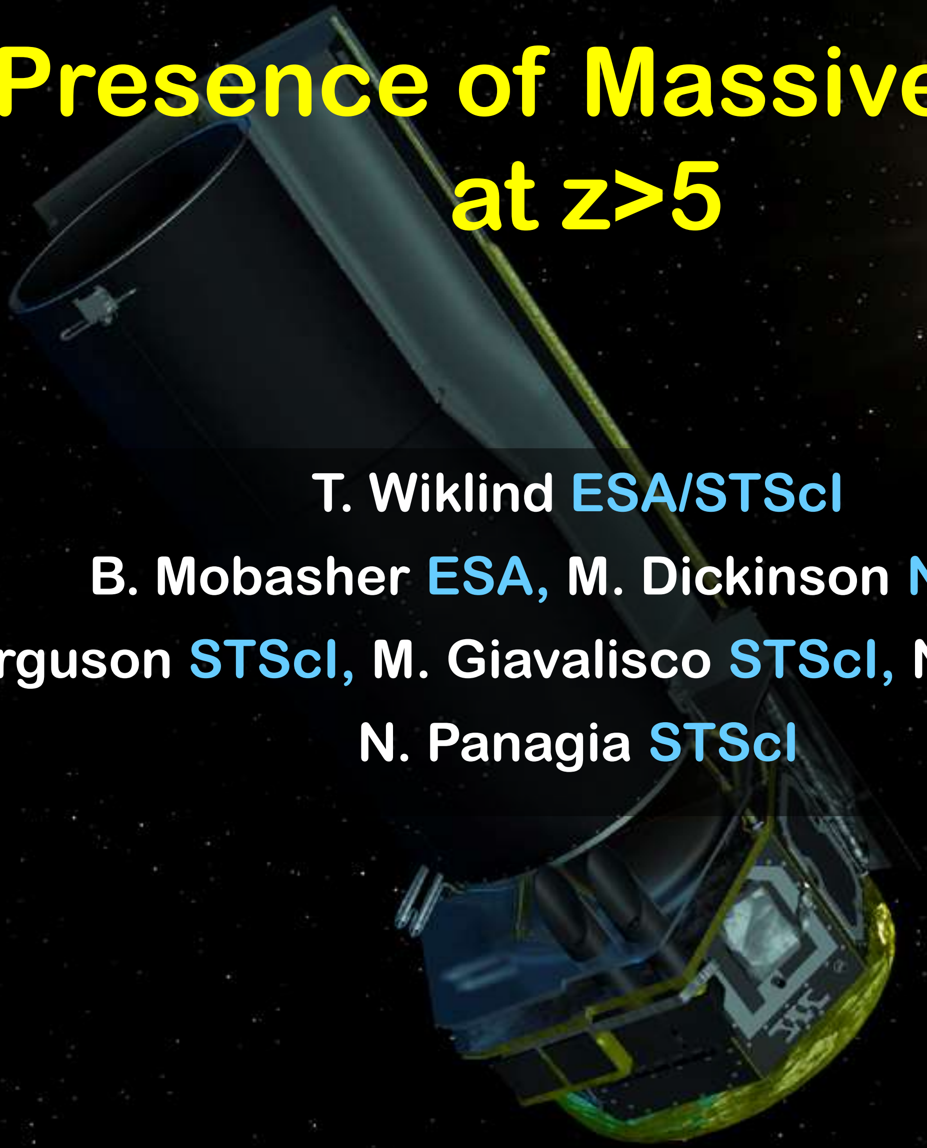
The Presence of Massive Galaxies at z>5



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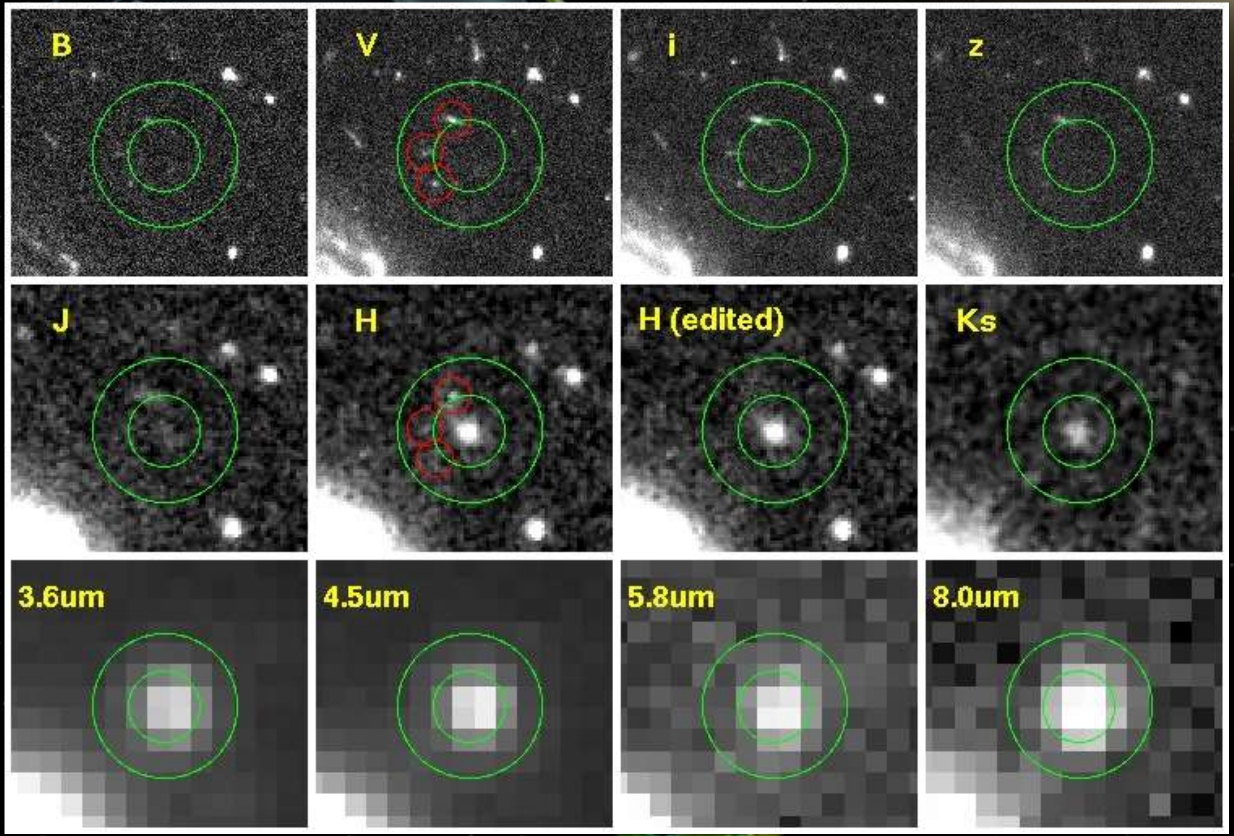
N. Panagia STScI

- ✓ Massive galaxies are found at z ~ 5 – 6 (10^{10} – 10^{11} M_o) in dropout samples *(Yan et al. 2004, 2006; Eyles et al. 2005; Stark et al. 2006; …)*
- ✓ One very massive galaxy (5 10^{11} M_o) was found in HUDF (J–band dropout) *(Mobasher et al. 2005)*
- ✓ These galaxies are 'old' (several 100 Myrs) with low levels of star formation and usually little dust
- ✓ Most have photometric redshifts – some with z_{spec} exist

One evolved and massive galaxy found in the Hubble Ultra Deep Field *at $z=6.5$ and with $M_*=5\ 10^{11}\ M_o$ (Mobasher et al. 2005)*

HUDF–JD2

B > 30.61
V > 31.02
i > 30.88
z > 30.26

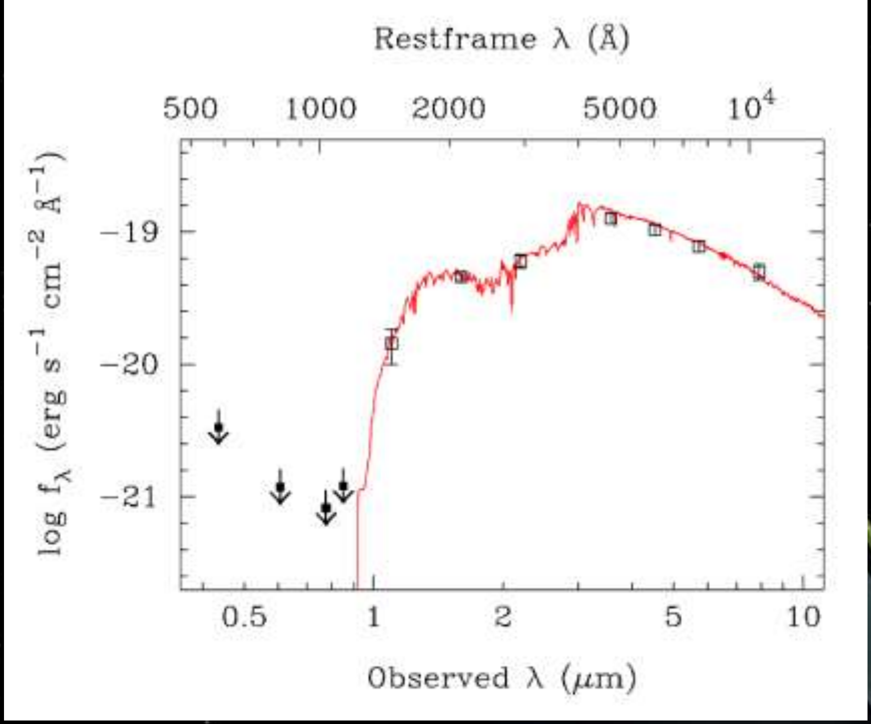


HST/ACS

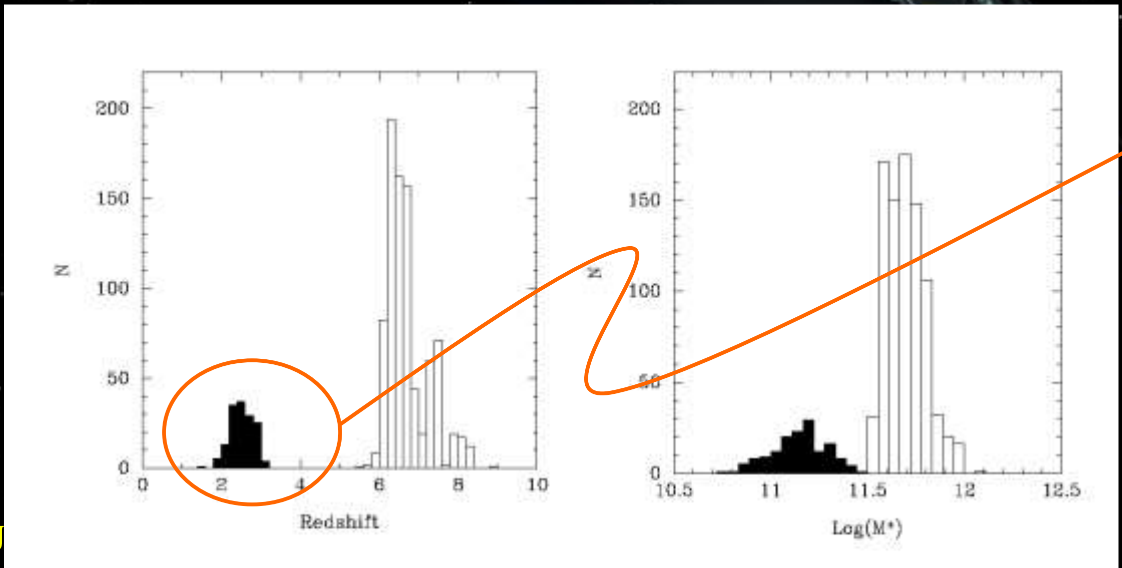
VLT/ISAAC

SST/IRAC

JD2 (J-dropout) in HUDF

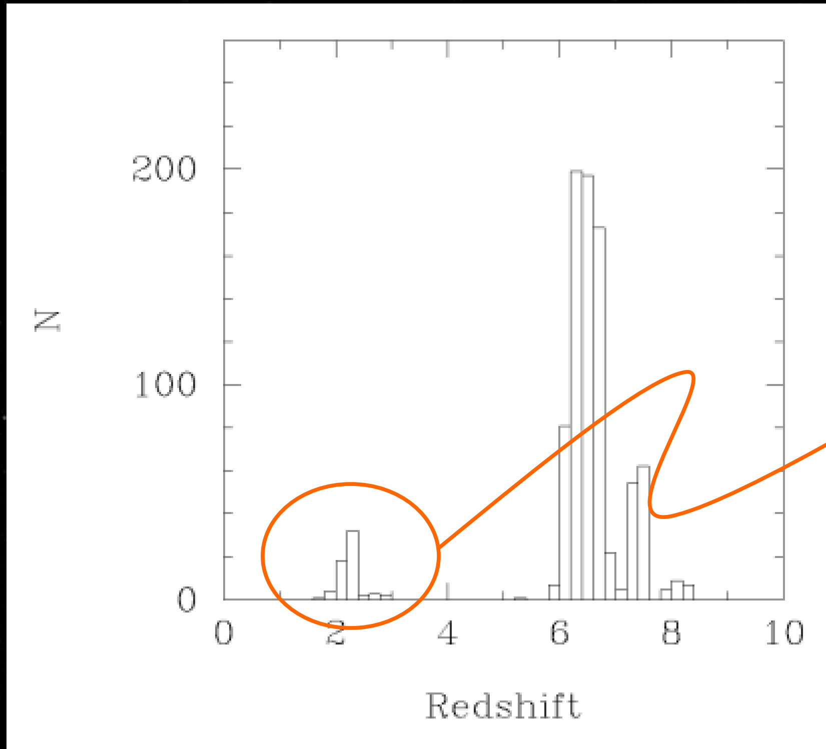


$z = 6.5$
no current star formation
age ~ 0.65 – 1.0 Gyr
$E_{B-V} = 0.0$
$M_* = 5\ 10^{11}\ M_o$
$Z \sim 0.2 – 1.0\ Z_o$



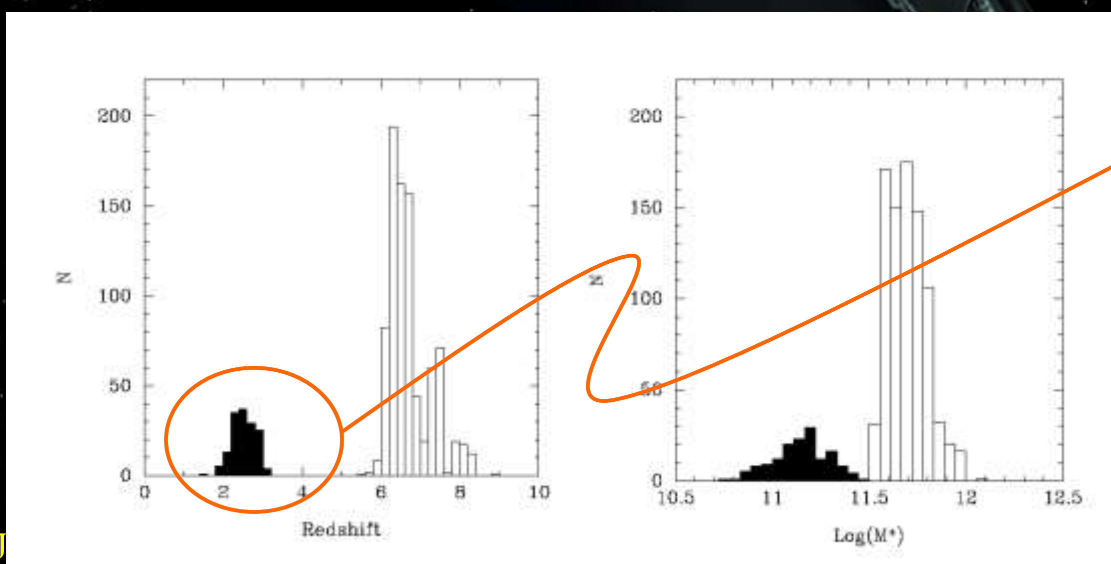
Monte Carlo simulations results in ~15% low-z solutions

J



JD2 (J-dropout) in HUDF

Removing very dusty passively evolving galaxies at z < 4
~ 5% low-z solutions



Monte Carlo simulations results in ~15% low-z solutions

Are there more galaxies at z>5 of similar type, and if so, how do we find them?

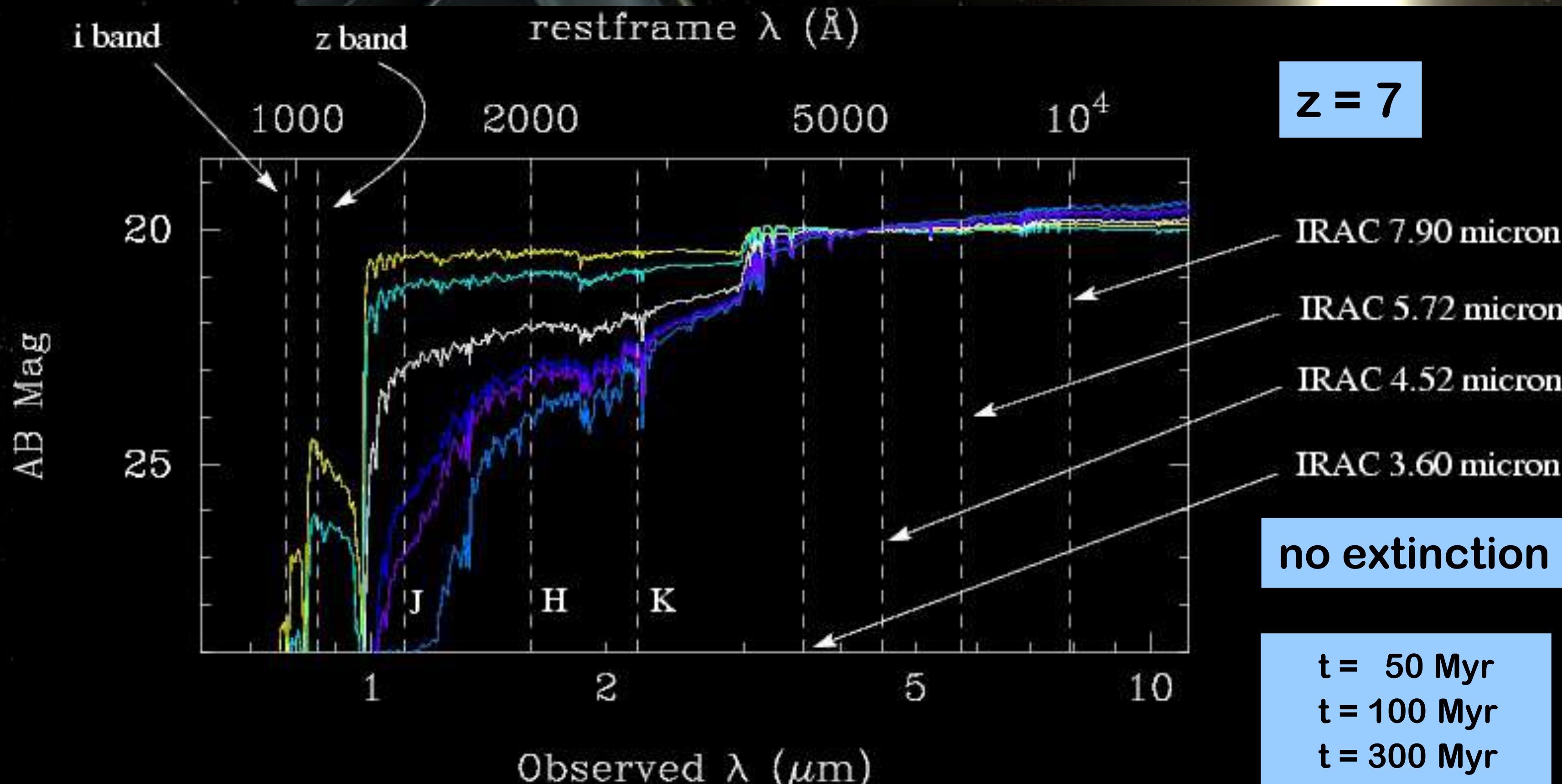
Spitzer/IRAC is crucial for these studies
Probes the optical bands for z>5

Population synthesis fitting at z ~ 5:

1. Redshift (Lyman– and Balmer break)
2. $m_{3.6}$ (~V-band)
3. Age (Balmer break at ~4000Å)
4. Other parameters: dust, metallicity, SFH, IMF, …

	z = 4	z = 5	z = 6	z = 7
3.6μm	7200	6000	5143	4500 Å
4.5μm	9000	7500	6429	5625 Å
5.7μm	11400	9500	8143	7125 Å
8.0μm	16000	13333	11429	10000 Å

The Balmer break is a prominent feature for stellar populations age t > 100 Myrs



z = 7

no extinction

t = 50 Myr
t = 100 Myr
t = 300 Myr
t = 500 Myr
t = 600 Myr
t = 800 Myr

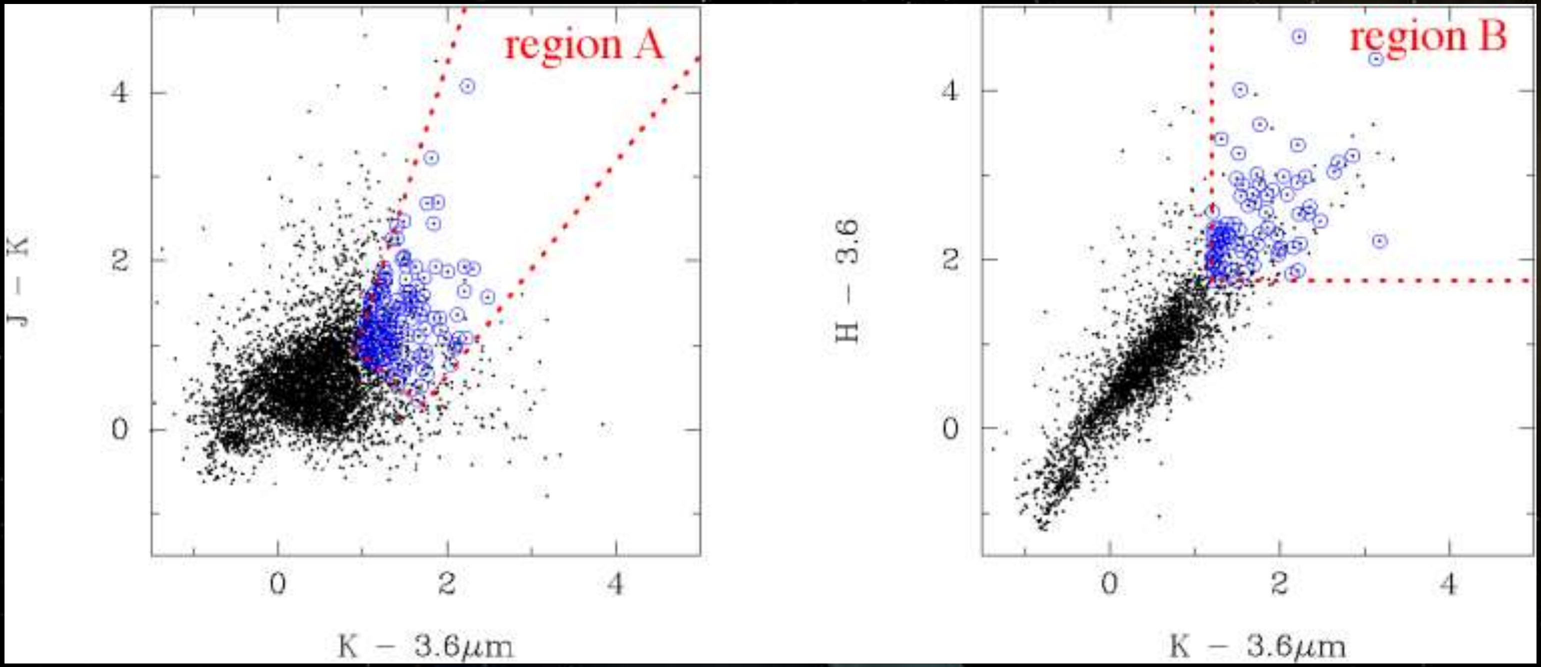
There is no 'clean' way of color selecting old z > 5 galaxies
Use a two-step process:

Color selection:

- The main index is the K_s–3.6μm color
- Use J–K and H–3.6μm as secondary color
- This will result in a relatively large fraction of interlopers

Population synthesis models (Bruzual & Charlot 2003):

- Redshift range z = 0.2 - 8.6
- Age range = 5 Myr - 2.4 Gyr
- Calzetti attenuation law E_{B-V} = 0.0 - 1.0
- IGM absorption
- Metallicities Z = 0.2, 0.4 1.0, 2.5 Z_o
- Salpeter IMF: 0.1 – 100 M_o
- Star formation history: exponentially declining SFR
  τ = 0 - 1.0 Gyr

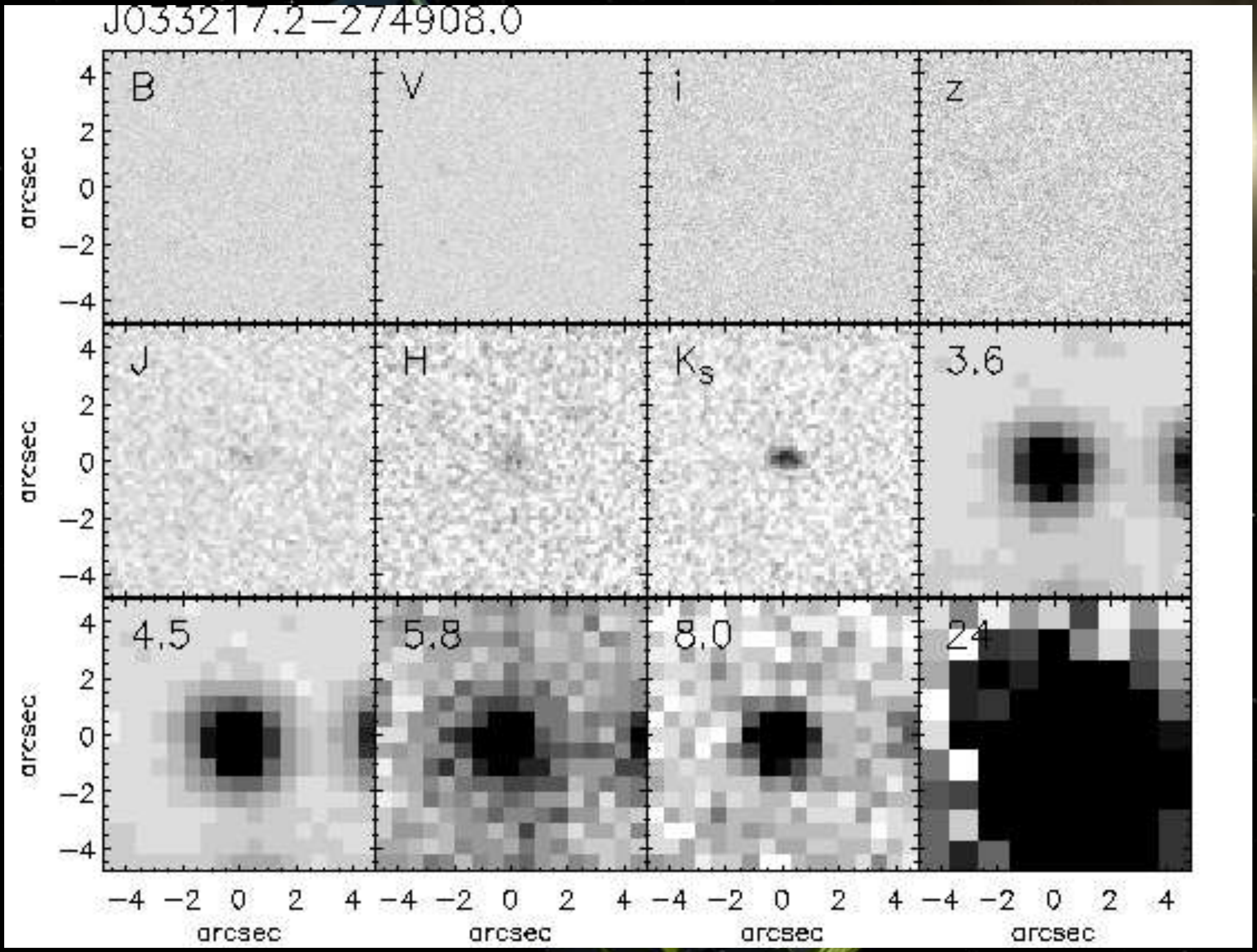


K-selected sample from GOODS-S

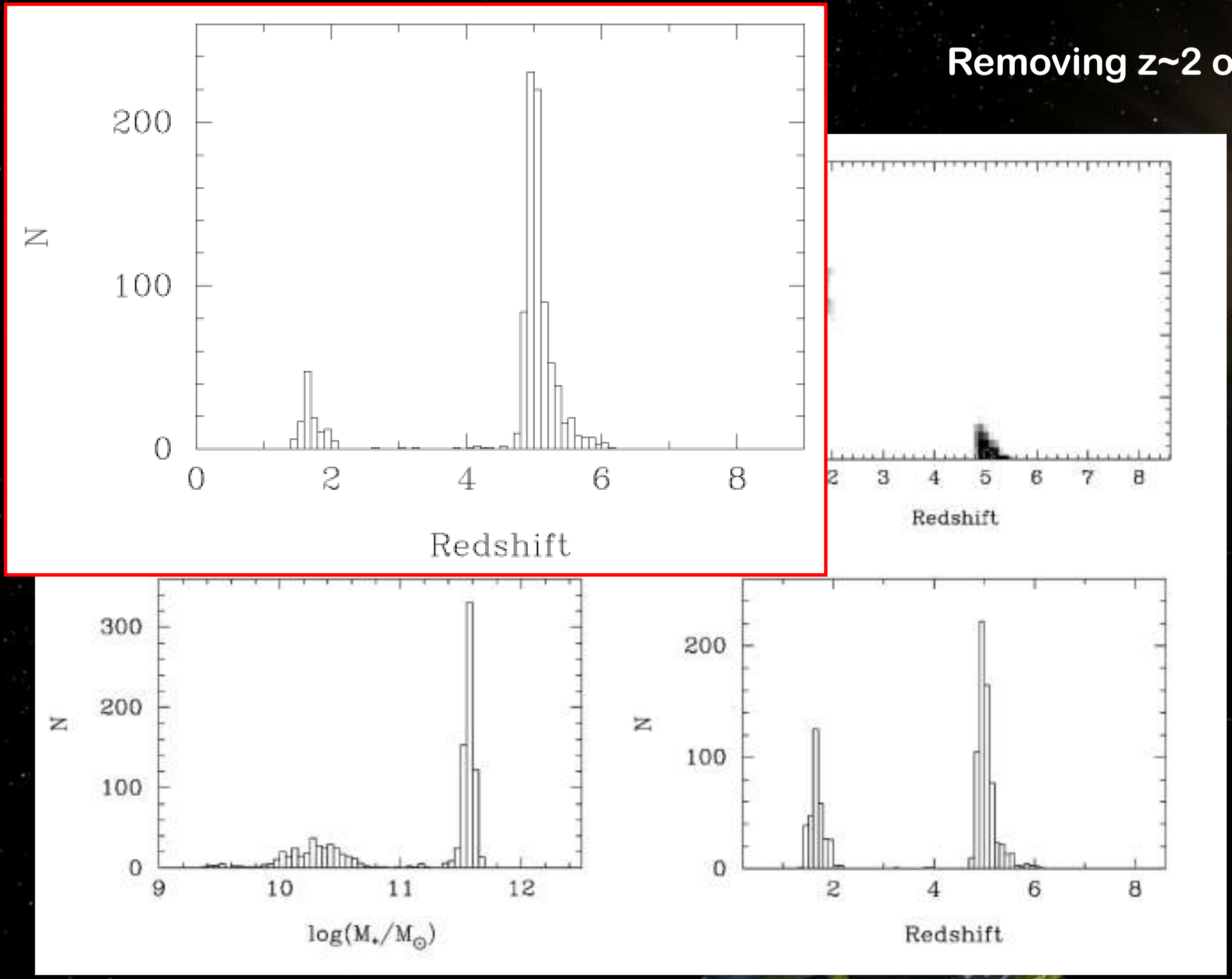
HST/ACS (BV*iz*); VLT/ISAAC (JHK$_s$); SST/IRAC (3.6, 4.5, 5.8, 8μm)

5754 sources: 155 / 85 selected; 14/12 z > 5 (total 17)

~82% complete at K_{AB} = 23.5

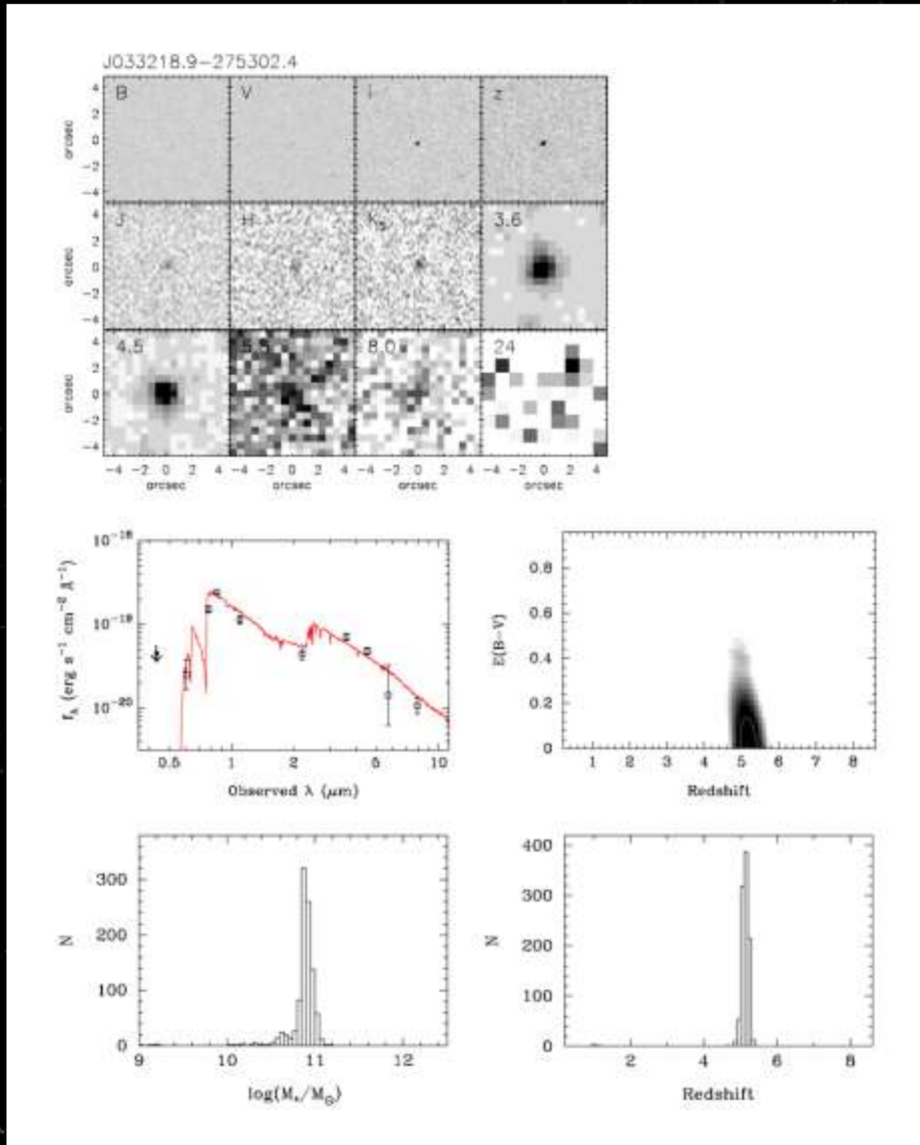

J033217.2−274908.0
B
V
i
z
J
H
Ks
3.6
4.5
5.8
8.0
24
arcsec

Removing z~2 old and dusty galaxies



Best-fit parameters

- $z = 5.1$
- $E_{B-V} = 0.0$
- age = 0.8 Gyr
- $\tau = 0$
- $Z = 0.2\,Z_o$
- $z_{form} = 12$
- $M_* = 4\,10^{11}\,M_o$
- SFR ~ 0 M_o/yr



Best-fit parameters

$z = 5.2$

$E_{B-V} = 0.0$

age = 0.9 Gyr

$\tau = 0.3$ Gyr

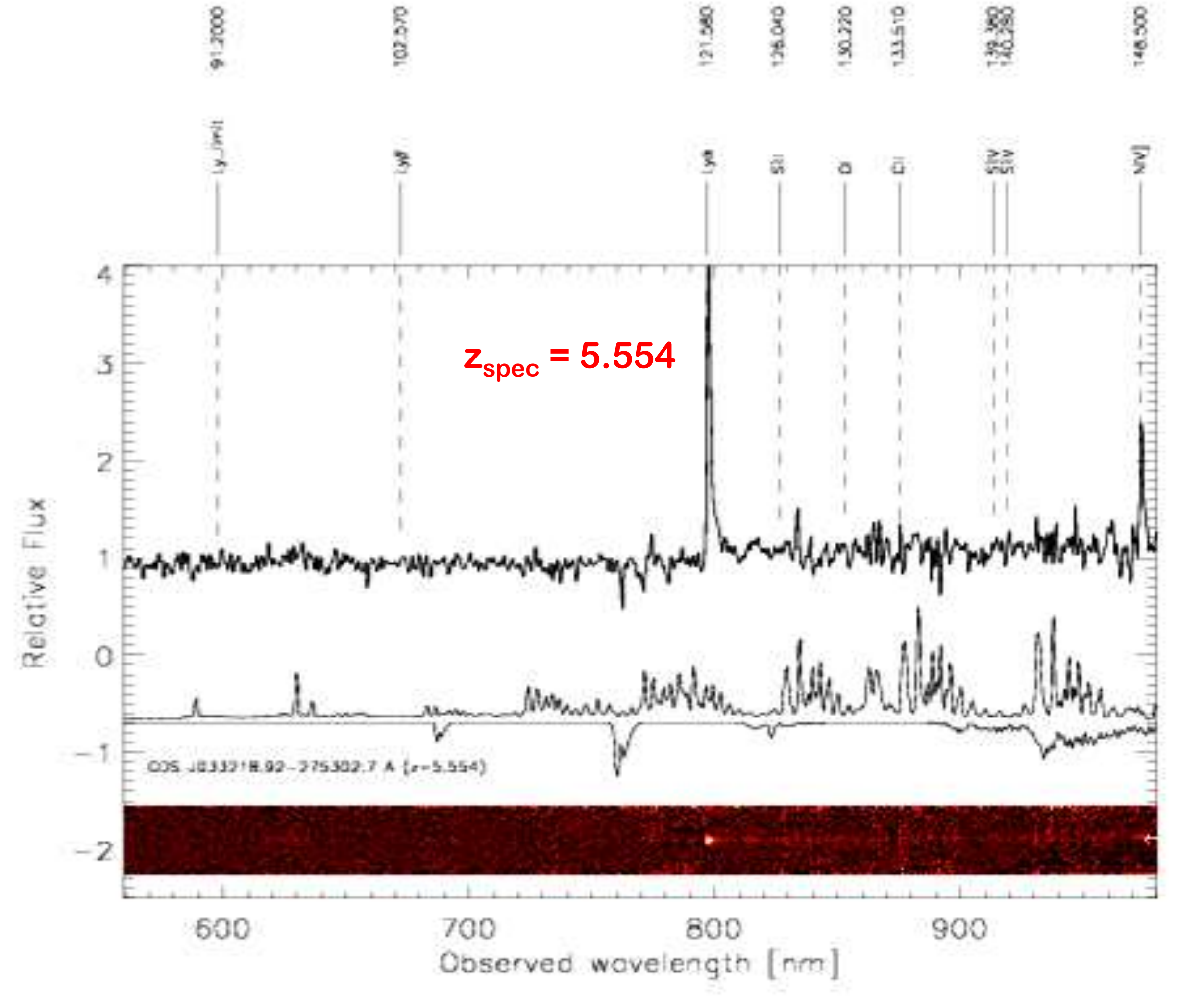
$Z = 0.2\ Z_o$

$z_{form} = 17$

$M_* = 0.7\ 10^{11}\ M_o$

SFR ~ 12 M_o/yr

VLT/FORS2 *(Vanzella et al. 2006)*



Also in the sample studied by Stark et al. 2006 (astro-ph/0604250)

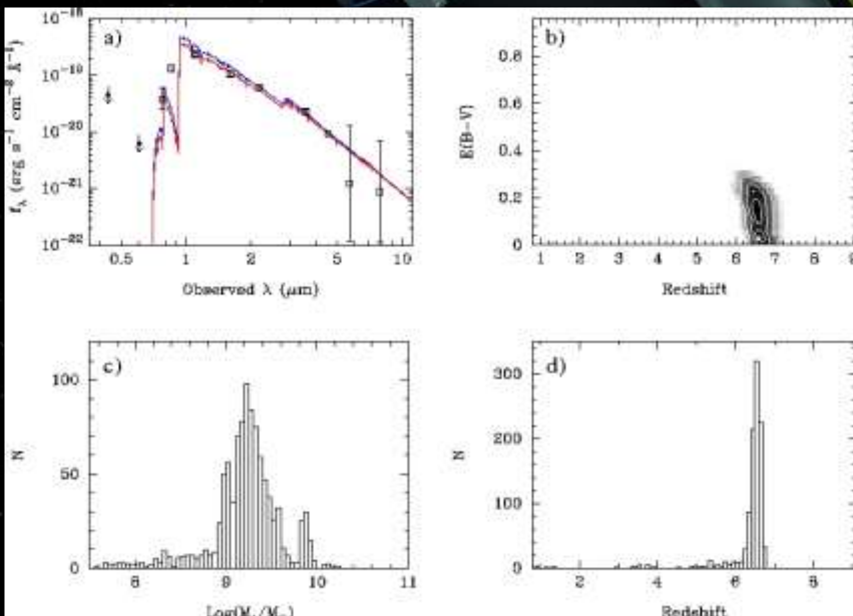
A total of 11 BBGs at $z > 5$ (including JD2)

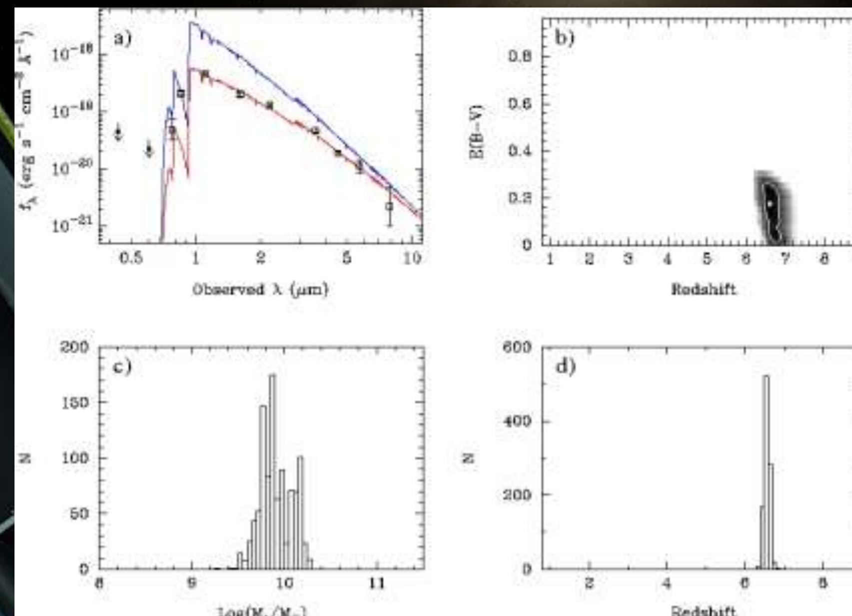
Typical values:

- Stellar masses ~ $2\ 10^{11}\ M_o$
- Ages 0.2 – 1.0 Gyr
- Modest extinction
- Little or no ongoing star formation
- Formation redshift 6 – 25+
- ~60% detected with MIPS at 24μm
- Small systems (radii ~ 2–3 kpc)
- Not detected in X-rays / radio continuum

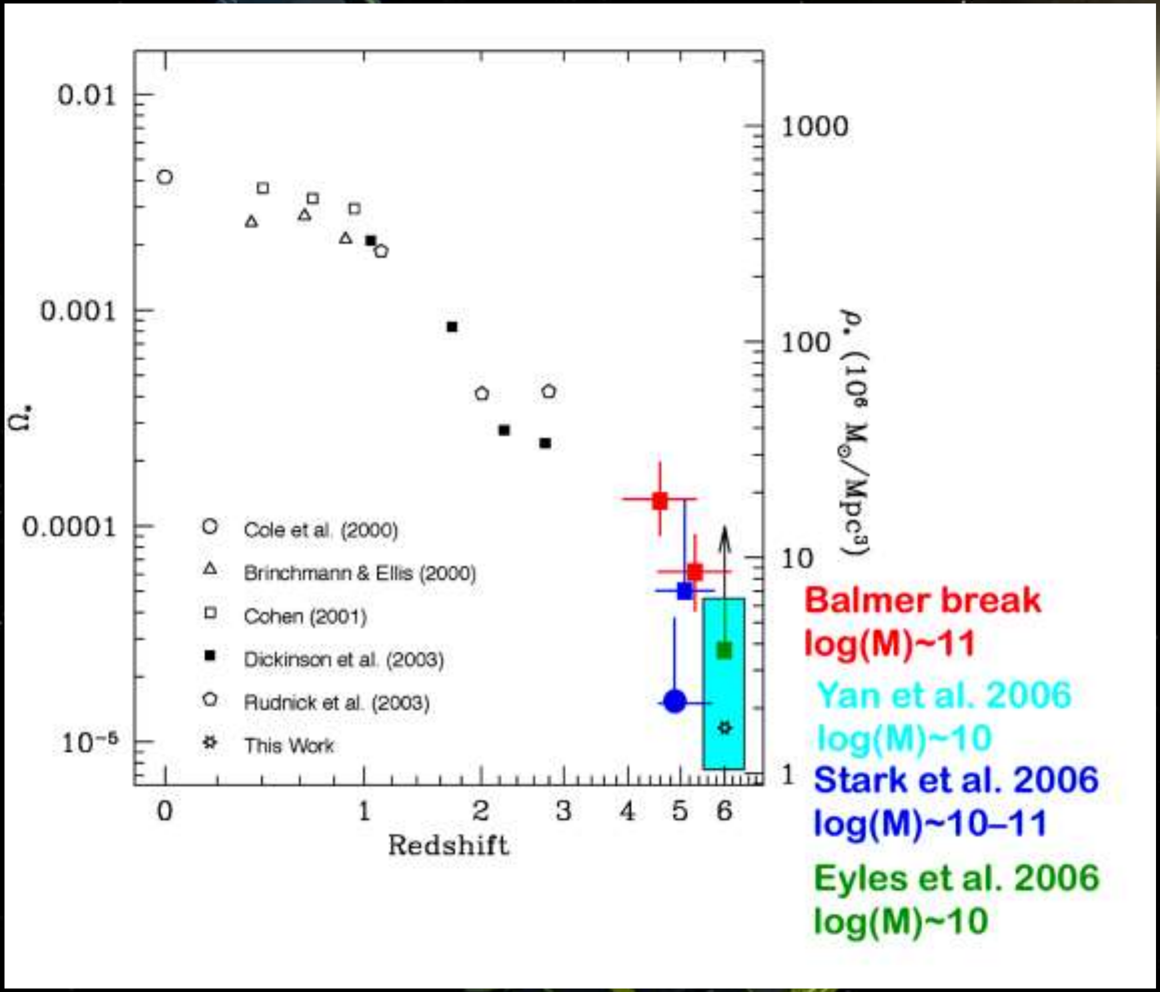
  (except one case: weak X-ray emission $3\ 10^{43}$ erg s^{-1})

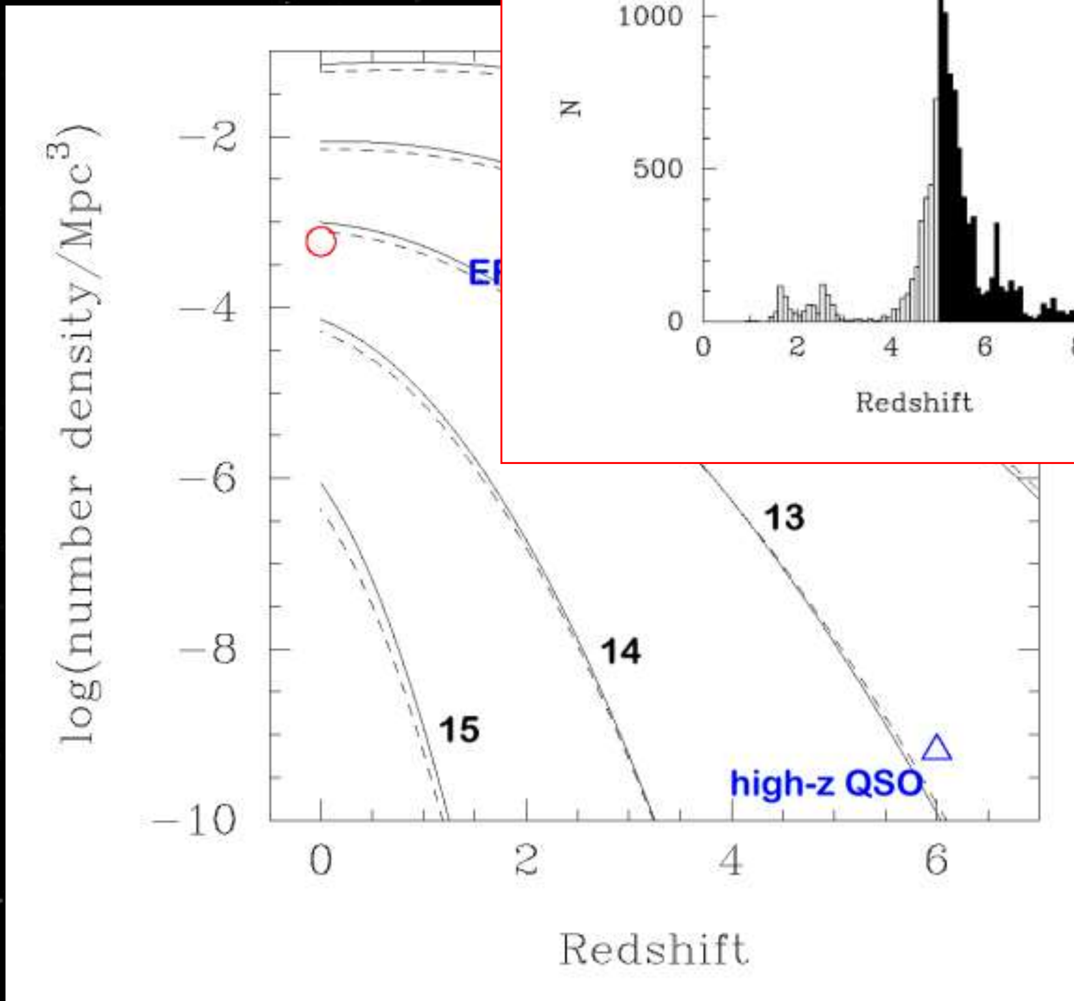
Star forming galaxies at z = 6.5

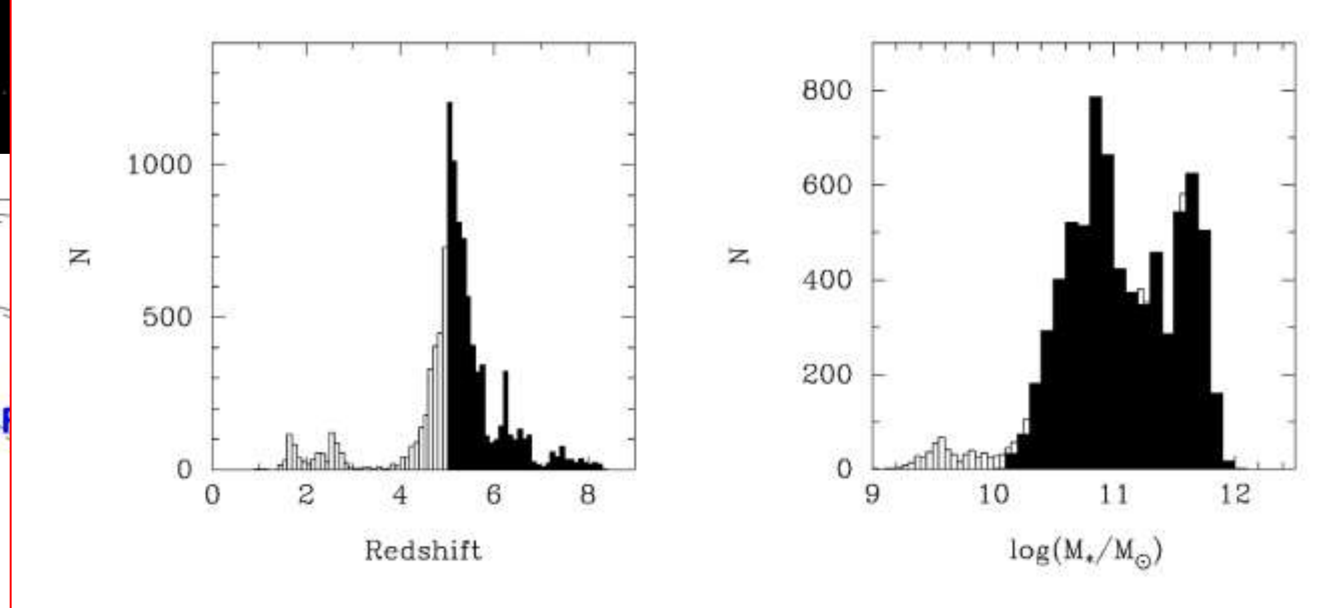




From Yan et al. 2006







z>5 galaxies:
M_*/M_{halo} ~ 0.15

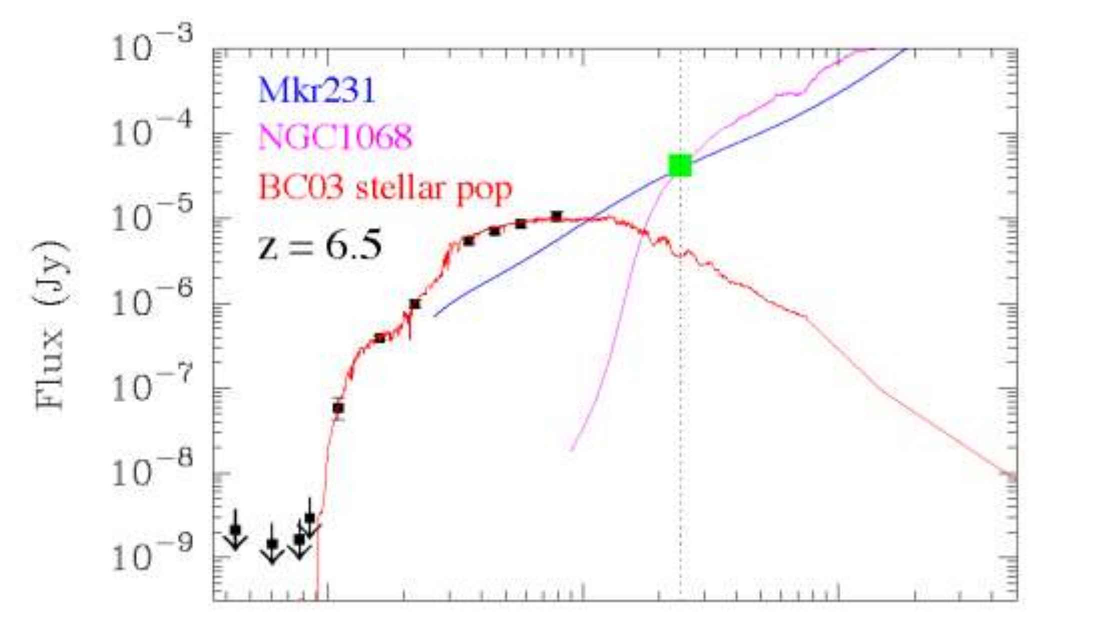
Milky Way and M31:
M_*/M_{halo} ~ 0.06
(Klypin et al. 2002)

Most baryons turned into stars

How well can we trust the results?

- Photometric redshift
  - reasonably robust (Lyman break + Balmer break)
- Completeness
  - possibly significant completeness corrections
  - definition of the selection function and effective volume
  - brings the number/stellar mass densities upwards
- MIPS 24μm detections
  - usually interpreted as PAHs in star forming systems
  - low–z solutions: very dusty passively evolving galaxies
  - dust obscured AGNs at z ~ 5 ?
- Stellar mass estimates
  - model dependent (M/L different in BC03 and M05)
  - IMF and star formation history
  - dust properties different at z>5

MIPS 24μm detections in 6 out of 11 BBGs
(restframe 4μm if sources at z ~ 5)



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

Alternatively, all MIPS detected galaxies at z~2, but most z ~ 2 solutions are for dusty old and passively evolving galaxies

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The M05 models vs. BC03 models

BC03 (Bruzual &Charlot 2003)

Padova tracks:
convective overshooting
—> longer MS life times for given stellar mass and RGB develops after ~1.0Gyr

TP–AGB calibration:
reproduce the maximum TP–AGB luminosity (LMC clusters)

M05 (Maraston 2005)

Frascati tracks:
no convective overshooting
—> shorter MS life times for given stellar mass and RGB develops after ~0.5Gyr

TP–AGB calibration:
the fractional contribution of the TP–AGB to total bolometric light (LMC clusters)

The net effect is that M05 are redder for a given age (0.2 – 2 Gyr). Difference most pronounced at NIR wavelengths

…but, degeneracies may still dominate

ID	z_{spec}	z_{phot}	E_{B-V}	age Gyr	τ Gyr	Z Z_o	$\log(M_*)$ Mo	$M_*(BC03)/M_*(M05)$
BC03 (age < 2.5 Gyr)								
8238	1.39	1.0	0.700	0.9	0.3	0.4	10.440	0.61
4650	1.55	1.6	0.200	1.8	0.4	0.4	11.366	0.46
1025	1.73	1.6	0.250	2.0	0.6	0.4	10.875	1.21
3523	1.76	1.6	0.300	0.3	0.0	2.5	10.501	0.50
3650	1.91	1.8	0.200	0.6	0.0	1.0	10.885	0.92
3574	1.98	2.0	0.150	0.9	0.1	0.4	10.592	0.93
1446	2.47	3.0	0.200	0.5	0.0	0.4	10.947	3.28
BC03 (age <1.1 Gyr)								
8238	1.39	1.0	0.700	0.9	0.3	0.4	10.440	0.61
4650	1.55	1.6	0.325	0.9	0.2	0.2	11.304	0.40
1025	1.73	1.7	0.225	0.9	0.2	1.0	10.817	1.06
3523	1.76	1.6	0.300	0.3	0.0	2.5	10.501	0.50
3650	1.91	1.8	0.175	0.8	0.1	1.0	10.906	0.97
3574	1.98	2.0	0.150	0.9	0.1	0.4	10.592	0.93
1446	2.47	3.1	0.175	0.8	0.1	0.2	10.978	3.52
M05 model								
8238	1.39	1.39	0.15	0.7	0.3t	2.0	10.653	0.61
4650	1.55	1.55	0.15	3.5	1.0	0.5	11.699	0.40
1025	1.73	1.72	0.07	1.4	0.3	1.0	10.792	1.06
3523	1.76	1.68	0.40	0.3	0.1t	0.2	10.799	0.50
3650	1.91	1.88	0.20	0.3	0.0	2.0	10.919	0.97
3574	1.98	1.94	0.30	0.2	0.0	2.0	10.623	0.93
1446	2.47	2.74	0.00	0.4	0.0	2.0	10.431	3.52

using 10 photometric data points allowing a larger parameter space

using 14 photometric data points

SUMMARY

- Color selection (NIR & IRAC) + photometric redshift can identify $z>5$ galaxies with ages >100 Myr and M_* in excess of $10^{11}\ M_o$. The selection is mainly based on identifying the Balmer break over K-3.6μm

- In the GOODS South field we find 11 such candidates (including JD2)

- The objects found are characterized by little or no ongoing star formation, ages of several 100 Myrs, masses of $\sim 10^{11}\ M_o$ and little or no dust extinction.

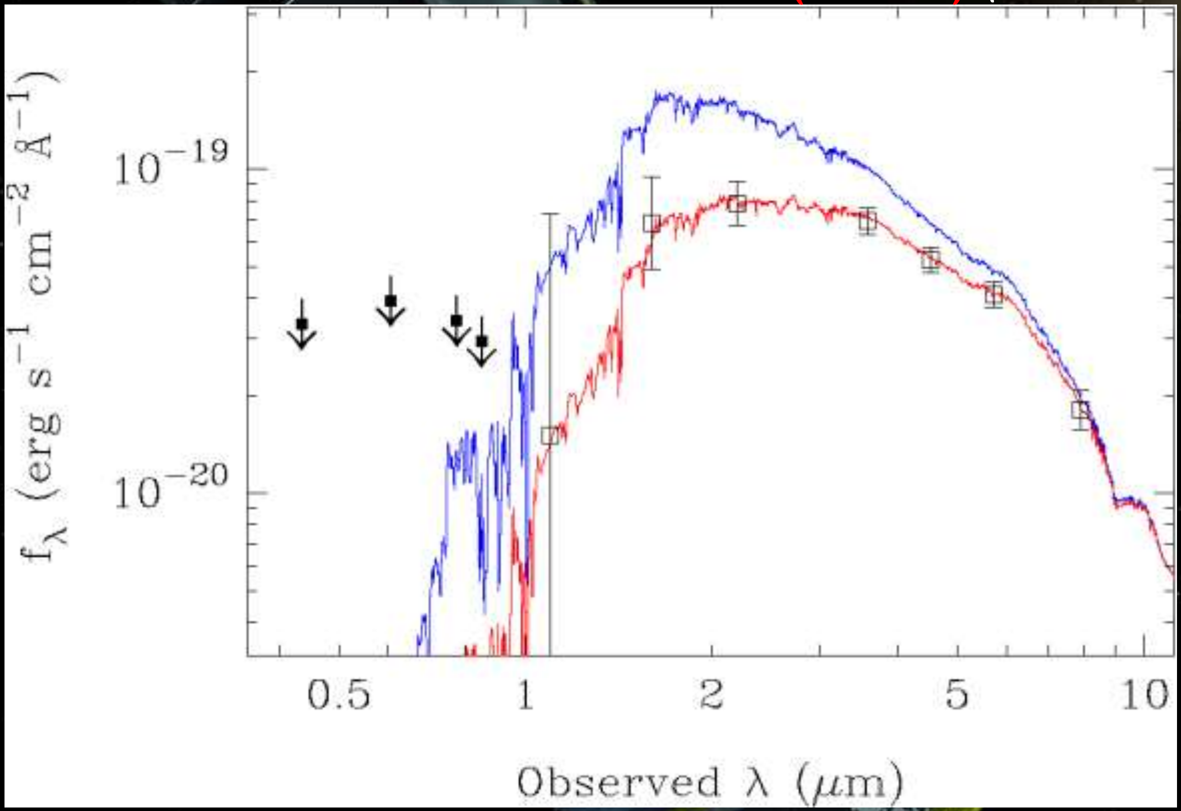
- The number density of the 'Balmer break' galaxies corresponds to dark matter halos of $\sim 1.3\ 10^{12}\ M_o$, giving $M_{baryon}/M_{halo} \sim 0.15$

- Stellar mass could be overestimated if: IMF more top–heavy, population synthesis models systematically wrong

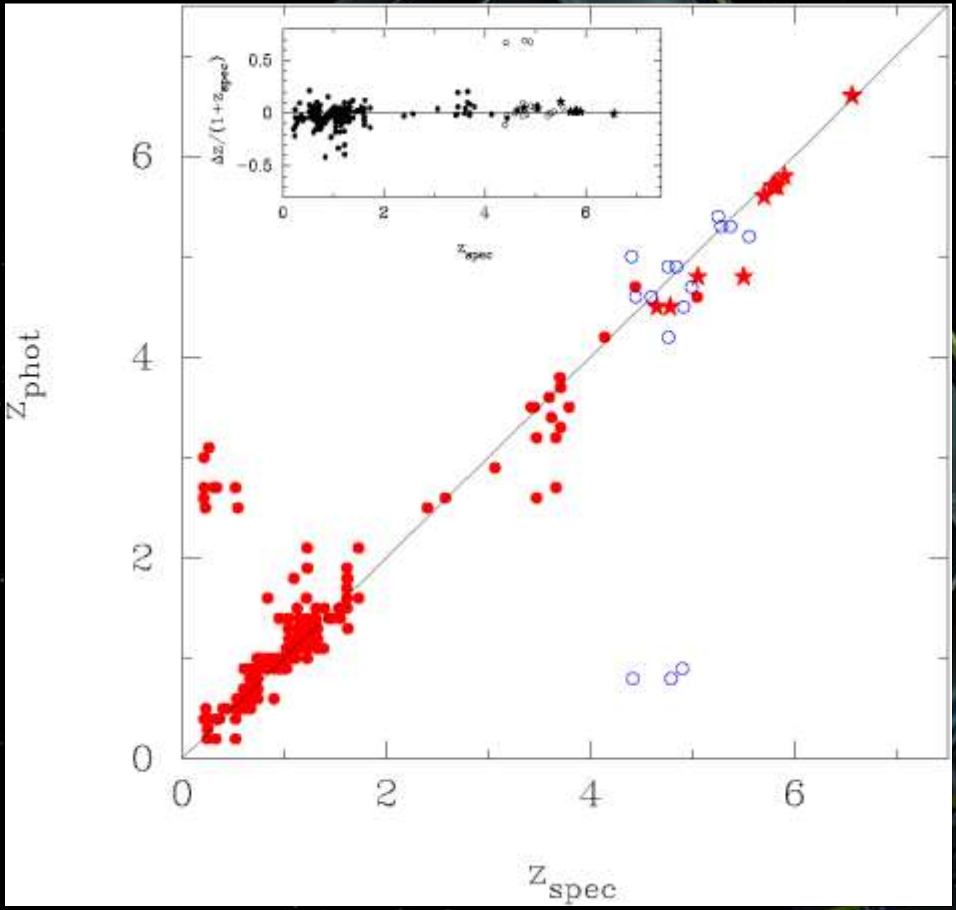
- Formation redshifts range 6 – 25+, within the reionization era

$z = 2.6$, $E_{B-V} = 0.2$, age = 1.8 Gyr, $\tau = 0.1$, $Z = Z_o$

similar to IRAC selected EROs (IEROs) *(cf. Yan et al. 20*

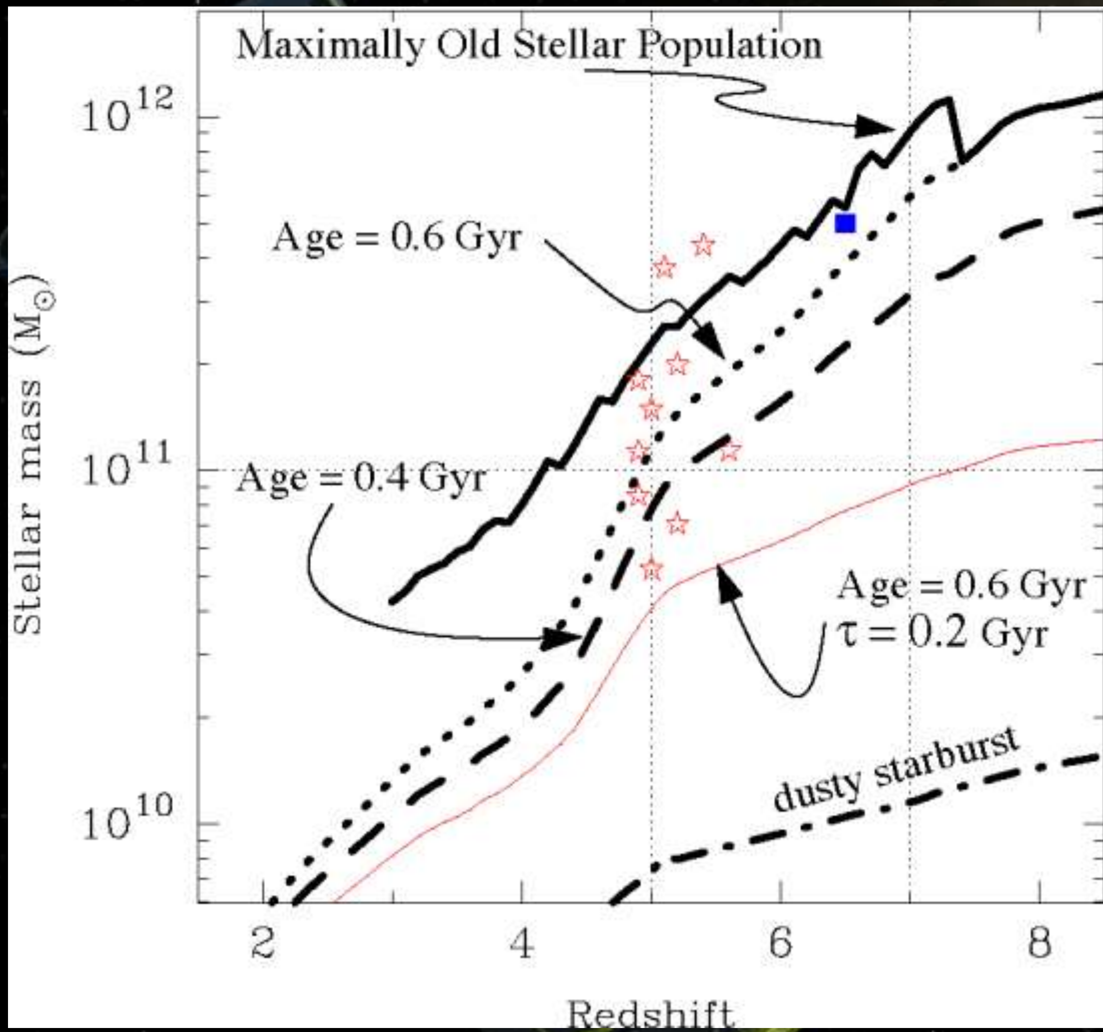


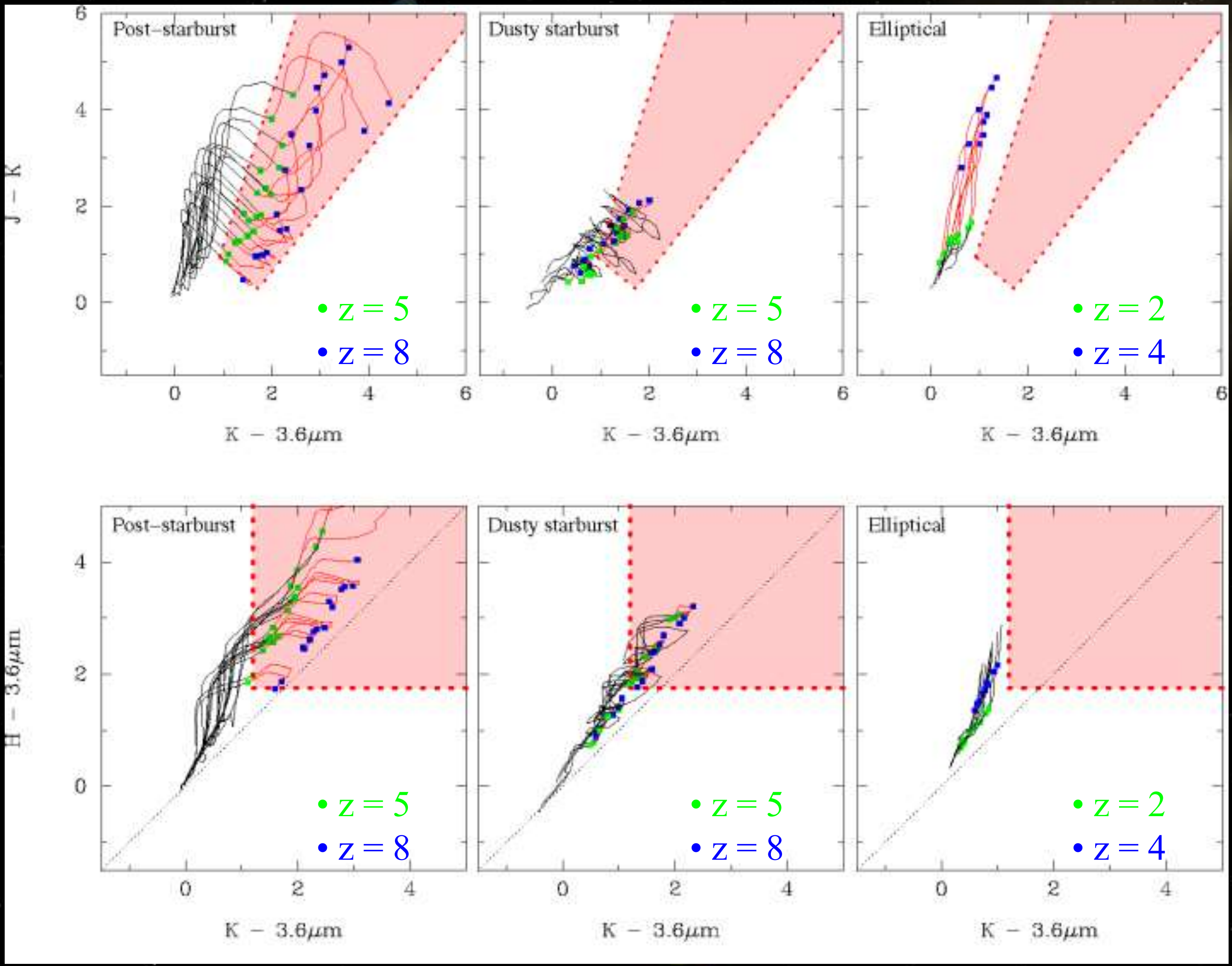
How secure are the photometric redshifts?

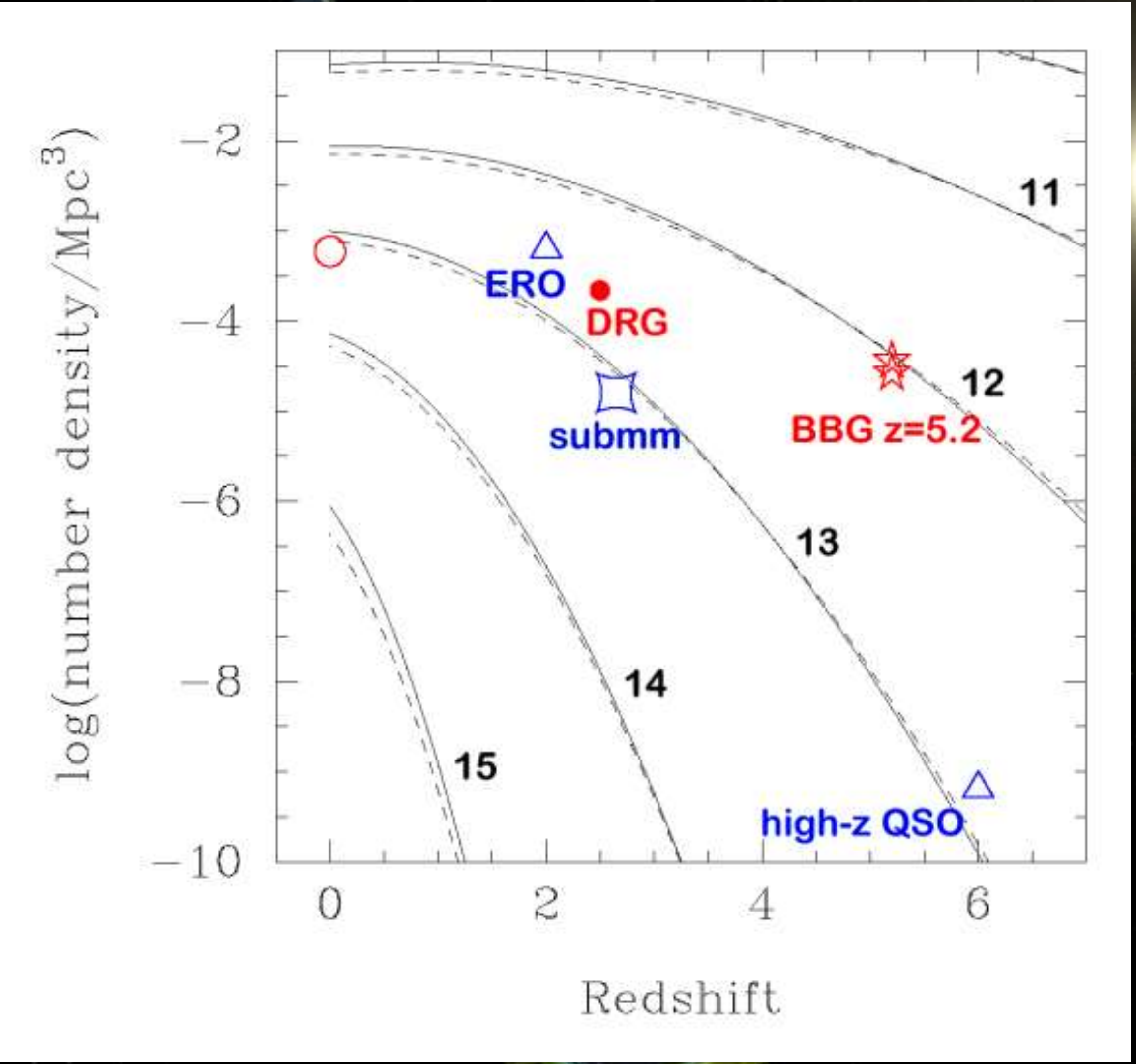


Test the method on galaxies with spectroscopic redshift.
Works well for ~95% of the test sample.

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


Maximally Old Stellar Population
Age = 0.6 Gyr
Age = 0.4 Gyr
Age = 0.6 Gyr
τ = 0.2 Gyr
dusty starburst
Stellar mass ($M_{\odot}$)
10^{12}
10^{11}
10^{10}
2
4
6
8
Redshift


Post–starburst
Dusty starburst
Elliptical
J – K
H – 3.6μm
K – 3.6μm
K – 3.6μm
K – 3.6μm
K – 3.6μm
K – 3.6μm
K – 3.6μm
• z = 5
• z = 8
• z = 5
• z = 8
• z = 2
• z = 4
• z = 5
• z = 8
• z = 5
• z = 8
• z = 2
• z = 4


log(number density/Mpc^3)
−2
−4
−6
−8
−10
0
2
4
6
Redshift
11
12
13
14
15
ERO
DRG
submm
BBG z=5.2
high-z QSO