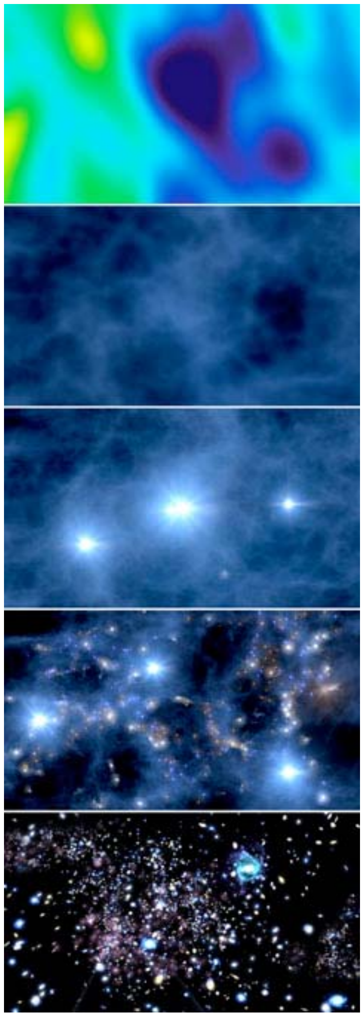
Evidence for a Significant Population of Feeble Star-Forming Sources at z>7



Richard Ellis (Caltech)

with

Dan Stark, Johan Richard (Caltech)
Eiichi Egami (Arizona)
Jean-Paul Kneib (Marseille),
Andy Bunker, Laurence Eyes (Exeter)
Avi Loeb (Harvard)
Mark Lacy (SSC)

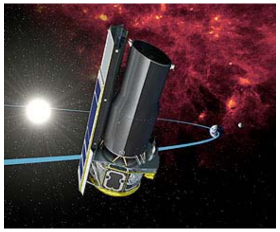
HI Survival through Cosmic Times **11 June 2007**

Motivation

- Continue to seek sources responsible for cosmic reionization via direct imaging/spectroscopy in near-IR
- Their study, with present & future facilities, will complement HI surveys and define physics of reionization process and implications for future galaxy assembly

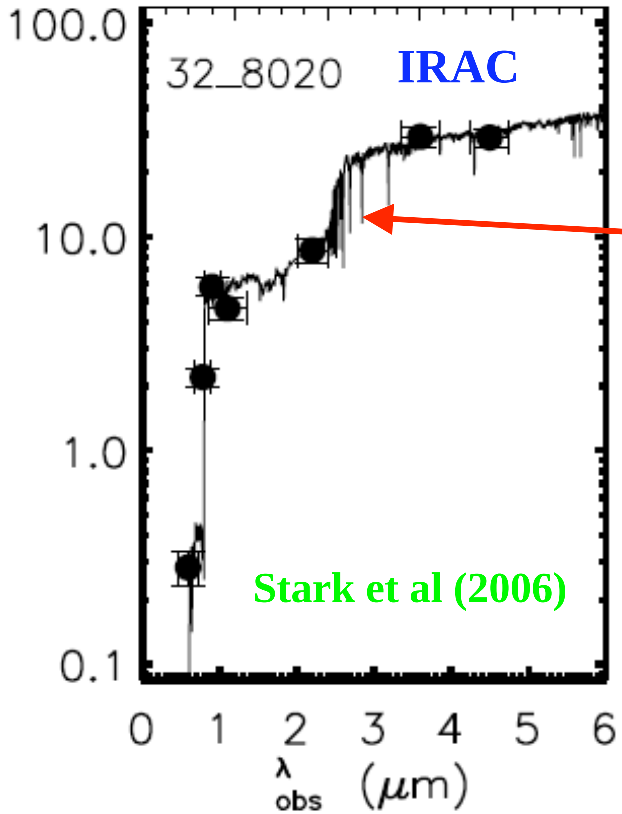
Evidence for early (z>7) star formation

- Surprisingly mature galaxies at z~5-6 with established (>100Myr) stellar populations (Spitzer/HST)
- Present of metals in intergalactic medium in spectra of highest z QSOs
- Insufficient abundance of high z luminous star forming galaxies to account for assembled stellar mass at later epochs
- Direct detection of many promising strongly-lensed candidates at z > 7



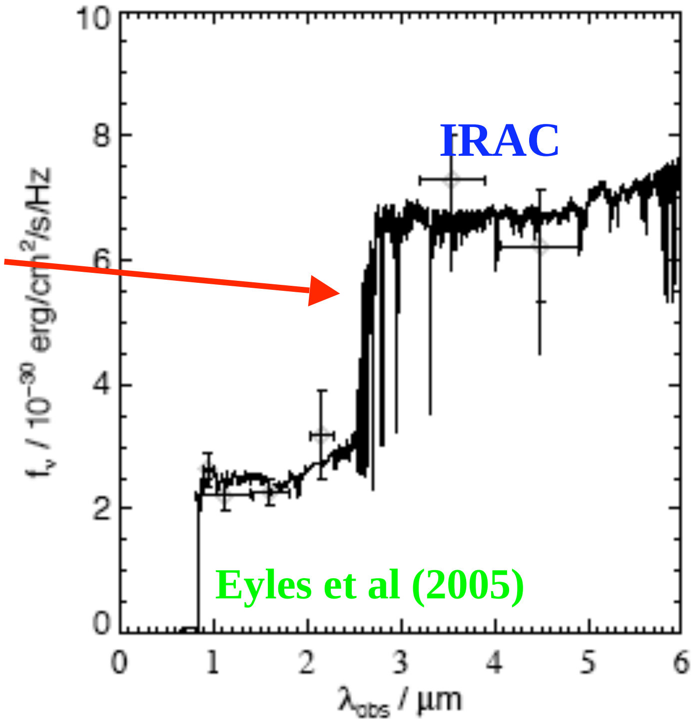
Established Stellar Populations at z~5-6

z=5.55 M = 1.1 10^{11} $M_\odot$

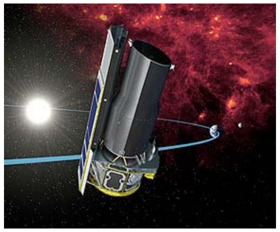


Balmer break

z=5.83 M= 2-4 10^{10} $M_\odot$

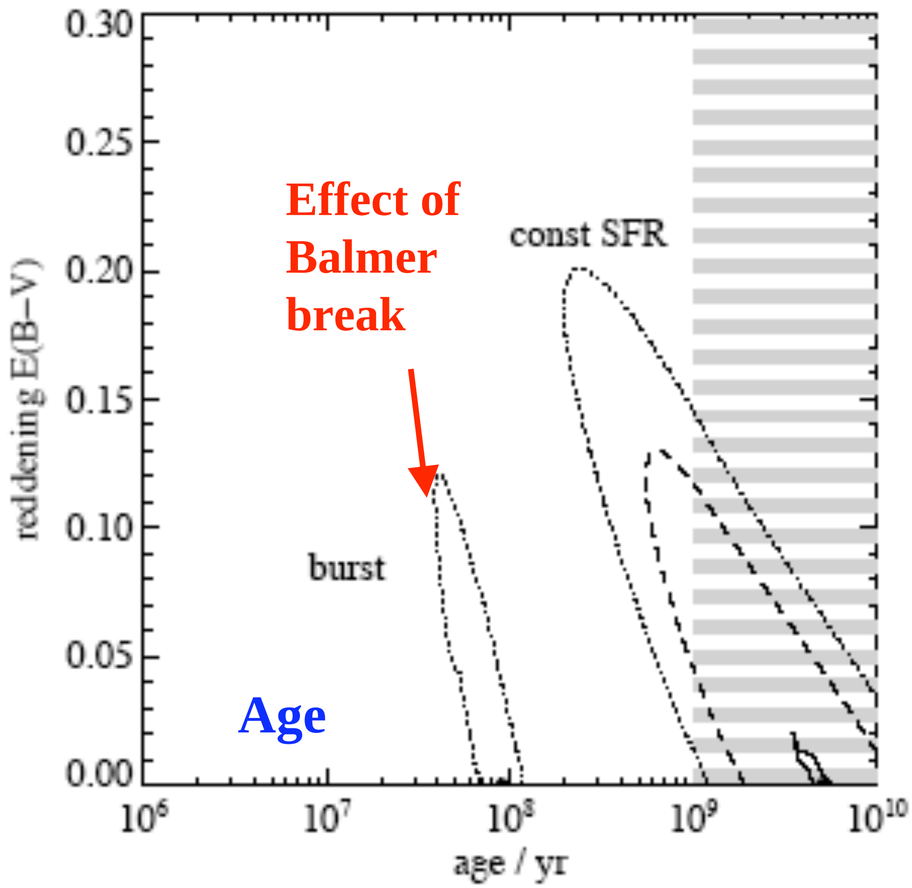


`Balmer break' in many (~20) spectroscopically-confirmed z~5-6 galaxies points to significant star formation in earlier progenitors



Old Stars at z~6

E(B-V)



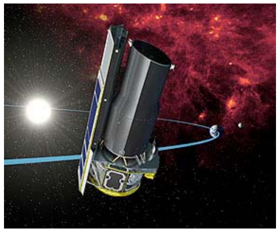
Eyles et al (2005)

How old?

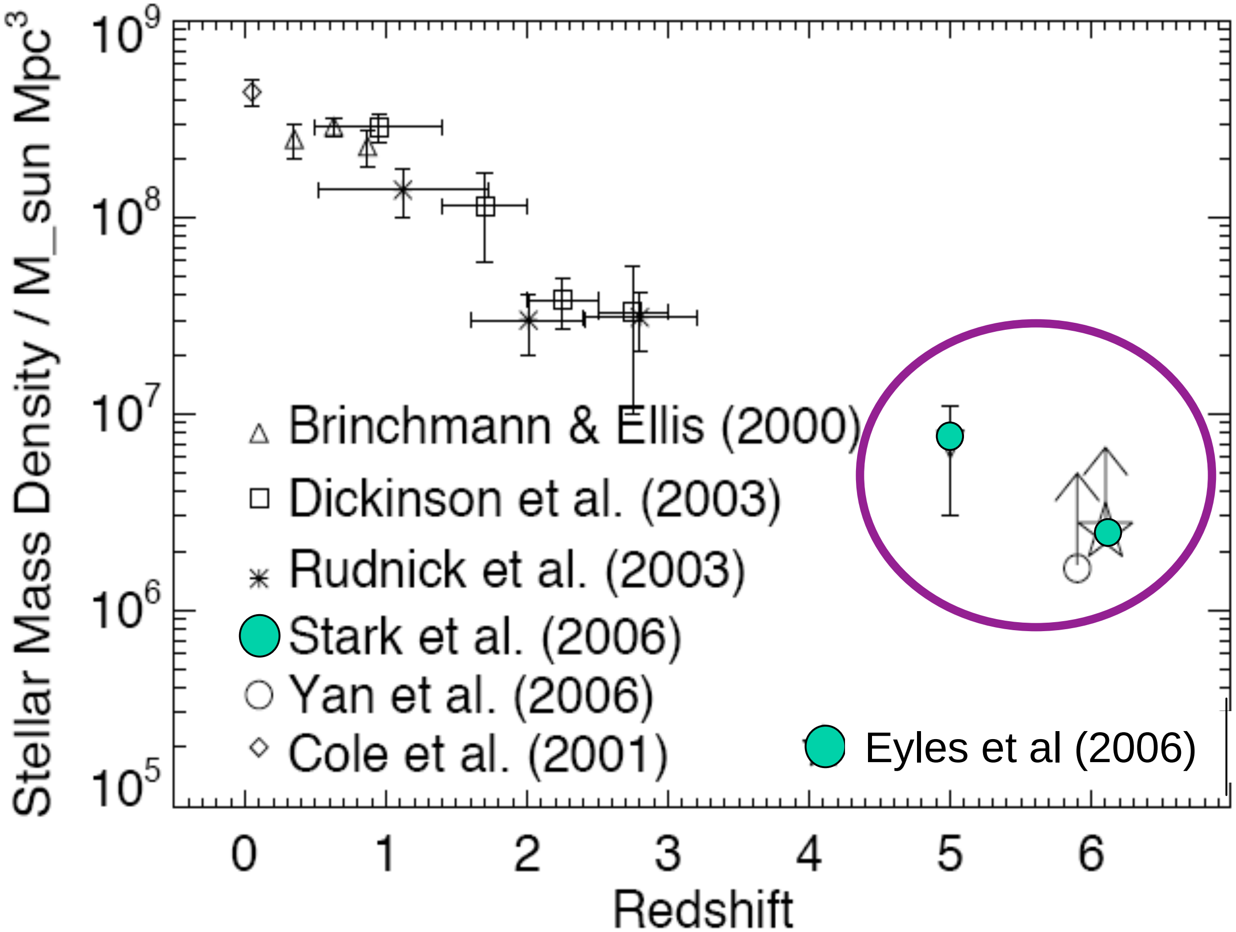
- Depends on past star formation history *not* dust extinction

- Δt ~ 100 Myr even for burst model, older (<650 Myr) permitted

- Significant SF occurred during \`unobserved' era 7 < z < 14

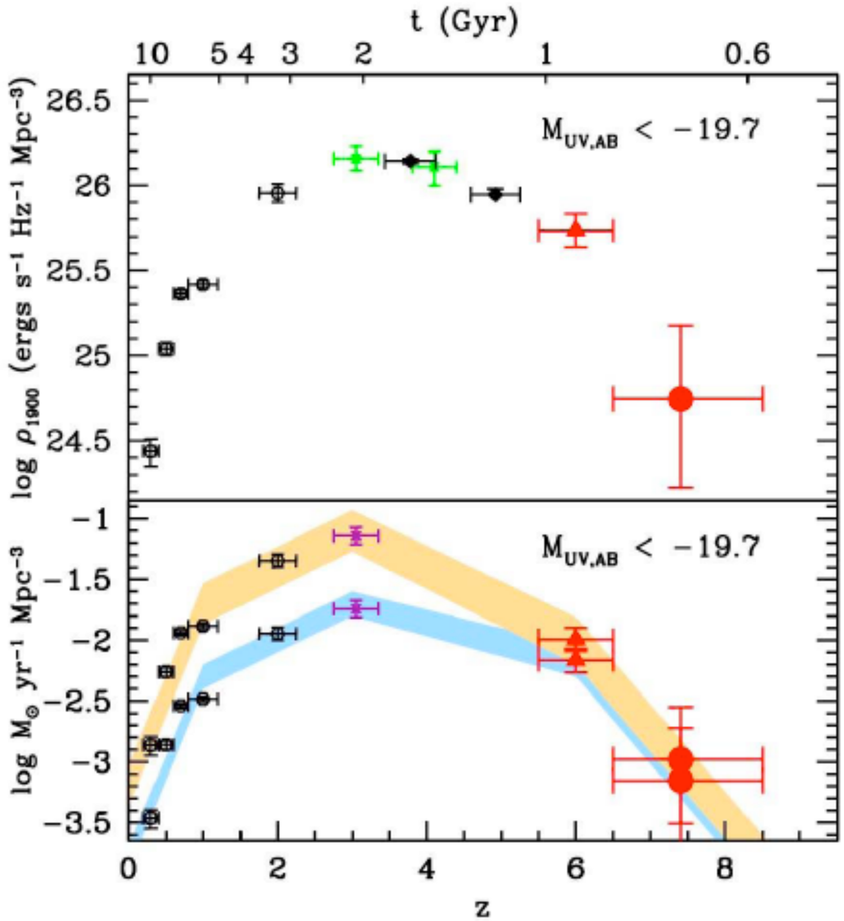


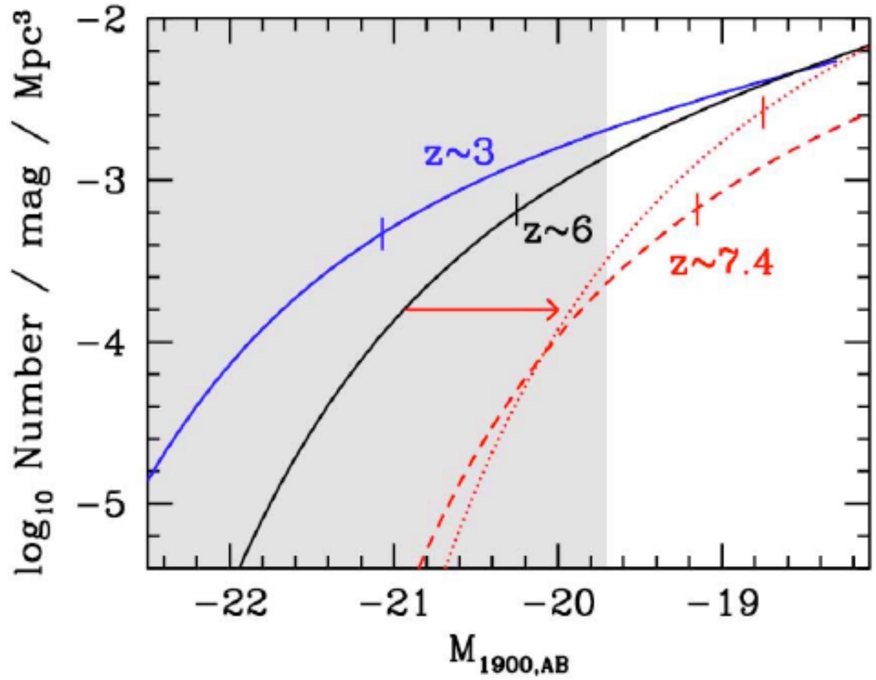
Stellar Mass Assembled by z ~ 5-6



Assembled stellar mass density at z~5-6 is surprisingly high
Possibly a lower limit (although estimates v. uncertain)
Can this be reconciled with earlier observed star formation?

Declining UV luminosity density of dropouts



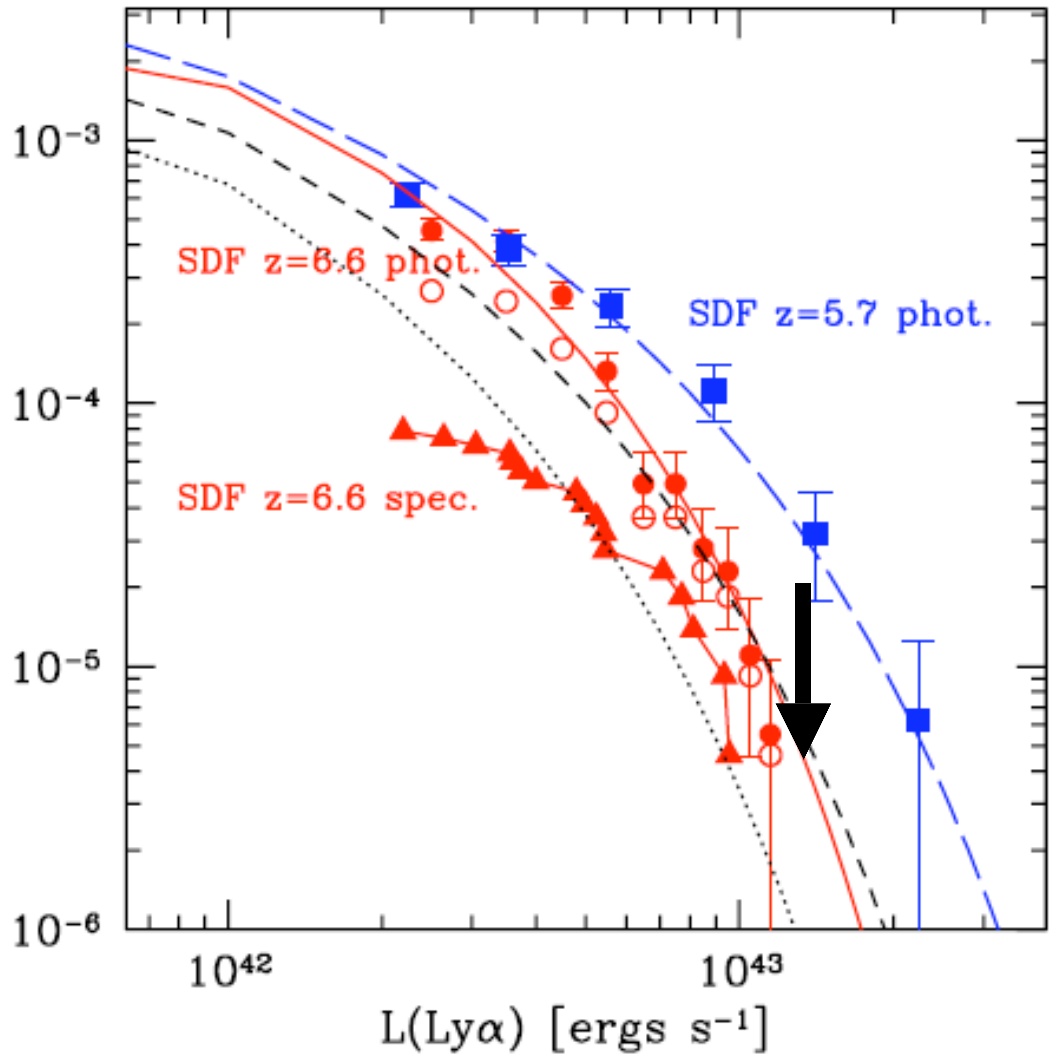


Bouwens & Illingworth (2006)

Rapid decline in UV luminosity density 3<z<7
Possible steepening of LF faint end slope with increasing z

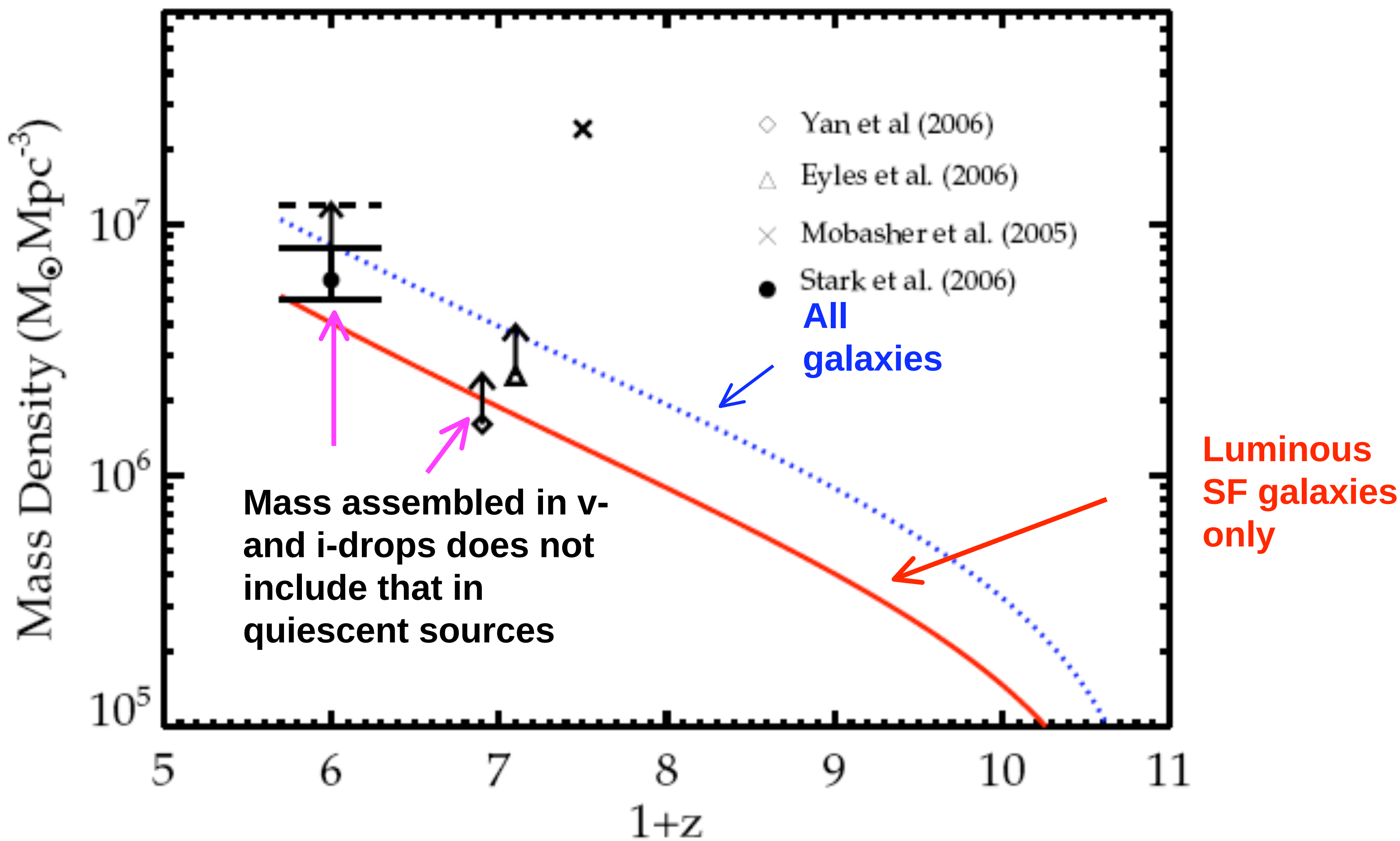
Luminosity Dependent Evolution of Lyα Emitters

- Decline also seen in the LF of Ly α emitters over smaller redshift interval 5.7<z<6.6
- Similar evidence for steepening of LF as we proceed to higher redshift



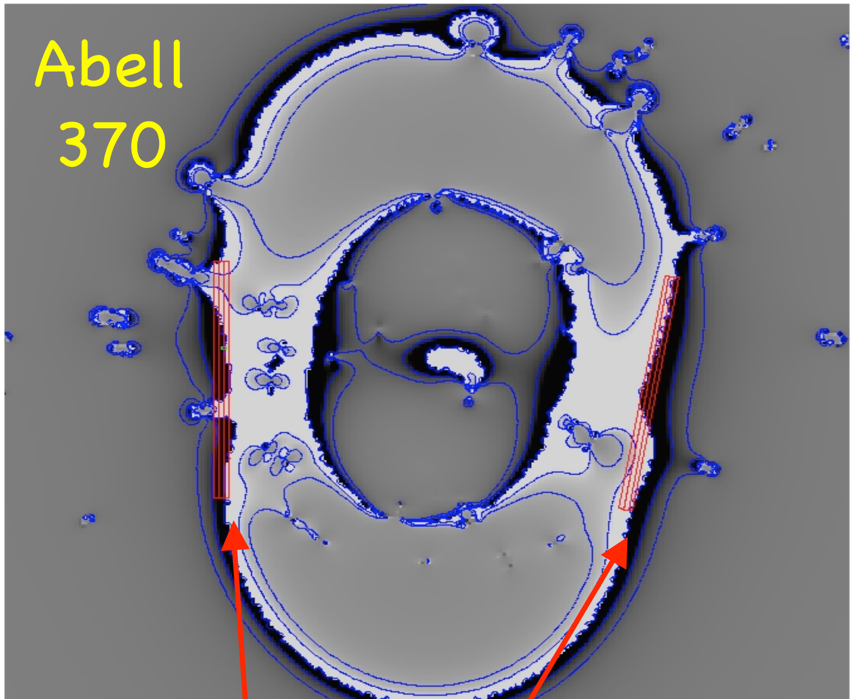
Kashikawa et al (2006)

Predicting the z~5-6 Stellar Mass Density



Observed high z SF underestimates assembled mass at z~5-6
Either high z SF is obscured or lower luminosity sources dominate

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



NIRSPEC Slit Positions

Critical line mapping of 9 clusters in J-band, corresponding to Lyα at $8.5 < z < 10.4$

Clusters limited to those where the location of the critical line is precisely known from earlier work

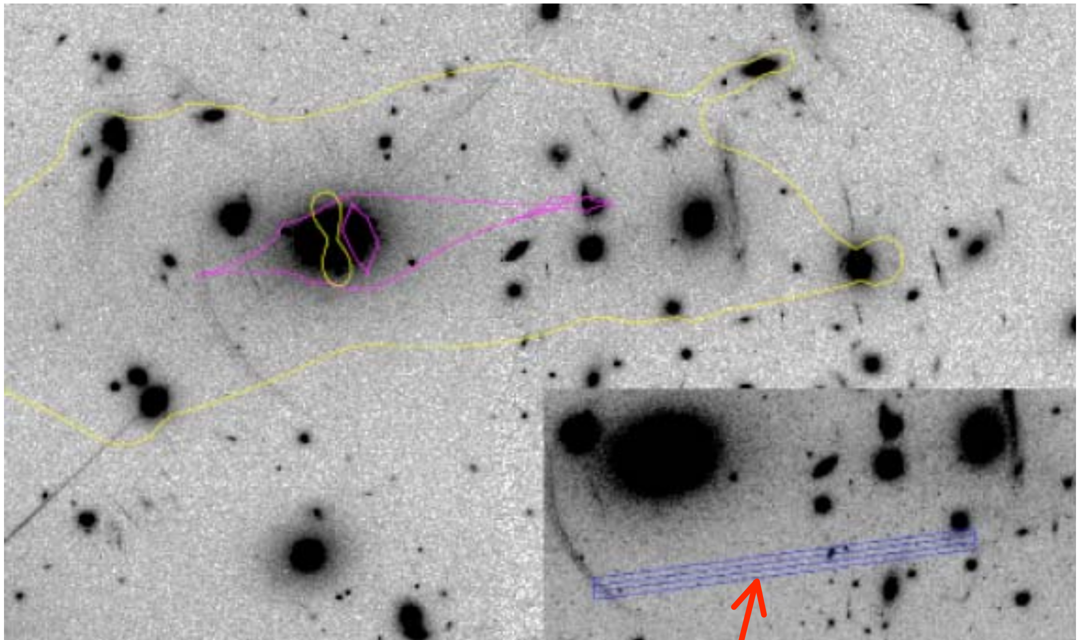
Sensitive to sources magnified by at least ×20 corresponding to intrinsic SFR~0.1 $M_{\odot}$ yr^{-1}

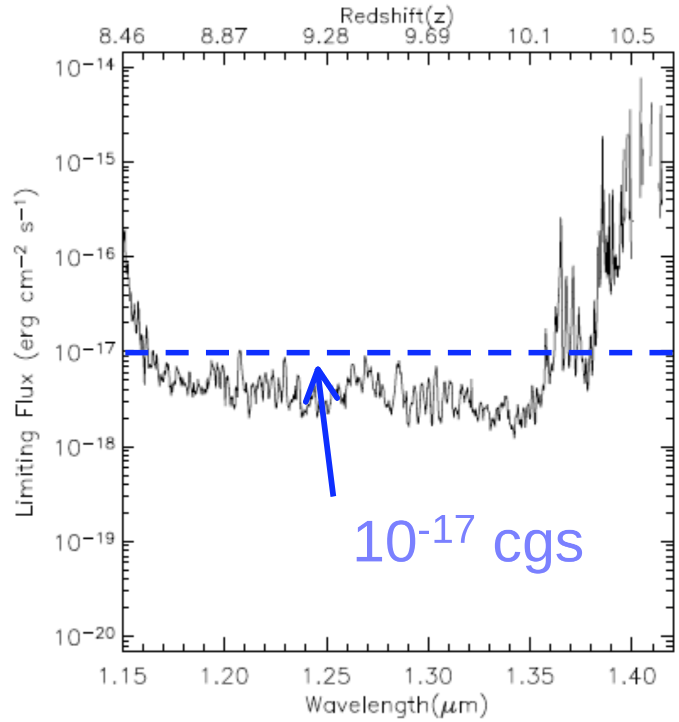
Stark et al (Ap J in press, astro-ph/0701279)

Example: Abell 2390

Cluster critical line for $z_S > 7$

Wavelength sensitivity (1.5hr)



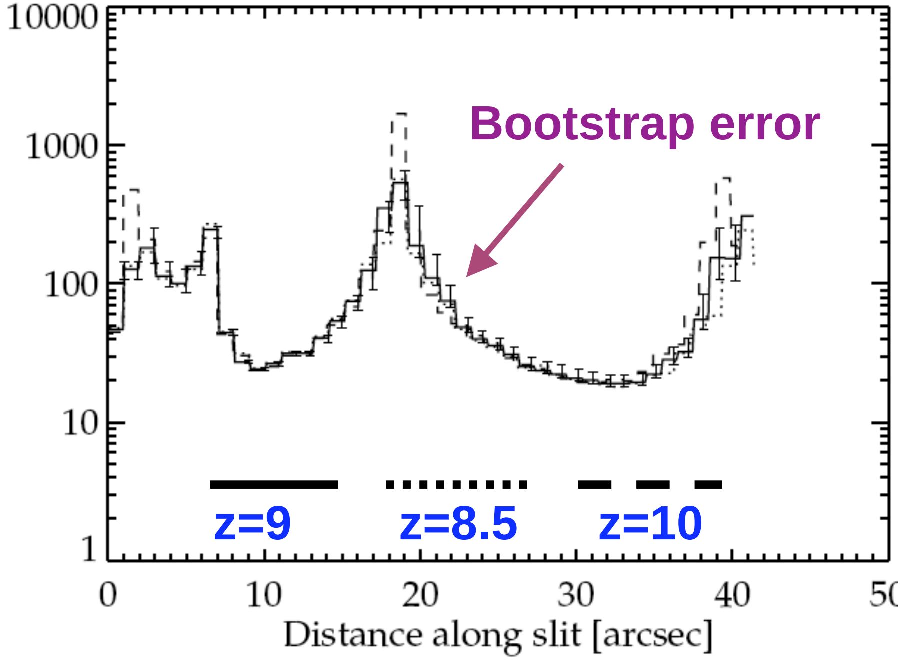


NIRSPEC slit positions

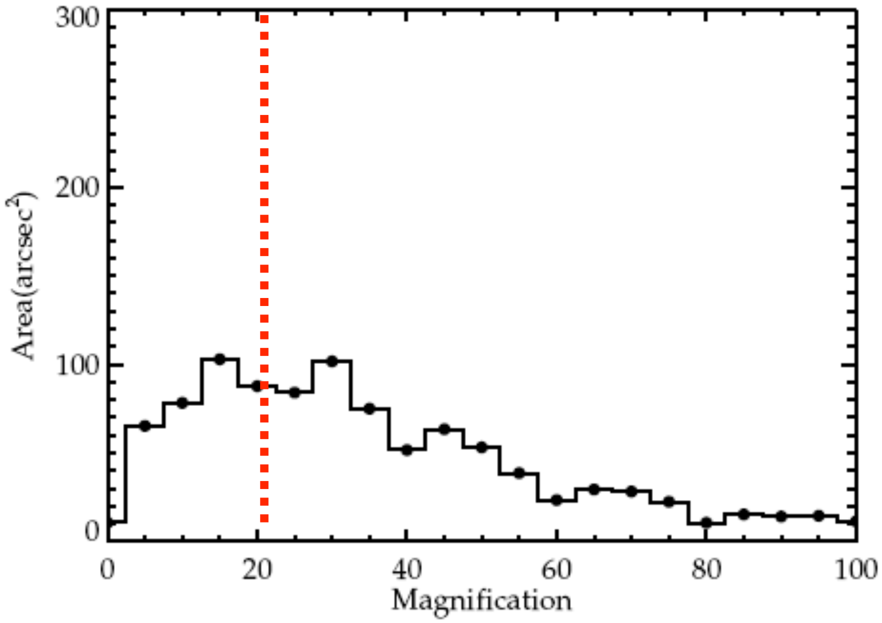
- 9 clusters with well-defined mass models & deep ACS imaging
- Obs. sensitivity ~ 3-9.10^{-18} cgs; magn. > ×15-20 throughout
- Sky area observed: 0.3 arcmin^2; V(comoving) ~ 50 Mpc^3
- 6 promising lensed emitter candidates (>5σ)
- 8.6 < z < 10.2; L ~ 2 - 10. 10^{41} cgs; SFR ~ 0.2 -1 $M_{\odot}$ yr^{-1}

How Reliable are Mass Models and Magnifications?

Magnification along slit



Sky area versus magnification

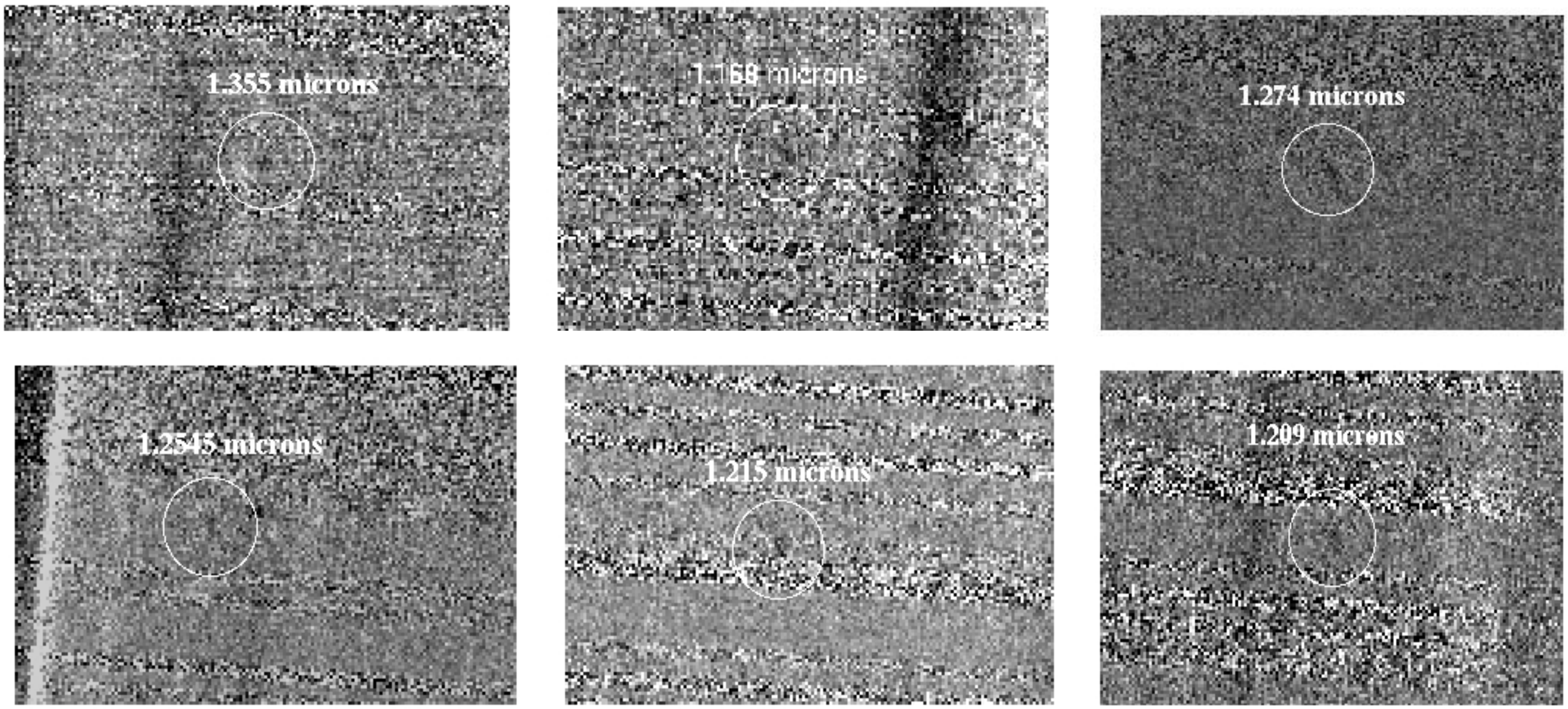


$$\mathcal{M}(\Omega, z) = \frac{1}{[1-\kappa(\Omega, z)]^2 - \gamma(\Omega, z)^2}$$

- Magnification $\mathcal{M}$ depends strongly on position Ω, less so on z
- Error in magnification $\mathcal{M}$ determined by Markov Chain MC sampling of multiple images of known spectroscopic redshift
- Bulk of survey has magnification $\mathcal{M}$ > ×20 and error in $\mathcal{M}$ is ~20%

Candidate Lyα Emitters

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



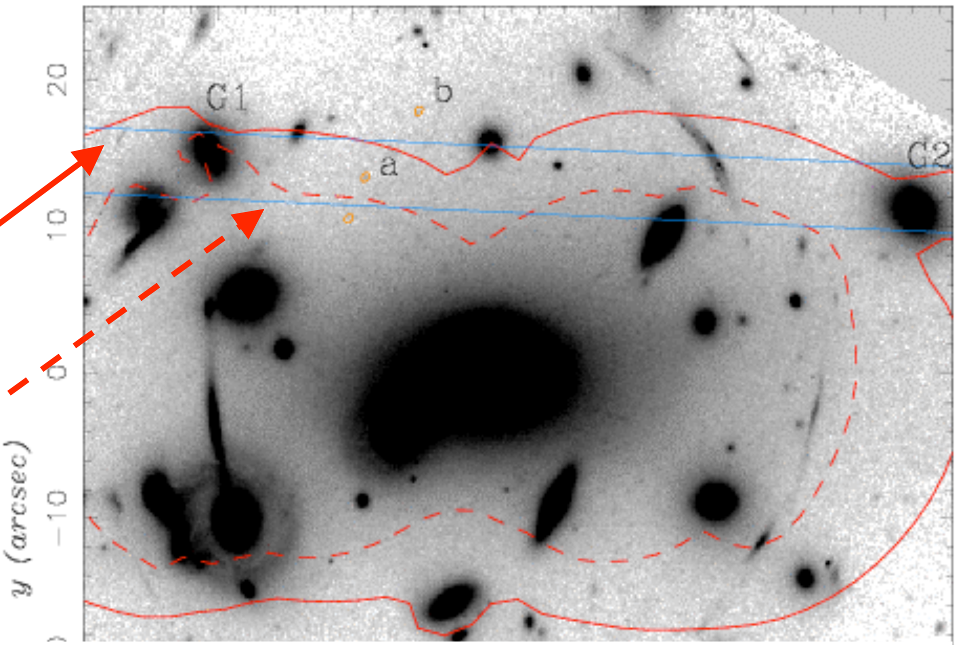
Recognize burden of proof that these are z~10 emitters is high

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

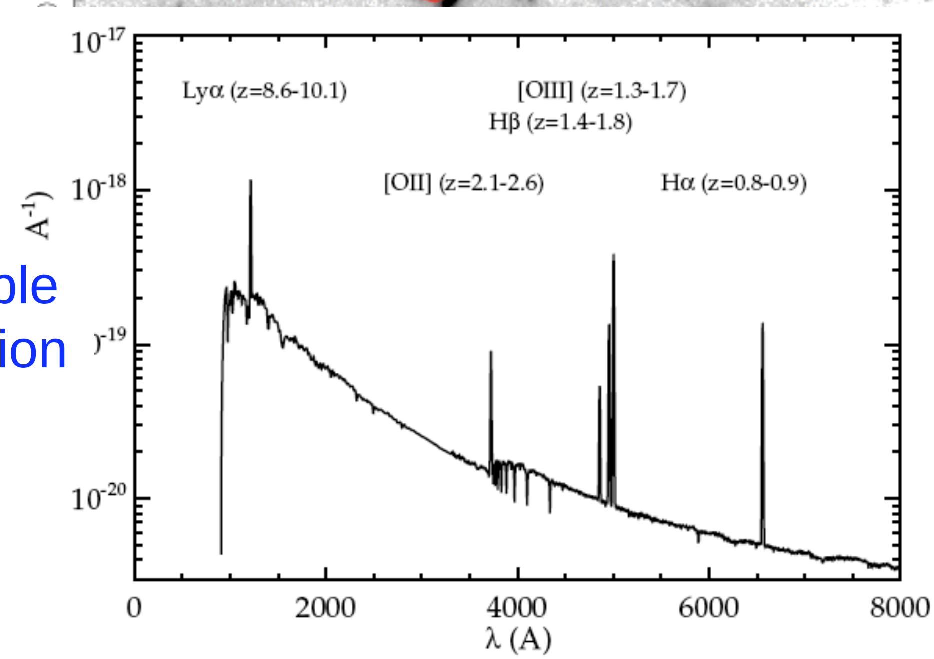
Interlopers? Critical Line Location Depends on z

z=5

z=1



Possible emission lines



<u>Bonus of strong lensing:</u>

By only searching the z>5 critical line, we minimize contamination from magnified interlopers at 1<z<3 which would lie elsewhere in the image plane.

So contamination is <u>less likely</u> than in non-lensed searches

Spectroscopic Elimination of Interlopers

Various explanations for a single emission line in the J-band

Line	Redshift	$\lambda_{Ly\alpha}$ (μm)	$\lambda_{[OII]}$ (μm)	$\lambda_{H\beta}$ (μm)	$\lambda_{[OIII]}$ (μm)	$\lambda_{H\alpha}$ (μm)
Hα	0.91	0.2324	0.7124[a]	0.9292	0.9479/0.9571	1.2545
[OIII]	1.51[b]	0.3047	0.9338	1.2179	1.2425/1.2545	1.6444
	1.53[c]	0.3076	0.9428	1.2297	1.2545/1.2666	1.6603
Hβ	1.58	0.3138	0.9618	1.2545	1.2797/1.2922	1.6937
[OII]	2.37	0.4093	1.2545	1.6362	1.6692/1.6854	2.2091
Lyα	9.3	1.2545	3.8388	5.0149	5.1160/5.1655	6.7708

- Deeper LRIS spectroscopy (Santos et al 2004) from 4000-9400Å eliminates Hα and [O II] as source of emission (4/6 candidates)
- H-band spectra eliminates [O III] as source (3/6 candidates)
- IRS spectroscopy (~7μm) is in progress to verify Hα at z~10 (2/6 candidates)

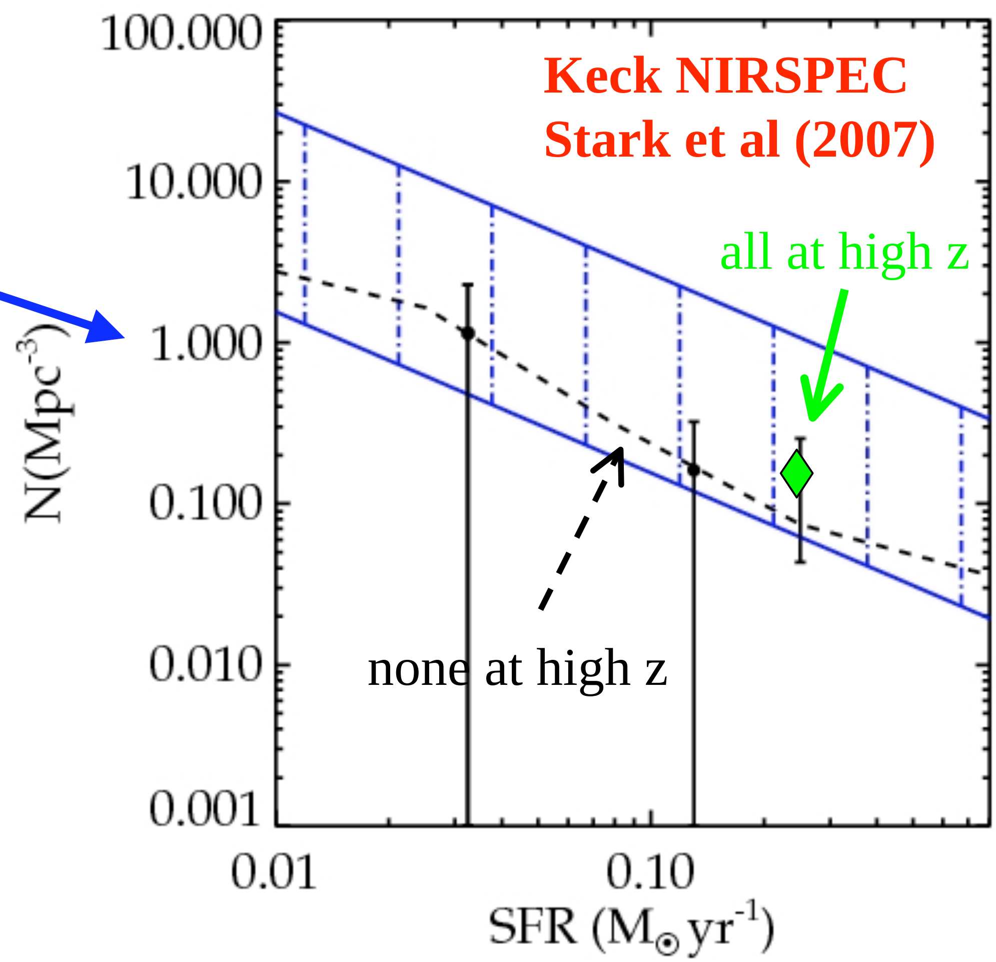
Now believe >3/6 candidates likely to be 8<z<10 sources

Did faint SF galaxies at z~10 cause reionization?

$$n = \left(\frac{B}{10}\right)\left(\frac{n_H}{10^{-7}\ \mathrm{cm}^{-3}}\right)\left(\frac{f_c}{0.1}\right)^{-1}\left(\frac{\mathrm{SFR}}{1.0\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}}\right)^{-1}\left(\frac{n_c}{3\times10^{53}}\right)^{-1}\left(\frac{\Delta t}{575\ \mathrm{Myr}}\right)^{-1}$$

Consider range:

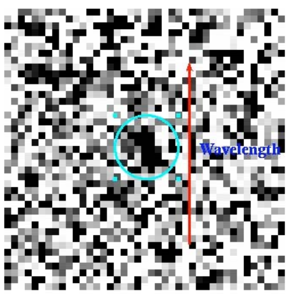
$f_c \sim 0.02\text{-}0.5$
$\Delta t \sim 250\text{-}575$ Myr
B ~ 5-10

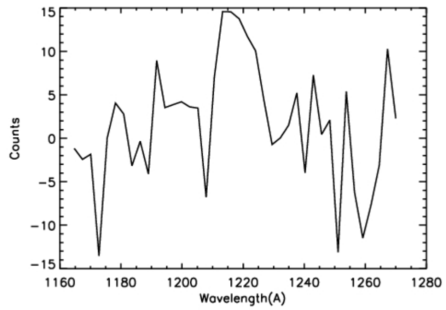


If >3 of our 6 candidates are at high z, low luminosity galaxies may play a dominant role in cosmic reionization

Further Confirmation of z>8 Candidate Lyα Emitters?

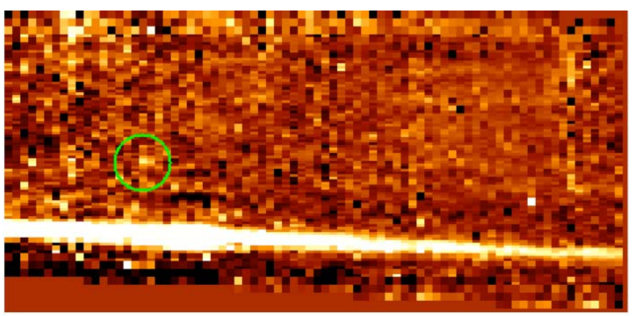
- Stacking spectra to see if line profile is asymmetric?





- NIRSPEC R~2000 too coarse
- How to centroid faint line?

- Detecting Hα at $\lambda \sim 6\ \mu$m in deep IRS data?



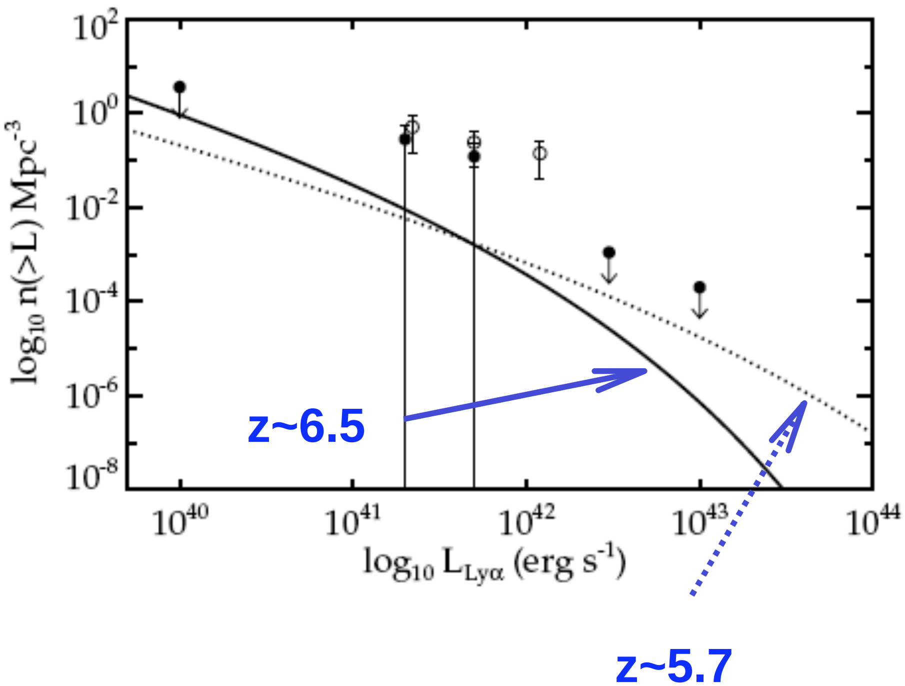
- IRS 24hr exposures of 2 candidates
- Will only see Hα if Lyα/Hα ~1, i.e. if Lyα is suppressed

- More ambitious follow-up with NIRES R~4000 echellette (requires 8-10hrs per target)…coming soon!

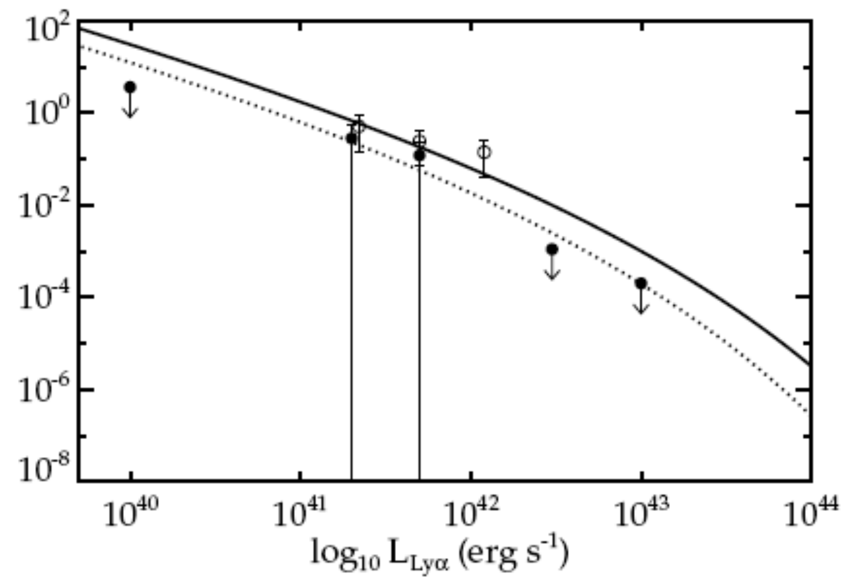
Is High Abundance of z~9 Lyα Emitters Plausible?

Predicted z~9 LF based on semi-analytic fit to lower z LFs

Standard model



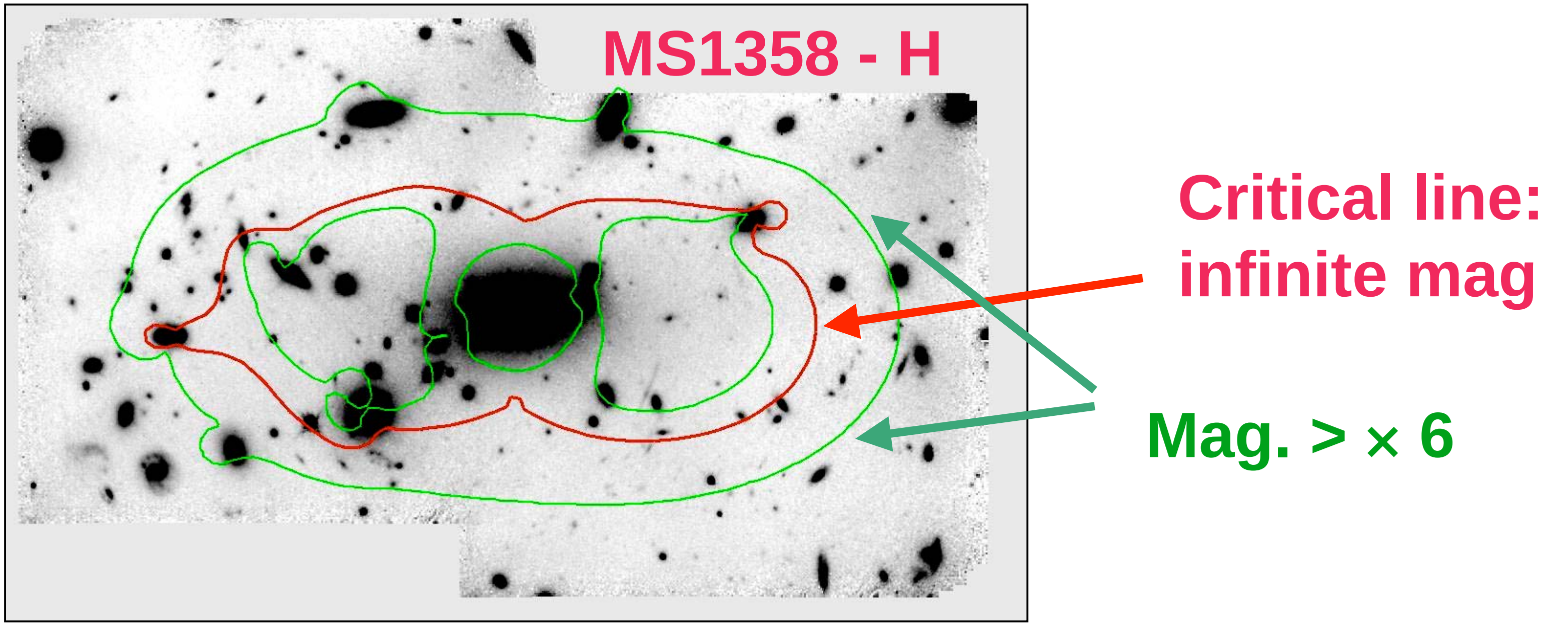
Higher SF efficiency or Pop III IMF



If 3 of the 6 z~9 candidates are at high z, the LF is only marginally consistent with semi-analytic extrapolation of that at z~6 but compatible with change to a top-heavy IMF or increase in SF efficiency at z~9

Stark, Loeb & Ellis (2007)

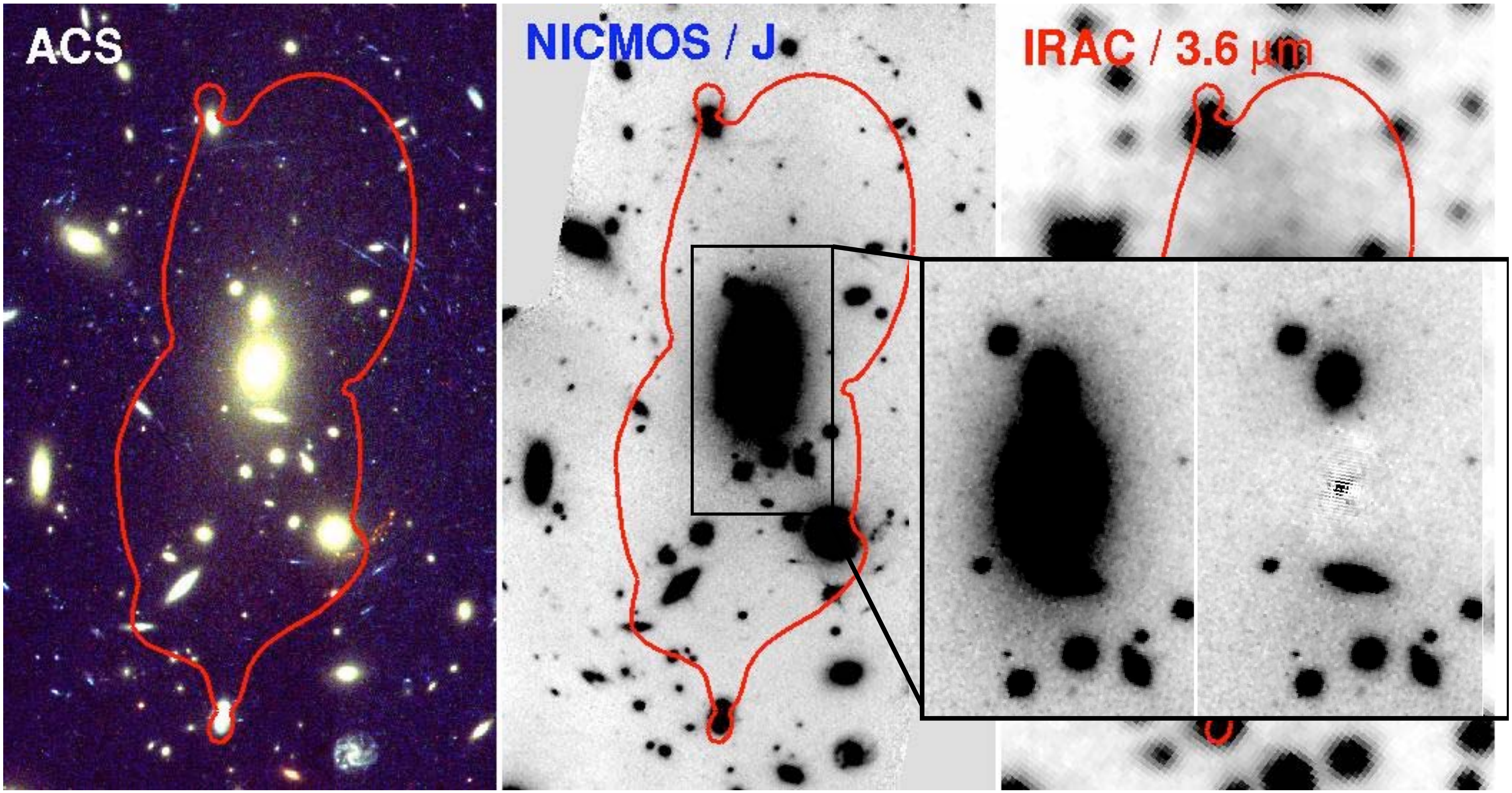
Searching for Lensed Dropouts with HST/Spitzer



- 8 well-constrained clusters with deep IRAC imaging (Egami & Rieke)
- 11 NICMOS pointings in 6 lensing clusters
  (4 orbits J/F110W, 5 orbits H/F160W)
- ACS/F850LP imaging of all 8 clusters
- K-band ground based imaging with Keck/NIRC + Subaru/MOIRCS

Richard et al (2007)

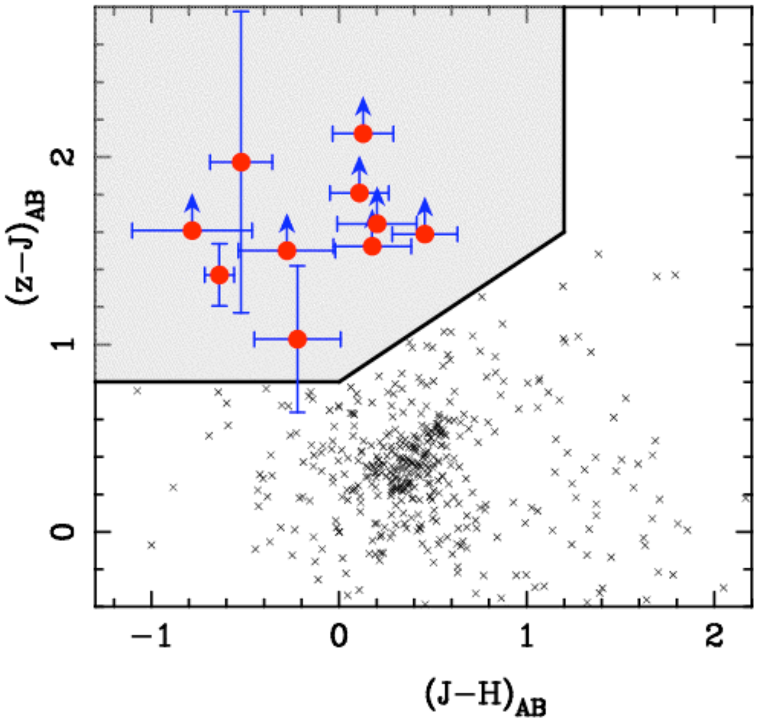
Combining ACS, NICMOS & Spitzer

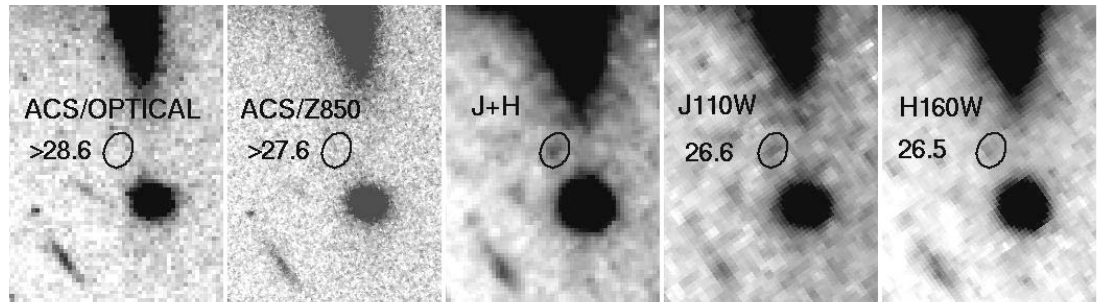


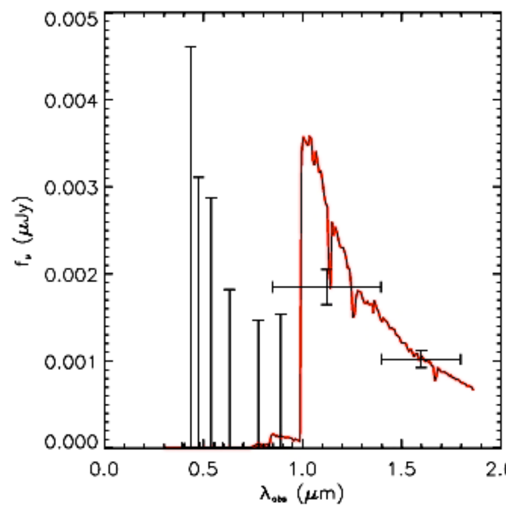
Importance of foreground removal

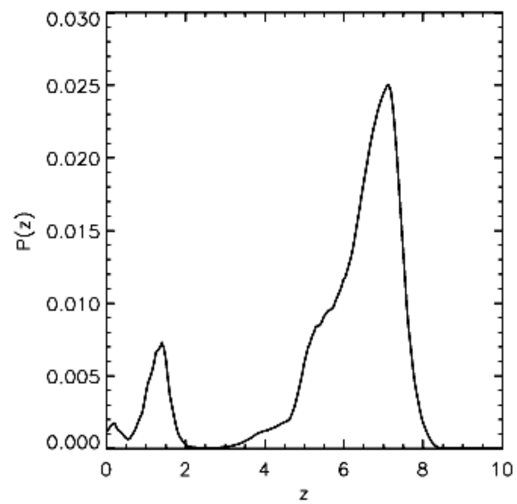
MS1358: 5σ limit: J_{AB}=26.7, H_{AB}=26.7

Lensed z-band dropouts (z~7-8)



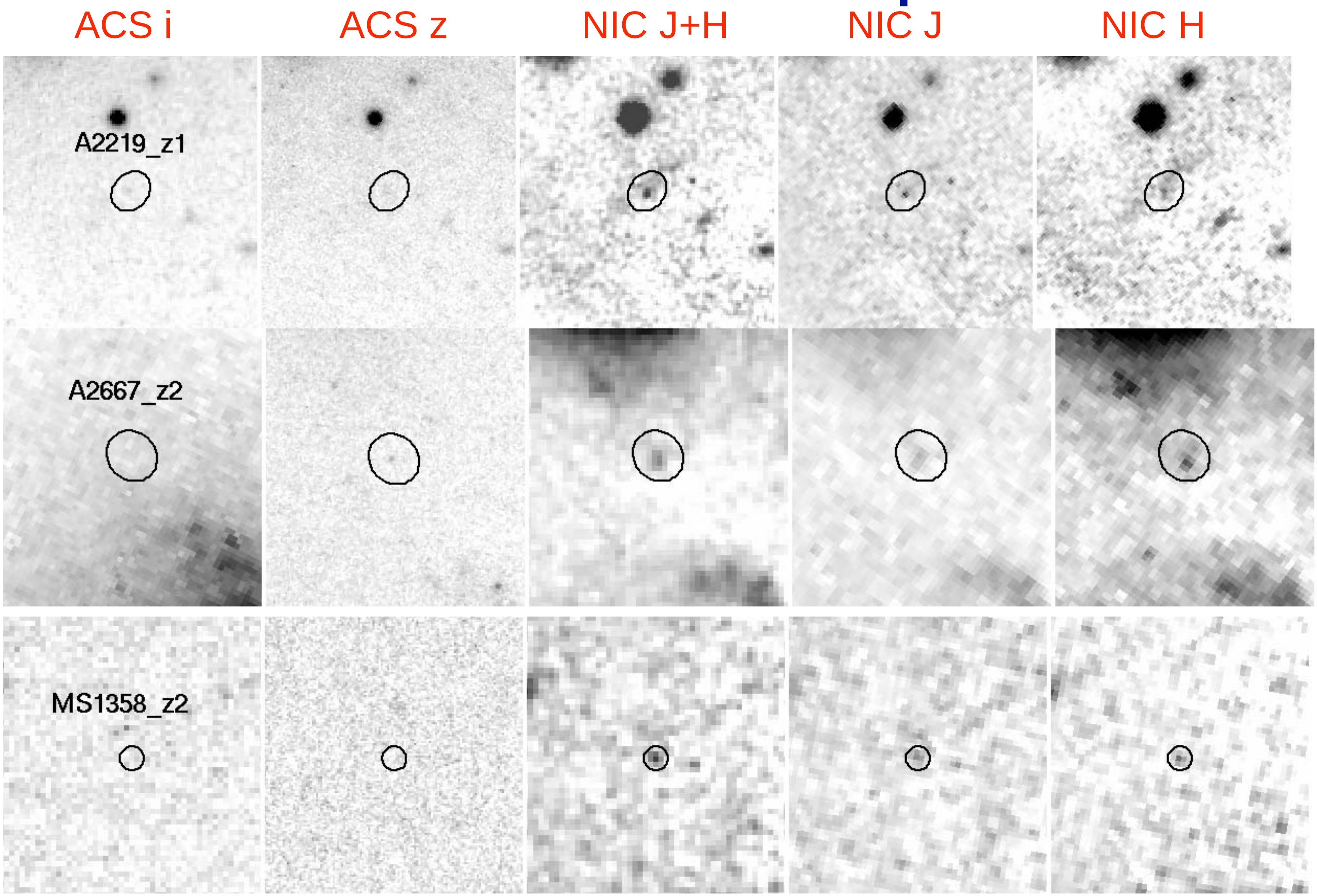




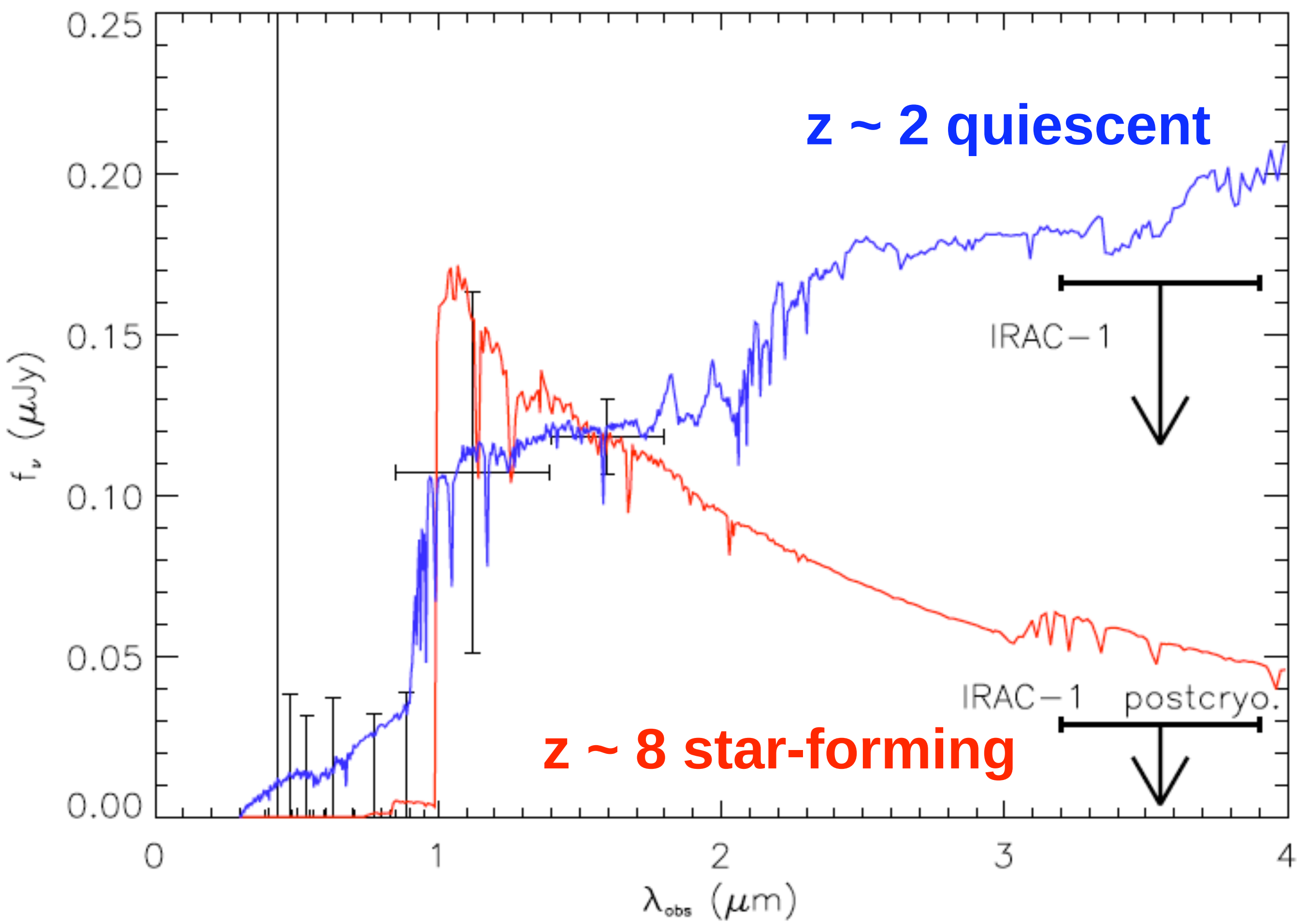


- **10 candidate z-drops in the 6 clusters surveyed to H_{AB} ~ 26 - 26.8**
- **Implied SFR ~ 0.1 - 2 $M_{\odot}$ yr^{-1} (unlensed)**
- **Spectroscopic follow-up with NIRSPEC**
- **z~1-2 red galaxies expected to be main contaminants**

More Candidate z-Drops



Bulk of candidates unlikely to be z~2 interlopers

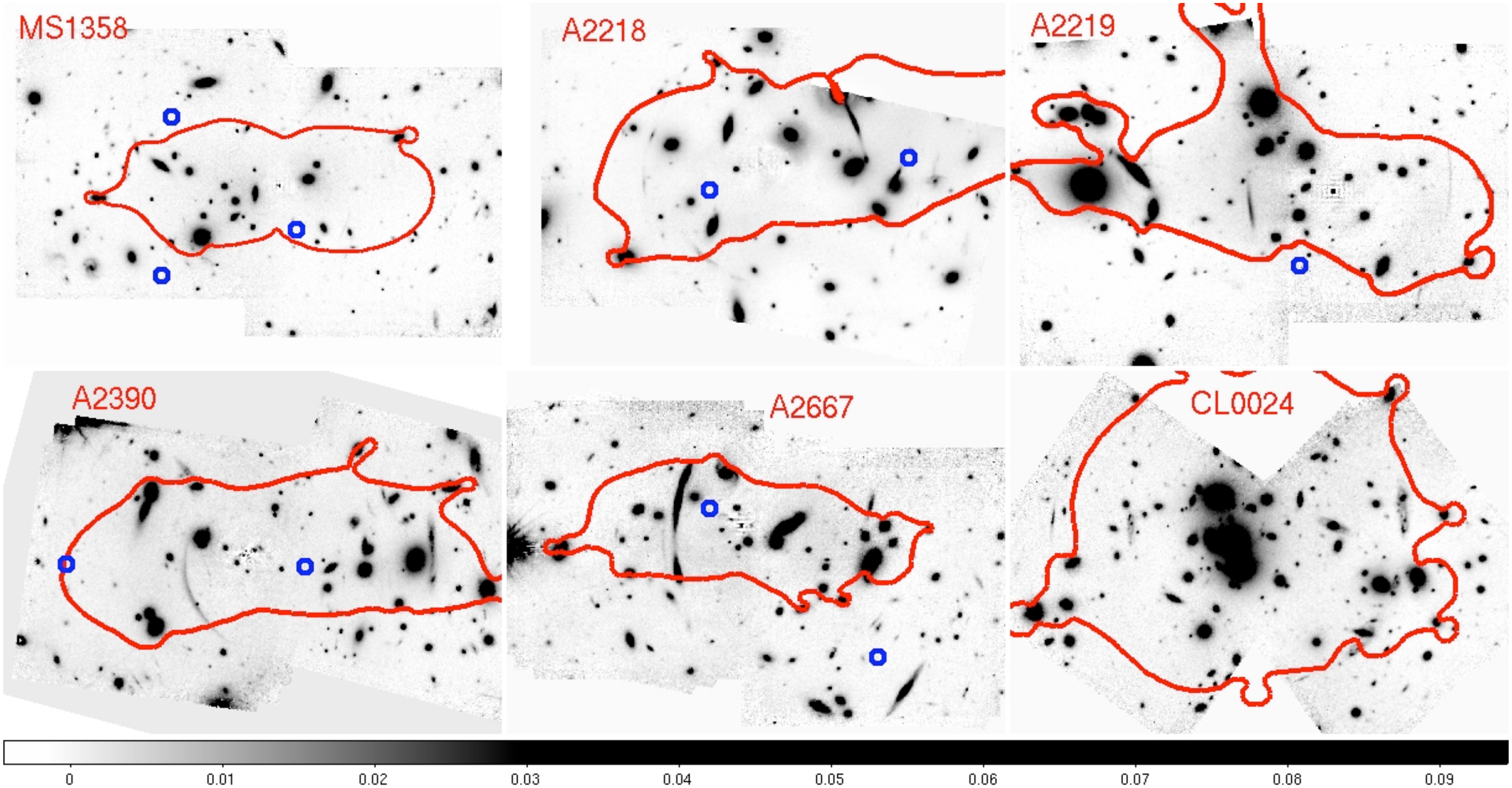


Current limit

Possible limit in warm mission

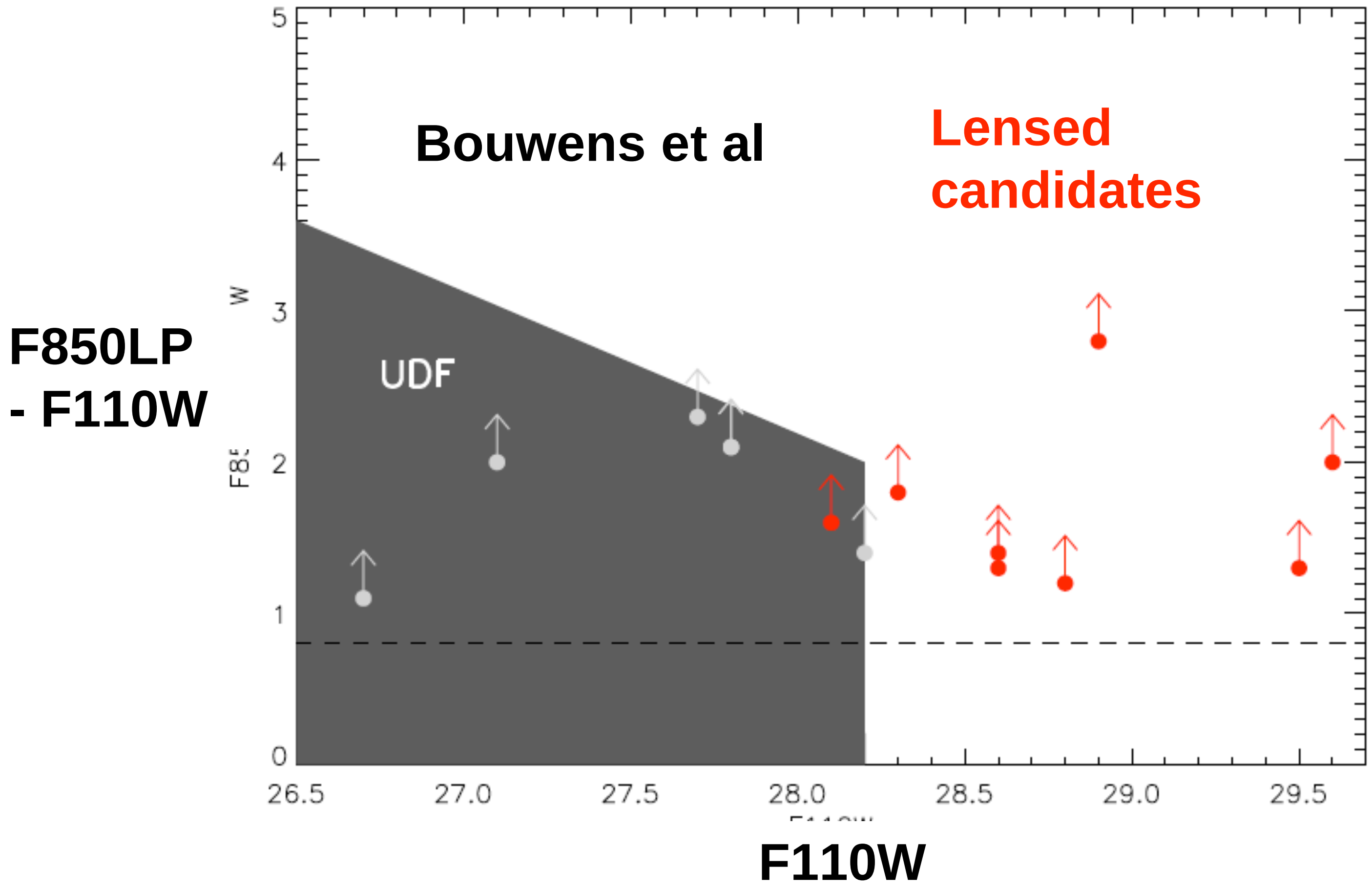
Stacked IRAC limit for 8 unconfused candidates gives upper limit at 3.6 microns rejecting passive z~2 population as primary population

Angular Distribution of Candidates



Angular distribution with respect to z~8 critical lines gives further indication of low foreground contamination

Deeper than UDF

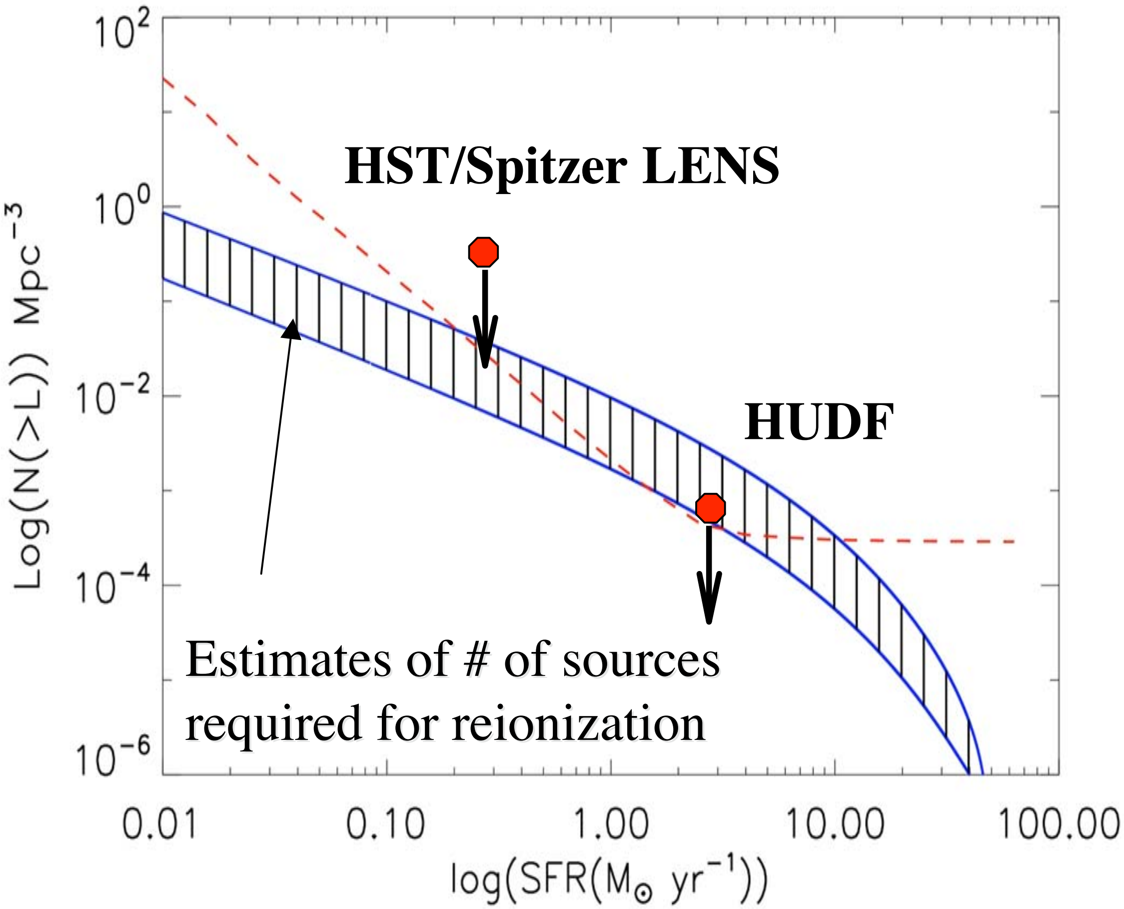


Strong lensing permits us to probe z-band dropouts ~1-1.5 magnitudes deeper than the UDF in a field of ~2.5 arcmin^2

Implications for Reionization from Lensed Dropouts

Spectroscopic confirmation underway (Richard et al)

4 hours with NIRSPEC recovers Lyα implied from UV continuum



- **Even if a few are real, suggests significant contribution to reionization from low luminosity galaxies**

- **Consistent with picture revealed by lensed Lyα emitters (Stark et al 2007)**

Summary

- Evidence from Balmer breaks and assembled stellar mass at z~5-6 suggests more star formation occurred beyond z~7 than is seen in current surveys: this occurred either in extincted objects or, more likely, in low luminosity systems
- Strong lensing surveys are finding an abundant population of candidate faint Lyα emitters and dropouts at z~7-10 with SFR <1 $M_\odot$ yr^{-1} and masses of 10^6 $M_\odot$ < M < 10^8 $M_\odot$
- Spectroscopic and imaging follow-up supports hypothesis that at least some lensed sources are at z~10; given the small volumes probed it seems low luminosity sources contributed significantly to cosmic reionization
- Via these programs & upcoming dedicated instruments, we will get our first glimpse of star formation at z~10, and more effectively plan ambitious programs with JWST and TMT

TMT

THIRTY METER TELESCOPE

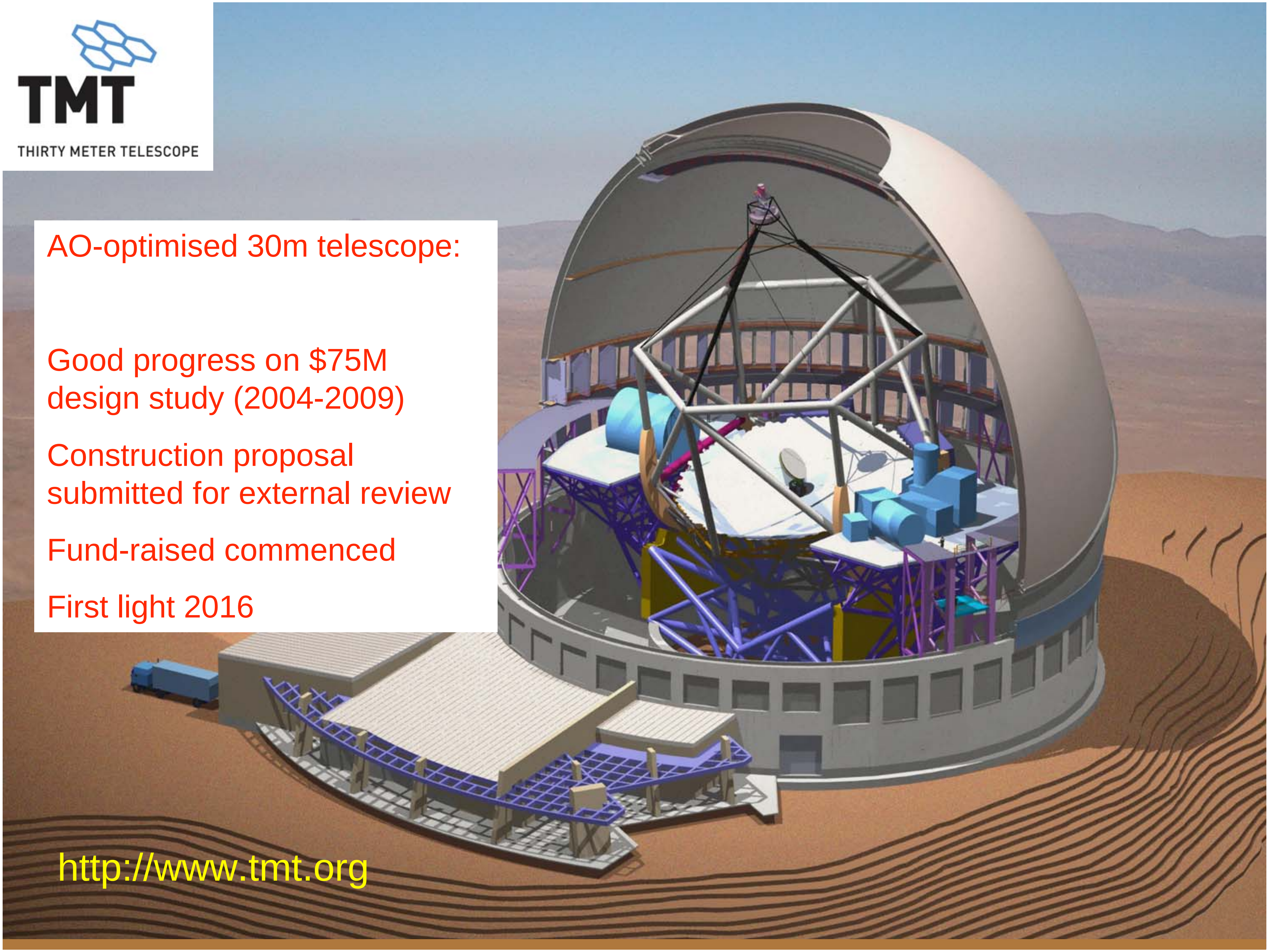
AO-optimised 30m telescope:

Good progress on $75M design study (2004-2009)

Construction proposal submitted for external review

Fund-raised commenced

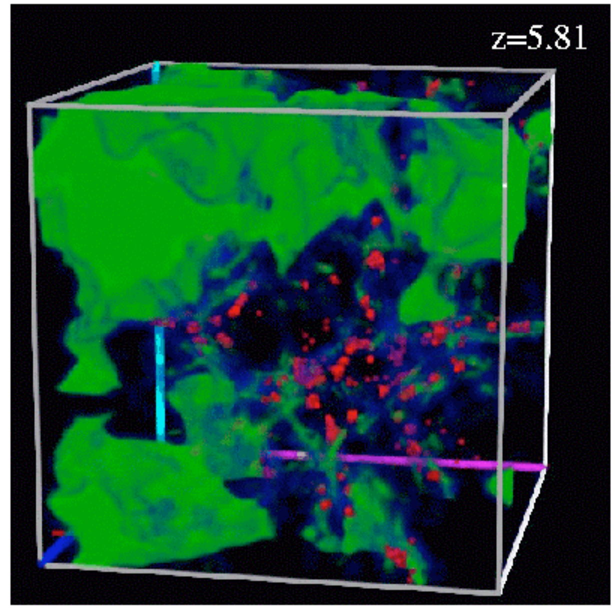
First light 2016

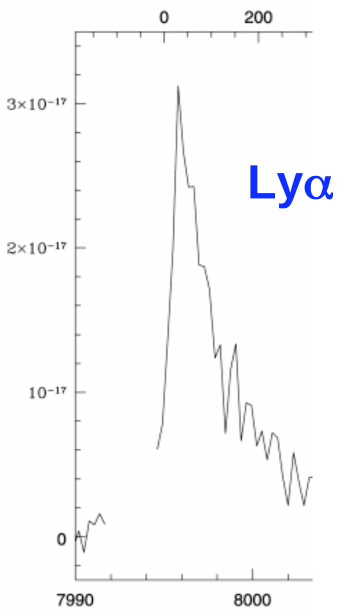


http://www.tmt.org

JWST/TMT Complementarity

In the era of TMT+JWST we won't be interested in <u>when</u> reionization occurred but rather the <u>physical process</u> as tracked by the topology and structure of ionization bubbles





TMT gains in sensitivity, angular & spectral resolution
but not field of view

Lyα emitters require adaptive optics:
- lensed examples are <30 mas across;
TMT offers 9 mas (50pc @z~7)!
- typical line-widths <100-200 km/s

JWST finds luminous sources, TMT scans vicinity to determine topology of ionized shells via fainter emitters - in conjuction with HI surveys