Galaxies in the early Universe, Reionization and the History of Star Formation

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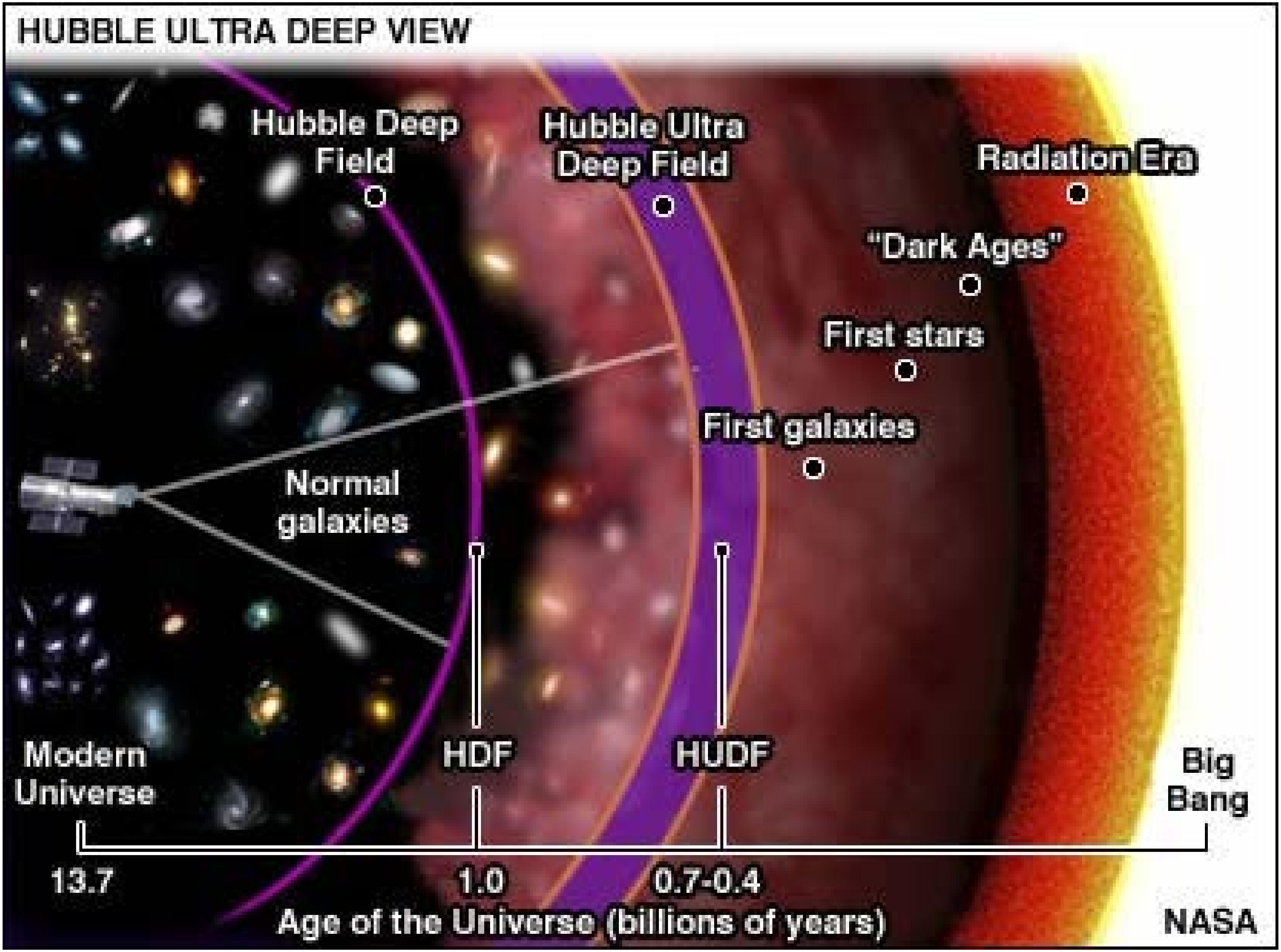
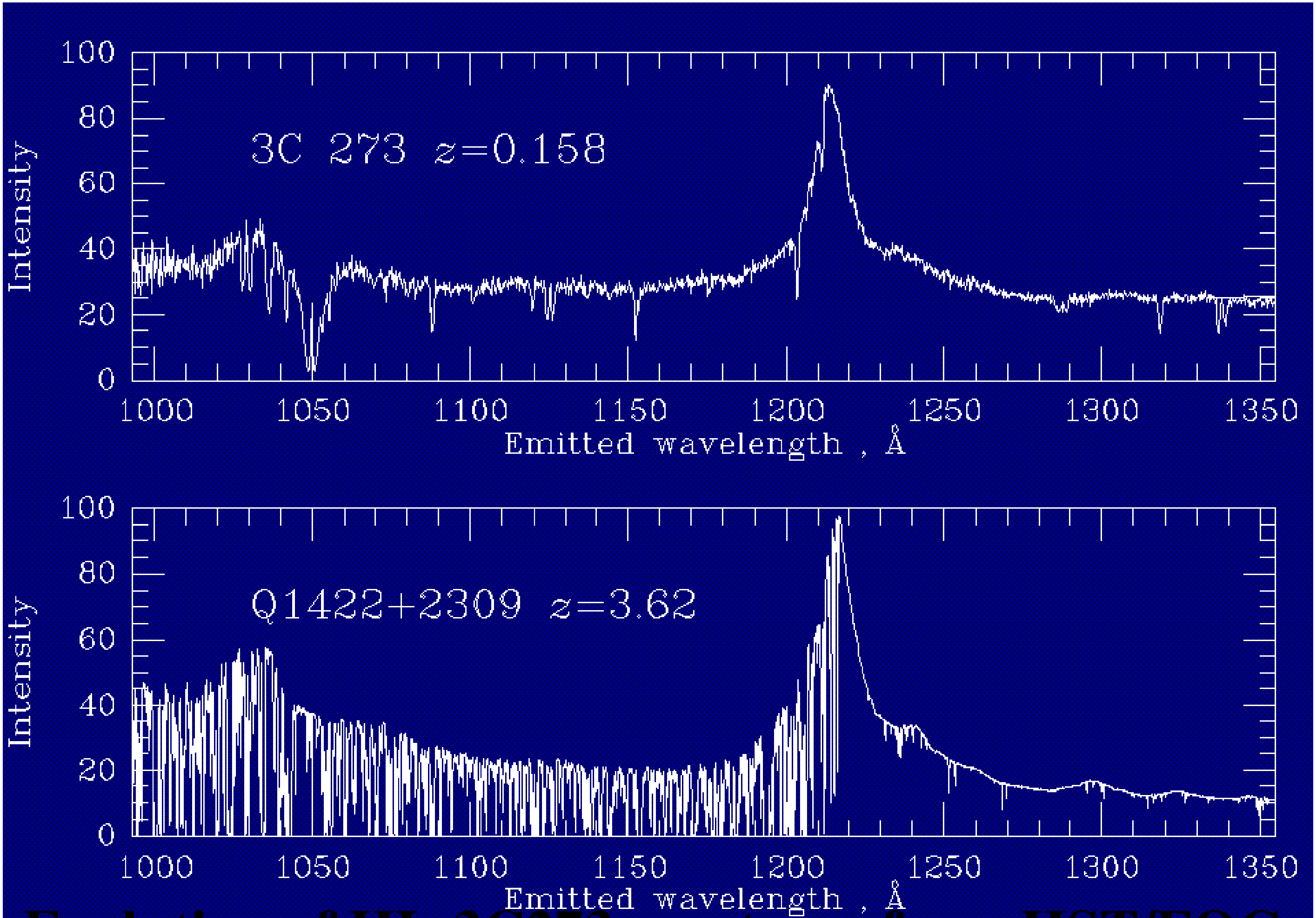
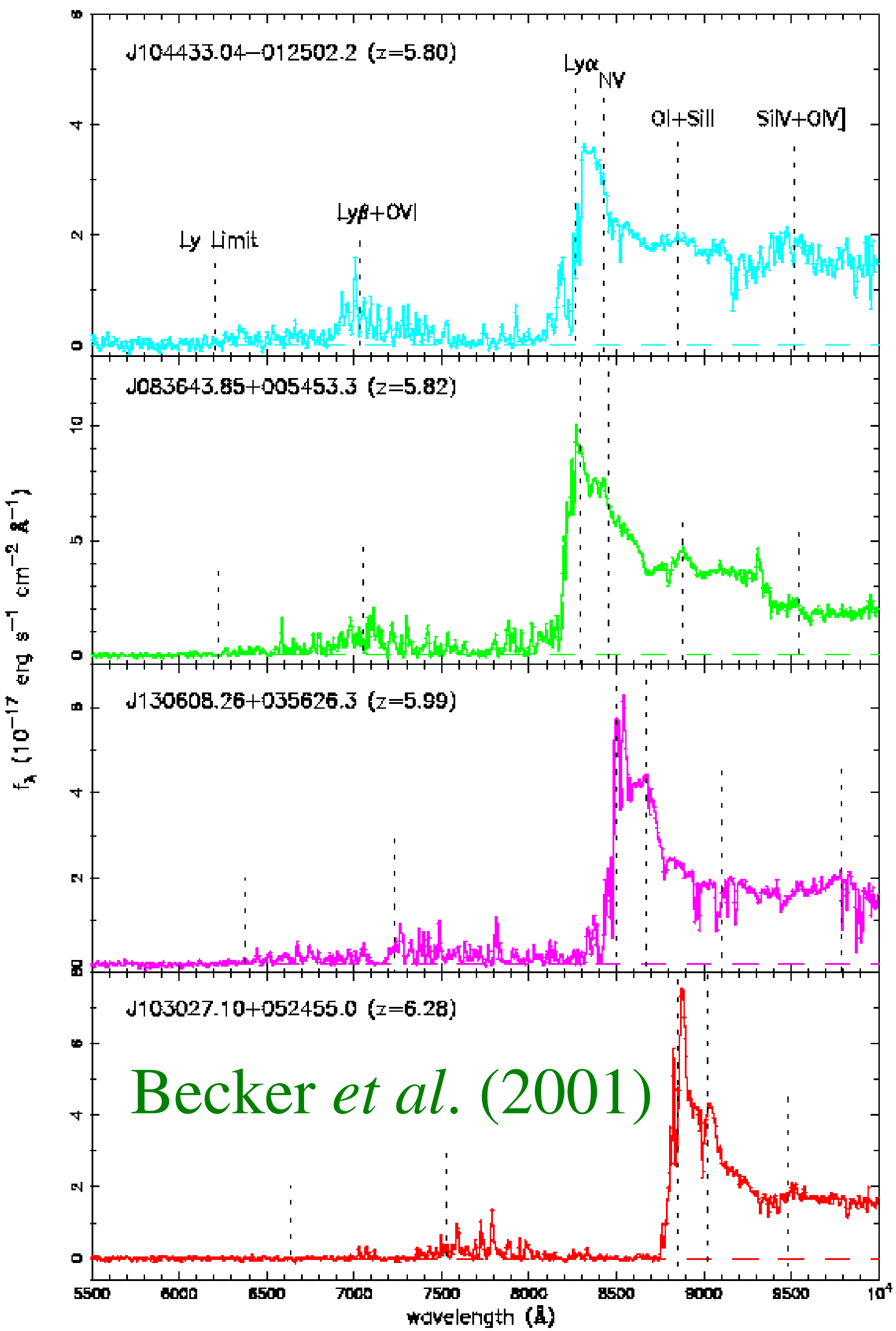
Texas@Stanford, 14 Dec 2004


HUBBLE ULTRA DEEP VIEW
Hubble Deep Field
Hubble Ultra Deep Field
Radiation Era
"Dark Ages"
First stars
First galaxies
Normal galaxies
Modern Universe
HDF
HUDF
Big Bang
13.7
1.0
0.7-0.4
Age of the Universe (billions of years)
NASA



Evolution of HI: 3C273 spectrum from HST/FOC z=0; z=3.6 QSO HIRES/Keck spectrum from M. Rauch

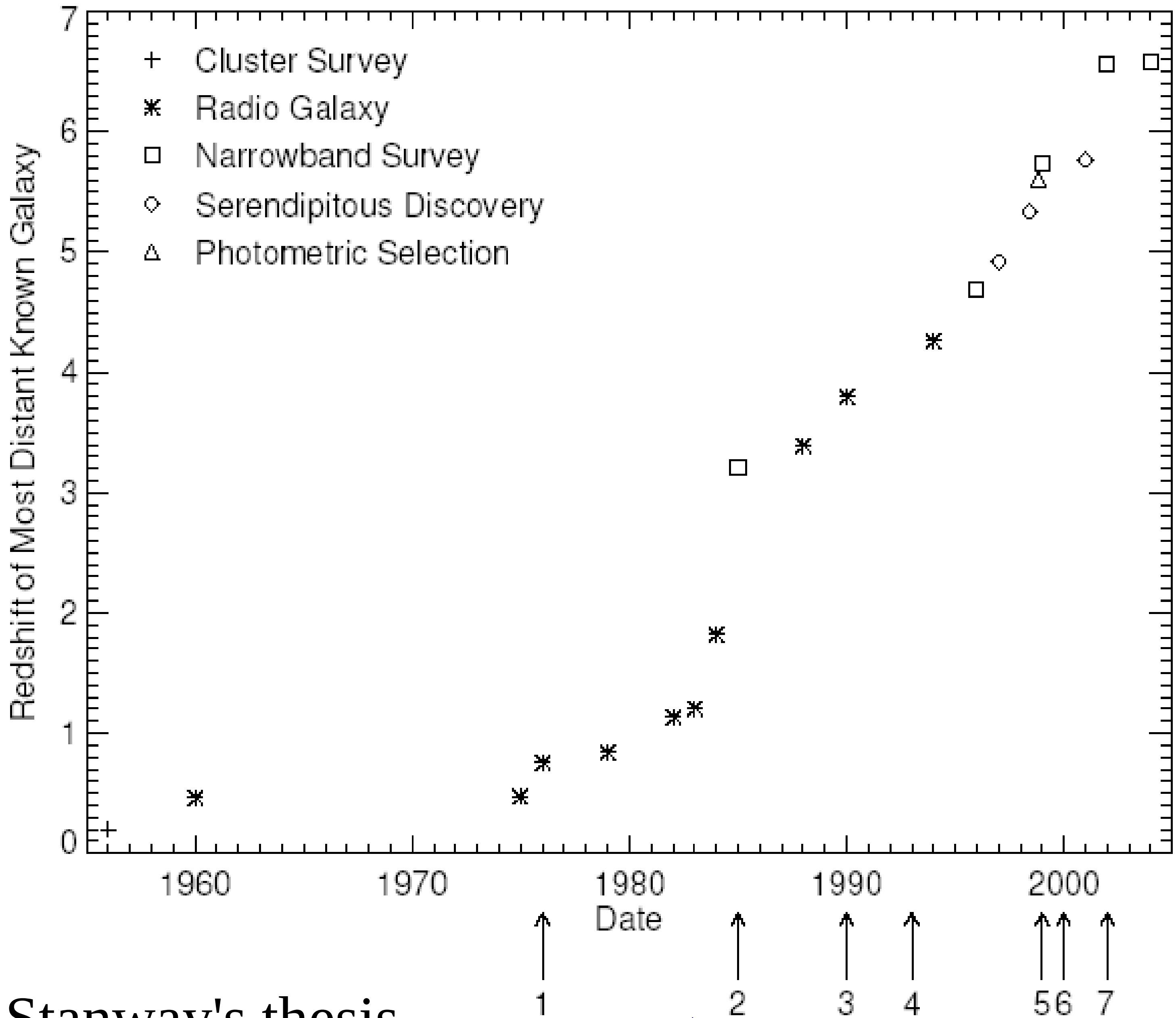


Becker *et al.* (2001)

Reionization

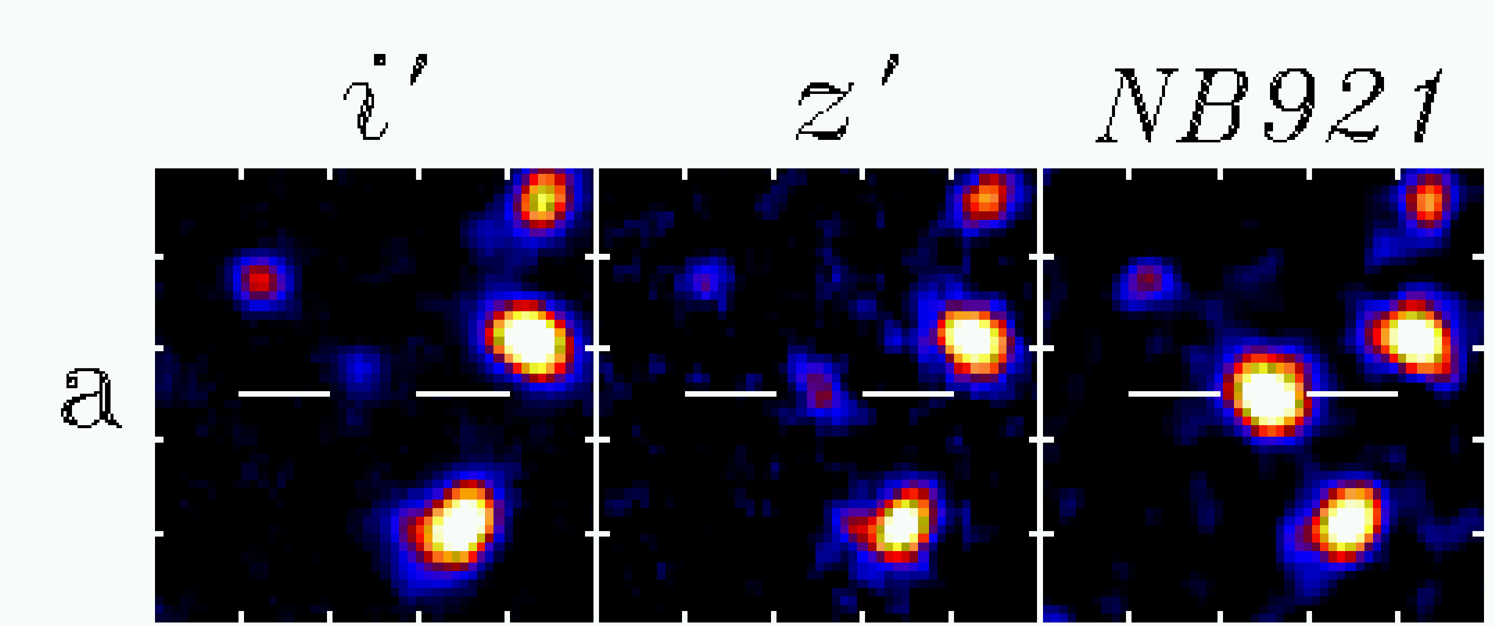
At high-redshift, the Lyman-α forest can absorb most of the flux below λ_{rf}=1216Å. Indications from *z*=6.3 SDSS QSO that Universe may be optically thick at z~6 (see talk by Fan). BUT confusing messages from WMAP CMB satellite: reionization z~10-30? (Kogut et al. 2003)

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

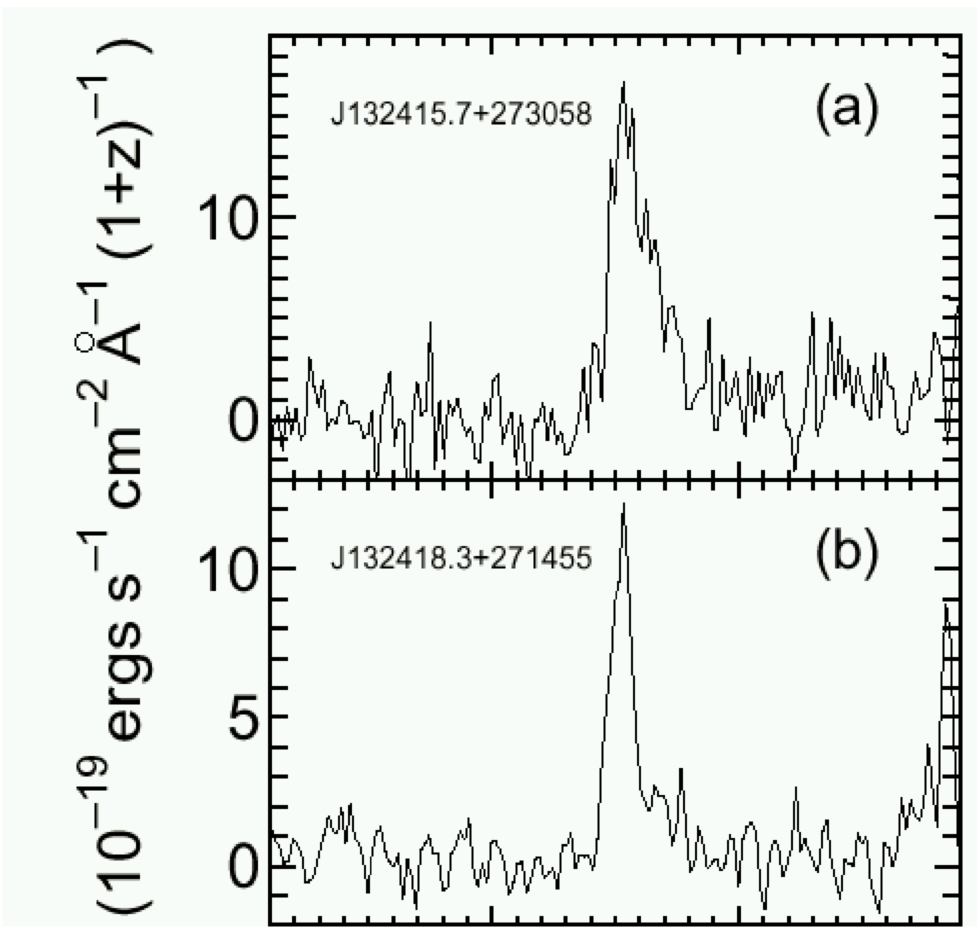


VLA
QSO field
Keck
HST (fix)
Subaru
Gemini

From Elizabeth Stanway's thesis (2004), updated from review of Stern & Spinrad (1999)

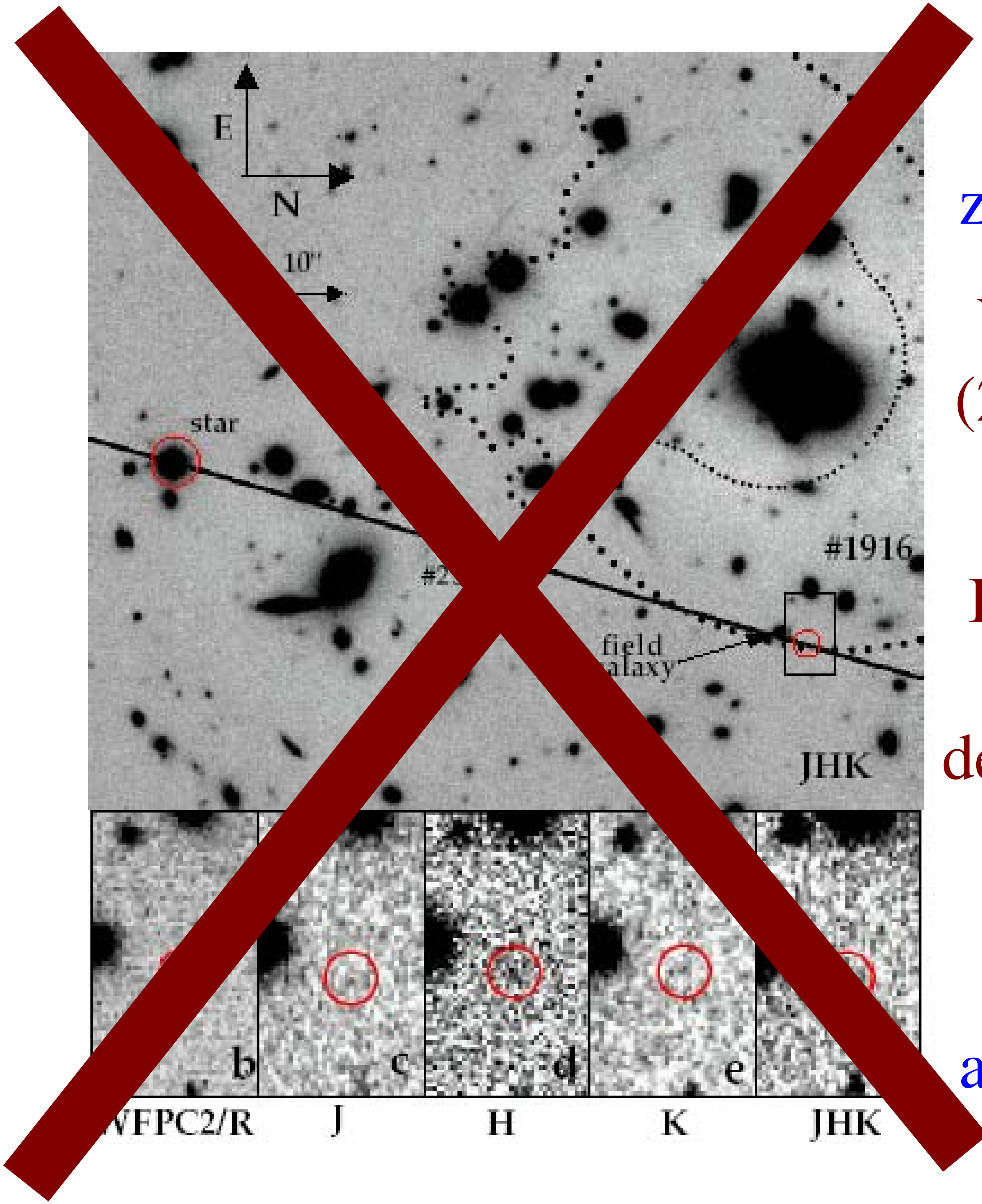


Kodaira et al. (2003) z=6.58 Ly-alpha galaxy (narrow-band)



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



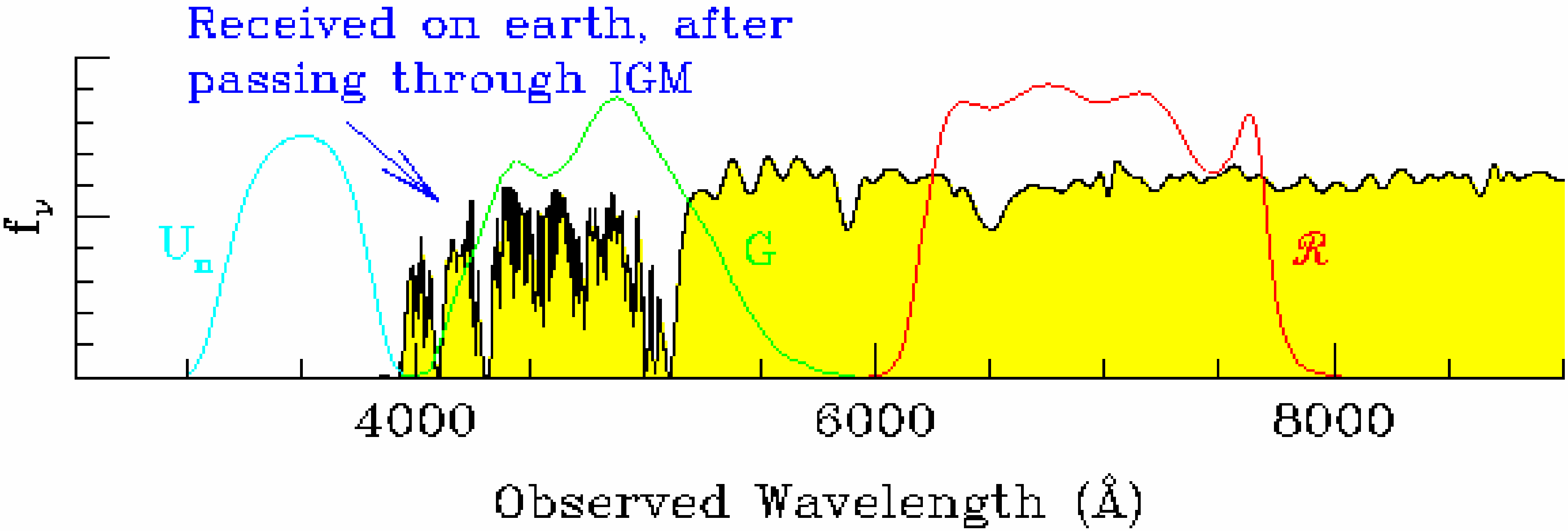
Pello et al. (2004) z~10 lensed galaxy?

Weatherly & Warren (2004) did not confirm emission line in data

Bremer et al. (2004) could not confirm detection in new near-IR imaging

Similar fate met previous high-z Ly-alpha galaxy at z=6.6 (Chen et al. 1999)

"Photometric redshifts" – estimating redshift from broad band colours (flux in different filters), less accurate that spectroscopic redshifts (and can suffer catastrophic degeneracies) but more efficient in telescope time, and can pre-select likely high-z



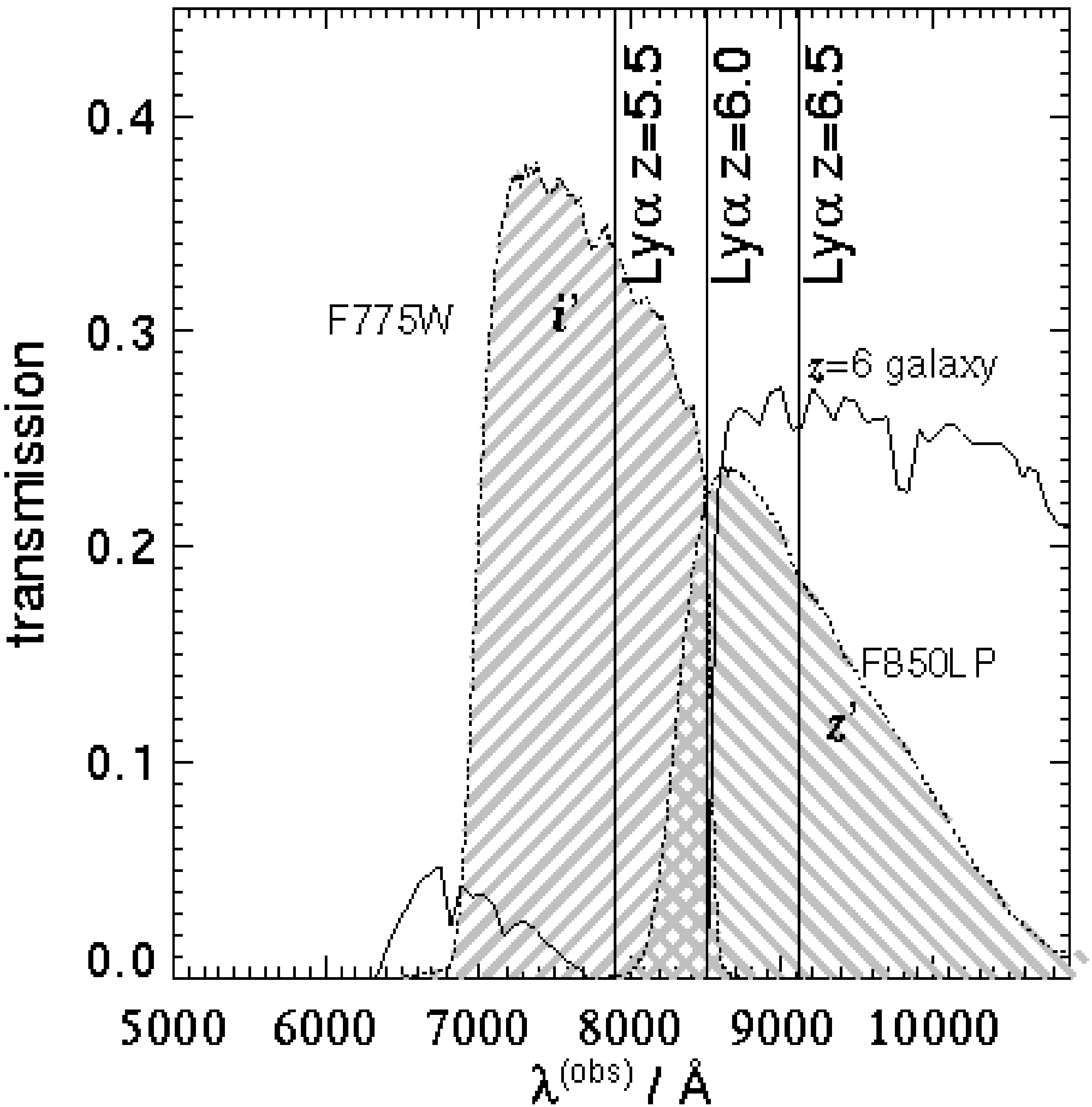
"Lyman break technique" - sharp drop in flux at λ below Ly-α. Steidel et al. have >1000 z~3 objects, "drop" in U-band. Problems with resonant Ly-alpha as star formation measure

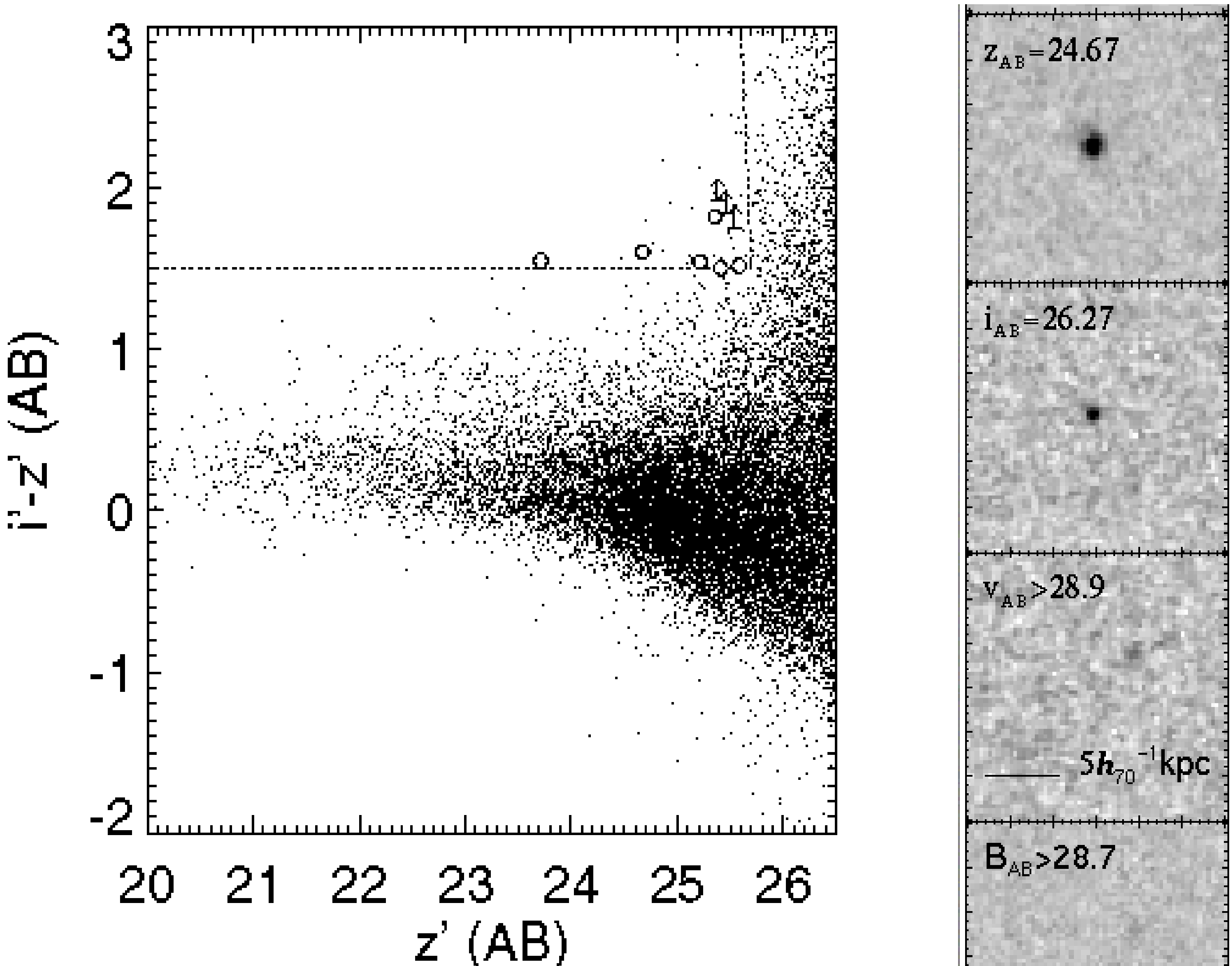
The z~5 "Barrier"

- "Hubble Deep Field" (Williams et al. 1996) contained only one galaxy confirmed to be at z>5.5 (Weymann et al 1998). Small field of view and choice of filters with WFPC2.
- CCDs inefficient at ~0.9-1.0 micron, which is Lyman-alpha and rest-frame UV continuum at z~6.
- Advanced Camera for Surveys (ACS) on HST offered SDSS filters and good senstivity at long wavelengths, coupled with better spectrographs on the ground (DEIMOS on Keck, and nod&shuffle technique with GMOS on Gemini to beat sky lines)


HUBBLE SPACE
TELESCOPE
9 07:06:57

Pushing to higher redshift- Finding Lyman break galaxies at z~6 with HST/ACS: Elizabeth Stanway's PhD, using *i*-drops (Stanway, Bunker & McMahon 2003); also GOODS team (Dickinson et al., Giavalisco et al. 2004) and Bouwens group (UCSC) and Yan & Windhorst (2004)

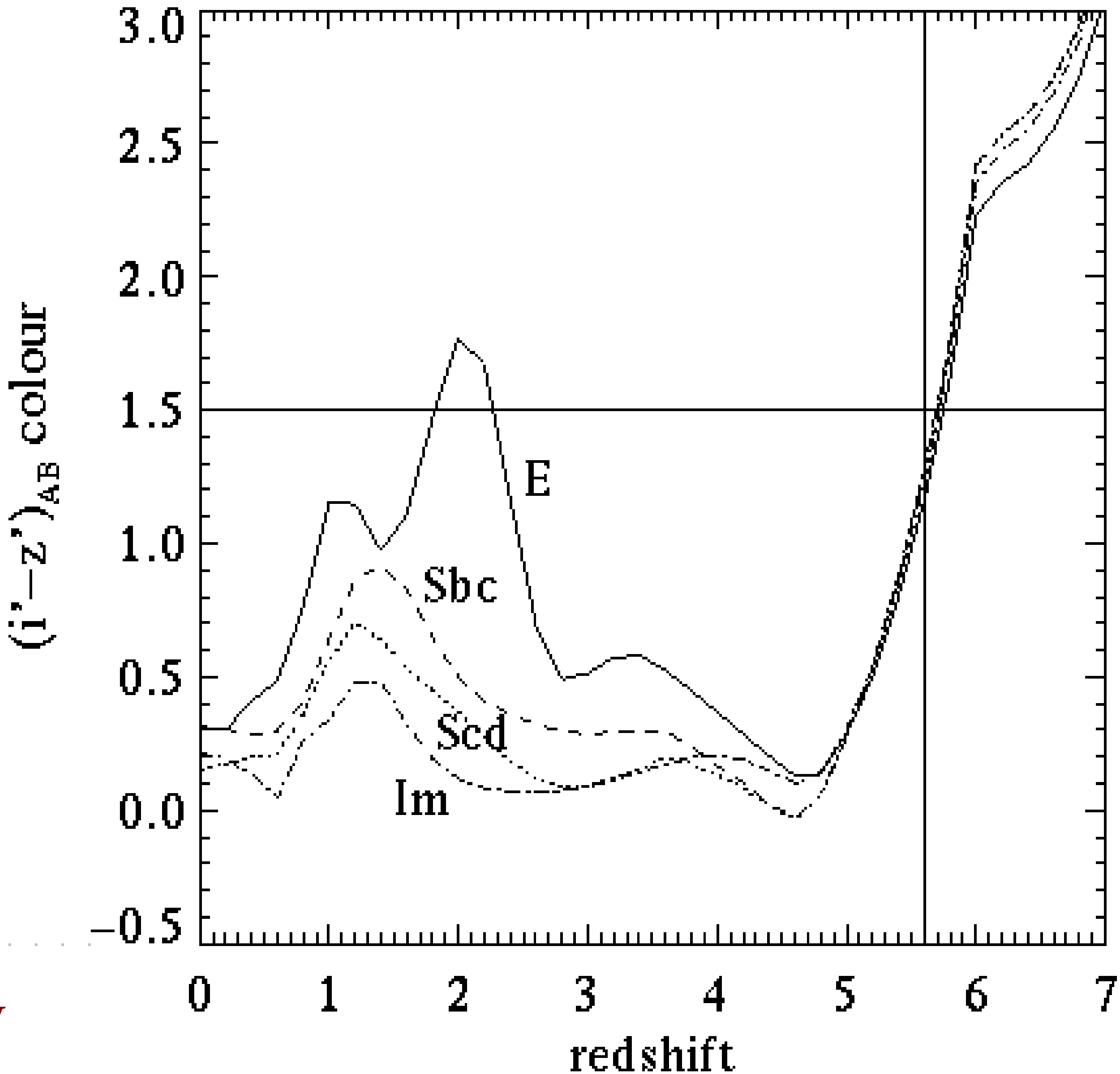


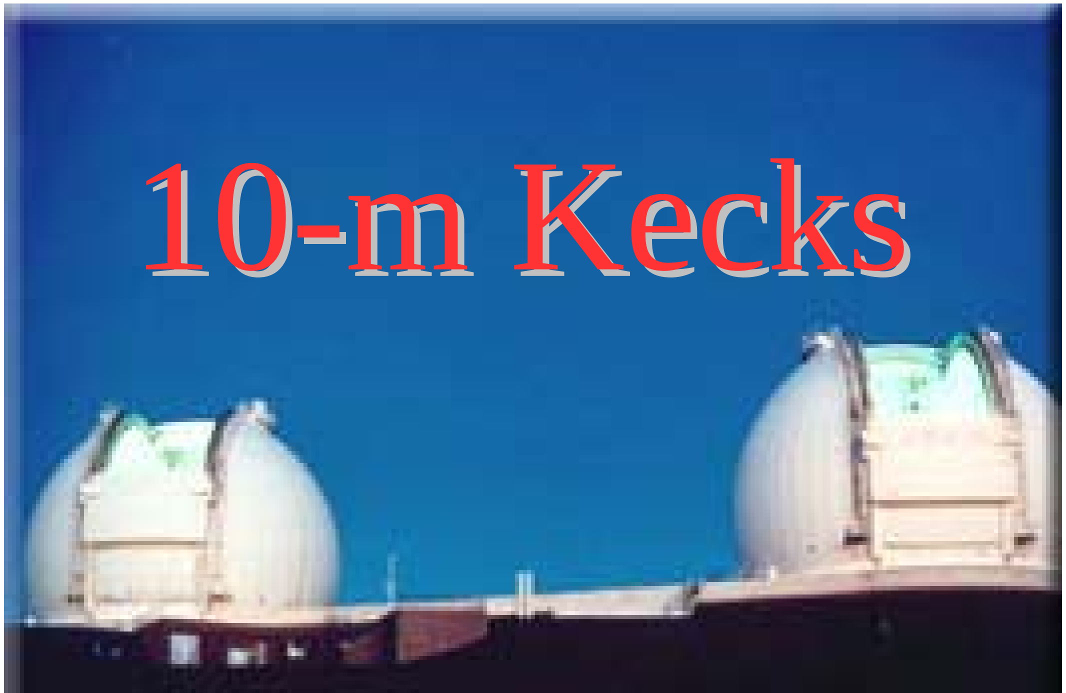


Using HST/ACS GOODS data - CDFS & HDFN, 5 epochs B,v,i',z'

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.



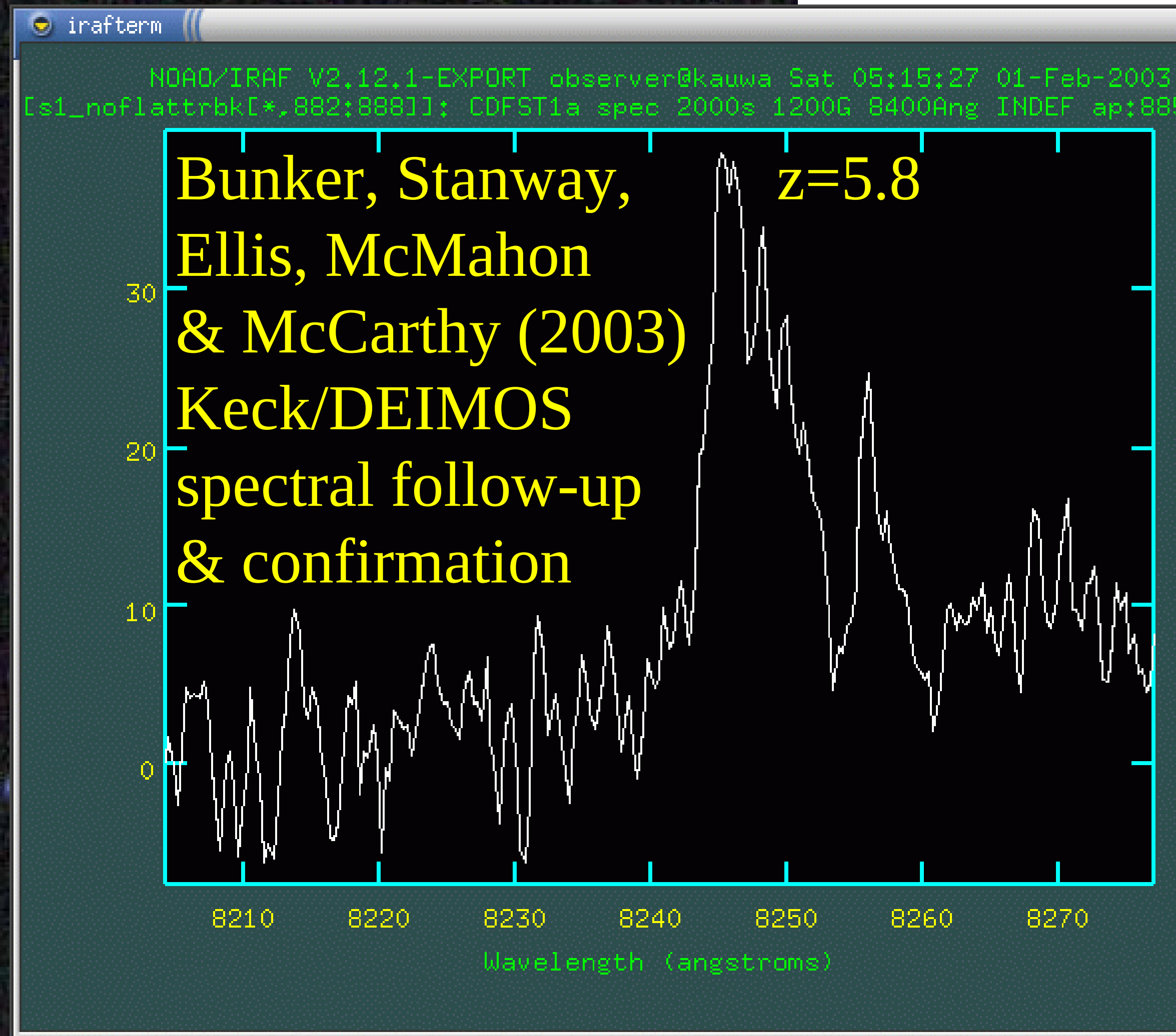

10-m Kecks


ESO VLTs


Photo © Neelon Crawford/Polar Fine Arts

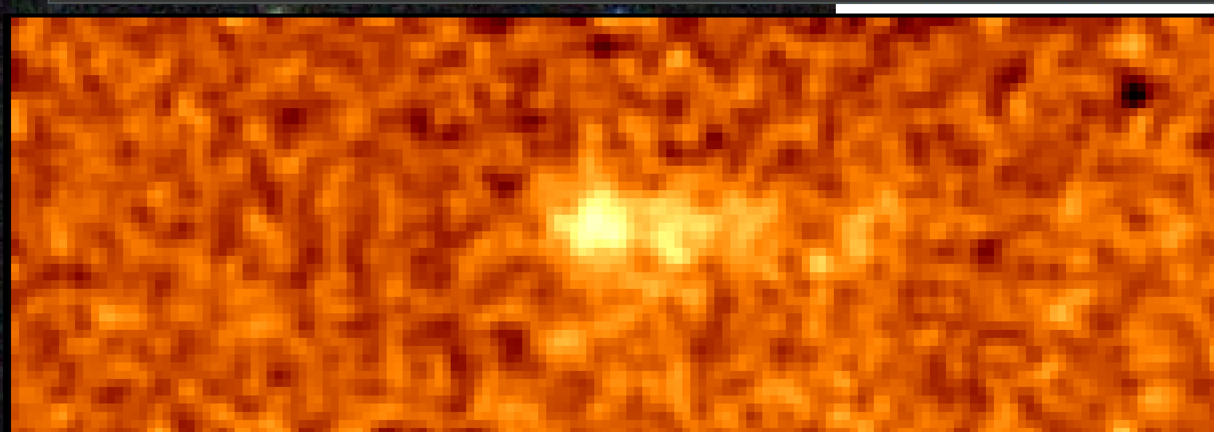

8-m Gemini

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)



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 (Steidel et al.)
- 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 4 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)

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

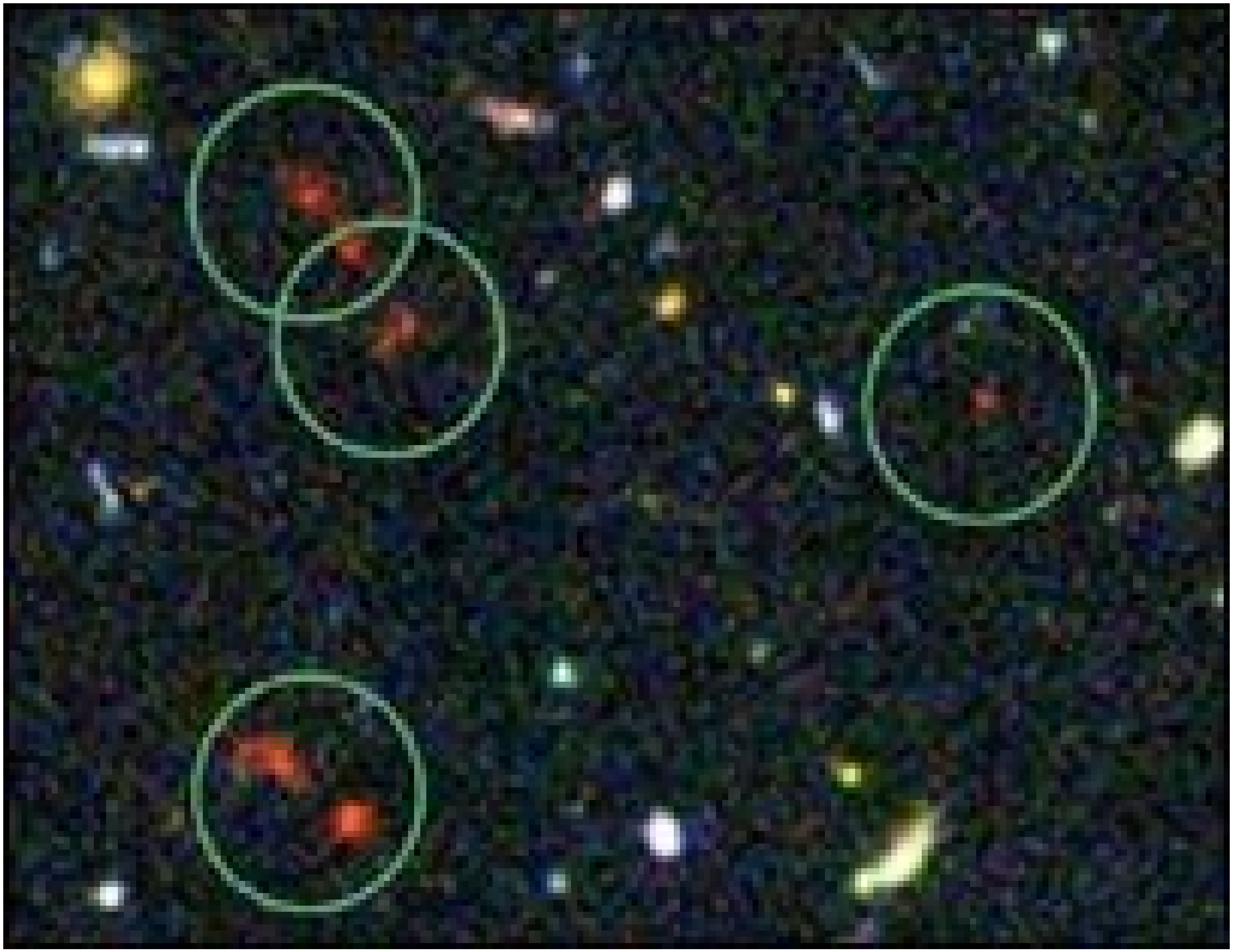
-We only probe bright end of luminosity function: ~1L*(UV) at z~3, equivalent to 15M_sun/yr

- 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!***

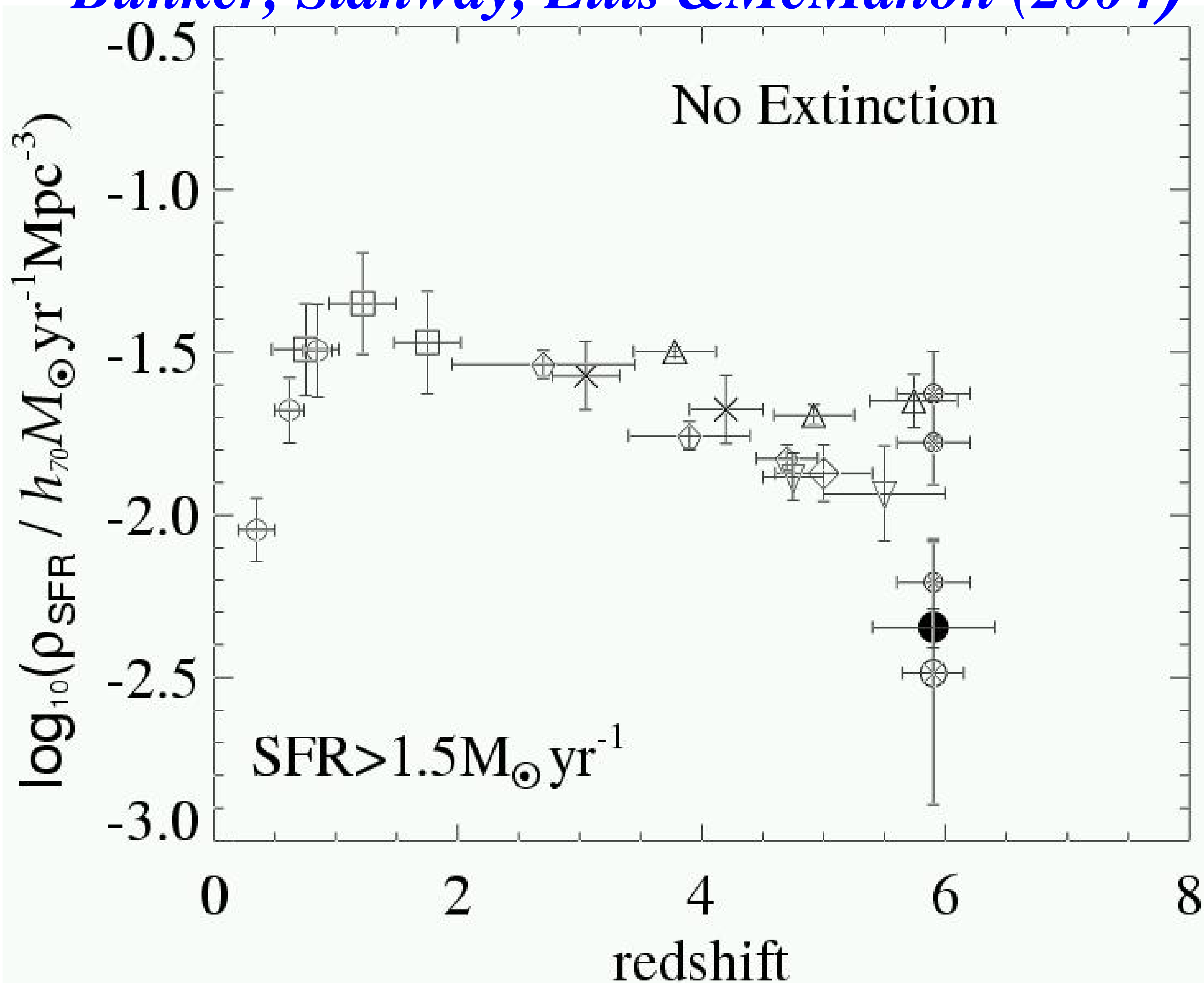
- Other groups make a correction for the faint galaxies they don't see. Depends crucially on the faint end slope of the luminosity function (α~-1.1 locally, α=-1.6@z~3)

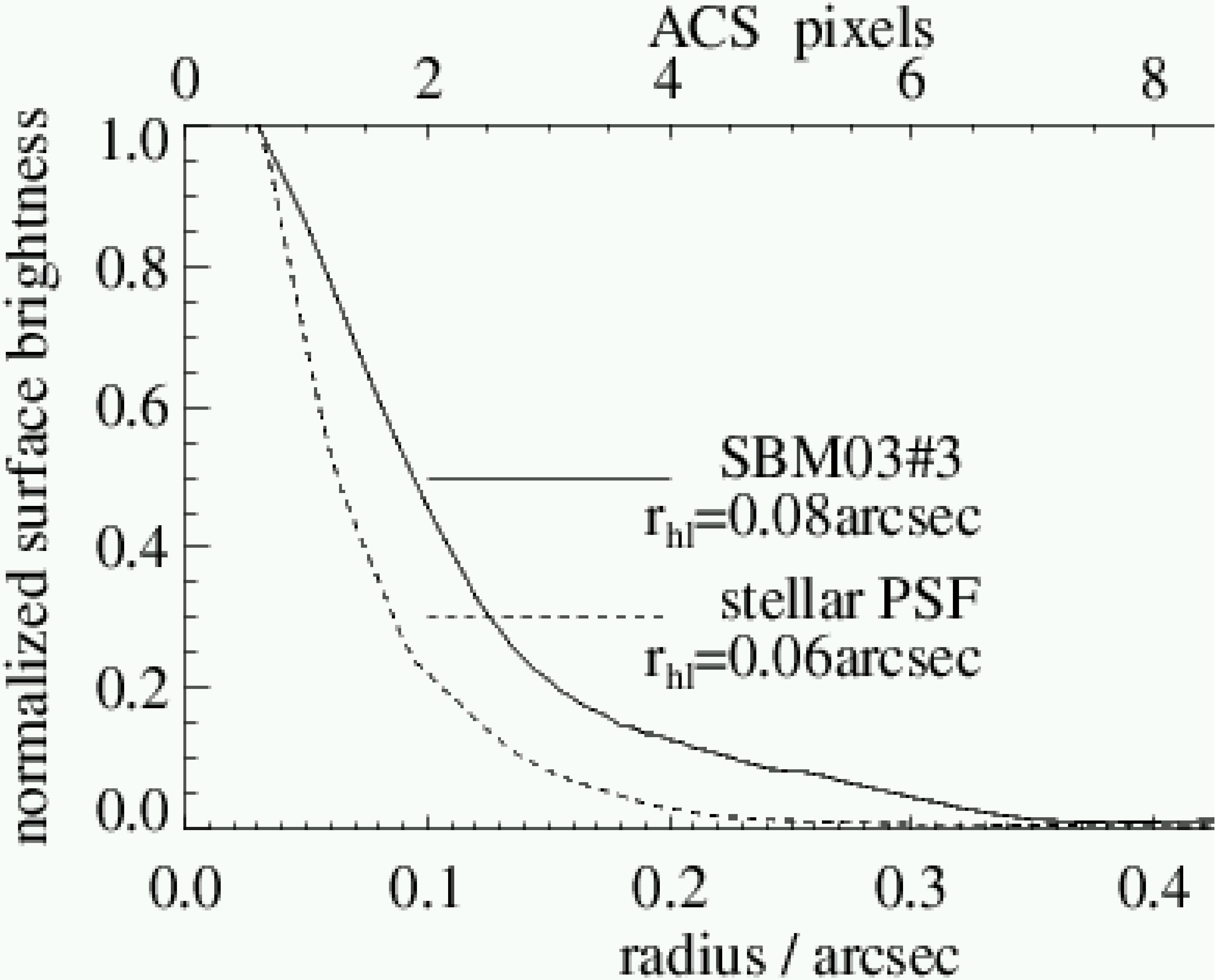
- Need recent Ultra Deep Field to address total star formation, but we had proved ***strong evolution***.



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

Bunker, Stanway, Ellis &McMahon (2004)



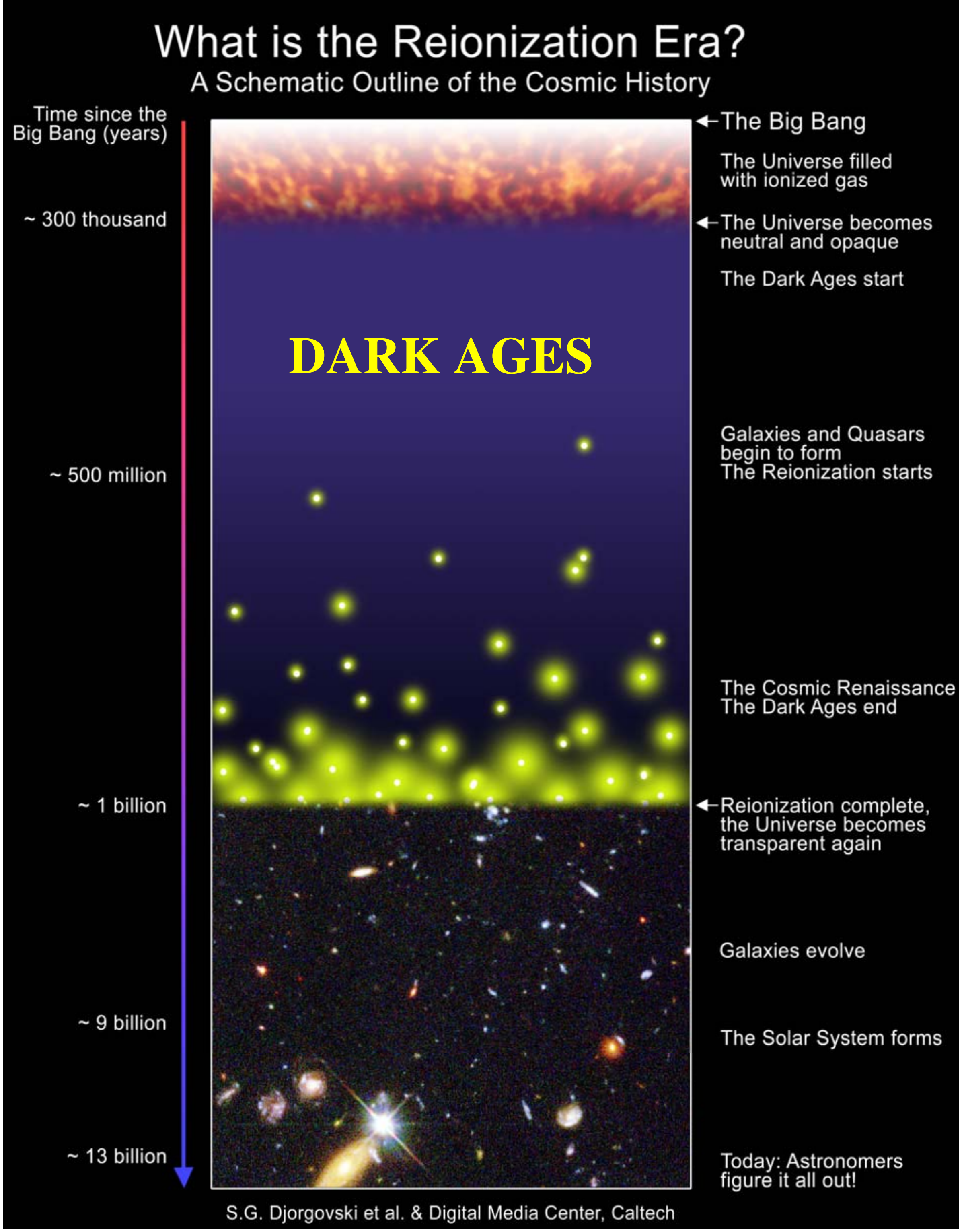

ACS pixels
0
2
4
6
8
1.0
0.8
0.6
0.4
0.2
0.0
normalized surface brightness
SBM03#3
r_{hl}=0.08arcsec
stellar PSF
r_{hl}=0.06arcsec
0.0
0.1
0.2
0.3
0.4
radius / arcsec

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

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?)

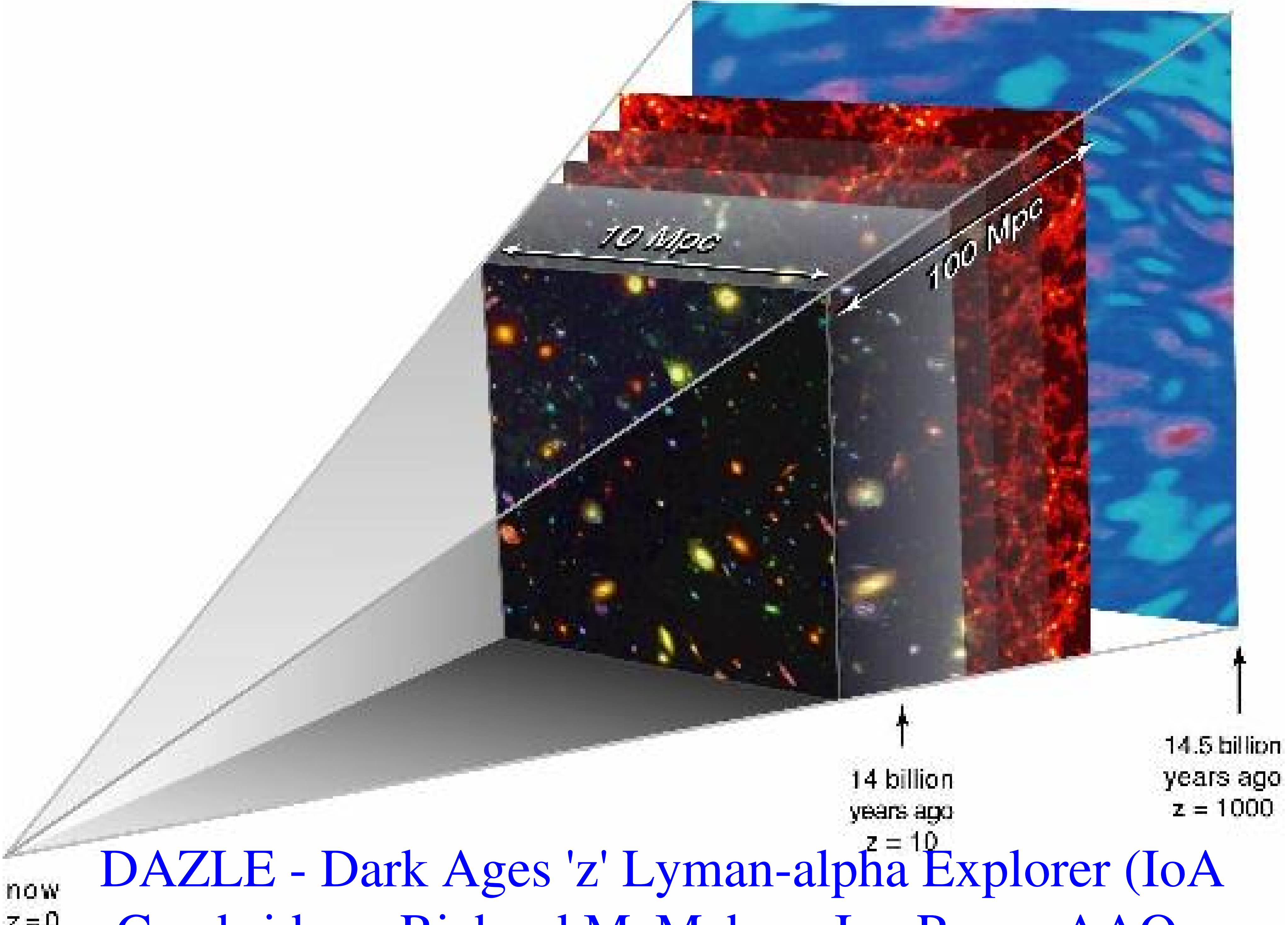
Ways out of the Puzzle

- 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?



DAZLE - Dark Ages 'z' Lyman-alpha Explorer (IoA Cambridge - Richard McMahon, Ian Parry; AAO - Joss Bland-Hawthorne

JAMES WEBB SPACE TELESCOPE – successor to Hubble (2010)