

# Luminosities, Masses And Star Formation



UNIVERSITY OF  
OXFORD

## Rates of Galaxies at High Redshift

Andy Bunker, Stephen Wilkins,

Joseph Caruana, Silvio Lorenzoni (Oxford)

Dan Stark (Arizona), Richard Ellis

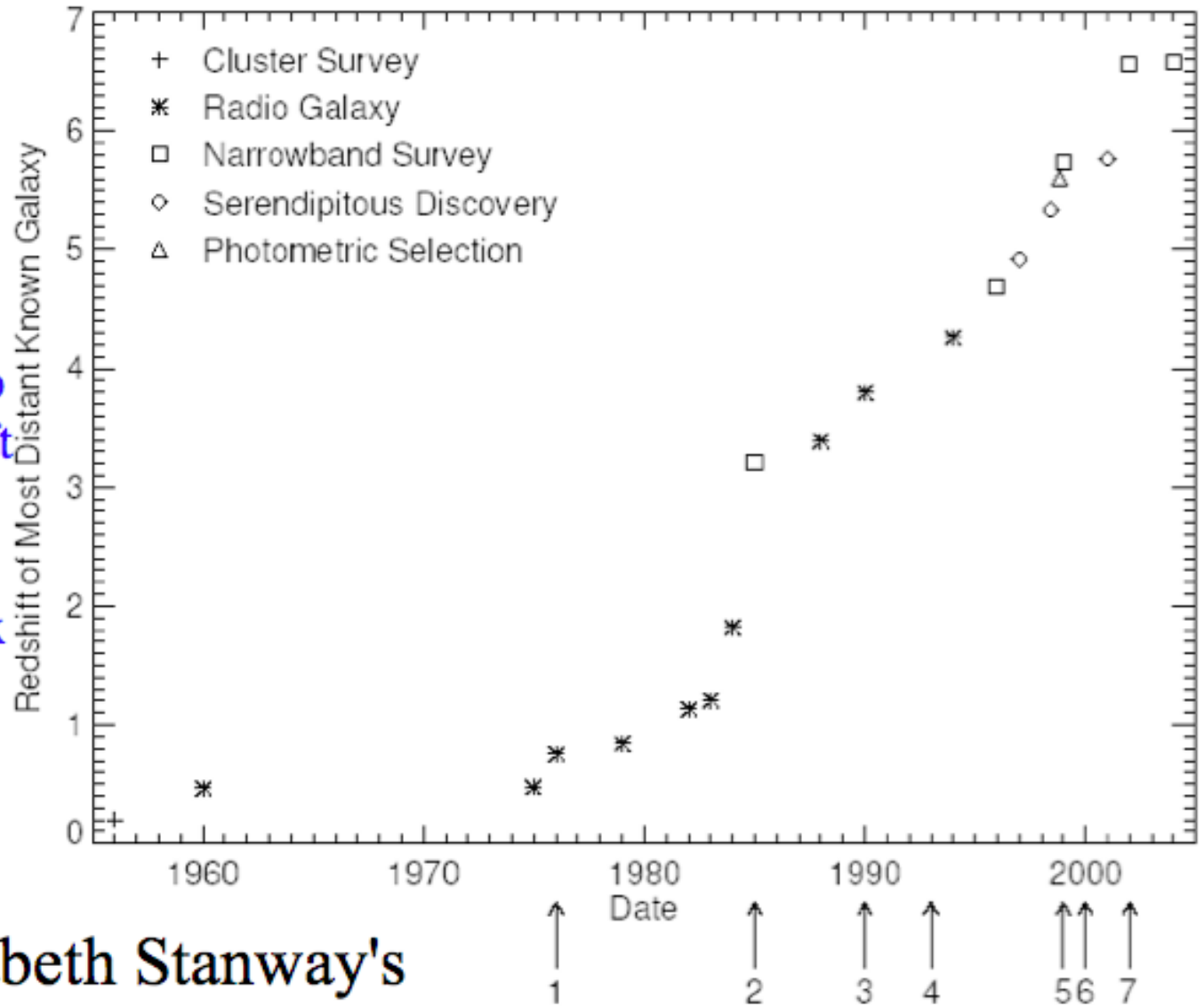
(Caltech), Elizabeth Stanway (Warwick)

Laurence Eyles (Exeter)

Mark Lacy (NRAO)

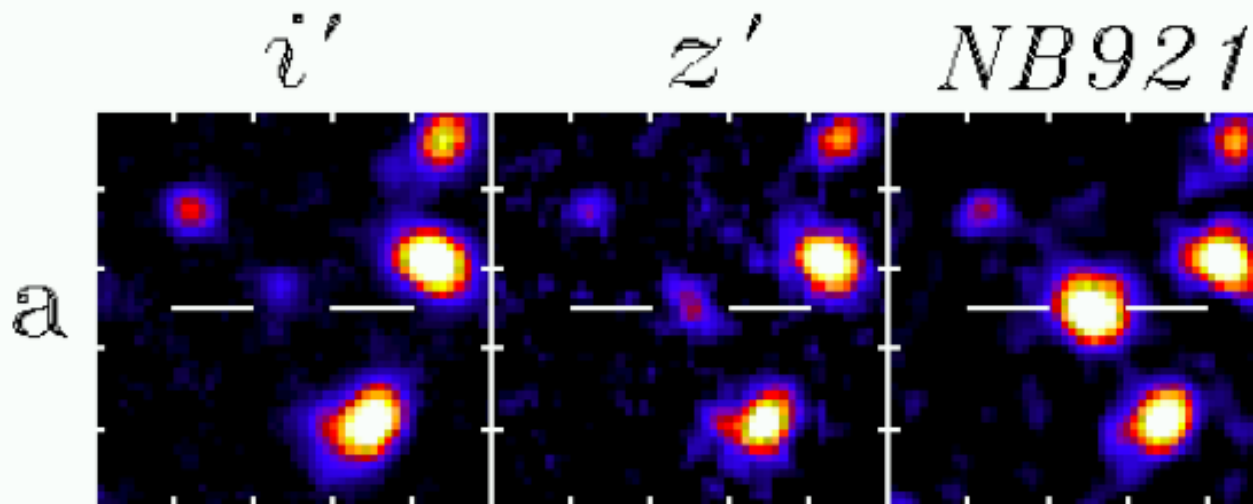


Early strategy:  
 most massive  
 short-lived OB  
 stars produce  
 ionizing UV  
 photons. Want to  
 find high-redshift  
 star forming  
 galaxies, and  
 measure UV flux  
 (or  
 recombination  
 lines e.g. Ly- $\alpha$ )



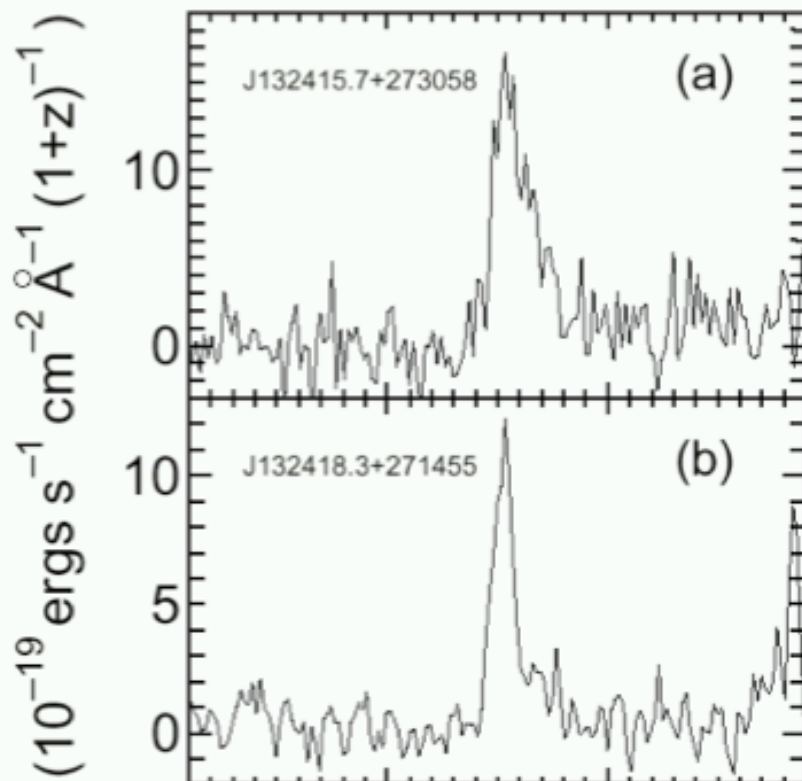
From Elizabeth Stanway's  
 thesis (2004), updated from  
 review of Stern & Spinrad

field  
 (X)

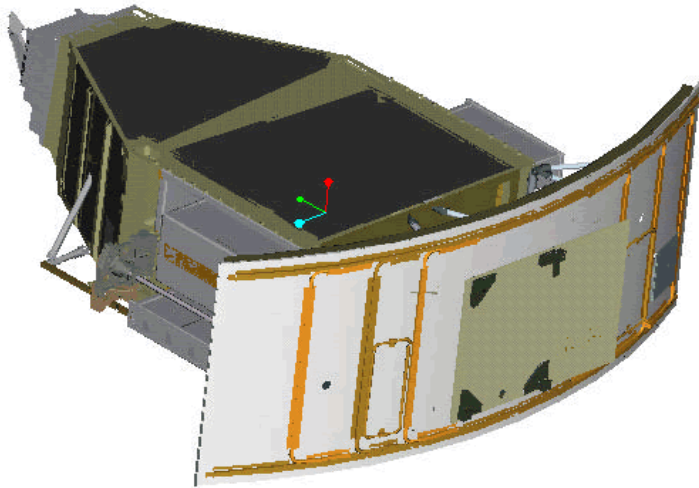


Kodaira et al.  
(2003)  $z=6.58$   
Ly-alpha galaxy  
(narrow-band)

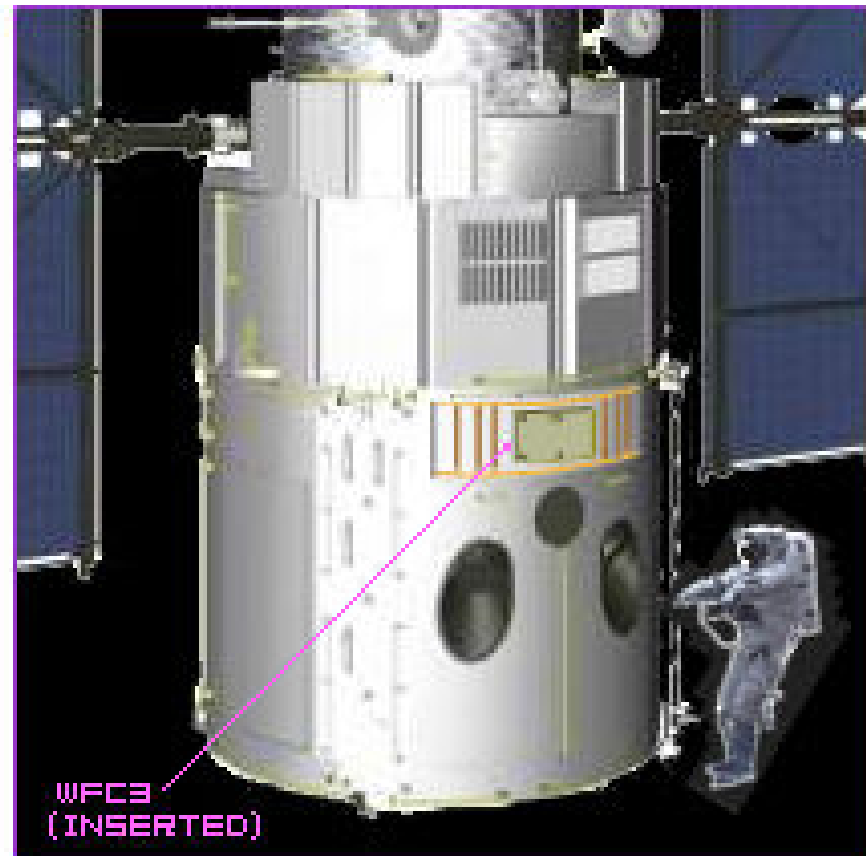
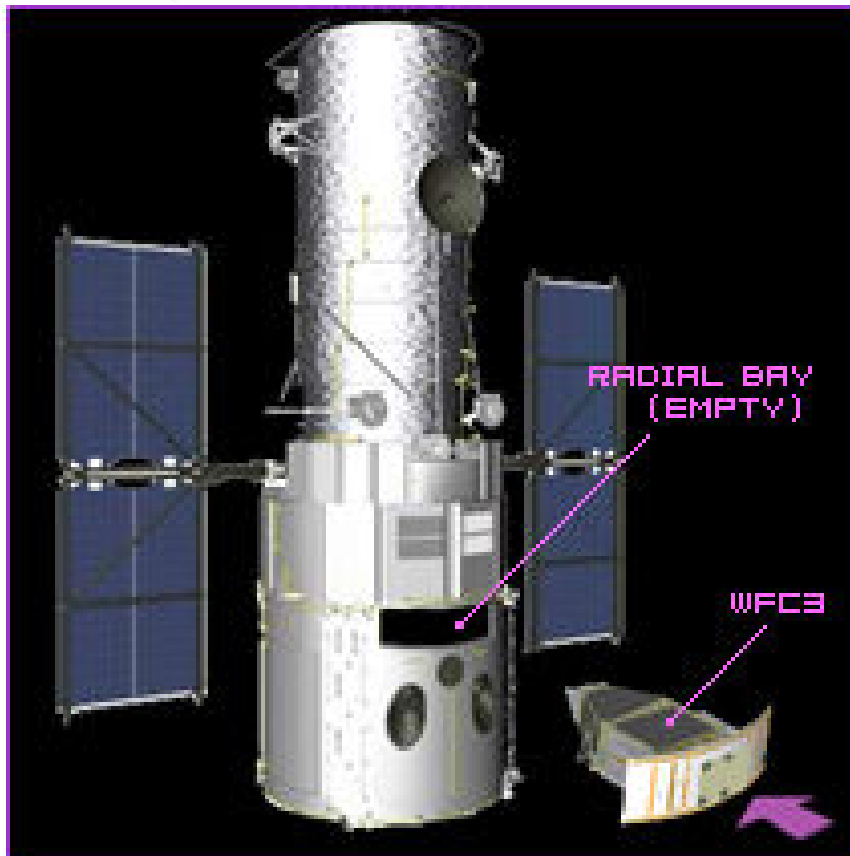
Current narrow-band  
record now  $z=6.96$



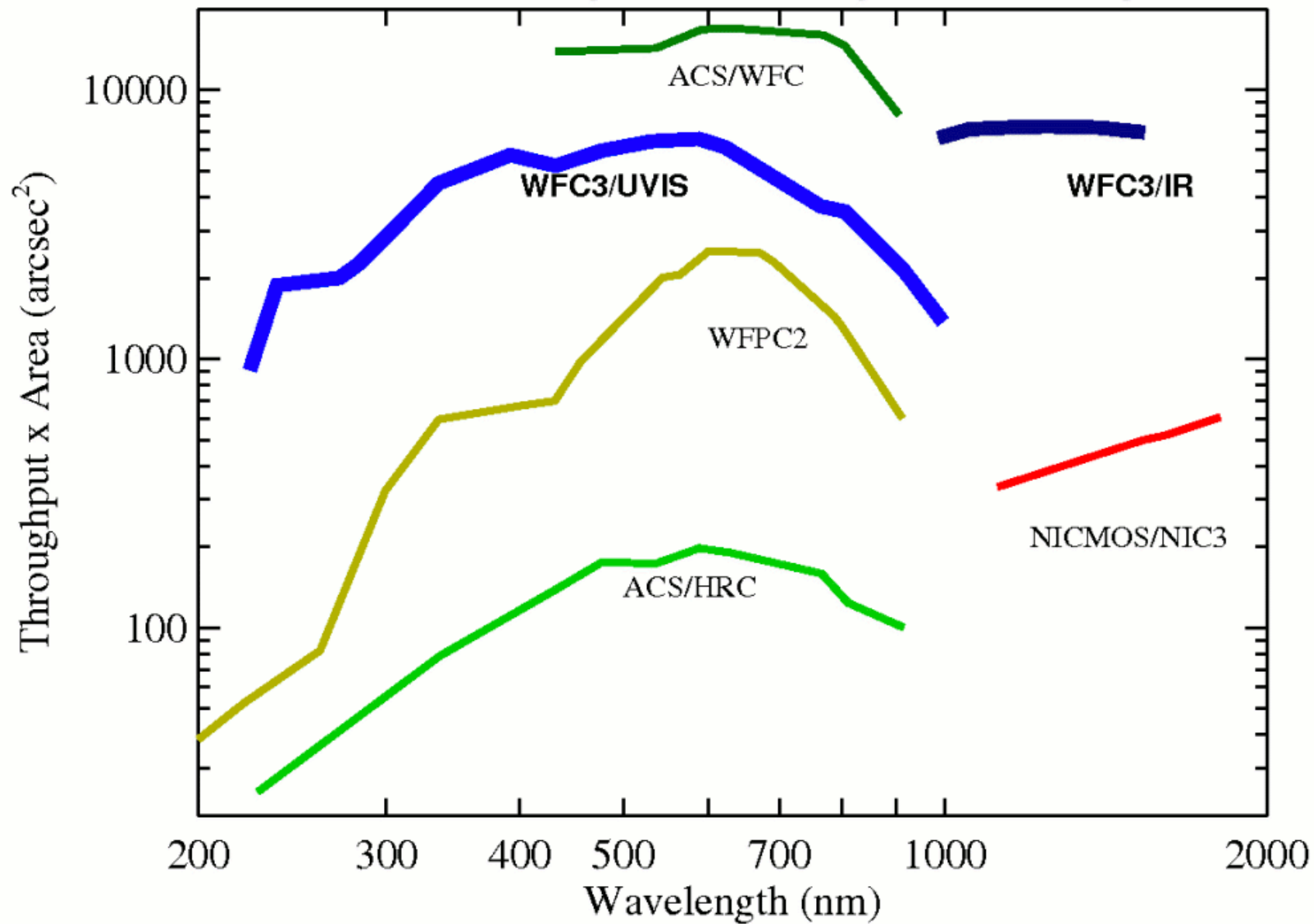
Also: Hu et al. (2002)  
 $z=6.56$ , lensed by  
Abell 370 cluster  
Both use narrow-band  
filter in low-  
background region  
between sky lines, and  
follow-up spectra



# HST WFC3



# HST Survey Discovery Efficiency



# Observations:

Very-Deep ACS imaging over the entire GOODS-South Field [GOODS]

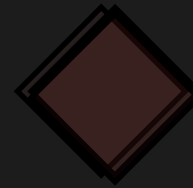
Ultra-Deep ACS imaging in the HUDF and two flanking fields (each a single ACS field) [HUDF, HUDF05, HUDF09]

**HUDF09** Ultra-deep (29.0-30.0 (AB) in  $J_{125w}$ ,  $5\sigma$ ) in 3 fields (~15 arcmin<sup>2</sup> total)

**ERS** Very-deep (~28.5 (AB) in  $J_{125w}$ ,  $5\sigma$ ) contiguous over ~40 arcmin<sup>2</sup>

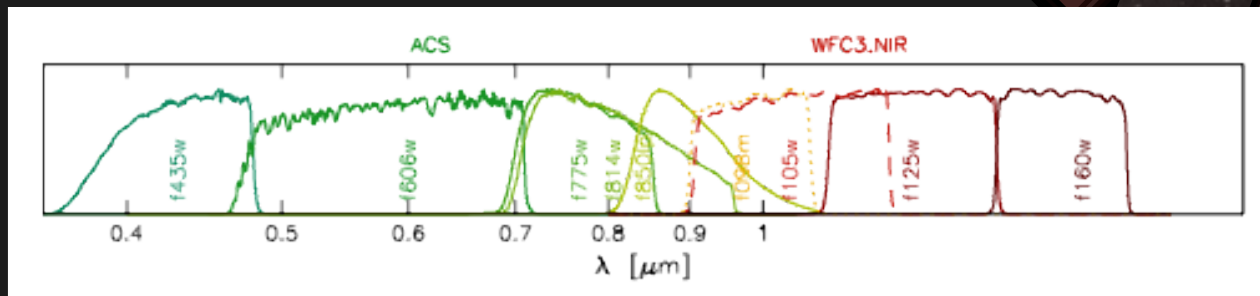
**CANDELS** Pretty-deep (28.0-28.5 (AB) in  $J_{125w}$ ,  $5\sigma$ ) contiguous over ~100 arcmin<sup>2</sup>  
GOODS-South

GOODS South ACS mosaic



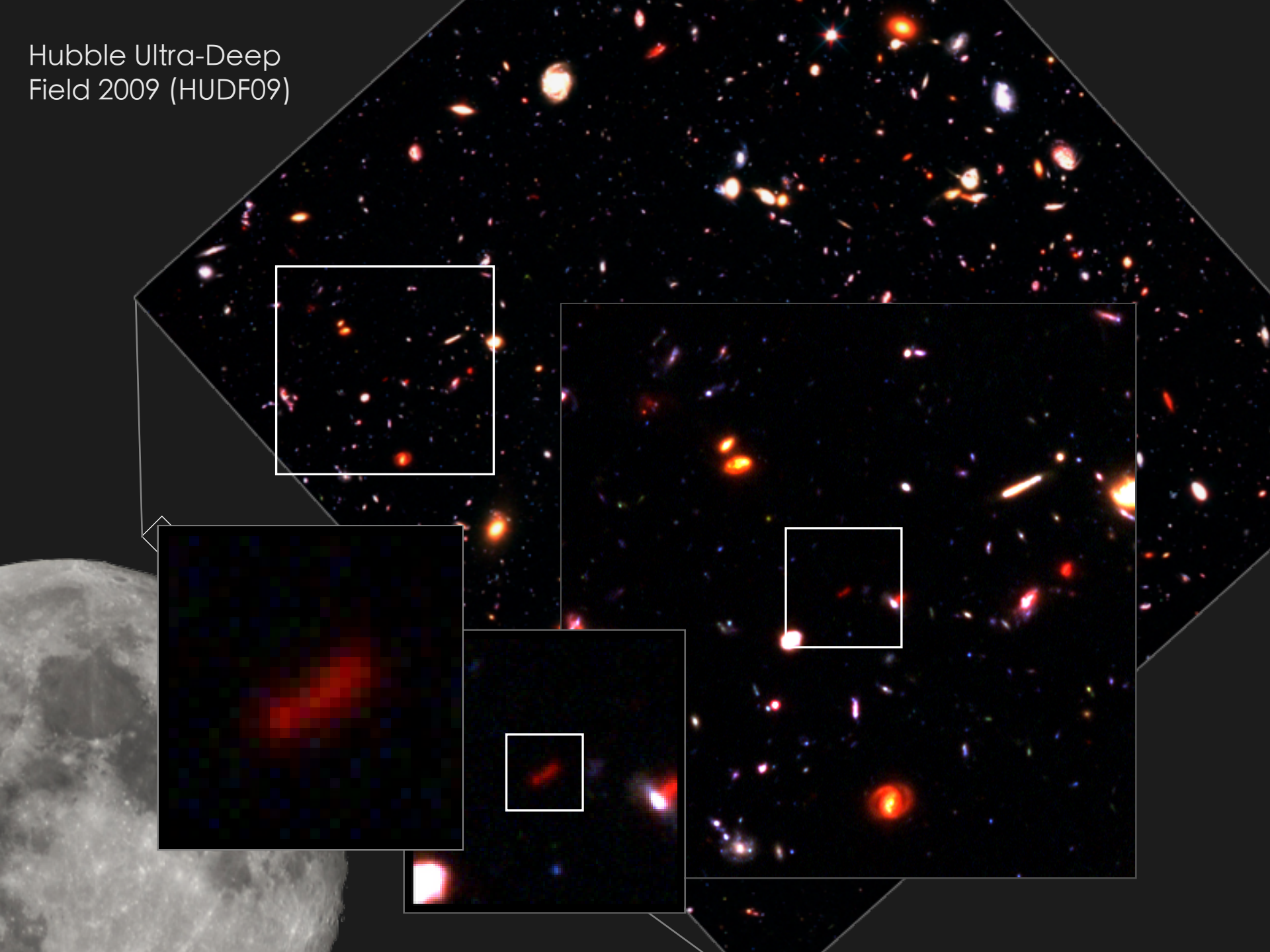
CANDELS GOODS-South DEEP

CANDELS GOODS-South 'WIDE'  
curiously narrower than the 'DEEP' field



Filter transmission functions of the filters available.

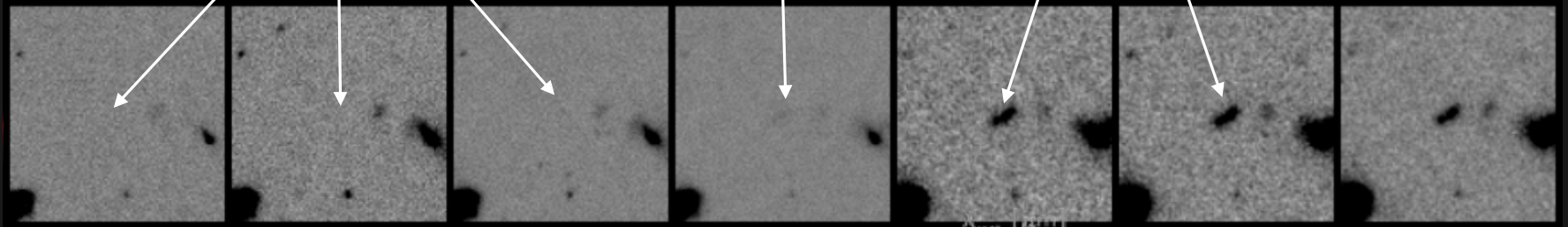
Hubble Ultra-Deep Field 2009 (HUDF09)



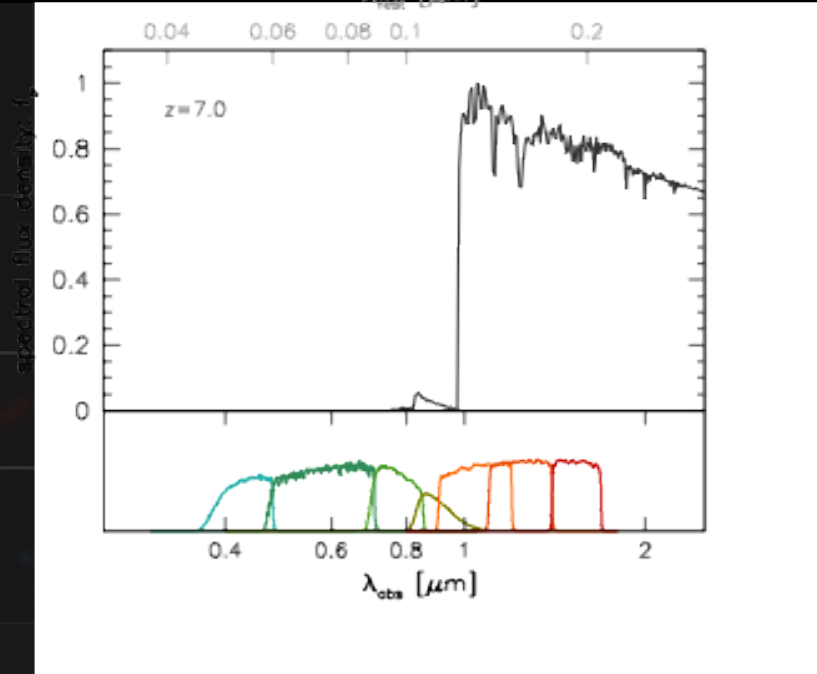
detected at low significance (to be expected)

no detection at  $1.5\sigma$

detected at high significance, blue colour

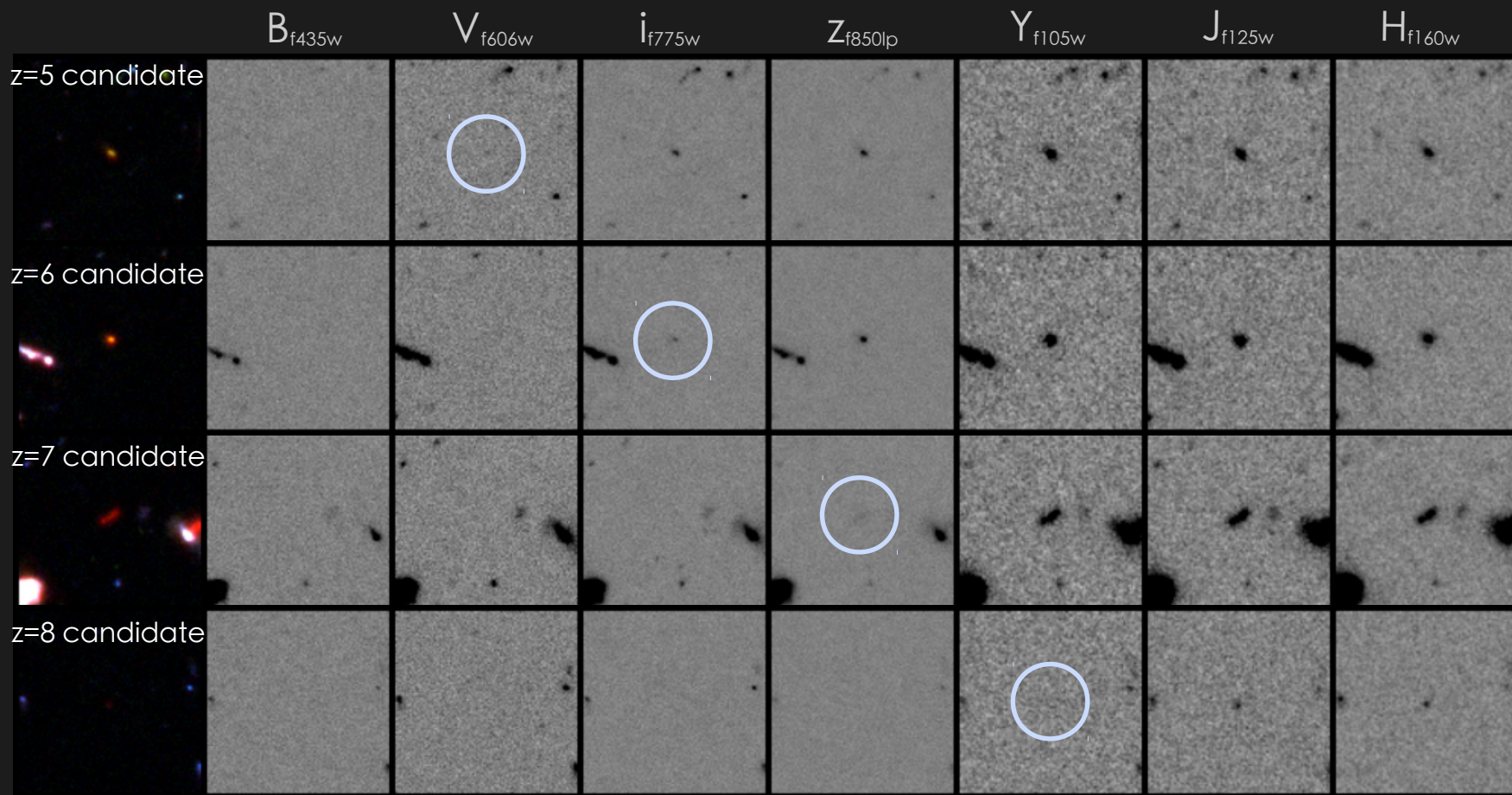


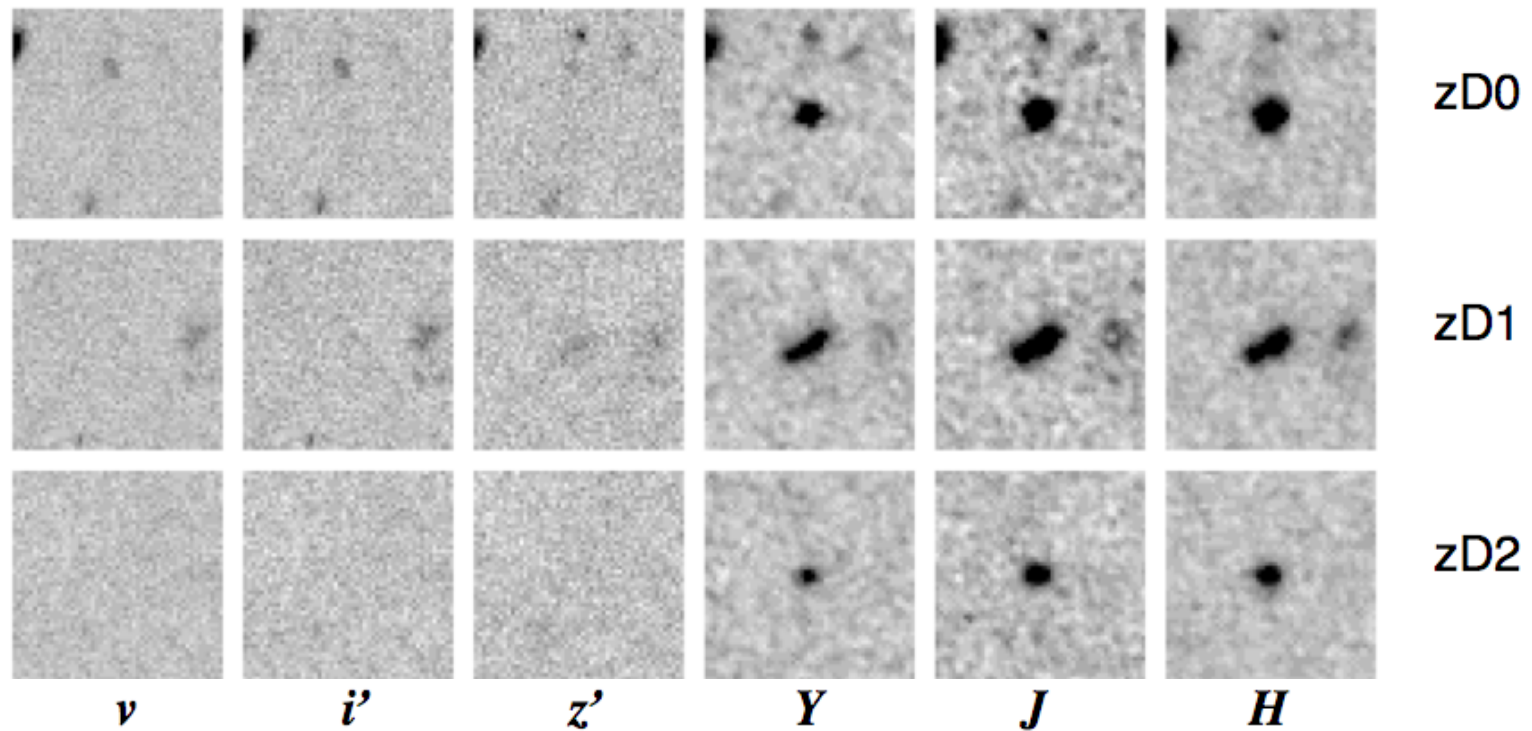
Candidate Star Forming Galaxy at  $z=7$



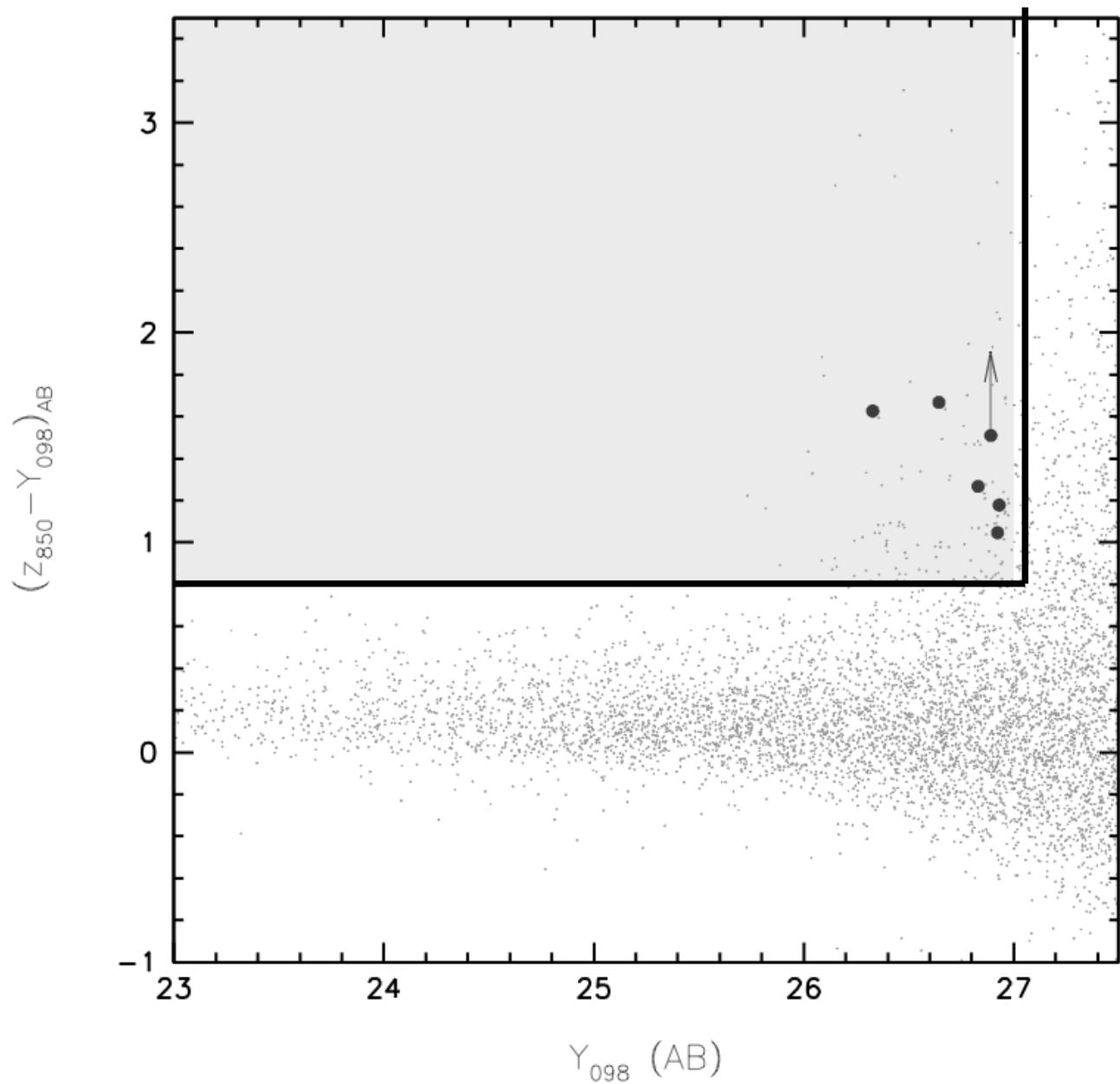


# an ensemble of High-redshift Galaxies



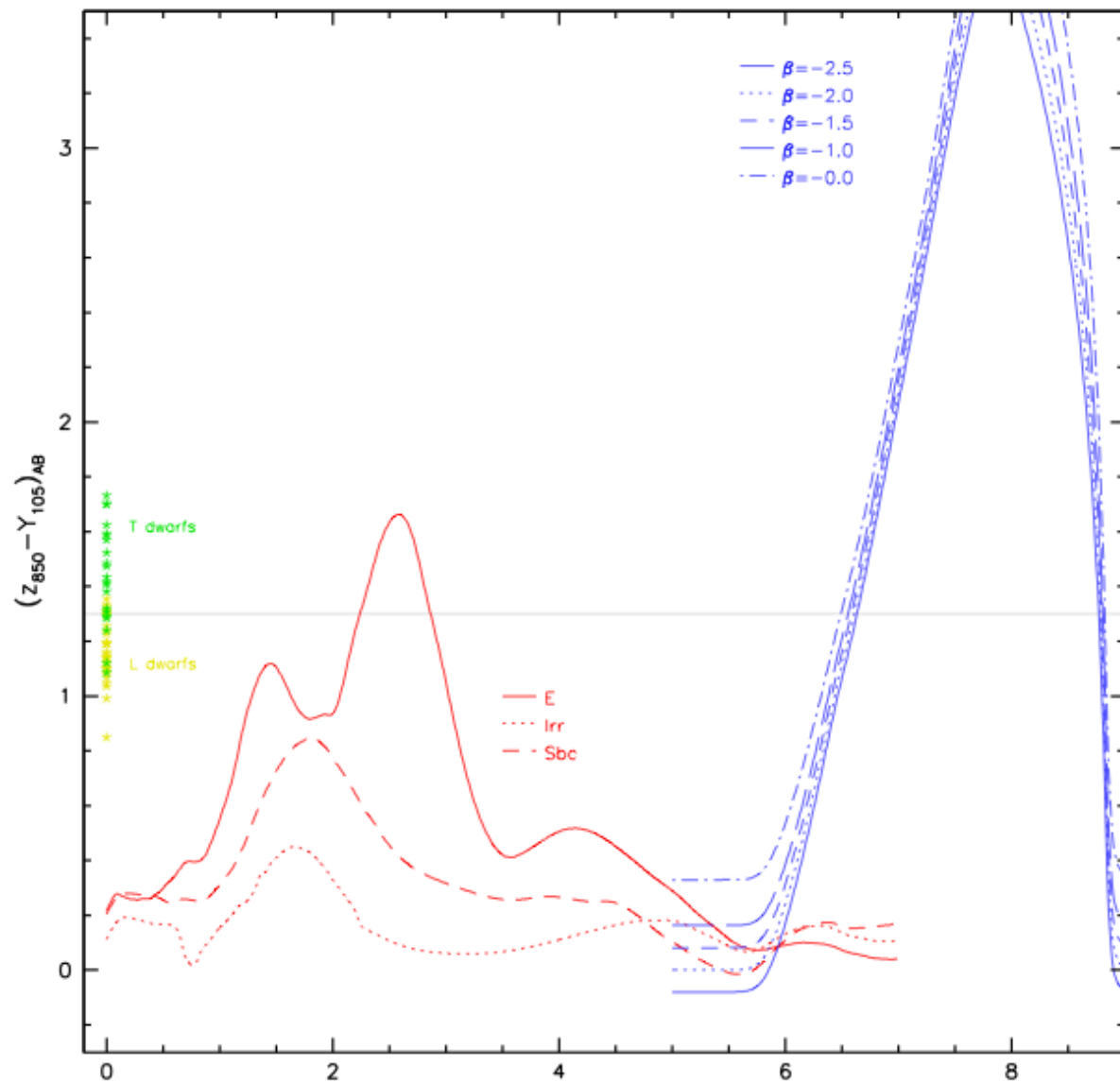


RECENT EXCITEMENT - 100 orbits of HST with WFC3 in 3 near-IR filters on Hubble Ultra Deep Field. Galaxies at  $z=7-9$ ! Data first taken in August-Sept. 2009 4 papers immediately (Bouwens et al., Bunker et al., McLure et al., Oesch et al.) and 7 more since. Large HST surveys Illingworth UDF ; WFC3 ERS team – O’Connell ; CANDELS

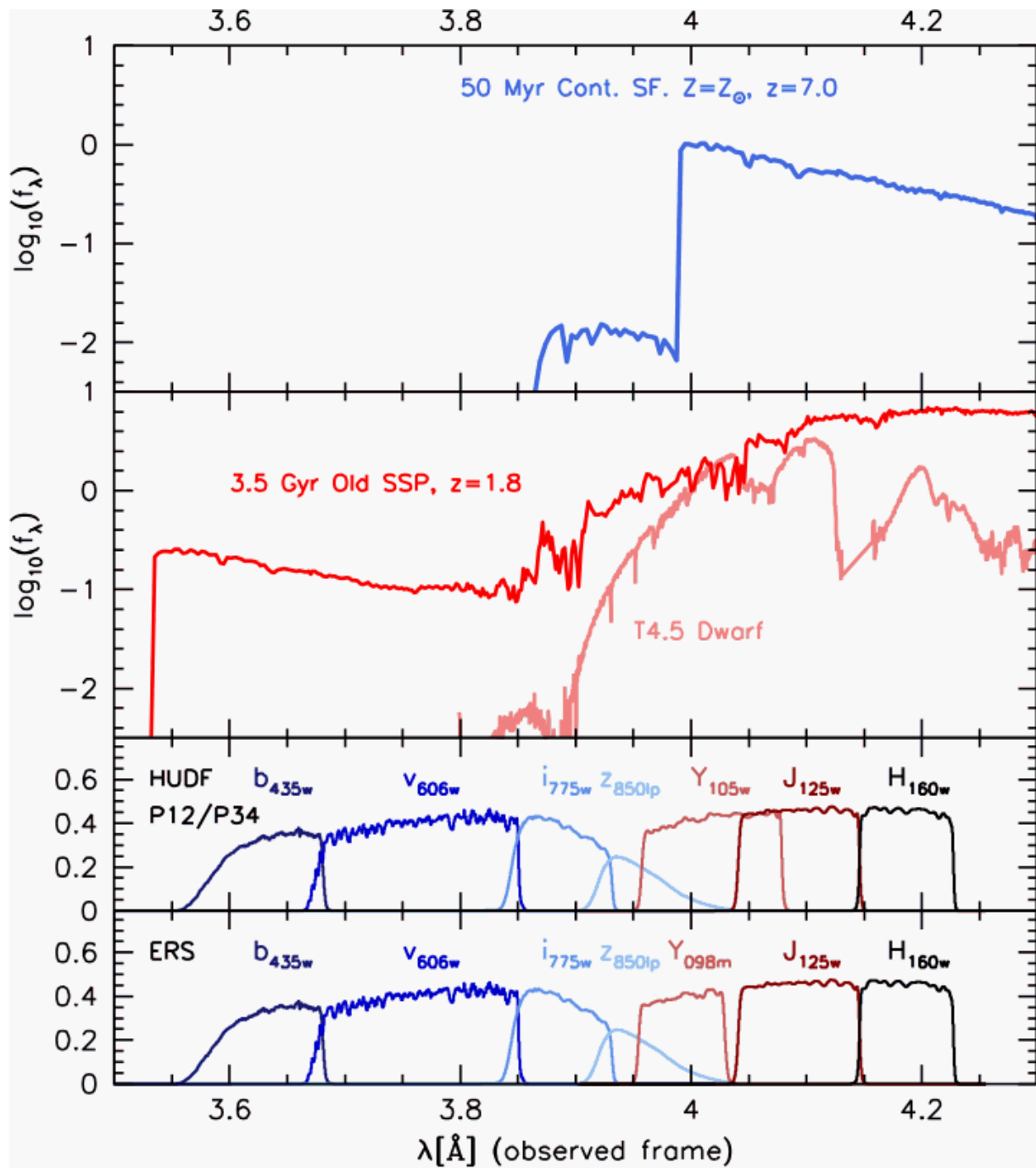


Wilkins et al. (2010): z-drop selection in ERS/GOODS

By selecting on rest-frame UV, get inventory of ionizing photons from star formation. Stanway, Bunker & McMahon (2003 MNRAS) selected i-drops  $5.6 < z < 7$  - but large luminosity bias to lower  $z$ . Contamination by stars and low- $z$  ellipticals.

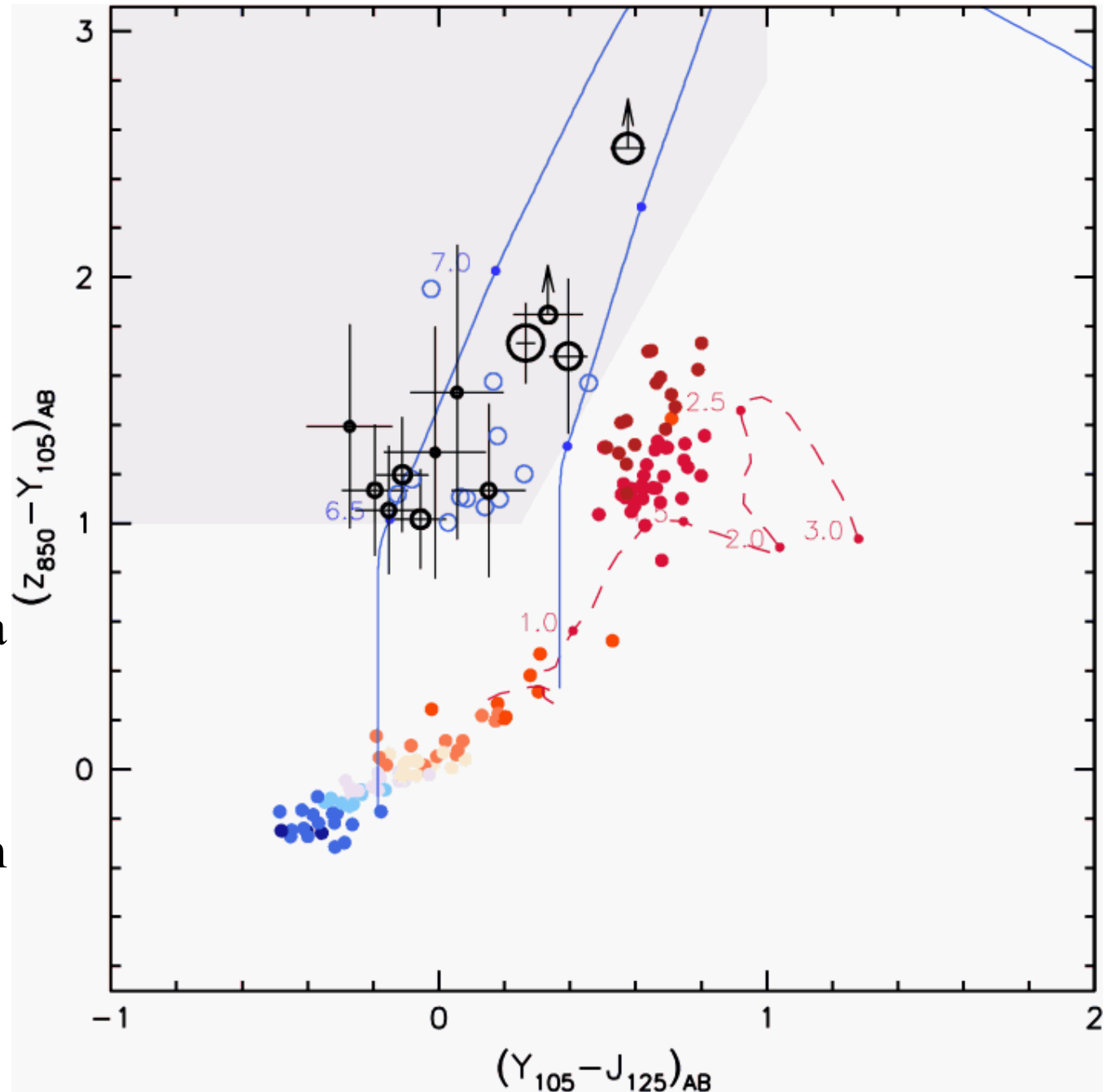


Pushing to  $z \sim > 7$  using WFC3 and z-drop colours (also Y-drops), Bunker et al. (2010)



Latest results:  
Wilkins et al.  
(2010) MNRAS  
ArXiv:  
1002.4866

We studied 3  
deep fields (each  
5sq.arcmin) and a  
larger  
40sq.arcmin field  
in GOODS-South  
to search for  
 $7 < z < 10$  galaxies.  
Found 44



# Gemini



# ESO VLTs

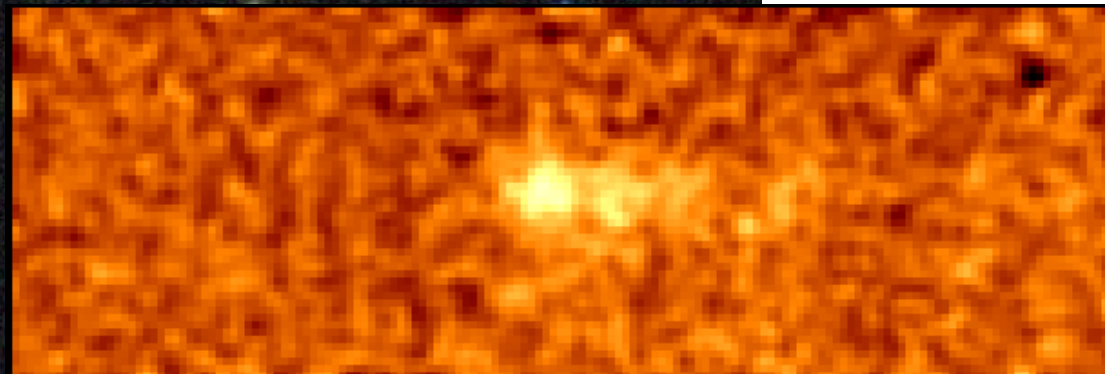
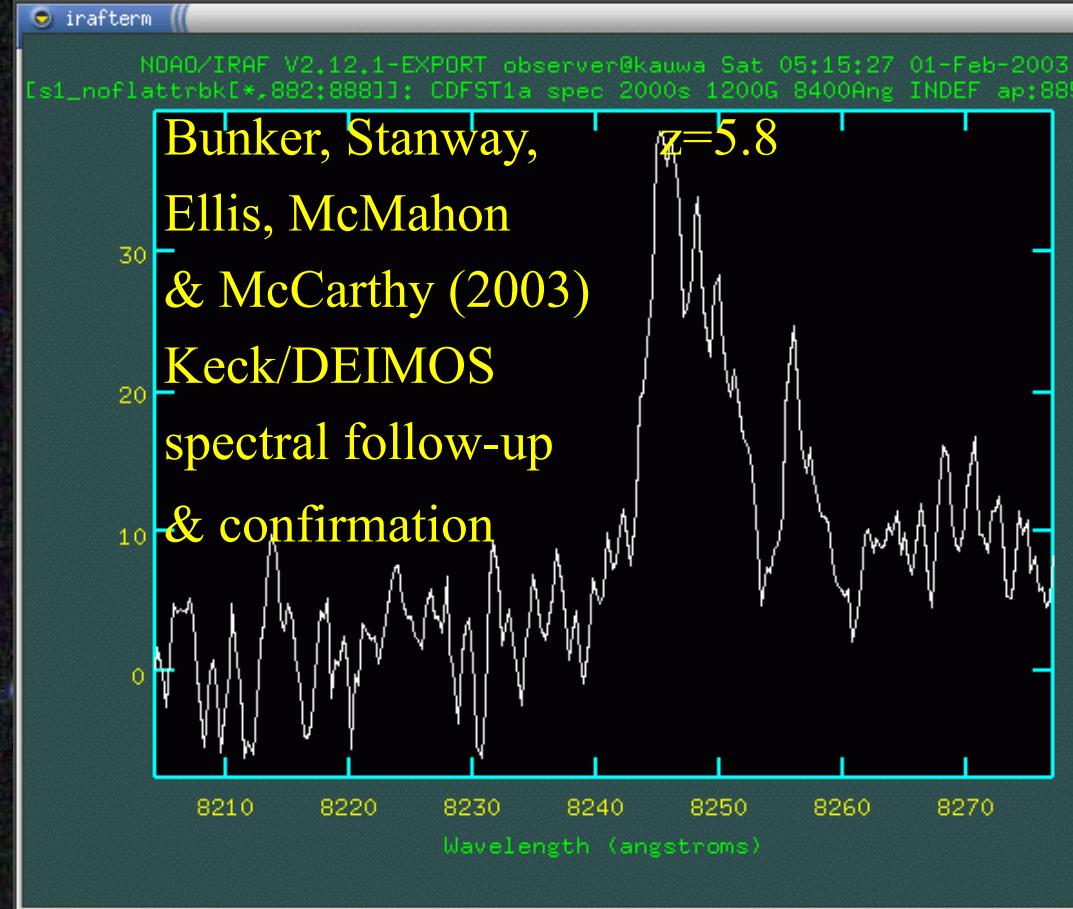


# 10-m Kecks

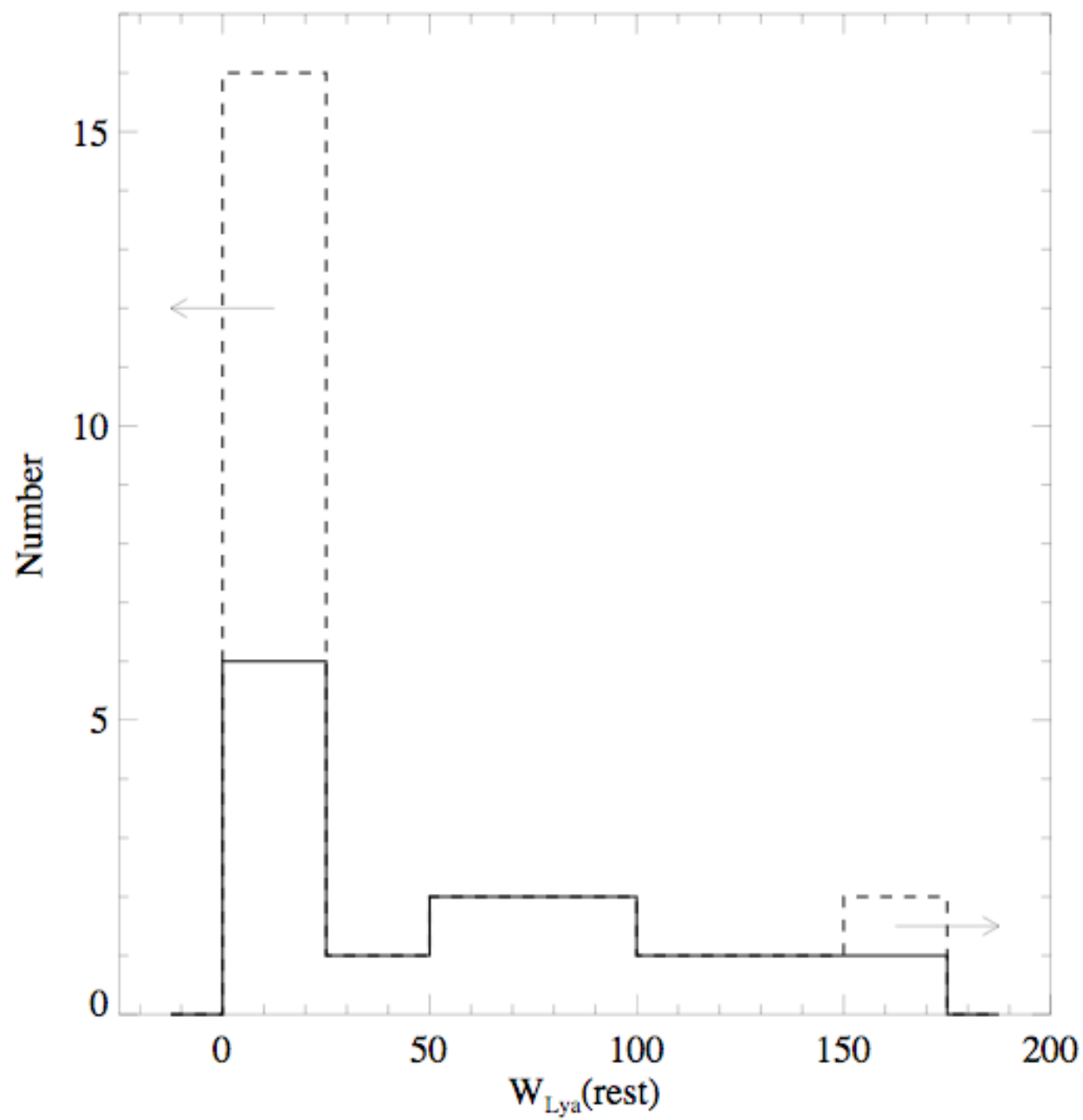


# The Star Formation History of the Universe

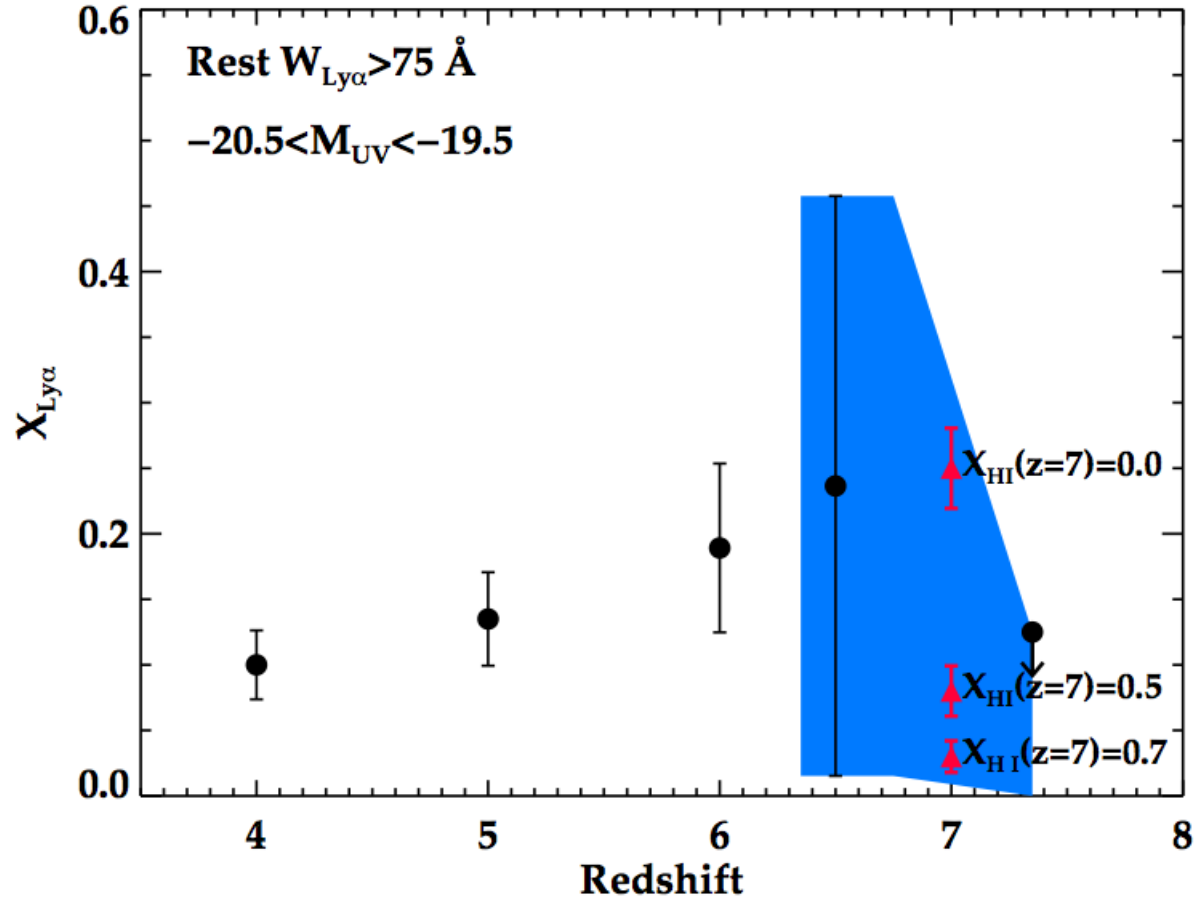
I-drops in the Chandra Deep  
Field South with HST/ACS  
Elizabeth Stanway, Andrew  
Bunker, Richard McMahon  
2003 (MNRAS)







# Ly-alpha fraction (Stark et al. 2010)



Brightest HUDF Y-dro

Found in Sept 2009.

YD3 in Bunker et al

UDFy-31835529 in

Bouwens et al.;

#1721 in McLure et al.

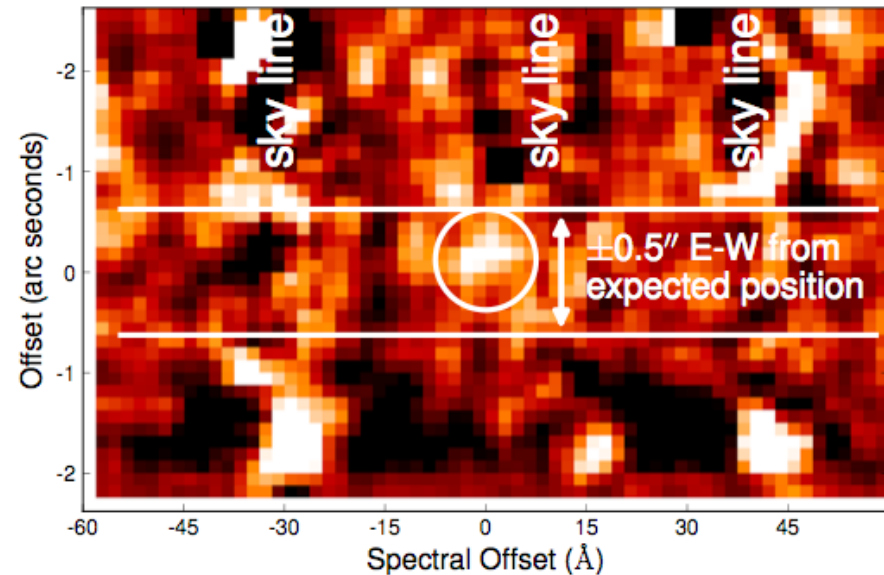
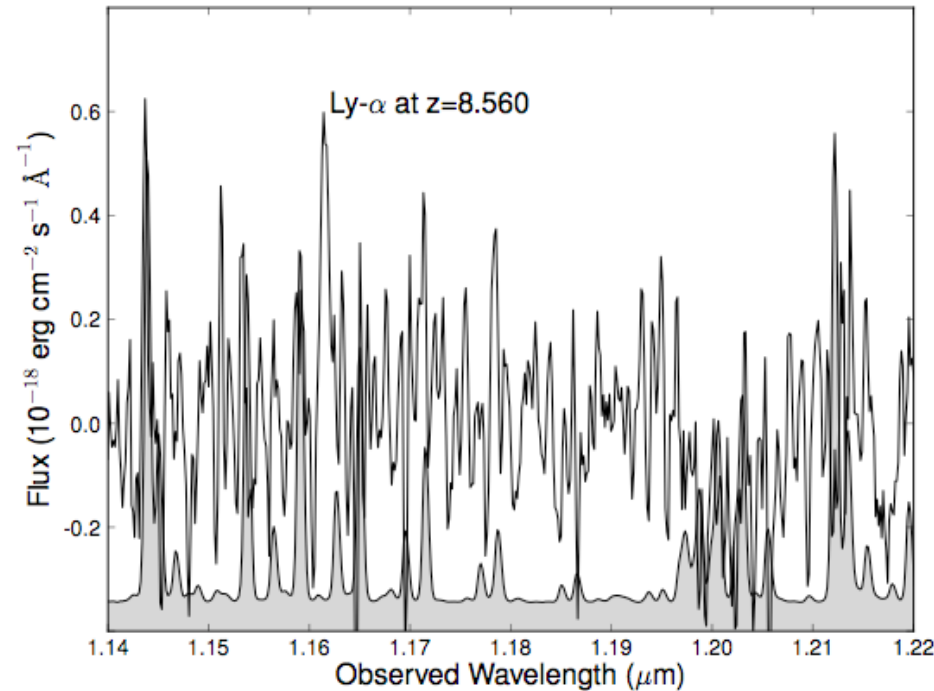
In late 2009, Nature paper

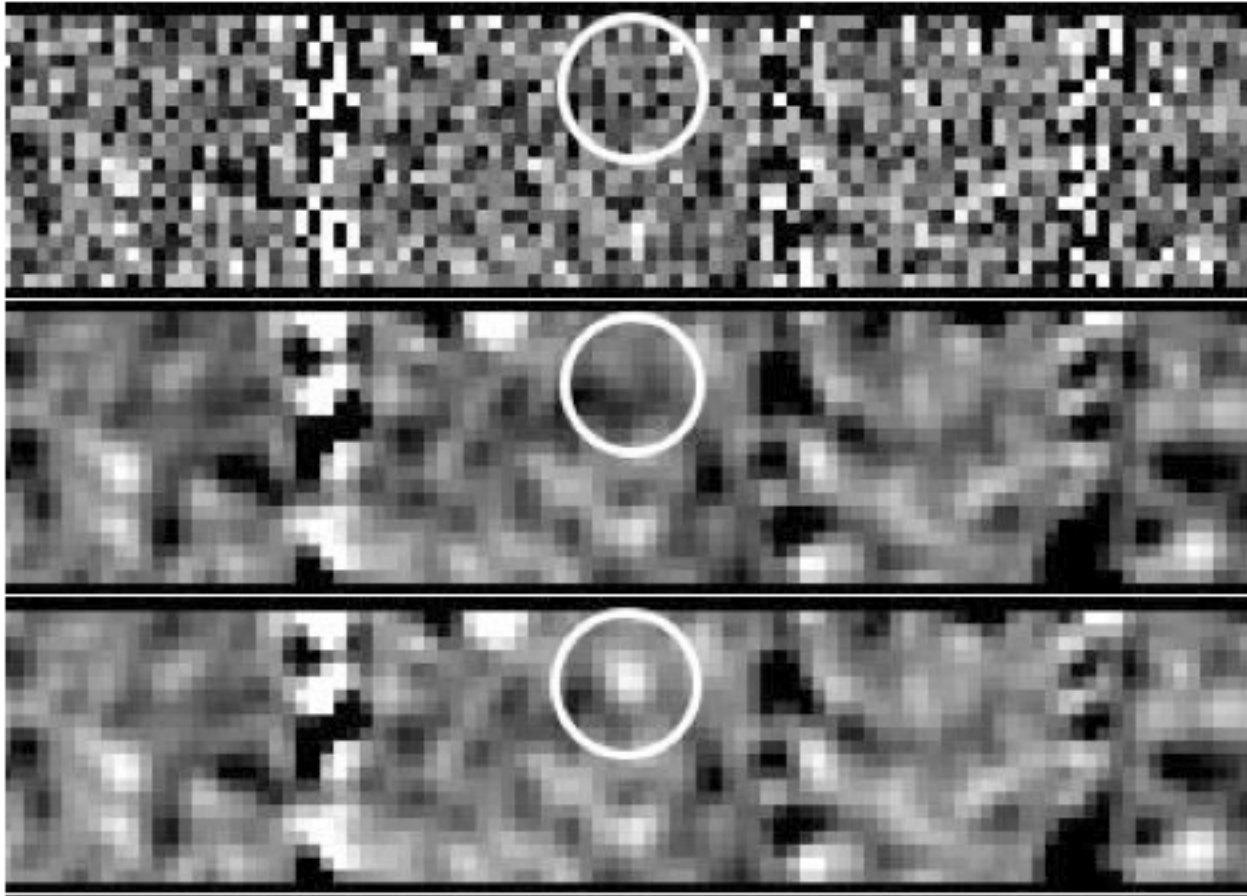
Lehnert et al. claiming

spectroscopic confirmation

of Ly-alpha at  $z=8.55$

with SINFONI-IFU on VLT



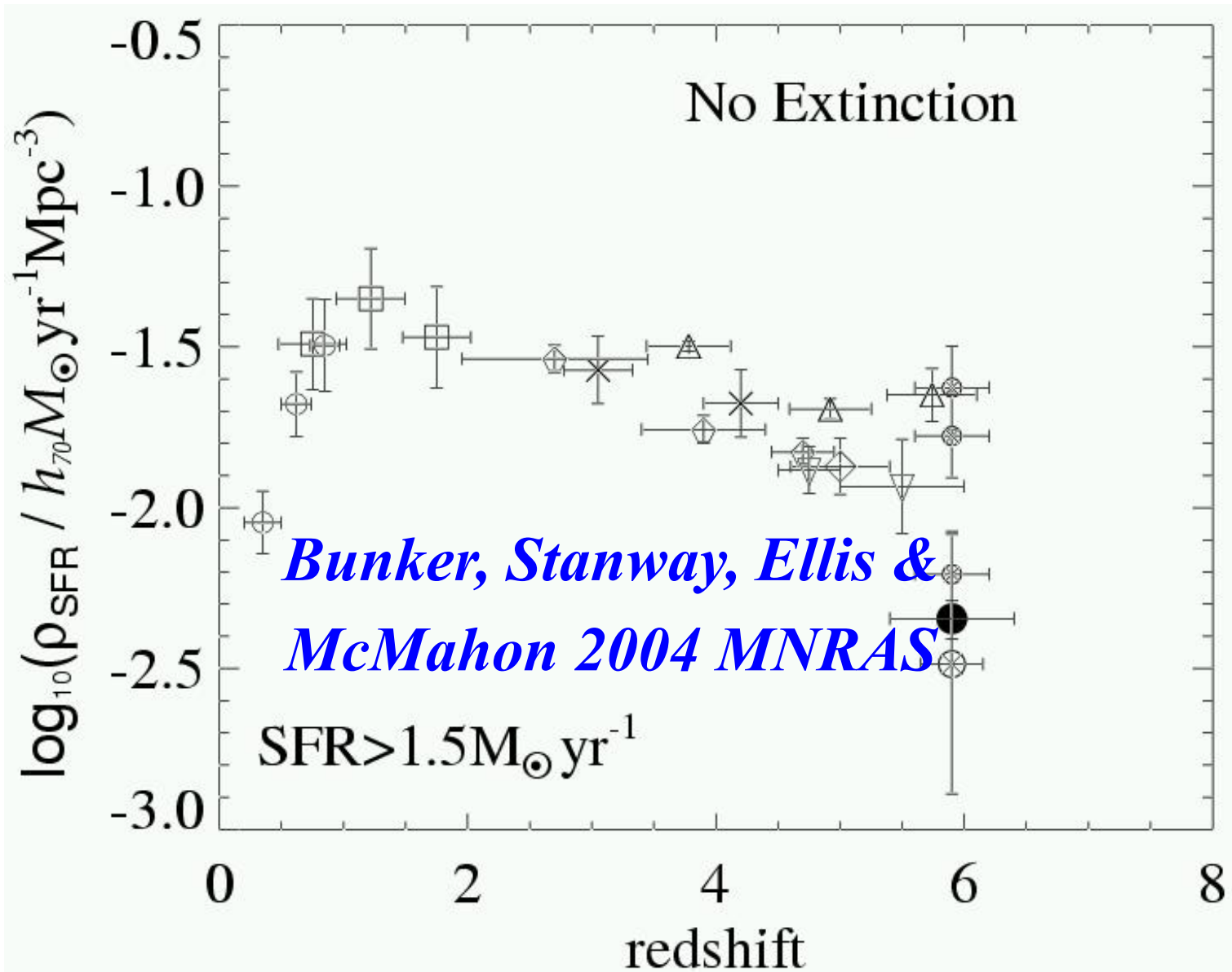


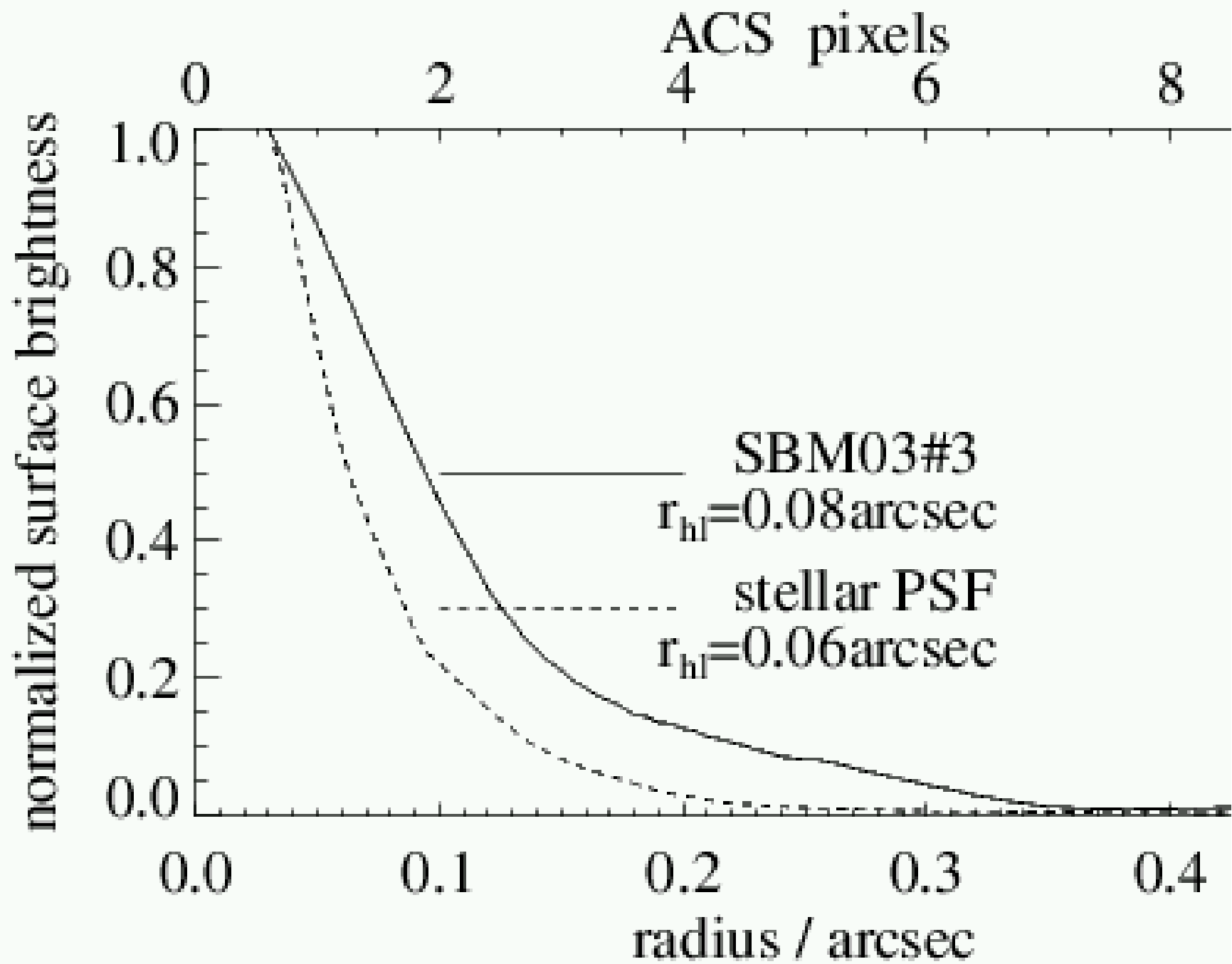
No evidence of Ly-alpha at  $z=8.55$  in 5-hour VLT/XSHOOTER

And 11-hour Subaru/MOIRCS spectrum.

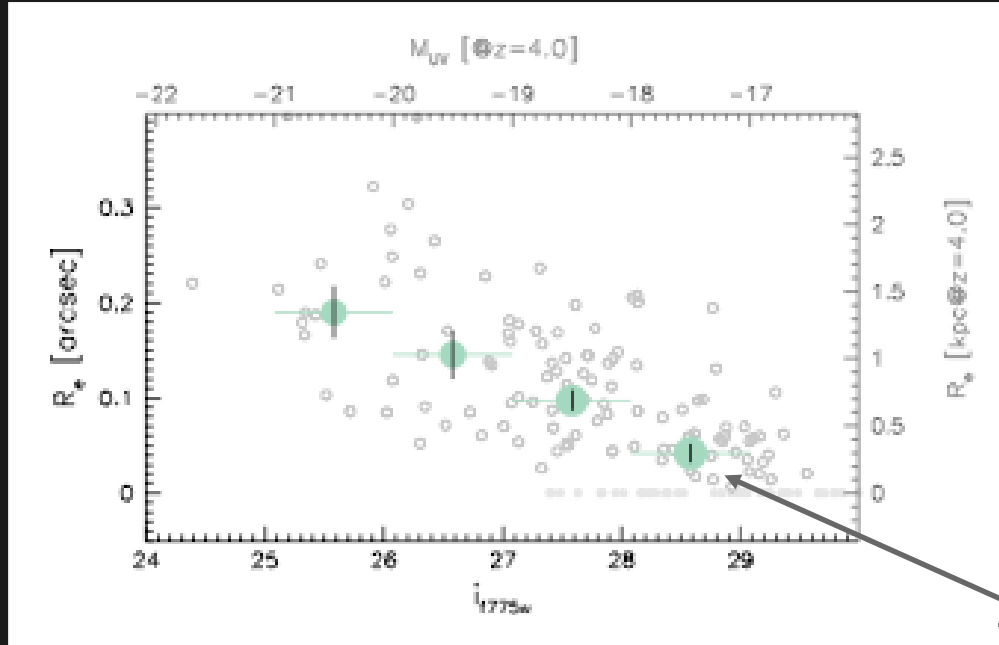
Also, the deep HST/WFC3 Y-band encompasses Ly-alpha, should be detected  
at  $\sim 4\sigma$  but is undetected

*Looking at the UDF (going 10x deeper,  $z'=26 \rightarrow 28.5$  mag)*



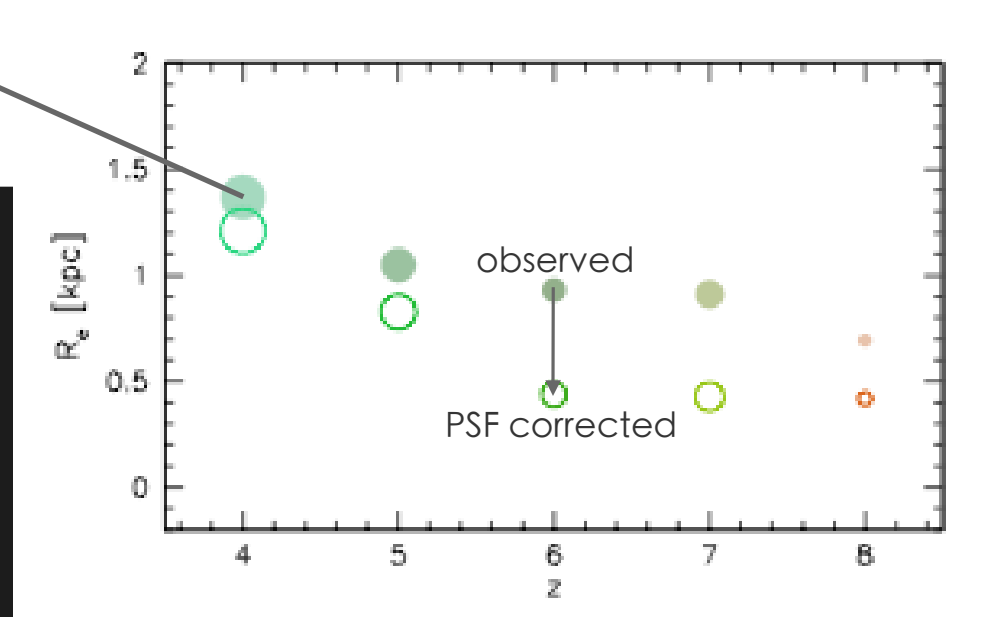


# What Can we Learn about High-redshift Galaxies: Morphologies



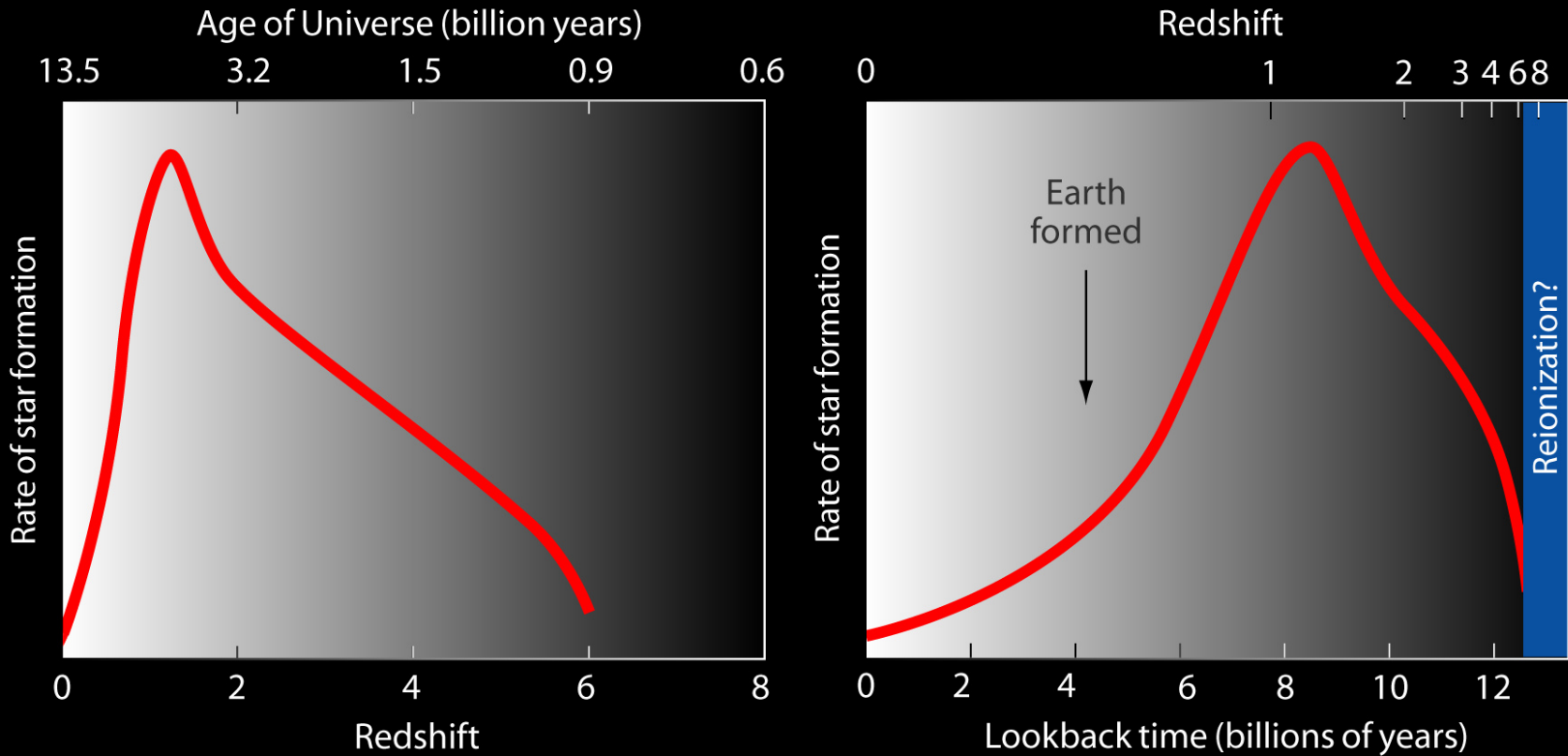
size - luminosity relation  
(only HUDF field, PSF corrected)

size evolution (only HUDF field)



Coupled with the evolution of  $d_a(z)$ \* the intrinsic size evolution results in galaxies at  $z=4-8$  having roughly the same apparent size.  
\* remember at  $z > 1.5$  the angular diameter distance decreases.

# Star formation history of the Universe

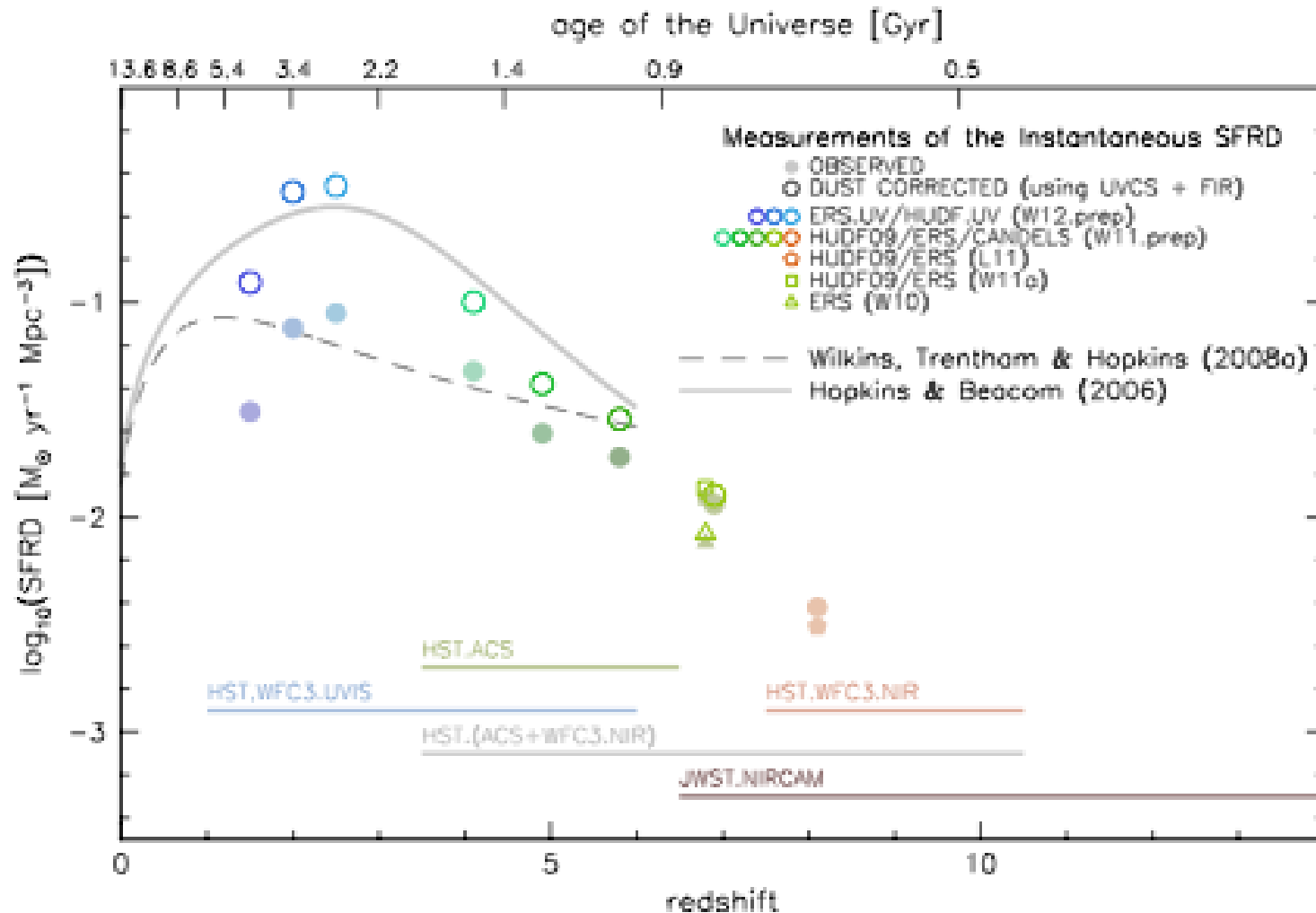


- ***UDF enables us to identify even fainter galaxies at these times (end of dark ages)***
- ***We were first to analyse & publish 50 high redshift galaxies in the UDF***
- ***Confirms our previous work: much LESS star formation than in more recent past***



# What Can we Learn about High-redshift Galaxies:

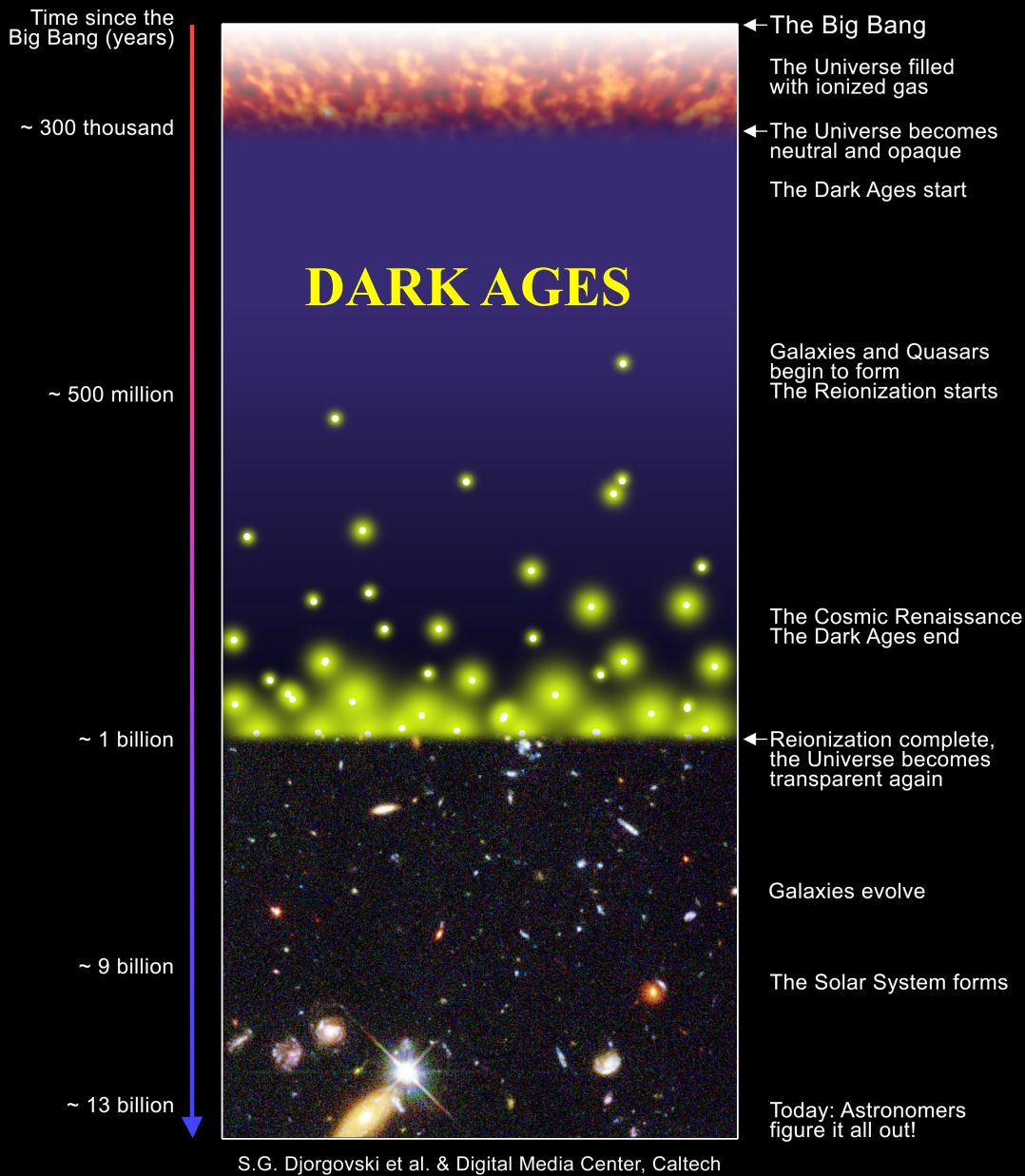
⇒ star formation rate density ⇒ cosmic star formation history



The (mostly) UV inferred Cosmic Star Formation History

# What is the Reionization Era?

A Schematic Outline of the Cosmic History



## Redshift $z$

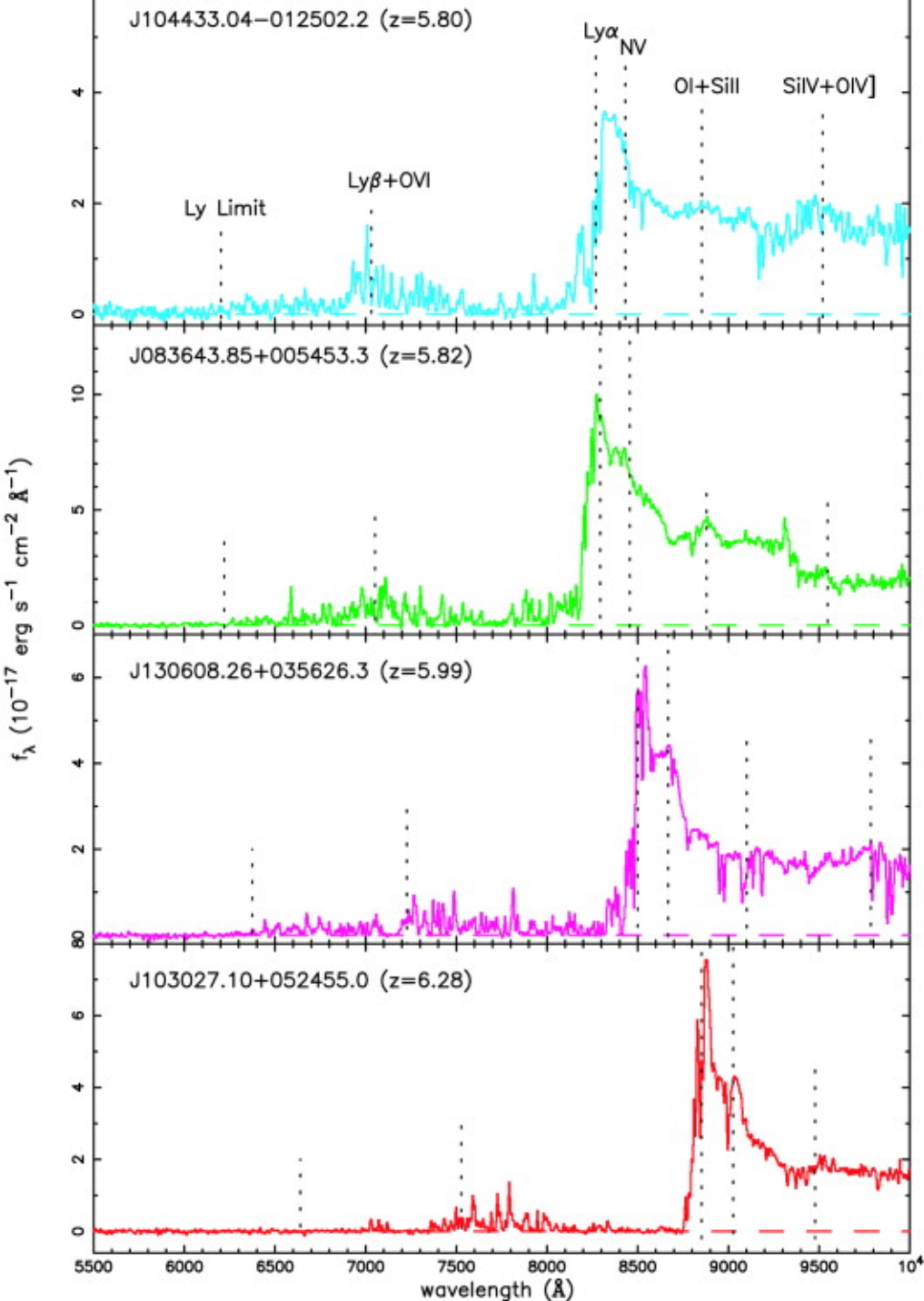


After era probed by WMAP the Universe enters the so-called “dark ages” prior to formation of first stars

Hydrogen is then re-ionized by the newly-formed stars

When did this happen?

What did it?



## Reionization

At high redshift, the Lyman- $\alpha$  forest can absorb most of the flux below  $\lambda_{\text{rest}}=1216\text{\AA}$ . Indications from  $z>6.3$  SDSS QSOs that Universe may be optically thick (Fan et al. 2001; Becker et al. 2001). BUT confusing message from WMAP CMB - reionization at  $z\sim 11$ ? (Dunkley et al. 2010).

# *Implications for Reionization*

$$\dot{\rho}_{\text{SFR}} \approx 0.013 f_{\text{esc}}^{-1} \left(\frac{1+z}{6}\right)^3 \left(\frac{\Omega_b h_{50}^2}{0.08}\right)^2 C_{30} M_{\odot} \text{ yr}^{-1} \text{ Mpc}^{-3}$$

From Madau, Haardt & Rees (1999) -amount  
of star formation required to ionize Universe

( $C_{30}$  is a clumping factor; early work adopted  $C=30$ , but might be as low as  $C=5$  with re-heating - Pawlik, Schaye & van Scherpenzeel 2009).

This assumes escape fraction=1 (i.e. all ionizing photons make it out of the galaxies). Observationally, this is only a few percent locally, and essentially unconstrained at high- $z$  (with some claimed limits of  $f_{\text{esc}} \sim 0.1$ )

Our HUDF data has star formation at  $z=6$  which is 3x *less* than that required! AGN cannot do the job.

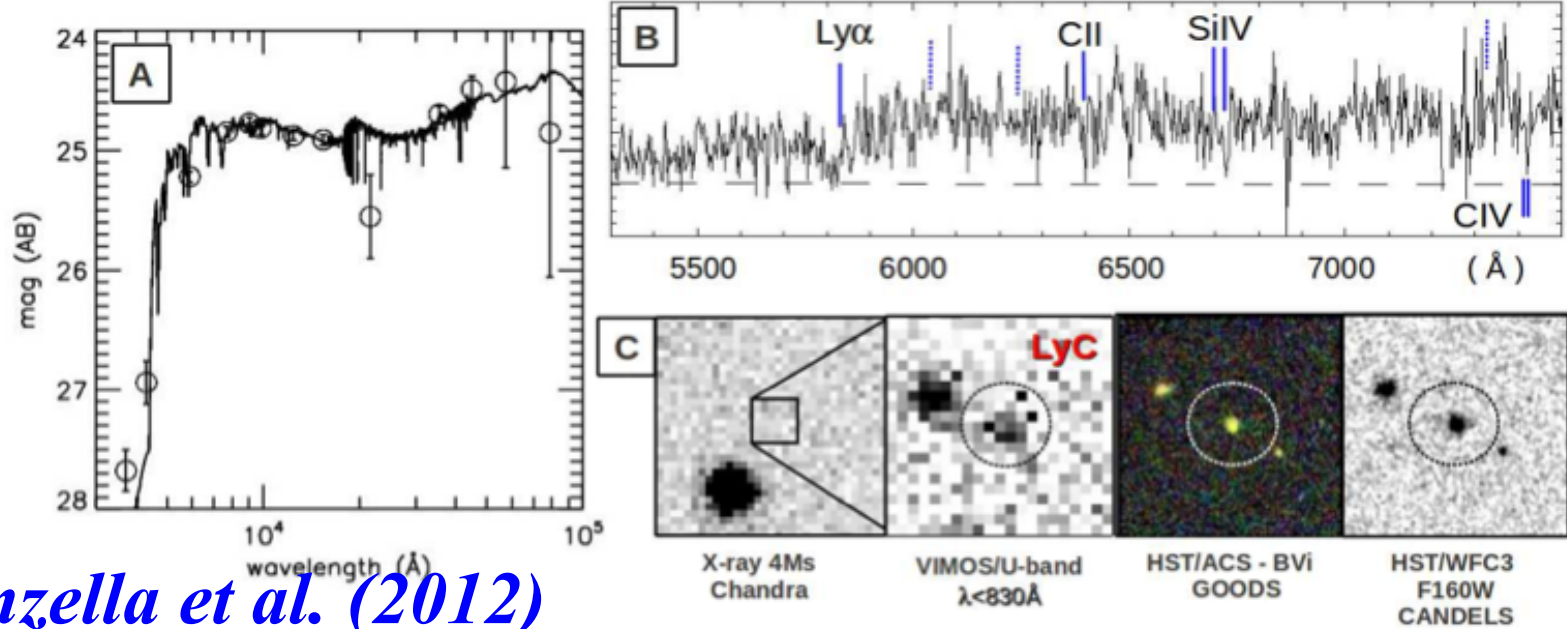
Even with revised clumping factor, still need  $f_{\text{esc}} > 0.5$

(see also Stiavelli, Fall & Panagia 2005)

We go down to  $1 M_{\text{sun}}/\text{yr}$  - but might be steep  $\alpha$  (lots of low luminosity sources - forming globular clusters?)

# ***Ionizing Photon Escape Fraction***

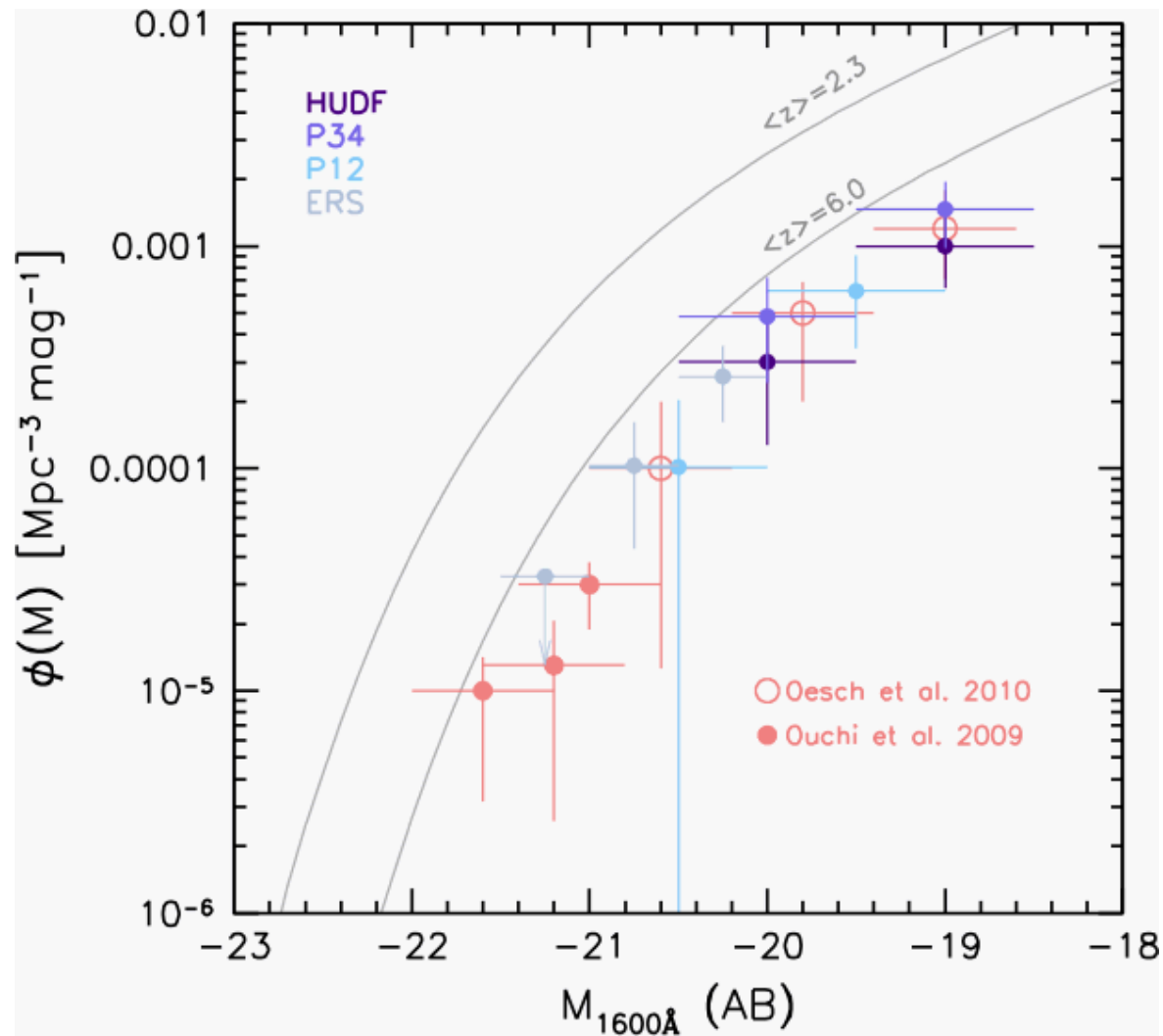
Ion1 : J033216.64-274253.3, redshift 3.795



***Vanzella et al. (2012)***

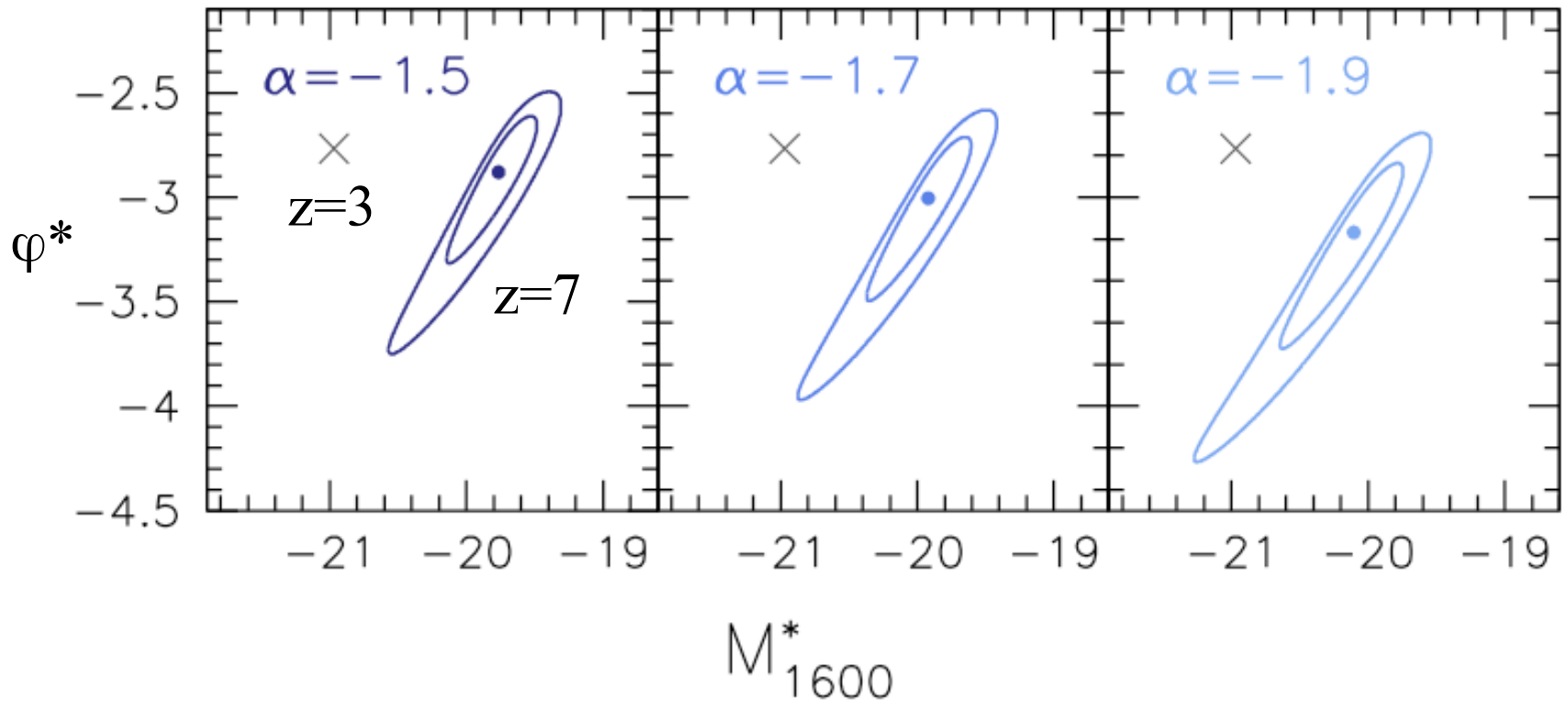
We are interested in photons with wavelength  $< 912 \text{ \AA}$  (which can ionize hydrogen), but have to infer these from brightness at  $> 1216 \text{ \AA}$  (not absorbed by Ly-alpha forest)

Indications are at  $z \sim 3$  that escape fraction is very small (Vanzella et al. 2012, Nestor et al. 2011, Siana et al. 2007, Shapley et al. 2006, Iwata et al. 2008)



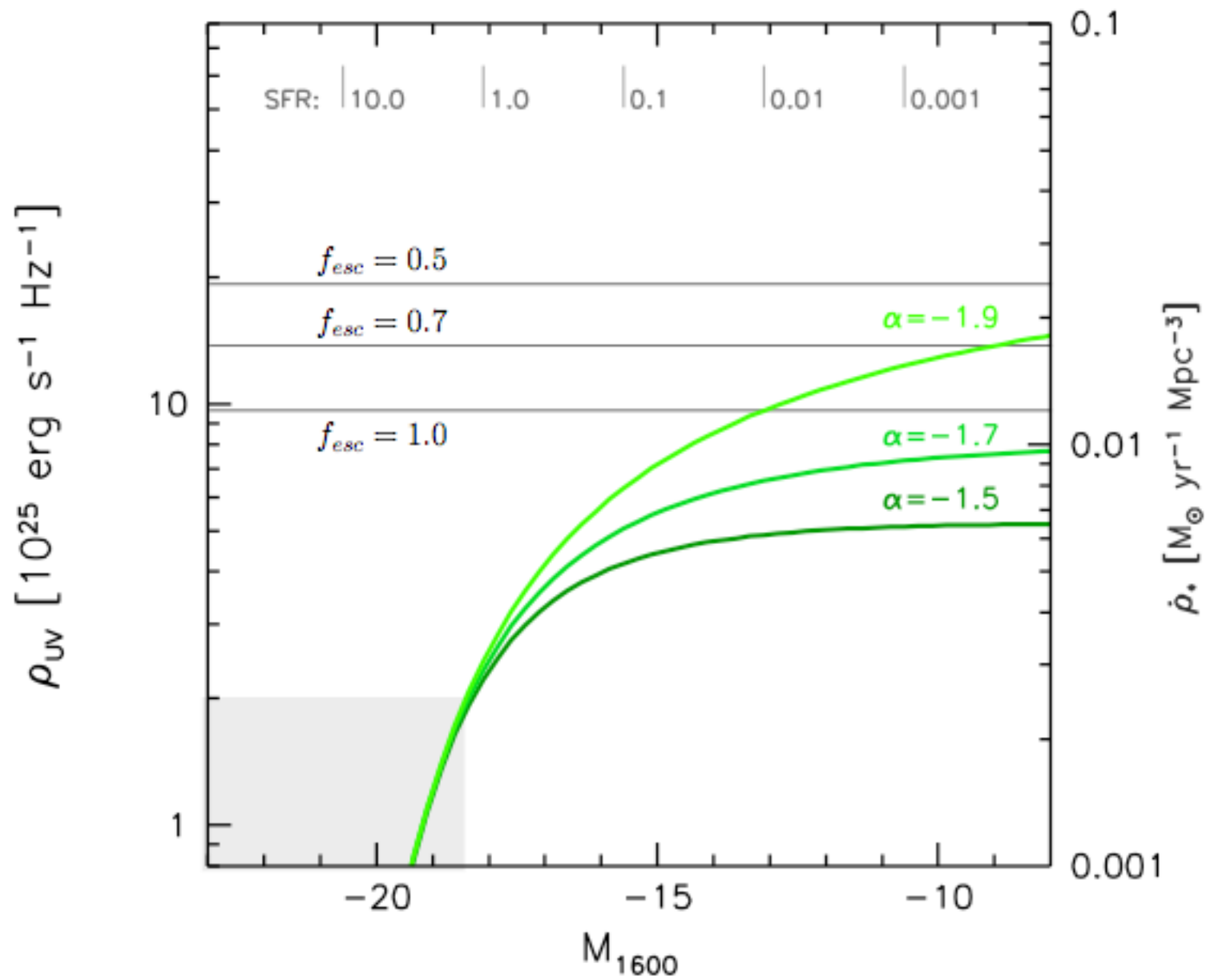
Wilkins et al.  
(2010) MNRAS  
The Luminosity  
Function at  $z \sim 7$

An increasing problem for reionization: requires steep faint-end slope ( $\alpha < -1.7$ ), large contribution from unobserved faint galaxies, high escape fraction ( $f_{\text{esc}} > 0.5$ ) and very smooth IGM (low clumping,  $C \sim 5$ )



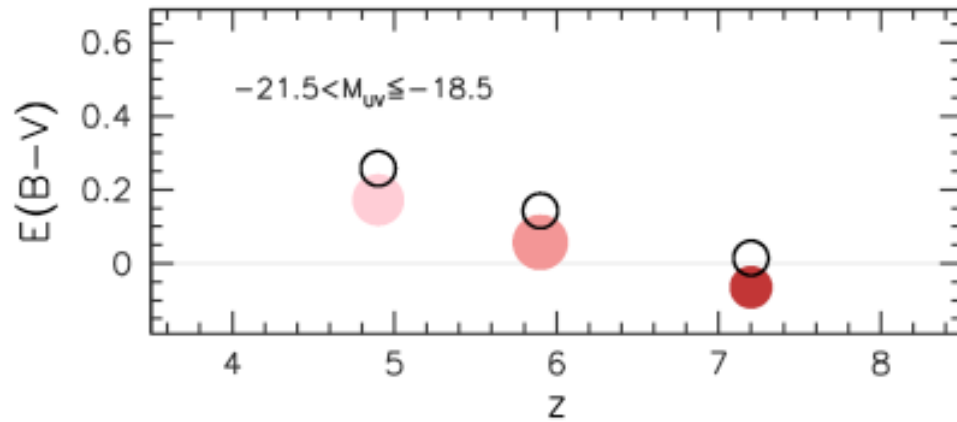
Evolution of luminosity function  
(note  $M^*$  is correlated with  $\phi^*$ )

Wilkins et al. (2011)

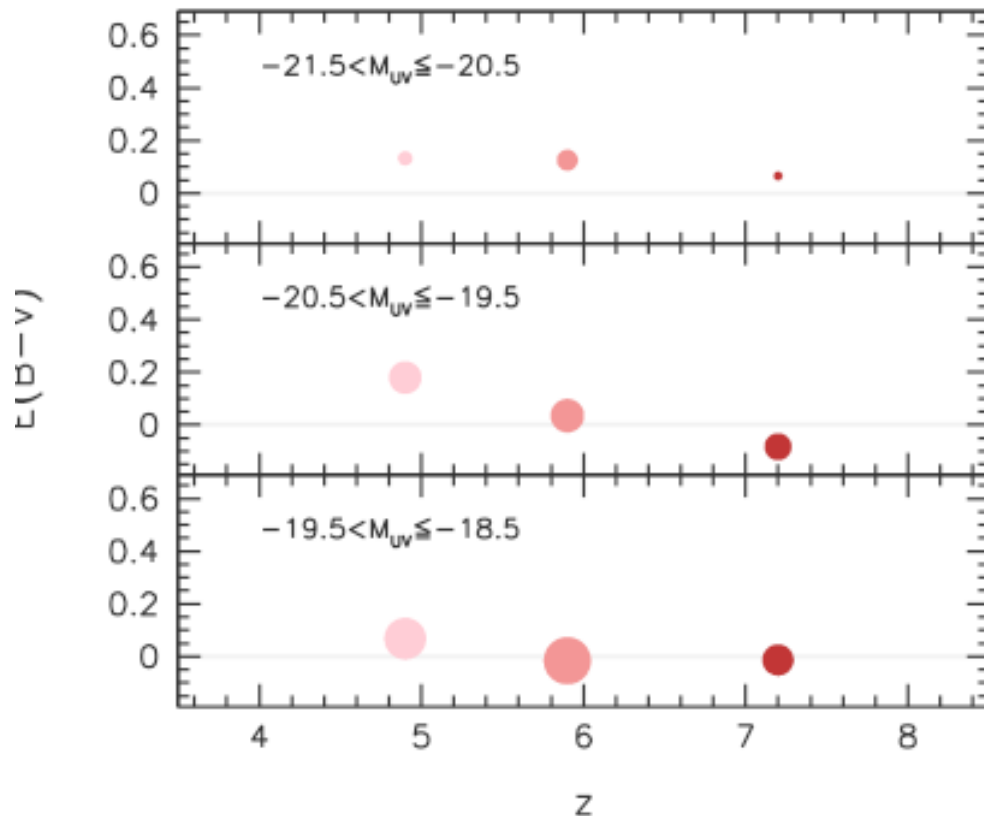


Wilkins et al. (2010)

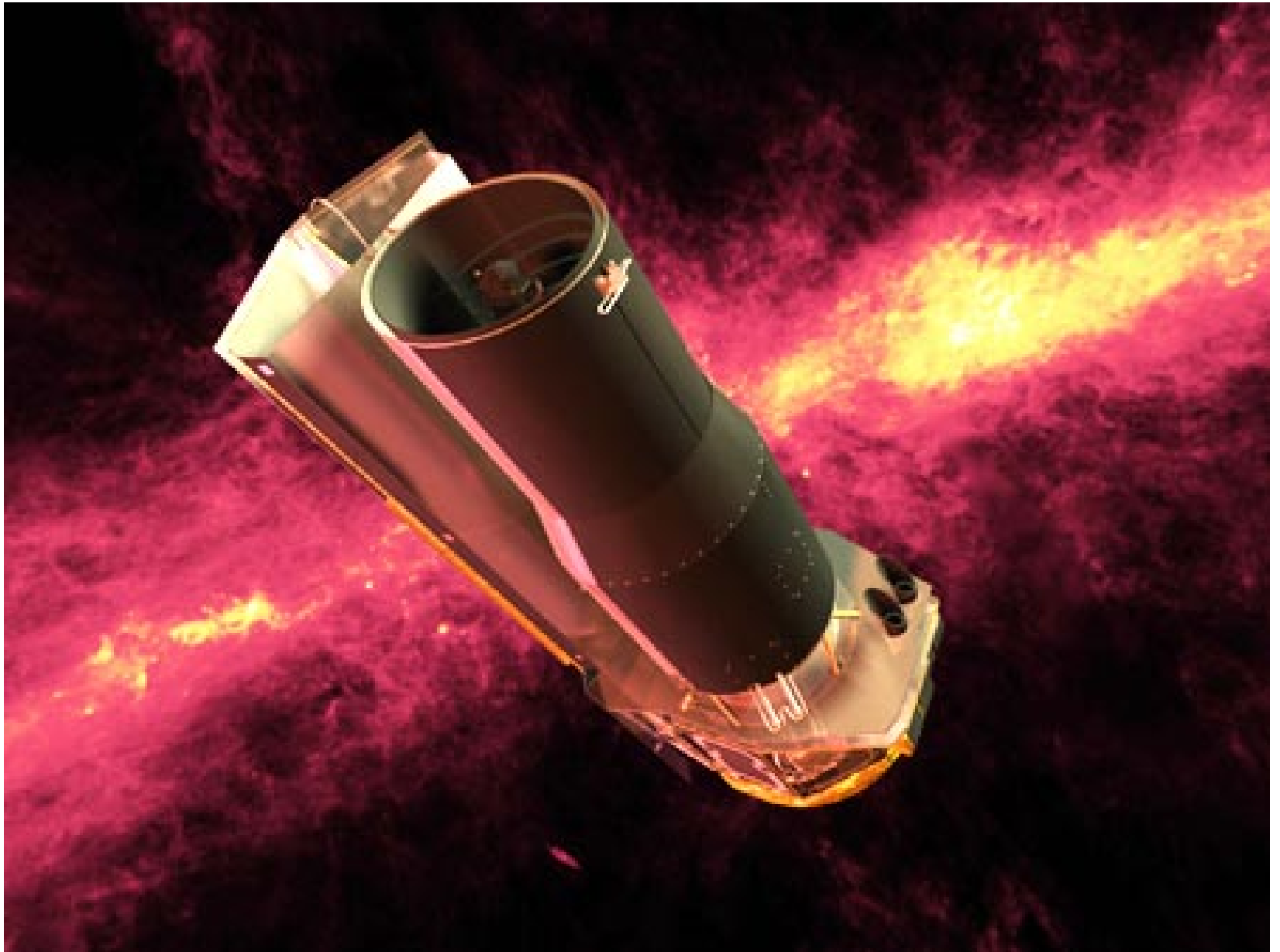




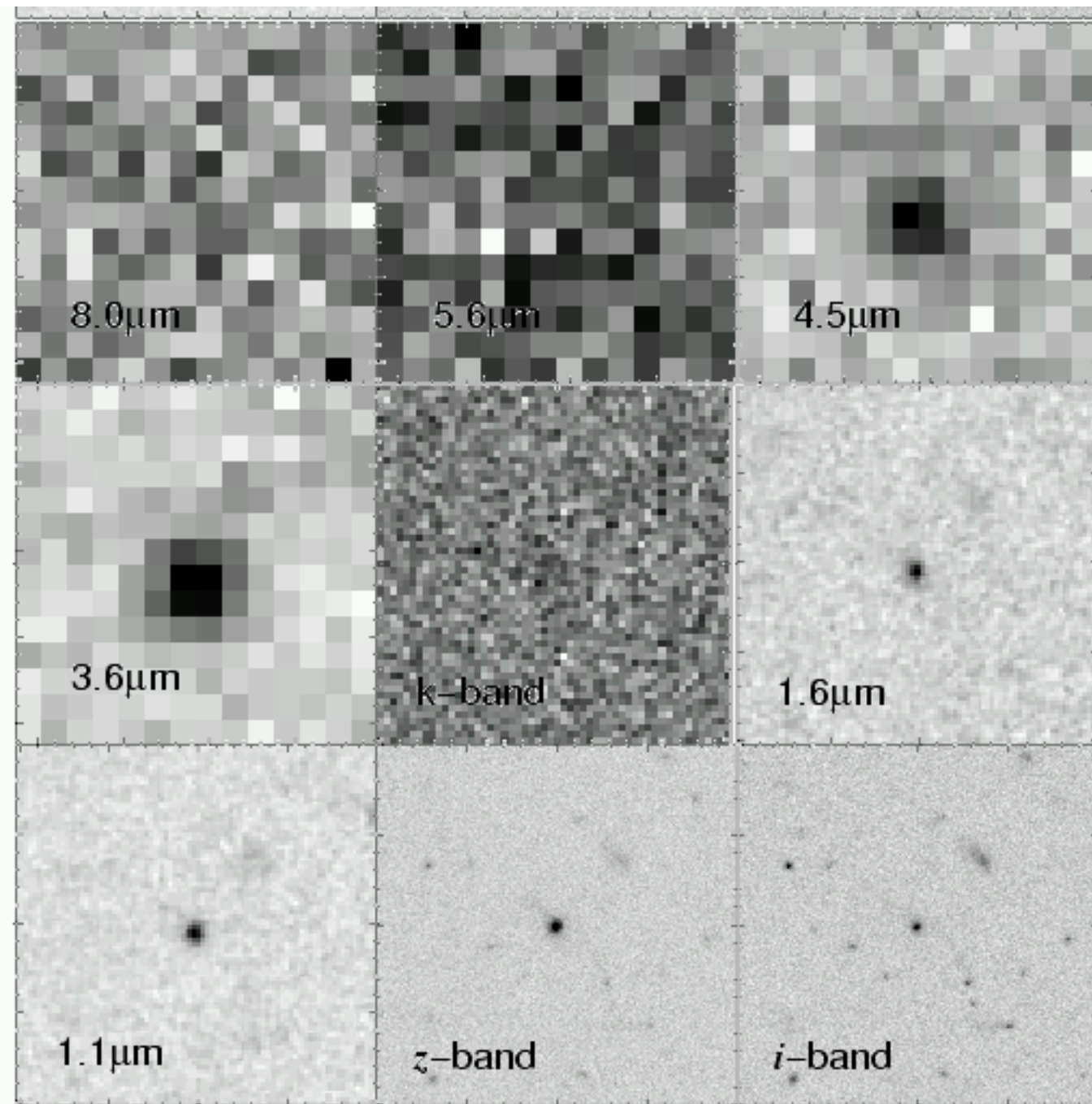
- From Wilkins et al. (2011) MNRAS



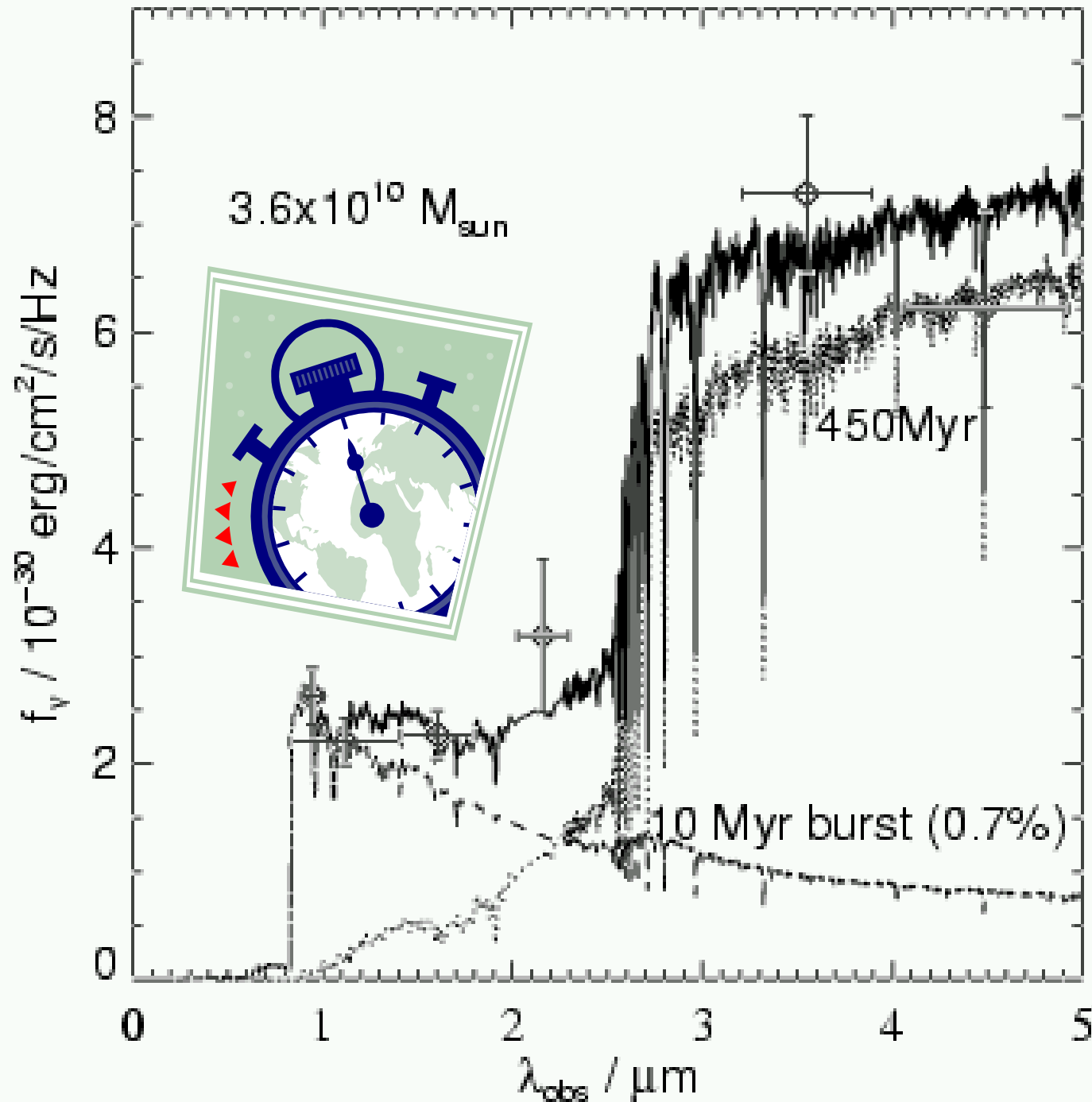
- Weak dependence of beta evolution on luminosity
- Careful on filters - the Lyman-alpha break will redden intrinsic colours



*Spitzer – IRAC (3.6-8.0 microns)*

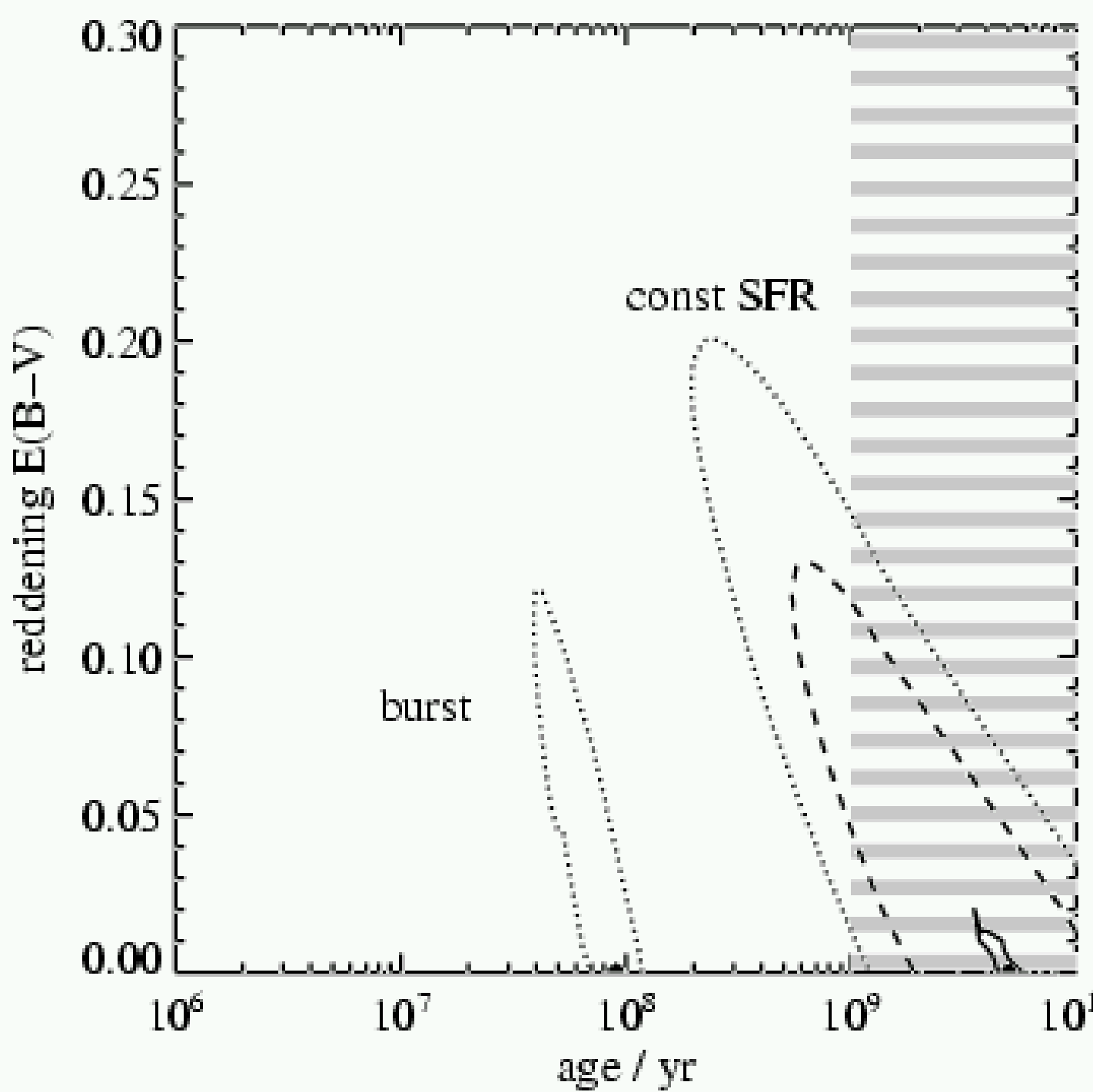


-  $z=5.83$  galaxy  
#1 from  
Stanway, Bunker  
& McMahon  
2003 (spec conf  
from Stanway et  
al. 2004,  
Dickinson et al.  
2004). Detected  
in GOODS  
IRAC 3-4 $\mu$ m:  
Eyles, Bunker,  
Stanway et al '04



Eyles et al.  
(2005) MNRAS

Emission line  
contamination  
does not  
seriously affect  
the derived  
ages and  
masses



# JAMES WEBB SPACE TELESCOPE

– successor to Hubble (~~2013+~~)

2018



# Conclusions

- Have found star-forming galaxies at  $z=6-10$  (Lyman breaks), and spectroscopic confirmation at  $z\sim 6$
- However,  $z>7$  number counts from HST/WFC3 imply the newly-discovered galaxies would struggle to reionize
- Many of these have very blue rest-UV spectral slopes
- High escape fraction/Steep faint end slope/low metallicity/smooth IGM?
- JWST spectroscopy should resolve many questions