A Search for the Sources of Reionization at z = 5.75 with IMACS on Magellan

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Project: Use *multislit narrow-band spectroscopy (MNBS)* with the exceptionally large field of the IMACS spectrograph to push as faint as possible into the luminosity function of Lyα emitters at z = 5.75, both as a probe of galaxy evolution and the sources of IGM reionization.

Conclusion: Based on two searches for Lyα emitters, one in 2004, 2005 down $f_\lambda \sim 10^{-17}$ ergs cm^{-2} s^{-1} and the other in 2008 a factor of 4 deeper, we find an order-of-magnitude increase in sources -- a luminosity function that can plausibly complete reionization at $z \sim 6$.

Techniques of searching for faint emission-line galaxies:

Narrow-band imaging -- e.g. Shimasaku et al. (2006 PASJ 58, 313) cover the widest area (volume), efficient, limited in sensitivity $f_\lambda > 10^{-17}$ ergs cm^{-2} s^{-1}. Ambiguous by itself -- which line have you got?

Gravitation lensing detects very faint sources, e.g. Ellis et al.'s (2001 ApJ 560, L119) Keck spectroscopy along lensing caustics reached $f_\lambda \sim 10^{-18}$ ergs cm^{-2} s^{-1}, but surveyed volume is small, cosmic variance is large.

Multislit narrow-band spectroscopy offer the middle path.
MNBS probes more deeply than narrow-band *imaging* because the sky background is reduced -- typically by an order-of magnitude -- to that of the spectral resolution and seeing (unresolved sources), or image size.
Long integrations with an ~8-m telescope reach $f_\lambda \sim 10^{-18}$ ergs cm^{-2} s^{-1}.
MNBS covers large volume: IMACS yields a volume of ~5×10^4 Mpc^3 per pointing in our survey.

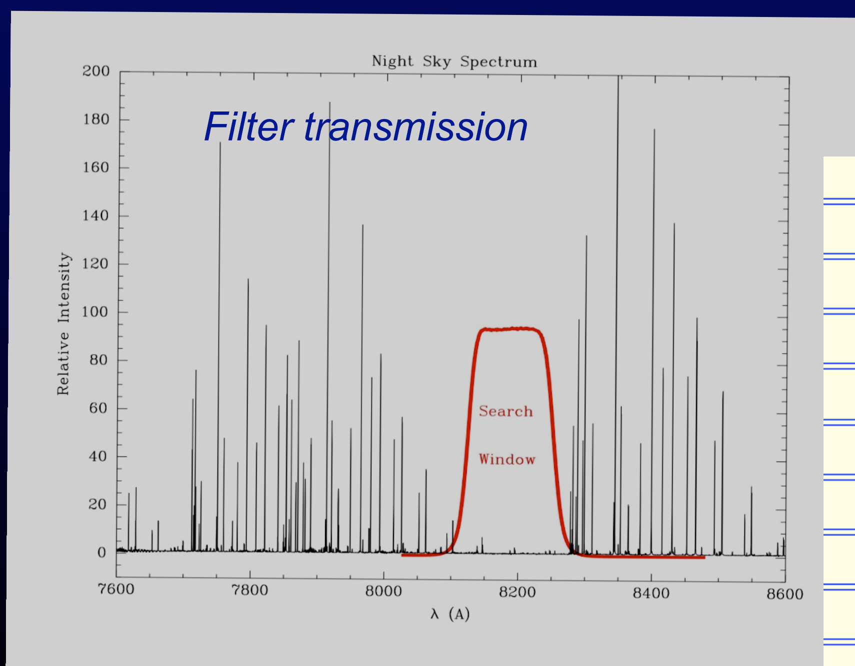
• Narrow-band spectroscopy was pioneered by Crampton & Lilly (1999) and Sawicki et al. (2004), although no Lyα sources were found in these blind searches.

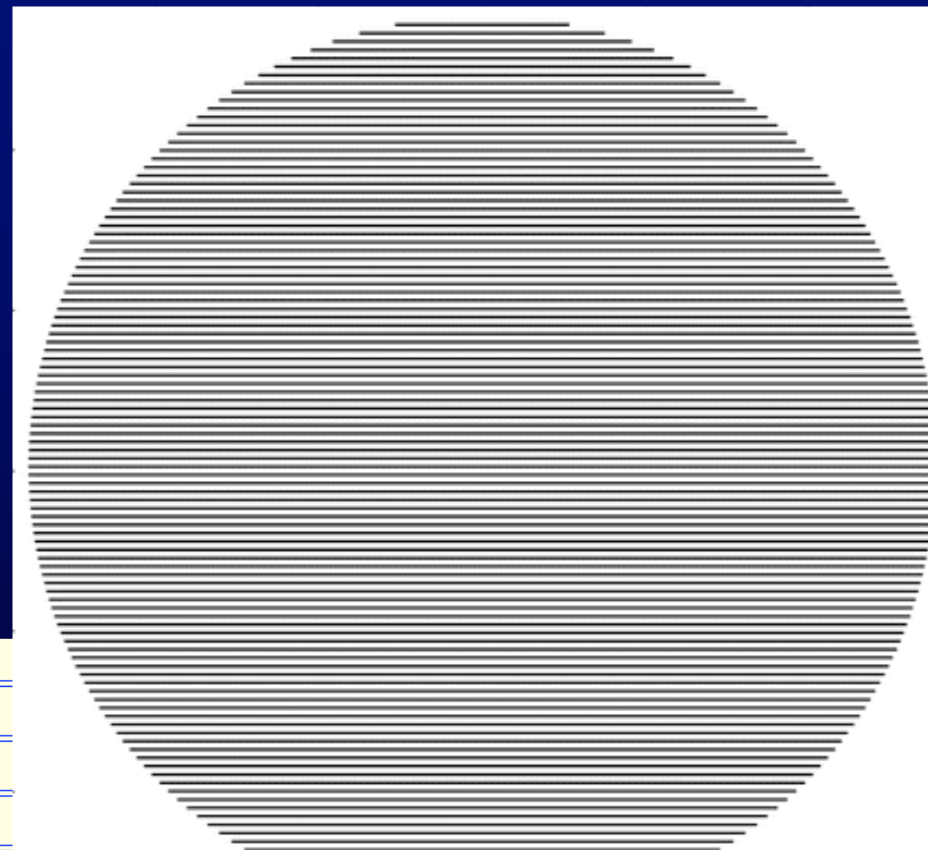
OUR SETUP

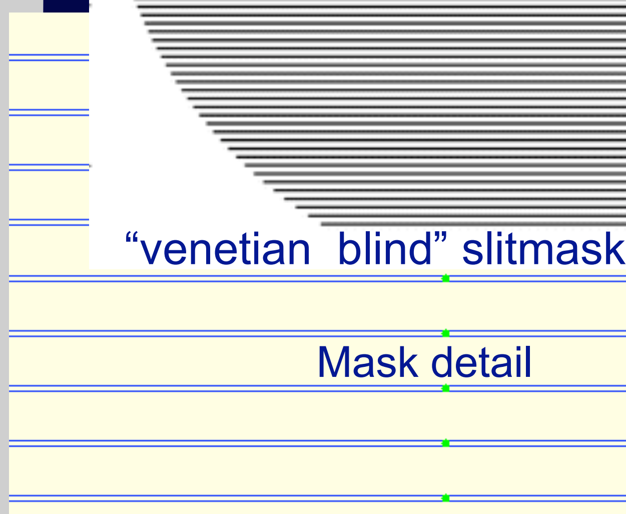
6.5-m Magellan Baade + IMACS f/2 camera: 27-arcmin dia field, 8K x 8K E2V CCD Mosaic Camera

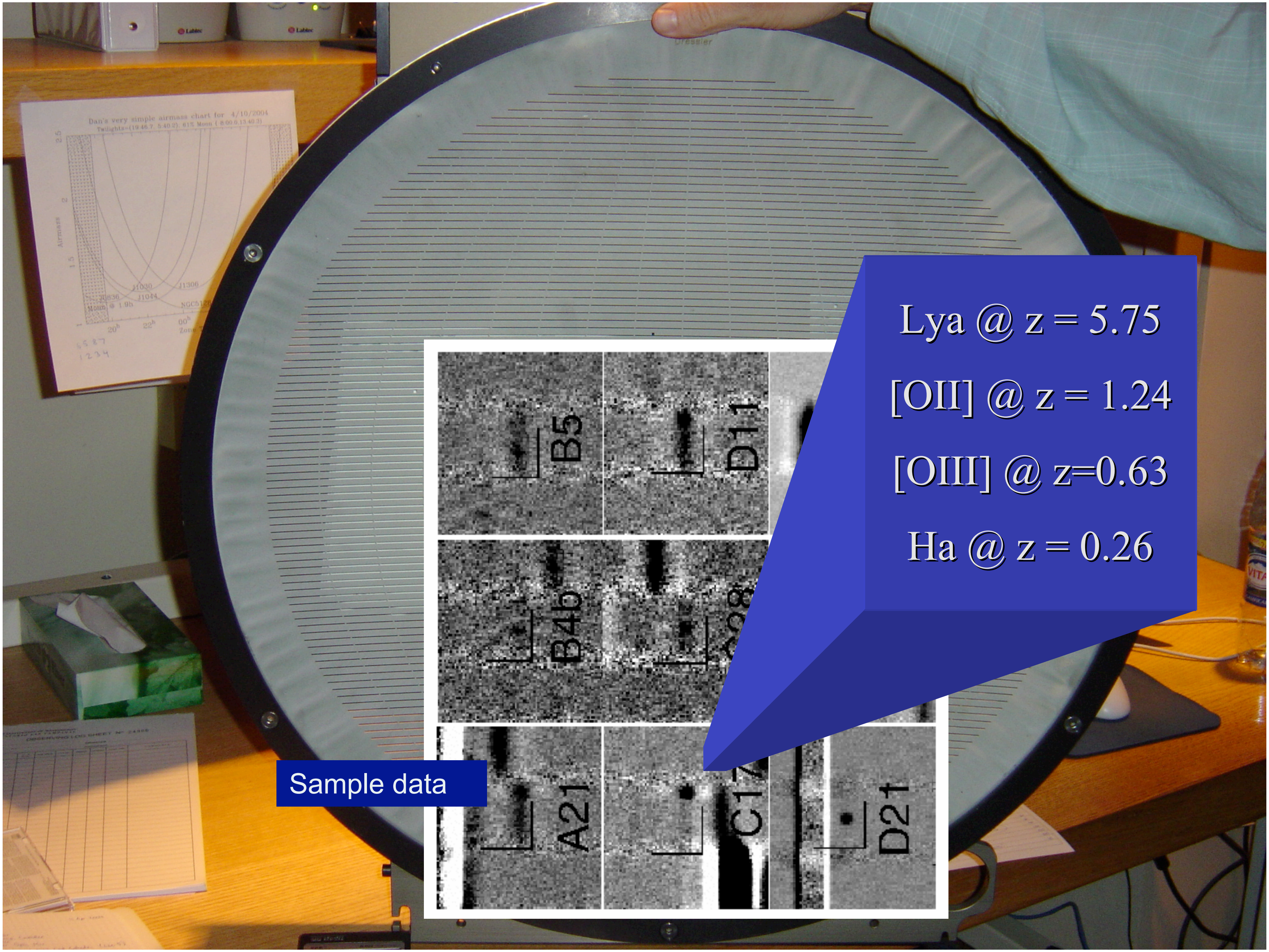
Slitmask: 100 slits, 1.5” wide, separated by ~15” (10% fill factor) ~50 sq arcmin

200-l grism ➡120 Å of spectrum at 2 Å/pix, repeated 100 times




“venetian blind” slitmask


Mask detail


Lya @ z = 5.75
[OII] @ z = 1.24
[OIII] @ z=0.63
Ha @ z = 0.26
Sample data
B5
D11
B4b
A21
D21

First results published, Martin et al. 2008 ApJ 2008, ApJ, 679, 942:

"A Magellan-IMACS Spectroscopic Search for Lyα Emitting Galaxies at Redshift 5.7"

- In 2004 and 2005 we surveyed in 2 positions in 2 fields (4 x 50 sq arcmin) for 6-10 hours each ➡ an average of ~70 emission-line sources per observation

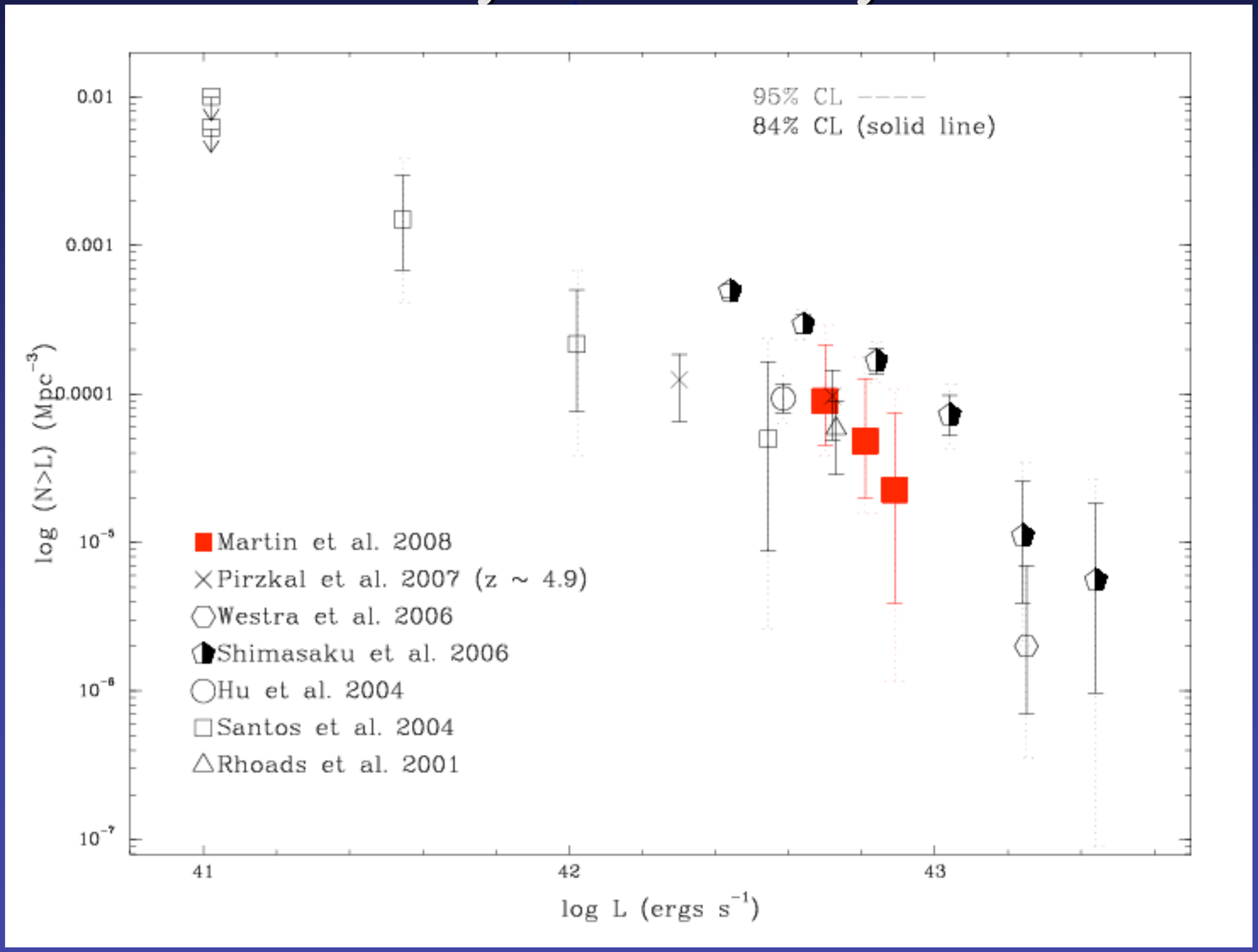
- Half identified as foreground by the presence of continuum, or multiple emission-lines within the 120 Å band. The other half -- 36, 33, 42, & 25 objects -- were single-emission-line candidates, possibly Lyα at z ~ 5.75. About 85% were followed-up in 2006 and 2007 with low- and/or high-resolution spectroscopy.

- Only 3 in total were positively identified as Lyα (first detected with this technique), the faintest with $f_\lambda=1.4 \times 10^{-17}$ ergs cm^{-2} s^{-1}

- Most of the remaining 16 sources that had not been followed up with high-resolution spectroscopy were determined to be [O II] at z=1.24, not Lyα, from the coincidence of these sightlines with foreground galaxies with photo-z ~ 1.2 -- most are star formation regions or excited gas associated with these foreground galaxies.

In summary only 3, and possibly 5-6 in total, of the identified single line sources were Lyα emission at z=5.75.

Cumulative Lyα Luminosity Function



Constraints on LAE LF

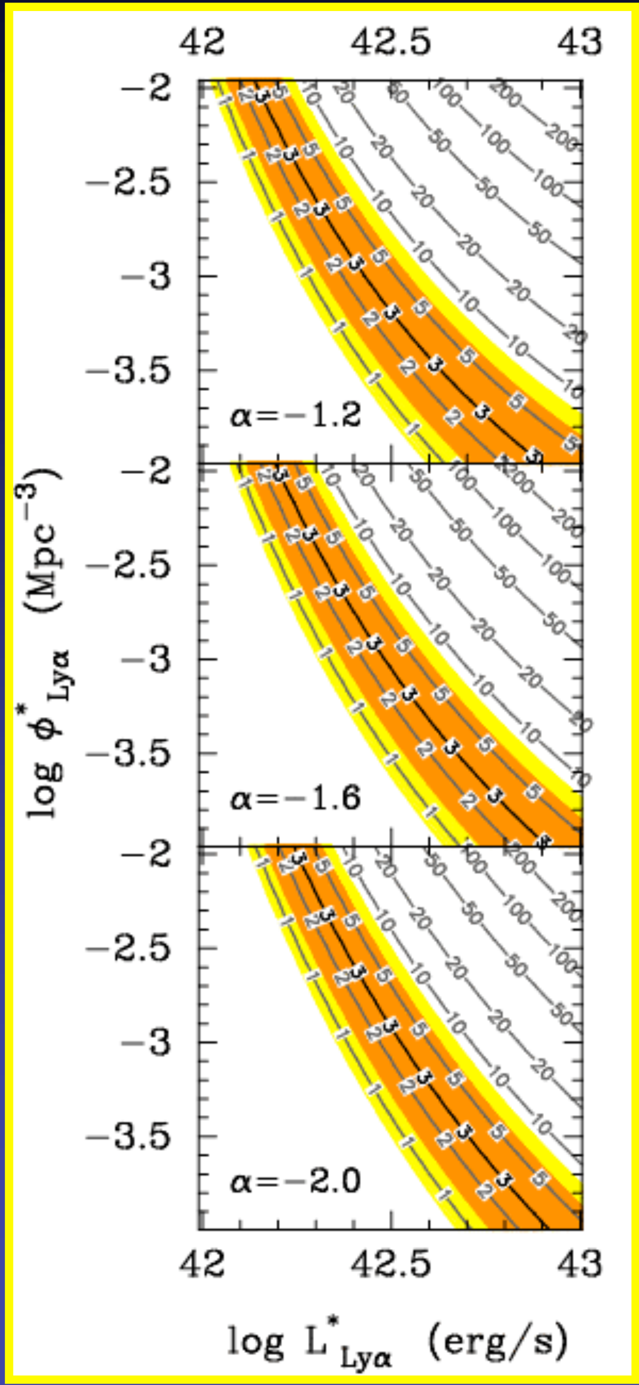
$$d\Phi(L) = \mathbf{\Phi_0}\, (L/\mathbf{L^*})^{-\alpha}\, e^{(-L/\mathbf{L^*})}\, d(L/\mathbf{L^*})$$

- Faint-end slope
- Exponential cut off
- Normalization

LOTS OF ➡ COVARIANCE!

- Fold model through experimental response function to get average number recovered.
- Poisson errors on our 3 confirmed LAEs define the range of acceptable LF parameters.

Next question: What is the contribution to IGM ionization at z=5.75?



Lya Luminosity Density

Integrate from Log L_{min}(Lya) = 42.57, 41.0

Photon production rate to ionize intergalactic gas…

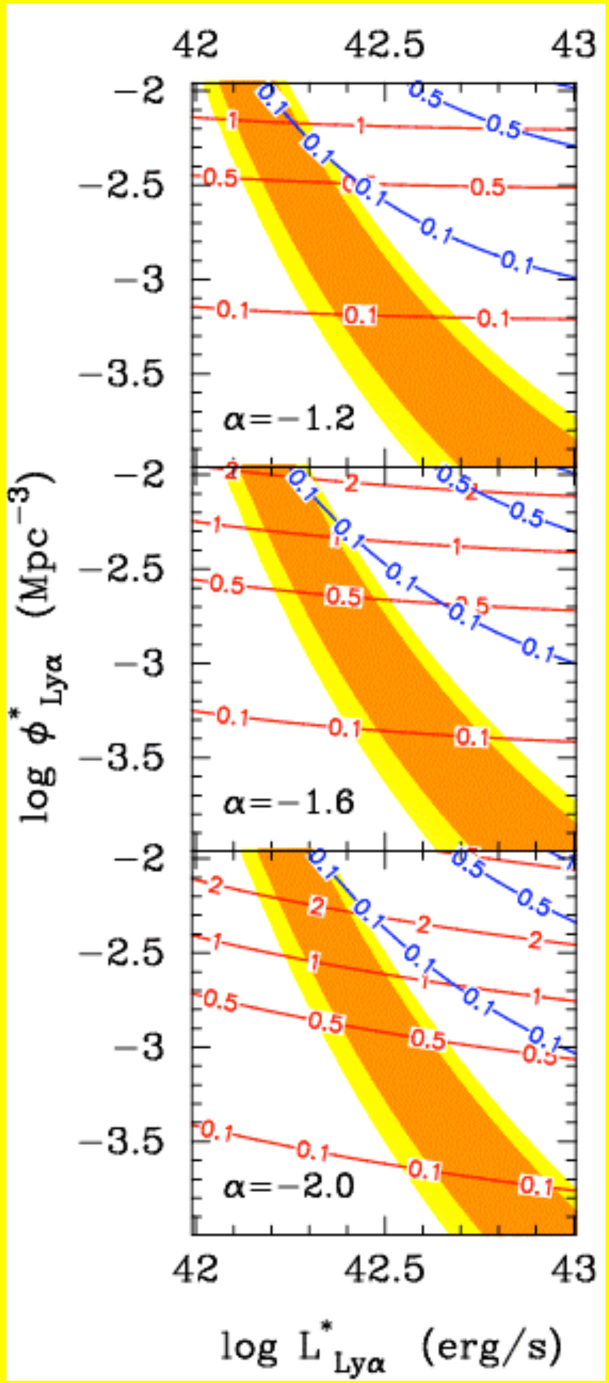
$$\dot{N}_H = 10^{50.72}\ \mathrm{s^{-1}\ Mpc^{-3}}\ \underbrace{C_6}\left(\frac{1+z}{6.7}\right)^3\left(\frac{\Omega_b h_{70}^2}{0.047}\right)^2$$

Assume stellar IMF to get SFR…

$$\dot{\rho}_* = 0.02\ \mathrm{M_\odot\ yr^{-1} Mpc^{-3}}\ \underbrace{C_6 f_{LyC,0.1}^{-1}}\left(\frac{1+z}{6.7}\right)^3\left(\frac{\Omega_b h_{70}^2}{0.047}\right)^2$$

CASE B Recombination Lya emission…

$$L_{Ly\alpha} = 3.0\times10^{40}\ \mathrm{erg\ s^{-1}Mpc^{-3}}\ \underbrace{C_6(1-f_{LyC,0.1})\left(\frac{f_{Ly\alpha,0.5}}{f_{LyC,0.1}}\right)}_{=\ 0.1,\ 0.5,\ 1,\ 2}\left(\frac{1+z}{6.7}\right)^3\left(\frac{\Omega_b h_{70}^2}{0.047}\right)^2$$



Technique appeared to be capable of achieving a significantly lower flux.

Our new goal became a deeper search to better constrain the luminosity function, as parameterized by a Schechter function: faint-end slope “α” and L* “break luminosity” .

An increase in sensitivity from 2004 & 2005 search to 2008 of about a factor of 4 (1.5 mag) The new flux limit is $F_{\lambda} \sim 3 \times 10^{-18}$ as faint as has been done (not lensed)

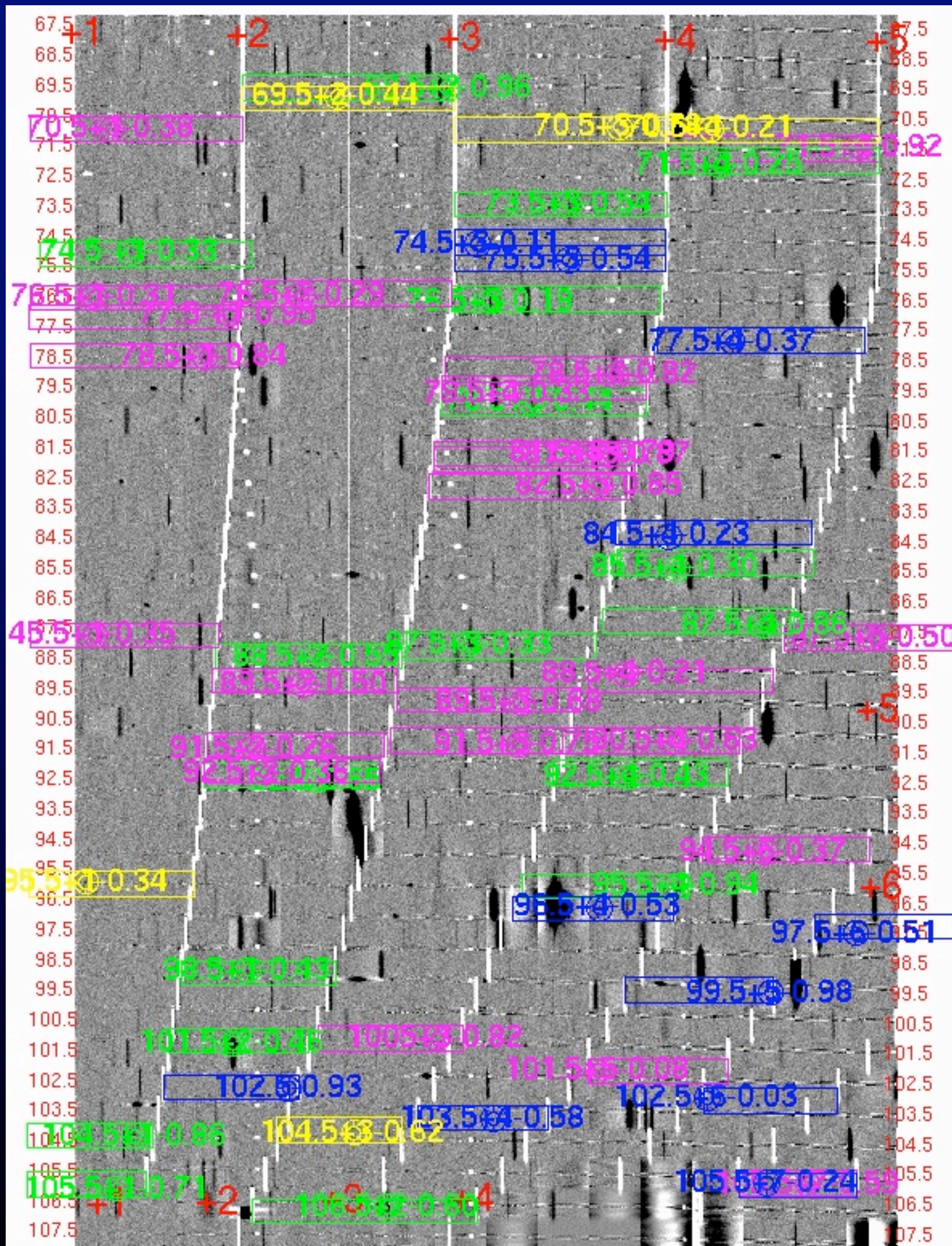
Three factors went into achieving this large step:

1) New CCD camera with E2V CCDs replacing SITe CCDs
   - ➡ throughput of system at 8200 Å rose from 14% to 22% (factor of 1.6)

2) Improved f/2 camera optics (eliminated coma) and much better seeing:
   - ➡ typical images dropped from 0.7-0.8 arcsec FWHM to 0.4-0.5 arcsec FWHM

   These are delivered images on the exposures, implying seeing often < 0.3”

3) Exposure times increase from 10h to 20h, in photometric conditions



April 2008 IMACS observations

20-hour observations on 2 fields, -- Cosmos & 15h LCIRS

Observations scanned independently by Martin, Dressler, and McCarthy to identify emission-line sources: ~300 sources found per field.

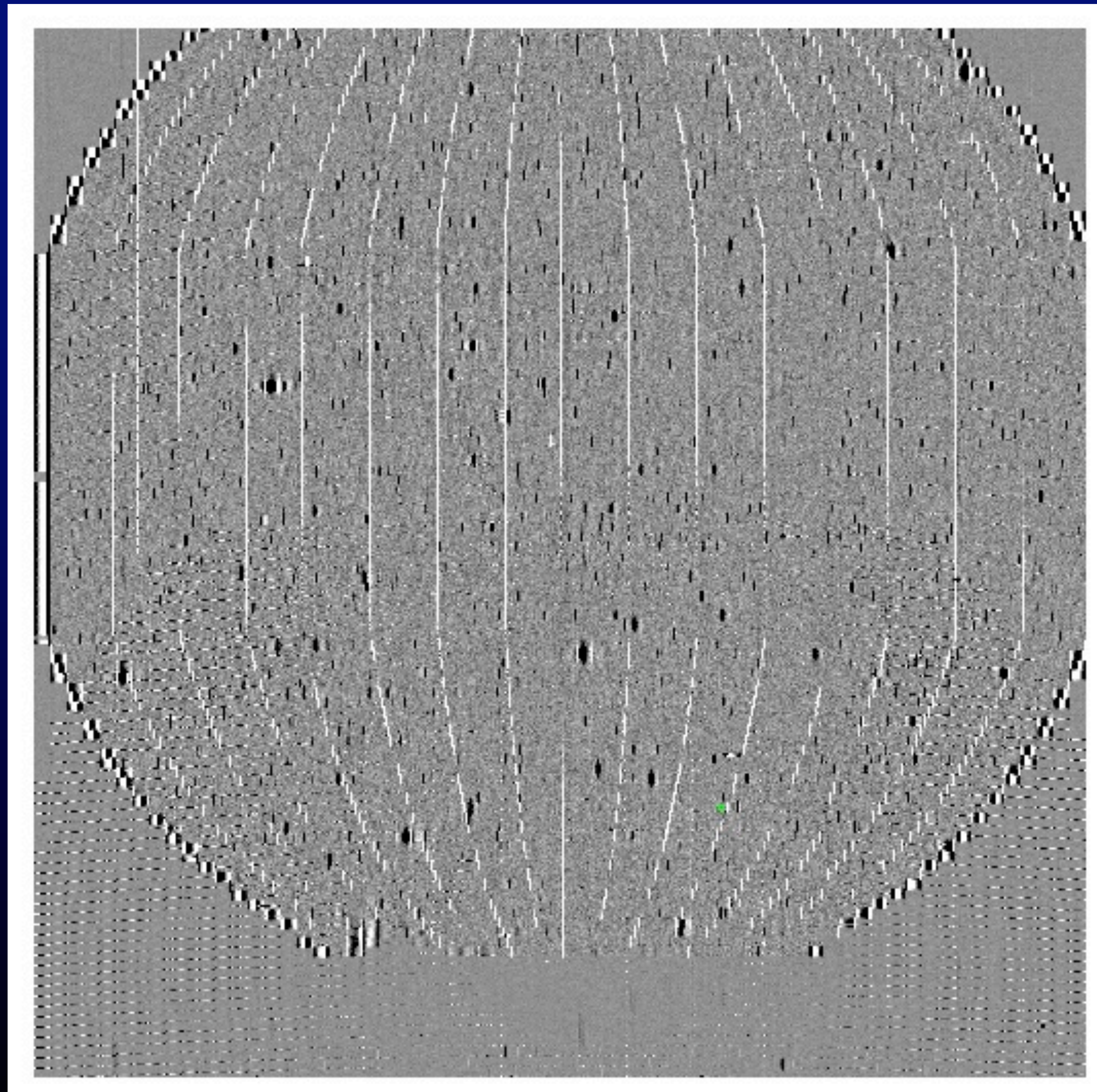
Because of this large number of candidates, these were prioritized into 4 classes for follow-up spectroscopy.

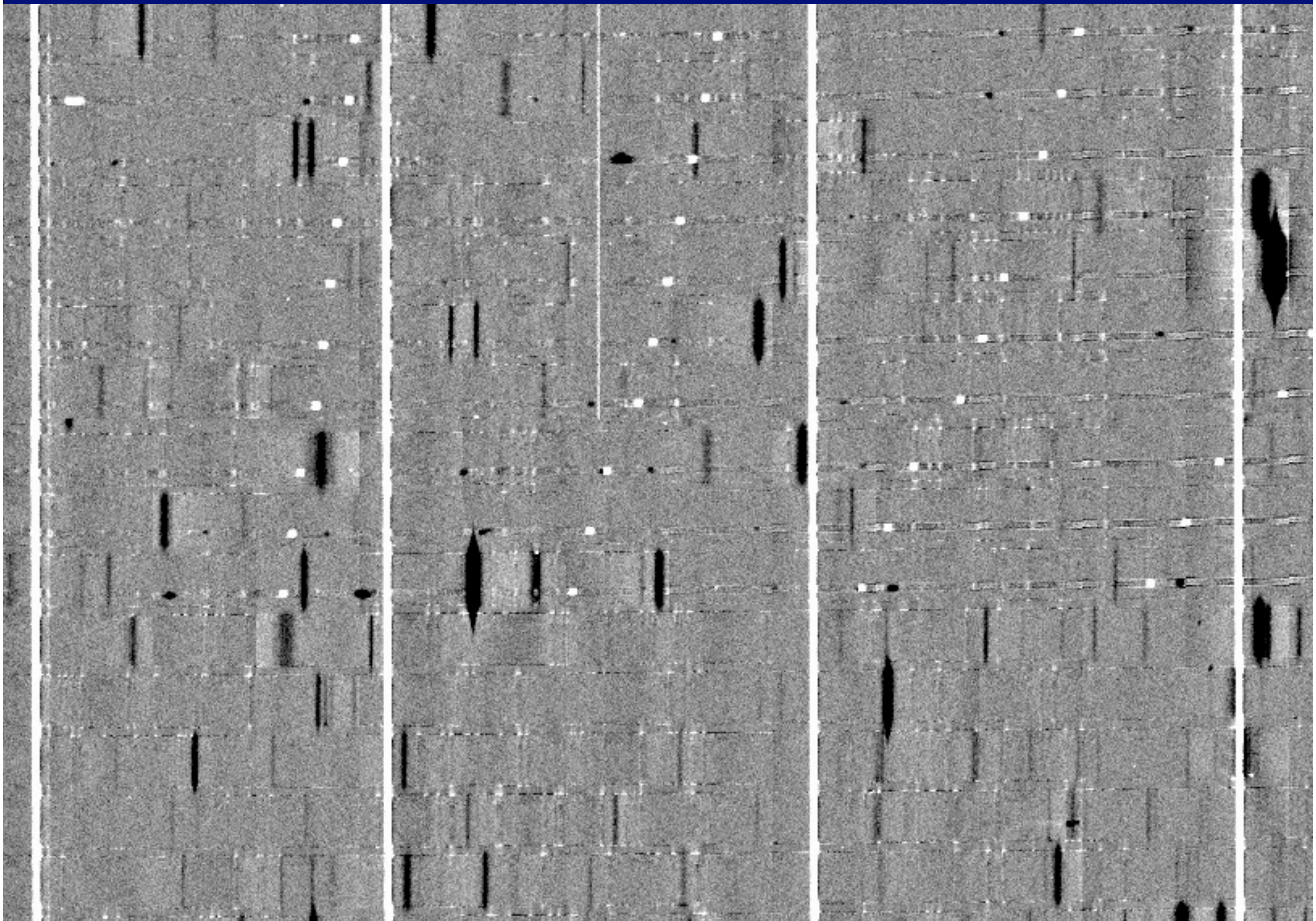
- Lyα candidate -- solid
- Lyα candidate -- possible
- Probable foreground
- Possible artifact (not real)

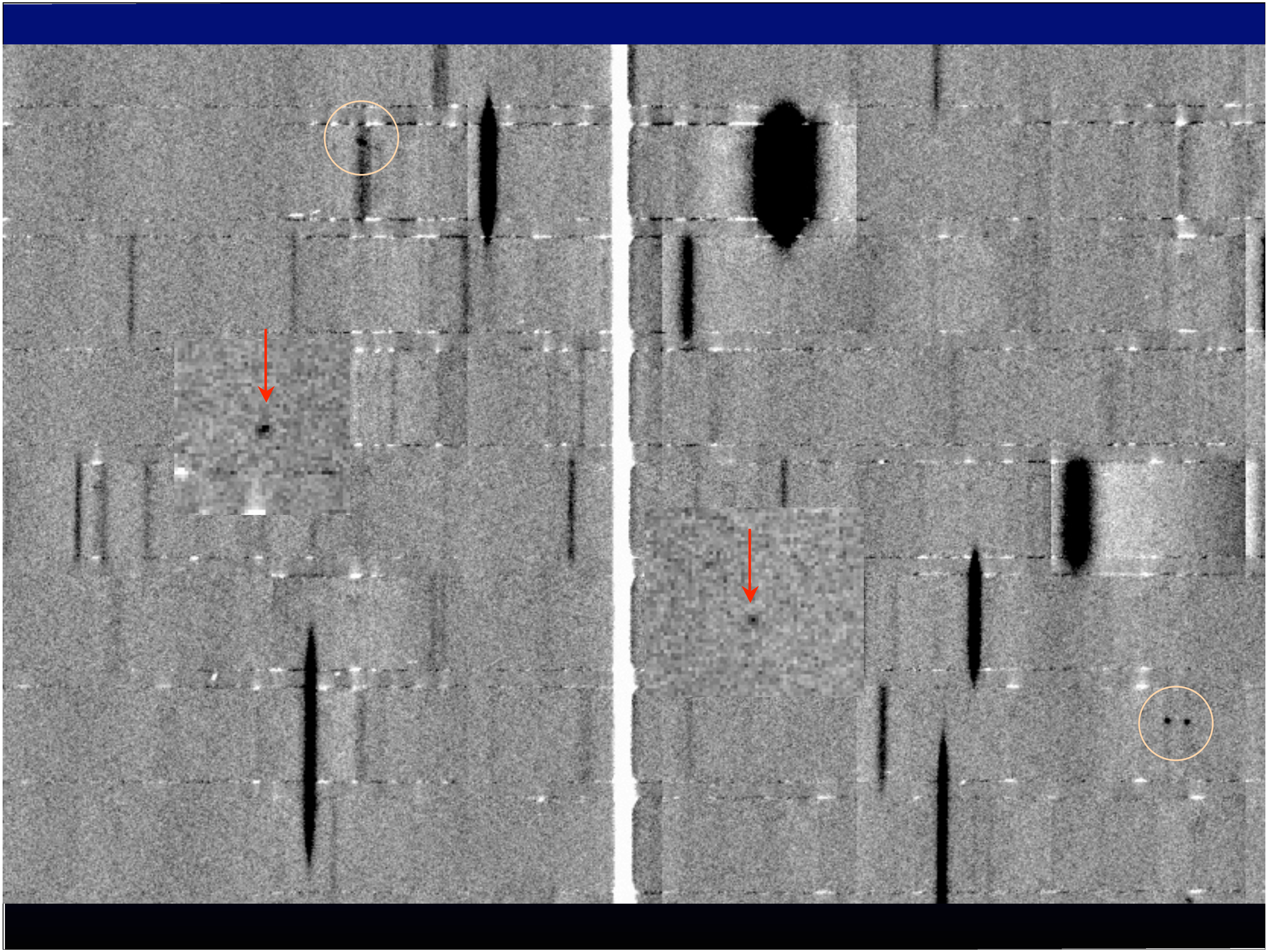
What it looks like:
20-hours of data collected in April 2008 in the Cosmos field. ~50 sq arcmin with 120 Å of spectrum

The full IMACS 8k x 8k array shows the spectra of the 100 separate slits

(The white “map lines” are the small metal bridges that give each slit stability.)







Preliminary Results from the 2008 search:

Factor of 4 increase in all emission-line detections:

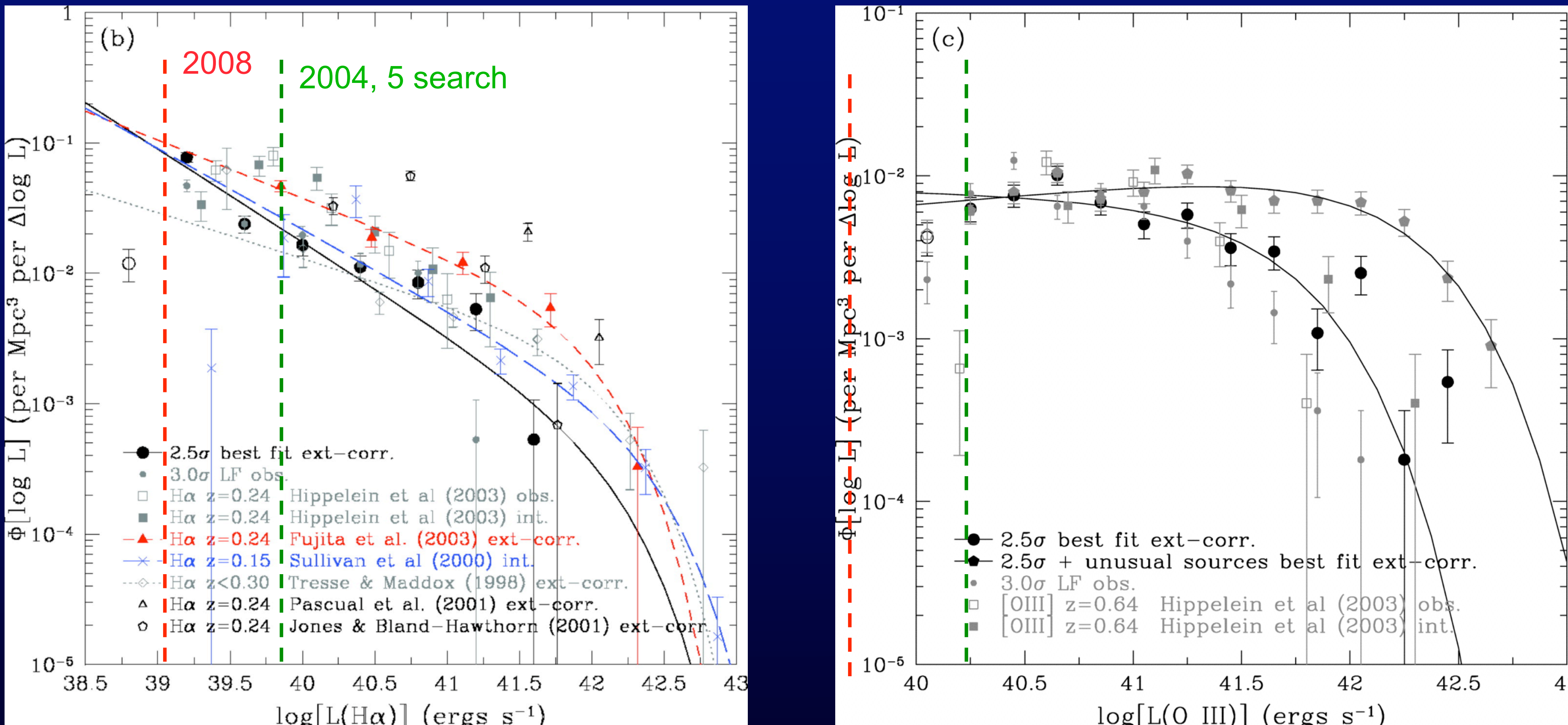
10h (COSMOS) field: 69 ➡ 263   15h (LCIRS) field: 82 ➡ 356

Similar factor after eliminating objects with continuum or obvious foreground emission lines:

10h field: 35 (average) ➡ 89 (all blue + 1/3 yellow) -- factor of 2.5

15h field: 33 (average) ➡ 102 (all blue + 1/3 yellow) -- factor of 3.1

We *think* that this increase in the foreground population is consistent with work by others, but we are (of course) dropping off the end of those populations studied previously, so our numbers may be more appropriate.



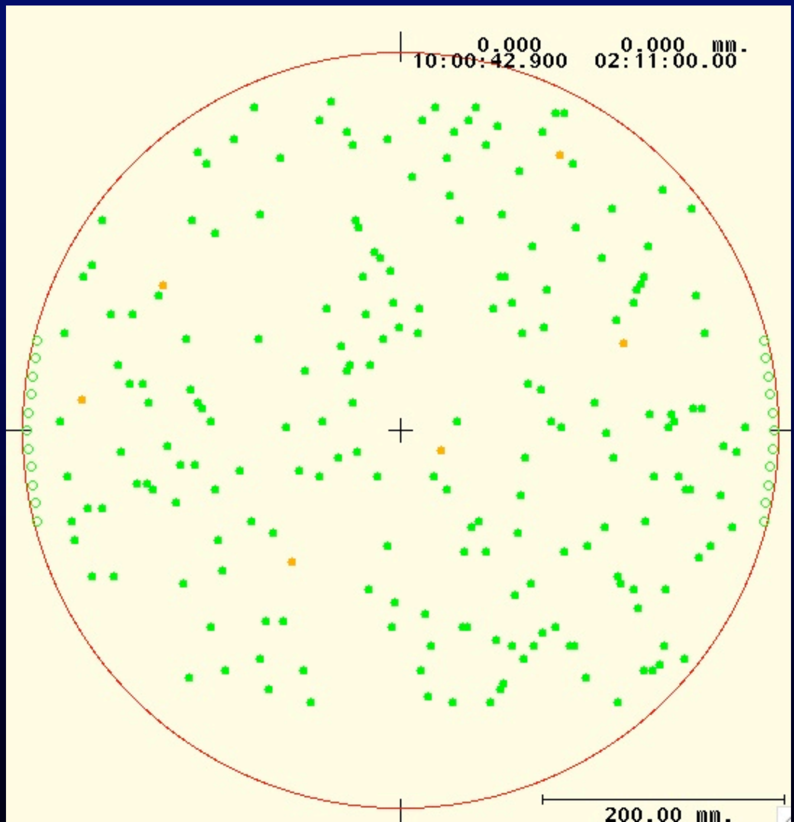
From Ly et al. 2007, luminosity functions for Hα (& Hβ) at z=0.26 and for [O III] at z=0.63. The dashed green line corresponds to the $F_\lambda = 10^{-18}$ ergs $s^{=1}$ cm^{-2} flux of our 2004 & 2005 searches for Lyα at z = 5.75. The dashed red line is the limit of the 2008 search.

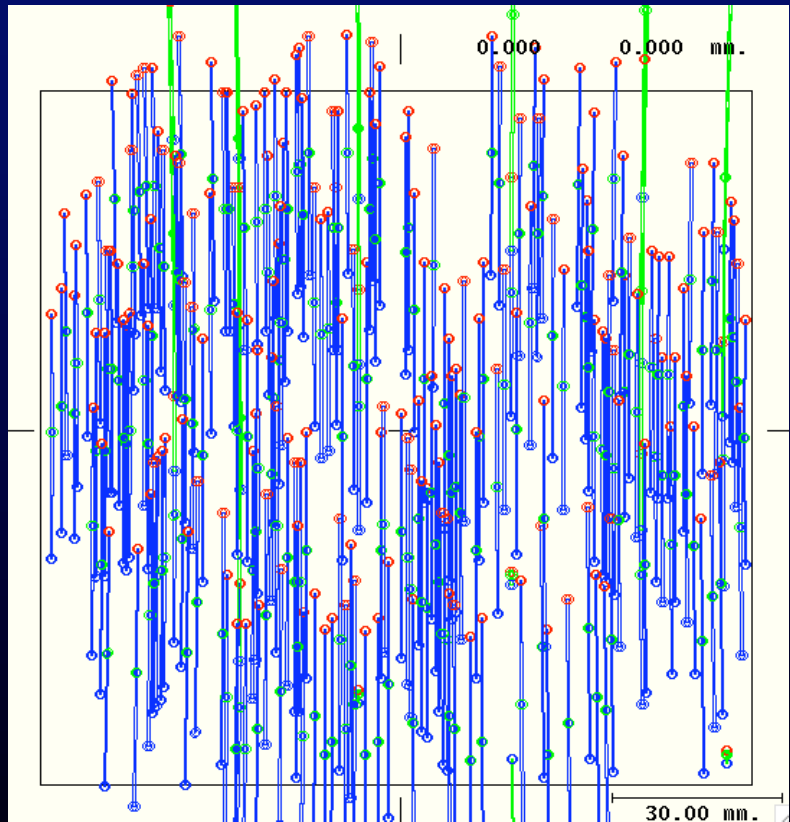
Next step was follow-up observations: March 23-26, 2009

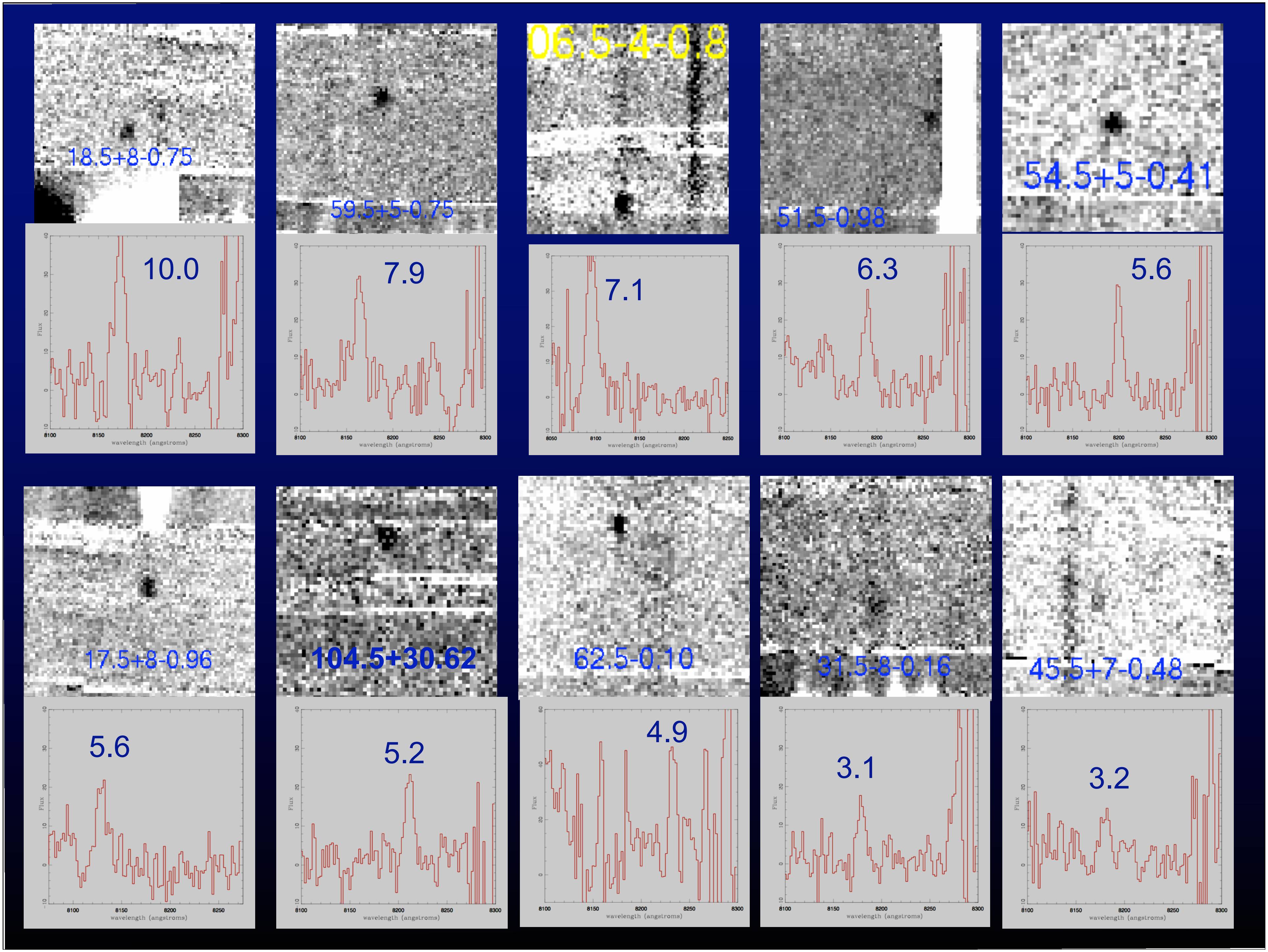
Target candidate single-line sources without continuum, and fill with others. A wide wavelength coverage (4500 A < λ < 9000 A) coverage to eliminate foreground objects. Confirm and increase S/N of 2008 "search" detections.

Results: Cosmos field, 200 objects on mask, 16 hours integration, FWHM = 0.55"

15h field, 243 objects on mask, 15.3 hours integration, FWHM = 0.58"






18.5+8-0.75
10.0
59.5+5-0.75
7.9
06.5-4-0.8
7.1
51.5-0.98
6.3
54.5+5-0.41
5.6
17.5+8-0.96
5.6
104.5+30.62
5.2
62.5-0.10
4.9
31.5-8-0.16
3.1
45.5+7-0.48
3.2

Preliminary Results from the 2008 confirmation:

Recall a factor of 4 increase in all emission-line detections from search:

10h (COSMOS) field: 69 ➡ 263   15h (LCIRS) field: 82 ➡ 356

And also a factor of 4 increase in single-line, no continuum candidates for Lyα emitters:

10h field: 35 (2 pointings) ➡ 89 (all blue + 1/3 yellow) -- factor of 2.5

15h field: 33 (2 pointings) ➡ 102 (all blue + 1/3 yellow) -- factor of 3.1

From the 2009 confirmation observations for the COSMOS field:

Confirmed single emission lines, either [O II] or Lyα increased from 5 ➡ 42, a factor of ~8! --- compare to factor 2.5 - 4 increase in foregrounds

(15h field also observed, data reduced but not yet analyzed.)

From these ~42 single line, no-continuum detections, they could be [O II] or Lyα, as before. We will make high-resolution observations to look for [O II] doublet splitting to make this distinction. Also, we can correlate lines-of-sight with foreground galaxies with photo-z ~ 1.2, based on the very deep photometry of the COSMOS field, to see if, like before, most of these are foreground too.

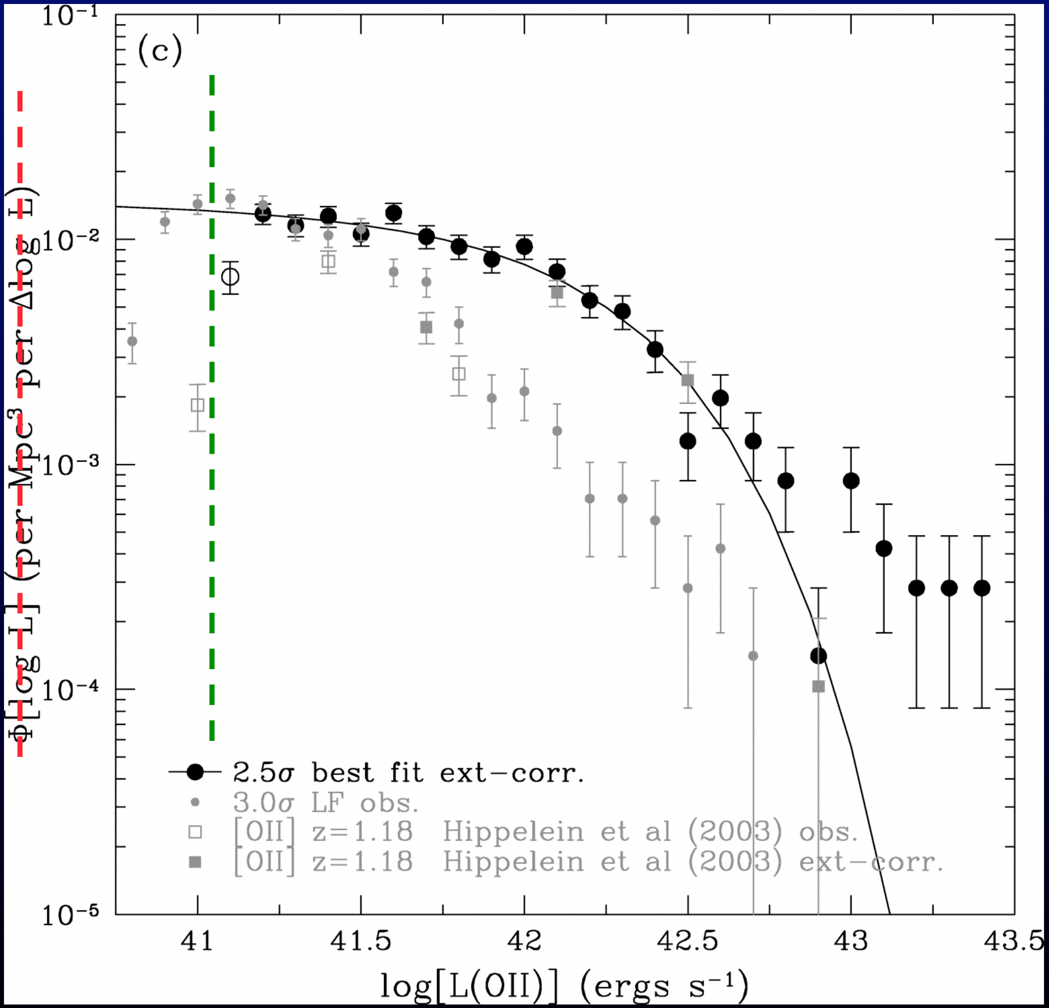
Today, however, we offer two pieces of information that argue that about 1/2 - 3/4 of this sample of 42 are in fact Lyα emitters at z = 5.75:

1. Base the increase in [O II] emitters based on how the foreground contamination has increased for <u>all</u> foreground sources in these two fields

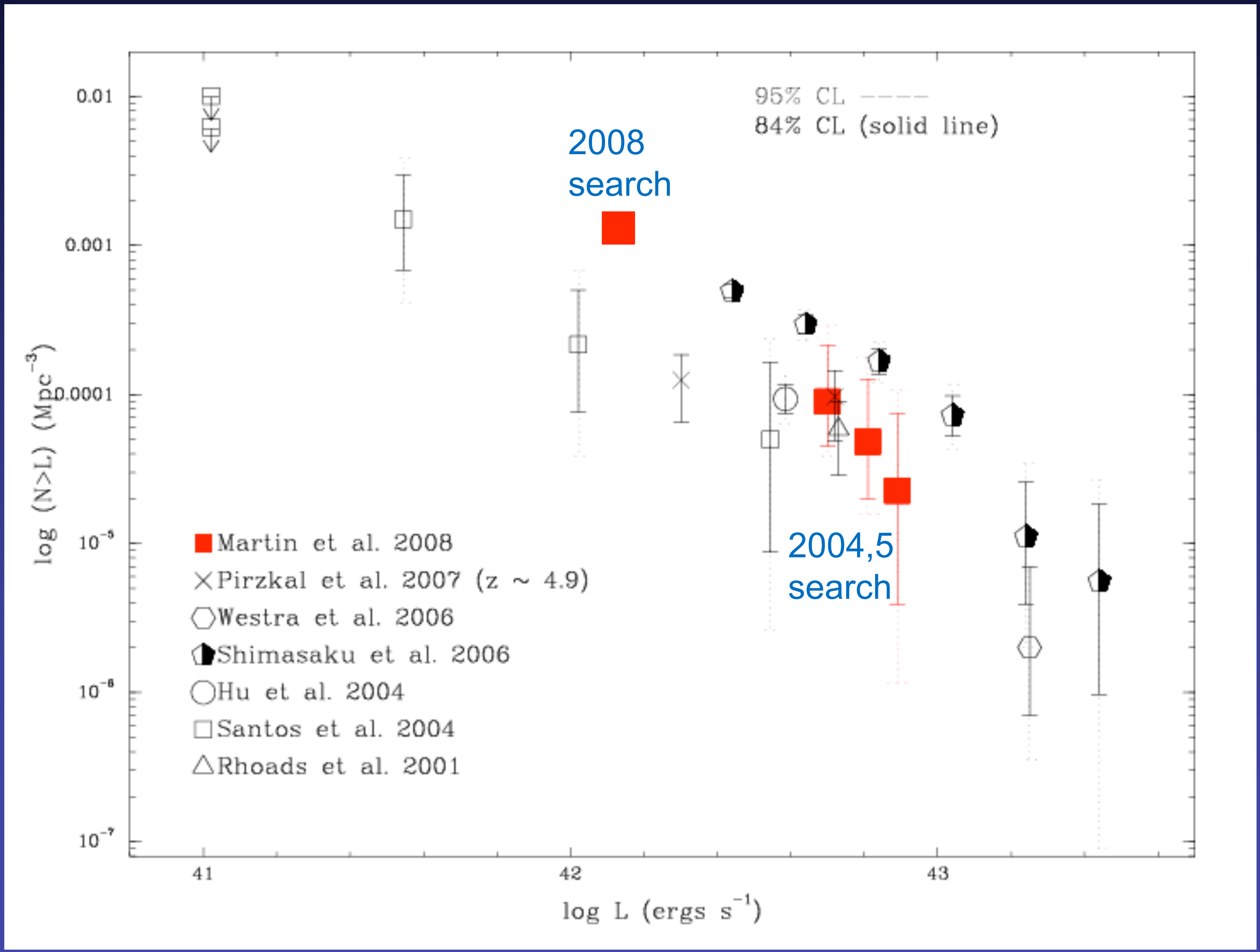
   ➡ Factor of 3-4 increase for both all foreground and emission-line only data, which suggests that this makes up <u>half</u> of the factor of 8 increase. The other half, by inference, is due to Lyα.

2. Use previous measurements of [O II] LF to predict, explicitly, how much our [O II] contamination should have increased.

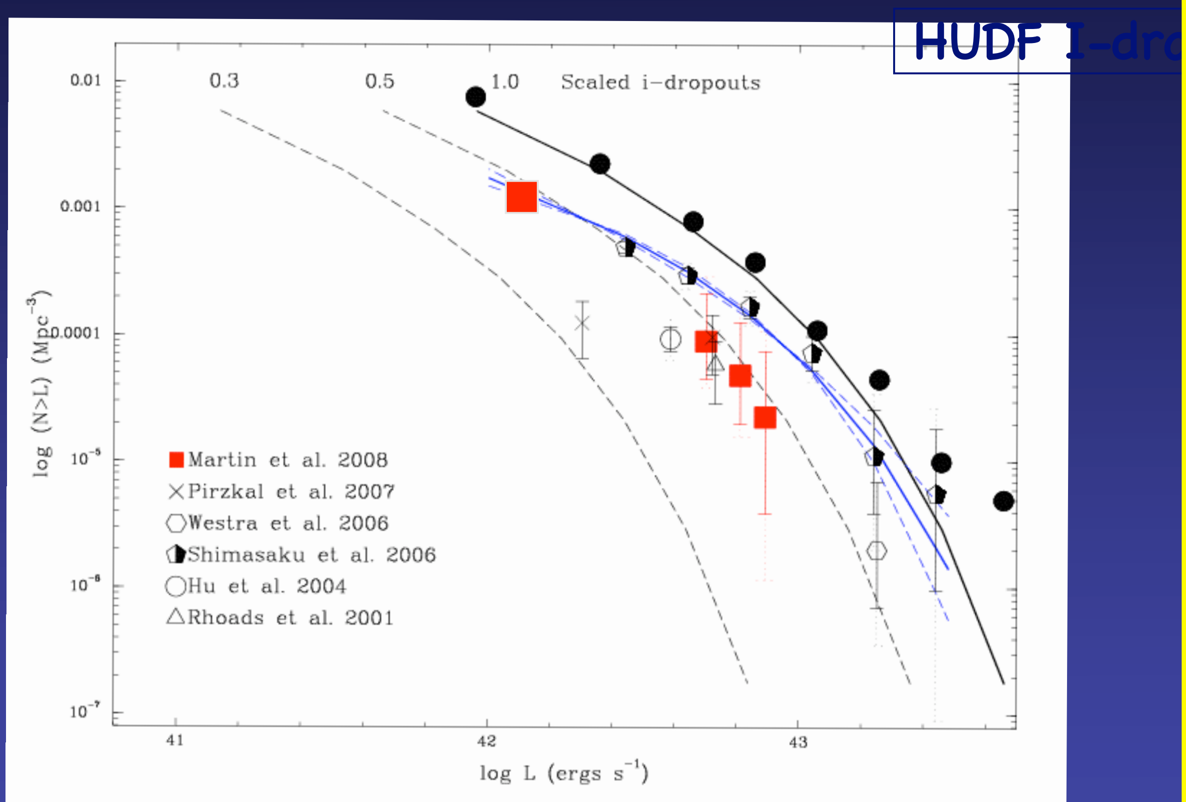
An approximate integration of the <u>observed</u> LF (not extinction corrected) suggests that down to log L = 41.0, φ = 0.05, and for Δlog L = 0.6 fainter, another φ = 0.05 ➡ [O II] sources should double. In 2004, 2005 search and 2006, 2007 confirmation data, ~10 [O II] sources without continuum were identified per pointing. This suggests that only ~20 of th 42 would be [O II].

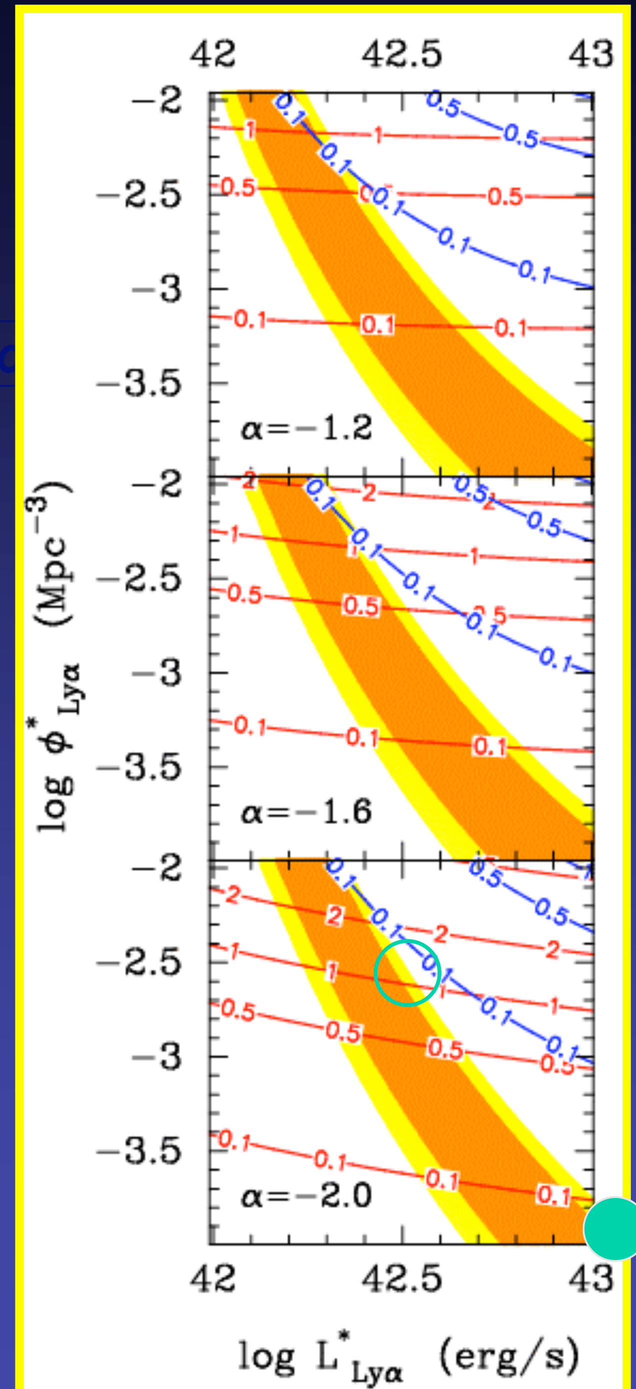


Cumulative LyA Luminosity Function



If these numbers are correct, they are well described by the 50% escape-fraction shown below with LF with α =-2.0, L*=1.6 x 10^{43}, and φ^* = 1.6 x 10^{-4}





An indication that this will provide sufficient flux for reionization is that the blue dot is within the orange zone -- a fit with lower L* and higher φ^* is consistent, because these are co-variant.

Further work:

- Analyze data from the 15h field!
- Follow-up high resolution observations to distinguish [O II] from Lyα, and to measure kinematics, outflows, etc.
- To extent possible, identify the different foreground populations [O II] -- test our model of the foreground
- Incompleteness and slit-loss corrections by Sextractor simulations
- Constraints on Lyα LF from 2008 search and implications for reionization.