Studying the Very High Redshift Universe with Gravitational Telescopes

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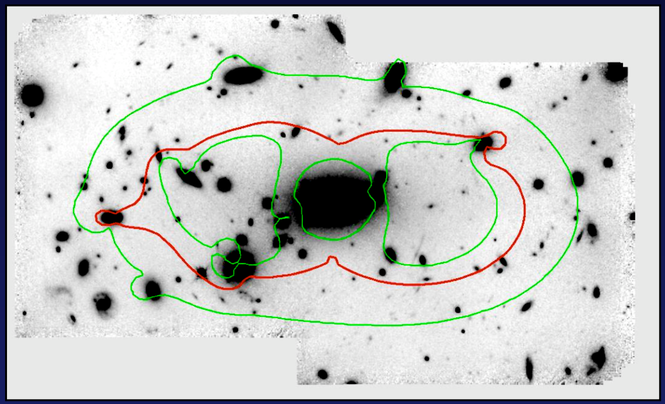
Outline

- Motivation : *towards the Dark Ages*
  - Use of **Lensing clusters** as Gravitational Telescopes
- Targetting z > 7 Galaxies with VLT/ISAAC
- Surveys towards the central regions of Massive Clusters
  - Search for lensed dropouts selected with HST (ACS/NIMOS)

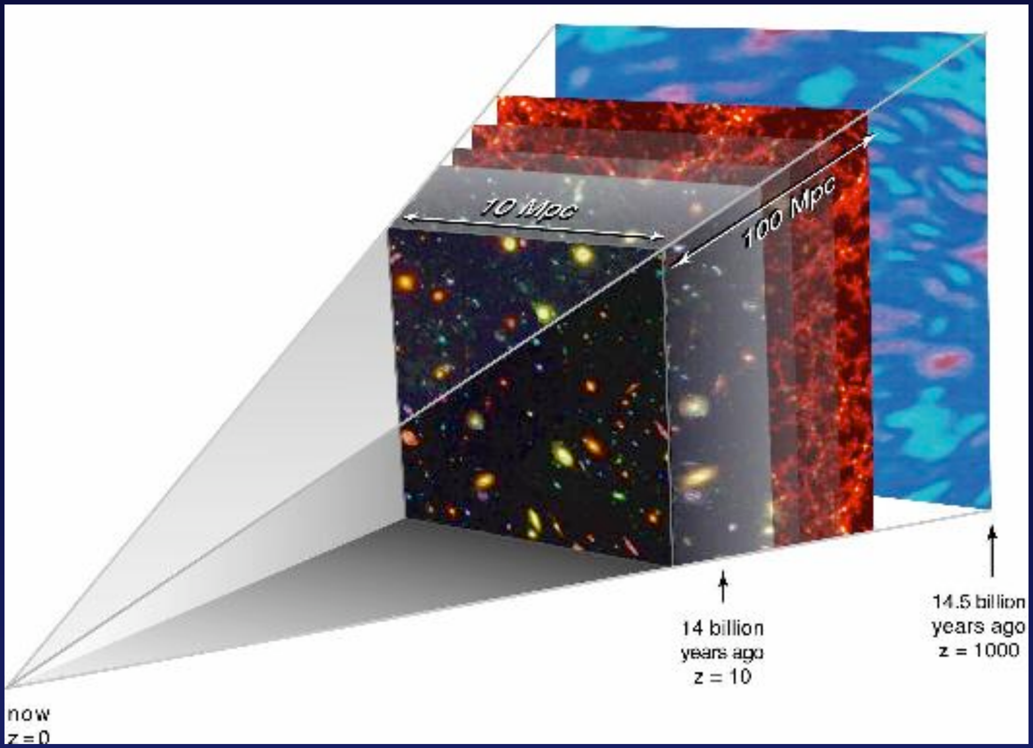


Motivation : end of the Dark Ages

- WMAP :
  Reionization epoch : z ~ 10-12 (Spergel et al. 2006)
- QSOs :
  I.G.M. fully reionized at z ~ 6 (Fan et al. 2002).

- Get constraints on :
  - Nature (stars, AGNs)
  - Physical properties
  - Formation epoch

of the sources responsible
for reionizing the IGM.



Identification of high redshift galaxies

Selection with Broad Band Filters
Lyman-Break Galaxies (LBG)

2.5 < z < 4.5 *Steidel et al (96 -> 05)*

Ex: Bouwens et al. 2004, z~7-8

Candidates at z~7-8 selected on HST/UDF field

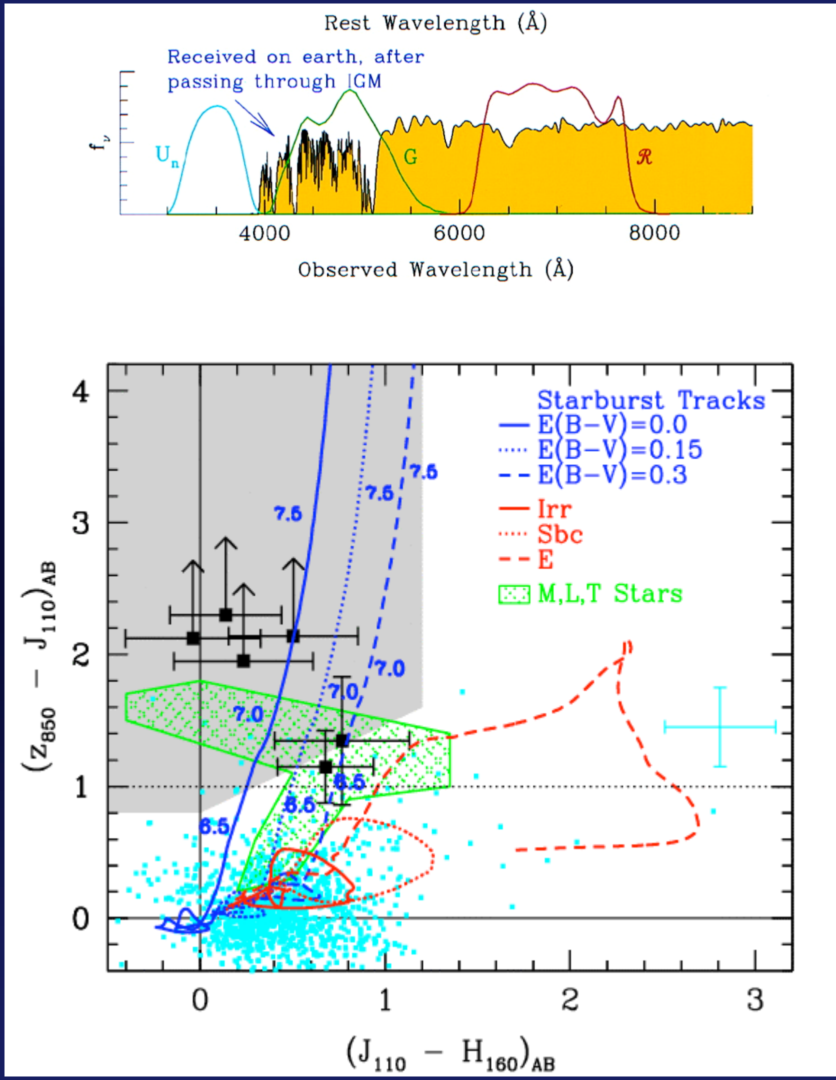
zJH photometry

Our current motivation is exploratory :

- no clear spectroscopic confirmation of a galaxy at z > 7
- number counts of earliest galaxies
- contribution of stellar formation to reionization

Complementary techniques :

- Study of photometric dropouts in optical/IR
- Use of strong lensing by massive clusters: extend these techniques to faint luminosities



Looking for z > 7 galaxies: prototypal observing program with VLT/ISAAC

Richard et al. 2003, Pello et al. 2004, Richard et al. 2006
See also talk by Roser Pello

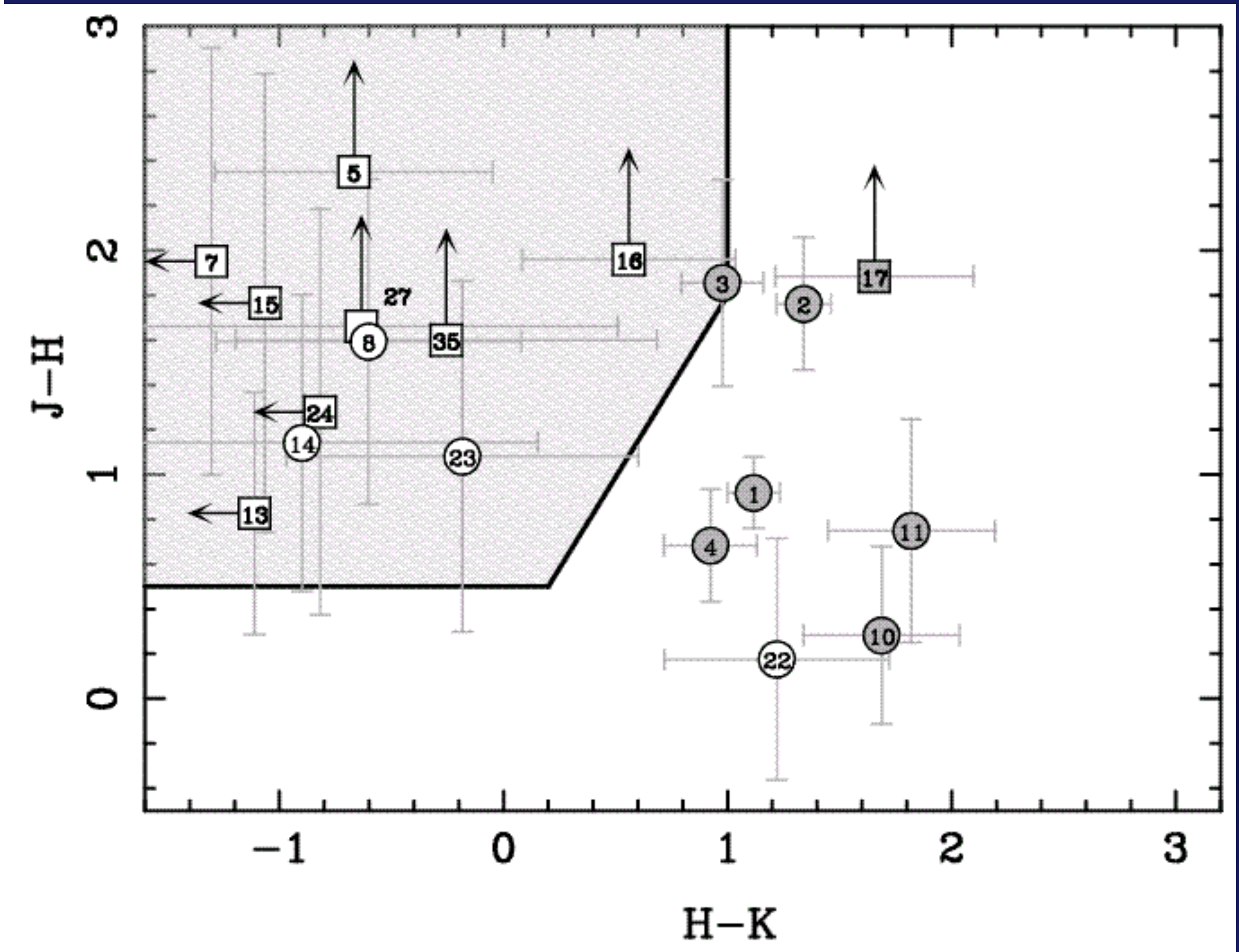
- Main features in NIR part of the spectrum
- science case of future massive field surveys

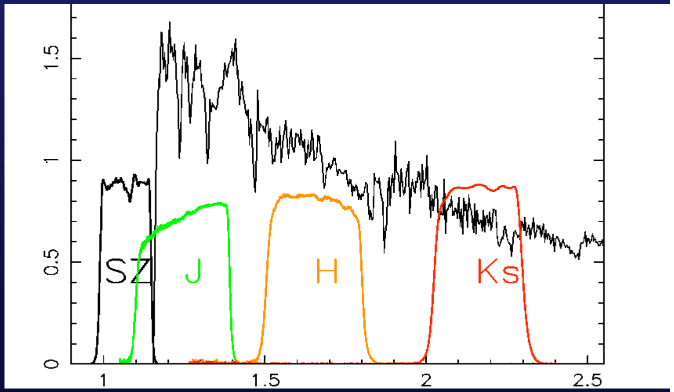
  (EMIR/GTC, KMOS/VLT2, JWST...).

- Magnification factor $\Delta m \sim 0.5 - 3$ magnitudes in the core of 2 lensing clusters : *A1835* et *AC114* (intermediary to strong regime)
- Photometric selection of candidates with ultra-deep ISAAC/VLT (SZ,J,H,K) + optical photometry, including HST images (unresolved sources).
- Sample: J < 26.5, H < 26.5 and Ks < 26.5 to 27.0 (AB),

  + 0.5-3 mags magnification.
- Spectroscopic follow-up of candidates (ISAAC/VLT).

Color-Color Selection of (z/I) dropouts





- (J-H) (H-Ks) : *8 < z < 10*
- (SZ-J) (J-H) : *7 < z < 8.5*
- (z-SZ) (SZ-J) : *6 < z < 7.5*

+ Photometric Redshift Estimate

HyperZ

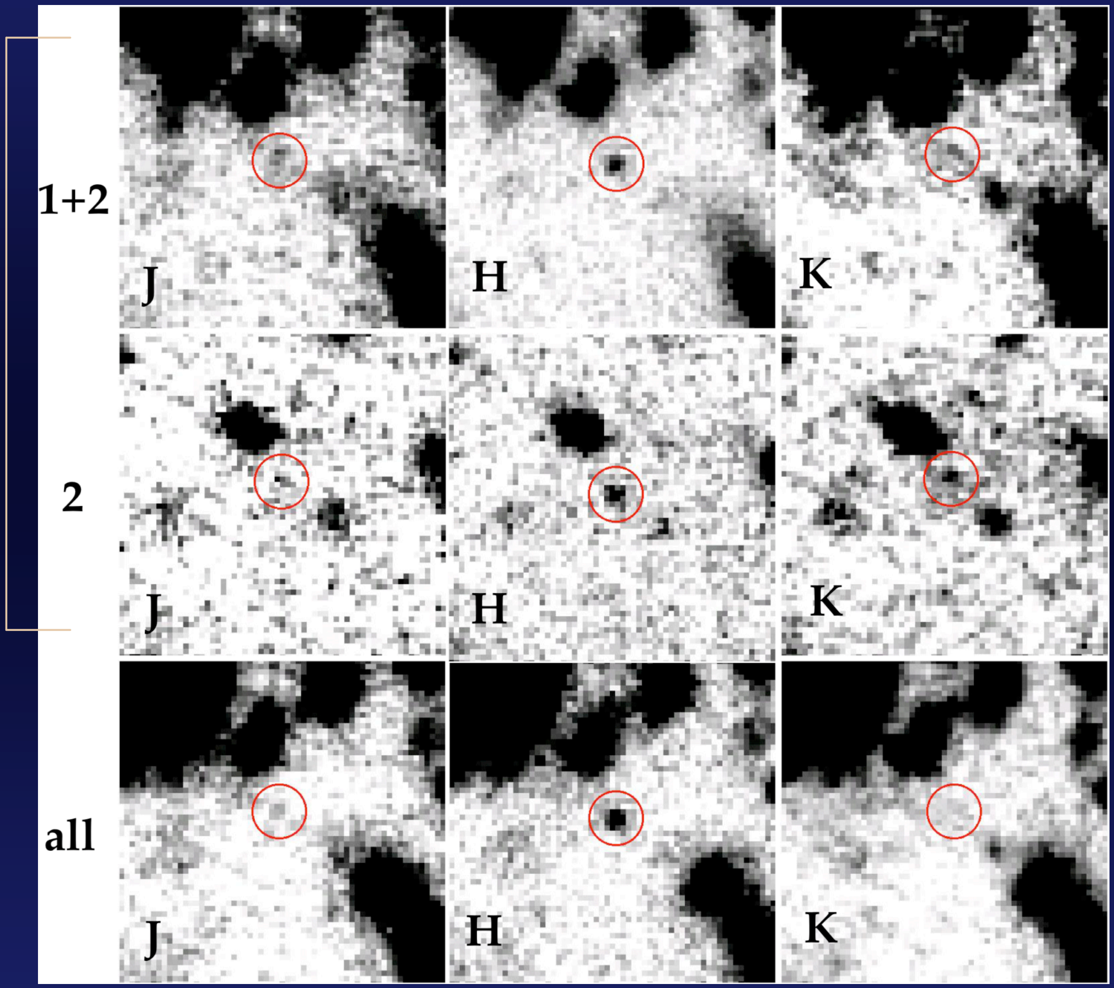
Photometric selection VLT/ISAAC : candidates

Richard et al. 2006

First priority :

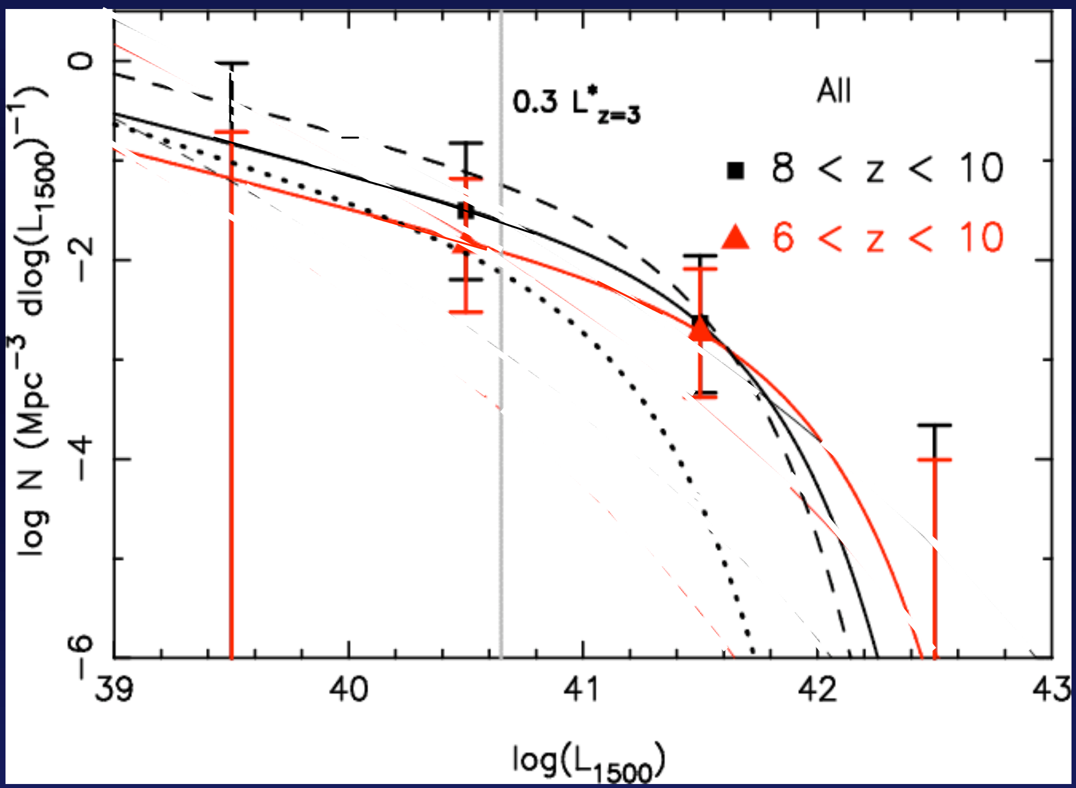
- 1 : $\Delta m(H) < 0.4$
- 2 : $\Delta m(H) > 0.4$

All candidates



UV Luminosity Function

L_{1500} Schechter Luminosity Function fit, α=1.6



Steidel et al. 99
(z ~ 4)

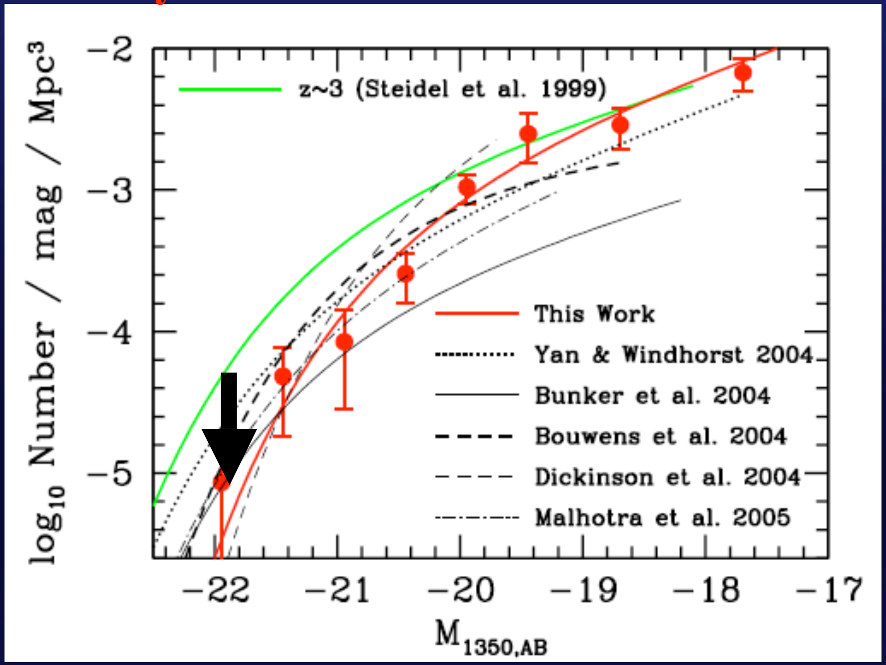
Bouwens et al. 06
(z ~ 6)

Difference between Steidel (z~4) and Bouwens (z~6) LFs not seen at high luminosities

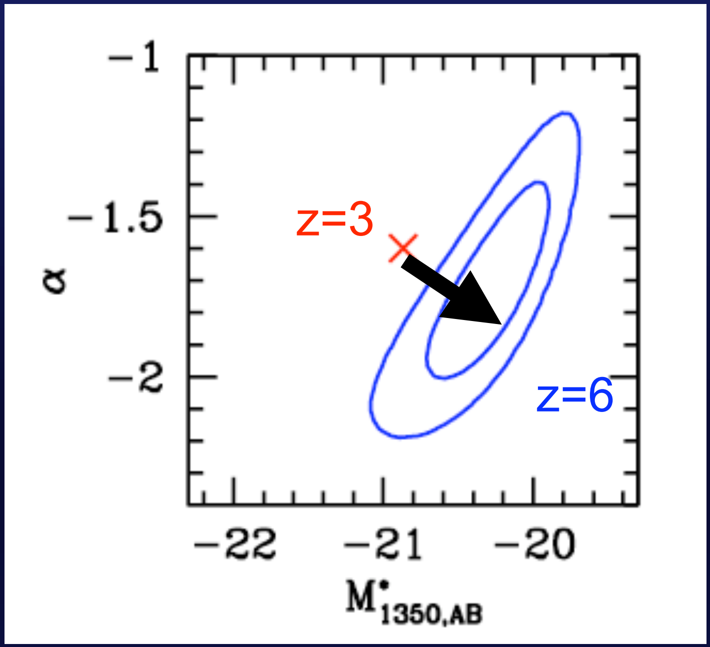
Results hard to reproduce with semi-analytical models (Samui et al 2007, Stark et al. 2007b)

Evidence for Luminosity-Dependent Evolution

Luminosity Function Bouwens et al. 2006



Schechter parameters



L-dependent evolution, constraints quite poor on the slope

- decline in abundance over 3 < z < 6 *mostly for luminous sources.*

It is unclear whether we have enough UV radiation to reionize the Universe

Q: Is star formation increasingly dominated by low luminosity sources for z>6?

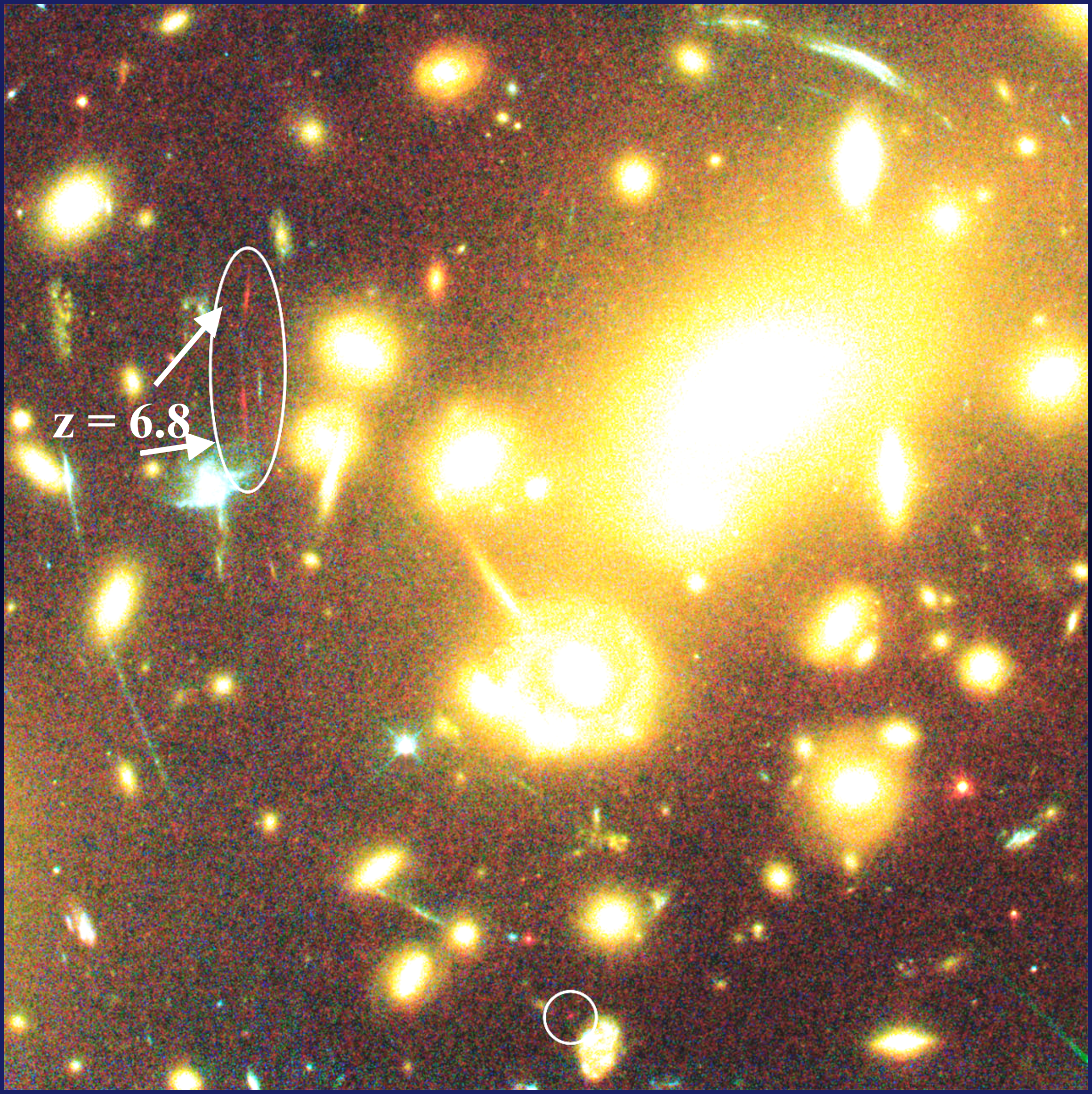
Beyond z~6 with Strong Gravitational Lensing

Kneib, Ellis, Santos, Richard 2004:

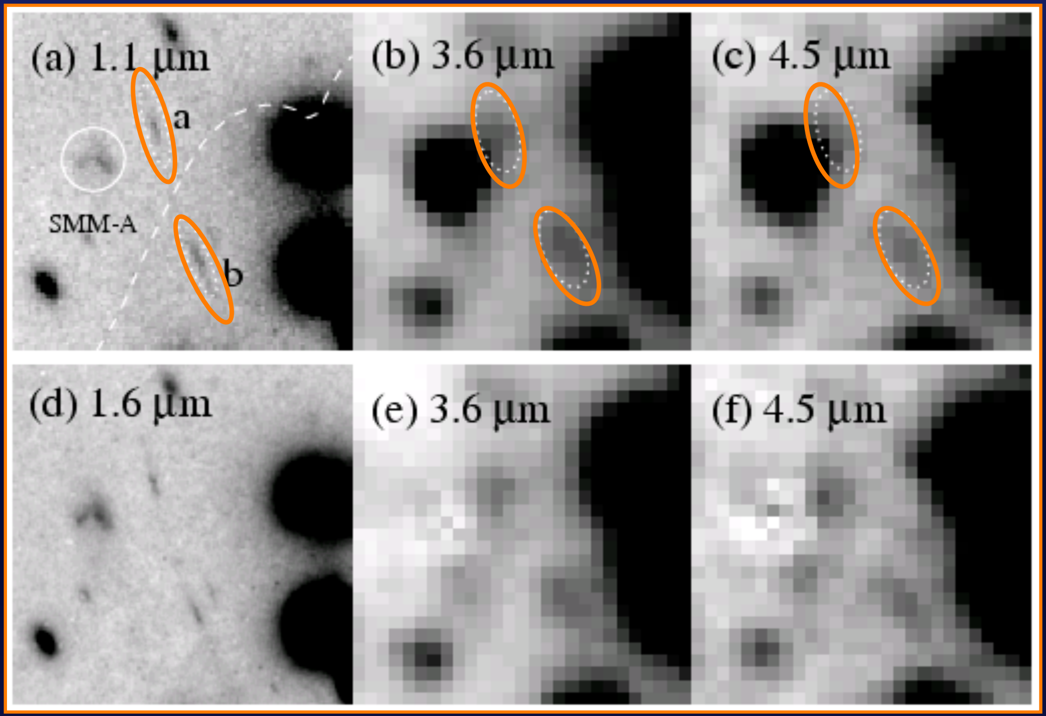
z ~ 6.8   I-dropout

Confirmed with the well-constrained lensing model + photometric redshift

(No Ly-α emission detected)



Detection of the z~7 object with SPITZER



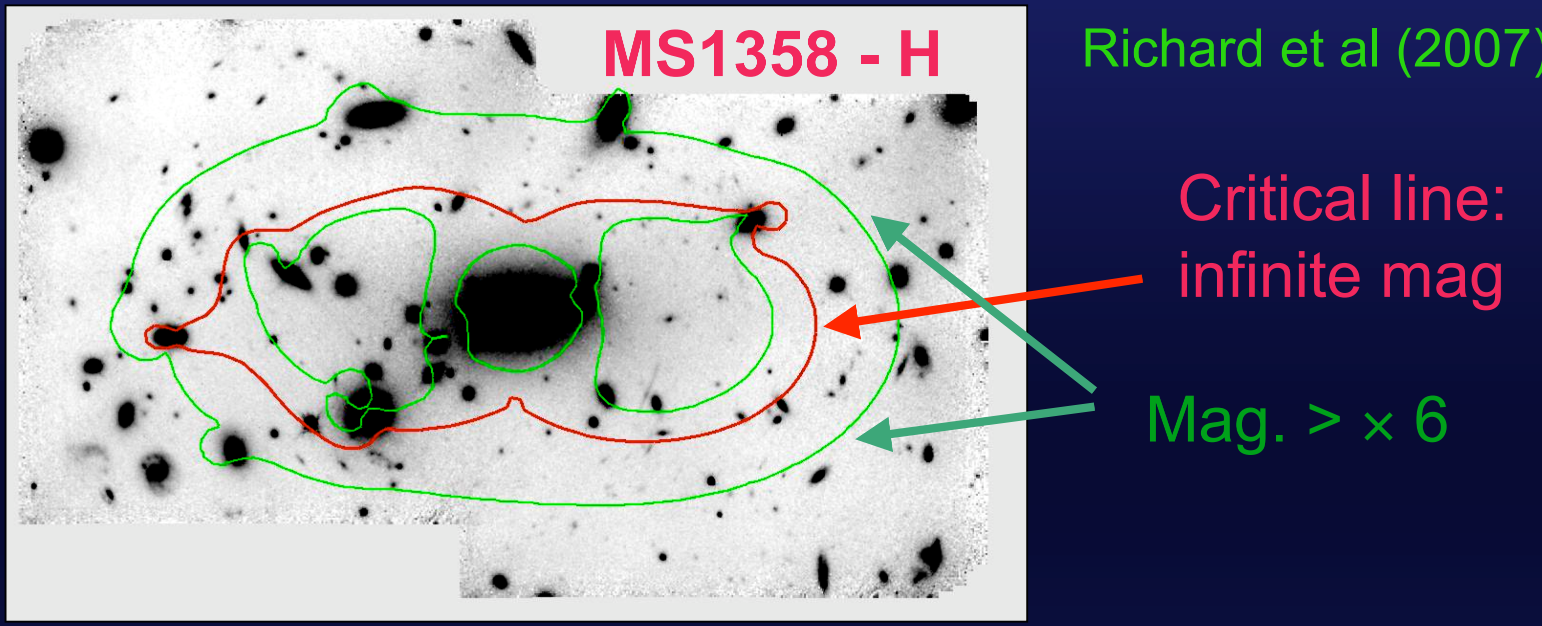
(SMM source substr.)

Detection of both images at λ> 4000 Å (Rest-frame) :

➔ study of detailed physical properties

(Egami, Kneib, Rieke, Ellis, Richard et al. 2005, ApJL)

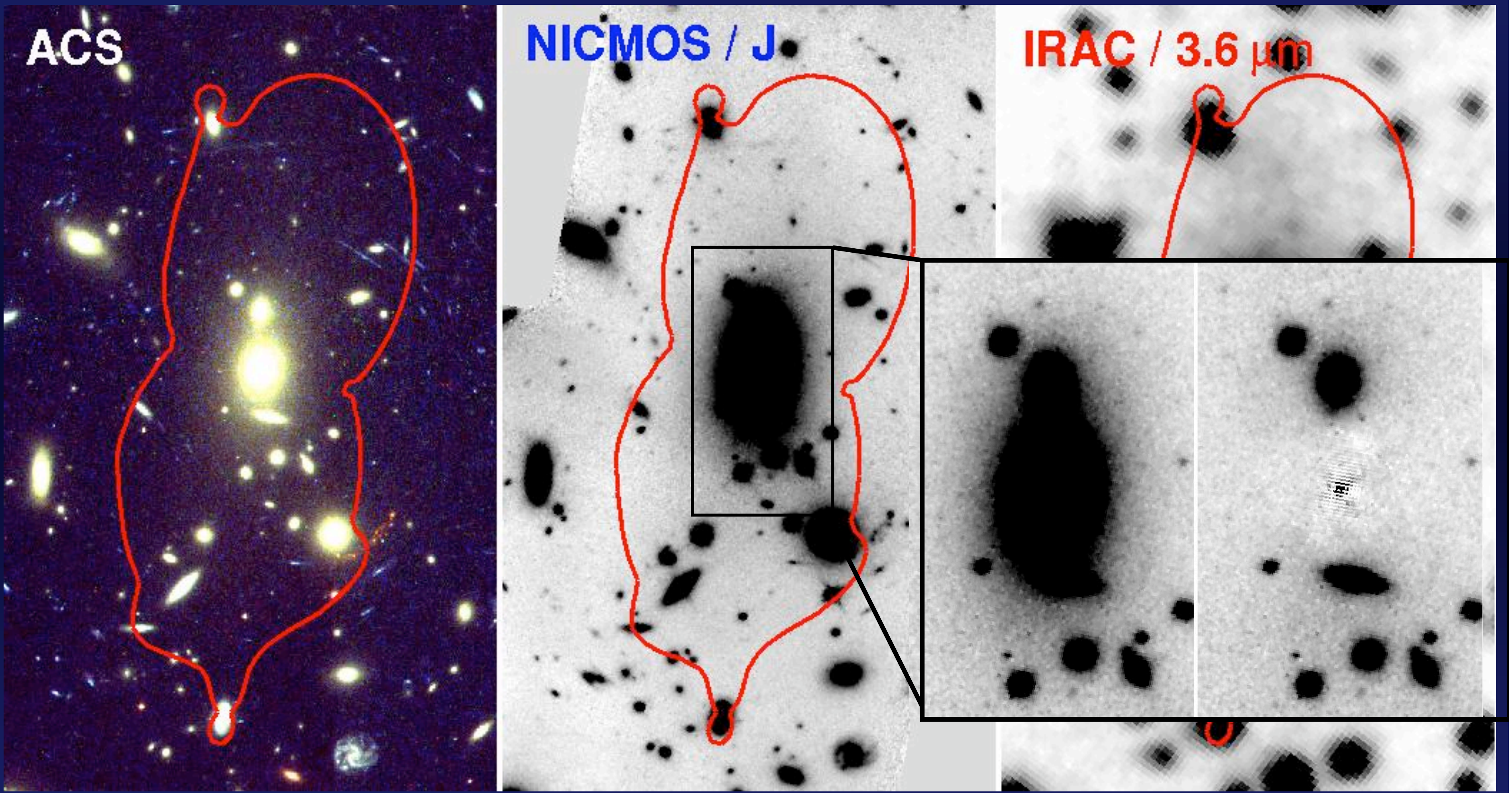
Searching for Lensed Dropouts with HST/Spitzer



- 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

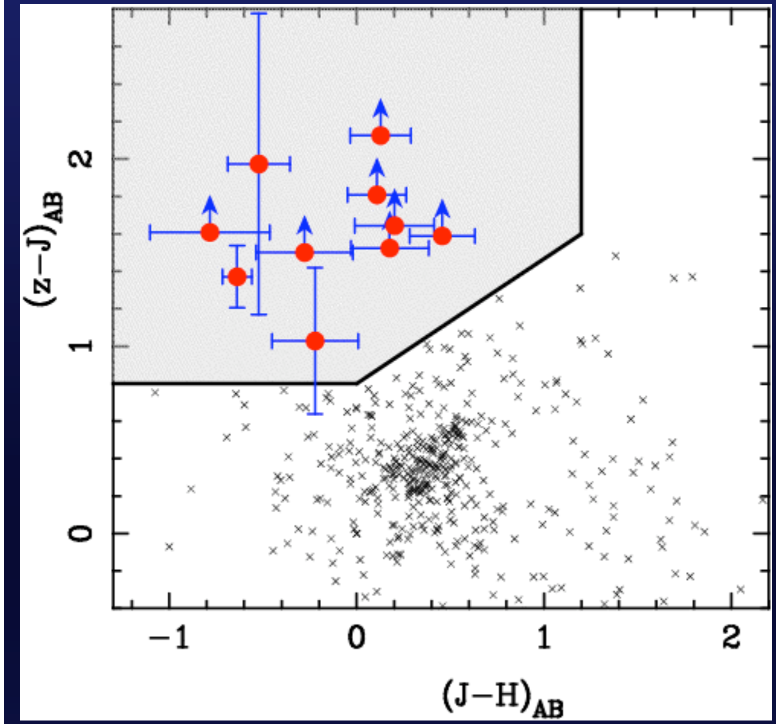
Combining ACS, NICMOS & Spitzer

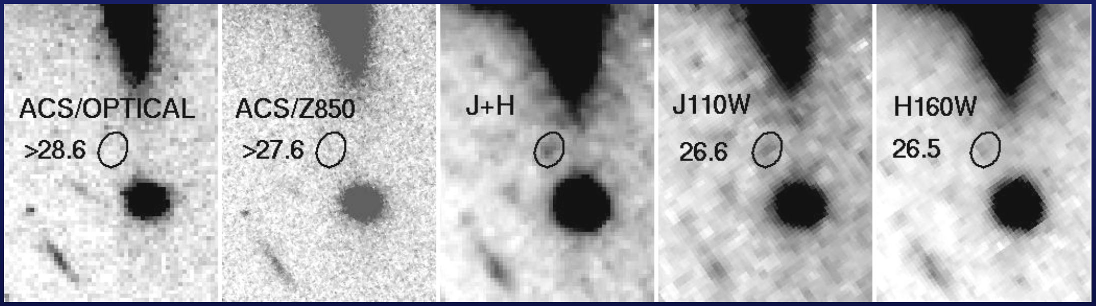
MS1358: 5σ limit: J_{AB}=26.7, H_{AB}=26.7

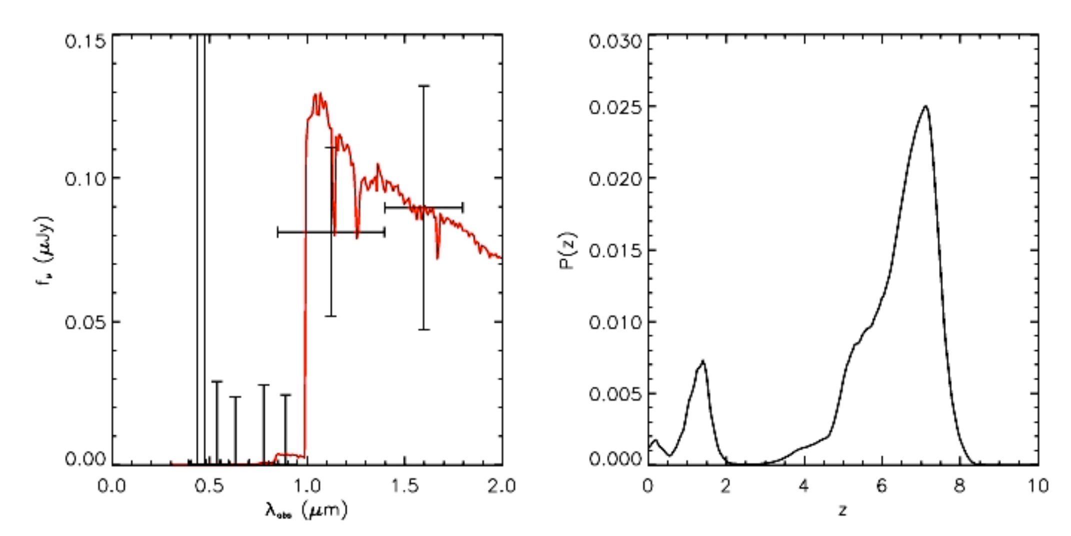


Importance of foreground removal

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

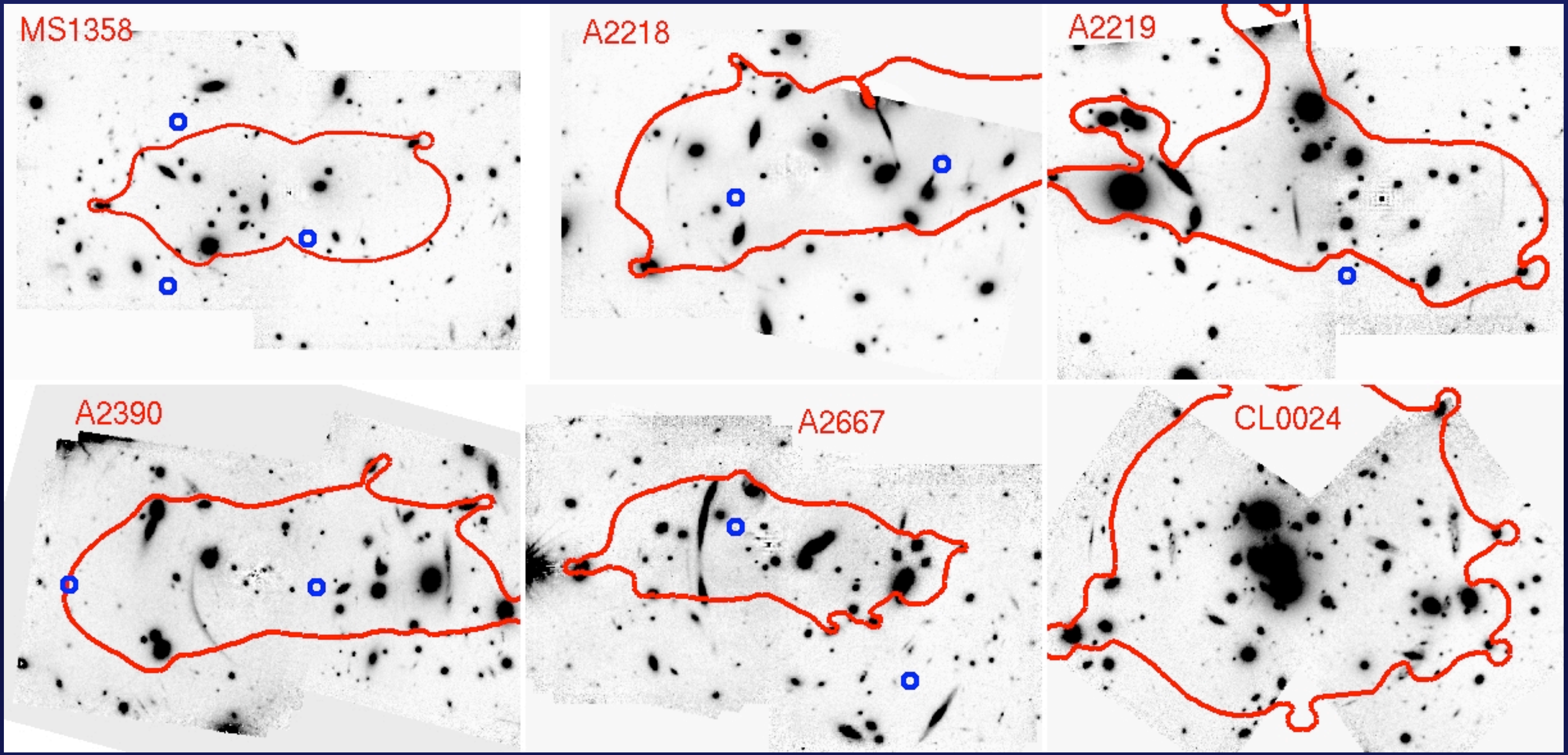






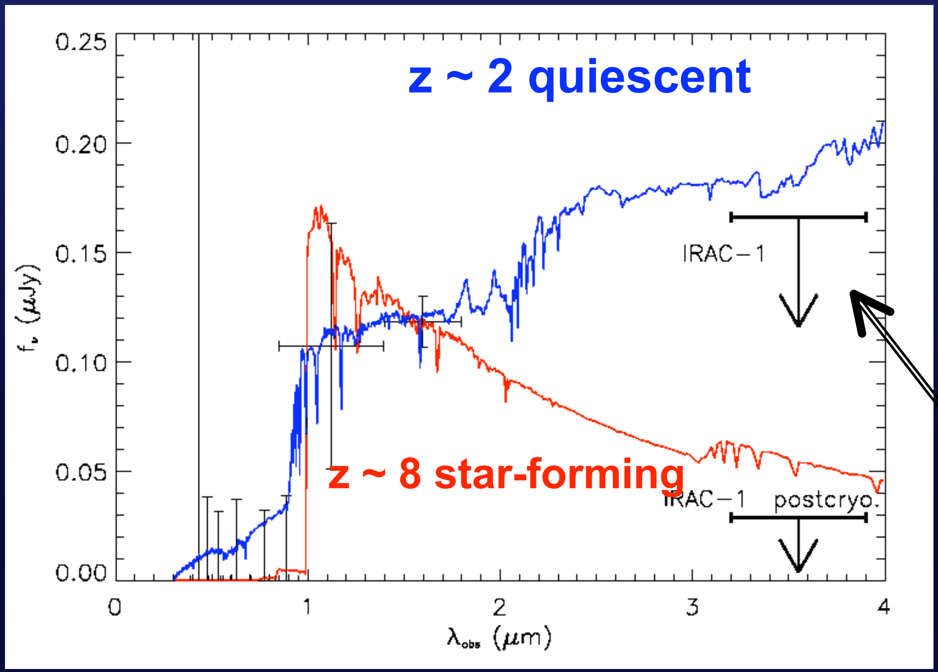
- **10 candidate z-drops in the 6 clusters surveyed with H ~ 26 - 26.8**
- **Implied SFR ~ 0.1 - 2 $M_\odot$ yr^{-1} (unlensed)**
- **Spectroscopic follow-up with NIRSPEC**
- **z~1-2 red galaxies expected to be main contaminants**

Angular Distribution of Candidates



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

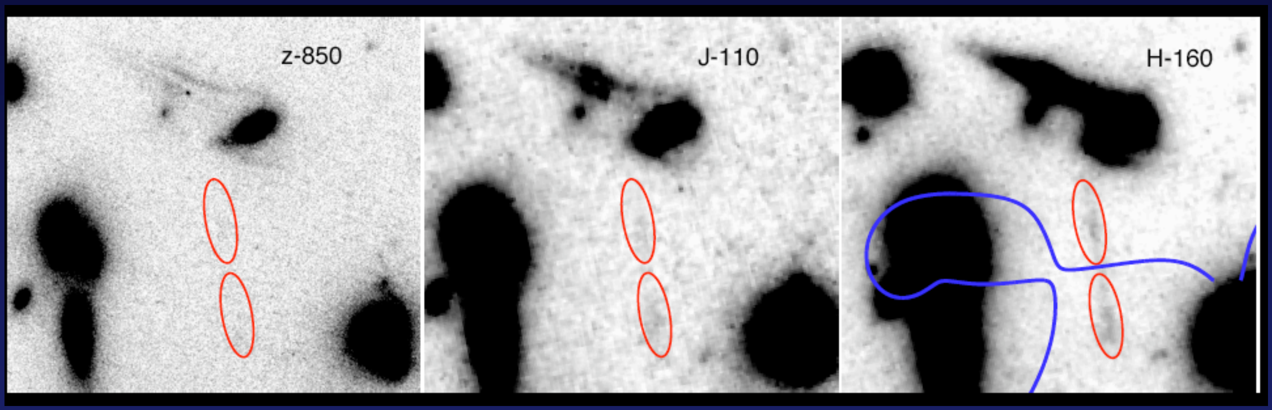
Bulk of candidates unlikely to be z~2 interlopers



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

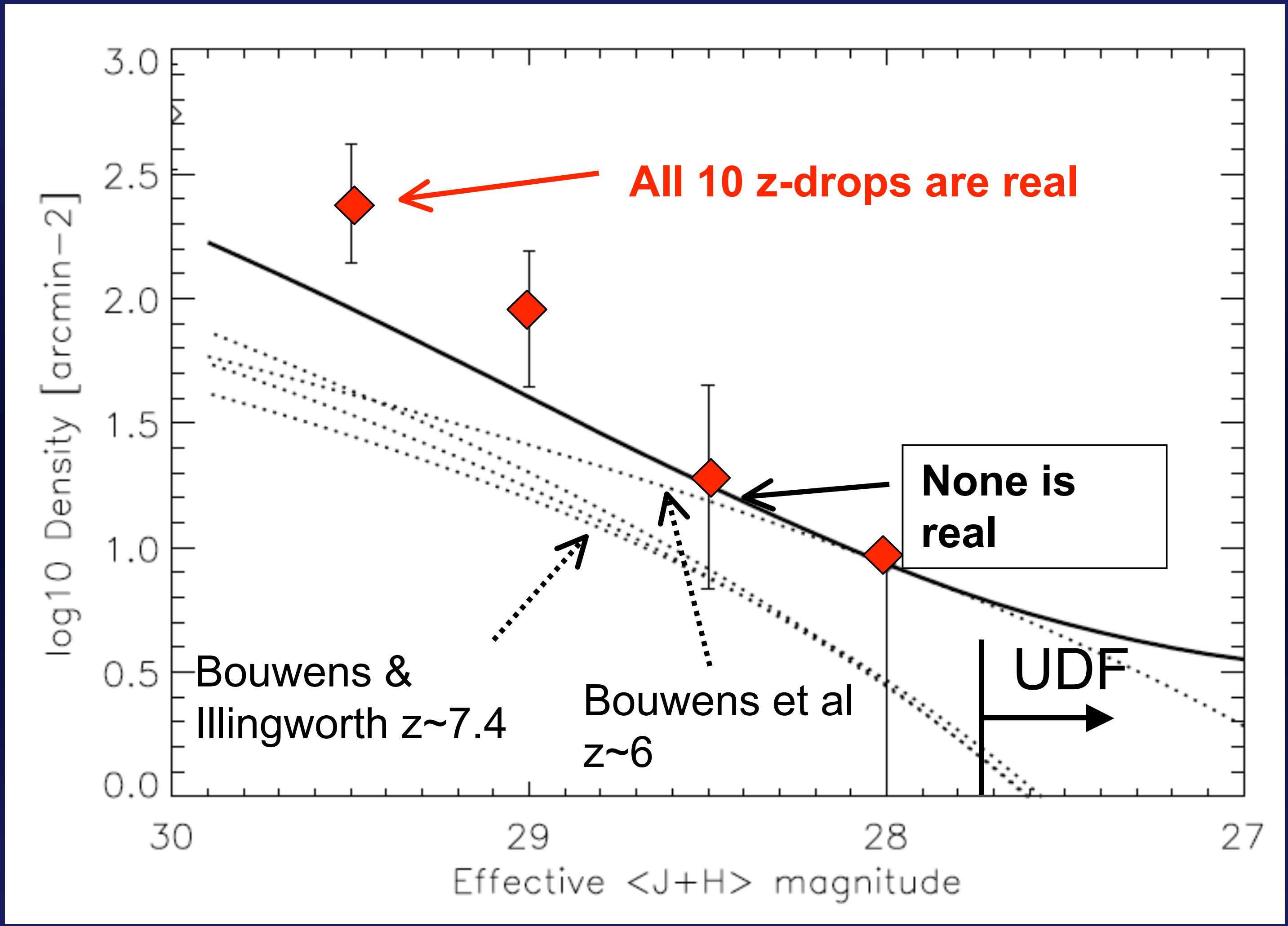
Current limit

Possible limit in warm mission



Proof of Method: we do see z~2 multiple sources…

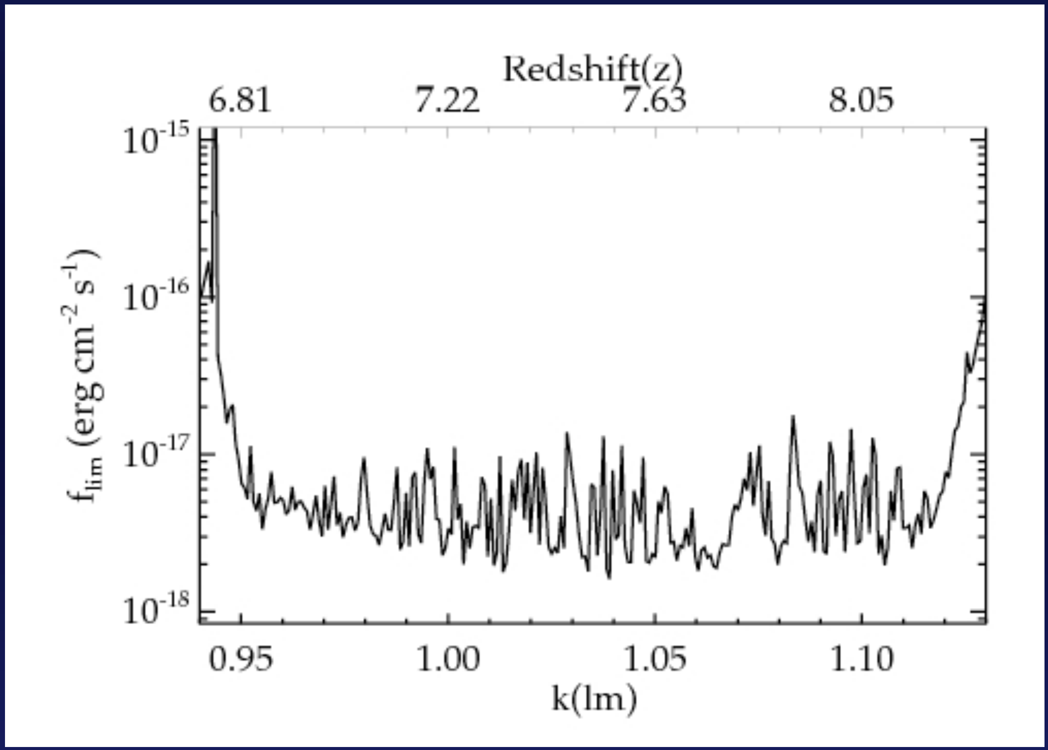
Implied Luminosity Function z~7.5



No significant overlap between UDF and lensed survey

Keck/NIRSPEC spectroscopic follow-up

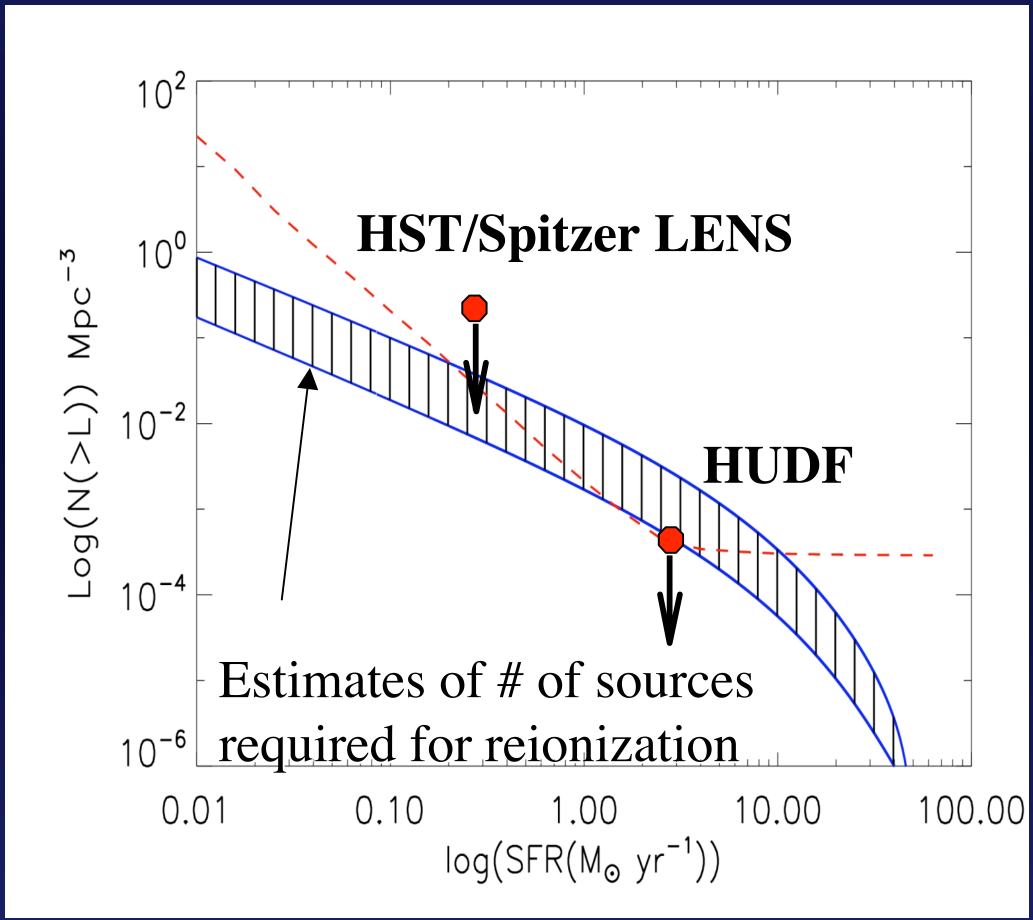
Optimization to follow-up both a candidate and its predicted counter-image



- 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 6 candidates

Sensitivity to lyman α flux: we would detect an emission line at 5 sigma downto an espace fraction between 20 and 40%.

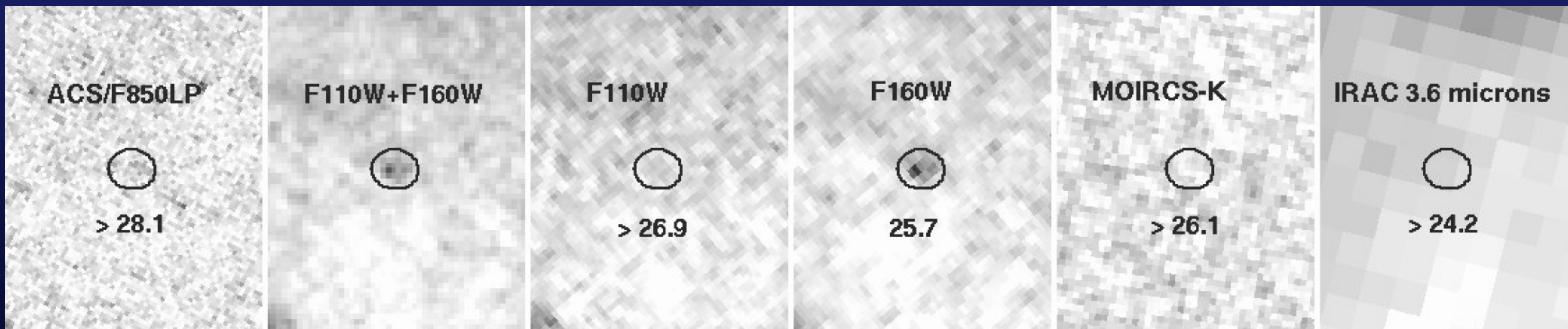
Implications for Reionization from Lensed Dropouts



- 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, c.f. talk by Richard Ellis)

Galaxies at z ~ 10



- Selection criterion : J-H > 1.8
- 2 good candidate J-drops all 6 clusters, each with H_{AB}~25.5 - 25.7
- SFR ~ 0.1 - 1 $M_{\odot}$ yr^{-1} (unlensed)
- Now verifying detections in K-band with Keck/Subaru

Summary

• Evidence for early star formation beyond z ~ 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 ~ 7-10, with SFR < ~ 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