The properties of z>5 star-forming Lyman Break Galaxies in ERGS and other Surveys

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Identifying the most distant galaxies

Until turn of the century, few z>5 galaxies known. Narrow band Lyα searches (Hartwick, Pritchett etc) failed, not deep enough. One or two sources known from HDF and other deep fields.

z>5 key epoch:

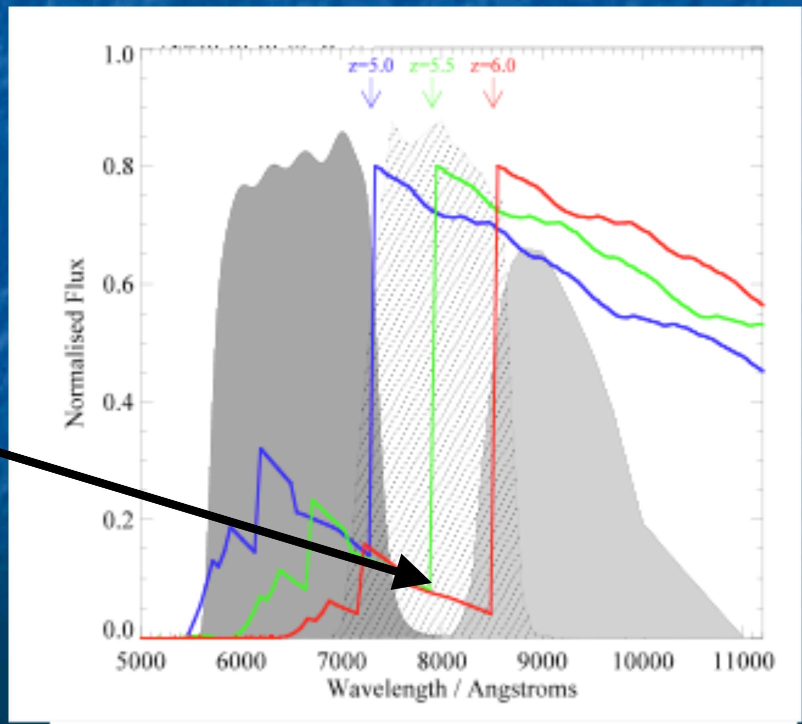
- ~1Gyr after Big Bang. Epoch when halos with mass of Milky Way are being assembled (Mo, White 2002).
- Most stars in today's massive galaxies formed at *z*~5 (Panter et al 2007, Thomas etal 2005):- Key epoch of galaxy formation.
- Much more difficult to follow up at *z*>6, gain only about 200Myr, lose signal-to-noise and wavelength coverage.

Identifying the most distant galaxies

With the advent of 8m imagers/spectrographs and deep fields (proprietary & public) can select & study the *z*>5 population.

Lyman Break technique at *z*>5 gives samples with best set of observables for future study (other techniques are also used).

Lyman Break Caused by intervening Hydrogen absorbing photons with wavelengths <1216 Angstroms in rest frame

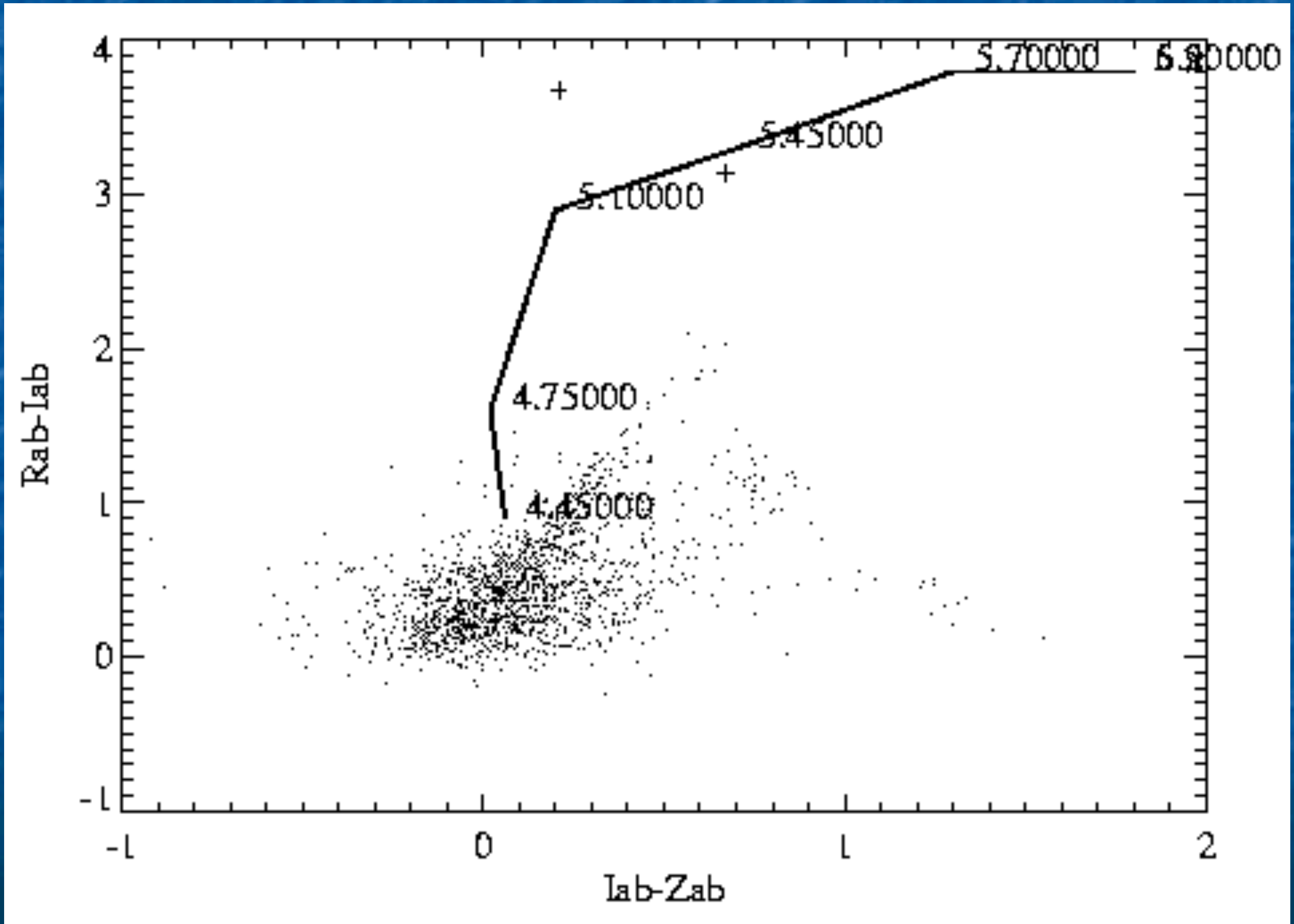


Selecting unobscured star formers: The Lyman Break technique

Pioneered by Steidel etal in 90's for z~3.

Then by Lehnert & Bremer (2003) for z~5.

Now > 100 galaxies with spectroscopic redshifts at z>5 (Douglas etal 2008, Davies etal 2008)



Selecting star formers: Our surveys

Want to observe z~5 sources, as comparatively easy to confirm & explore in detail. Only 200 Myr later than z~6 (much harder). Want to avoid cosmic variance-> multiple widely-spread fields.

Lehnert & Bremer 2003: 6 redshifts 4.8<z<5.8 in single ~40 sq arcmin VLT/FORS2 field. Selected from RIz ground-based imaging. Davies etal 2008 expands this to ~160 sq arcmin and 20 redshifts with VLT/FORS2.

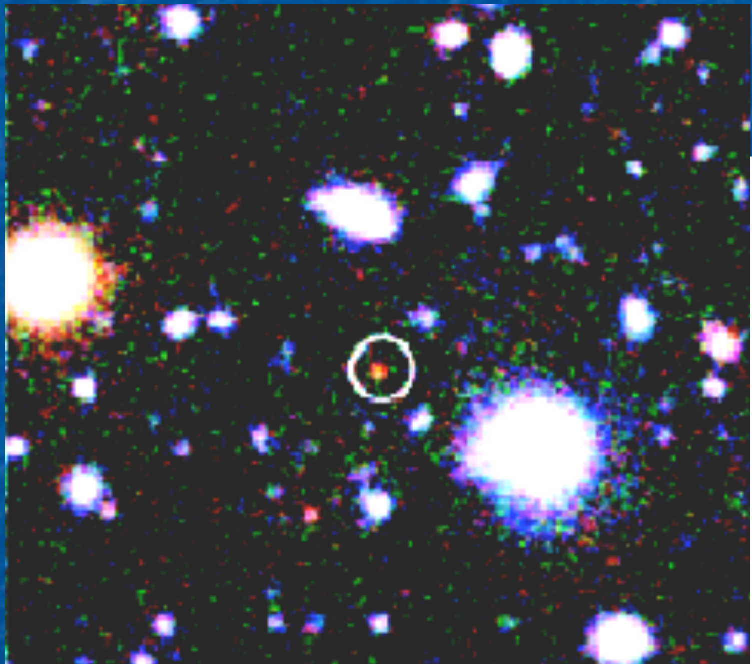
Douglas etal 2008: The ESO Remote Galaxy Survey (ESO LP, P.I. Bremer, Thesis of Laura Douglas). 64 redshifts from ten 40 sq arcmin VLT/FORS2 fields spread over sky. VRIZJK ground-based imaging and I HST/ACS (originally from EDisCS). 2-sigma limits:

V=28.1, R=28.1, I=27.2, z= 26.0 J=24.6, K=23.8, all AB

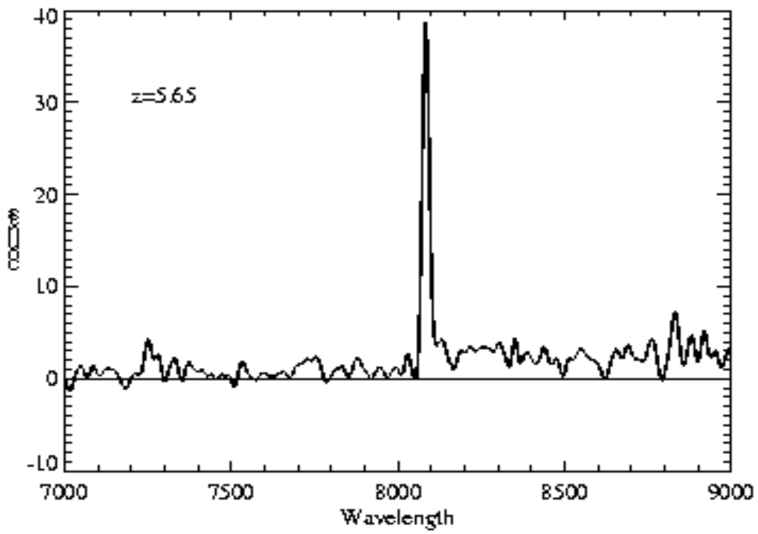
GOODS-South: Public & private photometry & spectroscopy, Bremer etal 2004, Verma etal 2007, Stanway etal 2008.

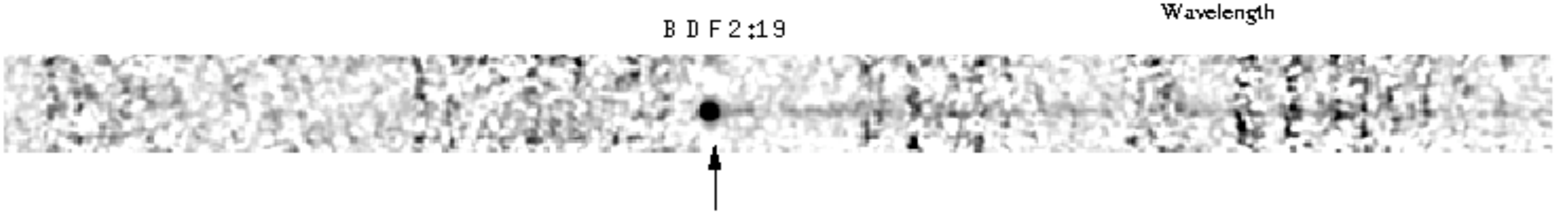
Example of z>5 star forming galaxy

Typically select object from $I_{AB}<26.3$, $R-I>1.3$, reject clear IR detections.
Follow up with typically 4hrs spectroscopy



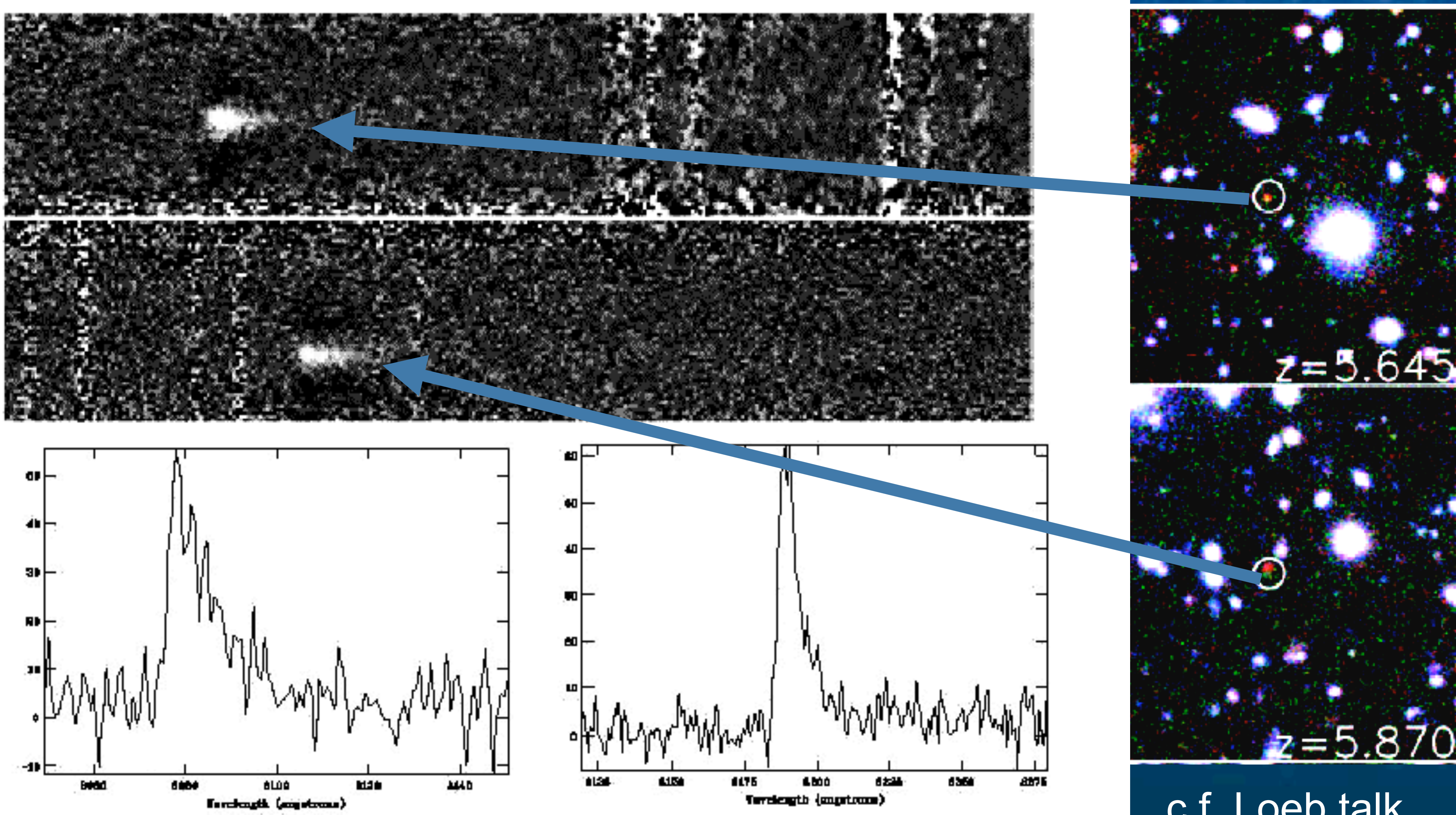
Example object from Lehnert & Bremer 2003, $I_{AB}=26$, $z=5.65$
See also Laura Douglas poster





Ly alpha line shape indicates strong wind

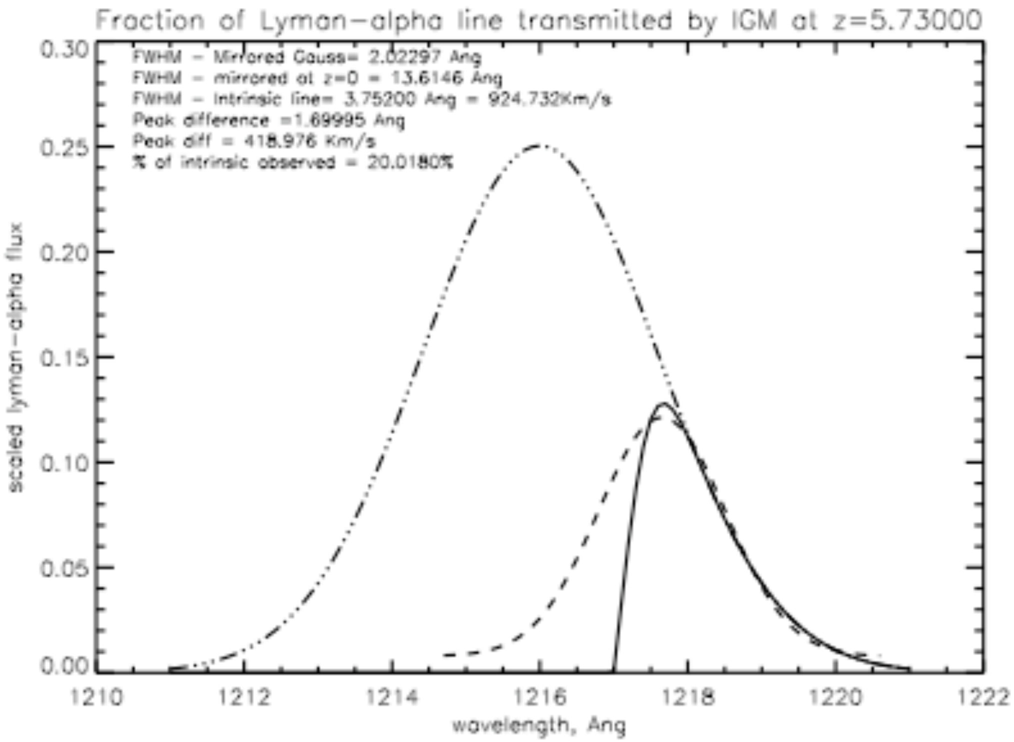
~50% have detectable Ly alpha. Strong ongoing but recent star formation

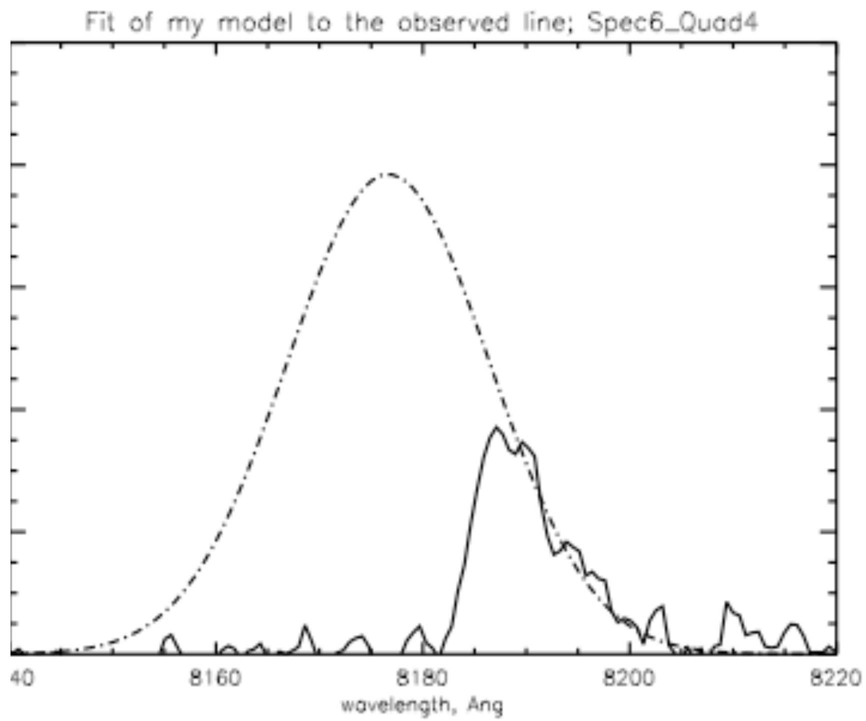


c.f. Loeb talk

Ly alpha line shape indicates strong absorption

Models adapted from Dijkstra etal 2008 show we could be observing <20% total line emission, and intrinsic line could be wider than 500km/s due to winds. Ly alpha redshift is higher than systemic redshift.

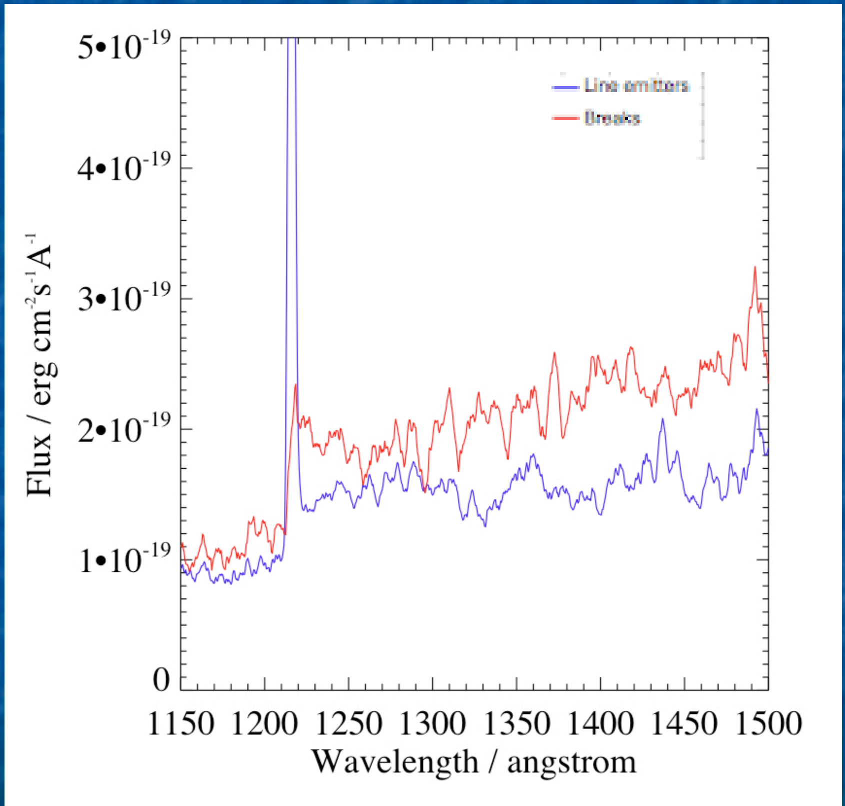




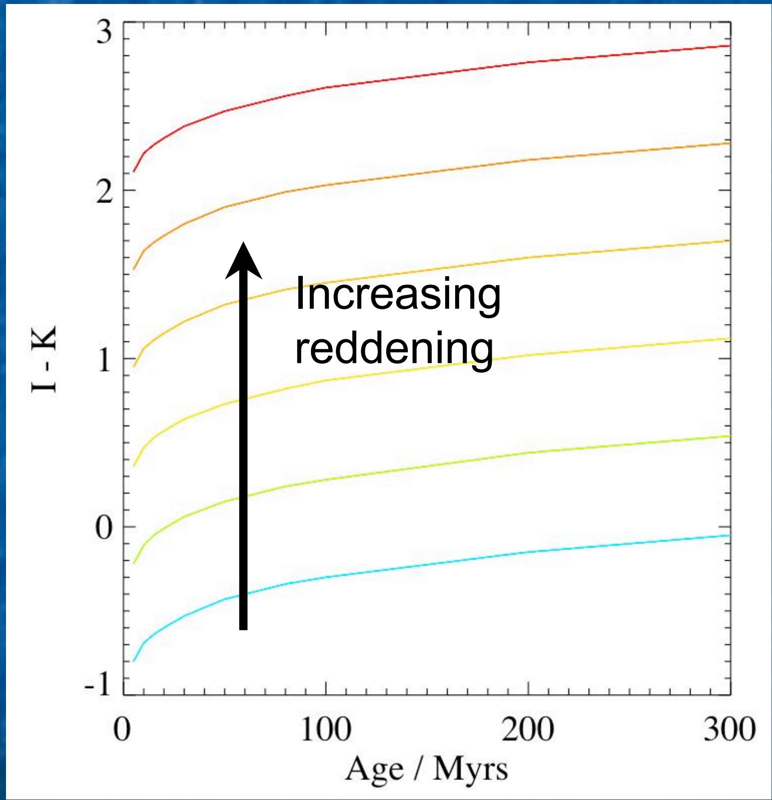
See poster by Luke Davies & next talk

Stacking the data:
Stellar Age *vs* line properties

Line emitters & non line emitters have different spectral slopes

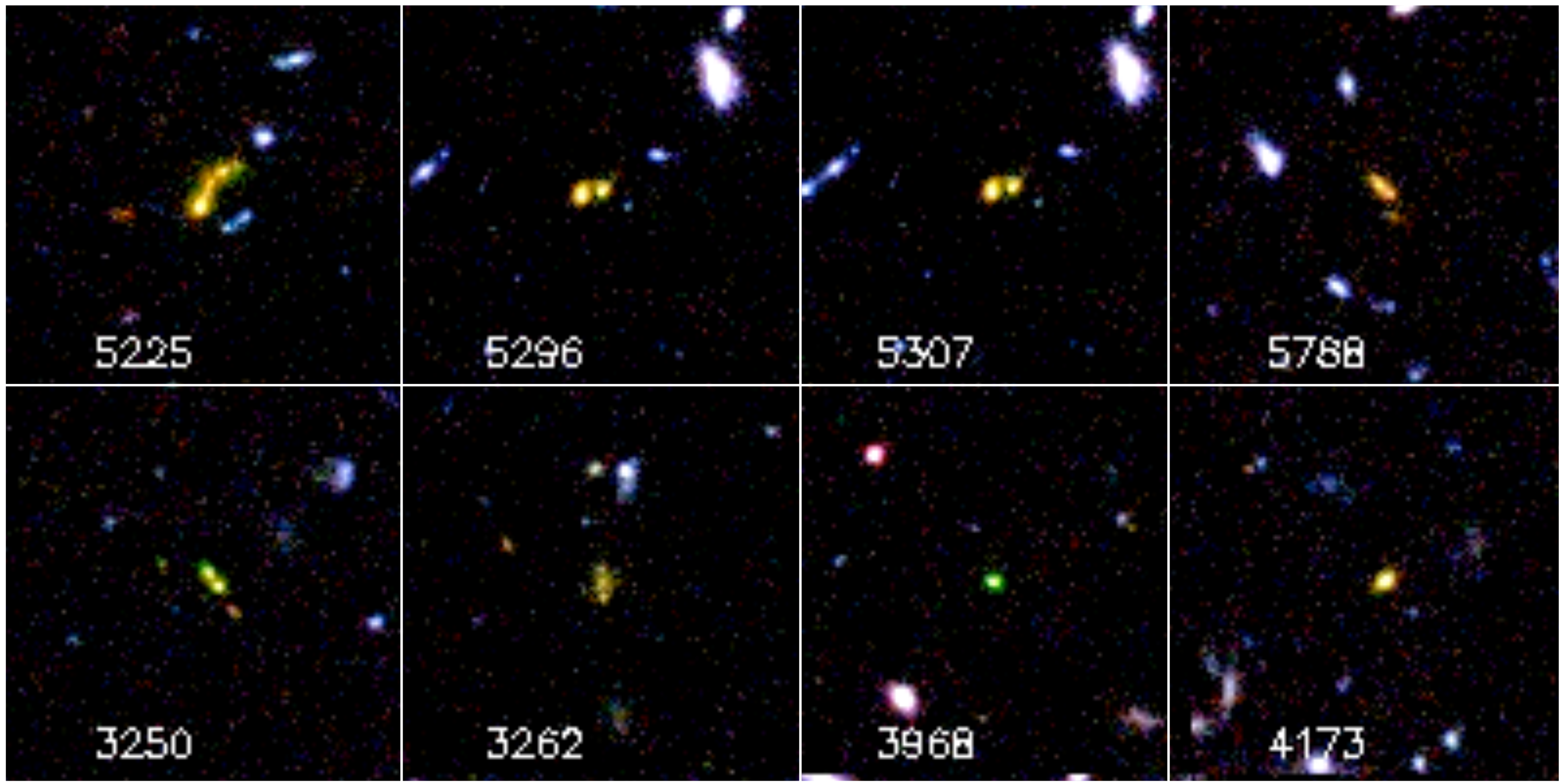


Maraston+Calzetti. Increments of 0.1 in *E(B-V)*



Difference clear but small, seen in I-K stack -> difference of about 0.5 in I-K ->Probably not dust, but age difference in stellar pops.

UV morphologies



Rest-frame UV emission redshifted into the optical. Sources resolved with r_h~1kpc, sometimes (25 %) double or triple on scales of <10kpc. Stellar density like most massive spheroids seen today (Verma etal 2007). High UV surface density-> Very high specific star formation rates. No correlation with Ly alpha.

See poster by Laura Douglas

Studies with near-IR And Mid-IR data

•Optical studies can say little about many of the important properties of these galaxies as they only detect light from ongoing star formation.

•Using optical, near IR and SPITZER IRAC imaging, the rest-frame UV-optical SEDs of these galaxies can be studied, elucidating many key diagnostics of these galaxies:

•Age/star formation history of stellar population
•Stellar mass & density
•Metallicity/extinction
•Influence on IGM

•So to explore this,we used HST/ACS, VLT/ISAAC and SPITZER/IRAC data to study the properties of z~5 galaxies in the CDFS
•**Verma etal, 2007 MNRAS 377, 1024**

Results from combined optical and IR study

•Compared the multi-band measurements to Bruzual & Charlot models with a Salpeter IMF, a variety of metallicities and extinction laws and a range of star formation histories (constant, exponential decay etc)

• Found that stellar masses were typically a few $10^9 M_\odot$, a minority are more massive (few $10^{10} M_\odot$). Galaxies are compact (~1 kpc) in UV.

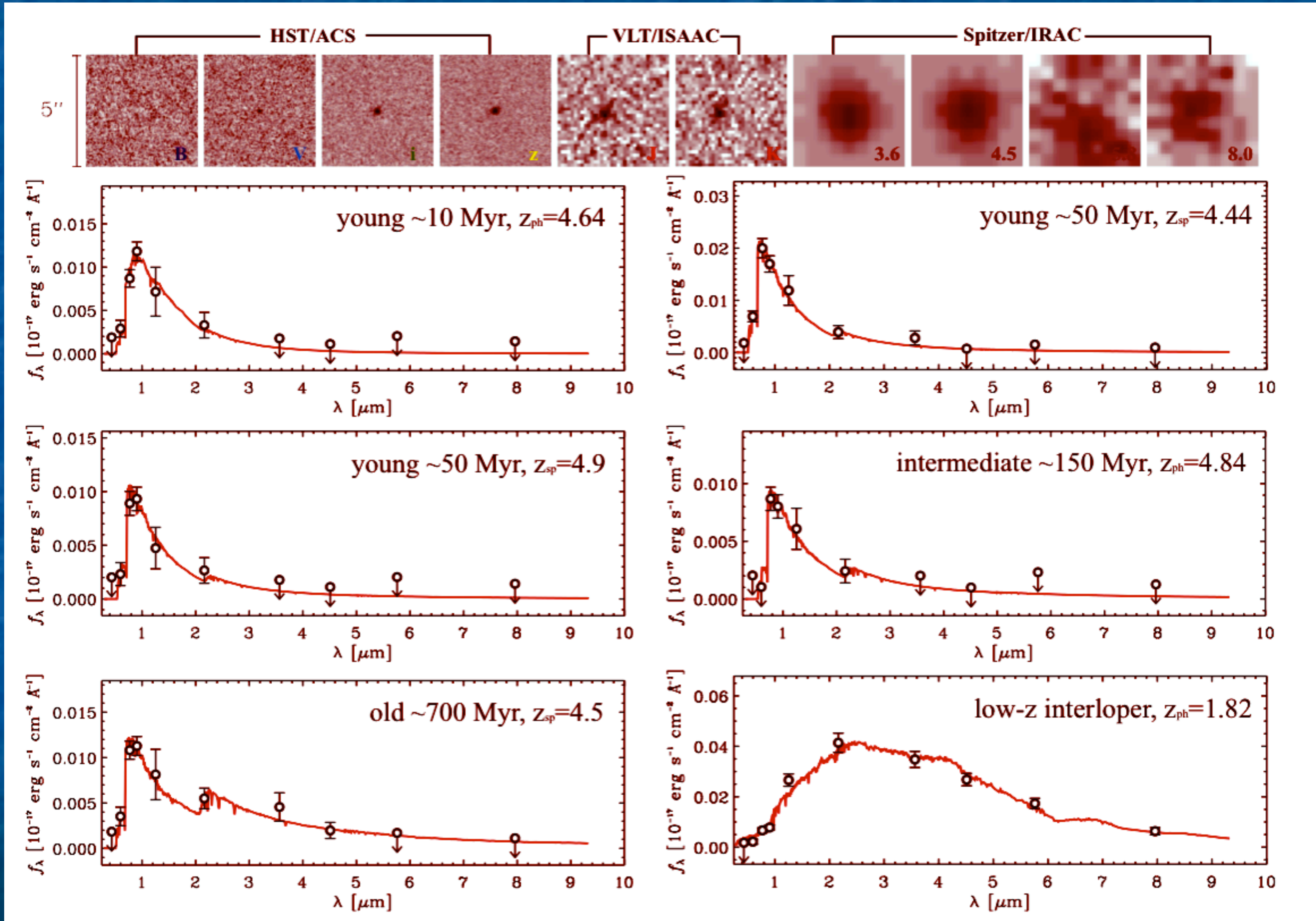
• Stellar populations have young ages (<100 Myr), a minority are older (few hundred Myr, z_f~8). Young ages comparable to galaxy crossing times.

•Low metallicity (~0.2 $Z_\odot$) and extinction (SMC-like A_v~0.3 mag)

•Specific star formation rates ver high, several 10s $M_\odot$/yr/kpc^2

•**Verma etal, 2007 MNRAS 377, 1024**

Age of Starburst from SED fits

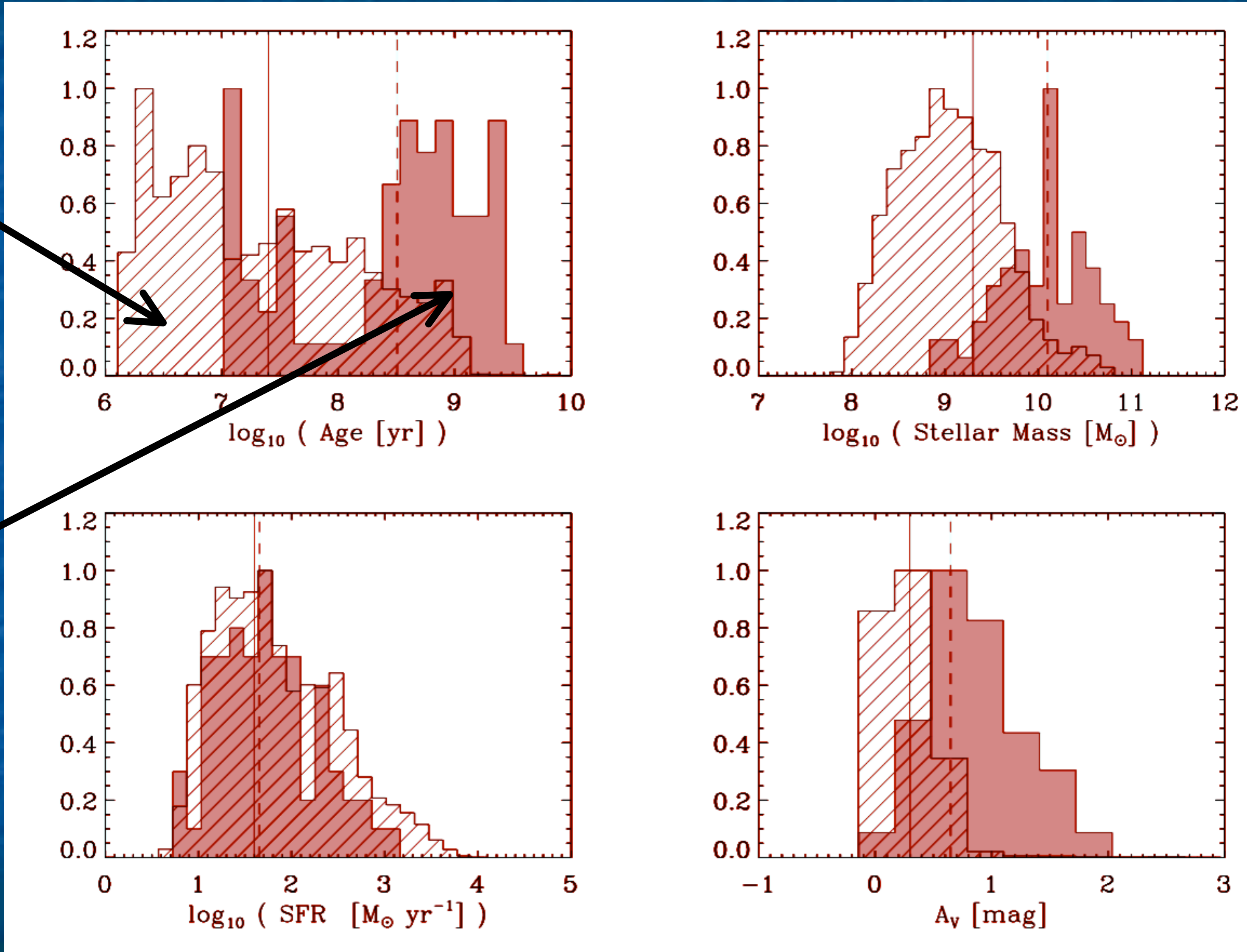


Verma, etal MNRAS 377, 1024

Properties different to those of z~3 LBGs

Z=5 from Verma etal '07

Z=3 from Shapley etal '01

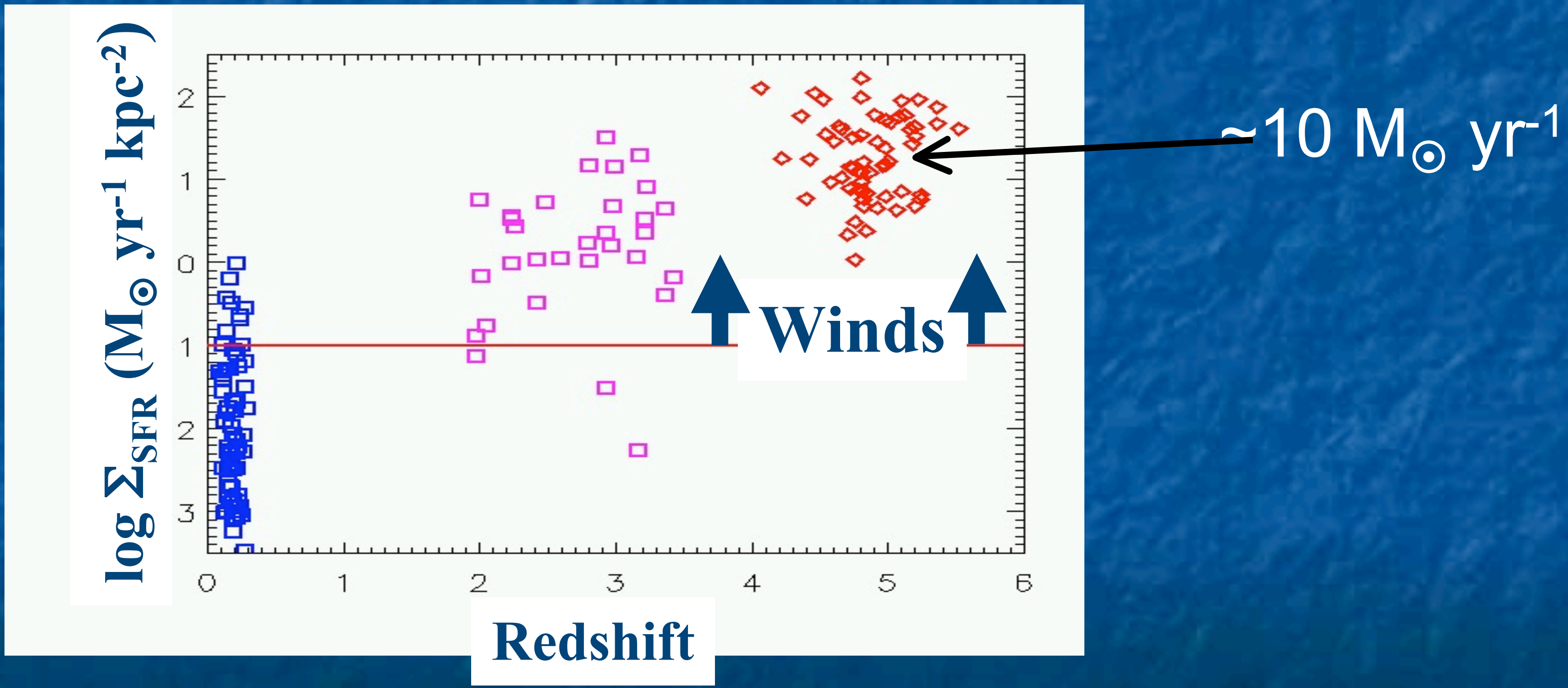


Verma, etal 2007 MNRAS 377, 1024

High intensity starbursts

•Small size & high star formation rate means they are extremely high intensity star bursts, to >100 $M_{\odot} yr^{-1} kpc^{-2}$, driving extremely strong winds. Stellar density same as centres of massive current-day spheroids.
•Star formation lifetimes similar to their dynamical crossing times:- protogalaxies undergoing their first substantial burst(s) of star formation

Impact on pre-enrichment problem?



Papovich et al. (2001), Heckman et al. (2005)

Summary of intrinsic properties

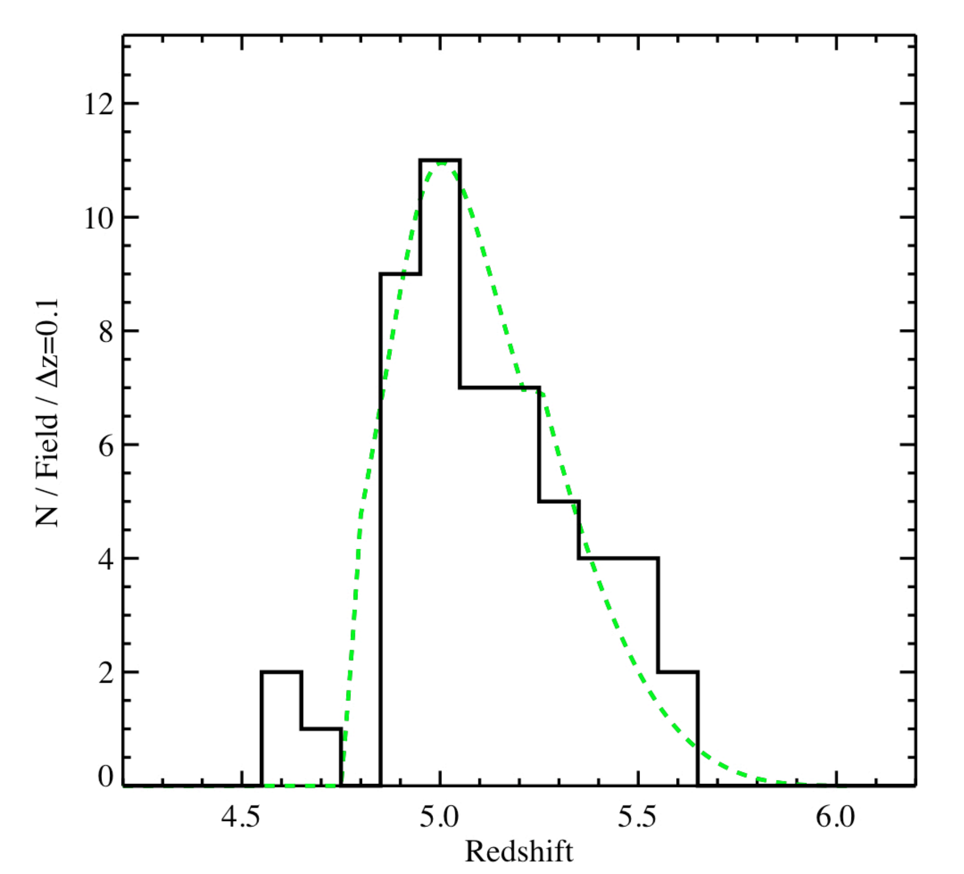
•Most LBGs at z~5 are young (<100 Myr),and compact (~1kpc) intense starbursts (> 10 $M_{\odot} yr^{-1} kpc^{-2}$) driving extremely strong winds. Their star formation timescales are comparable to galaxy crossing times:- They are undergoing their first significant generations of star formation-> Protogalaxies

•Stellar densities comparable to those of massive spheroids today. Stellar masses of a few x $10^9 M_{\odot}$. 10 times less massive than z~3 LBGs. Younger, smaller and less enriched than z~3 LBGs. Are occasionally older, more massive systems (>200 Myr, z_f~8, M~$10^{11} M_{\odot}$):- Earliest known stars formed at z>8.

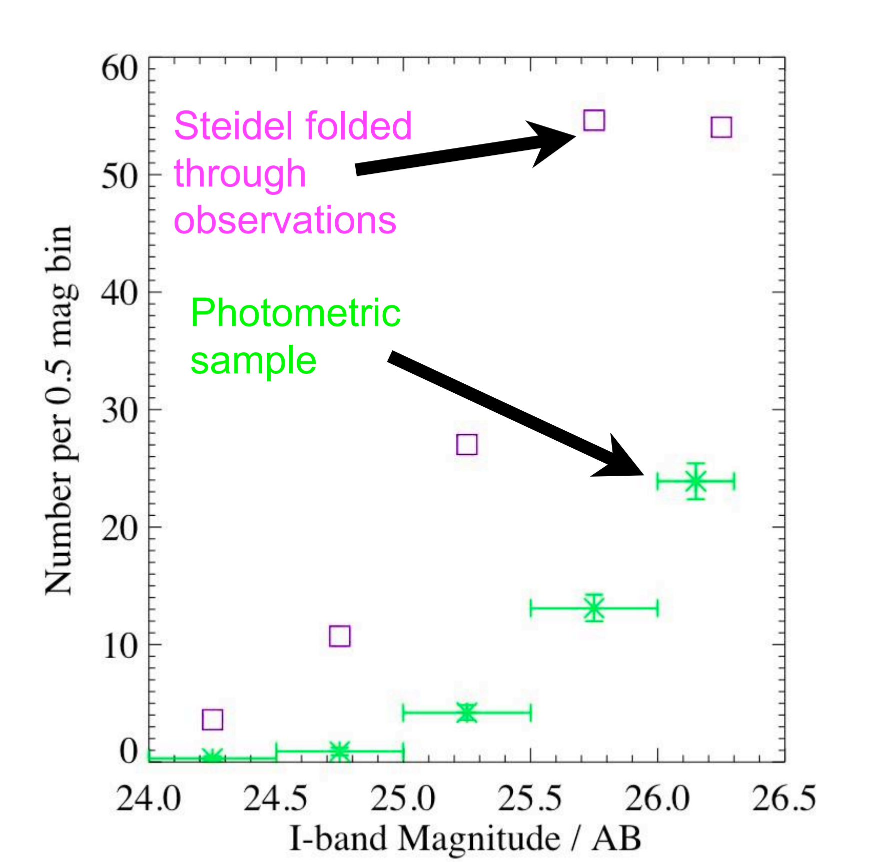
Statistical Properties: Number Counts

Factor of 3 or more decrease in space density of LBGs between z=3 and 5.5 for $M_{1700Ä}$ <-20.5. Similar drop in UV luminosity, but not star formation density.

Redshift distribution *vs* scaled simulation

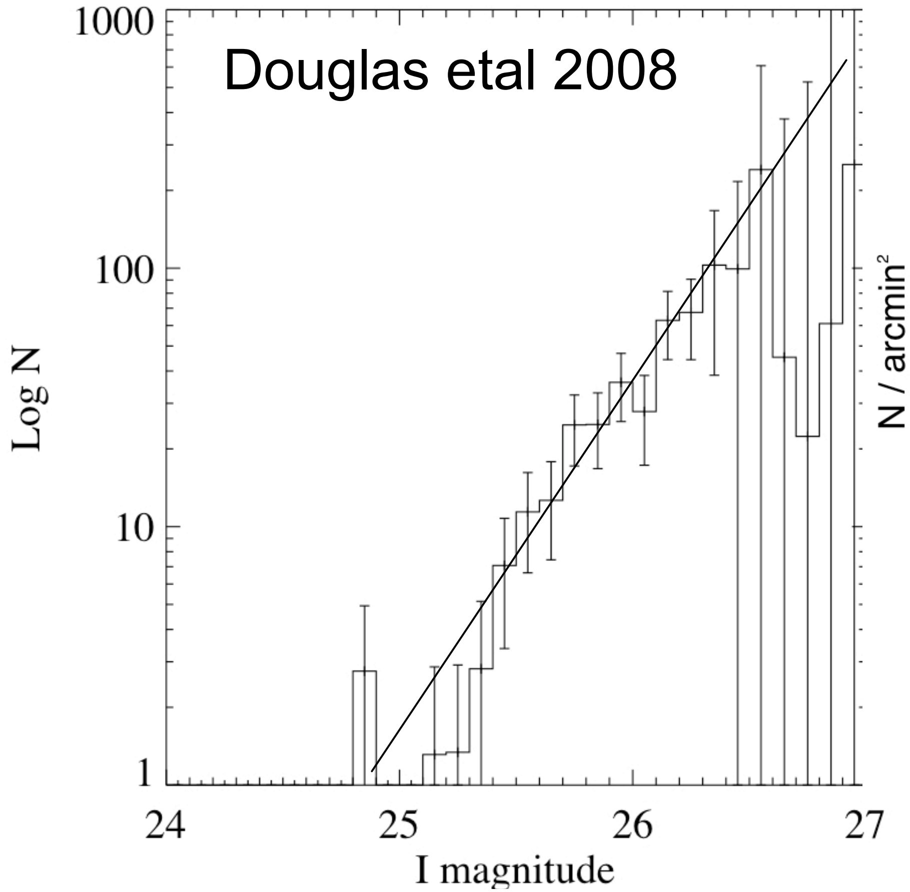


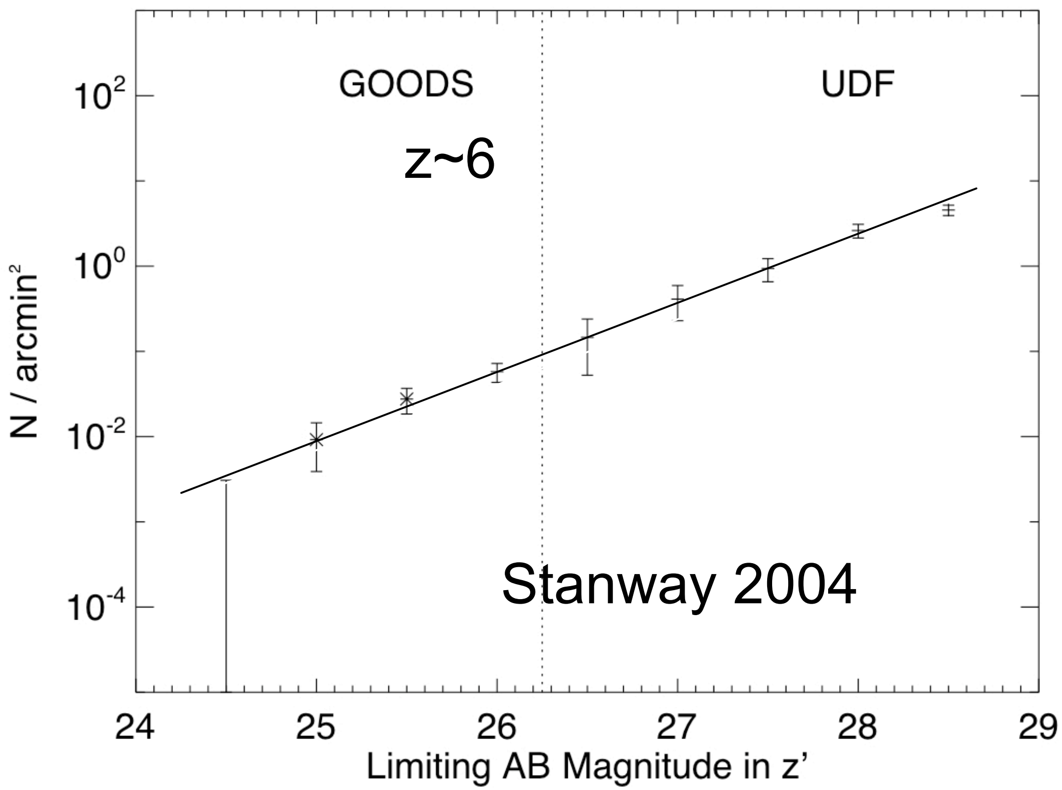
Number counts *vs* Steidel z=3-4 lum fn



Douglas etal 2008, after Lehnert & Bremer (2003)

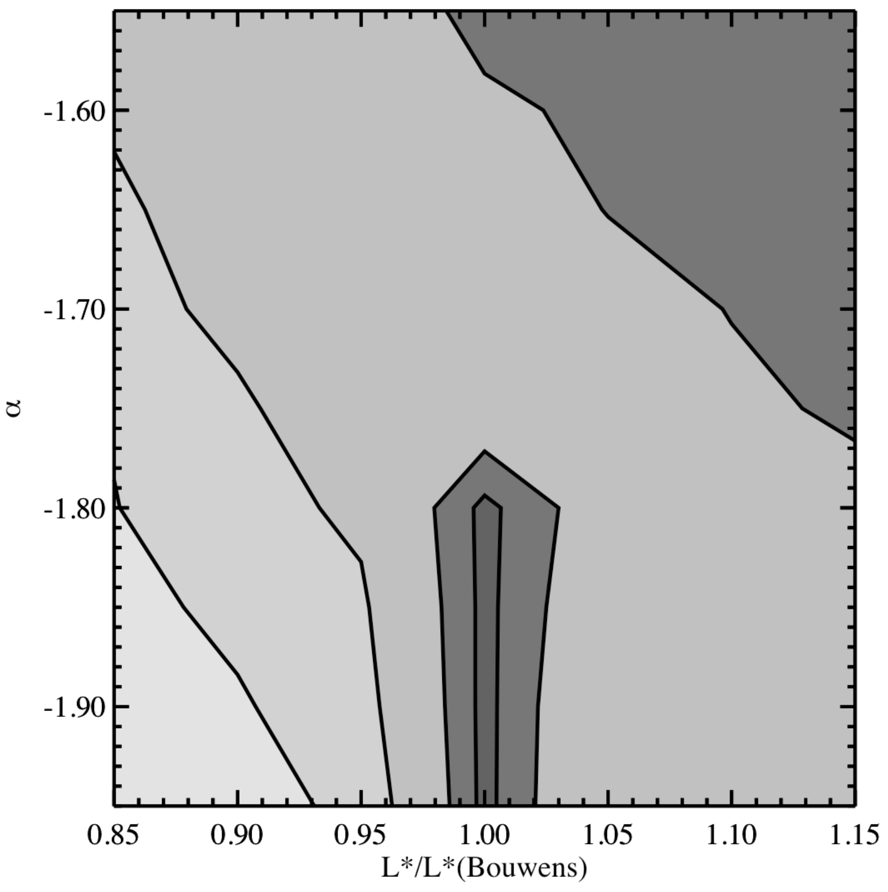
Shape of the luminosity function: Implications for reionization

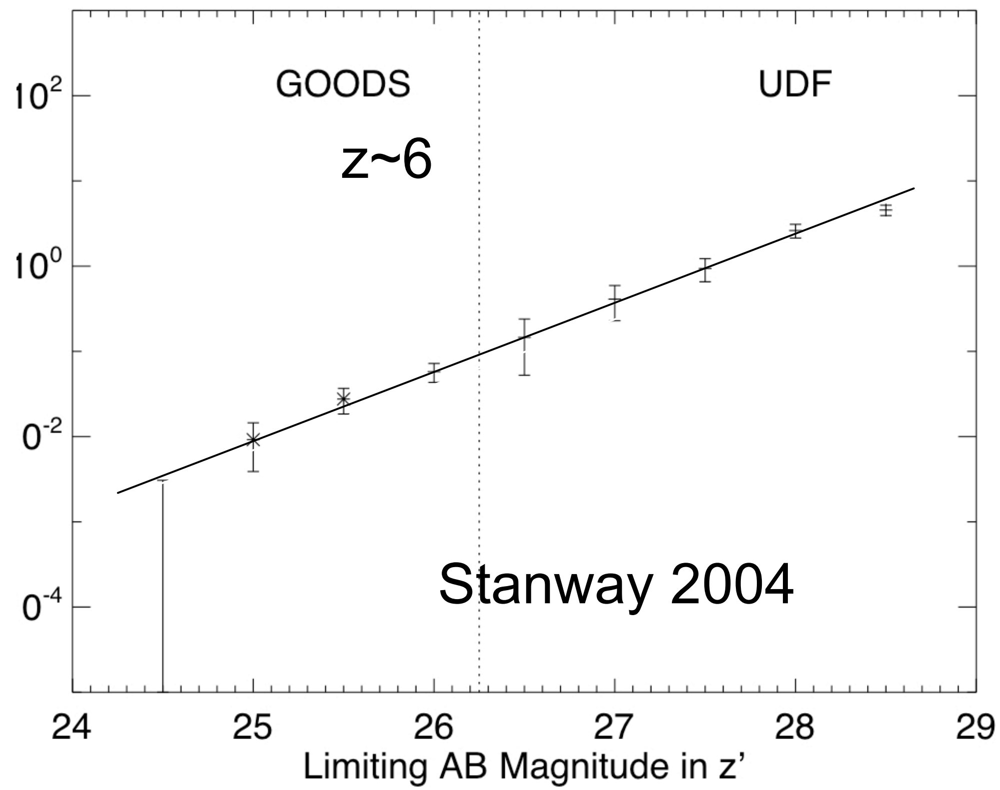




Number counts at z>5 show no strong evidence for break in lum fn -> Lots of faint sources -> strong contribution to reionization

Shape of the luminosity function: Implications for reionization





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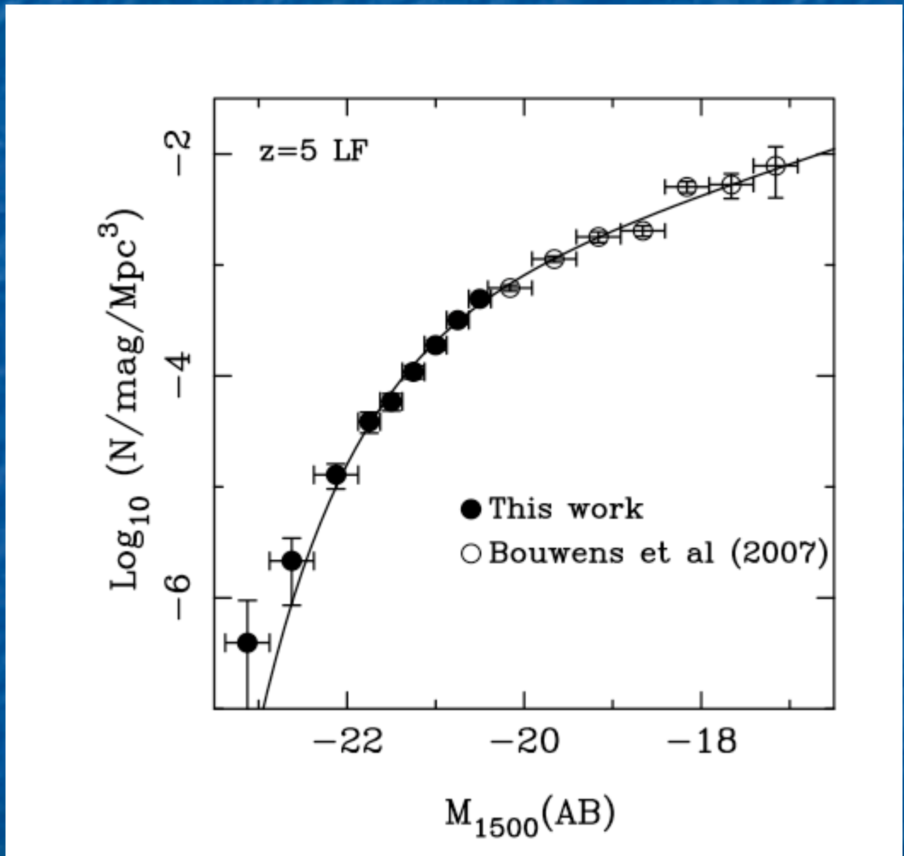
What does the UV luminosity function mean given short-lived star formation?



This is a UV lum fn, 1500 Angstrom in rst frame, arising from light emitted by recently formed stars.

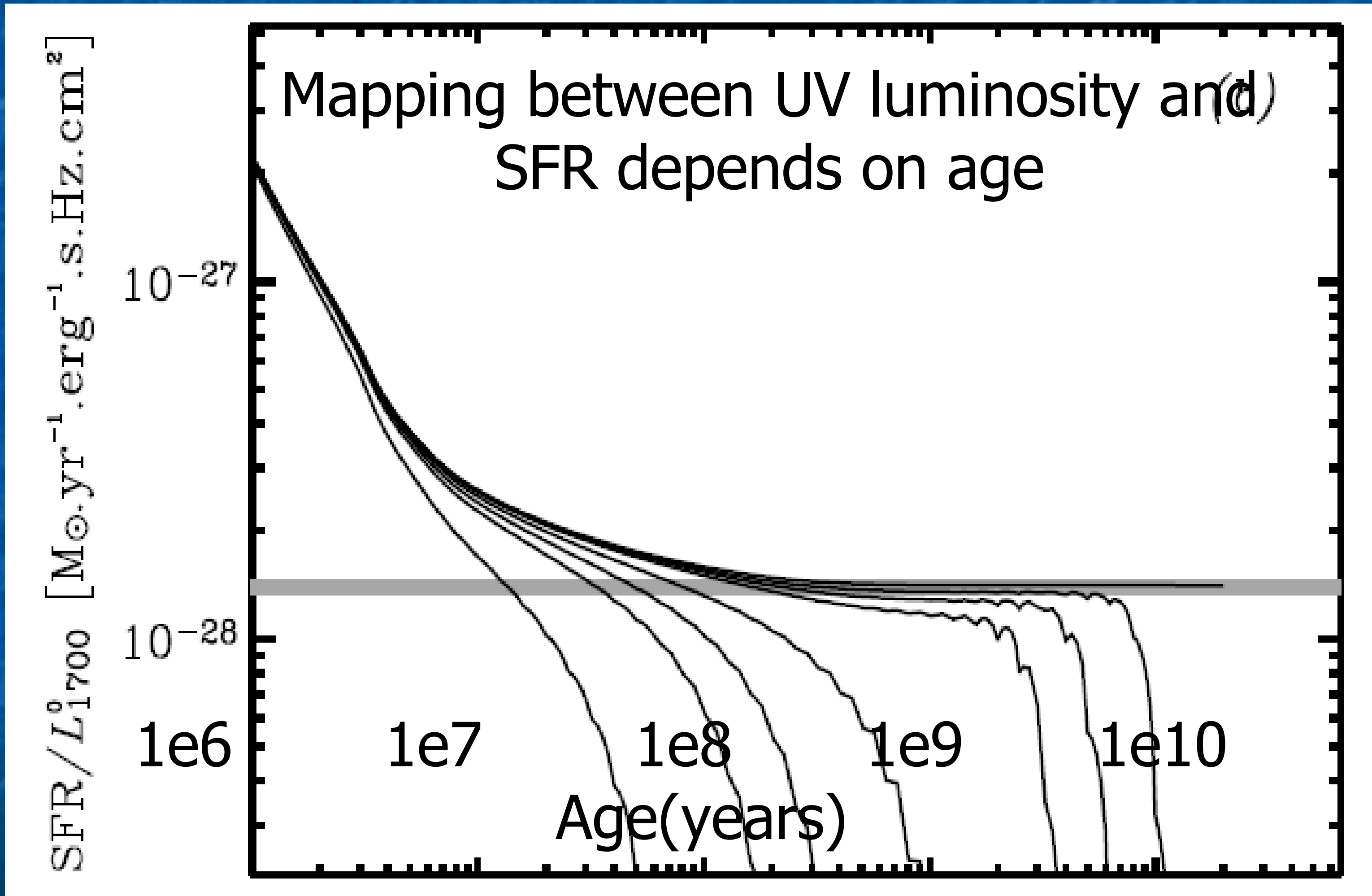
NOT necessarily well-coupled to mass of system :- Stochasticity of SHORT-LIVED star formation dominates.

Why should a Schechter function be appropriate? Lum fn might be decay curve of star formation in single galaxy!

McLure etal 2008 Φ^*~9.4+/-1.9 x10^{-4} Mpc^{-3}
"Knitting together" multiple surveys. Cosmic variance at faint end?

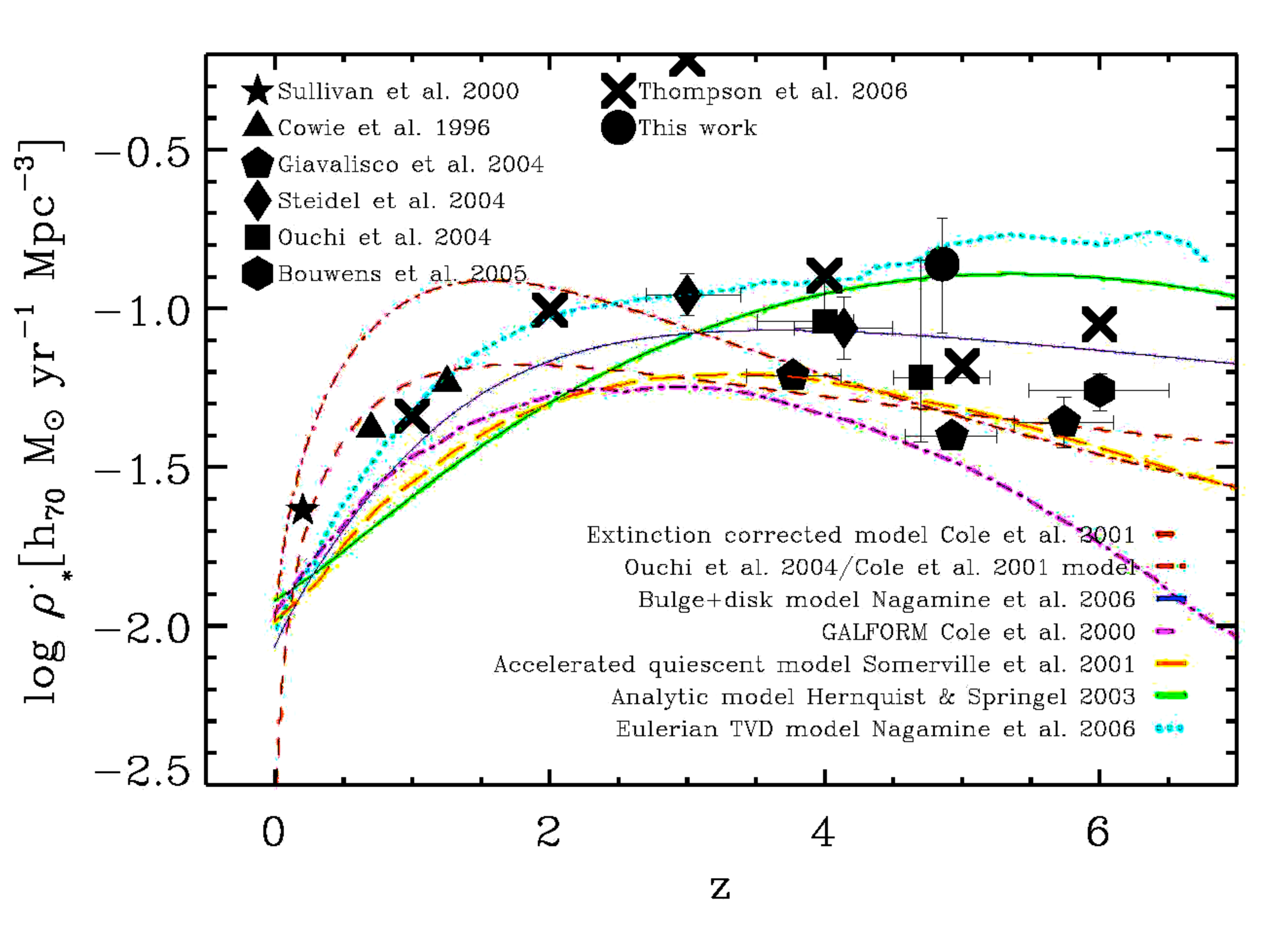
Star formation history: Kennicutt relation inappropriate

A drop in UV luminosity density does not necessarily indicate a drop in star formation density



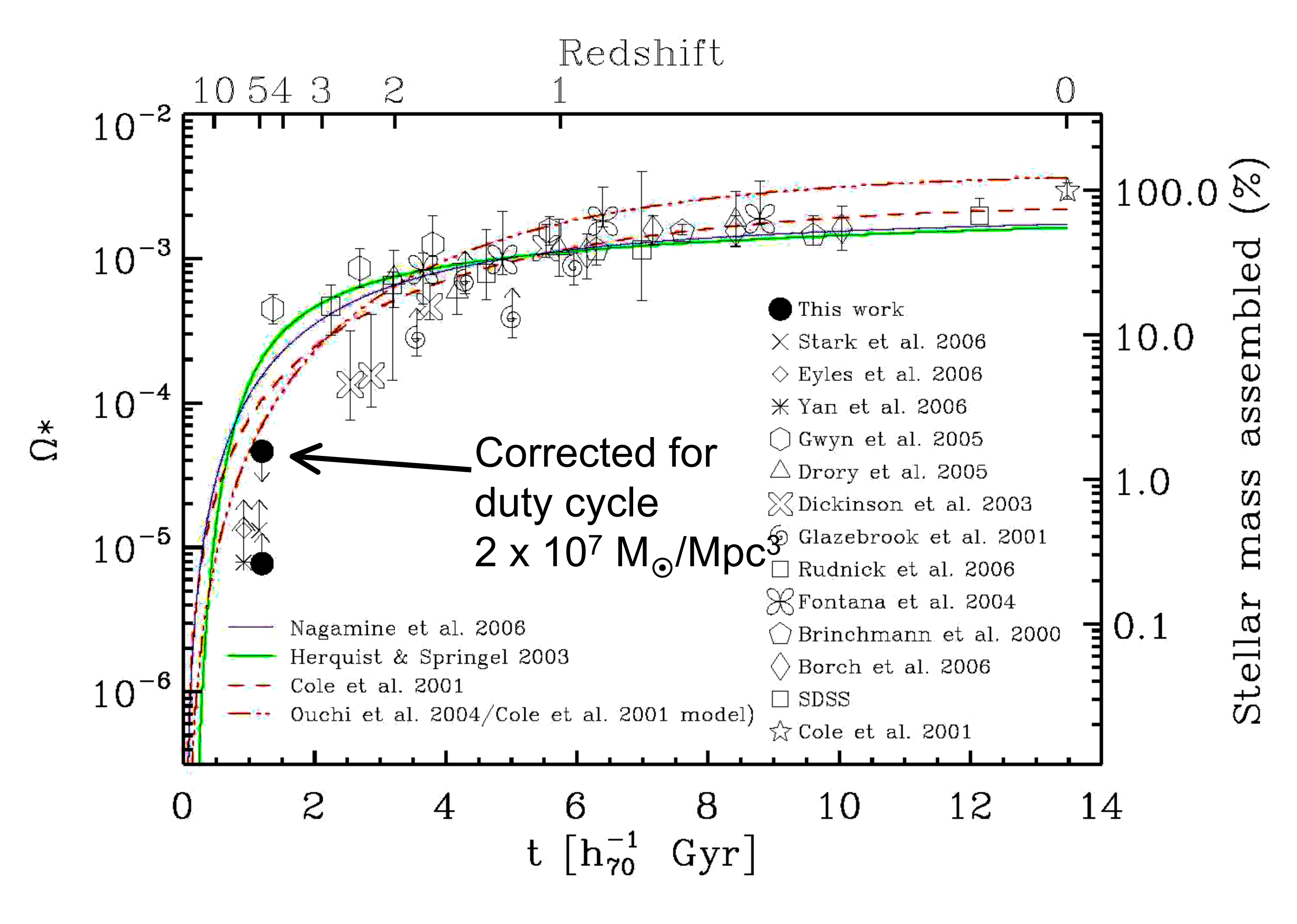
(Verma, Forster-Schreiber)

Star formation History



Verma, etal 2007 MNRAS 377, 1024

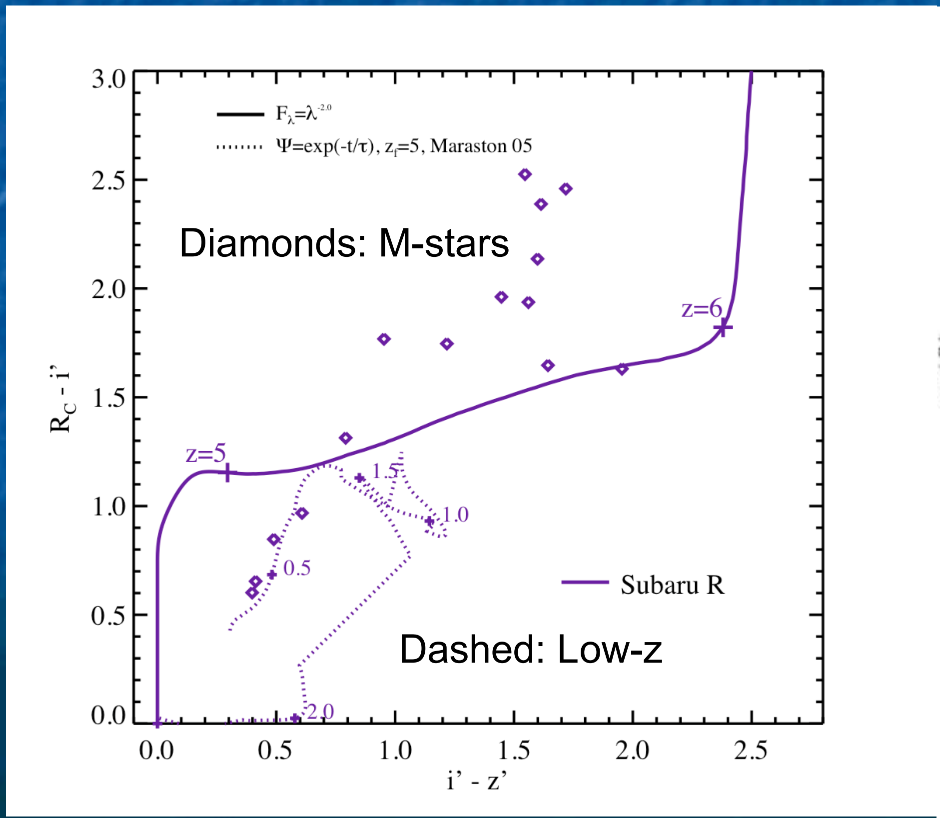
Stellar mass density

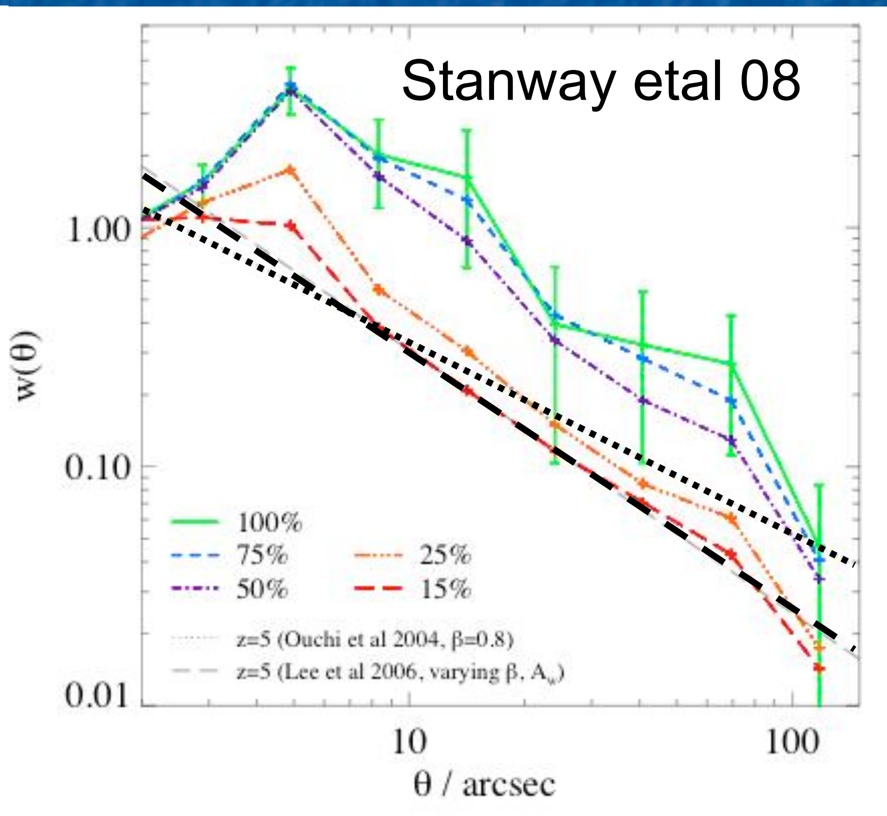


Verma, etal 2007, MNRAS 377, 1024

Comment on contamination in ground-based photometric samples

Typical contaminants of photometric samples at z~5 are M/L/T stars and z~1 ellipticals. Latter share same clustering stats as expected for z~5 LBGs. Are clustering, LF, SFR, age estimates meaningful using photometric samples? Our spectroscopy can give indication of reliability of photometric sample drawn from same initial photometry.





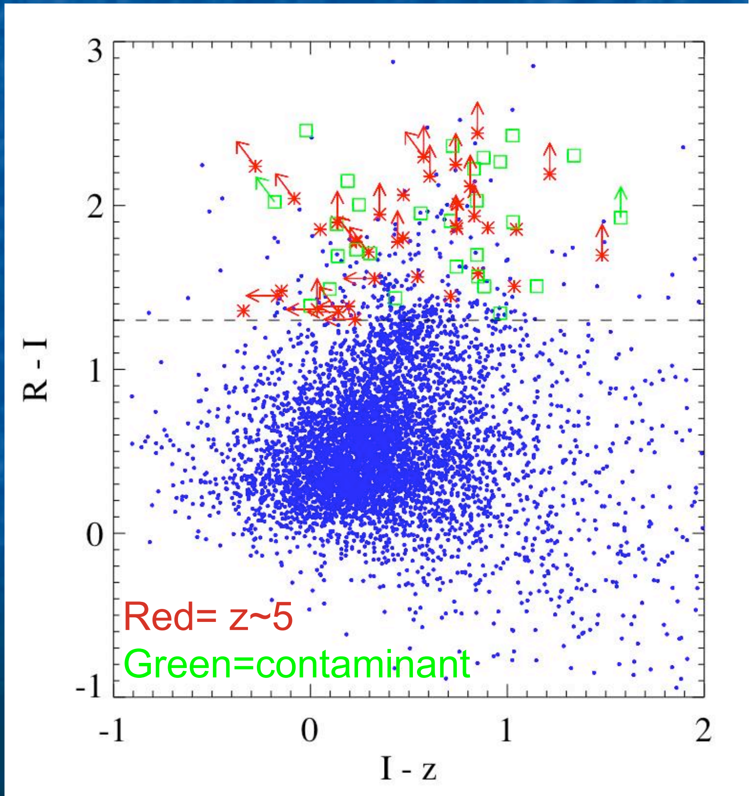
Comment on contamination in ground-based photometric samples

We can assess reliability of a purely photometric sample using spectra.
Start with ~400 objects selected according to R-I>1.3, I<26.3, V>27.5.
This amounts to a typical ground-based optical photometric sample.

Split resulting sample by eye into grade 1&2 through mix of objective & subjective criteria.

Of ~ 200 Grade 1 objects with spectroscopy: 50% at z~5, 5% confirmed contaminants, rest unknown. Average I-K colour of these indicates about 30-40% contaminants:-> Grade 1 is 75% reliable.

Of ~200 Grade 2 5-10% confirmed high redshift -> reliability an order of mag less then Grade 1
Can strongly affect any statistical results based on purely optical GB photometric samples.



Conclusions

•Most LBGs at z~5 are young (<100 Myr), dense & compact (~1kpc) intense starbursts (> 10 M yr $^{-1}$ kpc $^{-2}$) driving extremely strong winds, with masses of a few x 10^9 $M_{\odot}$. Star formation timescales are comparable to galaxy crossing times:- They are undergoing their first significant generations of star formation- one definition of a protogalaxy.

•Younger, smaller, lighter and less enriched than z~3 LBGs. Lower comoving number density & UV lum density than at z~3, but potentially constant star formation rate between z=5 and 3. Are occasionally older, more massive systems (>200 Myr, z_f~8, M~10^{11}M$_\odot$):- Earliest known stars formed at z>8. Stellar content of all systems is 1% of today's total.

•Bright end of Lum fn clearly evolved between z=5 and 3, faint end slope potentially very steep. BUT what is the Lum fn telling us if UV emission is highly stochastic?

•Despite very careful selection of candidates, samples are contaminated at the 10-40% level:- Poses significant problems for interpretation of current ground-based photometric samples. Affects clustering, ages, SFR, etc etc.