Studying the Very High Redshift Universe with Gravitational Telescopes

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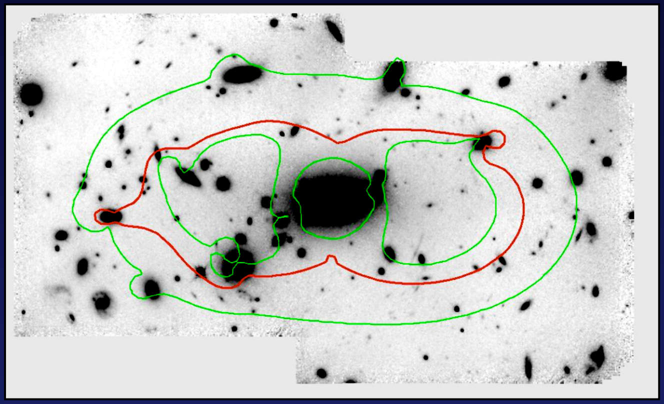
Outline

- Motivation : *towards the Dark Ages*
  - Use of **Lensing clusters** as Gravitational Telescopes

- Search for lensed dropouts with HST (ACS/NIMOS)
  - **Photometric selection and dropout candidates**
  - **Reliability and redshift estimation**
  - **Spectroscopic follow-up**
  - **Implications**

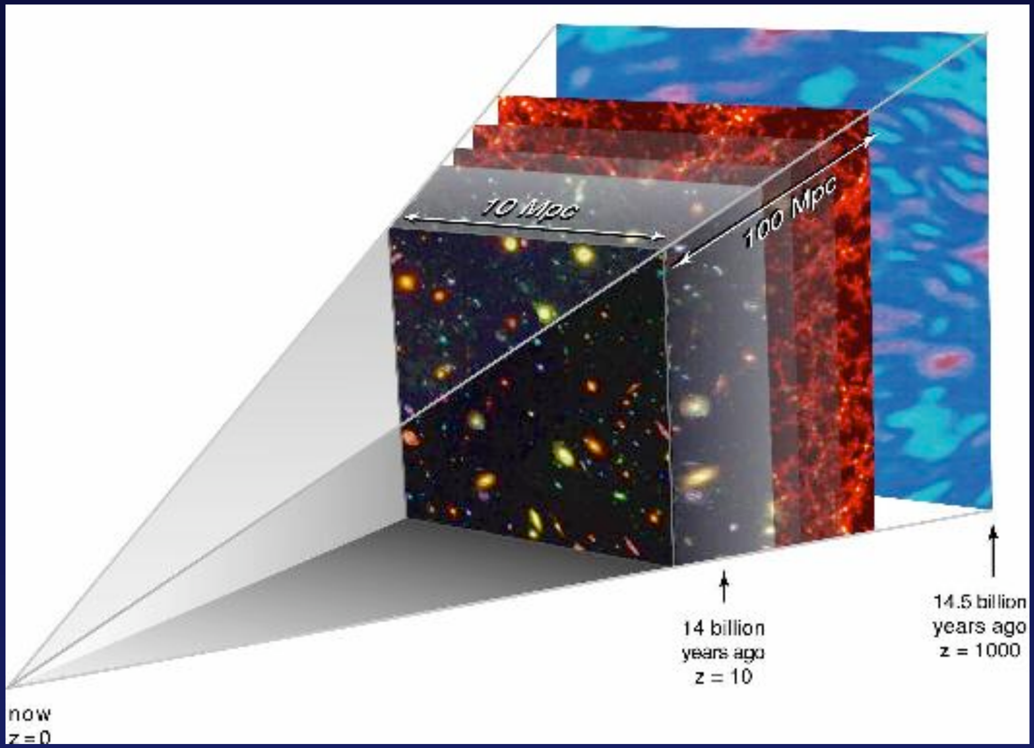


Motivation : end of the Dark Ages

- WMAP :
  Reionization epoch : z ~ 10-12
- QSOs :
  I.G.M. fully reionized at z ~ 6

- 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, 2006, z~7-8

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

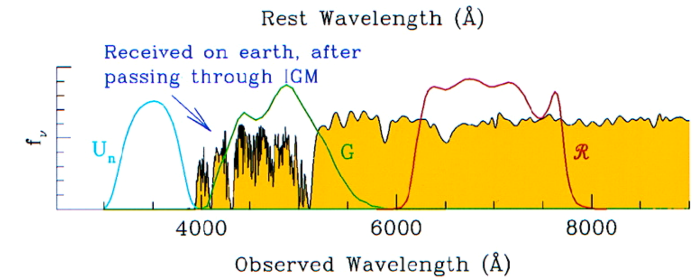
zJH photometry

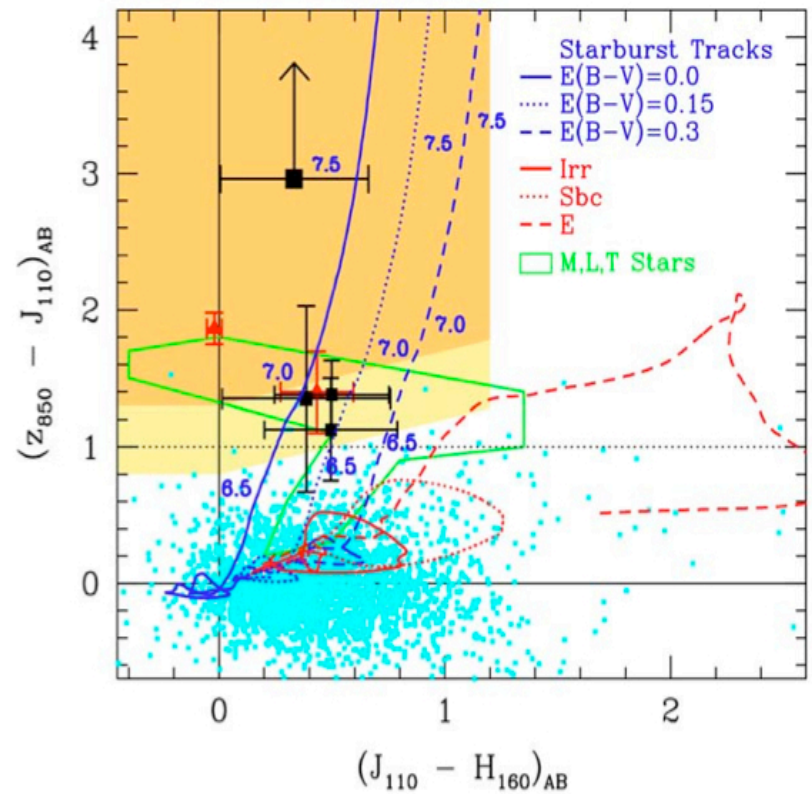
Our current motivation is exploratory :

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

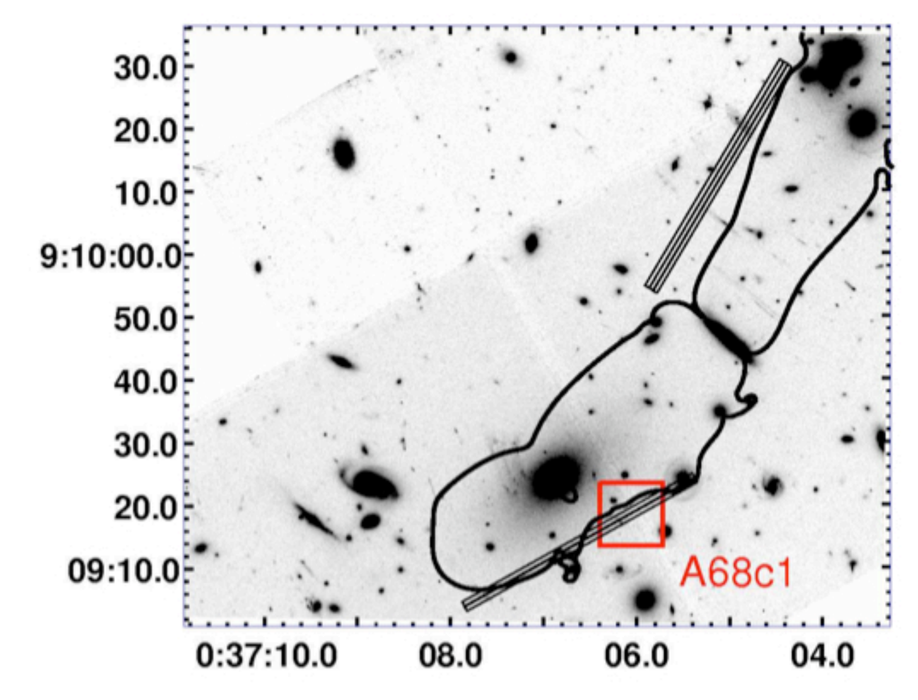
Techniques used:

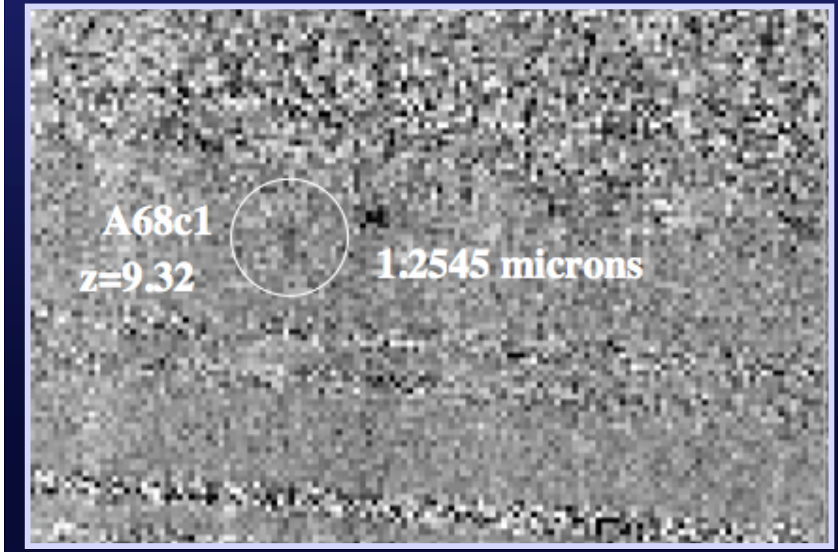
- Study of photometric dropouts
- Use of strong lensing by massive clusters: extend these techniques to faint luminosities





Strongly-lensed Lyman-α emitters : Stark et al. 07





Systematic survey with NIRSPEC/Keck of the critical lines in 10 redshift clusters, produced 6 Lyman-α candidates at $8.5 < z < 10.4$

$\Rightarrow$ high density of low luminosity SF galaxies at $z \sim 10$?

We would like to check this with another technique: **lensed dropouts**.

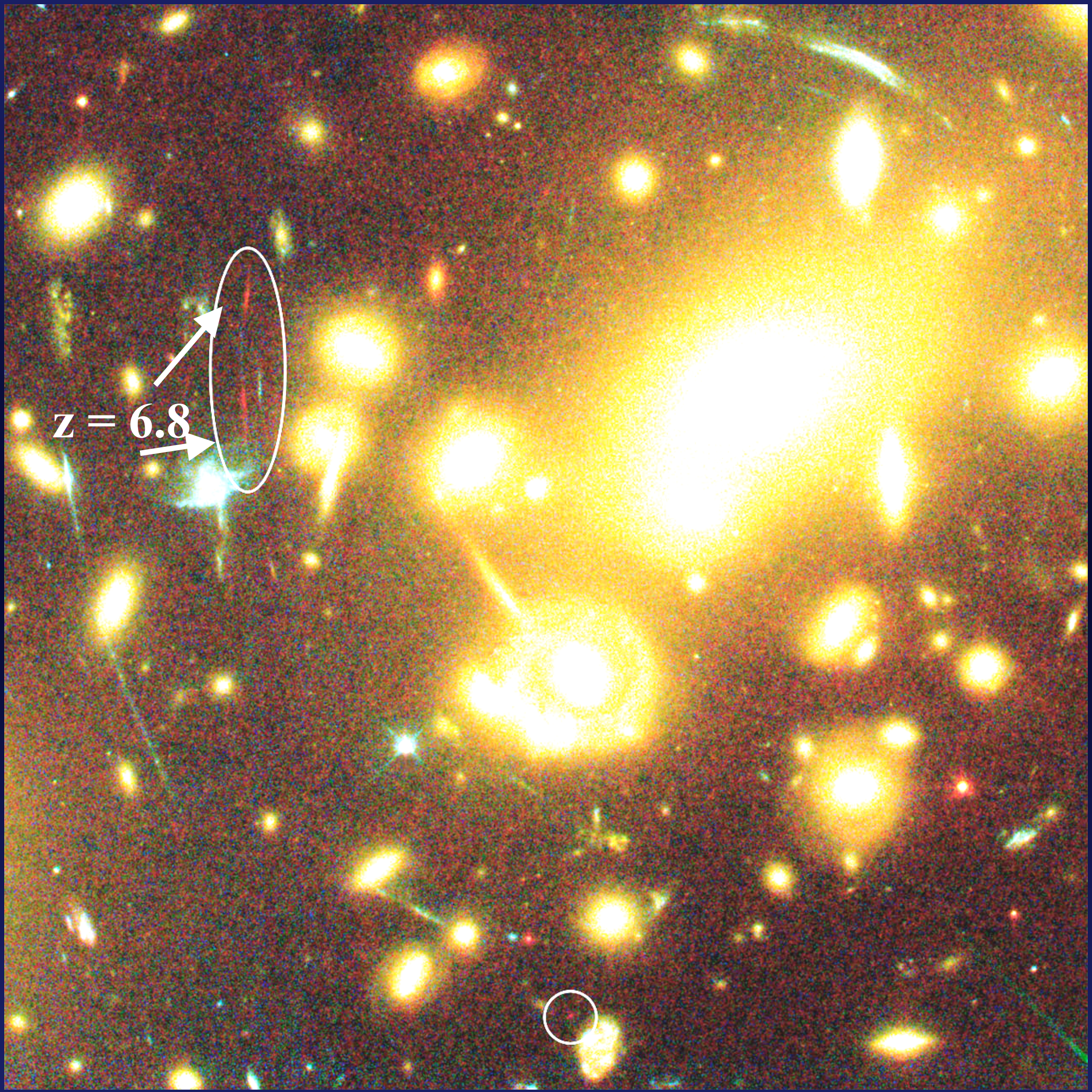
Beyond z~6 with Strong Gravitational Lensing

Kneib, Ellis, Santos, Richard 2004:

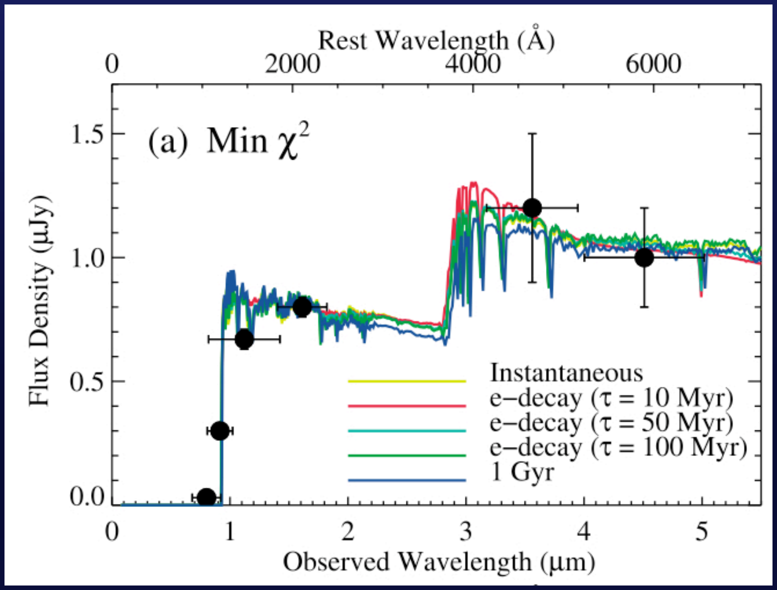
z ~ 6.8 I-dropout

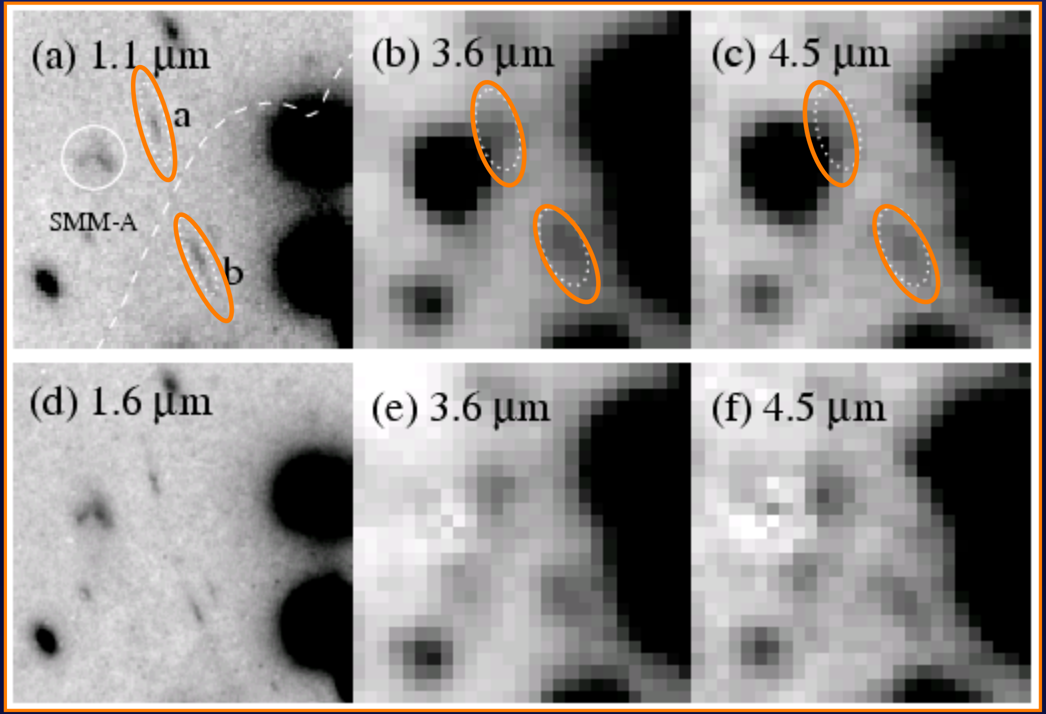
Confirmed with the well-constrained lensing model + photometric redshift

(No Ly-α emission detected)



Detection of the z~7 object with SPITZER



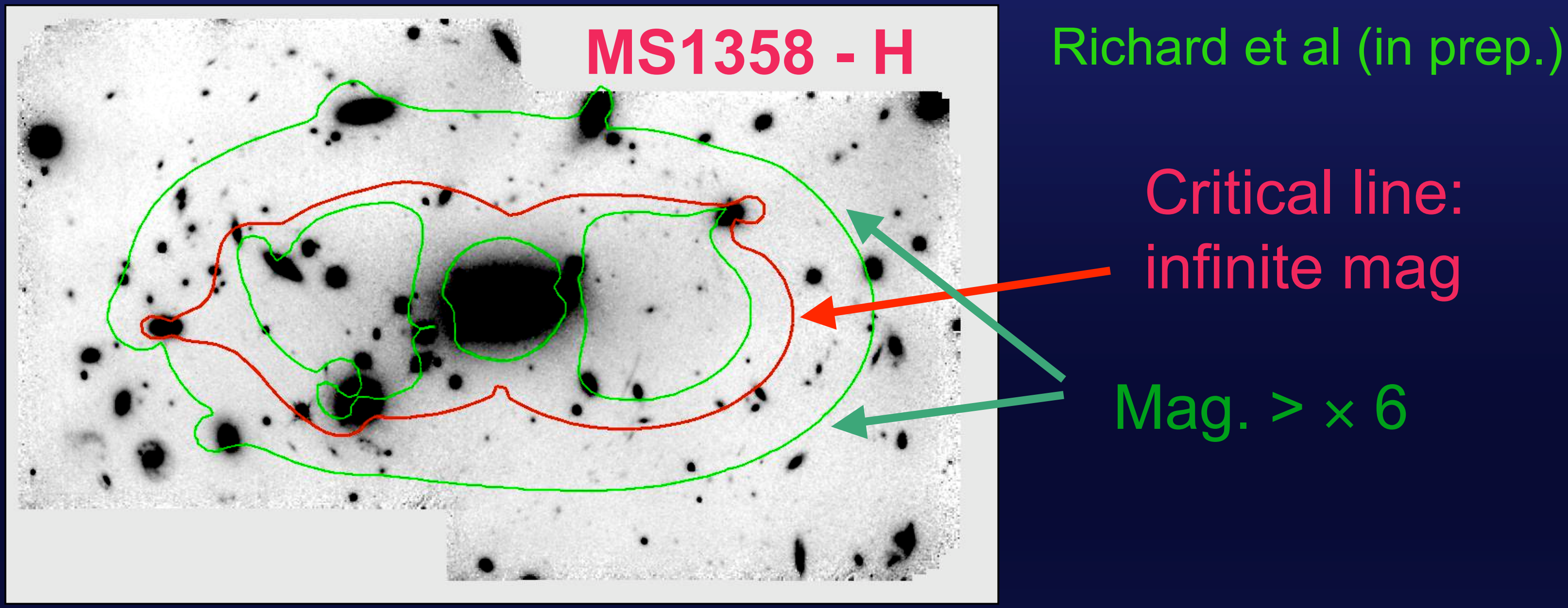


Detection of both images at λ> 4000 Å (Rest-frame) :

➔physical properties indicate earlier star-formation

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

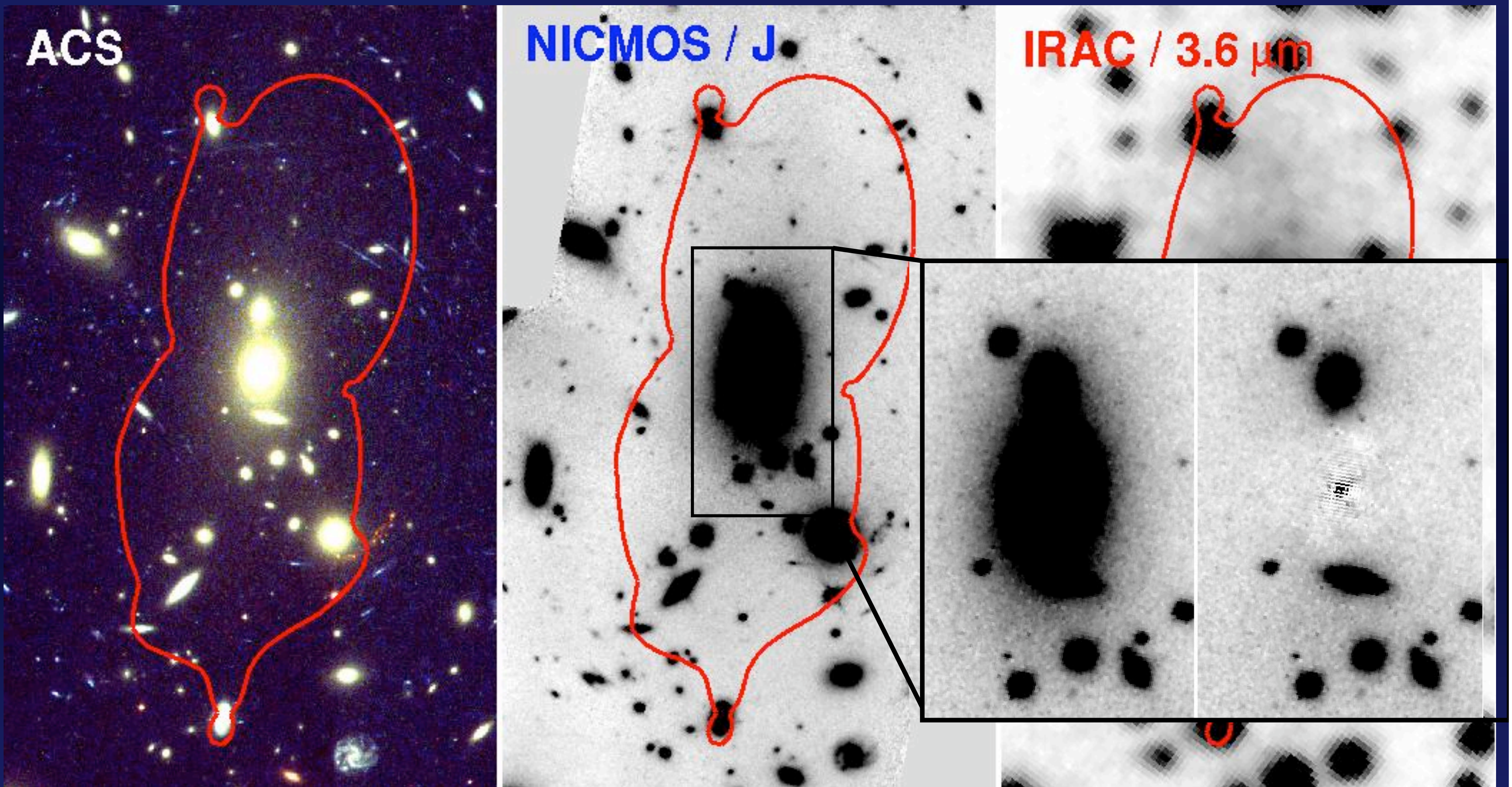
Searching for Lensed Dropouts with HST/Spitzer



- 6 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 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

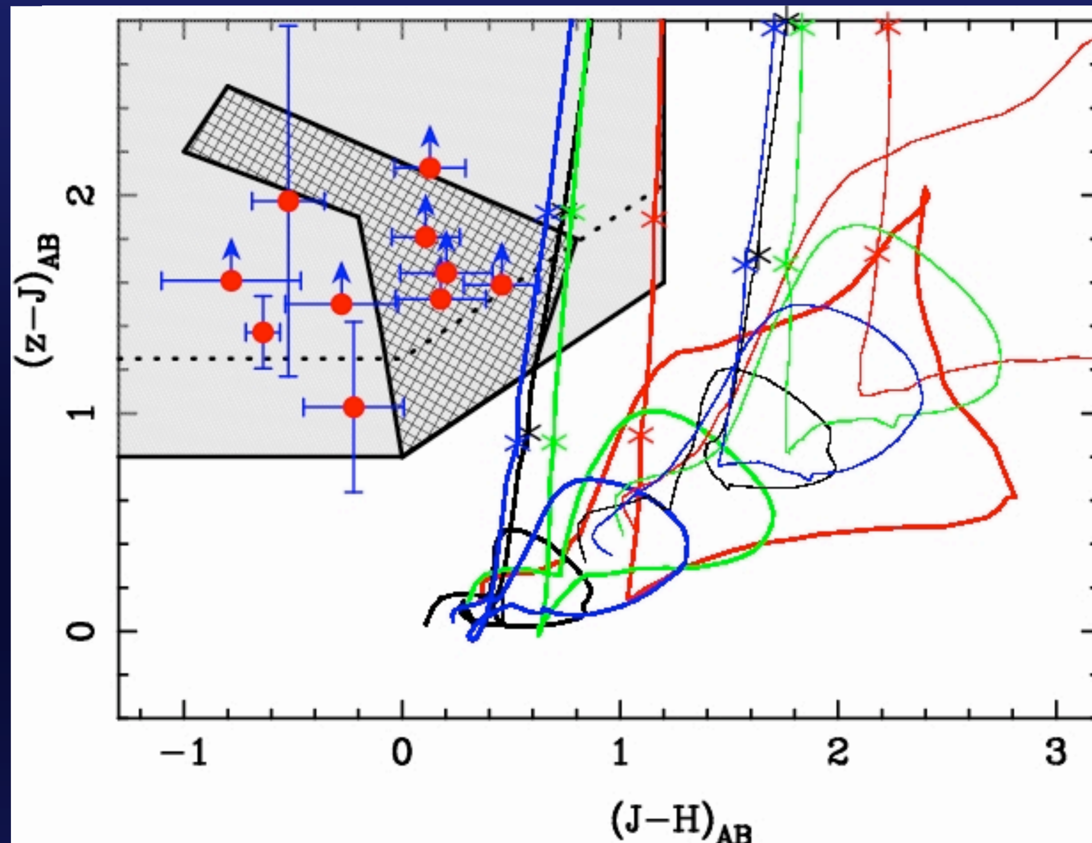


Importance of foreground removal

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

- NIR colors evolution with redshift for E, Sb, Sc and Im templates + reddening

- Including two variations of color-color criteria, with z-J > 0.8 or z-J > 1.2

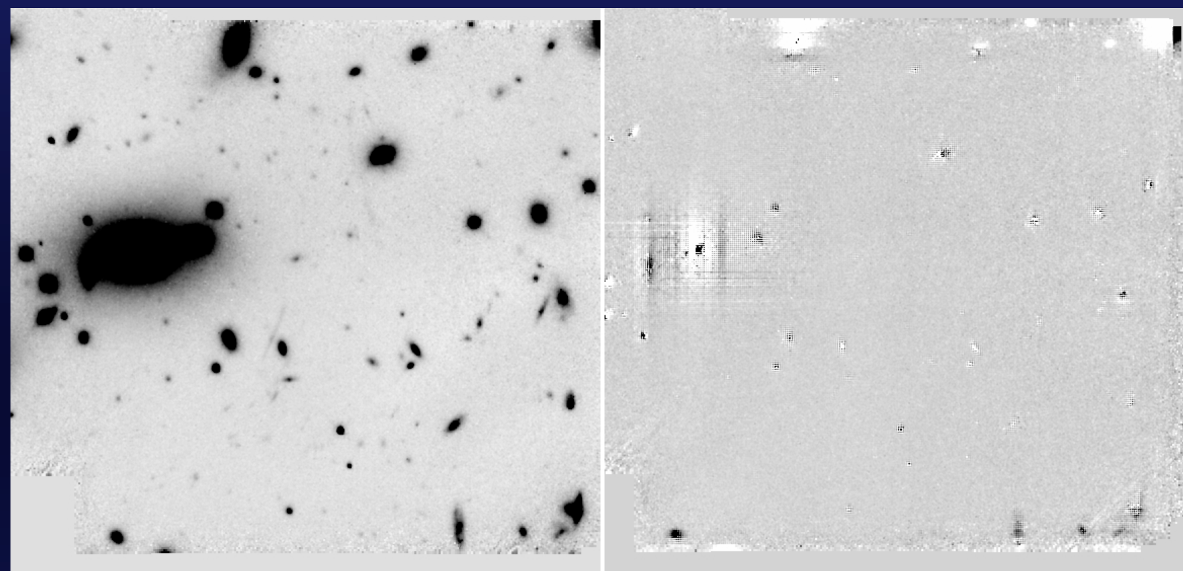


- **10 candidate z-drops in the 6 clusters surveyed with H ~ 26 - 26.8**
- **z ~ 1-2 red galaxies expected to be main contaminants**

Reliability and redshift estimation (1)

- False positive detections : tests on “noise image”

Noise image created by subtracting in pairs NICMOS science frames.



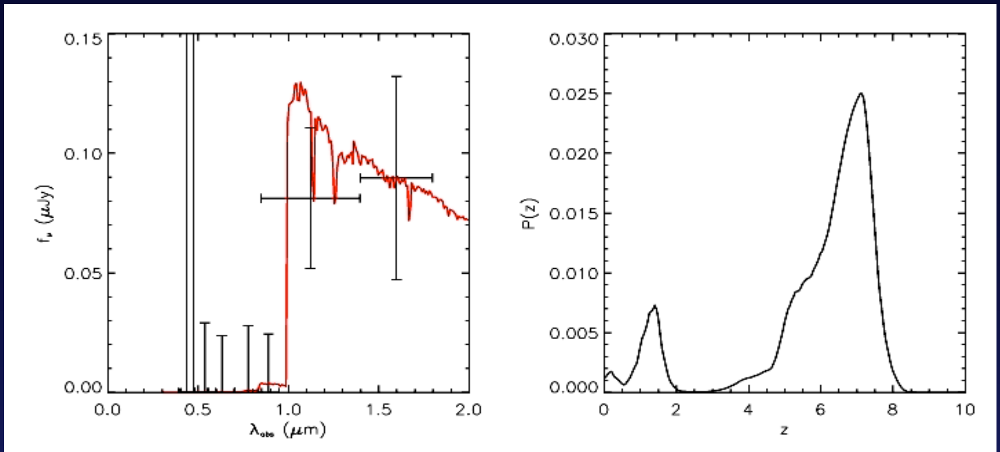
- **Estimation:** in the magnitude range of the dropouts, we expect ~ 10 % spurious detections (i.e. 1 out of the 10 dropouts)

Reliability and redshift estimation (2)

• Effects of post-overexposures on the detector :
measurements from our own data and 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



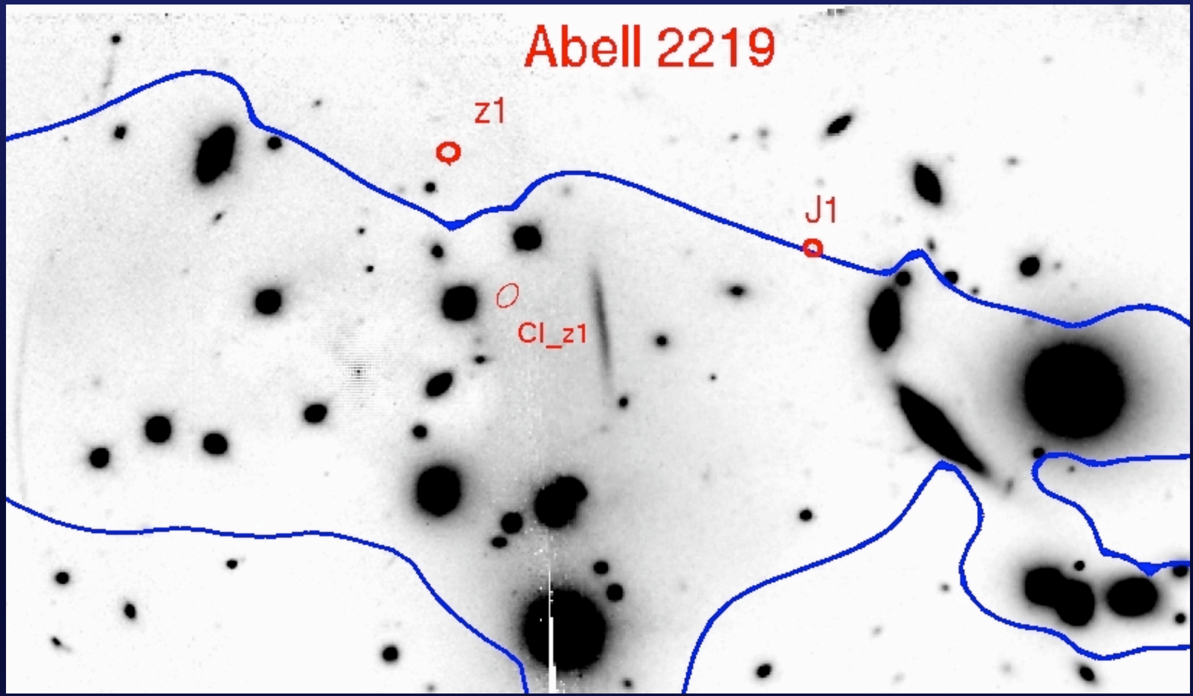
Contamination by lower z galaxies: estimation of 25 % from P(z)

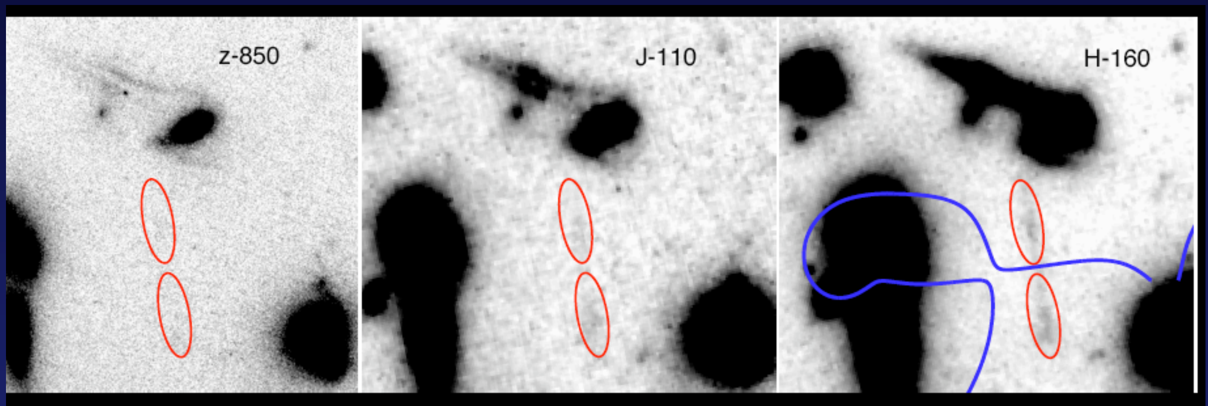
⇒ statistically expect 6 out of 10 dropouts likely to be at high z

Search for multiple images

- Counter-images predictions from lensing model

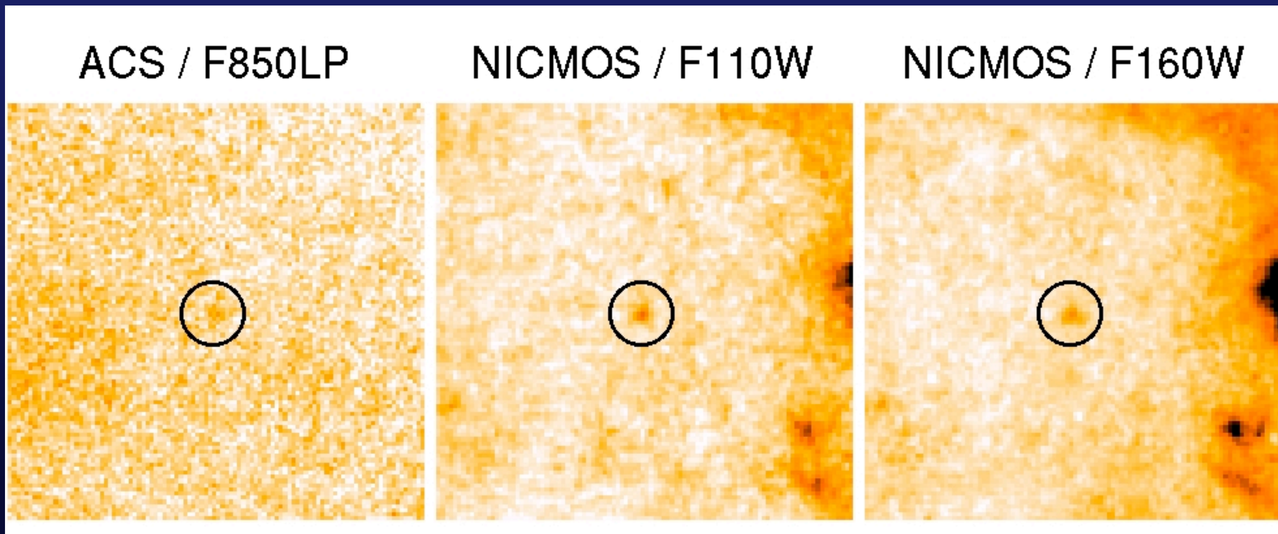
2 candidates with possibly “merging” images



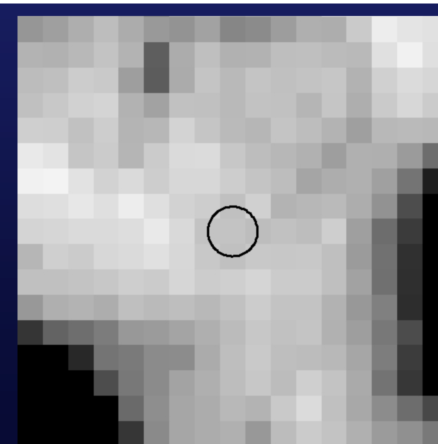


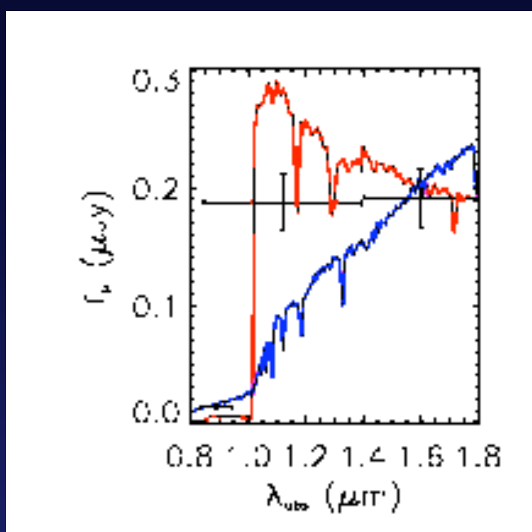
Proof of Method: we do see z~2 multiple sources…

Properties of stacked SED for the z-dropouts



IRAC 3.6 μm (x 0.5)





Best fit z_{ph}=7.35 +/- 0.12

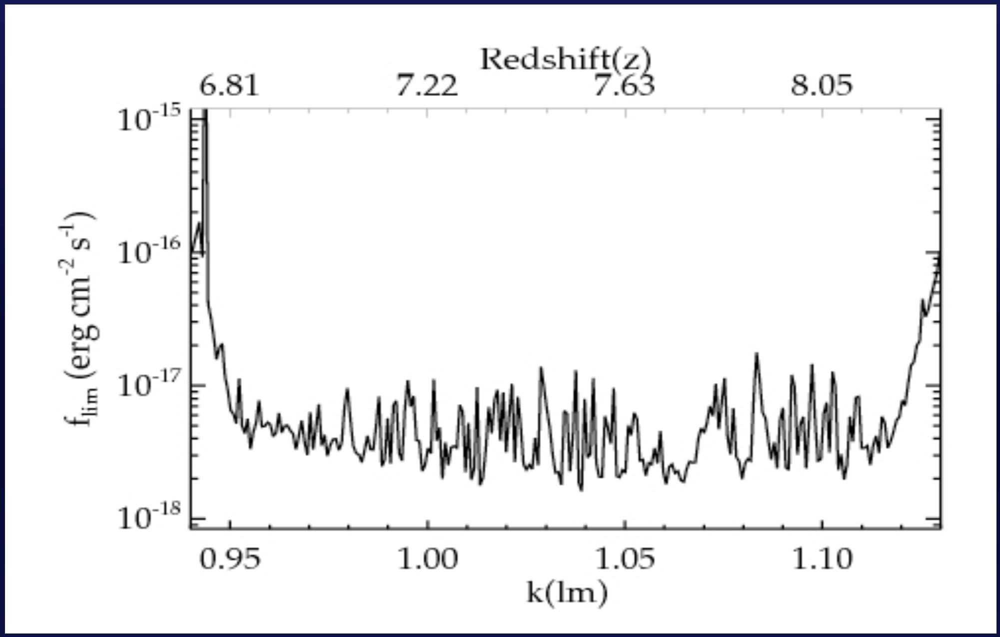
$(J - H)_{AB} \sim 0.05$

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

$\beta \sim 2.6\text{-}2.8$

Keck/NIRSPEC spectroscopic follow-up

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



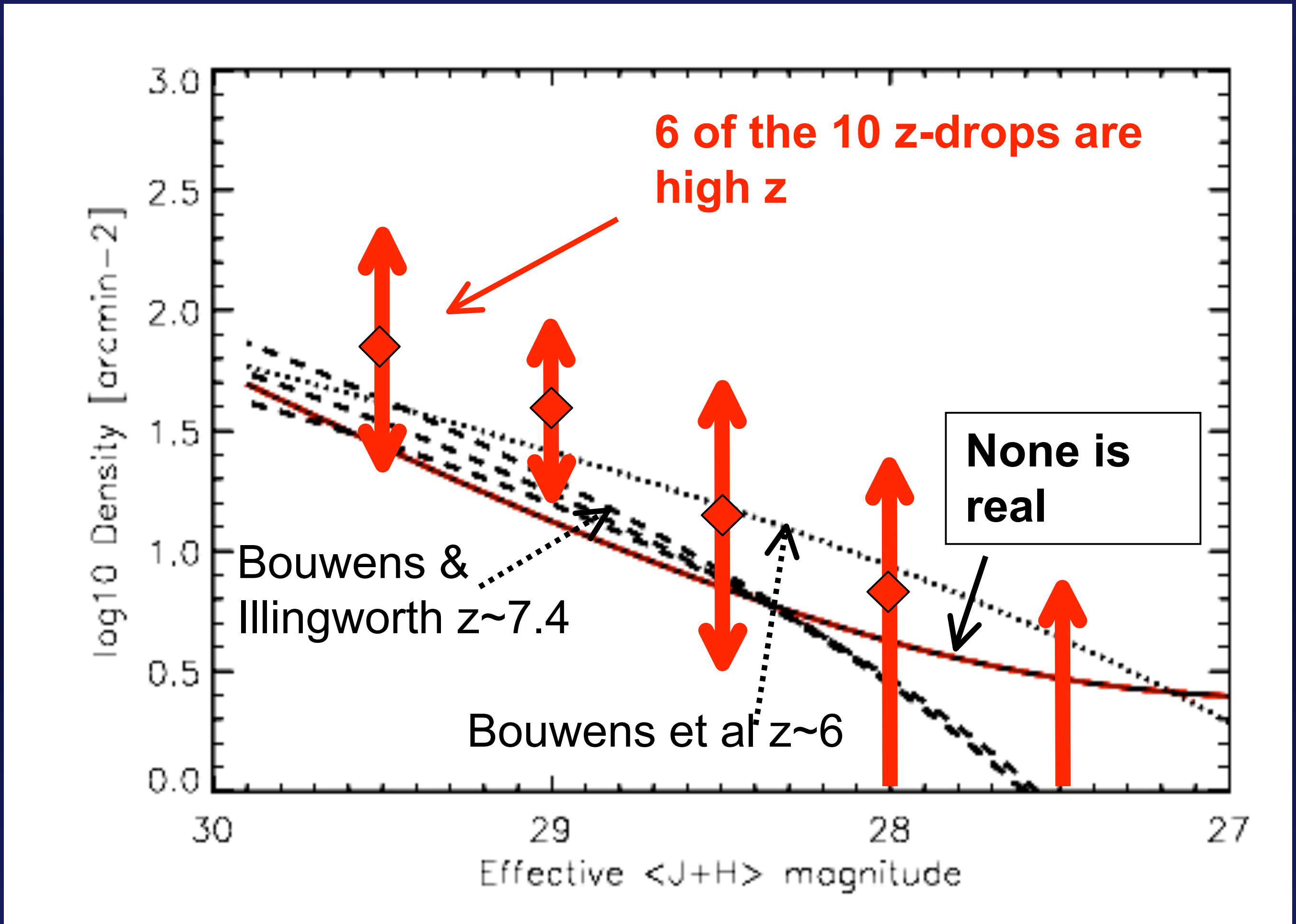
- NIRSPEC slit : 0.76” x 42”
- Follow-up in the Z band (6.8<z<8.3 for Lyman-alpha)
- 3 to 4 hours on 7 candidates

Sensitivity to lyman α flux:
3 e-18 erg/s/cm2 in 50% of the spectrum, or W>25 Angstr.

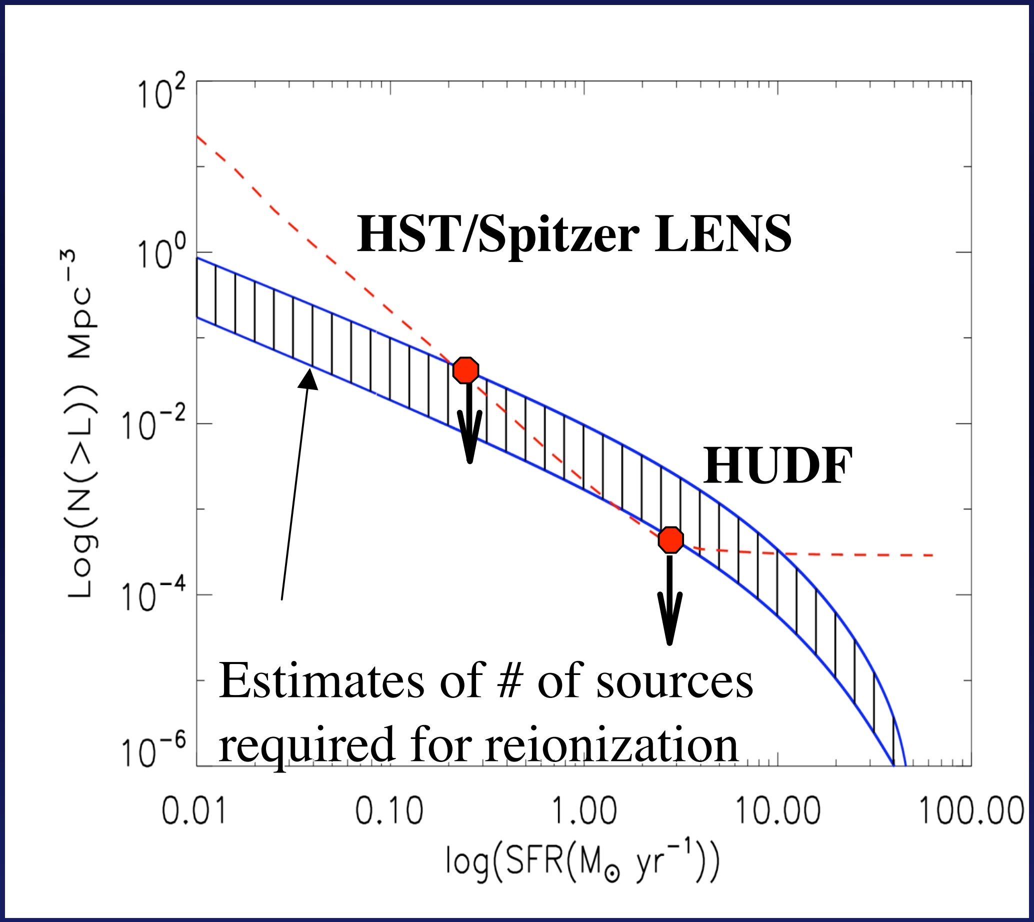
No detection of Ly-α : possibly different distribution of equivalent widths between z ~ 6.0 (Stanway 07) and z~7.5

Implied Luminosity Function z~7.5

No significant overlap between UDF and lensed survey



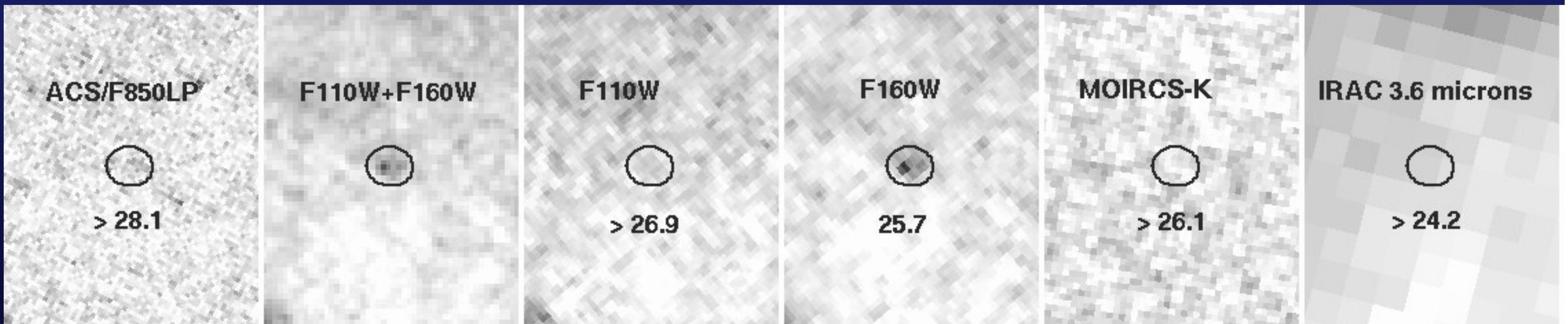
Implications for Reionization from Lensed Dropouts



- **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)**

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)
- 1 of them not detected in K-band with MOIRCS/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 shows no detection of Ly-a : possibly different distribution of equivalent widths between z ~ 6.0 and z~7.5

• 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