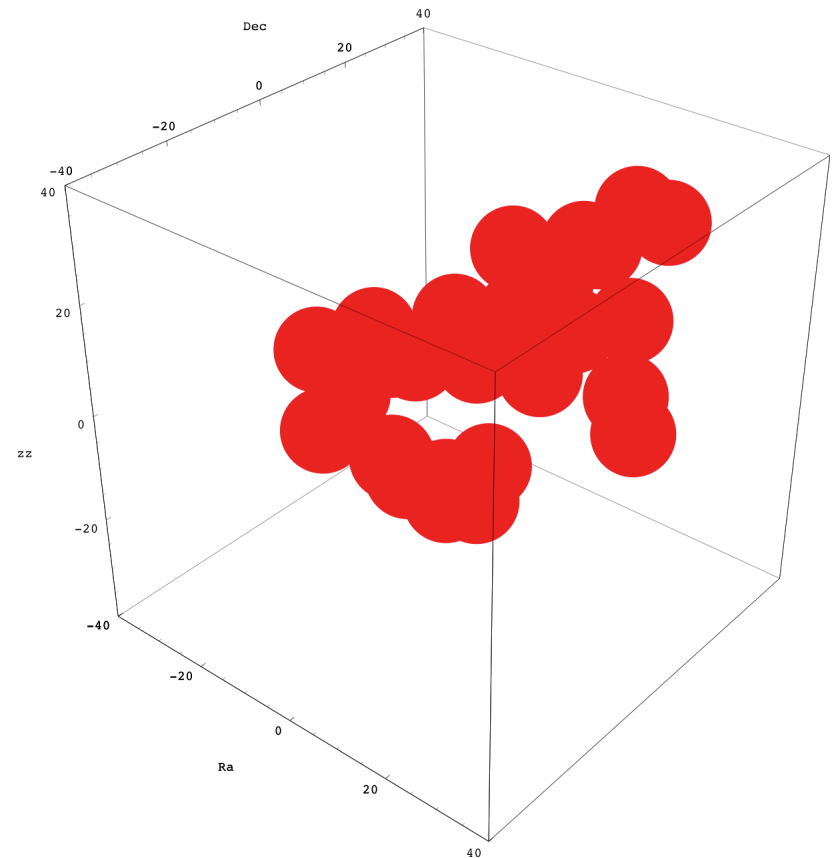
If we compared  $z=6.5$  from K06 to any other  $z=5.7$  LF, the difference would be smaller... Field to field variations?

# The volume test:

(Malhotra & Rhoads, 2006)

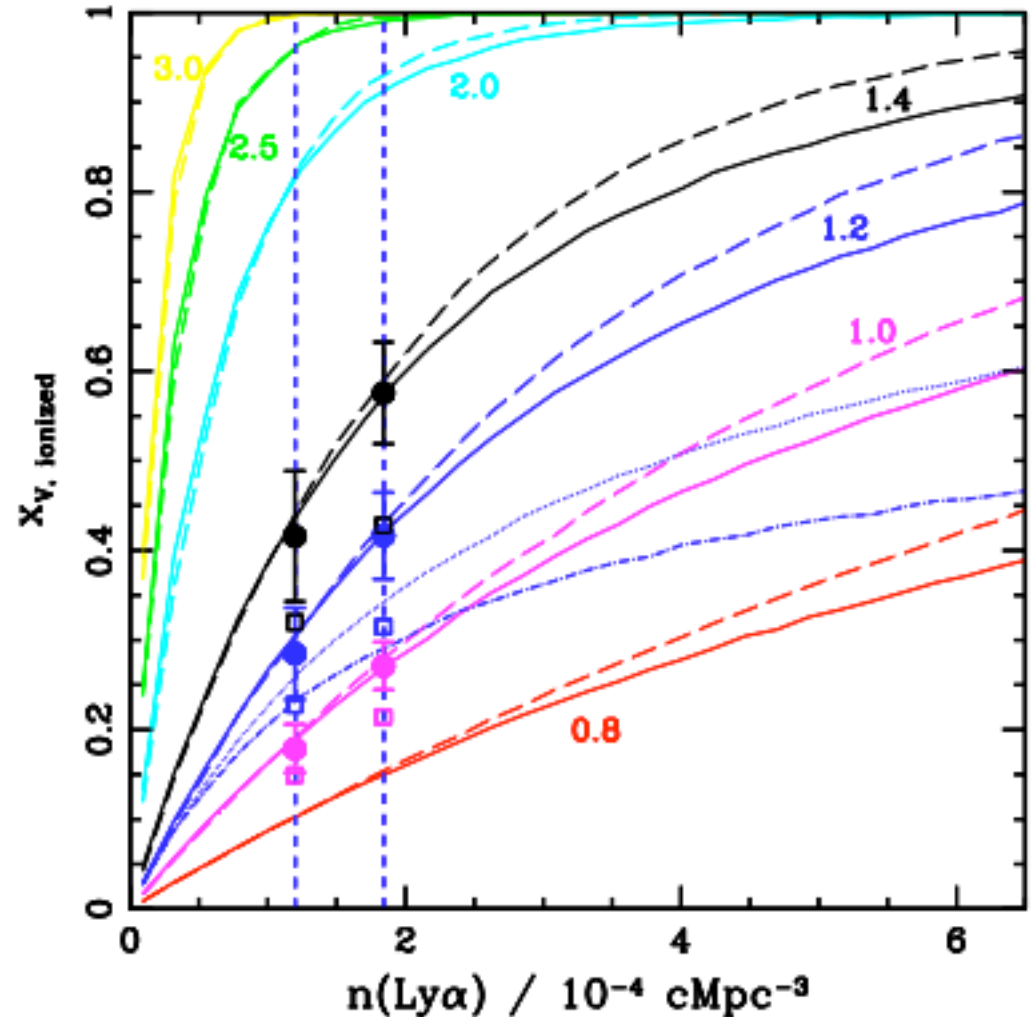
*Suppose each Lyman- $\alpha$  emitter is visible because of a local Stromgren sphere, created by neighboring undetected dwarf galaxies, hidden AGNs, decaying dark matter...*

- We know the space density of Lyman- $\alpha$  galaxies at  $z=6.5$ :  
 $n > 1 \times 10^{-4} \text{ cMpc}^{-3}$  (Taniguchi et al. 2005)
- Place each in the smallest ionized bubble that allows half the line flux to escape
  - $V_{\text{HII}} > 4\pi R_{\text{ss}}^3 / 3$
- Get a filling factor:  $f = n V_{\text{HII}}$
- 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  $z=6.5$ .**



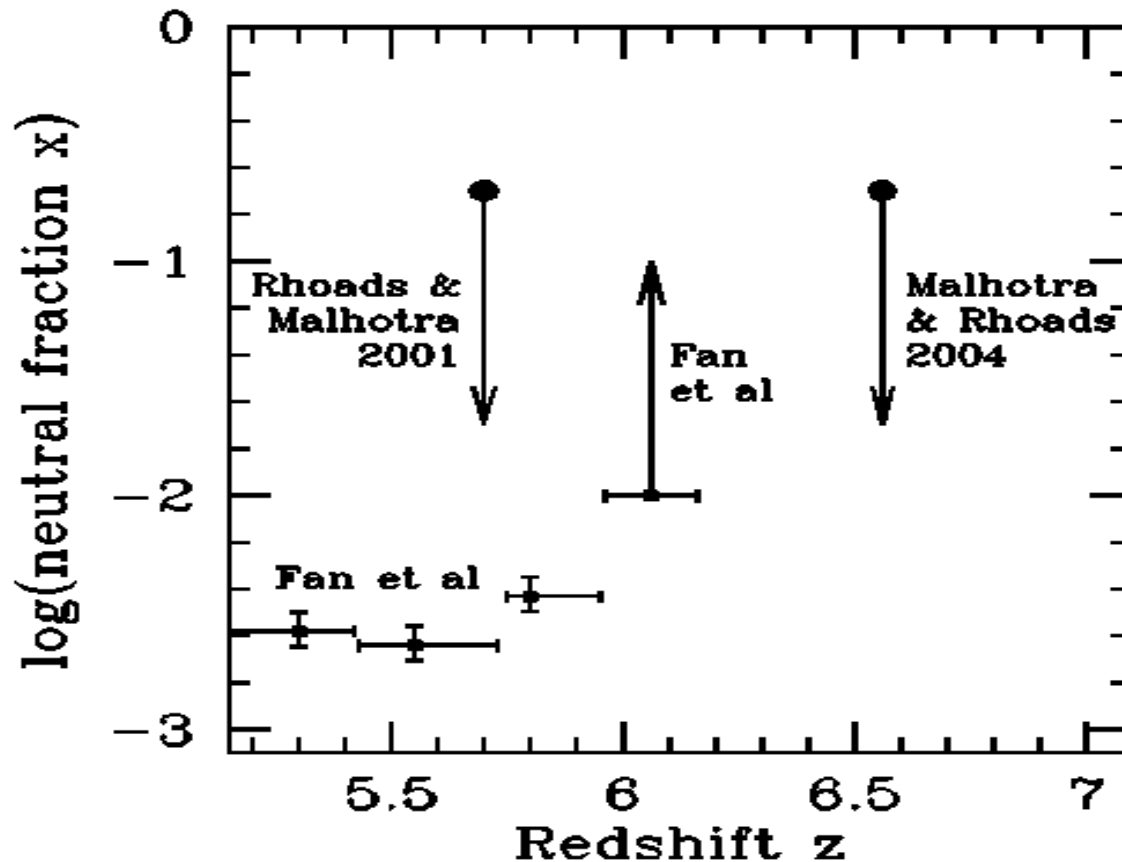
# The Volume Test - more details

- 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

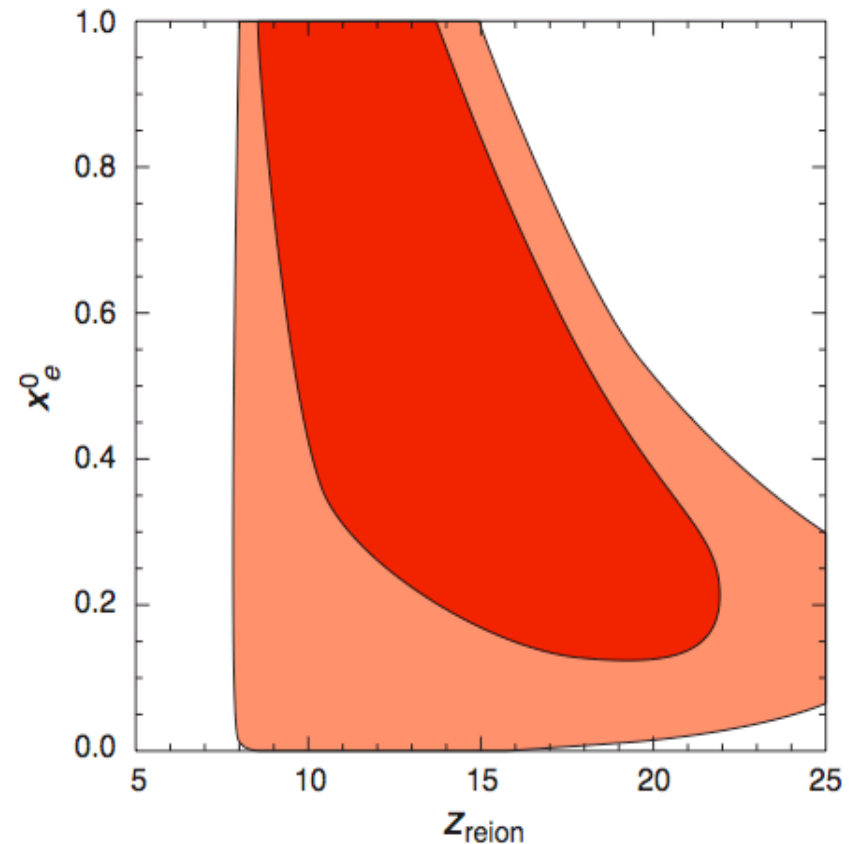
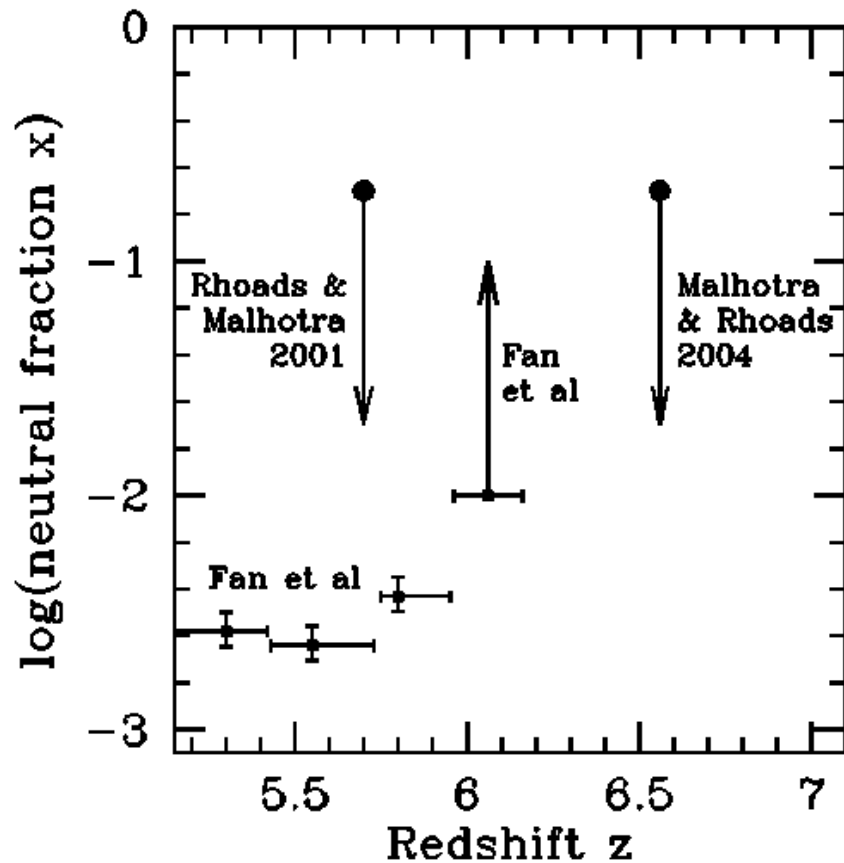
Current evidence: Combine the Lyman  $\alpha$ , Gunn-Peterson, and dark gap statistic tests (Fan et al 2006) to study the evolution of the mass averaged neutral fraction,  $x$ :



There is no contradiction between the GP effect at  $z=6.2$  and the Ly  $\alpha$  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  $x_e^0$  for  $7 < z < z_{\text{reion}}$ ; 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  $\Delta\Omega$  sufficient for plausible Ly- $\alpha$  searches.
- Several efforts under way...
  - Horton et al 2004 (DAzLE project): VLT + DAzLE,  $z \sim 7.7$
  - Smith et al (see Barton et al 2004): Gemini + NIRI,  $z \sim 8.2$
  - Willis et al (“ZEN” project): VLT +ISAAC,  $z \sim 8.8$
  - Cuby, Hibon, et al: VLT+ISAAC,  $z \sim 8.8$ ; CFHT+WIRCAM,  $z \sim 7.7$
  - Nilsson, Fynbo, et al: VISTA + NB,  $z \sim 8.8$
  - Veilleux, Rhoads, Malhotra, et al: KPNO 4m + NEWFIRM,  $z \sim 7.7$

# Spatial Correlations and Reionization

- We can map ionized bubbles by studying the Ly $\alpha$  galaxy distribution.
- Patches of neutral and ionized gas will cause a patchy Ly $\alpha$  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  $2\sigma$  result; will improve with larger data sets.

# Summary

- Lyman- $\alpha$  galaxies afford a test of reionization that is sensitive to neutral fractions  $\sim 30 - 50\%$ .
- 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  $\alpha$  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- $\alpha$  galaxies.

# Where to find me later...



## 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)

James Rhoads - Paris - 8 July 2008

