Living fossils: New Clues on Distant Starburst Galaxies based on local Analogs of Lyman break galaxies

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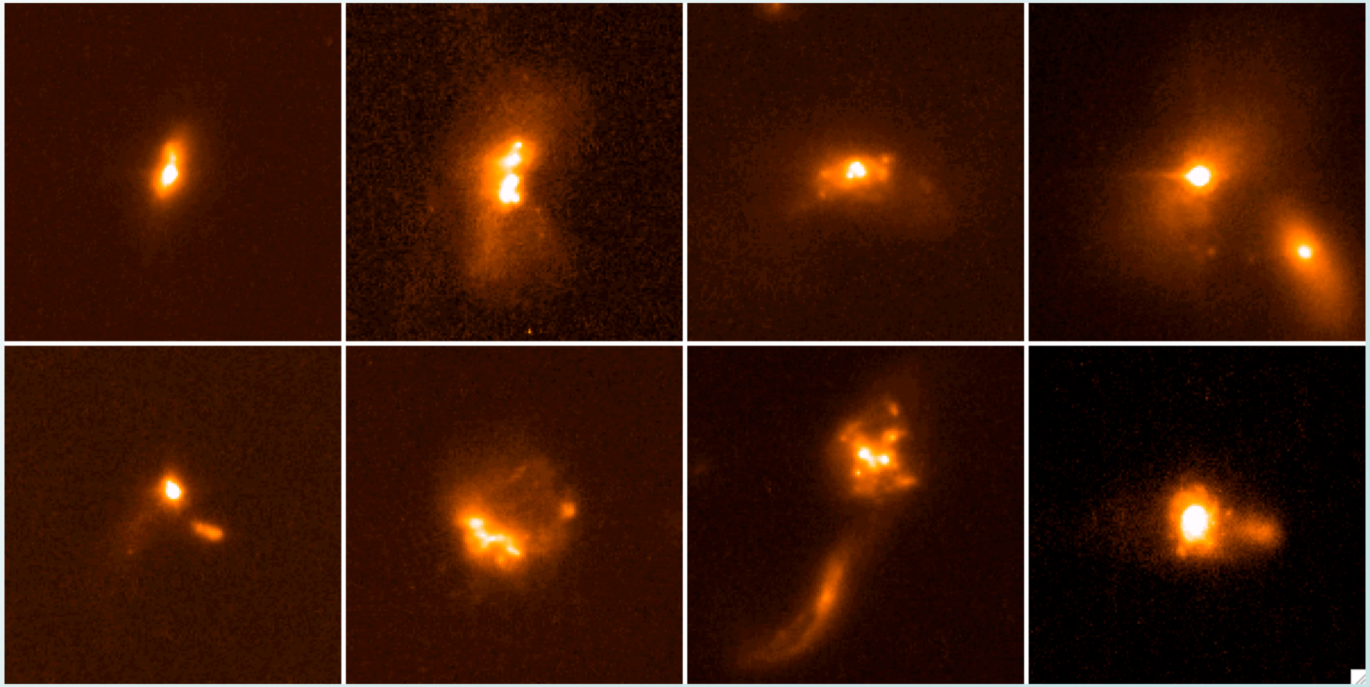


(ApJ, in press)

Overview

Introduction

- Starbursts, Galaxy Interactions, AGN
- High redshift starburst galaxies: Lyman break galaxies

GALEX/SDSS selected sample of ``UV-luminous galaxies''

- Local Analogs to Lyman break galaxies ? (yes)

HST observations

- Morphological analysis
- Connection between morphology and starburst
- AGN (black hole) formation ?

Updates on the story of galaxy formation at high redshift

SB-AGN-merger connections by N-body/hydro simulations

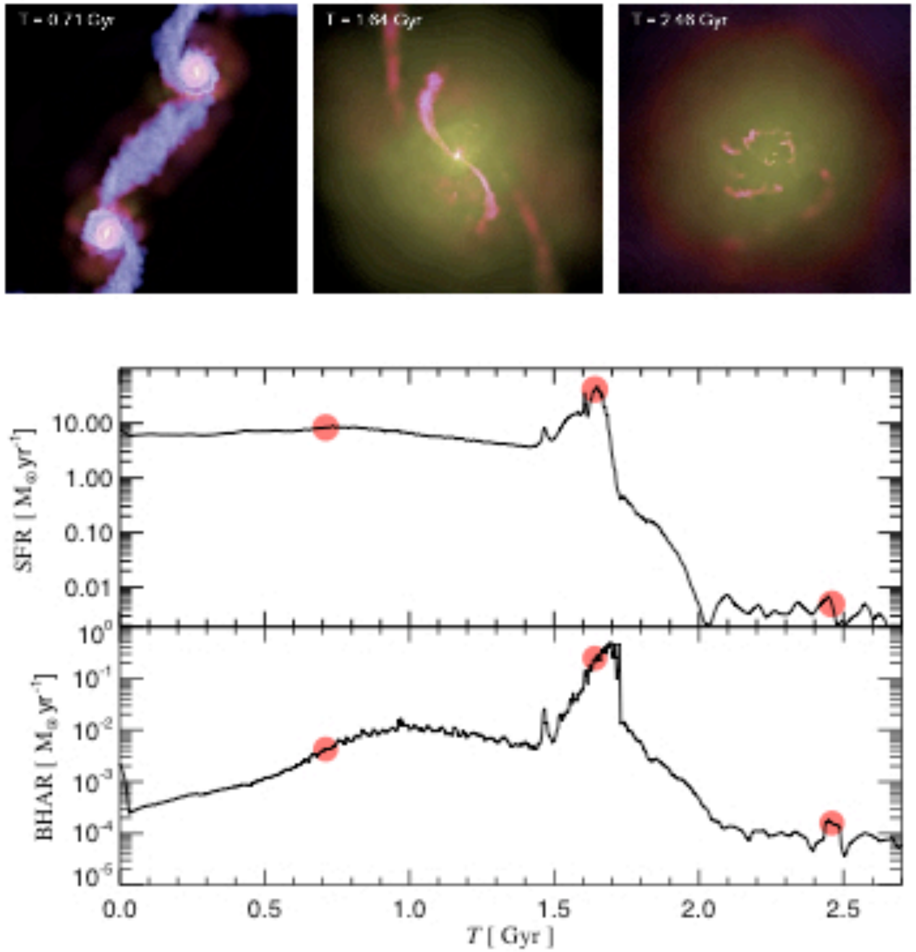
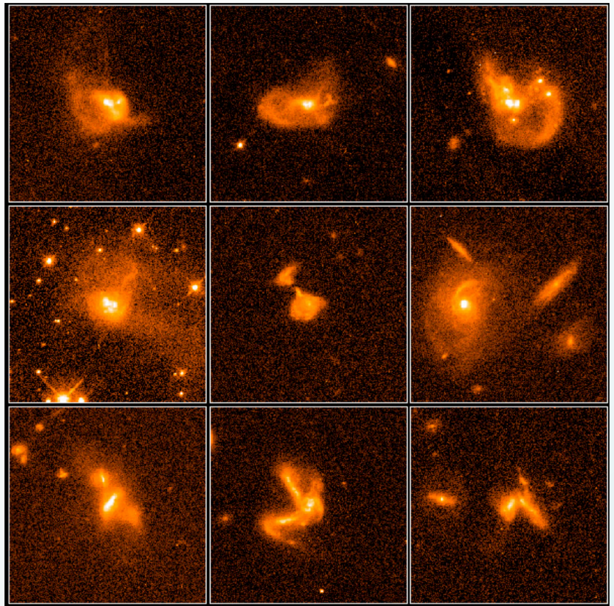


Figure: Merger of two disc galaxies (Springel et al. 2005)

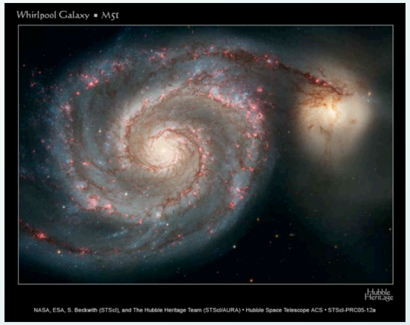
- Interactions can bring gas from the disc to the central regions $\longrightarrow$ enhanced star formation in the bulge
- Some of this gas can be accreted onto the central BH $\longrightarrow$ nuclear activity

(See also Toomre & Toomore '72; Barnes & Hernquist '92; Mihos & Hernquist '96; Springel '00; Tissera et al. '02; Meza et al. '03; Kapferer et al. '05; Cox et al. '06; Di Matteo et al. '07)

It is well established that galaxy interactions and mergers lead to enhanced star formation (starbursts)

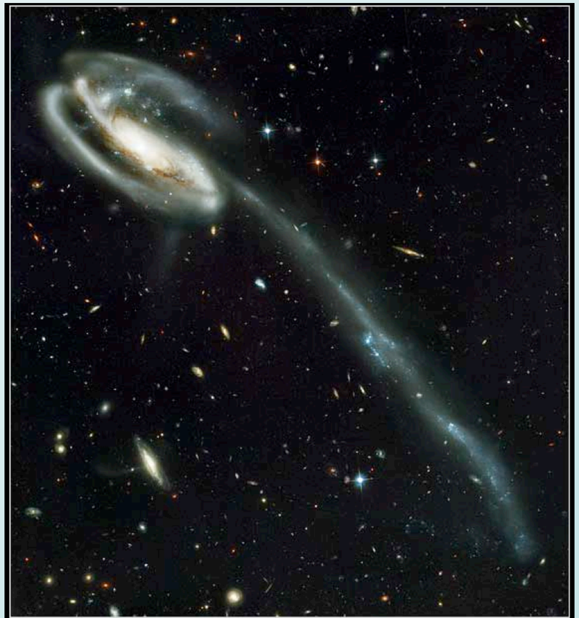


Ultraluminous Infrared Galaxies **HST** • WFPC2
NASA and K. Borne (Raytheon ITSS and NASA Goddard Space Flight Center), H. Bushouse (STScI), L. Colina (Instituto de Fisica de Cantabria, Spain) and R. Lucas (STScI)

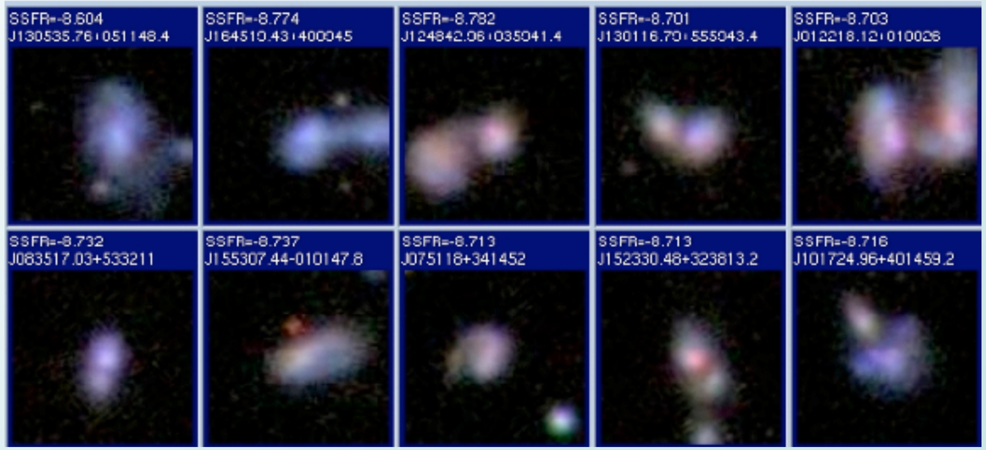


Colliding Galaxies NGC 4038 and NGC 4039 HST • WFPC2
PRC97-34a • ST ScI OPO • October 21, 1997 • B, Whitmore (ST ScI) and NASA

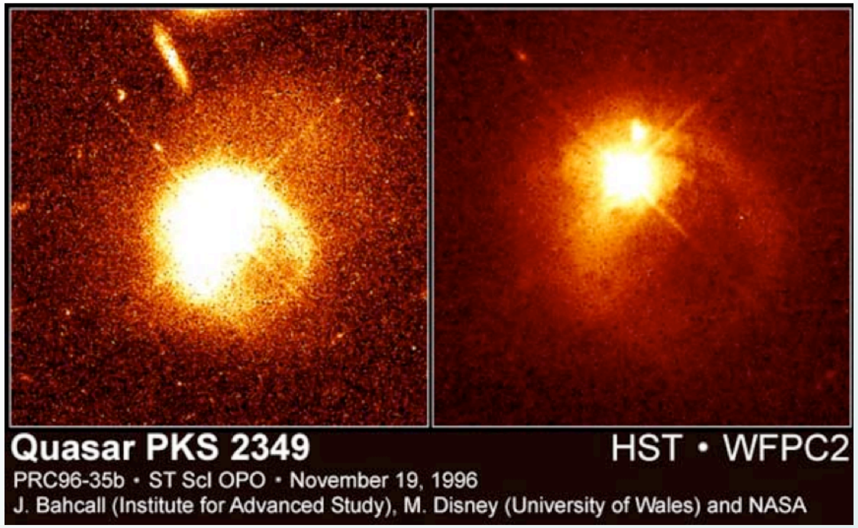
The Mice • Interacting Galaxies NGC 4676 **HST** • ACS
NASA, H. Ford (JHU), G. Illingworth (UCSC/LO), M. Clampin (STScI), G. Hartig (STScI), the ACS Science Team and ESA • STScI-PRC02-11d

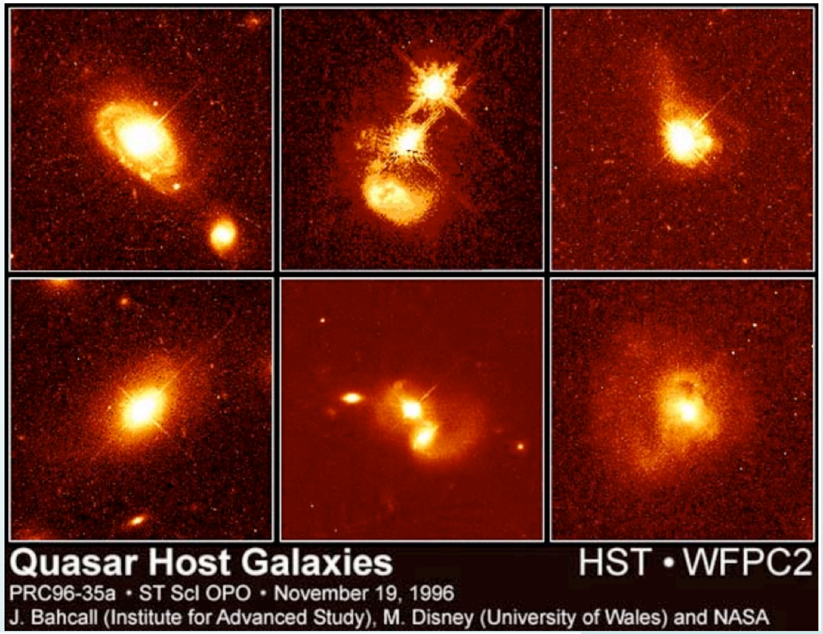


Tadpole Galaxy • UGC 10214 **HST** • ACS
NASA, H. Ford (JHU), G. Illingworth (UCSC/LO), M. Clampin (STScI), G. Hartig (STScI), the ACS Science Team and ESA • STScI-PRC02-11a



Are AGN (black hole growth) the result of galaxy interactions as well?





Do AGN have excess near neighbours relative to non-AGN?		
"Yes!"	Seyferts	Petrosian '82; Dahari '84; Keel et al. '85
	QSOs	Serber et al. '06
"No!"	Seyferts	Schmitt '01; Miller et al. '03
	X-ray	Grogin et al. '05; Waskett et al. '05

Largest SDSS-based study on QSO clustering (Li et al. 2007ab):

- Only $\sim 1\%$ AGN have an extra neighbour within 70 kpc, and the neighbour counts do not depend on $\log(L[OIII]/M_{BH})$
- Nuclear activity is not enhanced, but suppressed, as the pair separation decreases.

Conclusions on the connections between Starbursts + Galaxy Interactions + AGN:

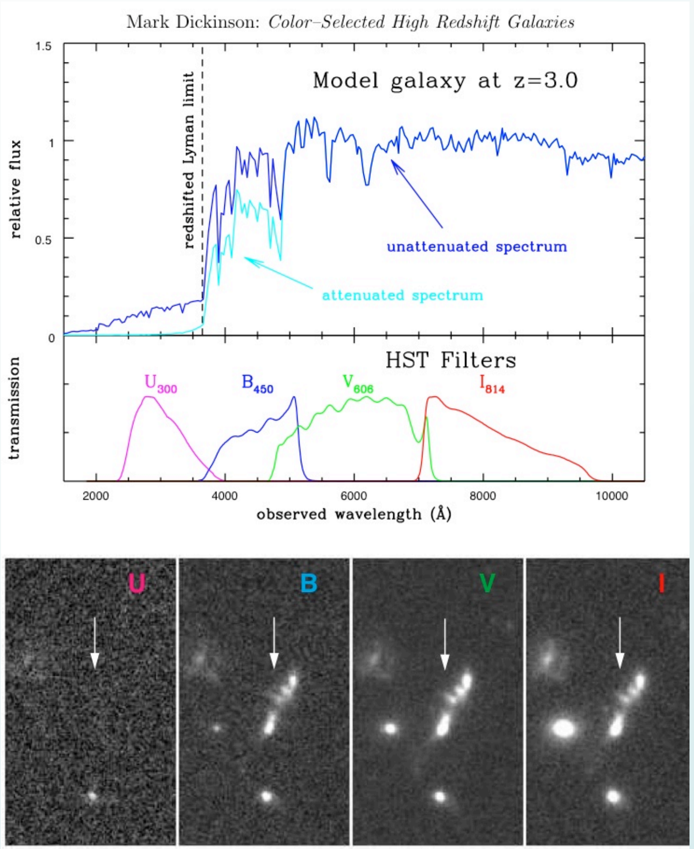
Observations:

- There is a physical connection between starbursts and AGN.
- There is also clear physical connection between starbursts and galaxy interactions. This is true not only for "normal" galaxies, but also for "active" galaxies.
- But a third connection is missing... (interactions-AGN)

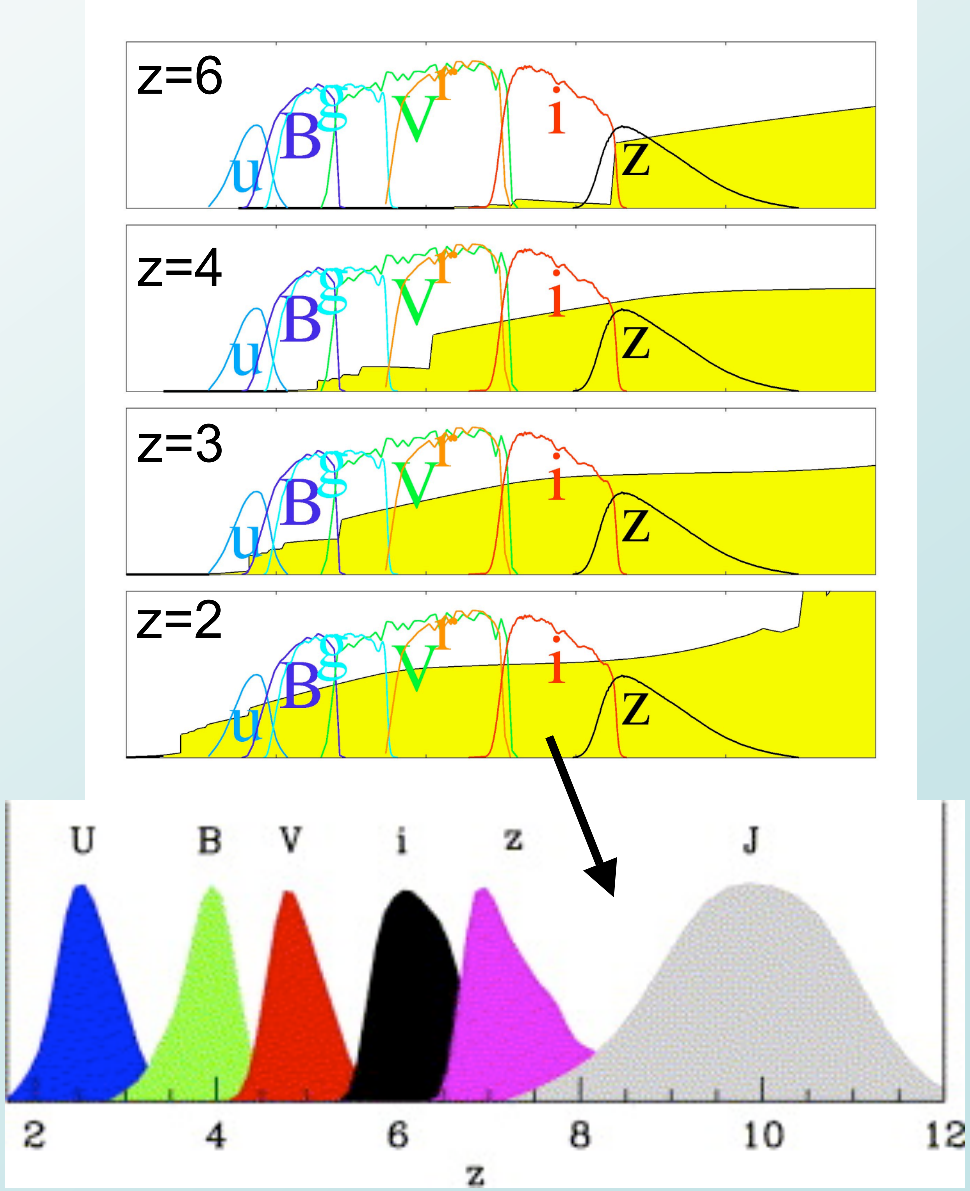
Implications:

- SF enhancement due to a close companion (the SB-merger connection) and SF enhancement due to an accreting BH (the SB-AGN connection) are two separate and distinct events.
- These two events may be part of the same underlying physical processes (such as a merger), provided that they are well separated in time. Accretion onto the BH and its association SF would occur only after the two galaxies have already merged.

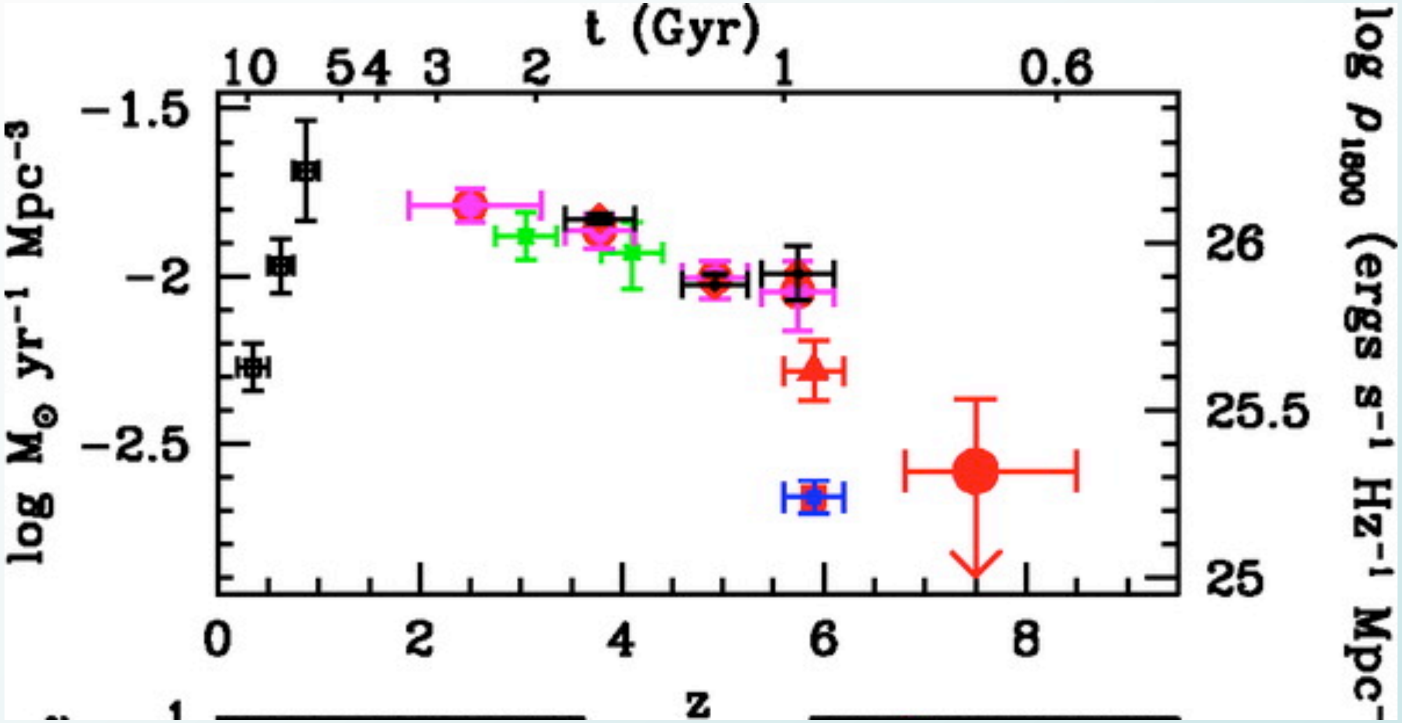
Lyman break galaxies: The typical galaxies that are forming stars at high redshift



Resulting in "Lyman break" or "dropout" samples:



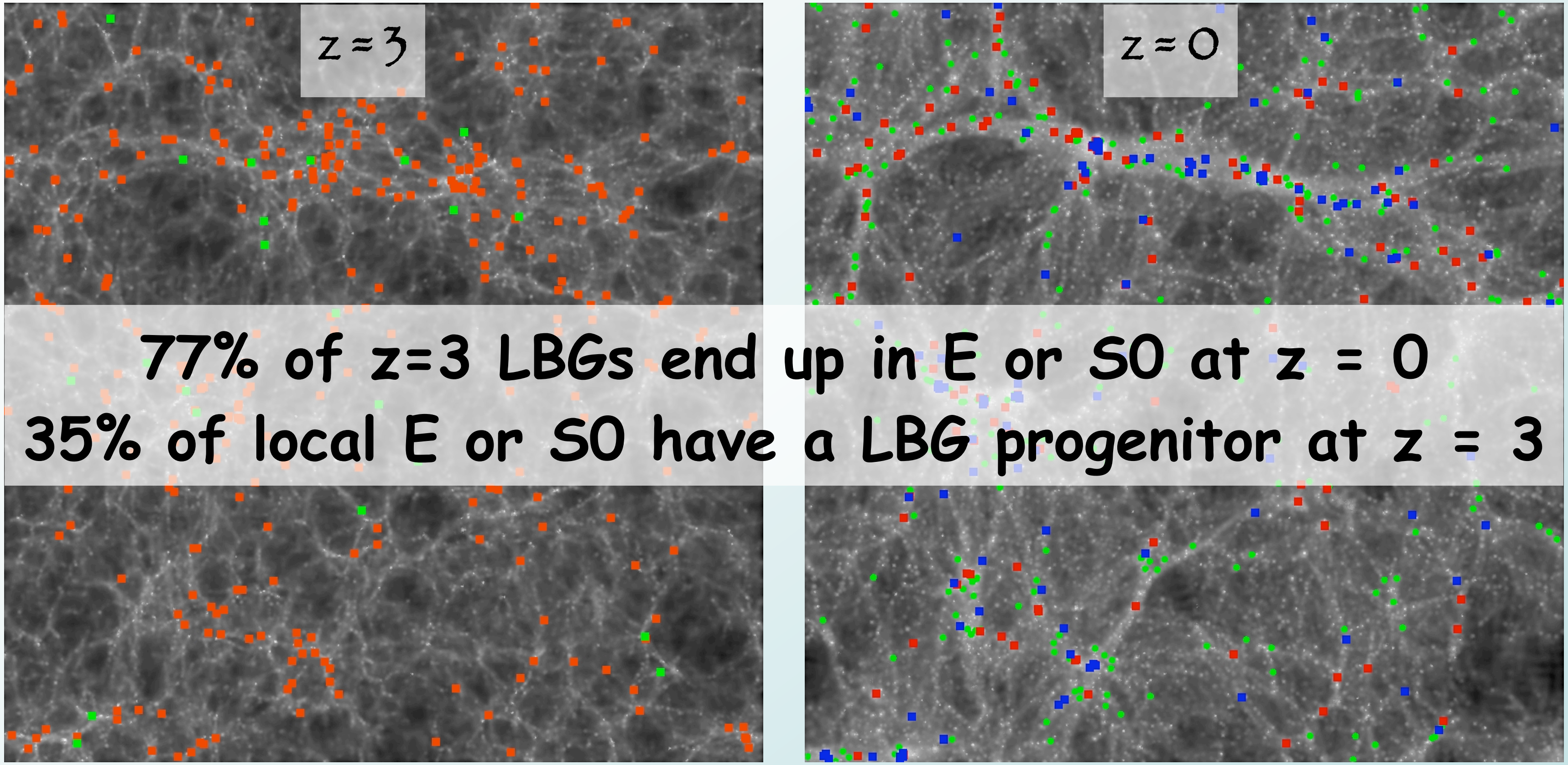
LBGs are used to probe, e.g., Cosmic star formation history



- modest rise in cosmic SFR from z~6 to z~3 (Bouwens et al. 2006,2007)
- maximum at z~1-3 (Lilly et al. 1996, Madau et al. 1998, Giavalisco et al. 2004)
- dramatic decline towards z~0 (e.g. Schiminovich et al. 2005)

- AGN history has a similar shape: AGN/BH formation more important at high-z!

Important links between local galaxies and high redshift Lyman break galaxies



77% of z=3 LBGs end up in E or S0 at z = 0

35% of local E or S0 have a LBG progenitor at z = 3

LBGs at z=3

E + S0 with LBG prog. at z=3

Sp with LBG prog. at z=3

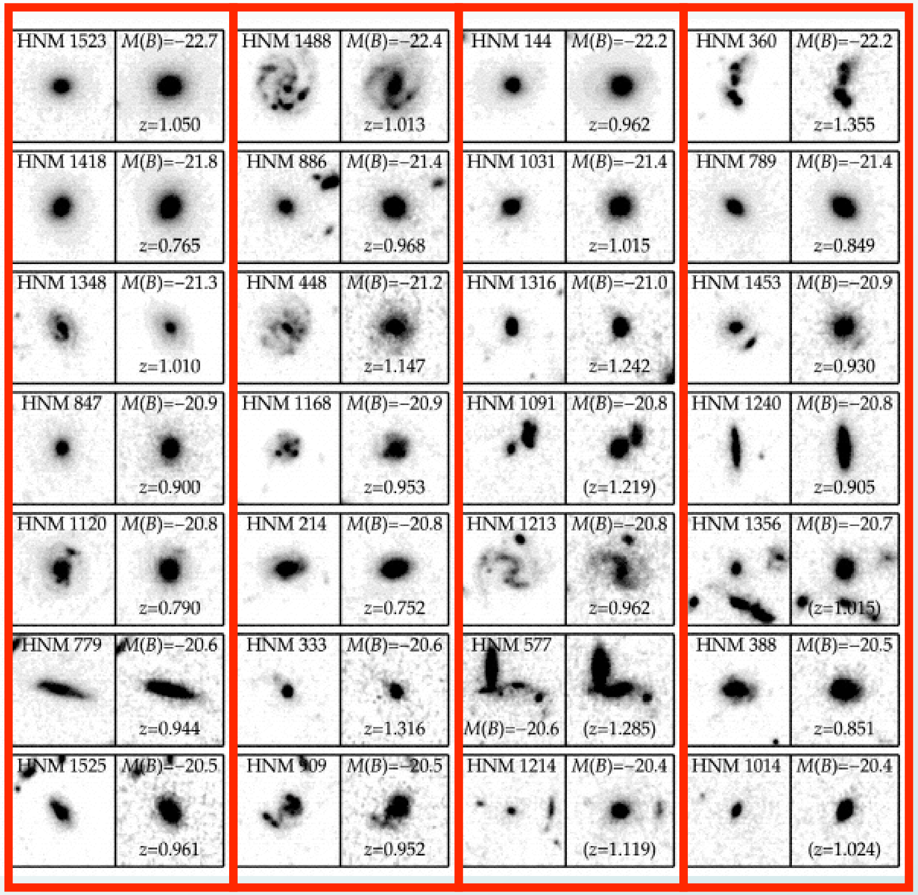
Other E + S0

Blaizot et al. 2005

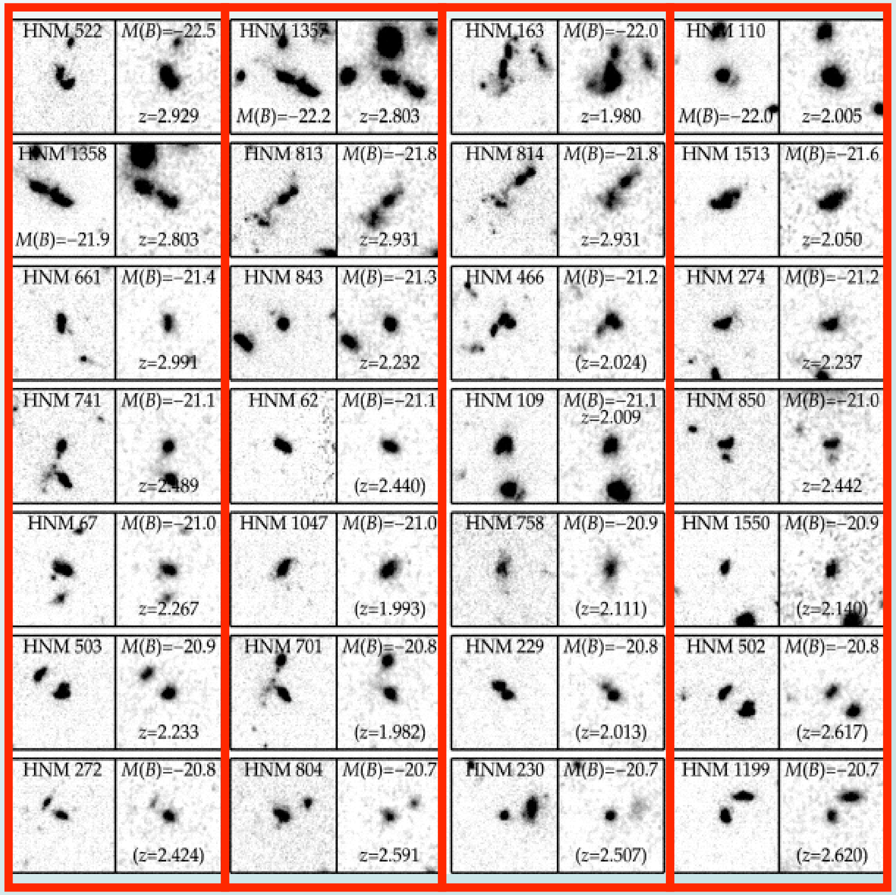
(Slide courtesy from J. Blaizot)

Rest-frame UV vs. optical morphologies of galaxies at z~1 and LBGs at z~3

galaxies at z~1



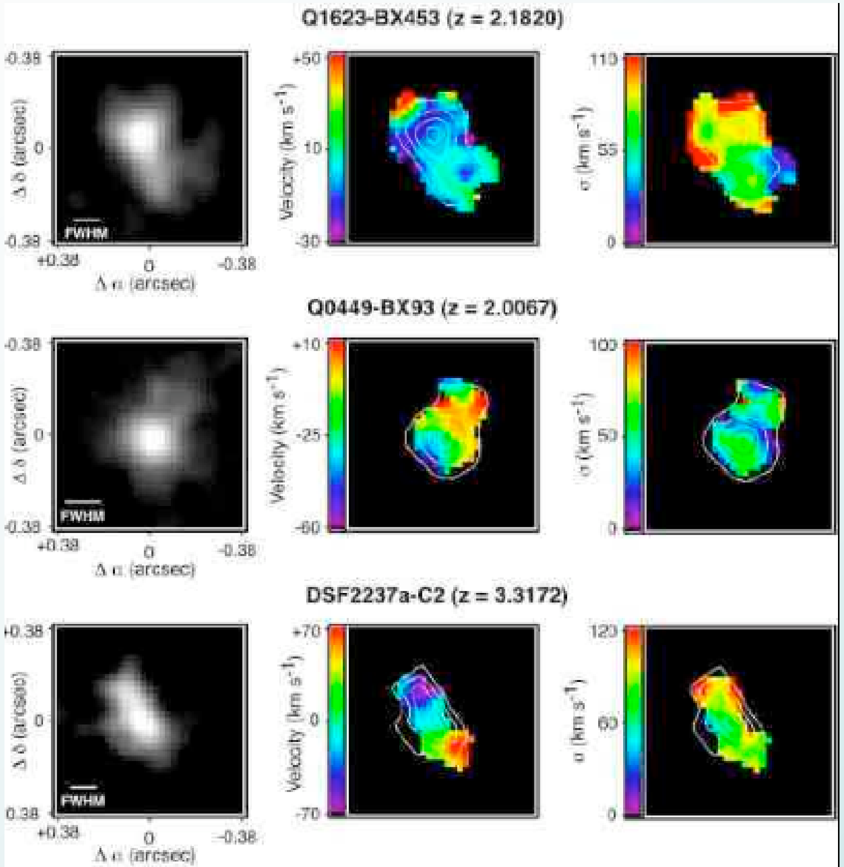
LBGs at z~3

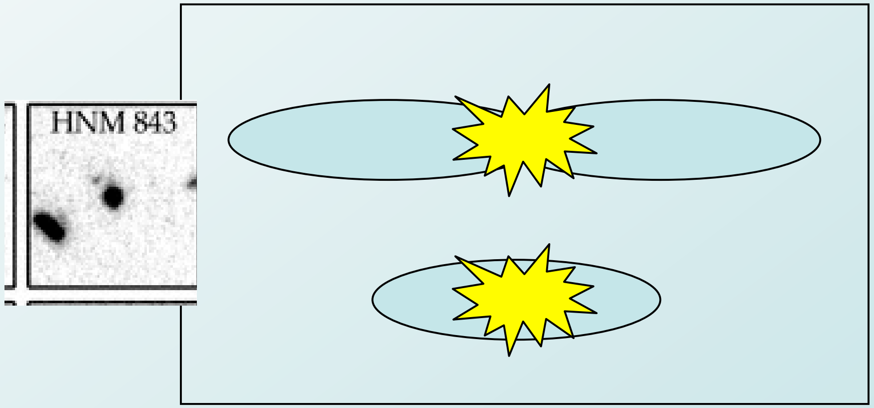


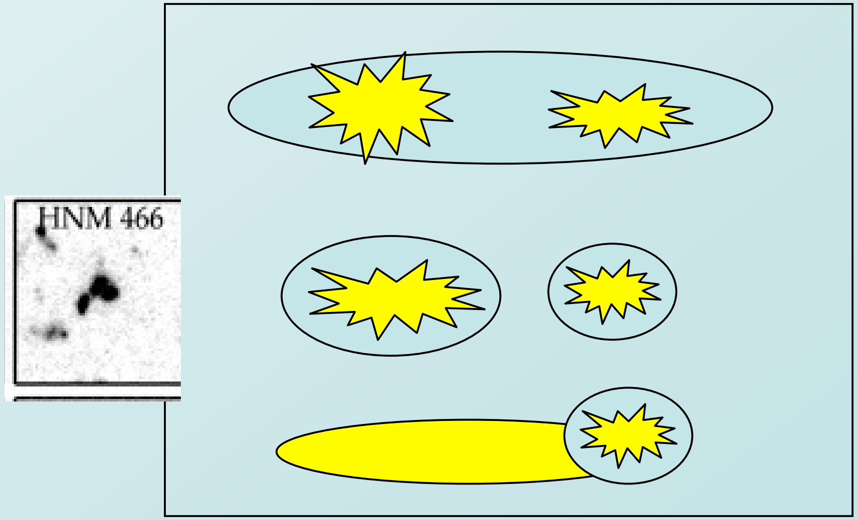
Papovich et al. (2005)

How to interpret LBG kinematics and morphologies?

Fragmented SF in a (rotating) gaseous disk or merging (or both)?







(Forster Schreiber et al. 2006, Law et al. 2007)

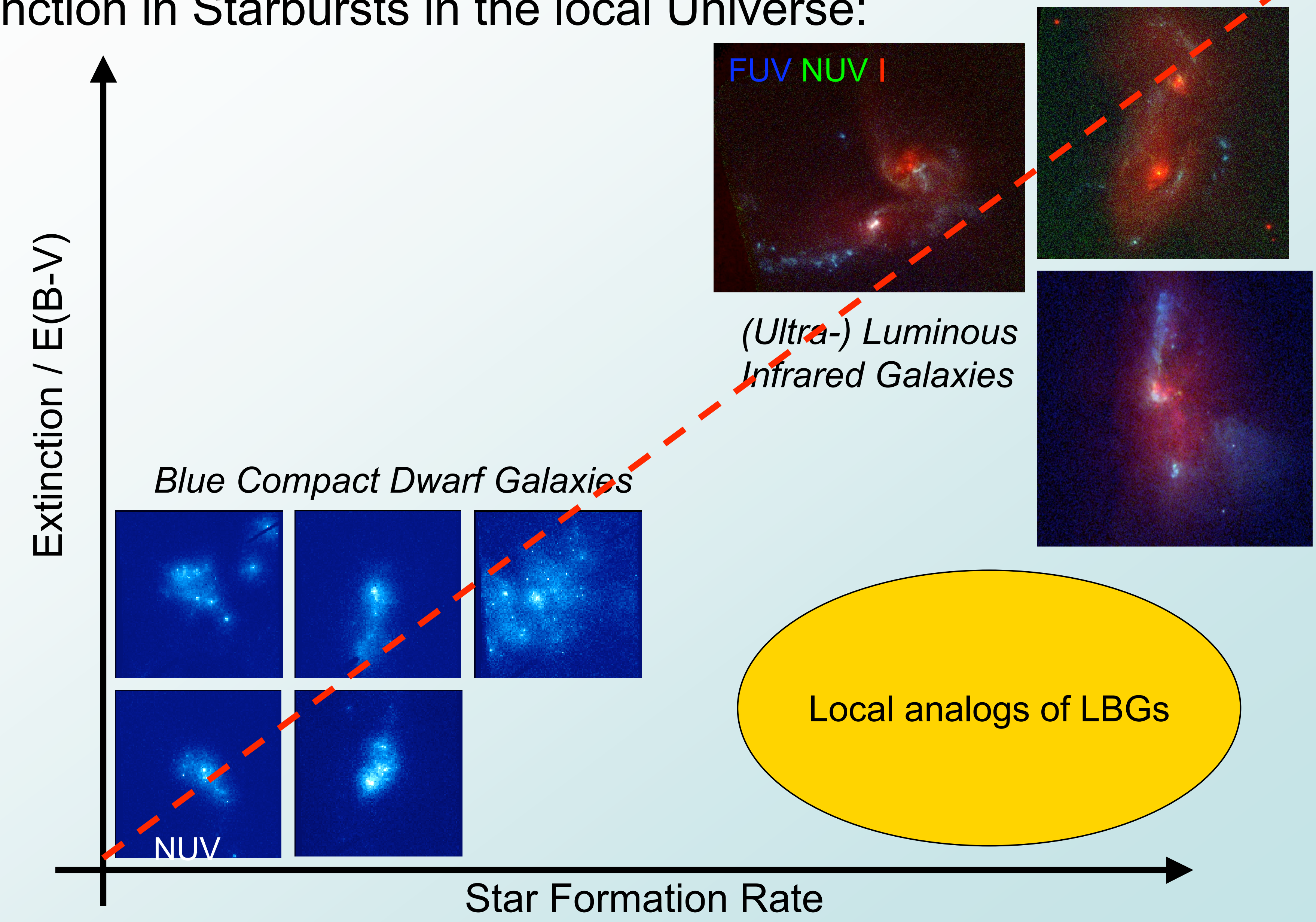
Finding Local Analogs to Lyman break galaxies

Why look for local analogs of LBGs?
- LBGs are the dominant star forming population at high redshift (2<z<10)
- they are nothing like ordinary (star-forming) galaxies in local Universe
- represent major, early phase in galaxy formation (proto-galaxies that may merge to form present-day ellipticals)
- what are the mechanisms that form them (merging, cold accretion, etc)?

Advantages of a local sample:
- not affected by cosmological surface brightness dimming (~10-250x for z=1-3)
- spatial resolution up to ~5 times better (~1 kpc at z=1-3 to ~200 pc at z=0.1)
- all important spectral line diagnostics are in the rest-frame optical

Local starbursts have been used to study LBG properties, but this is problematic:
- Ordinary late-type galaxies (too large, too low SFR)
- Blue compact dwarf galaxies (right metallicity and dust, but too low SFR)
- Luminous infrared galaxies (right SFR, but too much dust, metals and mass)

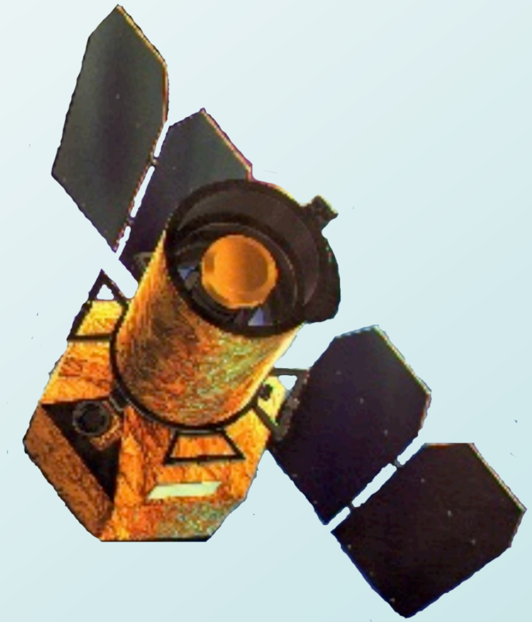
Strong Correlation between SFR and extinction in Starbursts in the local Universe:



Discovery of a significant GALEX/SDSS sample of local LBG analogs

GALEX (PI: Chris Martin)

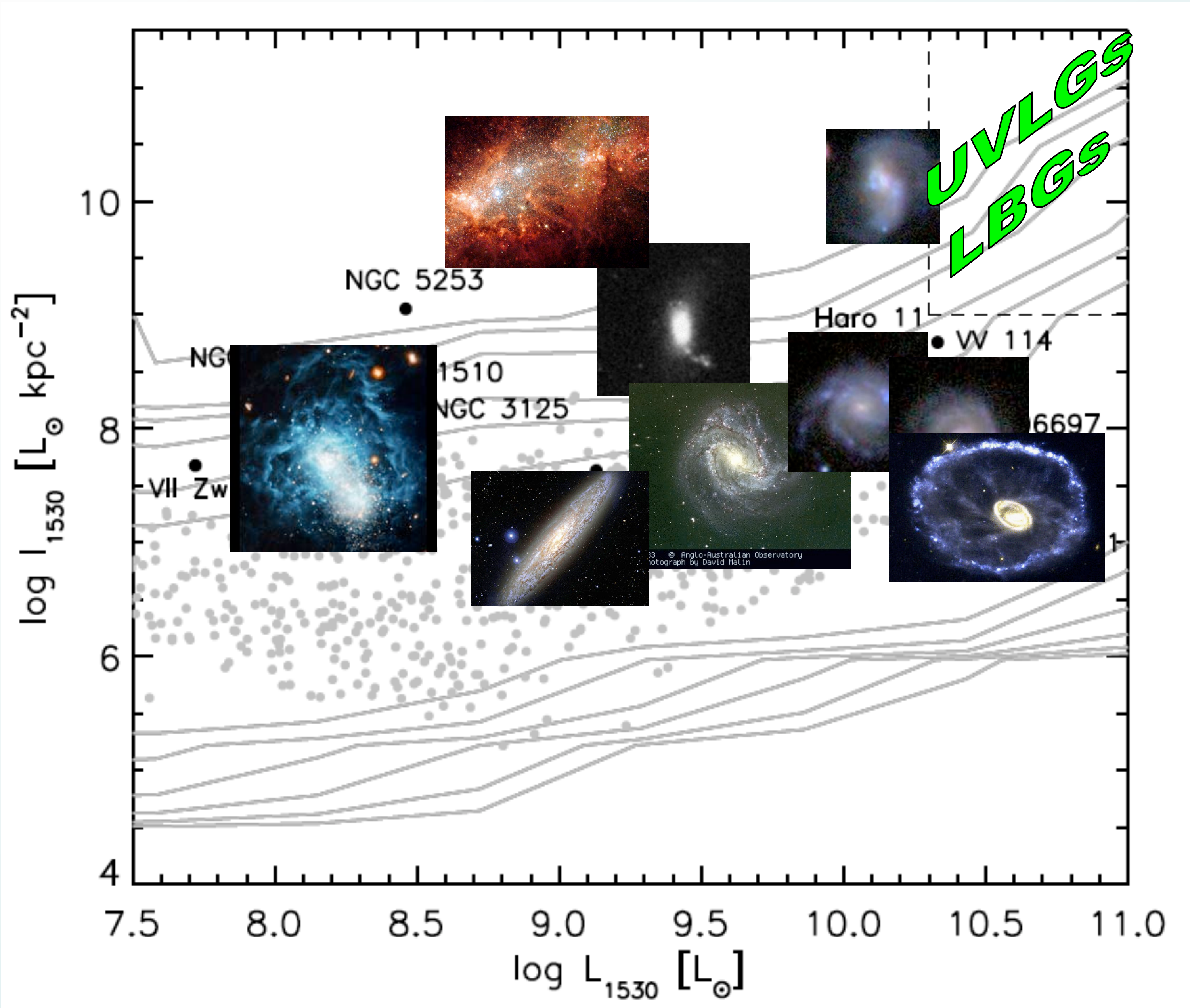
- NASA small explorer
- UV satellite with 40 cm mirror
- Capable of imaging in the Far- (1500A) and near-UV (2300A)
- PSF ~4-5 arcsec
- Survey telescope probing local (z=0-1) star formation history



Heckman et al. (2005) and Hoopes et al. (2006)
made a crossmatch between SDSS and the GALEX
All-sky Imaging and Medium-deep Imaging Surveys (AIS/MIS)

To match typical selection criteria of LBGs at high redshift:

search for objects having both a large L_{FUV} (SFR) and a
large FUV surface brightness (compact in size), like this:

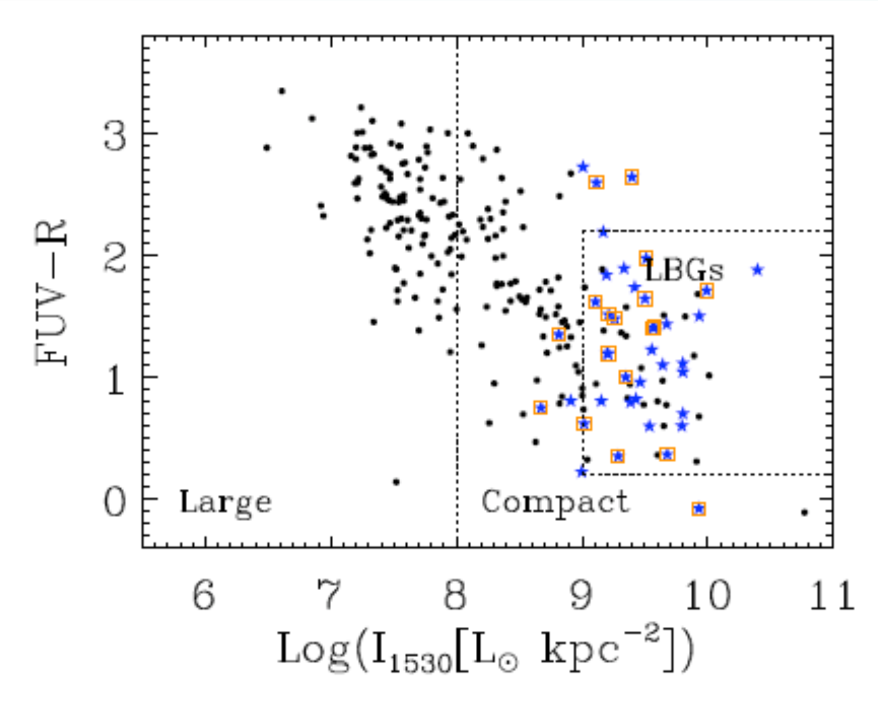


Far-UV Surface Brightness ($L_{FUV}/2\pi R_h^2$)

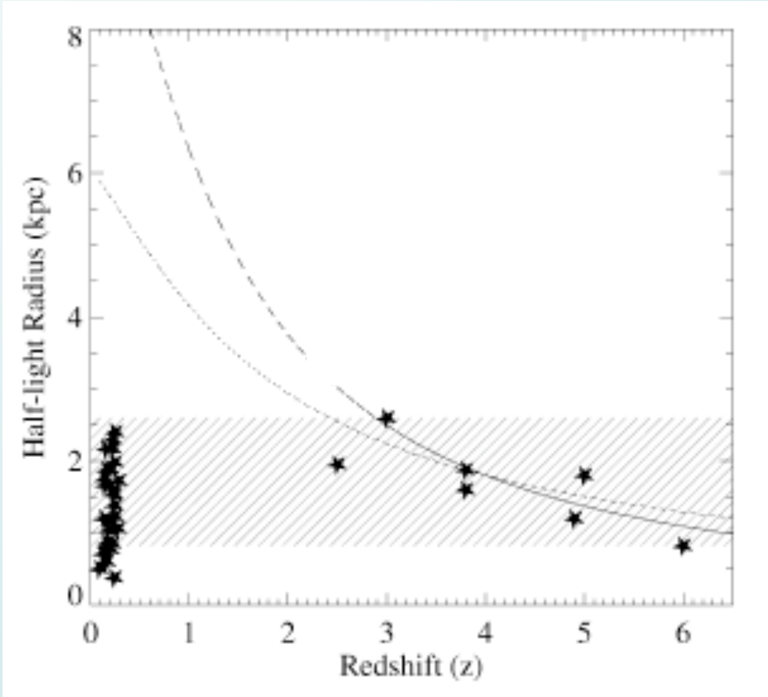
Far-UV Luminosity

Properties of UVLGs

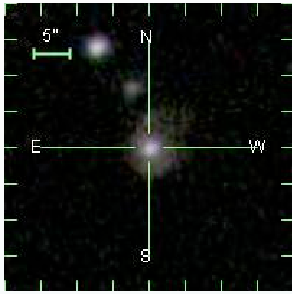
UV-optical colors

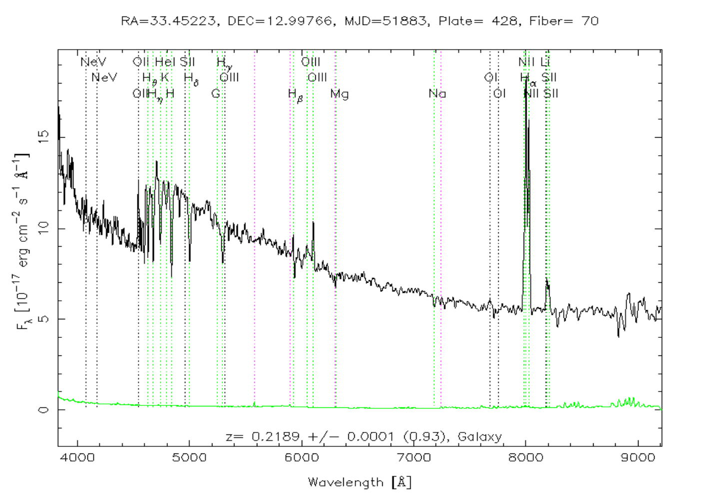


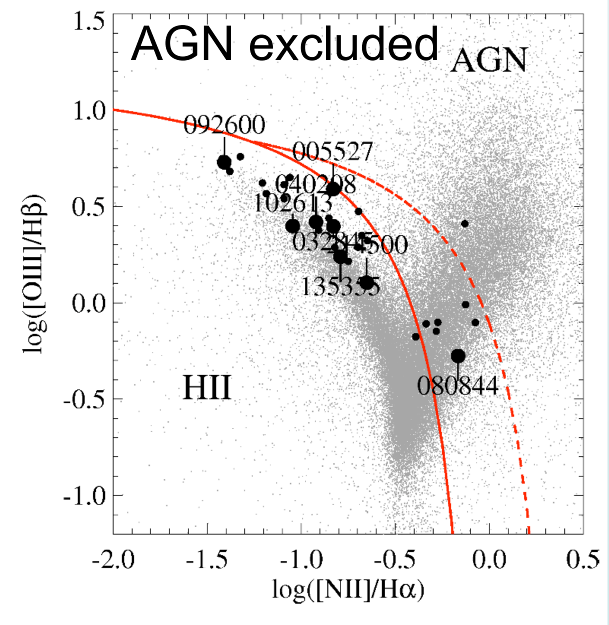
Halflight radius (SDSS u-band)

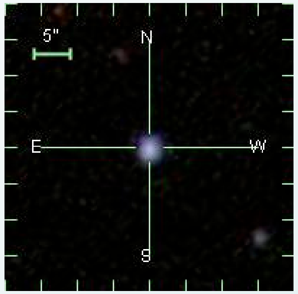


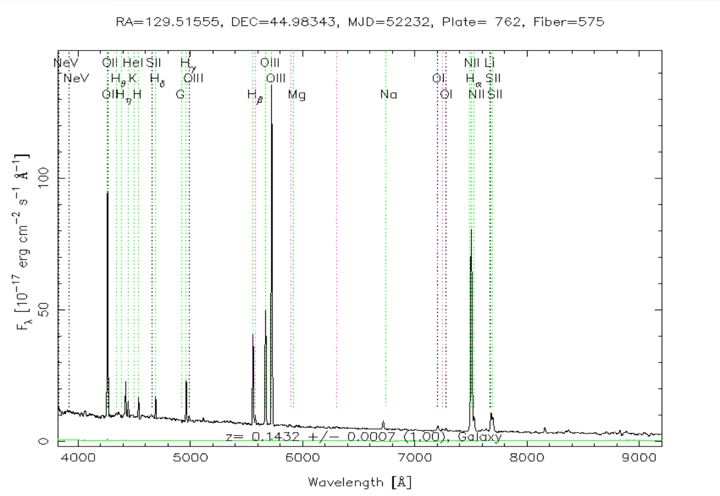
SDSS Spectra indicate typical starburst spectra

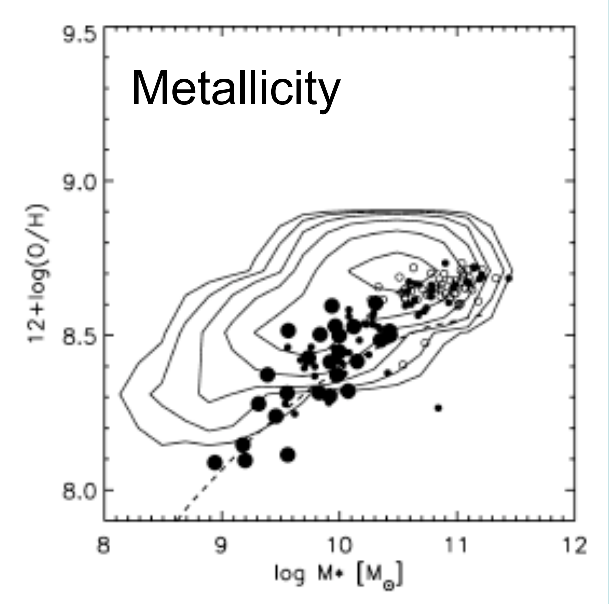






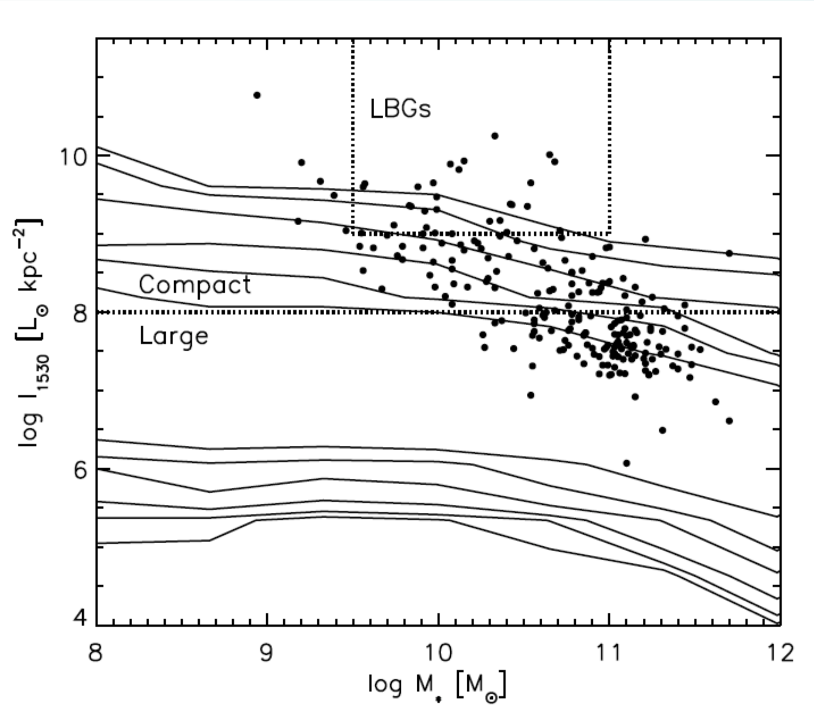




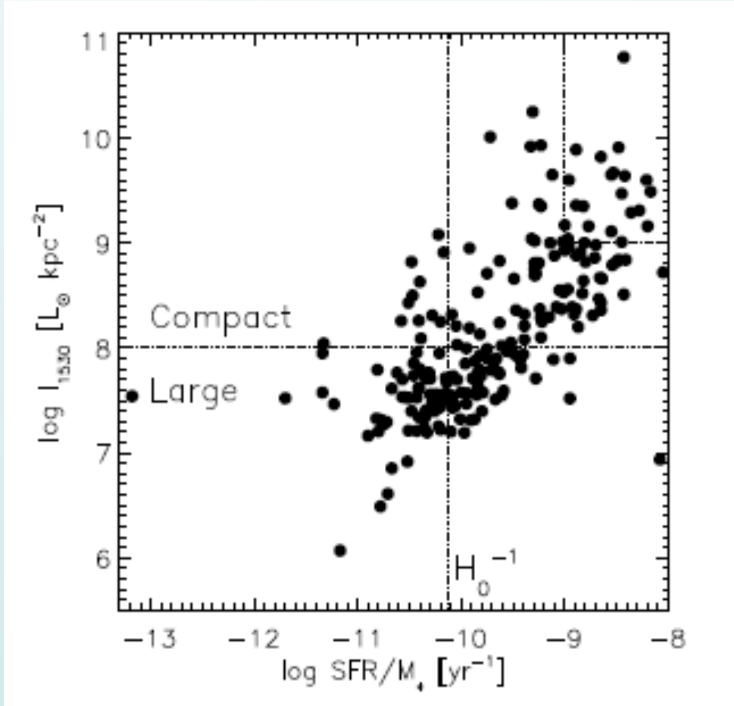


Properties of UVLGs

Stellar masses



Specific star formation rate



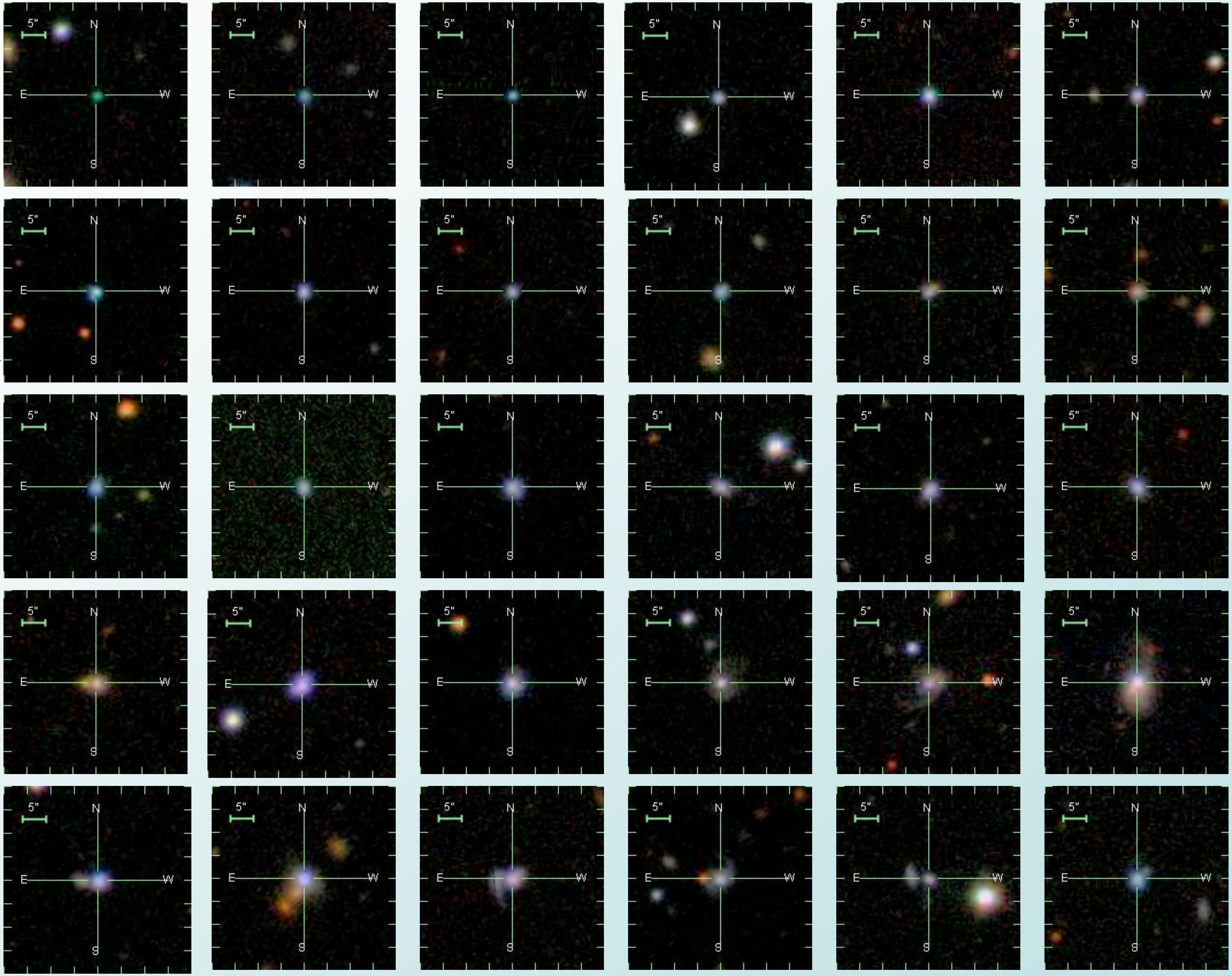
Summary of properties of `supercompact UVLGs'

- Starburst galaxies at $0.1<z<0.3$
- SDSS u' half-light radius of 1-2 kpc ($<r_{hl}>$ of LBGs at z=3-5; Ferguson et al. 2004)
- UV-optical colors $0<FUV-R<2$ (similar to $(R-K)_{AB}$ of LBGs; Shapley et al. 2003)
- metallicity $0.2Z_o$-Z_o(Shapley et al. 2004, Pettini et al. 2001)
- steep UV slopes, E(B-V)=0-0.2 (see Shapley et al. 2003, Bouwens et al. 2006)
- stellar masses of 10^{10} M_o → *Specific SFR* $10^{8.3}$-10^{9} yr
- SFRs of 5-50 M_o yr^{-1}
- emission line velocity disp. of 60-130 km s^{-1} (Pettini et al. 2001, Erb et al. 2006)

So far, every physical property we could measure is similar to that of LBGs!

What are they?

SDSS Images of Compact UVLGs show… compact-ness mostly



HST imaging program Cycles 15 & 16 (~100 orbits)

31 nearest and brightest UVLGs (0.04 < z <0.30)

• F330W (U-band) with HRC (0.025 arcsec/pixel)

HRC PSF: ~0.072 arcsec (FWHM) or 120-310 pc for 0.1<z<0.3

- What is the UV morphology of the starburst?

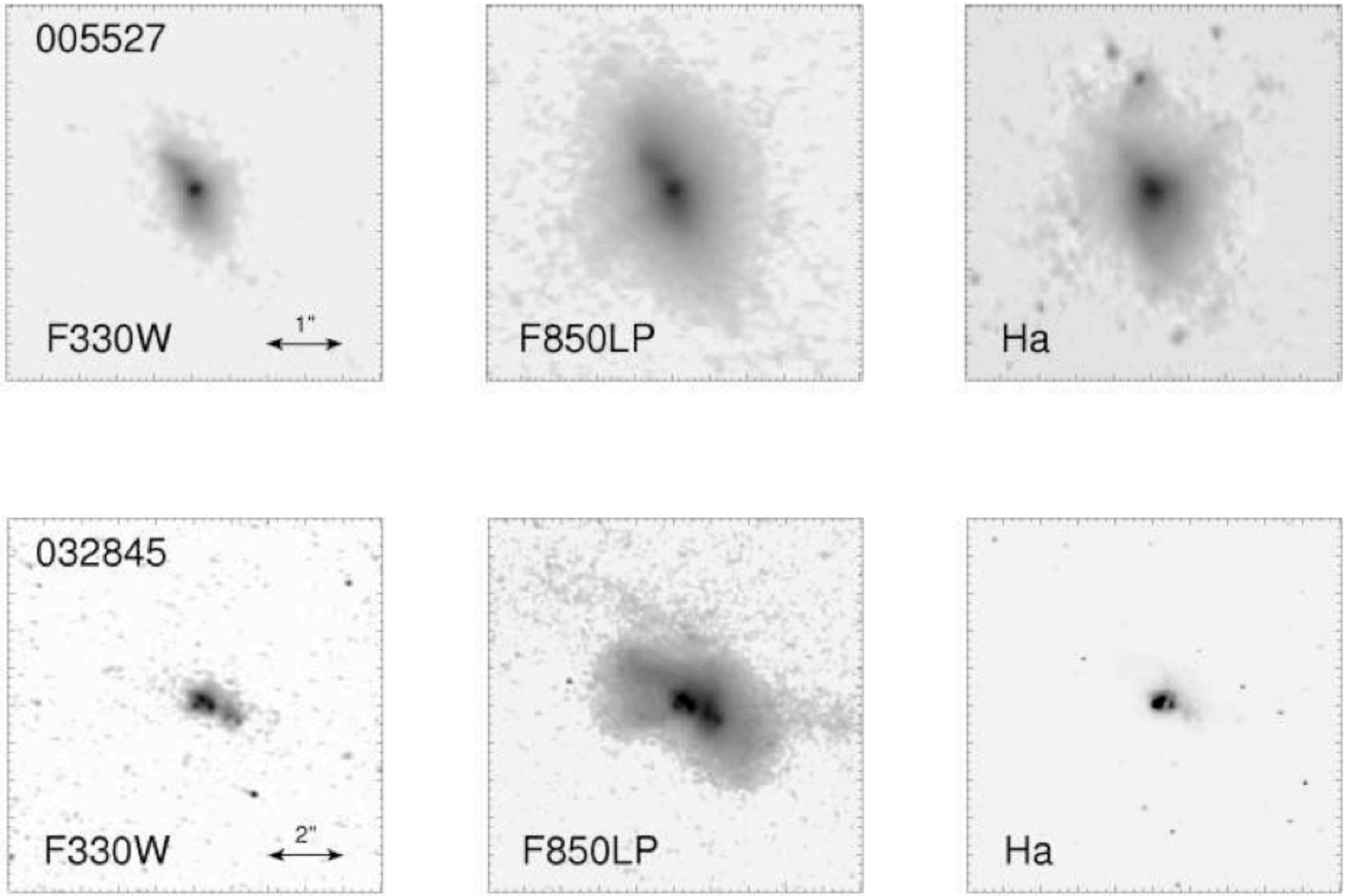
• Hα ramp filter and F850LP (z-band) with WFC (0.05 arcsec/pixel)

WFC PSF: ~0.12 arcsec (FWHM) or 210-520 pc for 0.1<z<0.3

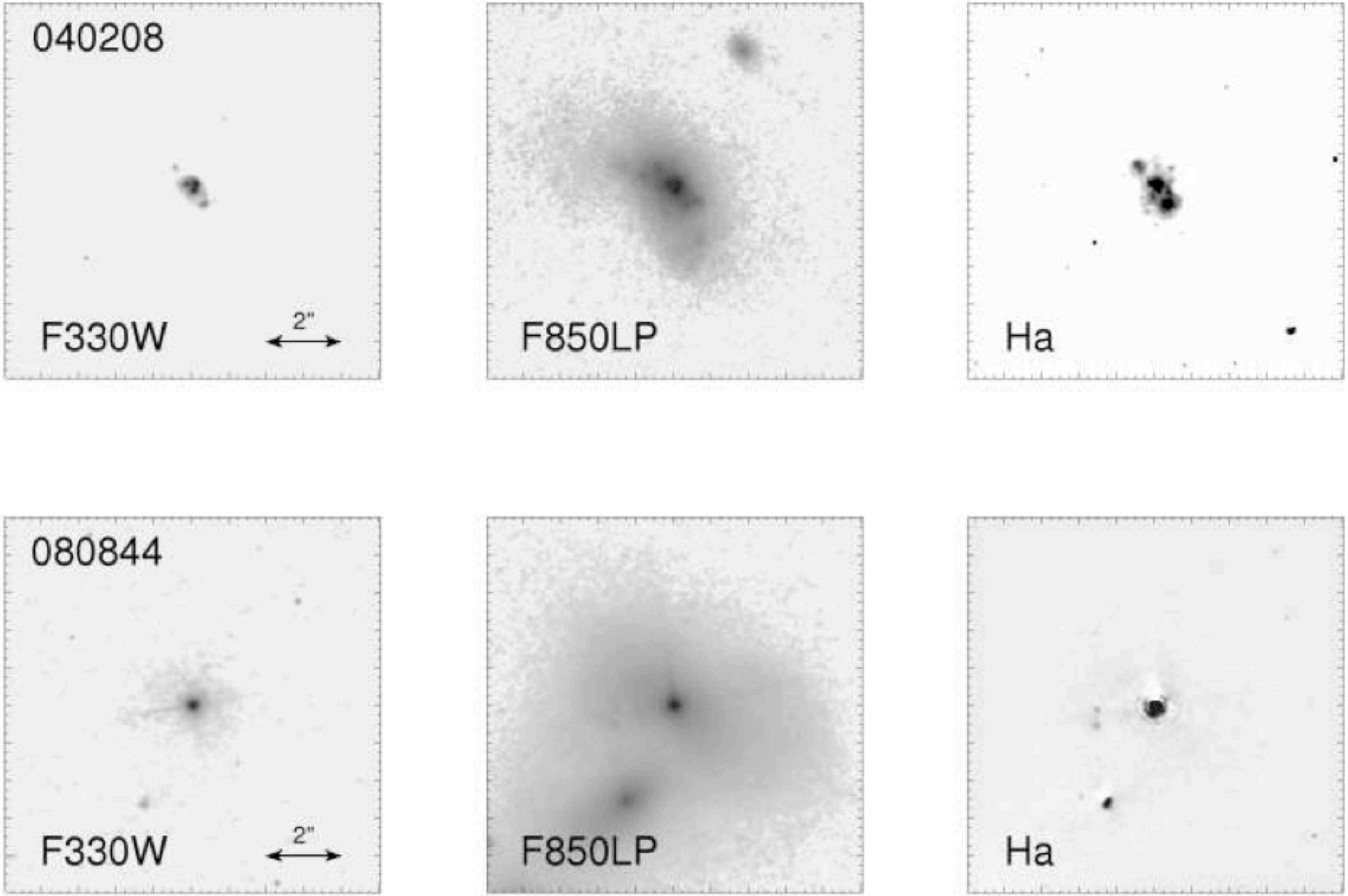
- What is the morphology of the youngest (Ha) and oldest (z) stellar population?

How do these UV and optical morphologies compare to high-z LBGs?

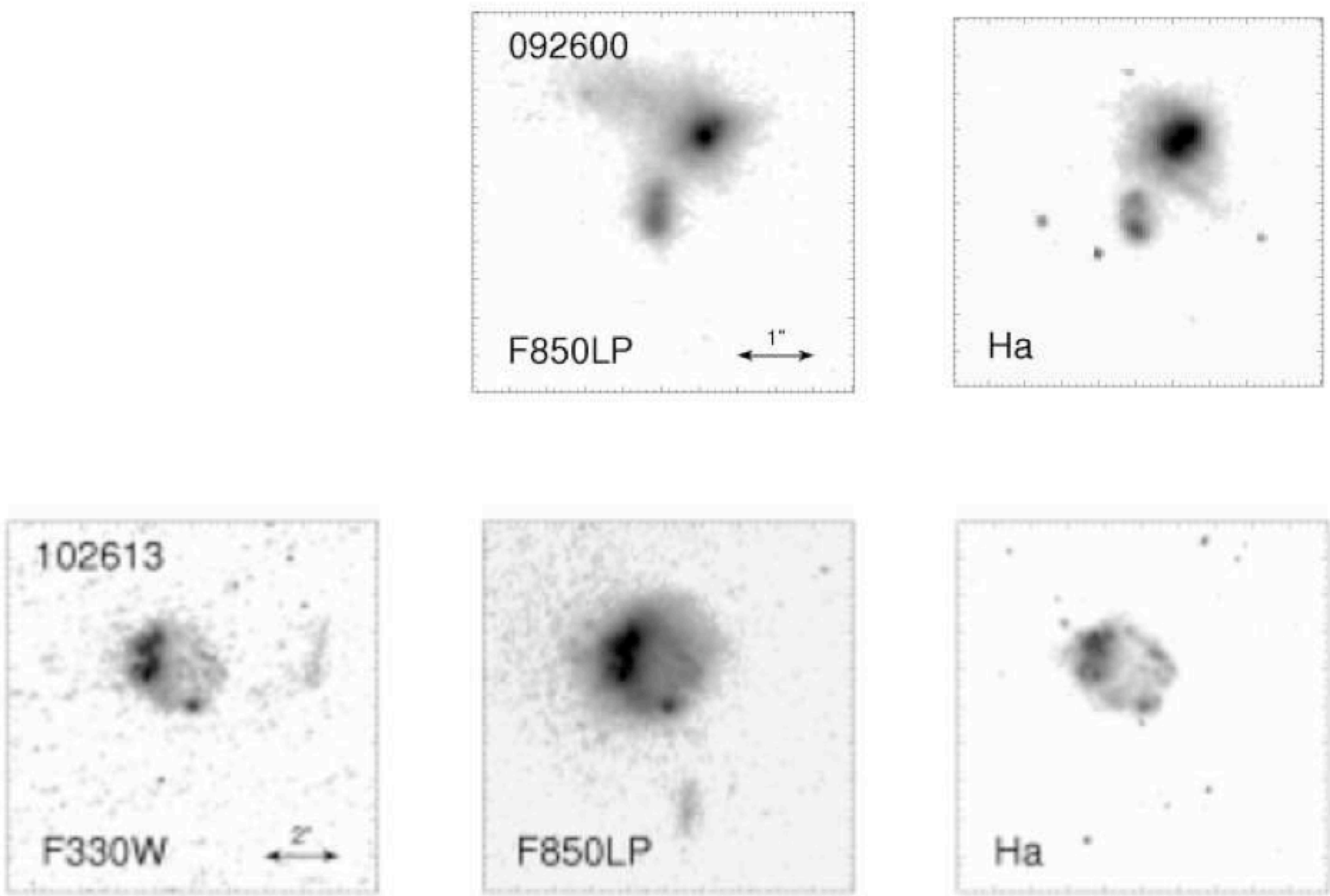
UVLG morphologies I



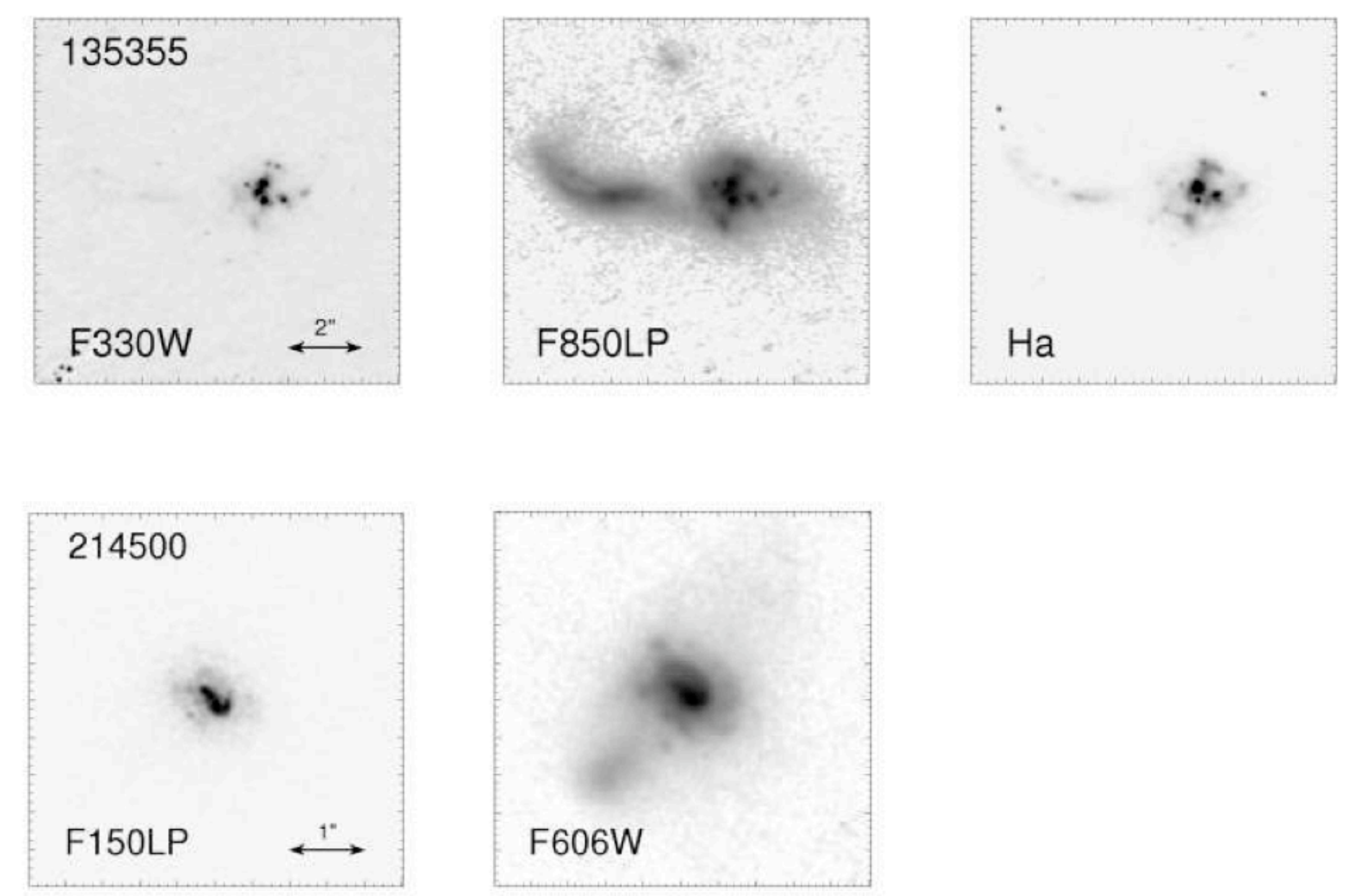
UVLG morphologies II



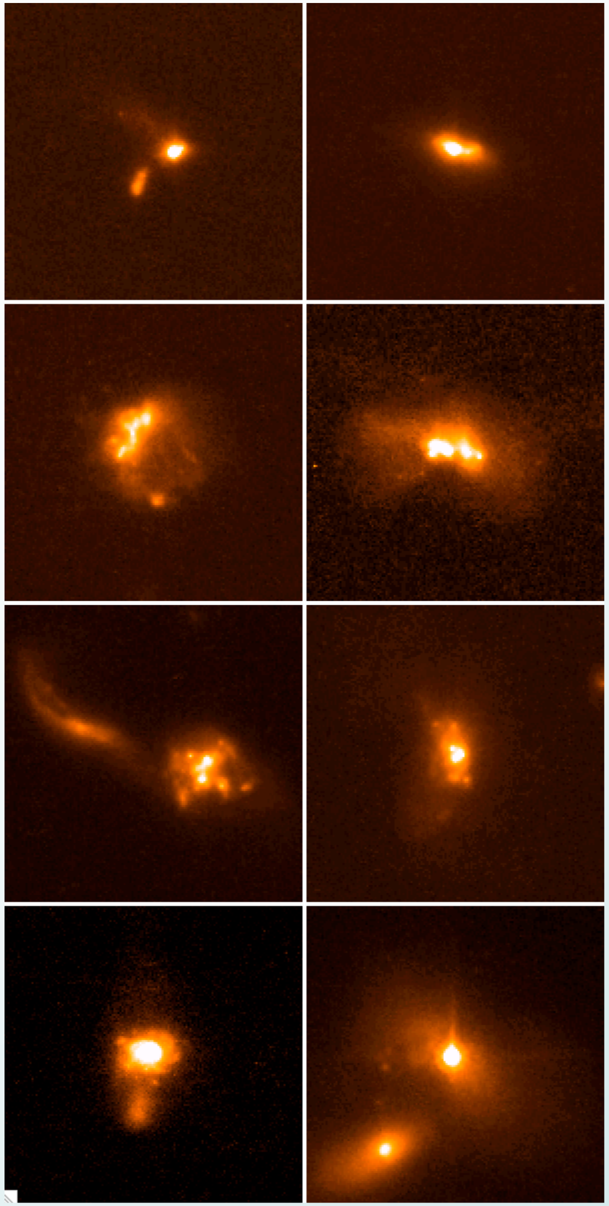
UVLG morphologies III



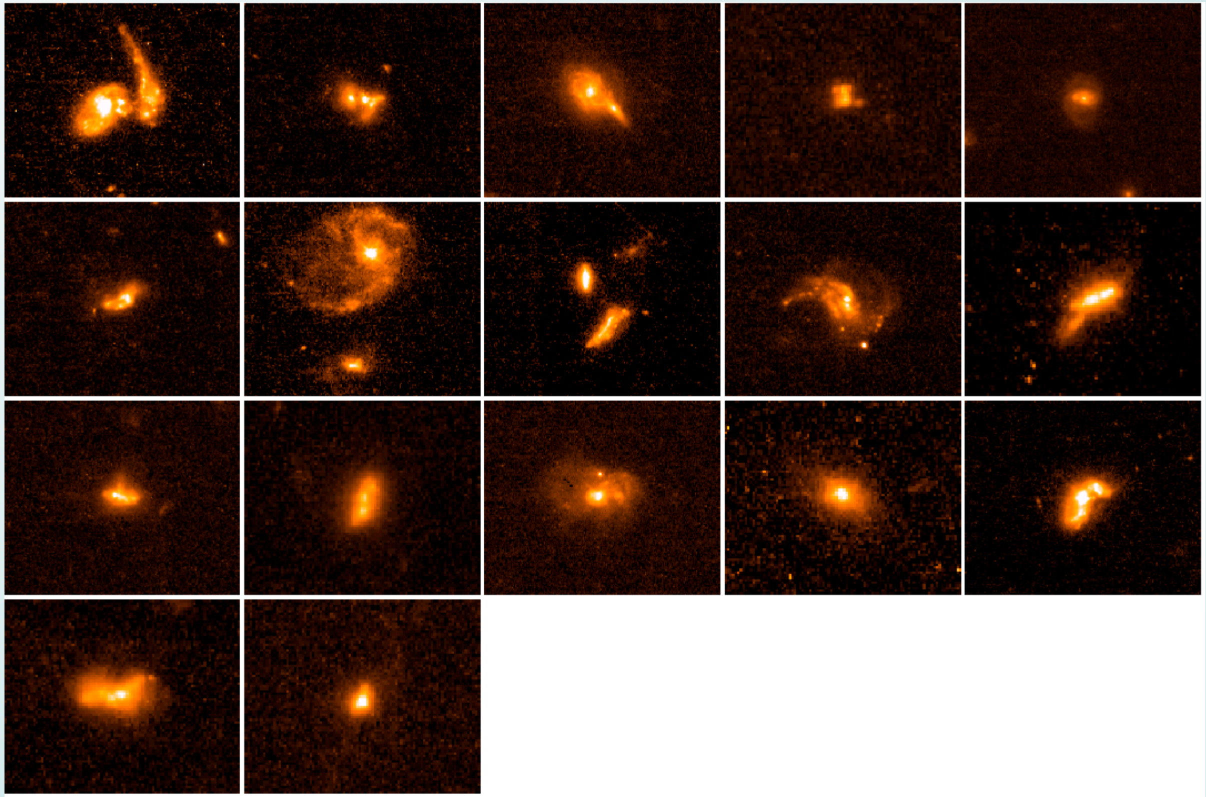
UVLG morphologies IV



Summary of UVLG morphologies



- Evidence for merger/interaction in each case
- Evidence for merger only seen in optical, not in UV!
- Starbursts concentrated in very small regions



Quantifying the Morphologies

Low redshift: high S/N and well-behaved galaxies:
• visual classification (E,S0,Sp,Irr,merger,etc)
• automated classification through profile fitting (Sersic,etc)

High redshift: low S/N, different wavelengths (mostly UV), and galaxies have non-standard types (LBGs):
• Morphological parameters

Gini Coefficient
M_{20}
CAS (Concentration, Asymmetry, Smoothness)

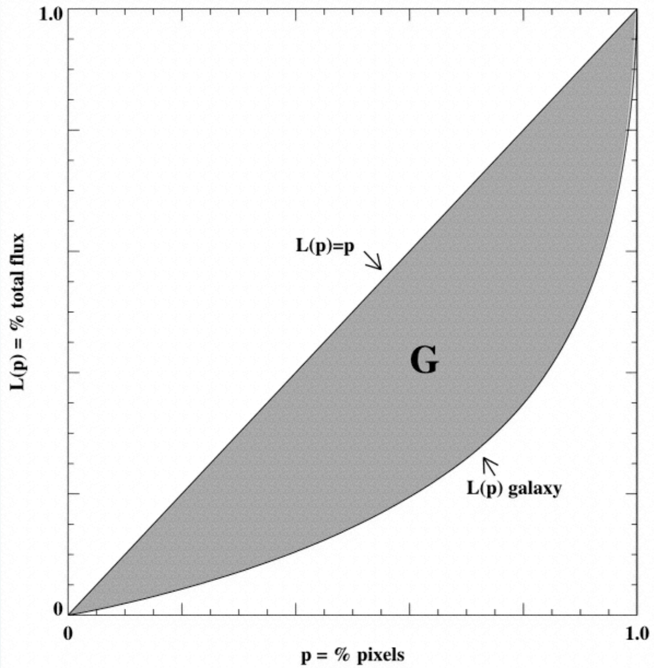
(e.g. Abraham et al. 1996; Conselice et al. 2003; Lotz et al. 2004,2006; Scarlata et al. 2006)

Interpretation of high redshift morphologies usually relatively with respect to common local redshift morphological types (artificially redshifted to higher redshift)

However, this has several problems:
• Low redshift galaxies not representative for high redshift galaxies (size, luminosity scaling)
• No absolute morphologies at high redshift

The UVLG sample offers a unique test for LBG morphologies and trigger of star formation !

Measuring Morphological Parameters



• Gini Coefficient (G) is a measure of the fairness of distribution of the wealth (light) of a society (galaxy) over its people (pixels)

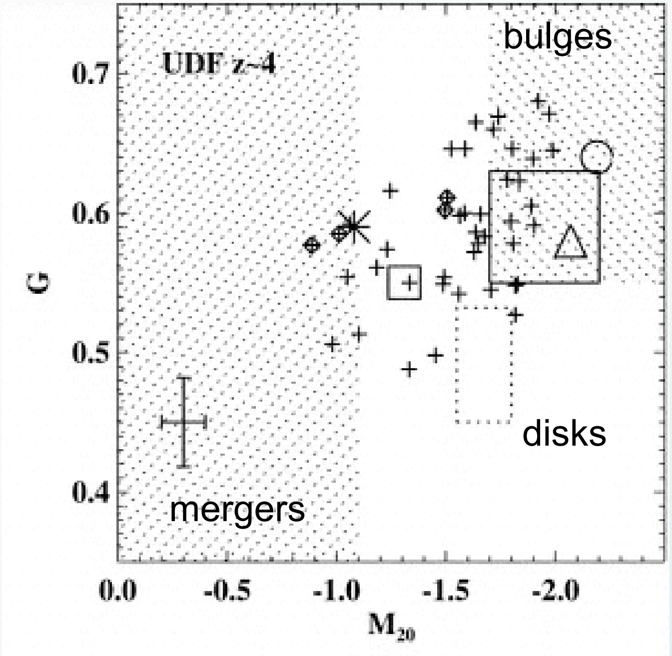
$$G = \frac{1}{|\bar{X}|\, n(n-1)} \sum_{i}^{n} (2i - n - 1)\, |X_i|$$

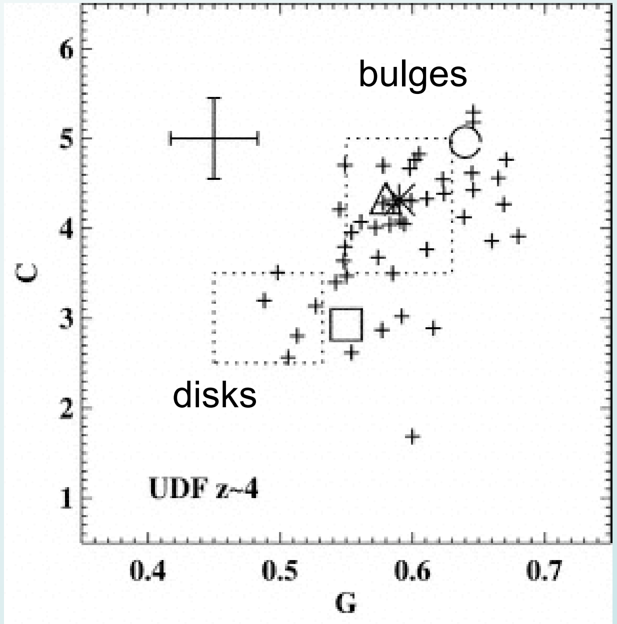
• M_{20} is the second order moment of a galaxy's 20% brightest pixels

• C is the concentration = 5 log(r_{80}/r_{20})

Outcome may depend on S/N (z, L and, size, instrument), aperture diameter,

Morphologies of star forming galaxies at z=2-4 observed with HST





- *Morphologies of LBGs lie in between spheroids and double-nucleated mergers*
- *LBGs are more spheroid-like than disk-like*

z=4: 10-25% double (major merger?)
30% spheroidal (bulge?)
50% indetermined (minor mergers/SF disks/post-SB?)

(from Lotz et al. 2004, 2006)

Artificial redshifting the observed morphologies to z=1-4

$\theta_2 = \theta_1(D_{A1}/D_{A2})$
$\theta_1/s_1 = b\ (\theta_2\ /s_2)$, b = binning factor

Conservation of luminosity:

$4\pi D^2_{L1} N_1 f_\nu(z_1)(1+z_1)^{-1}$

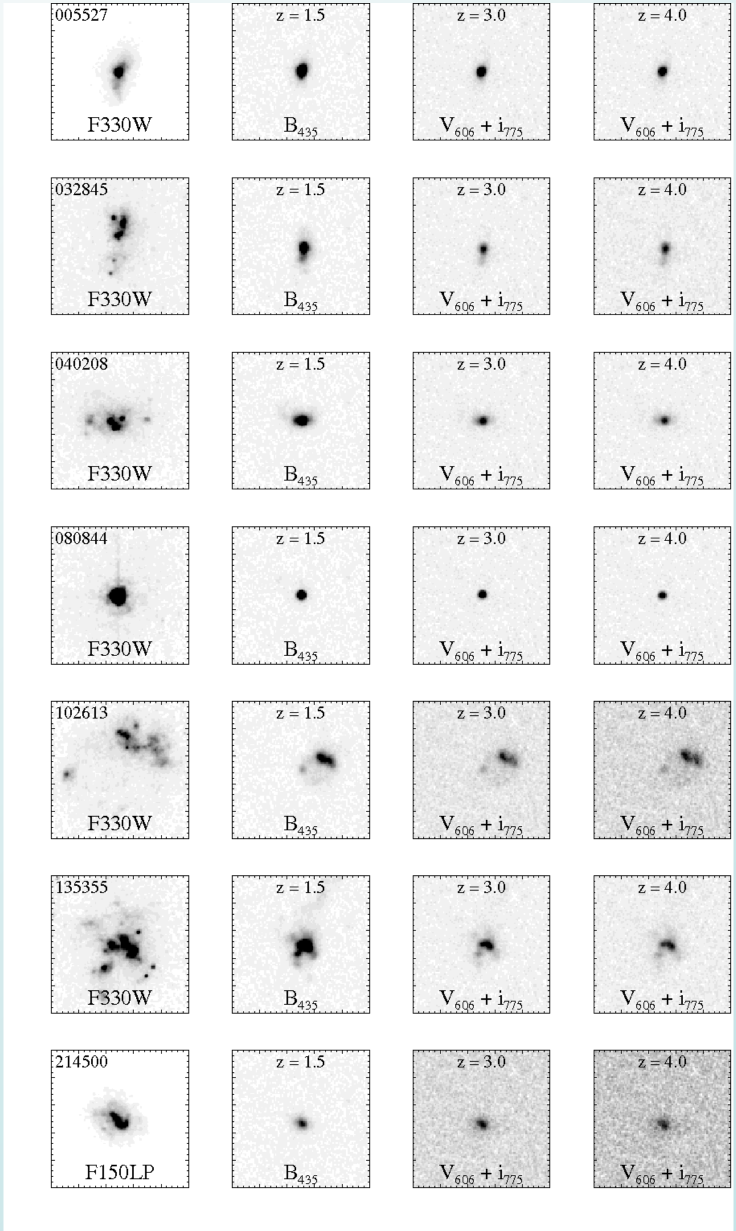
$= 4\pi D^2_{L2} N_2 f_\nu(z_2)(1+z_2)^{-1}$

In ADU/s:

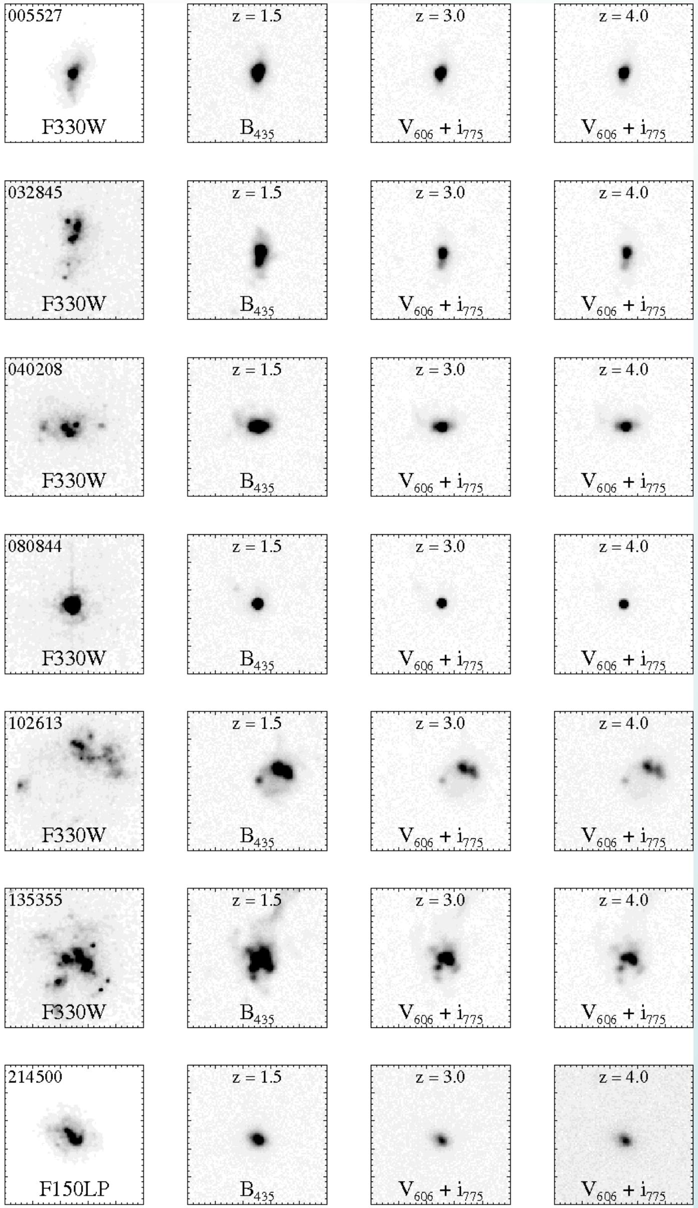
$p(z_2)/p(z_1) \propto [(1+z_1)/(1+z_2)]^3$

Create `GOODS' images of UVLGs
z=1.5 (B),
z=3-4 (V+i),

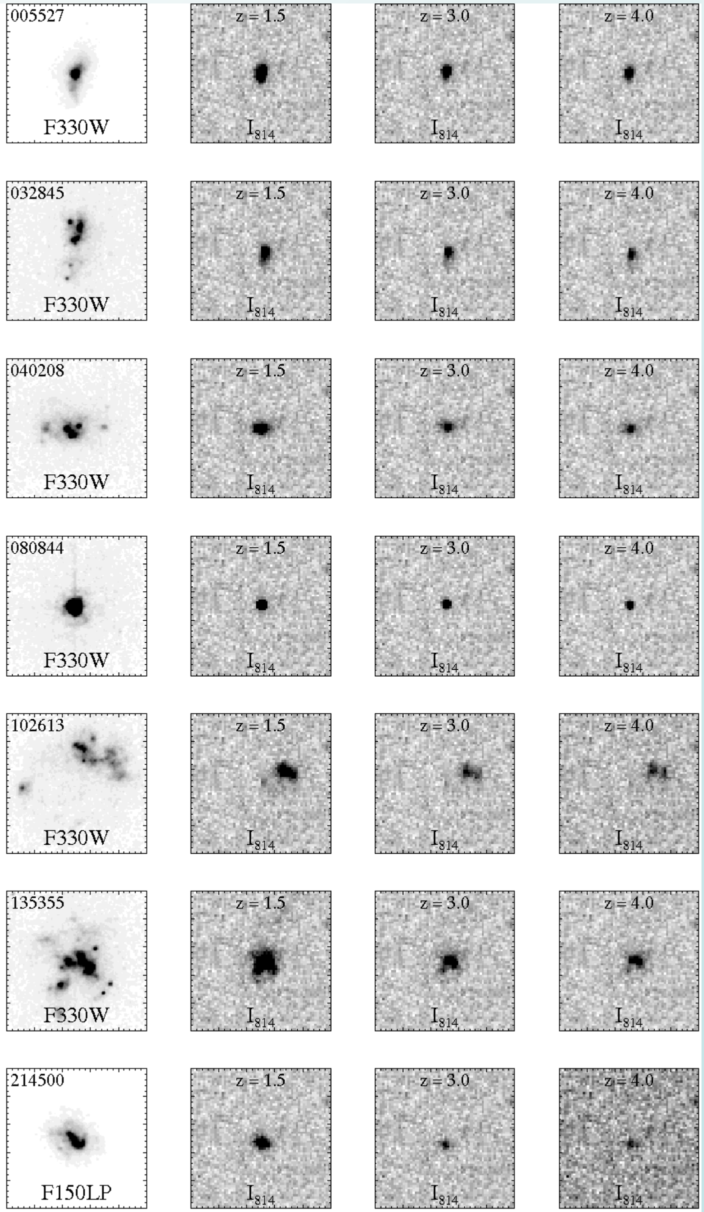
Output scale 0.03 arcsec/pixel
PSF ~ 0.12 arcsec



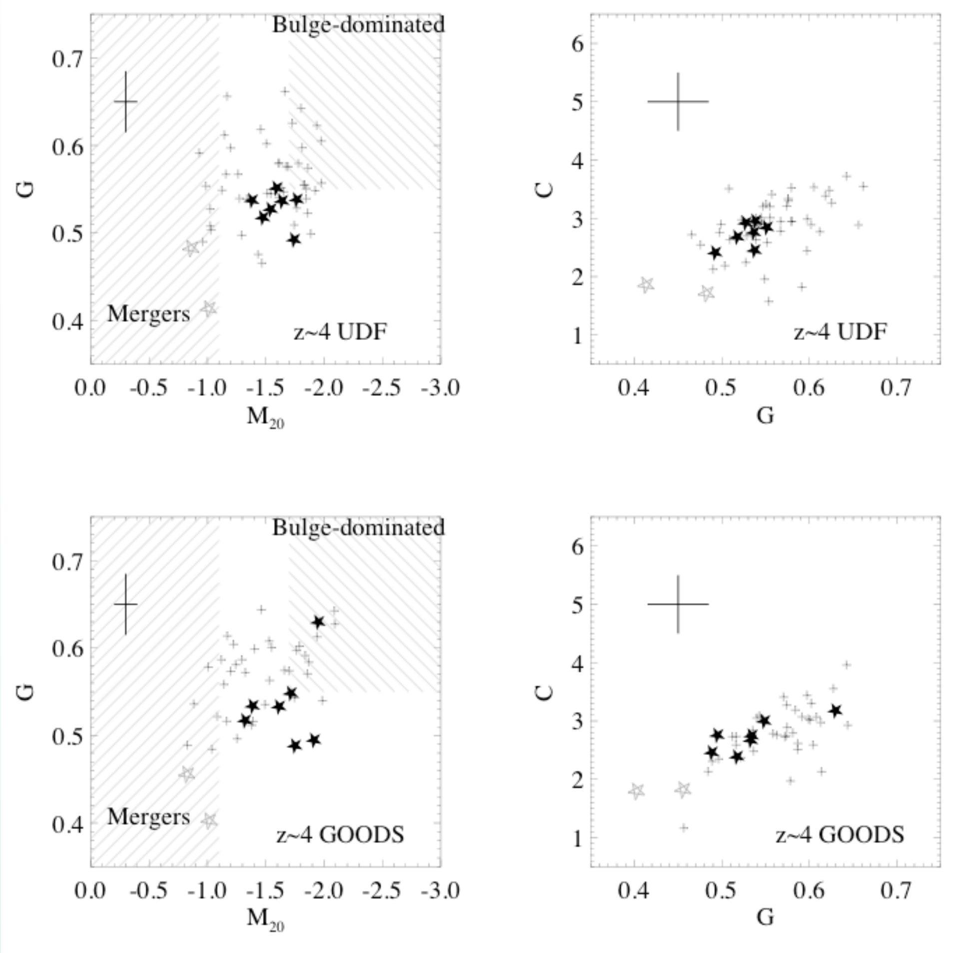
UDF depth



COSMOS depth



Comparison of morphologies of UVLGs and LBGs - Results



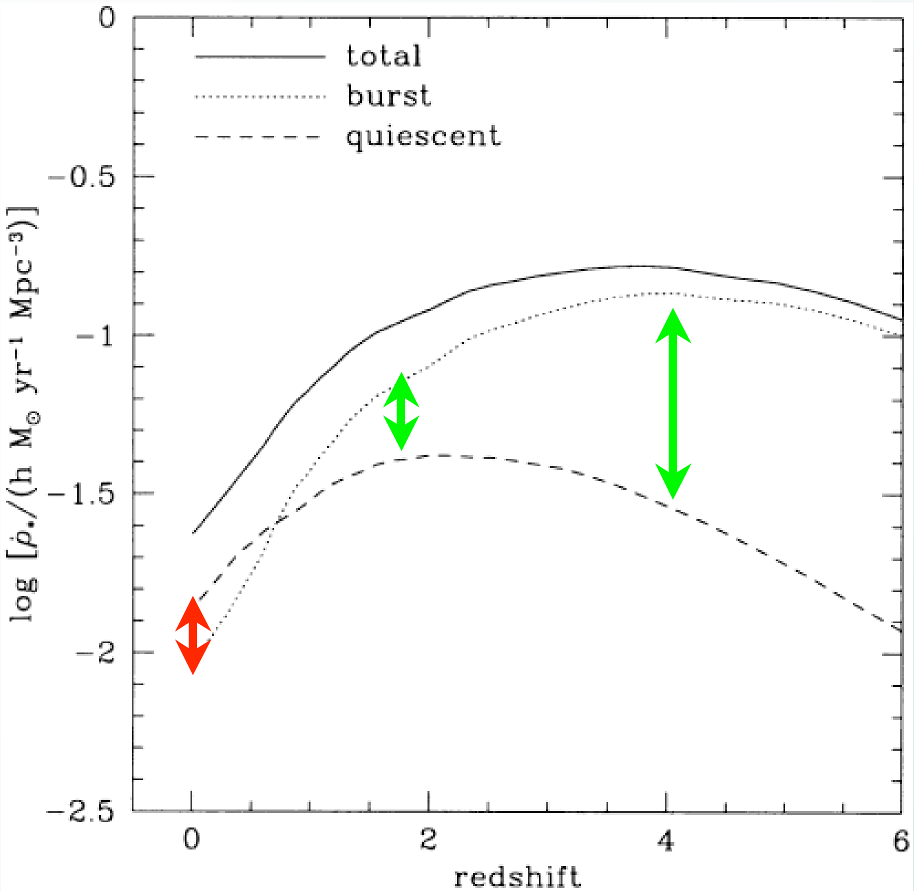
The morphologies of the resimulated UVLGs are very similar to those of LBGs in GOODS/UDF:

UVLGs are thus similar to LBGs in every physical property that we can measure

The undegraded, optical HST images showed mergers/interactions in each case *(as evidenced by companions, tidal tails/debris, and isophotal twists)*:

It is therefore, by extrapolation, reasonable to conclude that LBGs are starbursts triggered during collisions of relatively low mass, gas rich systems

Collisional starbursts have been suggested to be the dominant mechanism to turn gas into stars at high redshift:



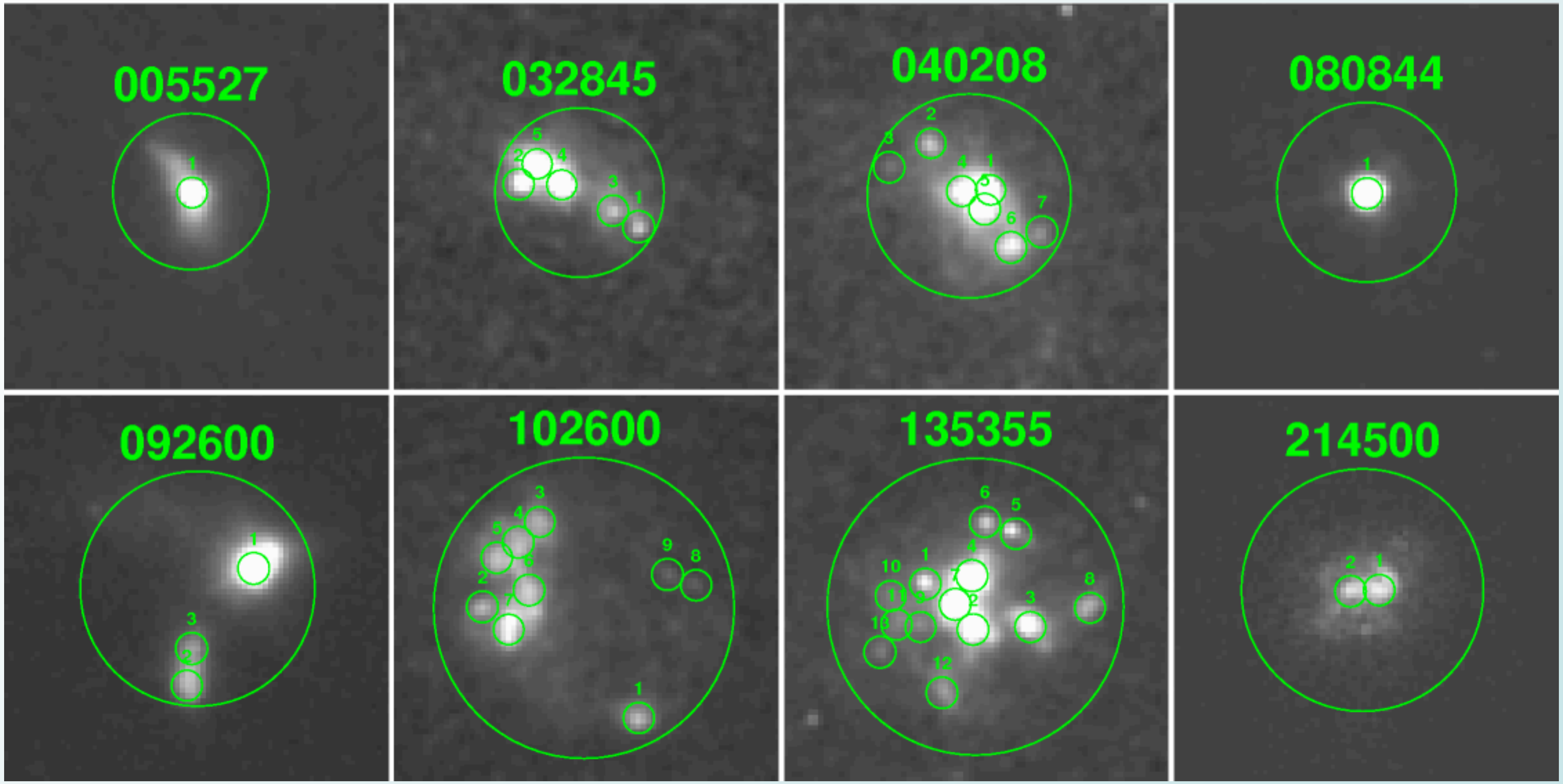
(Somerville, Primack & Faber 2001)

Simulations/models predict that Collisional starbursts triggered by (minor) mergers are responsible for

- 70% of SFRD at z=4
- 45% at z=1.5
- quiescent star formation dominates now

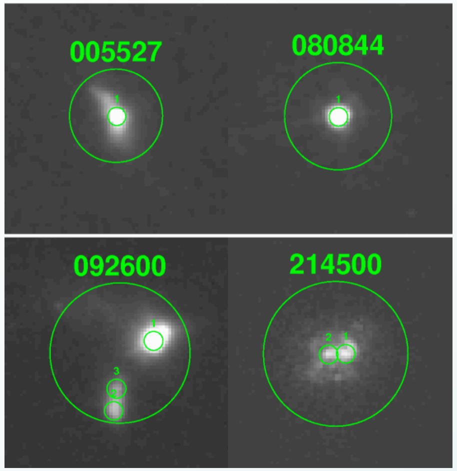
This scenario seems to have been confirmed based on the sample of local LBG analogs

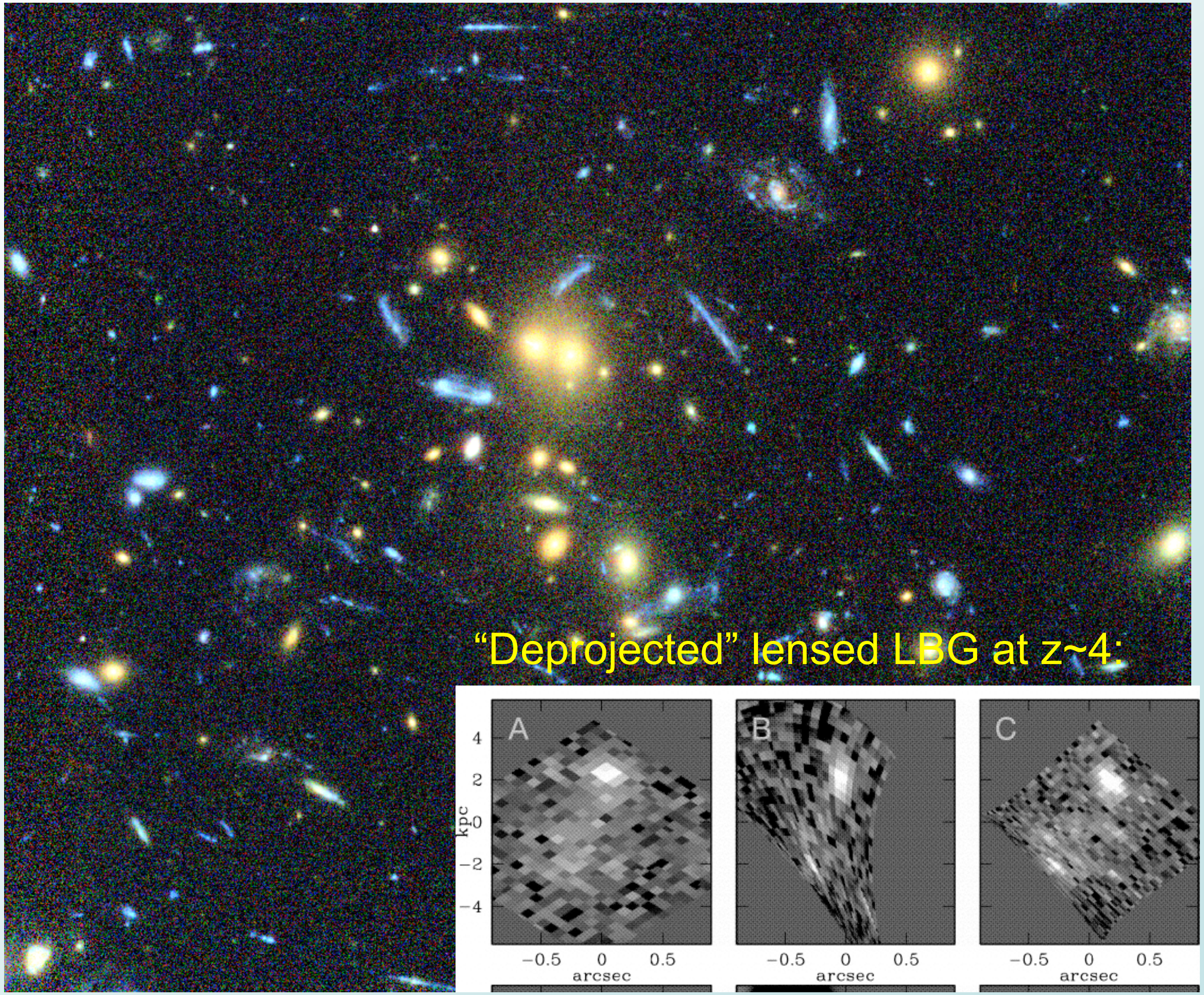
Star formation dominated by Super Starburst Regions (SSBs)



- Contain typically 30-80% of the UV light!
- 1 to several per galaxy
- unresolved even with HST at z=0.1 (~100-300 pc)

Is there any evidence to suggest that the substructure of high-z LBGs is similar to the local LBG analogs? Compare with LBGs that are gravitationally lensed:

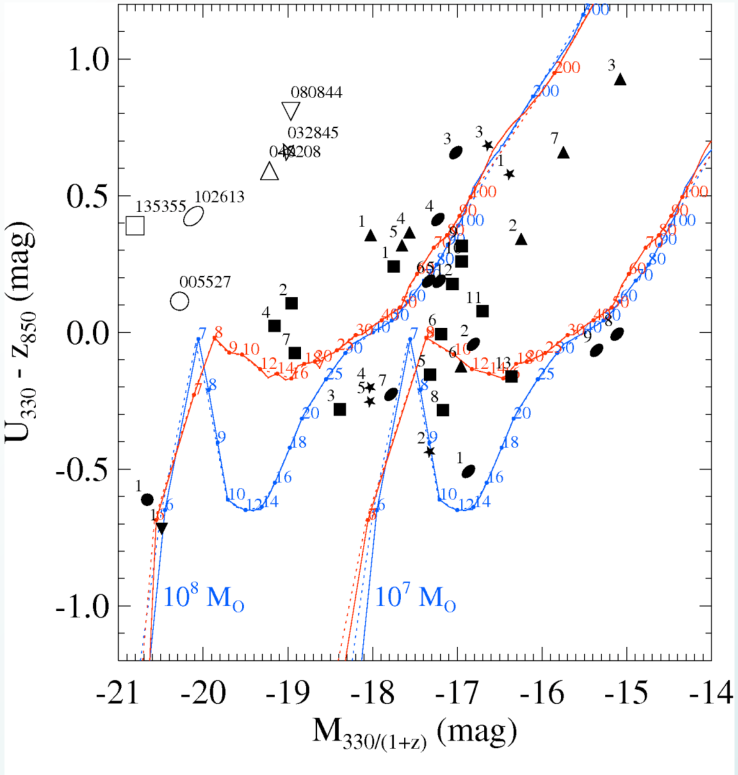


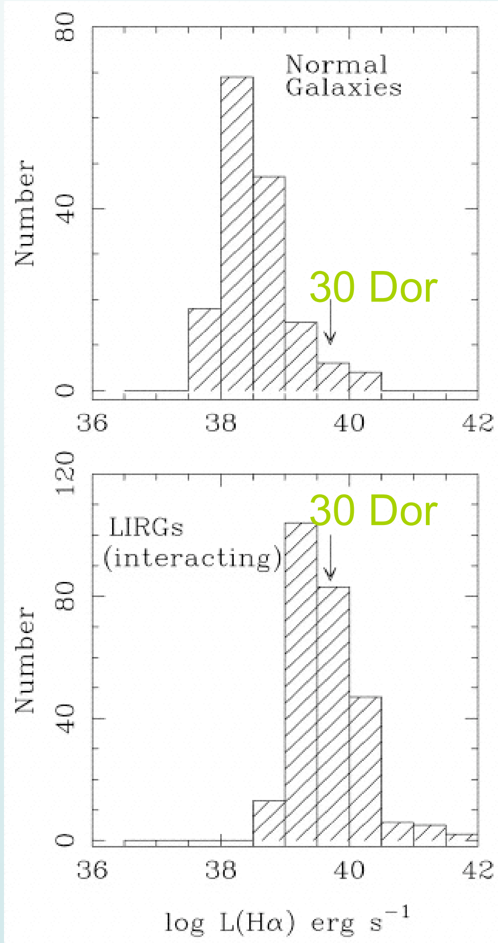


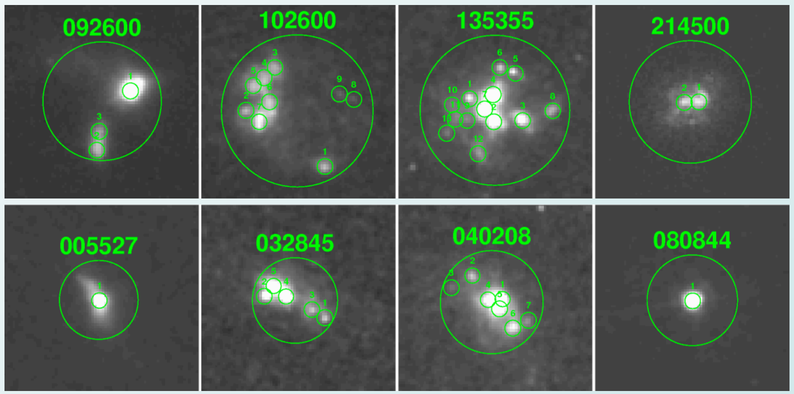
Substructure of lensed LBGs very similar in luminosity (=SFR/mass) and size !

(Franx et al. 1997, Ellis et al. 2003)

Properties of the Super Starburst Regions:

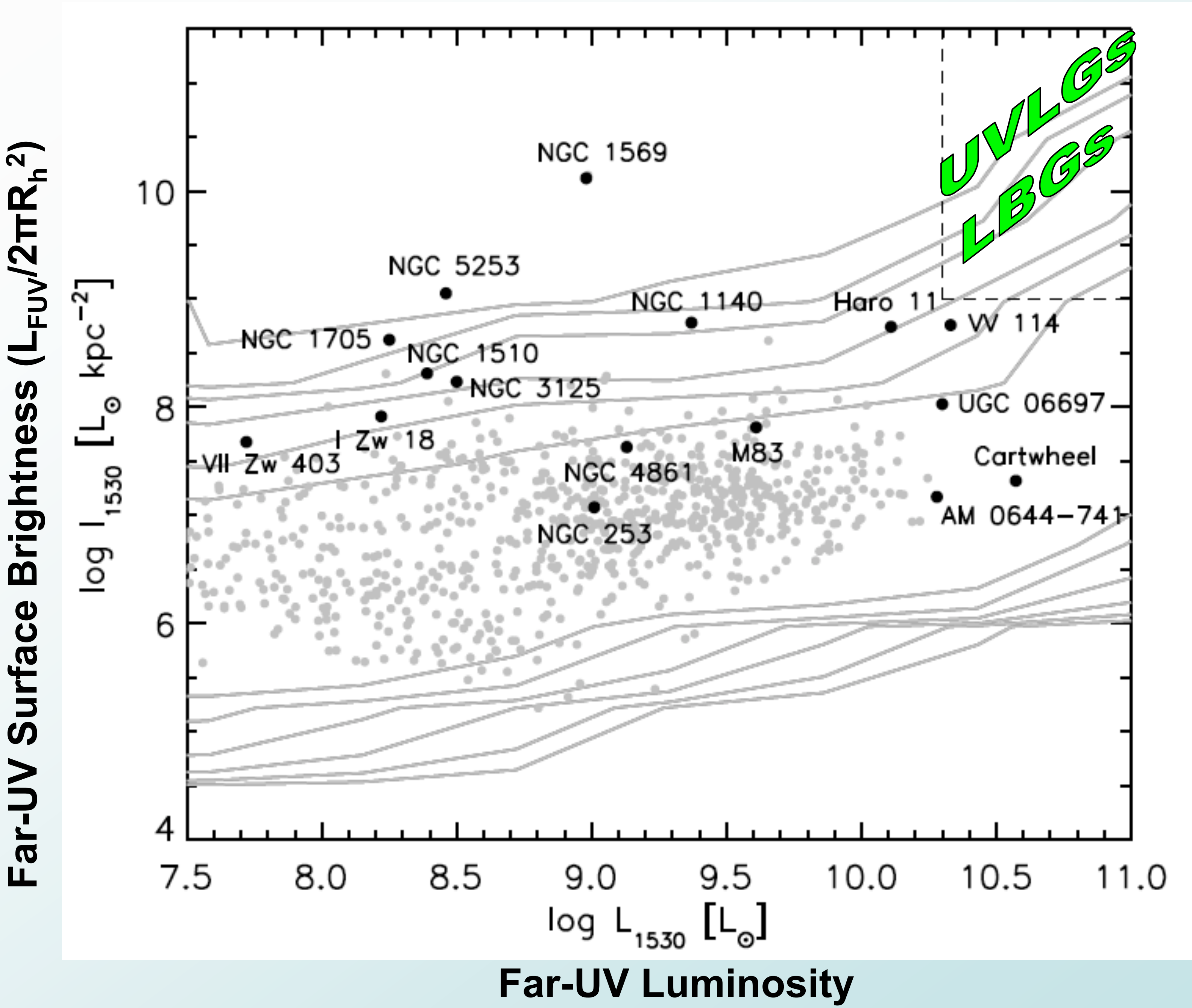






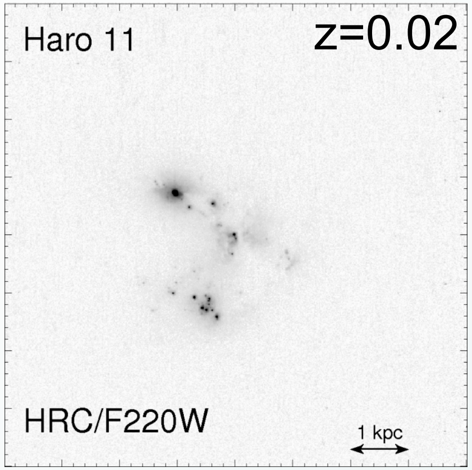
- masses ~ 10^7 to 10^8 M_o,
- ages ~ 6 Myr to few 100 Myr,
- SFRs ~ 0.1 to 1 M_o/yr,
- may host (forming) globular clusters

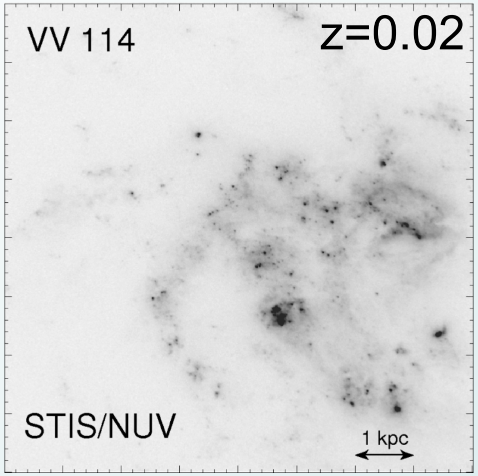
for a cluster formation efficiency of ~1%

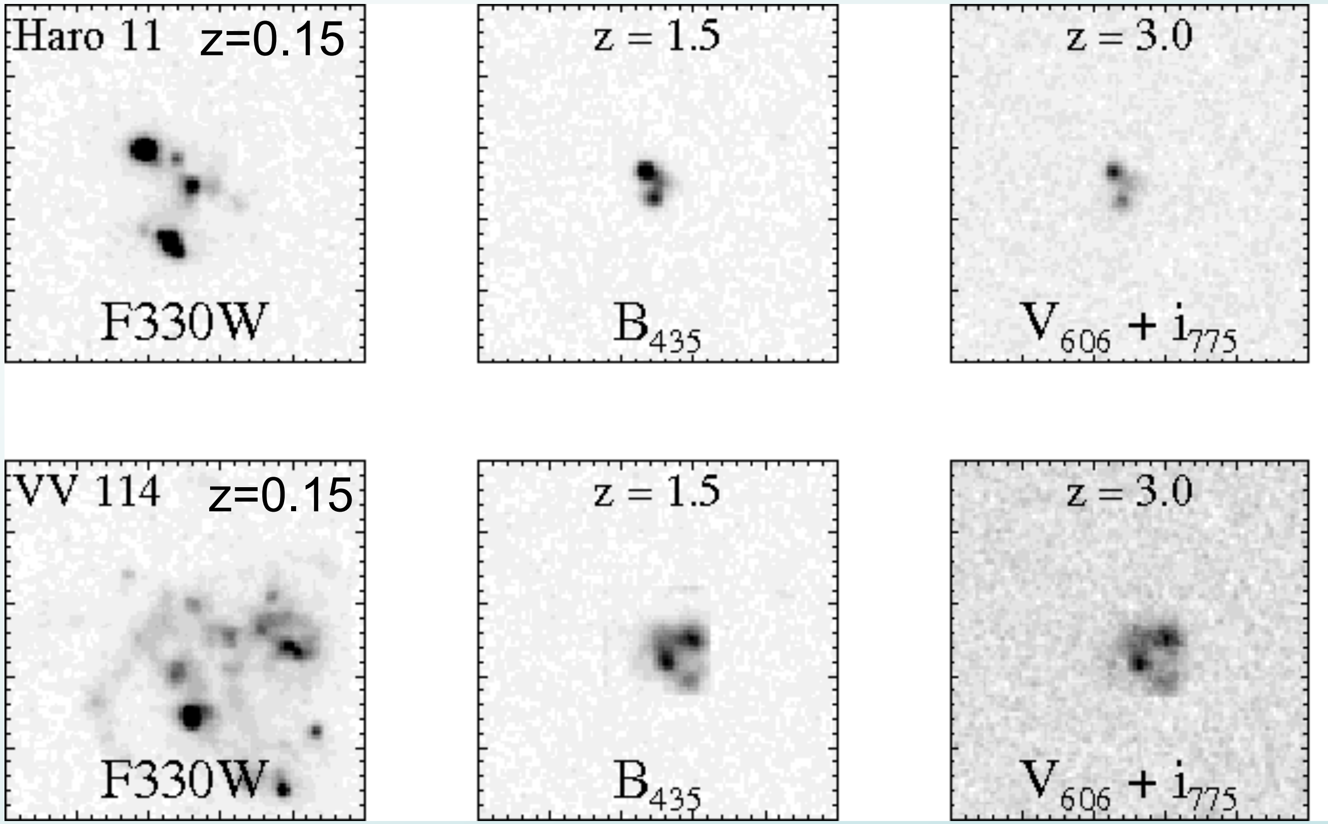


UVLGs
LBGs
NGC 1569
NGC 5253
NGC 1140
Haro 11
VV 114
NGC 1705
NGC 1510
NGC 3125
UGC 06697
VII Zw 403
I Zw 18
M83
NGC 4861
Cartwheel
AM 0644-741
NGC 253
10
8
6
4
7.5
8.0
8.5
9.0
9.5
10.0
10.5
11.0
log I_{1530} [$L_{\odot}$ kpc^{-2}]
log L_{1530} [$L_{\odot}$]
Far-UV Surface Brightness ($L_{FUV}/2\pi R_h^2$)
Far-UV Luminosity

What do the “super starburst regions’’ and LBG ‘”knots’’ consist of







- LBG “knots” (~1 kpc) are blends of SSBs (~0.1-0.2 kpc)
- SSBs are blends of bright star clusters ($10^{4\text{-}6}M_o$, <10 pc)
- but also single, compact, supermassive star clusters
- may be used to “improve” resolution of simulations?
- implications for very first objects at high redshift?

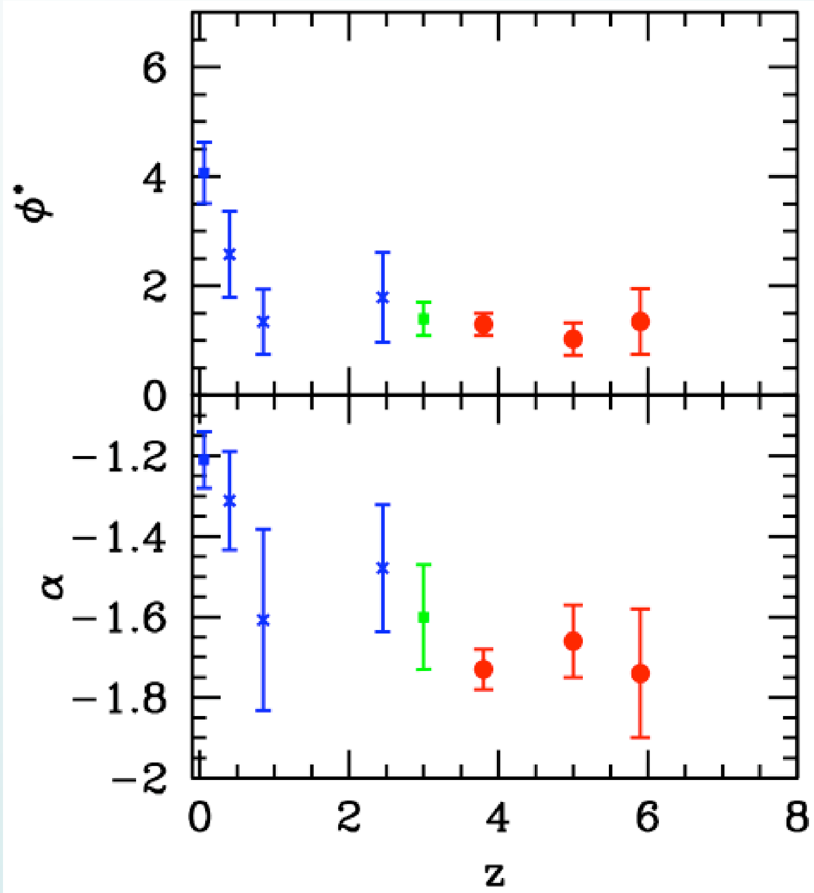
An interpretation of the high redshift UV Luminosity Function (LF)

Faint-end slope of UV LF:

α=-1.2 at z=0

but

α=-1.8 at z=6



(Wyder et al. 2005, Bouwens et al. 2007)

Can we explain the steep faint-end slope of the high redshift LF using SSBs?

Can we explain the steep faint end slope of the high redshift LF using SSBs?

The UV luminosity of an `LBG' at time t is the sum of the luminosities due to all its prior starburst `events':

$$L_{\mathrm{LBG}}^{UV}(t) = \sum_i L_i(t).$$

Distinguish between a slowly evolving, diffuse component, and a series of N discrete `bursts':

$$L_{\mathrm{LBG}}^{UV}(t) = L_{\mathrm{diffuse}}(t) + \sum_{i=1}^{N} L_{\mathrm{burst}}^{i}(t).$$

We have learned that LBGs come in `knots' (~1 kpc), and each knot consists of smaller `SSBs':

$$L_{\mathrm{LBG}}^{UV}(t) = L_{\mathrm{diffuse}}(t) + \sum_{i}^{N_{\mathrm{knot}}} \sum_{j}^{N_{\mathrm{SSB}}} L_{\mathrm{SSB}}^{i,j}(t),$$

It follows that at early times (z~6) the faint end of the UV LF will essentially be a sampling of galaxies creating their first knot/SSB (N_{knot}~N_{SSB}~1, $L_{diffuse}$~0)

The LF of star-forming regions from HII region to kpc scale is known to have a slope of $\alpha \approx -2$!
(Kennicutt et al. 1989, Meurer et al. 1995, Elmegreen & Efremov 1997, Zepf et al. 1999, Alonso-Herrero et al. 2002, Bradley et al. 2006)

Thus, assuming that the physics of star-formation does not change with redshift, we expect a steep(er) faint-end slope of the LF at high redshift compared to low redshift.

Summary

- the GALEX/SDSS sample of compact UVLGs are LBG analogs in every measurable physical property (now also morphology)
- the high resolution HST imaging offers a rare view of the relationship between morphology and the main driver of star formation at high redshift
- results indicate that local LBG analogs are all associated with highly dissipational mergers turning gas-rich galaxies into stars
- consistent with collisional starburst predictions for high redshift galaxies
- rest-frame UV images not sufficient for establishing that they are mergers! (need faint features in rest-frame optical images)
- predominance of unresolved SSBs are key to the correct interpretation of LBG properties (e.g. sizes, morphologies, star clusters and evolution)
- local LBG analogs may have a considerable AGN fraction, which could be important for BH/bulge growth when extrapolated to high redshift LBGs

Thanks!