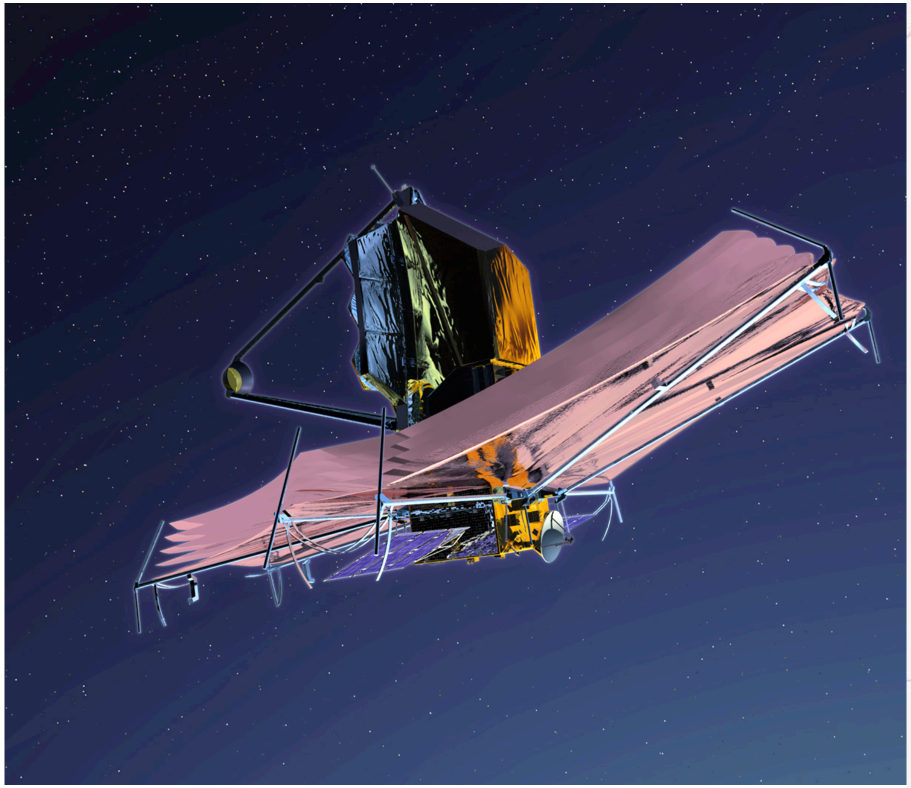
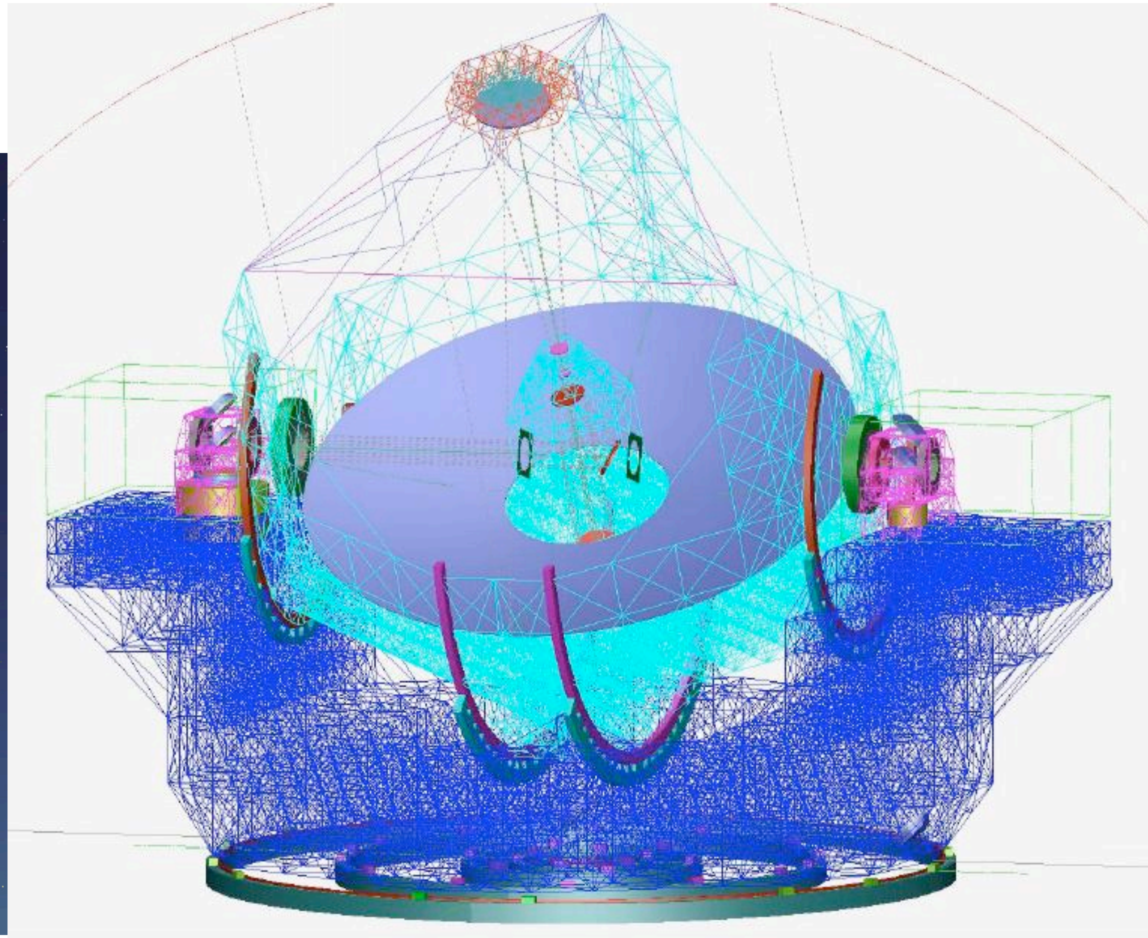
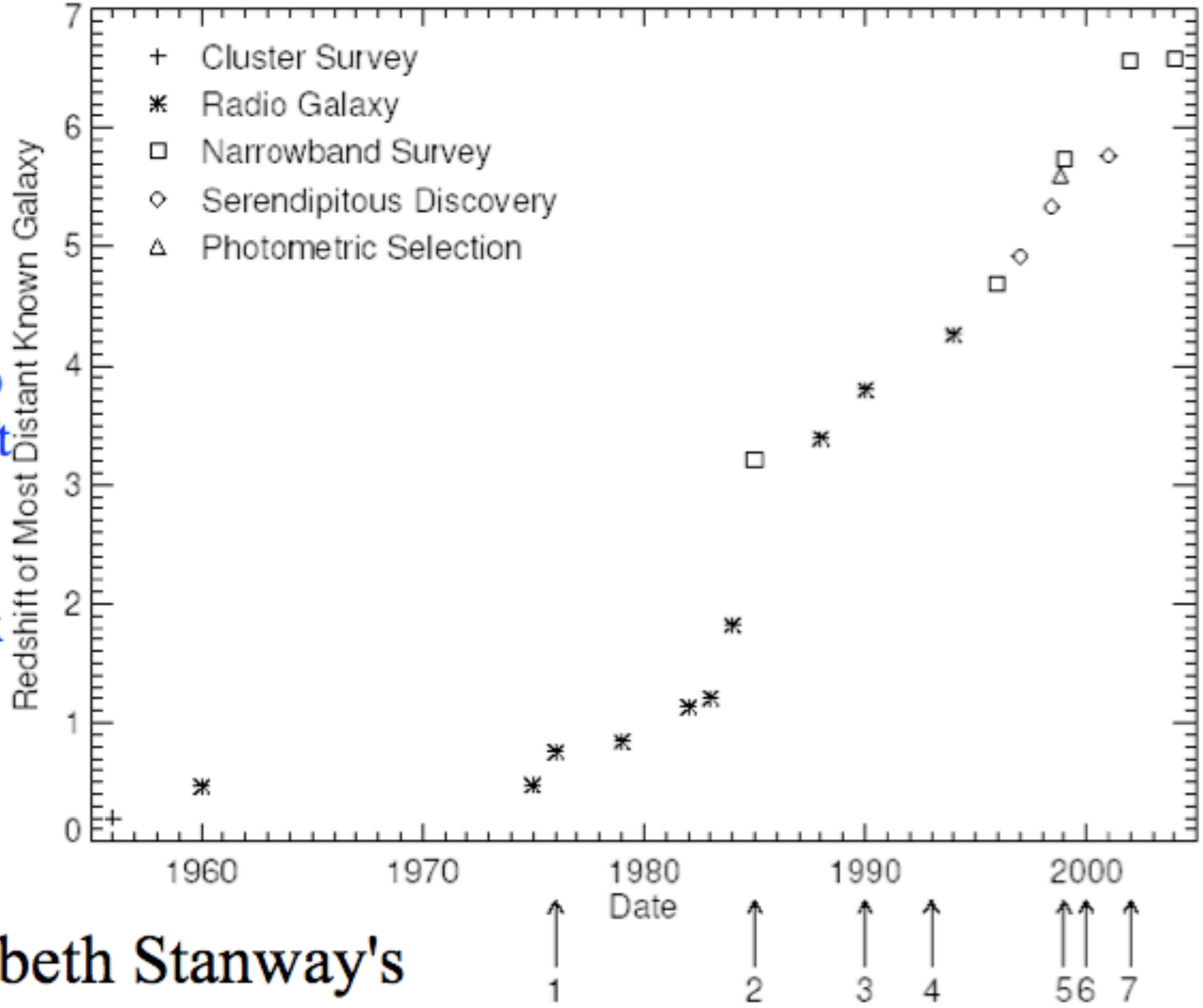
Astronomy at the End of the Dark Ages



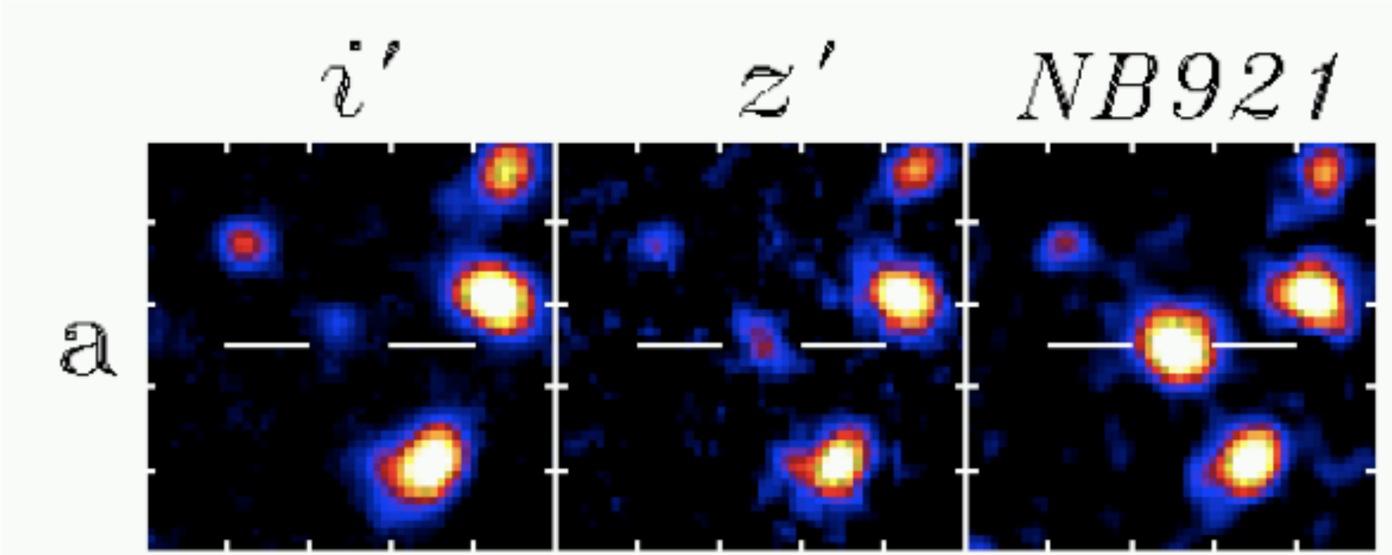


Andrew Bunker (Oxford)

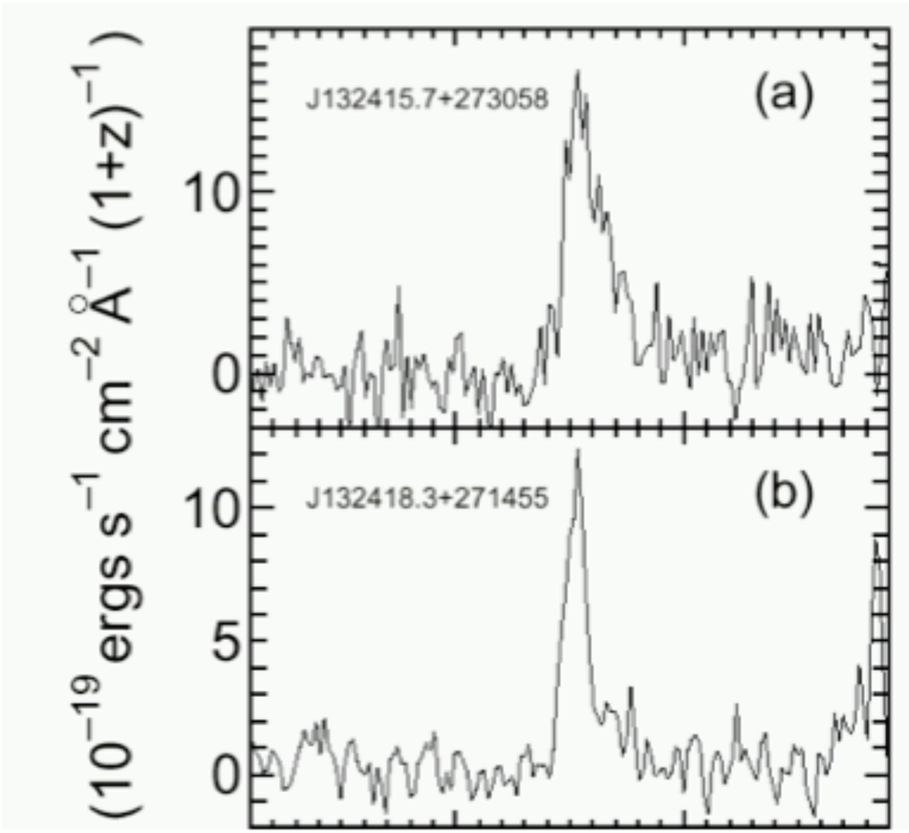
Early strategy: most massive short-lived OB stars produce ionizing UV photons. Want to find high-redshift star forming galaxies, and measure UV flux (or recombination lines e.g. Ly-α)



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



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



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

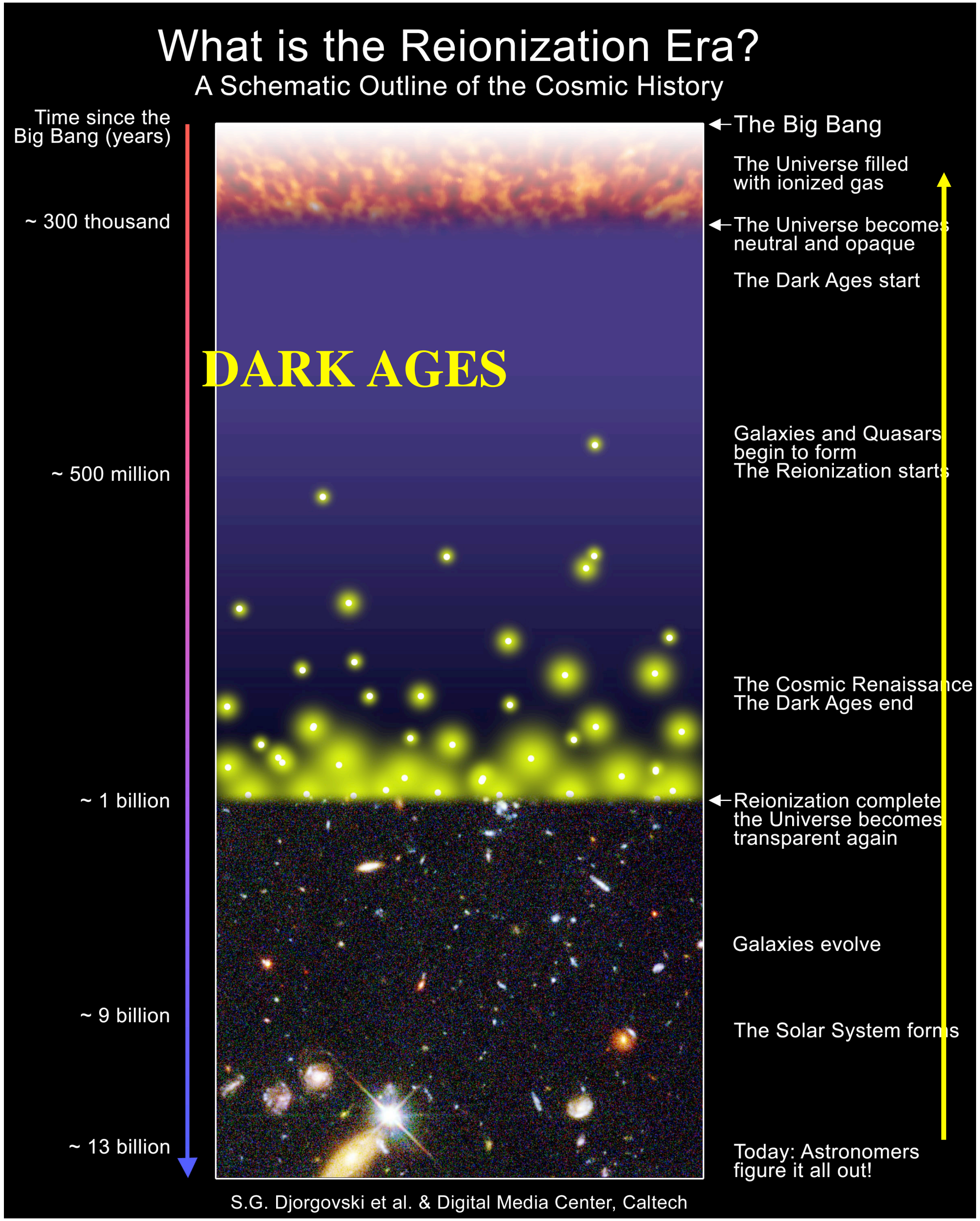
Both use narrow-band filter in low-background region between sky lines, and follow-up spectra

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?



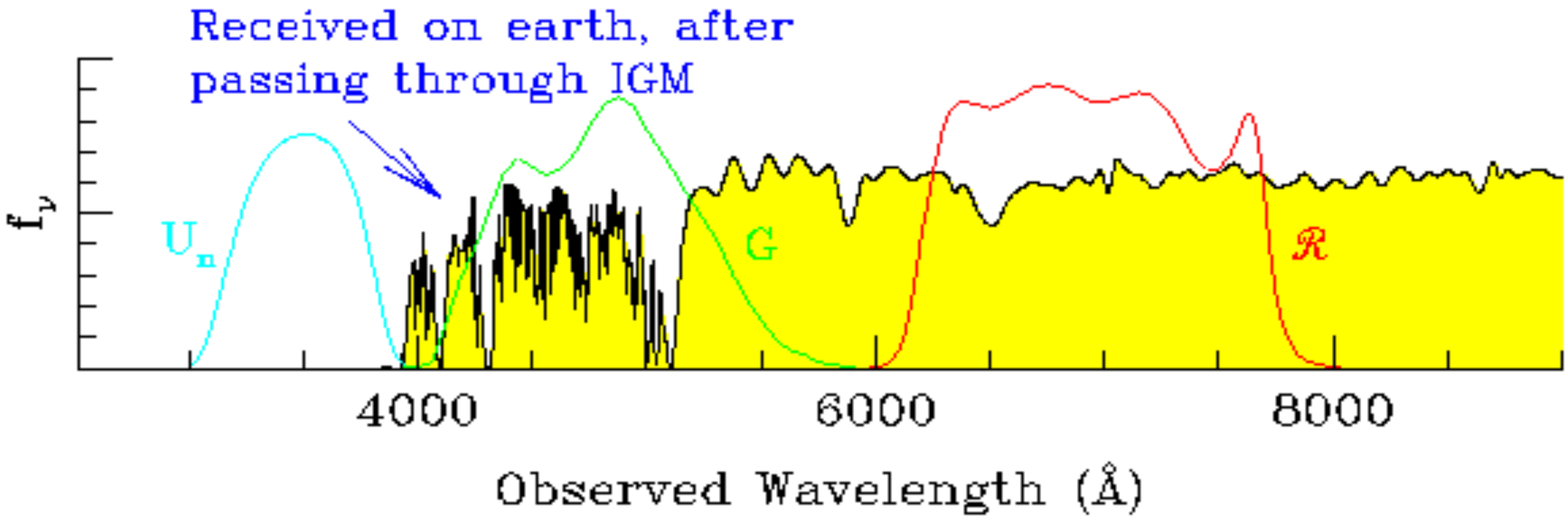
Redshift z

1100

10

5

0



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

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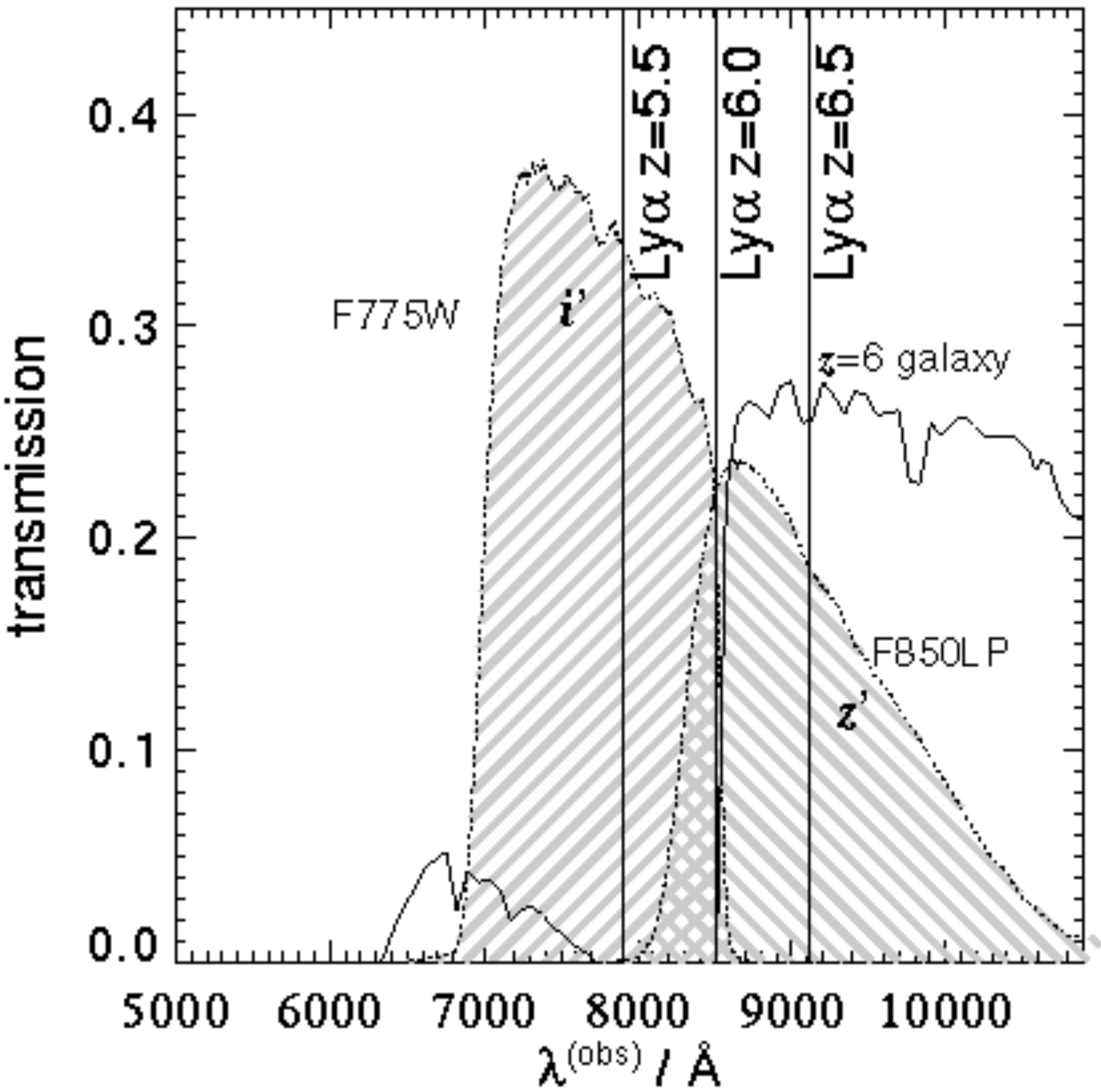
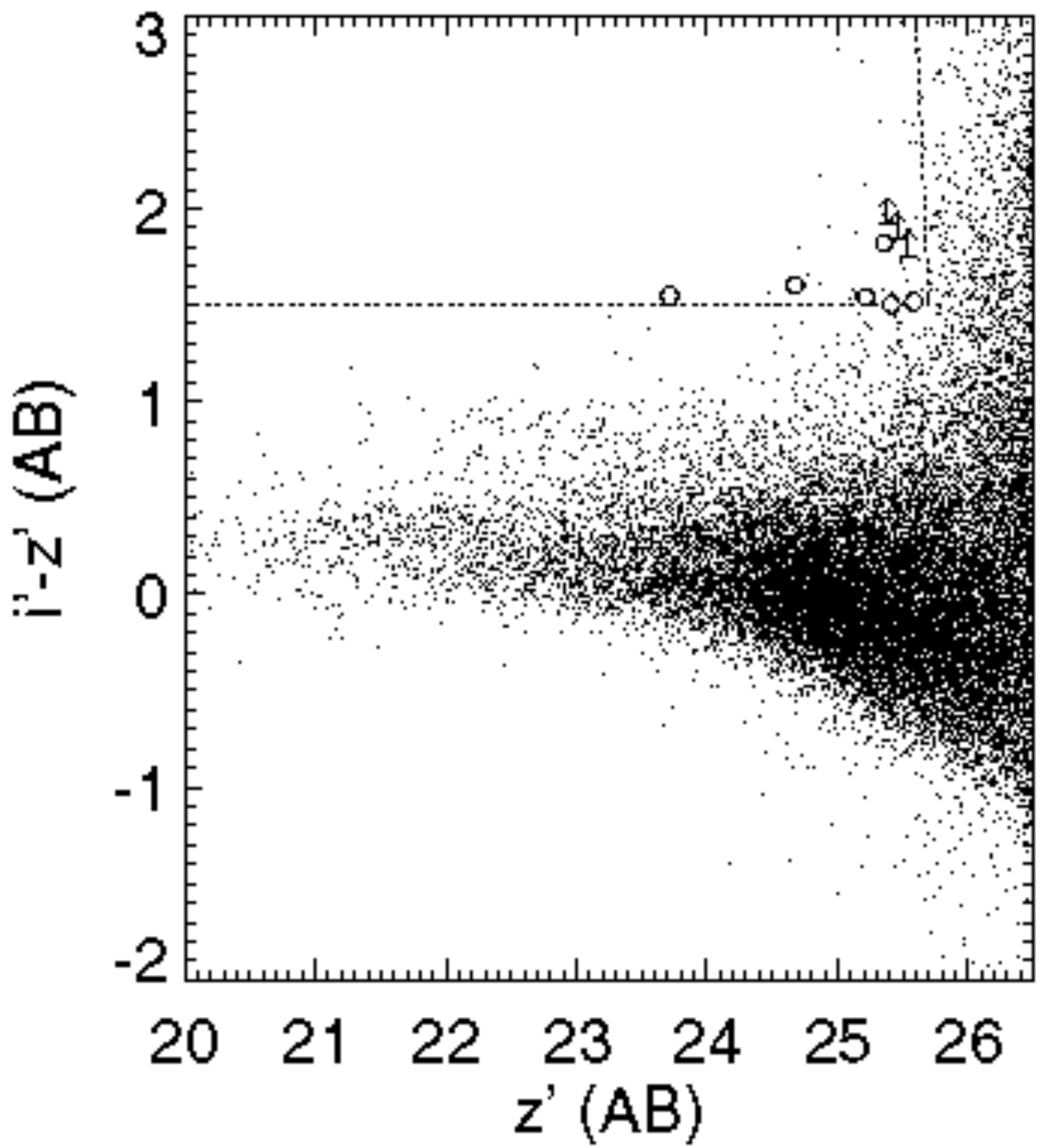
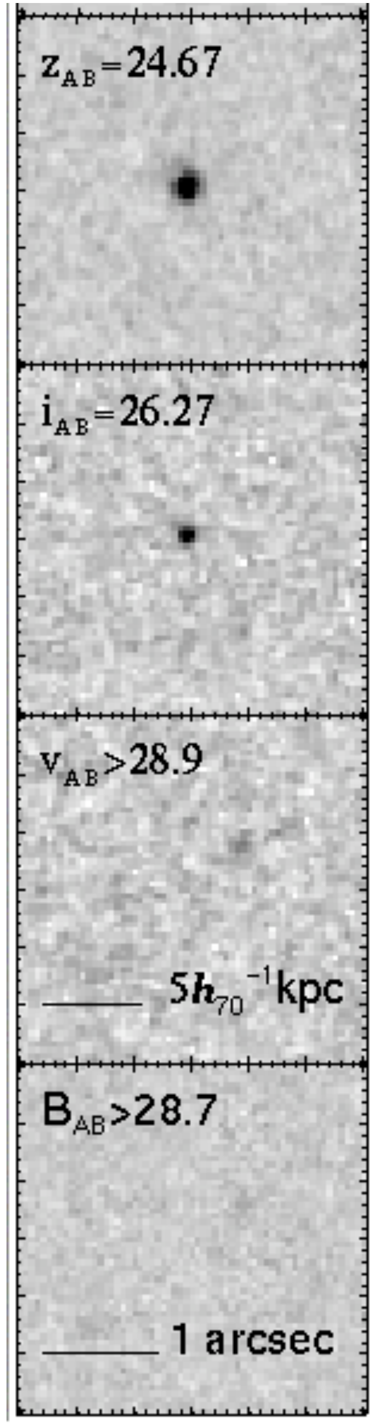
Pushing to higher redshift - Finding Lyman break galaxies at z~6 : using *i*-drops.

Stanway, Bunker & McMahon (2003)







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

Why are we bothering?

Want to find the sources which reionized the Universe, and chart the history of galaxy (mass) assembly & star formation

Lyman-alpha (if it emerges at all pre-Gunn Peterson) then it will be a good way to find galaxies, but the flux does not tell us the star formation rate (but EW might provide clues to the IMF). Pop III??? Hints from HeII 1640Ang

Spectra at longer wavelengths for other diagnositc lines (also get reddening, metallicity)

Couple with SEDs from imaging

Brightest sources: some hope of velocity dispersions

Want overall luminosity functions, EW distributions.

Evolution of size & morphology

Role of ELTs at the Highest Redshifts

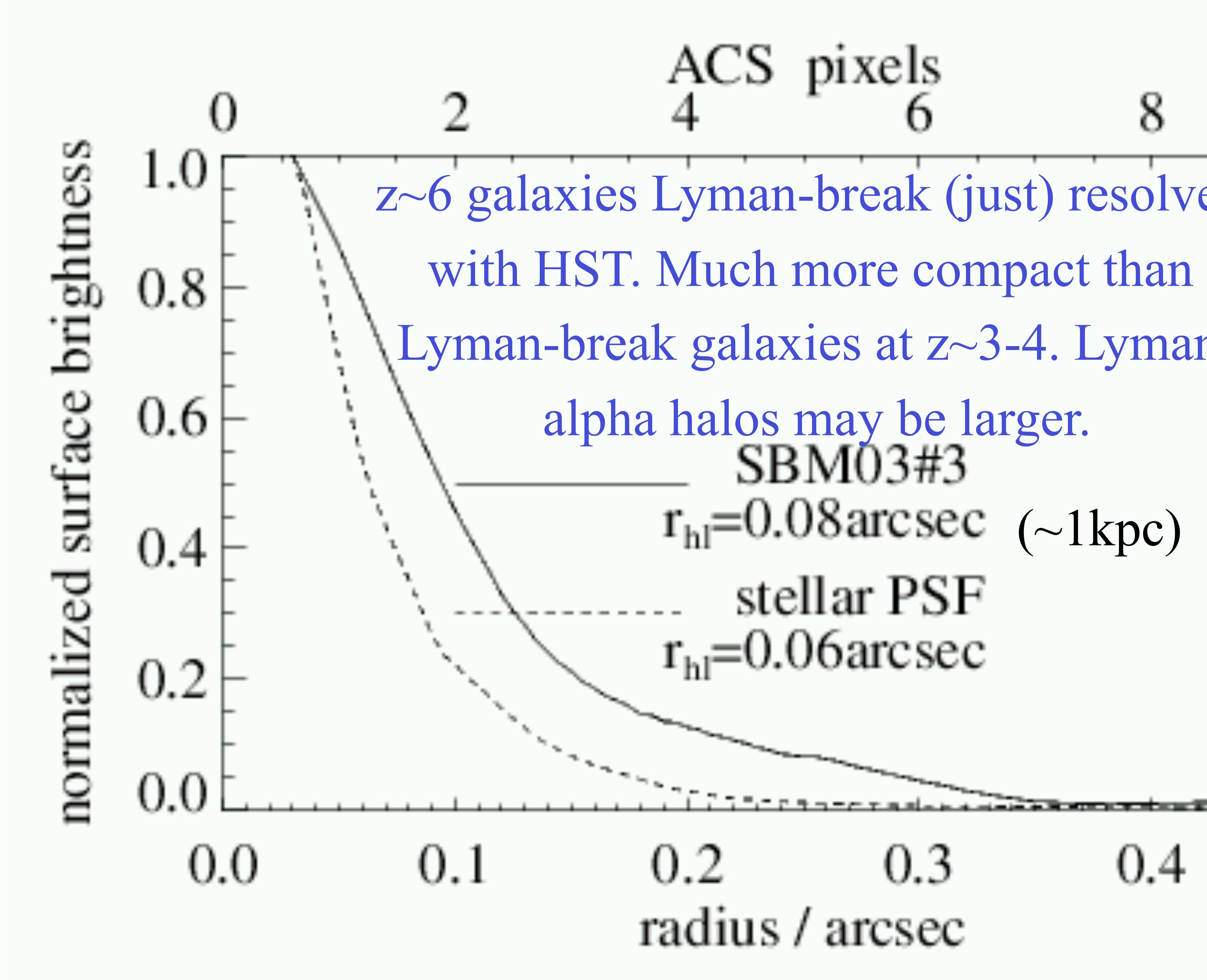
Probably use deep JWST imaging fields (~3'x3') to locate targets

ELT wins out for detailed studies of individual objects because of better diffraction limit - matched to HII region size (HARMONI, EAGLE).

IR MOS capability critical for multiplex (e.g. OPTIMOS)

IFU capability desirable, even better if several deployed over ~3', for best exploitation of target density (e.g. EAGLE). Resolution R>4000

Want to chart history of star formation;
History of mass assembly (IFUs);
History of metal enrichment.
Impact of galaxies on reionization,
and the evolution of feedback.
Nature of Pop III stars.



z~6 galaxies Lyman-break (just) resolved with HST. Much more compact than Lyman-break galaxies at z~3-4. Lyman-alpha halos may be larger.

(~1kpc)

Key is Spectroscopy with ELTs

-We have samples of ~10/sq arcmin I-drop z~6 galaxies (in HUDF to z'=29 AB) and larger shallower samples of bigger fields (thanks to Subaru/SuprimeCam). HST/WFC3 at z>7

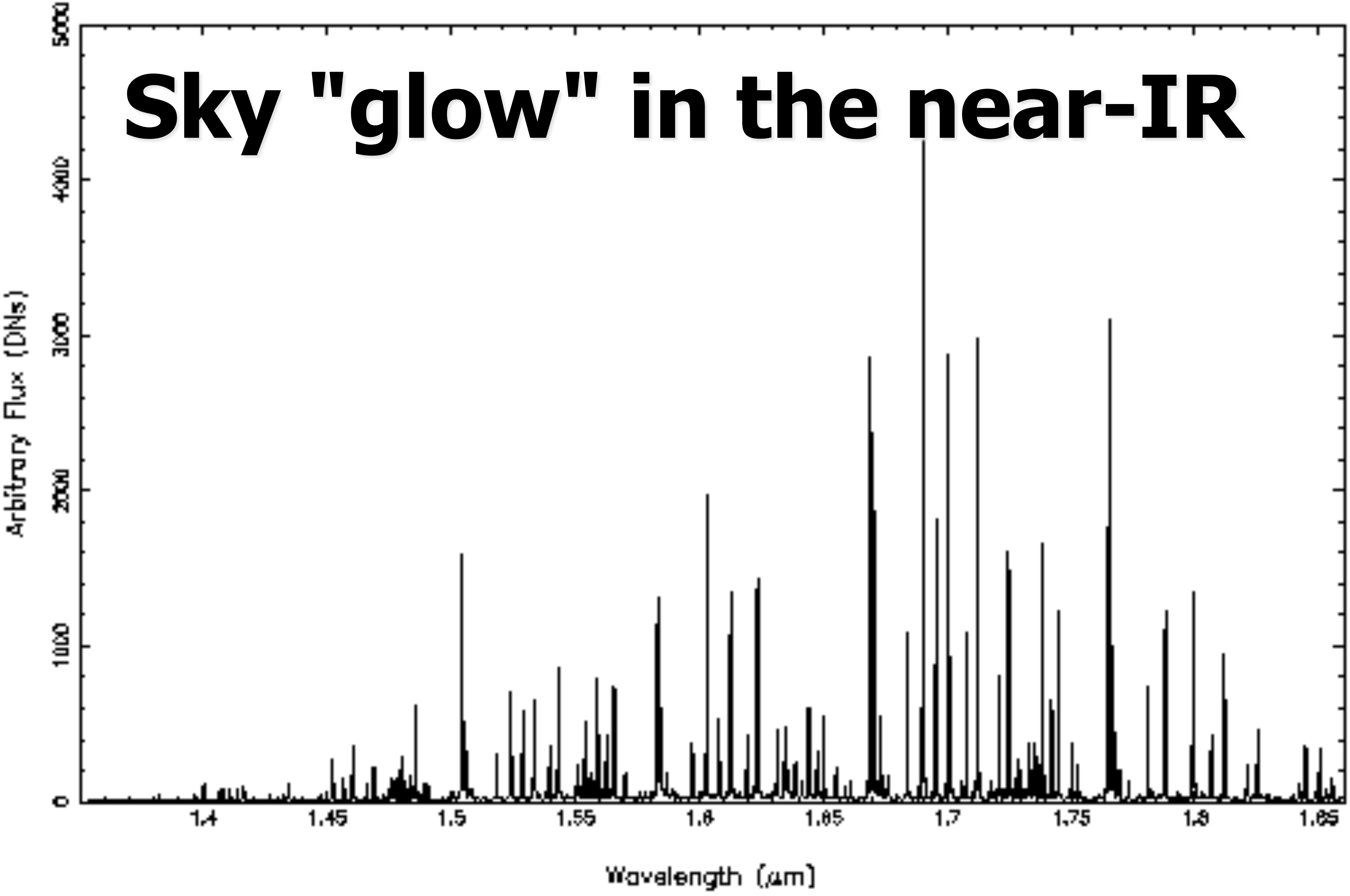
-- Only small fraction have spectroscopic redshift from strong Ly-alpha

-Want to reach smaller equivalent widths (the distribution of Ly-alpha tells us about the ionization fraction of the IGM), and want to reach the continuum

--UV absorption lines and P-Cygni profiles will tell us about mass/kinematics, metallicity, outflows and the IMF (the work at z~3 from the Steidel group)

-- OPTIMOS has ~200 multiplex. EAGLE for kinematics

Sky "glow" in the near-IR

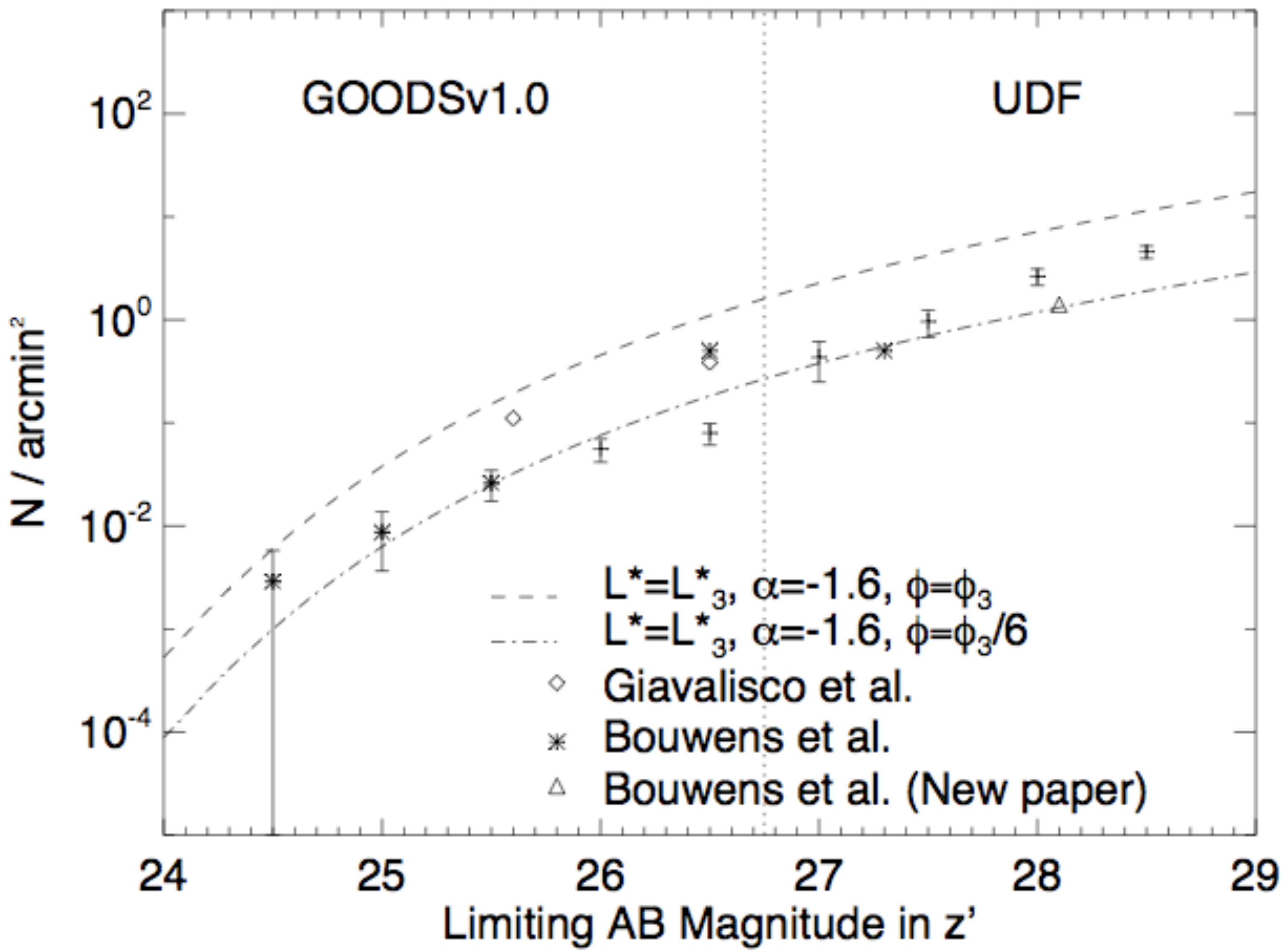


Understanding Galaxies at z>~6

• How to find galaxies at z~6, and the incompleteness in the selection methods (tend just to find actively star-forming galaxies). Might look for signature of old stars.

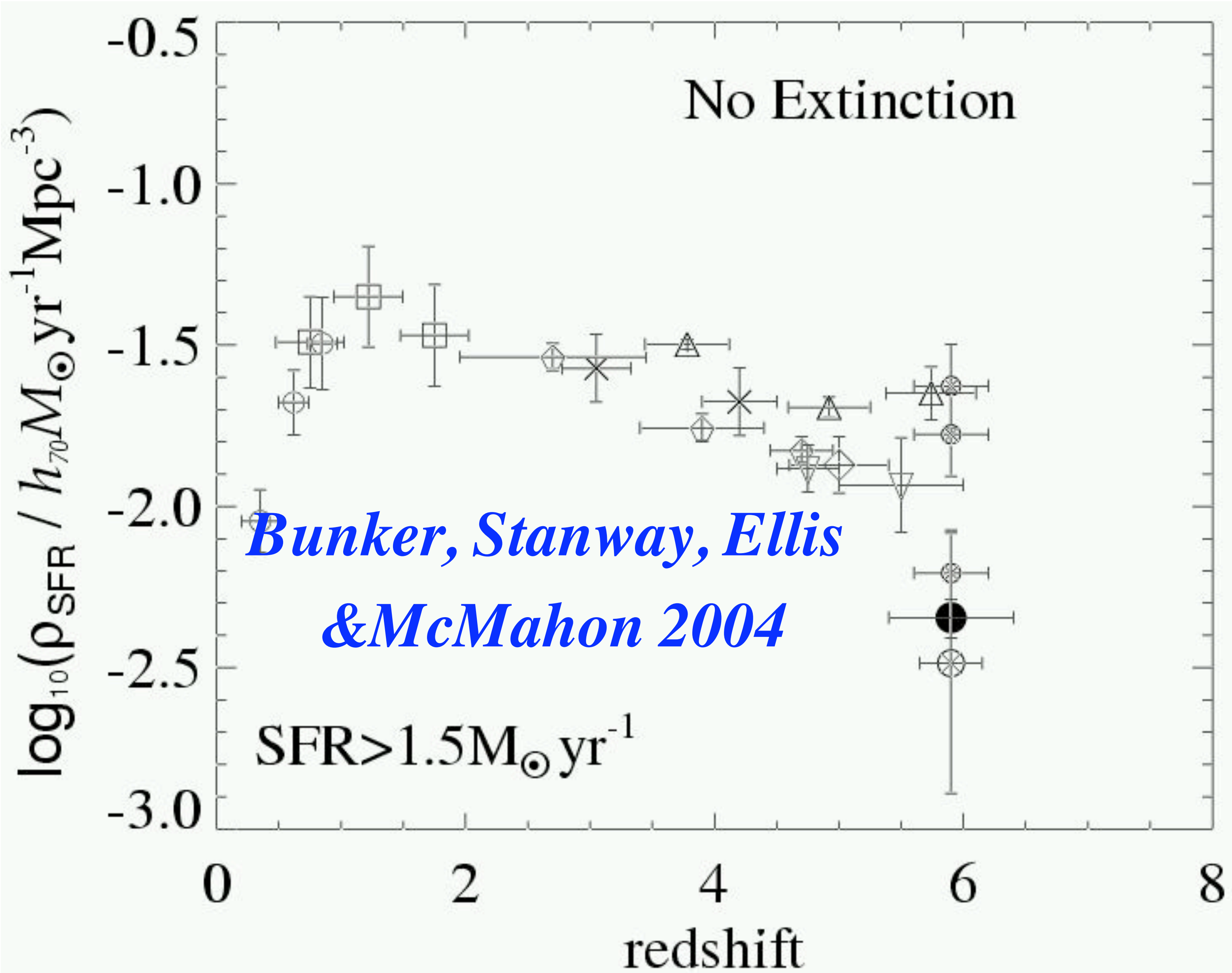
• Spectroscopy does not reach the continuum (lucky if you get one line - Lyman-alpha), so rely on fitting SEDs with broad-band imaging (which may come from imaging with very different spatial resolutions). Get SFR/ionization from rest-UV.

• Most high-redshift candidates have no spectroscopic redshift - might be mis-led in stellar population fits by erroneous photometric redshifts. But broad-band SEDs can tell us a lot.



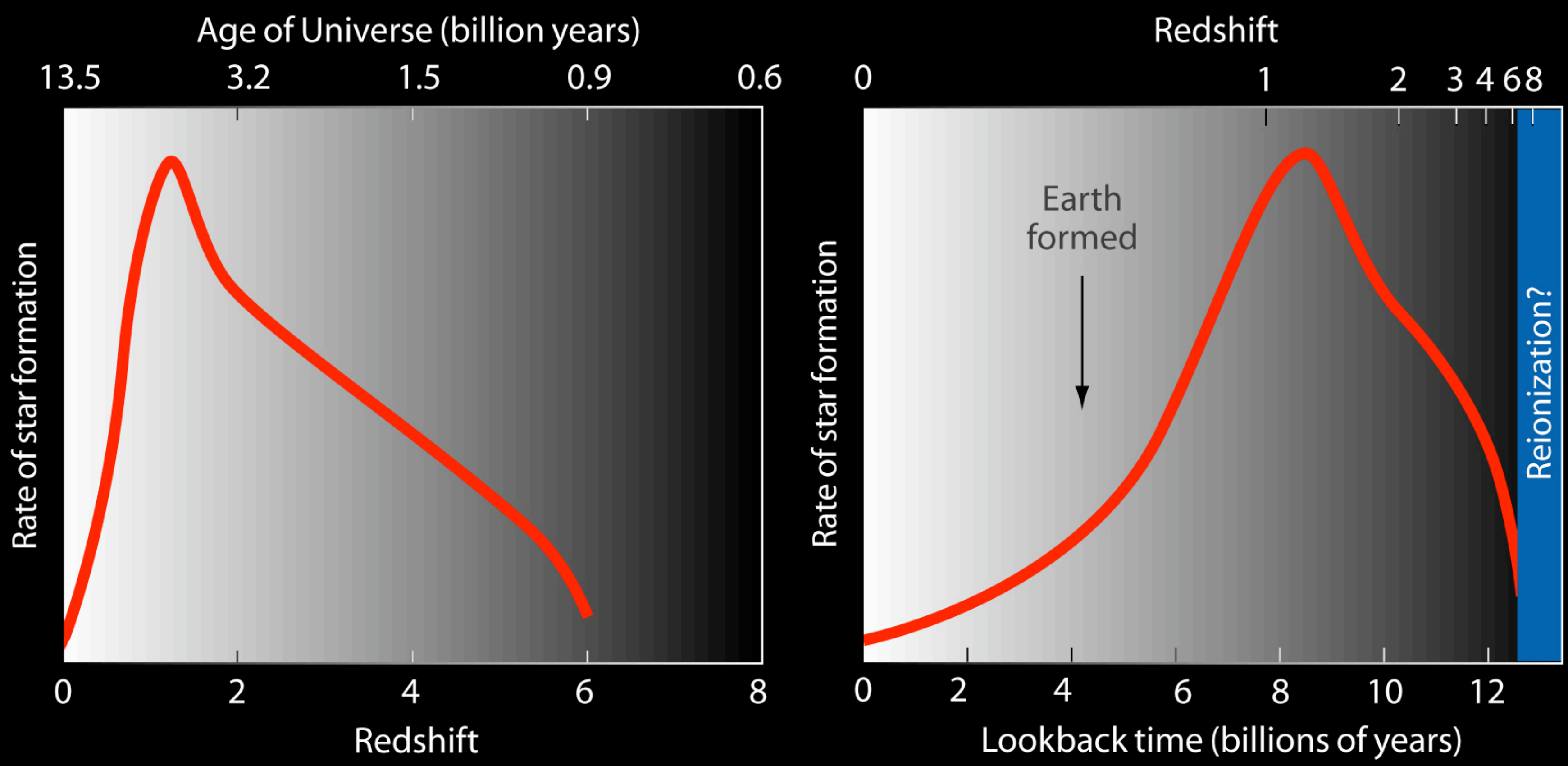
For I-drops (z~6) would only get ~1 per NIRSpec field bright enough for S/N~3 in continuum in 1000sec for abs line studies. ELT could go deeper at <2microns

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



Bunker, Stanway, Ellis &McMahon 2004

Star formation history of the Universe



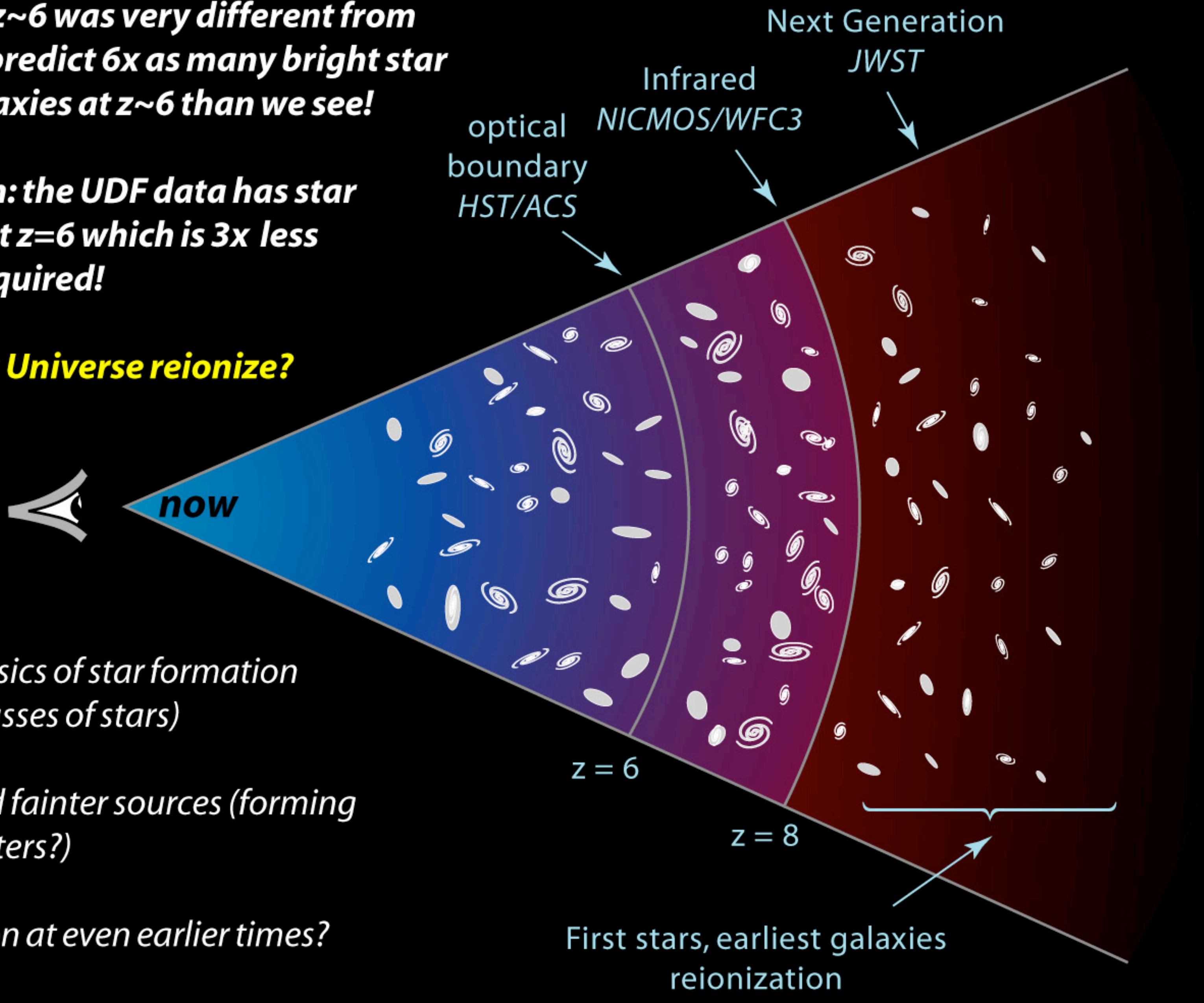
- ***UDF enables us to identify even fainter galaxies at these times*** *(end of dark ages)*
- ***We were first to analyse & publish 50 high redshift galaxies in the UDF***
- ***Confirms our previous work: much LESS star formation than in more recent past***

Probing the dark ages

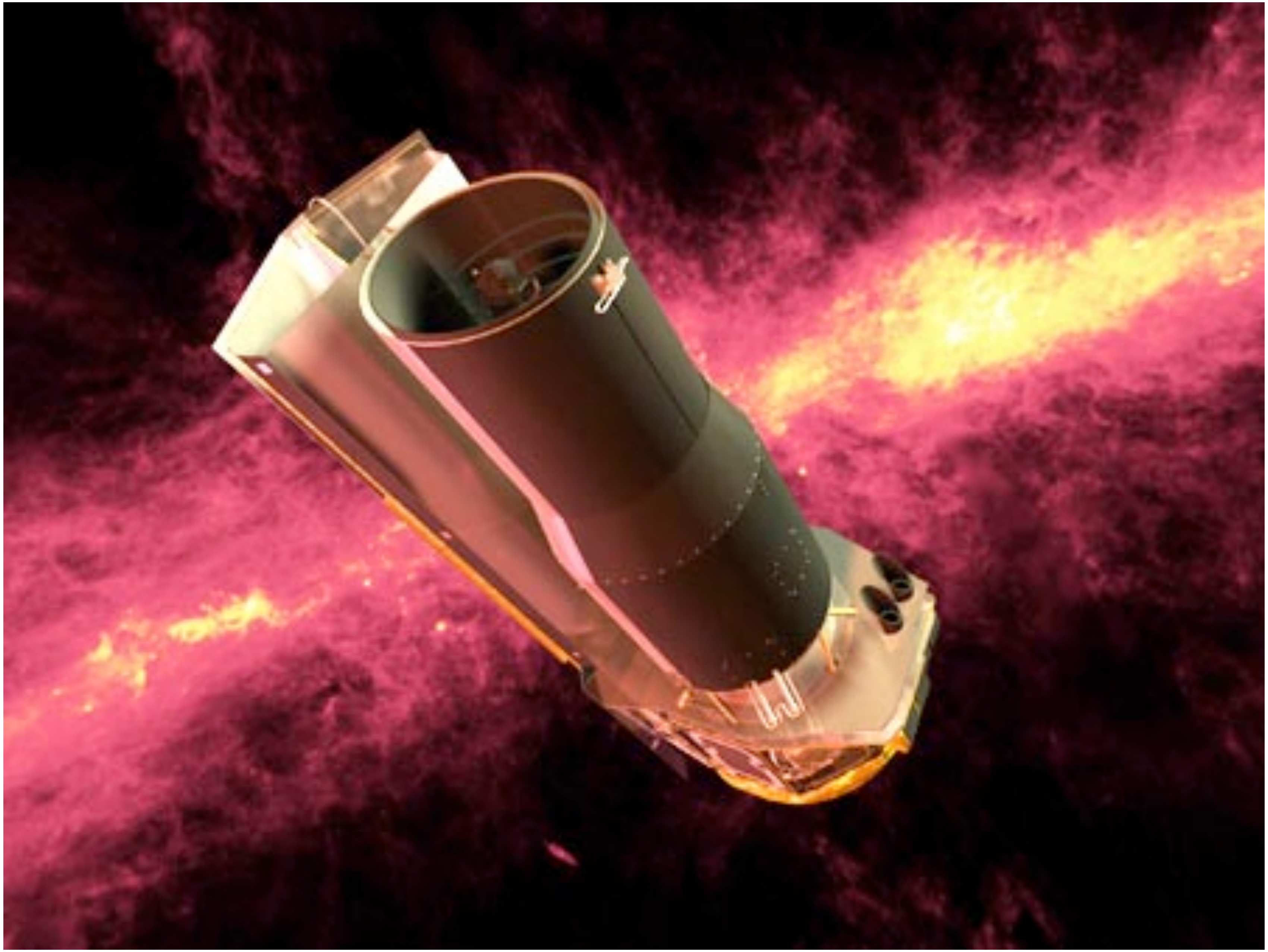
reionization and distant galaxies

- ***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!***

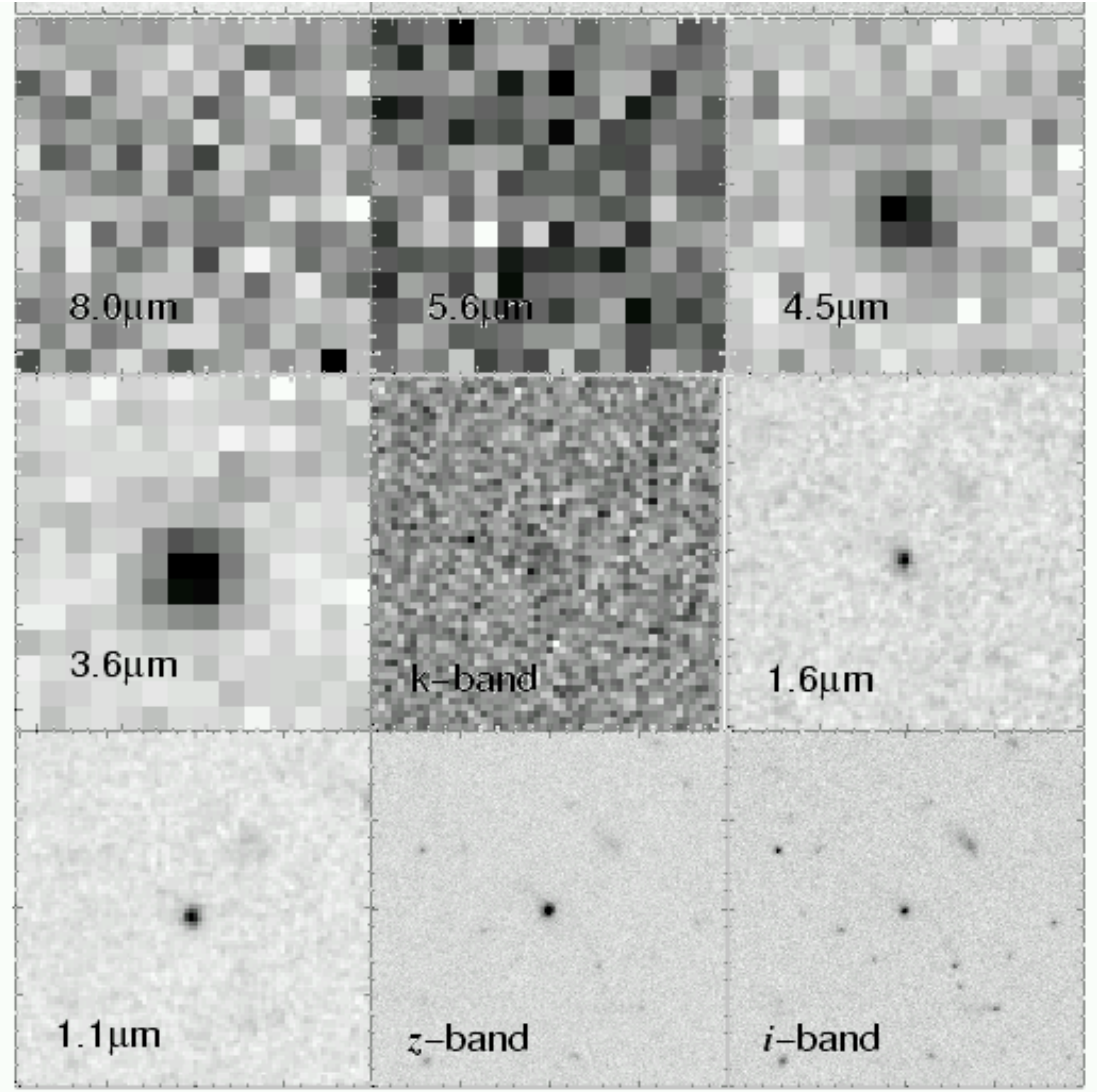
So how does Universe reionize?



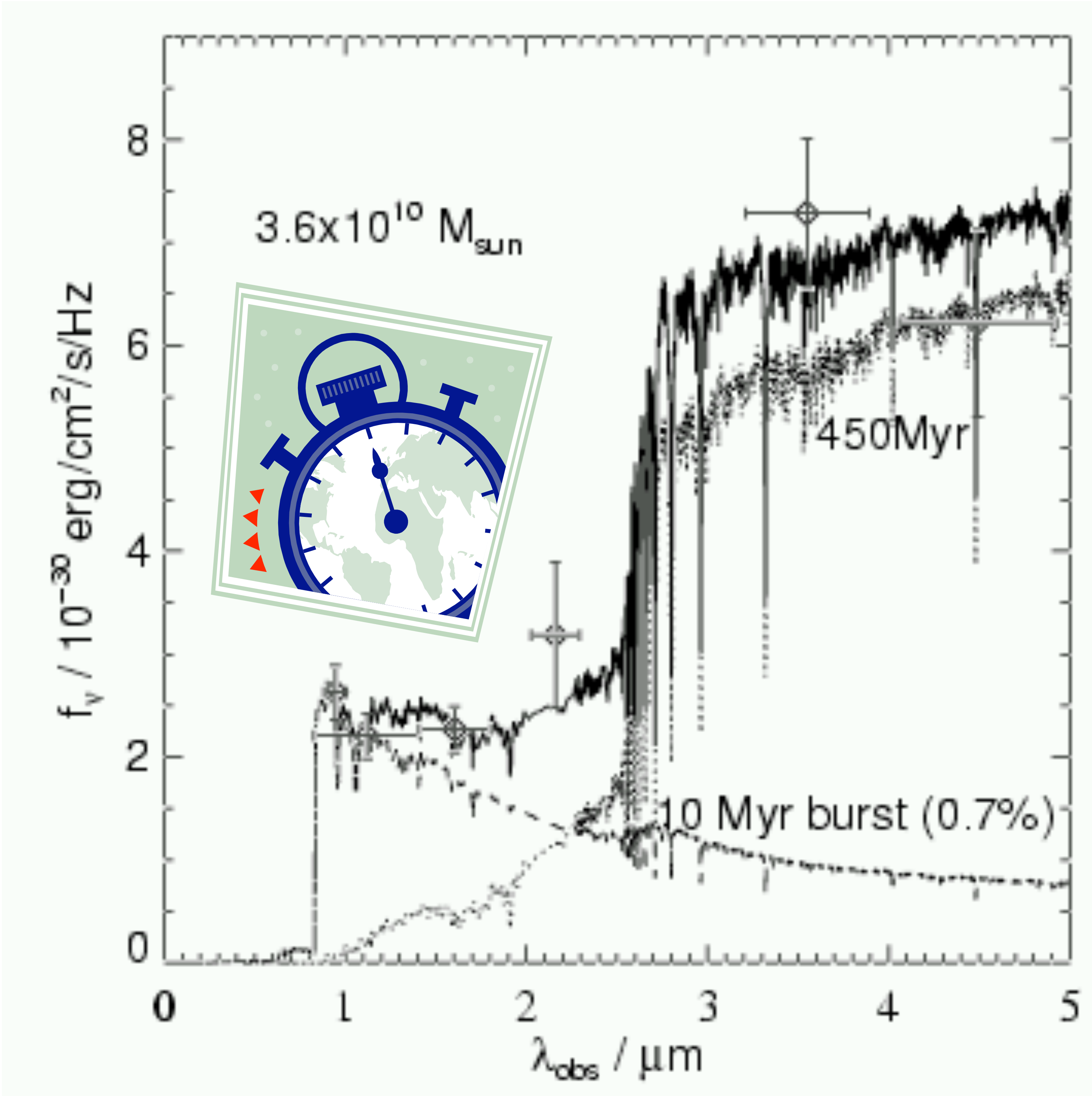
- *Different physics of star formation early on? (masses of stars)*
- *Undiscovered fainter sources (forming globular clusters?)*
- *Star formation at even earlier times?*



Spitzer – IRAC (3.6-8.0 microns)

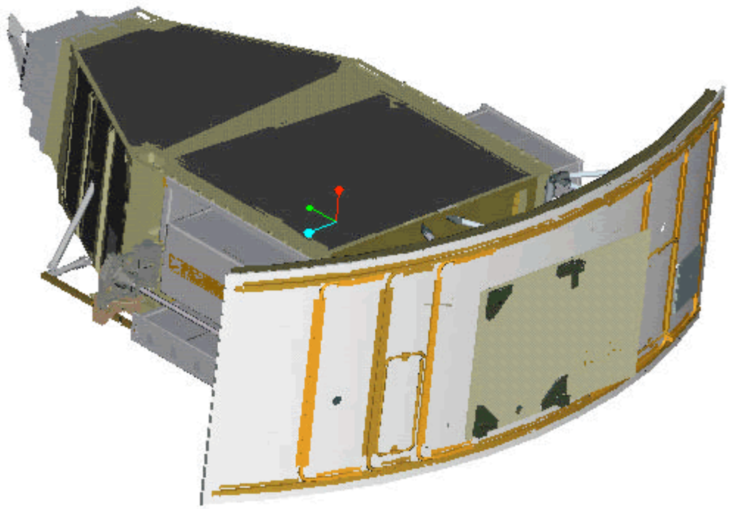


- z=5.83 galaxy #1 from Stanway, Bunker & McMahon 2003 (spec conf from Stanway et al. 2004, Dickinson et al. 2004). Detected in GOODS IRAC 3-4μm: Eyles, Bunker, Stanway et al. 2005

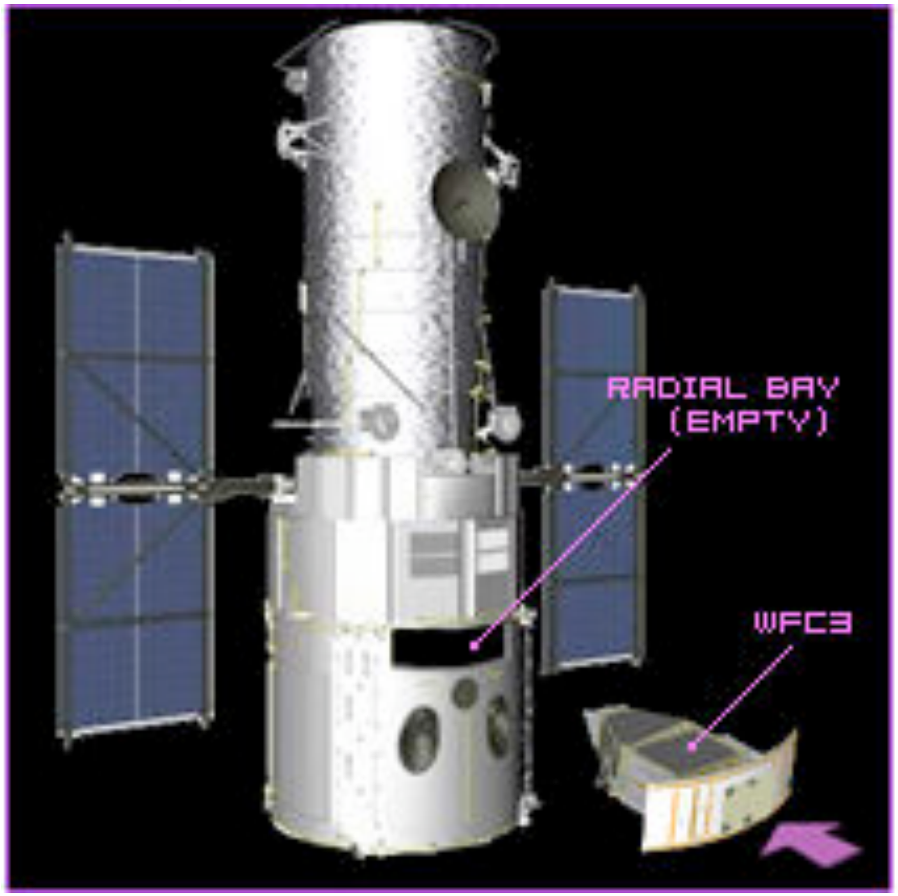


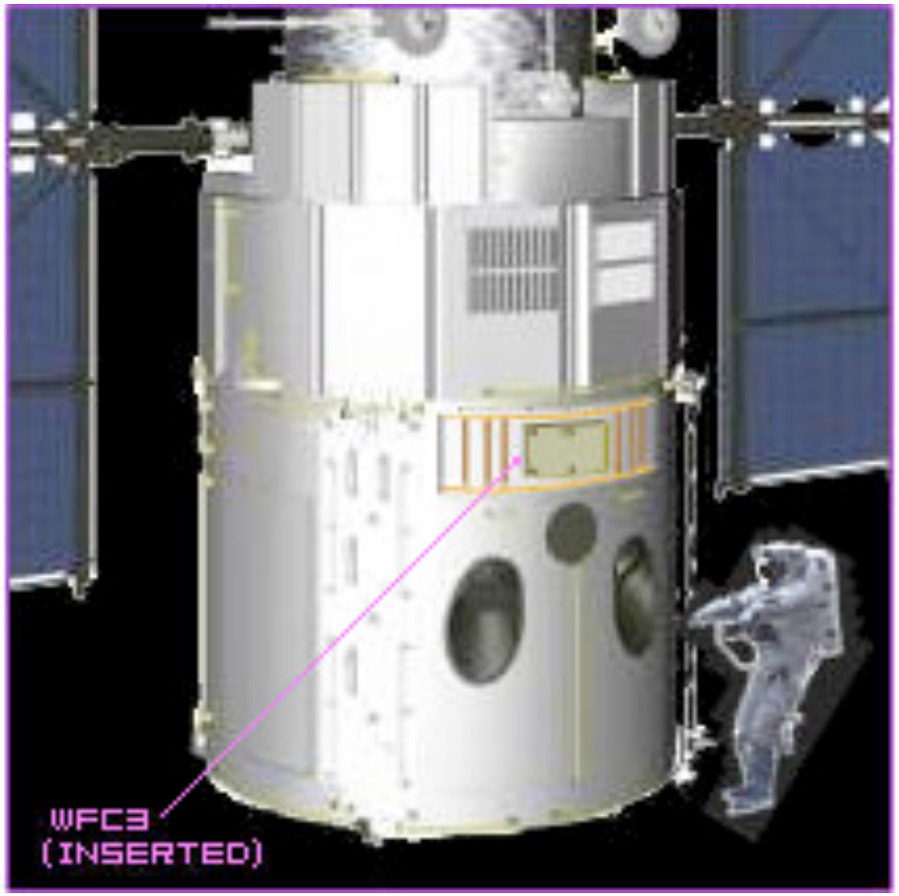
Eyles et al. (2005)

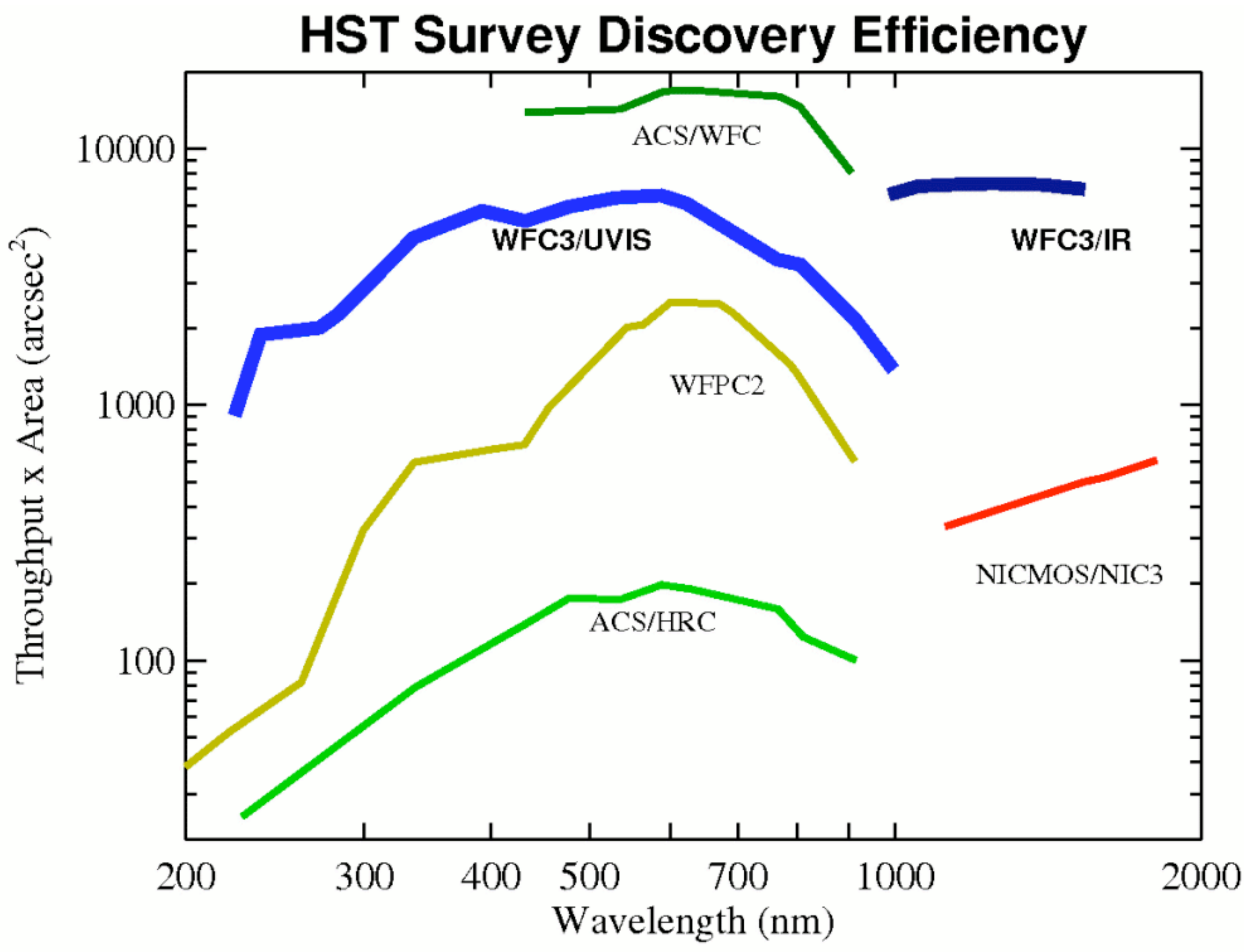
Emission line contamination does not seriously affect the derived ages and masses



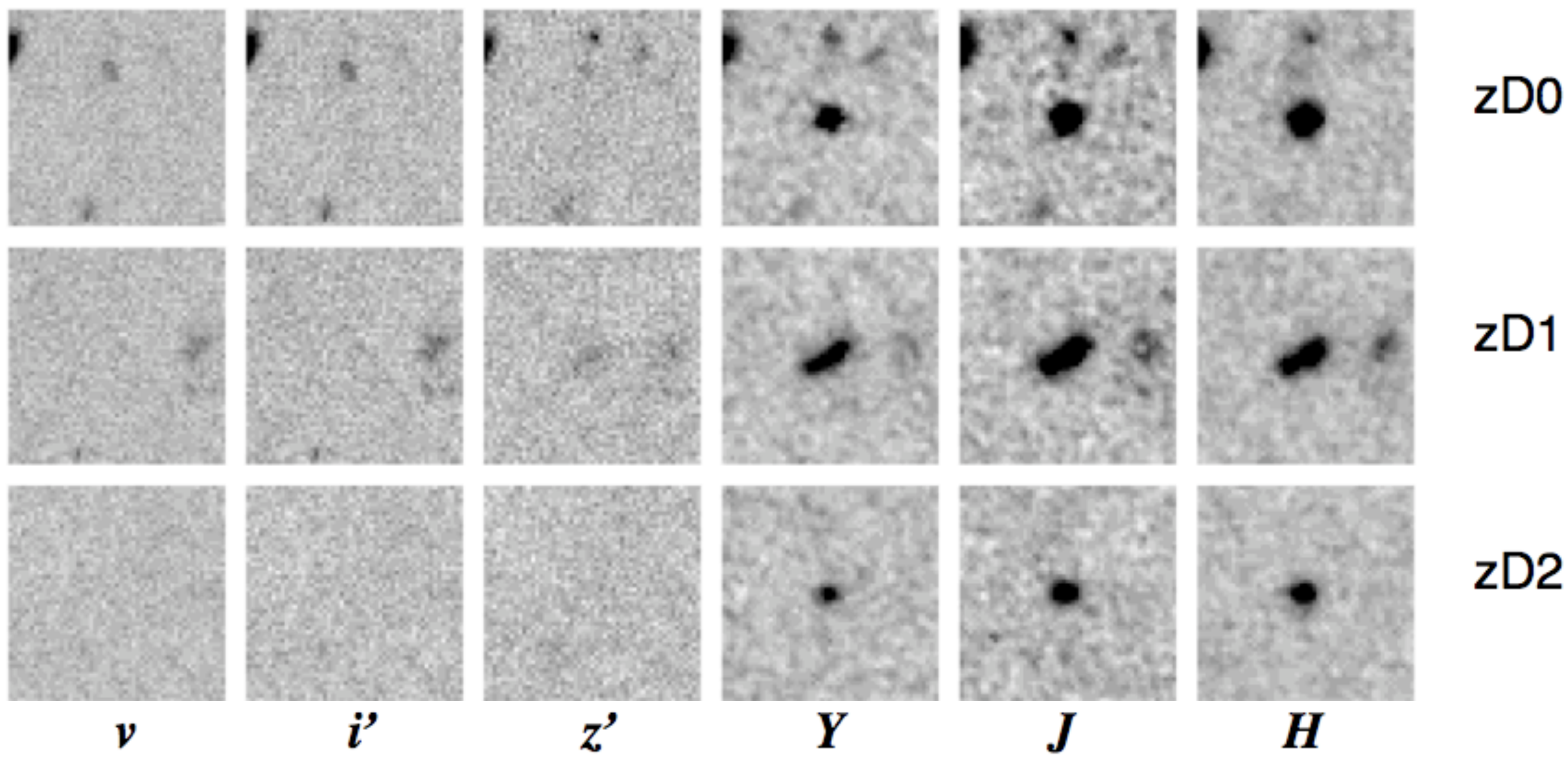
HST WFC3



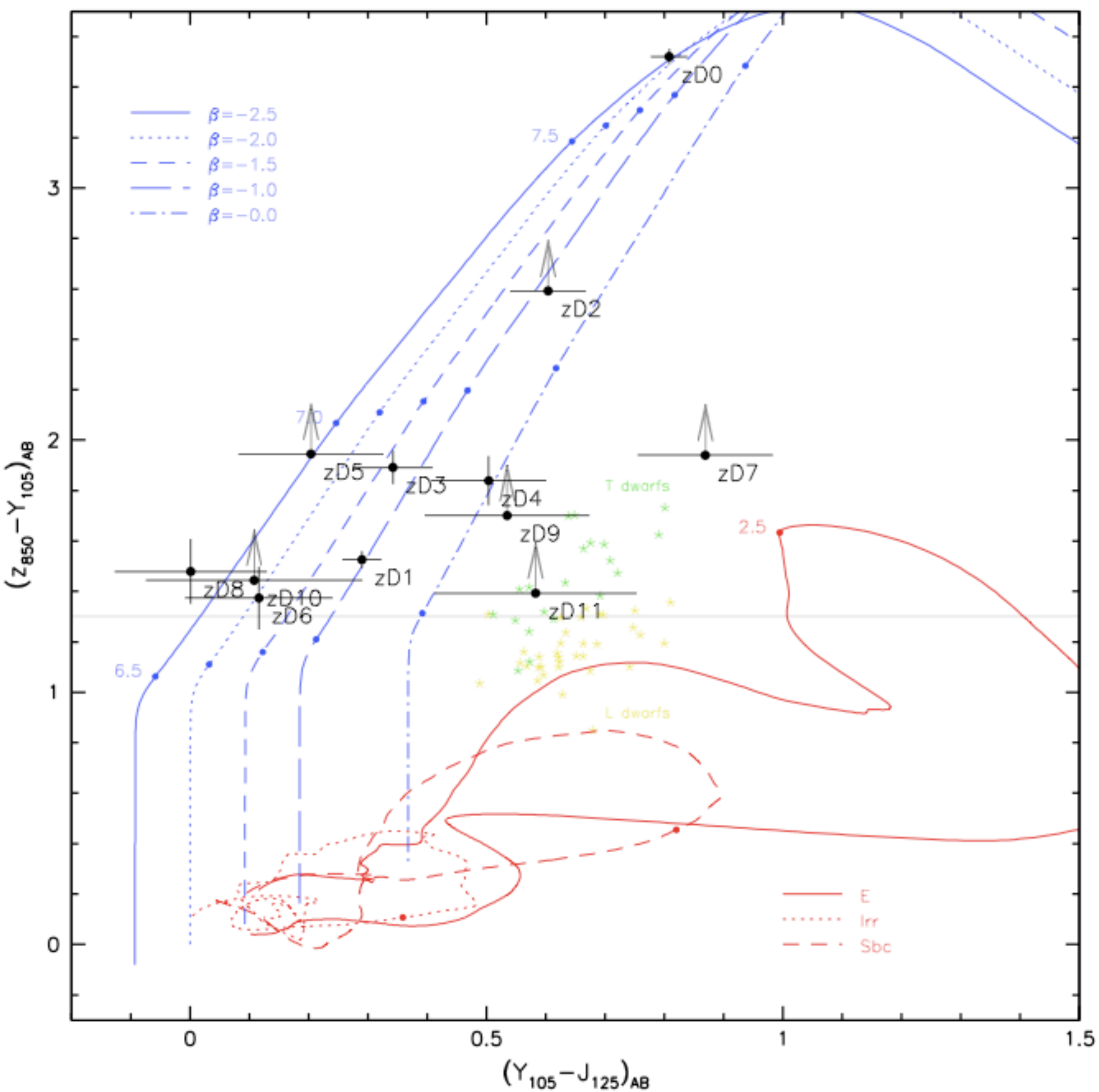




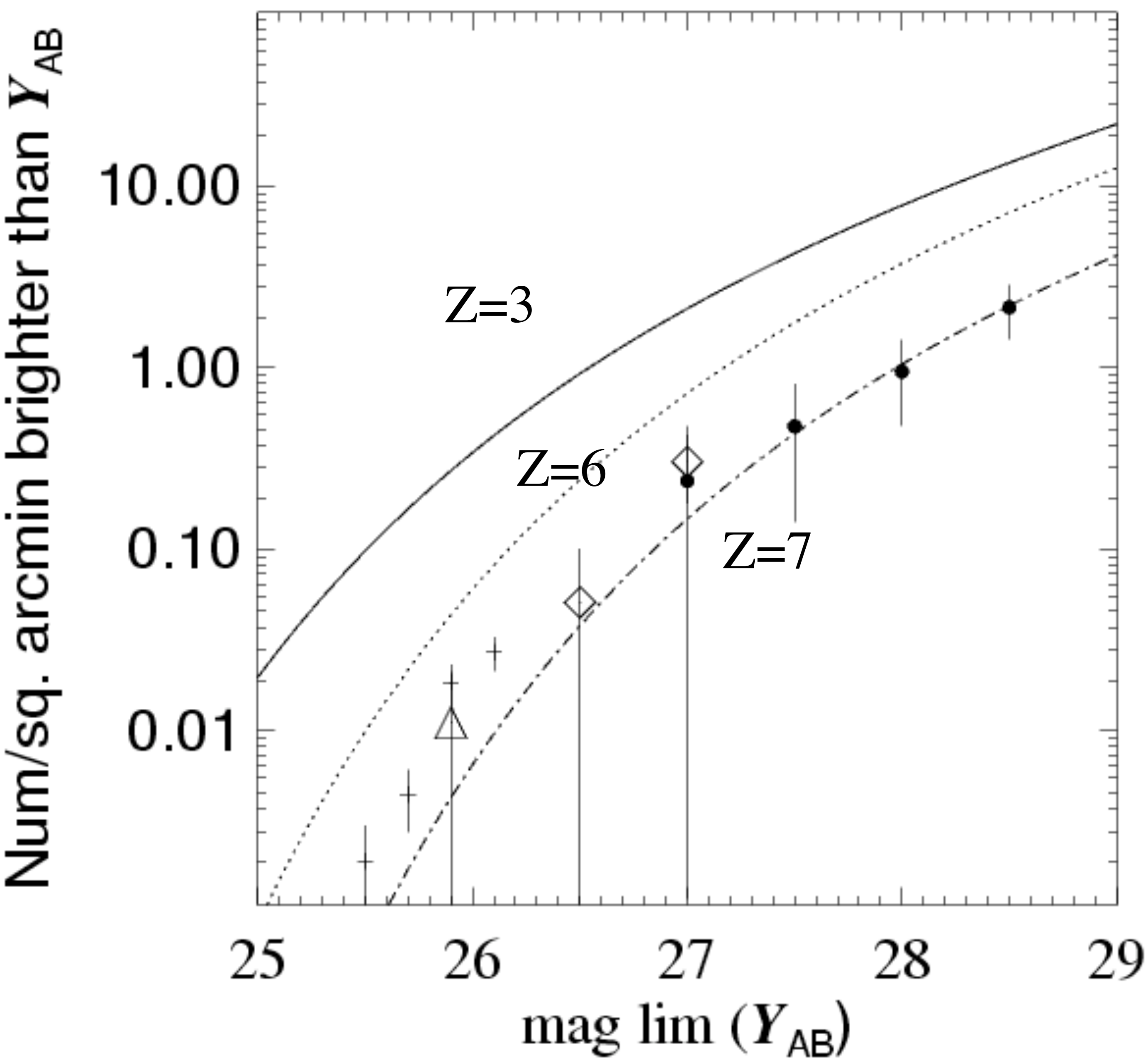
HST Survey Discovery Efficiency
ACS/WFC
WFC3/UVIS
WFC3/IR
WFPC2
NICMOS/NIC3
ACS/HRC
10000
1000
100
Throughput x Area (arcsec^2)
200
300
400
500
700
1000
2000
Wavelength (nm)



RECENT EXCITEMENT - 100 orbits of HST with WFC3 in 3 near-IR filters on Hubble Ultra Deep Field. Galaxies at z=7-9! Data taken last in last 7 months. 4 papers immediately (Bouwens et al., Bunker et al., McLure et al., Oesch et al.) and several more since. Also Early Release Science - Wilkins et al. has analysed



Bunker et al (2009) - HST/WFC3 near-IR imaging of the HUDF

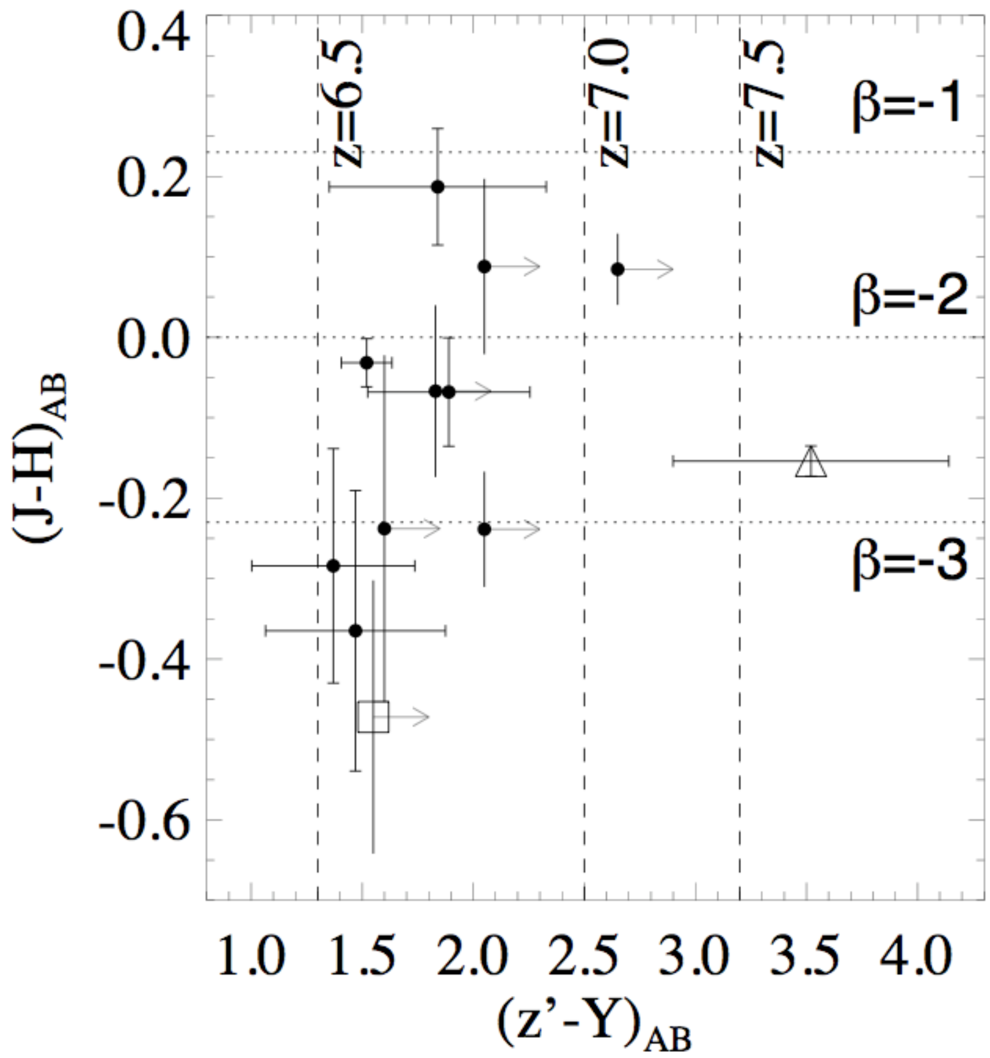


Num/sq. arcmin brighter than Y_{AB}
10.00
1.00
0.10
0.01
Z=3
Z=6
Z=7
25
26
27
28
29
mag lim (Y_{AB})

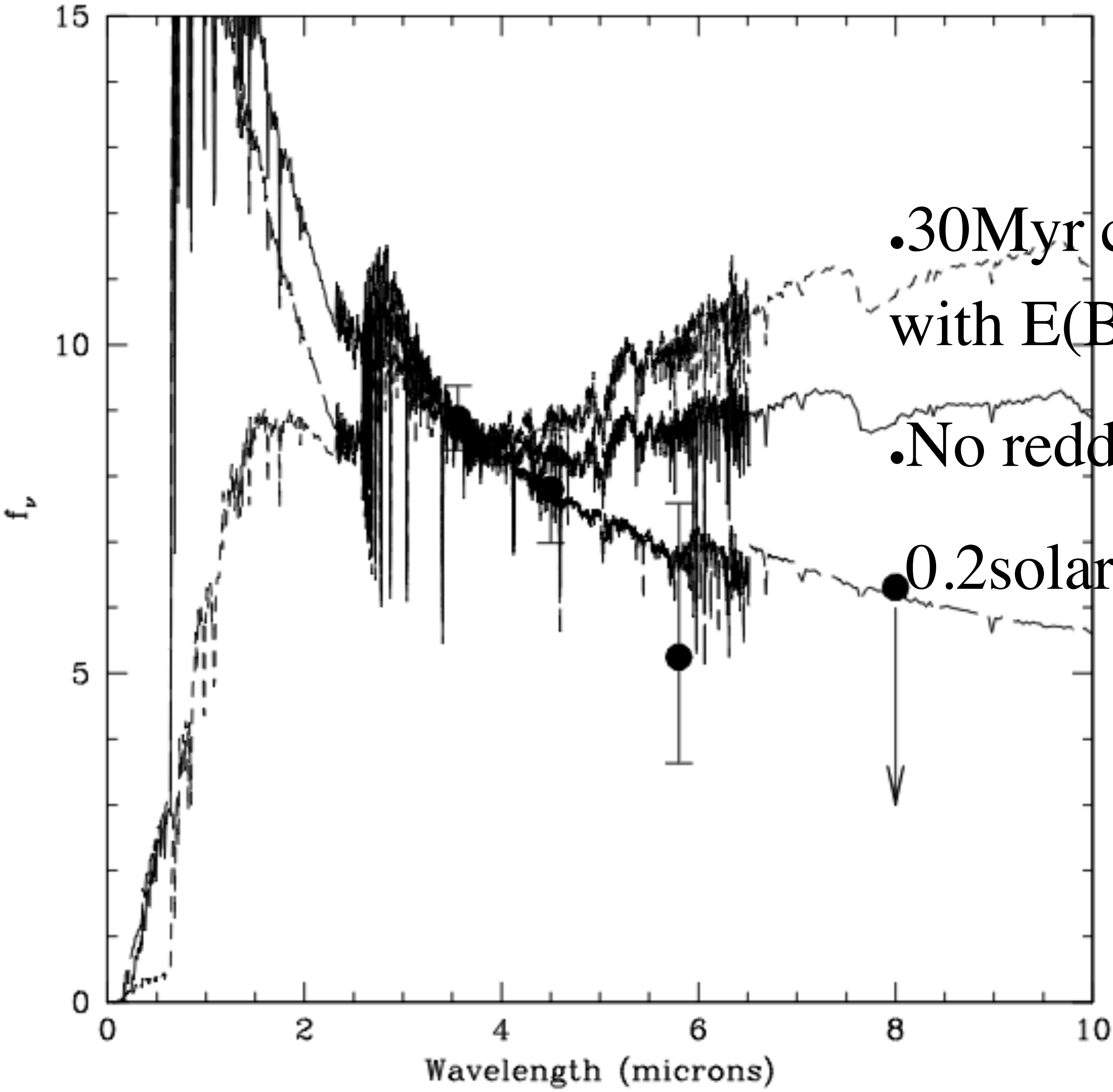
The rest-UV slope at z~6

- In Stanway, McMahon & Bunker (2005) we used the NICMOS J- and H-band images of the UDF to show that the I-band drop-outs at z~6 had remarkably blue rest-UV spectral slopes, $f_{\lambda} \propto \lambda^{\beta}$, with β=-2.2 (compared to β=-1.1 to -1.6 for the Lyman-break galaxies at z~3)

- Can use the full SED fits across the rest-UV and optical with Spitzer to further explore evolution in the dust-reddening (and potentially the IMF)

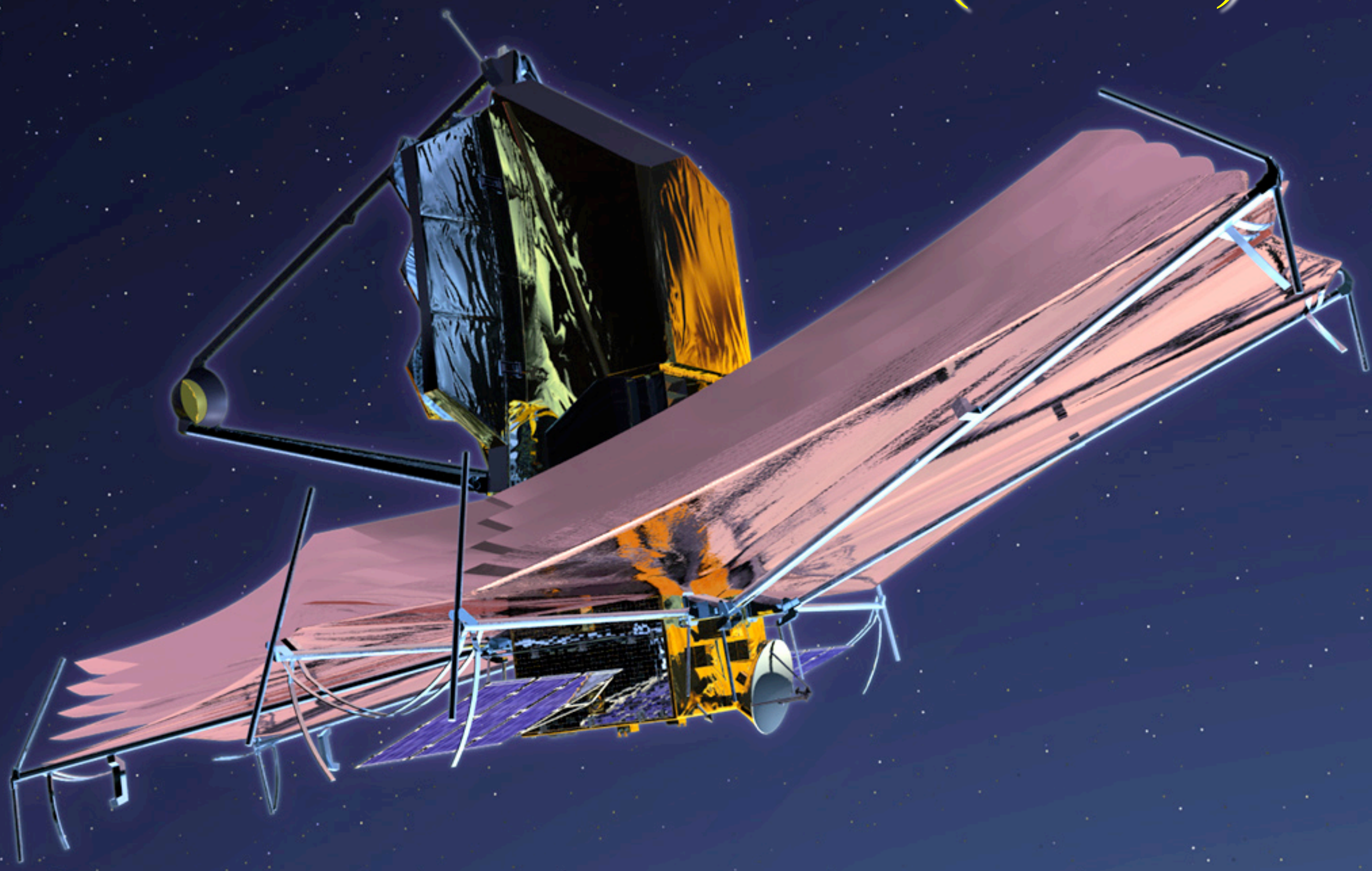


Very blue colours - different IMF? No dust? Low metallicity?



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

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

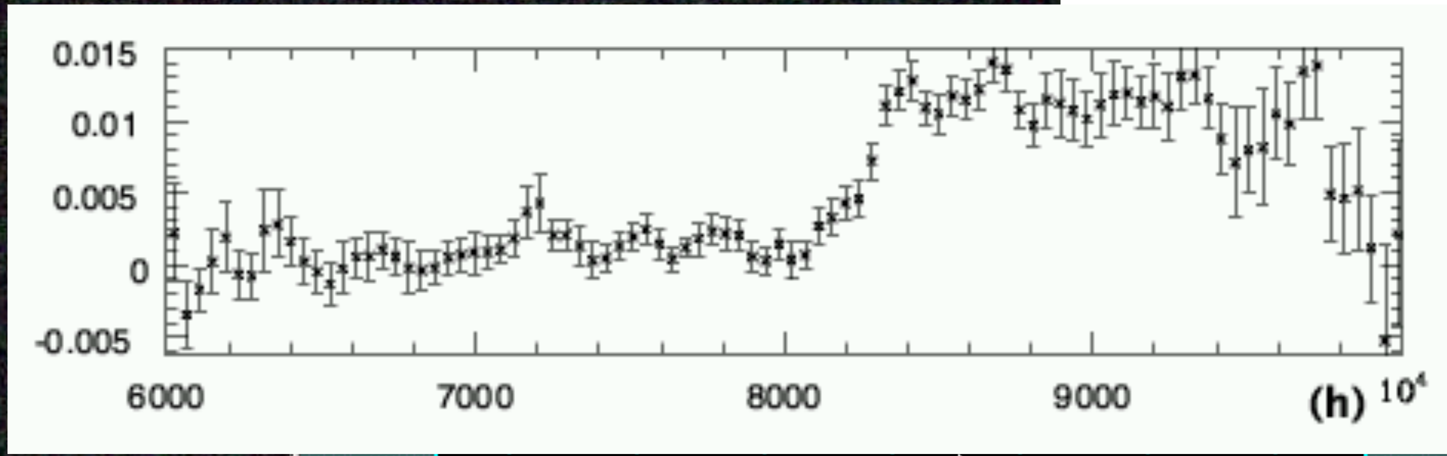


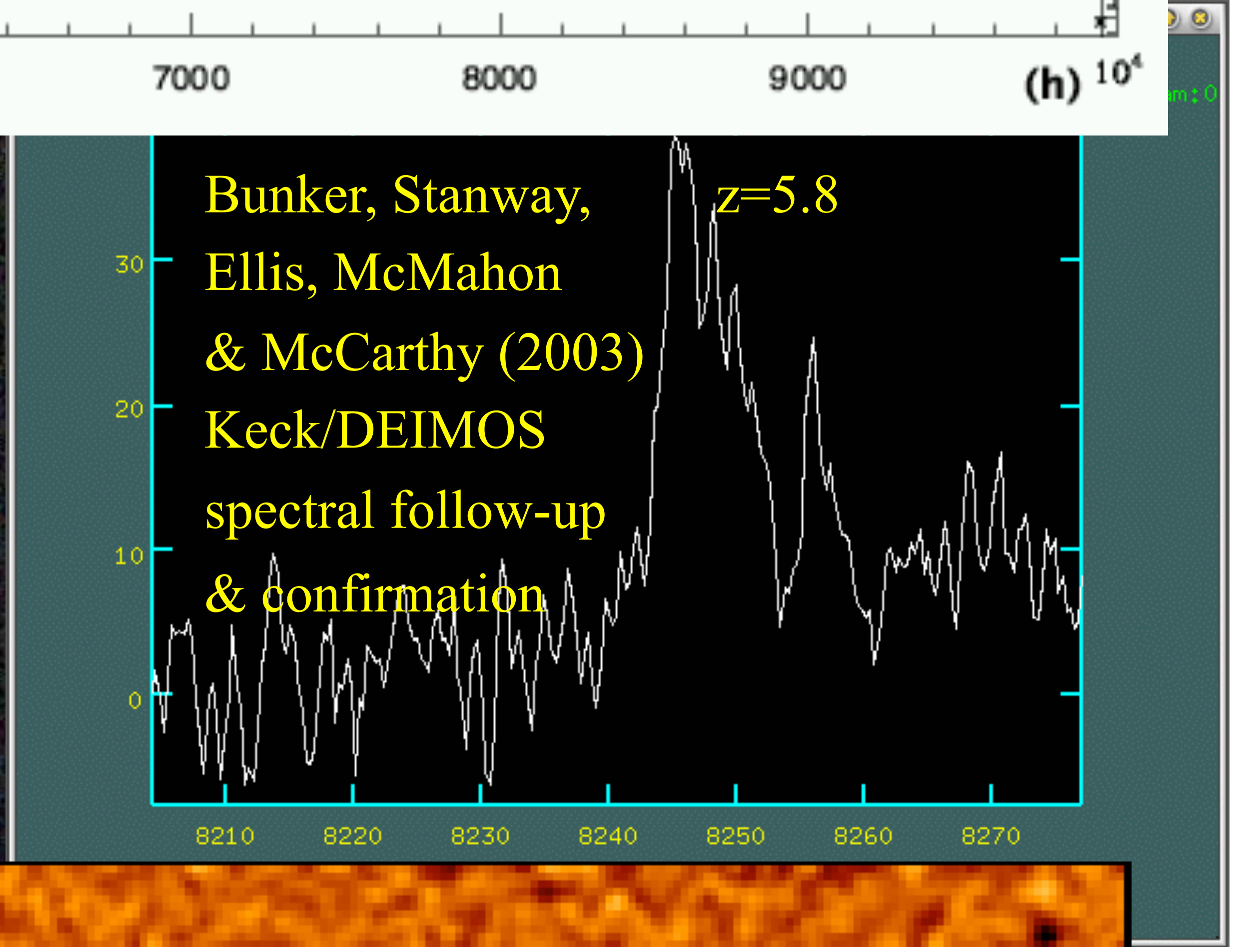
The Star Formation History of the Univese

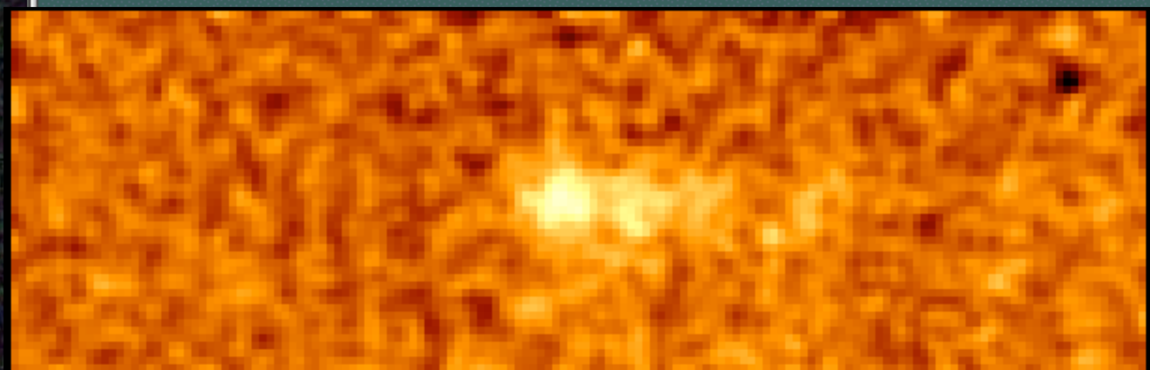
I-drops in the Chandra Deep Field South with HST/ACS

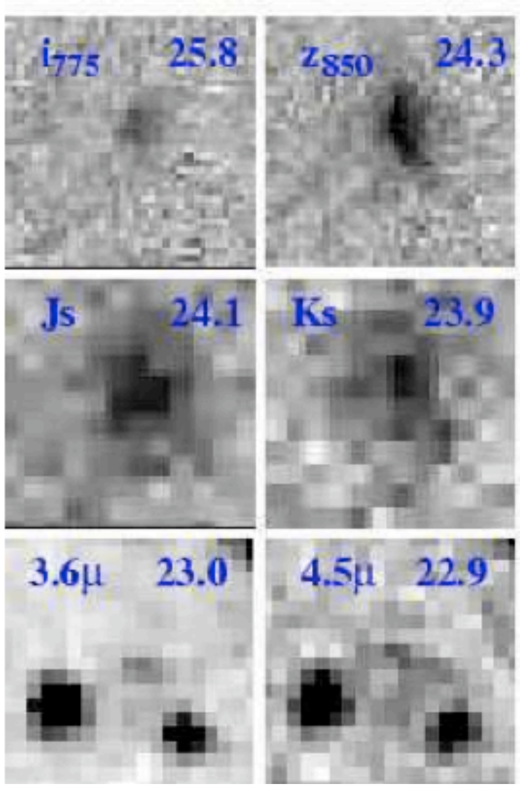
Elizabeth Stanway, Andrew Bunker, Richard McMahon

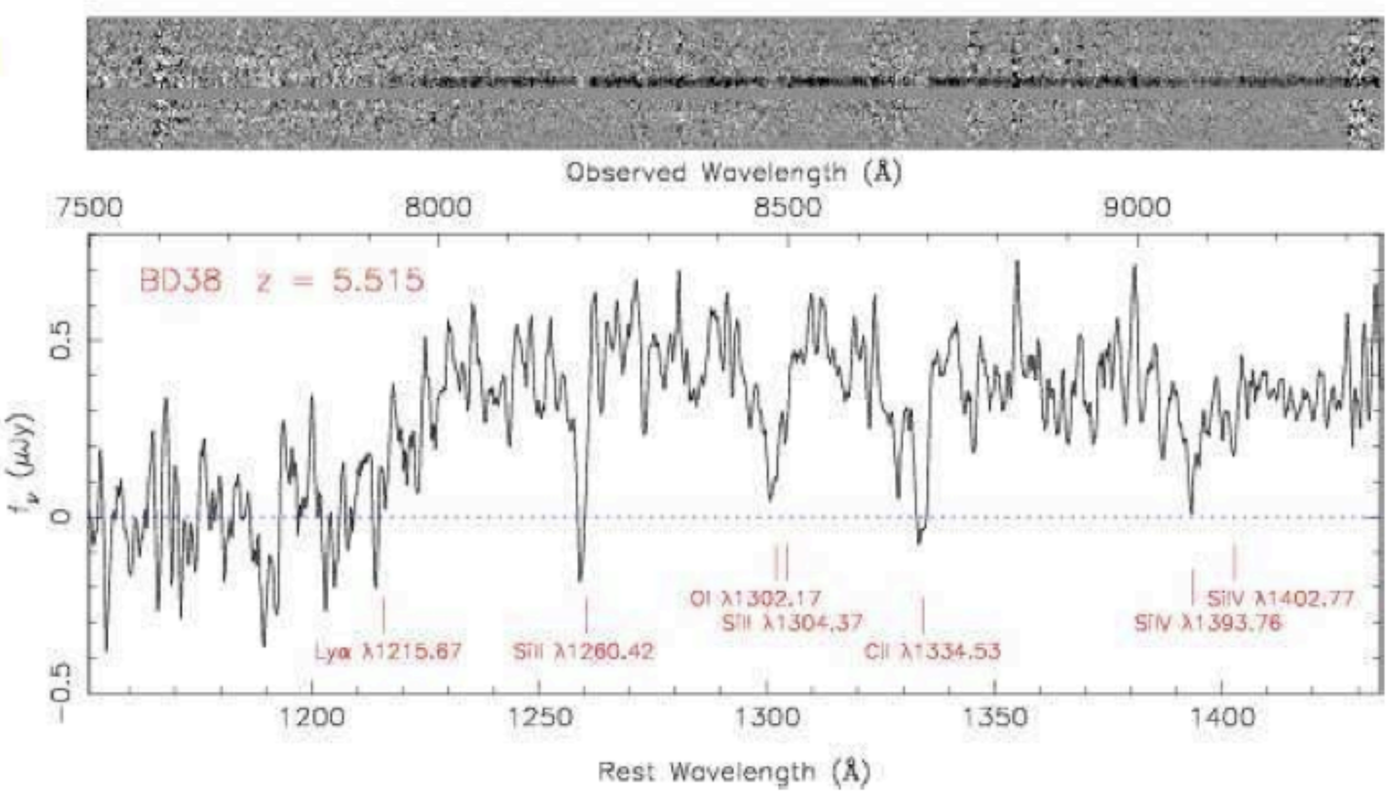
2003 (MNRAS)

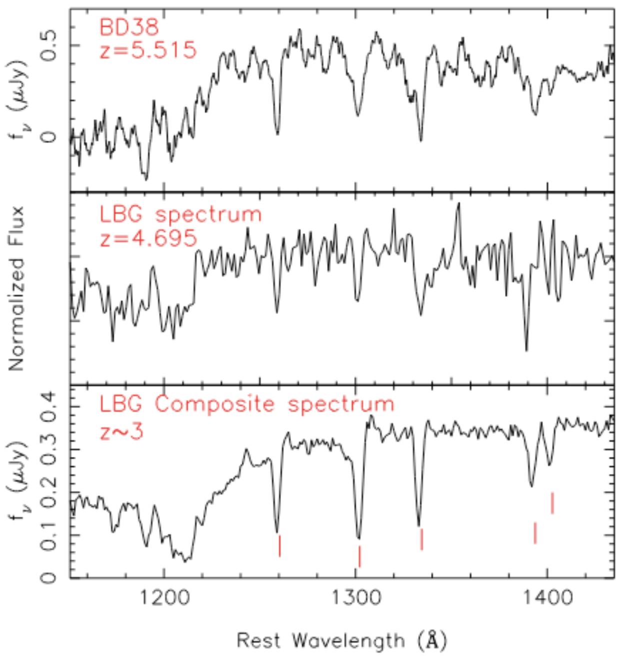




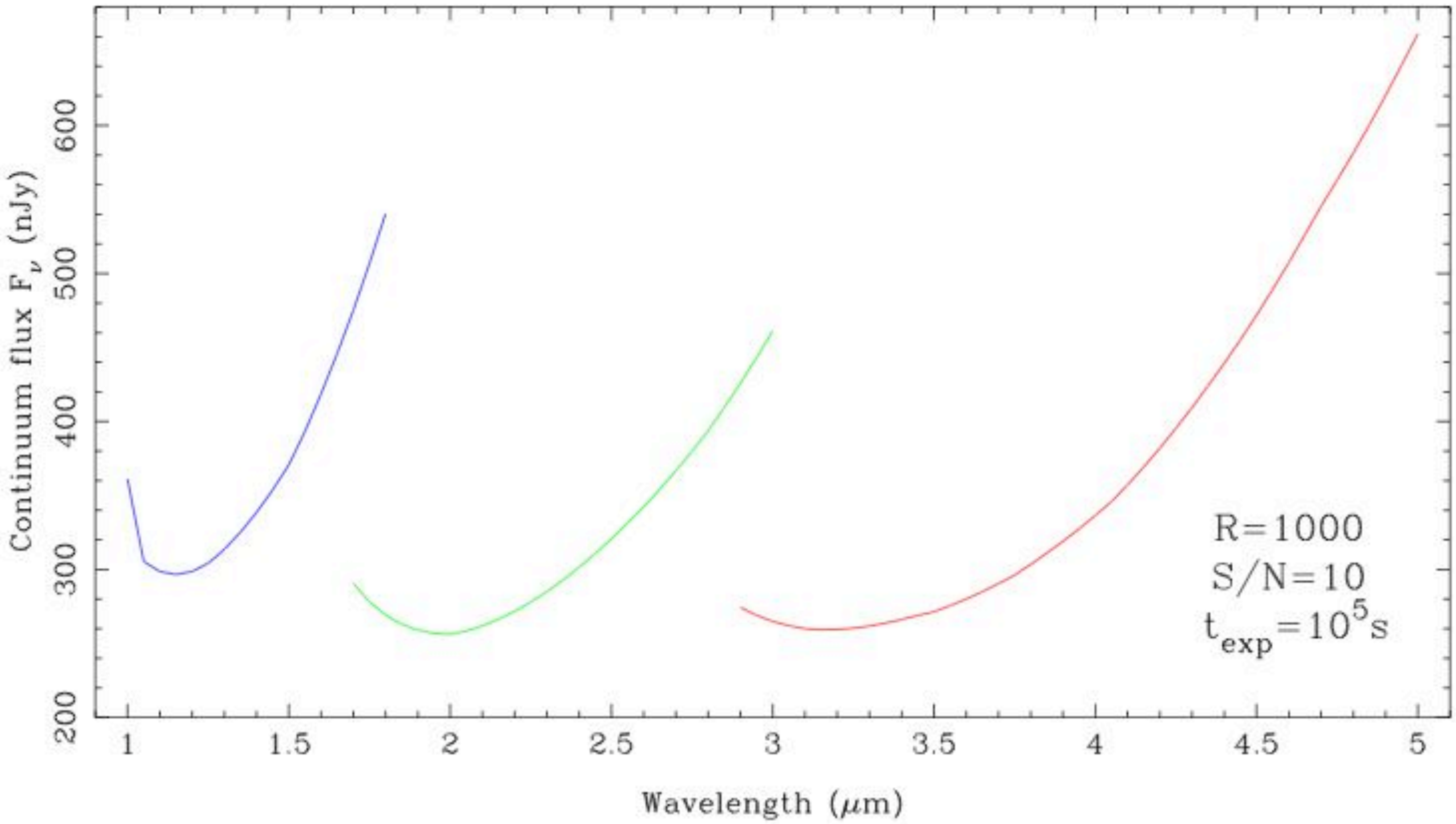






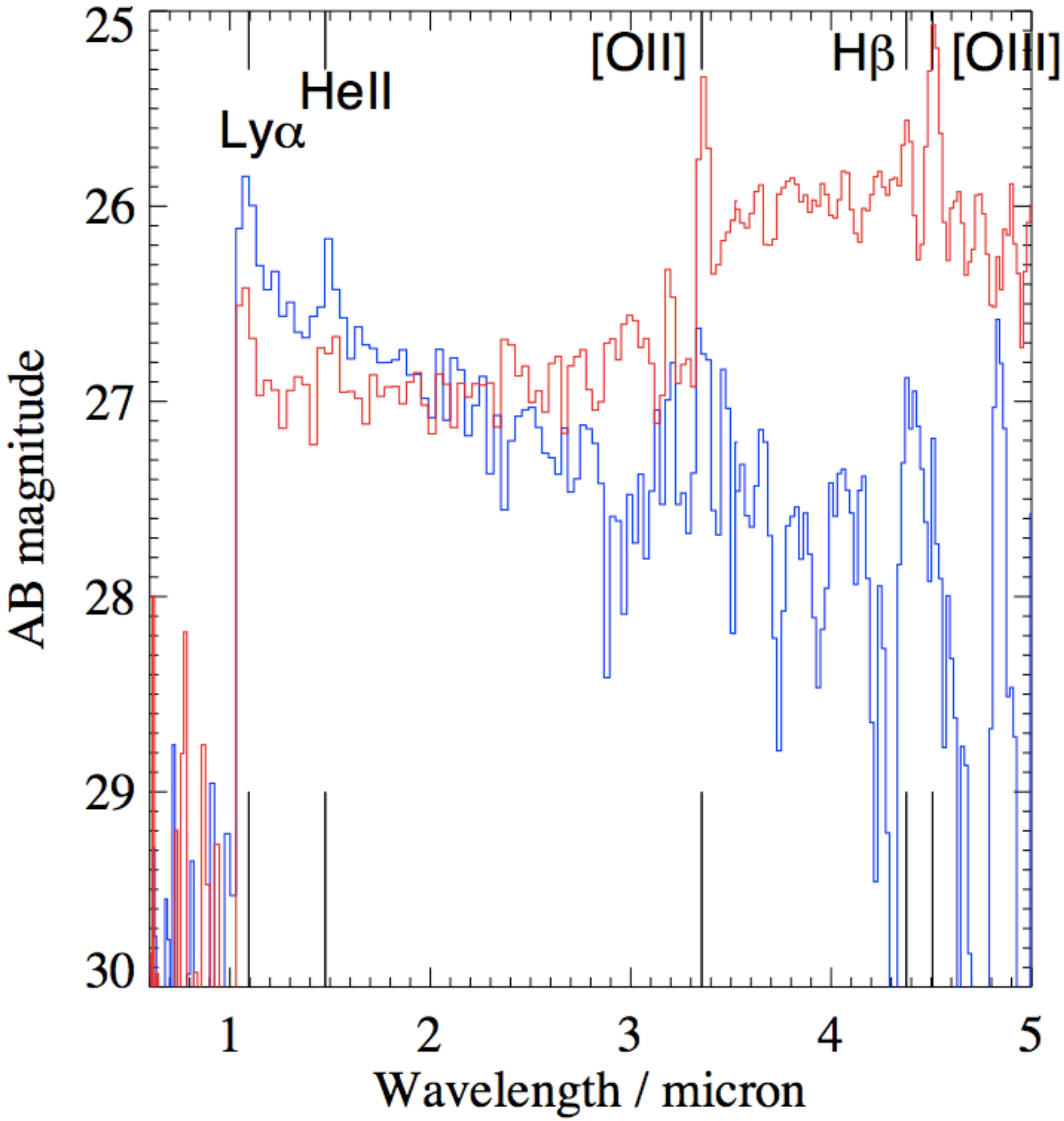


Absorption lines at z>5 - a single v. bright Lyman break z=5.5 galaxy, Dow-Hygelund et al (2005), AB=23-24, VLT spectrum (22 hours), R~3000; S/N=3-10 at R=1000,2700 in 1000sec NIRSpec



10sigma 10^5sec (or 1 sigma in 1000sec)

300nJy = 25.2 mag



Lyα
HeII
[OII]
Hβ
[OIII]
AB magnitude
Wavelength / micron
25
26
27
28
29
30
1
2
3
4
5

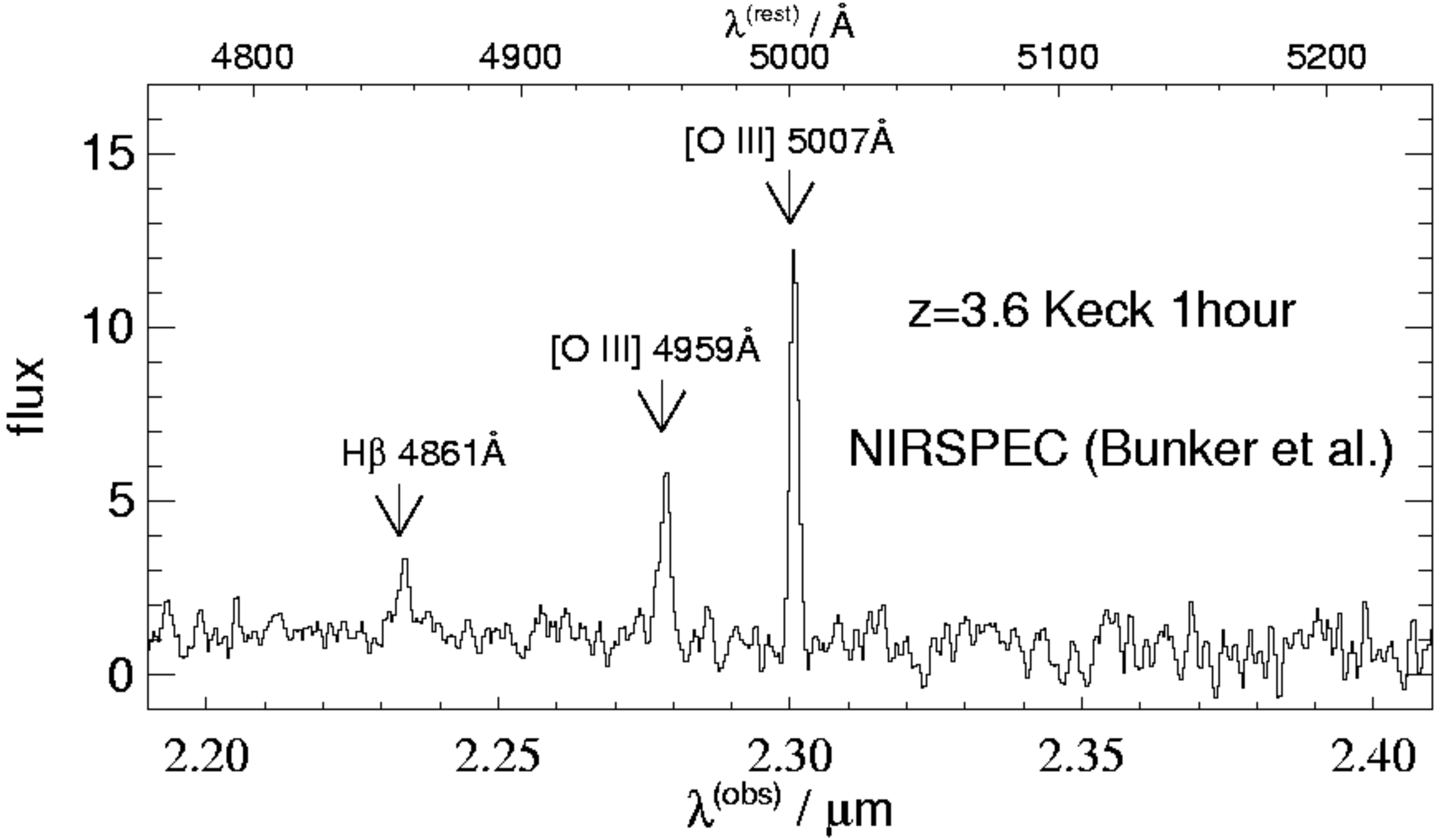
Lyman-alpha Searches : JWST strategies

1) Follow-up Lyman break galaxies from NIRCAM (J-drops @z=10, H-drops @z=15, K-drops @z-20), hope to get Ly-alpha with NIRSPEC (perhaps even continuum - maybe in QSOs only)

2) Use FGS tunable filter to get emission line objects, and follow up with R=1000-3000 to determine if H-alpha/[OIII] etc at low-z, [OII] at intermediate-z, or Ly-alpha at high-z

3) Slitless NIRSPEC survey (less sensitive than FGS, but larger volume). Critical line mapping in gravitational lenses?

Emission lines ⇒ Star formation rates, metallicity (oxygen, R_{23}), dust extinction ($H\alpha/H\beta$), line widths/rot curves ⇒ kinematics/masses

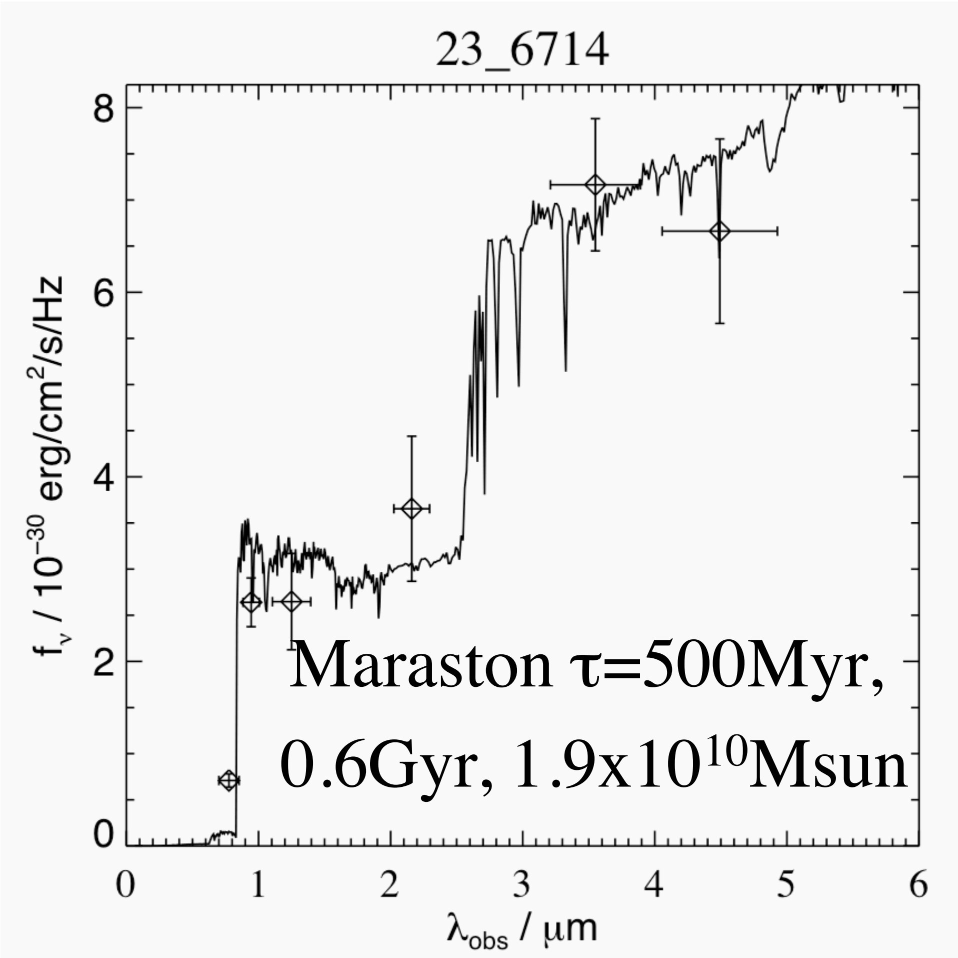


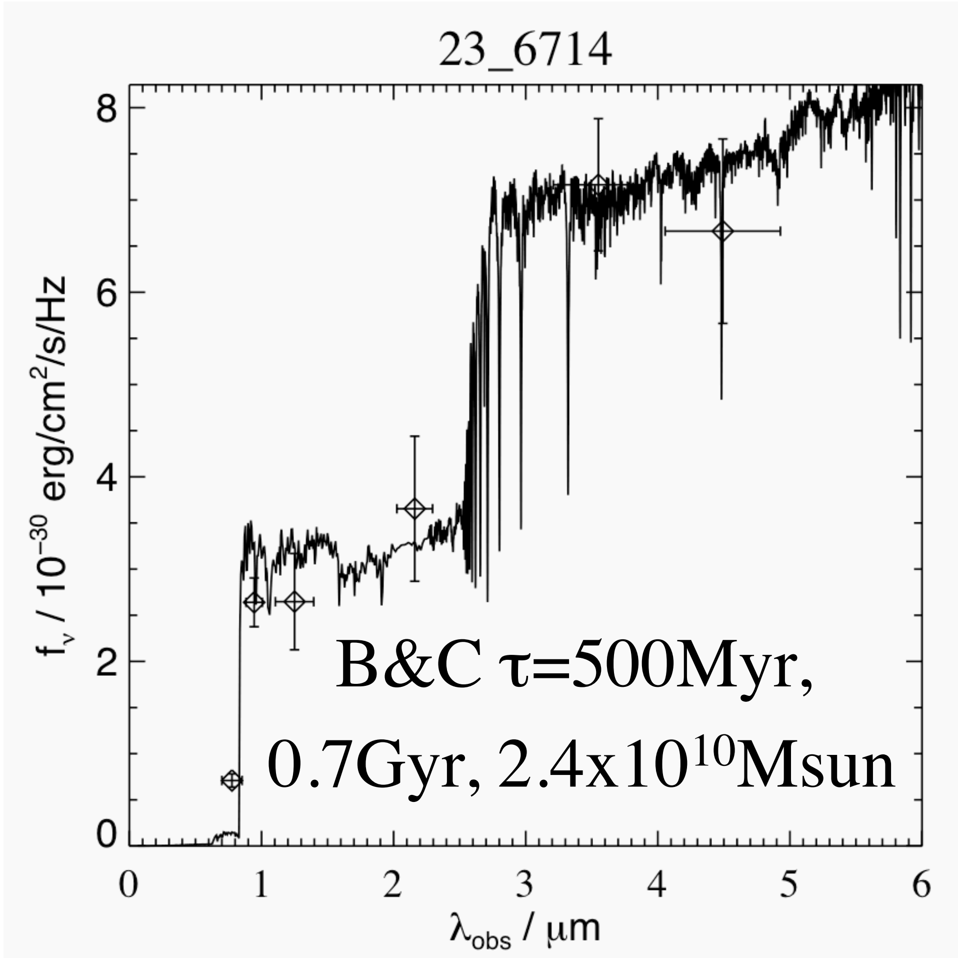
Experience with HST and Keck (& 8m telescopes) tells us the effectiveness of ELT will be multiplied if it happens while JWST is running (2014 onwards - 5+year mission).

Don’t want ELT timescales to slip by much… and first light instruments must deliver


NIRSpec IST
Near Infrared Spectograph
(NIRSpec) Mockup
Please don't touch!

Other Population Synthesis Models





Maraston vs. Bruzual & Charlot