The Most Massive Galaxies in the First (almost) Two Billion Years

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- Searching for massive galaxies
- Results for ‘Balmer Break Galaxies’
- Problems and Caveats
- New models, new photometry, new IMF

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CDM Merging Tree

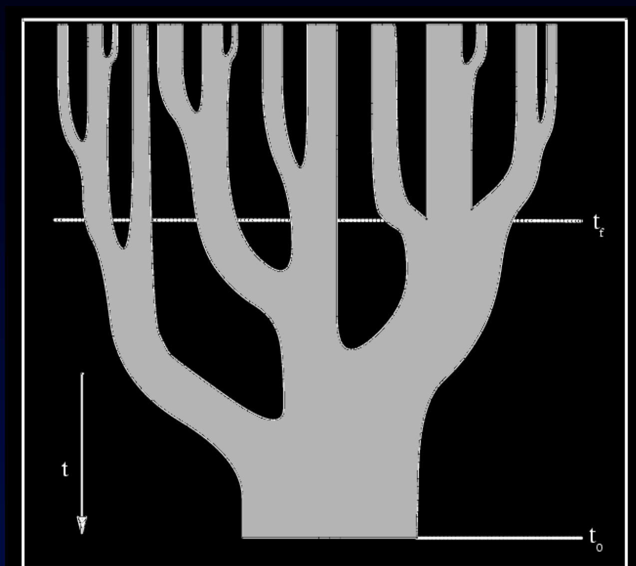
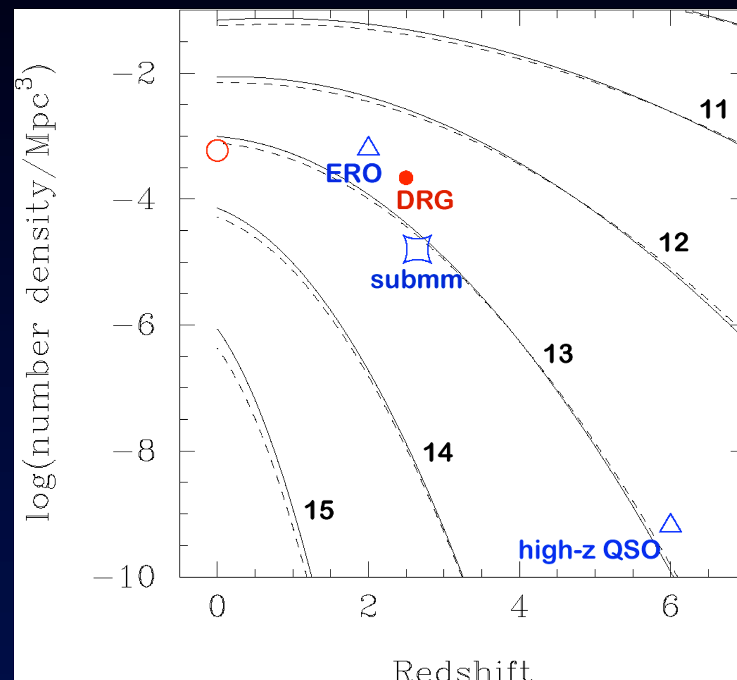


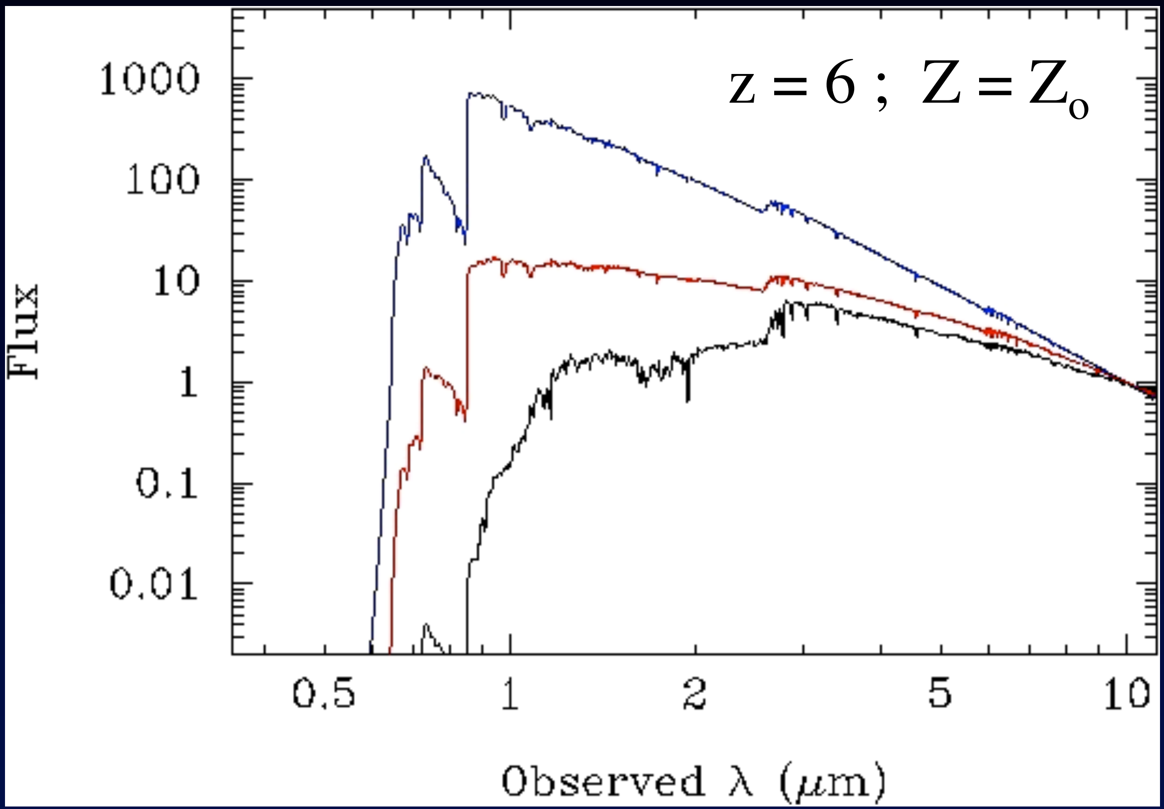
Figure 6. A schematic representation of a "merger tree" depicting the growth of a halo as the result of a series of mergers. Time increases from top to bottom in this figure and the widths of the branches of the tree represent the masses of the individual parent halos. Slicing through the tree horizontally gives the distribution of masses in the parent halos at a given time. The present time t_0 and the formation time t_f are marked by horizontal lines, where the formation time is defined as the time at which a parent halo containing in excess of half of the mass of the final halo was first created.

Density of halo masses vs. z
Sheth-Tormen formalism



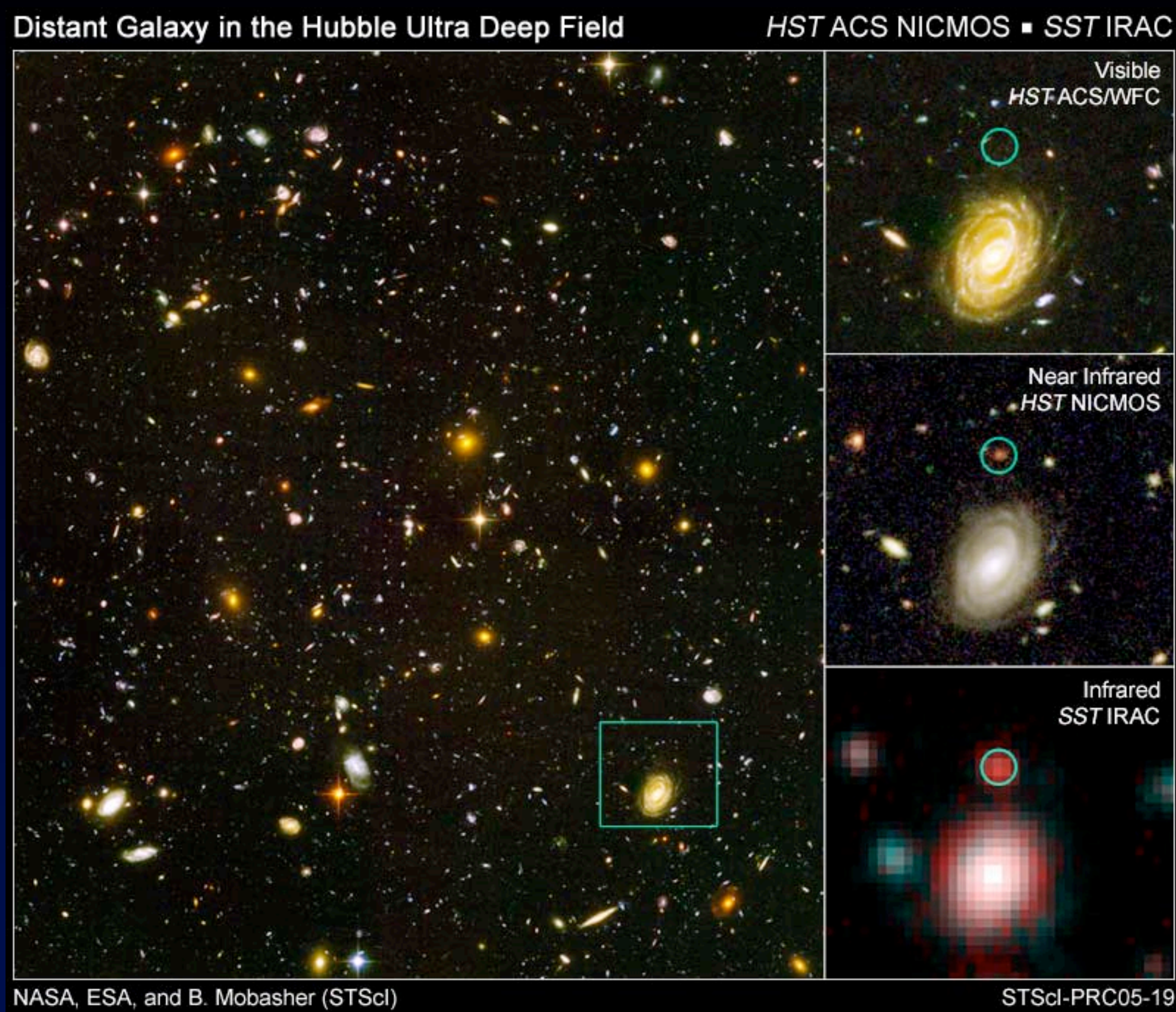
The presence of massive galaxies at high–z 'allowed' by CDM models as long as the number densities are the same as that of the corresponding dark matter halos

Finding massive and evolved galaxies at high redshift

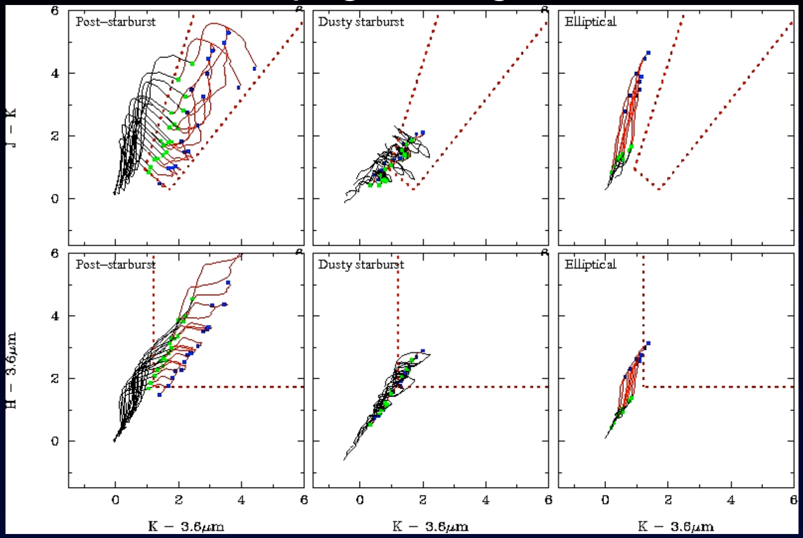


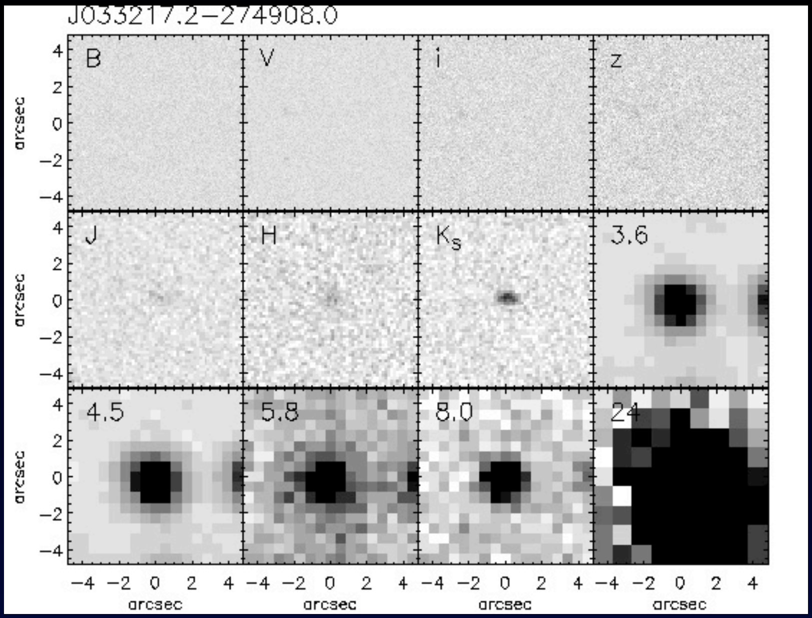
5 Myr, $E_{B-V} = 0.0$
5 Myr, $E_{B-V} = 0.4$
500 Myr, $E_{B-V} = 0.0$

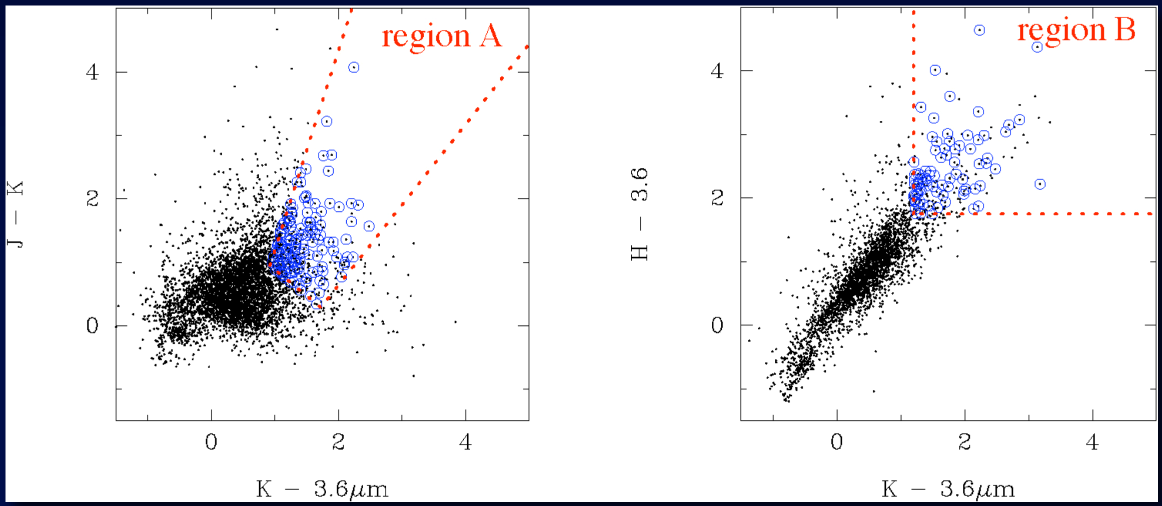
JD2


Distant Galaxy in the Hubble Ultra Deep Field
HST ACS NICMOS ▪ SST IRAC
Visible
HST ACS/WFC
Near Infrared
HST NICMOS
Infrared
SST IRAC
NASA, ESA, and B. Mobasher (STScI)
STScI-PRC05-19

“Spagetti diagrams”



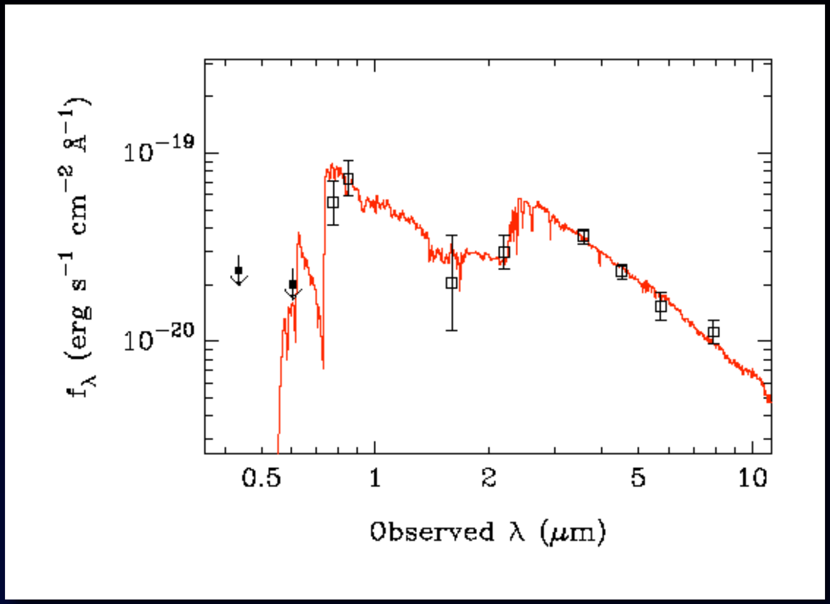




Color selection
of candidates
for z>5 old galaxies

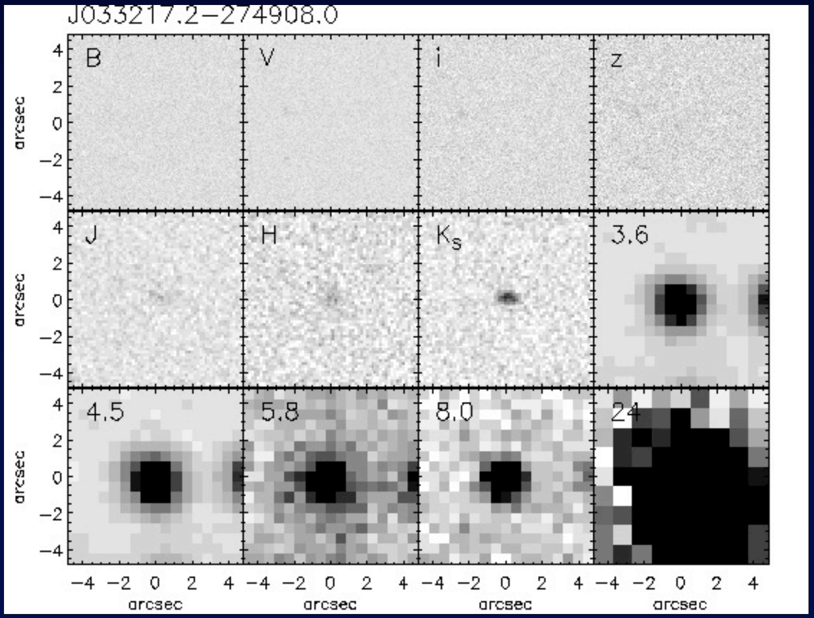
K-selected catalog from
GOODS-S

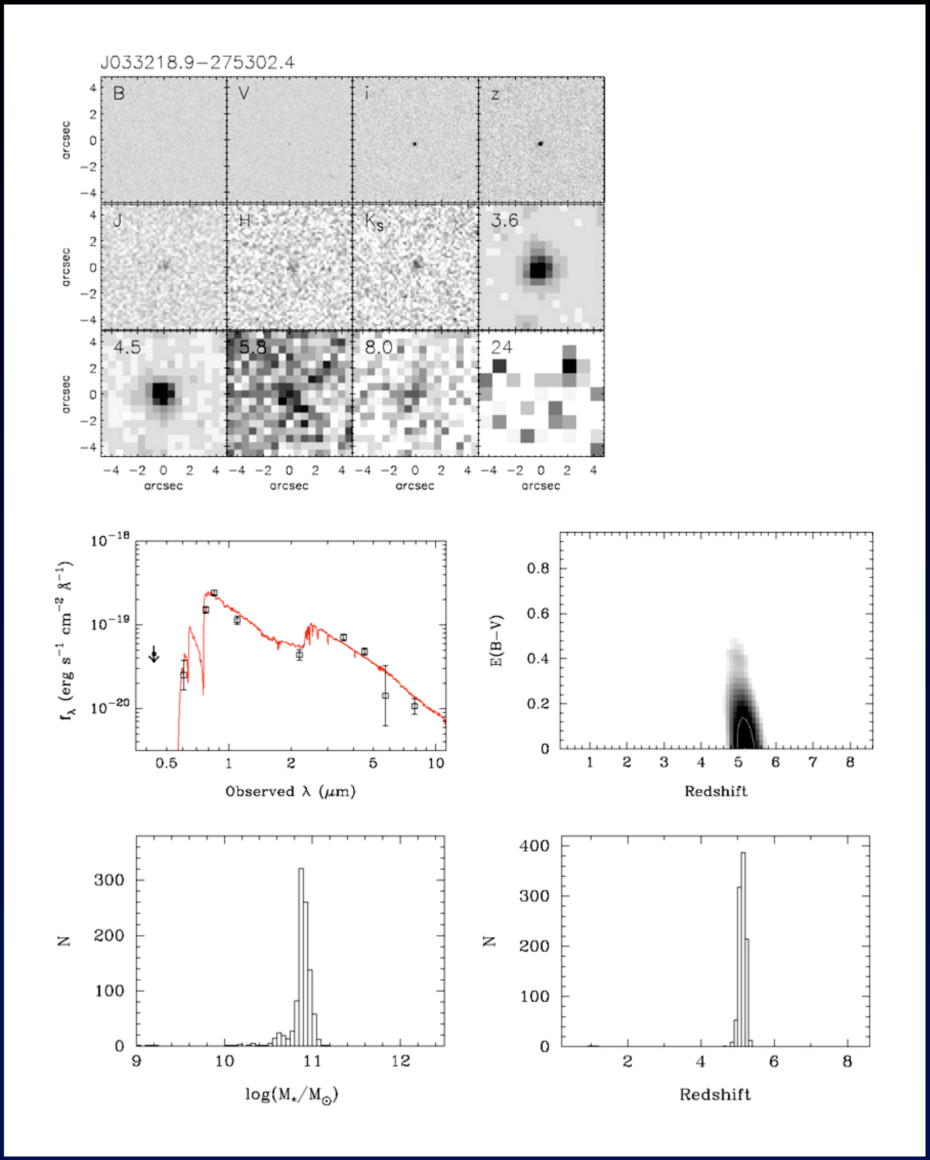
(Not a clean selection)



Population synthesis models to find the 'real' targets

Using Bruzual & Charlot 2003 (BC03)





Monte Carlo simulations:

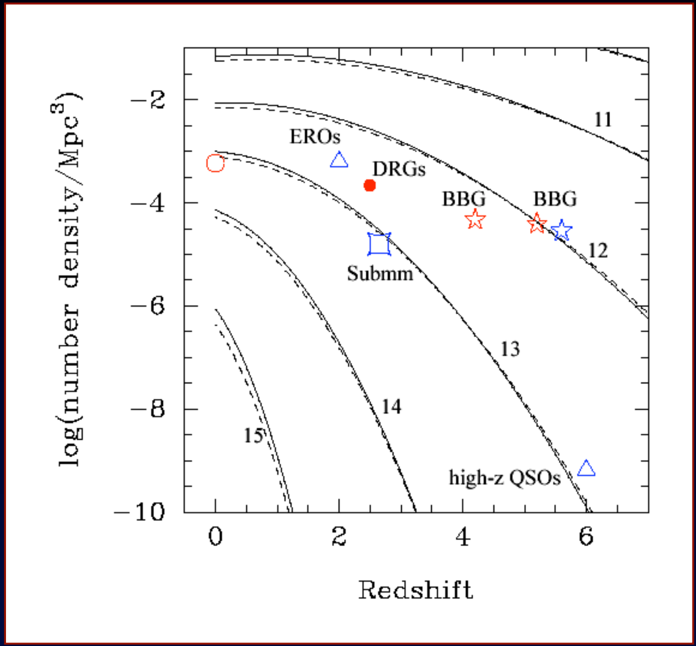
- Allowing the photometry to vary within their formal errors
- find the best fit solutions with the new photometric set
- repeat 1000 times

A total of 11 BBGs at z > 5 (including JD2)

Typical values:

- Stellar masses ~ 2 x 10^{11} M_o
- Ages 0.2 – 1.0 Gyr
- Modest extinction
- Little or no ongoing star formation
- Formation redshift 6 – 25+
- ~60% detected with MIPS at 24mm
- Small systems (radii ~ 2 kpc)
- Not detected in X-rays / radio continuum
  (except one case: weak X-ray emission
  3 x 10^{43} erg s^{-1})
- K_{AB} ~ 24.4

Number density of dark matter halos + BBGs



Sheth–Tormen
σ_8 = 0.74

Co-moving number density @ z ~ 5.2:
4 x 10^{-5} Mpc^{-3}

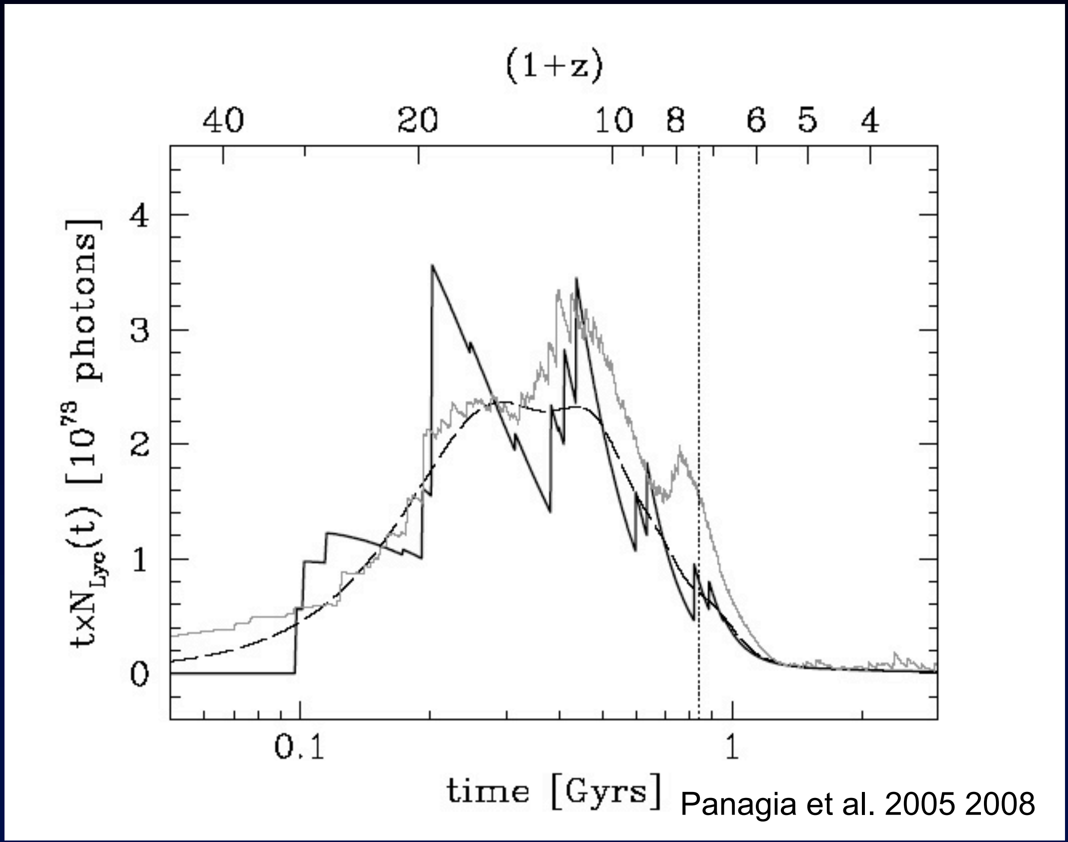
Corresponding halo mass ~ 1 x 10^{12} M_o

M_*/M_{halo} = 0.20β

β ~ 0.3 – 0.4 (the fraction of baryons turned into stars over the life time of the galaxy)

β ~ 0.4 – 1 for BBGs.
Most baryons turned into stars in these halos.

Number of Lyman continuum photons from BBGs



From the Balmer Break Galaxies we can reconstruct the output of ionizing photons.

With a clumping factor C=30 And escape fraction f=0.1, the BBGs account for 10-20% of the ionizing photons required to reionize the IGM.

With C=3 and f=0.2, The BBGs can account for most ionizing photons

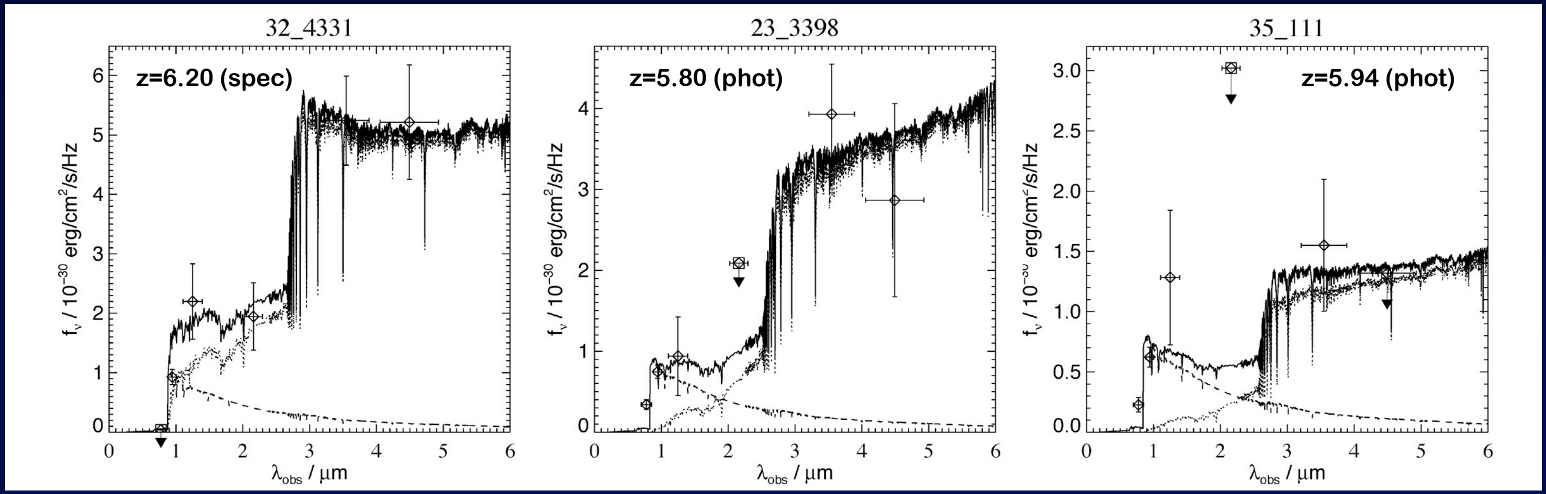
The maximum output occurs in a broad peak at z ~ 15 ± 5

Massive galaxies show up in deep multiwavelength surveys:
HST/VLT/Spitzer data on GOODS South

i-dropout selection in GOODS–South field

- 16 good candidates, 9 with spectroscopic redshift
- 40% show a clear Balmer break at ~4000Å
- Ages 0.2–0.7 Gyr
- Formation redshift $7<z_f<18$
- Stellar masses (1–3) x 10^{10} M_o

See also:
Yan et al. 2005, 2006
Stark et al. 2006
Schaerer et al. 2007,
Eyles et al. 2006,
Bunker et al 2005
etc.



Eyles et al. 2006

Caveats and Criticism
(clouds on the horizon?)

1. Photometric redshifts are wrong
   The BBGs are really dusty starbursts at z ~ 2

2. >50% of BBGs are detected at 24μm
   Hence, dusty starburst at z ~ 2 (Chary et al. 2007)

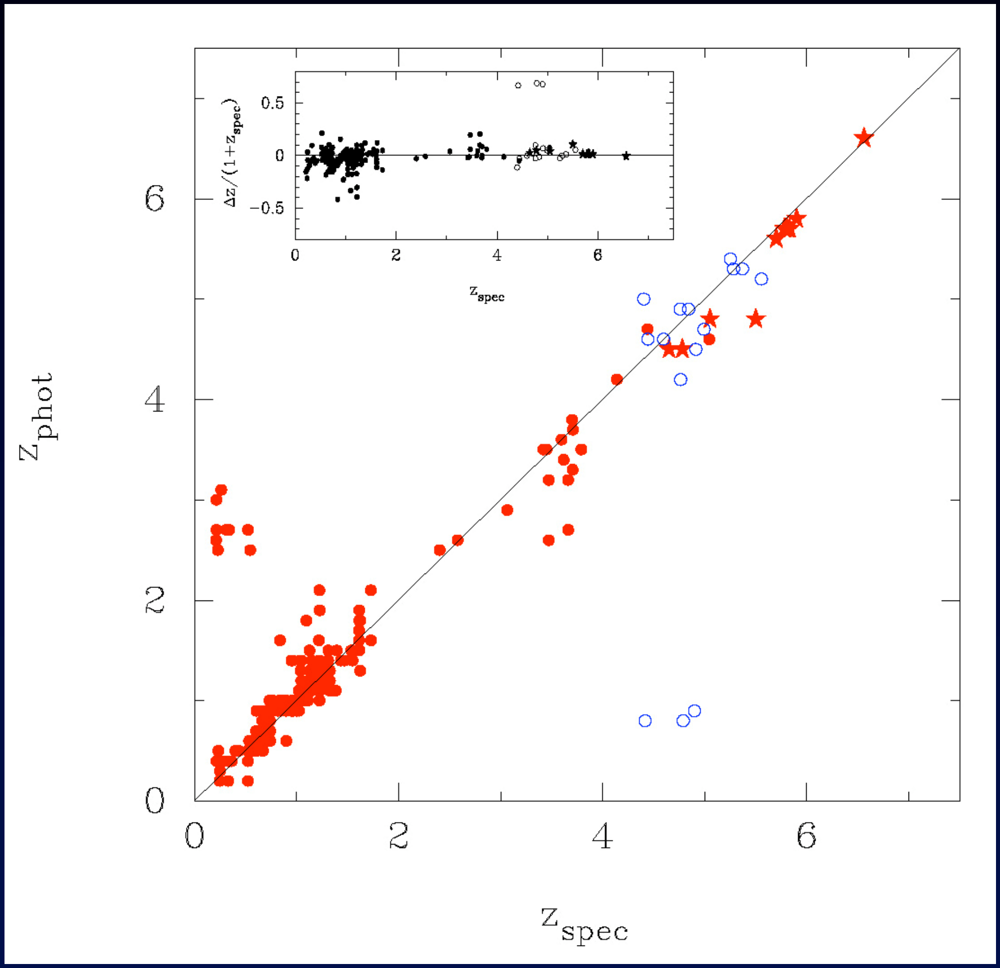
3. Mass estimates are wrong
   IMF, TP–AGB stars

4. Lack of neighbors
   Large scale overdensity should contain neighbors (Muñoz & Loeb 2008)

5. Misidentified low-mass stars
   Less of a concern

6. Star formation histories
   Too simple to account for stellar mass/ages

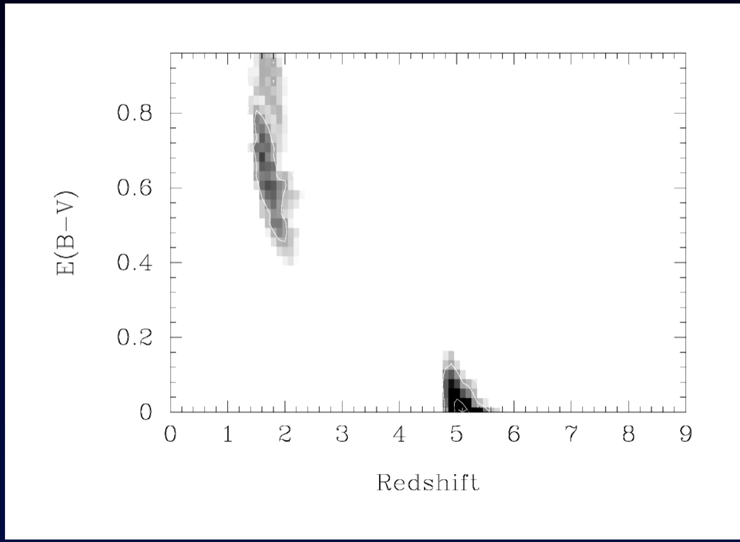
How secure are the photometric redshifts?

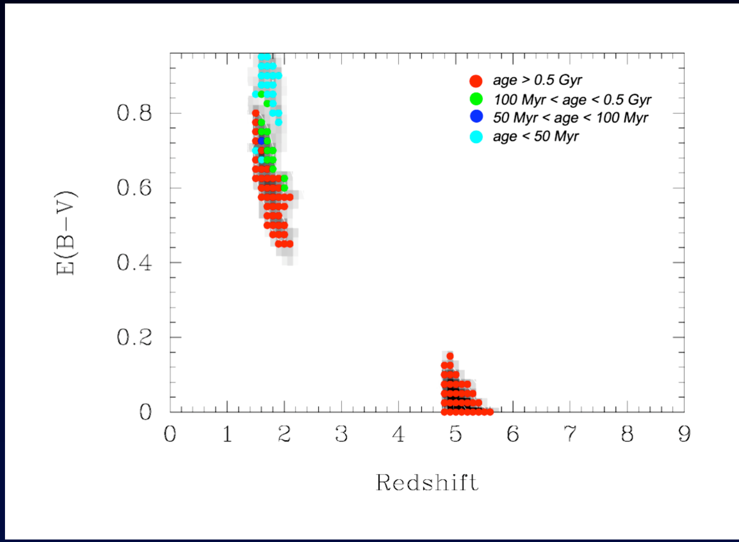


Test the method on galaxies with spectroscopic redshift.
Works well for ~95% of the test sample.

For Balmer break galaxies at high–z, the photometric redshift is determined by (1) the Balmer break, and (2) the Lyman break.
This makes the photo–z robust

A common 'feature' is dual χ^2 minima; one for z~2 and dusty, one for high-z and little extinction

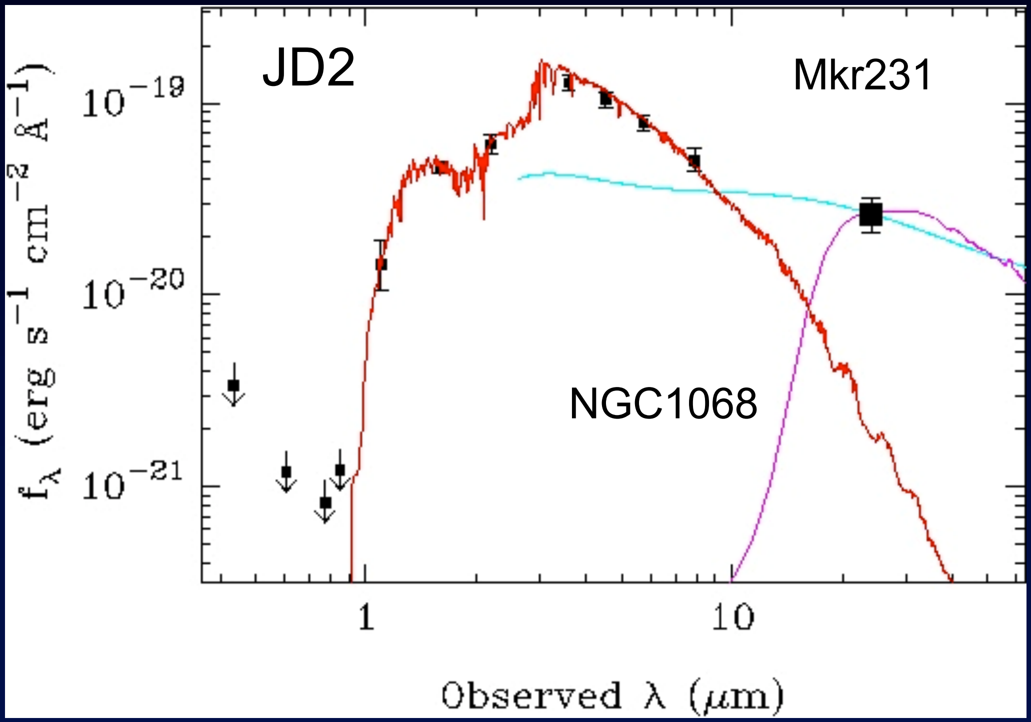




The secondary minimum is often characterized by a dusty Evolved galaxy, not a 'dusty starburst'

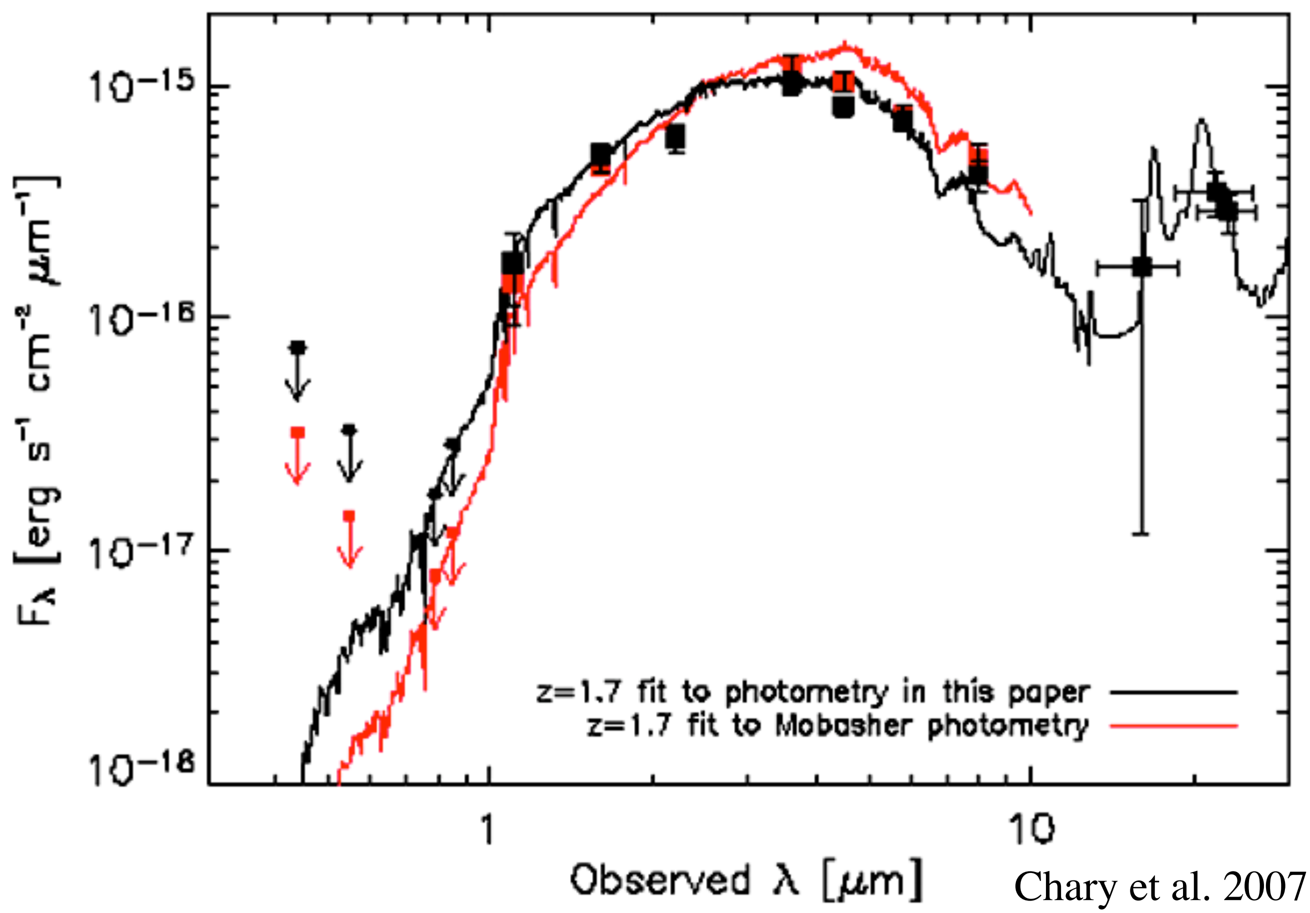
JD2 and BBGs as starburst galaxies at z~2?

MIPS 24μm detections in 6 – 7 out 11 BBGs
(rest-frame 4μm if sources at z ~ 5)



SED of obscured AGN would not contribute significantly to optical part of SED

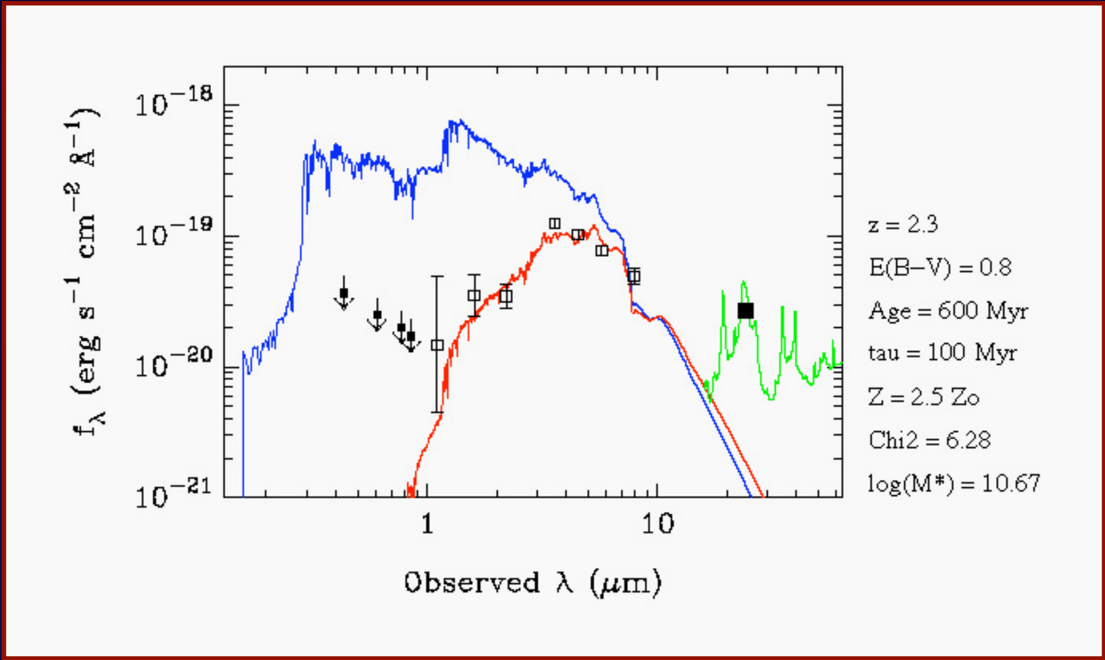
JD2 and BBGs as starburst galaxies at z~2?



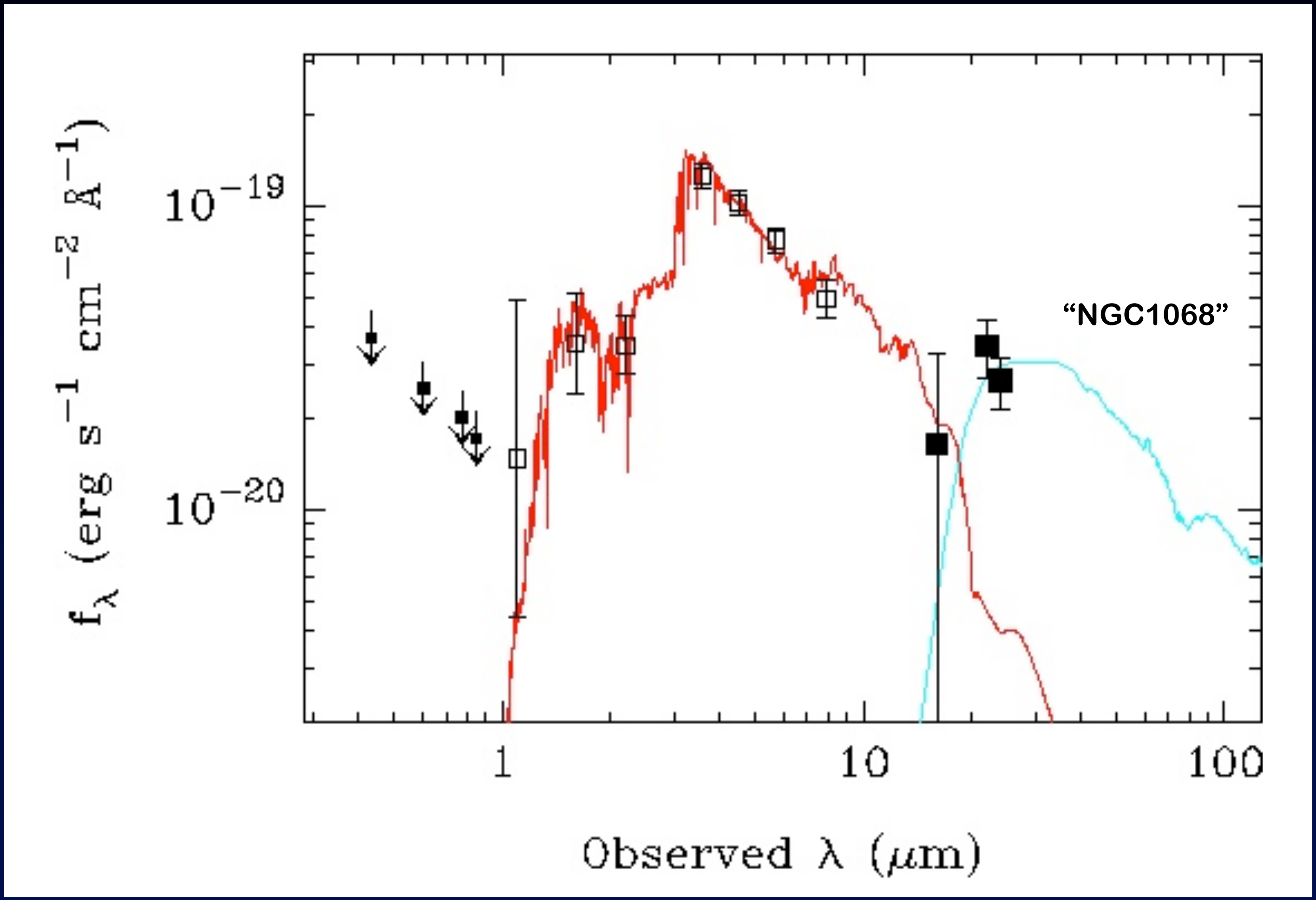
Chary et al. 2007

JD2 and BBGs as starburst galaxies at z~2?

- MIPS detection(s) are fit by a template PAH SED (Brandl et al. 2006)
- Rest–frame optical/UV/NIR is fit by the new CB07 stellar models
- Any reasonable solution requires a post–starburst population
  - Age ~600 Myr, SFR < 1 M_o/yr, $M_* =$ 5 x 10^{10} M_o, Z = 2.5Z_o, A_V~4–5
  - PAH portion suggests SFR~80–100 M_o/yr and A_V~10–20
  - The physical size of the old stellar population: r_h~1.2 kpc



JD2 and BBGs as starburst galaxies at z~2?



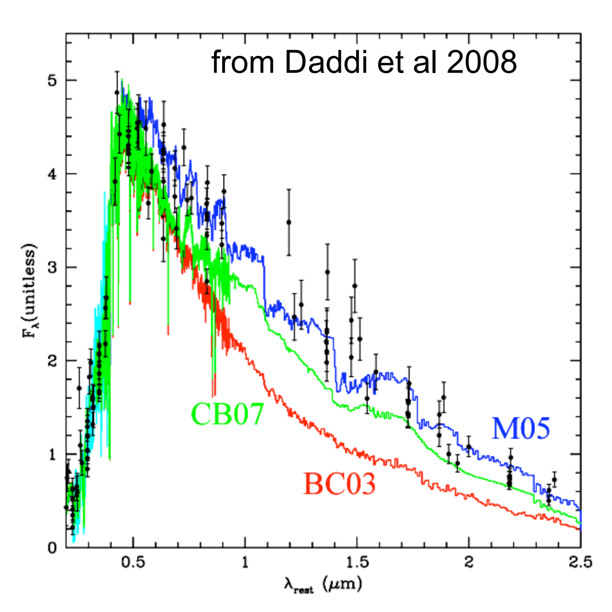
Initial Mass Function
&
Population Synthesis Models

BBGs were modeled using BC03 models with Salpeter IMF

Chabrier IMF will lower the estimated stellar mass

Thermally Pulsating AGB stars not included in BC03.

New models including TP-AGB stars:
Maraston (2005)
Charlot Bruzual (2007)

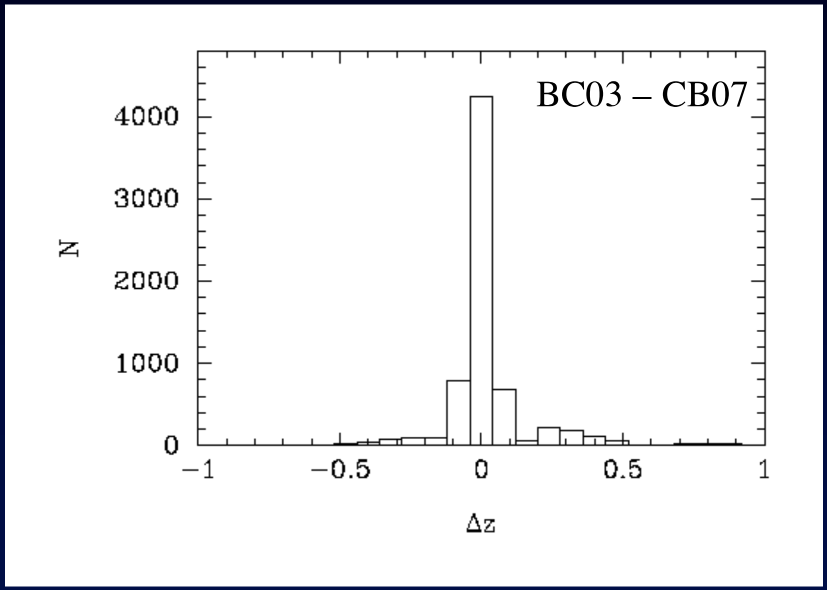


Redid the BBG analysis using CB07 models, Chabrier IMF and v1.9 GOODS release:

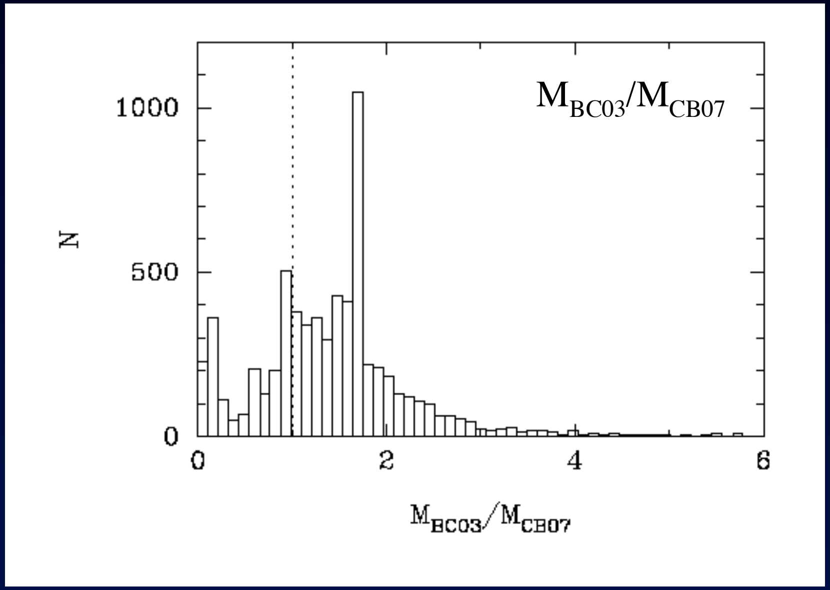
Overall properties does not change. Stellar masses lower, ages smaller

Entire K–selected catalog ~7000 galaxies

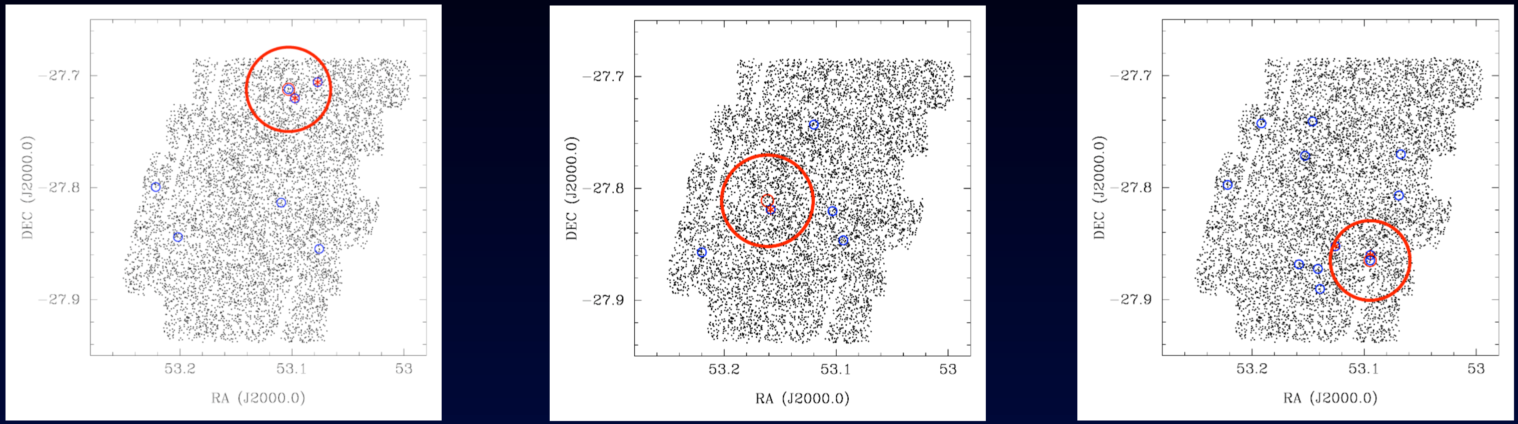
Redshift difference (BC03 – CB07)



Stellar mass ratio (BC03/CB07)

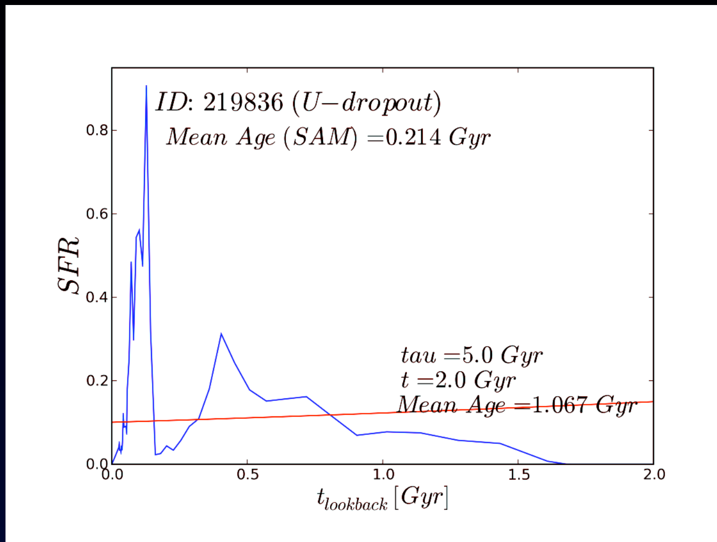


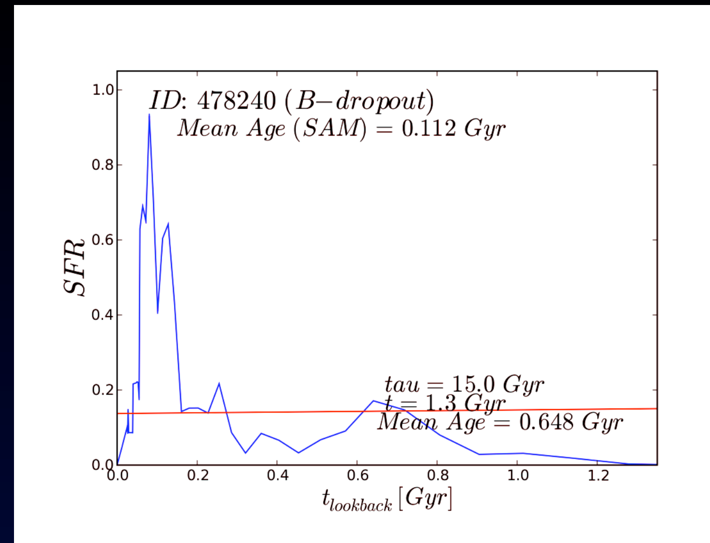
Lack of neighbors within overdense regions?



Radius = 800 kpc
$\Delta z = 0.2$
Sources from K-selected catalog (v1.9)

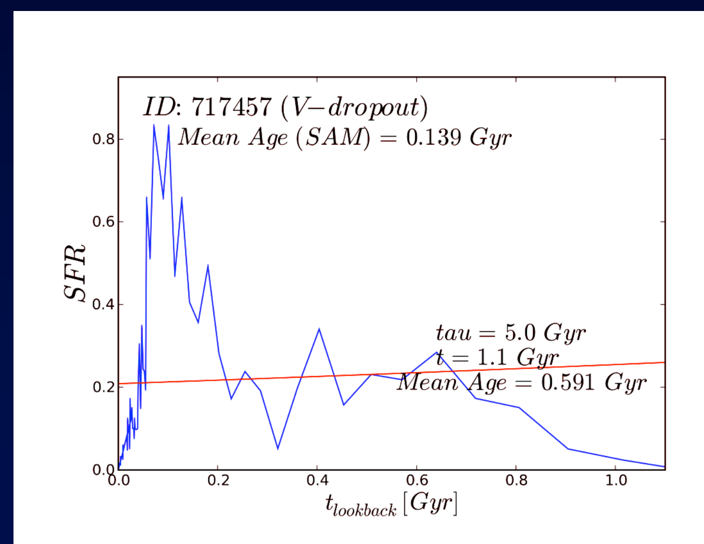
Photometric redshifts too uncertain to allow analysis of neighbor statistics





Star Formation History of UBV dropouts from semi-analytical models compared with results from population synthesis models – same parameters as used for BBGs (Joshua Lee 2008)

Model parameterization oversimplified for any galaxy experiencing a more complex evolutionary history than a single star formation period.



Summary and Future Progress

• Search for evolved galaxies at $z \geq 5$ (`post–starburst')

• K–band and color selected (JHK, 3.6μm) – restframe optical

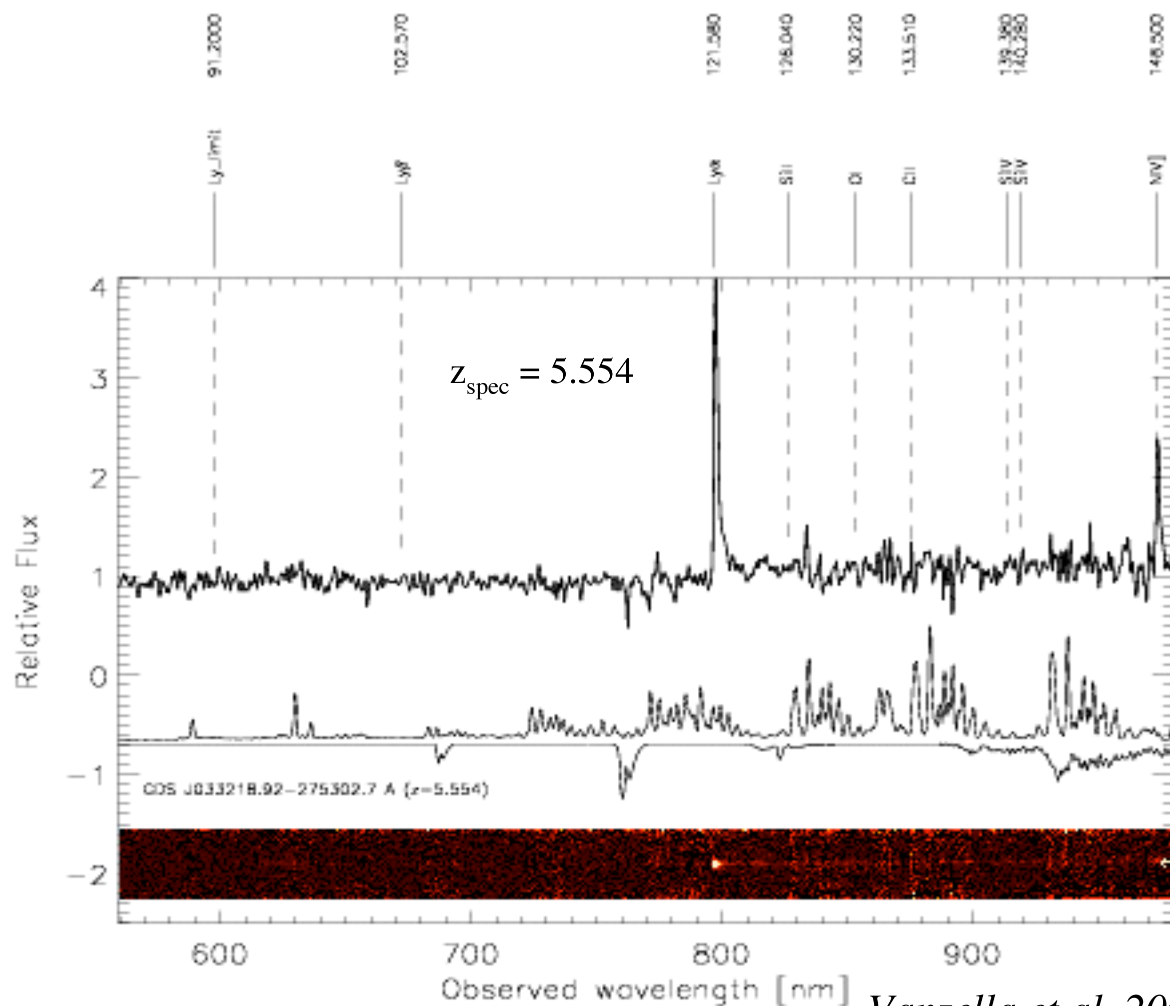
• Stellar populations are characterized as : Massive ~10^{11} M_o, old ~0.1 – 1.0 Gyr, and ultracompact r_h ~ 1–2 kpc

• BBGs not found in the local universe – too compact with too high central stellar densities

• Reconstructing the number of Lyman continuum photons in the reionization epoch. Broad distribution with a peak at $z = 15 \pm 5$

• BBGs contributes to the reionization, but its contribution depends on clumping and escape fraction

• Further progress needs spectroscopy at λ>3μm: JWST (optical efforts are difficult and depends on residual star formation)



Vanzella et al. 2007