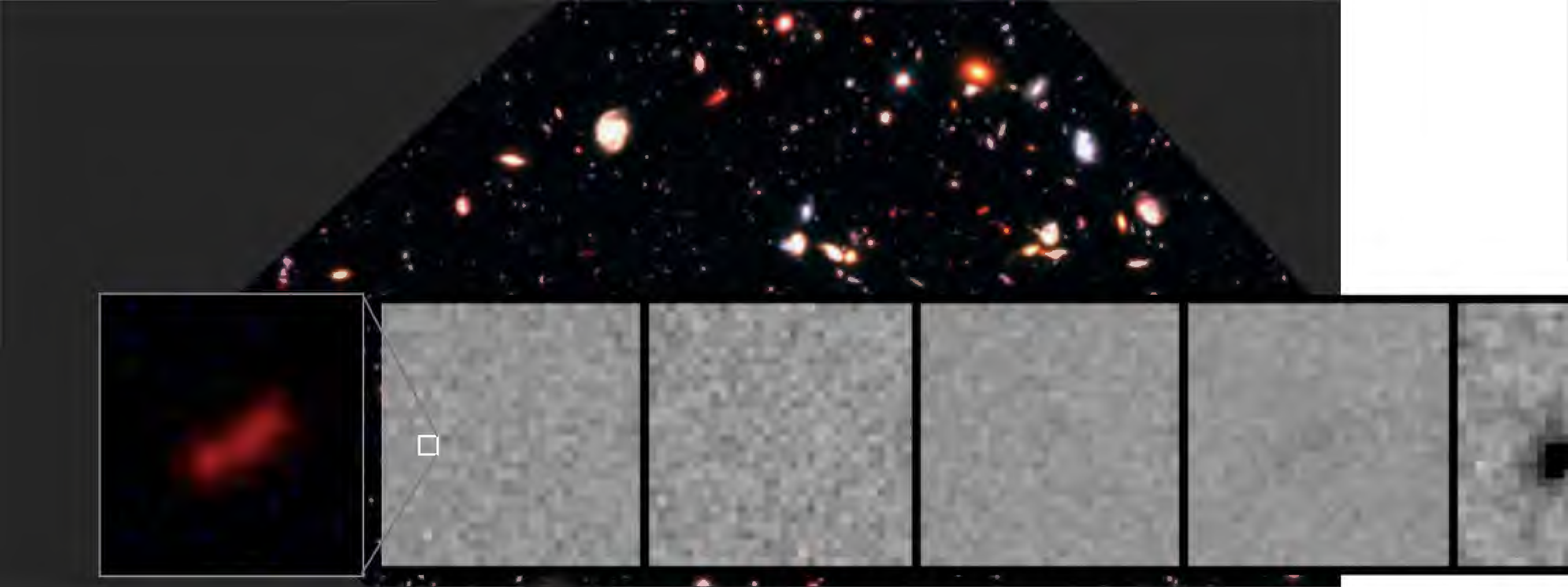


The First Billion Years of History - Star Formation at the Highest Redshifts

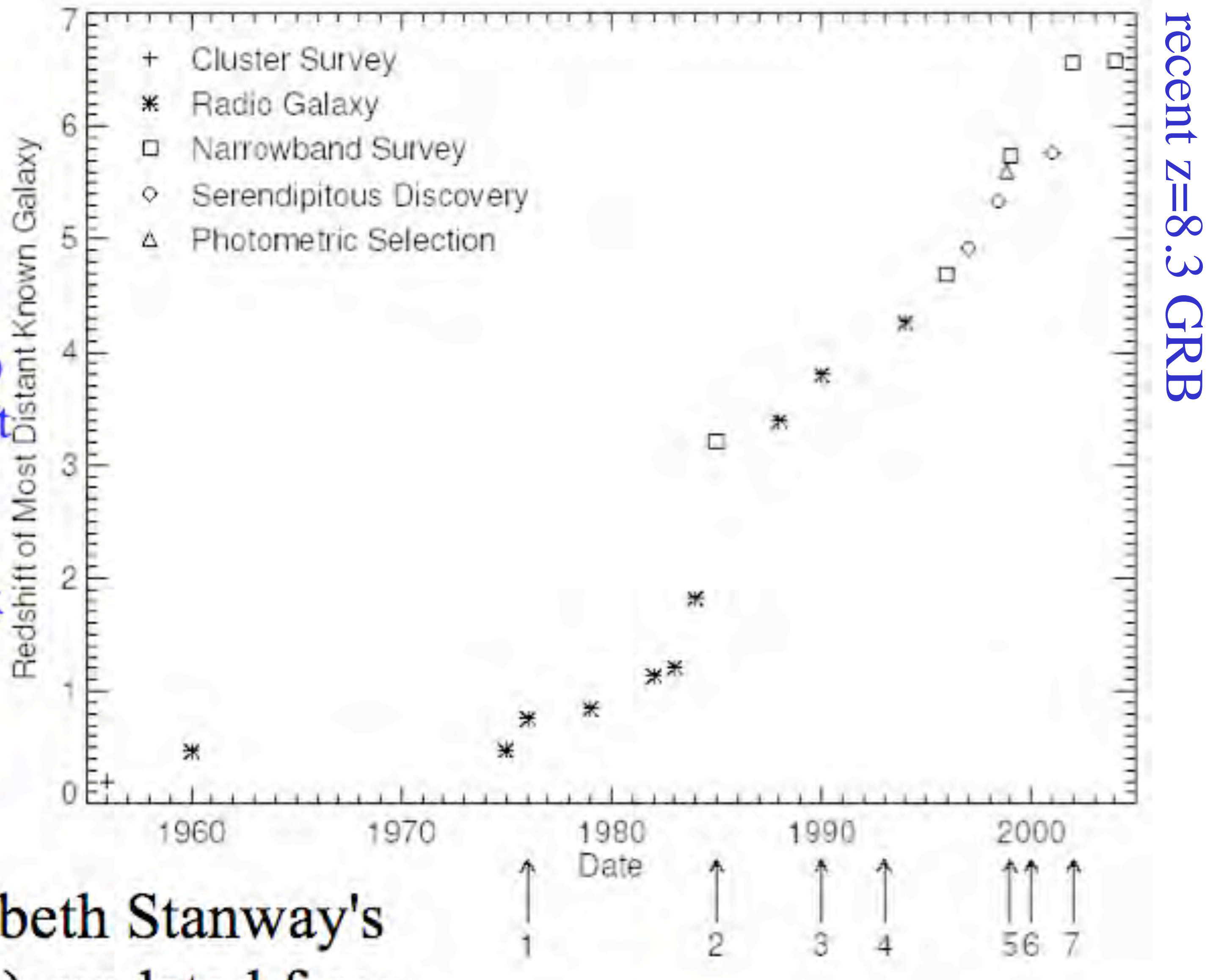
Andrew Bunker (Oxford)

Stephen WIlkins, Joseph Caruana, Silvio Lorenzoni, Laurence Eyles, Matt Jarvis, Elizabeth Stanway, Richard Ellis, Daniel Stark, Richard McMahon, Kuenley Chiu

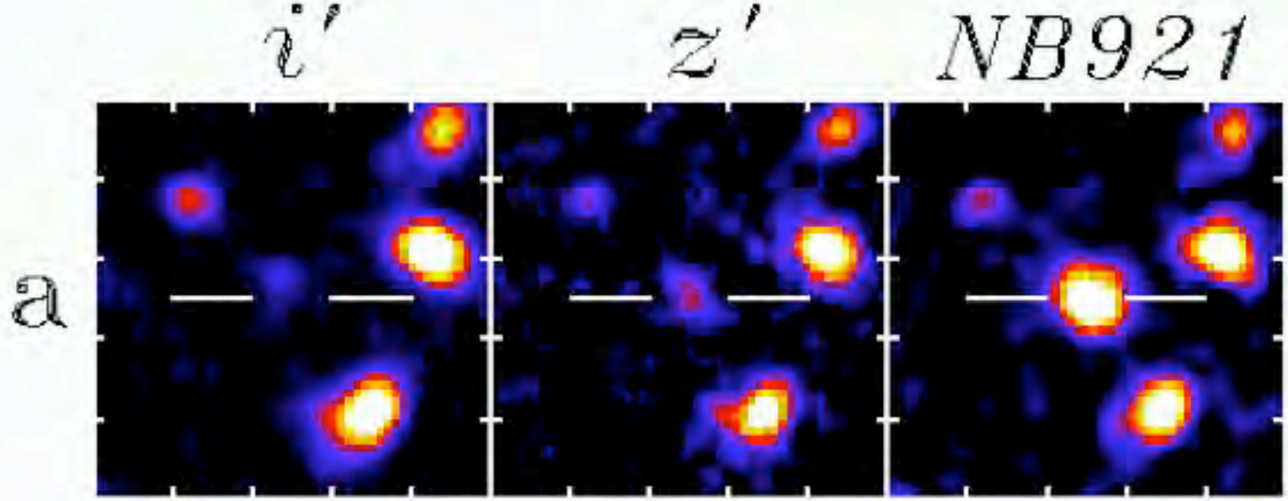
The Key Problem

- We know the intergalactic medium of the Universe reionizes at $z>6$ (probably around $z=10$-11)
- What is the source of the UV photons to do this?
- AGN are under-abundant at these high redshifts
- Can star formation do it? Or is it something else?
- Have been successful in recent years in finding star-forming galaxies at $z=6$ and beyond
- Insufficient photon density from the high redshift luminous galaxies we have found so far
- Is it the unobserved faint end of the luminosity function?

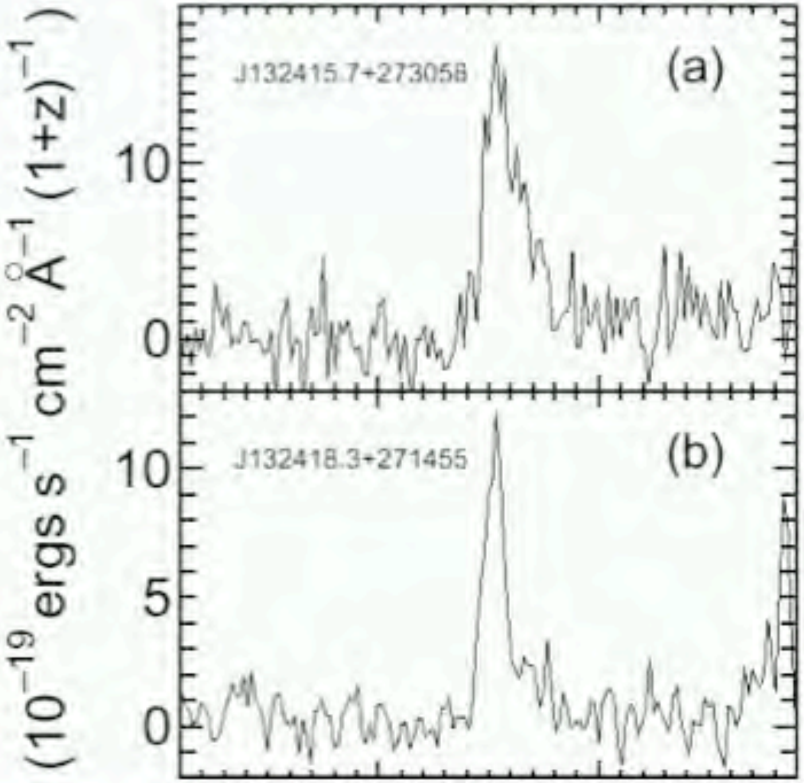
Early strategy: most massive short-lived OB stars produce ionizing UV photons. Want to find high-redshift star forming galaxies, and measure UV flux (or recombination lines e.g. Ly-α)



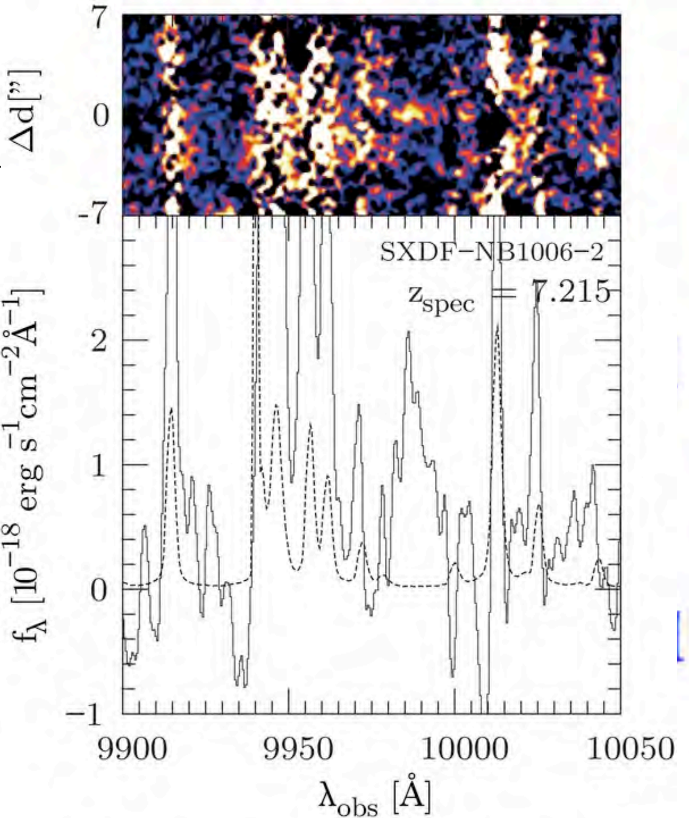
From Elizabeth Stanway's thesis (2004), updated from review of Stern & Spinrad

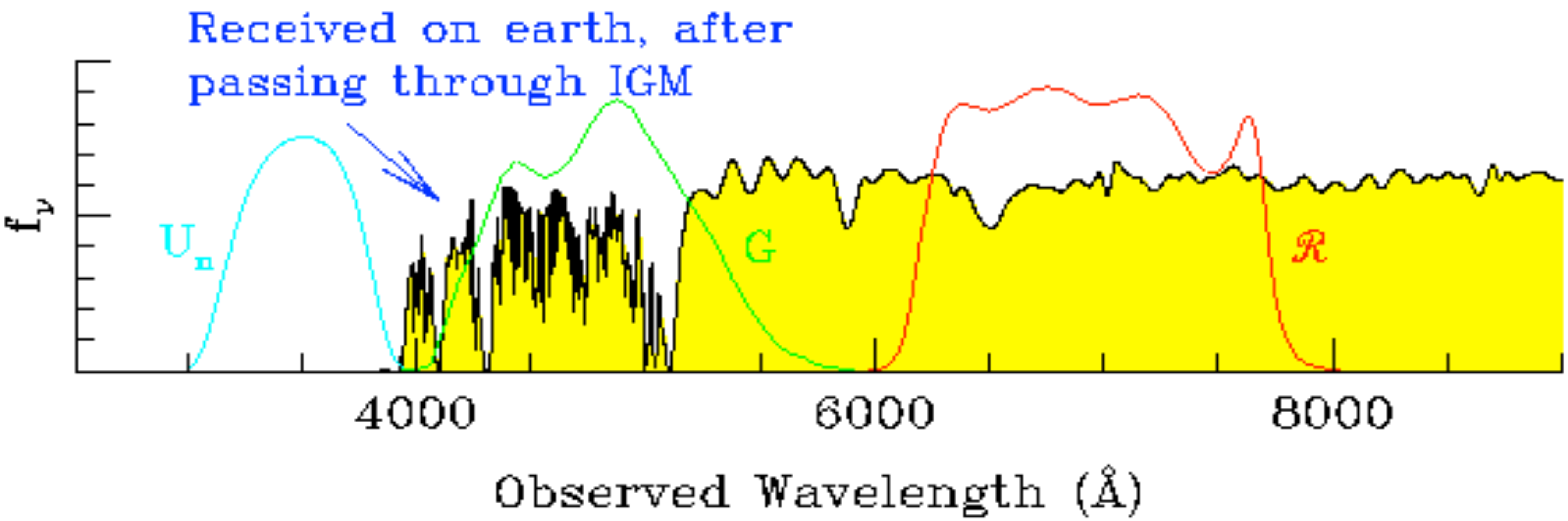


Kodaira et al. (2003) z=6.58 Ly-alpha galaxy (narrow-band)

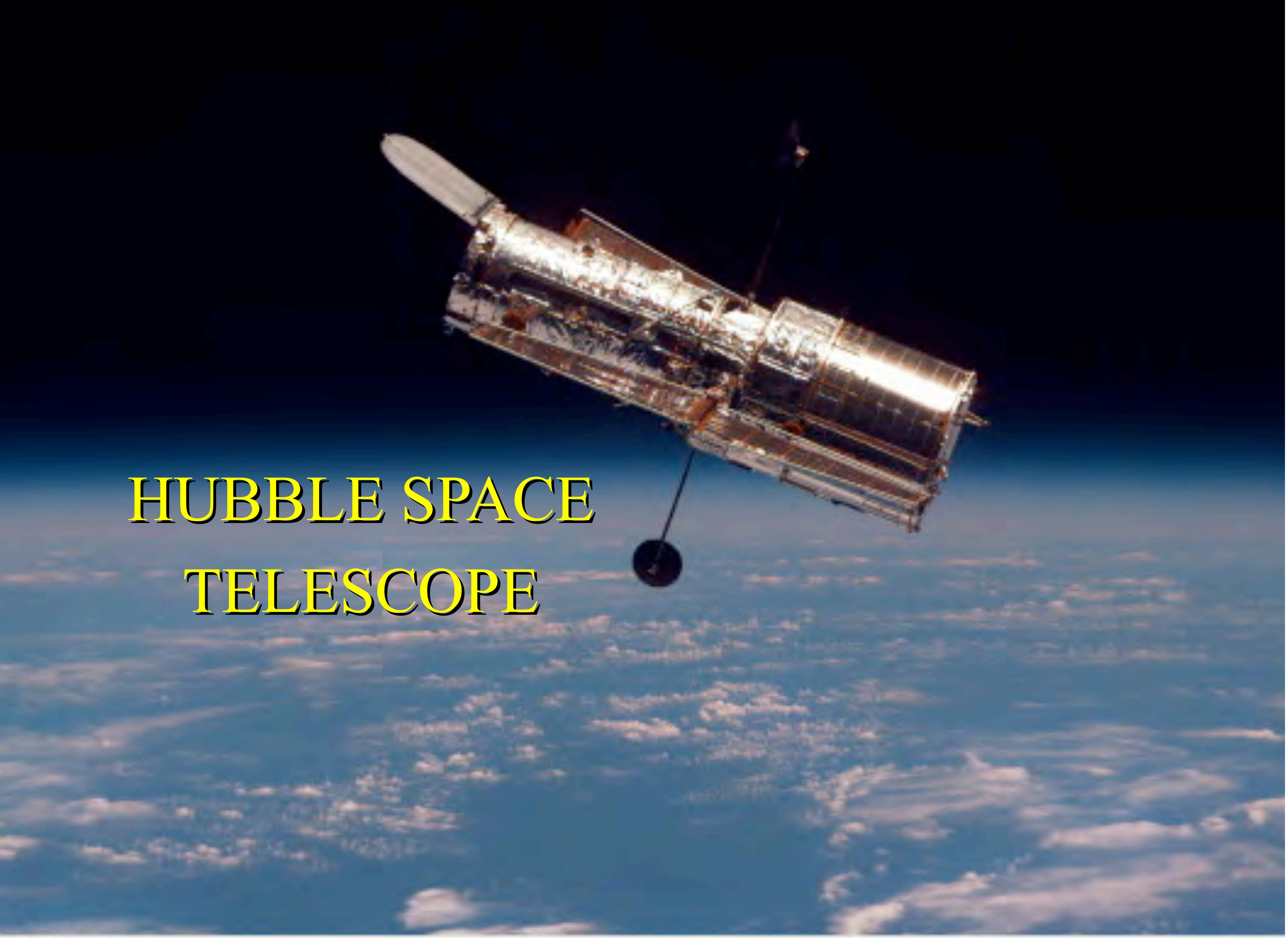


Current narrow-band record now z=7.215 Shibuya et al. 2012





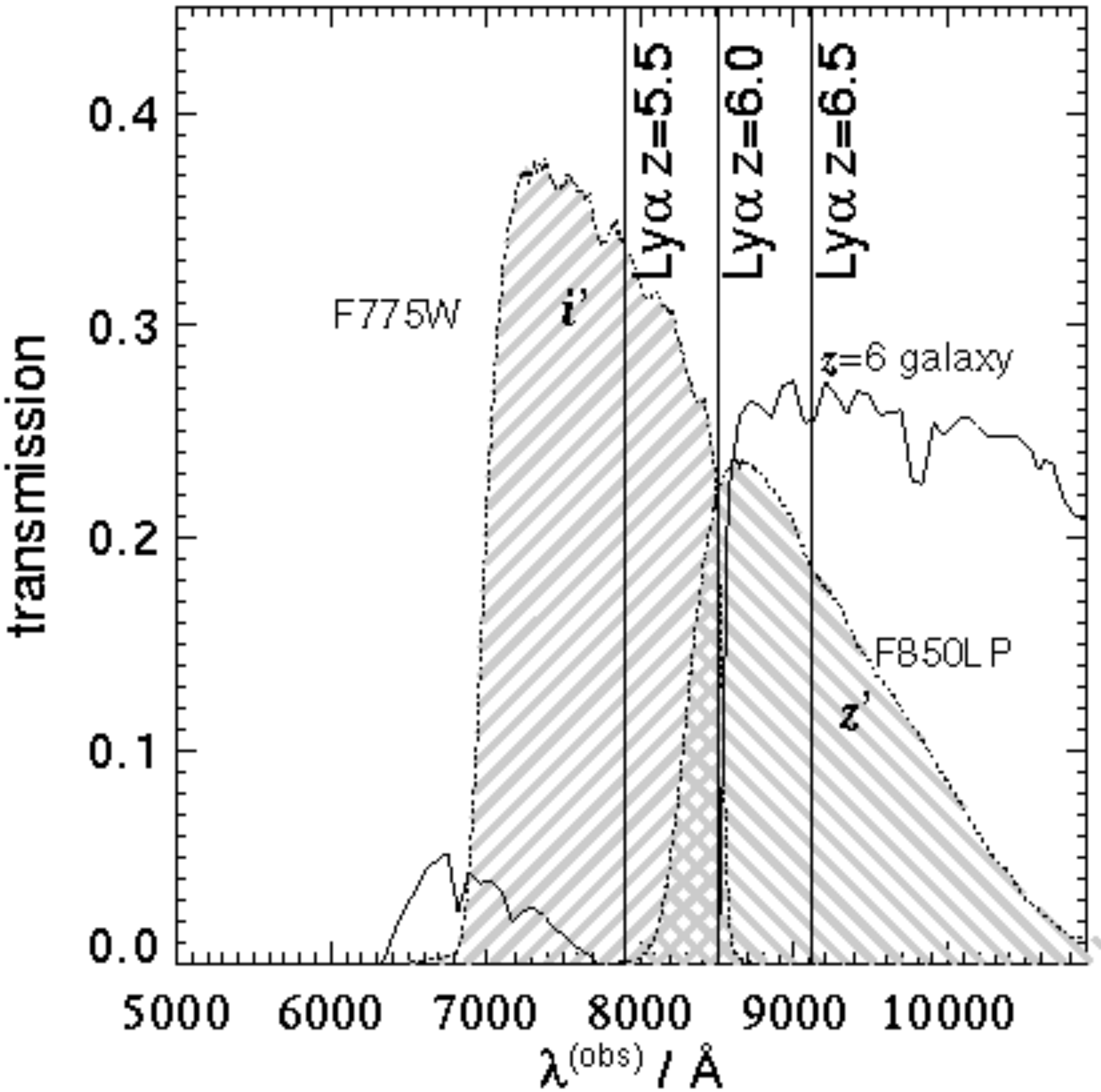
"Lyman break technique" - sharp drop in flux at λ below Ly-α. Steidel et al. have >1000 z~3 objects, "drop" in U-band.

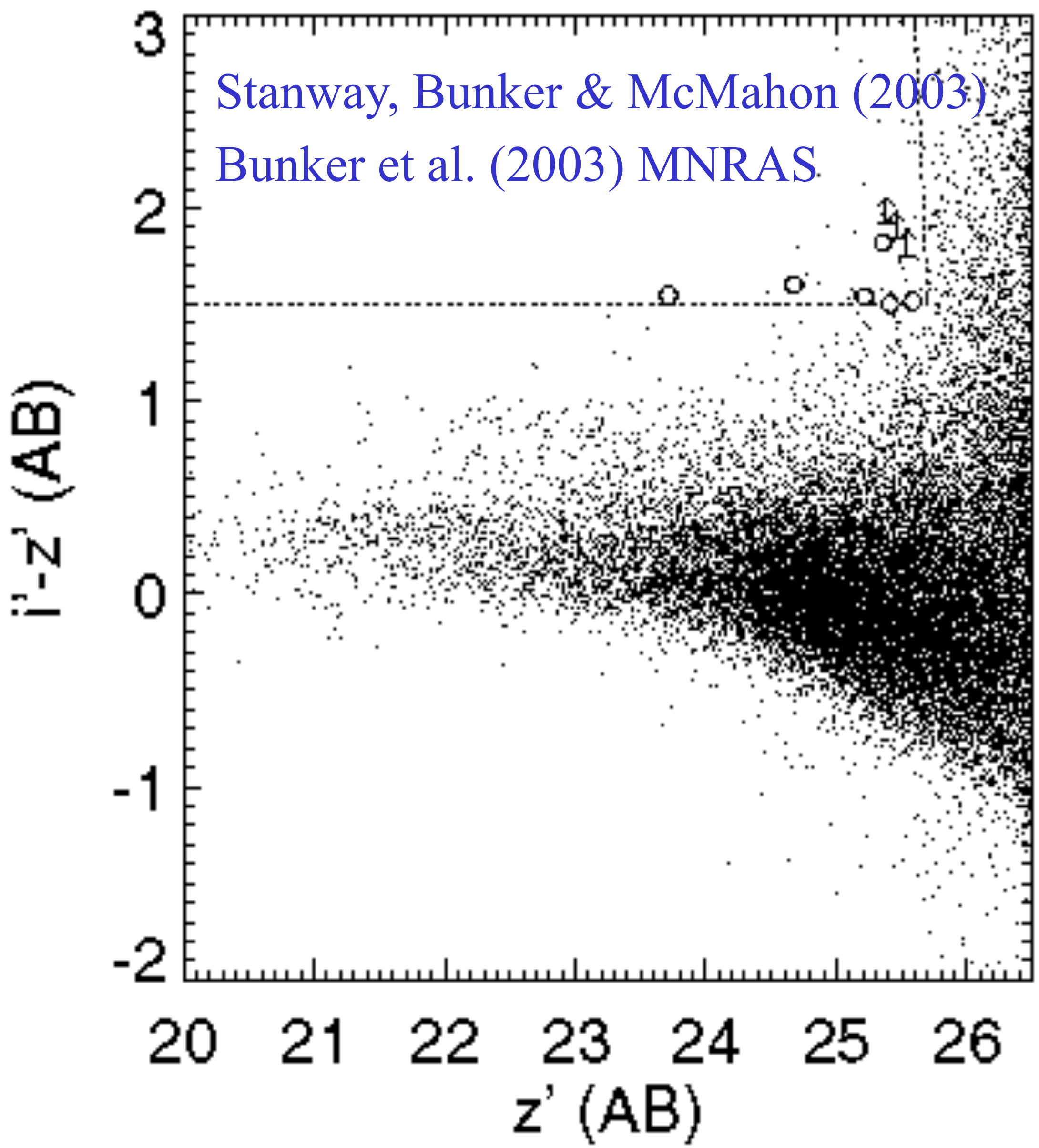


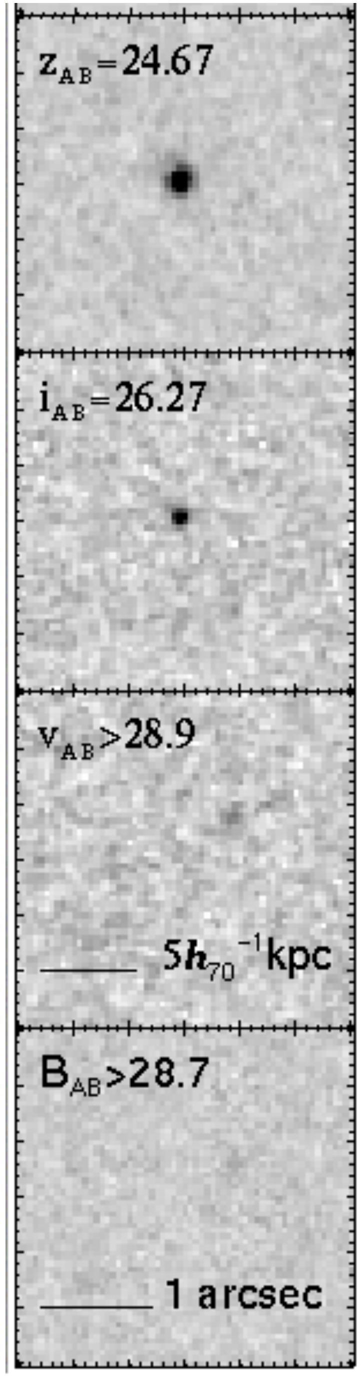
9 07:06:57

"Lyman break technique" - sharp drop in flux at λ below Ly-α. Steidel et al. have >1000 z~3 objects, "drop" in U-band.

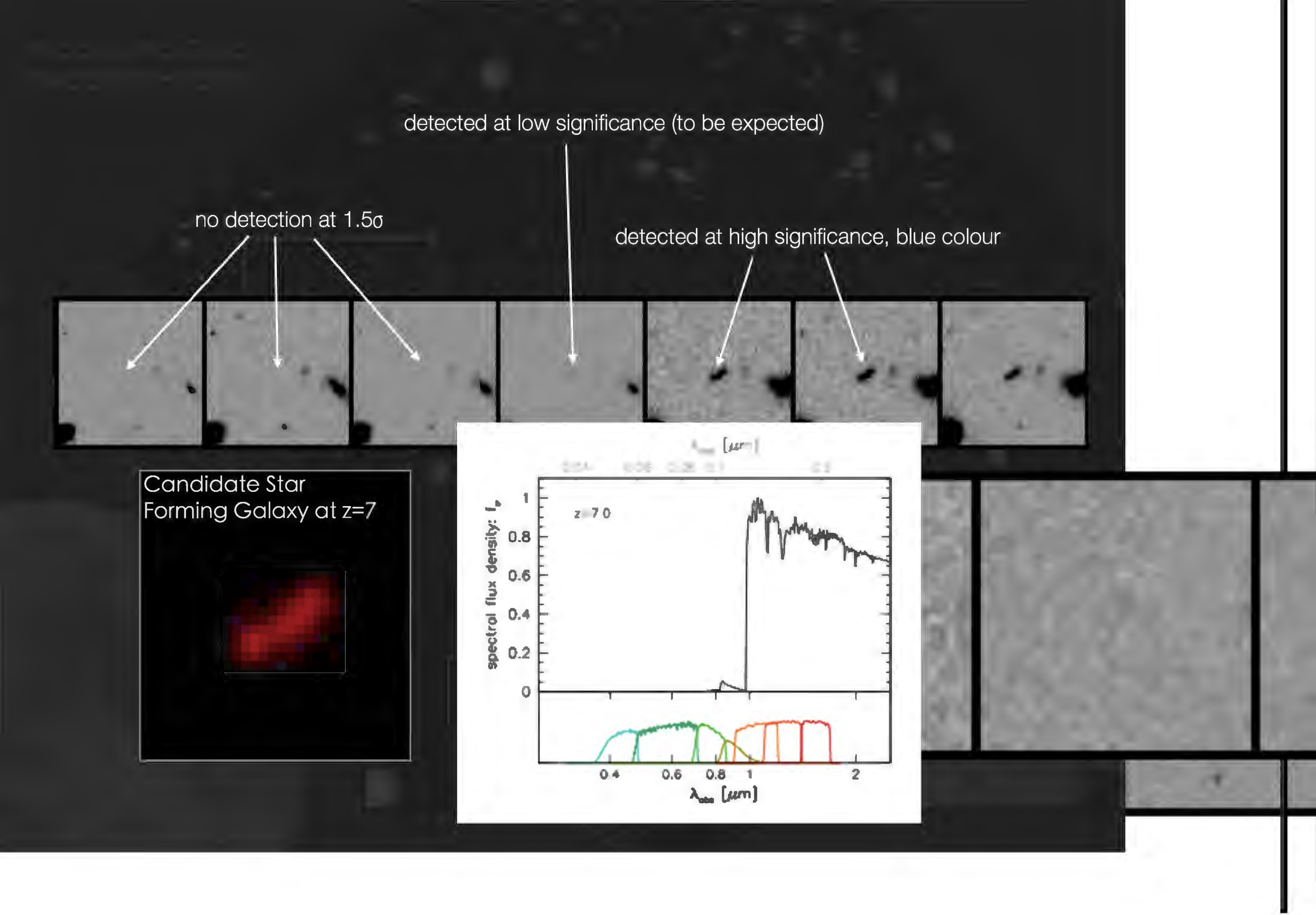
Pushing to higher redshift- Finding Lyman break galaxies at z~6 : using *i*-drops.



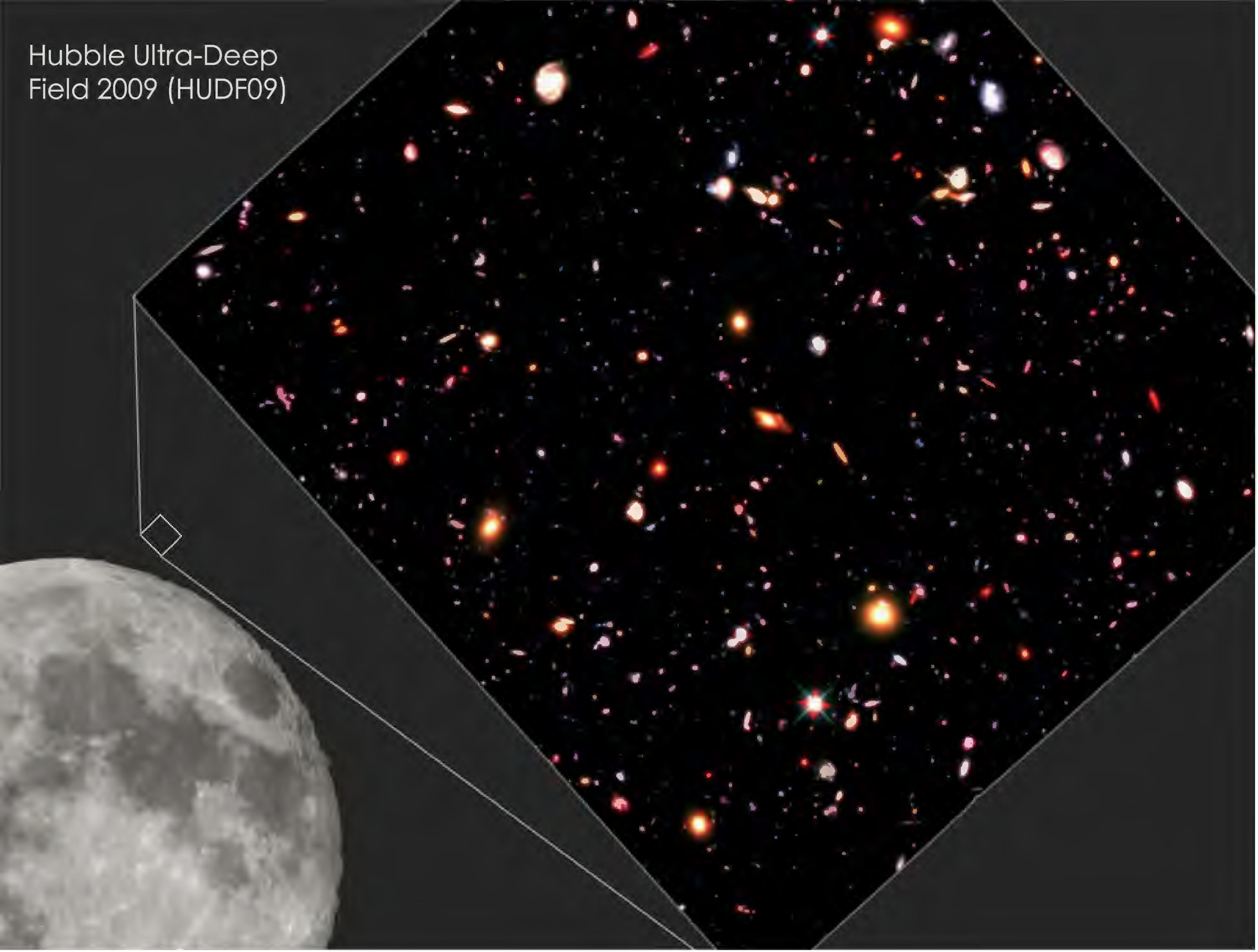


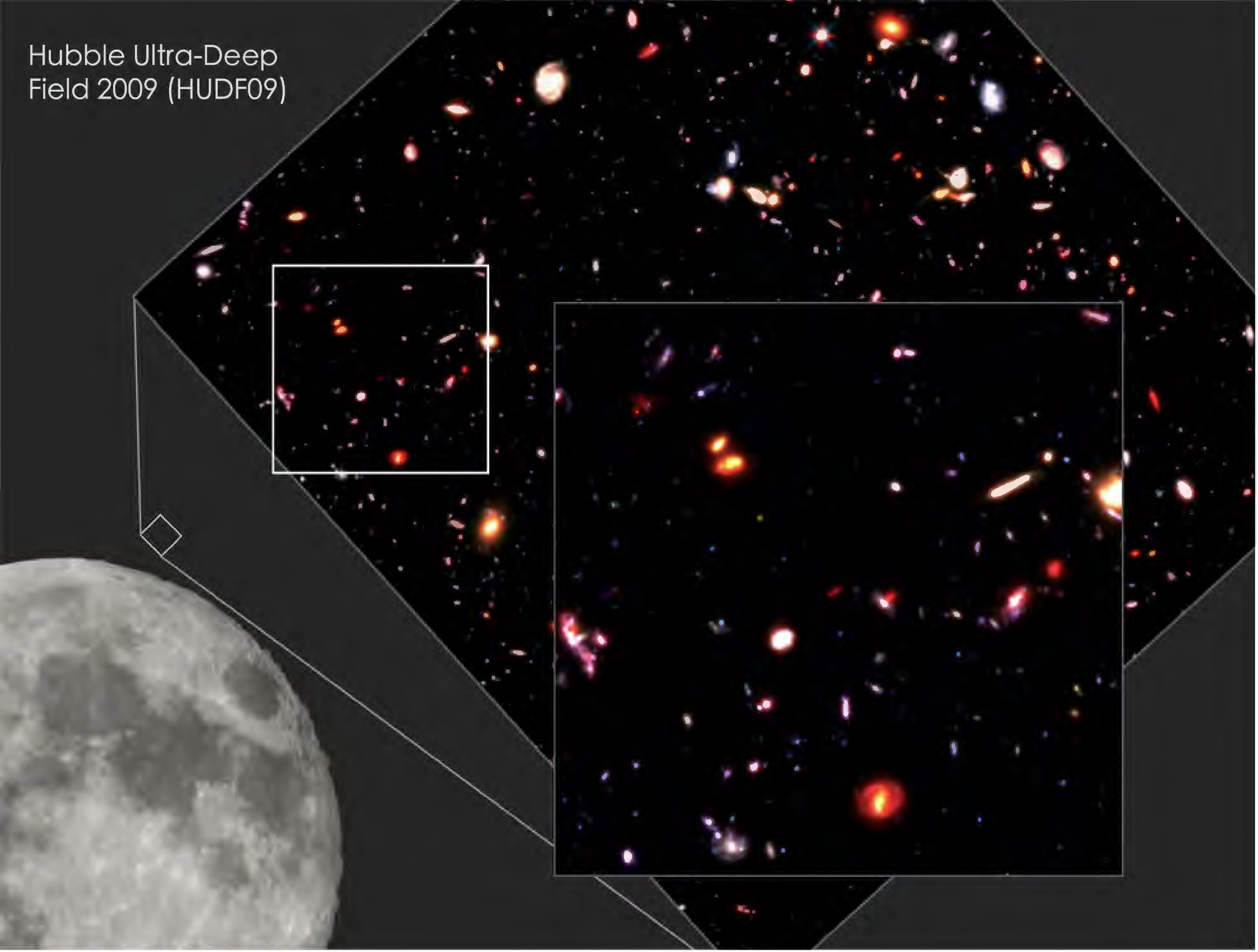


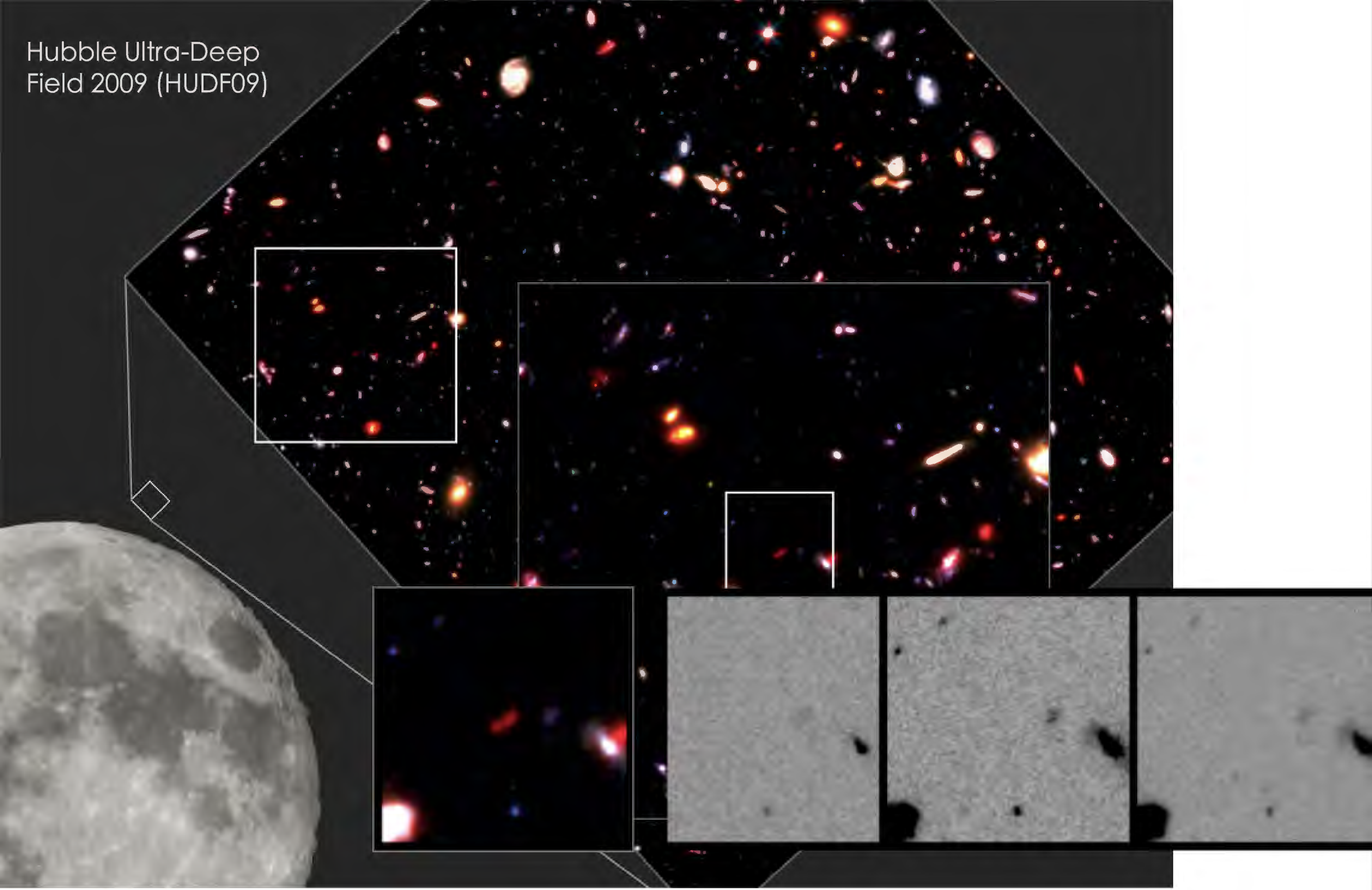
Using HST/ACS GOODS data - CDFS & HDFN, 5 epochs B,v,i',z'

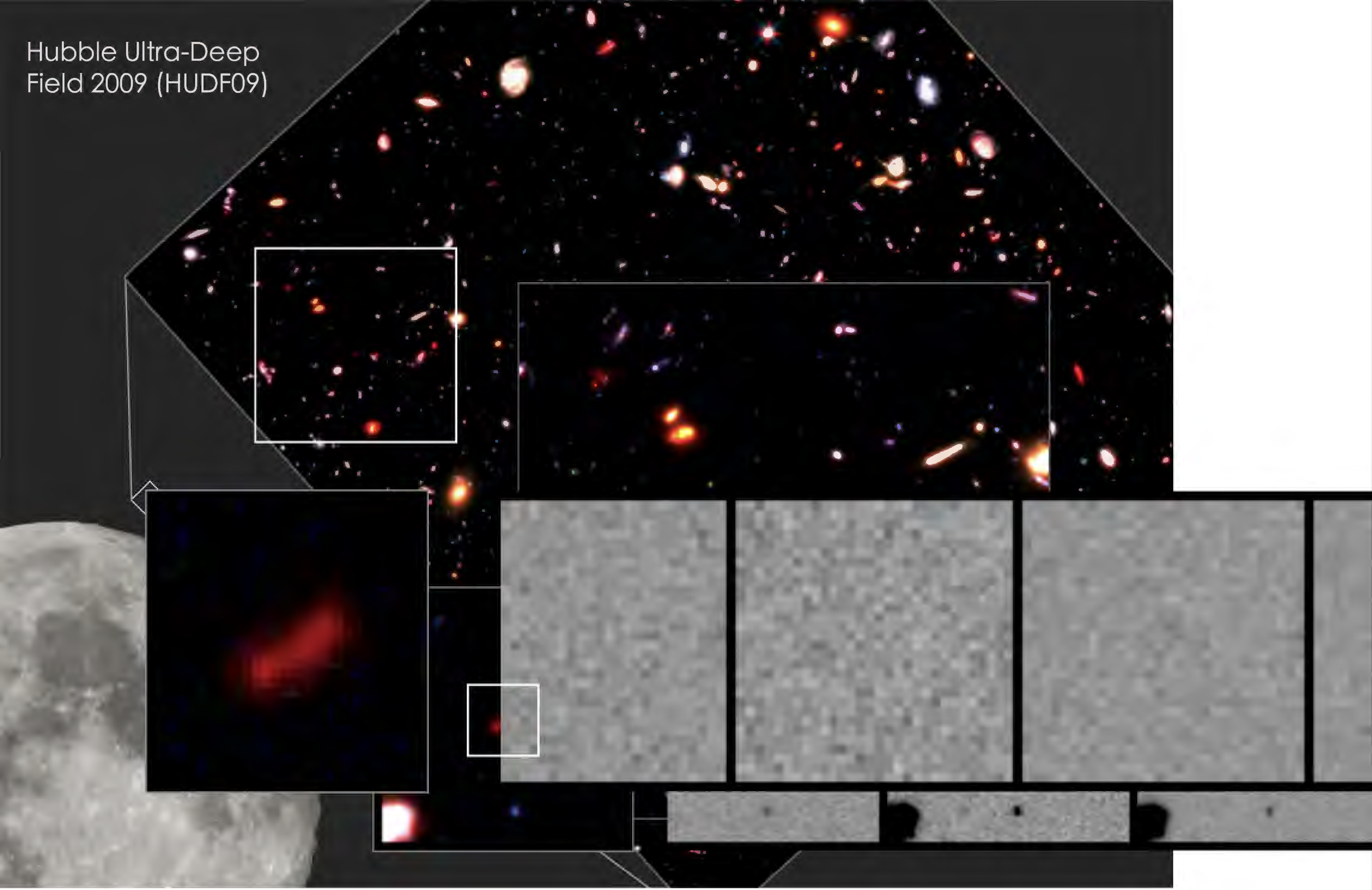


detected at low significance (to be expected)
no detection at 1.5σ
detected at high significance, blue colour
Candidate Star Forming Galaxy at z=7
spectral flux density: f_ν
z=7.0
1
0.8
0.6
0.4
0.2
0
0.4
0.6
0.8
1
2
λ_obs [μm]


Hubble Ultra-Deep
Field 2009 (HUDF09)


Hubble Ultra-Deep
Field 2009 (HUDF09)


Hubble Ultra-Deep
Field 2009 (HUDF09)


Hubble Ultra-Deep
Field 2009 (HUDF09)

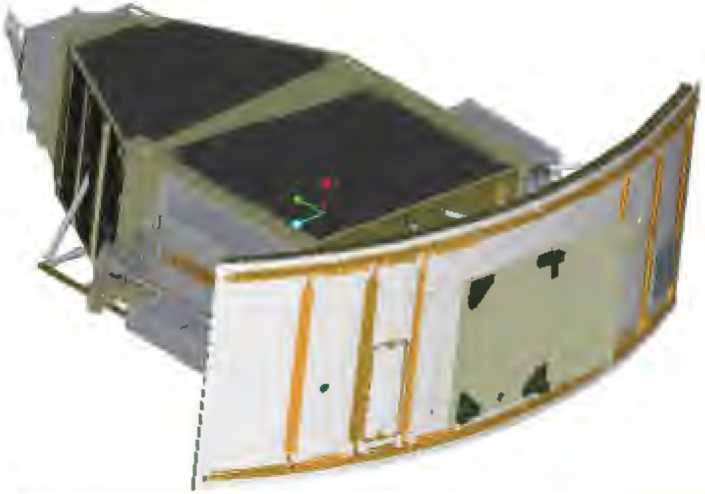
Wide Field Camera 3: WFC3

WFC3 was installed on HST as part of Servicing Mission 4.

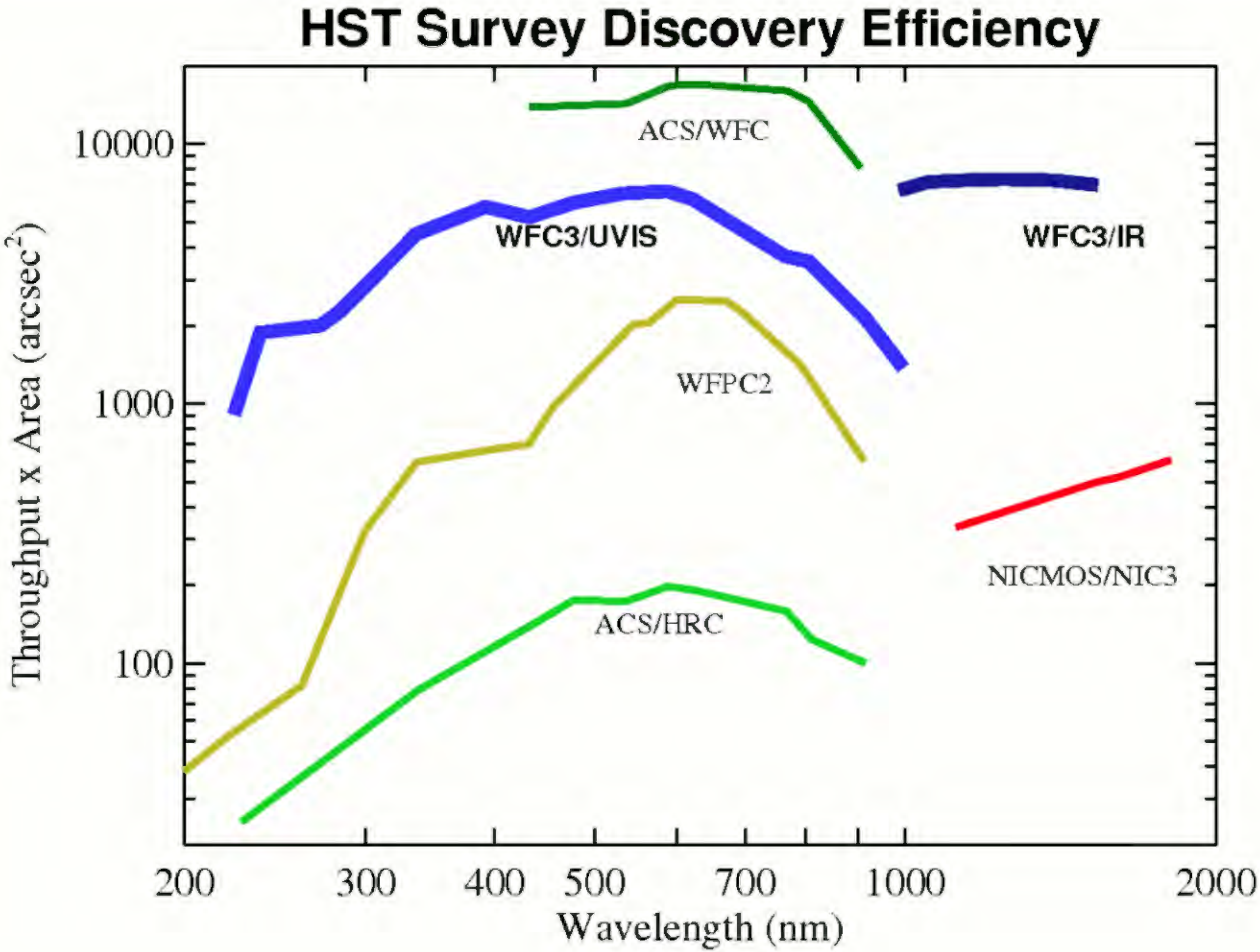
Provides both a UVIS and NIR channel covering 0.2-1.7μm

Stellar Jet in the Carina Nebula
Hubble Space Telescope • WFC3/UVIS/IR

NASA, ESA, and the Hubble SM4 ERO Team STScI-PRC09-25b



HST WFC3



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

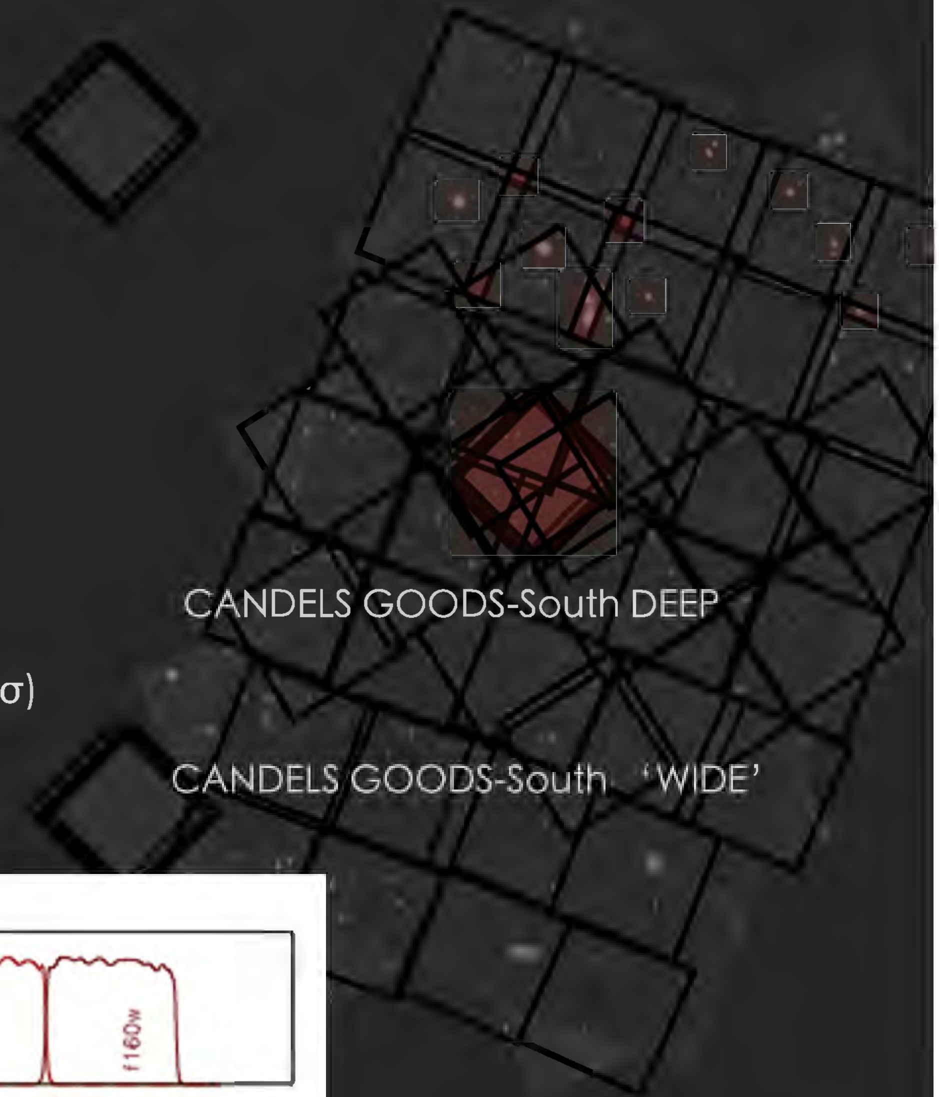
Observations:

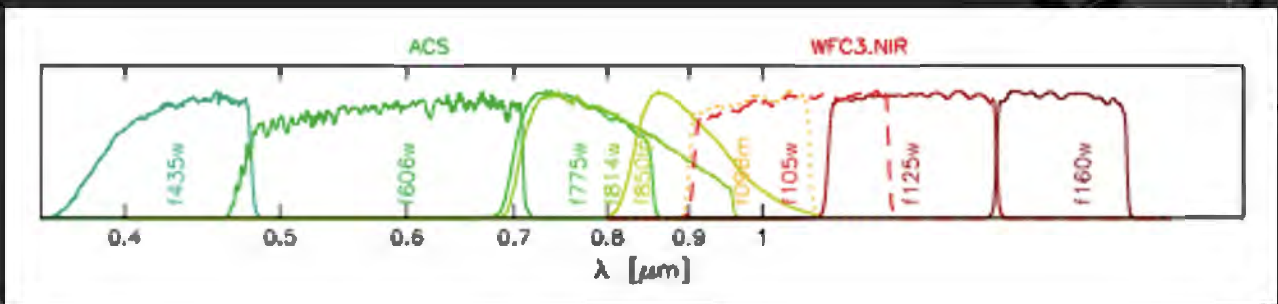
Very-Deep **ACS** imaging over the entire GOODS-South Field [GOODS]

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

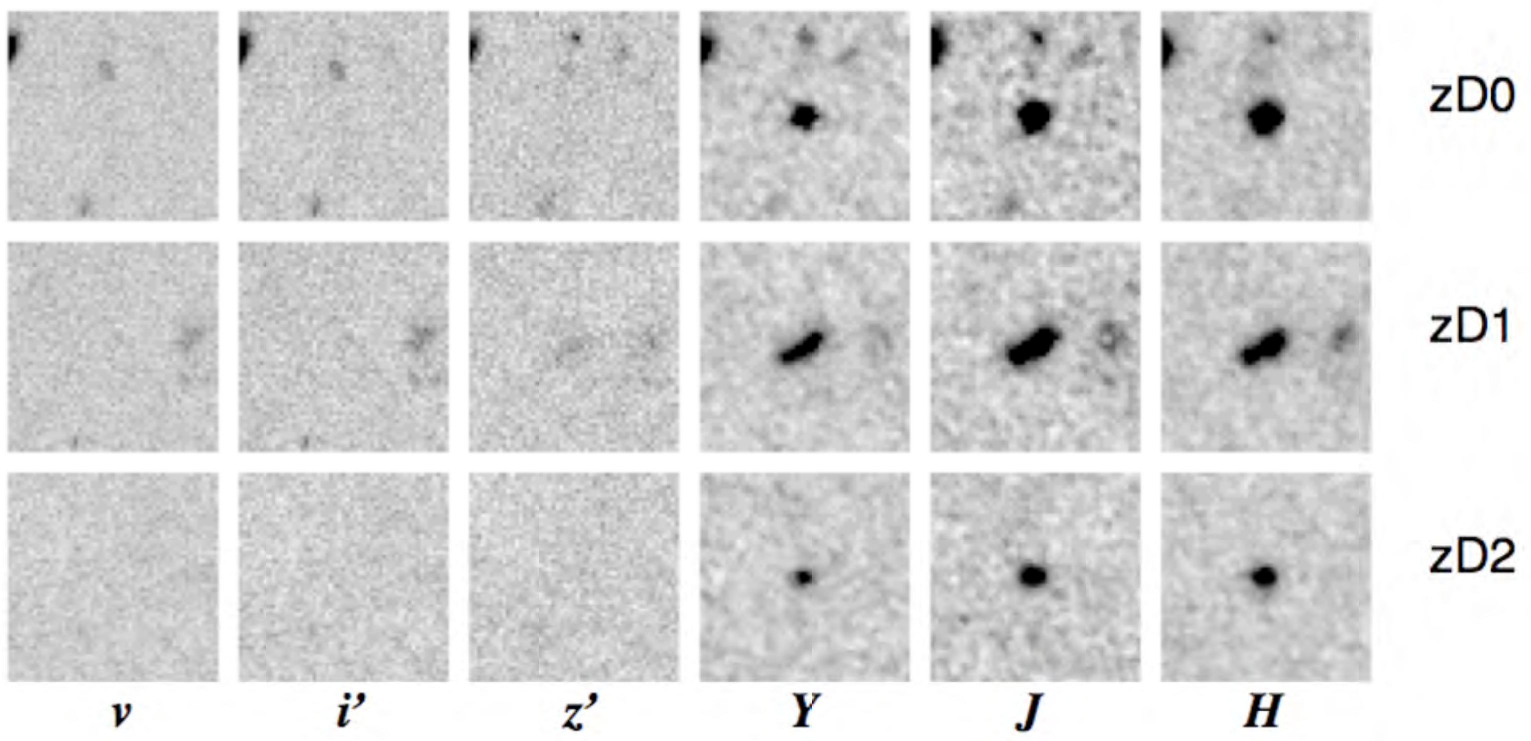
HUDF09	Ultra-deep (29.0-30.0 (AB) in J_{125w}, 5σ) in 3 fields (~15 $arcmin^2$ total)
ERS	Very-deep (~28.5 (AB) in J_{125w}, 5σ) contiguous over ~40 $arcmin^2$
CANDELS GOODS-South	Pretty-deep (28.0-28.5 (AB) in J_{125w}, 5σ) contiguous over ~100 $arcmin^2$

GOODS South ACS mosaic



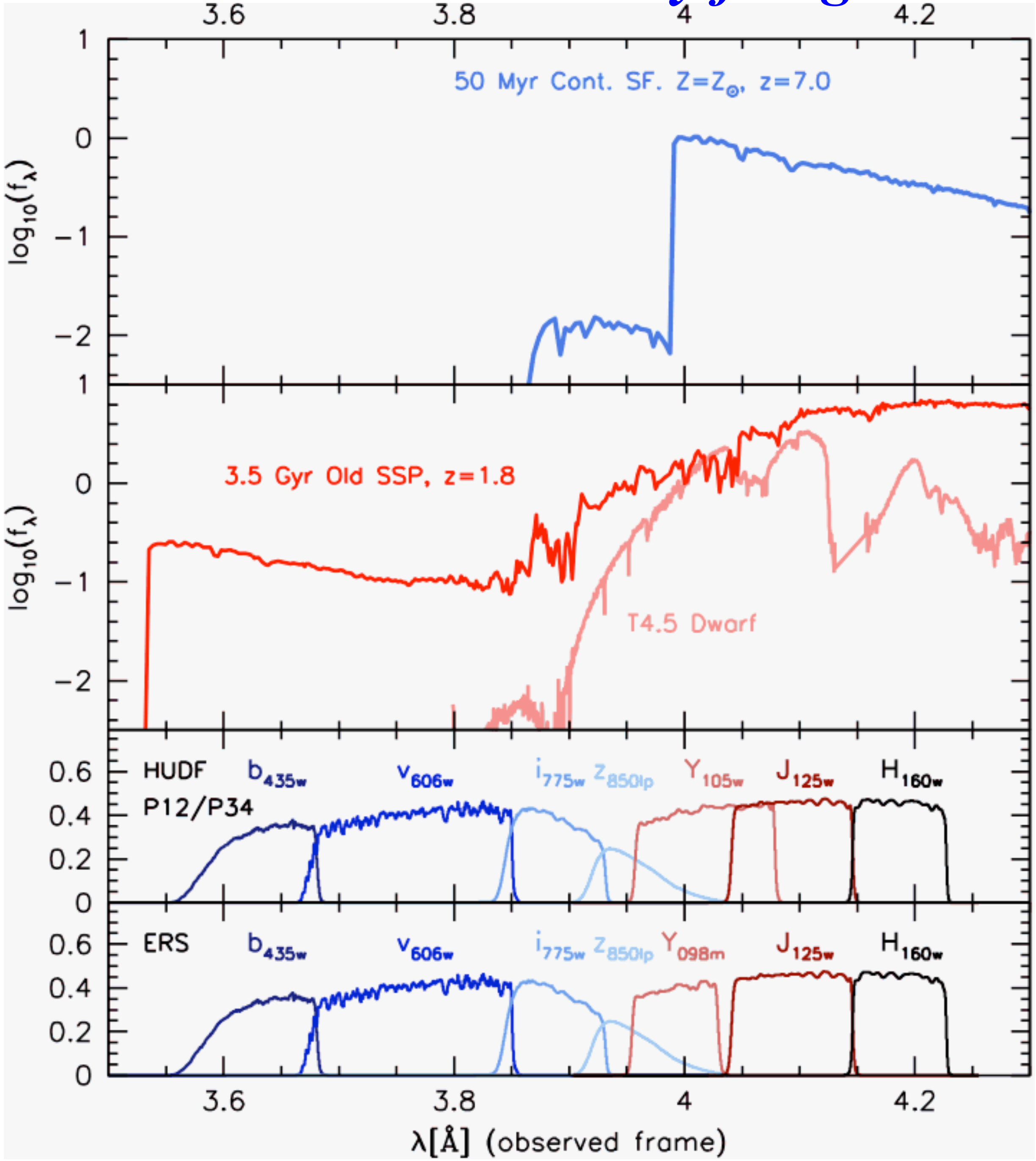


Filter transmission functions of the filters available.

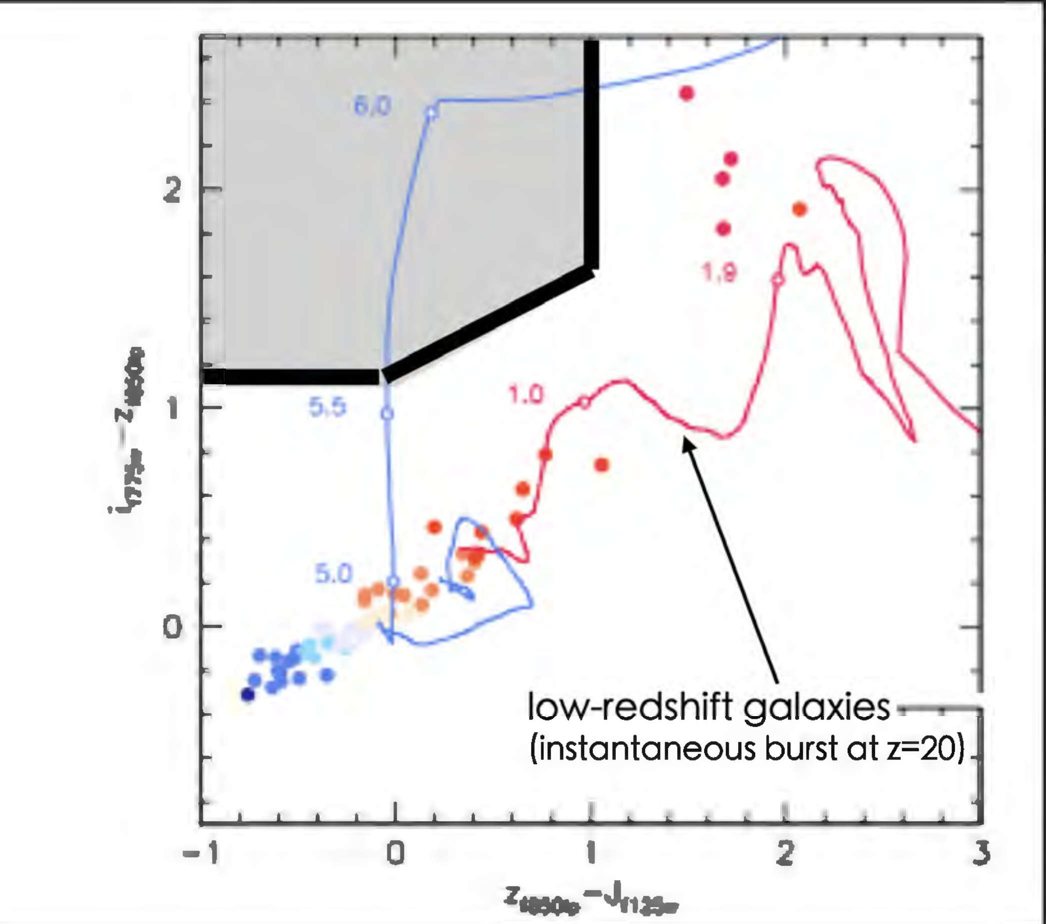


INITIAL EXCITEMENT - 100 orbits of HST with WFC3 in 3 near-IR filters on Hubble Ultra Deep Field. Galaxies at z=7-9! Data first taken in August-Sept. 2009 4 papers immediately (Bouwens et al., Bunker et al., McLure et al., Oesch et al.) and >10 more since. Large HST surveys Illingworth UDF ; WFC3 ERS team – O'Connell ; CANDELS; HUDF12

Concern about Contamination by foreground objects



Contamination: Avoiding stellar and low-redshift galaxy contamination using multiple colours



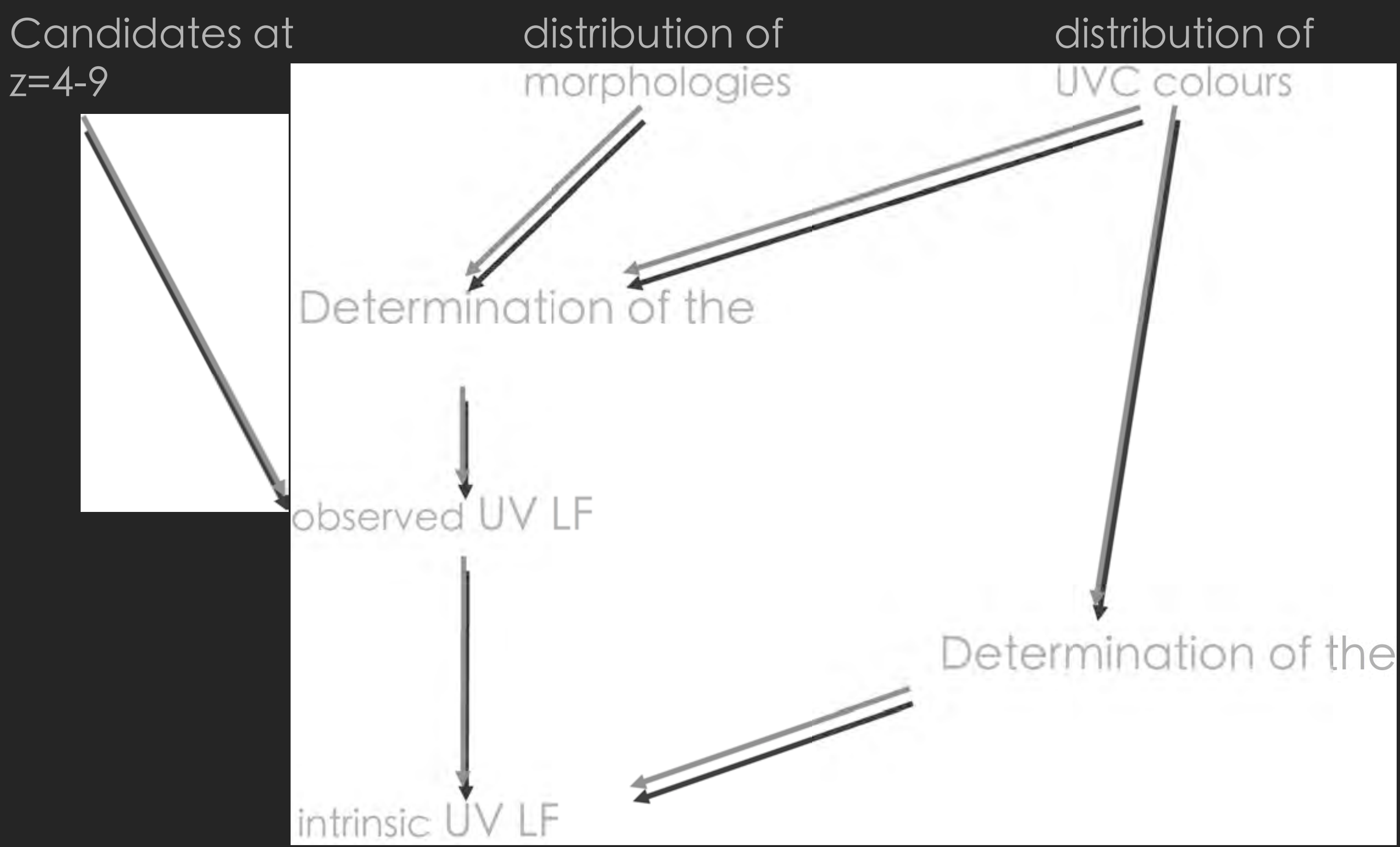
Stellar and low-redshift contamination can be reduced by using additional colour information - the redshift track of a high-redshift galaxy is distinct from lower-redshift and stellar contaminants.

ALSO: optical non-detection criteria further helps remove contamination.

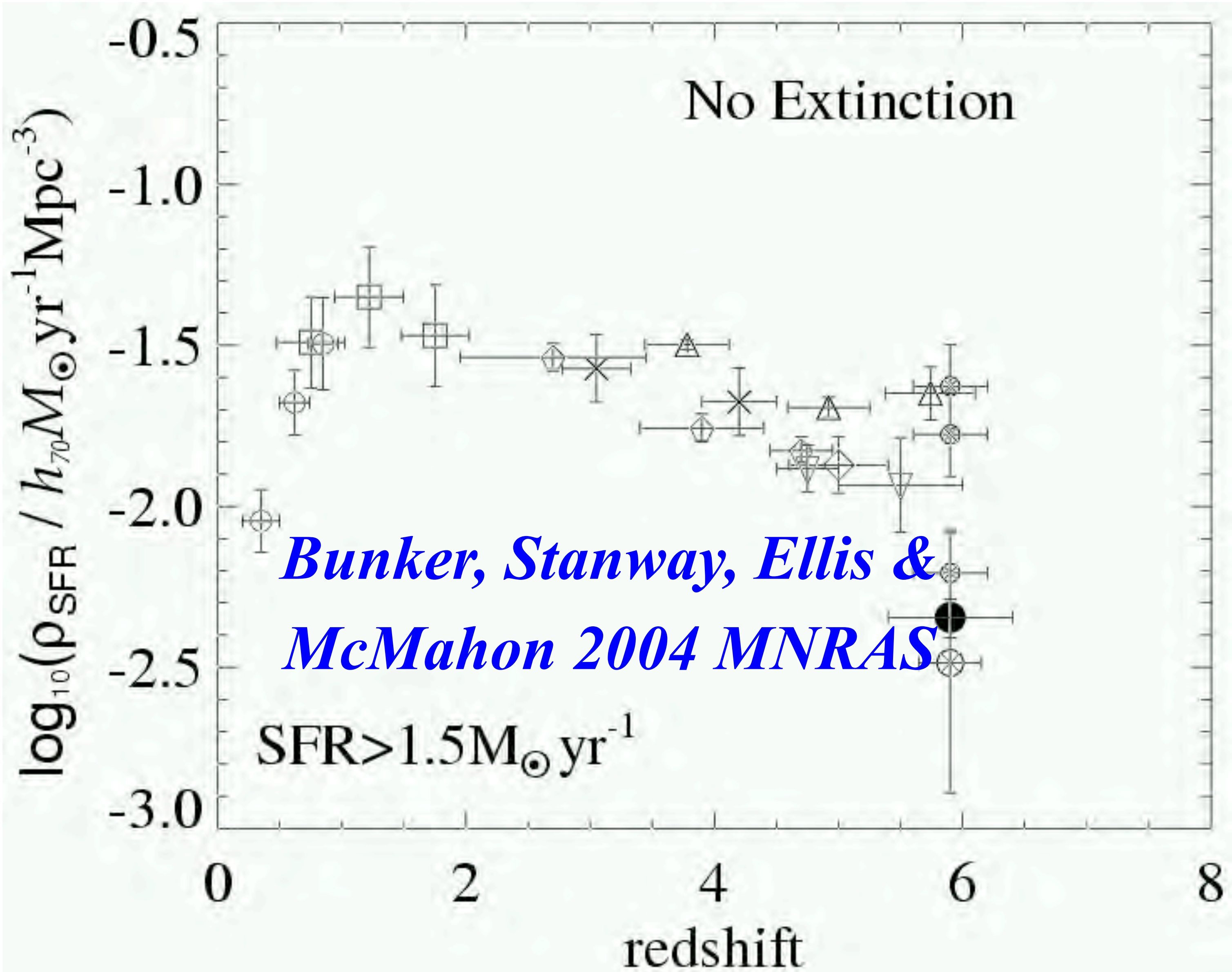
HOWEVER: at faint limits we are still affected by contamination due to photometric scatter. This is partly because the number of observable high-redshift galaxies is much smaller than the total number of observable sources.

What Can we Learn about High-redshift Galaxies:

observed UV Luminosity Function ➟ intrinsic UV Luminosity function



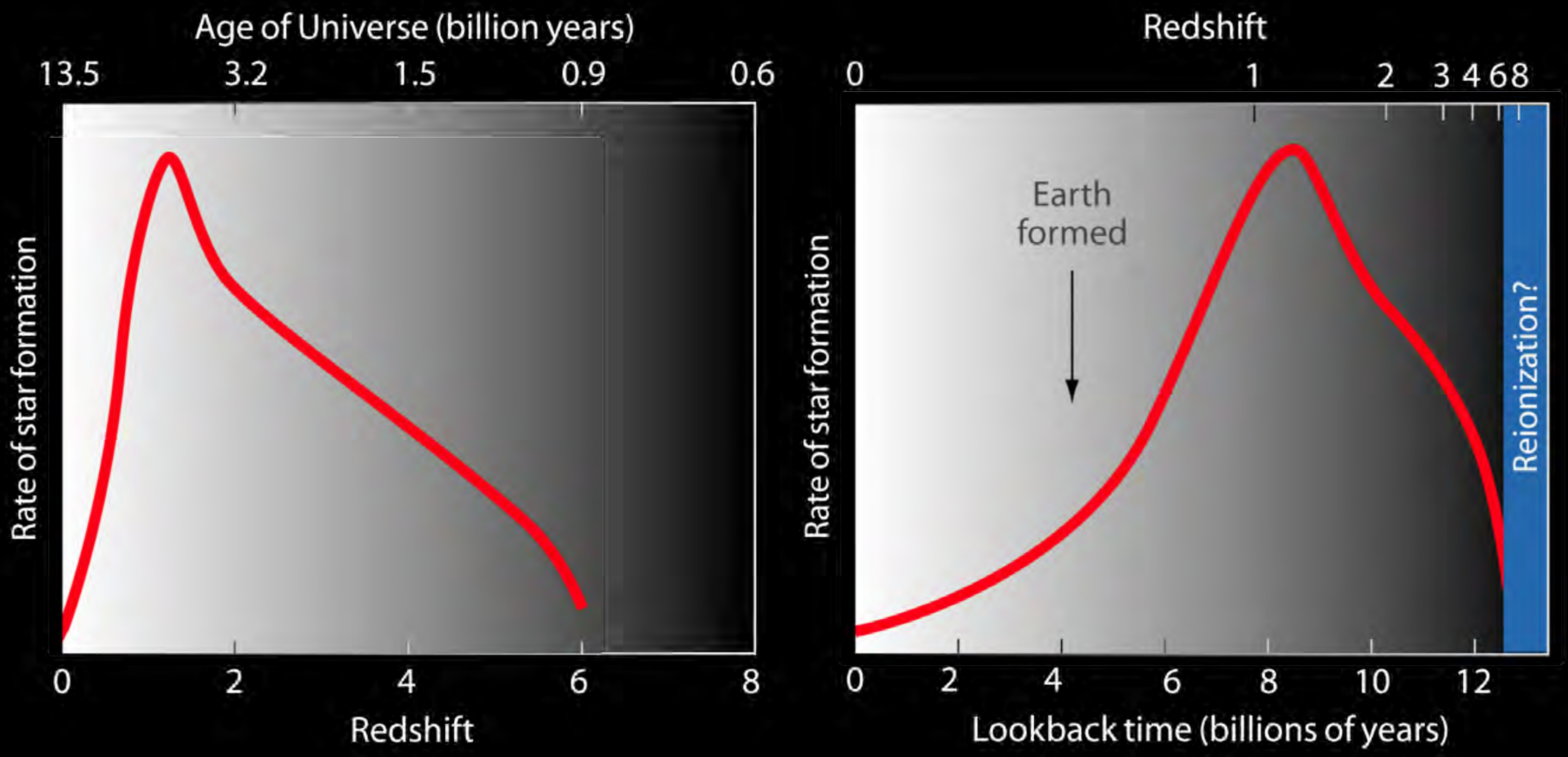
Looking at the UDF (going 10x deeper, z'=26→28.5 mag)



Is the Universe at z>~6 really forming fewer stars than at z~3?

-We only probe bright end of luminosity function:
~1L*(UV) at z~3, equivalent to 15M_sun/yr
- We try to make a fair comparison: impose exactly same selection at lower redshifts
- It seems clear that the Universe at z~6 was very different from z~3: if no evolution, would ***predict 6x as many bright star forming galaxies at z~6 than we see!***
- Other groups make a correction for the faint galaxies they don't see. Depends crucially on the faint end slope of the luminosity function (α~-1.1 locally, α=-1.6@z~3)
- Need Hubble Ultra Deep Field to address total star formation, but we had proved ***strong evolution***.

Star formation history of the Universe



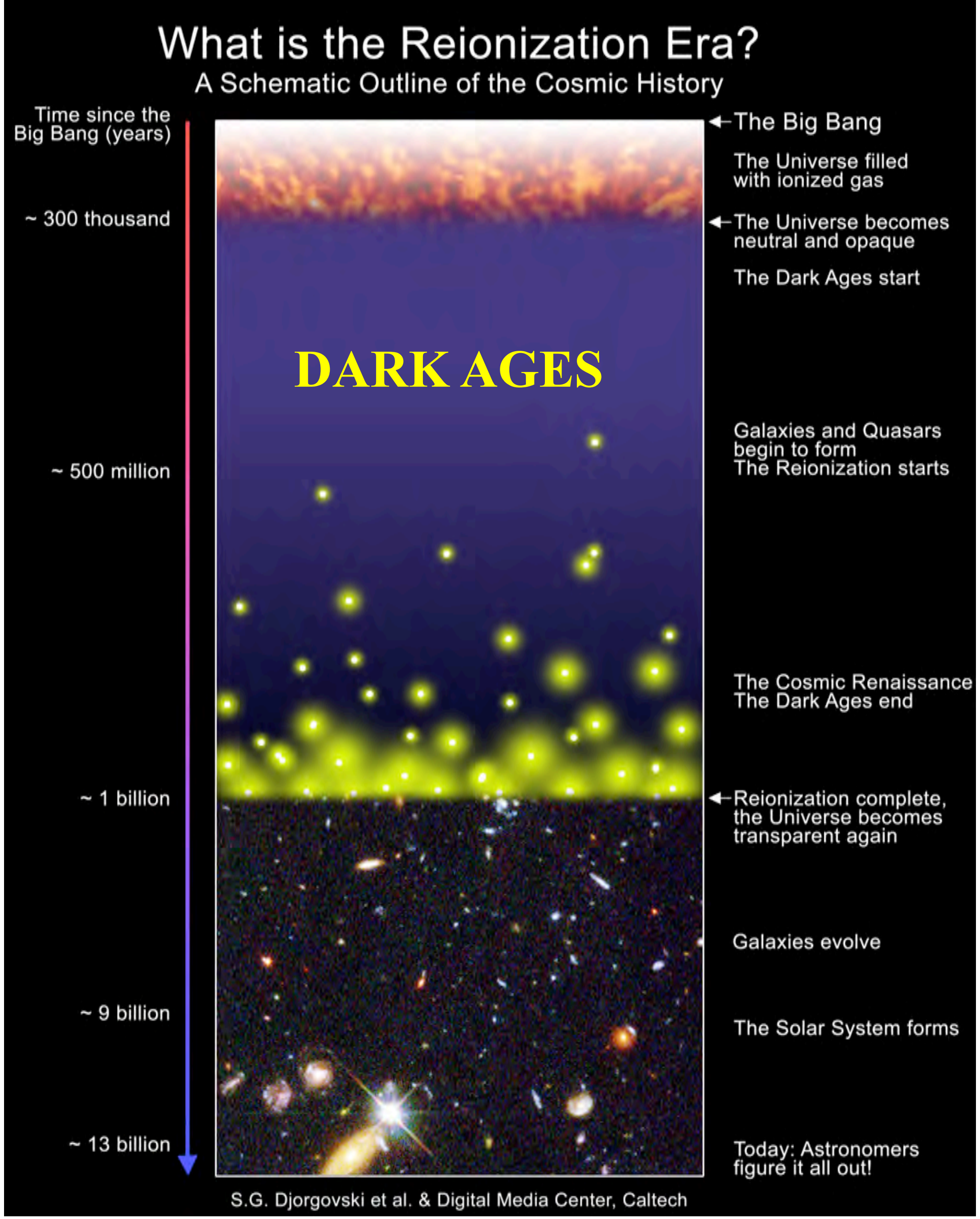
- ***UDF enables us to identify even fainter galaxies at these times*** *(end of dark ages)*
- ***We were first to analyse & publish 50 high redshift galaxies in the UDF***
- ***Confirms our previous work: much LESS star formation than in more recent past***

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?



Redshift z

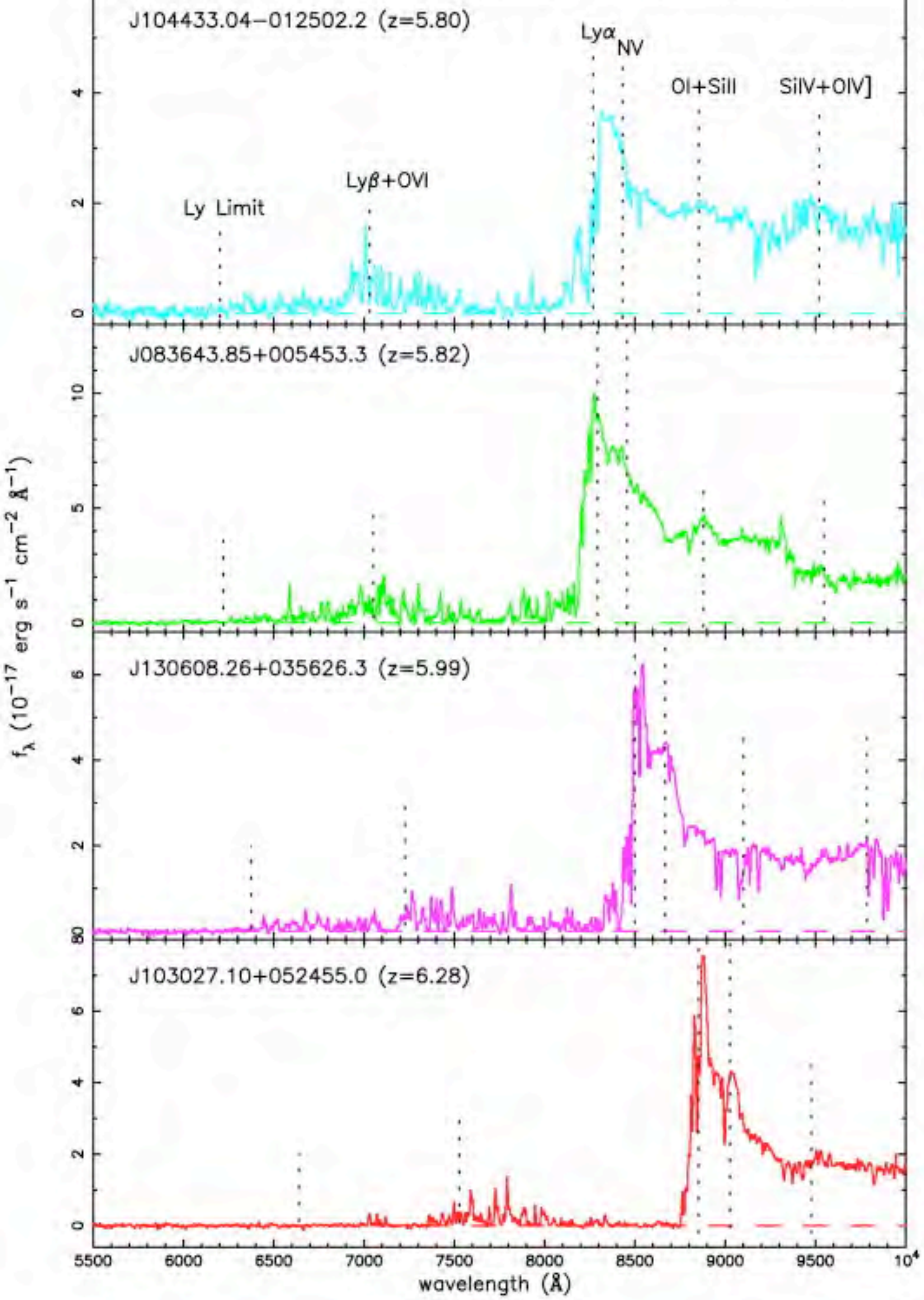
1100

10

5

2

0



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 messages from WMAP and Planck CMB - reionization at z~11.4? (Dunkley et al. 2010; Planck collab. 2013).

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)

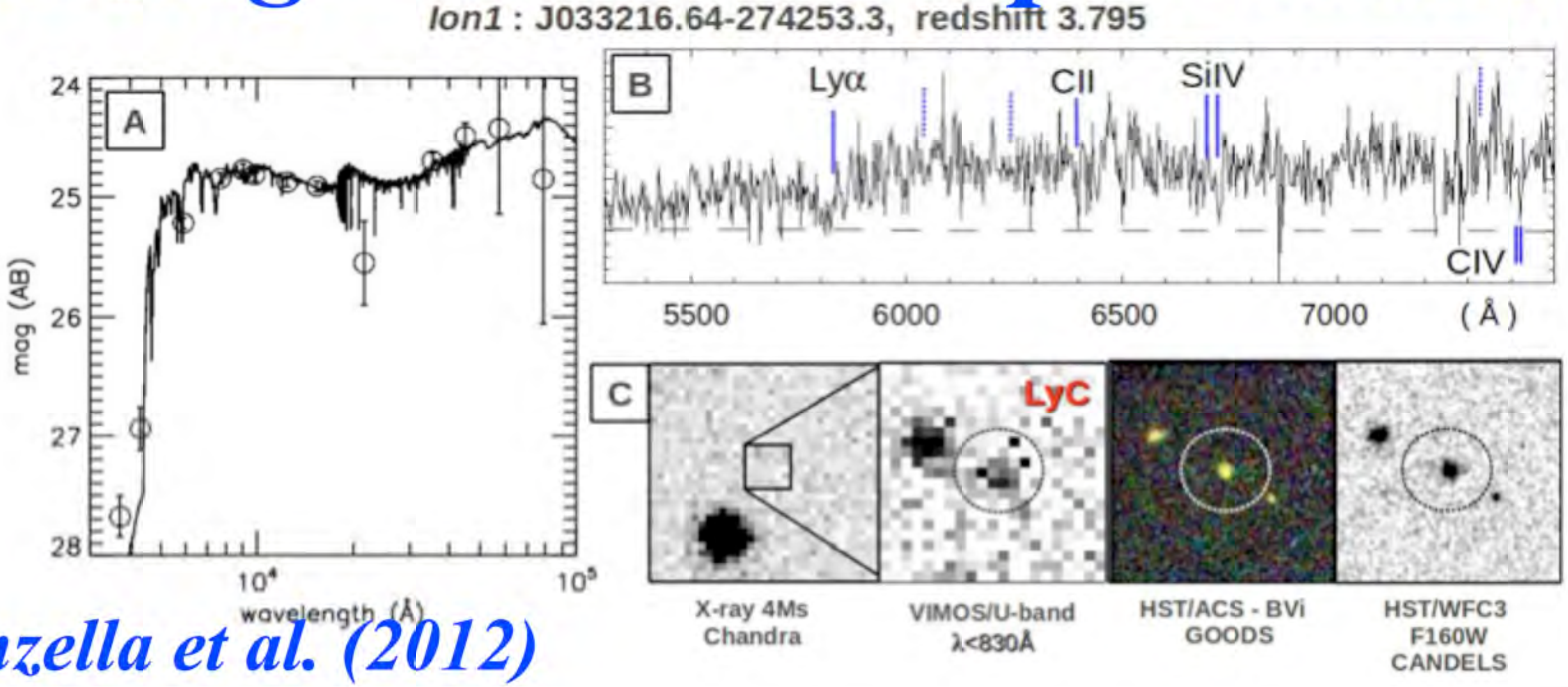
Our HUDF data has star formation at z=6 which is 3x *less* than that required! AGN cannot do the job.

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)

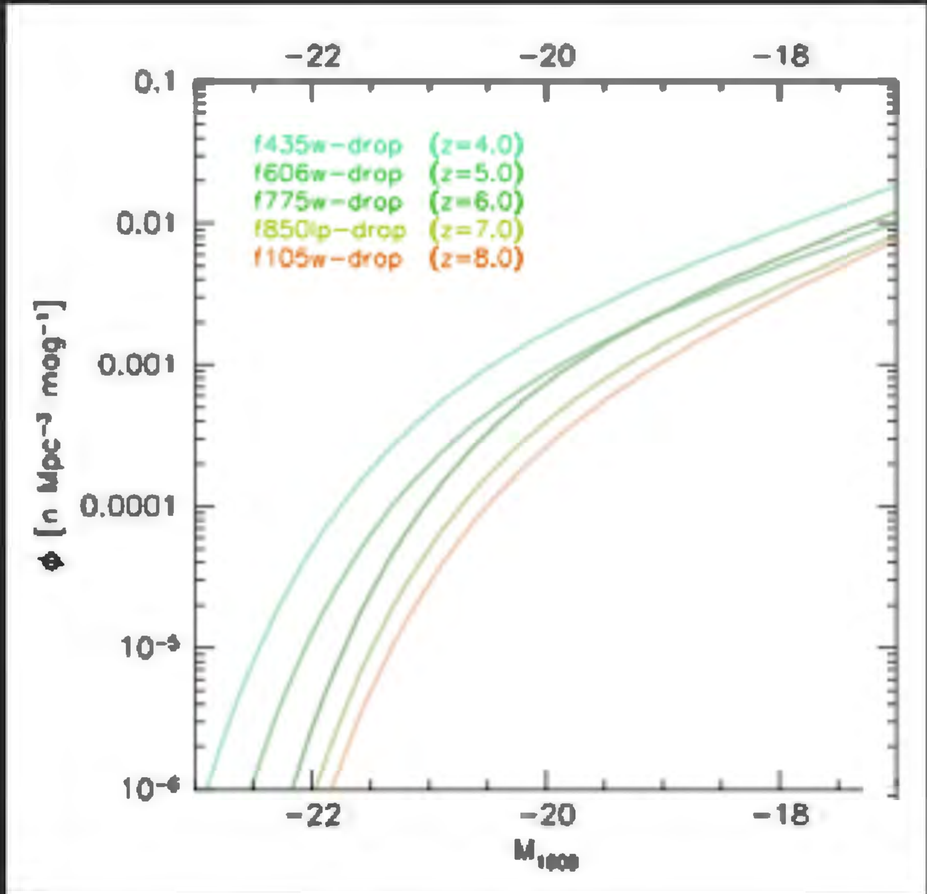
What Can we Learn about High-redshift Galaxies:

observed UV Luminosity Function

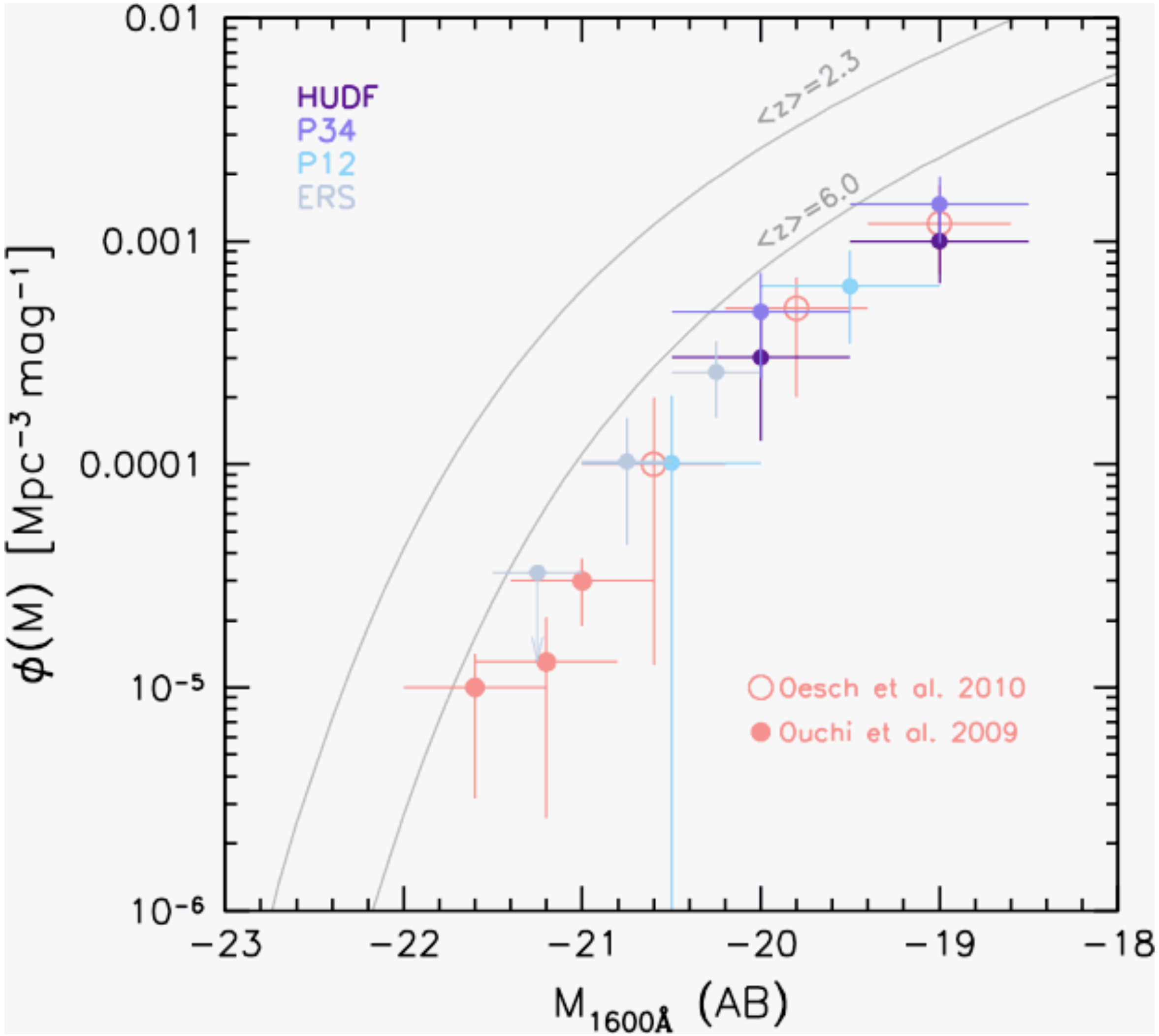
The accurate determination of the UV LF requires careful modelling of the various biases that may affect the ability to identify galaxies. These include the apparent magnitude (fainter galaxies are more difficult to select), the intrinsic colour (we are biased against red galaxies), and morphology (biased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

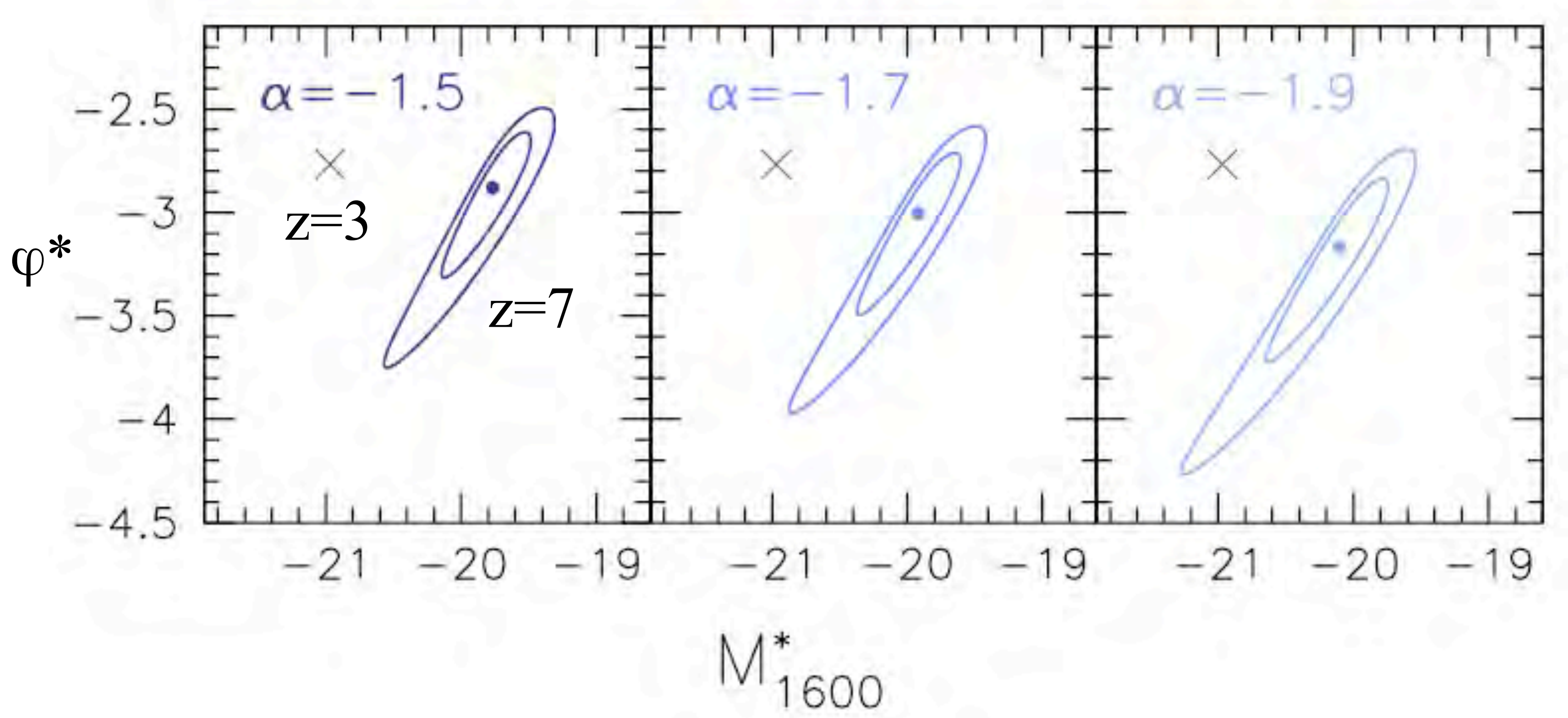


Observed UV LFs at various redshifts



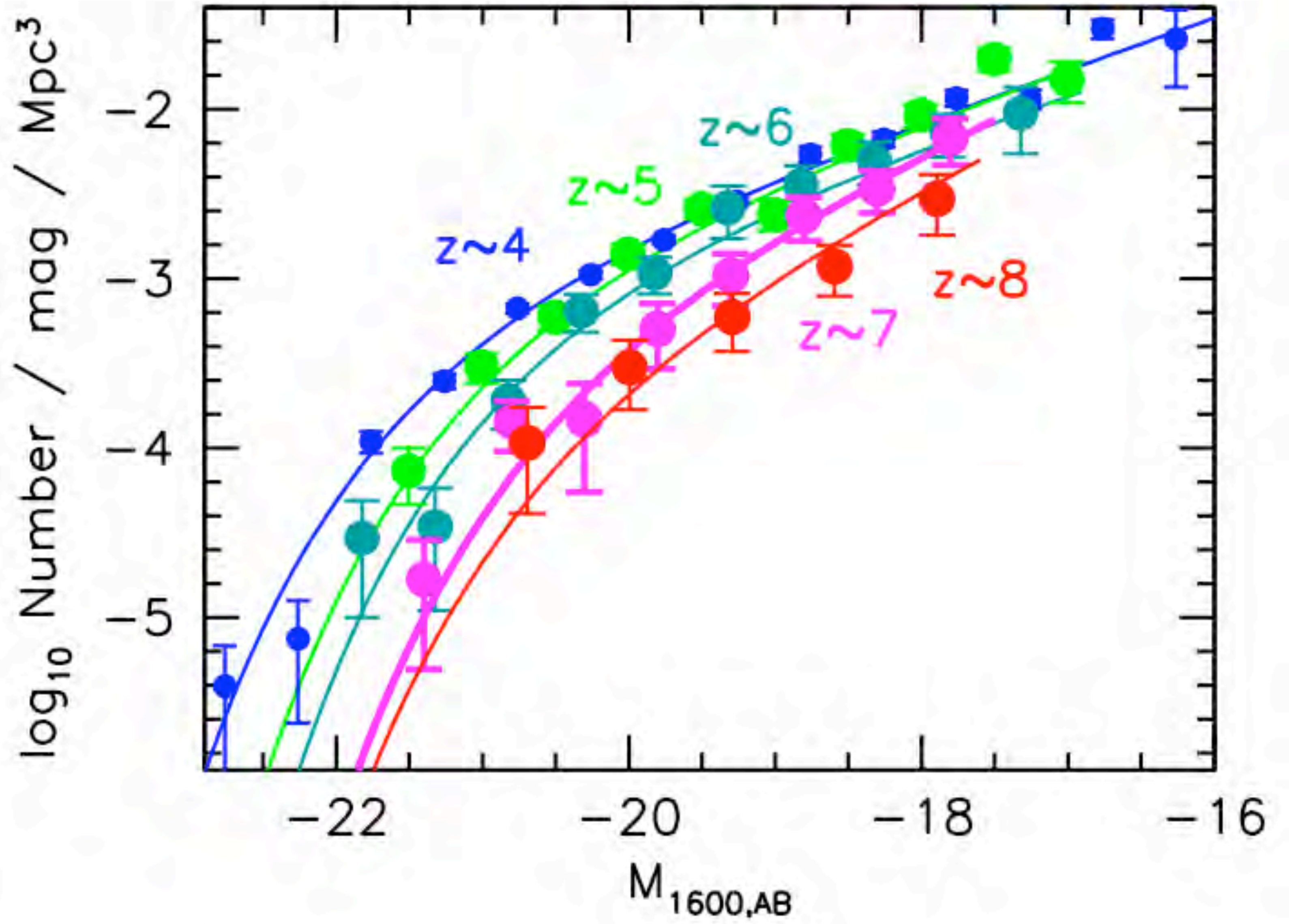
Wilkins et al. (2010) MNRAS The Luminosity Function at z~7

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)



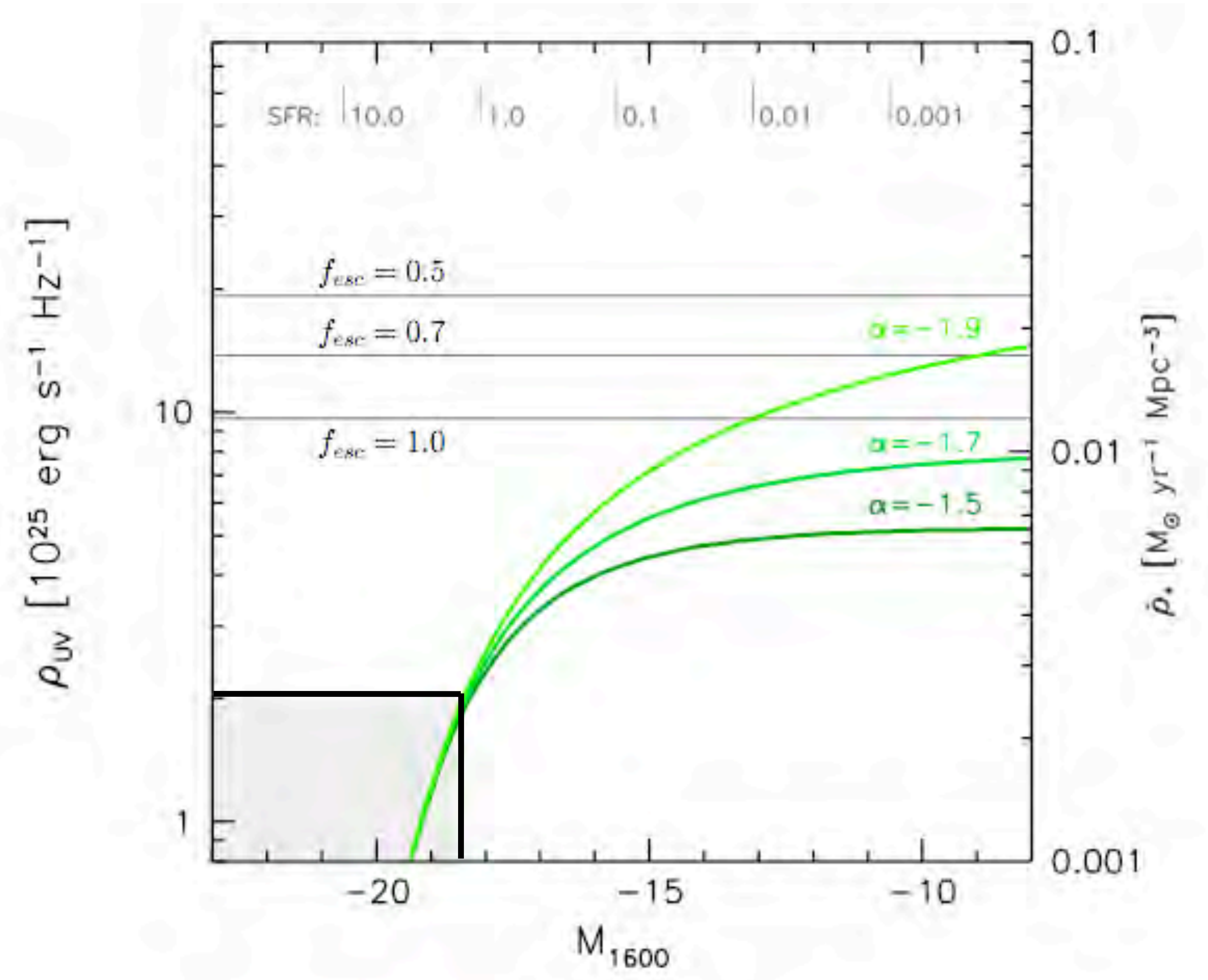
Evolution of luminosity function
(note M* is correlated with φ*)

Wilkins et al. (2011)

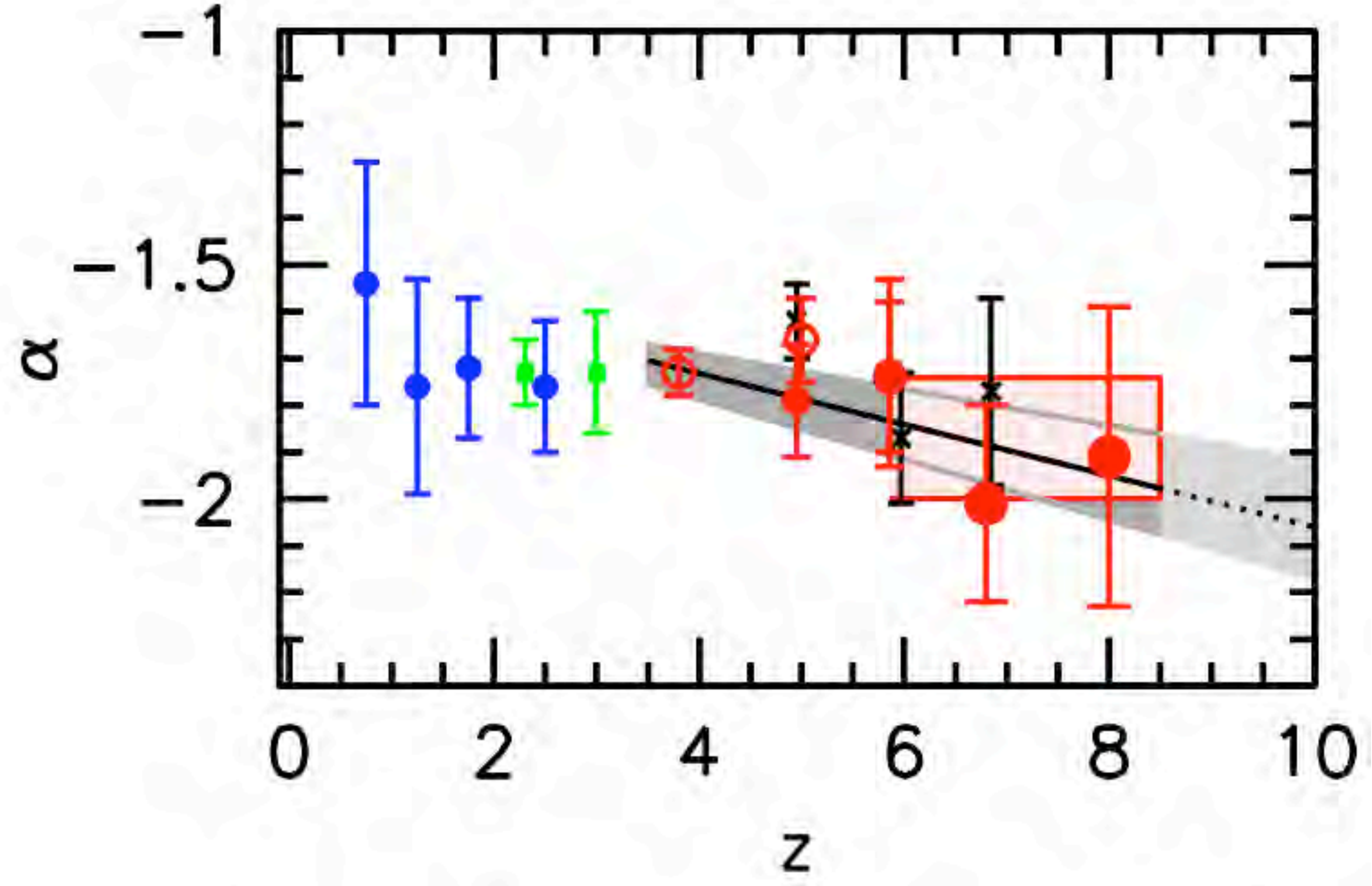


Evolution of the restframe UV luminosity function

From Bouwens et al. (2011)



Wilkins et al. (2010)



Evolution of the restframe UV faint end slope

From Bouwens et al. (2011)

The Importance of Dwarf Galaxies?

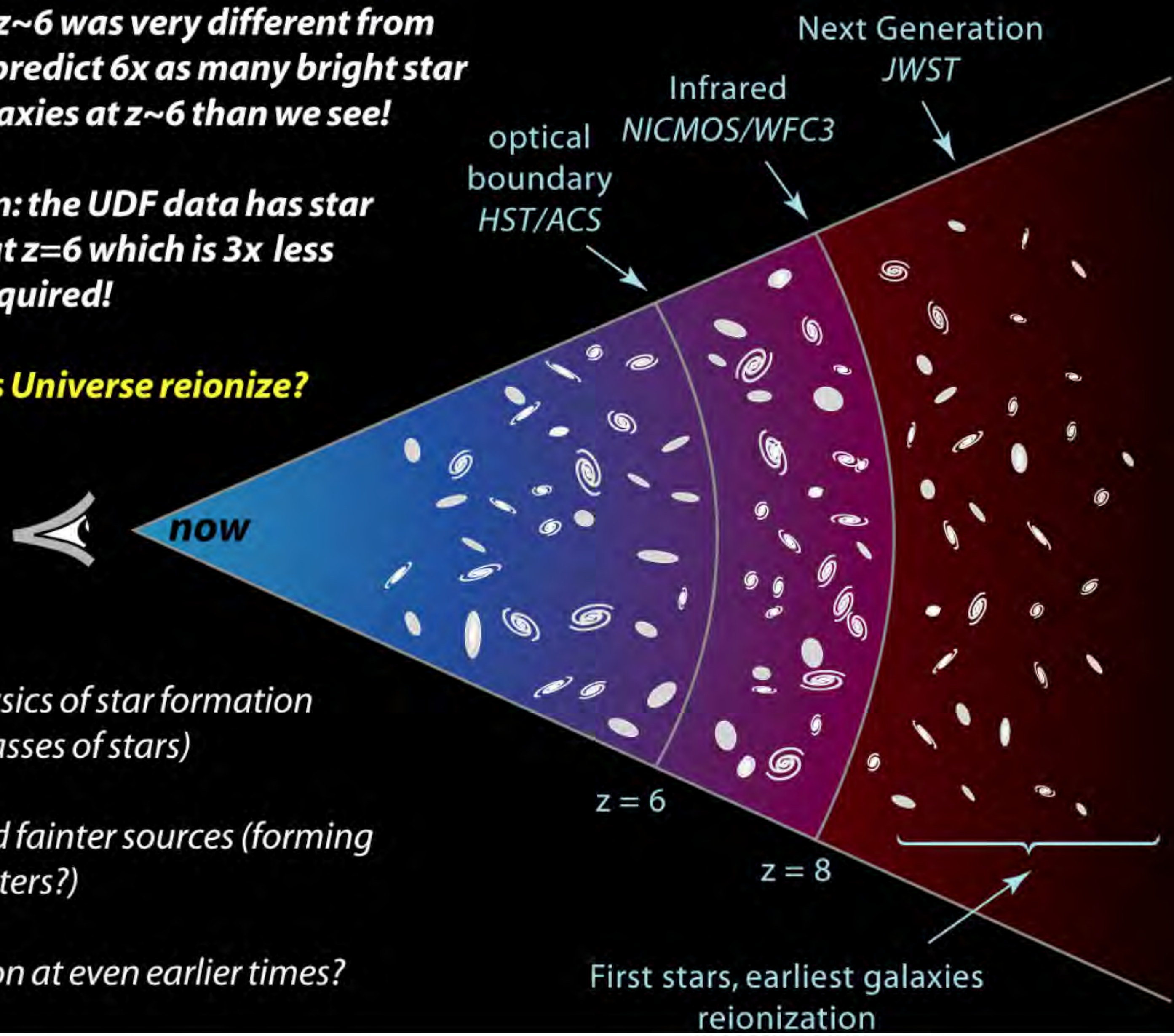
- Even with HUDF only get to M(UV)=-18.5 (AB mag), or ~1M_sun/year star formation rate
- Certainly insufficient UV photon density from these UV-luminous galaxies @z>6 for reionization
- Evidence for a steeper faint end slope at high-z
- At low-z, most of the photon budget comes from galaxies around L* if α~-1. NB: UV not stellar mass
- If α<-2 you get infinite luminosity (integrating to L=0); what should lower integral limit be?
- M_{UV}=-10? Or luminosity of a single OB star (-5)?
- What is local LF of dwarf galaxies in the rest-UV?

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?*

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?

Blue Rest-UV Colours at z~6 (Stanway et al. 2005)

Mon. Not. R. Astron. Soc. **359,** 1184–1192 (2005) doi:10.1111/j.1365-2966.2005.08977.x

Near-infrared properties of *i*-drop galaxies in the *Hubble Ultra Deep Field*

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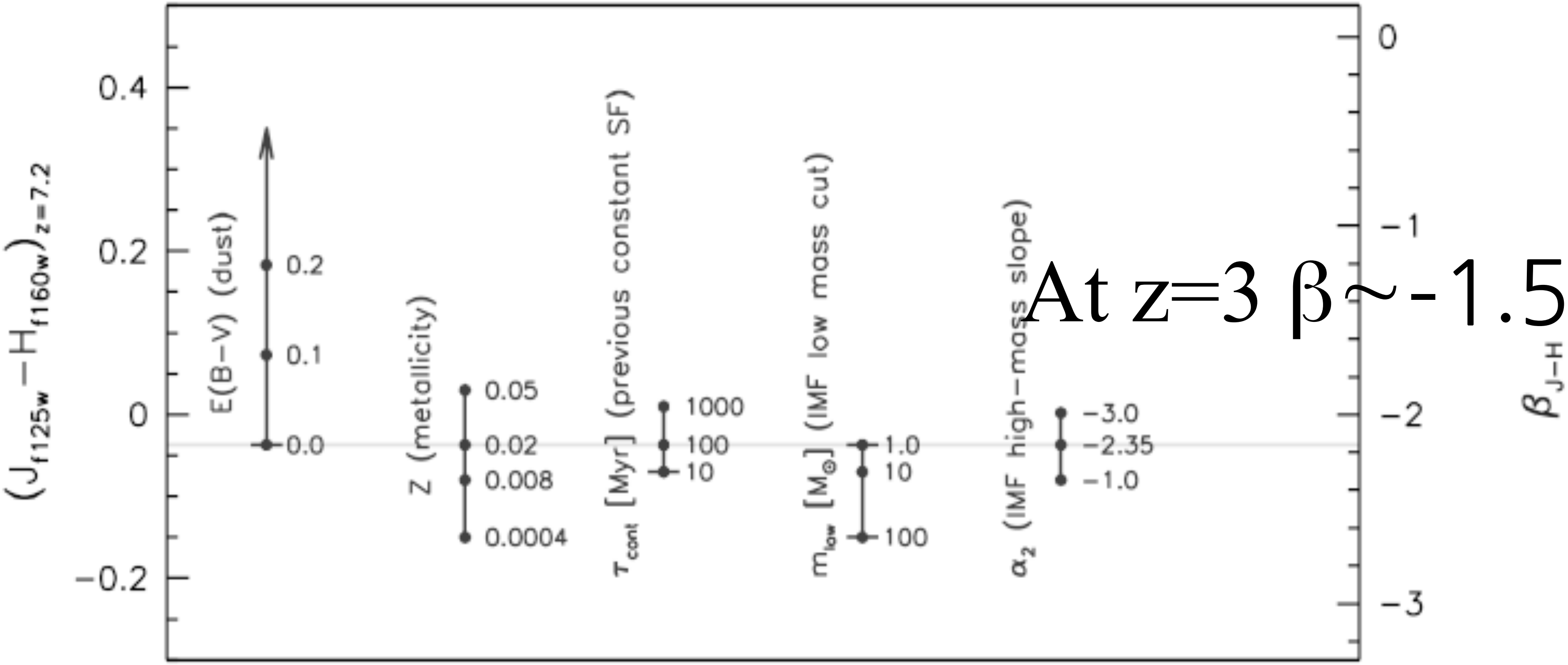
...extremely young starburst... or a top heavy IMF and little dust

ABSTRACT

We analyse near-infrared *Hubble Space Telescope* (*HST*)/Near-Infrared Camera and Multi-Object Spectrometer *F*110*W* (*J*) and *F*160*W* (*H*) band photometry of a sample of 27 i'-drop candidate $z \simeq 6$ galaxies in the central region of the *HST*/Advanced Camera for Surveys *Ultra Deep Field*. The infrared colours of the 20 objects not affected by near neighbours are consistent with a high-redshift interpretation. This suggests that the low-redshift contamination of this i'-drop sample is smaller than that observed at brighter magnitudes, where values of 10–40 per cent have been reported. The [illegible] consistent with a slope flat in $f_\nu (f_\lambda \propto \lambda^{-2})$ [illegible] be expected for an unreddened starburst. However, there is [illegible] marginally bluer spectral slope ($f_\lambda \propto \lambda^{-2.2}$), which is perhaps indicative of an extremely young starburst (~10 Myr old) or a top heavy initial mass function and little dust. The low levels of [illegible]mination, median photometric redshift of $z \sim 6.0$ and blue spectral slope, inferred [illegible] the near-infrared data, [illegible] earlier work in estimating the star formation rates, and that the majority of the *i*-drop candidates galaxies lie at $z \sim 6$.

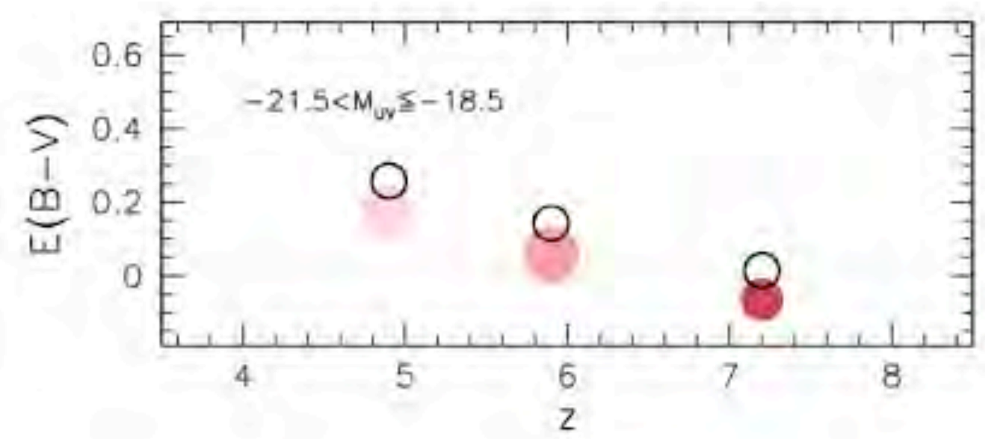
UV Spectral Slopes at z>6 : $f_\lambda \propto \lambda^{-\beta}$

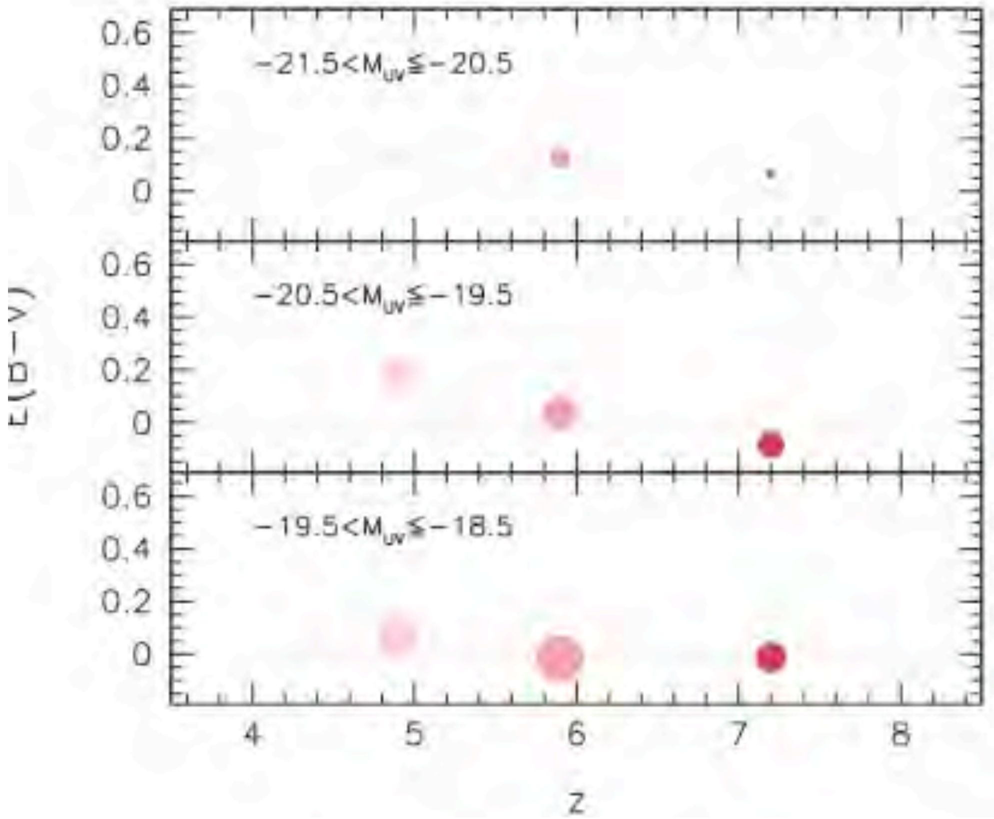


At z=3 β~-1.5

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

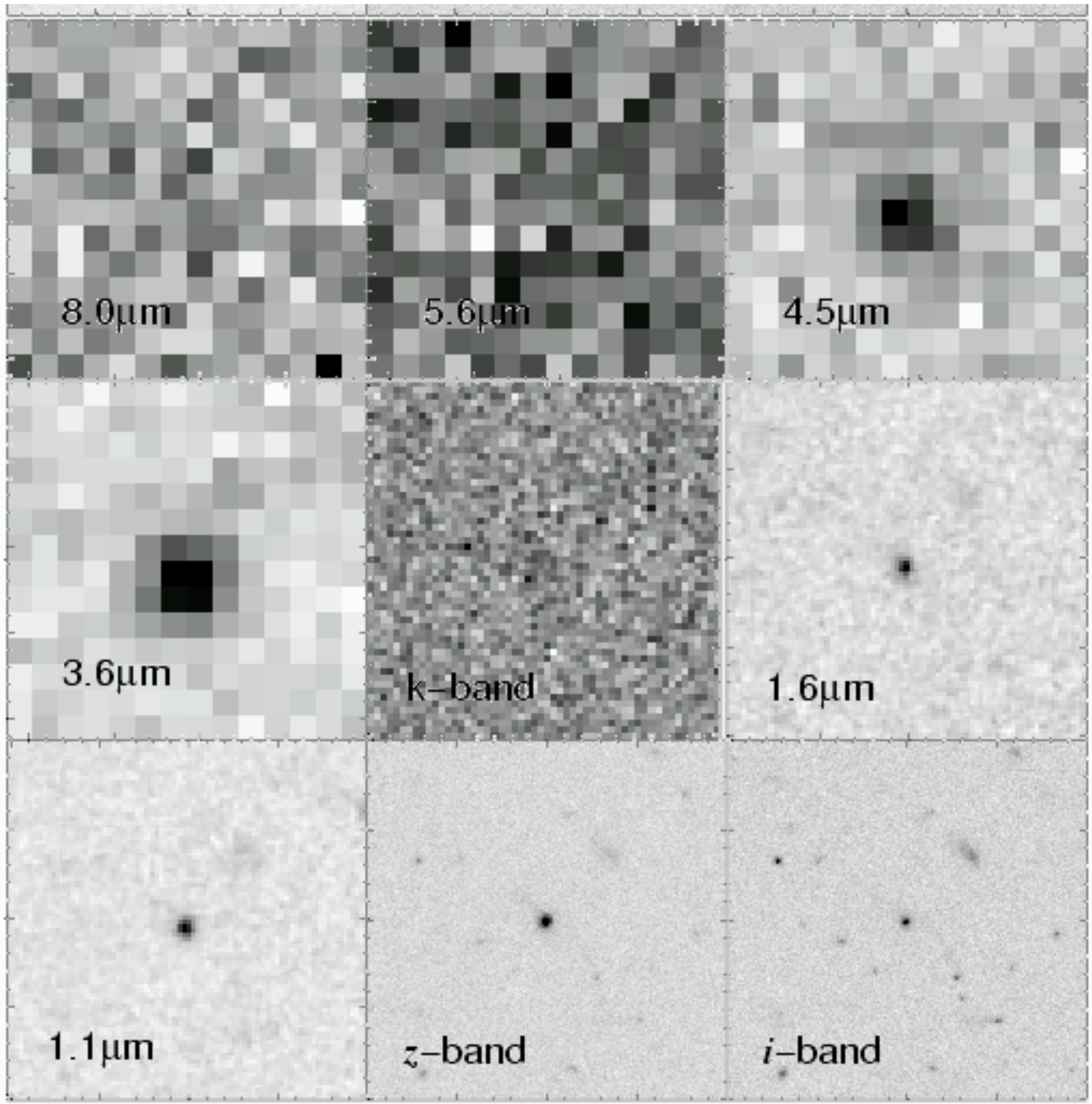
Also now seen in z-drops with WFC3 (Bouwens et al. 2011, Dunlop et al. 2011, Wilkins et al. 2011)



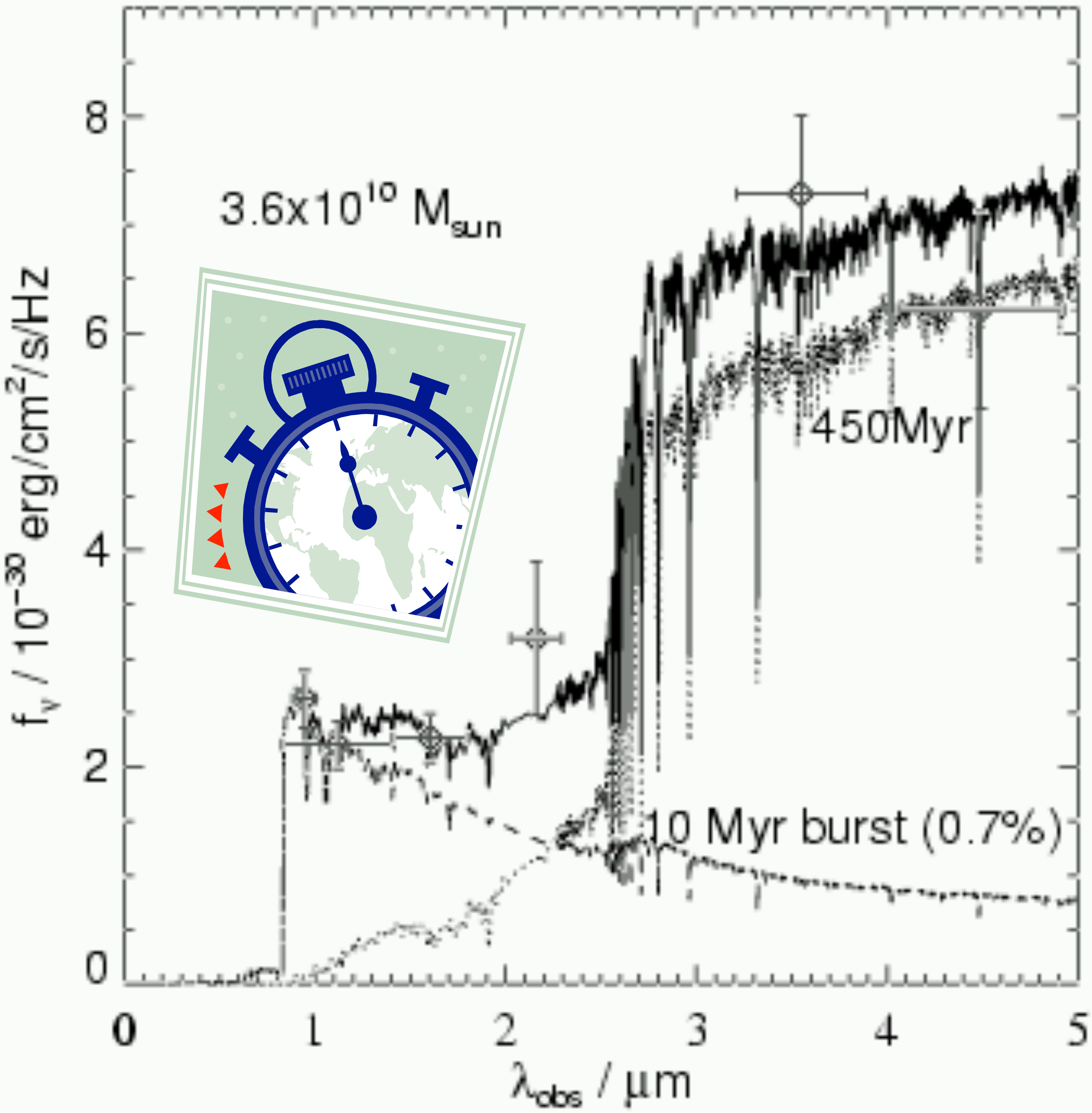


- From Wilkins et al. (2011) MNRAS
- Weak dependence of beta evolution on luminosity
- Careful on filters - the Lyman-alpha break will redden intrinsic colours
- Strong evidence of bluer spectral slopes at high z

Spitzer – IRAC (3.6-8.0 microns)



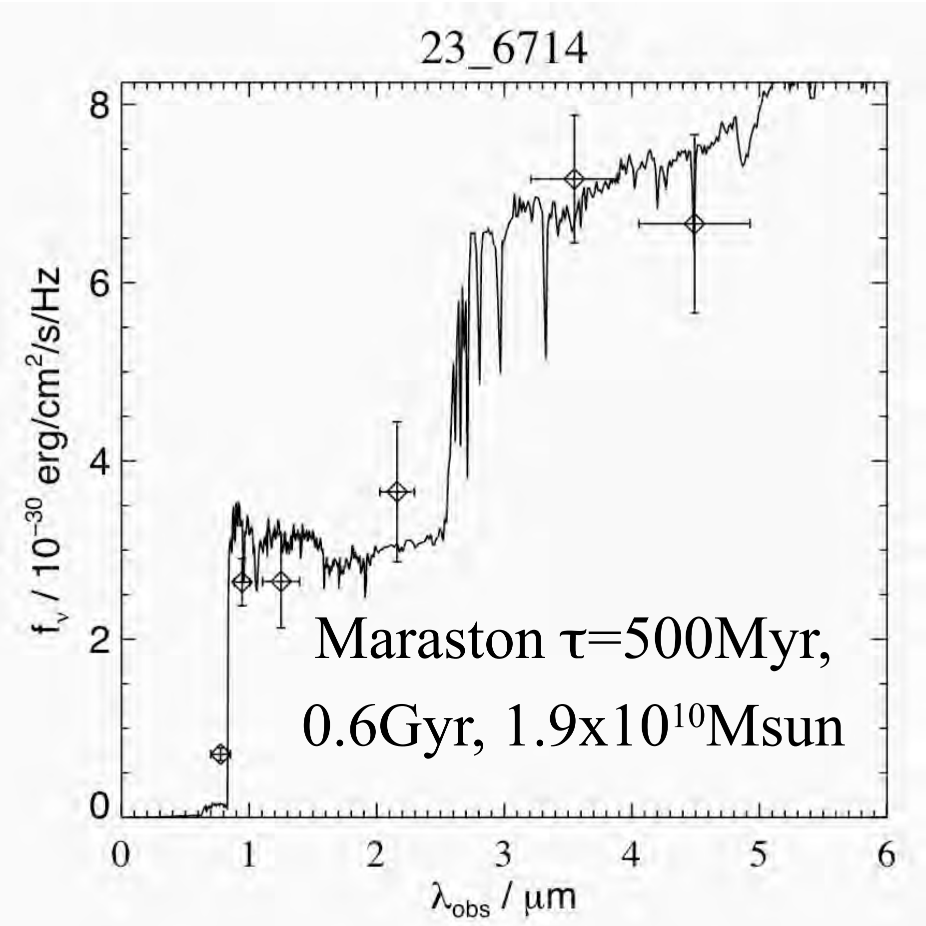
- z=5.83 galaxy #1 from Stanway, Bunker & McMahon 2003 (spec conf from Stanway et al. 2004, Dickinson et al. 2004). Detected in GOODS IRAC 3-4μm: Eyles, Bunker, Stanway et al ‘04

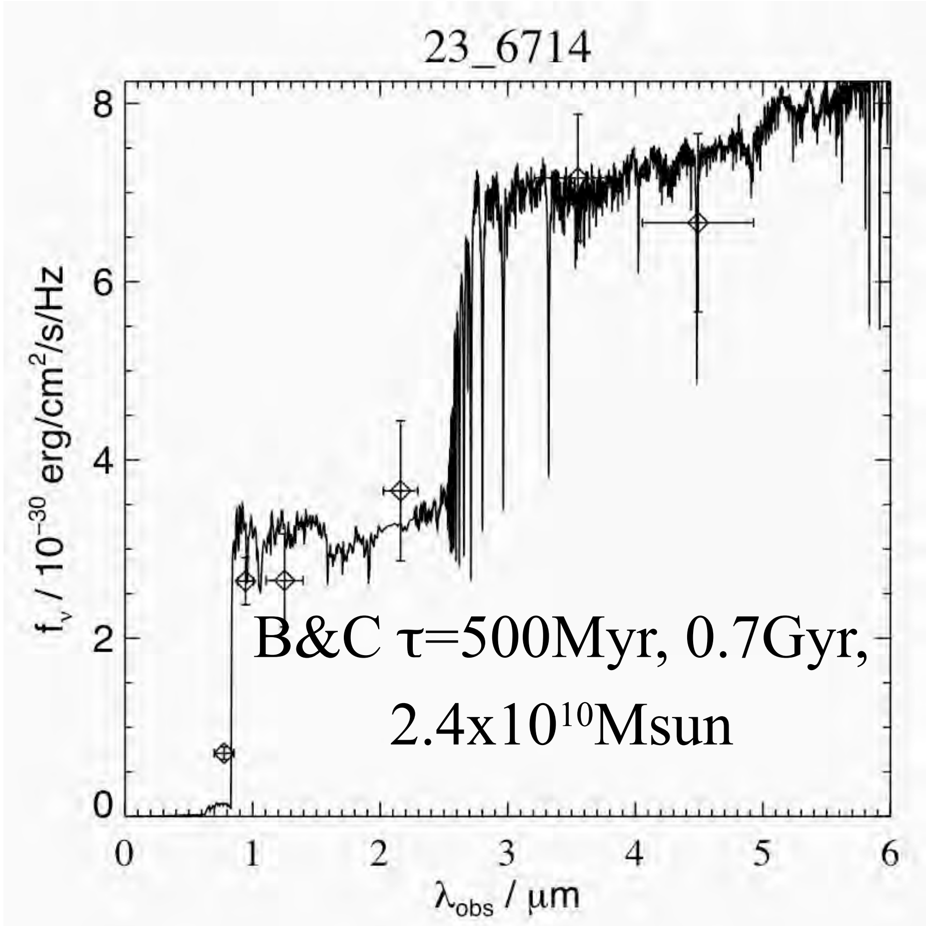


Eyles et al. (2005, 2007) MNRAS

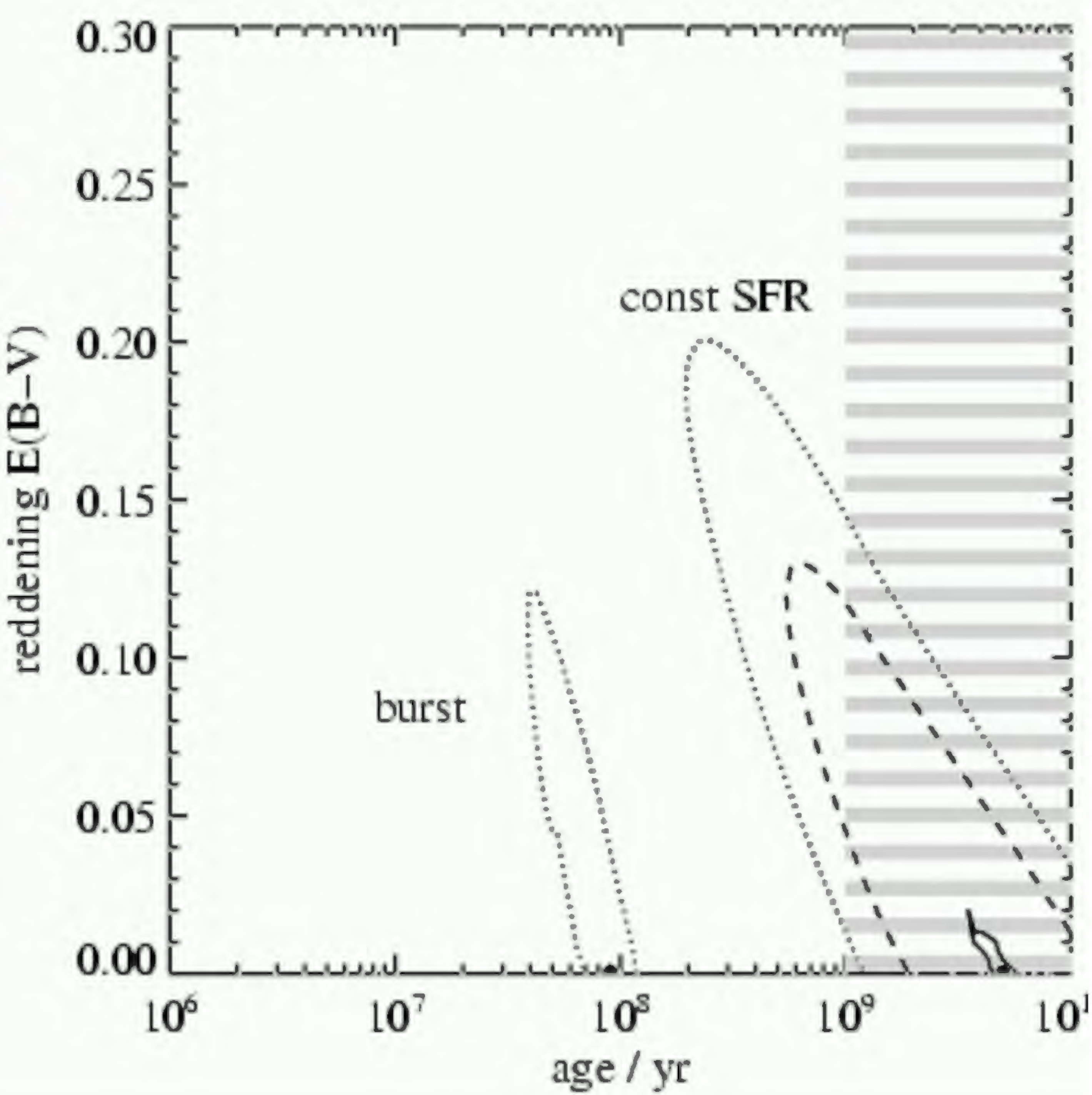
Emission line contamination from H-alpha/H-beta/[OIII] might affect the derived ages and masses

Other Population Synthesis Models

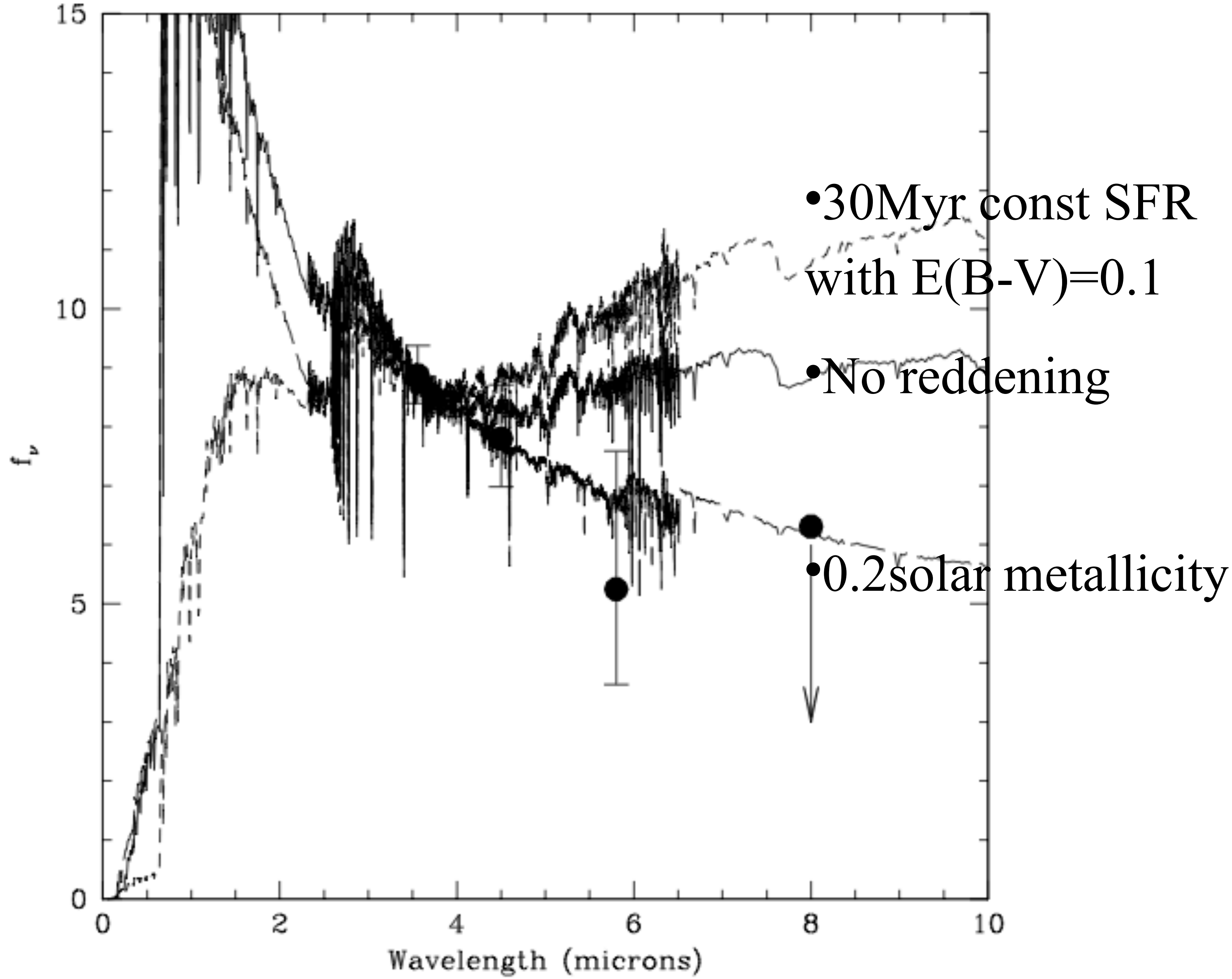




Maraston vs. Bruzual & Charlot - consistent



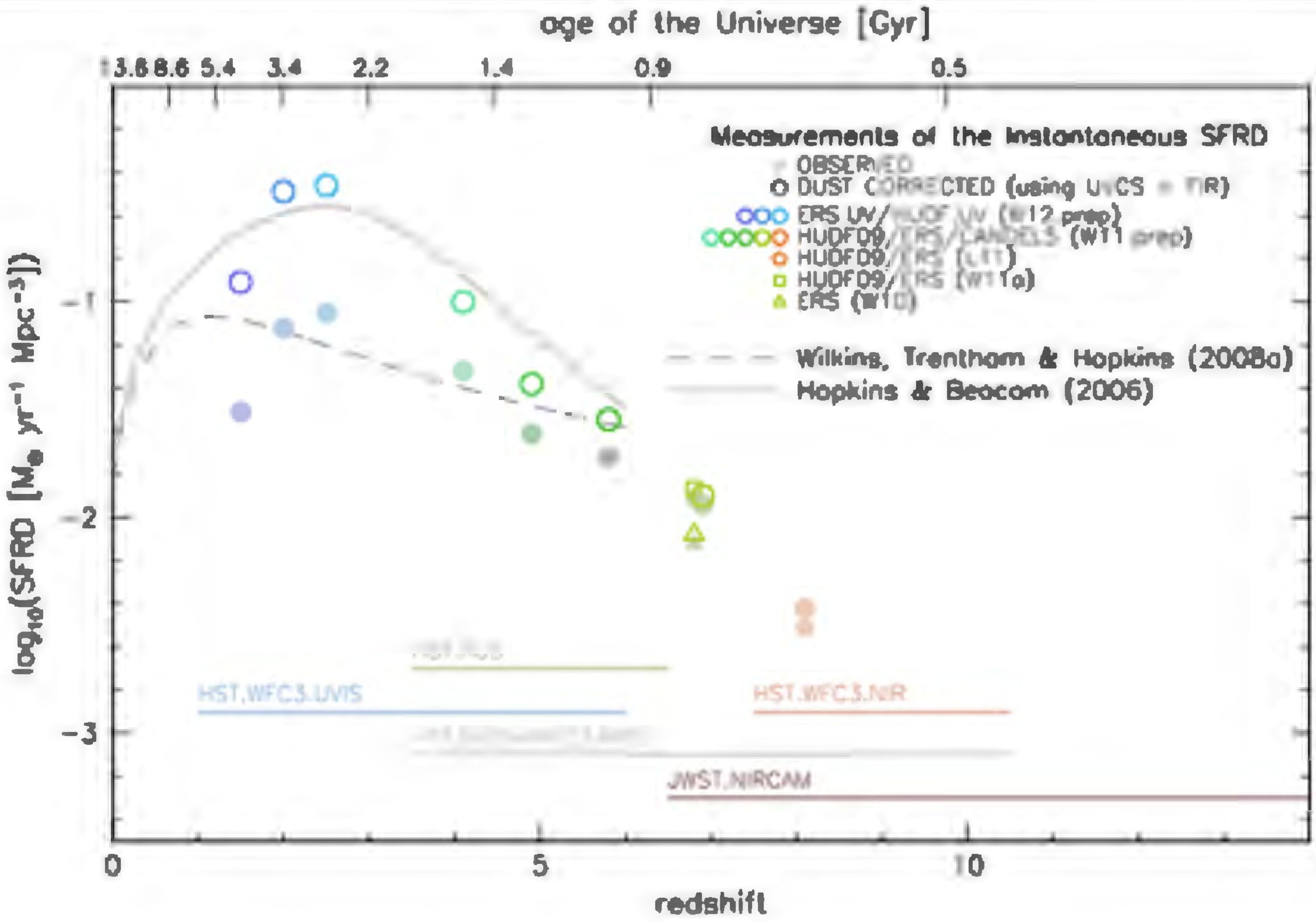
0.30
0.25
0.20
0.15
0.10
0.05
0.00
reddening E(B–V)
const SFR
burst
10^6
10^7
10^8
10^9
10^1
age / yr



•30Myr const SFR
with E(B-V)=0.1
•No reddening
•0.2solar metallicity
f_ν
Wavelength (microns)
0
2
4
6
8
10
5
15

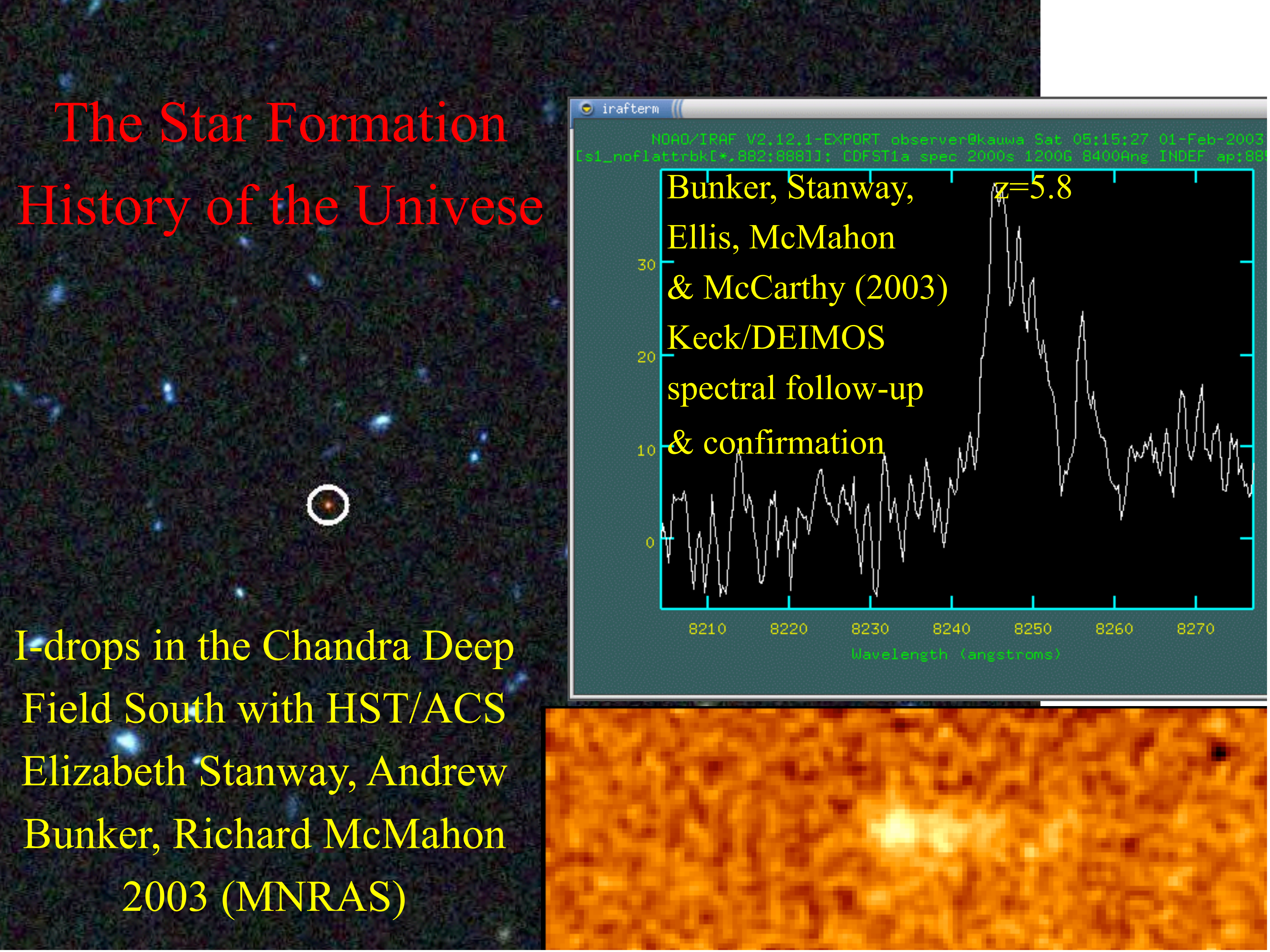
What Can we Learn about High-redshift Galaxies:

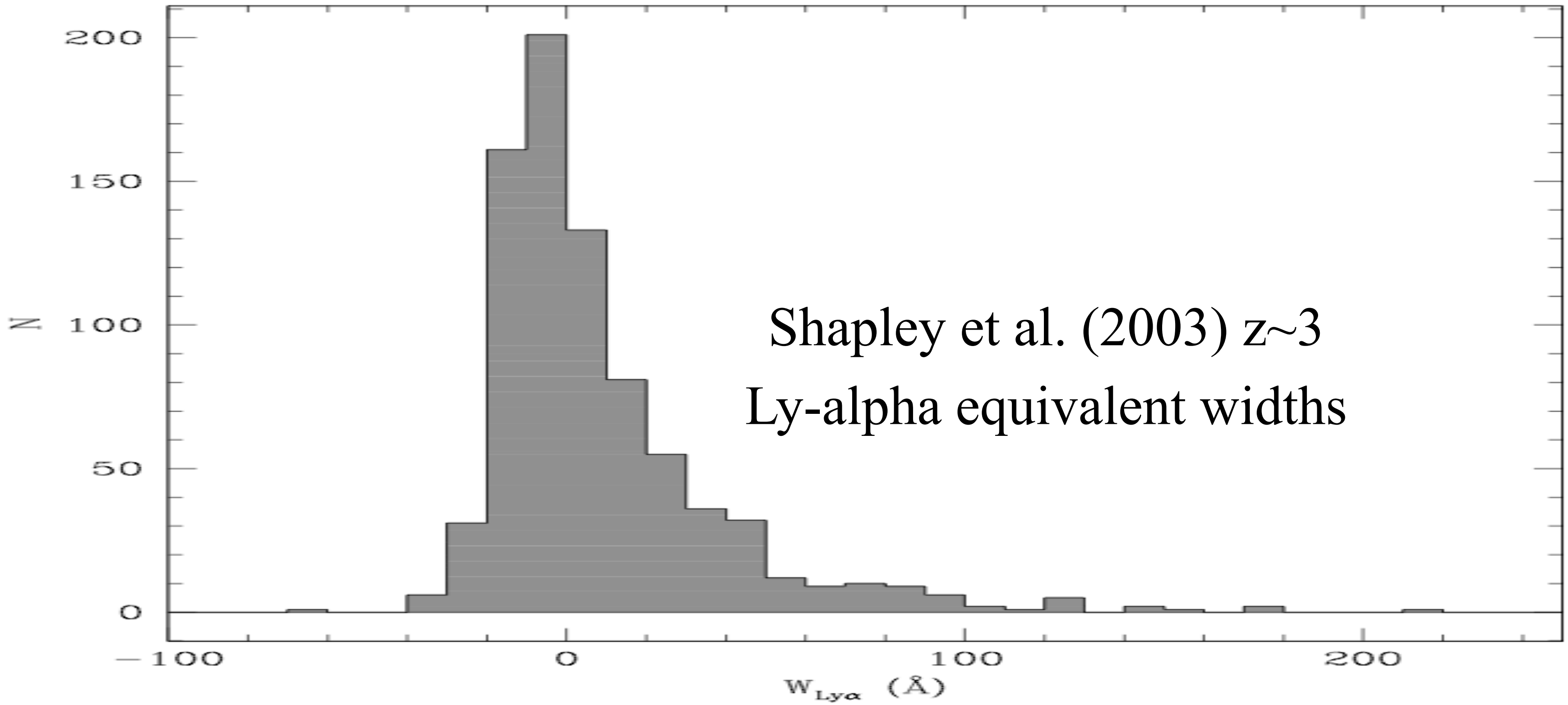
➠ star formation rate density ➠ cosmic star formation history



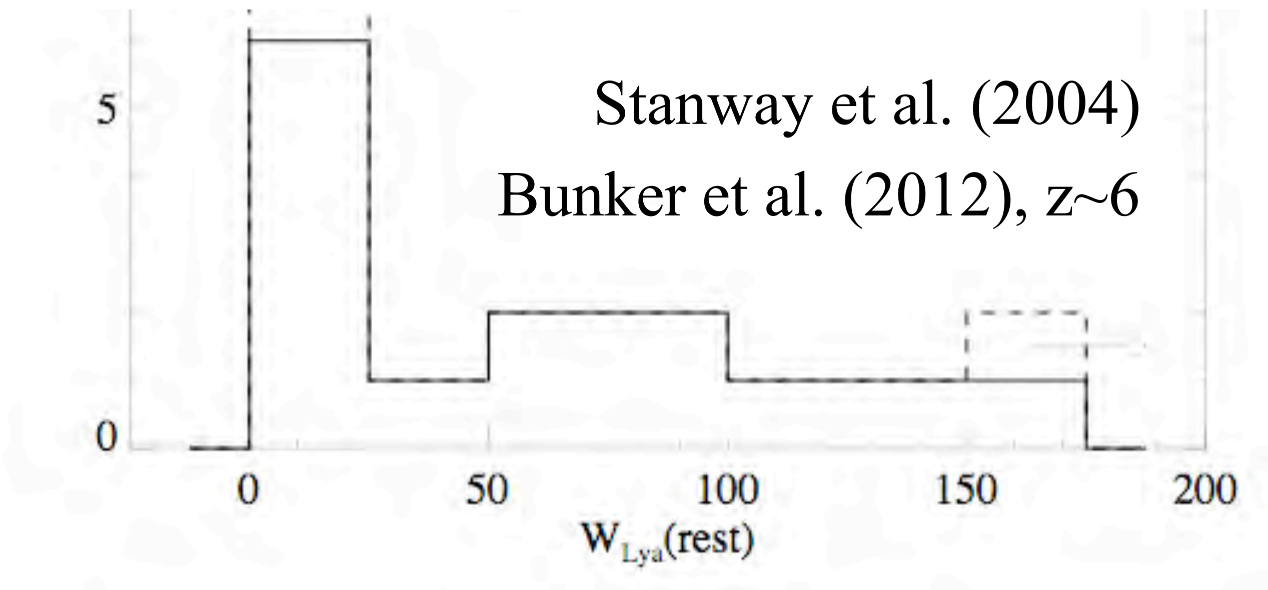
The (mostly) UV inferred Cosmic Star Formation History

Gemini


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)
irafterm
NOAO/IRAF V2.12.1-EXPORT observer@kauwa Sat 05:15:27 01-Feb-2003
[s1_noflattrbk[*,882:888]]: CDFST1a spec 2000s 1200G 8400Ang INDEF ap:88
Bunker, Stanway,
Ellis, McMahon
& McCarthy (2003)
Keck/DEIMOS
spectral follow-up
& confirmation
z=5.8
0
10
20
30
8210
8220
8230
8240
8250
8260
8270
Wavelength (angstroms)

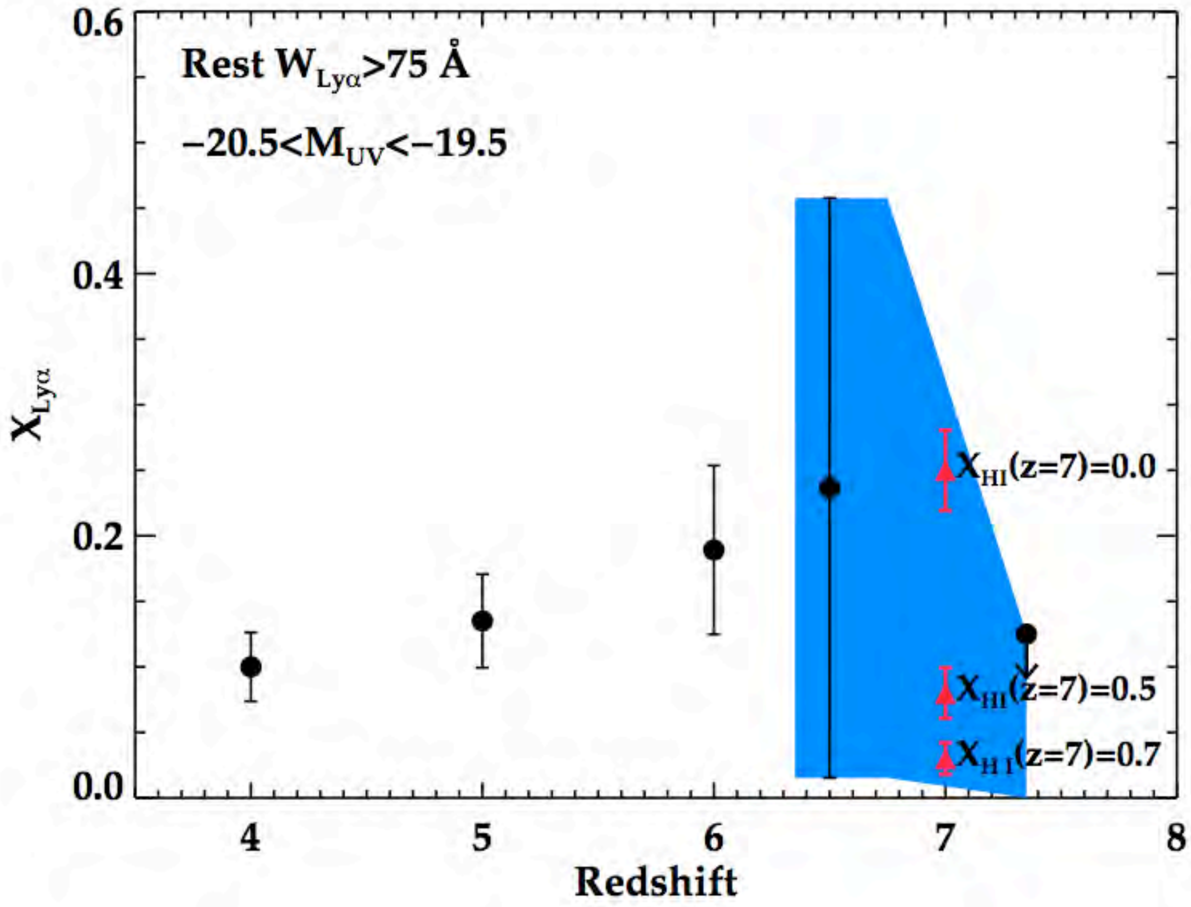


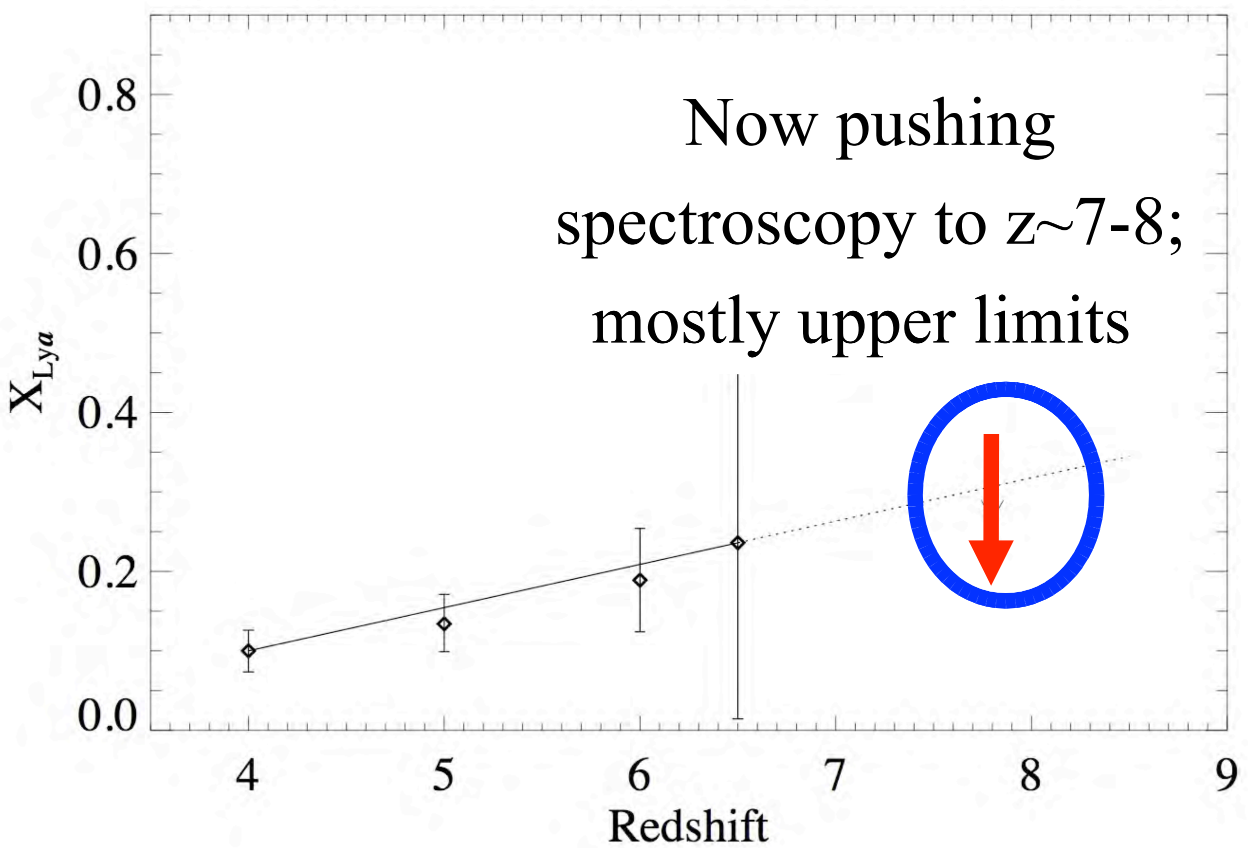
Shapley et al. (2003) z~3
Ly-alpha equivalent widths
N
0
50
100
150
200
−100
0
100
200
W Lyα (Å)



Stanway et al. (2004)
Bunker et al. (2012), z~6
0
5
0
50
100
150
200
W Lyα(rest)

Ly-alpha fraction (Stark et al. 2010)





Caruana et al. (2012)

Brightest HUDF Y-drop

Found in Sept 2009.

YD3 in Bunker et al

UDFy-31835539 in

Bouwens et al.;

#1721 in McLure et al.

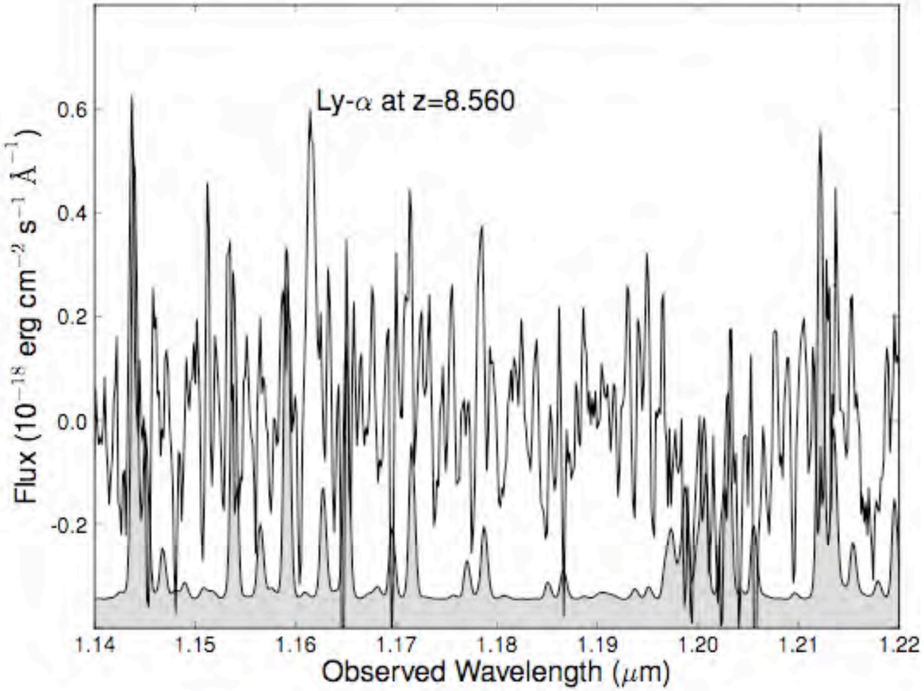
In late 2009, Nature paper

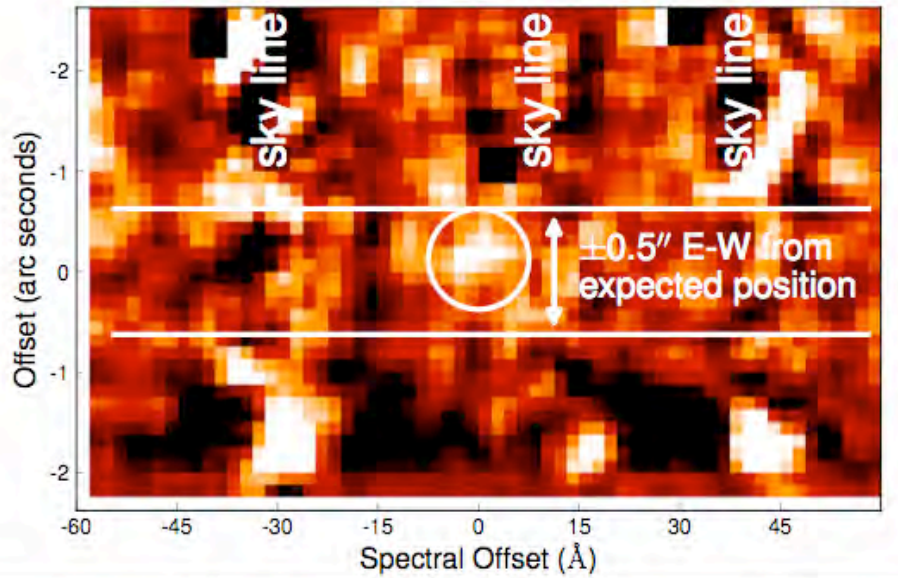
Lehnert et al. claiming

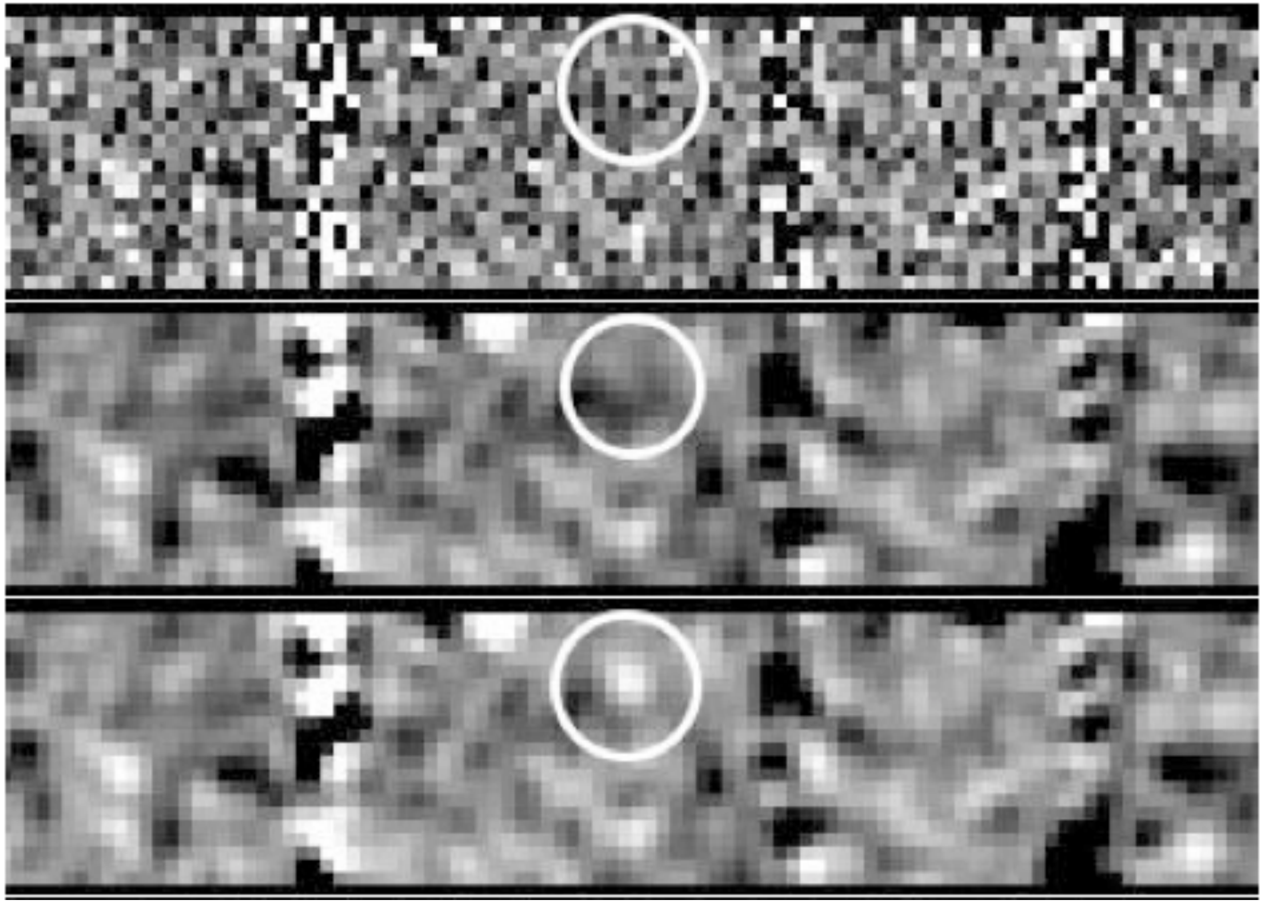
spectroscopic confirmation

of Ly-alpha at z=8.55

with SINFONI-IFU on VLT



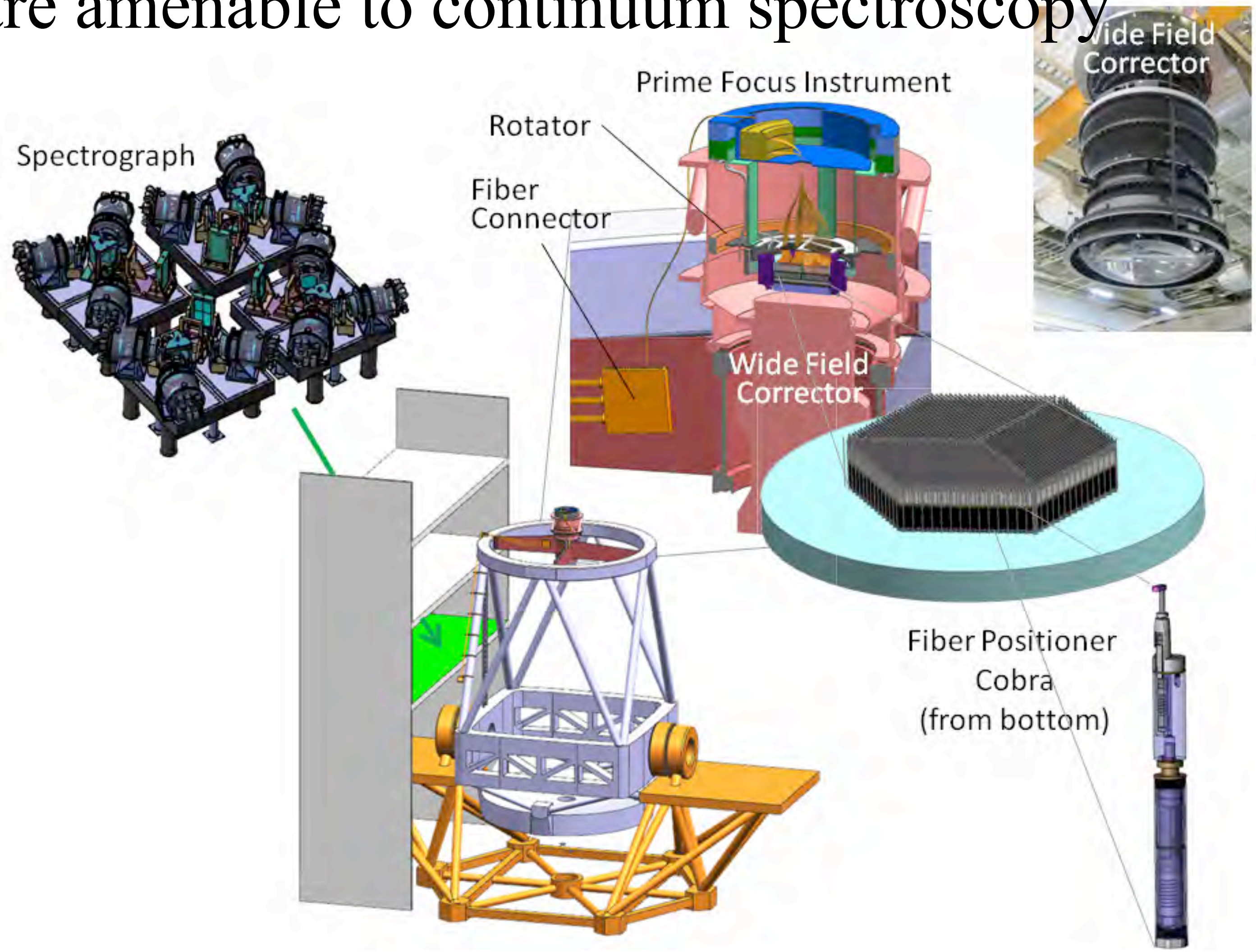




No evidence of Ly-alpha at $z=8.55$ in 5-hour VLT/XSHOOTER
And 11-hour Subaru/MOIRCS spectrum.
Also, the deep HST/WFC3 Y-band encompasses Ly-alpha, should be detected at ~4sigma but is undetected
Bunker et al. (2013, MNRAS 430, 3314)

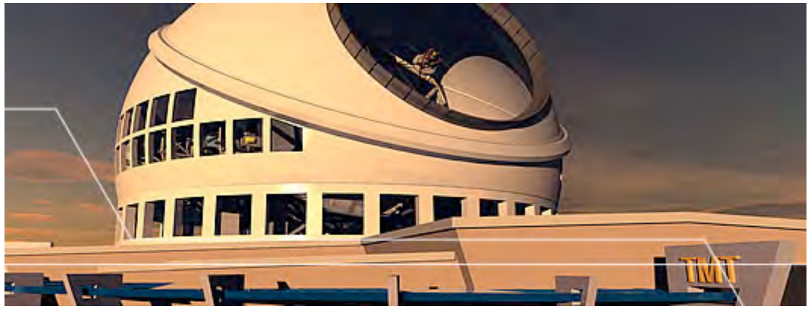
Future Prospects – Subaru HSC+PFS

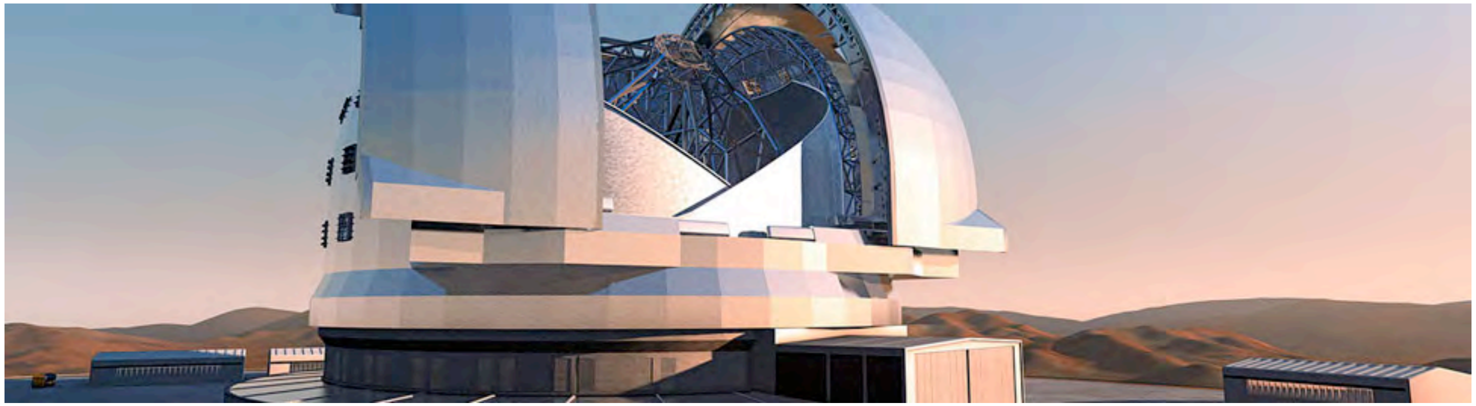
Find the brighter but rarer Lyman break galaxies at z>6 which are amenable to continuum spectroscopy



Extremely Large Telescopes

E-ELT, TMT etc have excellent spatial resolution with AO (better than HST), and working between the night sky lines in the near-IR the sky is dark for spectroscopy





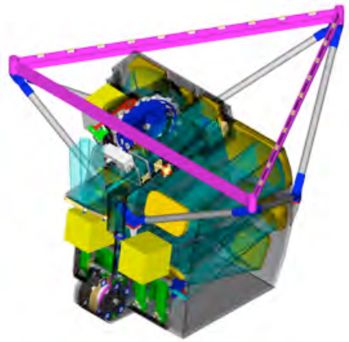

JAMES WEBB SPACE TELESCOPE
– successor to Hubble ~~(2013+)~~
2018


Goddard Space Flight Centre
Northrop Grumman
Operations:STScI
Project Scientist: John Mather

ESA Contributions to JWST

- NIRSpec
  - ESA Provided
  - Detector & MEMS Arrays fron NASA

- MIRI Optics Module
  - ESA Member State Consortiur
  - Detector & Cooler/Cryostat fror NASA

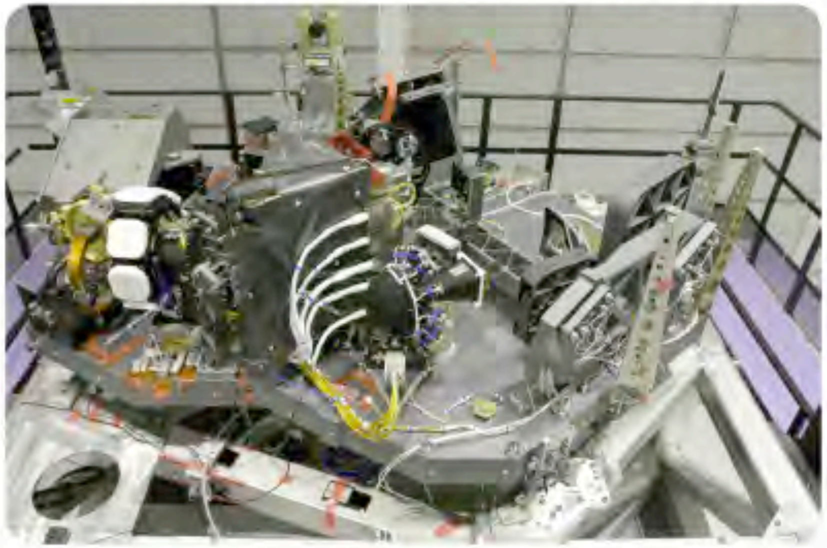


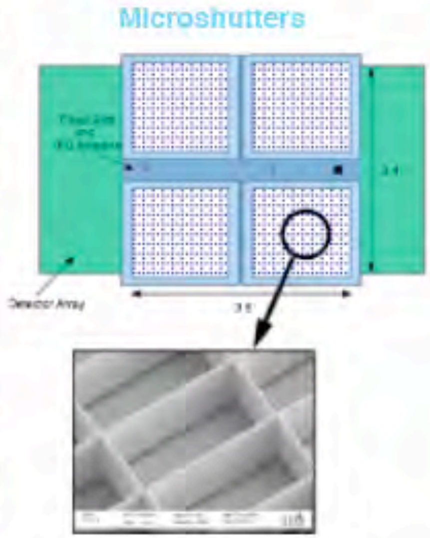
- Ariane V Launcher (ECA)

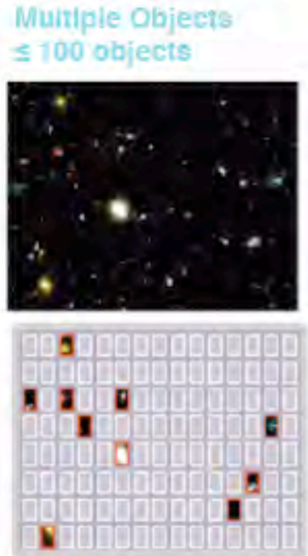

NIRSpec IST
Near Infrared Spectograph
(NIRSpec) Mockup

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



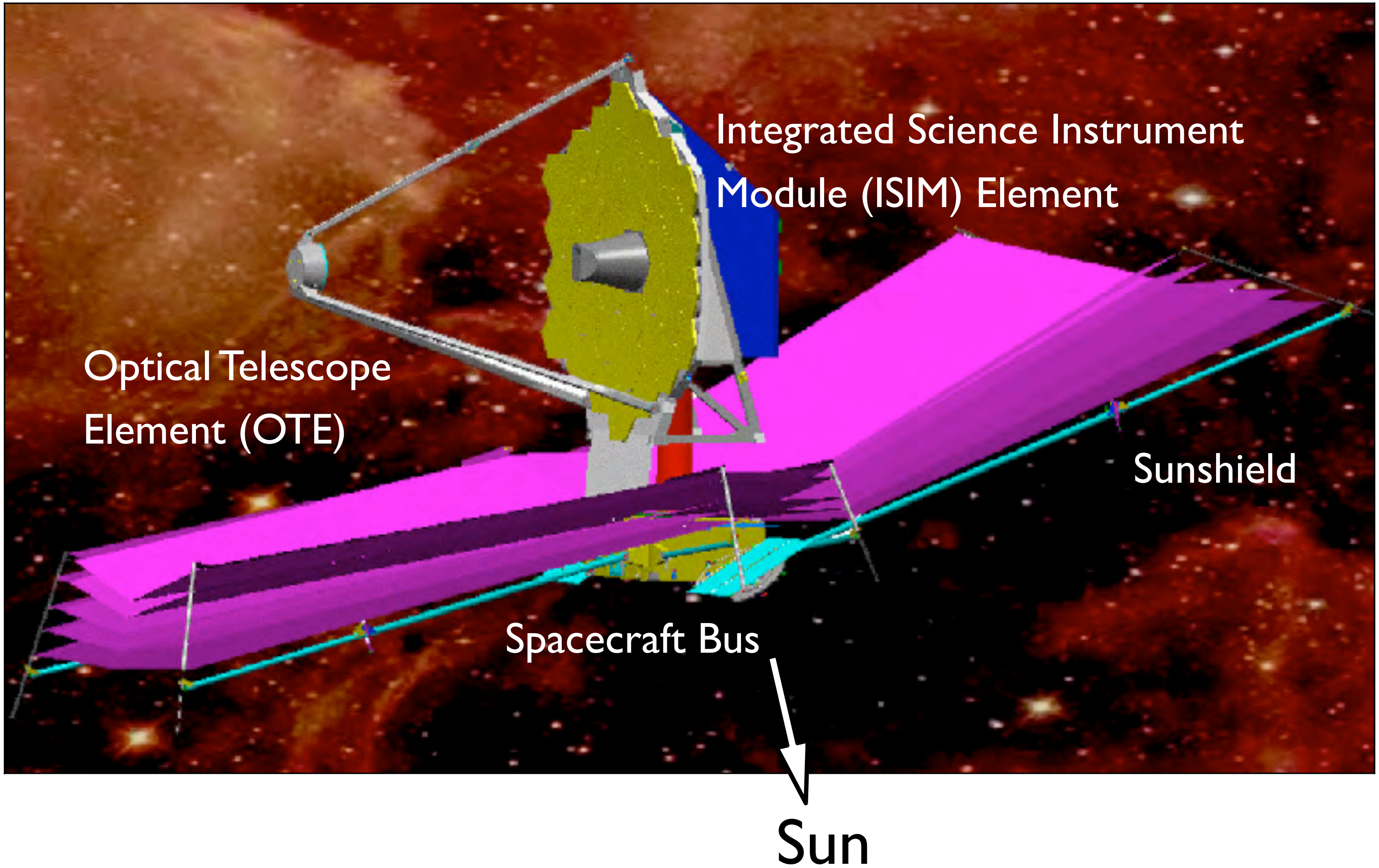




Stellar Populations at the Highest Redshifts: Conclusions

- Very blue rest-UV spectral slopes at $z>4$ (getting more blue at $z=6-7$, correcting for selection biases)
- With $\beta<-2.0$, little or no dust AND potentially v young stellar populations, low metallicity (top-heavy IMF?)
- Blue colours supported by Spitzer IRAC photometry
- Spectroscopy at $z=5-6.5$ implies a higher fraction of Lyman-alpha with high EW, consistent with steep blue UV slope (top-heavy IMF?)
- At $z>7$ less Ly-alpha emission probably due to neutral IGM

JWST Architecture

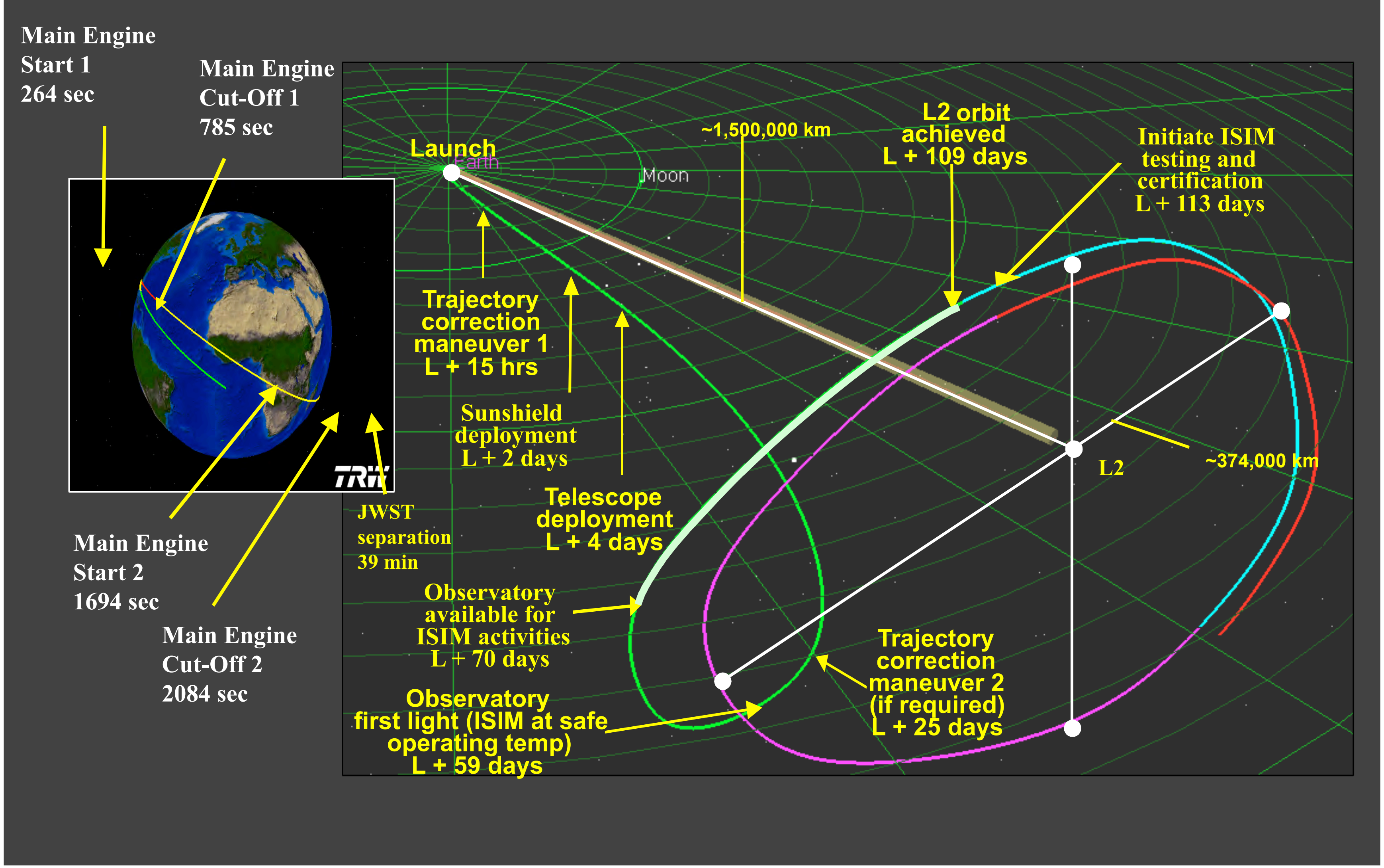


Who Was James Webb?

Edwin Hubble

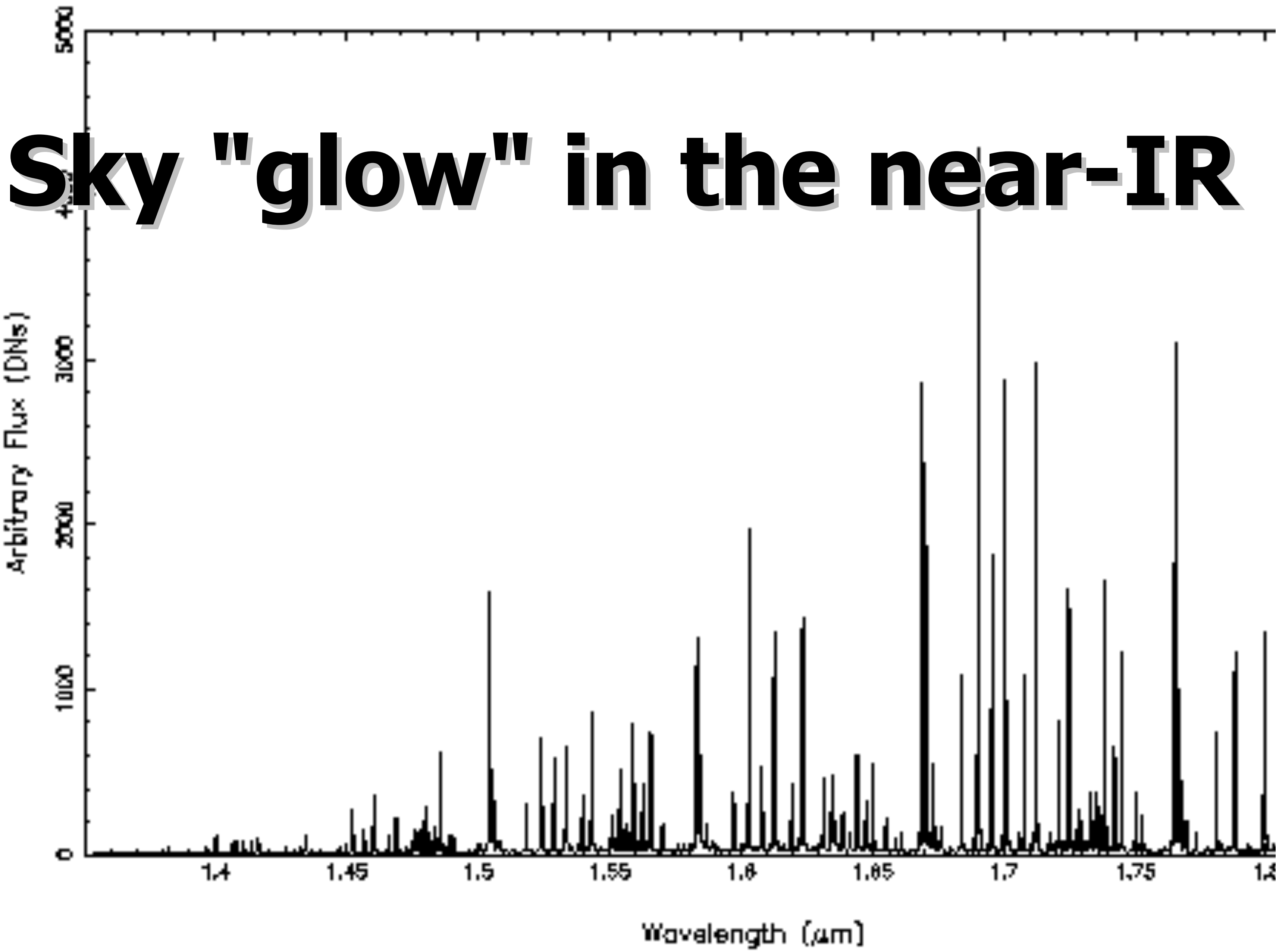
James E. Webb
Second NASA administrator, during Apollo

Orbit



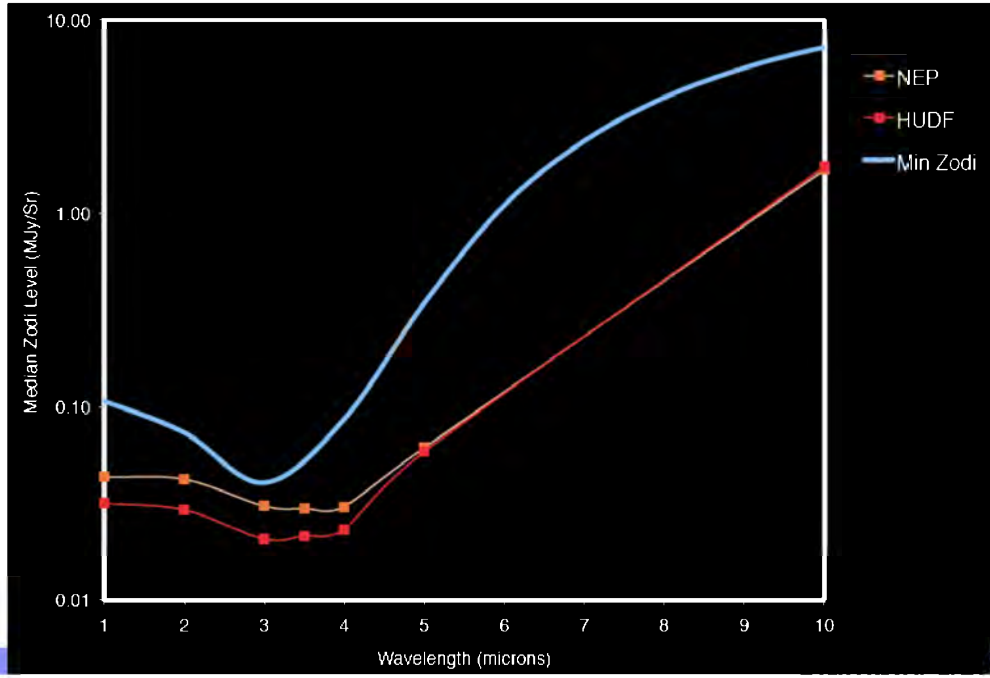
Main Engine Start 1 264 sec
Main Engine Cut-Off 1 785 sec
Main Engine Start 2 1694 sec
Main Engine Cut-Off 2 2084 sec
JWST separation 39 min
Launch
Earth
Moon
~1,500,000 km
L2 orbit achieved L + 109 days
Initiate ISIM testing and certification L + 113 days
Trajectory correction maneuver 1 L + 15 hrs
Sunshield deployment L + 2 days
Telescope deployment L + 4 days
Observatory available for ISIM activities L + 70 days
Observatory first light (ISIM at safe operating temp) L + 59 days
Trajectory correction maneuver 2 (if required) L + 25 days
L2
~374,000 km

Sky "glow" in the near-IR



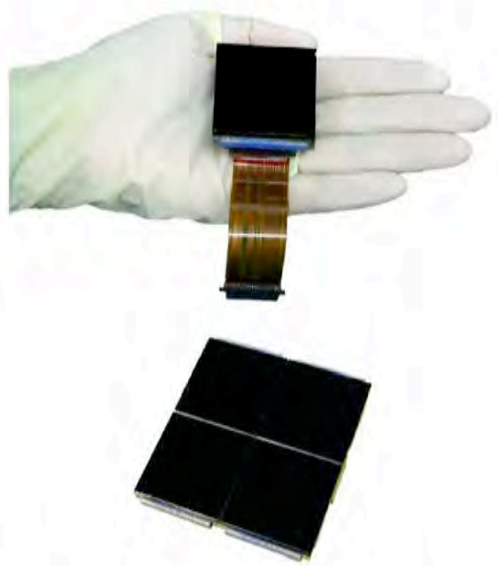
Sky Background

- JWST should be zodi-limited at $\lambda < 10$ μm
- Background levels will include contribution from stray light
- NIR stray light is controlled by baffling and contamination control of optical surfaces e.g. Mirrors, baffles, sunshield, struts



Detector Array

- 2K$\times$4K FPA comprised of two 2K$\times$2K sensor chip assemblies (SCAs)
- λ=0.6–5.0 μm HgCdTe detectors (Rockwell)
- FPA passively cooled to T=34–37 K
- Key Performance Parameters:
  - Total noise =6 electrons rms per t=1000 seconds exposure)
  - QE = >80%
- NIRSpec is detector background limited in nearly all modes (!)
- Non-stop (“up the ramp”) read and telemetry
  - 12 s frame time, 1 frame downlink each 50 s



Rockwell 2Kx2K NIR Module