# Galaxies, Cosmology and Dark Matter

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# Chapter 16

# Galaxy Evolution

## 16.1 Faint Galaxy Counts

The surface density of faint blue (and thus star-forming) galaxies increases faster with decreasing apparent magnitude than expected for constant galaxy density and luminosity.

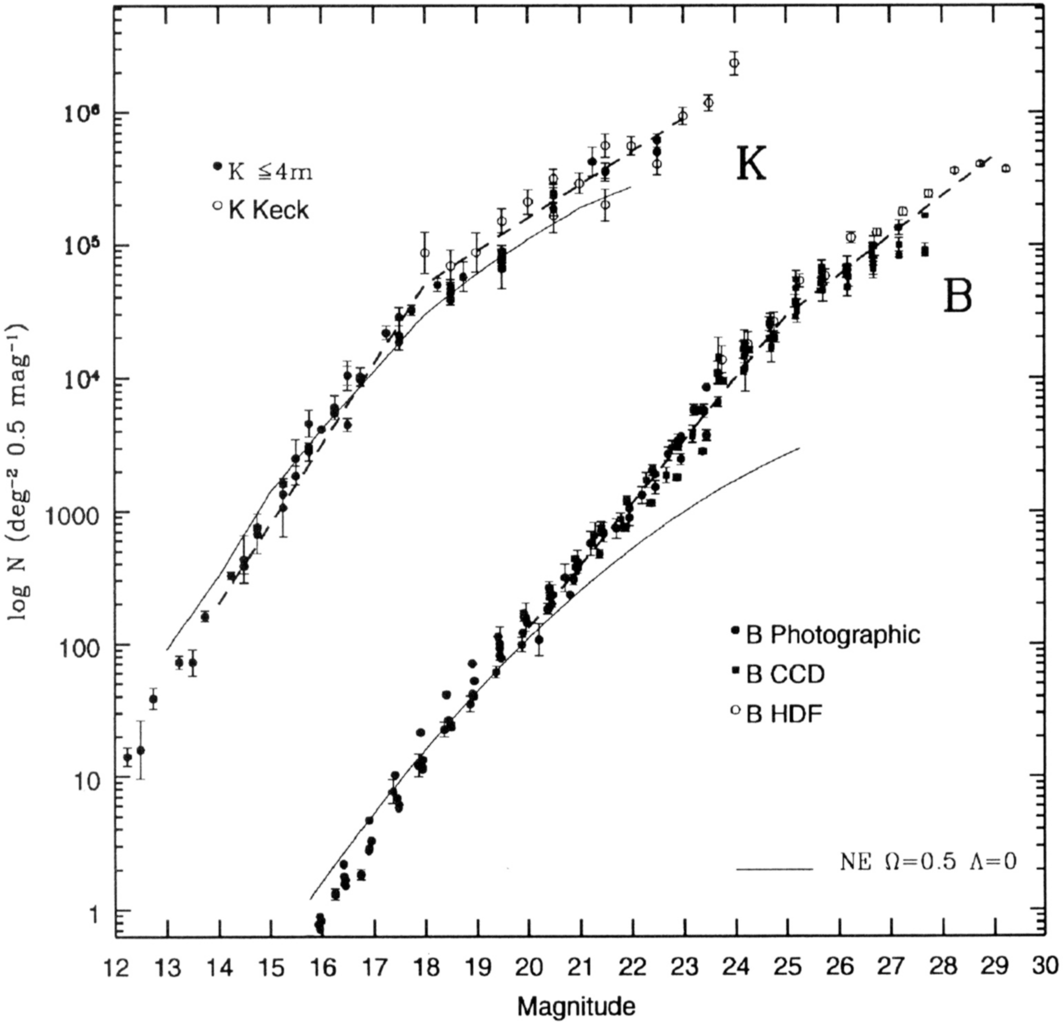
Possible explanations:

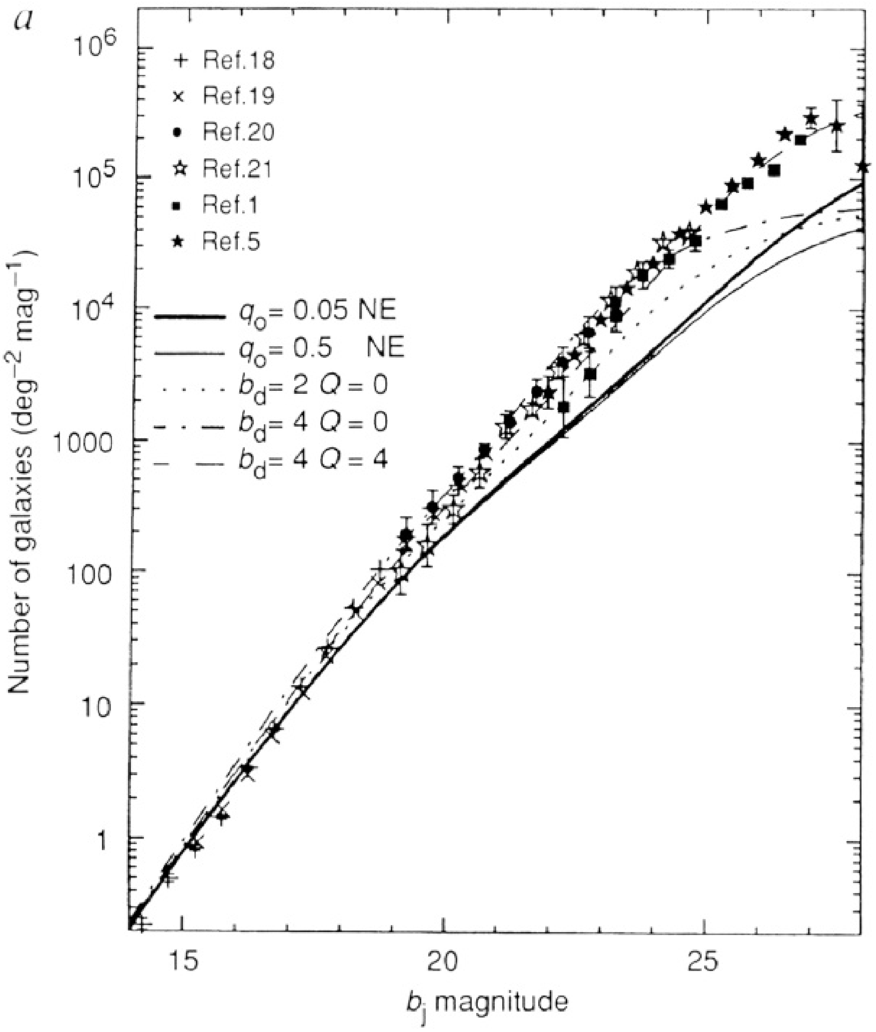
(a) The galaxy *luminosities* evolve with redshift $z$ (either passively, or because of a higher star-formation rate at earlier times).

(b) The *number density* of galaxies is higher at higher redshifts (for example due to later merging).

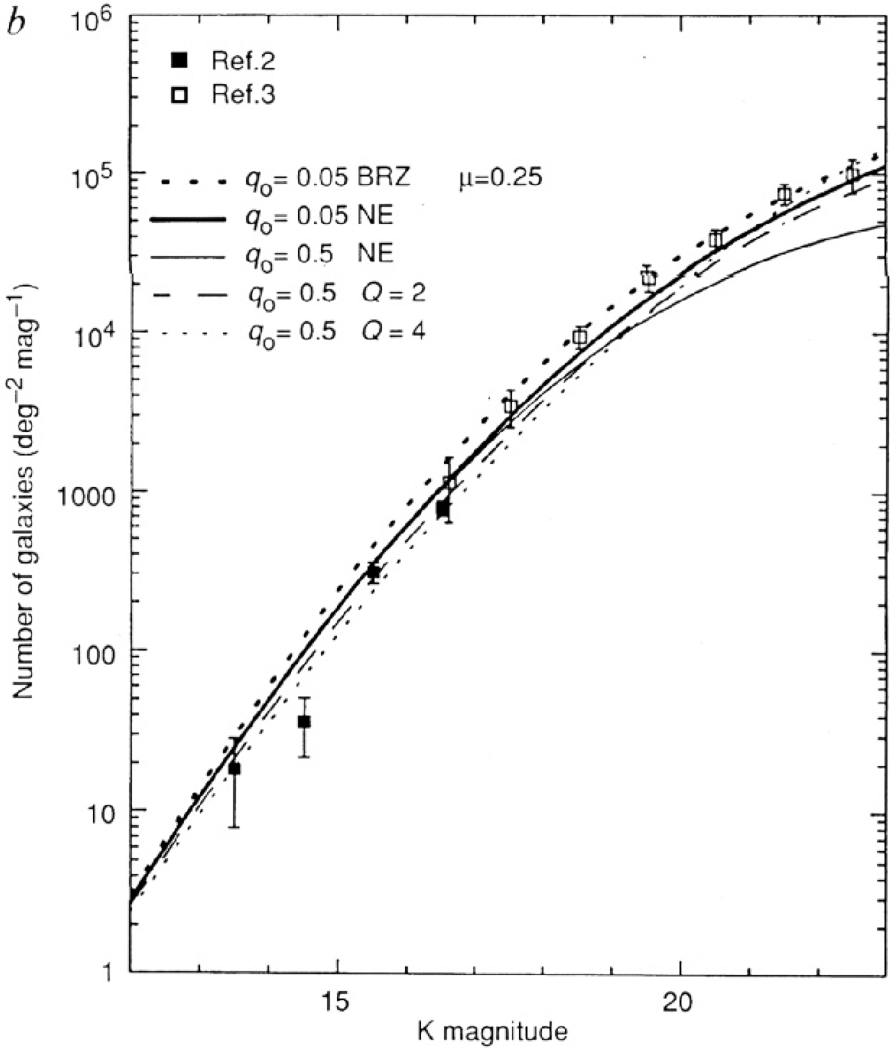
(c) The luminosity function for *local galaxies* is wrong, and the higher luminosities are not a real problem.

(Ellis, 1997, *ARAA*, **35**, 389)



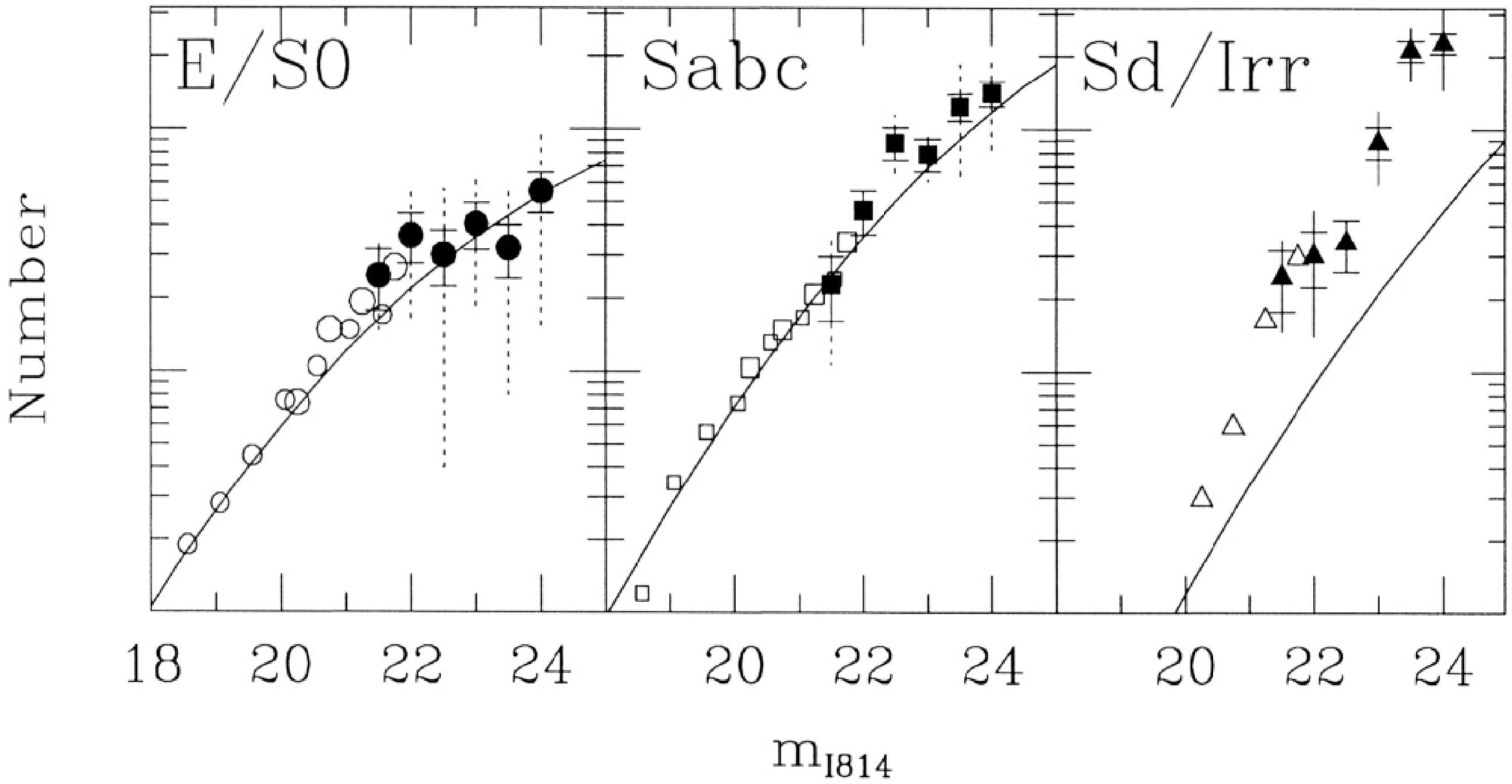


(Broadhurst *et al.*, 1992, *Nature*, **355**, 55)



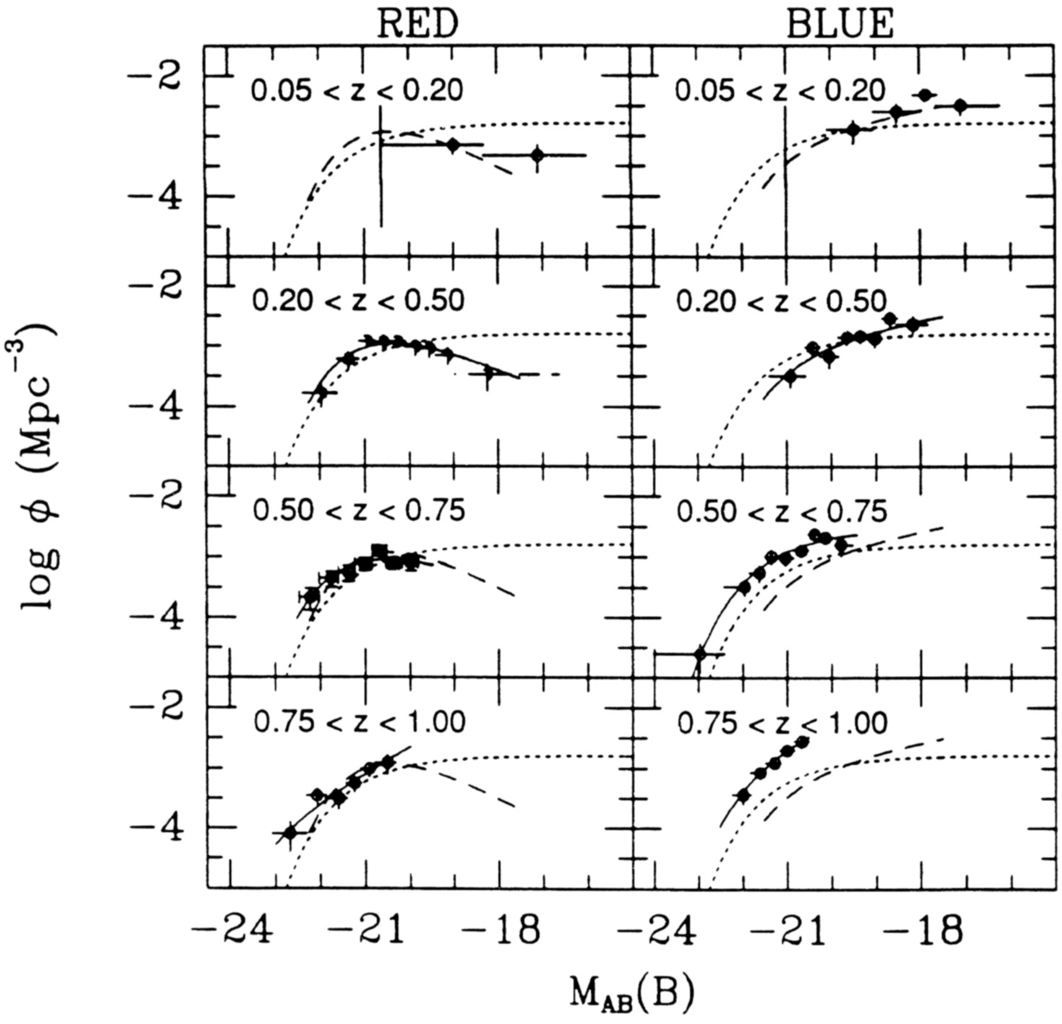
(Broadhurst *et al.*, 1992, *Nature*, **355**, 55)

*Hubble Space Telescope* observations show that the galaxy population *does* change with redshift, as does the luminosity function and the fraction of emission-line objects. Thus (c) alone does not solve the problem. Maybe a combination of (a), (b) and (c) is responsible for the faint blue galaxy problem.



(Driver *et al.*, 1996, in: IAU Symposium 171, ed. R. Bender, R.L. Davies, p. 221)

(Lilly *et al.*, 1996, in: IAU Symposium 171, ed. R. Bender, R.L. Davies, p. 209)



## An estimate of the number density of faint galaxies

Consider only one class of galaxies with given luminosity $L$. The flux $f$ reaching the observer in Euclidean space at distance $r$ is

$$f \;=\; \frac{L}{4\pi r^2}$$

The volume per sterad at distance $r$ is

$$V \;=\; \frac{\frac{4\pi}{3} r^3}{4\pi} \;=\; \frac{r^3}{3}$$

If we assume the mean density $n$ of galaxies to be constant, then the number $N\,(> f)$ of galaxies observable at a given limiting flux $f$ is given by

$$N\,(> f) \;=\; n\,V \;=\; \frac{n}{3}\left(\frac{L}{4\pi\, f}\right)^{3/2}$$

Translating this into magnitudes using $m \propto -2.5 \log f$ yields

$$N\,(< m) \;\propto\; n\,L^{3/2}\,10^{0.6\,m}$$

and thus

$$\boxed{\log N\,(< m) \;=\; 0.6\,m \;+\; \log n \;+\; \frac{3}{2}\,\log L \;+\; \text{const.}}$$

For a population of galaxies with different luminosities $L_i$ we have to form the sum

$$N\,(> f) \;=\; \sum_i \frac{n_i}{3}\left(\frac{L_i}{4\pi\,f}\right)^{3/2} \;\propto\; f^{-3/2}$$

similar to the result derived above.

Note that these considerations are only valid for local galaxies. For very faint galaxies, the cosmic expansion and effects of galaxy evolution have to be included.

## 16.2 Butcher–Oemler Effect

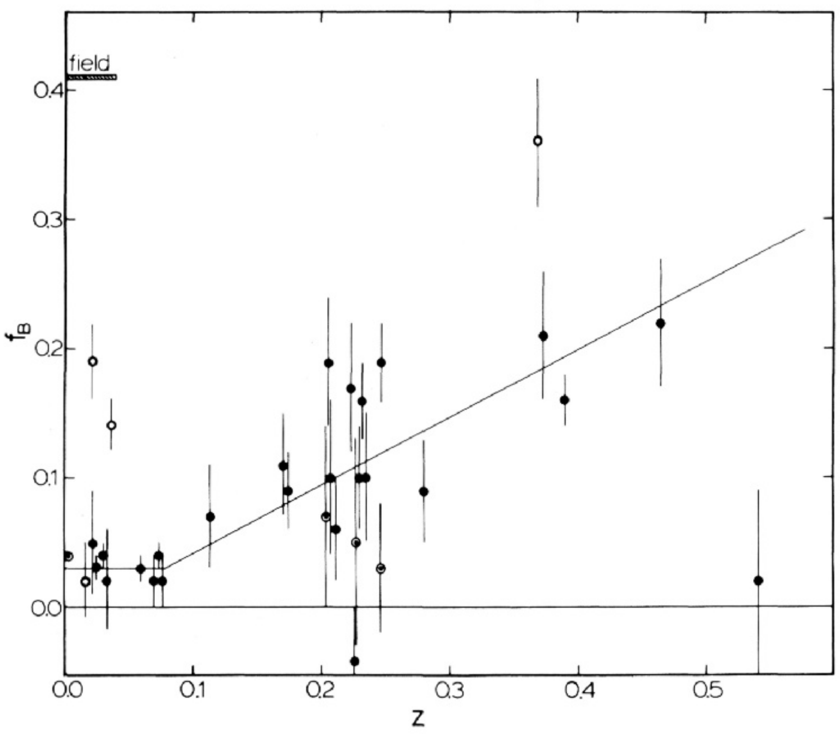
This effect describes the growing fraction of blue galaxies in clusters with increasing redshift $z$. This means that cluster galaxies had a higher star-formation rate at earlier times.

The Butcher–Oemler effect is difficult to measure, because without complete redshift measurements foreground spirals in the field can be incorrectly assigned to the cluster.

Nevertheless, the effect certainly is real, only its strength is still uncertain.

Explanation:

The fraction of spiral galaxies in clusters reduces with time due to high-speed encounters (‘galaxy harassment’) and mergers.



(Butcher & Oemler, 1984, *ApJ*, **285**, 426)

## 16.3 Lyman–$\alpha$ forest

High-redshift quasars show a large number of absorption lines on the blue side of their Ly-$\alpha$ line.

This shows that neutral HI gas is not uniformly distributed, but concentrated in small clouds out to redshifts of $z \simeq 5$.

- The number of Ly-$\alpha$ clouds strongly increases with redshift:

$$\boxed{\frac{dN_\alpha}{dz} = a\left(1+z\right)^{2.3\pm0.4}}$$

- The distribution of equivalent widths of the absorption lines is very broad, and corresponds to HI column densities of

$$\boxed{10^{13}\,\mathrm{cm}^{-2} \;\leq\; N_{HI} \;\leq\; 10^{22}\,\mathrm{cm}^{-2}}$$

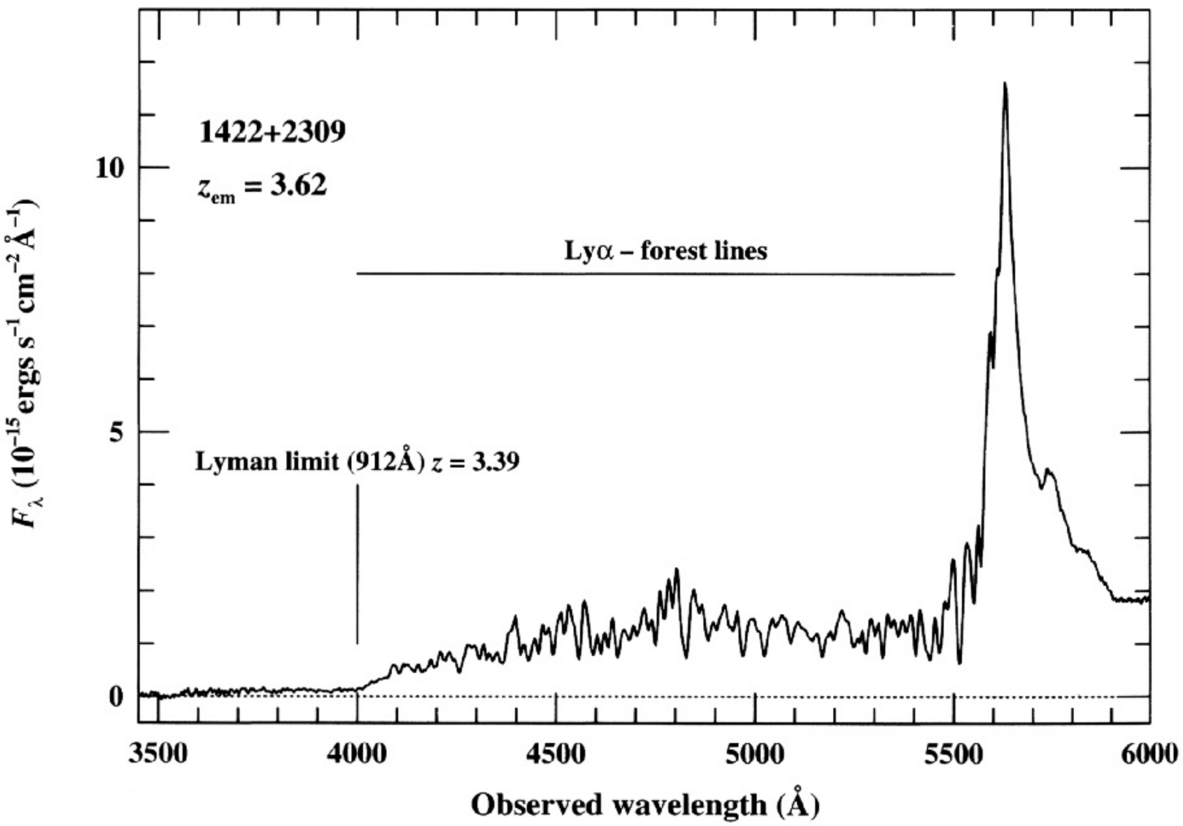
Whereas systems with small columns density show Lyman absorption only, metal absorption lines can be found in high-density clouds. A sub-class of these systems are the **damped Ly-$\alpha$ systems**, which are probably spiral galaxies at high redshift. The distribution of HI column densities is described by

$$\boxed{\frac{dN}{dN_{HI}} \propto N_{HI}^{-1.7}}$$

- The size of Ly-$\alpha$ clouds can be derived from observations of quasars with small angular separation or double quasars (gravitational lensing!):

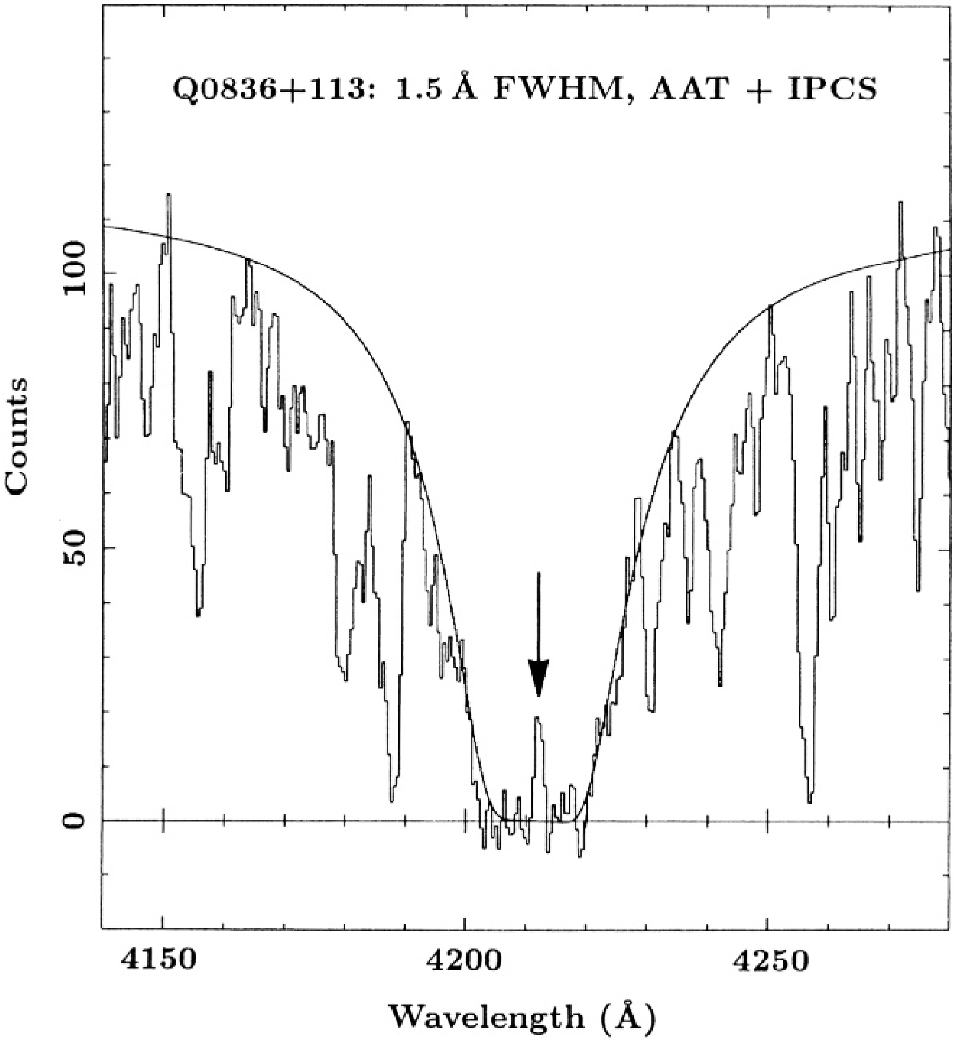
$$\boxed{5\,\mathrm{kpc} < R < 25\,\mathrm{kpc}}$$

- It is still unclear what happens to the Ly-$\alpha$ clouds. They might form dwarf galaxies, or evaporate, or merge to form larger objects.

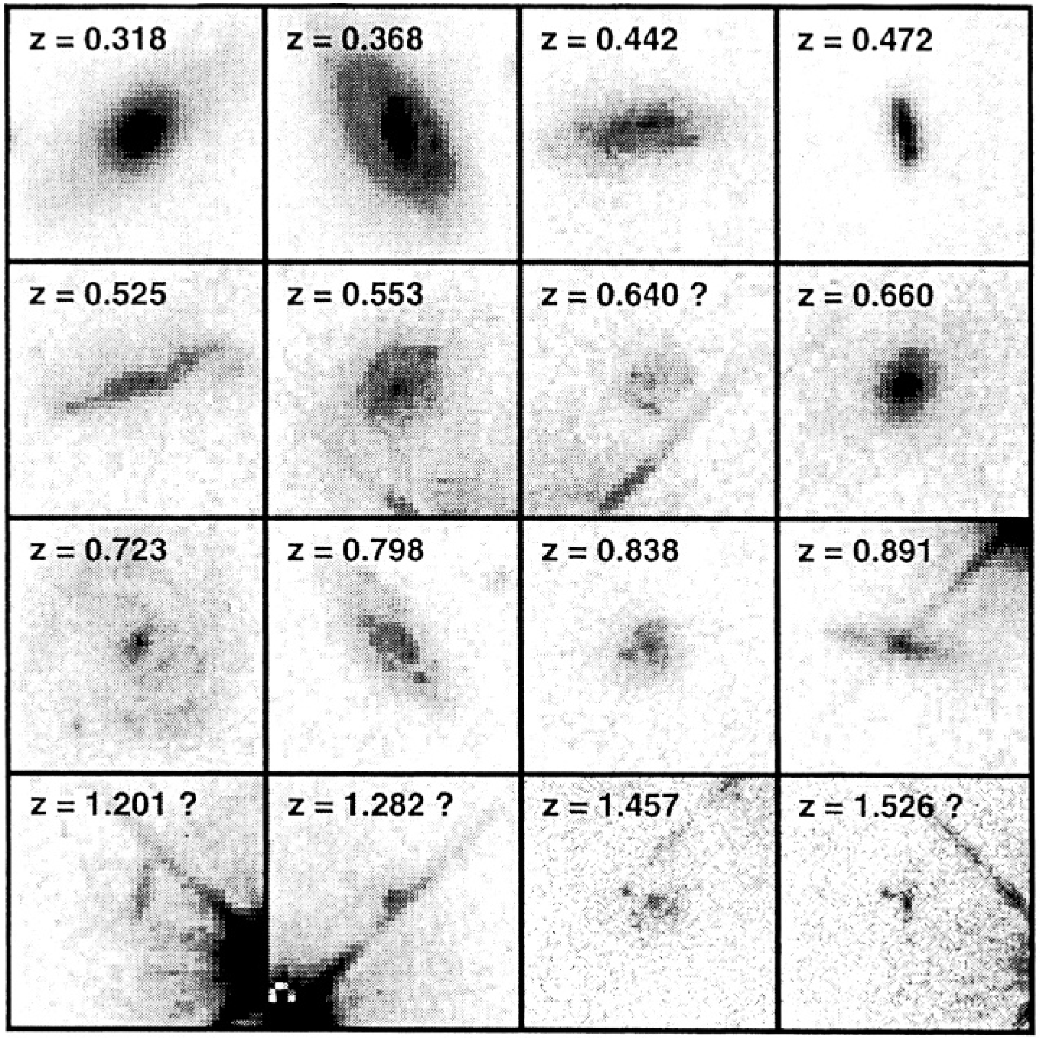


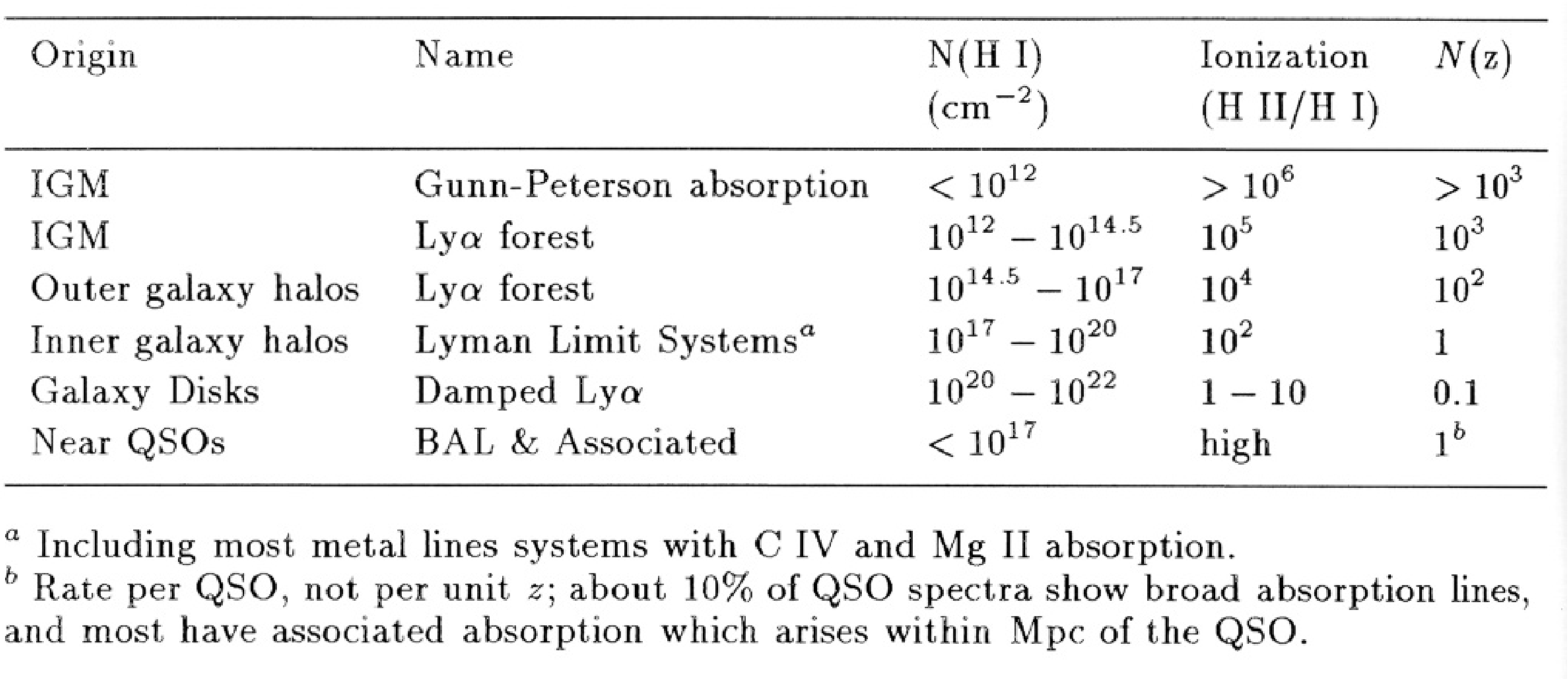
(Peterson: *Active Galactic Nuclei*, Cambridge 1997)

Damped Ly-$\alpha$ system (Hunstead & Pettini, 1989; in: *The Epoch of Galaxy Formation*, eds. C. Frenk *et al.*, Kluwer)



Damped Ly-$\alpha$ absorbers at high redshift
(Dickinson & Steidel, 1996, in: IAU Symposium 171, ed. R. Bender, R.L. Davies)





| Origin | Name | N(H I) ($\mathrm{cm}^{-2}$) | Ionization (H II/H I) | $N(z)$ |
|---|---|---|---|---|
| IGM | Gunn-Peterson absorption | $< 10^{12}$ | $> 10^{6}$ | $> 10^{3}$ |
| IGM | Ly$\alpha$ forest | $10^{12} - 10^{14.5}$ | $10^{5}$ | $10^{3}$ |
| Outer galaxy halos | Ly$\alpha$ forest | $10^{14.5} - 10^{17}$ | $10^{4}$ | $10^{2}$ |
| Inner galaxy halos | Lyman Limit Systems[a] | $10^{17} - 10^{20}$ | $10^{2}$ | 1 |
| Galaxy Disks | Damped Ly$\alpha$ | $10^{20} - 10^{22}$ | $1 - 10$ | 0.1 |
| Near QSOs | BAL & Associated | $< 10^{17}$ | high | 1[b] |

[a] Including most metal lines systems with C IV and Mg II absorption.

[b] Rate per QSO, not per unit $z$; about 10% of QSO spectra show broad absorption lines, and most have associated absorption which arises within Mpc of the QSO.

(Tytler, 1996, in: IAU Symposium 171, ed. R. Bender, R.L. Davies)

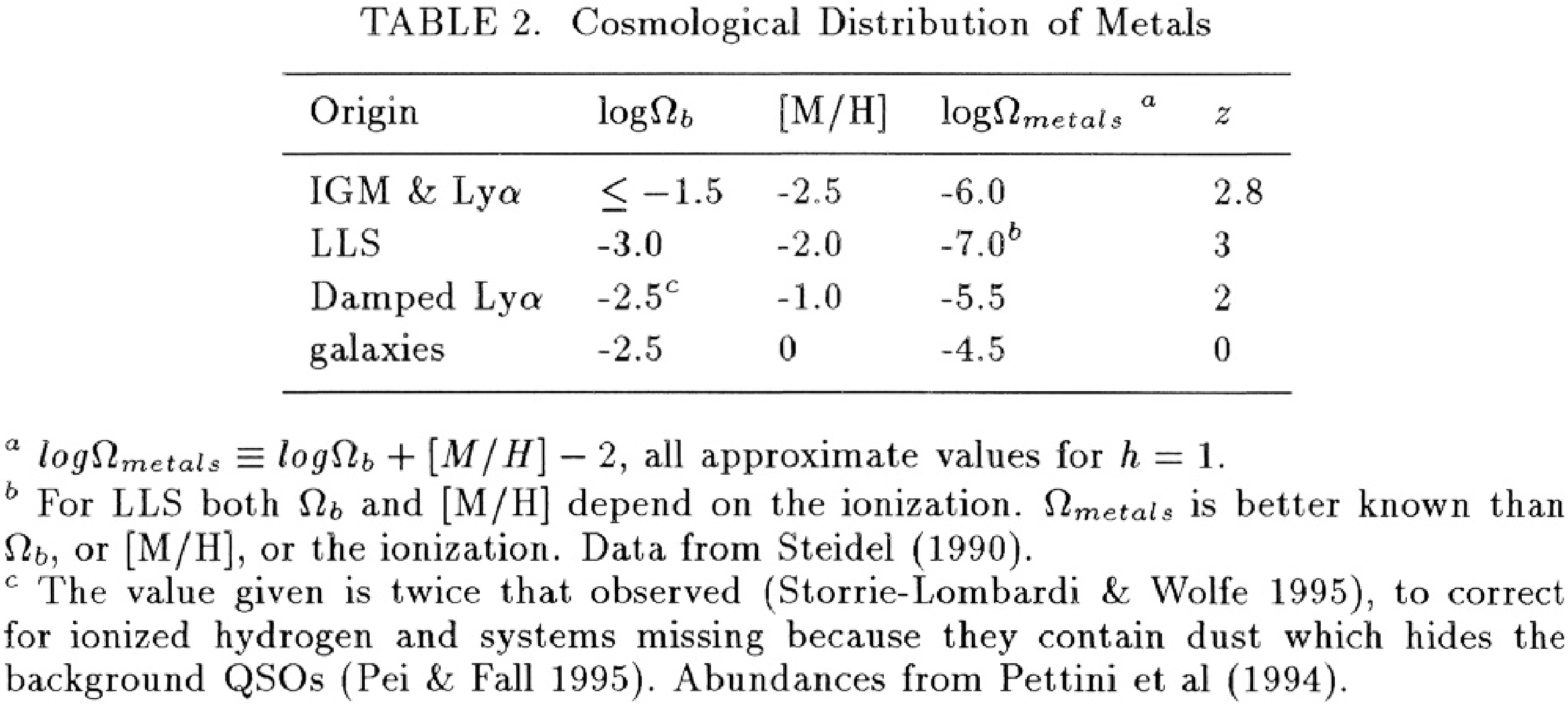


TABLE 2. Cosmological Distribution of Metals

| Origin | $\log\Omega_b$ | [M/H] | $\log\Omega_{metals}$ [a] | $z$ |
|---|---|---|---|---|
| IGM & Ly$\alpha$ | $\leq -1.5$ | -2.5 | -6.0 | 2.8 |
| LLS | -3.0 | -2.0 | -7.0[b] | 3 |
| Damped Ly$\alpha$ | -2.5[c] | -1.0 | -5.5 | 2 |
| galaxies | -2.5 | 0 | -4.5 | 0 |

[a] $log\Omega_{metals} \equiv log\Omega_b + [M/H] - 2$, all approximate values for $h = 1$.

[b] For LLS both $\Omega_b$ and [M/H] depend on the ionization. $\Omega_{metals}$ is better known than $\Omega_b$, or [M/H], or the ionization. Data from Steidel (1990).

[c] The value given is twice that observed (Storrie-Lombardi & Wolfe 1995), to correct for ionized hydrogen and systems missing because they contain dust which hides the background QSOs (Pei & Fall 1995). Abundances from Pettini et al (1994).

(Tytler, 1996, in: IAU Symposium 171, ed. R. Bender, R.L. Davies)

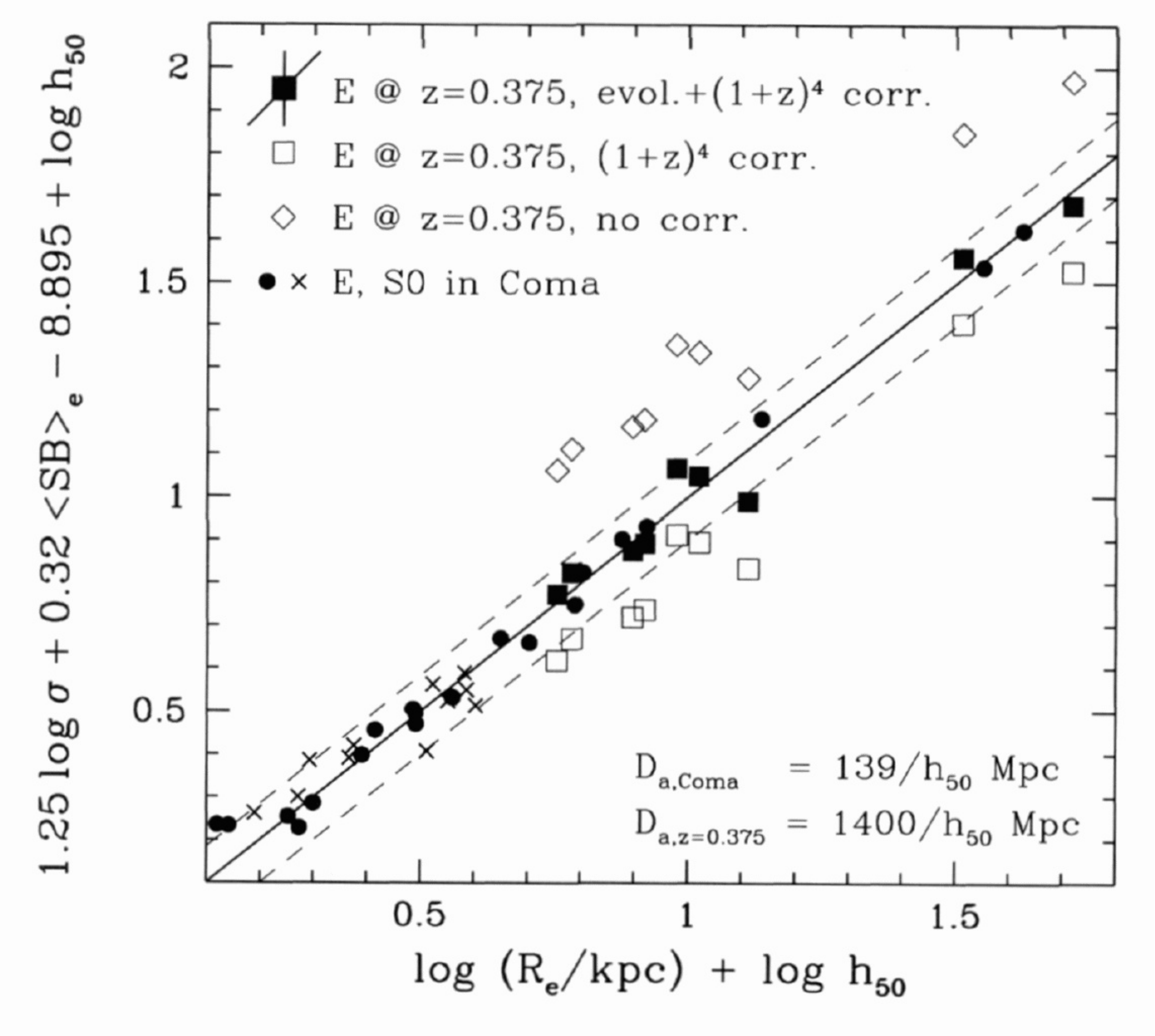
## 16.4 The Evolution of Elliptical Galaxies

- Elliptical galaxies have on average old stellar populations. They are probably the oldest galaxies in the universe. The redshift evolution of massive ellipticals is a sensitive test of cosmological models.
- If it is possible to calibrate the luminosity evolution, elliptical galaxies can be used as standard candles, e.g. to determine $q_0$.

First investigations show that the redshift evolution of absorption line strength and luminosity of elliptical galaxies is weak, which implies a high formation redshift for these objects.

The evolution of spiral galaxies is more difficult to understand, since increasing star-formation activity and decreasing mass may compensate. Thus the Tully–Fisher relation does not change dramatically with redshift.

A comparison of physical effective radii of elliptical galaxies in the $z = 0.375$ galaxy cluster Abell 370 and the local Coma cluster. The required distance to match the distant objects to the local ones constrains the geometry of the universe.
Bender *et al.* 1998,
*ApJ*, **493**, 529



# 16.5 The Evolution of Spiral Galaxies

Tully–Fisher relation for spirals

(Vogt *et al.*, 1997, *ApJ*, **479**, L121)

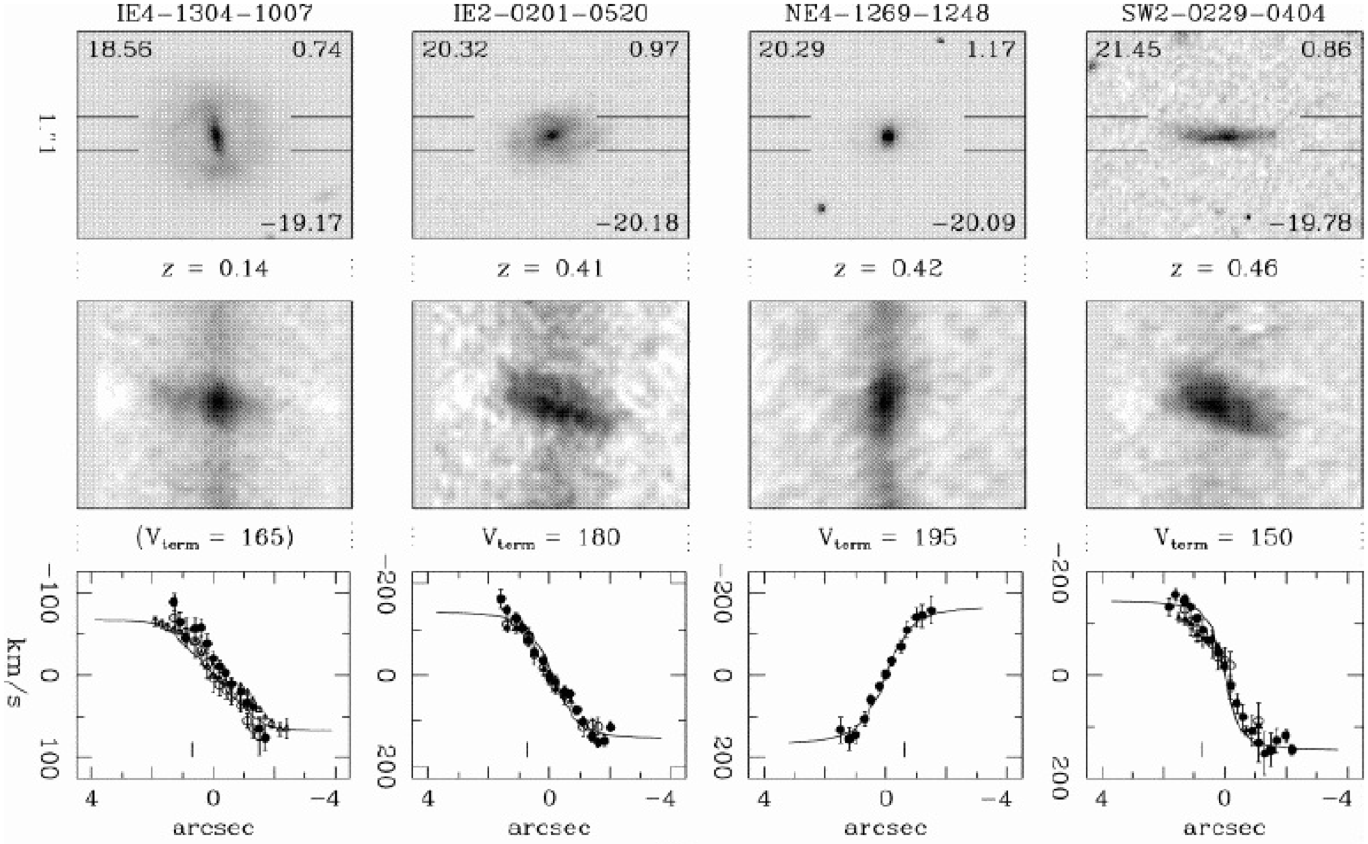


FIG. 1a

Tully–Fisher relation for spirals

(Vogt *et al.*, 1997, *ApJ*, **479**, L121)

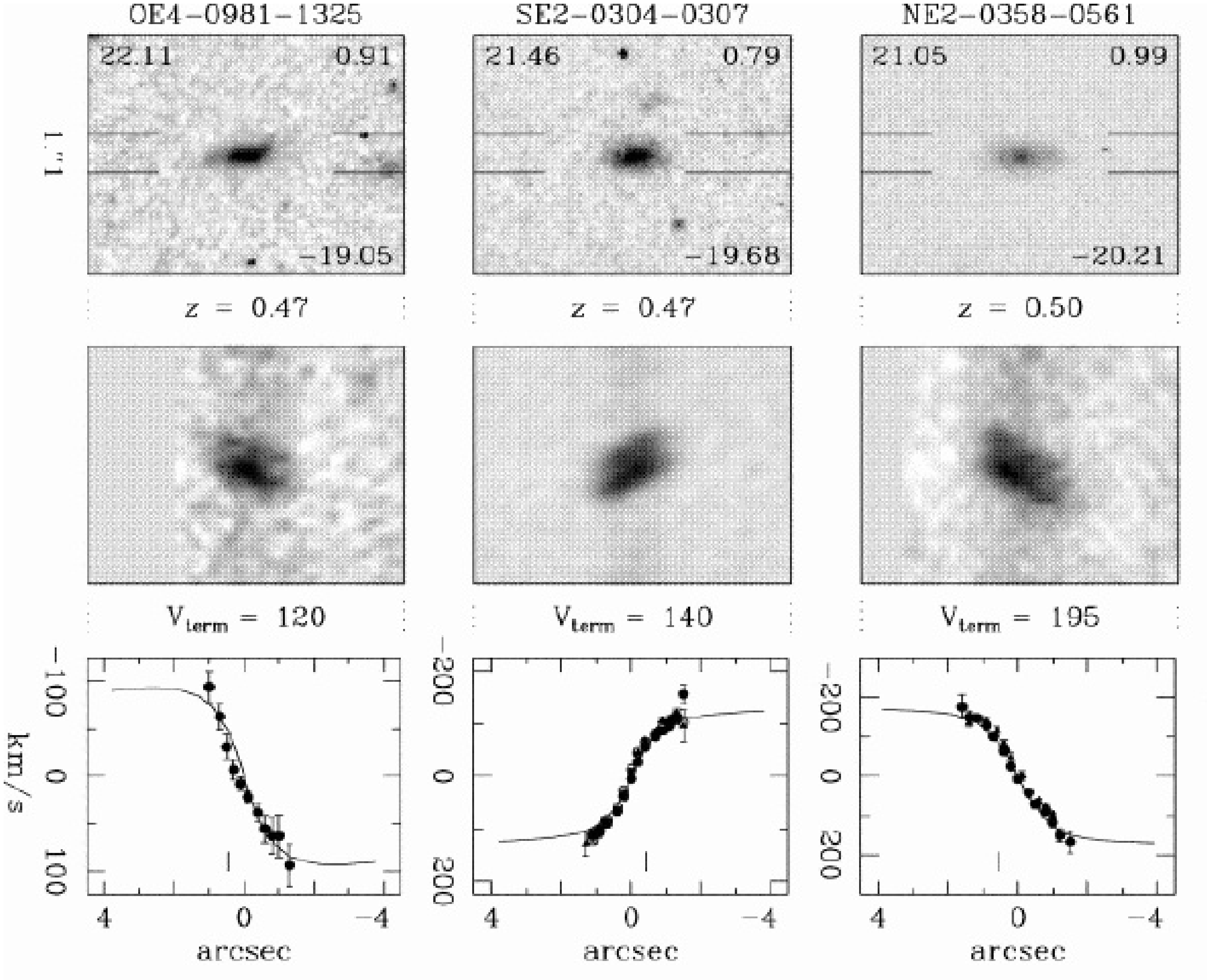


FIG 1b

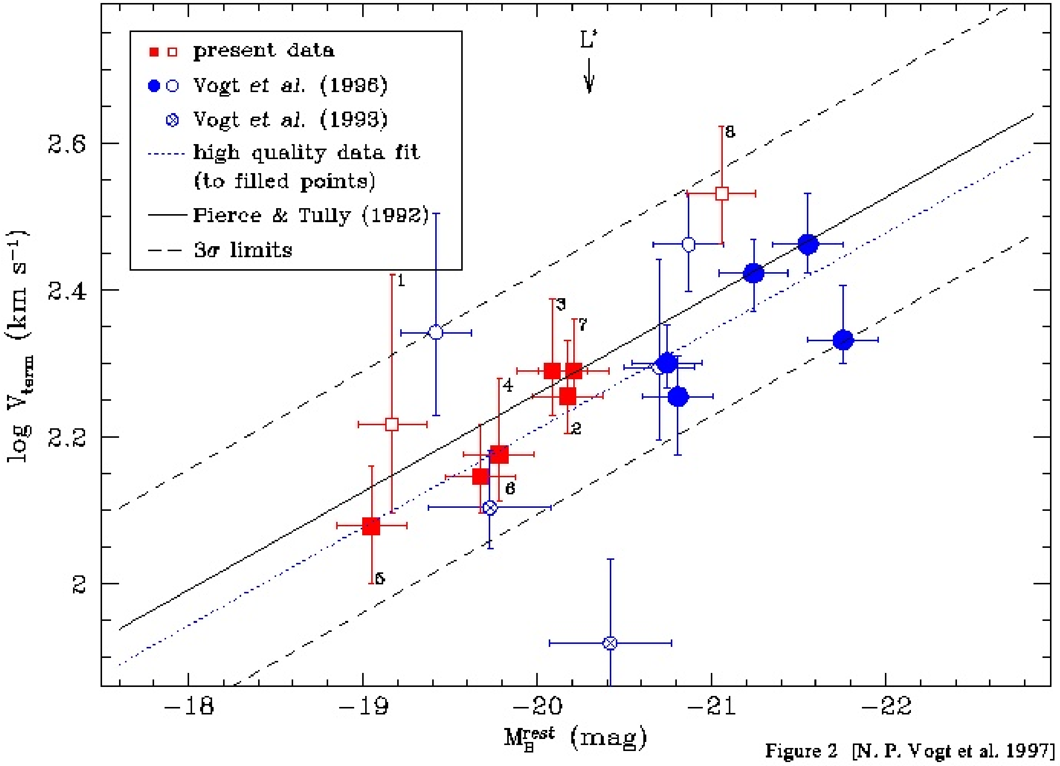


Figure 2 [N. P. Vogt et al. 1997]

(Vogt *et al.*, 1997, *ApJ*, **479**, L121)

## 16.6 High-Redshift Galaxies

Problem:

For a long time high-redshift galaxies were too faint for spectroscopic observations. (This situation has changed as more and more 8-m and 10-m telescopes have become available.)

Solution:

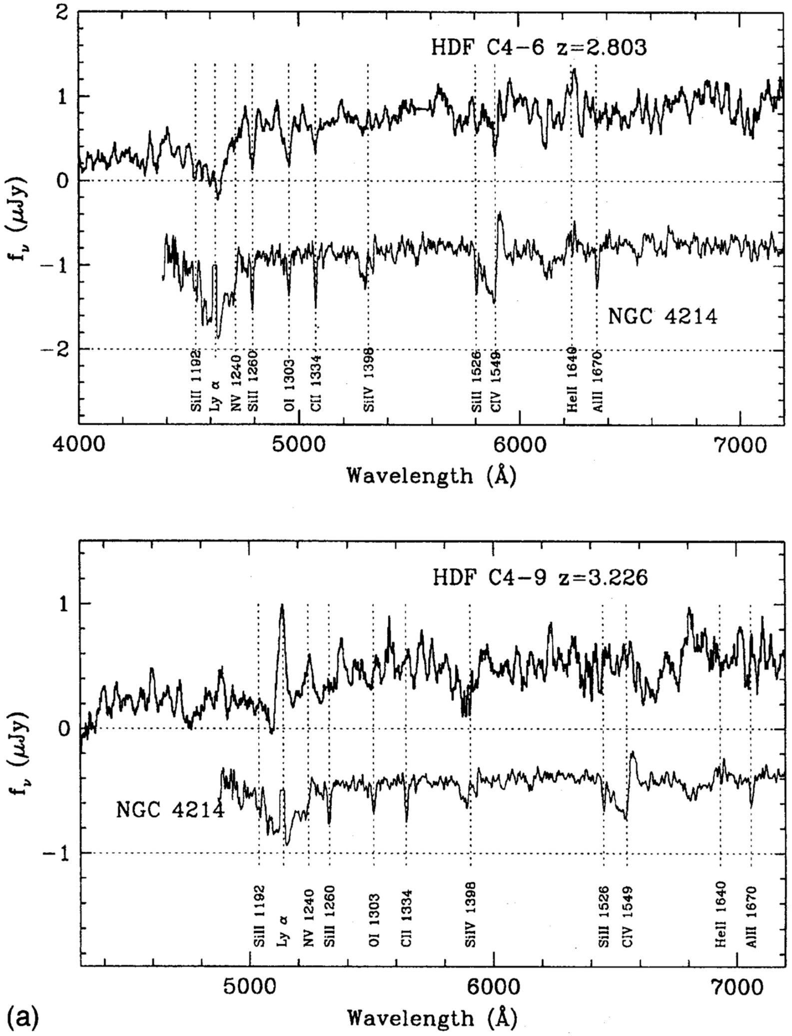
- Detection of the Lyman break by choosing appropriate filters (below the Lyman break practically all stars (and thus galaxies) do not emit much radiation).
- Search concentrated on fields pointed at quasars with known redshift (hoping to detect clusters of galaxies).

This method has lead to the detection of a number of galaxies at $z > 3$, the spectra of which can now be obtained with the Keck, VLT, . . .

High-redshift galaxies generally show slightly increased star-formation rates.

Normal galaxies at $z \simeq 3$

(Steidel *et al.*, 1996, *AJ*, **112**, 352)



(a)

## 16.7 The Hubble Deep Field (HDF)

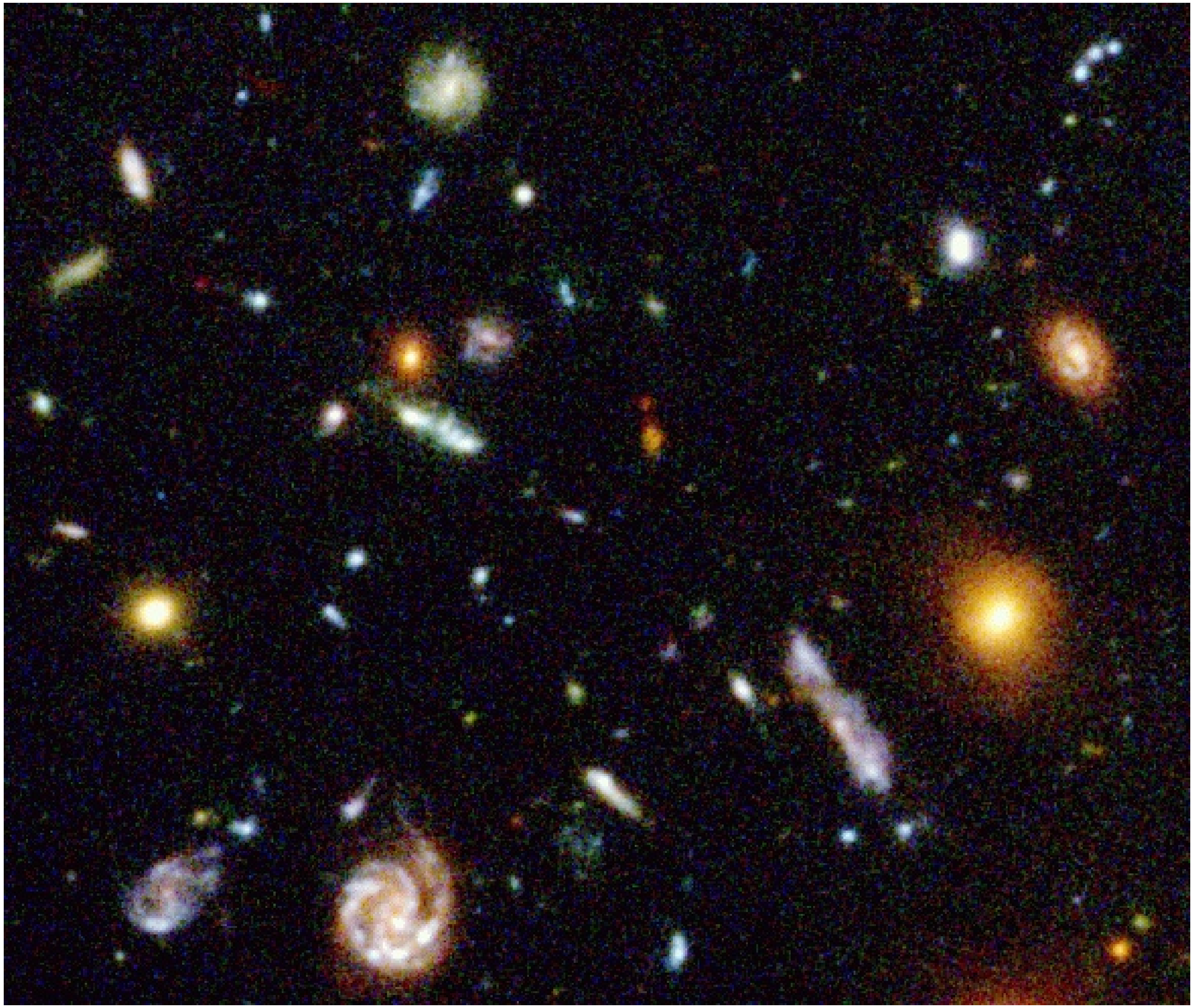
300 orbits of HST were dedicated to observations of one field in 4 colours, i.e. the total integration time was $\sim 50$ hours per filter.

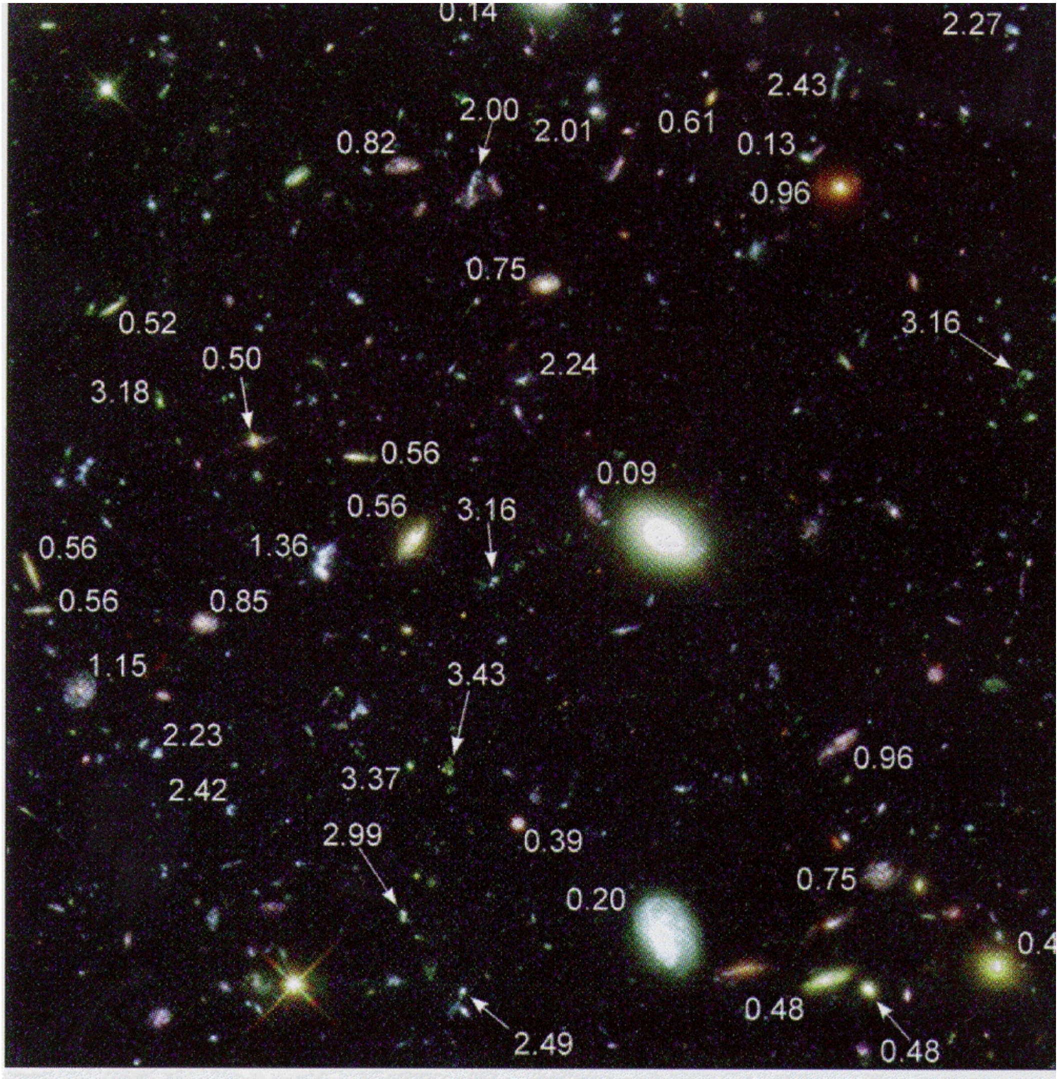
**Results:**

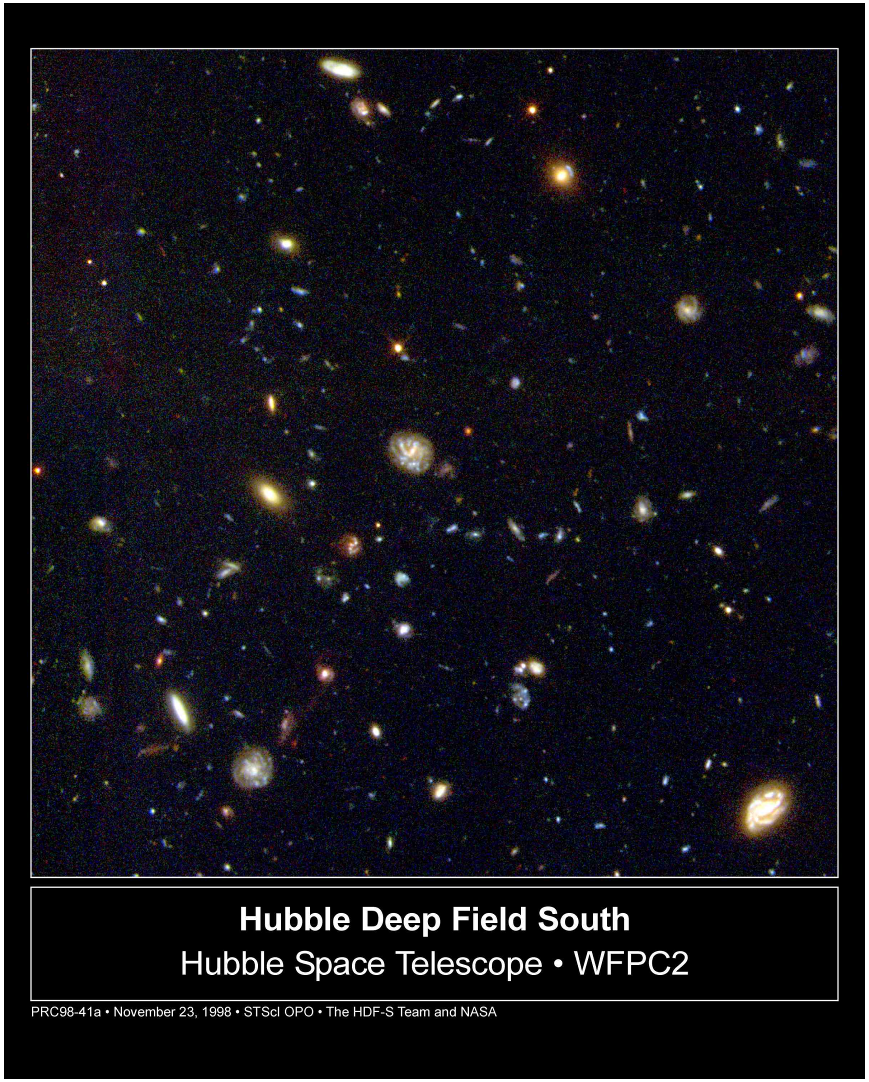
- The fraction of blue, disturbed galaxies is increased compared to the local population.

  (But note that the observed colours of high-redshift galaxies correspond to rest-frame UV colours, which are not well-known for local galaxies.)
- There are still many ‘normal looking’ spirals and ellipticals, which in some cases are very red (old?).
- First spectroscopic follow-up observations with the Keck telescope show that a significant fraction of the galaxies in the HDF are at redshifts $z > 2$.

Meanwhile also second deep field in southern sky: **Hubble Deep Field South**.




0.14
2.27
2.43
2.00
0.82
2.01
0.61
0.13
0.96
0.75
0.52
3.16
0.50
2.24
3.18
0.56
0.09
0.56
3.16
0.56
1.36
0.56
0.85
1.15
3.43
2.23
0.96
3.37
2.42
2.99
0.39
0.75
0.20
0.4
0.48
2.49
0.48



**Hubble Deep Field South**

Hubble Space Telescope • WFPC2

PRC98-41a • November 23, 1998 • STScI OPO • The HDF-S Team and NASA