Observing the most distant Galaxies through Lenses

Jean-Paul KNEIB

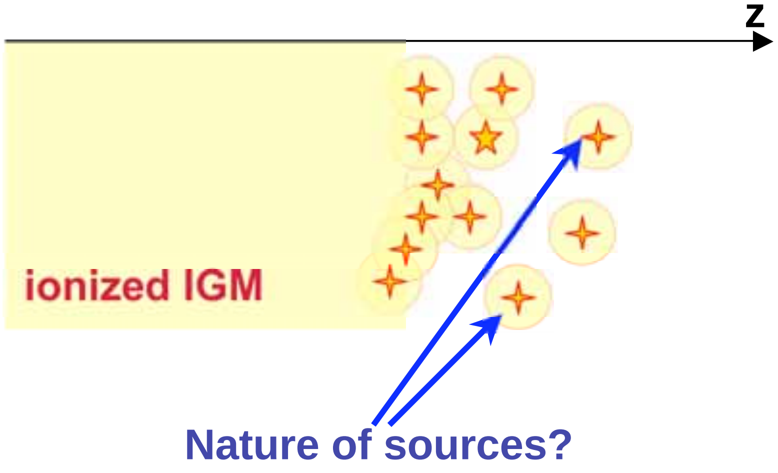
Laboratoire d'Astrophysique de Marseille, France

Johan Richard, Dan Stark, Richard Ellis, Eiichi Egami, Graham Smith,**Benjamin Clément**, **Eric Jullo**, Marceau Limousin, Roser Pello, Daniel Schaerer, Jon Willis, Frédéric Courbin, J.G. Cuby, …

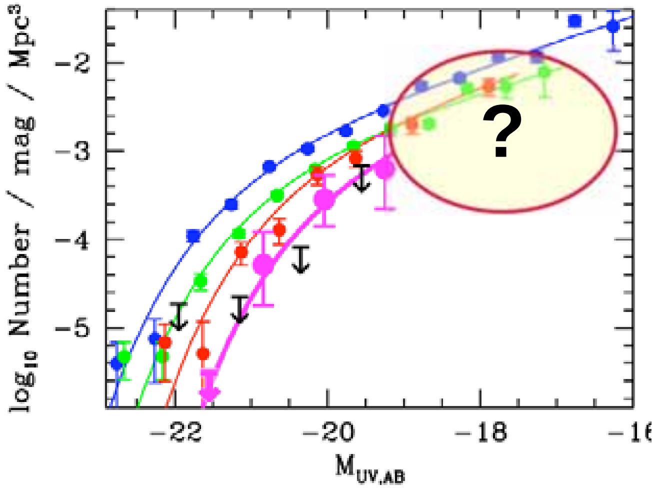
Outline

- Motivation
- How lensing helps ?
- Recent results
- Future

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)

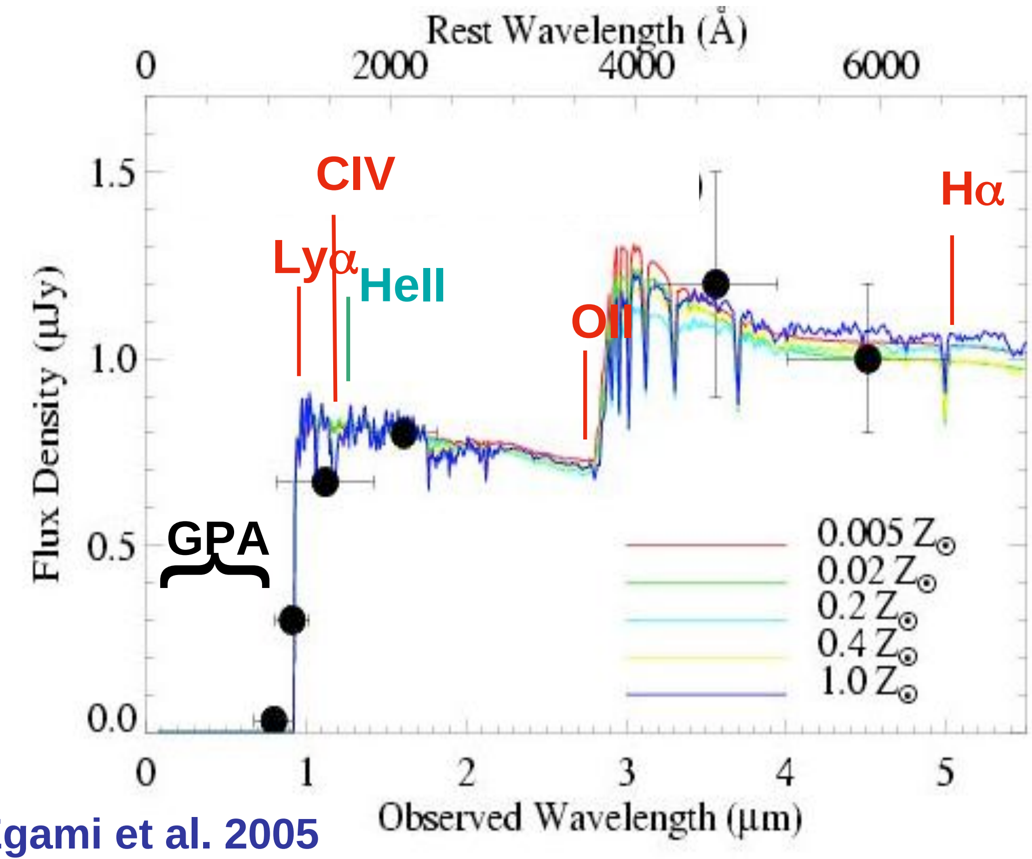
- **What sources ended Dark Ages?**
  - Sources with intense UV flux
  - First stars are thought to be: *Very massive/Low metallicity/UV luminous*
- **Mass of first DM halos?**
  - At z~10: halo mass of 10^{10} to 10^{11} solar mass
  - First objects could form at z~50 with at most 10^6 solar mass (Reed et al 2006)
- **Current exploration in UV restframe:**
  - Rapid decline in UV luminosity density 3<z<6 ? (Bouwens vs. Bremer)
  - Possible steepening of LBG LF faint end slope with increasing z?
  - No evolution of the LAE LF at high-z observed yet

$\Rightarrow$ **Importance to probe low-luminosity galaxies**

How to locate the “first” galaxies?

Features expected for a distant star-forming galaxy:

- *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.

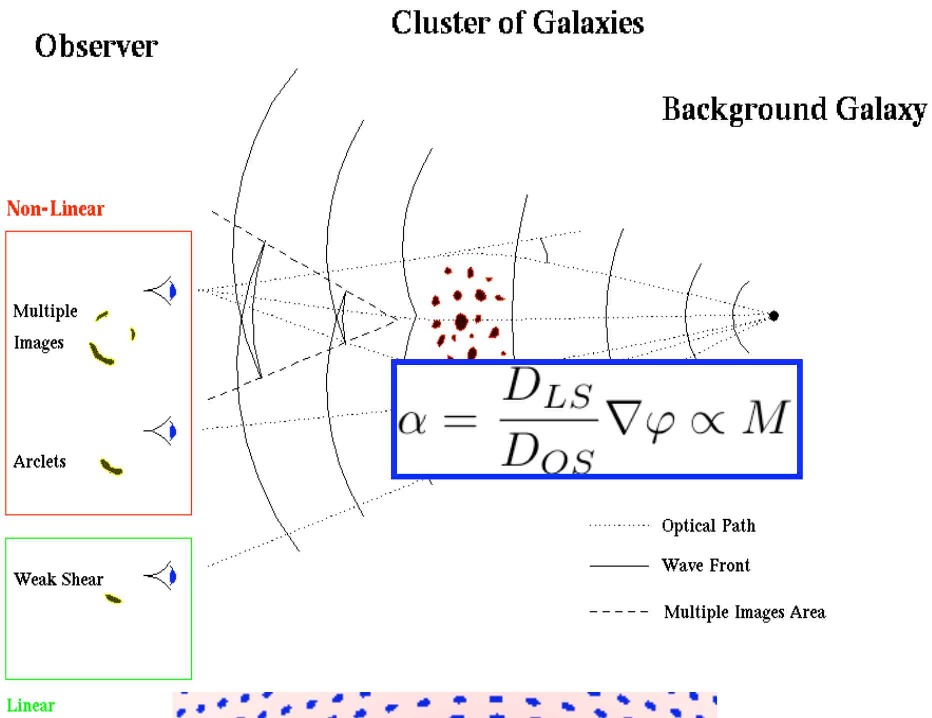


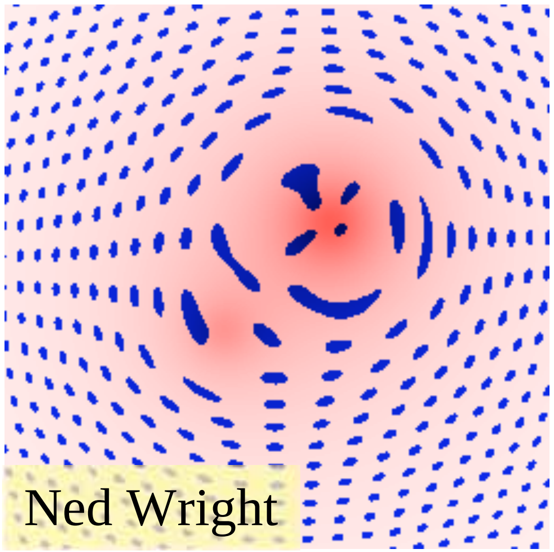
Egami et al. 2005

Route followed:

- Emission line (Lyman-α, Hα)
  - NB imaging: ZEN (**Courbin's** talk)
  - Blind spectroscopy (NIR-MIR)
- Continuum (Lyman-break+4000A break confirmation) (**Pello's** talk)
- ***Use of Gravitational Telescope (low luminosity)***

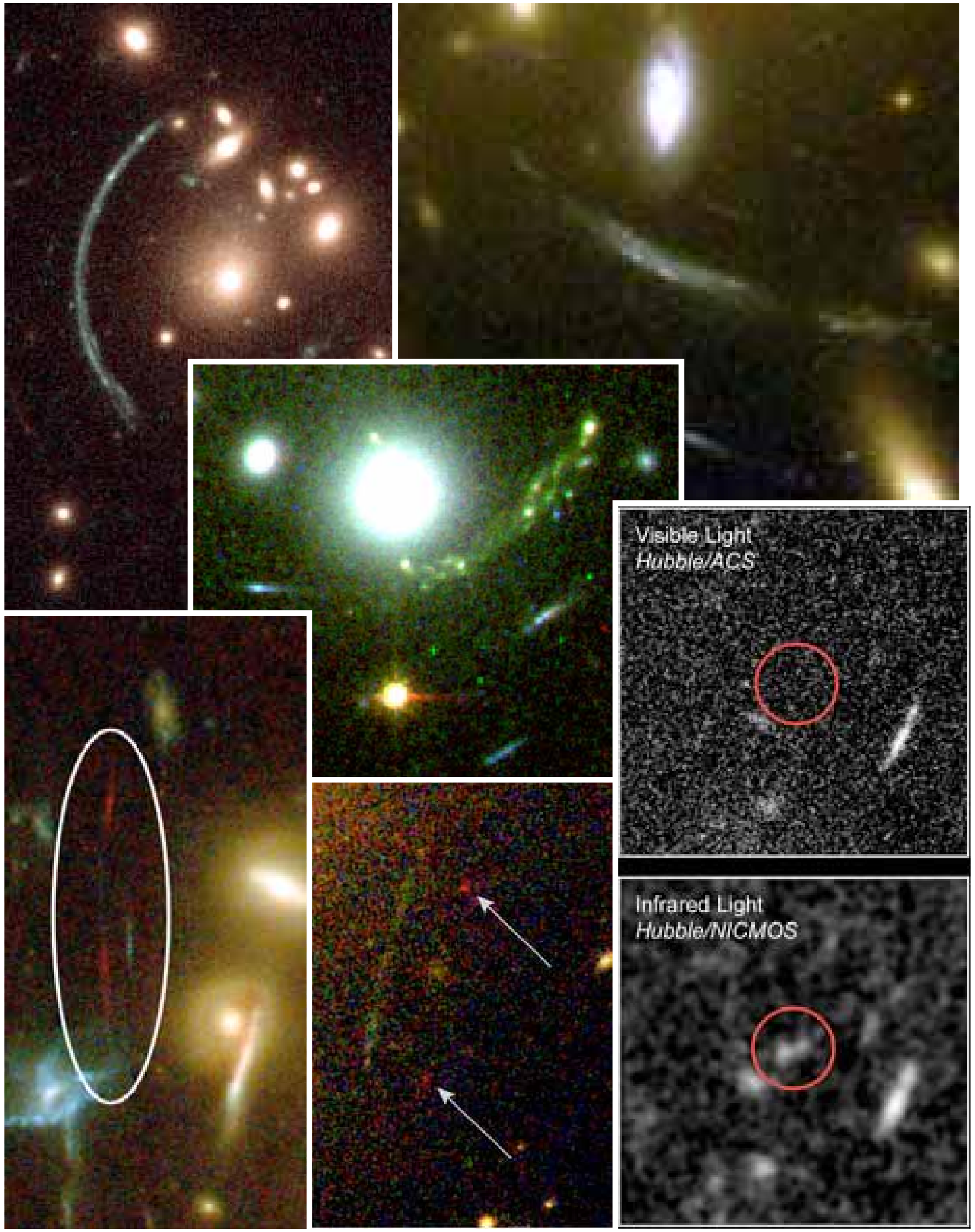
How Gravitational Lensing can help?





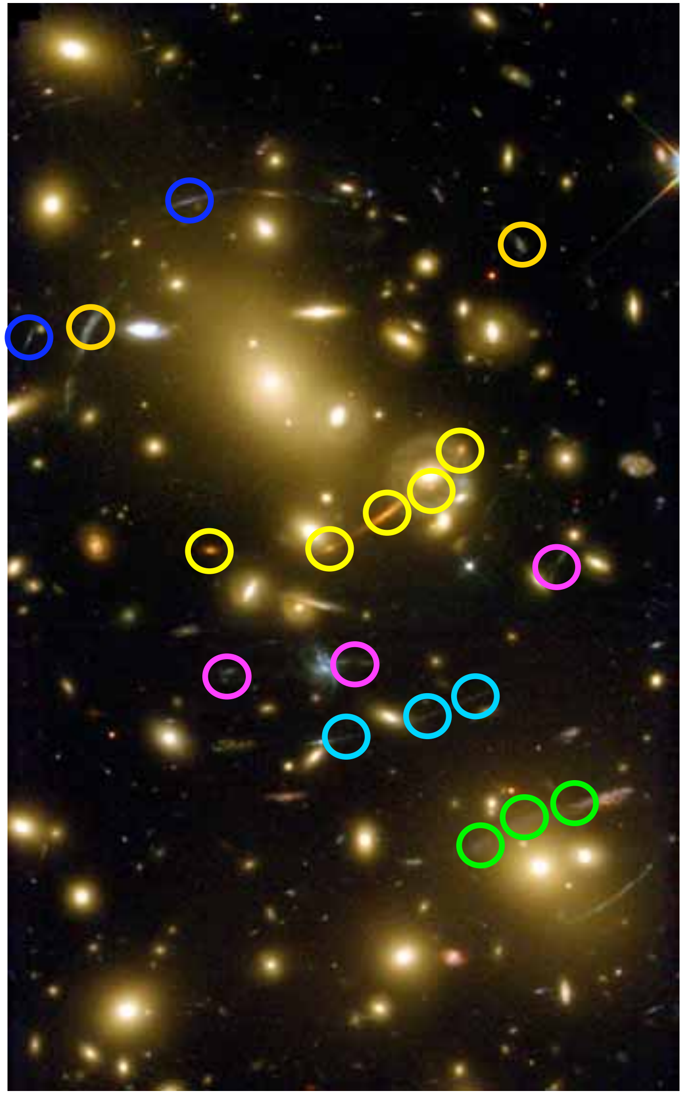
- **Basics of lensing:**
  - Important mass density locally deform the Space-Time,
  - *A pure geometrical effect, no dependence with photon energy*
  - *Multiple-images with large magnification >10*
- **Lensing by a (massive) galaxy**
  - Deflection of ~1 arcsec
  - strongly lens only ~one background 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. degree

History of searching hi-z lensed galaxies



- **1987**: Cl2244 one of the first gravitational arc, latter recognized as a z=2.2 galaxy
- Ebbels et al **1996**: a z=2.5 LBG in a2218
- cB58 z=2.7 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
- Bradley et al **2008**: LBG at z~7.6
- … and more …

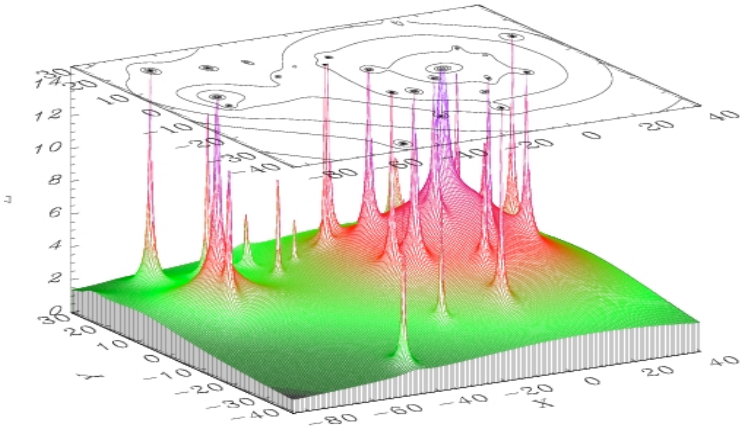
Lens Modeling and Errors



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

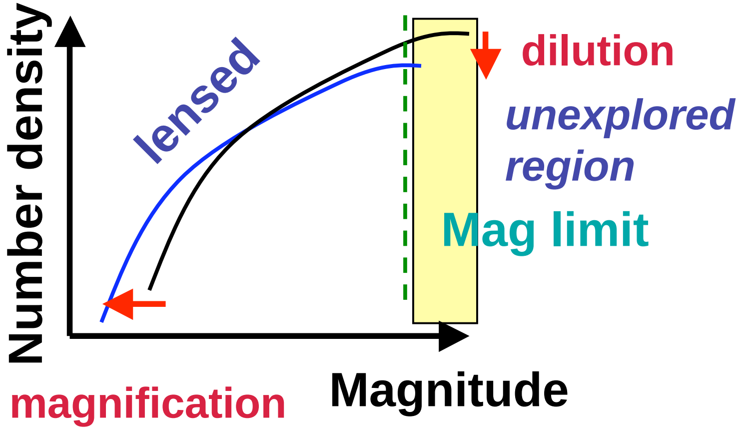
Model parameterization
- Need to include **small scales**: galaxy halos (parametric form scaled with light)
- Large scale: DM/X-ray gas (parametric form or multi-scale grid)

Model optimization
- Bayesian approach
- Not a unique solution, most likely model and errors
- Predict amplification value and errors

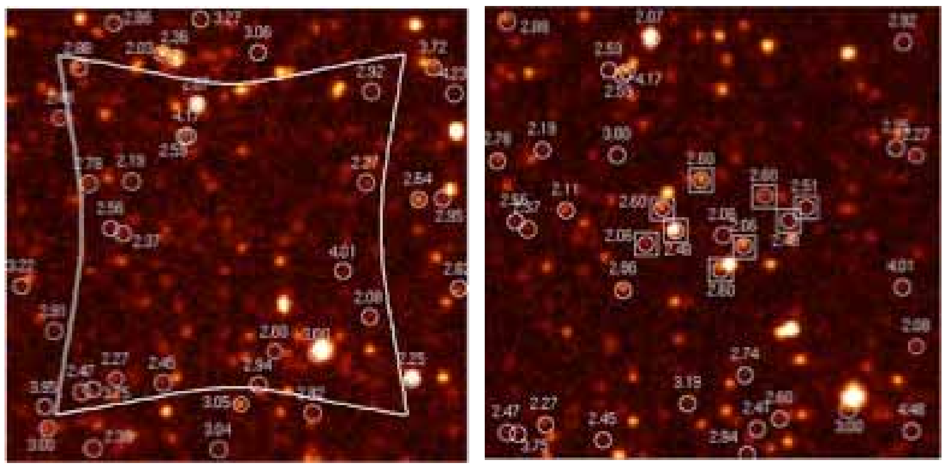


Jullo et al 2007, Jullo & Kneib 2008
***LENSTOOL* public software**
http://www.oamp.fr/cosmology/lenstool

Clusters as a Cosmic Telescope



7x7 arcmin^2 Herschel simulation



Unlensed field **Lensed field**

- Source plane, Image plane transformation

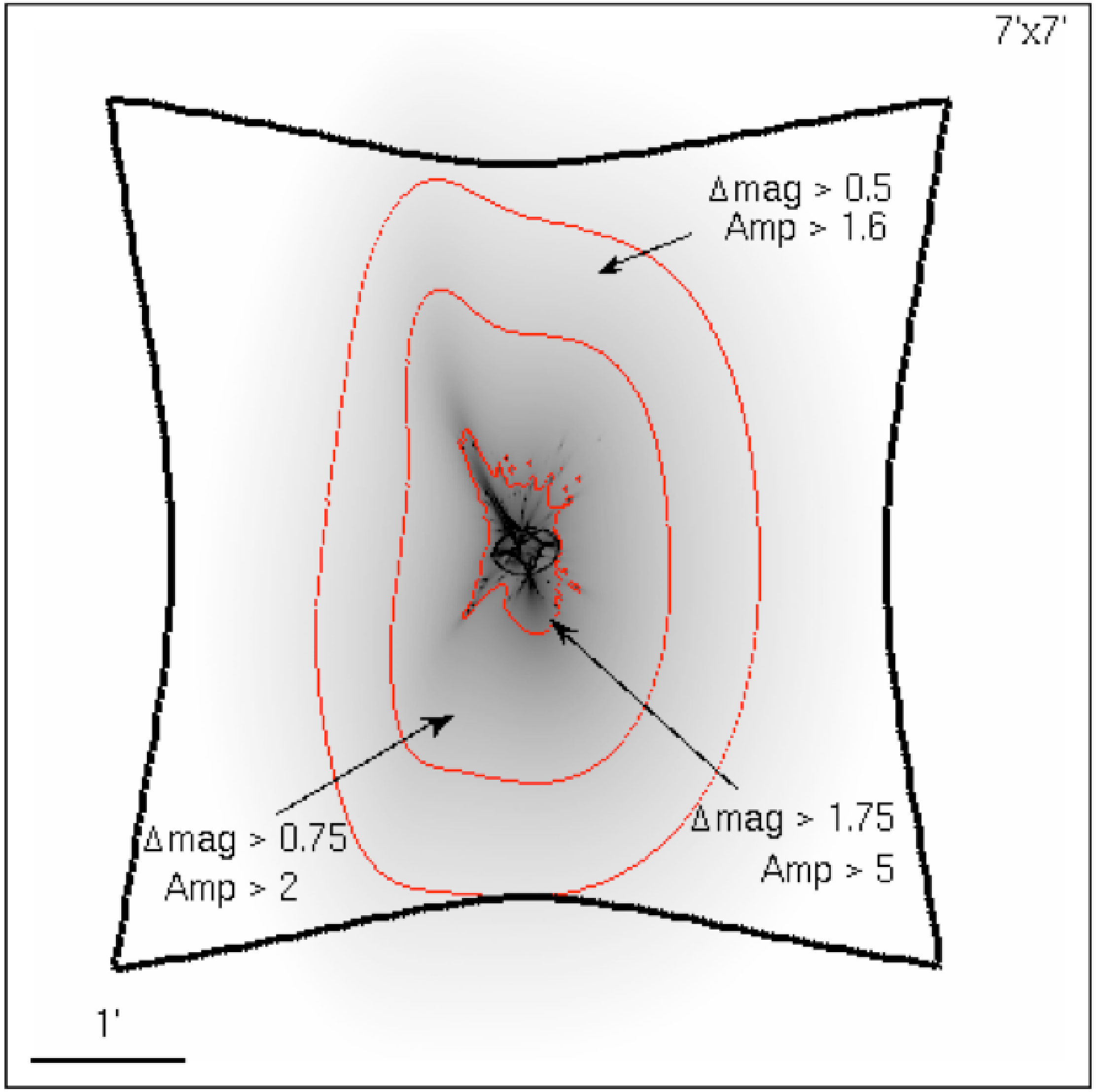
  $$N_L(f)=N_0(f/A)/A$$

  – 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 (important in FIR/Submm)

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*

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

Critical Line Mapping: finding LAEs

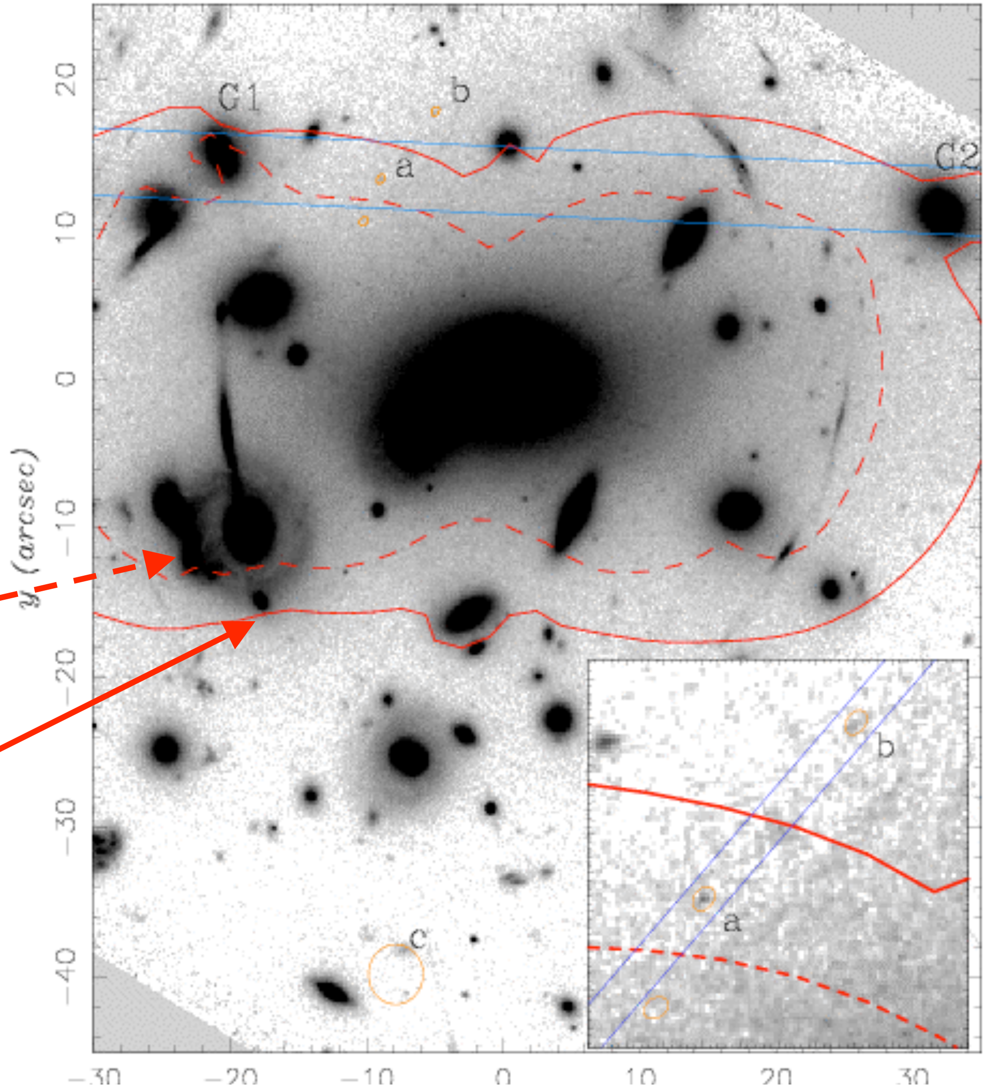
Ellis et al 2001

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

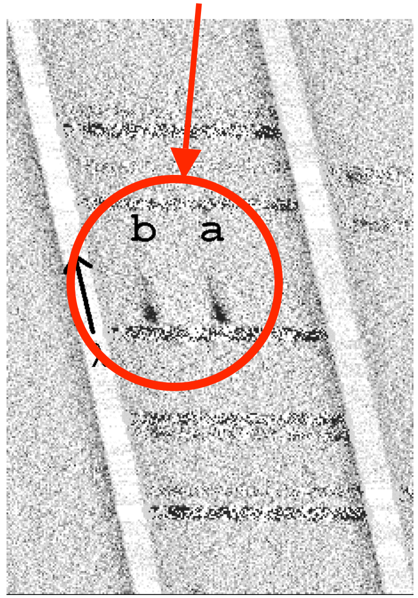
z=1

and for

z=5



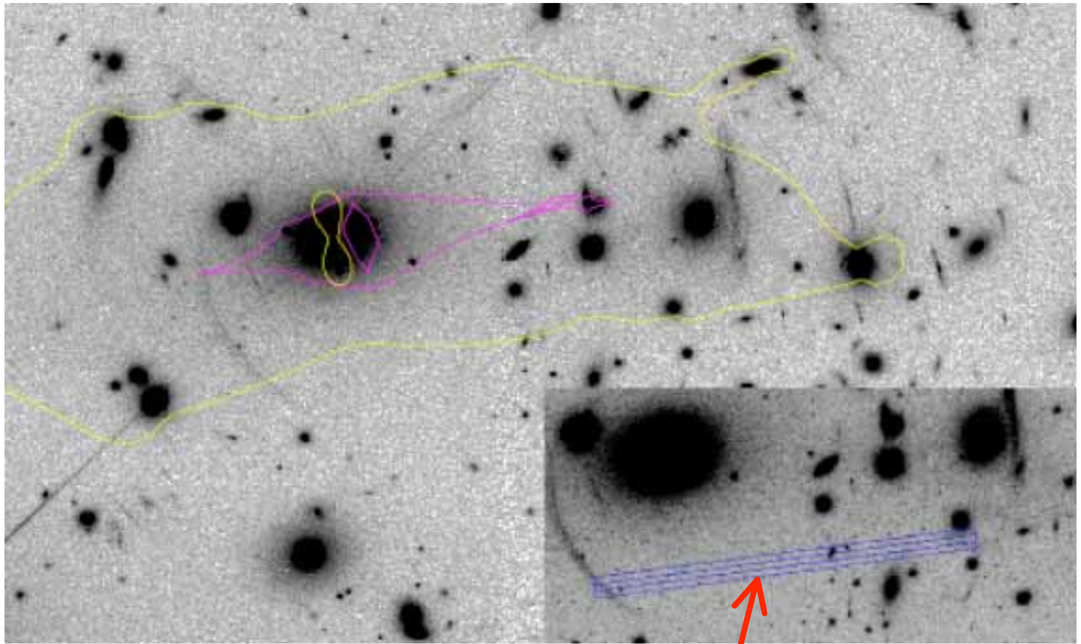
Blind Ly-a search with LRIS: hi-res follow-up with ESI



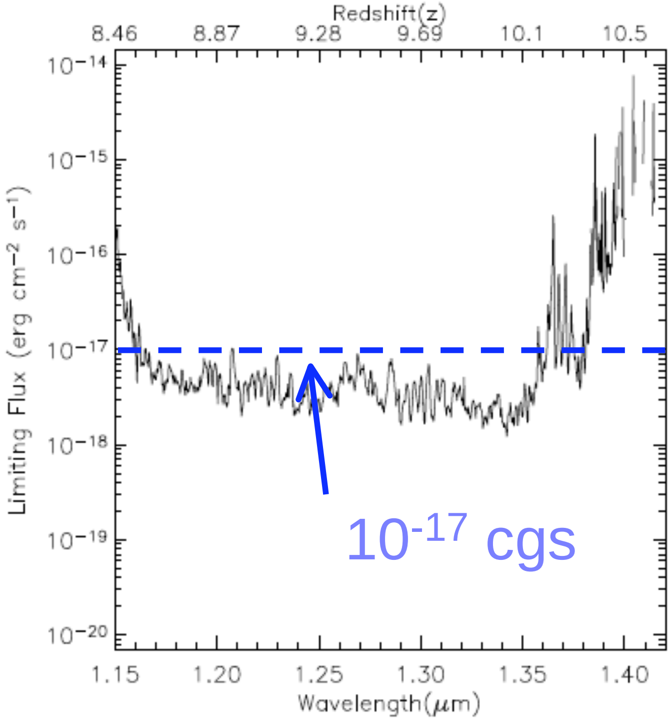
Utilizing strong magnification (´10-30) of clusters, probe much fainter than other methods in small areas (<0.1 arcmin2 cluster-1)

Low-luminosity z~9.5 Ly-α emitters

Cluster critical line for $z_S > 7$



Wavelength sensitivity (1.5hr)



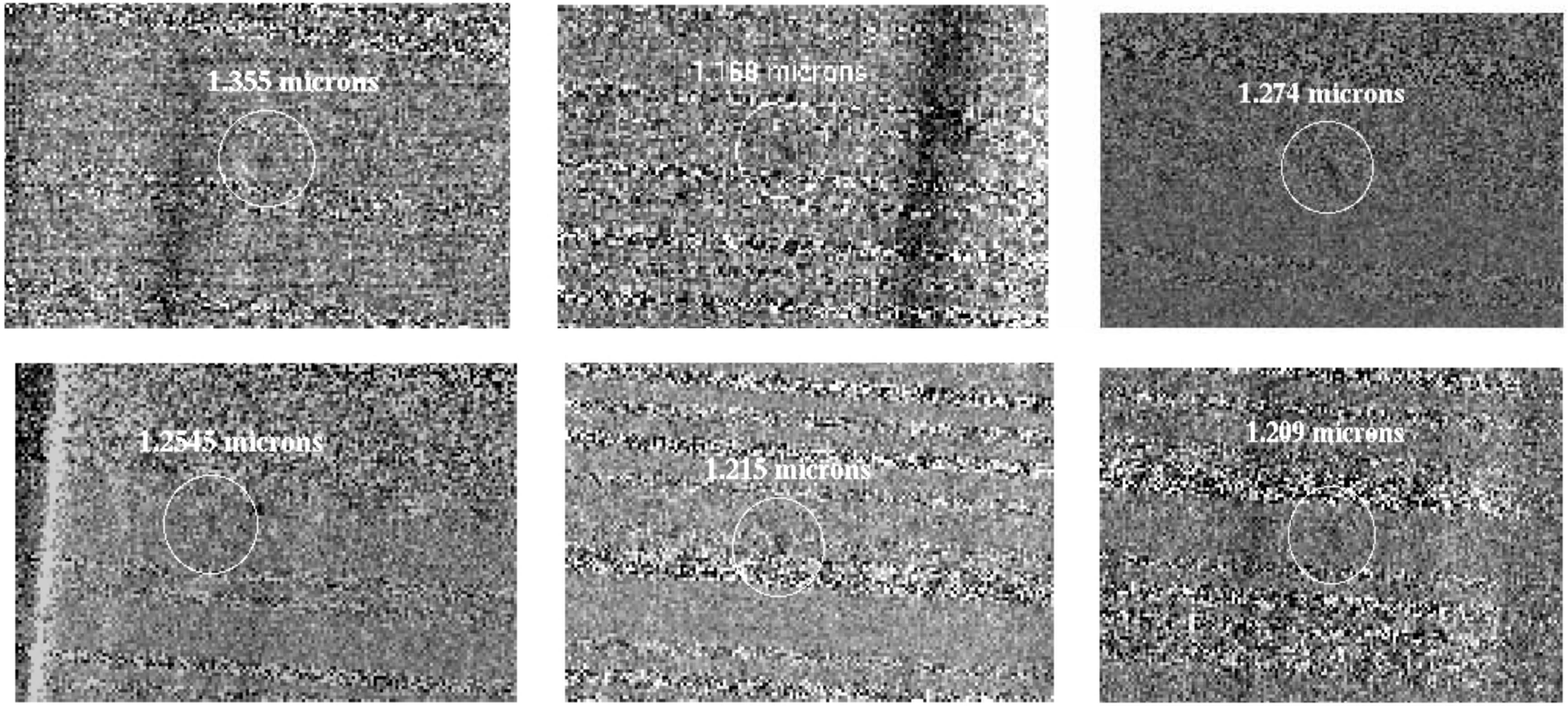
Stark et al 2007

NIRSPEC slit positions

- 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 promising lensed emitter candidates (>5σ)
- 8.6 < z < 10.2; L ~ 2 - 10. 10^{41} cgs; SFR ~ 0.2 -1 $M_\odot$ yr^{-1}

z~9.5 Candidates

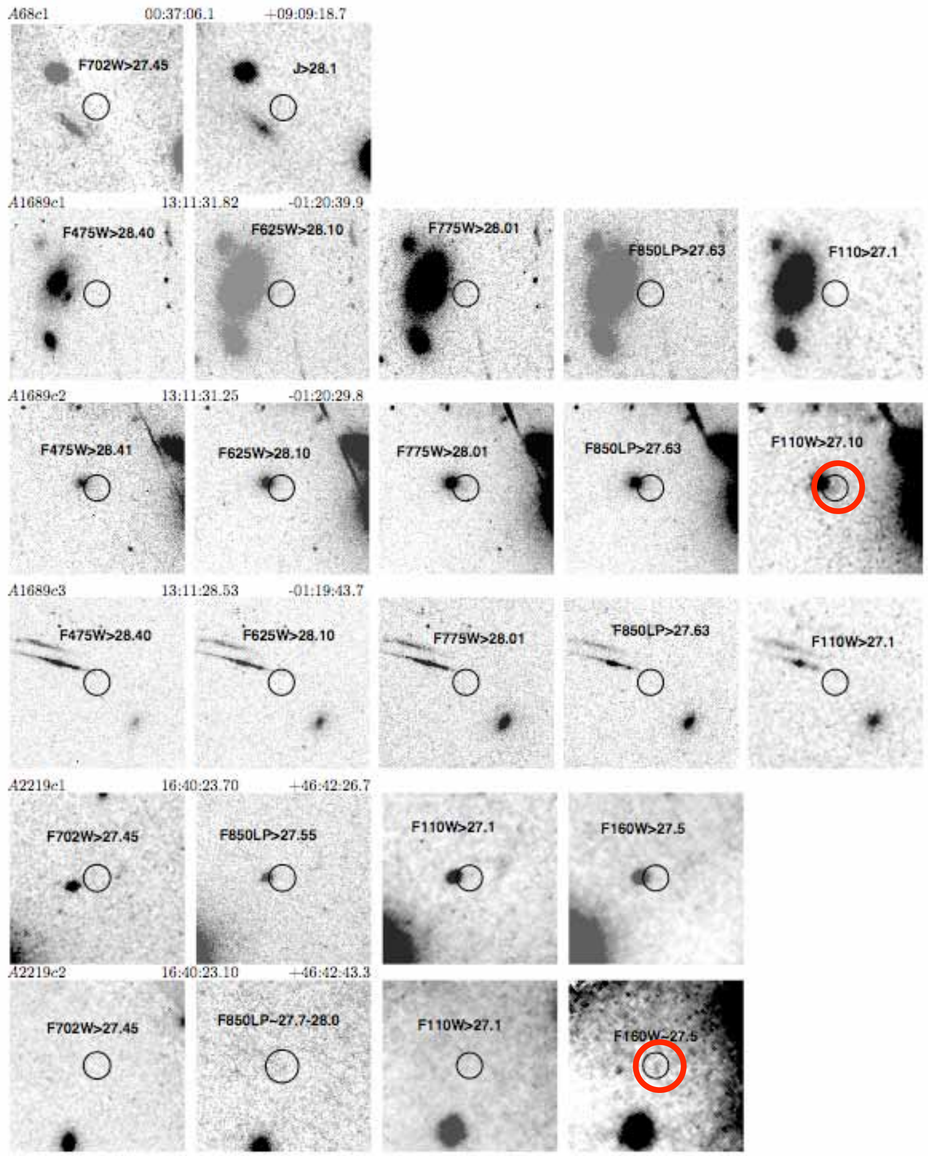
8.6 < z < 10.2; L ~ 2 - 10. 10^{41} cgs; SFR ~ 0.2 - 1 $M_{\odot}$ yr^{-1}



Definitely proving that these are z~9.5 emitters is hard.

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

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

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)

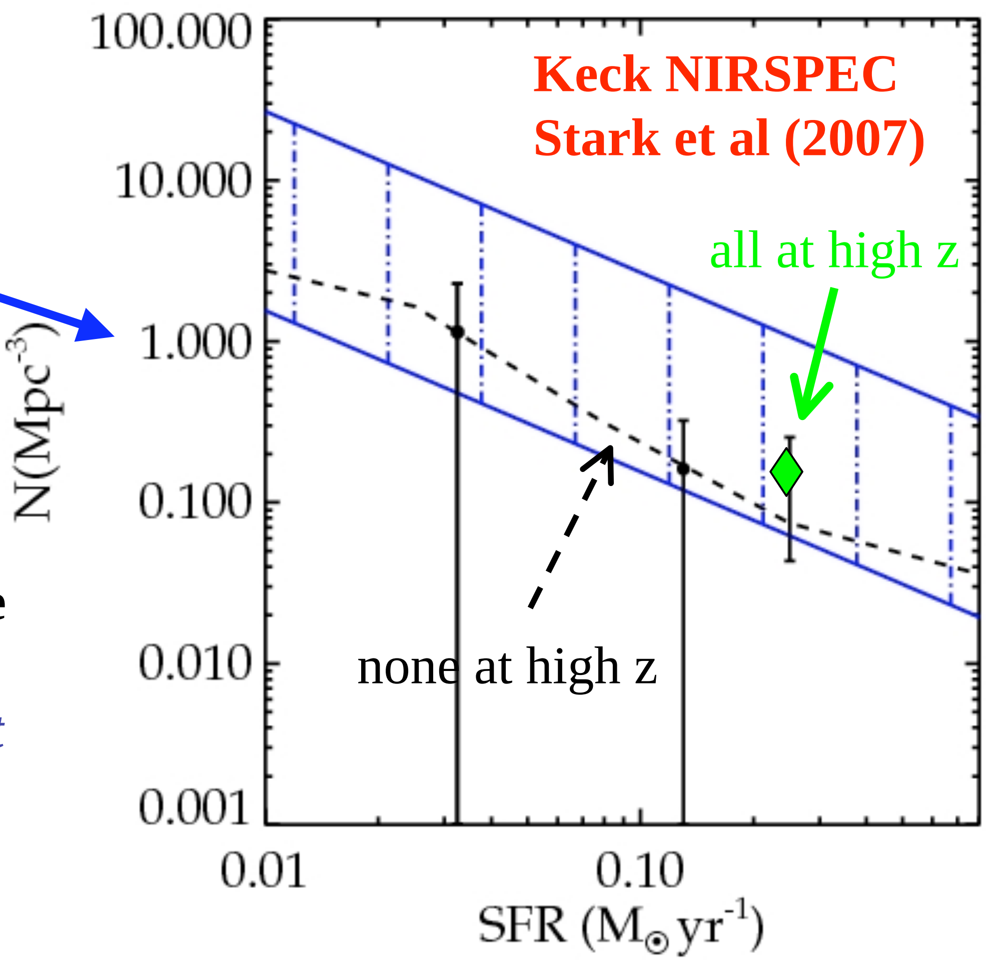
Now believe >3/6 candidates likely to be 8<z<10 sources

Low-luminosity sources responsible of reionisation?

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

Considering range:

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



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

Lensed dropout galaxies

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

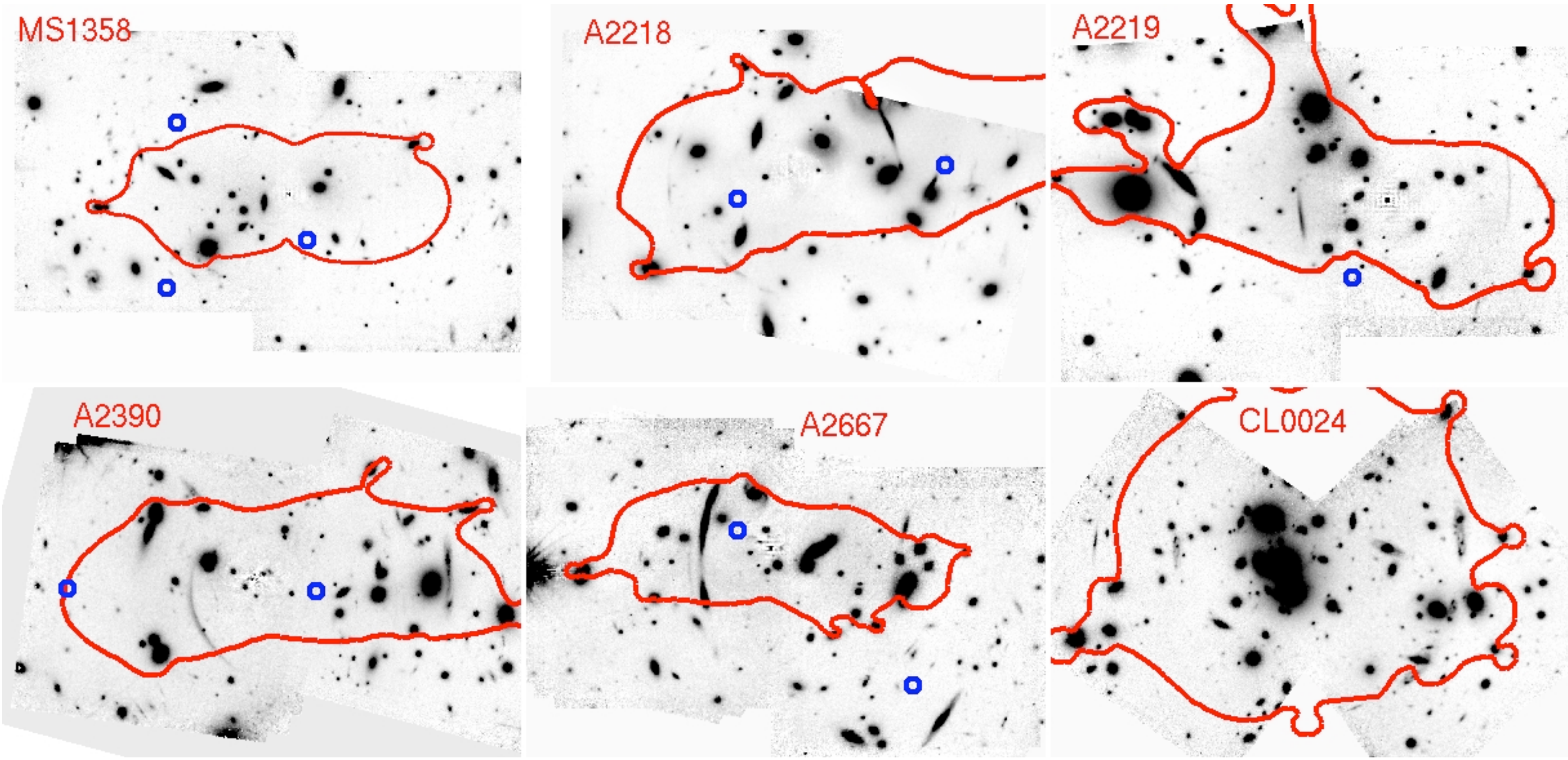
- First detection of a z~6.8 dropout galaxies in Abell 2218
- Redshift confirmed by multiple image detection
- Source identified in Spitzer data, showing an already “old” population of stars, arguing for a formation redshift of z~10

Kneib et al 2004, Egami et al 2005

z>7 lensed dropout with Hubble

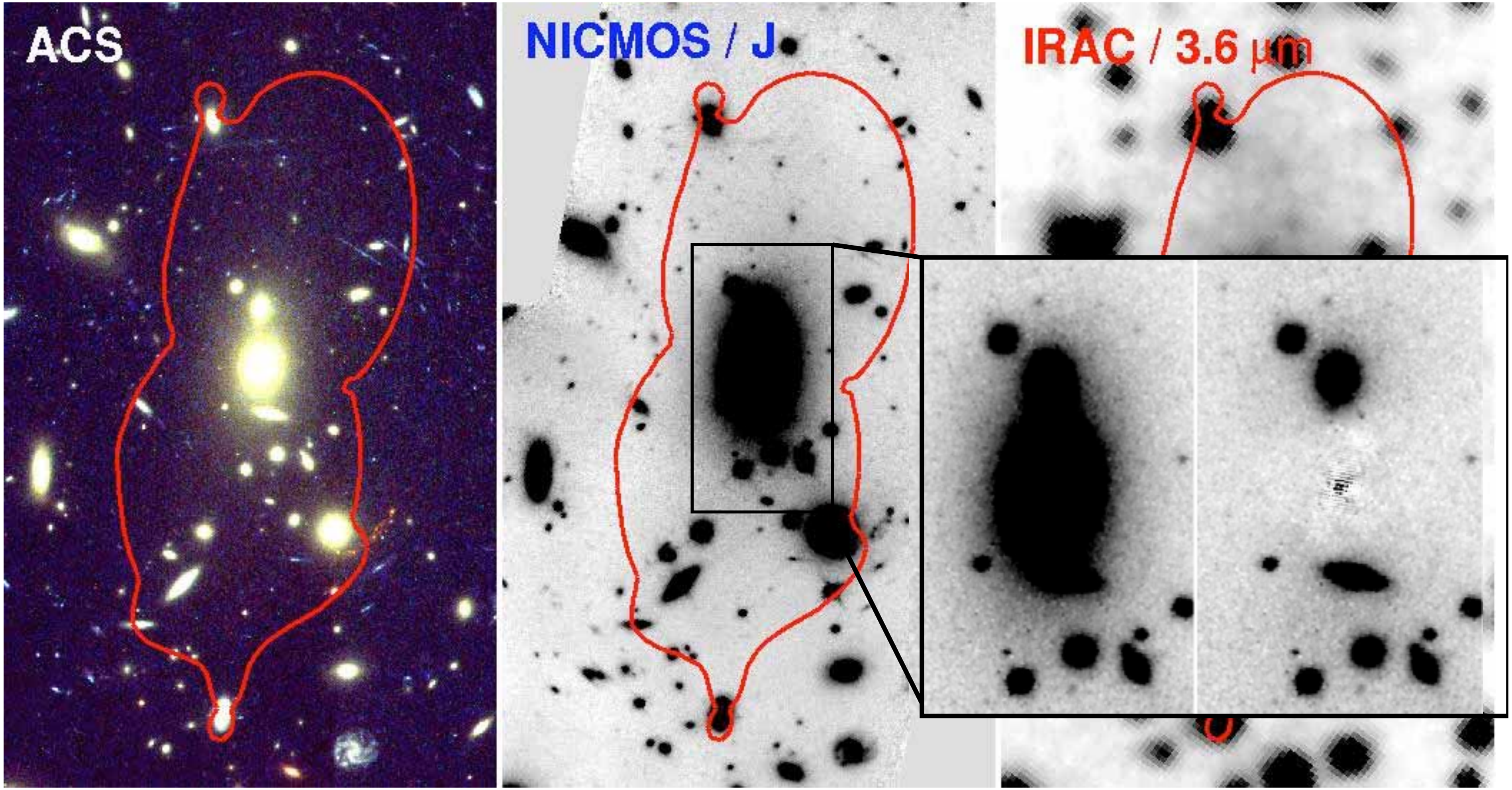
- Systematic extension: Study of 6 well-constrained clusters with optical (ACS/F850LP), near-infrared (HST/NICMOS+Ground-based) and mid-infrared (Spitzer/IRAC)
- Identification of “dropout” candidates

Richard et al 2008



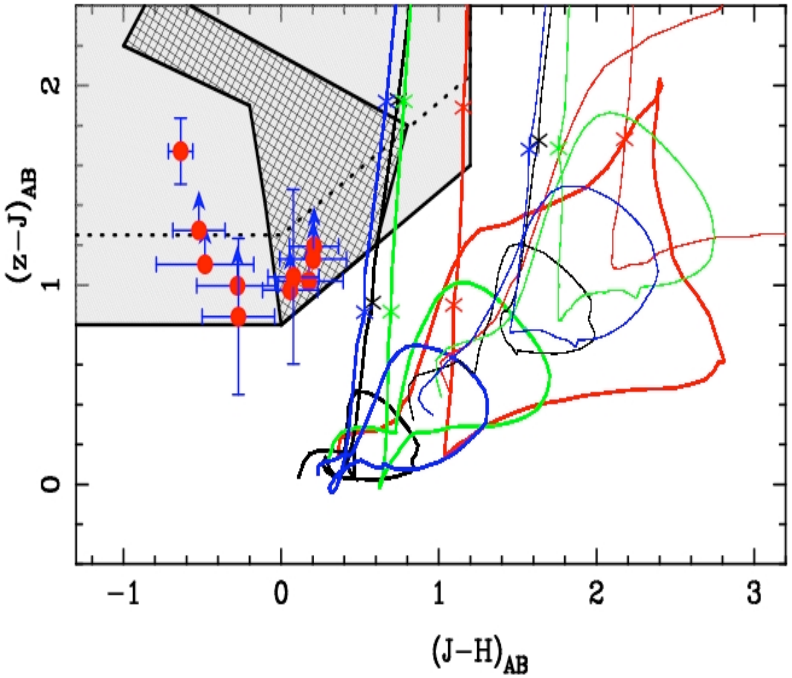
Combining ACS, NICMOS & Spitzer

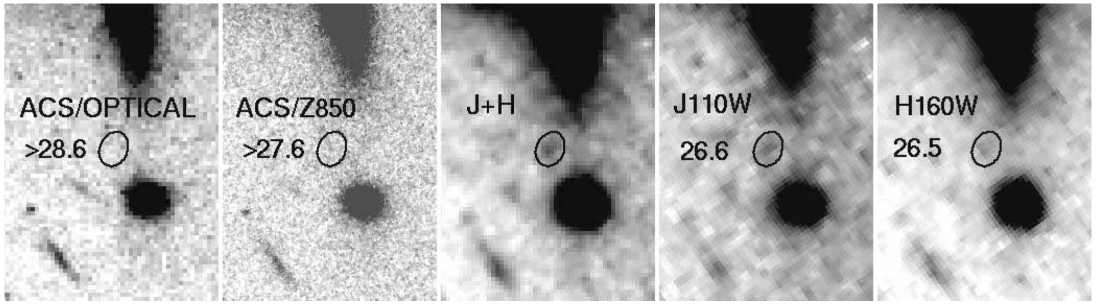
MS1358: 5σ limit: J_{AB}=26.7, H_{AB}=26.7



Importance of foreground removal

z>7 lensed dropout with Hubble



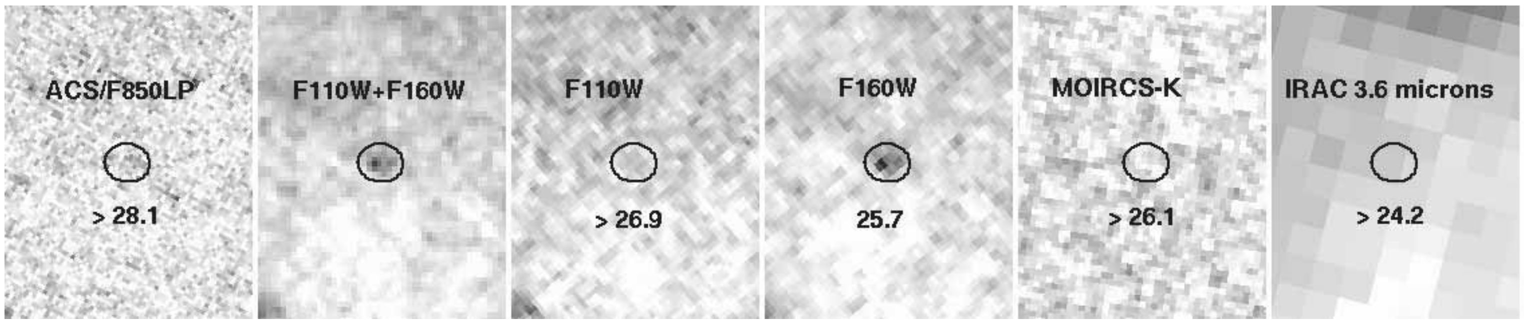


Z~7-8

Richard et al 2008

- 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

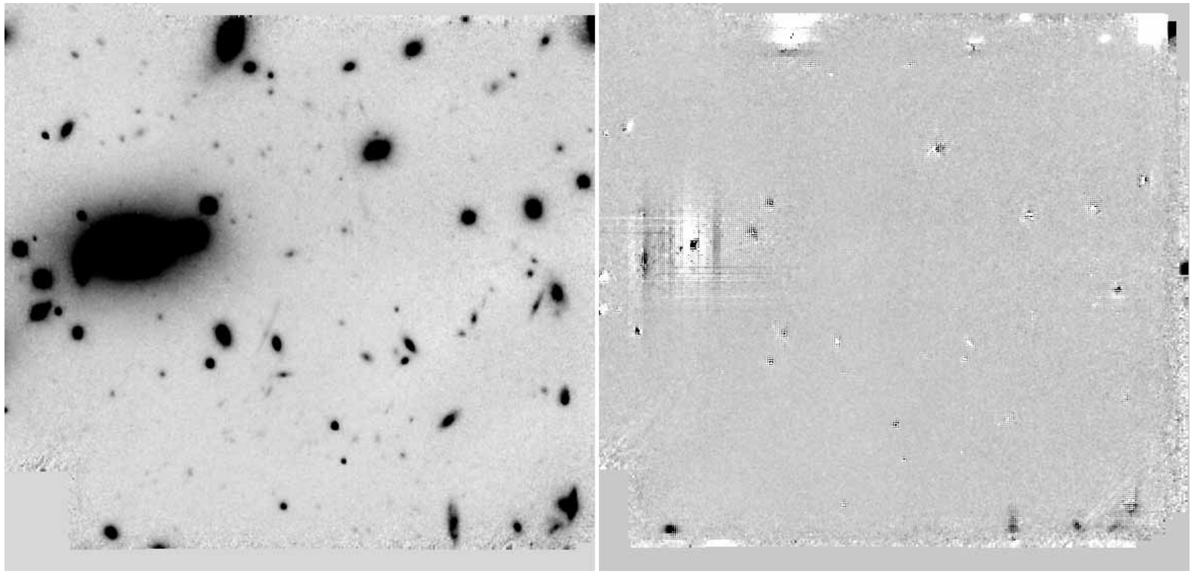
2 candidates J-drops (J-H>1.8) with H_{AB}~25.6
SFR ~ 0.1 - 1 $M_\odot$ yr^{-1} (unlensed)



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 :

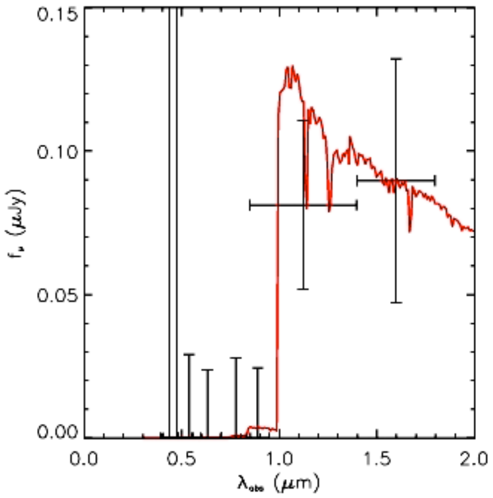
measurements from the archive: no effect

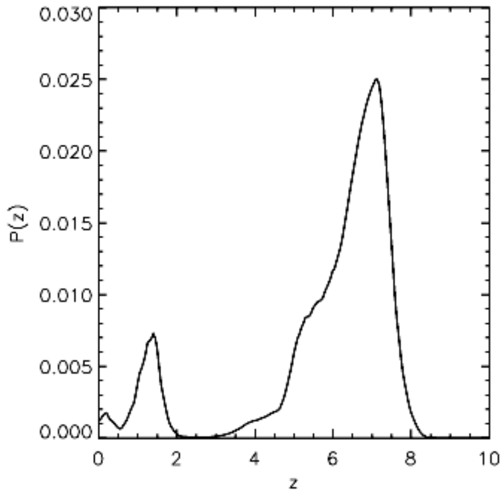
- Low-mass stars : L and T dwarfs are expected to contaminate the survey. Predictions: 1 star in entire survey.

- Photometric redshifts

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

⇒ 5 out of 10 dropouts truly at high z

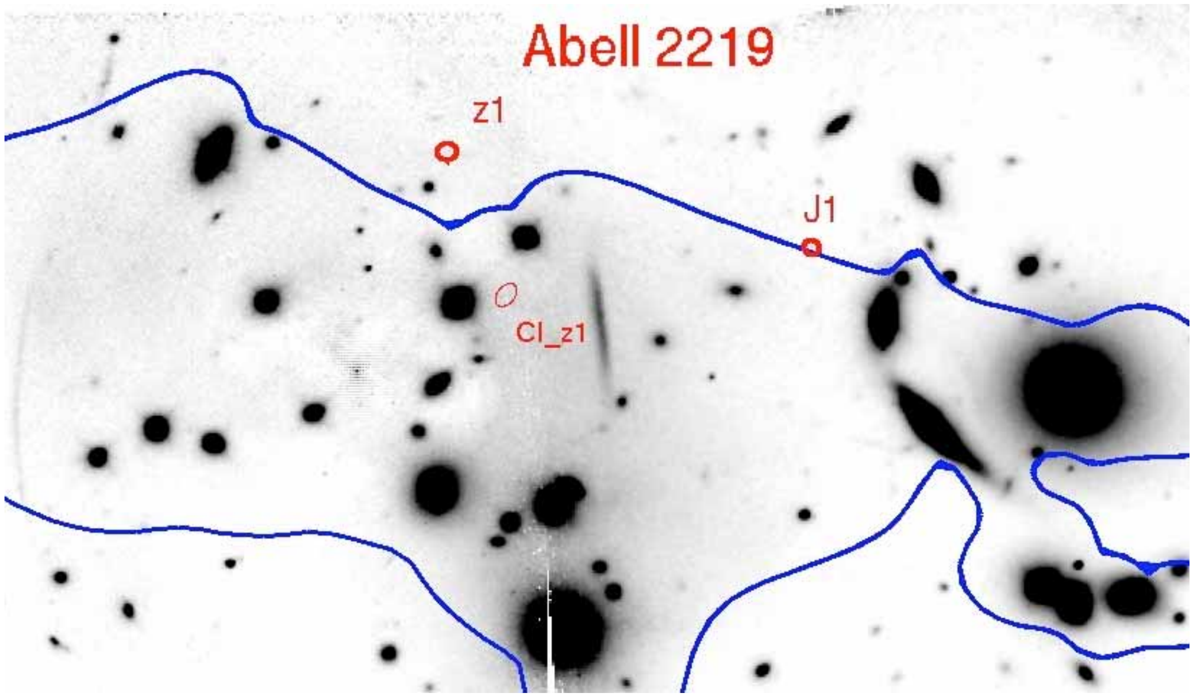




Search for multiple images

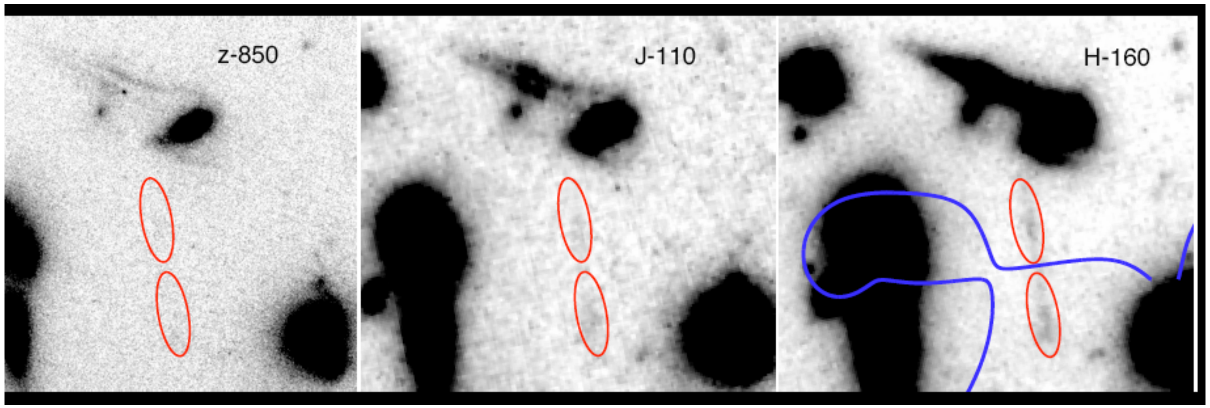
- Counter-images predictions from lensing model

2 candidates with possibly "merging" images

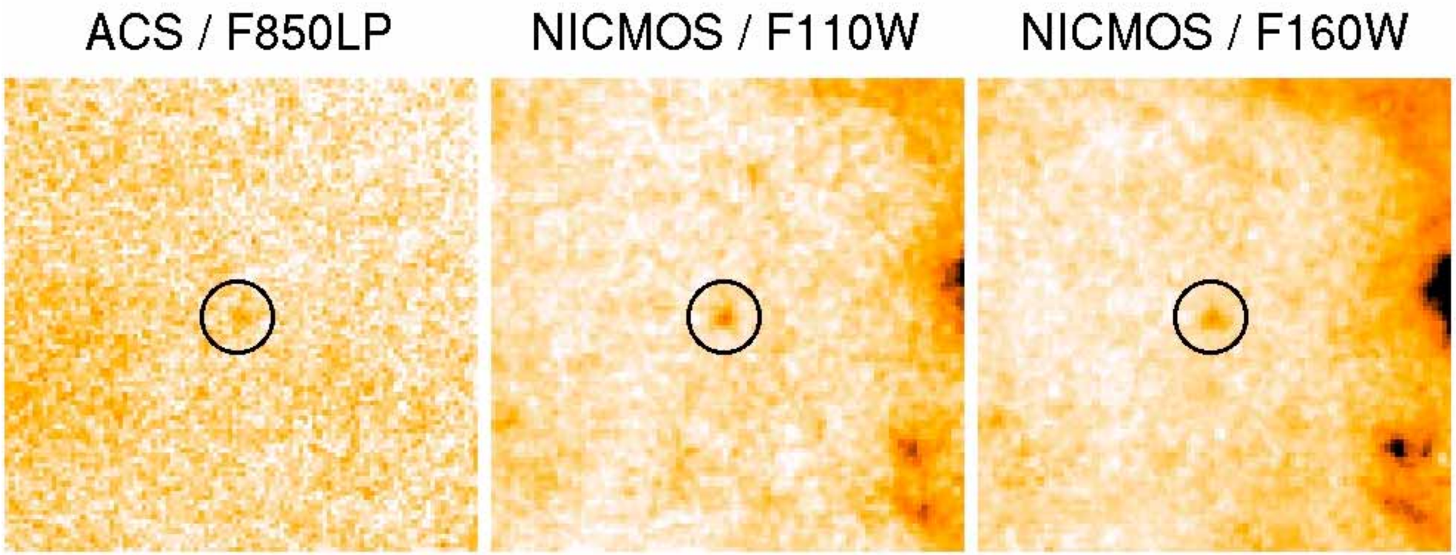


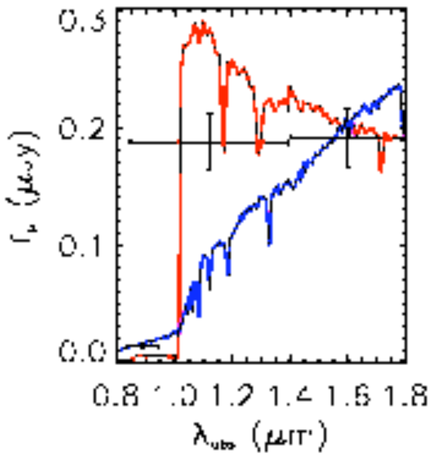
Proof of Method:

we do see z~2 multiple sources…



Properties of stacked SED for the z-dropouts





Average photometry

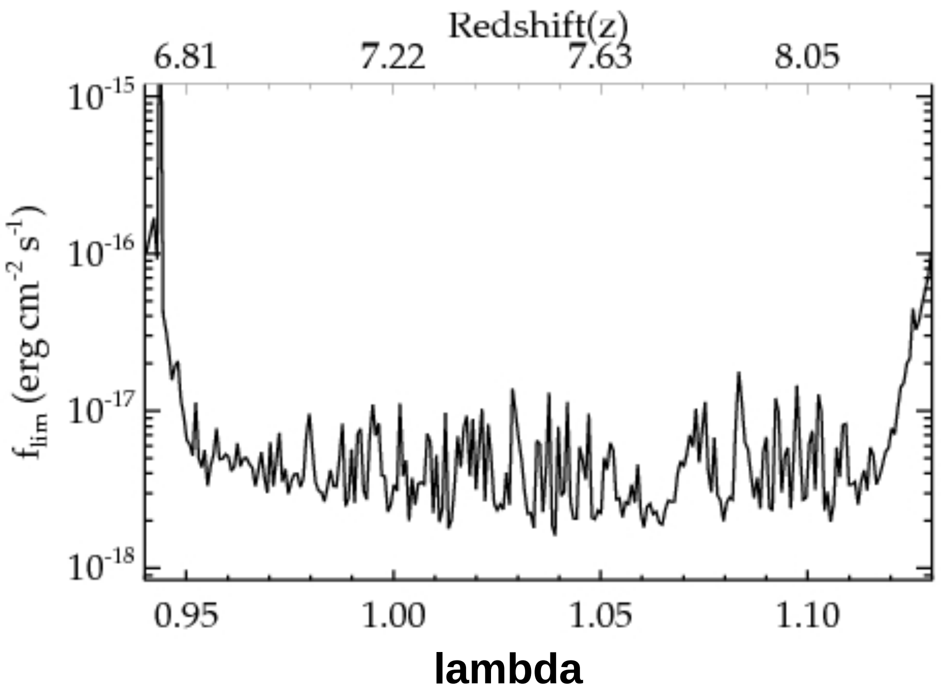
z=28.59±0.21 J=25.72±0.14 H=25.70±0.14

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

β ~ 2.7-2.8

Keck/NIRSPEC spectroscopic follow-up

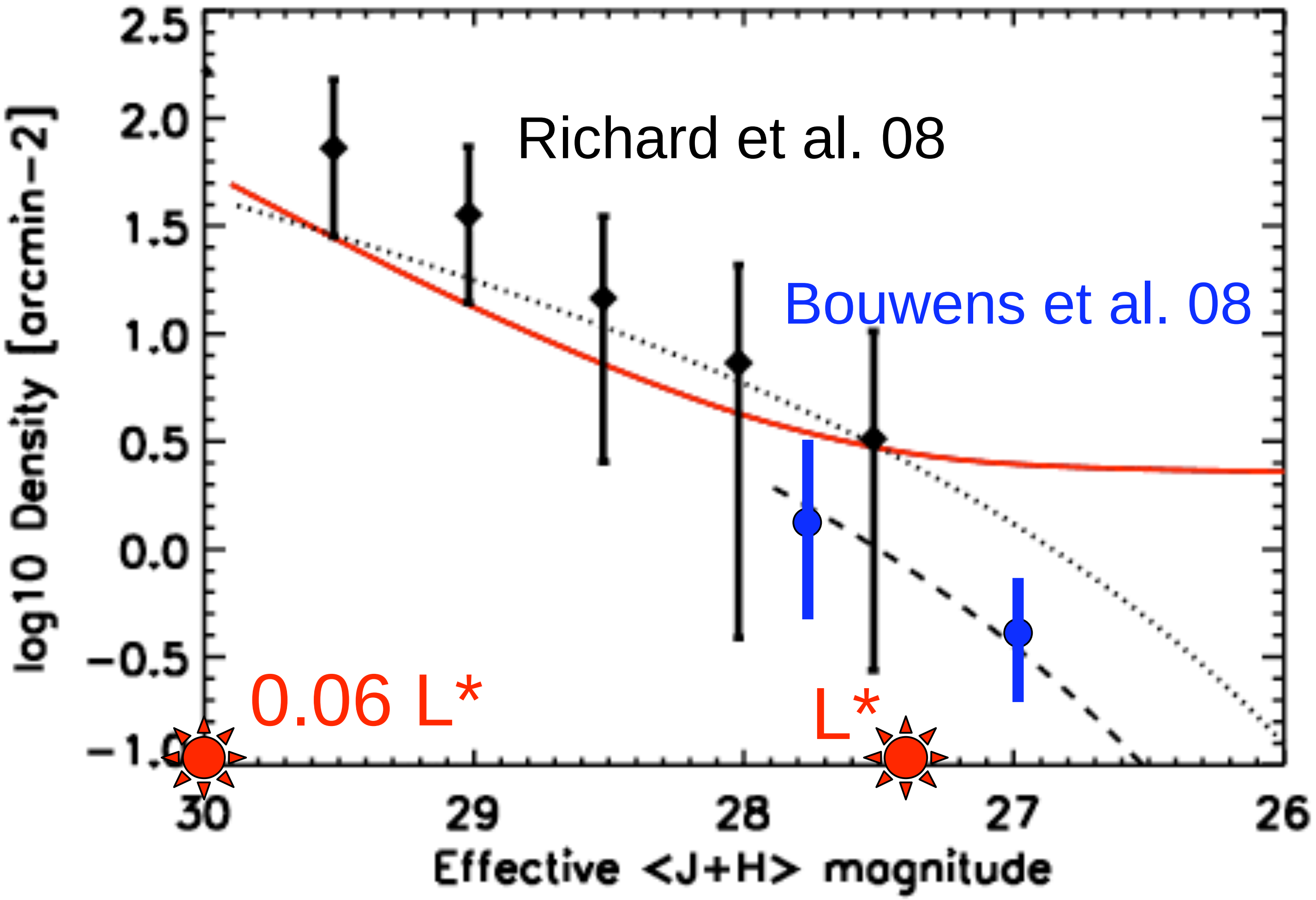
Optimization to follow-up both a candidate and its predicted counter-image



- 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%.

Derived Luminosity Function z~7.5



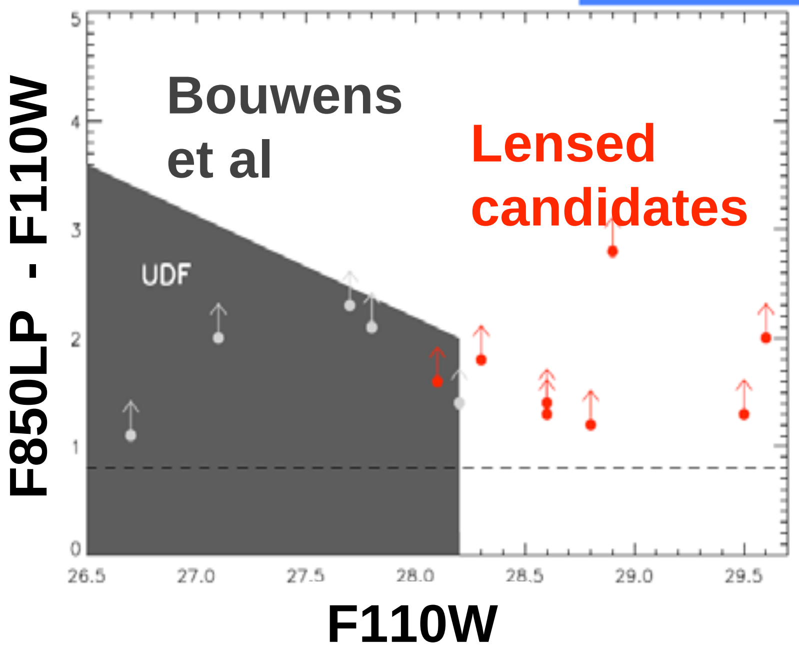
•No significant overlap between UDF and lensed survey - although in good agreement !

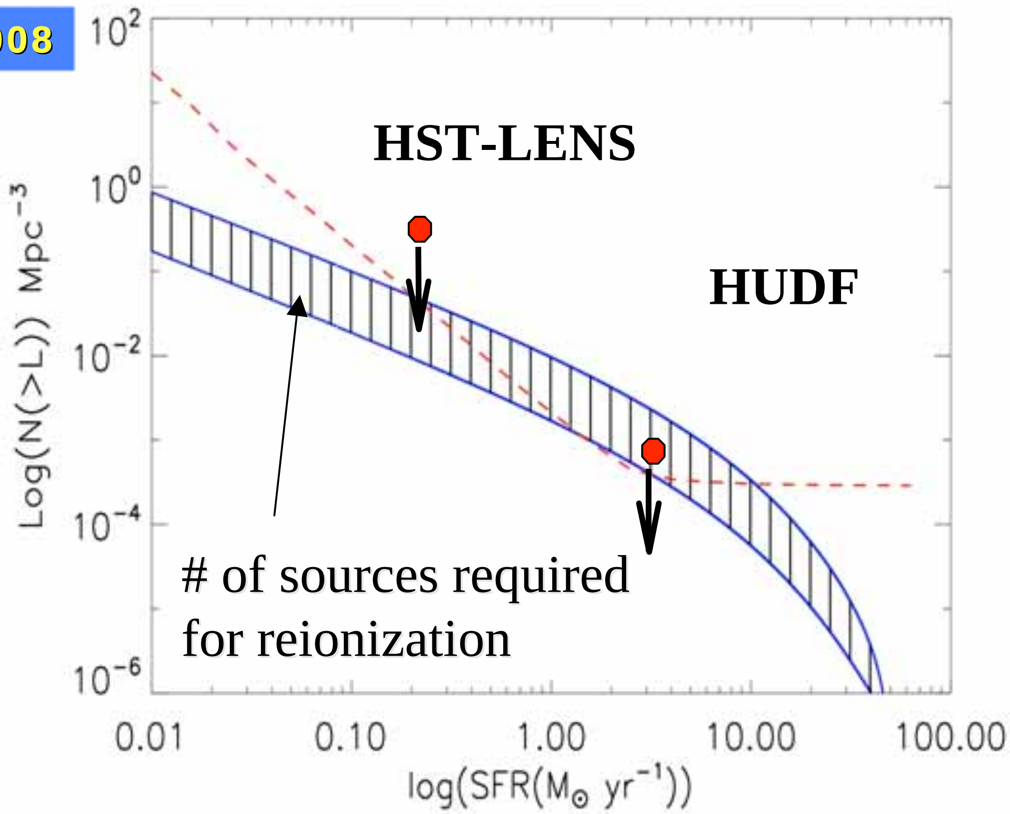
•Probing already 50% of the luminosity density !

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





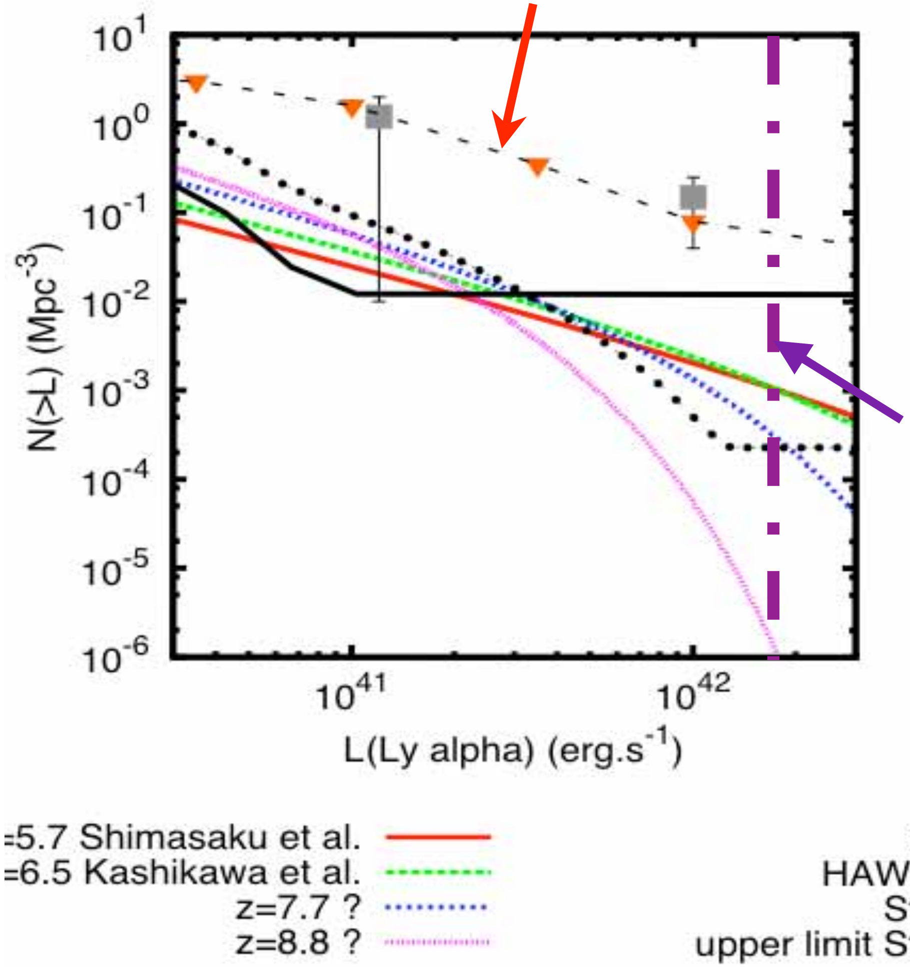
- **High surface density of z/J-drops (contamination to be checked)**
- **suggests *significant contribution to reionization from low luminosity galaxies***
- **lensing survey valuably extends constraints set by UDF**

Current Status

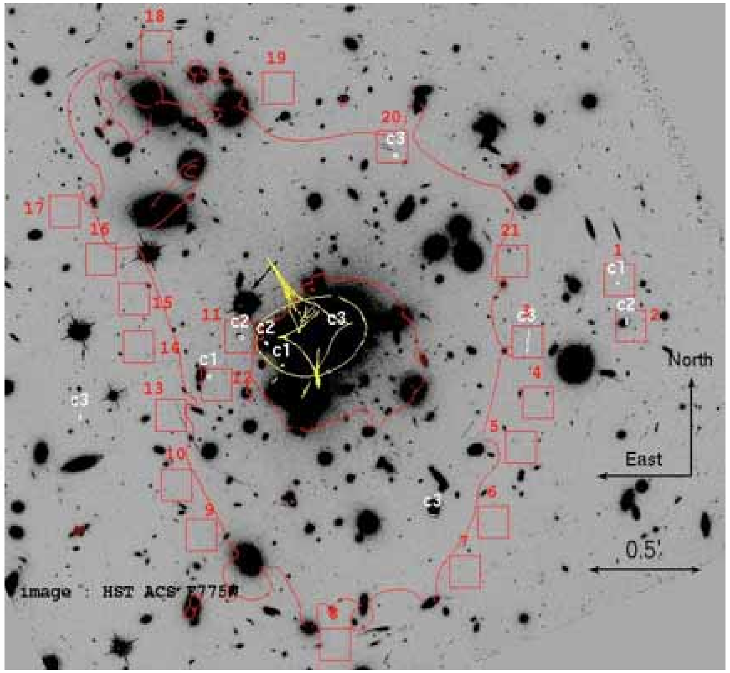
- Lensed z>7 searches provide complementary approach to blank field survey at lower cost (in observing time - not in terms of modeling !)
- Low-luminosity sources seem to be numerous and may contribute significantly to reionization

- Limited volume surveyed => very sensitive to cosmic variance
  - Need to increase number of cluster surveyed (~50 well-known massive cluster-lenses can be explored)
- Limited depth => some candidates may have biased photometry or even be spurious (lower-z, stellar objects etc)
  - Dedicate more time and use more efficient instruments/telescopes
- No strongly magnified and bright example yet found above z>8
  - Should be found eventually and will make possible detailed analysis

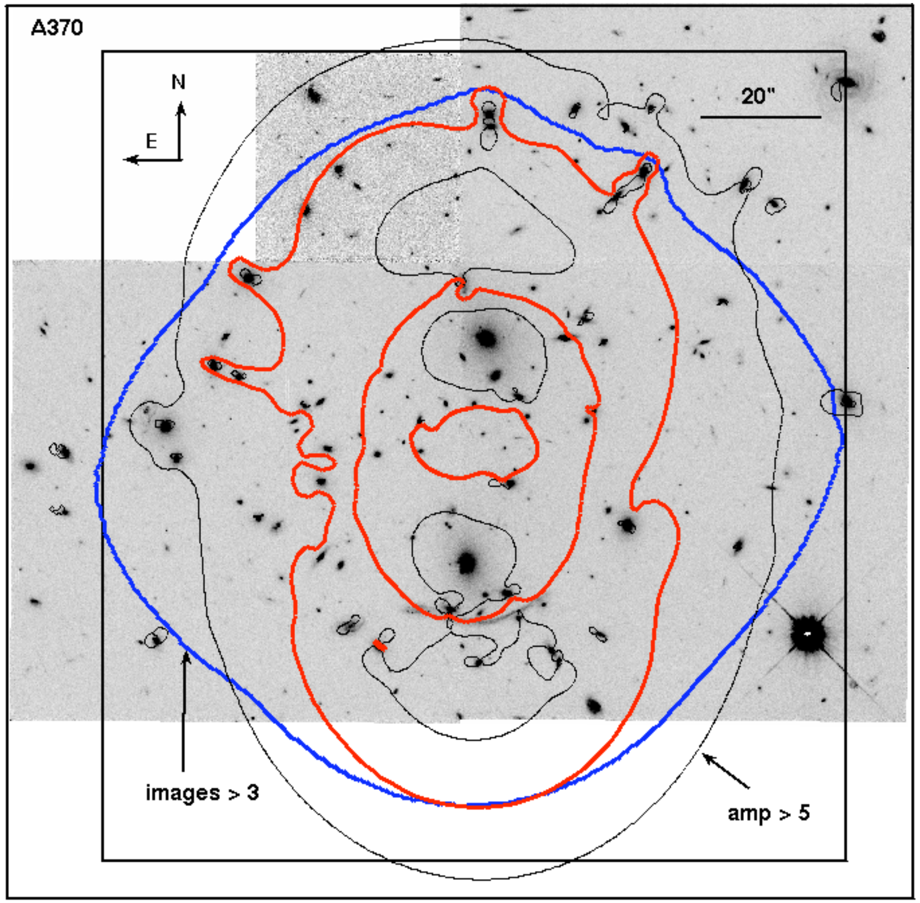
Future: LAE lensing survey

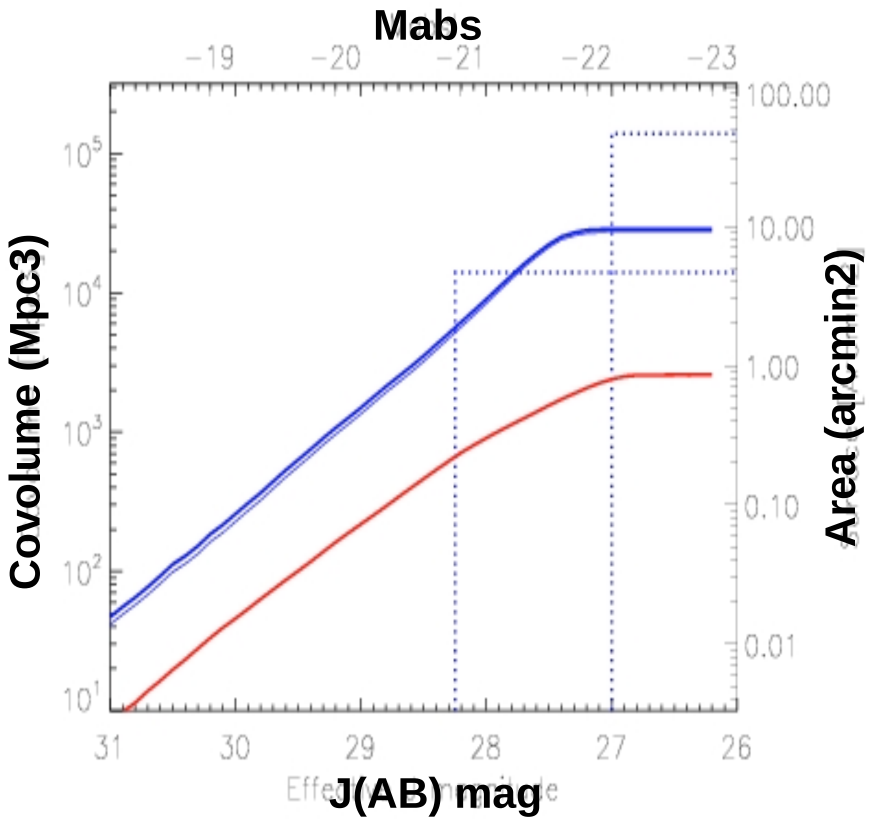


- Extend ZEN using Hawk-I (see **Courbin's Talk**); DAZLE
- Extend critical line mapping with SINFONI integral field spectrograph (Kneib et al) & Subaru MOIRCS (Egami et al)



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

Dotted blue: WFC3 field survey

Conclusion & Prospects

- Fast progress in identifying the most distant lensed galaxies, low-luminosity objects may play important role in the reionization.

- Further search are possible with the new facilities coming on line now and in the near future:
  - HAWK-I, HST/WFC3, VISTA, KMOS, JWST, JDEM/SNAP, TMT/ELT

- Short term projects: (identification of the first galaxies)
  - **LAE:** DAZLE in lensing clusters [some candidates],
    Hawk-I NB (Courbin's talk), SINFONI, MOIRCS spectroscopy
  - **LBG:** WFC3, Hawk-I (Pello's talk)
- Longer term projects: (physics of the first galaxies)
  - EMIR, MOSFIRE, KMOS
  - JWST/NIRSPEC+MIRI
  - SNAP/JDEM-SPACE (rarer objects - lensed z>7 QSOs)
  - ELT (EAGLE consortium to build a NIR multi-IFU spectrograph)