Summary: When did reionization happen and what did it?

- Theoretical speculations on First Light and generic reionization
    - Haiman, Miralda-Escude, Rees etc..
- Estimates of $x(z)$
    - Cowie, Fan, (WMAP in abstentia)
- Census of potential ionizers at $z \sim 6$
    - Cowie, Fan, Malhotra, Maier, Martin, Bremer, Hu, Illingworth
- State of the IGM
    - Shull, Barkana, Schaye

- Reionization: an “unobserved” cosmological phenomenon that we nevertheless know happened

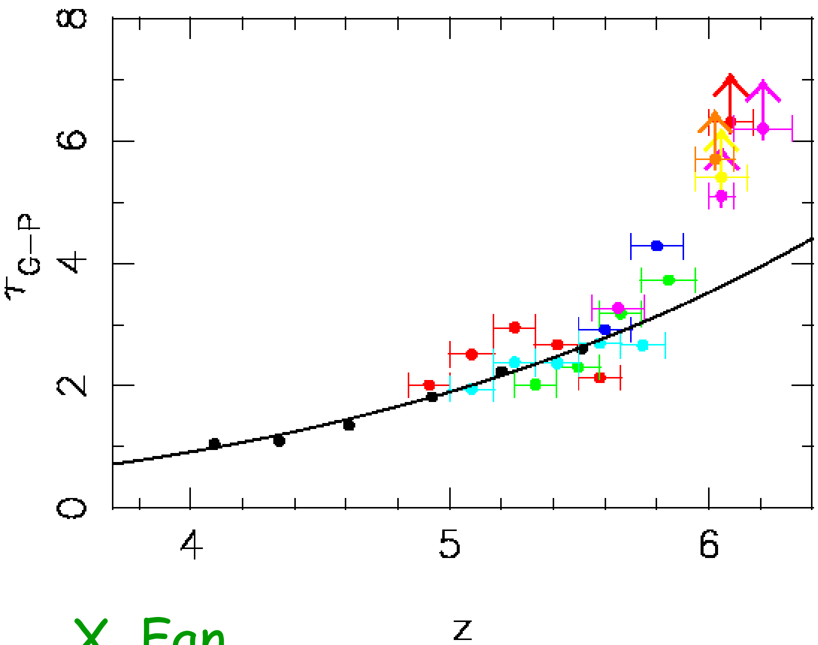
- underlying physics is (probably?) already in place
    - familiar mechanism (photo-ionization)
    - familiar astrophysical sources (stars, accretion disks) are available as potential photo-ionizers
    - at present no compelling incongruities:
        - standard ΛCDM cosmogony gives early collapse of bound objects $z >> 6$
        - CIV in IGM as evidence for widespread luminous activity at $z > 6$

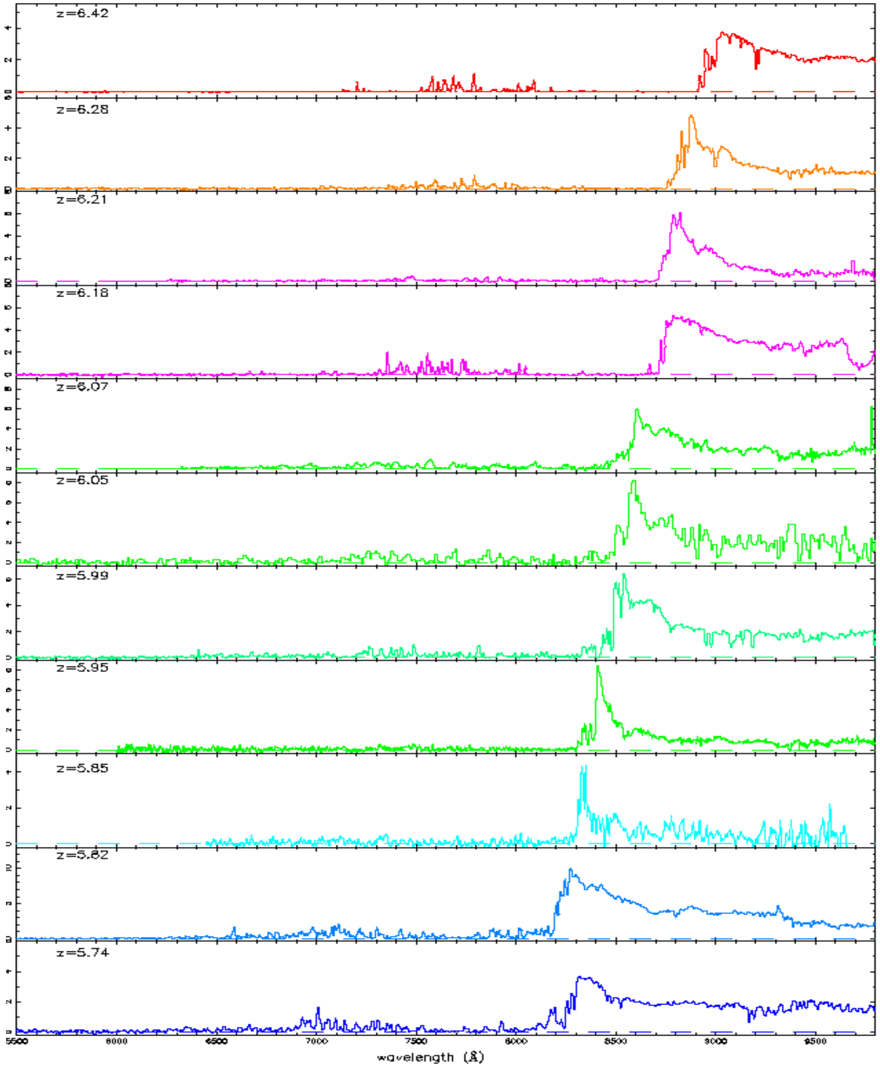
- likely to be complex in practice
    - interaction of complex first objects (feedback, etc etc) with inhomogeneous medium through radiative transfer effect

…. we don’t really know when and we don’t know how/what, and more exotic phenomena can’t be ruled out (decaying DM etc) – similar problems for galaxy formation as a whole

When?

(1) Did it really end at z = 6?
quasar spectra



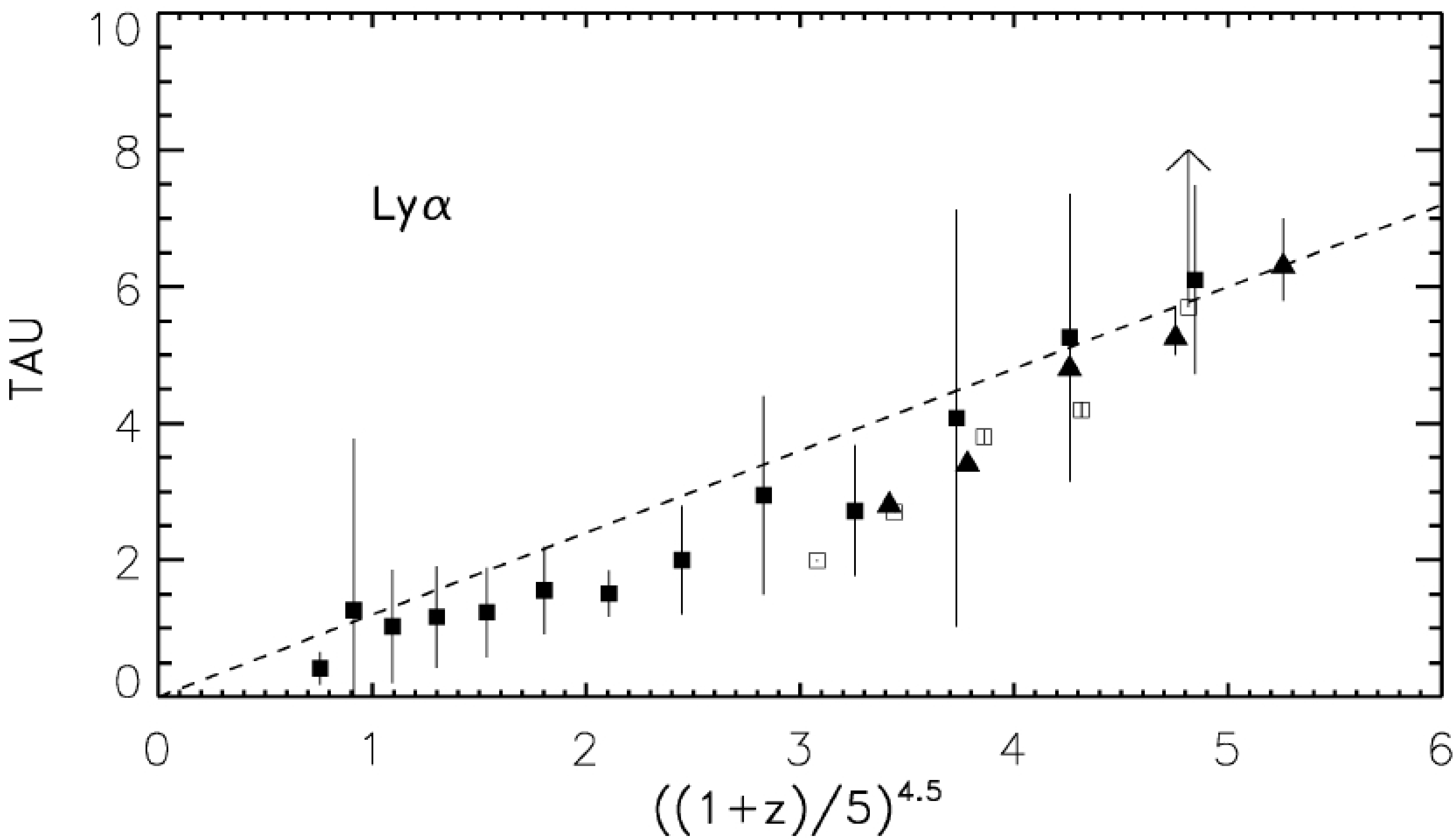


X. Fan

GP trough saturates at low τ_{HI}, which is produced by low x → would like to see "sharp feature"

(and find GRB…)

Len Cowie's more gradual $\tau(z)$



When?

(2) Did it really begin at $z \sim 20$?

$\tau_{fe} \sim 0.17$ in CMB large angle WMAP TE correlations

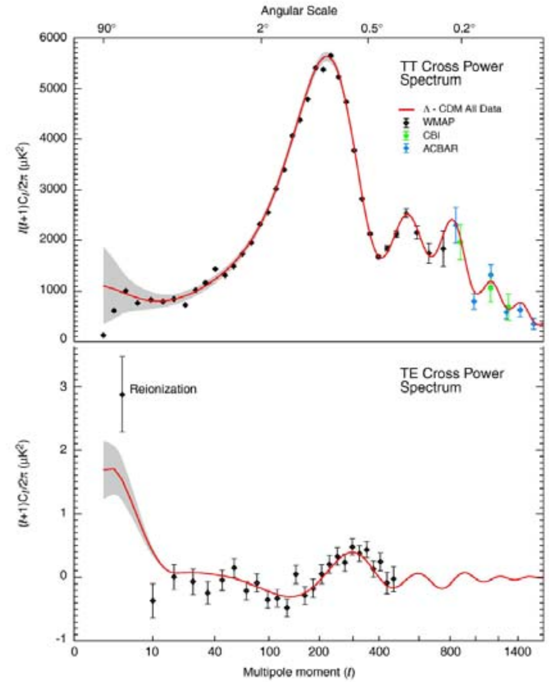


Fig. 12.— The *WMAP* angular power spectrum. (*top*:) The *WMAP* temperature (TT) results are consistent with the ACBAR and CBI measurements, as shown. The TT angular power spectrum is now highly constrained. Our best fit running index ΛCDM model is shown. The grey band represents the cosmic variance expected for that model. The quadrupole has a surprisingly low amplitude. Also, there are excursions from a smooth spectrum (e.g., at $\ell \approx 40$ and $\ell \approx 210$) that are only slightly larger than expected statistically. While intriguing, they may result from a combination of cosmic variance, subdominant astrophysical processes, and small effects from approximations made for this first year data analysis (Hinshaw et al. 2003b). We do not attach cosmological significance to them at present. More integration time and more detailed analyses are needed. (*bottom*:) The temperature-polarization (TE) cross-power spectrum, $(l+1)C_l/2\pi$. (Note that this is *not* multiplied by the additional factor of l.) The peak in the TE spectrum near $l \sim 300$ is out of phase with the TT power spectrum, as predicted for adiabatic initial conditions. The antipeak in the TE spectrum near $l \sim 150$ is evidence for superhorizon modes at decoupling, as predicted by inflationary models.

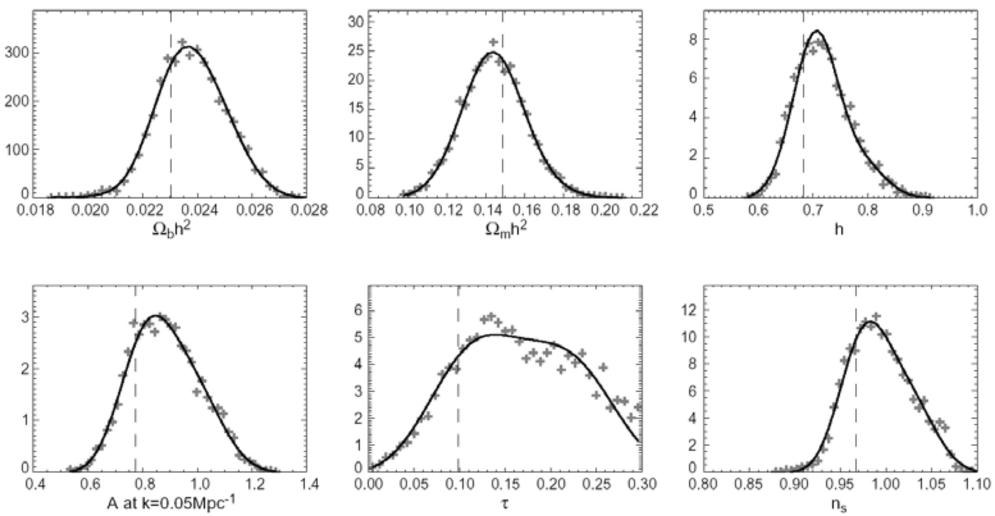
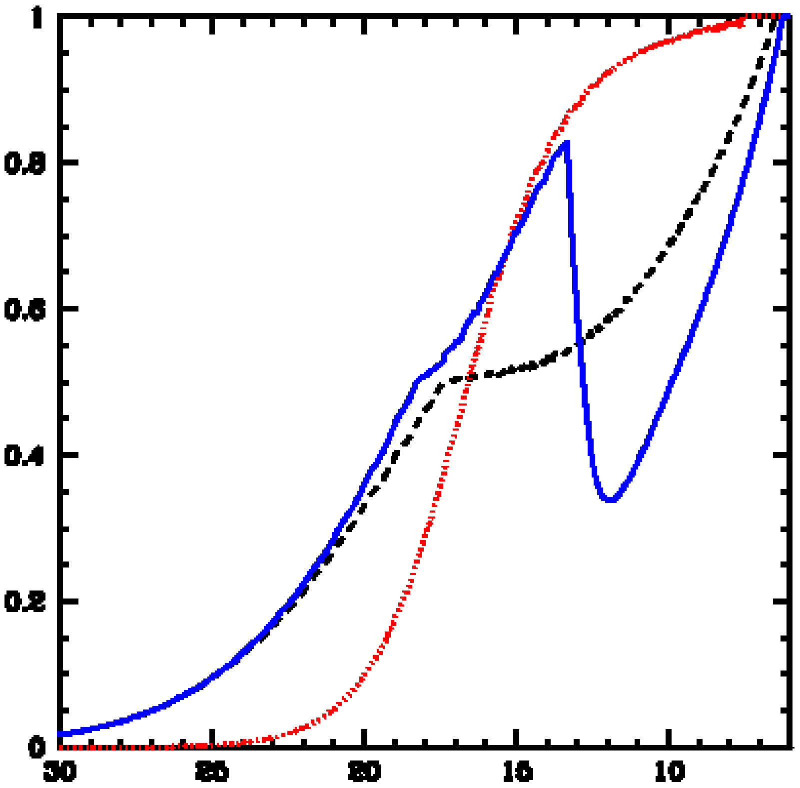
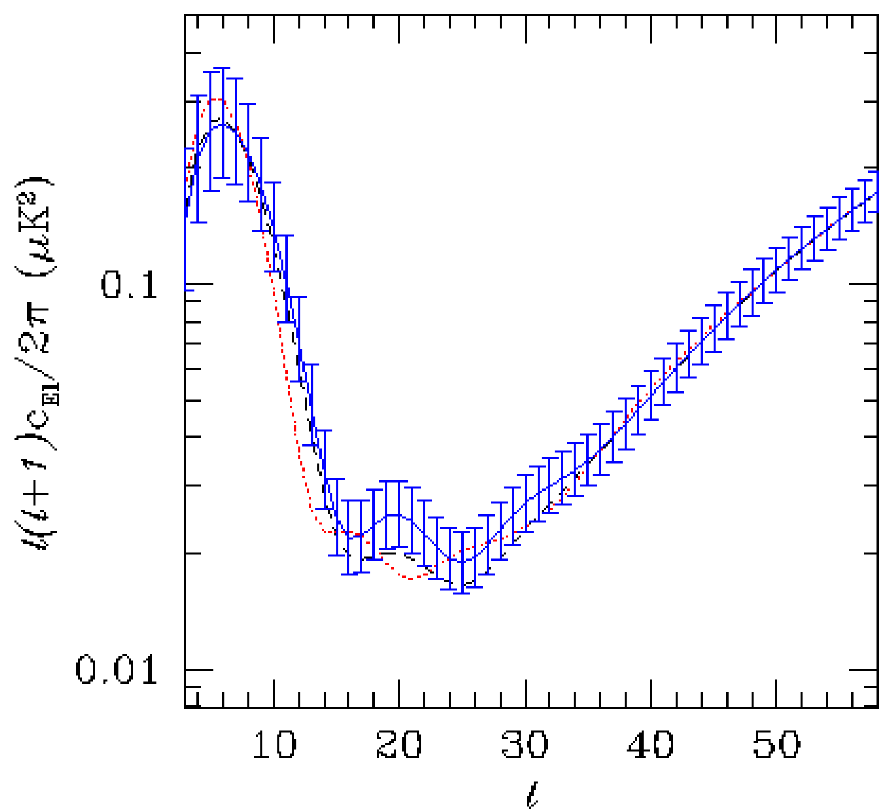


Fig. 3.— This figure shows the likelihood function of the *WMAP* TT + TE data as a function of the basic parameters in the power law ΛCDM *WMAP* model. ($\Omega_b h^2$, $\Omega_m h^2$, h, A, n_s and τ.) The points are the binned marginalized likelihood from the Markov chain and the solid curve is an Edgeworth expansion of the Markov chains points. The marginalized likelihood function is nearly Gaussian for all of the parameters except for τ. The dashed lines show the maximum likelihood values of the global six dimensional fit.





Various generic ionizers (Type 1a, 1b, and II !!!)

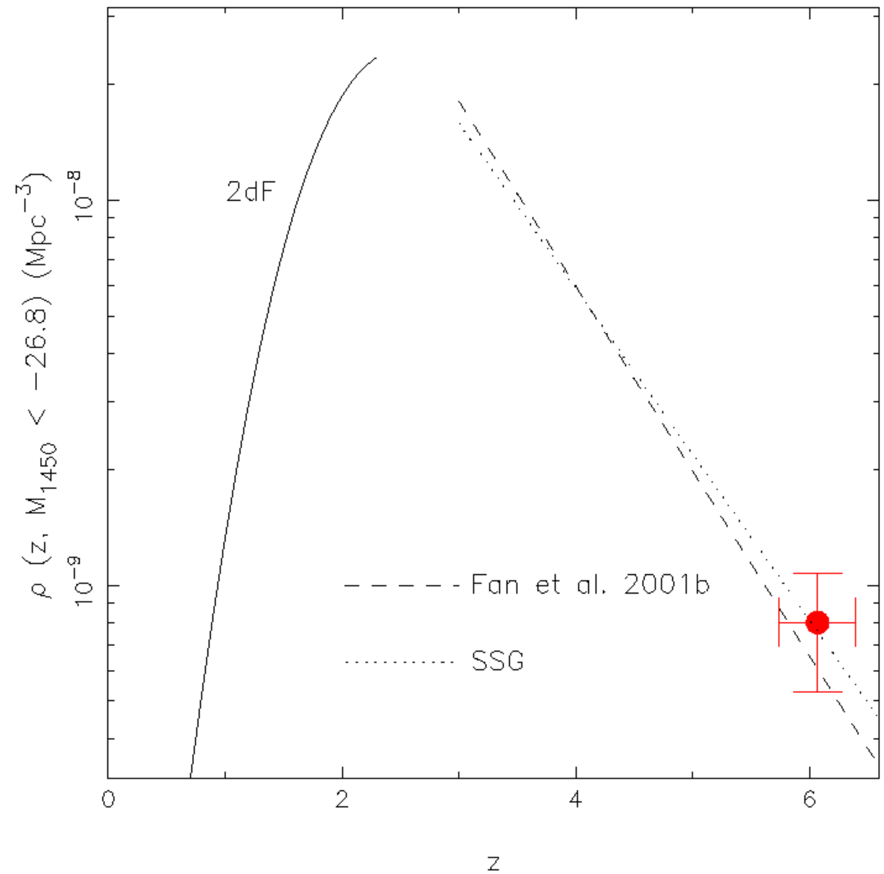
Features in extended x(z) due to evolution of ionizers (e.g. feedback, Z effects etc) may conceivably be detectable in CMB polarization spectrum

We need more "realistic" simulations of range of possibilities for details and if possible new observational tools

What did it?

Quasar Density at z~6

- Based on nine z>5.7 quasars:
  - Density declines by a factor of ~20 from z~3
  - Number density implies that quasars are unlikely to provide enough UV background if LF is similar to that at low-z → ***first stars ionized the universe!***
- Cosmological implication
  - M_{BH}~$10^{9\text{-}10}$ M_{sun}
  - M_{halo} ~ 10^{13} M_{sun}
  - ***How to form such massive galaxies and assemble such massive BHs in less than 1Gyr??***
    - The rarest and most biased systems at early times
    - Using Eddington argument, ***the initial assembly of the system must start at z>>10***



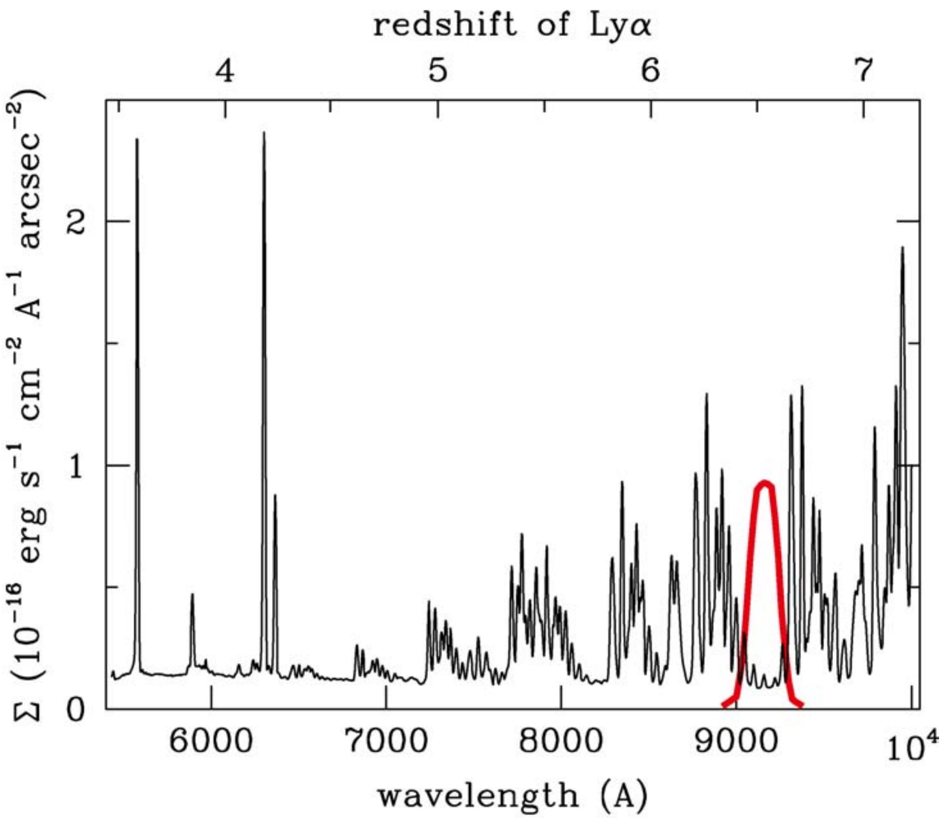
…probably not quasars at z ~ 6

Fan et al. in prep.

Searches for galaxies at z ~ 6

- Ly α galaxies
- Ly break galaxies (continuum)
- Obscured??

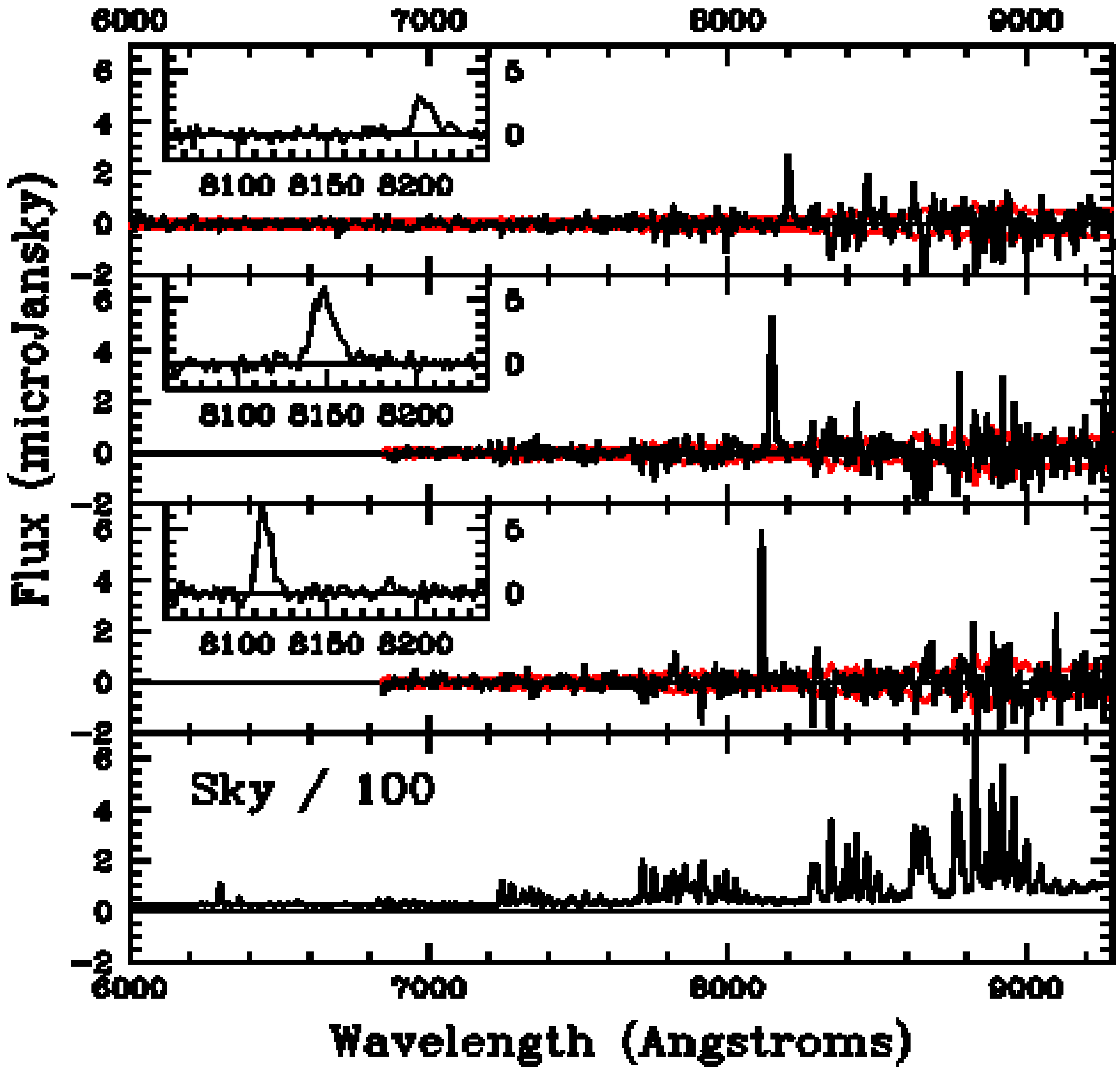
Many talks at this and slightly lower redshift → but still only a handful of sources, and these highly selective (c.f. Abraham, McCarthy, Franx at z ~ 2) etc.



Esther Hu	z = 6.6
[Subaru	2 @ z ~ 6.5]
…….	
Sangeeta Malhotra	3 @ z ~ 5.7
	1-2 @ z ~ 6.5
Christian Maier	2 @ z ~ 5.7
Malcolm Bremer	6 LBG @ 5 < z < 6
Garth Illingworth	60 I-band dropouts
Crystal Martin	none @ z ~ 5.7

CCD cut-off at ~ 1 μm: how did the Si band-gap possibly know about cosmic reionization and the Bohr atom?

Three z=5.7 Lyman Alpha Sources



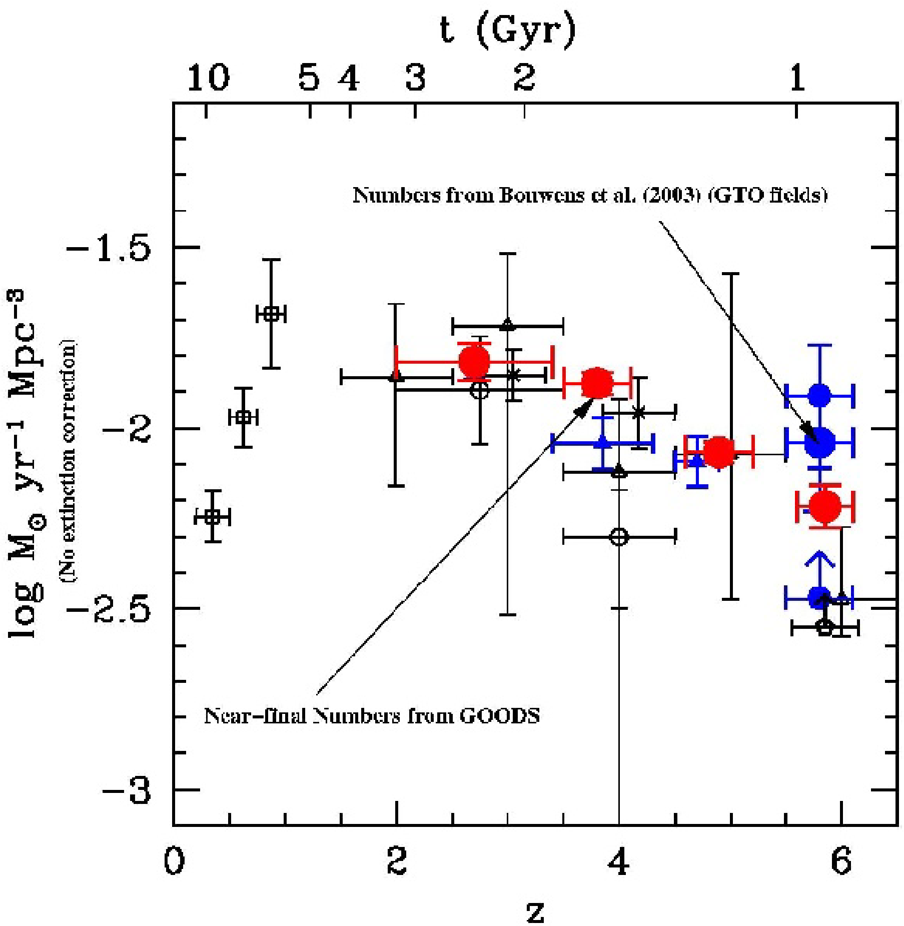
- Confirmed z=5.7 LALA sources.
- Three of four spectroscopically confirmed at Keck.

(Rhoads et al 2002, submitted to AJ)

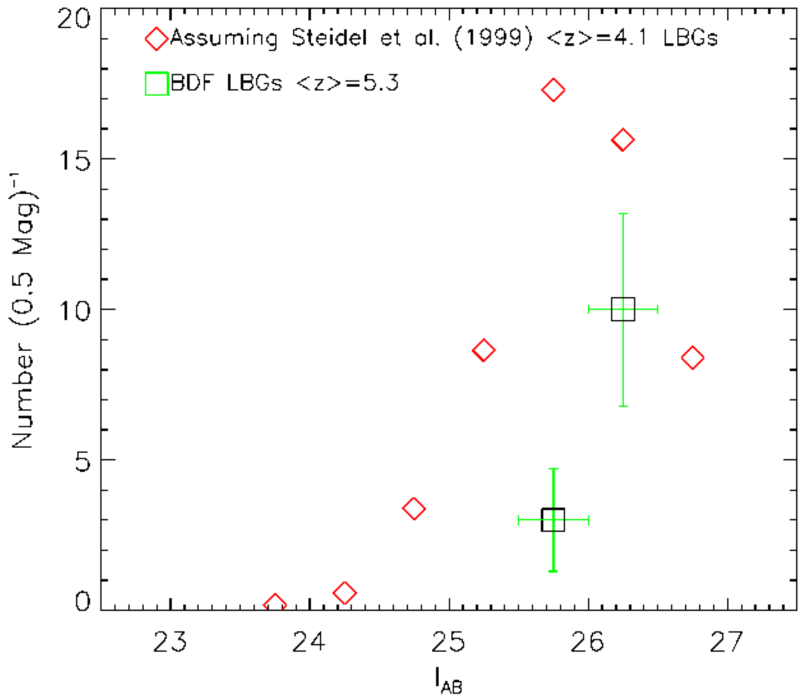
LALA survey

(Malhotra+Rhoads)

Declining ultraviolet luminosity density?

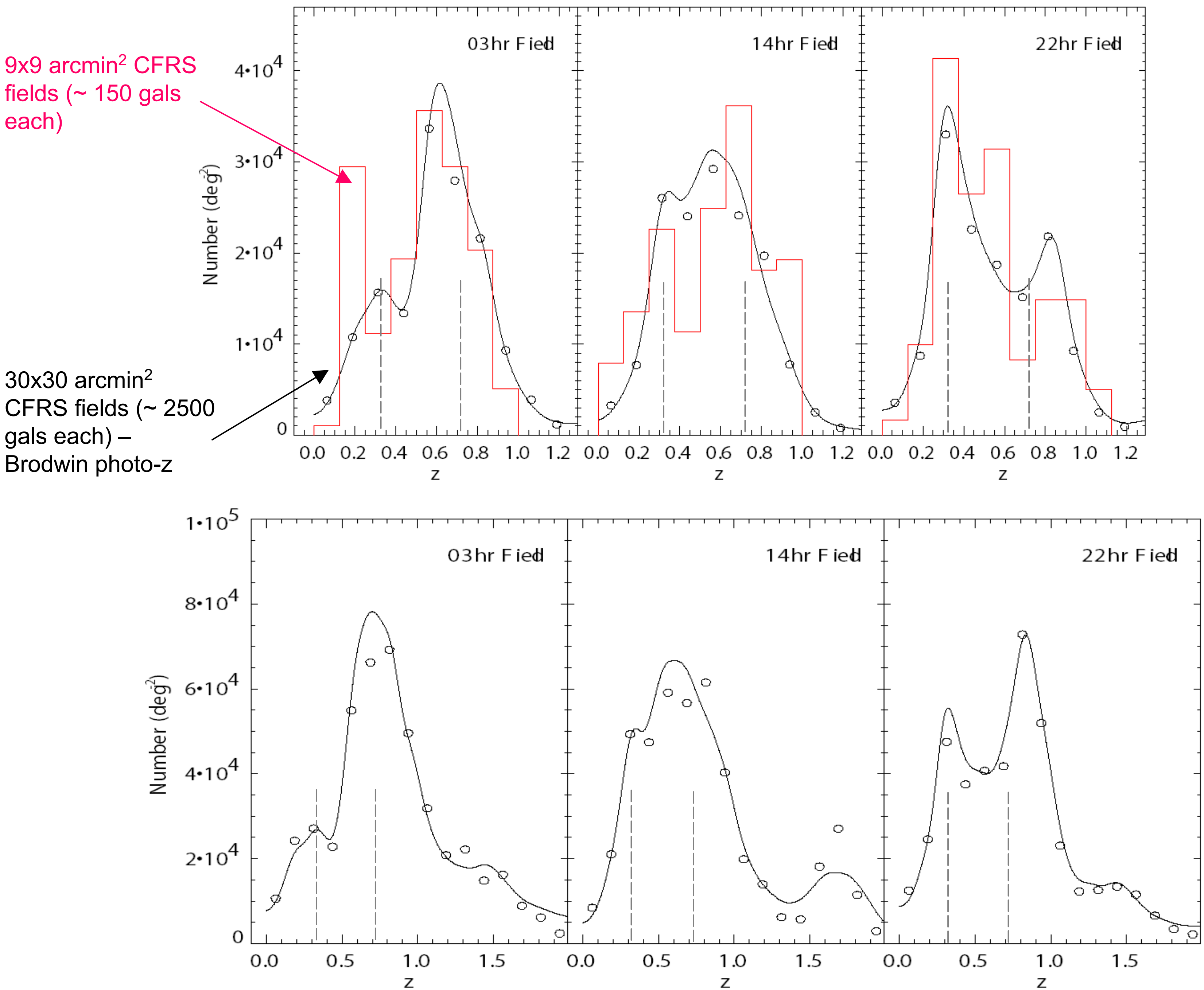


Garth Illingworth

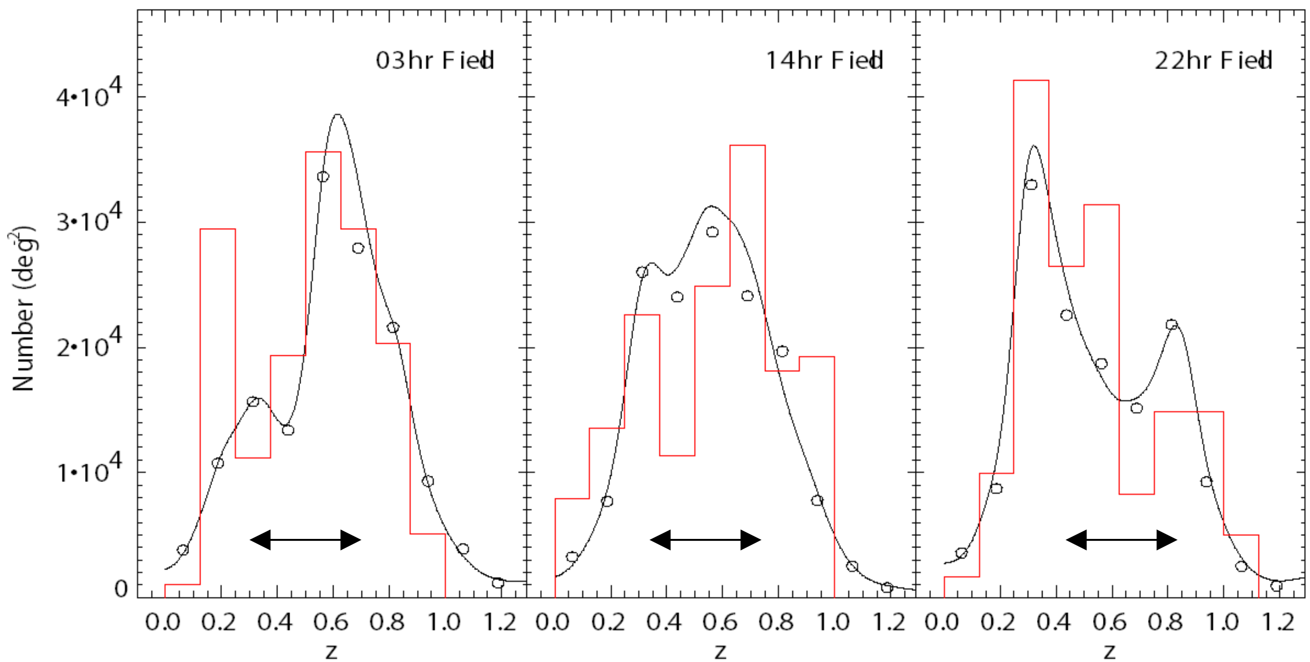


Malcolm Bremer

Cosmic variance… a (real) cautionary example

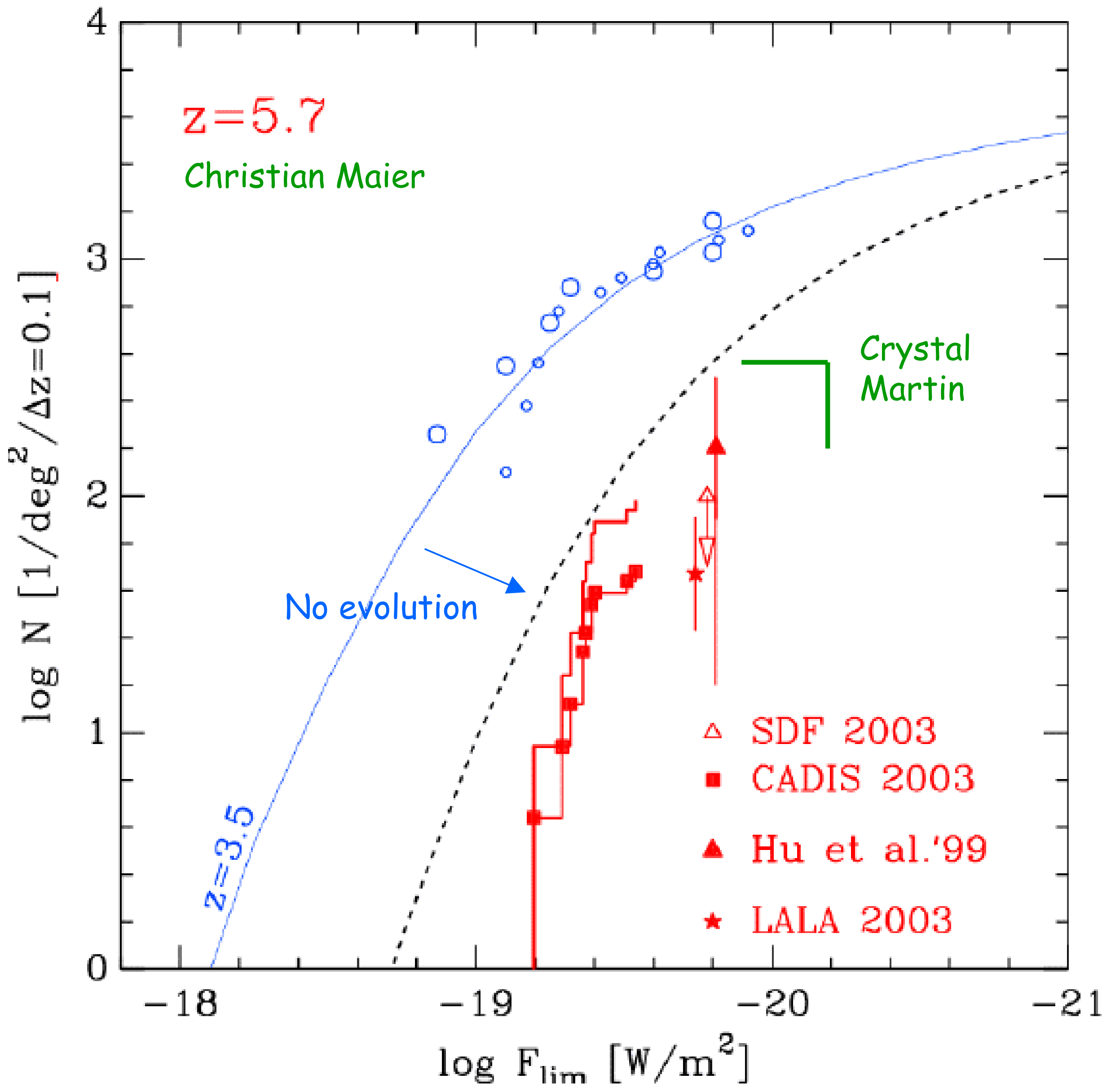


9x9 arcmin2 CFRS fields (~ 150 gals each)
30x30 arcmin2 CFRS fields (~ 2500 gals each) – Brodwin photo-z
03hr Field
14hr Field
22hr Field
Number (deg-2)
z

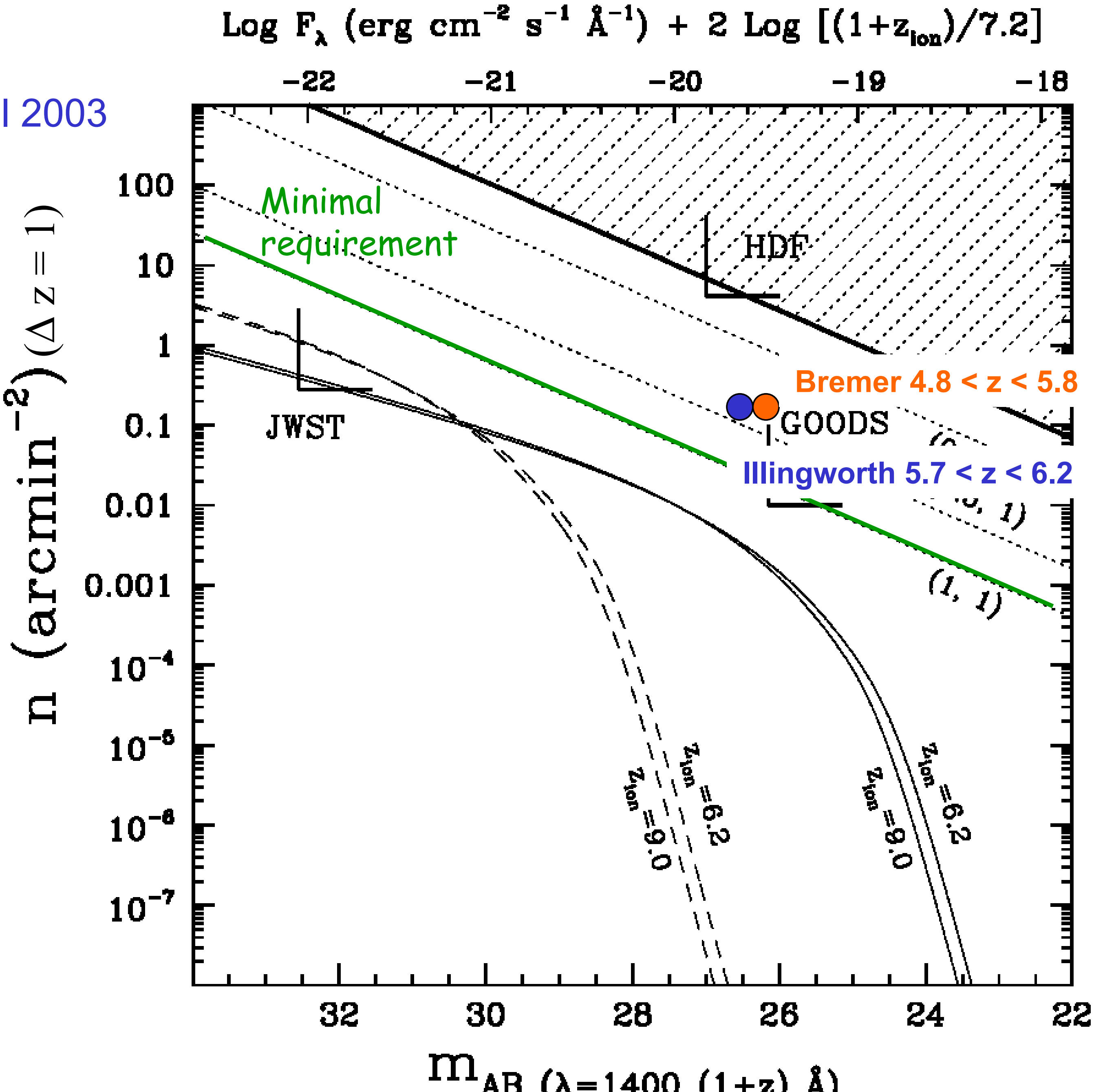


Equivalent surveys	30 arcmin at z = 0.7 (23 Mpc)	Δz = 0.4 at z = 0.7 (1200 Mpc)
At *z* ~ 1.5	15 arcmin	Δz = 0.8
At *z* ~ 3	10 arcmin	Δz = 1.6
At *z* ~ 6	8 arcmin	Δz = 3.5

Declining ultraviolet luminosity density?



Stiavelli et al 2003



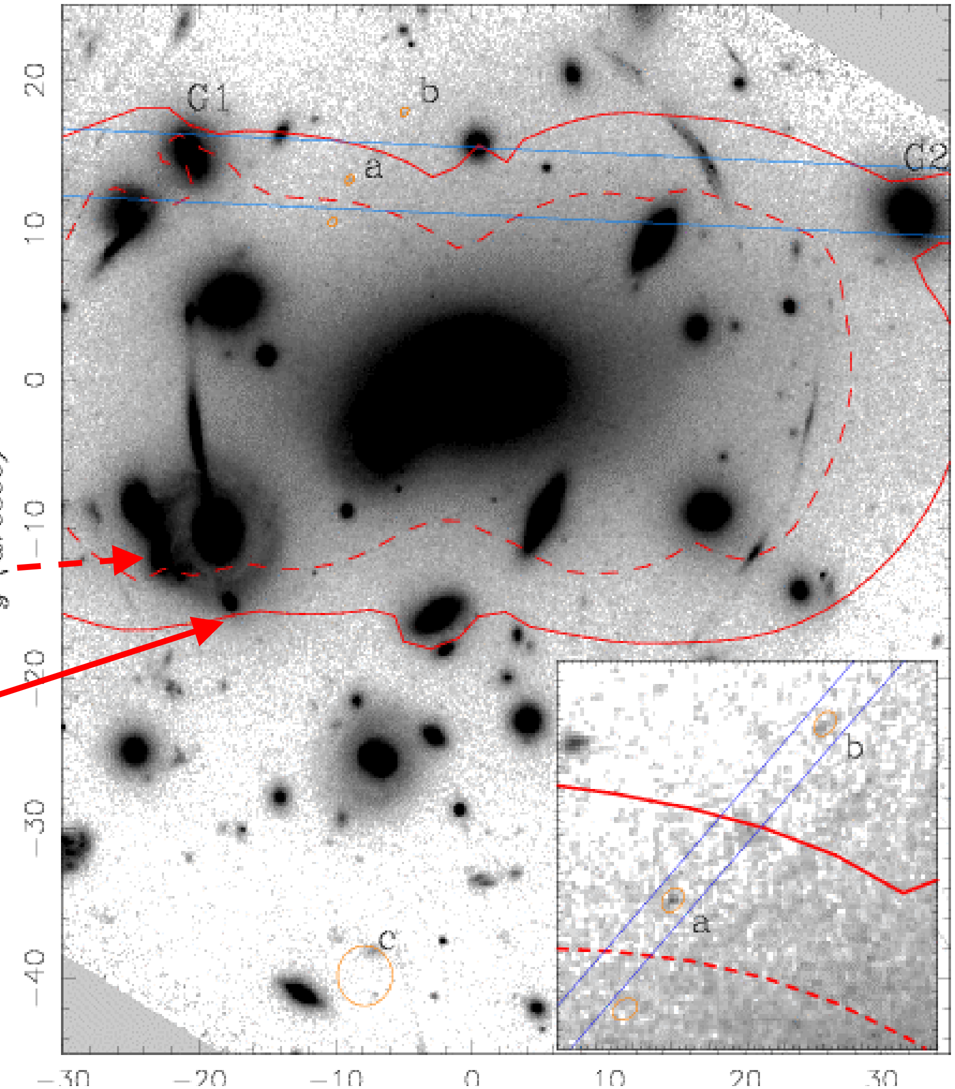
Critical Line Mapping with Keck (Ellis et al 2001)

From arclet spectroscopy the location of the "critical lines" is known precisely for

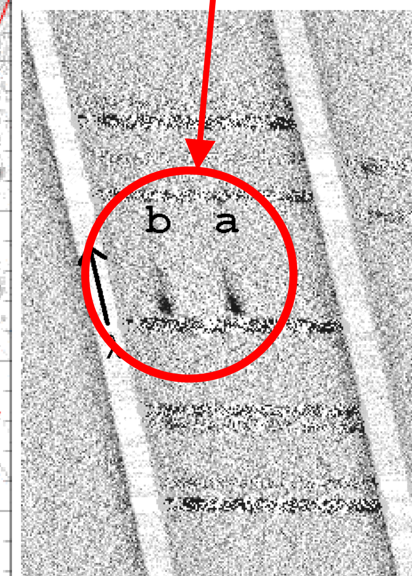
z=1

and for

z=5



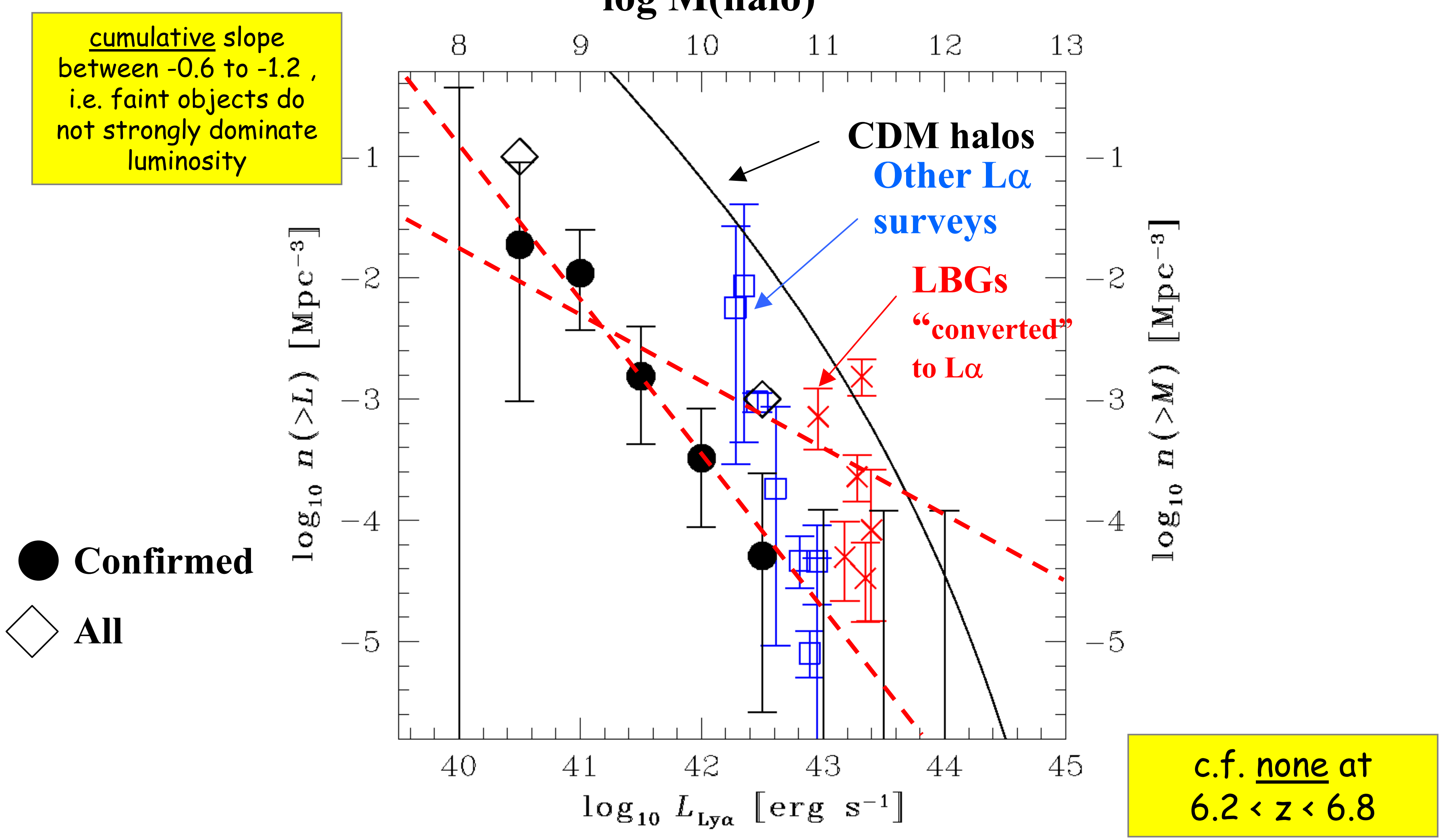
Blind Lyα search with LRIS: hi-res follow-up with ESI



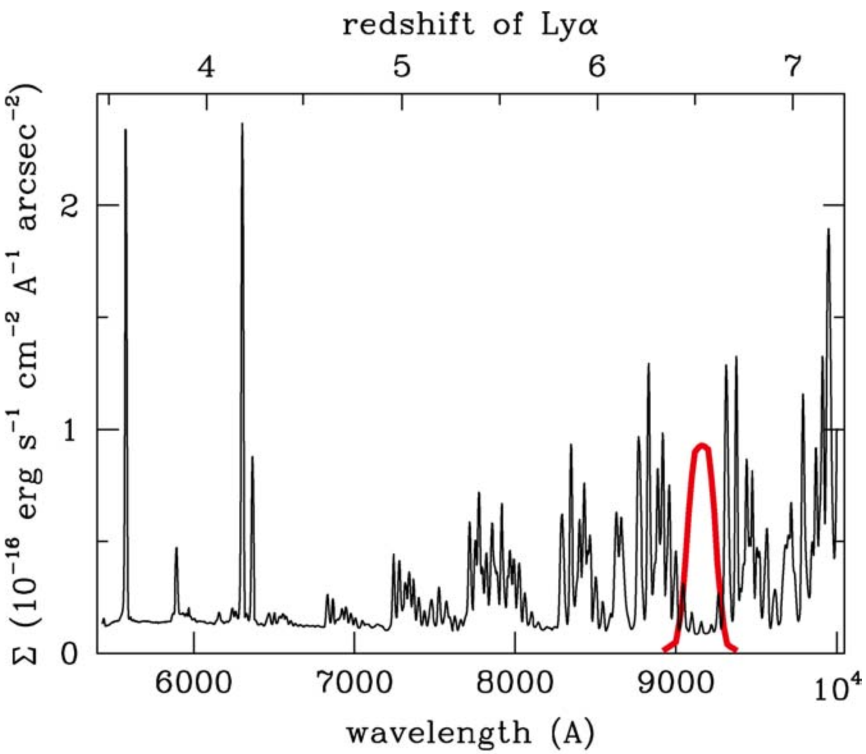
Utilizing strong magnification (×10-30) of clusters, probe much fainter than other methods but in tiny areas (<0.1 arcmin^2 cluster^{-1})

Cumulative Lyα LF: 4.7<z<5.7

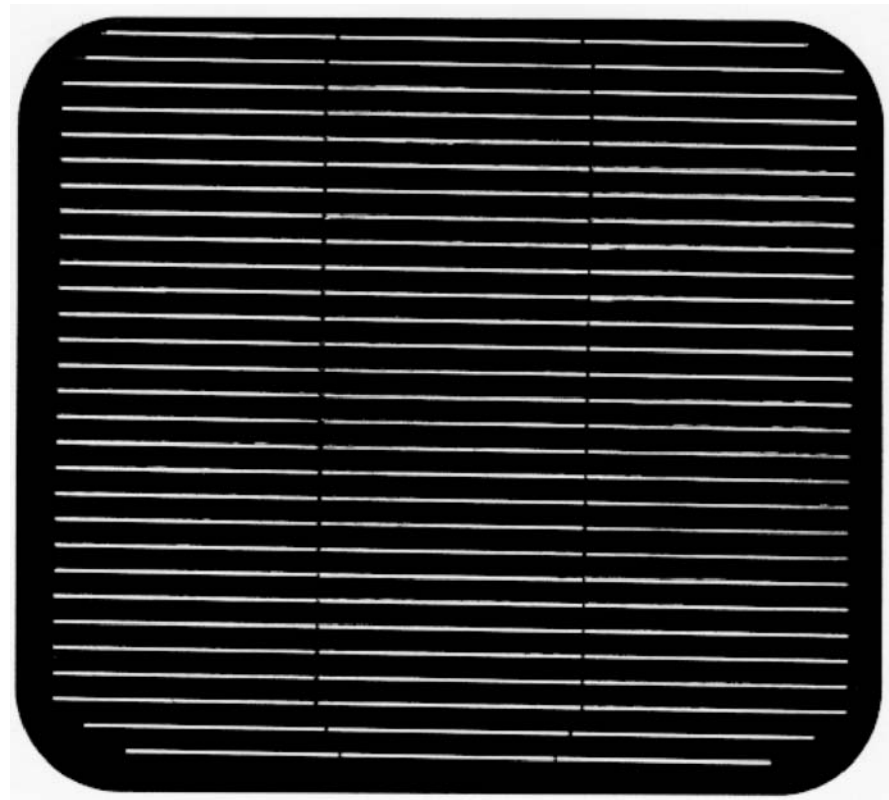
Santos, Ellis, Kneib & Kuijken (in prep)



Surveyed 9 clusters: 12 magnified Lyα emitters 3.5 < z <6.2



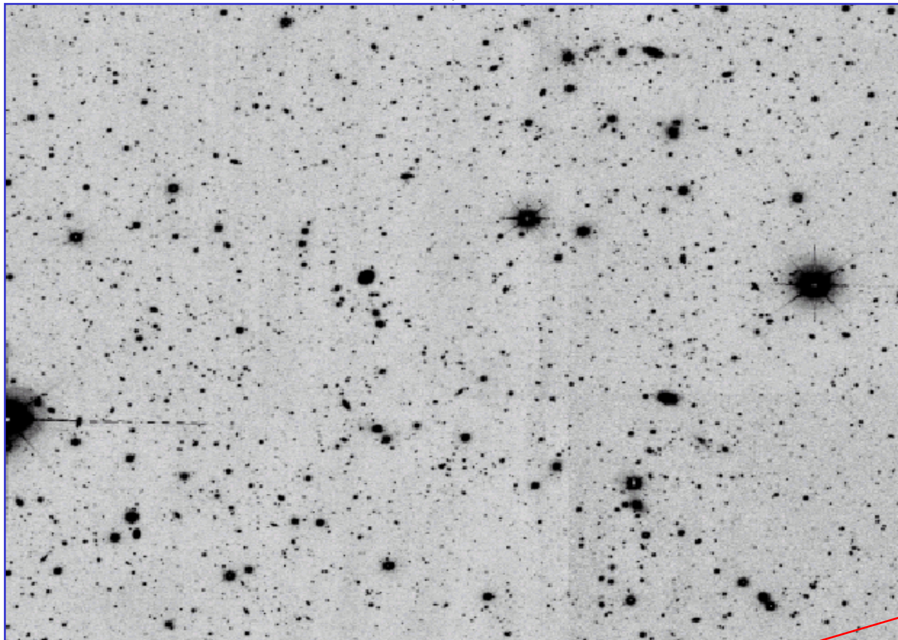
9000-9300 Å band-width limiting filter

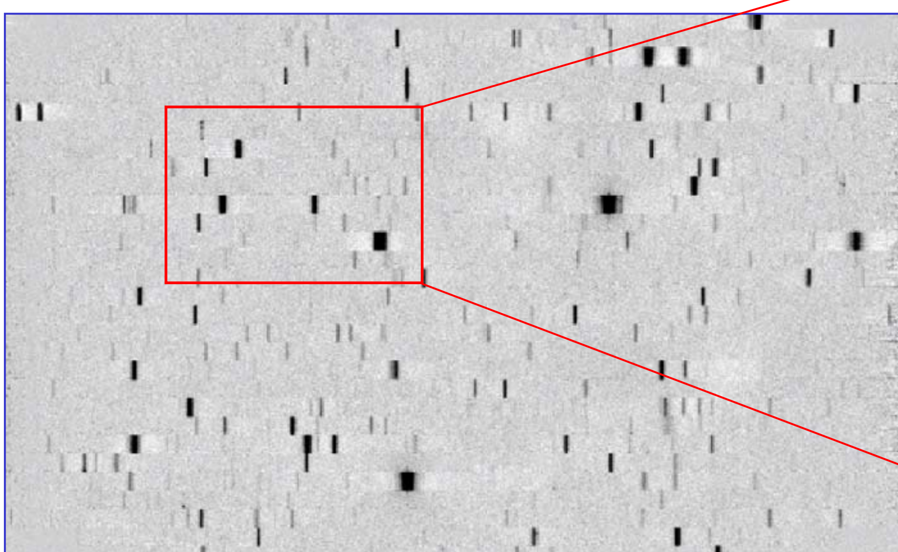


CFHT/MOS: 10Å/pix → 29 slits (9 armin^2)

Sensitivity gain w.r.t. imaging filter:	$(\Delta\lambda/\delta\lambda)^{1/2}$ ~ 6 absence of EQW selection/ immediate z etc
Multiplex gain w.r.t. long slit:	N_{slit}

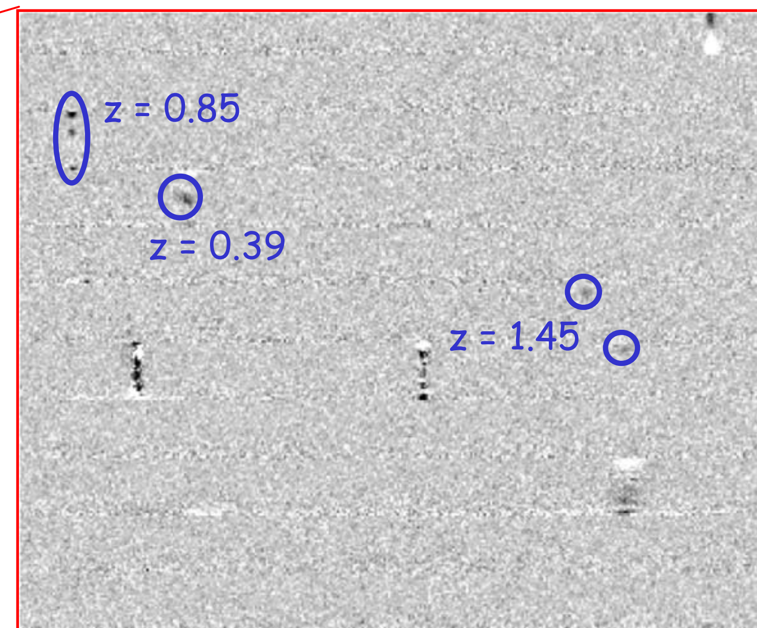
Finding emission lines in the 9200 Å atmospheric window

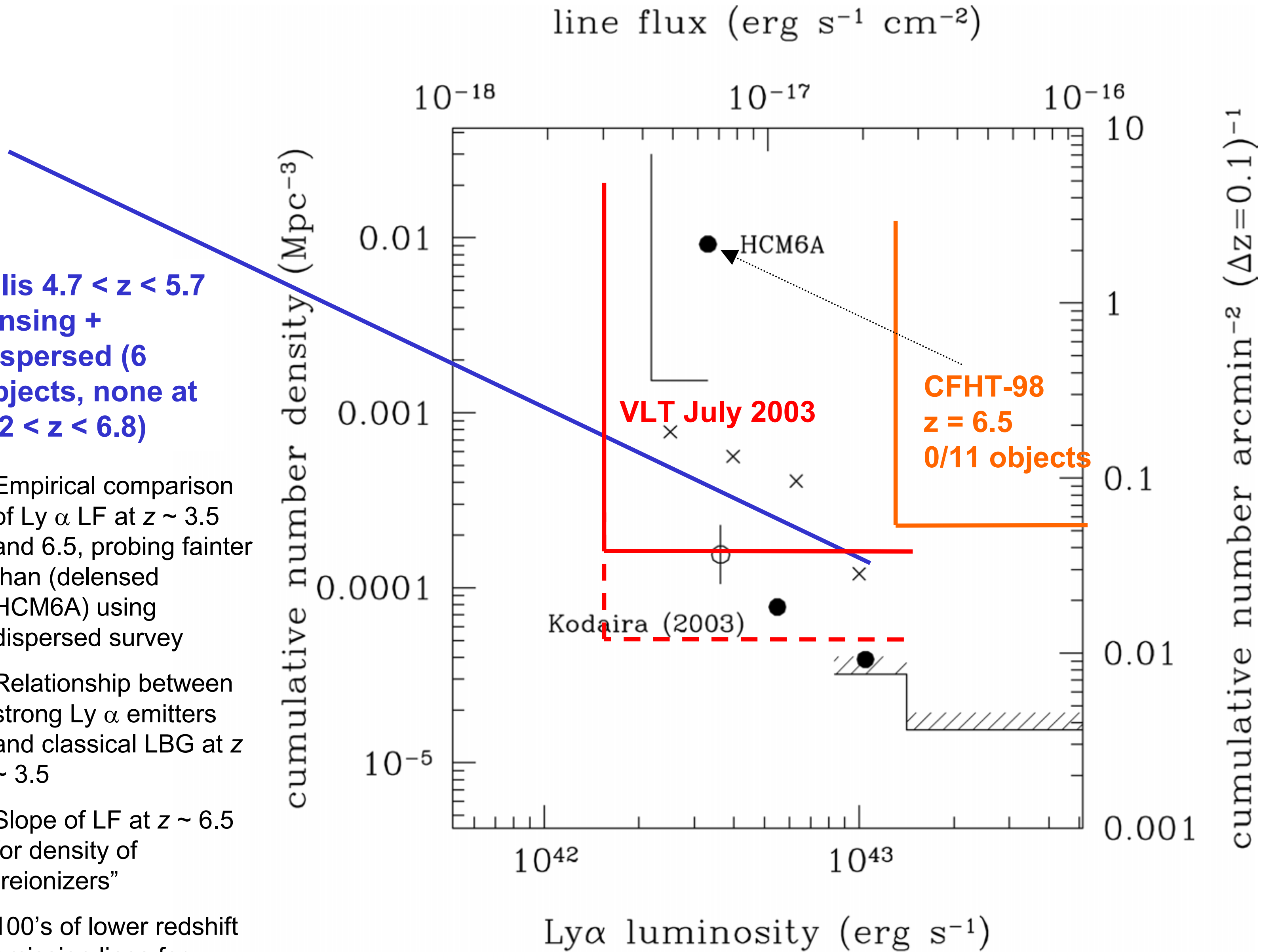




CFHT test data (Crampton & SJL 99) – re-analysed with Vy Tran and Mark Brodwin

- 0/11 objects at z = 6.5
- 2/11 objects have EQW > 200 Å (Ha and [OII] 3727)





Ellis 4.7 < z < 5.7 lensing + dispersed (6 objects, none at 6.2 < z < 6.8)

- Empirical comparison of Ly α LF at *z* ~ 3.5 and 6.5, probing fainter than (delensed HCM6A) using dispersed survey
- Relationship between strong Ly α emitters and classical LBG at *z* ~ 3.5
- Slope of LF at *z* ~ 6.5 for density of "reionizers"
- 100's of lower redshift emission lines for metallicity etc etc

Reionization may well have been completed around z ~ 6 but can't be completely sure because of $\tau(x)$ saturation

Reionization may well have started around z ~ 15 (but can't yet be completely sure – potential in future WMAP etc)

Known galaxies at z ~ 6 are not far from being able to do the job, but this doesn't mean they did, especially if reionization was early. Major uncertainties in f_{esc} etc, clumpiness etc.

Increasing sophistication of measurements of IGM post-reionization offer promise of providing fossilized information on energy/metyal injection etc

It would be very nice to have other probes of $x(z)$

Faint observations at λ > 1 μm are crucial – eventually JWST

This is an area where basic theory is still way ahead of observations, which are needed to indicate relevance and relative importance of different phenomena and produce realistic simulations