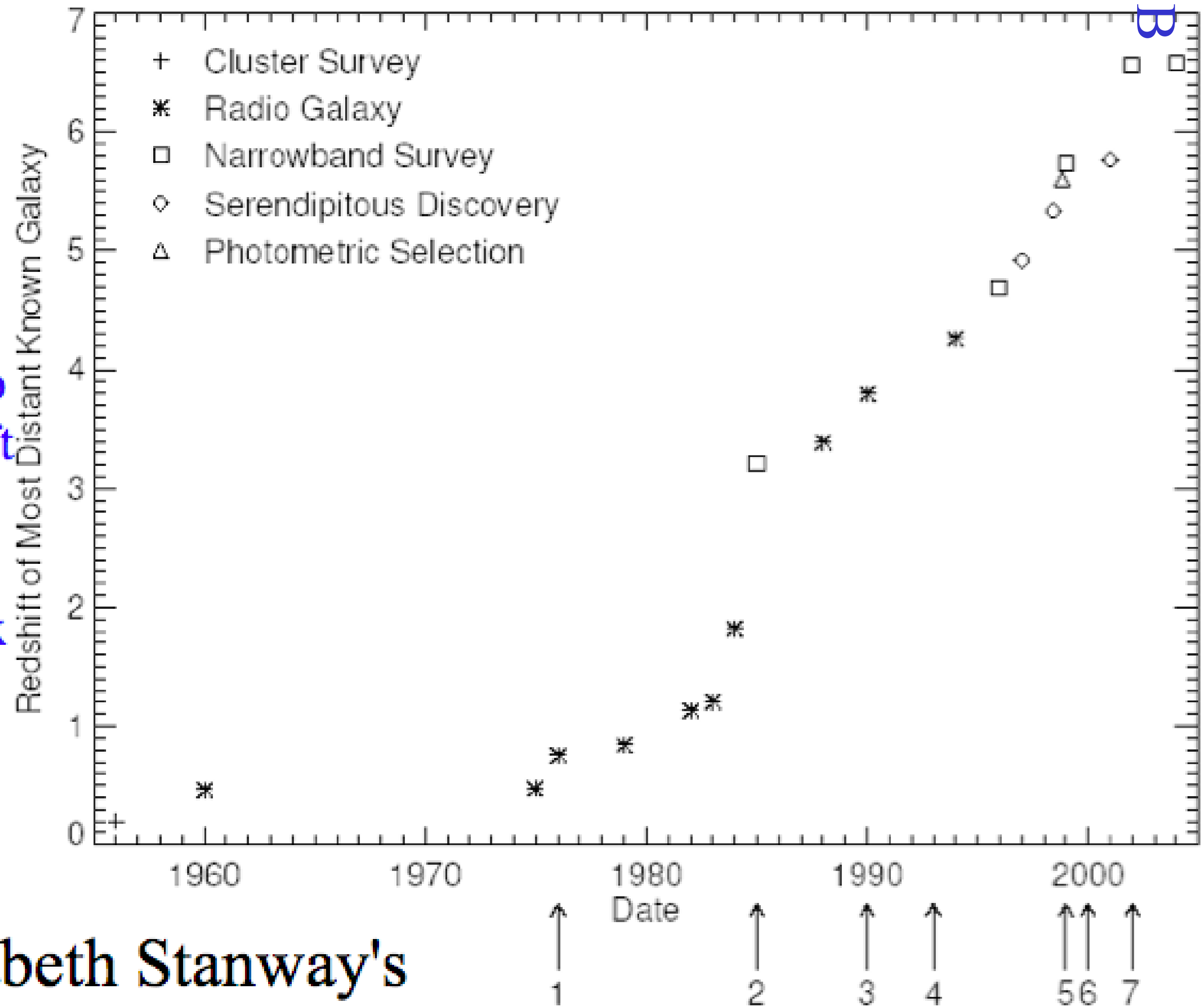
Star-Forming Galaxies in the Reionization Epoch

Andy Bunker, Stephen Wilkins, Joseph Caruana, Silvio Lorenzoni, Matt Jarvis (Oxford), Dan Stark (Arizona), Richard Ellis (Caltech), Elizabeth Stanway (Warwick) Laurence Eyles (Exeter) Mark Lacy (NRAO)

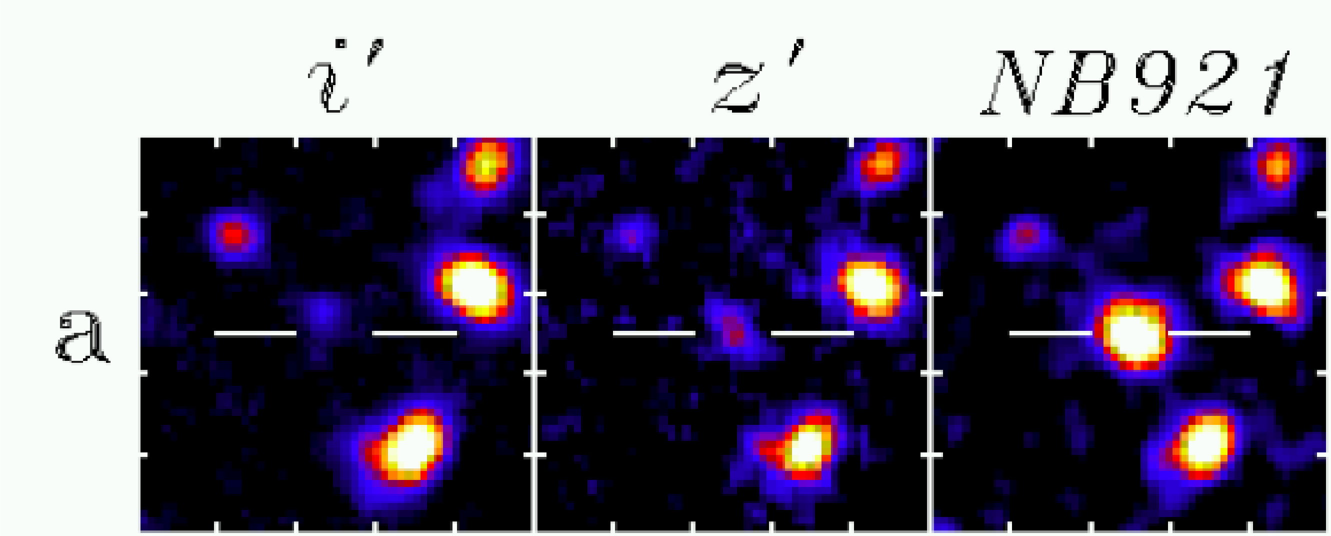
UNIVERSITY OF OXFORD

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-α)



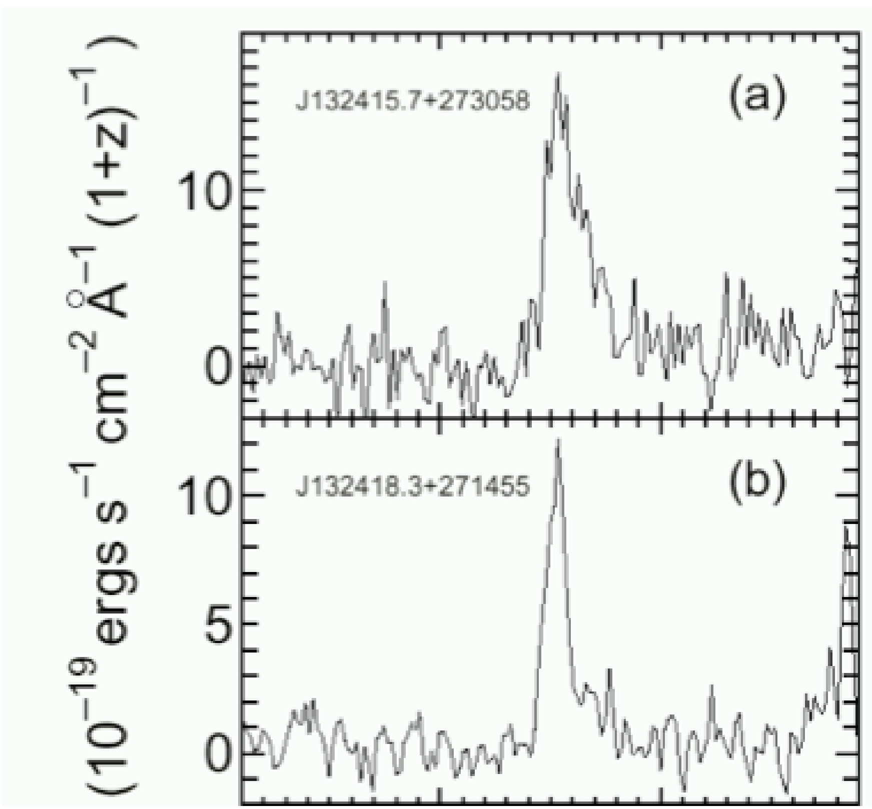
X recent z=8.3
GRB

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



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

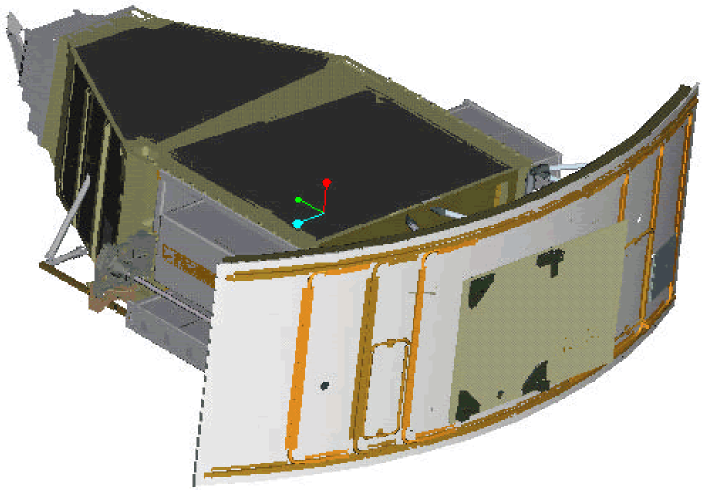
Current narrow-band record now z=6.96

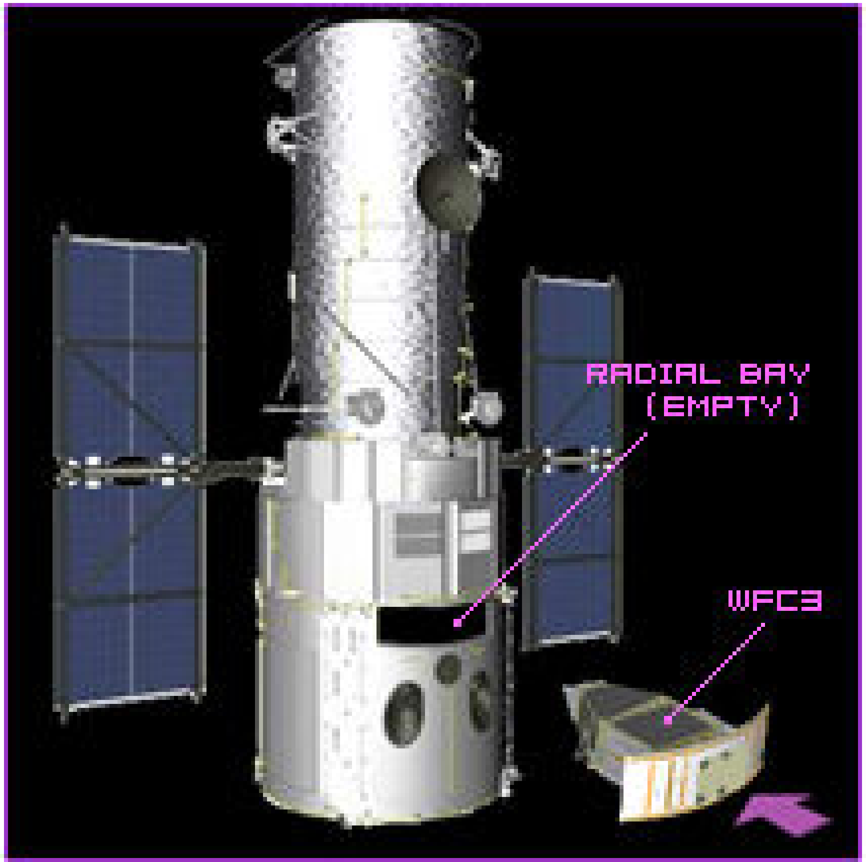


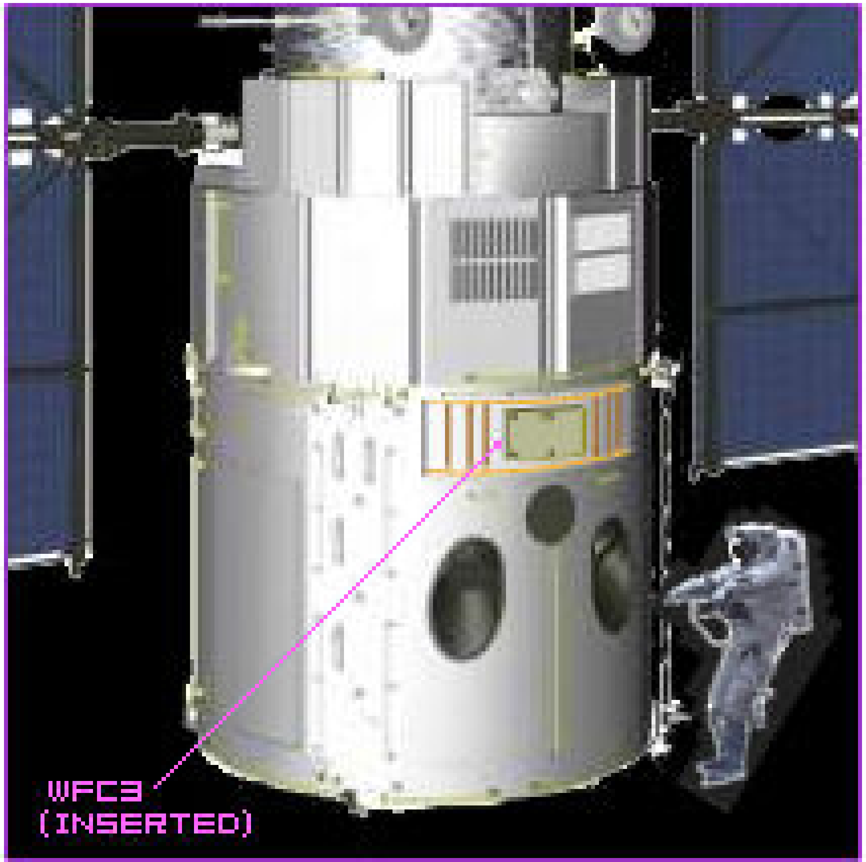
Also: Hu et al. (2002) z=6.56, lensed by Abell 370 cluster

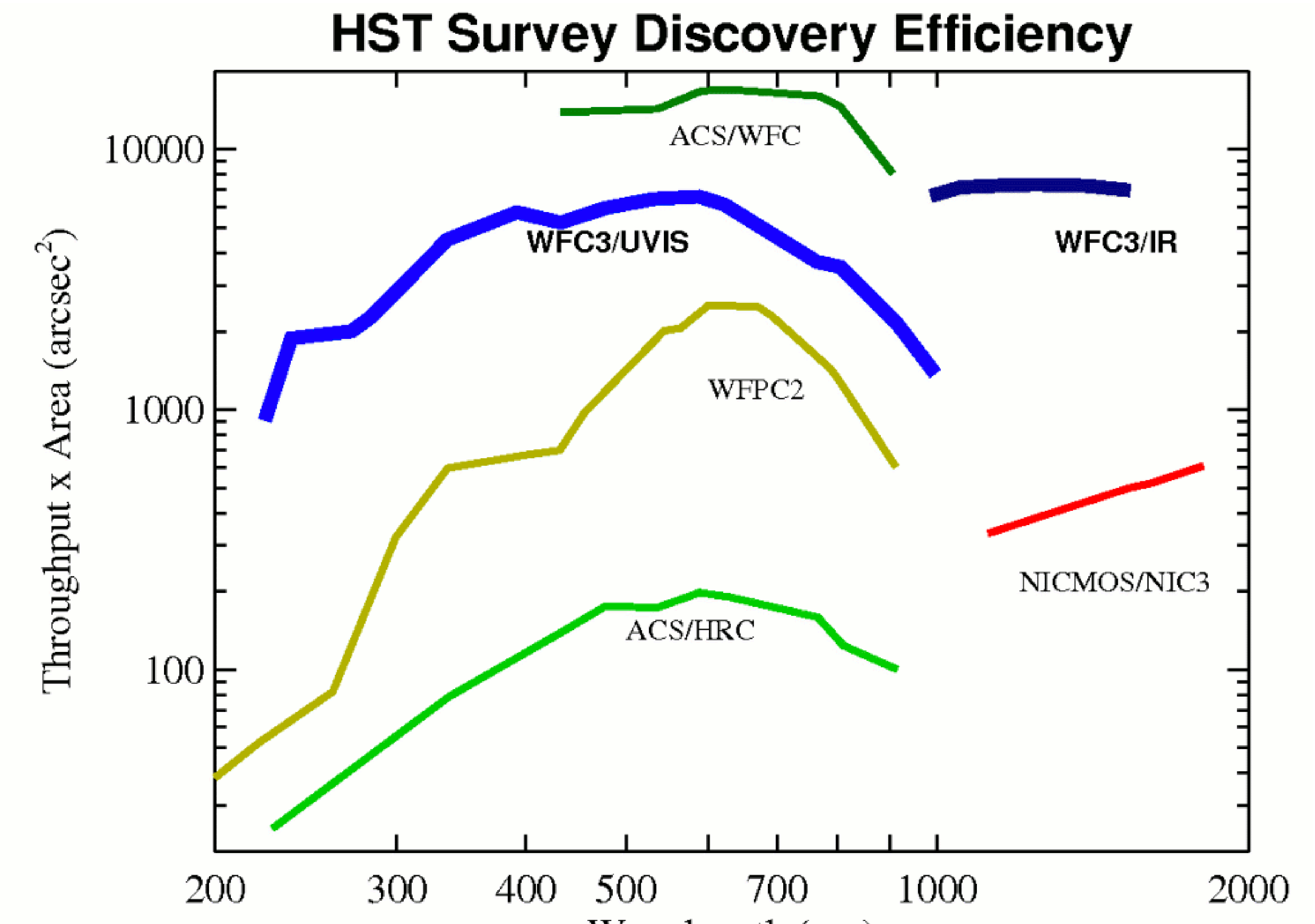
Both use narrow-band filter in low-background region between sky lines, and follow-up spectra

HST WFC3








HST Survey Discovery Efficiency
ACS/WFC
WFC3/UVIS
WFC3/IR
WFPC2
NICMOS/NIC3
ACS/HRC
10000
1000
100
200
300
400
500
700
1000
2000
Wavelength (nm)
Throughput x Area (arcsec^2)

Observations:

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

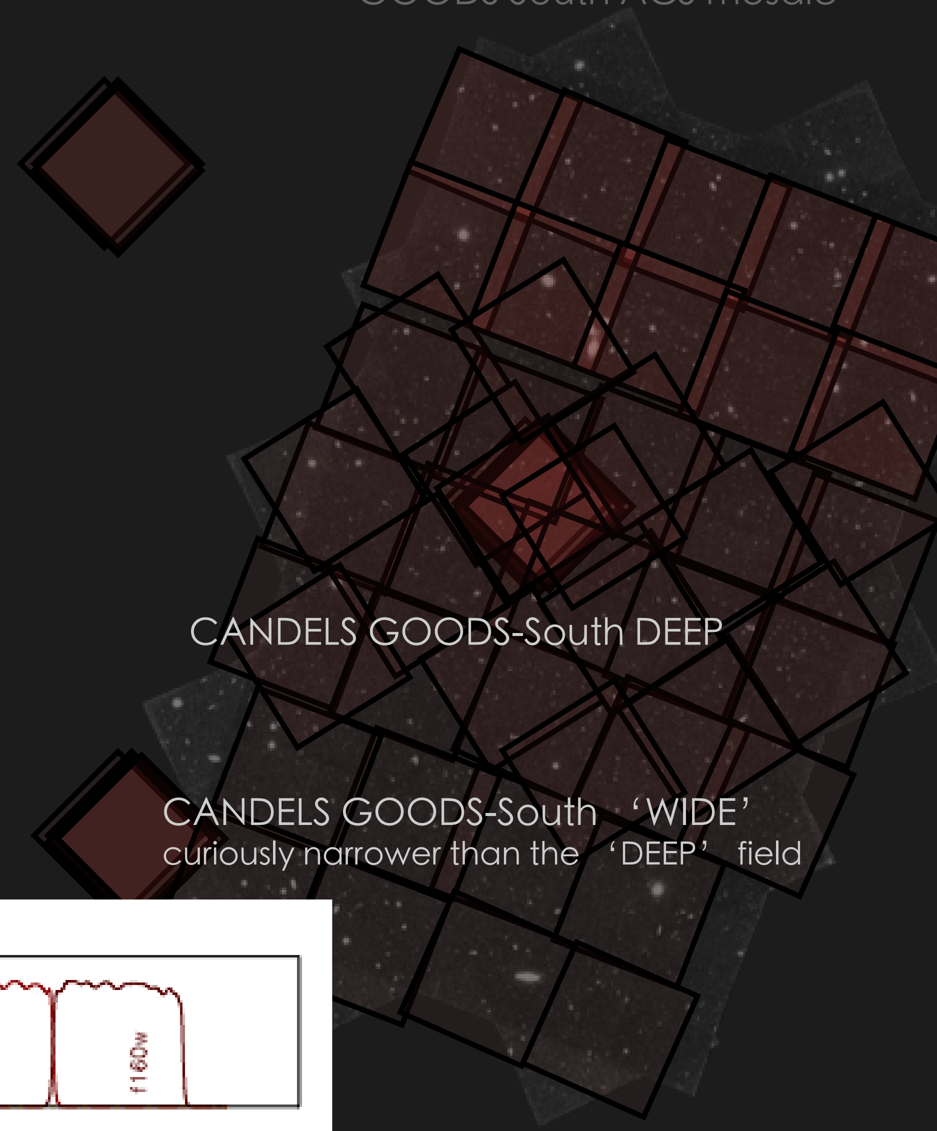
Ultra-Deep **ACS** imaging in the HUDF and two flanking fields (each a single ACS field) [HUDF, HUDF05, HUDF09]

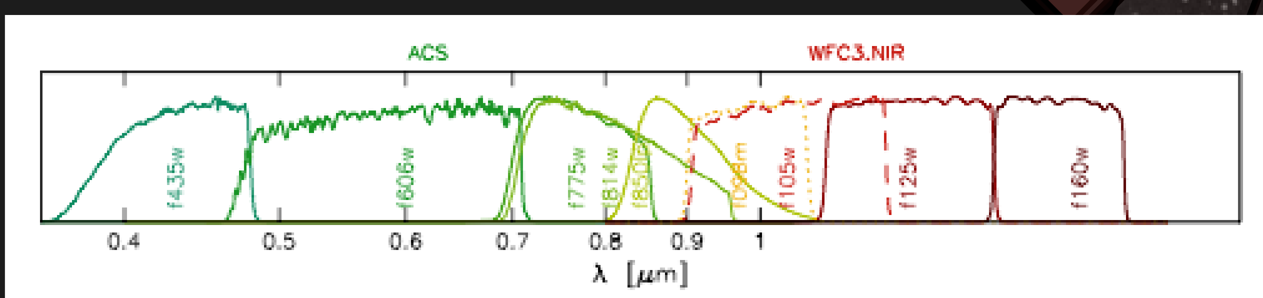
HUDF09 Ultra-deep (29.0-30.0 (AB) in J_{125w}, 5σ) in 3 fields (~15 arcmin^2 total)

ERS Very-deep (~28.5 (AB) in J_{125w}, 5σ) contiguous over ~40 arcmin^2

CANDELS GOODS-South Pretty-deep (28.0-28.5 (AB) in J_{125w}, 5σ) contiguous over ~100 arcmin^2

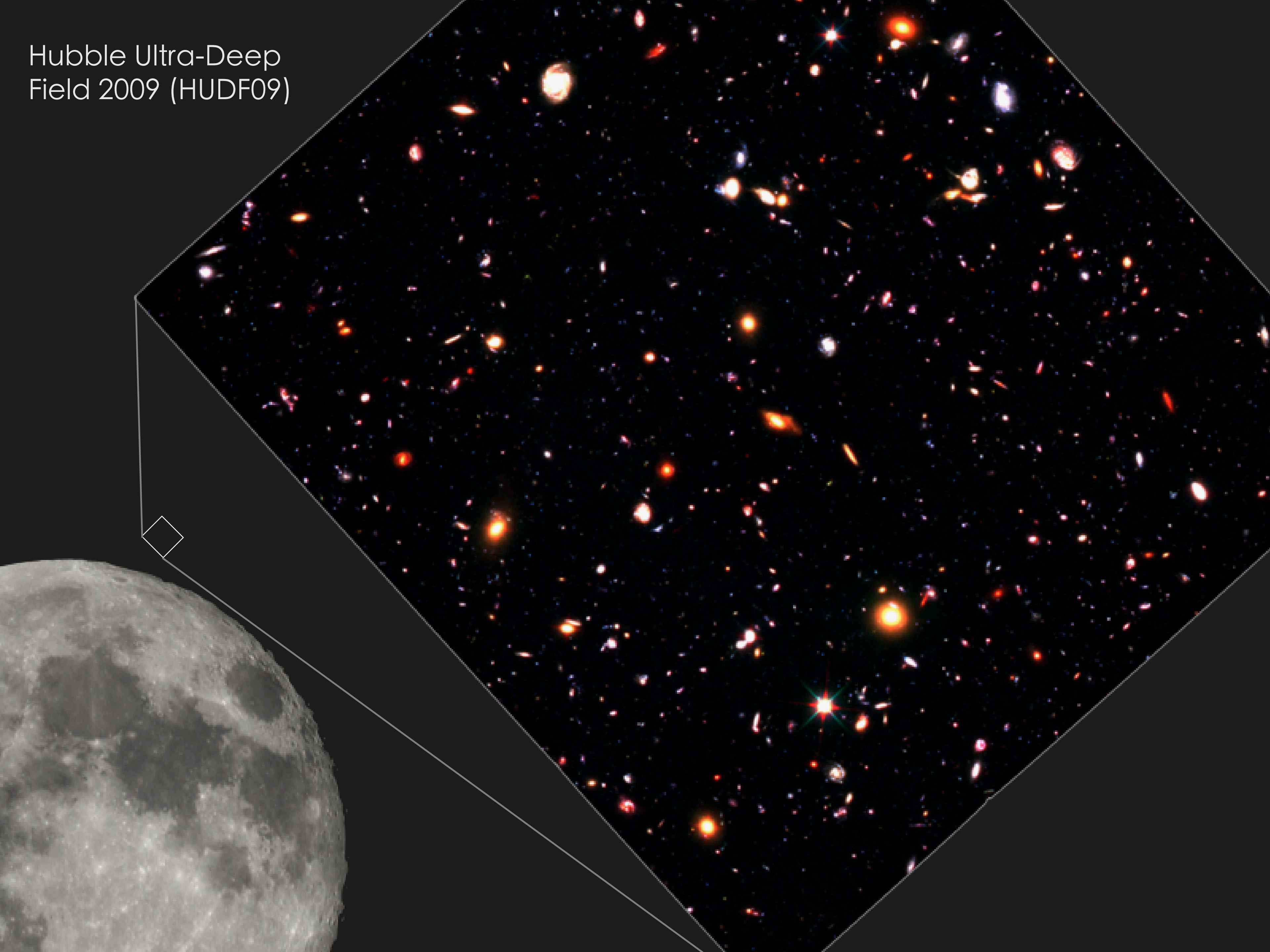
GOODS South ACS mosaic



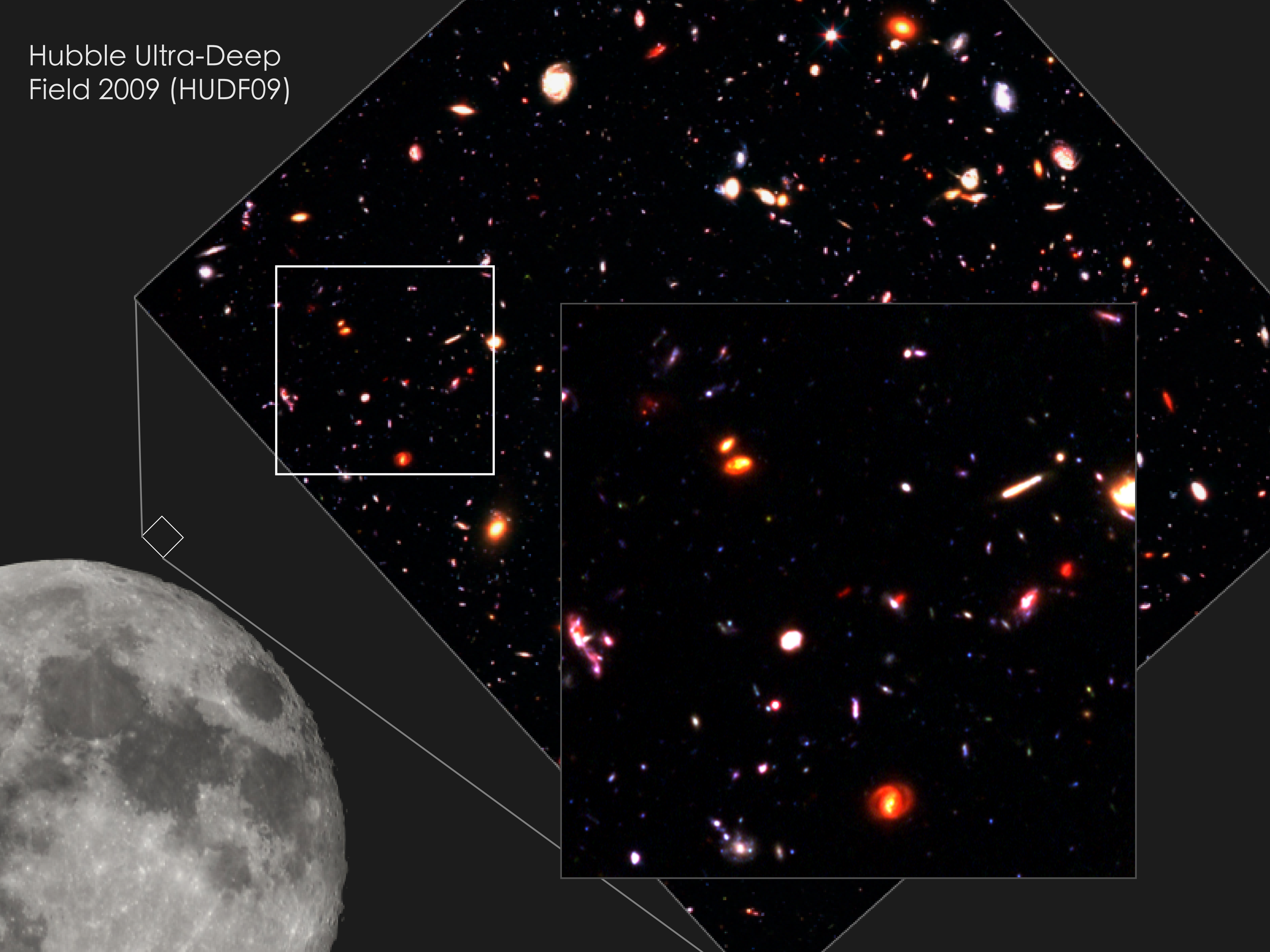


Filter transmission functions of the filters available.

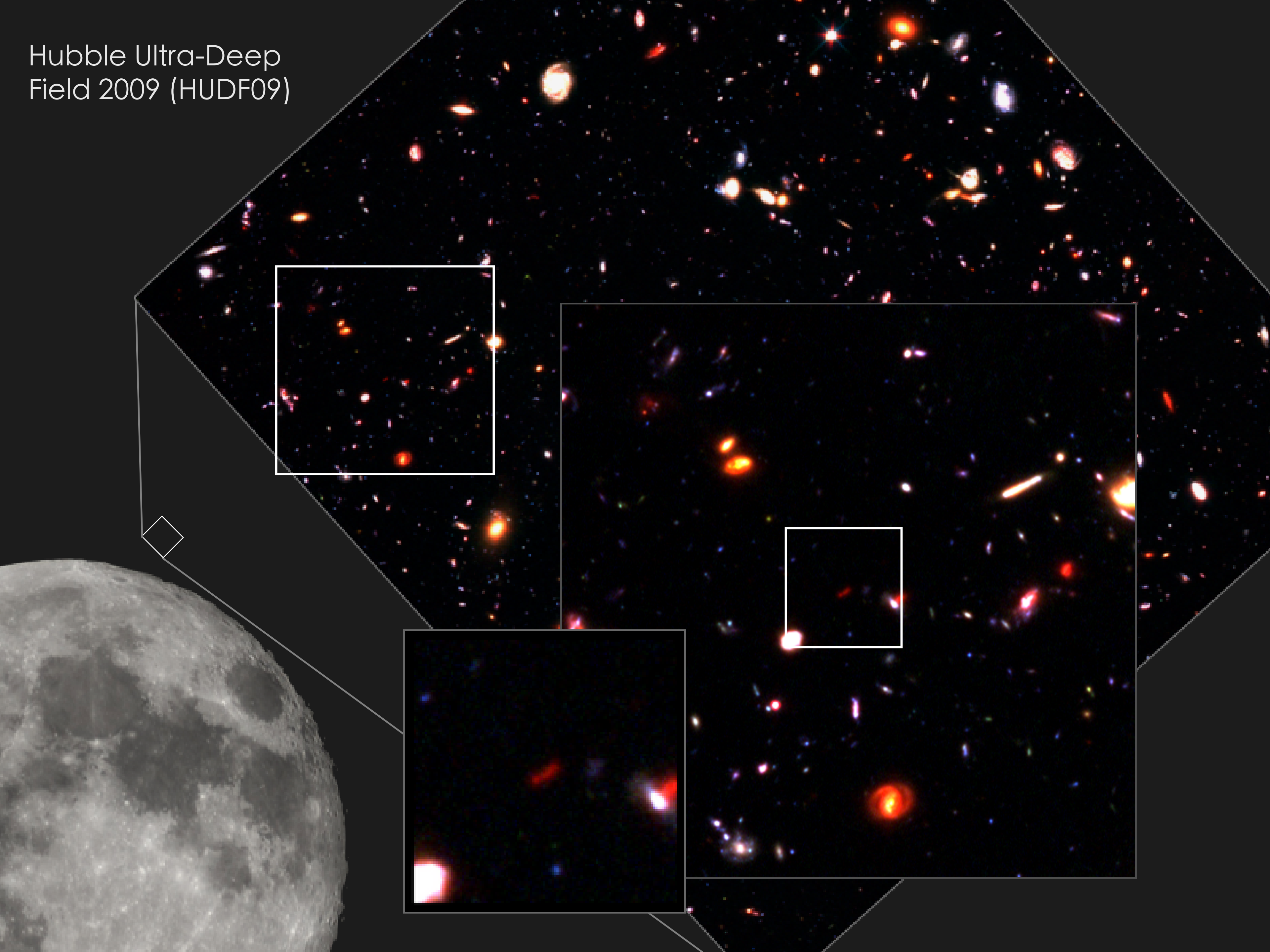
Hubble Ultra-Deep
Field 2009 (HUDF09)

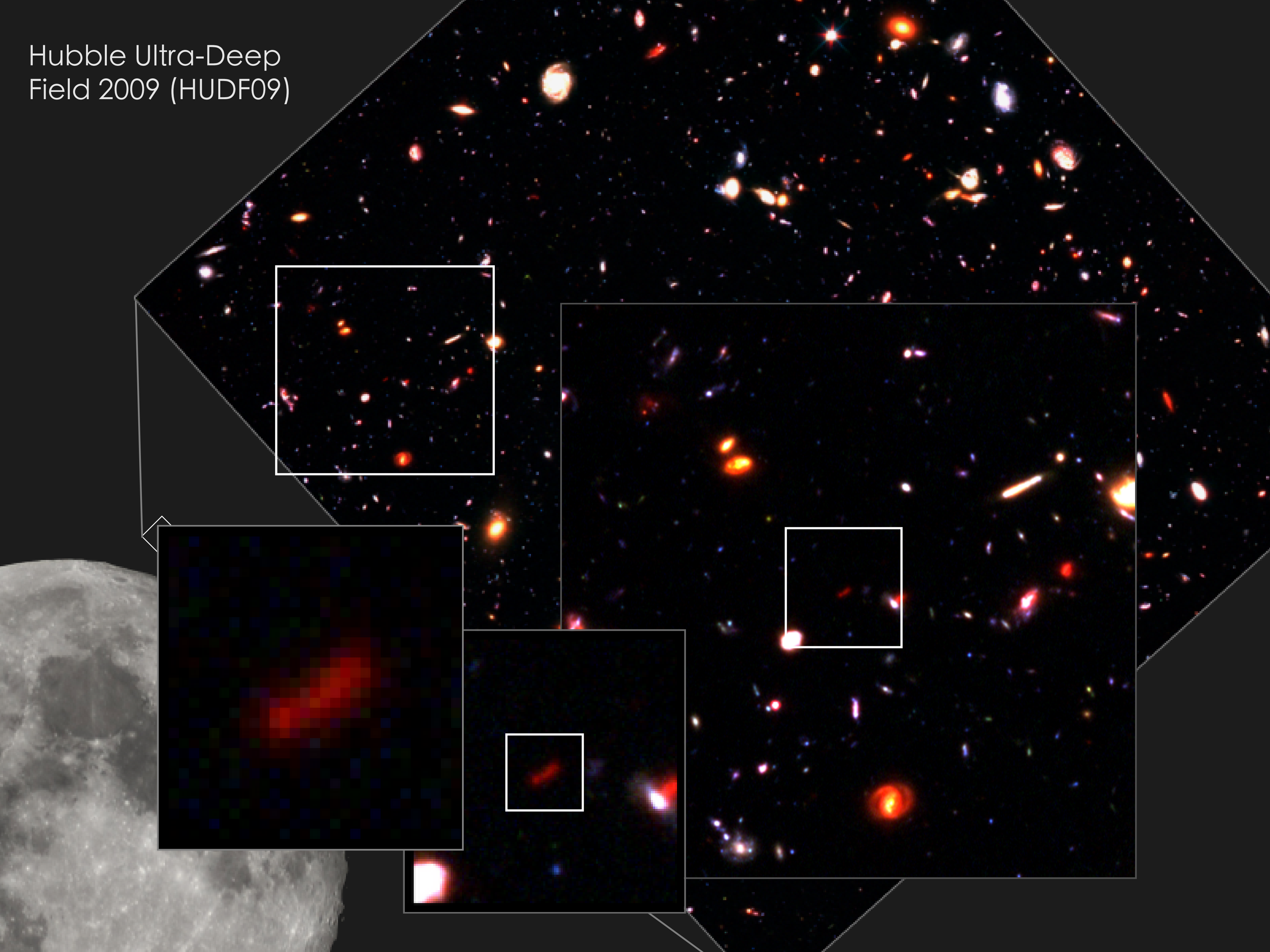


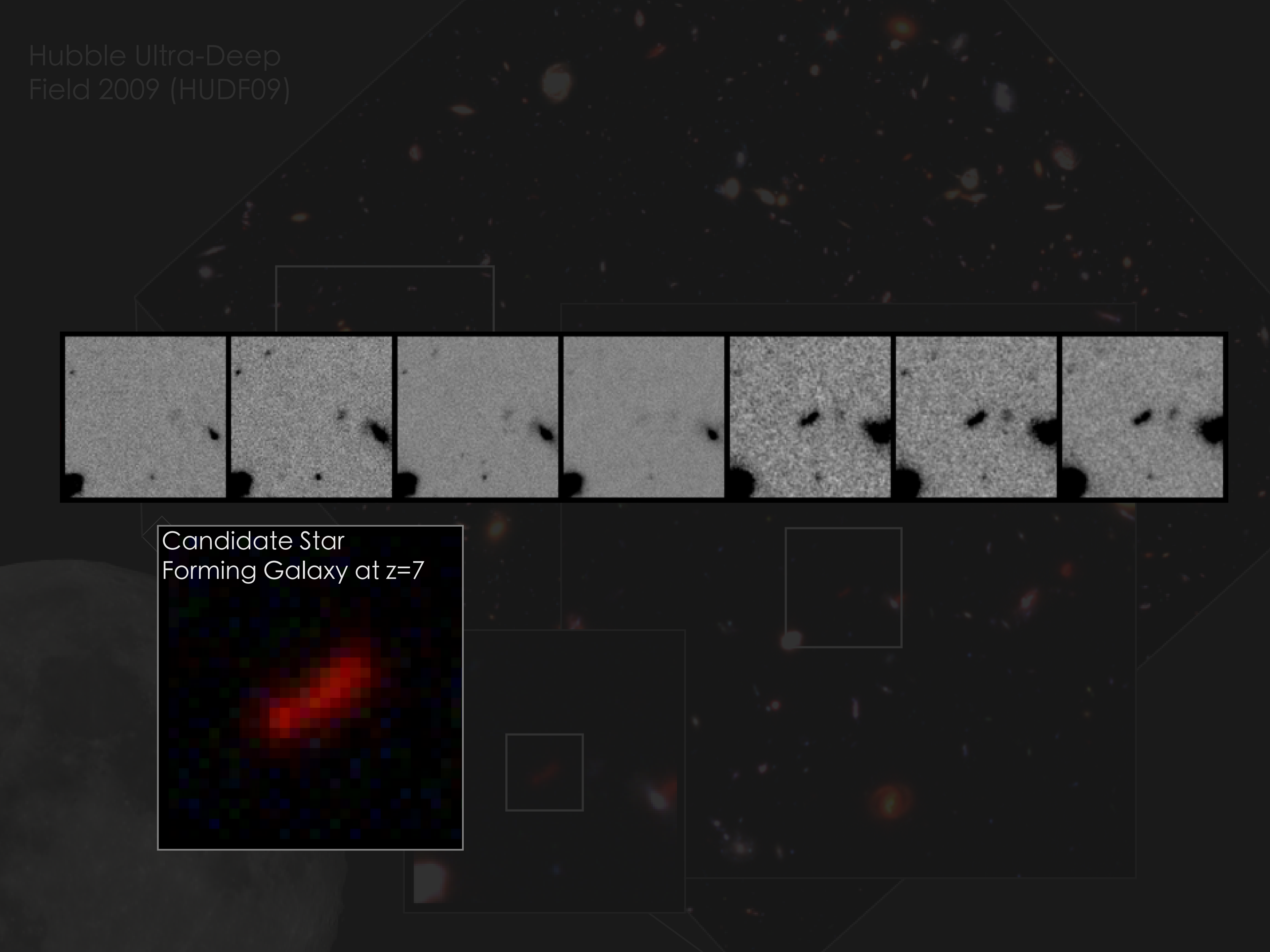
Hubble Ultra-Deep
Field 2009 (HUDF09)



Hubble Ultra-Deep Field 2009 (HUDF09)




Hubble Ultra-Deep
Field 2009 (HUDF09)

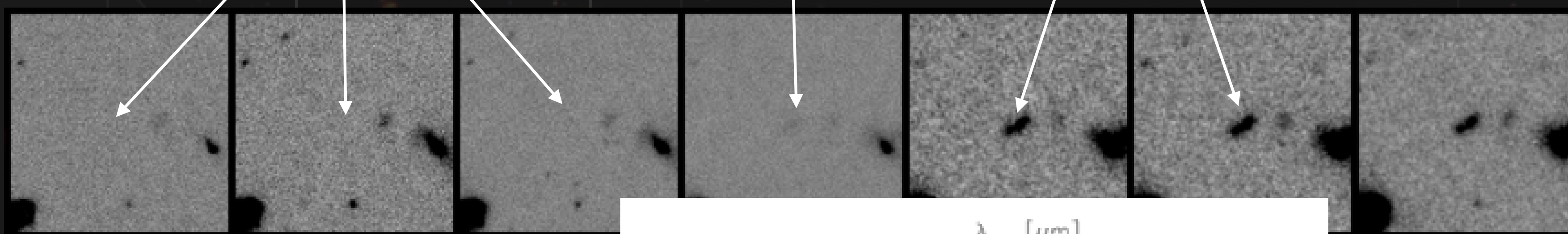

Hubble Ultra-Deep
Field 2009 (HUDF09)
Candidate Star
Forming Galaxy at z=7

Hubble Ultra-Deep Field 2009 (HUDF09)

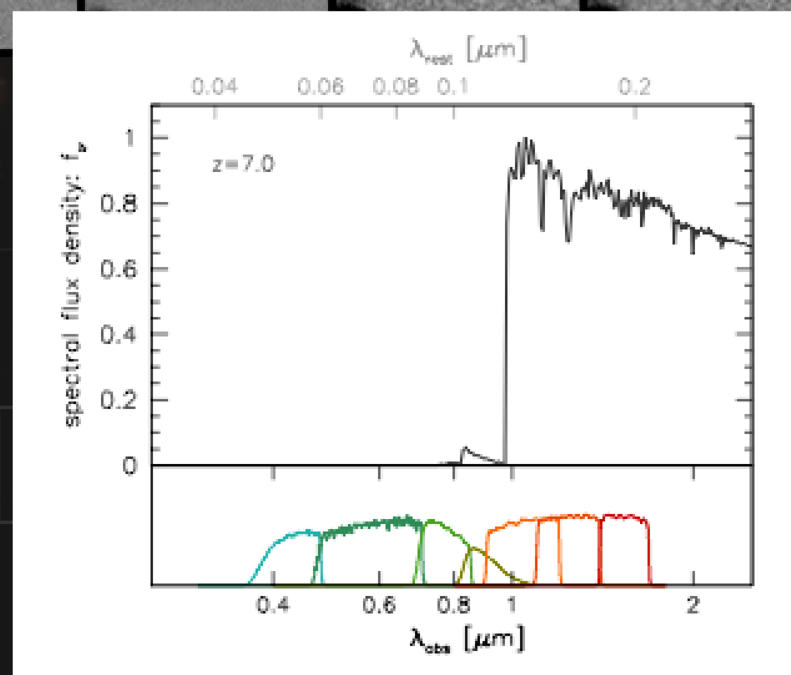
detected at low significance (to be expected)

no detection at 1.5σ

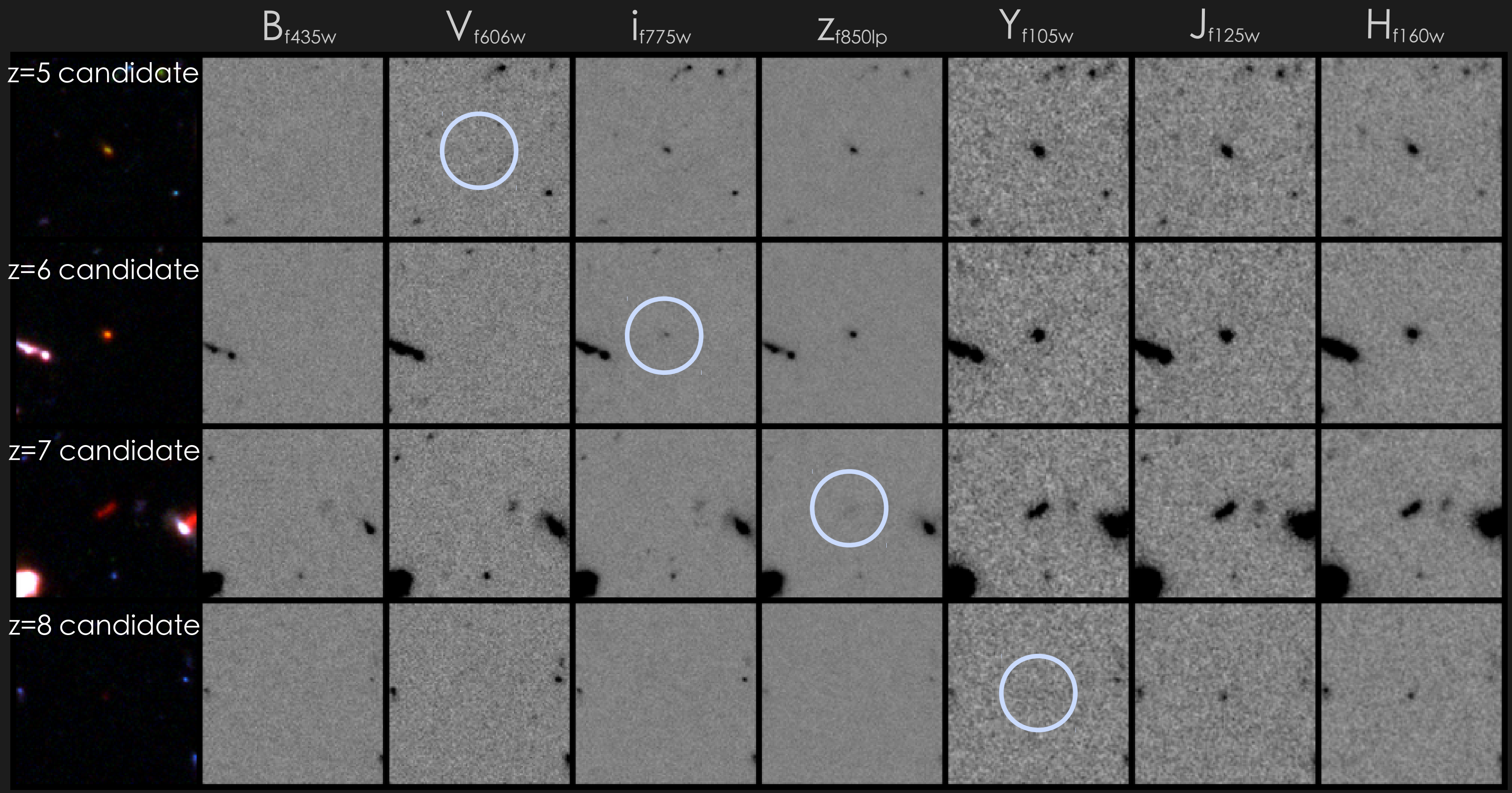
detected at high significance, blue colour

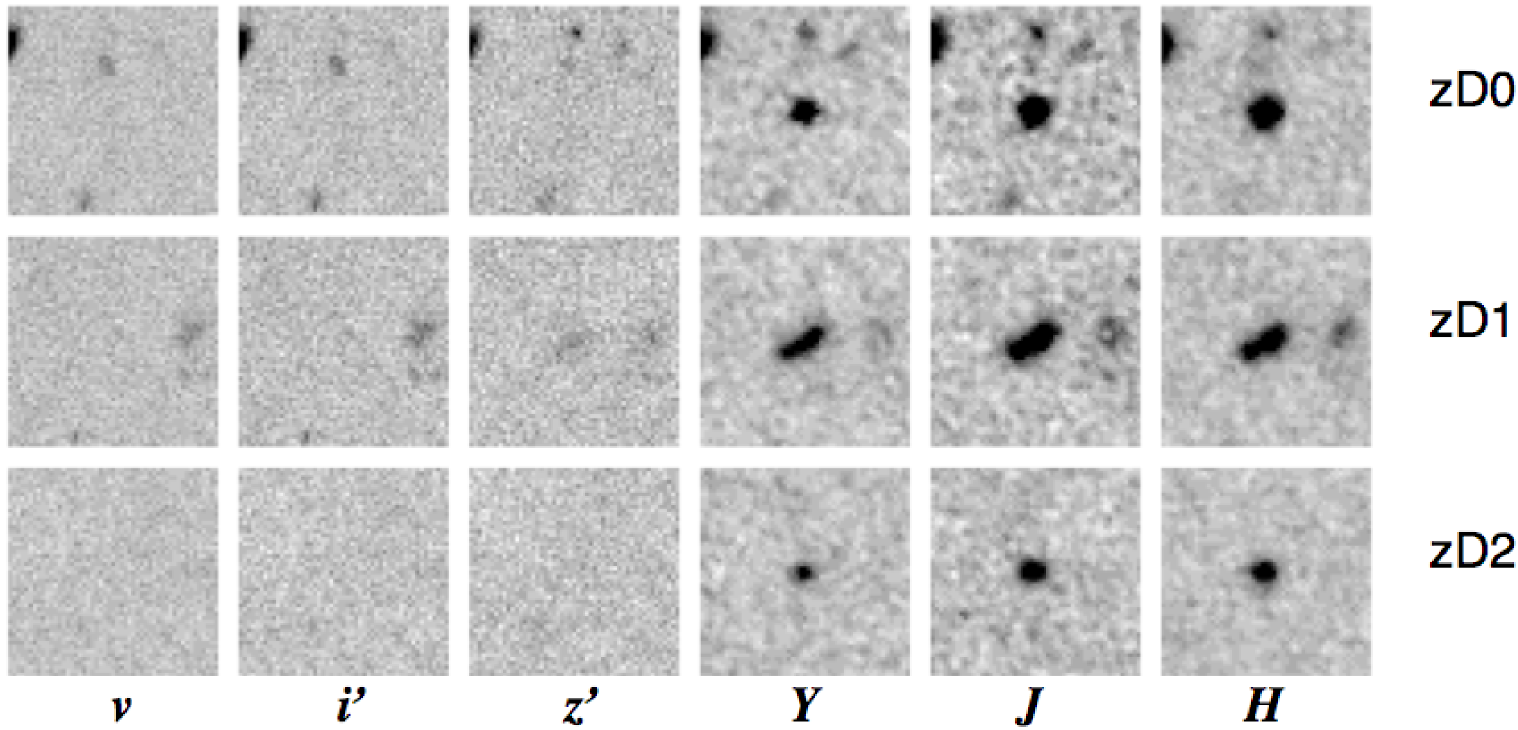


Candidate Star Forming Galaxy at z=7



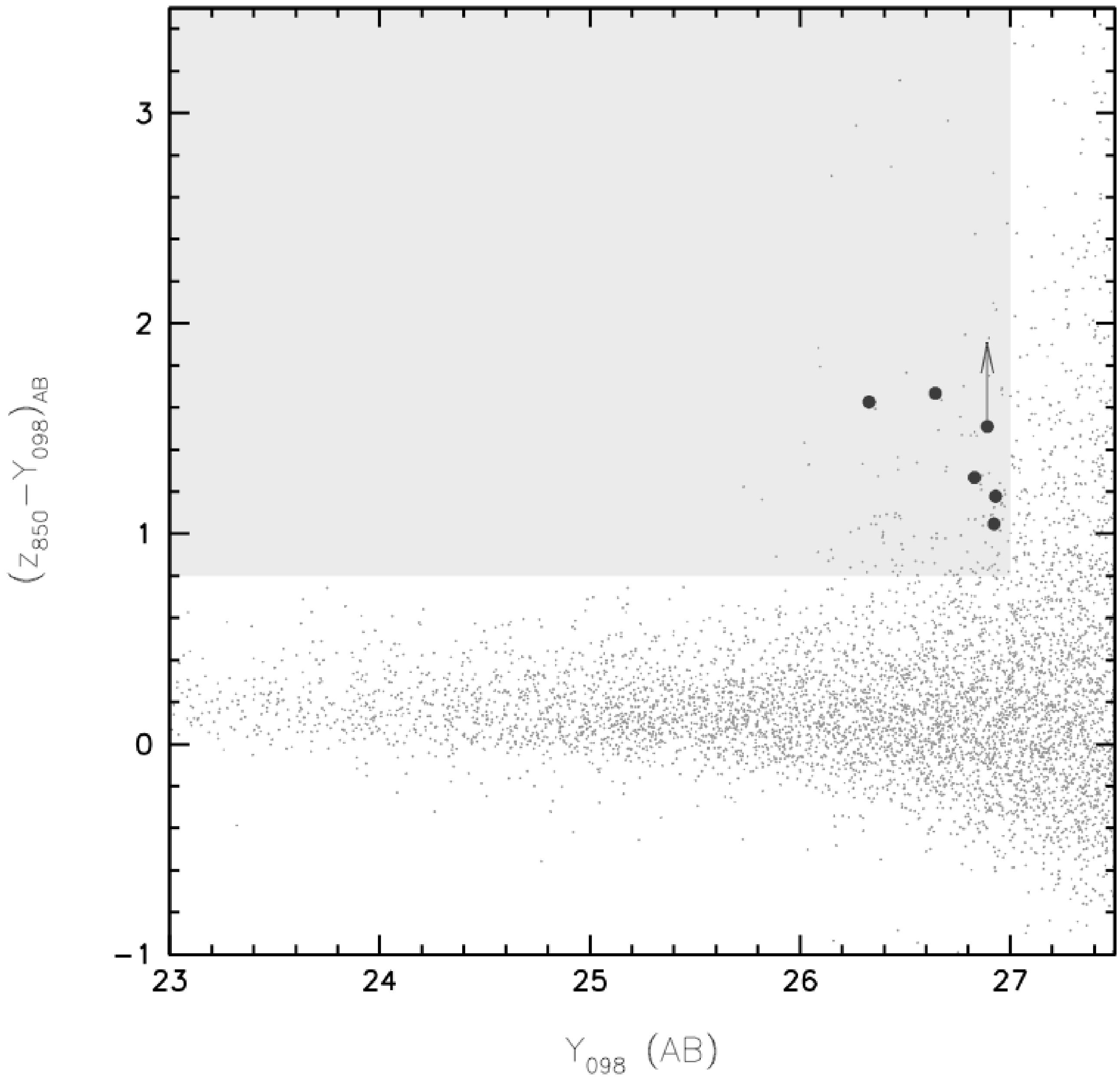
an ensemble of High-redshift Galaxies





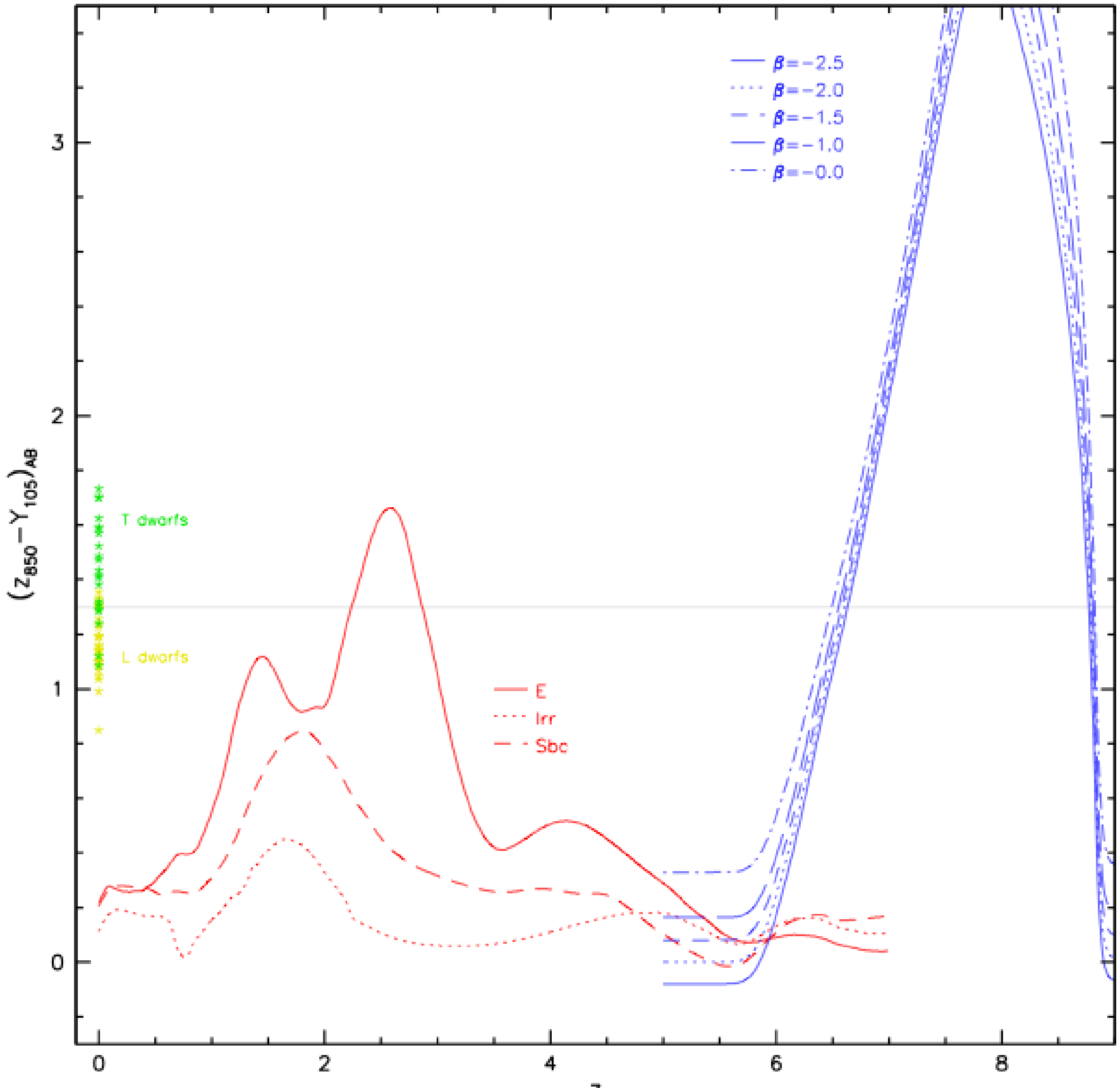
RECENT EXCITEMENT - 100 orbits of HST with WFC3 in 3 near-IR filters on Hubble Ultra Deep Field. Galaxies at z=7-9! Data first taken in August-Sept. 2009

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

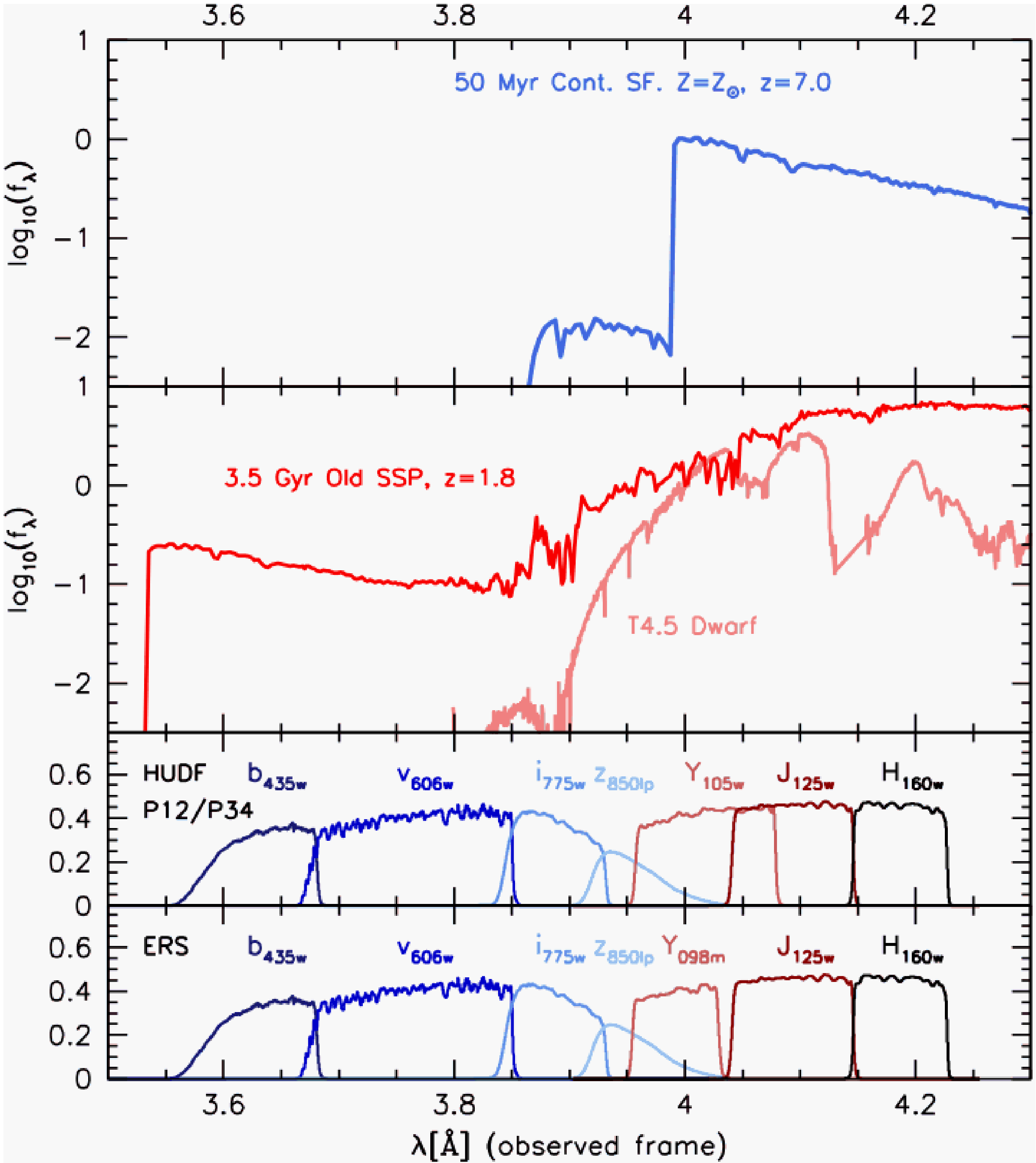


Wilkins et al. (2010): z-drop selection in the

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.



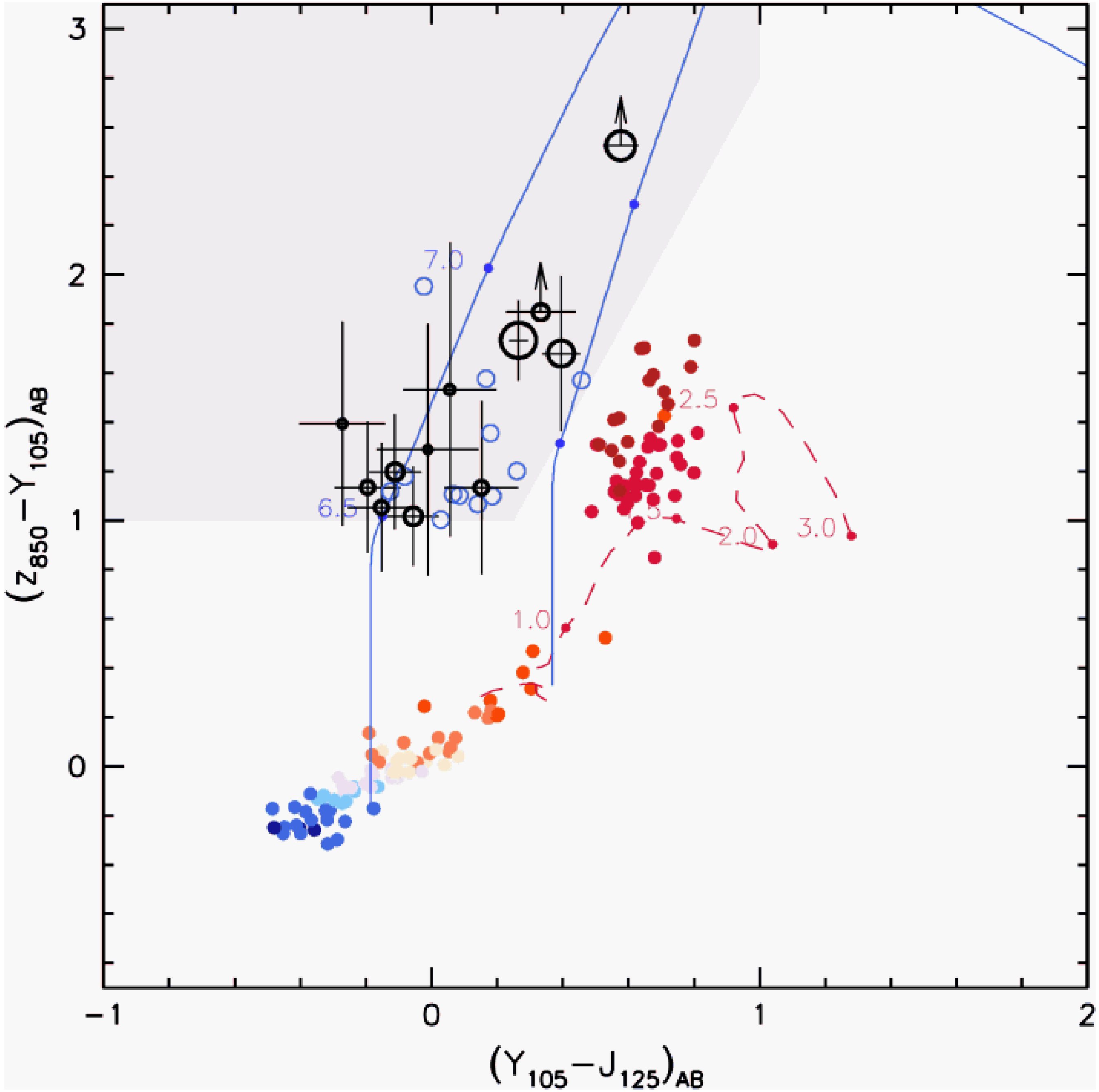
Pushing to z~>7 using WFC3 and z-drop colours (also Y-drops), Bunker et al. (2010)



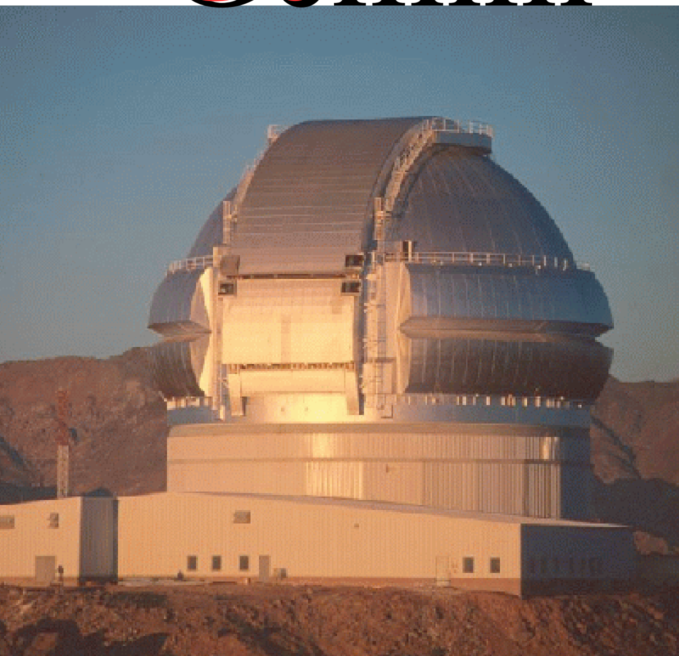
3.6
3.8
4
4.2
50 Myr Cont. SF. Z=Z☉, z=7.0
3.5 Gyr Old SSP, z=1.8
T4.5 Dwarf
log10(fλ)
1
0
−1
−2
HUDF
P12/P34
ERS
b435w
v606w
i775w
z850lp
Y105w
Y098m
J125w
H160w
0.6
0.4
0.2
0
λ[Å] (observed frame)

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



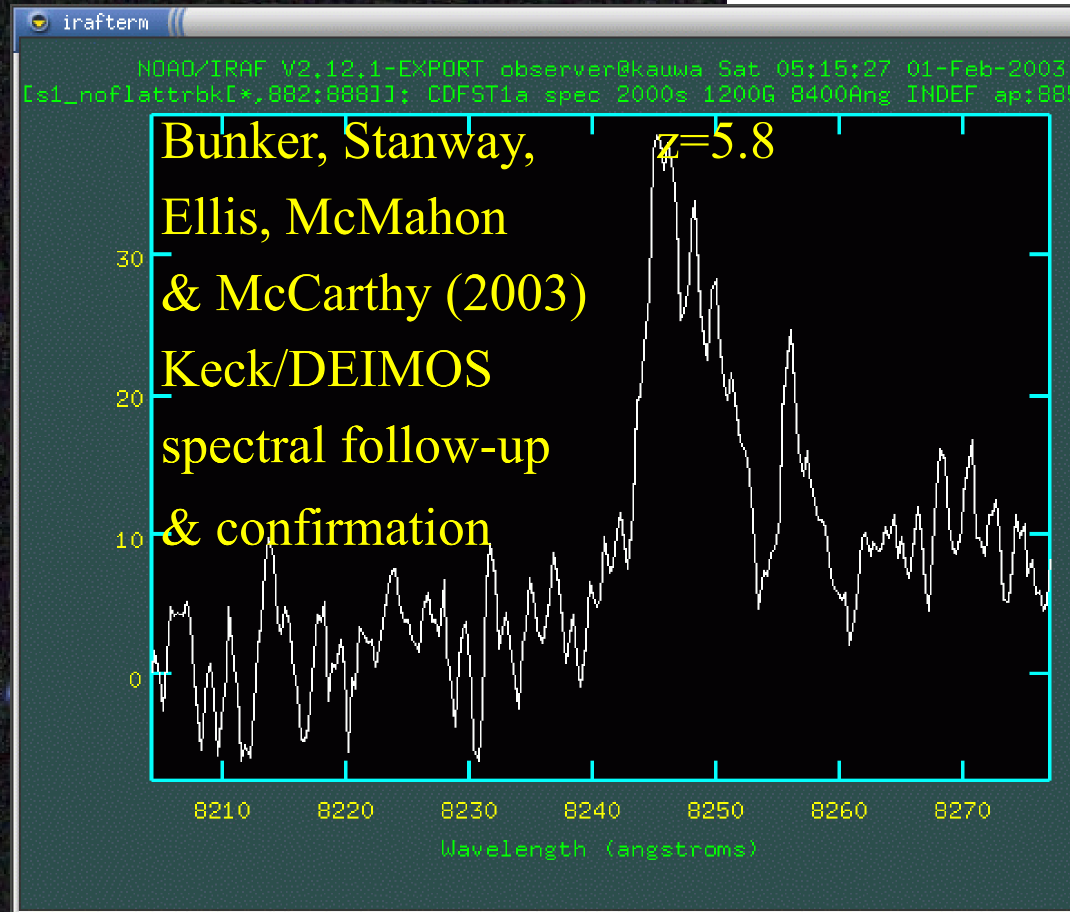
Gemini

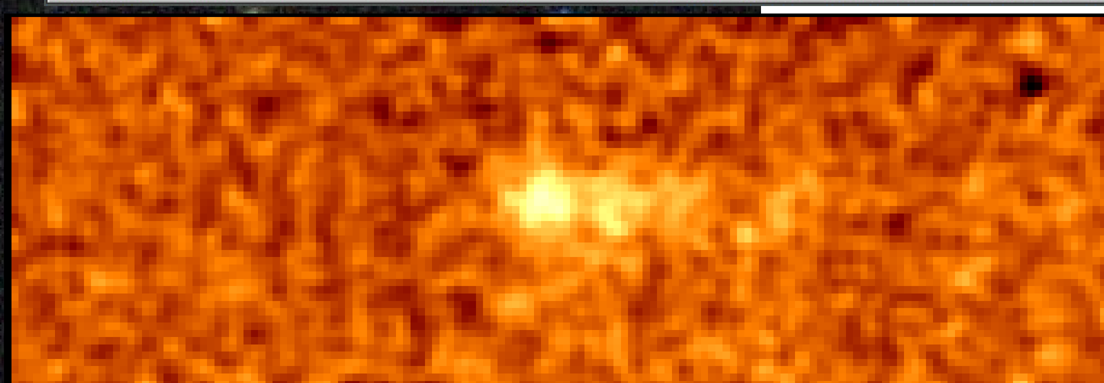


ESO VLTs

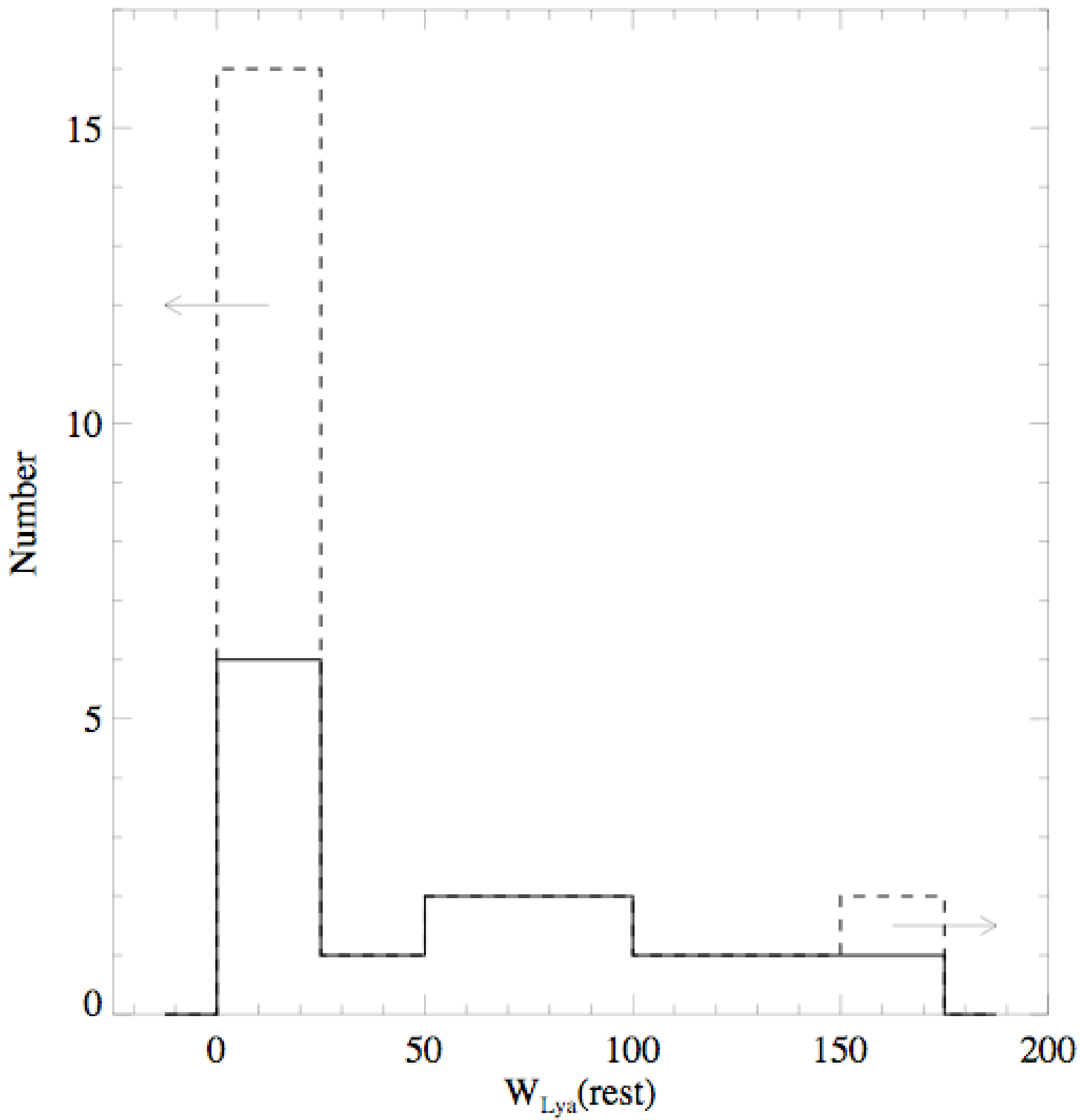
10-m Kecks

The Star Formation History of the Univese



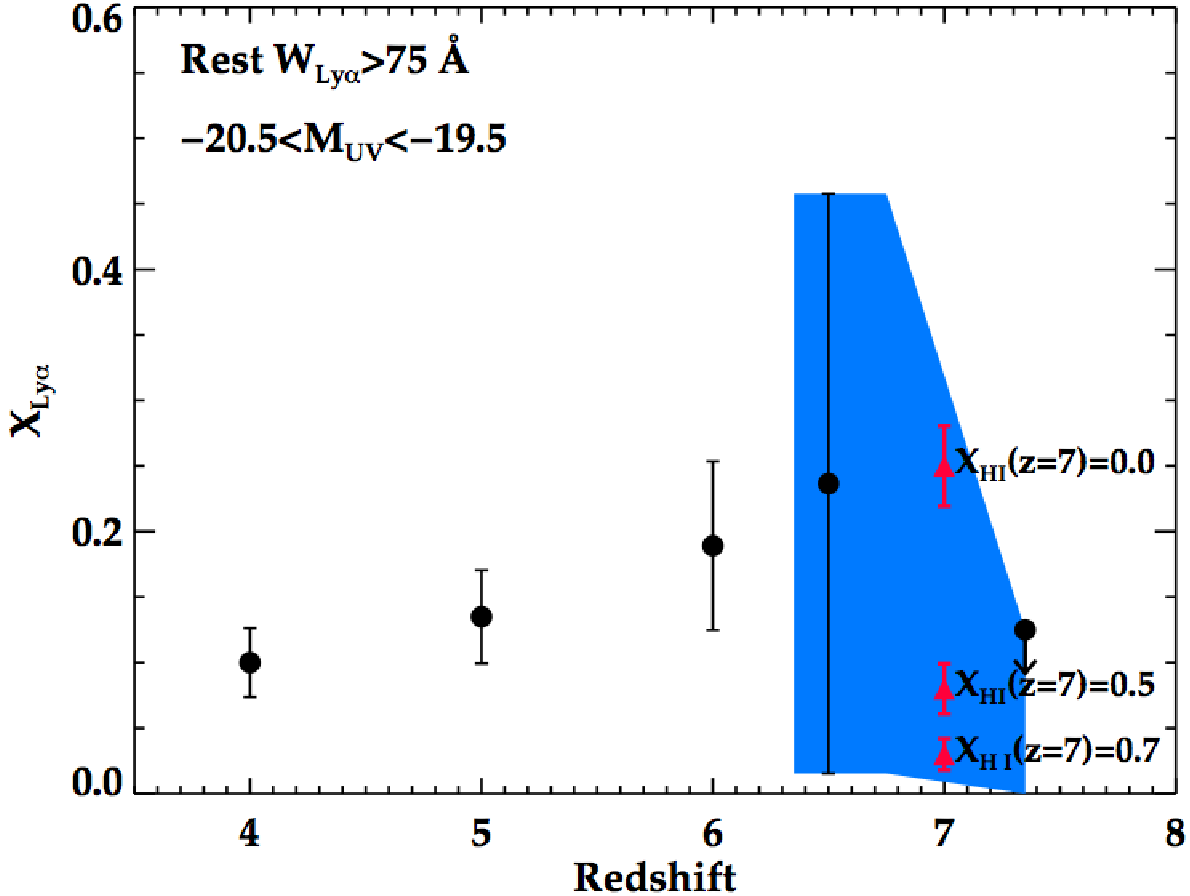


I-drops in the Chandra Deep Field South with HST/ACS Elizabeth Stanway, Andrew Bunker, Richard McMahon 2003 (MNRAS)



15
10
5
0
Number
0
50
100
150
200
W_Lya(rest)

Ly-alpha fraction (Stark et al. 2010)



Brightest HUDF Y-drop

Found in Sept 2009.

YD3 in Bunker et al

UDFy-31835539 in

Bouwens et al.;

#1721 in McLure et al.

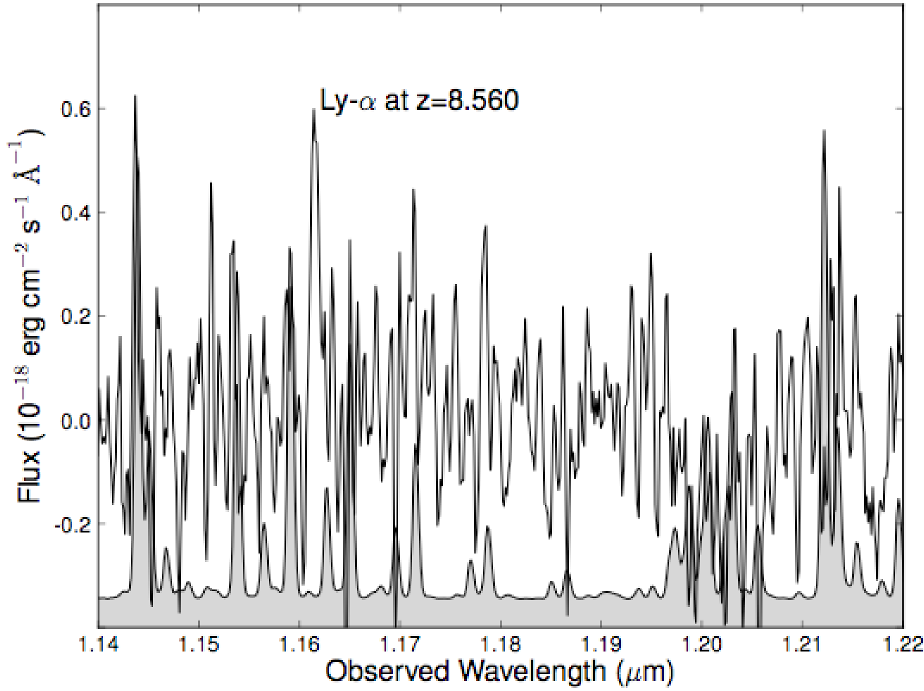
In late 2009, Nature paper

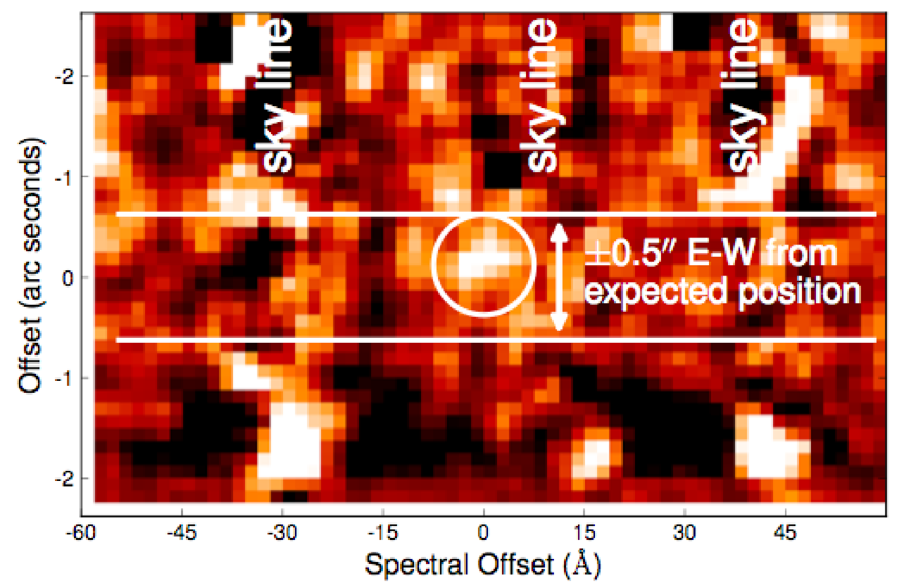
Lehnert et al. claiming

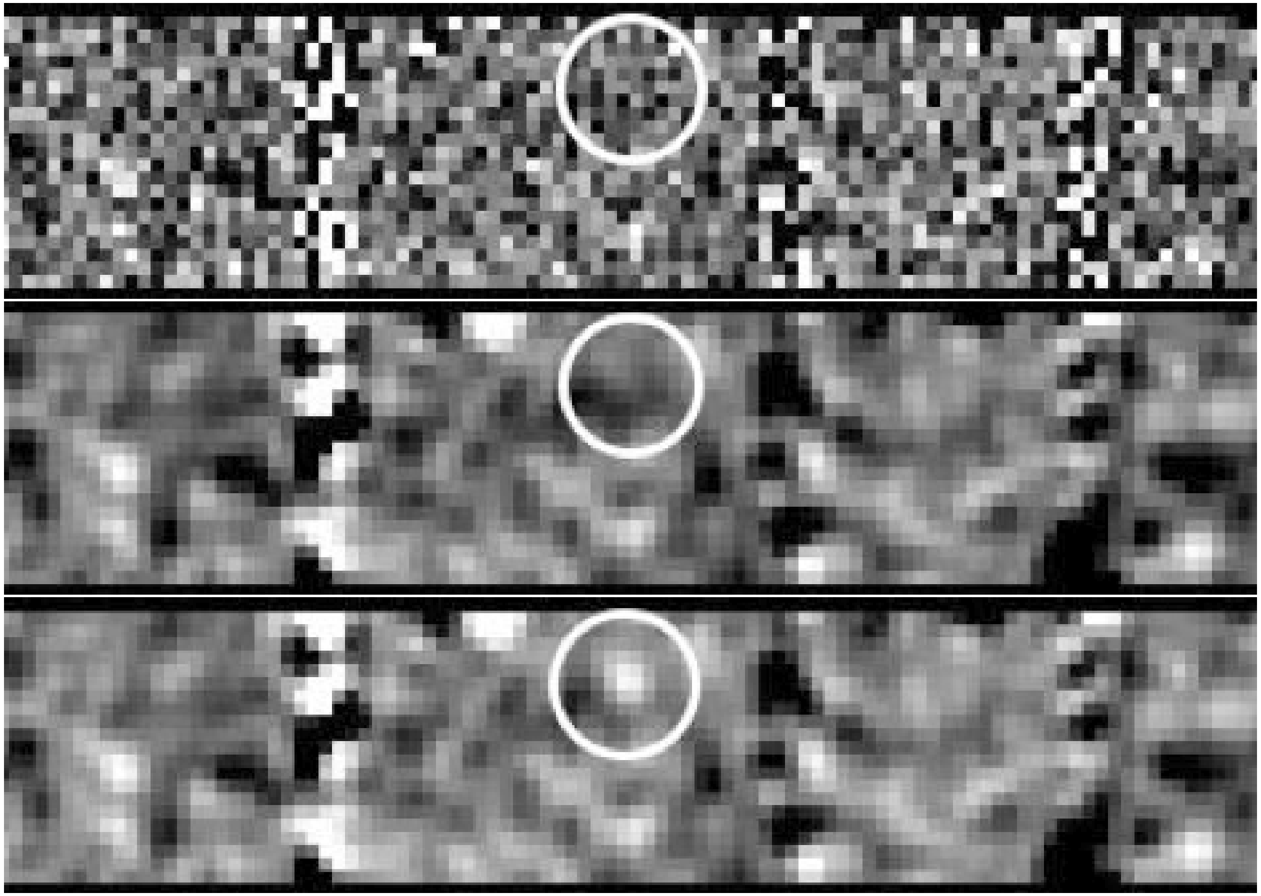
spectroscopic confirmation

of Ly-alpha at z=8.55

with SINFONI-IFU on VLT

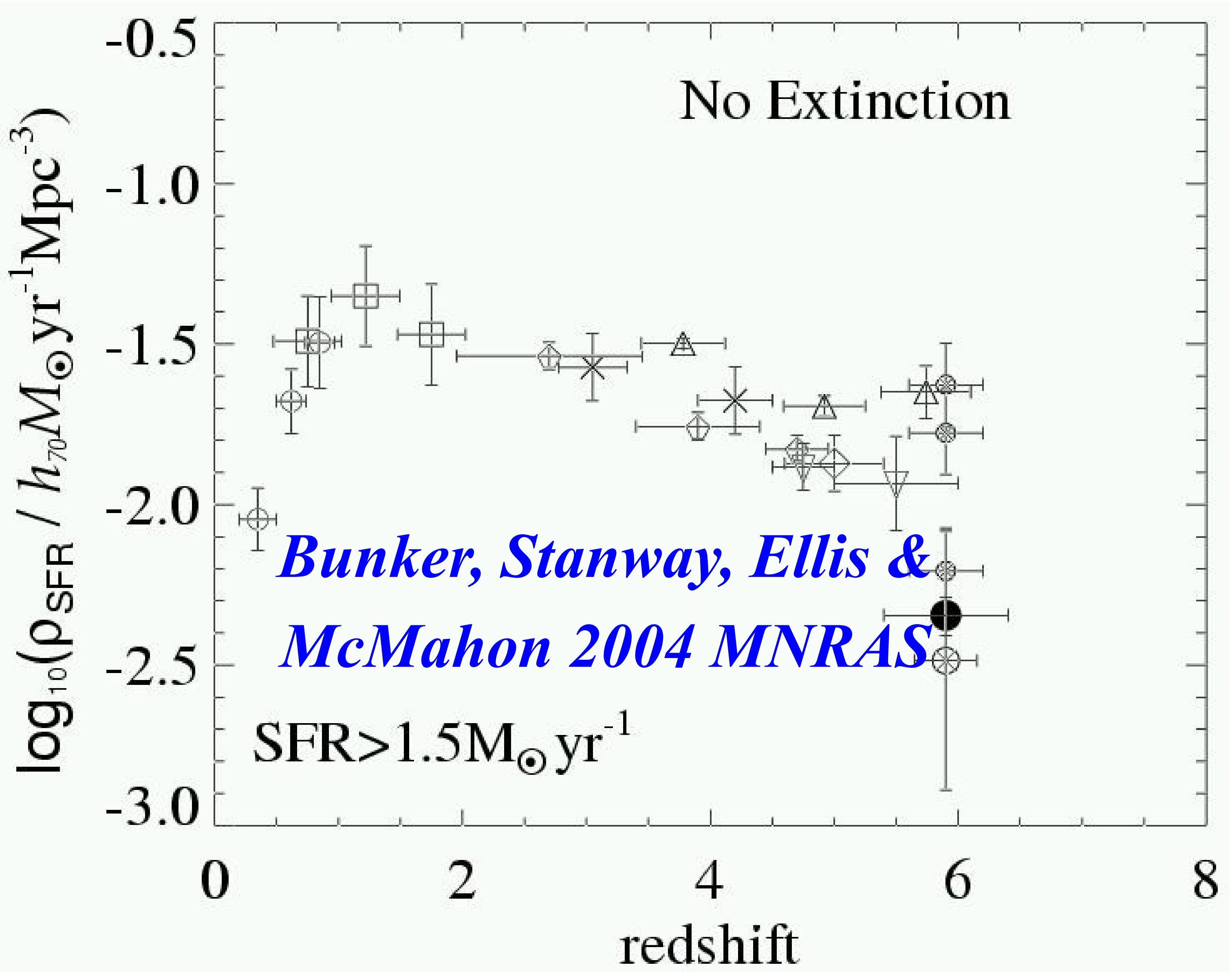


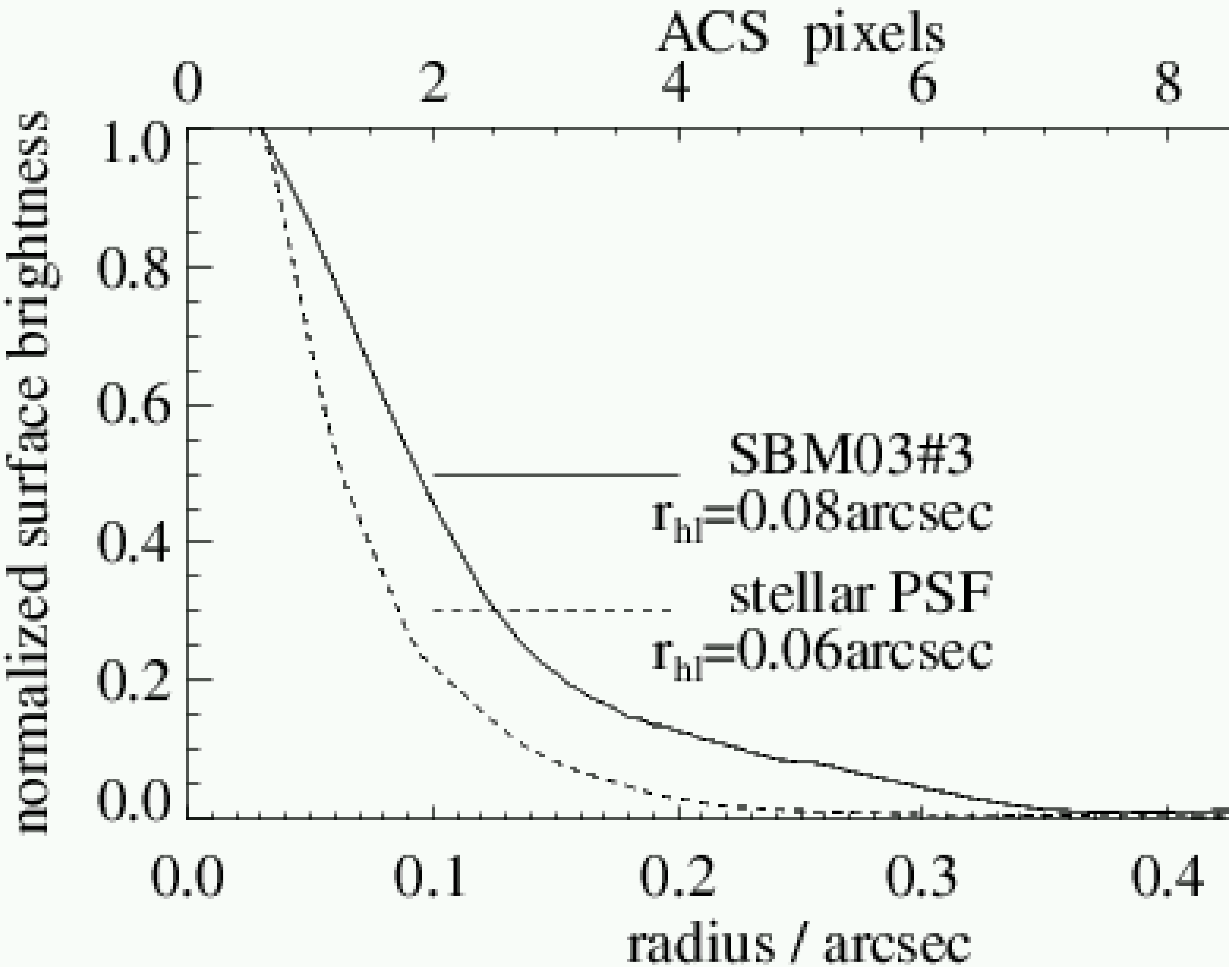




No evidence of Ly-alpha at z=8.55 in 5-hour VLT/XSHOOTER
And 11-hour Subaru/MOIRCS spectrum.
Also, the deep HST/WFC3 Y-band encompasses Ly-alpha, should be detected at ~4sigma but is undetected

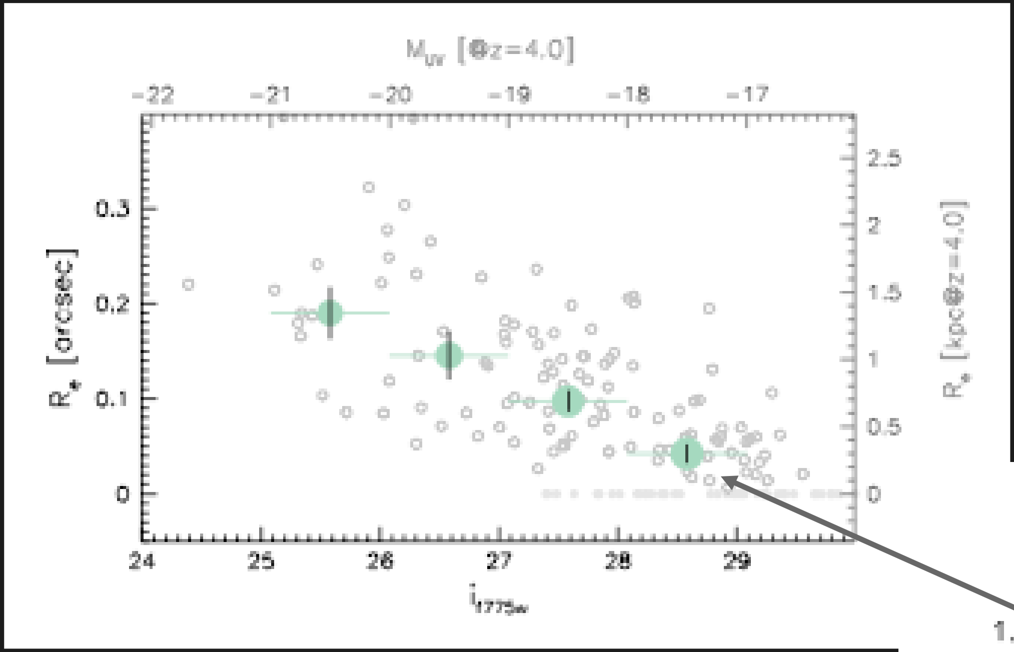
Looking at the UDF (going 10x deeper, z'=26→28.5 mag)





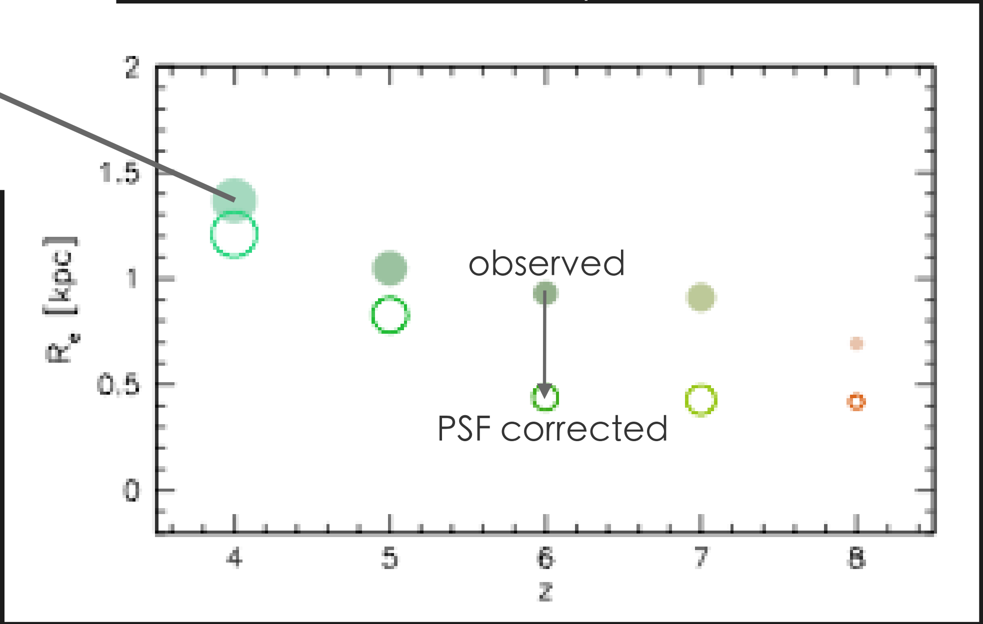
ACS pixels
0
2
4
6
8
normalized surface brightness
1.0
0.8
0.6
0.4
0.2
0.0
SBM03#3
r_hl=0.08arcsec
stellar PSF
r_hl=0.06arcsec
0.0
0.1
0.2
0.3
0.4
radius / arcsec

What Can we Learn about High-redshift Galaxies: Morphologies



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

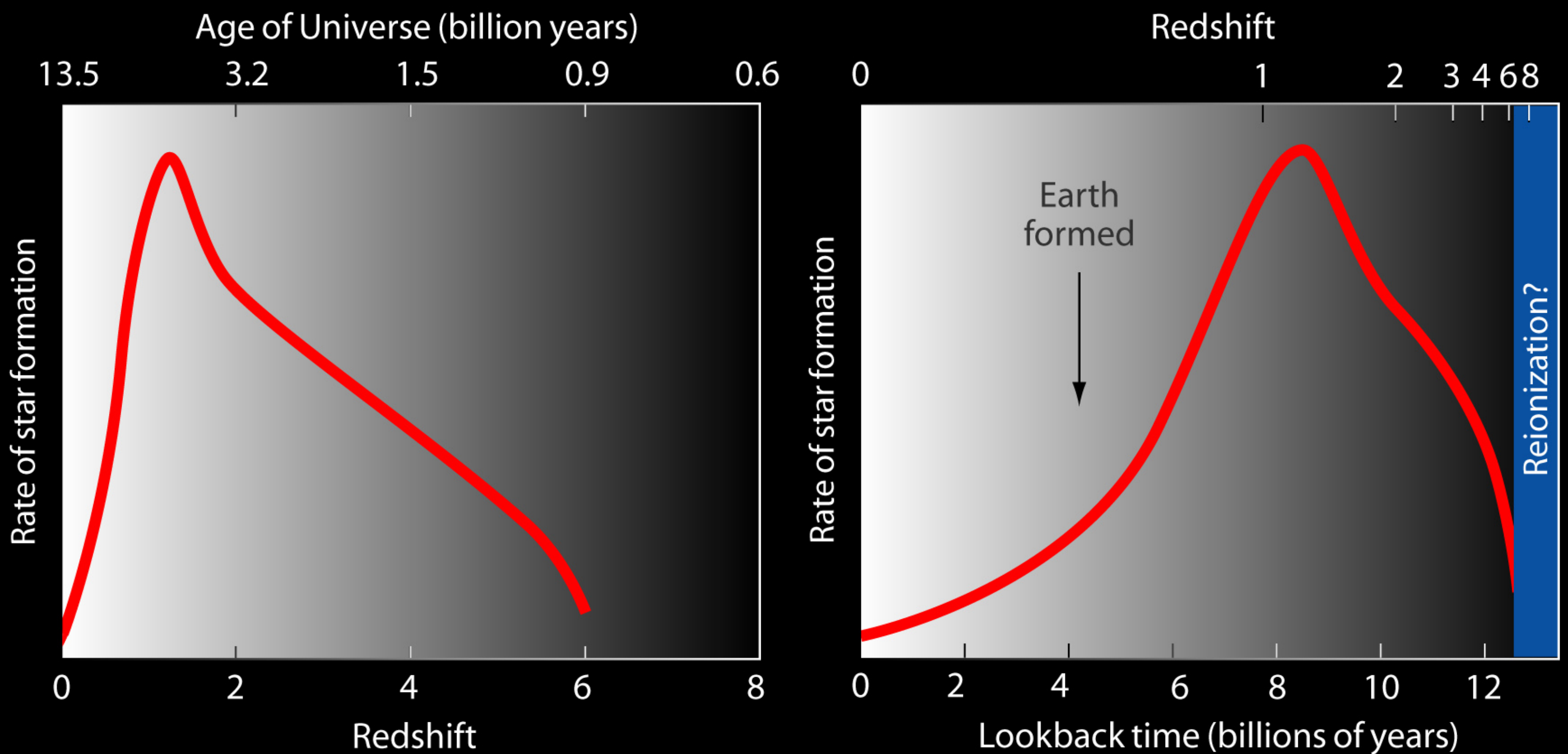
size evolution (only HUDF field)



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.

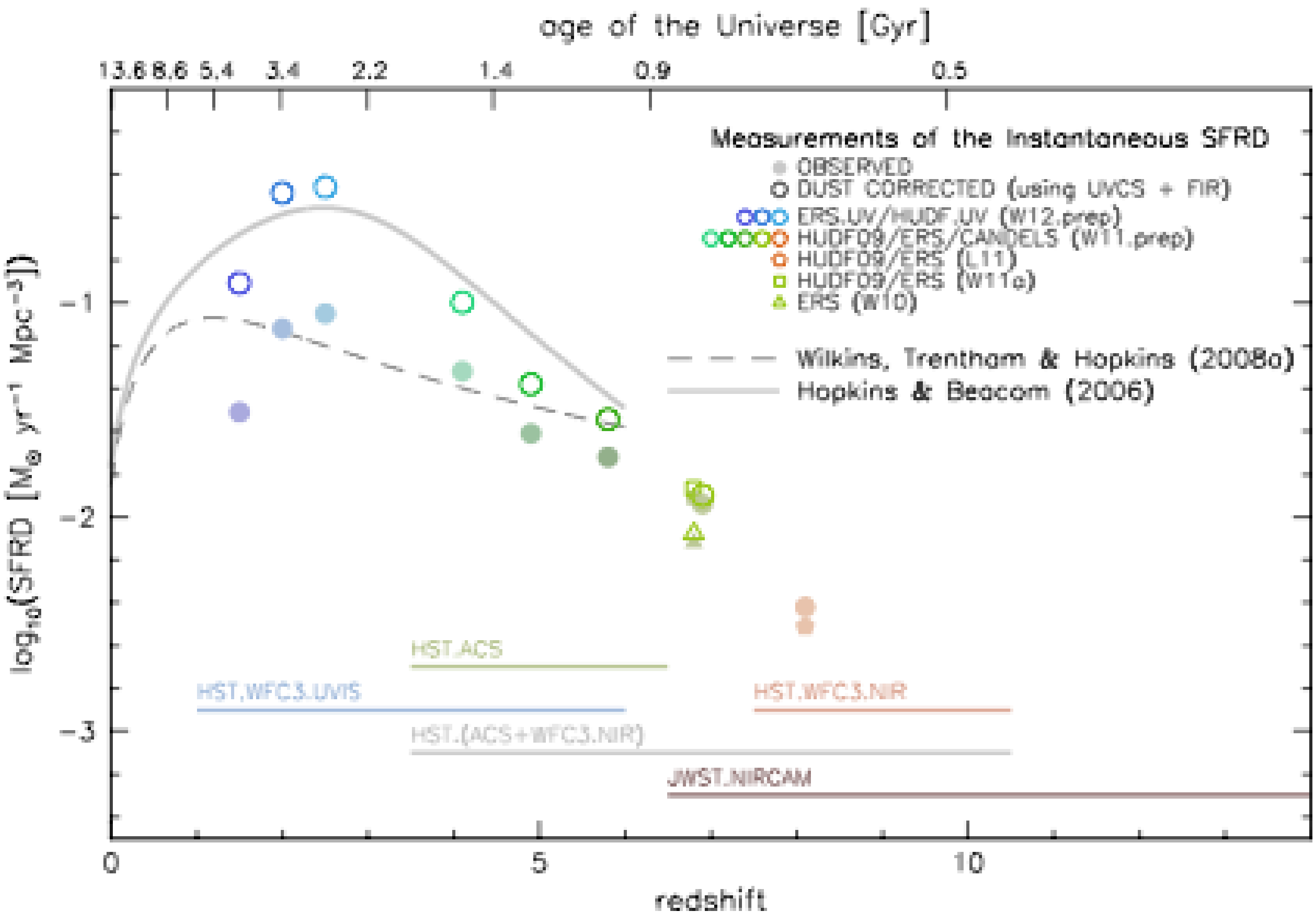
Star formation history of the Universe



- ***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



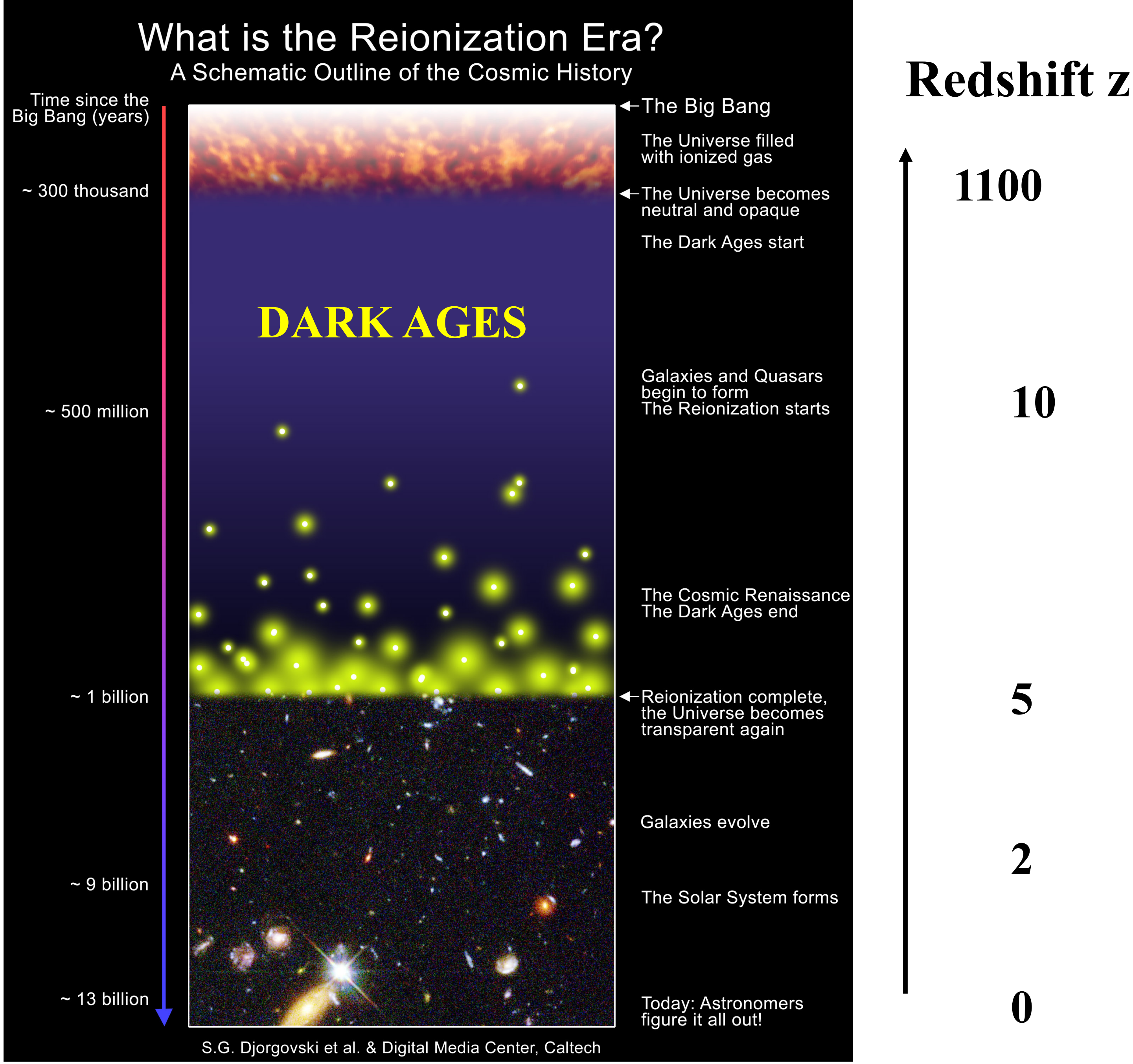
The (mostly) UV inferred Cosmic Star Formation History

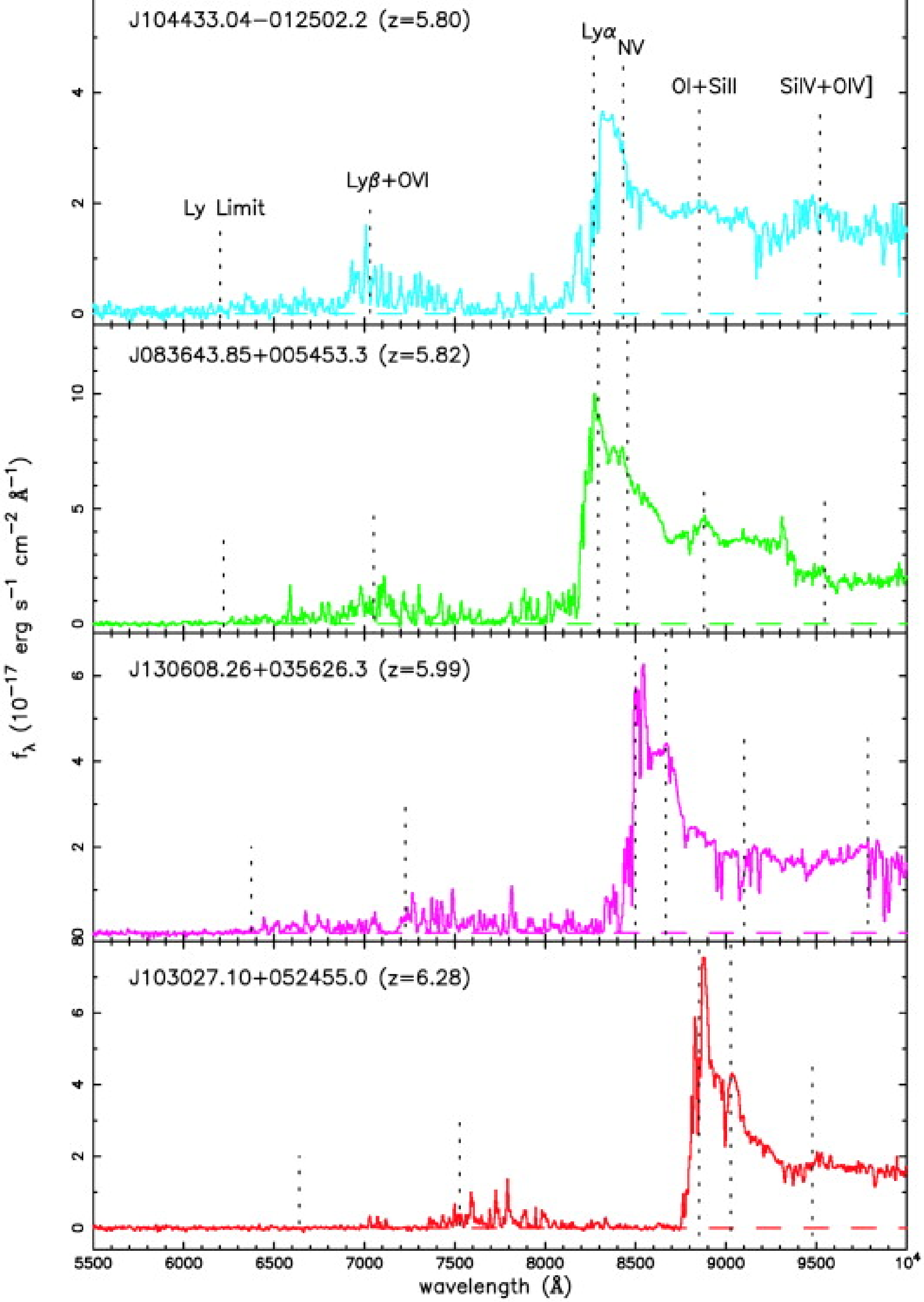
After era probed by WMAP the Universe enters the so-called “dark ages” prior to formation of first stars

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

When did this happen?

What did it?





Reionization

At high redshift, the Lyman-α forest can absorb most of the flux below λ_{rest}=1216Å. Indications from z>6.3 SDSS QSOs that Universe many be optically thick (Fan et al. 2001; Becker et al. 2001). BUT confusing messaged from WMAP CMB - reionization at z~11? (Dunkley et al. 2010).

Implications for Reionization

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

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).

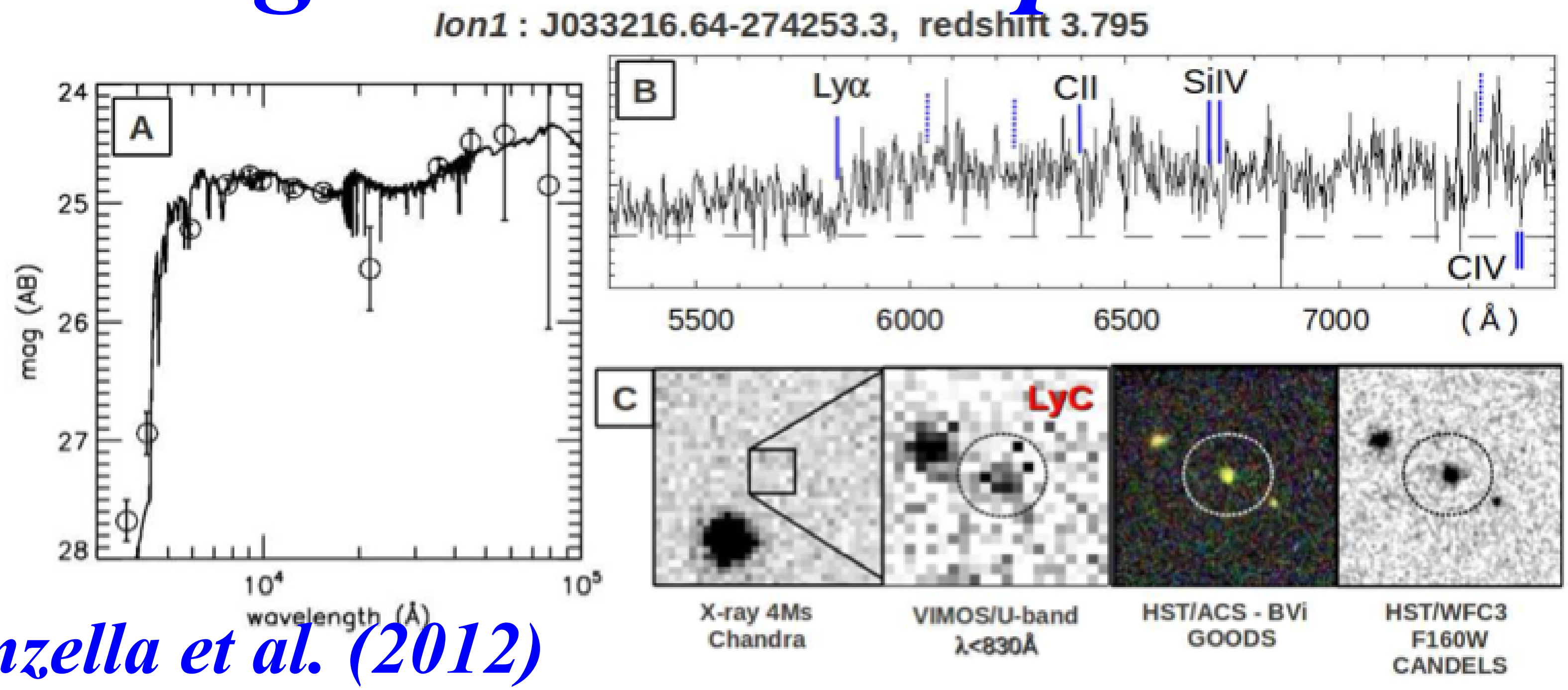
This assumes escape fraction=1 (i.e. all ionzing photons make it out of the galaxies). Observationally, this is only a few percent locally, and essentially unconstrained at high-z (with some claimed limits of f_{esc} ~0.1)

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_{esc}>0.5 (see also Stiavelli, Fall & Panagia 2005)

We go down to 1M_sun/yr - but might be steep α (lots of low luminosity sources - forming globular clusters?)

Ionizing Photon Escape Fraction



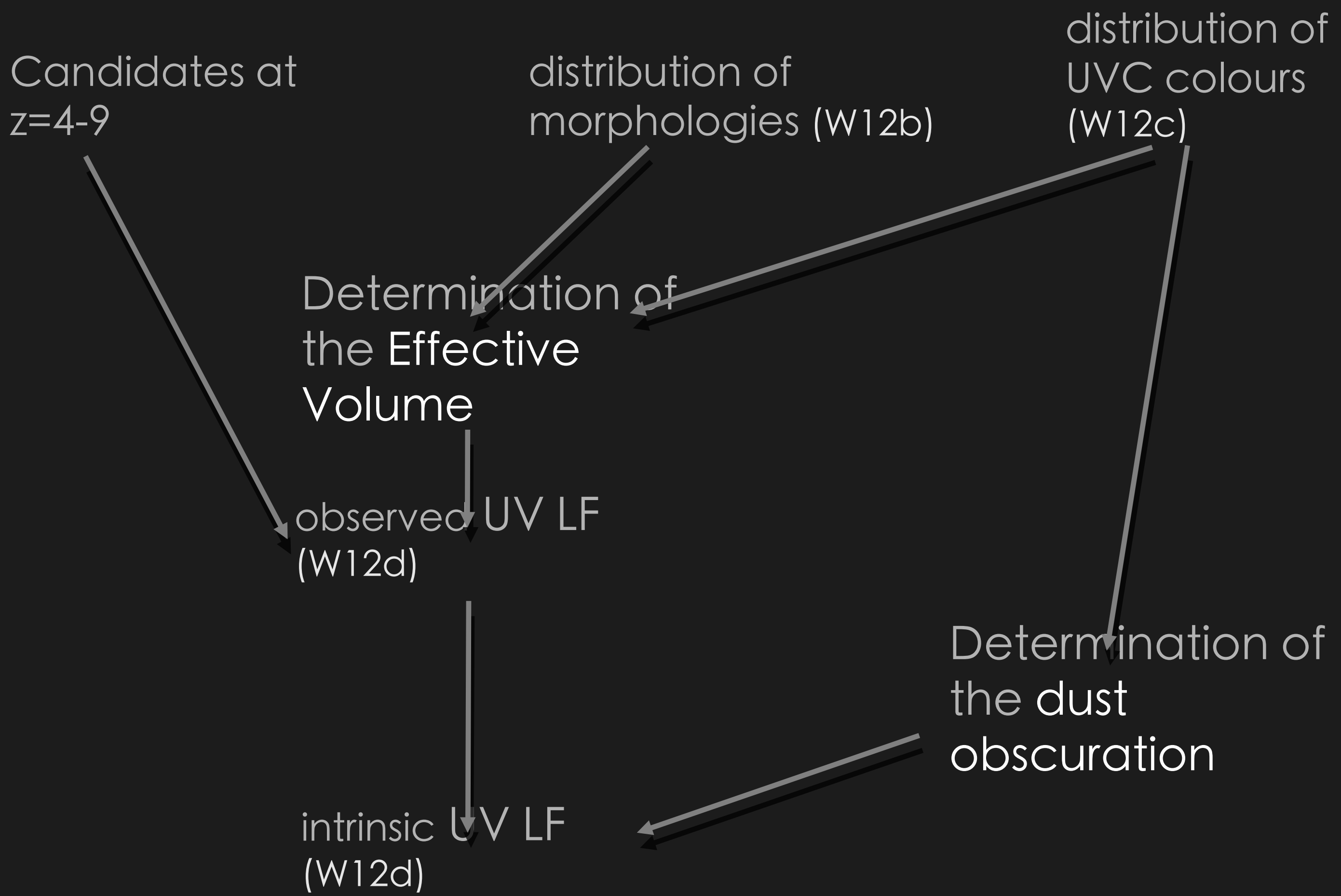
Vanzella et al. (2012)

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

Indications are at z~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)

What Can we Learn about High-redshift Galaxies:

observed UV Luminosity Function ➟ intrinsic UV Luminosity function



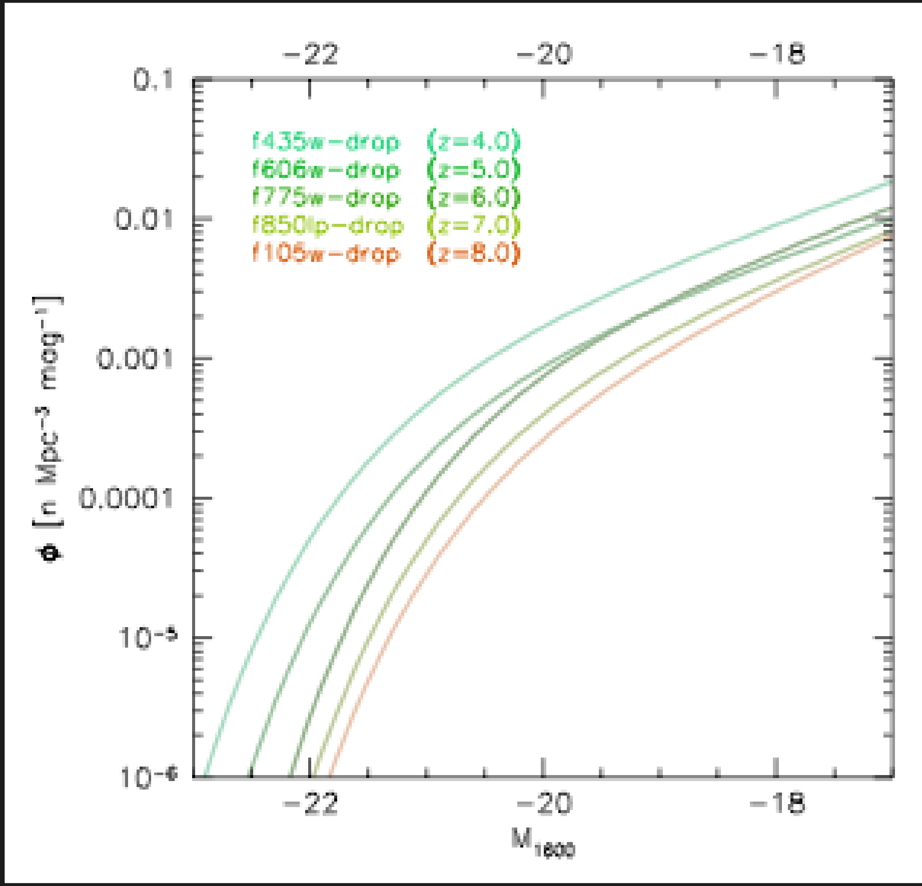
What Can we Learn about High-redshift Galaxies:

observed UV Luminosity Function

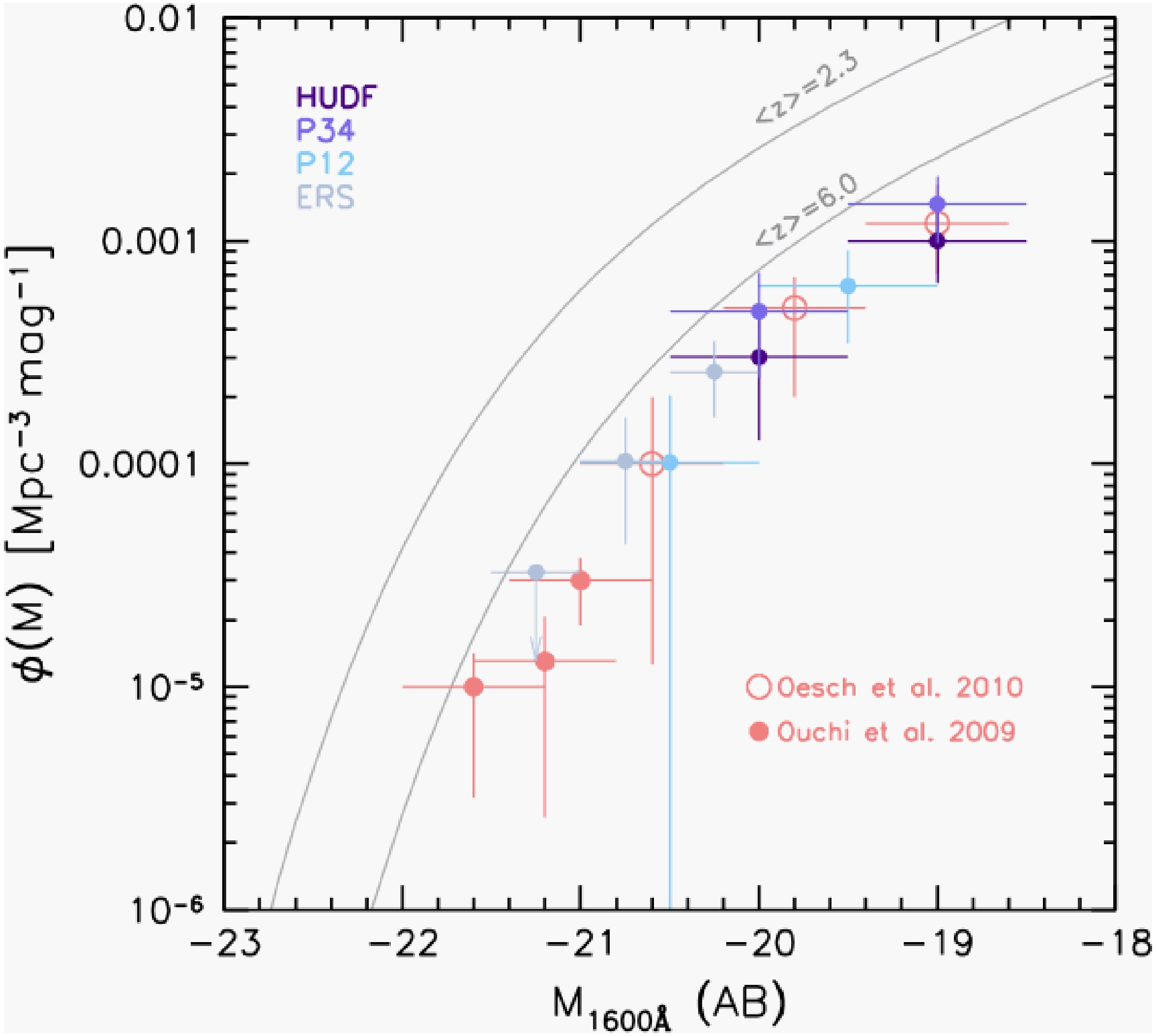
The accurate determination of the UV LF requires careful modelling of the various biases that may affect the ability to identify galaxies. These include the apparent magnitude (fainter galaxies are more difficult to select), the intrinsic colour (we are biased against red galaxies), and morphology (biased against extended galaxies).

The LF evolves!

Evolution of the UV LF:
Wilkins+11a, Wilkins+12d
see also: Bouwens+11(6,7,8,9,10), Oesch+10b

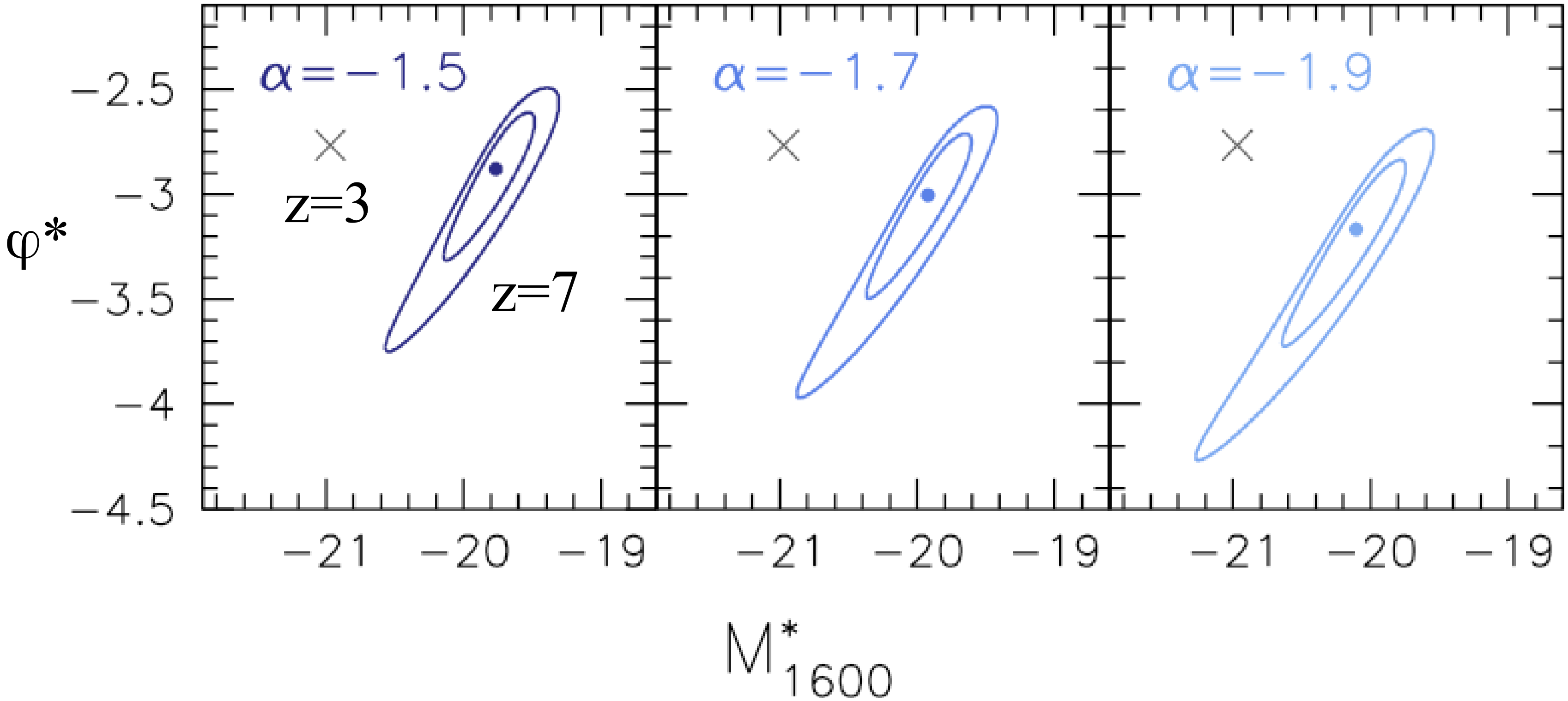


Observed UV LFs at various redshifts



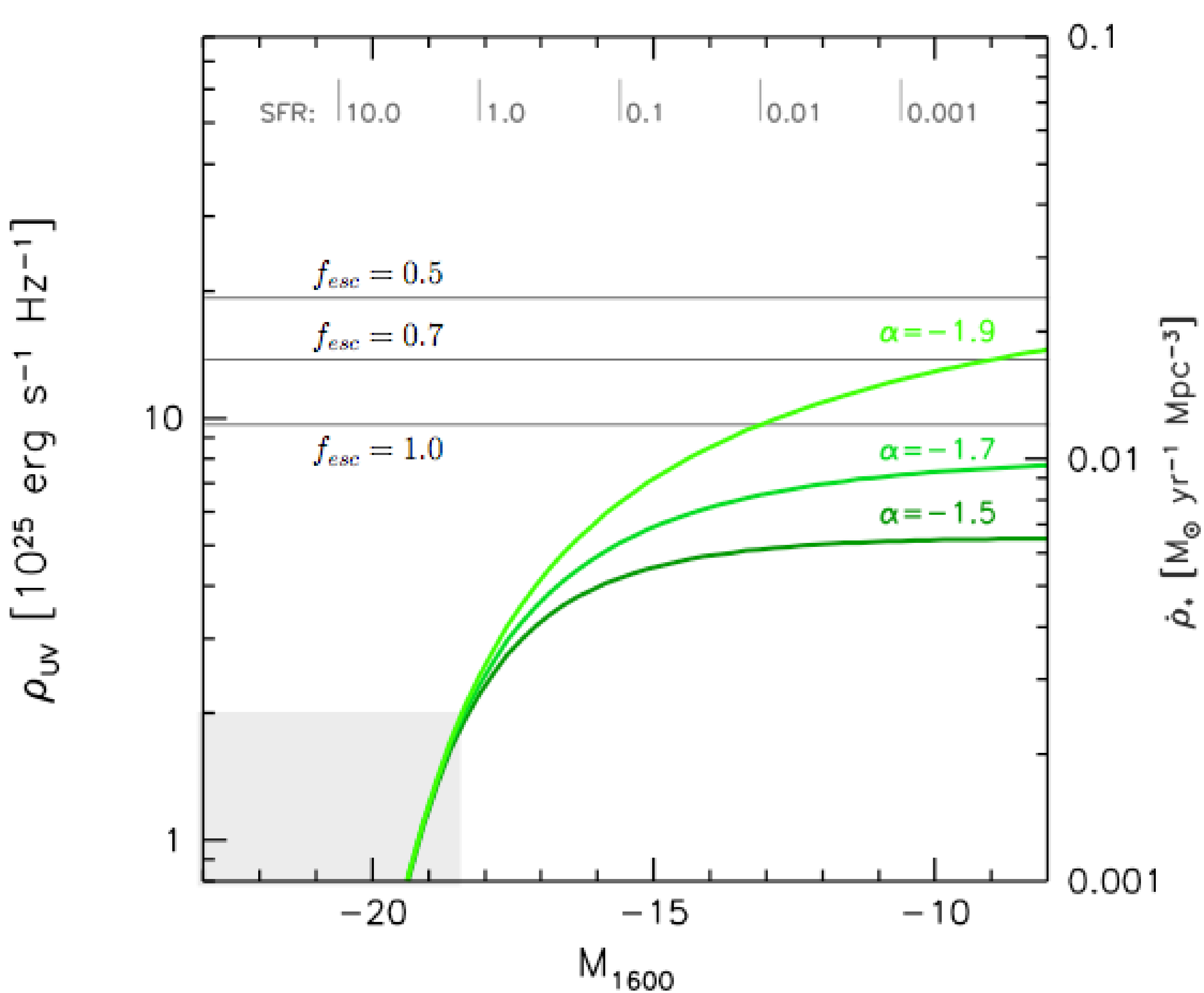
Wilkins et al. (2010) MNRAS The Luminosity Function at z~7

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



Evolution of luminosity function
(note M* is correlated with φ*)

Wilkins et al. (2011)



Wilkins et al. (2010)

Ways out of the Puzzle

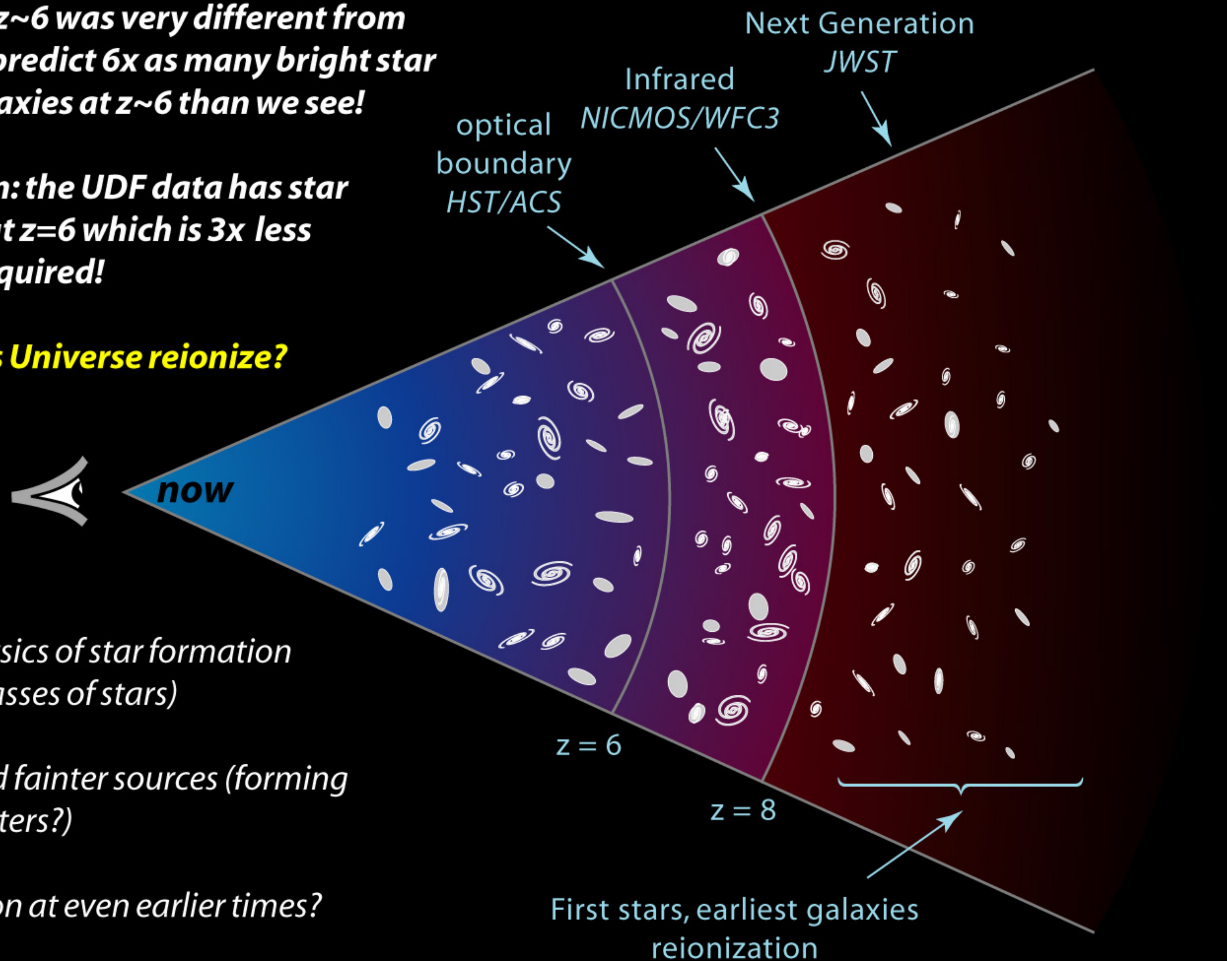
- Cosmic variance
- Star formation at even earlier epochs to reionize Universe (z>>6)?
- Change the physics: different recipe for star formation (Initial mass function)?
- Even fainter galaxies than we can reach with the UDF?

Probing the dark ages

reionization and distant galaxies

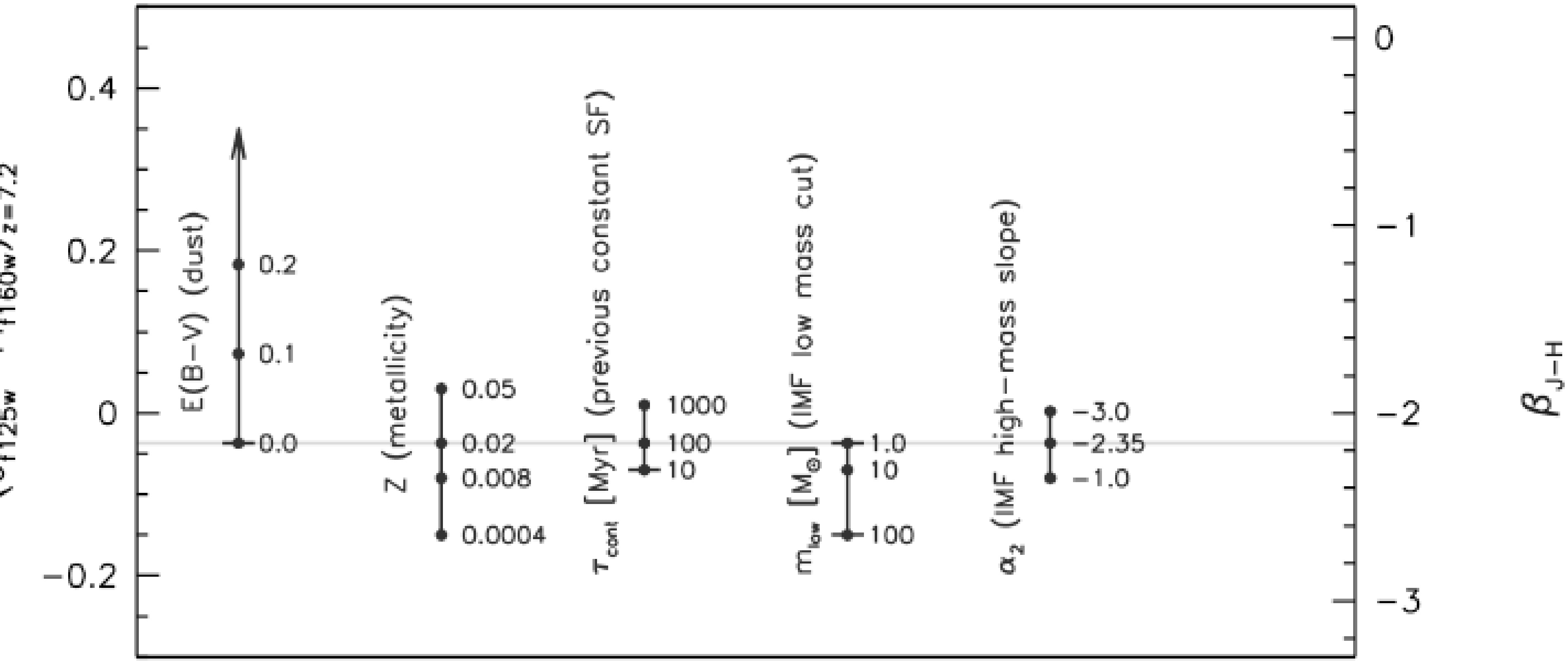
- ***Universe at z~6 was very different from z~3: would predict 6x as many bright star forming galaxies at z~6 than we see!***
- ***Reionization: the UDF data has star formation at z=6 which is 3x less than that required!***

So how does Universe reionize?



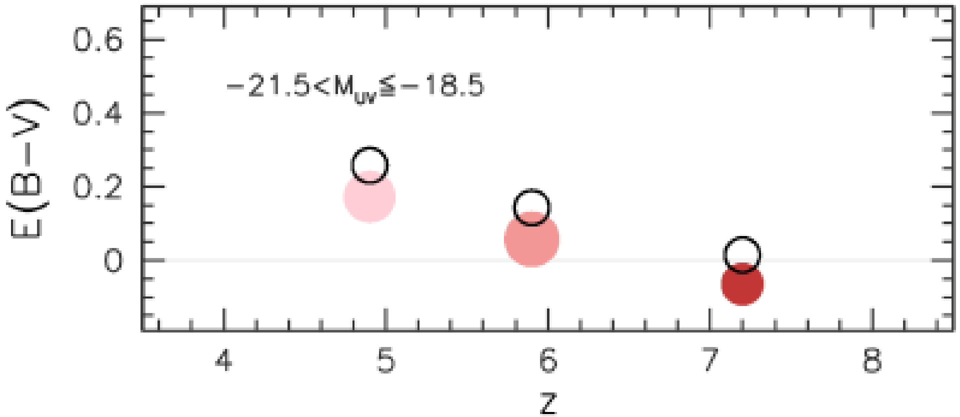
- *Different physics of star formation early on? (masses of stars)*
- *Undiscovered fainter sources (forming globular clusters?)*
- *Star formation at even earlier times?*

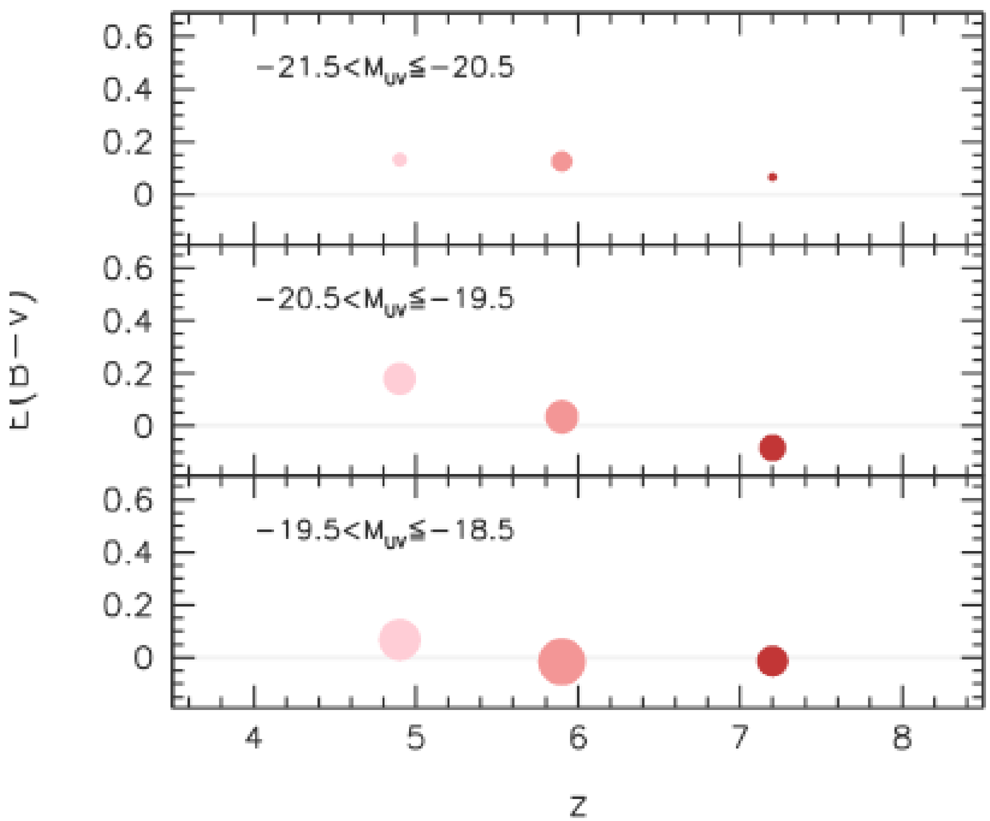
UV Spectral Slopes at z>6 : $f_\lambda \propto \lambda^{-\beta}$



Stanway, McMahon & Bunker (2005) - found very blue colours for i-drops in NICMOS UDF

Also now seen in z-drops with WFC3 (Bouwens et al. 2011, Dunlop et al. 2011, Wilkins et al. 2011)



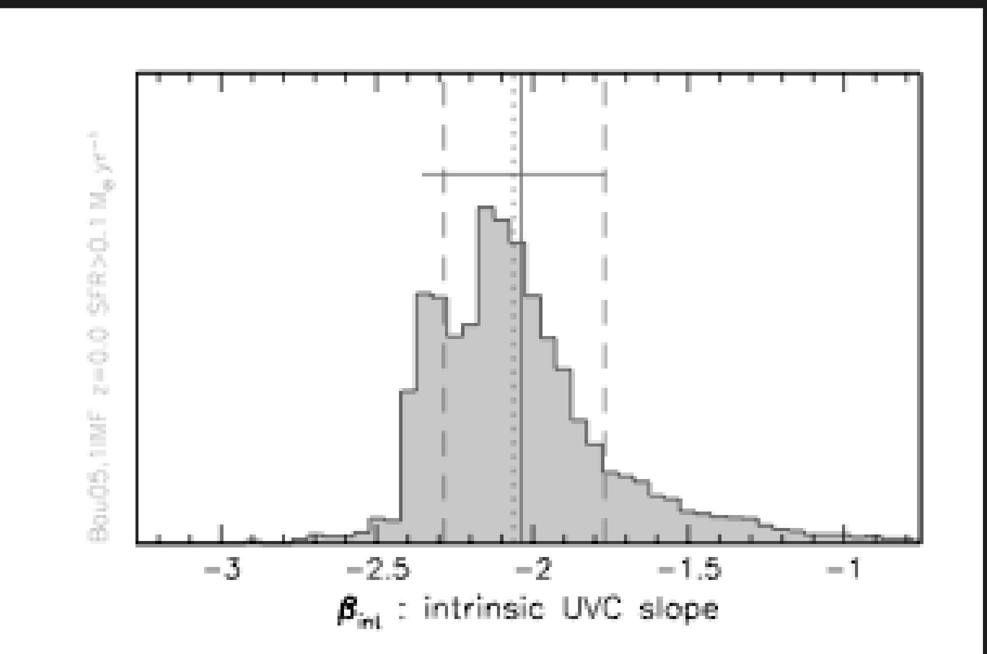


- From Wilkins et al. (2011) MNRAS
- Weak dependence of beta evolution on luminosity
- Careful on filters - the Lyman-alpha break will redden intrinsic colours

What Can we Learn about High-redshift Galaxies:

UV Continuum Properties ➟ dust

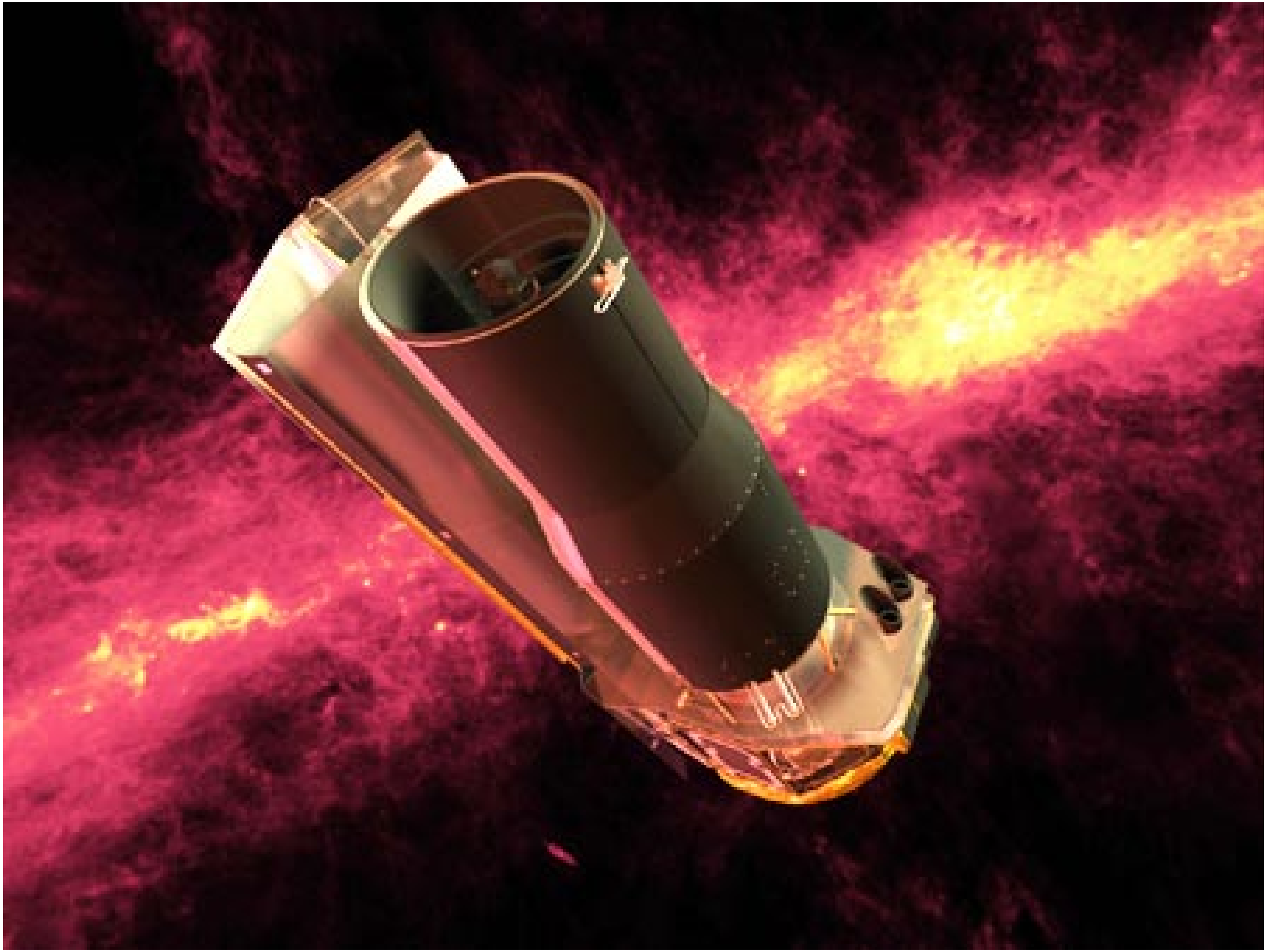
Interpreting the observed UVC slope in the context of dust requires knowledge of two uncertain quantities: the intrinsic UVC slope (distribution) and the reddening curve.



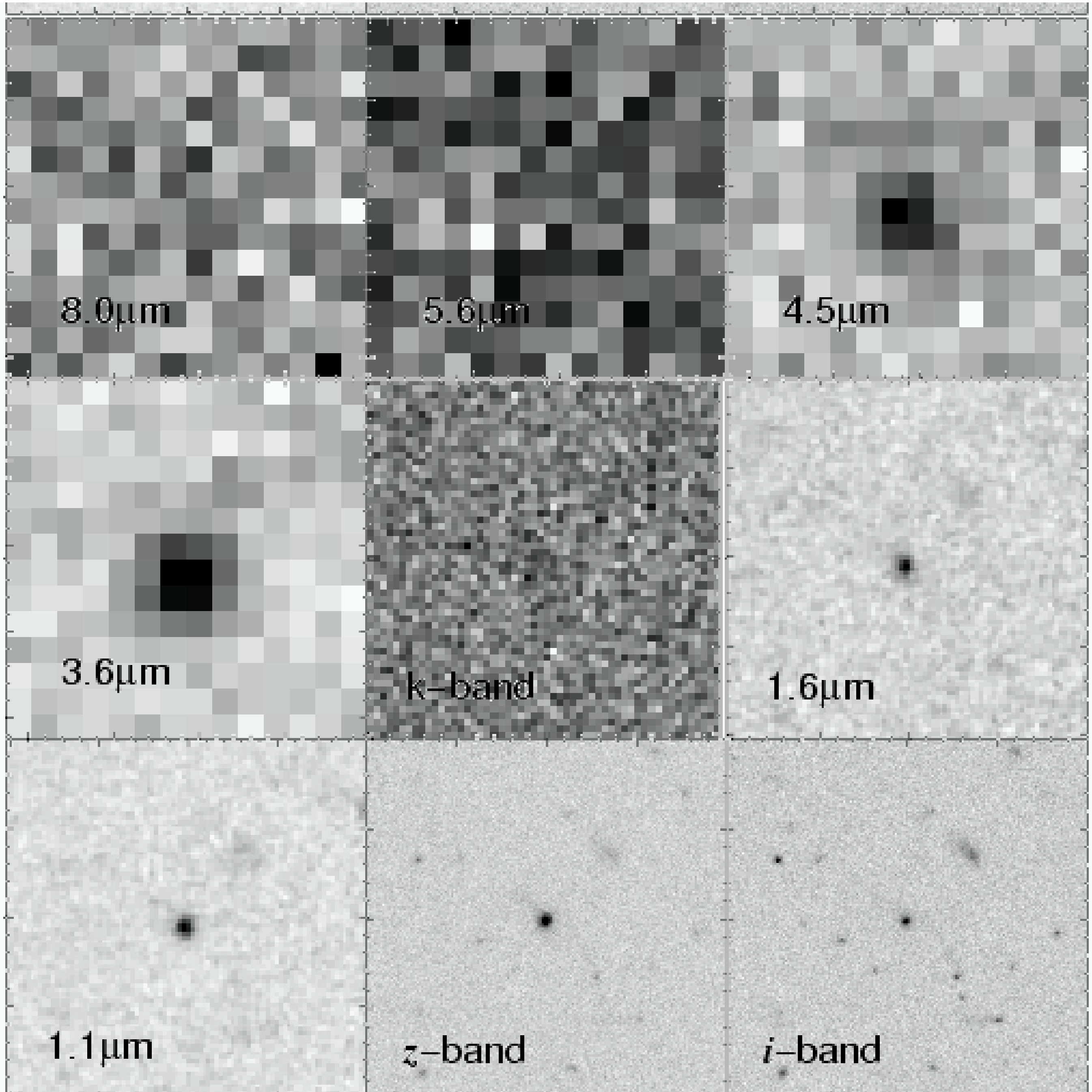
The intrinsic UVC slope is sensitive to the star formation and metallicity history, these can be predicted for large samples with galaxy formation models.

The fairly wide intrinsic distribution means that the use of the UVC as a diagnostic of dust attenuation for a single galaxy will be very uncertain (~0.5-1.0 mags assuming perfect photometry).

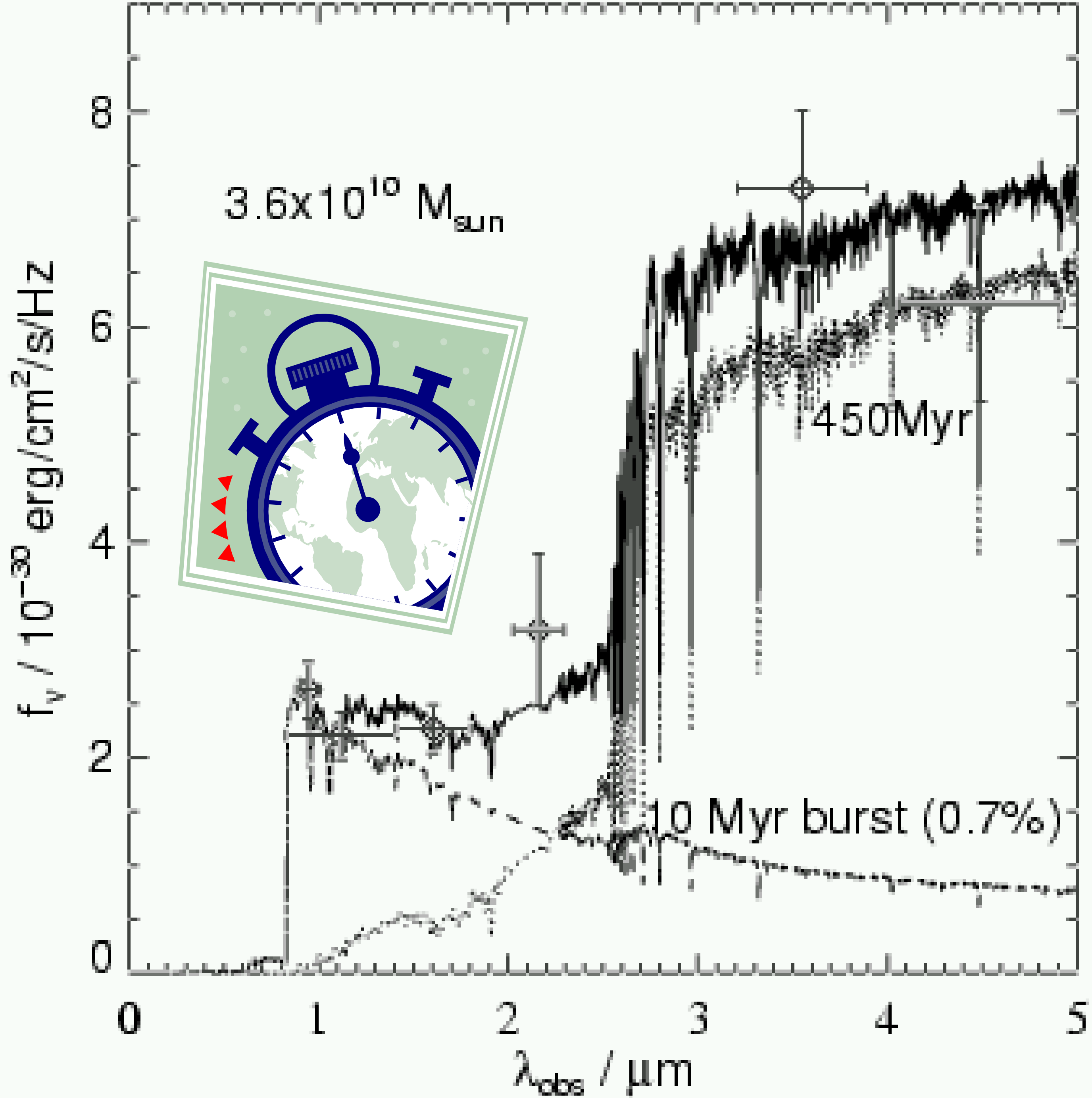
The intrinsic distribution of UVC slopes measured using the GALFORM semi-analytical model (Cole et al. 2001, Baugh et al. 2006, etc.). Wilkins et al. 2012 (to be submitted in the next couple of weeks).



Spitzer – IRAC (3.6-8.0 microns)



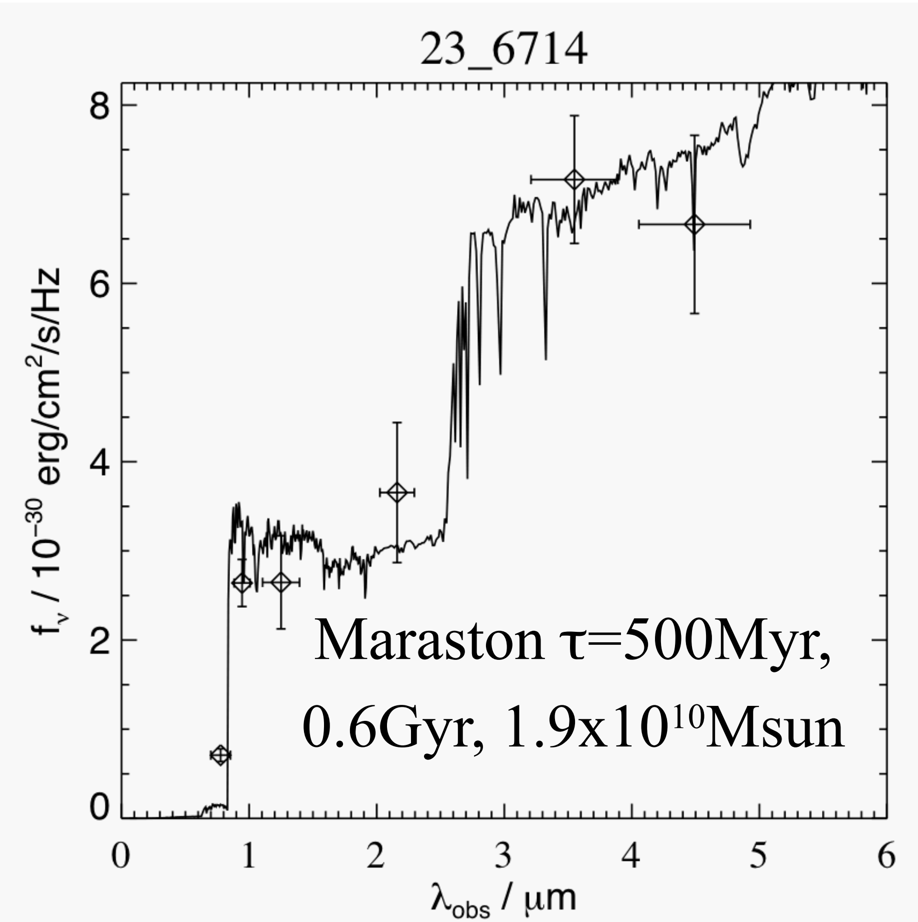
- z=5.83 galaxy #1 from Stanway, Bunker & McMahon 2003 (spec conf from Stanway et al. 2004, Dickinson et al. 2004). Detected in GOODS IRAC 3-4μm: Eyles, Bunker, Stanway et al '04

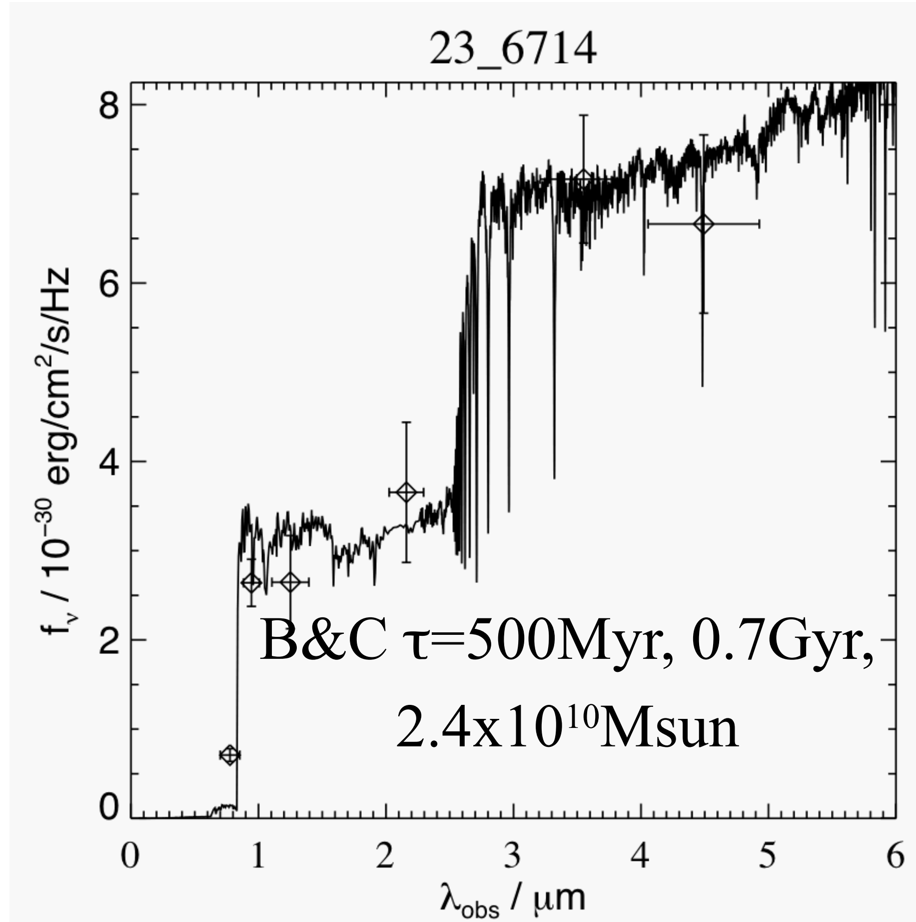


Eyles et al. (2005) MNRAS

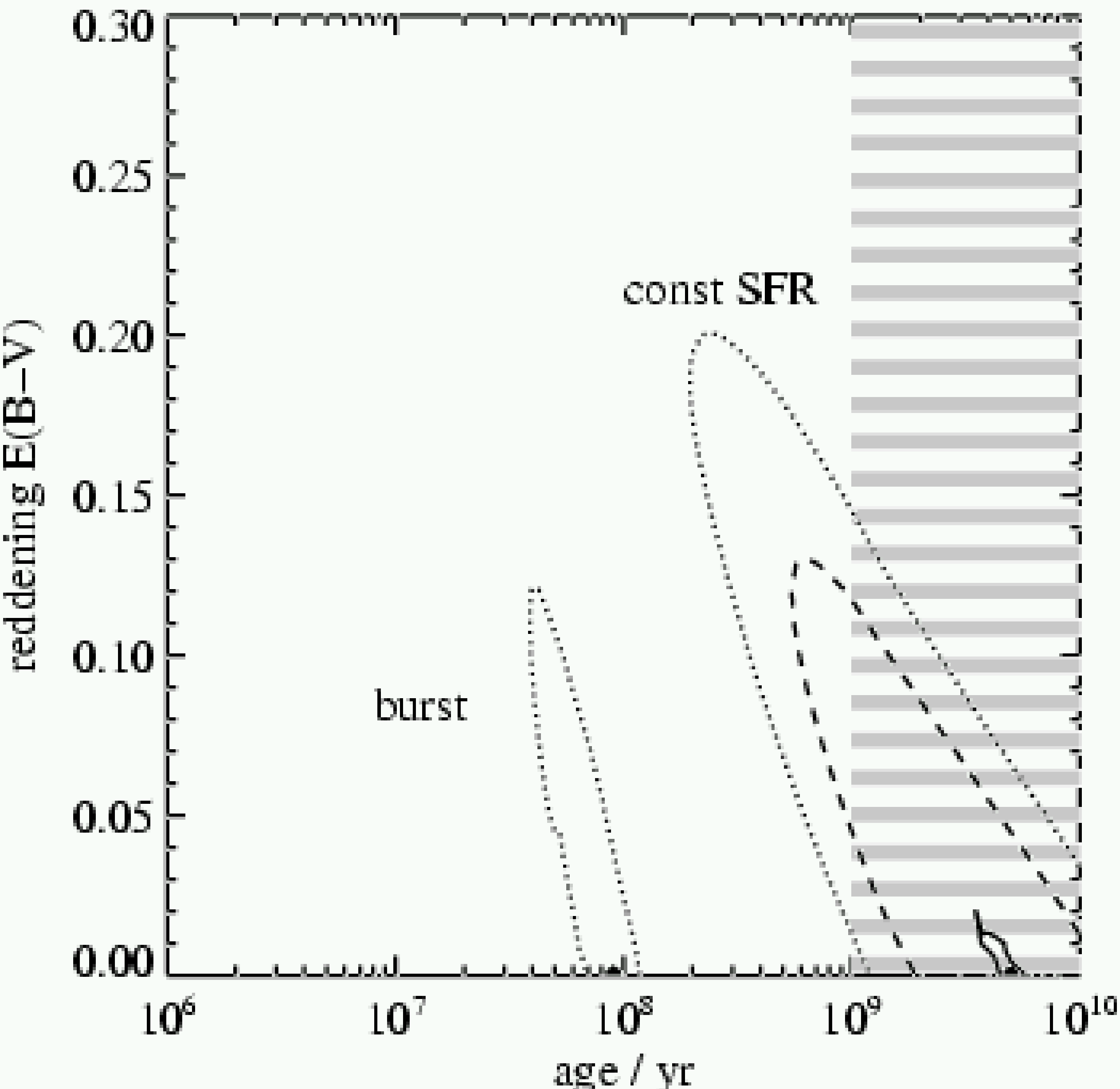
Emission line contamination does not seriously affect the derived ages and masses

Other Population Synthesis Models

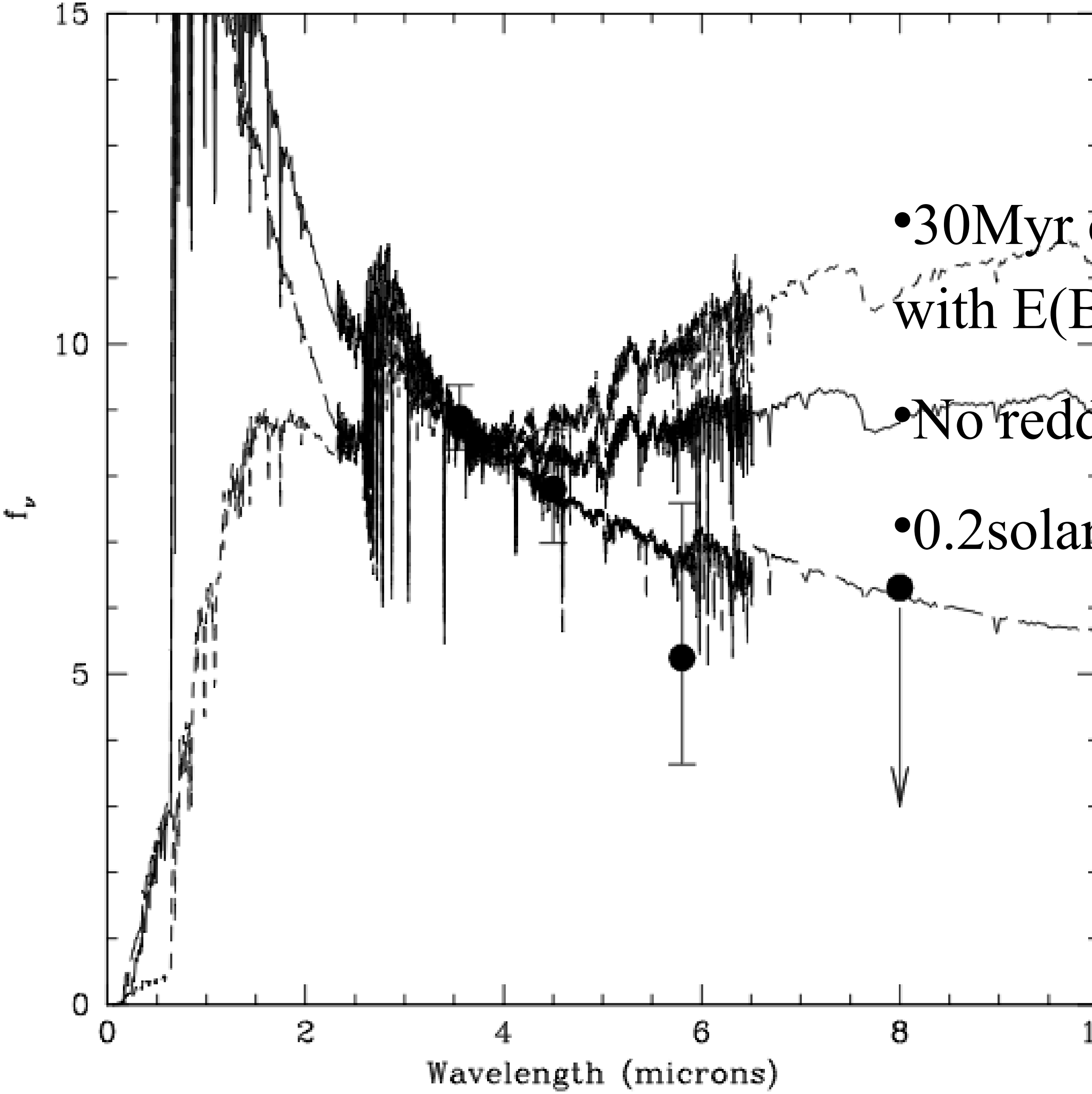




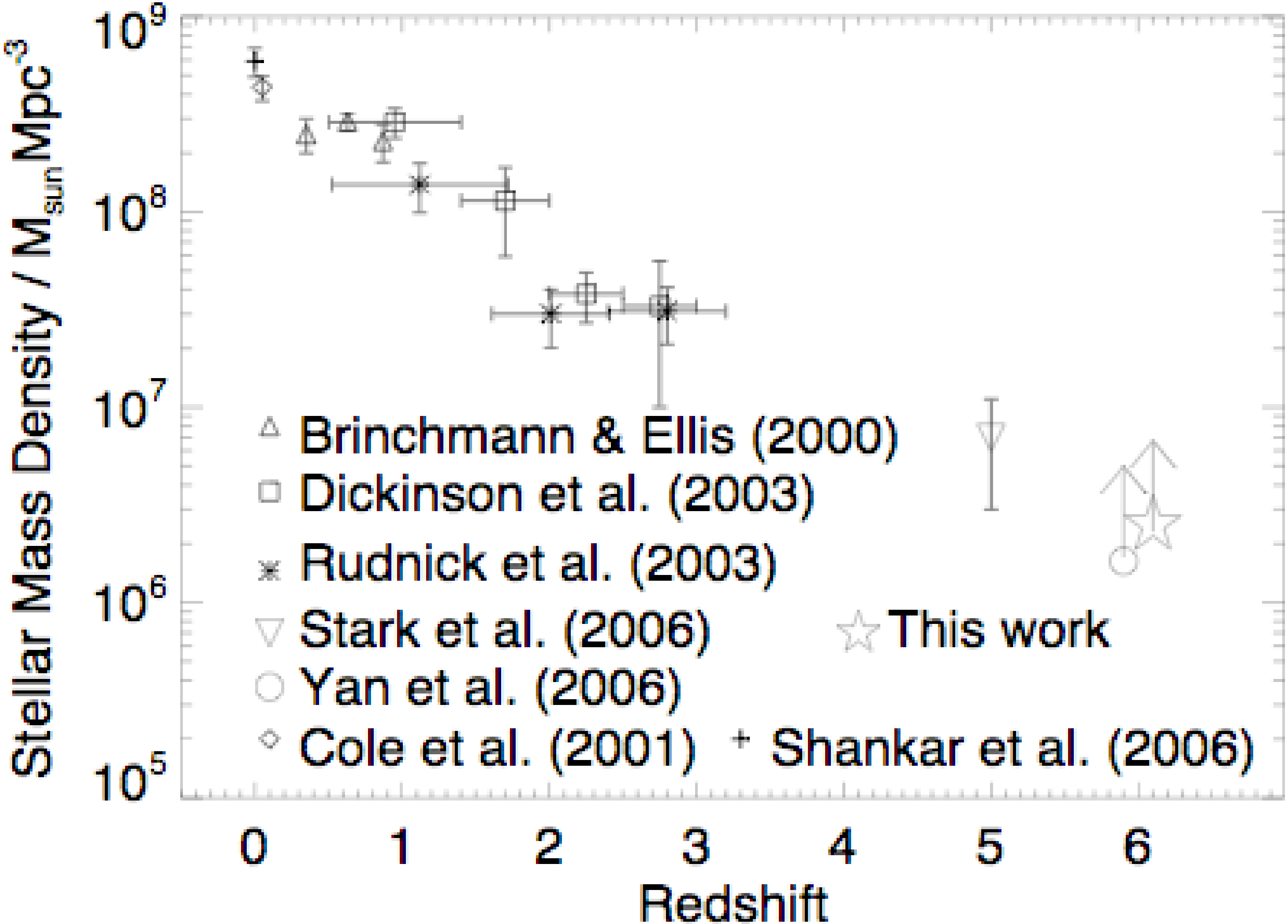
Maraston vs. Bruzual & Charlot - consistent

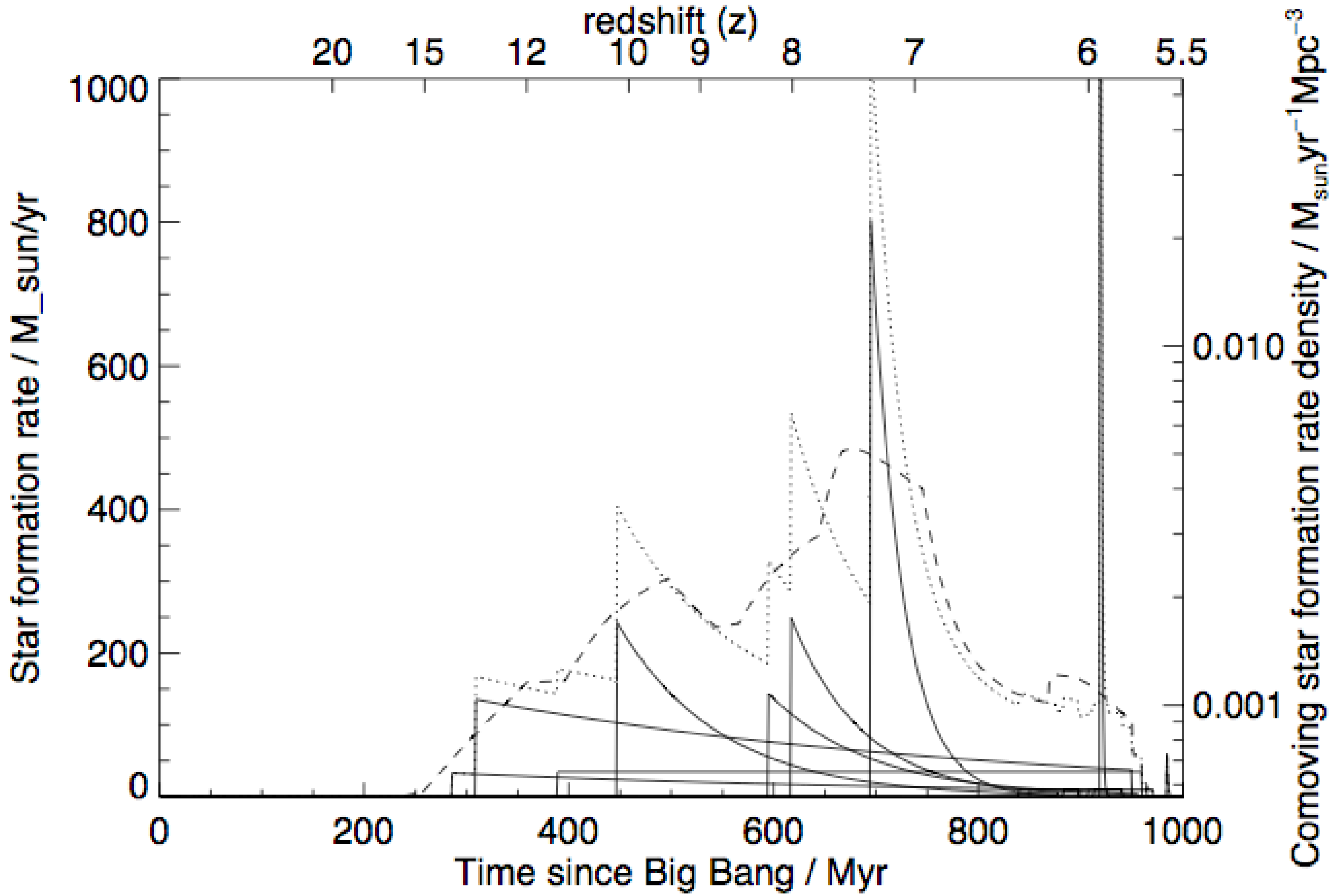


0.30
0.25
0.20
0.15
0.10
0.05
0.00
reddening E(B–V)
const SFR
burst
10^6
10^7
10^8
10^9
10^{10}
age / yr



- 30Myr const SFR with E(B-V)=0.1
- No reddening
- 0.2solar metallicity


Stellar Mass Density / $M_{sun} Mpc^3$
10^9
10^8
10^7
10^6
10^5
0
1
2
3
4
5
6
Redshift
Brinchmann & Ellis (2000)
Dickinson et al. (2003)
Rudnick et al. (2003)
Stark et al. (2006)
This work
Yan et al. (2006)
Cole et al. (2001)
Shankar et al. (2006)



Eyles, Bunker, Ellis et al. astro-ph/0607306

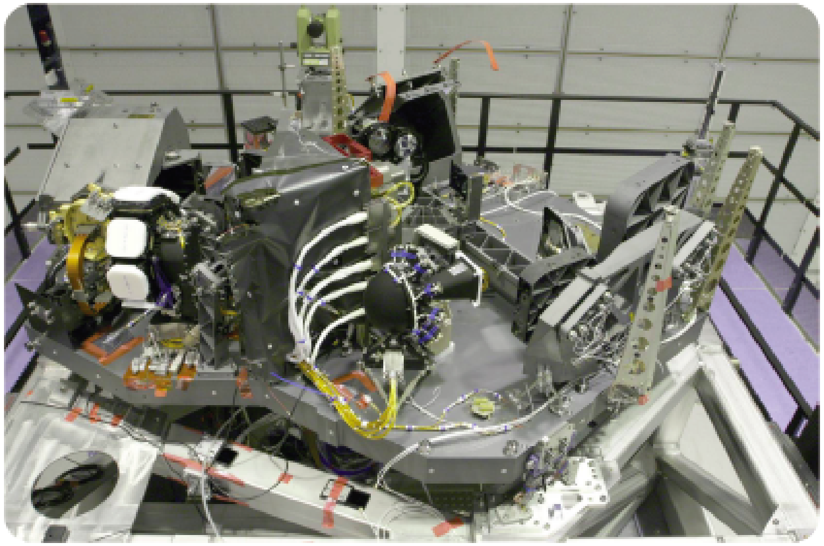
JAMES WEBB SPACE TELESCOPE

– successor to Hubble ~~(2013+)~~

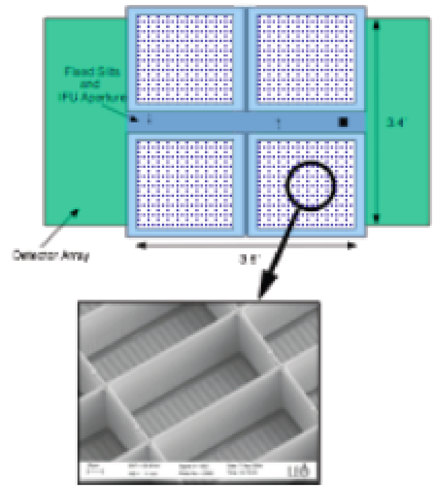
2018

NIRSpec

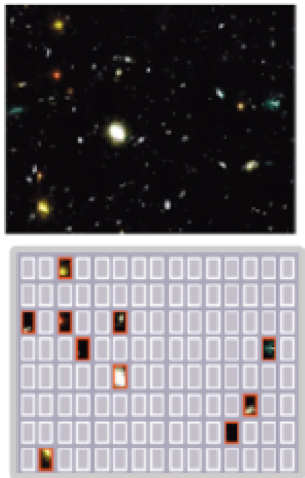
- Developed by the European Space Agency with Astrium GmbH and GSFC
  - ➟ Operating wavelength: 0.6 – 5.0 μm
  - ➟ Spectral resolution: 100, 1000, 3000
  - ➟ Field of view: 3.4 x 3.4 arc minutes
  - ➟ Aperture control: programmable micro-shutters, 250,000 pixels
  - ➟ Angular resolution: shutter open area 203 x 463 mas, pitch 267 x 528 mas
  - ➟ Detector type: HgCdTe, 2048 x 2048 pixel, 2 detectors, T_{op} = 37K (passive)
  - ➟ Reflective optics, SiC structure and optics



Microshutters



Multiple Objects
≤ 100 objects



Conclusions

- Have found star-forming galaxies at z=6-10 (Lyman breaks), and spectroscopic confirmation at z~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