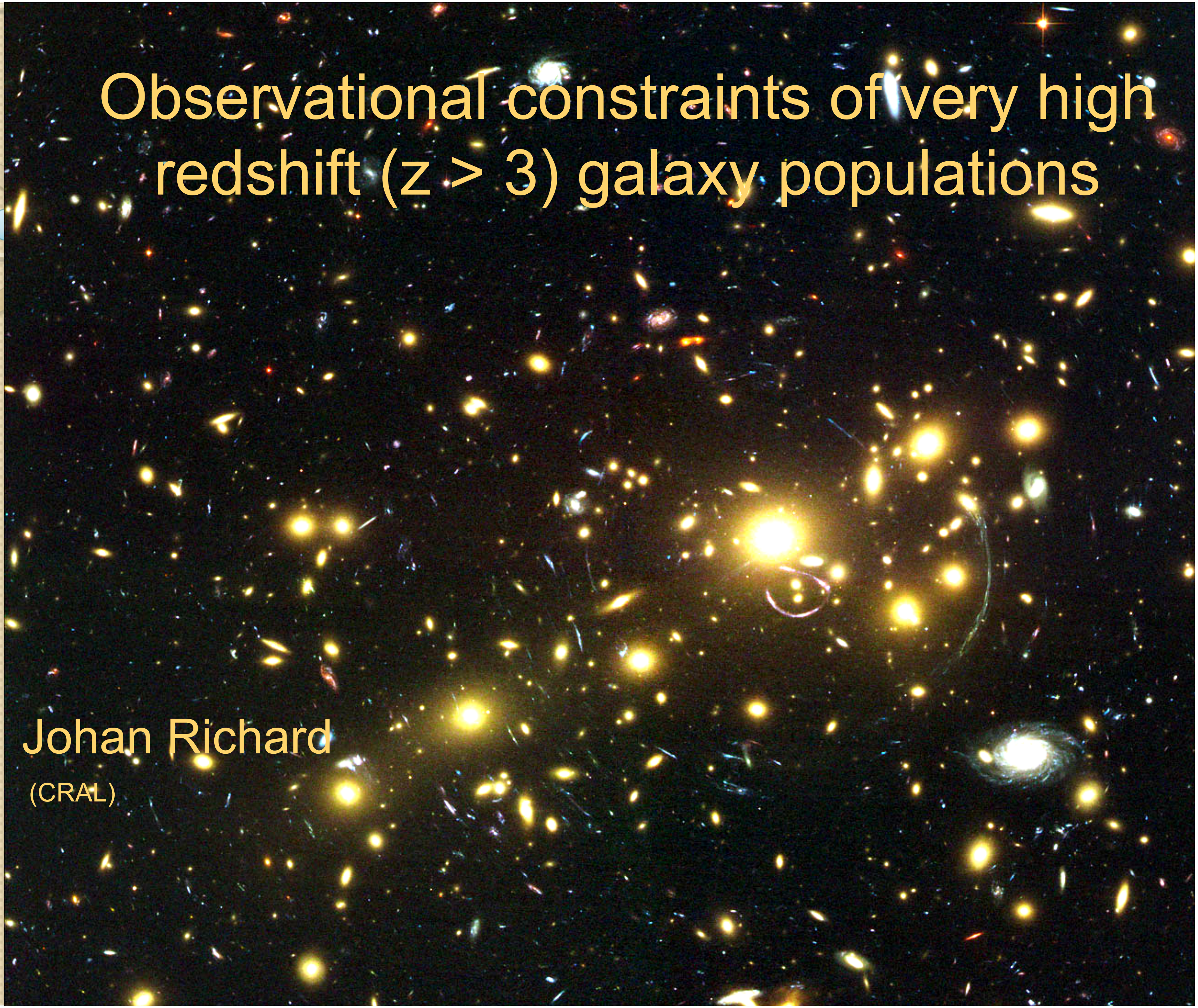
Observational constraints of very high redshift (z > 3) galaxy populations



Johan Richard

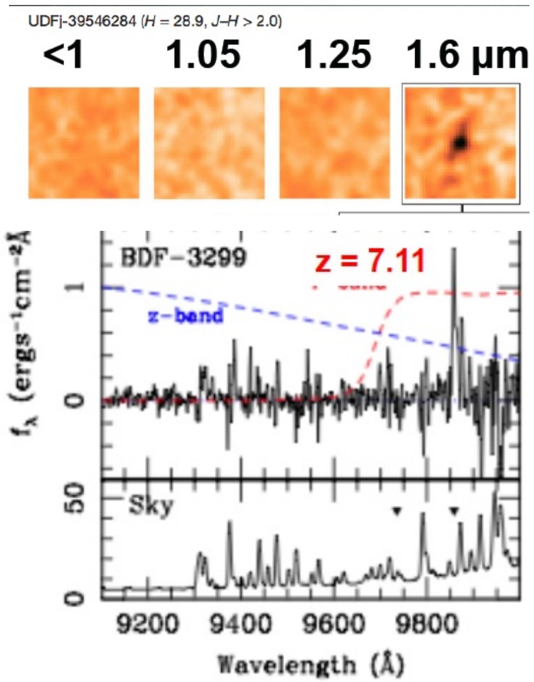
(CRAL)

Outline

• Motivations and observational techniques

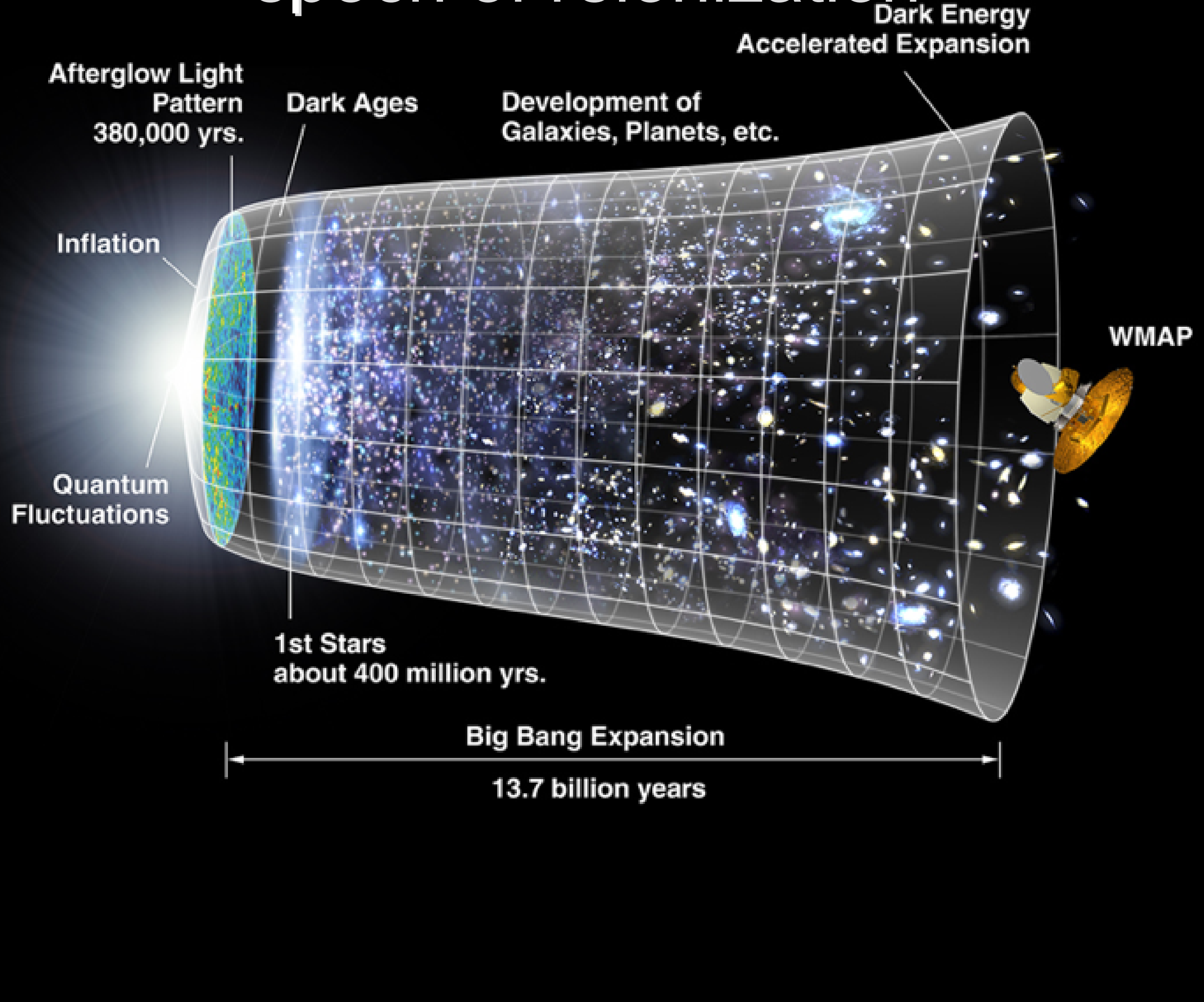
• Results from photometric, spectroscopic and narrow-band surveys

• Gravitational lensing can help you



Very high redshift:

epoch of reionization



Galaxy evolution at high redshift

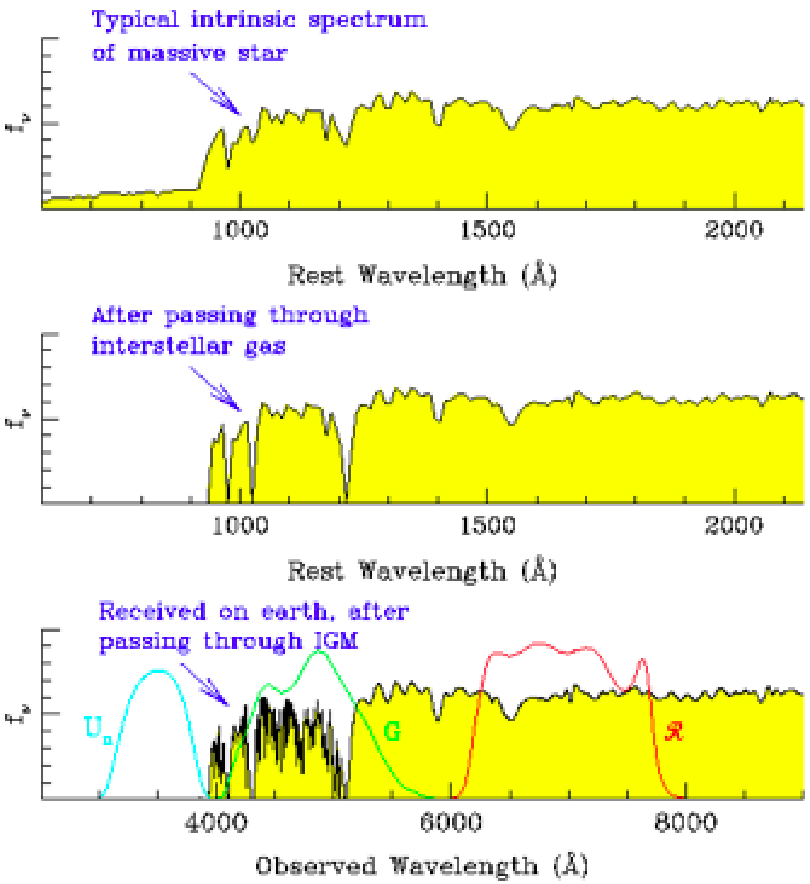
Study **galaxy assembling** at z > 3: test early stellar formation of massive galaxies observed at z=1-2

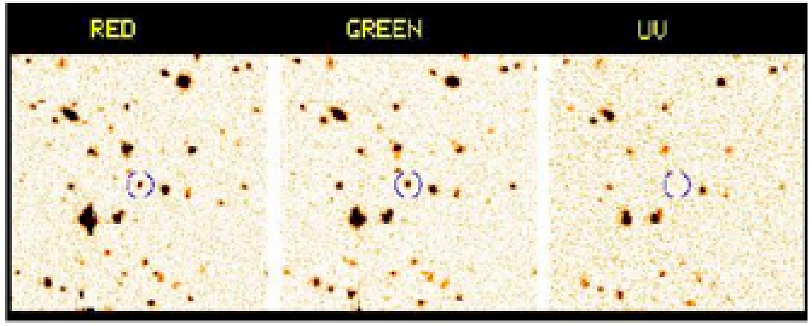
Internal properties of early galaxies, such as their dynamical state and the distribution of their star-forming regions, provide key tests of galaxy formation models.

In particular, **analysing the dynamics** of high redshift galaxies enables to distinguish chaotic or well-ordered velocity fields, depending on the maturity of the systems.

Obvious limitation: apparent size of the objects

Photometric techniques





Lyman-Break Galaxies

The Lyman continuum discontinuity is particularly powerful for isolating star-forming high redshift galaxies.

From the ground, we have access to the redshift range z~2.5-6.5 in the optical bands.

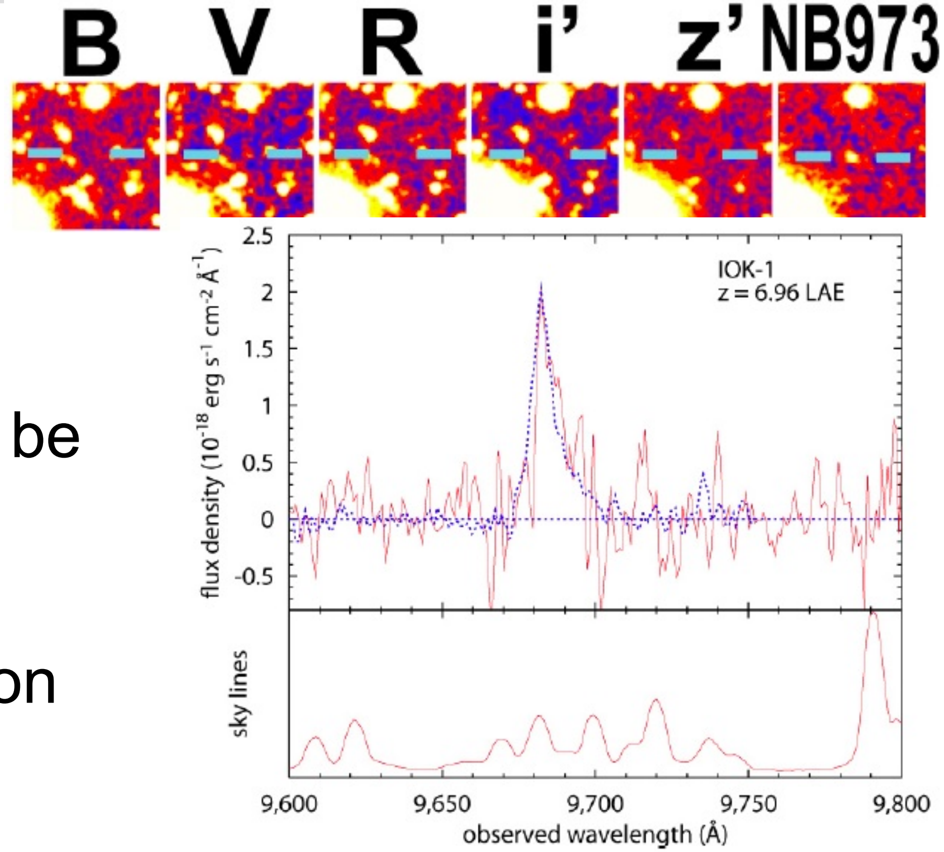
e.g. Steidel et al. 1999, 2004, 2008

Photometric Redshifts:

Generalization of LBG technique with more filters

Spectroscopic techniques

Lyman-α line



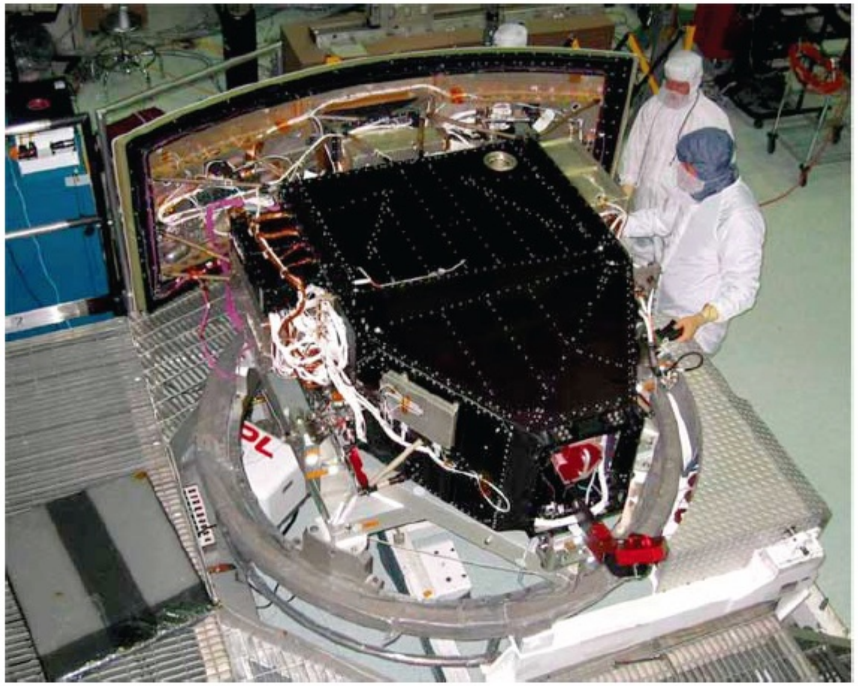
- Optical (z<~7.0) or near-infrared (z>~7.0)
- Main H line at high z, can be very strong (>50 A) and selected by NB filters
- Suffers from self-absorption and scattering

Nebular emission lines

[OIII] and Hβ are located in the K band at z < 4

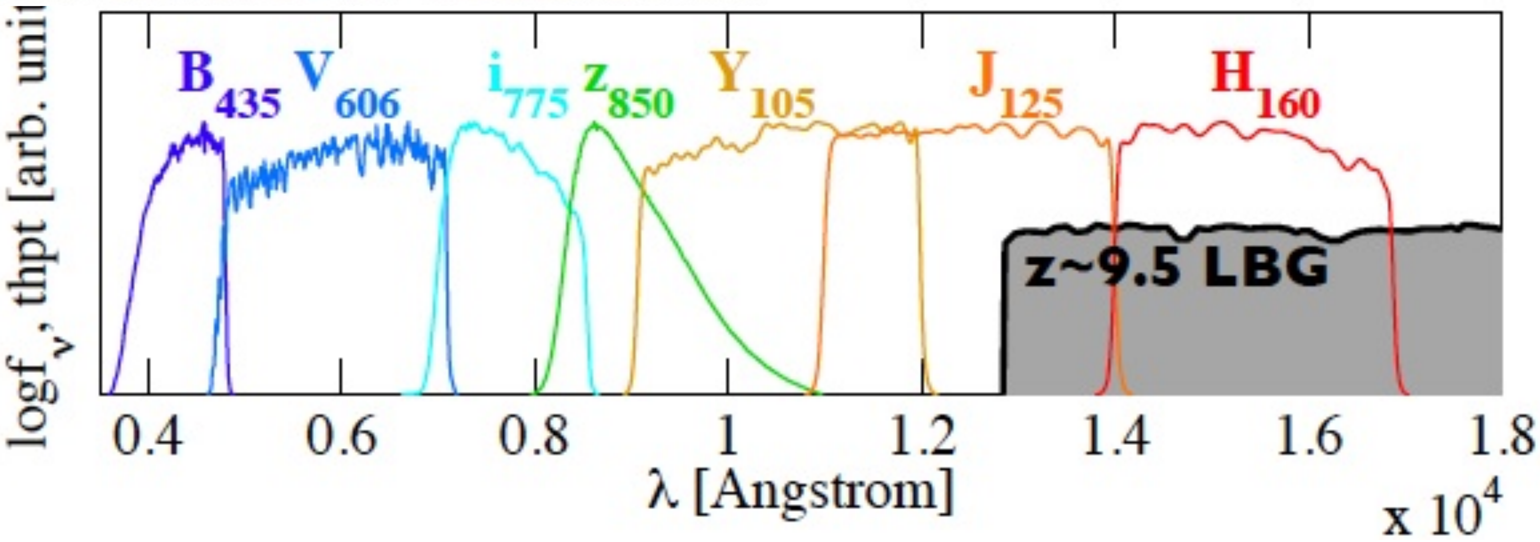
[OII] is potentially visible up to z=5.7

Importance of near-infrared

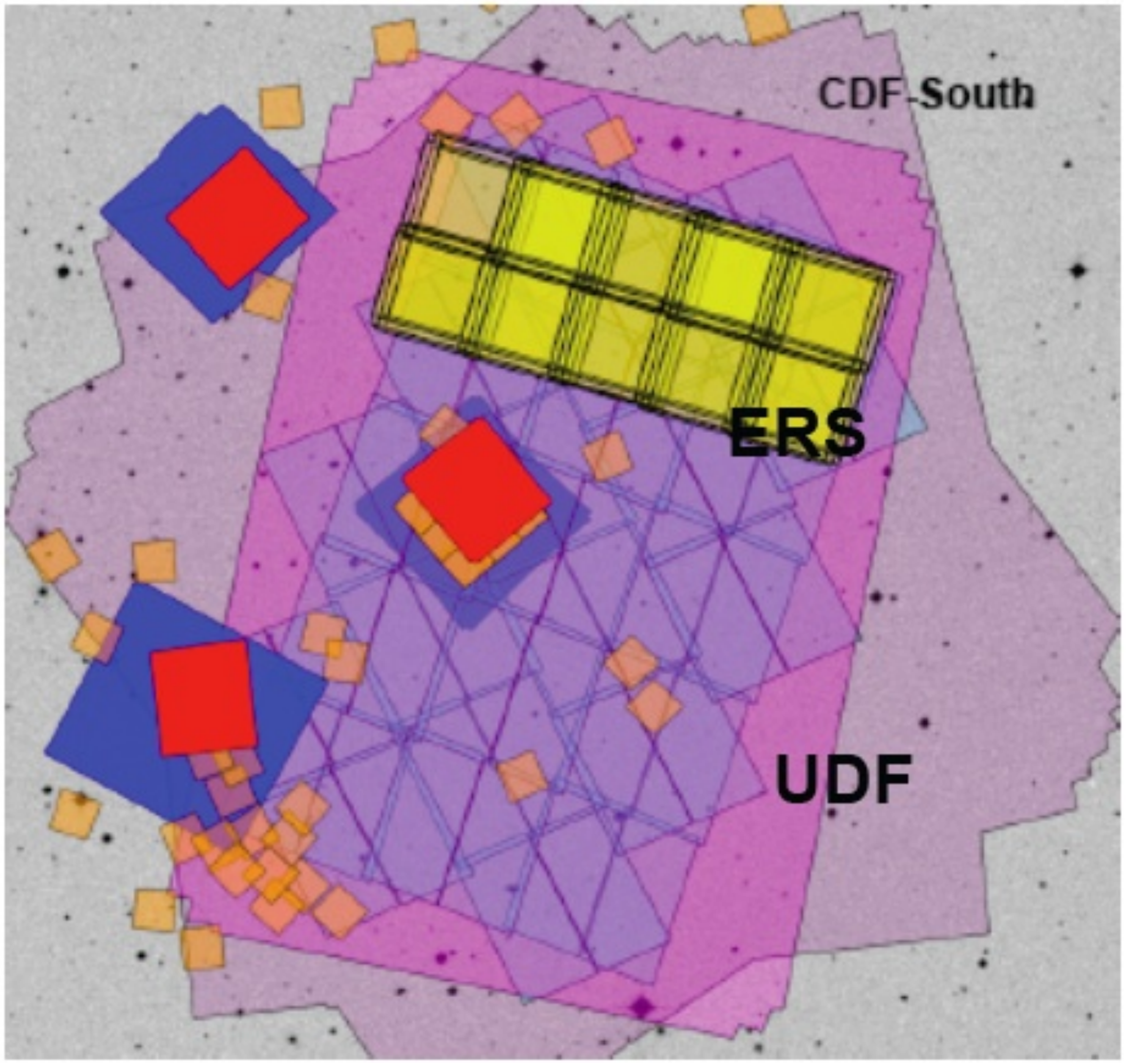


At z>7 both LBG and Lyman-α searches need deep near-infrared data.

WFC3: 2.1 x 2.3 arcmin, 0.13'' per pixel: 40x gain c.f. NICMOS



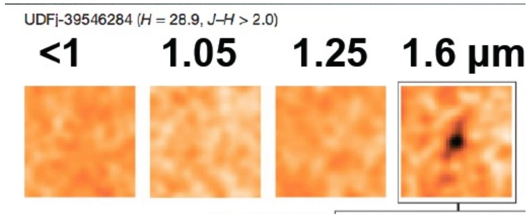
z > 7 WFC3 dropouts



At the bright end: CANDLES and BORG programs

~ 2 yrs after the 1st WFC3 data: 100 dropouts at z>7 confirmed by independent groups:

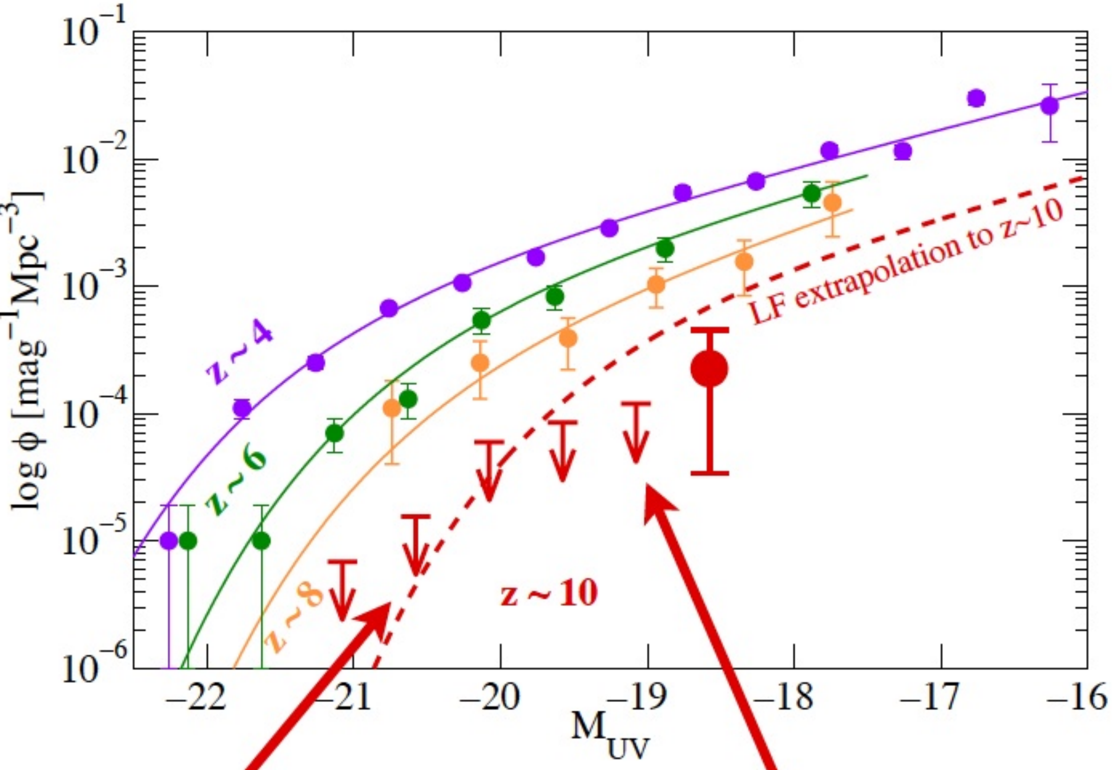
- *Finkelstein et al. 2010*
- *Bouwens et al. 2011a,b*
- *McLure et al. 2011*
- *Wilkins et al. 2011*

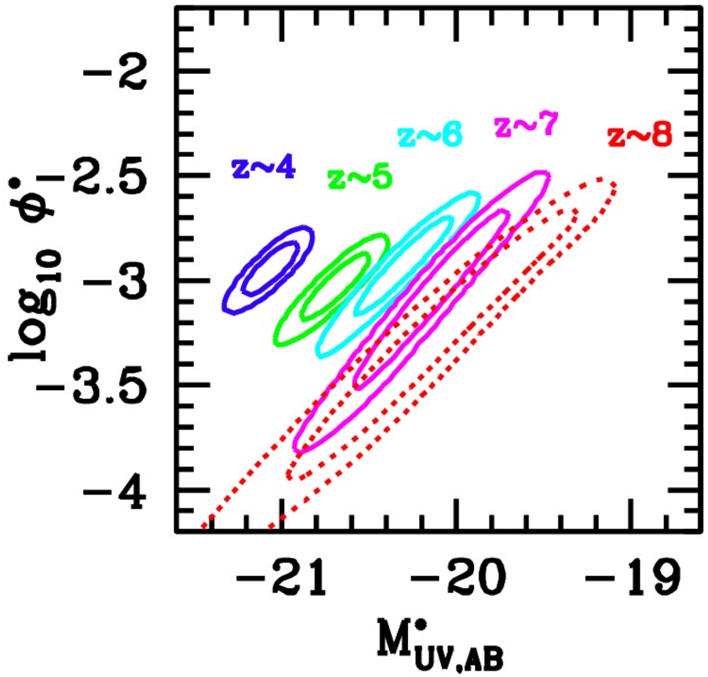


z ~ 10 candidate

Bouwens et al. 2011

Luminosity Function of LBGs





Three Wide Fields:
limits are below z~8

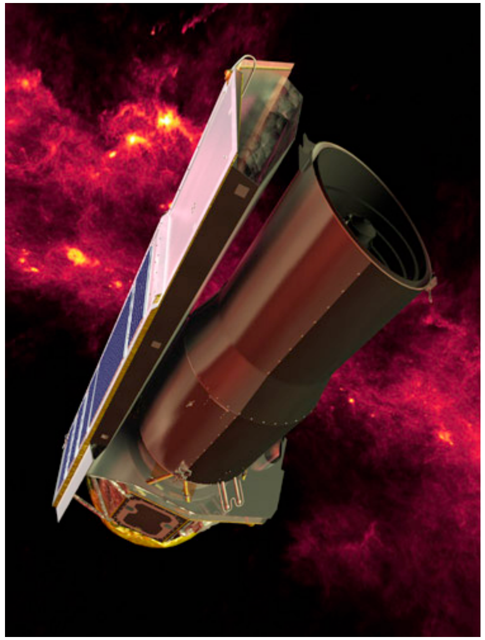
Three HUDF09 Fields:
z~10 limits are below extrapolation

Bouwens et al. (2010,2011) proposed an evolution of L* with z at z > 4

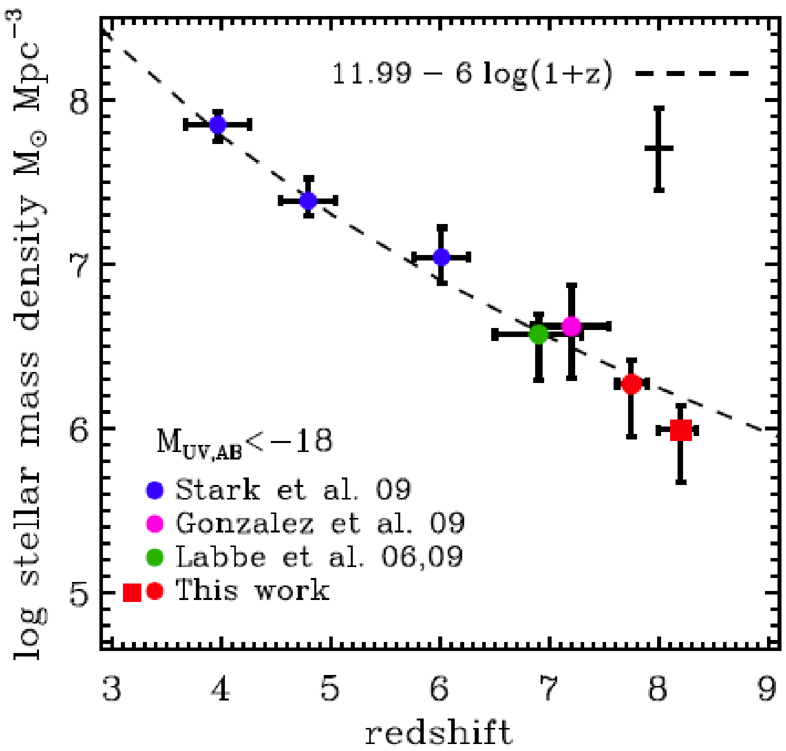
This result is ~ consistent with all searches for dropouts in WFC3 data

Stellar mass Functions

$$M_*(z) = \int_{z=5}^{z=10} \rho_*(z)\,dV(z)$$



Stellar masses and ages measured with Spitzer at z ~ 5 imply early star formation

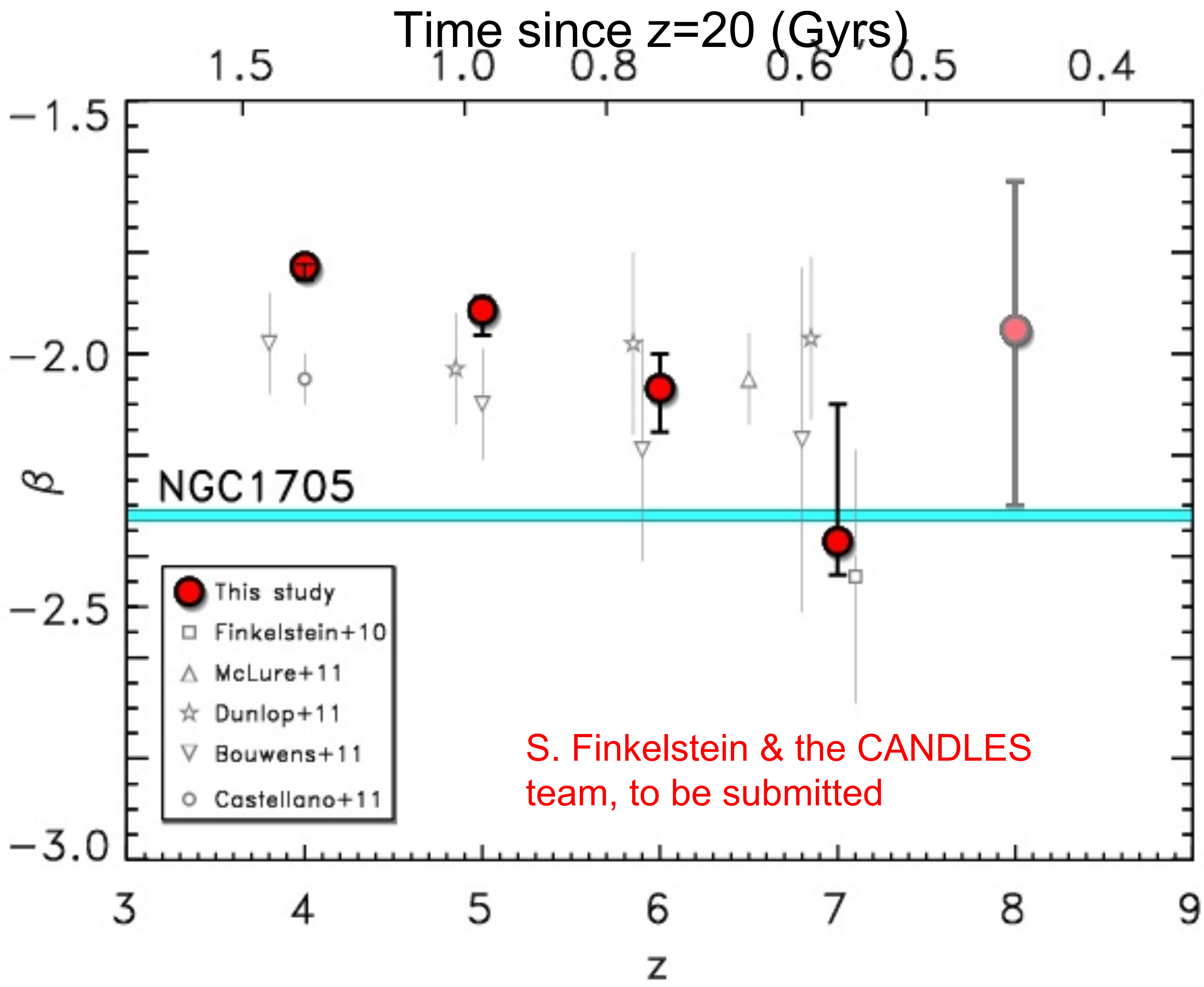


Stark et al 2007,2009; Labbé et al 2009ab, Gonzalez et al 2010

Steep mass functions at high redshift strengthen this result.

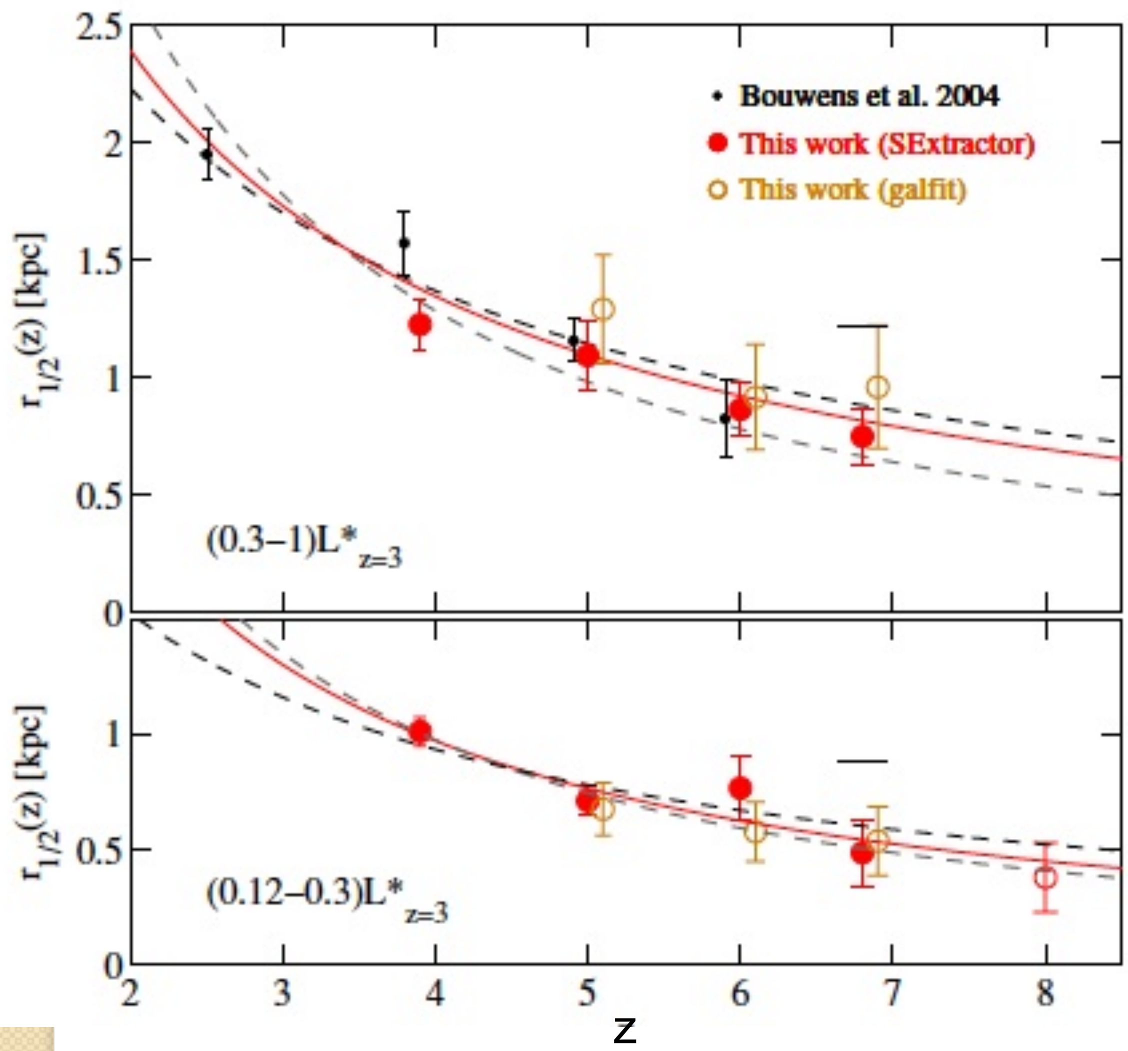
Need to match these mass functions with theoretical predictions!

UV continuum slope β



S. Finkelstein & the CANDLES team, to be submitted

Size evolution of WFC3 dropouts



PSF-corrected half-light measured from NICMOS and WFC3

Evolution seen as

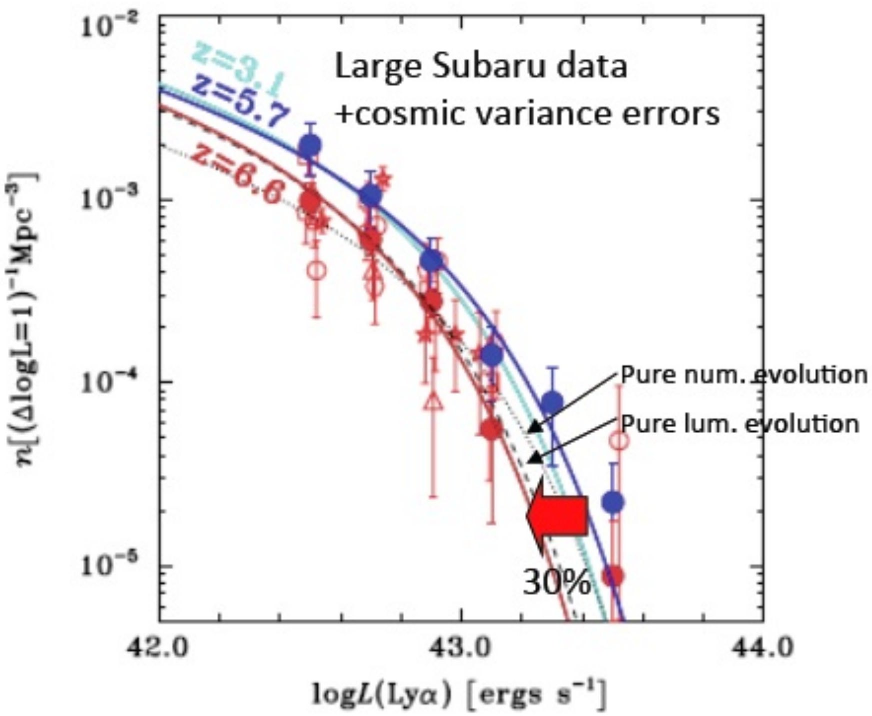
~ $(1+z)^{-1}$

Oesch et al. 2010

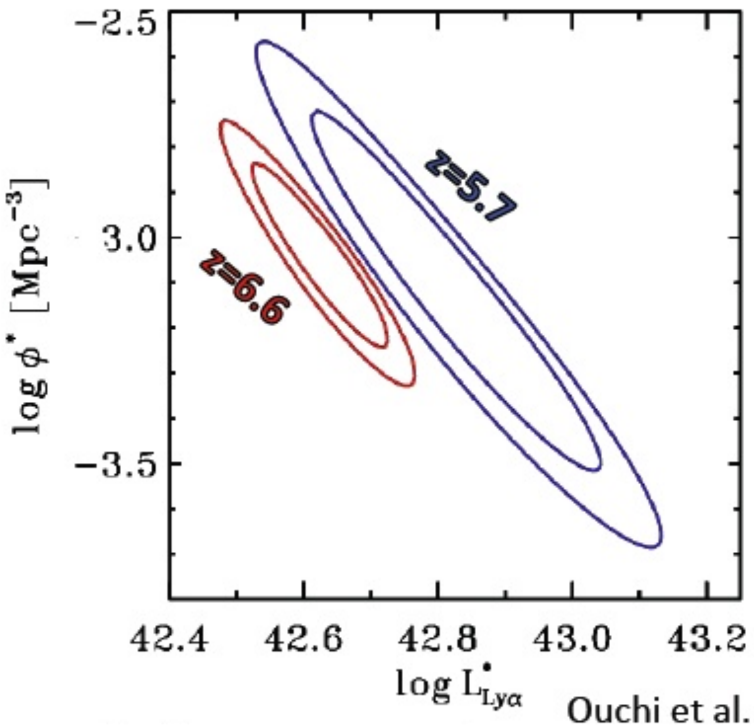
Results from LAEs

Narrow-band searches: Shimasaku et al., Kashikawa et al., Ouchi et al. (Subaru Fields)

Lya Luminosity Function (Lya LF)



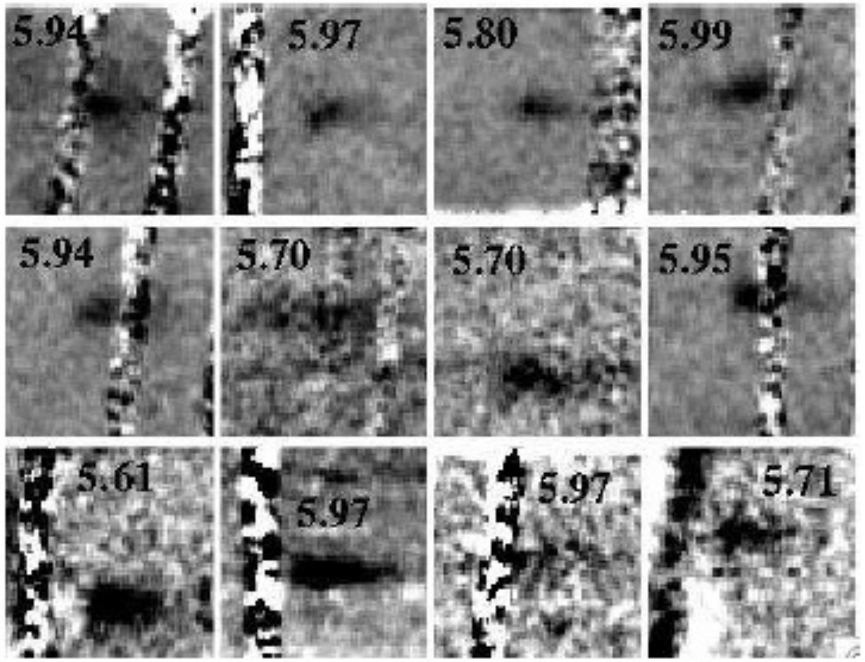
207 LAEs at z=6.5-6.7



Ouchi et al. (2010)

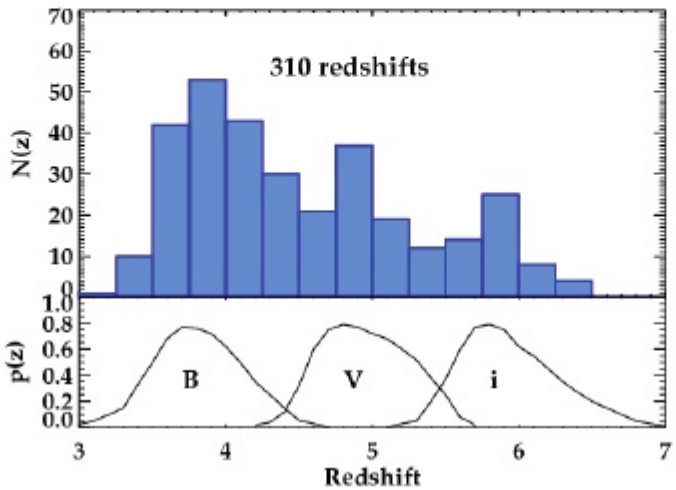
Mild evolution between z=5.7 and z=6.5, mainly in L* (by 30%): follows the trend seen in LBGs (rather than an effect from reionization)

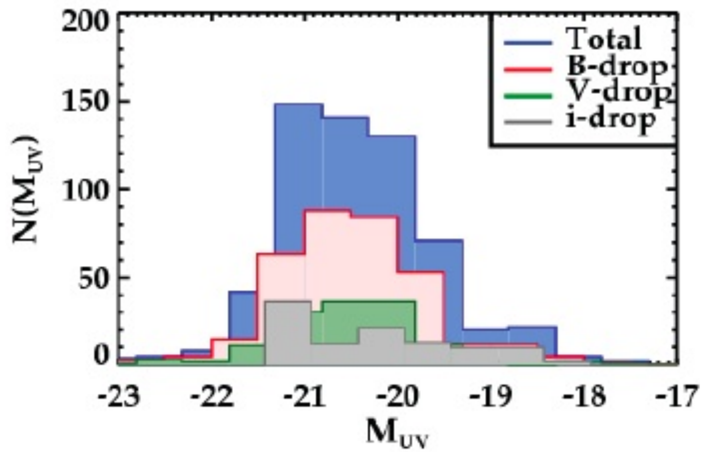
Spectroscopic follow-up surveys



Deep searches for Lyman-α in high z LBGs at z=4,5, and 6 (*Stark et al. 2009, 2010, 2011, Vanzella et al. 2009*).
e.g. DEIMOS 4-6 hrs / field

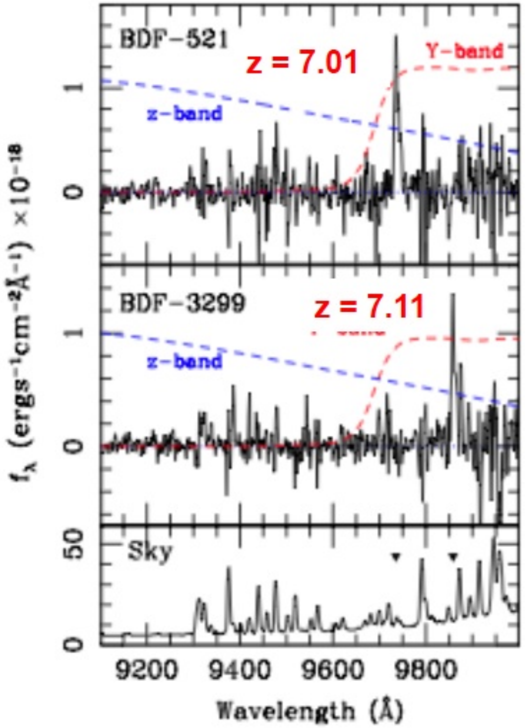
Issues with OH lines: searching a tree in a forest !

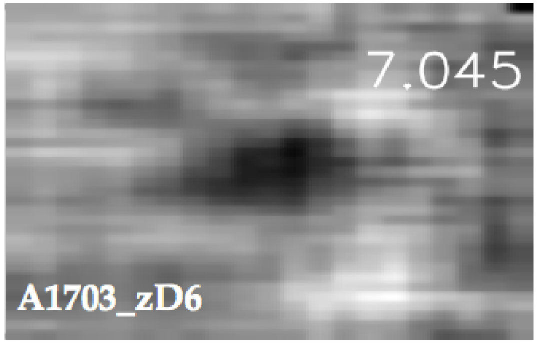


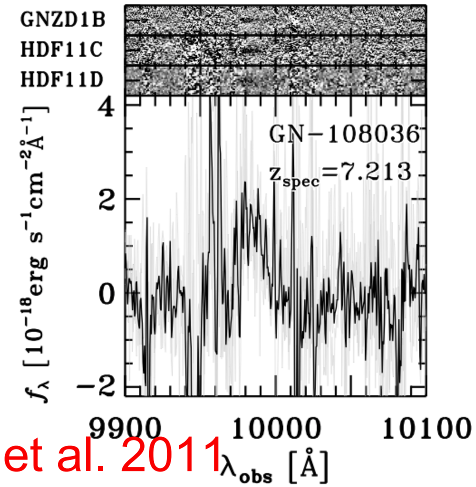


Spectroscopic follow-ups:

z=7 and evolution of LA fraction





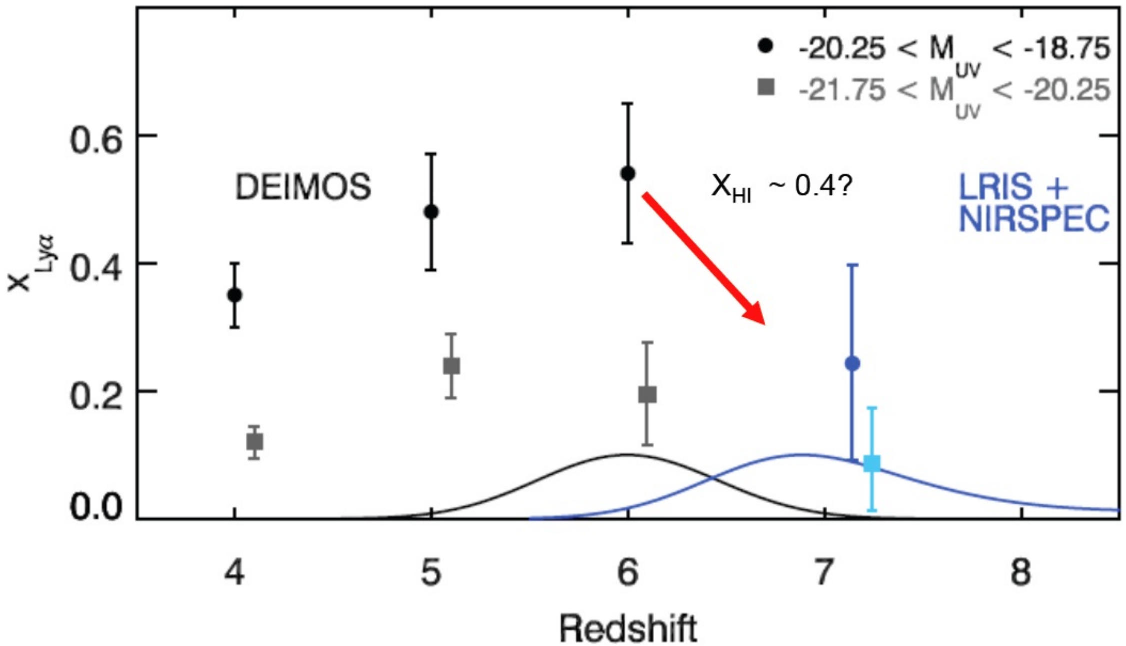


Vanzella et al.2011,

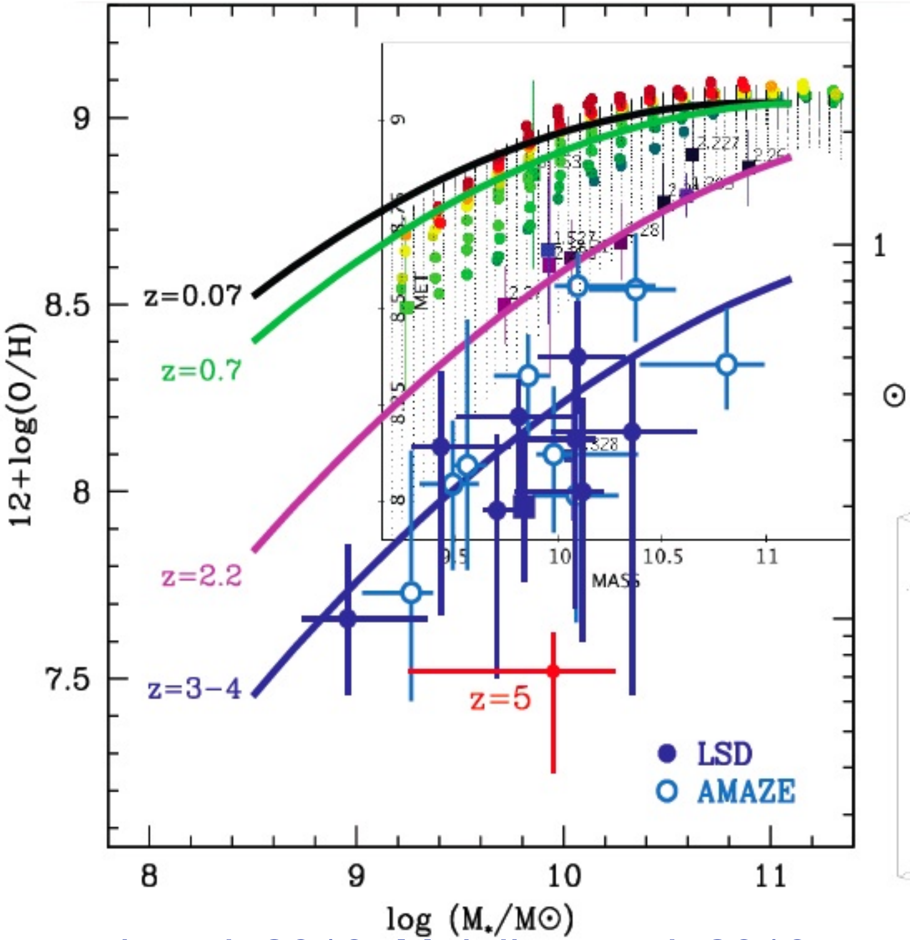
Schenker et al. 2011, Ono et al. 2011

First confirmations of LAEs at z>7

Evolution in the fraction of LBGs showing strong Lyman-α

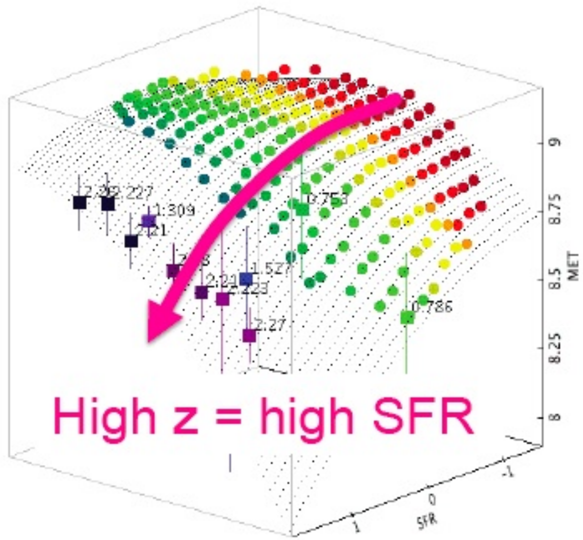


Results from near-infrared spectroscopy



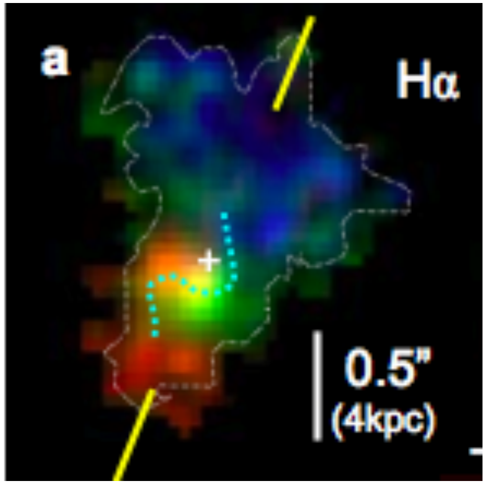
Evolution of mass-metallicity:

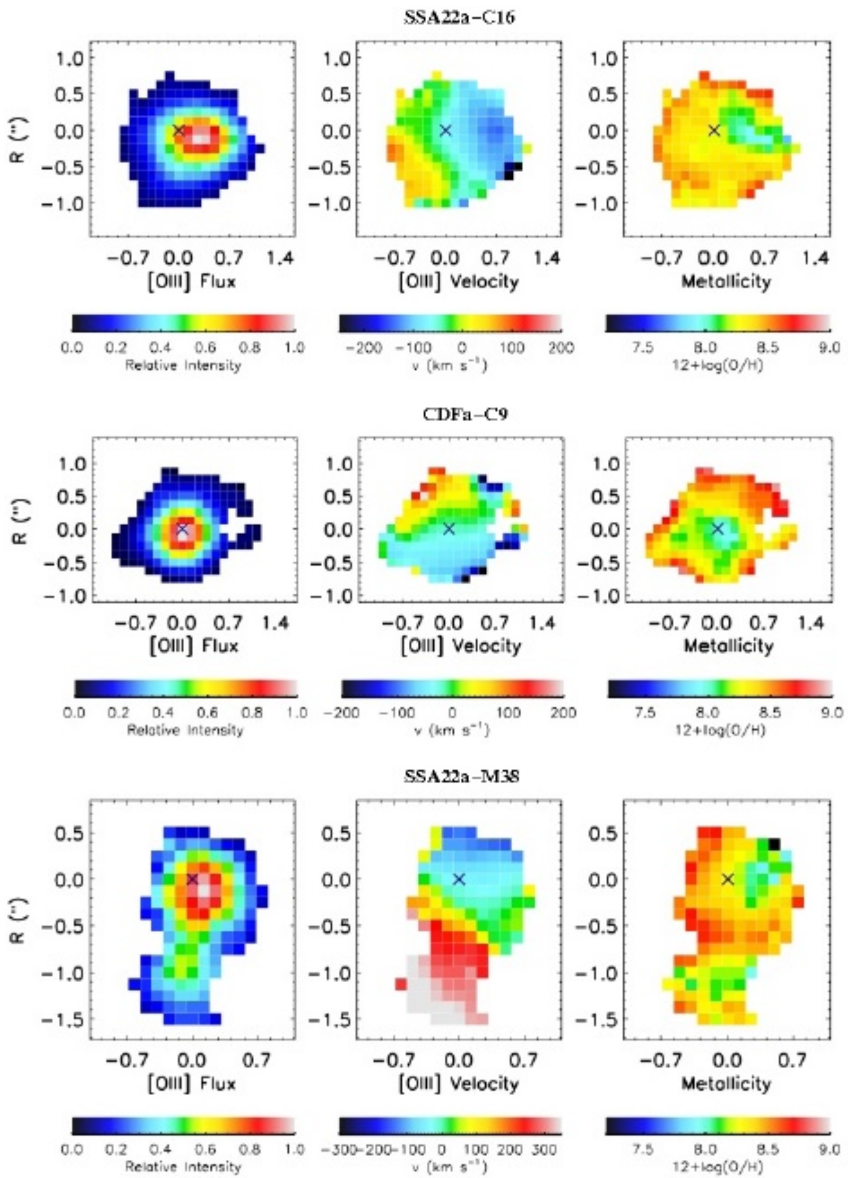
Sampling galaxies with higher SFR at higher redshifts



Mannuci et al. 2010, Maiolino et al. 2010

Resolved spectroscopy





Dynamics:

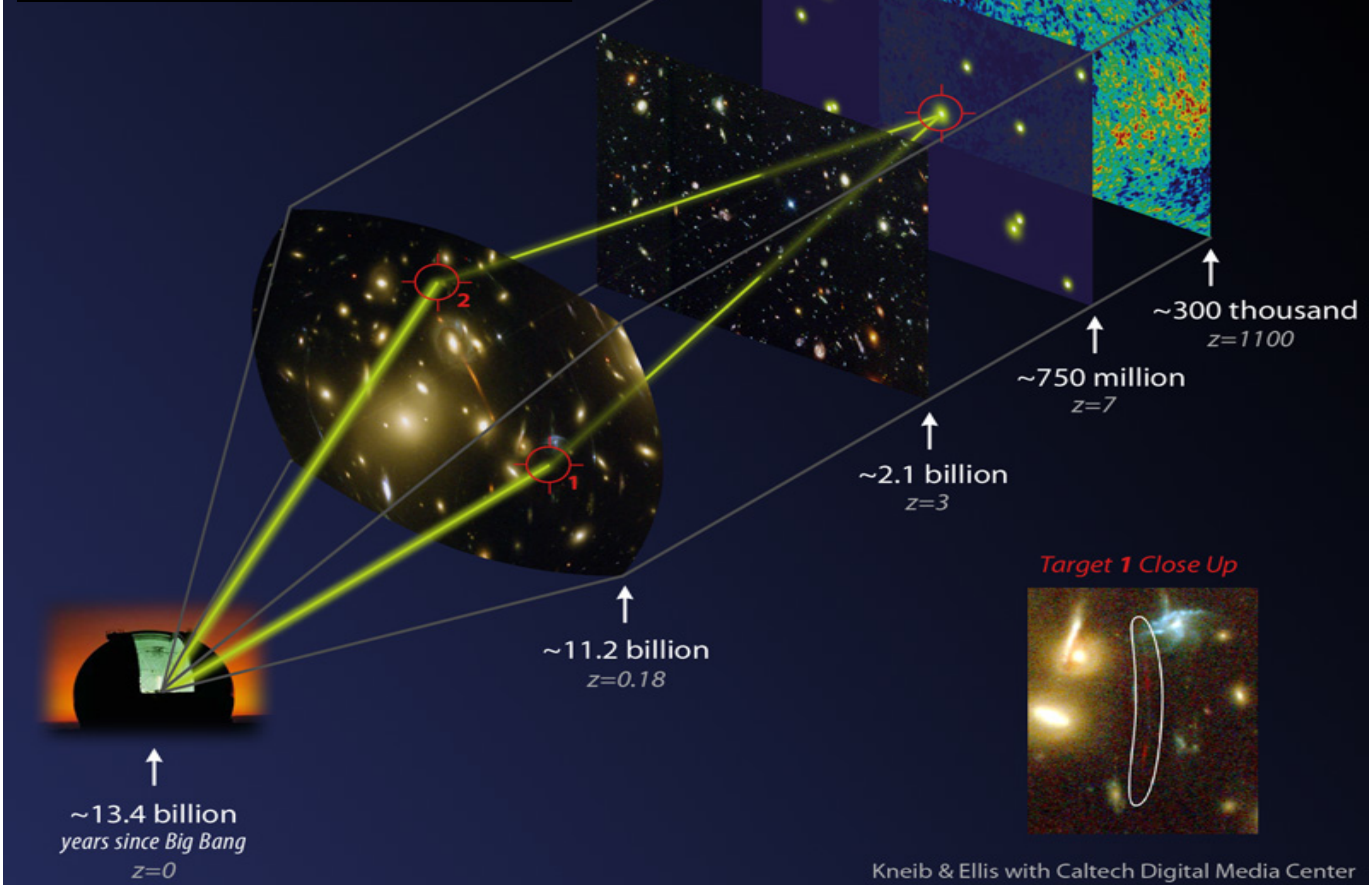
e.g. Genzel et al. 2006

Metallicity gradients

at z=3 Cresci et al. 2010

Still limited to the massive/bright-end of the MF/LF of LBGs

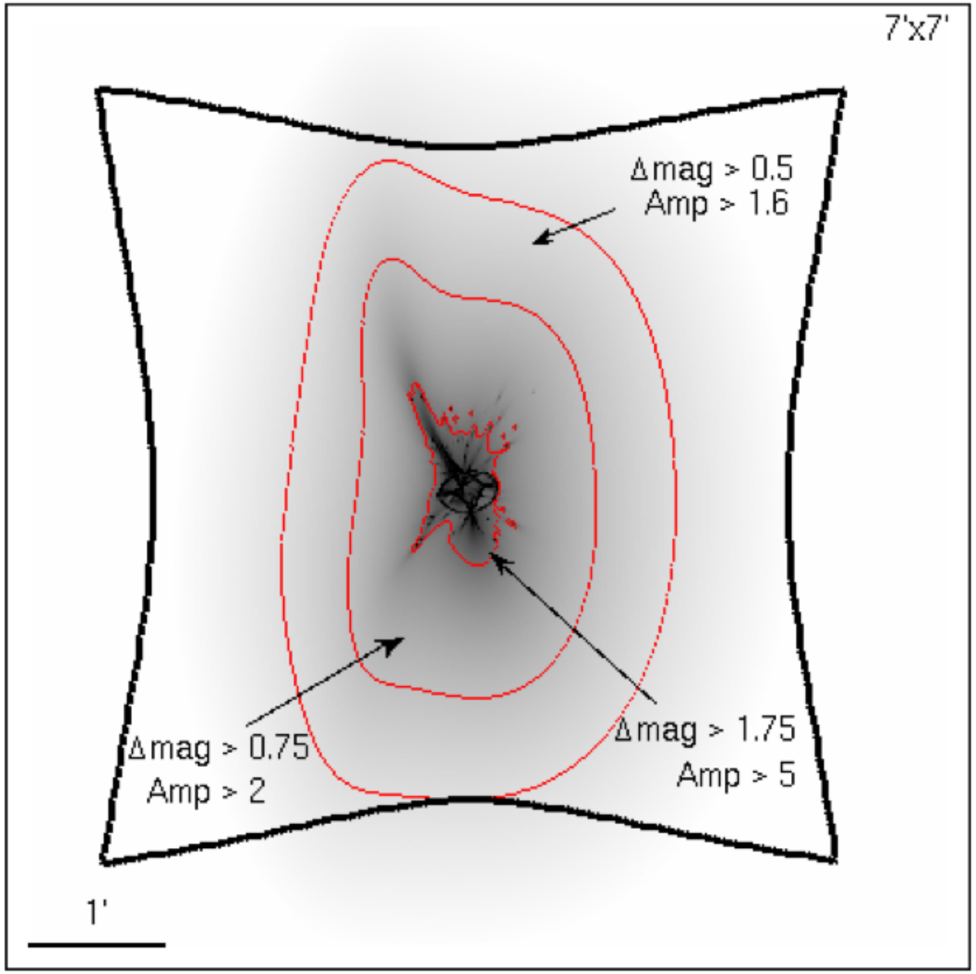
Lensing probing first objects



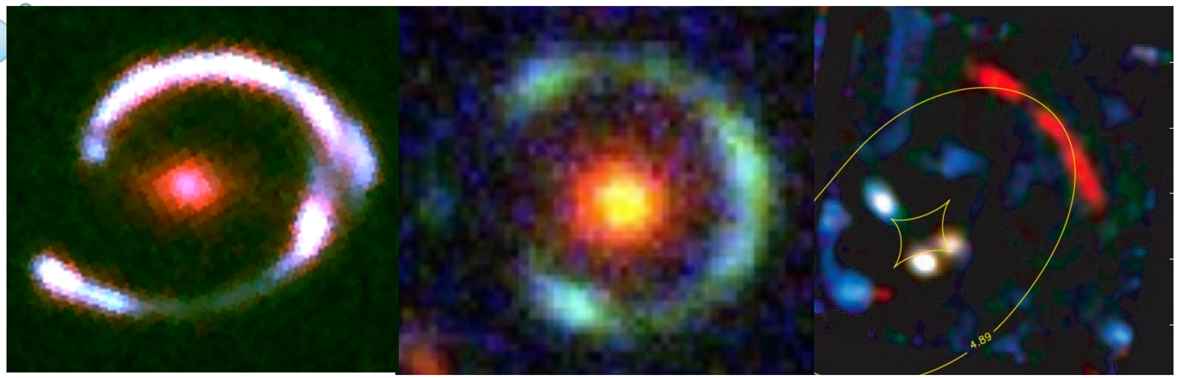
Gravitational telescopes:

- Advantages:
  - boosts the total flux by increasing the observed size of background sources (constant surface brightness)
  - efficient for unresolved sources
  - multiple images configuration gives a hint on z

- Drawbacks:
  - Effective area smaller in the source plane
  - Need to estimate the magnification to correct it



Lensed LBGs

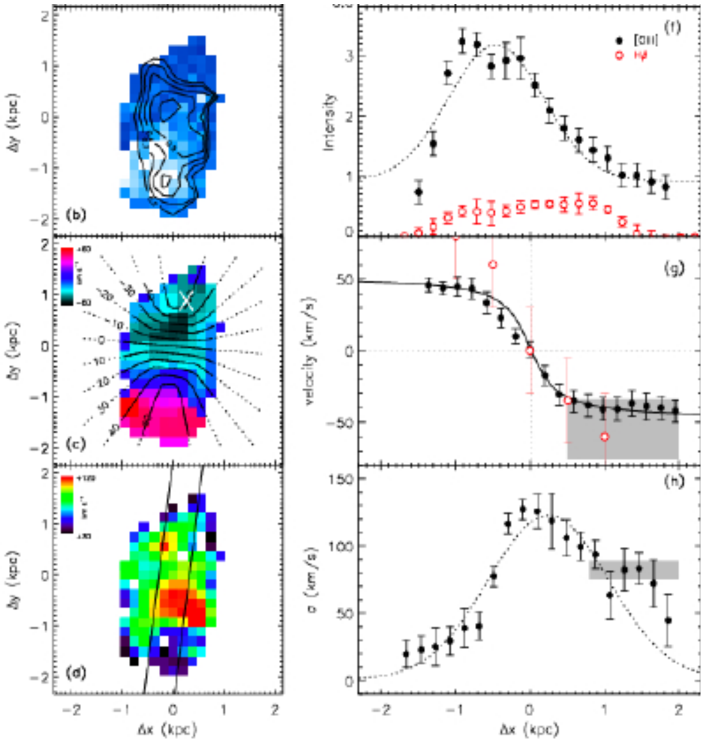


Typically 20-21 AB

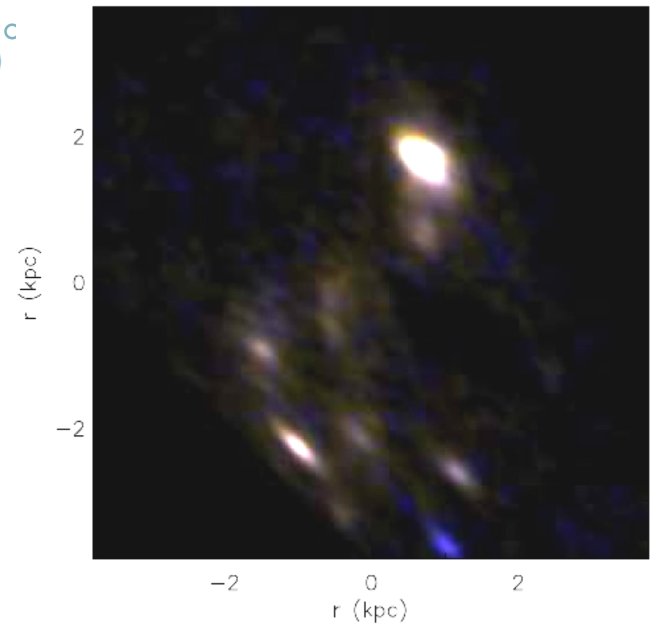
Extended by 5-10”

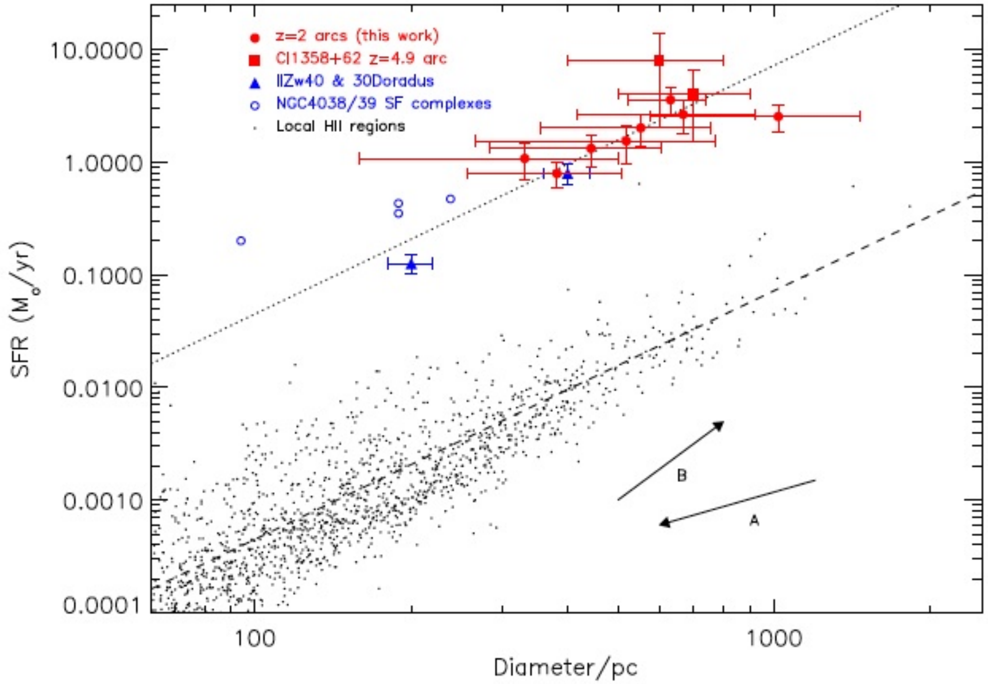
- Cb58 (**Seitz et al 98**): brightest LBG known until 2007
- The 8 o’clock arc (**Allam et al 07**)
- The Cosmic Eye (**Smail et al 07**)
- The Horseshoe (**Belokurov 07**)
- RCS0224 z ~ 5 (**Swinbank et al 07**)

Stark et al. 2008: IFU study of the Cosmic Eye: well-resolved velocity field in a < L* galaxy, fit by a rotation curve.



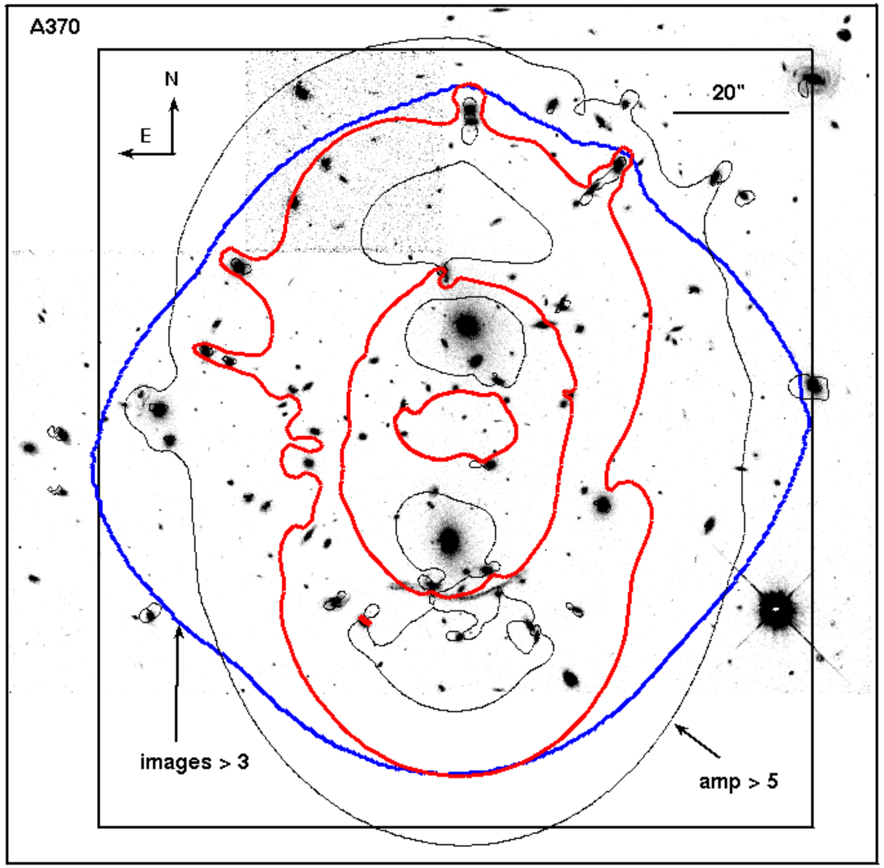
Resolved sources at z ~ 5





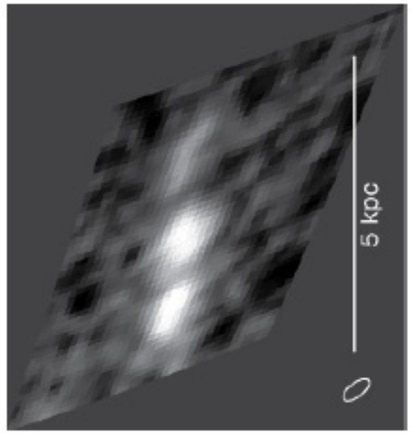
- Bright z ~ 5 strongly lensed source behind MS1358 (**Franx et al. 97**)
- NIFS spectroscopy: resolved [OII] emission in star-forming regions (**Swinbank et al. 09**)
- Star forming regions appear more concentrated compared to their local equivalents.

WFC3+lensing: cycle 16/17



Red : critical line at z=7
Blue: multiple image region
Black: amplification larger than 5

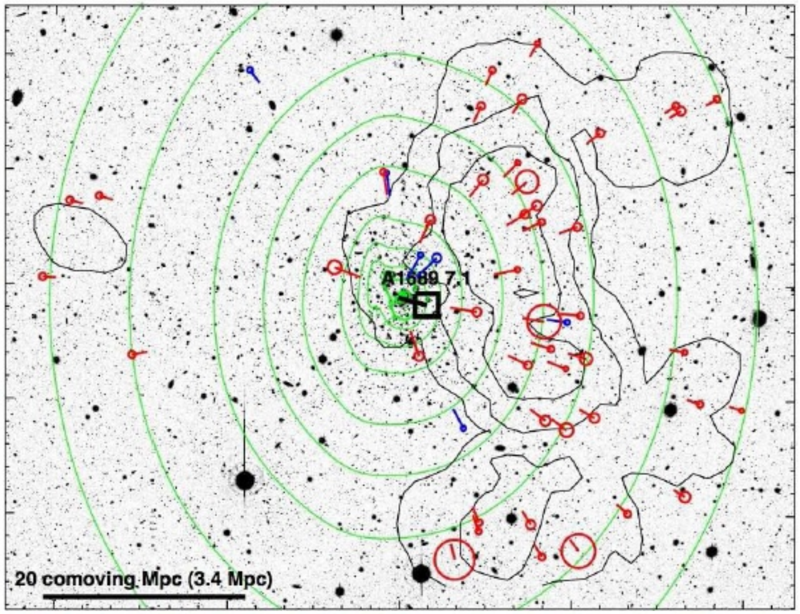
- **Hall et al. 11**: 10 z-dropouts behind bullet cluster
- **Bradley et al. 11**: 8 z ~ 7 candidates behind A1703, maybe multiple images

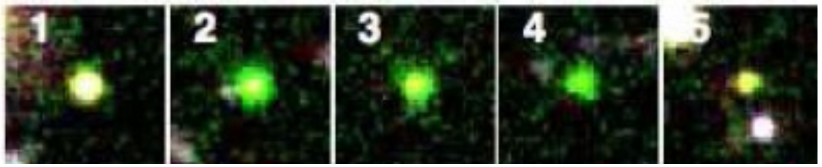


- Ongoing survey of 10 clusters (PI: Kneib), good candidates. *See talk by D. Paraficz*

Lensed LAEs : NB searches

- Narrow-band searches: wide field needed, limited gain of lensing magnification
- Searches behind lensing clusters:
  - ➢ **Hu et al. 02** z=6.56
  - ➢ **ZEN2** (**Willis et al. 07**):
    3 massive clusters, z ~ 9
  - ➢ **Matsuda et al. 09 / 11** in prep.
    z ~ 5 LAEs over-density behind A1689
  - ➢ HAWK-I narrow-band search.
    ESO-LP PI: J.G. Cuby, 120 hrs,
    2 clusters + 2 blank fields, z ~ 7.7





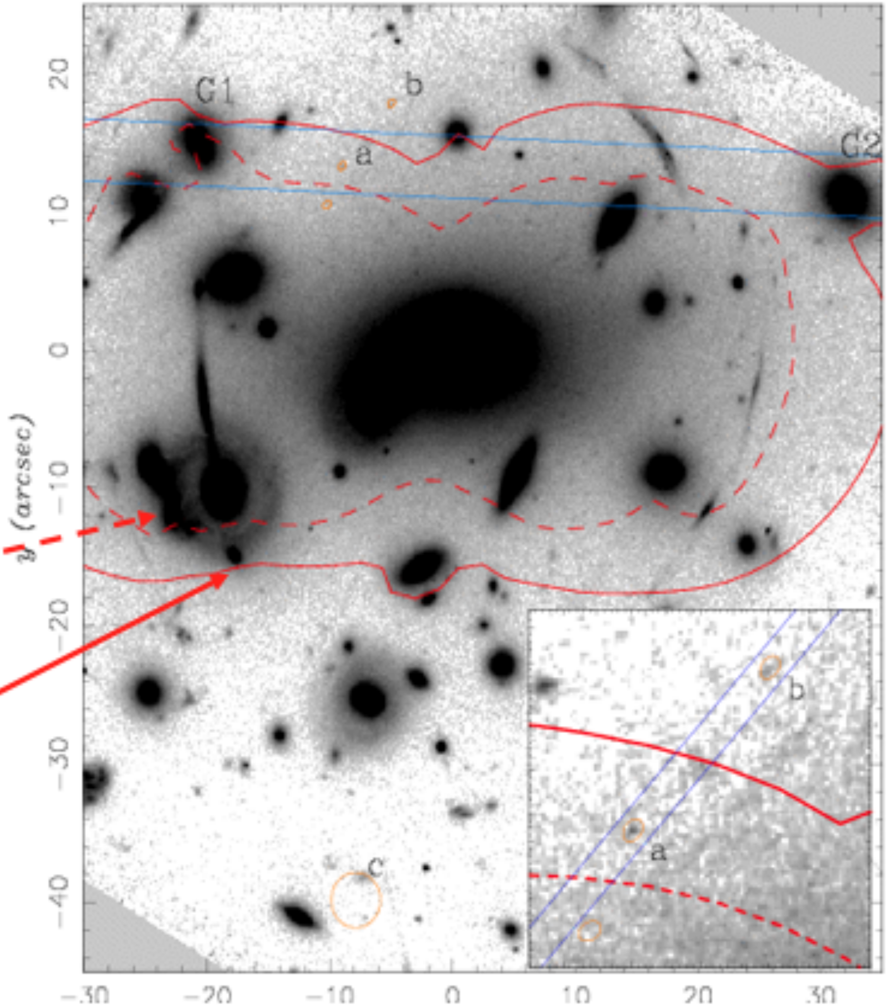
Lensed LAEs: Critical lines

- From lens modeling the location of the "critical lines" is known precisely for

  z=1

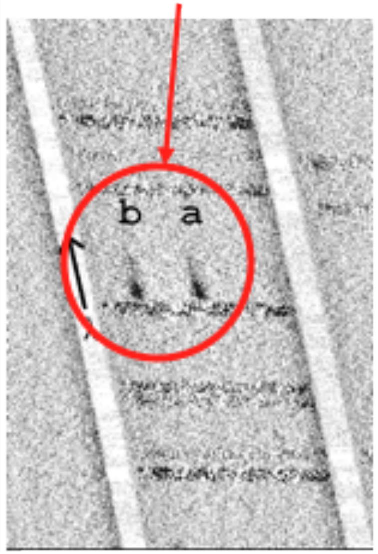
  and for

  z=5



Ellis et al 2001

Blind Ly-a search with LRIS: hi-res follow-up with ESI



Utilizing strong magnification (´10-30) of clusters, probe much fainter than other methods in small areas (<0.1 arcmin2 cluster-1)

SINFONI critical line survey

Clement et al. in prep.

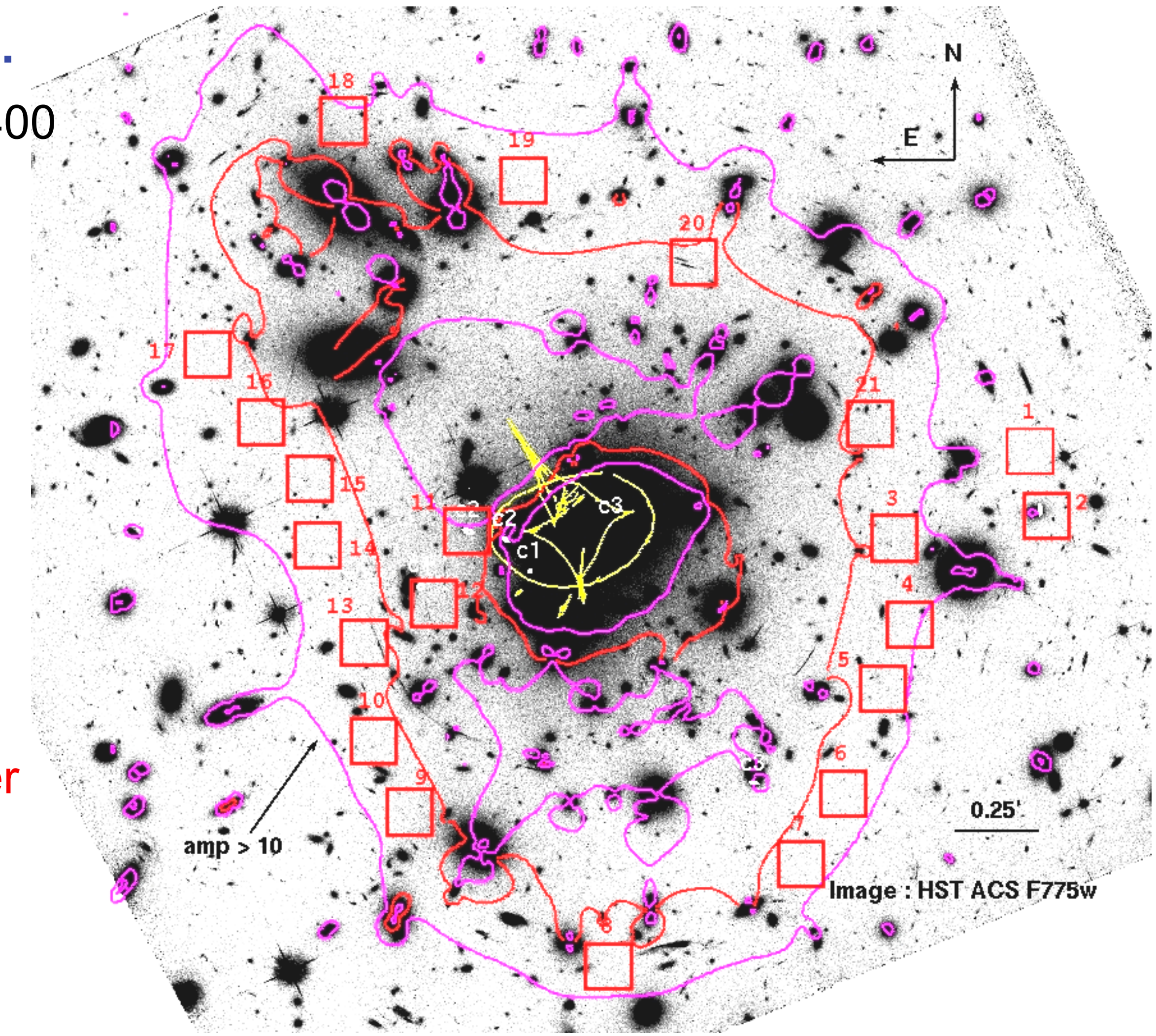
- 45min/pointing - R~1400
- 21 pointings (5"x6.5")
- effective area

680 sq." in image plane

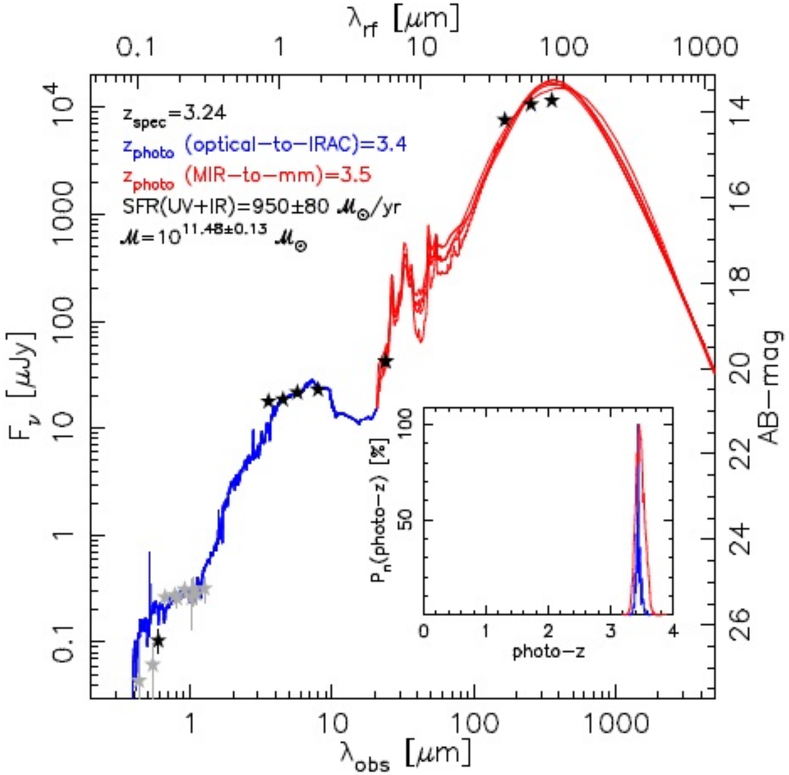
50 sq." in source plane

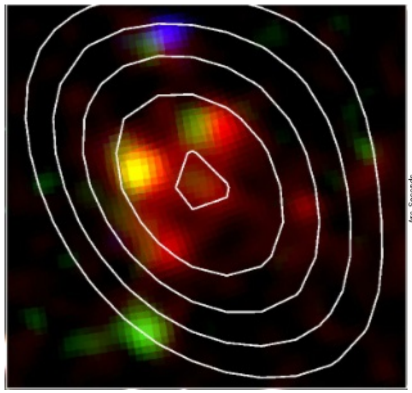
• probe ~ 10^{41} Ly-alpha luminosity at z~8.5

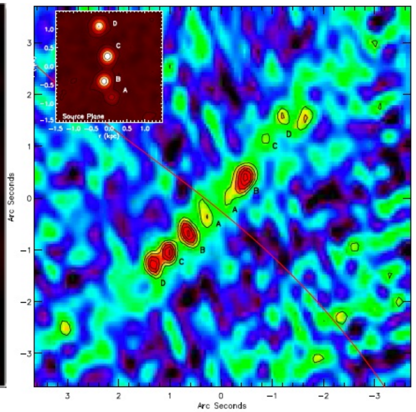
• down to ~3 times lower surface density than critical line survey



Herschel and ALMA







In the Rayleigh-Jeans tail of the dust blackbody spectrum, distant galaxies get ***brighter.***
Surveys with SCUBA/LABOCA/ Herschel detect sources z ~ 6

Lensing+Submm:

- **Knudsen et al. 09**
- **Swinbank et al. 10**
- **Gonzalez et al. 10**
- **H**erschel **L**ensing **S**urvey (**Egami et al. 10**, **Rex et al.10**)
- H-ATLAS survey (**e.g. Cox et al. 11)**

ALMA: follow-up of lensed submm sources + blind survey (IFU-like) behind clusters

Conclusions

❑ Current LBG and LAE surveys have given us good constraints on:

- the Luminosity Function and the Mass Function, as well as their evolution between z=7 and z=3

- the value and evolution of the UV slope β and size: high z galaxies get bluer and smaller

- the fraction of high z galaxies with strong Lyman-α , and its evolution

Evolution is due to galaxy formation and effect of reionization

- First results on rest-frame optical lines limited to massive galaxies and z~3-4

❑ Lensing is efficient to :

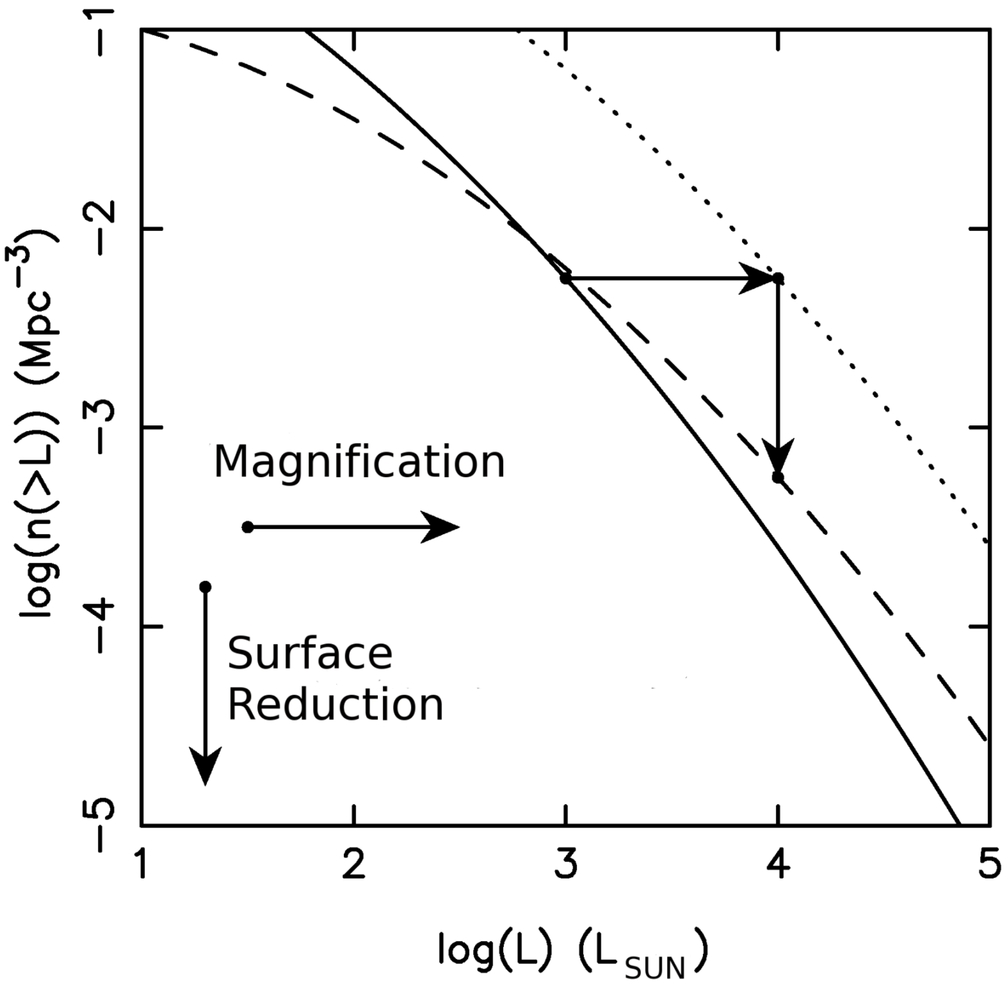
- find strongly lensed dropouts bright enough for spectroscopic follow-up

- faint LAEs when using current/future IFUs to cover the critical lines.

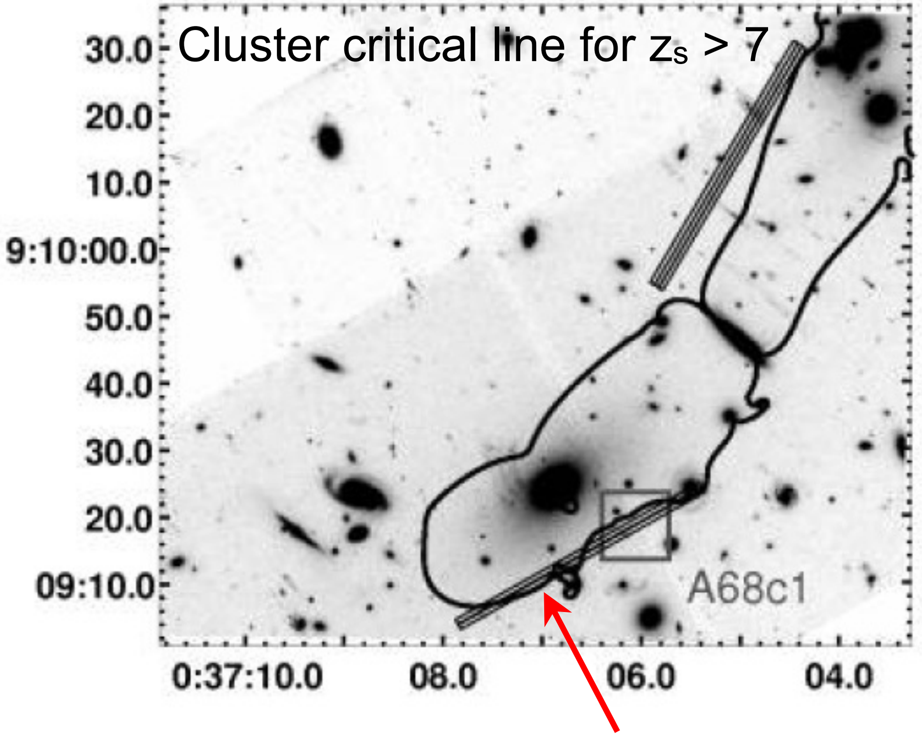
- resolve the inner morphology, dynamics and metallicity gradients in typical sources at z > 3

Magnification bias

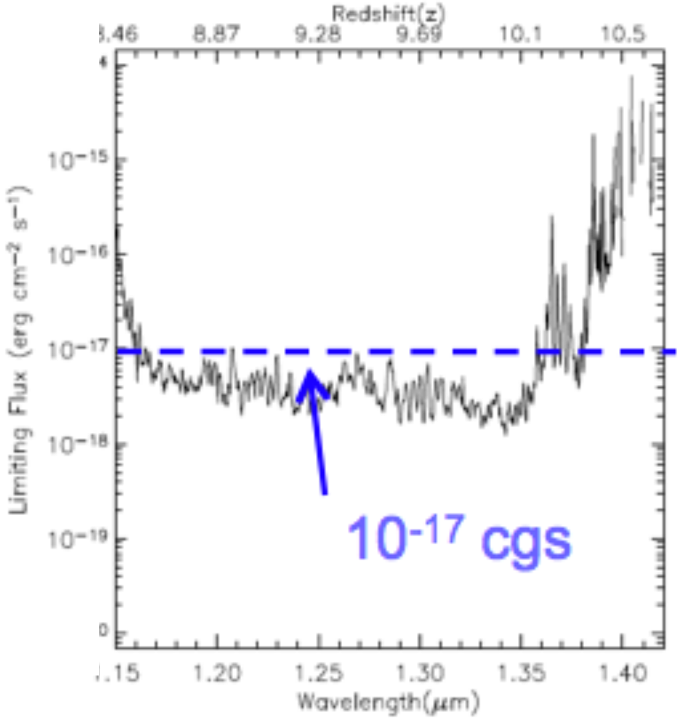
- The observed LF is offseted, with more or less objects than a blank field depending on the luminosity range (**Broadhurst 95**)
- Current LF fits at z > 6 suggest a positive magnification bias for unresolved sources down to ~ 27_{AB} (**Maizy et al. 10**)
- Lensing cluster fields are complementary to blank fields to probe the LF



NIRSPEC critical line survey



NIRSPEC slit positions



Stark et al. 07

- 9 clusters with well-defined mass models & deep ACS
- Obs. Sensitivity ~ 3-9. 10^{-18} cgs; mag > x 15-20 throughout
- Sky area observed: 0.3 arcmin^2 V(comoving) 50 Mpc^3
- LAE candidates $8.6 < z < 10.2$; L ~ 2 – 10. 10^{41} cgs; SFR ~ 0.2-1 $M_\odot$ yr-1

Power of Hubble

- First detection of a z ~ 6.8 dropout galaxies in Abell 2218
- Redshift confirmed by multiple image detection
- Source identified in Spitzer data, showing an already old population of stars, arguing for a possible formation redshift of z~10

Kneib et al 04

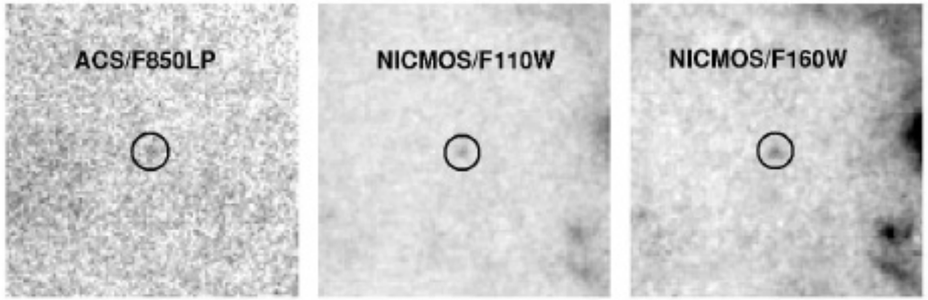
Egami et al 05

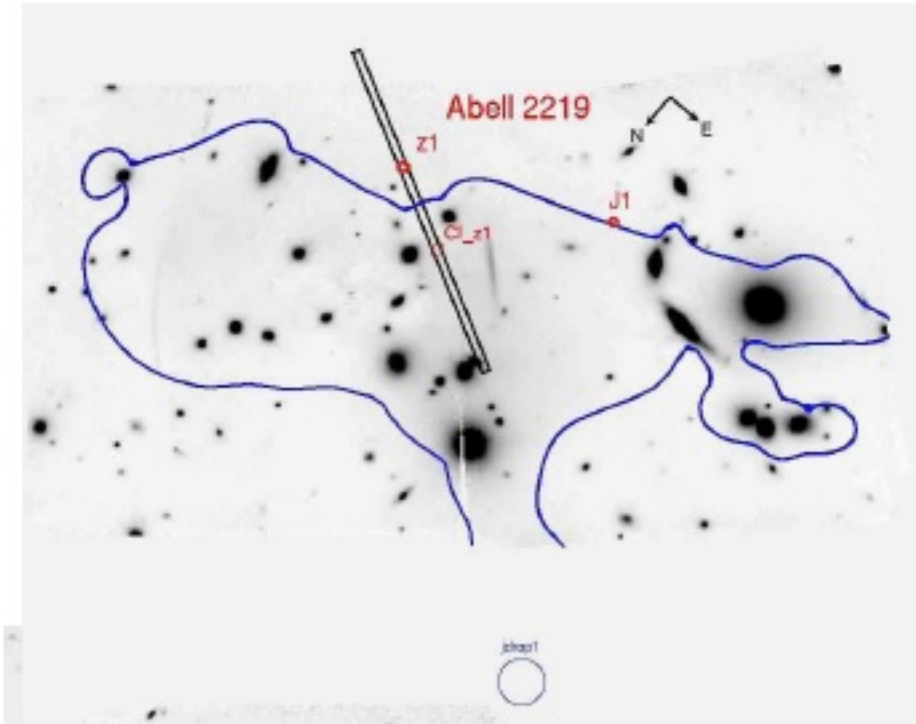
NICMOS lensed dropouts

• Survey of 6 massive clusters, 2 NICMOS pointings / cluster
(**Richard et al. 08**)

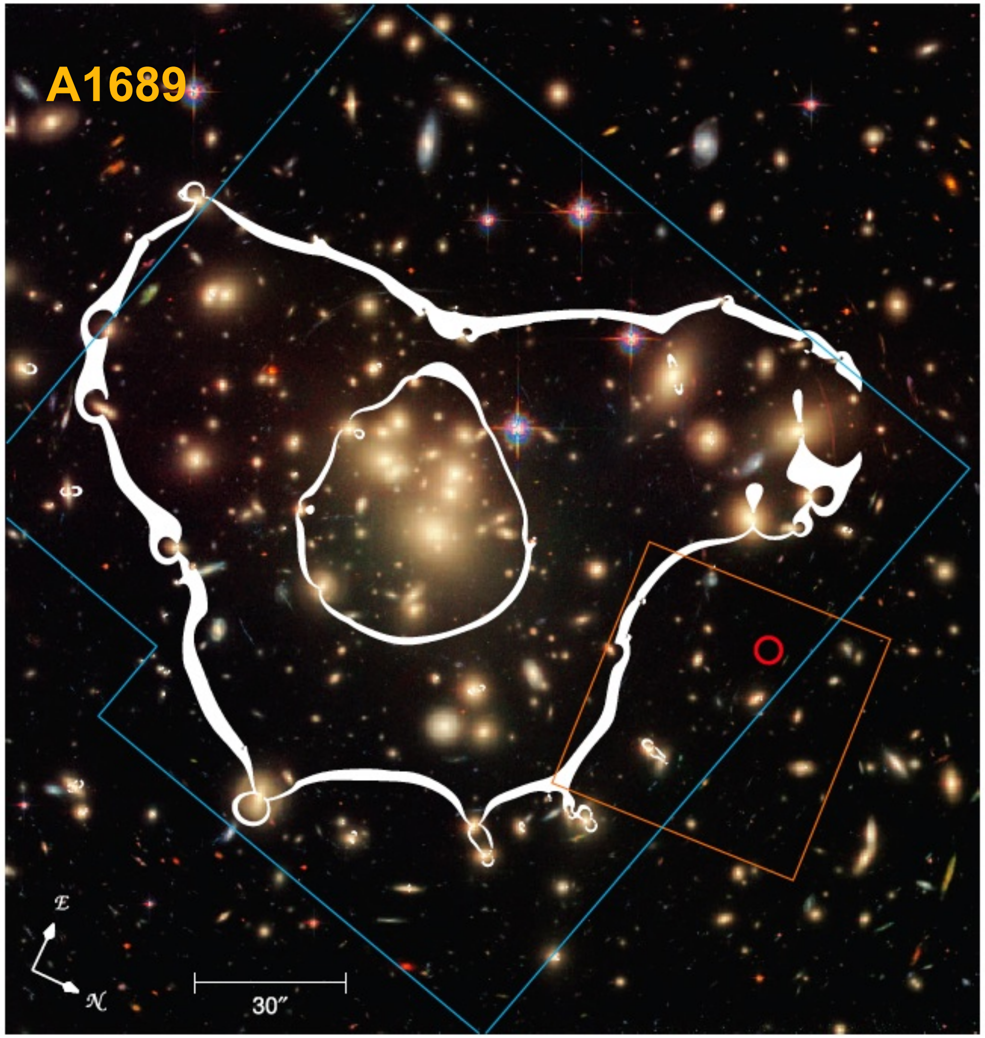
• Covers most of the critical line region

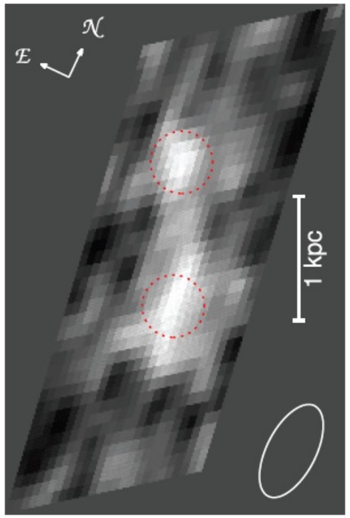
• Deep K band and IRAC images
• 10 faint z-dropouts, 4 possibly at z ~ 7 due to contamination
• Keck/NIRSPEC follow-up
• Constraints on the number densities down to AB ~ 29, compatible with extrapolation of LF.





NICMOS lensed dropouts



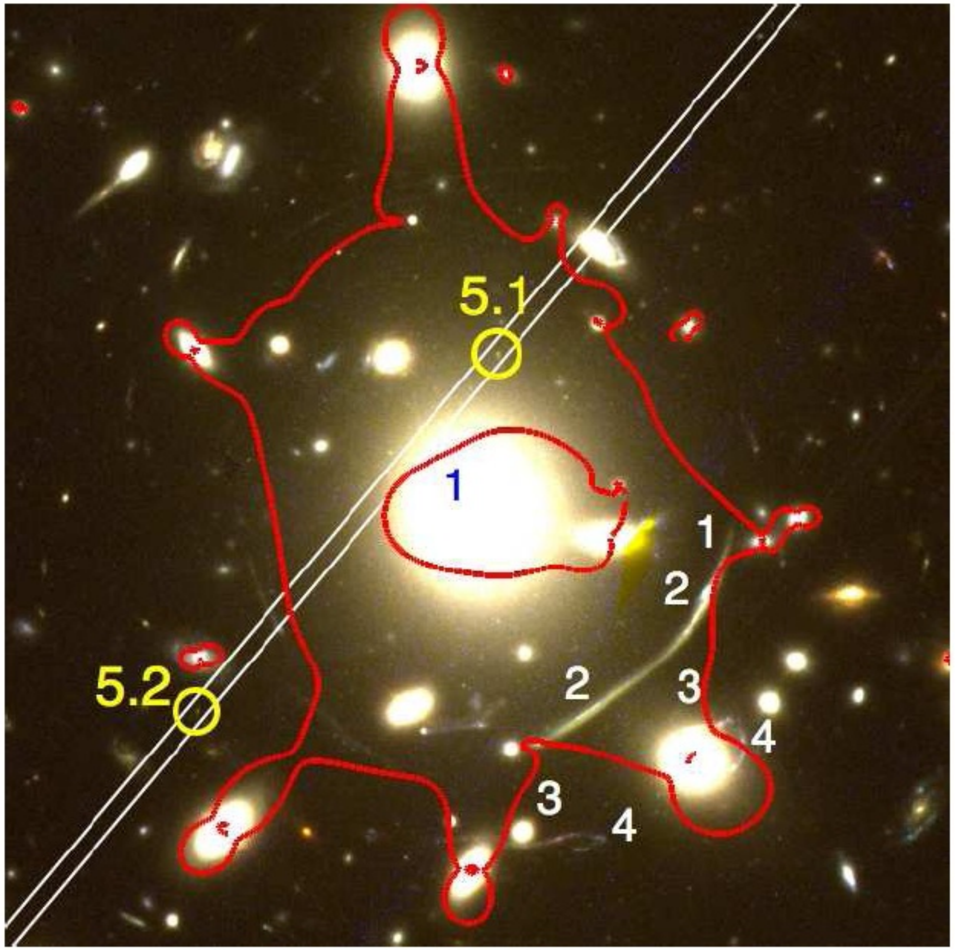


- **Bradley et al 08** z ~ 7.6
- **Richard et al 09,**

  Zheng et al 09 z = 5.9 – 7.0
- single images, μ ~ 5-10
- complex source morphology

Hubble Multi-cycle treasury program

CLASH

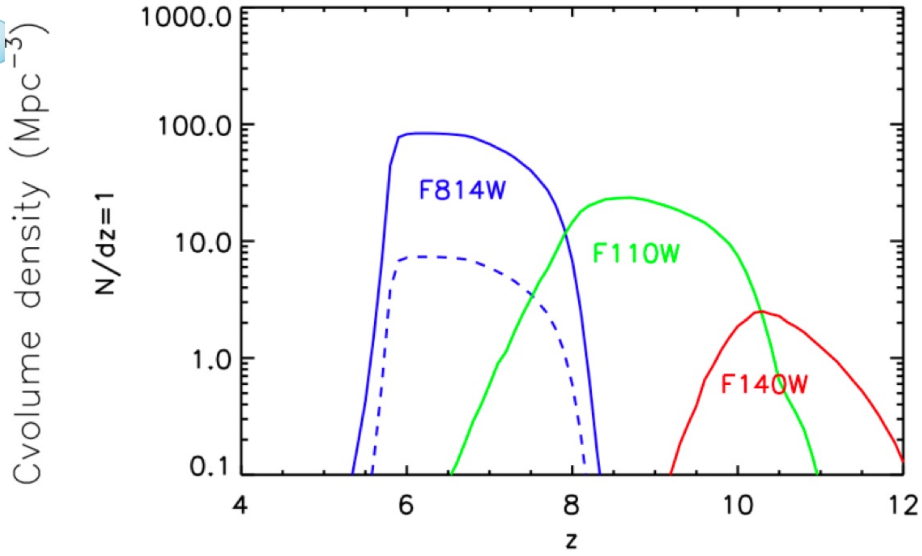


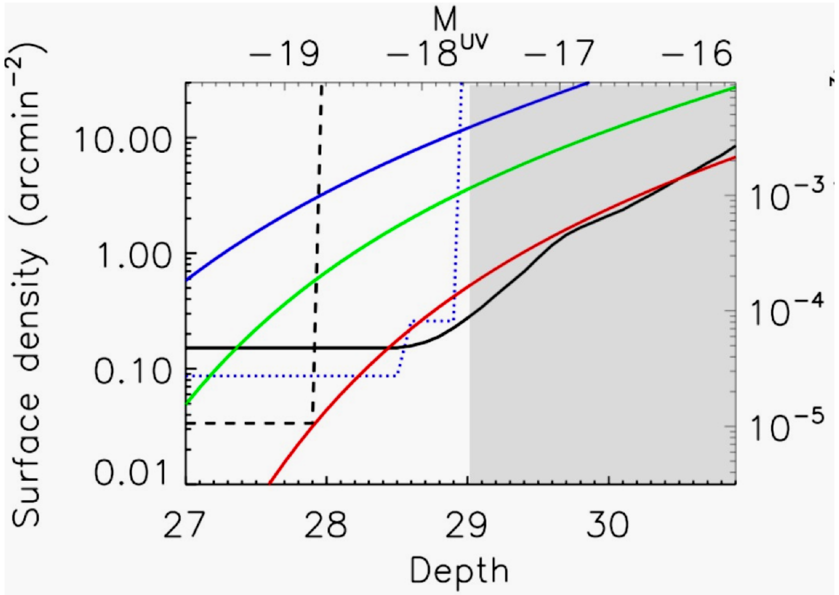
- PI: M. Postman
- ~ 500 orbits with HST/ACS and HST/WFC3, 25 clusters
- 16 UV/optical/NIR filters for accurate photo-z
- 1st cluster observed: A383

1 confirmed z=6.027 source (**Richard et al. 11**), accurate cluster mass model (**Zitrin et al. 11**)

~ 0.5 - 1 z > 6 dropout per cluster in the strong-lensing region

WFC3+lensing: perspectives





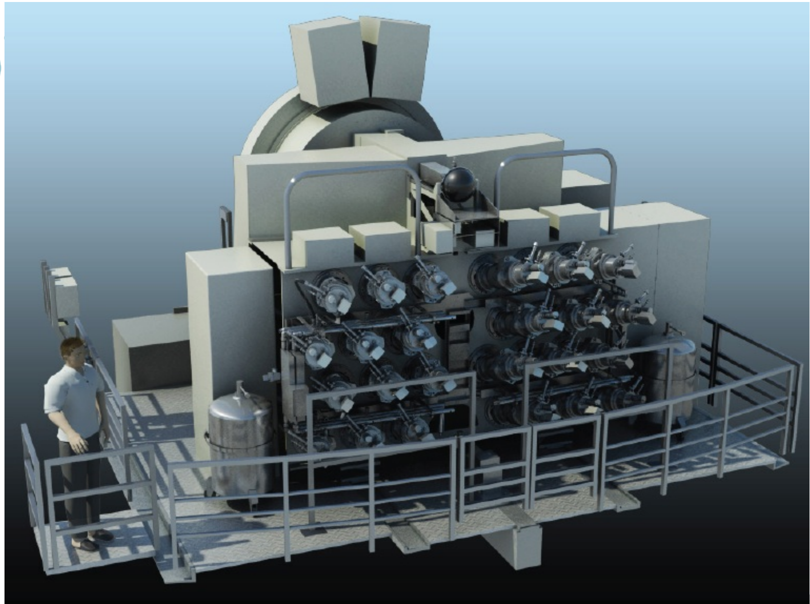
Deep survey of 8 clusters with WFC3 and ACS (4 filters): selection of F814W, F110W and F140W dropouts

~ 15 orbits/cluster

~100 z~7 galaxies
~20 z~9 galaxies
~3 z~10 galaxies

5% for which ground-based spectra can be acquired

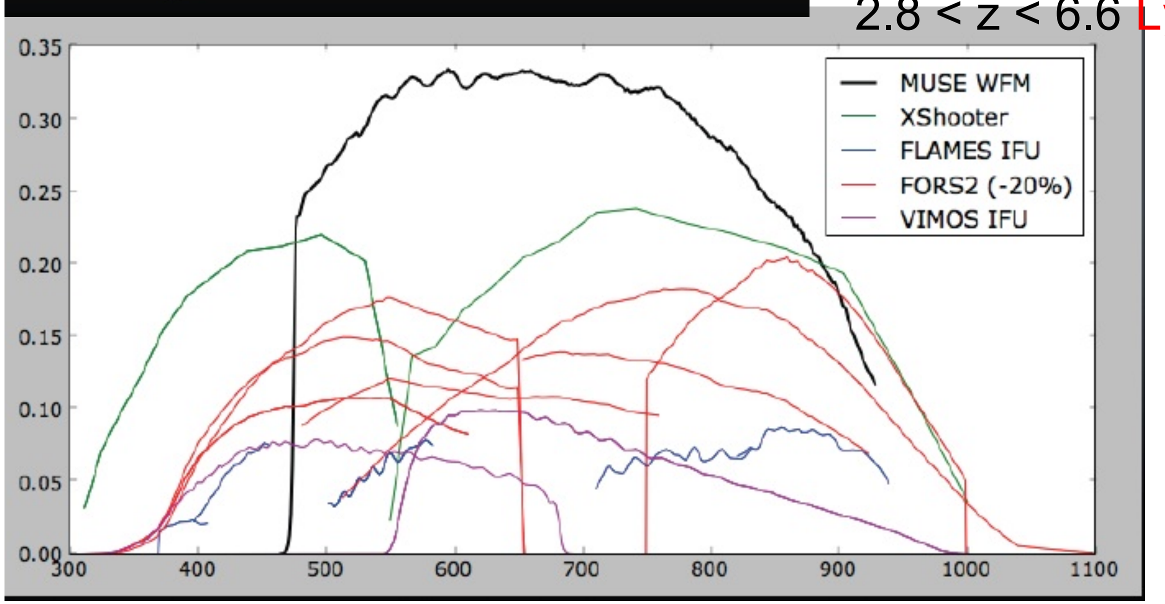
Perspectives: MUSE



- Multi Unit Spectroscopic Explorer
- 2nd generation VLT instrument
- PI: R. Bacon
- 24 IFUs, contiguous area 1’x1’ in Wide-Field Mode
- First light expected ~ Sep. 2012

- Wavelength coverage: 4700-9200 A.

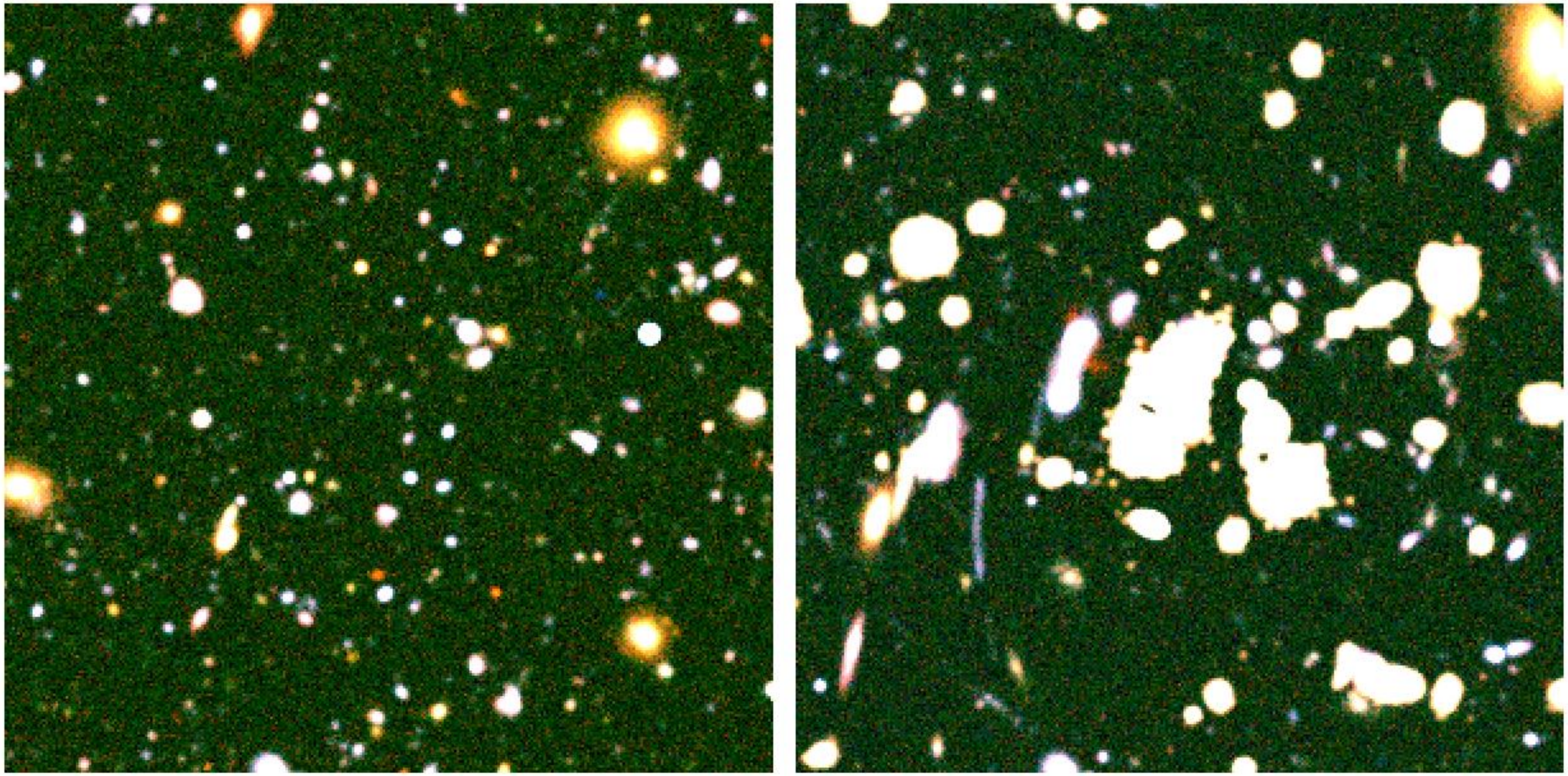
2.8 < z < 6.6 Lyman-α spectro-imager



Compared transmission with other VLT instruments

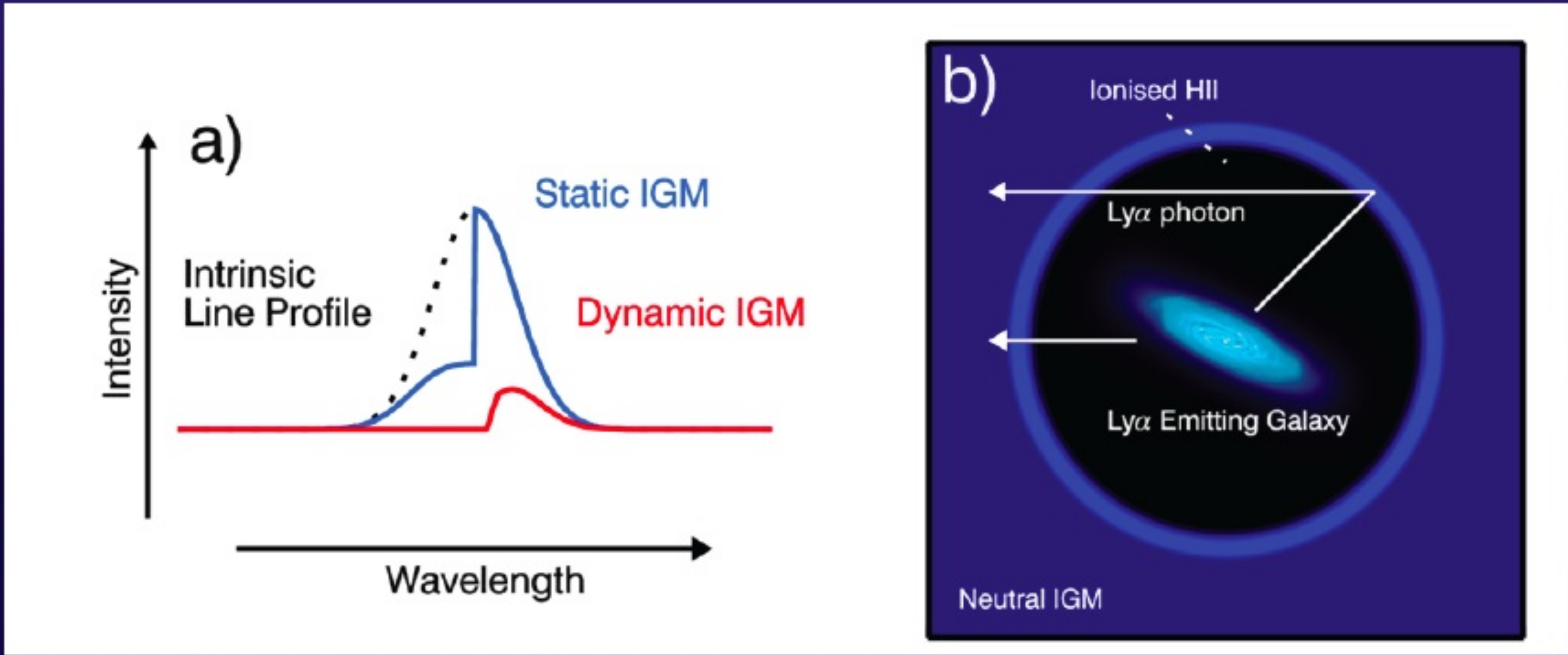
MUSE+lensing

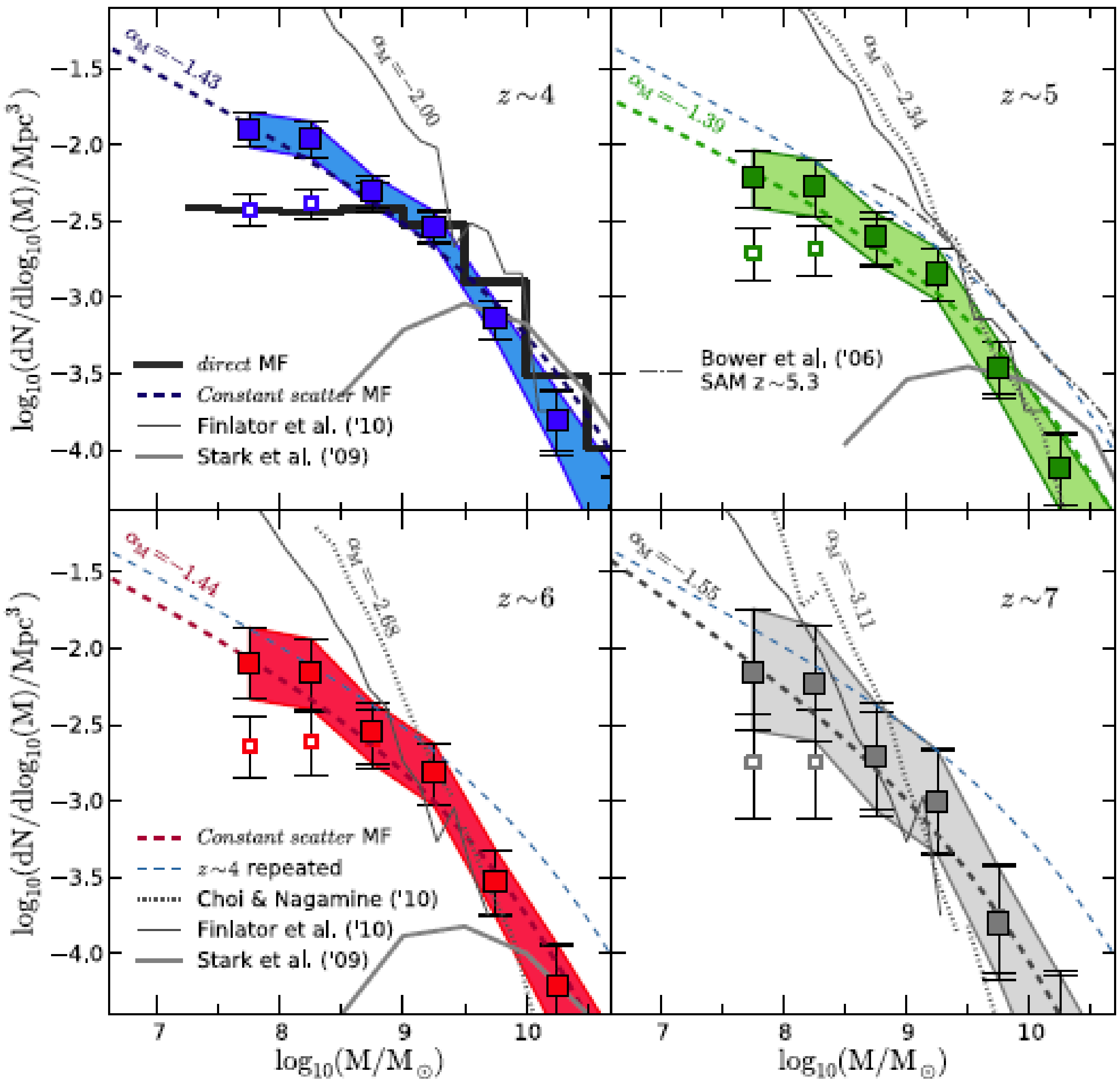
muse



MUSE fov is well adapted to the strong-lensing region, covering the critical lines and multiply imaged systems.
Simulation based from MareNostrum galaxy distributions at z > 3 and UDF for foreground galaxies + lensing cluster (AC114, z=0.3)

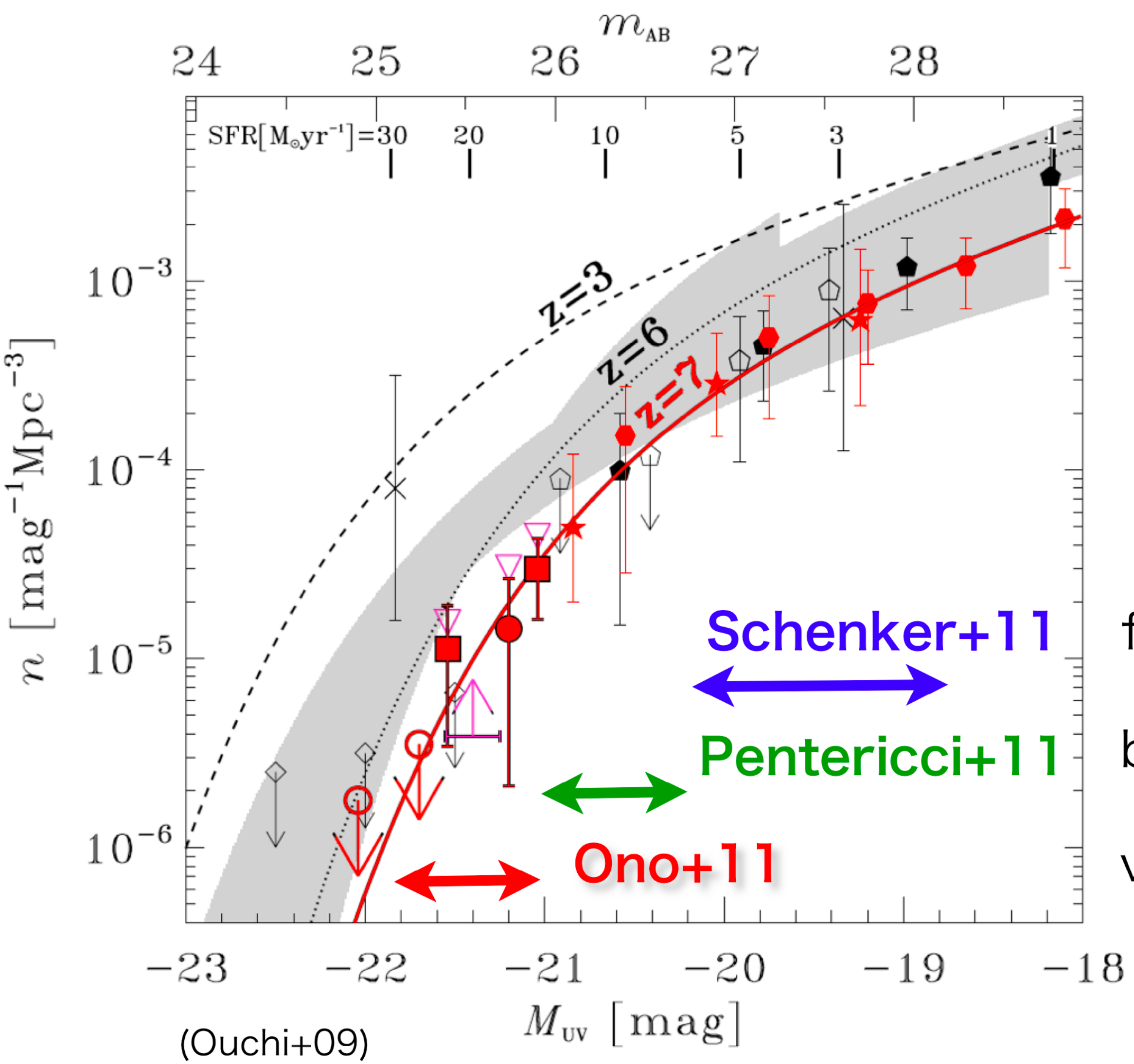
Neutral Hydrogen in IGM Scatters Lyα Photons





z ~4
z ~5
z ~6
z ~7
$\alpha_M = -1.43$
$\alpha_M = -2.00$
$\alpha_M = -1.39$
$\alpha_M = -2.34$
$\alpha_M = -1.44$
$\alpha_M = -2.68$
$\alpha_M = -1.55$
$\alpha_M = -3.11$
direct MF
Constant scatter MF
Finlator et al. ('10)
Stark et al. ('09)
Bower et al. ('06) SAM z~5.3
Constant scatter MF
z~4 repeated
Choi & Nagamine ('10)
Finlator et al. ('10)
Stark et al. ('09)
$\log_{10}(dN/d\log_{10}(M)/Mpc^3)$
$\log_{10}(M/M_\odot)$

Difference among the three studies



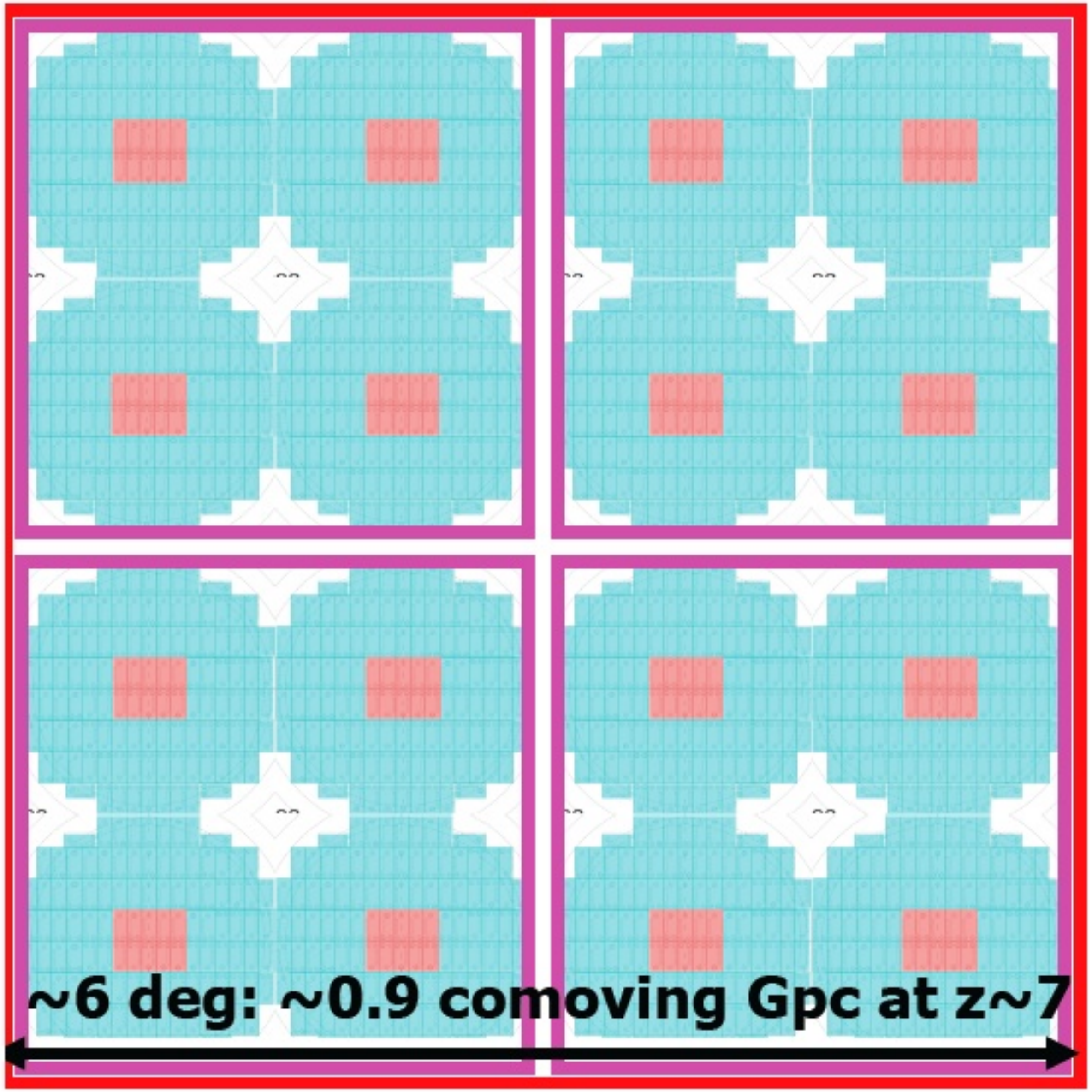
(Ouchi+09)

faint z-dropouts

bright z-dropouts

very bright z-dropouts

Hyper Suprime Cam (~ 2012)



Expect:

10 000 LAEs at z~7

Toward Accurate Stellar Masses: Spectroscopic Measurement of Nebular Line Contamination