

Testing the Topology of Reionization with Lyman α Emitters

James E. Rhoads
Sangeeta Malhotra

Reionization as a Topological Transition

The most dramatic and rapid phase of reionization is the overlap stage:

- HII regions from individual sources overlap.
- Ionizing background jumps sharply when a typical point sees radiation from many sources.

Overlap changes the topology of ionized regions:

- Before, isolated bubbles in a neutral medium.
- Afterwards, the ionized region percolates.

Topological statistics could detect this transition.

Genus Statistics

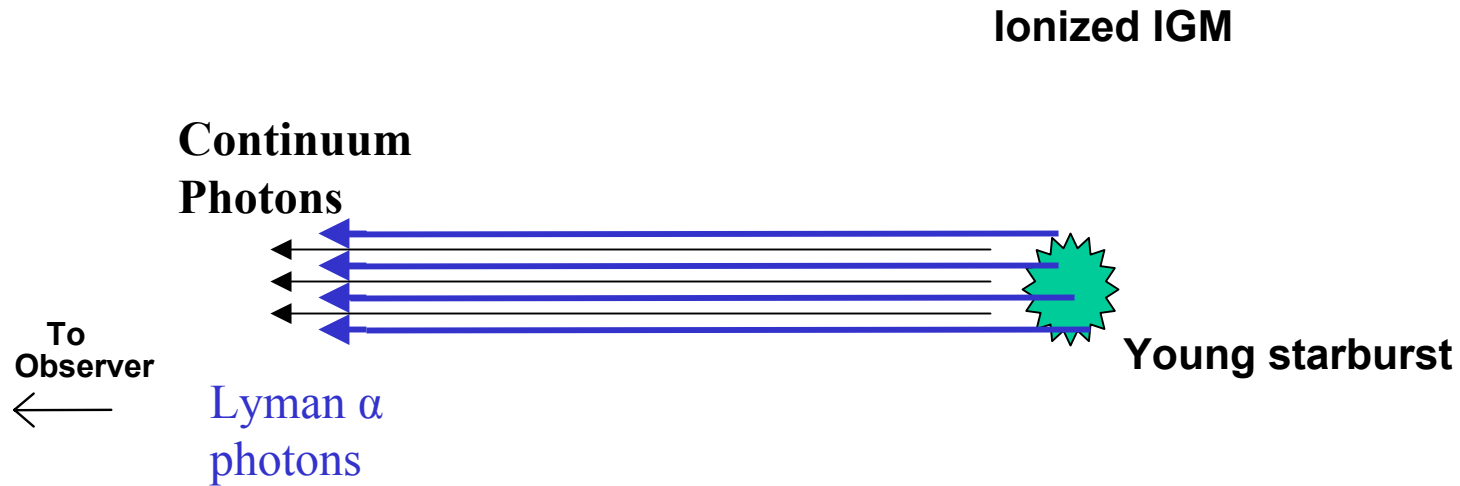
Topological tests are most powerful when two- or three-dimensional data are available.

- The 3D genus statistic characterizes the topology of a 2D surface (e.g., an isodensity contour) in 3D space: Every disconnected component contributes -1 to the genus number, and every “donut hole” contributes $+1$.
- The analogous 2D genus statistic counts the number of isolated high density regions minus the number of isolated low density regions.

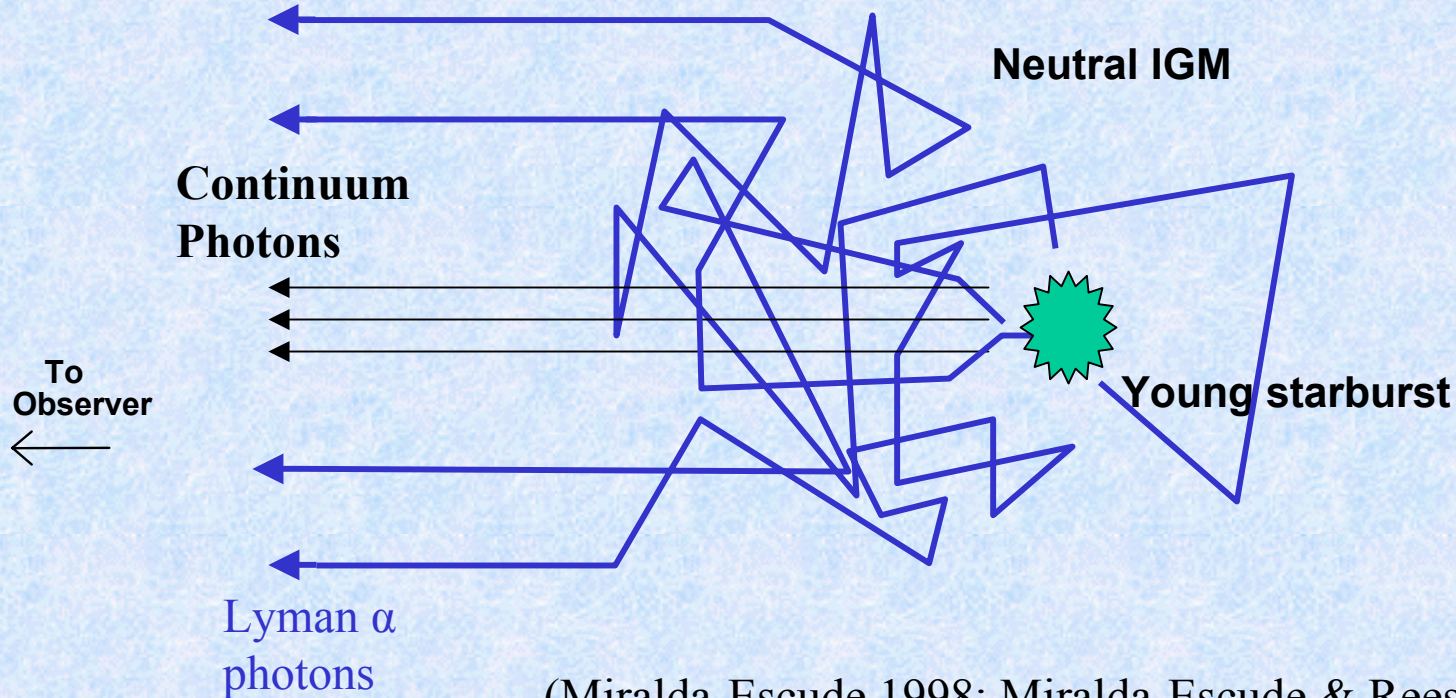
Available Probes

- Bright $z > 6$ quasars are much too rare to probe transverse structure of ionized bubbles with Gunn-Peterson measurements.
- Lyman α galaxies are much more numerous and are sensitive to neutral gas in the IGM.
- Mapping line emission from neutral and ionized regions would probe topology directly. Possible issues here: Signal strength; foregrounds; velocity effects.

The Lyman α Neutral Fraction Test



The Lyman α Neutral Fraction Test



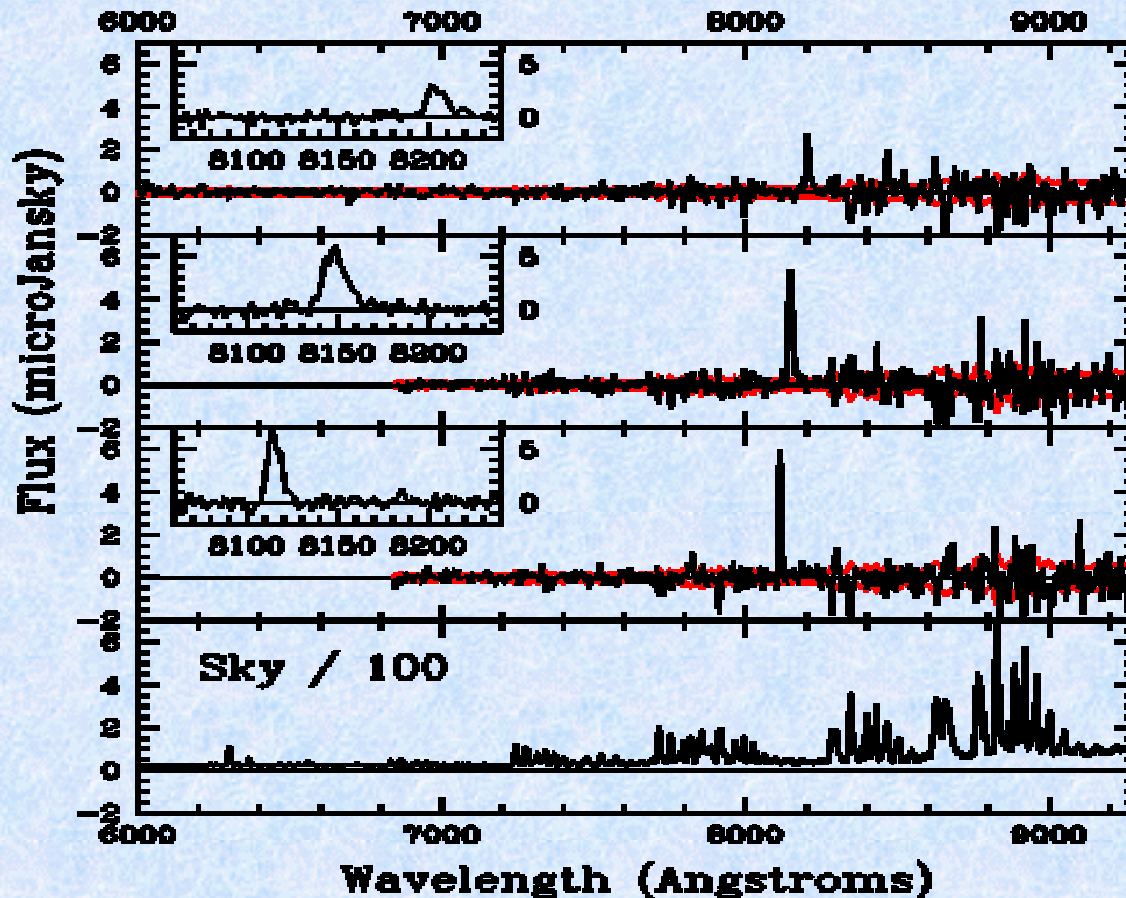
(Miralda-Escude 1998; Miralda-Escude & Rees 1998;
Haiman & Spaans 1999; Loeb & Rybicki 1999)

Comparing the Ly- α and Gunn-Peterson Reionization Tests

	Gunn-Peterson	Lyman α
Threshold neutral fraction in uniform IGM	10^{-4}	0.1
In nonuniform IGM	10^{-2}	> 0.1
Source luminosity	Very bright	Faint
Redshift coverage	Continuous	Discrete from ground; continuous above atmosphere.

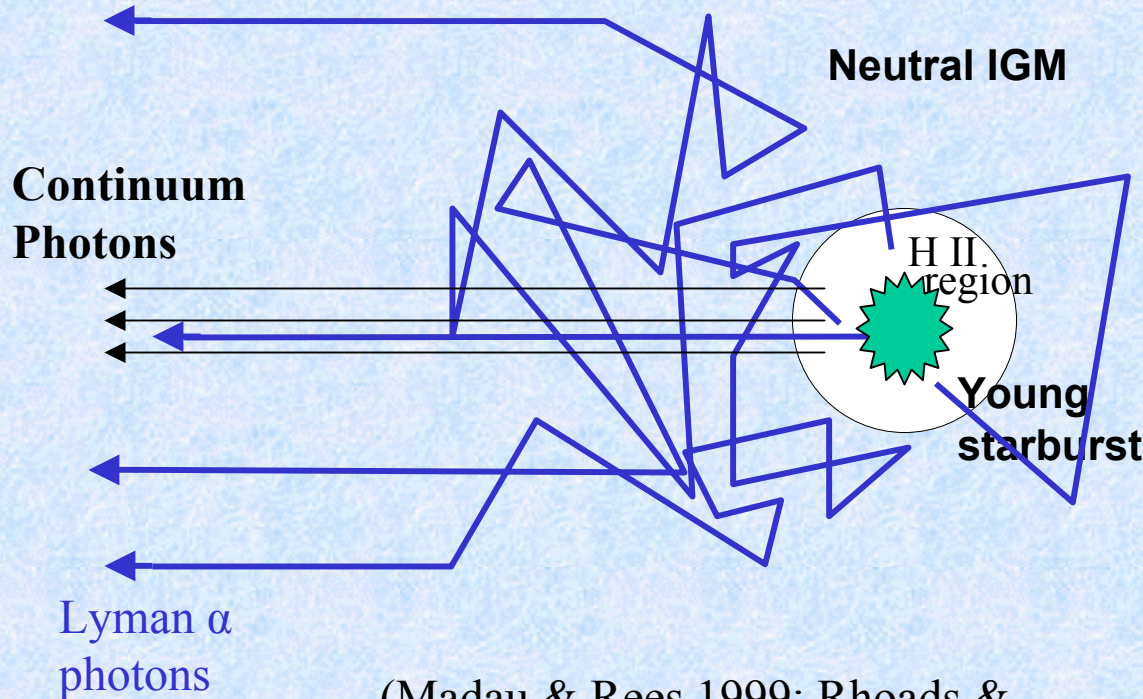
The Lyman- α Test: First Applications

• Rhoads & Malhotra (2001) outlined the Ly- α test, including consideration of HII regions, and applied it to show $z_{re} > 5.7$ with a sample of 18 photometrically selected candidates.



- 3 of first 4 LALA $z = 5.7$ candidates confirmed at Keck. (Rhoads et al 2003, March AJ)
- Extension to $z=6.6$ possible; see Hu et al and Kodaira et al.
- 3 LALA $z=6.5$ candidates; 1-2 spectroscopically confirmed.

The Lyman α Test, First Order Concerns: HII Regions



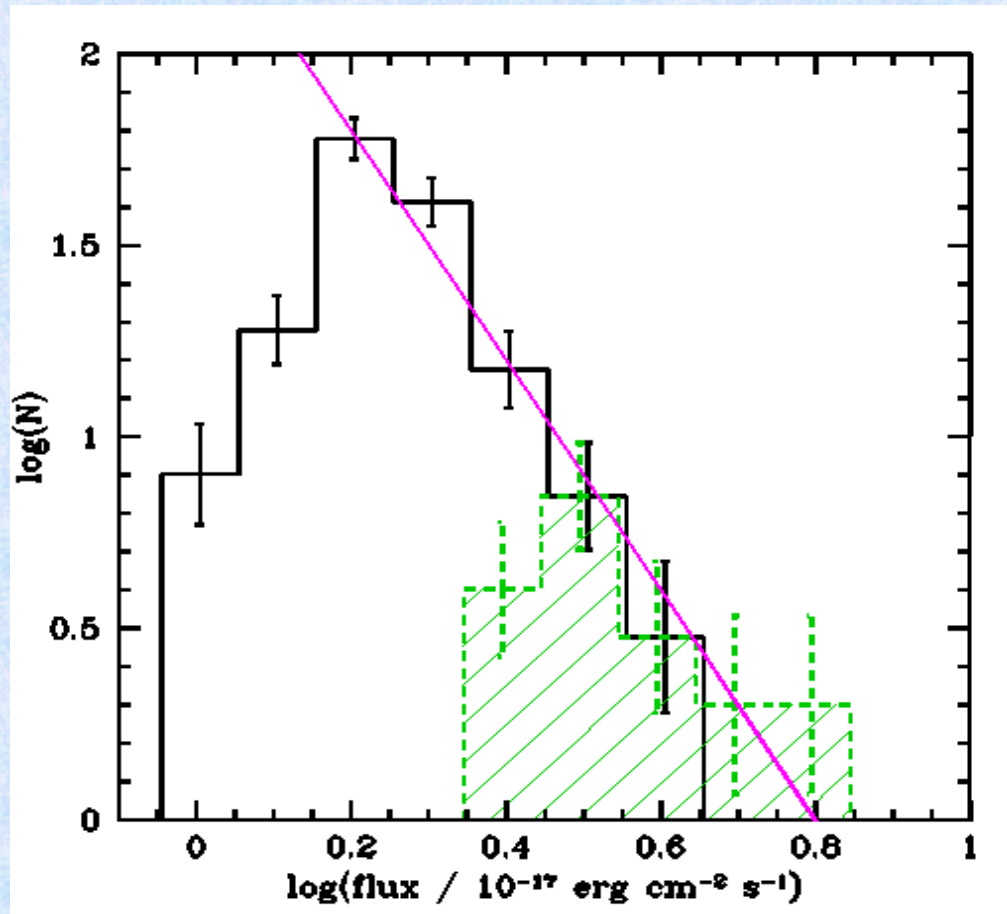
(Madau & Rees 1999; Rhoads & Malhotra 2001; Haiman 2002)

A 1.2 Mpc bubble gives line center optical depth $\tau = 1$.

Some Ly- α flux from the red wing of the emission line will escape from still smaller bubbles (Haiman 2002).

But, the Ly- α luminosity function is steep...

Steep Luminosity Function for Lyman α Galaxies



Number-flux relations for Lyman α galaxies from the LALA survey. Scaled to redshift $z=5.7$.

Black: $z=4.5$ data;
Green: $z=5.7$ data.

Red line: $N \sim f^{-3}$

Requirements for a Lyman- α Topological Test

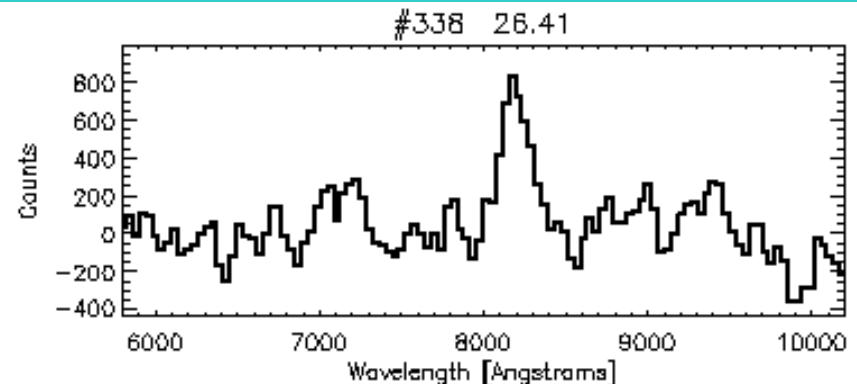
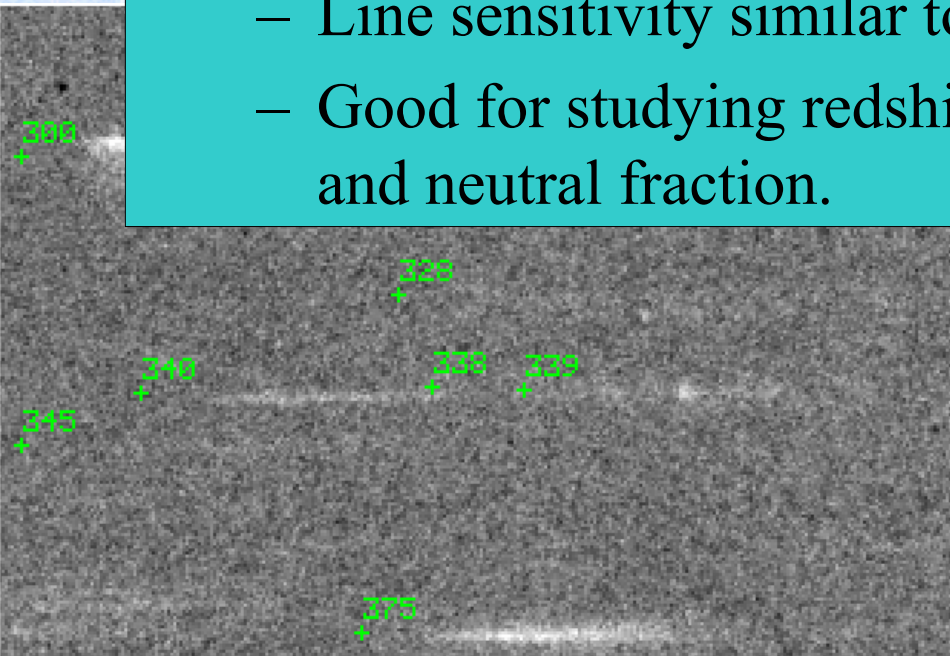
- Ionized bubbles large enough to yield $\tau < 1 \rightarrow R > 1.2 \text{ Mpc}$
- Multiple sources per bubble (to allow genus measurements unbiased by discreteness).
- Control sample (Lyman break galaxies) to determine intrinsic topology of galaxy distribution.

Observational Methods

- Narrowband imaging: E.g., the LALA survey.
 - Currently, two 0.3 square degree fields imaged at $\lambda = 662$ nm, and one also at 820 nm and 918 nm.
 - Redshifts $z(\text{Ly } \alpha) = 4.5, 5.7, \text{ and } 6.5$; $\Delta z = 0.1$ to 0.2 .
 - Sensitivity $\sim 2 \cdot 10^{-17}$ erg/cm²/sec (5σ) in 80 Å filter.
 - Corresponding volume is $1.3 \cdot 10^6$ comoving Mpc³, and line luminosity $5 \cdot 10^{42}$ erg/s ($H_0=70, \Omega_m=0.2, \Lambda=0$).
 - Good for 2D tests at fixed redshift windows.

Observational Methods

- (Slitless) spectra: E.g., the ACS Pure Parallel Lyman- α Emission Survey (APPLES) and the GRISM ACS Program for Extragalactic Science (GRAPES).
 - 11 deep APPLES fields (11 sq. arcmin each)
 - One UltraDeep GRAPES Field coming up
 - Uninterrupted redshift coverage, $4 < z < 7$.
 - Line sensitivity similar to LALA at APPLES depth.
 - Good for studying redshift evolution of Ly- α sources and neutral fraction.



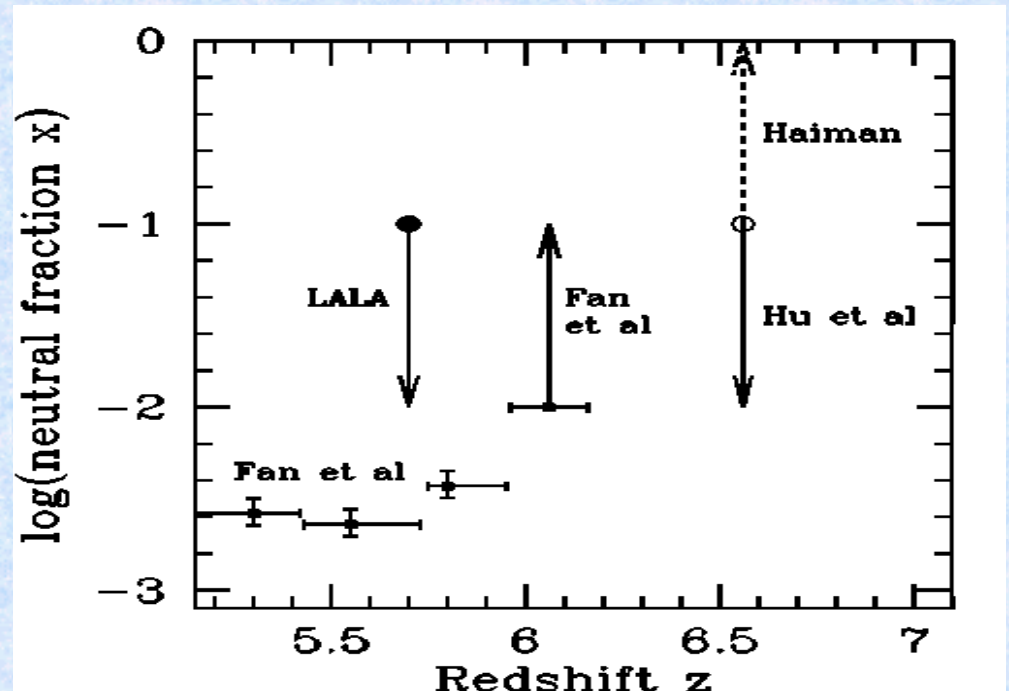
The 21 cm Line Test of Topology

- The 21cm line of neutral hydrogen is a promising alternative to Ly- α emission.
- Emission comes directly from the IGM \rightarrow “sampling” and minimum bubble size are lesser concerns than with Ly- α .
- Thin slices in velocity space \rightarrow 2D topology; data cubes \rightarrow 3D topology.
- Concerns: Peculiar velocities? Foregrounds?
...A cleaner test, but may not be practical so soon.

Expectations for $z=6.6$ window

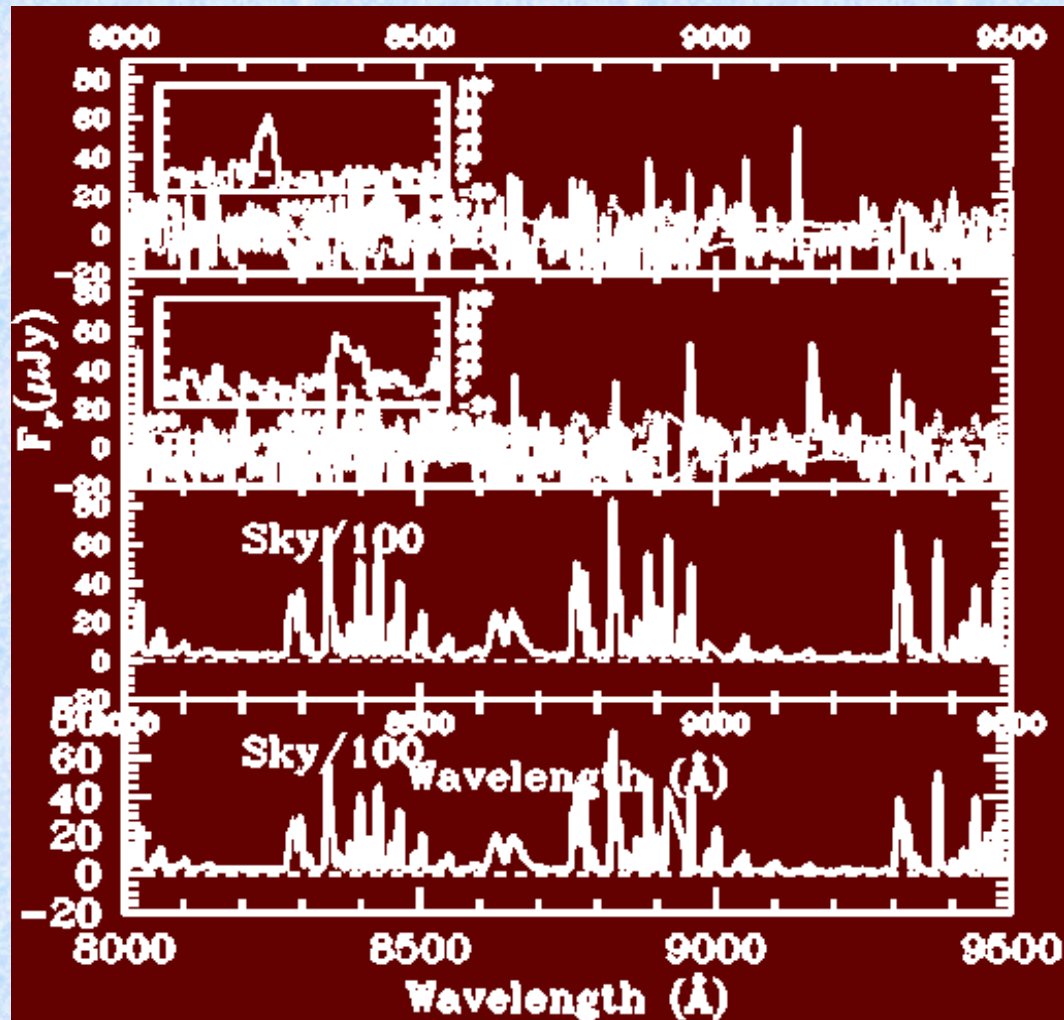
- The neutral fraction at $z=6.6$ may be too low to expect a strong signature in Lyman α sources. (Figure from Rhoads et al 2003)

- Equivalent widths in first $z=6.6$ sources are lower than $z=4.5$ LALA survey EWs; but LALA $z=6.5$ candidates **do** show large EW.



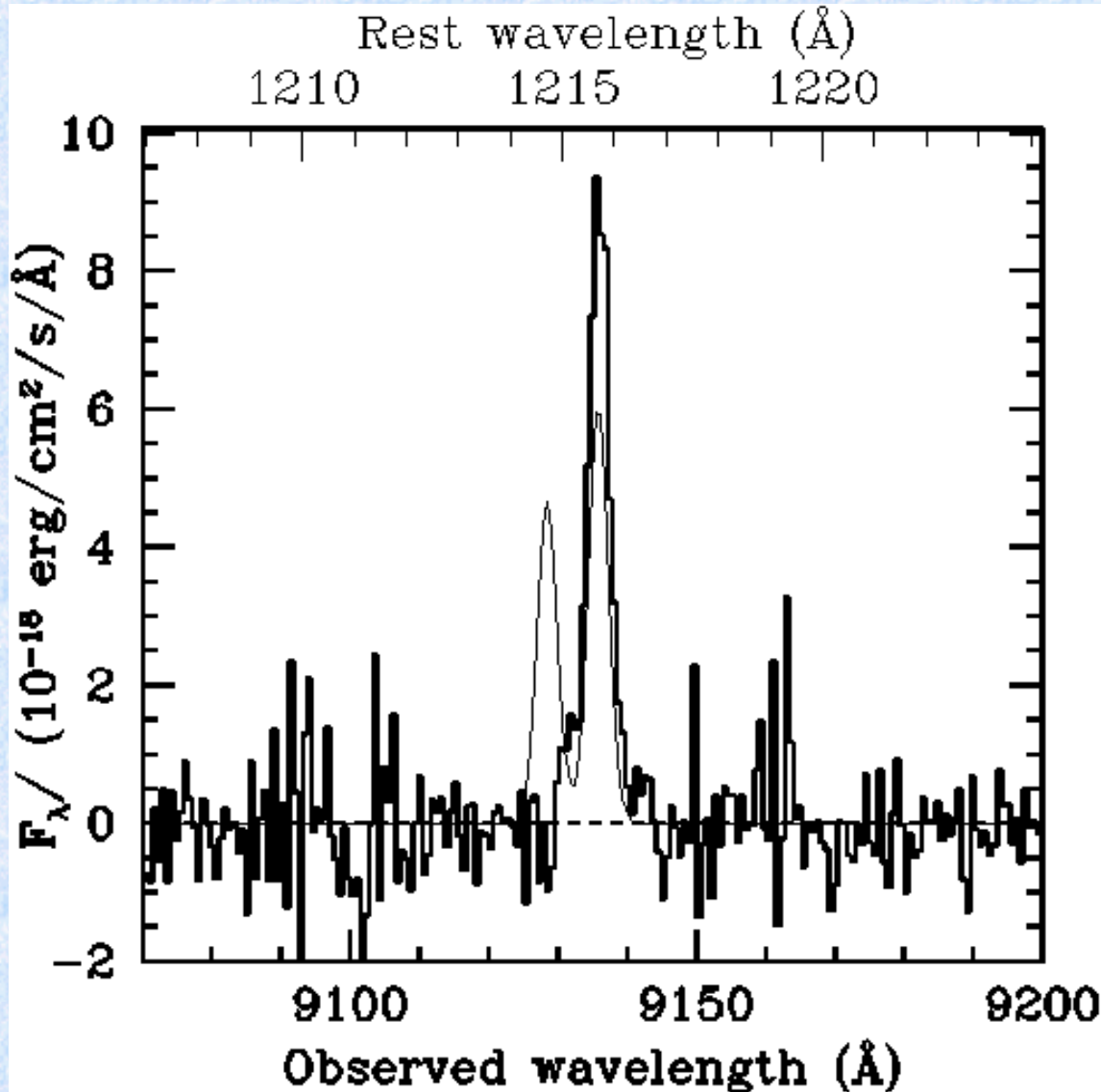
- So, large area surveys at 9200\AA might show a reionization signature. More data could resolve this shortly.

Z=6.5 Candidate Spectra from LALA



- Gemini + GMOS spectra of two z=6.5 candidates from LALA: Both show emission lines around 9150 \AA ; at least one is likely to be at z=6.5.

Z=6.5 Candidate Spectra from LALA



- Keck + DEIMOS spectrum of a $z=6.5$ candidate from LALA: The observed line is too narrow to match any physically plausible OII 3727 \AA doublet.

Conclusions

- For some wavelength, $0.9 < \lambda < 2.4 \mu\text{m}$, we will see a drop in Lyman- α source counts and a rise in 21cm brightness, indicating neutral gas.
- The Lyman- α source counts and 21cm maps near this redshift may show a topological transition from a percolating ionized medium to isolated bubbles.
- If Ly- α does not show this effect, the characteristic ionized bubble size before overlap should be < 1 Mpc (proper length), implying low-luminosity or short-lived sources.

Outline for Elba Reionization talk

- Critical review of Gunn-Peterson test: Above all, comment on min. neutral fraction
- Physical background for LyA emitter test: Mention Miralda-Escude 1998, M-E and Rees, Madau and Rees, Haiman and Spaans, Loeb and Rybicki
- Introduce LALA survey
- Compare statistics at $z=4.5$ and at $z=5.7$ as application of test.
- Show a couple $z=5.7$ spectra for completeness
- Mention the Hu et al object
- Loopholes: Mention them and close them.
 - HII regions
 - Winds
 - Broad lines
 - Neighbors?
 - $\tau=1$ not opaque (Haiman 2002)
- Advertise LALA $z=6.6$ search? (Try to do some basic statistics before finalizing this move...)

Outline for Tucson Reionization talk

- Discuss topological nature of the overlap transition
- Difficulty of 2D probes from rare quasars
- Physical background for LyA emitter test: Mention Miralda-Escude 1998, M-E and Rees, Madau and Rees, Haiman and Spaans, Loeb and Rybicki
- Mention LALA luminosity function; steepness of this is pretty important for the test to be a “slam dunk”
- Requirements for topological test with LyA emitters, caveats
 - Bubble size minimum, control sample, sufficient area, sufficient target density
- Observations: Mention LALA, mention APPLES, mention Hu and Kodaira
- Discuss topological expectations for $z=6.6$ window? Include figure from Rhoads et al 2003 to show that we may still have neutral fraction below 10%; perhaps show Equiv. Widths of three known sources.
- Close with “flow chart” discussion that shows even a non-detection of this signature to be interesting physically.

To Do for U of A talk

Check on number of sources per bubble down to LALA luminosity limit; estimate how much fainter one must go to get a few sources per bubble at the 1 Mpc proper size scale.

Draw sketches of genus vs. reionization phase. Appropriate X axis parameter is probably the volume fraction ionized. Assume that regions are either ionized or neutral. Disregard at first the likelihood of an early Pop III reionization... This part also contributes new material to the paper. After overlap, it is pretty clear that the low density regions are ionized and the high density ones are neutral, by and large; this comes both from Gnedin's simulations and from Miralda-Escude et al's analytical work. So after overlap, we are basically measuring an isodensity contour drawn to enclose the volume neutral fraction. And we therefore just sample the conventional genus curve at some value of v corresponding to the volume neutral fraction. Before overlap, though, we pretty much have only isolated bubbles— not much that is multiply connected. Estimate the volume neutral fraction at overlap from Gnedin's paper.

Can we *test* Cen's model using topological statistics? The recombined regions at $z \sim 8$ will be dominantly the densest ones. We can then use Gott's v to estimate the genus number of the interface as a function of the volume fraction that remains ionized.

Check the sign convention and definition of 2D genus. Pretty easy really: Every closed contour must contribute +1 if it encloses a high density region and -1 if a low density region, right? So a usual topo map would show mostly positive genus (hills on a plain) except near Arecibo (holes in the ground).

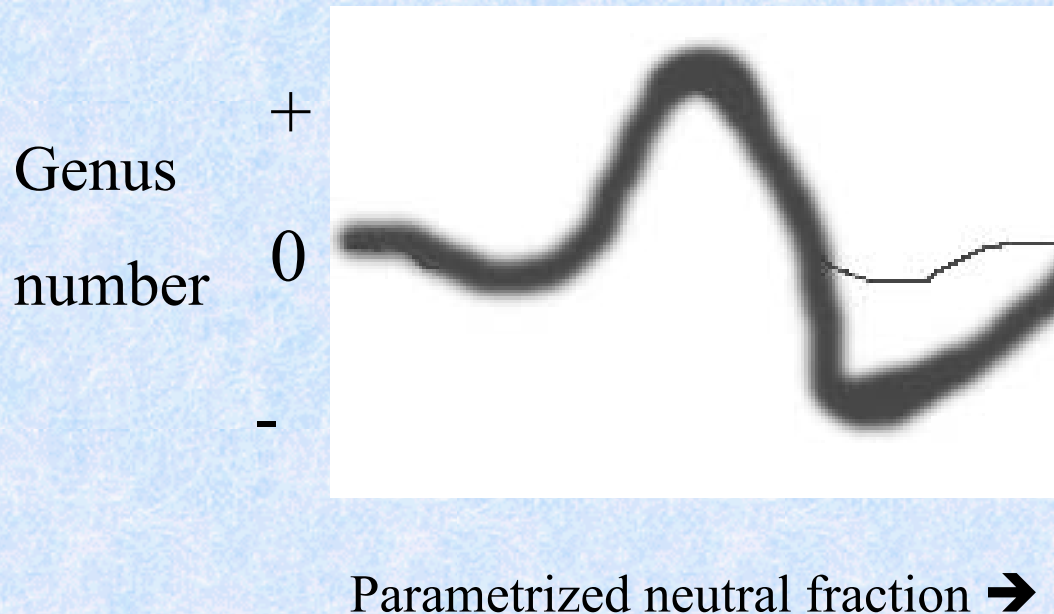
Work in more advertising for LALA, APPLES, and upcoming projects.

Estimate the solid angle required to sample a bubble at the 1.2 Mpc scale; see how this compares to LALA, use that to advertise LALA and say what more could be done with similar cameras.

Understand what kind of source corresponds to a 1.2 Mpc bubble anyway.

$G_{3,I}(z)$ and $G_{2,I}(z)$

- We can sketch the predicted genus number of the ionized/neutral interface as reionization proceeds:



The Gunn-Peterson Test

Gunn-Peterson Trough:

- Requires a highly luminous background source.
 - Proximity effect...
 - Cosmic variance...
- Sensitive to optical depths $\tau \sim 5$.
 - Corresponding neutral fraction $x \sim 10^{-4}$ if IGM uniform.
 - Even for clumpy IGM, $x \sim 10^{-2}$ (mass averaged) is enough (Fan et al 2001).
 - Overlap phase corresponds to $x \sim 10^{-1}$ (mass averaged) based on Gnedin 2000.

HII Regions in $z > 5$ Lyman α Samples

- An HII region must be > 1.2 Mpc (non-comoving) to reduce the line center optical depth to $\tau < 1$.
- This requires a minimum value of the ionizing photon production, $L_i t f_{\text{esc}}$.
- We have shown that $L_i t f_{\text{esc}}$ is $< 30\%$ of threshold in $z = 5.7$ Ly- α sources from the Large Area Lyman Alpha survey.
- At $z=6.6$, the limit for the Hu et al source is similar, thanks to its low physical luminosity. The Kodaira et al sample may have larger $L_i t f_{\text{esc}}$.

The Lyman α Test, First Order

Concerns: $\tau \sim 2 < \tau \sim \infty$

- Our threshold HII region size was based on $\tau_0 = 1$ at emitted line center, and of course $\tau < \tau_0$ in the red wing.
- Net effect: The Hu et al source could be embedded in a fully neutral IGM and still get 10 to 20% of its Lyman α flux out (Haiman 2002).
- However, the *observed number* of Lyman α emitters above a fixed threshold will still show reionization clearly.

The Large Area Lyman Alpha (LALA) survey

- In 1998, Sangeeta Malhotra and I started a project to identify a large sample of high redshift Lyman α emitters.
- We achieve unprecedented survey efficiency using the 8192^2 pixel Mosaic camera at the Kitt Peak National Observatory 4m Mayall telescope.
- $A\Omega(4m+Mosaic) = 5 \times A\Omega(\text{Keck}+LRIS \text{ imaging})$

LALA Survey Parameters

- Currently, two 0.3 square degree fields imaged at $\lambda = 662$ nm, and one also at 820 nm and 918 nm.
- Redshifts $z(\text{Ly } \alpha) = 4.5, 5.7, \text{ and } 6.5$.
- Sensitivity around $2 \cdot 10^{-17}$ erg/cm²/sec (5σ) line + continuum flux in 80 Å filter.
- Corresponding volume is $1.3 \cdot 10^6$ comoving Mpc³, and line luminosity $5 \cdot 10^{42}$ erg/s ($H_0=70, \Omega_m=0.2, \Lambda=0$).
- 20 Lyman α emitters spectroscopically confirmed, most at Keck (w. Spinrad, Stern, Dey, Dawson), rest at Gemini (w. Brown, Dey, Jannuzi).

Constraining Reionization with LALA

- We see Lyman α emitters at $z = 5.7$, and the luminosity function is effectively unchanged from that at $z = 4.5$.

- Thus, **the reionization redshift is $z > 5.7$.**

(Rhoads & Malhotra 2001, ApJ Lett 563, L5)

- Perhaps extended to **$z(\text{reionization}) > 6.56$.**

(Hu et al. 2002)

The Lyman α Test, Second Order Concerns

- Galactic winds?
- Infall?
- Bright neighbors?
- Strong evolution?

Quick estimates suggest that none are plausible loopholes (work in progress; Rhoads, Voit, Malhotra).

Charting Reionization

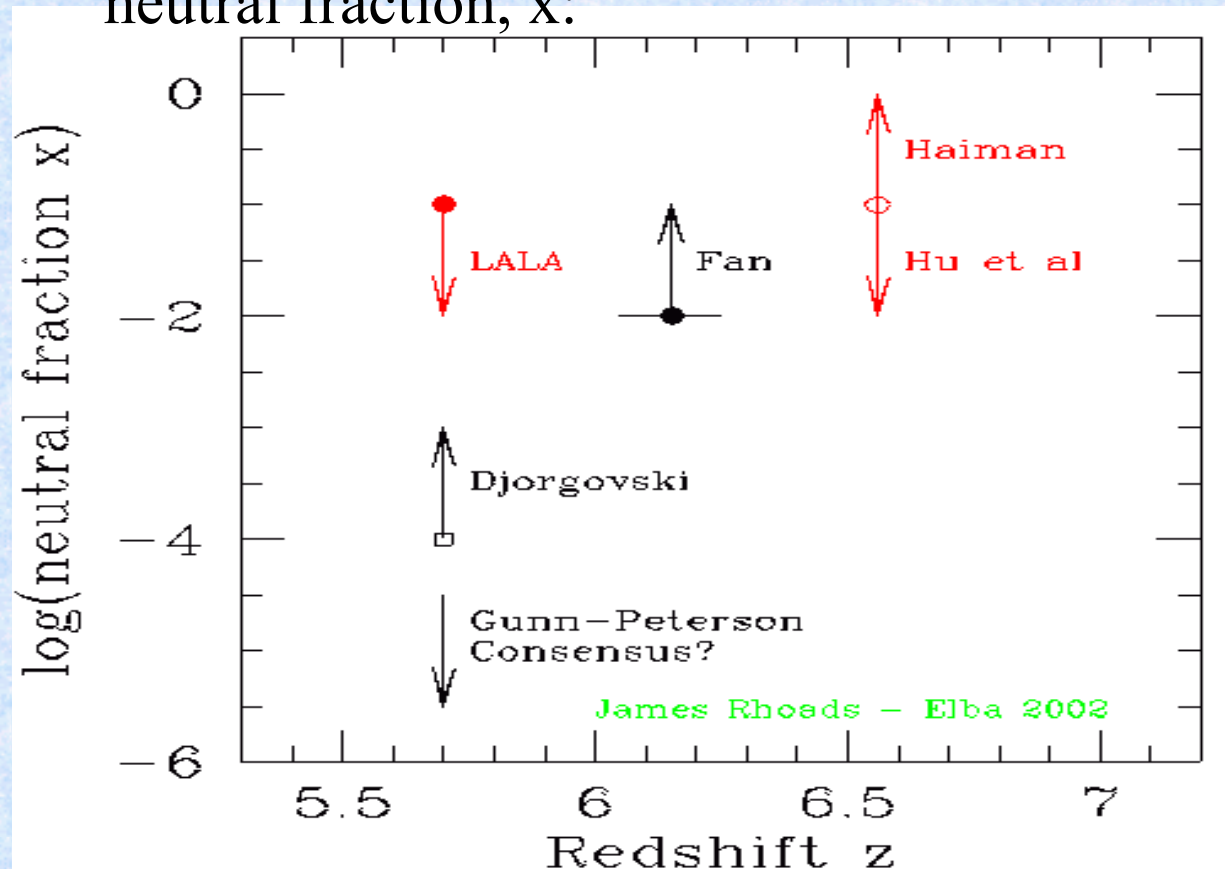
Current evidence: Combine the Lyman α and Gunn-Peterson tests so far to study the evolution of the mass averaged neutral fraction, x :

- $x \sim 0$ at $z = 5.7$ (Ly α : Rhoads & Malhotra 2001, GP: several);
- $x > \sim 0.01$ at $z = 6.2$ (GP; Fan et al);
- $x < \sim 0.1$ at $z = 6.56$ (Hu et al source; substantial systematic uncertainty due to sample of 1).

There is no contradiction between the GP effect at $z=6.2$ and the Ly α at $z=6.56$.

Charting Reionization

Current evidence: Combine the Lyman α and Gunn-Peterson tests so far 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 $z=6.56$.

The Lyman α Test: Future Prospects

Redshift 6.5 data from LALA is in hand; analysis underway.

The ACS Pure Parallel Lyman- α Emission Survey,

“APPLES”

Approved for 175 parallel orbits in HST cycle 11.

Team: J. Rhoads, S. Malhotra, C. Gronwall, Z. Tsvetanov, J. Walsh, Z. Haiman, A. Cimatti, S. Cristiani, E. Daddi, A. Pasquali, N. Pirzkal, S. di Serego Aligheri, J. Vernet

A slitless spectroscopic search to

- Find ~ 1000 Lyman α galaxies at $4 < z < 7$
- Study their evolution
- Determine the mean and scatter in $z_{\text{reionization}}$.
- Study star formation at lower redshifts with H and O lines.

Summary

- Lyman α galaxies offer a new probe of the reionization redshift.
- This test complements the Gunn-Peterson trough by probing higher neutral fractions.
- Current evidence: Mass avg. neutral fraction, x , is
 - $x \sim 0$ at $z = 5.7$ (Ly α : Rhoads & Malhotra 2001, GP: several);
 - $x > \sim 0.01$ at $z = 6.2$ (GP; Fan et al);
 - $x < \sim 0.1$ at $z = 6.56$ (Hu et al source).
- Future Directions: $z=6.5$ data from LALA and continuous $4 < z < 7$ coverage from APPLES.

Lyman α as a Signpost of Primordial Galaxies

We are looking for the first galaxies to form from primordial gas. Such objects should have...

- Young stars, with high ultraviolet luminosities.
- Considerable amounts of gas.
- Very low abundances of heavy elements, implying
 - Stars that are hotter than “normal” (for fixed mass);
 - Low dust abundances.

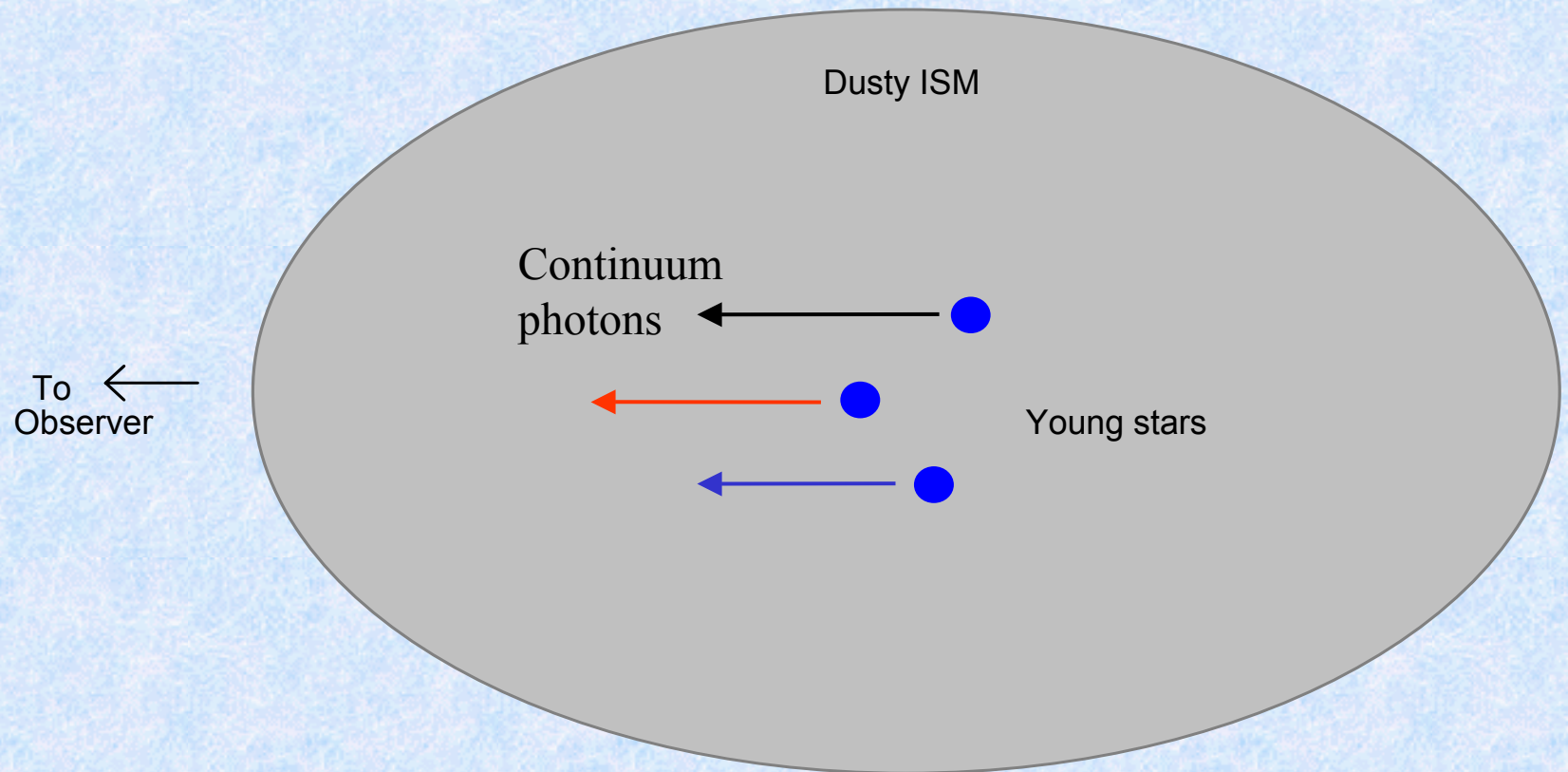
Lyman α Line Emission

- Ionizing flux + gas \rightarrow 2 Lyman α photons for every 3 ionizing photons absorbed by hydrogen.
- In principle, up to 6-7% of a young galaxy's luminosity may emerge in the Lyman α line.

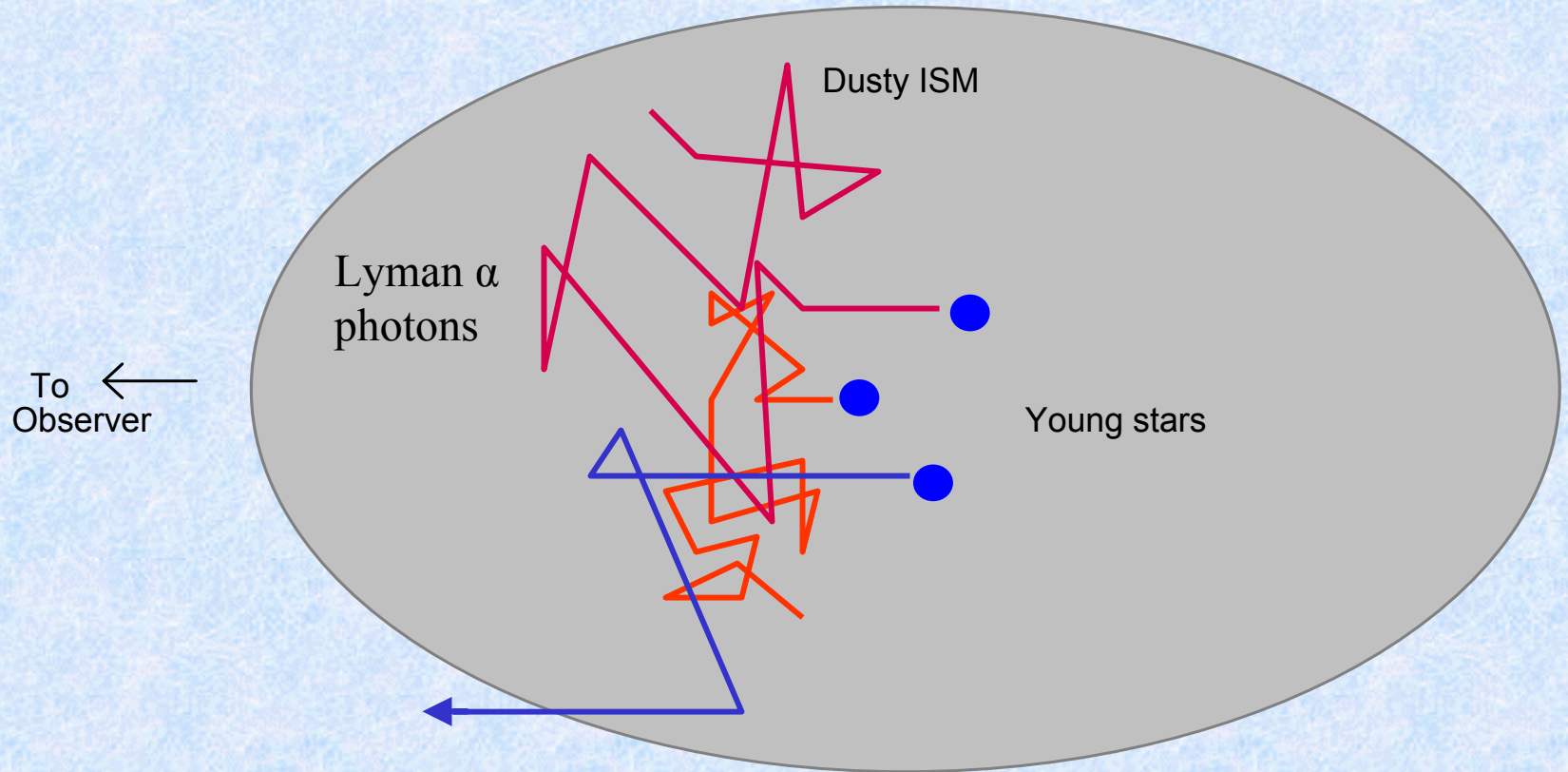
A Very Compressed History

- 1967: Partridge & Peebles proposed the Lyman α line as a signpost of galaxy formation.
- 1967-1997: Many searches, no galaxies (except near previously known high- z objects): (Koo & Kron 1980; Pritchett & Hartwick 1987, 1990; Cowie 1988; Rhee et al 1989; Smith et al 1989; Lowenthal et al 1990; Wolfe et al 1992; De Propris et al 1992; Macchetto et al 1993; Moller & Warren 1993; Djorgovski + Thompson + Smith + Trauger in various permutations, 1992 through 1995).
- Many explanations for the lack of bright Lyman α emitters. Chief among them: effect of dust.

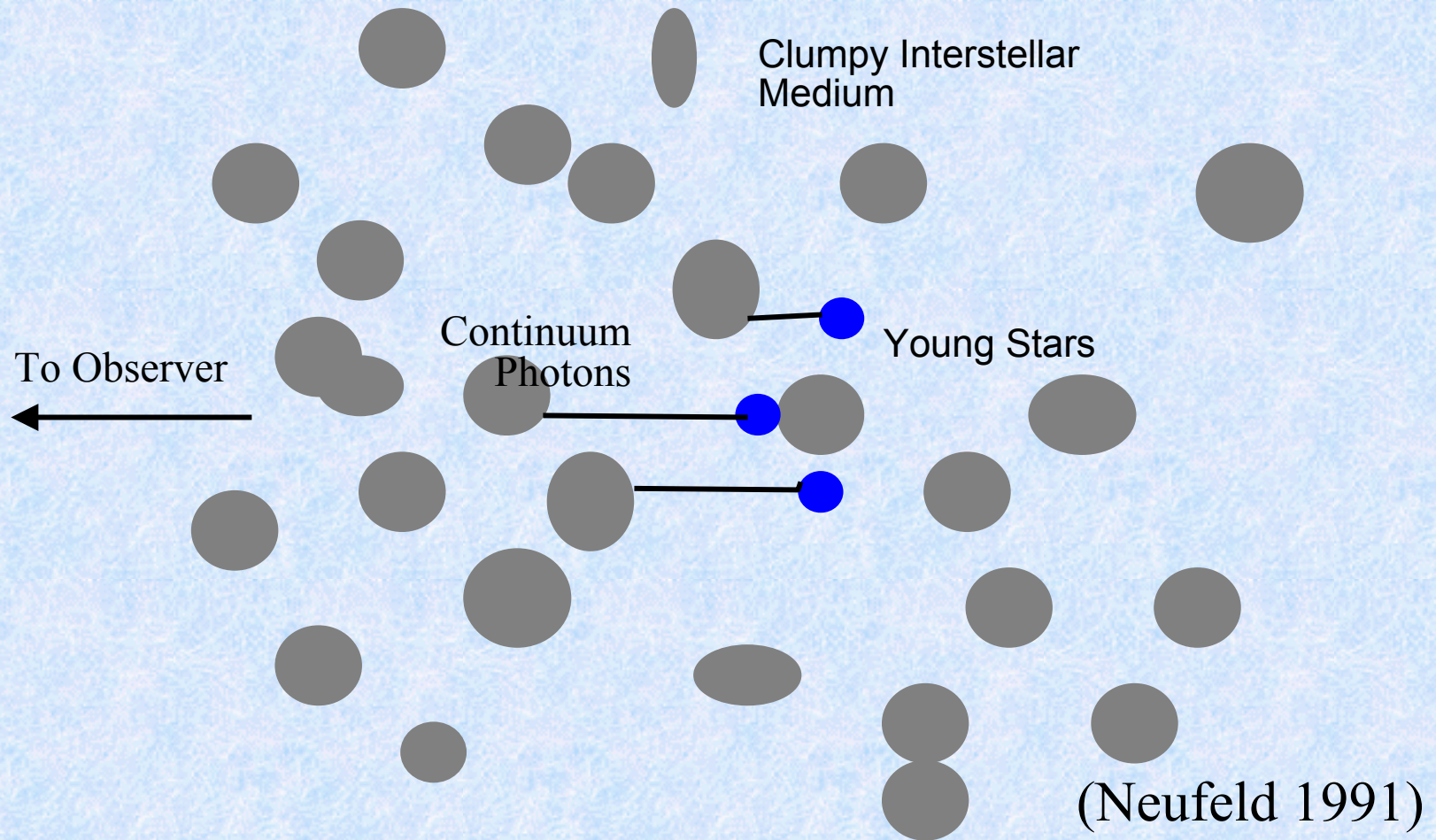
Resonant Scattering and Dust



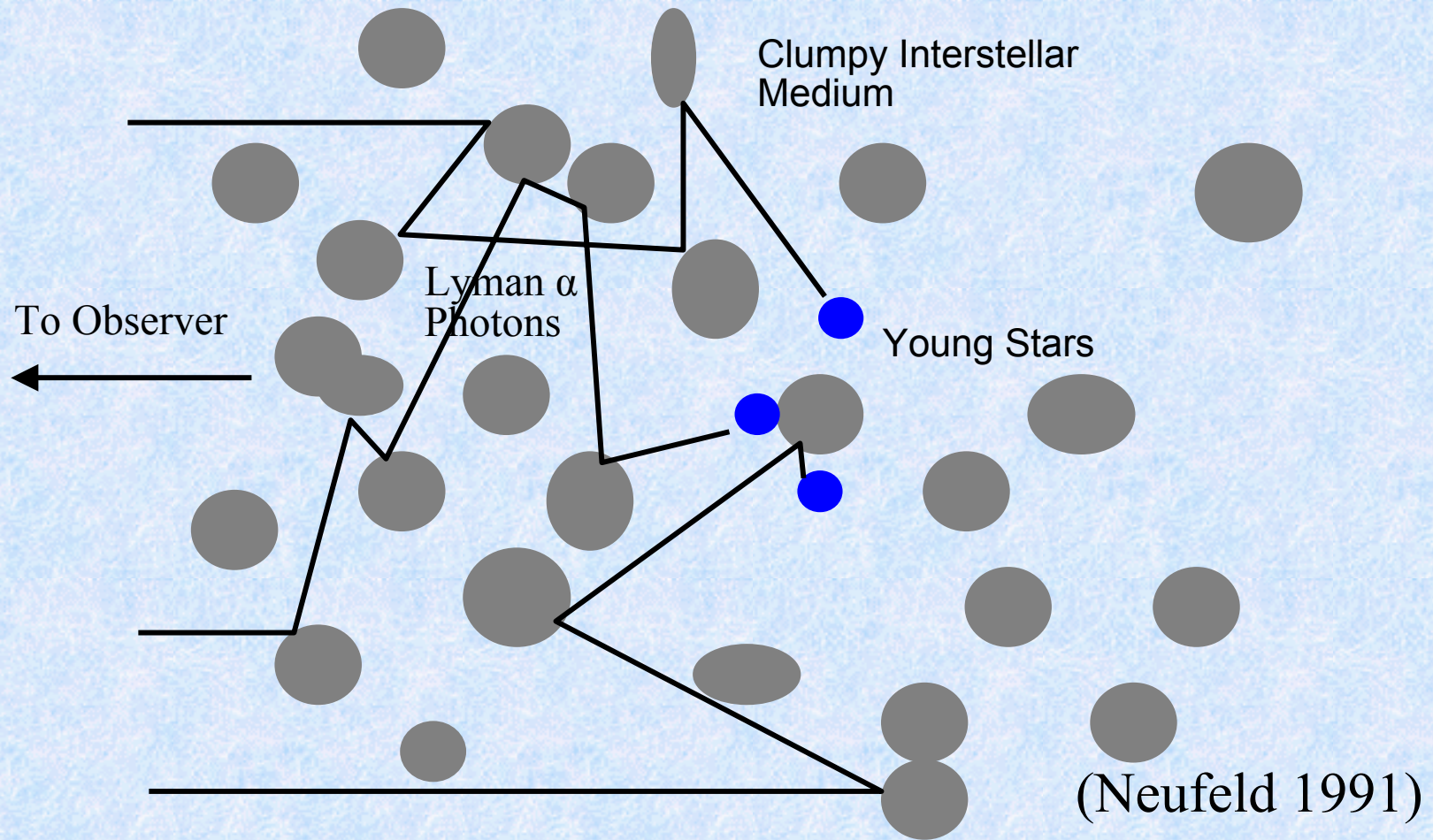
Resonant Scattering and Dust



Resonant Scattering in a Two Phase Medium



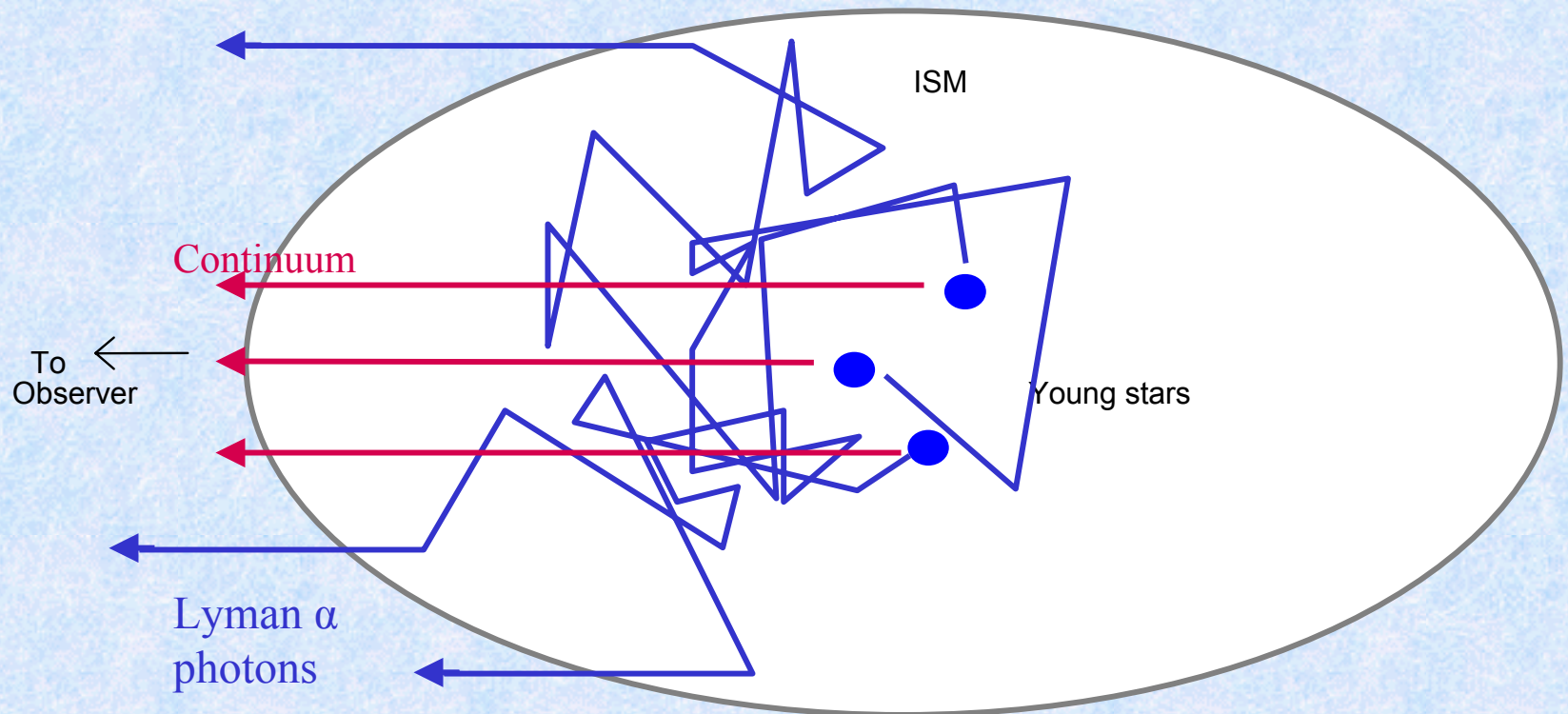
Resonant Scattering in a Two Phase Medium



Why are the Lyman- α sources so faint?

- Dust obscuration? (Low equivalent width.)
- Low surface brightness due to scattering.

Resonant Scattering *Without* Dust



Why are the Lyman- α sources so faint?

- Dust obscuration? (Low line to continuum ratio.)
- Low surface brightness due to scattering.
- Smaller star-formation units, which later merge to form bigger galaxies? (Low luminosity, but high equivalent width.)
- Star-formation protracted ($> 10^7$ years)? (Low luminosity, and low equivalent width.)

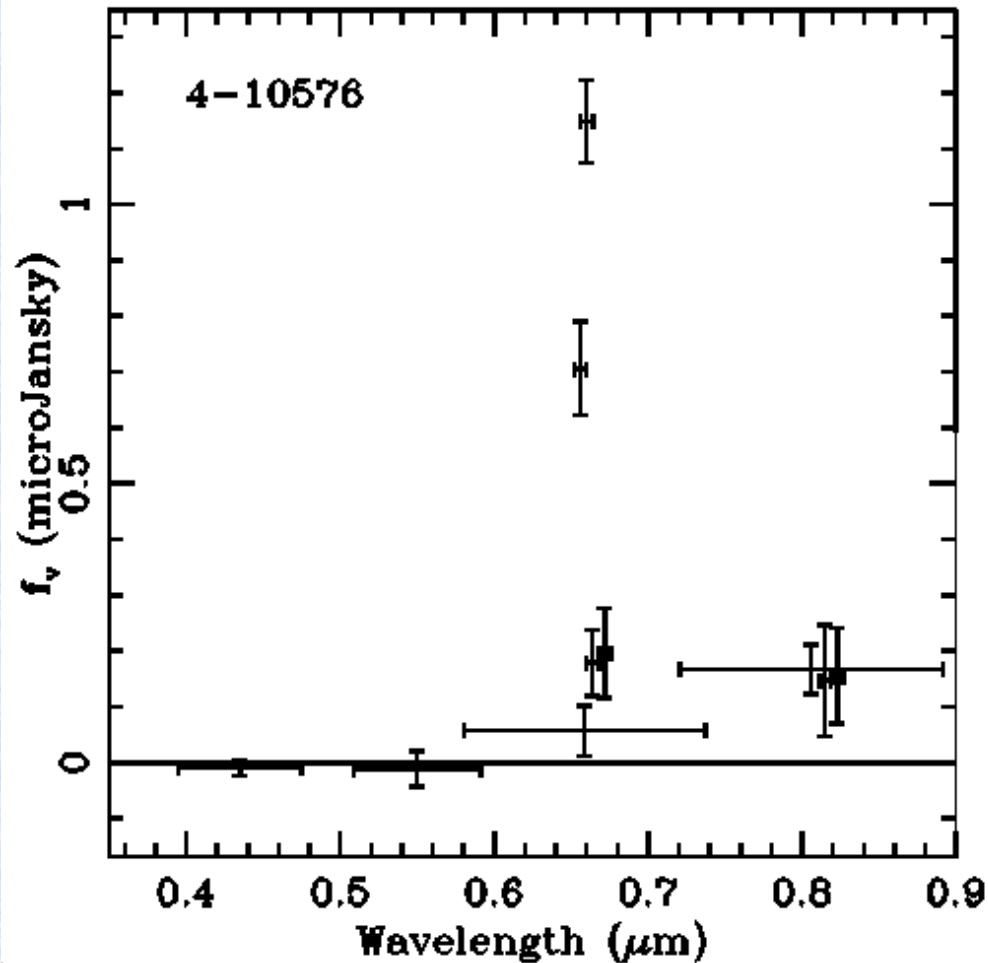
The Large Area Lyman Alpha (LALA) survey



In 1998, Sangeeta Malhotra and I started a new project to identify a large sample of infant galaxies at high redshift.

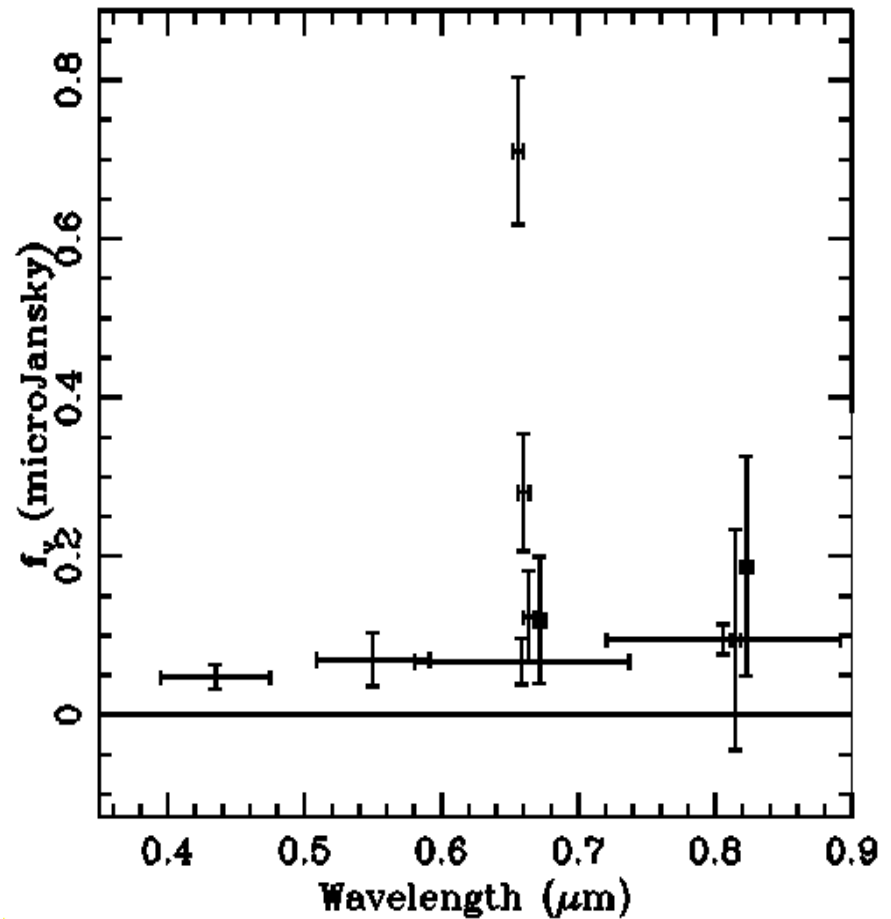
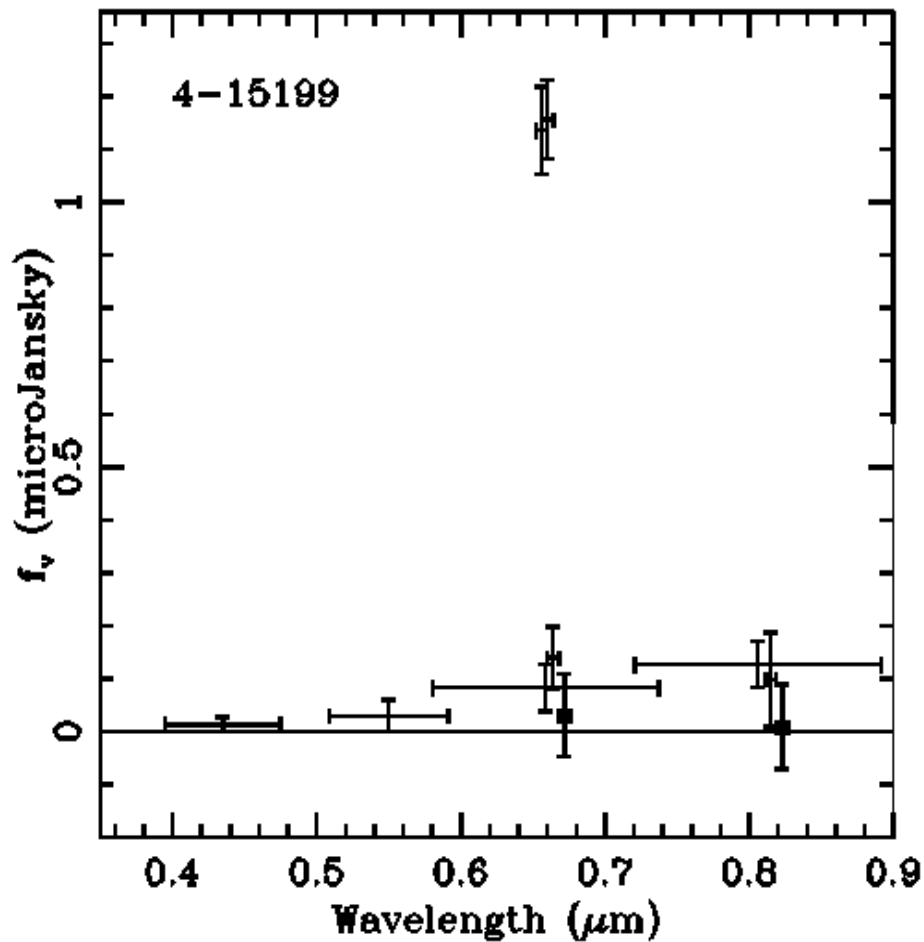
We achieve unprecedented survey efficiency by exploiting new large format detectors and narrow band filters.

Sample Mini-spectrum

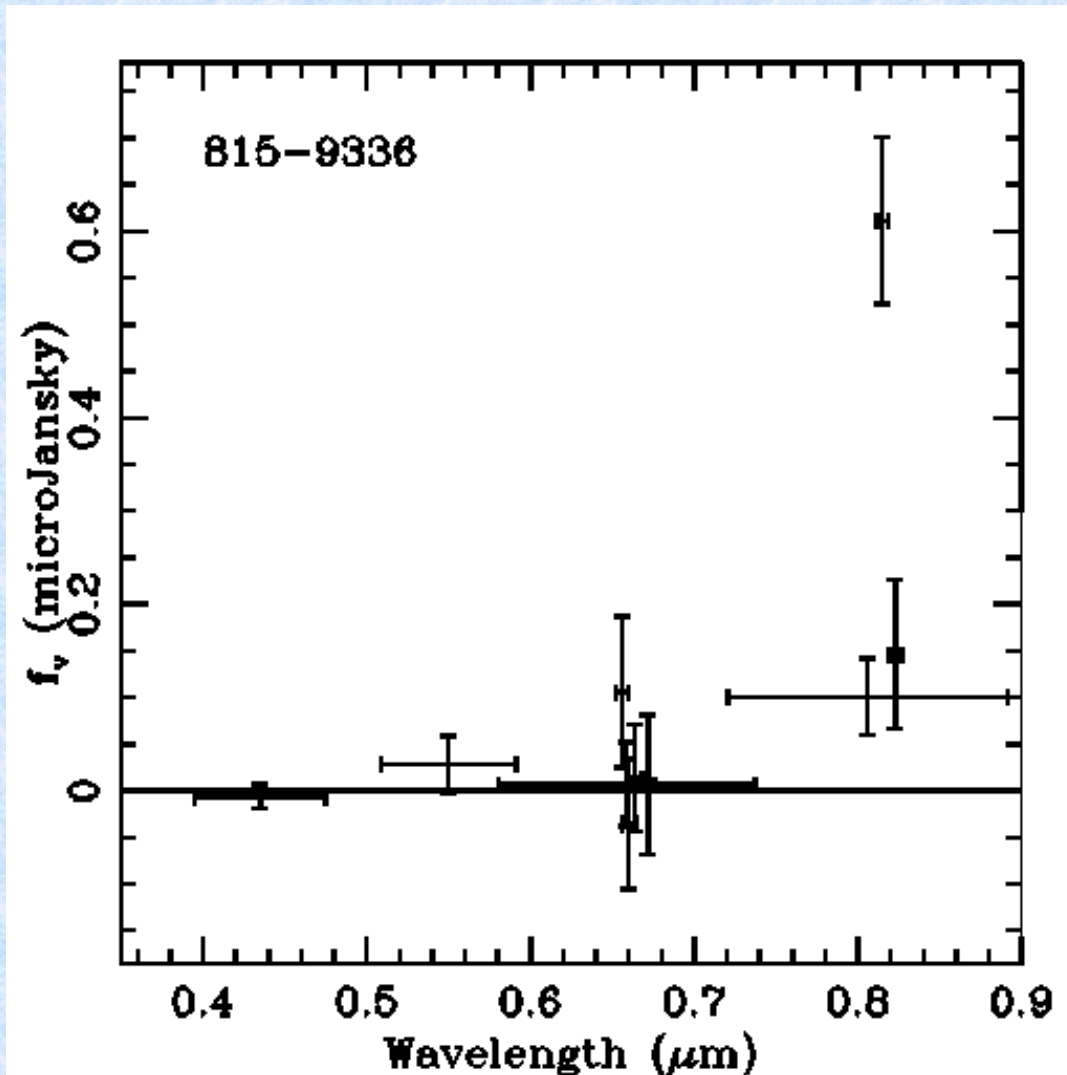


- A good candidate Lyman α emitter at redshift $z = 4.5$.
- The elevated narrowband fluxes show the presence of an emission line.
- The continuum is weakly detected on the red side of the line.

More good $z = 4.5$ candidates

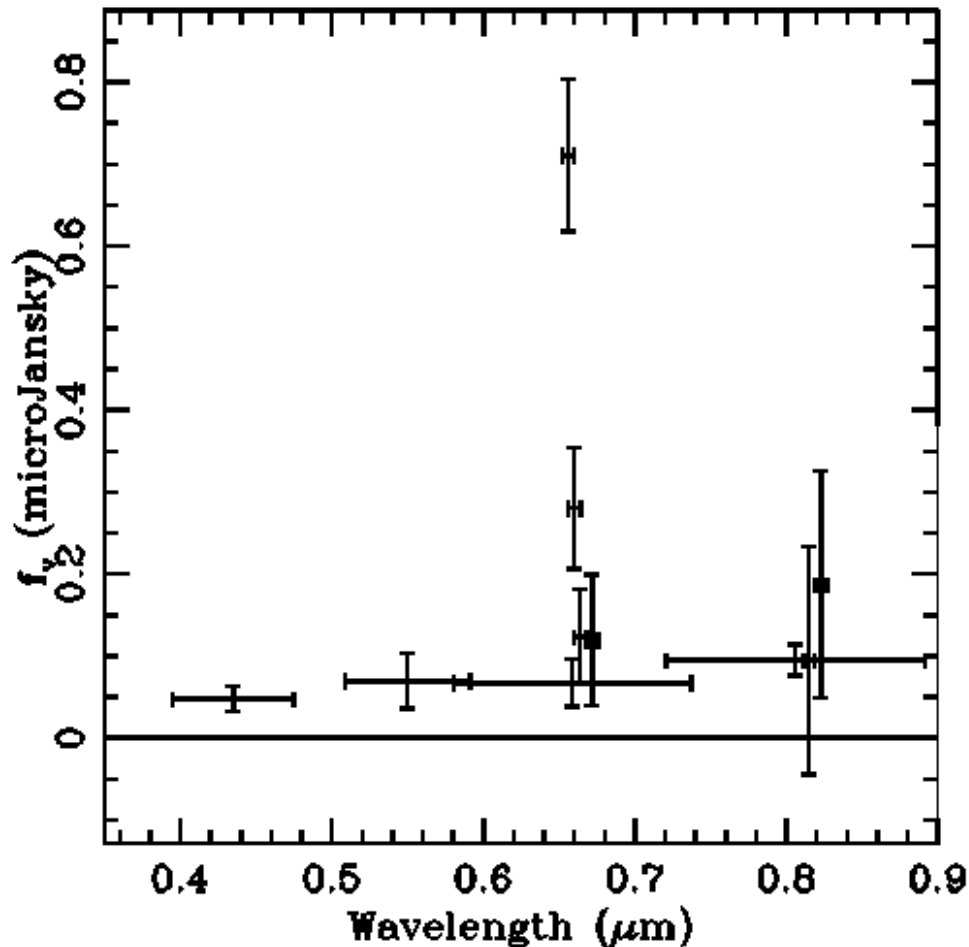


A good $z = 5.7$ candidate



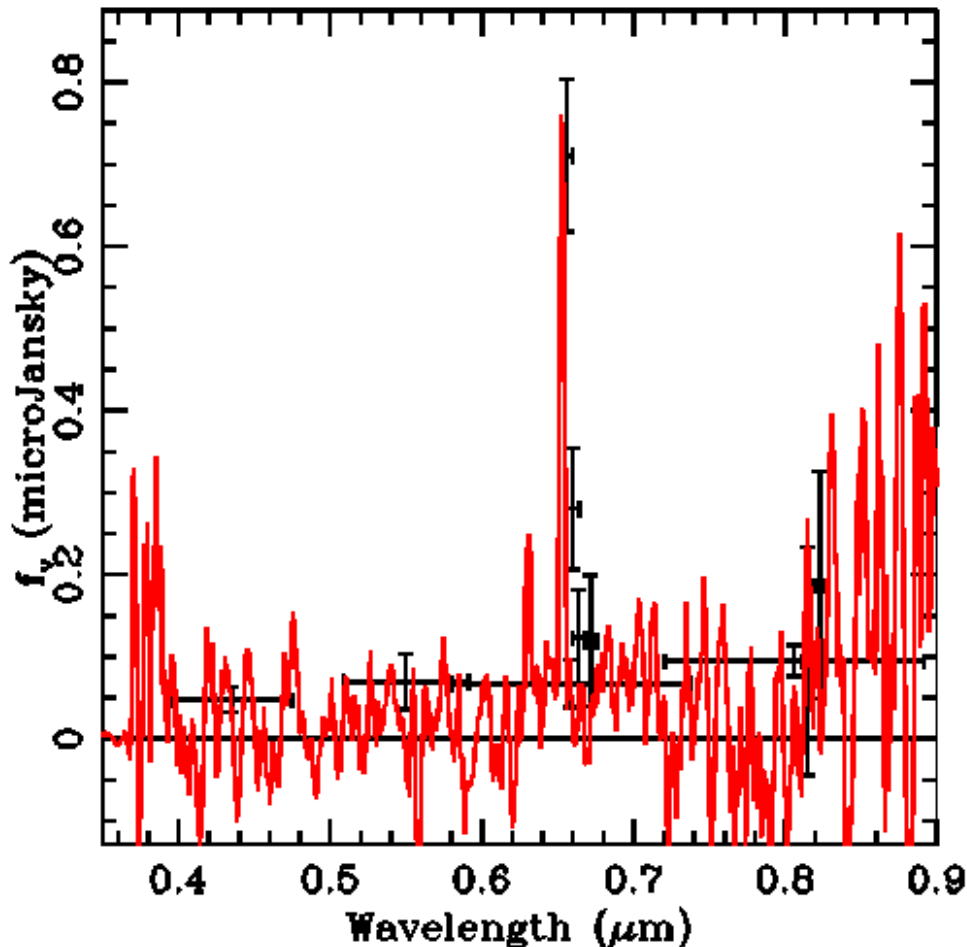
- The line is now at longer wavelength.

Benefits of real spectroscopy



- The “mini-spectra” are useful but have limitations.
- Only strong lines are apparent.
- The wavelength precision is limited with the narrow bands, and even worse where the narrow bands are unavailable.

Benefits of real spectroscopy



- Add a real spectrum (obtained at Keck by Dey, Spinrad, Stern, and collaborators).
- We can now confirm the presence of the line, look for other lines and/or continuum breaks, study line shapes, and measure precise redshifts.

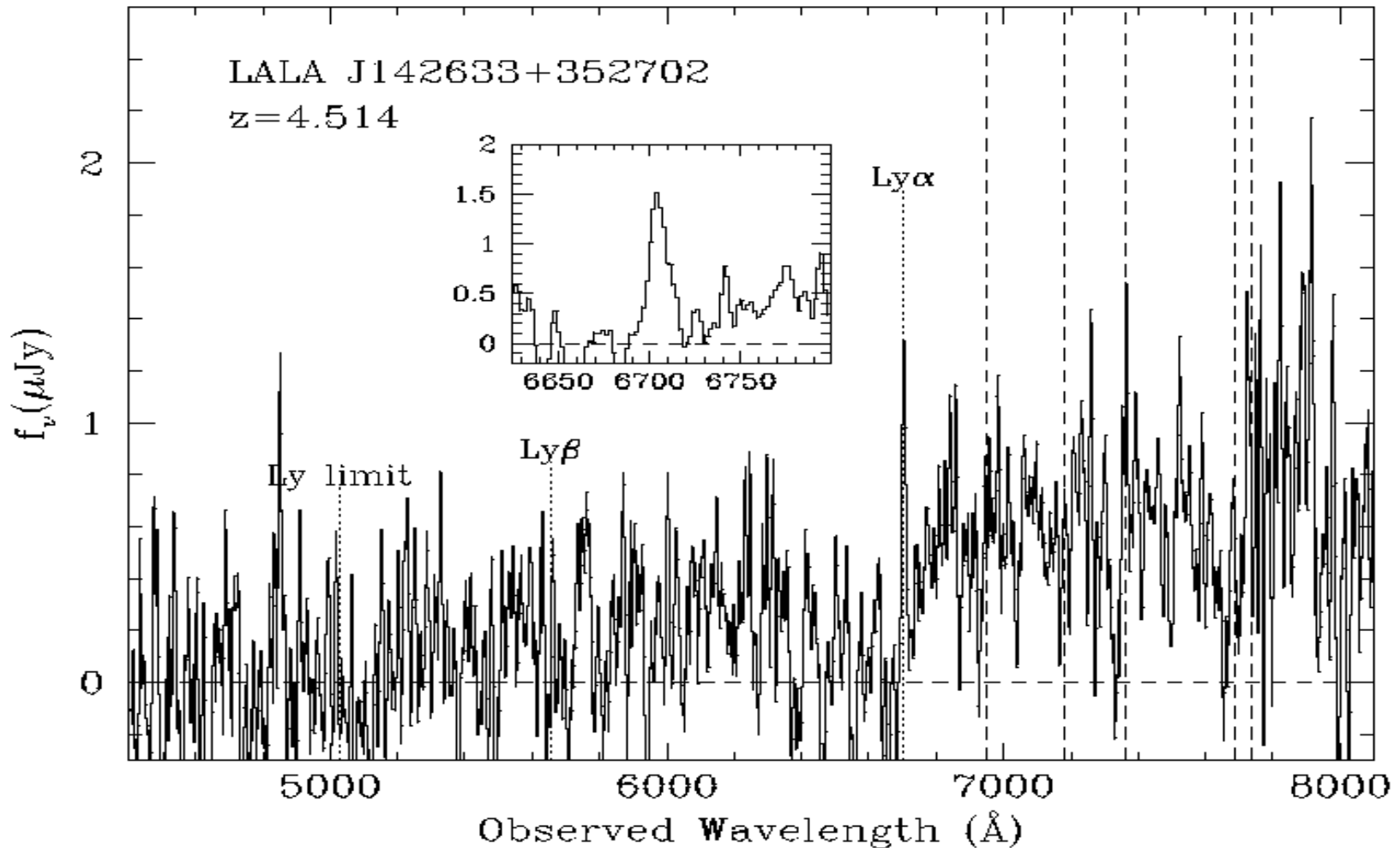
Spectroscopic Results

Pilot spectroscopy at Keck (Dey, Stern, Spinrad, Dawson):

- 14 confirmed Lyman α sources at $z = 4.5$;
- 3 confirmed Lyman α sources at $z = 5.7$;
- Most of these in the last 7 months.

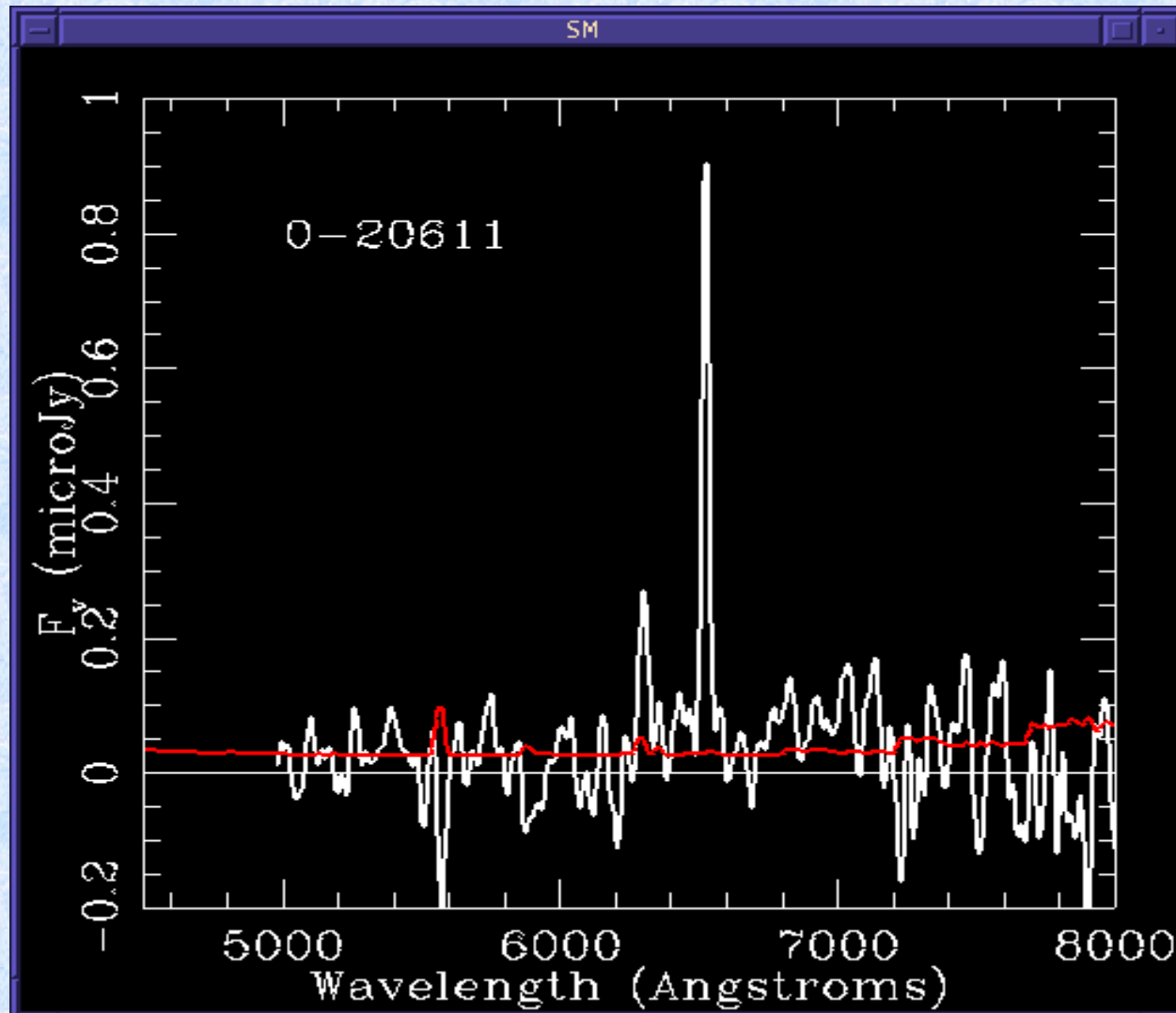
Ongoing work at Gemini should increase this sample substantially. Gemini has confirmed about 5 Lyman α sources from LALA so far.

A $z = 4.5$ Lyman α Emitter

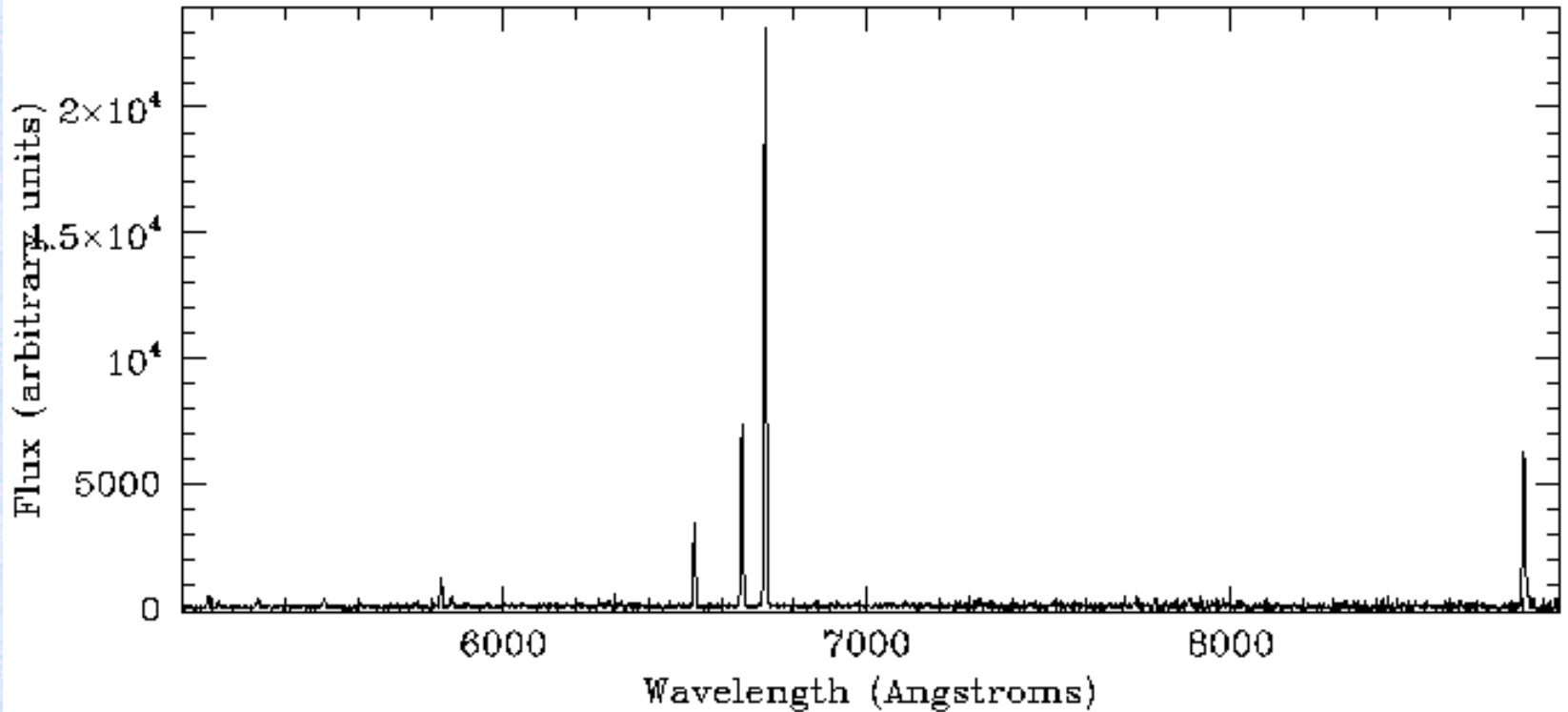


- A $z = 4.52$ Lyman α source. The line flux is $1.7 \cdot 10^{-17}$ erg/cm²/s.
- Note the strong break across the line, and the absence of flux beyond the Lyman limit.

Another $z = 4.5$ Lyman α Source

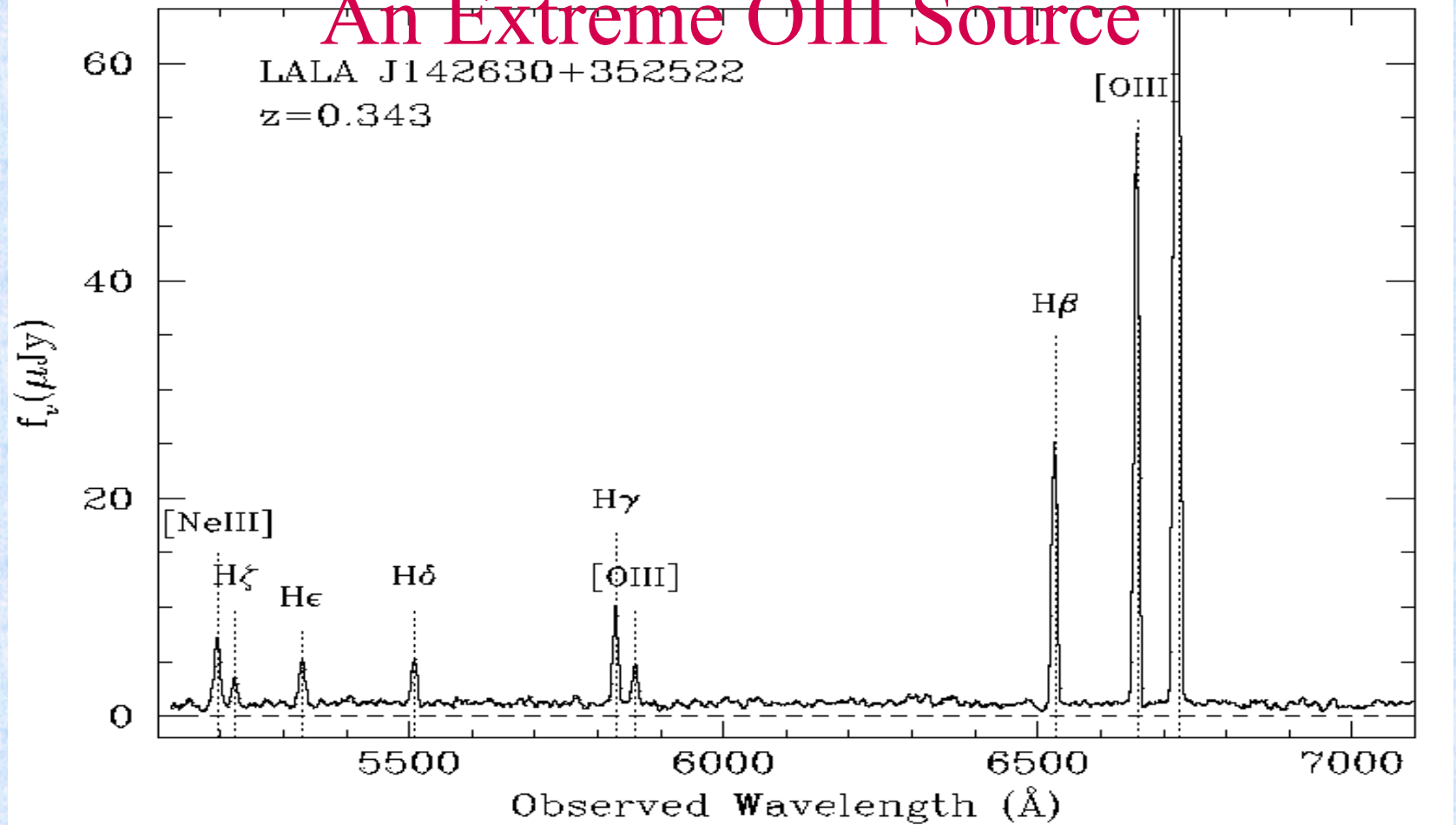


An Extreme OIII Source



- An extreme [OIII] emitter with an equivalent width around 1500 Å. Prominent lines (Right to Left): H α , OIII 5007, 4959, H β .

An Extreme OIII Source



- The same source, now shown for a more restricted wavelength range to highlight the weaker lines.

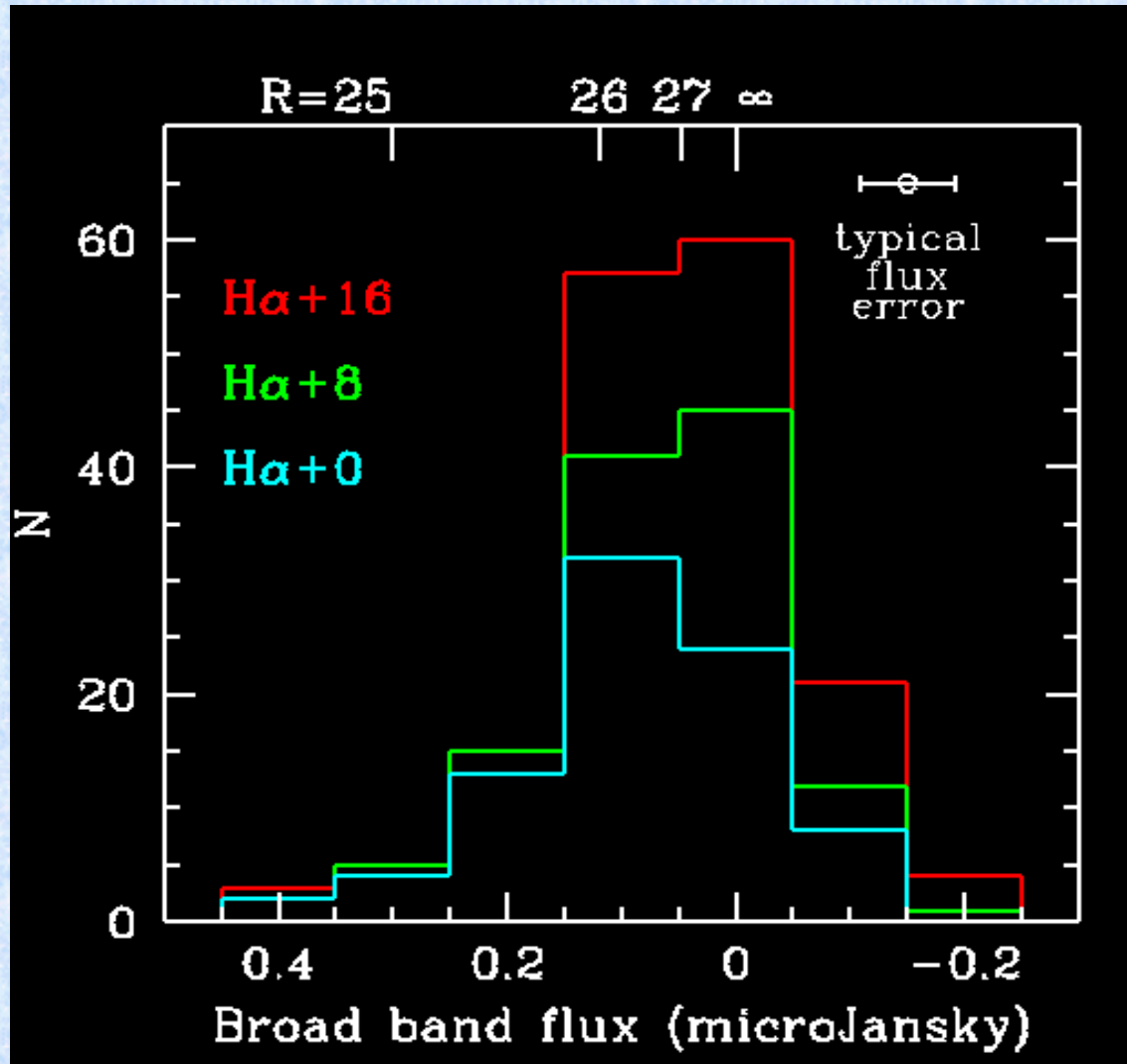
Local Analogs

- Local Lyman α emitters may offer insight into the high redshift sample.
- The local analogs are generally of substantially lower luminosity.
- A common property of local galaxies with Ly α emission is bulk outflow of the neutral Hydrogen (e.g., Kunth et al).
- This can Doppler-shift the resonant scattering wavelength so that Lyman α photons escape without a random walk.

The Fruits of our Labor

- The LALA survey is finding a large population of high redshift galaxies.
- Many of these have very little continuum emission and would be missed by conventional broad band surveys.
- The next step is to quantify this galaxy population.

Continuum Luminosity Function



- The luminosity function for the R band in the best $z = 4.5$ candidates.
- (Really a number-flux relation.)

Population Statistics

- We can estimate the counts of Lyman α emitters in a couple of ways:
 - Count emission line sources and correct for interlopers with spectroscopic statistics (see Rhoads et al 2000)
 - Count only those emission line sources consistent with zero blue flux.
- We infer ~ 4000 Lyman α emitters per square degree per unit redshift at $z = 4.5$ from either method.

Star Formation Rates

We can estimate star formation rates from the Lyman- α emitters in two ways.

- First, we measure the star formation rate from Lyman- α assuming case B recombination and no dust. The result is $\sim 2 \cdot 10^{-3} M_{\text{sun}} / \text{yr} / \text{Mpc}^3$ ($H_0 = 50$, $q_0 = 0.5$).
- Second, we measure the rest-UV continuum in a deep z' filter image, and convert to star formation rate using “standard” starburst models.
- The results are similar, suggesting that dust does not strongly quench the Lyman α emission in typical LALA galaxies.

Galaxy Population Models

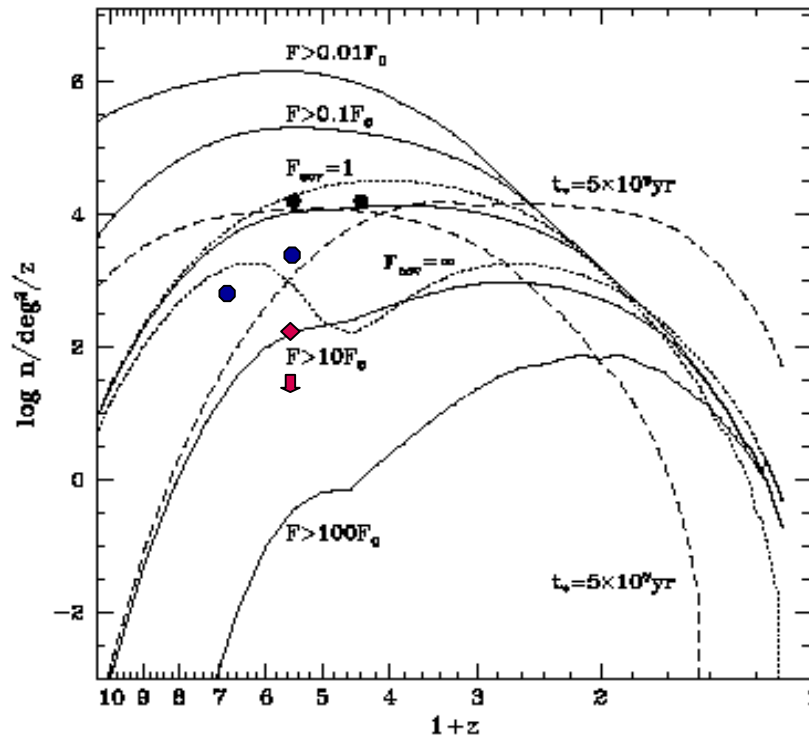


FIG. 3.—Surface density of Ly α emitters in our standard model (solid lines) with fluxes above different values of the detection threshold. The two data points are taken from Hu et al. (1998). For the fixed threshold $F_0 = 1.5 \times 10^{-17} \text{ ergs cm}^{-2} \text{ s}^{-1}$, the dashed lines show how the surface density changes if the assumed SFR is increased or decreased by a factor of 10. Similarly, the dotted lines show the surface density when the covering factor is changed to $F_{\text{cov}} = 1$ or ∞ .

- Haiman & Spaans (1999) predict significant numbers at higher z .
- Different combinations of galaxy evolution, star-formation rates and dust obscuration can explain current observations.
- Luminosity functions and $z > 5$ counts will distinguish among models.

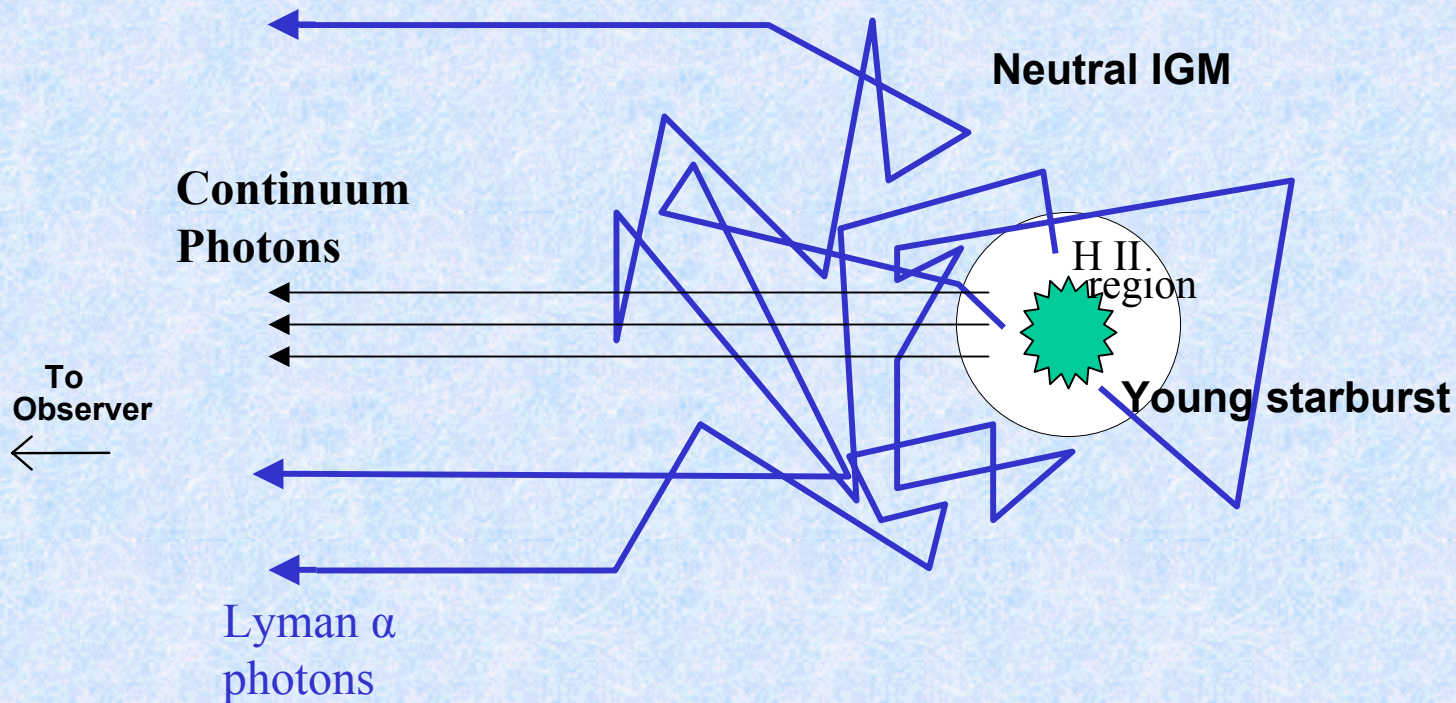
Constraining Reionization

“Normal” Lyman α sources should not be visible before reionization:

- Lyman alpha photons resonantly scatter in a neutral universe.
- This means they should not be apparent as compact sources, I.e., we expect a sharp drop in the Lyman alpha source counts at reionization.

(Miralda-Escude 1998; Miralda-Escude & Rees 1998;
Haiman & Spaans 1999; Loeb & Rybicki 1999;
Rhoads & Malhotra 2001; Hu et al 2002)

Resonant Scattering Before Reionization



See Loeb & Rybicki 1999.

Constraining Reionization

- Lyman alpha photons resonantly scatter in the neutral universe before reionization.
- This means they should not be apparent as compact sources, I.e., we expect a sharp drop in the Lyman alpha source counts at reionization.
- We still see low-luminosity Lyman alpha emitters in our $z=5.7$ sample.
- Thus, **the reionization redshift is $z > 5.7$.**

(Rhoads & Malhotra 2001, ApJ Lett 563, L5)

- ... extended to **$z(\text{reionization}) > 6.6$.**

(Hu et al. 2002)

Reionization Tests

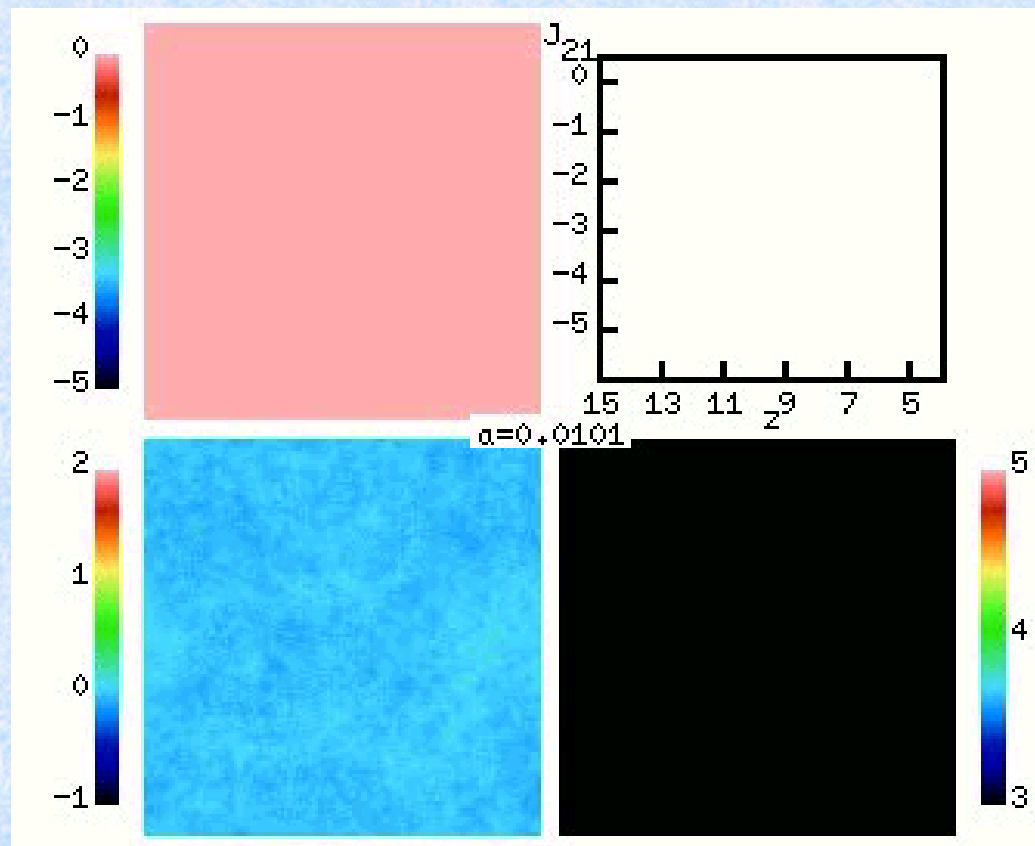
Gunn-Peterson Trough:

- Requires a highly luminous background source.
- Sensitive to optical depths $\tau \sim 5$.
- Proximity effect needs to be considered (at least for steady sources).

Lyman α Galaxy Counts:

- Requires low-luminosity sources.
- Sensitive to line center optical depths of $\sim 10^4$.

Reionization movie – Nick Gnedin





And now for our “On Core”...

The ACS Pure Parallel Lyman- α Emission Survey,

“APPLES”

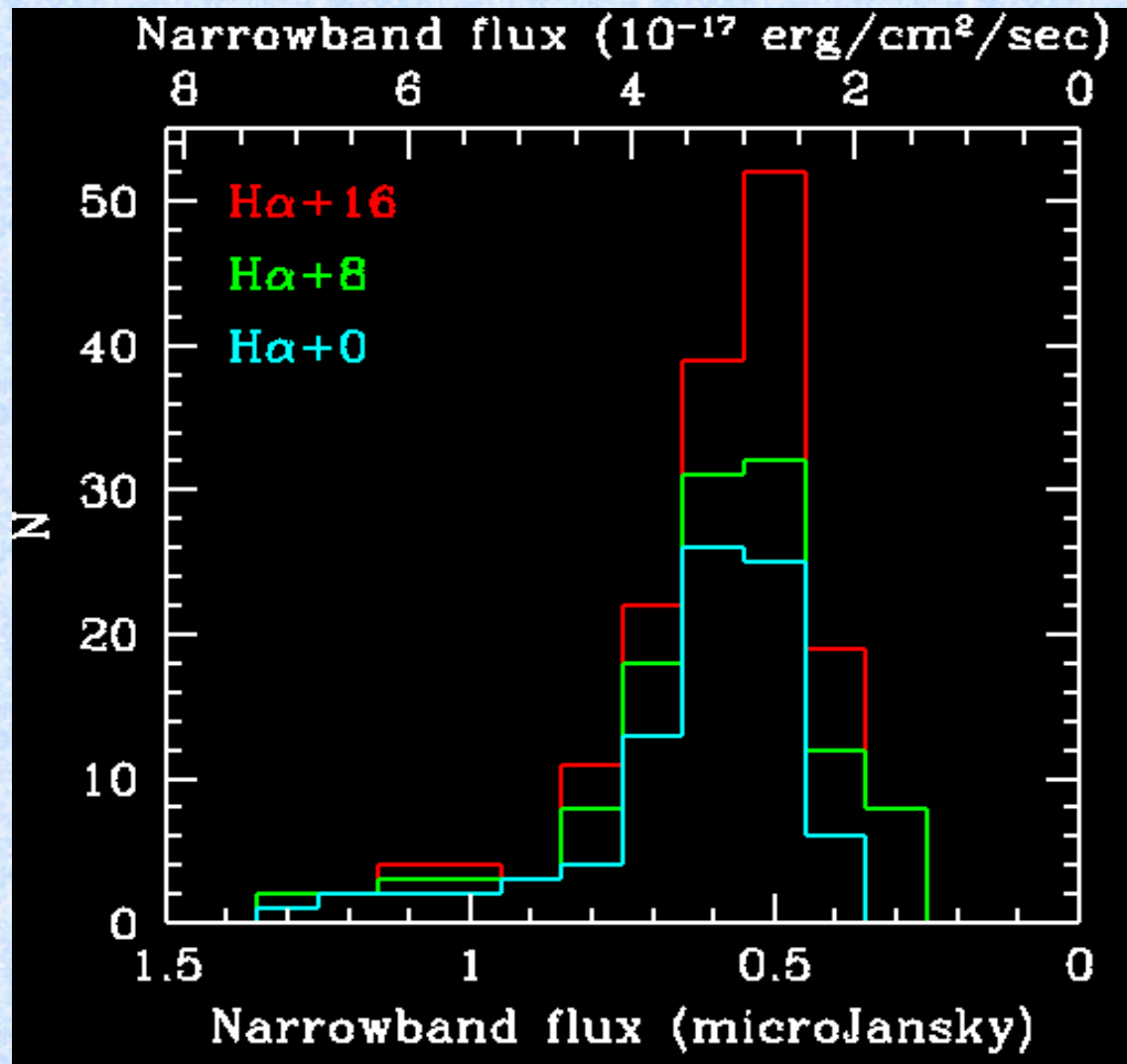
Approved for 175 parallel orbits in HST cycle 11.

Team: J. Rhoads, S. Malhotra, C. Gronwall, Z. Tsvetanov, J. Walsh, Z. Haiman, A. Cimatti, S. Cristiani, E. Daddi, A. Pasquali, N. Pirzkal, S. di Serego Aligheri, J. Vernet

A slitless spectroscopic search to

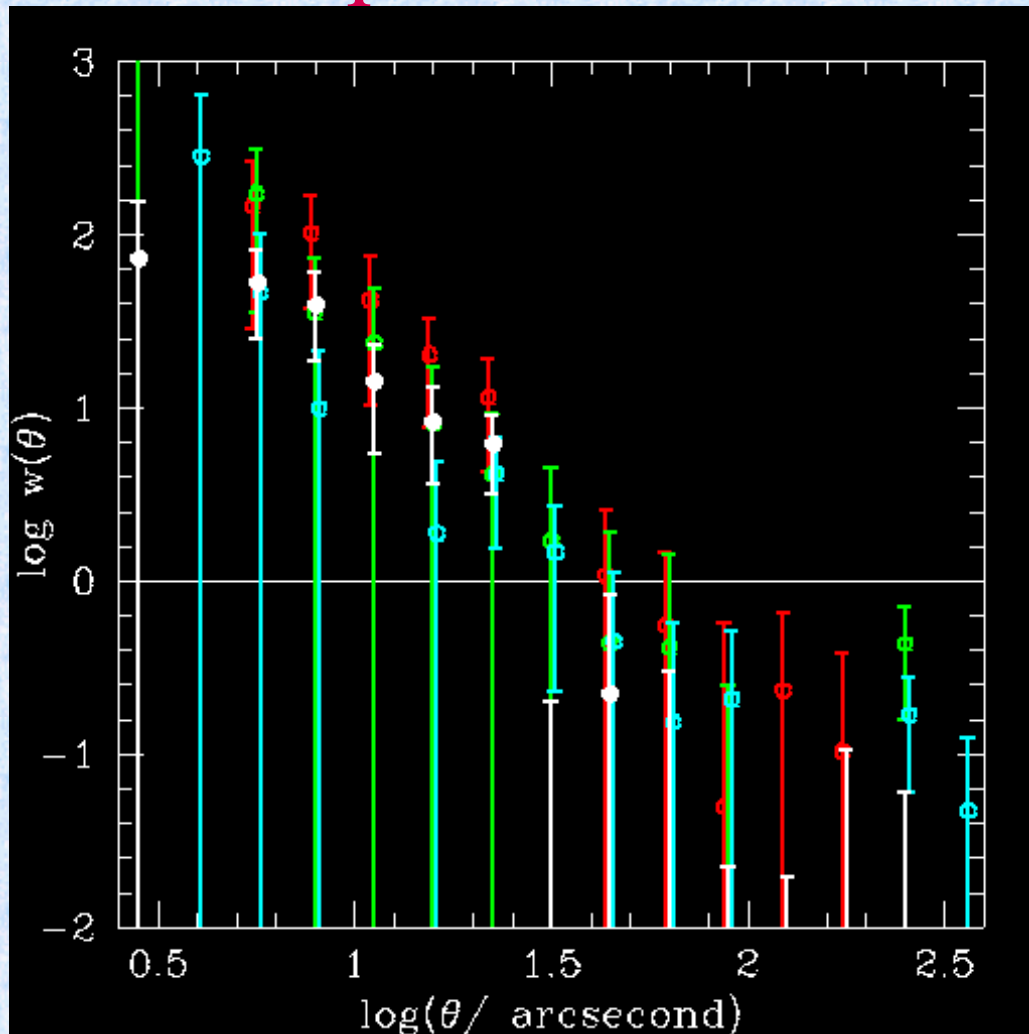
- Find ~ 1000 Lyman α galaxies at $4 < z < 7$
- Study their evolution
- Determine the mean and scatter in $z_{\text{reionization}}$.
- Study star formation at lower redshifts with H and O lines.

Line Luminosity Function



- The luminosity function for the Lyman α line in the best $z = 4.5$ candidates.
- (Really a number-flux relation.)

Spatial Correlation Function



Angular correlation function of $z = 4.5$ candidates.

- Red: Ha16
- Green: Ha8
- Cyan: Ha0
- White: first two together.

Collaborators

- Sangeeta Malhotra, James Rhoads: Co-PIs; leading narrowband survey effort
- Arjun Dey, Buell Jannuzi, Michael Brown: NOAO Deep Wide Field Survey core team
- Daniel Stern, Arjun Dey, Hy Spinrad, Steve Dawson: Spectroscopic followup with Keck
- Tim Heckman, Colin Norman: Co-Is on Chandra followup observations.