The 2009 View of Lyman-α Galaxies at Redshift Six and Beyond

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Drawing on collaborations with

Sangeeta Malhotra, Junxian Wang, V. S. Tilvi,

Sylvain Veilleux, Steven Finkelstein, Rob Swaters, Steve Dawson, Arjun Dey, Buell Jannuzi, Hy Spinrad, Dan Stern, Chun Xu, Ilian Iliev, Garrelt Mellema, Evan Scannapieco, and others.

Advantages of Lyman-α Reionization Tests

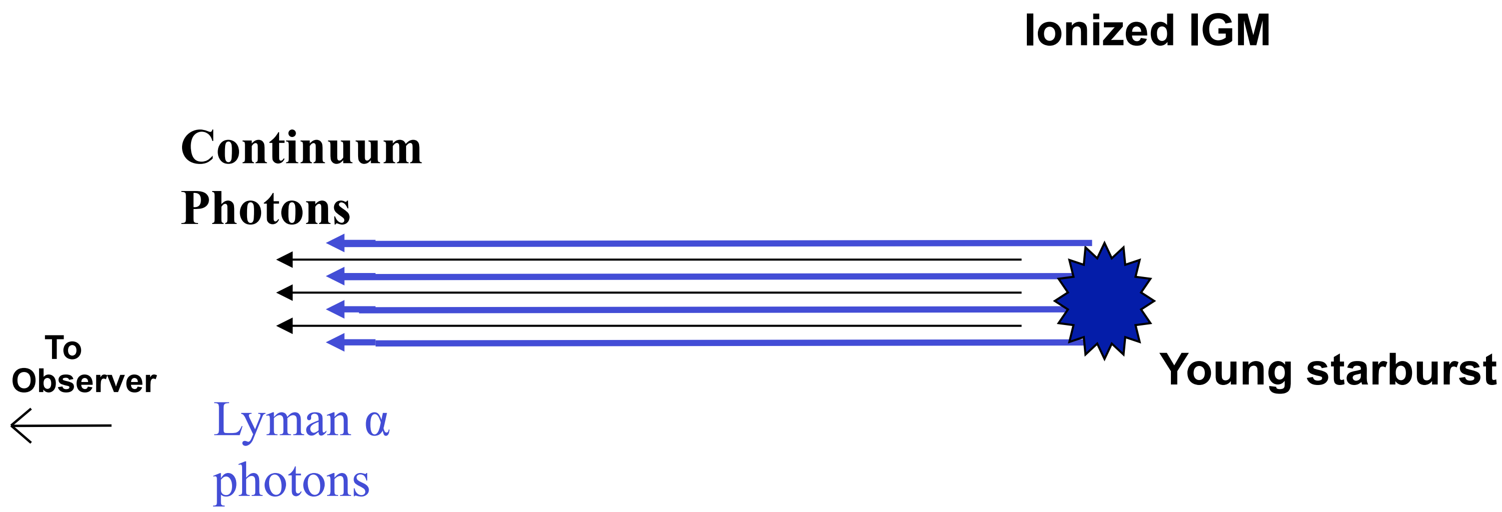
Tests for reionization based on Lyman-α galaxy statistics are…

- Applicable to the *central period* of reionization, when about half the gas was ionized.
- *Local:* They can map the neutral fraction as a function of both redshift and position on the sky.
- Practical with instruments that *already exist*.

These qualities make Lyman alpha galaxies a unique tool for reionization studies.

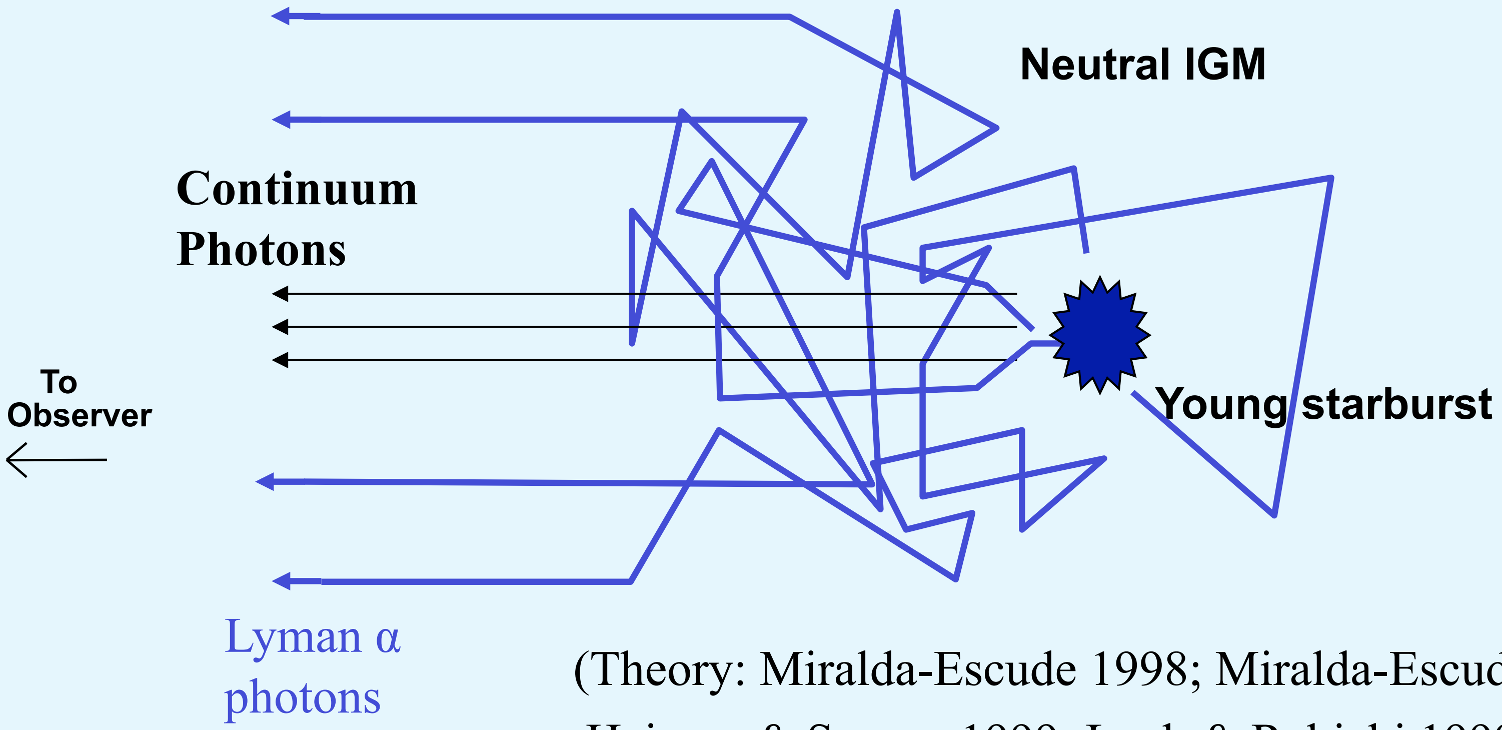
The Lyman-α ReionizationTest

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



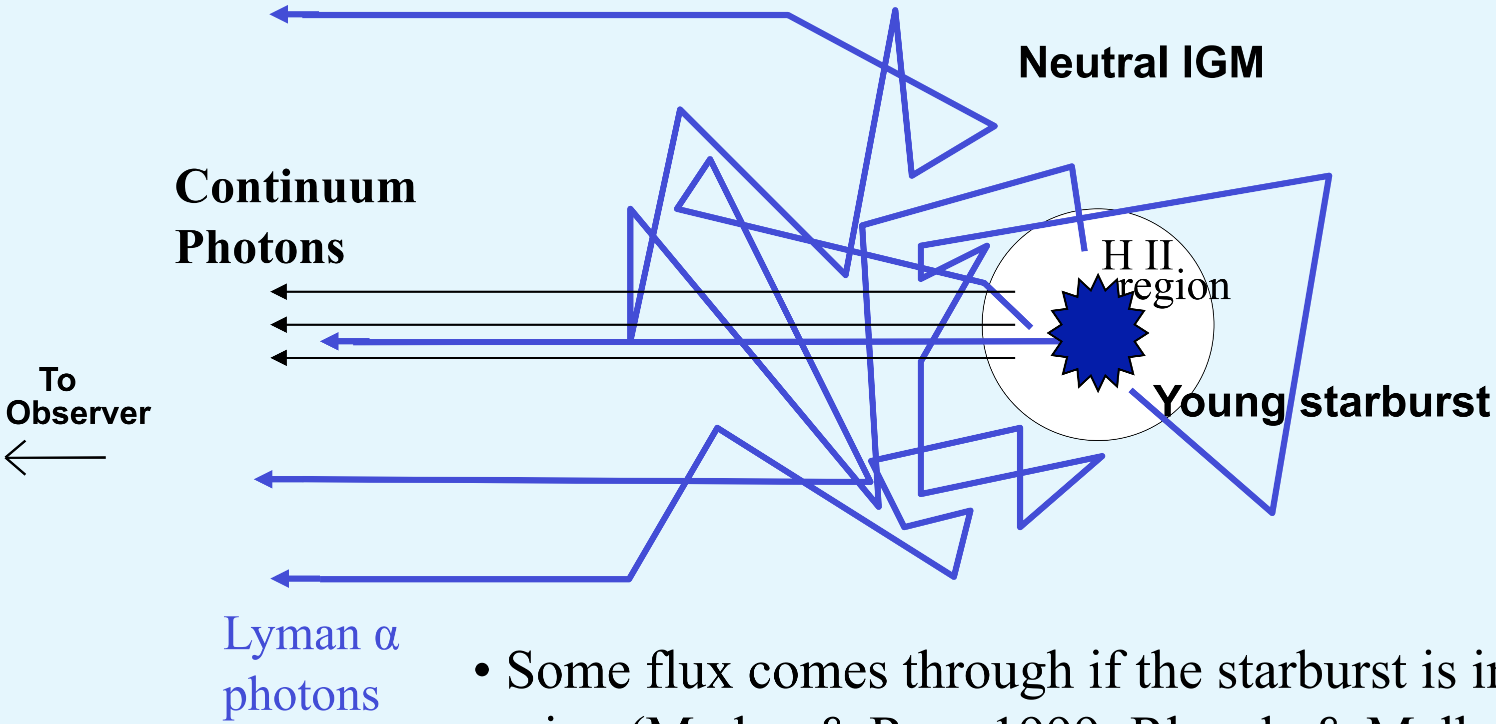
The Lyman-α Reionization Test

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!

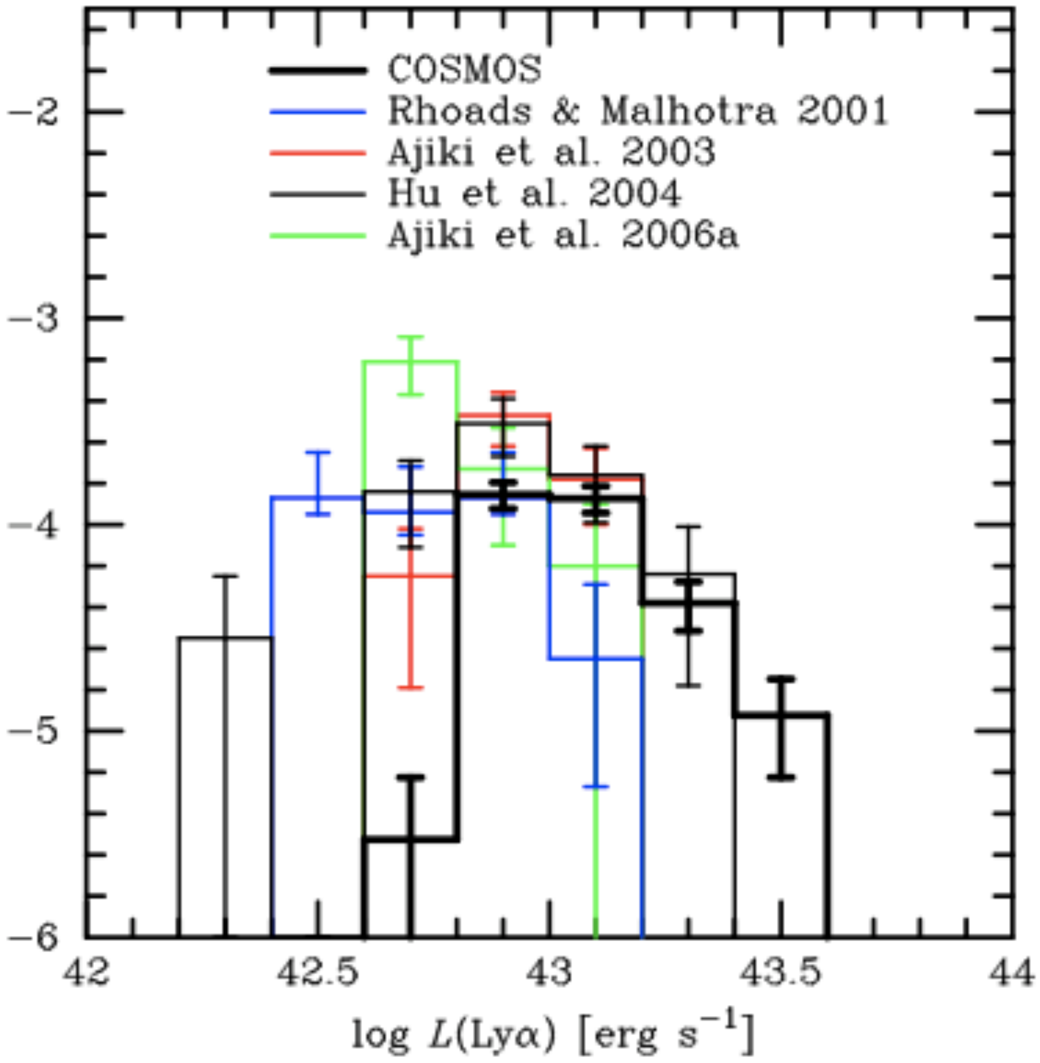


• Some flux comes through if the starburst is in a substantial HII region (Madau & Rees 1999; Rhoads & Malhotra 2001; Haiman 2002).

• The red wing of the line is less suppressed (Haiman 2002).

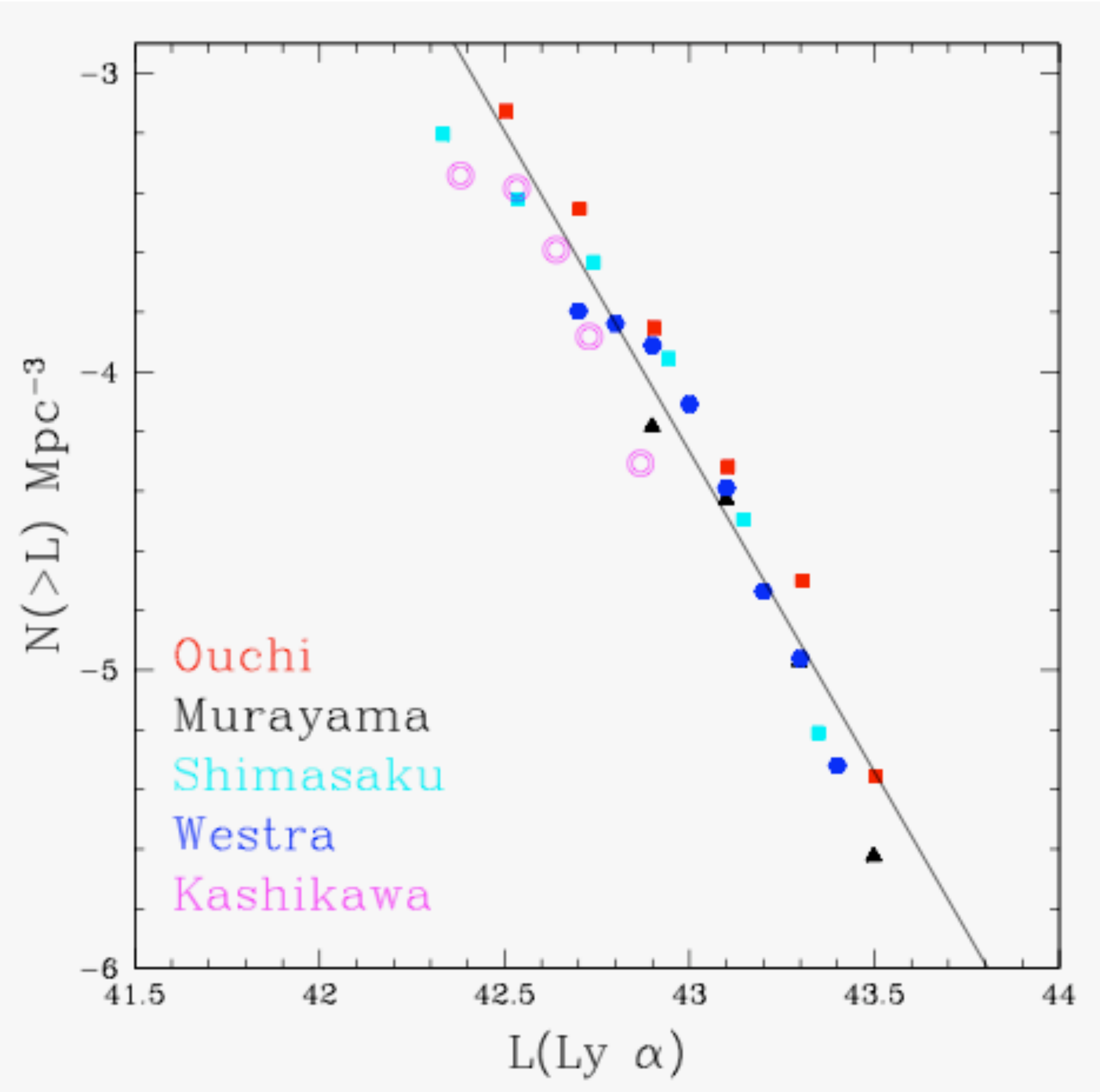
• Gas motions alter Ly-α radiative transfer (Santos 2004).

How good does it get at *one* redshift?



- Figure from Murayama et al, z=5.7 search in COSMOS
- (We should add Wang, Malhotra, & Rhoads 2005 data here! Z=5.7, CDFS.)

Luminosity function comparisons, again



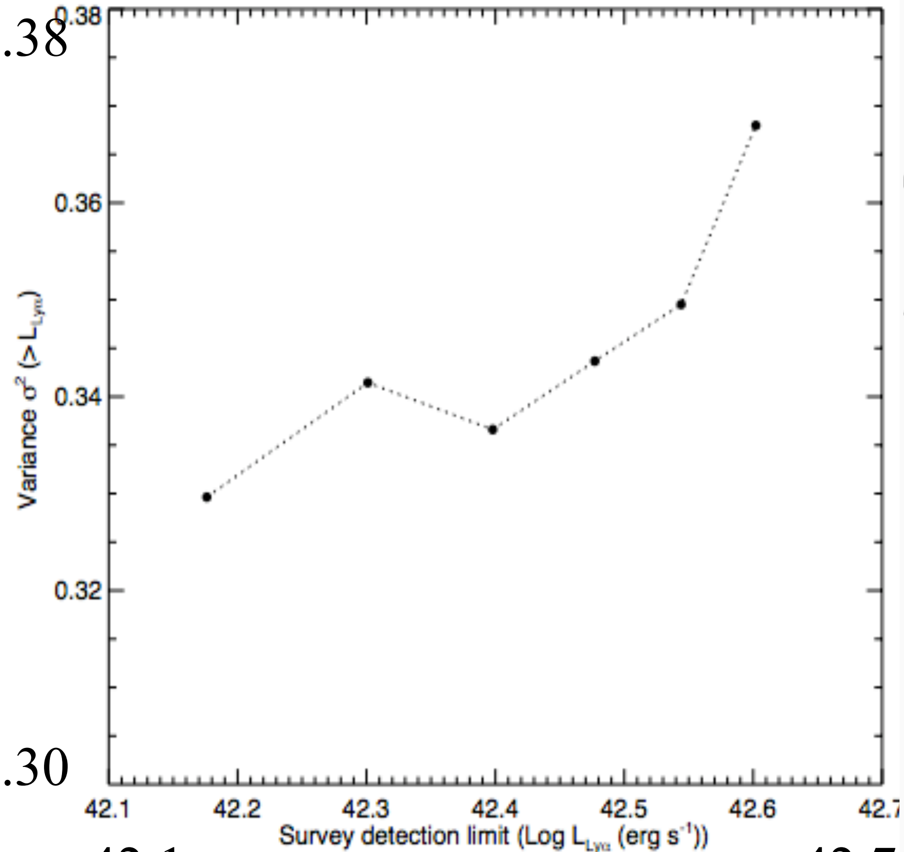
- The scatter among different LF determinations, at fixed L and fixed z=5.7, is about 0.2 dex, nearly a factor of 2.
- Steep slope! So…
- The offset in the log(L) direction is as little as 0.1 dex (25%).
- Good, consistent calibration of counts to luminosity matters here.

Possible Sources of Scatter in LFs

- Different groups, different luminosity functions.
  - Field to field variations?
  - Filter characteristics?
  - Differences in precise selection criteria?
  - Observational details: Corrections for crowding? Aperture corrections?
  - Spectroscopic completeness?
  - Corrections for continuum in the narrowband?

Field to Field Variations

In theory… (Fig. 4, Tilvi et al 2009, simulation subvolumes)



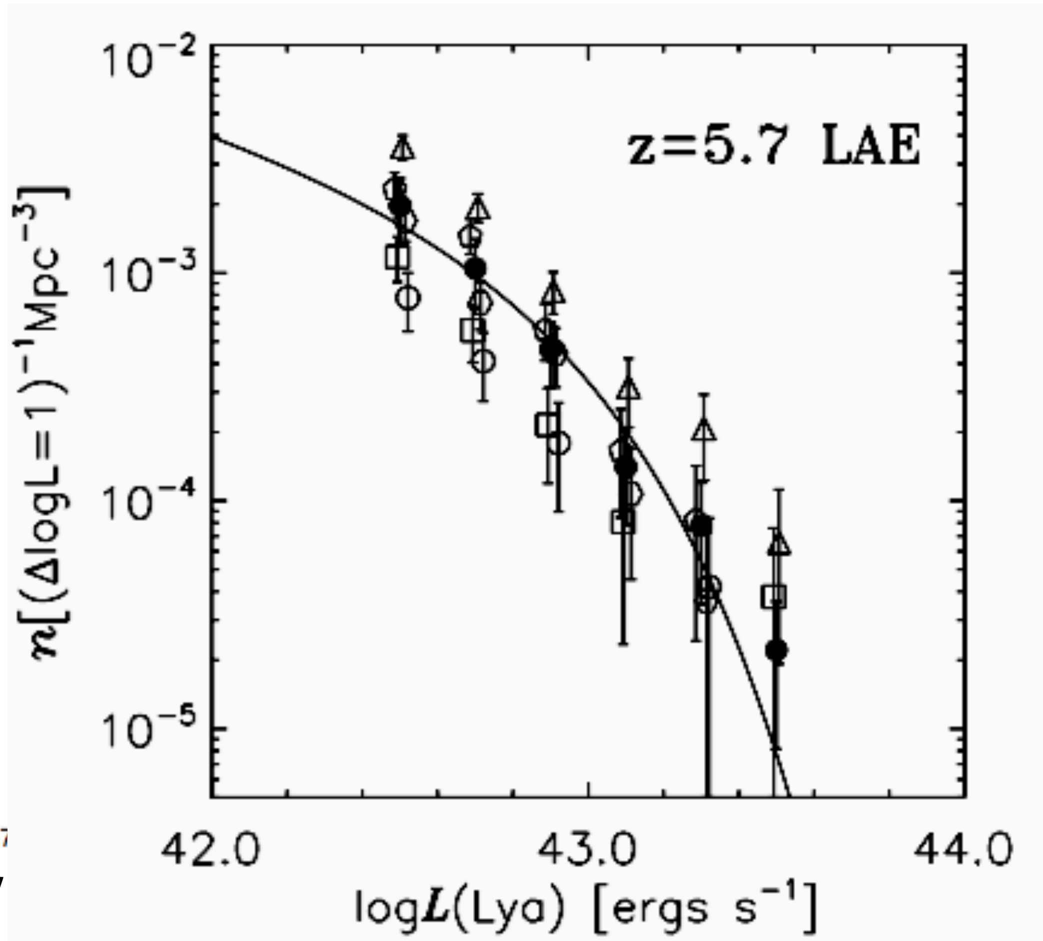
0.38

0.30

42.1 $\mathrm{Log}(L_{min})$ erg s^{-1} 42.7

Survey detection limit

And in practice (Ouchi et al 2007, five subfields)



Selection Criteria

- Small differences in selection criteria can make significant differences in sample sizes.
- E.g., if $P(EW) \sim \exp(-EW / EW_0)$ [Gronwall et al 07, Nilsson et al 08] then the population found should scale as $\exp(-EW_{min} / EW_0)$.
- Criteria are not so simple either…
  - E.g., we use a 4σ color difference requirement; some groups use 3σ.
  - E.g., we use 5σ detection requirement, some groups use 6σ or more.
  - E.g., broader filters tend to imply higher EW cutoffs; LALA filters are typically narrower than Subaru ones.

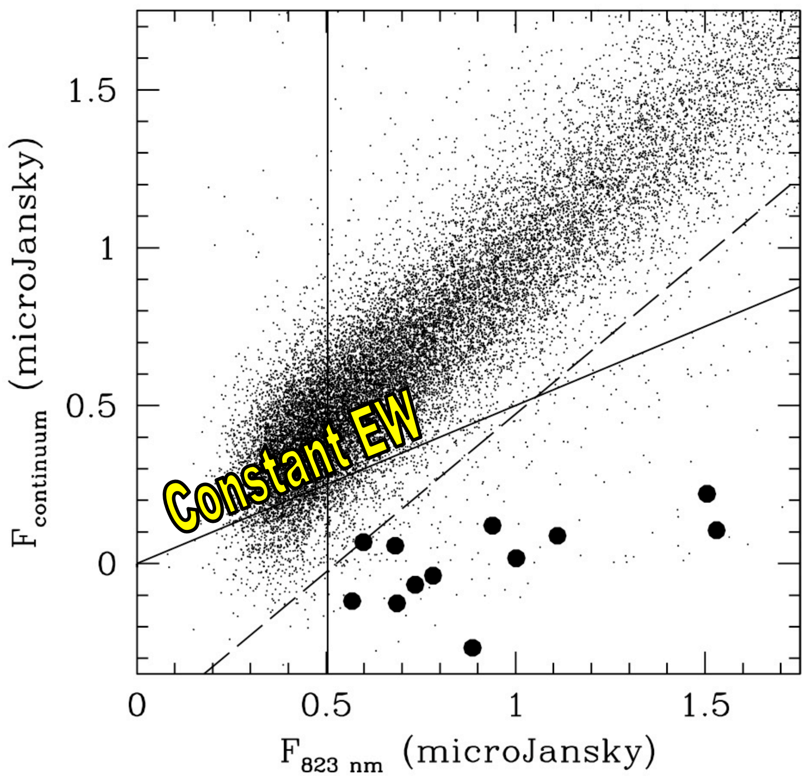
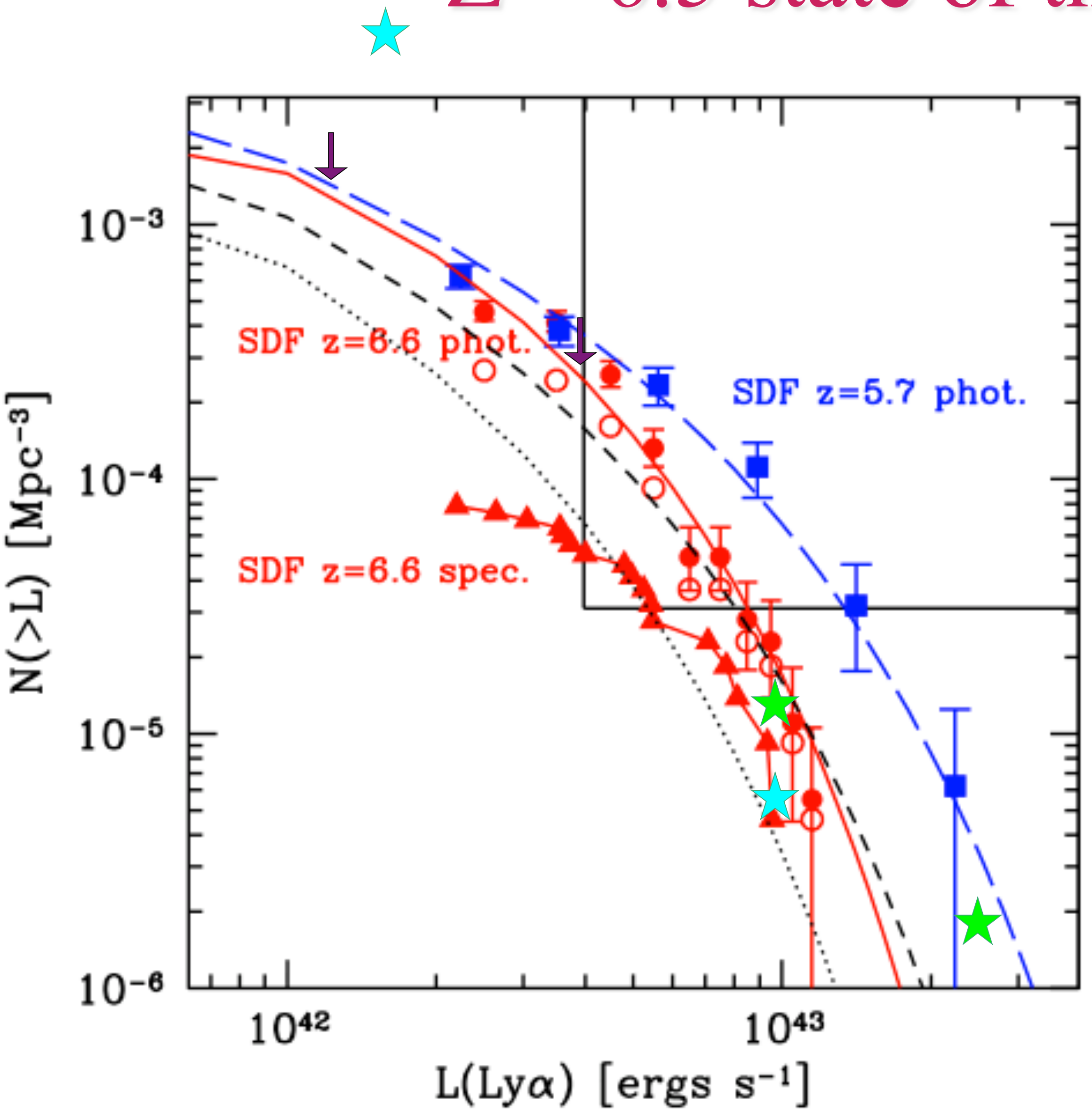


Figure 1b of Wang, Malhotra, & Rhoads 2005: z=5.7 LAEs in CDFS. 1 microJy -> 3.5e-17 erg/cm2/s -> 1.4 10 [43]

Z = 6.5 state of the art

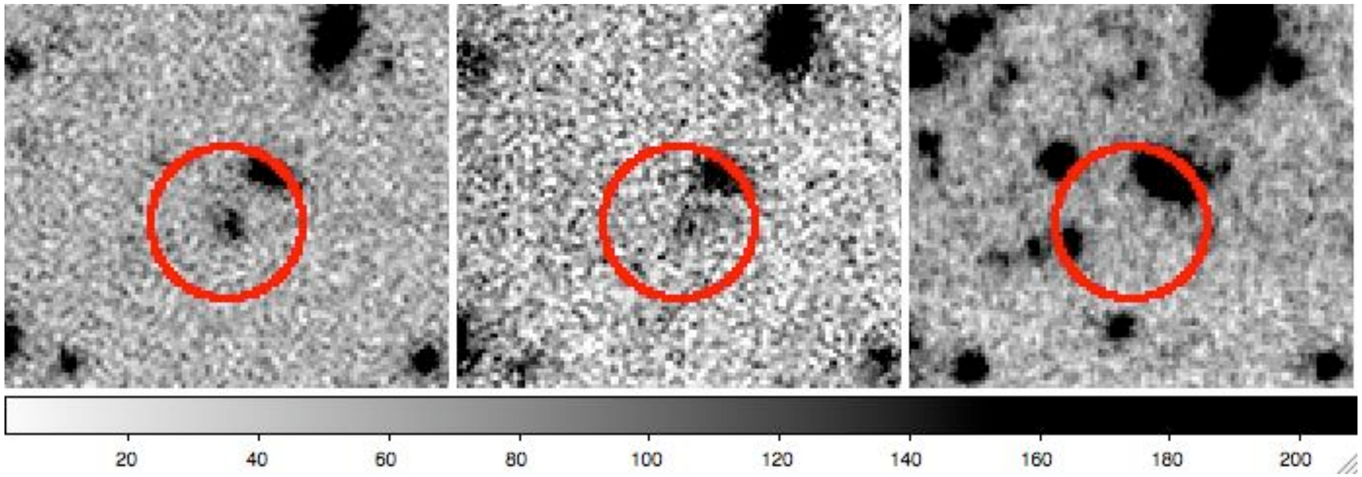


- Figure from Kashikawa et al 2006
- H Yan's points from this meeting added as green stars.
- HCM 6a and LALA points as cyan stars
- Santos lensing upper limits as purple arrows
- I think Esther Hu and Len Cowie have additional constraints, upcoming

Moving forward: New data at z=6.5

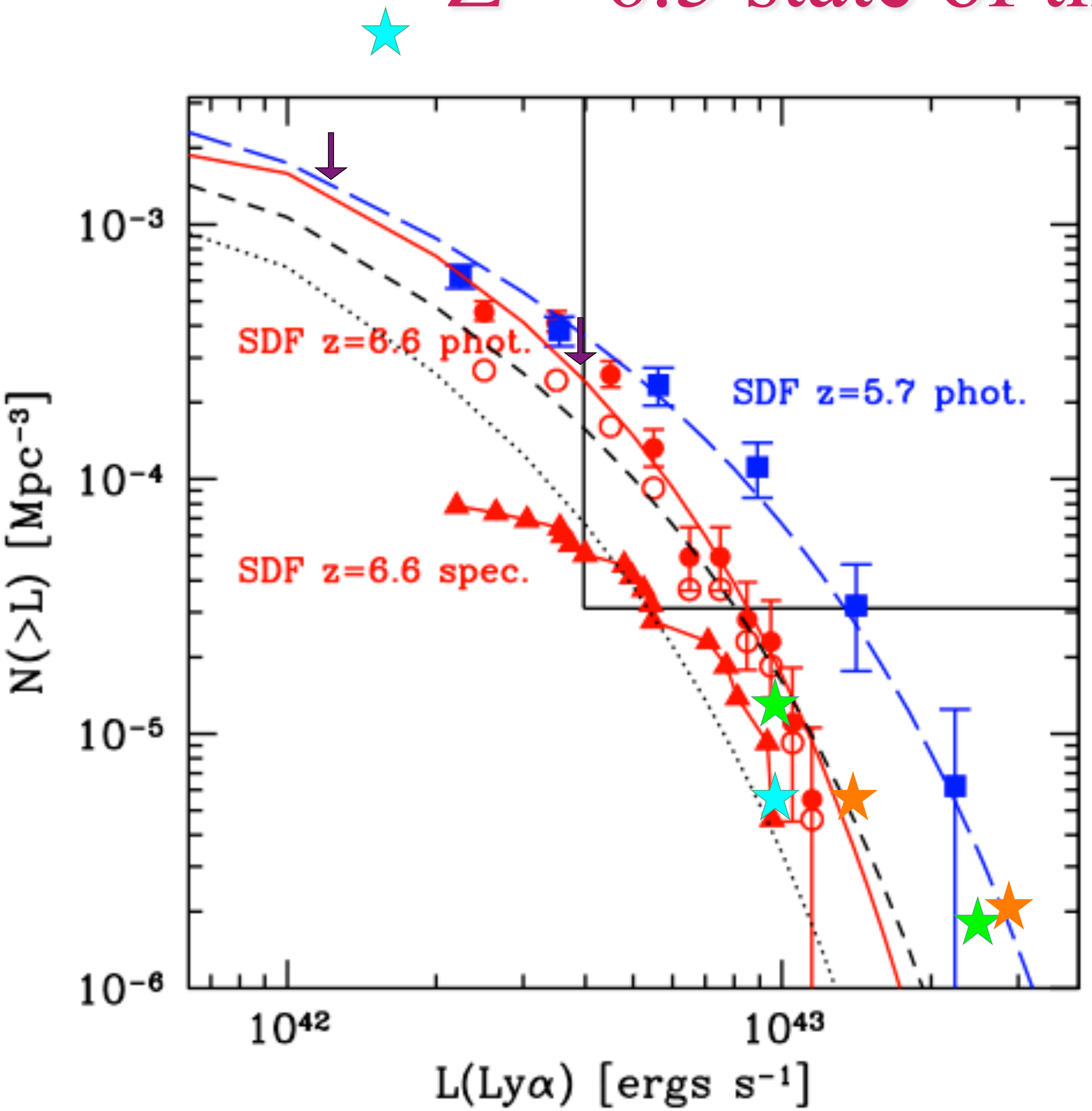
- We have new fields at z = 6.5 to beat down the field-to-field noise there.
- Observations with Magellan + IMACS in imaging mode, CDF-S field and COSMOS field.
- 28' diameter circular field, generally good seeing.
- Data reduced, a little spectroscopy done in CDFS.
- (Care to share slit masks in either field? Talk to us! We have z=3.1 candidates in COSMOS too; cf Emily McLinden's poster.)

Z = 6.5 search in COSMOS



- 2008 data (left), 2007 data (middle, older chips), combined COSMOS public u+B+V+g+r image.
- These sources- bright, 2.5e-17 to 4.5e-17. Expected limit ~ 7e-18 cgs.

Z = 6.5 state of the art



- Figure from Kashikawa et al 2006
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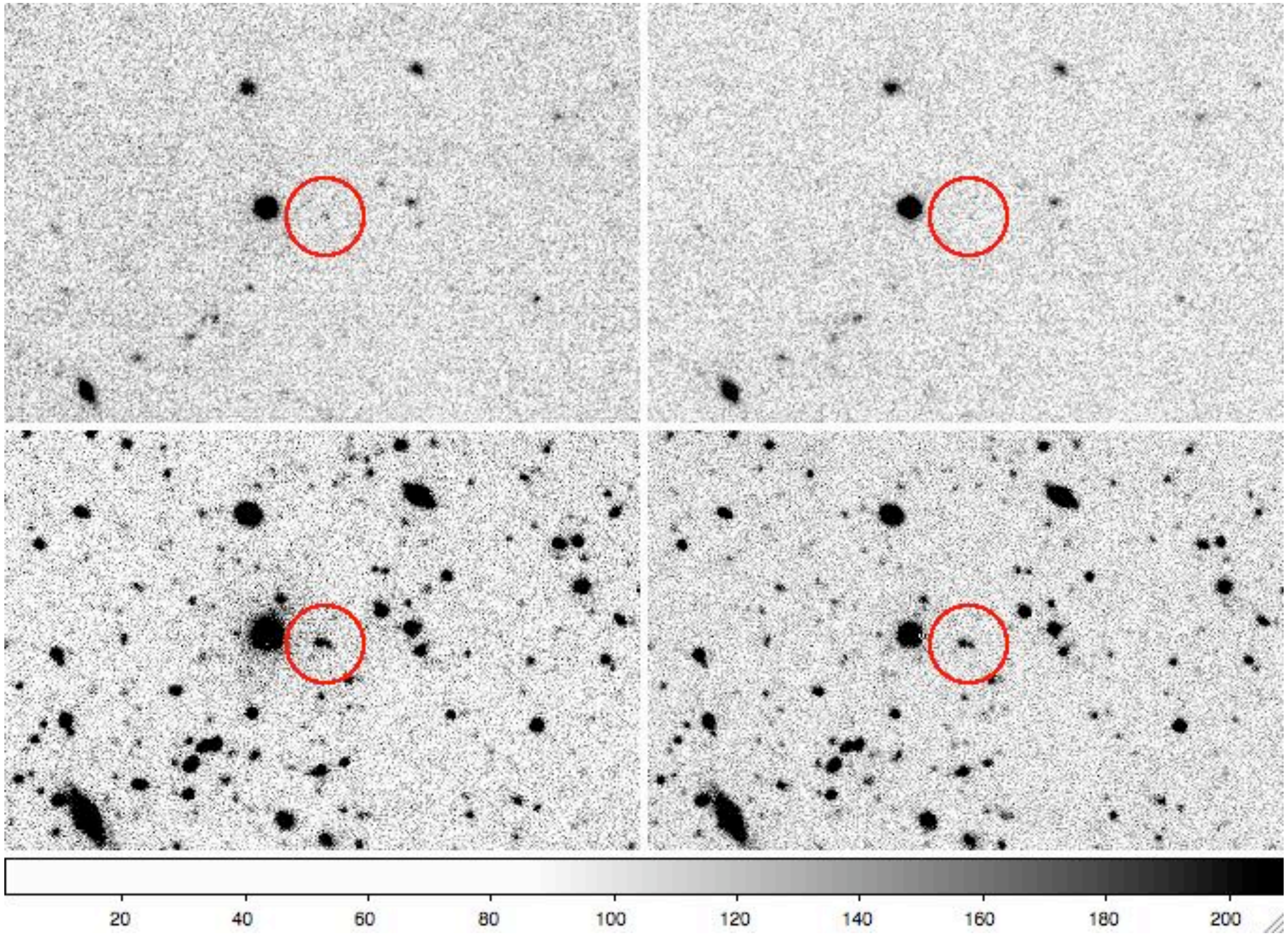
- Santos lensing upper limits as purple arrows
- First results from our COSMOS search as orange stars.

Our z = 7.7 Search

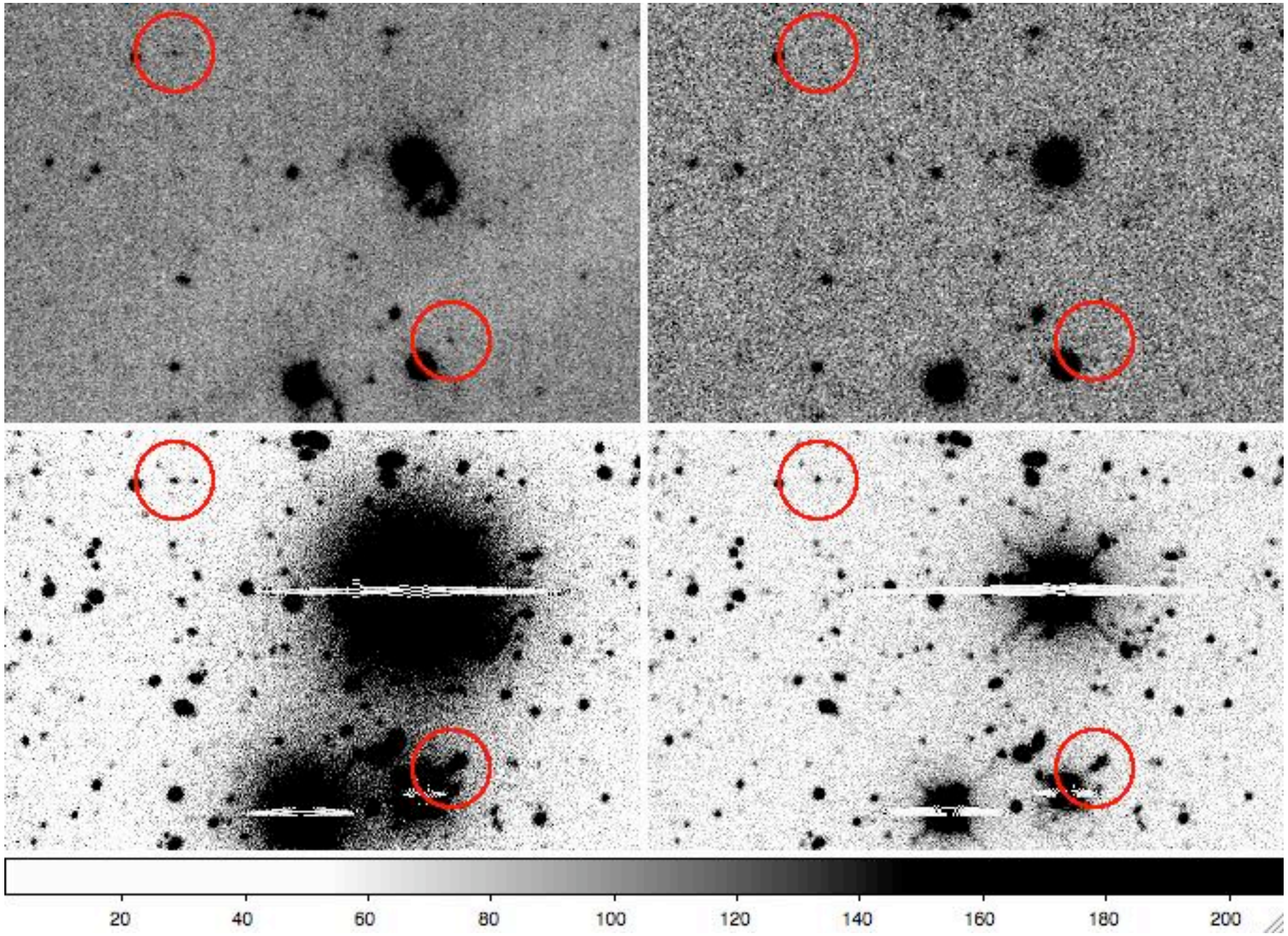
- We have pursued a redshift 7.7 narrowband Lyman alpha search with the 4m Mayall telescope at Kitt Peak National Observatory
- We used NEWFIRM: a 28'x28' field, 0.4"/pixel, YJHK + narrowband capable.
- "We" = V. S. Tilvi, James Rhoads, Sangeeta Malhotra, Steven Finkelstein, Ilian Iliev, Buell Jannuzi, Bahram Mobasher, Norbert Pirzkal, Ron Probst, Hyron Spinrad, Rob Swaters.
- Filter: 9 Angstrom DAzLE filter clone, volume 1.4e4 $cMpc^3$ per pointing.
- Depth: 29 hours / limiting flux ~ 5.5e-18 erg/cm2/sec.

Results - work in progress



- We have ~ 100 emission line candidates…
- Of which we expect 1-5 to be Lyman alpha…
- No definitive LyA line identified yet, but it's still early.

Results - work in progress



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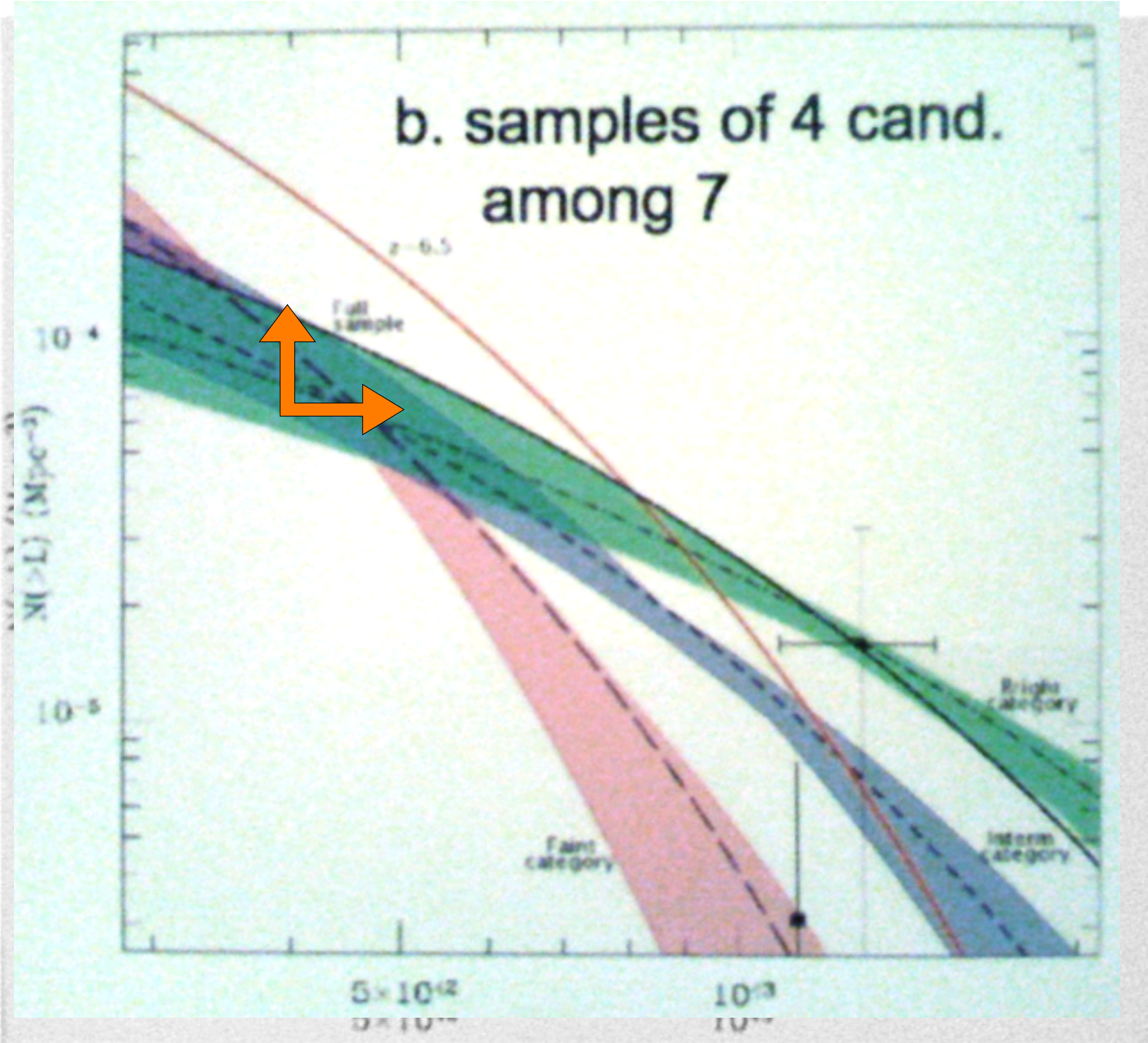
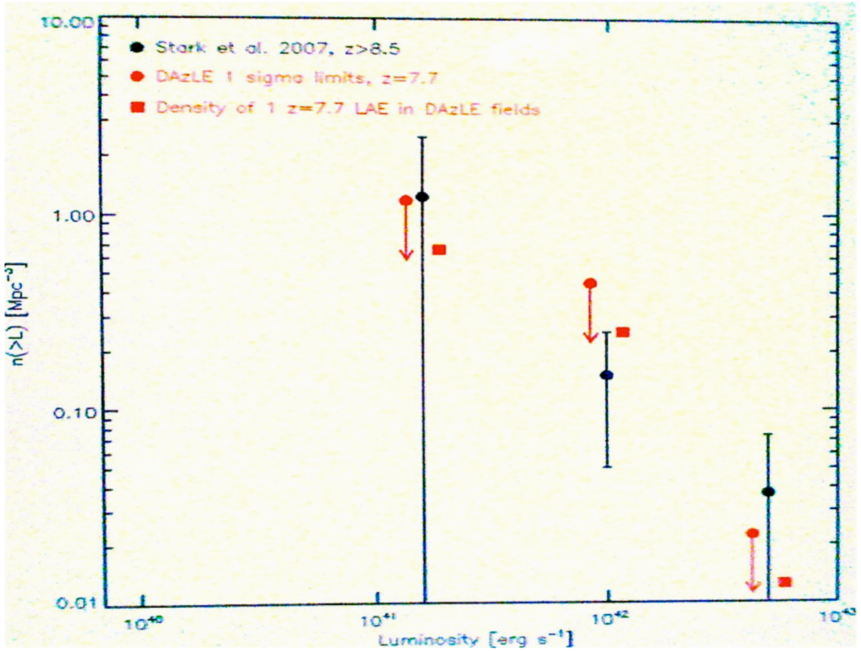
z = 7.7 searches in context

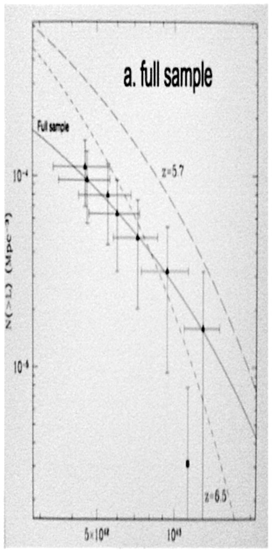


- Use figures from Hibon's poster as context…

z = 7.7 searches in context



- Use figure from DAzLE (Venemans poster/talk)
- Add ZEN3 constraints (Hibon's poster) *on the same axes.*

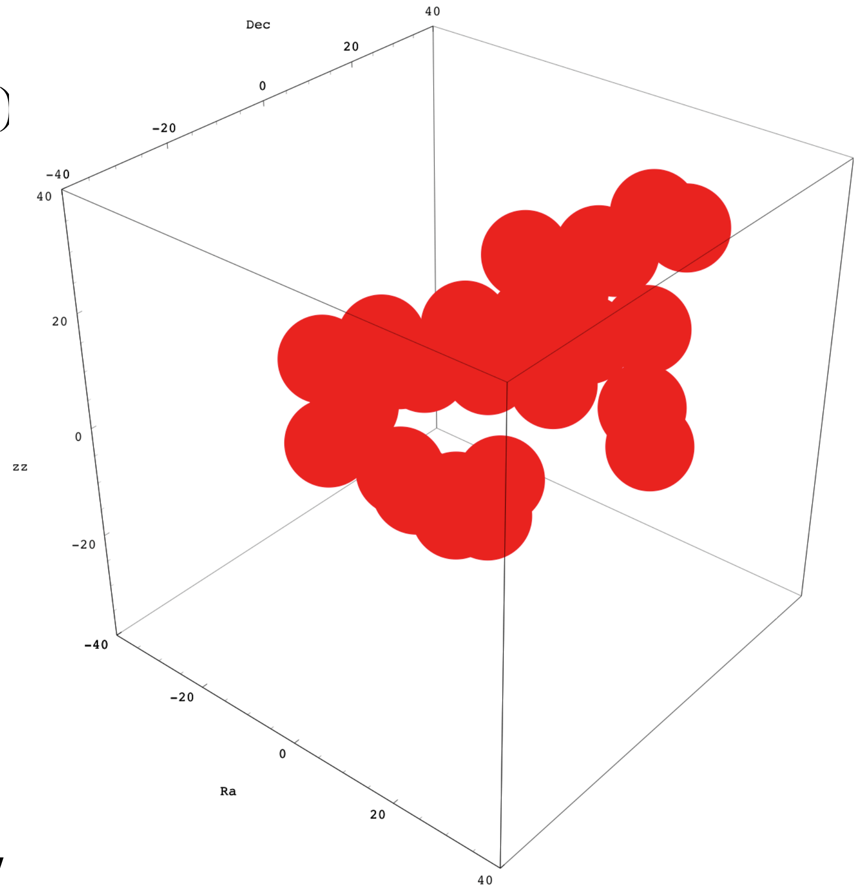


The volume test:

(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: $n > 1\times10^{-4}$ $cMpc^{-3}$ (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.**
- **For the Hibon et al sample of 7 candidates, we'd get ~ 30% * N_{real}/7**



The future

- Near term: Extension of blind Lyman alpha searches to redshift z=8.8 and beyond
  - VISTA / ELVIS (Nilsson et al),
  - Lensed cluster searches (Stark et al; cf. Kneib's talk here)
  - Maybe other efforts
- Longer term: Redshift 10 and beyond… until the Lyman alpha line is hidden by the neutral IGM.

Summary

•Lyman α galxies should play a major role in developing our knowledge of reionization.

•Careful attention to observational details, and a good understanding of galaxy population evolution, will be required.

•Ongoing work promises improved statistics at z=6.5 and 6.9, confirmed objects at z=7.7, and interesting constraints at z=8.8 in the coming year or two.

ARIZONA STATE UNIVERSITY

School of Earth and Space Exploration

- Astro Faculty: Desch, Groppi, Malhotra, Rhoads, Scannapieco, Starrfield, Timmes, Windhorst, Young
- Planetary / solar system: Christiansen, Greeley, Robinson, Wadhwa.
- 25 geology and 5 engineering faculty.
- Access to Arizona telescope system, including the LBT, MMT, Bok, and Magellan telescopes
- http://sese.asu.edu/astrophysics

Also ongoing at ASU

Wide area Lyman alpha search at z=3.1, led by Emily McLinden & Steve Finkelstein - see McLinden's poster. Good, bright sources for understanding the physical nature of these galaxies. Search with the Bok telescope, followup with MMT.

Spectra of 100 z=4.5 LAEs with Magellan: Wang et al 2009, arXiv 0907.0015

Ultradeep HST ACS grism spectroscopy- the PEARS and GRAPES projects, PI Sangeeta Malhotra

Drop by- for a day or for a PhD, depending on your circmustances!

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Where to find me later…

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- Access to Arizona telescope system, with facilities on four mountains in southern Arizona, plus Magellan in Chile.
- (LBT, MMT, Bok, Magellan, Catalina mountains)

Beyond Here there be Fossils

Lyman α Test Details

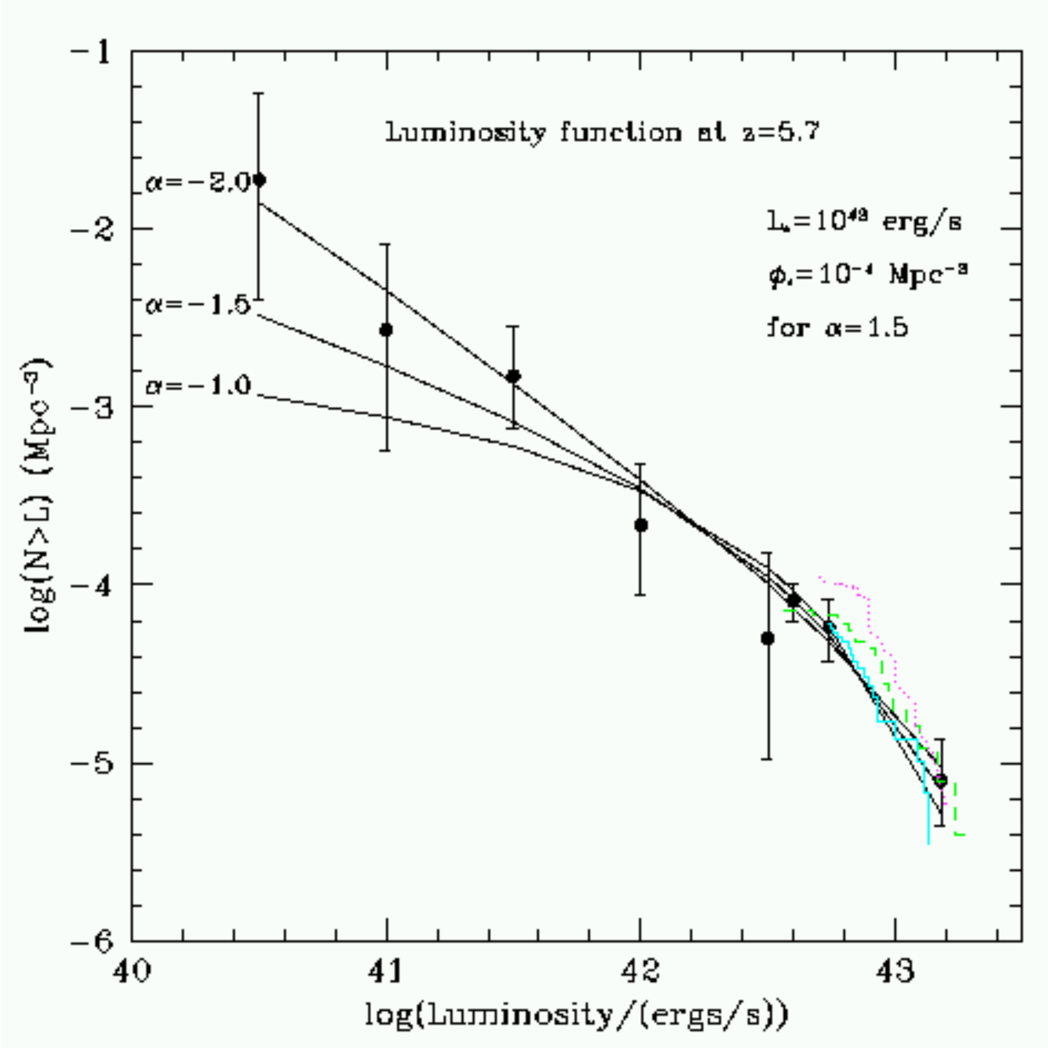
- **Bottom line**: Factors of ~ 3 reduction in Ly-α luminosity are unavoidable in neutral universe. Reduction larger in many models but not all.

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

The Luminosity Function Test

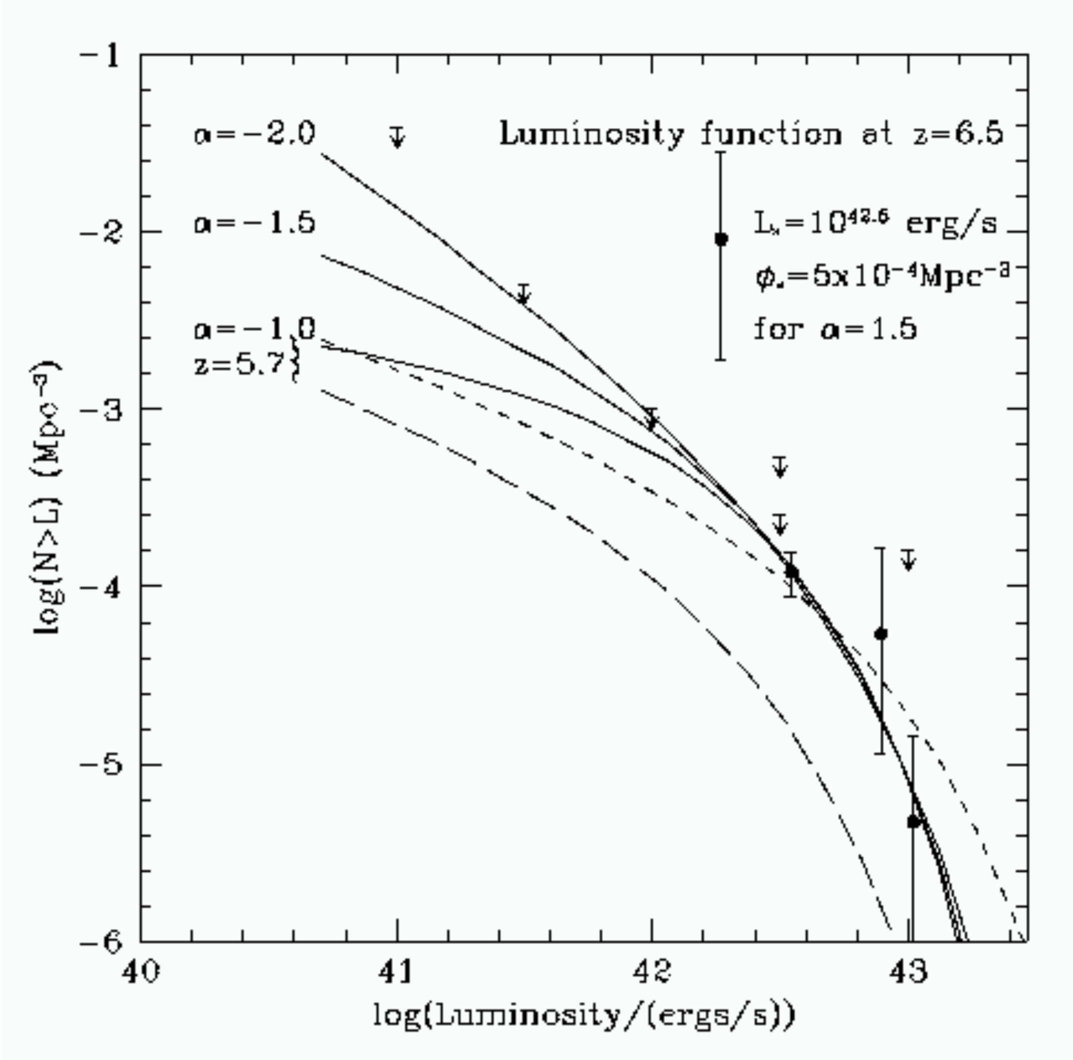
Malhotra & Rhoads 2004, *ApJ Letters* **617**, L5;
See also Stern et al 2005; Haiman & Cen 2005; Kashikawa et al 2006

- 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

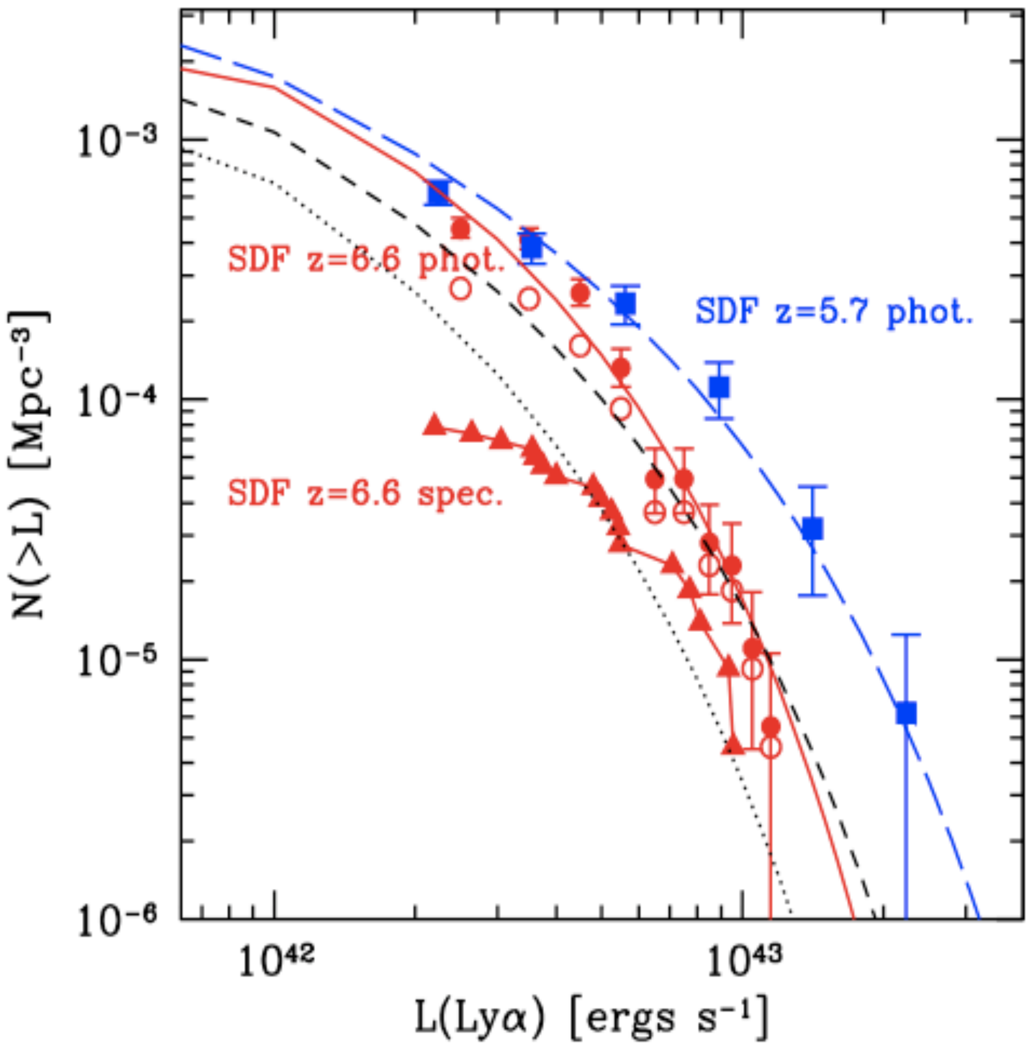
- Luminosity function fits for three faint-end slopes.
- z = 6.5 plot shows two null hypotheses:
  - z = 5.7 LF, or
  - z = 5.7 LF reduced by a factor of 3 in luminosity to approximate IGM absorption.
- ***No evidence for neutral IGM!***



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?



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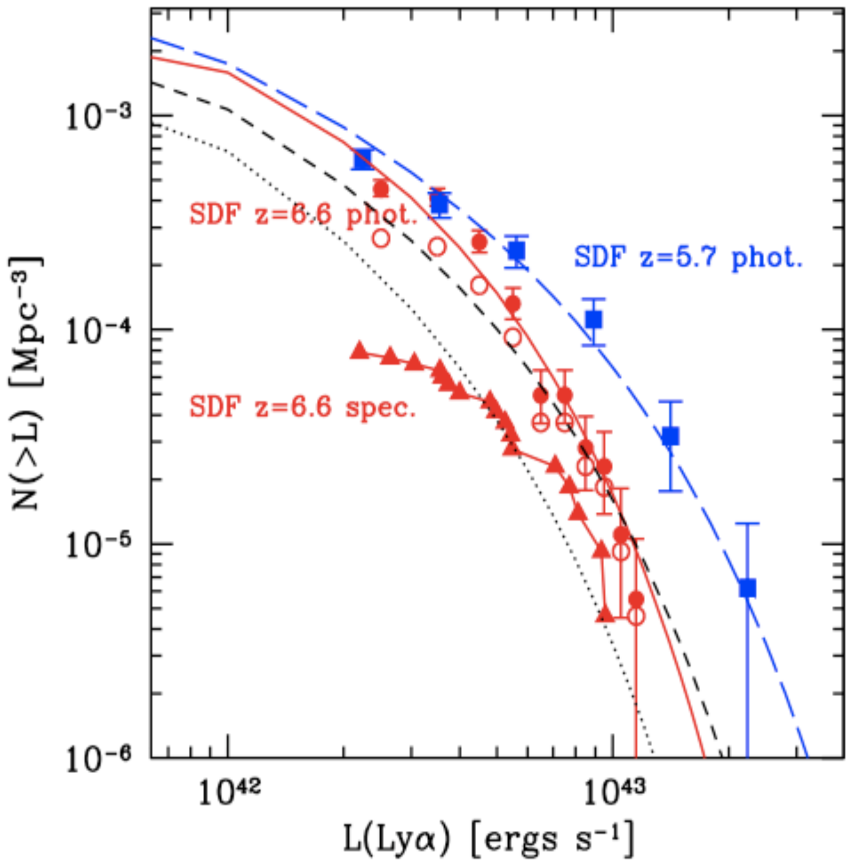
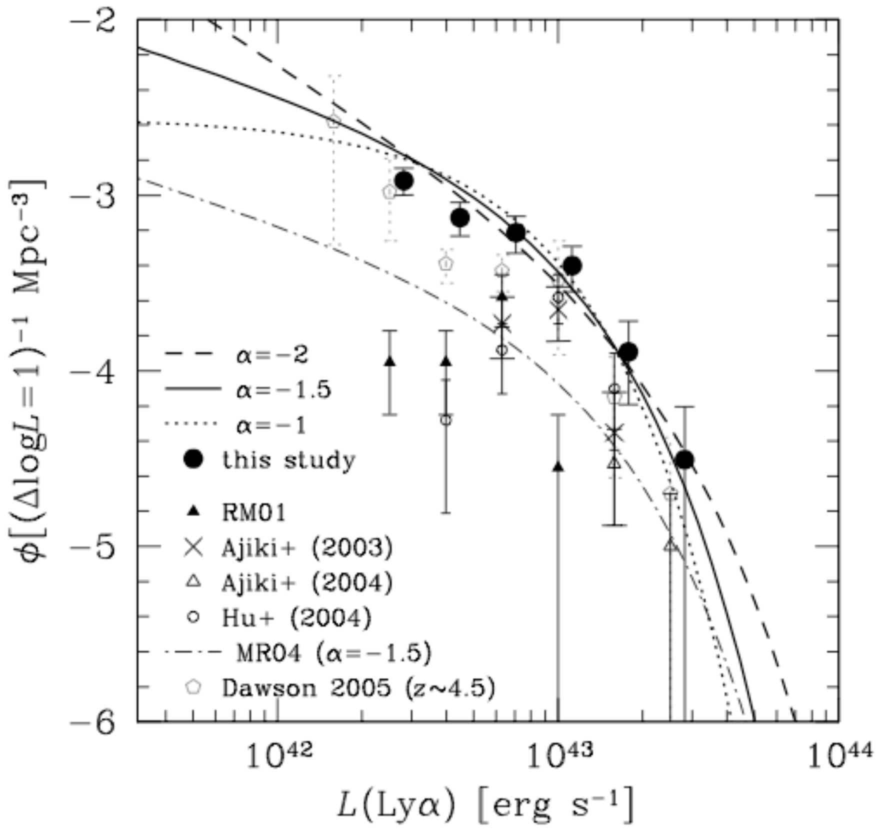


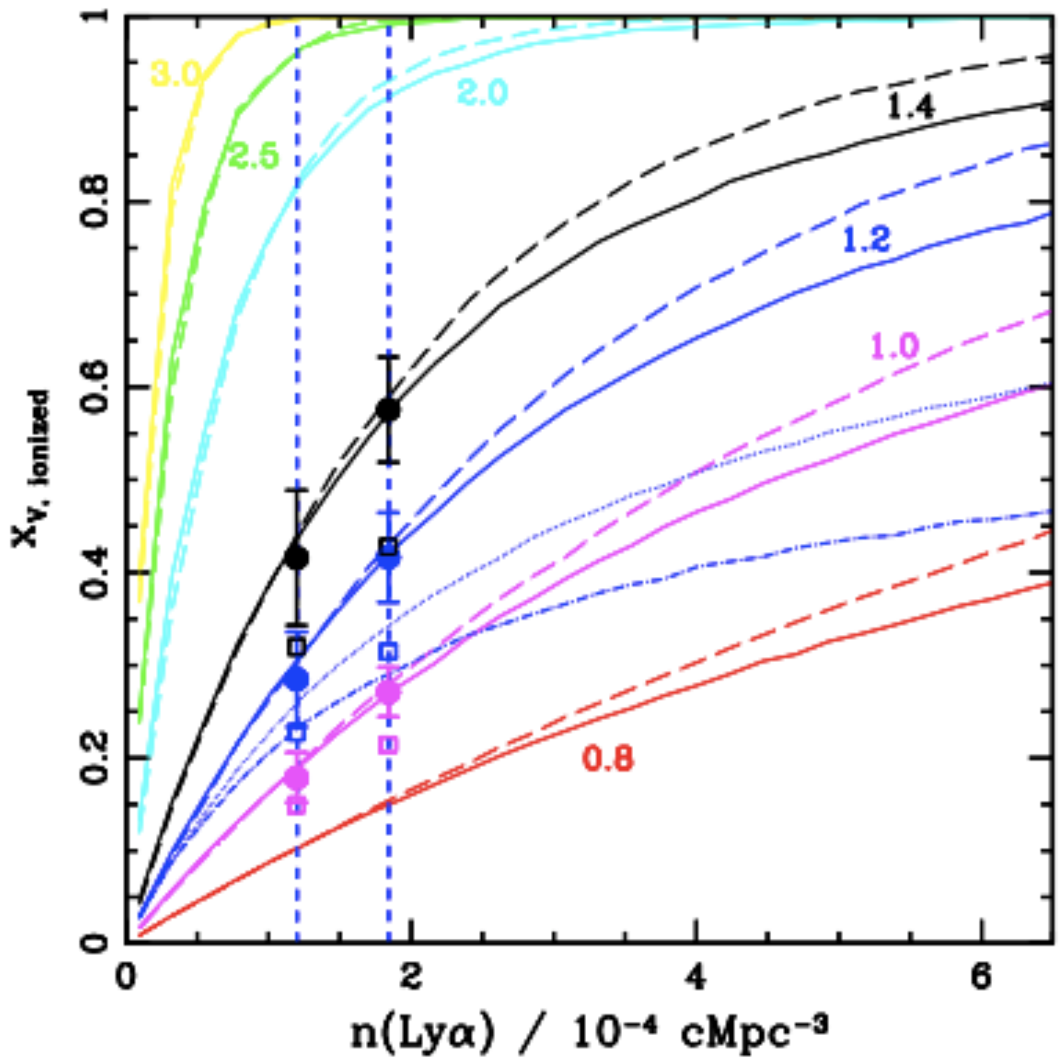


The z=5.7 LF from Shimasaku et al is the highest yet observed.

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

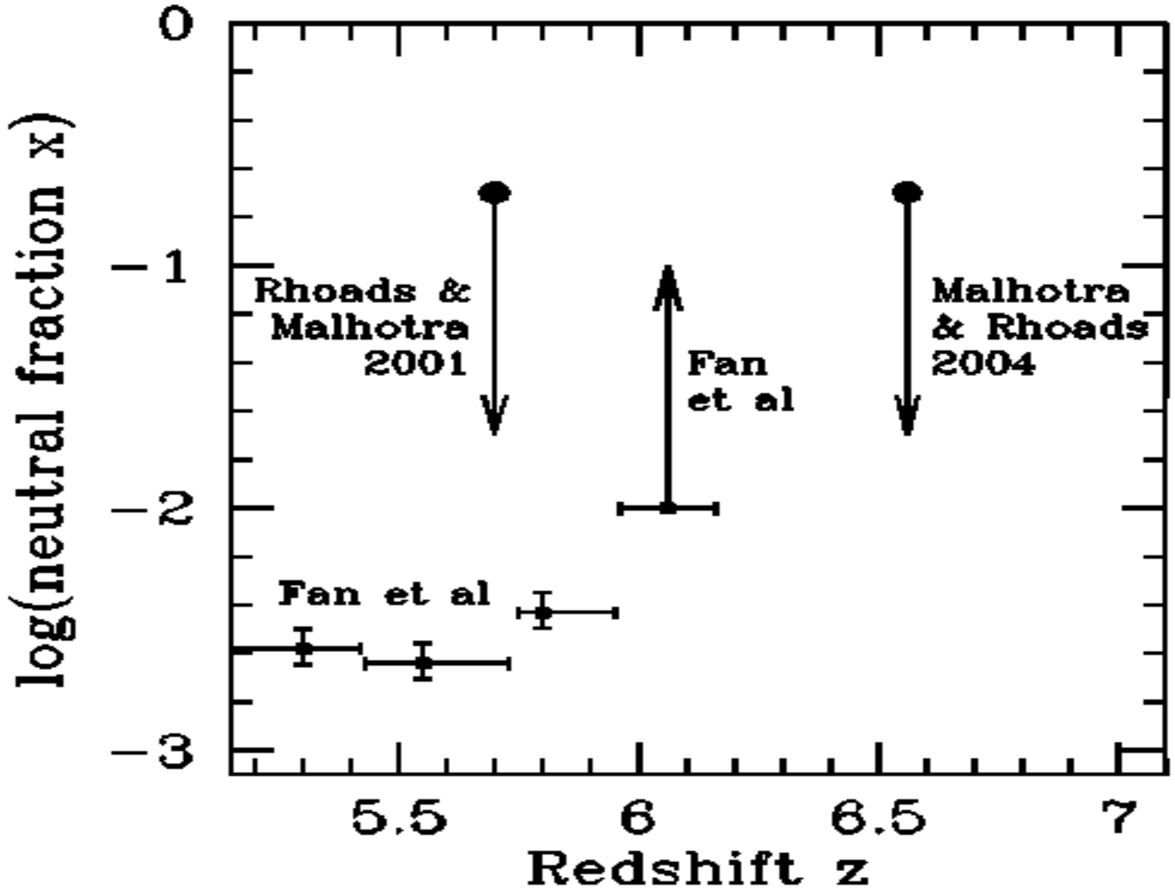
The Volume Test - more details

- 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

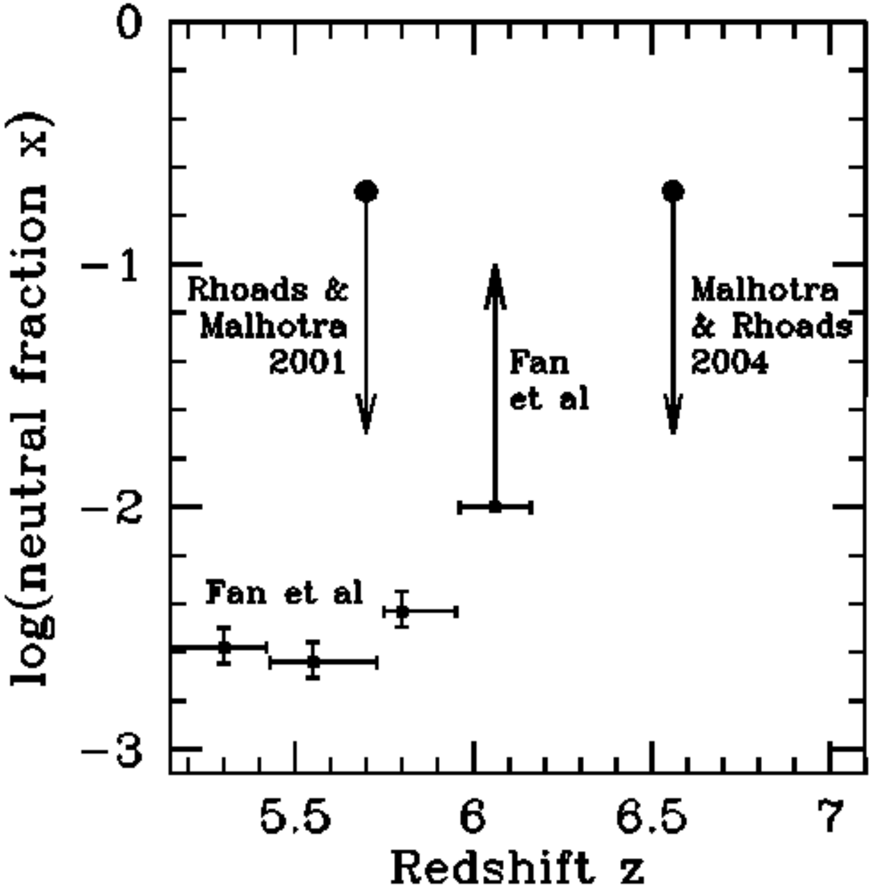
Current evidence: Combine the Lyman α, Gunn-Peterson, and dark gap statistic tests (Fan et al 2006) to study the evolution of the mass averaged neutral fraction, x:

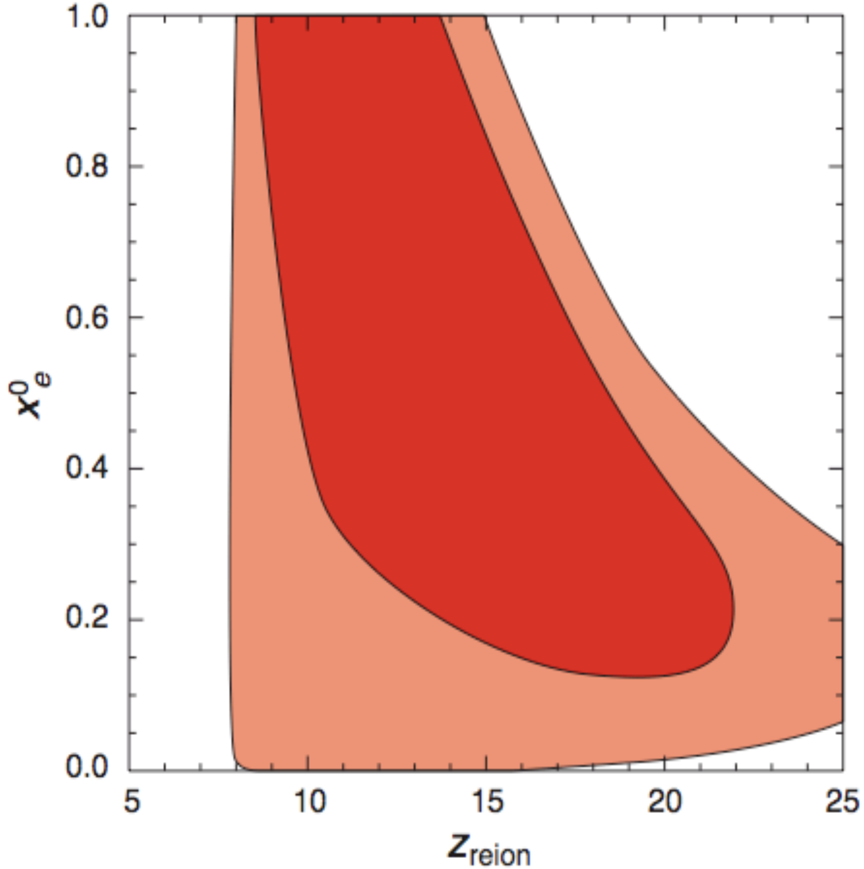


There is no contradiction between the GP effect at z=6.2 and the Ly α at z=6.5.

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.