Constraining Star Formation at z>7

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A Century of Cosmology, San Servolo, Italy, 27 August 2007

Characterizing Star Formation at z>7: the Current Frontier

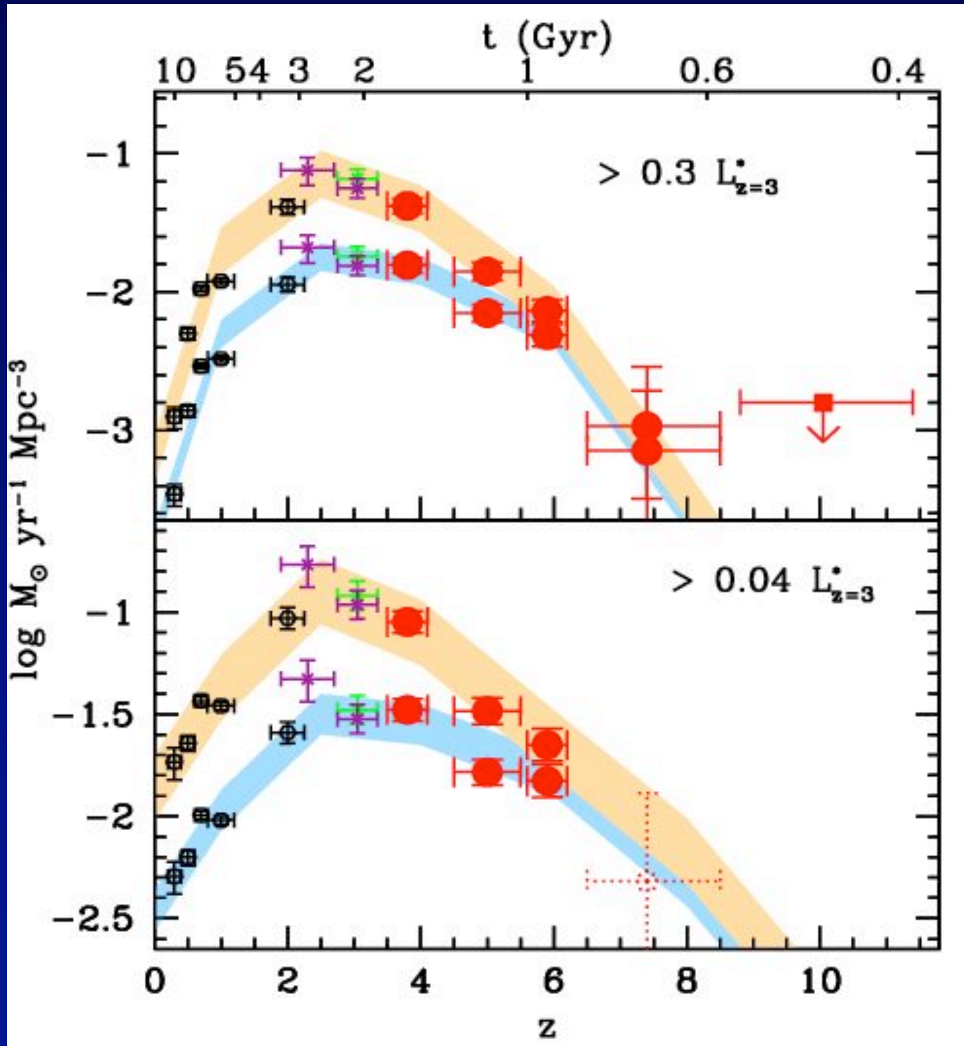
Motivation:

- Probing some of the earliest galaxies (t<750 Myr)
  - how does the global star formation rate density evolve?
  - what is the density and luminosity distribution of earliest star-forming systems?
  - what are physical properties (e.g. metallicity, stellar mass) of galaxies at the highest redshifts?

- contribution of early star formation to reionization
  - what were the objects that reionized the IGM?
  - what is the redshift distribution of the reionizing systems?
  - if star-forming galaxies, were the galaxies primarily low luminosity?

- *note: current mode of observational study of z>7 universe is exploratory in nature*

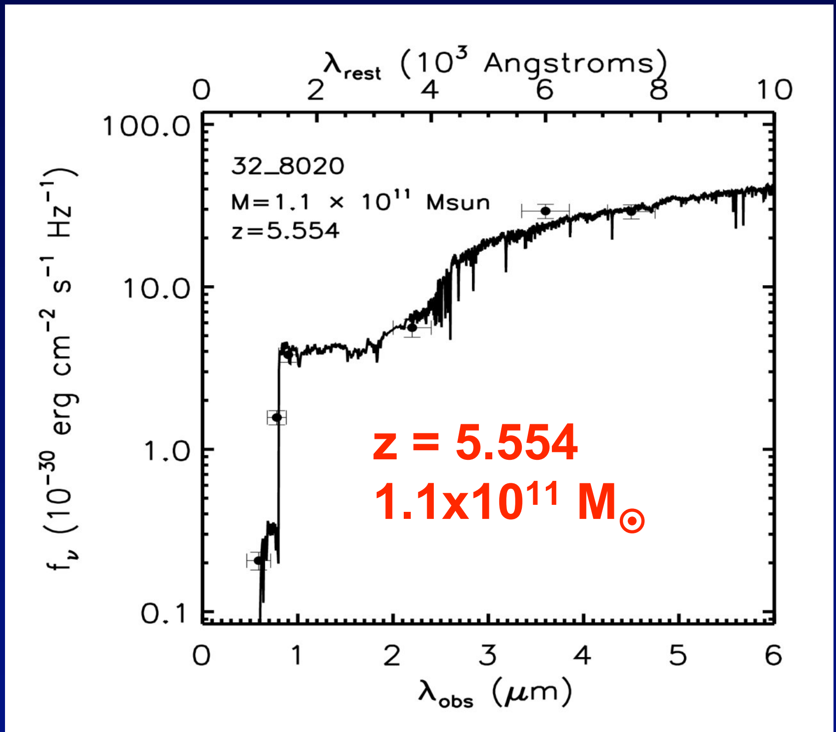
Decline in Star Formation Rate Density?



Bouwens et al., 2007
arXiv:0707:2080

Does decline in SFRD extend to higher redshifts?

Old stars at z~5-6 Implies Star Formation at z>6



Stark et al. (2007a) ApJ, 659, 84

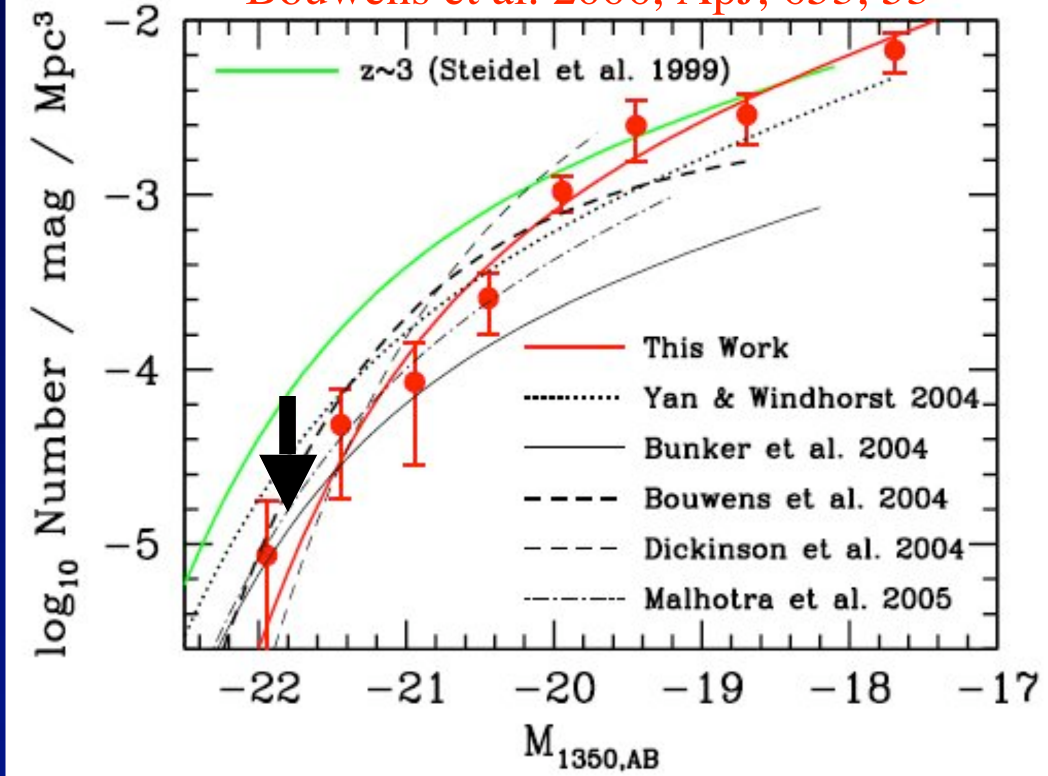
Measurement of stellar mass *density* allows constraints to be placed on required SF at z>5-6 to assemble galaxies (Stark & Ellis 2005, Stark et al. 2006, Yan et al. 2006, Eyles et al. 2006)

Assembled stellar mass density at z~5-6 requires greater star formation rate density at z>6 than has been observed thus far.

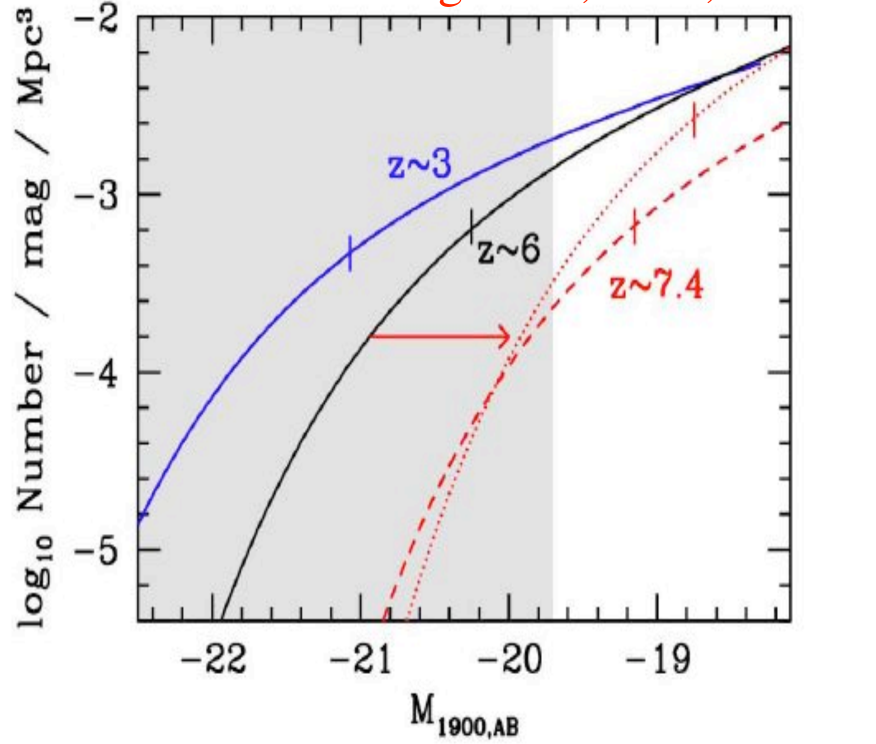
How do we directly observe missing sources at z>6?

Evidence for Luminosity-Dependent Evolution

Bouwens et al. 2006, ApJ, 653, 53



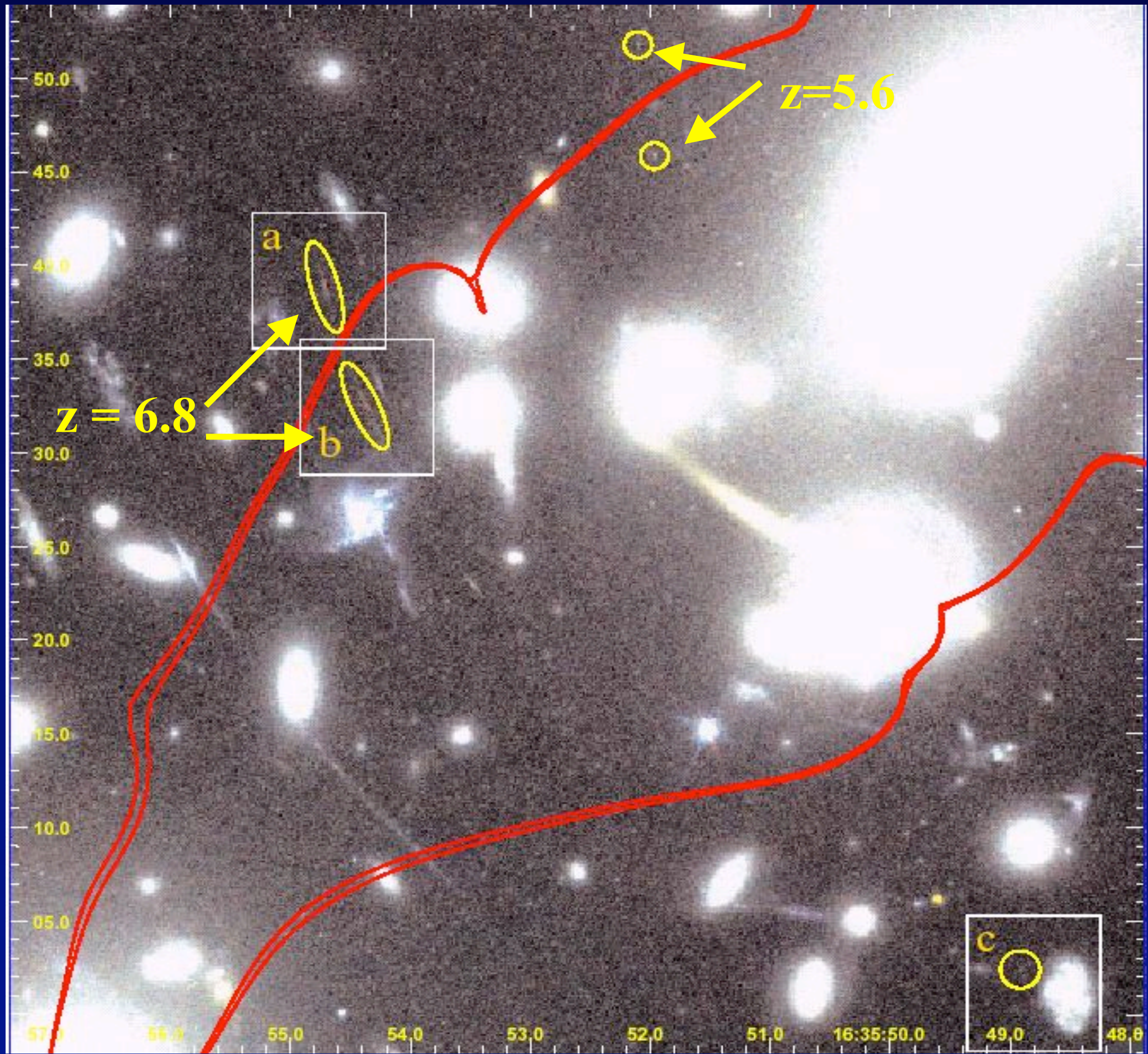
Bouwens & Illingworth, 2006, Nature



Bouwens et al (2006, 2007) and Yoshida et al. (2006) propose L-dependent evolution - decline in abundance over 3<z<6 *mostly for luminous sources*

Observations suggest star formation increasingly dominated by low luminosity sources for z>6?

Beyond z~7 with Strong Gravitational Lensing



Utilizing strong magnification (×10-30) of clusters, probe much fainter than other methods in small areas (<0.1 arcmin^2 /cluster)

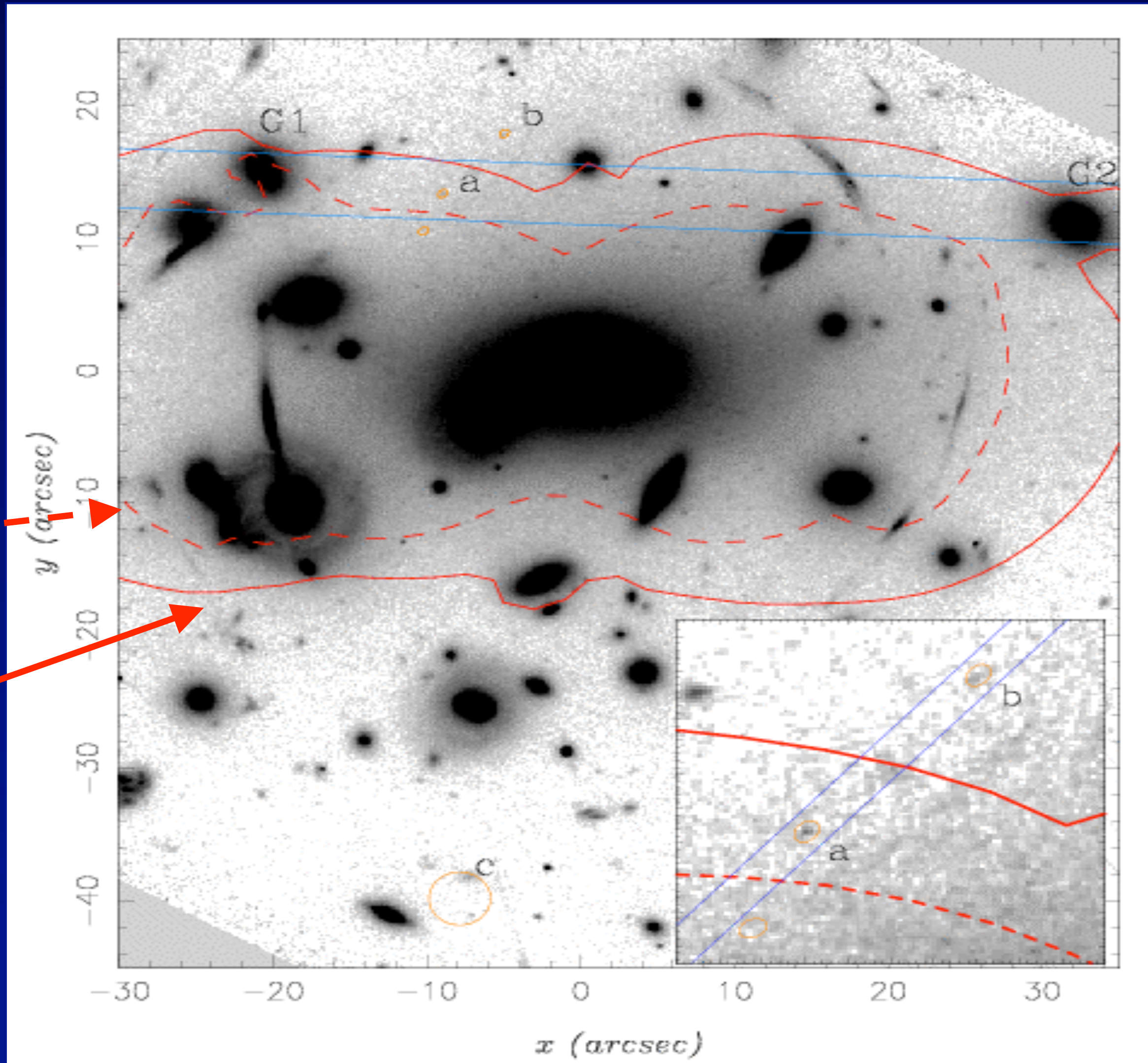
Spectroscopic Surveys for Lensed Lyman-alpha Emitters

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

z=1

and for

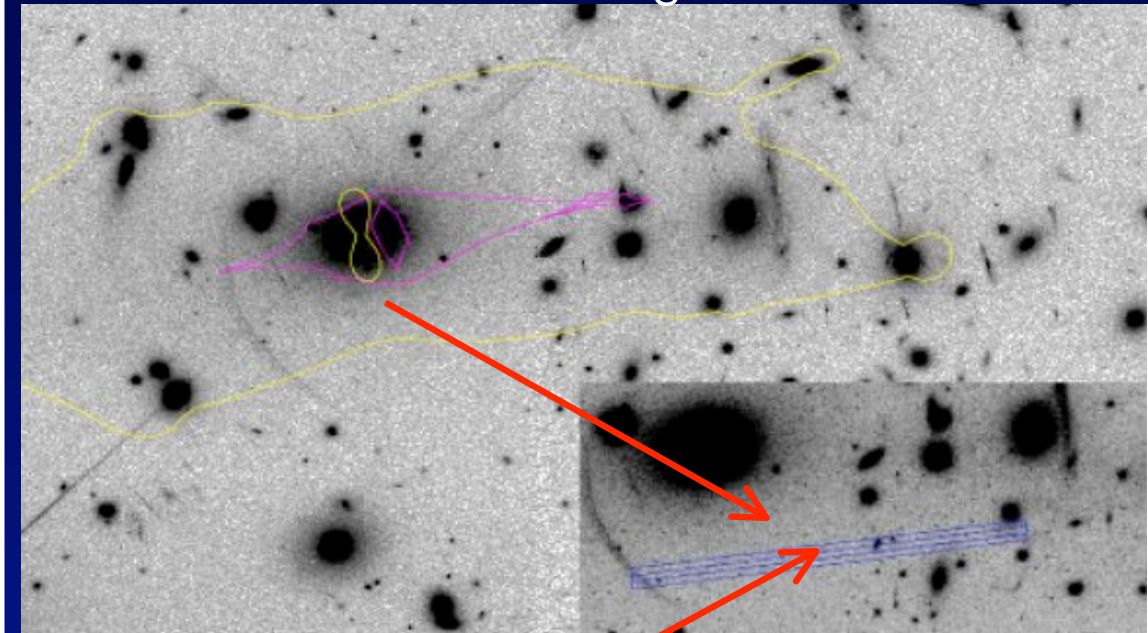
z=5



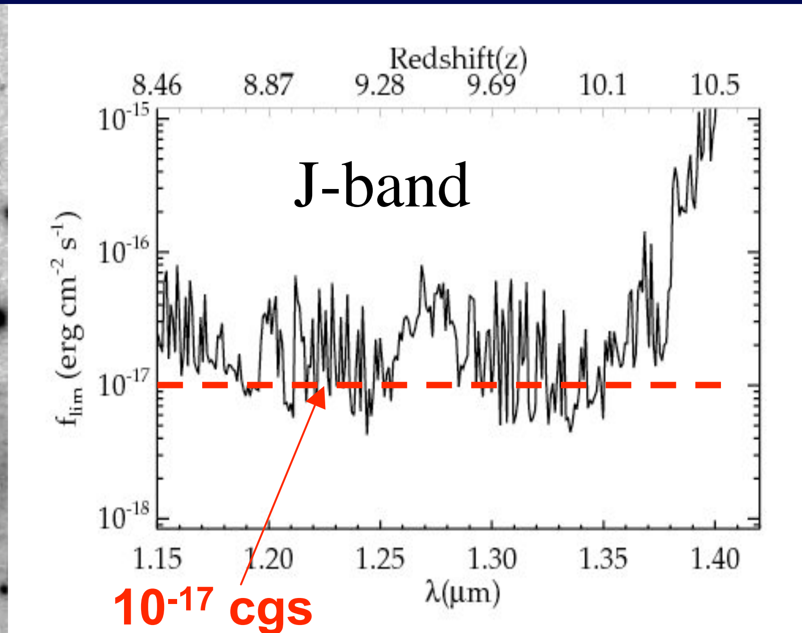
A Keck survey in the optical discovered 11 candidate LAEs between 2.2 < z < 5.6 -- Santos et al. ApJ 606, 683 (2004)

Low Luminosity z~10 Lyα Emitters: Critical Line Mapping With Keck NIRSPEC

Cluster critical line for $z_S > 7$



Wavelength sensitivity (1.5hr)

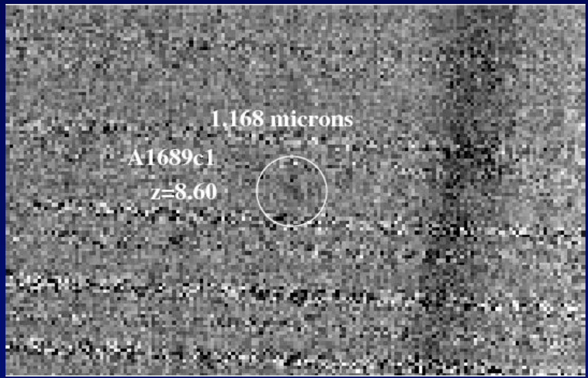


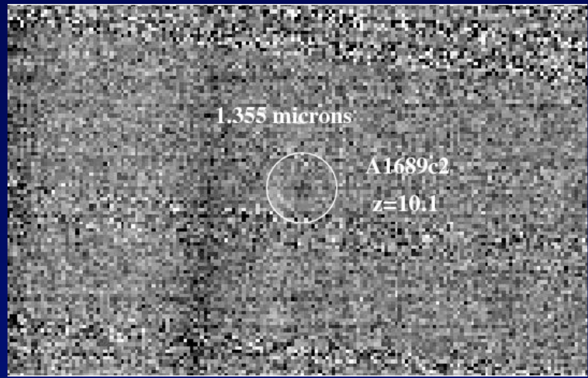
NIRSPEC slit positions

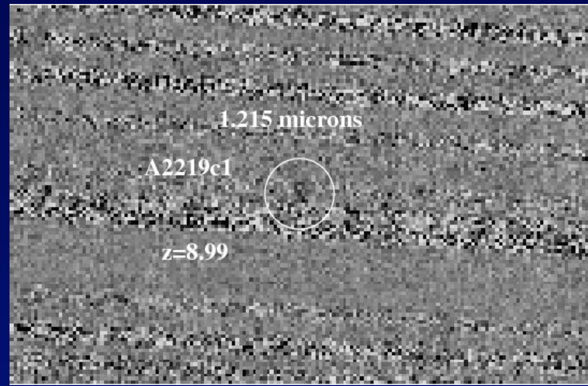
- 9 clusters completed between 04-05 (Stark et al. 2007b, ApJ, 663,10)
- Clusters have well-defined mass models & deep ACS imaging
- Obs. sensitivity ~ 0.6-2 x10^{-17} cgs; magn. > ×10-30 throughout
- Sky area observed: 0.3 arcmin^2; V(comoving)~30 Mpc^3
- 6 promising lensed emitter candidates (>5σ)
  - $8.6 < z < 10.2$; L ~ 2 - 50. 10^{41} cgs; SFR ~ 0.2 -5 $M_\odot$ yr^{-1}

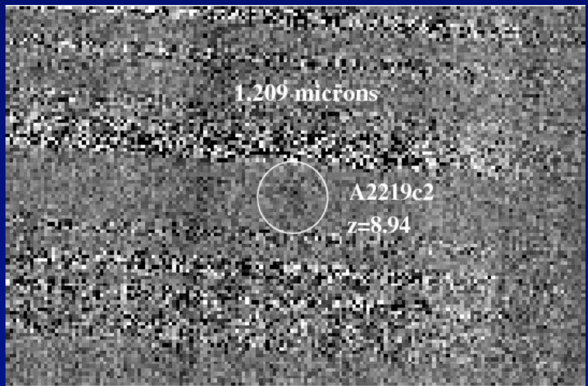
Candidate Lyα Emitters

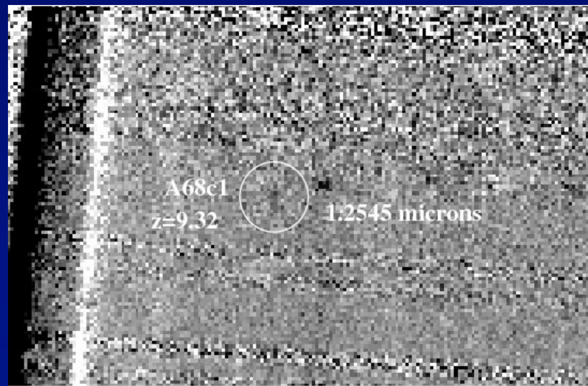
$8.6 < z < 10.2$; L ~ 2 - 50. 10^{41} cgs; SFR ~ 0.2 - 5 $M_\odot$ yr^{-1}

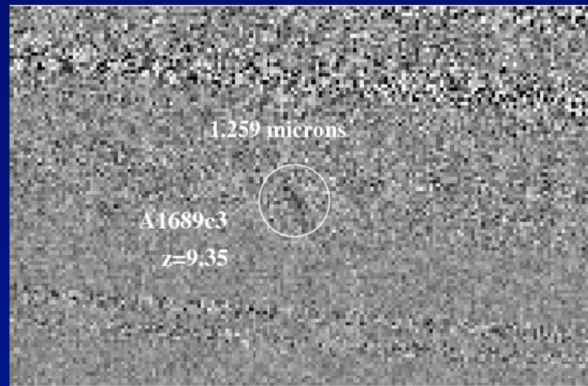












Recognize burden of proof that these are z~10 emitters is high!

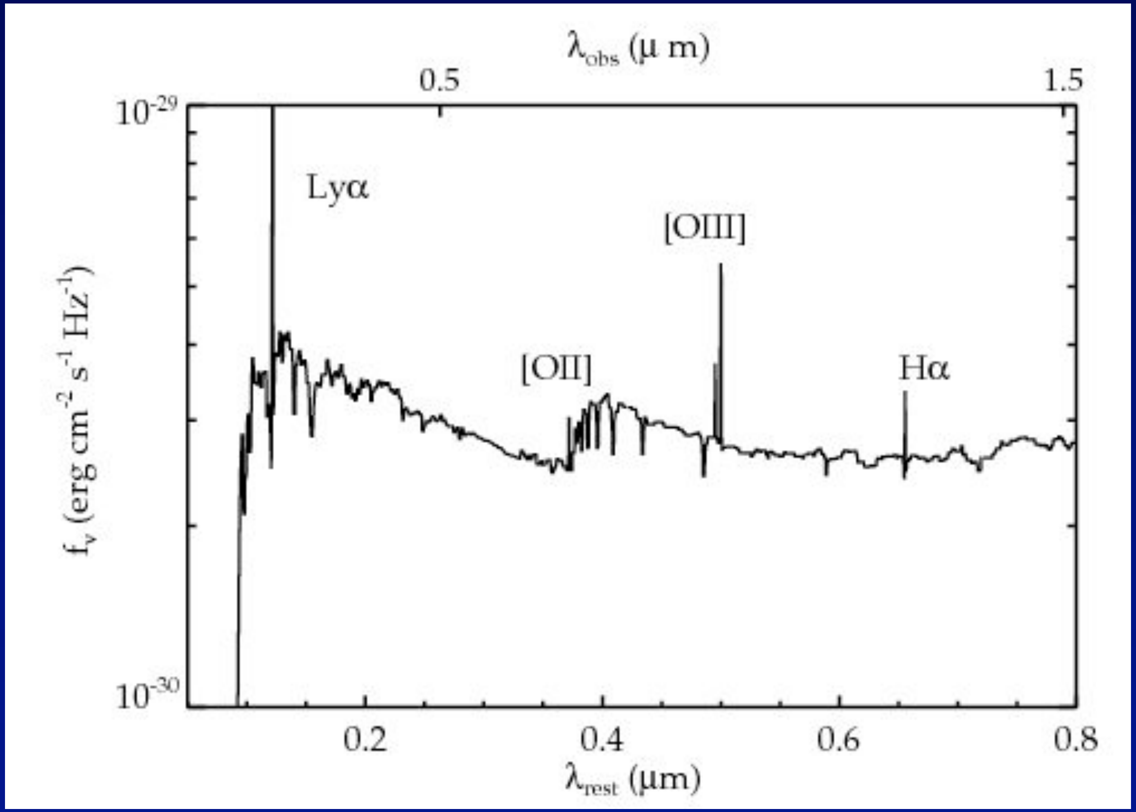
(see discussion in Stern et al. 2000ab, Bremer et al. 2004, G. Smith et al. 2006)

Each detection is > 5σ, seen in independent exposures/visits

Spectroscopic Elimination of Interlopers

If J-band emission is Hα…

z~0.9



Lyα, [OII], and [OIII] observable with optical spectroscopy

Spectroscopic Elimination of Interlopers

- Archival LRIS spectroscopy (Santos et al 2004) from 4000-9400Å available for all candidates
  - No emission lines detected: candidates are probably not Hα or [OII]
- H-band spectroscopy obtained for 3 candidates with NIRSPEC
  - No emission lines detected: 2/6 candidates are probably not Hβ, [O III]
- J-band spectroscopy available for all candidates with NIRSPEC
  - No additional emission lines detected: candidates are most likely not [OIII] λ4959
- optical broadband? one candidate has marginal z-band detection
  - remove from high-z sample

At least 2 candidates are most easily explained as z~10 sources, and an additional 3 candidates have strong case to be at z~10.

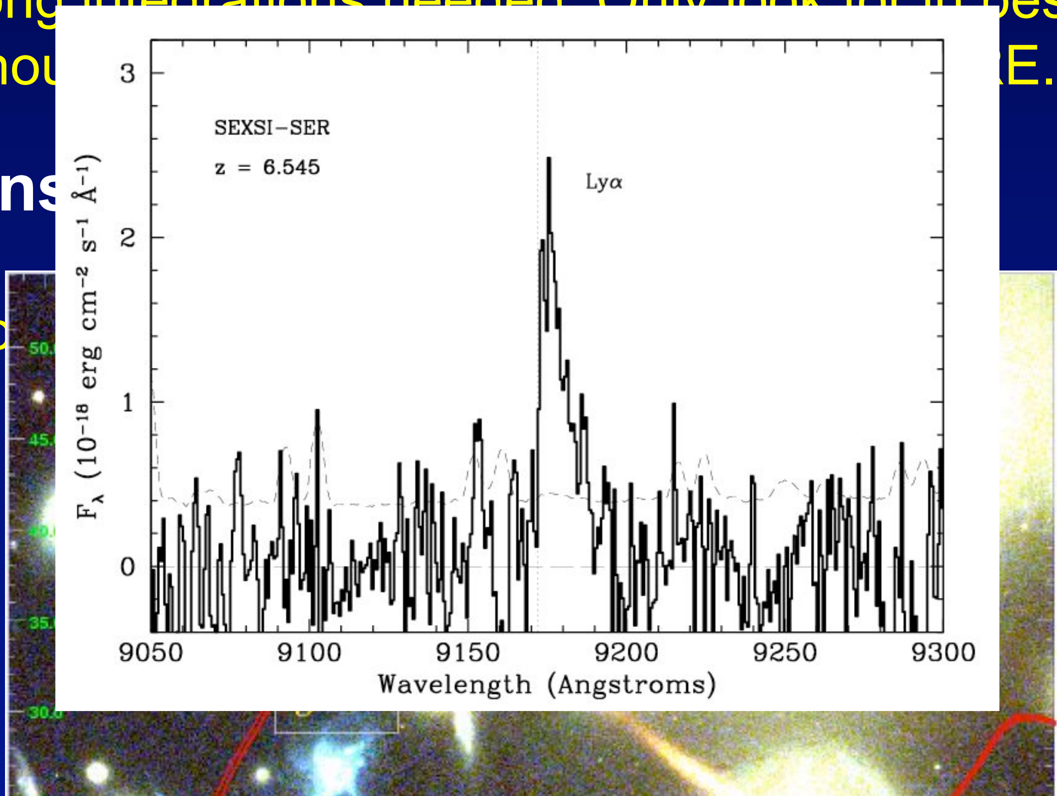
Confirming Galaxies at z>8

1. Asymmetric Line Profile?

Long integrations needed. Only look for in best candidates.
Shou ... E.

2. Lens

Co ... t spectrograph.



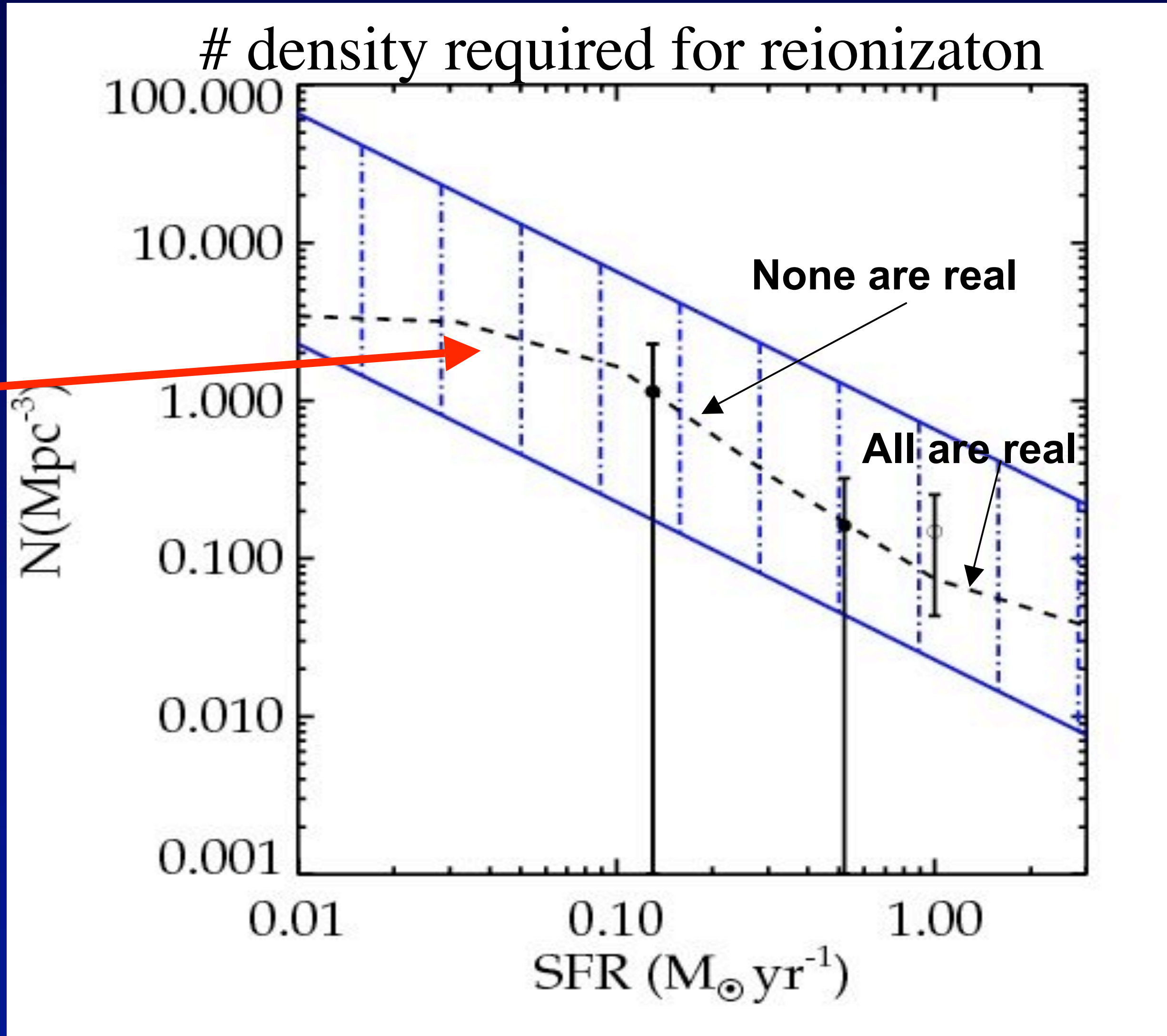
Stern et al. 2005, ApJ

Contribution to Reionization?

Consider range:

$f_{esc} \sim 0.02\text{-}0.5$
$\Delta t \sim 250\text{-}575$ Myr

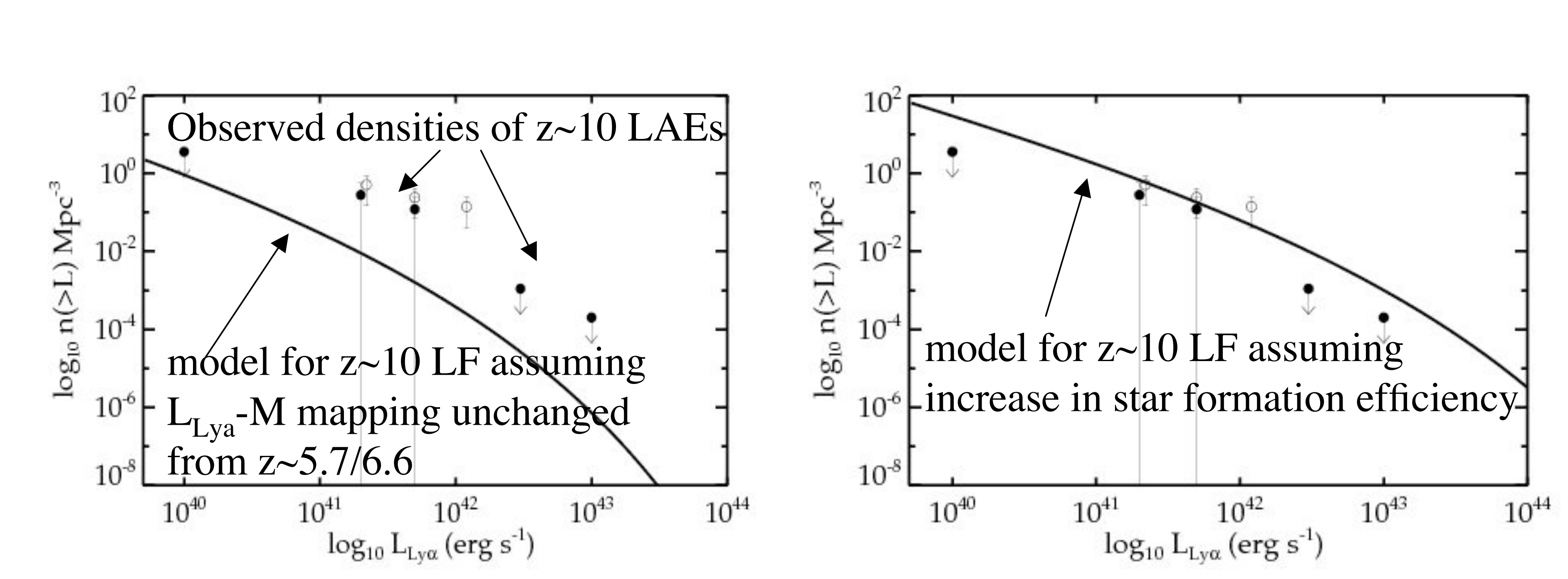
If even 1-3 of the 6 candidates is at z~10, low luminosity galaxies may play a dominant role in cosmic reionization



Key uncertainty: if candidates are at z~10, are observed densities characteristic given large cosmic variance?

A surprisingly large abundance of z~10 Lya Emitters?

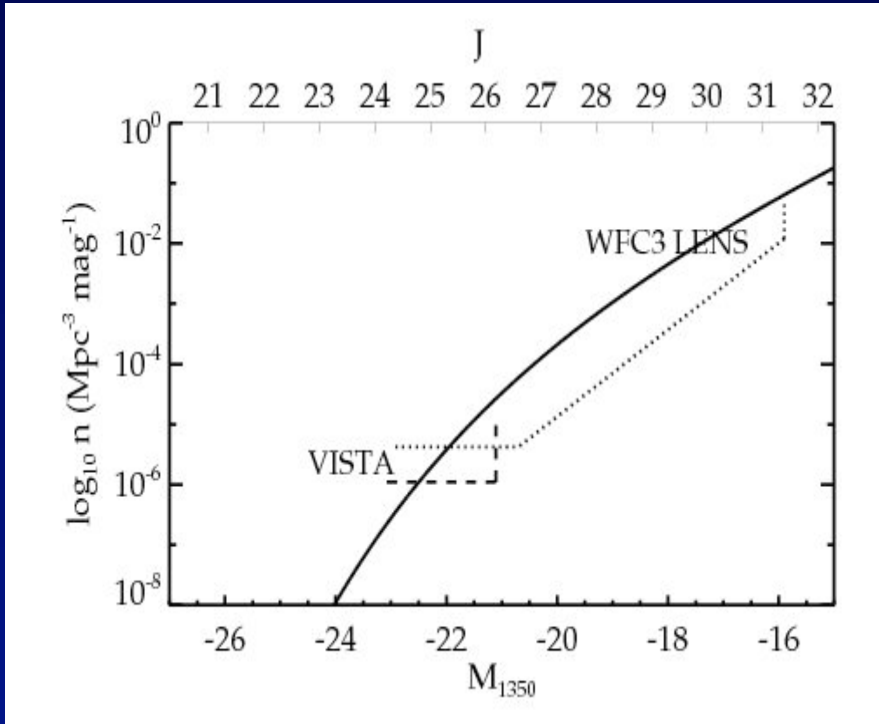
Stark, Loeb, & Ellis, 2007, ApJ, in press

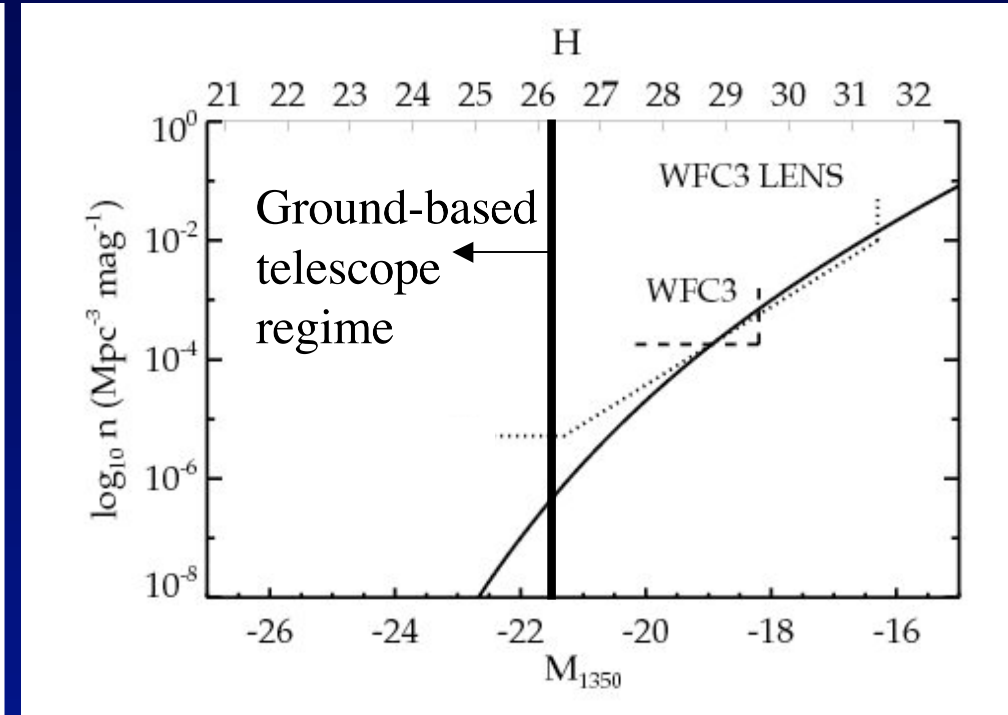


- abundances of z~10 Lya emitters not consistent with extrapolation from z~6
- require more Lya photons per unit halo mass, achievable through 1) increase in star formation efficiency or 2) change in IMF
- possibilities tantalizing but more work needed to confirm candidates and additional survey volume needed to confirm densities.

Predictions for future LBG surveys at z>7

Stark, Loeb, & Ellis 2007, ApJ, in press





- Upcoming surveys (e.g. VISTA / WFC3) should be able to detect large number of LBGs at z~7-8.
- If increase in density suggested by z~9-10 lensed LAE candidates proves false, probing to z~10 may be much more difficult, especially from the ground

Summary

- Strong lensing surveys are finding an abundant population of candidate faint Lyα emitters at z~8-10 with SFR <1 $M_\odot$ yr^{-1} - a population which may contribute significantly to reionization.

- Exhaustive spectroscopic and imaging follow-up supports hypothesis that many of lensed Lya emitters are at z~10 but additional follow-up still required. Final confirmation is especially difficult at z>7!

- Implied densities of z~9 LAEs still very uncertain, but if correct, would require increase in Lya photon output per unit halo mass from z~6.

- Even with conservative assumptions, new instruments should result in reasonably large samples of galaxies at z~7-8 in the next few years. If increase in density implied in lensed LAE survey proves false, z~10 objects may be difficult to find before JWST, especially for (non-lensing) ground-based imaging surveys