The Luminosity Function at High Redshift and Reionization: Do Dwarves do all the work?

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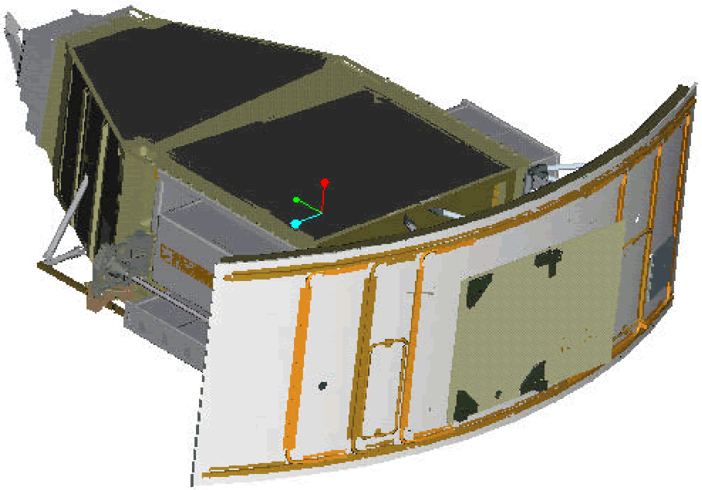
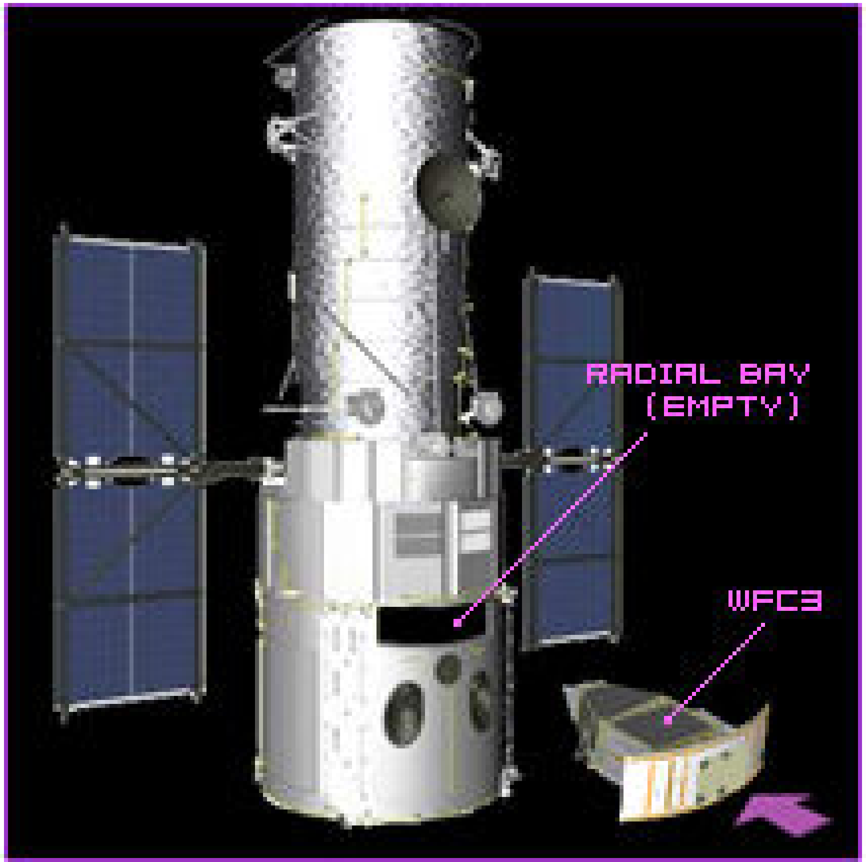
The Key Problem

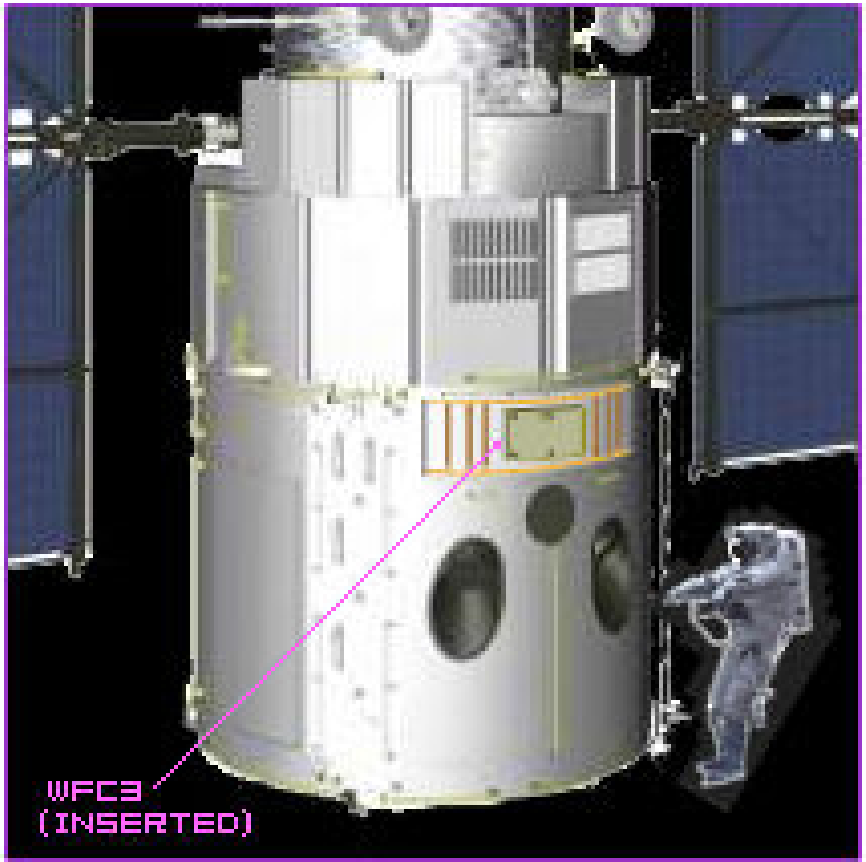
- We know the intergalactic medium of the Universe reionizes at $z>6$ (probably around $z=10\text{-}11$)
- What is the source of the UV photons to do this?
- AGN are under-abundant at these high redshifts
- Can star formation do it? Or is it something else?
- Have been successful in recent years in finding 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?


Finding Galaxies in the Epoch of Reionization with HST



HST WFC3





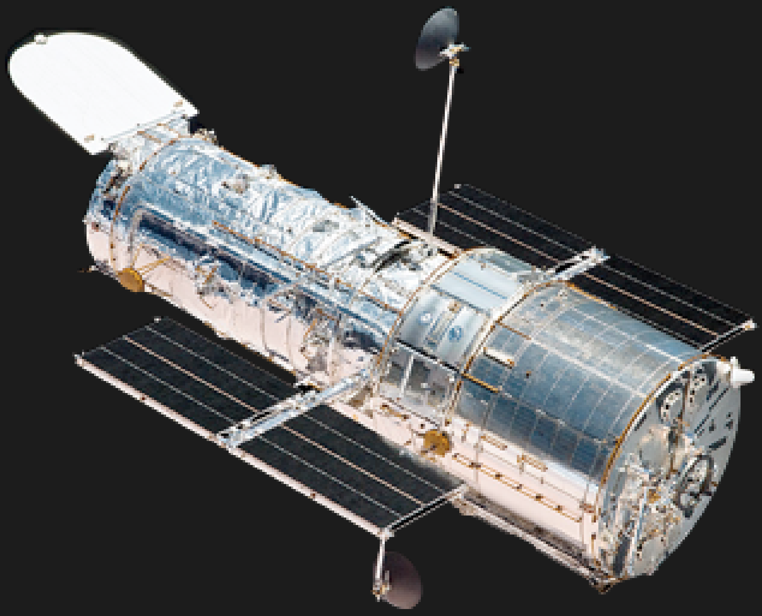
Wide Field Camera 3:

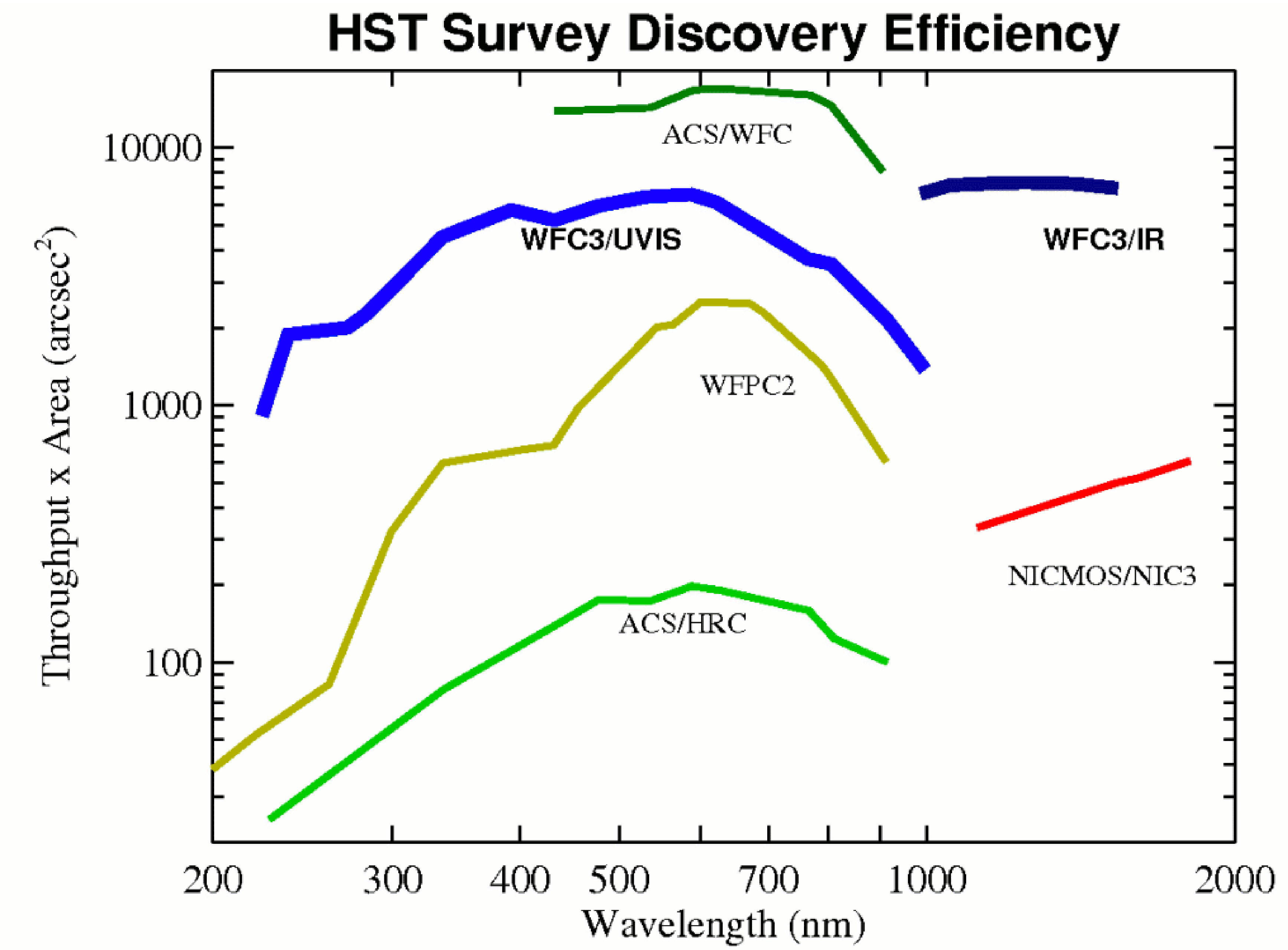
WFC3

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




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

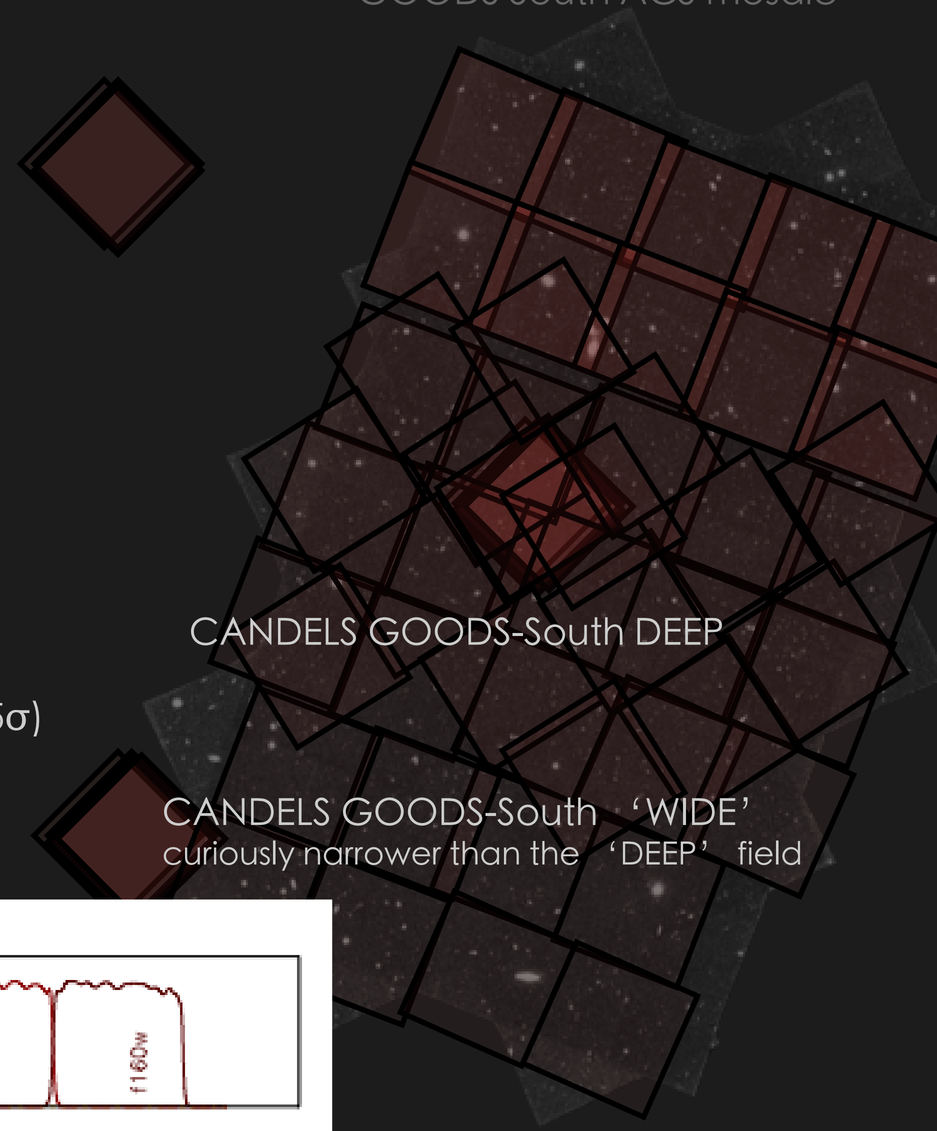
Observations:

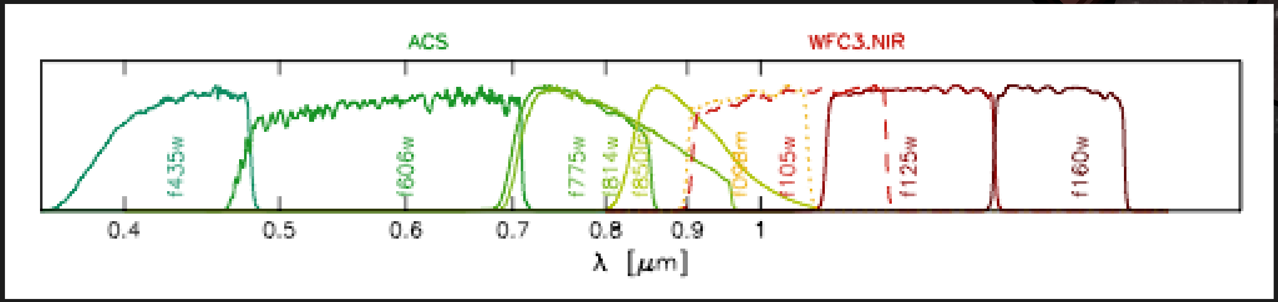
Very-Deep **ACS** imaging over the entire GOODS-South Field [GOODS]

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

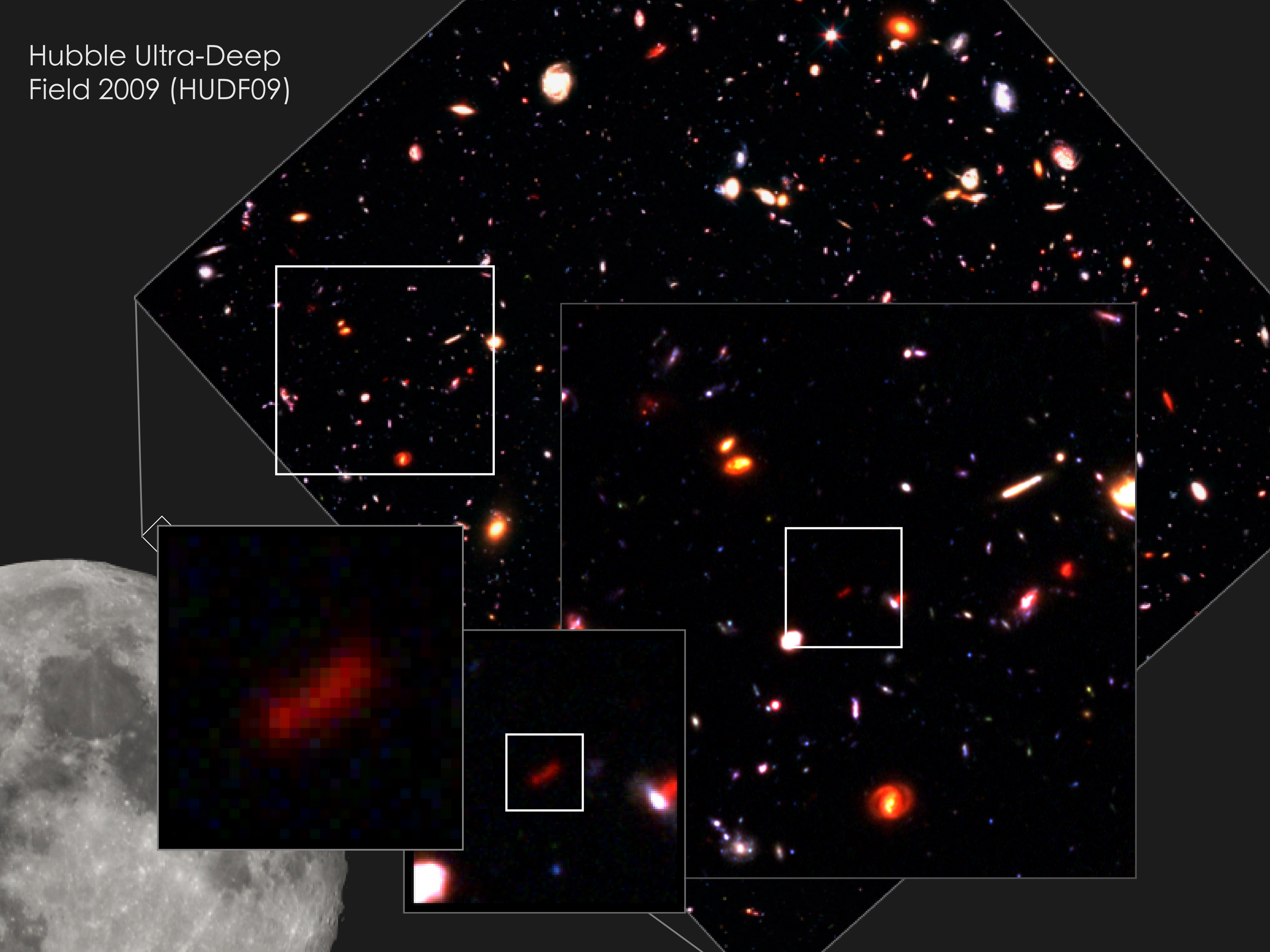
HUDF09	Ultra-deep (29.0-30.0 (AB) in J_{125w}, 5σ) in 3 fields (~15 arcmin^2 total)
ERS	Very-deep (~28.5 (AB) in J_{125w}, 5σ) contiguous over ~40 arcmin^2
CANDELS GOODS-South	Pretty-deep (28.0-28.5 (AB) in J_{125w}, 5σ) contiguous over ~100 arcmin^2

GOODS South ACS mosaic



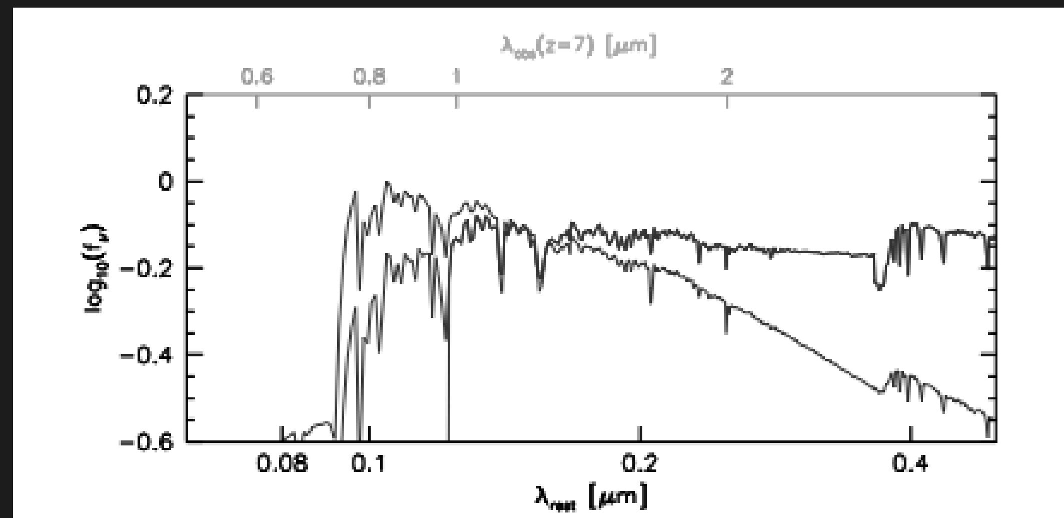


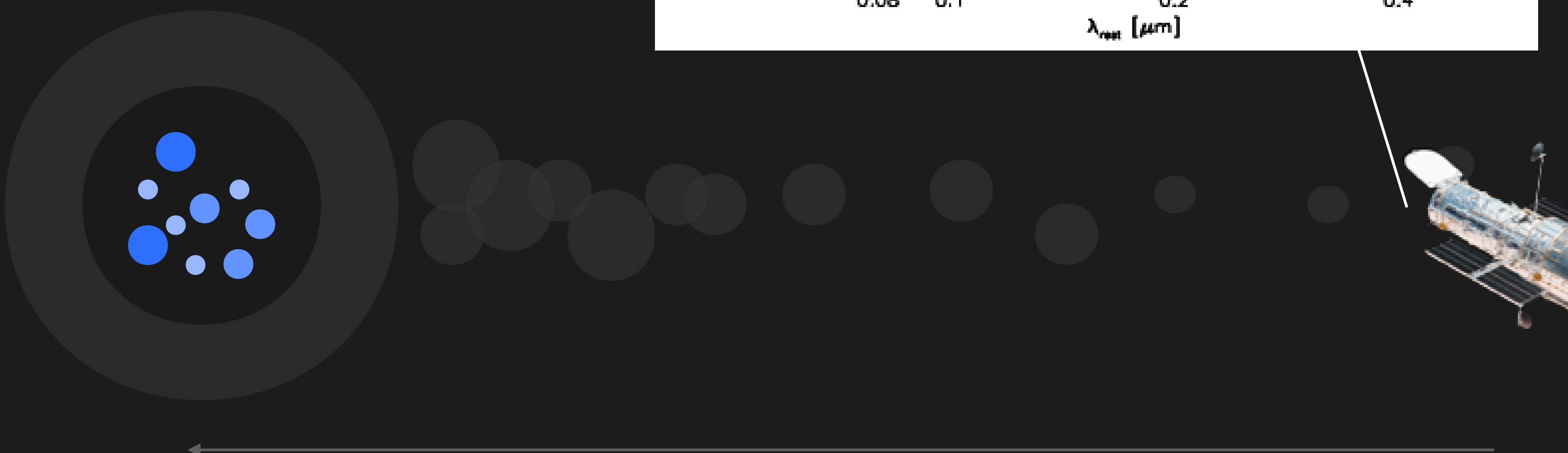
Filter transmission functions of the filters available.


Hubble Ultra-Deep
Field 2009 (HUDF09)

Identifying high-redshift star forming galaxies

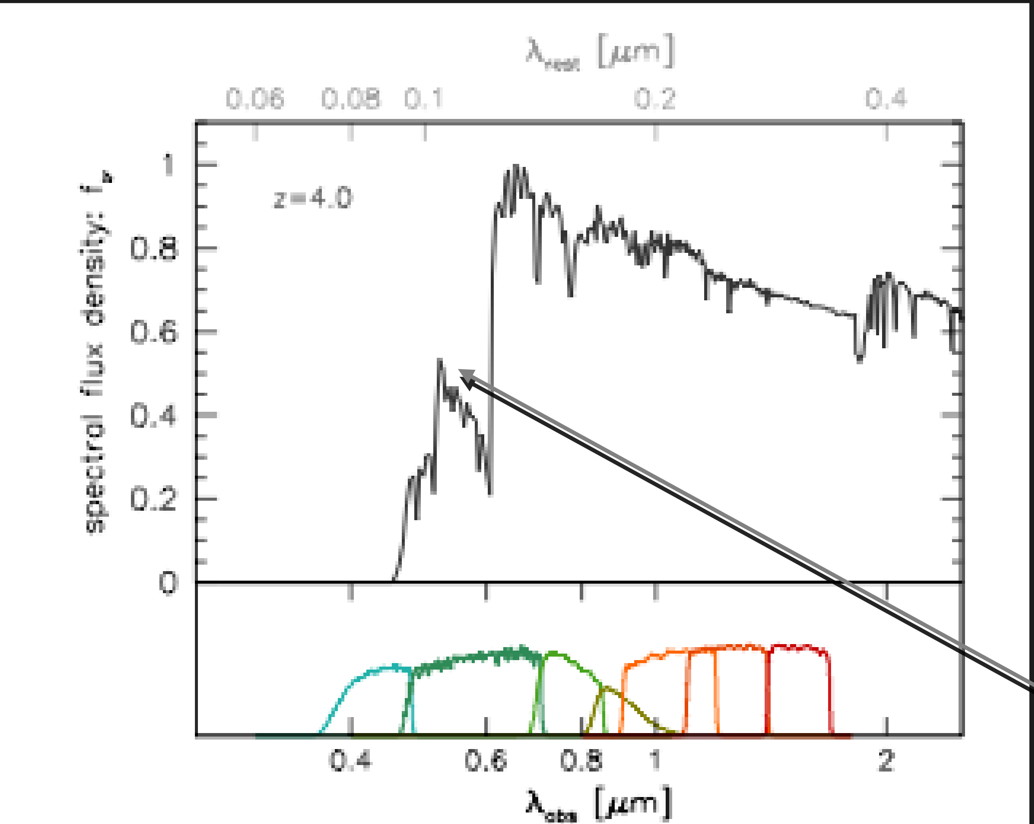
Lyman-alpha / Other absorption from intervening clouds results in Lyman-alpha forest or Gunn-Peterson trough (at very high-z, shown)





Increasing distance / lookback time

Identifying high-redshift star forming galaxies



Observed frame SED of a star forming galaxy at z=4.0

The theoretical (PEGASE.2+Madau96) SED of a z=4 galaxy with the ACS/WFC3 filter transmission curves.

Very-little flux is transmitted in the ACS B-band ⇒ B-drop

LyA Forest absorption

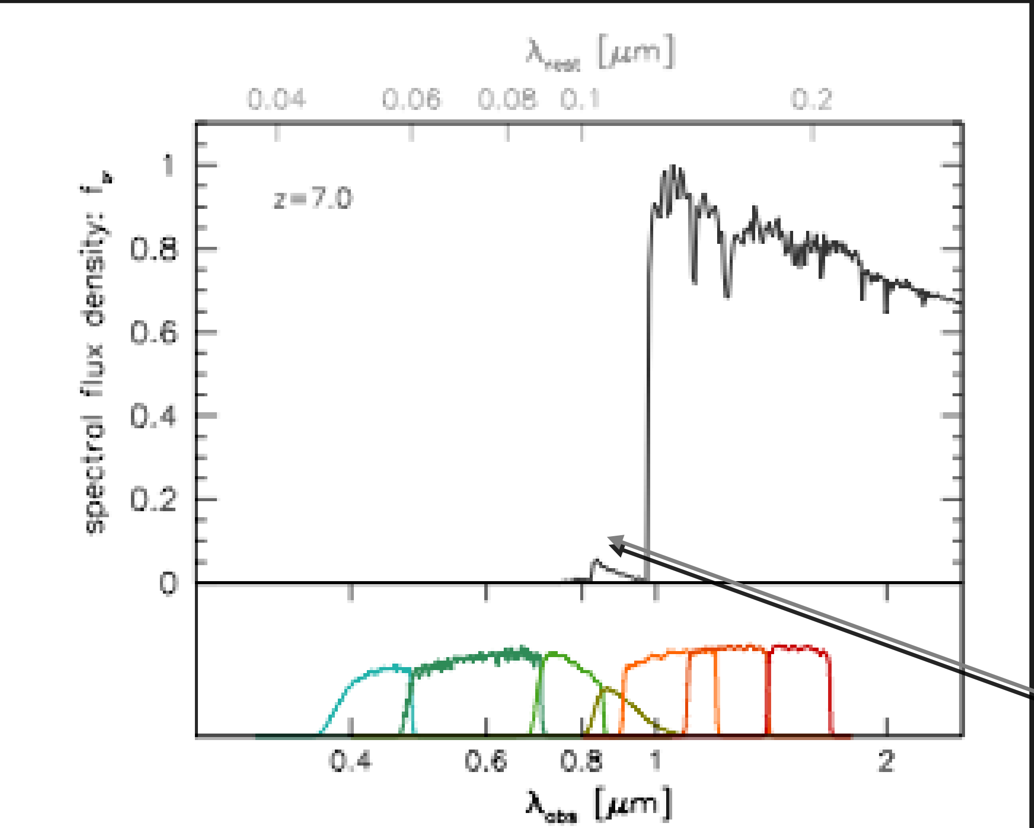
Note: Mean absorption calculated using Madau96 shown

Identification of high-redshift galaxies:

Bunker+10, Wilkins+10, Wilkins+11a, Lorenzoni+11

see also: Bouwens+10a/11a, Oesch+10a/11, Mclure+10/11, Finkelstein+10

Identifying high-redshift star forming galaxies



Observed frame SED of a star forming galaxy at z=7.0

The theoretical (PEGASE.2+Madau96) SED of a z=7 galaxy with the ACS/WFC3 filter transmission curves.

Very-little flux is transmitted in the ACS z-band ⇒ z-drop

LyA Forest absorption resulting in Gunn-Peterson Trough

Identification of high-redshift galaxies:

Bunker+10, Wilkins+10, Wilkins+11a, Lorenzoni+11

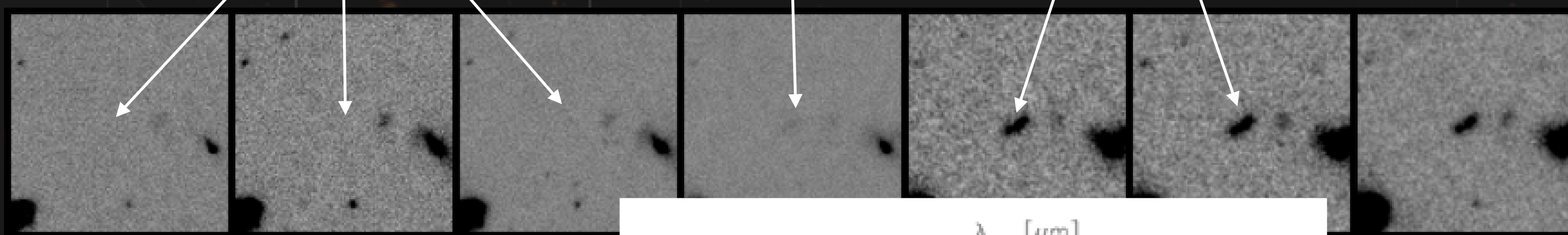
see also: Bouwens+10a/11a, Oesch+10a/11, Mclure+10/11, Finkelstein+10

Hubble Ultra-Deep Field 2009 (HUDF09)

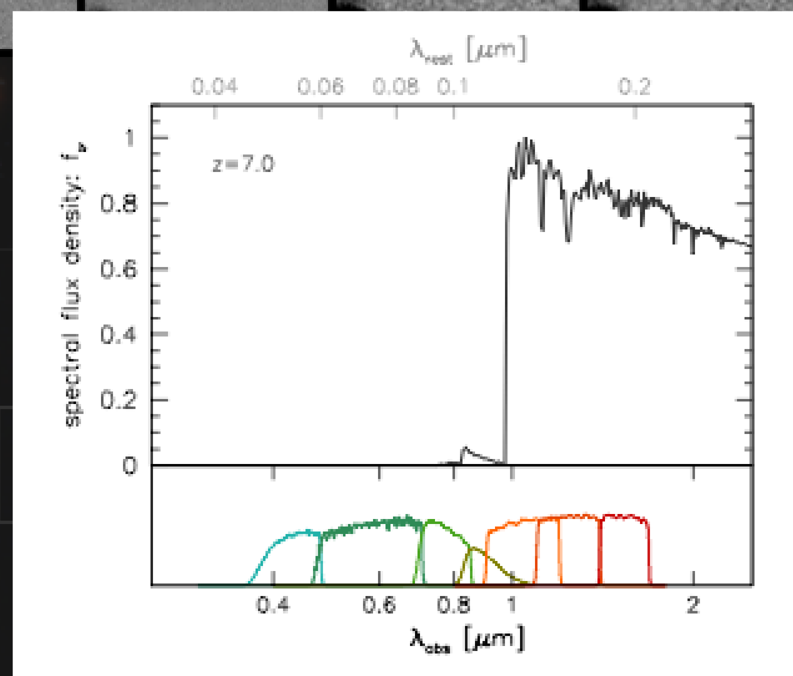
detected at low significance (to be expected)

no detection at 1.5σ

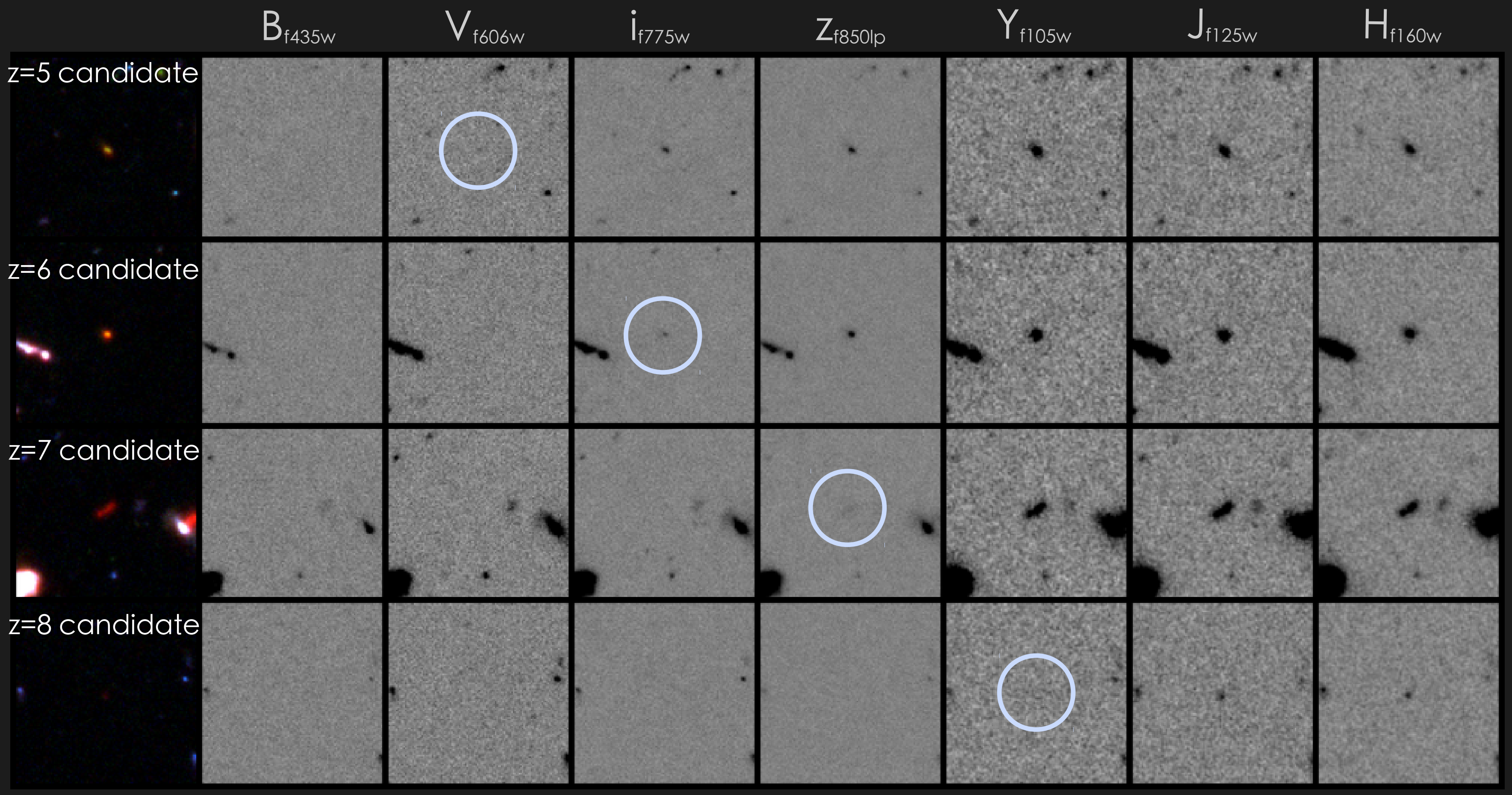
detected at high significance, blue colour

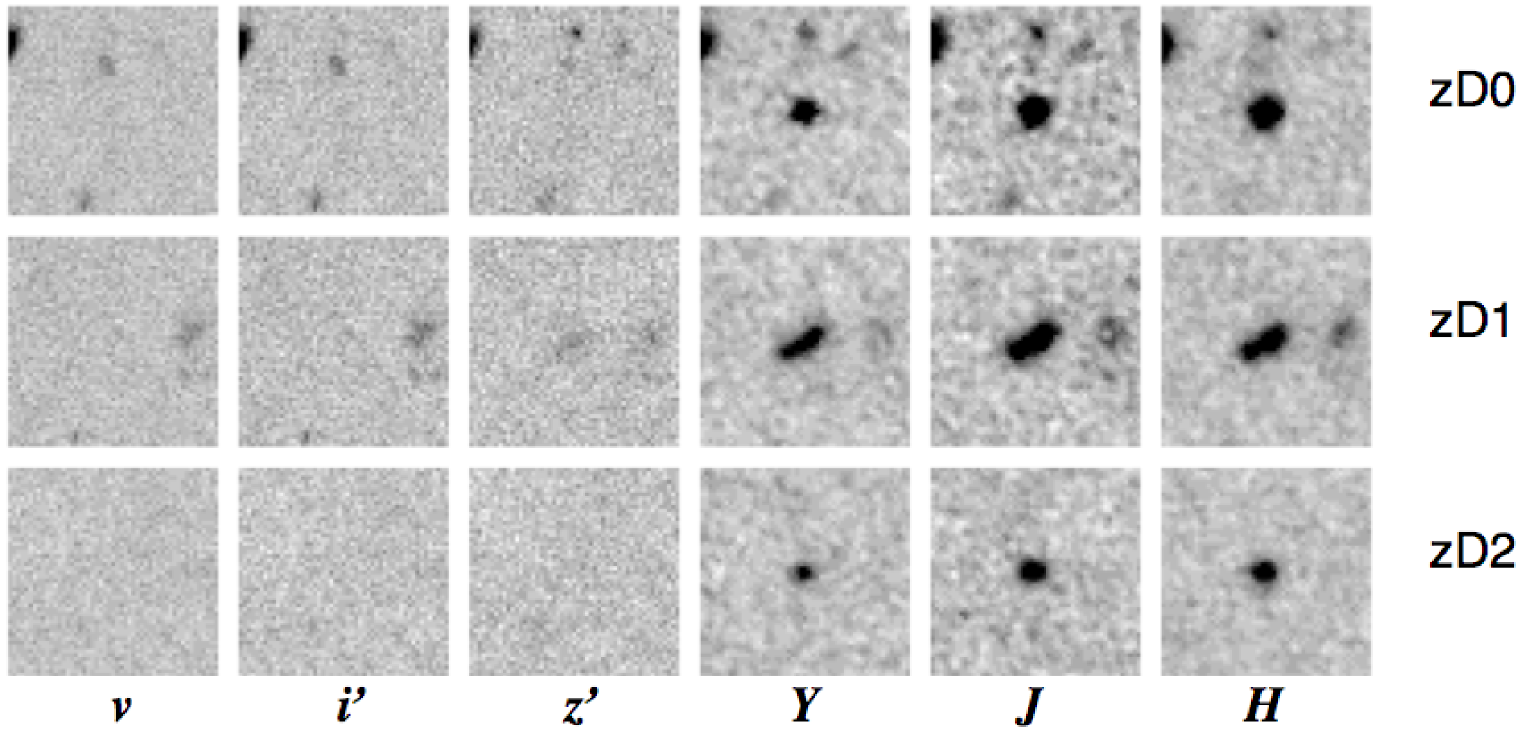


Candidate Star Forming Galaxy at z=7



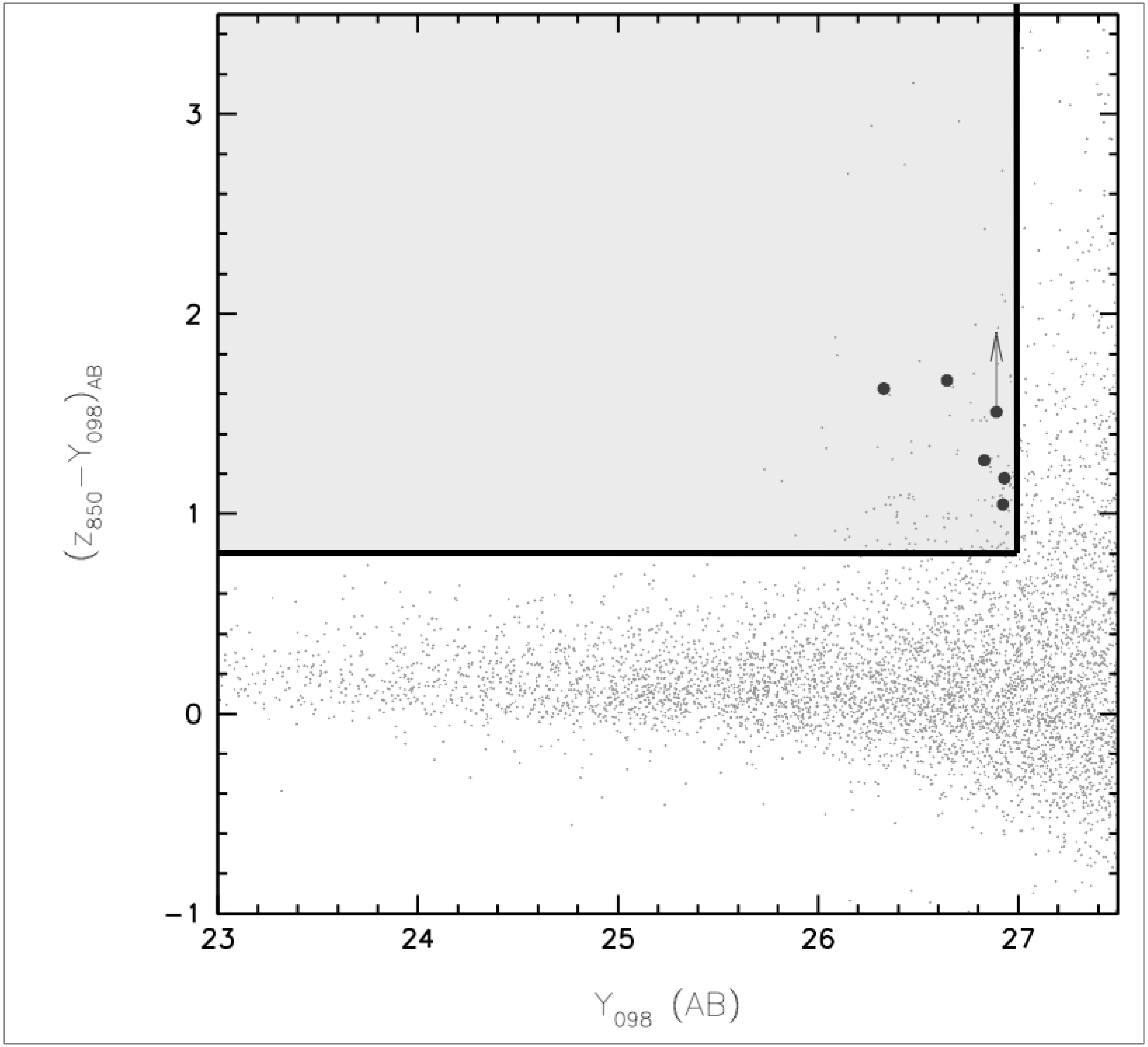
an ensemble of High-redshift Galaxies





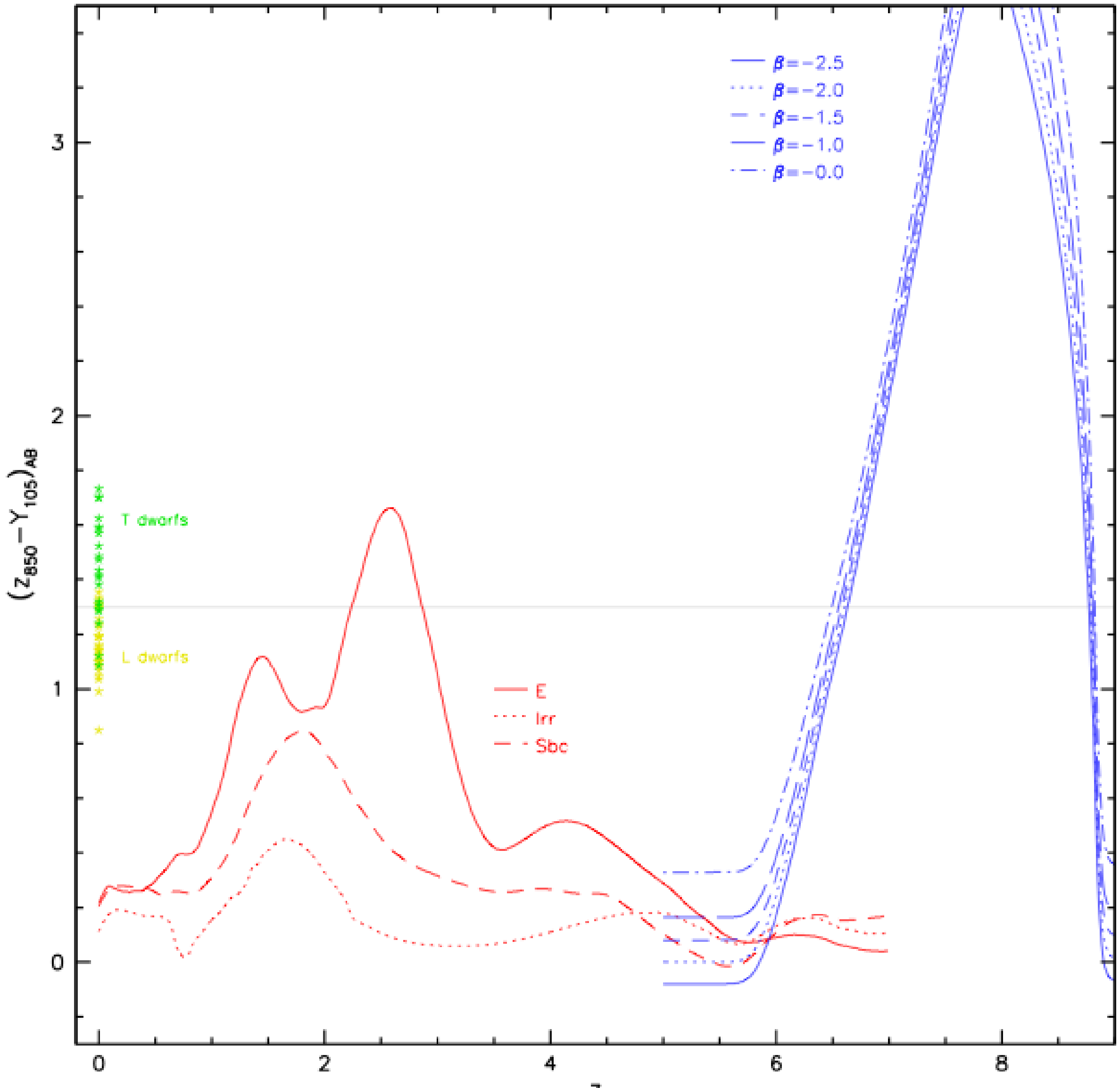
RECENT EXCITEMENT - 100 orbits of HST with WFC3 in 3 near-IR filters on Hubble Ultra Deep Field. Galaxies at z=7-9! Data first taken in August-Sept. 2009

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

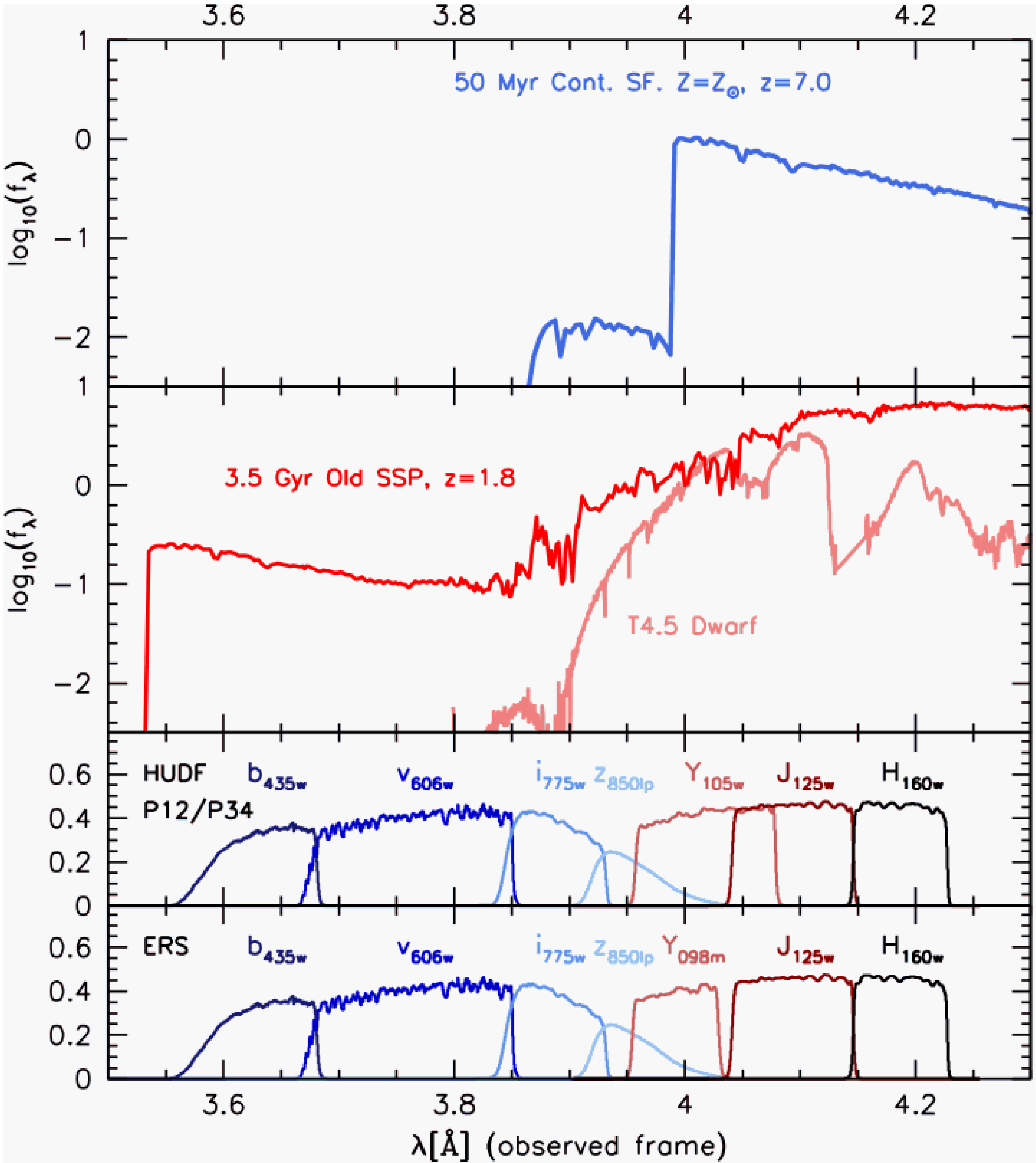


Wilkins et al. (2010): z-drop selection in ERS/GOODS

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

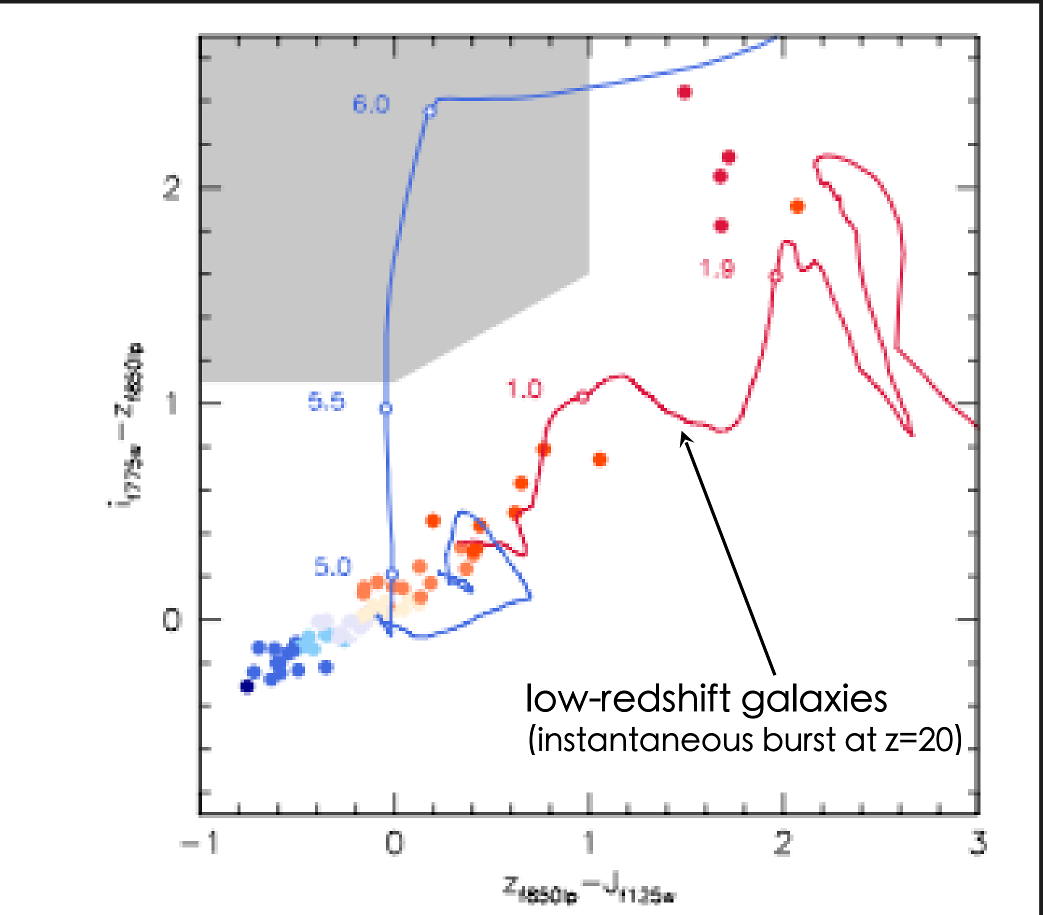


Pushing to z~>7 using WFC3 and z-drop colours (also Y-drops), Bunker et al. (2010)



50 Myr Cont. SF. Z=Z⊙, z=7.0
3.5 Gyr Old SSP, z=1.8
T4.5 Dwarf
HUDF
P12/P34
ERS
b_{435w}
v_{606w}
i_{775w}
z_{850lp}
Y_{105w}
Y_{098m}
J_{125w}
H_{160w}
$\log_{10}(f_\lambda)$
λ[Å] (observed frame)

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



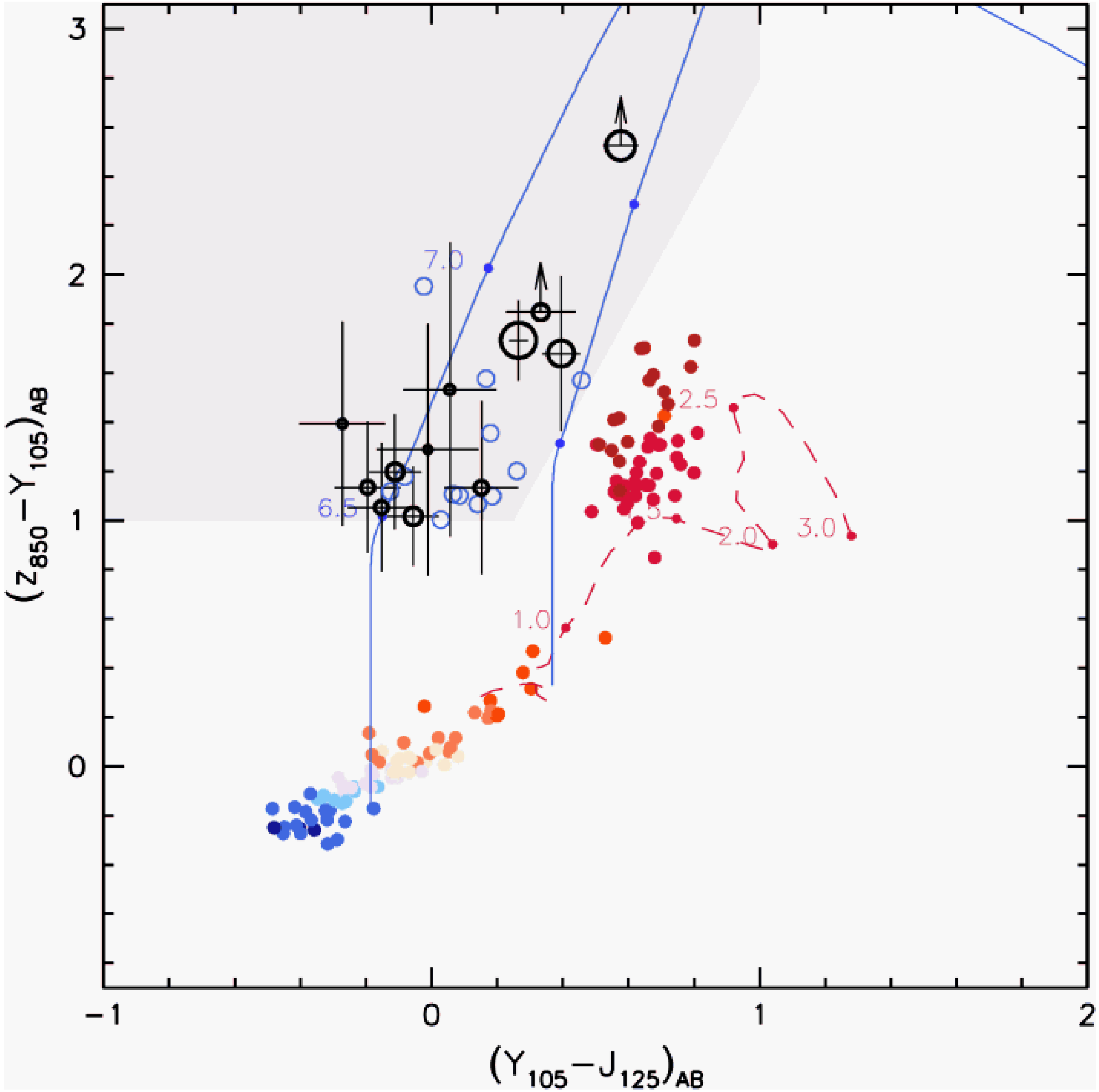
Stellar and low-redshift contamination can be reduced by using additional colour information - the redshift track of a high-redshift galaxy is distinct from lower-redshift and stellar contaminants.

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.

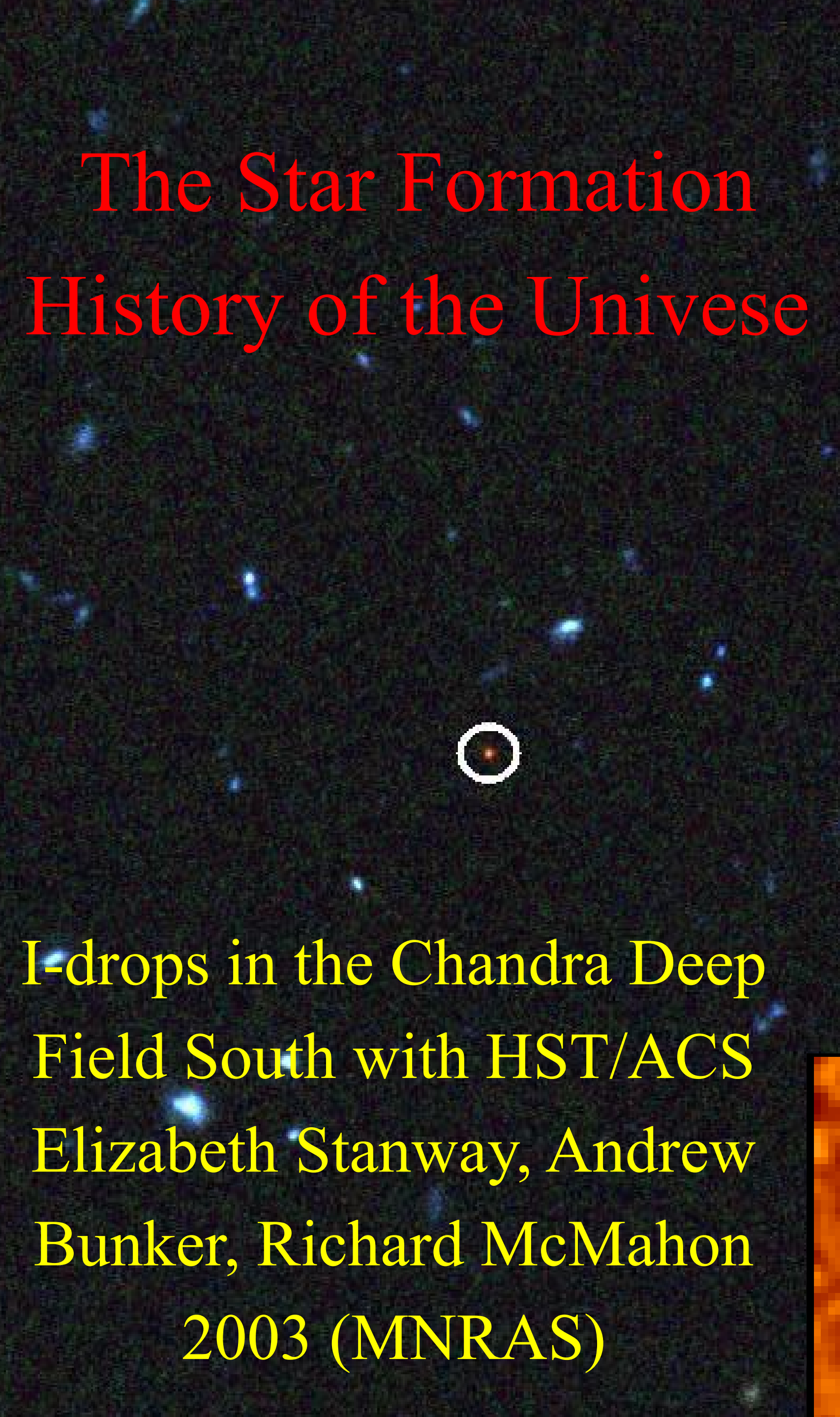
Recent results: Wilkins et al. (2011) MNRAS ArXiv: 1002.4866

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

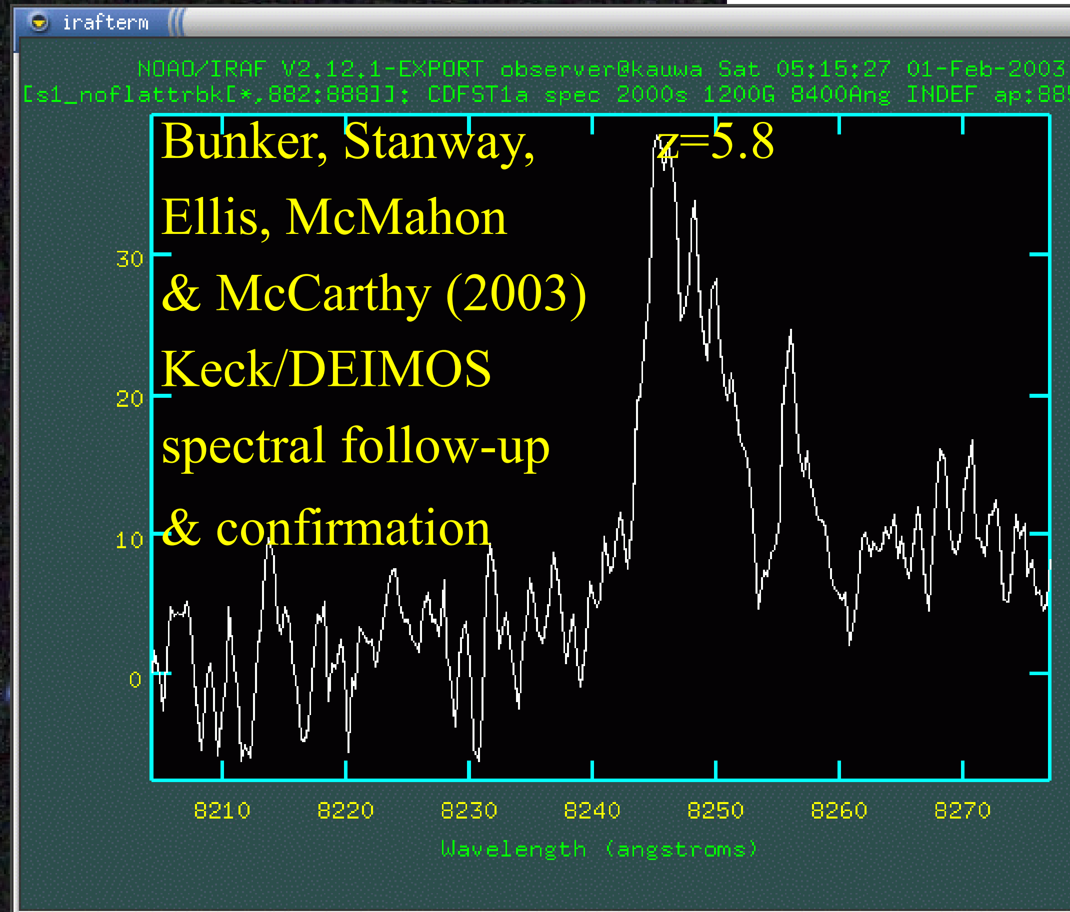


Gemini

The Star Formation History of the Univese

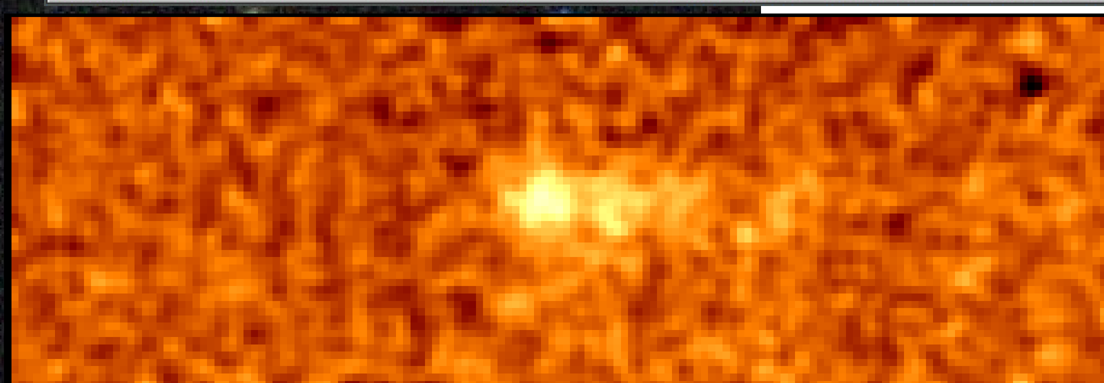


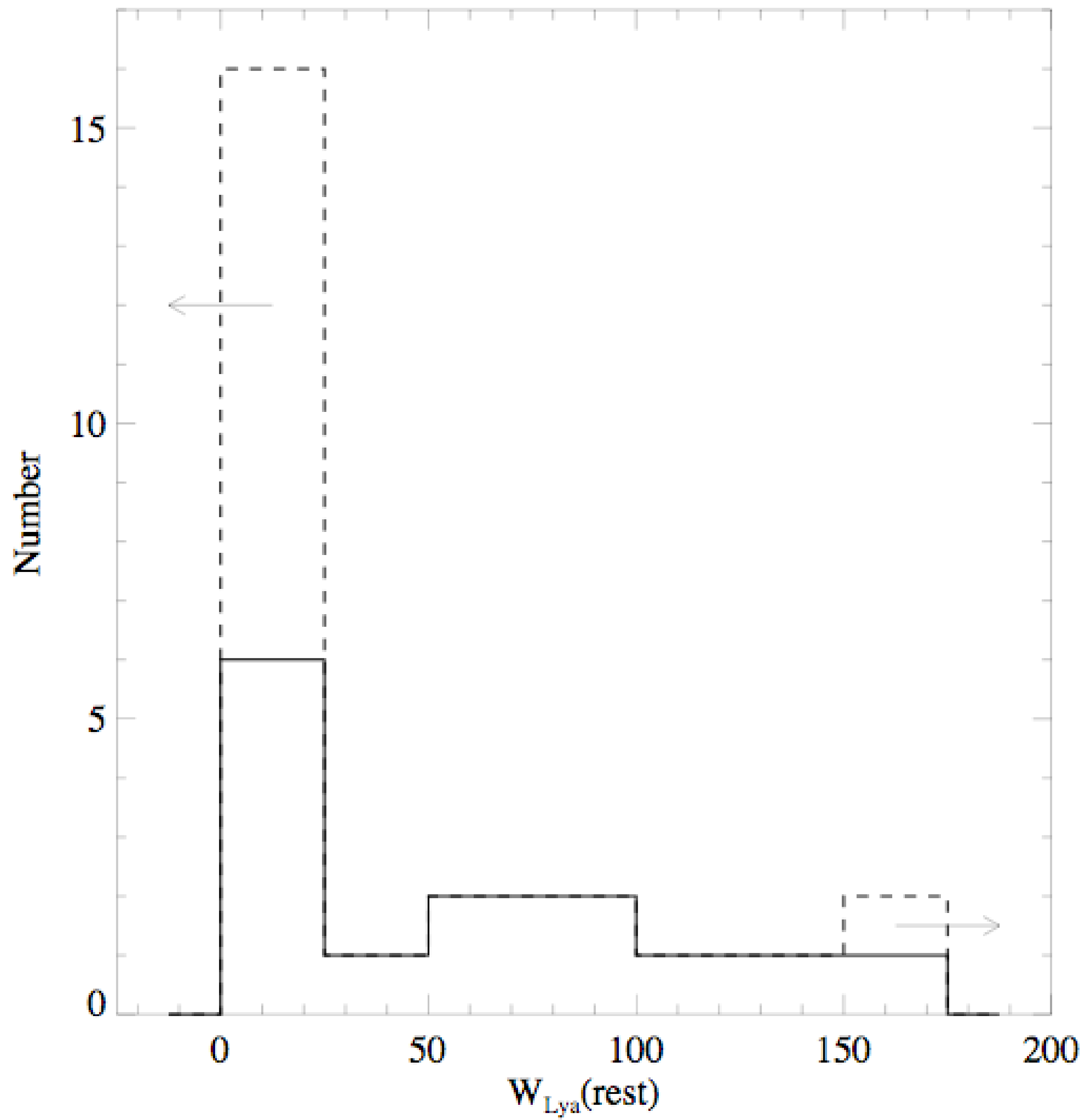
I-drops in the Chandra Deep Field South with HST/ACS Elizabeth Stanway, Andrew Bunker, Richard McMahon 2003 (MNRAS)



Bunker, Stanway, Ellis, McMahon & McCarthy (2003) Keck/DEIMOS spectral follow-up & confirmation

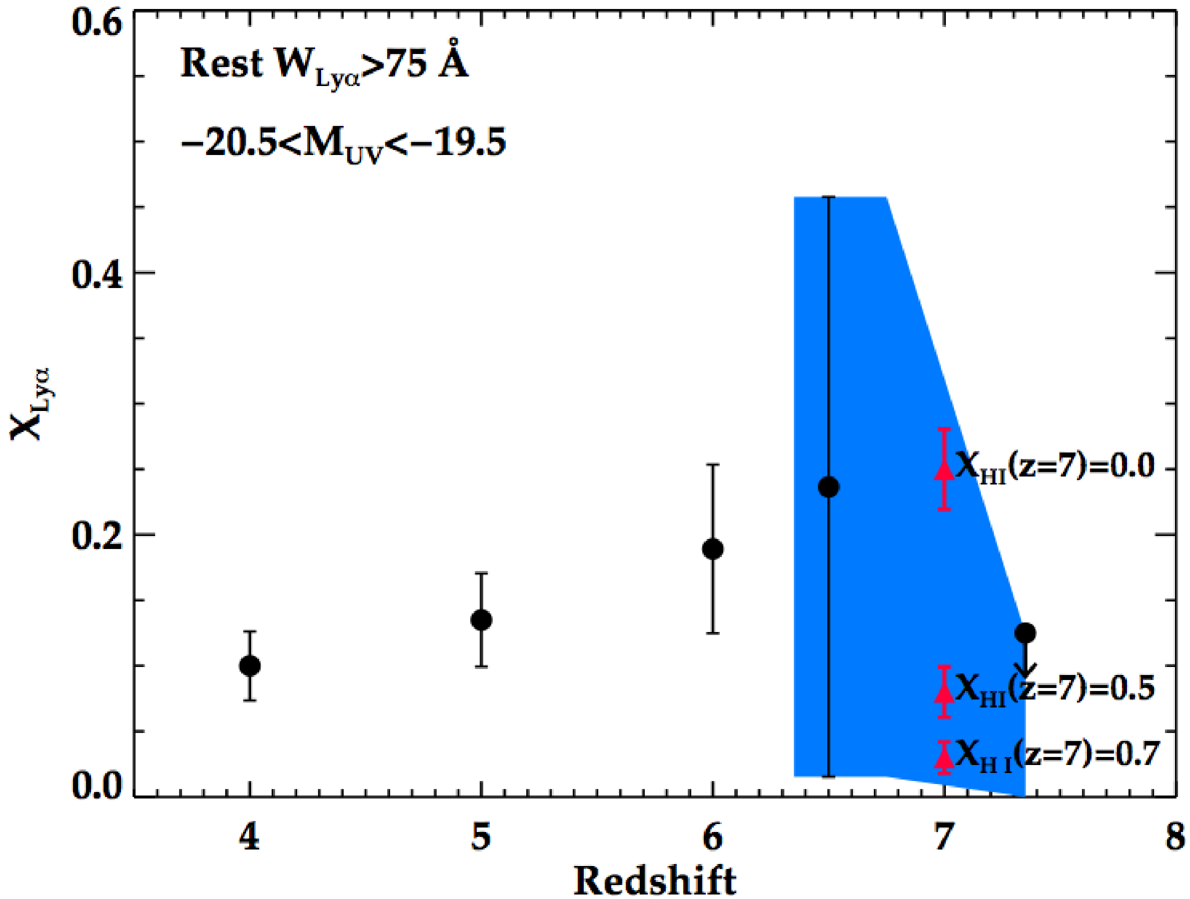
z=5.8





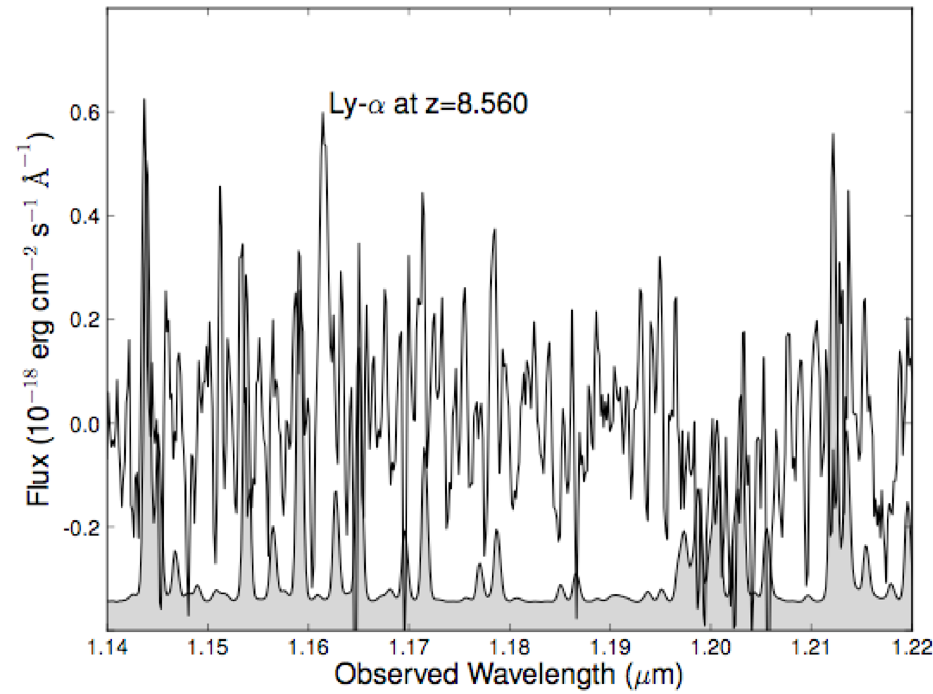
Number
0
5
10
15
0
50
100
150
200
W_Lya(rest)

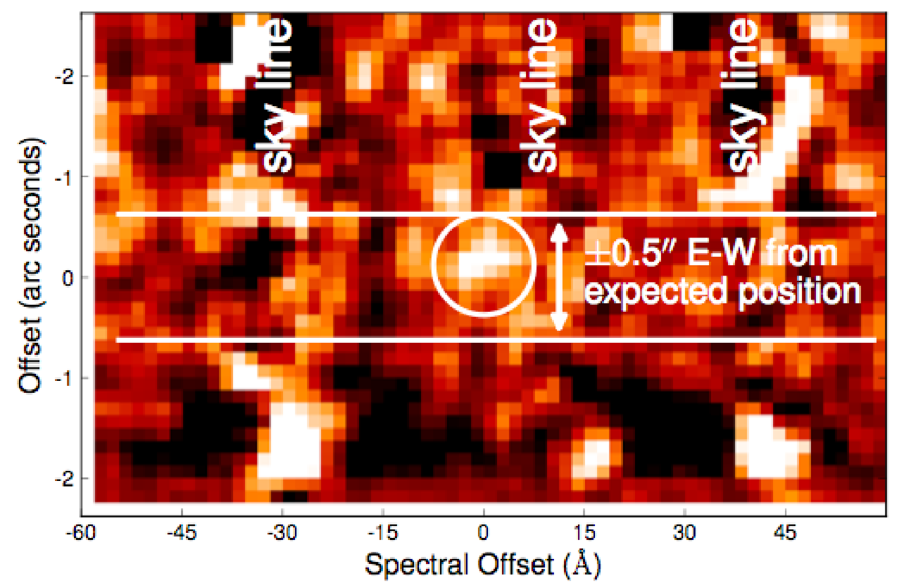
Ly-alpha fraction (Stark et al. 2010)

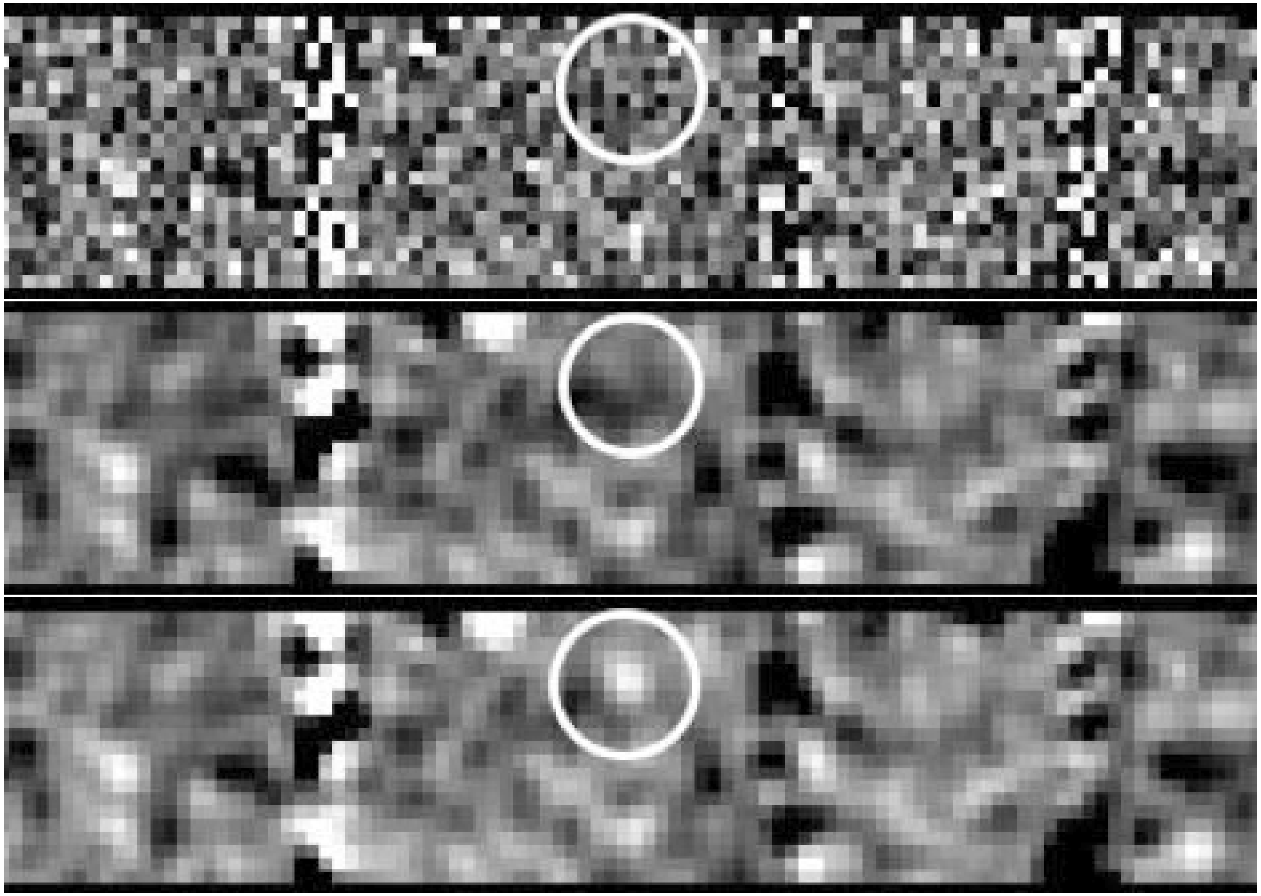


Brightest HUDF Y-drop
Found in Sept 2009.
YD3 in Bunker et al
UDFy-31835539 in
Bouwens et al.;
#1721 in McLure et al.

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

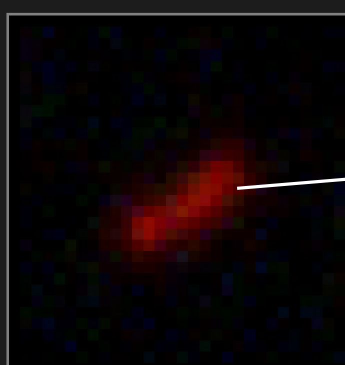
And 11-hour Subaru/MOIRCS spectrum.

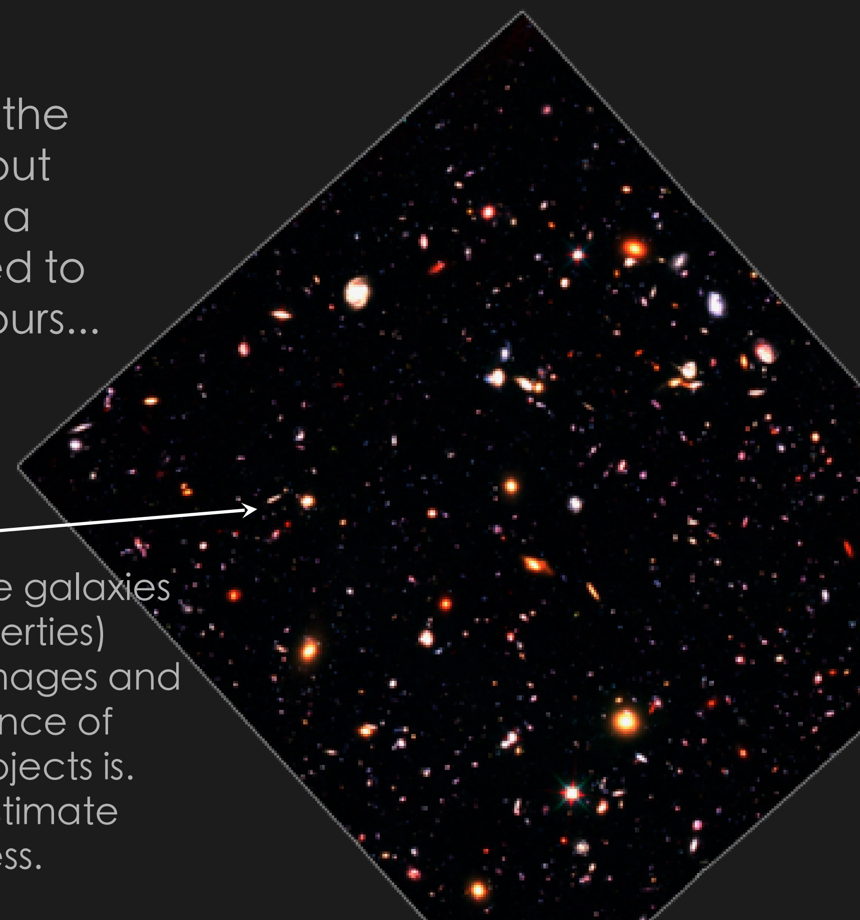
Also, the deep HST/WFC3 Y-band encompasses Ly-alpha, should be detected at ~4sigma but is undetected

What Can we Learn about High-redshift Galaxies: Number Counts / Surface Density

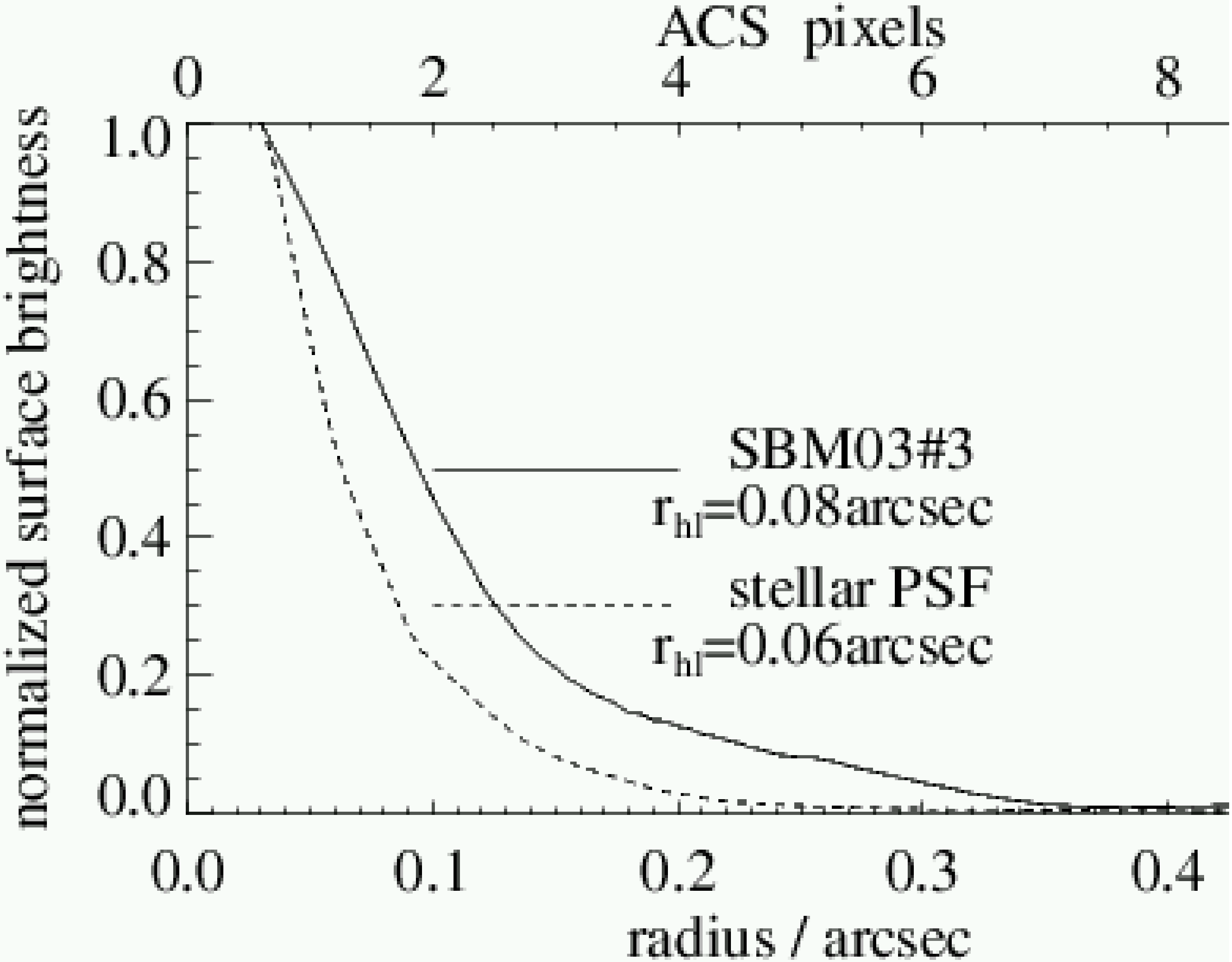
The simplest thing we can do is look at the observed distribution of rest-frame UV luminosities. However this isn't particularly useful - instead we really want the UV luminosity function (LF).

To get this we need to measure something like the effective volume, to get this we need to work out what the probability of selecting a galaxy with a given intrinsic M, and z is. But to get this we need to know the distribution of morphologies and colours...



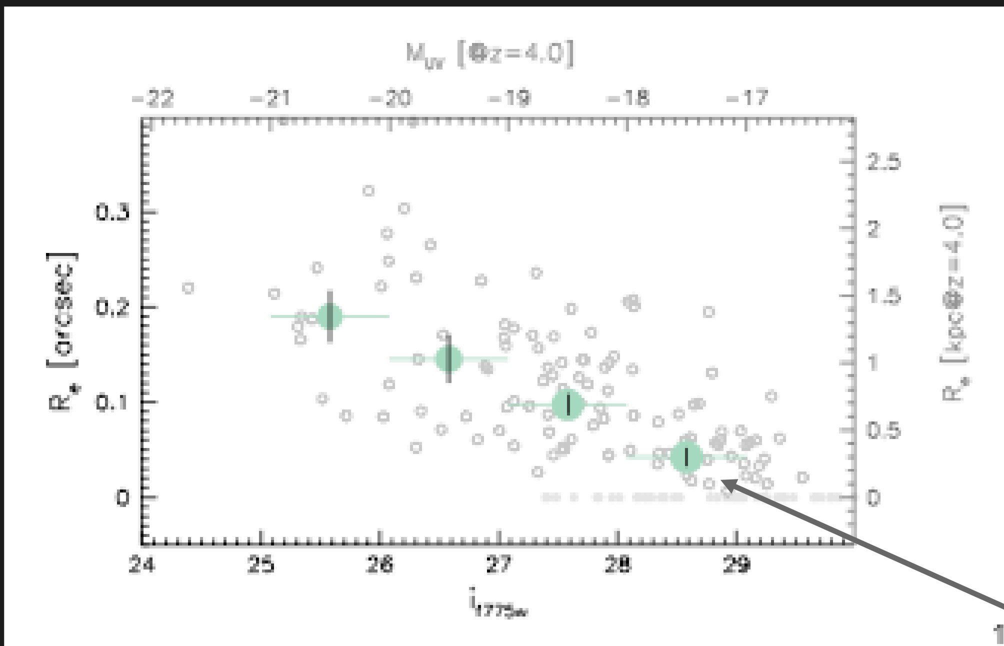


We can insert fake galaxies (with various properties) into the original images and test what the chance of selecting those objects is. This allows us to estimate the incompleteness.

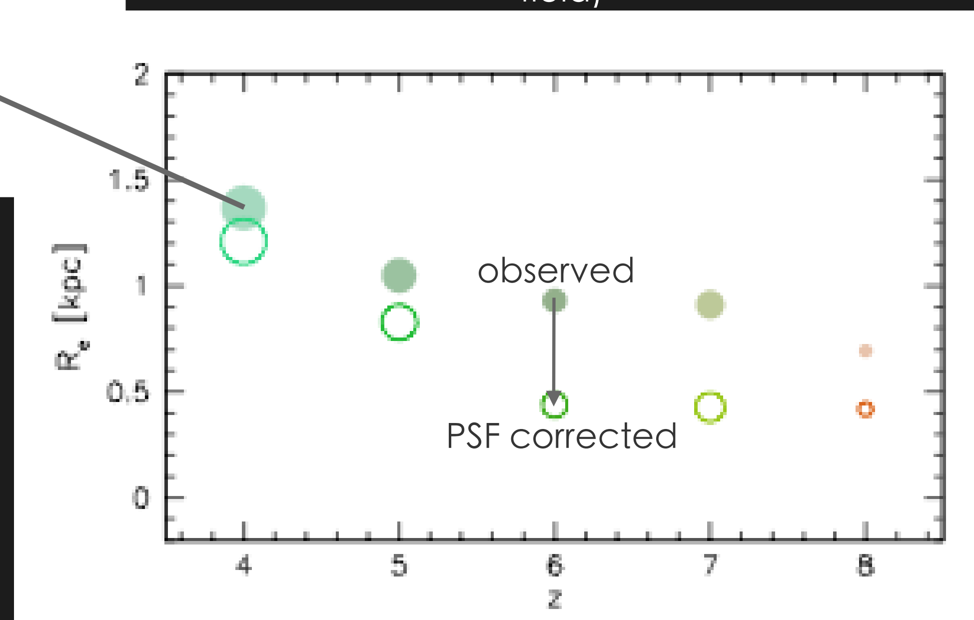

ACS pixels
0
2
4
6
8
1.0
0.8
0.6
0.4
0.2
0.0
normalized surface brightness
SBM03#3
r$_{hl}$=0.08arcsec
stellar PSF
r$_{hl}$=0.06arcsec
0.0
0.1
0.2
0.3
0.4
radius / arcsec

What Can we Learn about High-redshift Galaxies: Morphologies

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



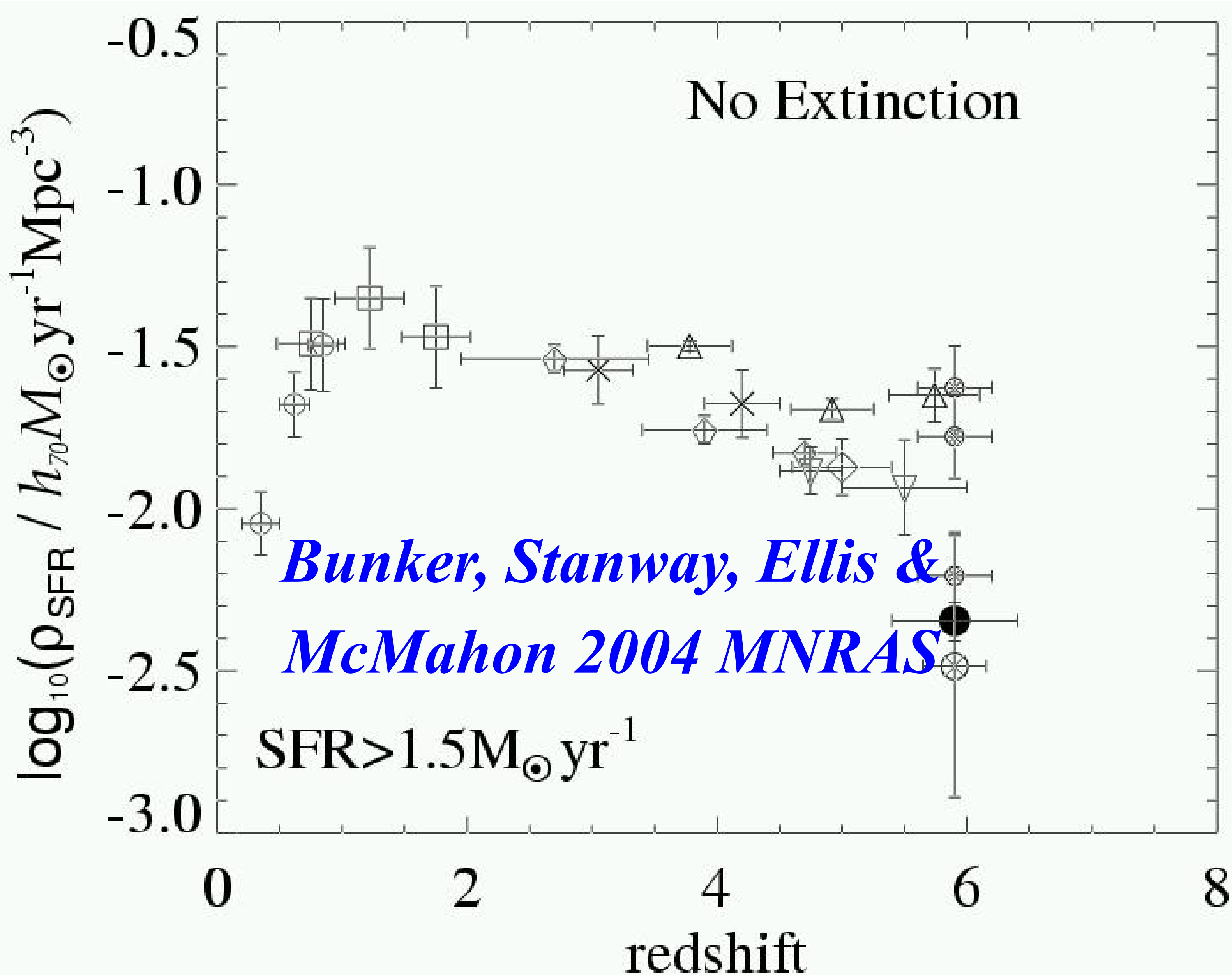
size evolution (only HUDF field)



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.

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



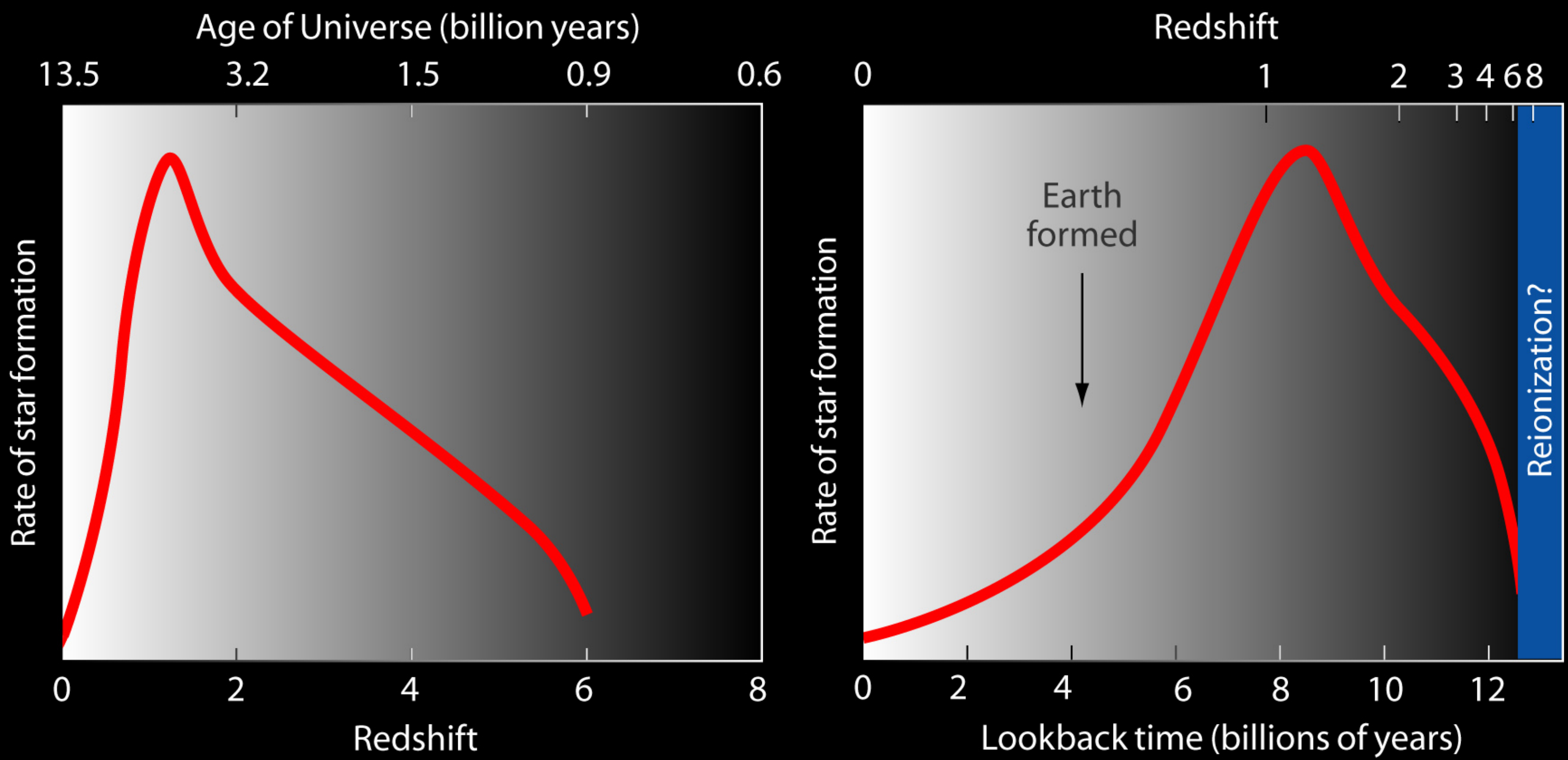
Bunker, Stanway, Ellis & McMahon 2004 MNRAS

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***.

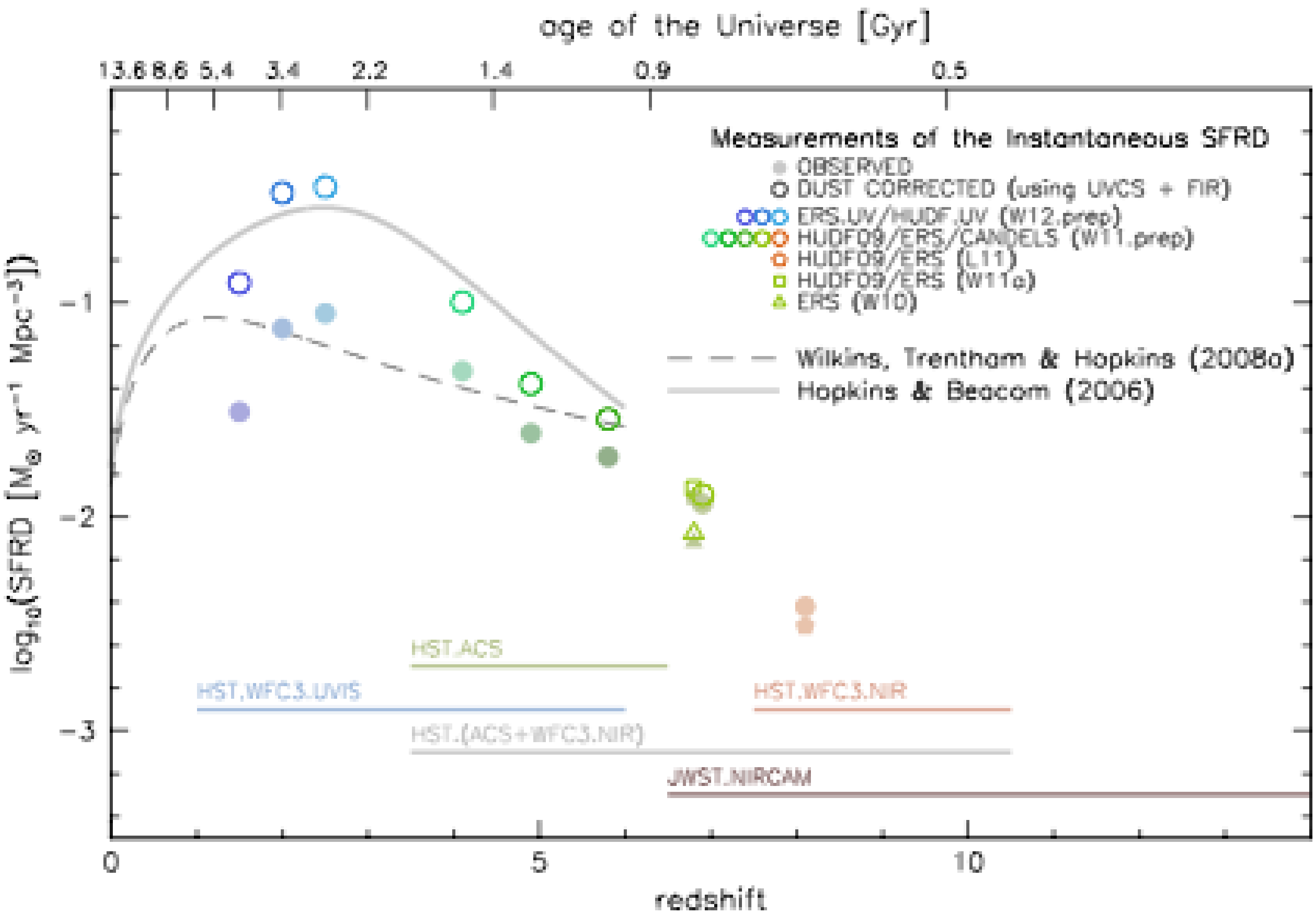
Star formation history of the Universe



- ***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***

What Can we Learn about High-redshift Galaxies:

➟ star formation rate density ➟ cosmic star formation history



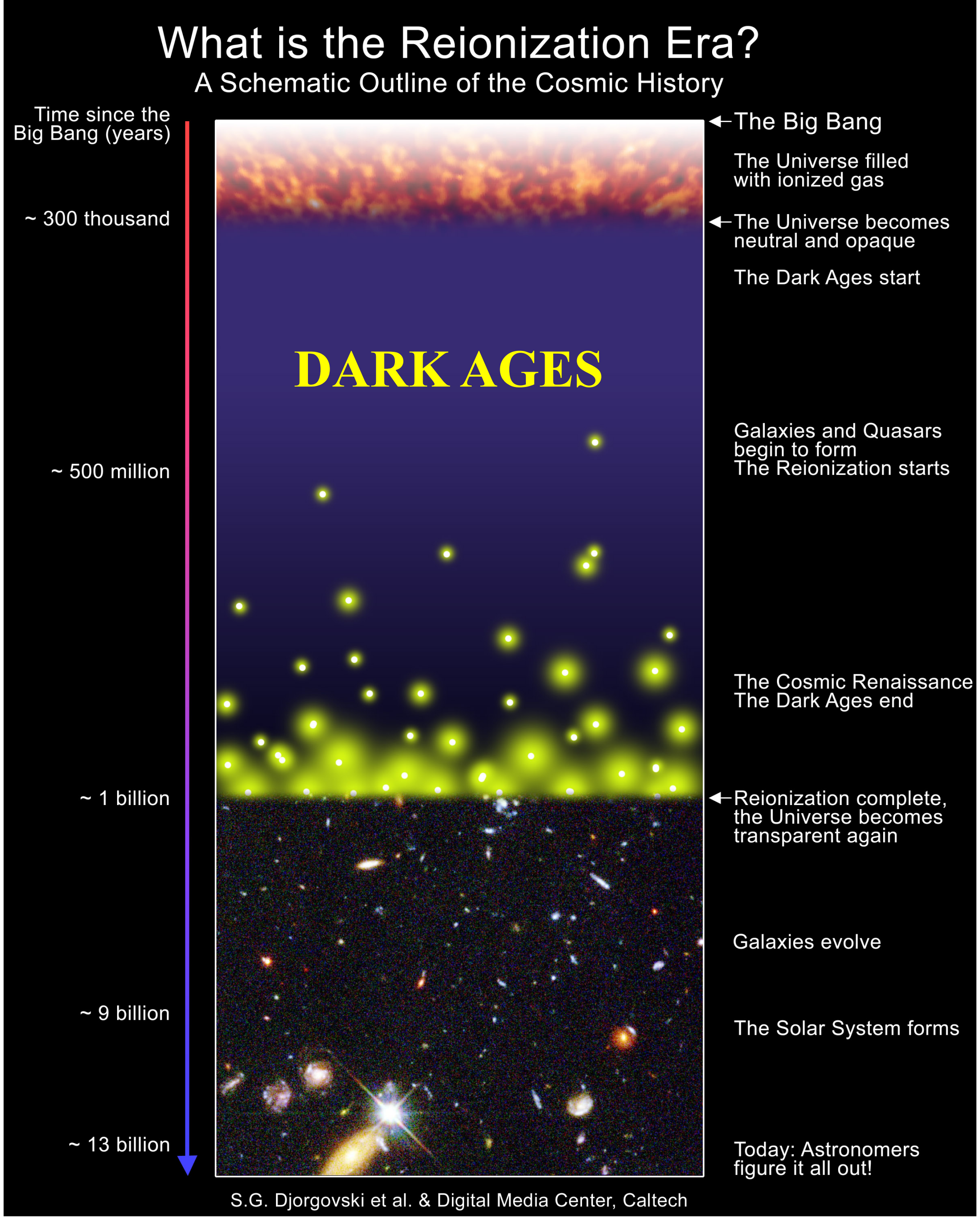
The (mostly) UV inferred Cosmic Star Formation History

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?



Redshift z

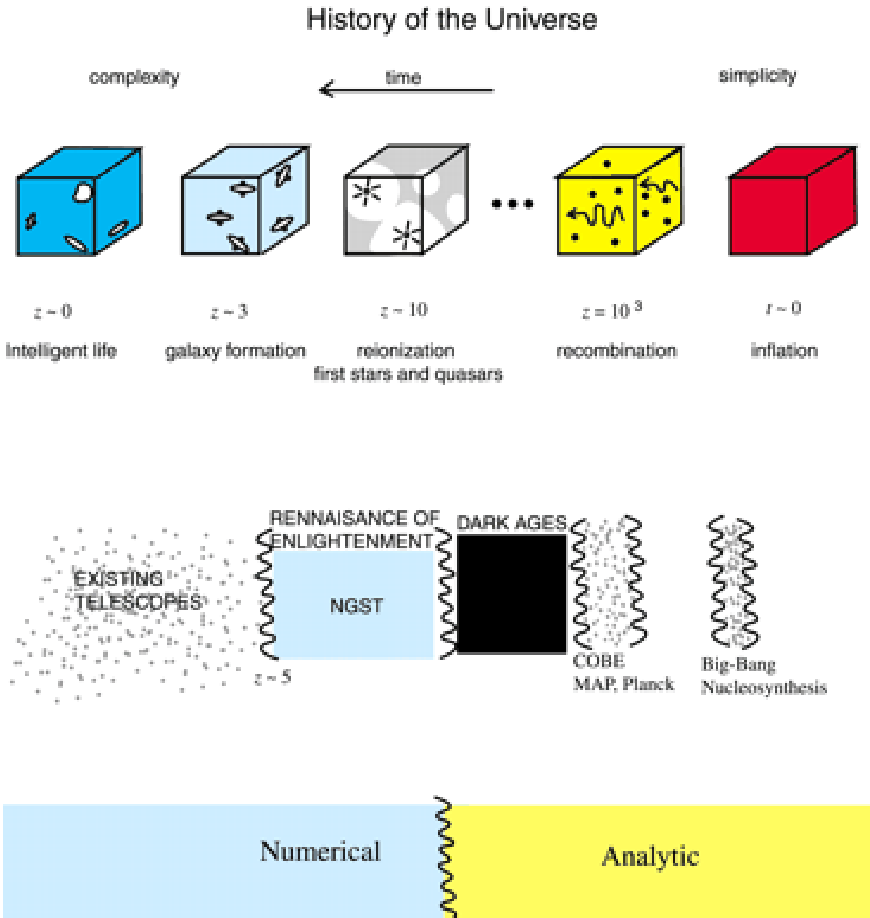
1100

10

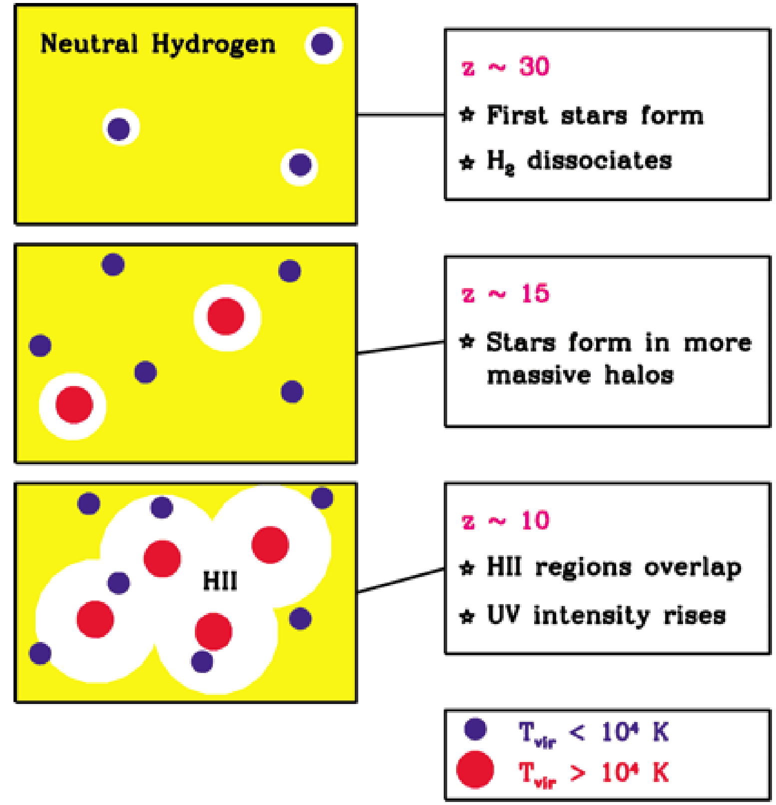
5

2

0

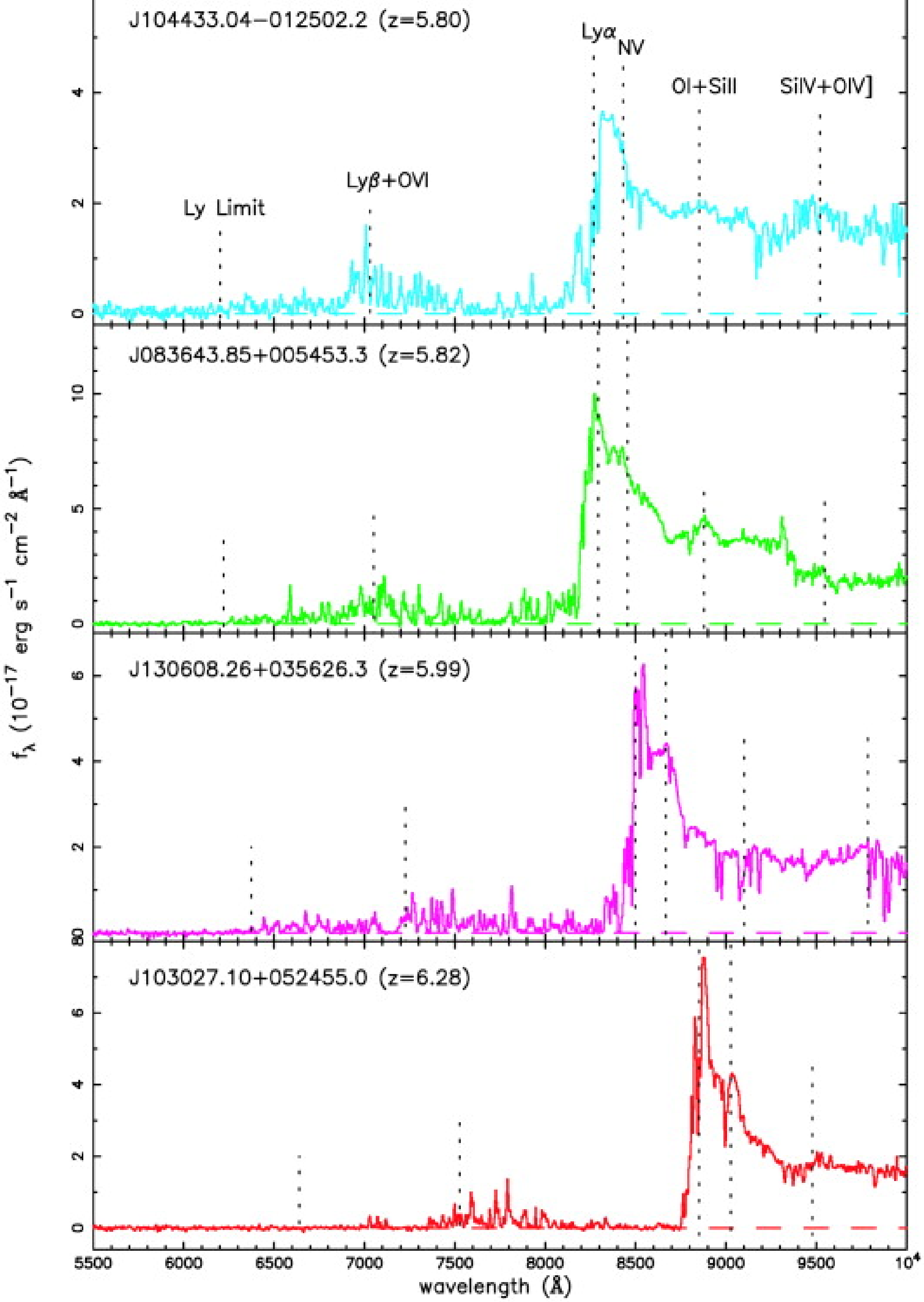


Reionization



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 messages 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)

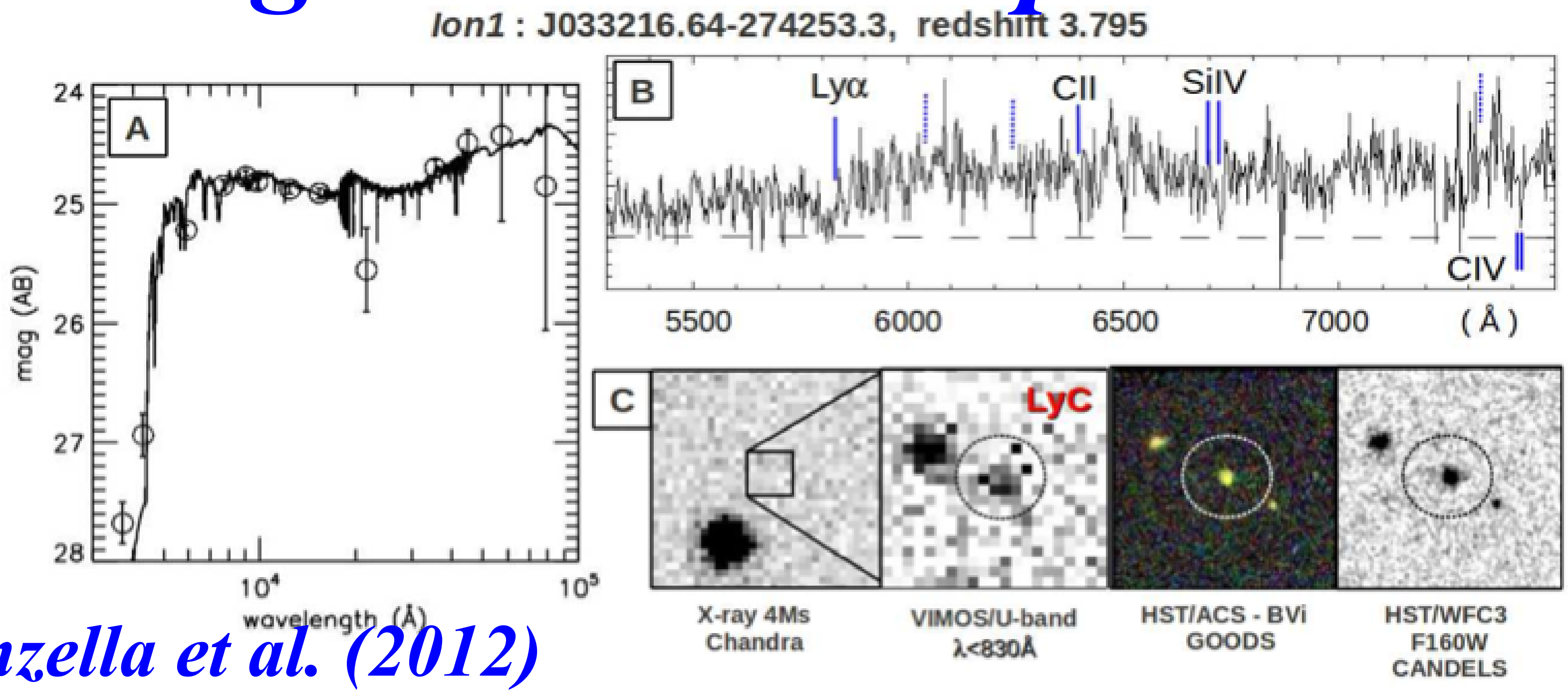
Our HUDF data has star formation at z=6 which is 3x *less* than that required! AGN cannot do the job.

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?)

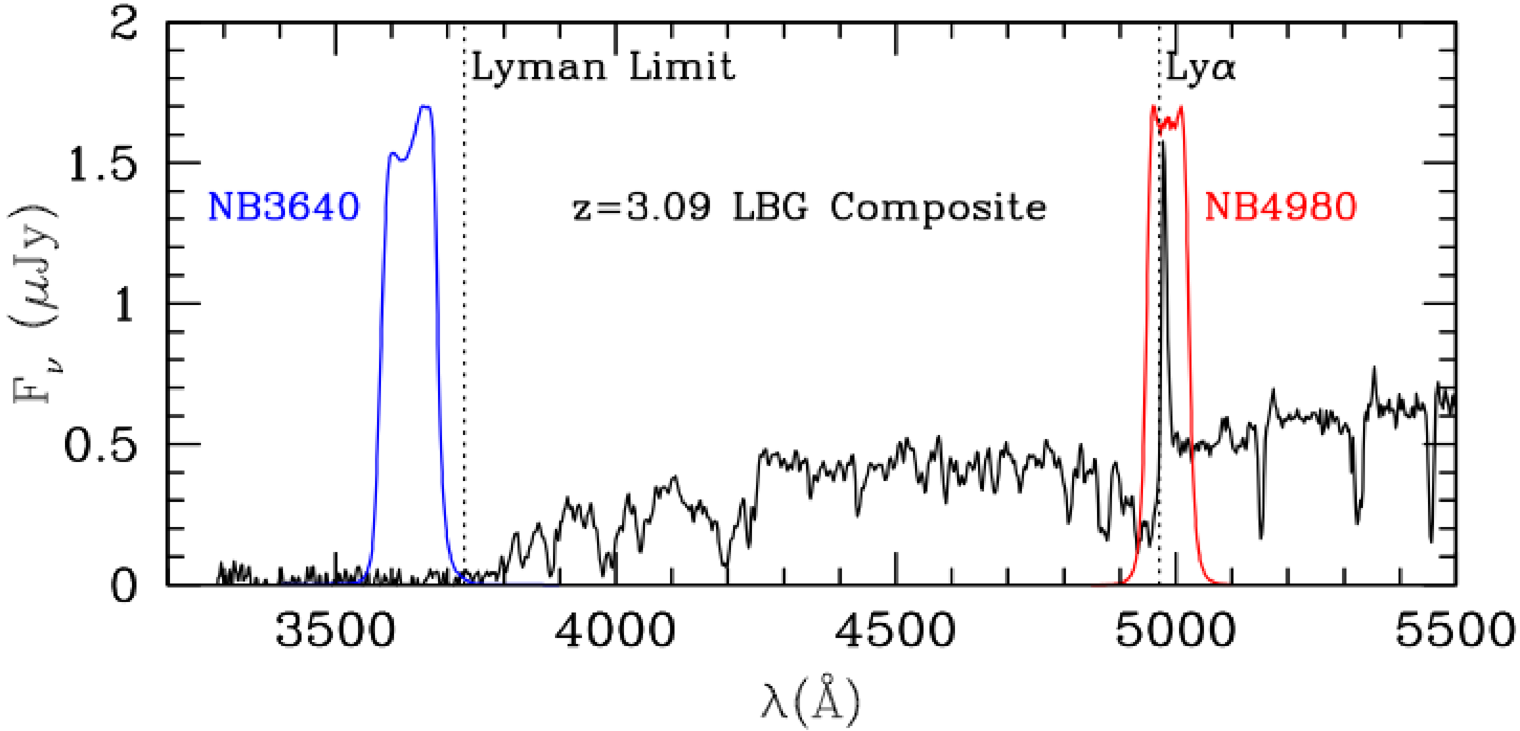
Ionizing Photon Escape Fraction



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)

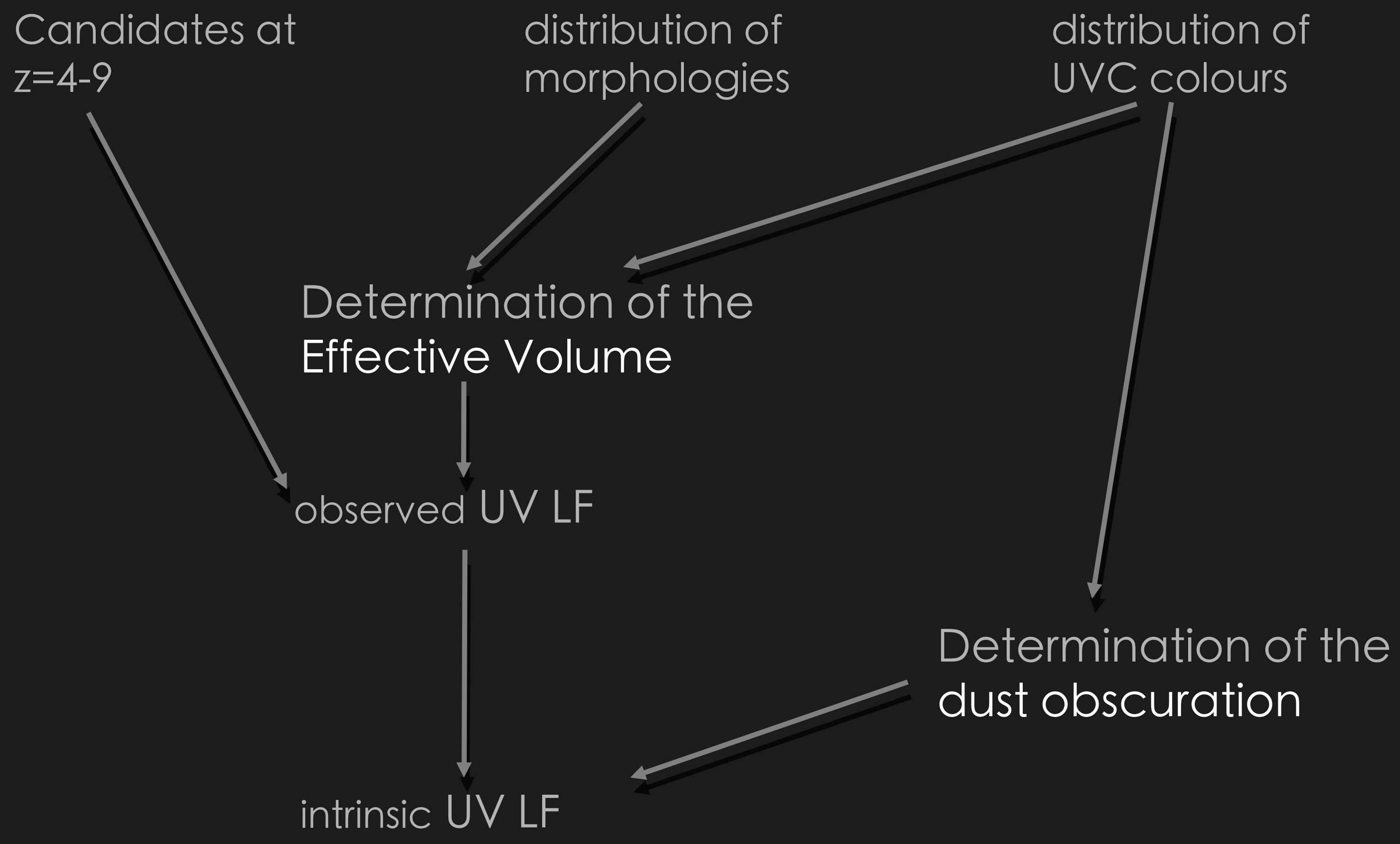
Indications are at z~3 that escape fraction is very small (Vanzella et al. 2012, Nestor et al. 2011, Siana et al. 2007, Shapley et al. 2006, Iwata et al. 2008)



(Nestor et al. 2011)

What Can we Learn about High-redshift Galaxies:

observed UV Luminosity Function ➟ intrinsic UV Luminosity function



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):

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

L^* and $\phi_\star$ are the characteristic luminosity and number density at the "knee" or break of the luminosity function.

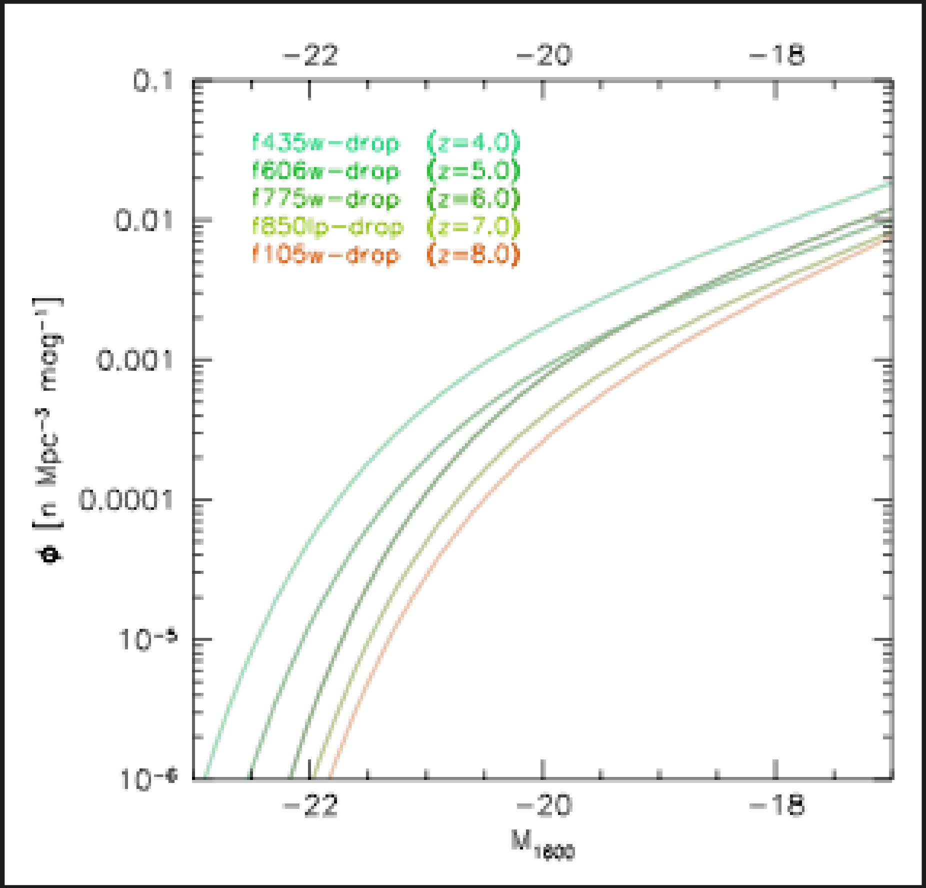
What Can we Learn about High-redshift Galaxies:

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).

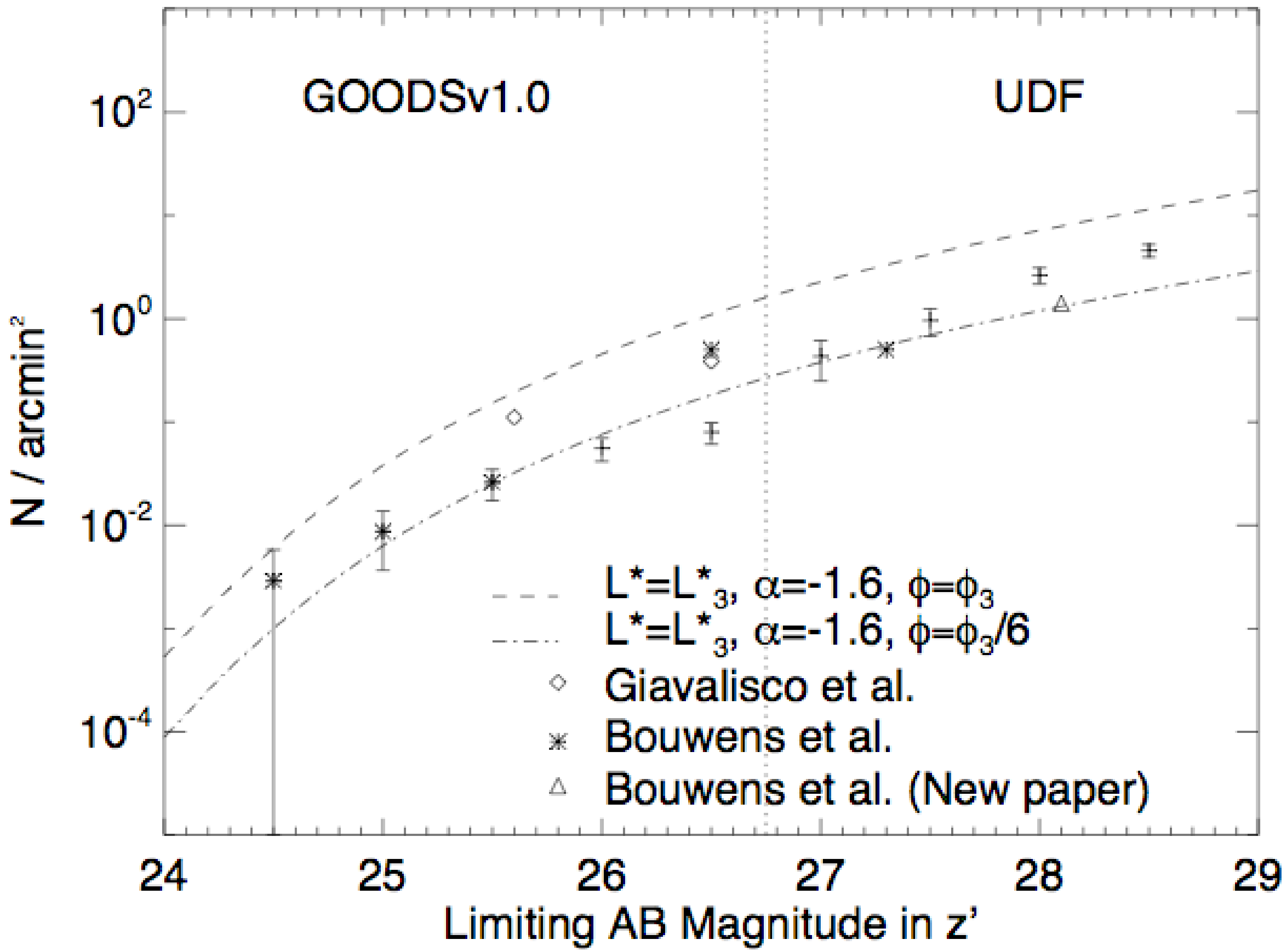
The LF evolves!

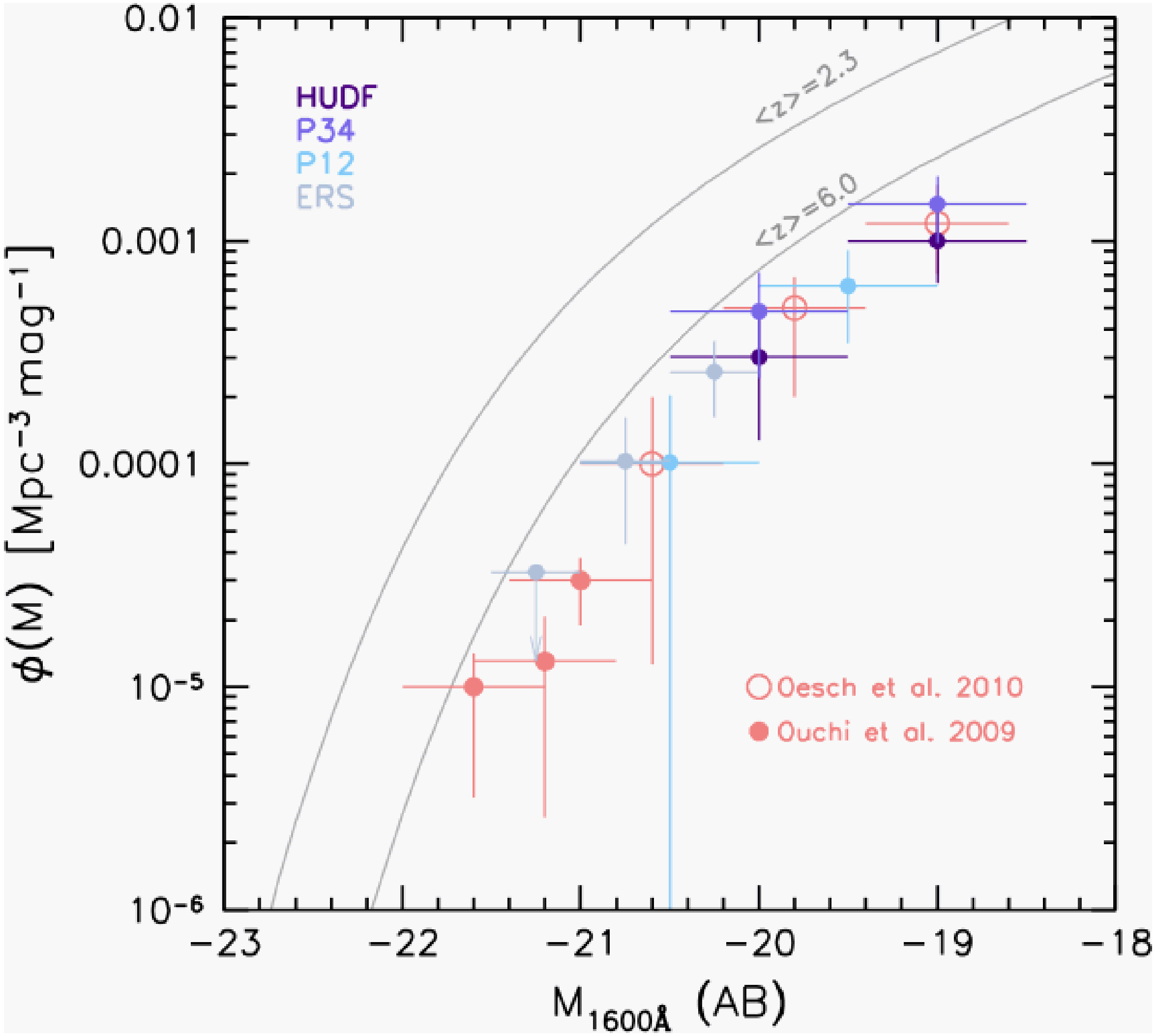
Evolution of the UV LF:
Wilkins+11a, Wilkins+12d
see also: Bouwens+11(6,7,8,9,10), Oesch+10b



Observed UV LFs at various redshifts

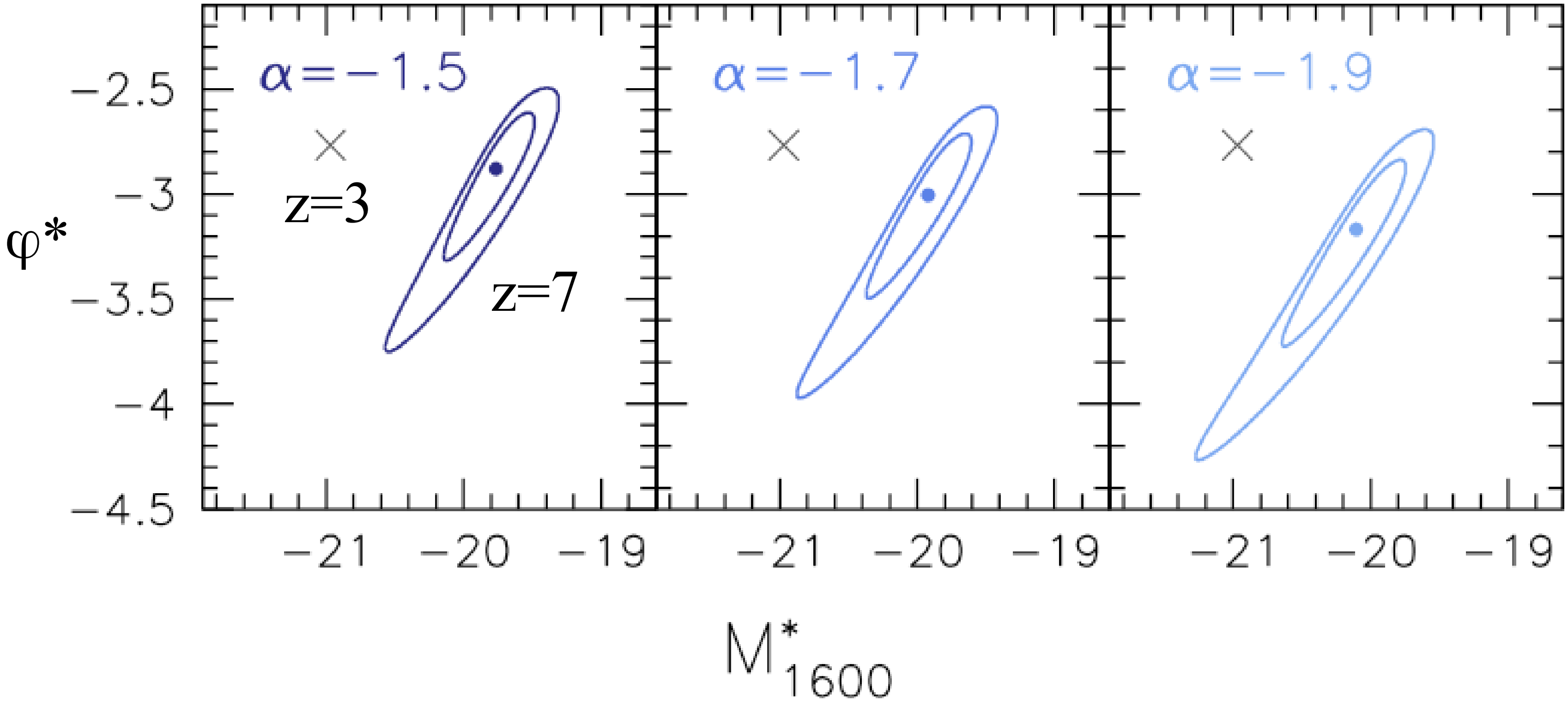
Steep faint end slope at z=6, α= -1.8 (at z=3, α= -1.6 and z=1, α=-1.3





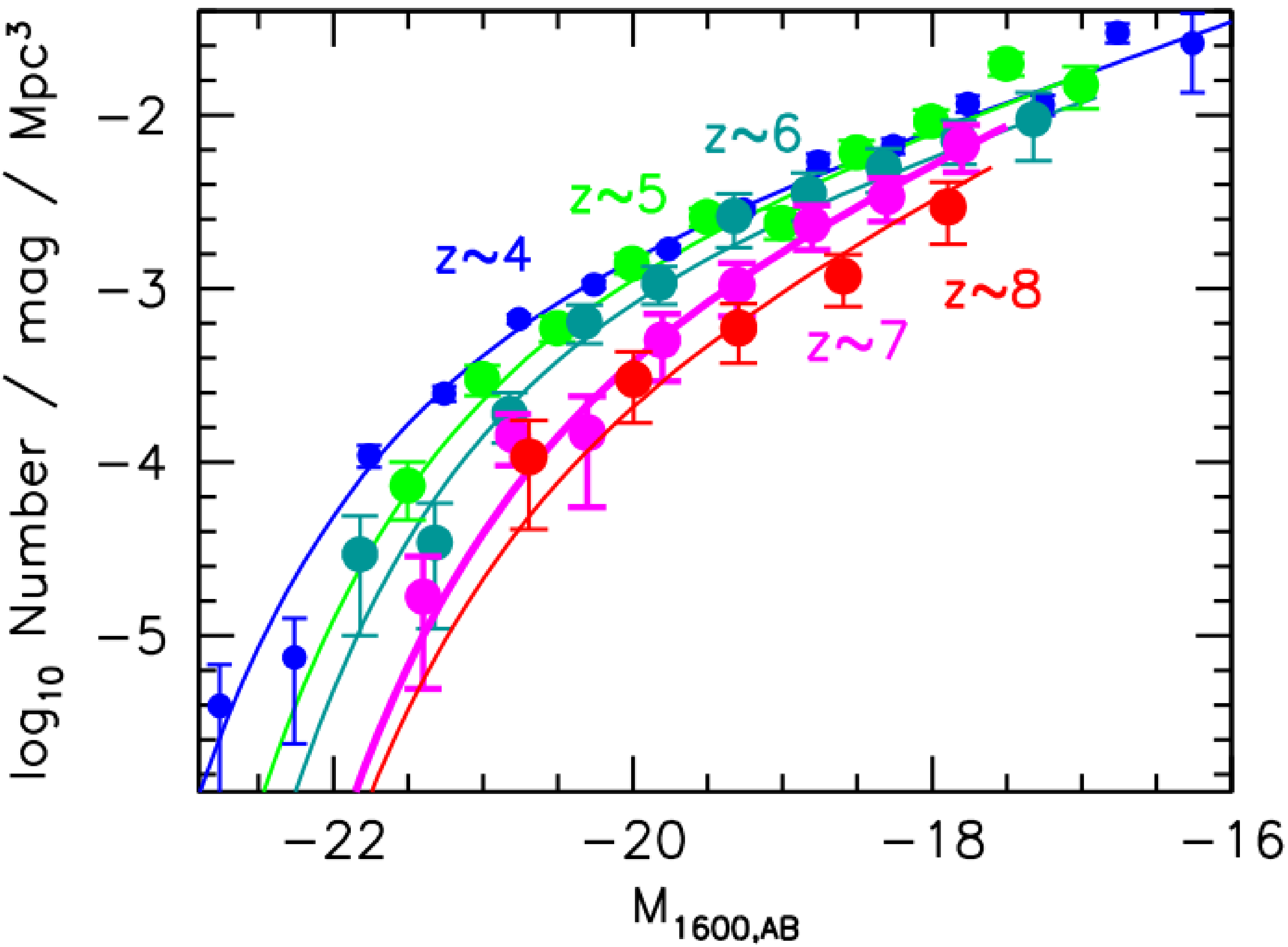
Wilkins et al. (2010) MNRAS The Luminosity Function at z~7

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



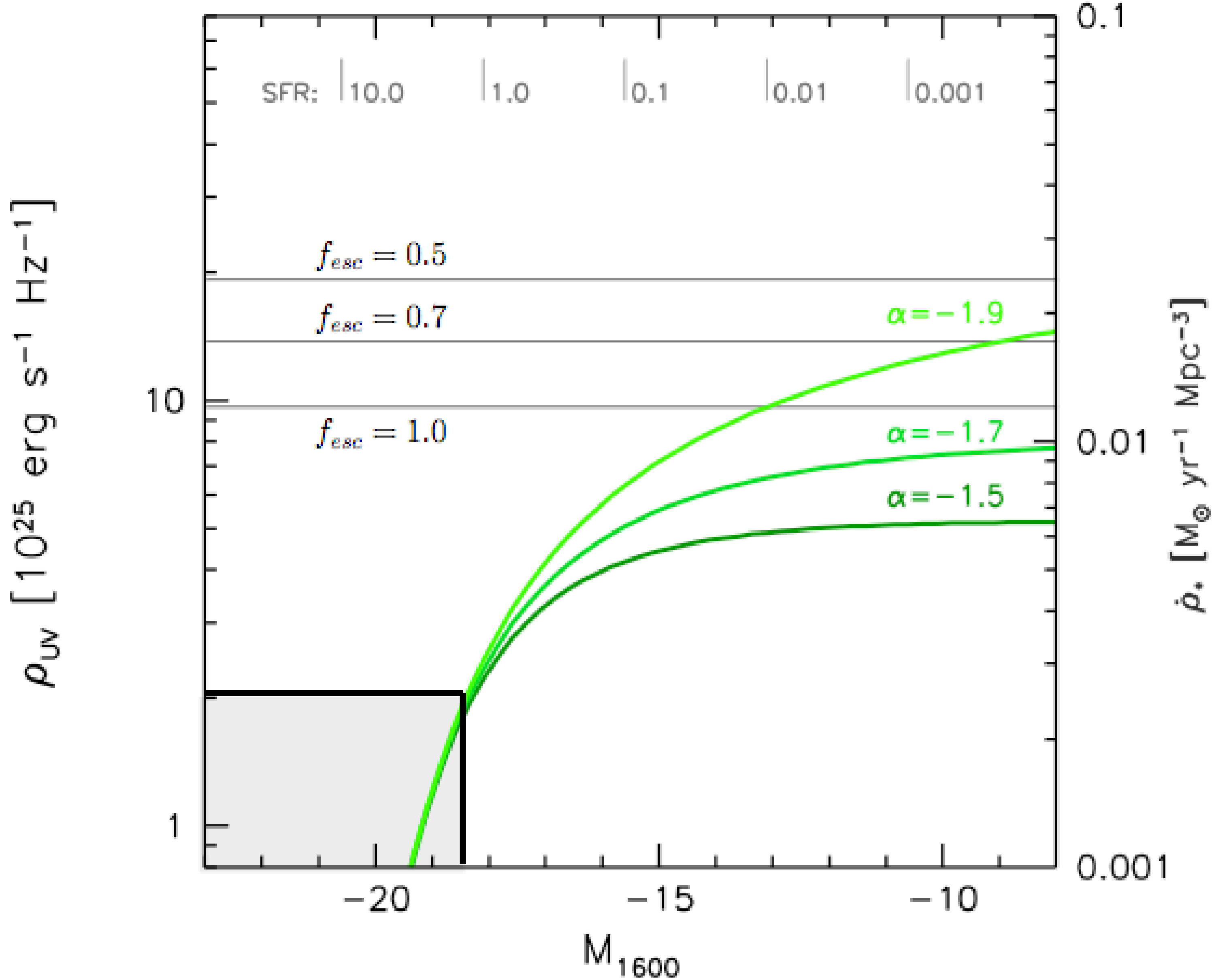
Evolution of luminosity function
(note M* is correlated with φ*)

Wilkins et al. (2011)

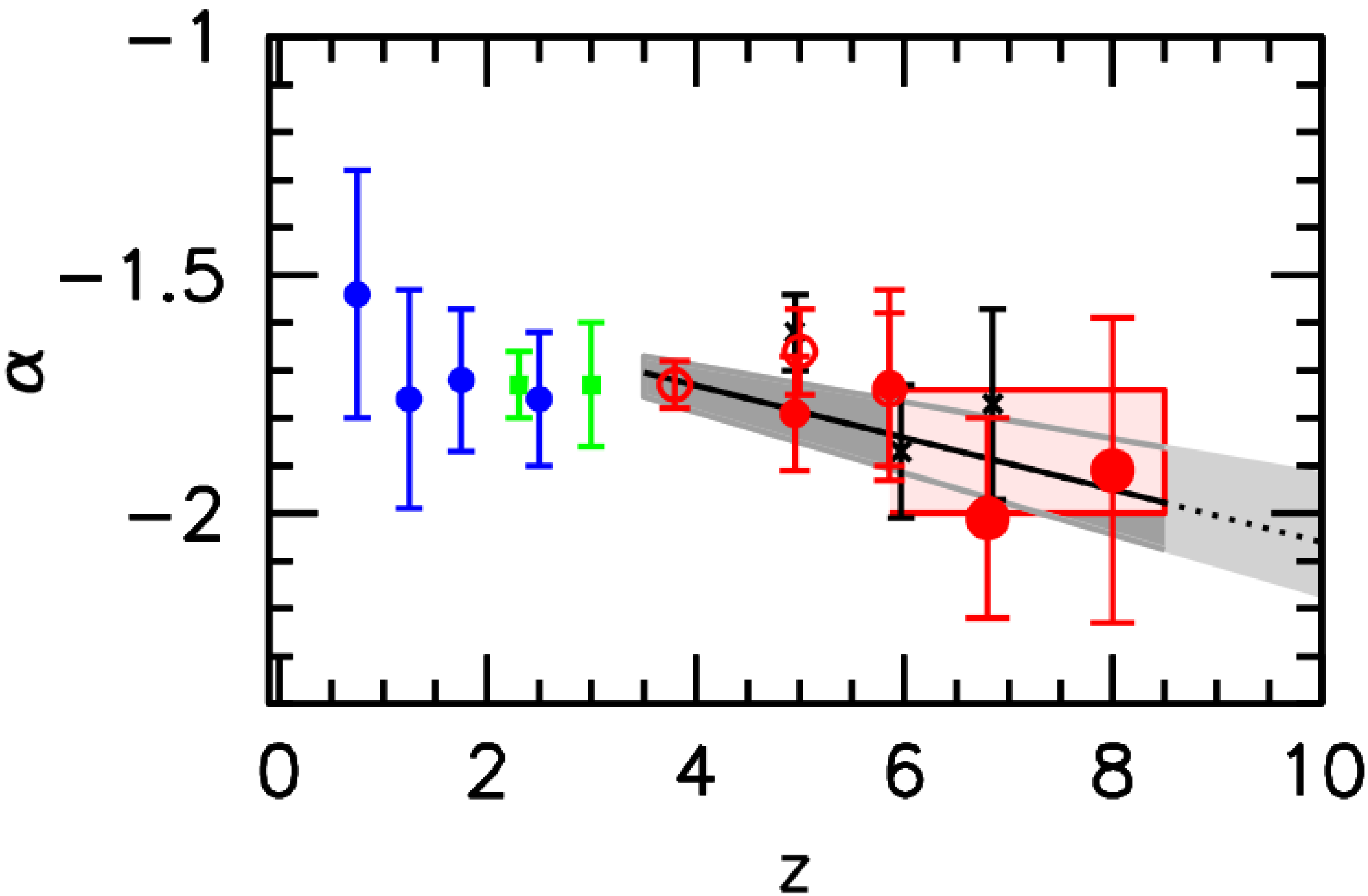


Evolution of the restframe UV luminosity function

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?

Ways out of the Puzzle

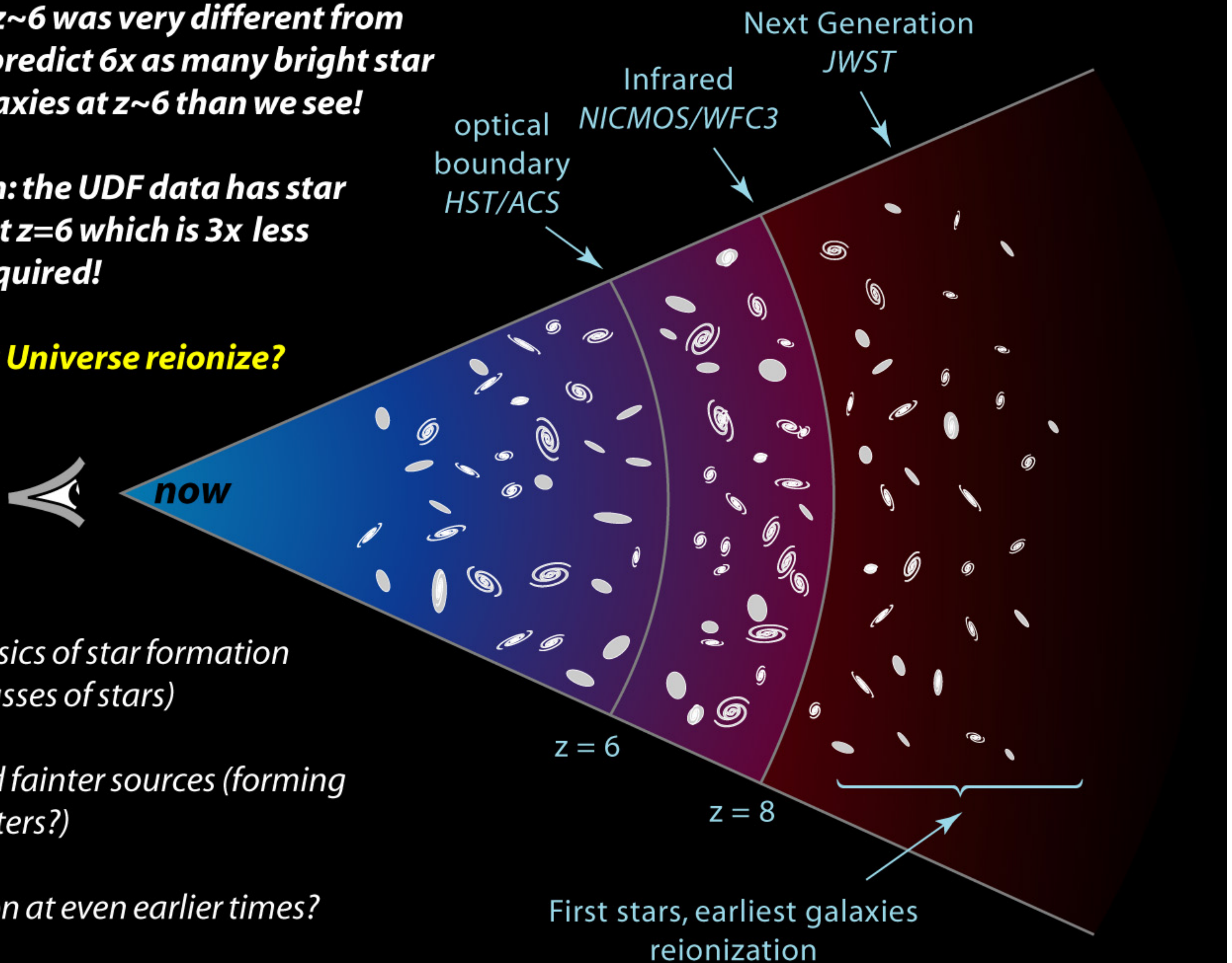
- Cosmic variance
- Star formation at even earlier epochs to reionize Universe (z>>6)?
- Change the physics: different recipe for star formation (Initial mass function)?
- Even fainter galaxies than we can reach with the UDF?

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?

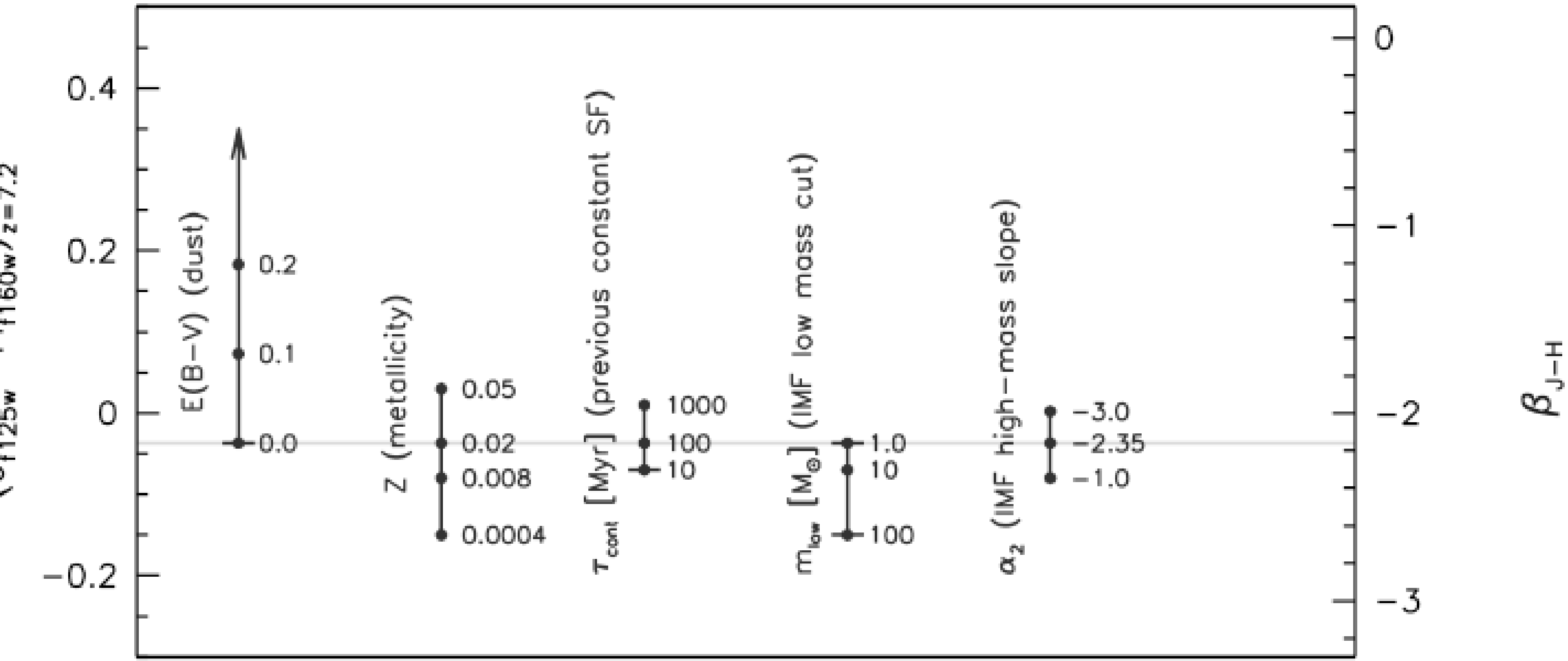


- *Different physics of star formation early on? (masses of stars)*

- *Undiscovered fainter sources (forming globular clusters?)*

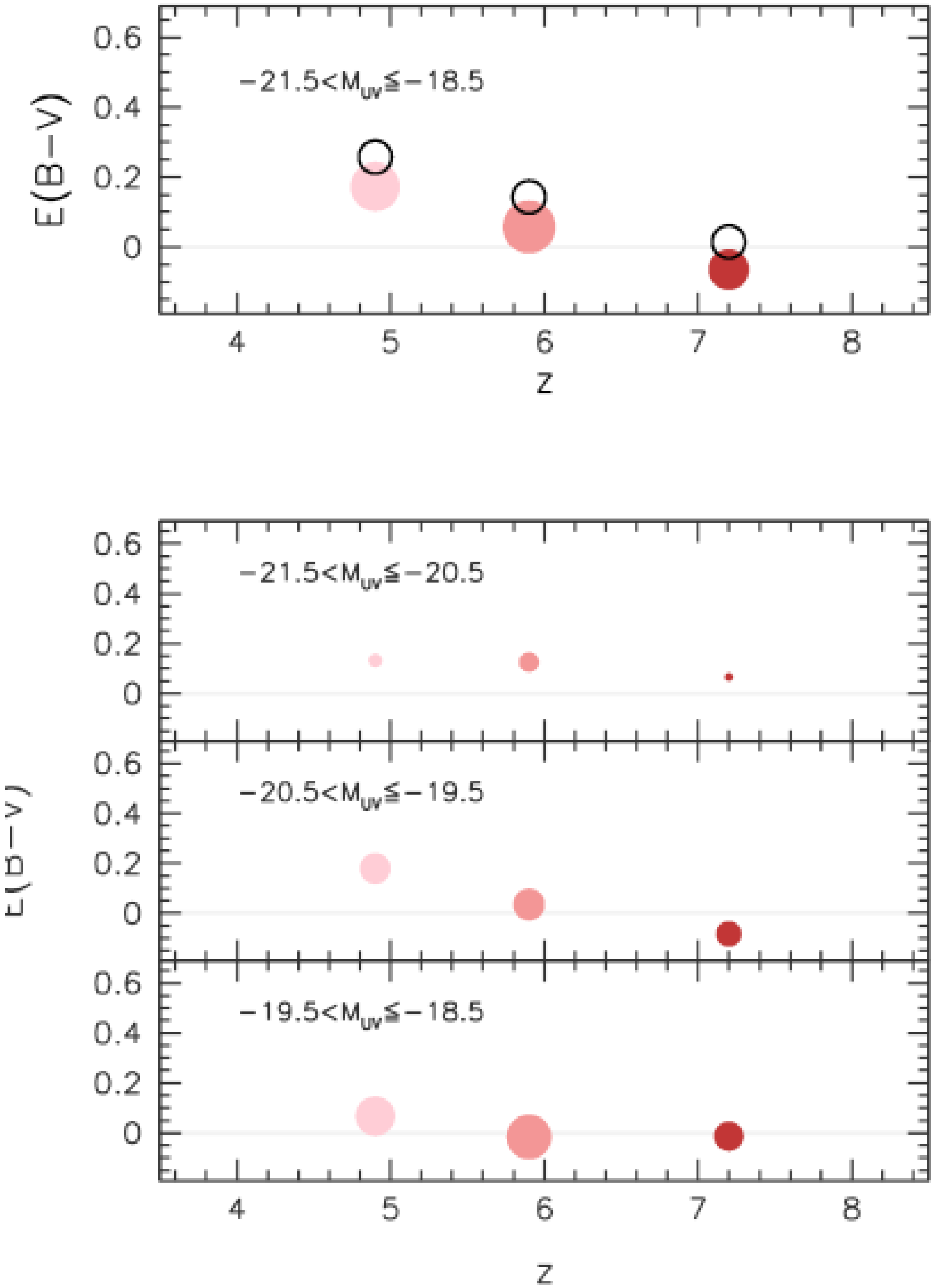
- *Star formation at even earlier times?*

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)

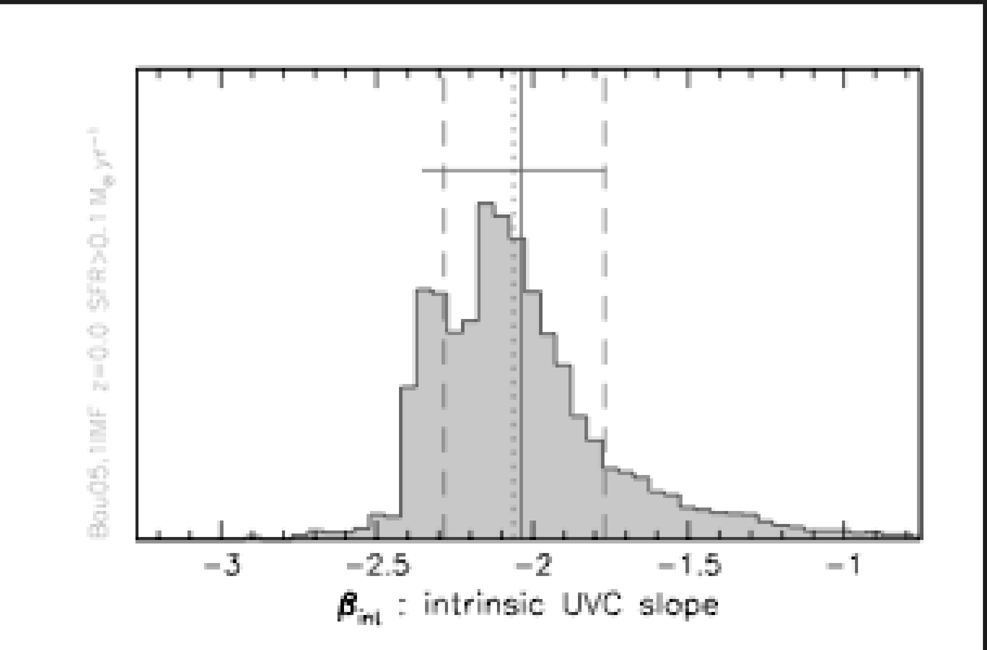


- From Wilkins et al. (2011) MNRAS
- Weak dependence of beta evolution on luminosity
- Careful on filters - the Lyman-alpha break will redden intrinsic colours

What Can we Learn about High-redshift Galaxies:

UV Continuum Properties ➟ dust

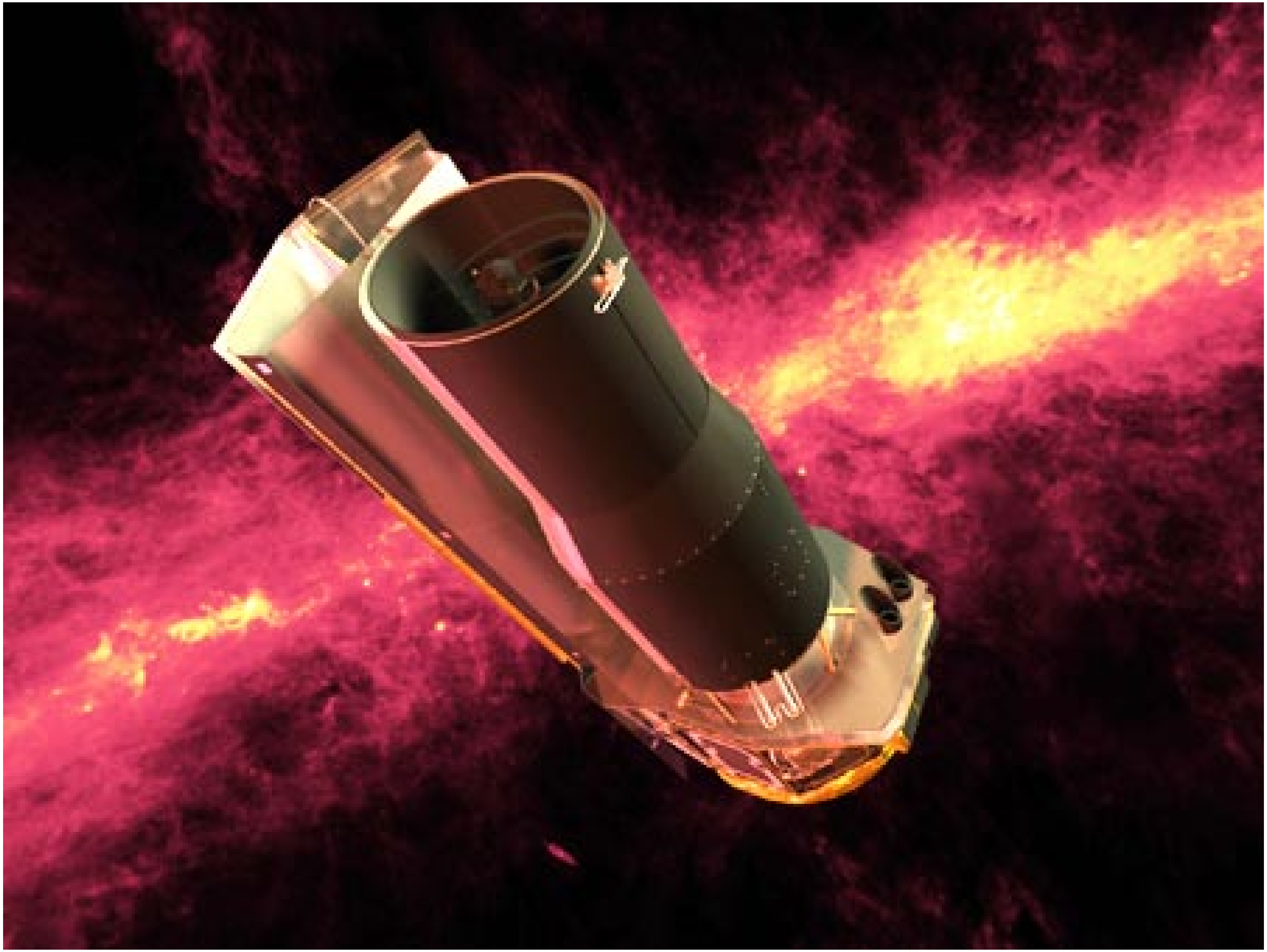
Interpreting the observed UVC slope in the context of dust requires knowledge of two uncertain quantities: the intrinsic UVC slope (distribution) and the reddening curve.



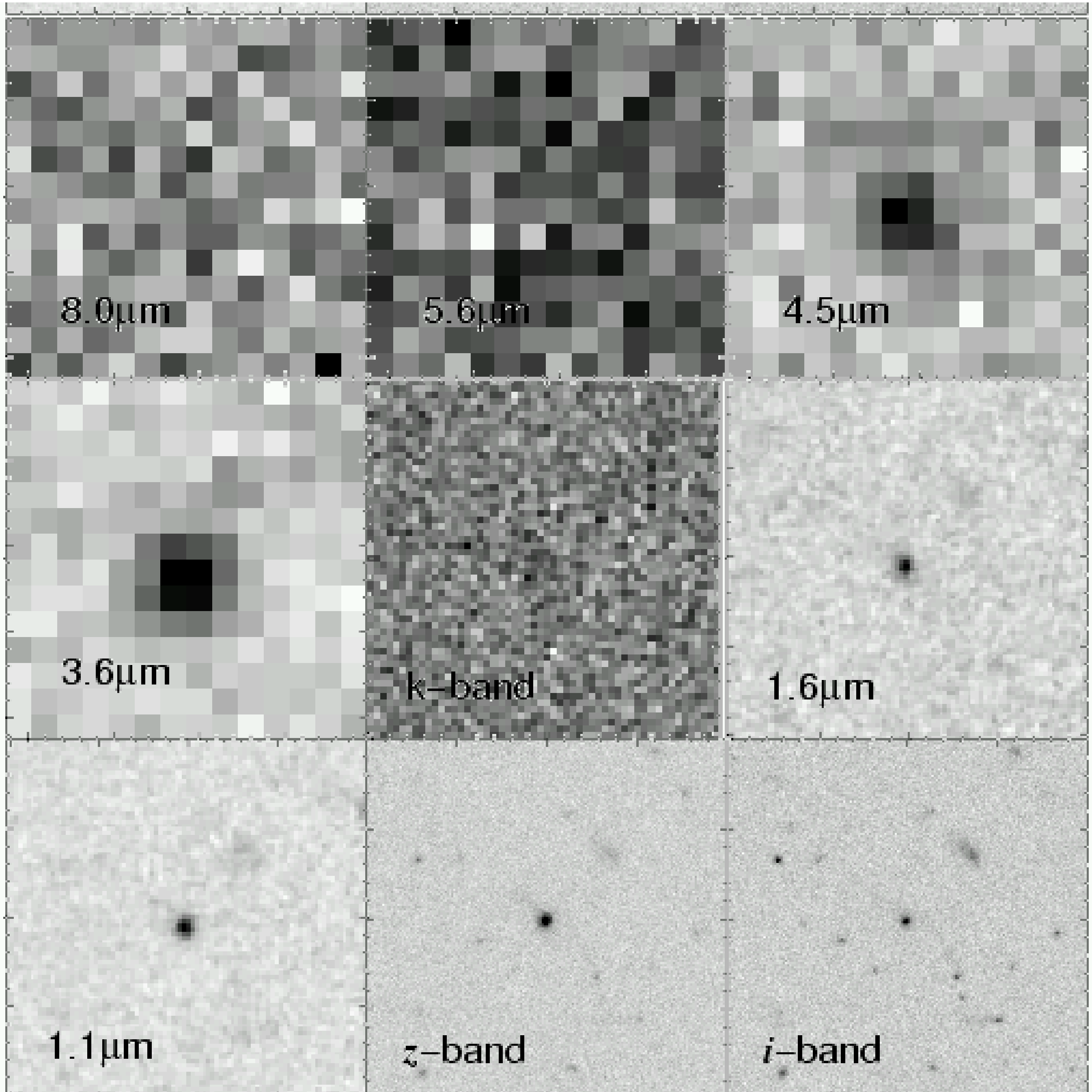
The intrinsic UVC slope is sensitive to the star formation and metallicity history, these can be predicted for large samples with galaxy formation models.

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).

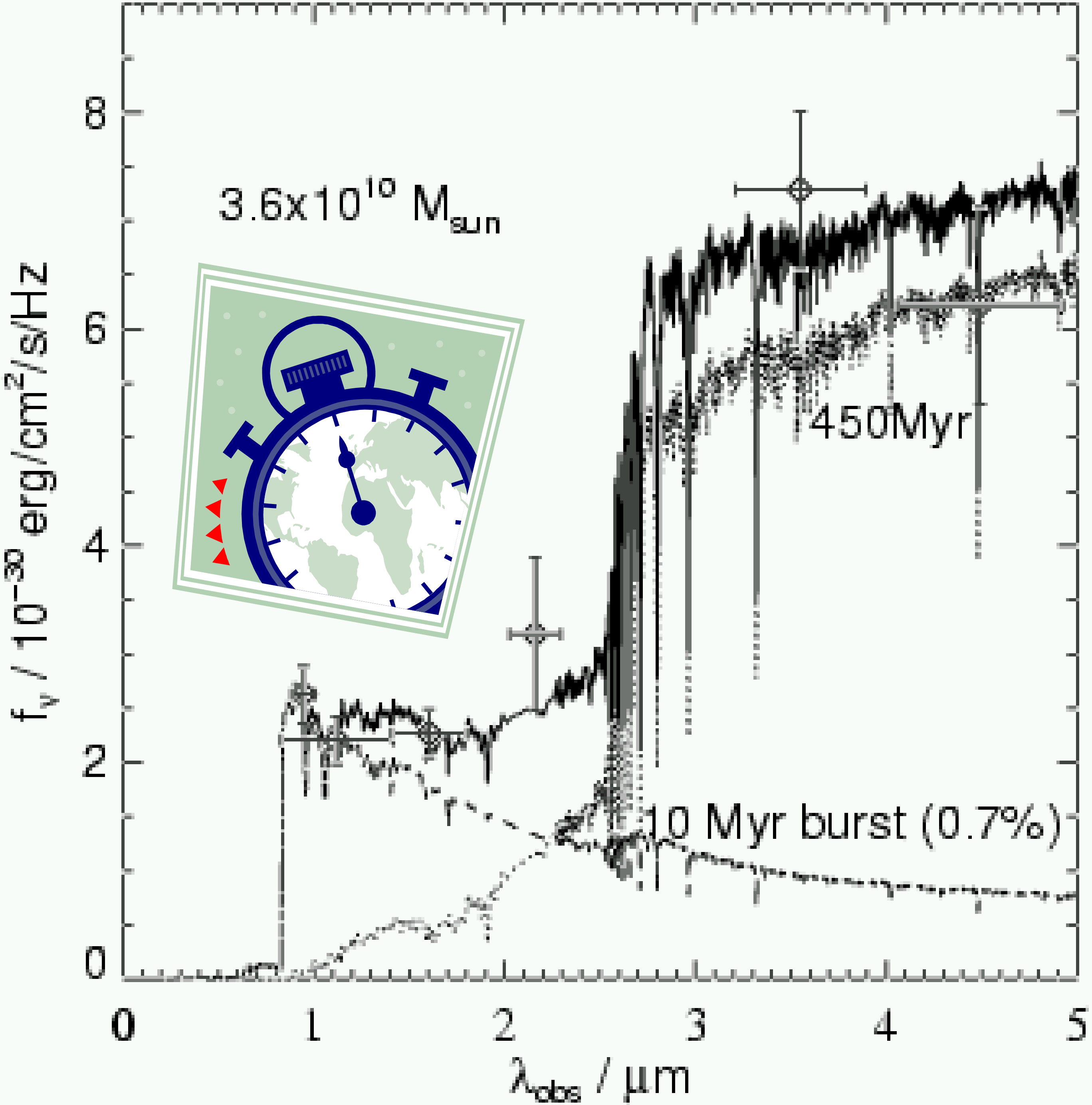
The intrinsic distribution of UVC slopes measured using the GALFORM semi-analytical model (Cole et al. 2001, Baugh et al. 2006, etc.). Wilkins et al. 2012 (to be submitted in the next couple of weeks).



Spitzer – IRAC (3.6-8.0 microns)



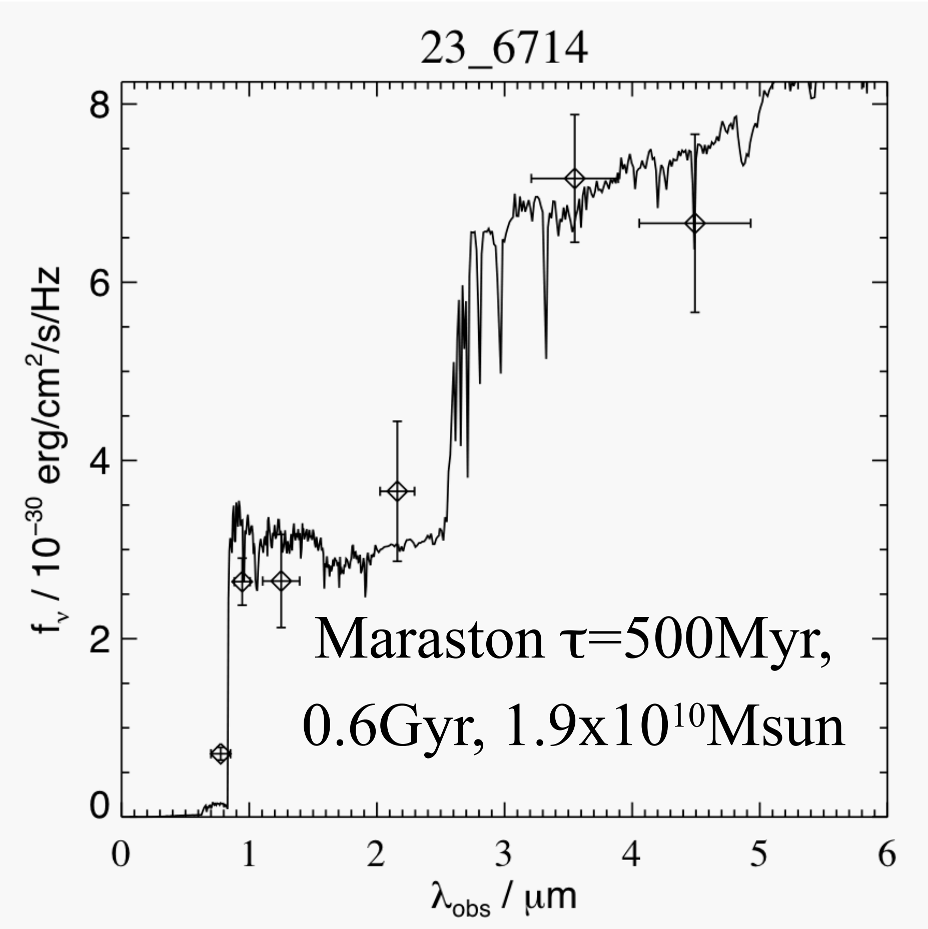
- z=5.83 galaxy #1 from Stanway, Bunker & McMahon 2003 (spec conf from Stanway et al. 2004, Dickinson et al. 2004). Detected in GOODS IRAC 3-4μm: Eyles, Bunker, Stanway et al '04

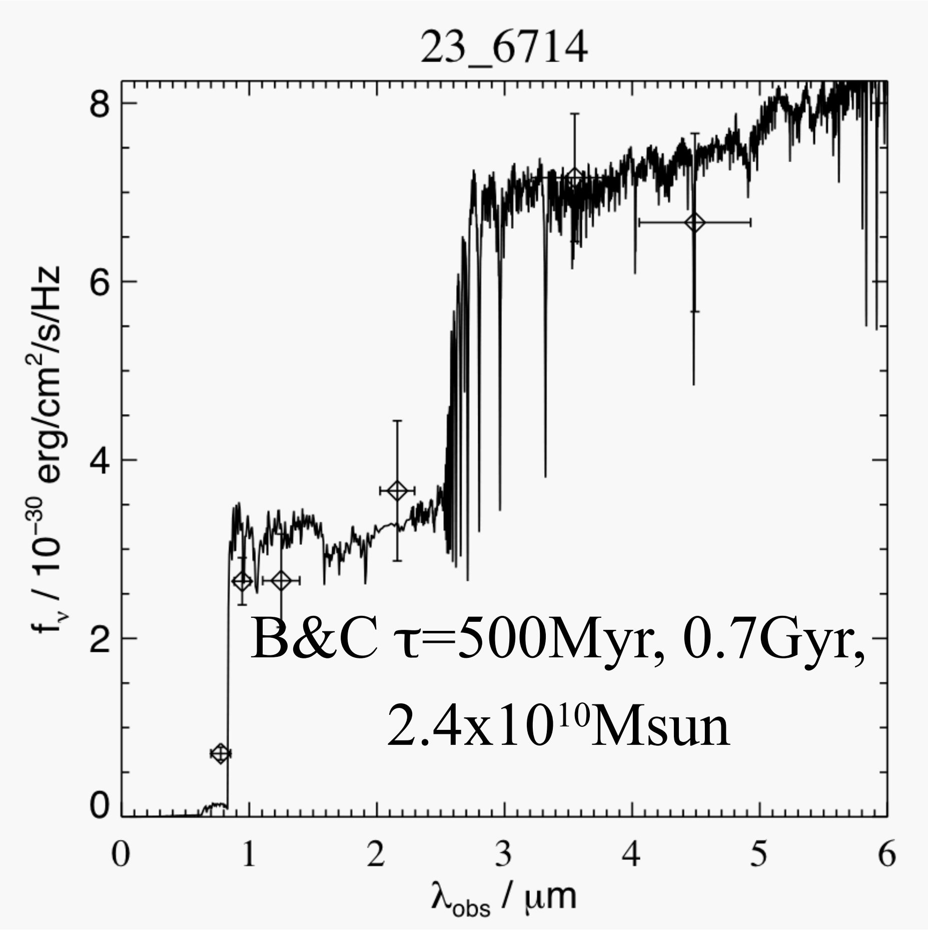


Eyles et al. (2005) MNRAS

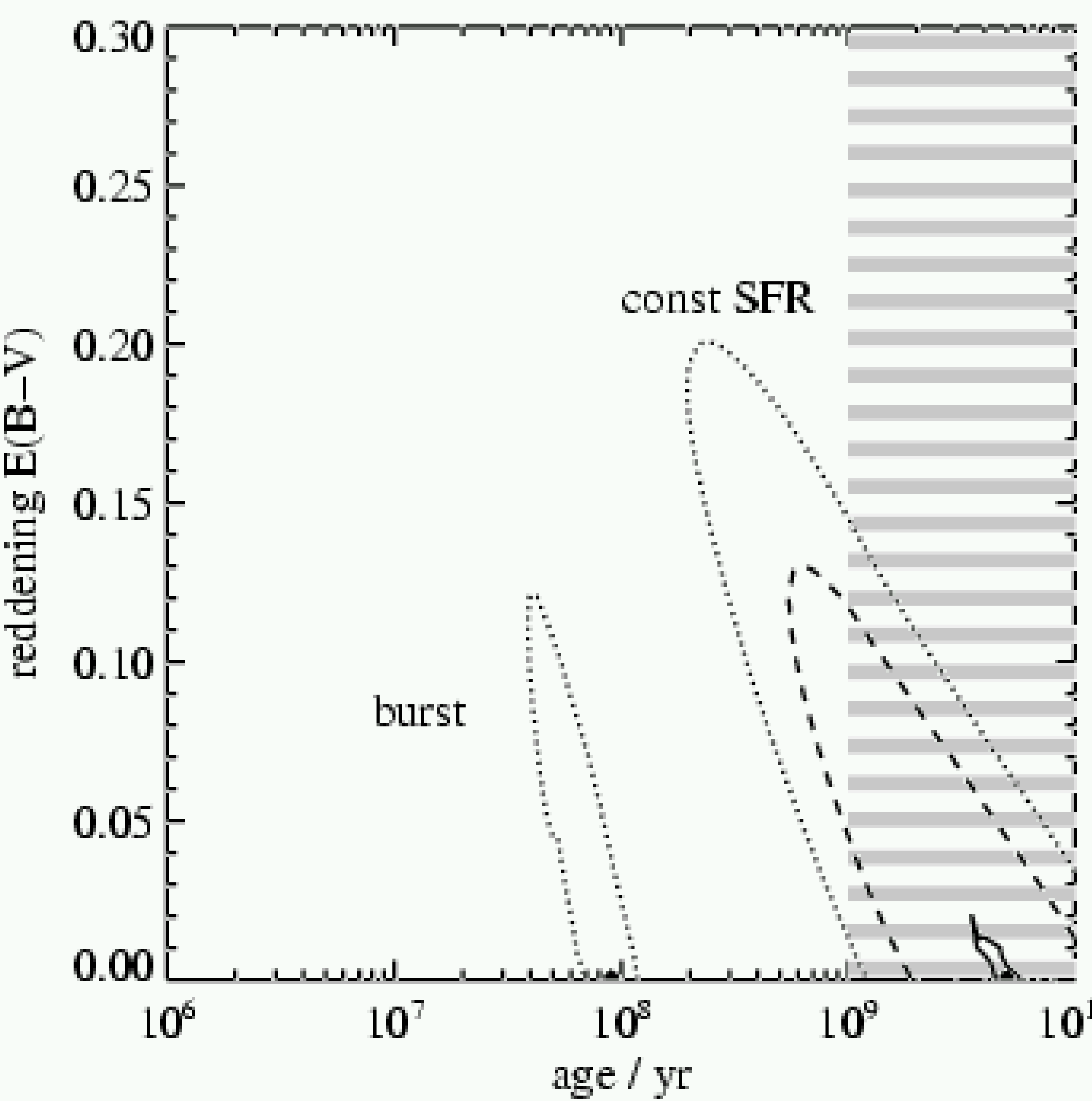
Emission line contamination does not seriously affect the derived ages and masses

Other Population Synthesis Models

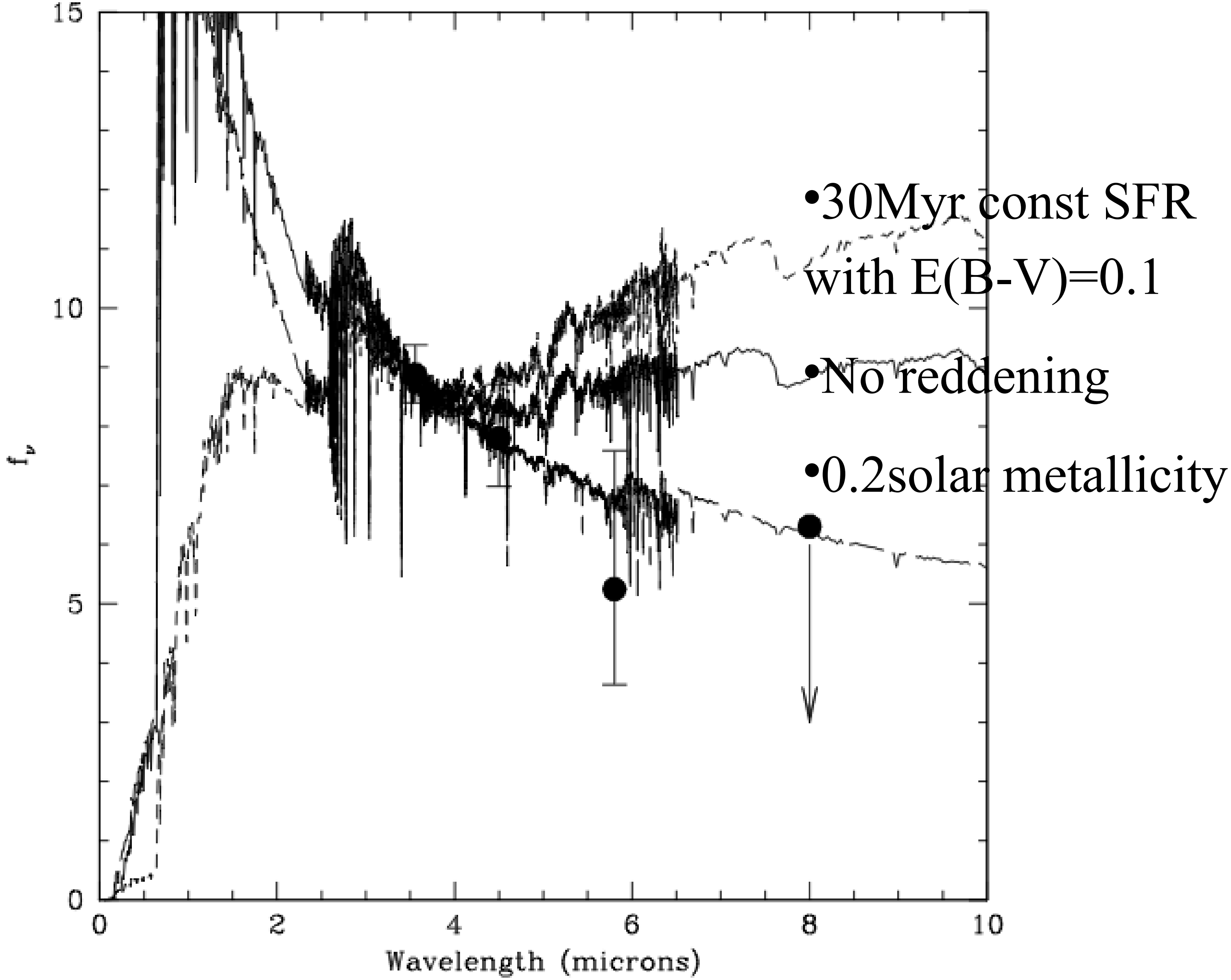


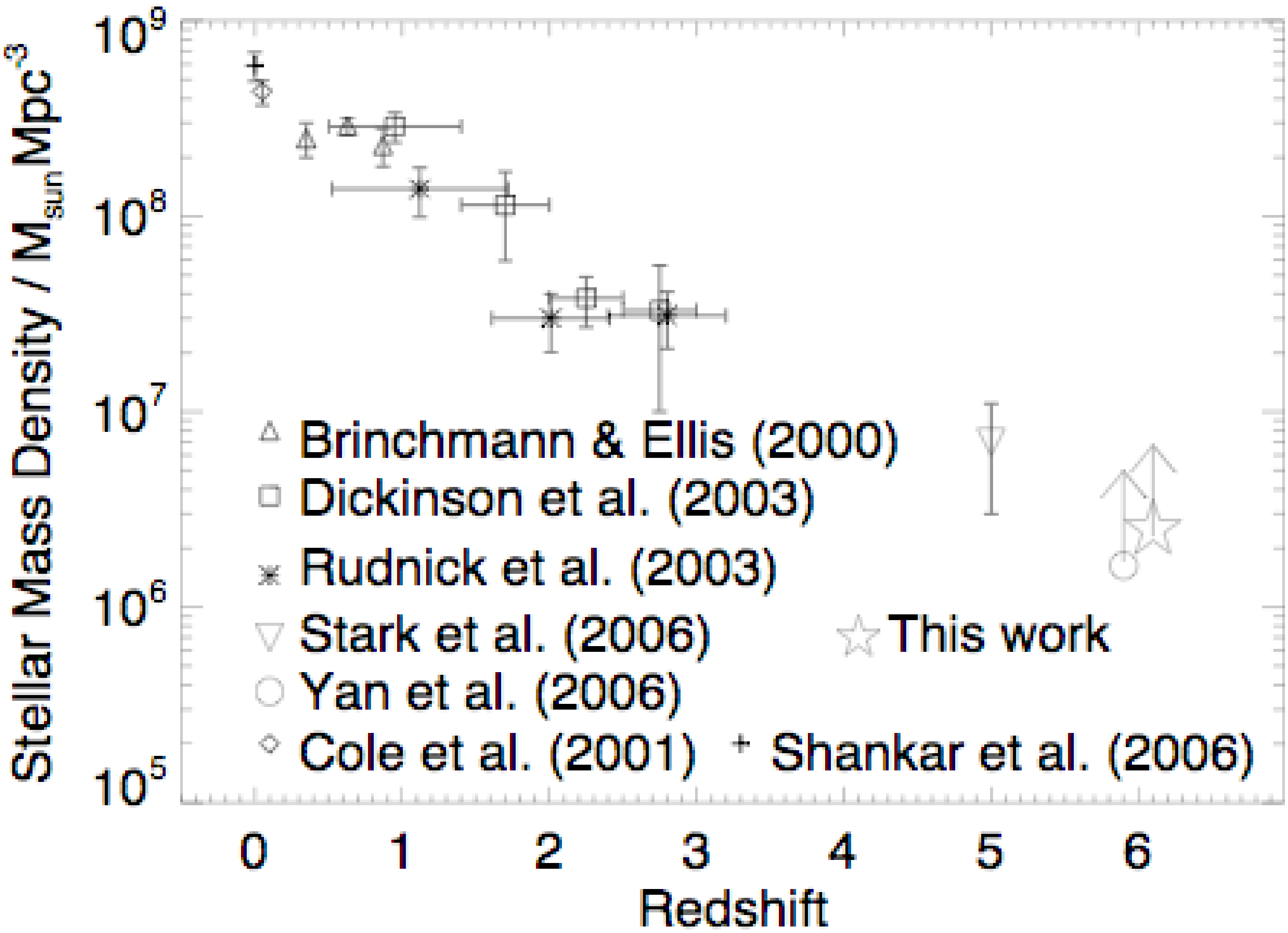


Maraston vs. Bruzual & Charlot - consistent

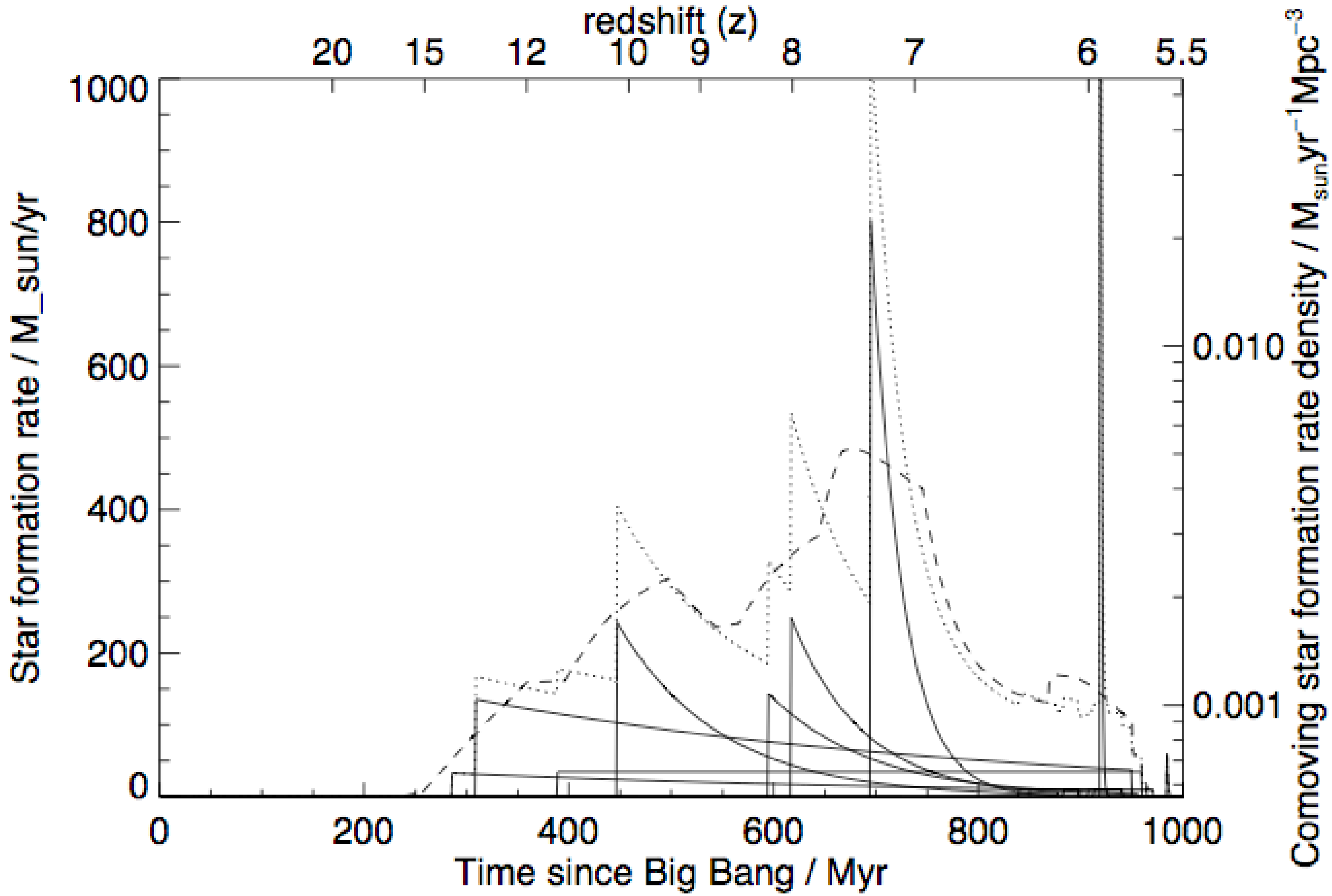


0.30
0.25
0.20
0.15
0.10
0.05
0.00
reddening E(B−V)
const SFR
burst
10^6
10^7
10^8
10^9
age / yr


15
10
5
0
0
2
4
6
8
10
Wavelength (microns)
f_ν
•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

If Galaxies Don't Do All the Reionization, What Does?

- Do QSOs still play a role? Paucity at z=7 and beyond indicates they have minimal contribution
- What about "mini-QSOs" from low-mass black holes? (Ricotti & Ostriker 2004; Mirabel et al. 2011)
- Something exotic (e.g. like Sciama's discredited decaying relic neutrions)

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