KITP, 03-06 October 2006

Gravitational Lensing: Unique Insights Into Galaxy Formation And Evolution.

Galaxies Surveys at the Epoch of Reionization with Gravitational Telescopes

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Observatoire Midi-Pyrénées

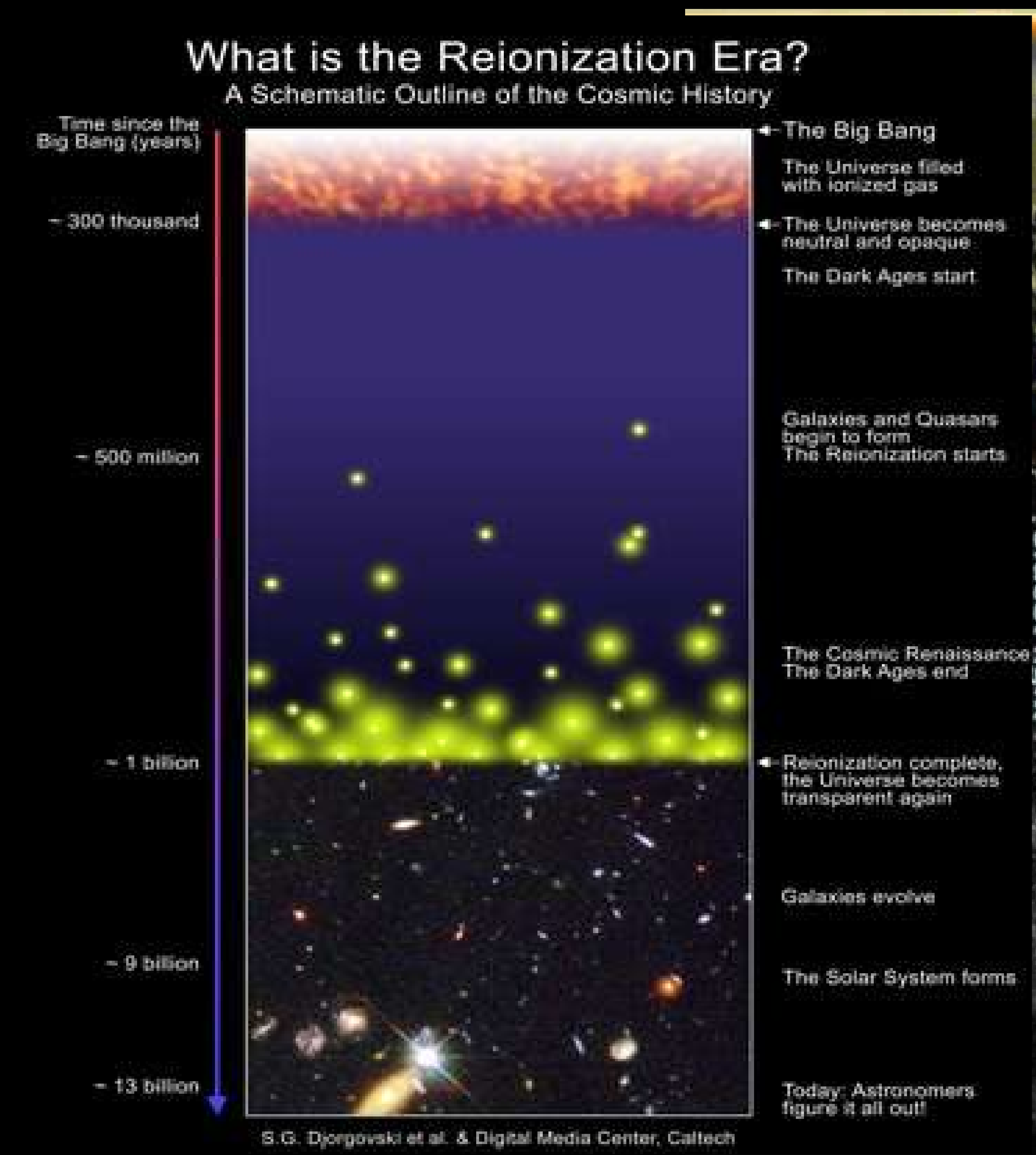
OUTLINE

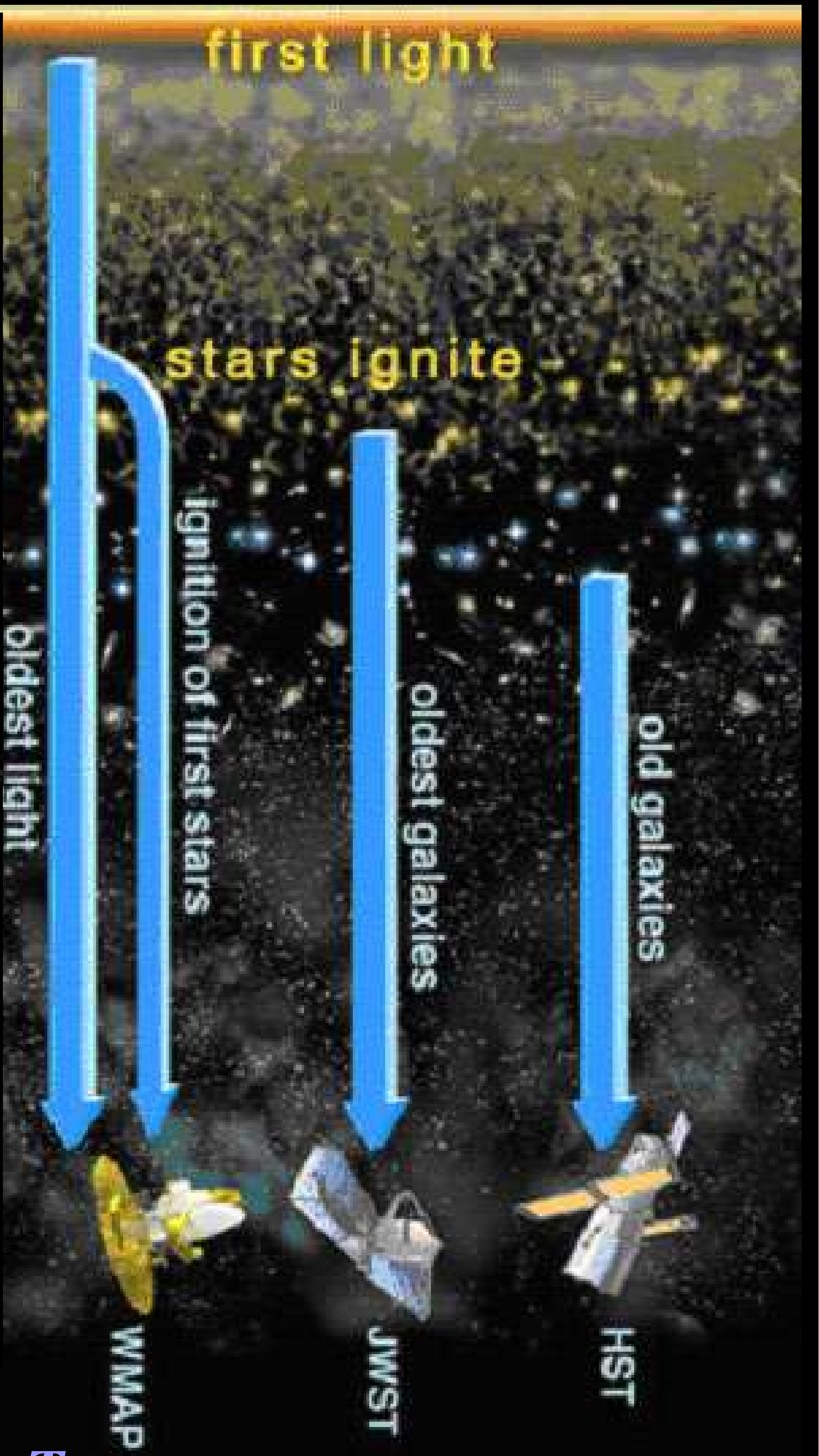
- **Looking for high-z galaxies: Motivation**
- **Lensing clusters as Gravitational Telescopes**
- **A first attempt to constrain the abundance and properties of star-forming galaxies at 6<z<10 using *Gravitational Telescopes***

  → ***Richard, Pello, Schaerer, Le Borgne & Kneib (2006)***

- **Discussion & Perspectives:**
  - ***Lensing or blank fields?***
  - ***Future surveys with the new generation of near-IR spectrographs (EMIR/ Goya Survey at GTC, Flamingos II, MOIRCS, KMOS, ...)***

Looking for high-z galaxies: Motivation



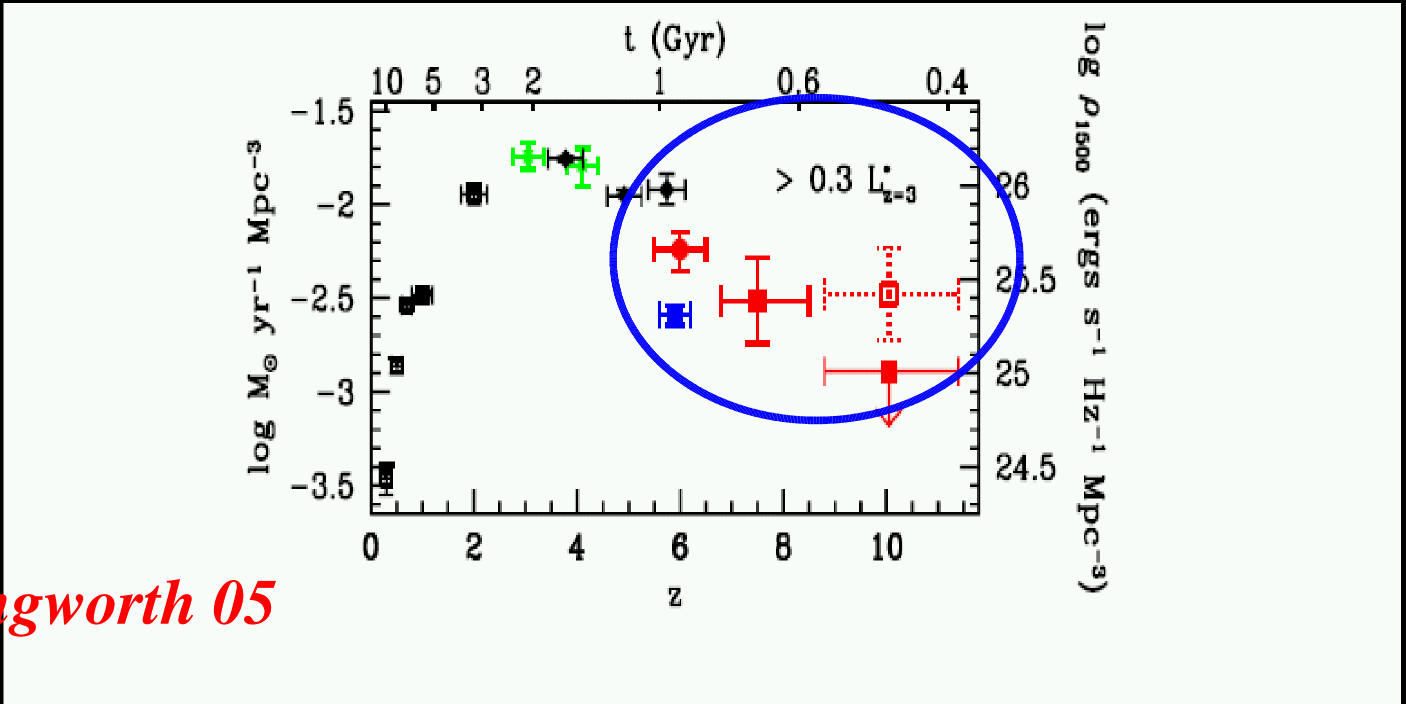


from Djorgovski et al & NASA/WMAP Science Team.

- **WMAP results: reionisation epoch z~9-13 (Spergel et al. 2006) → end ionisation: z~6-6.5 (Fan et al. 2002).**

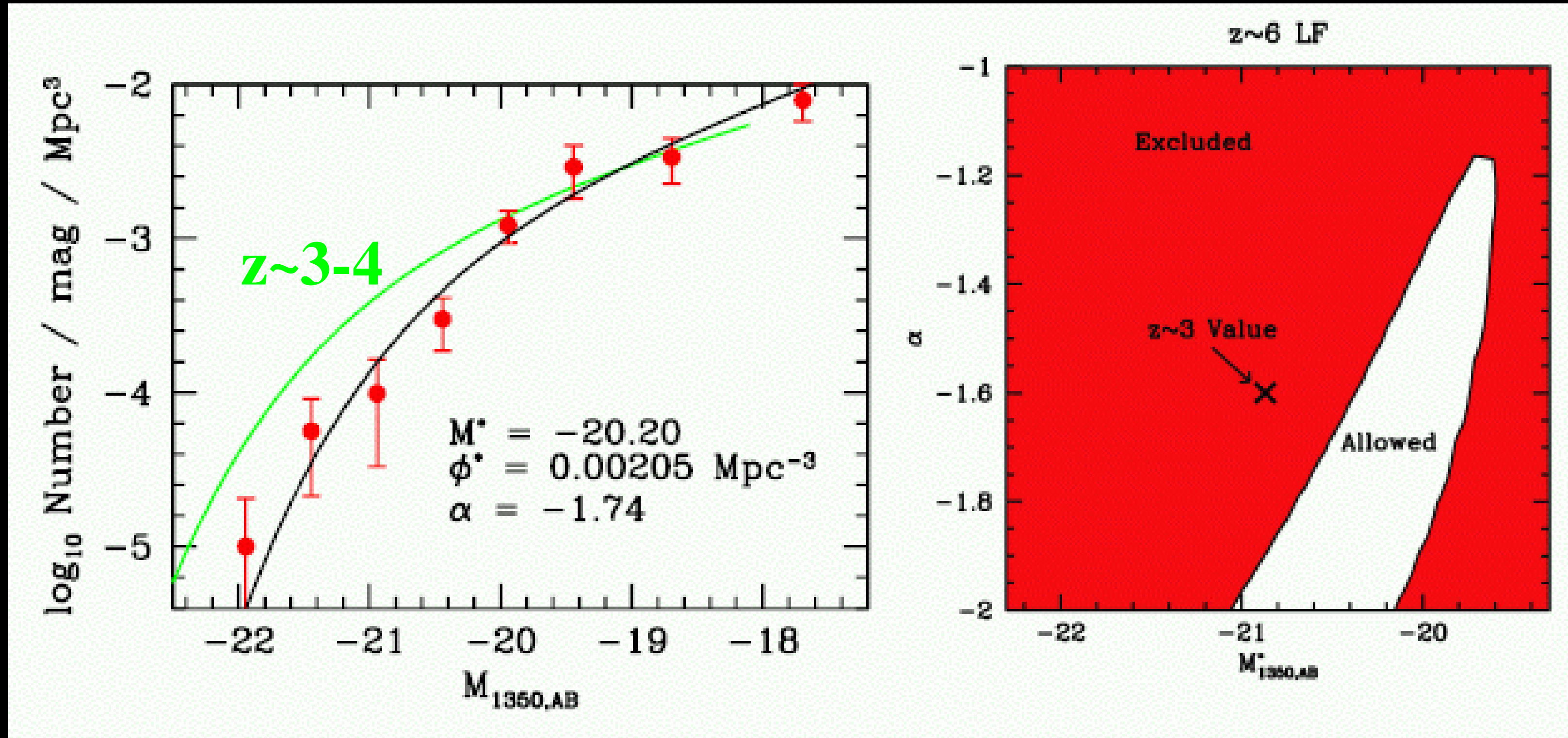
===> contribution of star-forming systems to cosmic reionization

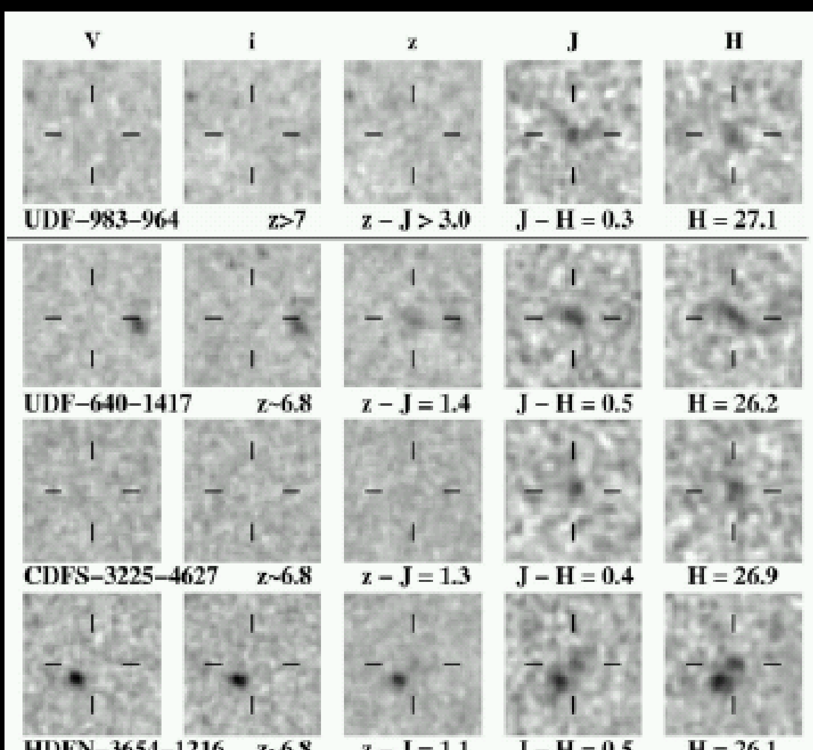
- **What are the physical properties of these objects: SFR, extinction, metallicity, IMF, ...?**
- **Start exploring a new domain and prepare for future studies on global properties: number counts, LF of Ly α emitters, clustering ...**



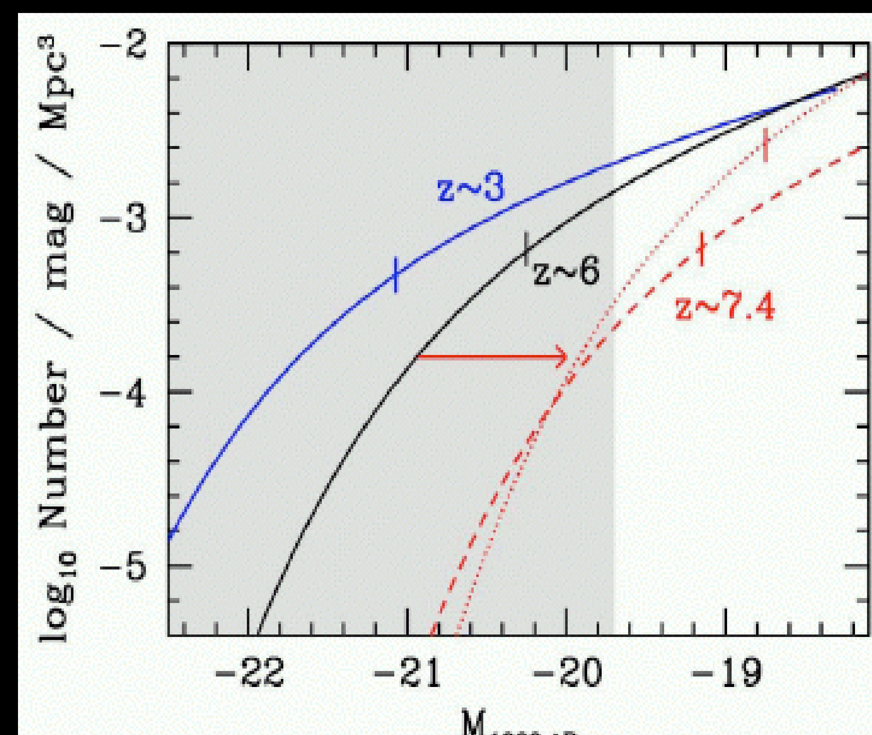
Bouwens & Illingworth 05

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

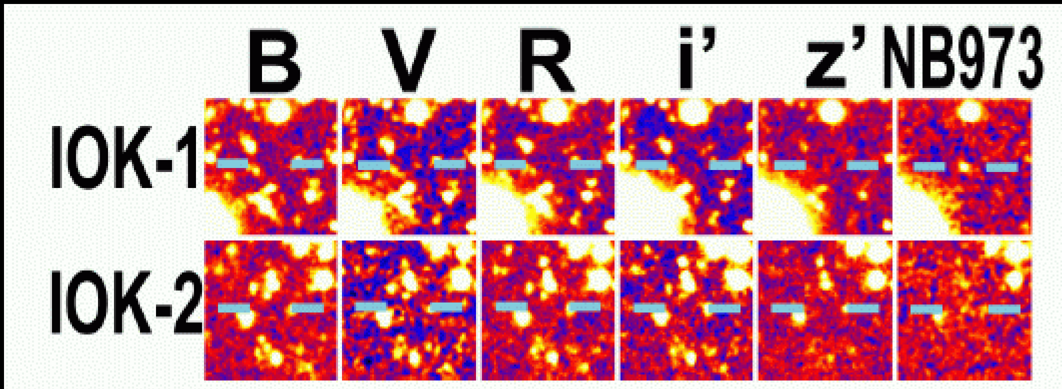




From Bouwens et al. 05:
4 photometric candidates at z>~7
(see also Bouwens & Illingworth 06)



Iye et al. 2006:



- 2 Lyman α emitters (LAEs) at z~7 (z=6.96; 1 + 1 candidate)
- NB 973 identification (last OH window) with Subaru Suprime-Cam
- SFR ~10 M_sol/yr
- Density of LAEs at z~7 seems to be ~18-36% of the density at z~6.6
- The **ZEN ("z equals nine") survey** reports a non detection of z~9 sources in the HDFS up to a flux limit in the NB(1.187 micron)> 3.28 × 10^{-18} erg/cm2/s (*Willis et al.06*)

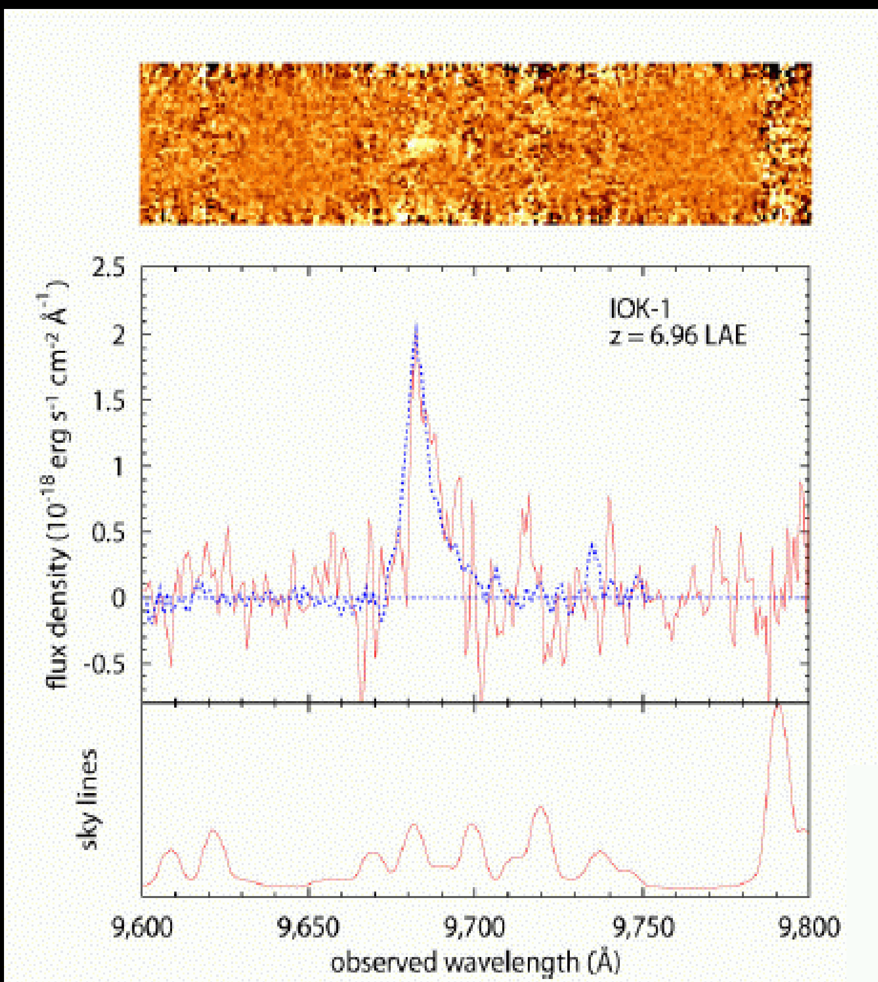
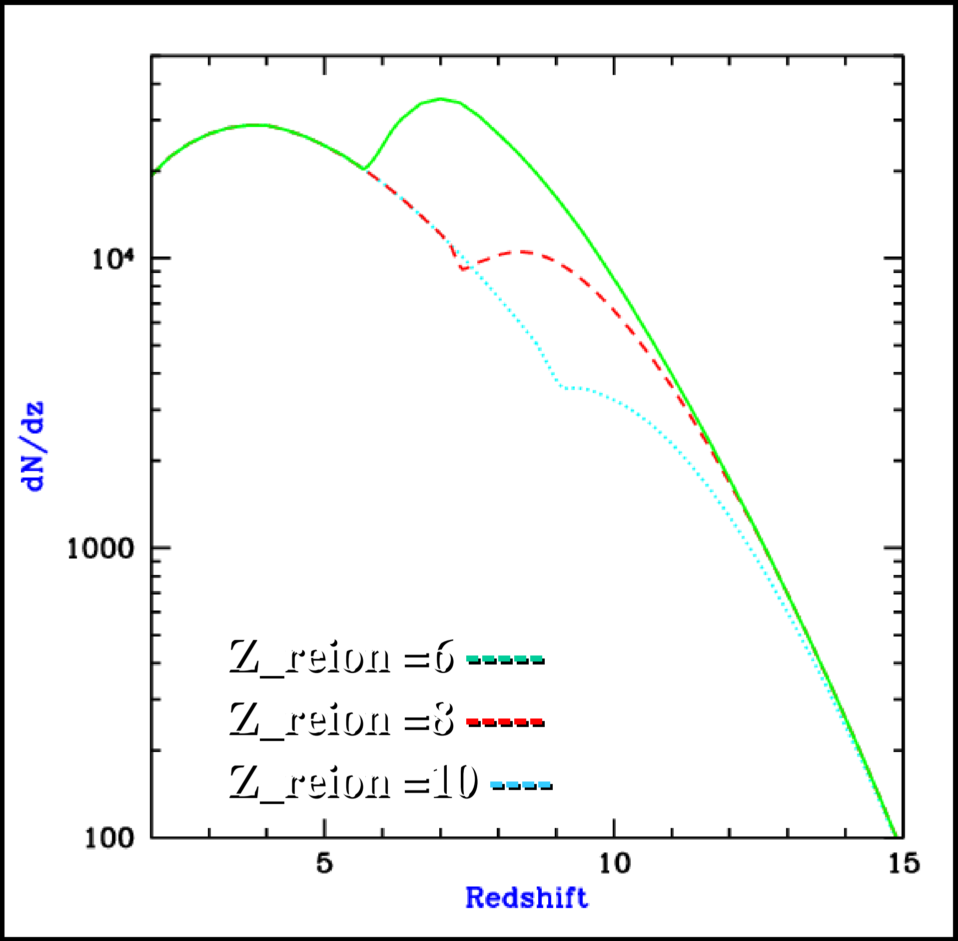


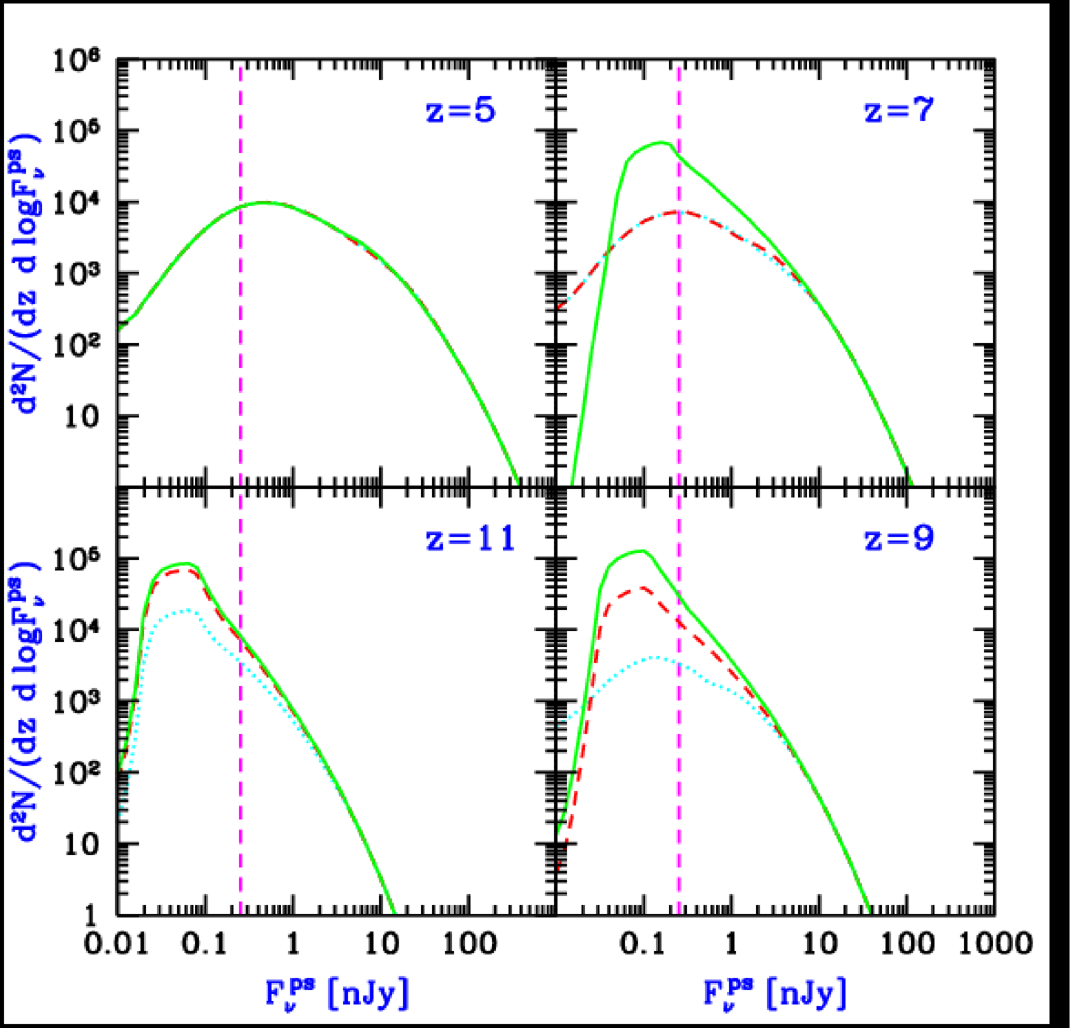
Table 1 Properties of $z \approx 7$ Lyman-α emitter candidates

ID		Position(j2000)	i '(mag)	z' (mag)	NB973 (2")	NB973 (total)	L(Lyα) (10^{43} erg s^{-1})	SFR(Lyα)ε ($M_\odot$ yr^{-1})
IOK-1		α=13^h 23^m 59.^{s}8 δ=+27° 24′ 55.″8	>27.84	>27.04	24.60	24.40	1.1±0.2	10±2
IOK-2		α=13^h 25^m 32.^{s}9 δ=+27° 31′ 44.″7	>27.84	>27.04	25.51	24.74	<1.1±0.2	<10±2

Theoretical models: Abundance of star-forming galaxies

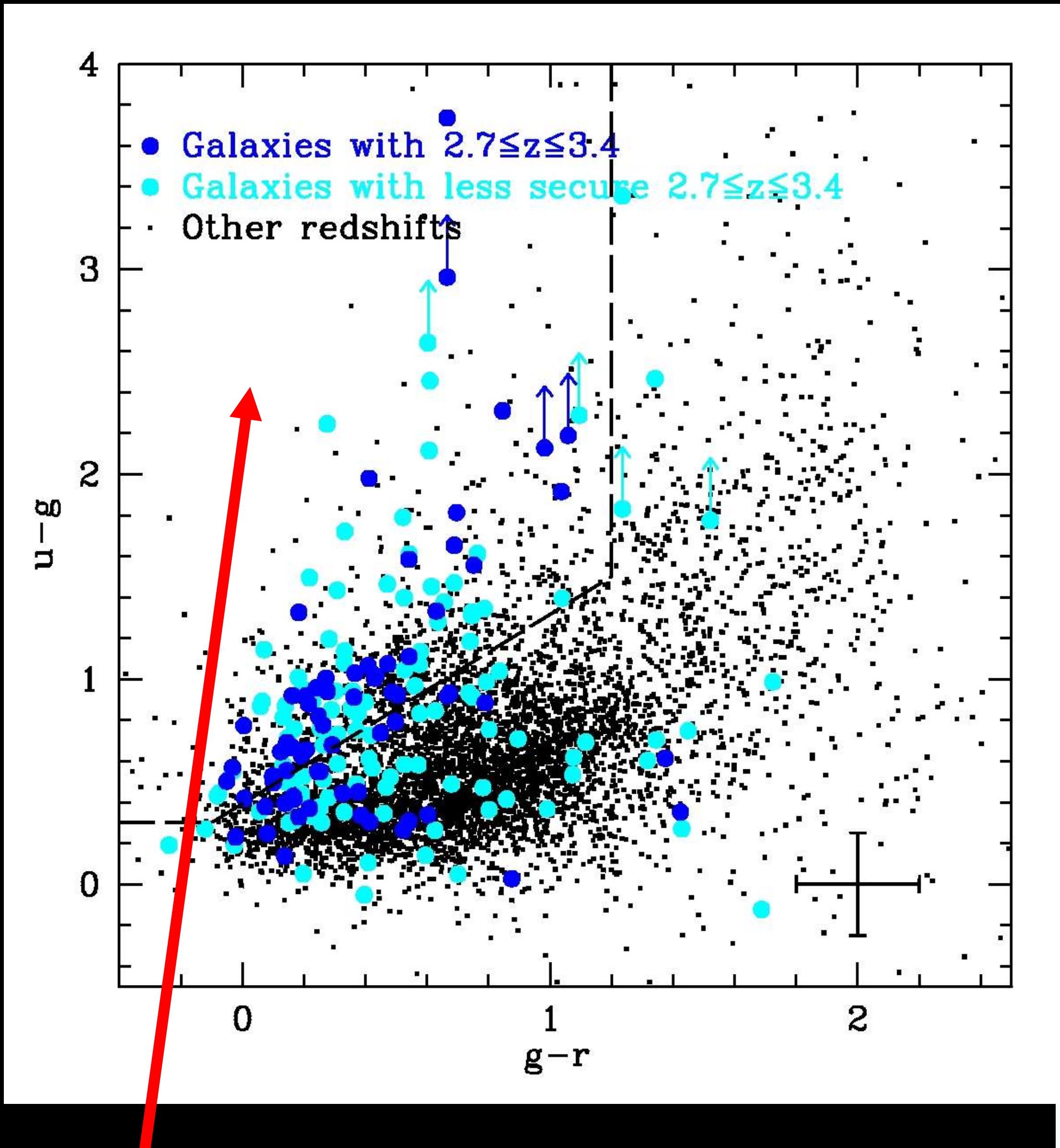


Redshift distribution of sources observed on 1deg2, up to the limits of JWST (0.25 nJy) (Barkana & Loeb 01)



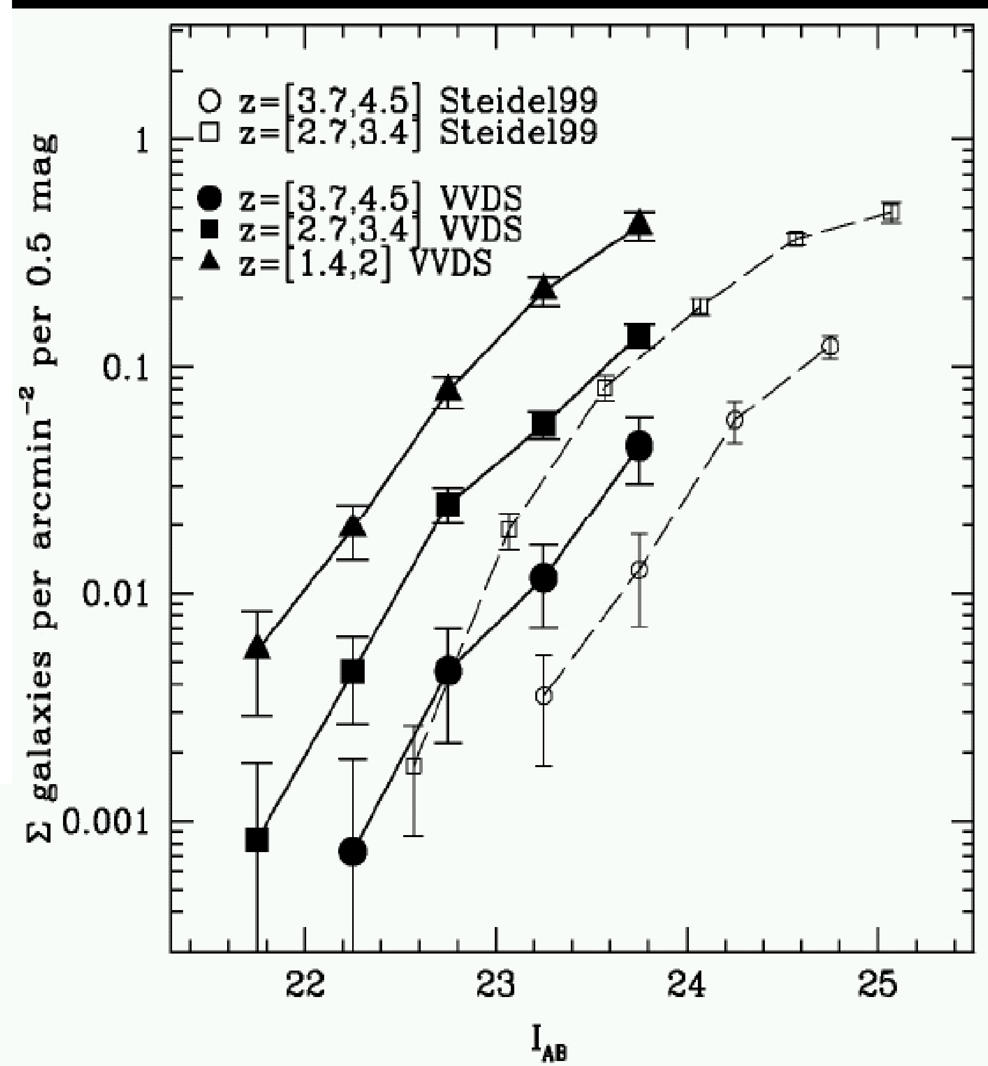
Luminosity Functions

A complete census of z~1.4-5 galaxies



Color selection bias at high-z:

Comparison between usual color selection and the VVDS magnitude selection in the I band

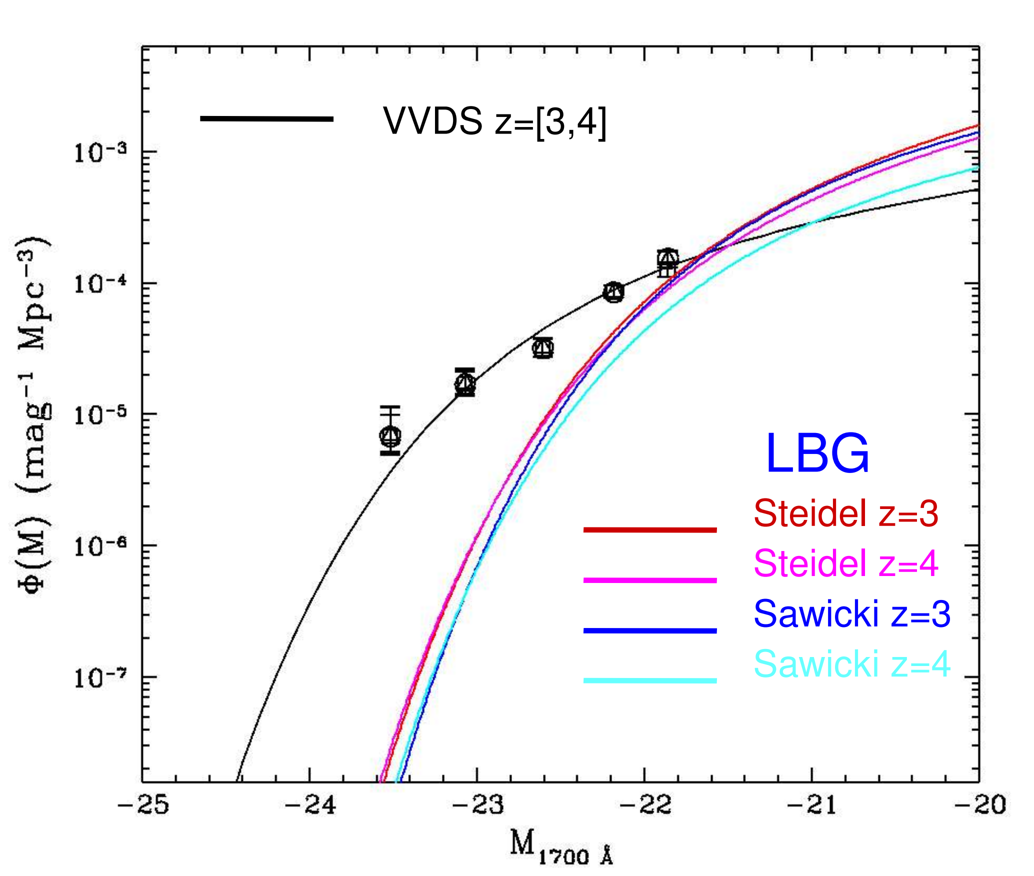


LBG selection window at z~3

Le Fèvre et al. (Nature, 2005)

Luminosity Function of galaxies with 3<z<4

I-band selected sample



Paltani et al., submitted

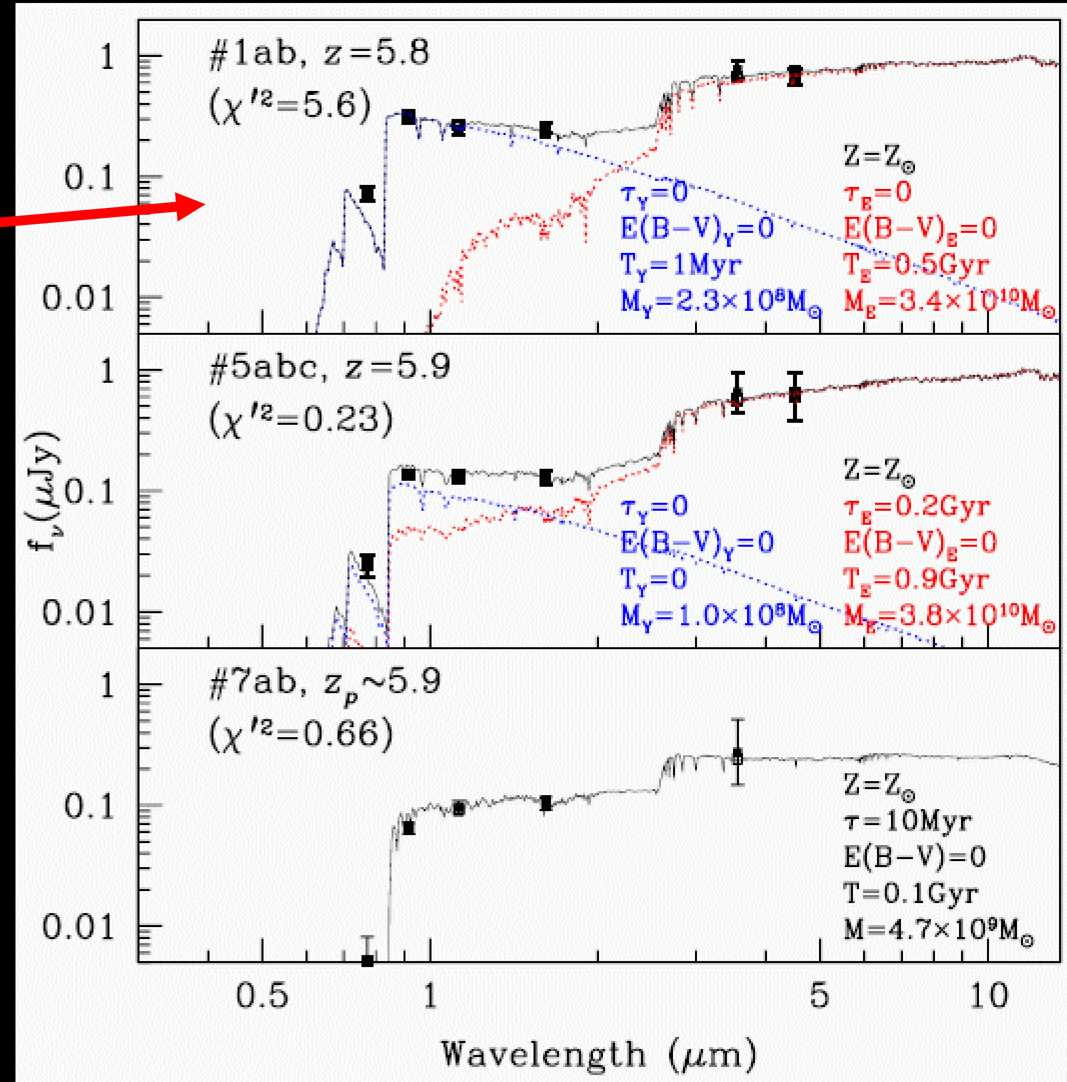
- **VVDS: 970 galaxies with 1.4< z< 5**
- **A large purely magnitude-selected sample in the high redshift universe**
- **An unbiased census of the star-forming galaxy population**
- **Luminosity function shows M* at least 0.5 mag. brighter than LBG selected sample**

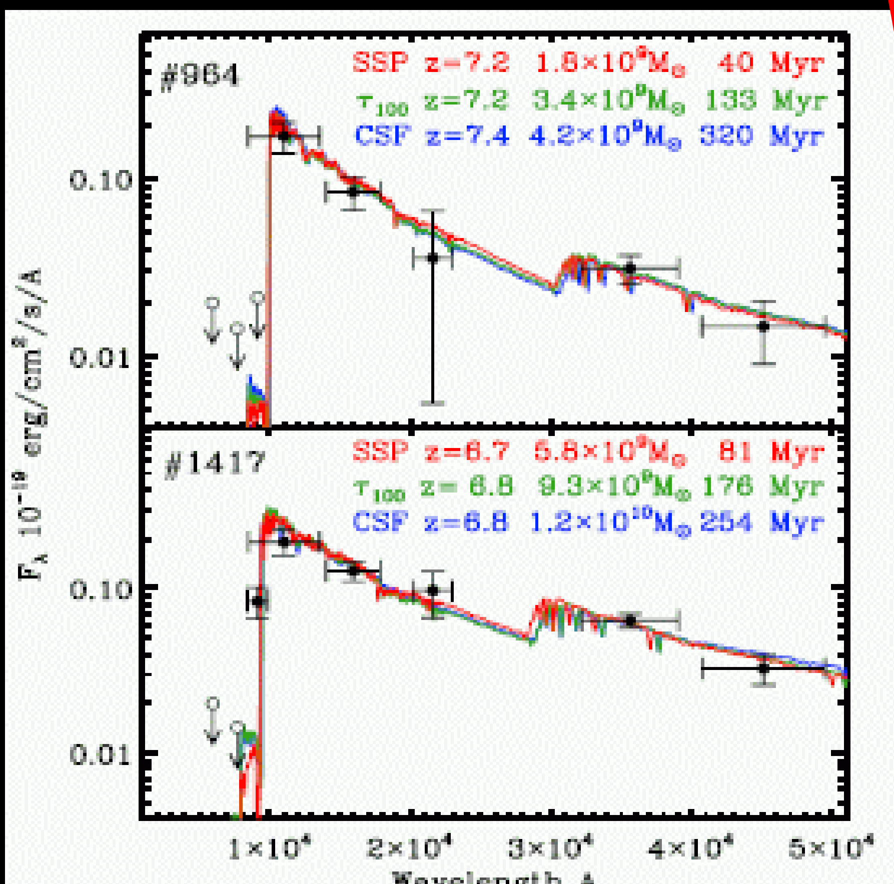
LD (VVDS) / LD (LBG) =2.8
(α=1.4, M_{1700}<-21, z=[3,4])

For integrated LD down to M_{1700} =-17, significant uncertainty remains (unconstrained slope α)

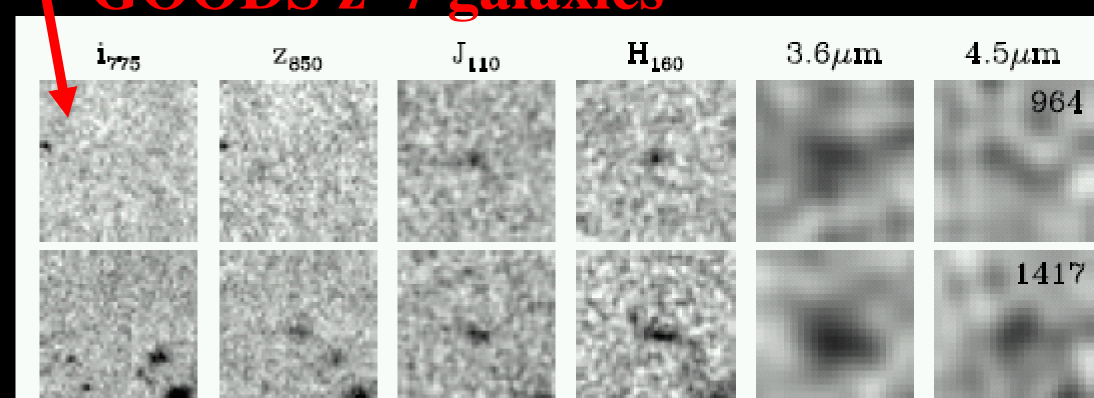
« Massif » objects are observed at z~5-6. (Mobasher et al. 05; Yan et al. 05, 06; McLure et al. 06; Labbé et al. 06)

==> early star formation at z > 7-9 ?





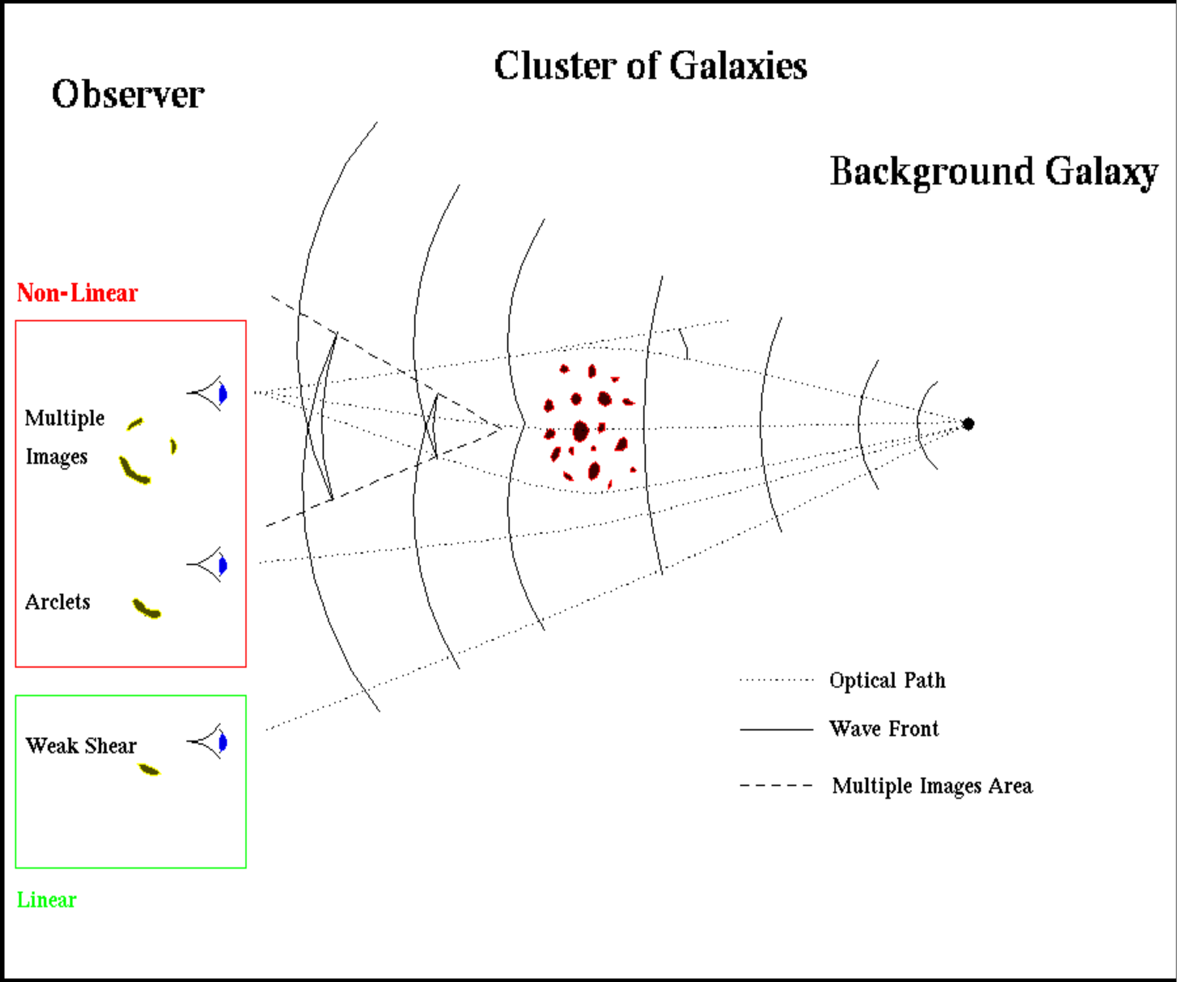
GOODS z~7 galaxies



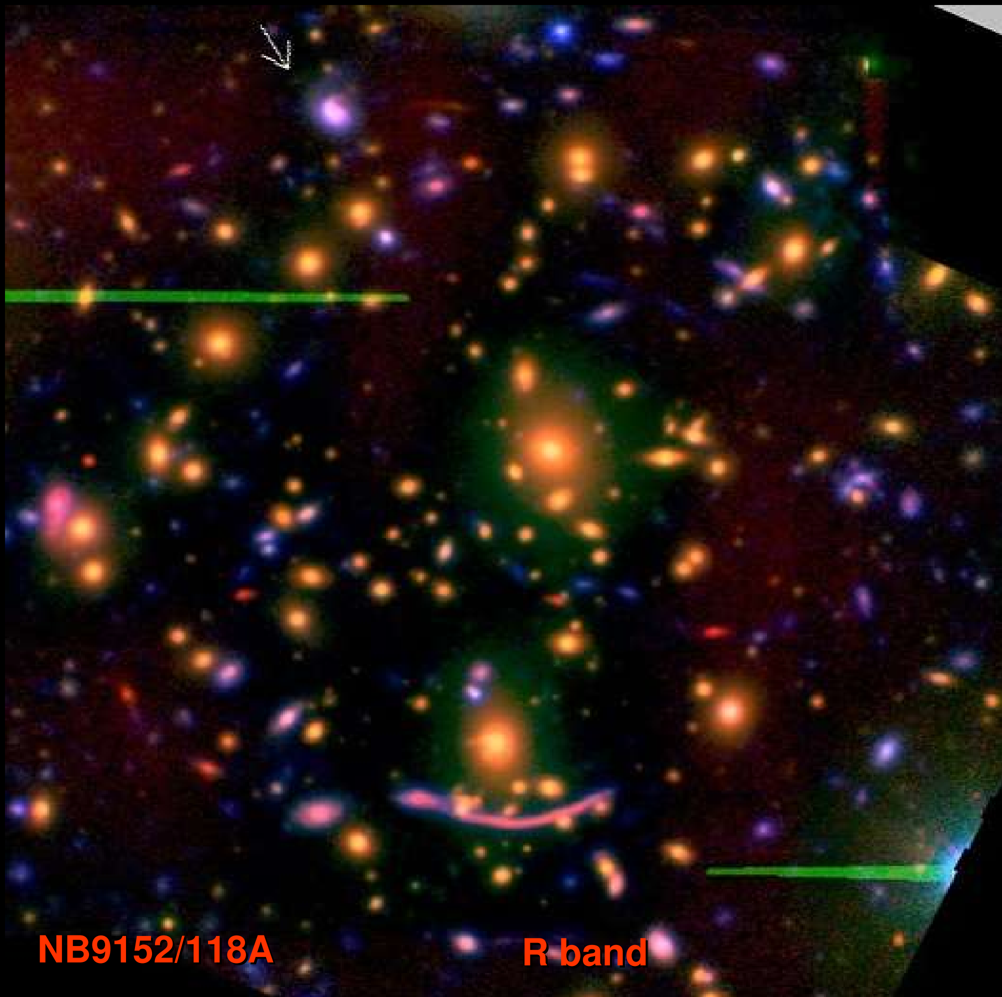
Lensing Clusters as Gravitational Telescopes

Lensing Clusters : genuine "gravitational telescopes"

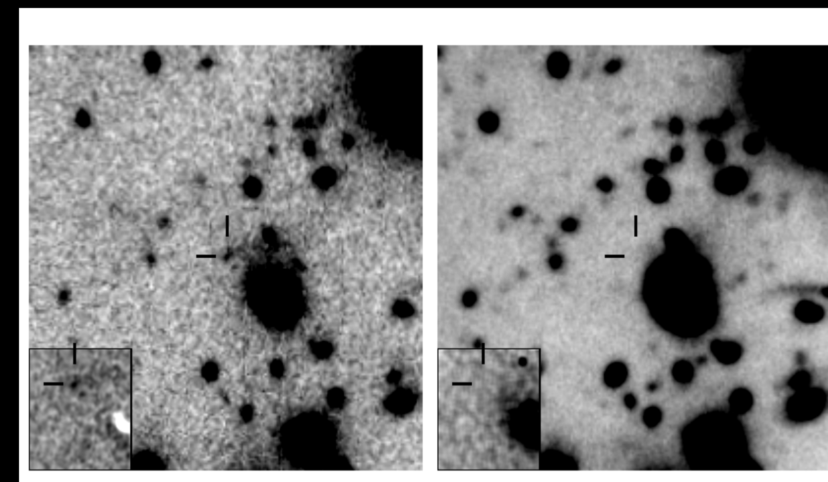
- **Lensing Clusters as Gravitational Telescopes (GTs, Zwicky): taking benefit from the magnification factor in the core of lensing clusters (typically 1 → 3 magnitudes) to study the properties of the background population of lensed galaxies → Spectroscopic follow up.**
- **GTs allow to construct and to study an independent sample of high-z galaxies, less biased in luminosity than the standard field (large) samples.**
- **GTs : an efficient tool to derive the physical properties of galaxies, and thus to set strong constraints on the scenarios of galaxy formation and evolution.**

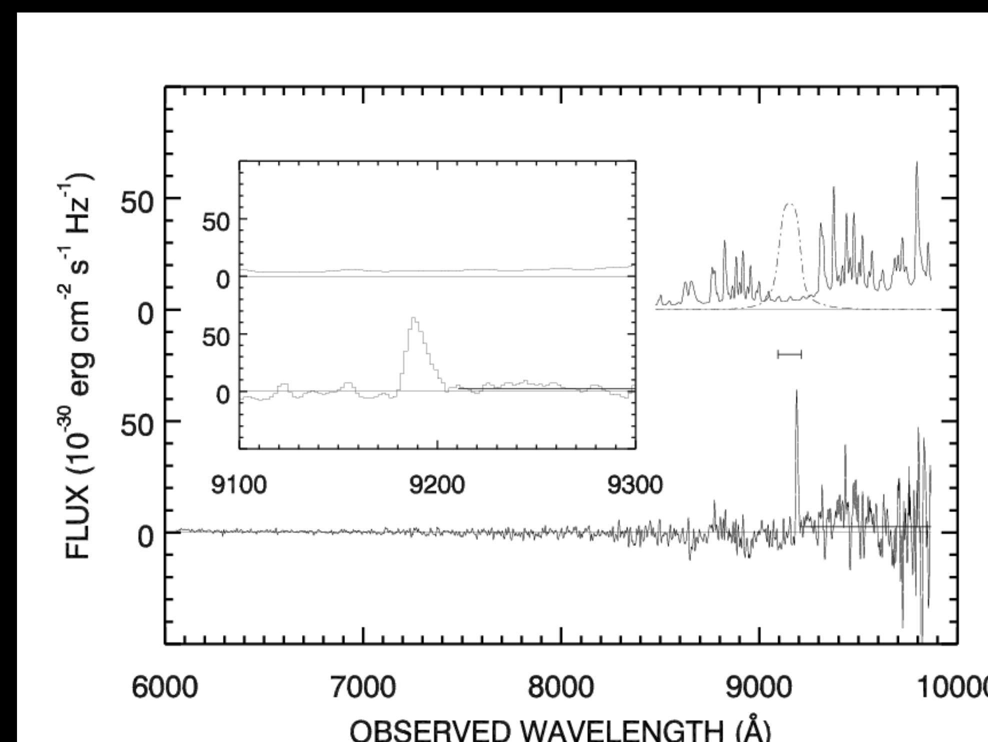


Magnification in the core of lensing clusters ~1 to 3 magnitudes



Hu et al. 2002 / A370

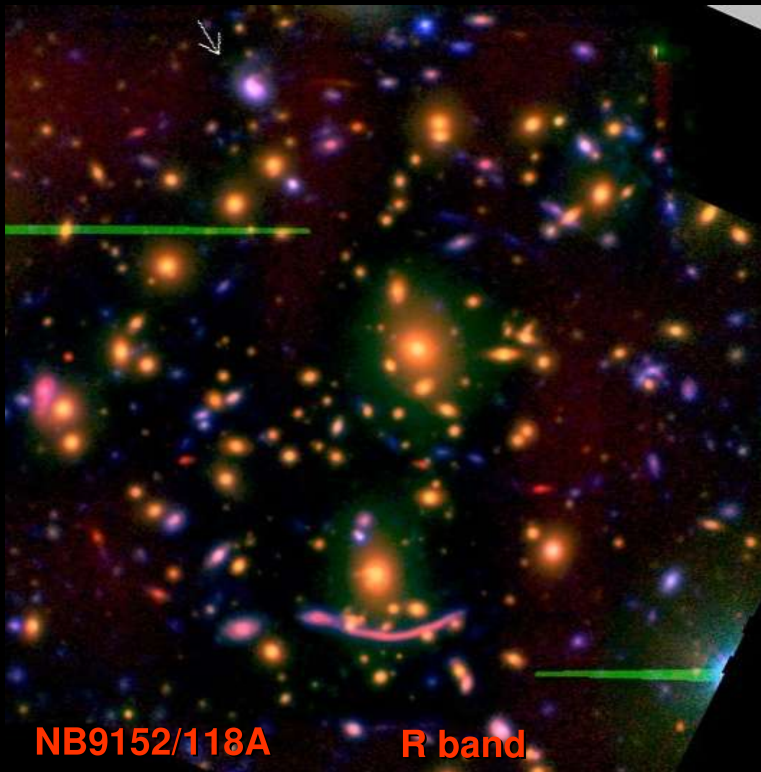




Lensed galaxy at z=6.56 behind the cluster A370

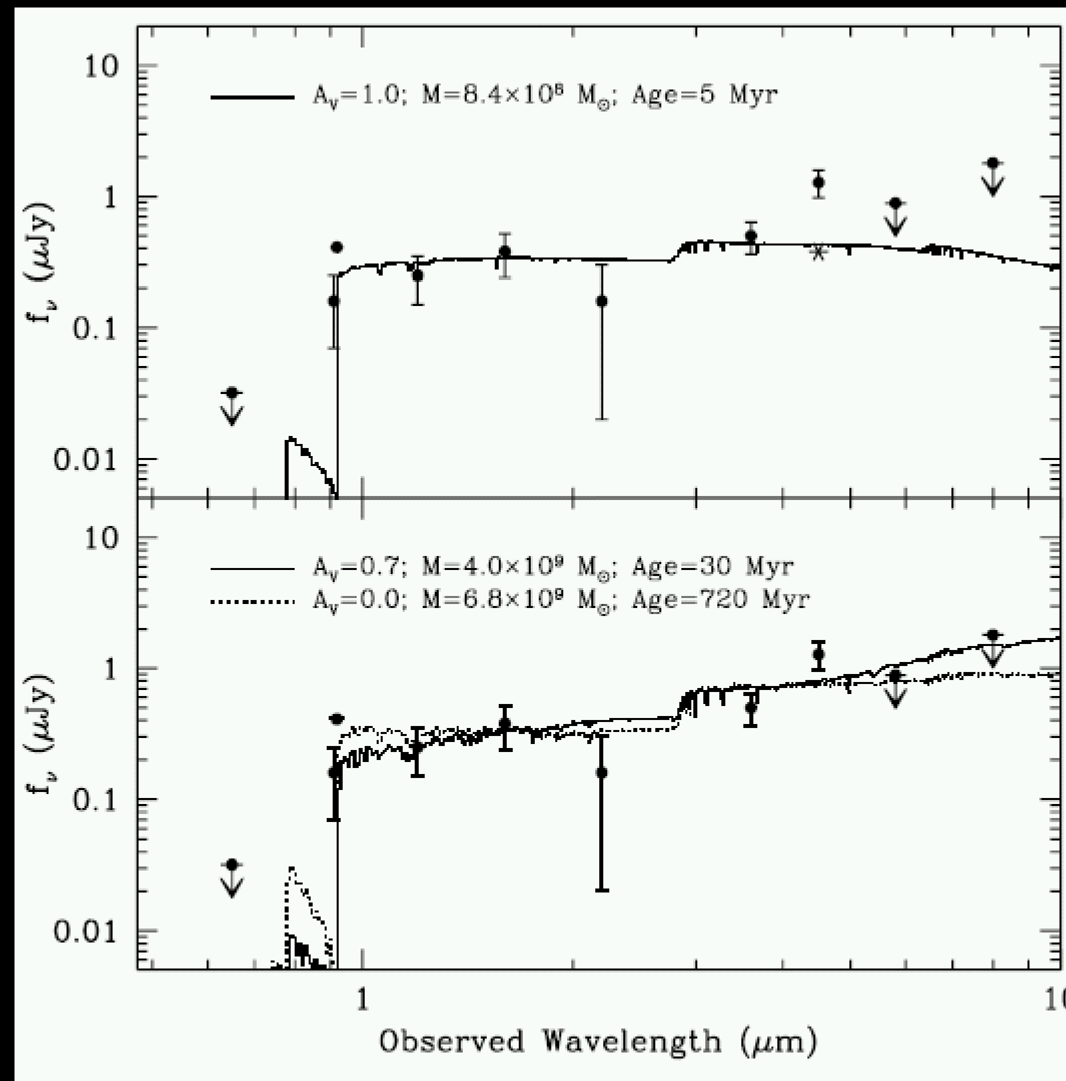
- → *NB research technique*
- → *recent analysis of it's stellar populations:*

Schaerer & Pello (2005, MNRAS 362, 1054)

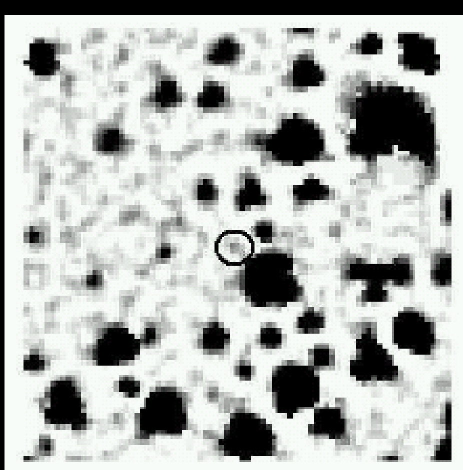


Chary et al. 06:

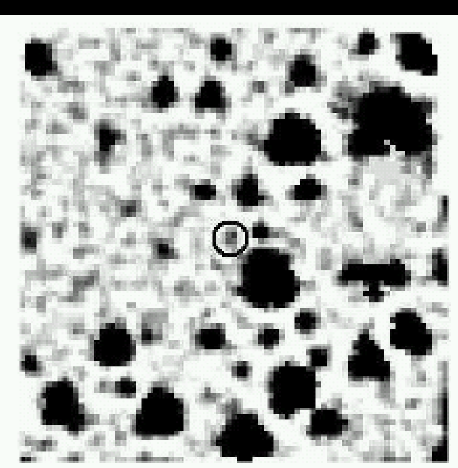
- SPITZER/IRAC observations at 3.6 and 4.5 microns
- SFR > 140 M(solar)/yr; Av~1 mag
- First star-formation at z~20



IRAC/3.6 micron

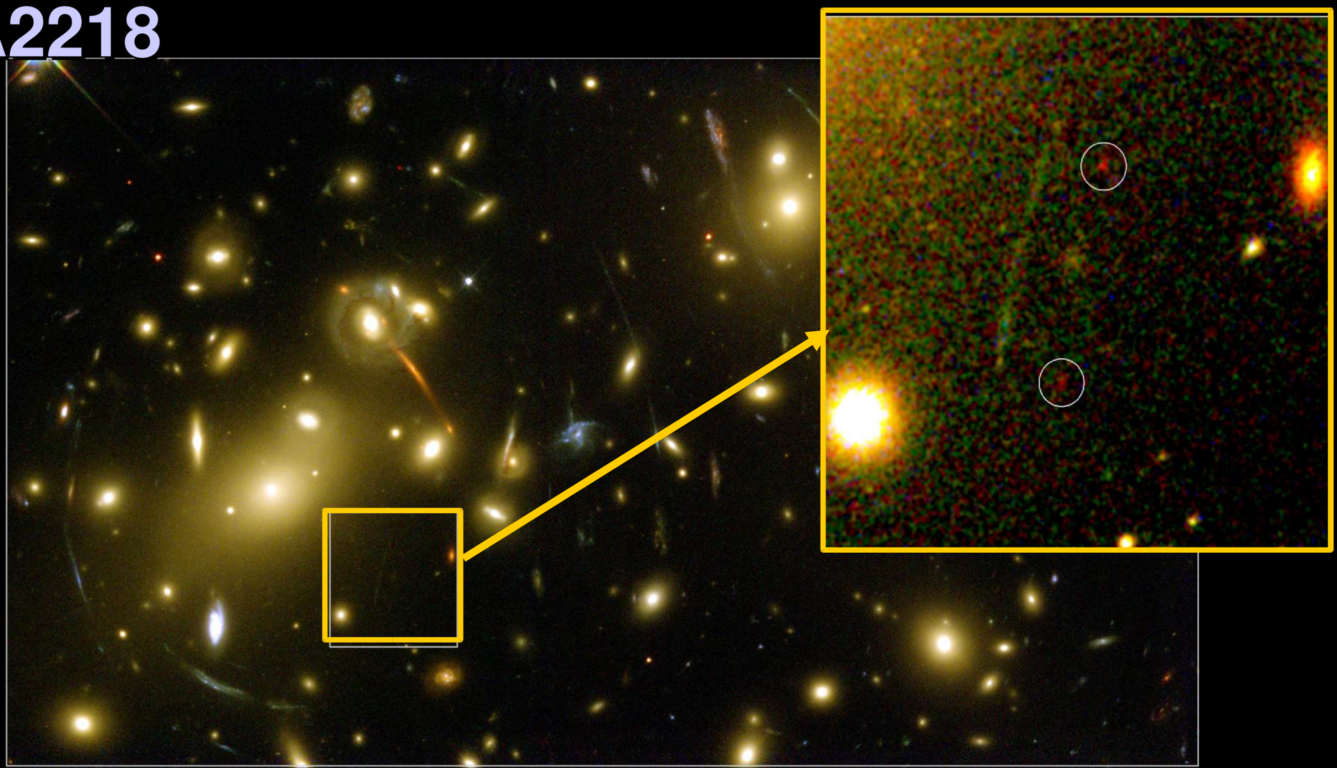


IRAC/4.5 micron



Systematic Research around the critical lines

A2218



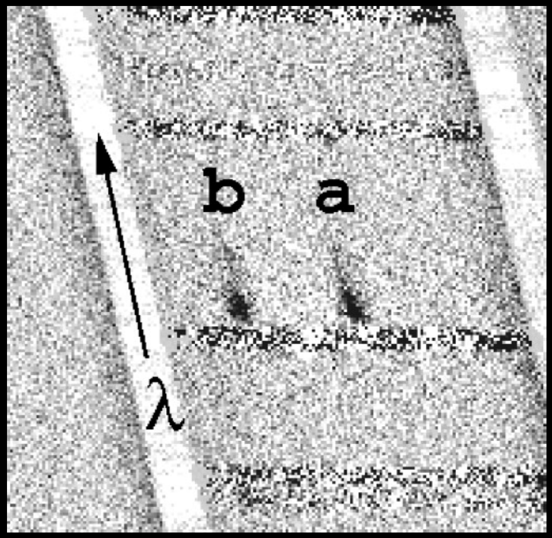
Ellis et al., 2001, ApJ 560, L119

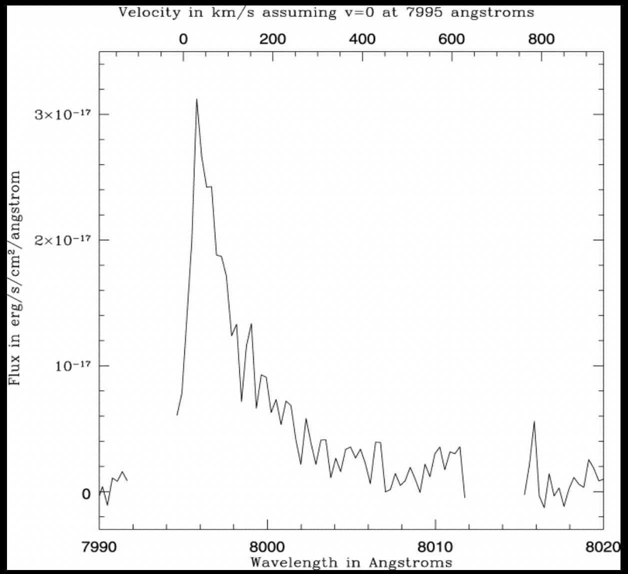
Lensed Galaxy at

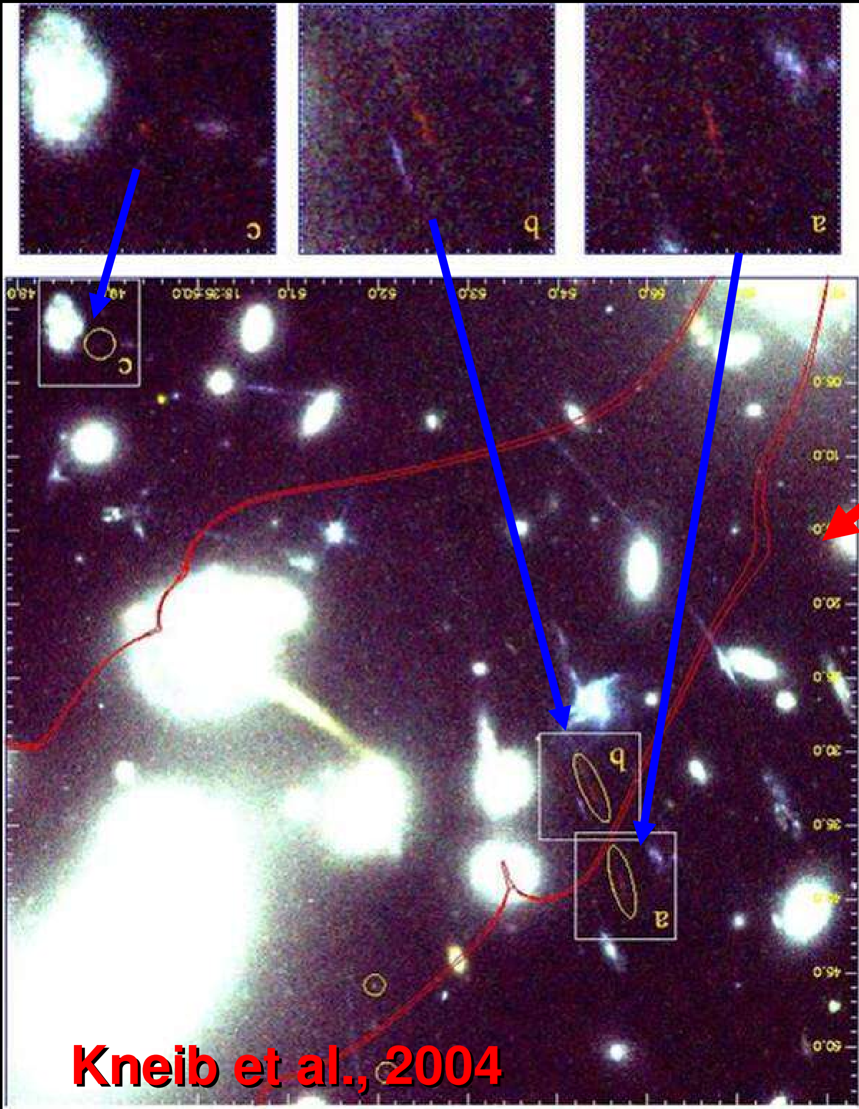
z=5.58 behind

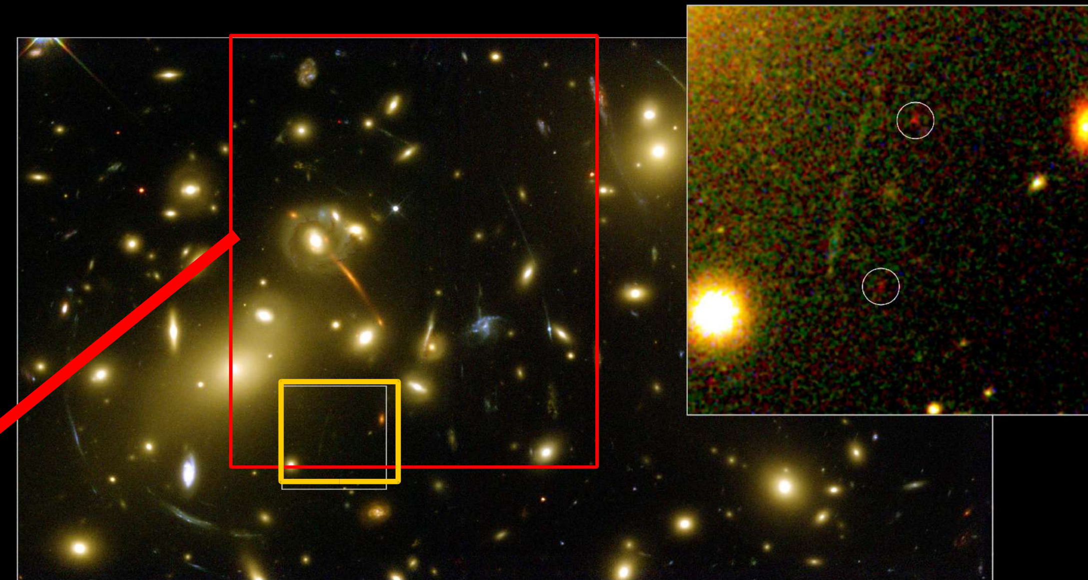
A2218.

- *Multiple images/ highly magnified source*
- *Lyman α emission line*





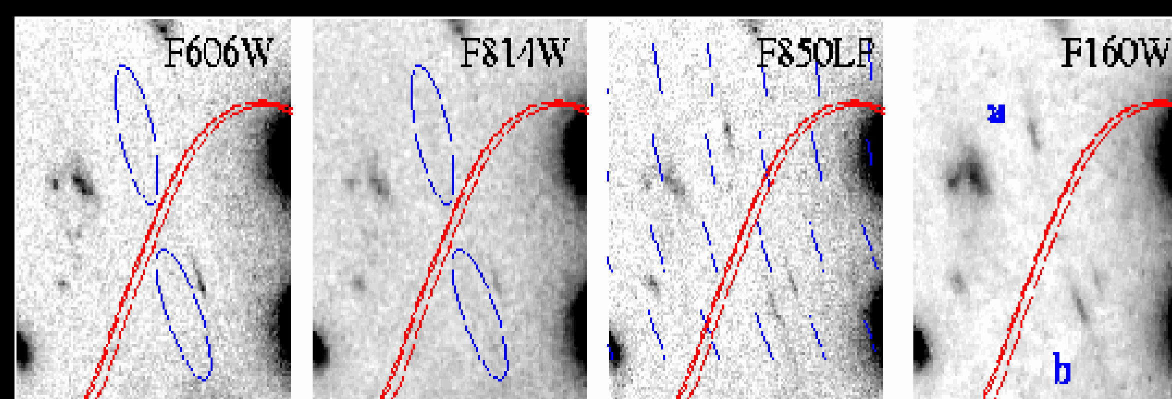




A2218

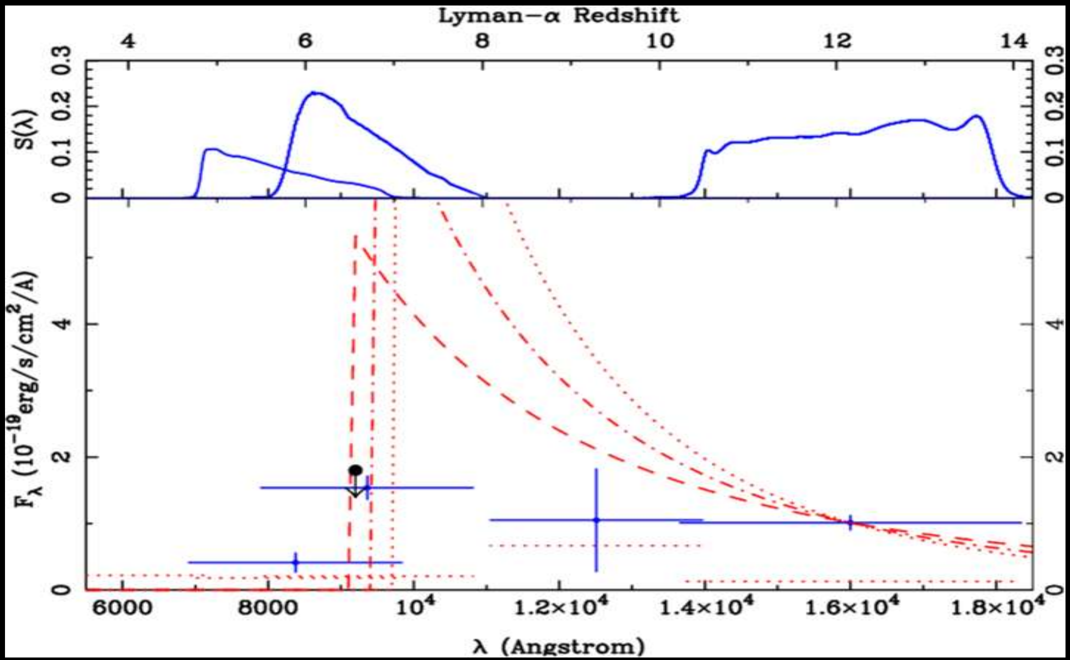
- Compact Lensed Galaxy at z≈ 7
- Multiple imaged
- No emission line detected. Robust photometric & lensing identification

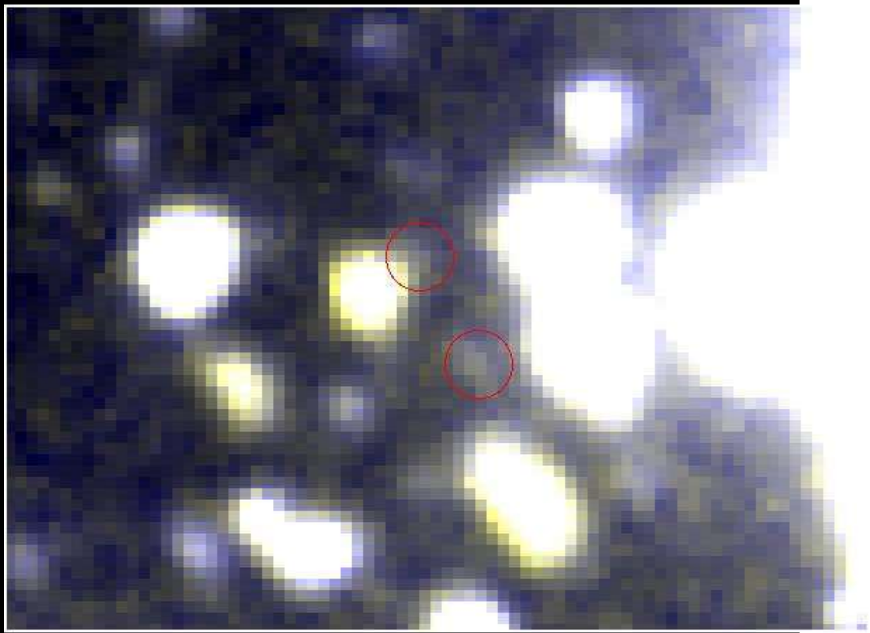
Detection by *Spitzer* of the z~7 pair in 2 bands of the IRAC camera: 3.6 mm and 4.5 mm (Egami et al. 05)

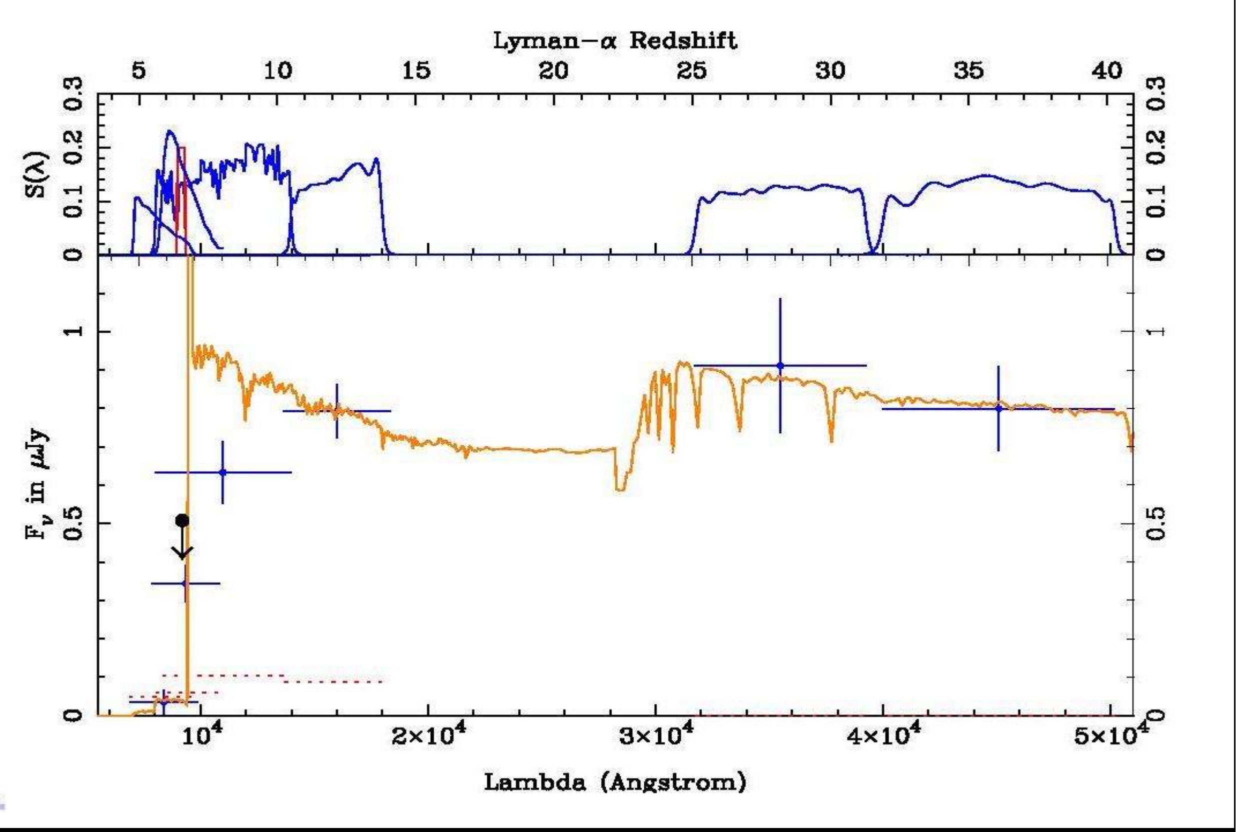


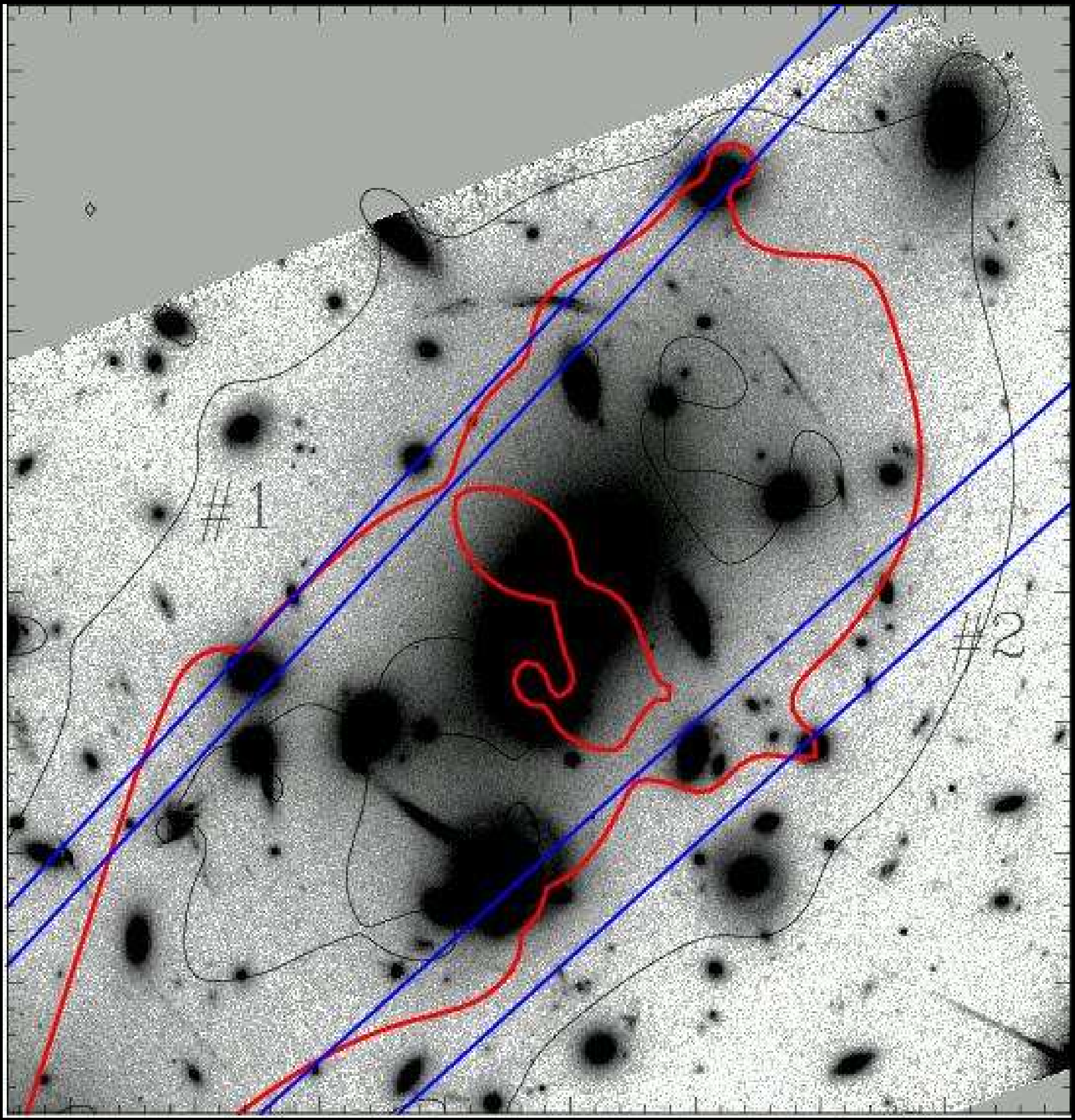
Combined with new observations from HST/NICMOS in the J band ne w constraints on the overall broad-band SED.

Example given is a z=6.75 model of 150 Myr continuous star formation (Egami et al. 05)







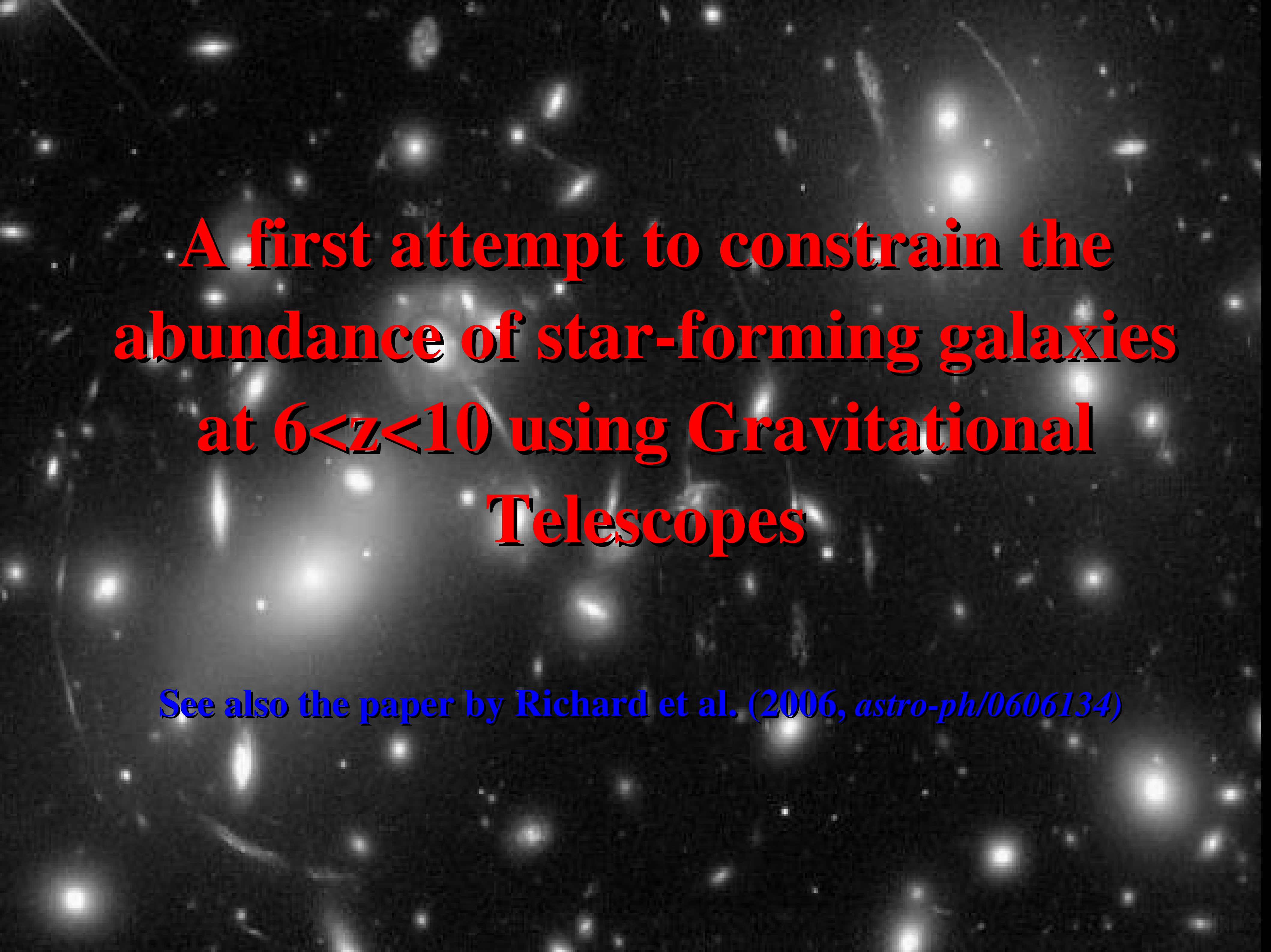


Santos et al. 2003:

- ***"Blind" survey around the critical lines***
- ***9 clusters; magnification > 10 at 4.5<z<6.7***
- ***Keck / LRIS long-slit spectra + Keck / ESI :*** *higher resolution to resolve the [OII]3727 doublet or Lyman-a asymmetric line*
- ***11 candidates confirmed at 2.2 < z < 5.6***

see also Ellis et al.06 (JDIAU06) and Stark & Ellis 05

==> see R. Ellis's talk



A first attempt to constrain the abundance of star-forming galaxies at $6<z<10$ using Gravitational Telescopes

See also the paper by Richard et al. (2006, *astro-ph/0606134*)

Observational Strategy

- 2001 -> SpectroPhotometric Simulations:
  * broad-band colors for "drop-out" selection at various redshifts (z>~6-7, z>~7-8, z>~8)
  * 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; final sample is H-band selected):
  * selection of optical drop-outs + blue rest-frame UV spectrum
  * objects detected in at least 2 bands longward of Ly-a break
- 2003 -> Spectroscopic Follow-up of best candidates
- 2005/06 -> Multi-wavelength follow up (Spitzer-IRAC, Chandra, IRAM, ...)

Properties of z>7 galaxies and observing strategy

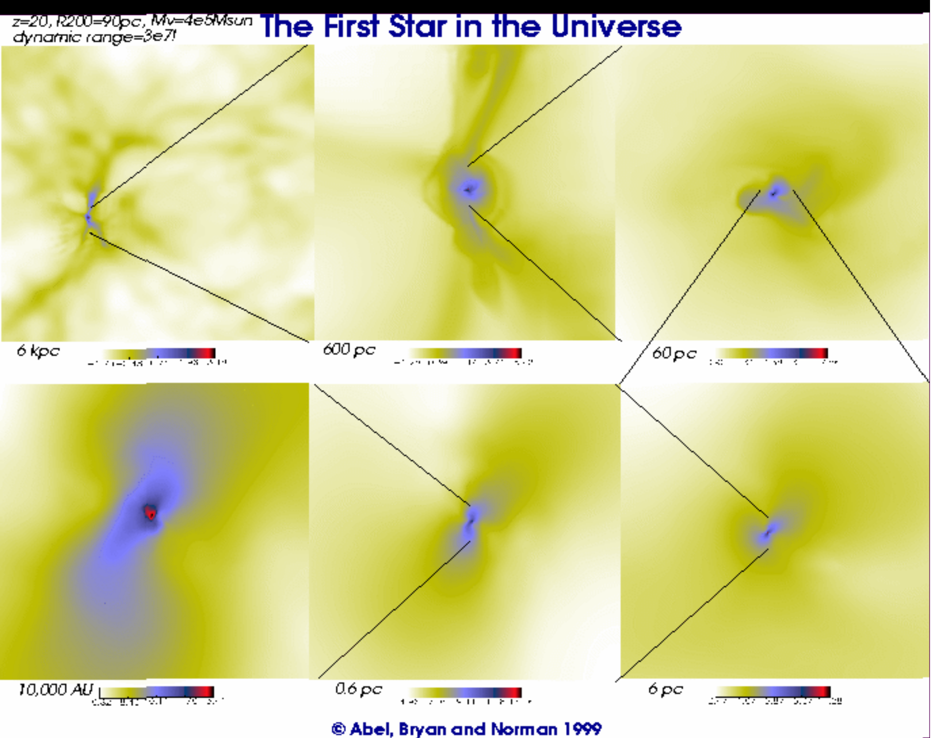
Initial mass function (IMF):

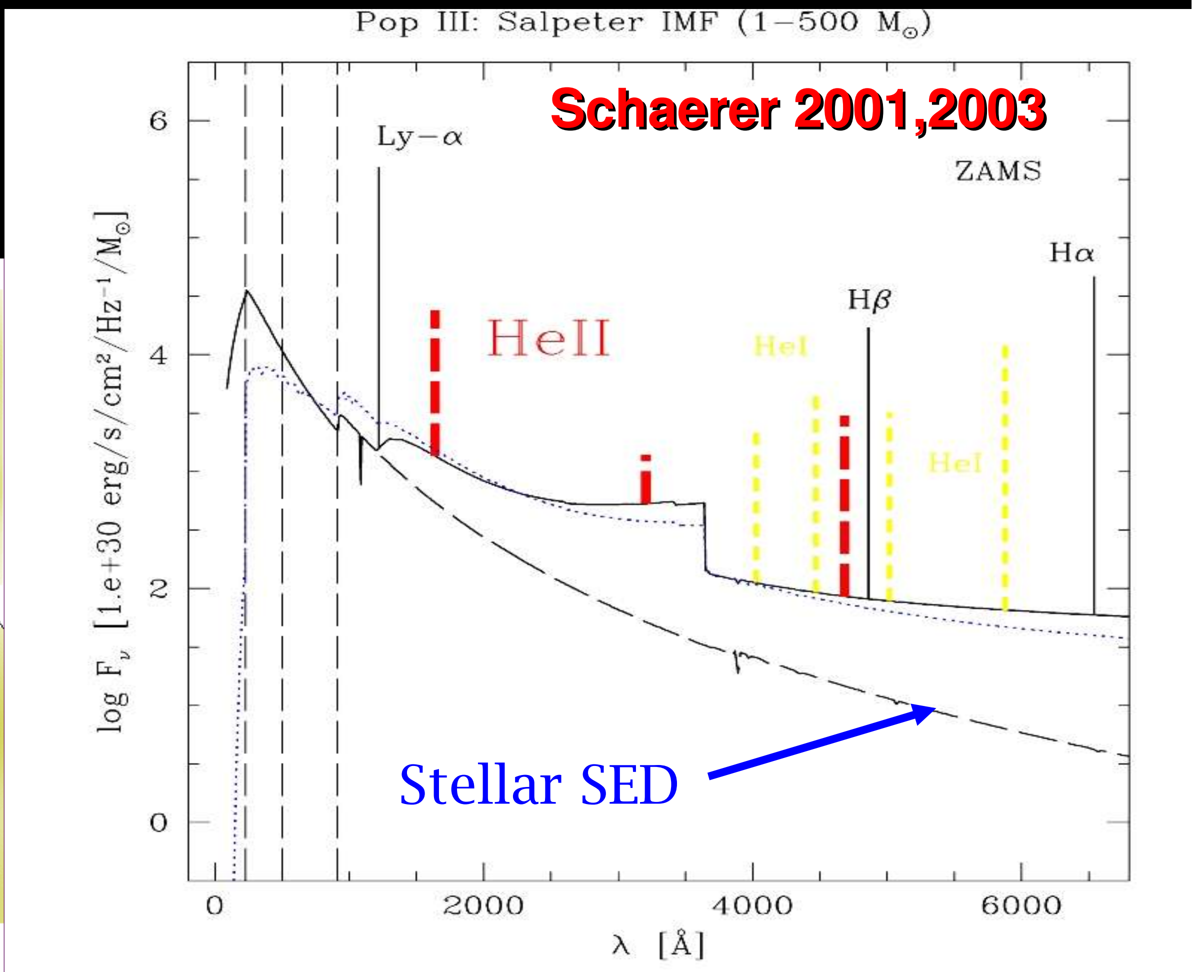
Existence of very massive stars: up to ~ 1000 M solar ?!

(e.g. Abel et al. 1998..., Nakamura & Umemura 1999, 2001, Bromm et al. 1999, ...)

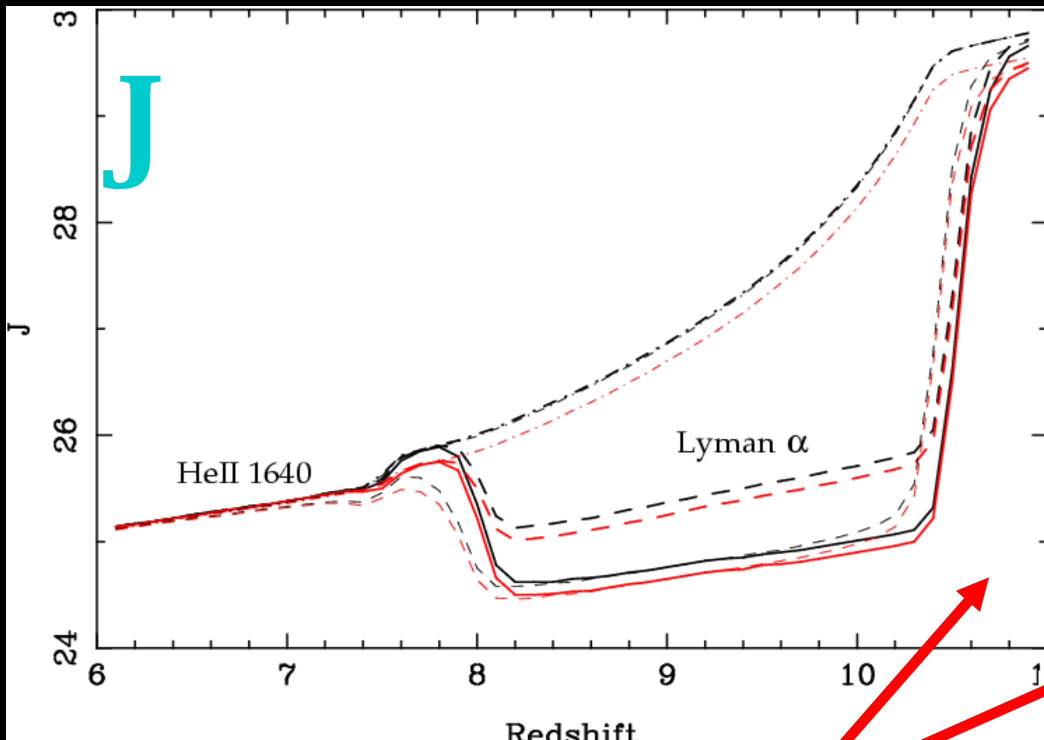
Nebular continuous emission ***dominates*** **the spectrum at λ> 1400 Å**

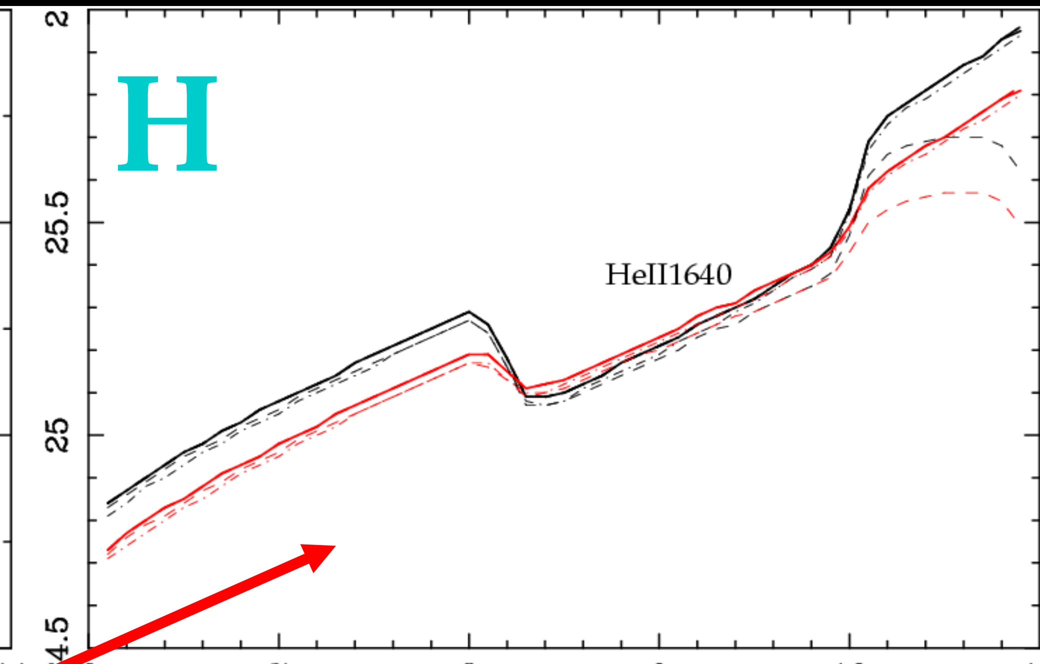
+ Strong HeII lines?: HeII λ1640, HeII λ3203, HeII λ4686, ...

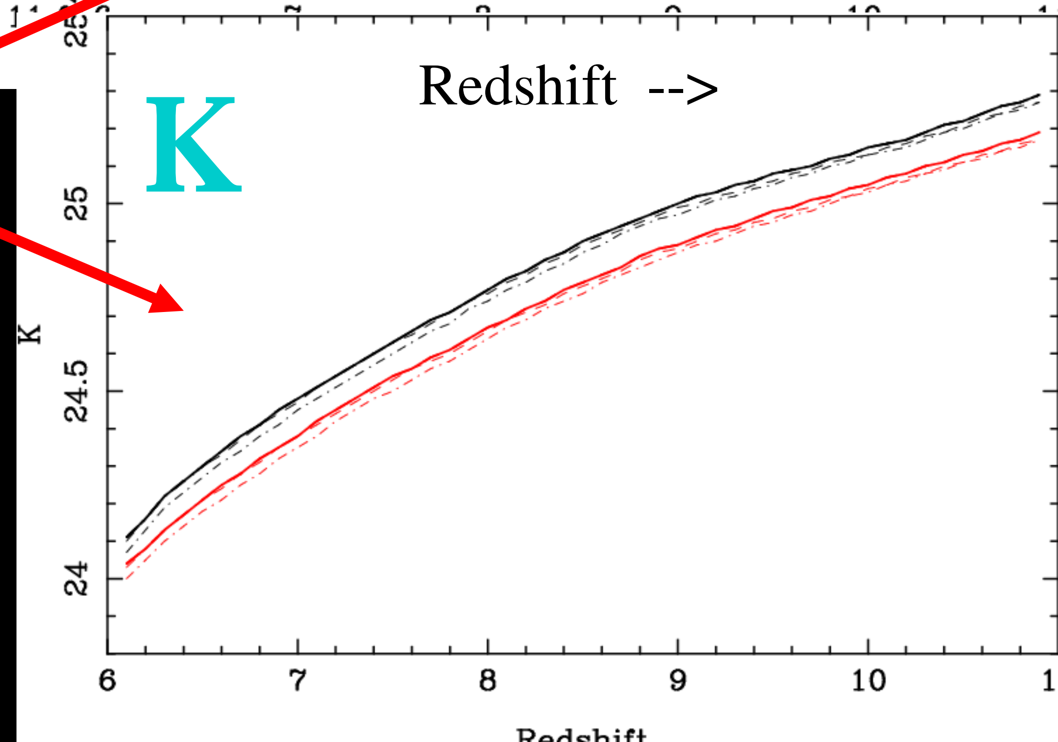




Near-IR Broad-Band magnitudes







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

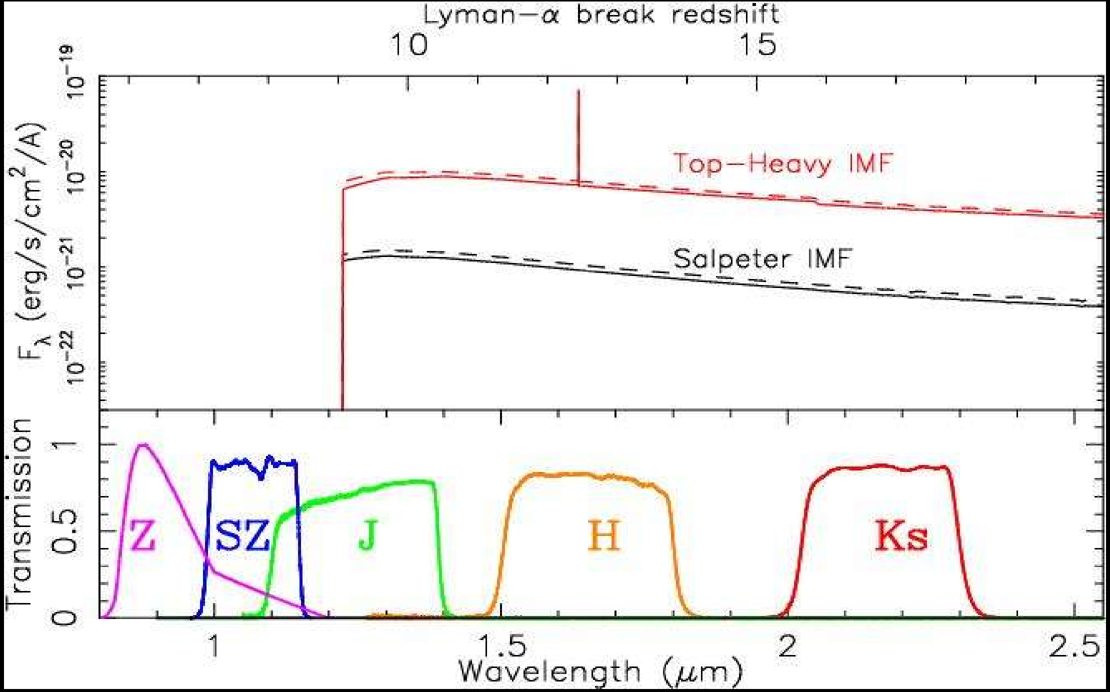
<u>With J(Vega)<25.0; H<24.0; K<23.8:</u>

Top heavy IMF 50-500 M_solar

M_halo(stars) >10^8 M_solar to z<10

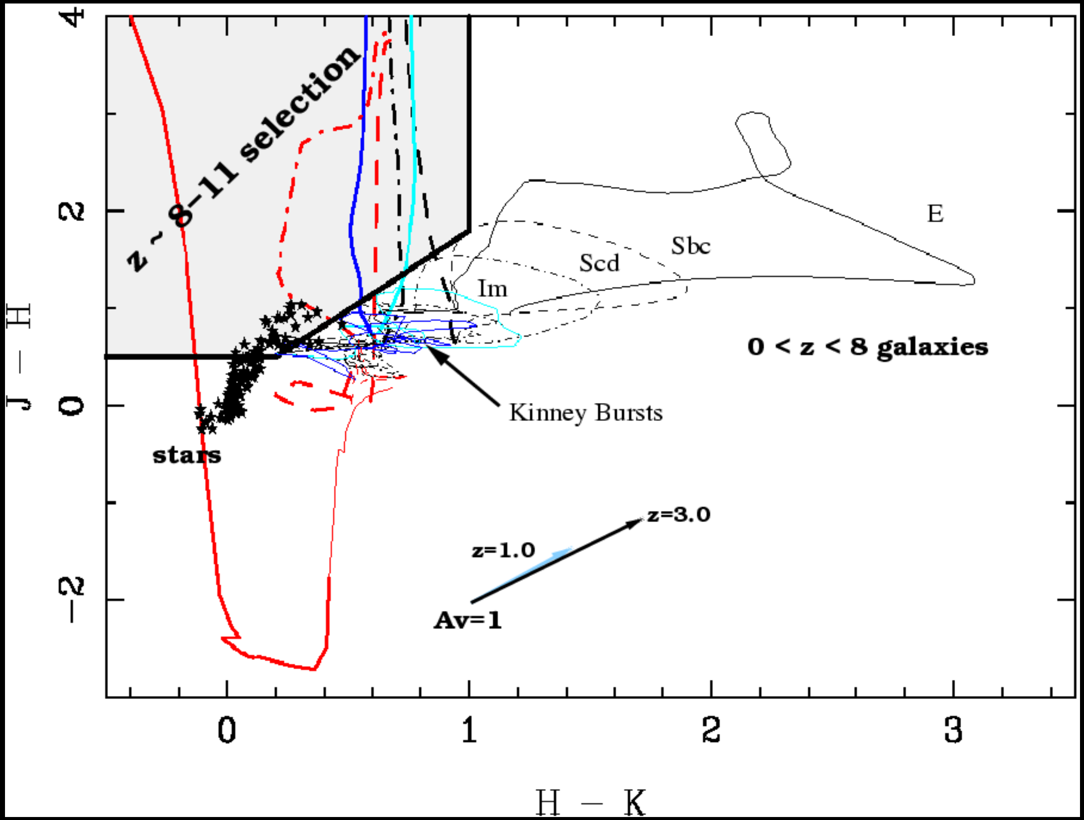
> 3-5 10^7 M_solar z<9

x 10 M_halo(stars) if standard Salpeter IMF

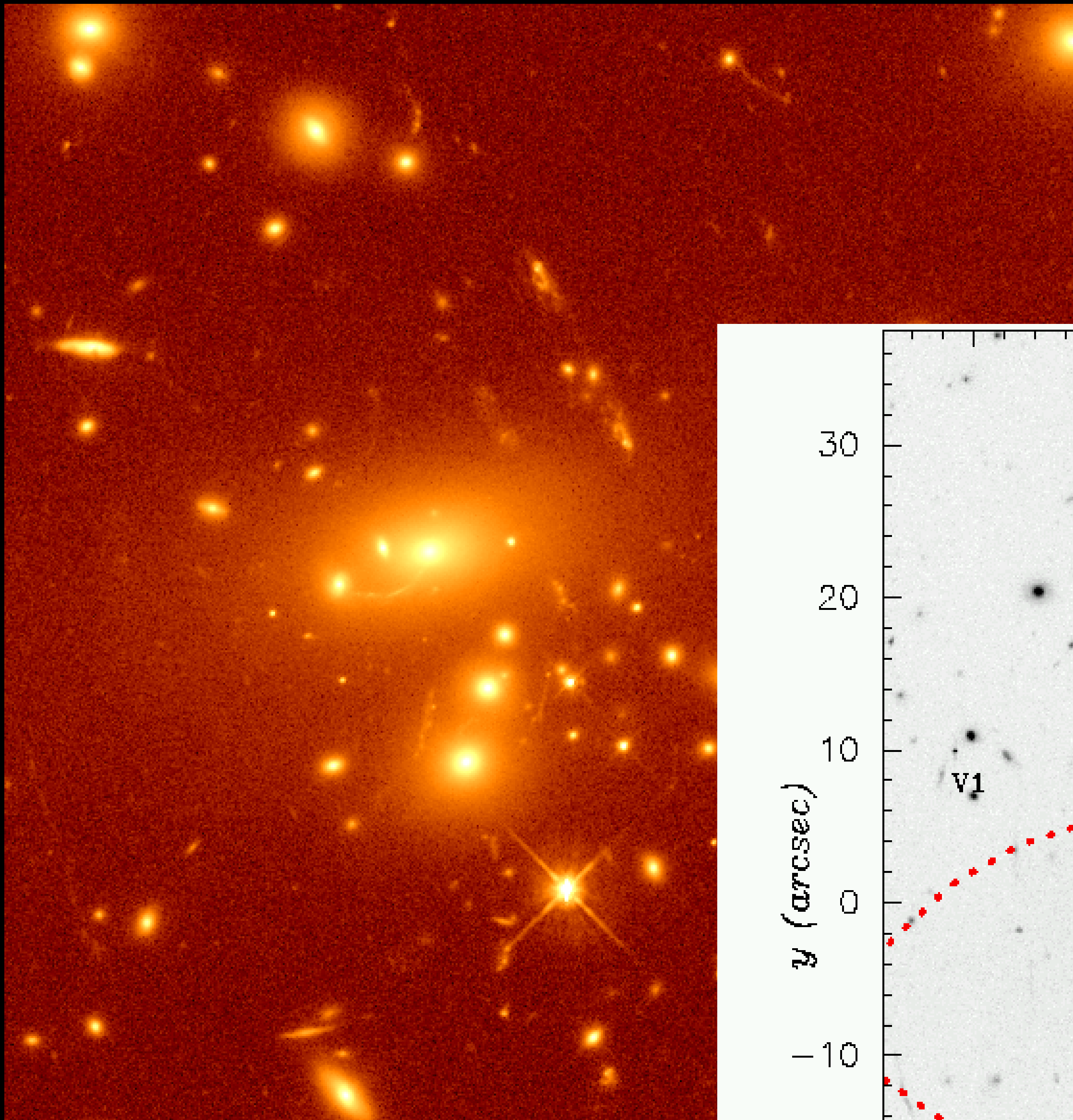


Broad-band Color Selection of high-z candidates (+ spectroscopic confirmation)

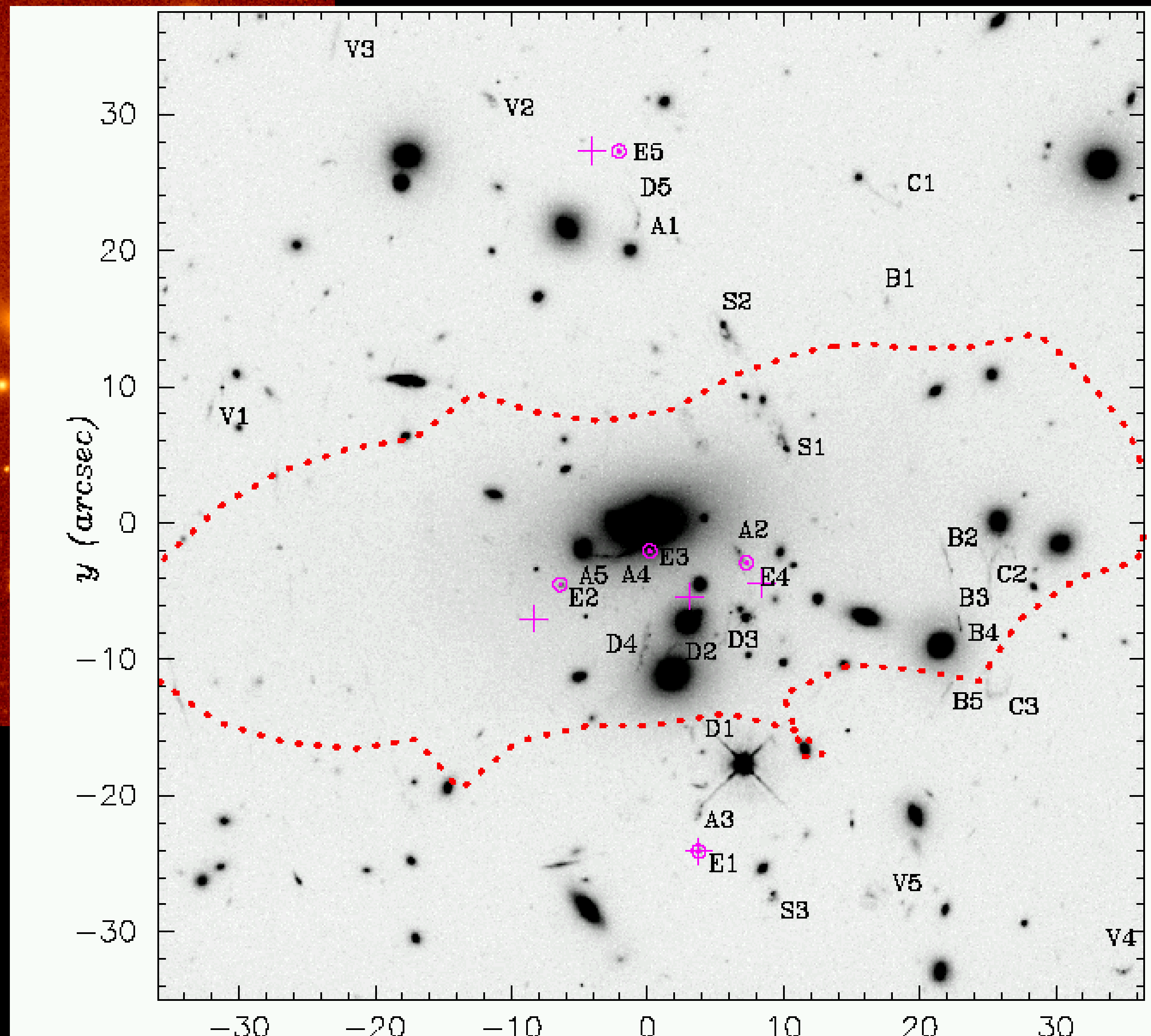
- Optical dropouts + near-IR colors
- Filter combinations:
  - z~6-7: zYJ
  - z~7-8: YJH
  - z > 8 : JHK



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

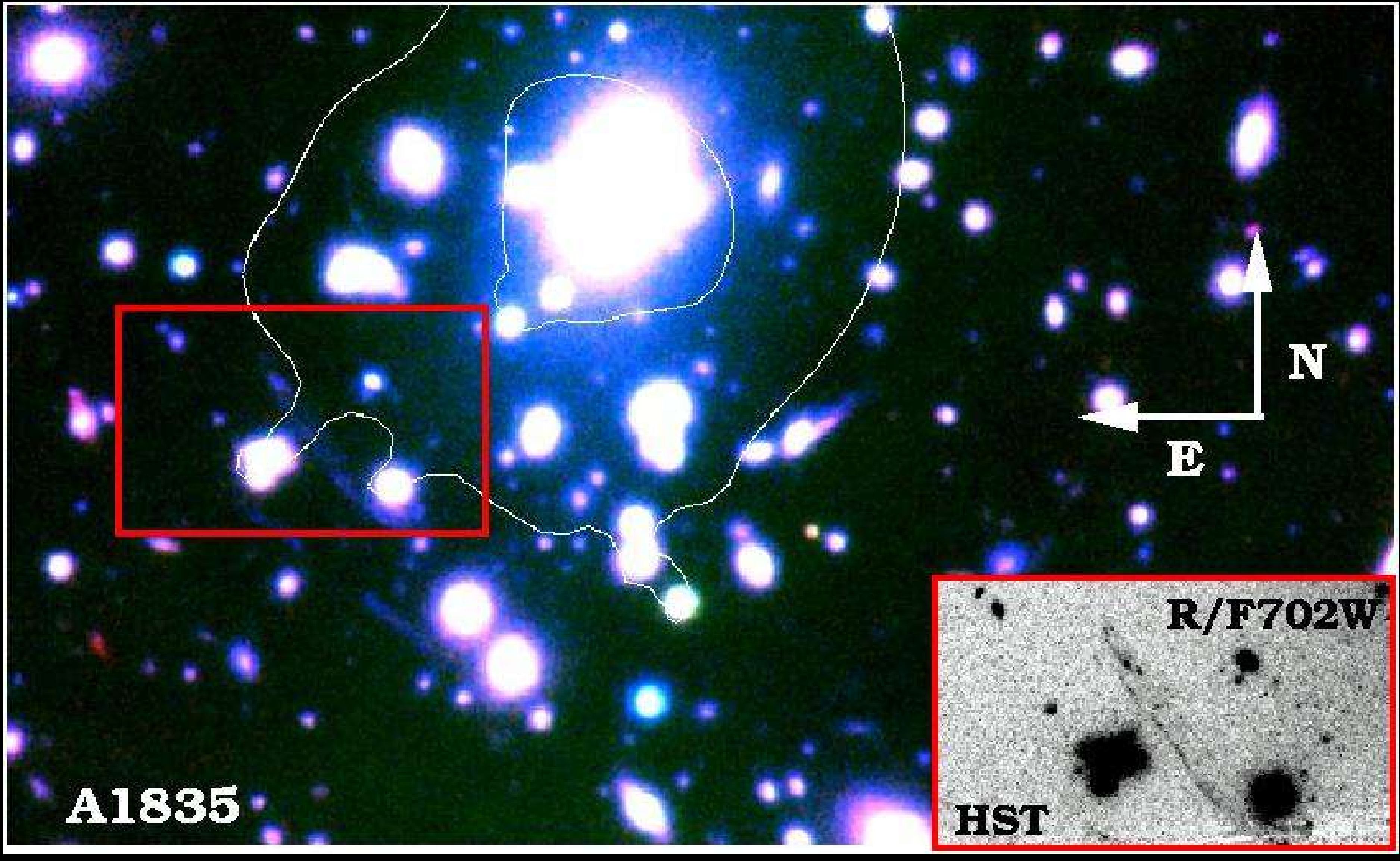


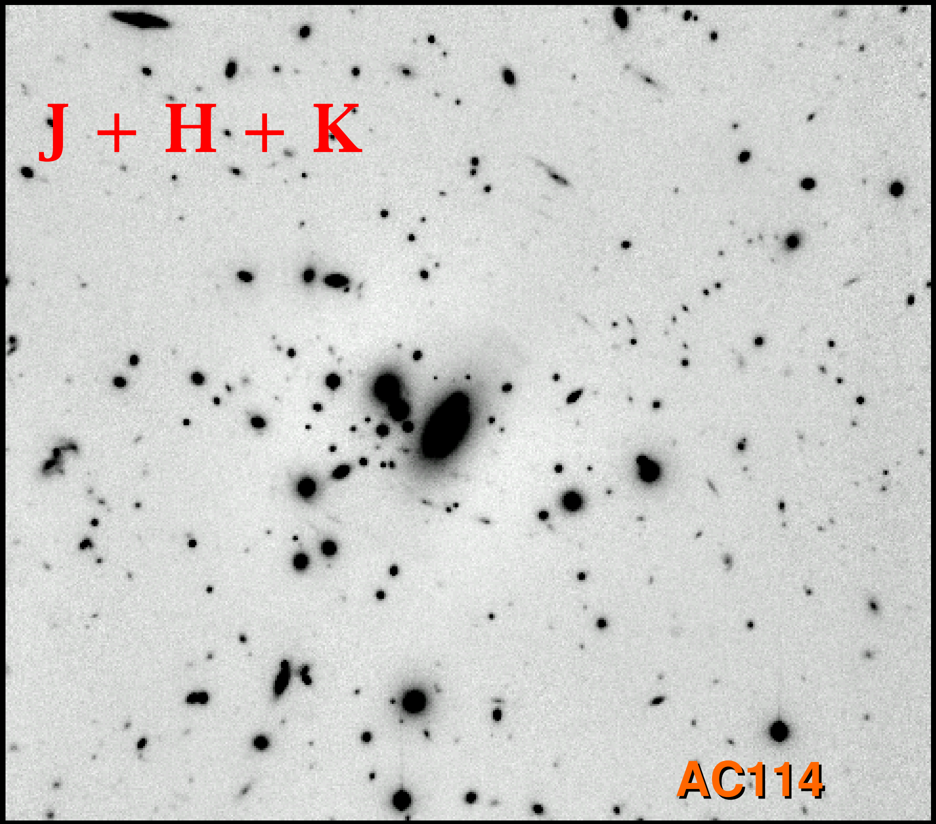
AC114 (z=0.312)

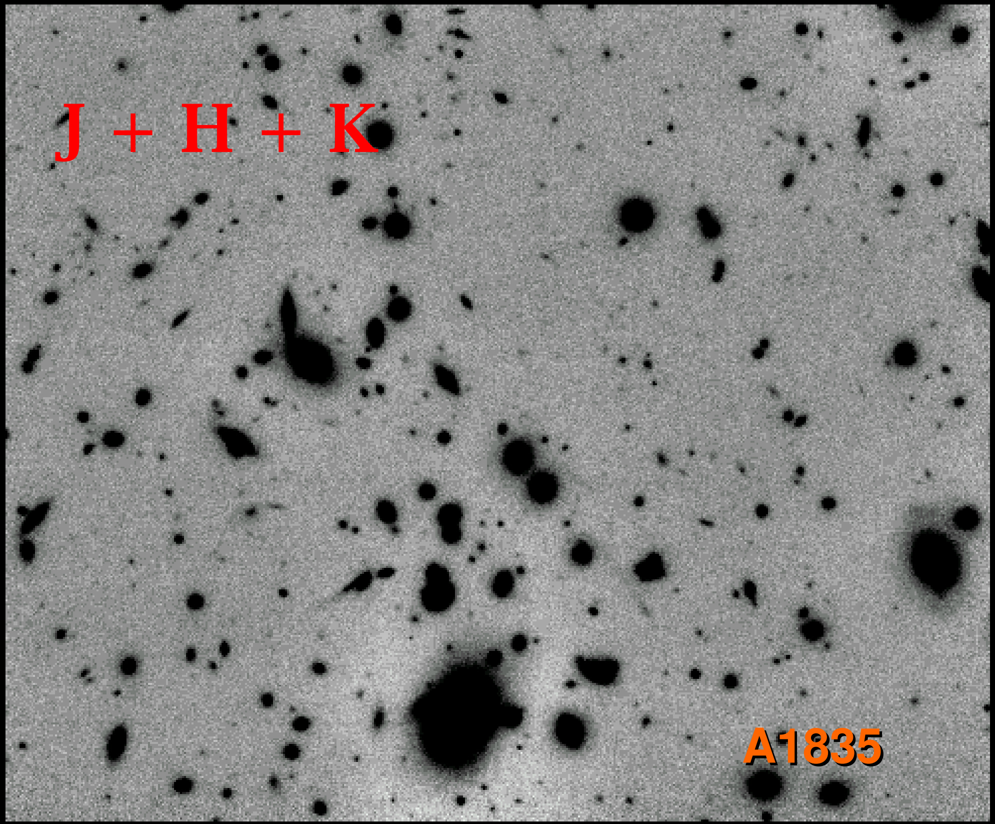


A1835 (z=0.252):

- 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)







AC114 (z=0.312):

ISAAC/VLT photometry (Vega system):

J : 2h (→ J = 24.3)

H : 4h (→ H= 23.5, 3σ)

K': 5.5 h (→ K'=23.1 → K(AB)=25.0)

seeing ~0.4-0.6''

+ UBVRI Optical data + HST R band

A1835 (z=0.253):

ISAAC/VLT photometry (Vega system):

J : 2h (→ J = 24.4)

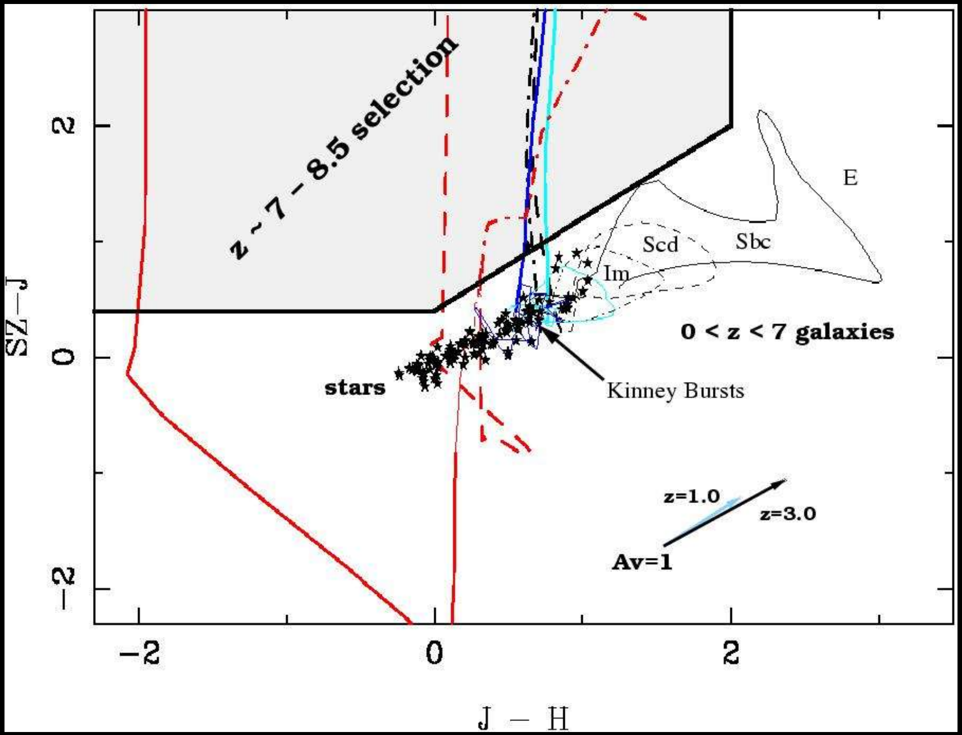
H : 4h (→ H= 23.5 , 3σ)

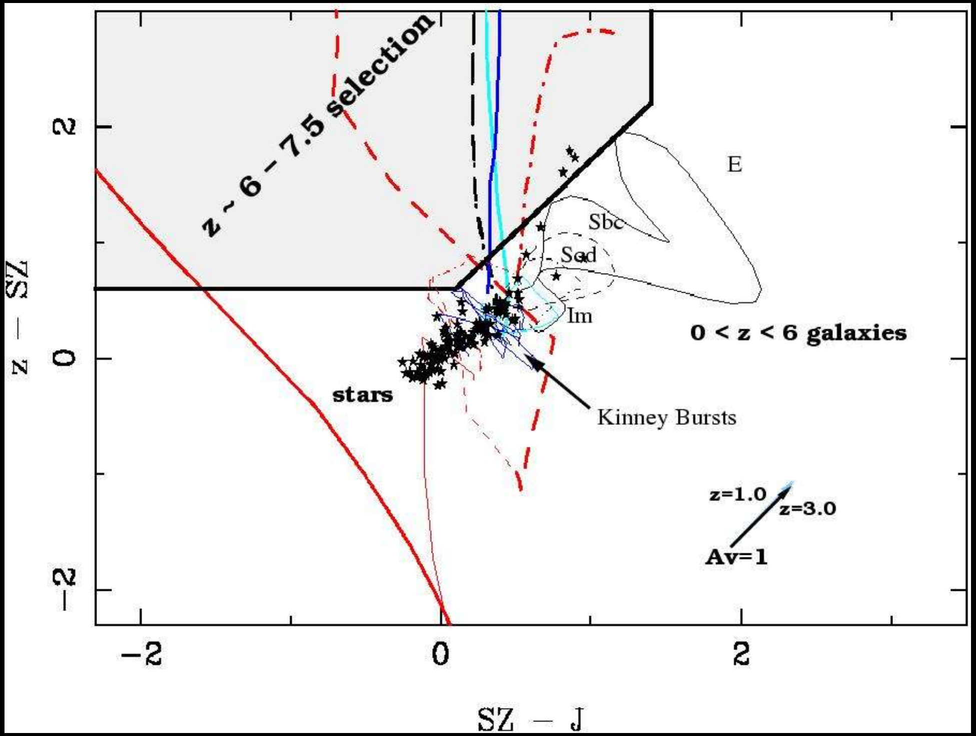
K': 5.5 h (→ K'=23.5 → K(AB)=25.4) +

z/FORS (→ z=25.5) + SZ (→ Z=25.7)

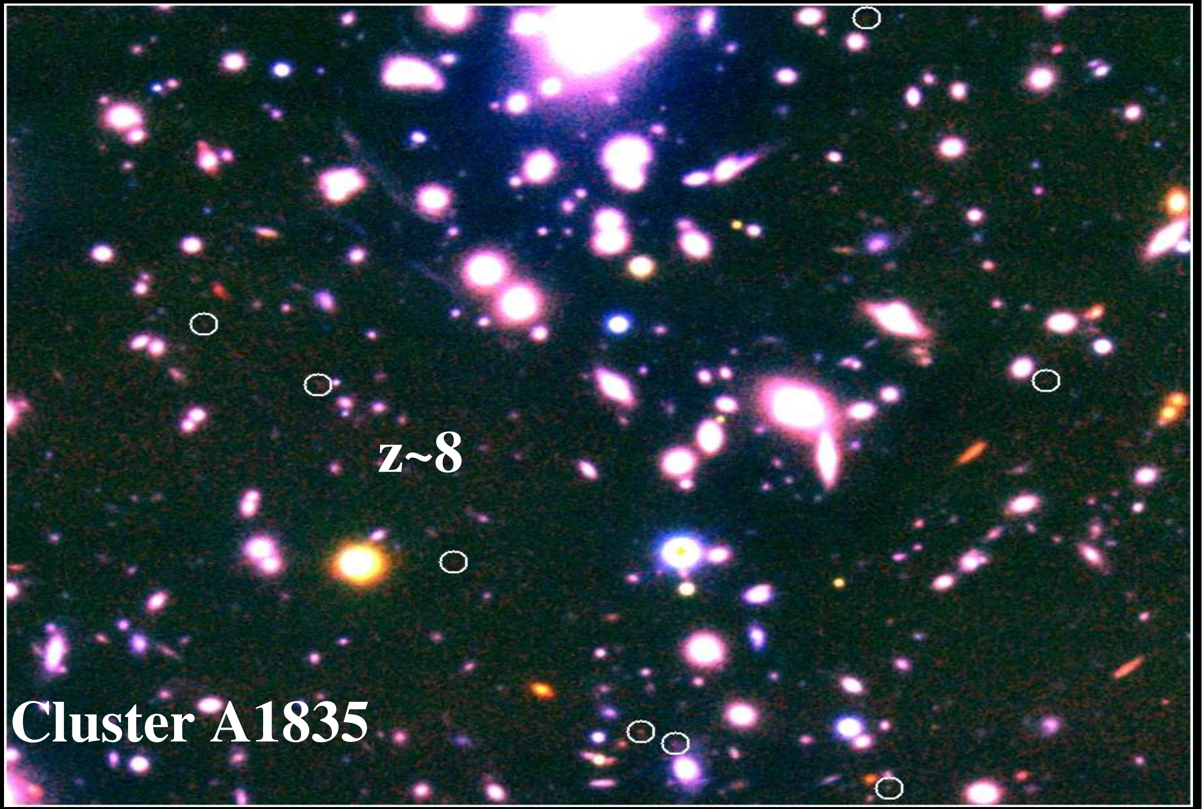
seeing ~0.4-0.6''

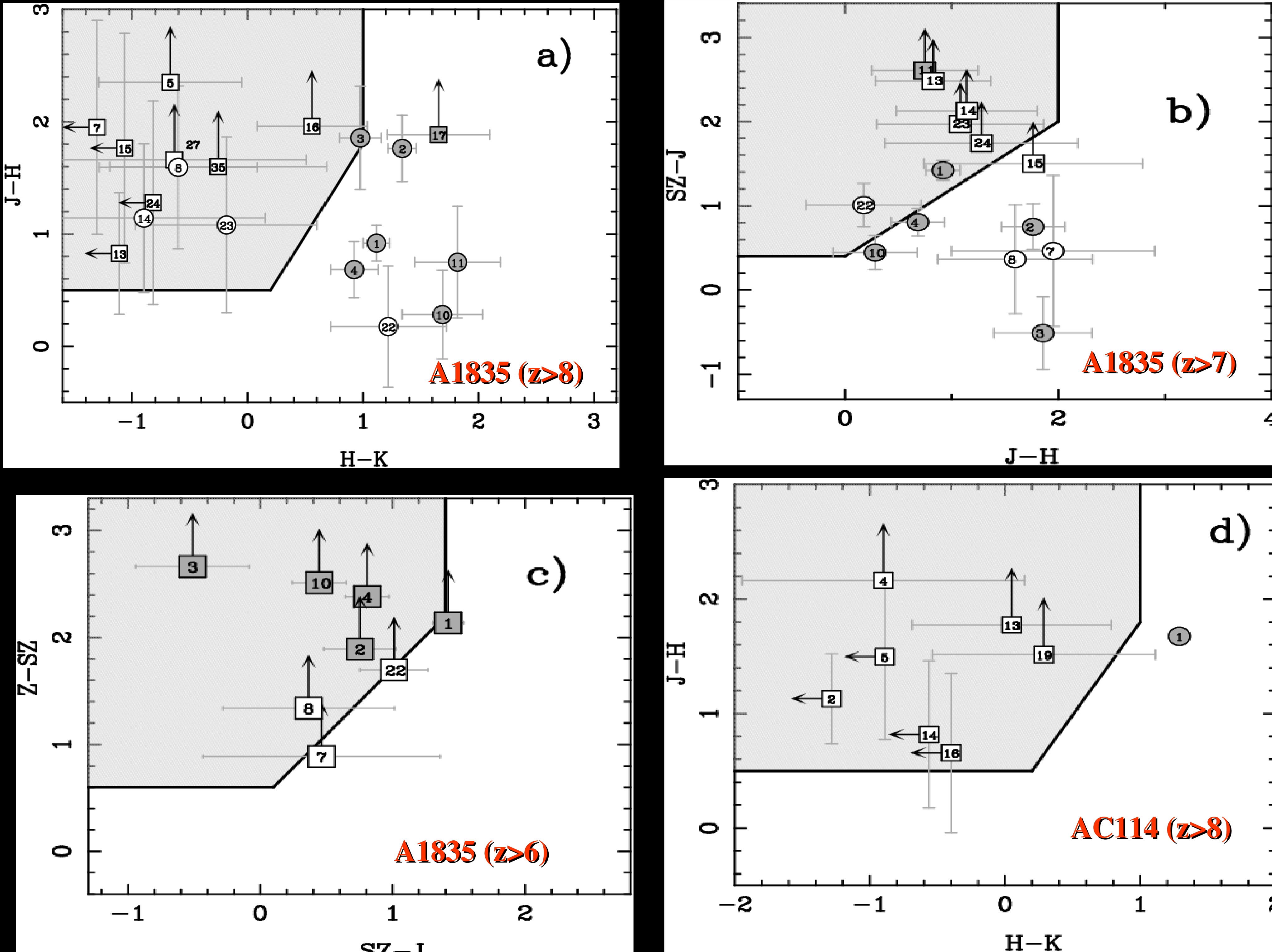
+ VRI Optical data + HST R band

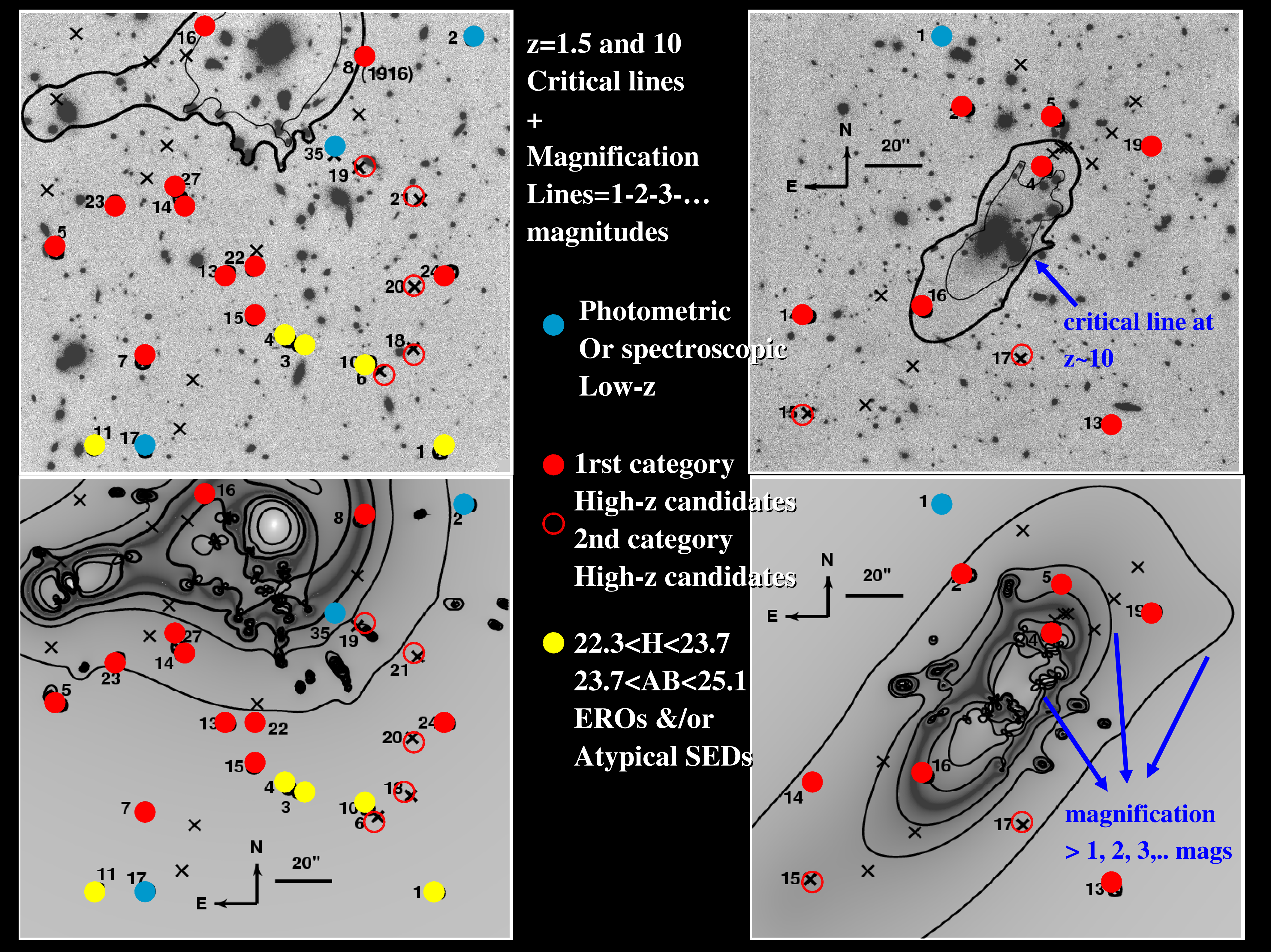




RZK composite image (0.65 à 2.5 microns) of A1835. Several « bright » optical dropouts are identified in this image




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

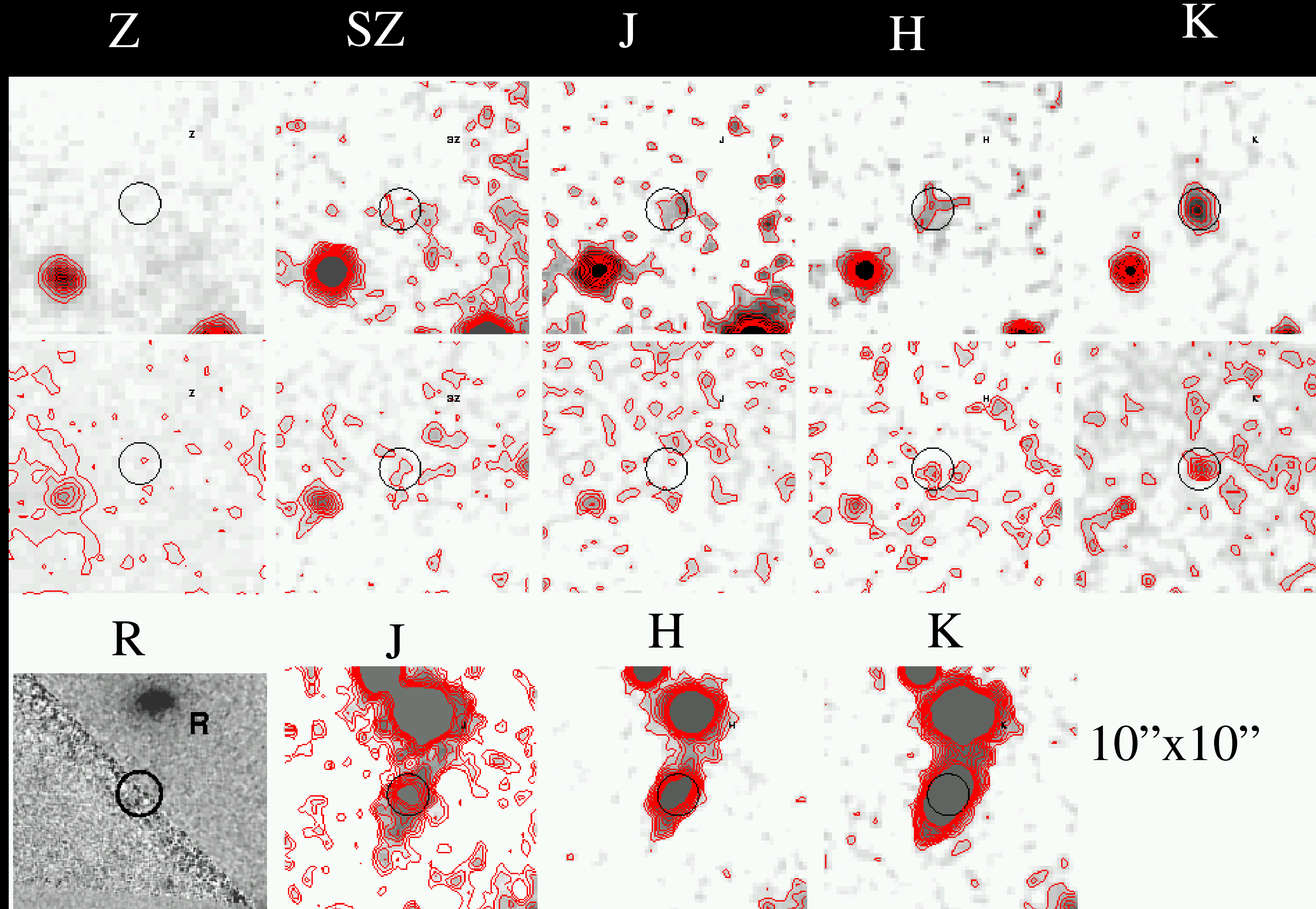

z=1.5 and 10
Critical lines
+
Magnification
Lines=1-2-3-…
magnitudes
Photometric
Or spectroscopic
Low-z
1rst category
High-z candidates
2nd category
High-z candidates
22.3<H<23.7
23.7<AB<25.1
EROs &/or
Atypical SEDs
critical line at
z~10
magnification
> 1, 2, 3,.. mags
N
E
20"
8 (1916)

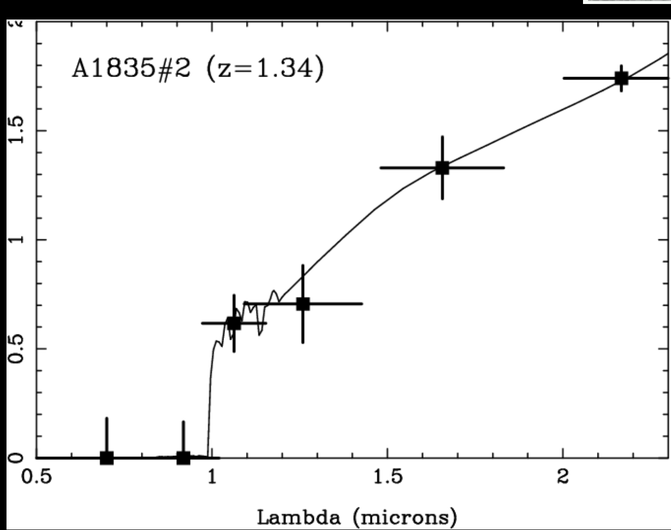
A1835-#2

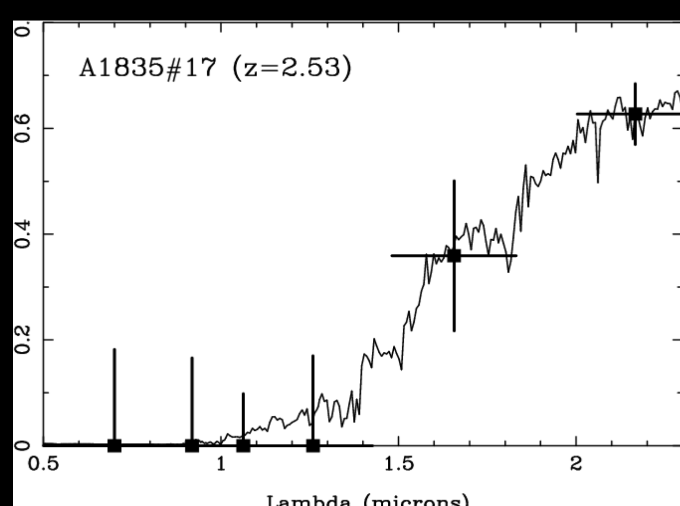
J5/SCUBA-selected galaxy SMMJ14009+0252 (Ivison et al. 2000, Smail et al. 2002)

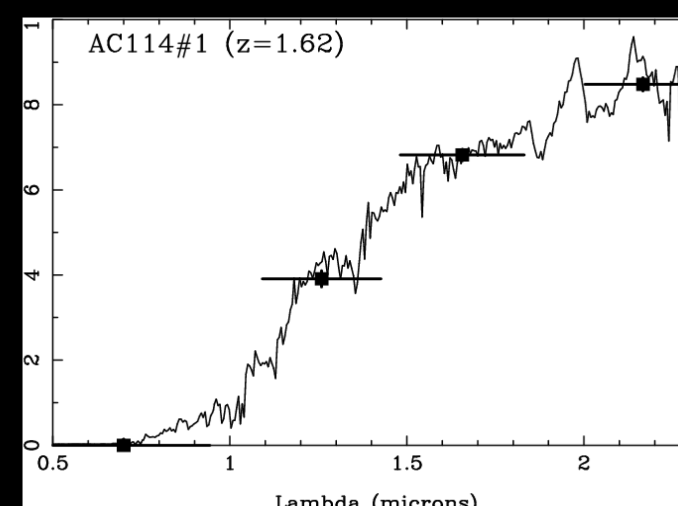
A1835-#17 +A1835-#35: spectroscopic determination (Richard et al. 03)

AC114-#1

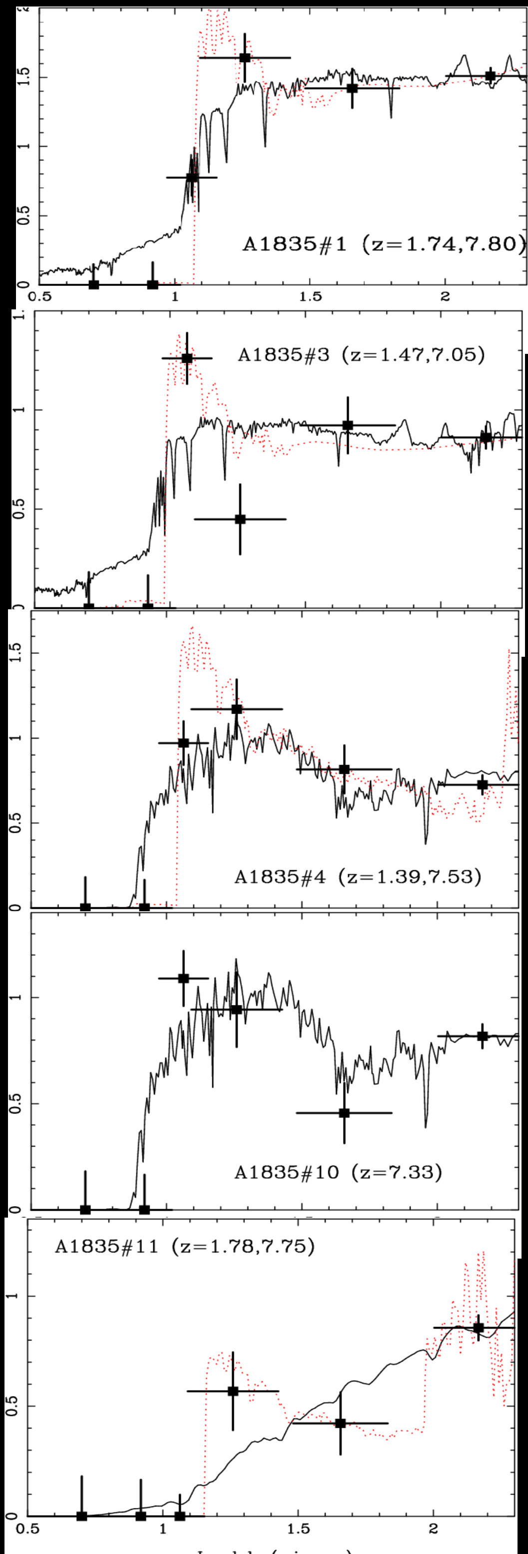






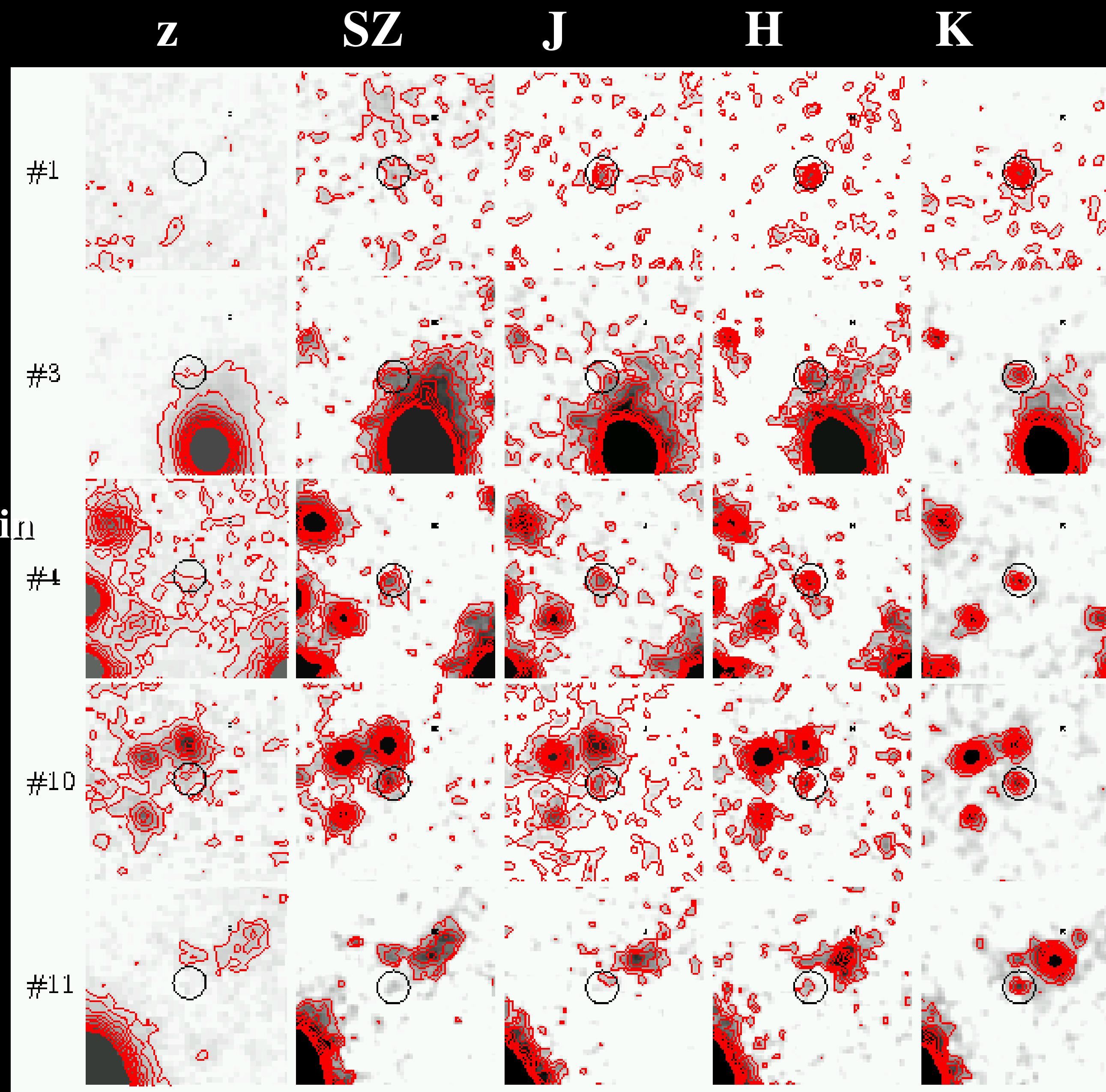


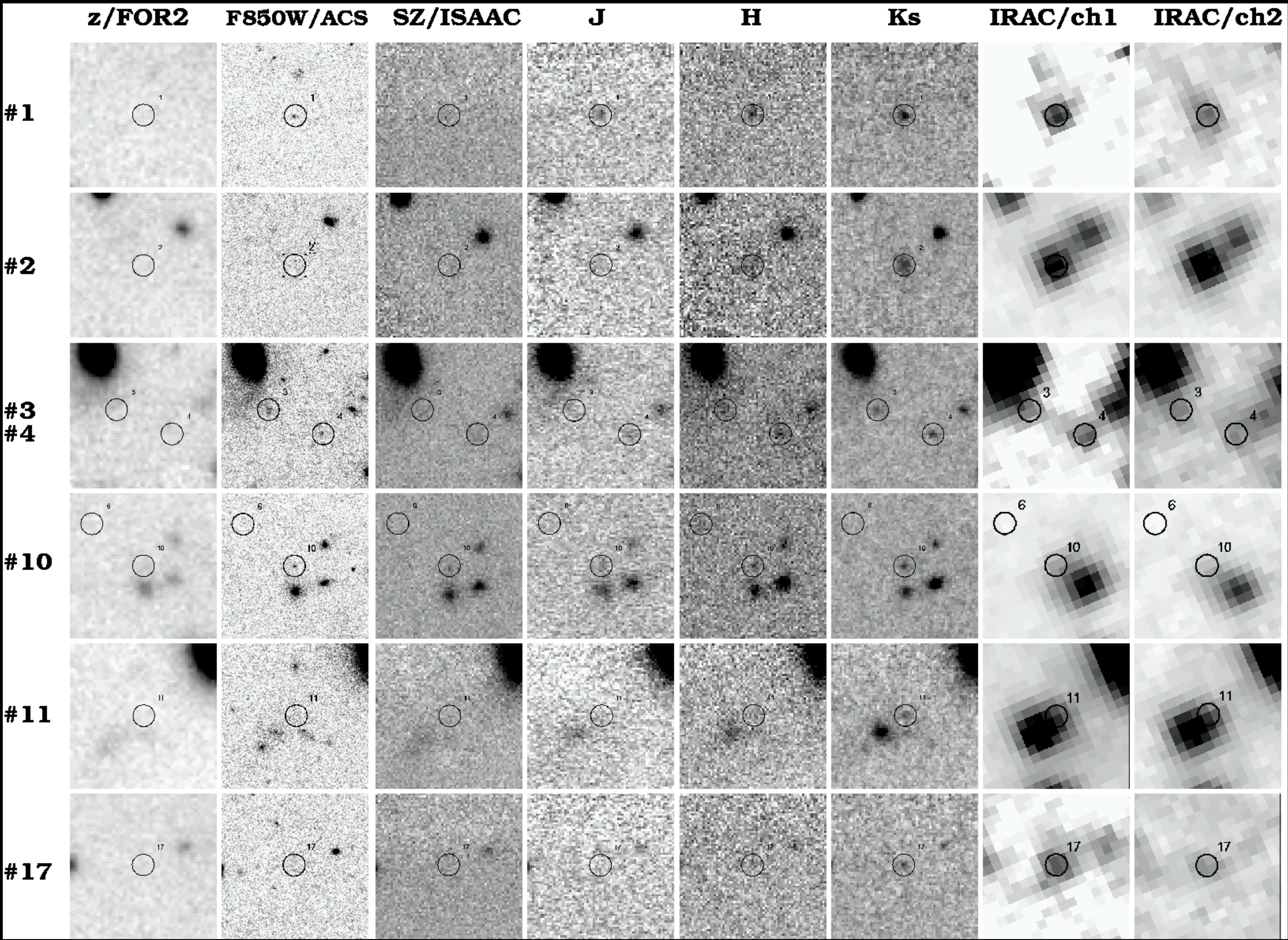
EROs & ambiguous SEDs



A1835

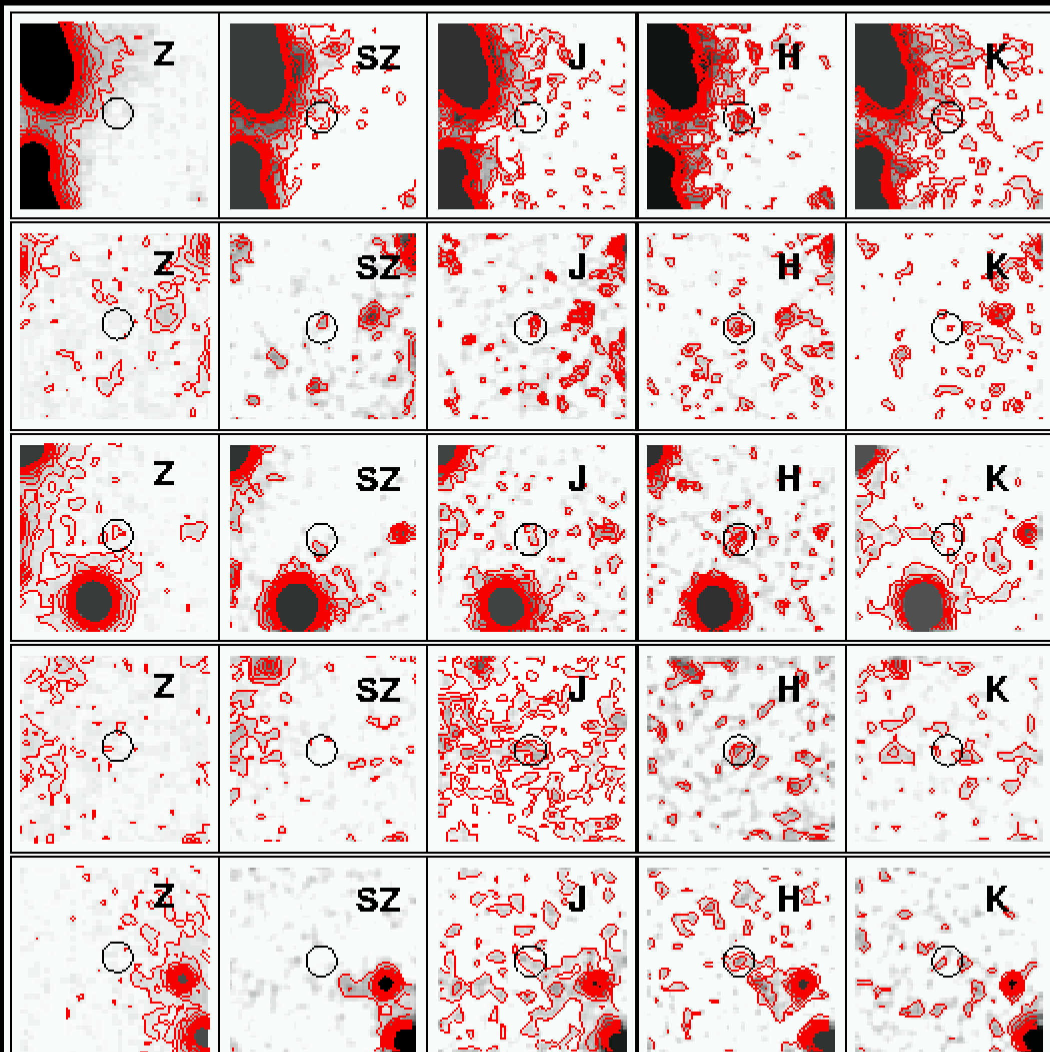
0.5 mags variability in SZ band

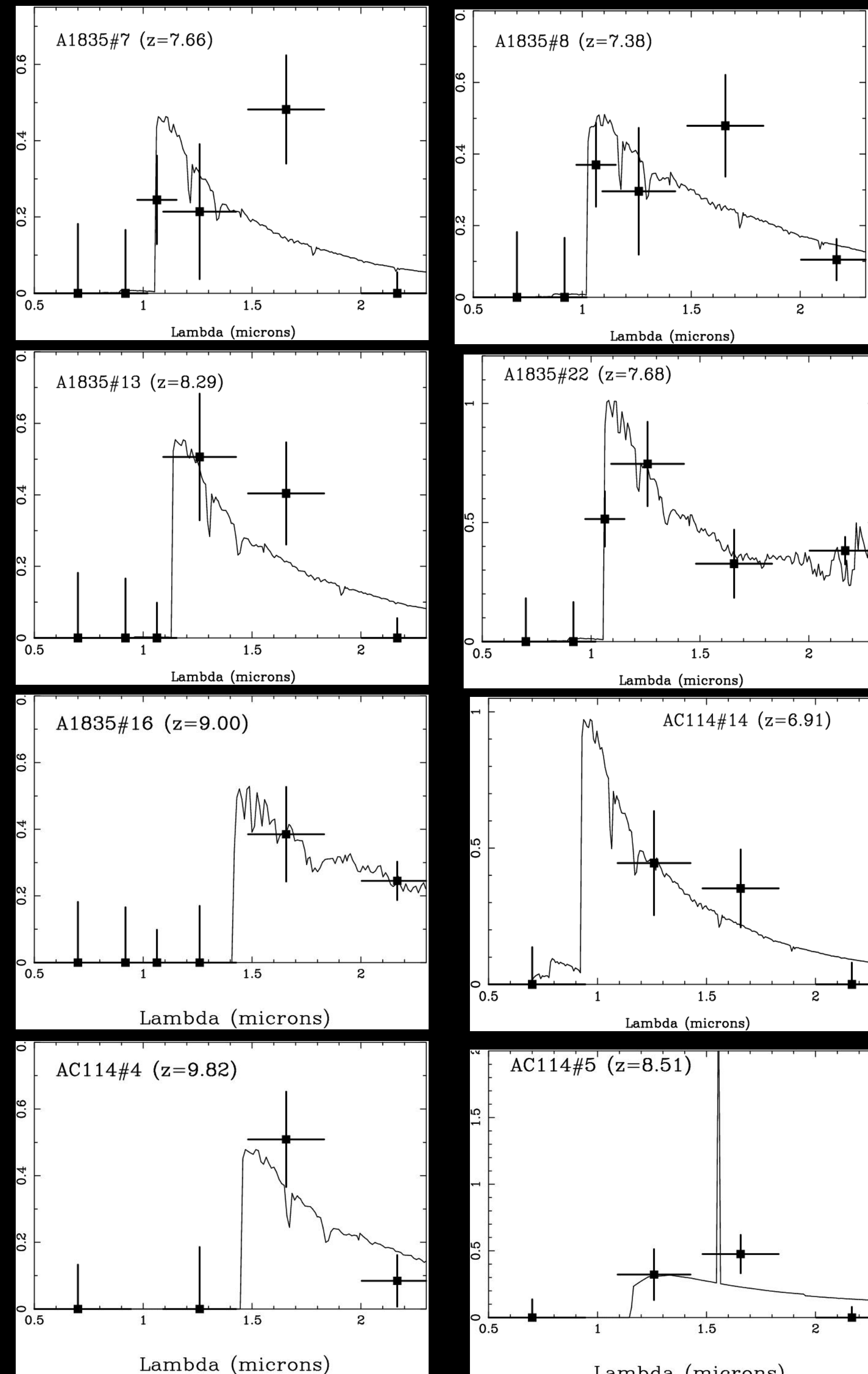




z/FOR2
F850W/ACS
SZ/ISAAC
J
H
Ks
IRAC/ch1
IRAC/ch2
#1
#2
#3
#4
#10
#11
#17

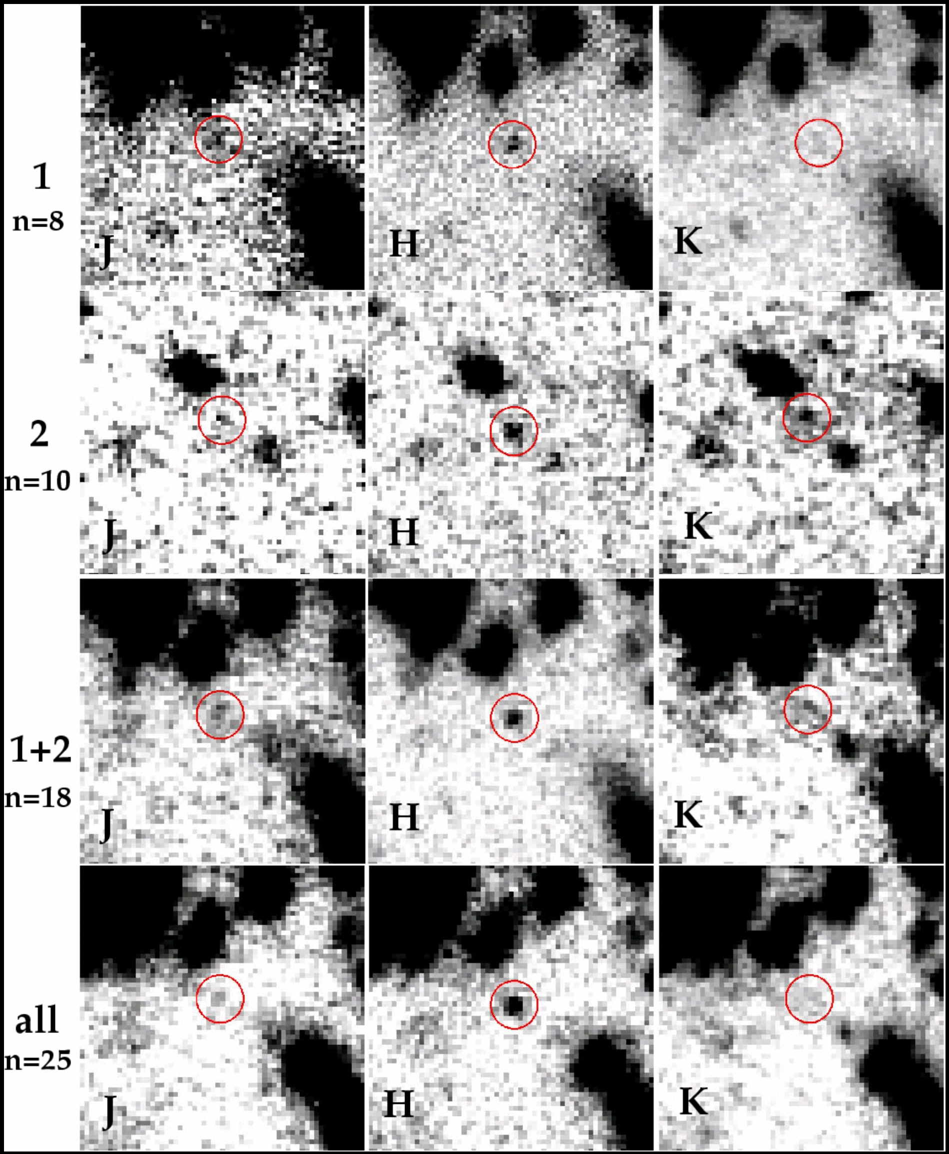
Some examples in A1835:





Examples of SEDs for faint sources in A1835 & AC114

Stacked images of high-z candidates



Corrections applied to these data

- **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)

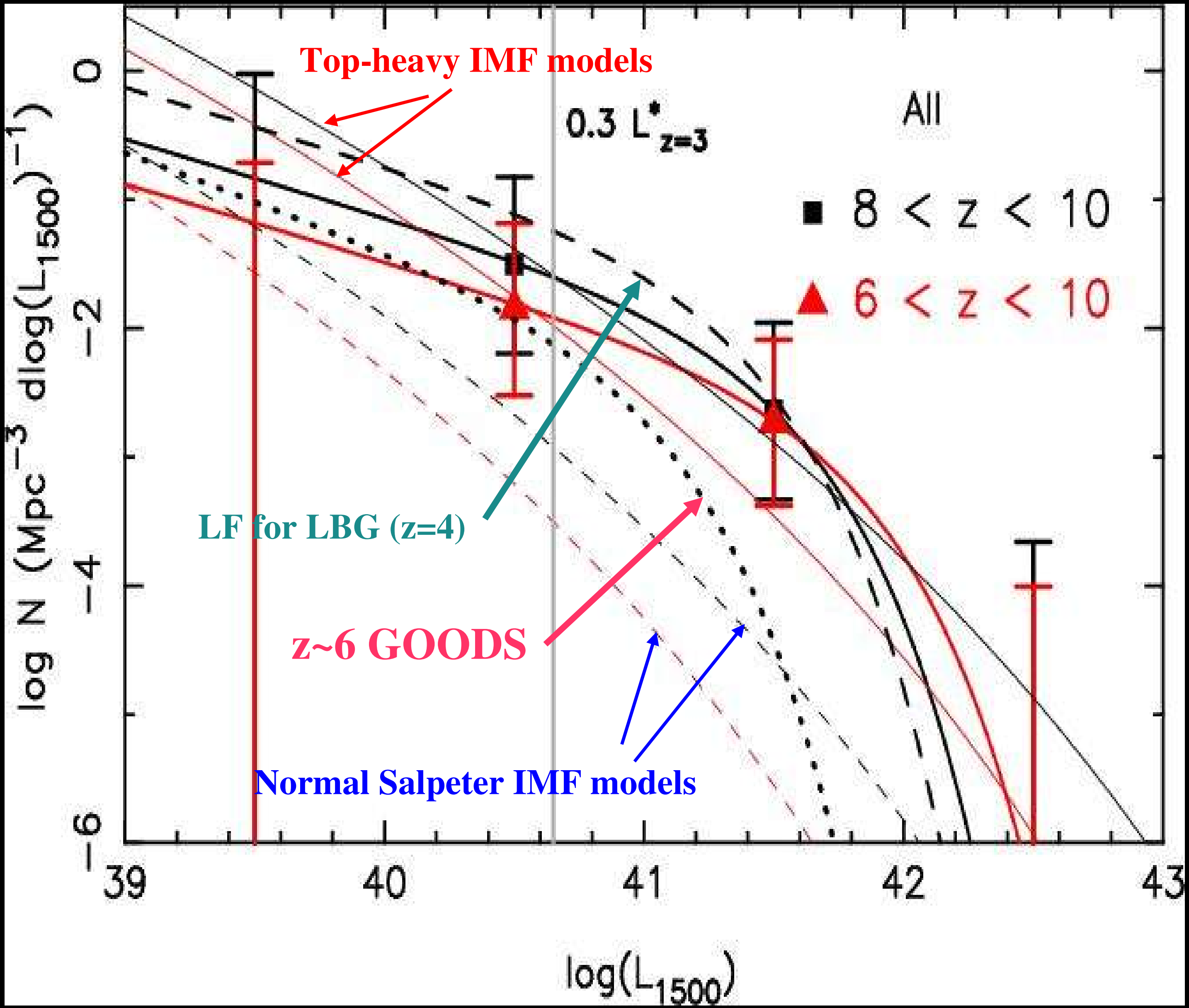
$$\eta\ (H_e, z) = \frac{\int_{\Delta\Omega} \frac{N(H_e, z)}{M(\Omega, z)} C(H_o) d\Omega}{\int_{\Delta\Omega} N(H_e, z) d\Omega} = $$

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

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

Luminosity Functions

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

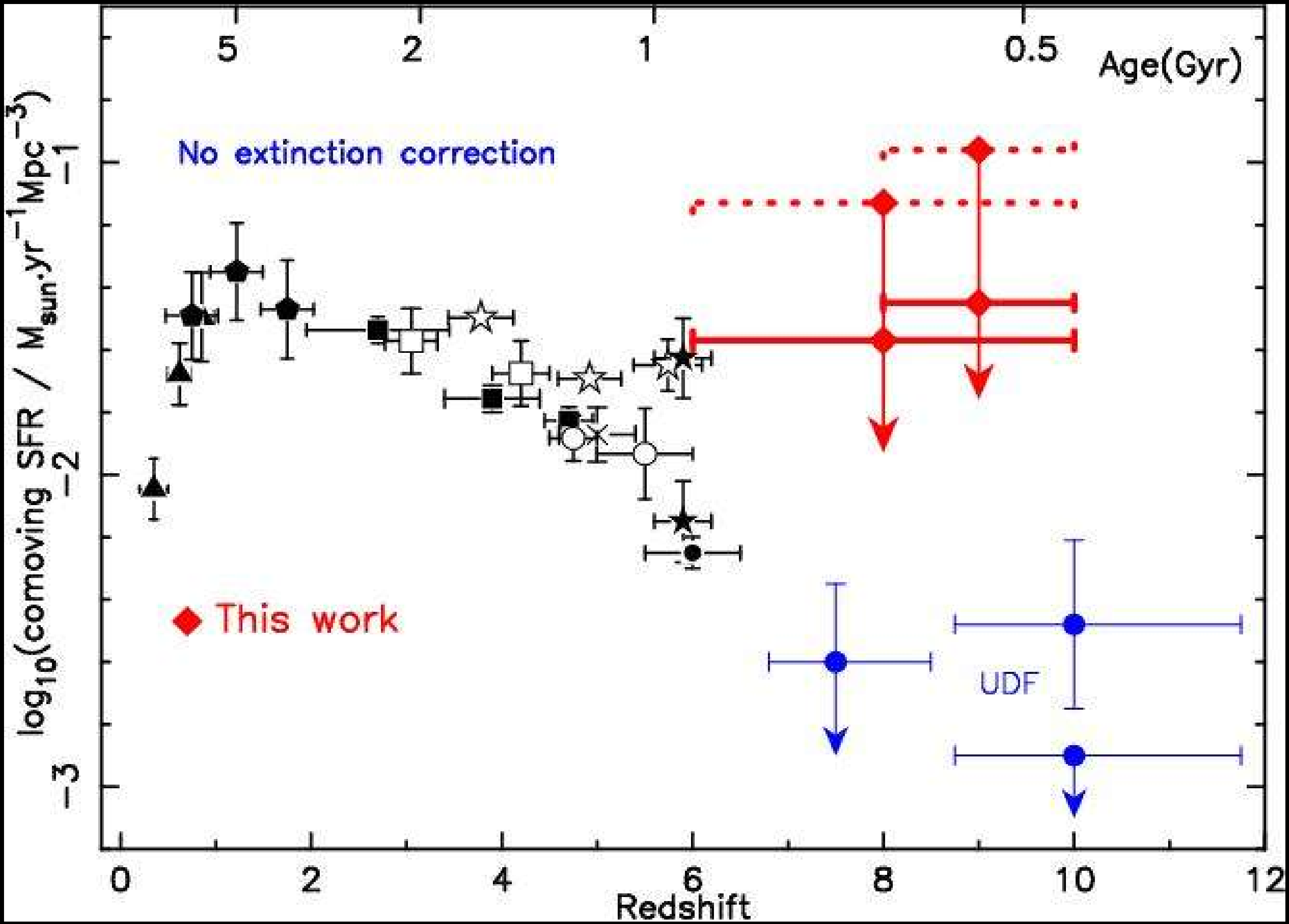


LF fit with

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.

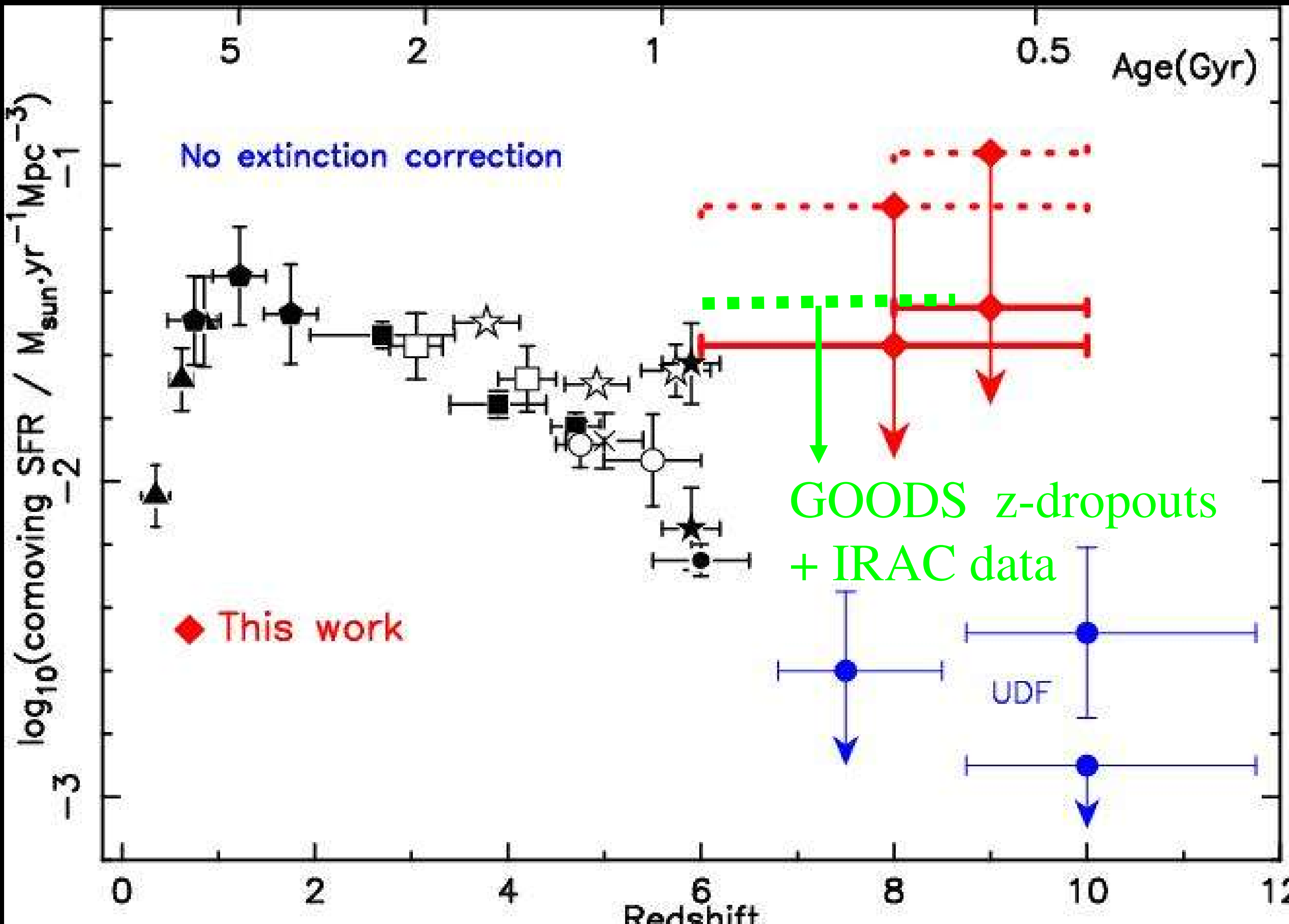
Cosmic SFR at z~6-10



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

- 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).

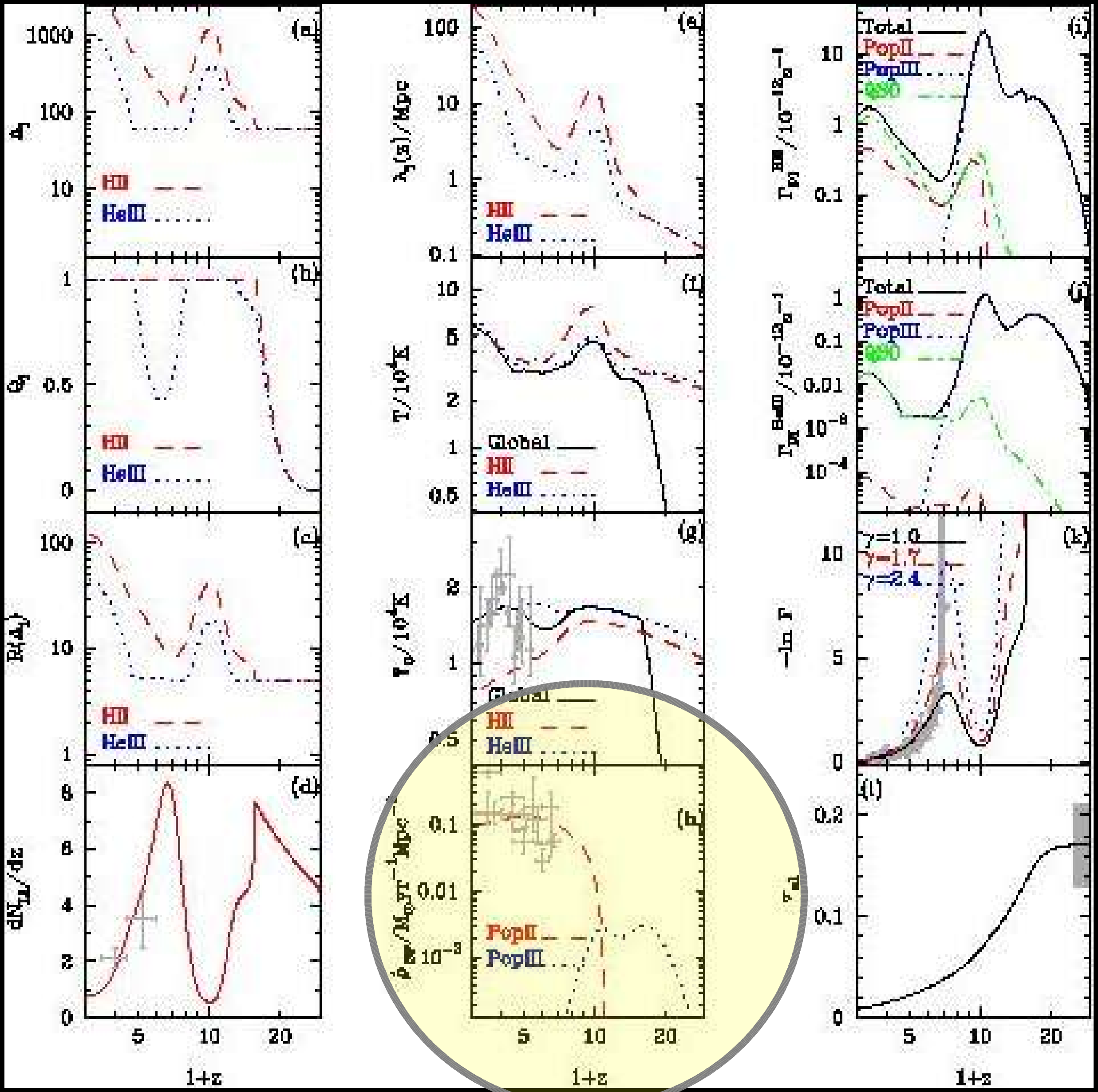
Cosmic SFR at z~6-10



- **Results in agreement with *maximum SFR density* derived from GOODS z~7 z-dropout sources with IRAC data (Labbé et al. 06)**

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

Cosmic SFR at z~6-10

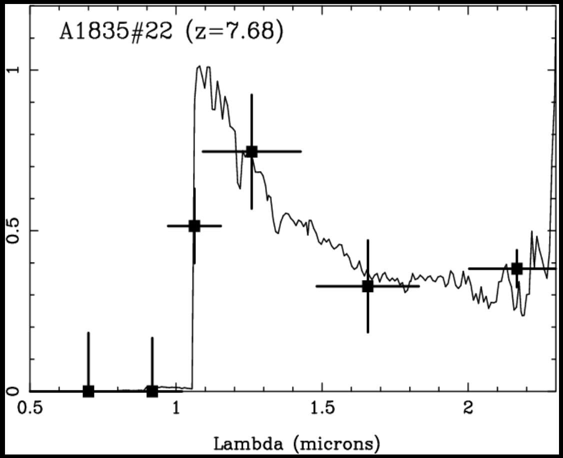


Fiducial model from Choudhury & Ferrara(2005)

- **Fair agreement e.g. with SFR density from Choudhury & Ferrara (2005) models** of consistent cosmic reionization and thermal history of IGM predicting quite high SFR up to z_{trans}~10
- **Discrepancies with other determinations in blank fields.** Some possible explanations:
  - **Sample variance**: 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

Intrinsic properties of high-z candidates

- Selection criteria based only on near-IR colors irrespective of magnitudes, *but most* photometric candidates turn out to be *fainter* than H = 23.0 (AB ~ 24.5). If z~6-10, young starbursts are typically a few 10^8 M_solar (standard IMF).
- Using Kennicut 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

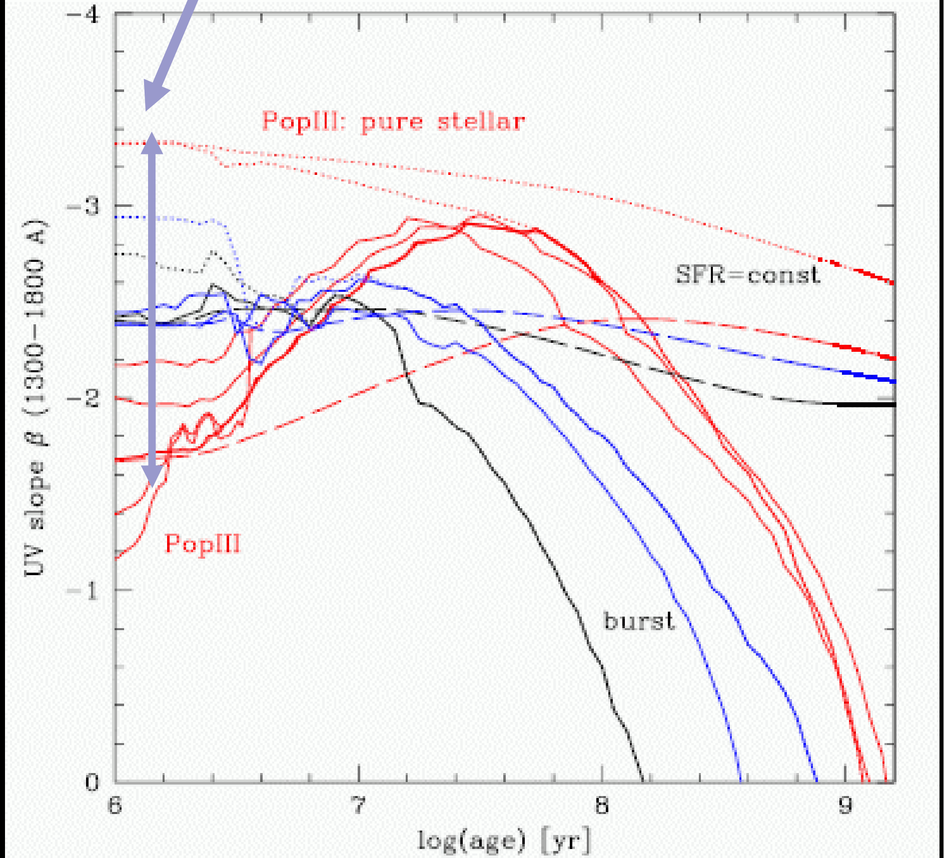


Figure 1. Temporal evolution of the UV slope β measured between 1300 and 1800 Å from synthesis models of different metallicities and for instantaneous bursts (solid lines) and constant SF (long dashed lines). Black lines show solar metallicity models, red lines metallicities between $Z = 10^{-5}$ and zero (PopIII), blue lines intermediate cases of $Z = 0.004$ and 0.0004. The dotted lines show β if nebular continuous emission is neglected, i.e. assuming

Intrinsic properties of high-z candidates

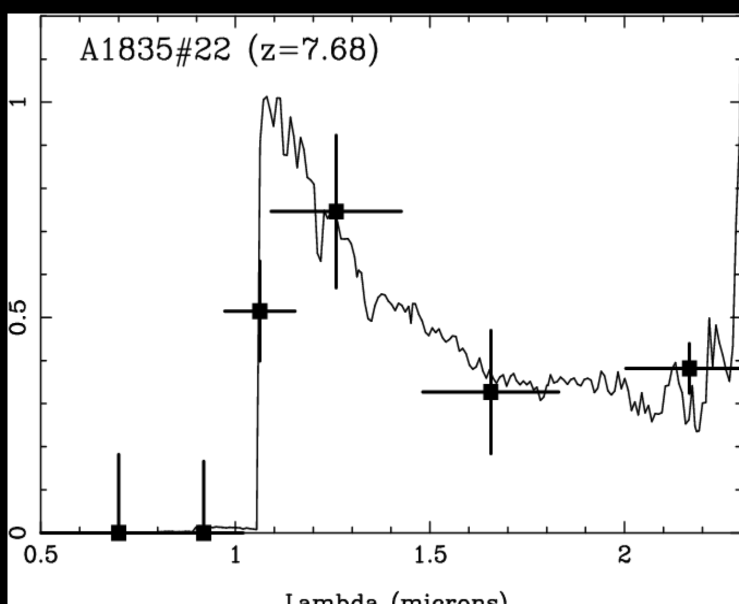
candidates in lensing fields

From Schaerer & Pello 05

- **Very blue UV slope:**
  (β~ -1.5 to -3.5)

  Cf. GOODS, UDF… surveys

==> INDICATION OF LITTLE OR NO EXTINCTION



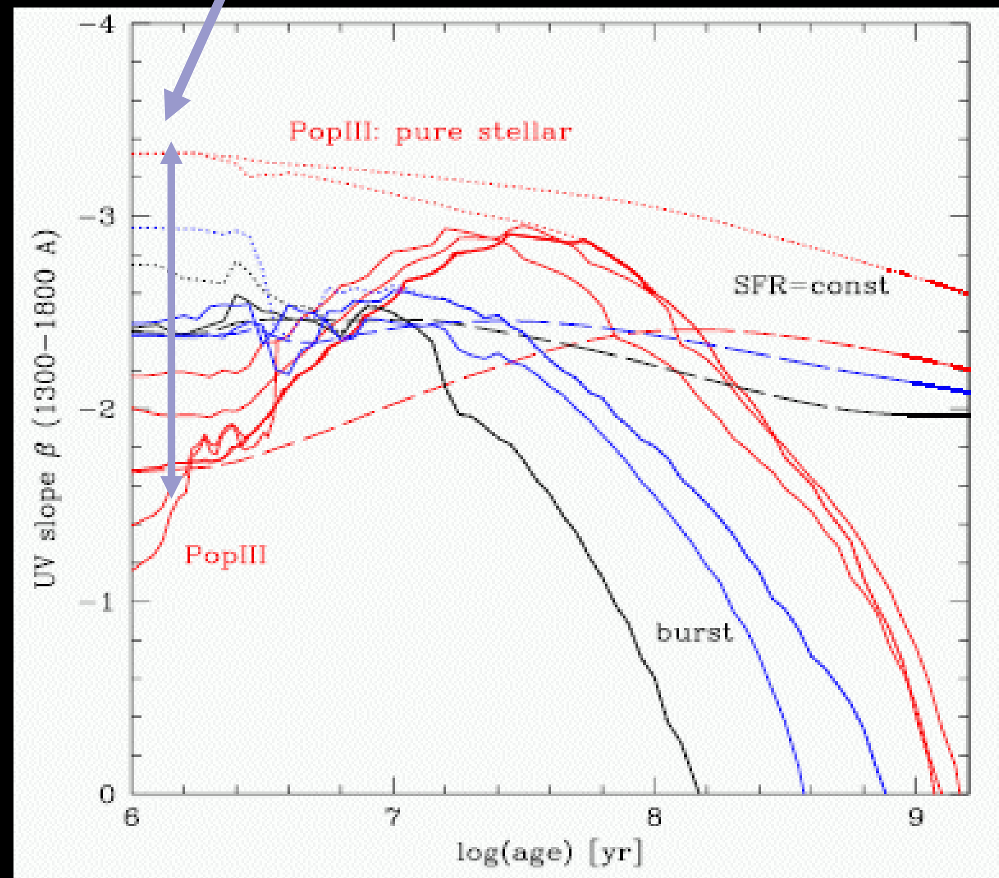
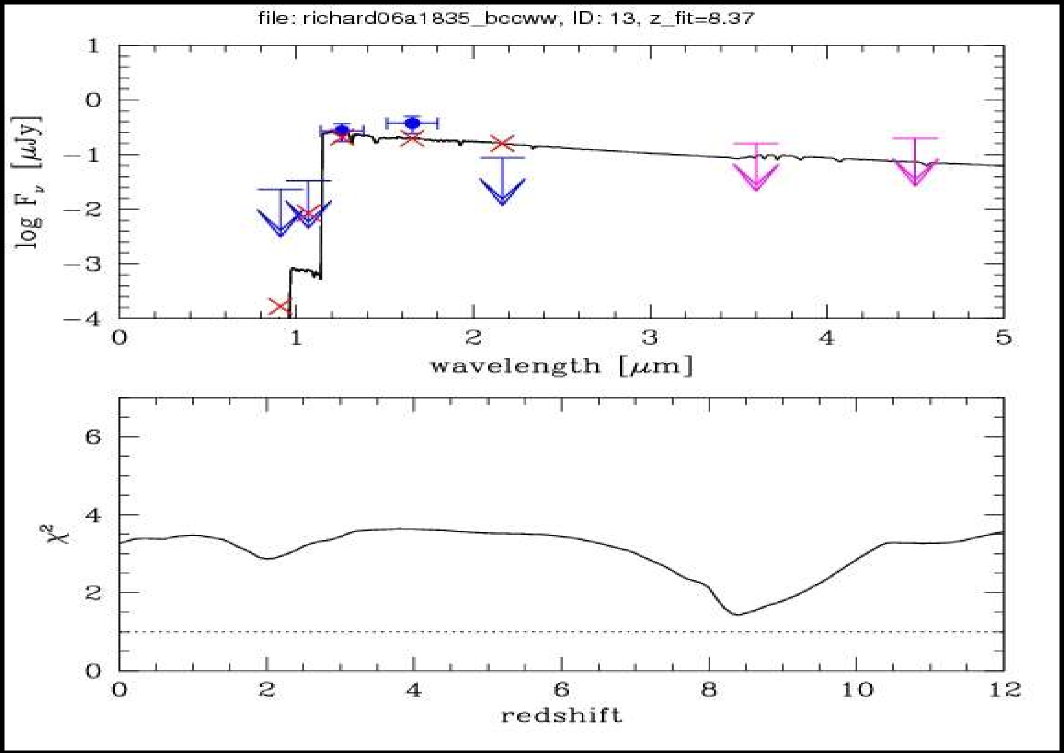
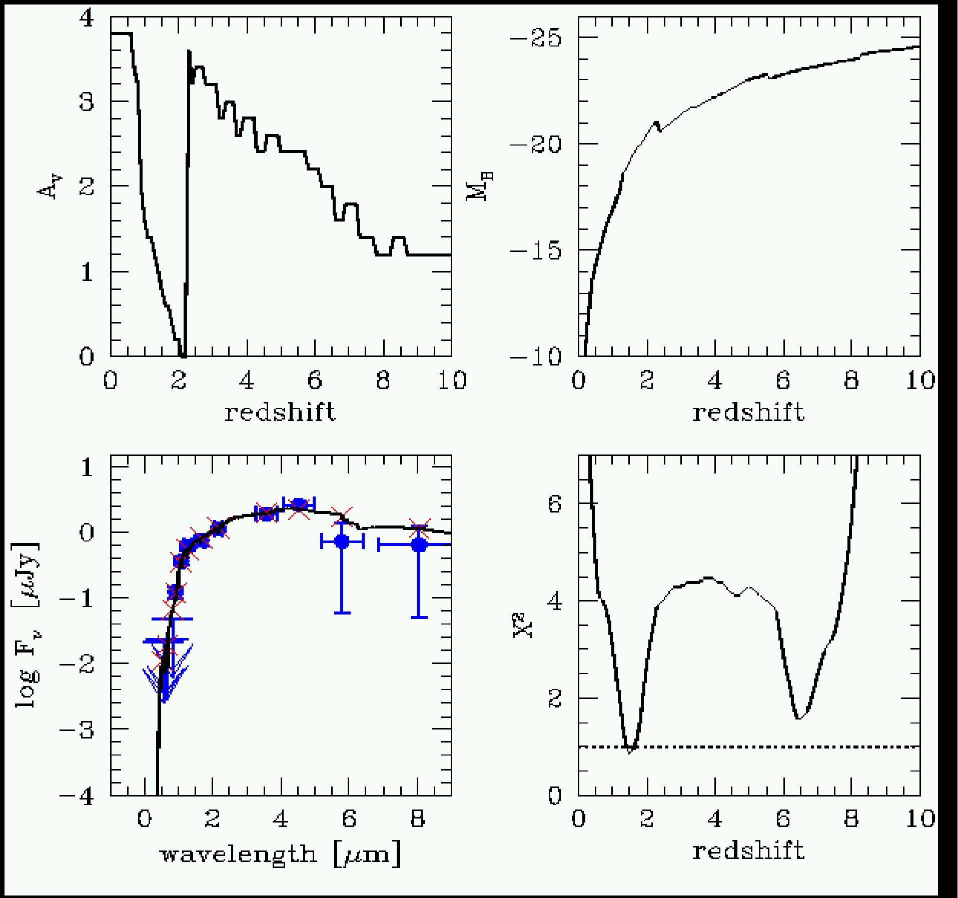


Figure 1. Temporal evolution of the UV slope β measured between 1300 and 1800 Å from synthesis models of different metallicities and for instantaneous bursts (solid lines) and constant SF (long dashed lines). Black lines show solar metallicity models, red lines metallicities between $Z = 10^{-5}$ and zero (PopIII), blue lines intermediate cases of $Z = 0.004$ and 0.0004. The dotted lines show β if nebular continuous emission is neglected, i.e. assuming pure stellar emission. Note especially the strong degeneracies of

Intrinsic properties of high-z candidates

- **ACS/HST** z-band observations (non-detection $Z850_{AB} > 28.$ to 28.3) confirm « dropout » nature of z>~7 candidates behind A1835 and AC114.
- **IRAC/Spitzer** detection of brightest objects (ERO) between 3.8 and 8 µm --> new constraints on their nature and redshift

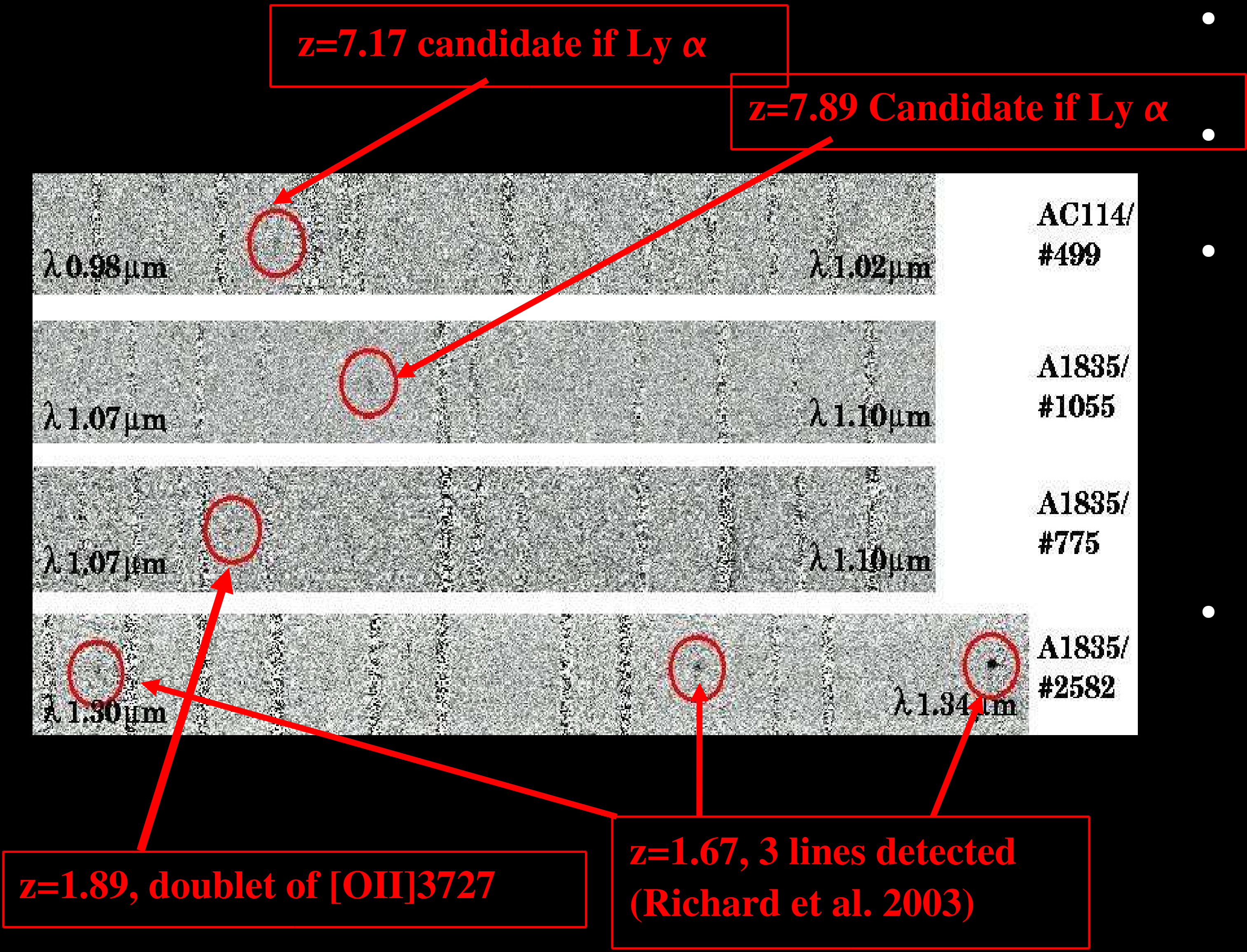




- **IRAC/Spitzer:** high-z candidates not detected as expected: beyond the detection limits if high-z or spurious

(Schaerer et al. 06, Hempel et al. 06)

Spectroscopic follow-up. Present state of the art



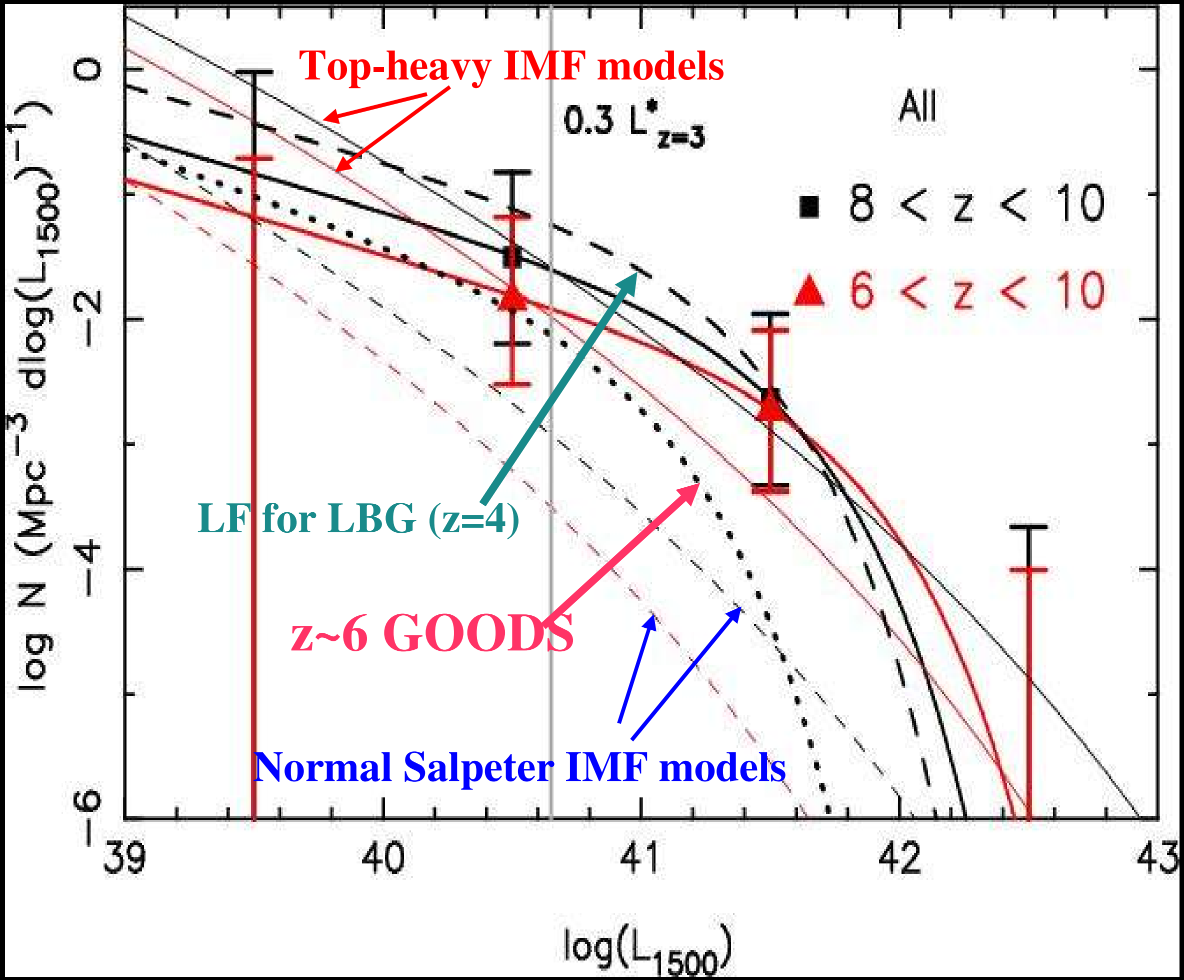
- **Ongoing Spectroscopic follow-up with ISAAC/VLT**
- **We explore the 0.9-1.4 microns domain, R~3100.**
- **Targets: 2 priority candidates in AC114, and 7 in Abell 1835 (4 ``first priority'‘ targets and 3 secondary ones). From this sample of 9 targets, 2/3 of the objects observed display emission lines.**
- **A large majority of our high-z candidates still need to be (re)confirmed, either by a redetection of a faint emission line, or by the non-detection of other lines expected at low-z.**

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


Discussion &
Perspectives

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 same factor (dilution).**



- *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":**

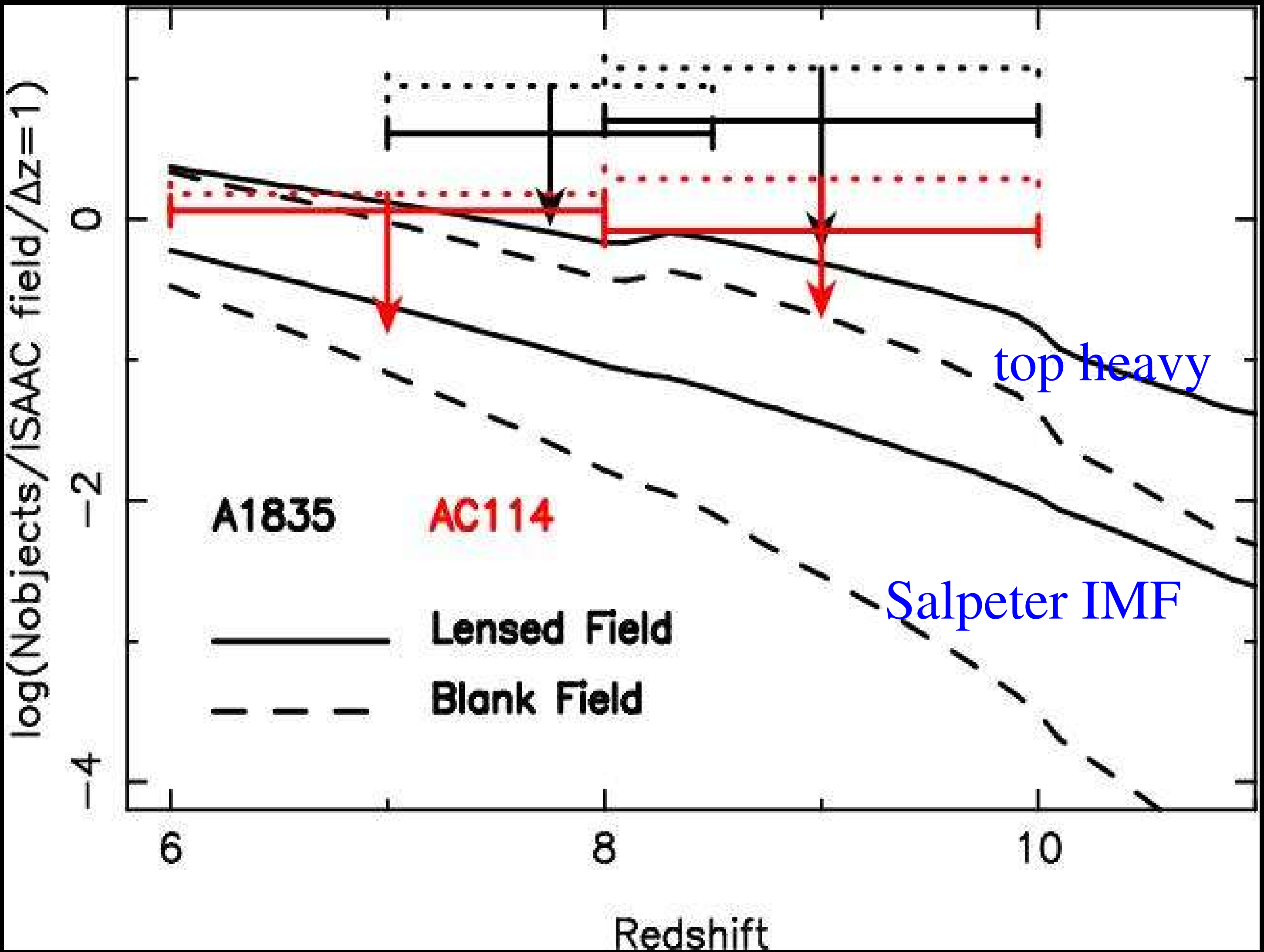
$$t_* (1+z)/(t_H(z) - t_H(17))$$

t_H(z): age of the universe at z

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

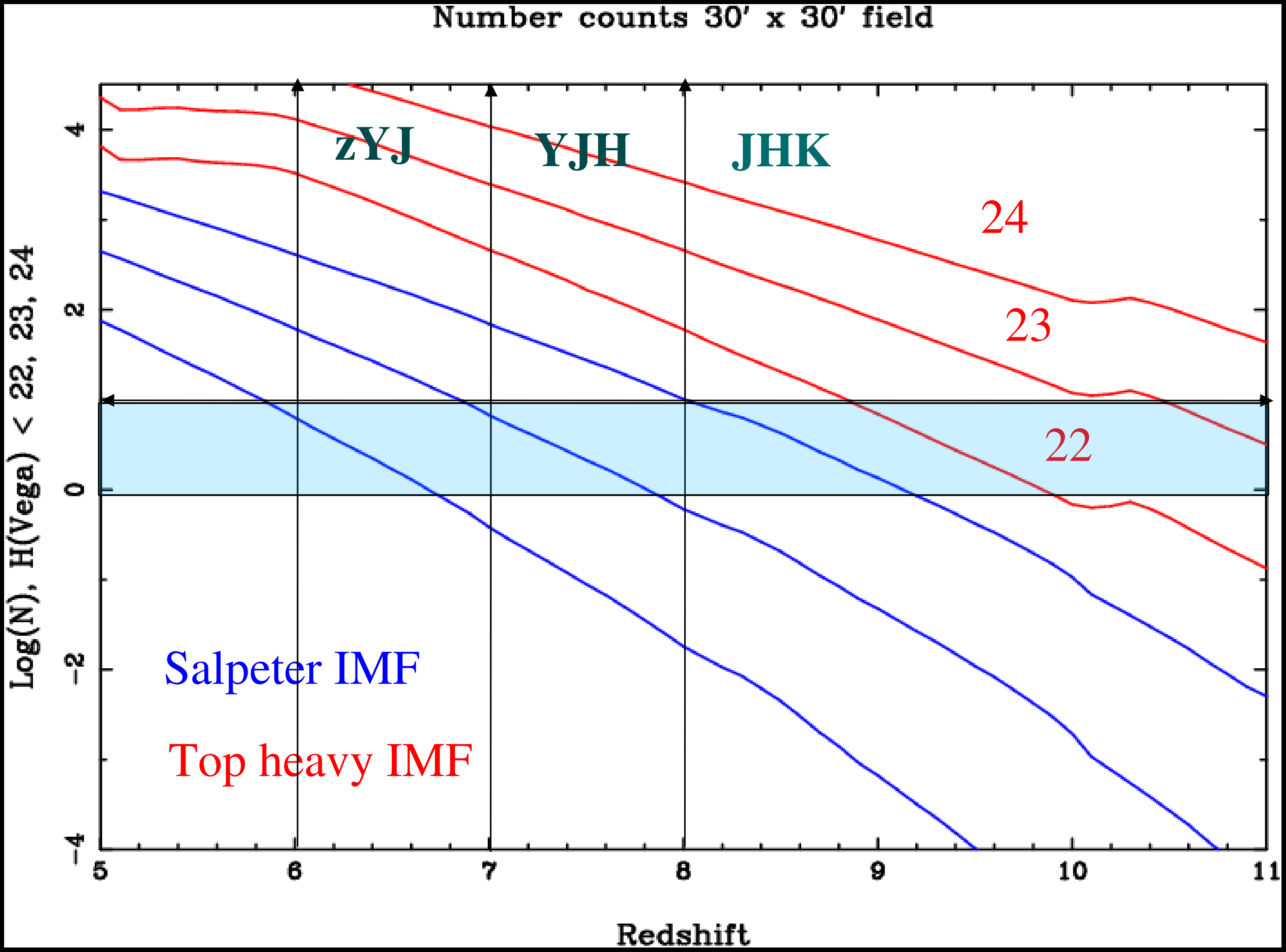
$$N_{lensed}(>L) = N(>L) \times \mu^{\alpha-1}$$ **with** $$\alpha = -d(log n)/d(log L)$$

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



- **Number of sources with H<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**

Lensing or Blank fields?



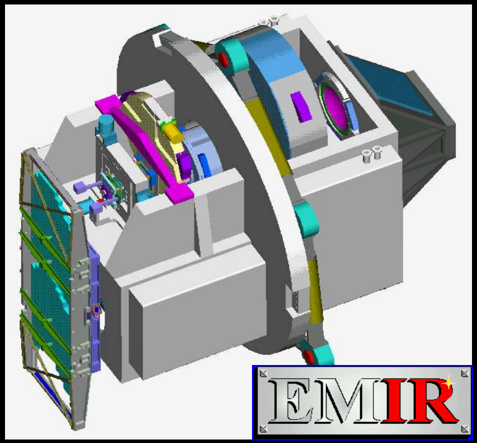
- Number counts within dz=1, for different depth in the H-band.
- FOV similar to CFHT/ WIRCAM

Constraining the bright end of the LF at z>~7 with a « reasonable » exposure time...

WIRCAM/ WUDS, UKIDSS, ...

A new generation of near-IR spectrographs

The GOYA/EMIR Survey at GTC



GTC -EMIR (~2008):

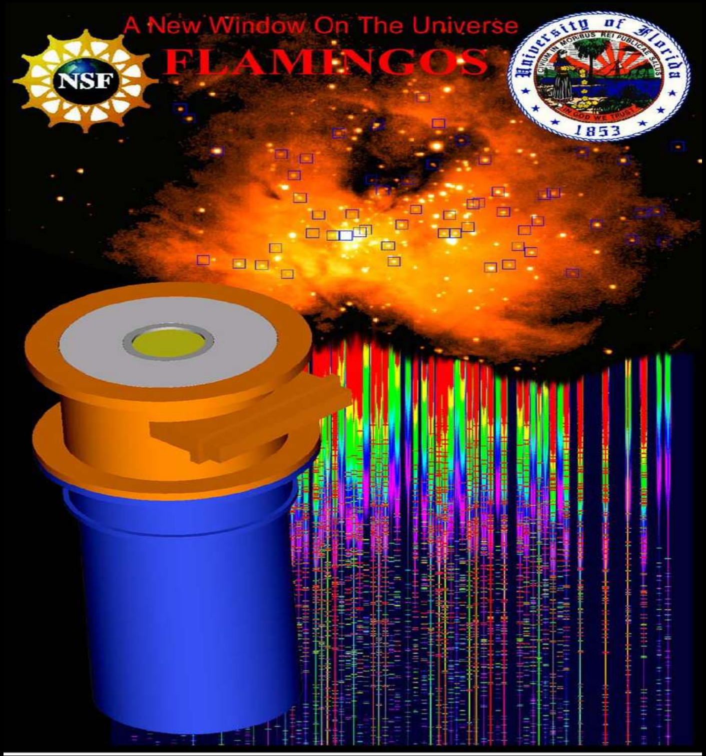
Spectral Range	0.9-2.5µm[1.1-2.5µm]	MOS mode	
Top priority	MOS in K band	FOV	6x4 arcmin (~50 slitlets)
Spectral Resol.	5000,4250,4000 (JHK)	Sensitivity	K~20.1 in 2h @ S/N=5 (continuum)
Spectral coverage	1 single window/exp.		$1.4x10^{-18}$ erg/s/cm^2/Å @ S/N=6 (line)
Detector	HAWAI2 2048^2	Image mode	
Plate Scale	0.2 arcsec/px	FOV	6x6 arcmin
Image quality	θ_{80} < 0.3 arcsec	Sensitivity	K~22.8 in 1h @ S/N=5 in 0.6 arcsec aperture

Gain : a factor of ~50 in lensing clusters with respect to ISAAC/VLT

• **Similar Instruments:**

• *Subaru/MOIRCS (2007A - shared risk)*

• *GeminiS/Flamingos2 (~2007 commissioning)*

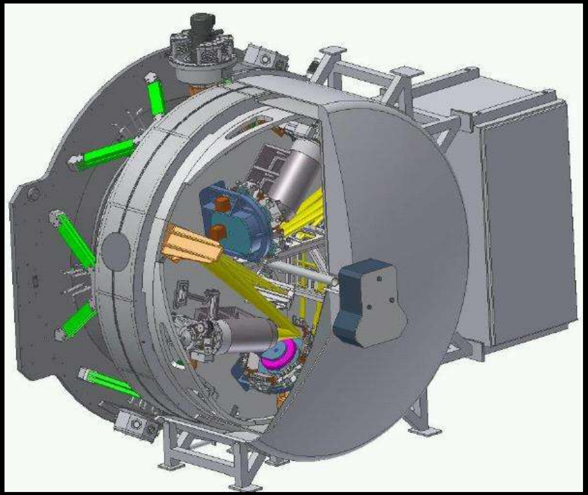


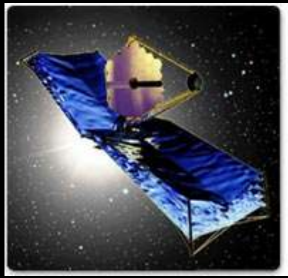
VLT 2nd generation (t>~2010)

kmos High priority for ESO community

Requirement	Baseline Specification
Optical Throughput	J>20%, H>30%, K>30%
Wavelength coverage	1.0 to 2.5 μm
Spectral Resolution	R~3400,3800,3800 (J,H,K)
Number of IFUs	24
Extent of each IFU	2.8 x 2.8 sq. arc seconds
Spatial Sampling	0.2 arc seconds
Patrol field	7.2 arcmin diameter circle
Close packing of IFUs	≥3 within 1 sq arcmin
Closest approach of IFUs	≥2 pairs of IFUs separated by 6 arcsec

Table 2: Summary of baseline technical requirements for the KMOS instrument





← **JWST (>~2012)**

.... + ELTs

Summary/Conclusions

- **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**
- **Gravitational lensing clusters seem more efficient than blank fields to explore the z~6-12 domain (same photometric depth and FOV). Positive magnification bias expected from simulations + our first results.**
  - ***--> potential problem: mid-z interlopers***
- **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.**


The end