Searches of Ly-alpha emitters beyond z~6

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Outline

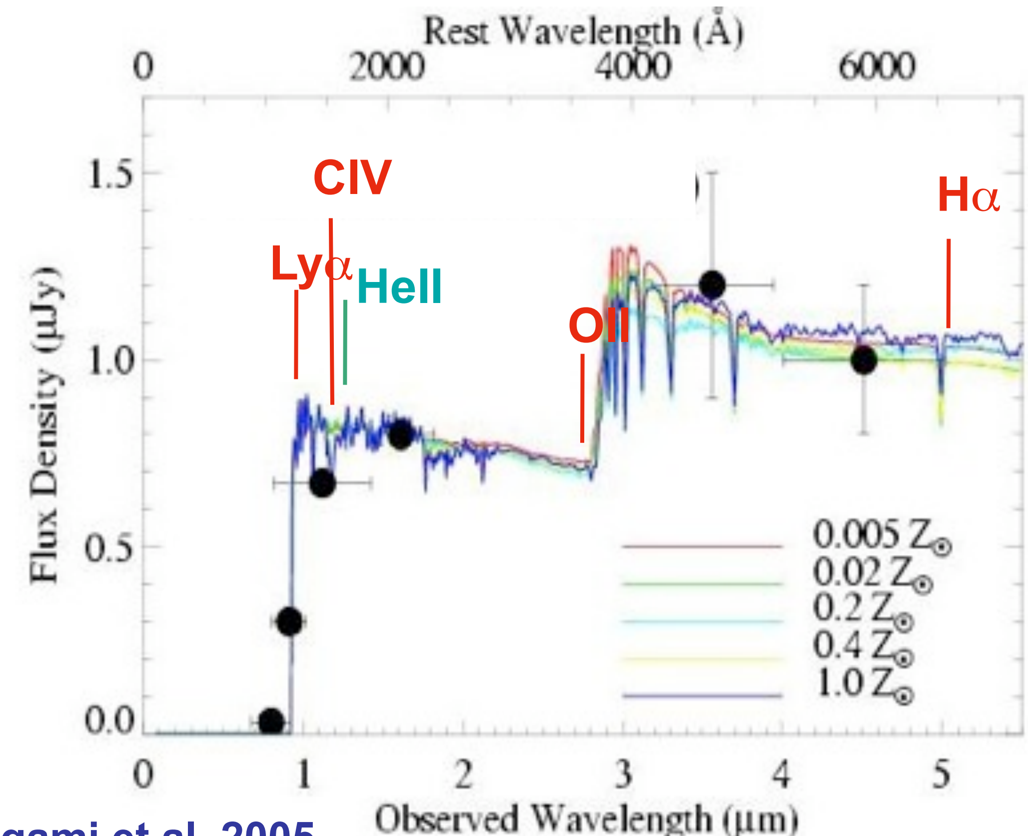
- **Motivation**: Pushing to the limits - probing the epoch of re-ionization!
- How Gravitational Lensing can help ?

- NB Imaging in cluster and blank fields
- NIR Spectroscopy of “Critical Line Mapping” with Keck/Nirspec, Subaru/ Moircs & VLT/Sinfoni
- Conclusion - Future prospects

Aim: to locate the “first” galaxies

Features expected for a distant star-forming galaxy (at z~7):

- *Continuum*: rest-frame UV redshifted to the NIR, contribution from old stars beyond 3 micron? Dust emission in the FIR?
- *Emission lines*: Lyα(?) OII, Hα, possibly HeII if metal-free stars, CO emission lines in the millimeter.

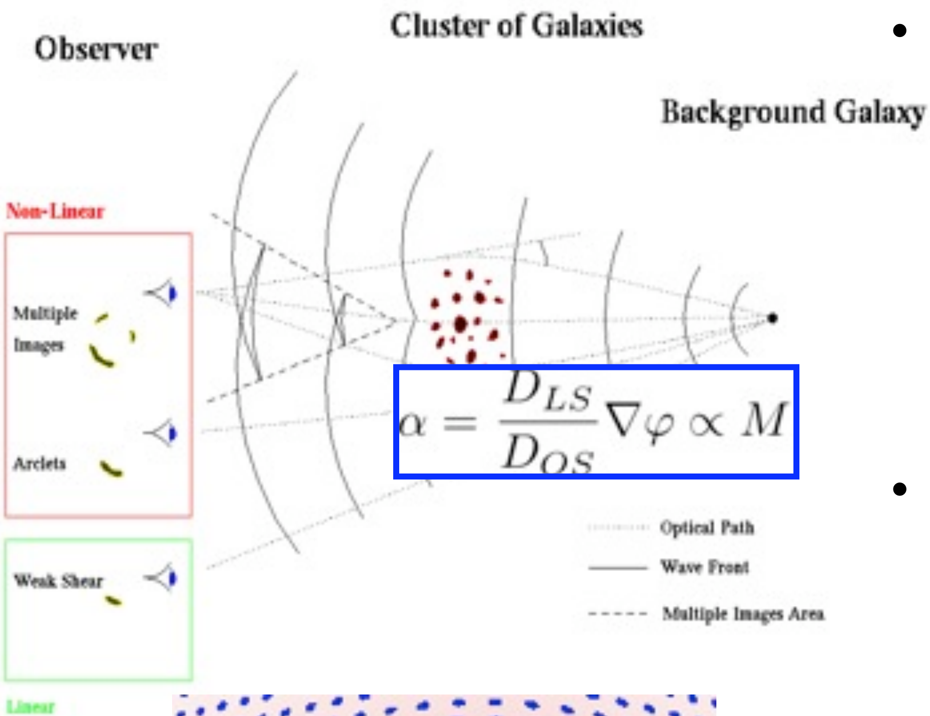


Egami et al. 2005

Route followed:

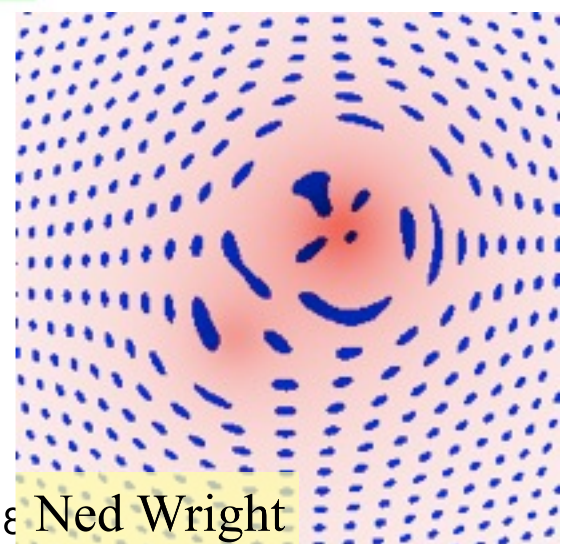
- Emission line (Ly-α, Hα)
  - **NB imaging**
  - **Blind spectroscopy** (**NIR**-MIR)
- Continuum (Lyman-break +4000A break confirmation)
- ***Use of Gravitational Telescope =>low luminosity galaxies***

How Gravitational Lensing can help?

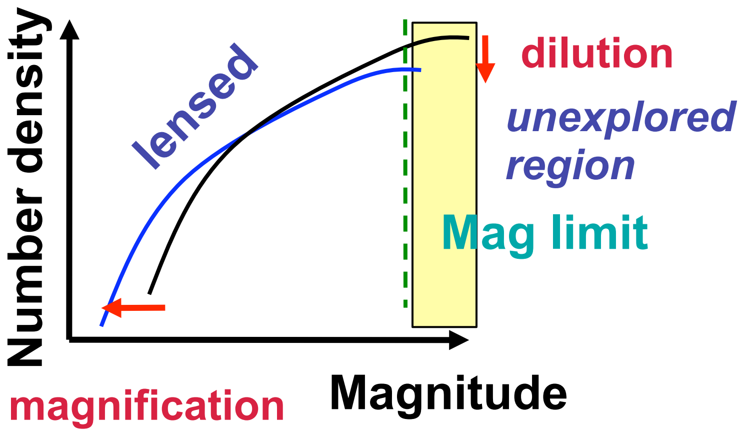


$$\alpha = \frac{D_{LS}}{D_{OS}} \nabla \varphi \propto M$$

- **Basics of lensing:**
  - Important mass density locally deform the Space-Time,
  - *A pure geometrical effect, no dependence with photon energy*
  - *Multiple-images with large magnification >10*
- **Lensing by a (massive) galaxy**
  - Deflection of ~1 arcsec
  - strongly lens only ~one bg source
  - ~10 galaxy-lens per sq.degree
- **Lensing by a (massive) cluster**
  - Deflection of ~10-50 arcsec
  - *strongly lens many background sources*
  - ~1 cluster-lens per ~50 sq.deg.
  - high amplification on a few sq.arcm.



Clusters as a Cosmic Telescope



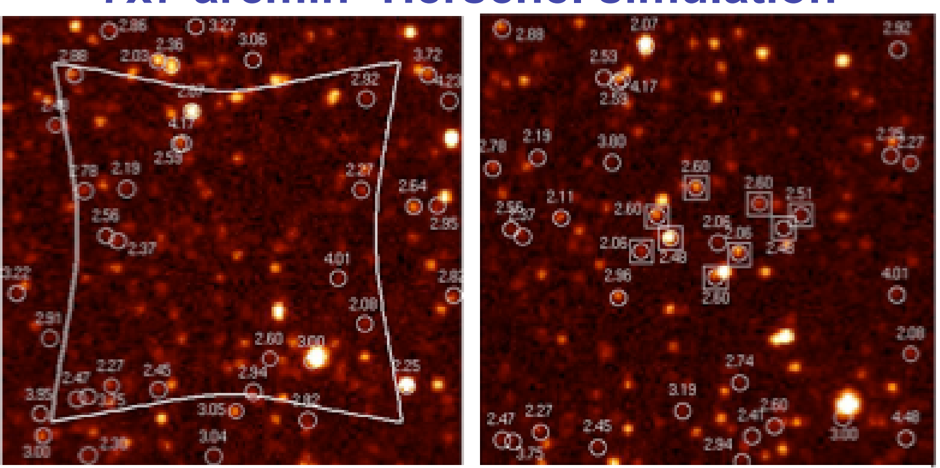
- Source plane, Image plane transformation

$$N_L(f)=N_0(f/A)/A$$

  - *Magnification of sources*
  - *Dilution of area*

- Benefits of cluster-lens obs:
  1. **Magnification**, makes spectroscopic follow-up/size measurement possible for rare and most amplified sources
  2. Observe below the usual detection limit (faint luminosity)
  3. Multiple images confirmation of strongly lensed sources
  4. Avoid confusion (critical in FIR/Submm)

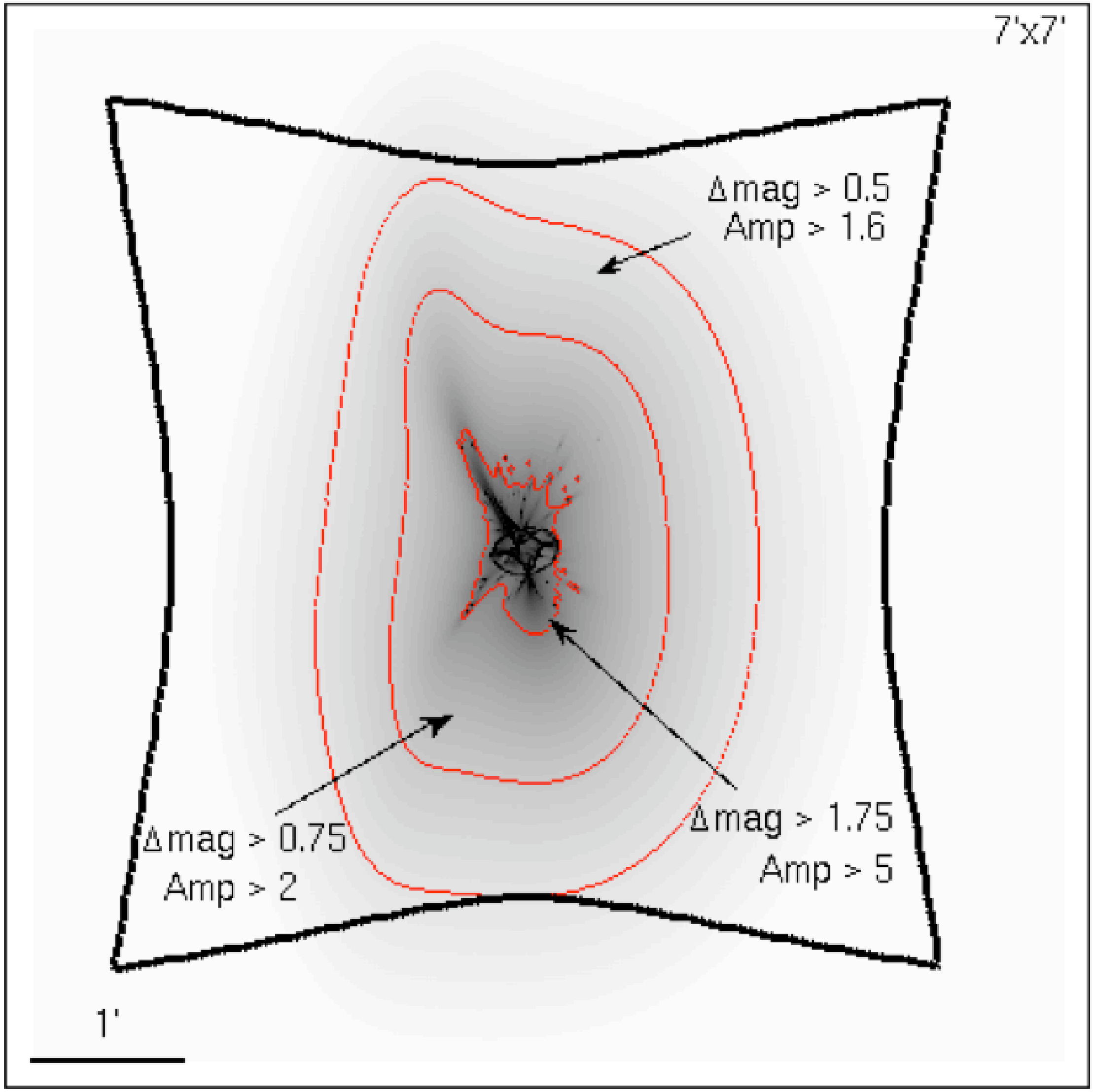
7x7 arcmin^2 Herschel simulation



Unlensed field **Lensed field**

man-alpha

Clusters as a Cosmic Telescope



Source plane view of a cluster lens field (non-linear mapping)

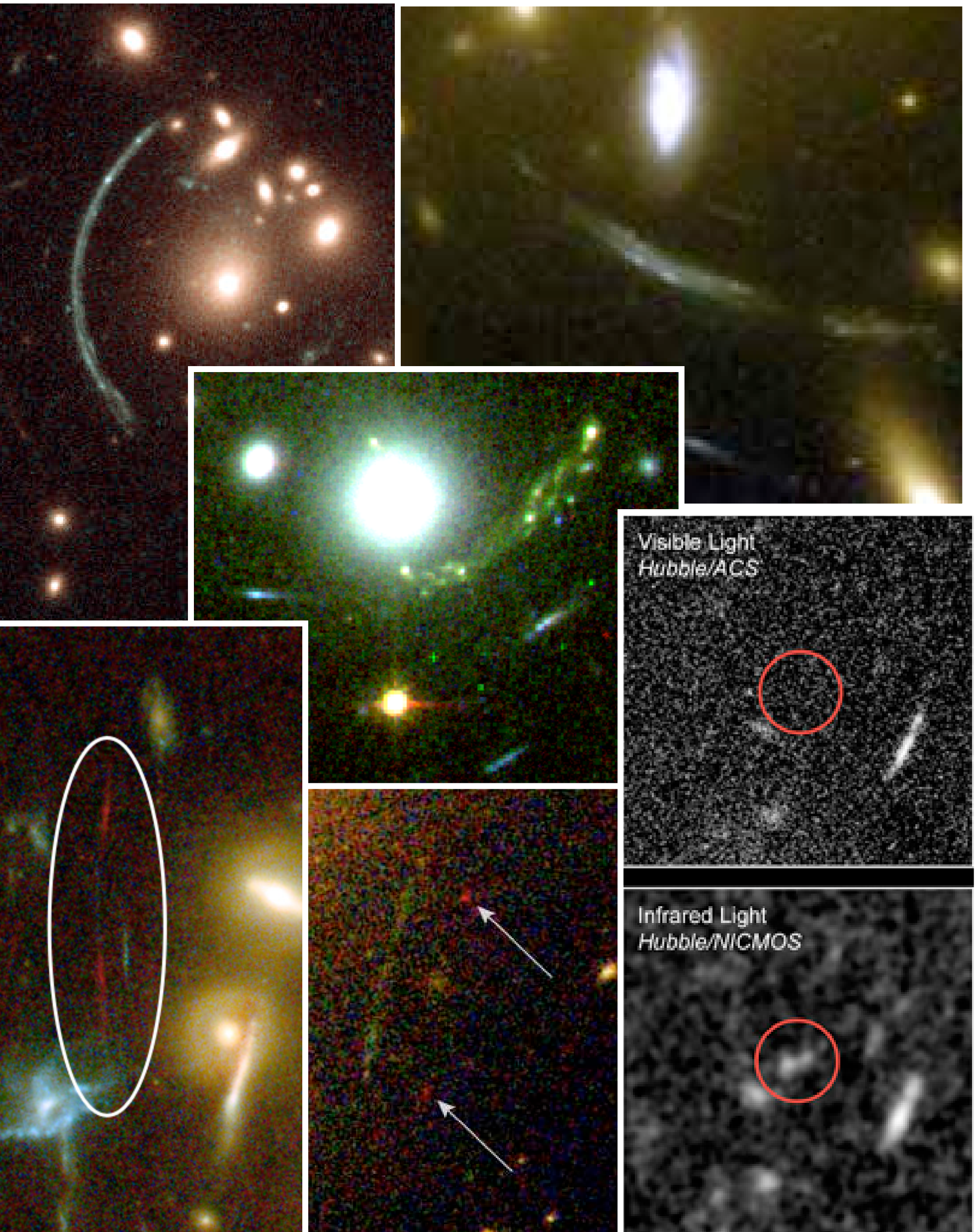
-Dilution effect (surveyed area is smaller)

- Magnification effect (larger sensitivity)

- *Larger amplification concern smaller area*

=> *to maximize the amplification concentrate on the central few sq.arcmin* ***(very wide-field imager not optimal for lensing work)***

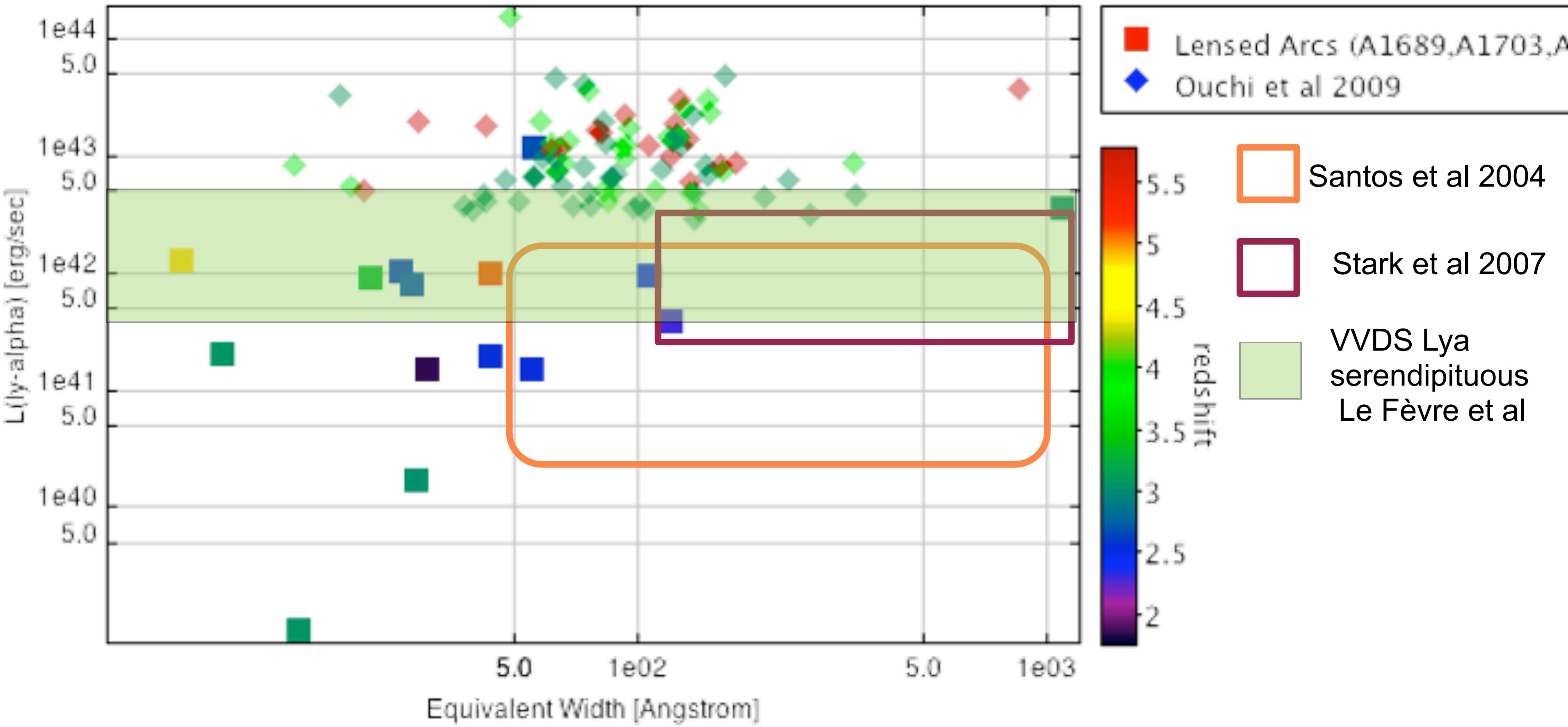
History of searching hi-z lensed galaxies



- **1987**: Cl2244 one of the first gravitational arc, latter recognized as a z=2.2 LAE galaxy
- Ebbels et al **1996**: a z=2.5 LBG in a2218
- cB58 z=2.7 LBG recognized as a strongly lensed source (Seitz et al **1998**)
- Franx et al **1997**: a LAE at z=4.9
- Ellis et al **2001**: LAE at z=5.6
- Kneib et al **2004**, Egami et al **2005**: LBG at z~6.8
- Stark et al **2007**: LAE candidates
- Richard et al **2008, Bouwens et**: LBG candidates
- Bradley et al **2008**: LBG at z~7.6
- … and more to be discovered …

n-alpha

Lensed Ly-alpha probes lower-luminosity

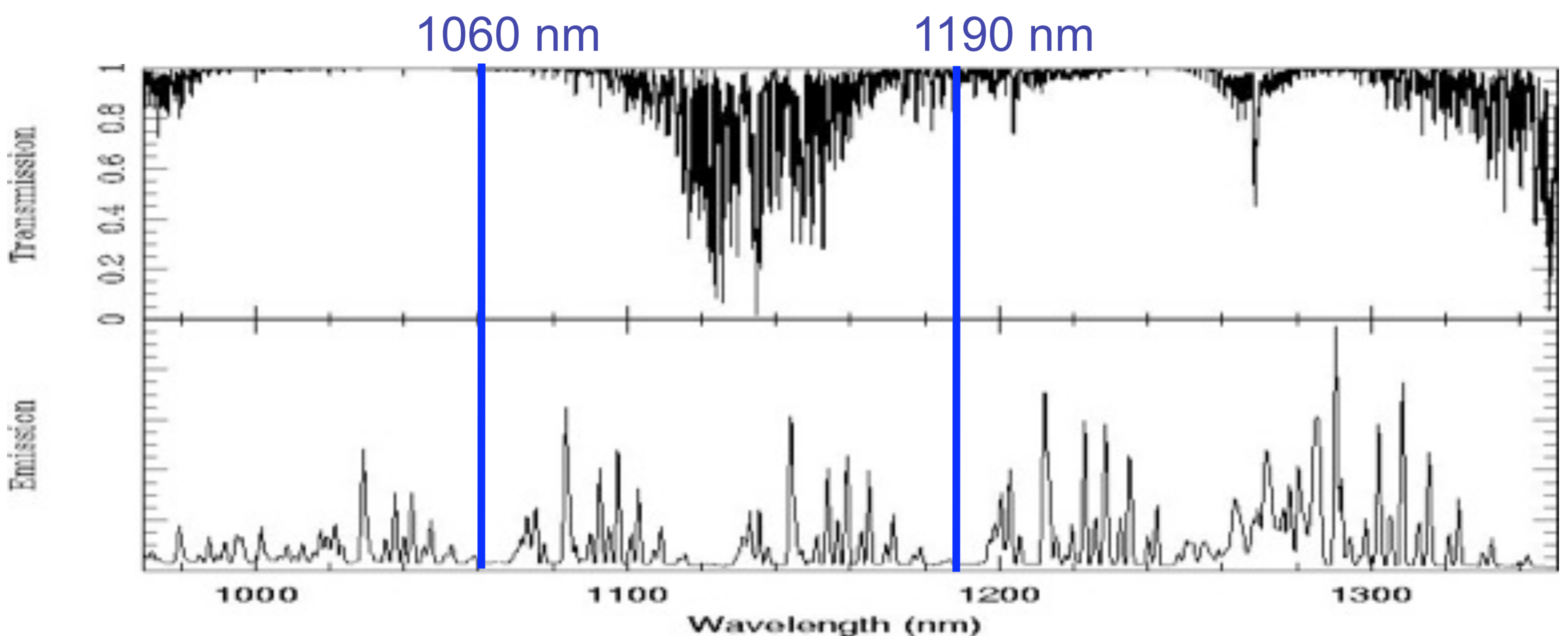


- **Lensed Ly-alpha emitters probed in massive clusters have lower luminosities than blind NB search or serendipituous spectroscopy in the field.**

Narrow Band Imaging Searching z>7 Galaxies

ZEN (z equal nine) Narrow Band Survey

- **ZEN1:** a single deep field within the HDF South (NB<25.5), NB119 is sensitive to z=8.8. Willis and Courbin (2005). And also Cuby et al 2007
- **ZEN2:** three fields containing massive lensing clusters (magnified background galaxies). Willis et al (2007).
- **ZEN3:** CFHT/WIRCam fields (0.1 deg2) located in CFHTLS D1 40h in NB:Low-OH1 (z=7.7): cf Hibon et al 2009 in press (see POSTER #11)
- **LP-ESO:** Hawk-I (z=7.7) - preliminary results: Clément et al 2009 in prep. (see POSTER #30)
- **(planned):** UltraVista (z=8.8) on COSMOS field - starting end 2009

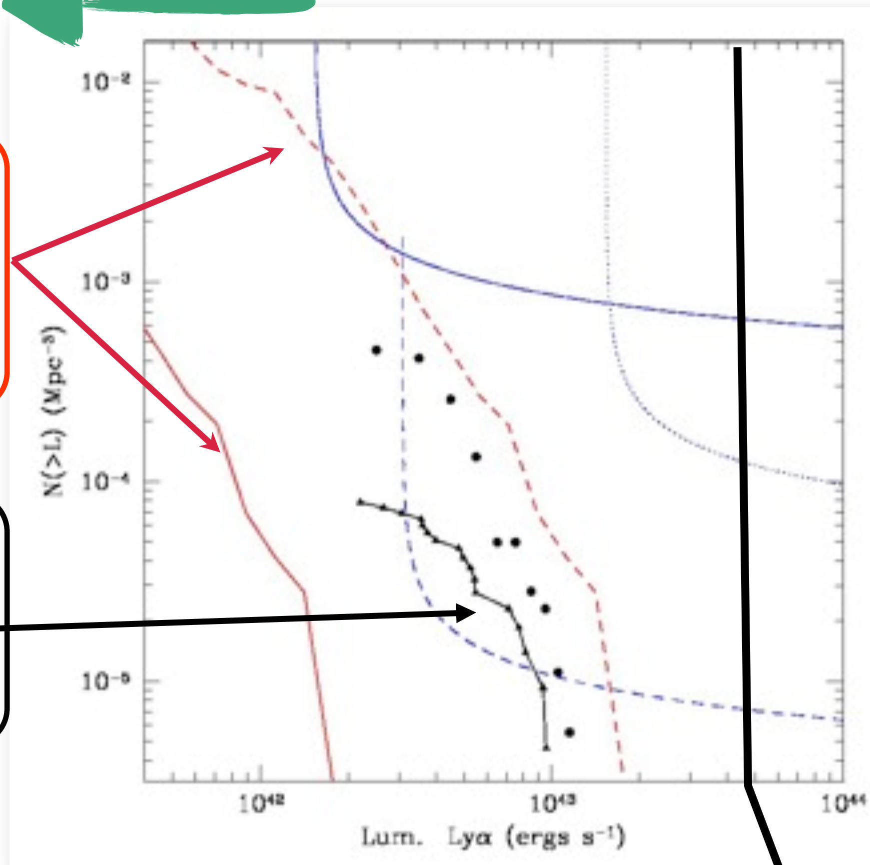


NB constraints (z>7, field+clusters)

Critical line mapping

Semi-analytic model of star forming galaxies at z=9 Le Delliou et al. (2006)

NB selected galaxies at z=6.6 Kashikawa et al. (2006)



ZEN 1+2

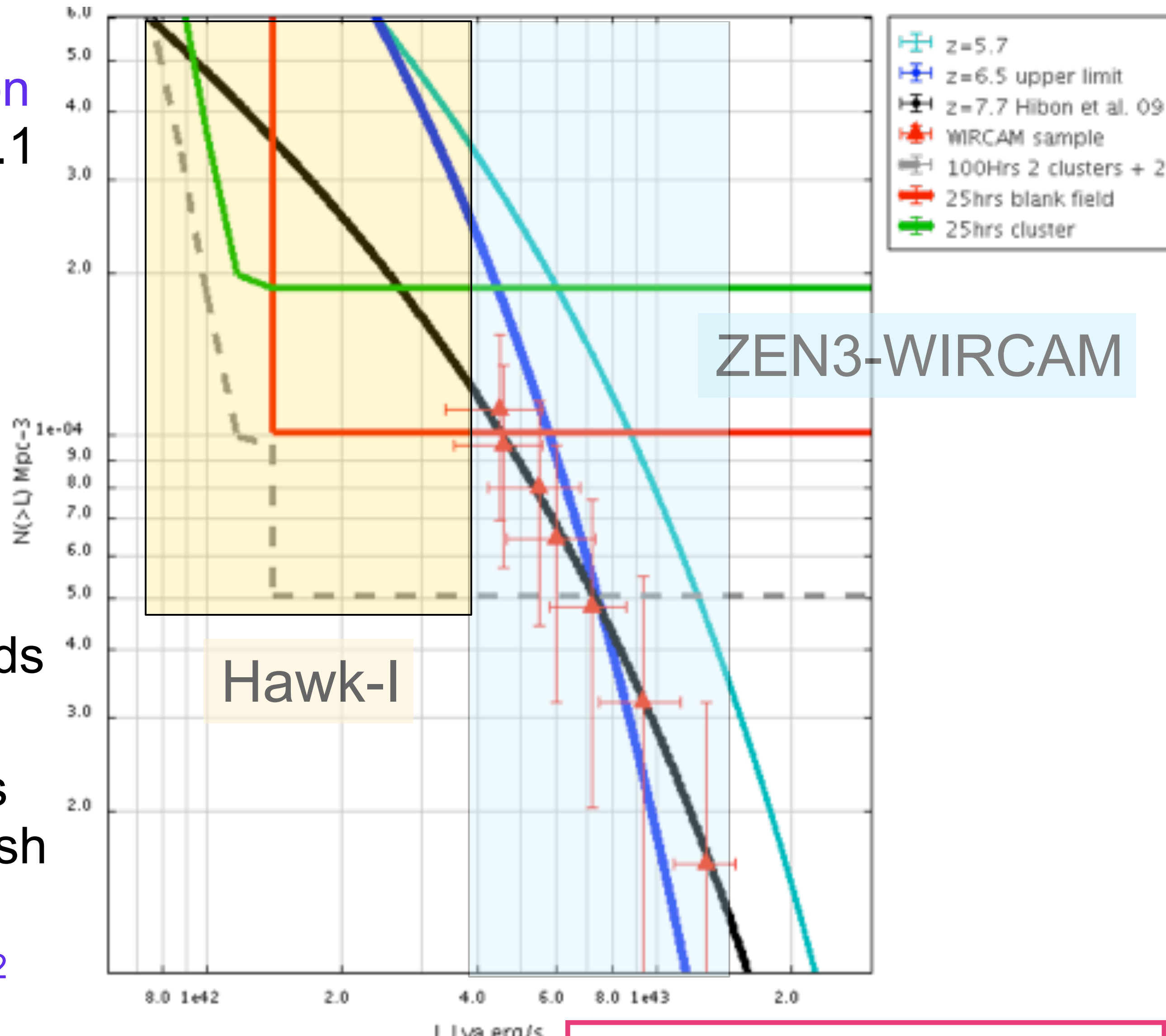
Cuby et al. (2007)

ZEN3: WIRCAM
Hibon et al 2009
7 candidates @ z~7.7

Sobral et al 2009, z~8.8

WIRCAM & HAWK-I NB Imaging LAE Sensitivities

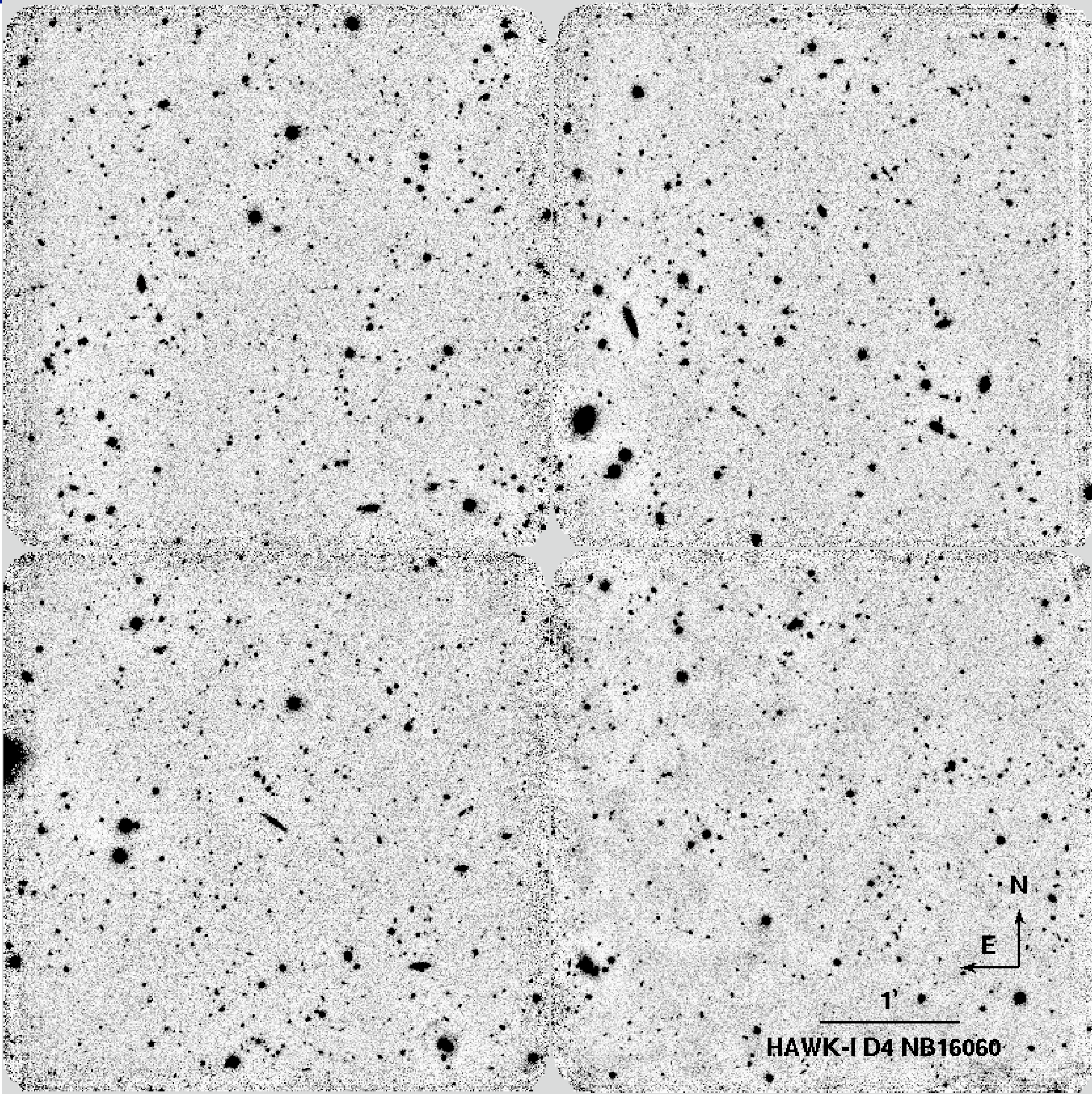
- WIRCAM data (Hibon et al 2009) 0.1 sq.deg on D1 field
- LP at ESO using Hawk-I (PI:Cuby)
- *120 hours* (2 yr project) NB+BB
- *4 fields*: 2 clusters (A1689, Bullet Cluster), 2 blank fields (D4, Goods South)
- 1st epoch on 4 fields acquired, survey finish by ~mid 2010
- Probe down to ~10^{42} erg/s in L(Ly-alpha)



See Hibon Poster #11

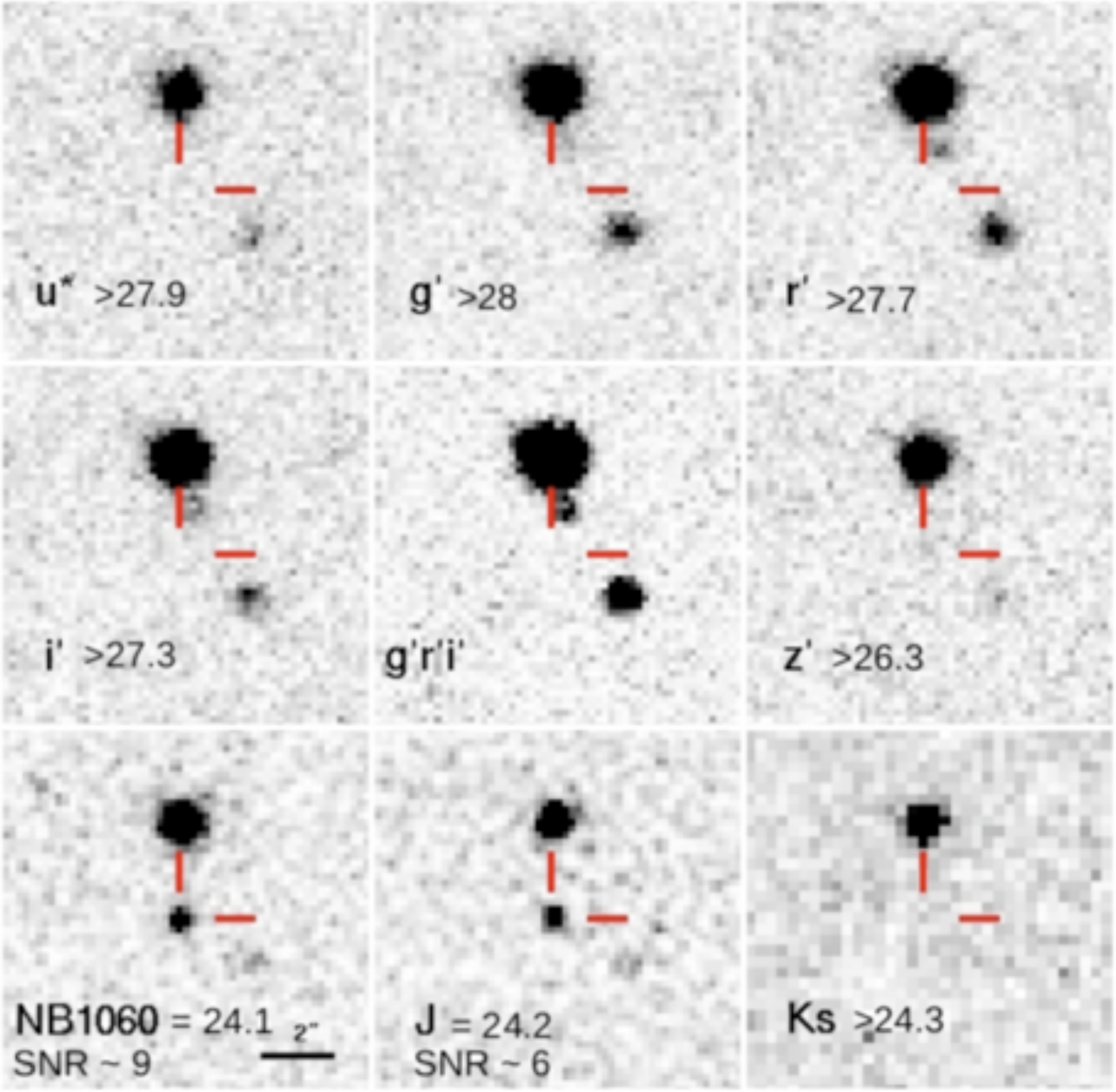
HAWK-I NB Imaging

- D4 pointing ~10 hours exposure in NB106
- AB mag limit of ~26.0 in 1.5 arcsec aperture (4sigma)
- Good cosmetics

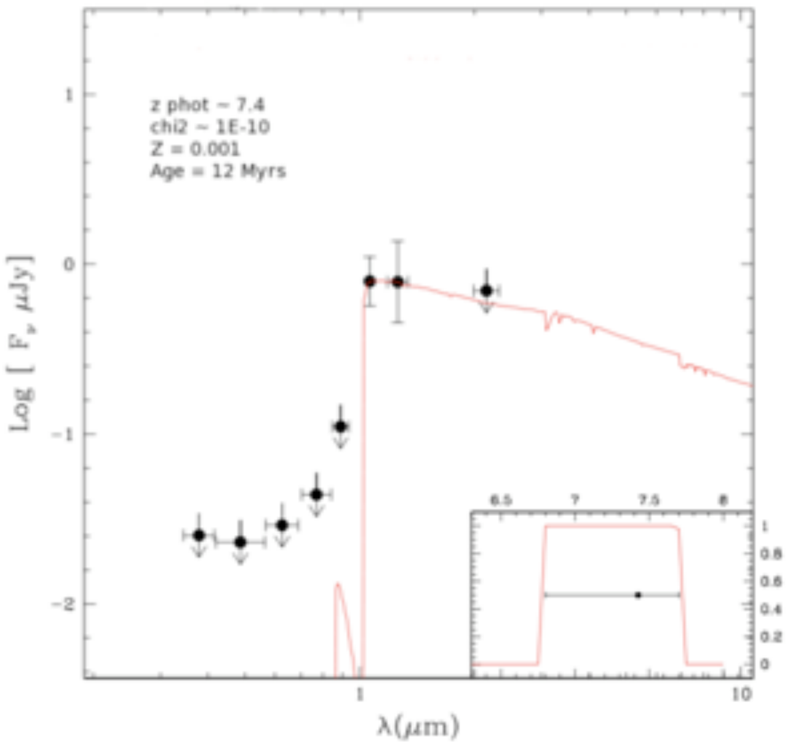


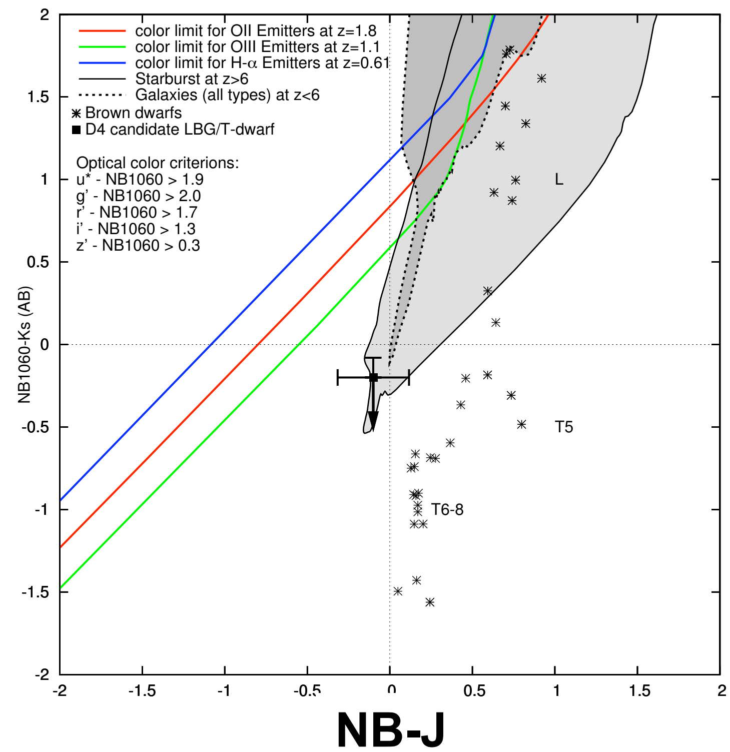
HAWK-I NB Imaging

- D4: NB hi-z candidate
- NB= 24.3+/-0.1 (9 sigma)
- J= 24.1+/-0.2
- Not detected in the CHFT-LS ugriz deep observations
- see poster by Clement et al #30



HAWK-I NB candidate





- D4: NB hi-z (preliminary) candidate z~7.4
- Need proper evaluation of other possible solution (but not lower-z emission line, & not a brown dwarf; qso? transient?)
- Expect 10-20 candidates when LP complete !! ... wait for next year hi-z conference :)

Critical Line Mapping

Critical Line Mapping: finding LAEs

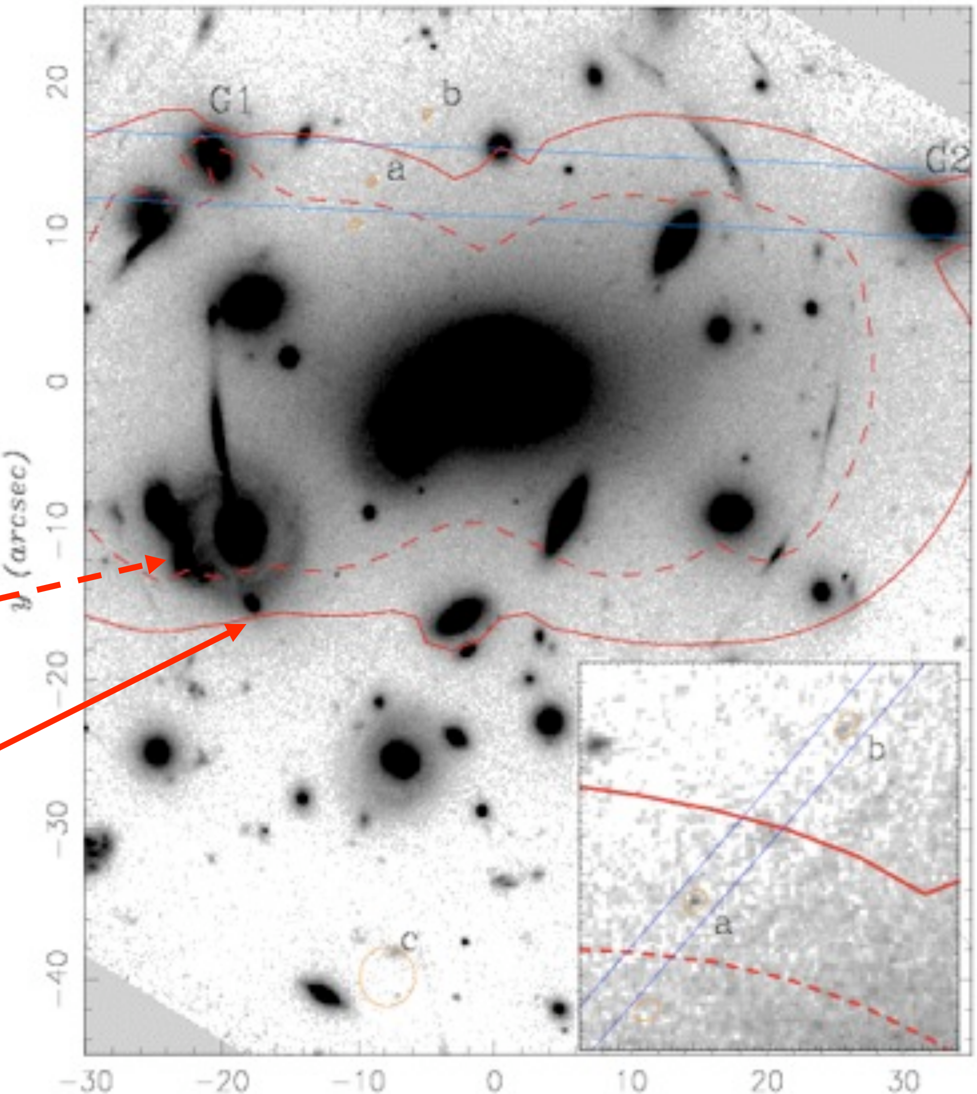
Ellis et al 2001

From lens modeling the location of the “critical lines” is known precisely for

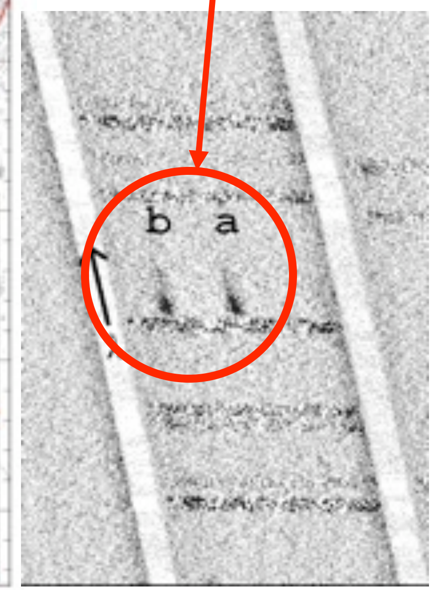
z=1

and for

z=5



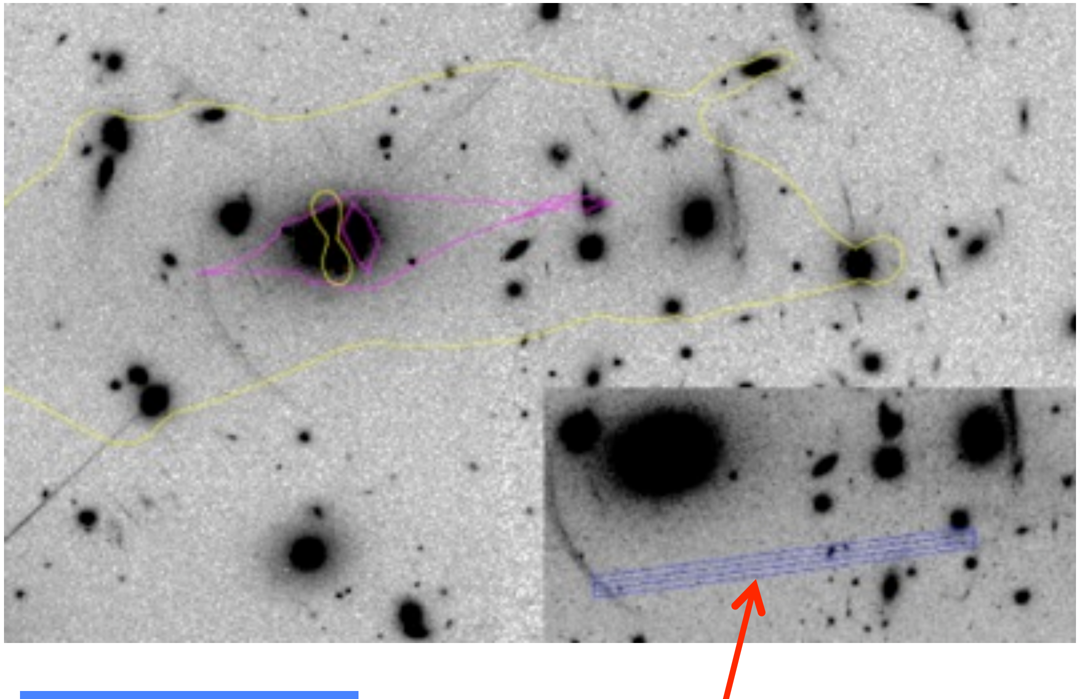
Blind Ly-a search with LRIS: hi-res follow-up with ESI



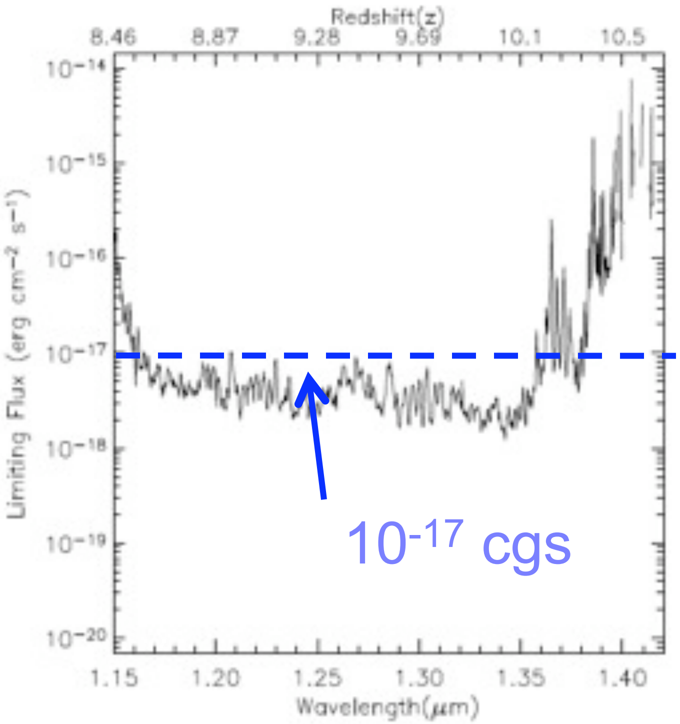
Utilizing strong magnification (´10-30) of clusters, probe much fainter than other methods in small areas (<0.1 arcmin2 cluster-1)

Low-luminosity z~9.5 Ly-α emitters

Cluster critical line for $z_S > 7$



Wavelength sensitivity (1.5hr)

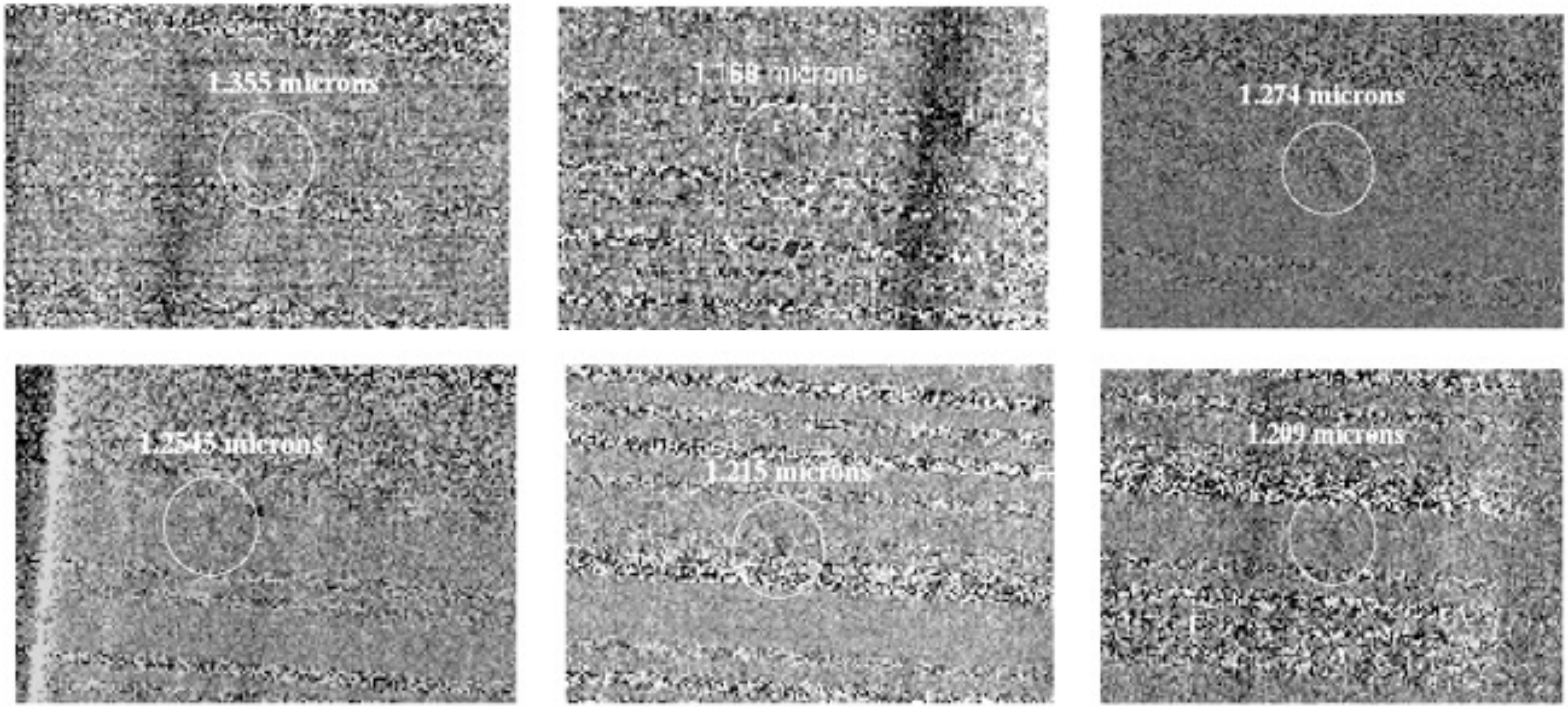


Stark et al 2007

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

z~9.5 Candidates

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

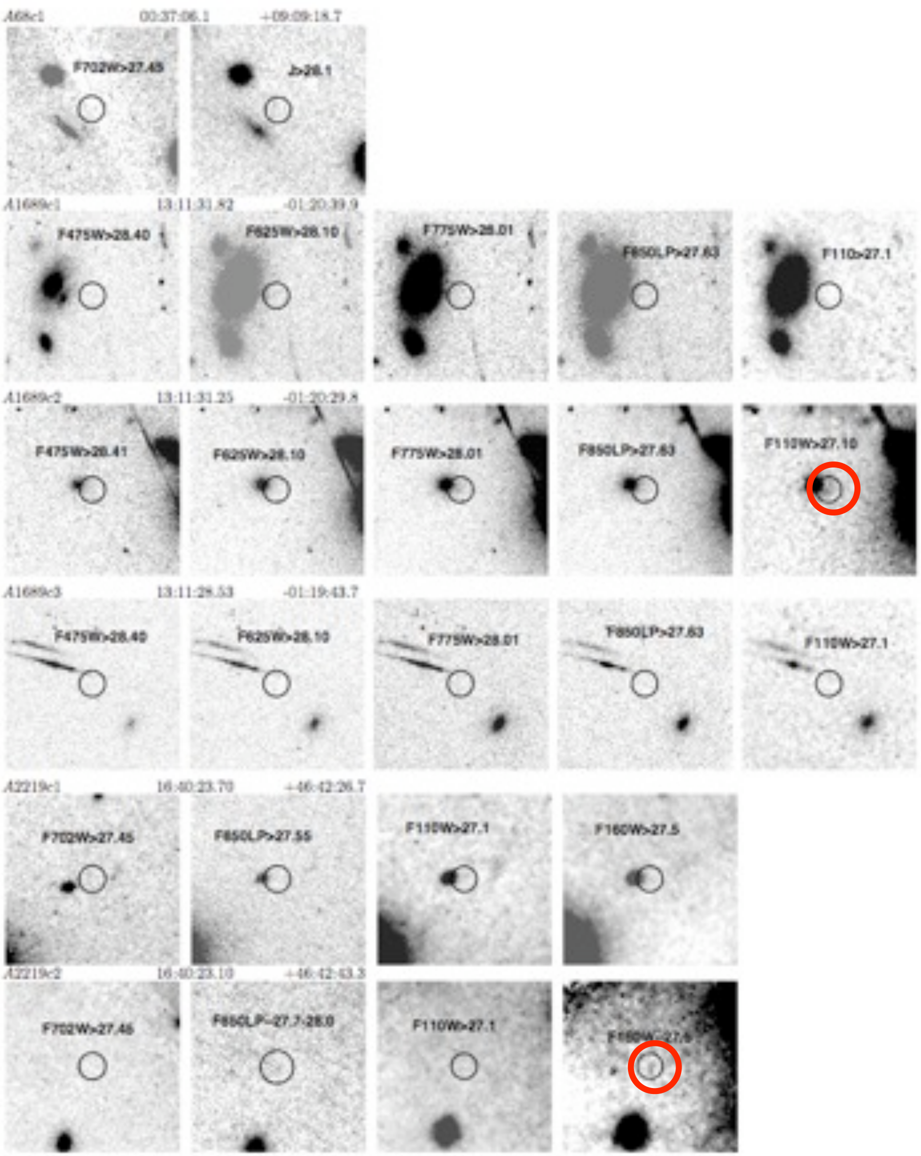


Proving that these are z~9.5 emitters is HARD (search of other lines if this is not Ly-alpha)

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

Revisit with different telescope: Subaru/MOIRCS, VLT/Sinfoni

Candidates continuum limits

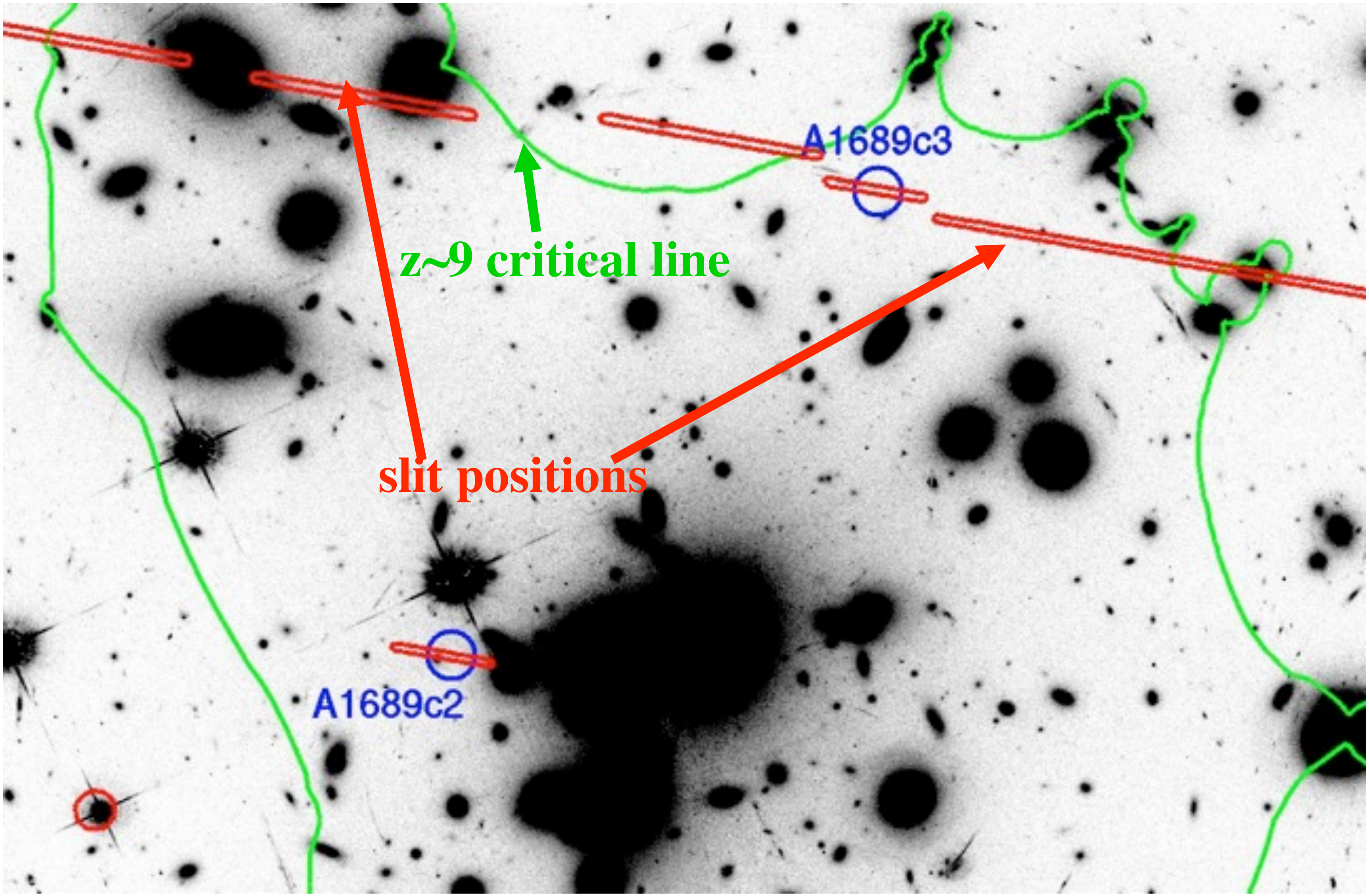


Very deep ACS and NICMOS imaging is available for most clusters with z~9.5 candidates:

- no optical detections to $m_{AB} > 27$
- two marginal J, H detections: still consistent with high z & modest SFR (Deeper imaging needed!)

an-alpha

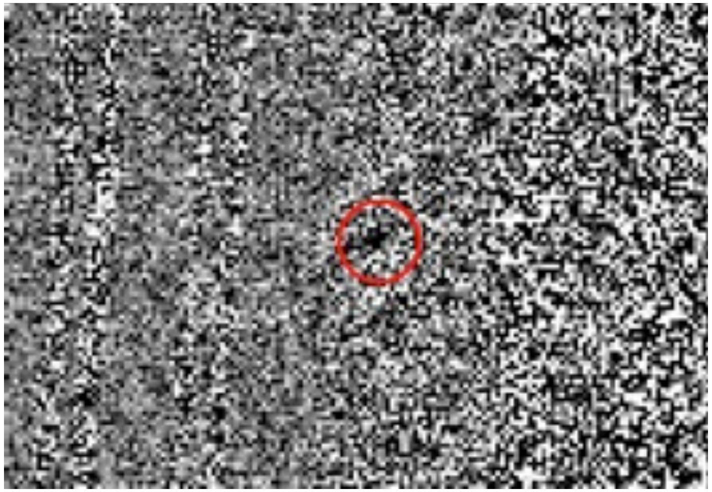
MOIRCS VPH Grism Observations of A1689



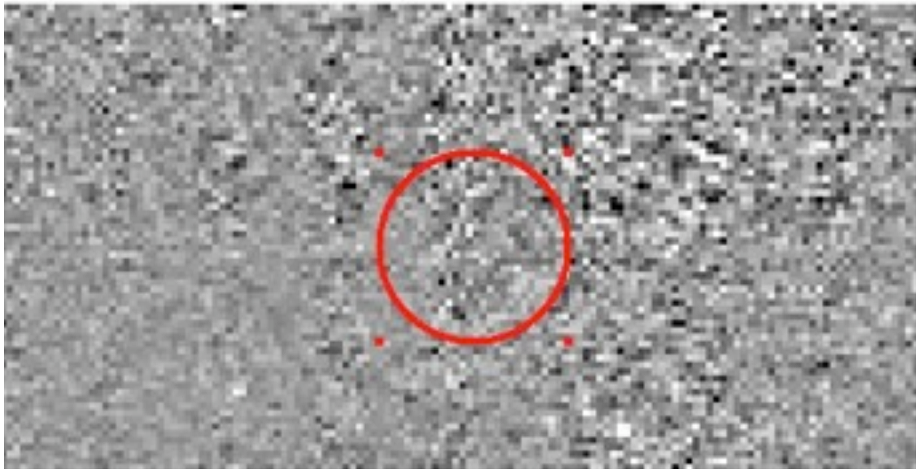
4h with VPH grism (1.14 to 1.34 micron), R~1900 - seeing ~0.3-0.4”

MOIRCS Observations of NIRSPEC z~9 candidates

A1689 c3 NIRSPEC

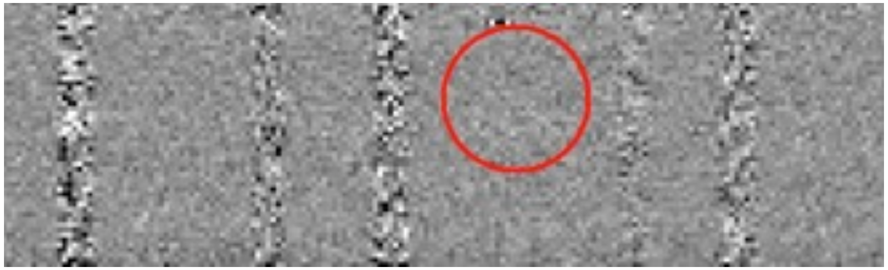


A1689 c3 MOIRCS



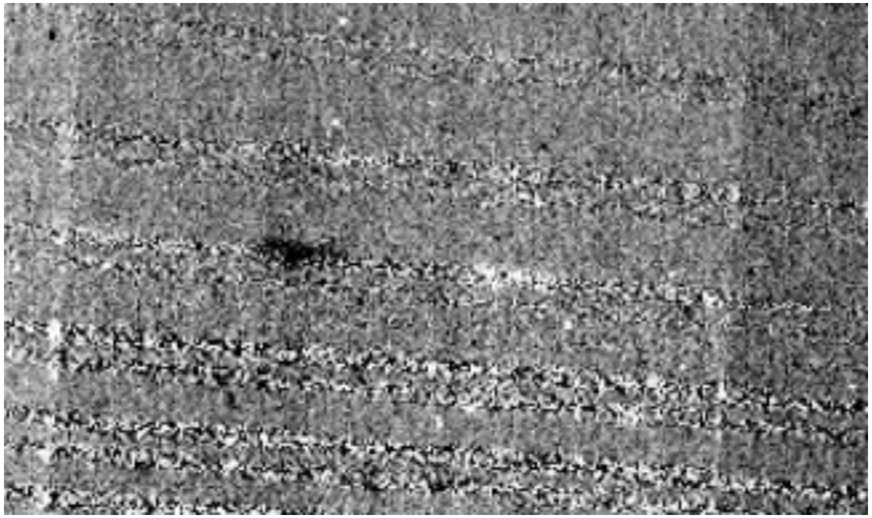
A1689 c2 NIRSPEC

A1689 c2 MOIRCS

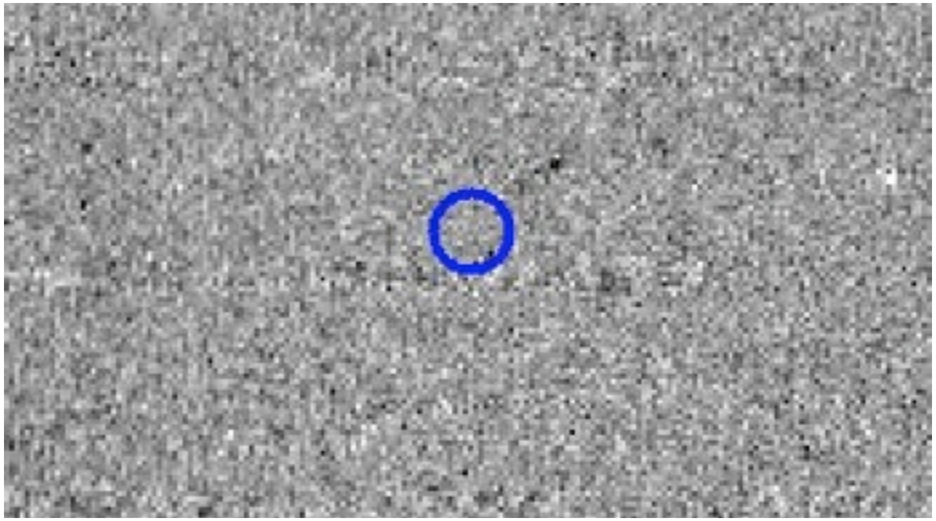


MOIRCS non-detection of bright z~2.5 arc !

NIRSPEC: 2 x 5 mins



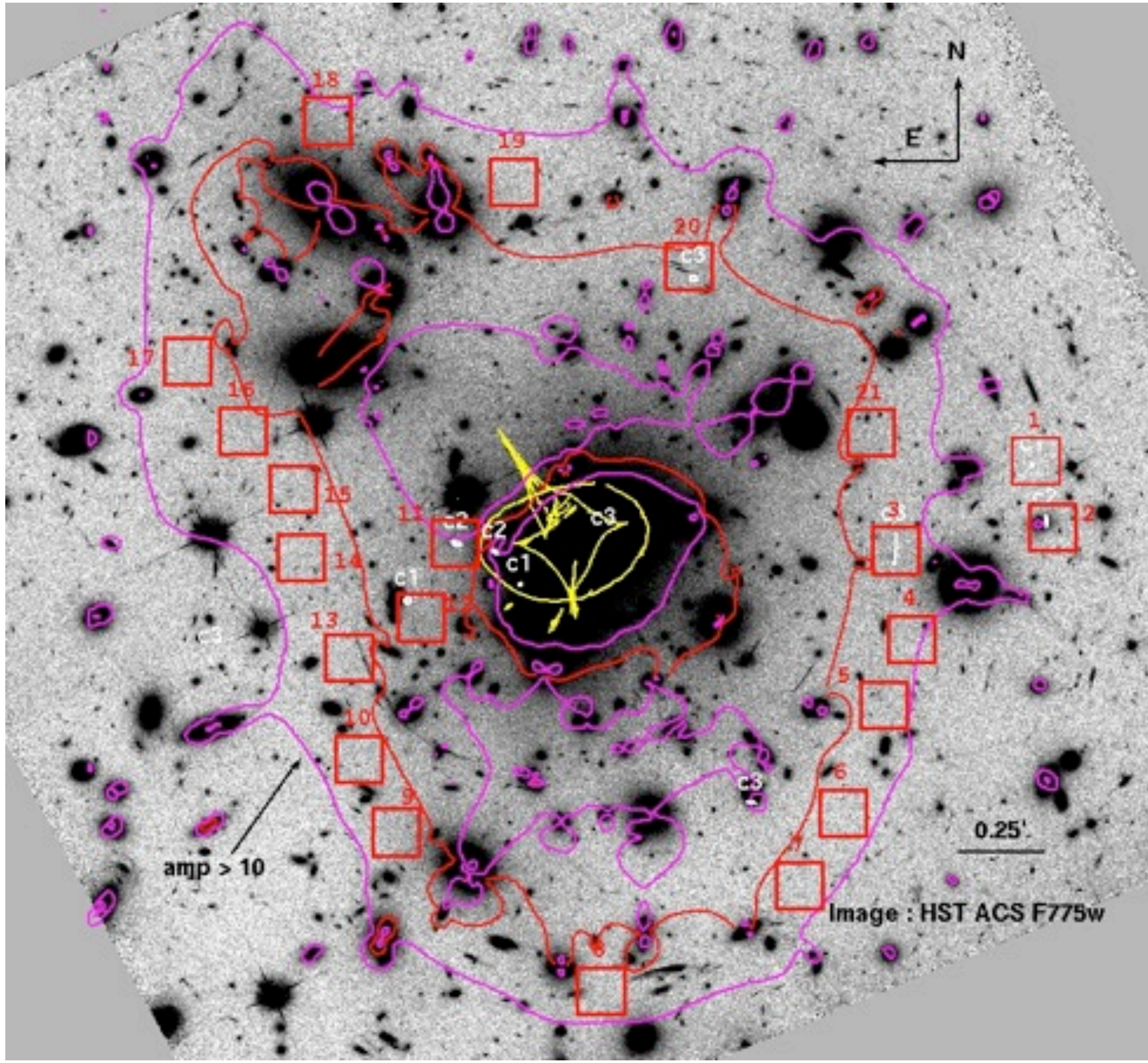
MOIRCS: 40 min



- Emission line at z~2.5 detected in single A+B pair of exposures with NIRSPEC
- Undetected in MOIRCS with 4x the exposure time of NIRSPEC.
- Check registration: slit mask was centered on arc.
- Efficiency of MOIRCS varies significantly across bandpass?
- Confuses interpretation of non-detection of z~9.5 NIRSPEC candidates!

SINFONI critical line mapping

- Mapping strategy
- 20hours - R~1400
- 21 pointings (5”x6.5” effective area =680 sq.arcsec in image plane)
- Equivalent to an area of ~50 sq.arcsec in the source plane, or a covolume of ~50 Mpc^3
- Probe ~10^{41} Ly-alpha luminosity

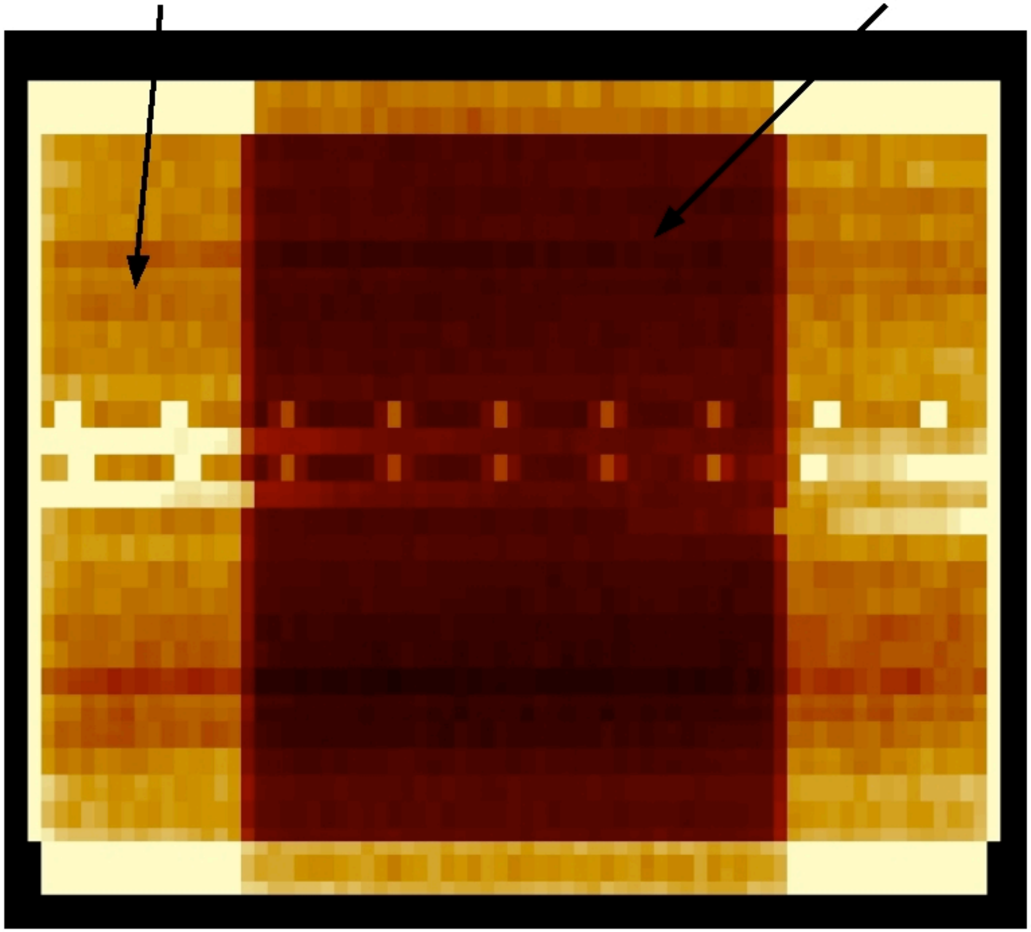


SINFONI critical line mapping

Noise cube:

SINFONI is ~8"x8"

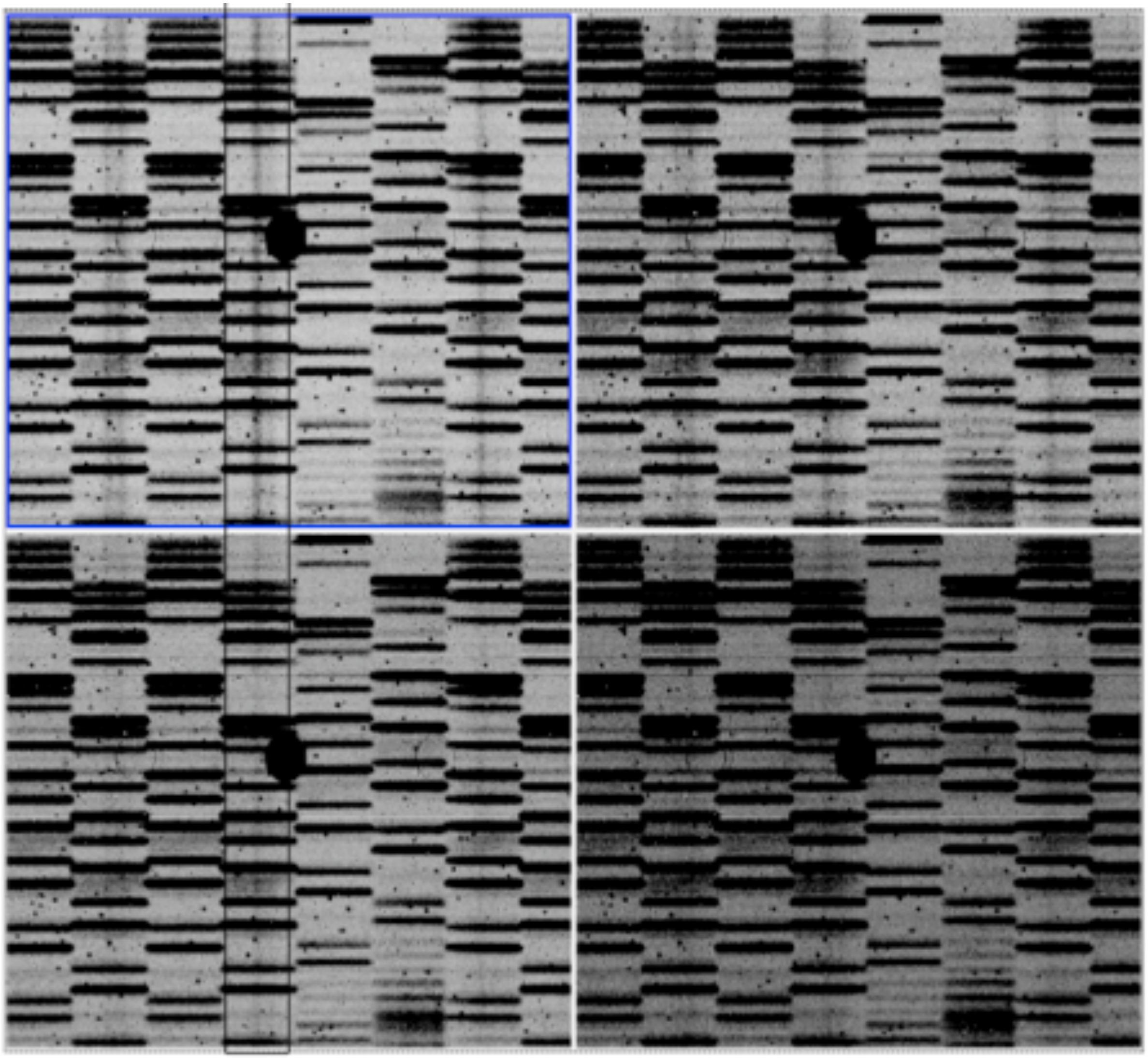
Dithering strategy for good sky subtraction, leaves a usable field of 5"x6.5"



SINFONI critical line mapping

Persistence issues

- In a few data-cubes a calibration star was observed just before the science observation
- Lead to some **persistence** - needing extra-work for the data reduction



SINFONI critical line mapping

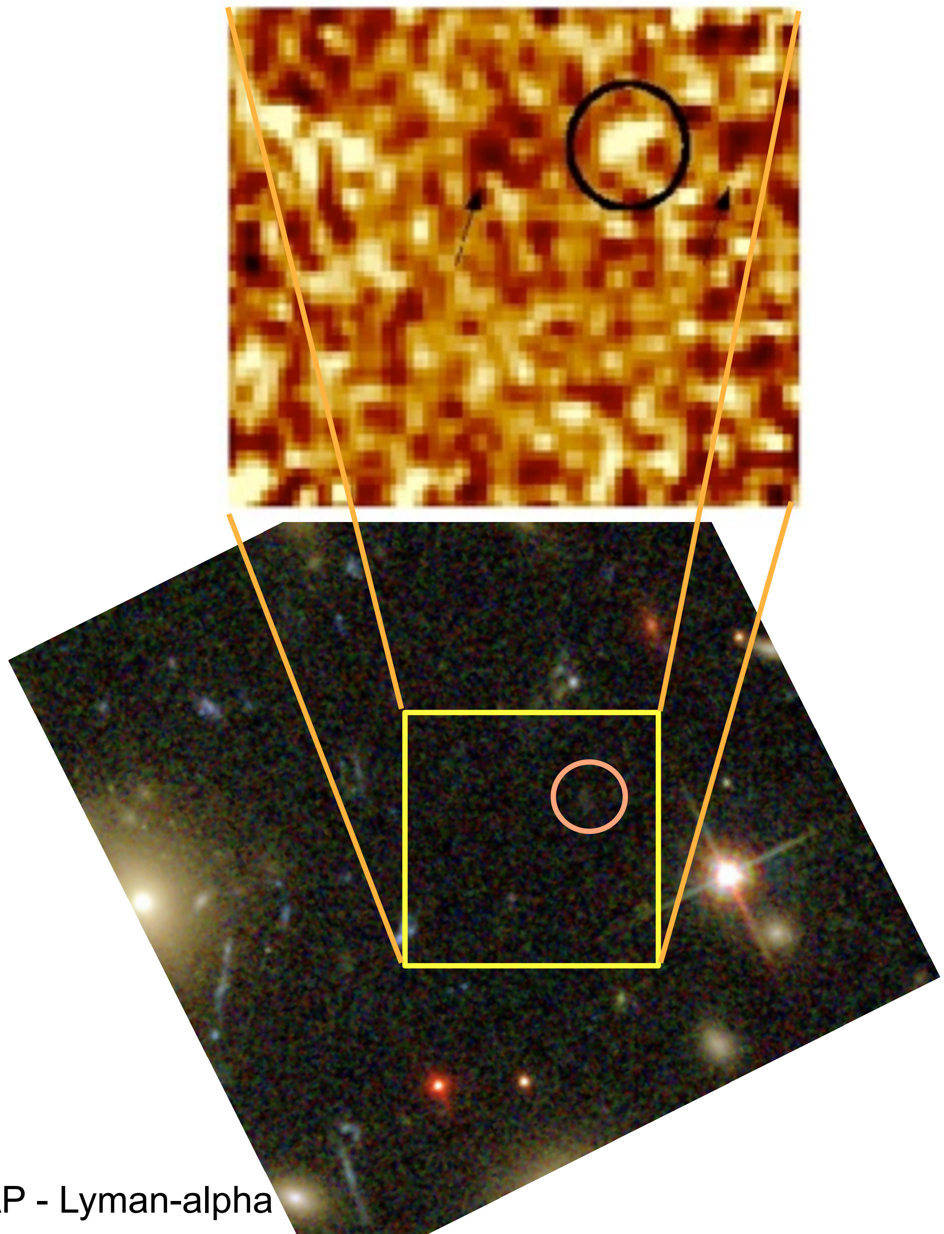
- Emission line detection (lambda=1.187 micron) of a galaxy, possibly

OII @ z=2.18 or

Ha @ z=0.808

- I_{AB}~26
- Line flux

~3e-17 erg/s/cm^2

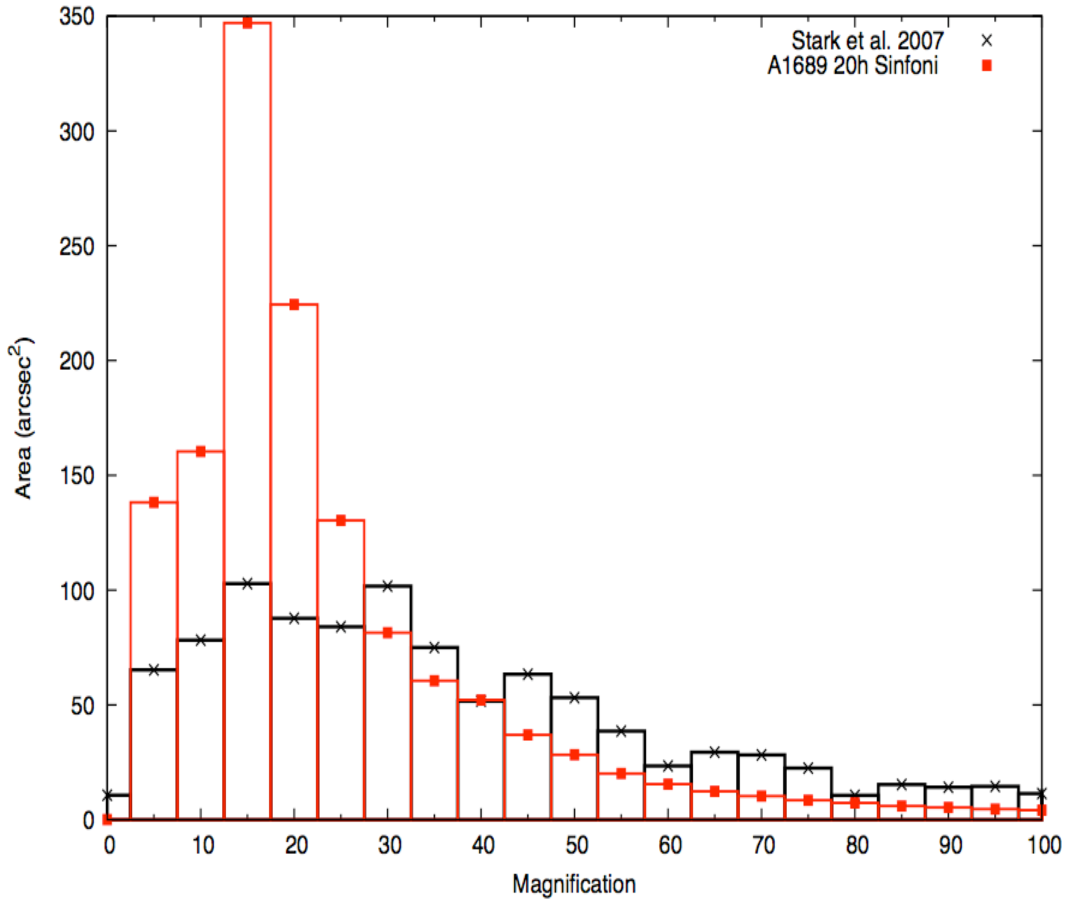


SINFONI critical line mapping

Magnification:

Comparison of

- SINFONI 3D spectroscopy (only the effective area - 4 exposures)
- and Keck/NIRSPEC slits



Line Sensitivity comparison

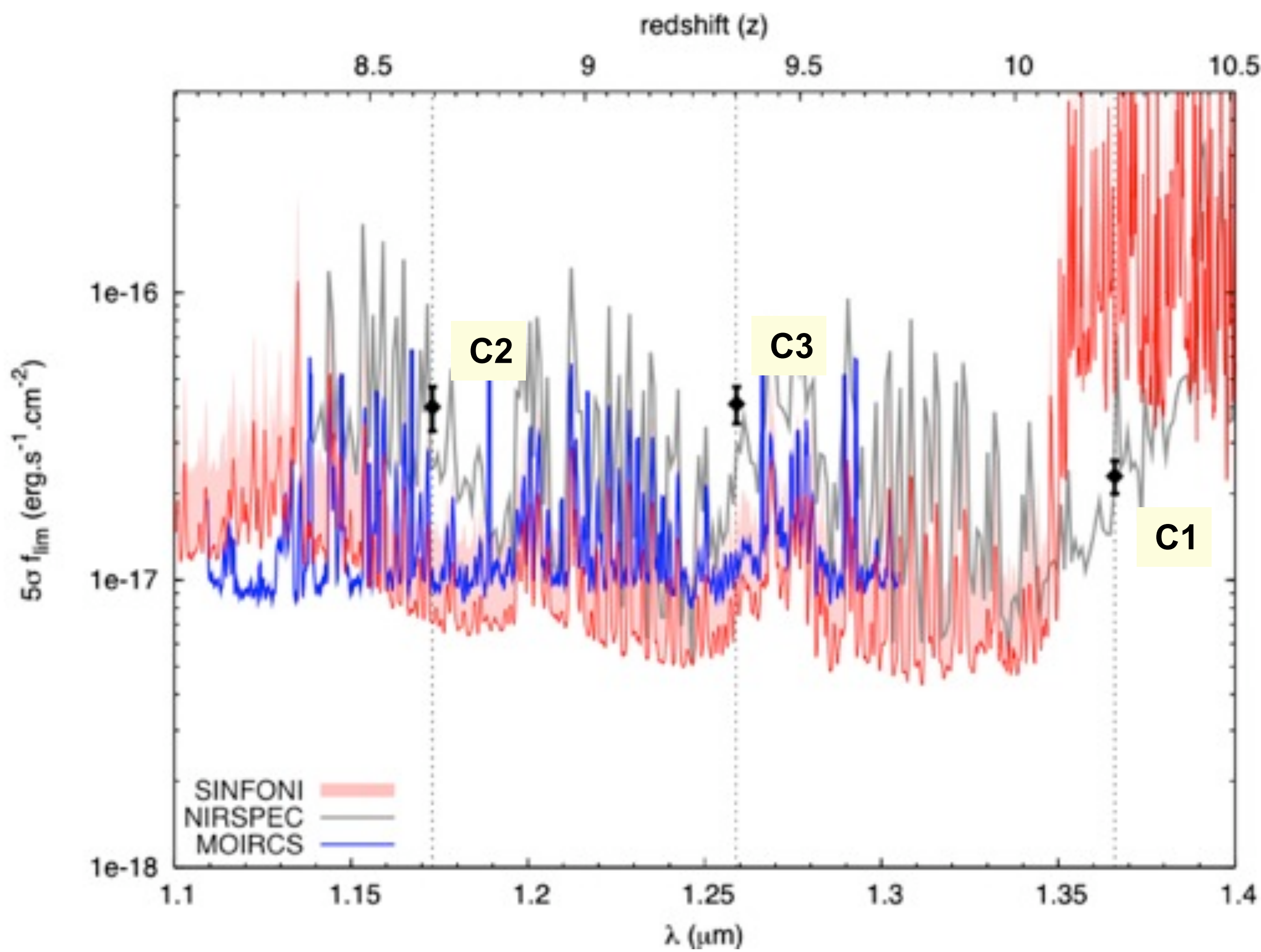
SINFONI (900sec exposure - median of 21 cubes),

Keck/NIRSPEC (1200sec, Stark et al 2007)

Subaru/MOIRCS (4h)

A1689 C2, C3 candidates not confirmed with Sinfoni & MOIRCS

A1689 C1 too faint for SINFONI, not in lambda range for MOIRCS.

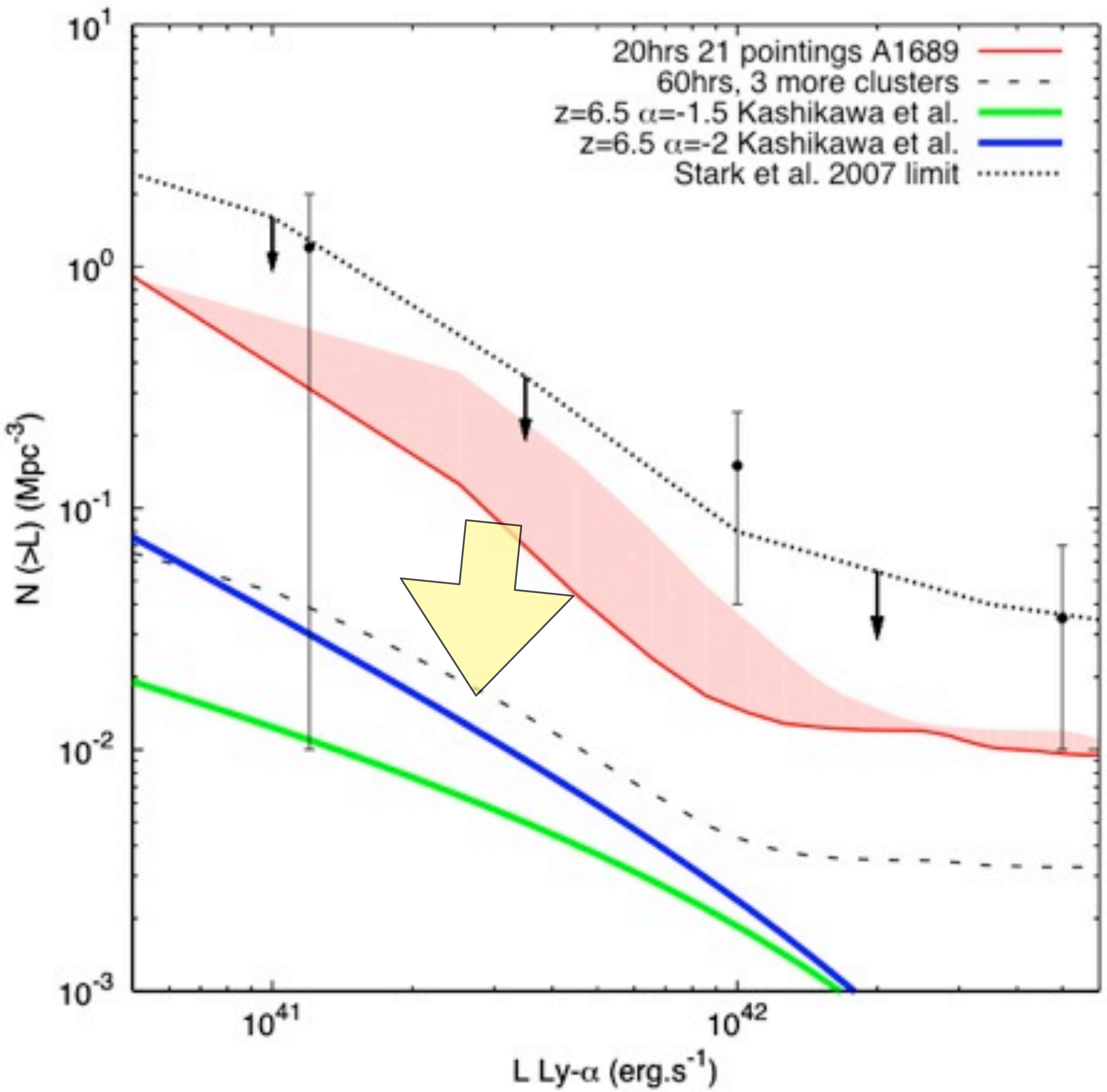


Constraints on the z~9 Luminosity Function

- SINFONI 20h
  (- - 60h)
- LF z=6.5 Kashikawa

(slope LF: **-1.5** **-2**)

- *Need more data for any useful constraints (more clusters = bigger volume)*
- Compatible with Stark et al 2007 if only ~2 of their candidates real => Need to increase the volume probed



Conclusion

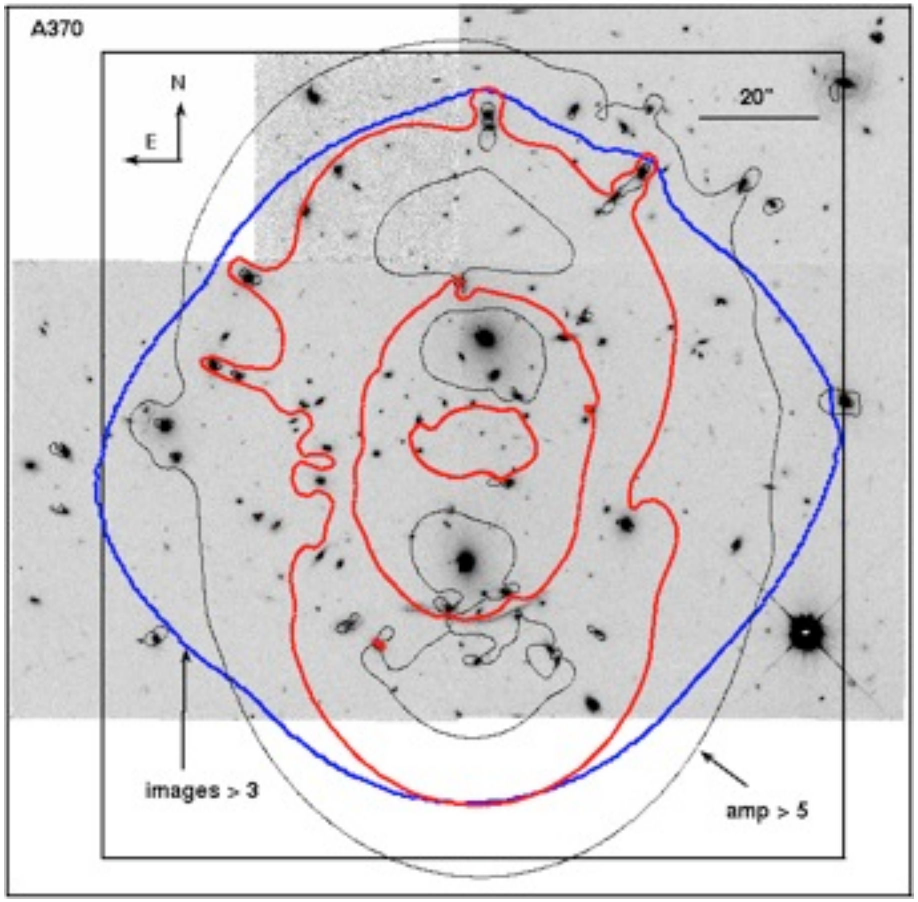
- NB imaging survey most efficient to probe Ly-alpha emitter at z>7 specially using the now common large format NIR cameras (log(L(Ly-a))~42)
- **NB candidates at z~7.7 with CFHT/WIRCAM and VLT/Hawk-I**
- *Lensed z>7 searches provide complementary approach to blank field survey looking at lower luminosity -- can test whether (numerous) low-luminosity sources could contribute significantly to re-ionization* (log(L(Ly-a))~40-41)
- Current volume surveyed are small => very sensitive to cosmic variance
  - *e.g.* Need to increase the number of cluster surveyed (TAC limitation)
- Confirmation of candidates are difficult !!!
  - Dedicate more time and use more efficient instruments/telescopes
- No strongly magnified and bright example of a LAE yet confirmed at z>7
  - Should be found eventually and will make possible detailed analysis

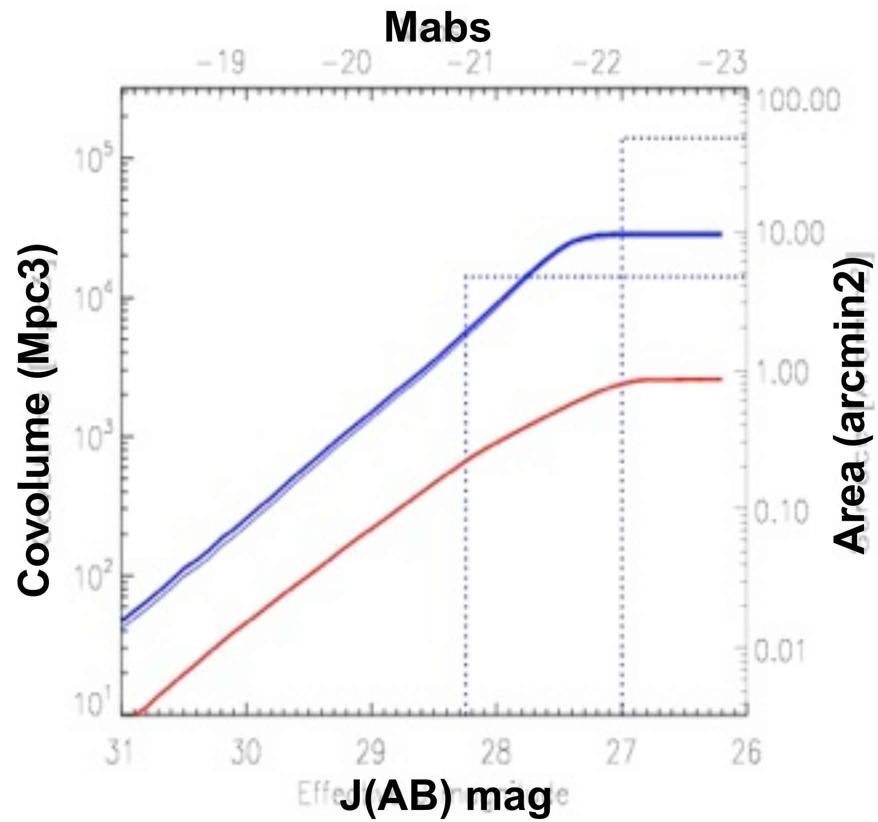
End

Conclusion & Prospects

- Short term projects: (identification of the first galaxies)
  - **LAE:** DAZLE, Hawk-I NB, SINFONI, MOIRCS spectroscopy
  - **LBG:** WFC3, Hawk-I (data acquisition in progress)
- Longer term projects: (physics of the first galaxies)
  - EMIR, MOSFIRE, KMOS
  - JWST/NIRSPEC+MIRI
  - JDEM/EUCLID (rarer objects - lensed z>7 QSOs)
  - ELT/EAGLE (NIR multi-IFU spectrograph)

Future: WFC3 z~7 lensing survey





Red : critical line at z=7

Blue: multiple image region

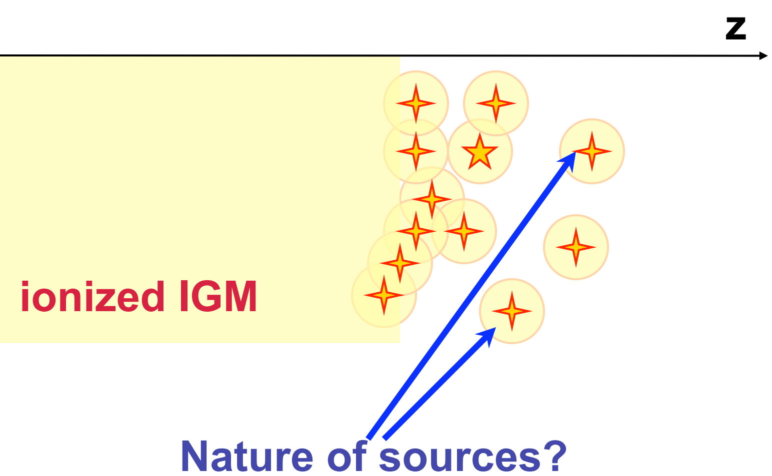
Black: amplification larger than 5

Red : NICMOS lens survey (Richard et al 2008)

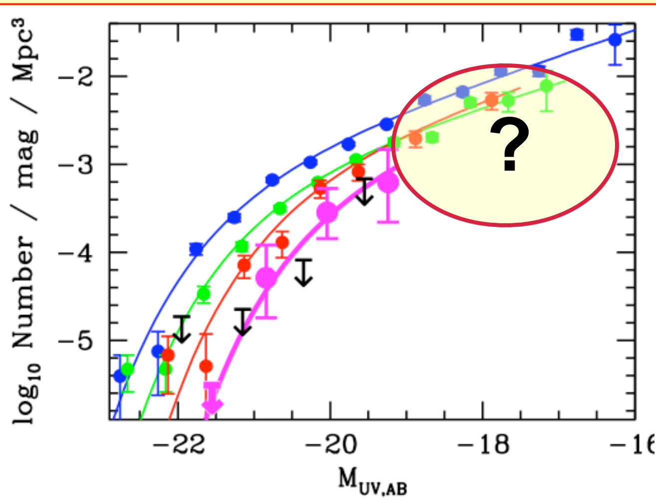
Blue: WFC3 cluster survey (10 Clusters)

Dotted blue: WFC3 field survey

How to find the Sources of Re-ionization?



L* galaxy at z~6 have AB~26 with density of 1 per sq.armin

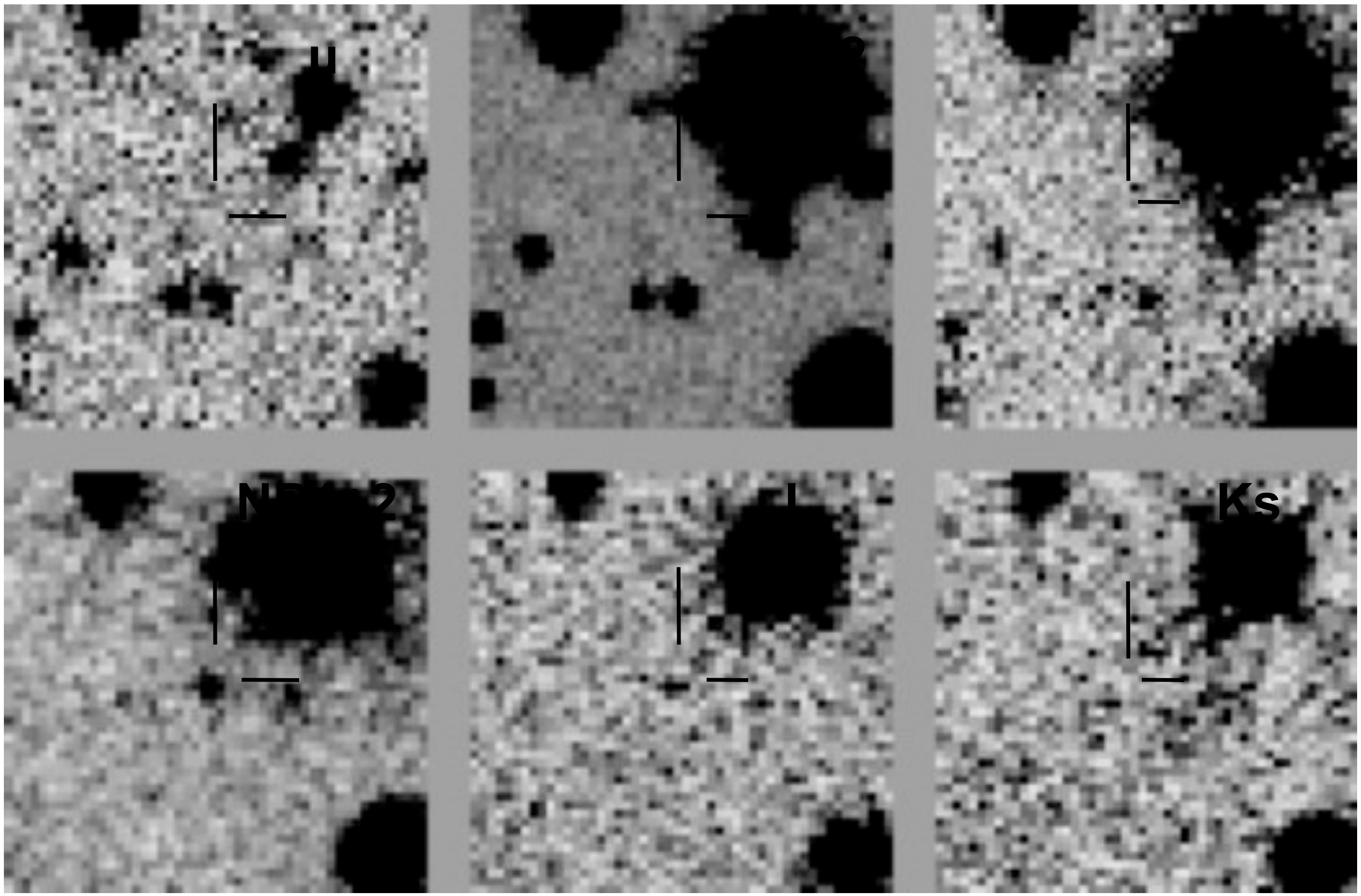


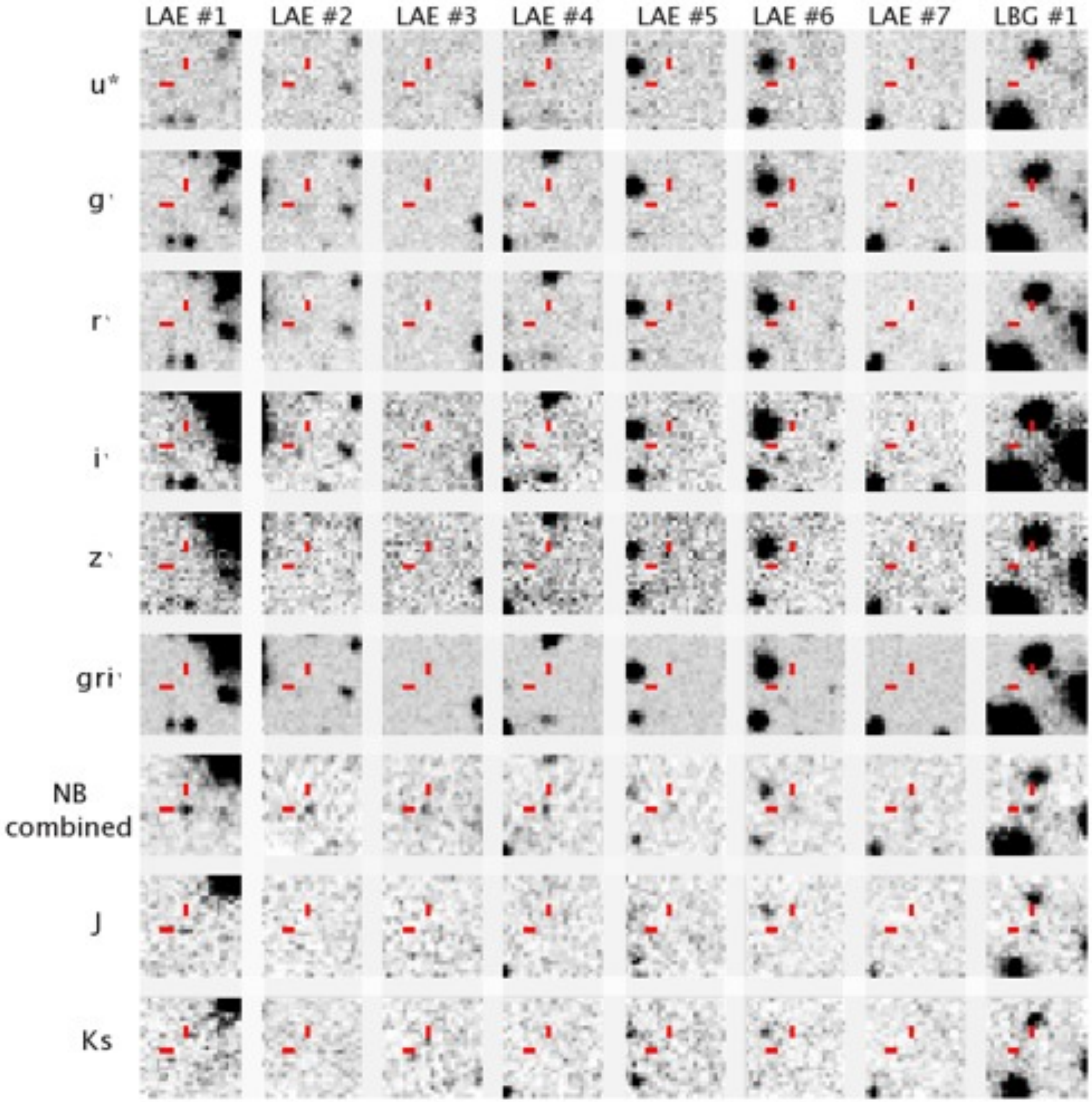
Bouwens et al (2008)

- **What sources ended Dark Ages?**
  - Sources with intense UV flux
  - First stars are thought to be: *Very massive/ Low metallicity/UV luminous*
- **Mass of first DM halos?**
  - At z~10: halo mass of 10^{10} to 10^{11} solar mass
  - First objects could form at z~50 with at most 10^6 solar mass (Reed et al 2006)
- **Current exploration in UV restframe:**
  - Rapid decline in UV luminosity density 3<z<6 ? (Bouwens, Bremer's work)
  - Possible steepening of LBG LF faint end slope with increasing z?
  - Evolution of the LAE LF at high-z ?

⇒ **Importance to probe the full luminosity function of z>7 galaxies**

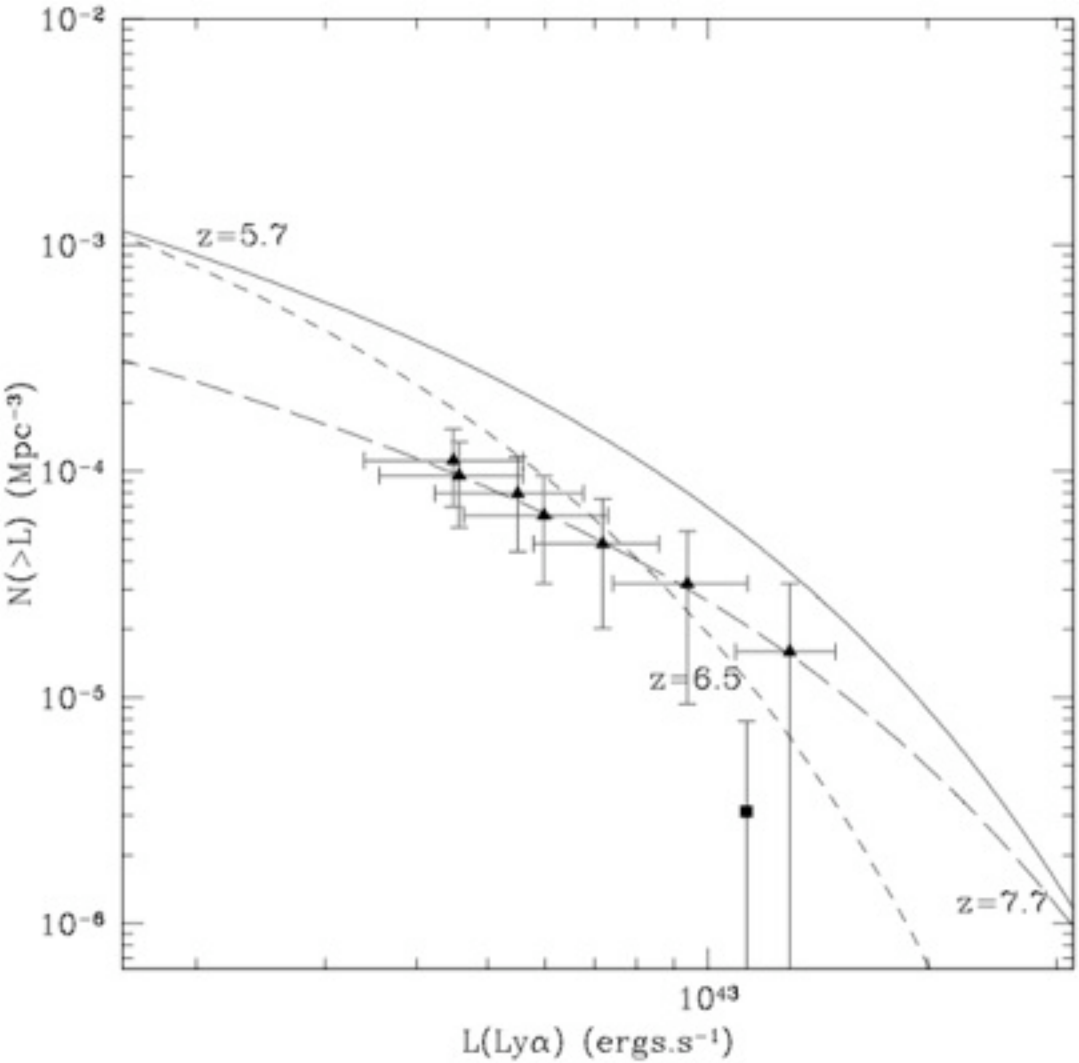
A WIRCam candidate





- 7 LAE at z = 7.7 candidates
- 1 LBG at z > 7 candidate

LF of z = 7.7 Lyα LAE



- Assumes that the 7 candidates are real
- Most serious candidates build up the bright end of the z=7.7 LF

-> bright end robust

Hibon et al. submitted

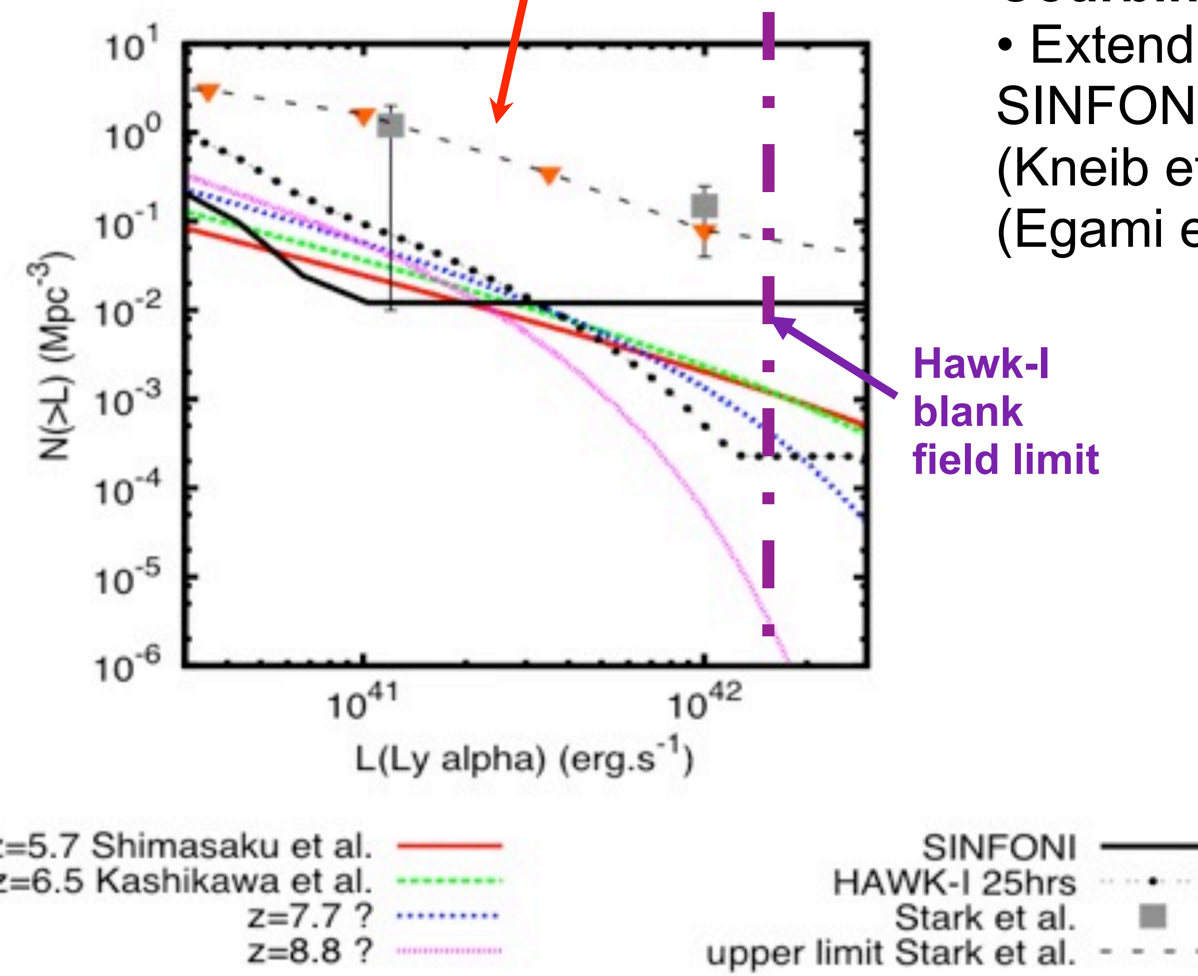
Possible sources of contamination

- Electronic crosstalk
  - Guide windows
- Persistence
- Noise

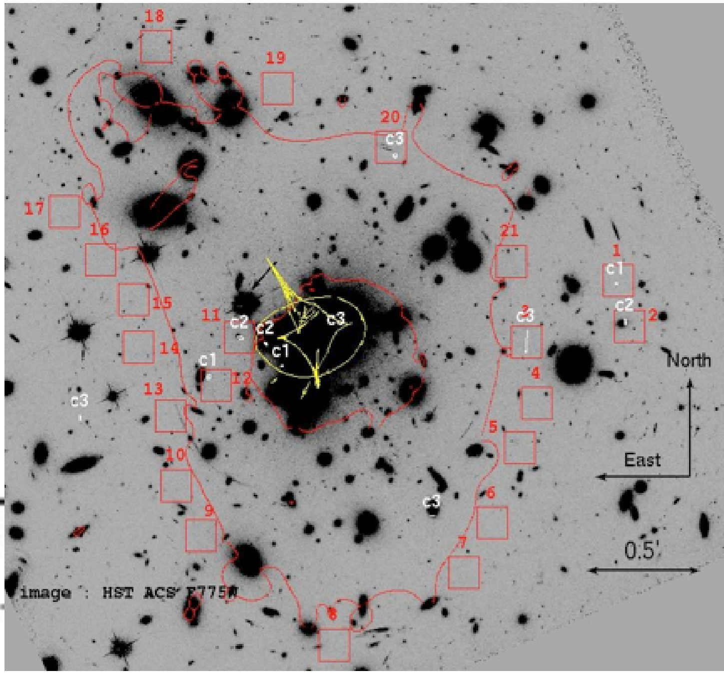
- Transients
  - 2 epoch data
- T-dwarfs

- EROs
  - K band rejection
- Low z interlopers
  - Ha at z = 0.61
  - [OIII] at z = 1.1
  - [OII] at z = 1.8
- High z (> 7) LBGs

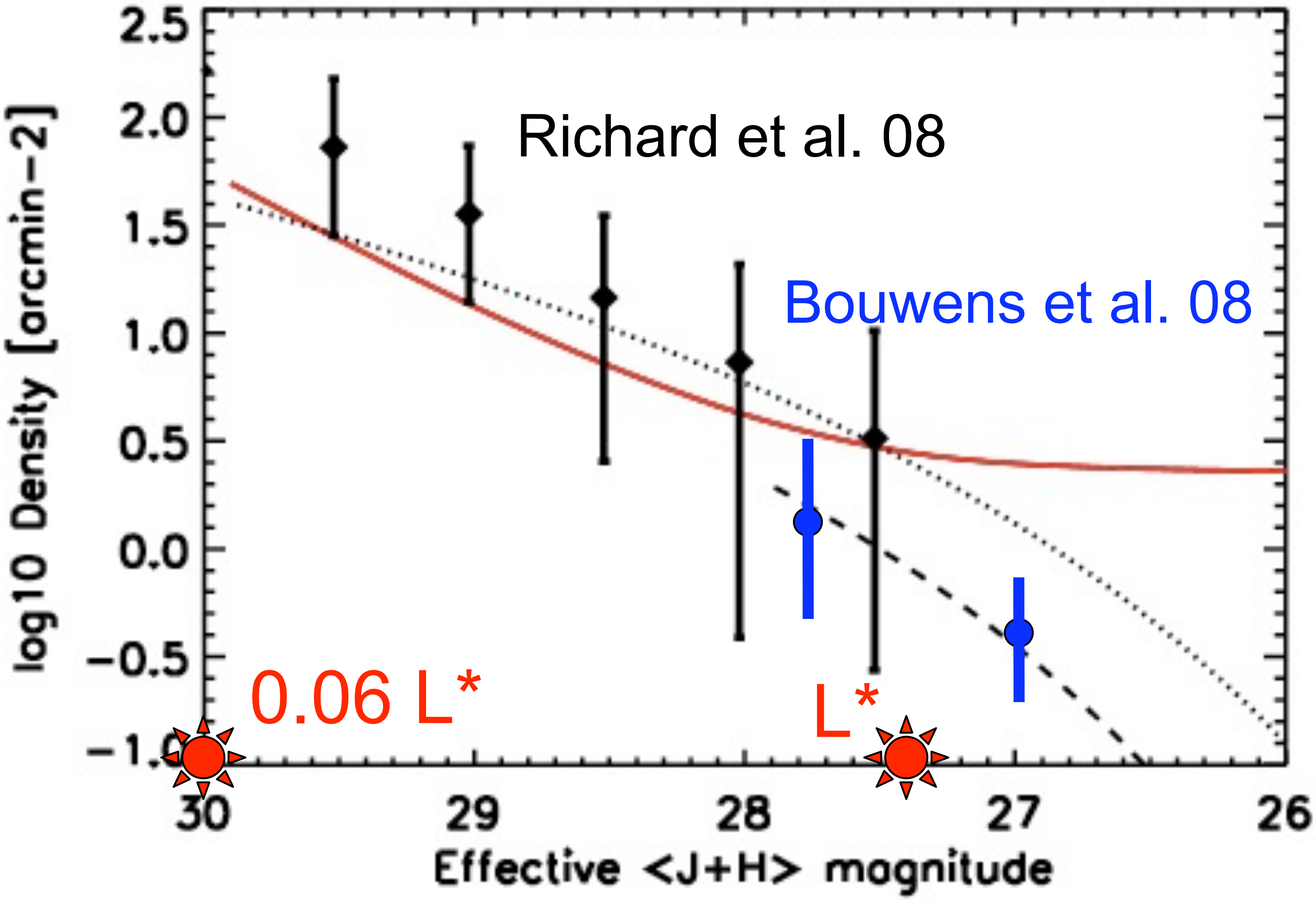
Future: LAE lensing survey



- Extend ZEN using Hawk-I (see **Courbin's Talk**); DAZLE
- Extend critical line mapping with SINFONI integral field spectrograph (Kneib et al) & Subaru MOIRCS (Egami et al)



Derived Luminosity Function z~7.5

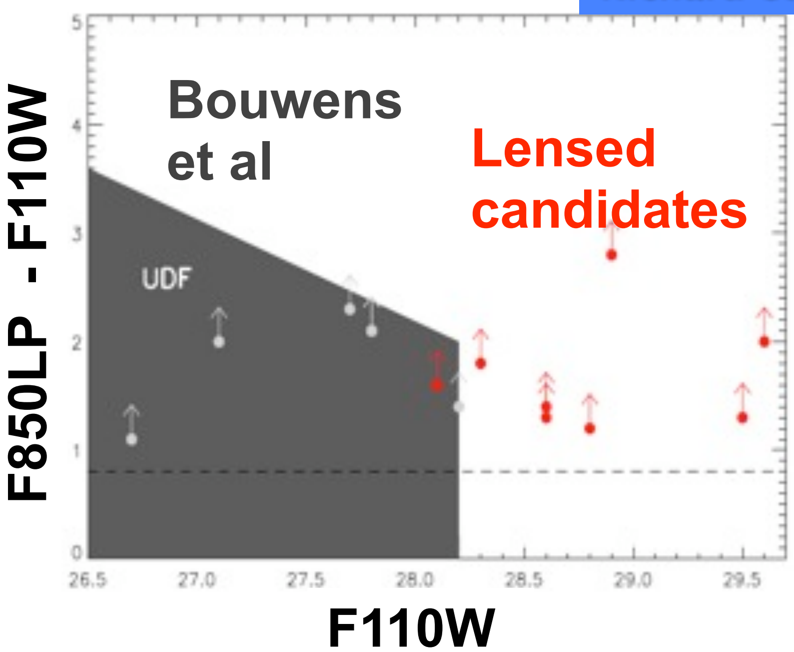


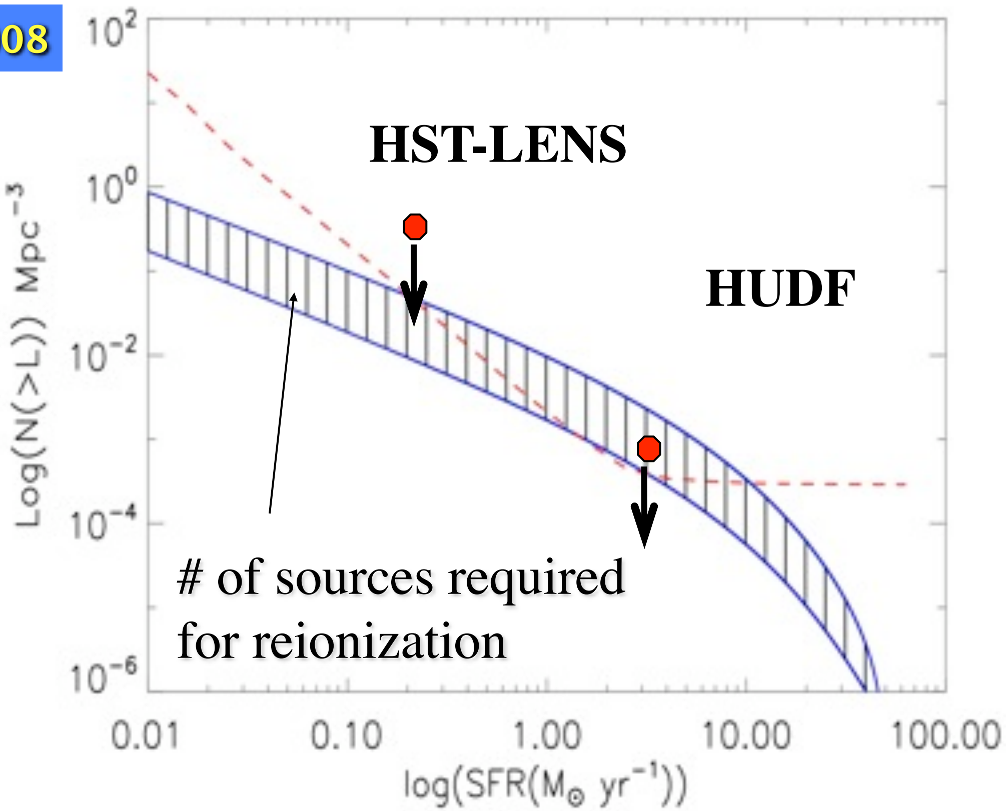
- No significant overlap between UDF and lensed survey - although in good agreement !
- Probing already 50% of the luminosity density !

Impact on re-ionization

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

Richard et al 2008





- **High surface density of z/J-drops (contamination to be checked)**
- **suggests *significant contribution to reionization from low luminosity galaxies***
- **lensing survey valuably extends constraints set by UDF**

Clusters as a Cosmic Telescope

Recipe to unfold lensing magnification:

1. *Properly compute lens model and errors*
2. Determine catalogue of lensed (z>7) sources, similarly as in blank field (including detection errors)
3. Unlens catalogue
4. Unlens surveyed area (remove area blocked by cluster galaxies) => allowing to compute surveyed volume for a given detection limit
5. Compute number density of galaxies detected as a function of their un-lensed flux and corresponding surveyed volume.
6. Fold-in completeness issues & spurious detections

Lensed dropout galaxies

- First detection of a z~6.8 dropout galaxies in Abell 2218
- Redshift confirmed by multiple image detection
- Source identified in Spitzer data, showing an already "old" population of stars, arguing for a formation redshift of z~10

UV continuum SFR ≈ 3 $M_\odot$ yr^{-1}

Stellar Mass: ~10^9 $M_\odot$

Size: 1.2kpc x 0.5 kpc

Number density: ~1 / arcmin2

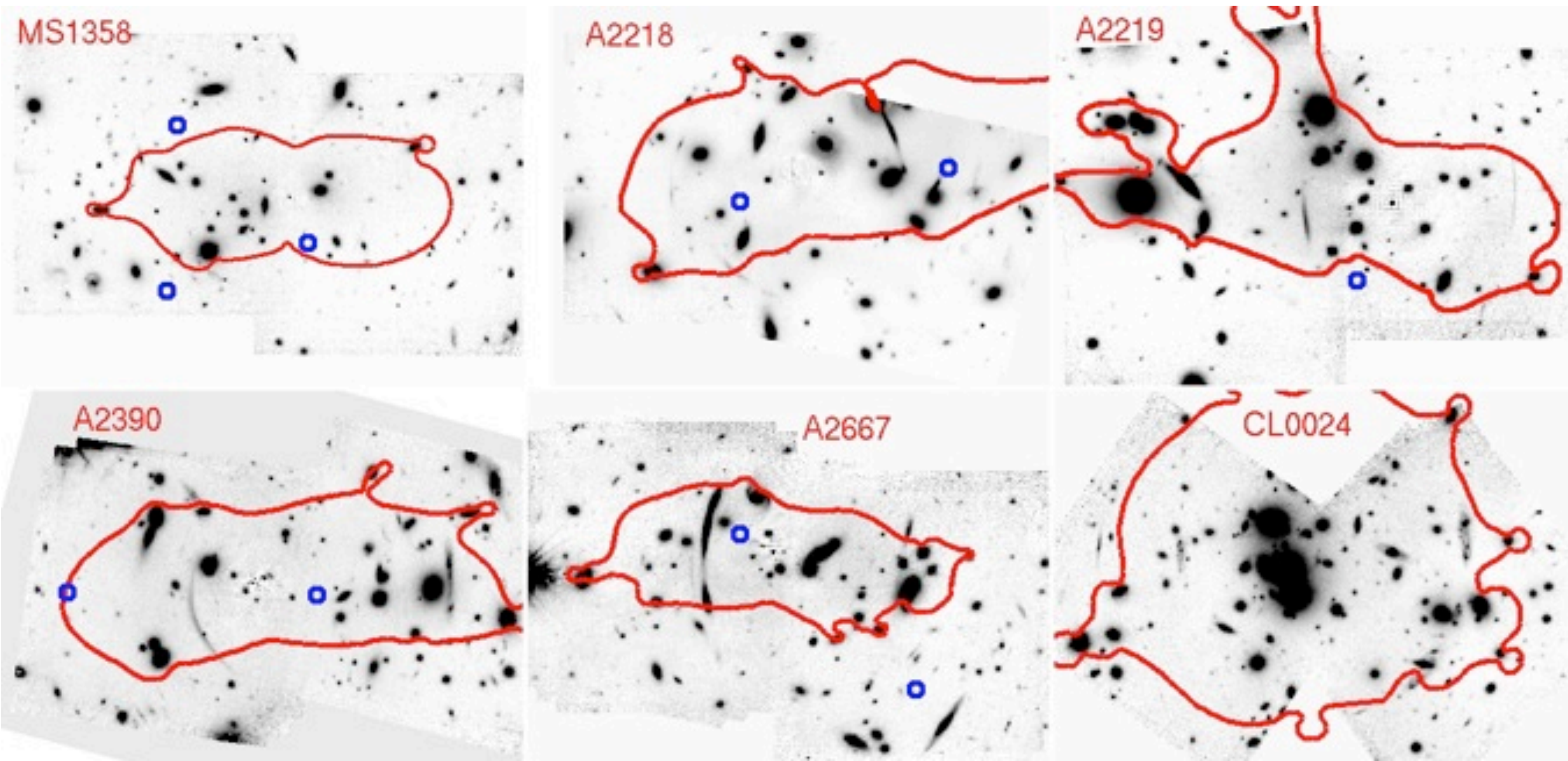
Kneib et al 2004, Egami et al 2005

z>7 lensed dropout with Hubble

• Systematic extension: Study of 6 well-constrained clusters with optical (ACS/F850LP), near-infrared (HST/NICMOS+Ground-based) and mid-infrared (Spitzer/IRAC)

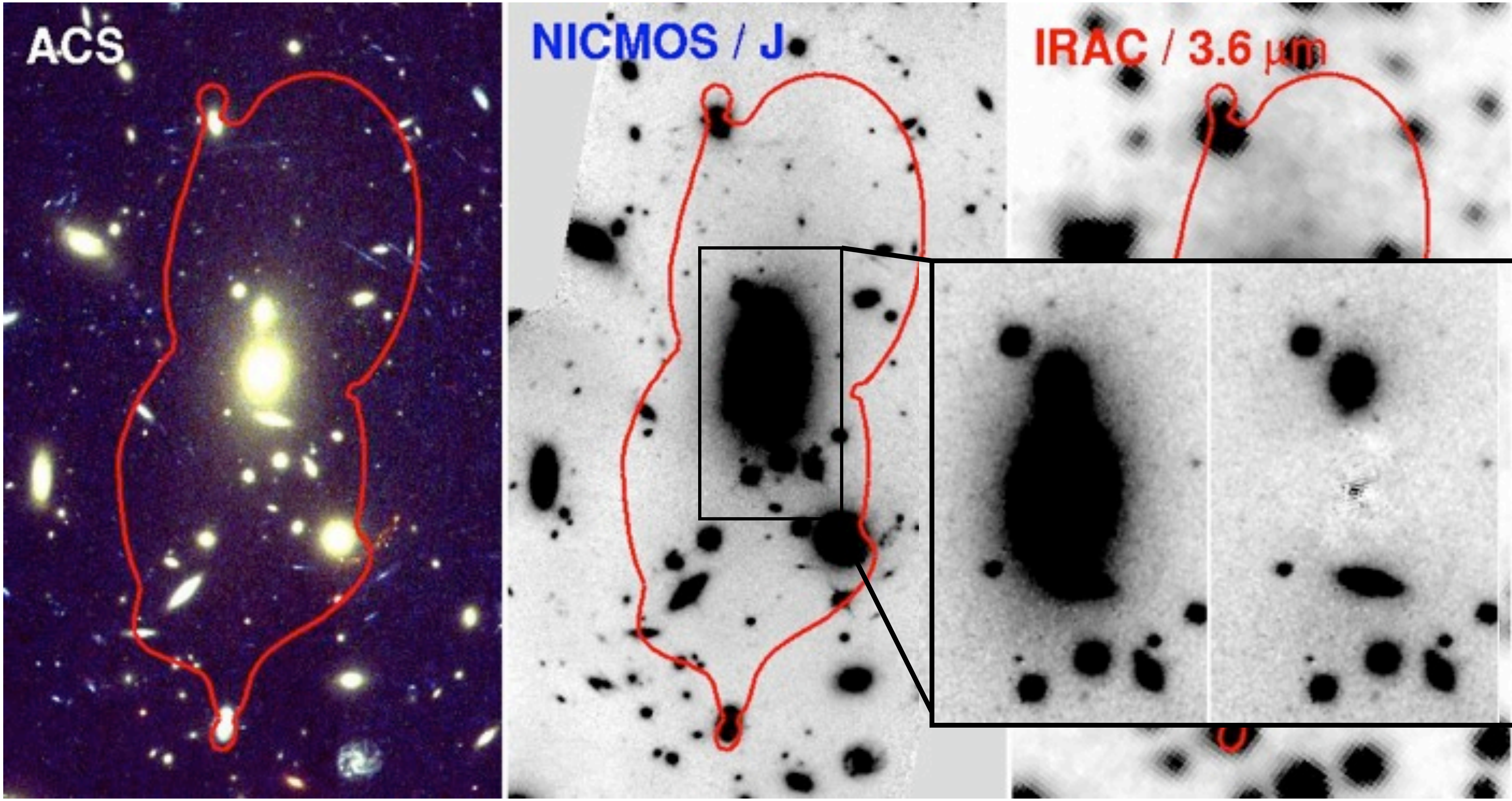
• Identification of "dropout" candidates

Richard et al 2008



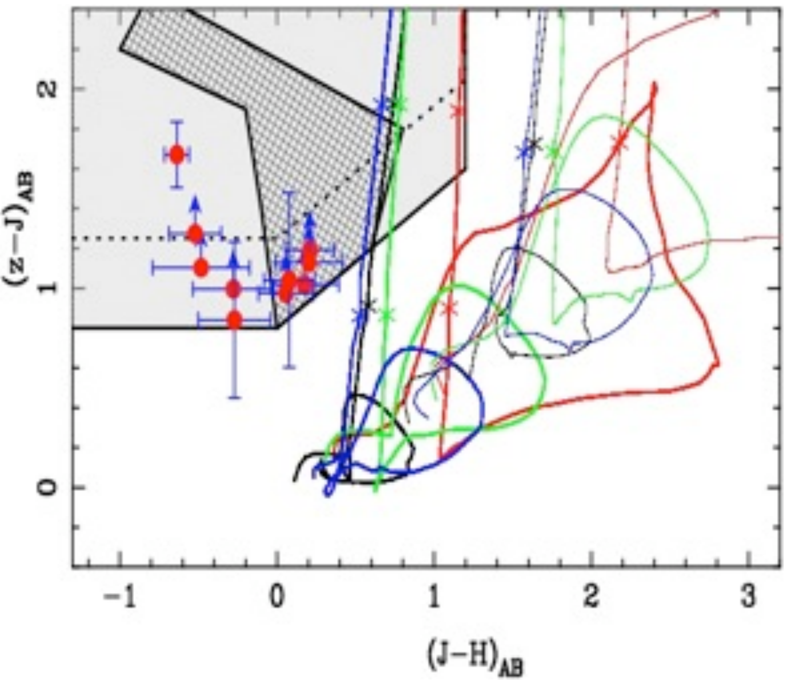
Combining ACS, NICMOS & Spitzer

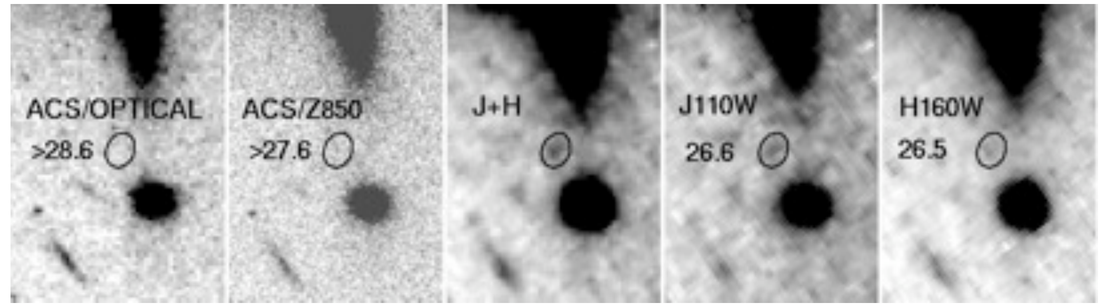
MS1358: 5σ limit: $J_{AB}=26.7$, $H_{AB}=26.7$



Importance of foreground removal

z>7 lensed dropout with Hubble





Z~7-8

- 10 candidate z-drops with H ~ 26 - 26.8
- Implied SFR ~ 0.1 - 2 $M_\odot$ yr^{-1} (unlensed)
- spectroscopic follow-up with NIRSPEC
- z~2 luminous red galaxies expected to be main contaminants

Richard et al 2008

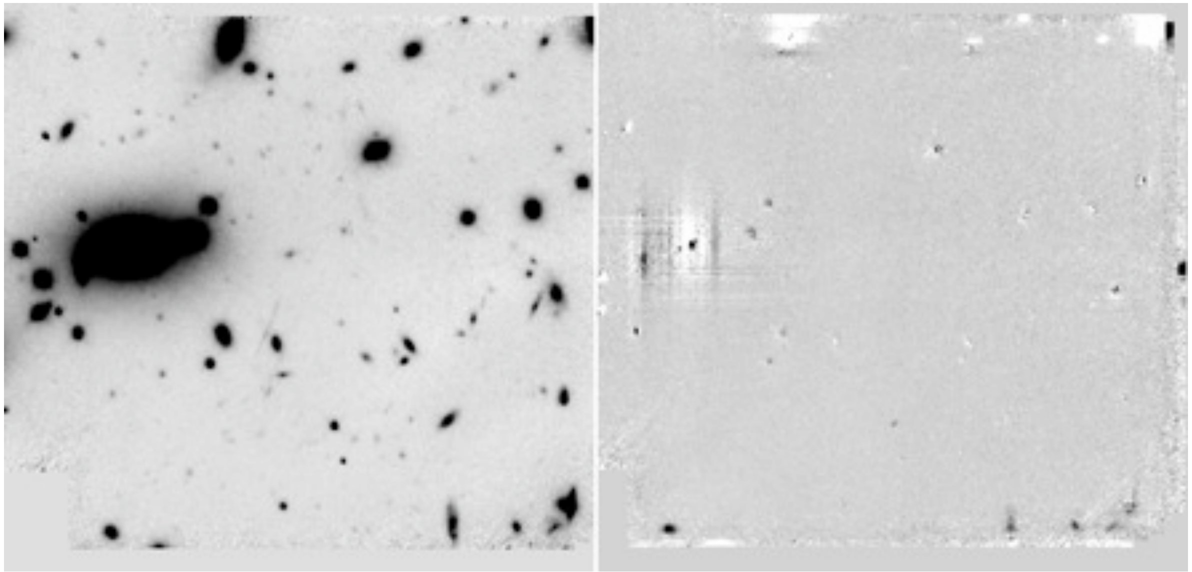
2 candidates J-drops (J-H>1.8) with H_{AB}~25.6

SFR ~ 0.1 - 1 $M_\odot$ yr^{-1} (unlensed)

Z~10

Reliability and redshift estimation (1)

• False positive detections : tests on "noise image"



• **Estimation:** in the magnitude range of the dropouts, we expect ~ 10 % spurious detections (i.e. 1 out of the 10 dropouts)

Reliability and redshift estimation (2)

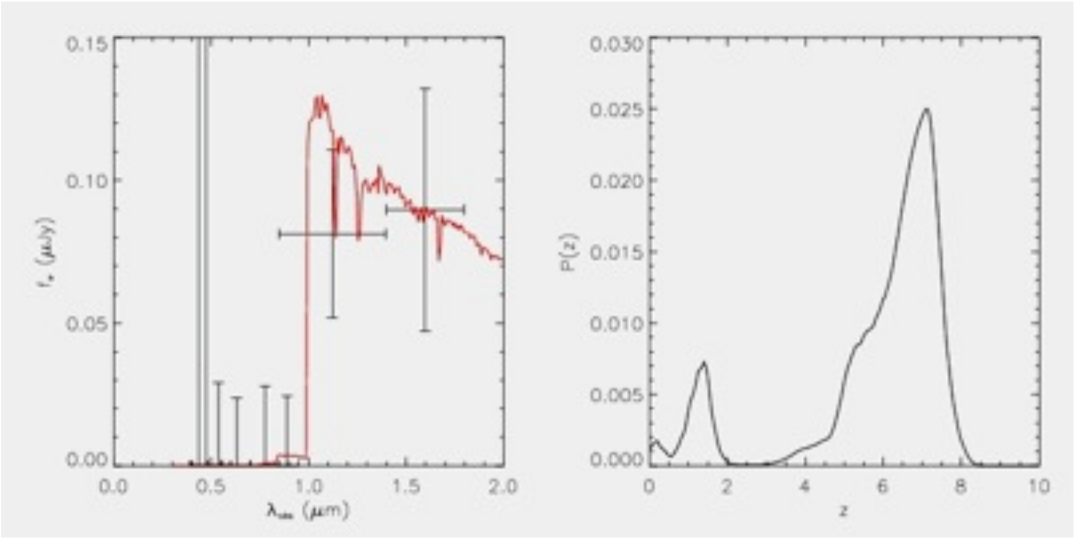
• detector remanence :
measurements from the archive: no effect

• Low-mass stars : L and T dwarfs are expected to contaminate the survey. Predictions: 1 star in entire survey.

• Photometric redshifts

Contamination by lower z galaxies: estimation of 25 % from P(z)

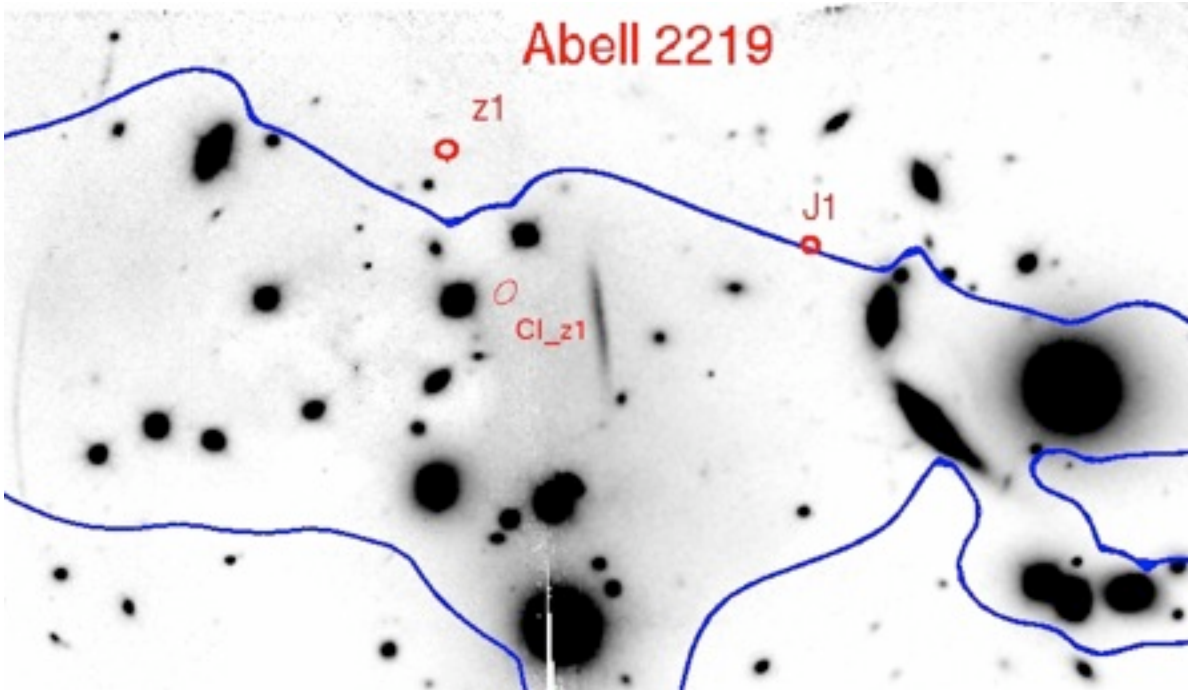
⇒ 5 out of 10 dropouts truly at high z

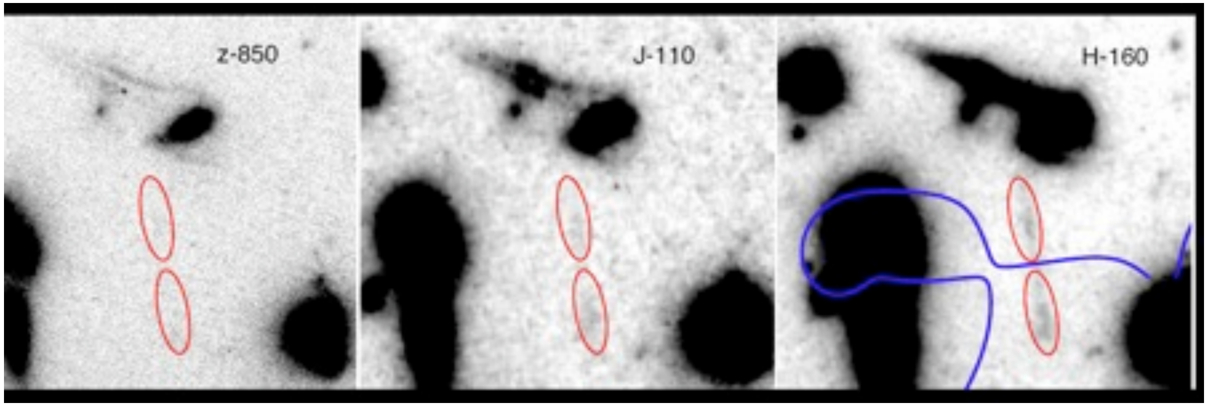


Search for multiple images

- Counter-images predictions from lensing model

2 candidates with possibly "merging" images

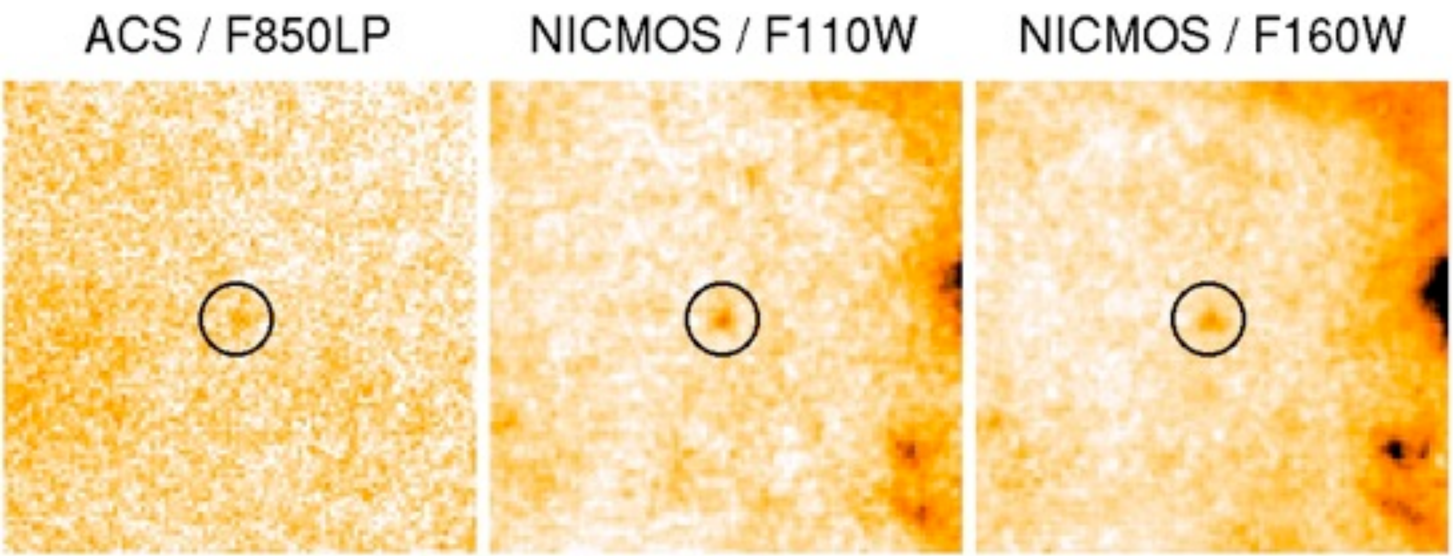


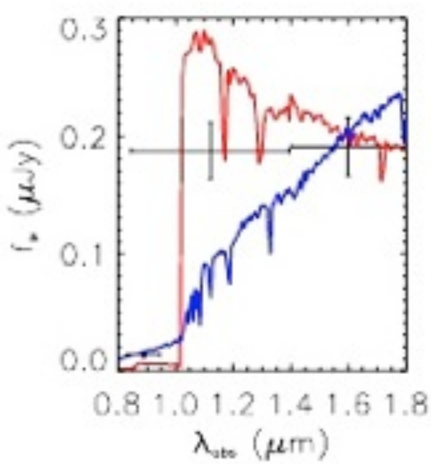


Proof of Method:

we do see z~2 multiple sources…

Properties of stacked SED for the z-dropouts





Average photometry

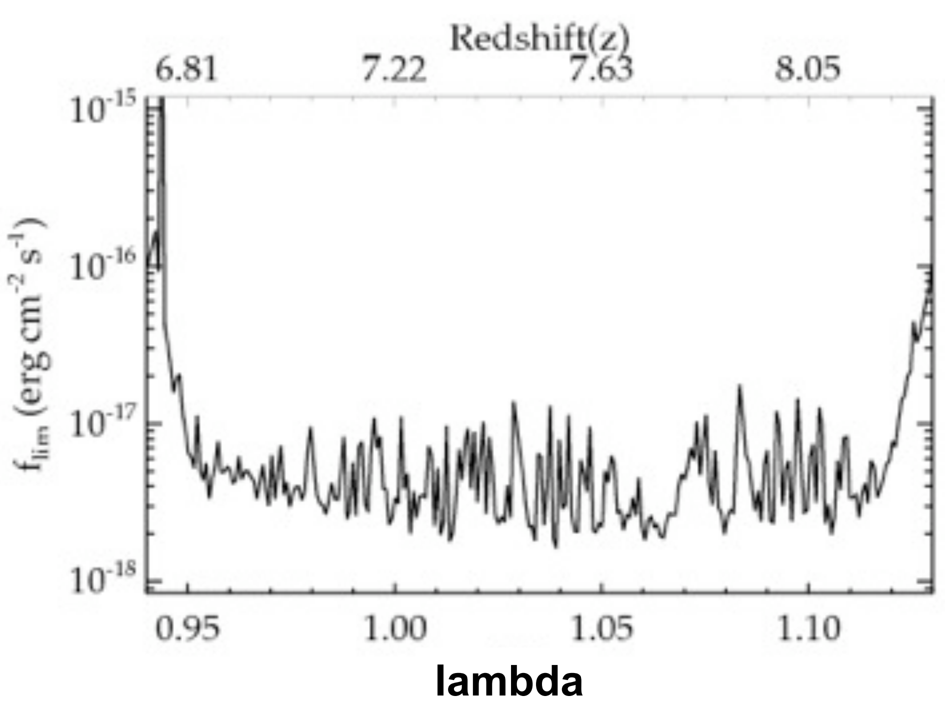
z=28.59±0.21 J=25.72±0.14 H=25.70±0.14

UV spectral slope best fit: $\lambda=\lambda^{-\beta}$

$\beta \sim 2.7\text{-}2.8$

Keck/NIRSPEC spectroscopic follow-up

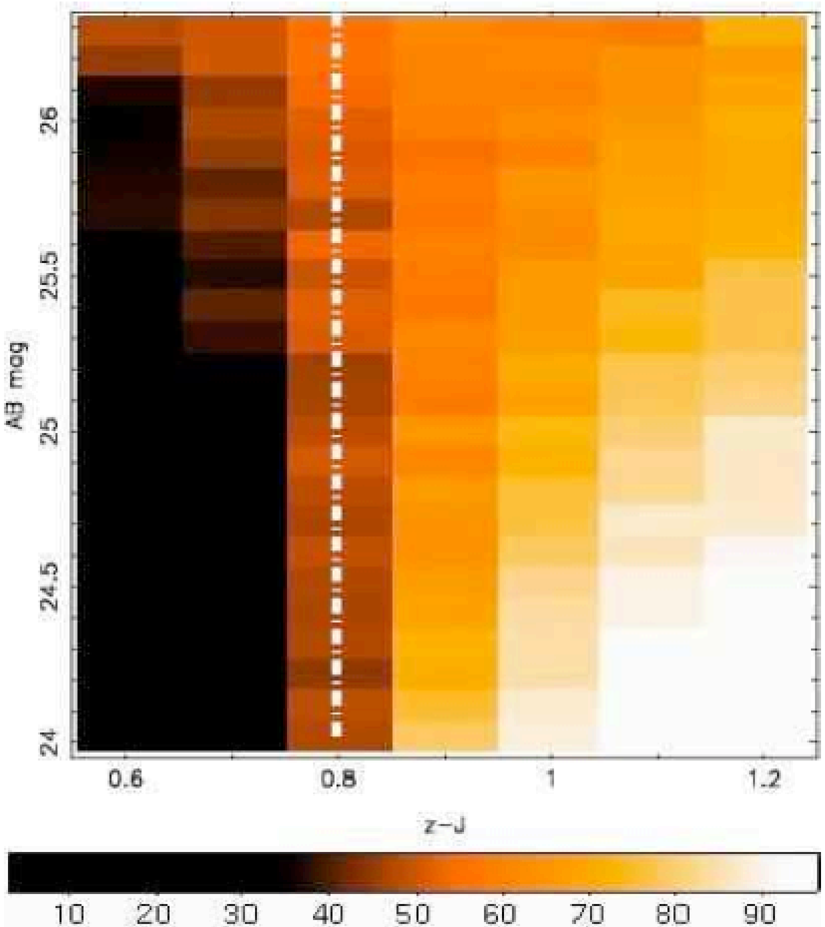
Optimization to follow-up both a candidate and its predicted counter-image

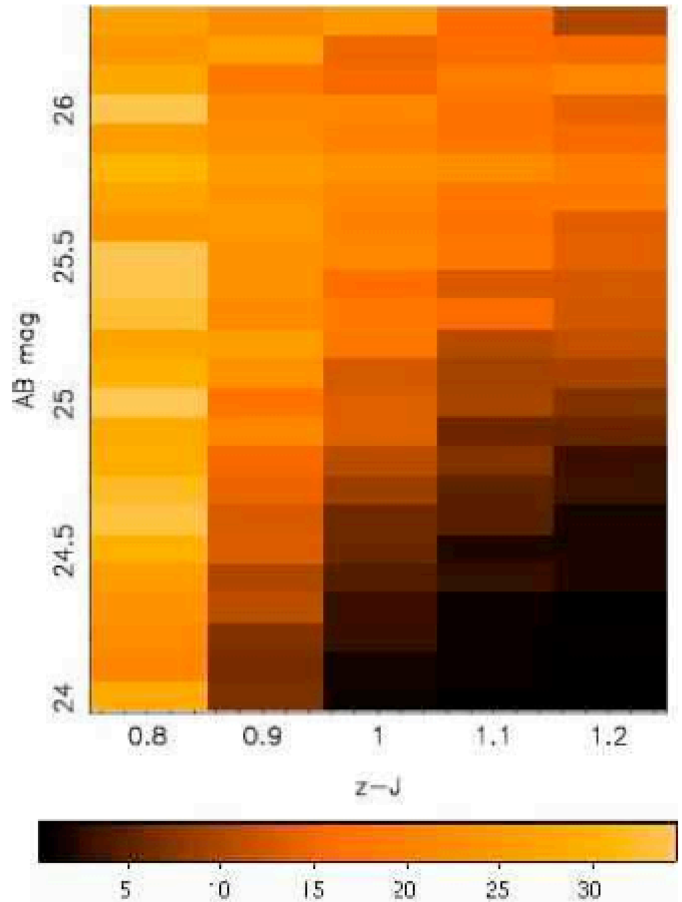


- NIRSPEC slit : 0.76 x 42 arcsecs
- Follow-up in the Z band ($6.8<z<8.3$ for Lyman-alpha)
- 3 to 4 hours on 7 candidates

Sensitivity to lyman a flux: should detect an emission line at 5 sigma down to an escape fraction between 20 and 40%.

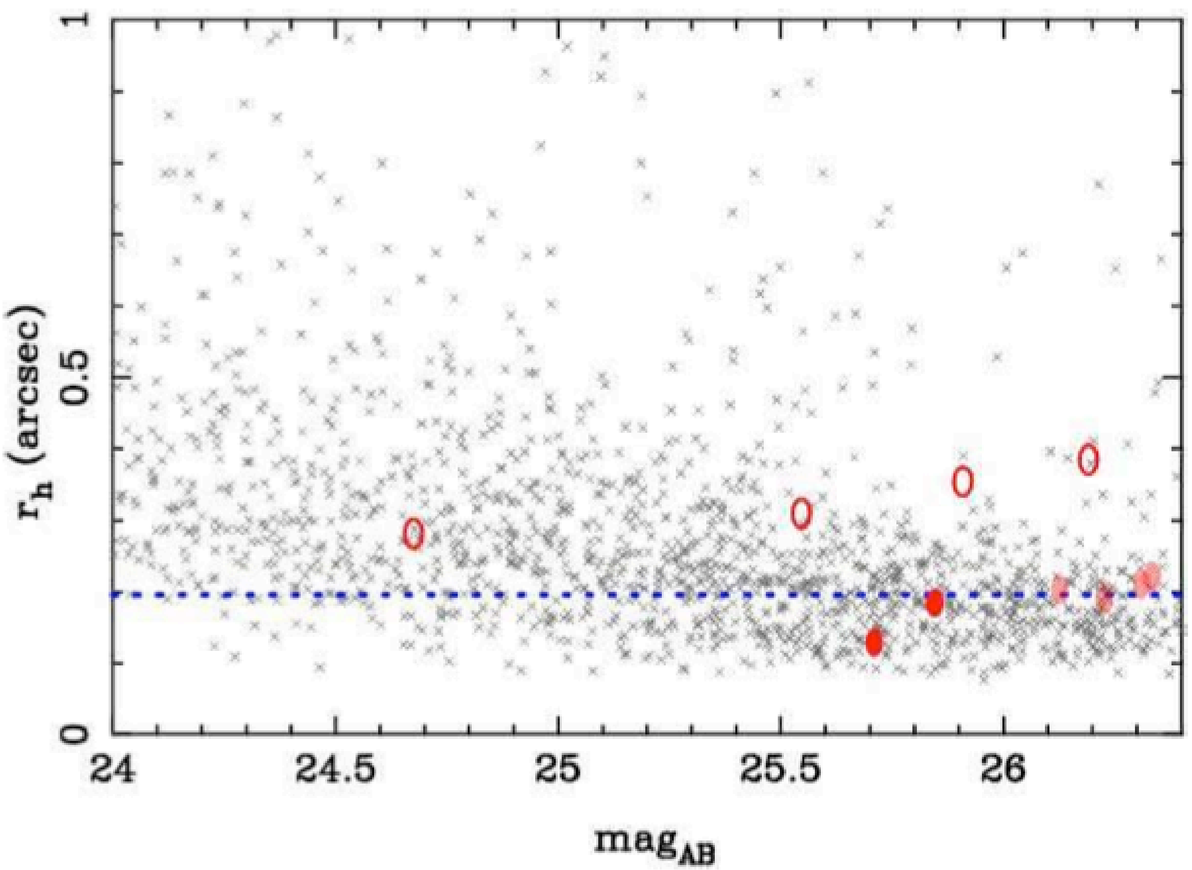
Completeness and contamination





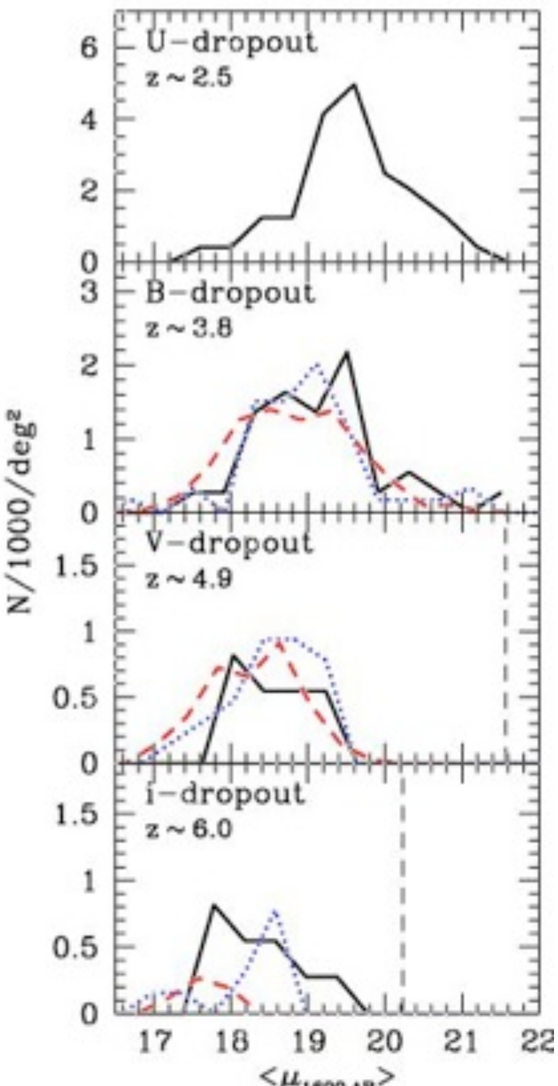
Completeness and contamination as a function of z-J color criteria

Size of candidates



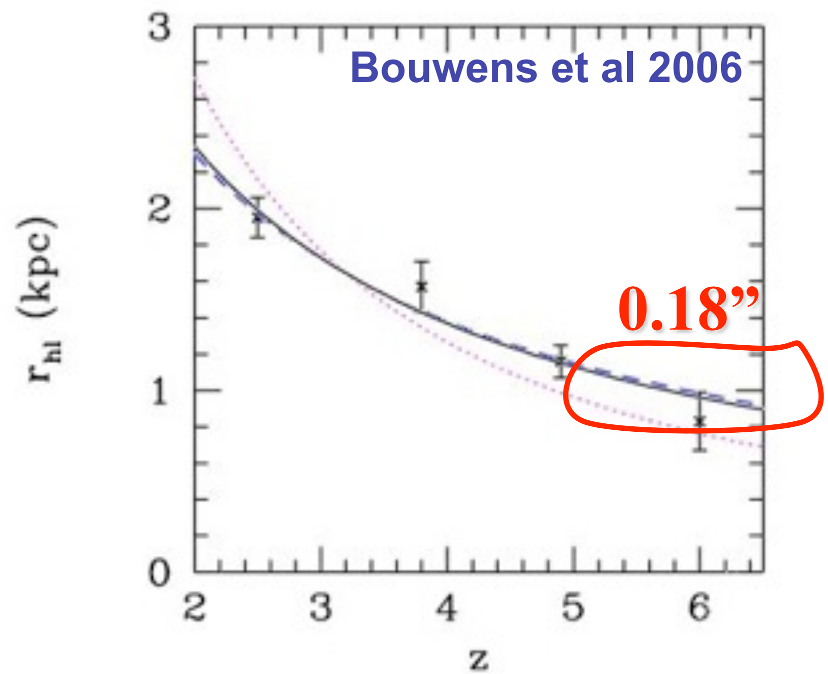
- 4 resolved
- 2 unresolved
- 4 at the limit

Galaxy Evolution: size and surface brightness



More distant galaxies are smaller in size, but with similar surface brightness.

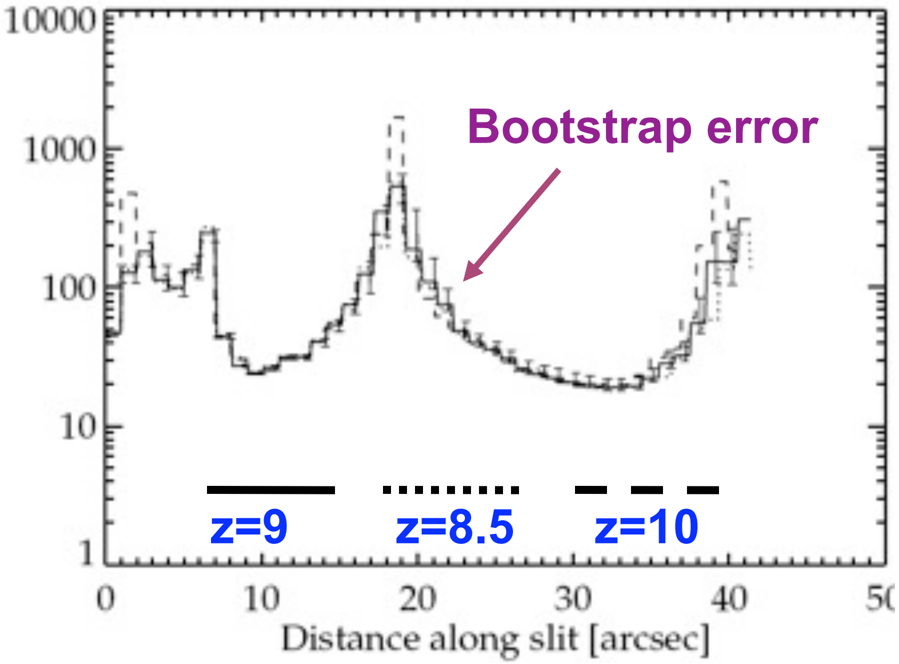
=> Importance of high resolution imaging



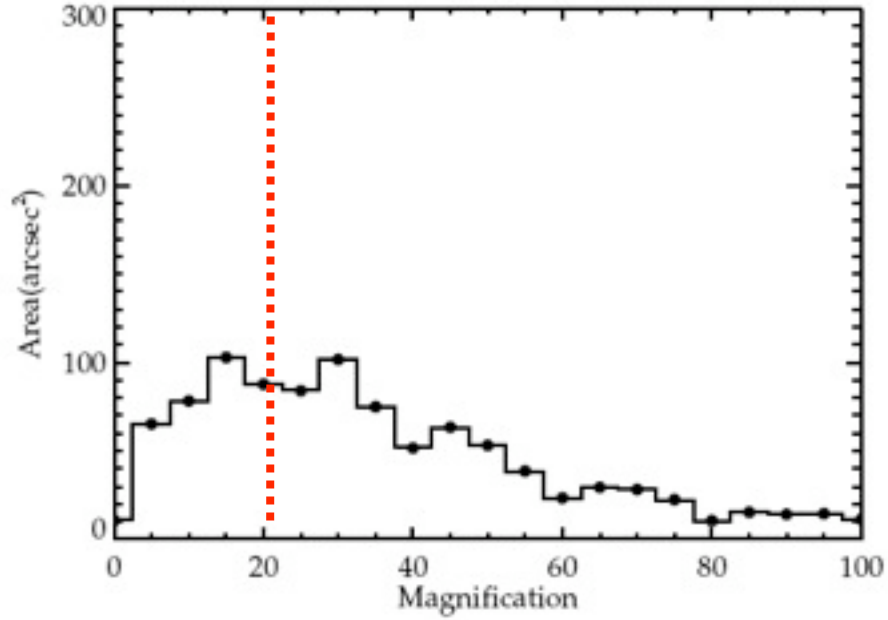
At higher redshift z>7
=> typical size down to 0.10”

Correcting from magnification

Magnification along slit



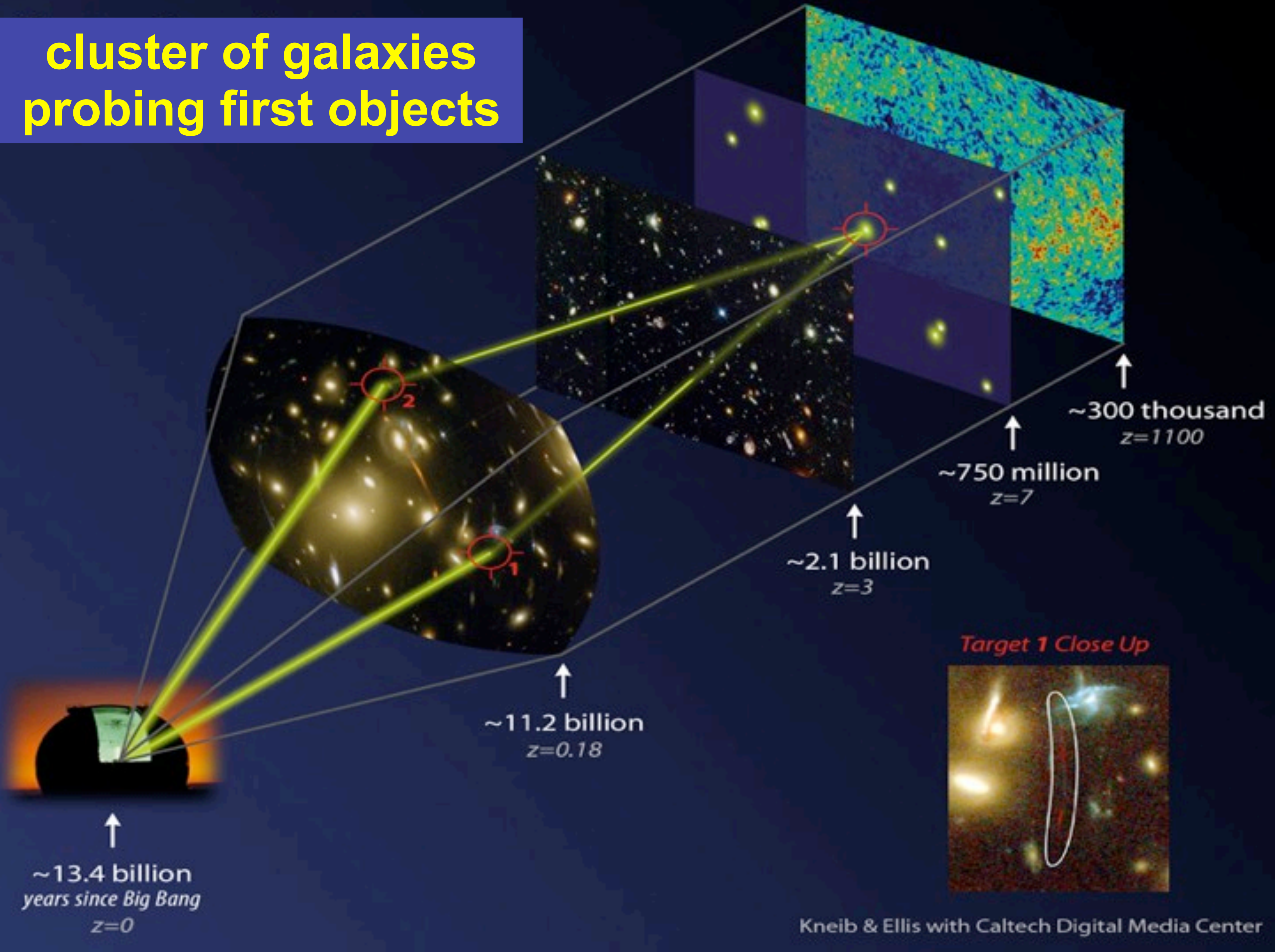
Sky area versus magnification



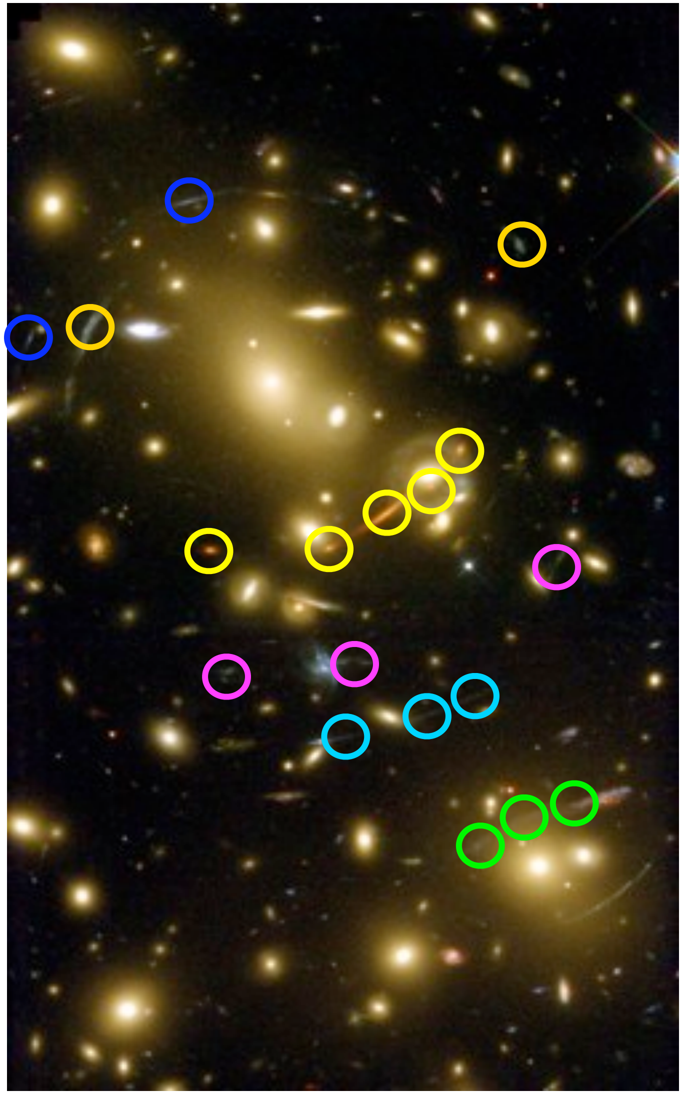
$$\mathcal{M}(\Omega, z) = \frac{1}{[1-\kappa(\Omega,z)]^2 - \gamma(\Omega,z)^2}$$

- 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%

cluster of galaxies probing first objects



Lens Modeling and Errors



Constraints:

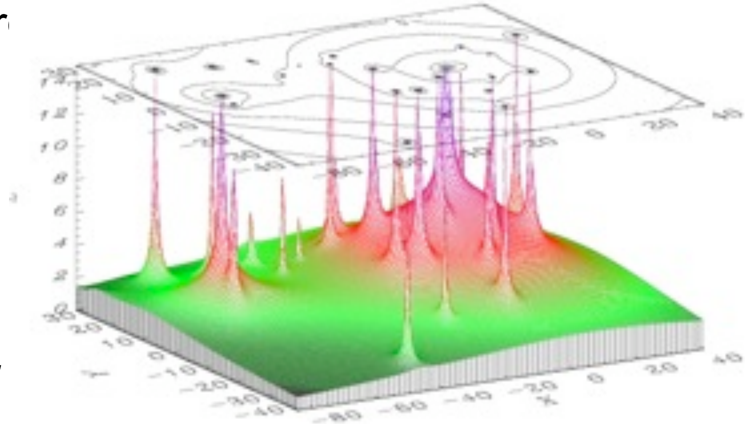
- Multiple images (position, redshift, flux)
- Single images with known redshift
- Light distribution

Model parameterization

- Need to include **small scales**: galaxy halos (parametric form scaled with light)
- Large scale: DM/X-ray gas (parametric form or multi-scale grid)

Model optimization

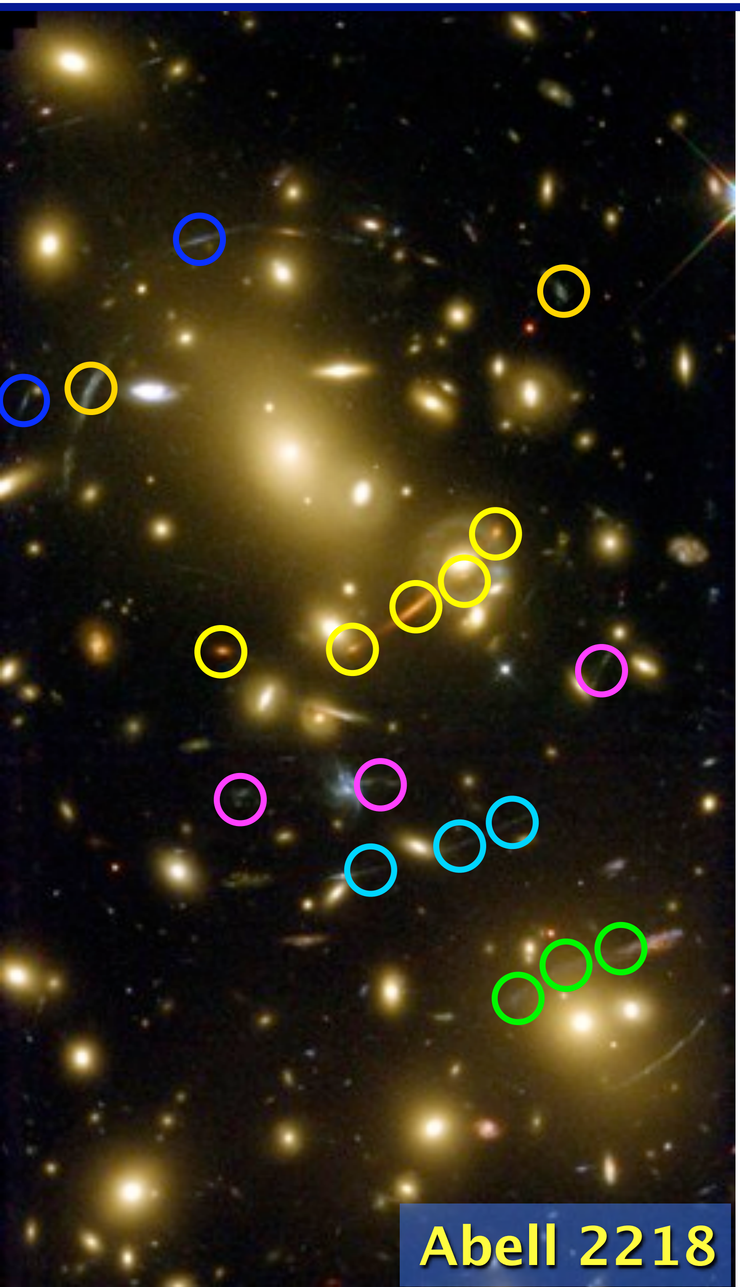
- Bayesian approach
- Not a unique solution, most likely model and errors
- Pr



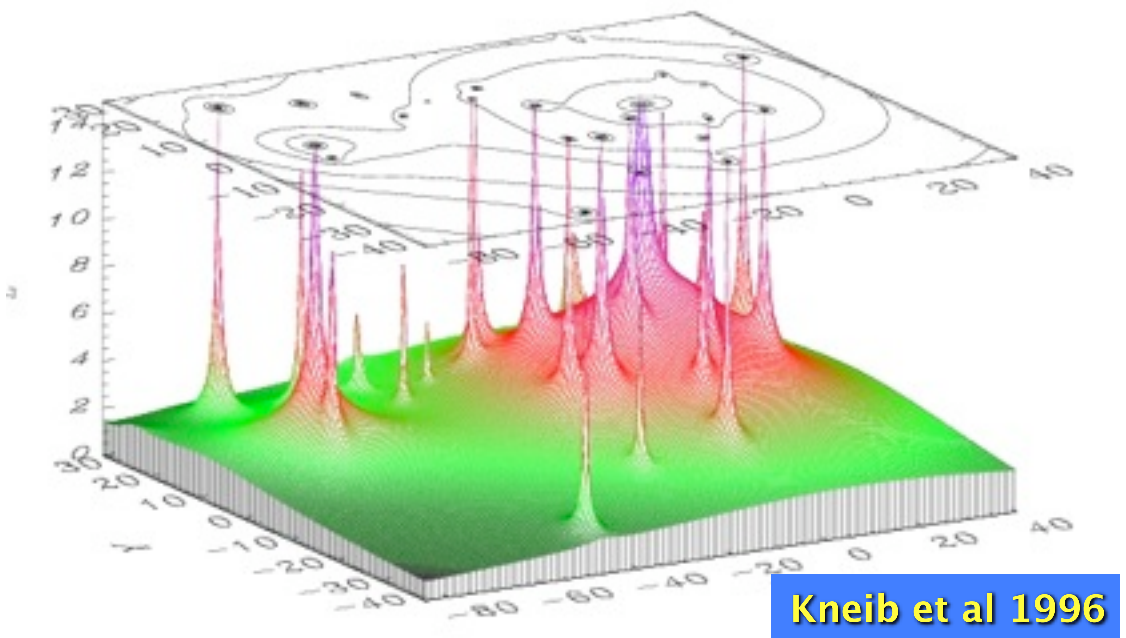
Jullo et al 2007, Jullo & Kneib 2008

***LENSTOOL* public software http://www.oamp.fr/cosmology/lenstool**

Cluster-lens modeling [LensTool]



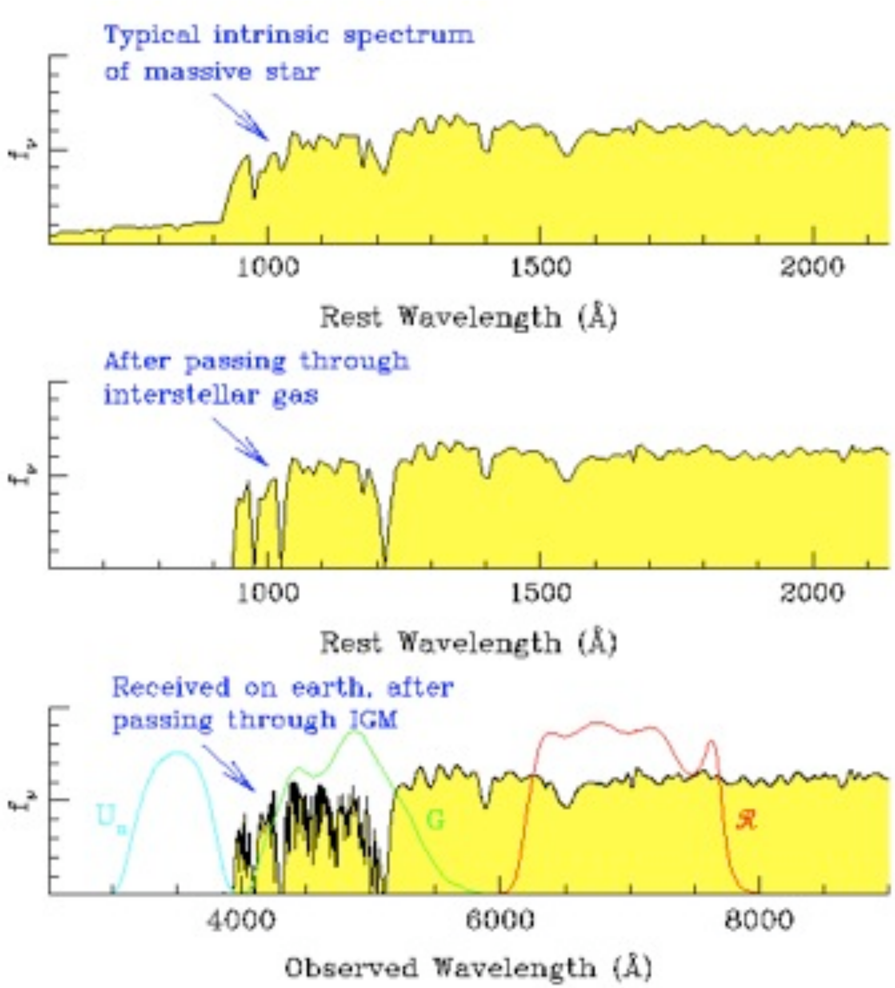
- Identification of multiple images, spectroscopy to measure their redshift.
- Constrain both the cluster mass as well as cluster galaxies and their halos that account for ~10% of the total mass
- Now using MCMC technique to better probe the many parameters space (Jullo et al 2007)
- **Produce mass map, and amplification map**

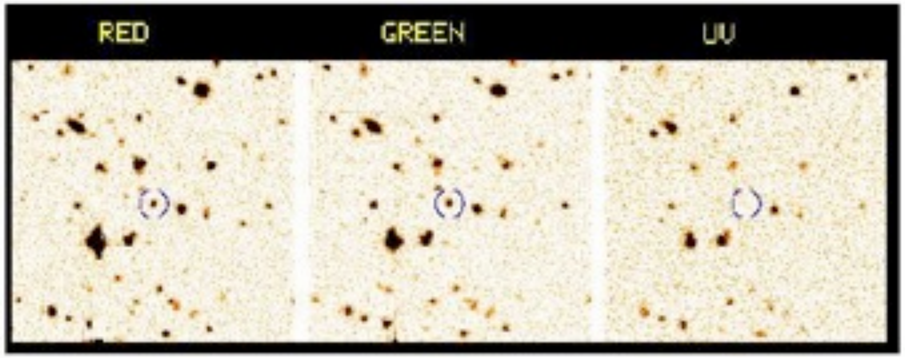


Summary

- Evidence for early star formation beyond $z \sim 7$ 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 faint dropouts at $z \sim 7$-10, with SFR $< \sim 1\ M_{\odot}\ yr^{-1}$
- Spectroscopic follow-up under way to confirm hypothesis that at least some dropouts are at very high z; thus low luminosity sources may contribute significantly to cosmic reionization
- These programs, and upcoming dedicated instruments such as WFC3 will give a first glimpse of the Universe at $z > 7$, and more effectively plan ambitious programs with EMIR/GTC, JWST and ELTs

Tail of the Redshift Distribution





The Lyman continuum discontinuity is particularly powerful for isolating star-forming high redshift galaxies.

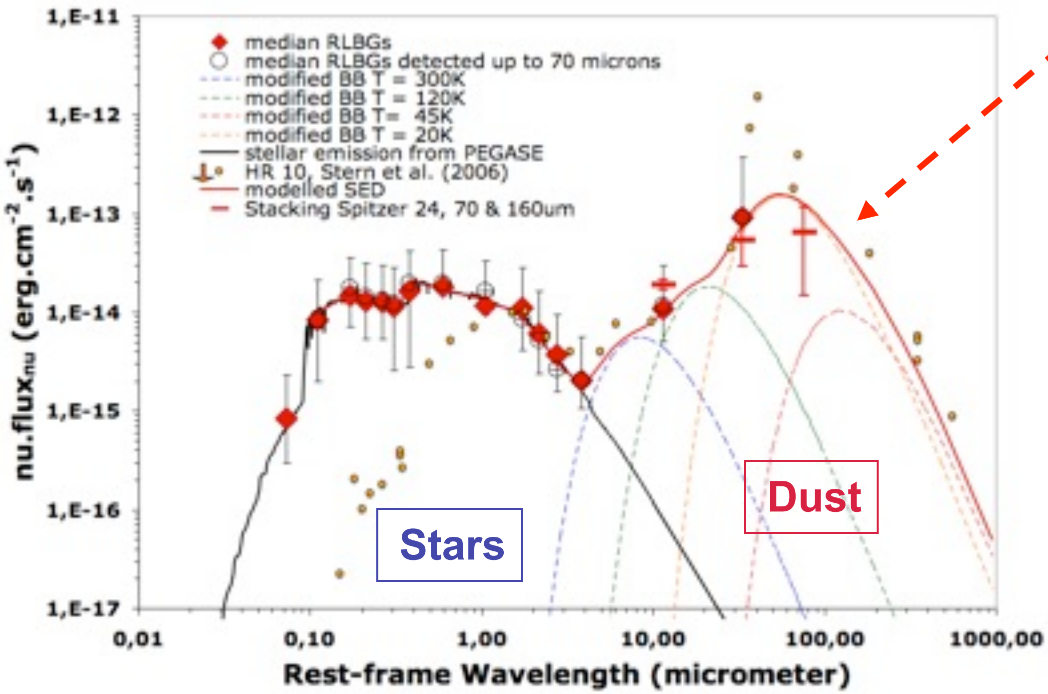
From the ground, we have access to the redshift range z=2.5-6.5 in the optical band.

To go beyond z>6.5 requires infrared observations.

Steidel et al 1999

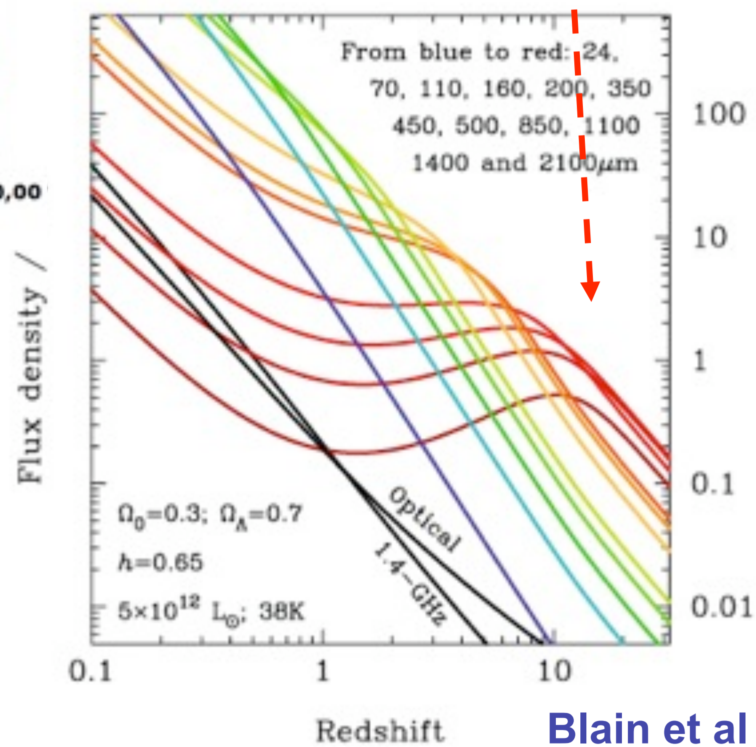
Steidel et al 2003

Dusty galaxies ?



Spectral Energy distribution of red « lyman-break »galaxies

In the Rayleigh-Jeans tail of the dust blackbody spectrum, galaxies get ***brighter*** as they are redshifted to greater distance!

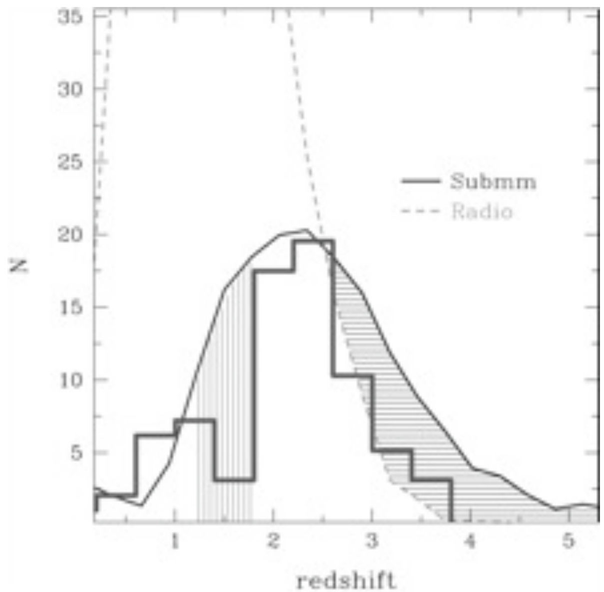


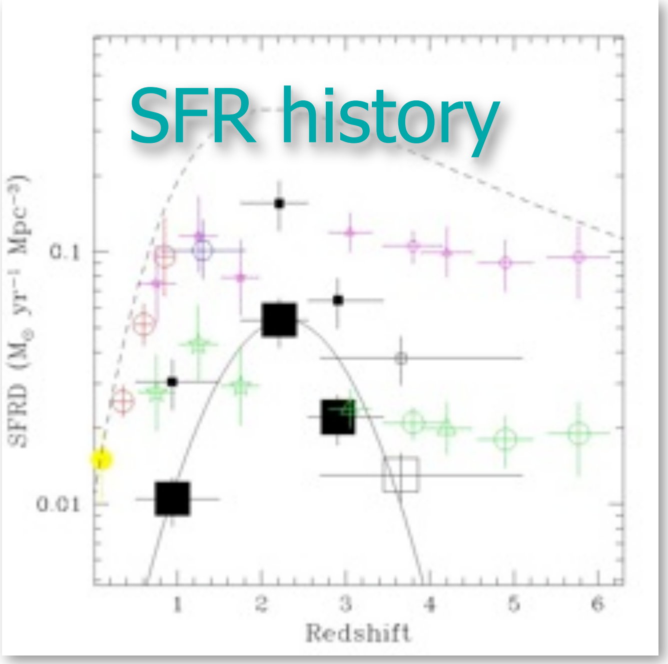
Blain et al (2002)

In principle z~10 dusty galaxies should be "easy" to detect in the millimeter domain.

Redshift of dusty galaxies

Chapman et al 2005





• Submm galaxies are located thanks to the radio position and then redshift is measured from the nearest optical counterpart: 50% completeness with Keck/ LRIS-B

•Peak z = 2.4 – comparable to that for AGN, All sub-mm sources have z<4 (selection effect?)

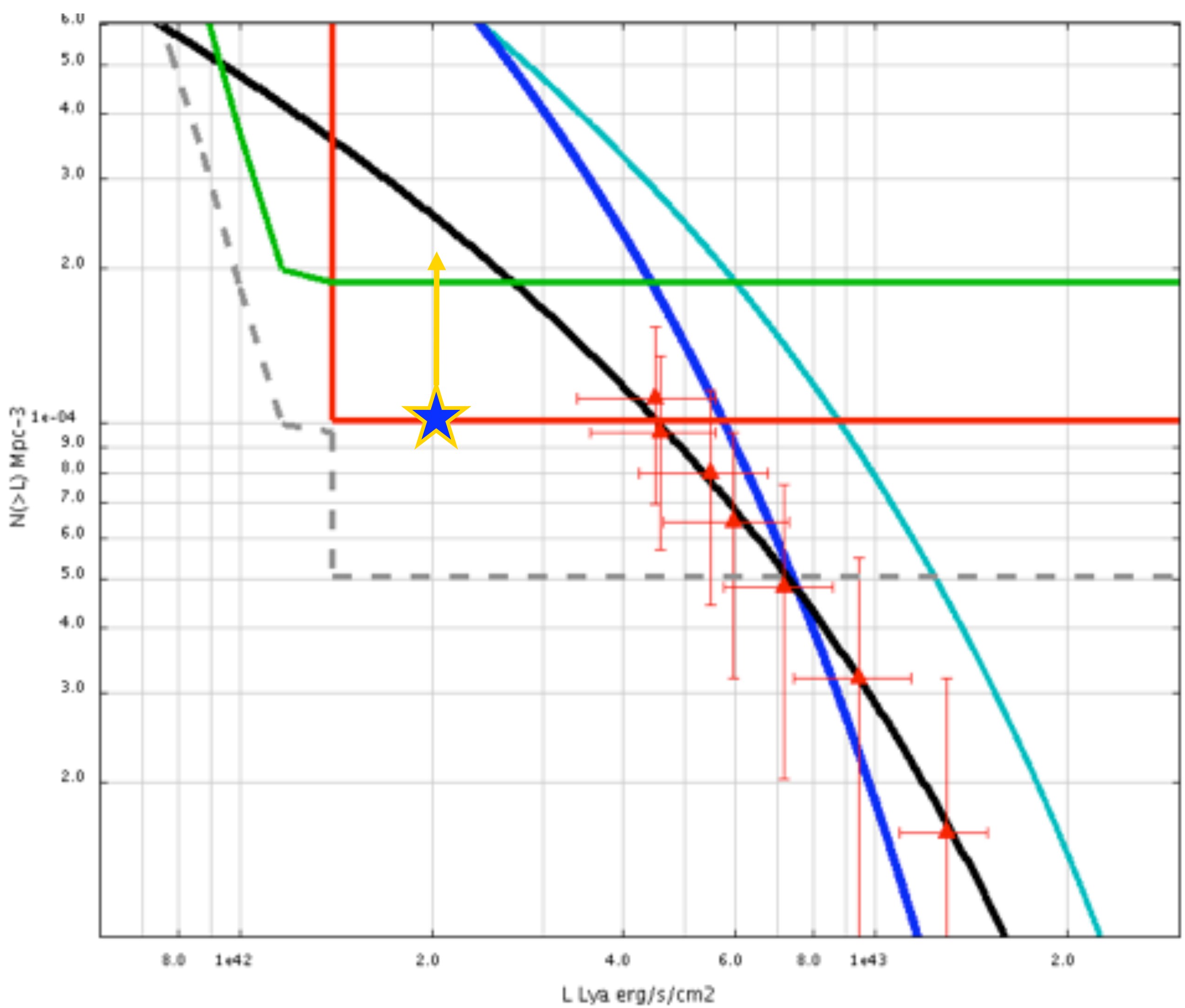
• Although ρ(LBG) ~ 10 ρ(SCUBA), luminosity/SF densities comparable

• Dust forms very quickly in the early Universe, are they any sub-mm galaxies beyond z>4? (recent paper on a possible z>4 in the GOODs field)

• **ALMA will solve this issue.**

HAWK-I NB Imaging

- LP at ESO using Hawk-I (PI:Cuby)
- *120 hours* (2 yr project) NB+BB
- *4 fields*: 2 clusters (A1689, Bullet Cluster), 2 blank fields (D4, Goods South)
- 1st epoch on 3 fields acquired.



Spectroscopic elimination of interlopers

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

Line	Redshift	λ Lyα (μm)	λ [OII] (μm)	λ Hβ (μm)	λ [OIII] (μm)	λ Hα (μm)
Hα	0.91	0.2324	0.7124[a]	0.9292	0.9479/0.9571	1.2545
[OII]	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
[OIII]	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~9.5 (2/6 candidates)

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

Low-luminosity sources responsible of reionisation?

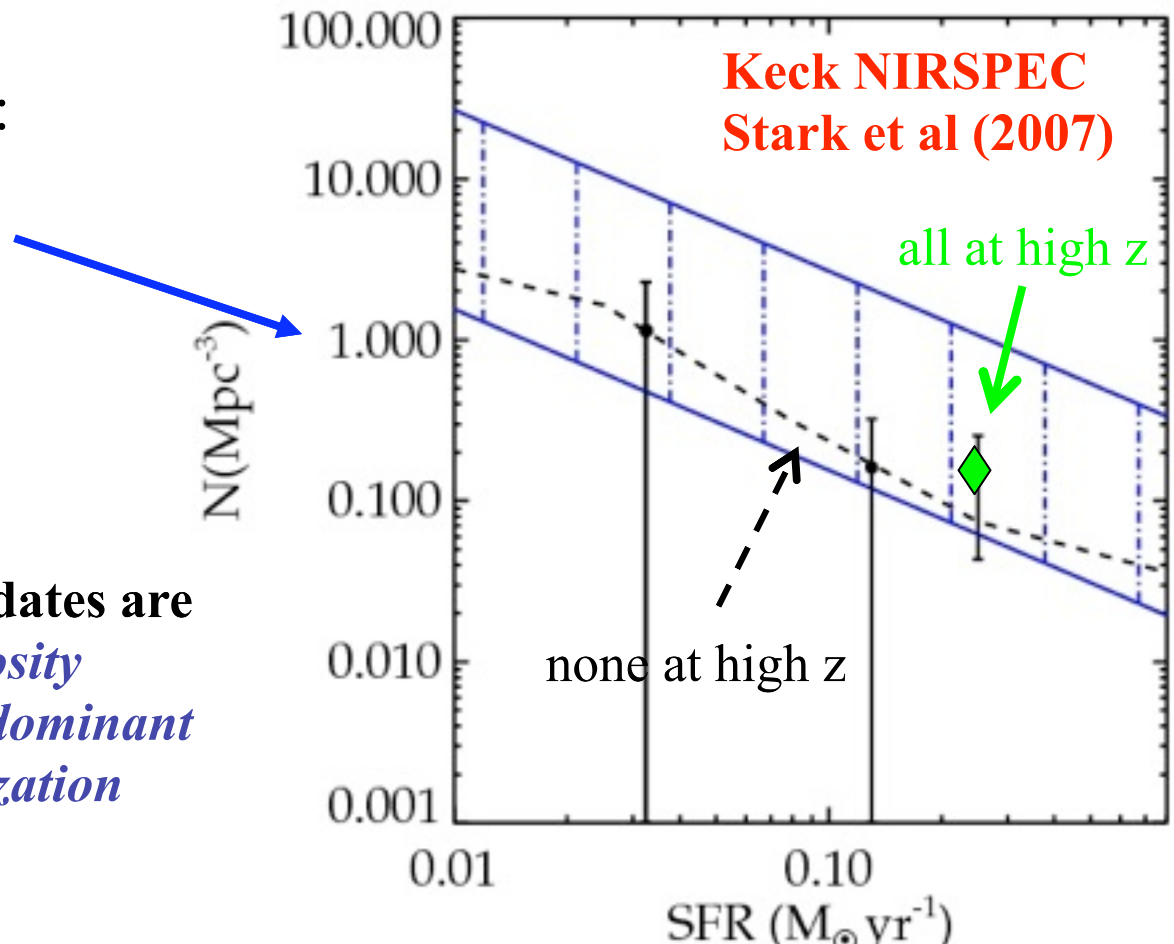
$$n = \left(\frac{B}{10}\right)\left(\frac{n_H}{10^{-7}\ \mathrm{cm}^{-3}}\right)\left(\frac{f_c}{0.1}\right)^{-1}\left(\frac{\mathrm{SFR}}{1.0\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}}\right)^{-1}\left(\frac{n_c}{3\times 10^{53}}\right)^{-1}\left(\frac{\Delta t}{575\ \mathrm{Myr}}\right)^{-1}$$

Considering range:

$f_c \sim 0.02$-0.5

$\Delta t \sim 250$-575 Myr

$B \sim 5$-10



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