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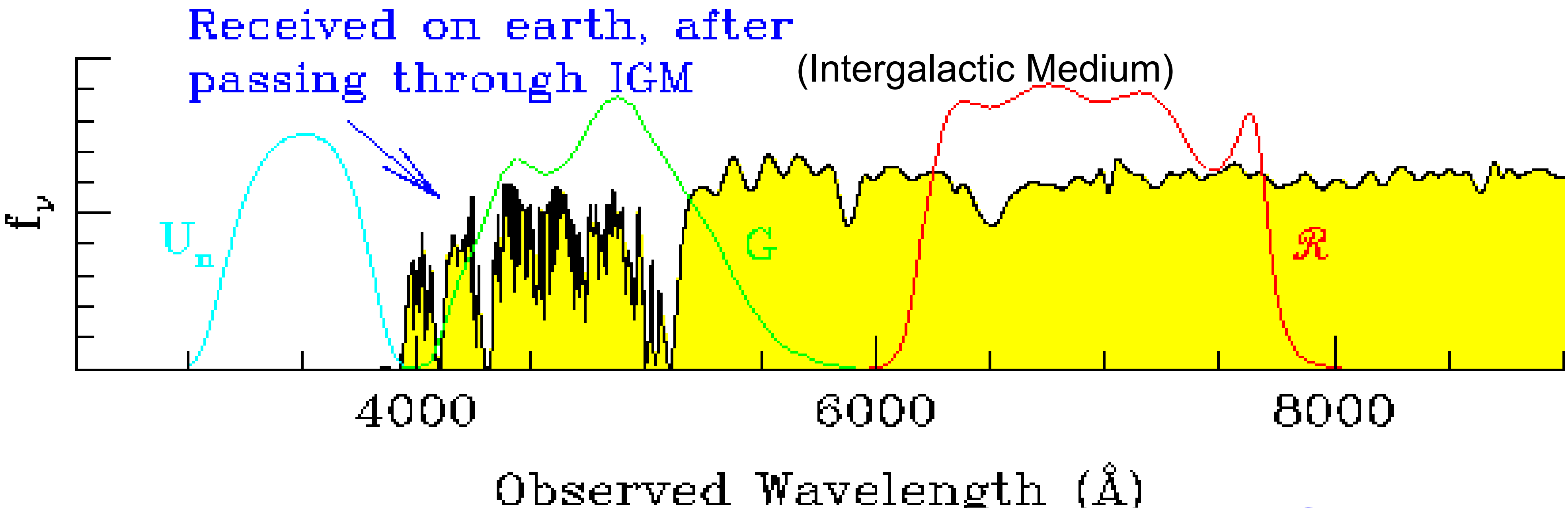
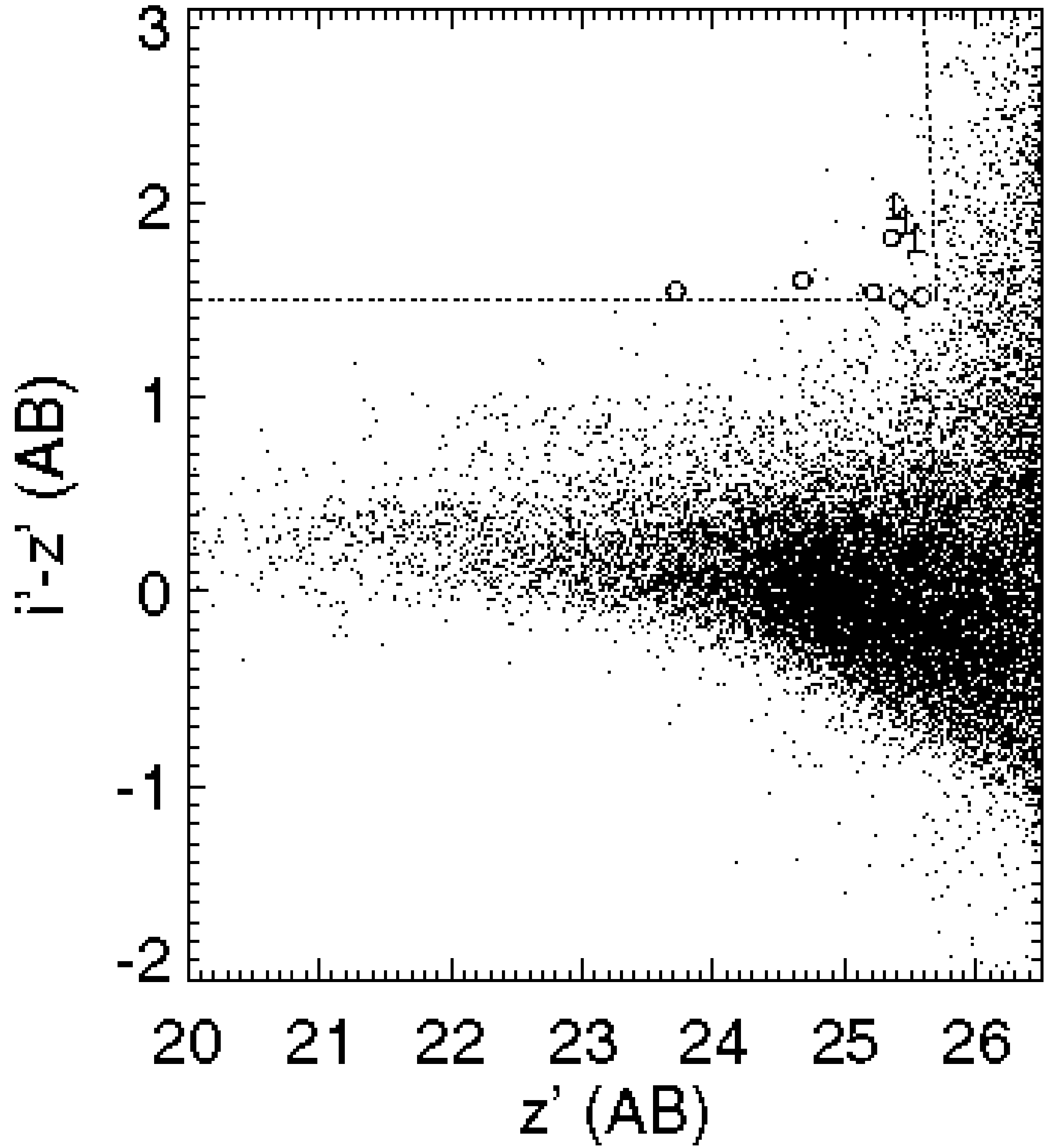
Lecture 2 – Properties of high reshift galaxies:

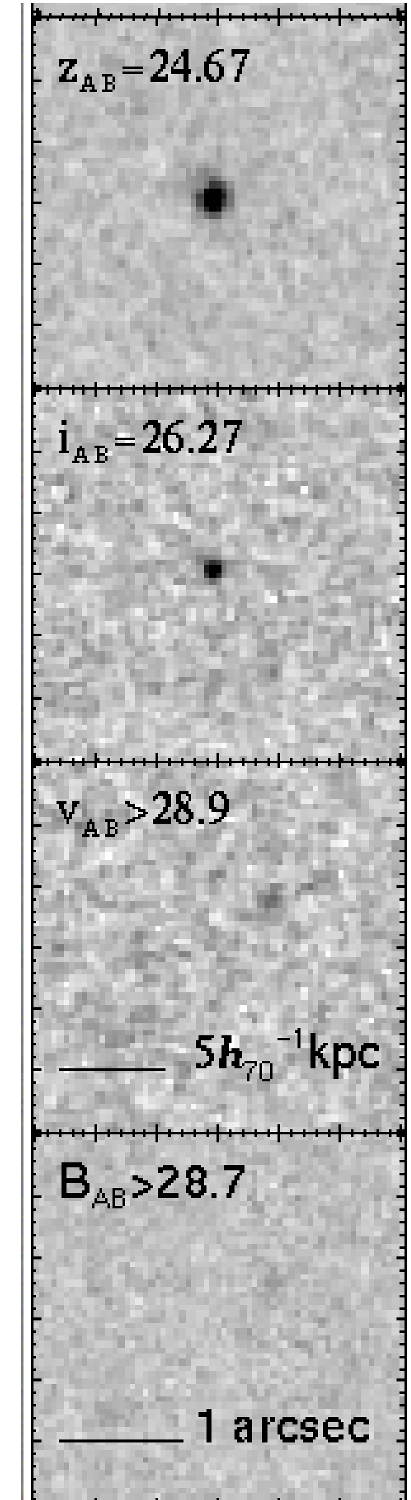
Their Evolution and Role in Reionization of the Universe

TIARA Winter School, Feb '12



"Lyman break technique" - sharp drop in flux at wavelengths less than Ly-α - hydrogen gas between us and the distant object absorbs light at the energy of quantum electron transitions. Lower redshift, so shorter wavelength. A distant (high redshift) object should have no detectable emission at short wavelength

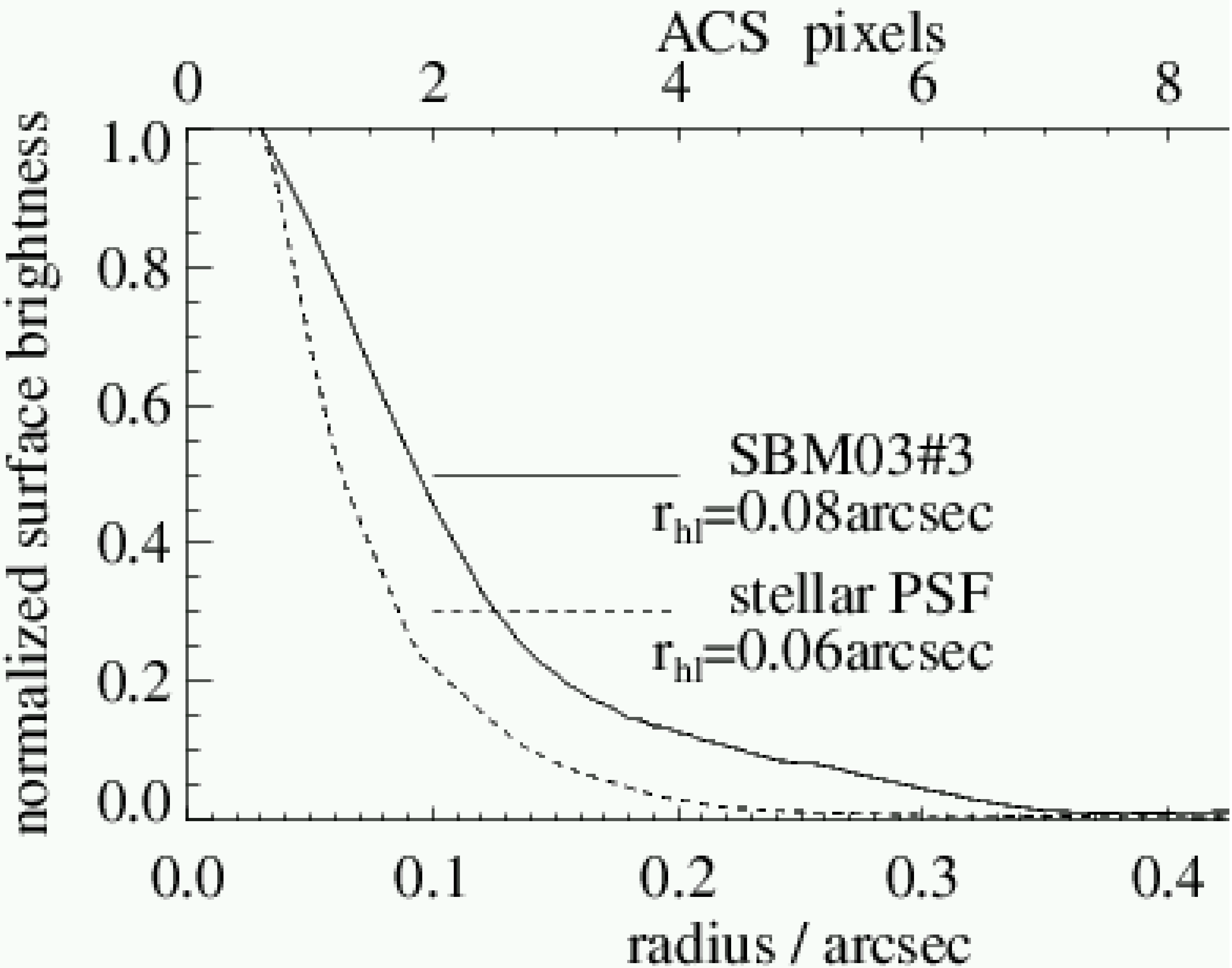




Using HST/ACS GOODS data - CDFS & HDFN, 5 epochs B,v,i',z'

The Star Formation @z~6 with HST imaging and Keck & Gemini spectra

- Select i'-z'>1.5 and z'>25.6 (AB mags) with GOODS
- Corresponds to 15M_sun/yr at z=5.9 (luminosity-weighted centre of selection window) - *prone to dust*
- this is ~1L* of the star-forming Lyman break population at z~3-4 - Survey about 200sq. arcmin (200,000 Mpc^3) each in 2 different GOODS fields, HDFN-N & CDFS-S
- Numbers consistent: about 6 in each (after removing M/L/T dwarf low-mass stars, major contaminant)
- Spectroscopic confirmation of some of these: see Lyman-α in emission in some (but not all). Using Keck/Deimos (with Richard Ellis) and Gemini/GMOS (GLARE project, with Karl Glazebrook, Bob Abraham etc., nod&shuffle). Other groups using FORS2/VLT.


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

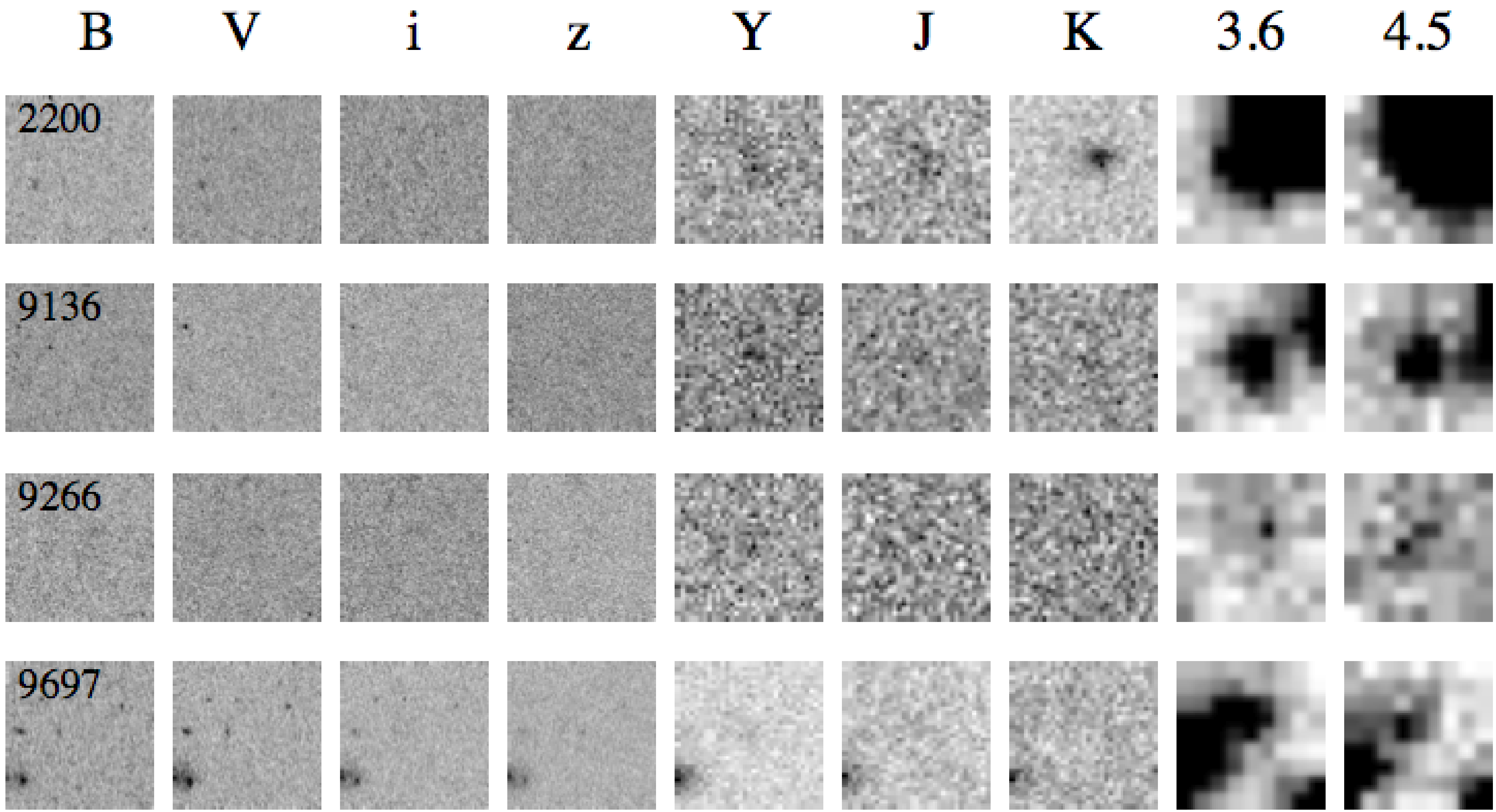
What about at z>7? (rest-UV at >1micron)

- these are the z-drops, Y-drops, J-drops

Mannucci, Buttery, Maiolino et al 2007
use J+K<25.5AB, see no non-stellar
drops in GOODS-S over 140sq.arcmin
Bouwens et al (2005) have ~4
candidates in 5sq.arcmin UDF-NICMOS
to AB=27.5mag

New ground-based instruments (e.g.
HAWK-I on VLT, and VISTA)

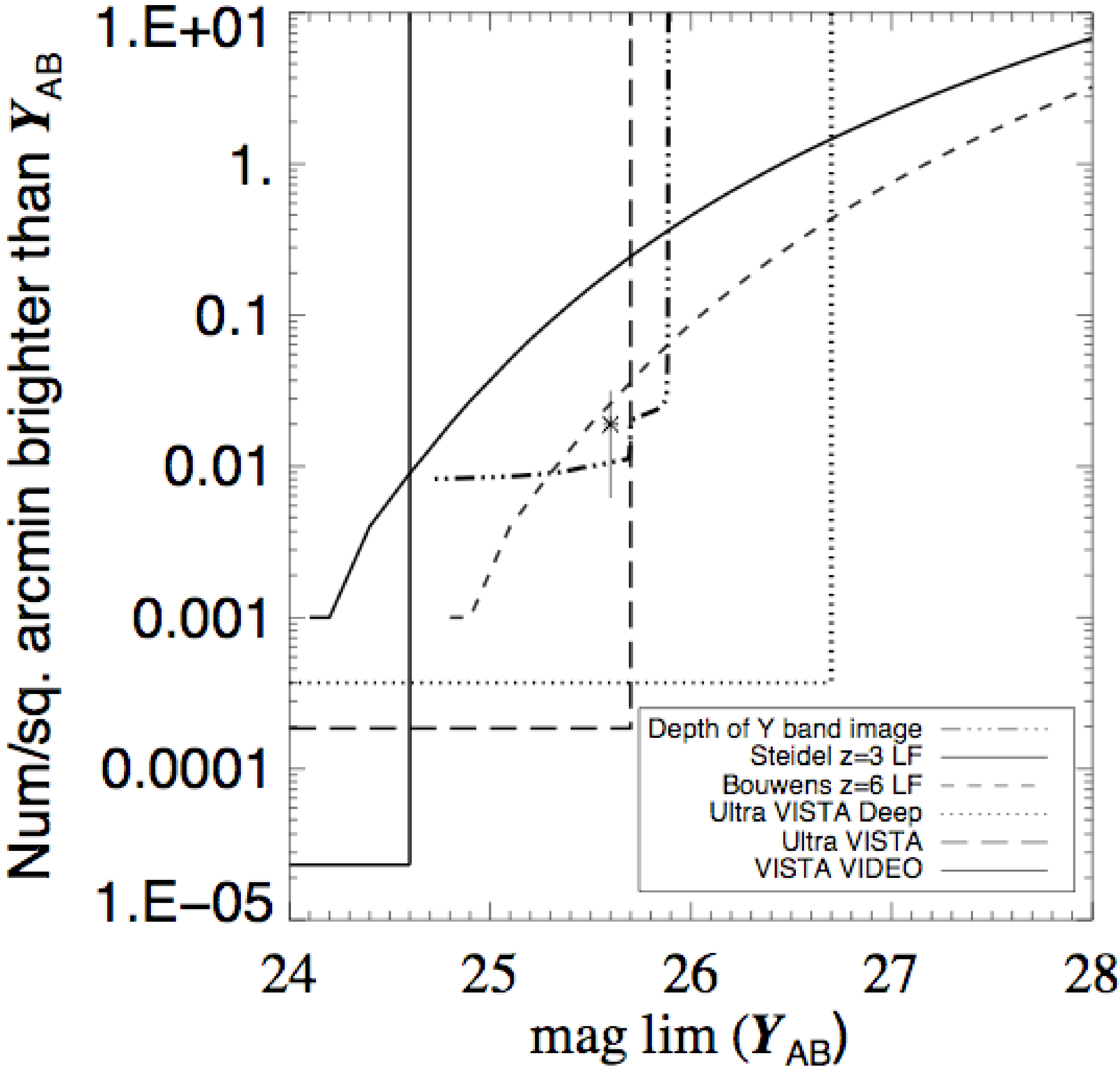
A WFC3 campaign is today exploring
larger fields to comparable depth or
deeper, match to NIRSpec field



Hickey, Bunker, Jarvis, Chiu & Bonfield (2010 MNRAS):

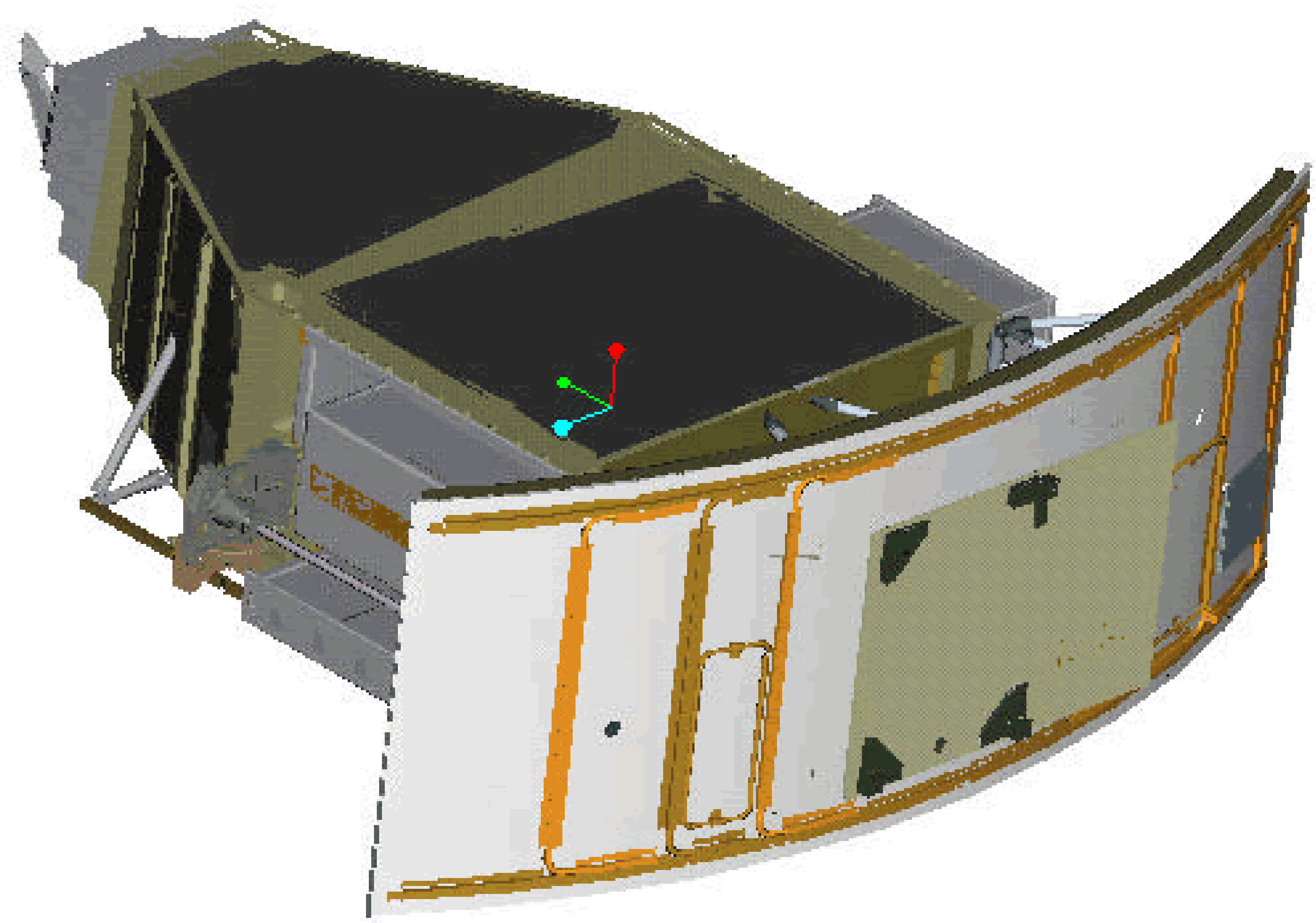
z-band dropout candidates in GOODS-South from HAWK-I

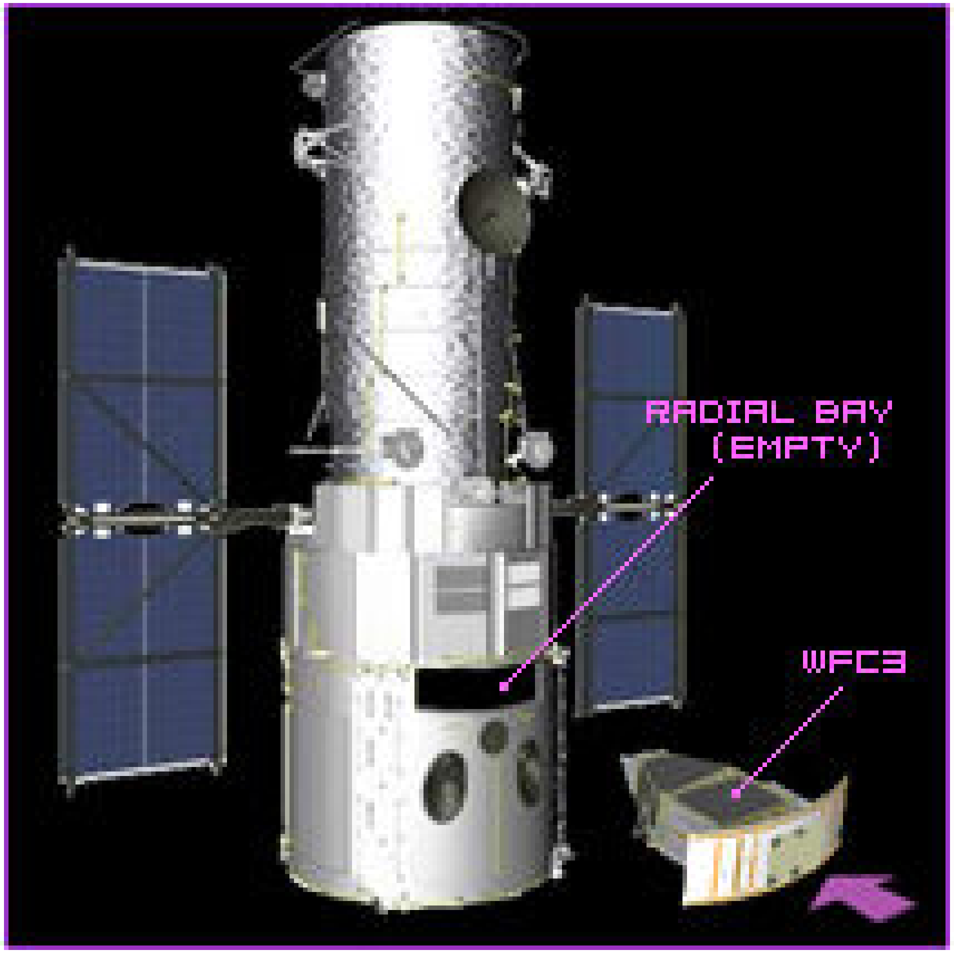
The next-step: finding galaxies at z>7 to explore stellar pops



ESO/VLT HAWK-I Y-band: look for z-band dropouts At z>7 Samantha Hickey, A. Bunker, Matt Jarvis et al. (2010) MNRAS

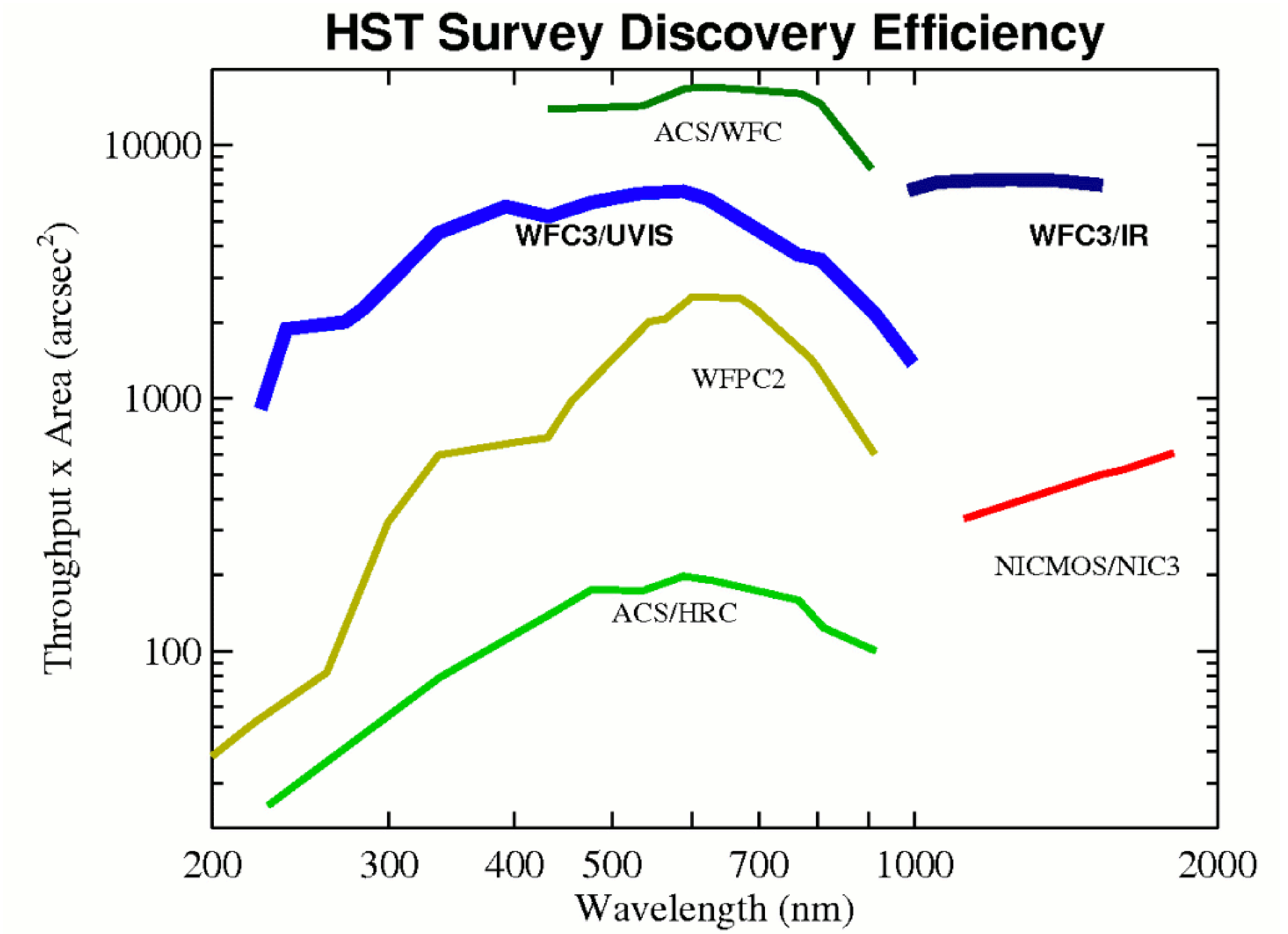
HST WFC3

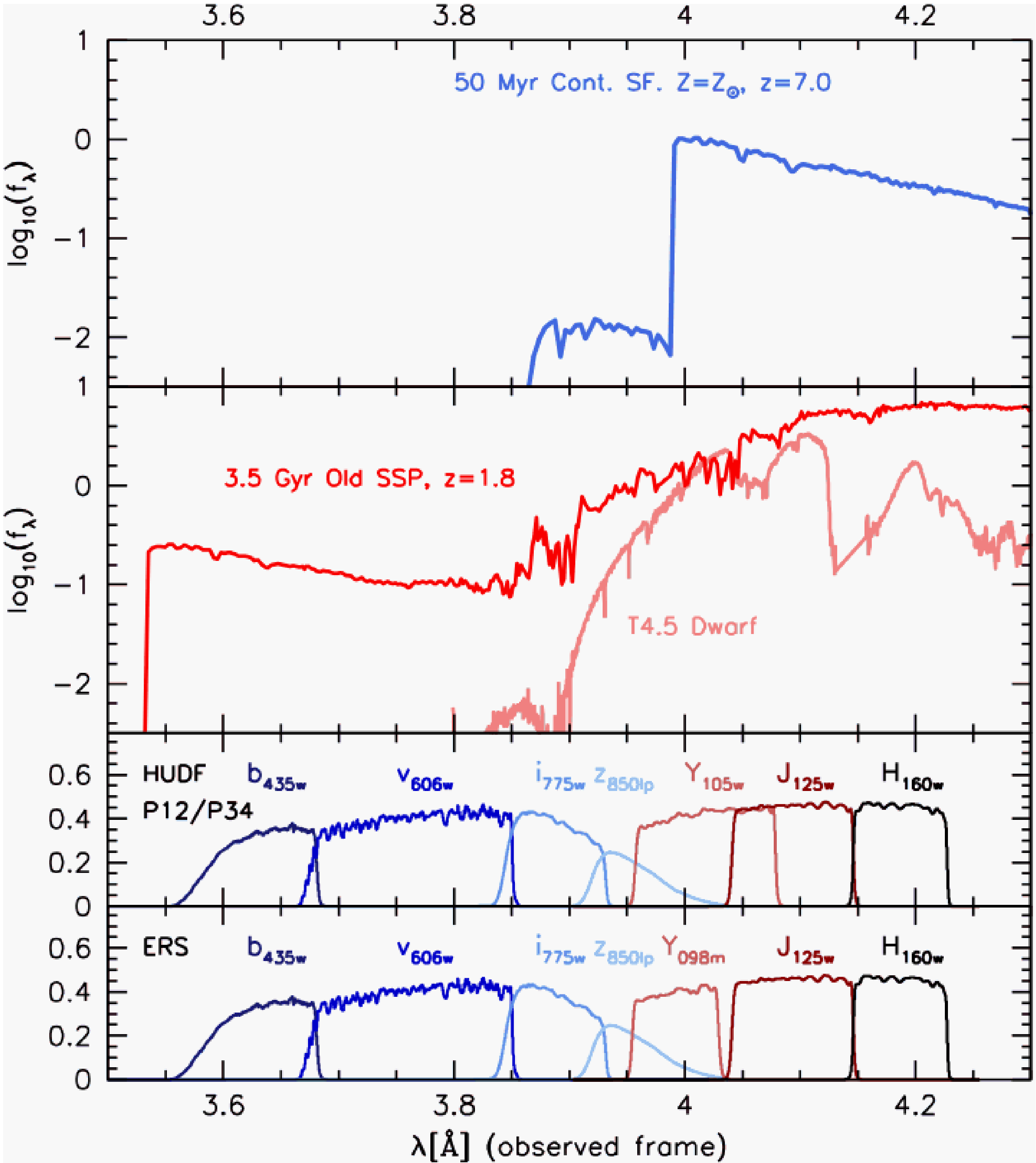



RADIAL BAY
(EMPTY)
WFC3

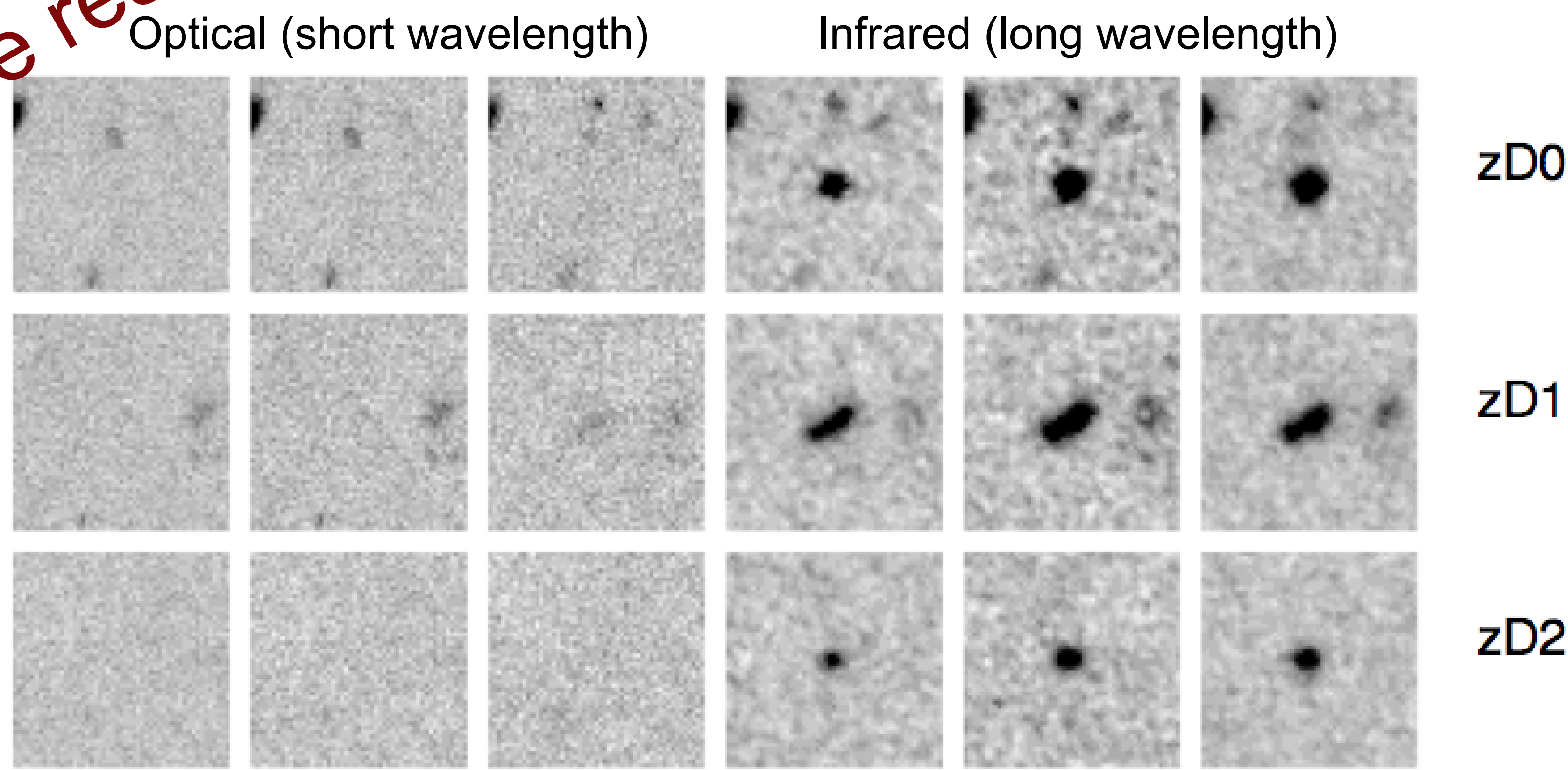

WFC3
(INSERTED)

S109E5660


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)


50 Myr Cont. SF. Z=Z⊙, z=7.0
3.5 Gyr Old SSP, z=1.8
T4.5 Dwarf
HUDF
P12/P34
ERS
b435w
v606w
i775w
z850lp
Y105w
Y098m
J125w
H160w
log10(fλ)
λ[Å] (observed frame)

New Hubble results



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

4 papers immediately (including by the Oxford group - my graduate students and postdoctoral researcher) and several more since. Probably most distant objects yet…

Definition of the Luminosity Function

The distribution of galaxy luminosities is quantified by the luminosity function, $\phi(L)$. The number of galaxies δN located in a volume δV with luminosity in the range $(L, L+\delta L)$ is:

$$\delta N = \phi(L)\,\delta L\,\delta V$$

This assumes (unrealistically) a universal luminosity function, independent of location! In principle we should have a luminosity function that depends on position, but we are making two approximations. Firstly, we're assuming the luminosity function is separable from the density function $\phi(L,\underline{r}) \sim \phi(L)\,D(\underline{r})$, and secondly we're assuming $D(\underline{r}) \sim$ *constant.*

In reality the luminosity function depends on morphology, environment, bandpass etc. The luminosity function also evolves with cosmic epoch...

History of the Luminosity Function

- Hubble (1936) believed the LF was a gaussian with σ~0.8 mag. (Sandage still argues this for some types).
- Zwicky (1942) believed the LF had an increasing faint-end tail.
- Abell (1962) believed the LF could be parameterized as a two-power law with a break.

We need to know the luminosity function to interpret:

- Galaxy number counts as a function of apparent magnitude and redshift
- Statistics of quasar absorption line systems
- Spatial distributions of galaxies and related phenomena (e.g. gravitational lenses)
- Total stellar mass and star formation rate densities

The Schechter Luminosity Function

The most common modern parameterization of the luminosity function is the Schechter function (Schechter 1976, ApJ, 203, 297).

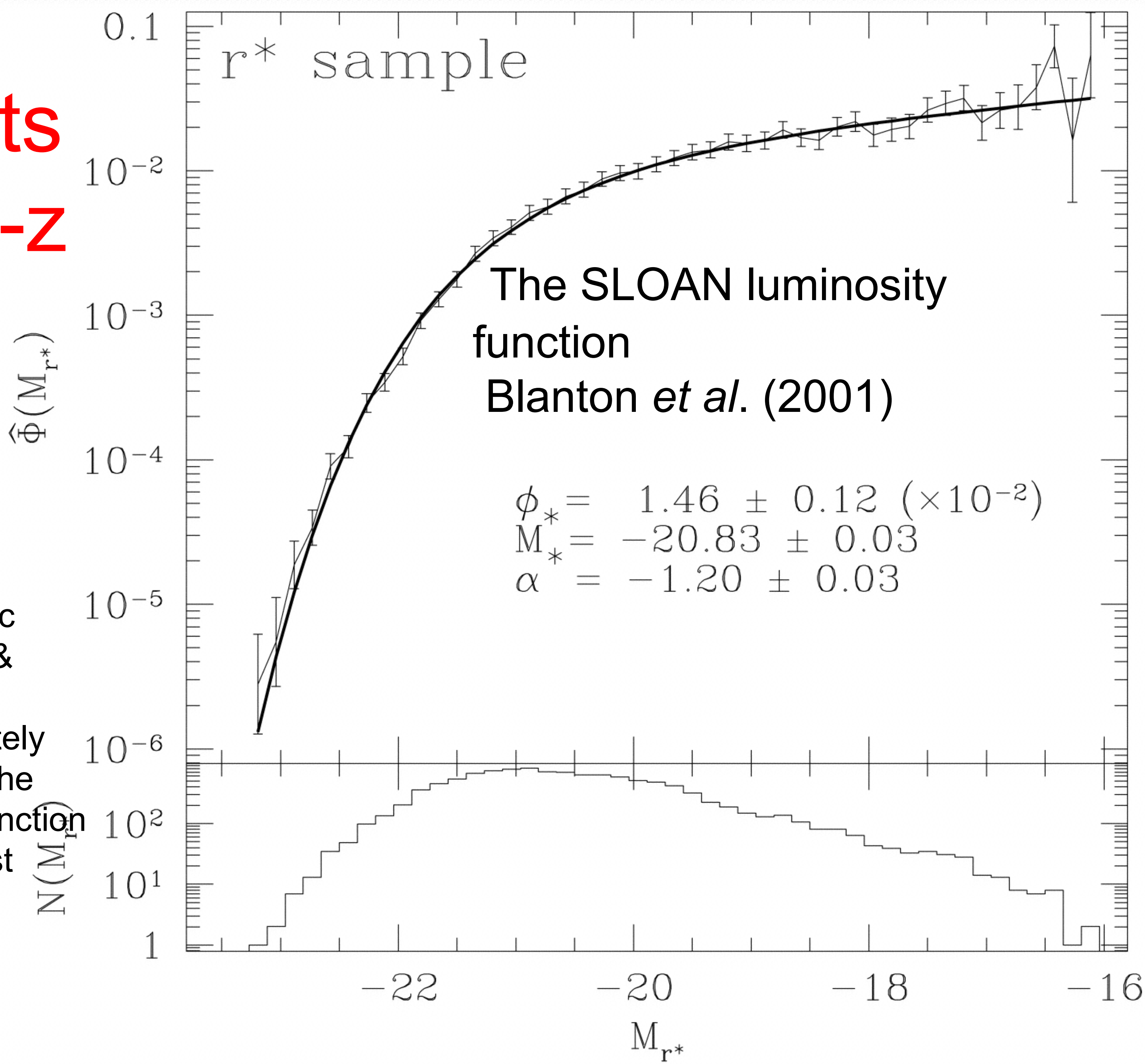
This is basically a power law truncated by an exponential (when expressed using linear flux units):

$$n(x)\,\delta x = \phi_* \; x^{\alpha}\, e^{-x}\, \delta x \qquad \text{where } x = L/L_*$$

L^* and ϕ_* are the characteristic luminosity and number density at the "knee" or break of the luminosity function.

Results at low-z

Wide-field spectroscopic surveys 2df & SLOAN have accurately determined the luminosity function out to modest redshift



The SLOAN luminosity function
Blanton *et al*. (2001)

Schechter Function

The Schechter function is characterized by:

- a knee at L^* - the number of galaxies brighter than this falls sharply
- a faint-end slope of $(1+\alpha)$
- an overall normalization of galaxy density ϕ^*

Some typical values for the local luminosity function in B:

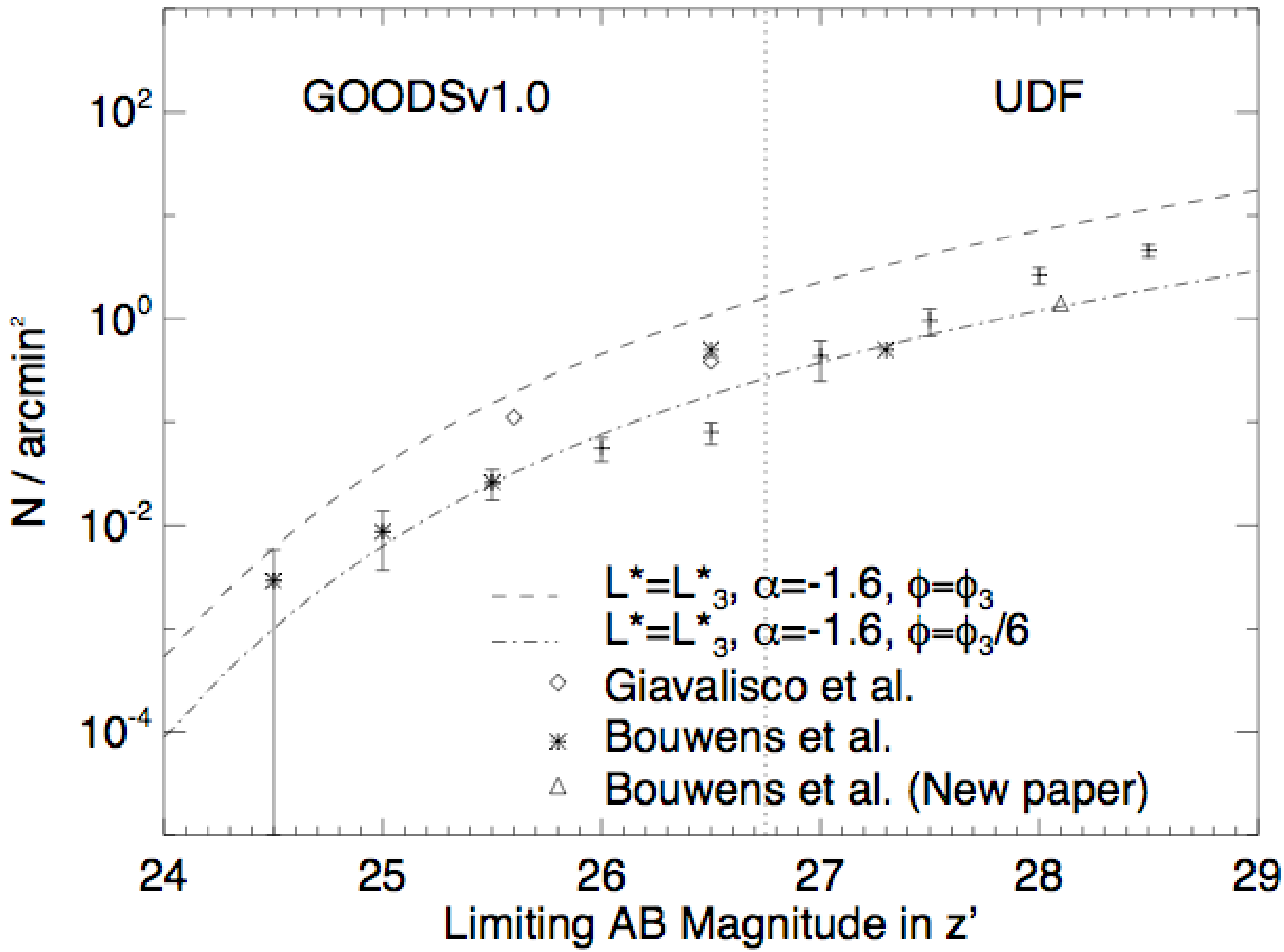
$\phi^* = 0.015\ h^3\ \mathrm{Mpc}^{-3}$ $M_B^* = -19.7 + 5\log_{10} h$ $L_B^* \approx 10^{10} h^{-2} L_\odot$

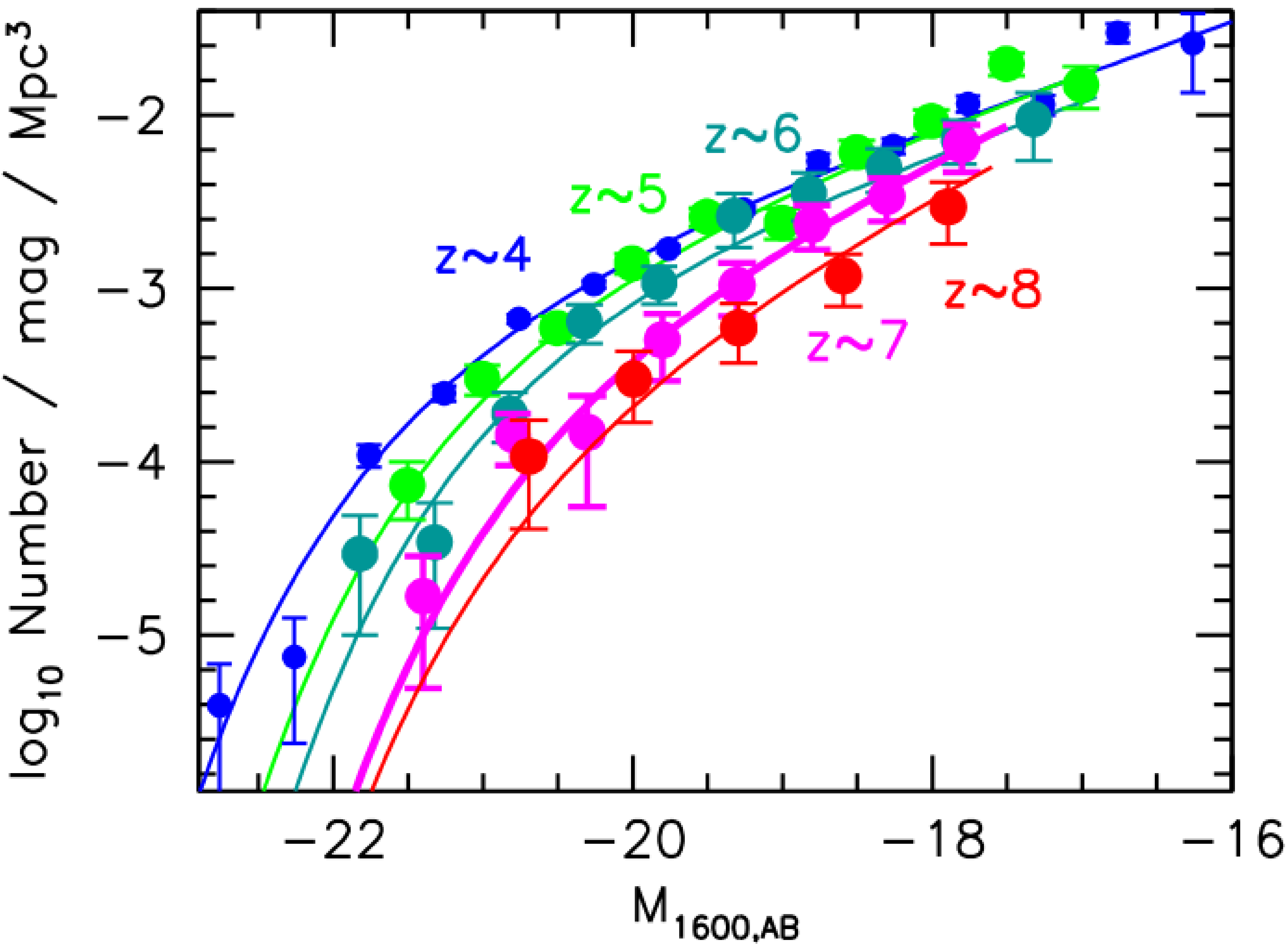
$\alpha \approx -1.1$ (Efstathiou, Ellis & Peterson 1988)

N.B. Scales with Hubble constant: $H_0 = 100\ h$ km/s/Mpc ($h \approx 0.7$)

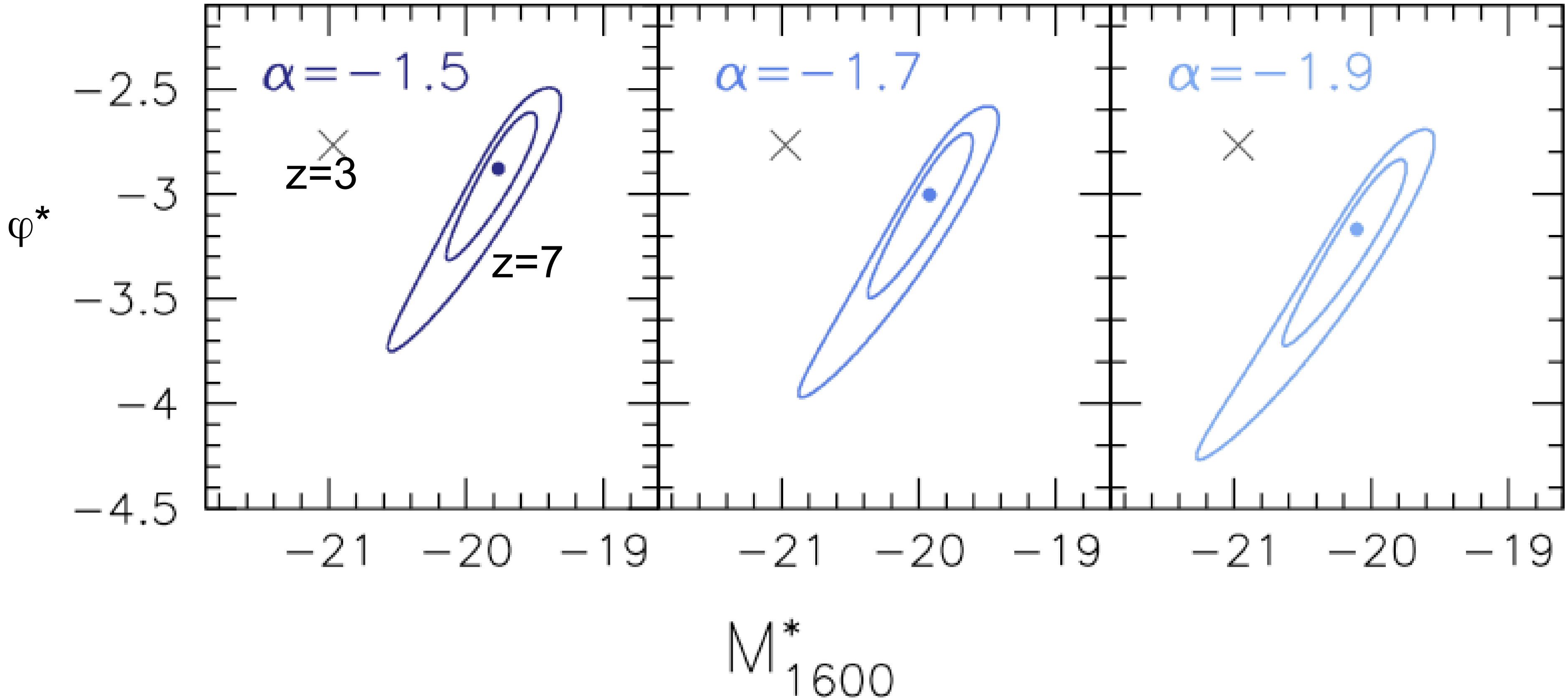
Solar luminosity units: $L_\odot = 3.9\times10^{26}$ W , $M_{B\odot} = +5.48$

Steep faint end slope at z=6, α= -1.8 (at z=3, α= -1.6 and z=1, α=-1.3



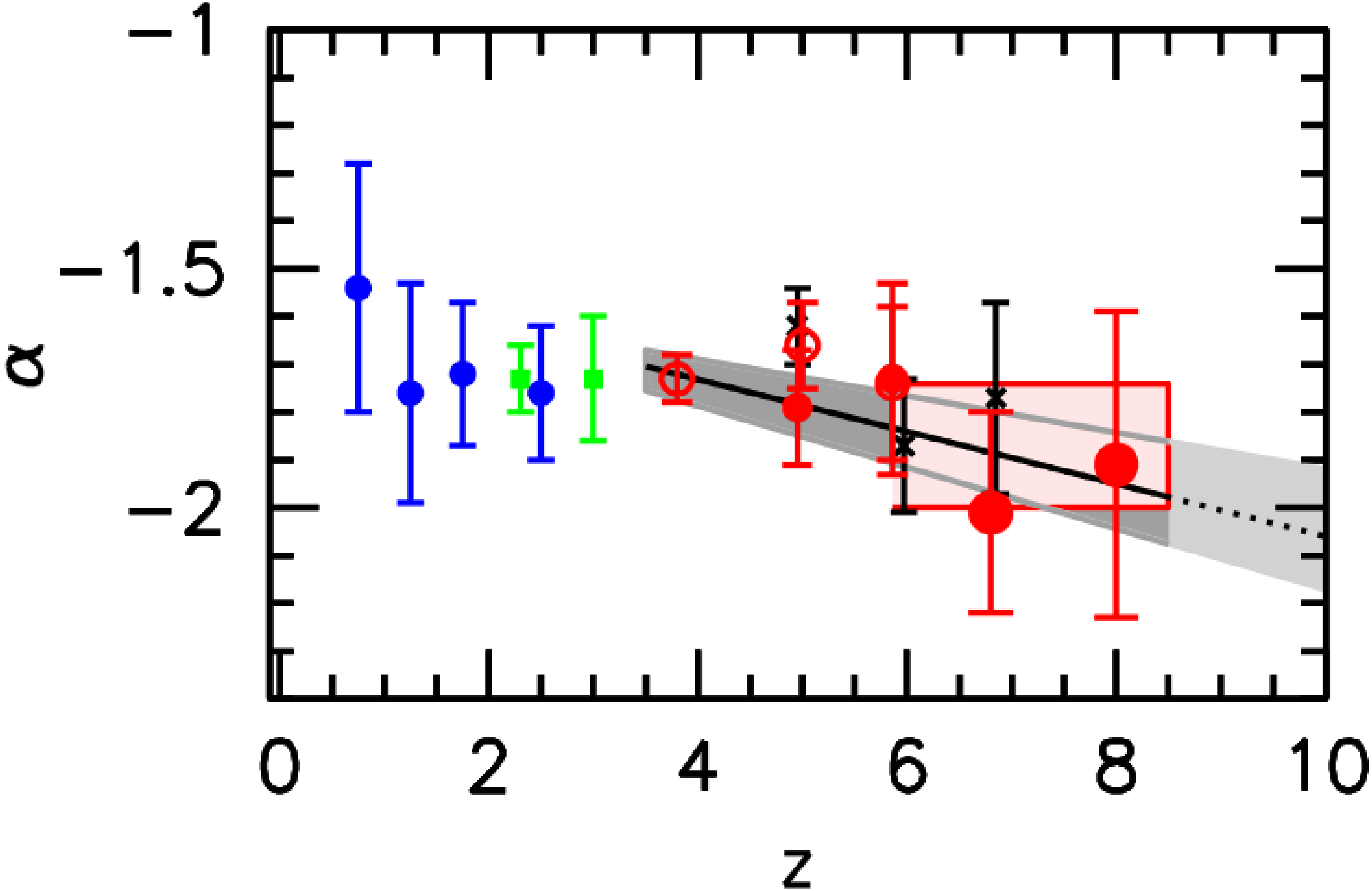


Evolution of the restframe UV luminosity function
From Bouwens et al. (2011)



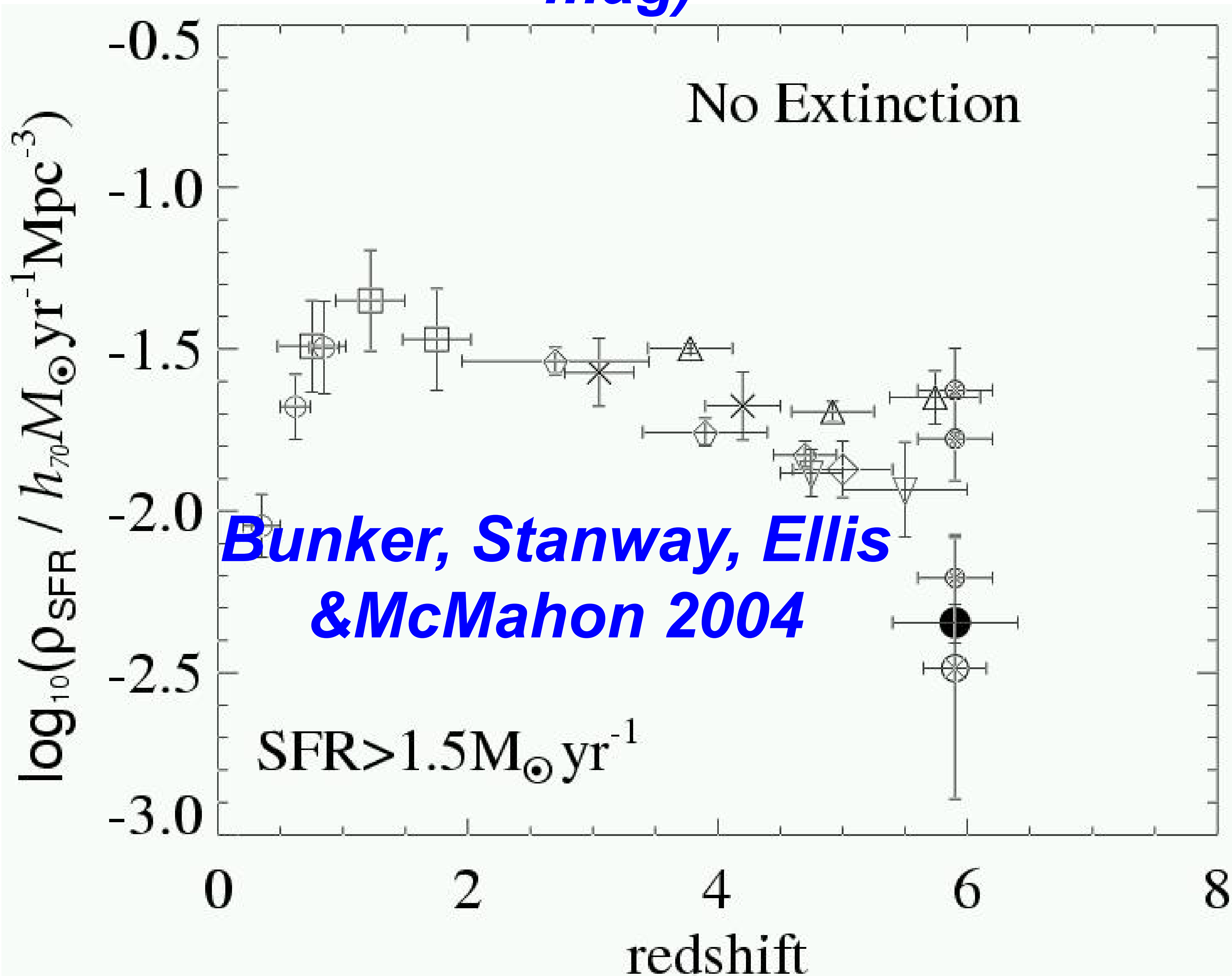
Evolution of luminosity function
(note M* is correlated with φ*)

Wilkins et al. (2011)



Evolution of the restframe UV faint end slope
From Bouwens et al. (2011)

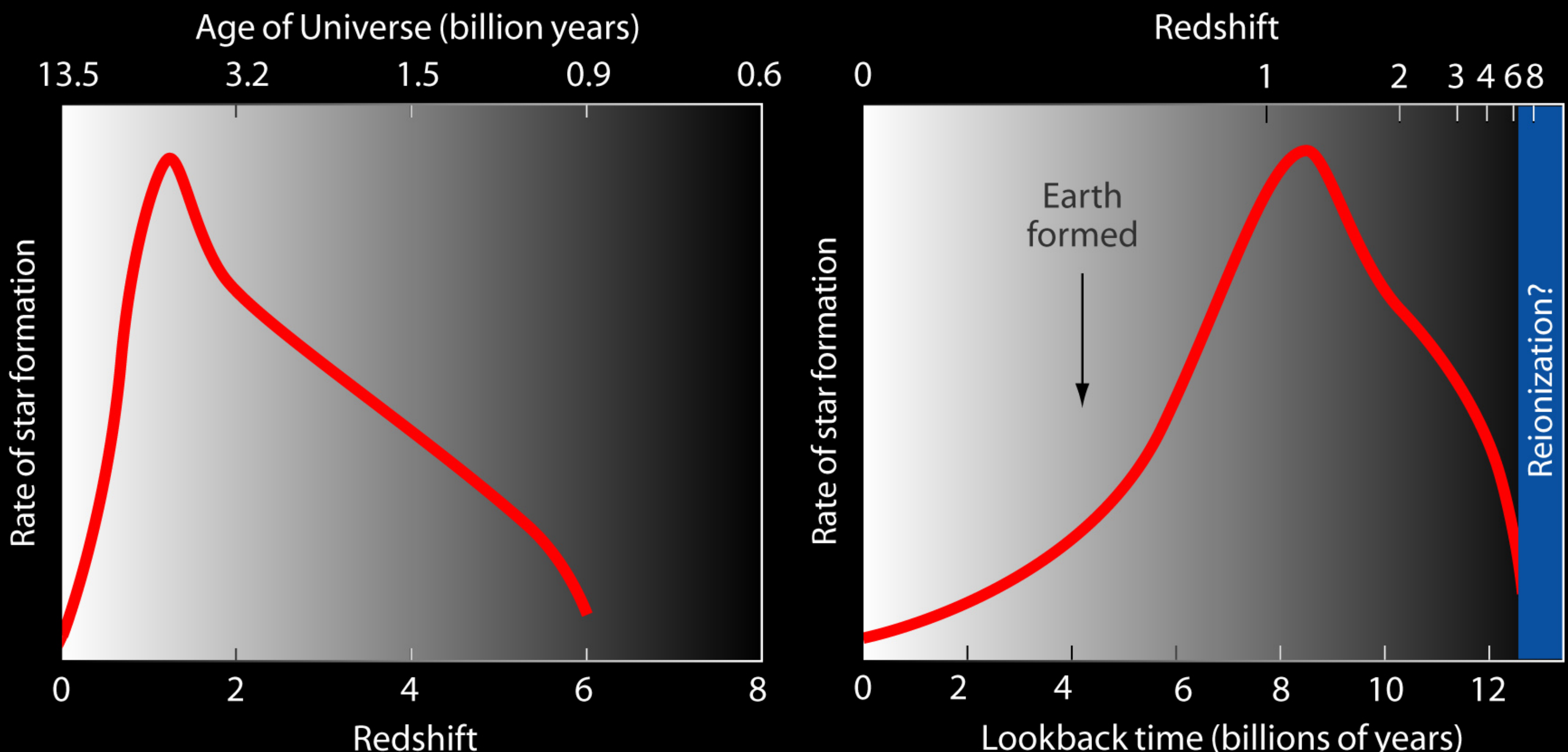
Looking at the UDF (going 10x deeper, z'=26 →28.5 mag)



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 recent Ultra Deep Field to address total star formation, but we had proved ***strong evolution***.

Star formation history of the Universe



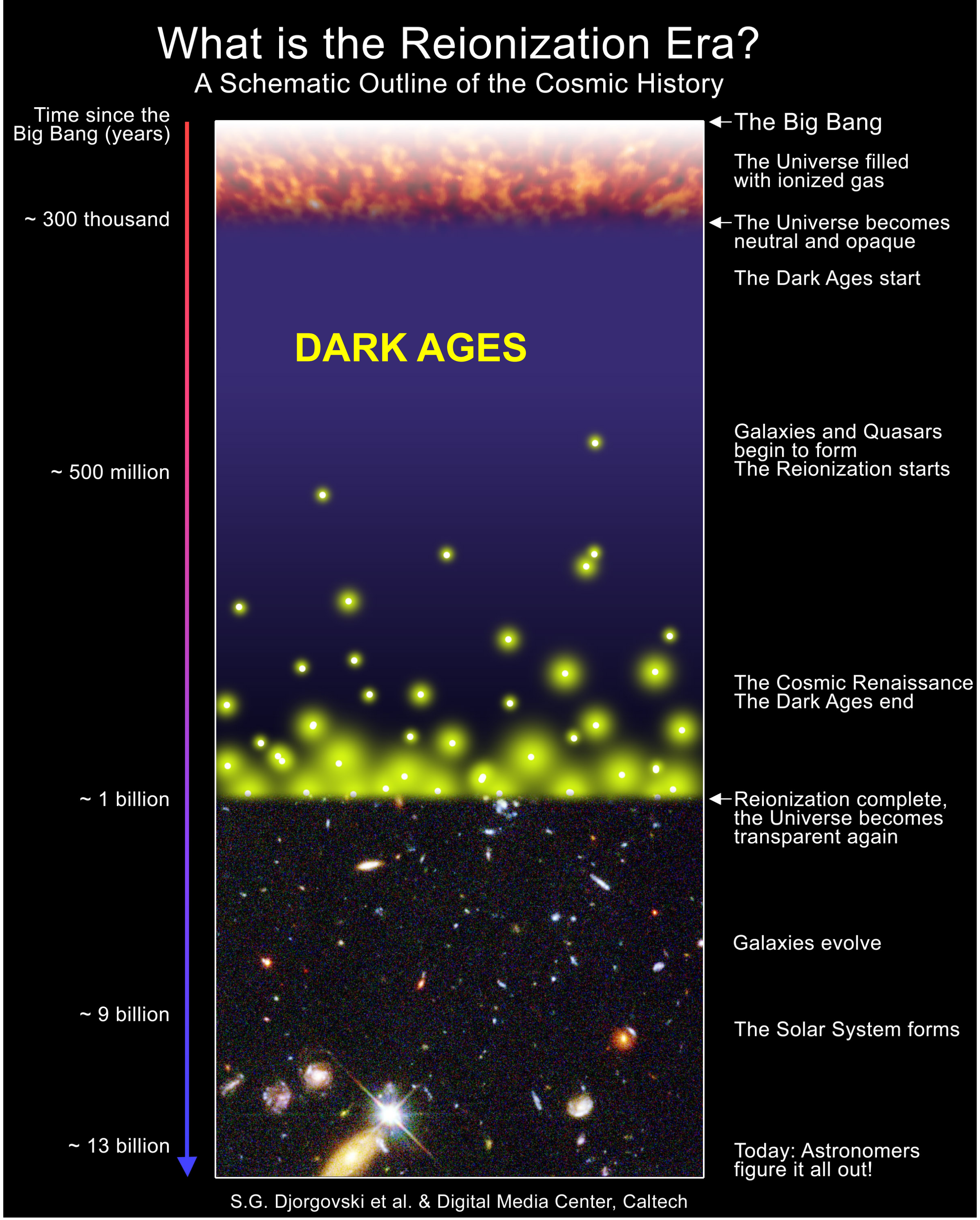
- ***UDF enables us to identify even fainter galaxies at these times*** *(end of dark ages)*
- ***We were first to analyse & publish 50 high redshift galaxies in the UDF***
- ***Confirms our previous work: much LESS star formation than in more recent past***

After era probed by CMBR 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

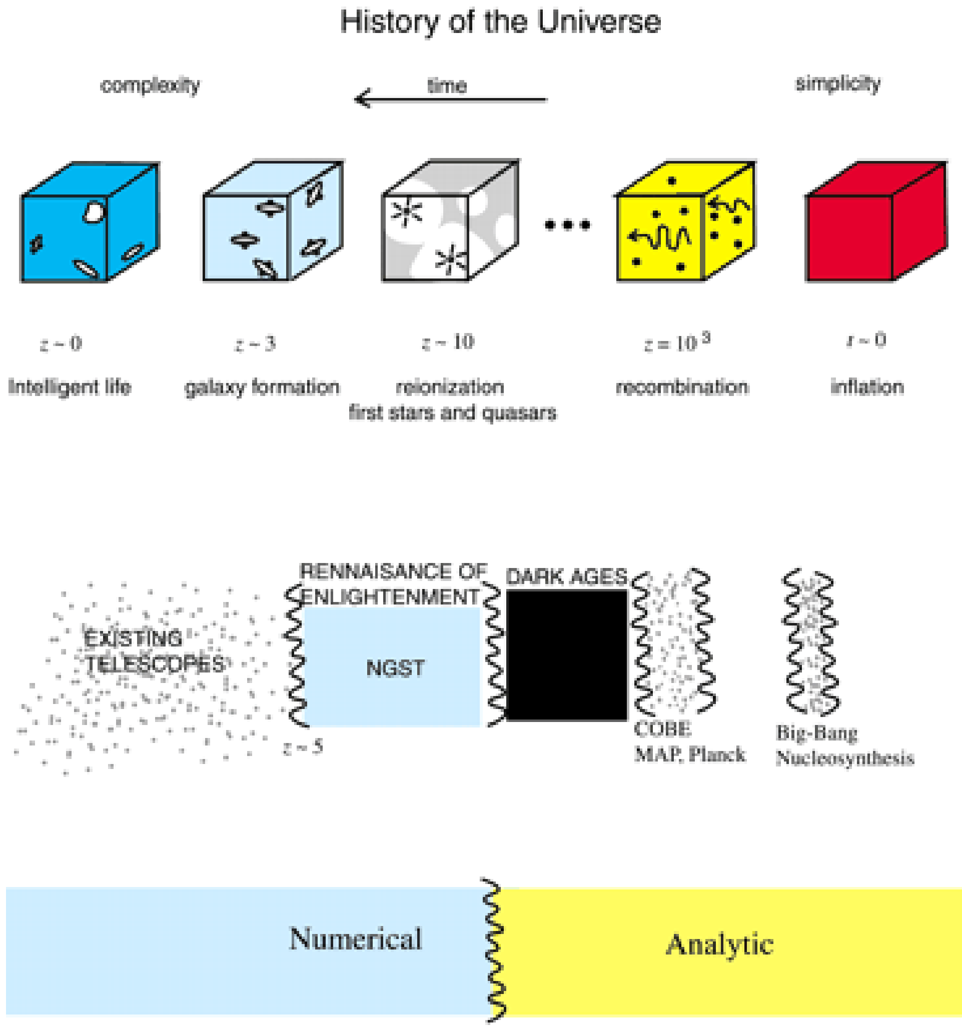
10

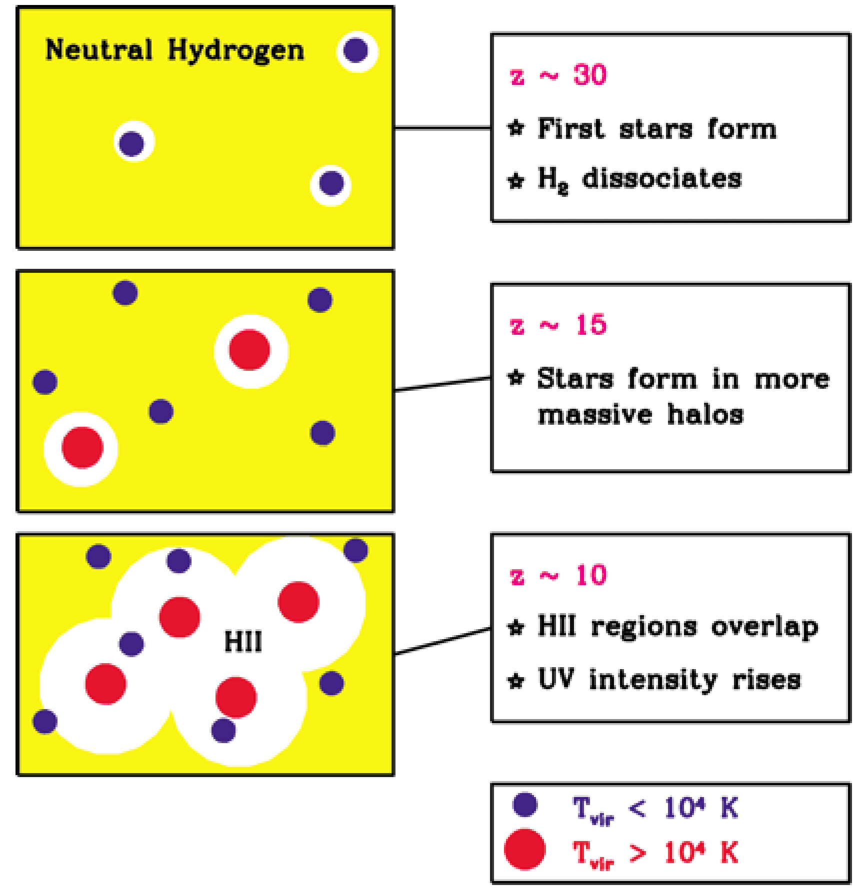
5

2

0

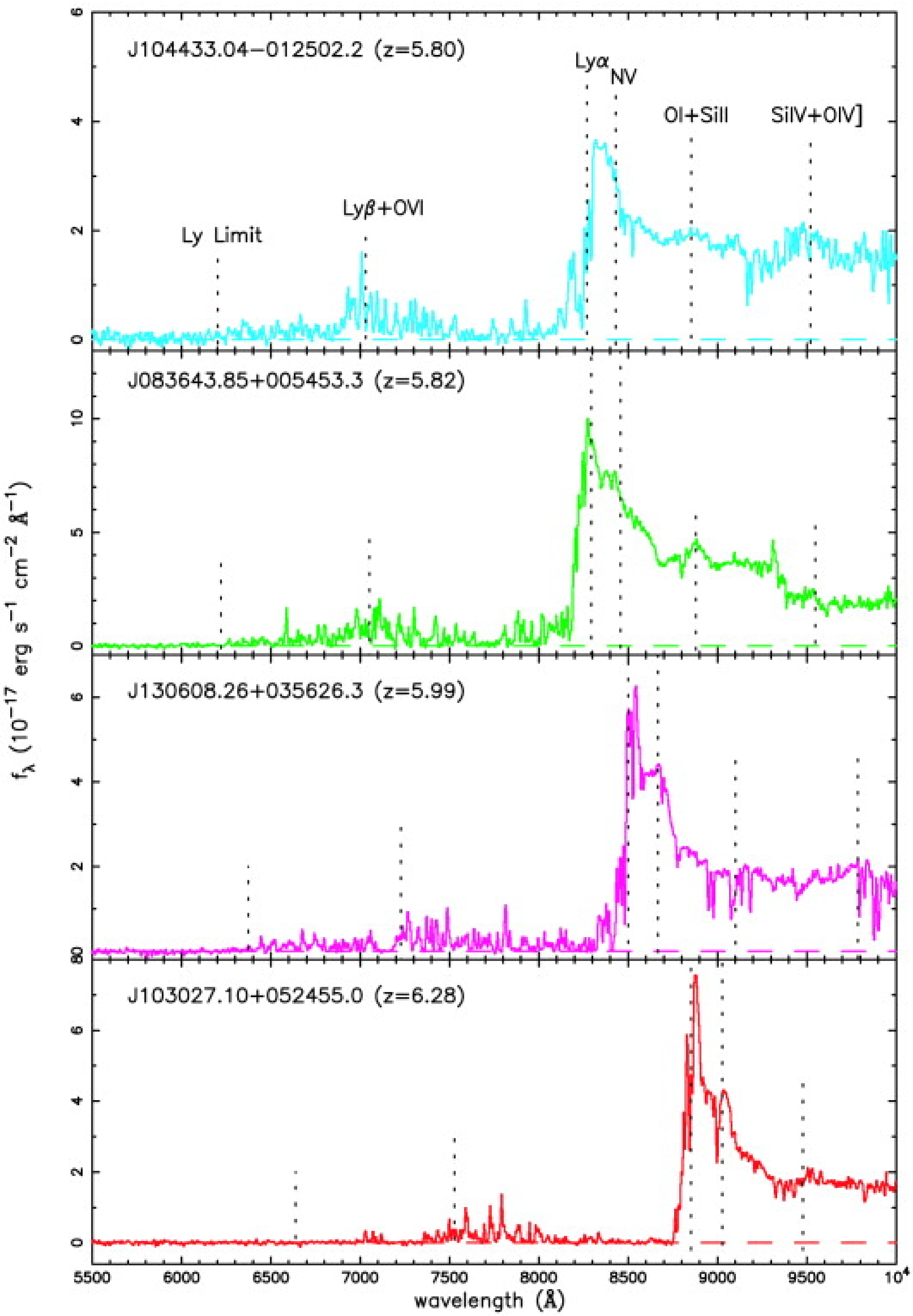
Reionization





It is unclear if Lyman-α line emission will actually emerge if the Universe is predominantly neutral (i.e. Before the Gunn-Peterson effect).

From Loeb & Barkana (2001 ARA&A **39**, *19*)



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

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

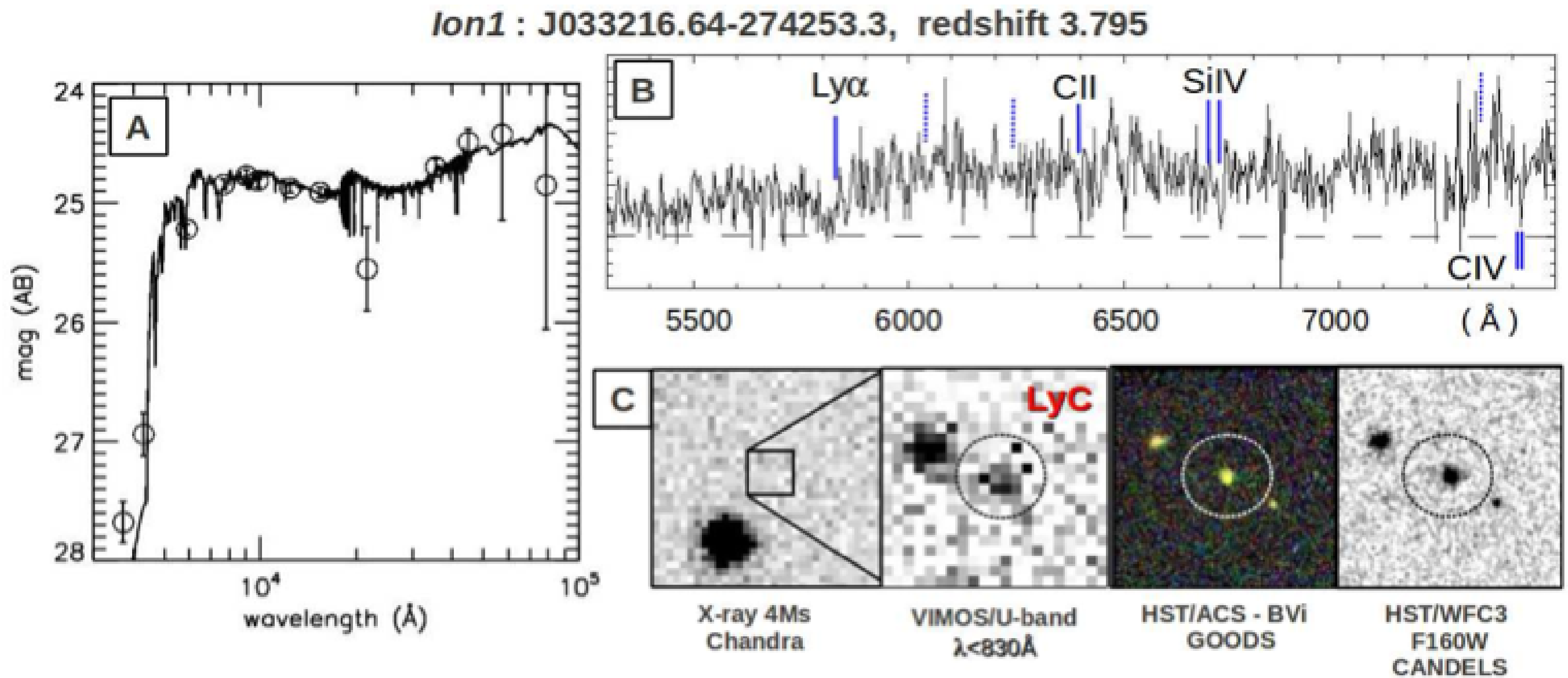
From Madau, Haardt & Rees (1999) -amount of star formation required to ionize Universe (C_{30} is a clumping factor).

This assumes escape fraction=1 (i.e. all ionzing photons make it out of the galaxies)

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

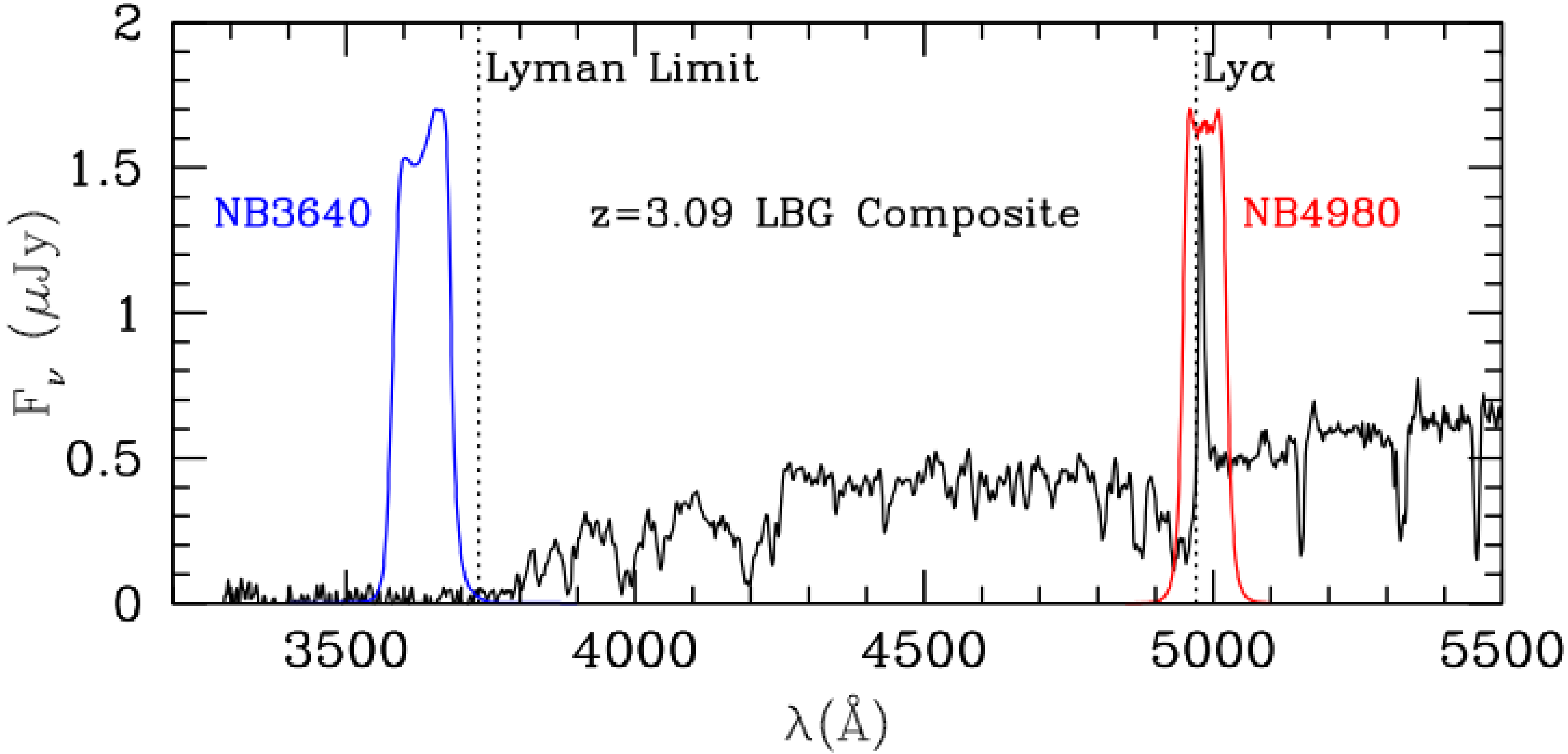
We go down to 1M_sun/yr - but might be steep α (lots of low luminosity sources - forming globulars?)

Ionizing Photon Escape Fraction

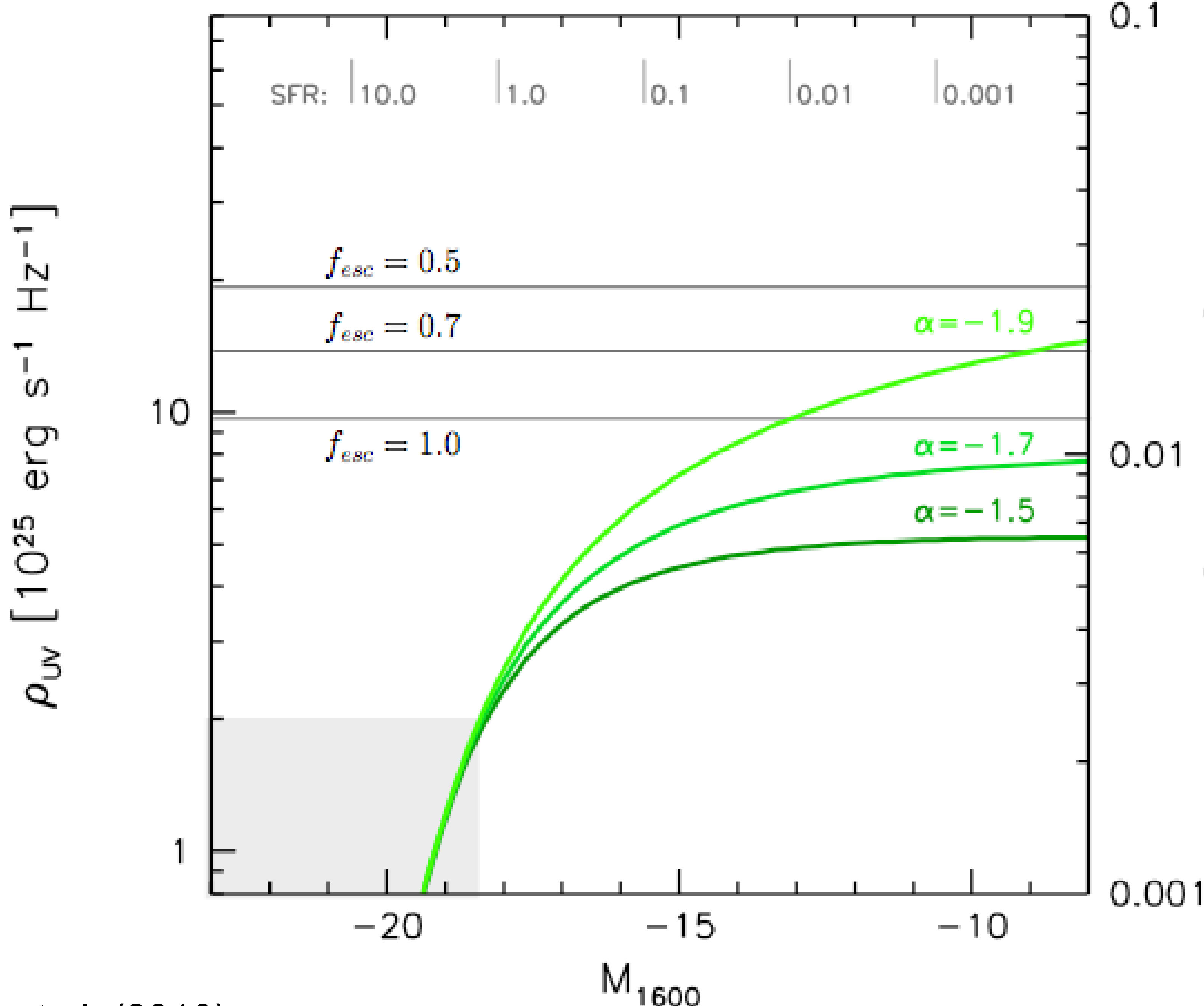


We are interested in photons with wavelength <912Ang (which can ionize hydrogen), but have to infer these from brightness at >1216Ang (not absorbed by Ly-alpha forest)

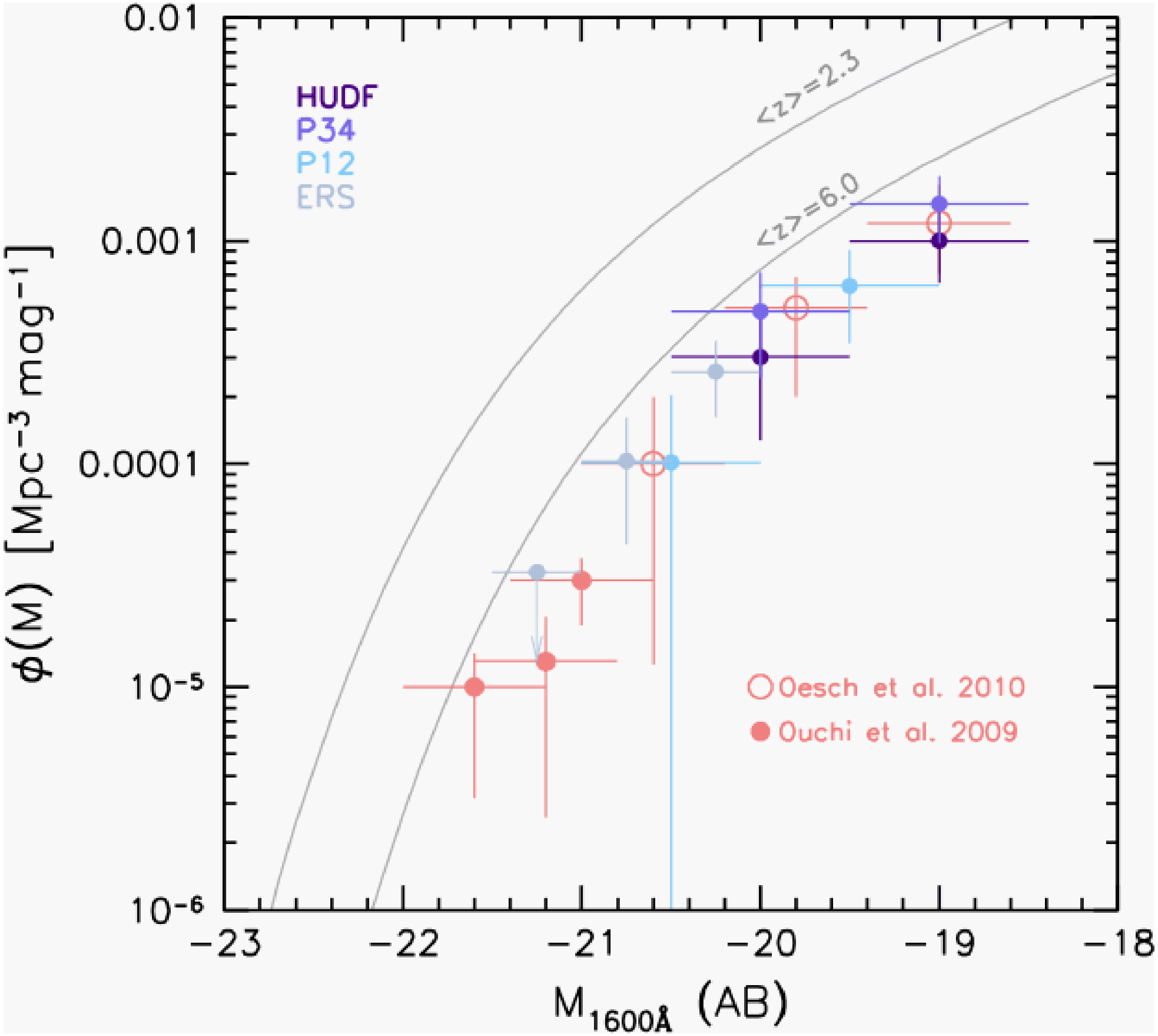
Indications are at z~3 that escape fraction is very small (Vanzella et al. 2012, Nestor et al. 2011, Siana et al. 2007, Shapley et al. 2006, Iwata et al. 2008)



(Nestor et al. 2011)



Wilkins et al. (2010)



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)

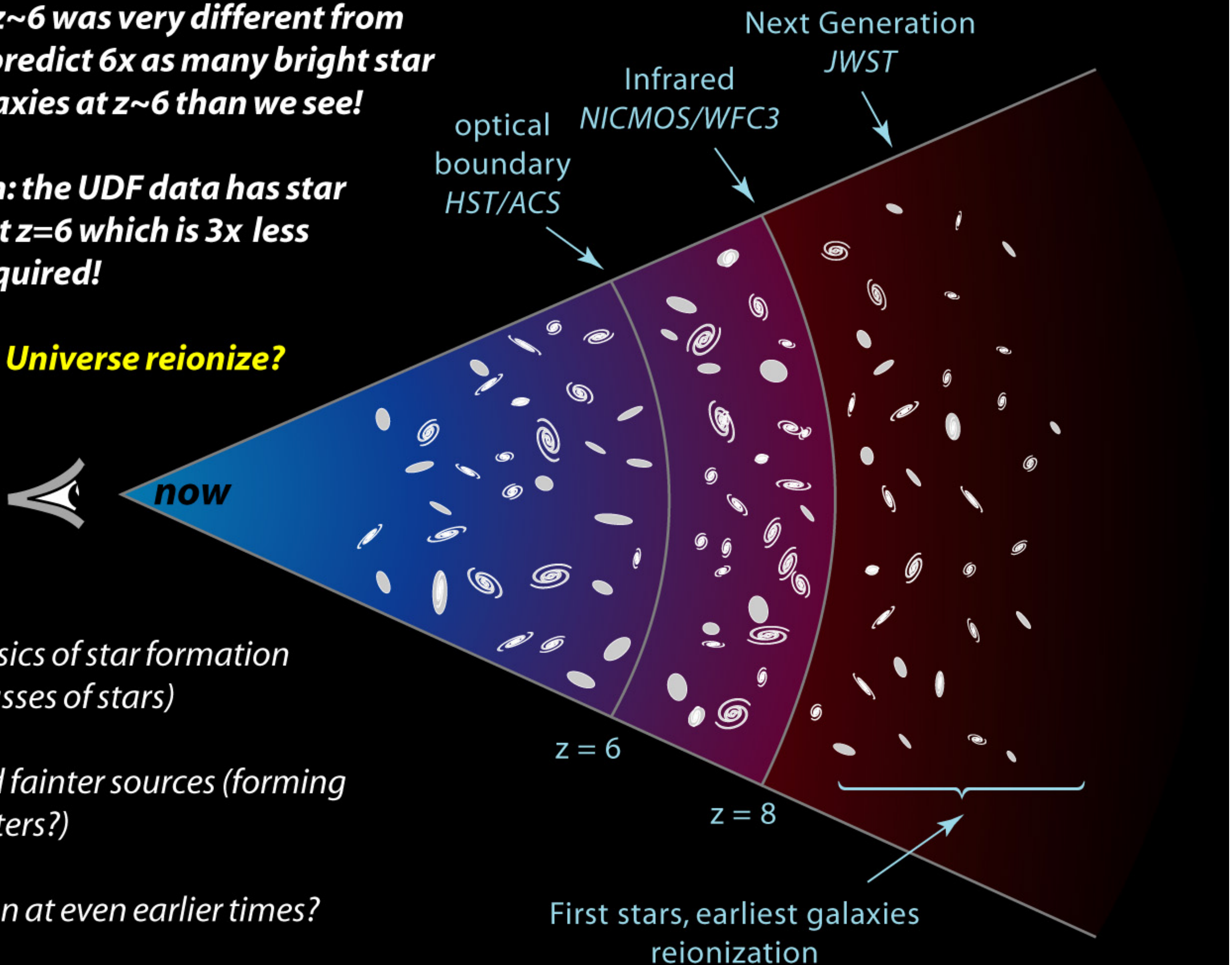
Ways out of the Puzzle

- 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

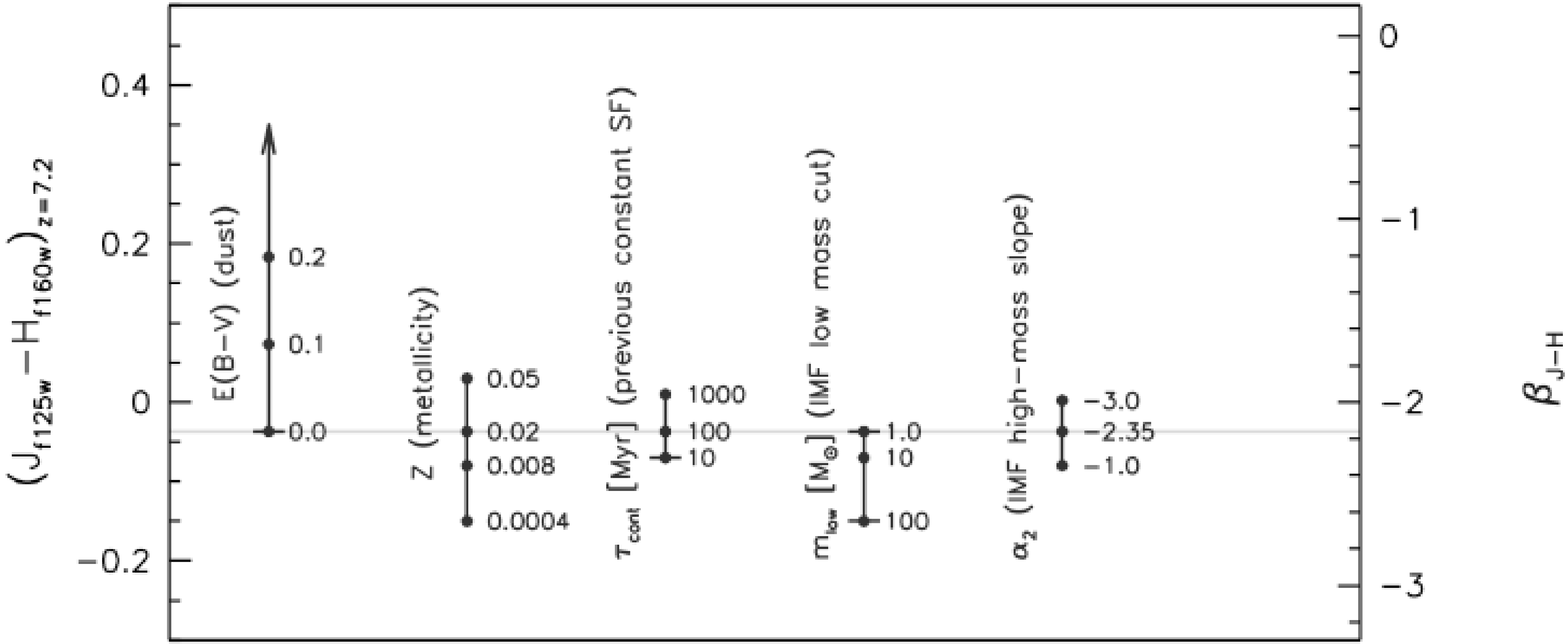
- ***Universe at z~6 was very different from z~3: would predict 6x as many bright star forming galaxies at z~6 than we see!***
- ***Reionization: the UDF data has star formation at z=6 which is 3x less than that required!***

So how does Universe reionize?

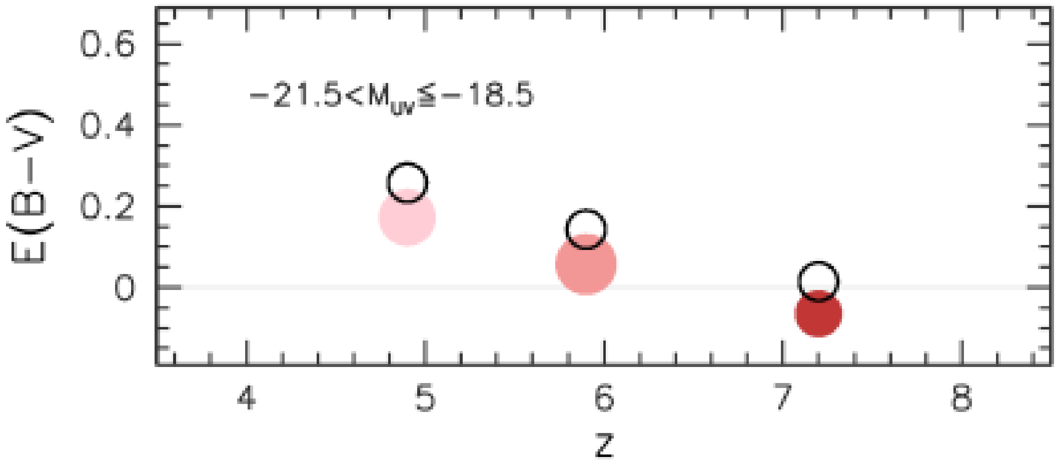


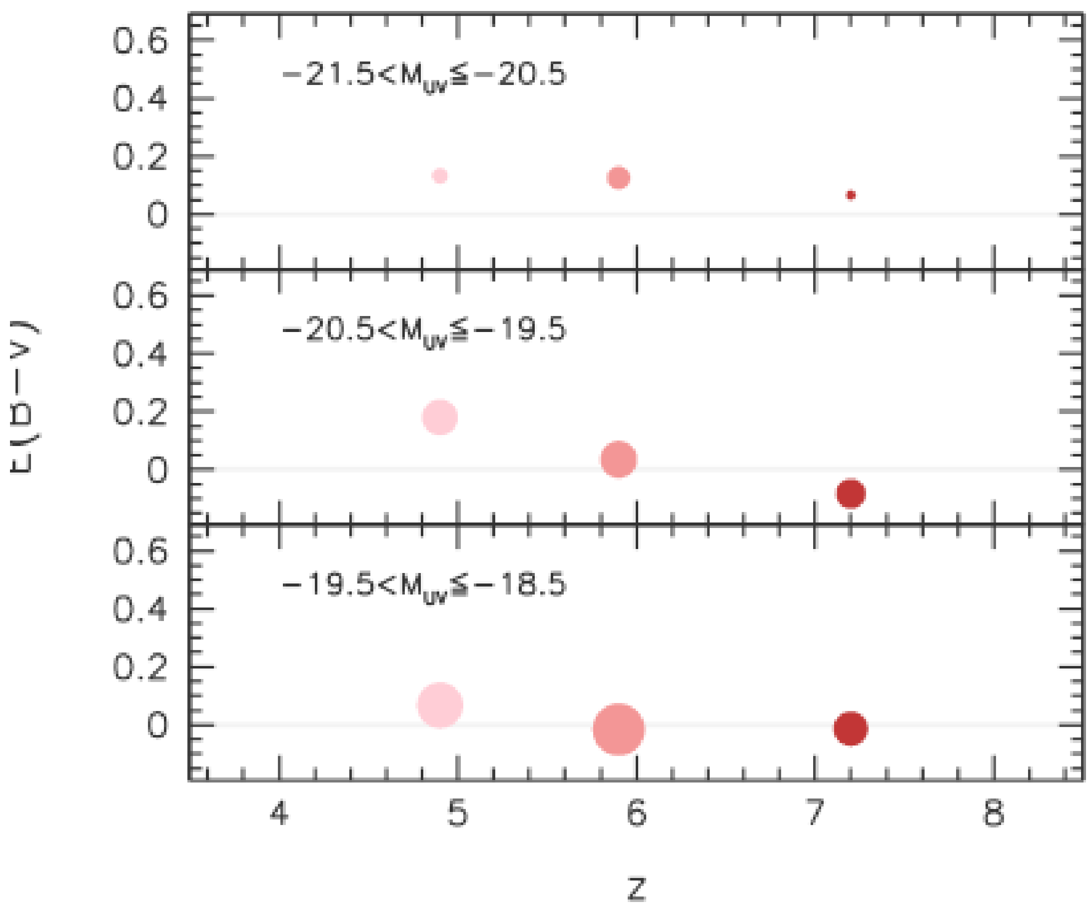
- *Different physics of star formation early on? (masses of stars)*
- *Undiscovered fainter sources (forming globular clusters?)*
- *Star formation at even earlier times?*

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)

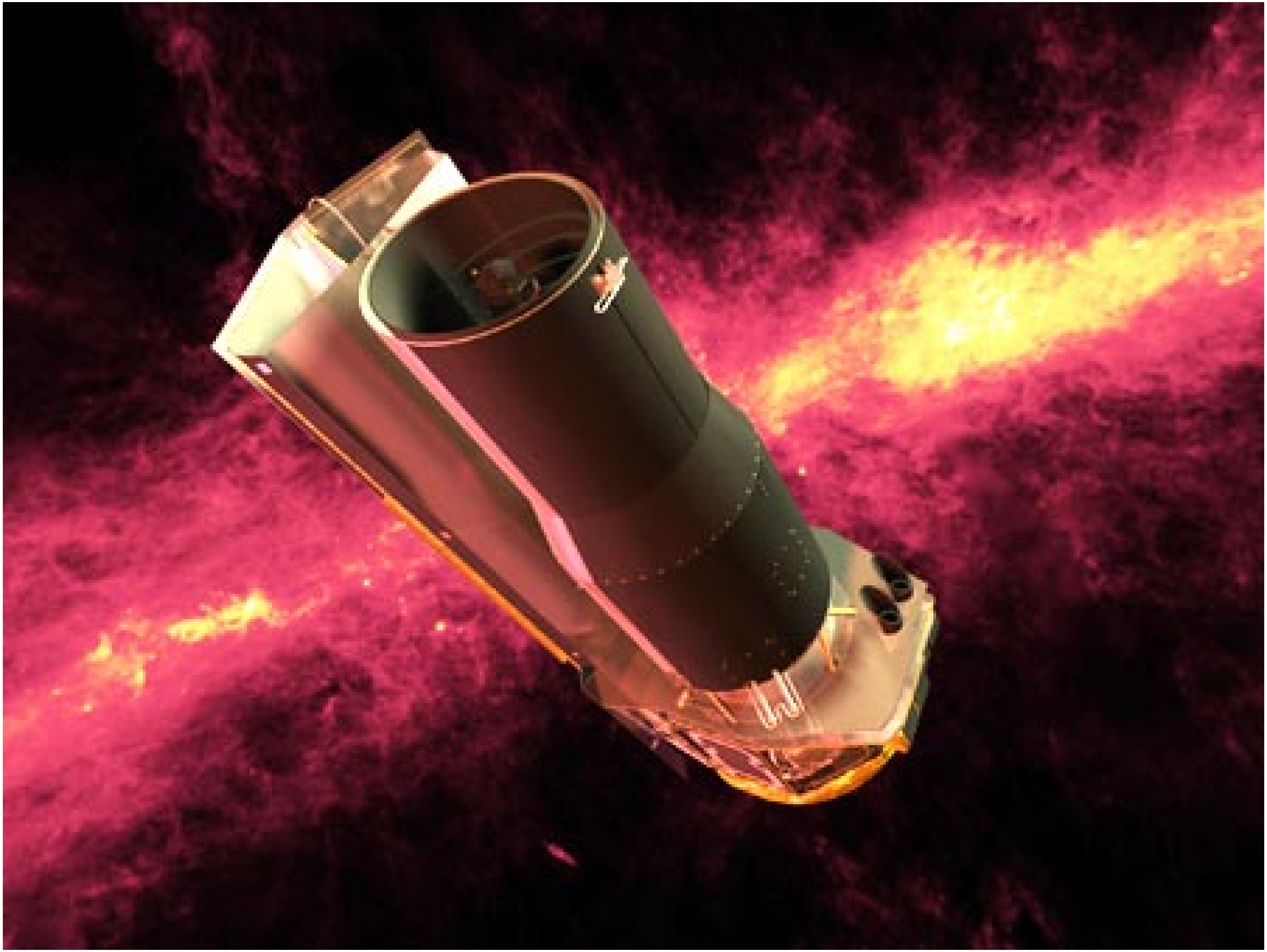




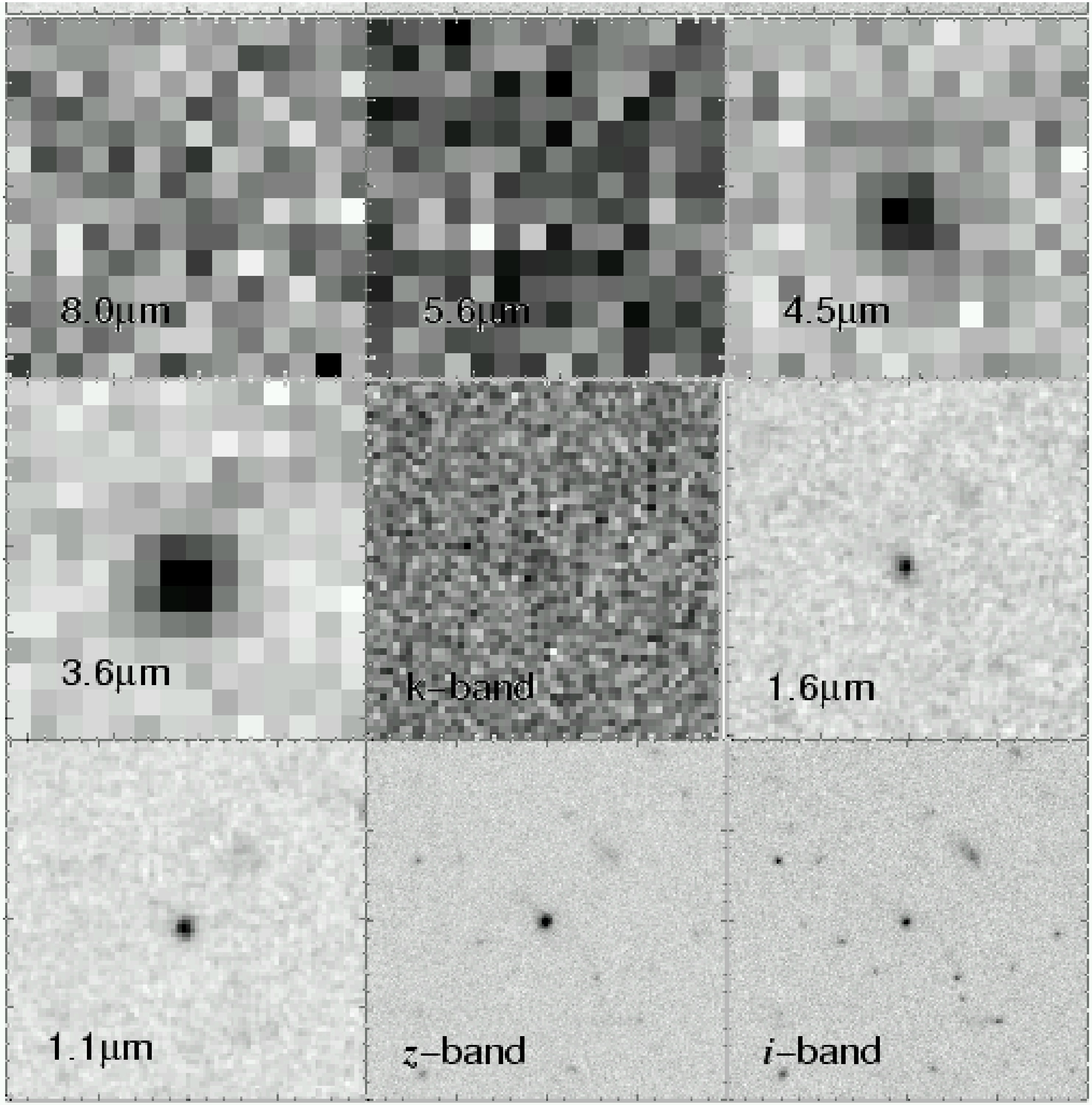
From Wilkins et al. (2011) MNRAS

Weak dependence of beta evolution on luminosity

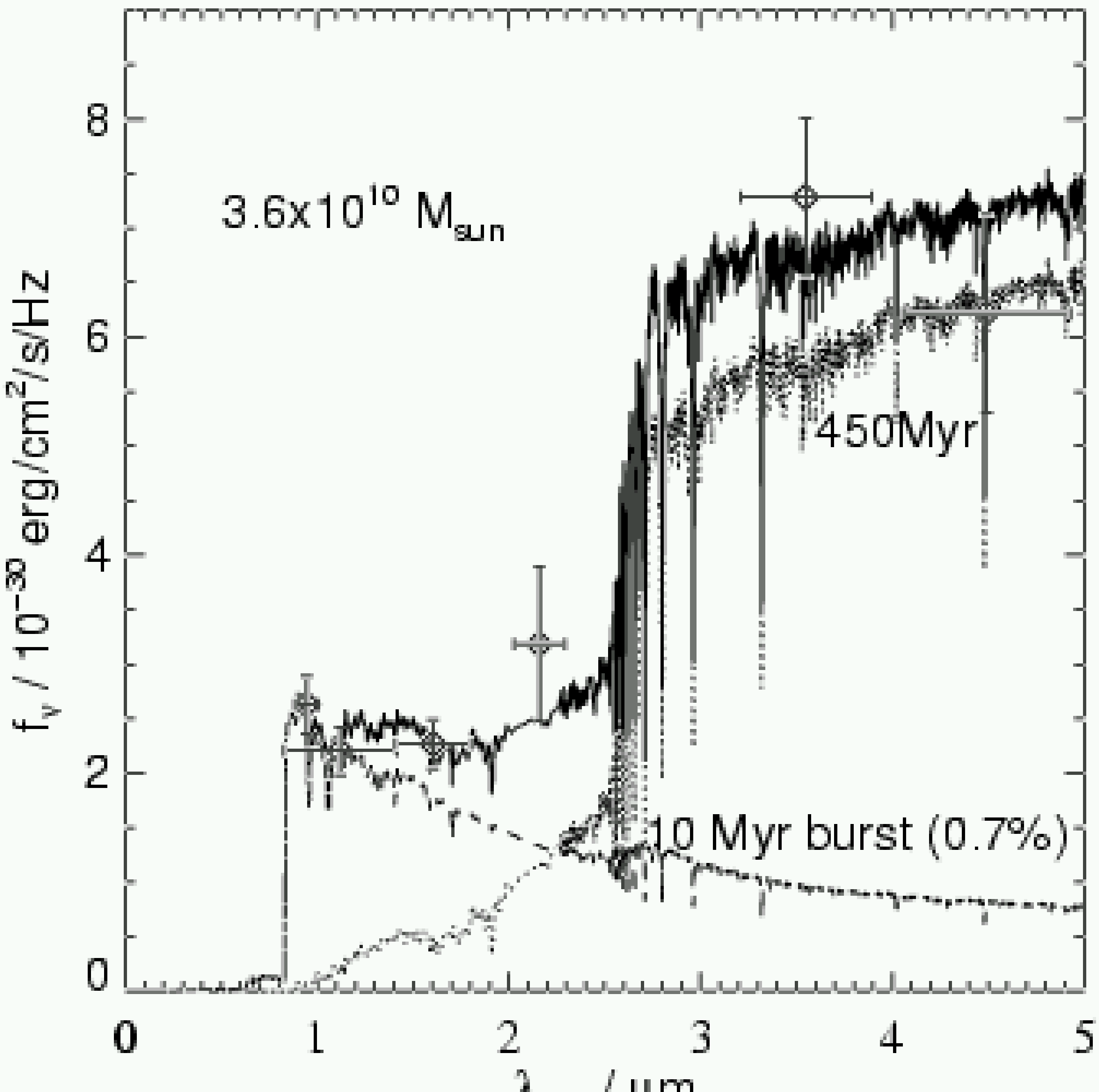
Careful on filters - the Lyman-alpha break will redden intrinsic colours



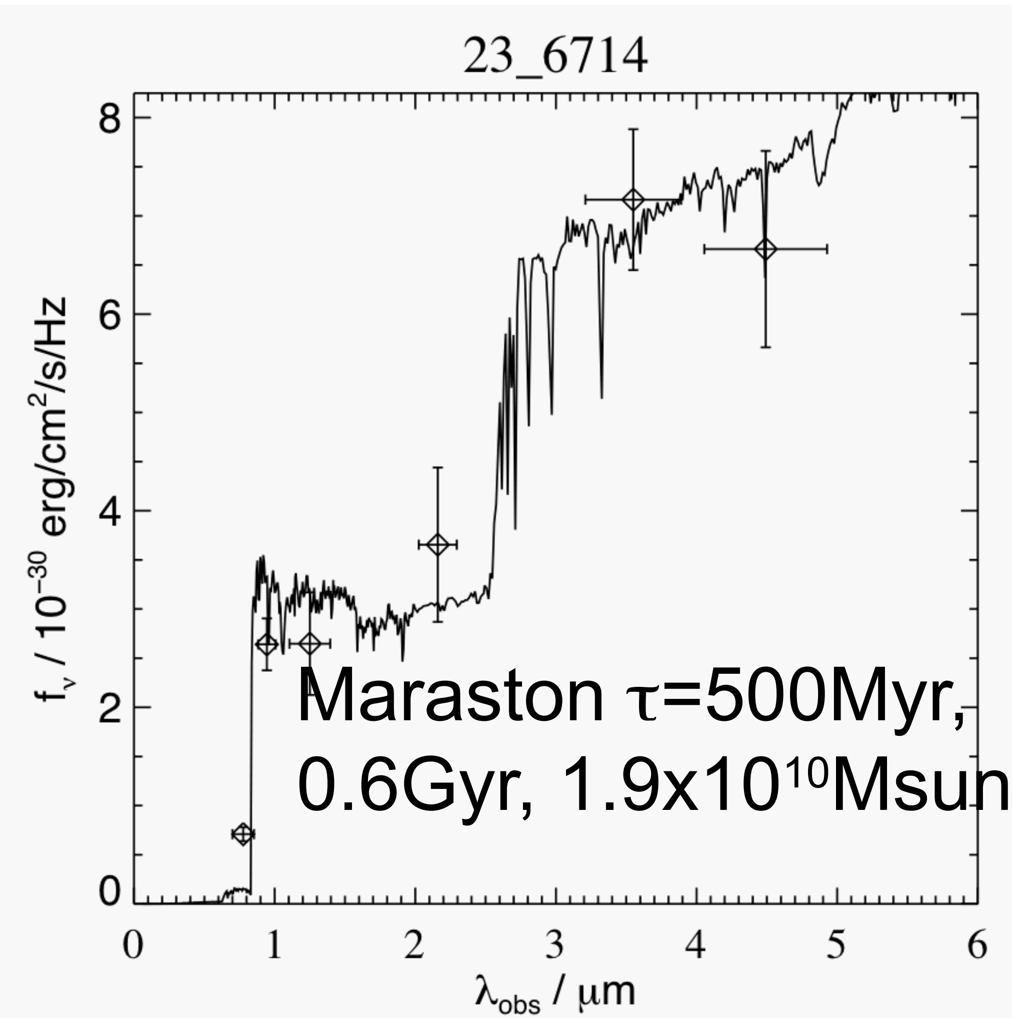
Spitzer – IRAC (3.6-8.0 microns)

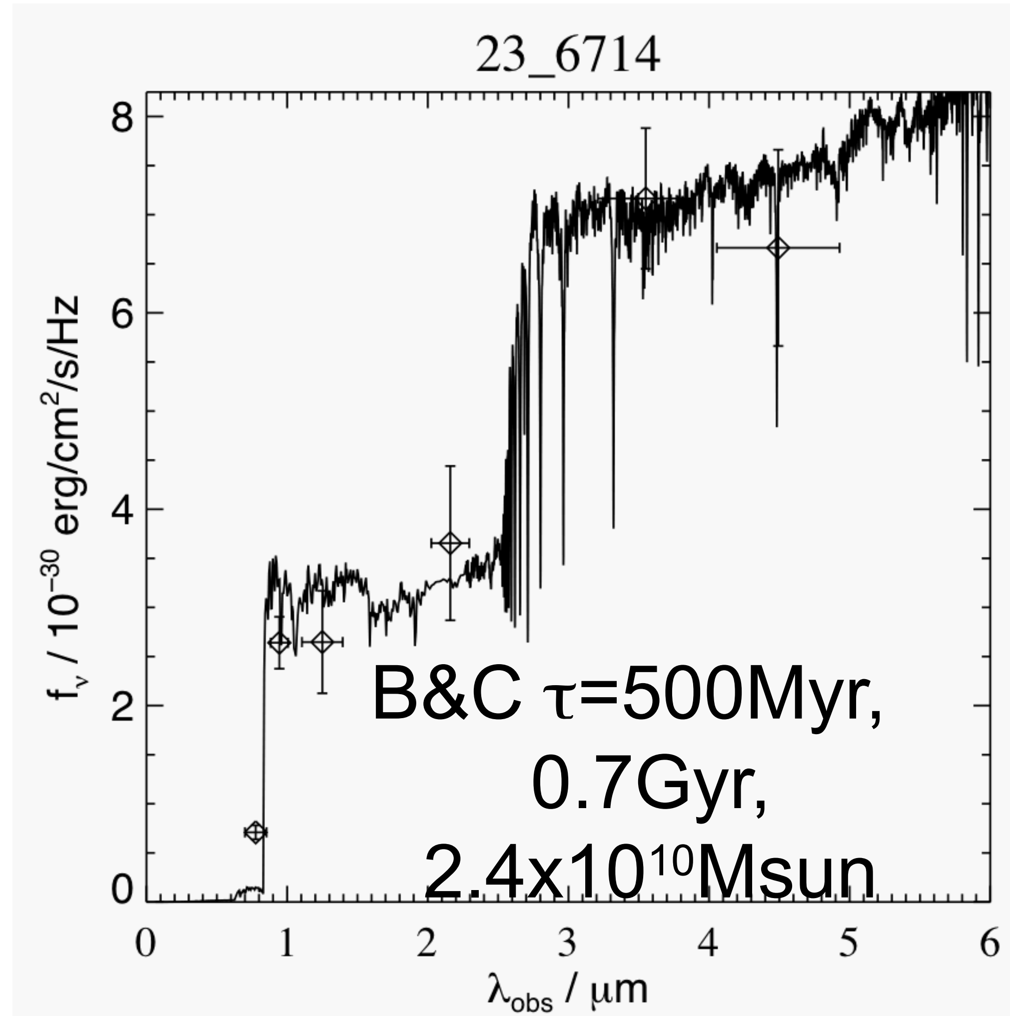


- z=5.83 galaxy #1 from Stanway, Bunker & McMahon 2003 (spec conf from Stanway et al. 2004, Dickinson et al. 2004). Detected in GOODS IRAC 3-4μm: Eyles, Bunker, Stanway et al.

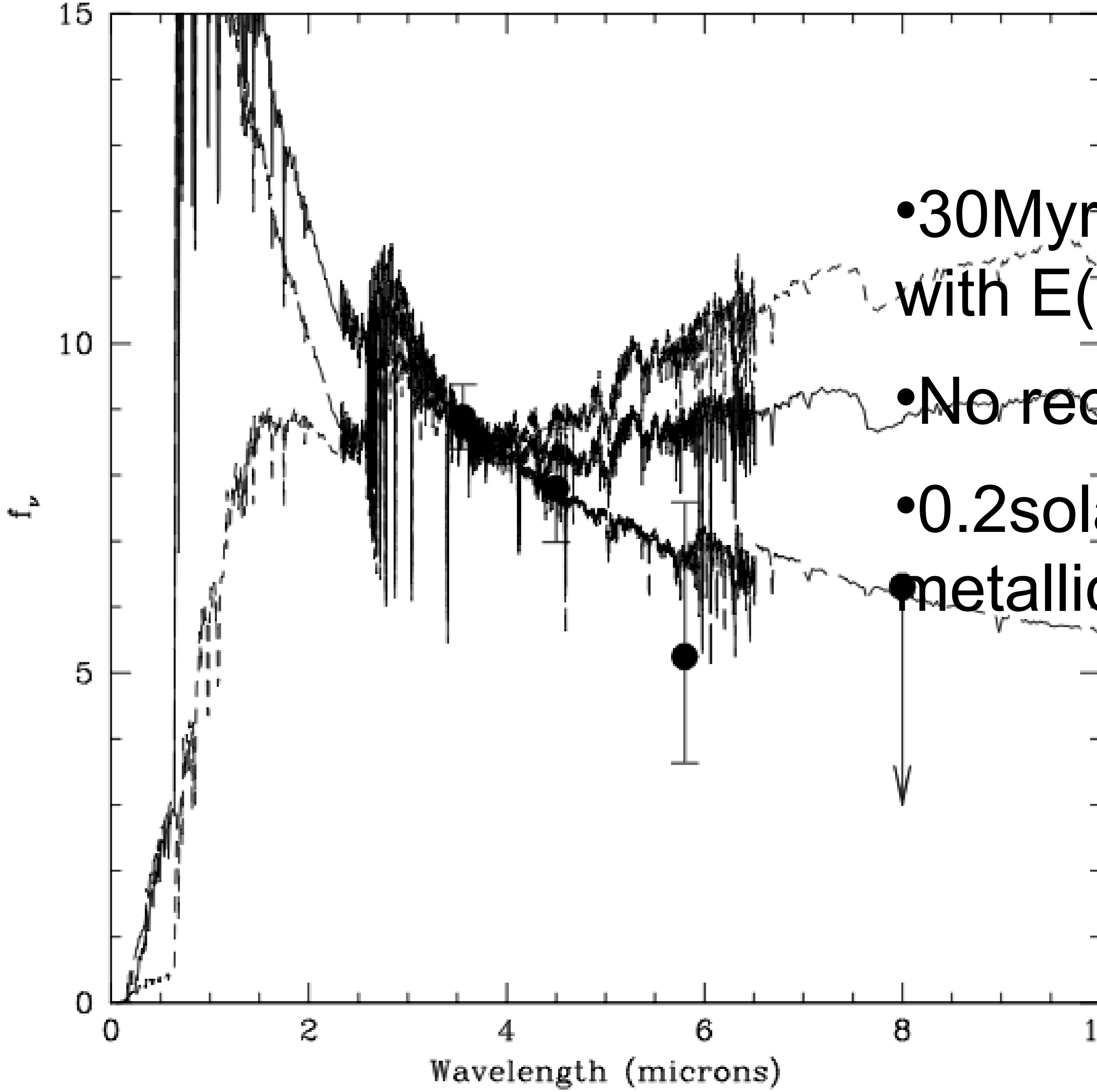

3.6x10^10 M_sun
450Myr
10 Myr burst (0.7%)
f_ν / 10^-30 erg/cm^2/s/Hz
λ_obs / μm
0
2
4
6
8
0
1
2
3
4
5

Other Population Synthesis Models



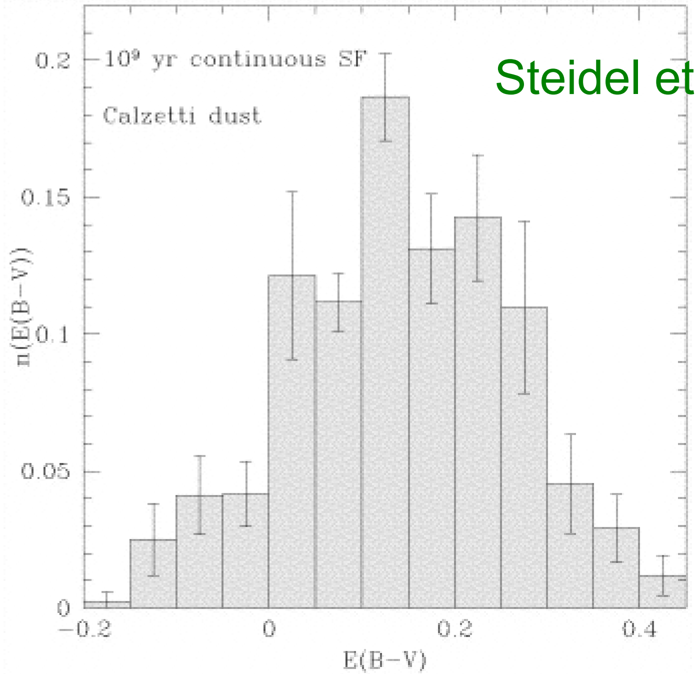


Maraston vs. Bruzual & Charlot

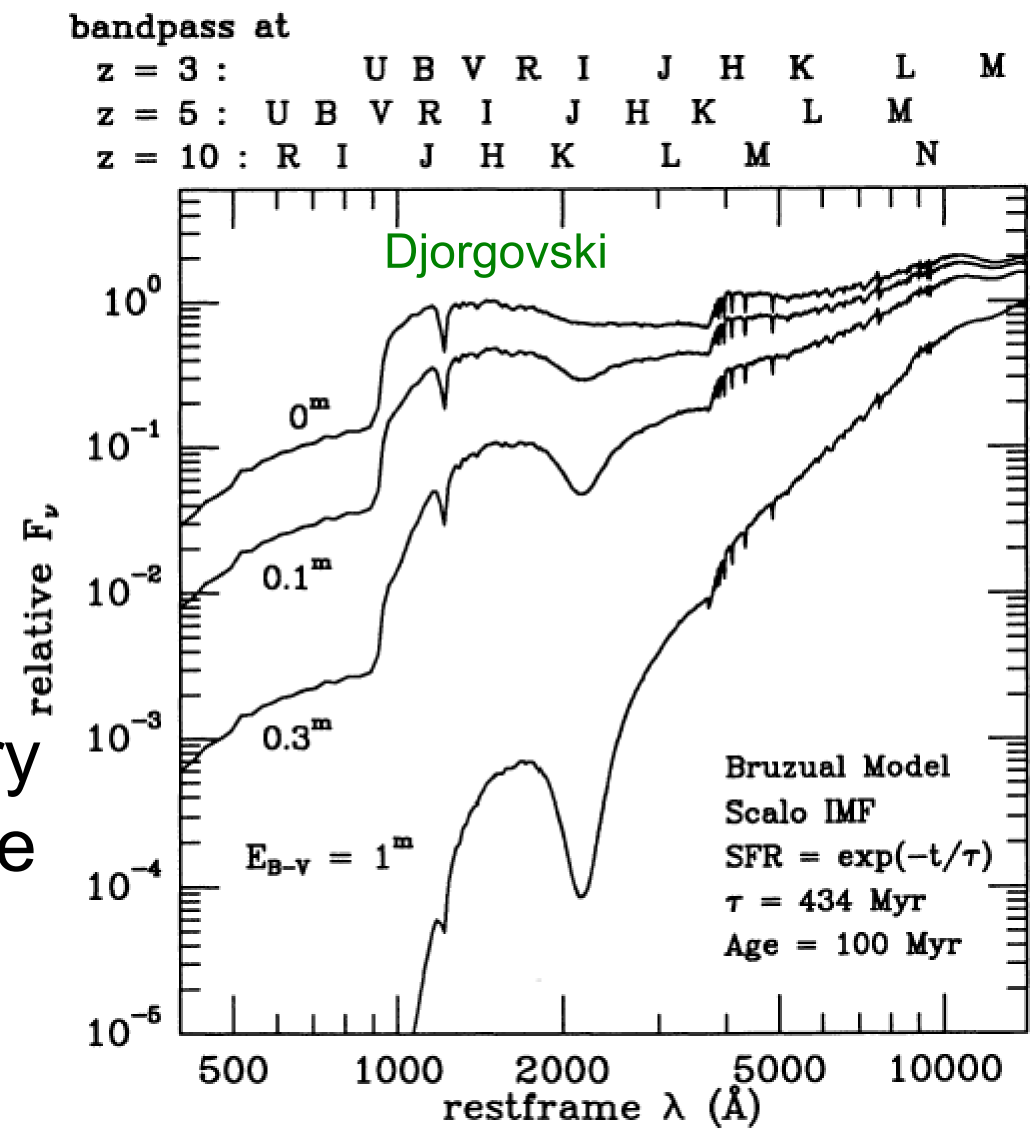


- 30Myr const SFR with E(B-V)=0.1
- No reddening
- 0.2solar metallicity

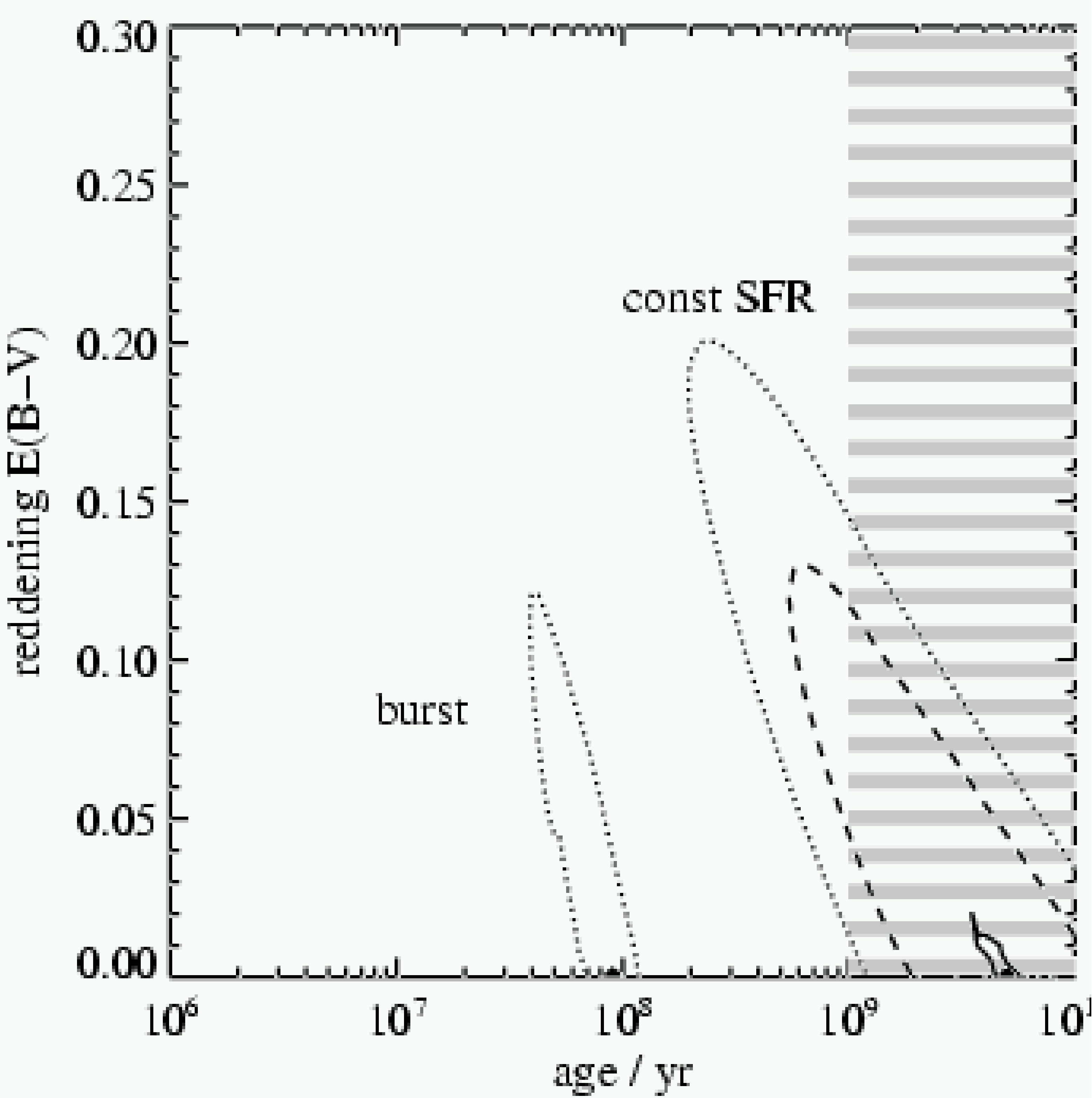
Obscuration of Distant Galaxies



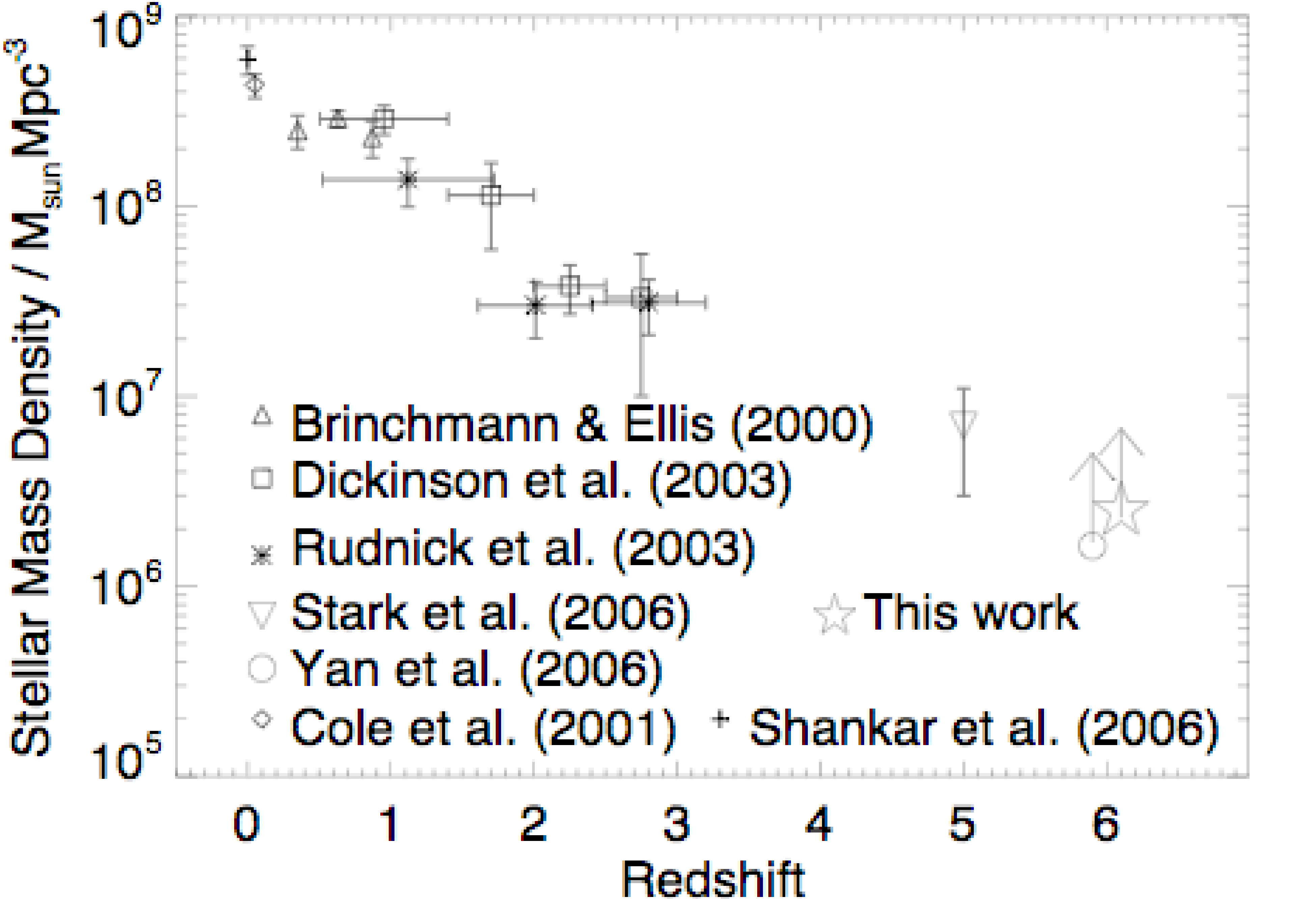
Steidel et al. (1999)



Dust can severely extinguish galaxies. The Lyman-break objects do not seem to be very dusty (but were selected in the rest-UV...). Might be a large obscured star-forming population out to high-z

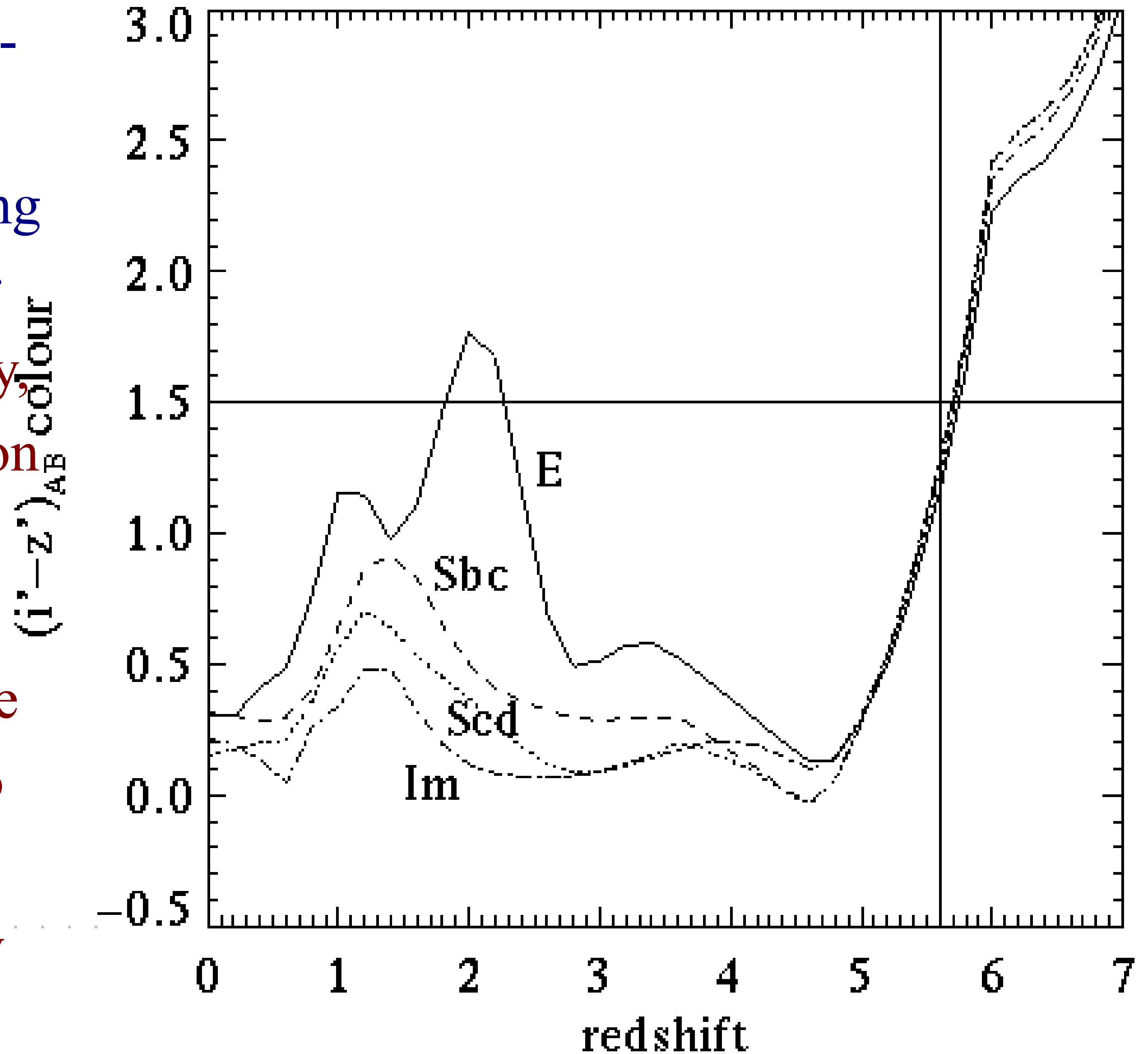


0.30
0.25
0.20
0.15
0.10
0.05
0.00
reddening E(B−V)
const SFR
burst
10^6
10^7
10^8
10^9
10
age / yr



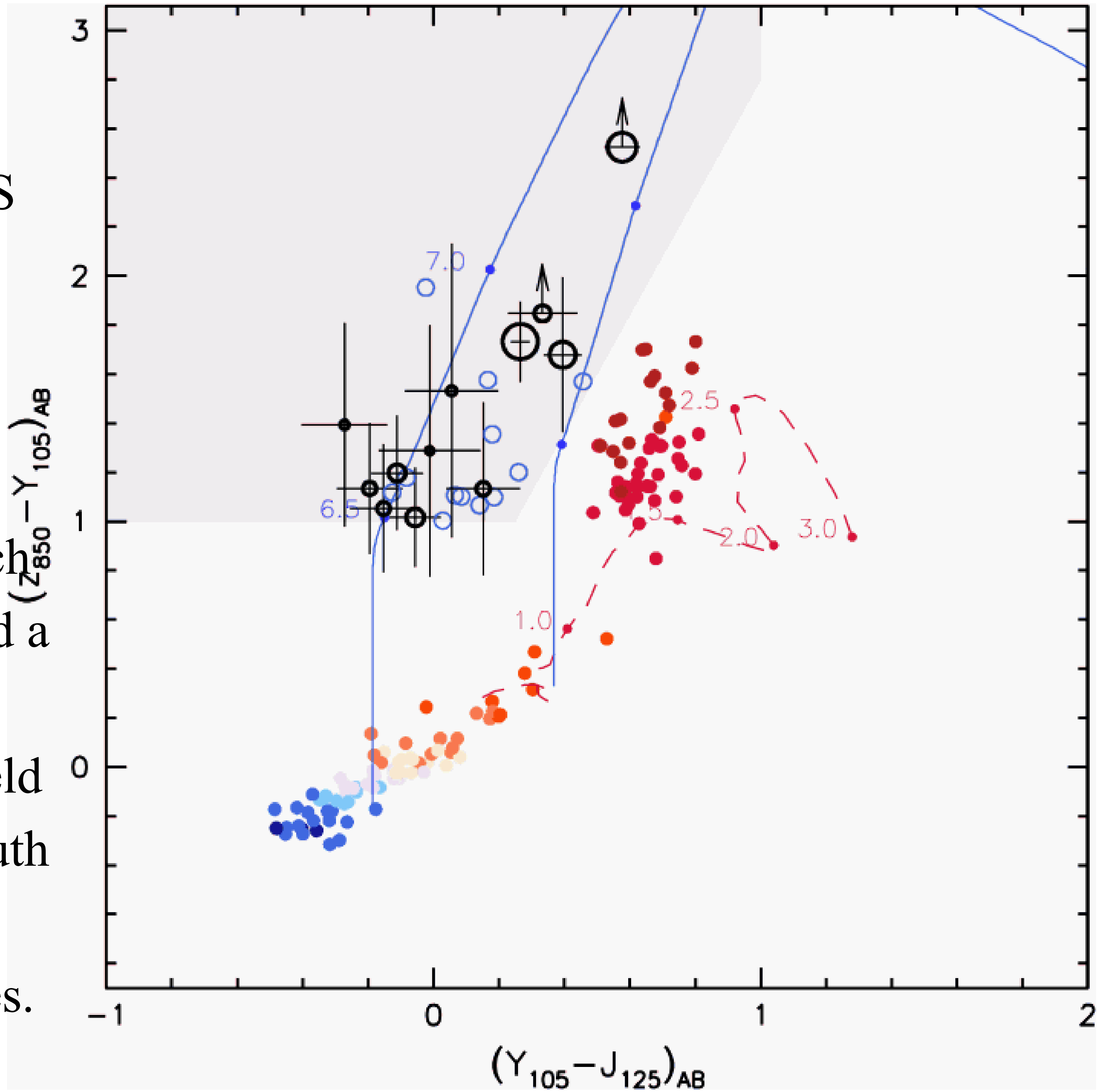
Stellar Mass Density / $M_{sun} Mpc^3$
10^9
10^8
10^7
10^6
10^5
Brinchmann & Ellis (2000)
Dickinson et al. (2003)
Rudnick et al. (2003)
Stark et al. (2006)
This work
Yan et al. (2006)
Cole et al. (2001)
Shankar et al. (2006)
0
1
2
3
4
5
6
Redshift

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



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



ESO VLTs

10-m Kecks

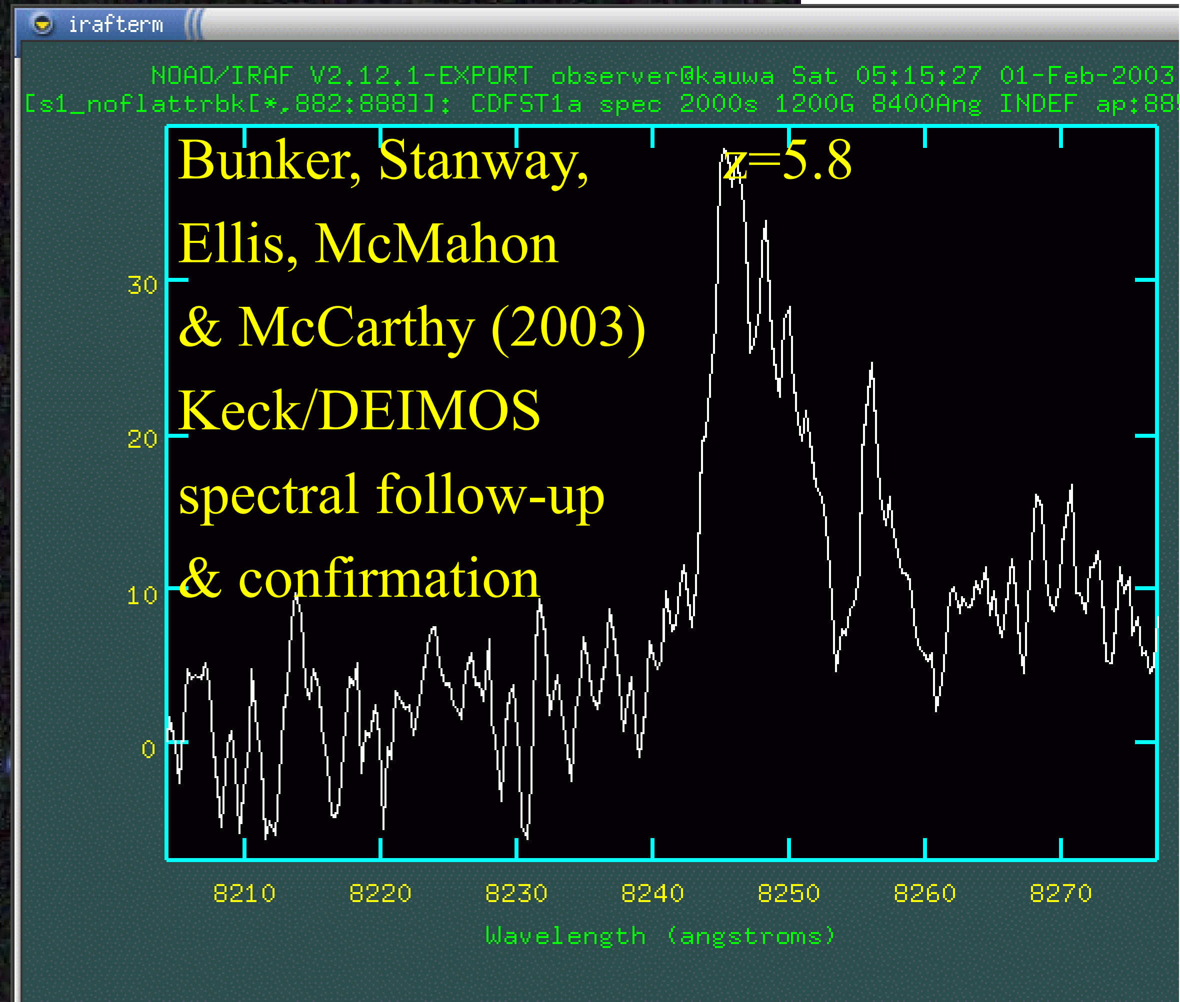

GEMINI-NORTH

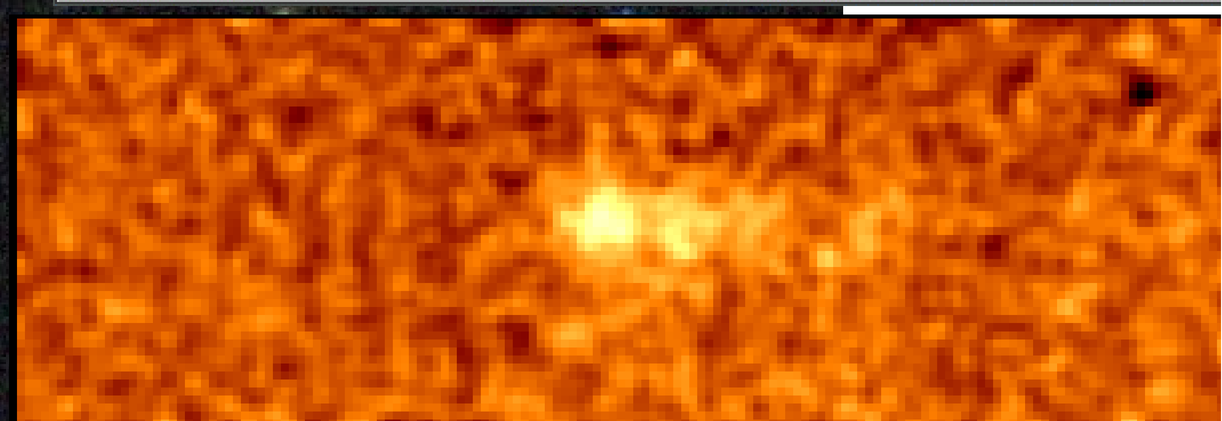

SOUTH-GEMINI


Photo © Neelon Crawford/Polar Fine Arts


10-m Kecks - largest telescopes in the world.
Summit of Mauna Kea, 14000ft, Hawaii

The Star Formation History of the Univese



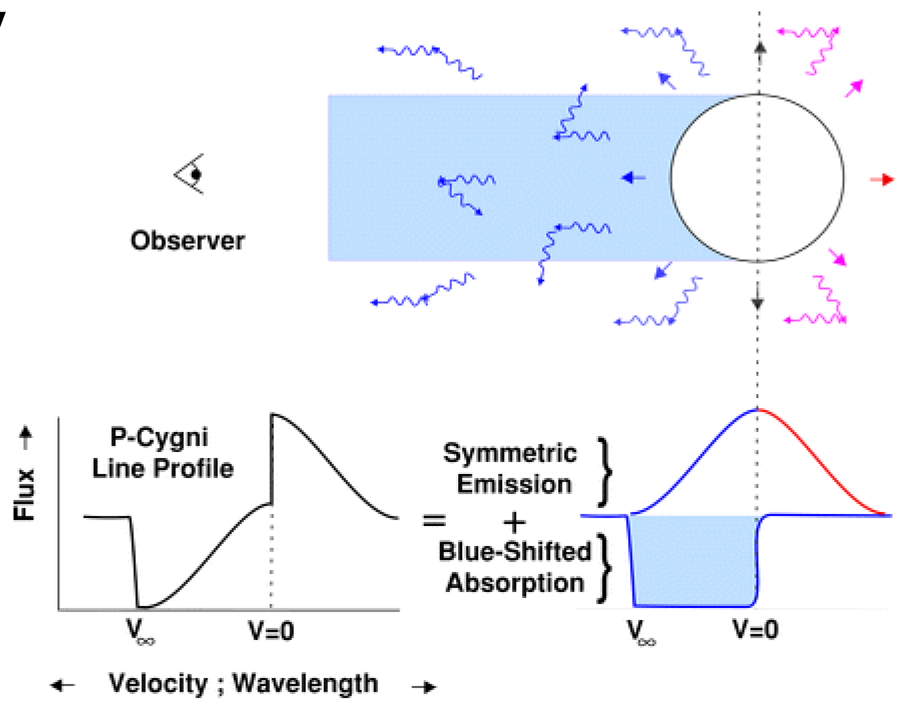


I-drops in the Chandra Deep Field South with HST/ACS
Elizabeth Stanway, Andrew Bunker, Richard McMahon 2003 (MNRAS)

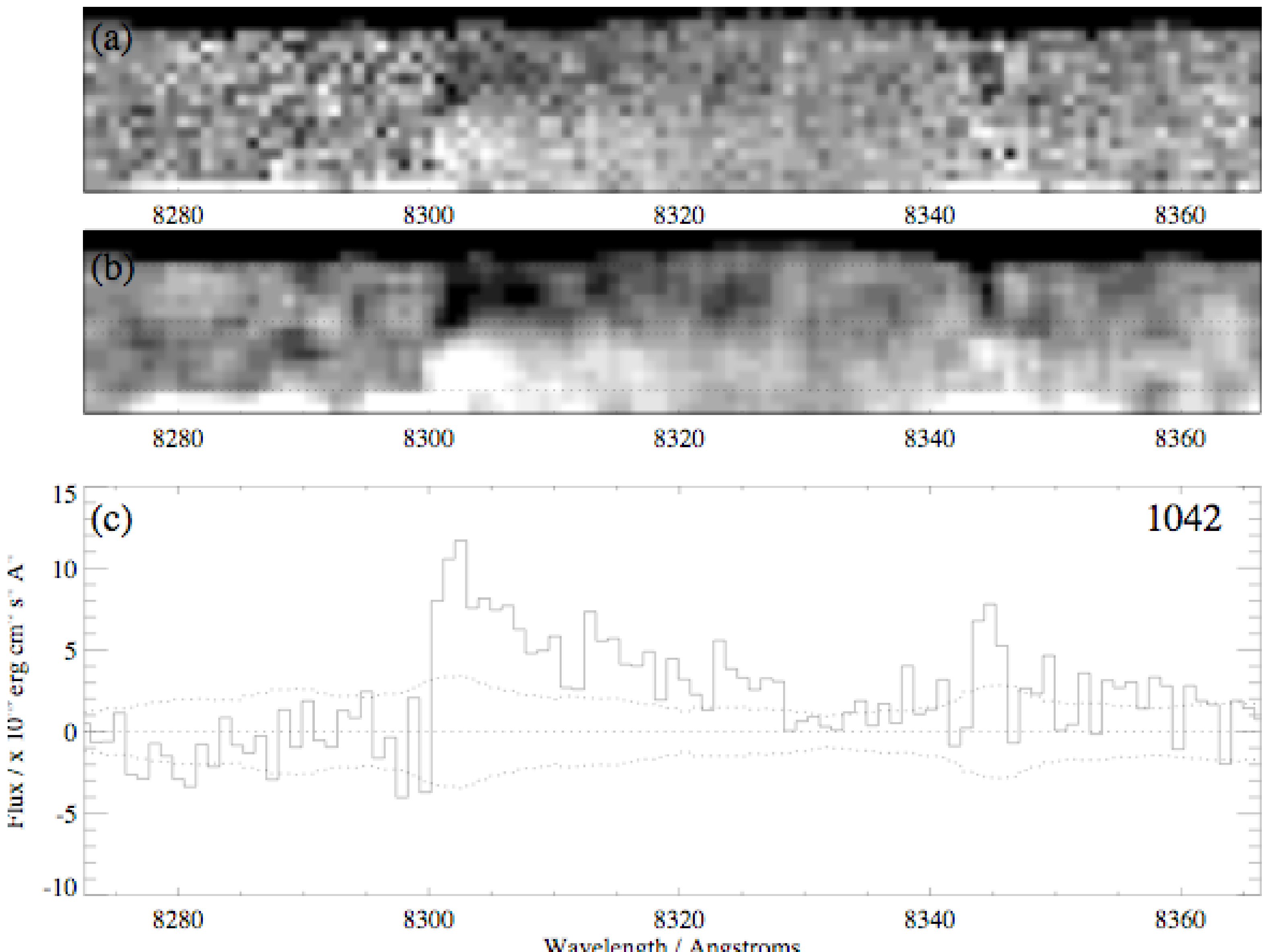
Line Profiles

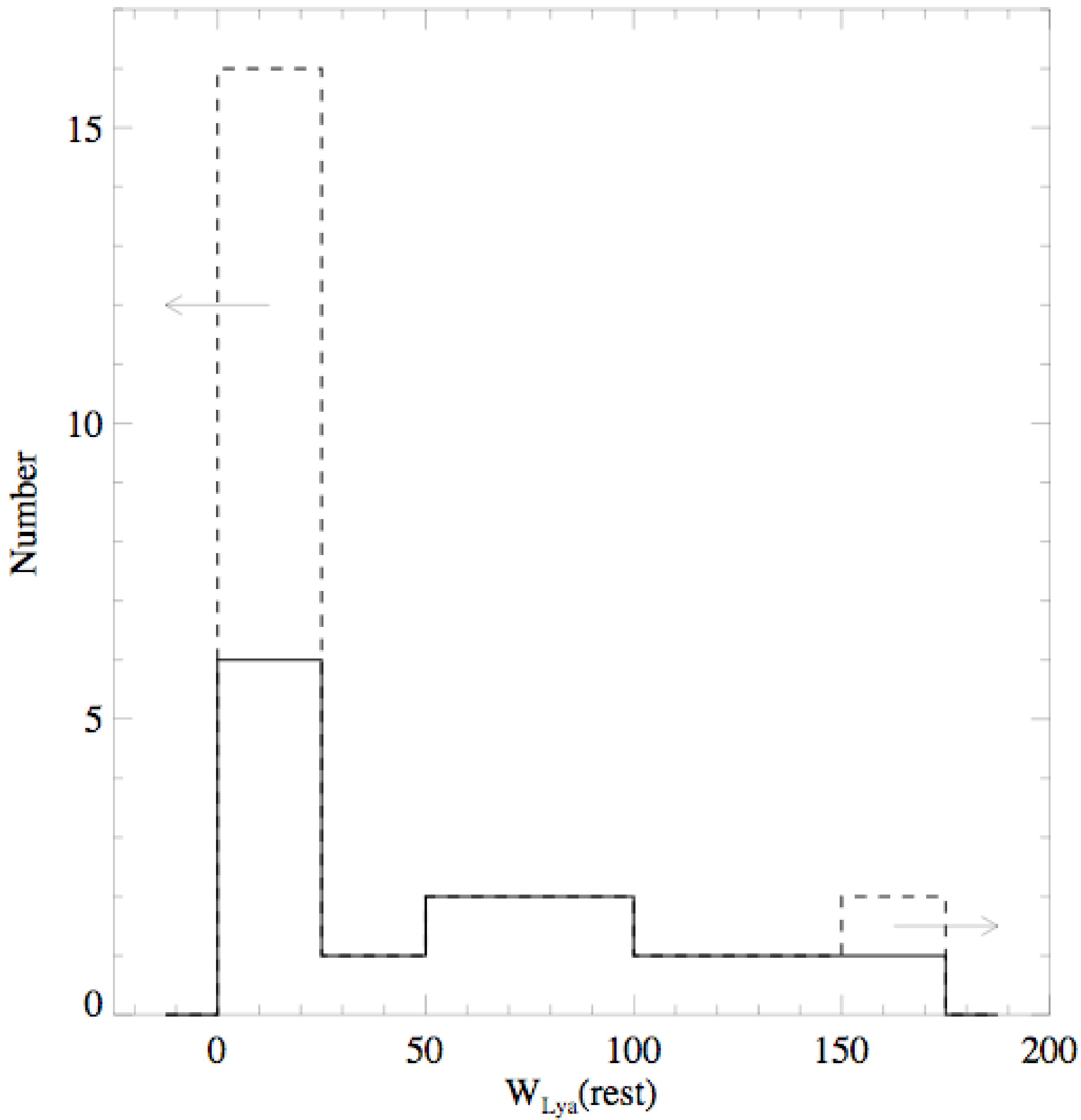
Lines can be broadened by galaxy kinematics, and stellar physics (surface gravity, pressure,...). Need moderately high spectral resolution to study.

P-Cygni profile - signature of stellar outflow. Strong in hot, young, massive stars - charactersitic red-wing emission and blue-wing absorption. Velocity spread increases with stellar mass. Seen in high-redshift galaxies.

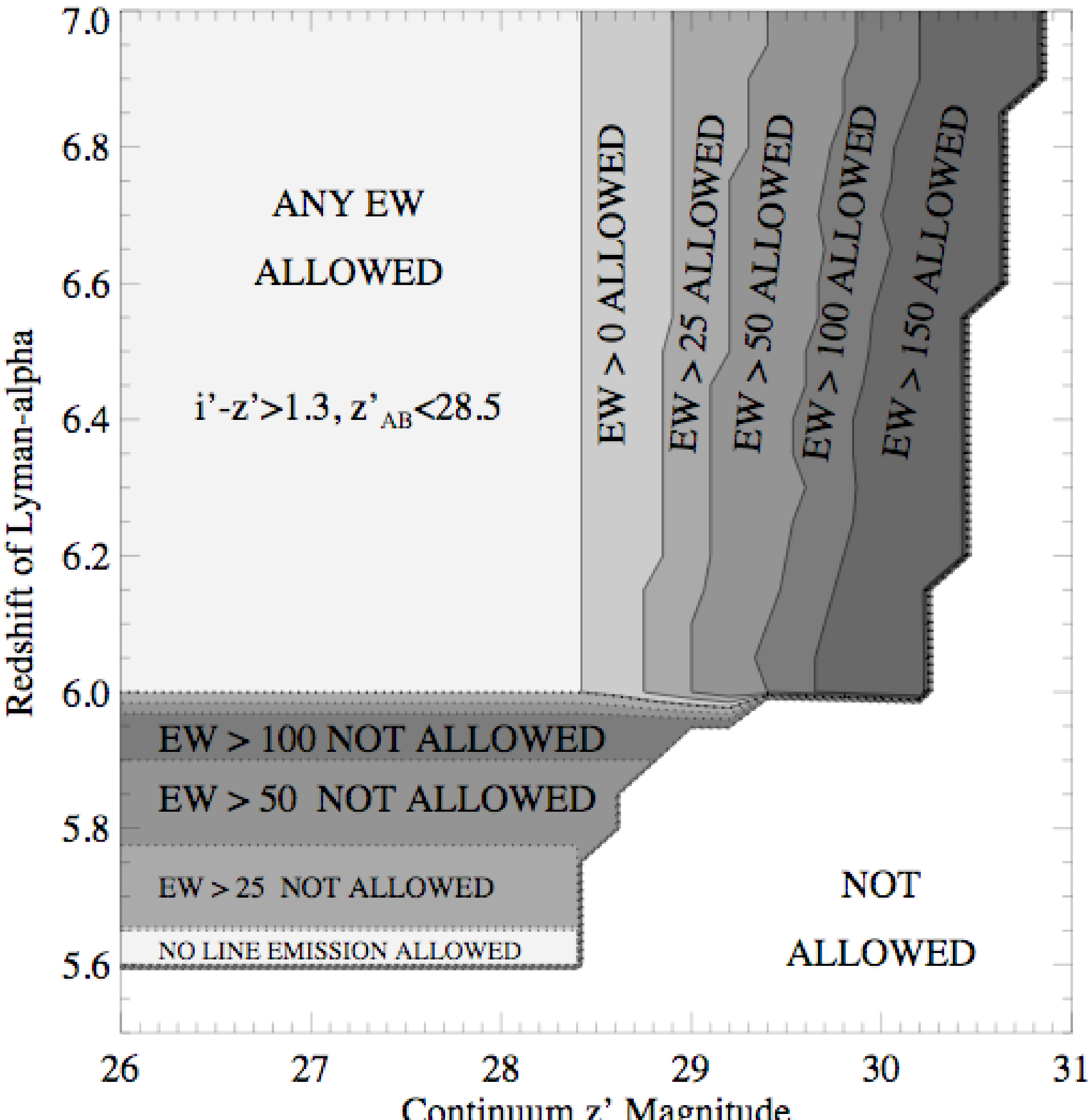


Owocki (2000)


(a)
(b)
(c)
1042
8280
8300
8320
8340
8360
15
10
5
0
-5
-10
Wavelength / Angstroms



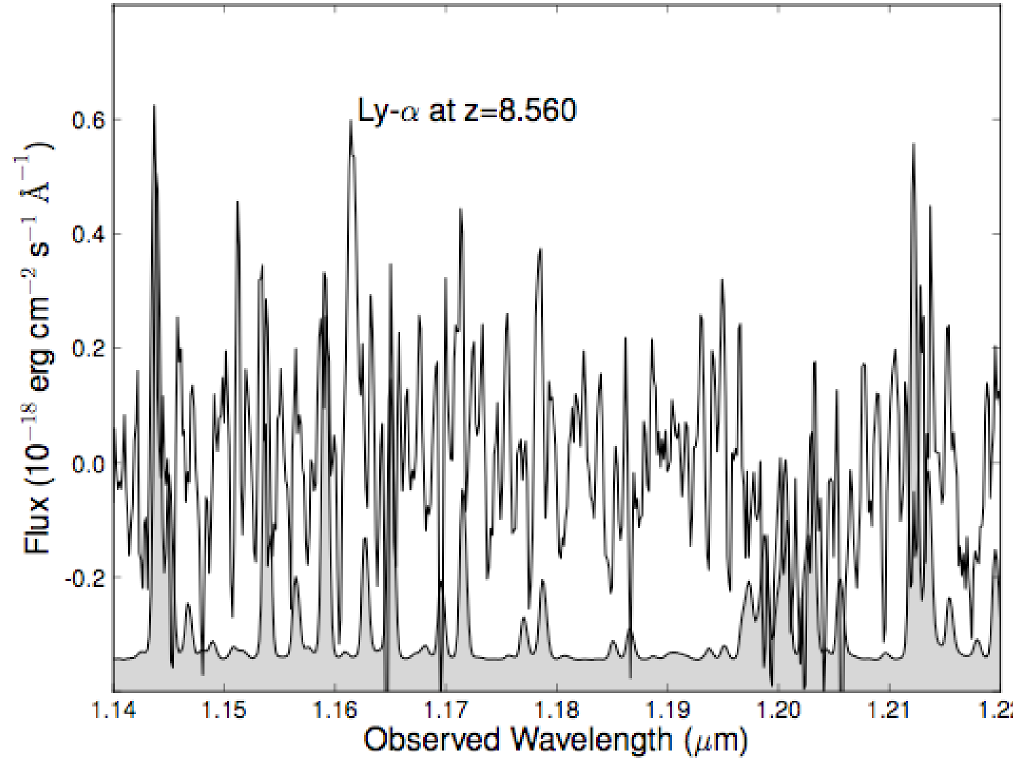
15
10
5
0
Number
0
50
100
150
200
W_{Lya}(rest)

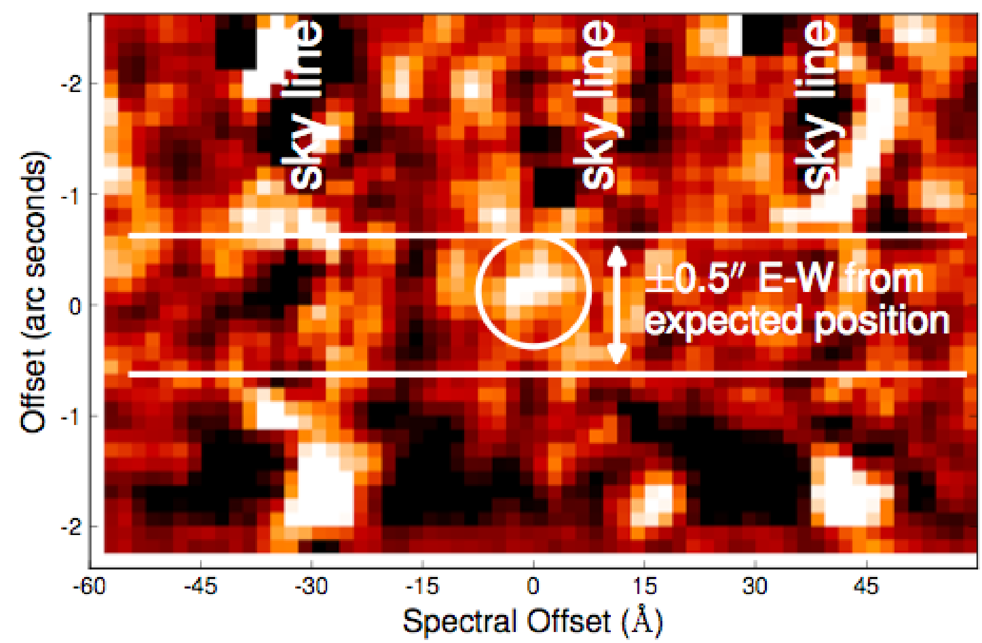


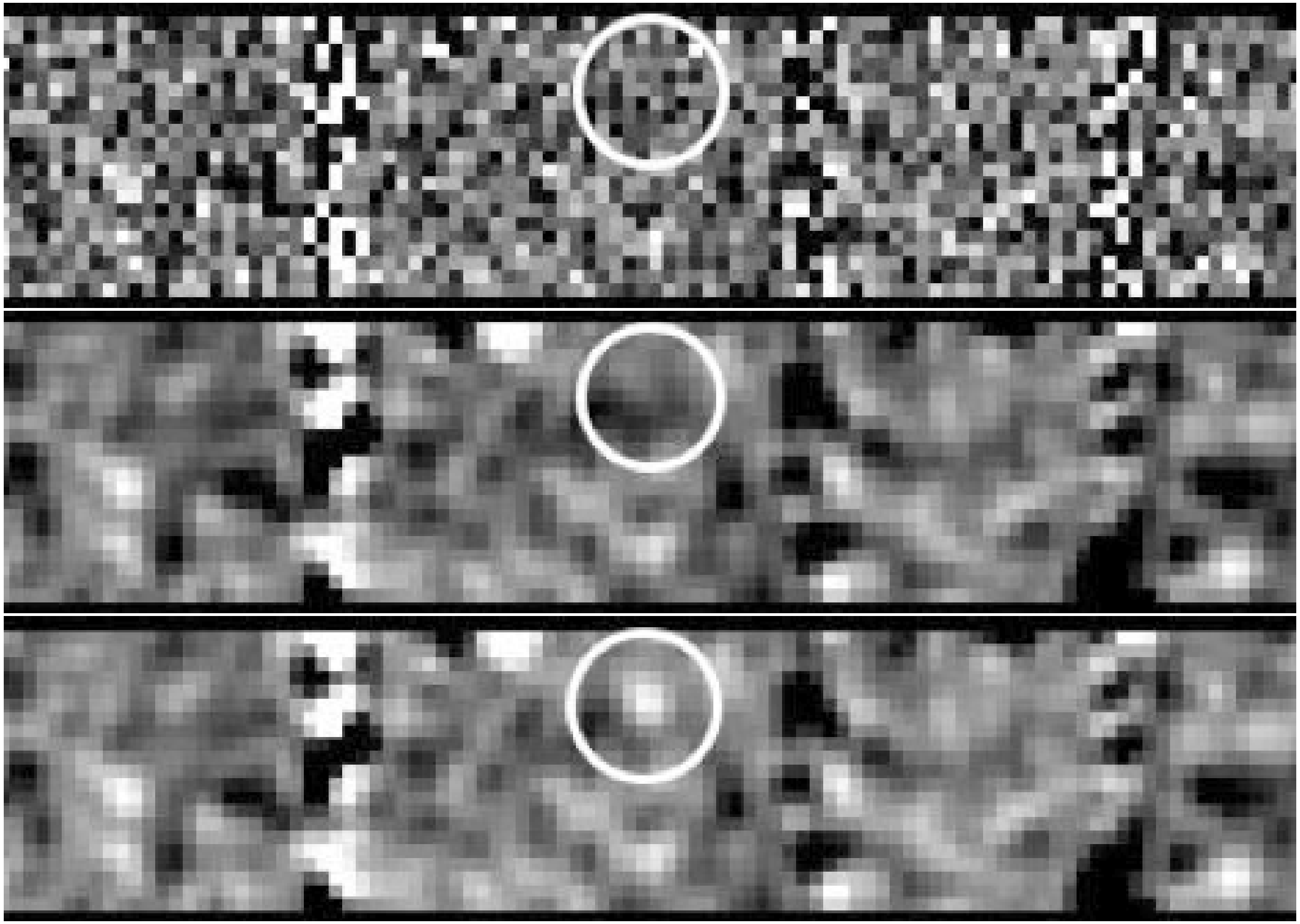
ANY EW
ALLOWED
i'-z'>1.3, z'AB<28.5
EW > 0 ALLOWED
EW > 25 ALLOWED
EW > 50 ALLOWED
EW > 100 ALLOWED
EW > 150 ALLOWED
EW > 100 NOT ALLOWED
EW > 50 NOT ALLOWED
EW > 25 NOT ALLOWED
NO LINE EMISSION ALLOWED
NOT
ALLOWED
Redshift of Lyman-alpha
Continuum z' Magnitude
7.0
6.8
6.6
6.4
6.2
6.0
5.8
5.6
26
27
28
29
30
31

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







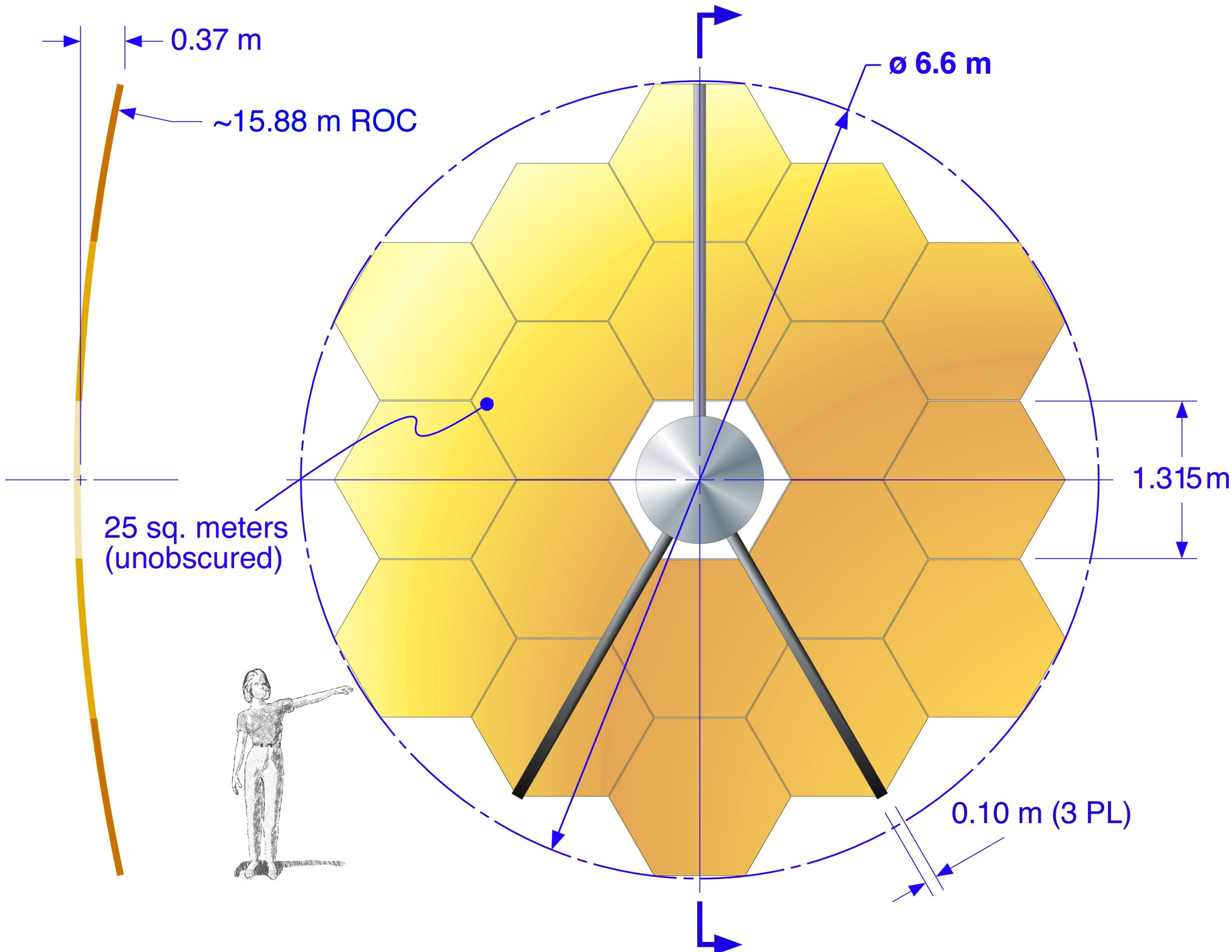
No evidence of Ly-alpha at z=8.55 in 5-hour VLT/XSHOOTER
And 11-hour Subaru/MOIRCS spectrum.
Also, the deep HST/WFC3 Y-band encompasses Ly-alpha, should be detected
at ~4sigma but is undetected

JAMES WEBB SPACE TELESCOPE –

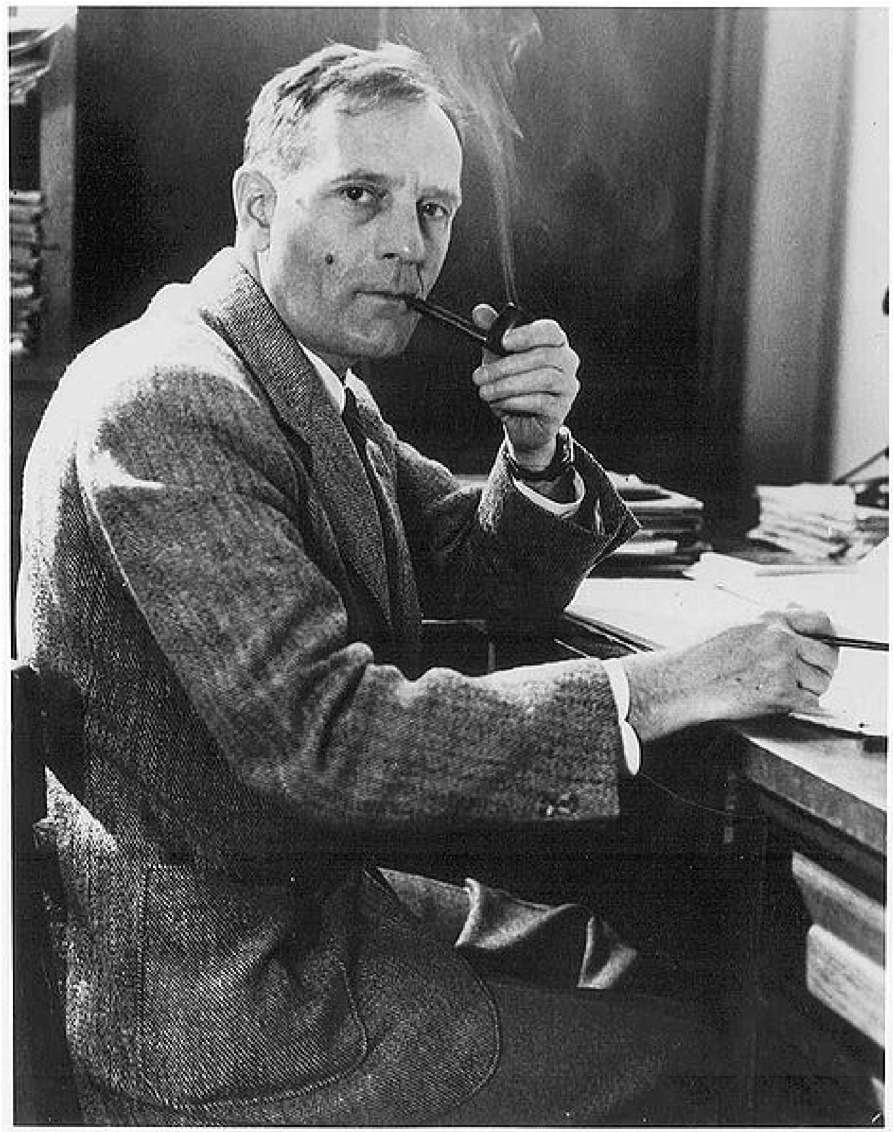
– successor to Hubble ~~(2013+)~~

2018

James Webb Space Telescope



Who Was James Webb?



Edwin Hubble

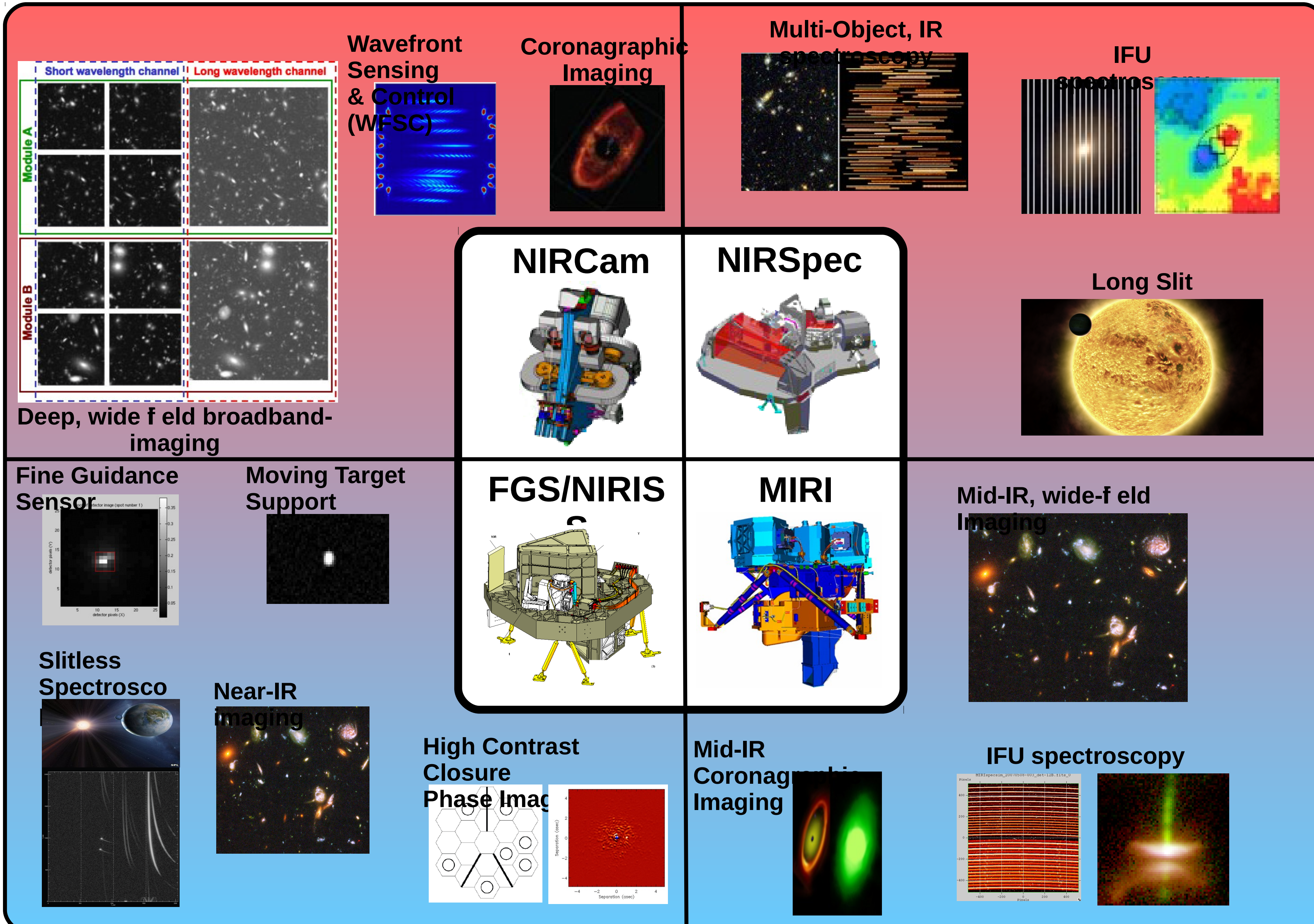
James E. Webb
Second NASA administrator, during Apollo moon missions

What is JWST?

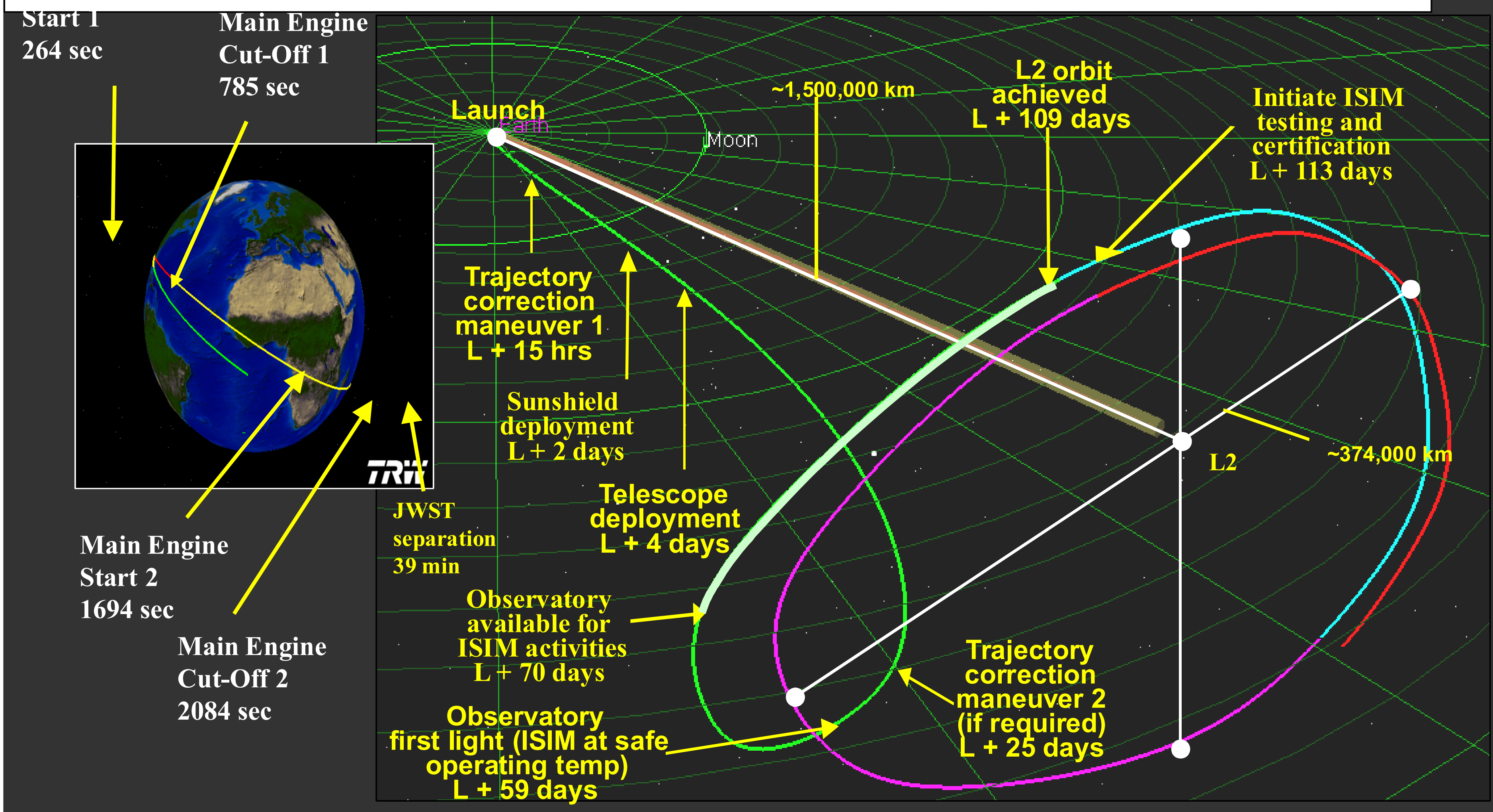
- 6.55 m deployable primary
- Diffraction-limited at 2 μm
- Wavelength range 0.6-28 μm
- Passively cooled to <50 K
- Zodiacal-limited below 10 μm
- Sun-Earth L2 orbit
- 4 instruments
  - 0.6-5 μm wide field camera (NIRCam)
  - 1-5 μm multiobject spectrometer (NIRSpec)
  - 5-28 μm camera/spectrometer (MIRI)
  - 0.8-5 μm guider camera (FGS/TF)
- 5 year lifetime, 10 year goal
- 2018 launch

QuickTime® and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

JWST Science Instruments



Orbit



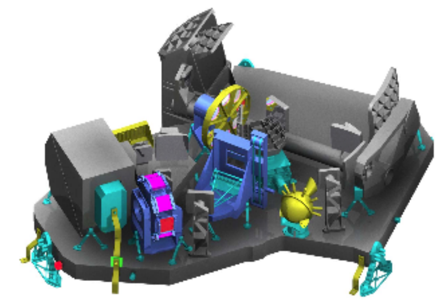
Start 1
264 sec
Main Engine
Cut-Off 1
785 sec
Main Engine
Start 2
1694 sec
Main Engine
Cut-Off 2
2084 sec
JWST
separation
39 min
Launch
Earth
Moon
~1,500,000 km
L2 orbit
achieved
L + 109 days
Initiate ISIM
testing and
certification
L + 113 days
Trajectory
correction
maneuver 1
L + 15 hrs
Sunshield
deployment
L + 2 days
Telescope
deployment
L + 4 days
L2
~374,000 km
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

…scientific objectives and requirements of the James Webb Space Telescope (JWST) Project.

JWST will be a large, cold, infrared-optimized space telescope designed to enable fundamental breakthroughs in our understanding of the formation and evolution of galaxies, stars, and planetary systems.

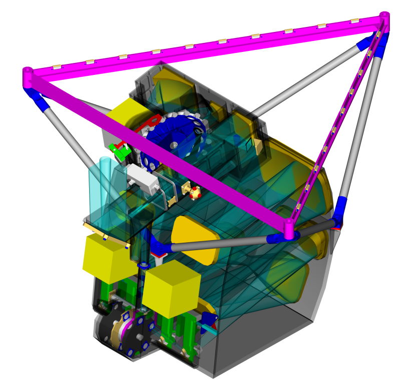
1. The End of the Dark Ages: First Light and Reionization
2. The Assembly of Galaxies
3. The Birth of Stars and Protoplanetary Systems
4. Planetary Systems and the Origins of Life

European Space Agency (ESA) Contributions to JWST



NIRSpec spectrograph 0.8-5 µm

- Multi-object; ESA-build
- Detector & Arrays from NASA



MIRI (long wavelength, 5-30µm)

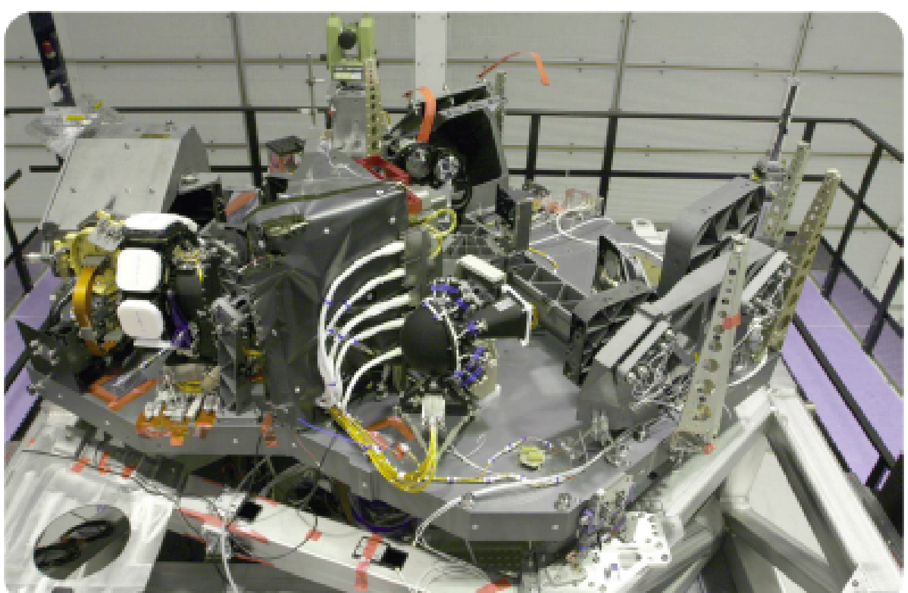
QuickTimeª and a TIFF (LZW) decompressor are needed to see this picture.

- ESA Member States & NASA
- Detector & Cooler/Cryostat from NASA

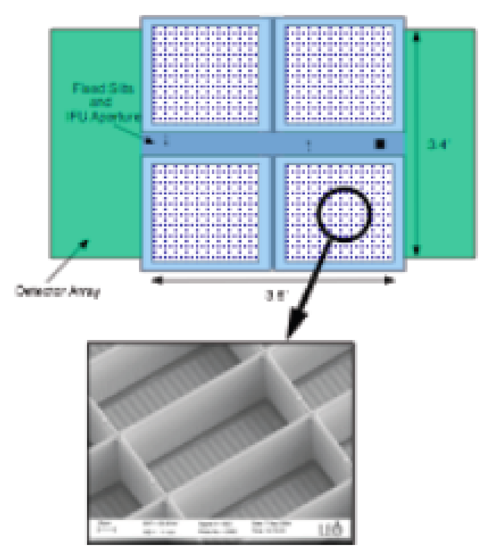
Ariane V Launcher

NIRSpec

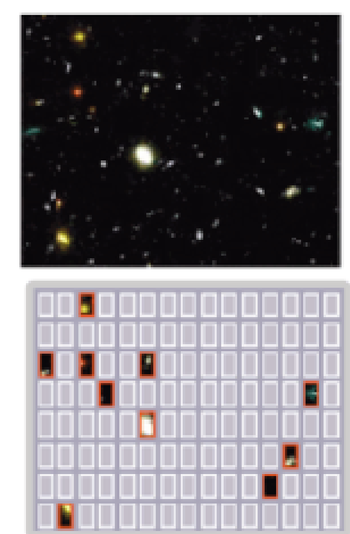
- Developed by the European Space Agency with Astrium GmbH and GSFC
  - Operating wavelength: 0.6 – 5.0 µm
  - Spectral resolution: 100, 1000, 3000
  - Field of view: 3.4 x 3.4 arc minutes
  - Aperture control: programmable micro-shutters, 250,000 pixels
  - Angular resolution: shutter open area 203 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



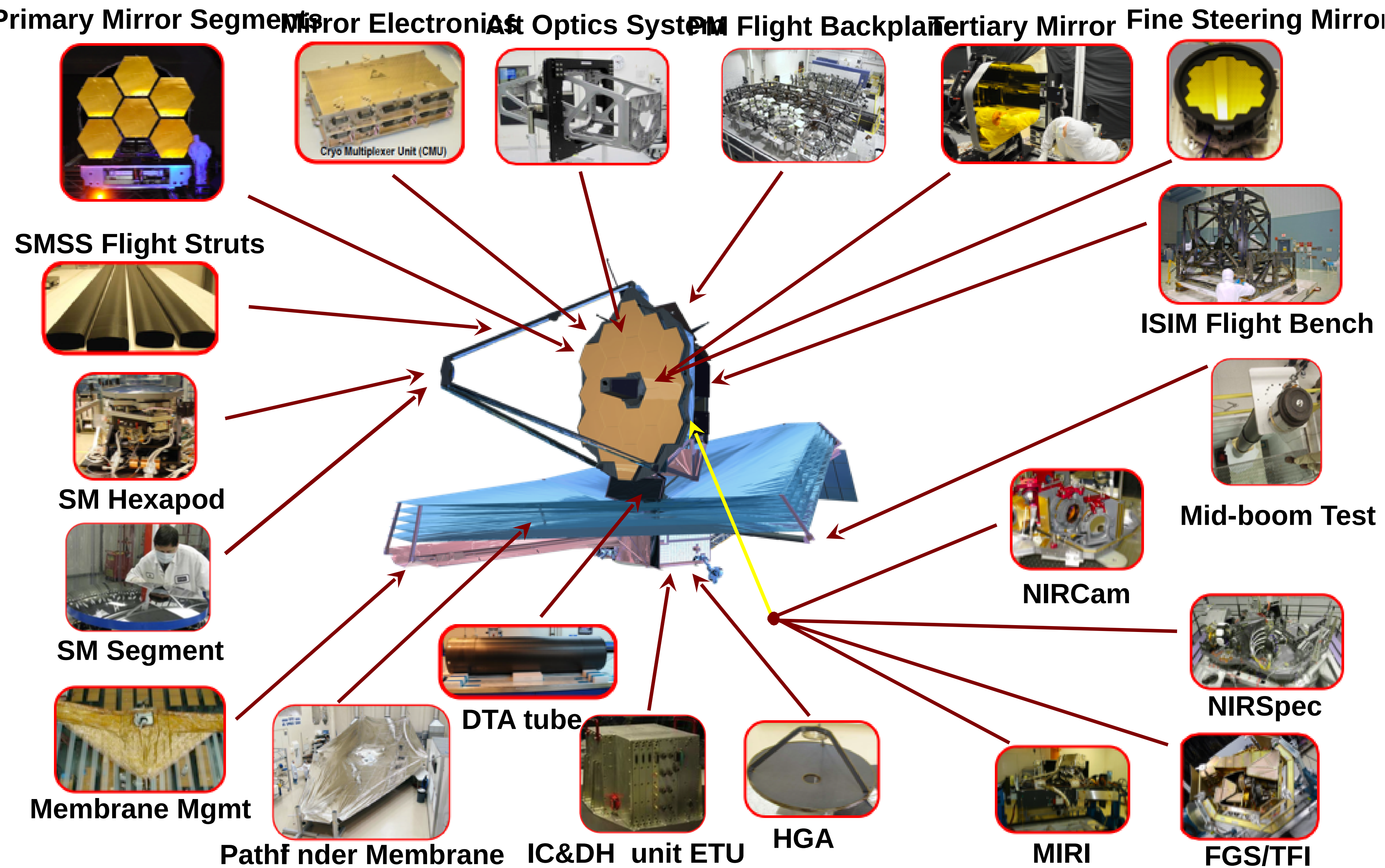
NIRSpec IST


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

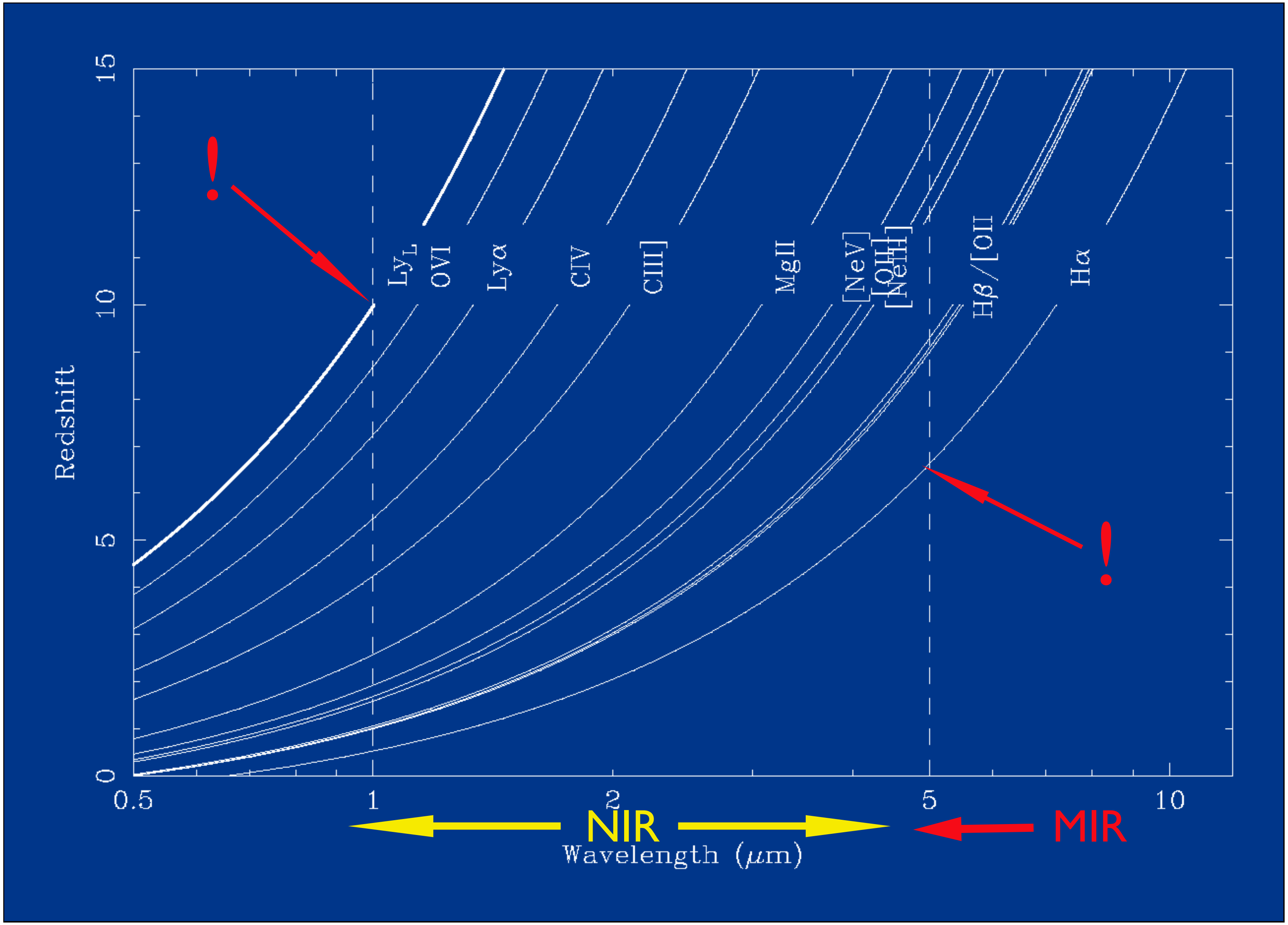
NIRSpec

- 3 x 3 arcmin FOV
- 1-5 μm coverage
- R~1000, R~100 multiplexed
- >100 sources simultaneously
- Configurable slit width/length
- MEMS array - “build your own slitmask in space”

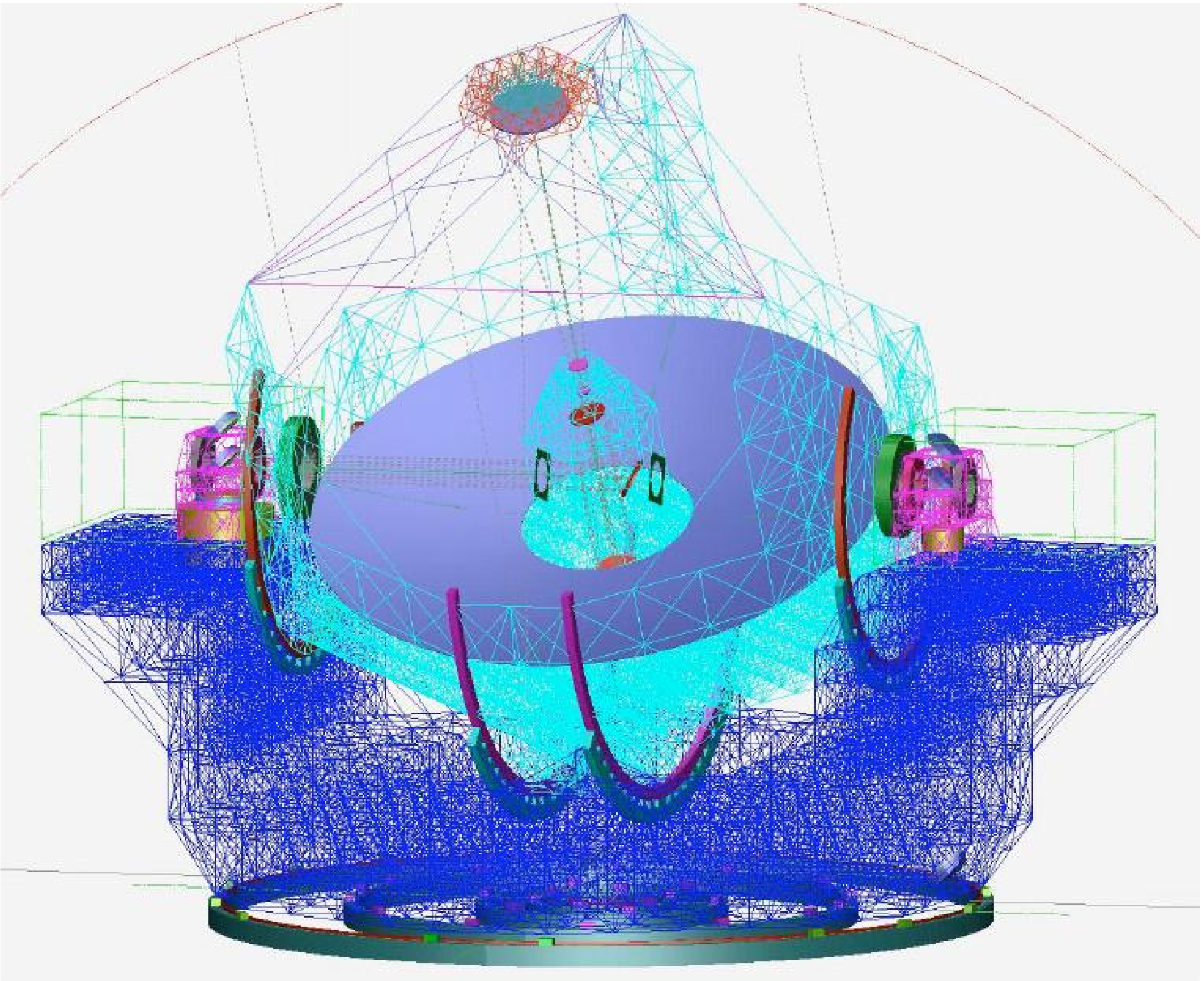
JWST: Under Construction



You Can't Fight Redshift



E-ELT (also TMT)



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