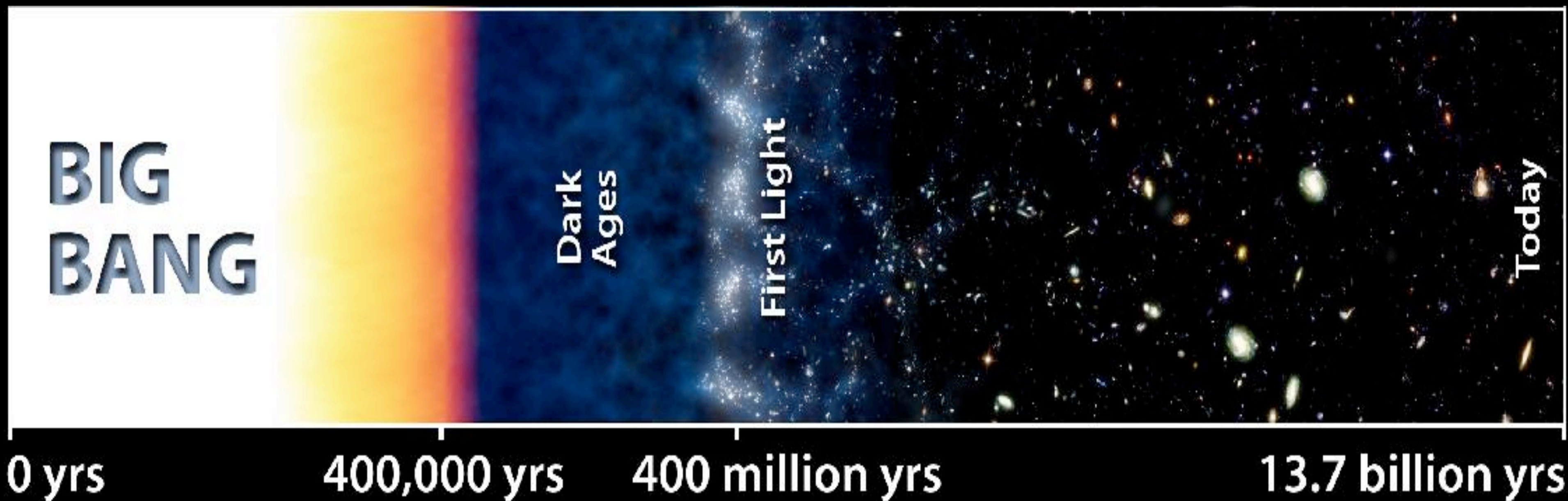
E-ELT & Galaxies in the first billion years



James Dunlop
Institute for Astronomy, University of Edinburgh

PLAN

1. Motivation

2. Current studies of extreme-redshift galaxies

3. E-ELT – what will we want at z > 7 ?

   E-ELT issue 1: Surface densities at z > 7
   E-ELT issue 2: Emission lines at z > 7
   E-ELT issue 3: Galaxy structures at z > 7 – IFUs ?

4. Conclusions

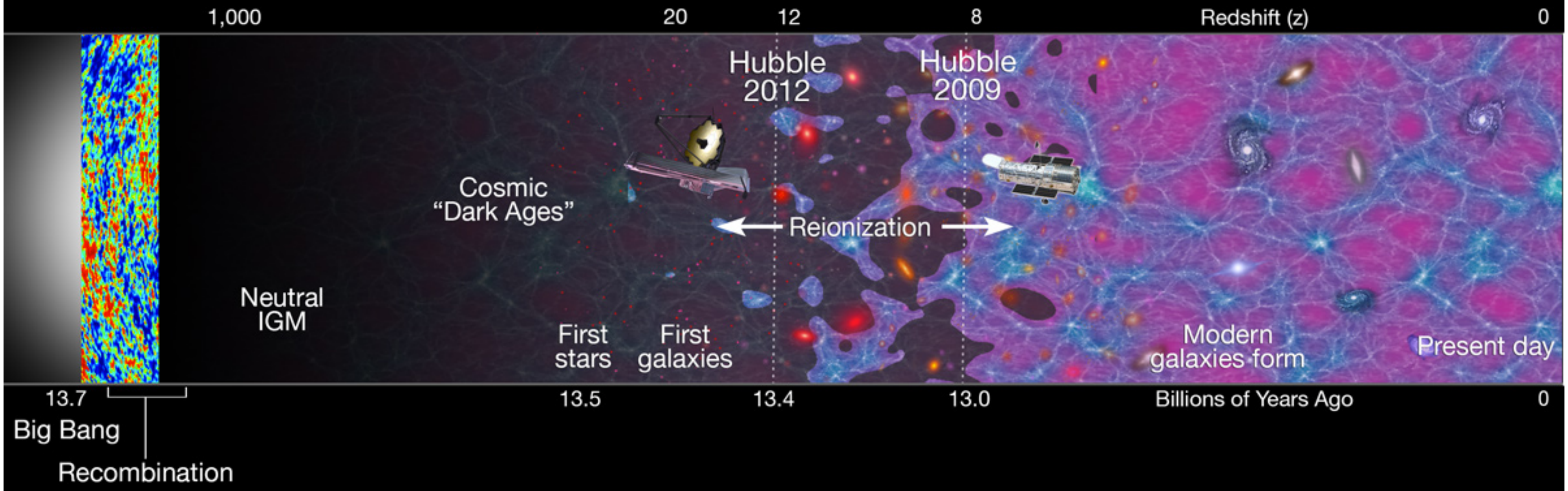
1. Motivation

First billion years = redshifts z > 6

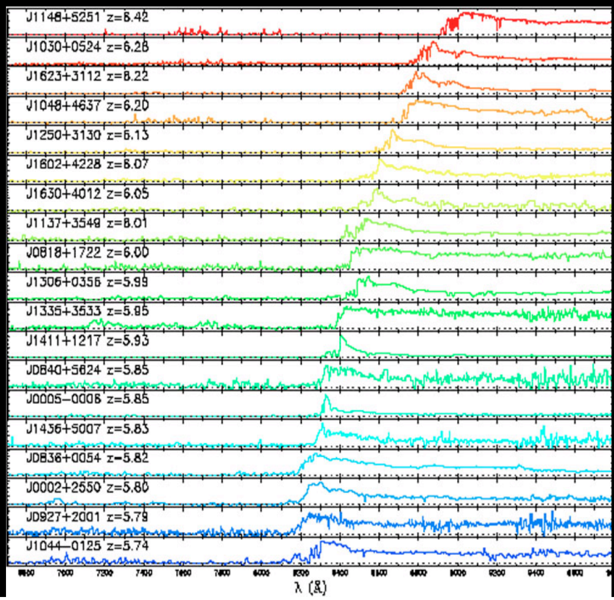
Why is this era of interest?

- When/how did the first galaxies form and grow
- Testing models of galaxy formation
- Establishing whether / when galaxies reionized the Universe

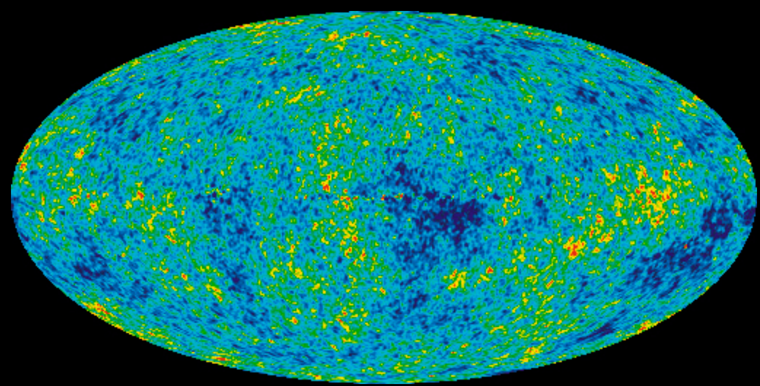
Cosmic Reionization



Finished by z ~ 6 (Fan et al. 2006)



But started at much higher redshift: WMAP-9 polarization results suggest reionization at z ~ 10 if instantaneous (Hinshaw et al. 2013)



Did the first galaxies reionize the Universe?

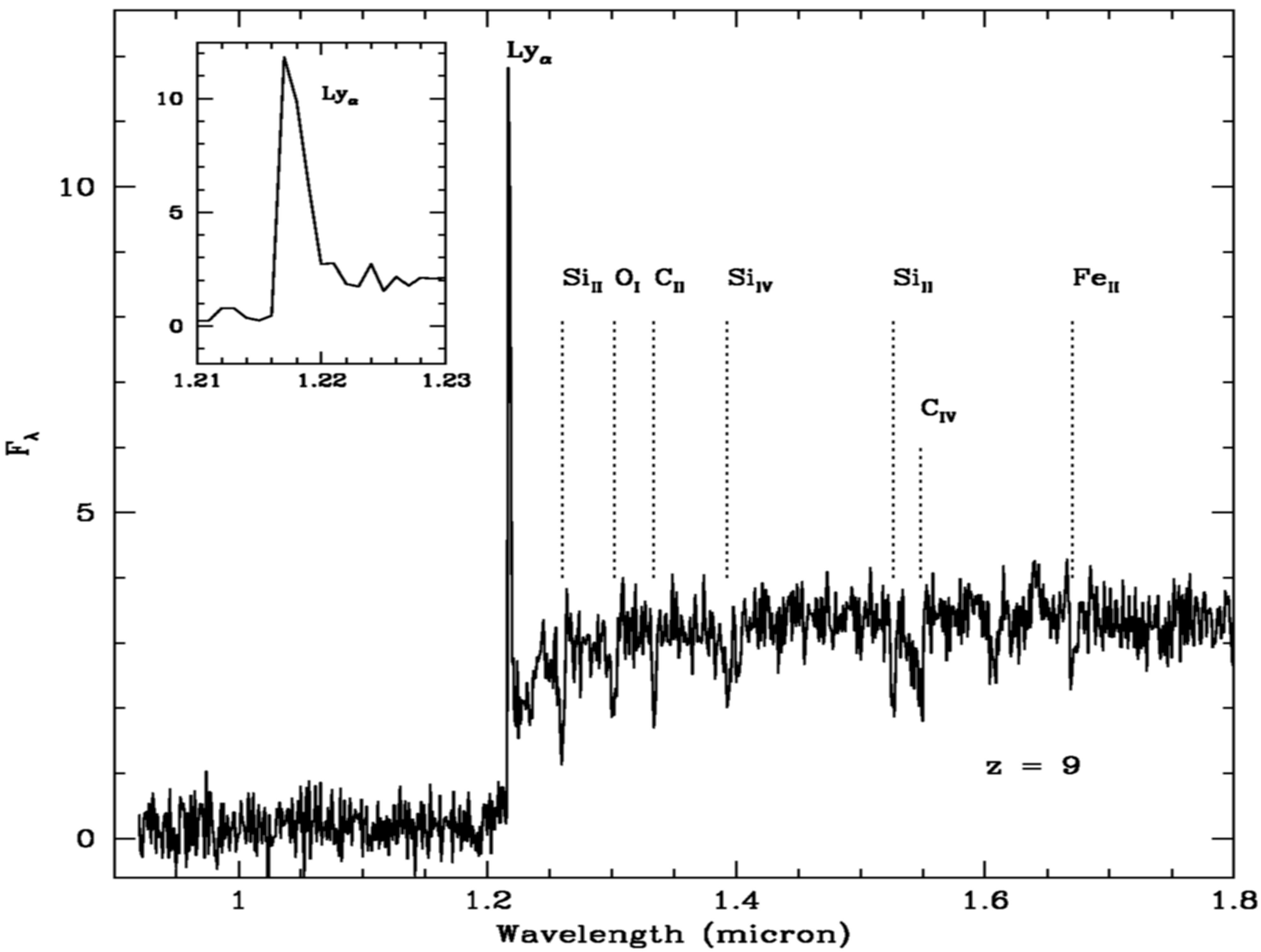
Want to establish 3 things:

1. Number density of galaxies
   = Luminosity function

2. Number of ionizing photons produced per galaxy
   = stellar populations

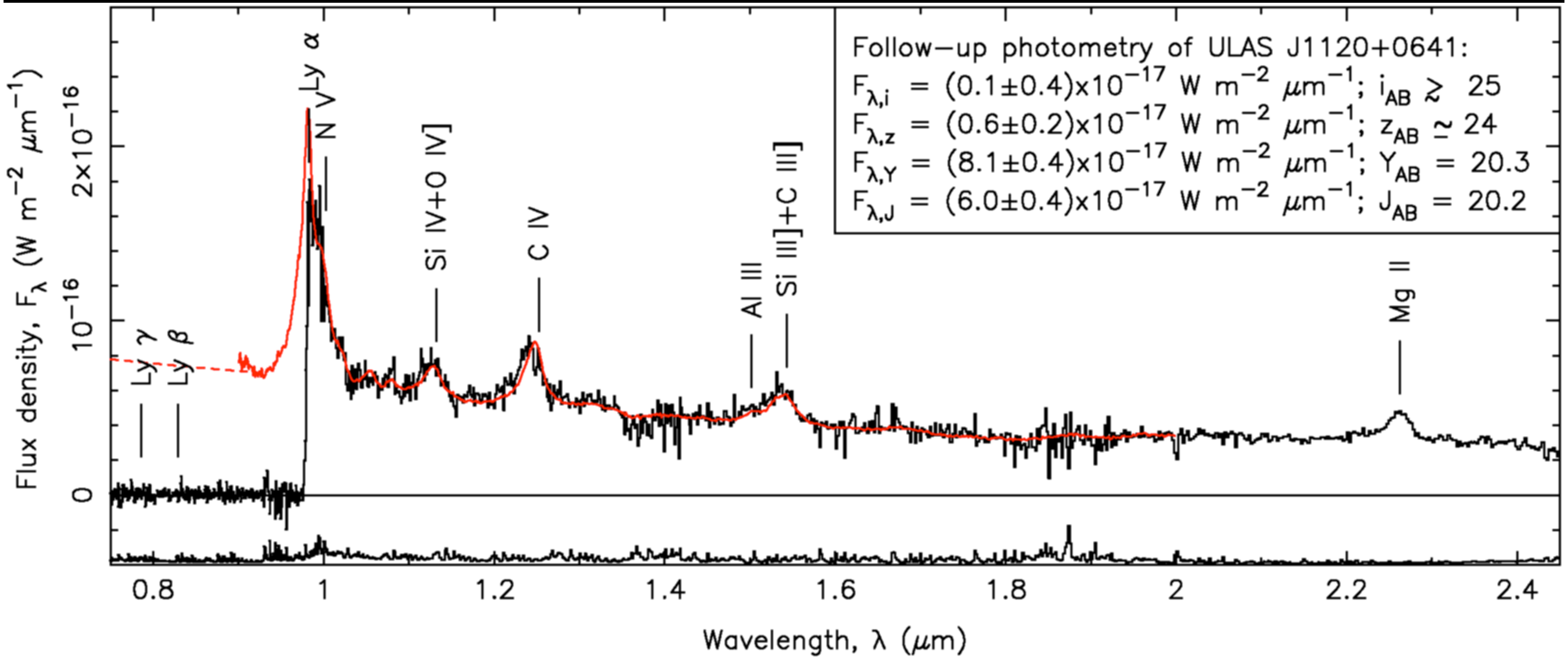
3. How many of these photons get out of galaxy to ionize the IGM
   = escape fraction

2. Current studies of extreme redshift galaxies



Ly$_\alpha$
Si$_{II}$
O$_I$
C$_{II}$
Si$_{IV}$
Si$_{II}$
C$_{IV}$
Fe$_{II}$
z = 9
F$_\lambda$
Wavelength (micron)
0
5
10
1
1.2
1.4
1.6
1.8
1.21
1.22
1.23

Observing a quasar at z = 7 is easy! (Mortlock et al. 2011)

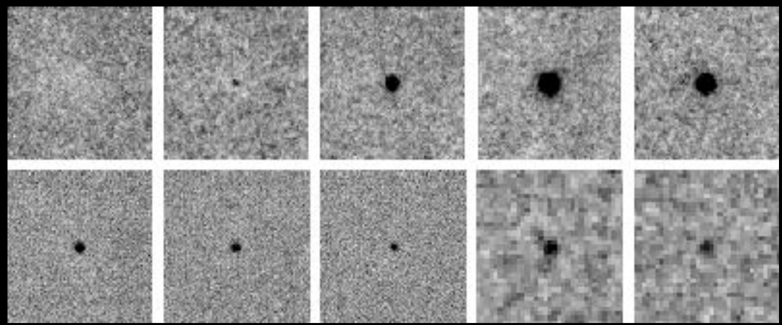


Raises issue of why not use Lyman-alpha emission to find galaxies ?

Selecting high redshift galaxies

Broad-band

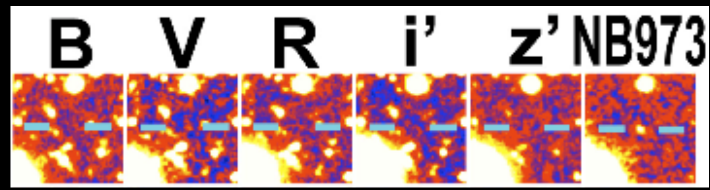
B V R i z

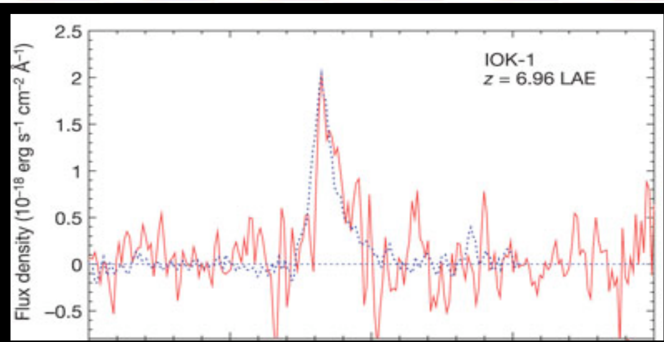


J H K 3.6μm 4.5μm

McLure et al. (2009)

Narrow-band





Iye et al. (2006)

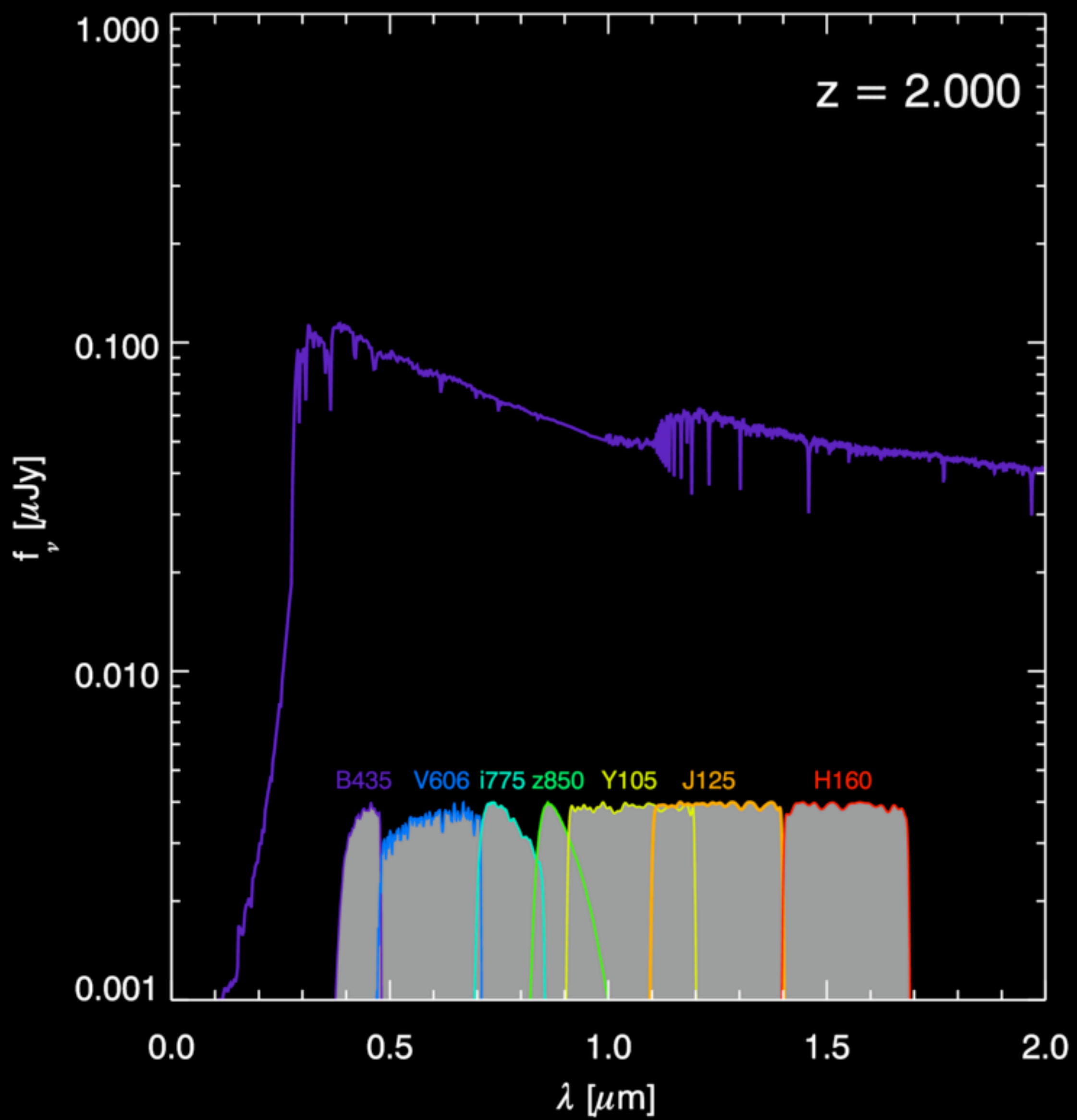
Strengths:
1. More complete
2. Larger sample volumes

Problems:
1. Less precise redshift information
2. Potential for low-z contamination

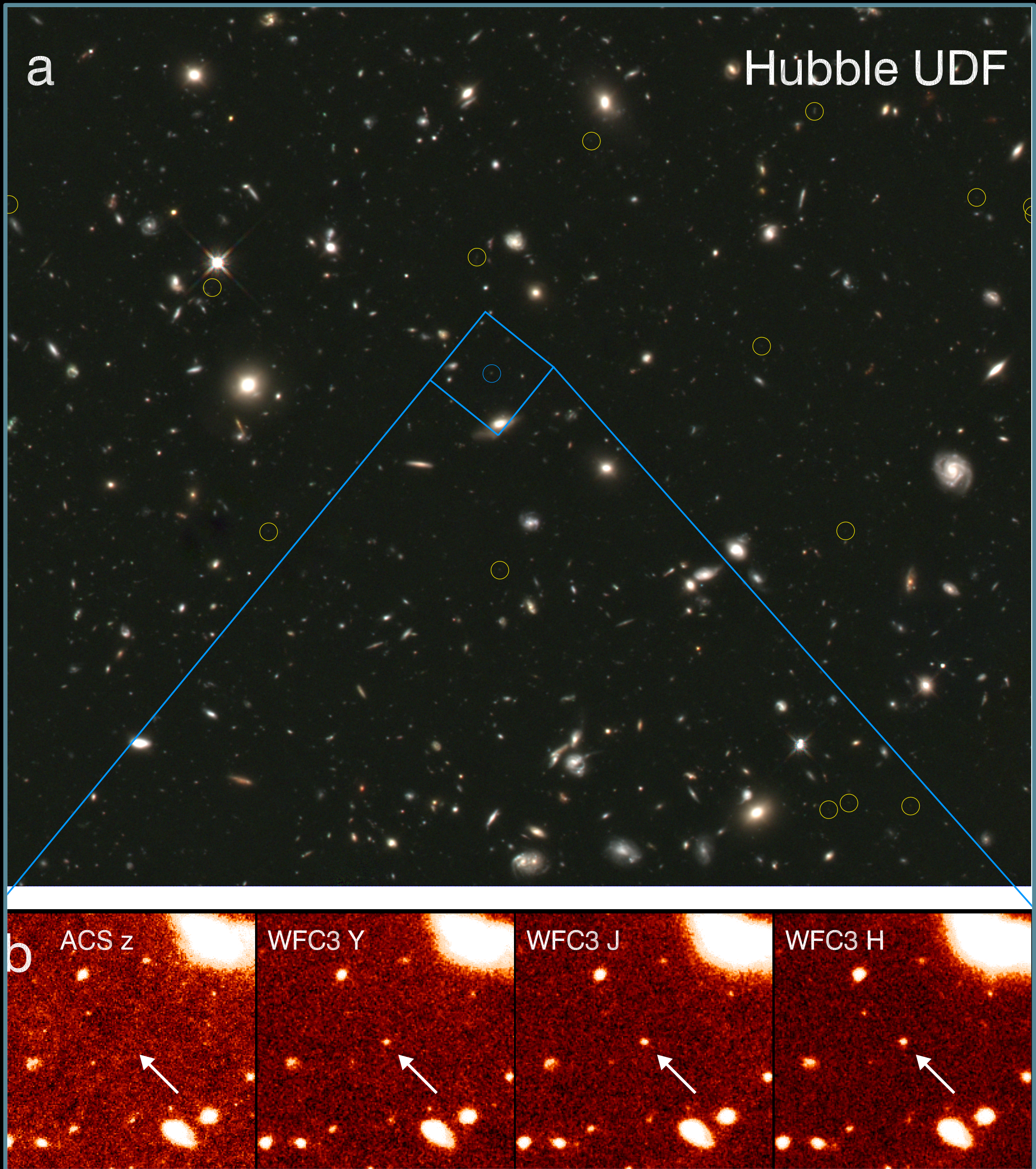
Strengths:
1. Precise redshift information
2. "Clean" selection method

Problems:
1. Sample very limited volume
2. Only select line emitters (<25%)

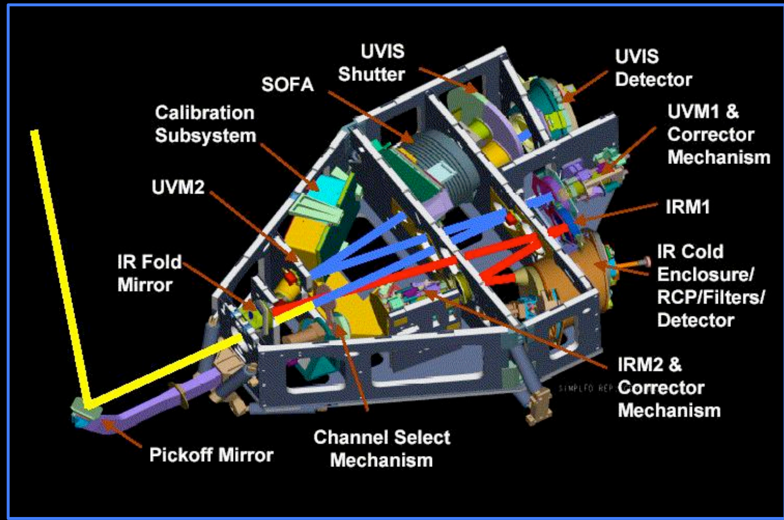
Lyman-break selection



z > 7 - HST Wide Field Camera 3 (WFC3)



McLure, Dunlop et al (2010)



Two channel, UVIS and NIR (YJH)

NIR channel has 4.5 square arcmin FOV

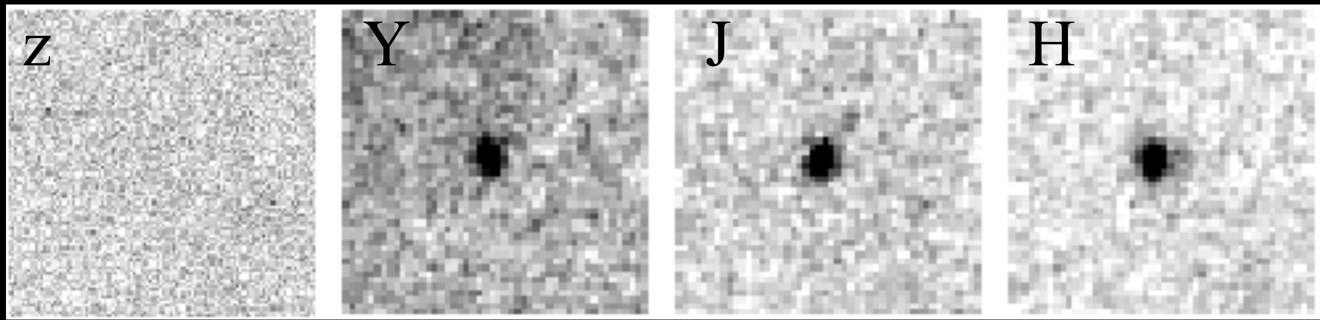
Image quality of ~0.15” FWHM

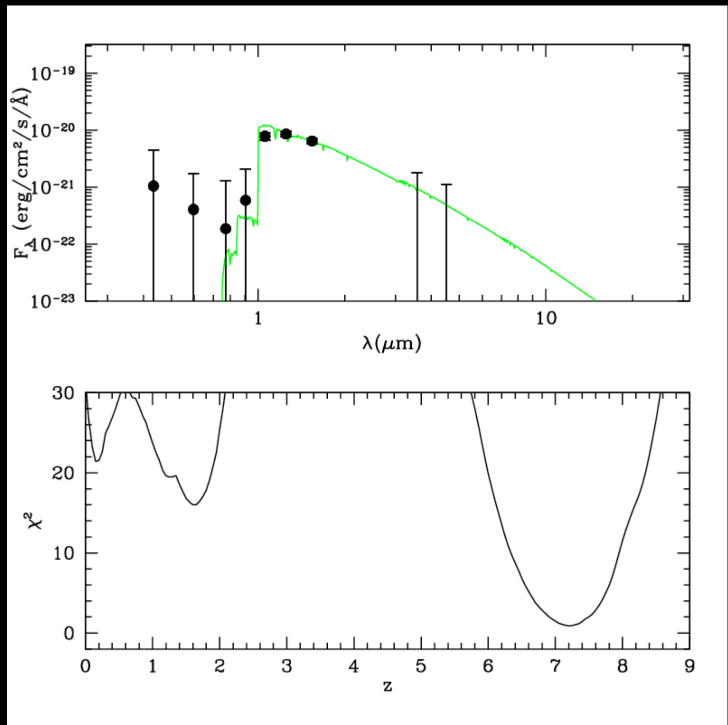
Order of magnitude better that NICMOS

Y J H =29(AB) imaging allows LBG selection out to 7 < z < 10

WFC3 Imaging of the HUDF: Example SED fits

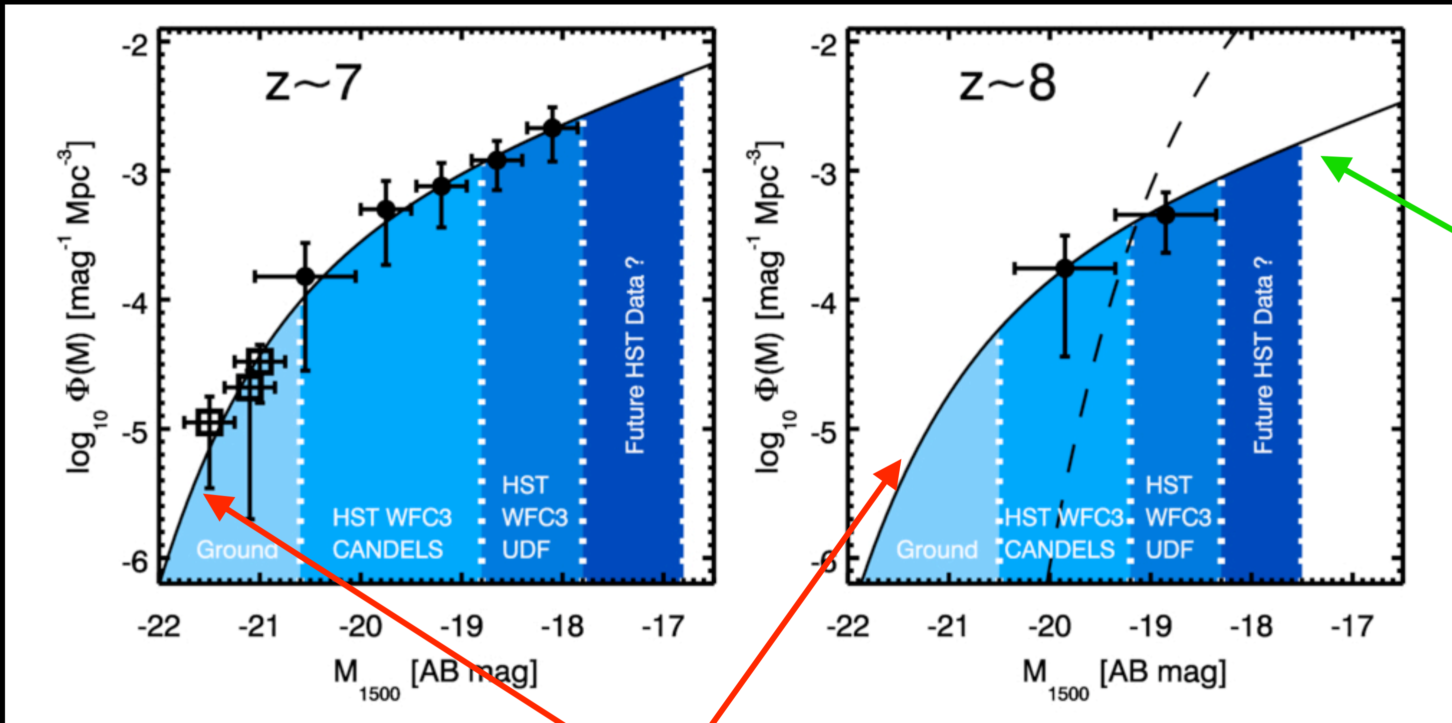
McLure, Dunlop et al. 2010





ID No. 835 $z_{phot} = 7.20$

Improving the LF at z = 7, 8 : building the wedding-cake……



Debate over faint-end slope

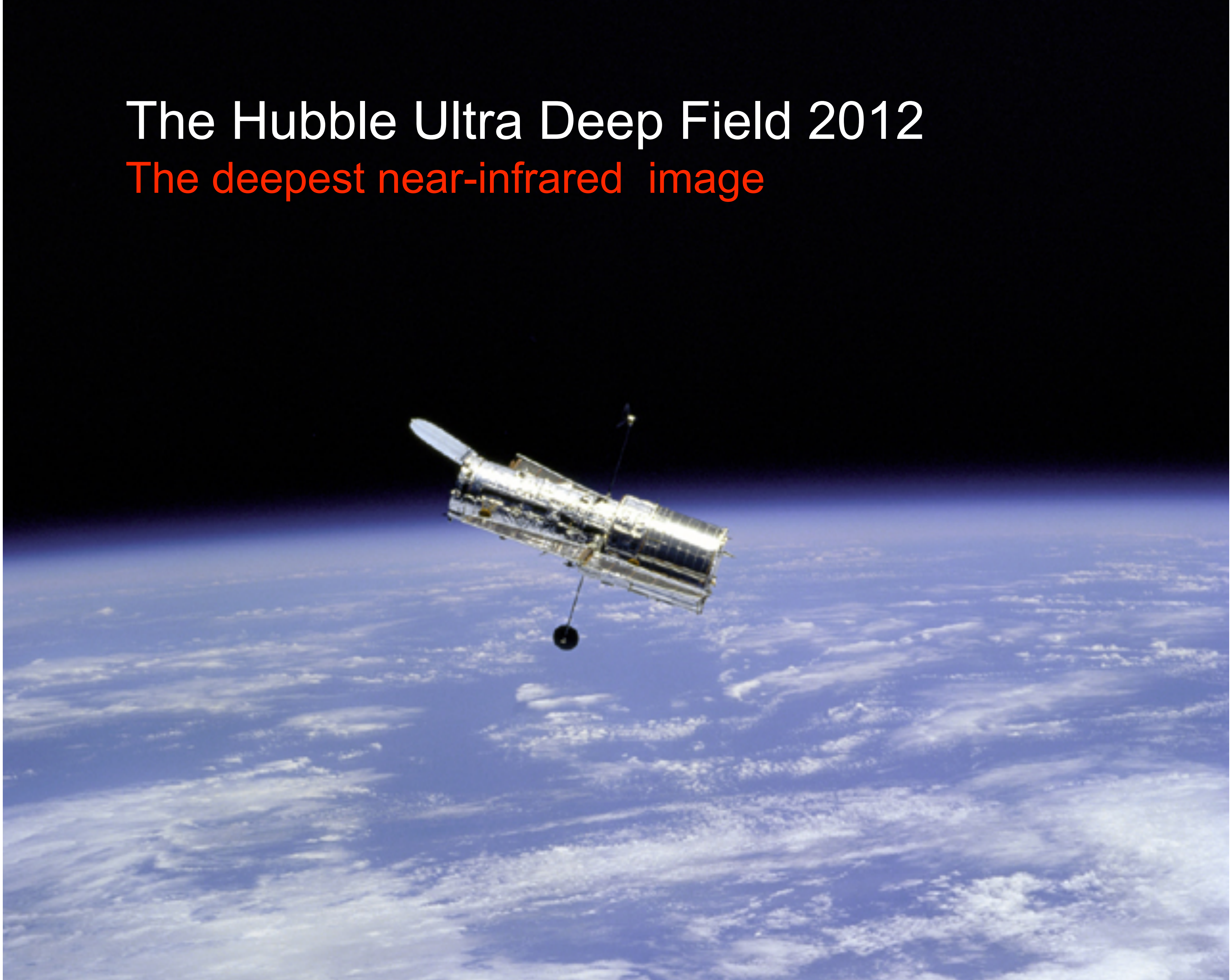
Important for reionization

Lack of constraint on exponential cut-off

Galaxy formation - onset of feedback?

The Hubble Ultra Deep Field 2012

The deepest near-infrared image



UDF12: Observational details

Final depths (AB):

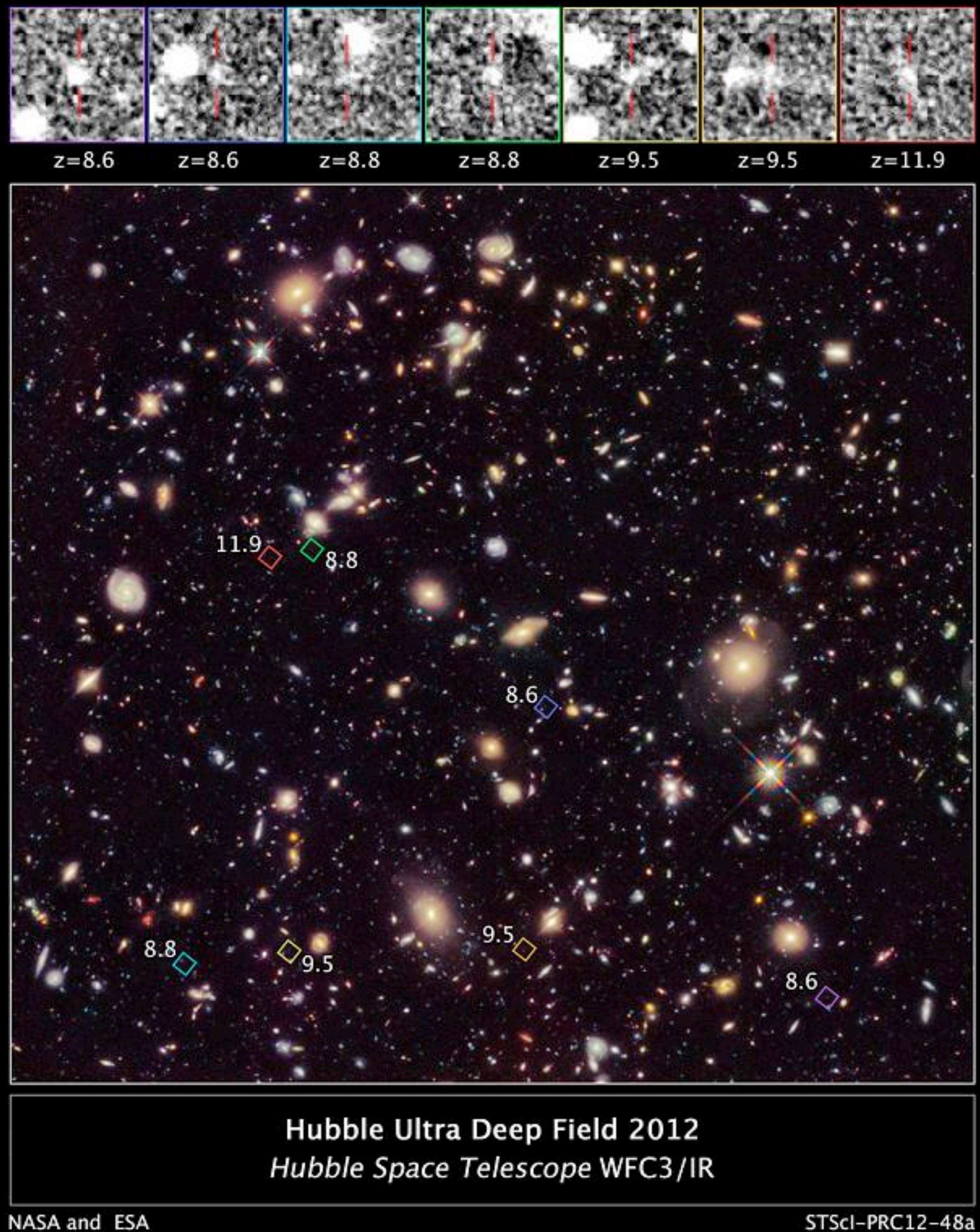
Y_{105} = 30.0

J_{125} = 29.5

J_{140} = 29.5

H_{160} = 29.5

Ellis, McLure, Dunlop et al., 2013, ApJ, 763, L7



First meaningful sample of galaxies at z > 8.5

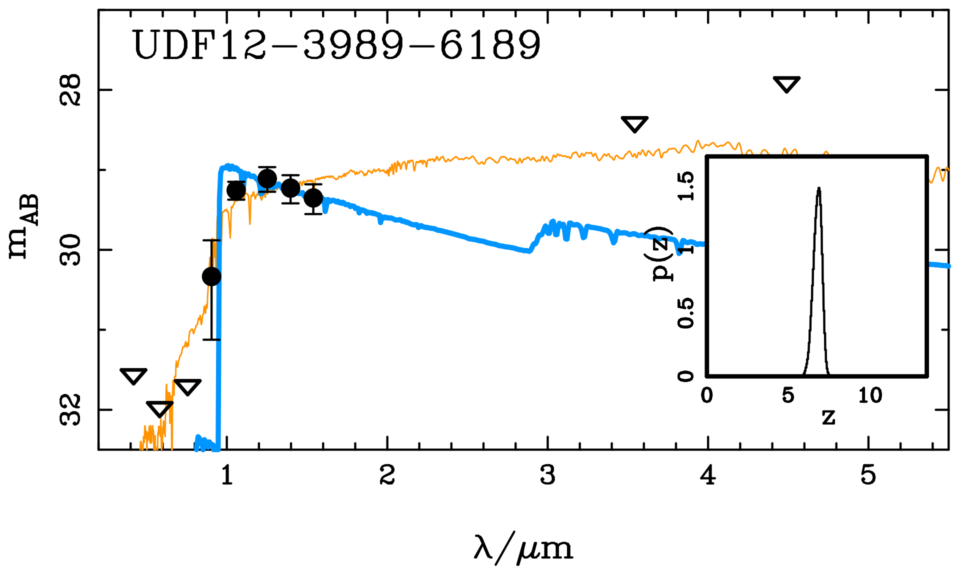
Ellis, McLure, Dunlop et al. (2013)

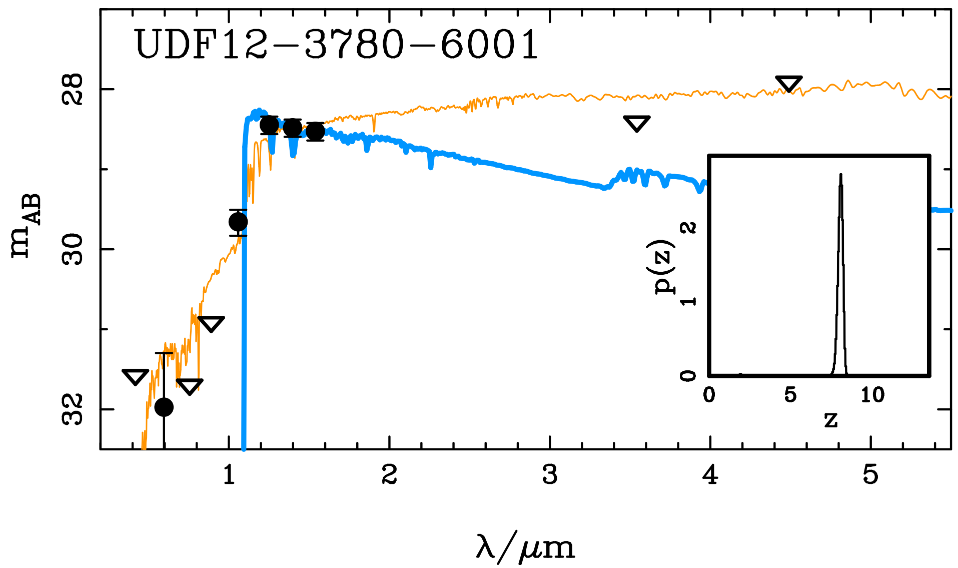
Now clear that galaxies exist and can be studied at z ~ 10 and beyond

The galaxy luminosity function at z=7 and z=8

McLure, Dunlop et al. (2013), arXiv:1212:5222

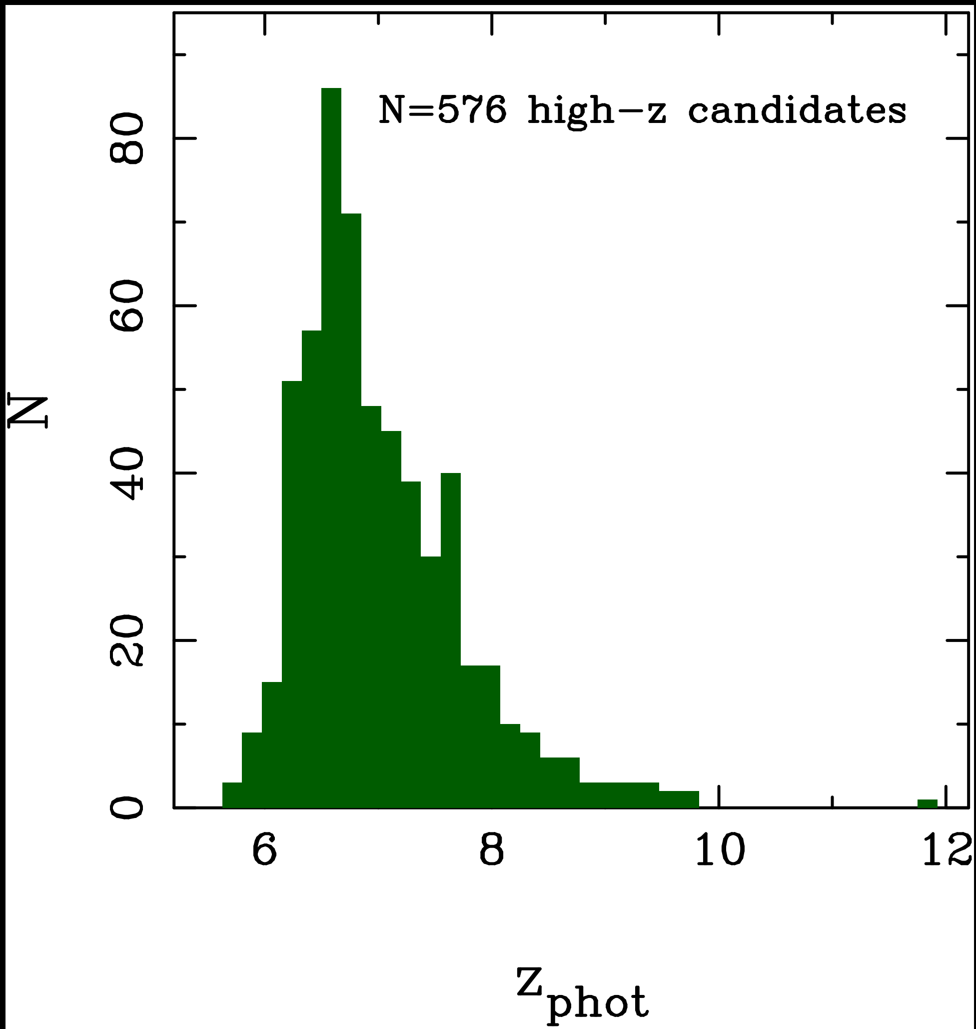
- Photometric redshift selection of z > 6.5 galaxies (10-band SED fits)
- Nested structure of deep/shallow WFC3/IR imaging fields
- Incorporate p(z) into maximum likelihood LF fitting





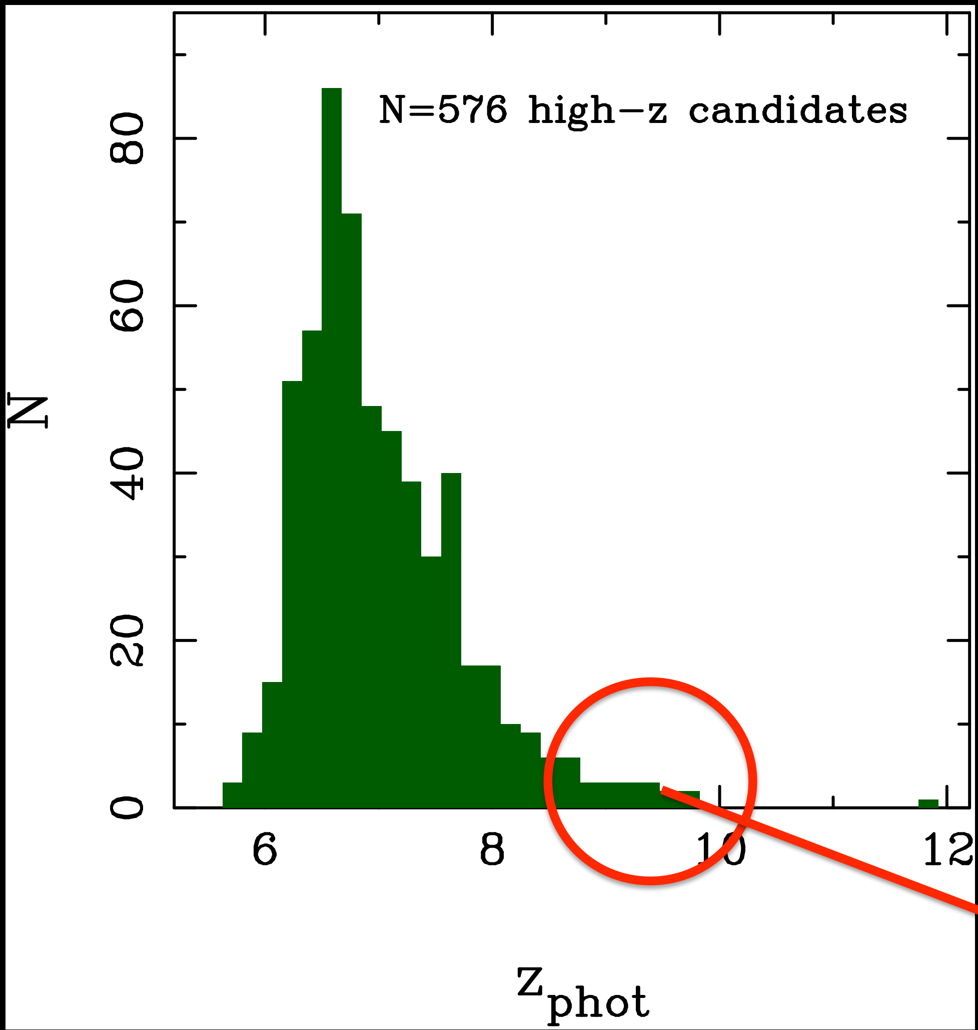
Example SED fits in UDF12 at z = 7 and z = 8

The galaxy luminosity function at z=7 and z=8



Final sample contains ~ 600 galaxies selected from 8 survey fields

The galaxy luminosity function at z=7 and z=8

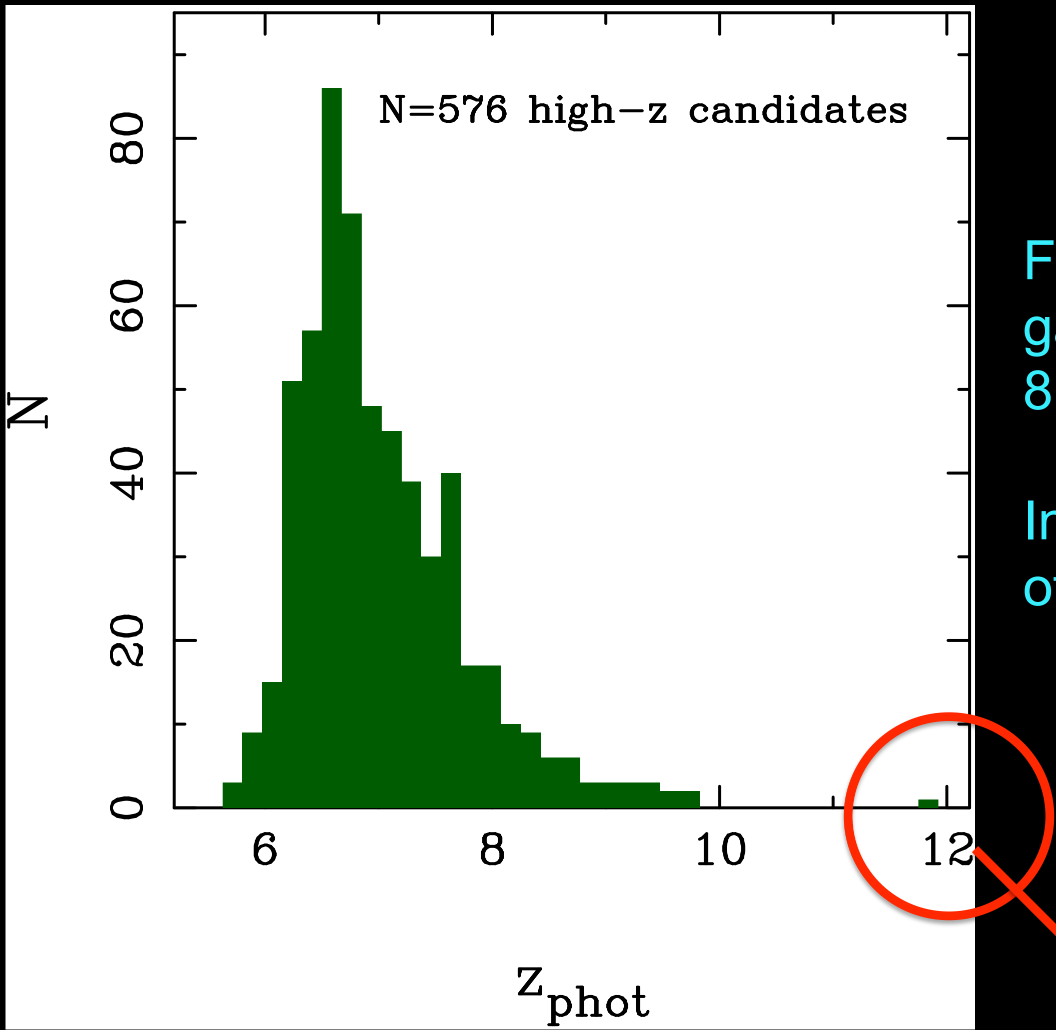


Final sample contains ~ 600 galaxies selected from 8 survey fields

Incorporates first robust sample of galaxies at z > 8.5

Ellis et al. (2013)

The galaxy luminosity function at z=7 and z=8

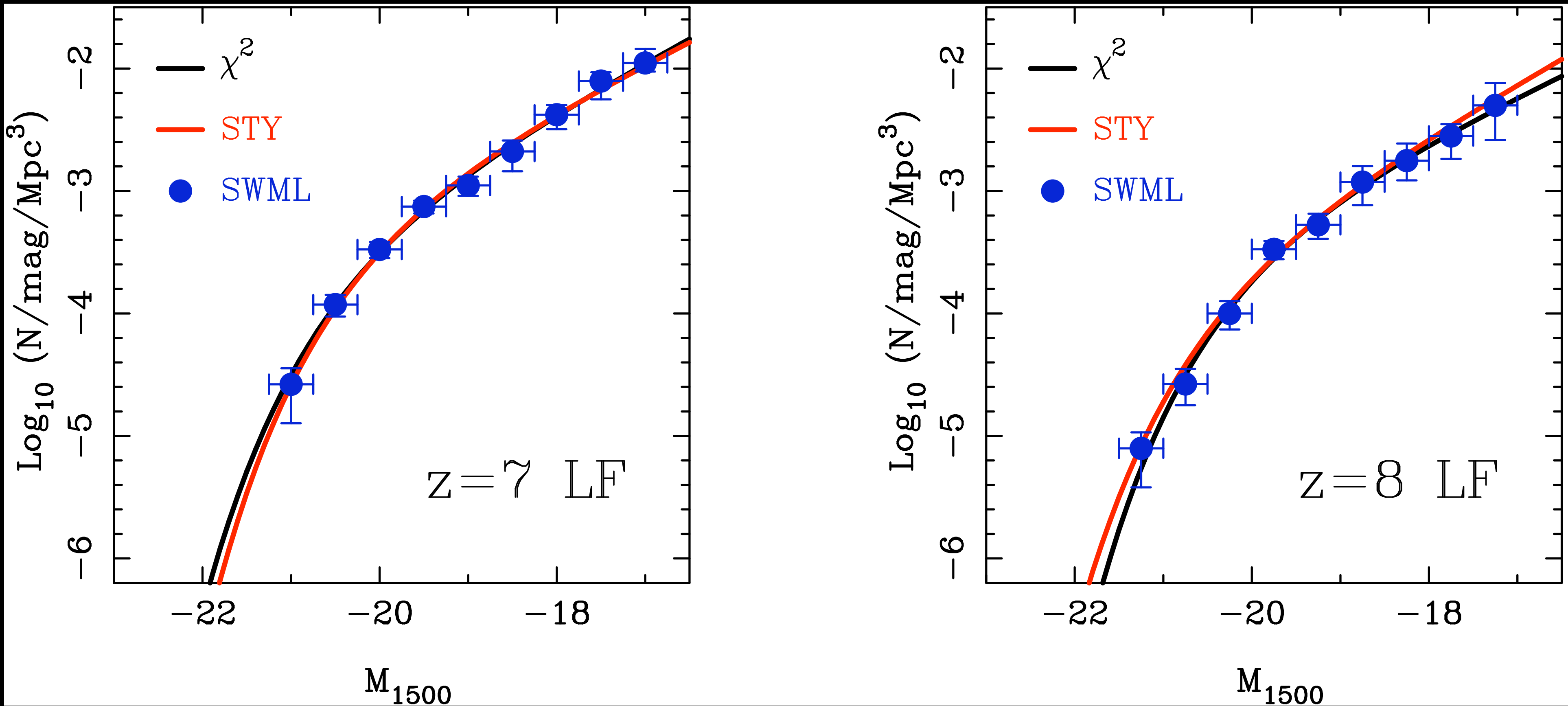


Final sample contains ~ 600 galaxies selected from 8 survey fields

Incorporates first robust sample of galaxies at z > 8.5

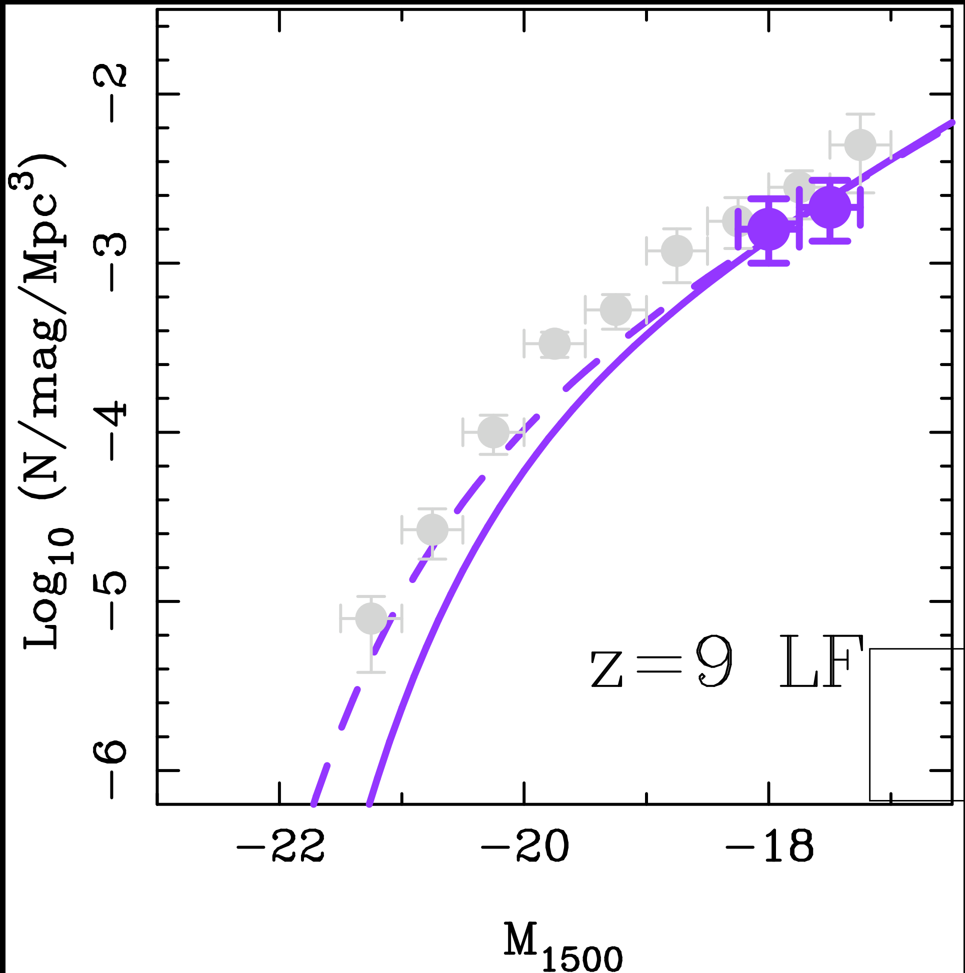
Redshift z=12 candidate?

The galaxy luminosity function at z=7 and z=8



- 0.75 - 1.0 magnitudes fainter at z = 7 and z = 8 than previously possible
- first, self-contained LF determination over large area
- both Schechter function fits suggest very steep faint-end slope (α = - 2)

First look at the z = 9 luminosity function



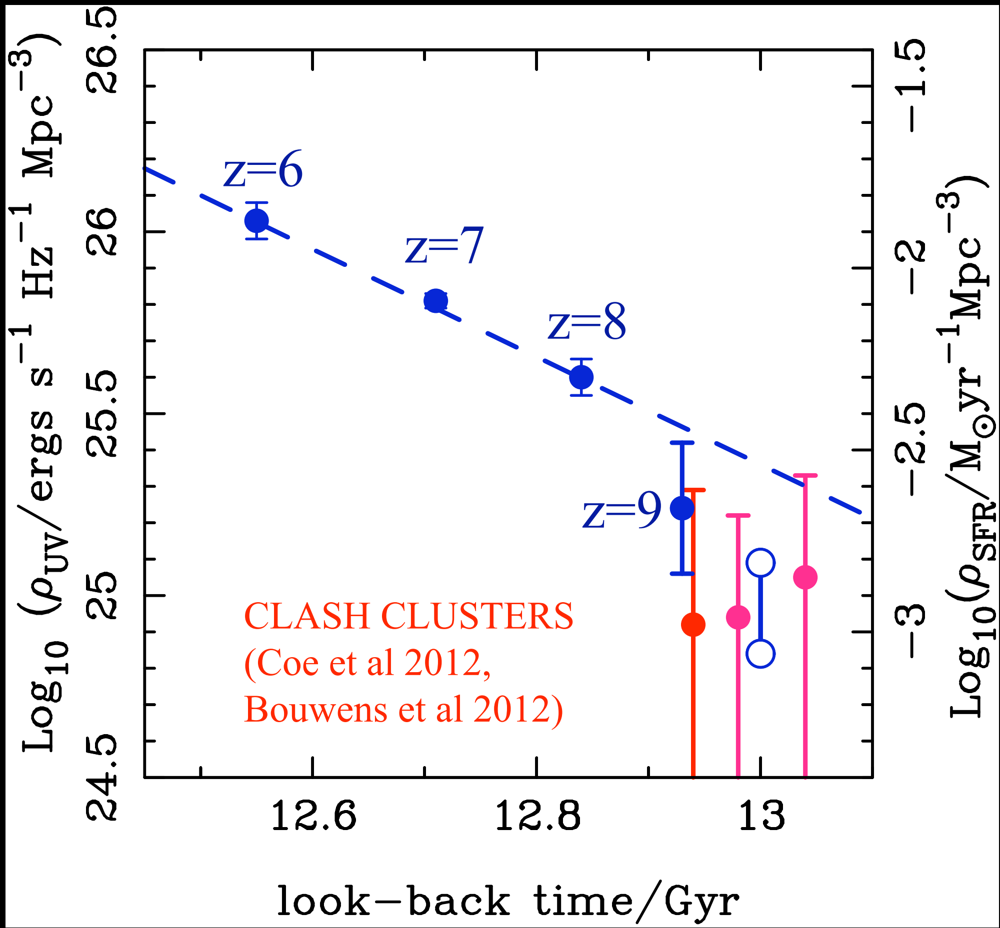
Purple data-points show two SWML bins at z = 9

Solid/dashed lines show luminosity/density evolution from z = 8 to z = 9

No dramatic drop in numbers of faint galaxies at z

Does at least allow an estimate of the star-formation rate density

Evolution of the star-formation rate density



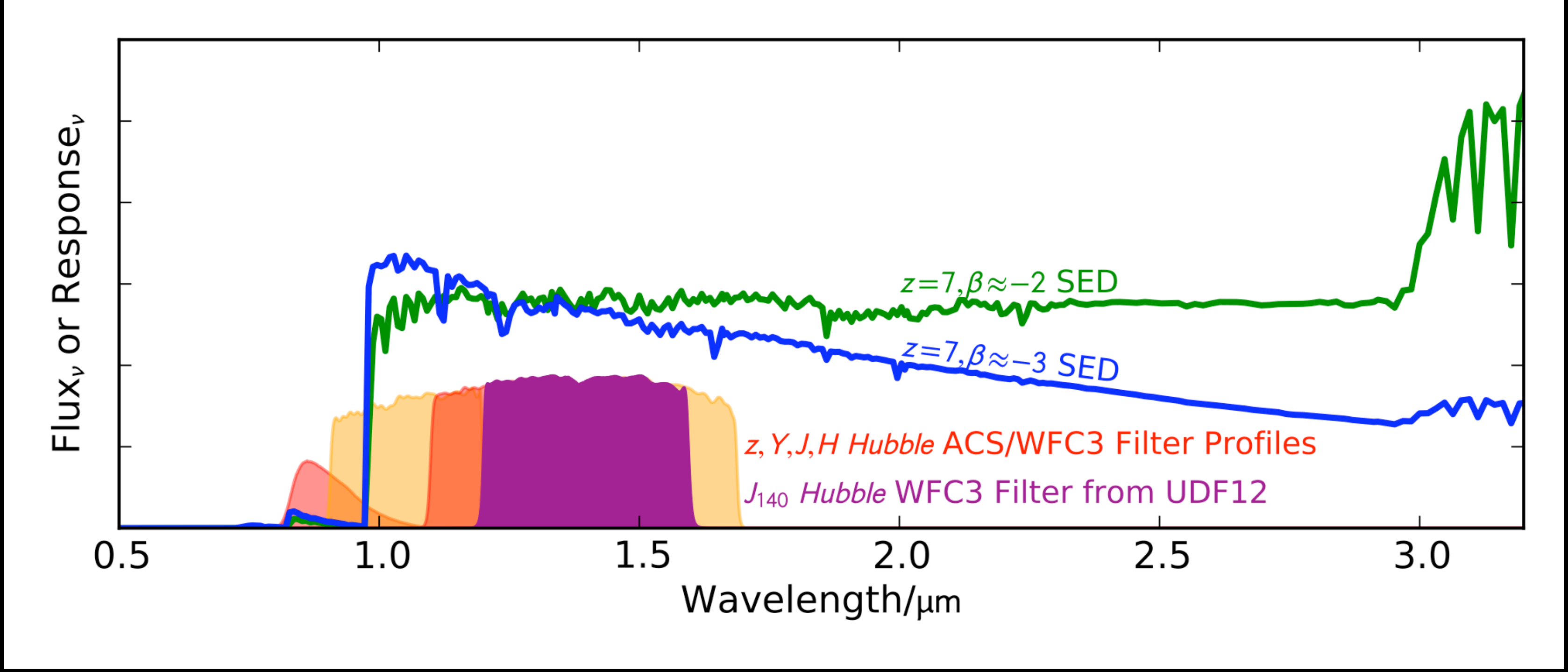
- Linear fall-off in star-formation density in redshift interval $6 < z < 8$
- Evidence for steeper fall-off at $z > 8$
- Important implications for reionization calculations

Physical properties of faint z = 7 - 8 galaxies

Dunlop et al. (2013) astro-ph 1212.0860

Can't measure much, but can make new unbiased measurement of UV continuum slope

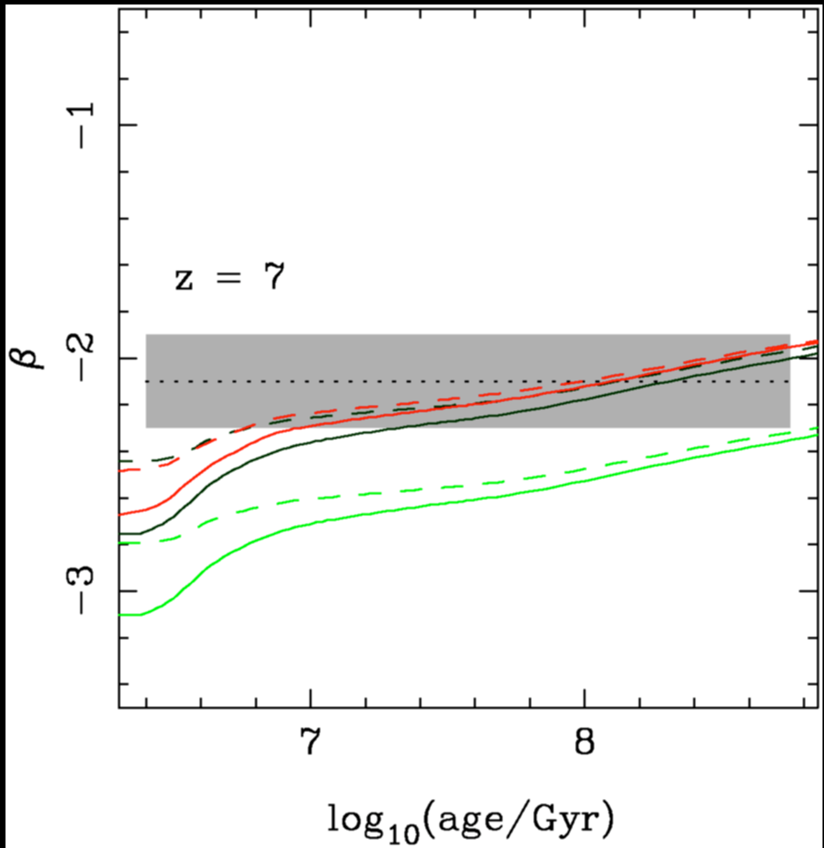
β, where F_{λ} = const x λ^{β}



Aided by selection in new J140W filter

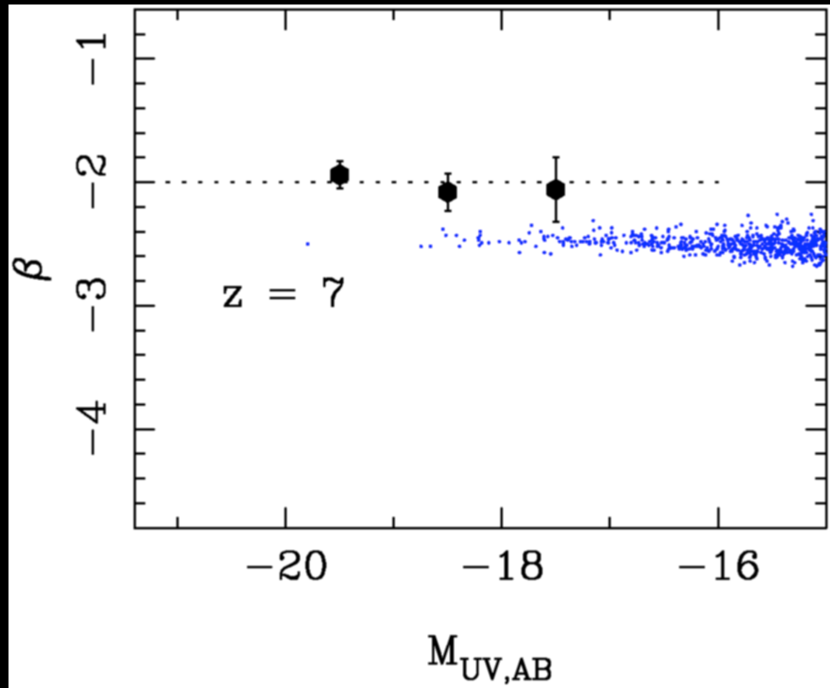
HUDF12 has enabled new, unbiased measure of average UV slope at z = 7 – 8

But what can this tell us?



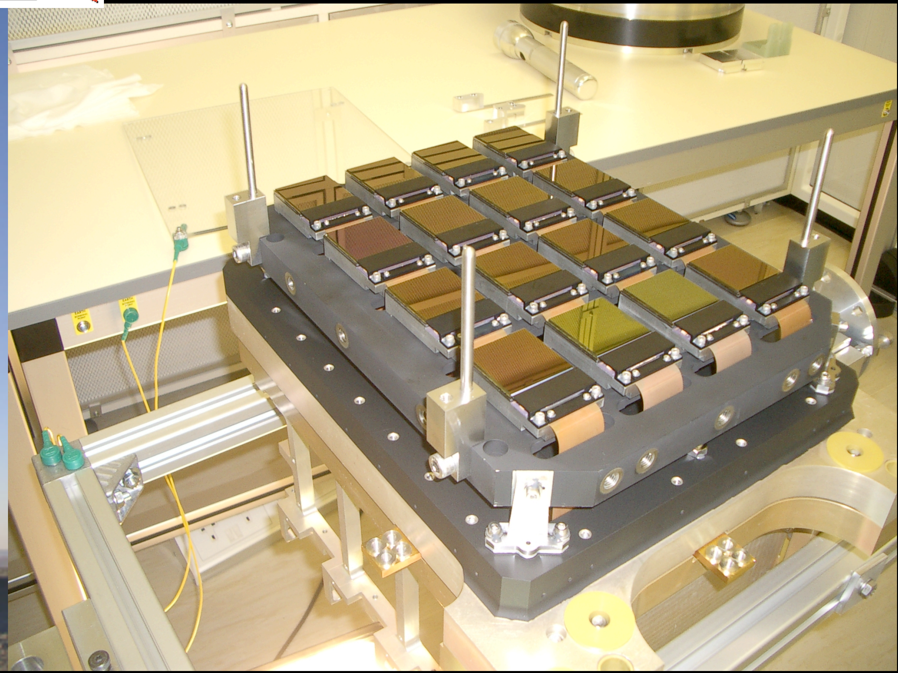
Burst models of galaxies
Constant star-formation

solar, 0.2 solar, 0.2 solar + dust
solar, 0.2 solar, 0.02 solar metallicity



cf predictions from galaxy formation simulation (Dayal et al. 2013)

Rare bright z > 7 galaxies: New ground-based near-IR surveys



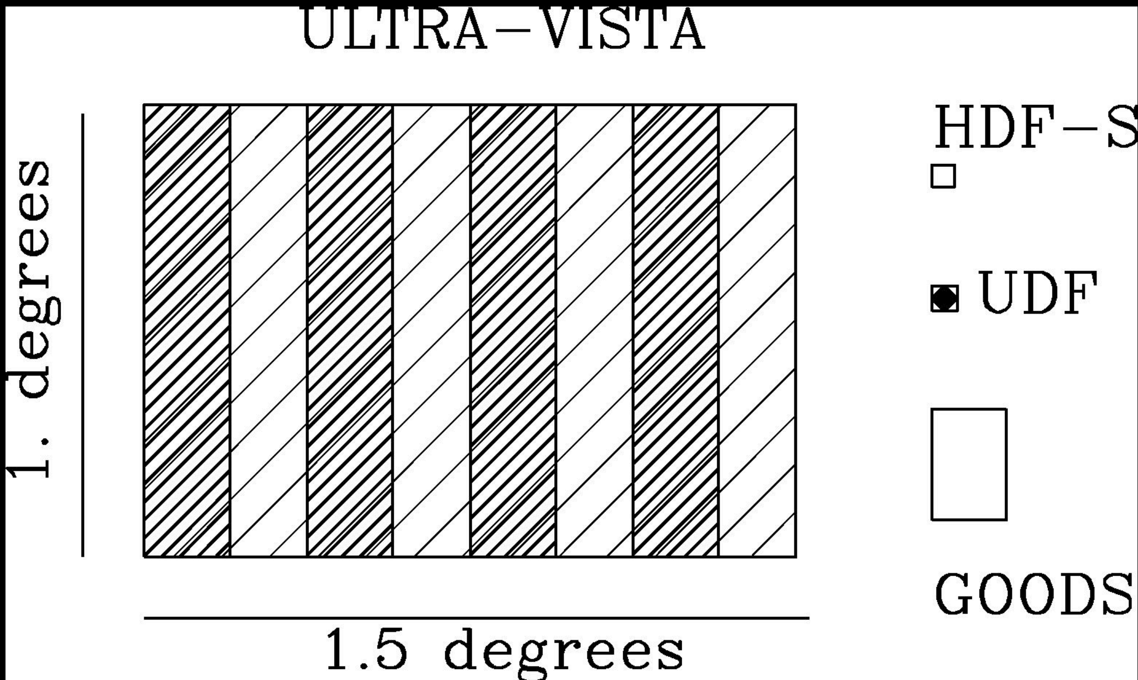
VISTA telescope: Paranal, Chile

67 mega-pixel camera (1.5 sq. deg)

Survey operations commenced in 2010

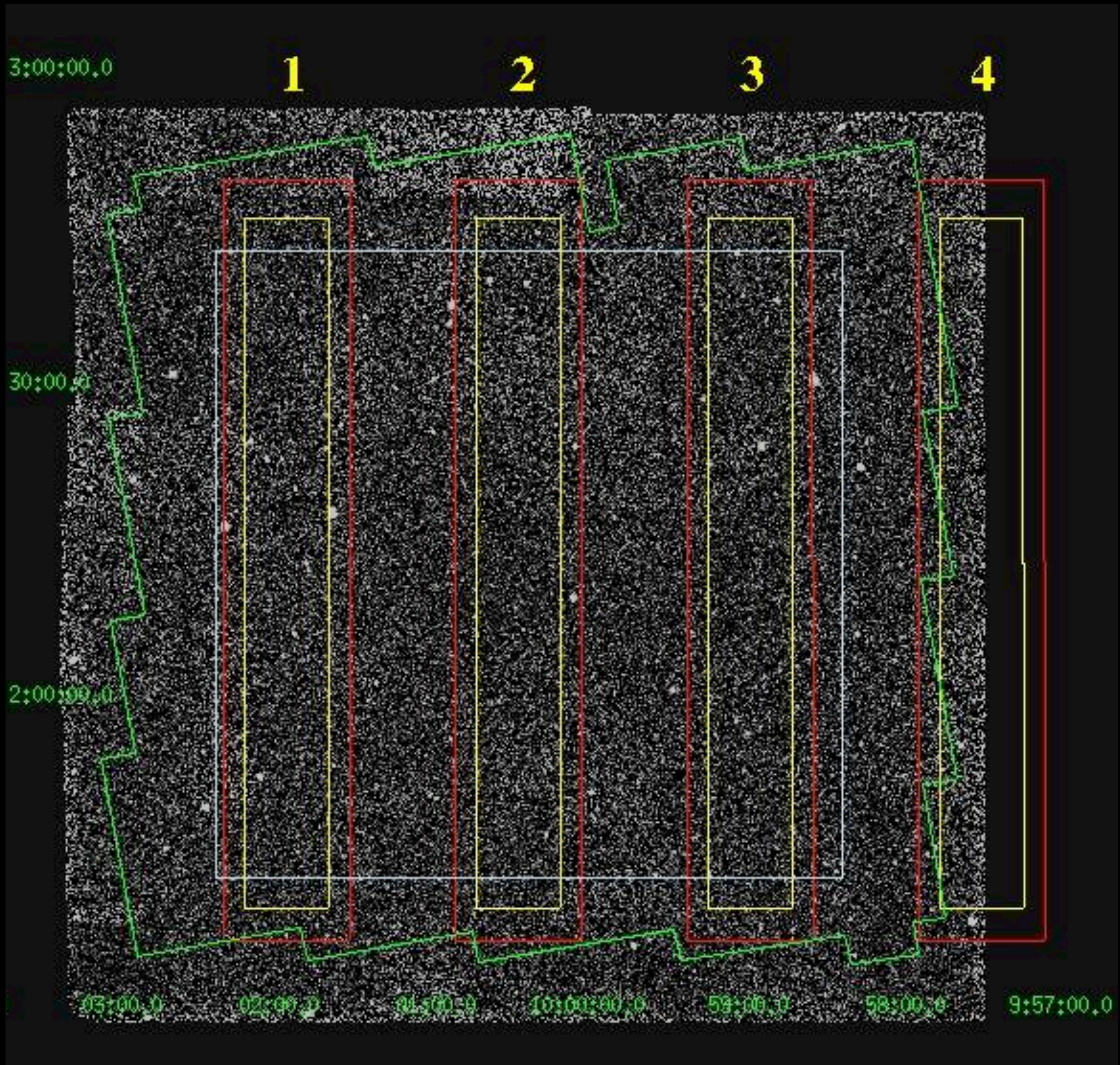
UltraVISTA – deepest public survey with Vista telescope

- PIs Dunlop, Franx, Le Fevre, Fynbo
- DEEP - 0.73 sq. deg., Y=26.7, J=26.6, H=26.1, K=25.6 (1408 hr)
- WIDE – 1.50 sq. deg., Y=25.3, J=25.2, H=24.7, K=24.2 (212 hr)
- Narrow-band survey, at 1.185 microns (z = 8.8 for Lyman-alpha) (180 hr)
- 1800 hours over 5 years – commenced Jan 2010



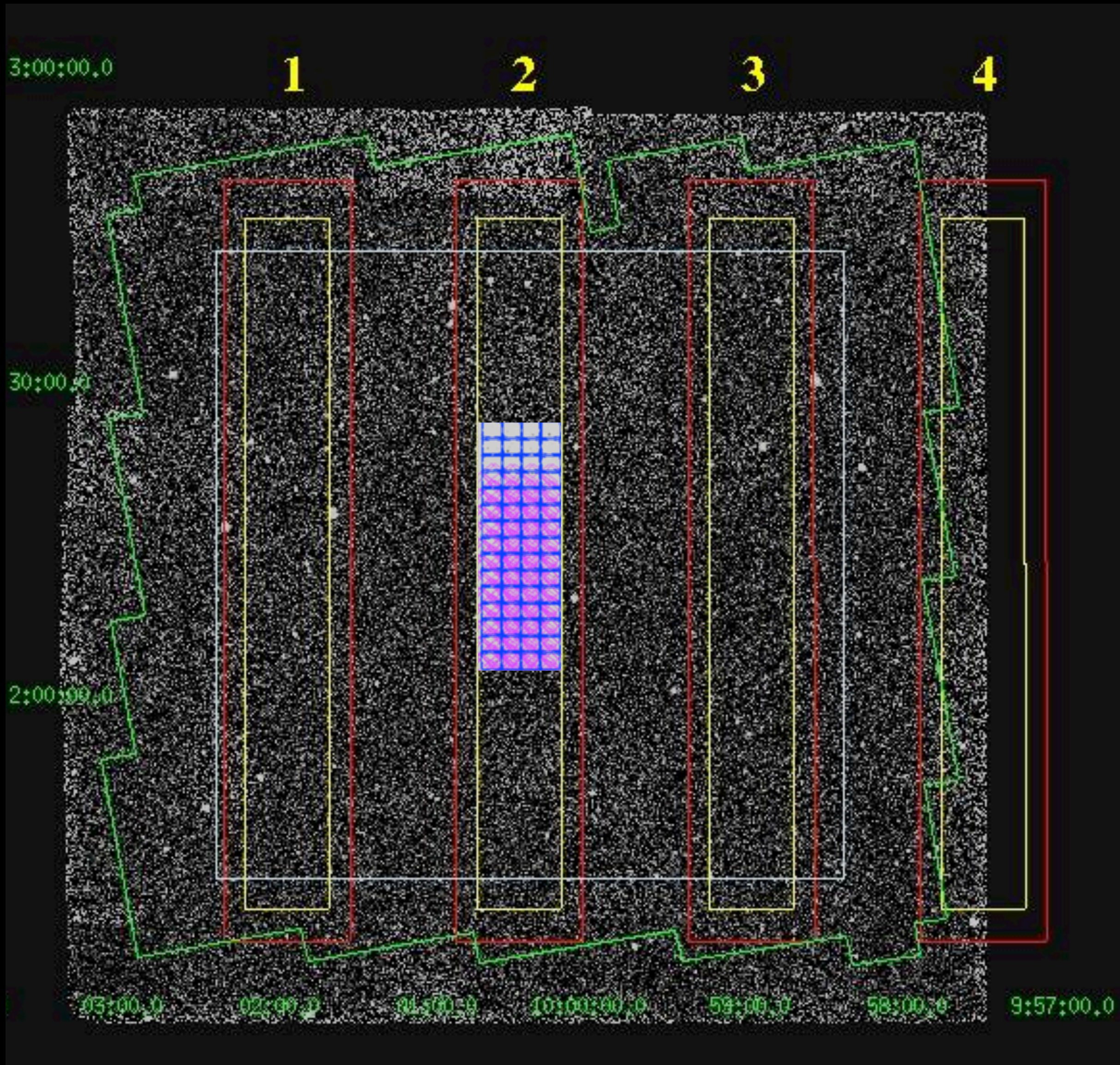
First ESO data release March 2012

UltraVISTA



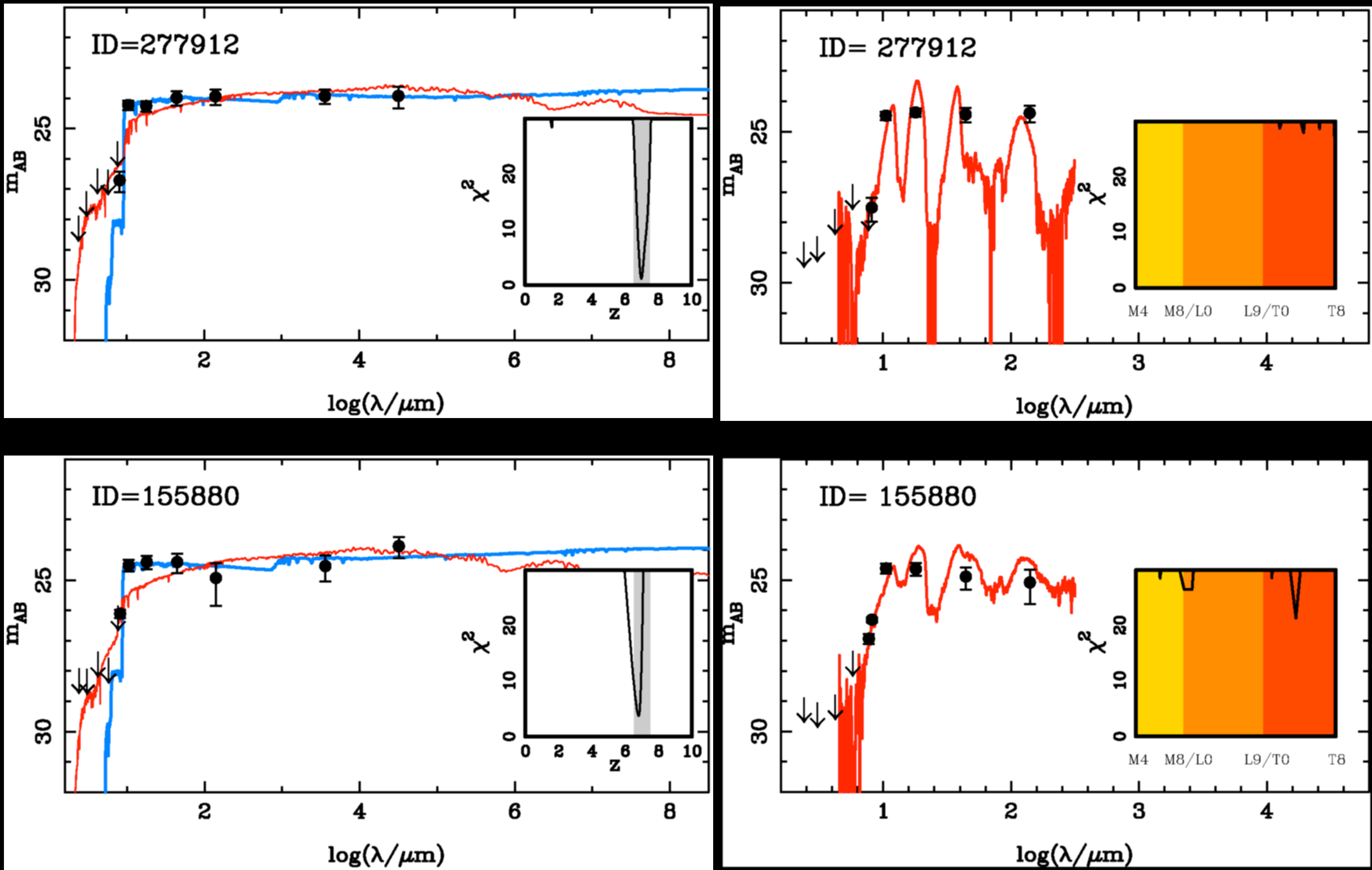
3:00:00.0
1
2
3
4
30:00.0
2:00:00.0
03:00.0
02:00.0
01:00.0
10:01:00.0
59:00.0
58:00.0
9:57:00.0

UltraVISTA + CANDELS



UltraVISTA robust z ~ 7 galaxies

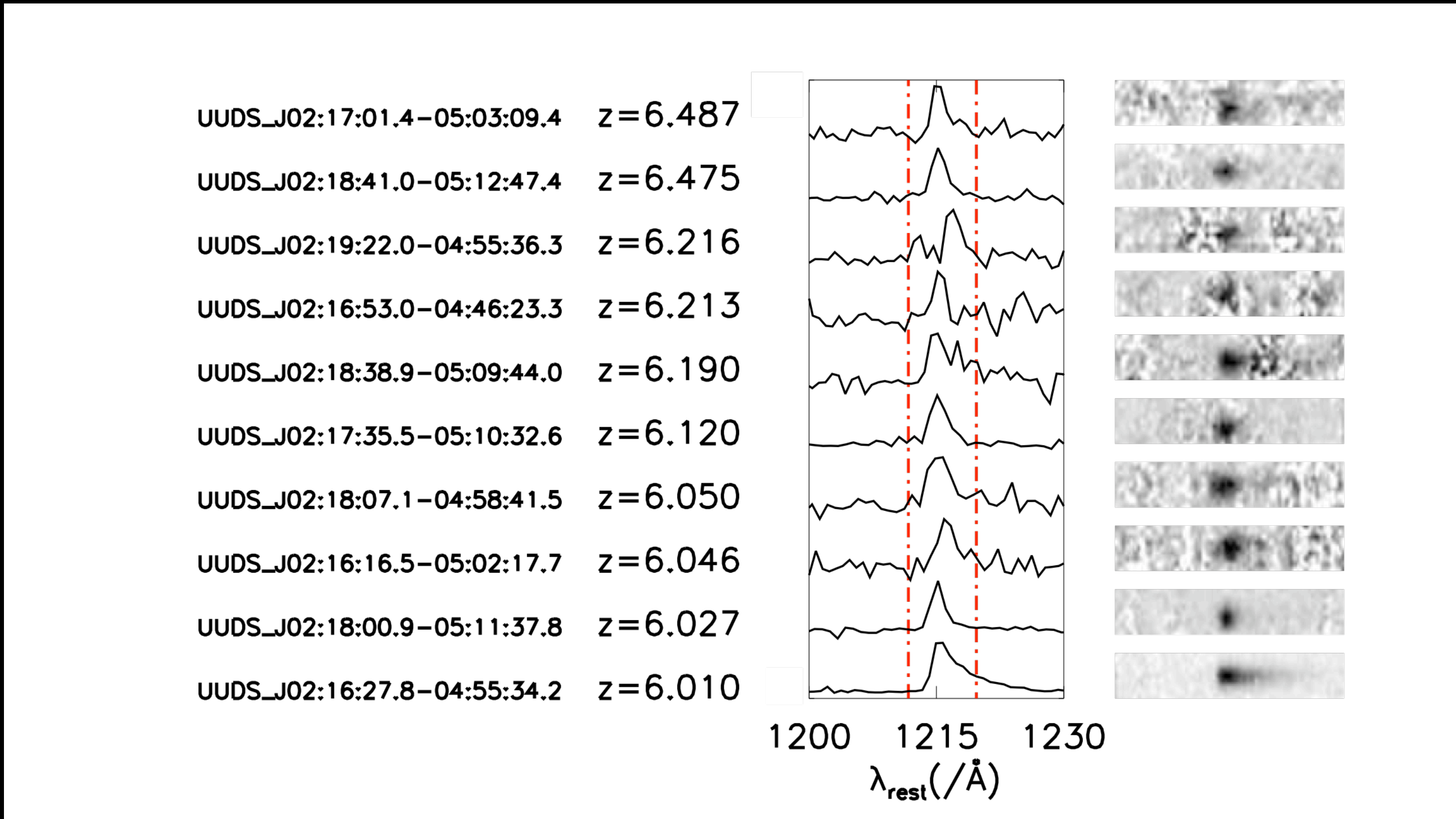
Bowler, Dunlop et al. (2012)



Spectroscopic Follow-up: Ly-α

- Feasible for brighter LBGs
- Gives precise redshifts
- Potential probe of dust content and reionization
- Becomes technically difficult at $z > 6.5$

VLT spectroscopy – zUDS Curtis-Lake et al. (2012)

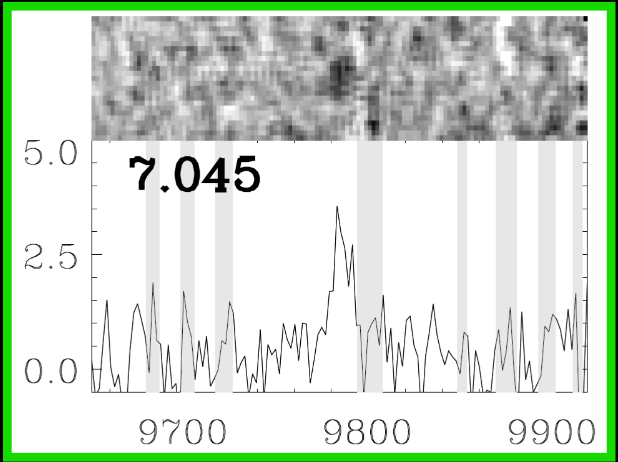


~50-70% of luminous (M_{UV} < -21) LBGs at z = 6–6.5 are strong LAEs (EW_0 > 25)

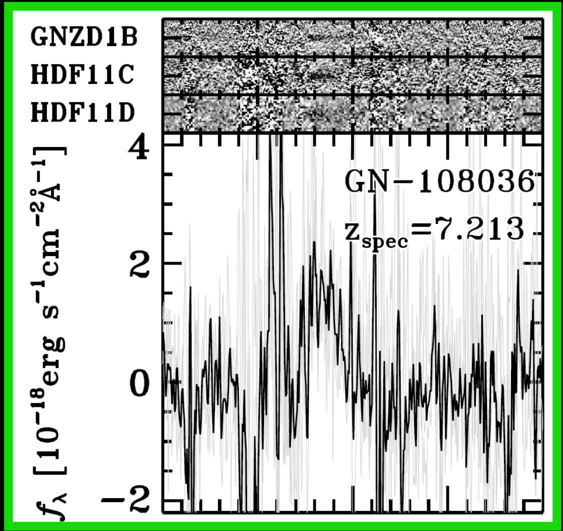
~ 2 x Stark et al. (2011) result - see also Dayal & Ferrara (2011)

Lyα line fluxes are typically 3×10^{-17} cgs (EW_0~35 Angstroms), i.e. SFR~10 $M_\odot$ yr^{-1}

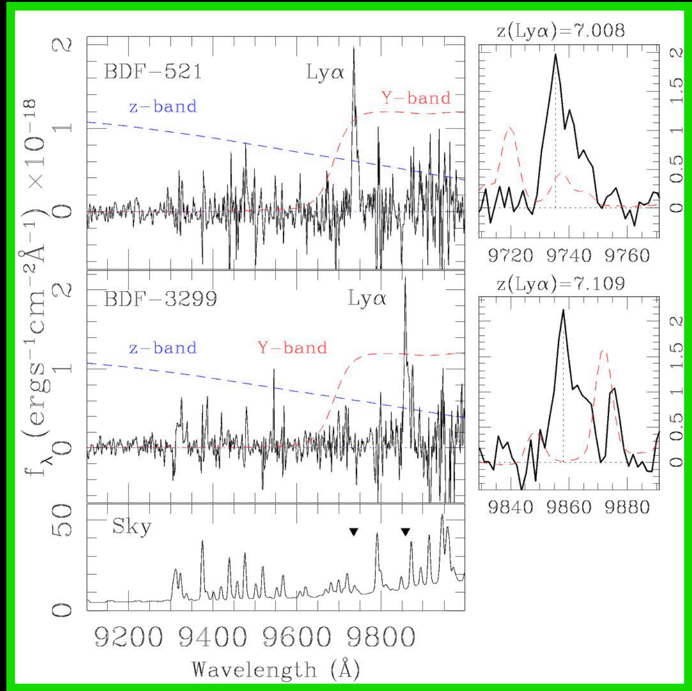
Spectroscopic confirmation at z>7



Schenker et al. (2012)



Ono et al. (2012)



Vanzella et al. (2011)

Lyman-α line fluxes:

Vanzella et al. (2011): ~1.5x10^{-17} erg s^{-1} cm^{-2} (16 hours on VLT)

Schenker et al. (2012): ~2.8x10^{-17} erg s^{-1} cm^{-2} (5 hours on KECK)

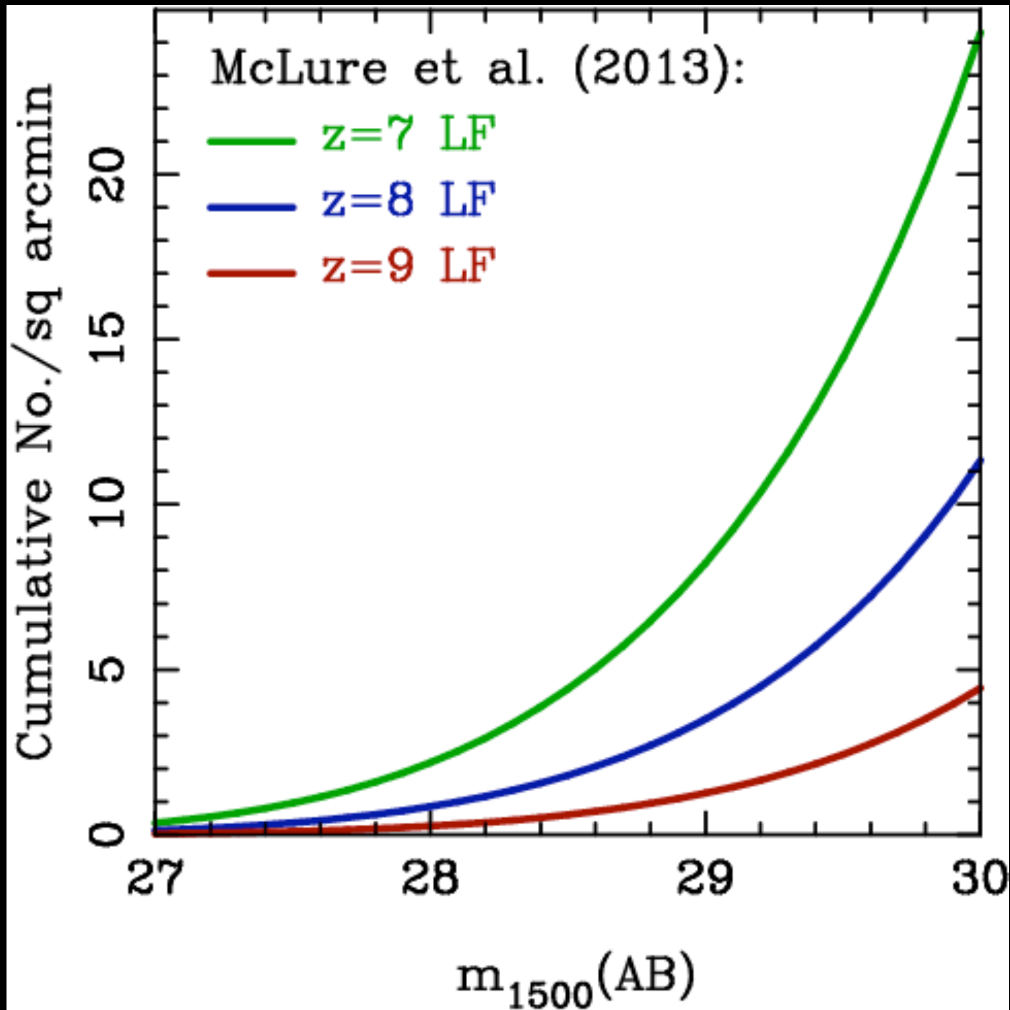
Ono et al. (2012): ~2.5x10^{-17} erg s^{-1} cm^{-2} (10 hours on KECK)

Only ~20% of targeted objects show strong Lyα

3. E-ELT – what will we want at z > 7 ?

- Redshift census, mapping out the reionization era
- High-resolution imaging spectroscopy – testing galaxy formation models
- Dynamics and metallicities

E-ELT issue 1: Surface densities



E-ELT issue 1: Surface densities

Mag limit (AB)	z > 7	z > 8	z > 9		
H < 25	5	1	0	/degree^2	(UltraVISTA)
H < 27	1	0.3	0.05	/arcmin^2	(HST CANDELS)
H < 29	10	3	1	/arcmin^2	(HST HUDF12)

MOSAIC: Deployable IFUs ~ 20 per field

MOSAIC: Fibres with GLAO ~ 200 per field

Argues for mixed architecture MOSAIC concept

E-ELT issue 2: Emission-lines at z > 7

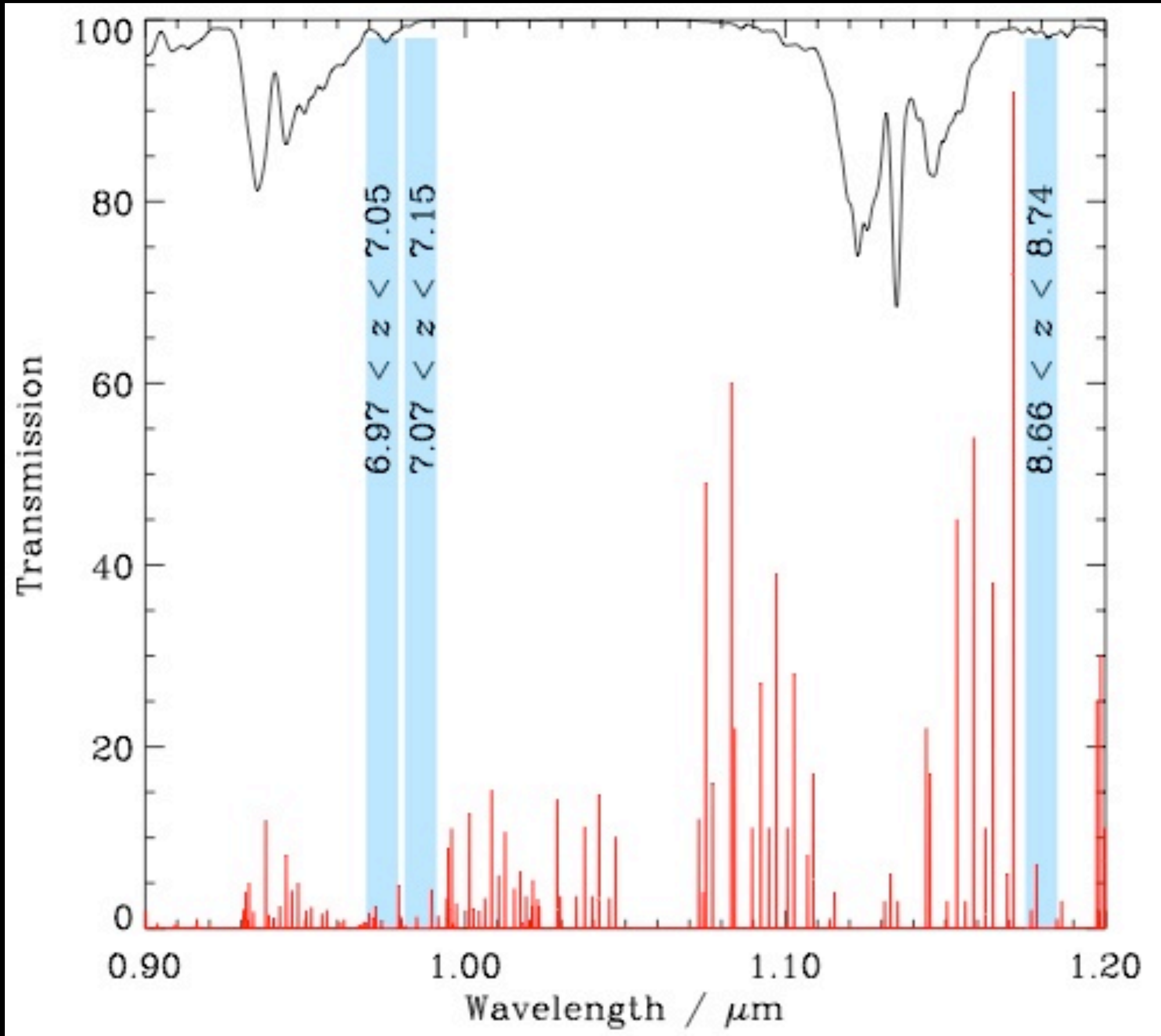
Lyman alpha ?

Can be nice and bright
– e.g. EW_0 ~ 200 Angstrom from “normal” star-forming galaxy

Seen in practice up to EW_0 ~ 50 – 100 Angstrom at z ~ 6

Recent claims of EW_0 ~ 400 – 800 Angstrom at z ~ 6.5
Kashikawa et al. (2012), arXiv:1210.4933

Issue 2: Emission-lines at z > 7



E-ELT issue 2: Emission-lines at z > 7

But evidence Lyman alpha rapidly killed at z > 7

Other options in rest-frame UV?

He II 1640: long sought signature of Pop III
- but never yet detected in a very high-redshift galaxy

New evidence of strong high-ionization nebular lines
[OIII] 5007
CIII] 1909

van der Wel et al. 2011: z ~ 2, [OIII] EW_0 up to 1000 Angstrom
Stark et al. 2013: z ~ 6-7, [OIII] EW_0 ~ 500 Angstrom
Labbe et al. 2013

E-ELT issue 2: Emission-lines at $z > 7$

Suggestion is that with low, but not zero metallicity a star-forming galaxy looks not unlike narrow-line AGN

Direct observation of low-mass star-forming galaxies at $z \sim 2$ support this

CIII] ~ 15% Lyman alpha – so CIII] $EW_0 \sim 30$ Angstrom

So…….
For $z = 7.5$ galaxy with $H = 27.5$: CIII] $\sim 3 \times 10^{-18}$ erg s^{-1} cm^{-2}
For $z = 7.5$ galaxy with $H = 30.0$: CIII] $\sim 3 \times 10^{-19}$ erg s^{-1} cm^{-2}

Observable to $z \sim 10$ if we have K-band

E-ELT issue 3: Galaxy structures at z > 7

Simulations

10 Mpc comoving, Gadget simulation

Dayal, Dunlop et al. 2013
Campisi et al. 2011; Maio et al. 2010

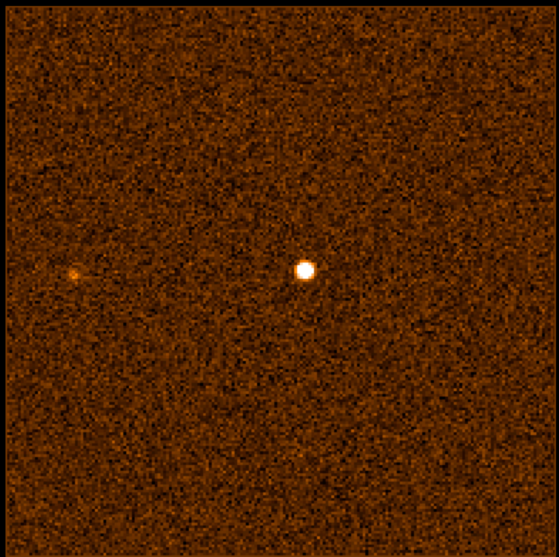
Brightest galaxy at z ~ 7 M_{UV} ~ -19.5
= H ~ 27 AB mag

Good agreement with Hubble Ultra Deep Field and LF
McLure, Dunlop et al. (2010; 2013)
Dunlop (2012)

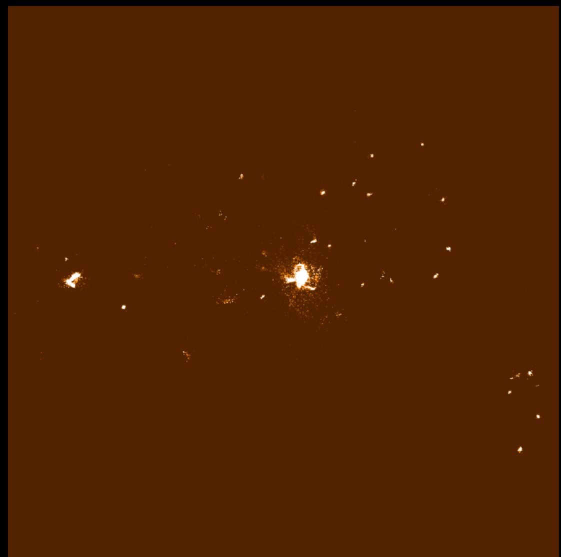
E-ELT issue 3: Galaxy structures at z > 7

Simulations – z = 6.5, H=27 AB mag

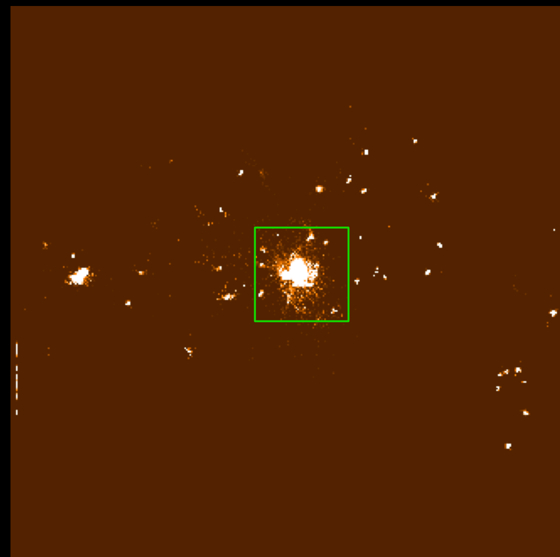
12 arcsec



CANDELS
HUDF12



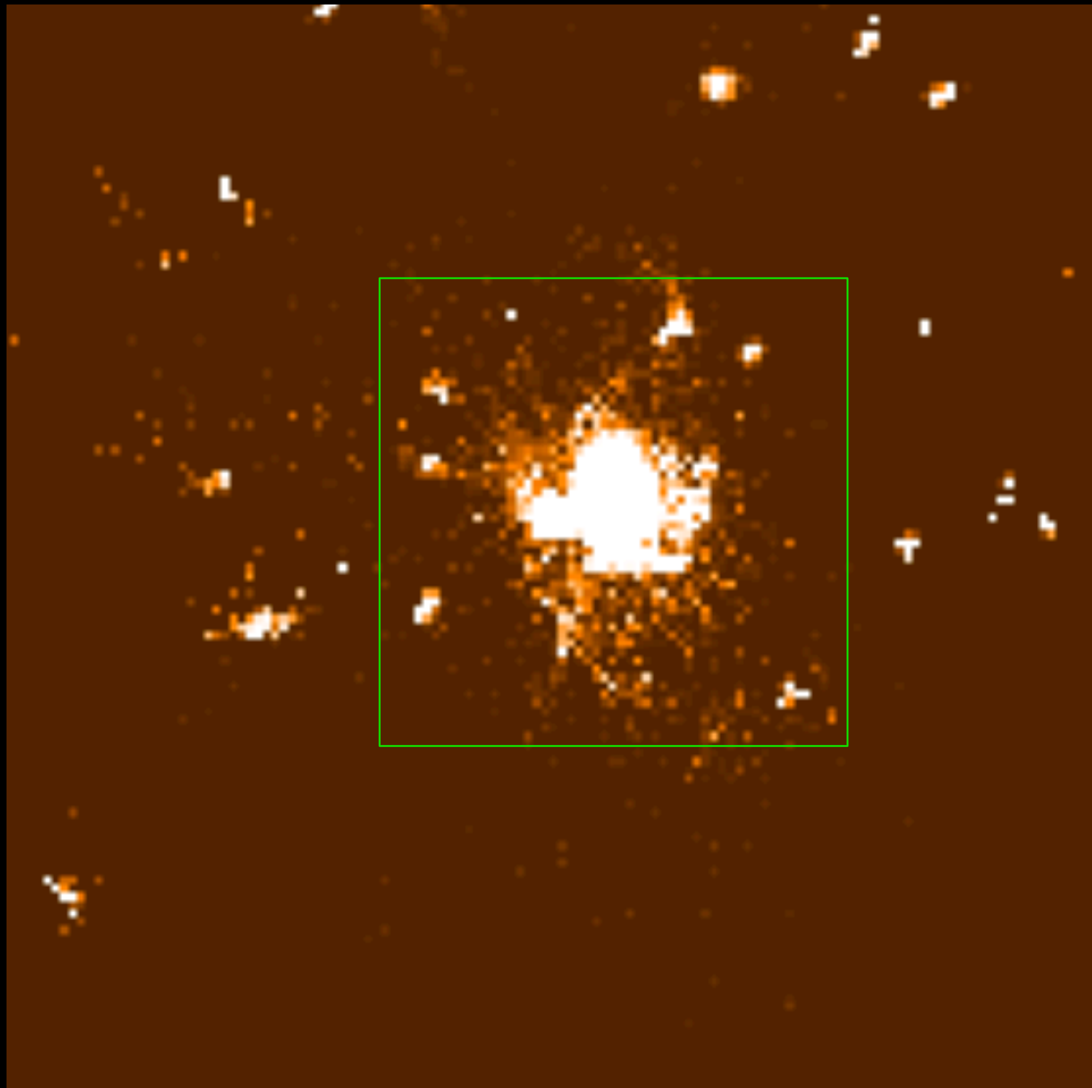
E-ELT diff limit
0.005 arcsec pix



EAGLE-ELT
0.037 arcsec pix

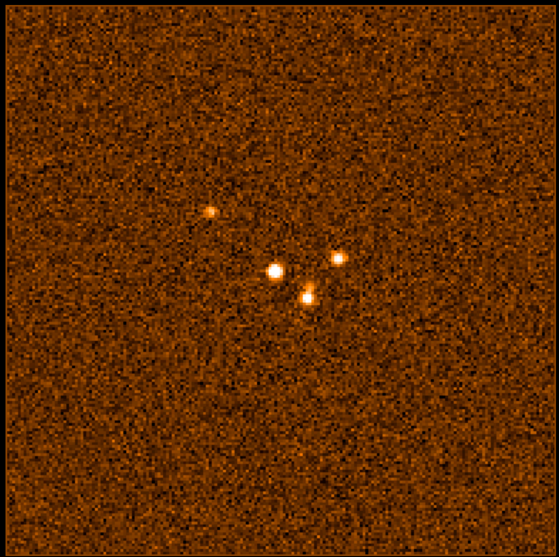
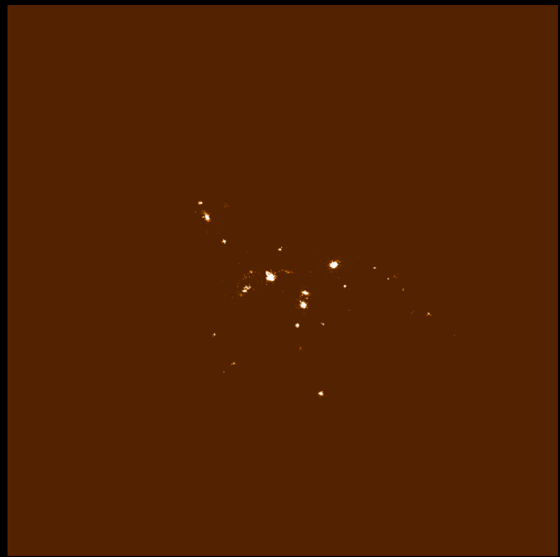
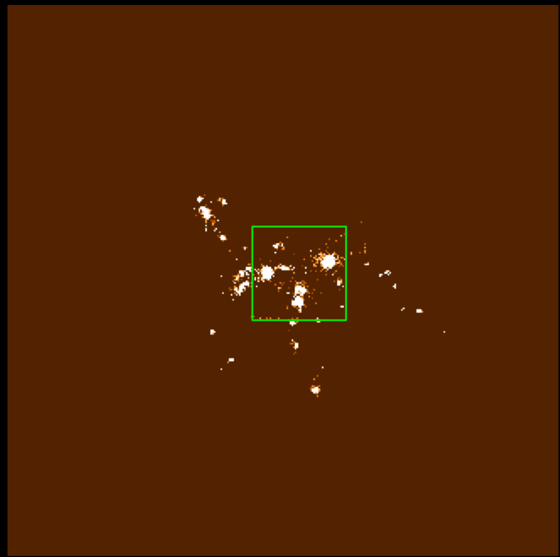
E-ELT issue 3: Galaxy structures at z > 7

Simulations – z = 6.5, H=27 AB mag



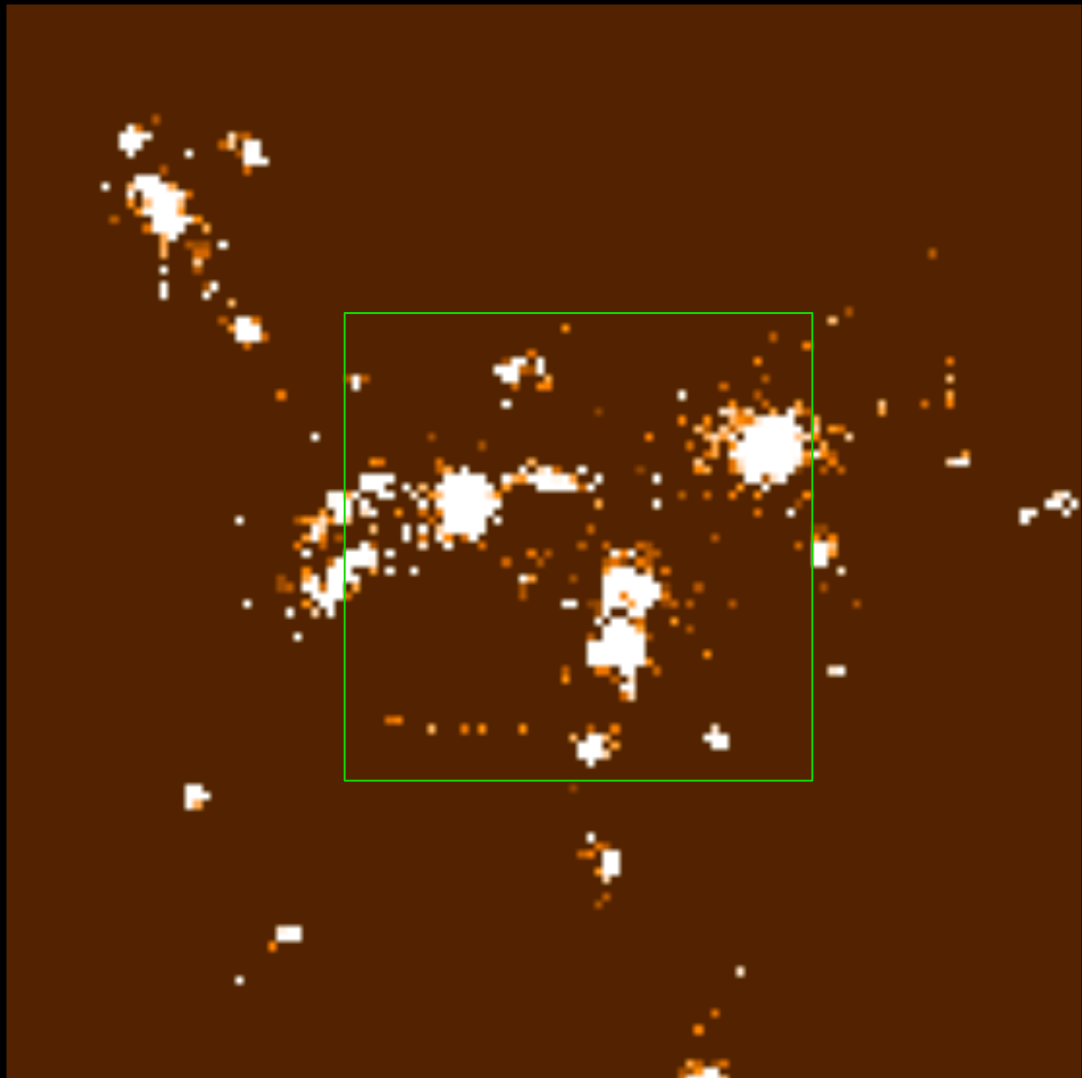
E-ELT issue 3: Galaxy structures at z > 7

Simulations – z = 7.5, H=27.5 AB mag

E-ELT issue 3: Galaxy structures at z > 7

Simulations – z = 7.5, H=27.5 AB mag



Conclusions

Many exciting possibilities for E-ELT studies of the reionization epoch

Need to carefully evaluate possible spectroscopic and imaging depths after, e.g., removing the OH sky lines

Galaxy target surface density is a strong function of depth:

1 $z > 7$ object arcmin^{-2} at $H < 27$ AB mag

10 $z > 7$ objects arcmin^{-2} at $H < 29$ AB mag

Argues for mixed-architecture MOSAIC concept ~20 IFUs + ~200 fibres

Emission lines other than Lyman alpha may permit

- good redshift census – argues for K-band to see CIII] at $z \sim 10$
- evolution of Ly-α alpha optical depth
- metallicity estimates and search for Pop III

Every reason to believe that $z > 7$ galaxies have much richer structures than implied by HST imaging

– good case for multi-object IFUs, with pixel scale ~ 0.05 arcsec