Galaxy Formation and Evolution

Lecture 10:

Morphological evolution and spiral galaxies

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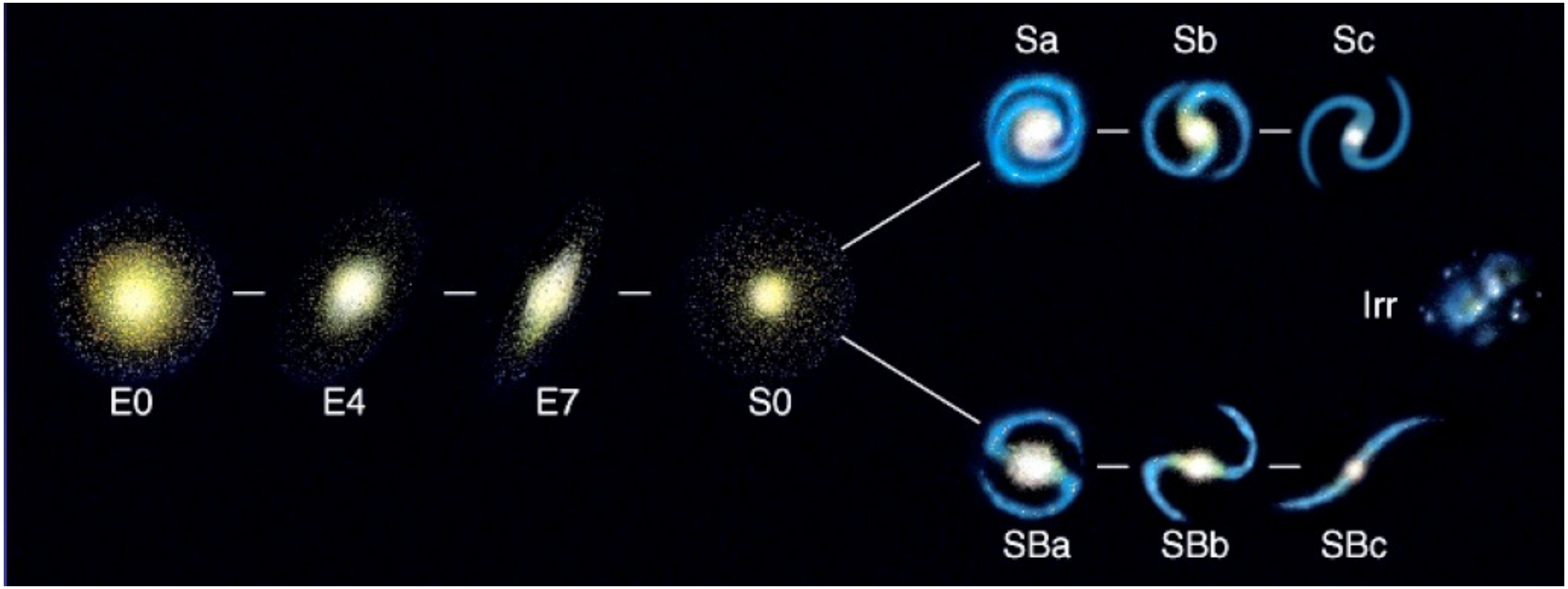
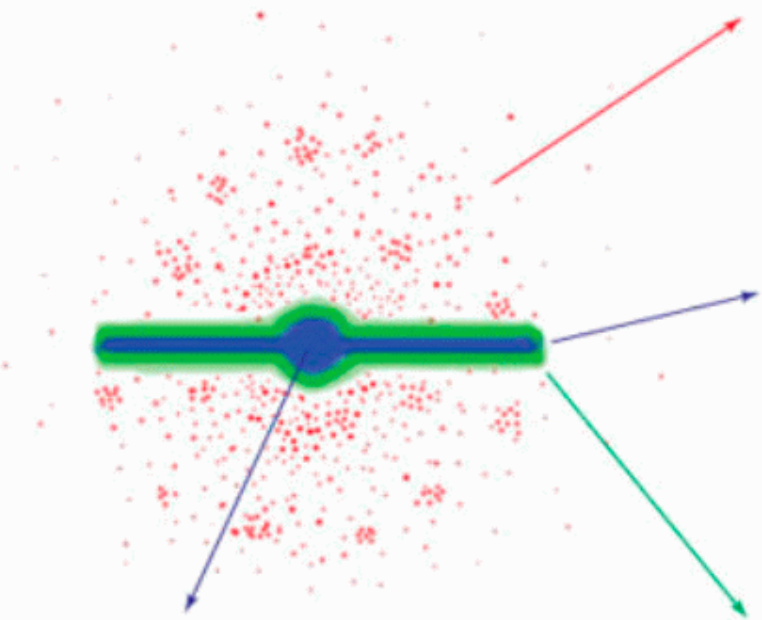
Galaxy morphologies: Hubble sequence



Late type galaxies

Conventional Picture of the Milky Way



Halo (Population II)

$\rho(r) \propto r^{-3}$
metal poor
$V_{rot} \sim -40$ km/s

Thin Disk (Population I)

$\rho(z) \propto e^{-z\,/\,325\,\mathrm{pc}}$
(exponential disk with 325 pc scale height)
metal rich
$V_{rot} \sim +220$ km/s

Intermediate Population II or Thick Disk

$\rho(z) \propto e^{-z\,/\,1000\,\mathrm{pc}}$
(exponential disk with 1000 pc scale height)
intermediate metallicity
$V_{rot} \sim +180$ km/s

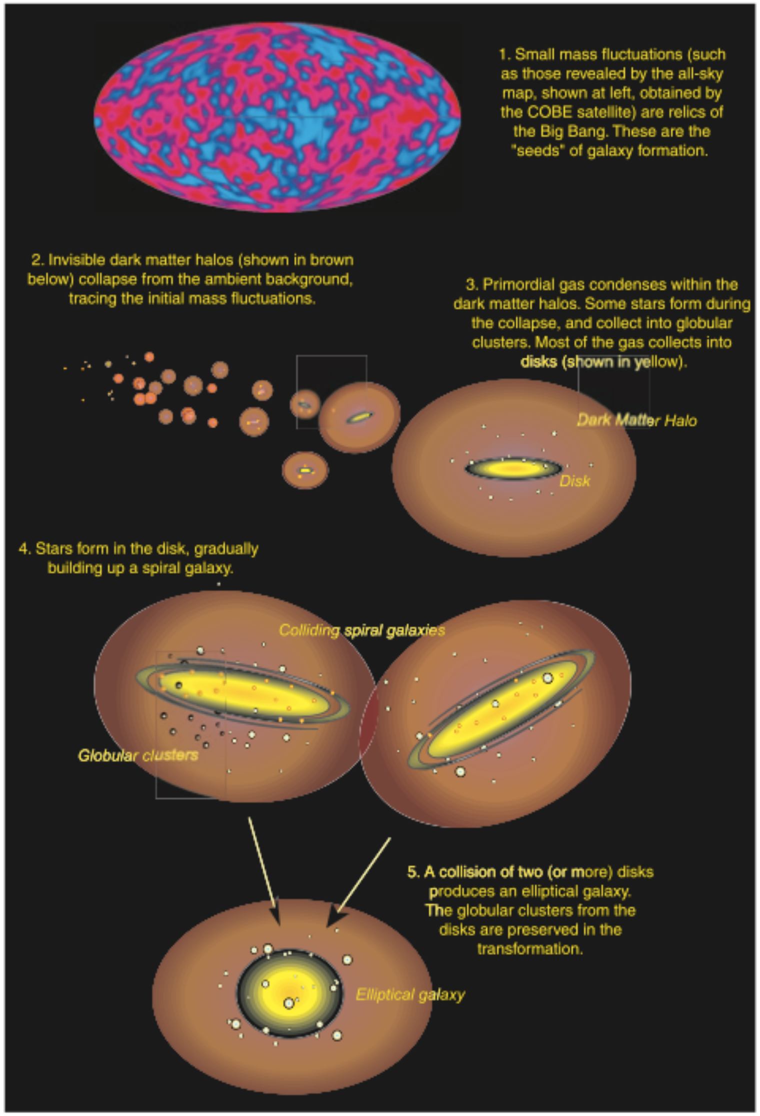
Bulge

$\rho(r) \propto r^{-2.2}$
metal rich – super metal rich
$V_{rot} \propto$ metallicity

Galaxy evolutionary scenario

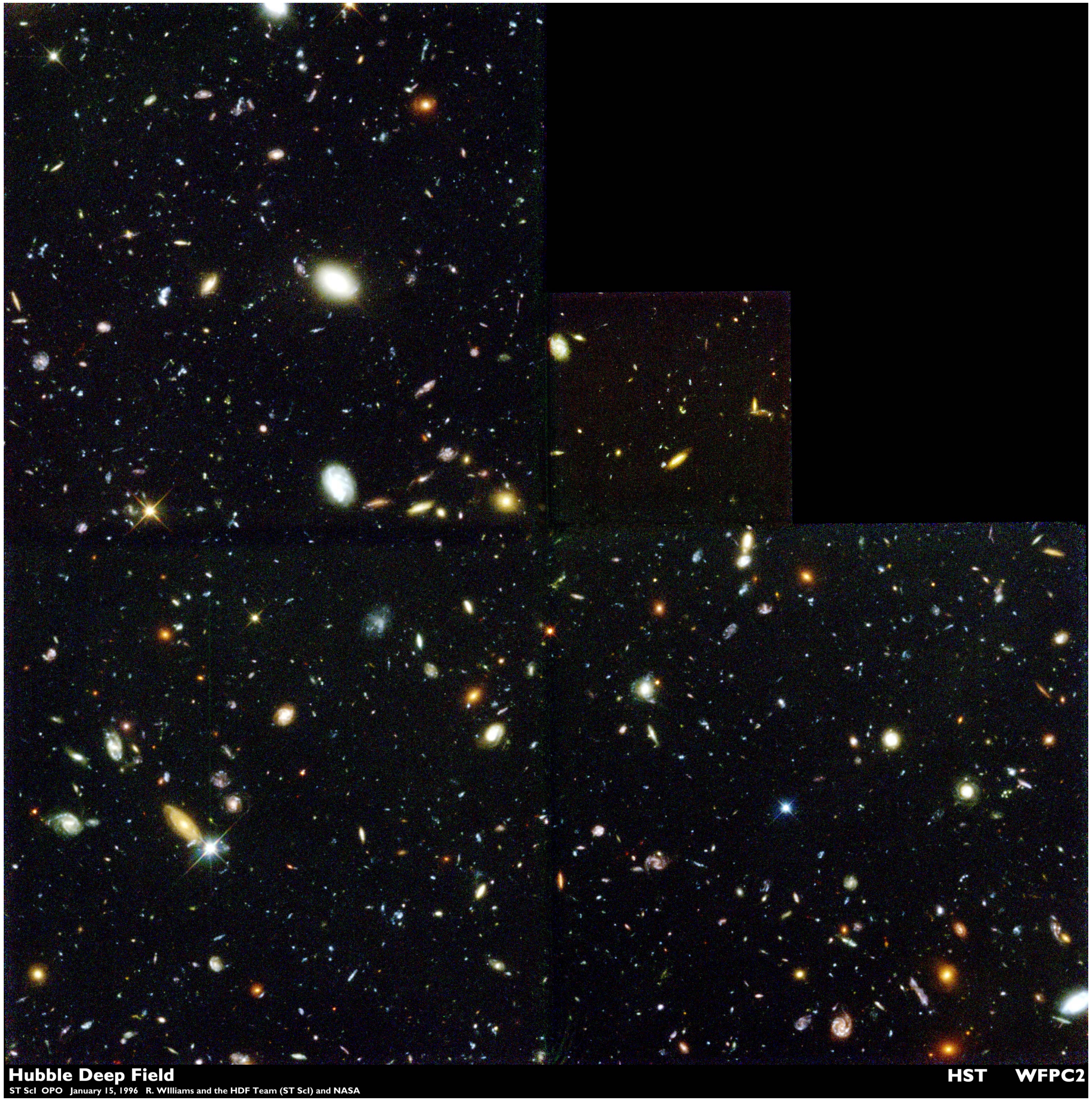
We would like to test galaxy evolution models by investigating how galaxy morphologies change with redshift and lookback time.

Detailed morphological studies are best carried out for galaxies with z<1.5 (to ensure good spatial resolution)



Abraham (2001)

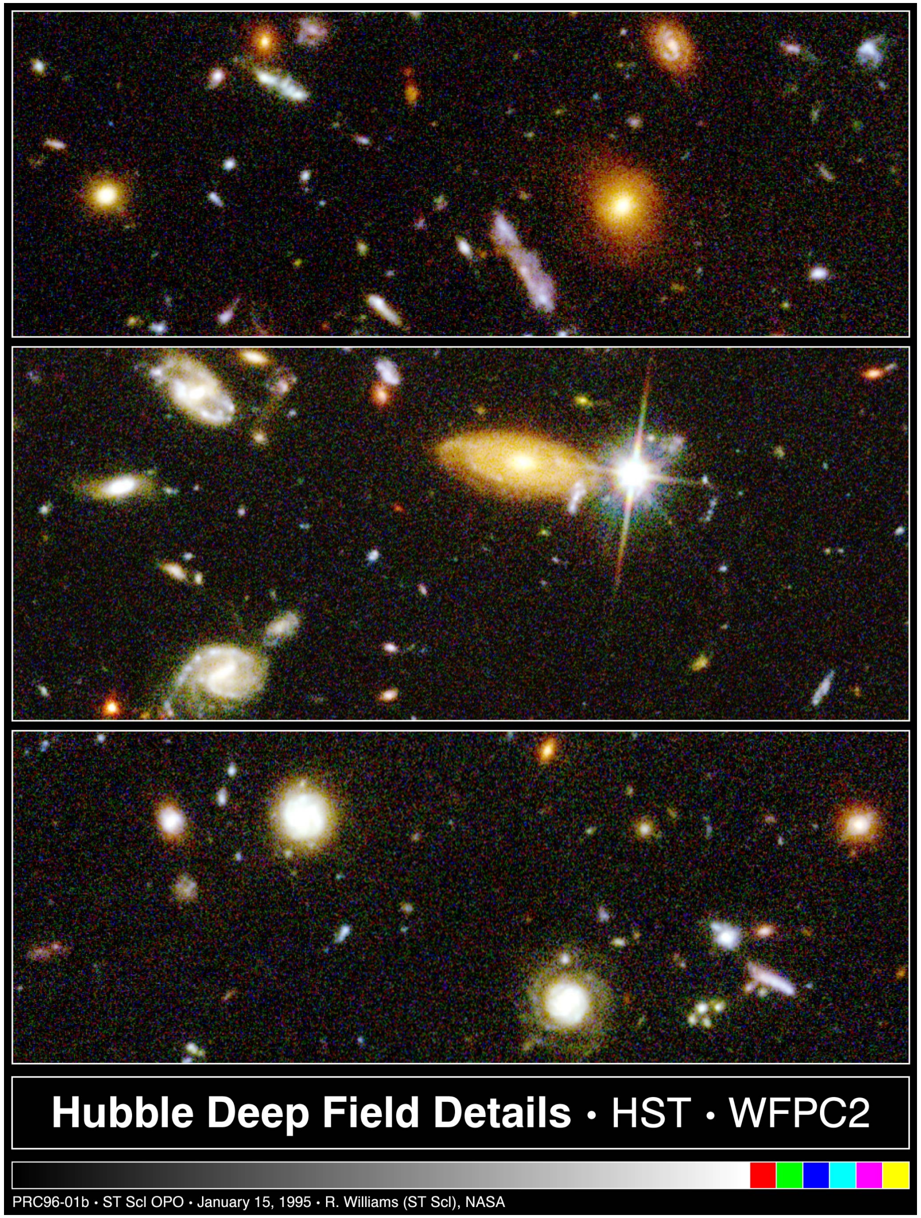
The Hubble Deep Field North - Full Field



Staircase pattern is a due to the fact that WFPC2 has 4 CCDs that take Images simultaneously

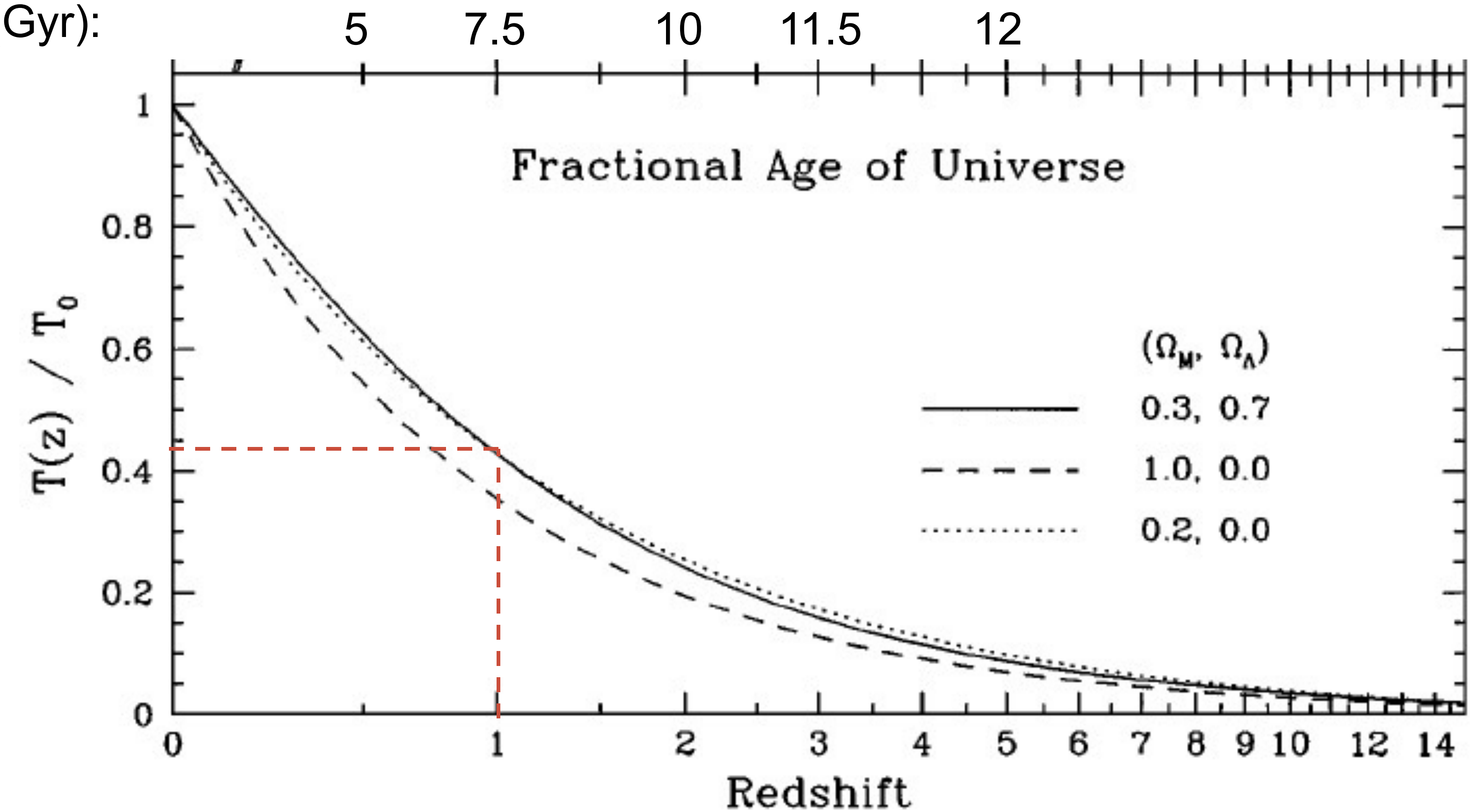
Williams et al. (1996)

Hubble Deep Field North in detail



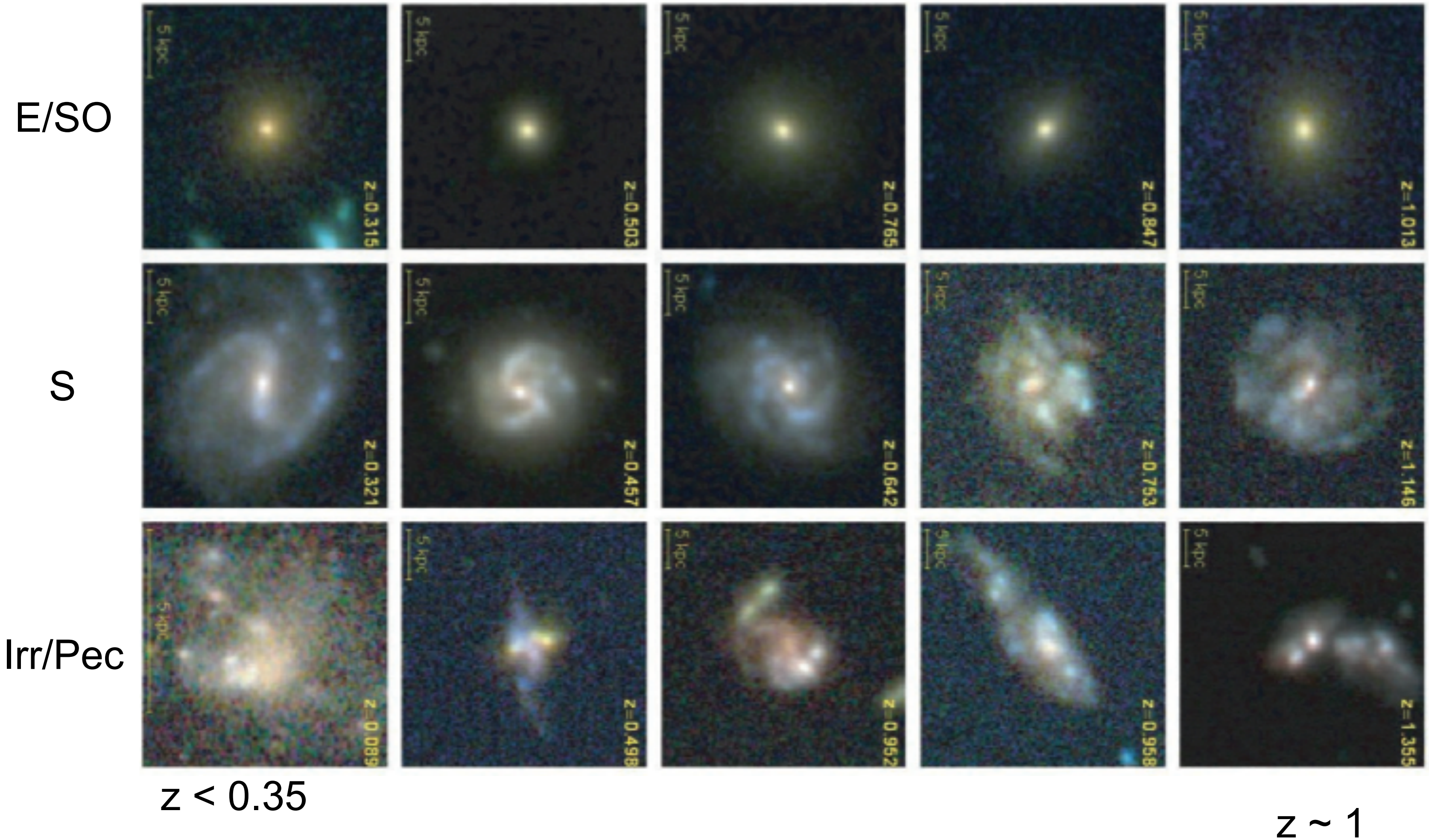
Lookback time vs. redshift

Lookback time (Gyr):



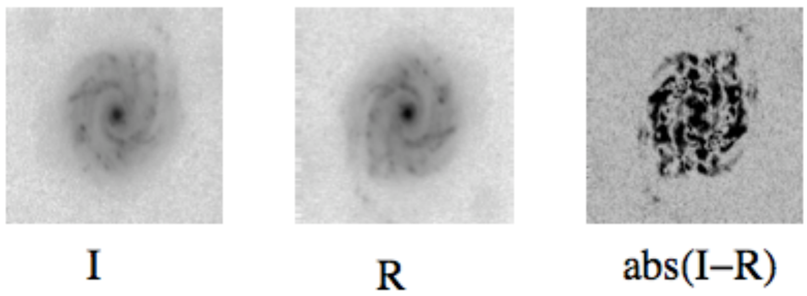
The lookback time is not linear with redshift. At redshift z~1 the Universe was less than half its current age (lookback time ~7.5 Gyr for or concordance cosmology).

Galaxy morphologies vs. redshift



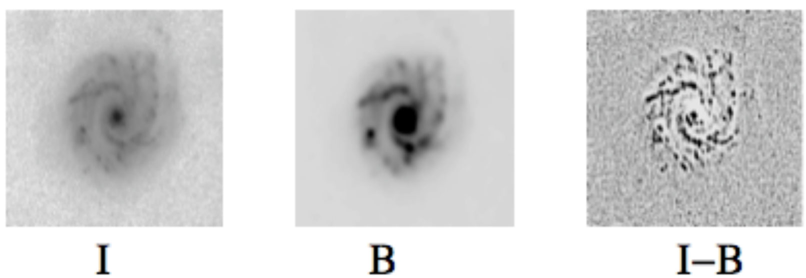
Abraham (2001)

Quantitative classification: the CAS parameters



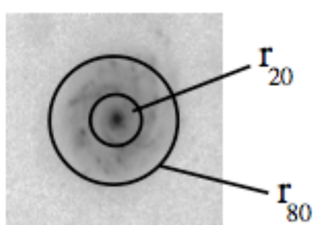
$$A = \frac{\mathrm{abs}(I-R)}{I}$$

<u>Asymmetry index (A):</u> rotate image through 180°, then subtract from unrotated image. Sum the absolute values of the intensities in the subtracted image, divide by the total intensity.



$$S = \frac{I-B}{I}$$

<u>Structure index (S):</u> smooth the image then subtract it from the un-smoothed image, sum the intensities in the subtracted image, divide by total intensity.



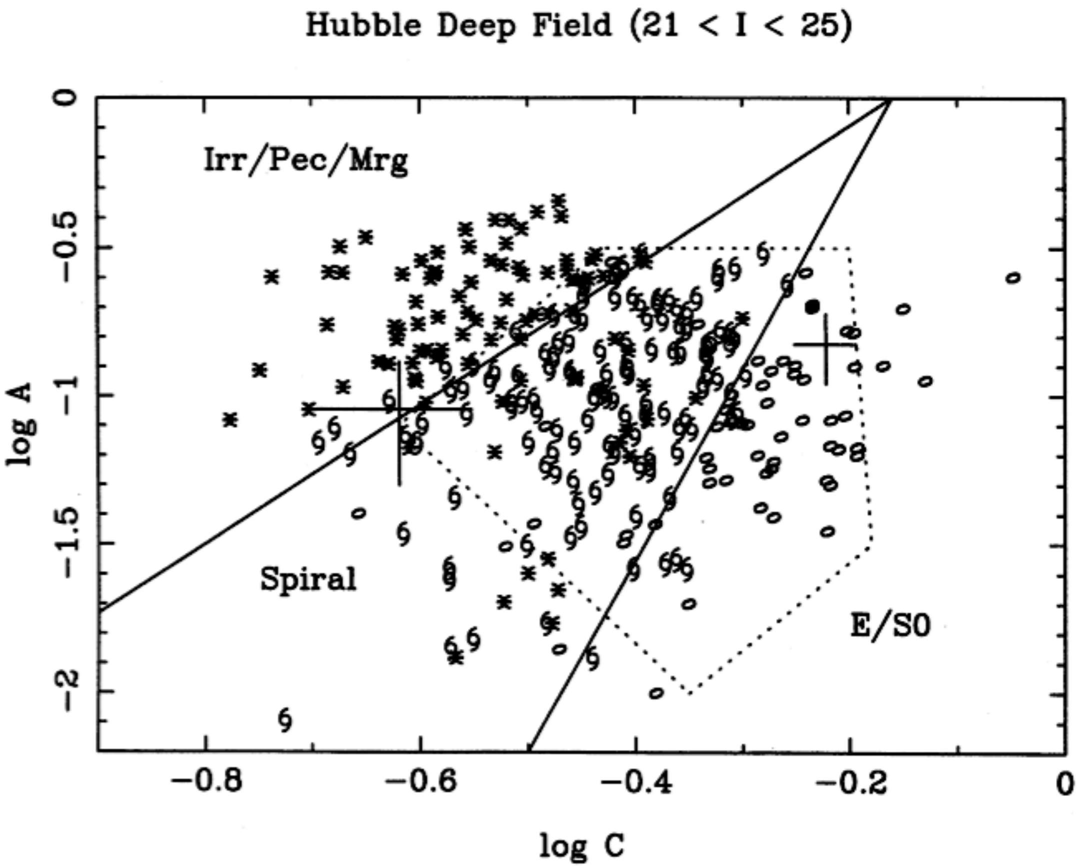
$$C = 5 \log\left(\frac{r_{80}}{r_{20}}\right)$$

<u>Concentration parameter (C):</u> measure the radii that contain 20% and 80% of the light. Divide the radii, take the log, multiply by 5.

Quantitative methods can take some of the subjectivity out of galaxy classification.

The utility of quantitative classification

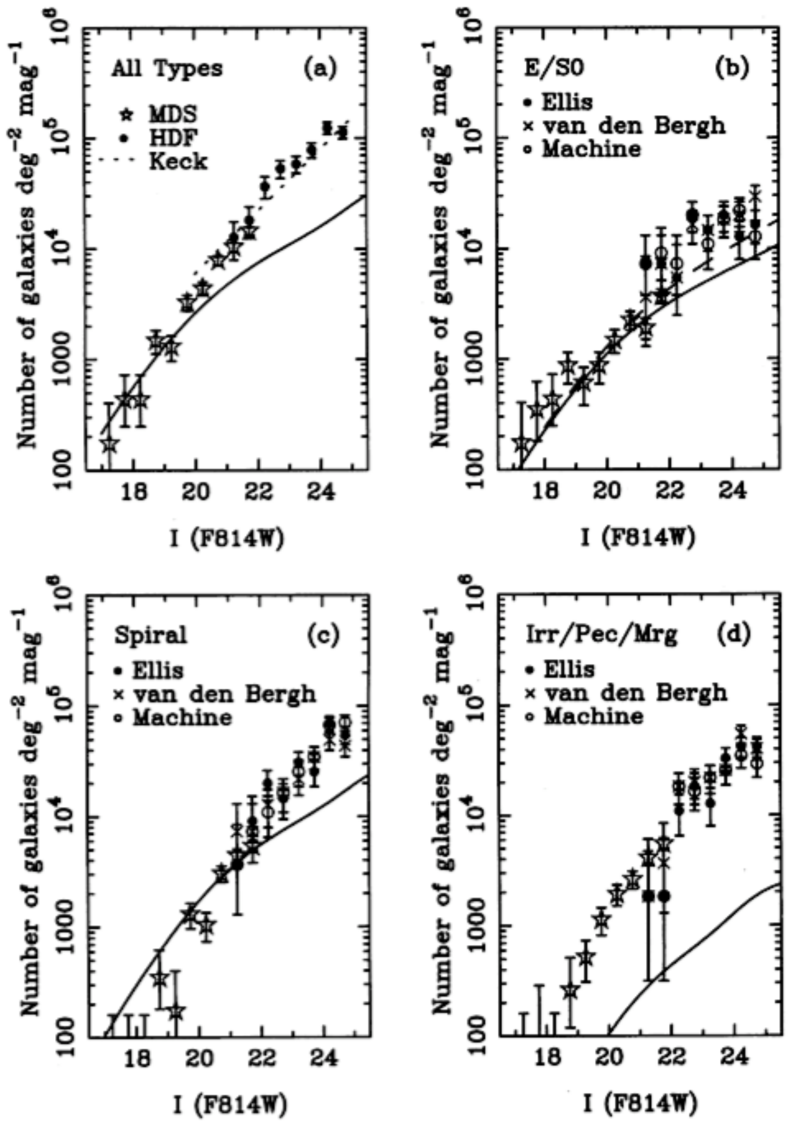
Abraham (1996)



Different types of galaxies (visually classified) occupy different parts of the logA vs. logC plane. The symbols are as follows: E/SO (ovals), Spirals (spirals), Irr/Pec/Mrg (stars).

Number counts in the Hubble Deep Field North

A large fraction of the over-abundance of faint galaxies relative to the no evolution models (shown by the solid line) is due to the Irr/Pec/Mrg and faint Spiral galaxies. Irr/Pec/Mrg galaxies of modest luminosity are extremely rare in the local Universe, but relatively common at high redshifts (z > 0.5).

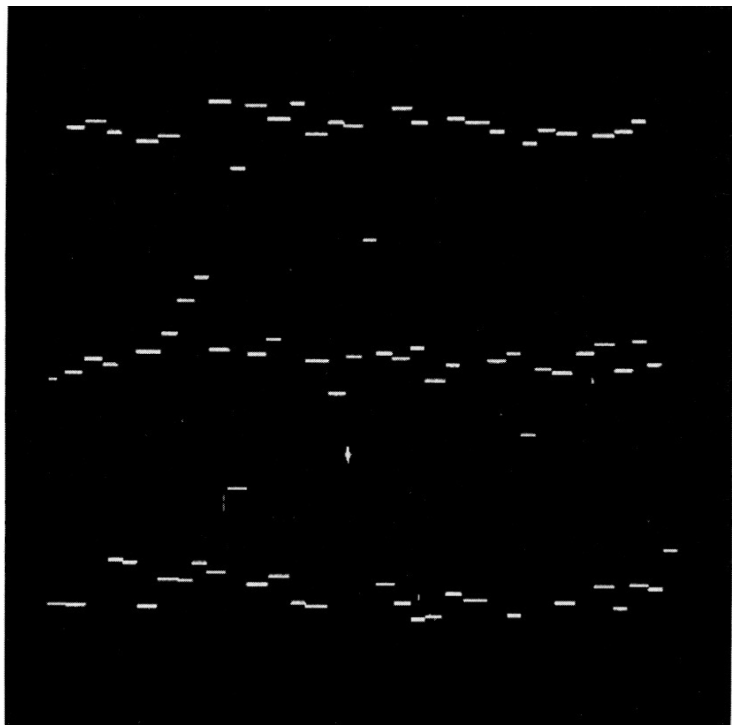


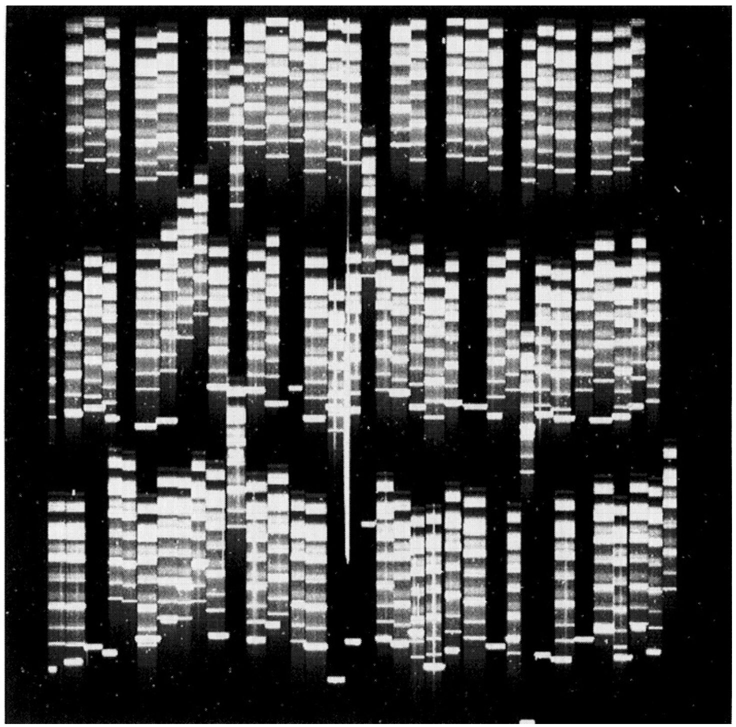
Abraham et al. (1996)

Summary of galaxy evolution up to z~1.5

- <u>z < 0.3 (≤3.5 Gyr look-back time)</u>: Grand-design spirals exist. Hubble scheme applies in full detail.
- <u>z ~ 0.5 (~5 Gyr):</u> Barred spirals become rare. Spiral arms are undeveloped. The bifurcated "tines" of the Hubble tuning fork begin to evaporate.
- <u>z > 0.6 (>6 Gyr):</u> The fraction of mergers and peculiar galaxies increases rapidly. By z = 1, ~30% of luminous galaxies cannot be placed on the standard Hubble sequence.

Multi-slit spectroscopy of the CFRS sample





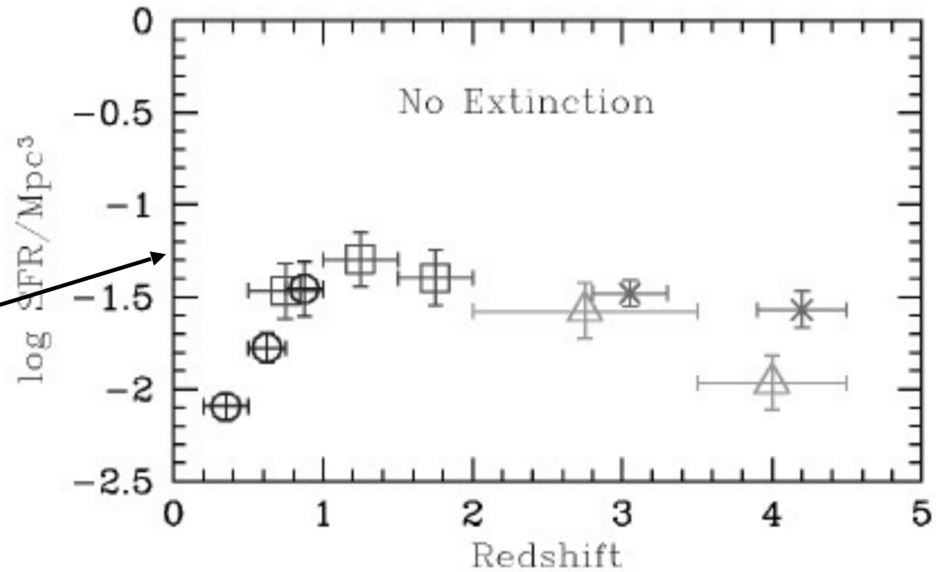
Multi-slit spectrograph at the Canada France Hawaii Telescope

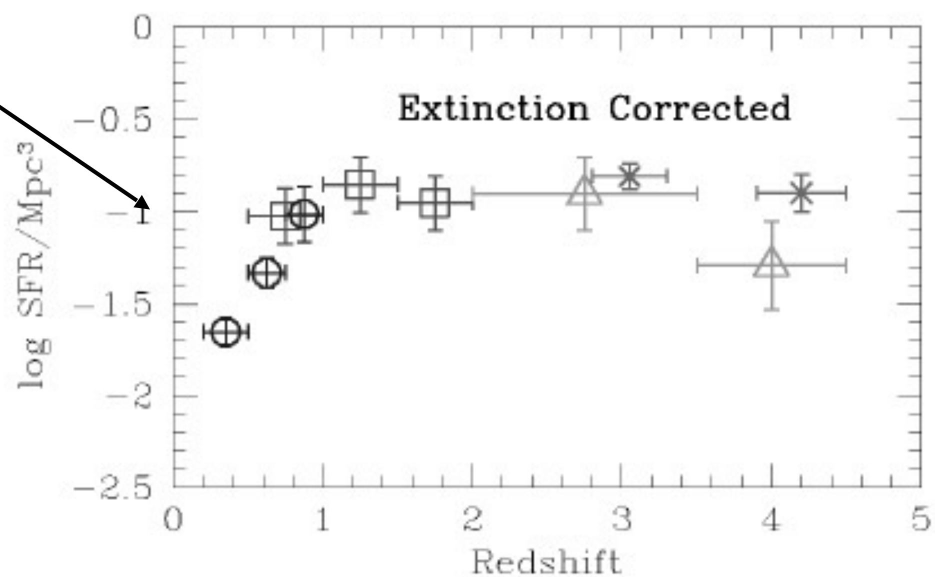
The CFRS sample: evolution of field galaxies to z~1

- The Canada France Redshift Survey (CFRS) sample of field galaxies is complete up to z~1 for galaxies with $M_b < -20.4$ and stellar masses in the range 3 - 30x10^{10} M_{sun} (i.e. the intermediate galaxy mass range).
- Most of the information we have about faint field galaxies at z < 1 is derived from the CFRS sample.
- Initially, the redshifts for the full sample were determined using multi-slit spectroscopy on the Canada France Hawaii telescope (CFHT).
- A sub-sample of 185 CFRS galaxies with z > 0.4 has been observed with deep HST (imaging), VLT (spectroscopy), ISO (mid-IR photometry) observations (Hammer et al. 2005).

Madau diagram revisited

The lower redshift (z < 1) section of the Madau diagram has been derived from the CFRS sample, using [OII] emission line luminosities to determine star formation rates.





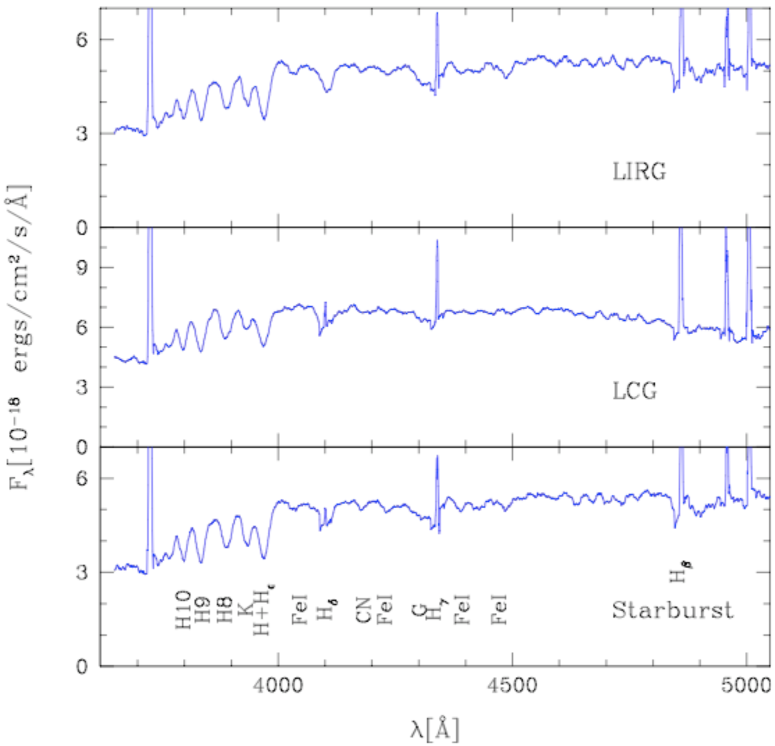
Mixture of galaxy types in the z > 0.4 CFRS sample

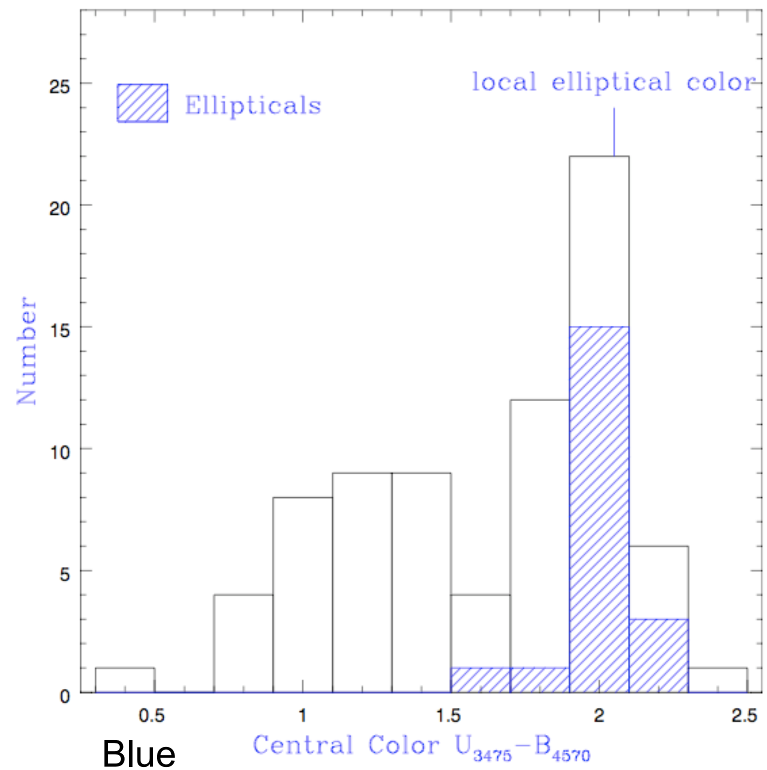
Type	$z > 0.4$ LIRGs	$z > 0.4$ non-LIRGs	$z > 0.4$ galaxies	local galaxies
E/S0	0%	27%	23%	27%
Spiral	36%	45%	43%	70%
LCG	25%	17%	19%	<2%
Irregular	22%	7%	9%	3%
Major merger	17%	4%	6%	<2%

Irr/Pec/Mrg (in other schemes)

- Luminous compact galaxies (LCG) are absent (or extremely rare) in the local Universe; they are classified as Irr/Pec/Mrg in other classification schemes for high-z galaxies.
- 15% of the sample are LIRGs ($L_{ir} > 10^{11}$ L_{sun}) compared with only 0.5% of galaxies of similar mass in the local Universe, and 70% of the sample show evidence for some starburst activity, compared with only ~17% locally.
- The proportion of galaxies with LCG, Irregular or Major Merger morpholgies is much higher at z > 0.4 than it is locally, particularly amongst the z > 0.4 LIRGs.

Spectra and colours for the z > 0.4 CFRS sample





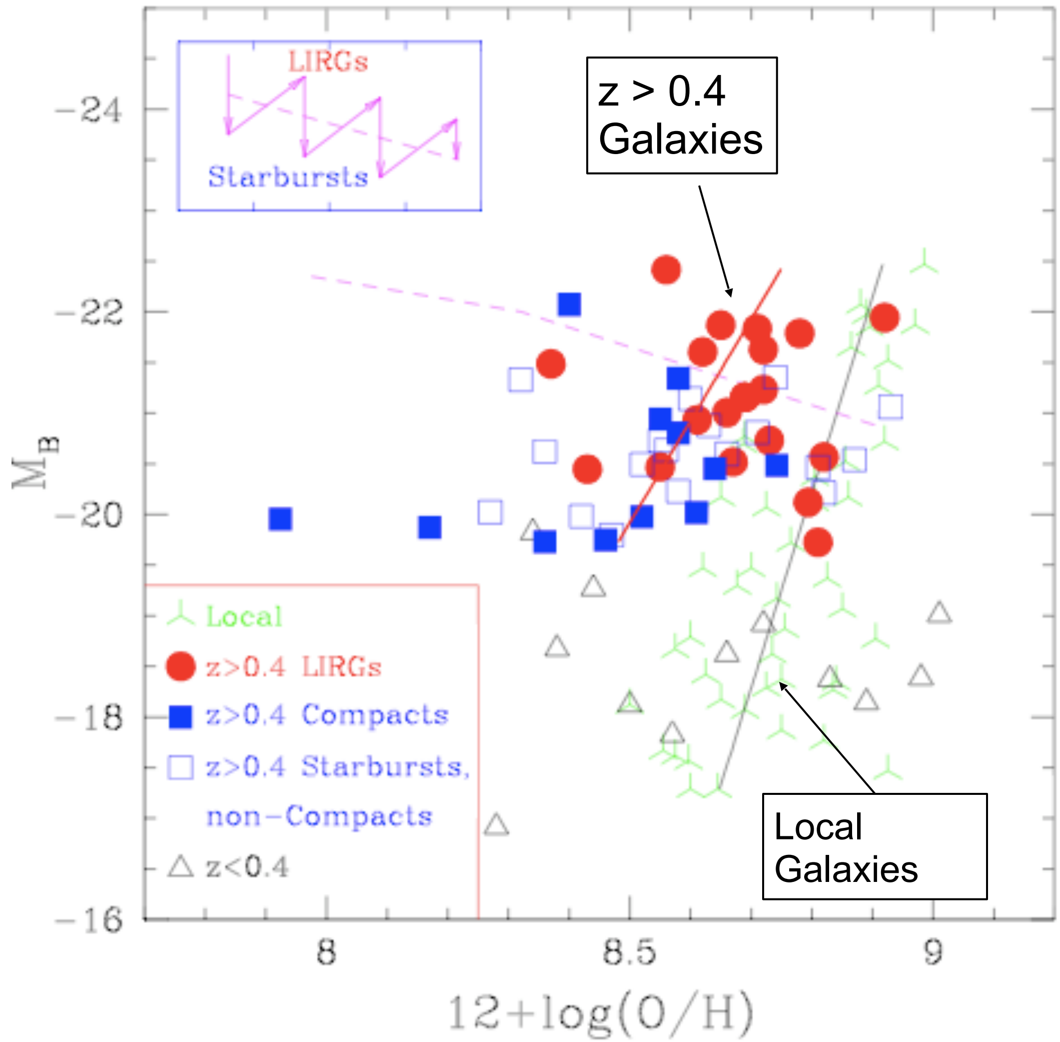
Regardless of their morphological classification, the star forming z > 0.4 galaxies have similar spectra, with strong Balmer absorption lines typical of intermediate-age (0.1 - 1 Gyr) post-starburst stellar populations.

Most z > 0.4 galaxies (apart from the E/S0 type) have nuclei that are significantly bluer that the bulges of Spiral galaxies in the local Universe, which tend to have red colours typical of E galaxies [(U-B)~2].

Gas abundances in the z>0.4 CFRS sample

The z > 0.4 galaxies have gas metal abundances that are on average a factor x2 lower than those of local spiral galaxies of similar luminosity.

This suggests that the stellar masses (and gas metallicity) of the galaxies must have doubled in the last 5 Gyr as a result of ongoing star formation activity.



Gas metallicity

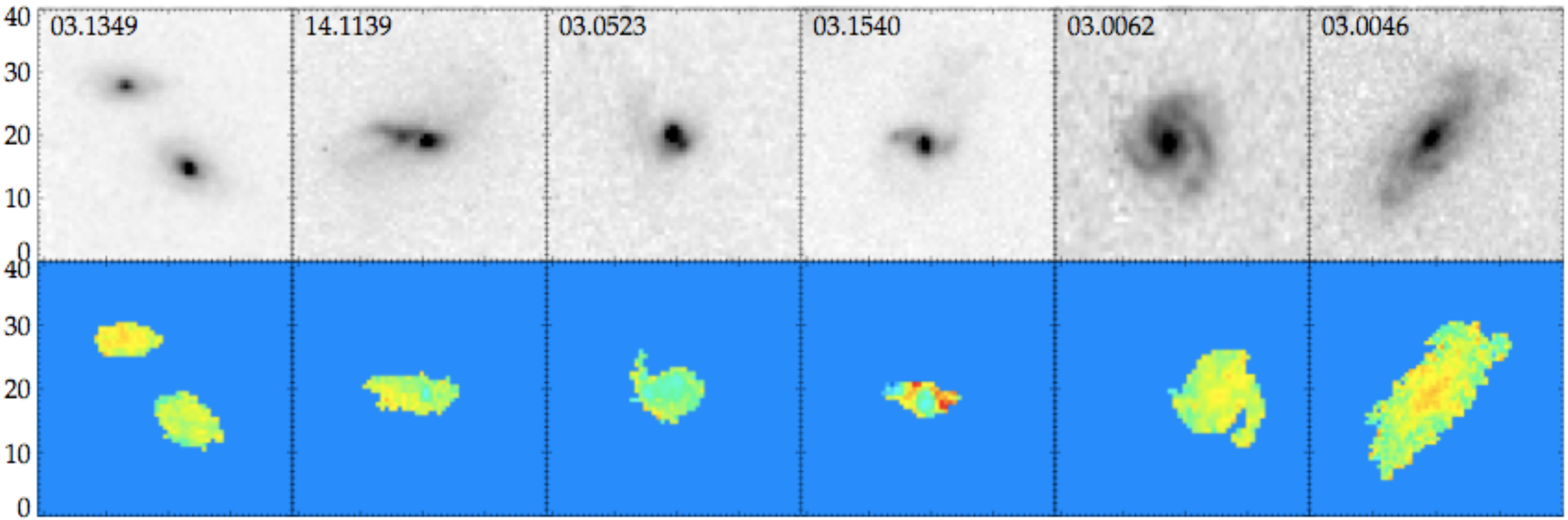
(from emission line ratios)

Summary of 0.4 < z < 1 CFRS galaxy properties

- LCG, Irr and Mrg morphological types are far more common at $z > 0.4$.
- A much larger fraction of $z > 0.4$ galaxies show evidence for current or recent star formation activity in the form of strong [OII] emission lines, post-starburst optical spectra and/or LIRG activity in the far-IR.
- The nuclei of most $z > 0.4$ galaxies are significantly bluer than local spiral galaxy bulges.
- The gas metal abundances are a factor x2 lower at $z > 0.4$.

➔ Together these results suggest that the moderate mass ($3 - 30 \times 10^{10}$ M_{sun}) field galaxy population has shown considerable evolution since $z \sim 1$, with the galaxies approximately doubling their stellar masses over this ~5 - 7 Gyr period.

Possible evolutionary scenario for spiral galaxies



Mergers/interacting phase:
During the last 8 Gyrs, most luminous galaxies are expected to have experienced a major merger. During a major collision with a companion with mass above 1/4 of the main galaxy mass, the disk is naturally suppressed as matter is falling to the mass barycenter, producing a compact morphology. Associated with short (0.1 Gyr) and strong peaks of star formation (most of them are LIRGs)

Compact galaxy phase:
Merger remnants linked to the formation of a significant fraction of stars in bulges : they show very blue central colours. Correspond to a decrease over 0.6-2 Gyr of the enhanced star formation due to the merging. Additional occurrence of gas infall may subsequently wrap around the bulge to form a new disk-like component as seen in many LCGs.

Growth of disk phase:
The star formation spreads over the entire forming disk as fed by large amounts of gas infall (from internal reservoir or accreted from the vicinity). Some of them show irregularities, which is interpreted to be related to minor merger events. Most distant spirals show a core much bluer indicating a recent and active star formation.

LIRG → LCG → Spiral

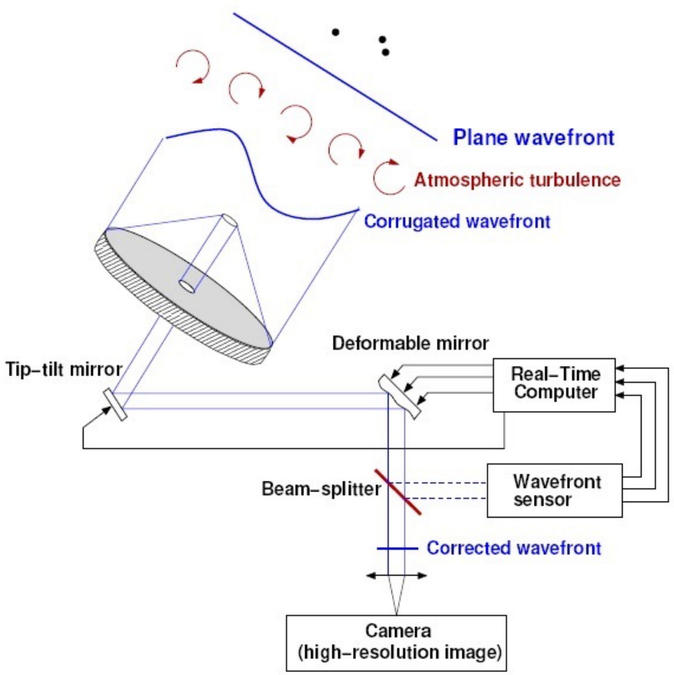
Summary of galaxy evolution up to z~1

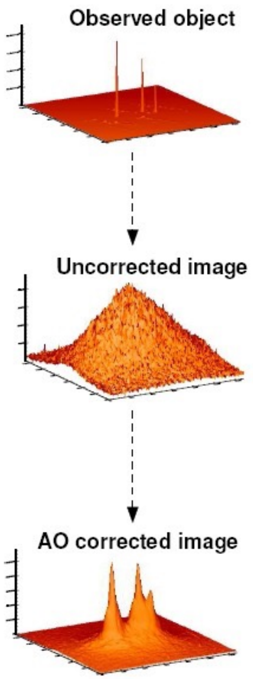
For intermediate-mass galaxies:

- In contrast to the most massive early-type galaxies, galaxies of intermediate mass have shown considerable evolution since z~1.
- This is reflected in the evidence for: morphological evolution (less grand design spirals, more LCG/Irr/Mrg types at $z > 0.4$); increased star formation activity (bluer galaxy cores, more LIRGs, more [OII] emission); 2x lower abundances at $z > 0.4$.
- Spiral galaxies have actively formed via galaxy mergers and gas accretion over the redshift range $0.4 < z < 1$ (e.g. LIRG➔LCG➔Spiral), but some of the more massive spirals may have formed at higher redshifts ($z > 2$).
- It is estimated that ~75% of intermediate mass spiral galaxies have experienced a merger since z~1 (last 7 Gyr).

Adaptive Optics on the ESO VLT Telescopes

VLT, Paranal, Chile

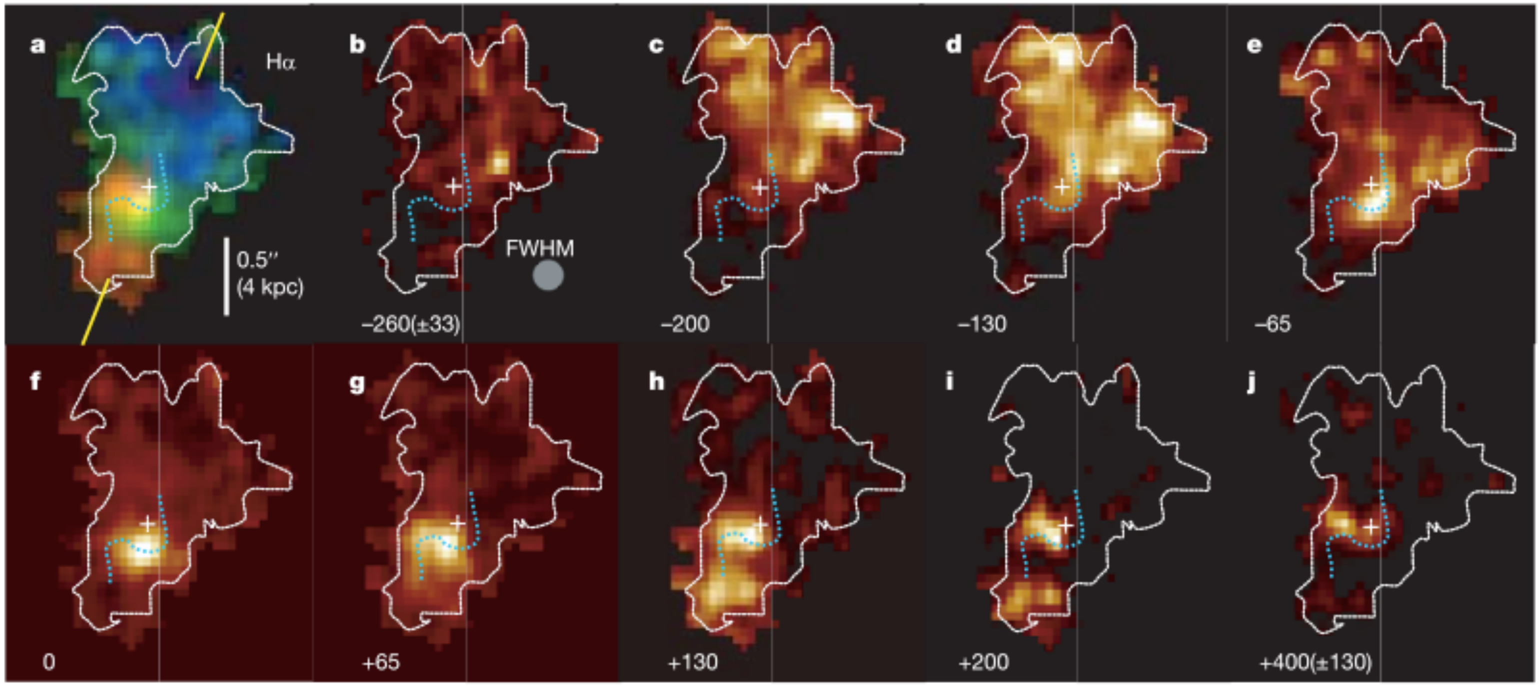




The adaptive optics system on the ESO VLT 8m telescopes can be used to achieve a marked improvement in spatial resolution for spectroscopic observations at IR wavelengths of distant galaxies (spatial resolution better than 0.15 arcseconds).

A forming disk in a galaxy at z=2.38? - I

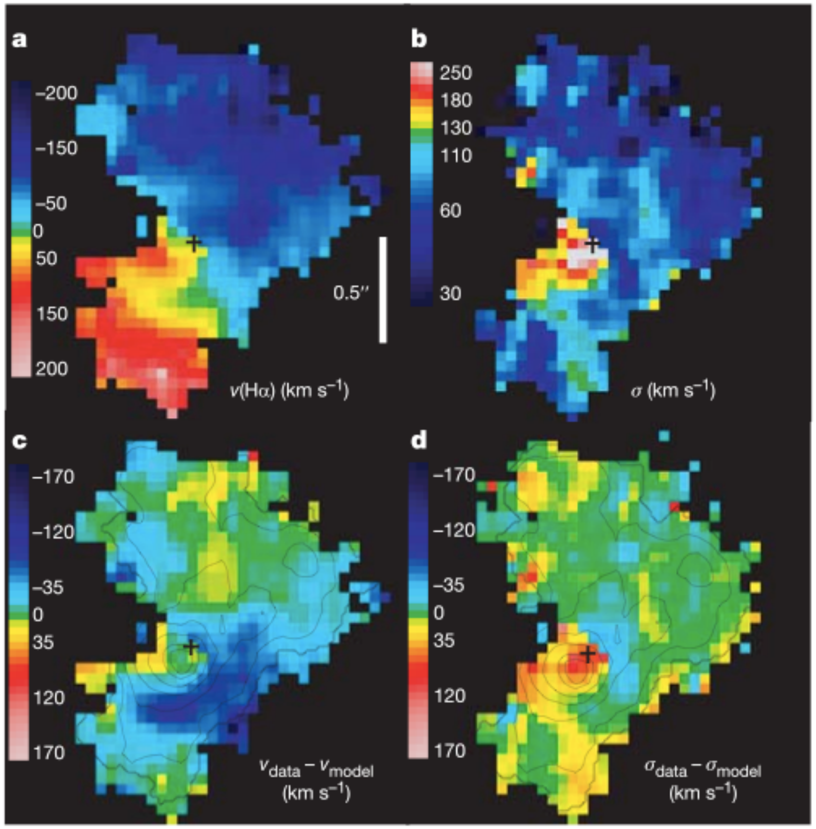
VLT images of the z=2.38 gas structure at different velocity slices

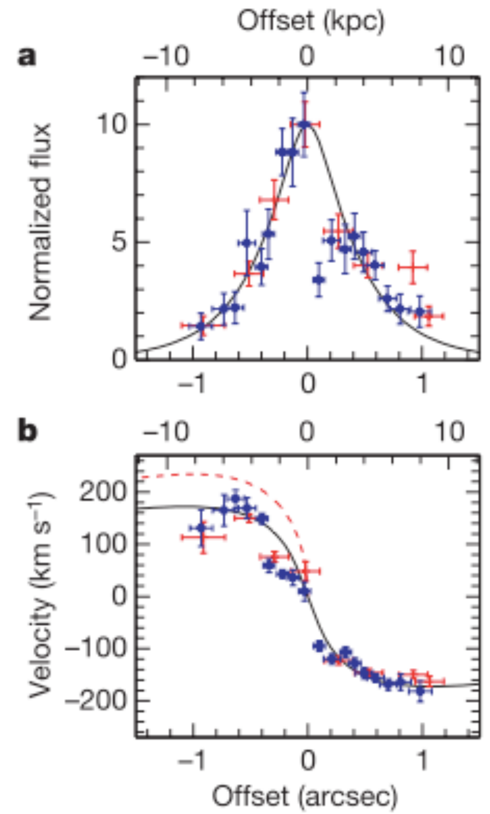


Near-IR spectroscopic observations with the VLT of the redshifted Hα line in the z=2.38 galaxy BzK-15504 show a gas structure with diameter ~13kpc. The structure is only 1.6 arcseconds across, and adaptive optics (resolution ~0.15 arcseconds) are required to reveal the full detail in the velocity structure.

A forming disk in a galaxy at z=2.38? - II

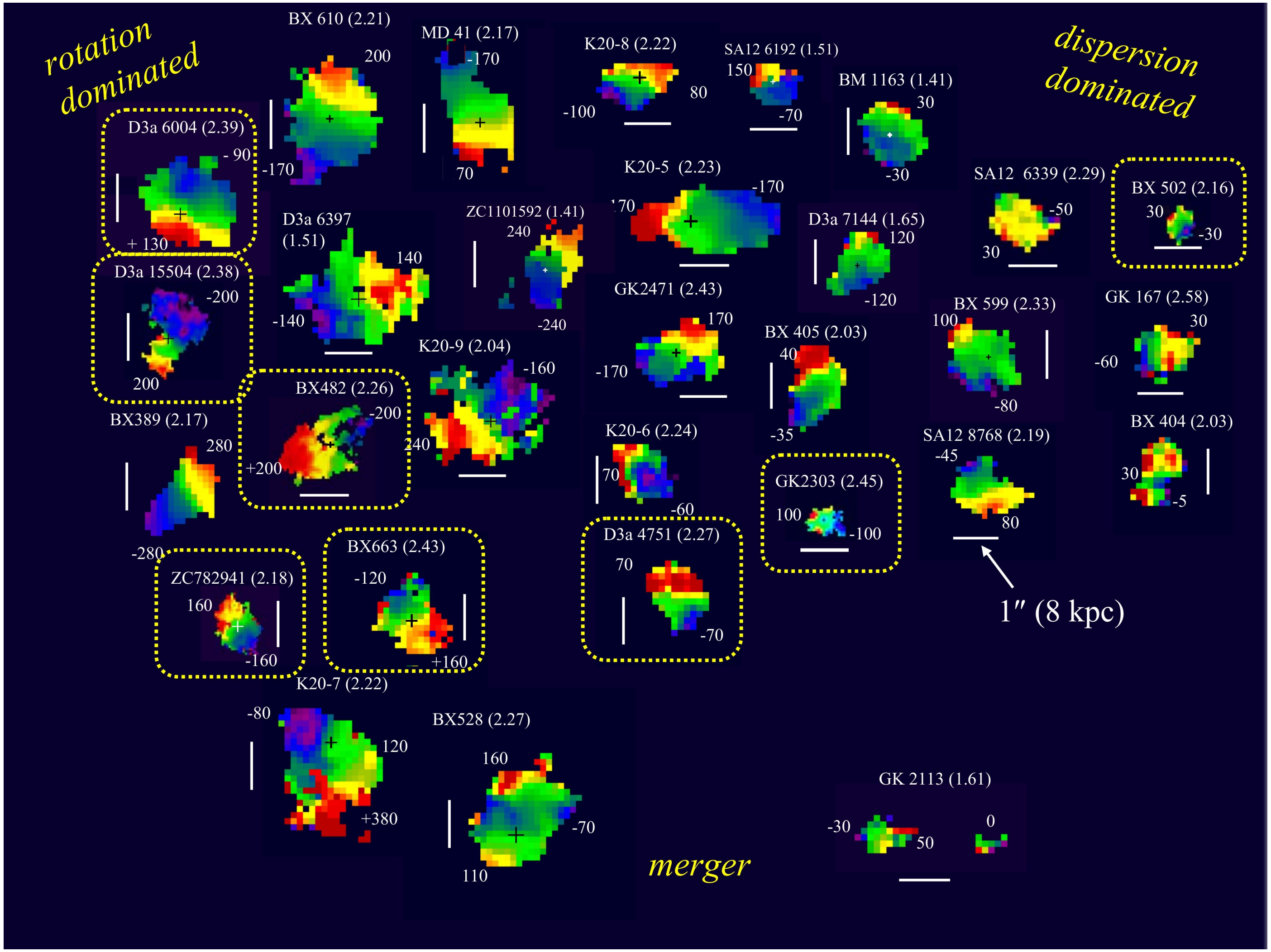
Velocity shift Velocity dispersion





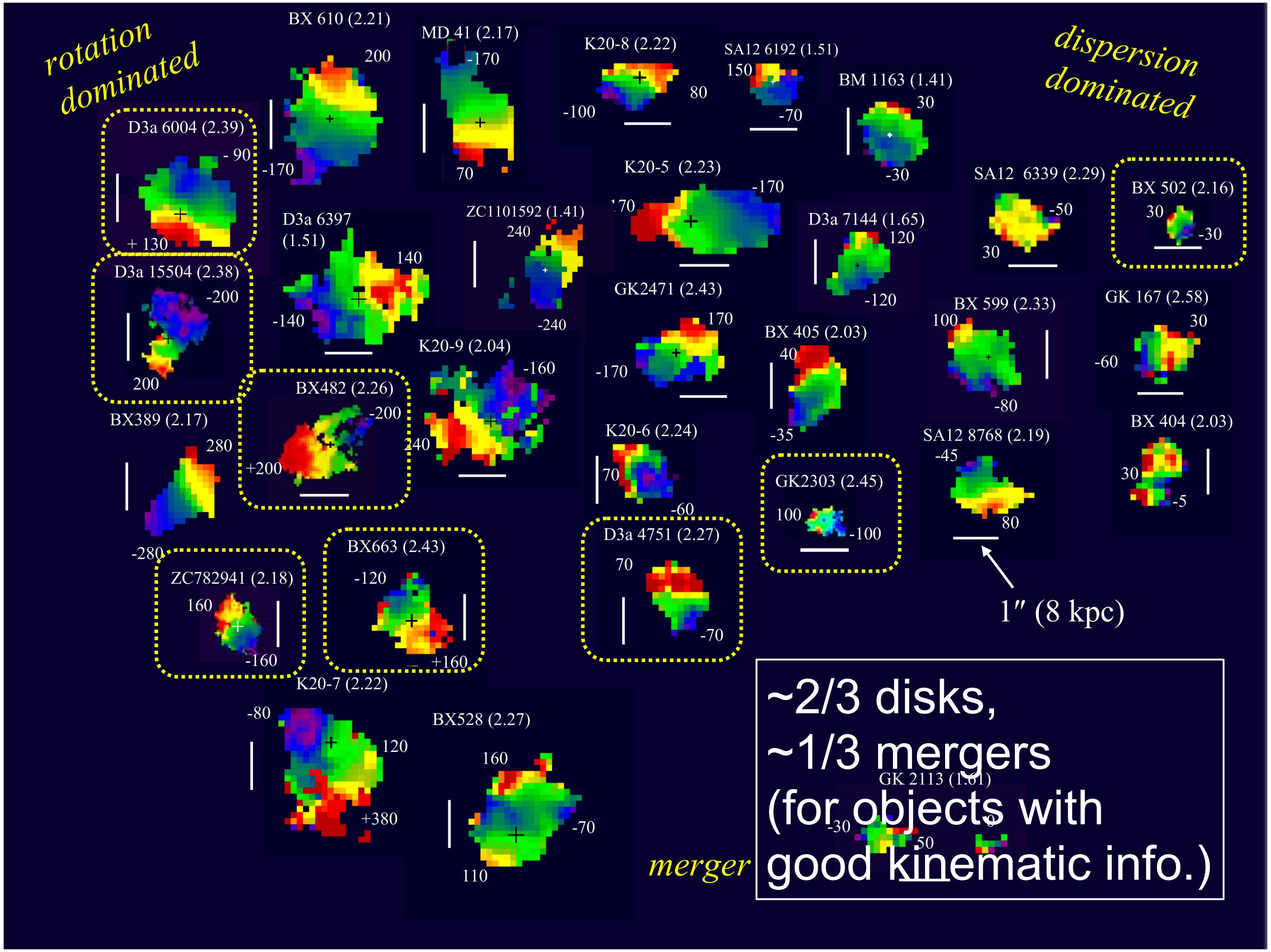
Because of the apparent rotation pattern, and lack of obvious signs of a merger it has been suggested that the structure represents a protodisk. The estimated dynamical mass is $(1.1\pm1)\times10^{11}$ M_{sun}, and the gas mass is $\sim4\times10^{10}$ M_{sun}. But the rotation curve is not perfect, and it may be possible to explain the velocity field in other ways (e.g. bi-polar outflows).

Kinematics of a larger sample of z~2 star forming galaxies



Forster Schreiber et al. (2009)

Kinematics of a larger sample of z~2 star forming galaxies



~2/3 disks,
~1/3 mergers
(for objects with
good kinematic info.)

Forster Schreiber et al. (2009)

Lecture 8: learning objectives

- Knowledge of the morphological evolution of galaxies up to z~1.5 from HST observations
- Knowledge of the variation in star formation rate, elemental abundances and colours of intermediate mass galaxies up to z~1, and their correlations with morphology
- Appreciation of the importance of correcting for dust extinction to derive accurate star formation rates
- Knowledge of possible examples of the spiral galaxy populations at z>1.5
- Understanding of scenarios proposed for the evolution of late type galaxies since z~1