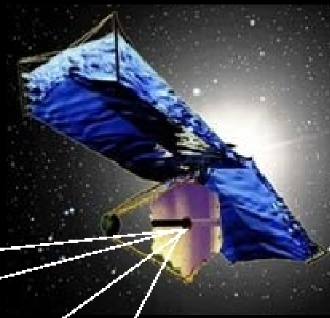
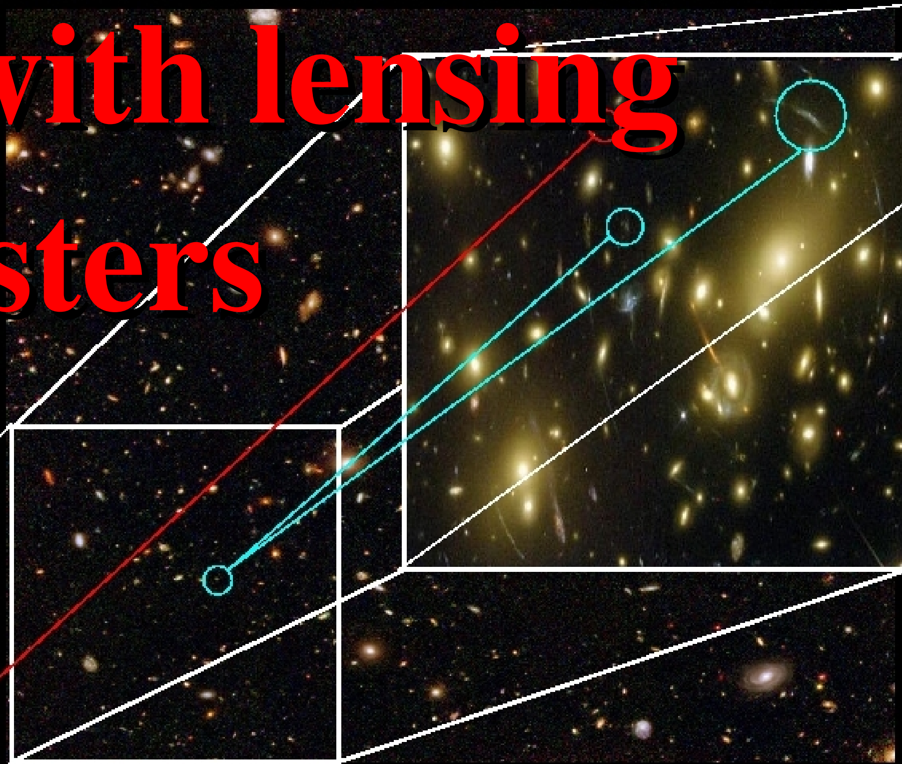
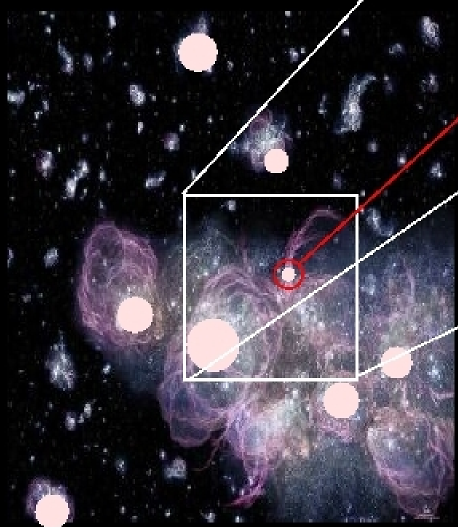
Studying the first galaxies with lensing clusters





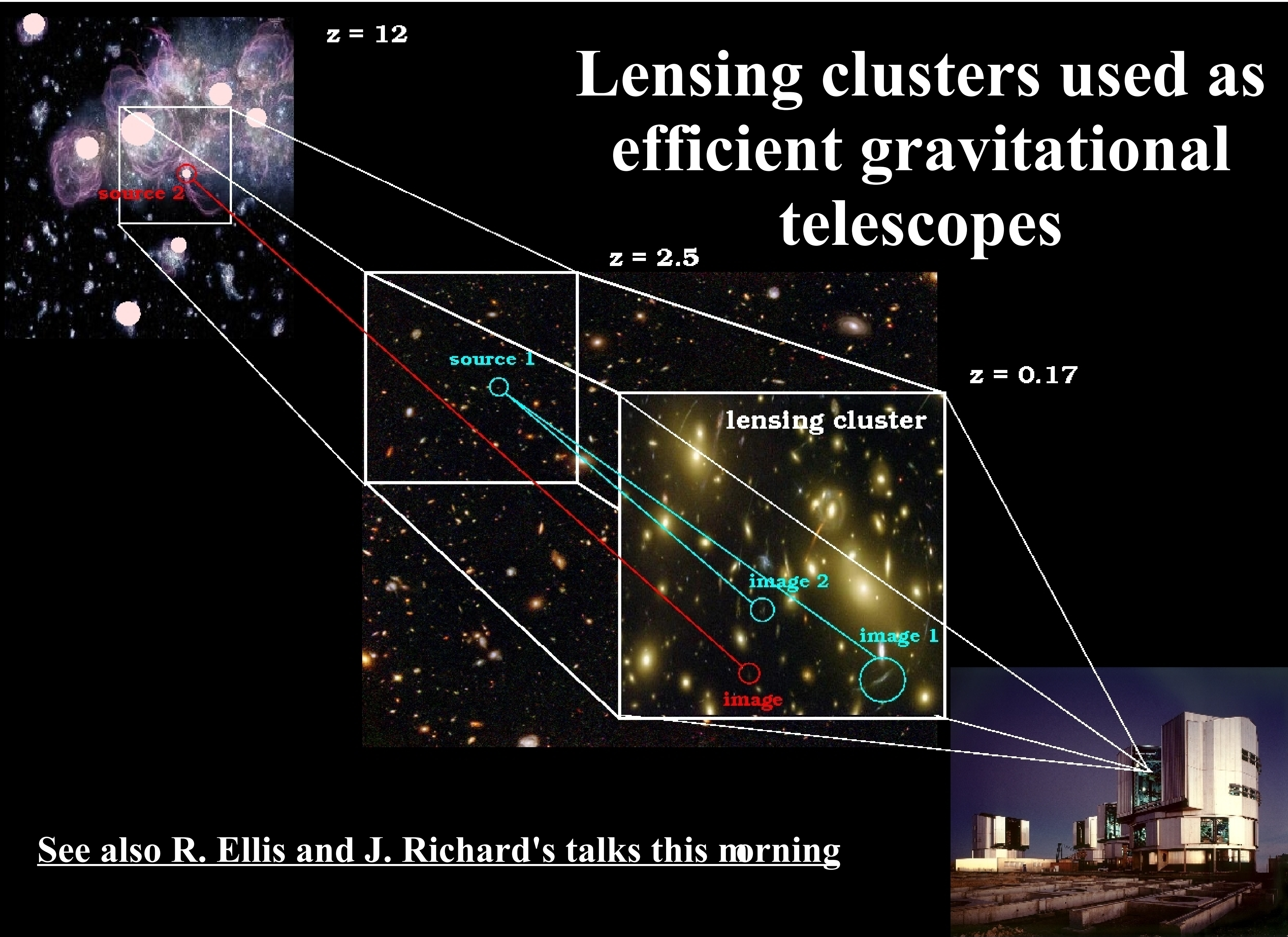


Roser Pelló

LATT - Laboratoire d'Astrophysique de Toulouse-Tarbes

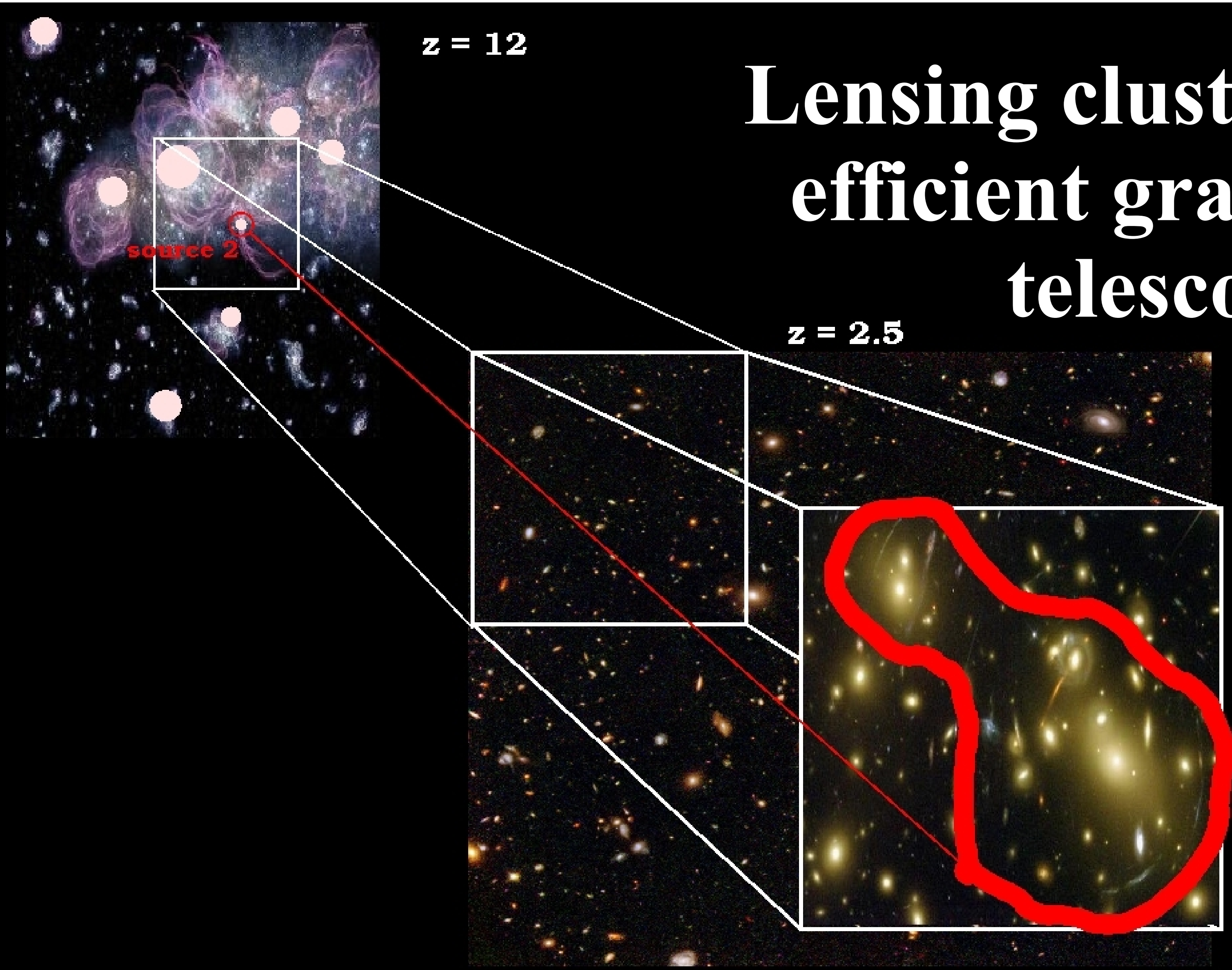
J. Richard (Caltech)- A. Maizy (LATT) - D. Schaerer, A. Hempel (O. Genève)-J.F. Le Borgne (LATT) - J. P. Kneib (LAM, Marseille)- E. Egami (Tucson) - M. Wise (MIT/NL) - F. Boone, F. Combes (O. Paris) - A. Ferrara (Trieste) – M.A. De Leo (UNAM)

Lensing clusters used as efficient gravitational telescopes

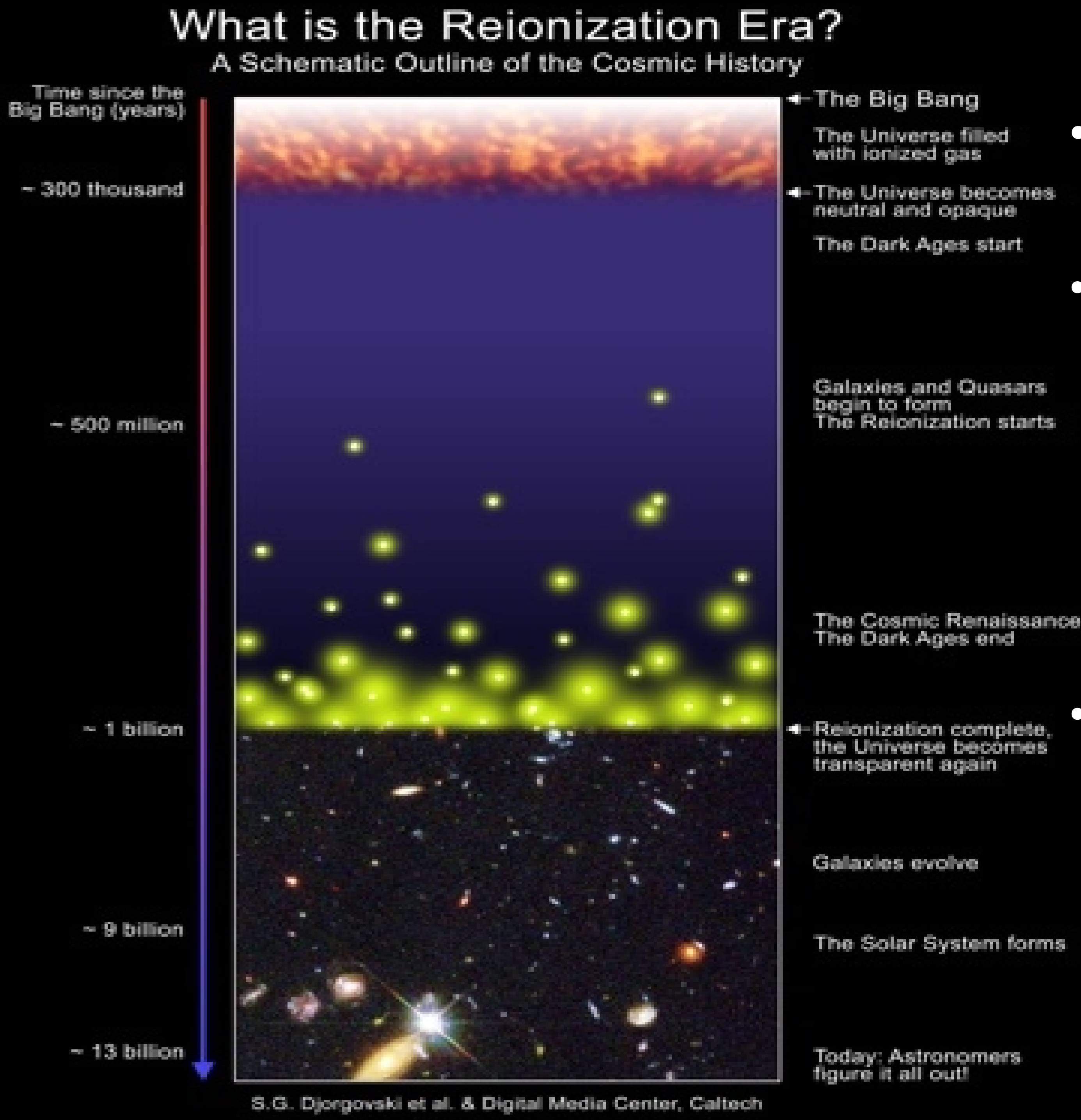


<u>See also R. Ellis and J. Richard's talks this morning</u>

Lensing clusters used as efficient gravitational telescopes



See also R. Ellis and J. Richard's talks this morning



- **WMAP results:** reionization epoch **z~9-13** (Spergel et al. 2006)
- **Reionization completed at z~6-6.5 (Fan et al. 2002)**

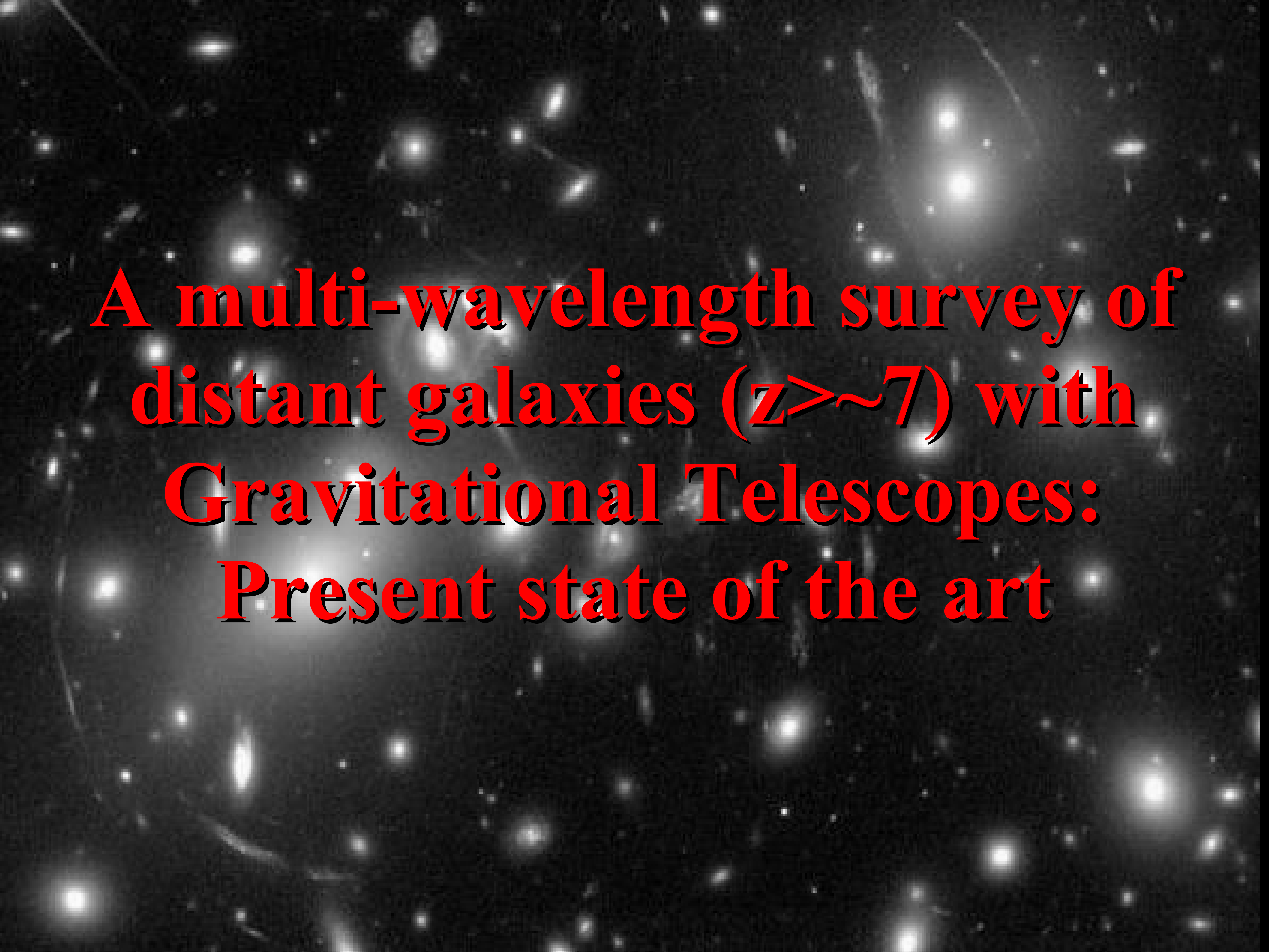
===> contribution of star-forming systems to cosmic reionization

- **What are the physical properties of these objects: SFR, extinction, metallicity, IMF, ...?**

from Djorgovski et al & NASA/WMAP Science Team.

Outline:

1. A multi-wavelength survey of distant galaxies (z>~7) with Gravitational Telescopes: present state of the art.
   - Project design and selection of photometric candidates
   - Summary of photometric results (UV LF and ρ(SFR))
   - Spectroscopic follow-up and multi-wavelength analysis.
2. Designing future surveys: a matter of efficiency.
   - Lensing or blank fields?
   - Towards an « ideal » sample of lensing clusters.



A multi-wavelength survey of distant galaxies (z>~7) with Gravitational Telescopes: Present state of the art

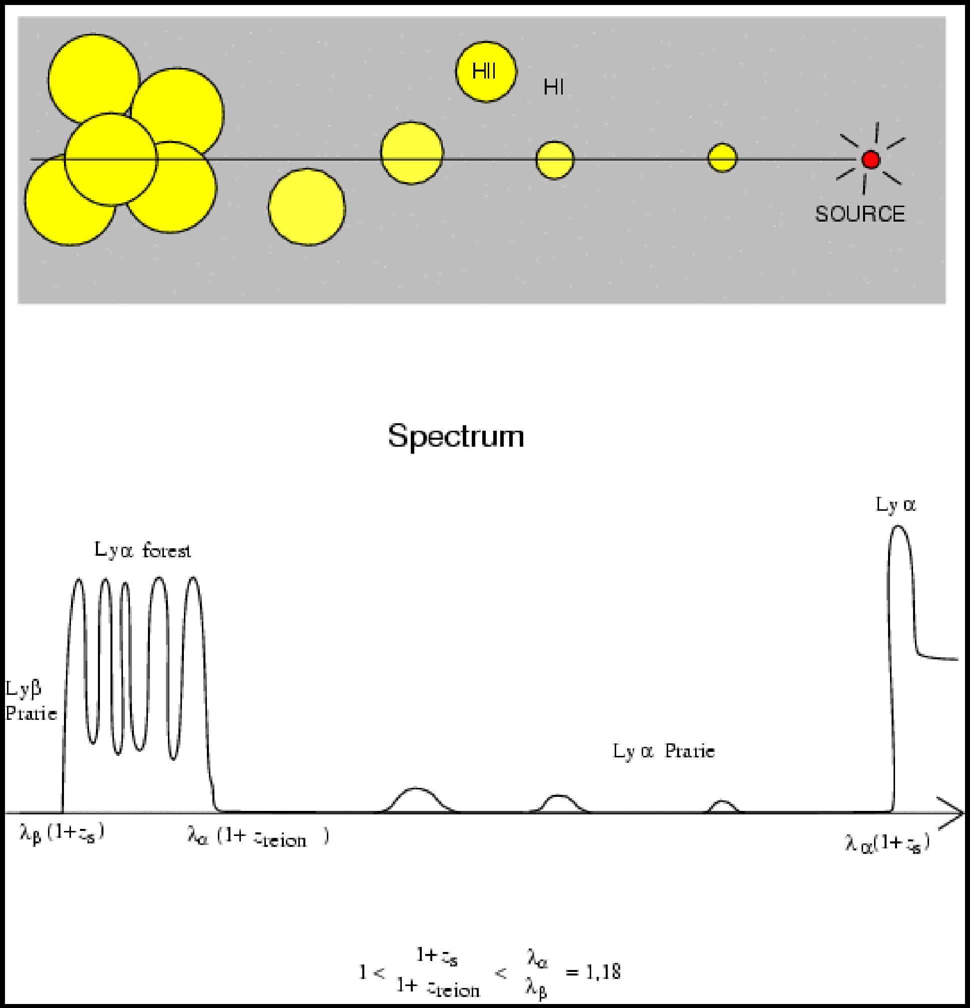
Project Design

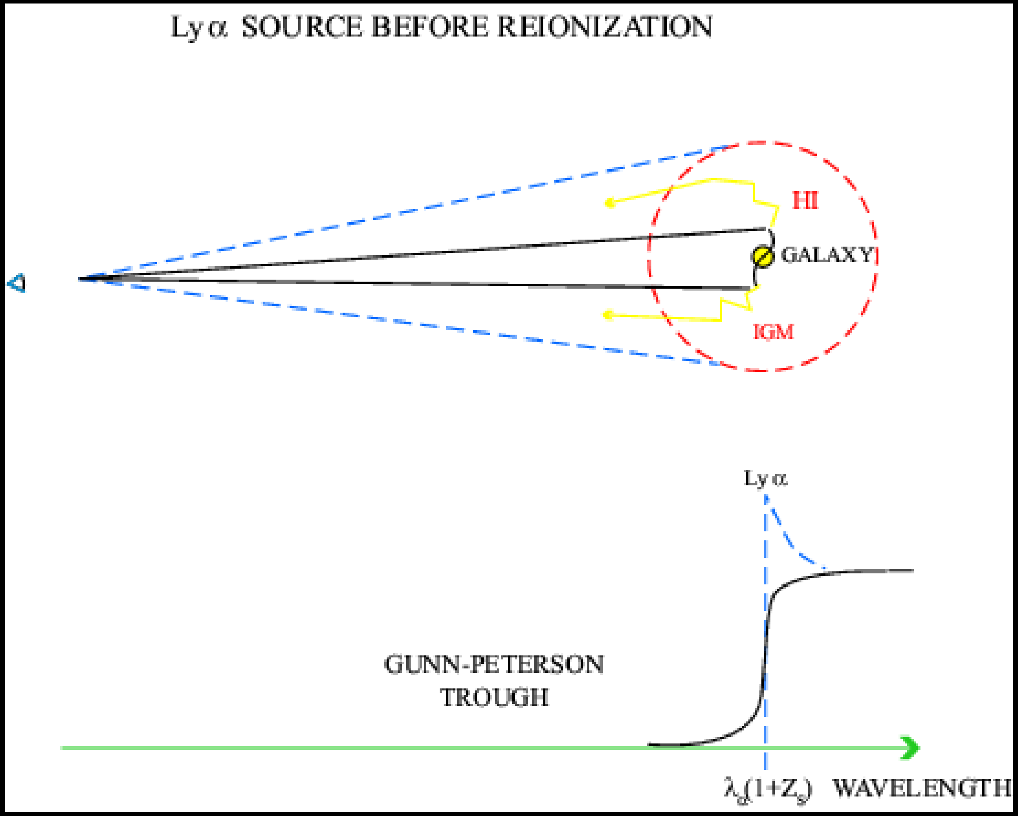
- **2001 ---> SpectroPhotometric Simulations:**
  - Broad-band colors for "drop-out" selection at various redshifts (z~6-7, z~7-8, z~8-12).
  - Expected magnitudes for normal, low metallicity, and PopIII starbursts with different IMF, SF histories.
  - Feasibility studies: lensing vs. blank fields; pilot studies for the new generation of near-IR instruments .

- **2002 ---> Deep near-IR (JHK, SZ) Imaging of well studied lensing clusters with ISAAC/VLT combined with deep optical imaging, including HST imaging.**
- **2003 ---> High-z Candidate Selection. Different detection criteria. Exploitation of final H-band selected sample.**
- **2003/04 ---> Pilot Spectroscopic Follow-up of best candidates ISAAC/VLT.**
- **2005/06 ---> Multi-wavelength follow up (Spitzer-IRAC, Chandra, IRAM, …)**

Next generation of multi-object near-IR spectrographs

Project Design



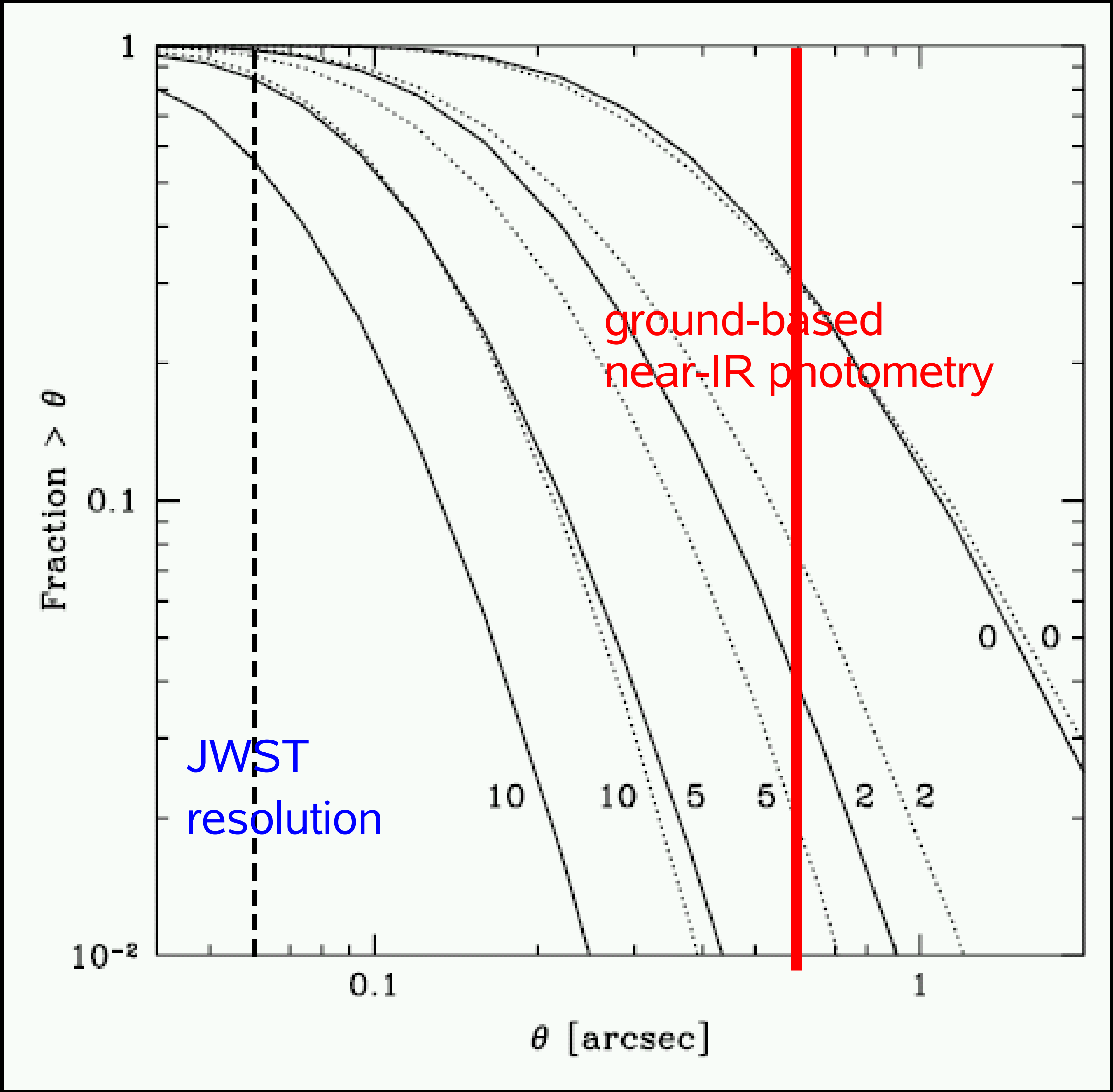


SED of a source at $z > z_{reionisation}$

From Loeb & Barkana 00

Scattering of Ly α photons in the spectrum of a source at $z > z_{reionisation}$, for a galaxy within a neutral IGM

Project Design

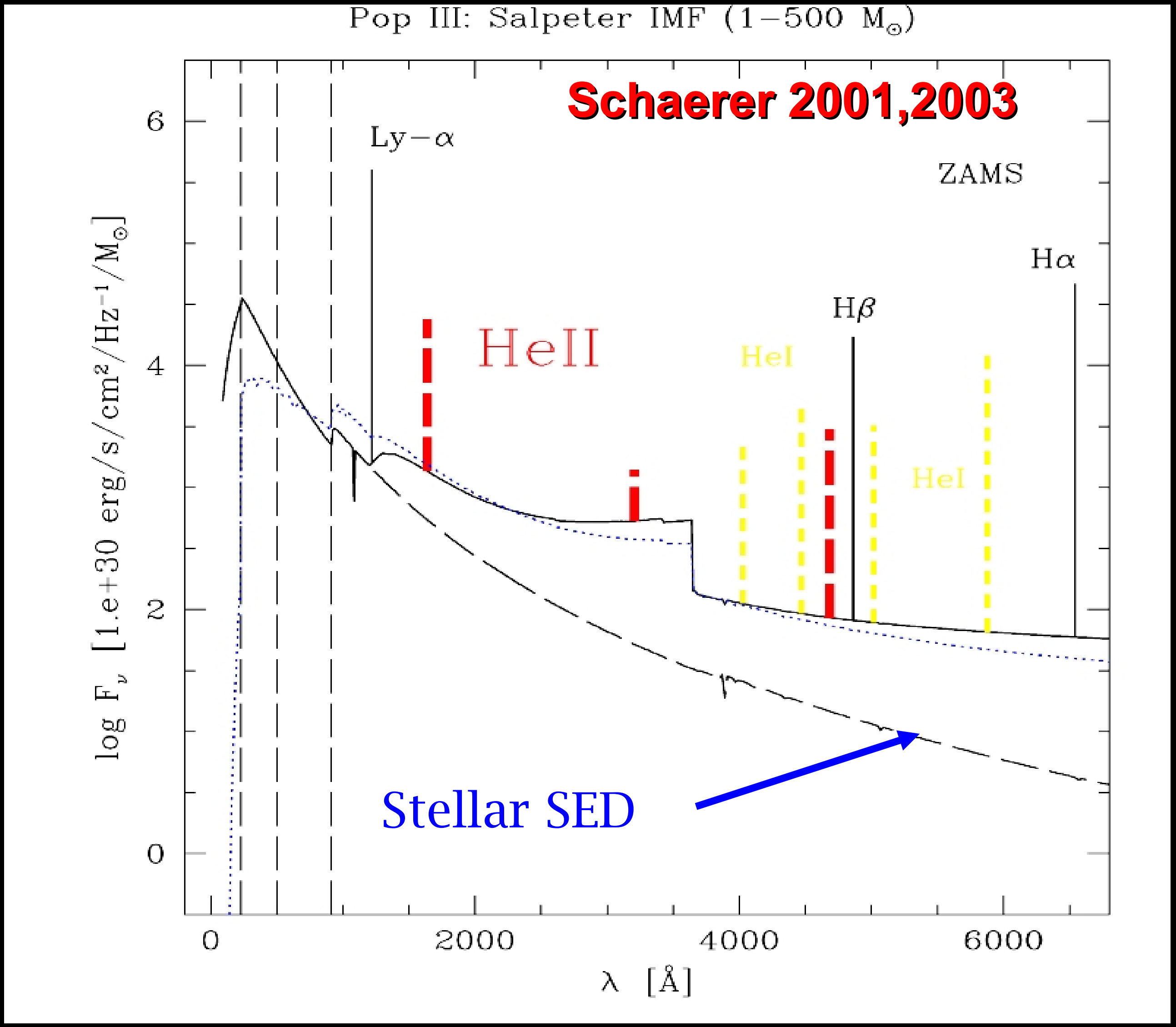


- Distribution of disk sizes in ΛCDM model.
- Diameter measured out to one exponential scale length.
- Limiting point-like source flux of 1nJy.
- Most z~10 sources are expected to remain non-resolved, even with a magnification factor μ~10.

From Barkana & Loeb 2000

Project Design

- « Normal », low-metallicity and genuine PopIII starbursts

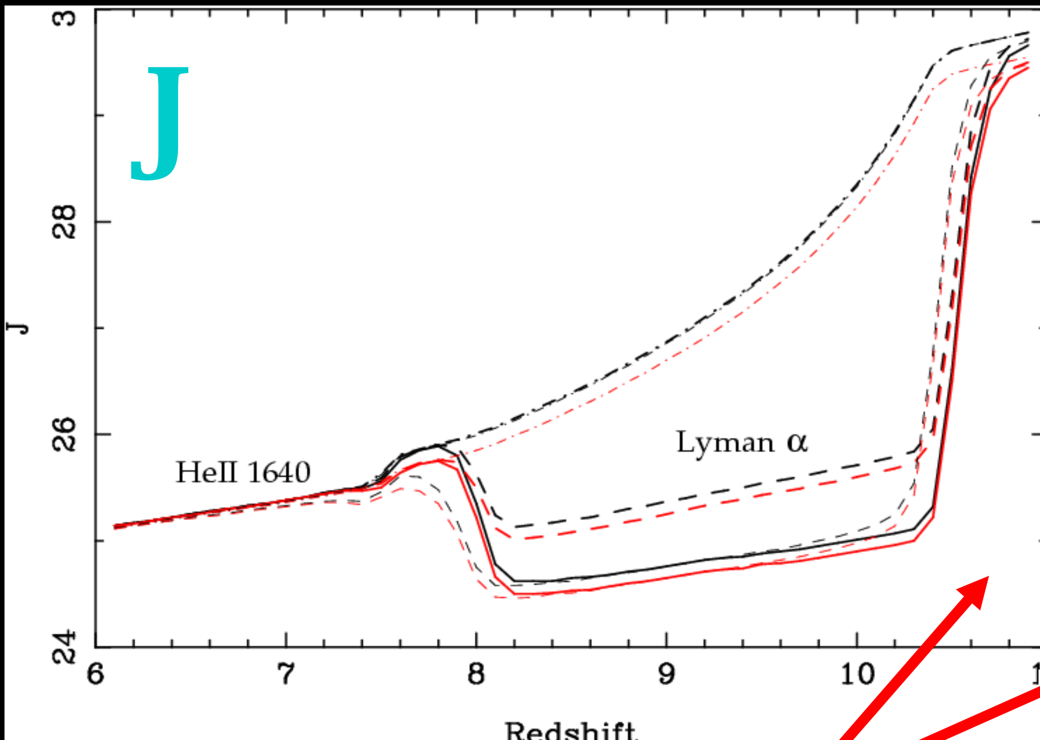


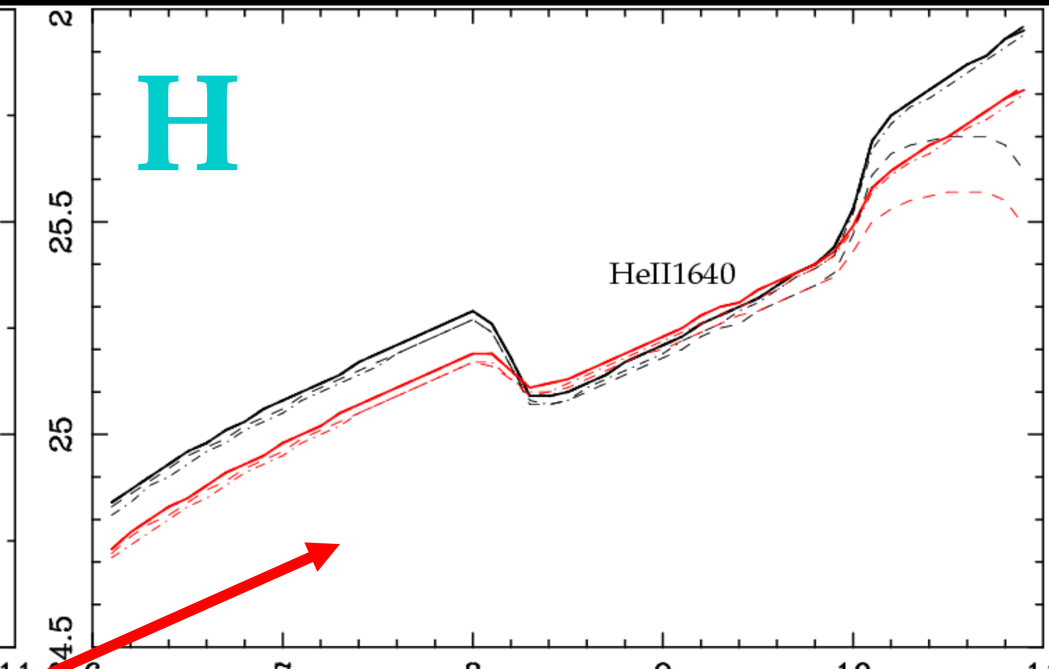
Genuine PopIII starbursts:

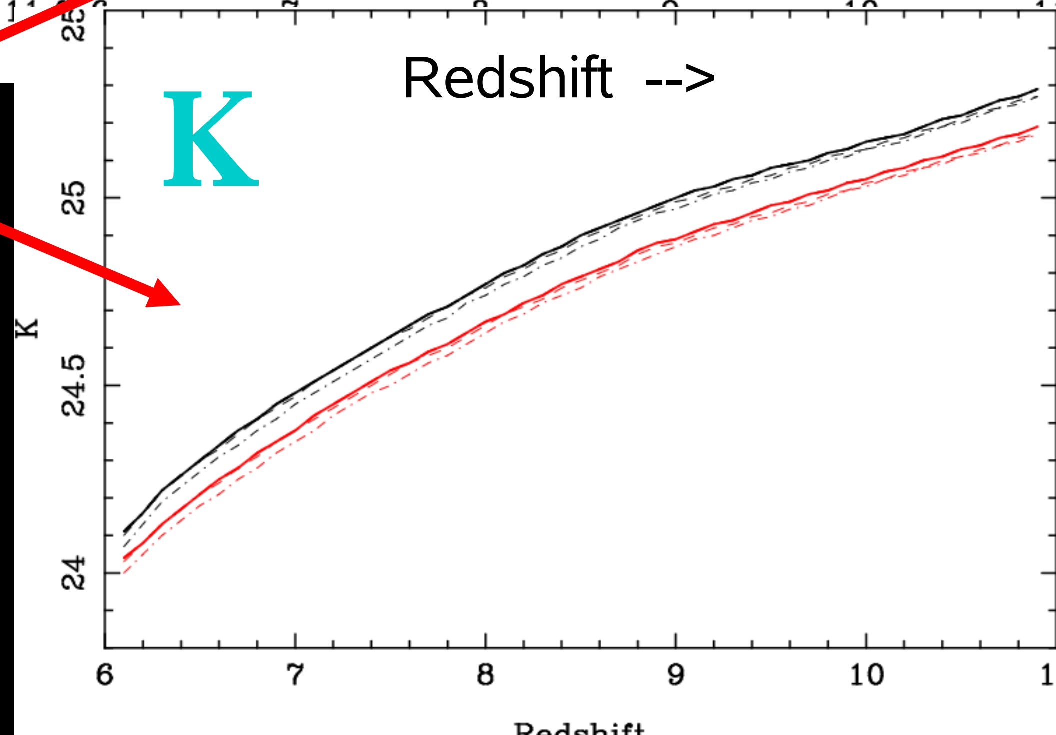
- Top - heavy IMF
- Very massive stars, up to ~500-1000 M_solar

Nebular continuous emission *dominates* the spectrum at λ > 1400 Å
+ Strong HeII lines?: HeII λ1640, HeII λ3203, HeII λ4686, ...

Near-IR Broad-Band magnitudes





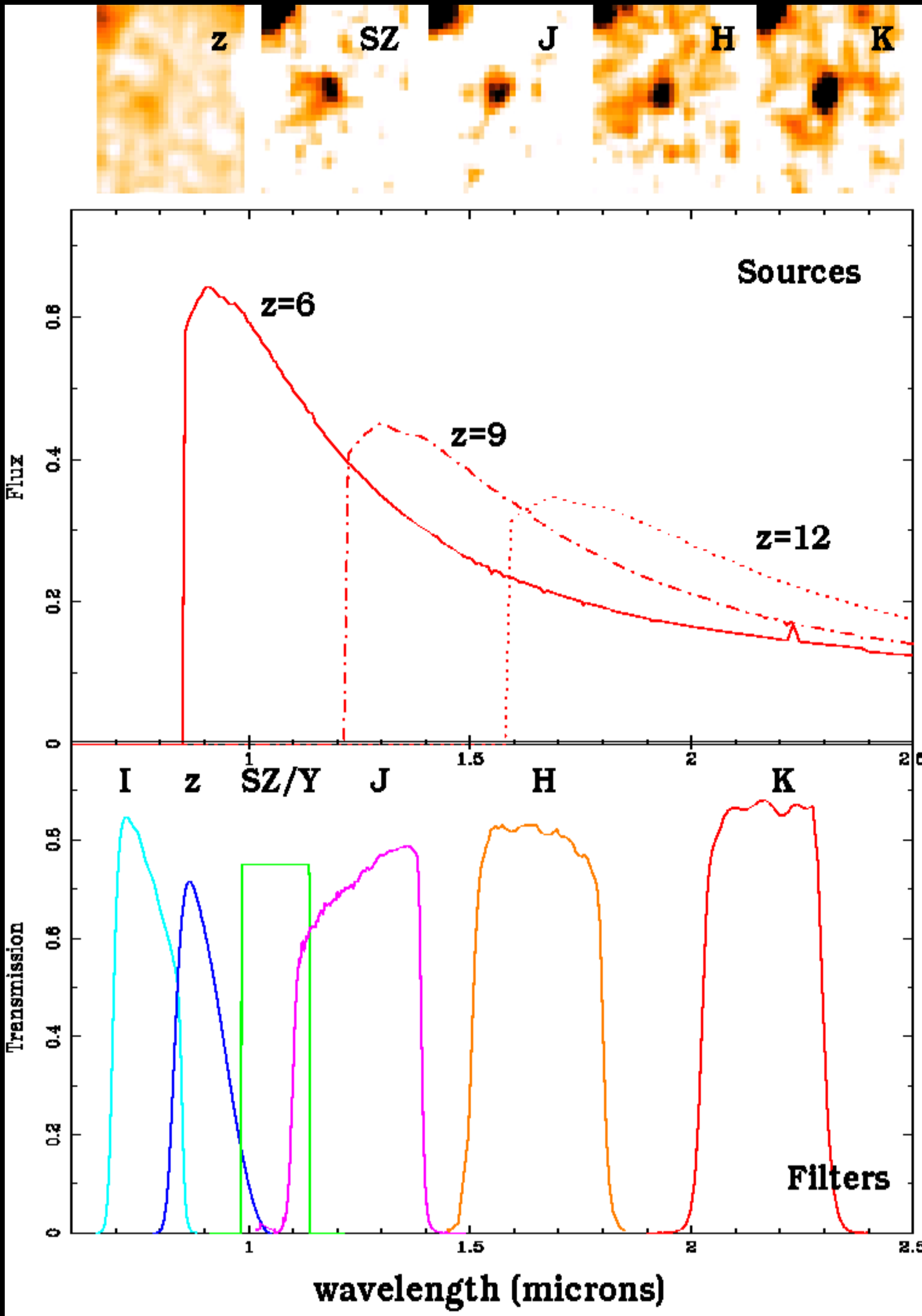


Fiducial 10^7 M_solar stellar halo
m_λ - 2.5 mags for 10^8 M_solar
m_λ - 5.0 mags for 10^9 M_solar

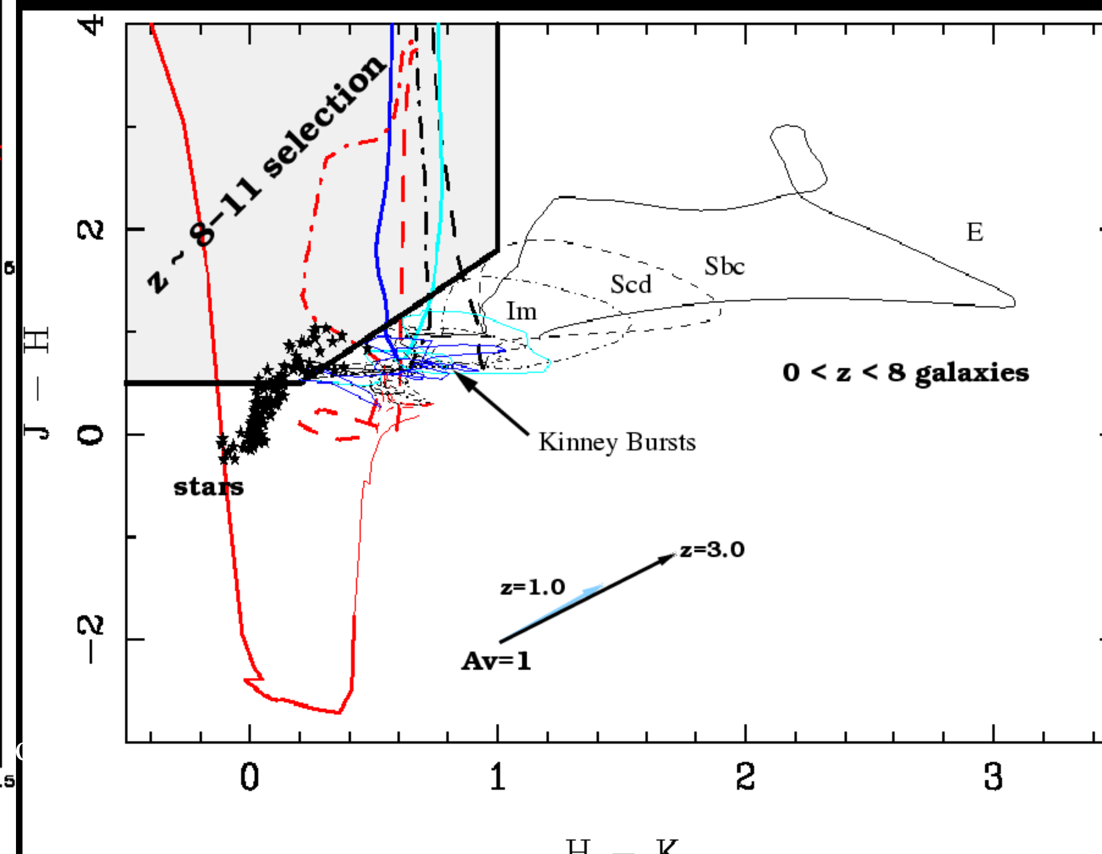
<u>With J(Vega)<26.0; H<24.0; K<23.5:</u>
Top heavy IMF 50-500 M_solar
M_halo(stars) >10^8 M_solar to z<10
> 3-5 10^7 M_solar z<9

x 10 M_halo(stars)
if standard Salpeter IMF

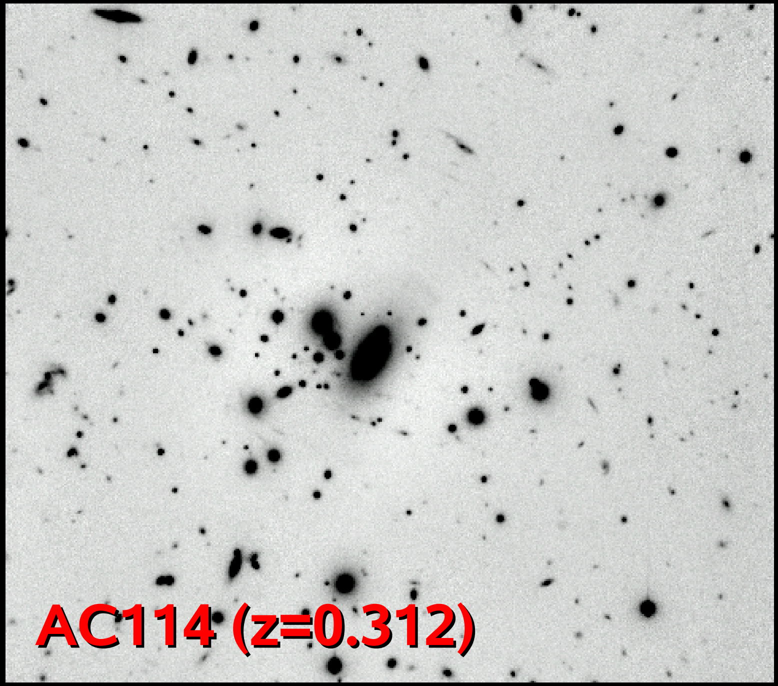
Selection of photometric candidates

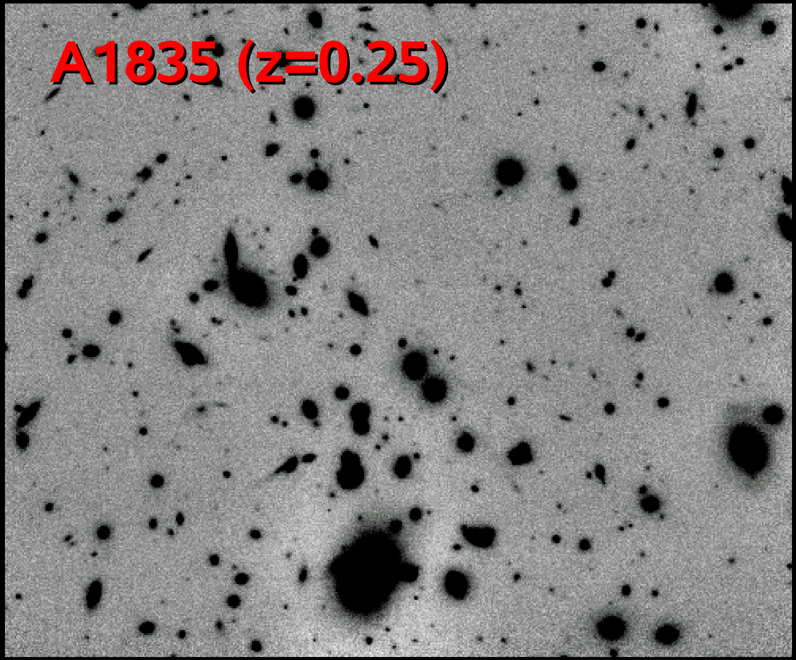


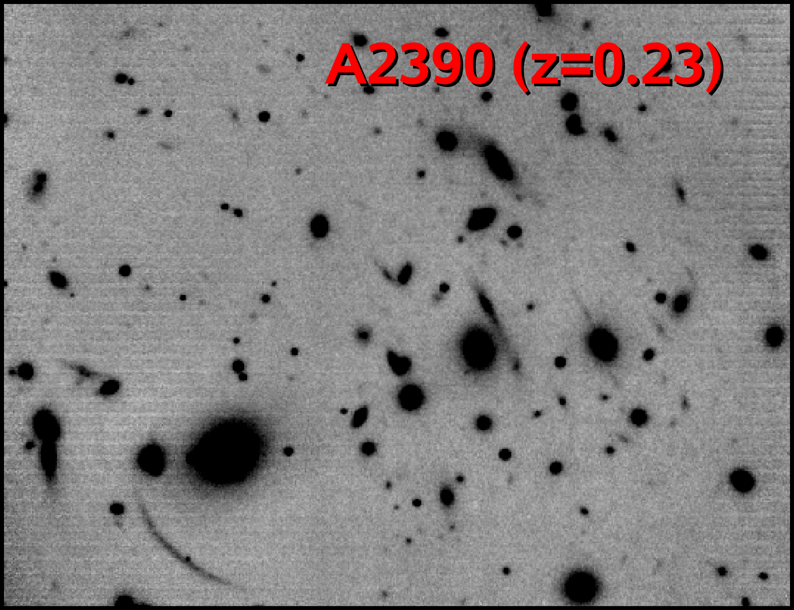
- Optical dropouts + near-IR colors
- Filter combinations:
  - z~6-7: zYJ
  - z~7-8: YJH
  - z ~8-12 : JHK
- SED-fitting and photo-zs (adapted version of Hyperz)

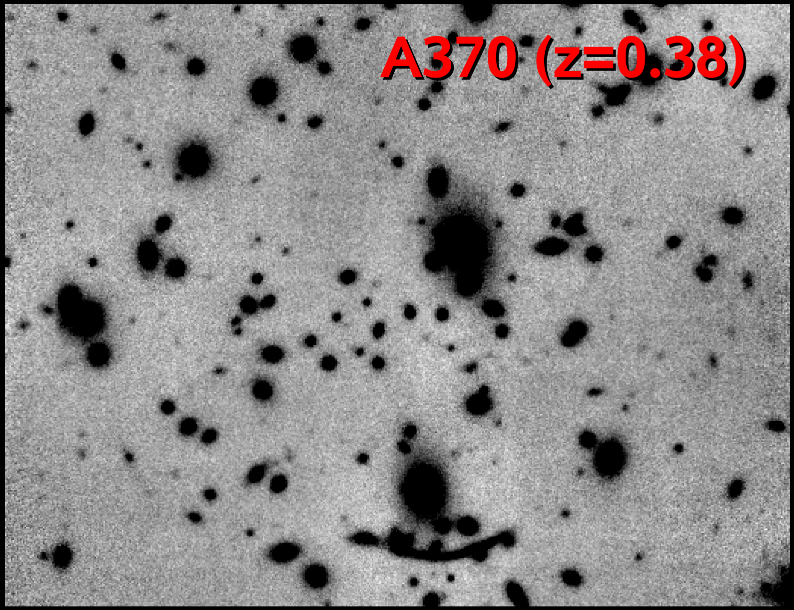


Summary of photometric results

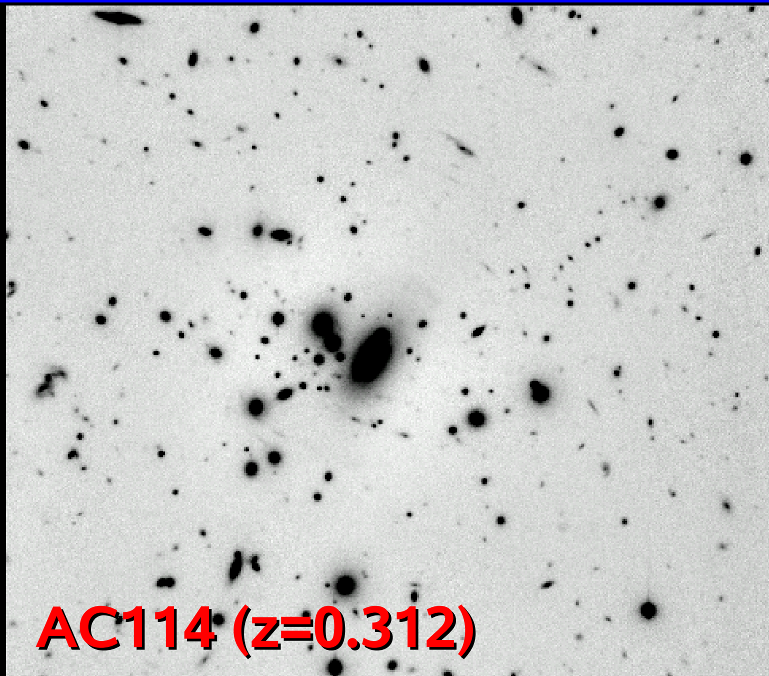


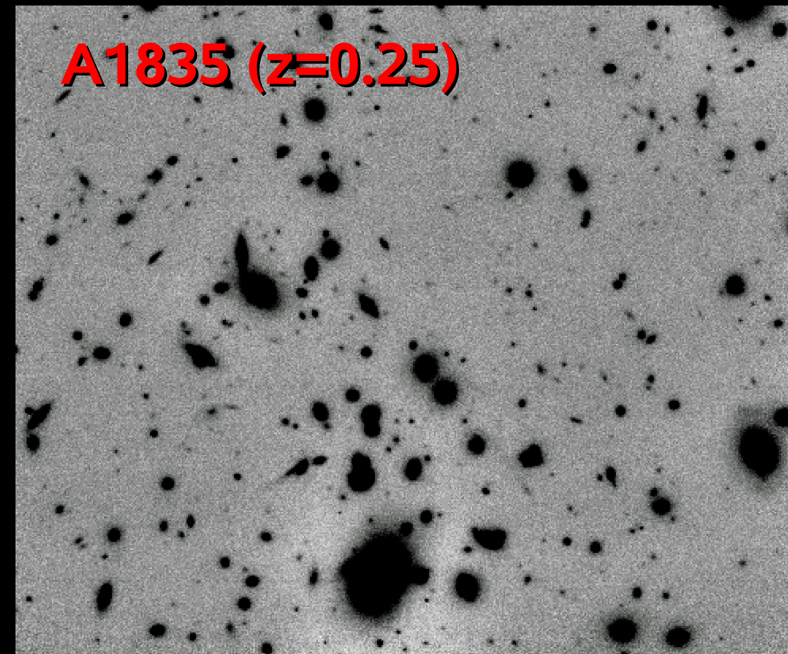


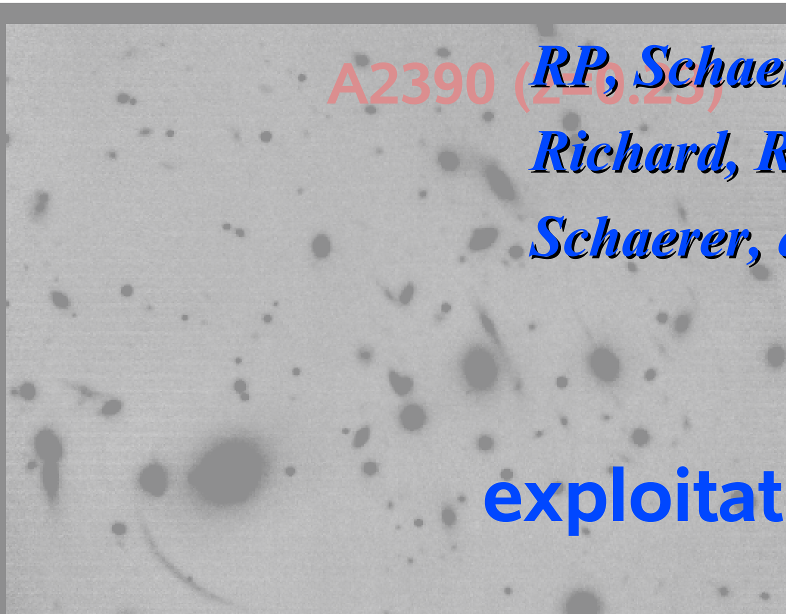




Summary of photometric results





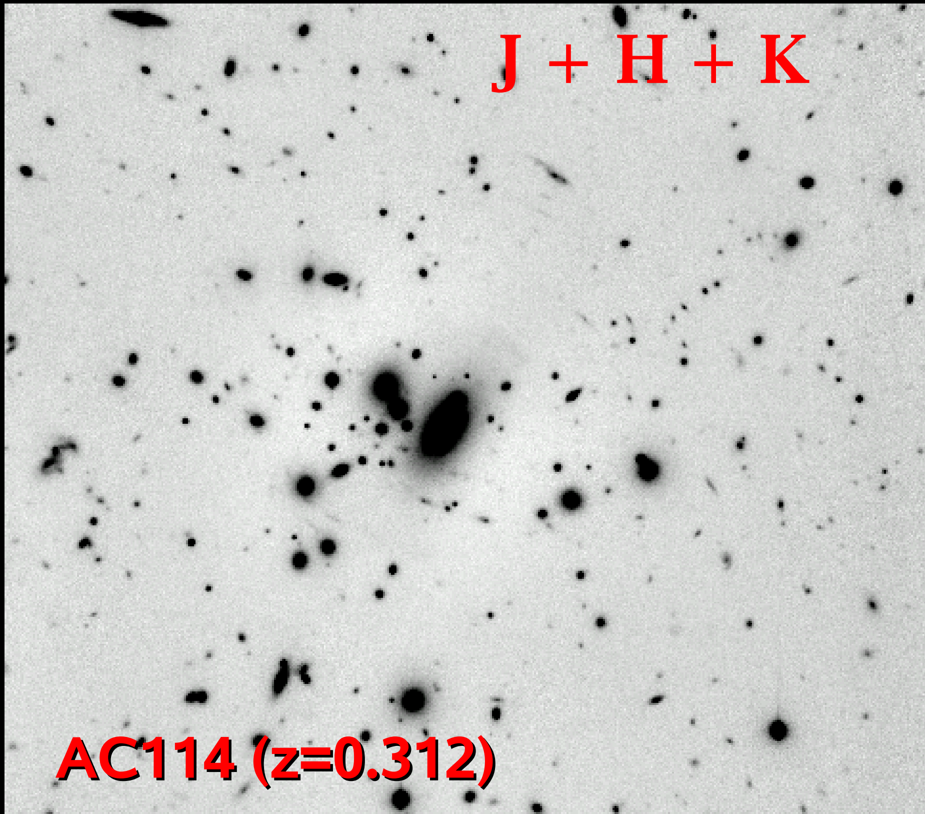


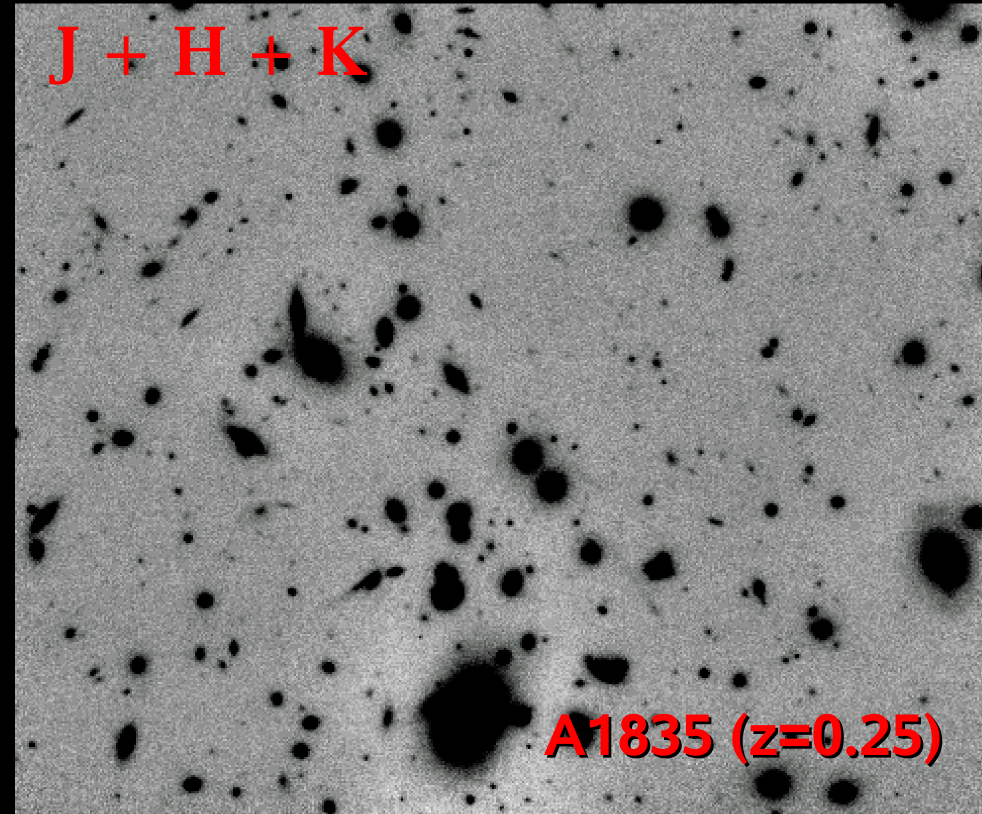
RP, Schaerer, Richard, Le Borgne & Kneib (2004ab)

Richard, RP, Schaerer, Le Borgne & Kneib (2006)

Schaerer, et al. (2007), Hempel, et al. (2007)

exploitation ongoing





<u>ISAAC/VLT photometry</u> (Vega system, 3σ):

J : 2h (J = 24.3)

H : 4h (H= 23.5)

K': 5.5 h (K'=23.2 --> K(AB)~25.0)

seeing ~0.4-0.6"

+ UBVRI Optical data + HST R band

<u>ISAAC/VLT photometry</u> (Vega system, 3σ):

J : 2h (J = 24.4)

H : 4h (H= 23.5)

K': 5.5 h (K'=23.6 --> K(AB)=25.4) +

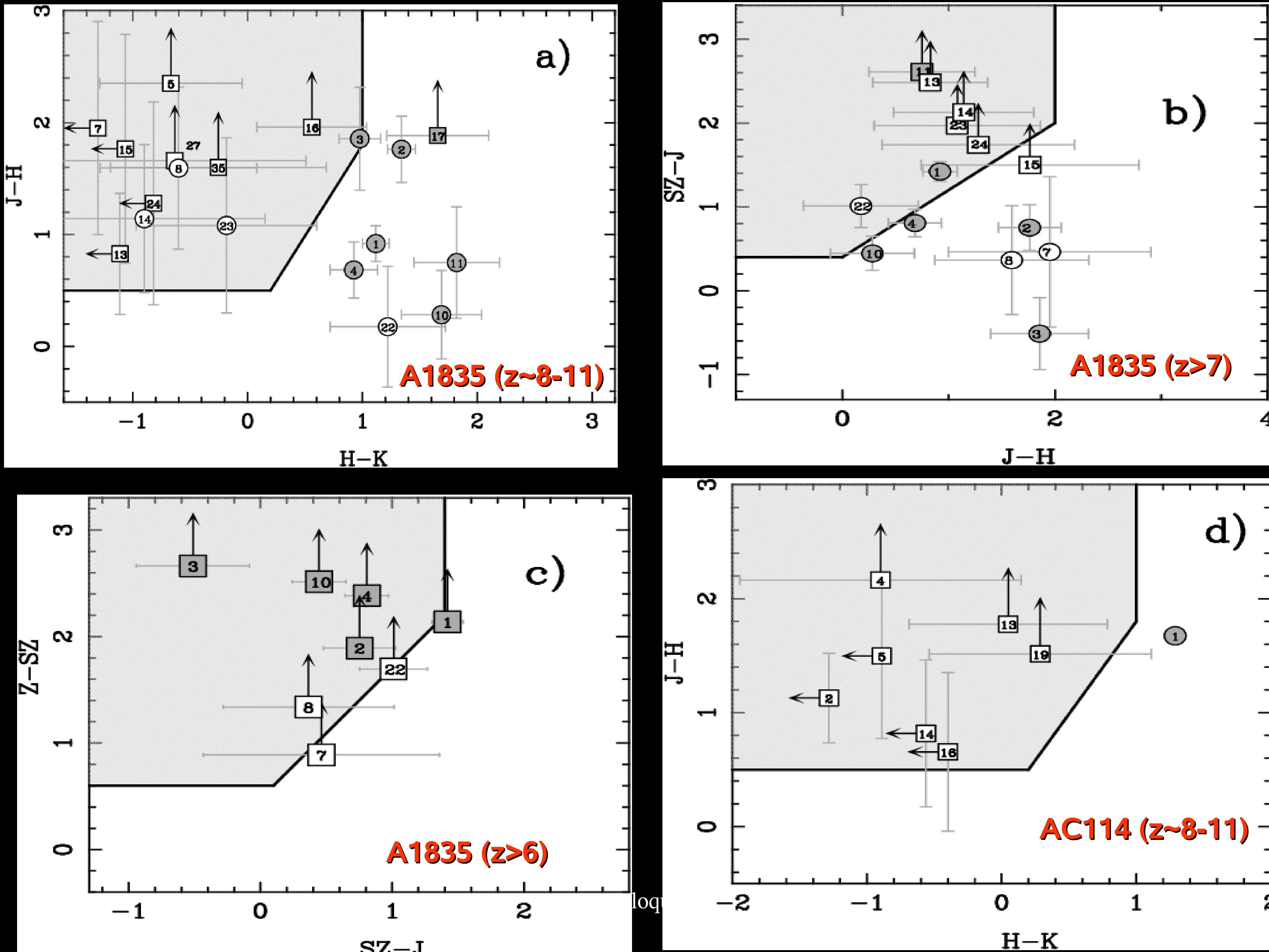
z/FORS (z=25.5) + SZ (Z=25.7)

seeing ~0.4-0.6"

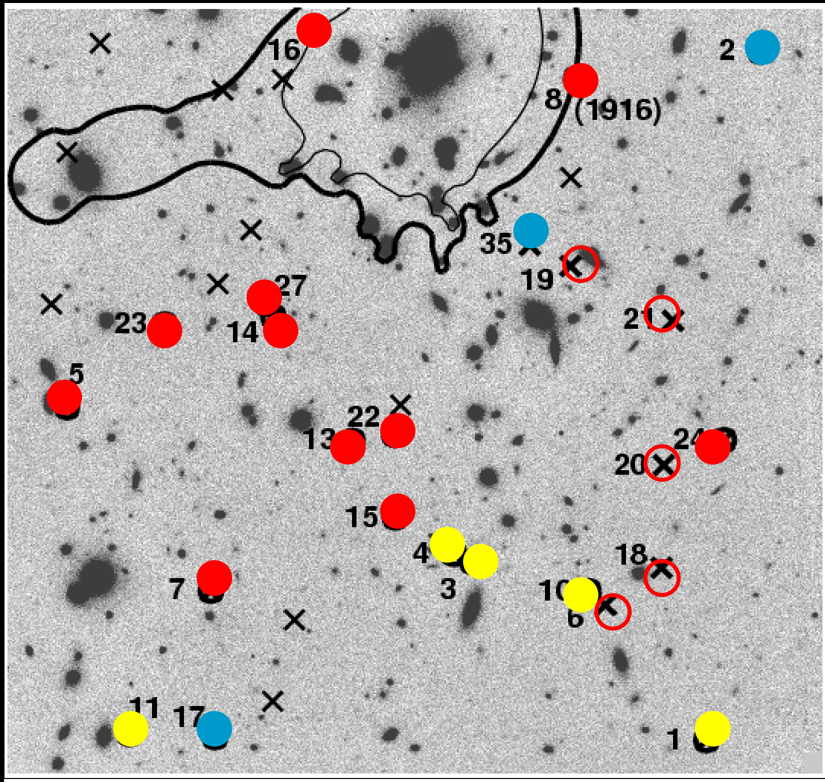
+ VRI Optical data + HST R band

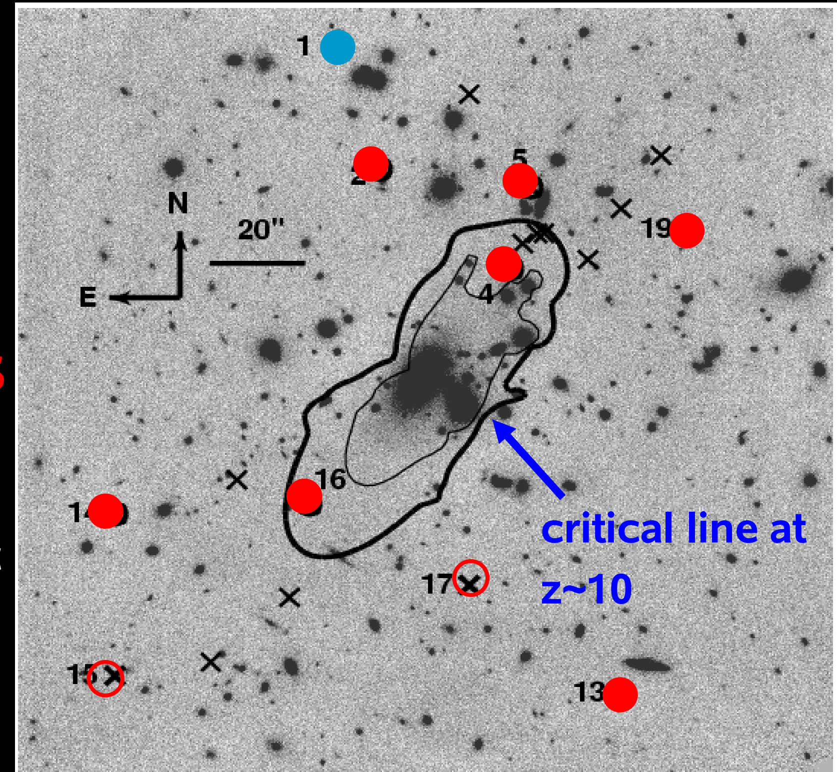
+ ACS/F850W (~28 AB)

+ HST/NICMOS (½ pointings) + IRAC/SPITZER new data


a)
A1835 (z~8-11)
J−H
H−K
b)
A1835 (z>7)
SZ−J
J−H
c)
A1835 (z>6)
Z−SZ
SZ−J
d)
AC114 (z~8-11)
J−H
H−K

Location of optical dropouts wrt the critical lines



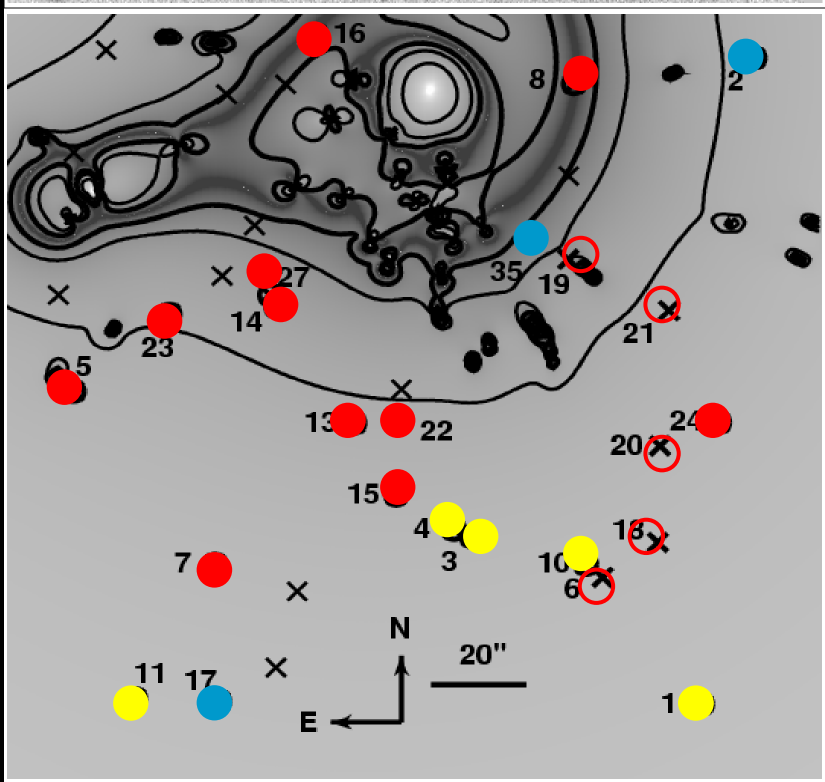


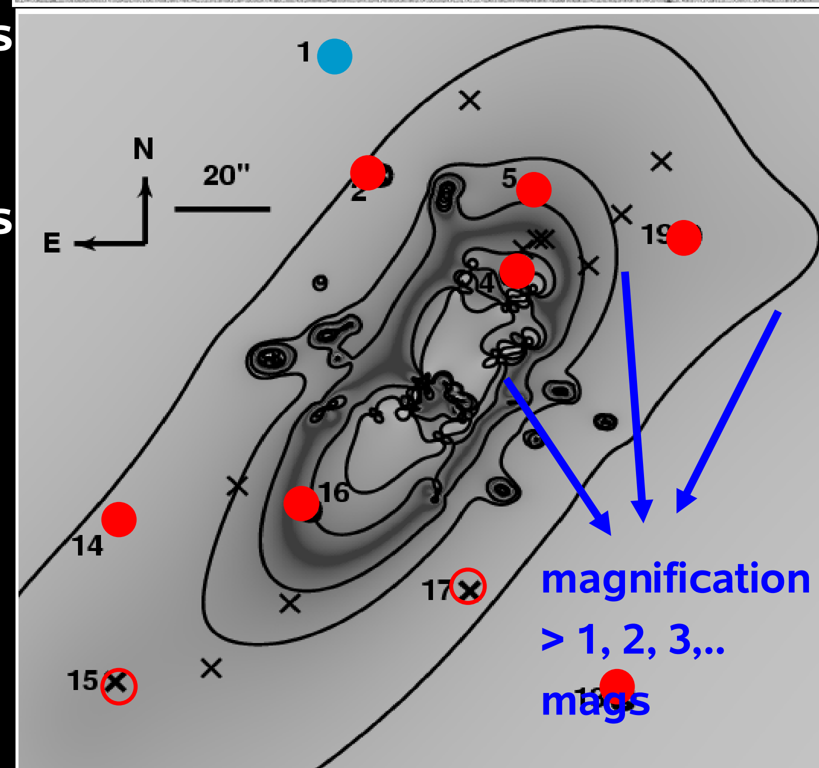
Photometric Or spectroscopic Low-z (blue dot)

1rst category High-z candidates (filled red dot)

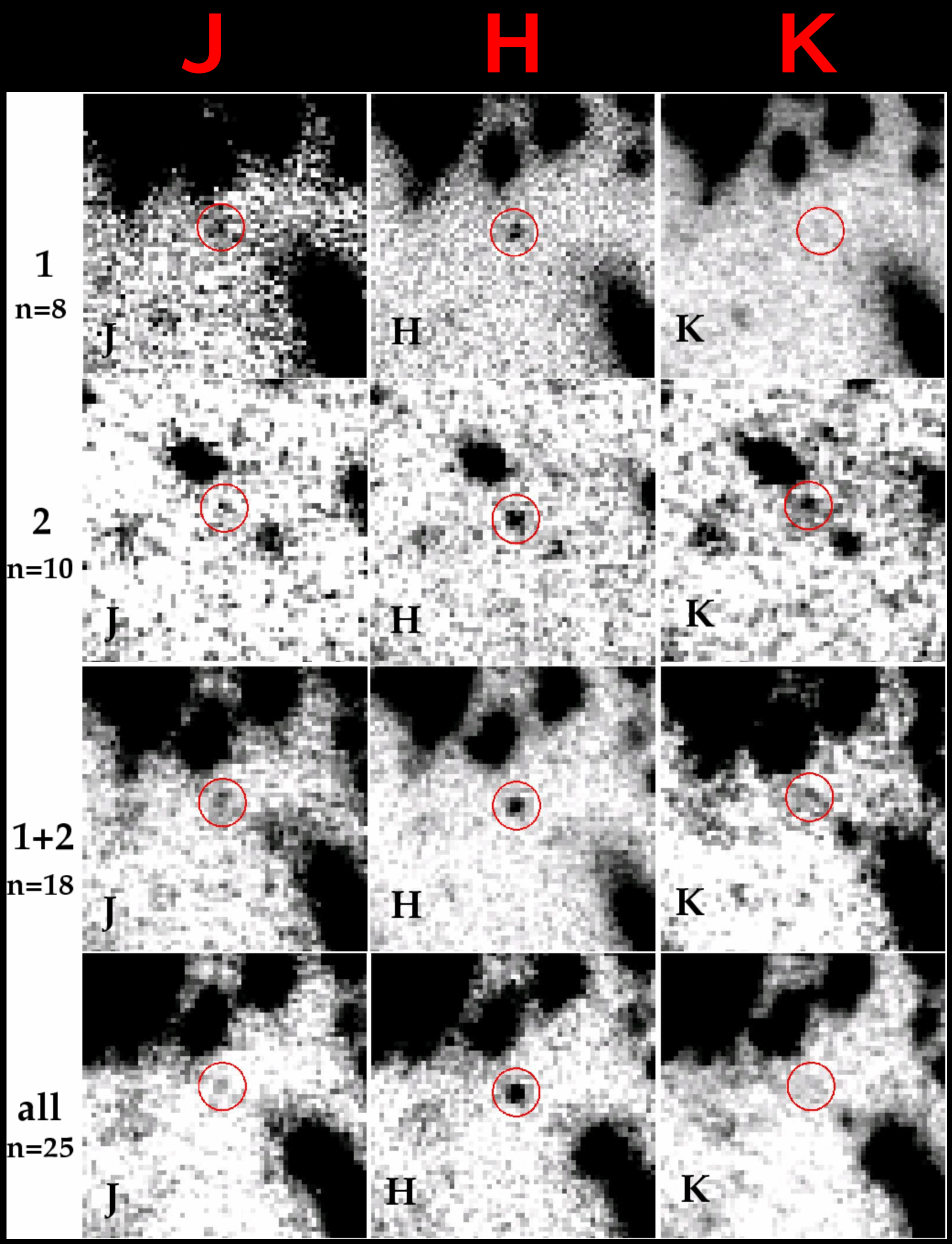
2nd category High-z candidates (open red circle)

22.3<H<23.7 23.7<AB<25.1 EROs &/or Atypical SEDs (yellow dot)





Stacked images of high-z candidates



- 18(8) first & second-category candidates in A1835(AC114)

CORRECTIONS:

- Lensing:

$$\eta\ (H_e, z) = \frac{N_o(H_e, z)}{N(H_e, z)}$$

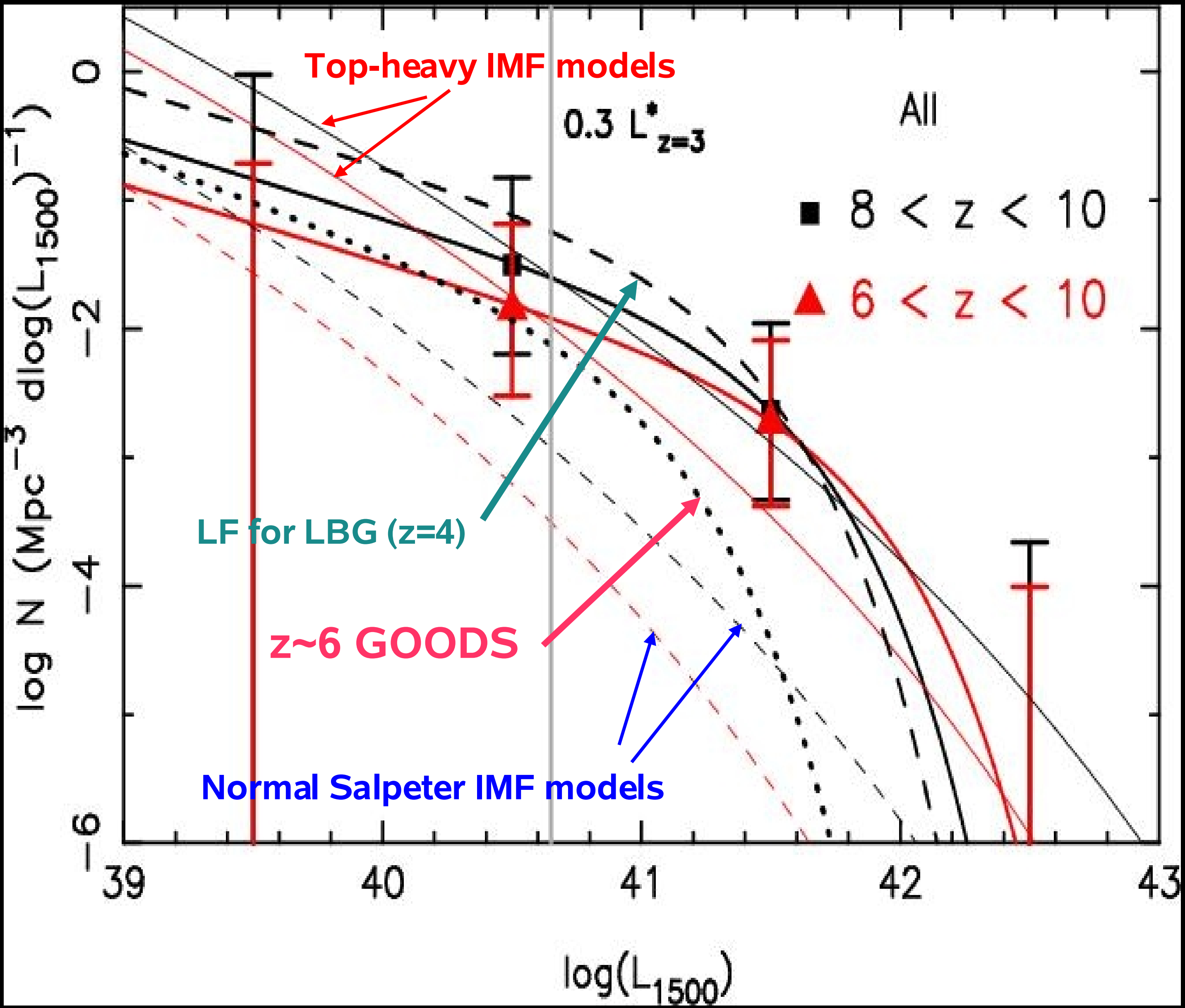
= observed number counts up to He/ number counts in a blank field (same depth and FOV)

$$\eta\ (H_e, z) = \frac{\int_{\Delta\Omega} \frac{N(H_e, z)}{M(\Omega, z)} C(H_o) d\Omega}{\int_{\Delta\Omega} N(H_e, z) d\Omega} = \frac{1}{\Delta\Omega} \int_{\Delta\Omega} \frac{C(H_e - 2.5\ log_{10} M(\Omega, z))}{M(\Omega, z)} d\Omega$$

- Photometric incompleteness
- False positive detections (depending on the detection filters)

Luminosity Functions

- Correction for lensing effects and incompleteness using the lensing model:



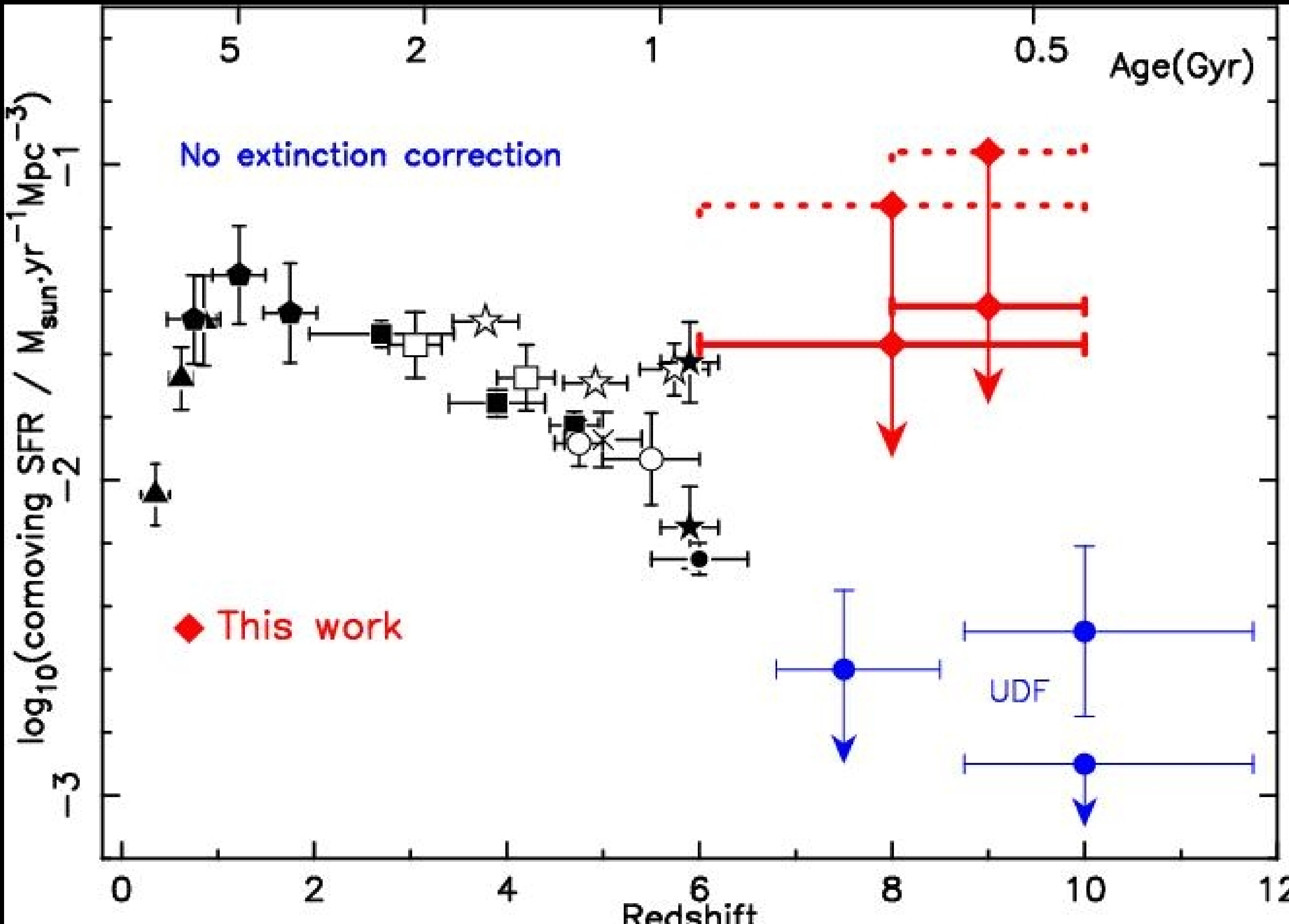
LF fit with

α = -1.6 fixed (as for LBGs z~ 3-4 (Steidel et al. 99)):

- STY fit to LF gives: L* ~ 10^41.5 erg/s/A
- Compatible with Steidel's LF (z~4) without any renormalization
- The turnover observed by Bouwens et al. 05 in the UDF, towards the bright end of the LF is not observed in this sample.

Richard et al. 06

Cosmic SFR at z~6-10

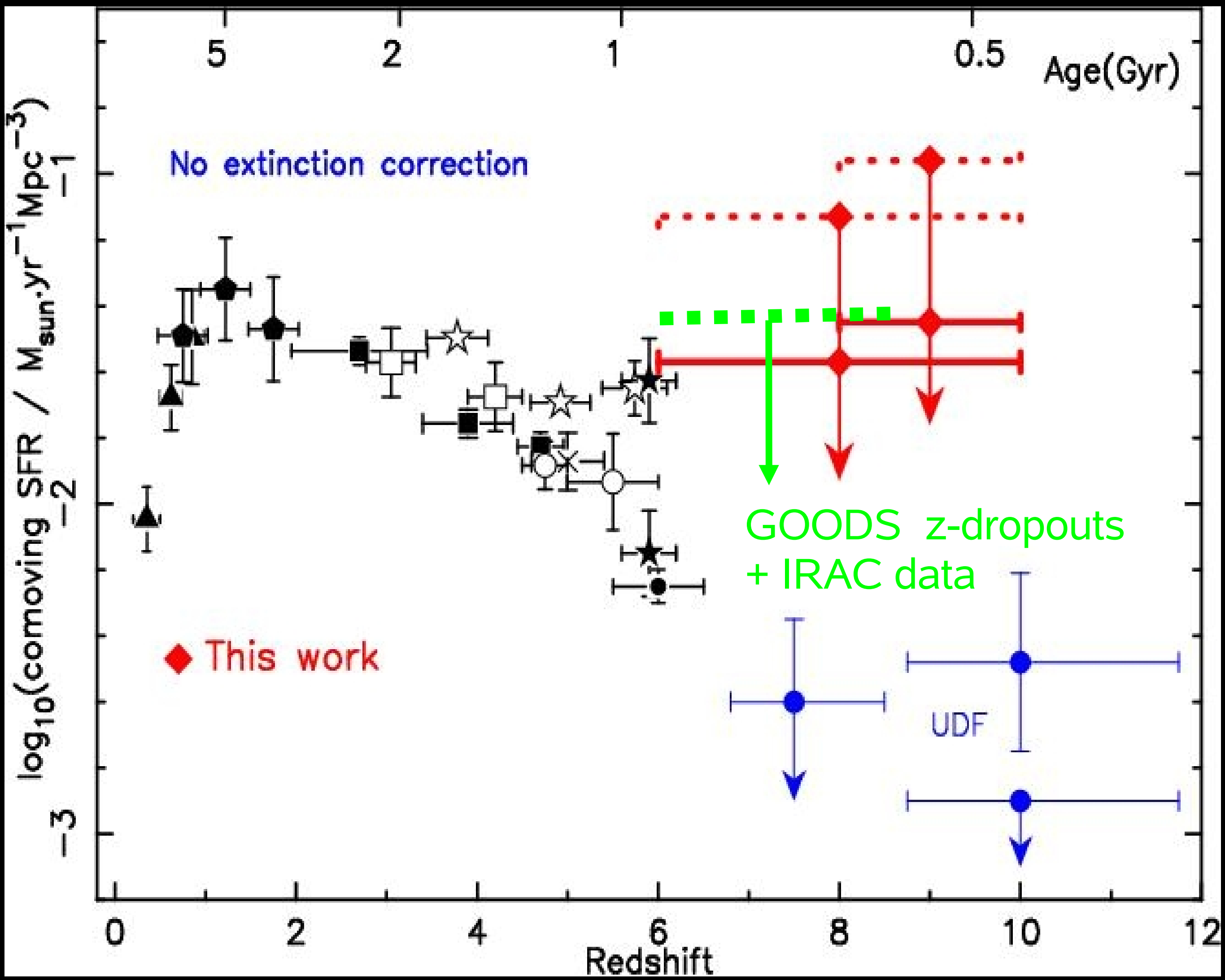


- LF integrated up to 0.3 L*(z=3)
- Results fairly compatible with previous findings at z<6, but a factor ~10 higher than present z~6-10 studies (UDF, (Bouwens et al. 2004, 2005).

Plot adapted from Bunker et al. 04, normalized to our settings and adopted cosmology.

Richard et al. 06

Cosmic SFR at z~6-10



Plot adapted from Bunker et al. 04, normalized to our settings and adopted cosmology.

- **Results in agreement with *maximum SFR density* derived from GOODS z~7 z-dropout sources with IRAC data (Labbé et al. 06)**
- **Discrepancies with other determinations in blank fields. Possible explanations:**
  - ➔ ***Strong field-to-field variance expected in small fields.***
  - ➔ ***Positive magnification bias in our sample due to mid-z interlopers.***
  - ➔ ***Residual contamination by fake detections***

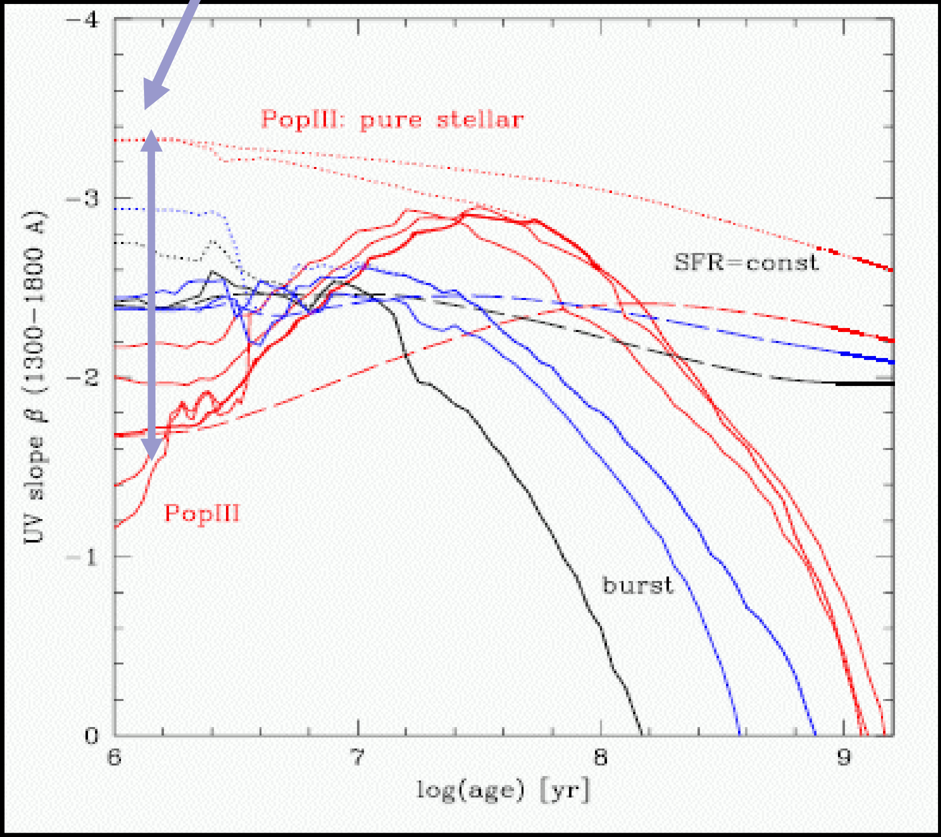
Richard et al. 06

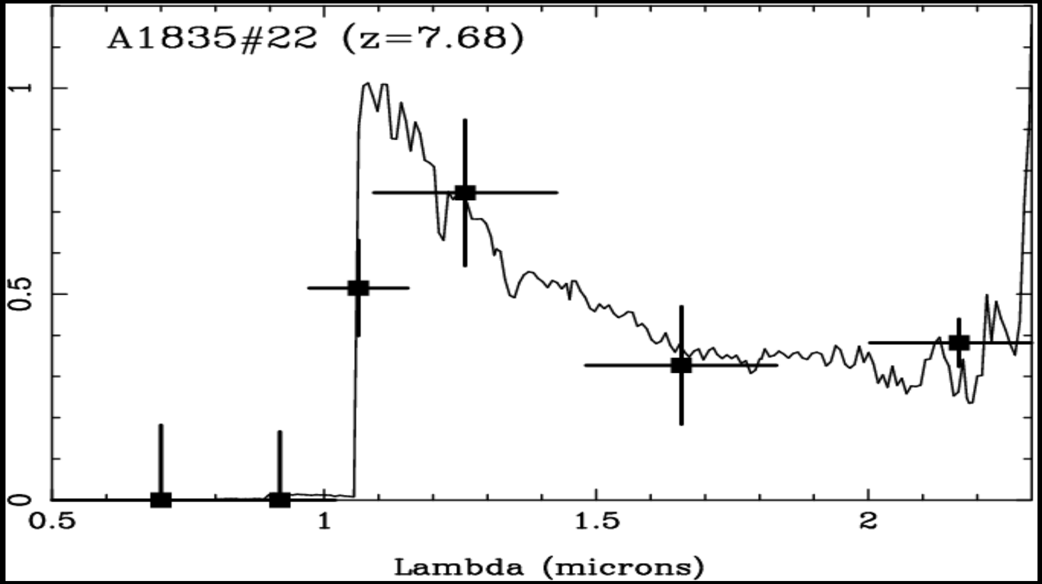
Intrinsic properties of high-z candidates

- Selection criteria based only on near-IR colors irrespective of magnitudes. Most photometric candidates turn out to be fainter than H = 23.0 (AB ~ 24.5 + 2.5log μ). If z~6-10, young starbursts are typically a few 10^8 M_solar (standard IMF).
- Using Kennicutt 1998 relation L_1500 --> SFR ranging between a few units and 20 M-solar/yr…… But equilibrium conditions are not necessarily reached in this objects!

candidates in lensing fields

From Schaerer & Pello 05





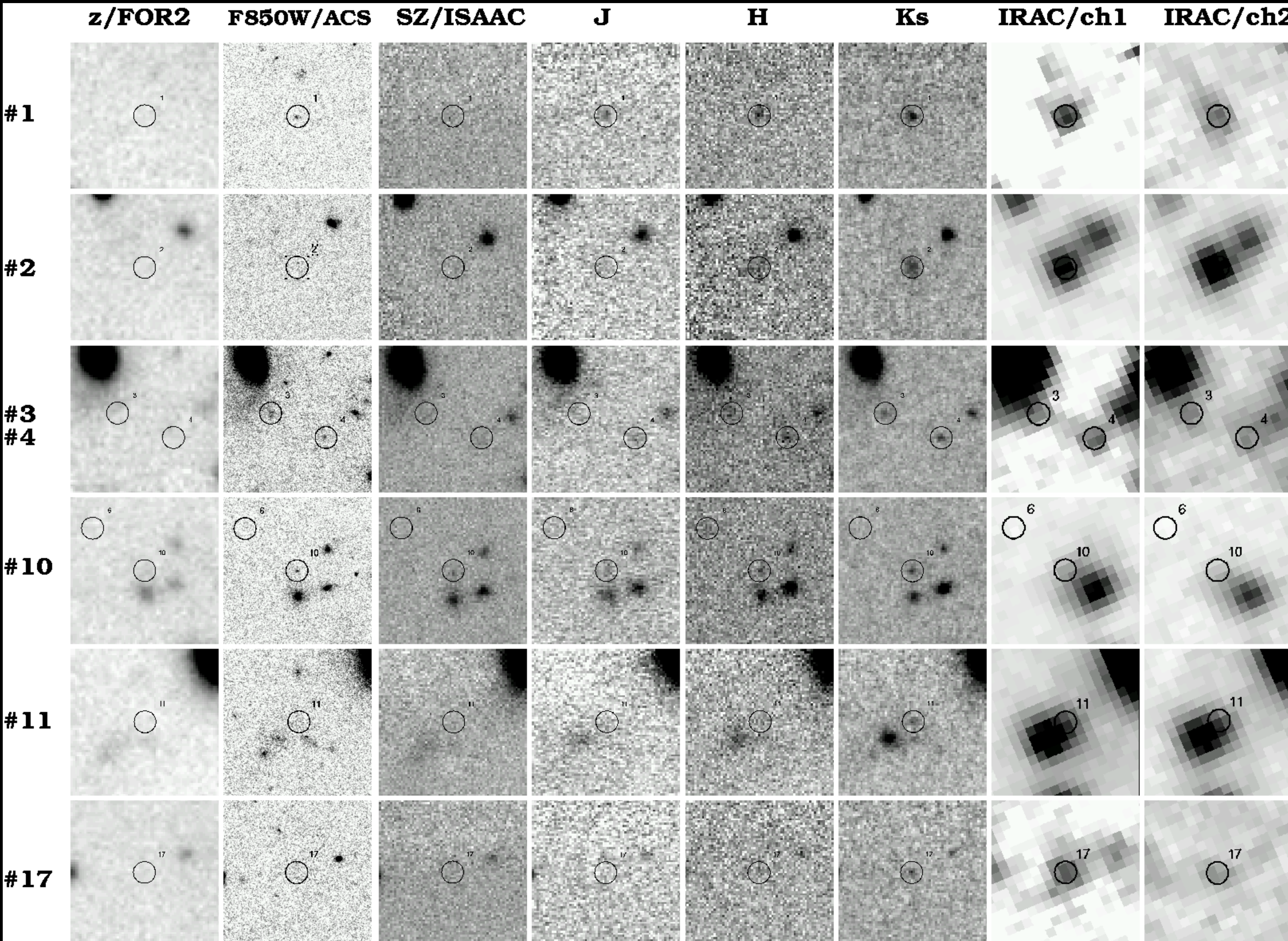
Very blue UV slope: β~ -1.5 to -3.5

Cf. GOODS, UDF… surveys

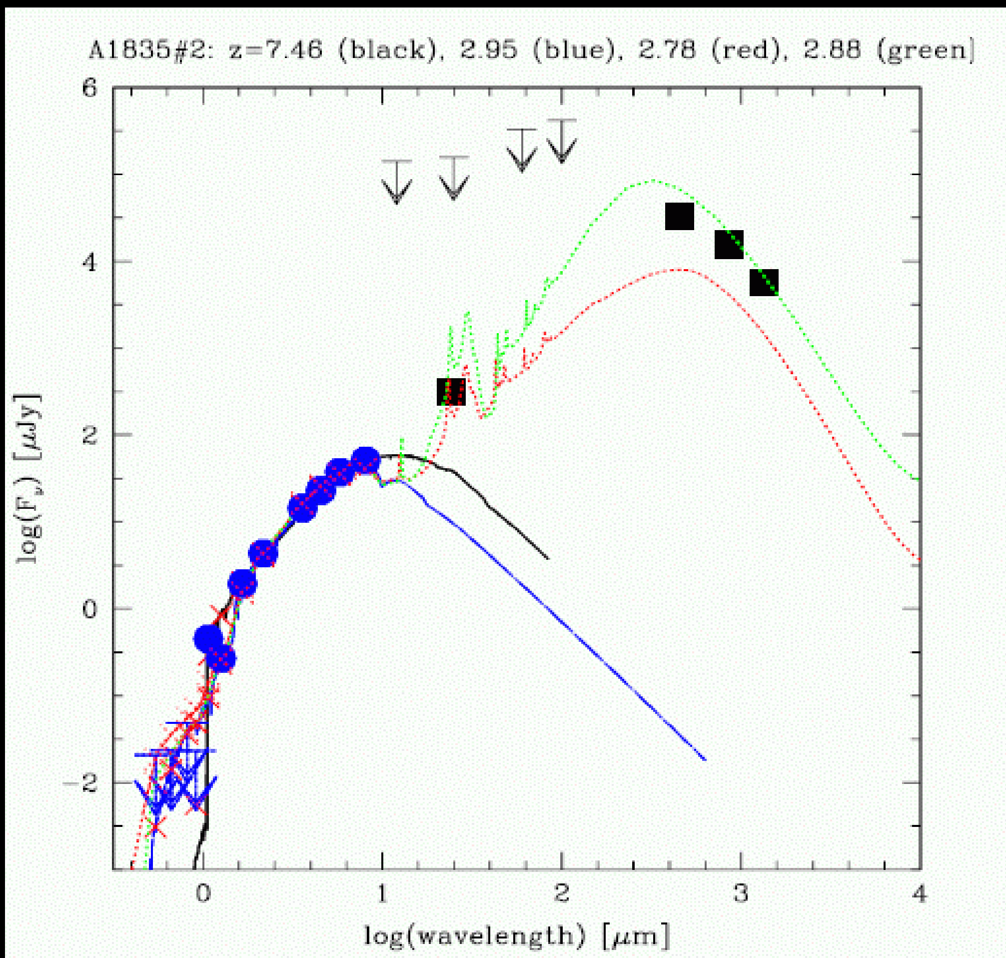
==> INDICATION OF LITTLE OR NO EXTINCTION

Multi-wavelength analysis

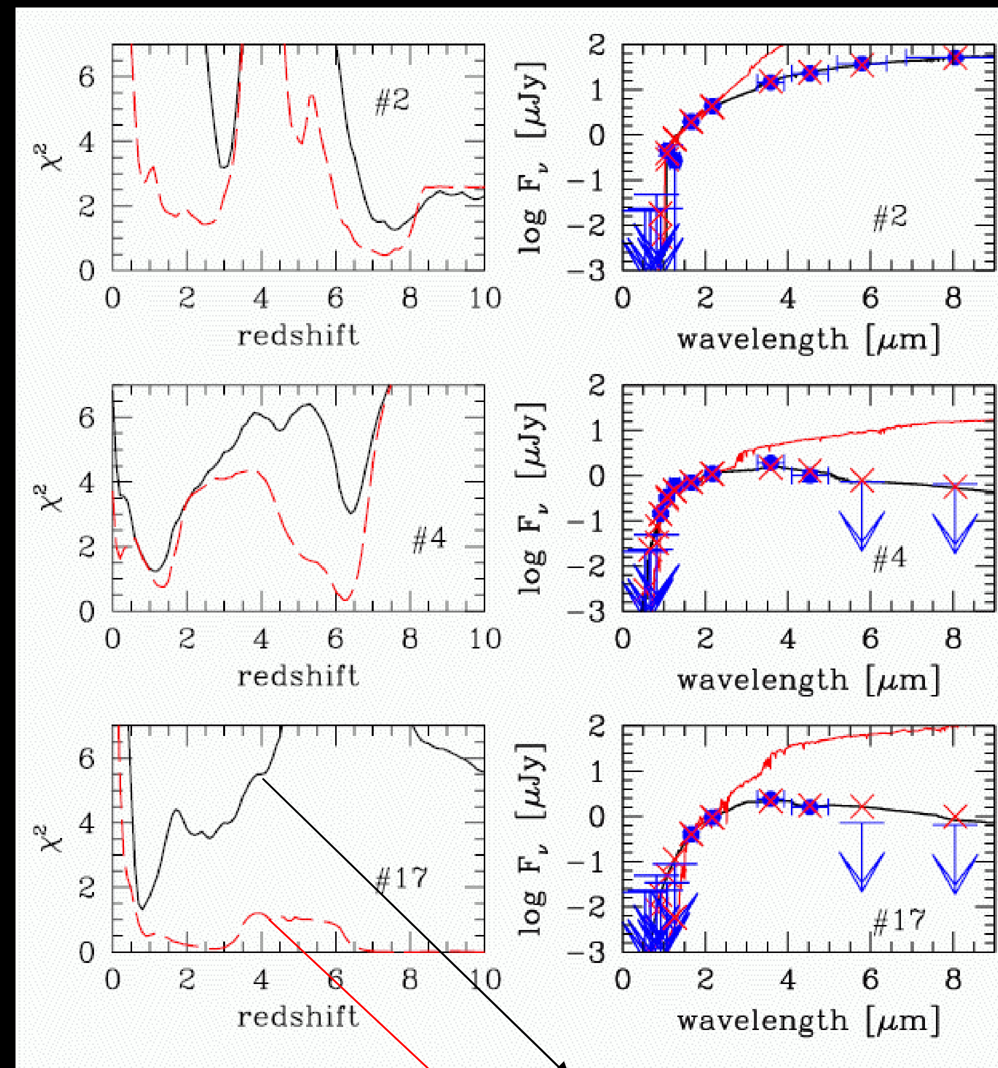
« Bright » optical dropouts in A1835



- **IRAC/Spitzer :**
  - Detection of brightest objects (ERO) between 3.8 and 8 µm --> new constraints on their nature and redshift
  - high-z candidates not detected as expected



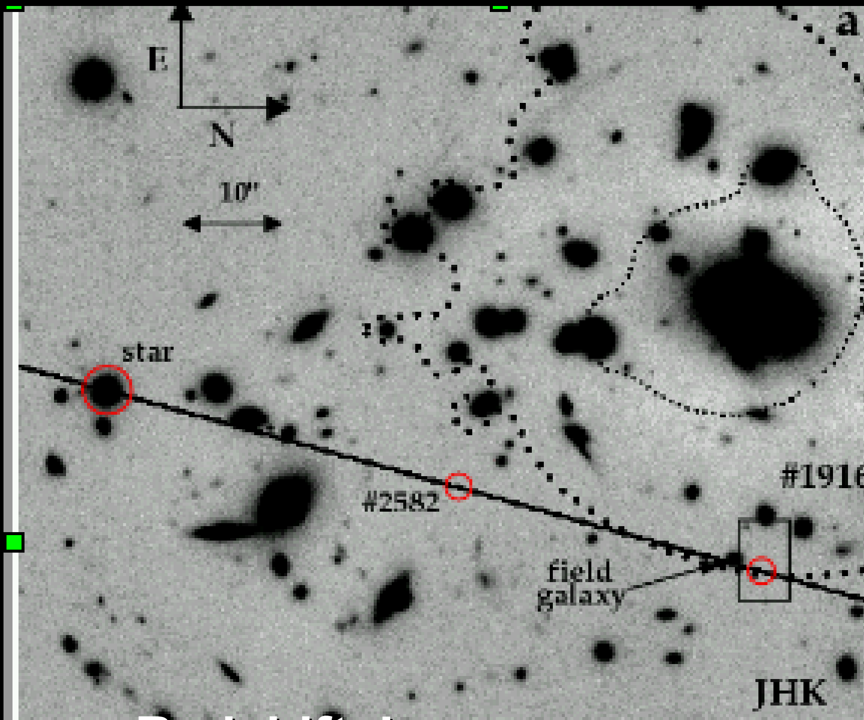
ACS/HST z-band observations (non-detection $Z850_{AB} > 28.$ to 28.3) confirm « dropout » nature of z>~7 candidates behind A1835 and AC114.



with IRAC data
without IRAC data

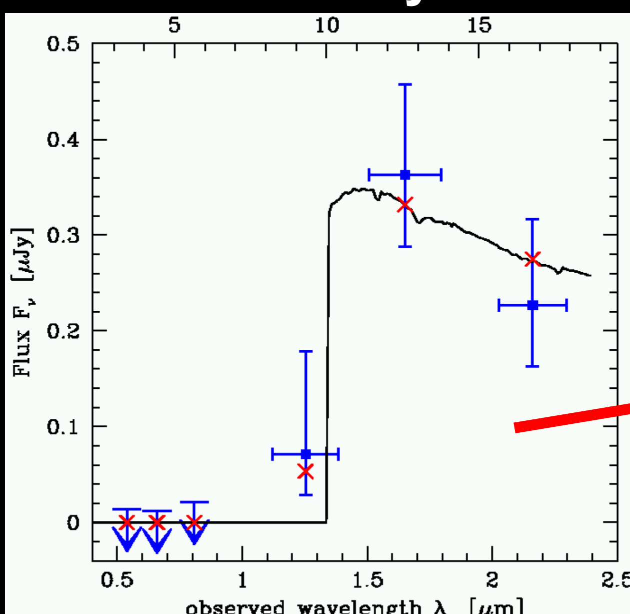
(Schaerer et al. 07, Hempel et al. 07)

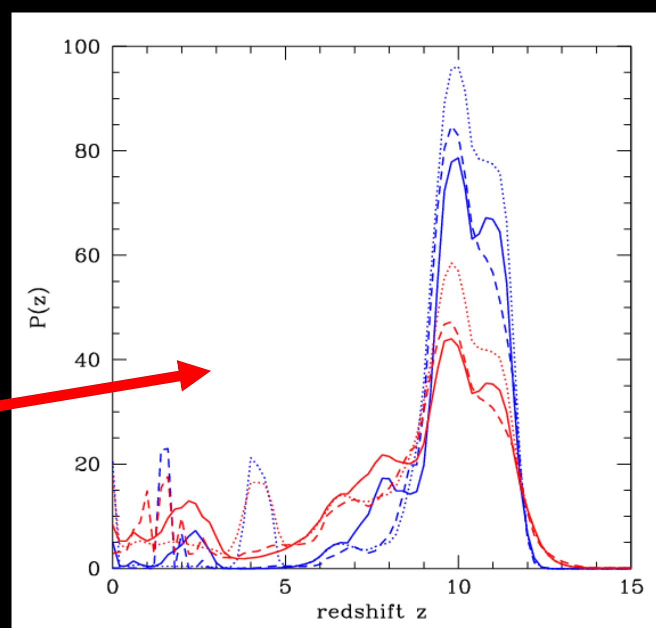
Spectroscopic follow-up

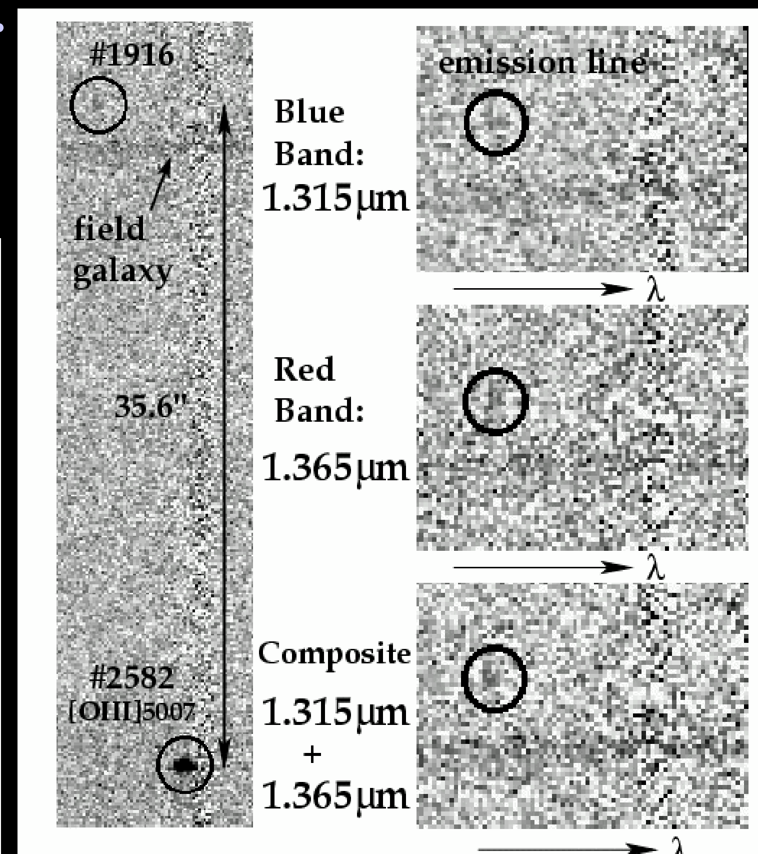


- Ongoing Spectroscopic follow-up with ISAAC/VLT
- We explore the 0.9-1.4 microns domain, R~3100 (5 bands!). 2 observing runs:
  - Detection run (visitor mode): looking for e-lines with priorities according to photometric P(z).
  - Confirmation run (service): re-detecting e-lines and excluding low-z interlopers.

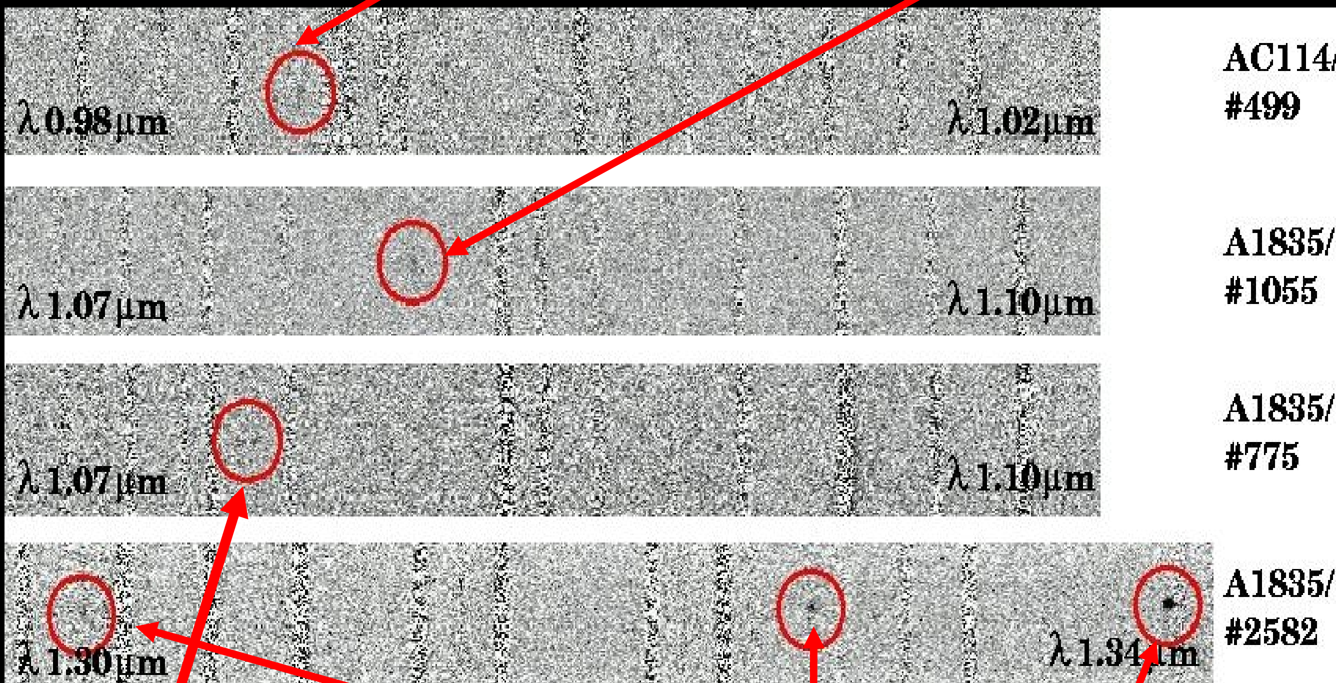
Redshift Ly α







Spectroscopic follow-up.

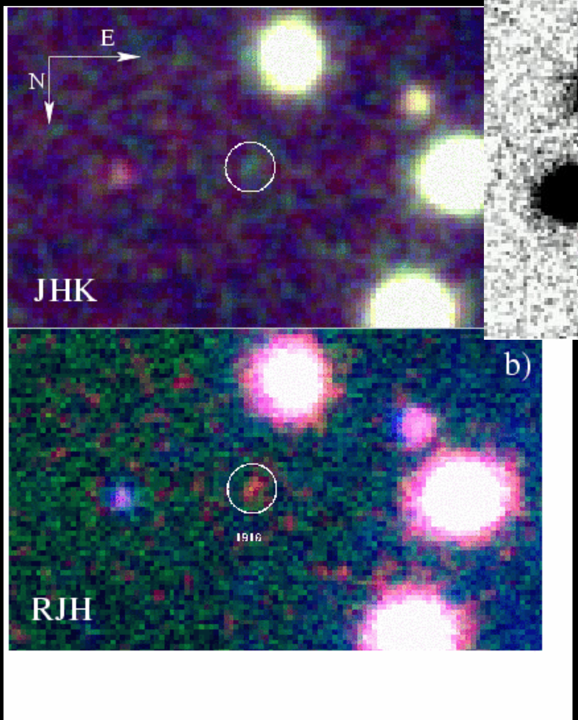


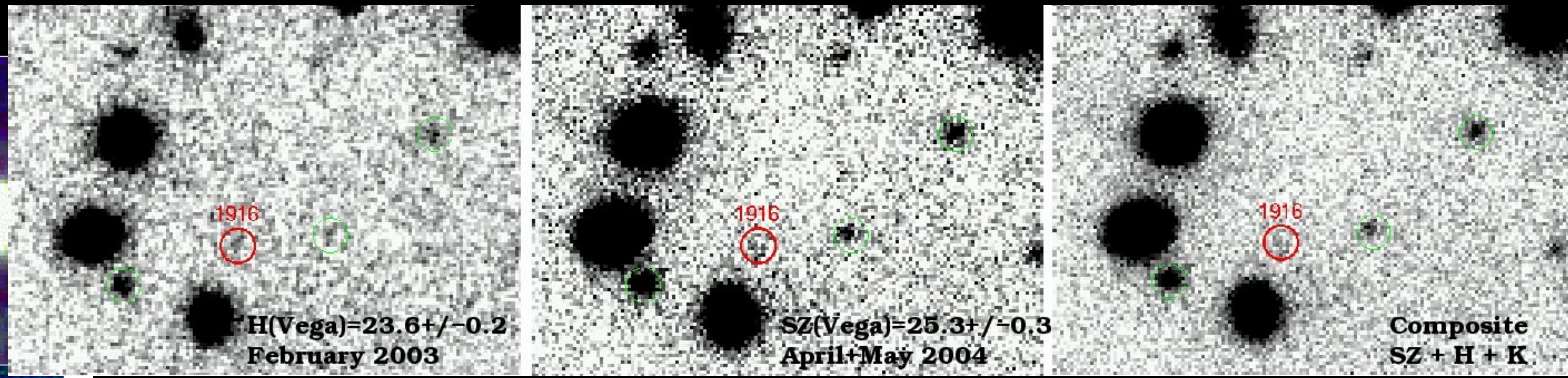
A tedious and highly inefficient process with ISAAC/VLT…

- Targets: 2 priority candidates in AC114, and 7 in Abell 1835 (4 ``first priority" targets and 3 secondary ones). From this sample of 9 targets, 2/3 of the objects observed display emission lines.
- A large majority of our high-z candidates still need to be (re)confirmed, either by a re-detection of a faint emission line, or by the non-detection of other lines expected at low-z.
- FORS/VLT z-band spectra on the “bright” EROs.

See also Pello et al 04, A&A 416, L35; and astro-ph/0410132

A puzzling source: A1835#1916, a distant AGN?





New photometry ==> INTRINSIC VARIABILITY OF THE SOURCE: AGN?

-Non-detection in H (29/06/04; Bremer et al 2004)
-Re-detection at 1.06 microns (05/04) ==> more likely z~7-8.
- Non-detection on deep images in the visible bands (Keck & VLT; e.g. Lehnert et al. 2005) confirms the « optical dropout »)

New spectroscopy in the H band: low-z solutions excluded/unlikely

- 1.6915 to 1.8196 microns, 2 adjacent bands (30/36 frames x 900 sec).
- No other lines detected (e.g. HeII 1640 …)

All solutions at low-z between z~2 - 2.6 seem excluded, as well as most solutions at z<2.

Re-analysis of original ISAAC spectra:

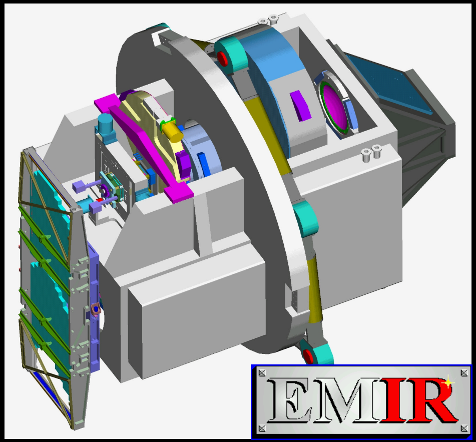
Absolute wavelength calibration was ~4.5A off (=>7-9 pixels in blue-red bands) in original paper: line detected at 1.33790 (+/- 0.0001) microns (instead of the 1.33745 microns). Photometric constraints :more likely CIV1550 at z = 7.6.

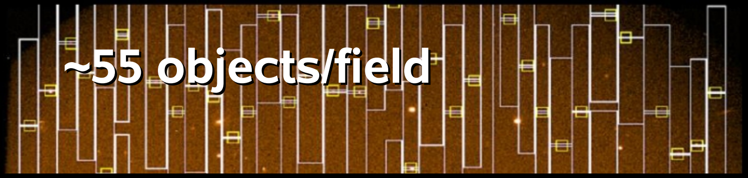
Joint detection in H, K, SZ, and emission line --> probability of spurious detection is low!


Designing future surveys:
A matter of efficiency

A new generation of near-IR spectrographs

An example: EMIR/ GTC





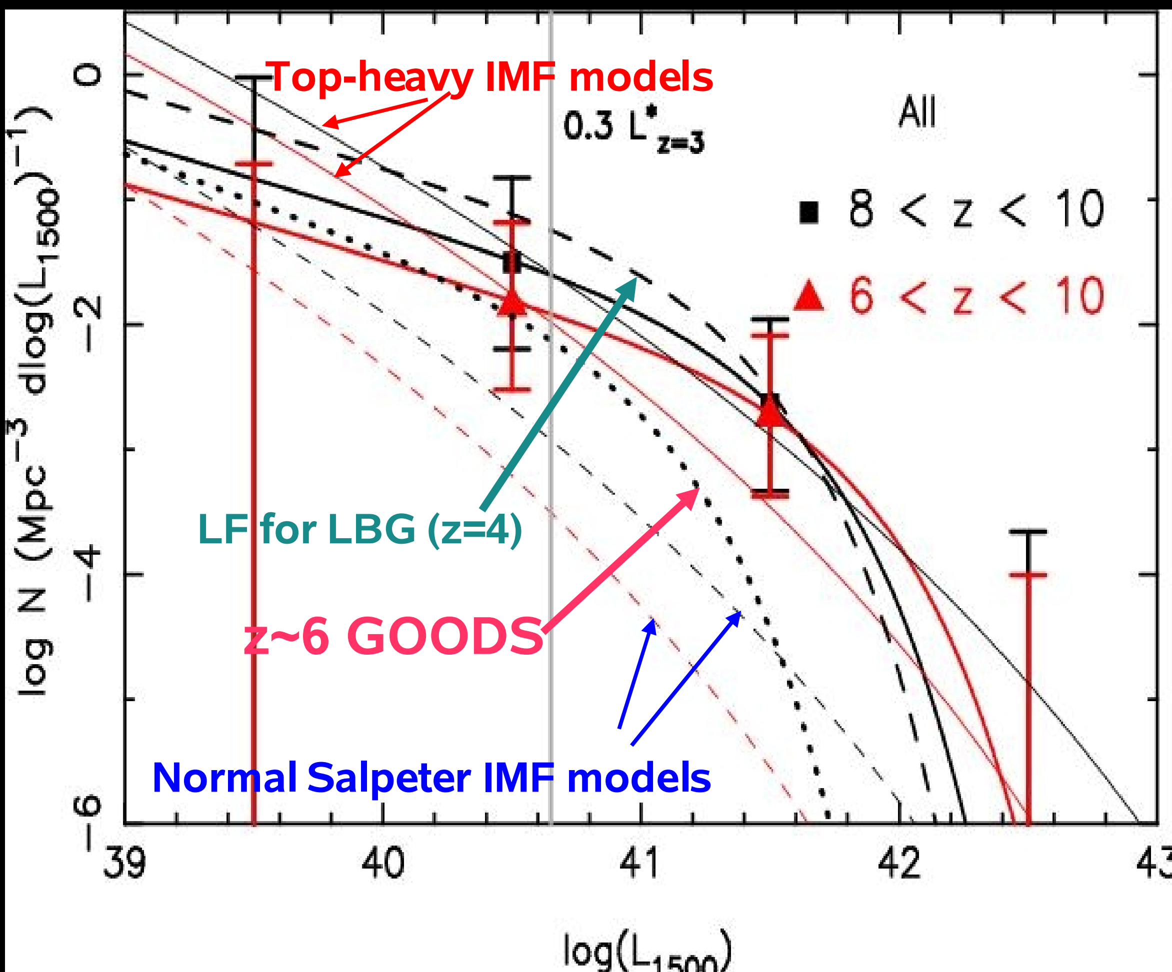
EMIR/GOYA Survey (~2009):

- Near-IR multi-object capabilities (~20 to 60 targets) in 10m class telescopes
- Large FOV (~4' to 6' wide)
- Optimal spectral resolution: R~3000 to 6000 (large sky-free wavelength coverage)
- "Deep" Spectroscopic follow up from the ground (JWST synergy).

Other examples: MOIRCS/Subaru (in high-resolution mode) – Flamingos2/Gemini-S – KMOS/VLT 2nd generation

Lensing or Blank fields?

- **Evaluation of lensing clusters efficiency to find z>6 galaxies with model expectations and simple assumptions. A lensing field introduces 2 opposite trends on the observed sample as compared to blank fields: 1) gravitational magnification and 2) reduction of the effective surface by the**



- *A toy model to estimate the expected number counts:*
  - **Press-Schechter formalism (Press & Schechter 1974)**
  - **10% of the baryonic mass converted into stars between 6<z<17**
  - **2 extreme assumptions for the IMF: standard Salpeter & top-heavy IMF**
  - **Visibility time estimated according to a "duty-cycle":**

P

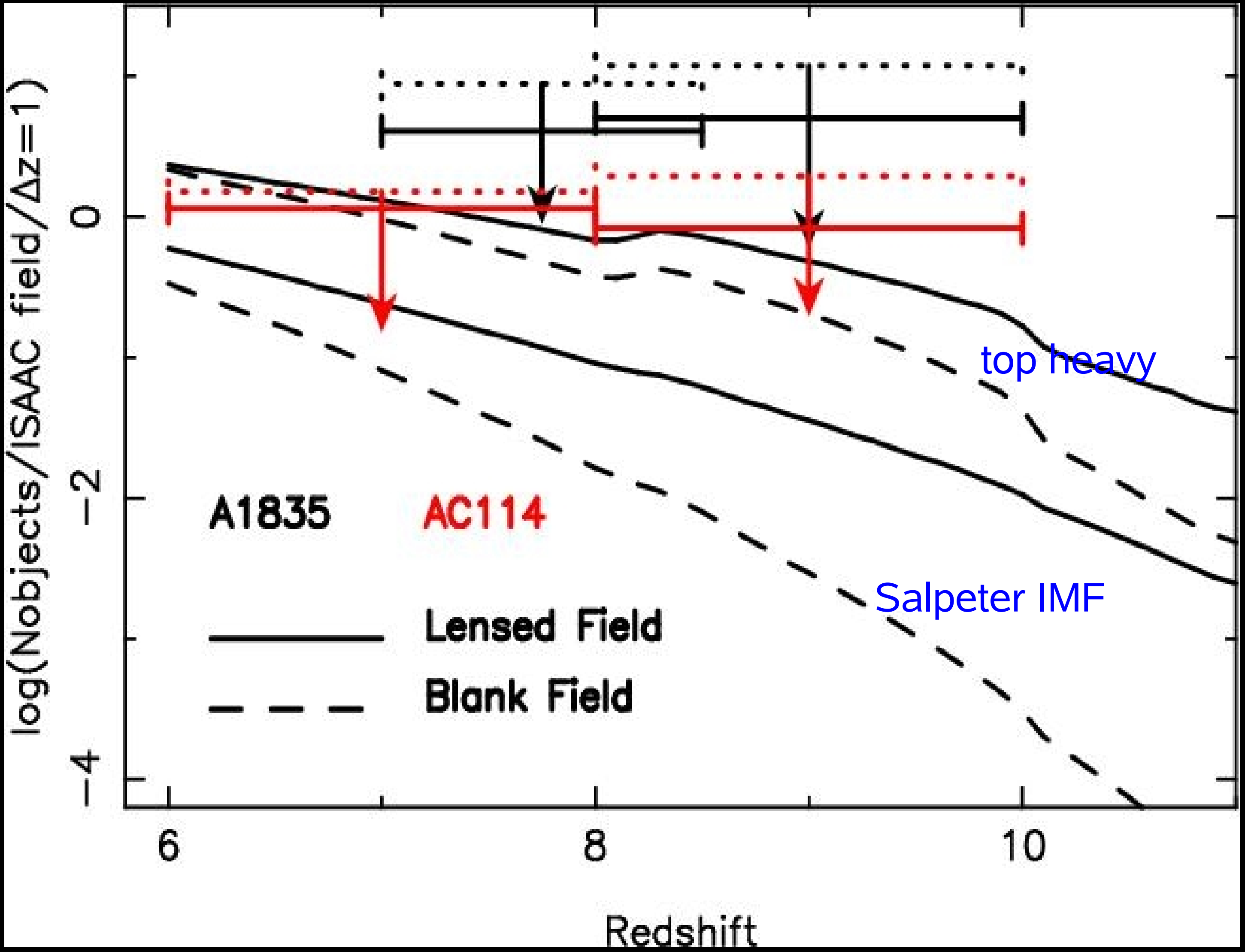
$$t_* \, (1+z)/(t_H(z) - t_H(17))$$

z

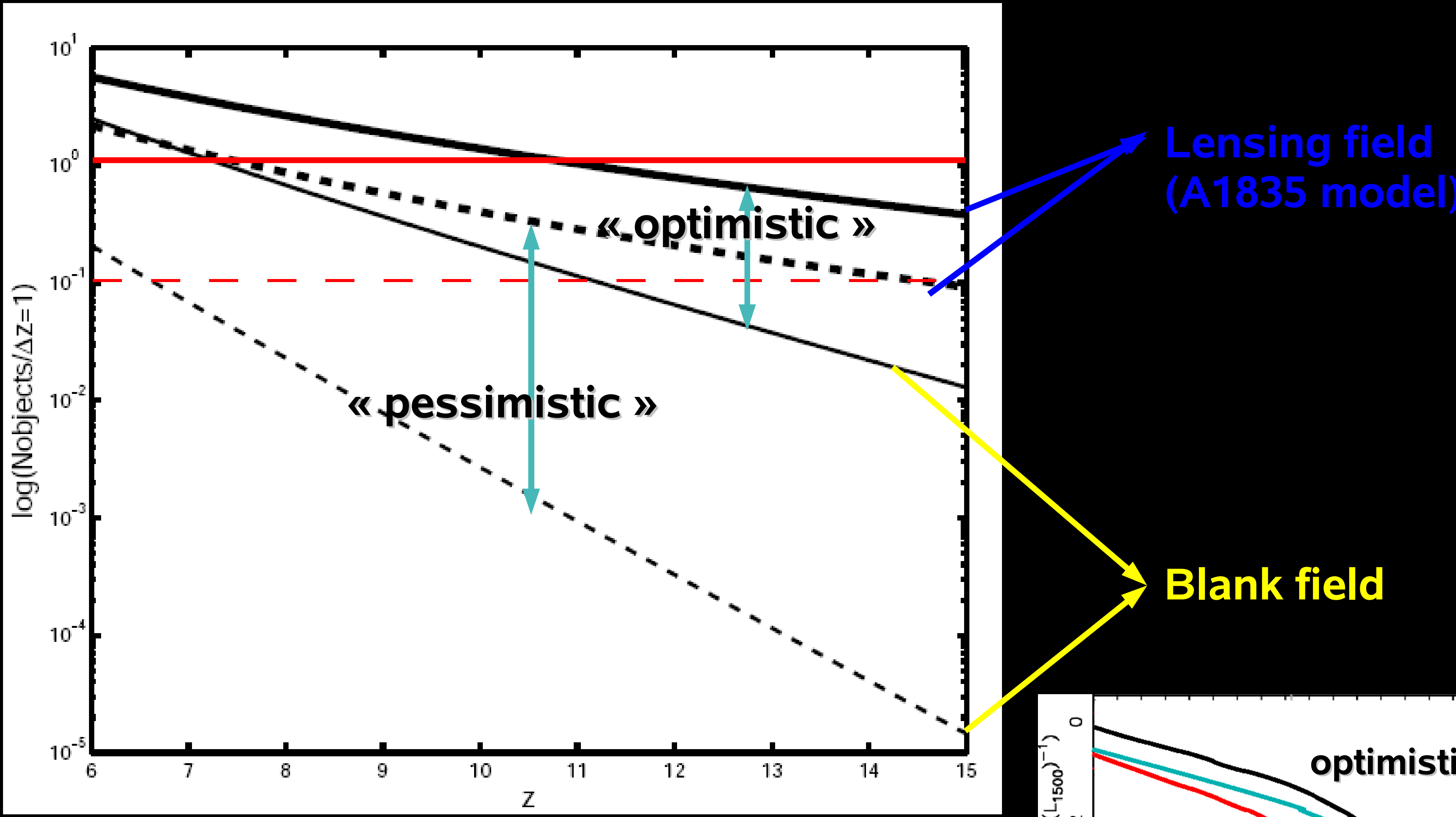
- <u>Positive</u> magnification bias is expected from this simple model:

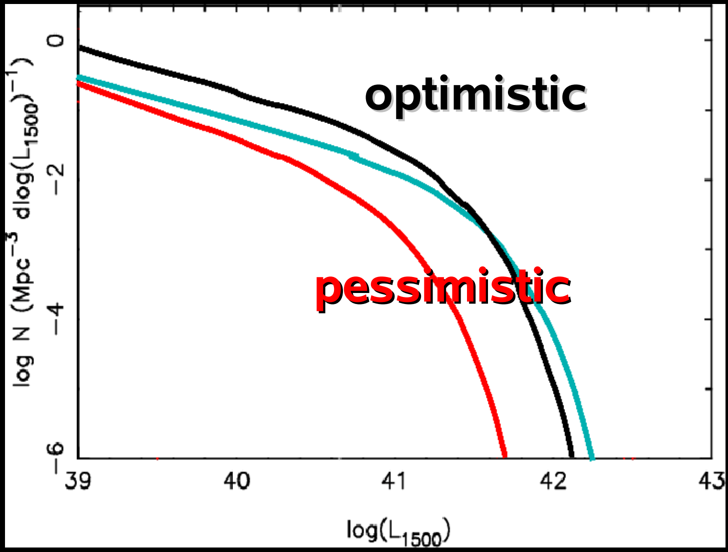
$$N_{lensed}(>L) = N(>L) \times \mu^{\alpha-1}$$ with $$\alpha = -d(log n)/d(log L)$$

(see e.g. Broadhurst et al. 95)



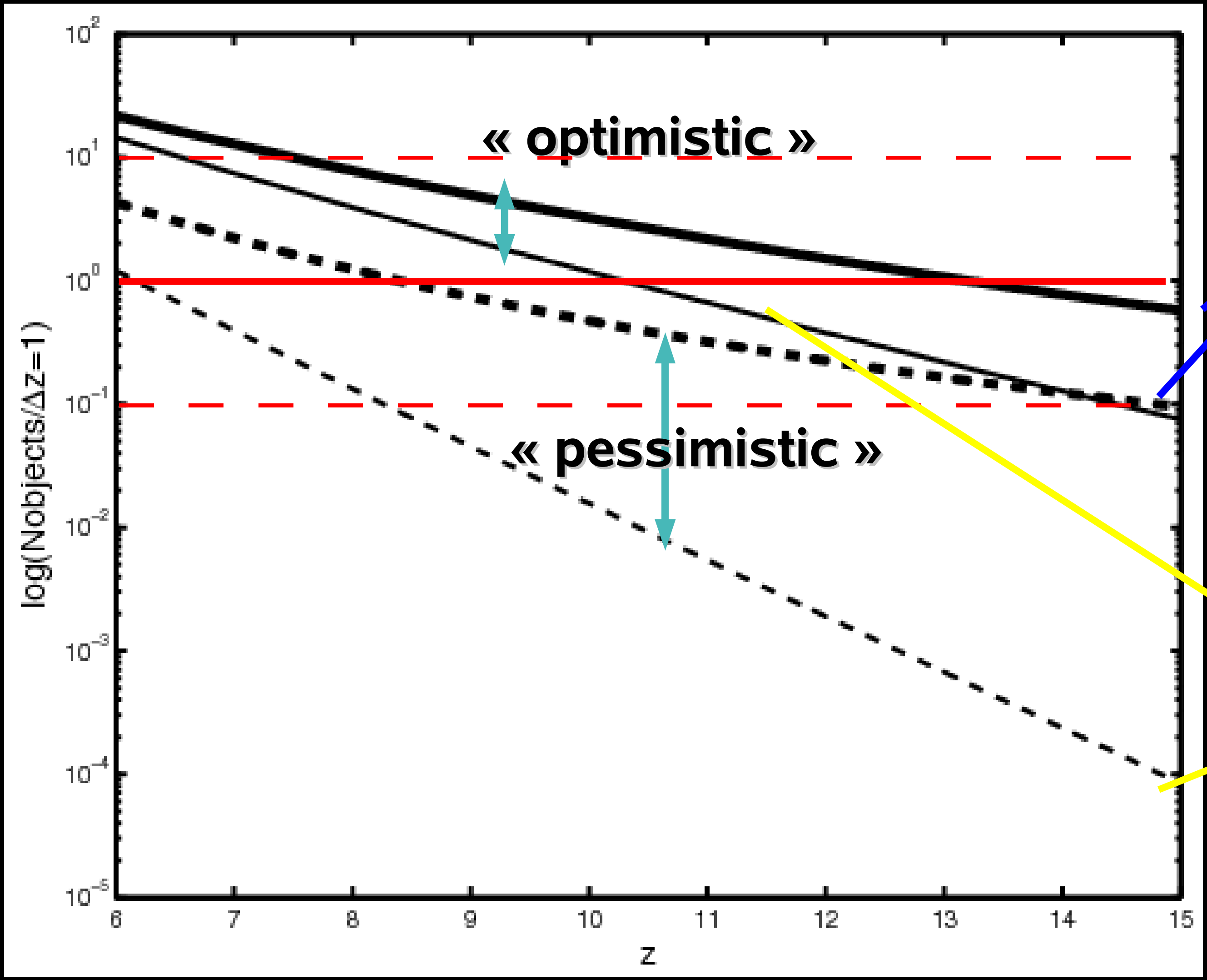
- Number of sources with H(Vega) <24, within a redshift bin dz=1.
- Pixel-to-pixel integration of magnification maps, with the same lensing models and bright-objects masking.
- Lensing clusters are expected to be a factor of 5-10 more efficient than blank fields in the 7<z<11 domain

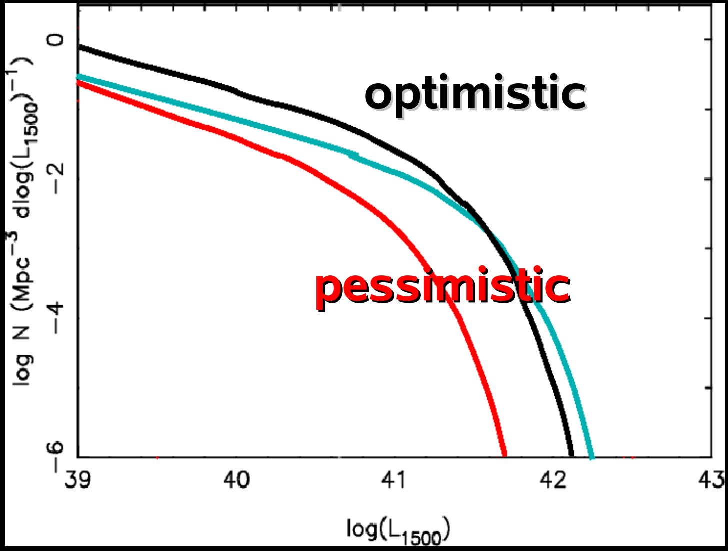




« BRIGHT » SPECTROSCOPIC SAMPLE

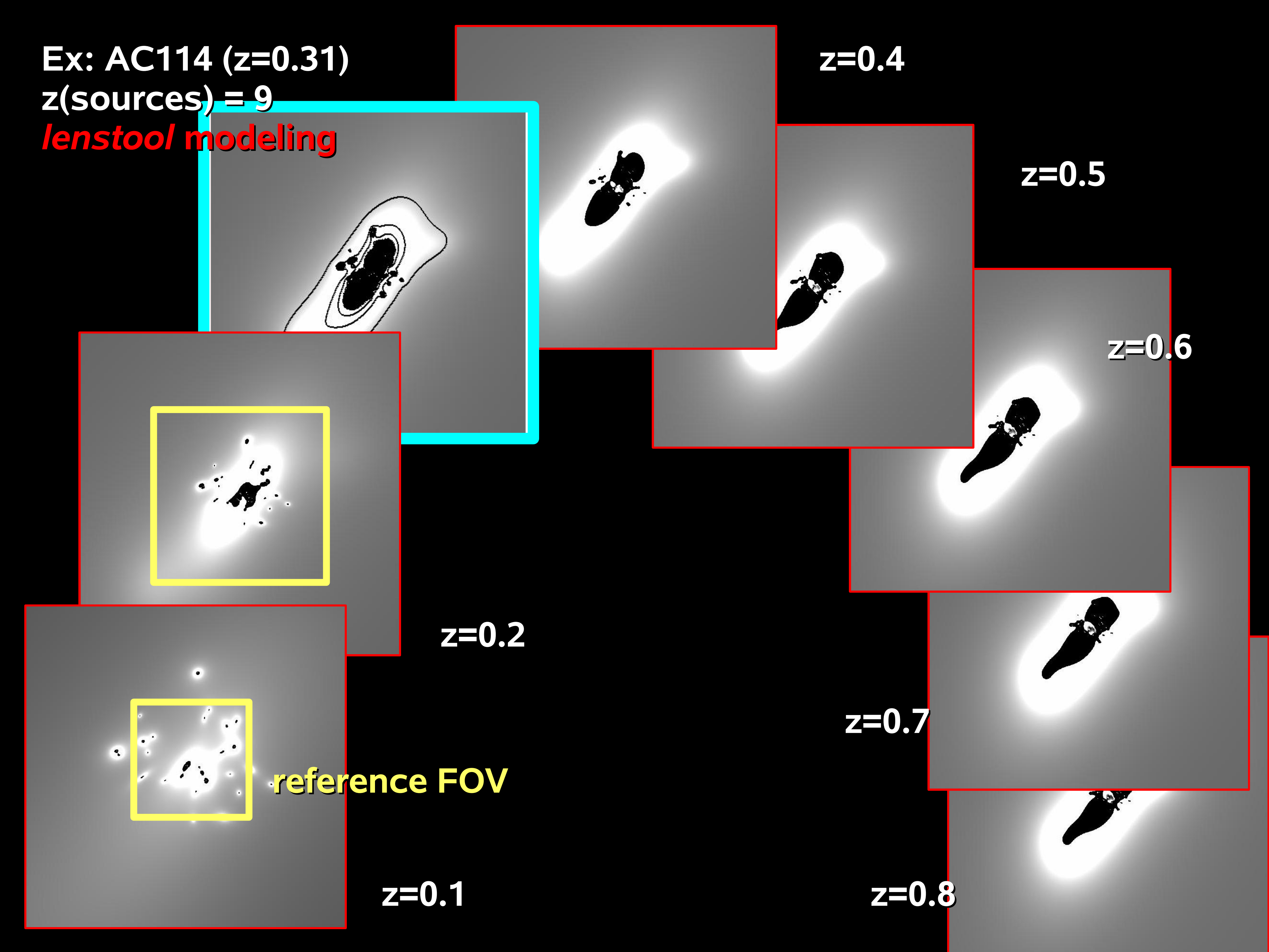
H(AB)<~25.5 in a 2.5' x 2.5' FOV

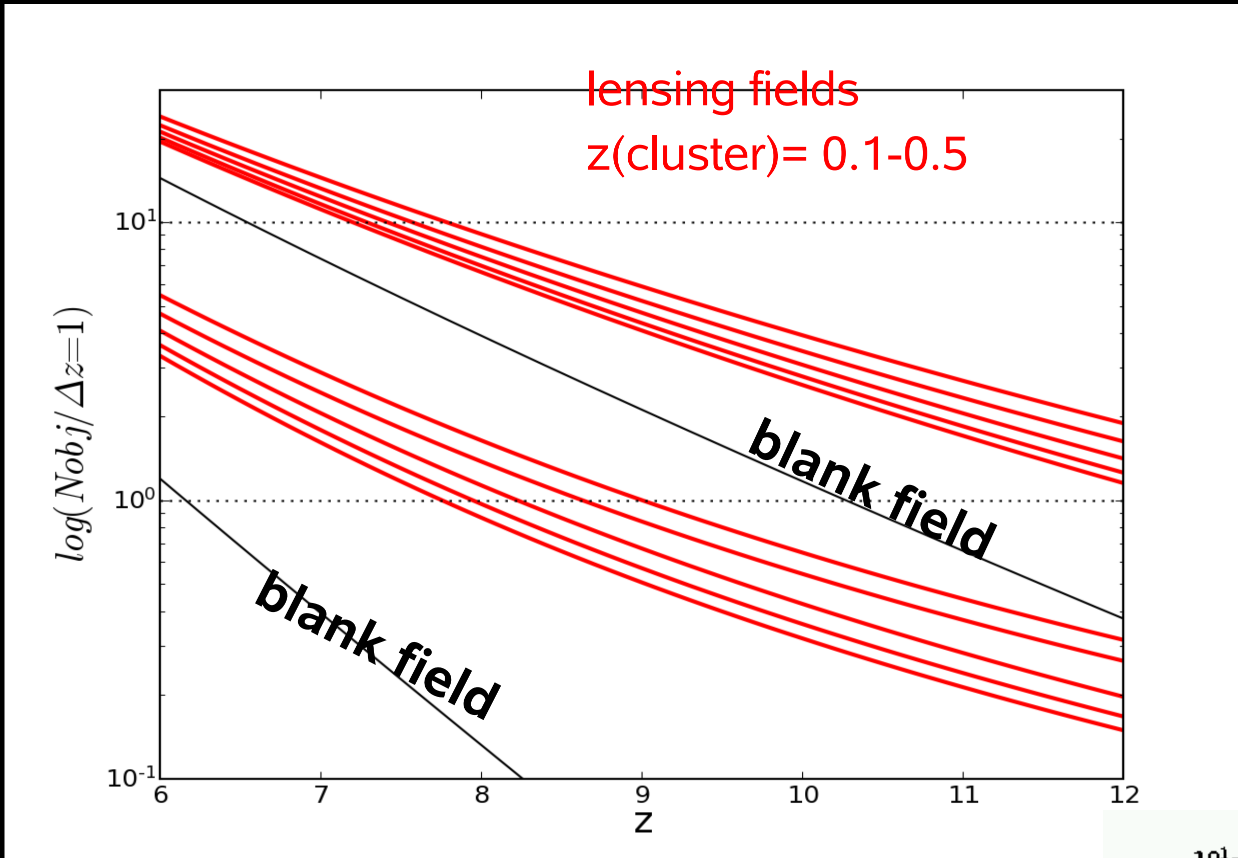




« BRIGHT » SPECTROSCOPIC SAMPLE

H(AB)<~ 25.5 in a 6' x 6' FOV


Ex: AC114 (z=0.31)
z(sources) = 9
lenstool modeling
z=0.4
z=0.5
z=0.6
z=0.2
z=0.7
reference FOV
z=0.1
z=0.8

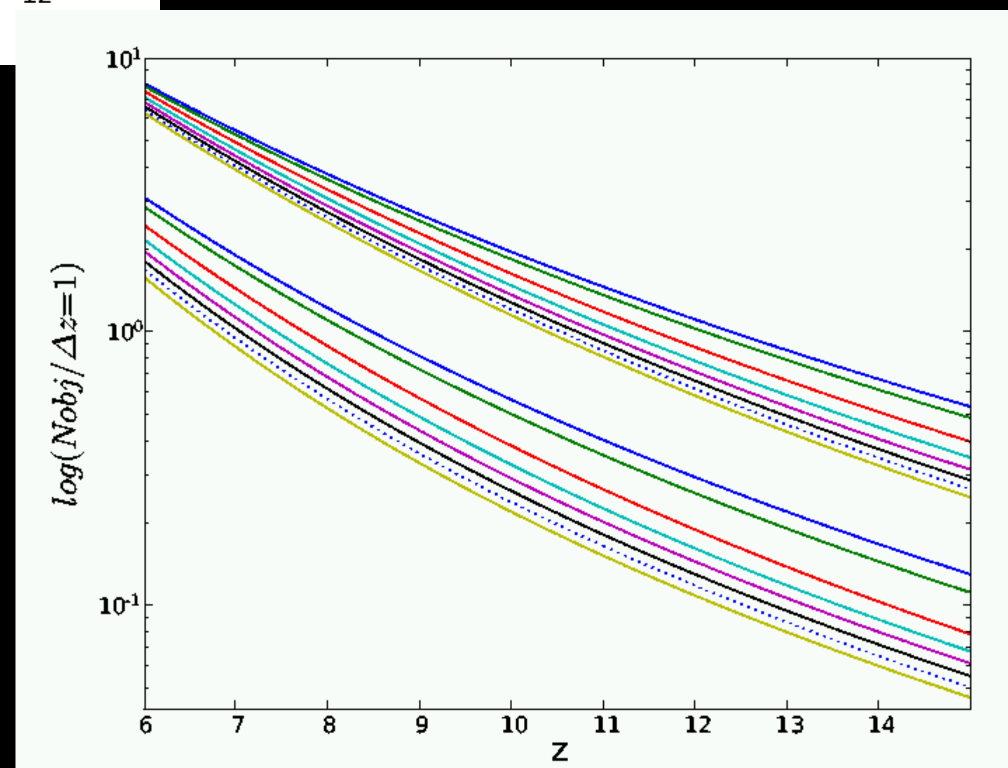


- H(AB)<25.5
- EMIR 6' x 6' FOV
- Reference: A1835
- Extrapolation of L(1500) Observed LF for photometric z~>6 candidates

- H(AB)<25.5
- 3' x 3' FOV

Up to a factor ~2 difference in number counts between different cluster models (e.g. A1689 vs AC114)

z(cluster)= 0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8



Summary/Conclusions

1. First 6<z<10 results consistent with a ~constant SFR density up to z~10. The turnover towards the bright end of the LF is not observed. However:

--> strong field-to-field variance

--> large corrections have been applied to a relatively small sample

--> contamination (with respect to blank fields) cannot be excluded

==> spectroscopic/photometric confirmation is needed

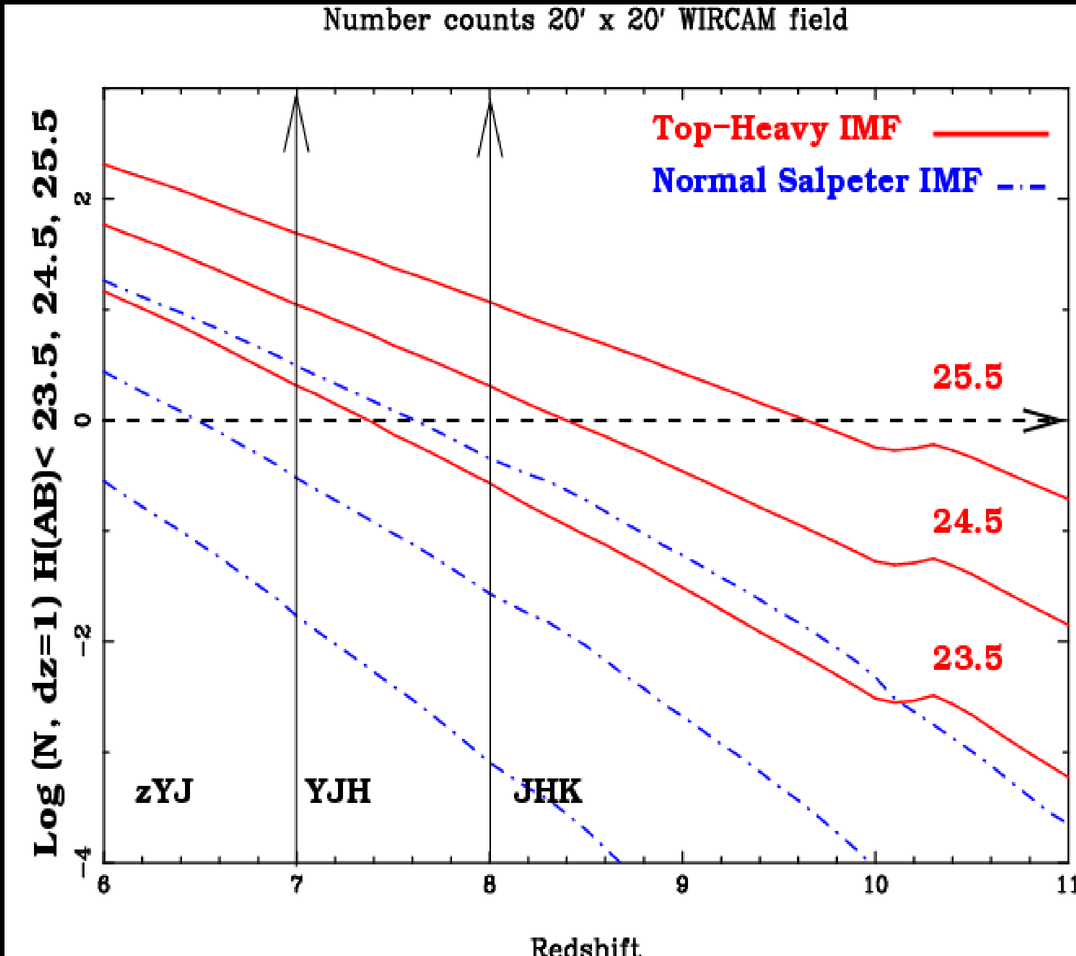
2. Gravitational lensing clusters seem more efficient than blank fields to explore the z~6-7 to 12 domain (same photometric depth and FOV). Positive magnification bias expected from simulations (+ our first results from pilot program).

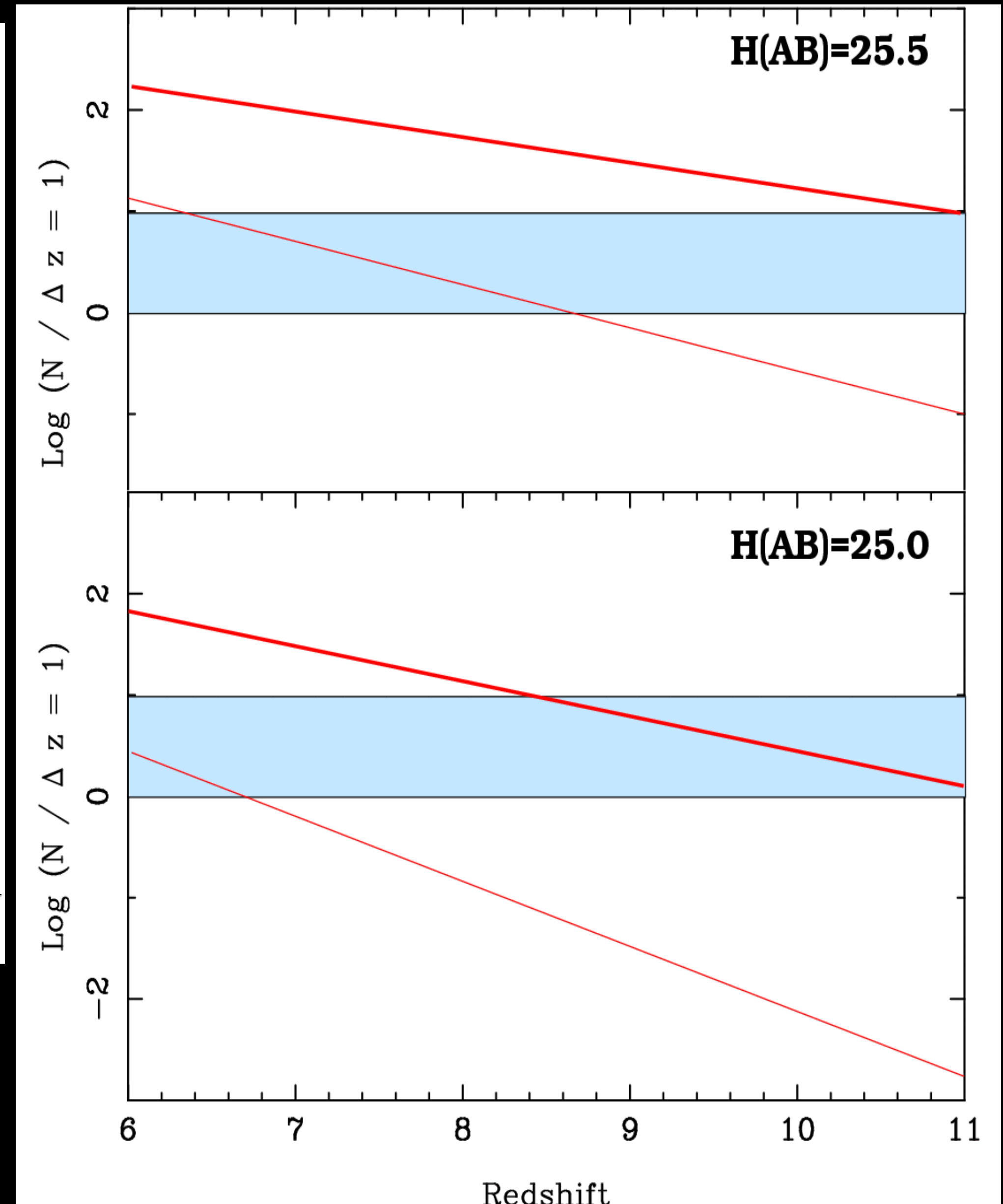
--> potential problems: mid-z interlopers, strong field-to-field variance

- Spectroscopic follow up optimized in lensing fields with the new generation of near-IR multi-object spectrographs (FOV, multiplexing and spectral resolution)
- Large field-to-field variance in the strong magnification regime and towards the bright end of the LF ==> Wide Field Surveys needed.


Thanks!

Constraining the bright end of the LF

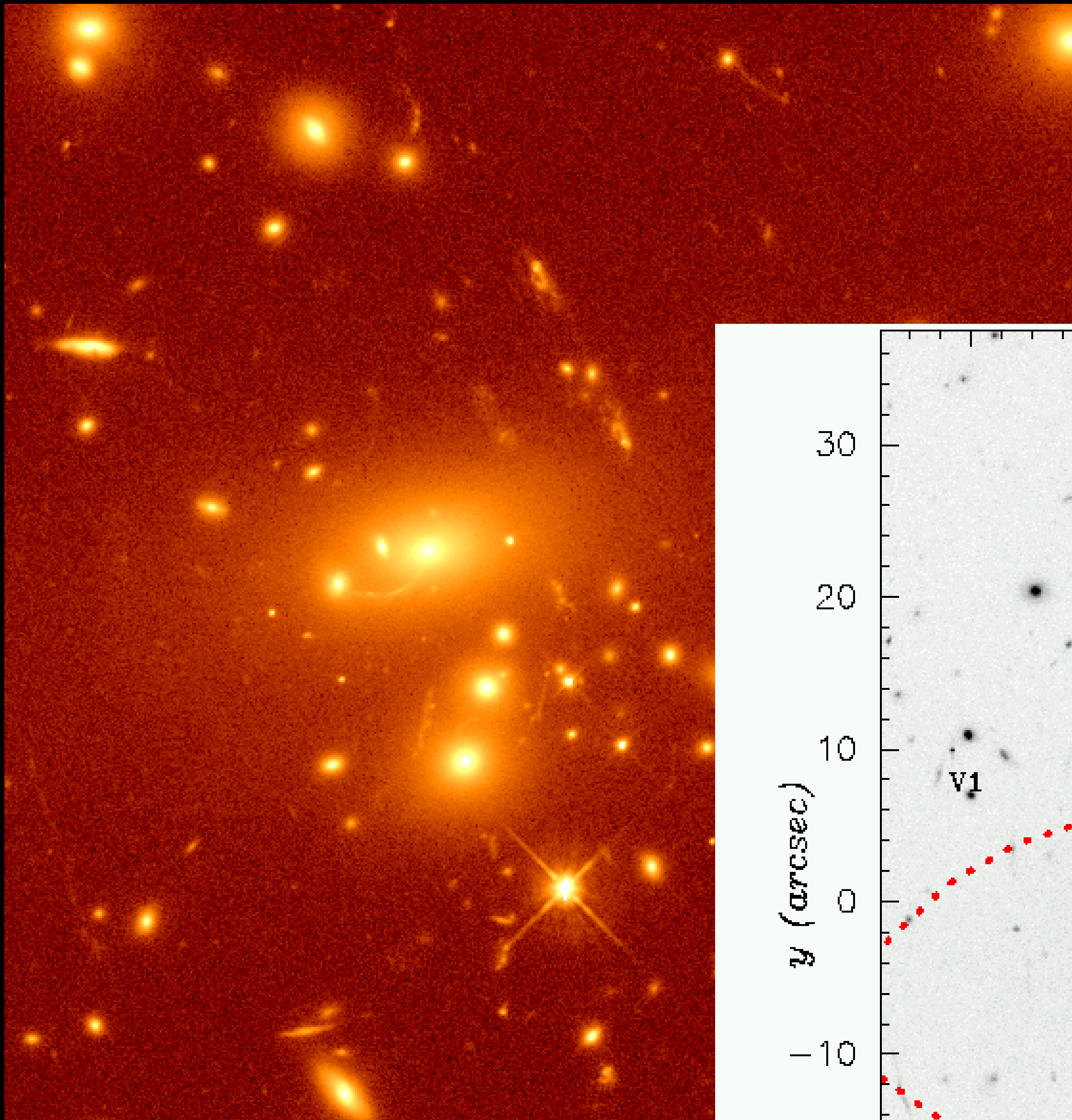




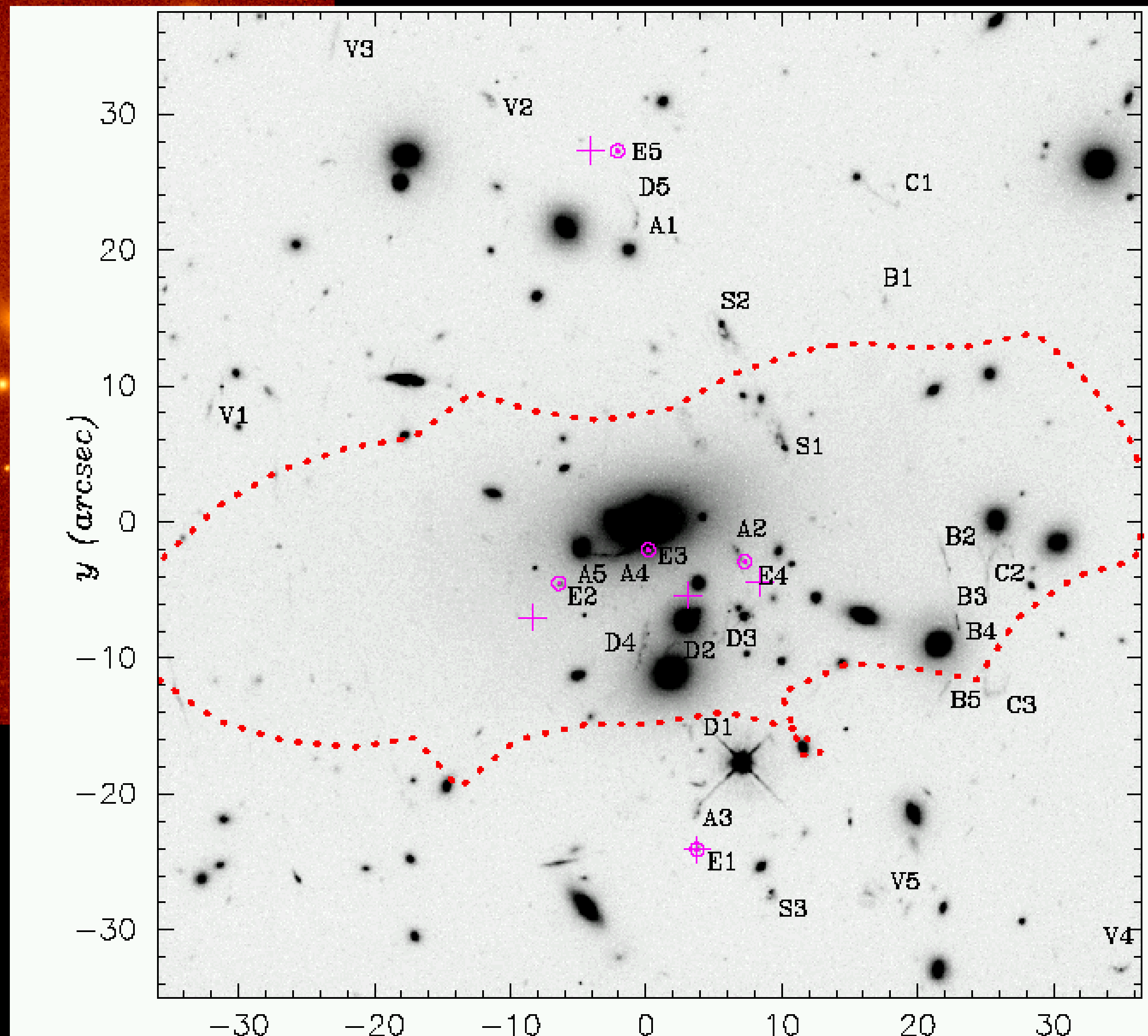
- Number counts within dz=1, for different depth in the H-band.
- FOV similar to CFHT/ WIRCAM

Constraining the bright end of the LF at z>~7 with a « reasonable » exposure time… (WIRCAM/ WUDS, UKIDSS, …)

Multiple arcs systems with z~1 to 4: Smail et al.95; Natarajan et al. 1998; Campusano et al. 01; Lemoine-Busserolle et al. 03

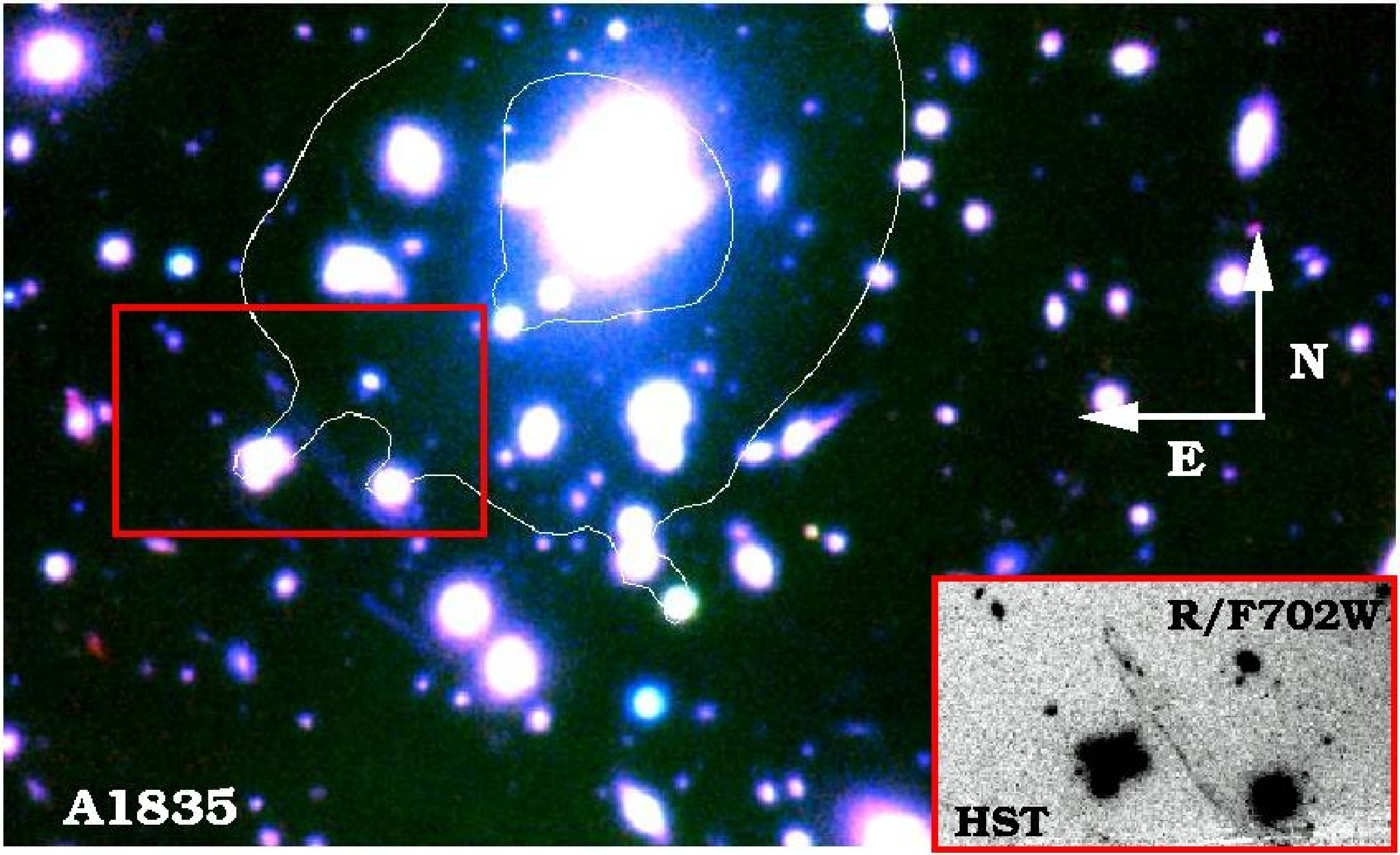


AC114 (z=0.312)



A1835 (z=0.252):

- The most luminous X-ray cluster in the ROSAT Bright Cluster Survey (Ebeling et al. 98).
- Spectroscopic survey (Czoske et el 04): R<23, VIMOS, sigma=1500 km/s (~600 gal.)
- Strong lensing (Smail et al. 99; mass model: J.P. Kneib)
- Weak shear analysis (Limousin et al., in preparation)



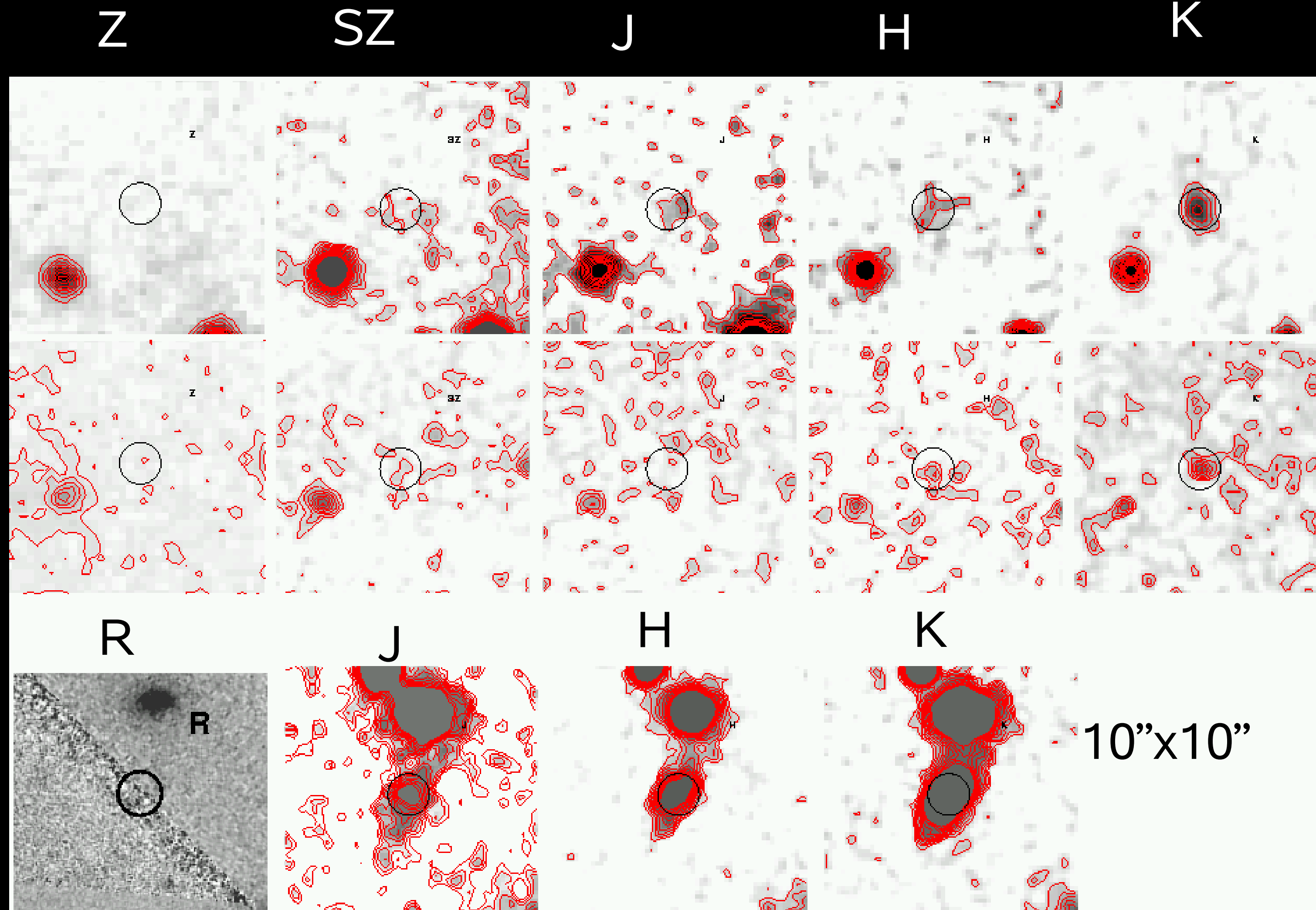
A1835-#2

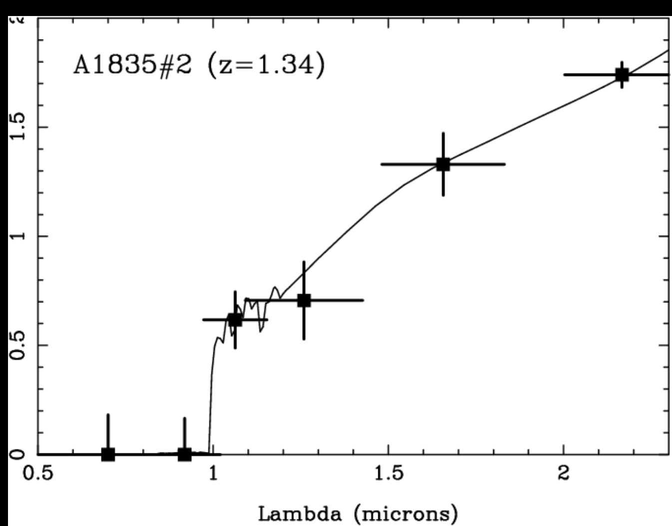
J5/SCUBA-selected galaxy SMMJ14009+0252 (Ivison et al. 2000, Smail et al. 2002)

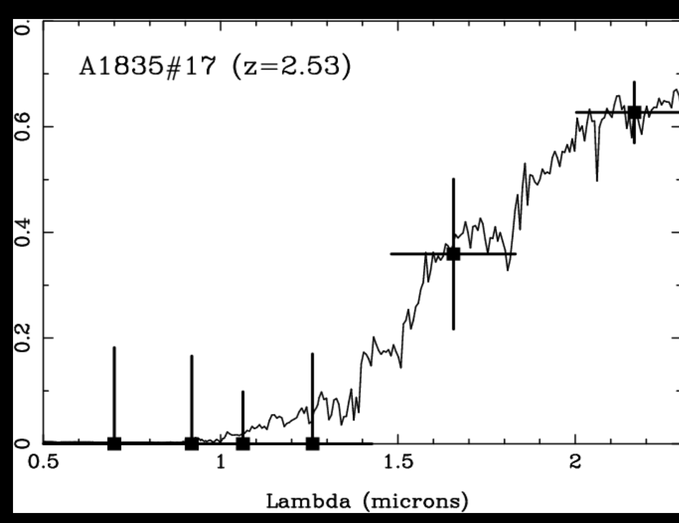
A1835-#17

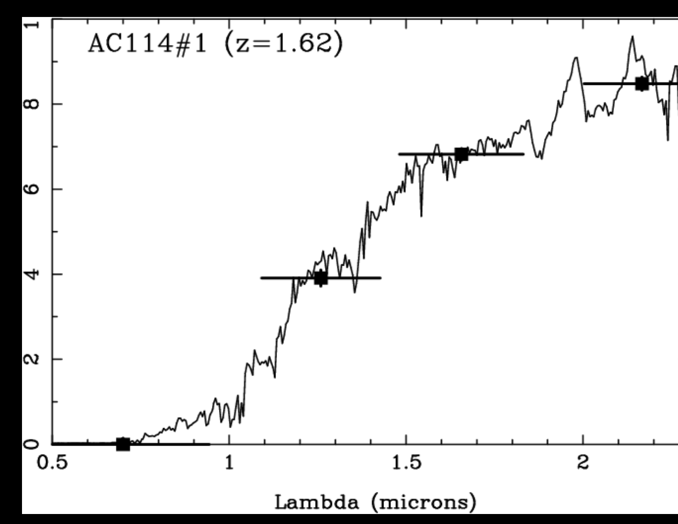
+A1835-#35: spectroscopic determination (Richard et al. 03)

AC114-#1

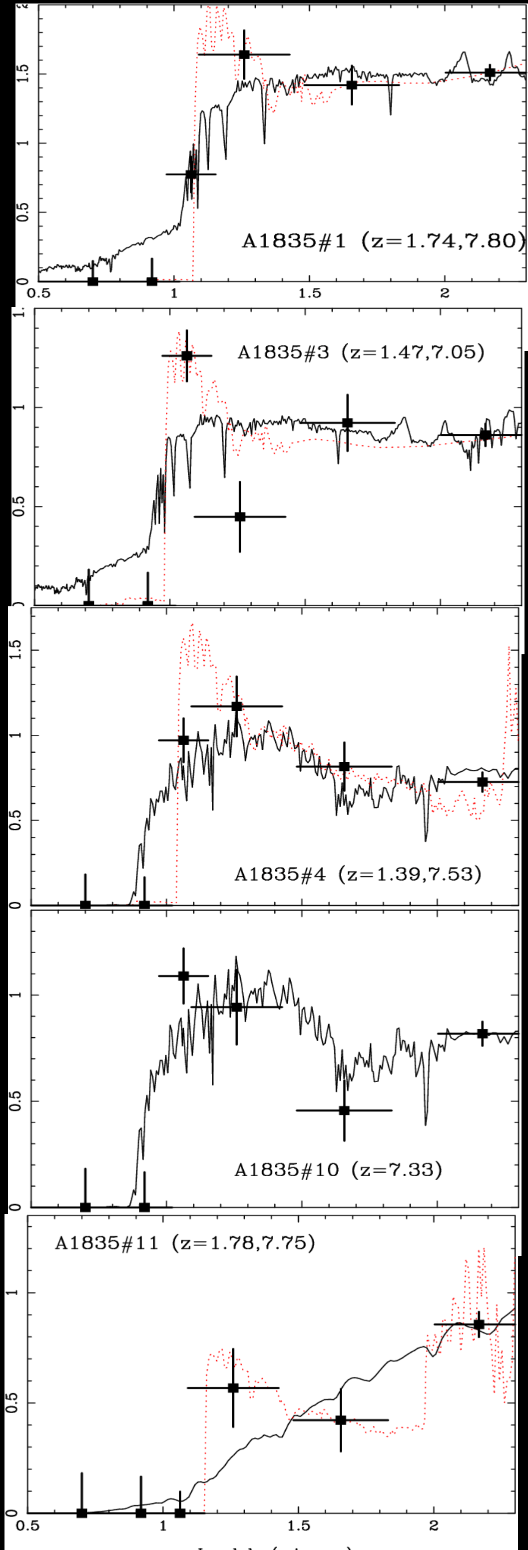






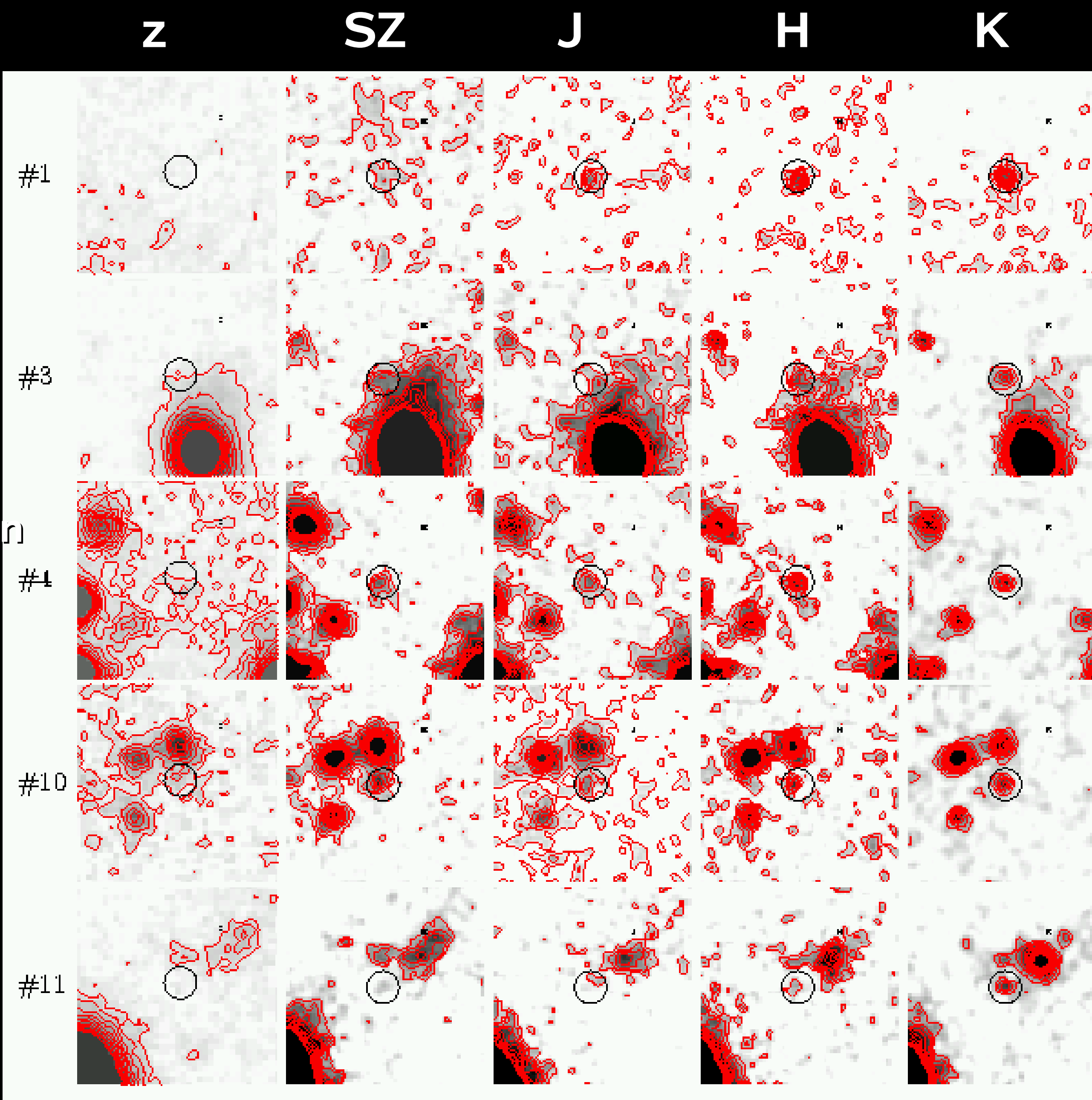


EROs & ambiguous SEDs

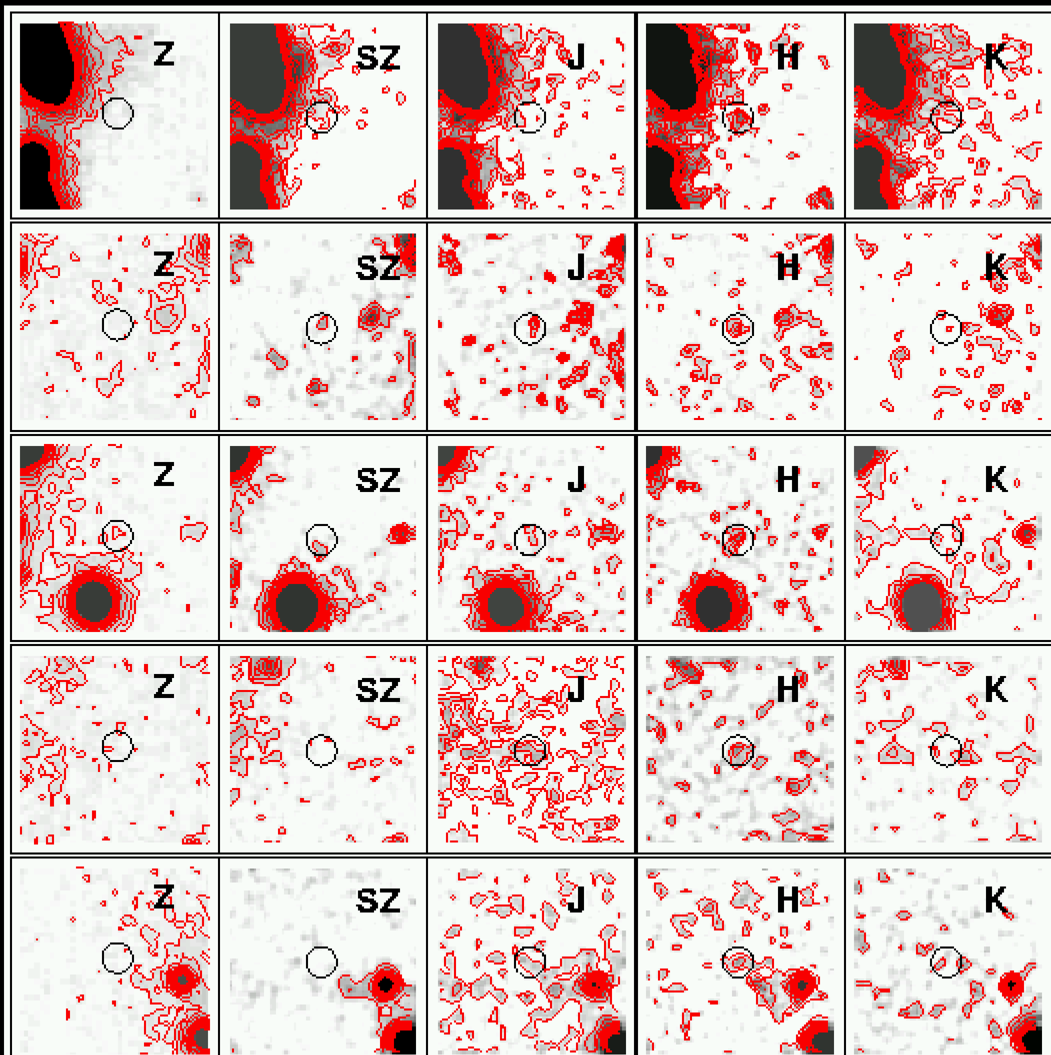


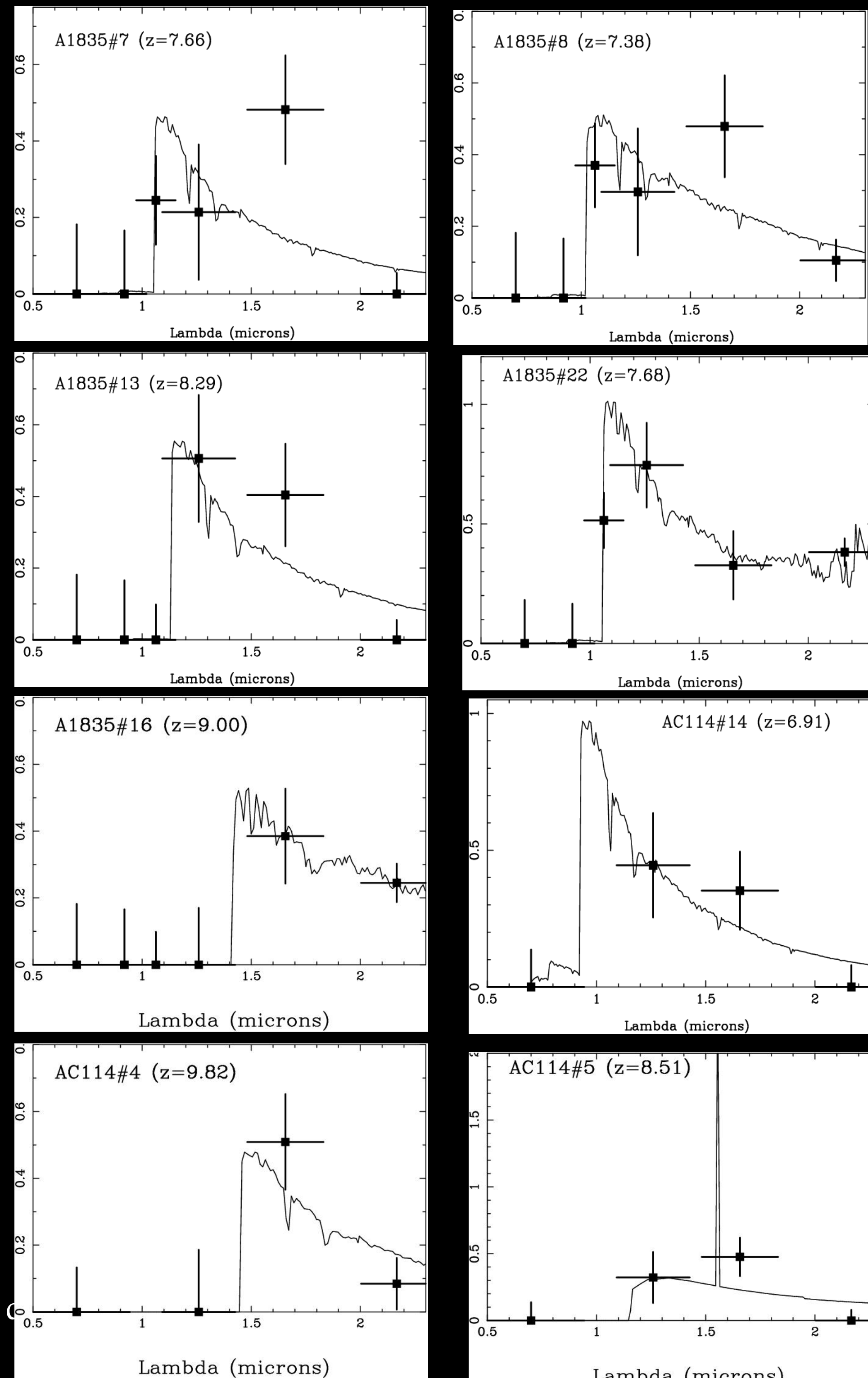
A1835

0.5 mags variability in SZ band



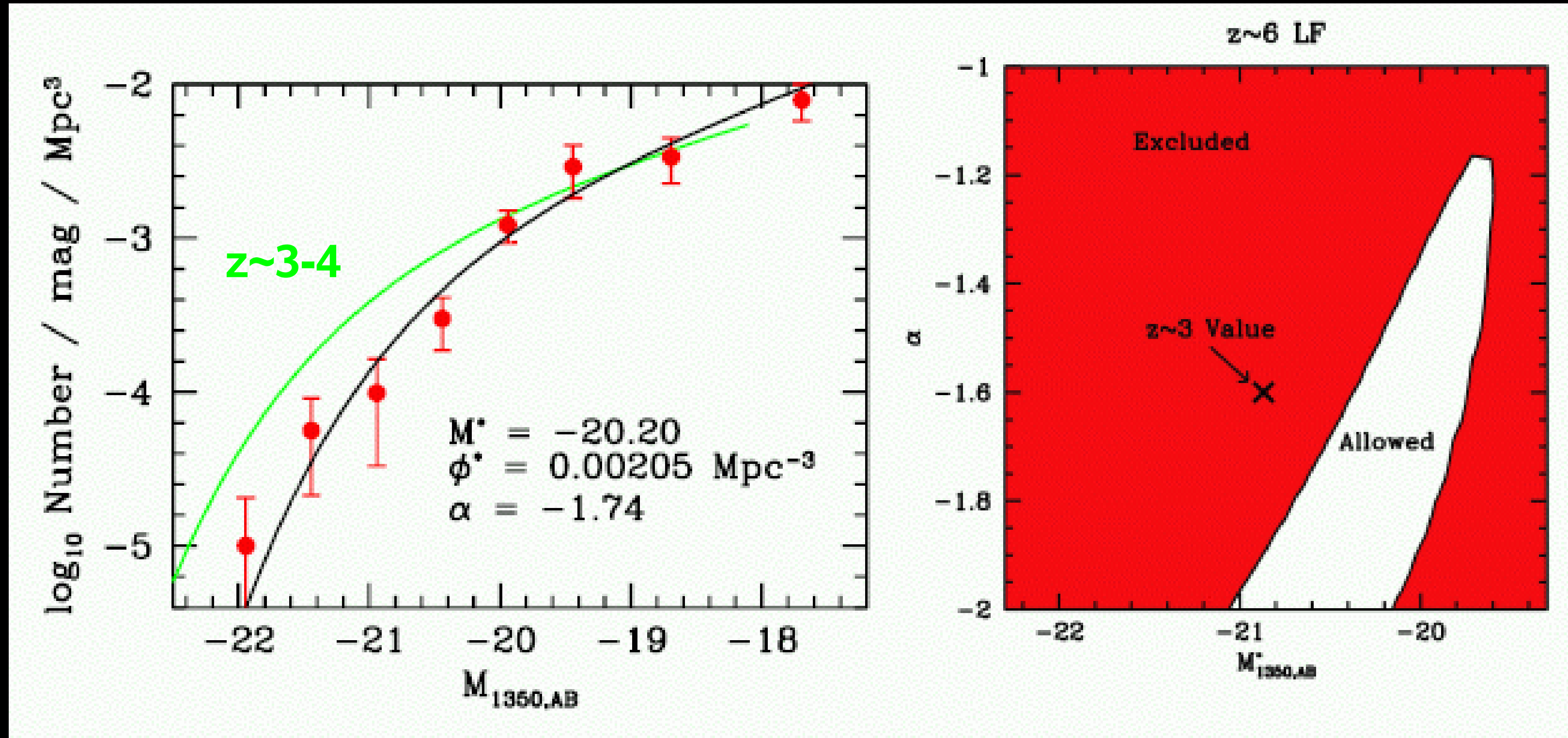
Some examples in A1835:

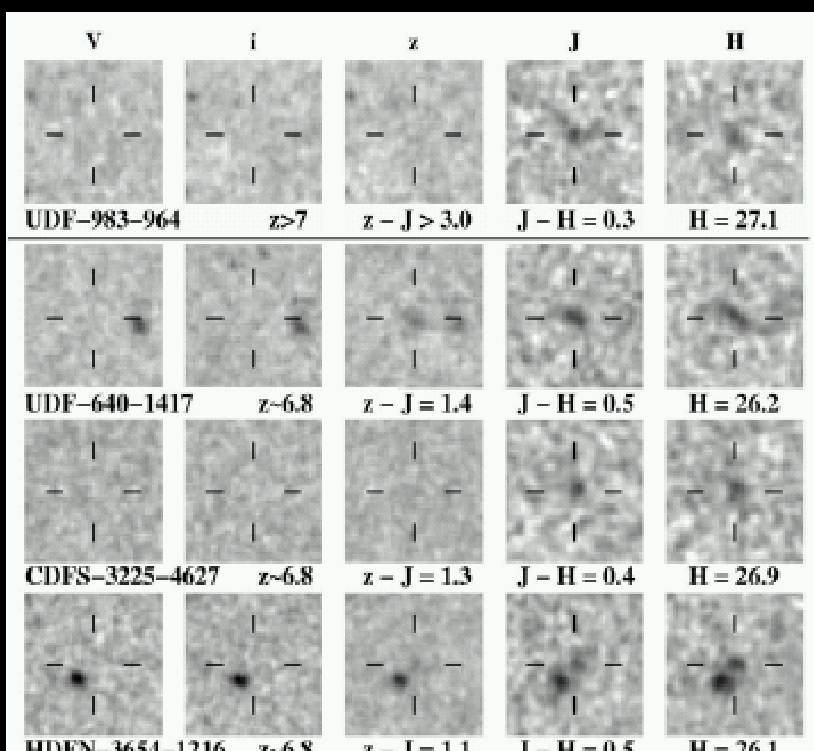




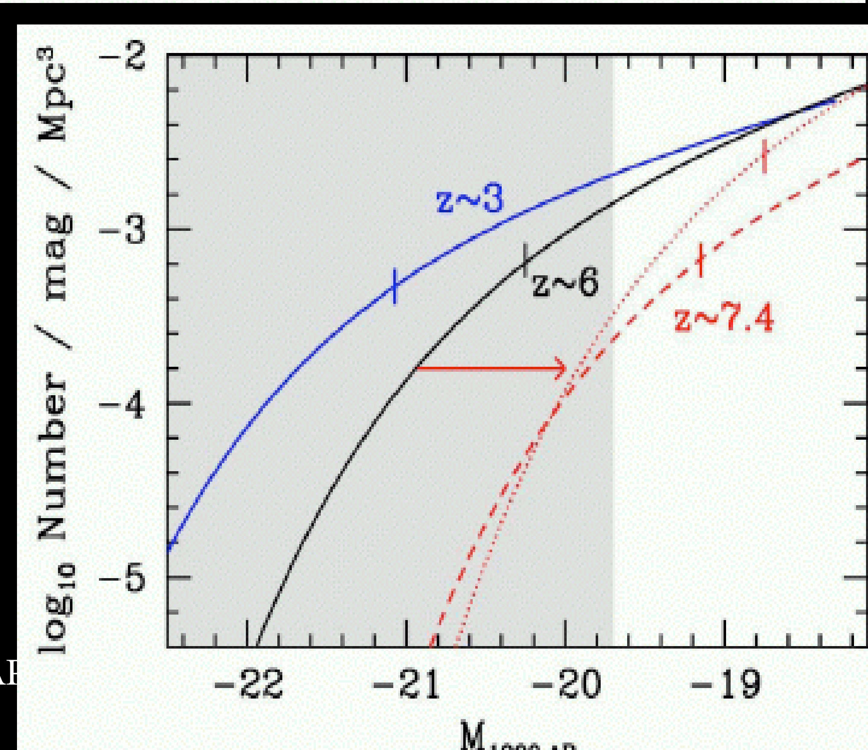
Examples of SEDs for faint sources in A1835 & AC114

From Bouwens et al. 05:
~500 i-band dropouts (GOODS) z~6 photometric candidates

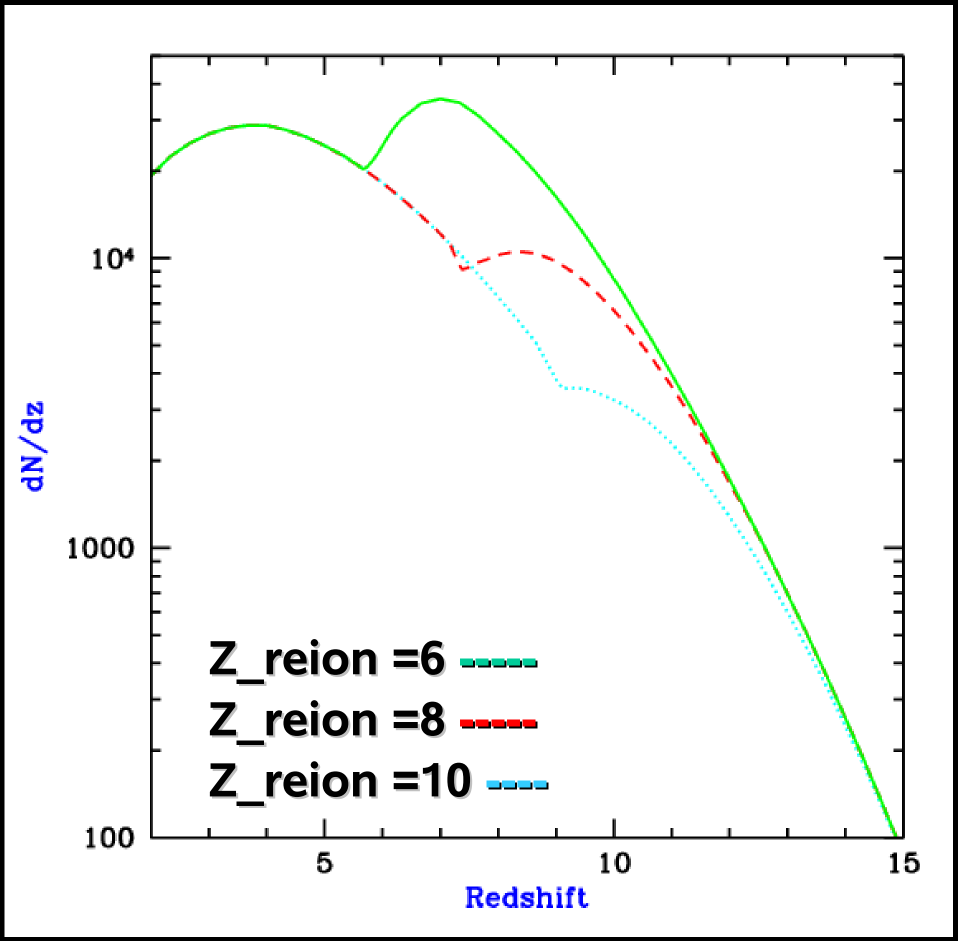


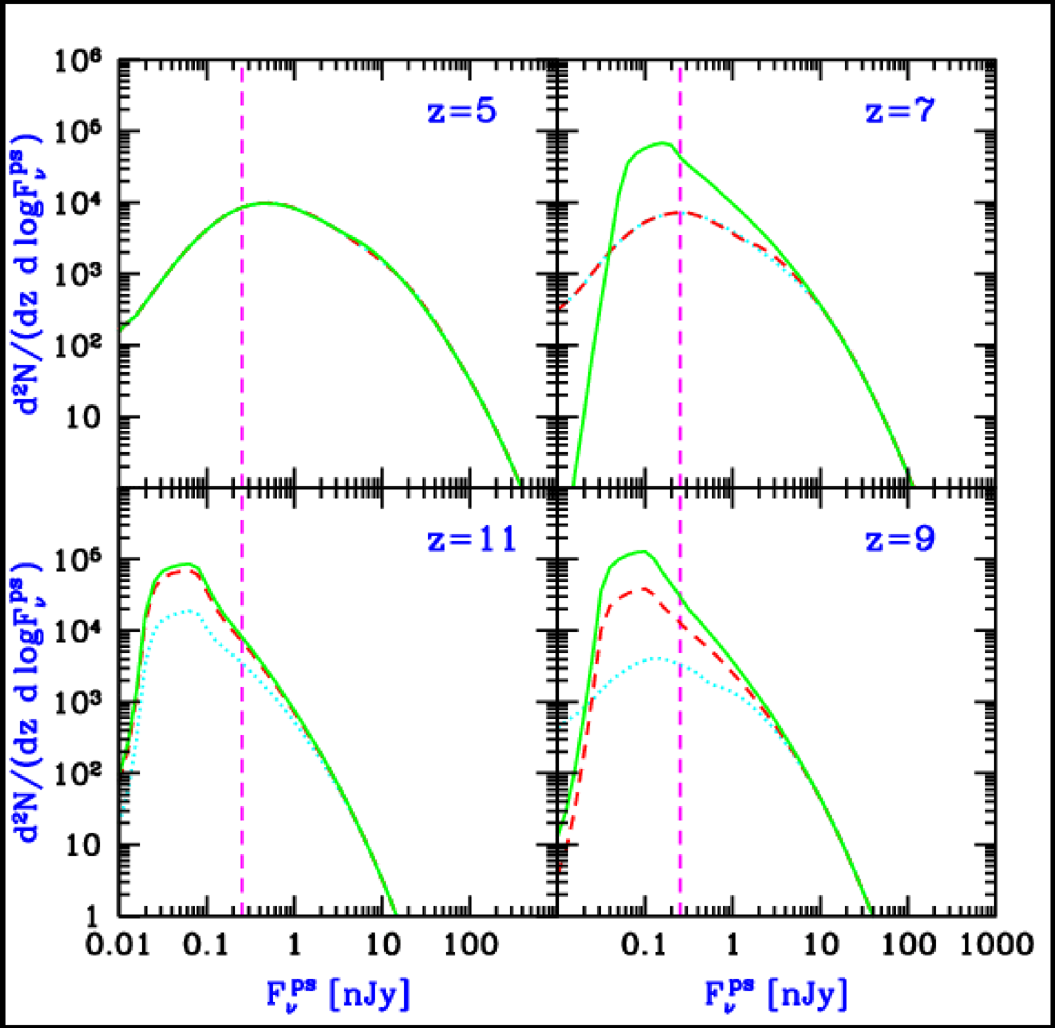


From Bouwens et al. 05:
4 photometric candidates at z>~7
(see also Bouwens & Illingworth 06)



eoretical models: Abundance of star-forming galaxies





Redshift distribution of **sources observed on 1deg2, up to the limits of JWST (0.25 nJy) (Barkana & Loeb 01)**

Luminosity Functions