Observatoire Midi-Pyrénées
OMP

irap
astrophysique & planétologie

# Search for the FIRST GALAXIES

**R. Pelló**

**IRAP - Institut de Recherche en Astrophysique et Planétologie**

***XIème Ecole de Cosmologie : 17-22 Sep 2012 (Cargèse)***

# Outline

## 1. Looking for the first galaxies

a) Introduction

b) Theoretical considerations

c) Observable properties of the first galaxies

d) Present constraints

(based on observations)

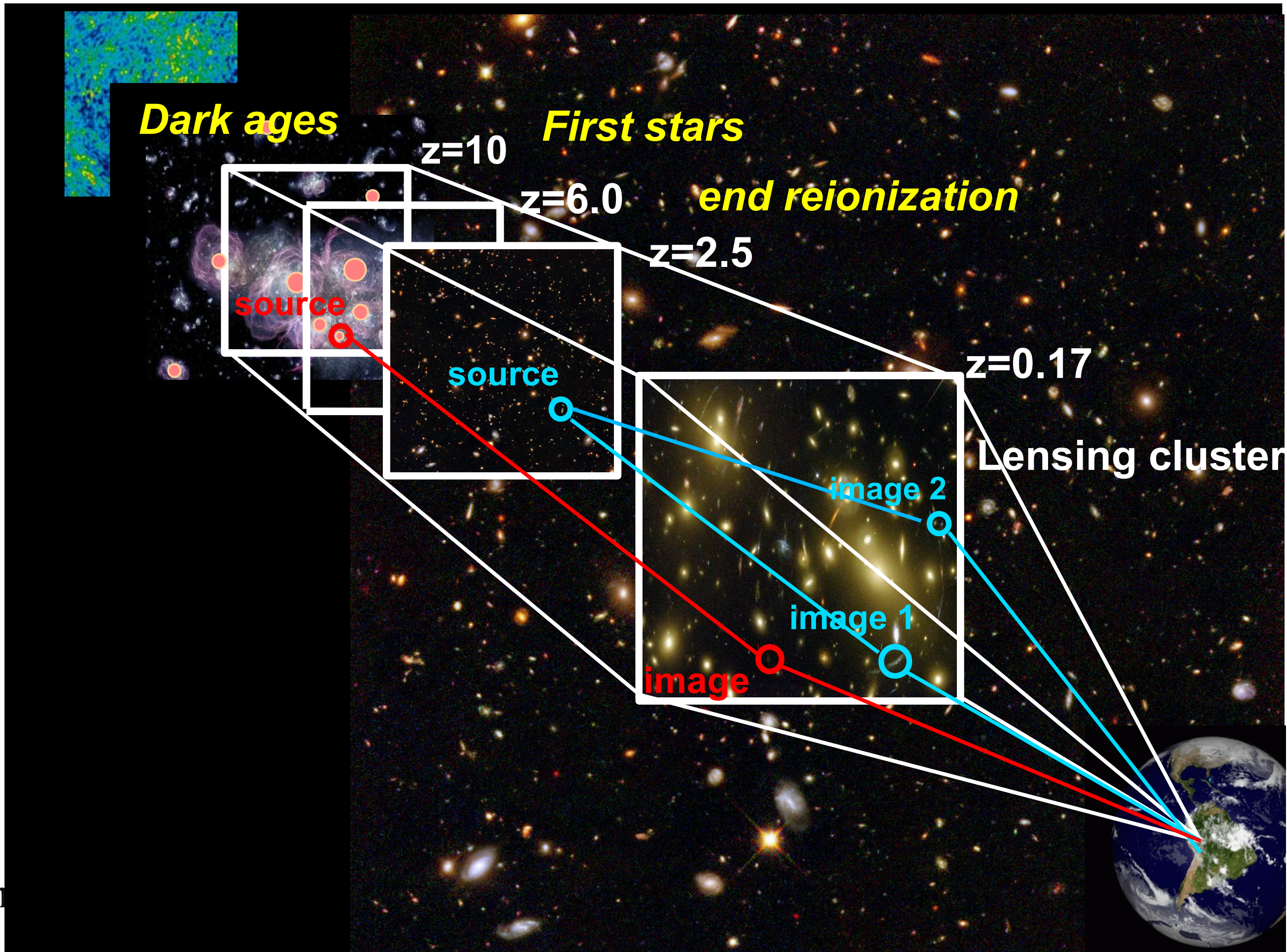
## 2. First galaxies & gravitational telescopes

a) Historical overview

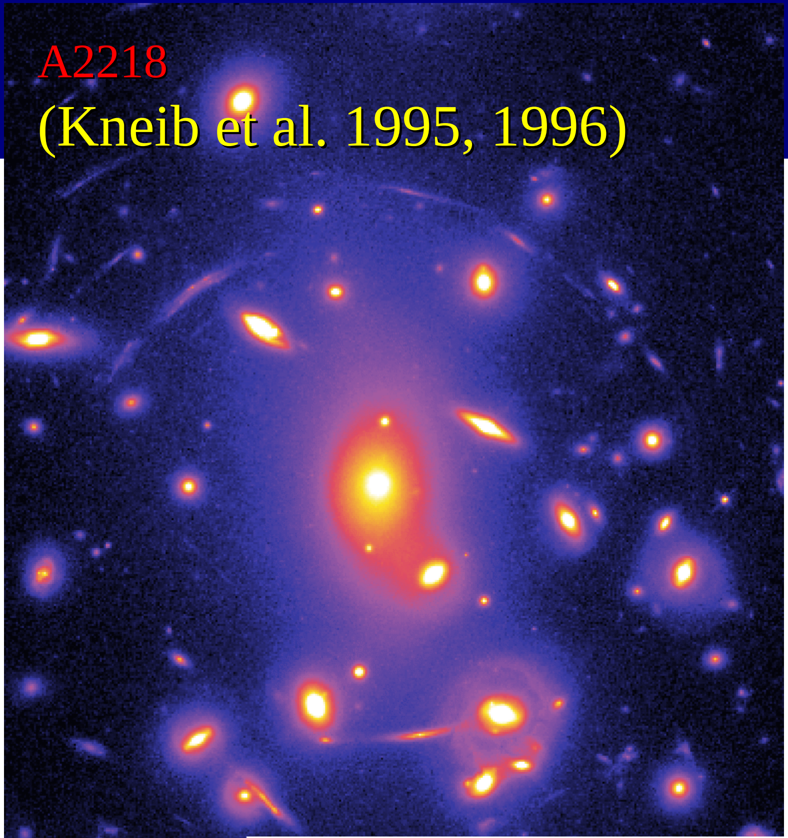
b) Lensing versus blank fields : a matter of efficiency

c) Current surveys and (expected) results

d) Future developments

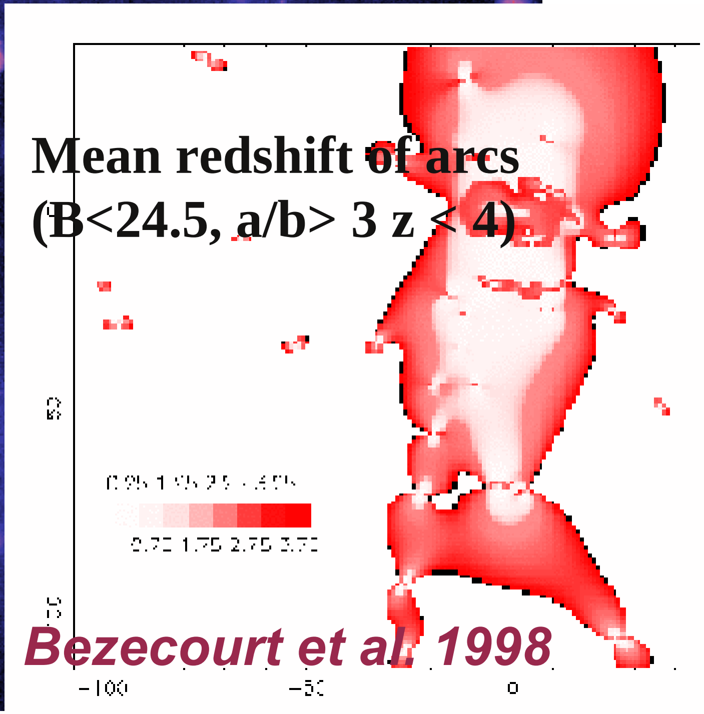


# Historical overview (I)



A2218

(Kneib et al. 1995, 1996)



**Mean redshift of arcs**
**(B<24.5, a/b> 3 z < 4)**

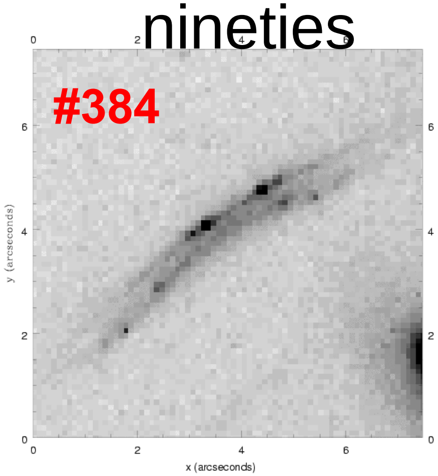
*Bezecourt et al. 1998*

## Why lensing clusters ?

- Main goal: to take 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. Gravitational Telescopes (GT)
- GTs provide access to an independent sample of high-z galaxies, less biased in luminosity than standard BF surveys.
- 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.
- Only well known lensing clusters, with a fairly well constrained mass distribution, can be used as efficient GTs.

# Historical overview (II)

- The first lensed galaxy spectroscopically confirmed at z~2 was the spectacular arc in Cl2244 (Mellier et al. 1991)
- First detailed LBG studies using lensing clusters started in the nineties



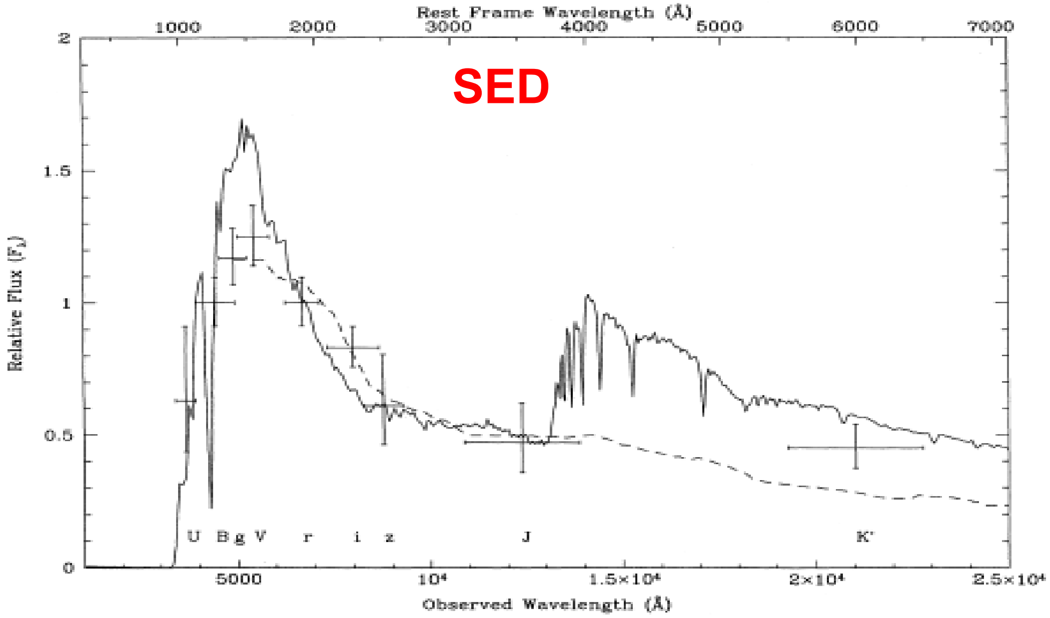
**Ebbels et al. 1996**

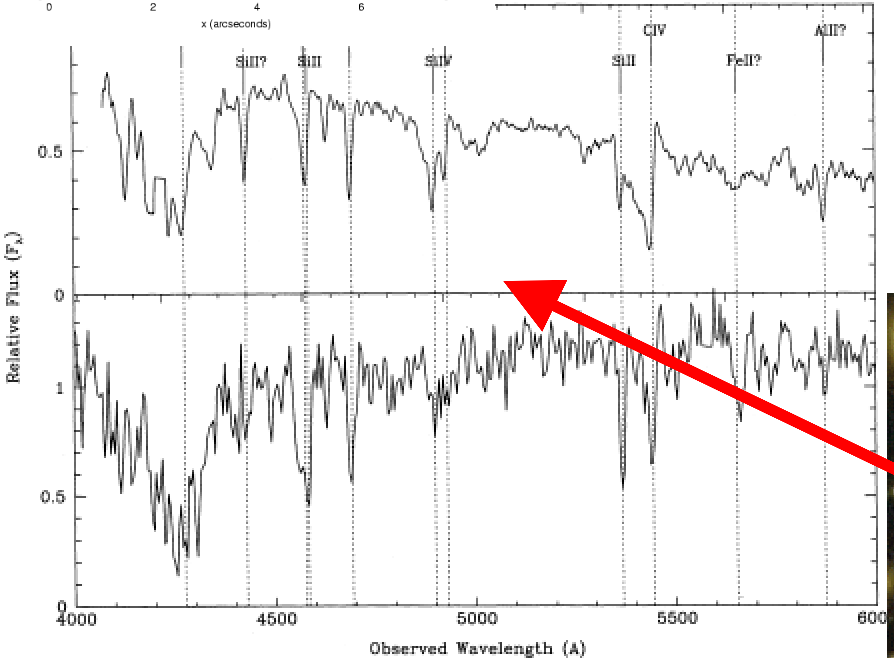
A2218

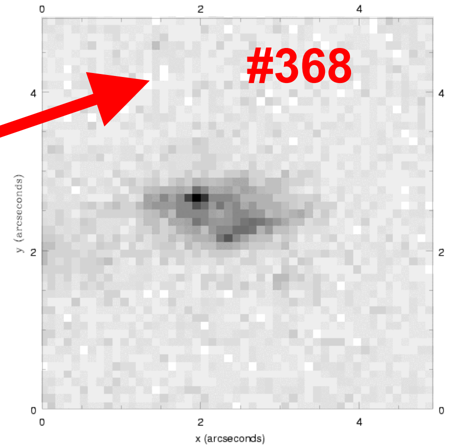
multiple-imaged

LBG at z=2.5

SFR~ 10 M_solar/yr

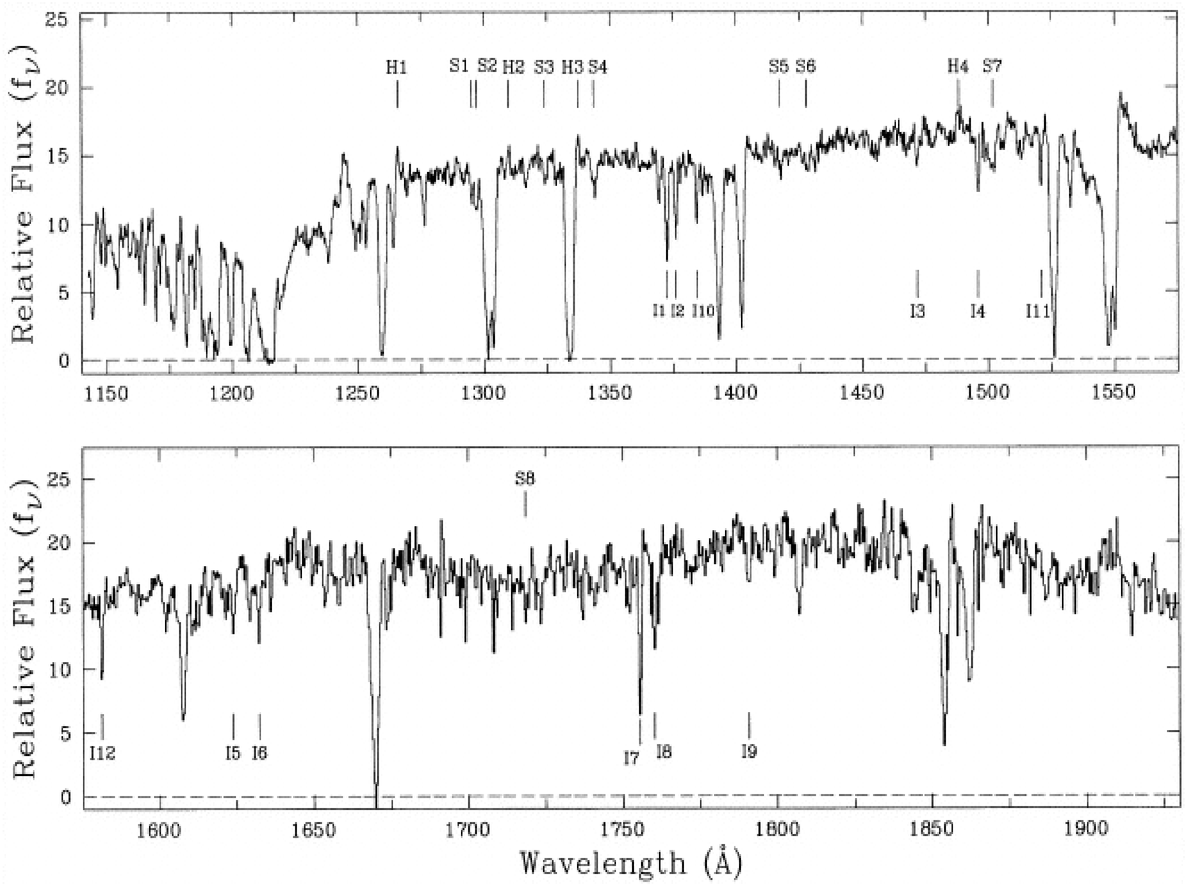






# Historical overview (III)

- Possibly the most spectacular case : the lensed source cB58 behind **MS1512 (z=2.7)**



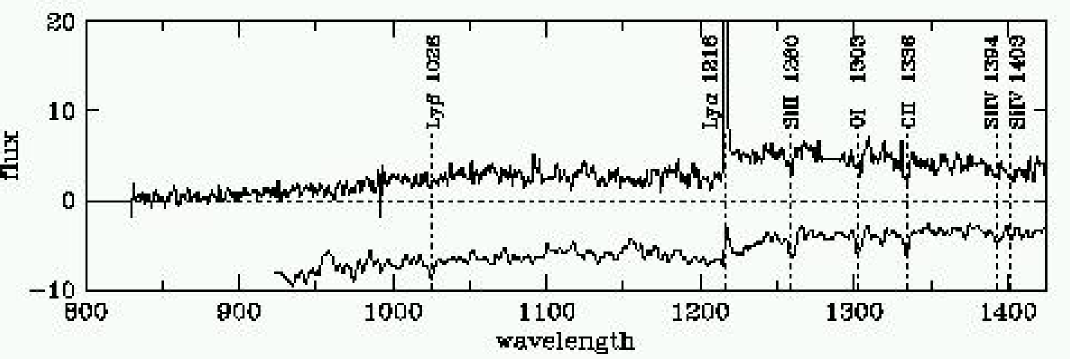
Yee et al. 1996, Ellingston et al. 1998, Seitz et al. 1998, de Mello et al. 2000, Teplitz et al. 2000, Pettini et al. 2000, Leitherer et al. 2001, Baker et al 2001, Savaglio et al. 2002, Siana et al 2008 ...

me

Magnification ~ 30
L_bol=1.5 x 10^12 L_solar
M = 1.2 x 10^10 M_solar
SFR~ 44-83 M_solar/yr (low value)
620 +/- 18 M_solar/yr (high value)
Z~ ¼ to 1/3 Z_solar

# Three z~4 galaxies behind Cl0939+47

Trager et al. 1997



L_bol=3x10^11 L_solar, SFR~30 M_sol/yr

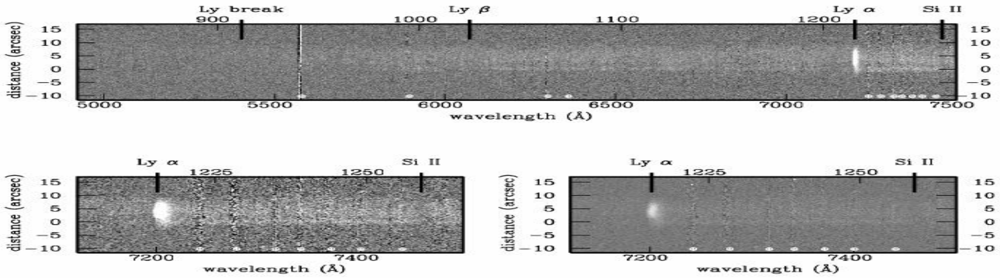
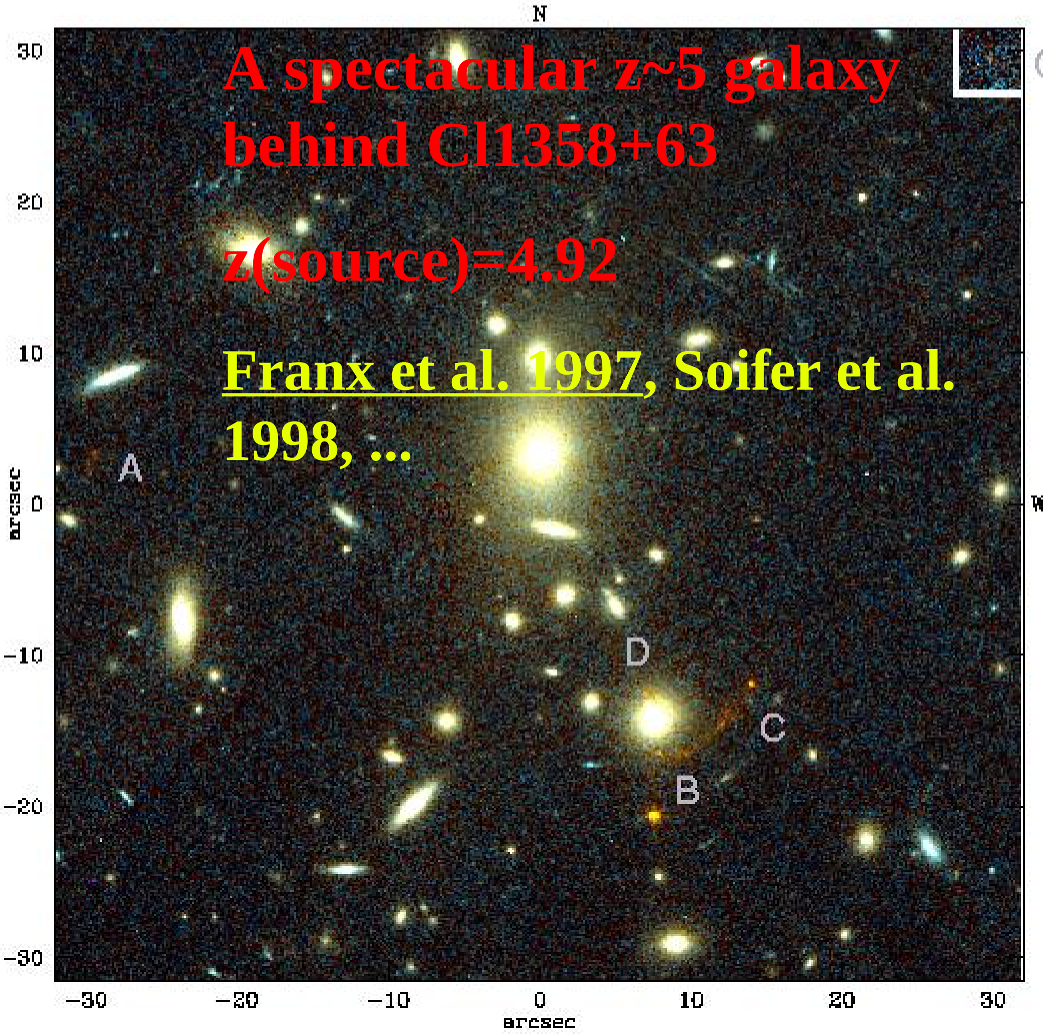


Figure 2 - Plate 2 - Franx et al

# A spectacular z~5 galaxy behind Cl1358+63

z(source)=4.92

Franx et al. 1997, Soifer et al. 1998, ...



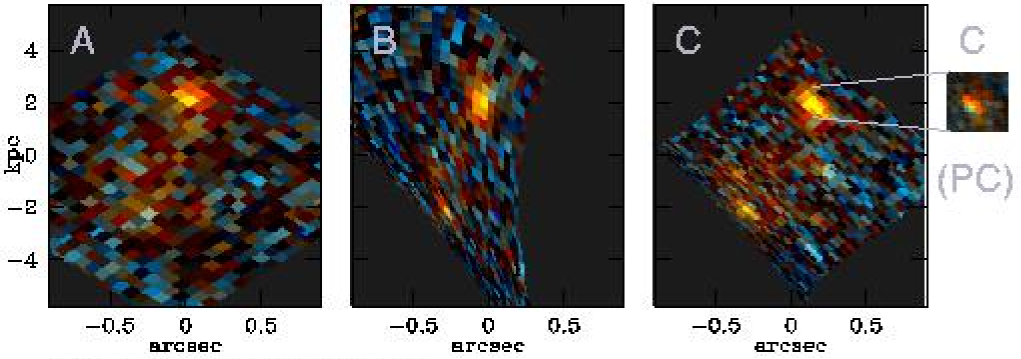
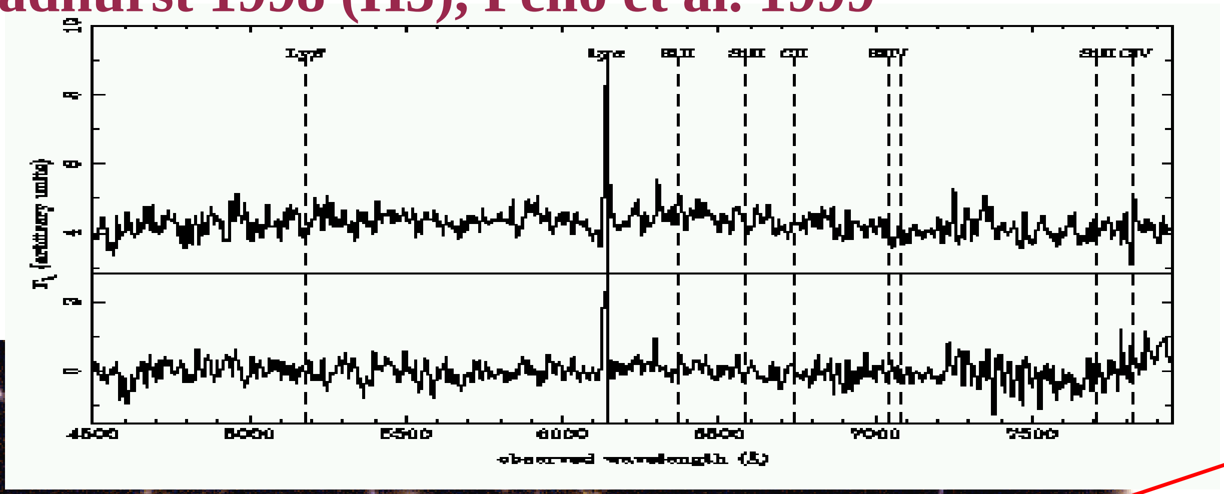


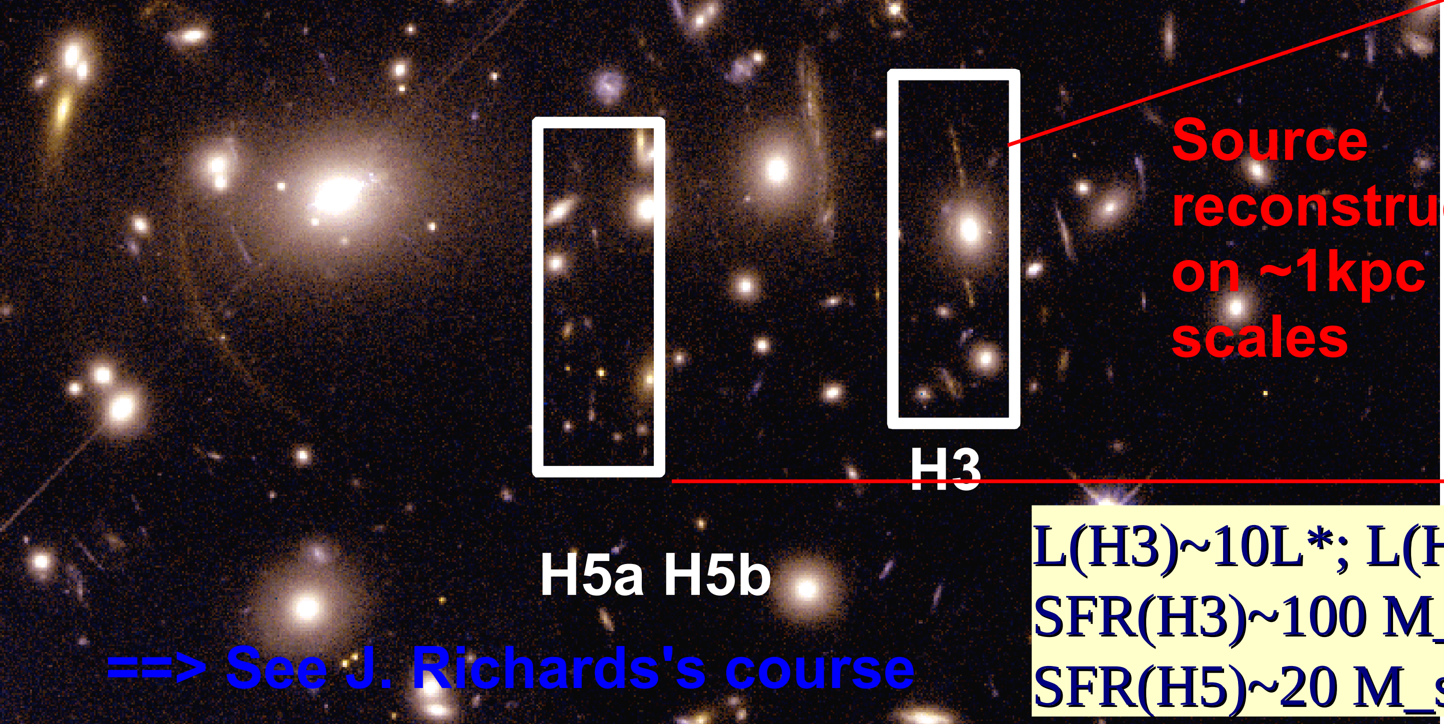
Figure 1 - Franx et al ApJ L486, L75, in press

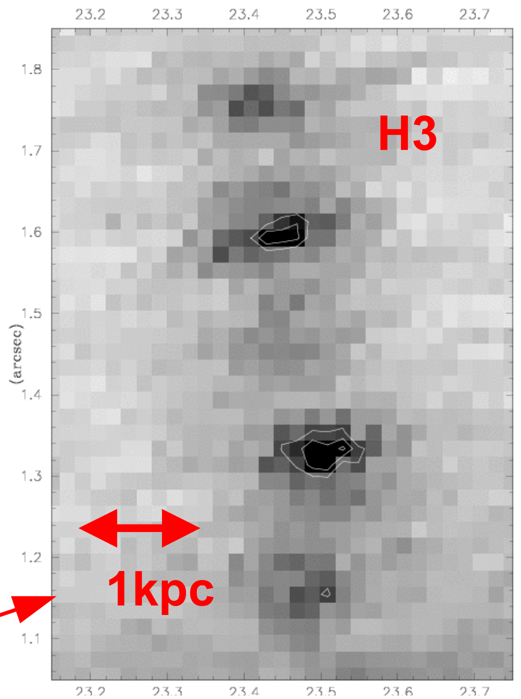
# Historical overview (V)

## Two multiple images at z=4.0 behind  A2390

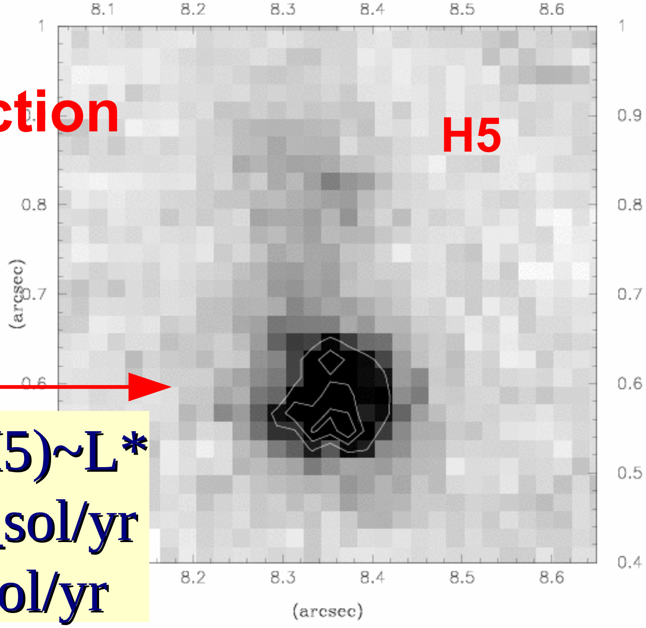
Fry & Broadhurst 1998 (H3), Pello et al. 1999







Source reconstruction on ~1kpc scales



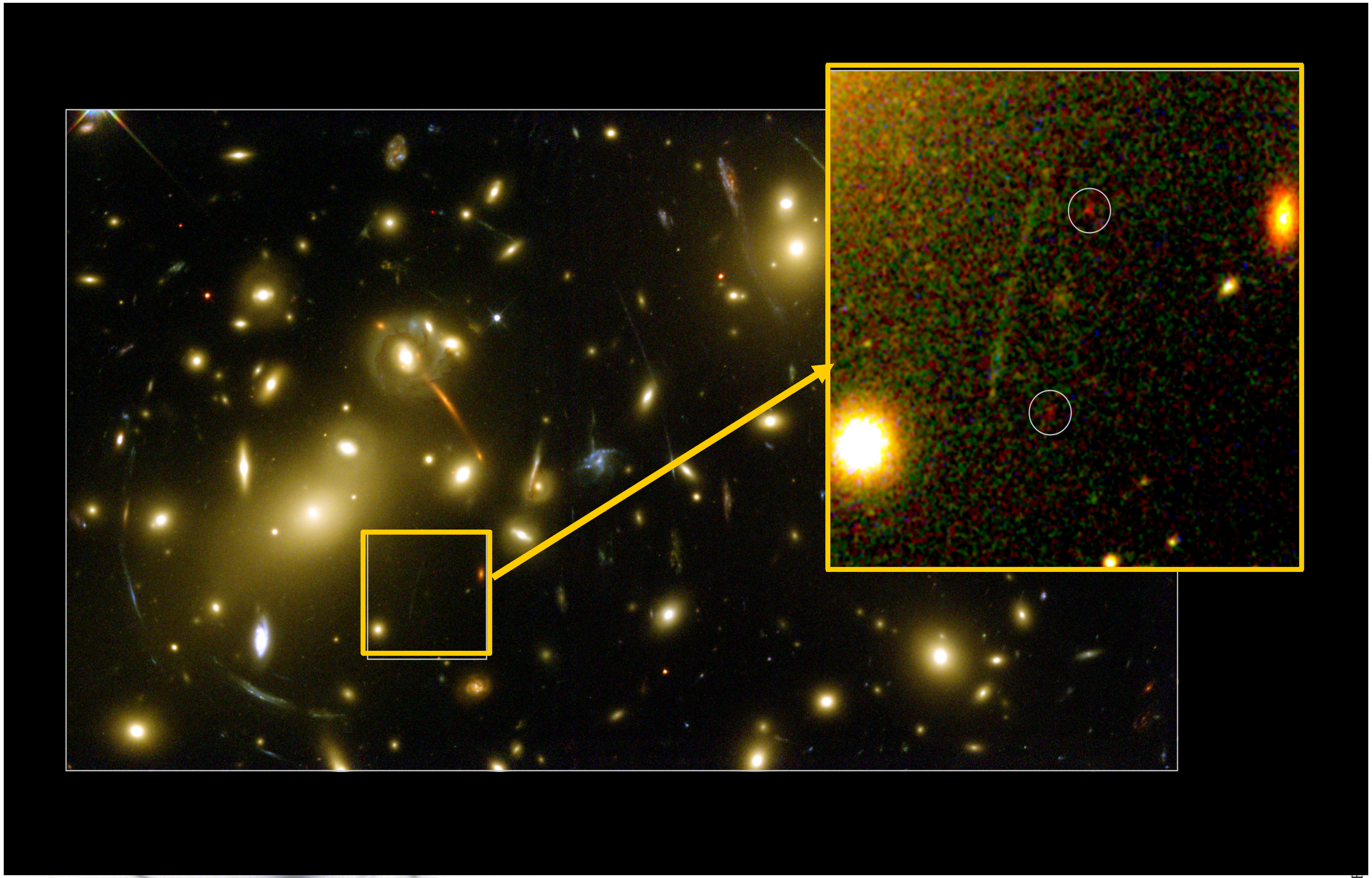
L(H3)~10L*; L(H5)~L*
SFR(H3)~100 M_sol/yr
SFR(H5)~20 M_sol/yr

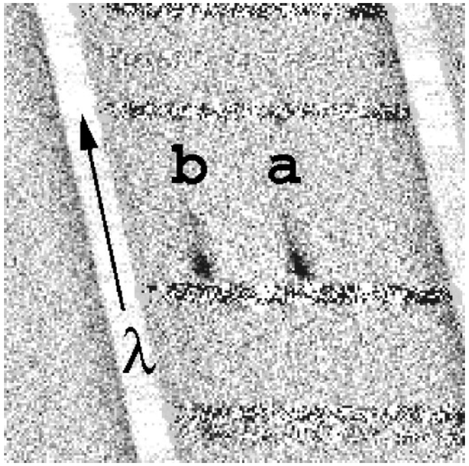
==> See J. Richards's course

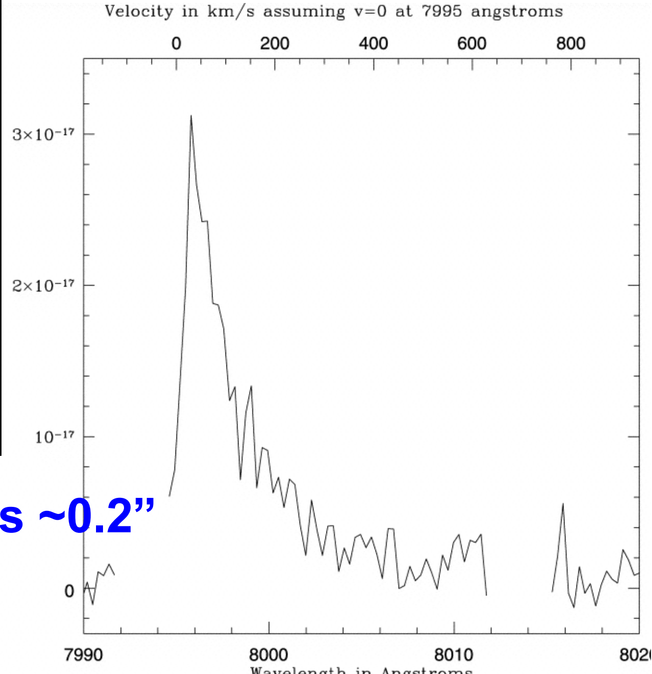
# Historical overview (VI)

## A multiple image at z=5.58 behind  A2218

Ellis et al., 2001, ApJ 560, L119







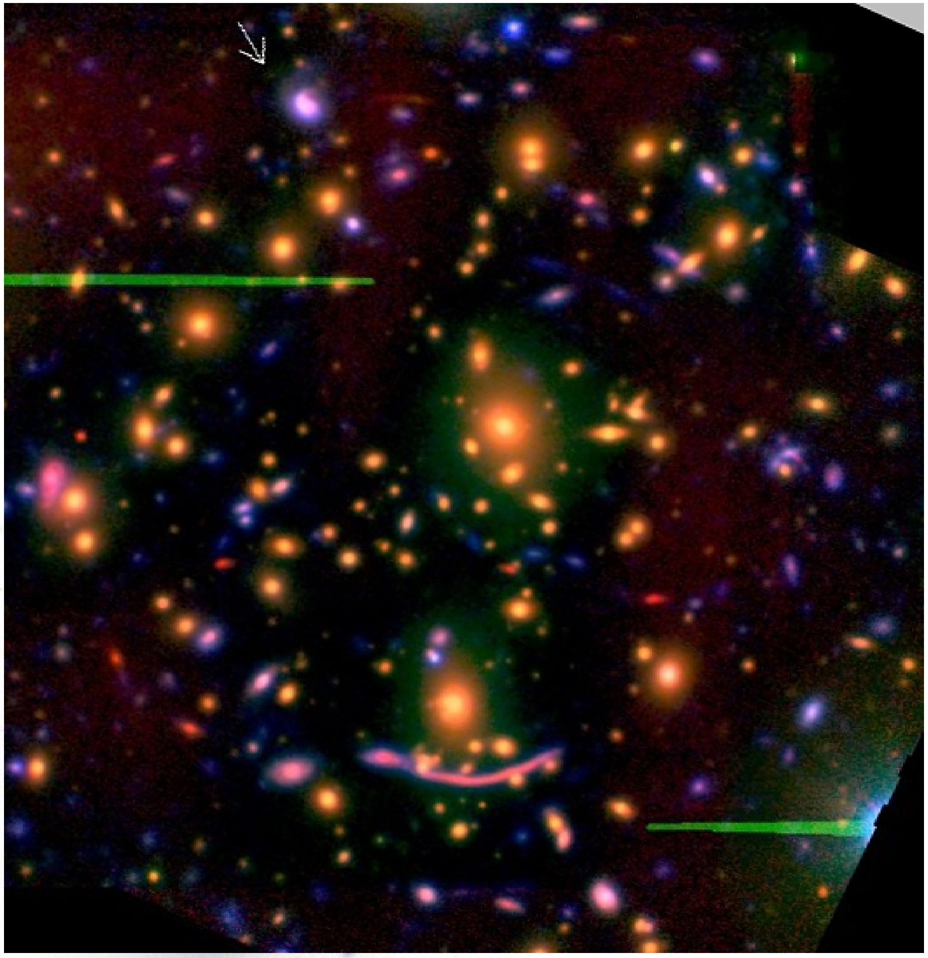
**Magnification ~30 => unlensed I=29.7 mags with half-light radius ~0.2”**

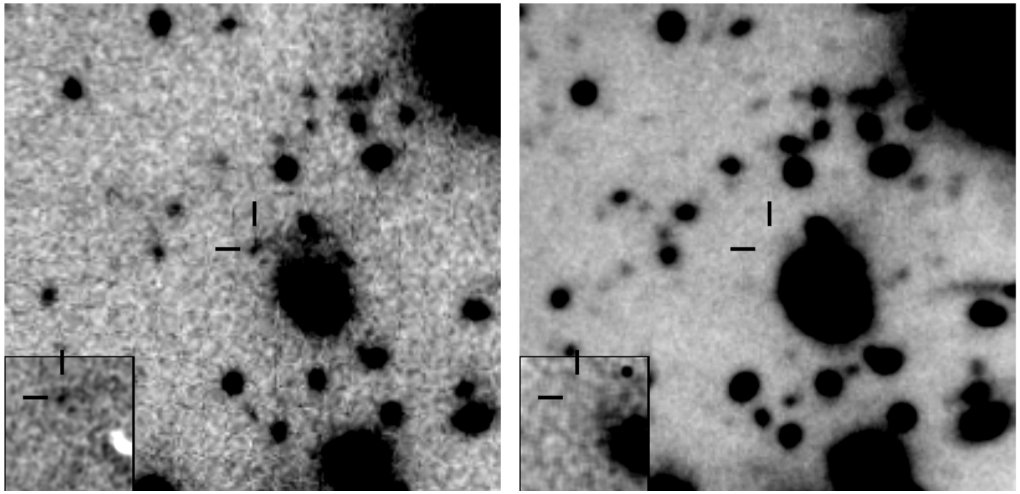
# Historical overview (VII)

**Lensed galaxy at z=6.56 behind A370**

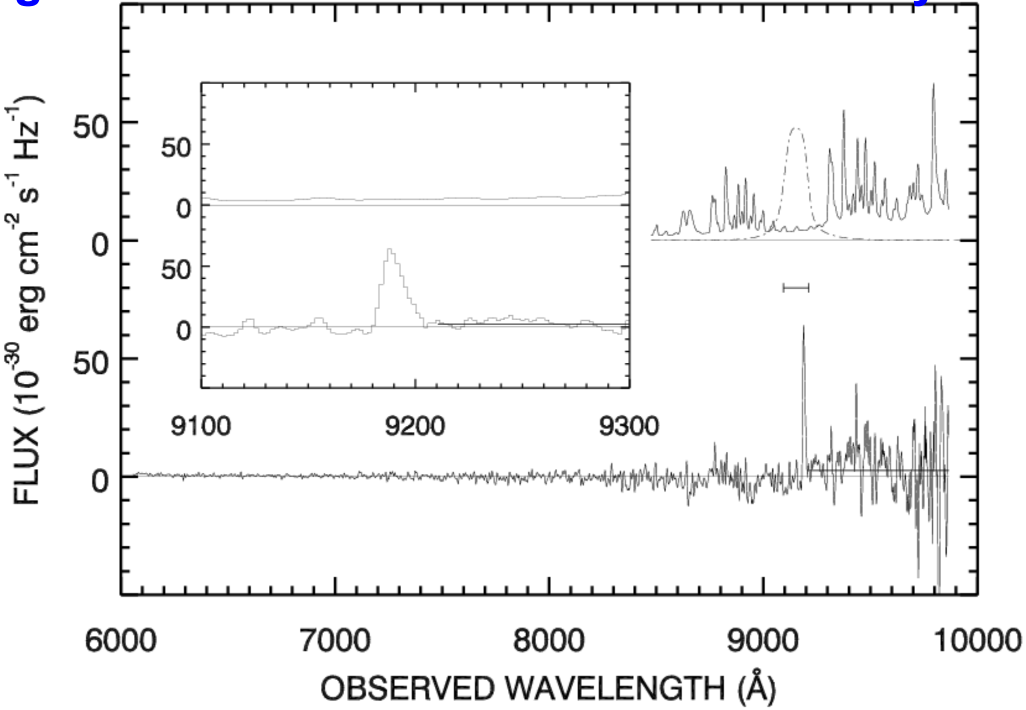
**NB identification**

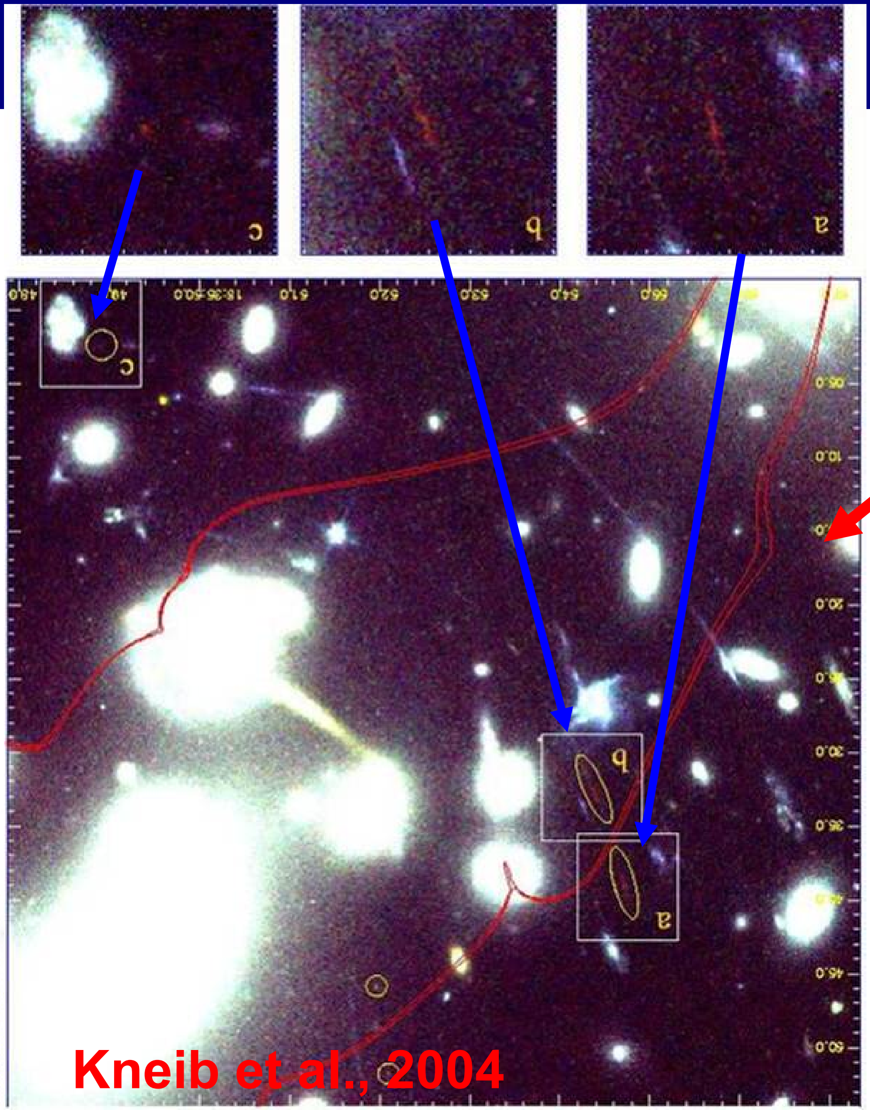
**Hu et al., 2002**



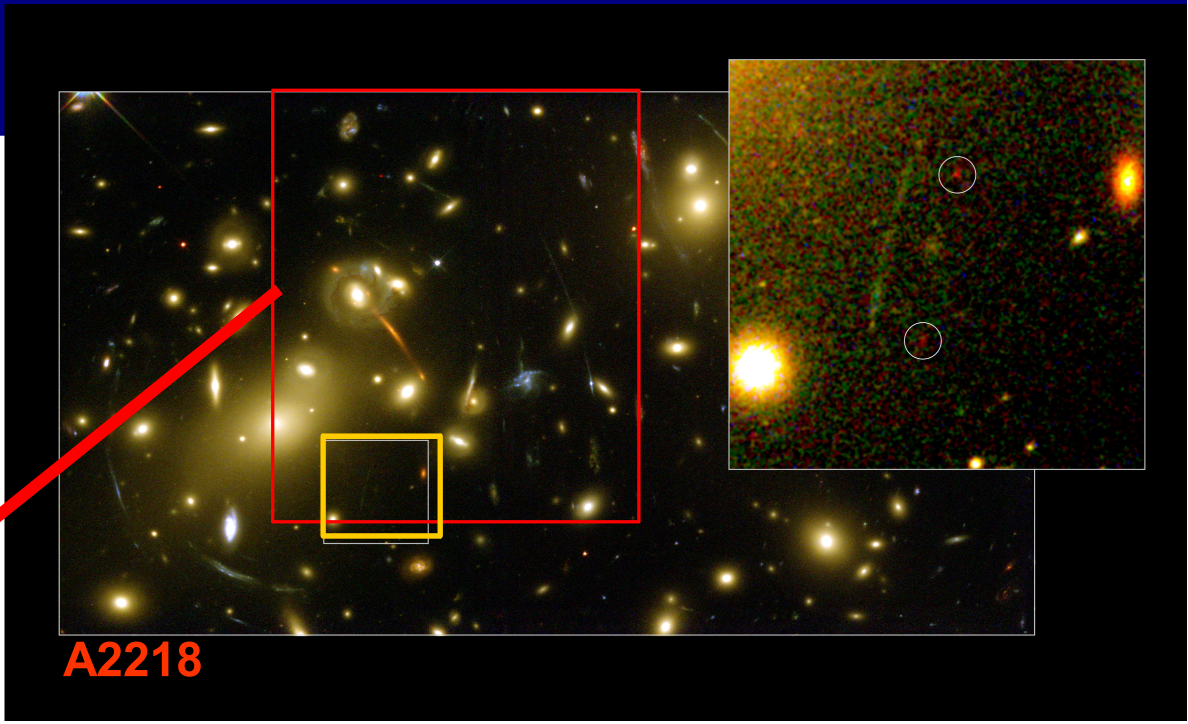


**Magnification~4.5 – SFR ~ 9 solar masses/yr**



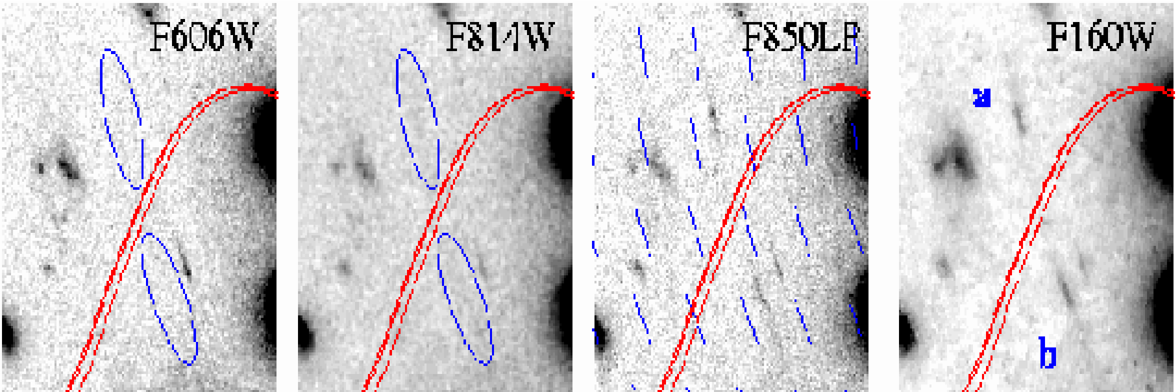


Kneib et al., 2004



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

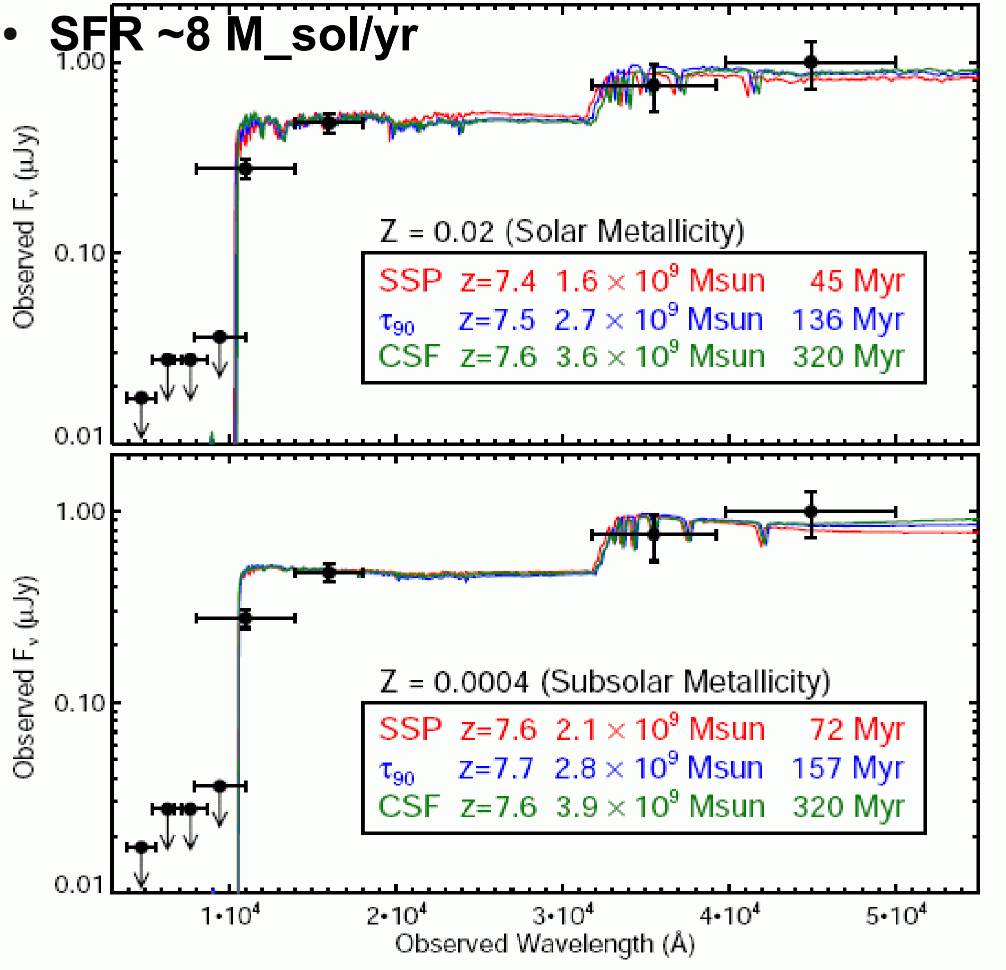
**Detection by *Spitzer* of the z~7 pair in 2 bands of the IRAC camera: 3.6 mm and 4.5 mm (Egami et al. 05)**

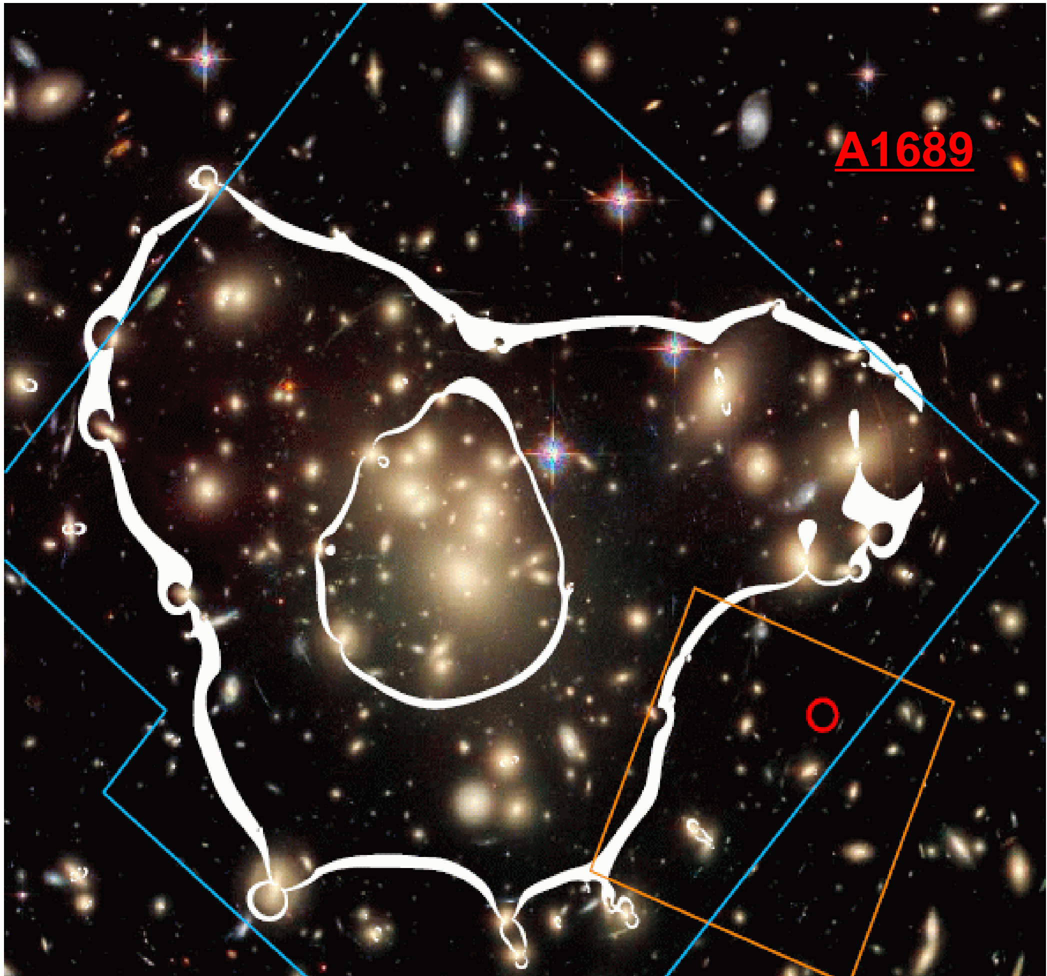


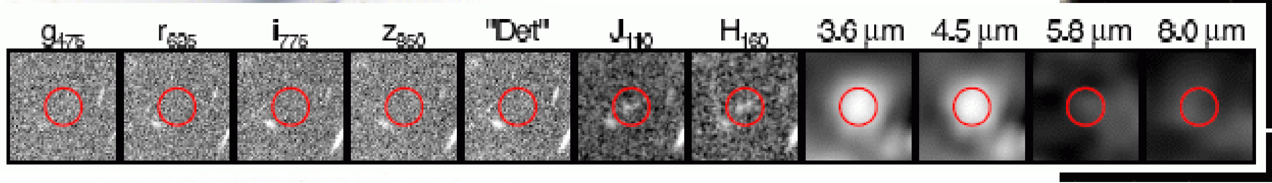
# Historical overview (IX)

**Bradley et al. 2008:**

- **Bright galaxy at z~7.6 candidate behind the lensing cluster A1689. Photometric redshift**
- **SFR ~8 M_sol/yr**



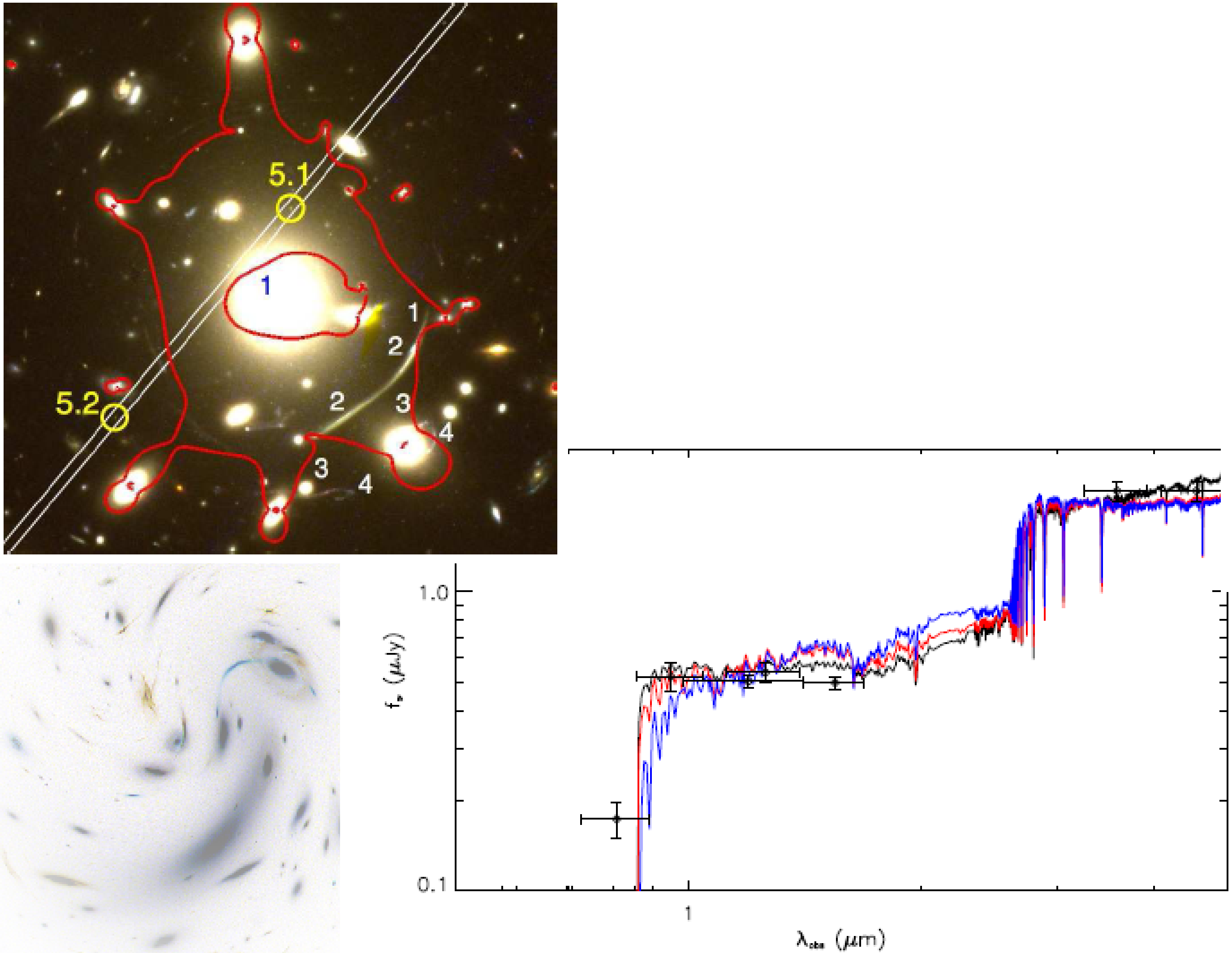


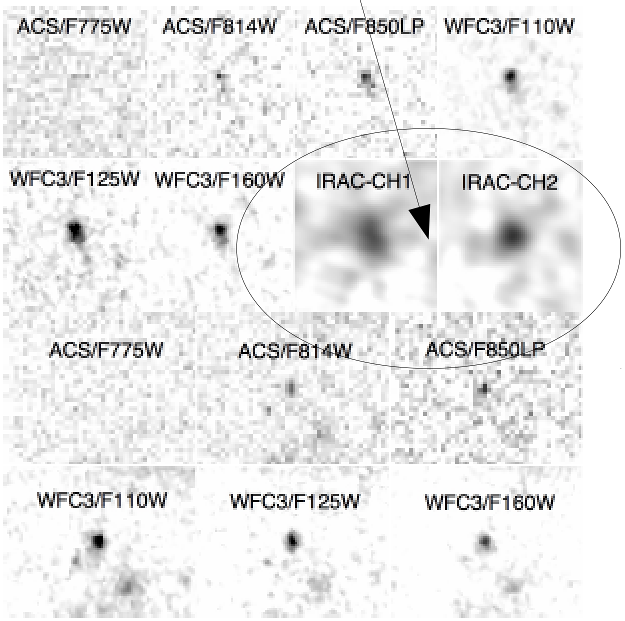


# Historical overview (X)

***Richard et al. 2011:***

- **A z=6.03 multiple-imaged galaxy behind the lensing cluster  A383. Spectro redshift**
- **Magnification~11, AB(intrinsic)=27 ==> 0.4L*, M(stellar)~$10^9$ solar masses**

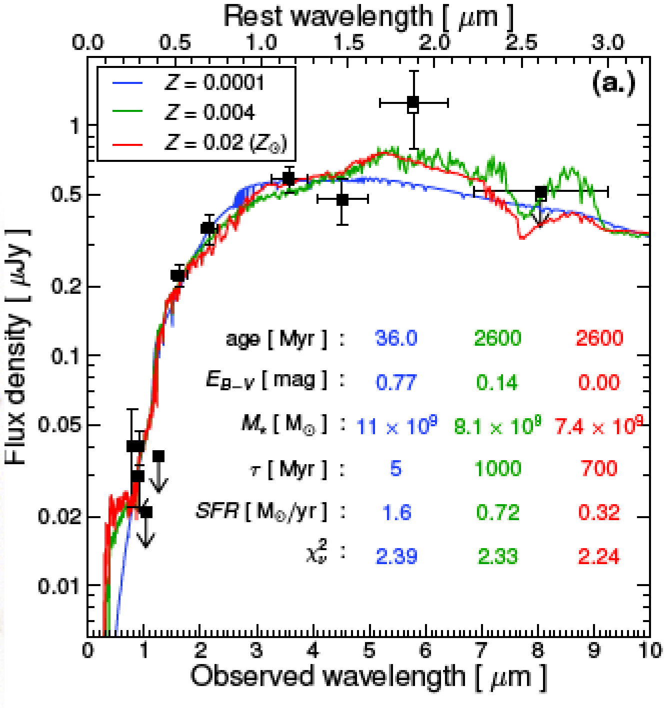


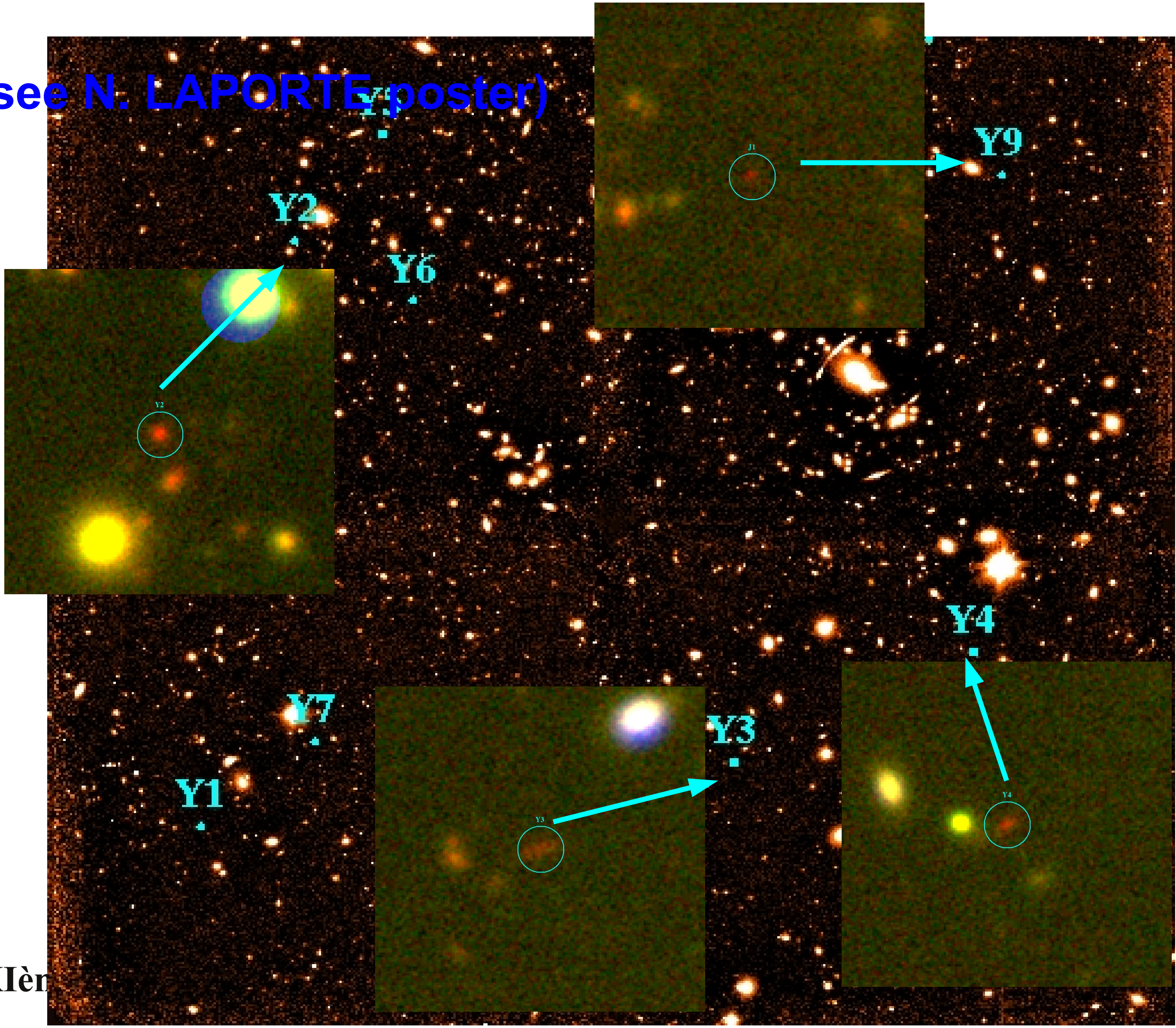


# Historical overview (XI)

***Laporte et al. 2011:***

- **Several “bright” z~>7 candidates behind the lensing cluster  A2667. Photometric redshifts**
- **Strong contamination (see N. LAPORTE poster)**

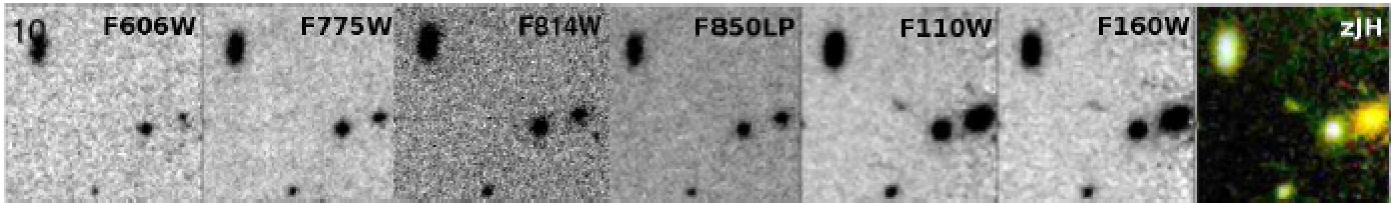


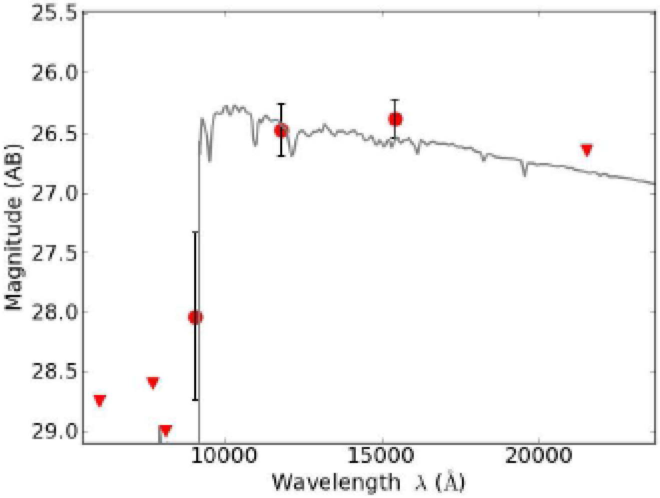


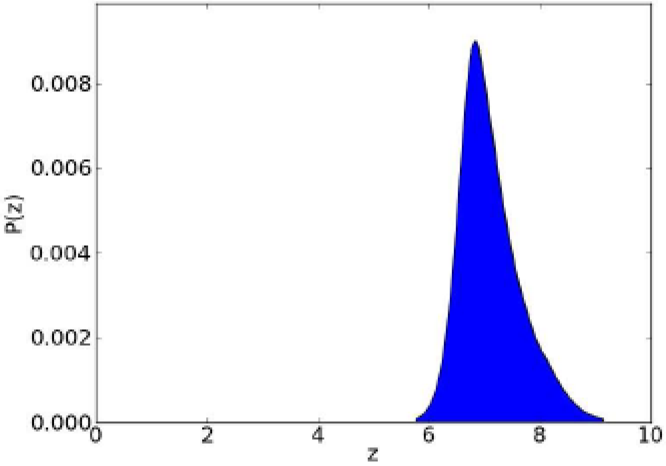
# Historical overview (XII)

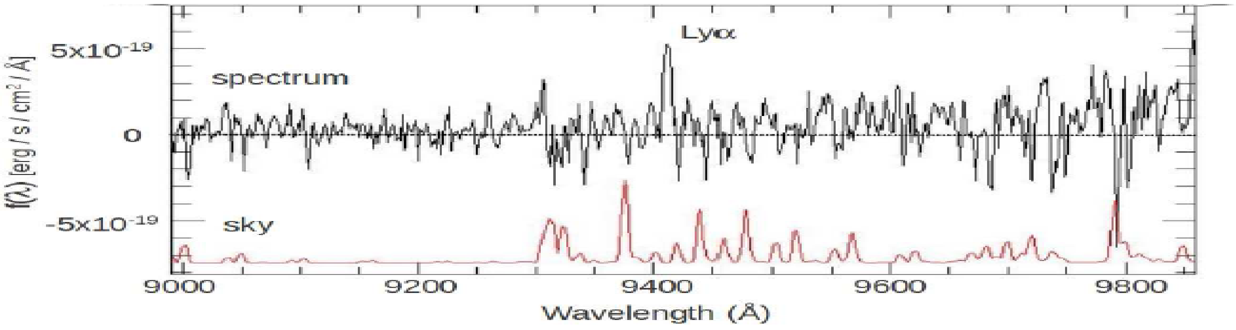
## Bradac et al. 2012:

- **A z=6.72 galaxy behind the Bullet Cluster. Spectro redshift**
- **Magnification~3, AB(intrinsic)=27.6 ==> 0.5L*, SFR~9 solar masses/yr**





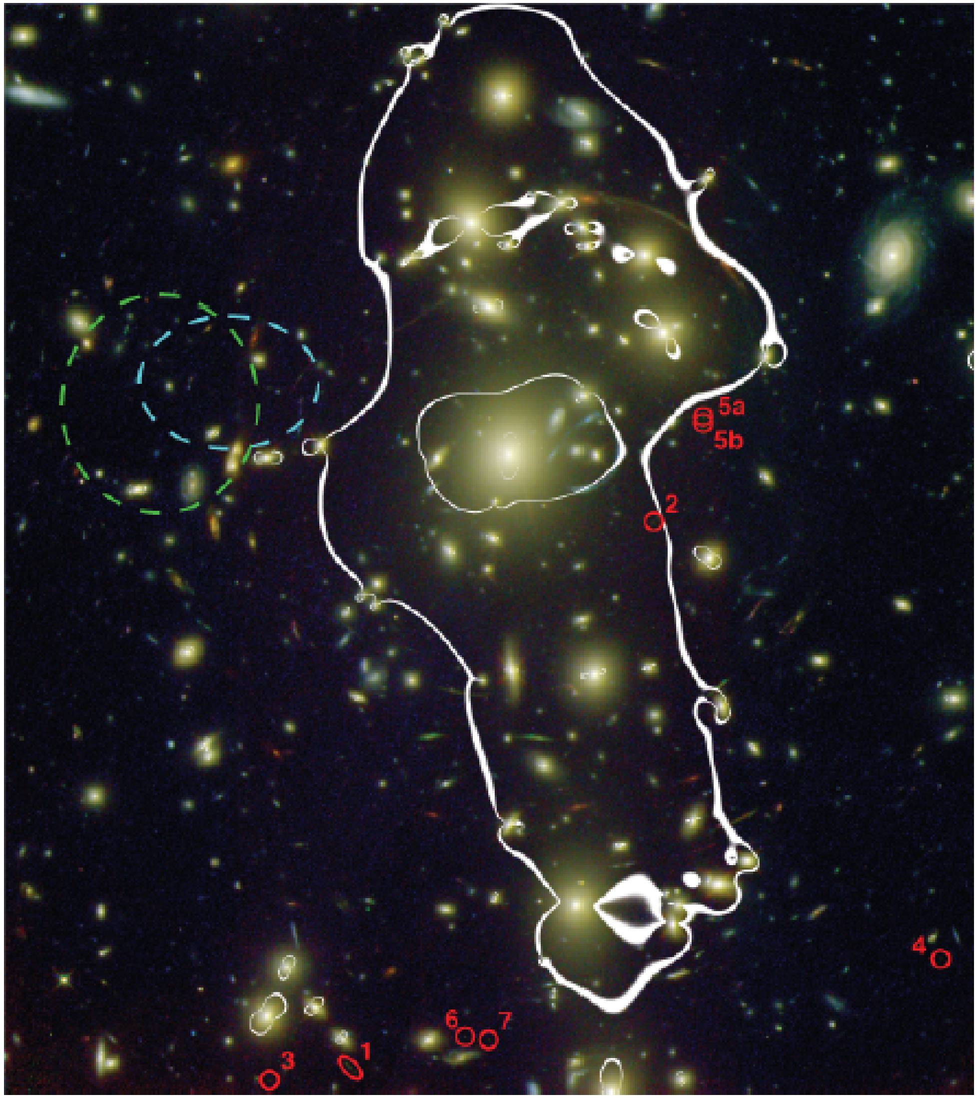


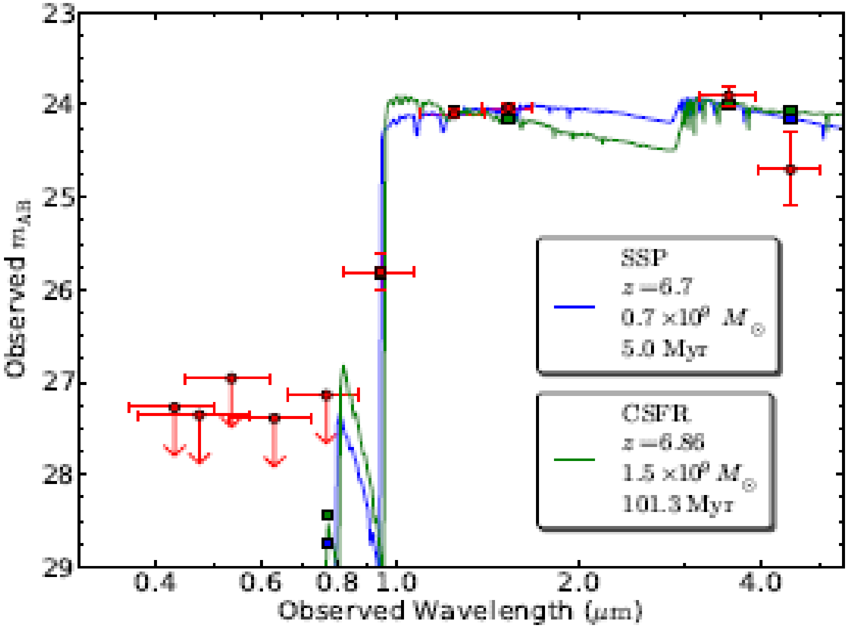


# Historical overview (XIII)

**Bradley et al. 2012:**

- **Seven z~7 galaxy behind A1703. Photometric redshifts**
- **Magnification~3-40, M(stellar)~$10^9$ solar masses, SFR~8 solar masses/yr**

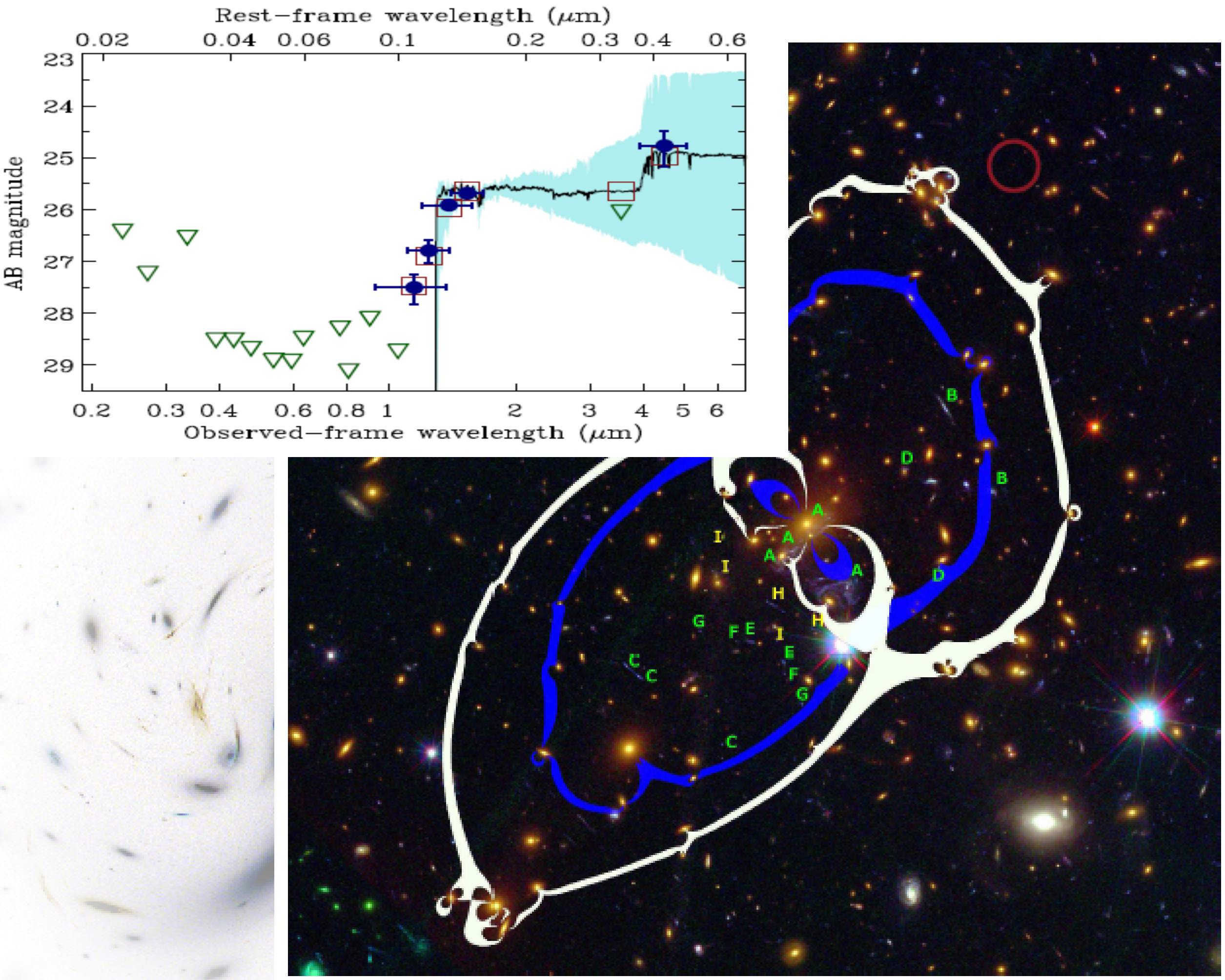


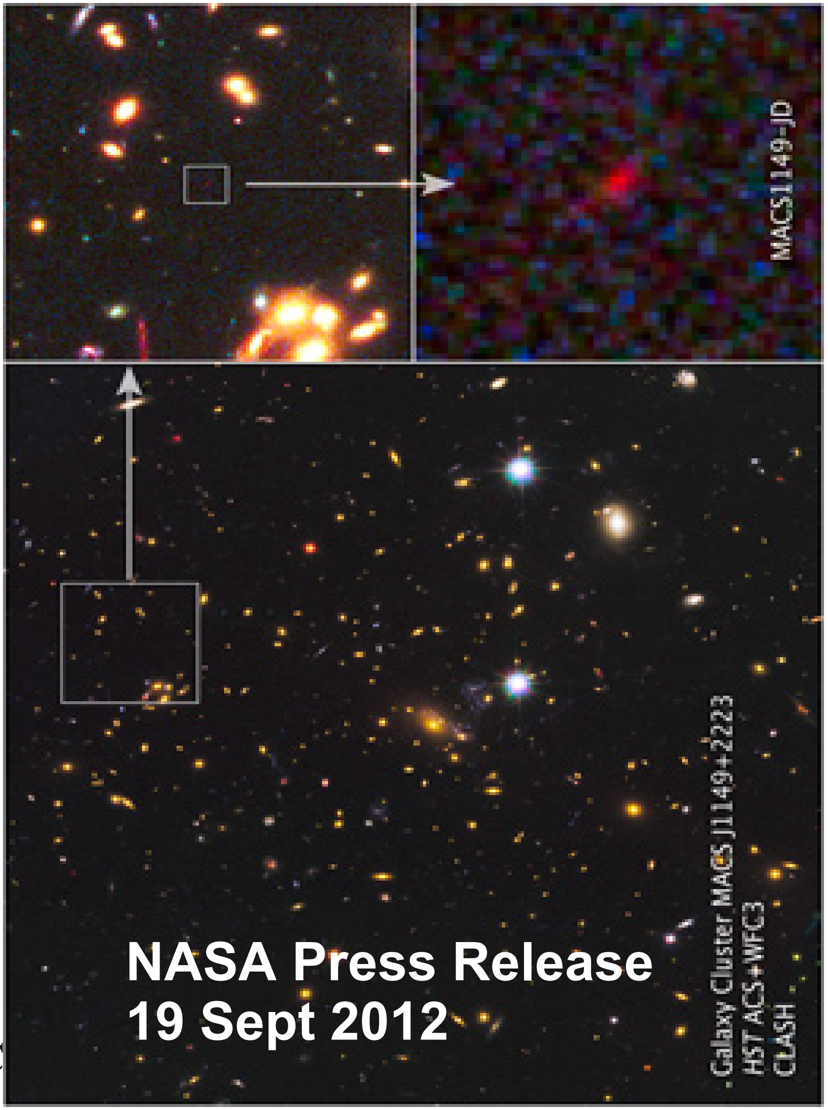


# Historical overview (XIV)

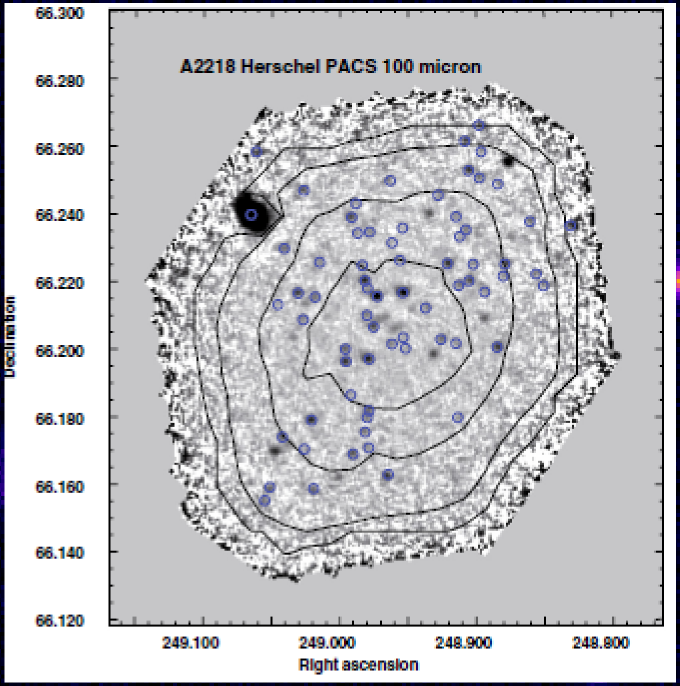
## Zheng et al. 2012:

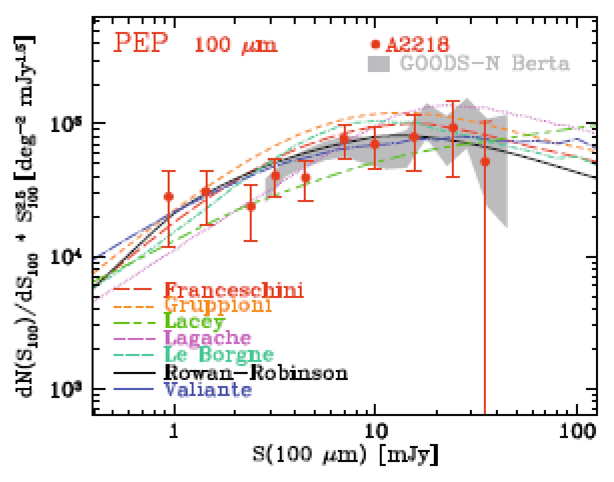
- A z~9.6 (+/-0.2) galaxy behind MACS1149+22. Photometric redshift
- Magnification>15, large uncertainties on physical parameters





NASA Press Release
19 Sept 2012





**Herschel deep far-IR counts behind A2218 (Altieri et al. 2010)**

**+ Results of utra-deep MIR -> Submm Surveys**

**(Altieri et al. 1999, Smail et al. 98, Blain et al. 99, … Altieri et al. 2010, ...)**

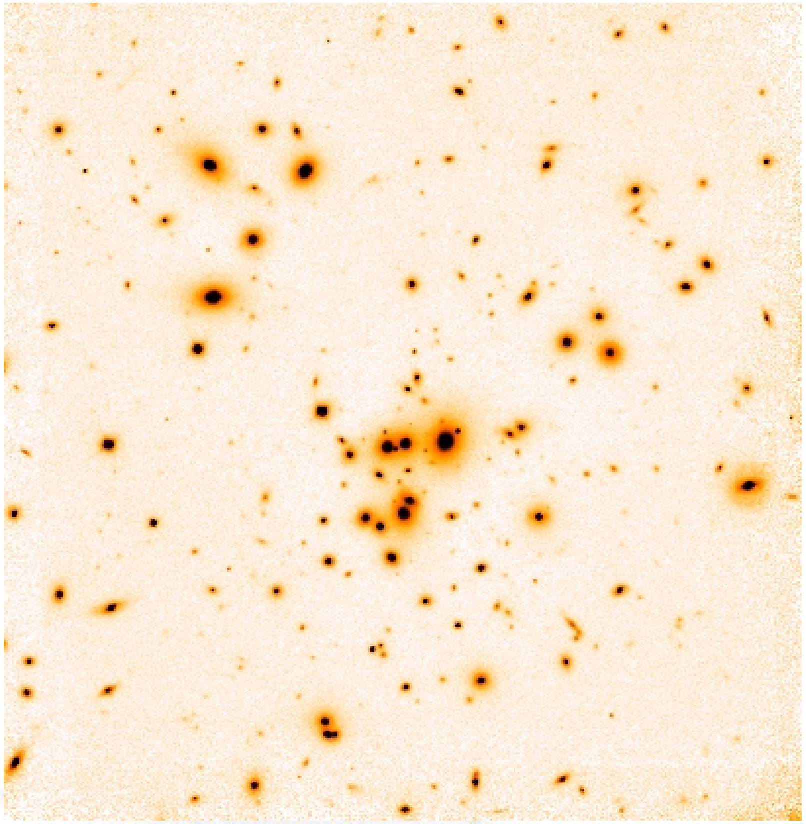
**⇒ see JP KNEIB's lectures**

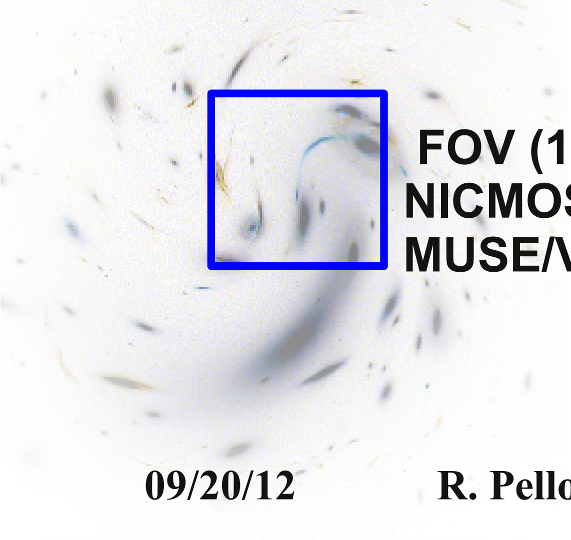
# Historical overview : summary

- Few (~10!) galaxies at z~>7 (lensed or BF) have been spectrosopically confirmed (e.g. *Kodaira+ 2003, Hu+ 2002, Cuby+ 2003, Taniguchi+ 2005, Iye+ 2006, Lenhert+ 2011, Bradac+2012...)*. Controversial results in some cases.
- The large majority of samples beyond z~>7 (lensed or BF) are mainly supported by pure photometric considerations (photoz) (e.g. *Kneib+ 2004, Pello+ 2004, Bouwens+ 2004 to 2011, Richard+ 2006, 2008; Bradley+ 2008, Laporte+ 2011, Bradley+ 2012, ... )*
- Important contribution of lensing fields to this effort :
  - First detailed studies on the physical properties of LBGs : stellar populations, Lyman alpha emission, stellar masses and SFR, image reconstruction=> sizes, …
  - First photometric surveys devoted to z~>7 LBGs (2000-05) started in lensing clusters (HST+ground-based observations). Difficult spectroscopic confirmation. Controversial results... but stimulating discussions
- New promising lensing surveys ongoing (*e.g. CLASH survey)*

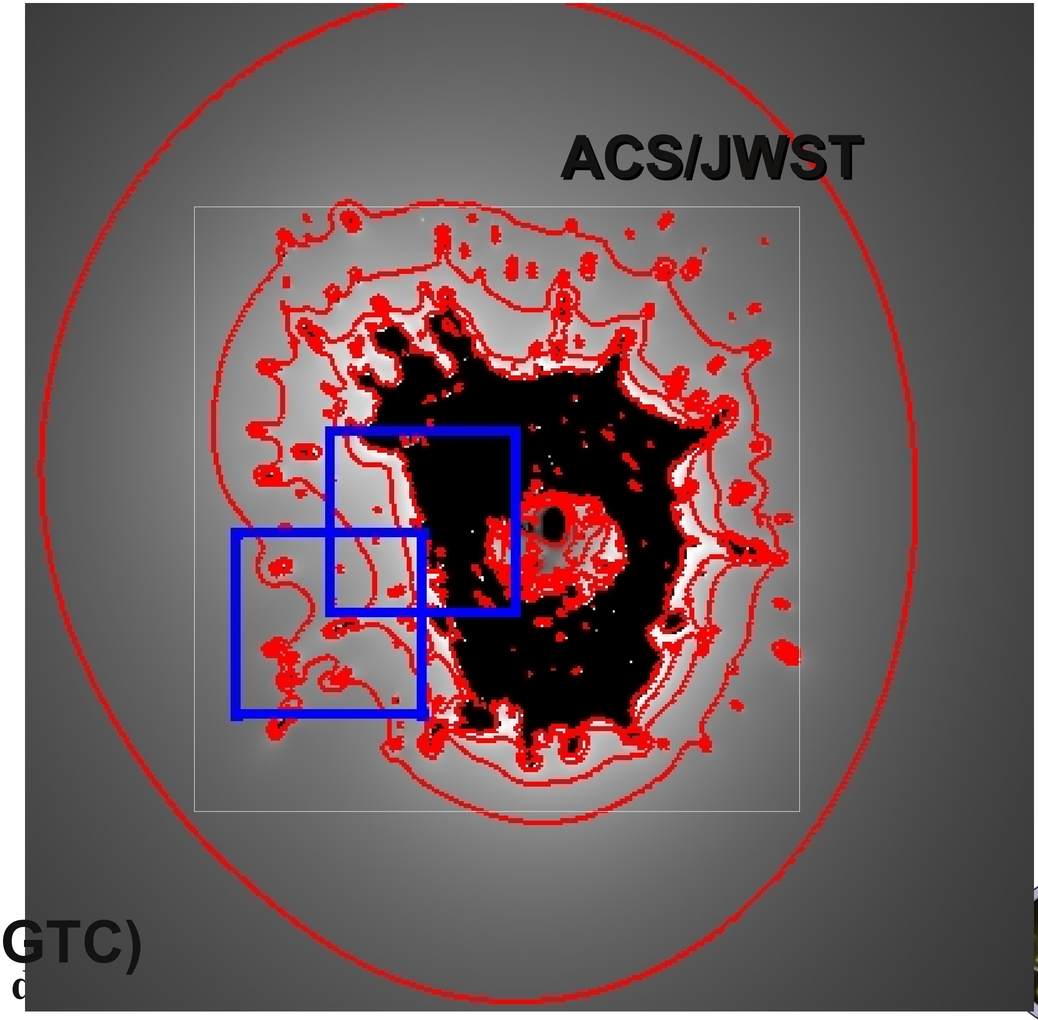
# Lensing versus blank fields : a matter of efficiency

- Example: A1689 (z(cluster)=0.184)
- *Lenstool* modeling of cluster mass distribution
- Magnification (z(source)=6): 2, 5, 10, 25





**FOV (1'x1')**
**NICMOS-NIC3**
**MUSE/VLT FOV**

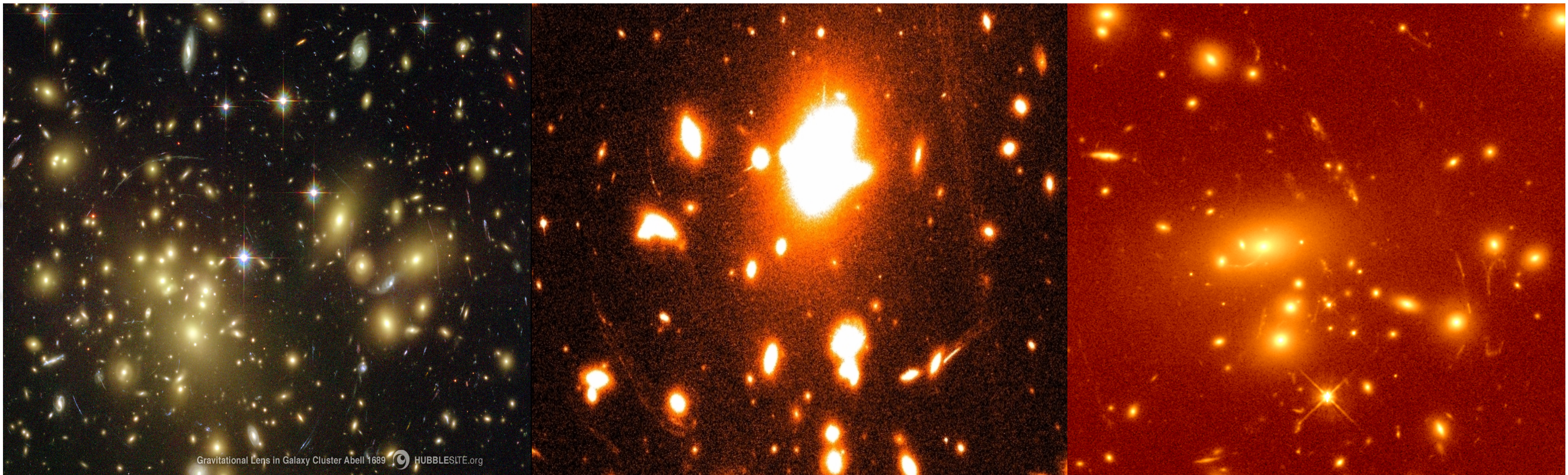


**6' x 6' FOV**
**(e.g. EMIR/GTC)**

# Lensing versus blank fields : a matter of efficiency

## Deriving expected number-counts

- **Deriving expected number counts from realistic/observed UV LFs at $6 < z < 12$.**
- **Comparison between expected N(z,m) in blank & lensing fields**
- **Pixel-to-pixel integration of magnification maps, using lensing models and bright-objects masking**

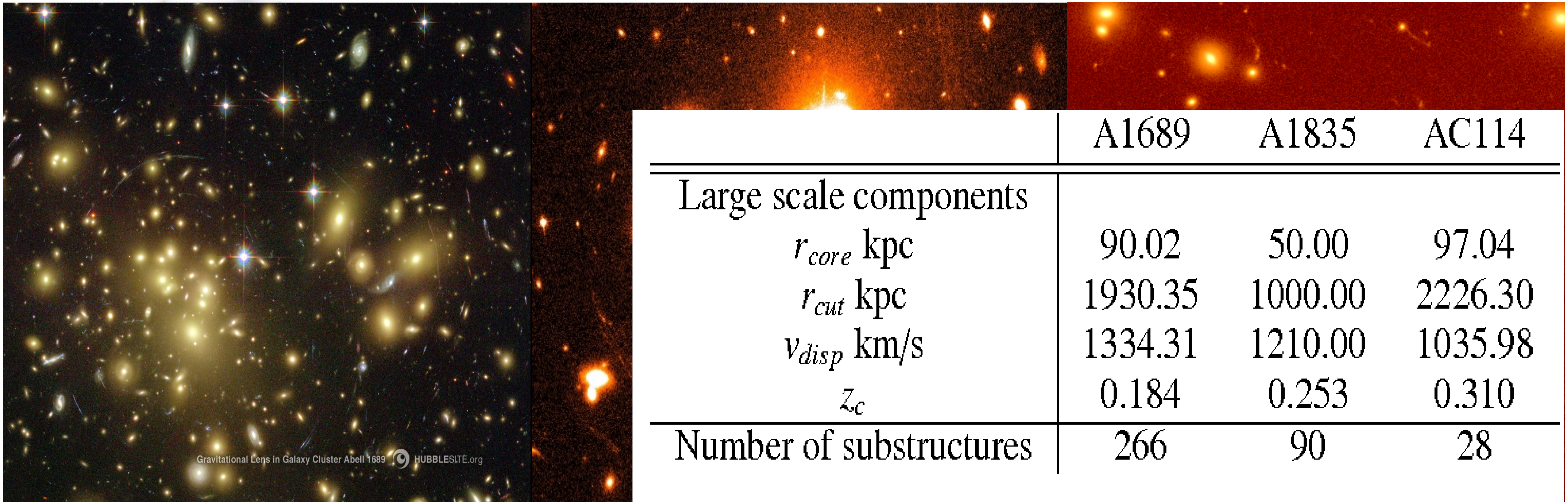


# Lensing versus blank fields : a matter of efficiency

## Deriving expected number-counts

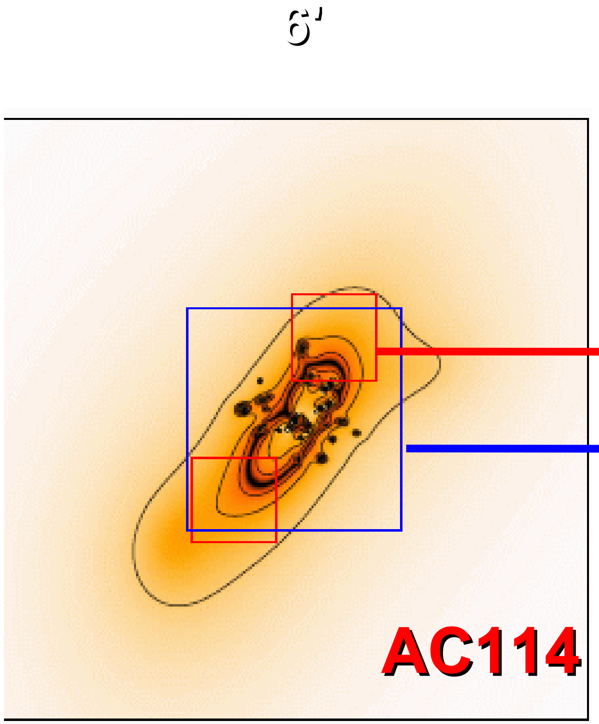
- **Pixel-to-pixel integration of magnification maps, using lensing models and bright-objects masking**
- ***Lenstool* lensing models for “reference” lensing clusters: A1689 (z=0.184), A1835 (z=0.25), and AC114 (z=0.310) *(see Maizy et al. 2010)***
  - ***cluster scale mass component***
  - ***galaxy scale mass component***

==> see Graham”s 2nd lecture
JPK's 1rst lecture



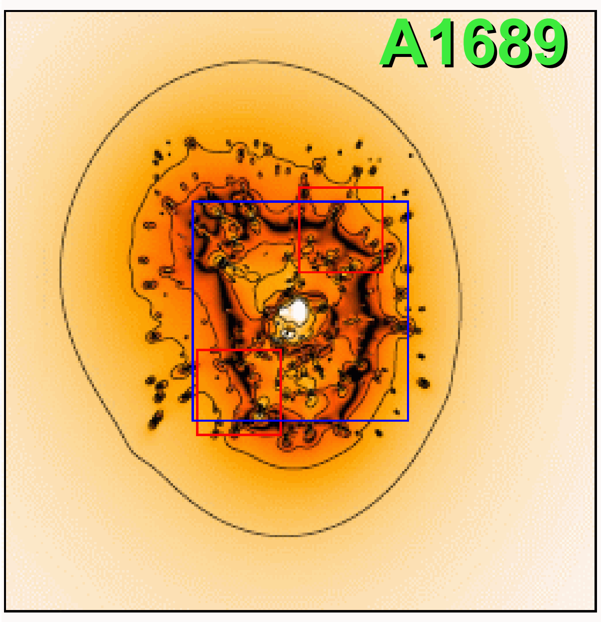
| | A1689 | A1835 | AC114 |
|---|---|---|---|
| Large scale components | | | |
| $r_{core}$ kpc | 90.02 | 50.00 | 97.04 |
| $r_{cut}$ kpc | 1930.35 | 1000.00 | 2226.30 |
| $v_{disp}$ km/s | 1334.31 | 1210.00 | 1035.98 |
| $z_c$ | 0.184 | 0.253 | 0.310 |
| Number of substructures | 266 | 90 | 28 |

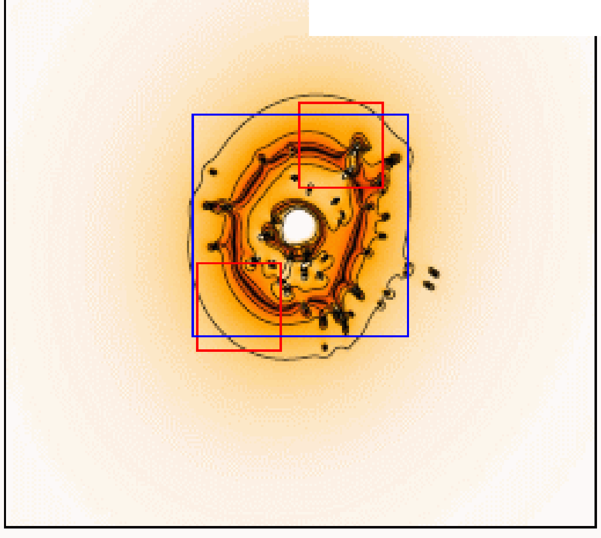
# Lensing versus blank fields : a matter of efficiency

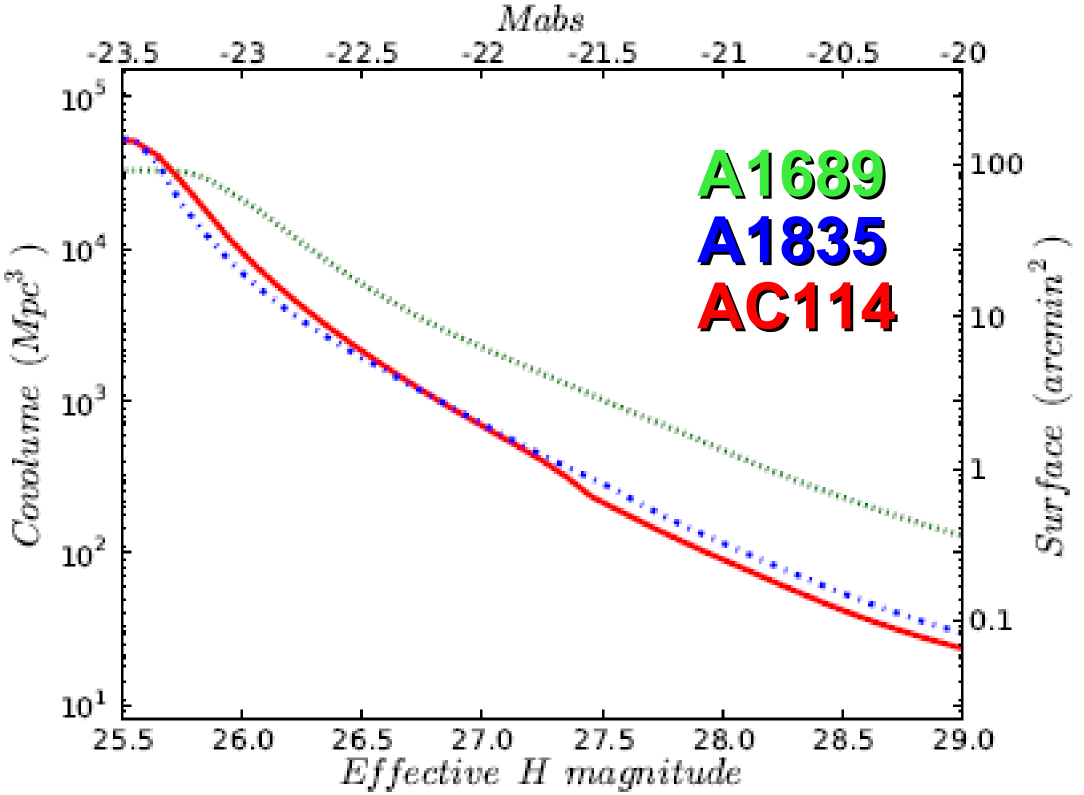


**MUSE/ NIC3**

**JWST/ WFC3**





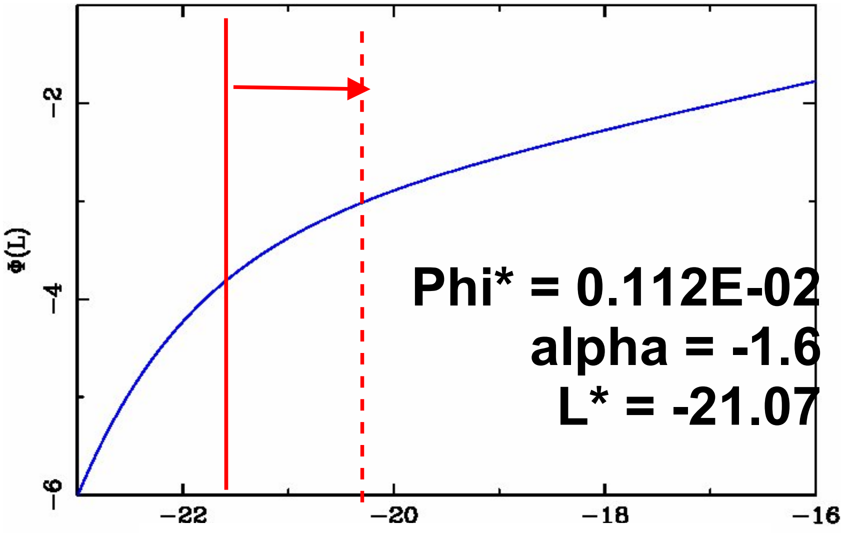


**Example:**
**6' x 6' FOV**
**z = 6.6-7.5**
**AB < 25.5**

*Maizy et al. 2010*

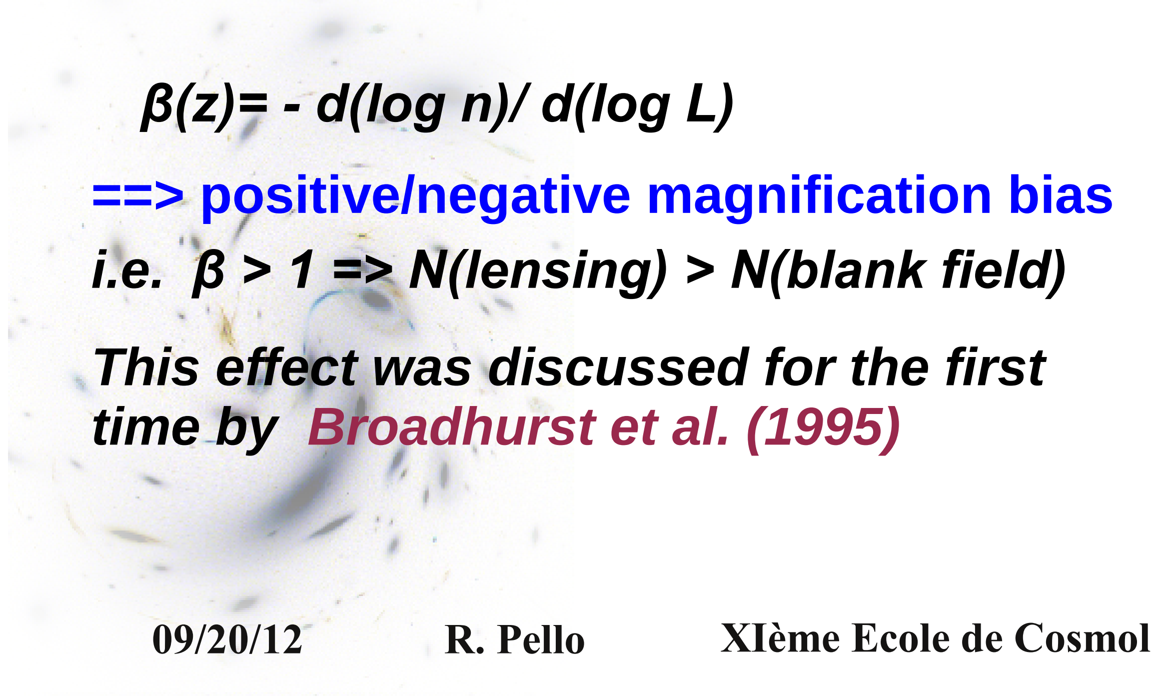
# Lensing versus blank fields : a matter of efficiency

- **Two opposite effects of lensing:**
  - ***magnification μ(z)***
  - ***dilution 1/μ(z)***



$$\phi(L)\,dL = \phi^* \left(\frac{L}{L^*}\right)^{\alpha} \exp\left(-\frac{L}{L^*}\right) d\left(\frac{L}{L^*}\right)$$

$$n'_{lensing}(>L,z) = N(>L/\mu,z)/\mu(z)$$
$$\simeq \mu^{\beta(z)-1}\, n(>L,z)$$

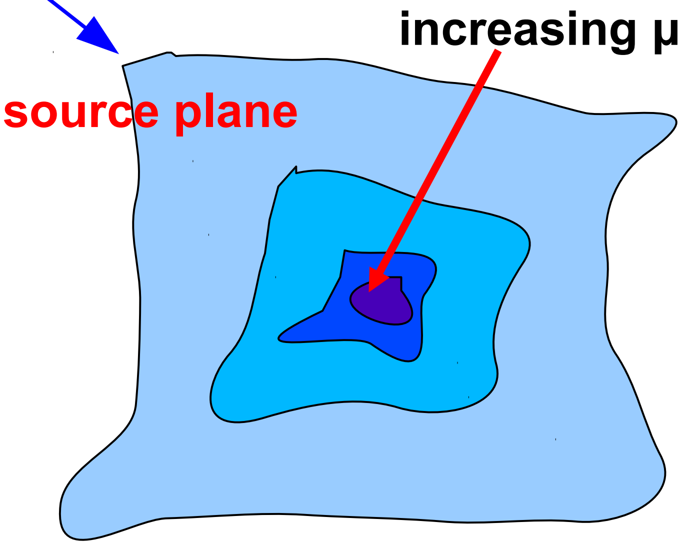


***β(z)= - d(log n)/ d(log L)***

**==> positive/negative magnification bias**

***i.e. β > 1 => N(lensing) > N(blank field)***

***This effect was discussed for the first time by Broadhurst et al. (1995)***



# Lensing versus blank fields : a matter of efficiency

## Deriving expected number-counts

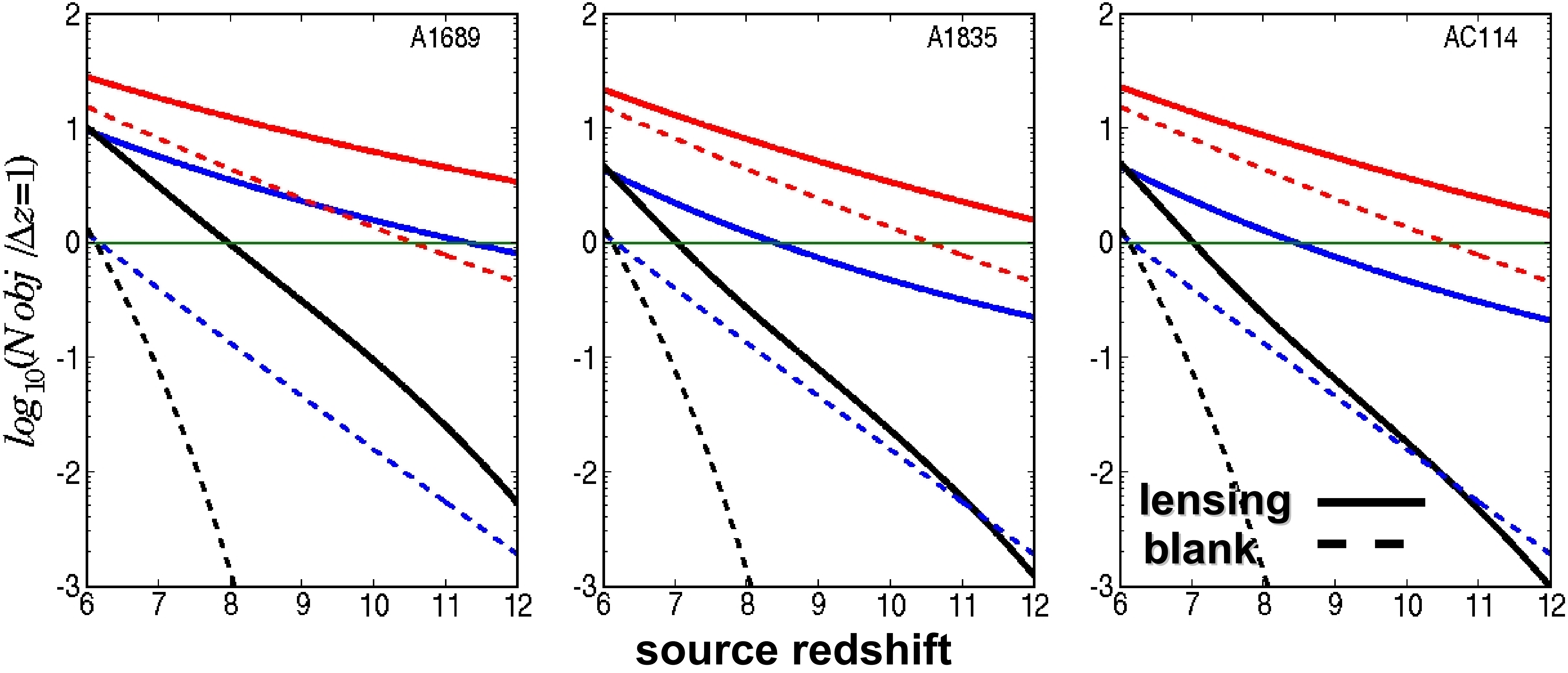
- **Deriving expected number counts from realistic/observed UV LFs at 6 < z < 12.**
- **Comparison between expected N(z,m) in blank & lensing fields**
- **Pixel-to-pixel integration of magnification maps, using lensing models and bright-objects masking.**

$$N(z,m_0) = \phi^* \int_{x,y} M(x,y) \int_{L(\mu,z,m_0)}^{\infty} \frac{Cv(x,y,z)}{\mu(x,y,z)} \left(\frac{L(\mu,z,m_0)}{L^*}\right)^{\alpha} \cdot exp\left(-\frac{L(\mu,z,m_0)}{L^*}\right) d\left(\frac{L}{L^*}\right) dx\,dy$$

*Number counts are very sensitive to β ==> the comparison between N(lensing) and N(BF) helps constraining the shape of the LF*

# Lensing versus blank fields : a matter of efficiency

**« Bright » spectroscopic sample:** **H(AB)<~ 25.5 in a 6' x 6' FOV, Δz=1**

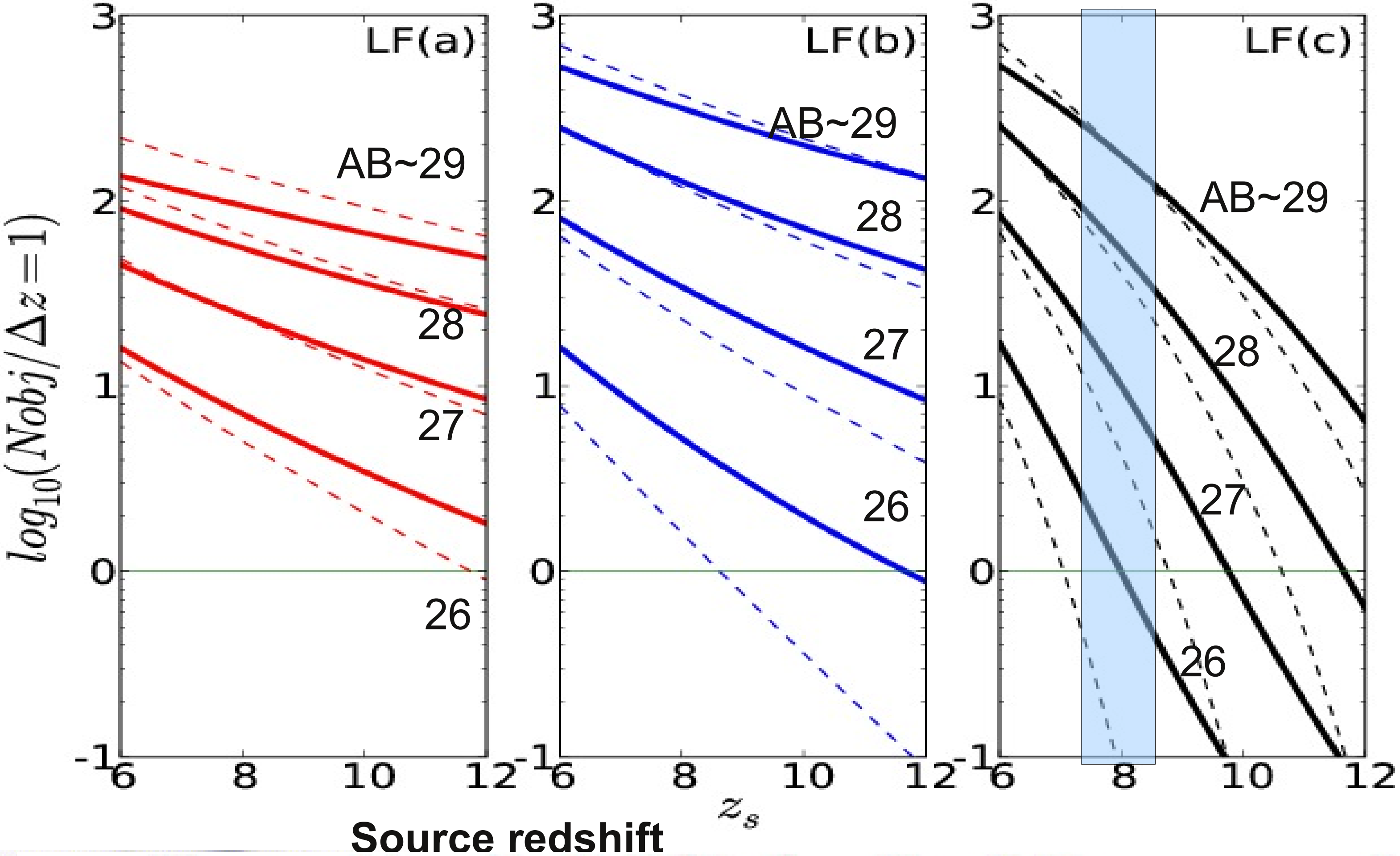


| | | | | |
|---|---|---|---|---|
| $< z >= 4.0$ | $\alpha = 1.6,$ | $\phi^* = 1.3\ 10^{-2}\mathrm{Mpc}^{-3},$ | $M^* = -21.07$ | Steidel et al. (1999) |
| $< z >= 5.9$ | $\alpha = 1.74,$ | $\phi^* = 1.1\ 10^{-3}\ \mathrm{Mpc}^{-3},$ | $M^* = -20.24$ | Bouwens et al. (2006) |
| $3.8 < z < 7.4$ | $\alpha = 1.74,$ | $\phi^* = 1.1\ 10^{-3}\ \mathrm{Mpc}^{-3},$ | $M^* = -21.02 + 0.36\,(z - 3.8)$ | Bouwens et al. (2008) |

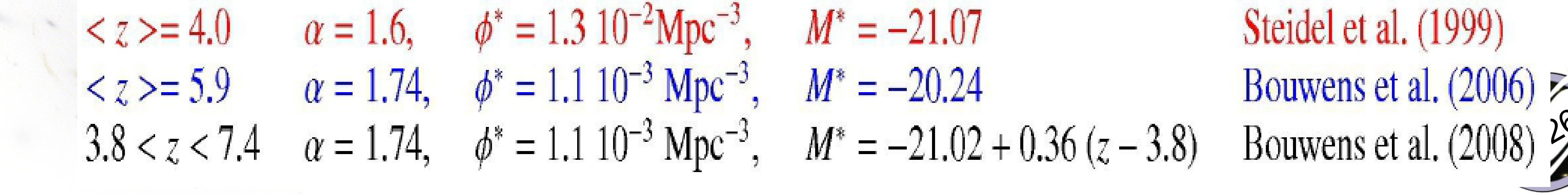
# Lensing versus blank fields : a matter of efficiency

***Maizy et al. 2010***

**lensing** ▬▬
**blank** ▬ ▬

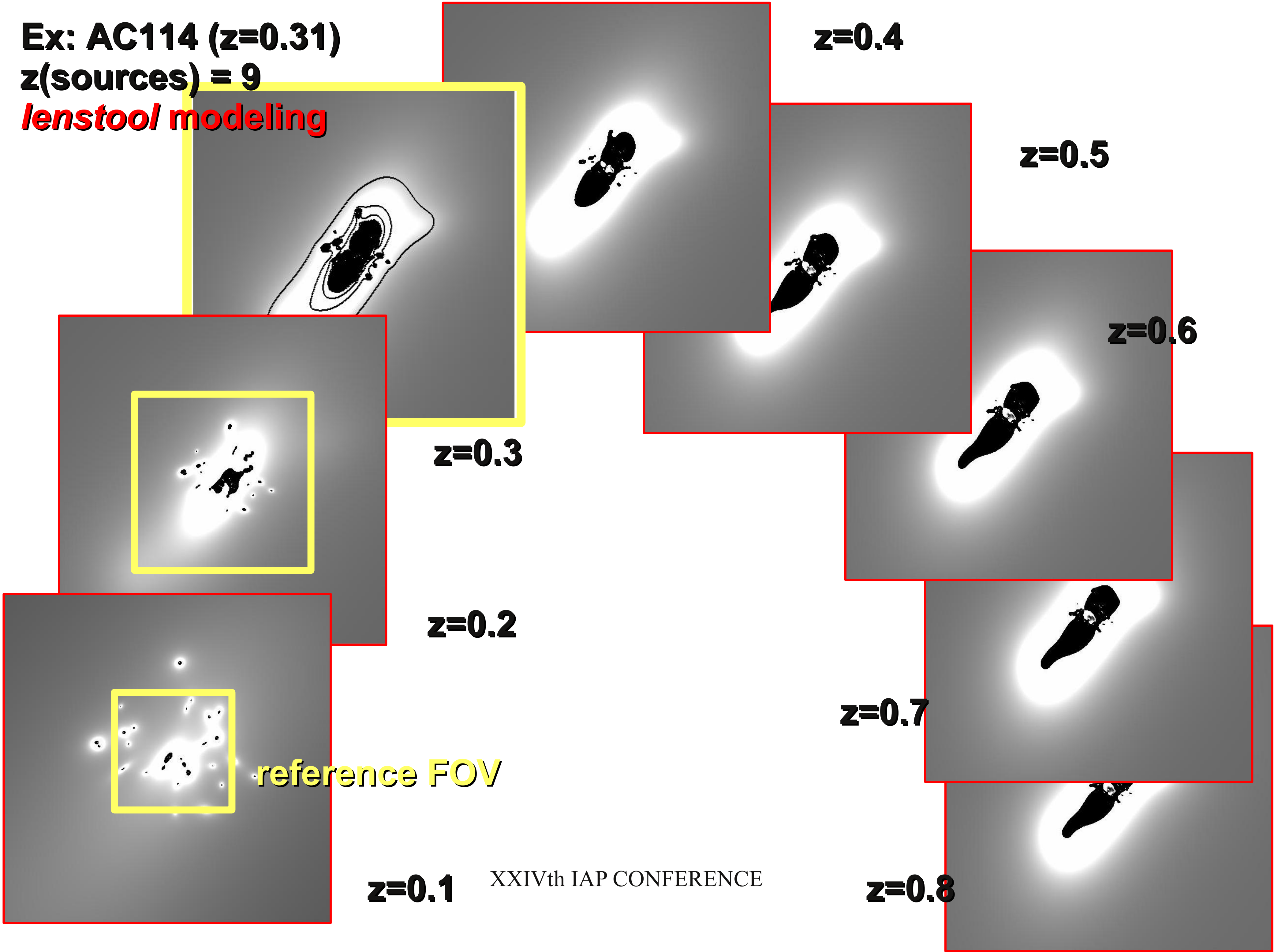


- **Number counts vs redshift and depth, ~6'x6' FOV, behind the lensing cluster AC114**



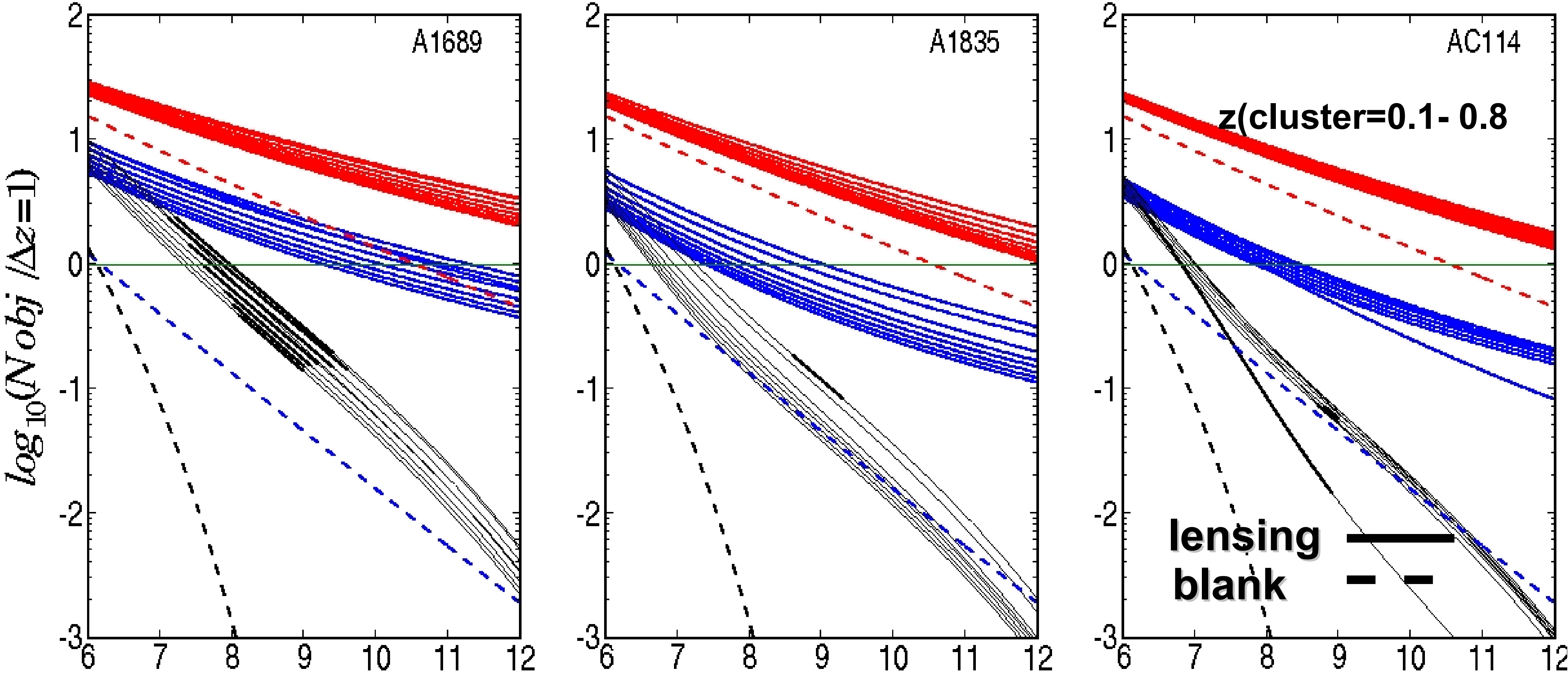
| | | | | |
|---|---|---|---|---|
| $<z>= 4.0$ | $\alpha = 1.6,$ | $\phi^* = 1.3\ 10^{-2}\mathrm{Mpc}^{-3},$ | $M^* = -21.07$ | Steidel et al. (1999) |
| $<z>= 5.9$ | $\alpha = 1.74,$ | $\phi^* = 1.1\ 10^{-3}\ \mathrm{Mpc}^{-3},$ | $M^* = -20.24$ | Bouwens et al. (2006) |
| $3.8 < z < 7.4$ | $\alpha = 1.74,$ | $\phi^* = 1.1\ 10^{-3}\ \mathrm{Mpc}^{-3},$ | $M^* = -21.02 + 0.36\ (z - 3.8)$ | Bouwens et al. (2008) |

**Ex: AC114 (z=0.31)**
**z(sources) = 9**
***lenstool* modeling**



# Lensing versus blank fields : a matter of efficiency

**« Bright » spectroscopic sample:** **H(AB)<~ 25.5 in a 6' x 6' FOV, Δz=1**

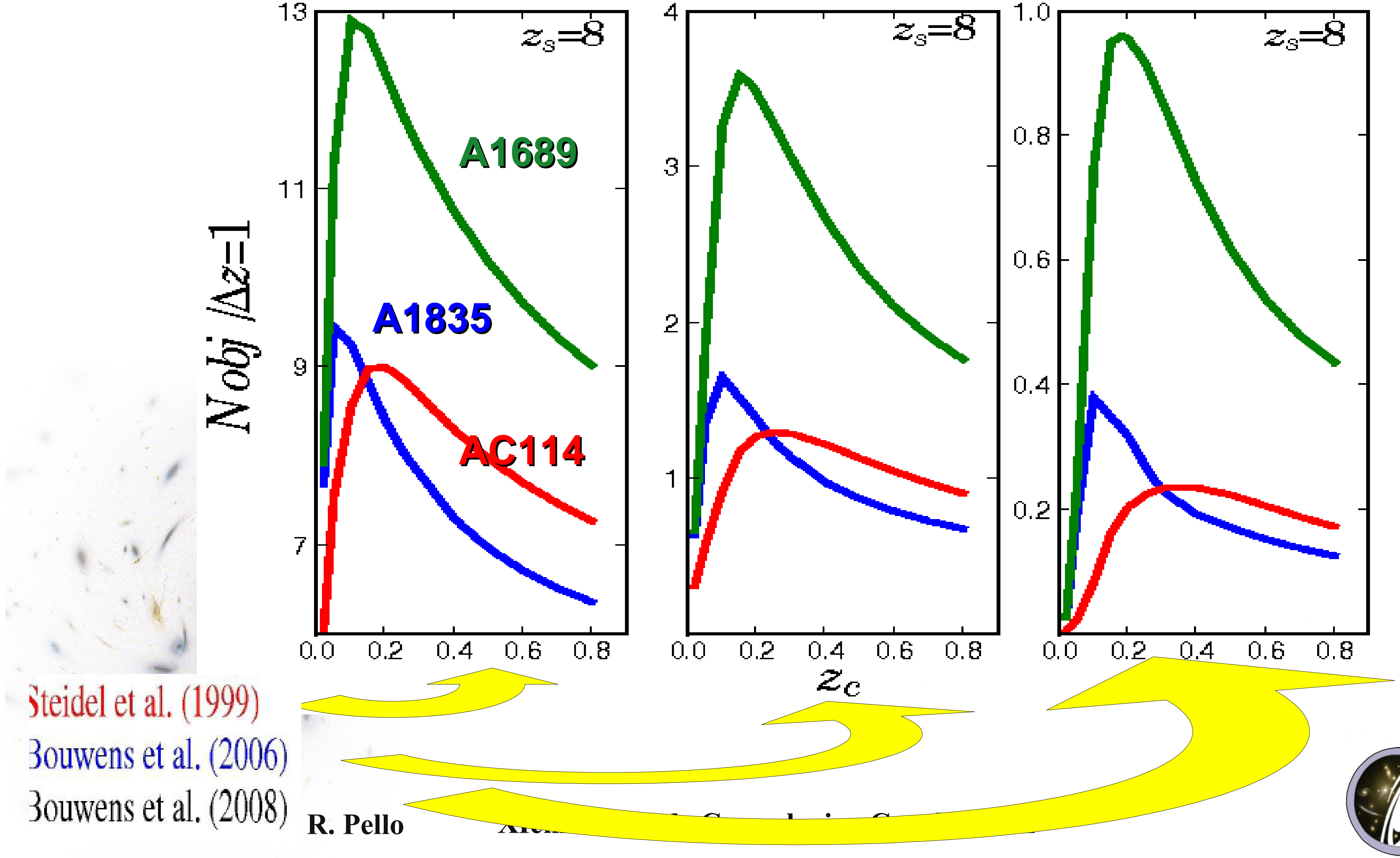


source redshift

| | | | | |
|---|---|---|---|---|
| $<z>= 4.0$ | $\alpha = 1.6,$ | $\phi^* = 1.3\ 10^{-2}\mathrm{Mpc}^{-3},$ | $M^* = -21.07$ | Steidel et al. (1999) |
| $<z>= 5.9$ | $\alpha = 1.74,$ | $\phi^* = 1.1\ 10^{-3}\ \mathrm{Mpc}^{-3},$ | $M^* = -20.24$ | Bouwens et al. (2006) |
| $3.8 < z < 7.4$ | $\alpha = 1.74,$ | $\phi^* = 1.1\ 10^{-3}\ \mathrm{Mpc}^{-3},$ | $M^* = -21.02 + 0.36\,(z - 3.8)$ | Bouwens et al. (2008) |

# Lensing versus blank fields : a matter of efficiency

**« Bright » spectroscopic sample:** **H(AB)<~ 25.5 in a 6' x 6' FOV, $\Delta z=1$**



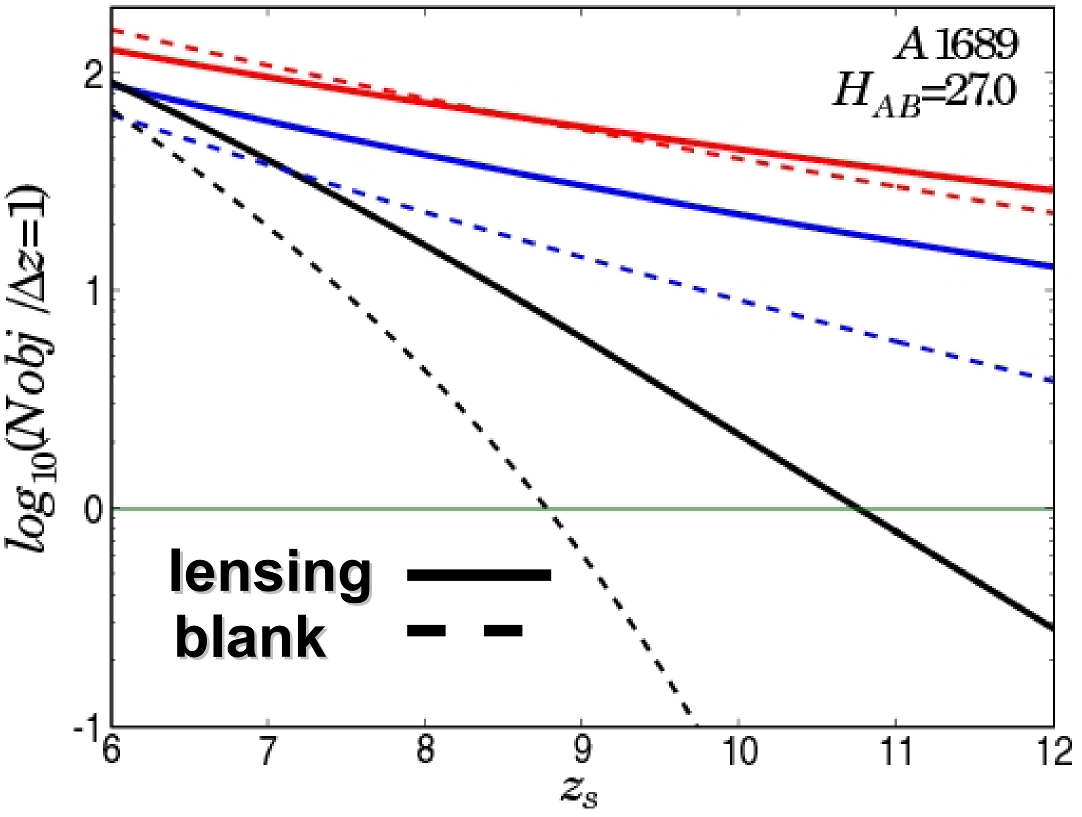
Steidel et al. (1999)

Bouwens et al. (2006)

Bouwens et al. (2008)

# Lensing versus blank fields : a matter of efficiency

**« Faint » photometric sample:** **H(AB)<~ 27.0 in a 6' x 6' FOV, Δz=1**



- **A lensing cluster along the line of sight has an increasingly positive influence on observation efficiency for:**

**➔ "shallow" surveys**

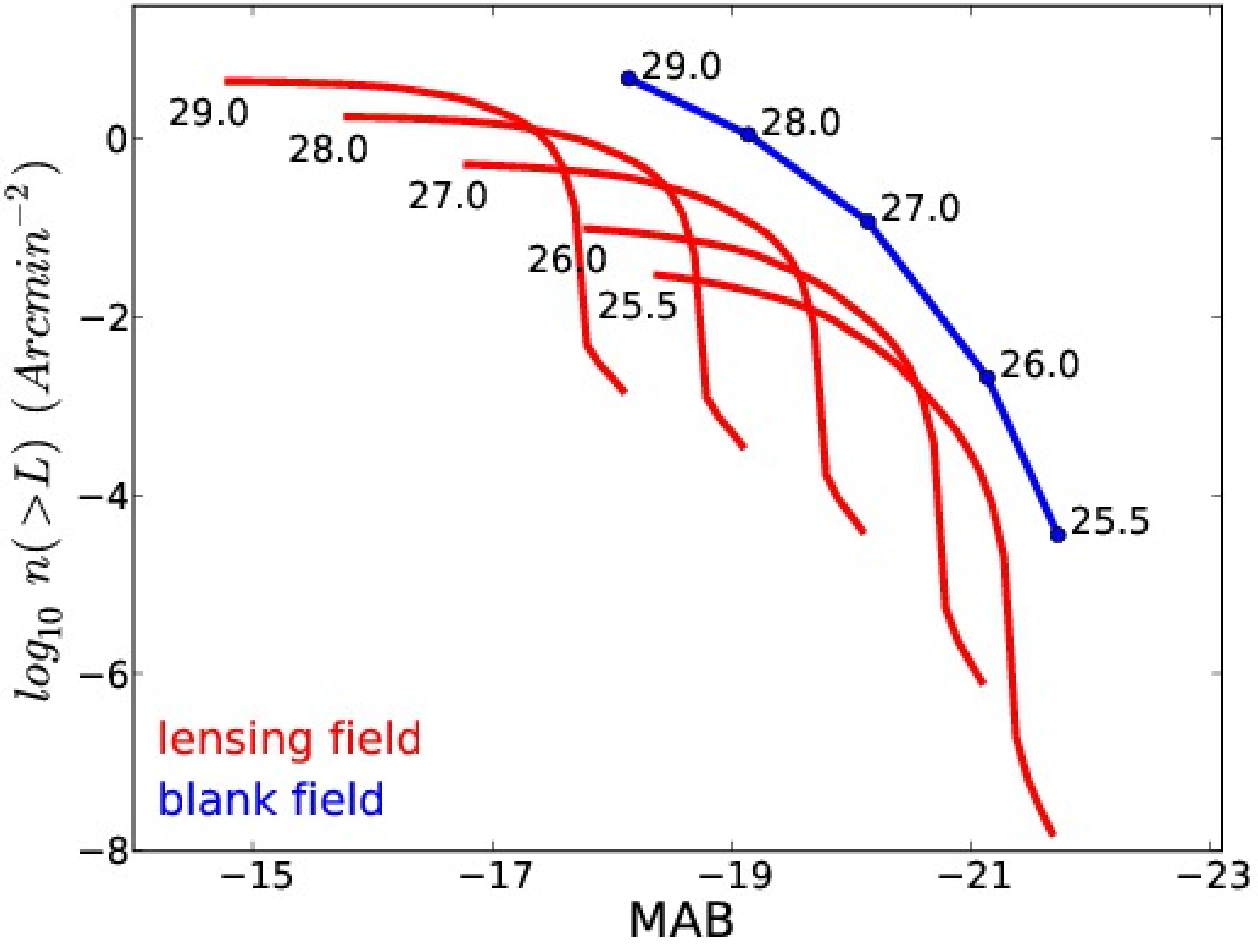
**➔ strongly evolving LFs**

**➔ increasing with z(sources)**

# Lensing versus blank fields : a matter of efficiency

- **Lensing and blank fields explore different domains in terms of <u>intrinsic</u> luminosities.**
- **A careful <u>optimization</u> of the survey strategy will be needed to take a maximum benefit from GT.**
- **Ideal survey : A combination between lensing (faint sources) & BF (bright sources)**

***Maizy et al. 2010***

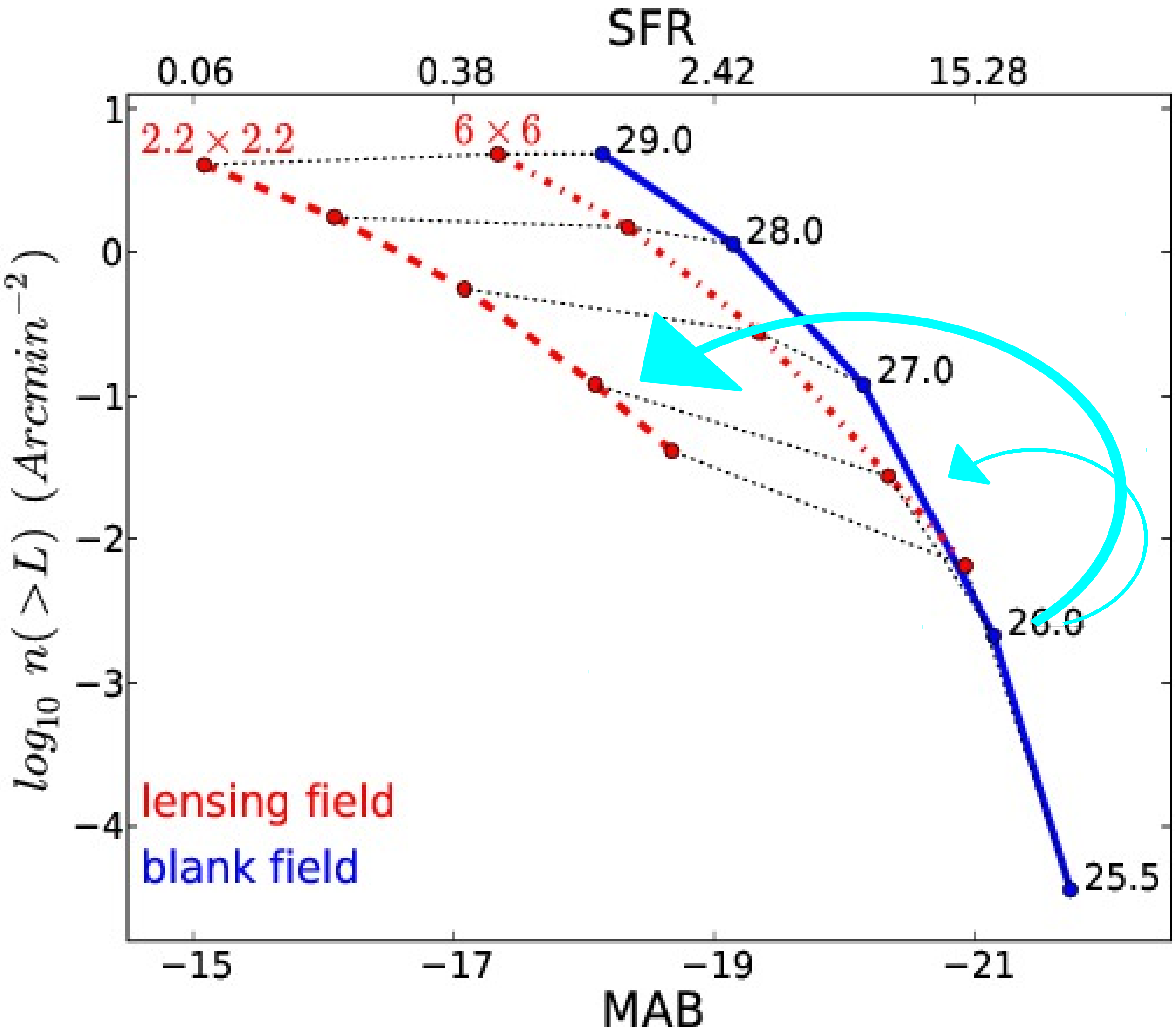


**Ex. AC114, 5 arcmin$^2$ FOV, z=[7.5-8.5], evolving LF**

# Lensing versus blank fields : a matter of efficiency

- **Lensing and blank fields explore different domains in terms of intrinsic luminosities.**
- **A careful optimization of the survey strategy will be needed to take a maximum benefit from GT.**
- **Ideal survey : A combination between lensing (faint sources) & BF (bright sources)**

*Maizy et al. 2010*



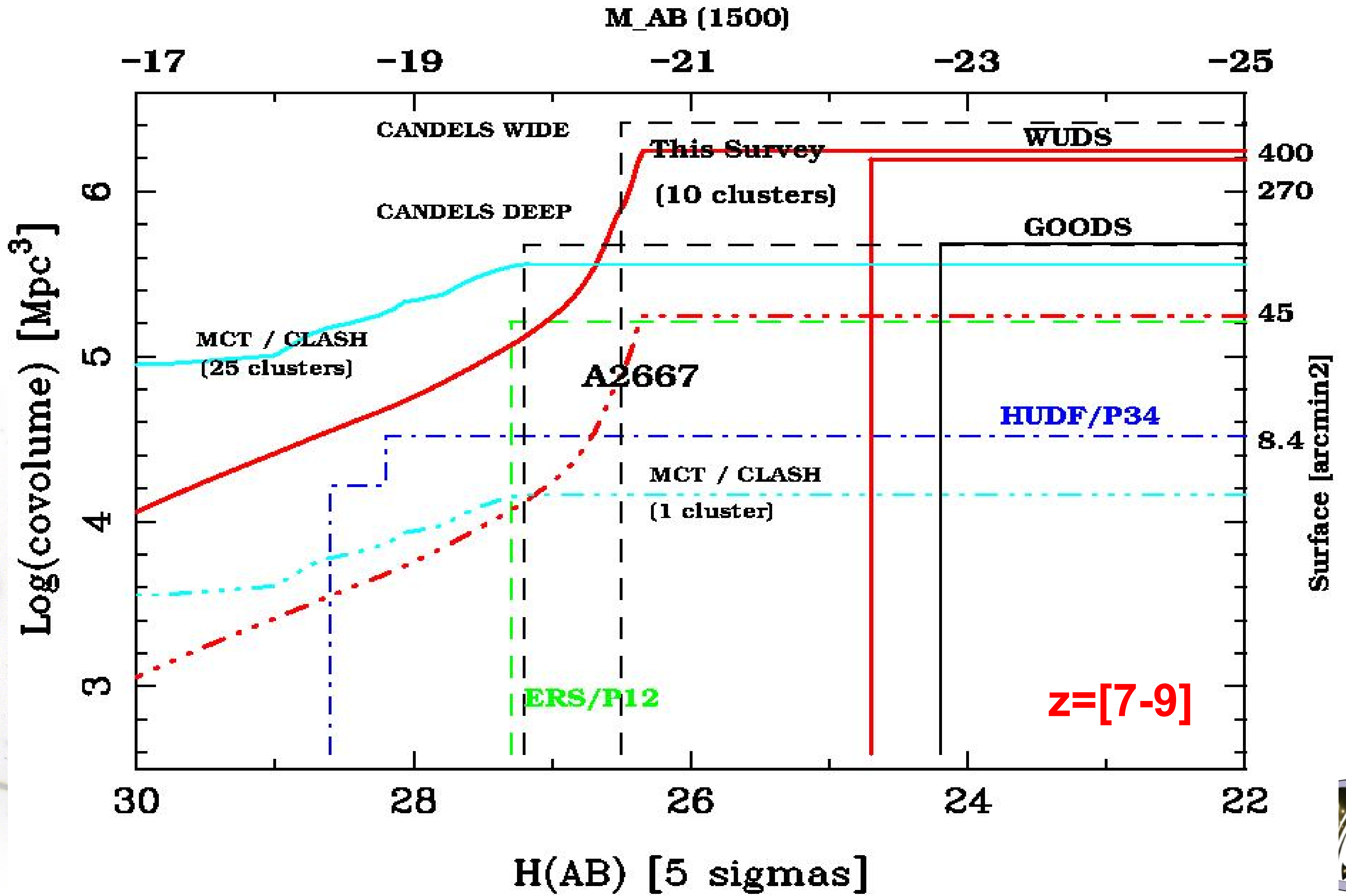
**Ex. AC114, z=[7.5-8.5], evolving LF**

# Lensing versus blank fields : a matter of efficiency

- **Summary :**
  - For magnitude-limited samples of z>6-7 LBGs, magnification efficiency increases with z, and decreases with survey depth & area.
  - Given the typical FOV of NIR facilities, maximum efficiency is reached for z(cluster)~0.1-0.3.
  - Relative efficiency between lensing and BF strongly depends on the actual shape of the LF
  - Lensing fields are particularly efficient for “shallow” (ground based &/or spectroscopic) surveys. The strong evolution observed in the LF increases this effect!
  - A combination between (wide) blank and lensing fields is needed to correctly probe the bright & faint end of the LF

# Current surveys & (future) results

**Current lensing & BF surveys, looking for LBGs** (a personal view...)



# Current surveys & results

## CLASH Survey (Cluster Lensing And Supernova survey with Hubble)

*Postman et al. (2012)*

Multi-cycle Treasury Program

- 524 HST orbits
- 25 clusters
- 20 are X-ray massive clusters (reducing biaises...)
- 5 are well-known lensing clusters
- Deep exposures in 16 broad-band filters, from near-UV to NIR ==> reliable photometric redshifts up to AB~ 26

CLASH Cluster Sample

| Cluster name | $z$ | Cluster name | $z$ |
|---|---|---|---|
| Abell 383 | 0.187 | MACSJ0416–24 | 0.420 |
| Abell 209 | 0.206 | MACSJ1206–08 | 0.440 |
| Abell 1423 | 0.213 | MACSJ0329–02 | 0.450 |
| Abell 2261 | 0.224 | RXJ1347–1145 | 0.451 |
| RXJ2129+0005 | 0.234 | MACSJ1311–03 | 0.494 |
| Abell 611 | 0.288 | MACSJ1149+22 | 0.544 |
| MS 2137–2353 | 0.313 | MACSJ1423+24 | 0.545 |
| MACSJ1532+30 | 0.345 | MACSJ0717+37 | 0.548 |
| RXJ2248–4431 | 0.348 | MACS2129–07 | 0.570 |
| MACSJ1931–26 | 0.352 | MACSJ0647+70 | 0.584 |
| MACSJ1115+01 | 0.352 | MACSJ0744+39 | 0.686 |
| MACSJ1720+35 | 0.391 | CLJ1226+3332 | 0.890 |
| MACSJ0429–02 | 0.399 | | |

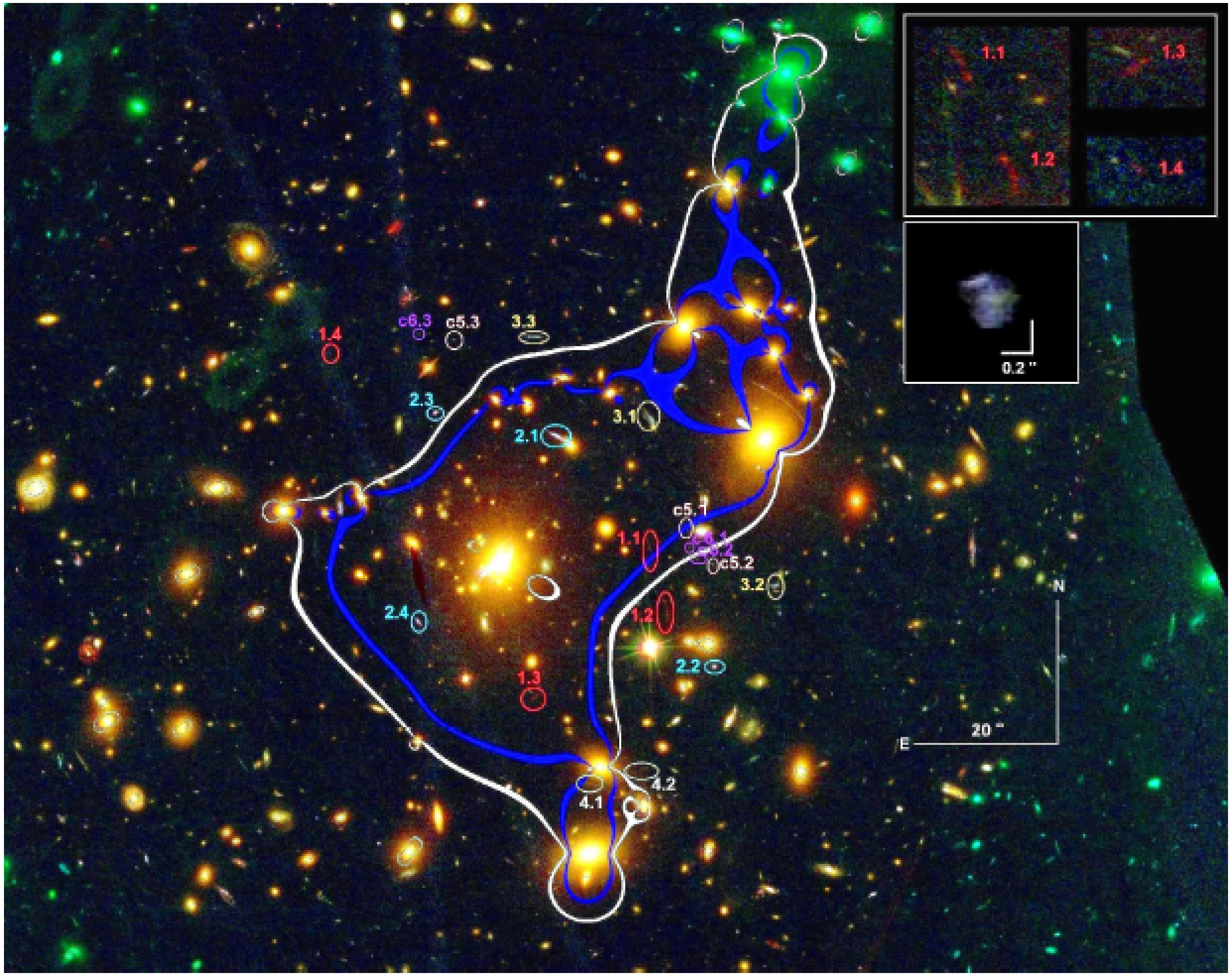
# Current surveys & results

## CLASH Survey (Cluster Lensing And Supernova survey with Hubble)

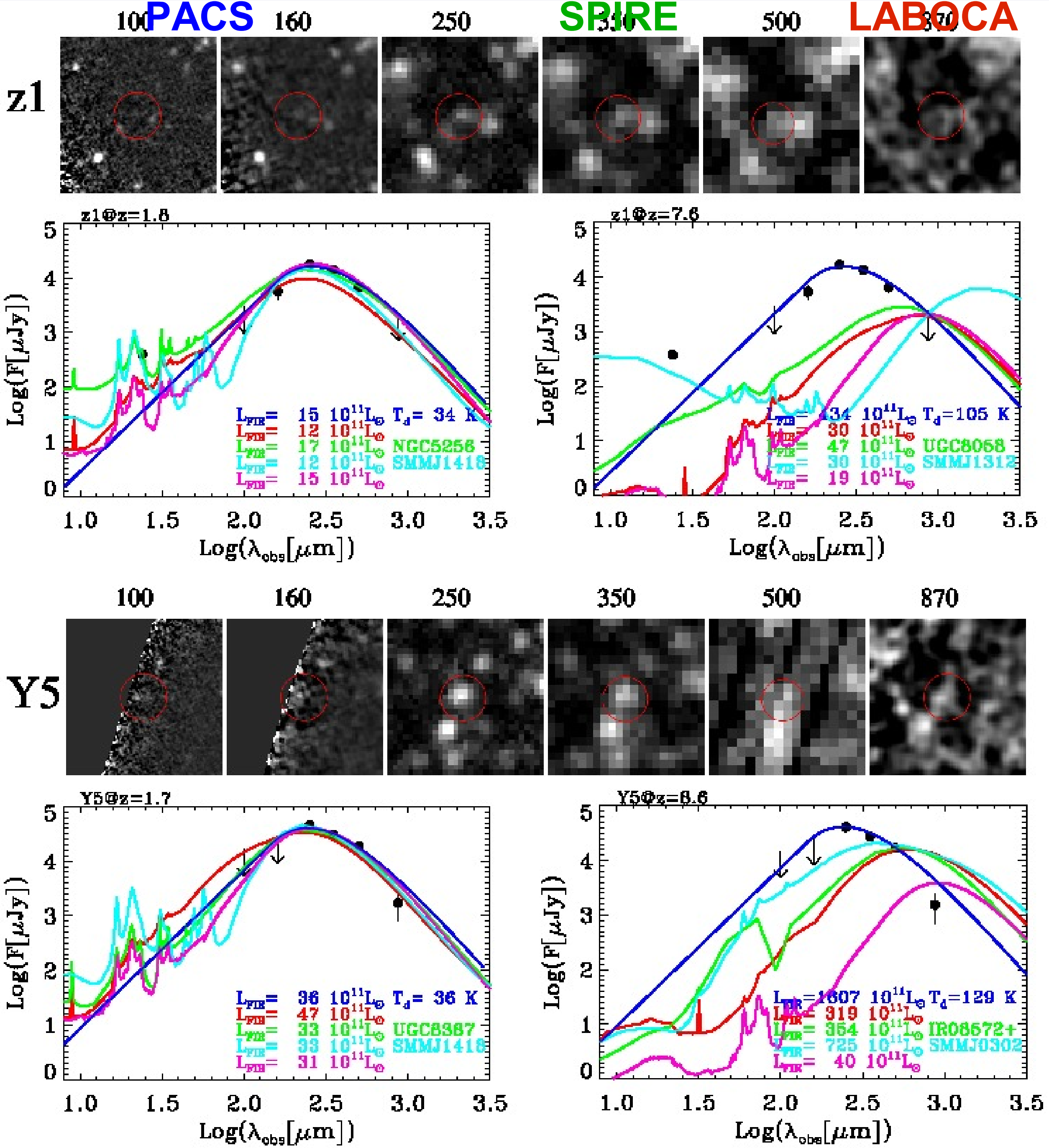
*Zitrin et al. (2012)*

A quadruply-lensed galaxy at z~6.2 behind MACS J0329

- z(photomectric)=6.18
- Magnification ranging between 3 and 17
- SFR ~ 3 solar masses/yr
- M(stellar) ~ $10^9$ solar masses



# Survey Results: mid-z contamination



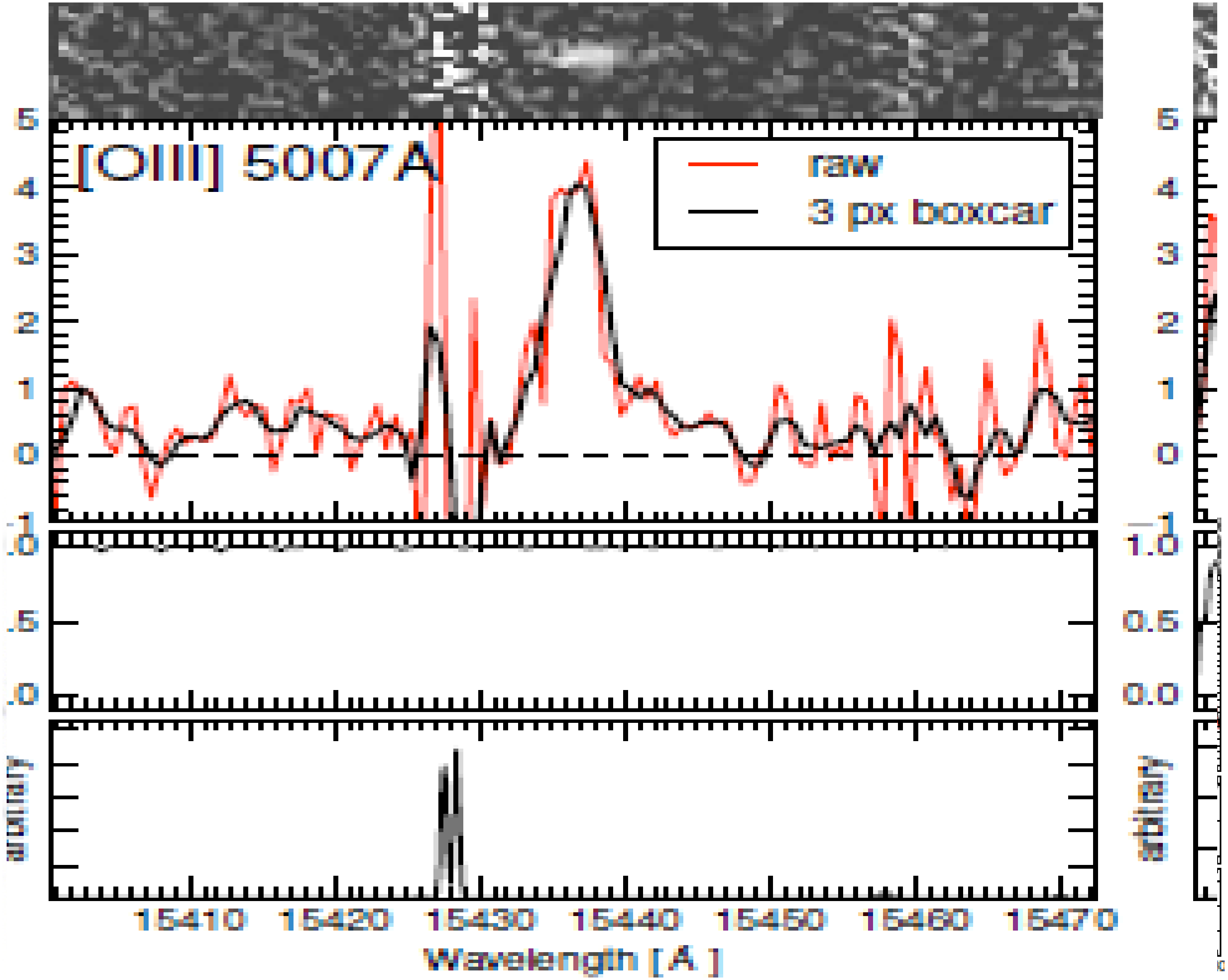
**HERSCHEL LENSING SURVEY (HSL) +**

**LABOCA/APEX**

- Two out of 10 candidates clearly detected
- Based on analysis of FIR SED: ***Bonne et al. 2011***
  - Typical ULIRGs/SMGs at z~2 (more likely!)
  - Z~7.5-8.5 galaxies with dust T~100K and L~$10^{13}$ L_solar
- If at mid-z, standard templates fail to reproduce the optical-near-IR par of the SED

# Survey Results: mid-z contamination

*Hayes et al. 2012*



**Spectroscopic observations of A2667-J1 with X-Shooter**

- “Bright” m(H)~25.4 candidate
- ~1h exposure time !
- A prominent, asymetric, e-line
- Several additional emission-lines detected after further inspection : z=2.08 interloper
- 2 stellar populations : old dominant + young SF

# Survey Results: mid-z contamination

***Hayes et al. 2012***

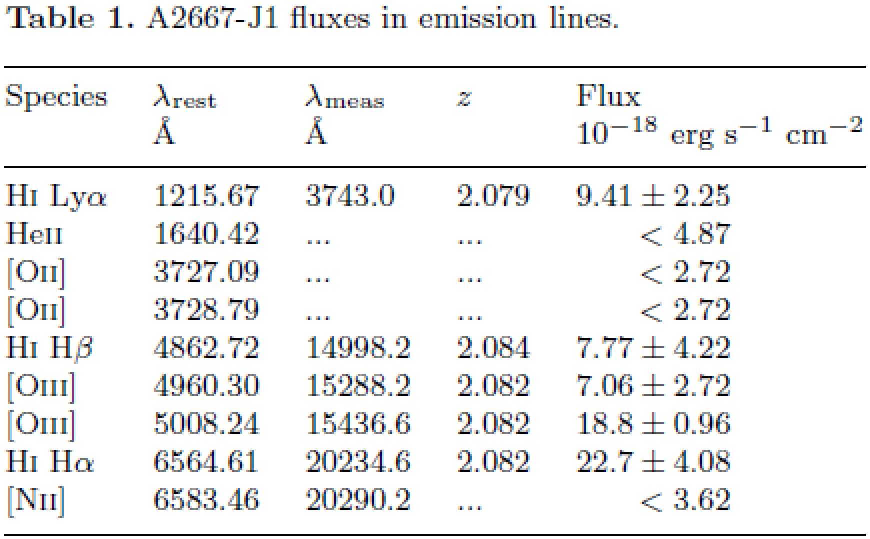
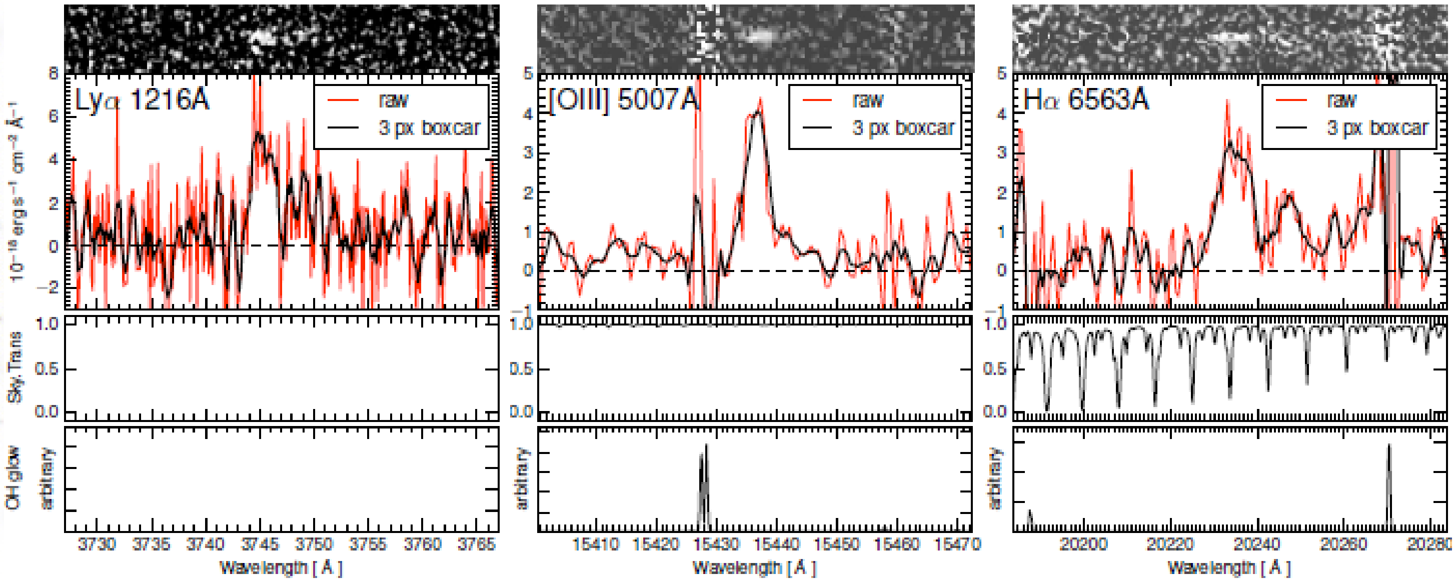


Table 1. A2667-J1 fluxes in emission lines.

| Species | $\lambda_{\rm rest}$ Å | $\lambda_{\rm meas}$ Å | $z$ | Flux $10^{-18}$ erg s$^{-1}$ cm$^{-2}$ |
|---|---|---|---|---|
| HI Ly$\alpha$ | 1215.67 | 3743.0 | 2.079 | $9.41 \pm 2.25$ |
| HeII | 1640.42 | ... | ... | $< 4.87$ |
| [OII] | 3727.09 | ... | ... | $< 2.72$ |
| [OII] | 3728.79 | ... | ... | $< 2.72$ |
| HI H$\beta$ | 4862.72 | 14998.2 | 2.084 | $7.77 \pm 4.22$ |
| [OIII] | 4960.30 | 15288.2 | 2.082 | $7.06 \pm 2.72$ |
| [OIII] | 5008.24 | 15436.6 | 2.082 | $18.8 \pm 0.96$ |
| HI H$\alpha$ | 6564.61 | 20234.6 | 2.082 | $22.7 \pm 4.08$ |
| [NII] | 6583.46 | 20290.2 | ... | $< 3.62$ |

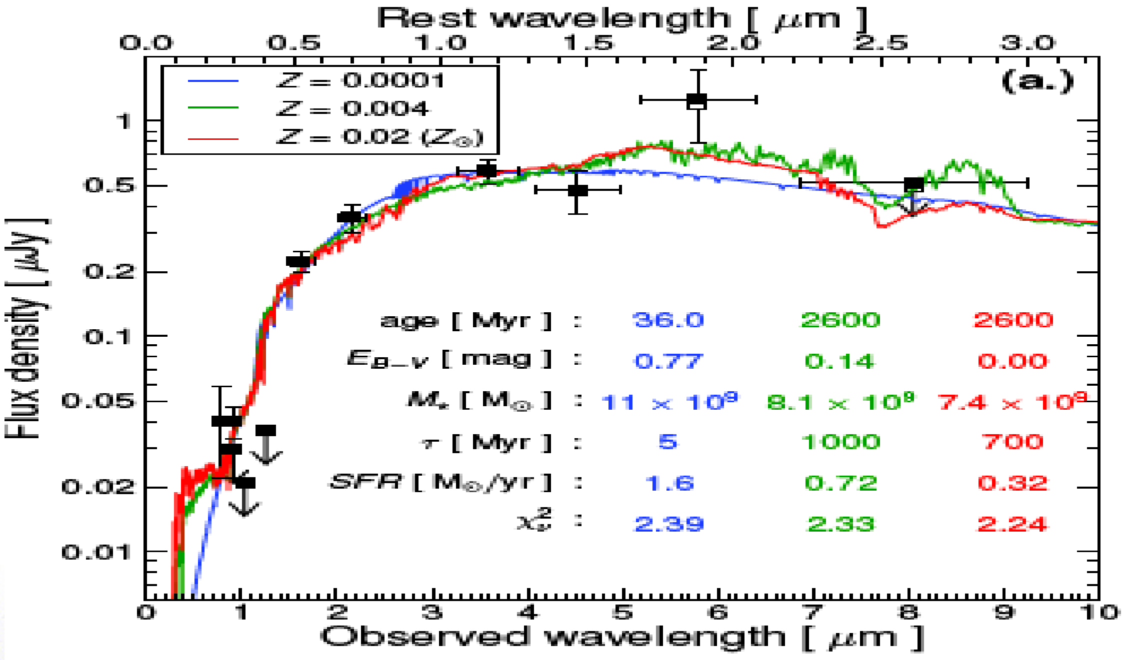


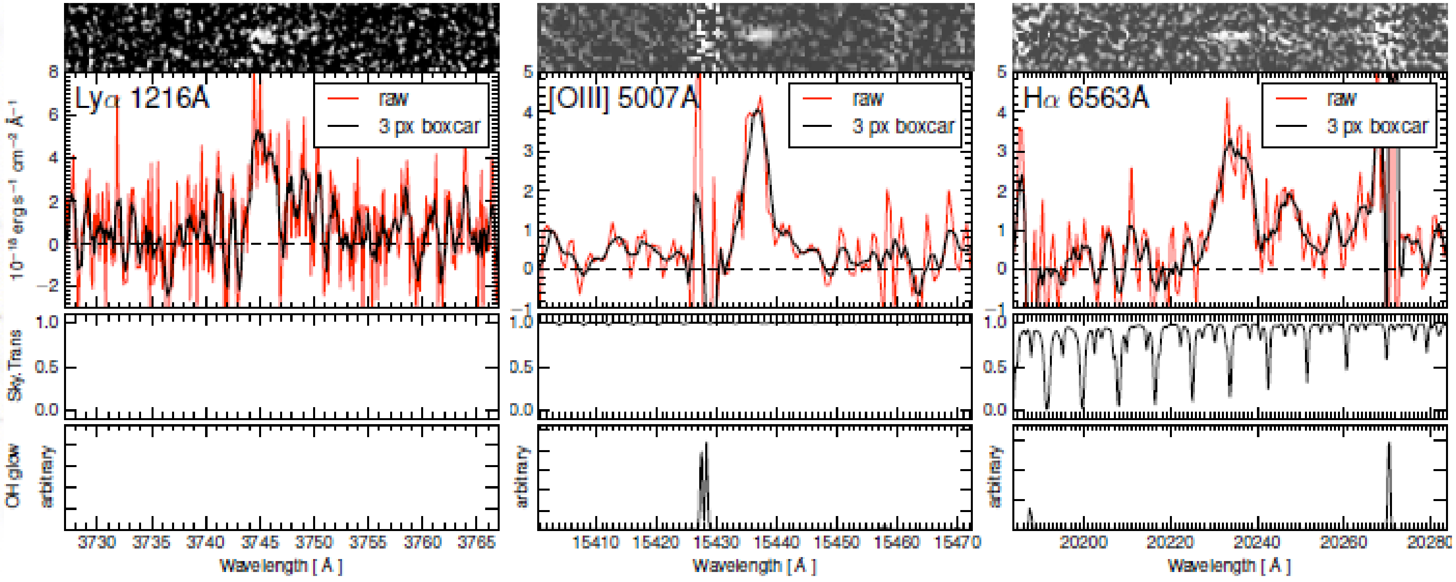
## Spectroscopic observations of A2667-J1 with X-Shooter

- “Bright” m(H)~25.4 candidate
- ~1h exposure time !
- A prominent, asymetric, e-line
- Several additional emission-lines detected after further inspection : z=2.08 interloper
- 2 stellar populations : old dominant + young SF

# Survey Results: mid-z contamination

***Hayes et al. 2012***





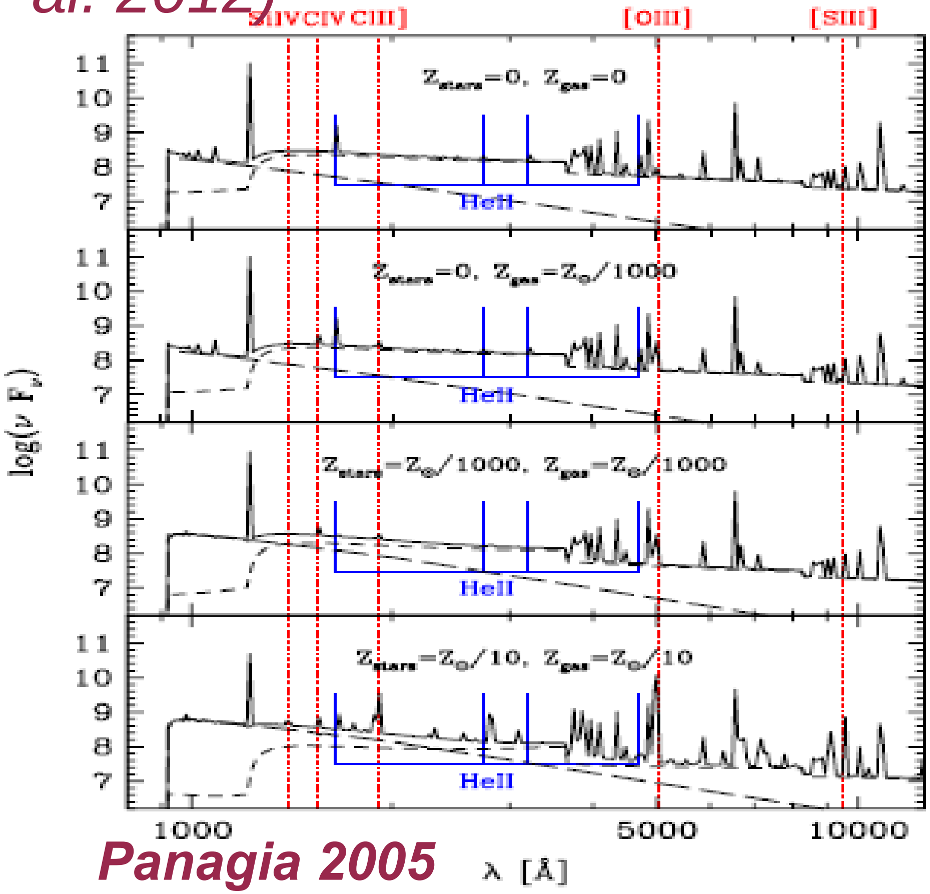
**Spectroscopic observations of A2667-J1 with X-Shooter**

- 2 stellar populations : old dominant one (break) + young SF one (e-lines)
- **If such contaminants are present on H(AB)~28 samples, utra-deep V(AB)~32 will be needed to suppress these interlopers !**

# Survey Results: physical parameters

- Several approaches:
  - SED fitting procedures. Rely on “template” libraries, dependence on the parameter space and effective wavelength coverage. Degenerate solutions.
  - Spectroscopy : poor S/N of high-z sources. Limited wavelength coverage. No multi-object NIR spectrographs available (coming soon...)
  - A combination of both...

- *Nebular e-lines are susceptible to contribute to broad-band integrated flux ==> errors in redshift for LBGs & SED-fitting degeneracies (see e.g. Schaerer+ 2011, De Barros et al. 2012)*



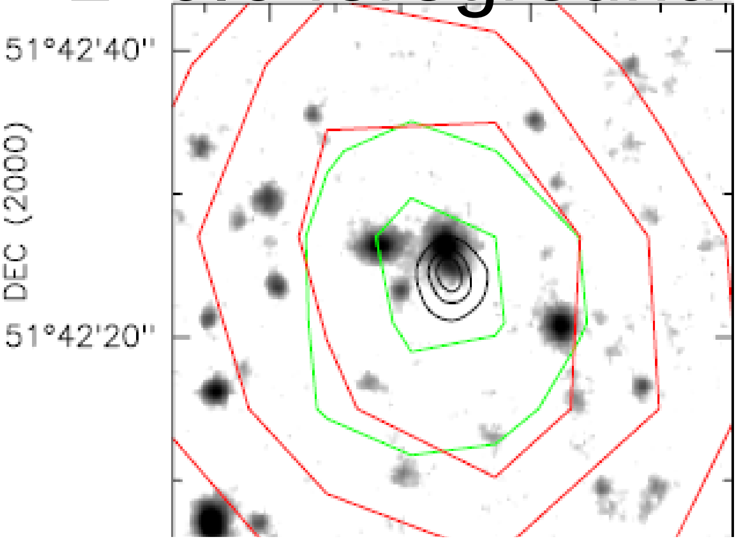
***Panagia 2005***

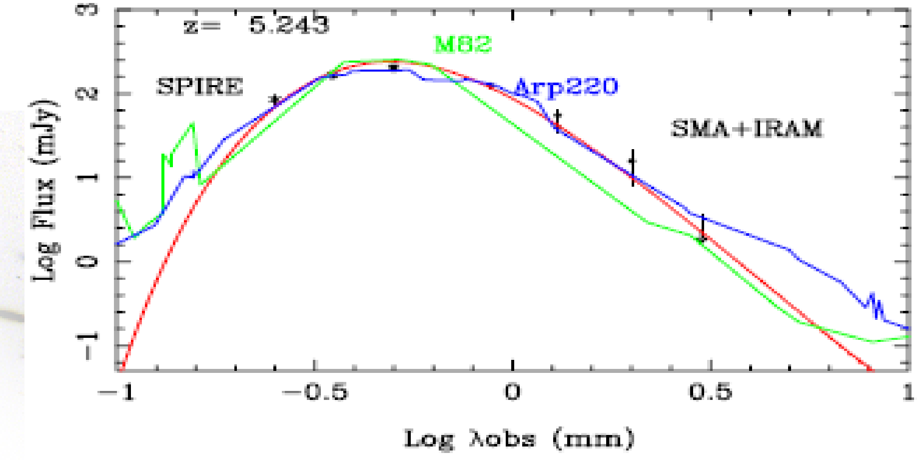
# Survey Results: physical parameters

## A bright z = 5.2 lensed submillimeter galaxy in the field of Abell 773

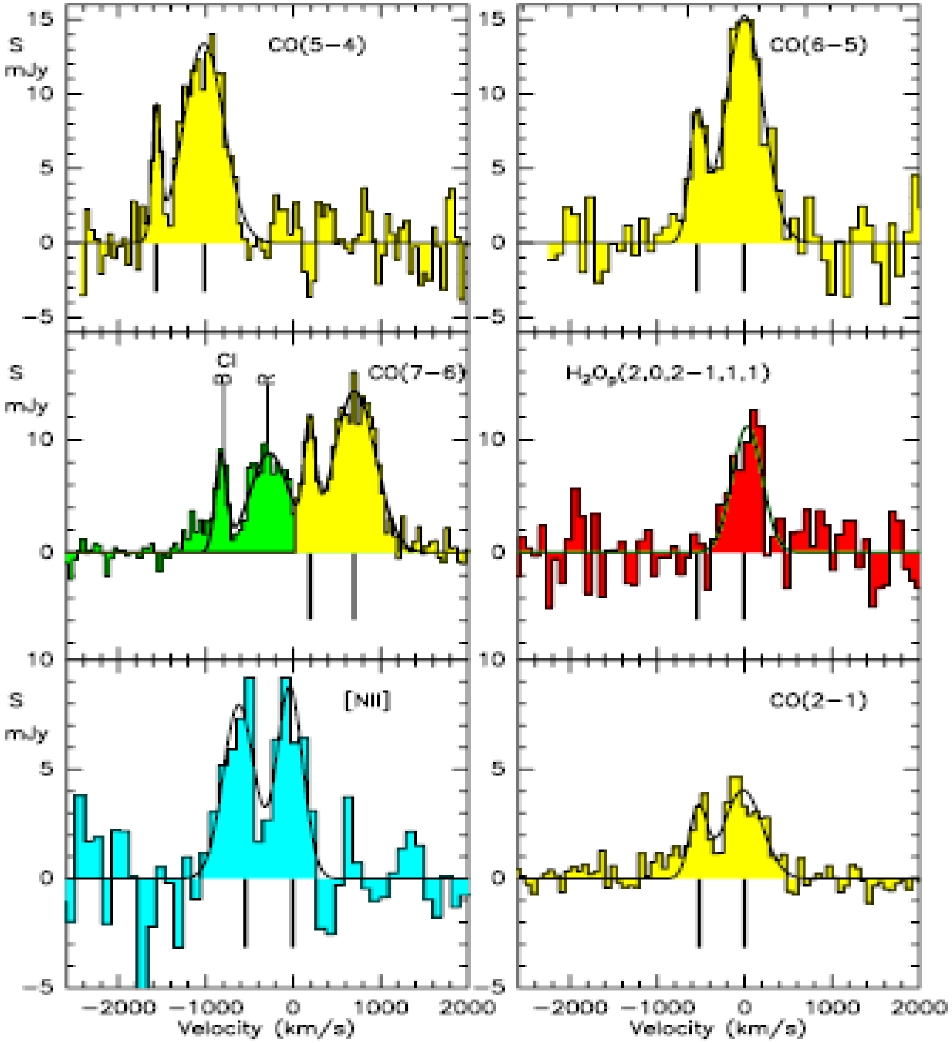
- Double-lensed by a z=0.6 foreground galaxy

*Combes et al. (2012)*





s: ]

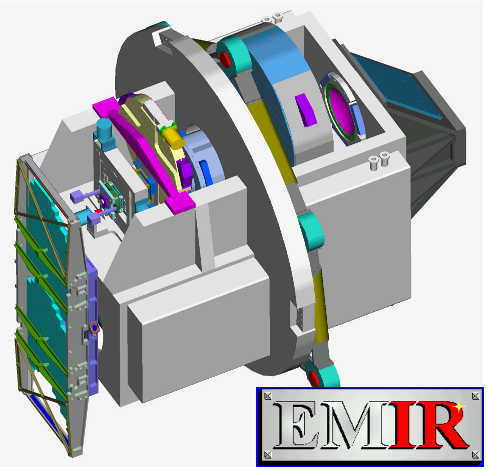


# Future developments

- New “massive” surveys are expected, some already planned (e.g. EUCLID)
  - Finding new z~> 6-7 sources (large FOV), bright enough to be studied in details
  - Finding new lensing clusters susceptible to be used as GTs
- Arrival of new ground-based & space facilities with improved efficiency
  - Multi-object spectrographs in the NIR
  - 3D spectrographs in the visible & NIR
  - ALMA, JWST, ELTs, …

# A new generation of NIR spectrographs :

GTC Installations at ORM 28/06/2002 14:00



## GTC -EMIR (~2013?):

Looking for galaxies at $z > 7$
goal of the Survey GOYA/GTC

VIMOS Mask Design on Pre-Image

ESO PR Photo 09k/02 (13 March 2002 ) © European Southern Observatory

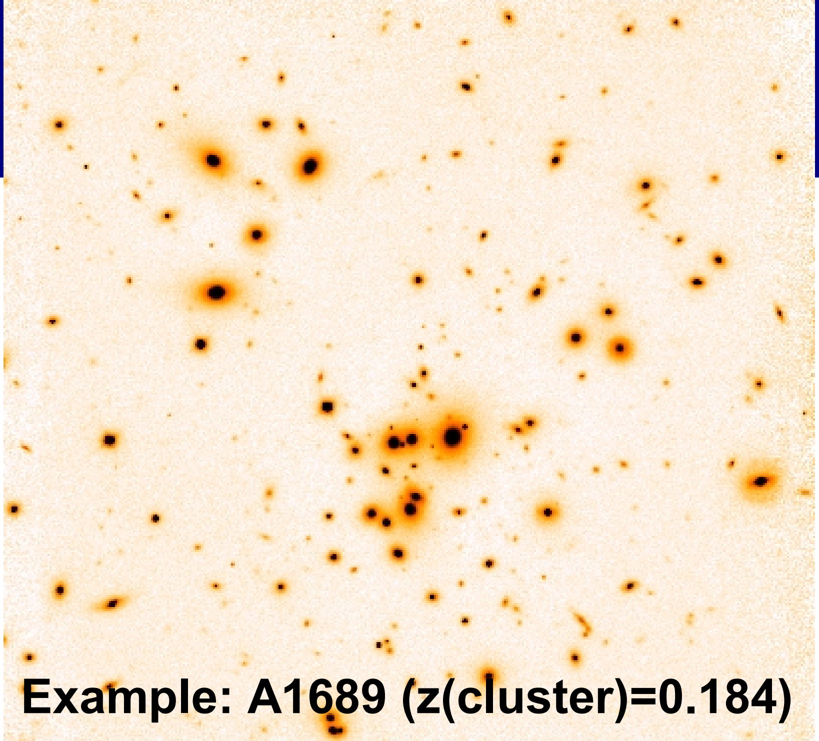
**Gain : a factor of ~50 in lensing clusters with respect to current facilities**

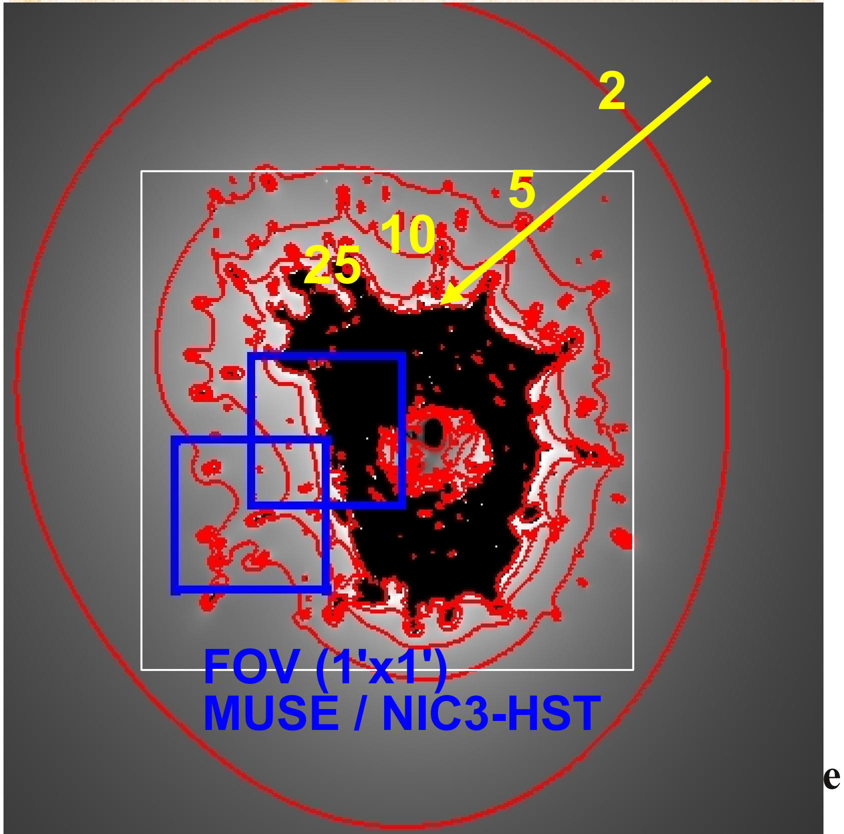
## VLT 2nd generation (~2013)

**KMOS : NIR**

**MUSE : Optical domain (3D)**

# Future developments

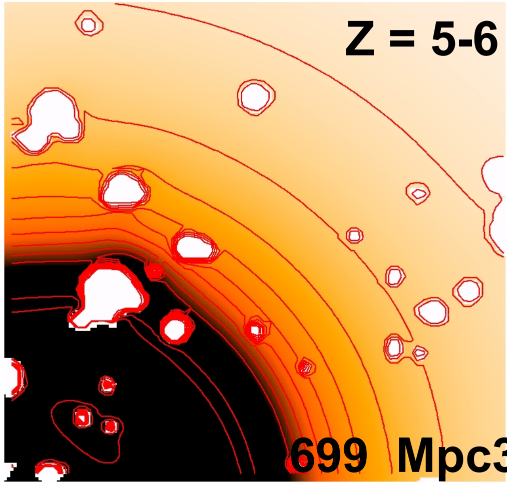

Example: A1689 (z(cluster)=0.184)



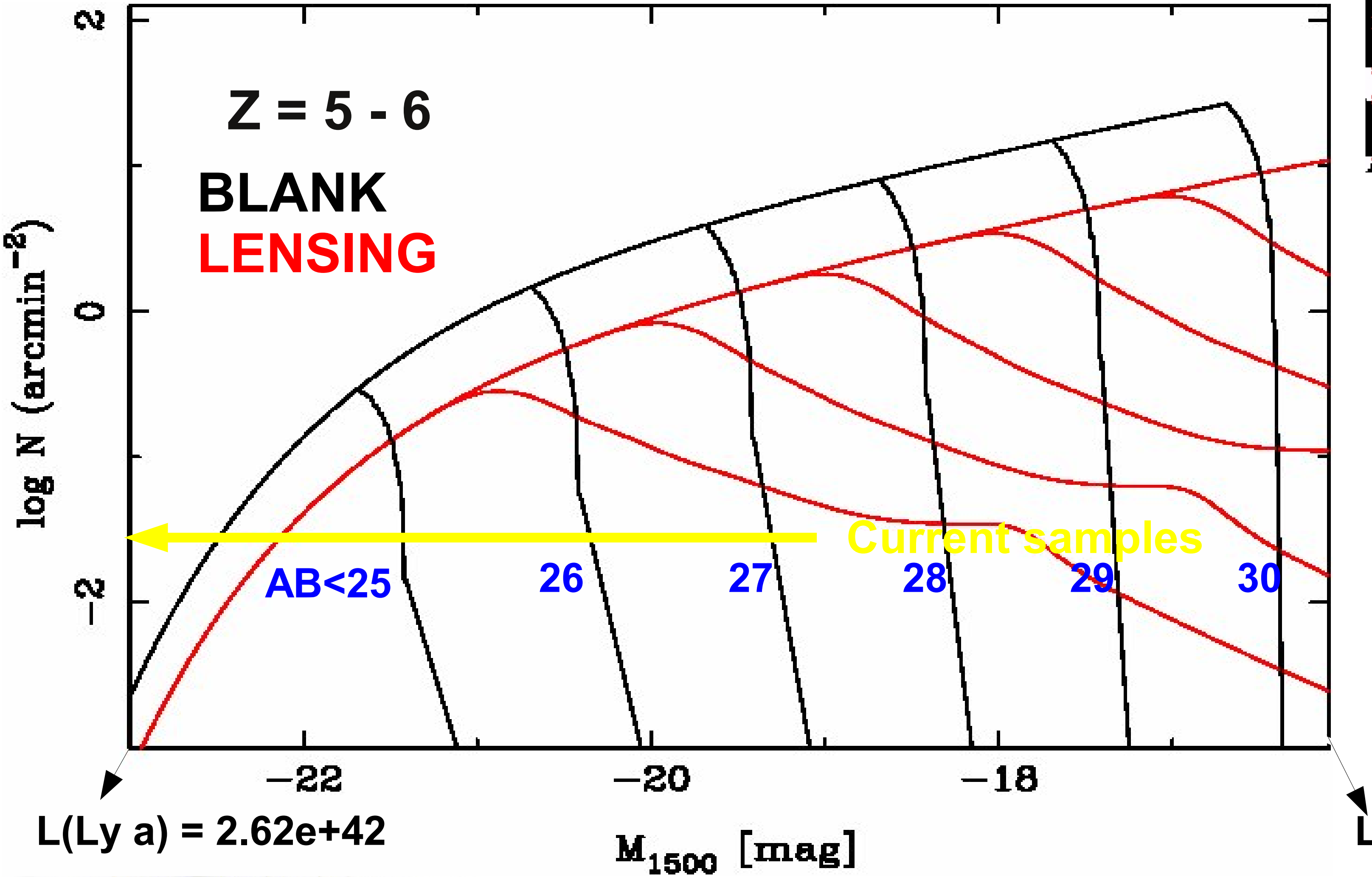
## 3D Spectroscopy around the critical lines in lensing clusters (MUSE & KMOS @ VLT)

- **Gain in the number of sources accessible for detailed studies because the slope of the LF is relatively steep (Bradac et al. 2010, Maizy 2010)**
- **First blind comparison between LBGs and LAEs within the same volume, for z~5 to 8.**
- **Characterization of (intrinsically) faint star-forming galaxies responsible for the reionization.**

# Future developments



Lensing and BF sample **different intrinsic luminosities.**



**L(Ly a) = 2.62e+42**

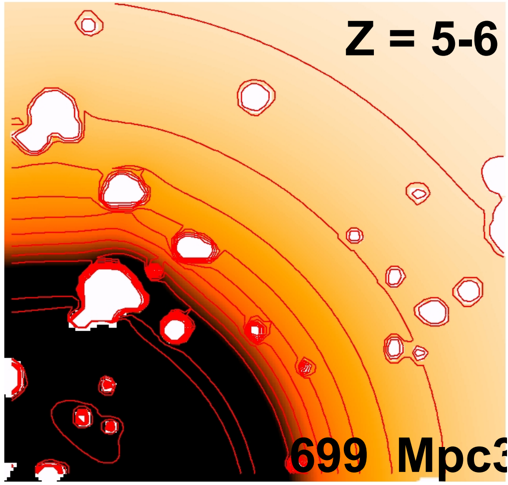
**L(Ly a) = 4.15e+39**

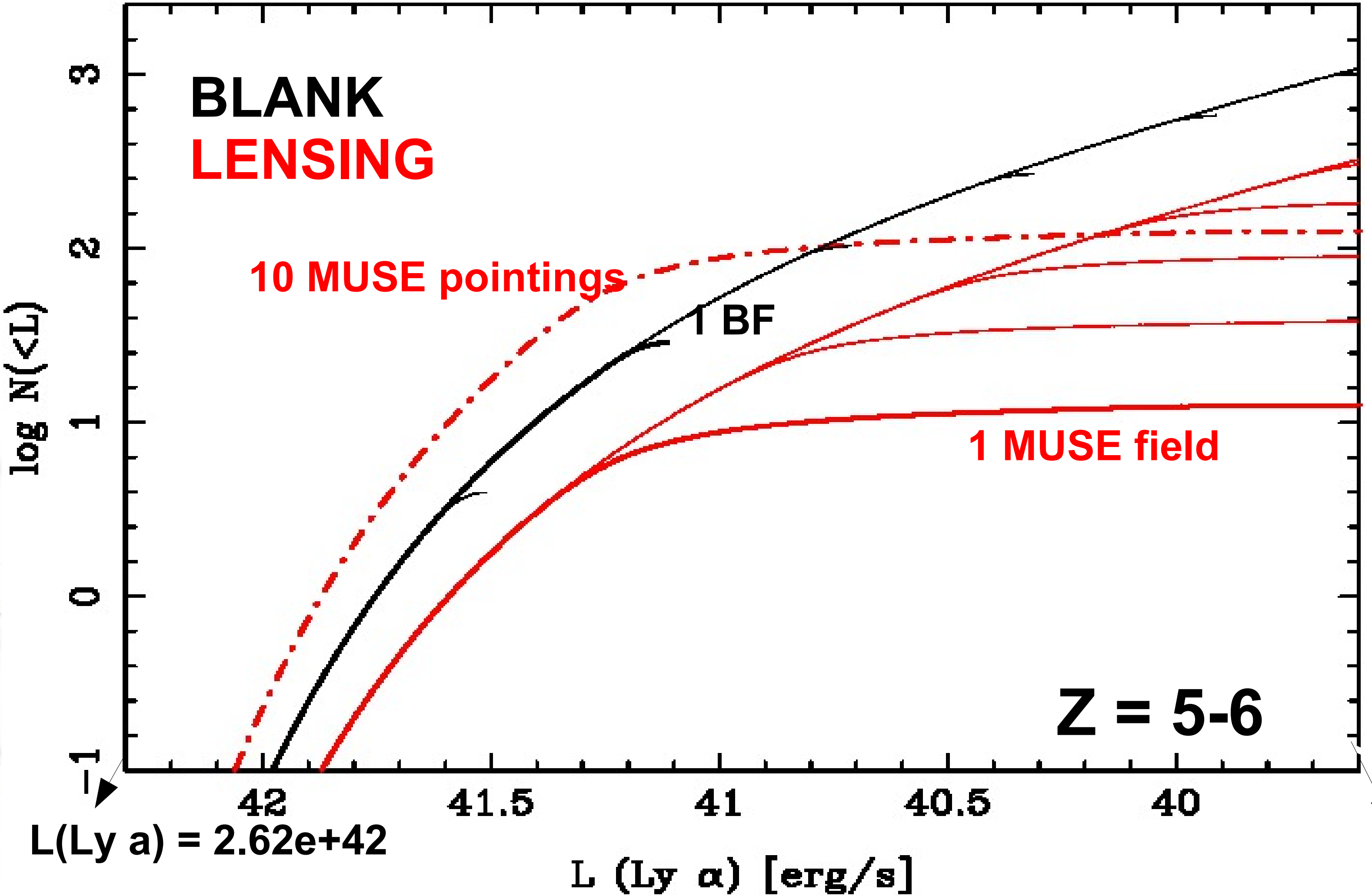
**Mean magnification Factor μ ~ 34**

**When limited to μ < 100 :**
**<μ> ~ 8.7**
**(median ~ 3.2)**

# Future developments

Lensing and BF sample **different intrinsic luminosities.**





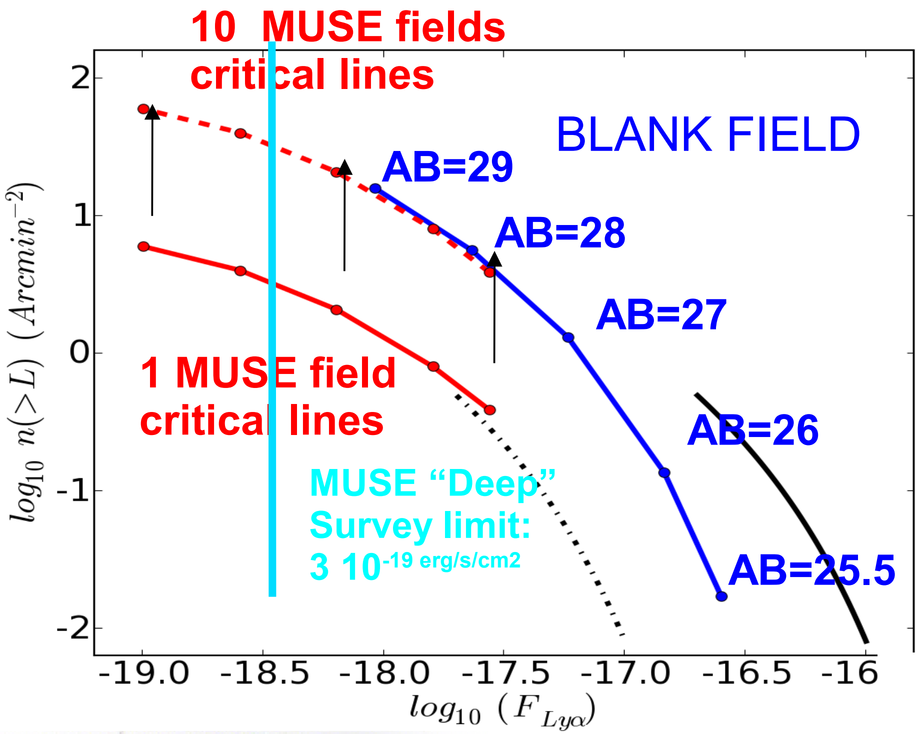
**L(Ly a) = 2.62e+42**

**L(Ly a) = 4.15e+39**

**Mean magnification Factor $\mu \sim 34$**

**When limited to $\mu < 100$ : $\langle\mu\rangle \sim 8.7$ (median ~ 3.2)**

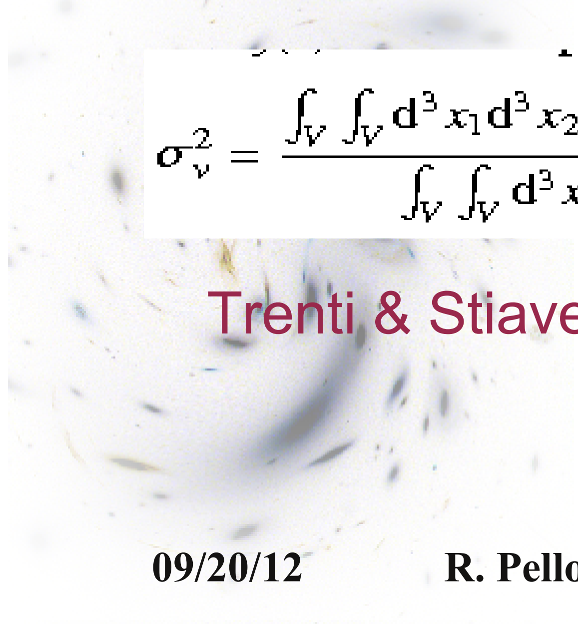
# Future developments



**Errors in Lensing models:**

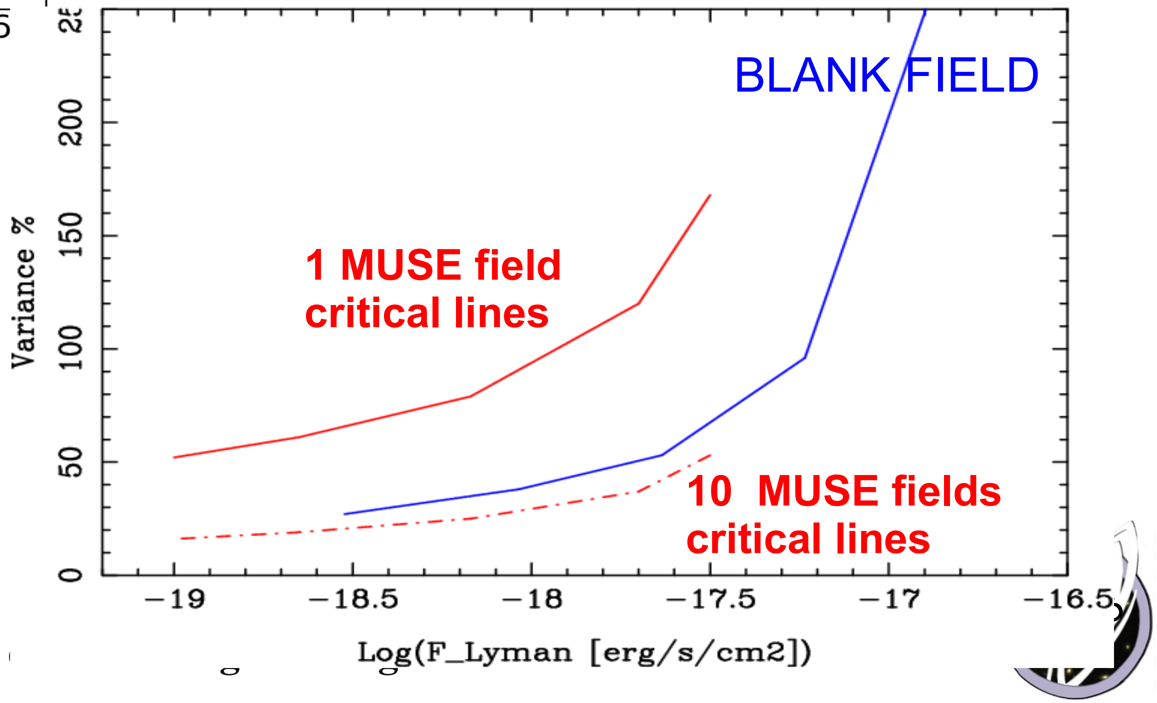
**m_AB=25.5 => 23%**
**m_AB=26.0 => 17%**
**m_AB=27.0 => 11%**
**m_AB=28.0 => 7%**
**m_AB=29.0 => 5%**

**1 MUSE field /**

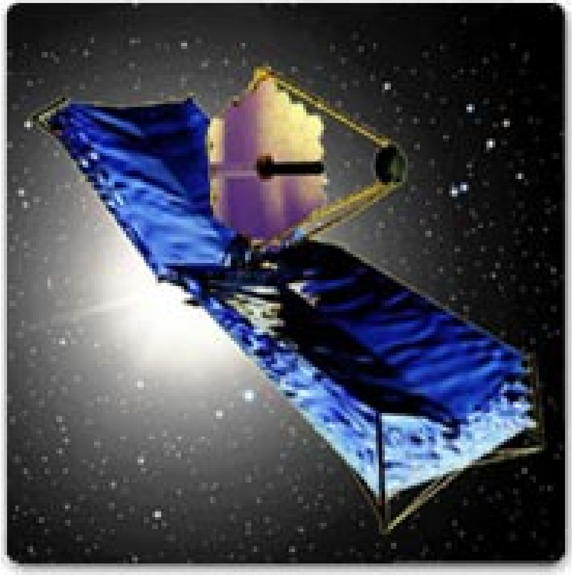


$$\sigma_v^2 = \frac{\int_V \int_V d^3x_1 d^3x_2 \xi(|x_1 - x_2|)}{\int_V \int_V d^3x_1 d^3x_2}$$

Trenti & Stiavelly (2008)

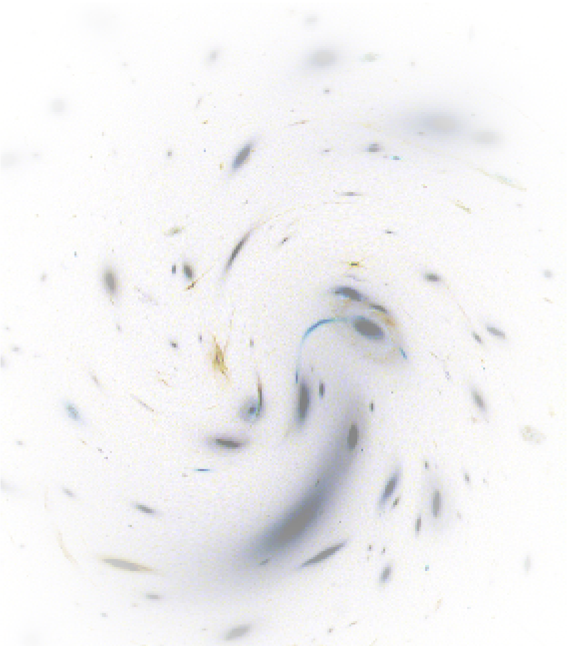


# The new generation of space telescopes :

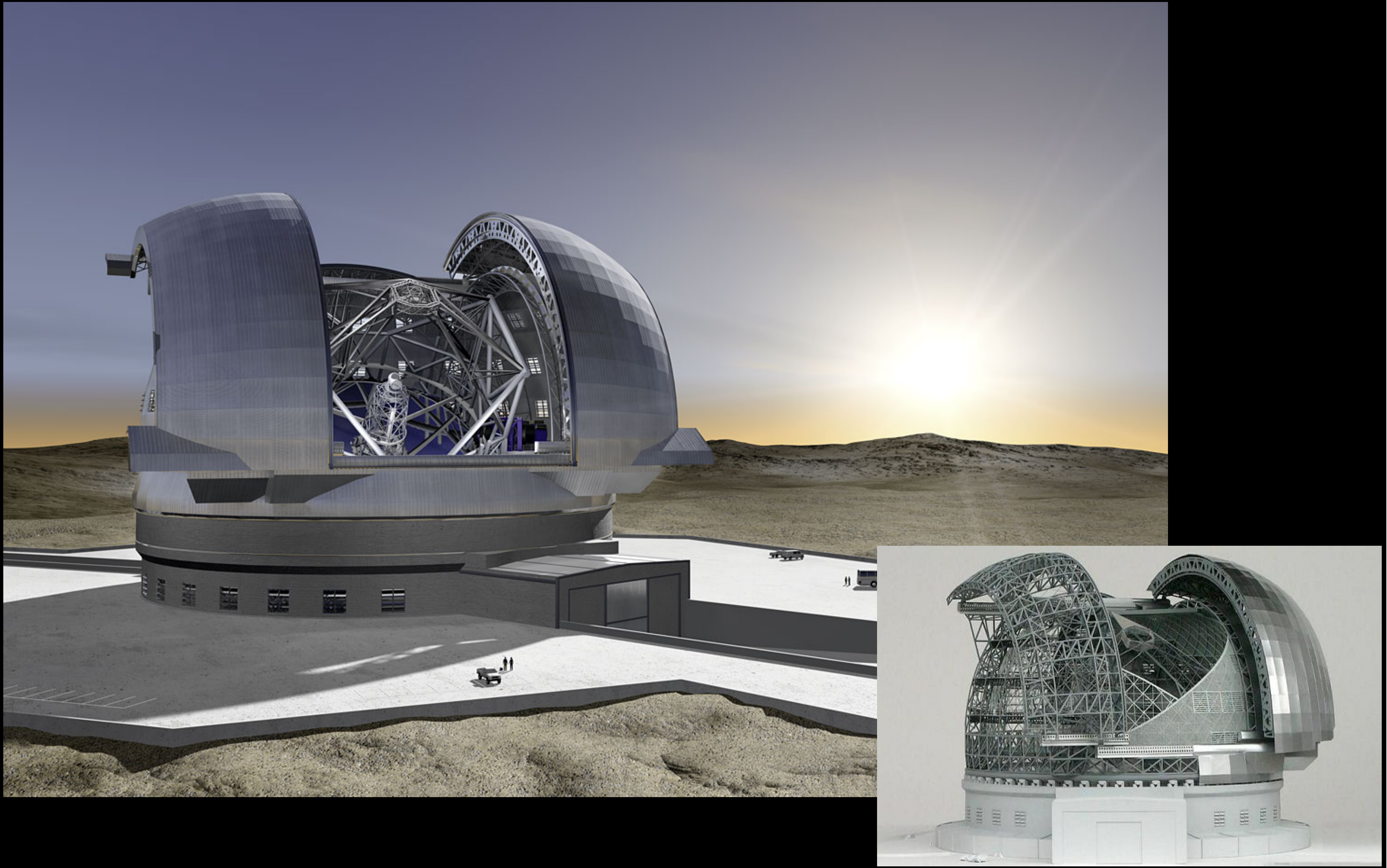


**JWST (>~2017 ???):**

**Systematic search for z~>10 galaxies**



# Les “Extremely Large” télescopes (ELT)



# Discussion/Conclusions

- Lensing fields have contributed and should continue to play a major role in the study of the most distant galaxies (see also JPK and JR's lectures).
- The relative efficiency of lensing with respect to blank fields strongly depends on the shape of the LF, for a given photometric depth and FOV. Efficiency of GTs increases with z, in particular for “shallow” (ground-based & spectroscopic) surveys, and for strongly evolving LF. The combined use of lensing and blank fields is likely to yield strong constraints on the LF around L* to 10L*. Lensing fields are more efficient for L<<L* (see e.g. Richard et al. 2008)
- Spectroscopy (in particular in the NIR, and using 3D facilities) is needed, not only to prevent for contamination, but also to determine the physical properties of the first galaxies ==> breaking degeneracies wrt theoretical/numerical models (Lecture 1)

# Thanks !