Interacting Galaxies

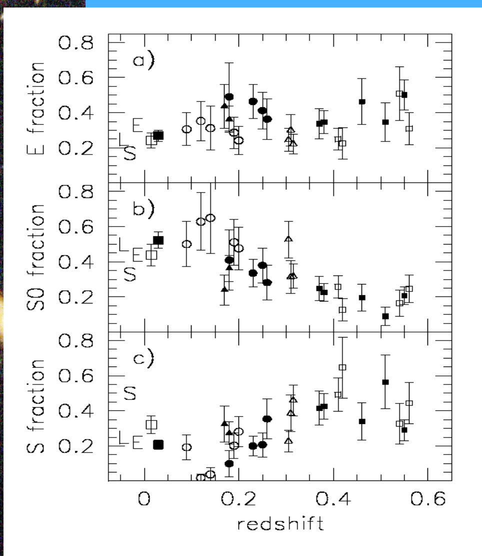
Observations & Theory

Local Universe to High Redshift

Prof. Dr. Uta Fritze

Dates: 17.4. Overview & basic concepts
(1.5. Holiday)
(15.5. HST Panel meeting)
22.5. Dyn. models & obs. examples
19.6. Star Bursts & Star Cluster Formation
3.7. Galaxy transformation in clusters
17.7. Interactions @ high redshift

Evolution in the Cluster Galaxy Population



Redshift evolution of galaxy morphologies (MORPHS sample)

E fraction ~const.

S0 fraction ↘ for z ↗

Spiral fraction ↗ for z ↗

(Fasano et al. 2000, 2001, Couch et al. 1998)

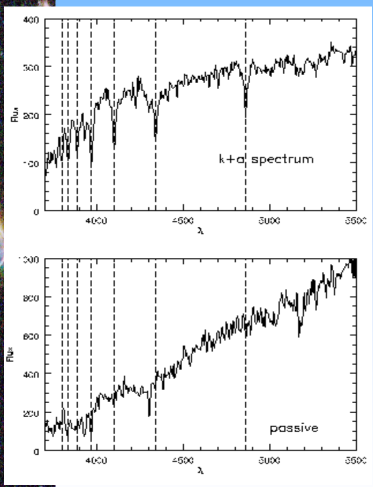
significant transformation : spirals ➜ S0s from z~0.5 to z=0 within the last 5 Gyr

Field Spirals -> Cluster S0s

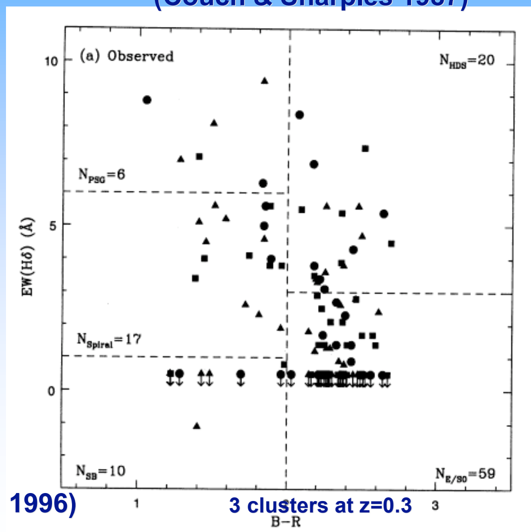
Spectral Transformation : transition types

5 spectral categories for cluster galaxies :

(Couch & Sharples 1987)



(Barger et al. 1996)



3 clusters at z=0.3

U. Fritze, Goettingen 2008

Field Spirals ➜ Cluster S0s

Galaxy Numbers & Morphologies (Kodama & Smail 2001)

>50% cluster galaxies accreted since z~0.5

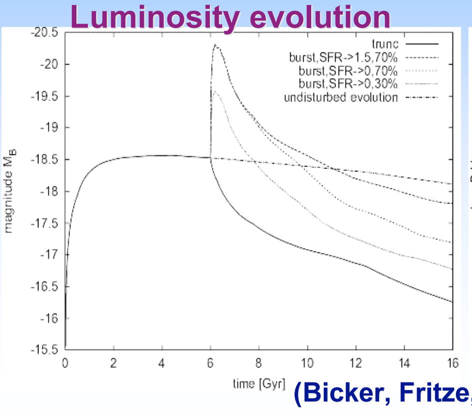
most accreted spirals up to Scdm transformed into S0s

t_{morph} ~1−3 Gyr

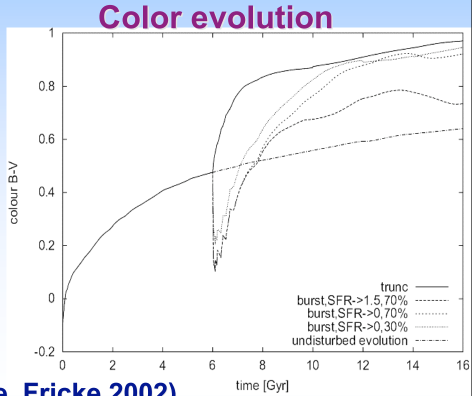
Spectrophotometric Aspects (Bicker+02, Shioya+02, 04)

spiral galaxy types ± Starburst + SF truncation/strangulation

Luminosity evolution



Color evolution



(Bicker, Fritze, Fricke 2002)

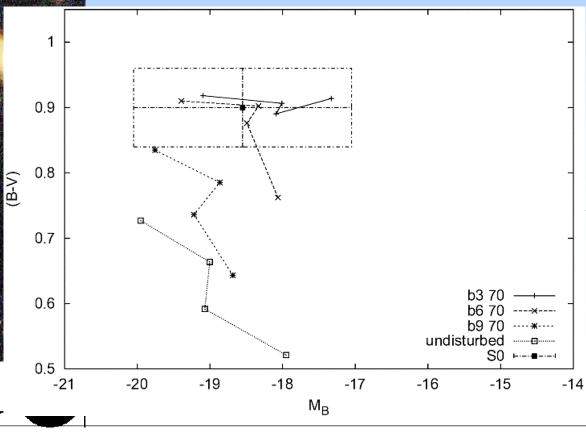
U. Fritze, Goettingen 2008

Field Spirals ➜ Cluster S0s

Low-luminosity S0s :
- Sa/Sb/Sc with bursts (strong or weak) > 3 Gyr ago
- Sa/Sb + SF trunc. at 6 Gyr < age < 9 Gyr
- Sc + SF trunc. at ~ 9 Gyr

gradual ICM build-up

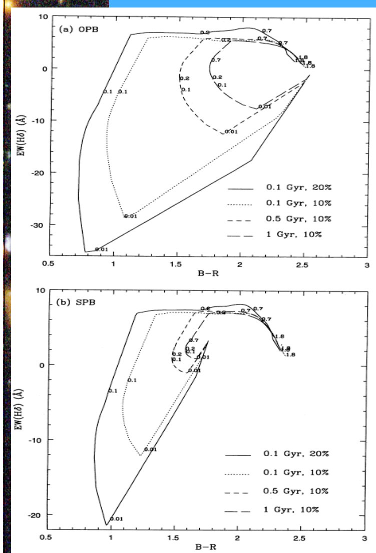
High-luminosity S0 :
- Early-type spiral (Sa) mergers + bursts at ages < 9 Gyr



Spiral-spiral mergers + Starbursts

(Bicker, Fritze, Fricke 2002)

Field Spirals ➜ Cluster S0s



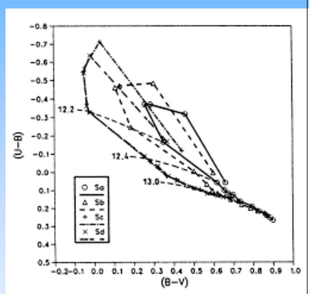
Spectral Transformation Models :

Sp + SF trunc. t<1 Gyr
-> intermed. Hδ -> S0

Sp + SF strang. t>1 Gyr
-> weak Hδ -> S0

Sp + Starburst + SF trunc.
-> strong Hδ -> S0

(Barger et al. 1996)



(Fritze & Gerhard 1994)

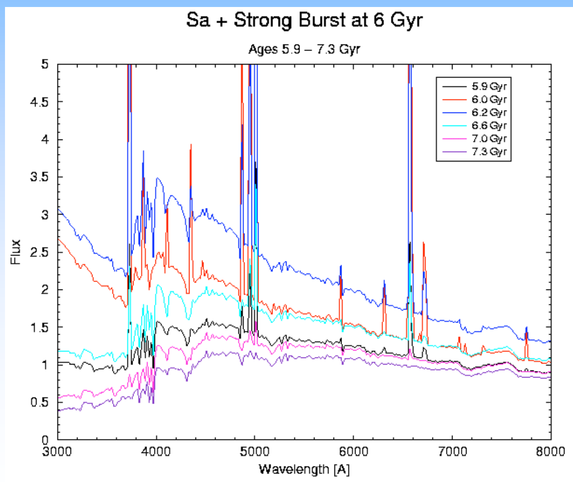
E+A ~ k+a ~ Hδ - strong phase : duration ~1.5 Gyr

(Poggianti et al. 1999, Barger et al. 1996)

Field Spirals ➜ Cluster S0s : Transition Types

Sa + Sa + strong burst
➜ blue H_δ- strong ➜ red H_δ- strong ➜ luminous S0
(e(a)) (E+A, k+a)

(Tyra & Fritze in prep.)



U. Fritze, Goettingen 2008

Field Spirals ➜ Cluster S0s : Transition Types

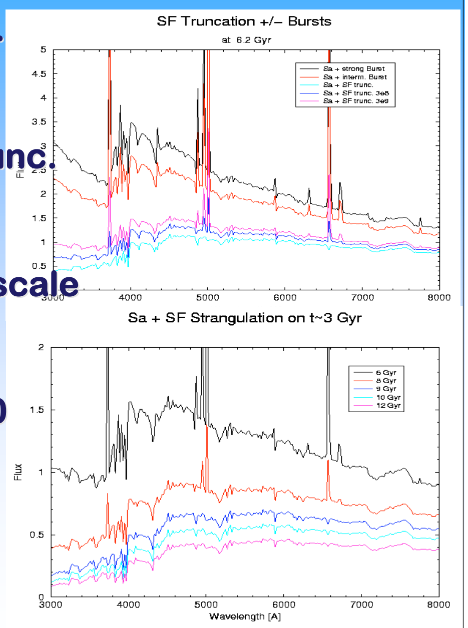
Sa + strong burst + SF trunc.
➜ H_δ - strong ➜ bright S0

Sa + intermed. burst + SF trunc.
➜ H_δ - intermed. ➜ S0

Sa + SF trunc. on short timescale
(1– 3) 10^8 yr
➜ H_δ - interm. /weak
➜ faint S0

Sa + SF strangulation
10^9 yr
➜ H_δ - weak ➜ faint S0

(Tyra & Fritze in prep.)



U. Fritze, Goettingen 2008

Cluster E+A Galaxies

E+A galaxies in clusters :
-5 (E) ≤ HT ≤ 3 (Sb),
mostly disk dominated with 0≤B/T≤0.7
>50% have significant asymmetry -> recent interaction
(Tran et al. 2003)
➜ t(spectral) < t(morphological)

most Hδ – strong galaxies are regular spheroids
➜ t(spectral) > t(morphological)
(Couch & Sharples 1987)

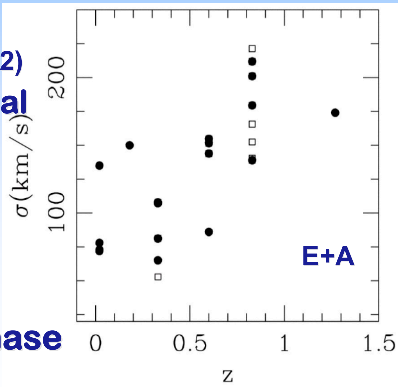
➜ timescales may depend on type of transformation process !?

diverse properties of E+As :
➜ heterogeneous parent population
➜ more than 1 transformation channel

Cluster E+A Statistics

high redshift clusters : E+A & k+a galaxies luminous & massive, starbursts strong ΔS/S~0.3
low redshift clusters : only low luminosity/mass E+A & k+a, starbursts weaker ΔS/S~0.1
➜ 2-fold downsizing effect (also for SFing field galaxies)
(Bower et al. 1999, Cowie et al. 1996)

ISOCAM midIR data for A1689 (z~0.2)
~90 % SF hidden by dust in optical
(Duc et al. 2002)



Lifetime statistics

➜ 30 – 100% E/S0s have undergone E+A phase

(Tran et al. 2003, Poggianti et al. 2003)

266 field E+As from SDSS

E+A's have excess of local galaxy density
on scales < 100kpc (=group scales),
not on larger (=cluster) scales,
nor on very large (=Large Scale Structure) scales

➜ E+A related to close companions

Almost all E+A's have bright compact cores
~ 30 % have dynamically disturbed signatures
or tidal tails

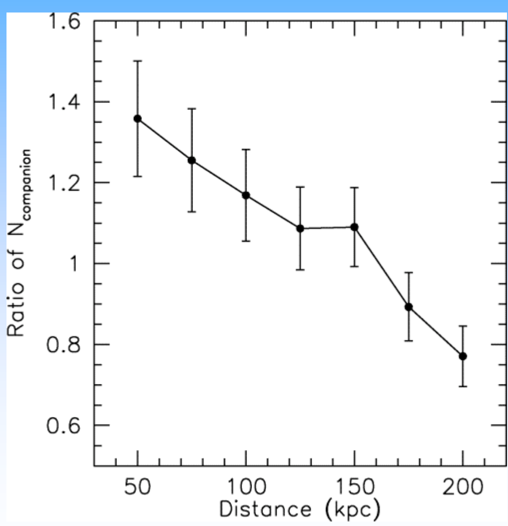
➜ E+A related to (weak?) interaction with companion

(Goto 05)

Dust plays important role for starburst galaxies,
not any more during E+A – phase

266 E+As from SDSS

(Goto 05)



Field E+A Galaxies

E+A galaxies also exist in the field

E+A galaxy fraction in the field : 2.7±1.1% at $0.3 < z < 1$, $50 \leq \sigma \leq 220$ km/s

E+A galaxy fraction in clusters : 11.0±3.0% at $0.3 < z < 1$

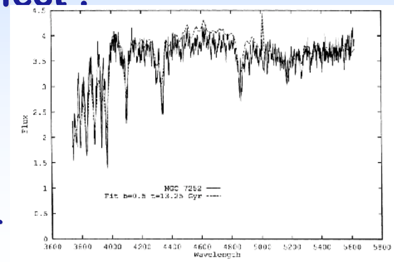
80% field E+As morphologically irregular

➜ major & minor mergers

4/5 field E+As with WFPC2 imaging show B/T≤0.5

➜ minor mergers or timescale effect ?

(Tran et al. 2004)



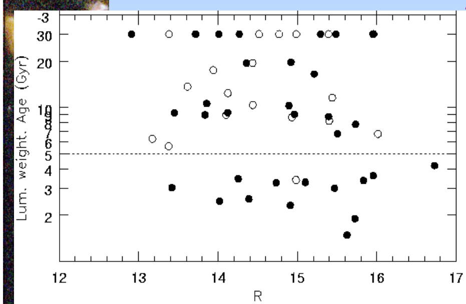
NGC 7252 = field E+A
= major merger
Spectrum : F. Schweizer
(Fritze & Gerhard 1994)

U. Fritze, Goettingen 2008

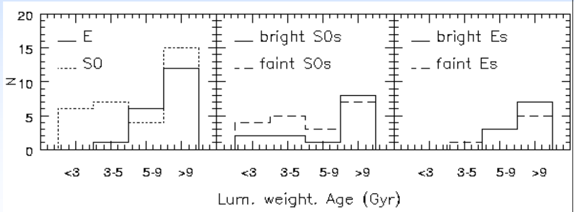
Stellar Population Ages in Cluster S0s

Spectroscopy of 19 Es & 33 S0s in Coma over wide range $-20.5 < M_B < -17.5$ * (Poggianti et al. 2001)

* ~ 40% S0s (one of the Es) had significant SF in their central regions during last 5 Gyr
* fraction of S0s with recent SF ↗ with L ↘



* key to series of discrepant results : magnitude limit of sample



also found from optical + NIR photometry in Abell 2218 (z=0.17) (Smail et al. 2001)

U. Fritze, Goettingen 2008

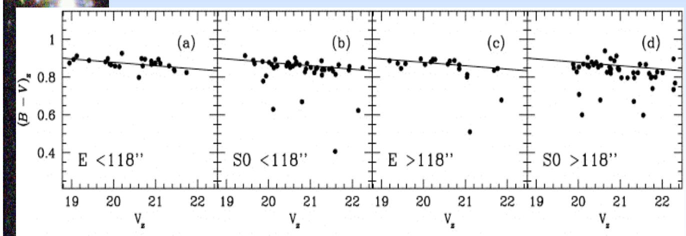
Redshift Evolution of the CMR

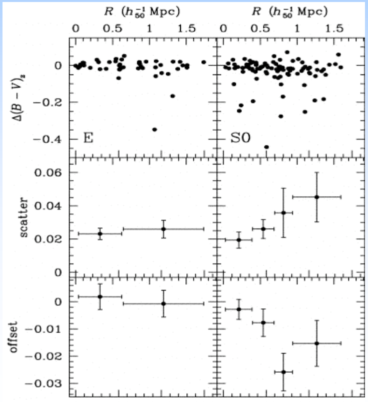
194 E/S0s in CL1358+62 at $z=0.3$ (van Dokkum et al. 1998)

scatter* for Es very small, not dependent on R_{cl}

- ☛ scatter for S0s small at center, larger at larger R_{cl}
- ☛ offset of S0s to bluer colors at larger R_{cl}
  - ➜ Es terminate SF well before accretion
  - ➜ S0s stop SF in outer parts of cluster

*scatter <-> age spread





Redshift Evolution of the CMR

Massive Es form before the clusters : ev. in groups

S0s form after cluster virialisation : by transformation

Low luminosity systems : harassment and/or fading

SFR – Galaxy Density Relation

Global <--> local effects

ICM, cluster potential <--> interactions within groups

(Lewis et al. 2002, Gomez et al. 2003, Gerken et al. 2004)

11006 galaxies (M_b<-19, z<0.1) from 2dF GRS in 17 clusters
8598 galaxies (M_r<-20.5, z<0.1) from SDSS in field, groups, clusters

galaxies out to ~3 R_{vir} in low L_x clusters at z~0.2

μ^* := SFR(Hα) / L^* ↗ with R_{cc} ↗
reaches field galaxy SF level at ~3 R_{vir}

ICM ram pressure not efficient at ~3 R_{vir}

μ^* ↗ with Σ ↘
reaches field galaxy SF level at Σ_{crit} ~ Σ (3 R_{vir})

same for galaxies in rich & poor clusters, groups & field
? what quenches SF in low density environments ?
➜ group activity/merging

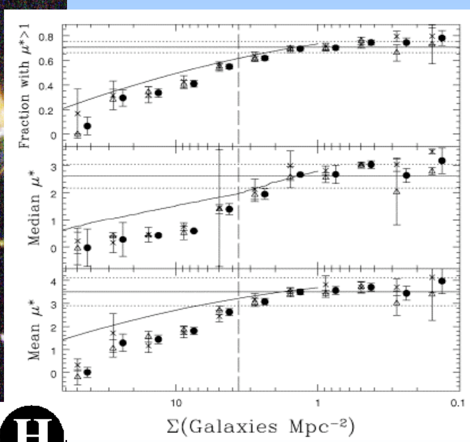
U. Fritze, Goettingen 2008

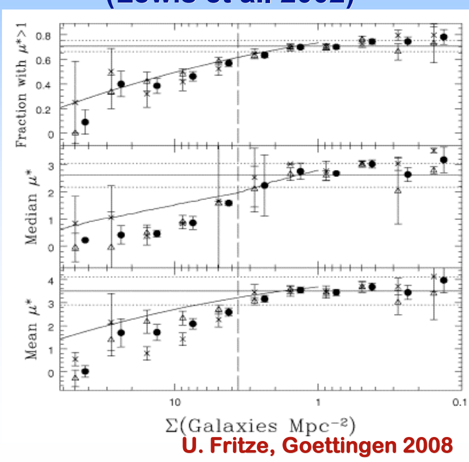
SFR – Galaxy Density Relation

μ^* := SFR(Hα) / L^* ↗ with R_{cc} ↗
reaches field galaxy SF level at ~3 R_{vir}

μ^* ↗ with Σ ↘
reaches field gal. SF level at Σ_{crit} ~ Σ(3 R_{vir})

same for galaxies in rich & poor clusters, groups & field
(Lewis et al. 2002)





U. Fritze, Goettingen 2008

Local Morphology – Density Relation

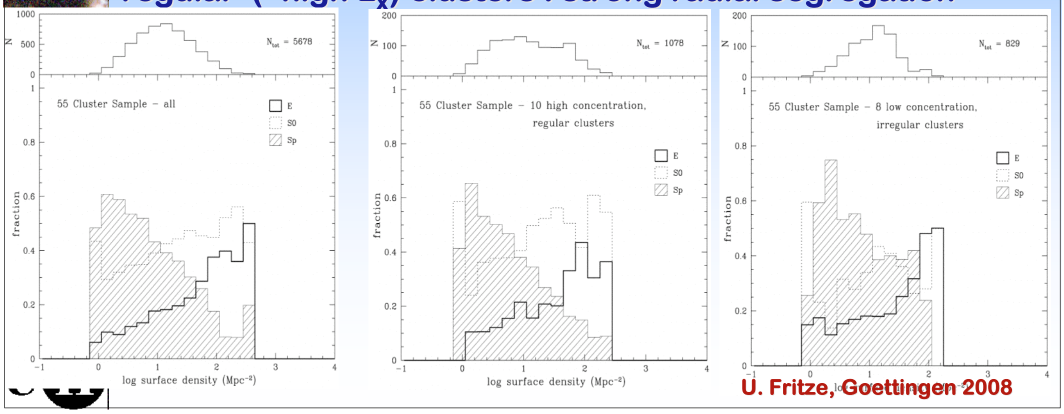
~6000 galaxies in 55 low-redshift rich clusters (Dressler 1980)

spiral, S0, E fractions correlate with local galaxy surface density

T−Σ relation for regular & irregular clusters

irregular (=low L_X) clusters : no radial segregation of gal. population

regular (=high L_X) clusters : strong radial segregation



U. Fritze, Goettingen 2008

Evolution in Morphology – Density Relation

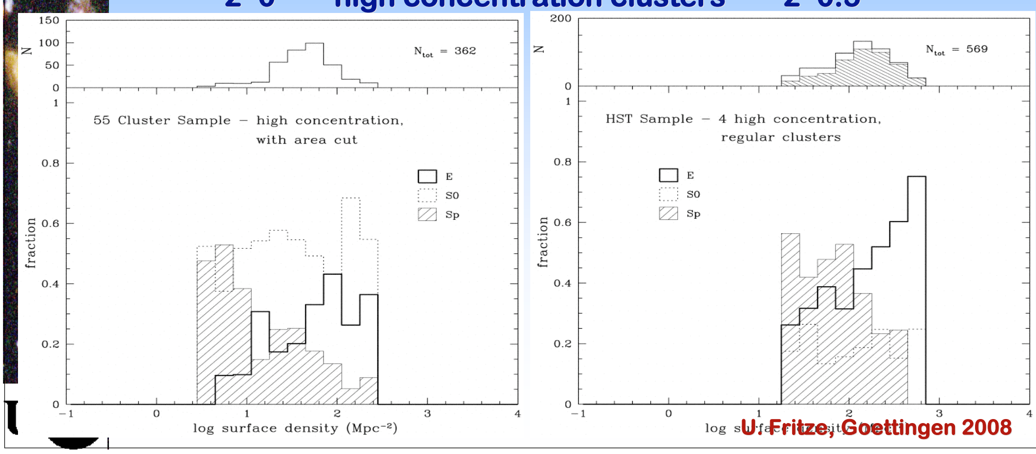
10 intermediate-redshift (z~0.5) clusters (Dressler et al. 1997)

T−Σ relation strong for regular clusters,

nearly absent for irregular clusters

in all z~0.5 clusters $f_E \sim f_E$(local), $f_{S0} \leq (1/2-1/3)\, f_{S0}$(local), $f_{Sp} > f_{Sp}$(local)

z~0 high concentration clusters z~0.5



U. Fritze, Goettingen 2008

Summary: Galaxy Populations in Clusters

Cosmological structure formation & evolution intimately linked with galaxy formation & evolution.
Massive Es form before the clusters, spirals are transformed into S0s & dwarf galaxies as they are accreted by clusters.
A variety of transformation scenarios are at work: harassment, ram pressure, merging within infalling groups. All affect the morphology as well as the spectral properties, timescales may be different.
Recent surprise: transformations already occur at 3 R_{vir} from the cluster centre, local galaxy density effects must be important -- and are also seen in groups and the field.
We still lack a complete census of the relative role of the various transformation channels, timescales, transition stages and their dependence on galaxy/cluster properties.

Galaxies at High Redshift

Cosmological model $(H_o, \Omega_o) = (70, 1)$

$(\Omega_m, \Omega_\Lambda) = (0.3, 0.7)$

Big Bang → Universe expanding

Hubble's law : distant galaxies recede : $v = H_o \cdot r$

recession velocity v → redshift z (relativistic Doppler effect)

redshift z = measure of distance r

c finite → distant galaxies seen in earlier evolutionary stages

Lookback time

$$t_0 - t_1 = H_0^{-1} \int_0^{z_1} (1+z)^{-1} [(1+z)^2 (1+\Omega_M z) - z(2+z)\Omega_\Lambda]^{-1/2} \, dz.$$

z =	0	1	2	4	6
age =	14	5	3	1	0.5 Gyr

Cosmological Effects

Light dimming : luminosity distance D_L

$$d_L = \left(\frac{\mathscr{L}}{4\pi\mathscr{F}}\right)^{1/2}$$

= analogue to Euklidian distance in curved spacetime

$$H_0 d_M = \frac{1}{|\Omega_k|^{1/2}} \operatorname{sinn}\left\{|\Omega_k|^{1/2} \int_0^{z_1} [(1+z)^2(1+\Omega_M z) - z(2+z)\Omega_\Lambda]^{-1/2}\, dz\right\},$$

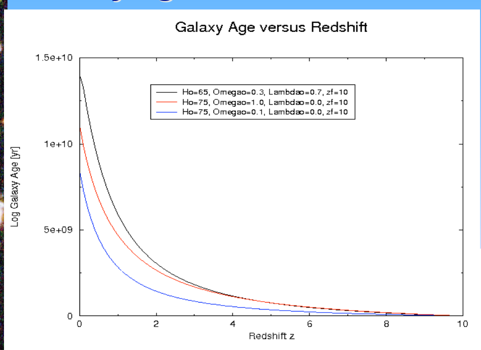
sinn = sinh for $\Omega_k > 0$

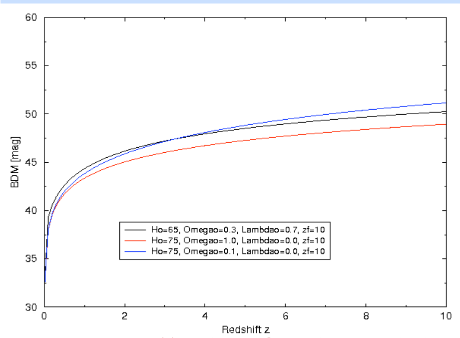
sinn = sin for $\Omega_k < 0$

Bolometric distance modulus BDM = - 5 log D_L - 25

High Redshift Galaxies

Galaxy age and BDM as a function of redshift





High Redshift Galaxies

Light from distant galaxies :

★ redshifted & diluted in expanding Universe

$$\lambda_{obs} = \lambda_0 \cdot (1+z) \qquad F_\lambda^{obs} = F_\lambda^0 / (1+z)$$

Opt. observations of galaxy at $z > 1$ show restframe UV
NIR observations - " - - " - opt.

→ cosmological correction :

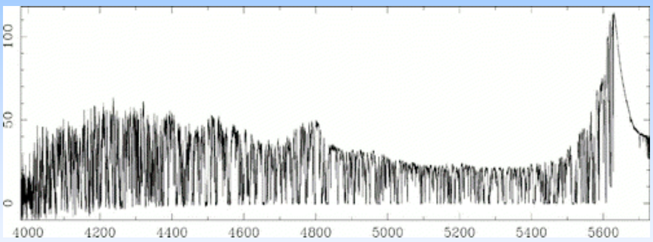
$$k_\lambda := M_\lambda(z, t_0) - M_\lambda(0, t_0) \text{ (gal. type)}$$

★ reddened & attenuated by intergalactic HI (Madau 1995)

"Attenuation" for wavelengths $\lambda_{restframe} < 1216$ A
seen in the optical for galaxies at $z > 2.5$
seen in the UV for galaxies at $z > 1$
→ GALEX data

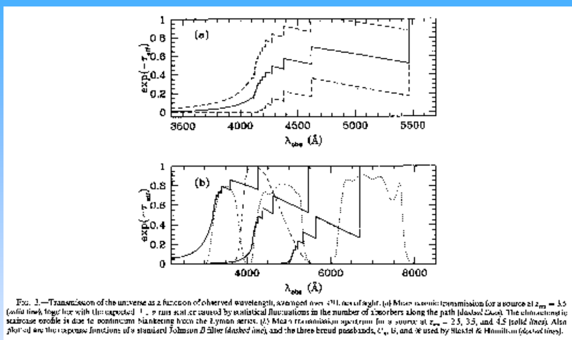
High Redshift Galaxies : Attenuation

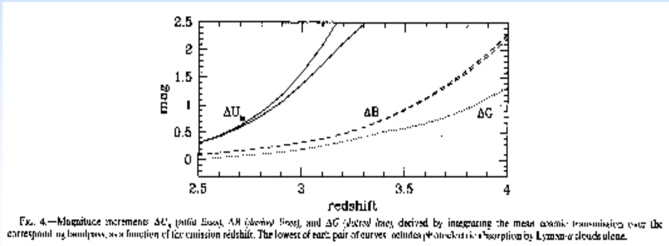
Intergalactic HI (Lyα clouds, Lyman Limit Systems and galaxy haloes) causes a forest of absorption lines shortward of Lyα @ 1215 A in the spectra of distant galaxies



High resolution (FWHM~6.6 km/s) spectrum of the z=3.2 QSO 1422+23 with Keck HIRES @ S/N~150 /resolution element (Fig. from Rauch 1998, ARAA)

High Redshift Galaxies : Attenuation





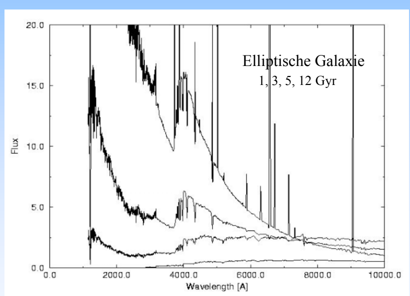
Madau 1995

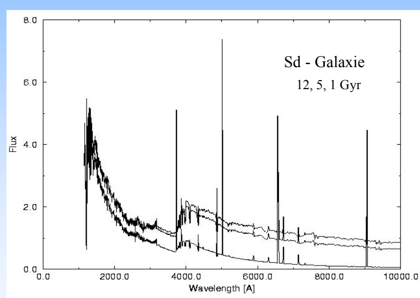
High Redshift Galaxies

★ Distant galaxies younger :

→ evolutionary correction

$e_\lambda := M_\lambda(z, t_{gal}(z)) - M_\lambda(z, t_0)$ (galaxy type)





evolutionary correction strong for galaxies with strongly variable SFR(t)

Redshift Surveys

Las Campanas Redshift Survey : R-band 26,418 redshifts over total field of 700 deg^2 , (N & S Galactic Caps), Large Scale Structure: voids, groups, clusters, filaments

<z> = 0.1

Canada France Redshift Survey CFRS : I-band 591 galaxies $17.5 < I_{AB} < 22.5$, $0 \le z \le 1.3$,   <z> = 0.56

Sloan Digital Sky Survey SDSS : 3rd data release: spectra of   528,640 objects over 4188 deg^2 ,
2.5m Apache Point Telescope
QSOs and galaxies to z~6
ongoing till 2008 (now @ data release #5)

huge amounts of observing time :
many galaxies @ low z, few @ high z

Redshift Surveys

huge amounts of observing time :
many galaxies @ low z, few @ high z

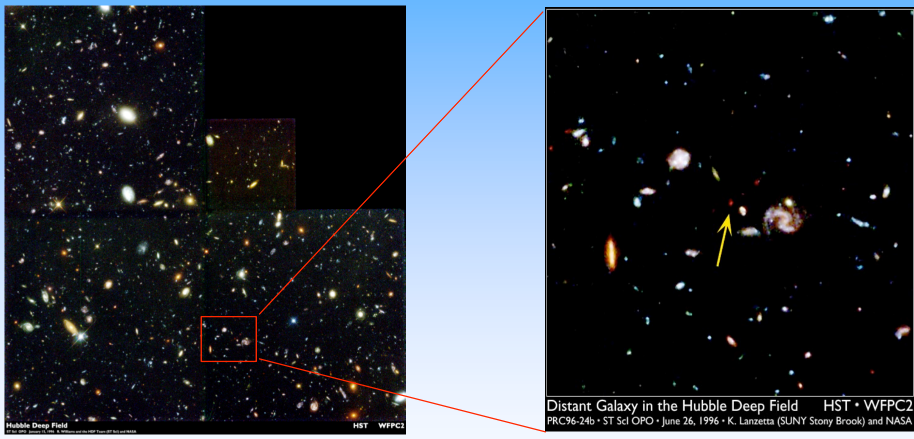
Look for other strategies to find & identify
high – z galaxies :

-- Lyman - α searches
-- QSO fields
-- optical identifications of QSO absorbers
-- drop out technique
-- color selection criteria for SFing and passive galaxies
-- photometric redshifts

U. Fritze, Goettingen 2008

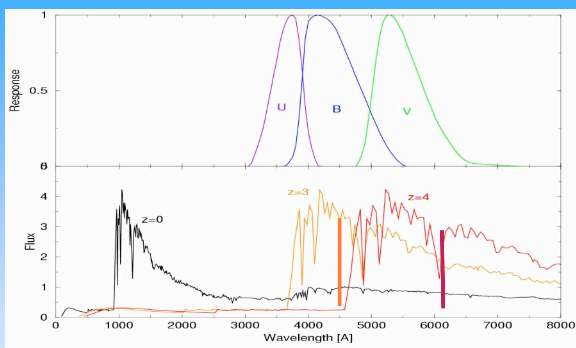
Deep Fields

Faintest galaxies : 29 mag (UBVRIJHK)
Spectroscop. limit : 25 mag (= factor 40 brighter)

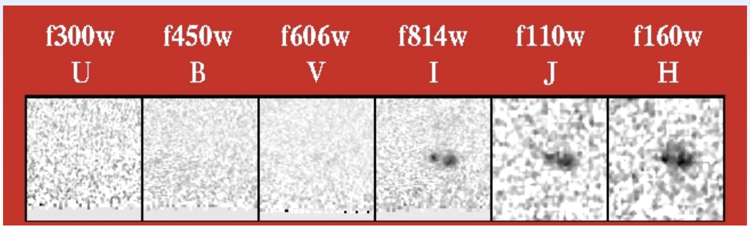


→ Drop Out technique & Photometric redshifts

Drop Out Technik - Lyman Break Galaxies



V drop out : Lyman Break Galaxy with z_{spec} = 5.3



High Redshift Galaxies

Chemically consistent GALEV models : E, S0, Sa, Sb, Sc, Sd, starbursts

Grid of spectral energy distributions (SED) ↔ observed SED

various galaxy types & all redshifts

χ^2 analysis

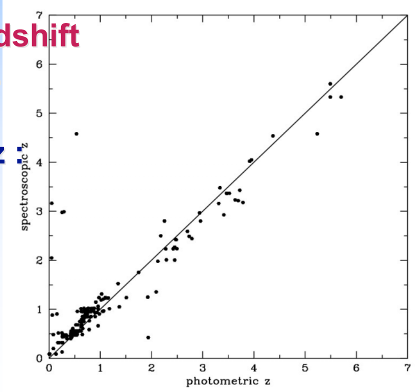
→ galaxy type + photometric redshift

→ SFR + age + metall. + . . .

photometric z vs. spectroscopic z :

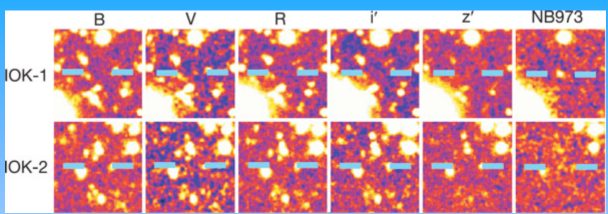
precision : $\Delta z / z \le 5\,\%$!

(Kotulla+08)

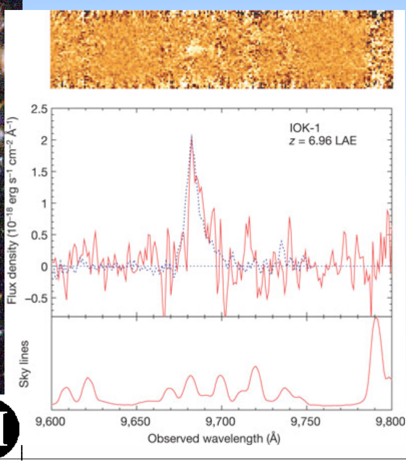


U. Fritze, Goettingen 2008

Redshift Record 2006

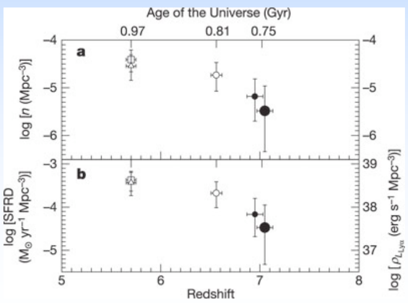


Subaru Deep Field z dropout at z=6.96 (Iye+06, Nat. 443, 186)



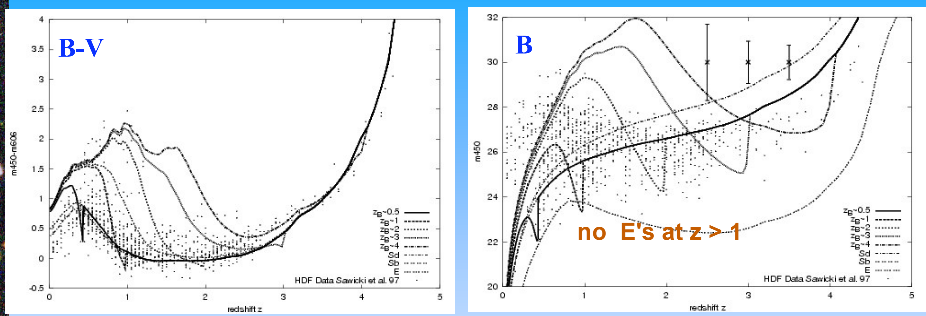
750 Myr after Big Bang, Lyα line,

SFR~10 Msun/yr



U. Fritze, Goettingen 2008

Galaxies at High Redshift



- ☛ trace evolution of normal galaxies to $z > 4.5$ (> 95 % t_{Hubble})
- ☛ identify high-z progenitors of local galaxy types
- ☛ many strong starbursts at $0.5<z<4.5$ $\Delta S/S>30\%$
- ☛ many very red post-starburst galaxies at $3.5 > z > 0.5$

  ~ EROs, strong bursts at $2<z<4$ & no SF since
- ☛ all galaxies in the HDF, UDF, FDF, GOODs well described by chemically consistent GALEV models for

  normal E . . . Sd or starbursts or post-starbursts

(Möller, Fritze, Fricke 98, Fritze, Möller, Fricke 99a,b, Bicker, Fritze, Möller 04, Fritze & Bicker 06)

SCUBA galaxies

Detected with SCUBA (submillimeter common user bolometric array) at CFHT @ 450 μm and 850 μm

very luminous @ 450 μm and 850 μm,

hard to detect @ shorter wavelengths

dominated by thermal reemission from dust heated by vigorous SF

> 30 mag extinction in restframe optical

~ no restframe opt. spectra, only SEDs & photometric redshifts

U. Fritze, Goettingen 2008

SCUBA galaxies

e.g. Dye+08: Optical/IR photometry for galaxies in the SCUBA HAlf Degree Extragalactic Survey (SHADES)

Optical images in B,R,I, z from SuprimeCam on the Subaru telescope.

5σ point source sensitivity of 26.8, 25.8, 25.7 and 25.0 mag (AB) in B,R,I and z, respectively, measured in a 3 arcsec diameter aperture.

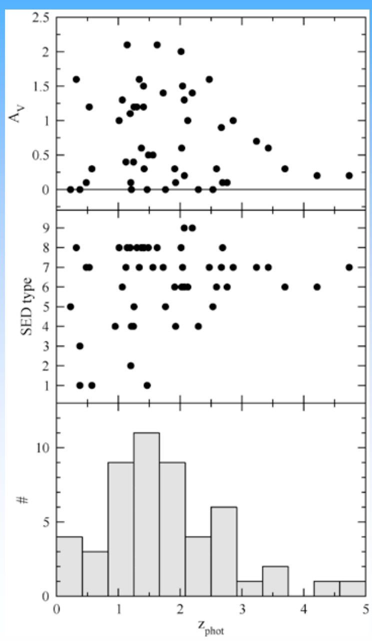
Total exposure times for B,R,I and z : 7200, 3360, 4730 and 4800 s.

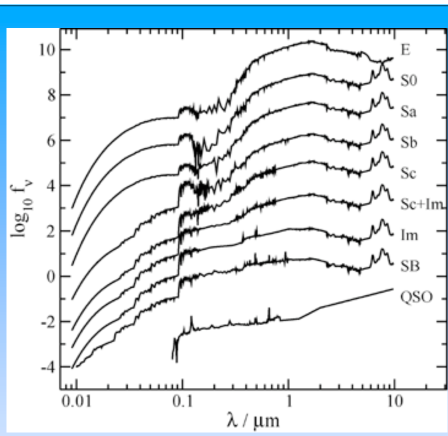
K-band image was obtained with the Wide Field Camera (WFCAM) on the United Kingdom Infrared Telescope (UKIRT).

Spitzer IRAC photometry at wavelengths 3.6, 4.5, 5.8 and 8µm

SCUBA galaxies

Templates for photometric redshifts:





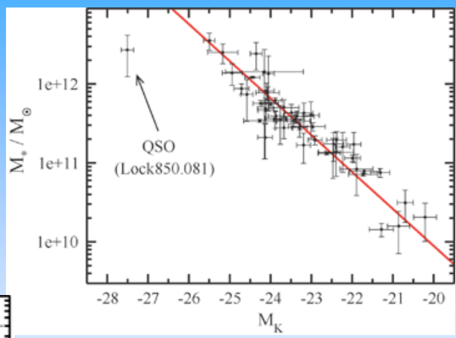
Results:
only 2 QSOs, mostly Sc … starburst.

dust attenuation
SED type
photometric redshift distribution
for 51 sources identified
in SHADE

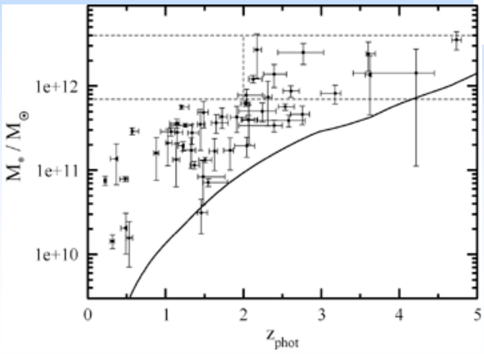
SCUBA galaxies

Stellar masses of 51 SCUBA galaxies from SED fitting (K-band!)

10^{11} - 10^{12} $M_\odot$



Redshift distribution of masses:
➜ downsizing!



SCUBA galaxies

Star formation rates of 51 SCUBA galaxies from SED fitting:

the average SCUBA galaxy is forming stars at a rate 6 - 30 times the rate implied from the rest-frame optical in a dust obscured burst

the burst creates 15 - 65 % of the total stellar mass

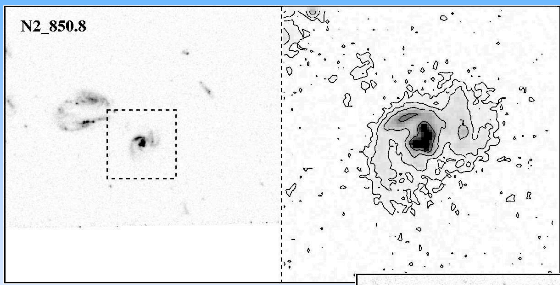
SCUBA galaxies are compact : nuclear starbursts

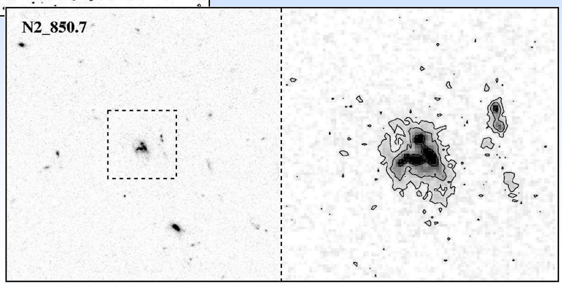
Estimate from the average star formation history that between one in five and one in 15 bright
($L^* + 2 < L_{optical} < L^* - 1$mag)
galaxies in the field over the interval $0 < z < 3$ will at some point in their lifetime experience a similarly energetic dusty burst of star formation.

SCUBA galaxies

Almaini+05: HST ACS imaging of 10 SCUBA galaxies:

most show compact disturbed morphologies, at least 6/10 are major mergers





Galaxy Mergers at High Redshift

Classification systems:

- **CAS (concentration, asymmetry, clumpiness),**
- **Gini,**
- **M20**

CAS system (Conselice 97 ff)

Asymmetry: take an original galaxy image and rotating it 180 degrees about the galaxy centre, and then subtract the two images (Conselice 1997).
Corrections for background and radius (cf Conselice et al. 2000a). The centre for rotation is determined by an iterative process which finds the location of the minimum asymmetry.

$$A = \min\left(\frac{\Sigma|I_0 - I_{180}|}{\Sigma|I_0|}\right) - \min\left(\frac{\Sigma|B_0 - B_{180}|}{\Sigma|I_0|}\right),$$

Galaxy Mergers at High Redshift

CAS Classification systems:

Asymmetry: $$A = \min\left(\frac{\Sigma|I_0 - I_{180}|}{\Sigma|I_0|}\right) - \min\left(\frac{\Sigma|B_0 - B_{180}|}{\Sigma|I_0|}\right),$$

I0 is the original image pixels, I180 is the image after rotating by 180˚. The background subtraction using light from a blank sky area, called B0, are critical and must be minimized in the same way as the original galaxy itself.

A lower value of A means that a galaxy has a higher degree of rotational symmetry. Higher values of A indicate an asymmetric light distribution.

Typical values:
A = 0-0.05 for ellipticals,
A ~ 0.10-0.3 for discs and irregulars, and
A > 0.35 for major galaxy mergers (in the nearby Universe)

Galaxy Mergers at High Redshift

CAS Classification systems:

Concentration : a measure of the intensity of light contained within the central region. C is the ratio of two circular radii which contain 20 and 80 % (r20, r80) of the total galaxy flux: $$C = 5\log\left(\frac{r_{80}}{r_{20}}\right).$$

This index is sometimes called C28.
High value of C : large amount of light in the central region.

Typical values:
C = 2-3 for discs,
C > 3.5 for massive ellipticals,
peculiars span the entire range C= 1.8 - 4.4.

Galaxy Mergers at High Redshift

CAS Classification systems:

Clumpiness : also called smoothness S : describes the fraction of light which is contained in clumpy light concentrations.
Galaxies with ongoing star formation have very clumpy structures, and high S values.
Clumpiness can be measured in a number of ways, the most common method used, as described in Conselice (2003) is

$$S = 10 \left\{ \left[\frac{\Sigma\left(I_{x,y} - I^{\sigma}_{x,y}\right)}{\Sigma I_{x,y}} \right] - \left[\frac{\Sigma\left(B_{x,y} - B^{\sigma}_{x,y}\right)}{\Sigma I_{x,y}} \right] \right\},$$

where the original image Ix,y is blurred to produce a secondary image, Iσx,y. This blurred image is then subtracted from the original image leaving a residual map, containing only high frequency structures in the galaxy.

Galaxy Mergers at High Redshift

CAS Classification systems:

To quantify the clumpiness S, we normalize the summation of these residuals by the original galaxy's total light, and subtract from this the residual amount of sky after smoothing and subtracting it in the same way. The size of the smoothing kernel σ is determined by the radius of the galaxy, and is σ= 0.2 × 1.5r(η= 0.2)*. Note that the centres of galaxies are removed when this procedure is carried out.

* = Petrosian radius

Typical values are
S < 0.1 for non-star-forming galaxies, as e.g. ellipticals,
S = 0.1-1 for star-forming galaxies, e.g. discs & irregulars.

Galaxy Mergers at High Redshift

Classification systems: the Gini coefficient

is a statistical tool originally used in economics to determine the distribution of wealth within a population, with higher values indicating a very unequal distribution

Gini = 1 means all wealth/light is in one person/pixel,
Gini < 1 indicates a more evenly distribution,
Gini = 0 means everyone/every pixel has an equal share.

The value of G is defined by the Lorentz curve of the galaxy's light distribution, which does not take into consideration spatial position.

Each pixel is ordered by its brightness and counted as part of the cumulative distribution (see Lotz et al. 2004, 2008).

The mean value of Gini in Conselice's UDF catalogue is 0.71.

Galaxy Mergers at High Redshift

Classification systems: the M20 parameter

is an indicator of light concentration similar to C but calculated slightly differently.

The total moment of light is calculated by summing the flux of each pixel multiplied by the square of its distance from the centre. The centre is deemed to be the location where M20 is minimized (Lotz et al. 2004). The value of M20 is the moment of the fluxes of the brightest 20 % of light in a galaxy, which is then normalized by the total light moment for all pixels (Lotz et al. 2004, 2008).

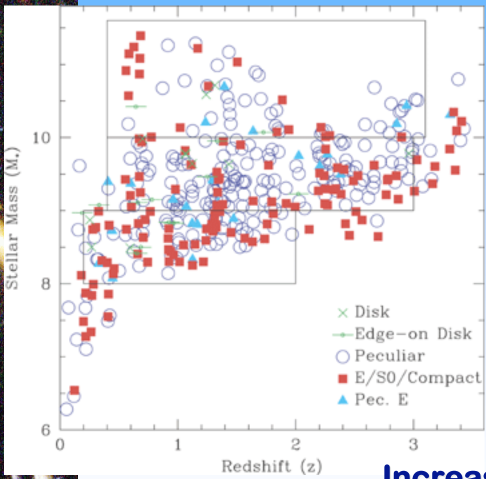
Main differences between M20 and C : the moments in M20 which depend on the distance from the galaxy centre.

M20 is therefore more affected by spatial variations, and also the centre of the galaxy is again a free parameter. This can make it more sensitive to possible mergers.

Galaxy Mergers at High Redshift : UDF

Results for the Hubble UDF: Conselice+08

the majority of galaxies with z_{850} < 27 are peculiar in appearance



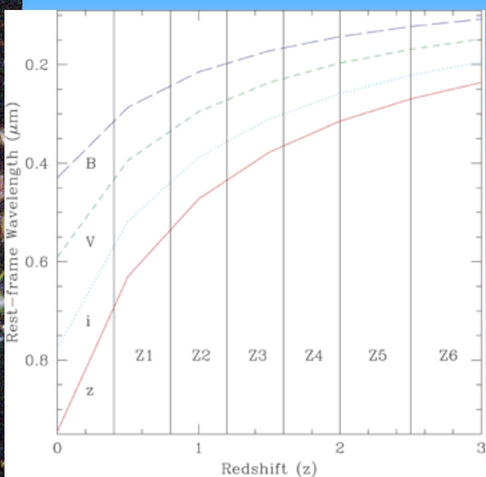
Open blue circles : peculiars
Solid red boxes : ellipticals, S0s & compacts
Cyan triangles : ellipticals with a peculiarity
Green crosses : face-on disc galaxies
Green dot with a solid line : edge-on disks
Boxes denote the regions in which we measure the merger fraction

Increase of peculiar fraction with z, decrease of E- & Sp- fractions.

U. Fritze, Goettingen 2008

Galaxy Mergers at High Redshift : UDF

Morphological k-corrections



The rest-frame wavelength probed as a function of redshift for each of our filters B450, V606, i775 and z850. Vertical line denotes our redshift ranges.

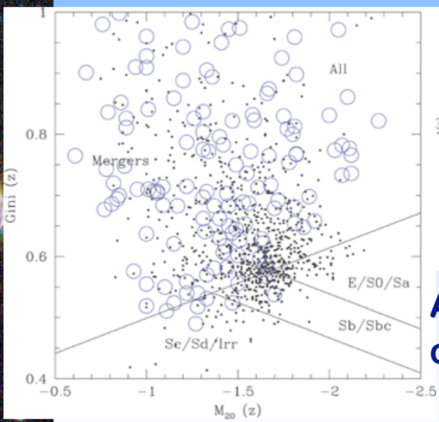
Conselice+08

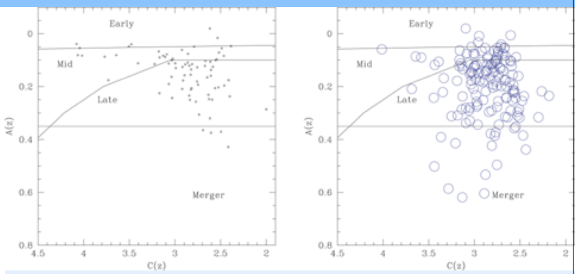
U. Fritze, Goettingen 2008

Galaxy Mergers at High Redshift : UDF

Conselice+08

Mergers are identified
by A > 0.35 and A > S (CAS)
by G > -0.115 M20 + 0.384 (Gini / M20)



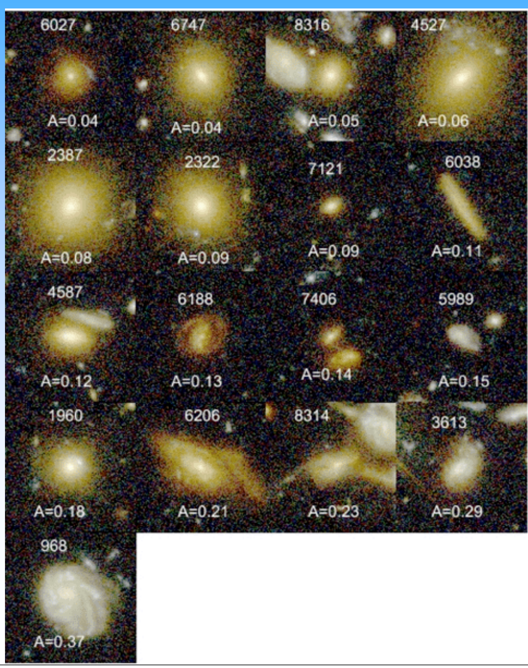


Agreement betw. CAS & Gini/M20 ✔

Gini/M20 finds sllightly larger number of mergers than CAS, but contains larger contamination from non-mergers

Galaxy Mergers at High Redshift : UDF

Galaxies with stellar masses $M^* > 10^{10} M_\odot$ at redshifts $0.5 < z < 1.2$

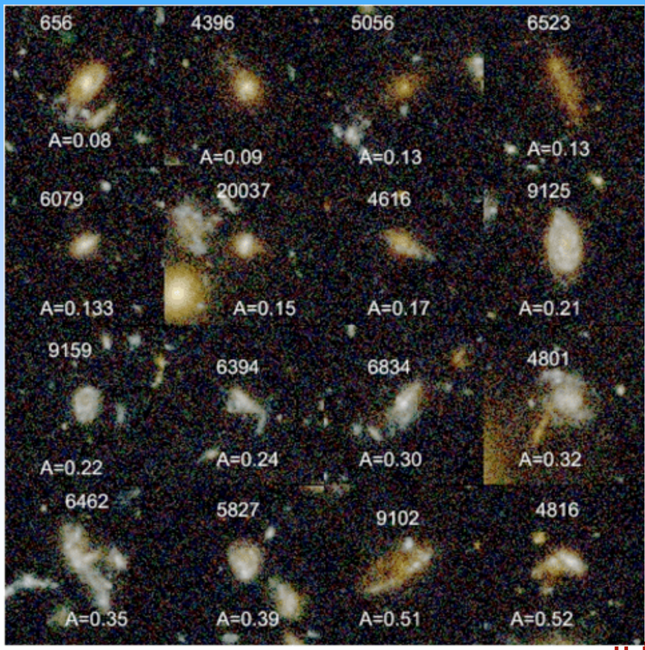


Conselice+08

most galaxies are normal (E … Sd)

Galaxy Mergers at High Redshift : UDF

Galaxies with stellar masses $M^* > 10^{10}\, M_\odot$ at redshifts $1.2 < z < 1.6$



Conselice+08

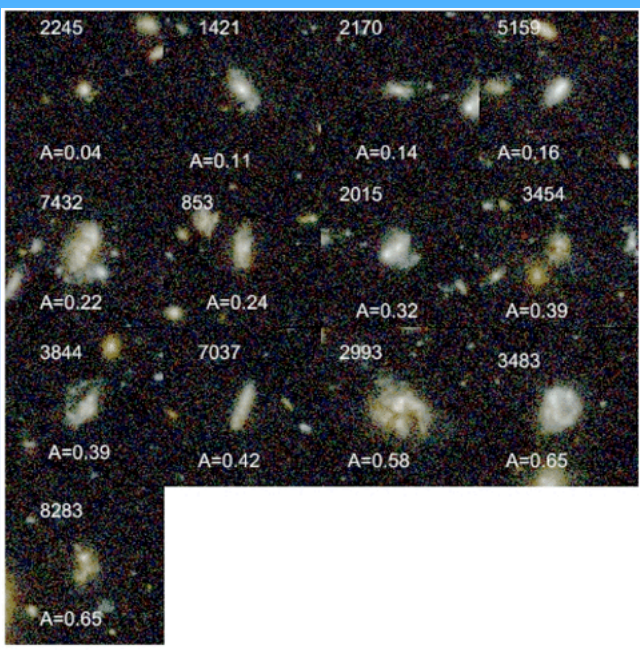
more disturbed galaxies

A > 0.35 : major mergers

U. Fritze, Goettingen 2008

Galaxy Mergers at High Redshift : UDF

Galaxies with stellar masses $M^* > 10^{10}\, M_\odot$ at redshifts $1.6 < z < 2.2$

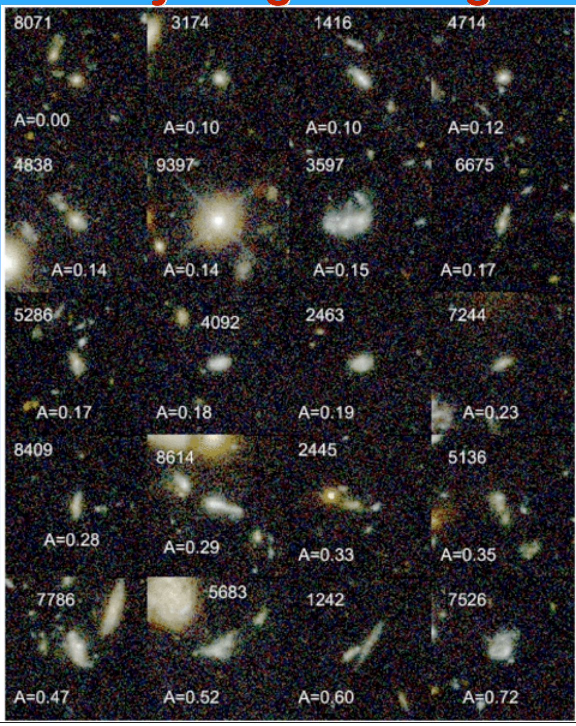


Conselice+08

more disturbed galaxies

U. Fritze, Goettingen 2008

Galaxy Mergers at High Redshift : UDF



Galaxies with stellar masses $M^* > 10^{10}\ M_\odot$ at redshifts $2.2 < z < 3$

Conselice+08

U. Fritze, Goettingen 2008

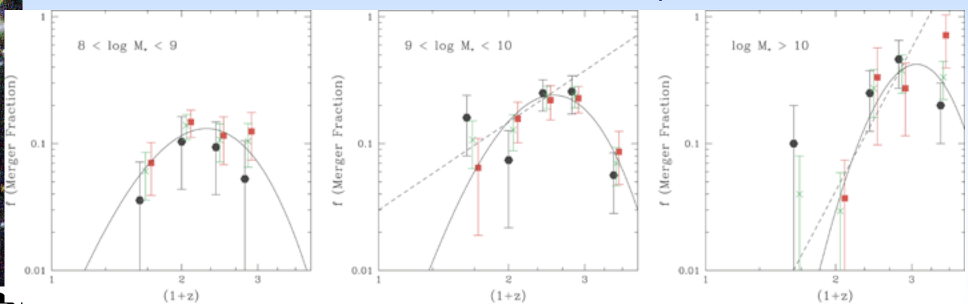
Merger Rates at High Redshift : UDF

Redshift evolution of the merger fraction :

$$f_m(z) = f_0\ (1+z)^{\ m}$$

with f_0 merger fraction @ z=0.

Merger fraction as a function of redshift and stellar mass.
Black circles : merger fraction in the UDF,
Red boxes : merger fractions from the HDF-N where we can probe the rest-frame optical (Conselice et al. 2003a).
Green crosses : combined UDF and HDF-N sample.

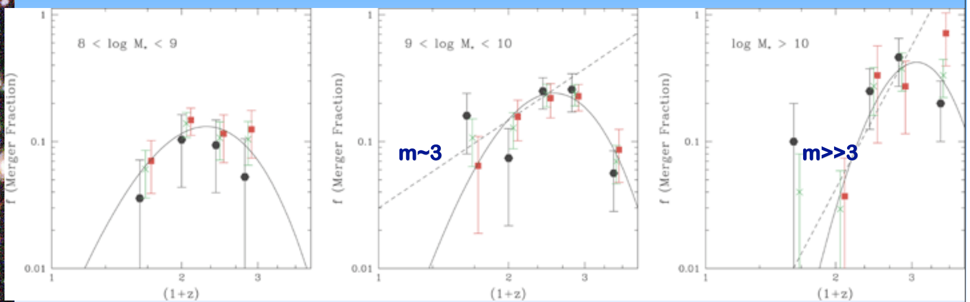


U. Fritze, Goettingen 2008

Merger Rates at High Redshift : UDF

Redshift evolution of the merger fraction :

$$f_m(z) = f_0\,(1+z)^{m}$$



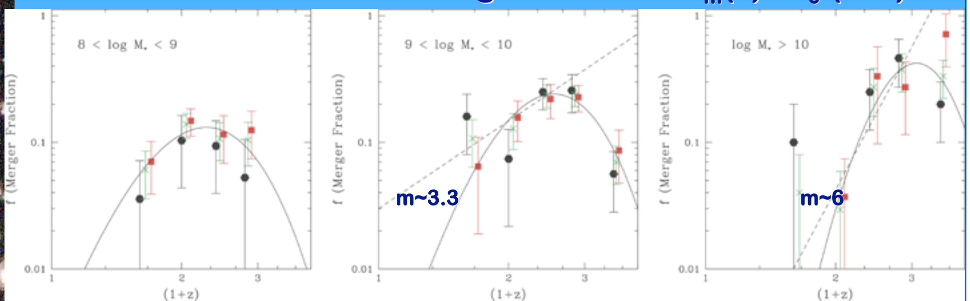
fit a power-law up to the redshift peak for all but the $10^8\,M_\odot < M_* < 10^9\,M_\odot$ galaxies where there are too few points

merger fraction increases strongly with redshift, more strongly for high mass galaxies than for low mass galaxies ➜ downsizing

U. Fritze, Goettingen 2008

Merger Rates at High Redshift : UDF

Redshift evolution of the merger fraction : $f_m(z) = f_0\,(1+z)^{m}$



The peak in the merger fraction occurs at redshifts

z_{peak} = 2.08 for galaxies with $M_* > 10^{10}\,M_\odot$

z_{peak} = 1.54 for galaxies with $10^9\,M_\odot < M_* < 10^{10}\,M_\odot$

z_{peak} = 1.28 for galaxies with $10^8\,M_\odot < M_* < 10^9\,M_\odot$,

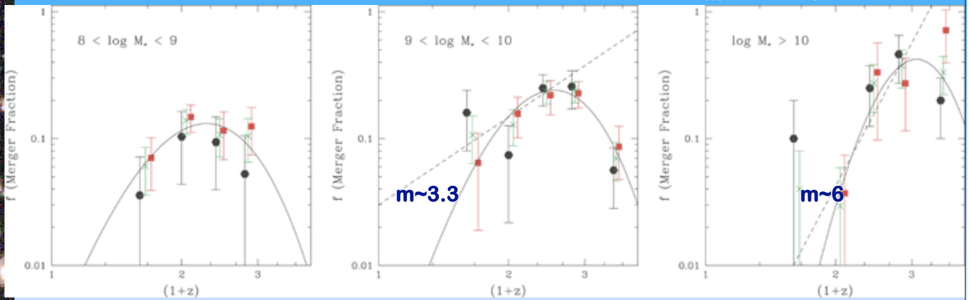
i.e. later for lower mass galaxies ➜ downsizing

➜ low mass galaxies do not merge as quickly as high mass galaxies

U. Fritze, Goettingen 2008

Merger Rates at High Redshift : UDF

Redshift evolution of the merger fraction : $f_m(z) = f_0 \, (1+z)^m$



Galaxies with $M_* > 10^{10} \, M_\odot$ undergo on average

4.3 ± 0.8 major mergers at $0 < z < 3$

with most of this merging occurring at $z > 1$.

Galaxy Mergers at High Redshift : Summary

The majority of faint galaxies in deep fields and/or at high redshift are peculiar or interacting.

Good agreement between galaxy classification by eye and through quantitative methods, as well as between the CAS and the Gini/M20 parameters.

The merger rate increases strongly with redshift (up to z ~ 3 in the UDF), more strongly for massive galaxies than for low-mass ones.

The peak in the merger rate occurs earlier for high mass galaxies than for low mass ones.

Starbursts were stronger at higher redshifts and starburst galaxies were more massive.

➜ downsizing