Galaxy Formation and Evolution

Lecture 2:
Challenges and recent advances

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Lecture 2: learning objectives

- In-depth knowledge of the difficulties faced when using distant galaxies to study galaxy evolution
- An appreciation and knowledge of the innovations over the last 10-20 years that have lead to rapid advancement in our understanding of galaxy evolution
- An appreciation of the impact of technology on studies of galaxy evolution

Progress up to early-1990s

- Much of the pre-1990 evidence for galaxy evolution was provided by observations of luminous AGN (relatively easy to trace at high redshift)
- By 1990 there was substantial evidence for evolution in the number density and luminosity function of quasars and radio galaxies
- Evidence was also starting to emerge for evolution in the "normal" galaxy populations from faint galaxy number counts and the Butcher-Oemler effect
- Also, in late 1980s and early 1990s the results of the first deep spectroscopic surveys of faint field galaxies (out to z~0.4) started to be reported

Difficulties with observing distant galaxies I

Dimming with redshift

- In a geometrically flat (Euclidean) universe all sources will be subject to $1/r^2$ geometrical dilution (inverse square law!)
- In addition to geometrical dilution, the total flux per unit wavelength interval will be diminished because of change in time interval, energy of photon, and wavelength interval with redshift -- as $1/(1+z)$
- The *surface brightness* (units: W m^{-2} nm^{-1} $arcsec^{-2}$) dims even faster -- as $1/(1+z)^3$ -- there is a danger that we will be biased towards the higher surface brightness peaks at high redshifts
- The actual degree of overall dimming depends on the cosmological model (not exactly $1/r^2$ geometrical dilution for curved space-time)

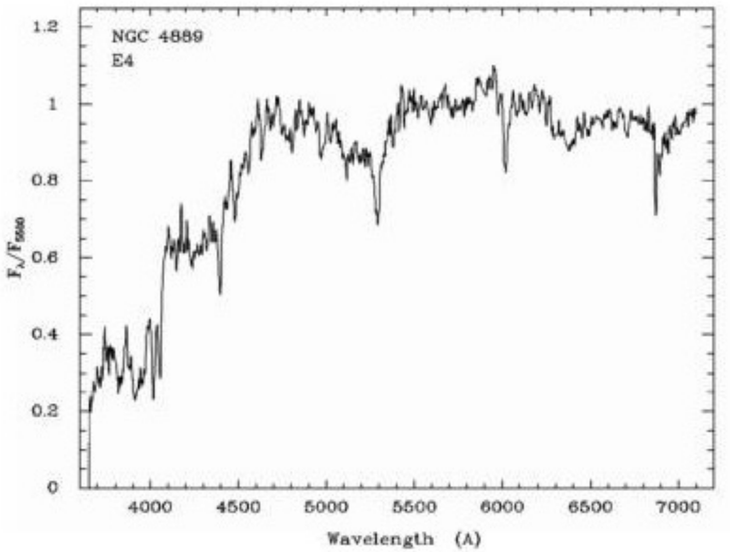
Difficulties with observing distant galaxies II

K-correction:

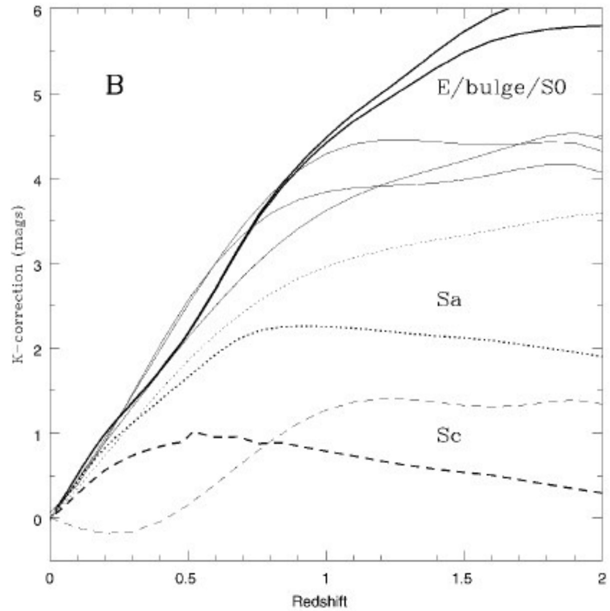
- The flux spectra of galaxies are not flat, but vary considerably with wavelength
- The detailed shapes of the spectra of individual galaxies will depend on the ages, metallicities and reddening of the stellar populations
- The relatively red spectra of galaxies with old, intermediate and/or heavily reddened spectra will cause a further dimming of an object with redshft at optical wavelengths
- The correction for this effect is called the “K-correction”

The K-correction

Elliptical galaxy spectrum:



K-correction in B-band:



Because galaxy spectra are not flat (see left image), to derive a rest frame magnitude for a galaxy in a photometric band we need to apply a correction factor to the measured magnitude in that band.

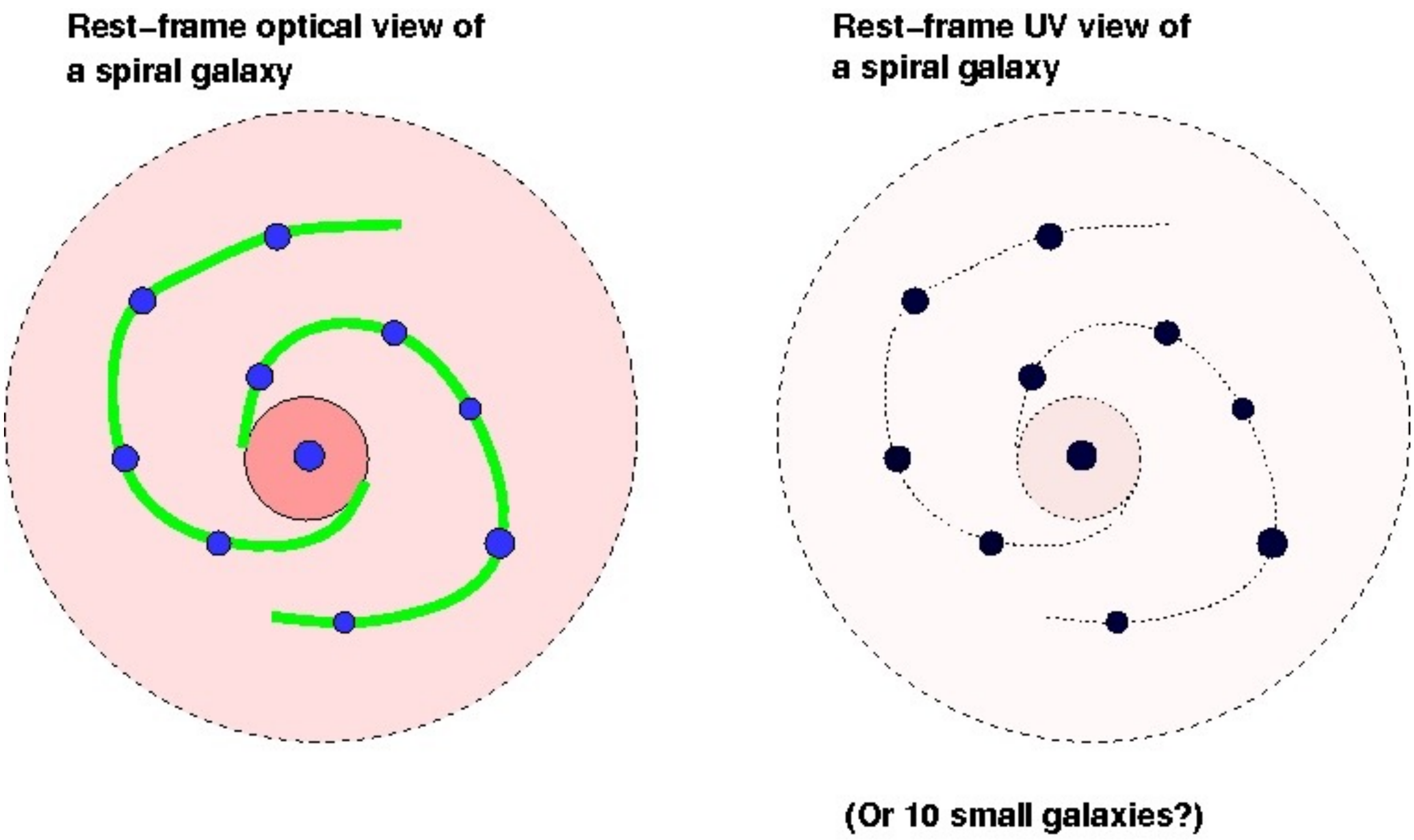
And because galaxy spectra (particularly E-galaxies) tend to decrease to the UV the K-correction is often negative at optical wavelengths (leading to a dimming as redshift increases)

Difficulties with observing distant galaxies III

Morphological K-correction

- Different structural components in galaxies can have different spectra/colours
- For example, the relatively old stellar populations in galaxy bulges are red, while the relatively young stellar populations in star forming regions in the disks of galaxies are relatively blue, and bright in the UV
- As a consequence, the appearance of a galaxy at optical wavelengths can change substantially with redshift (e.g. for optical observations the high surface brightness star forming regions become more prominent, bulges less prominent as redshift increases)

Morphological K-correction



Difficulties with observing distant galaxies IV

Progenitor bias

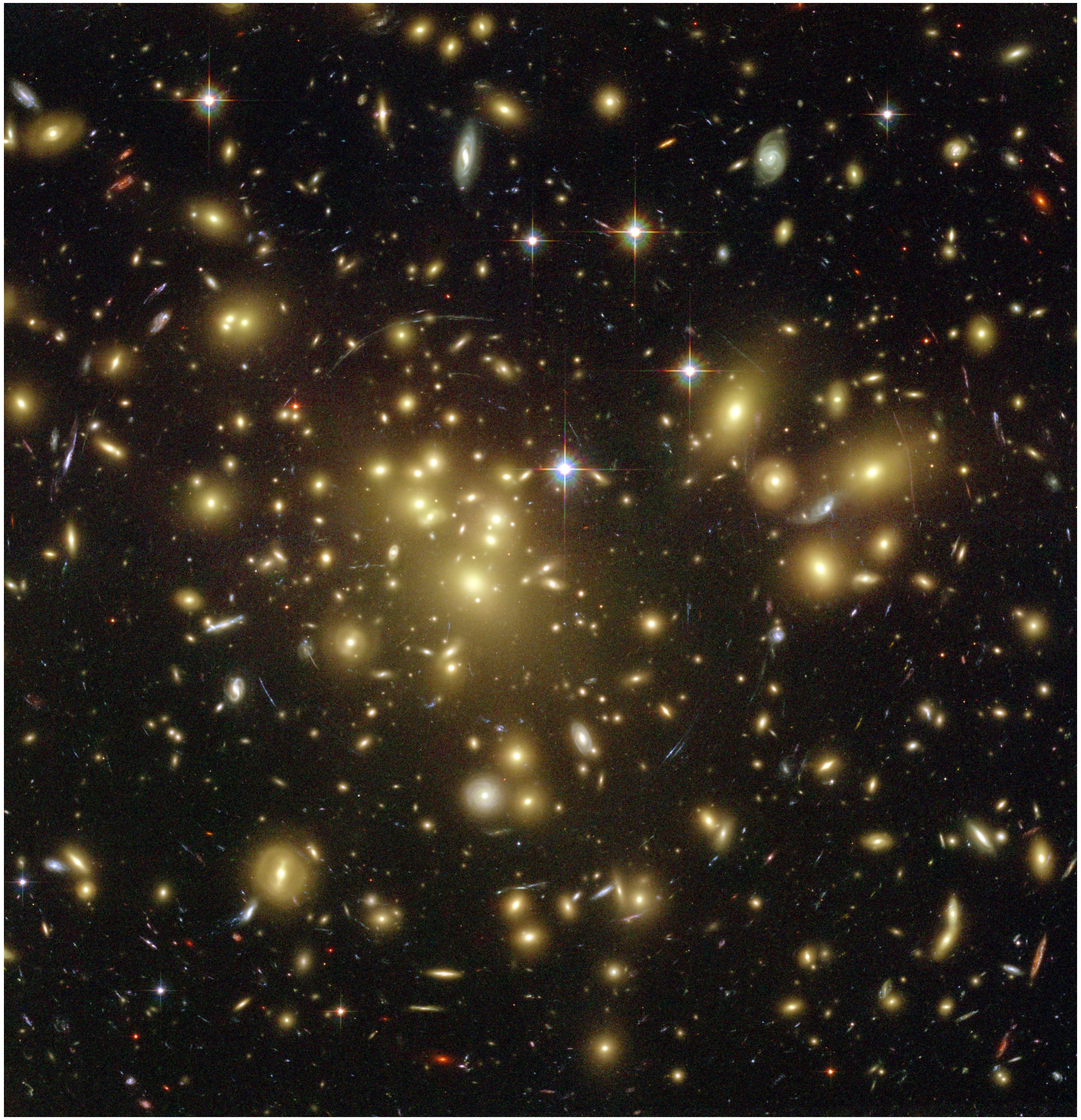
- Ideally we would like to track a particular population of galaxies (e.g. E/S0/S/Irr) over cosmic time,
- But the appearances of galaxies can change substantially as they evolve, particularly in hierarchical galaxy evolution models in which galaxies grow through mergers.
- Therefore we face the question: how do we recognise the progenitors of the nearby galaxies at high redshifts?
- Assuming particular properties for the progenitors based on the properties of nearby galaxies may lead to bias.

Difficulties with observing distant galaxies V

Cosmic variance

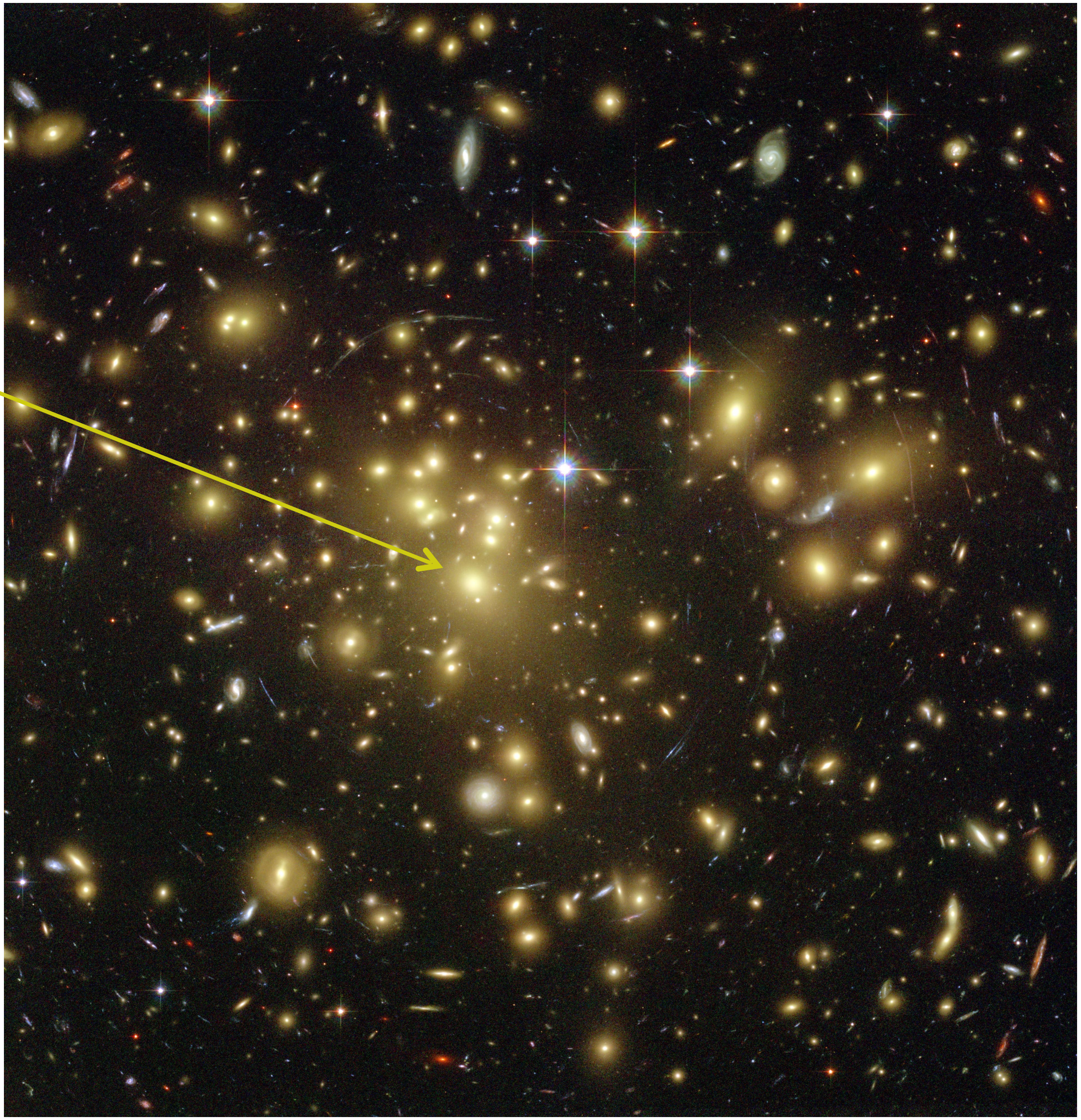
- Although the universe is believed to be homogeneous and isotropic on large scales, galaxies are also known to be strongly clustered, even in the distant universe.
- The properties of galaxy populations are known to depend on environment (e.g. cluster, group, field)
- Therefore, in deep surveys, it is important to sample a sufficiently large area/volume to build up good statistics on the properties of galaxy populations across the full range of environments
- Deep, small area surveys (e.g. the Hubble Deep Field) can give a misleading impression

Clustering of galaxies



Clustering of galaxies

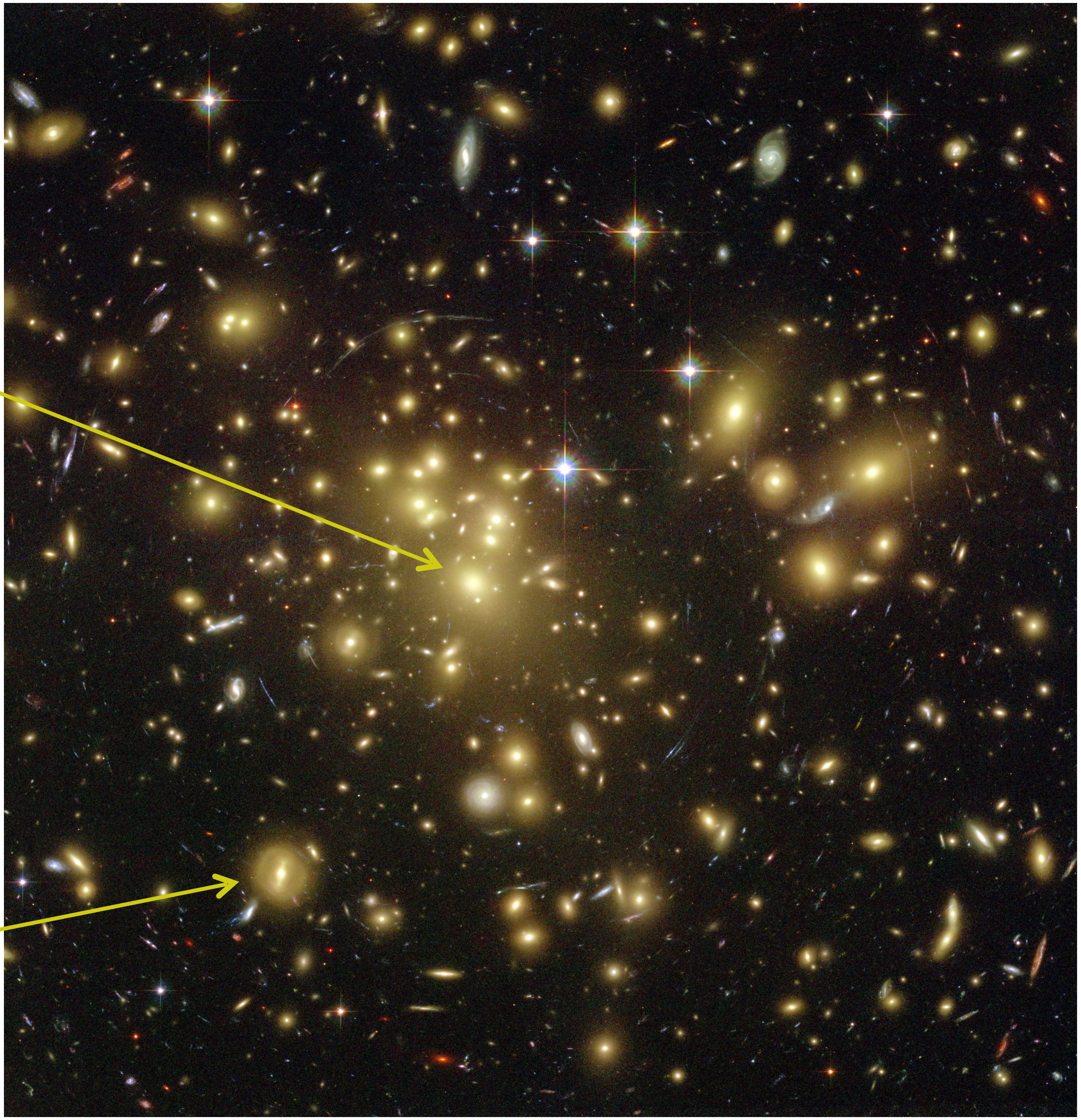
Elliptical galaxies are more common in galaxy clusters



Clustering of galaxies

Elliptical galaxies are more common in galaxy clusters

Spiral galaxies are more common in galaxy groups and the field



Difficulties with observing distant galaxies VI

Dependence on cosmological model

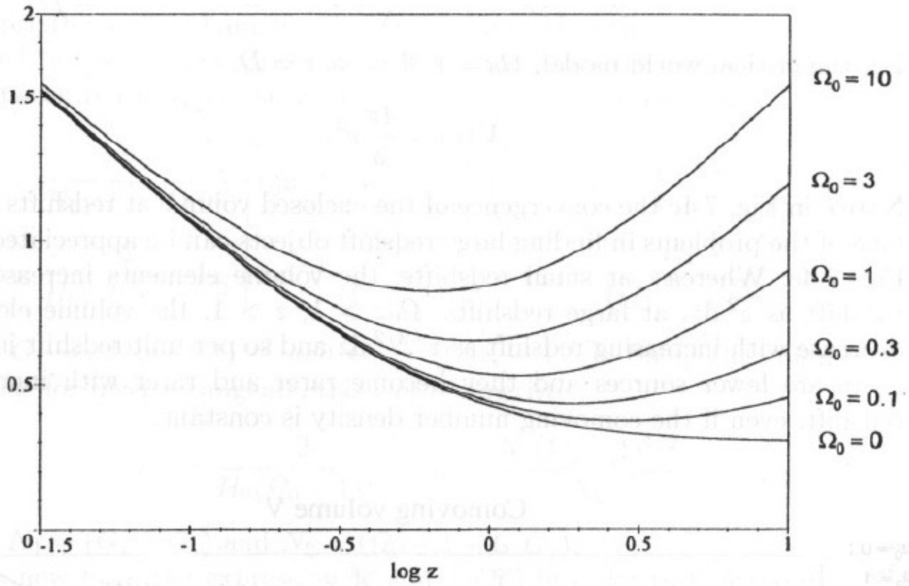
- Several key derived properties derived from observations of distant galaxies (e.g. luminosity, physical diameter, cosmic epoch) depend on the assumed cosmological model (e.g. H_0, Ω_λ,Ω_m)

- Under the assumption that certain types of galaxies (e.g. giant elliptical galaxies) are standard candles, observations of distant galaxies have been used in the past *to determine* cosmological parameters

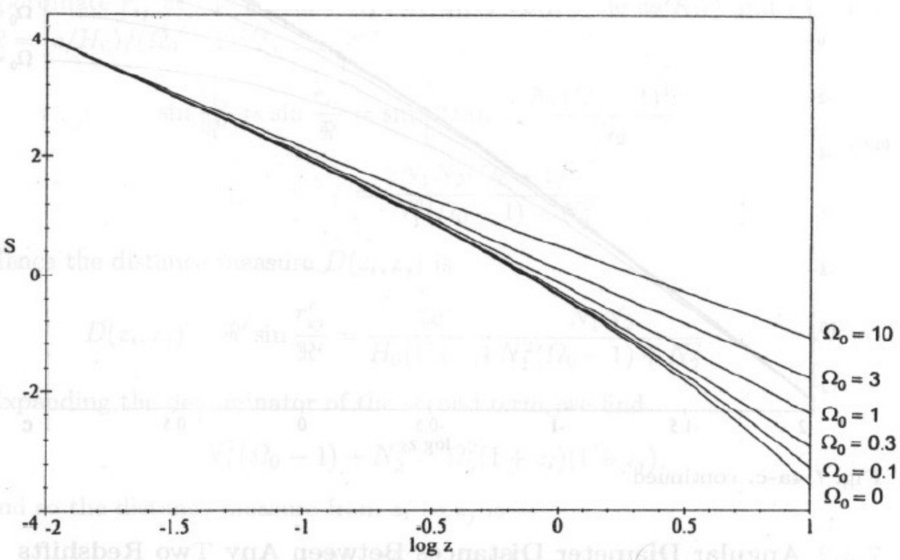
- It is important to disentangle the changes with redshift that are due to galaxy evolution, from those that are a consequence of the assumption of a particular cosmological model

Dependence of derived properties on assumed cosmology

Angular diameter vs redshift



Flux vs redshift



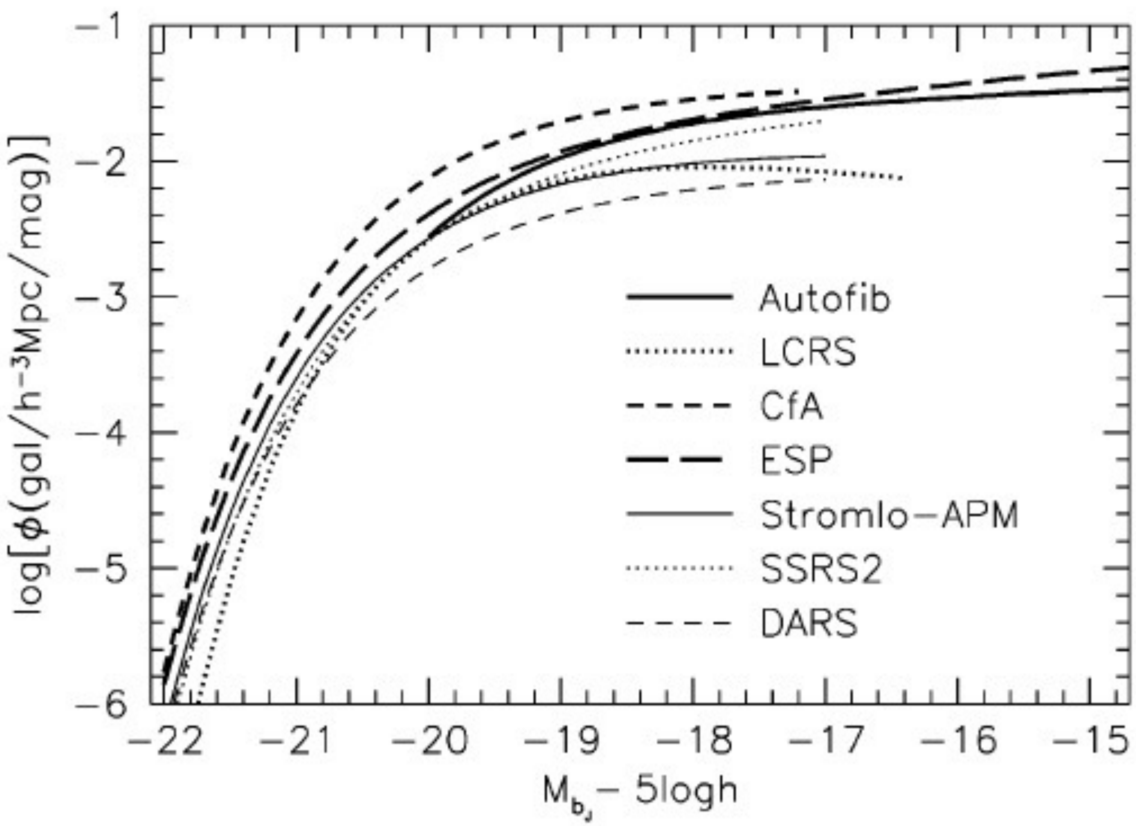
Difficulties with observing distant galaxies VII

Lack of knowledge of nearby galaxies

- Our ability to establish the evolution of galaxy populations in the distant Universe rests on our knowledge of the local galaxy populations, which provide a crucial point of comparison

- There is a surprising degree of uncertainty in certain properties of nearby galaxy populations (e.g. local galaxy luminosity function) because:
  - many results are based on old photographic data;
  - some data for nearby galaxies has an insufficiently wide field and sensitivity for accurate photometry;
  - the rest frame UV is is not accessible for deep spectroscopy from the ground for nearby galaxies.

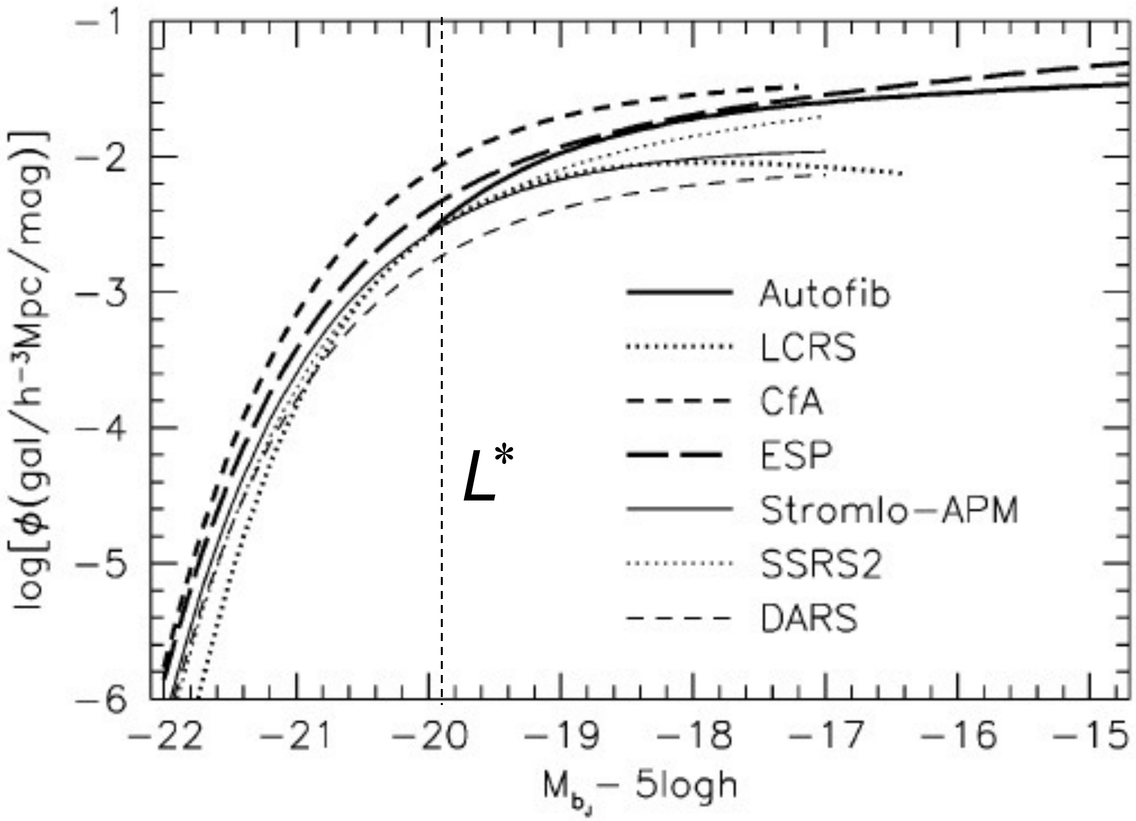
Local galaxy luminosity function



Schechter (1976) function:

$$\phi(L)dL = \phi^* \left(L/L^*\right)^{-\alpha} \exp\left(-L/L^*\right) dL/L^*$$

Local galaxy luminosity function



Schechter (1976) function:

$$\phi(L)dL = \phi^*\left(L/L^*\right)^{-\alpha}\exp\left(-L/L^*\right)dL/L^*$$

Characteristic luminosity: L^*

Summary of challenges

- Substantial dimming of sources with redshift (geometrical dilution, $(1+z)^{-n}$, cosmology)
- Negative K-corrections
- Change in appearance with redshift (fixed optical band)
- Progenitor bias
- Dependence on assumed cosmological model
- Cosmic variance
- Lack of knowledge of local galaxy populations

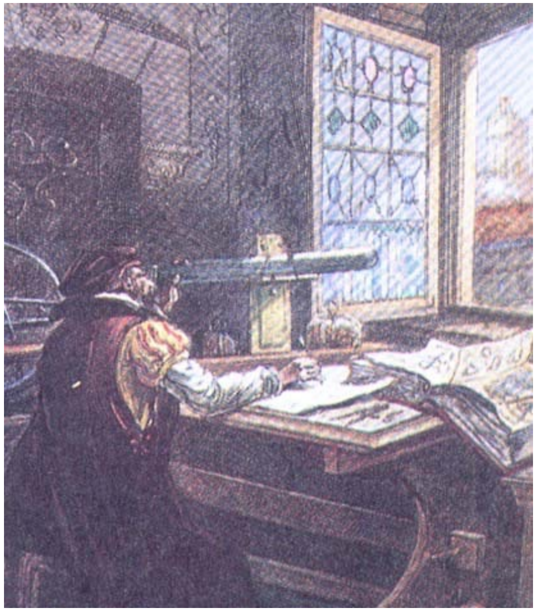
Progress depends on technological innovation that allows deep, panchromatic observations across a wide field.

Technological advances

Pre-1994

- 1917: building of 100”at Mount Wilson
- 1930s – 1950s: opening up of radio window for astronomy
- 1954: building of 200” at Mount Palomar
- 1970s: first 2D electronic image tube detectors developed
- 1980: charge couple device (CCD) detectors developed
- 1980s - 1990s: wide field spectroscopic capability developed

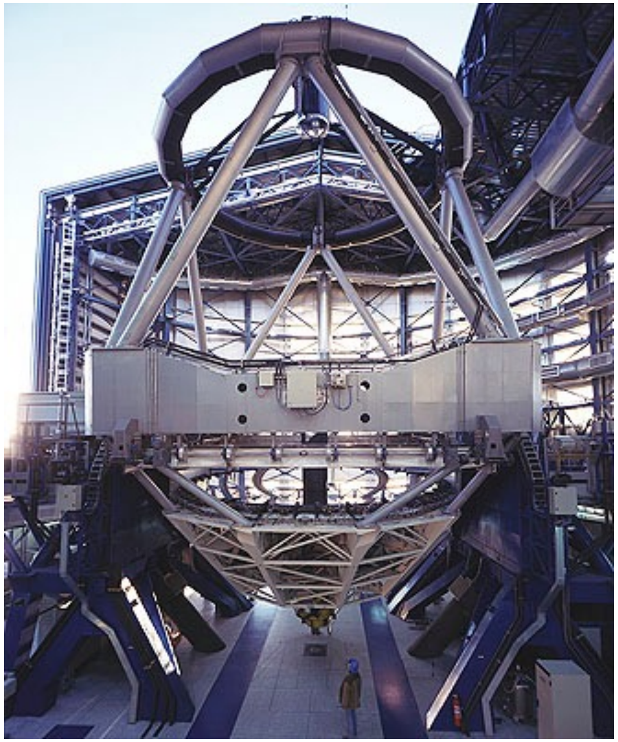
Technological advances in astronomy



Large optical telescopes
(since ~1609!)

Technological advances in astronomy

ESO VLT 8m



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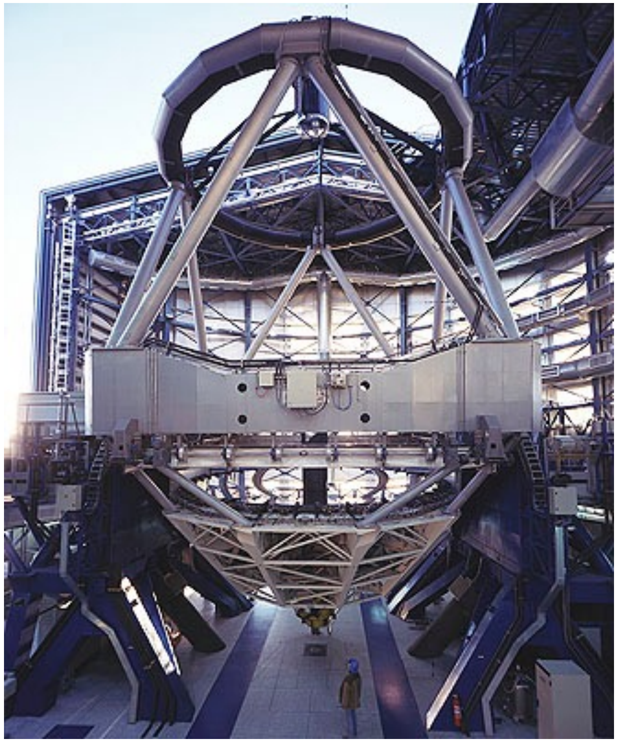

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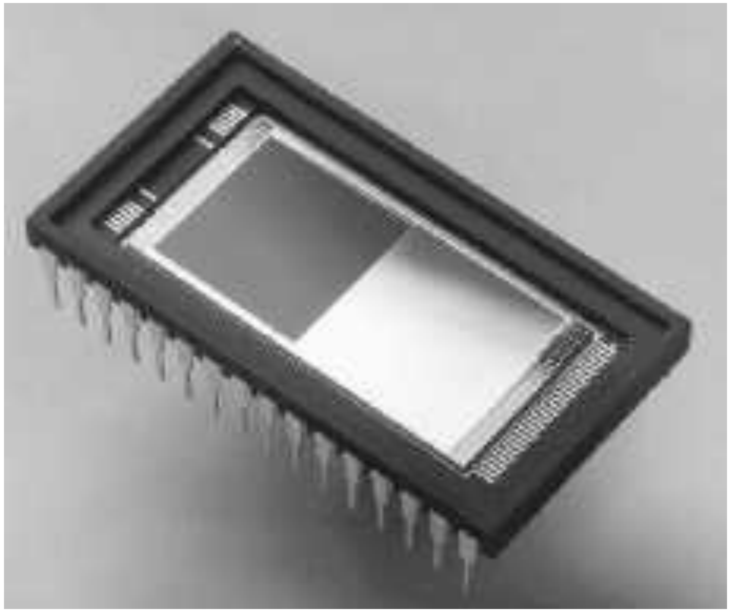
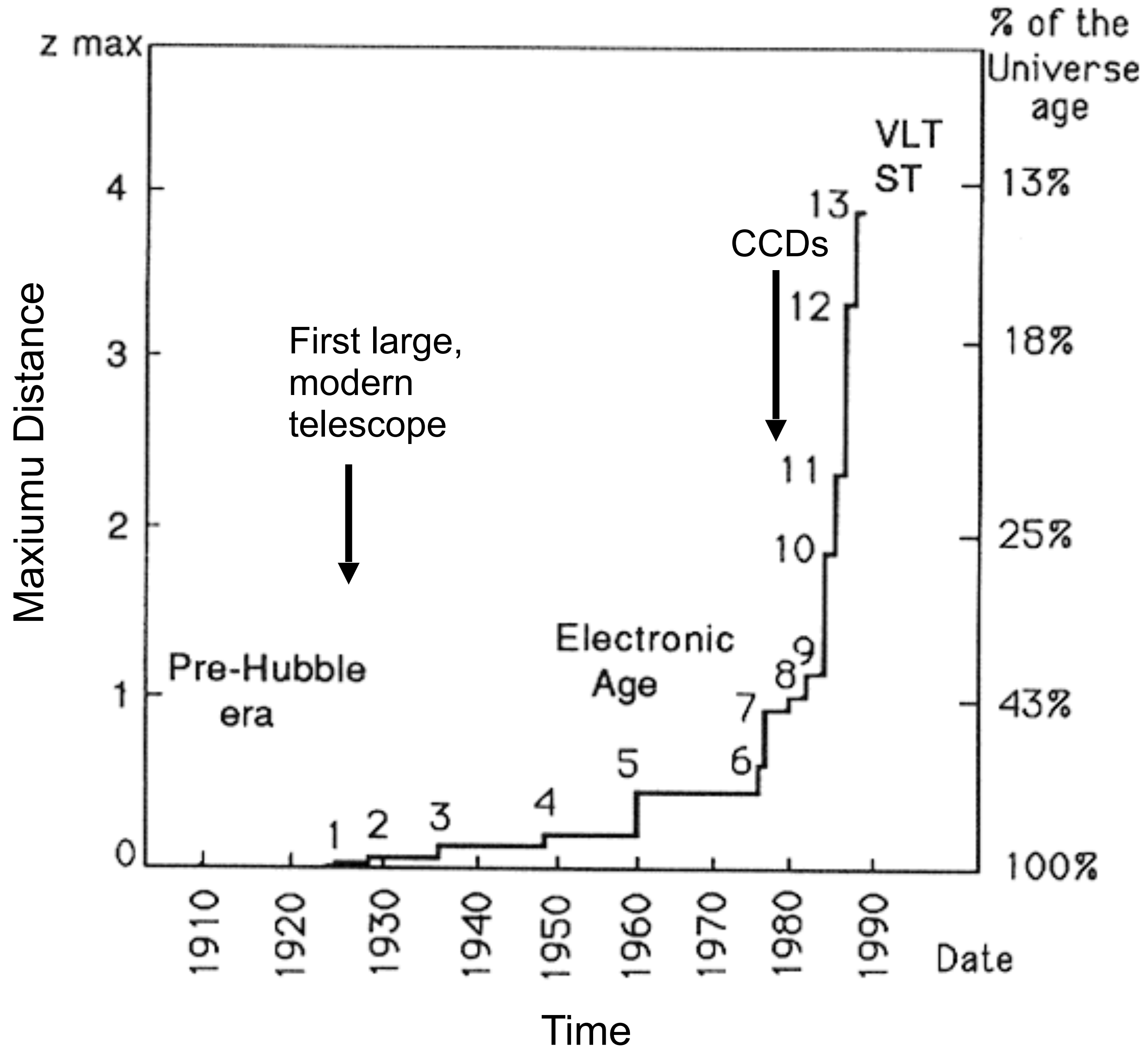


Large format CCDs

Impact of technology on astronomy



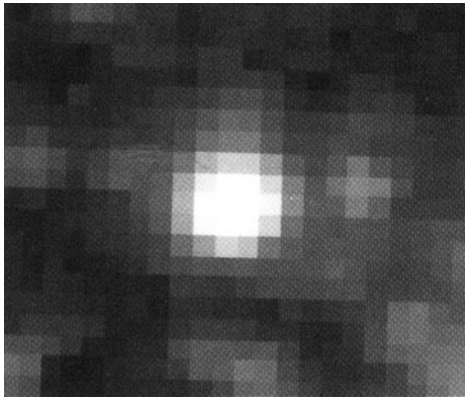
The post-1994 revolution

- 1994: refurbished Hubble Space Telescope becomes fully available
- 1995: new generation of 10m/8m telescopes commissioned
- 1990s: wide field survey capability further developed with dedicated facilities (e.g.SDSS, 2dF) and larger format CCD detectors
- 1995 – 2003: cosmological parameters determined with high accuracy using HST, SNe and WMAP, 2Df
- 1990s: rapid increase in computer power allows first realistic simulations of large scale structure and galaxy formation

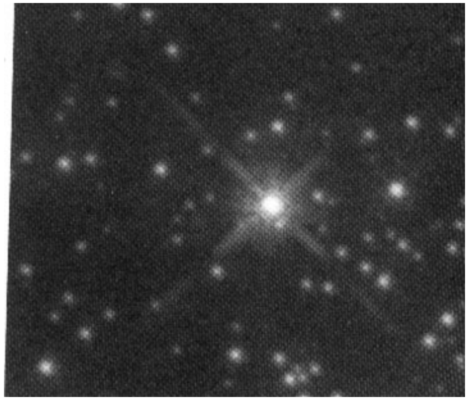
Hubble Space Telescope Capabilities

HST in orbit

Images of star cluster:
From ground
Resolution:~ 0.6”



From HST
Resolution: ~0.06”



Wide field spectroscopy I

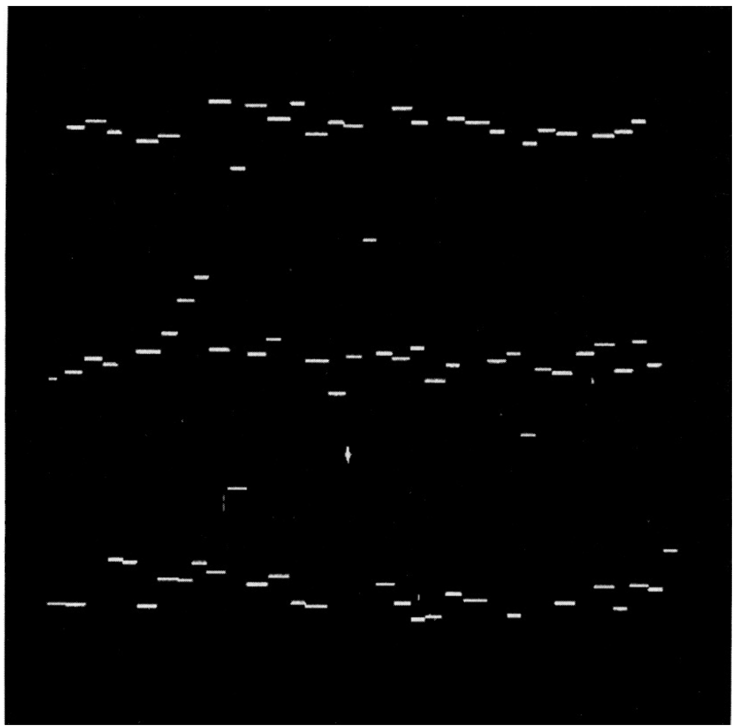
The 2dF instrument at the AAT (Anglo-Australian Telescope)

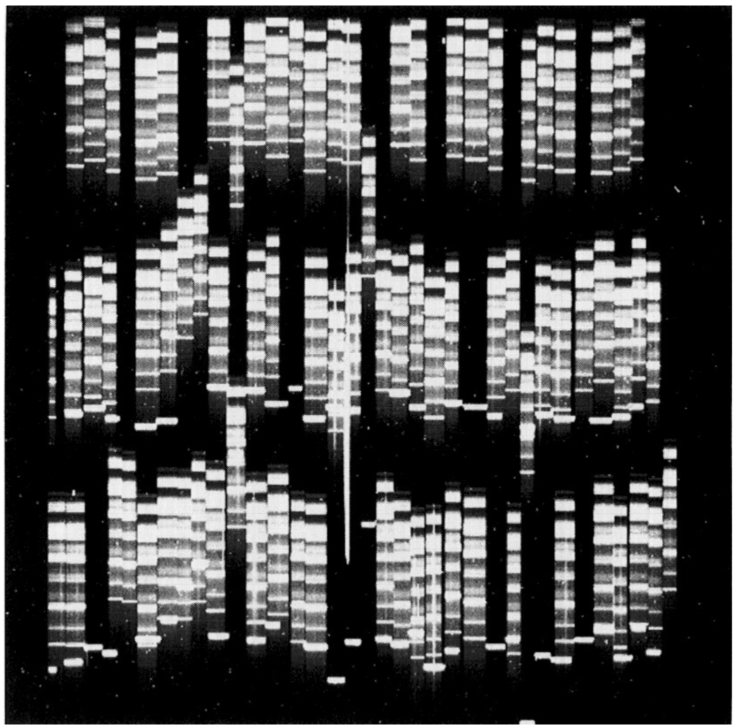
The 2dF allows simultaneous spectroscopy of up to 400 objects over a 2 square degree field

Fibre positioning plate

Wide field spectroscopy II

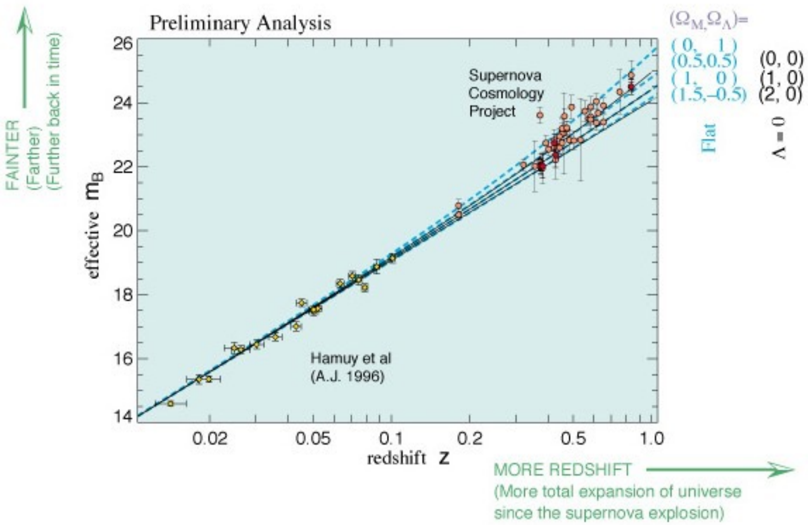
Multi-slit instruments



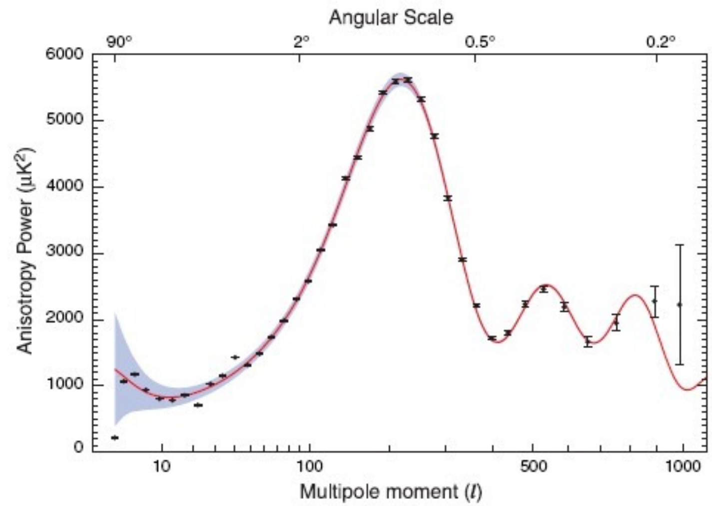


Multi-slit spectrograph at the Canada France Hawaii Telescope

Pinning down the cosmological parameters



SN cosmology project



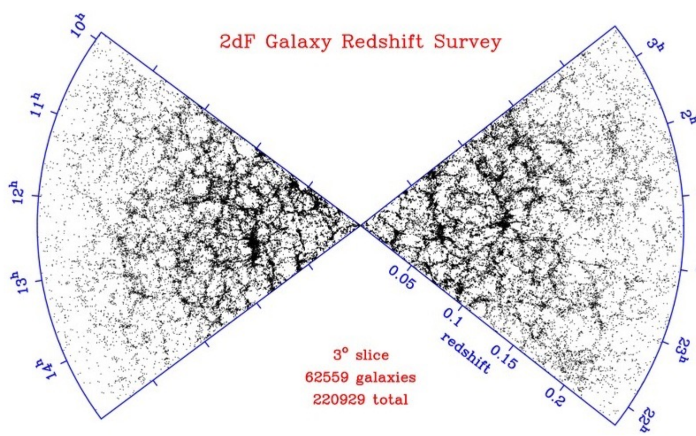
Acoustic oscillations in CMB

$$H_0 = 70.4 \pm 1.5$$

$$\Omega_\Lambda = 0.732 \pm 0.018$$

$$\Omega_m = 0.268 \pm 0.018$$

$$Age\ of\ Universe = 13.7 Gyr$$

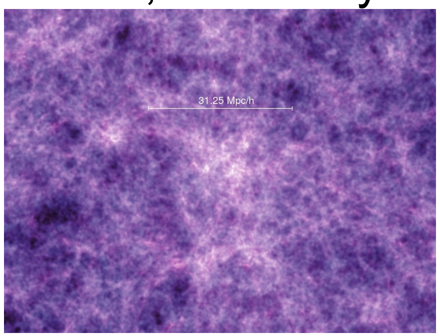


Large scale distribution of galaxies

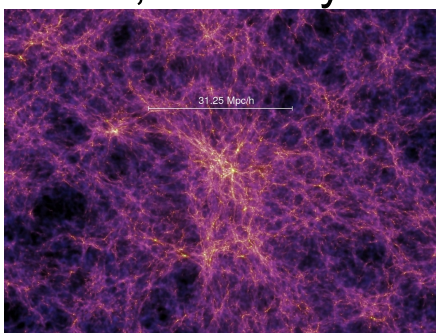
Millennium N-body simulation

…of the large-scale structure of the Universe (containing over a billion "particles"!)

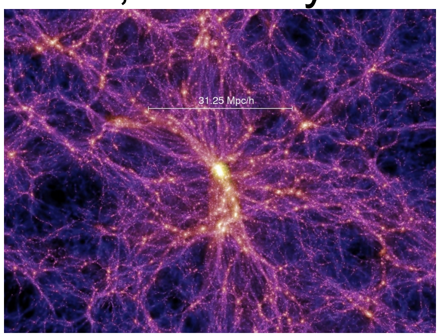
z=18.7, t=0.21 Gyr



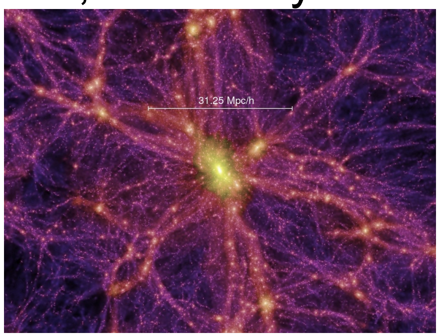
z=5.7, t=1.0 Gyr



z=1.4, t=4.7 Gyr



z=0, t=13.6 Gyr



30 Mpc

Millennium Project simulation of the growth of large-scale structure in dark matter haloes via mergers as a function of cosmic time/redshift

Lecture 2: learning objectives

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