Galaxy Formation and Evolution

Lecture 05:
The fossil record for local galaxies

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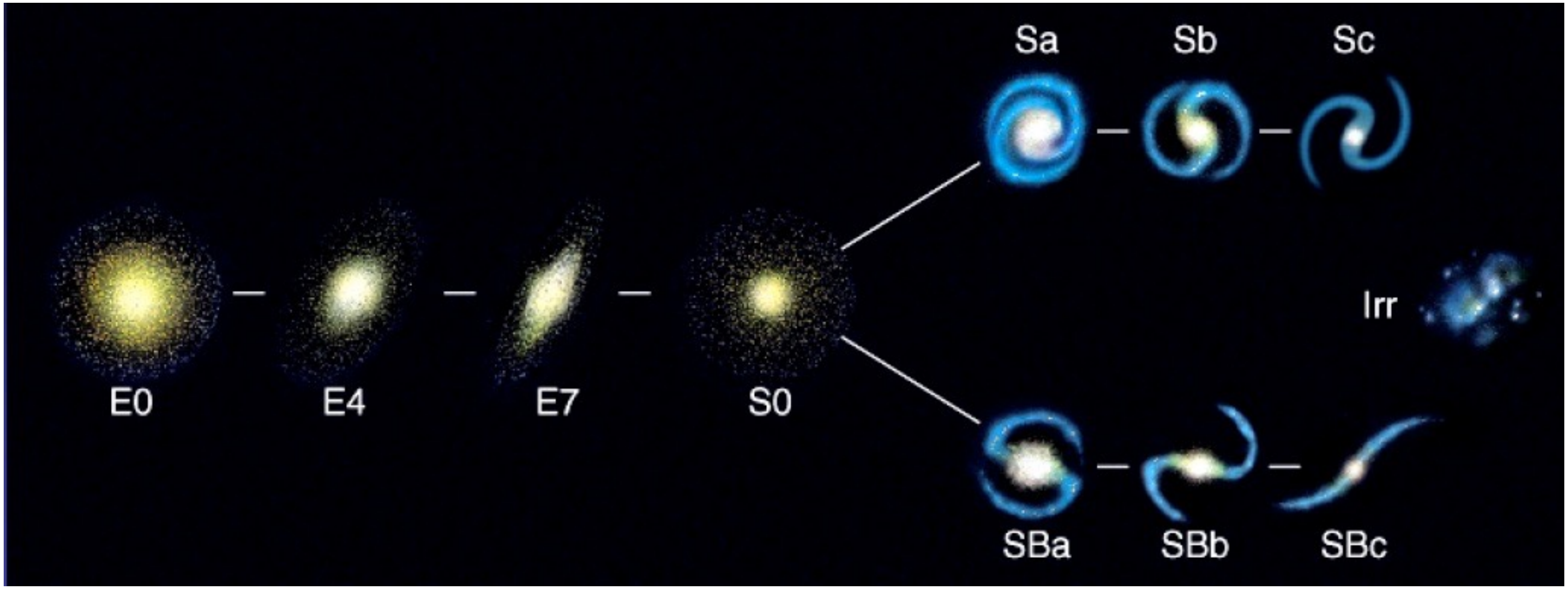
Observational approaches to understanding galaxy evolution

- Fossil approach. Examining the detailed structures, stellar populations, abundance patterns of galaxies in the local Universe -- the "fossil record".

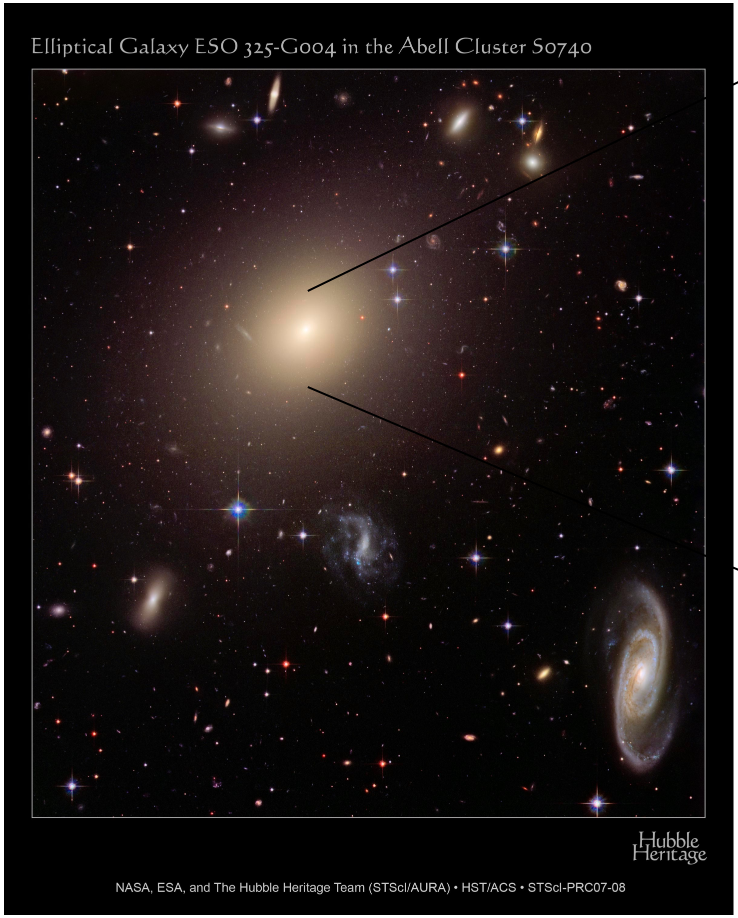
- High redshift approach. Examining the properties of distant galaxies as a function of redshift/ lookback time.

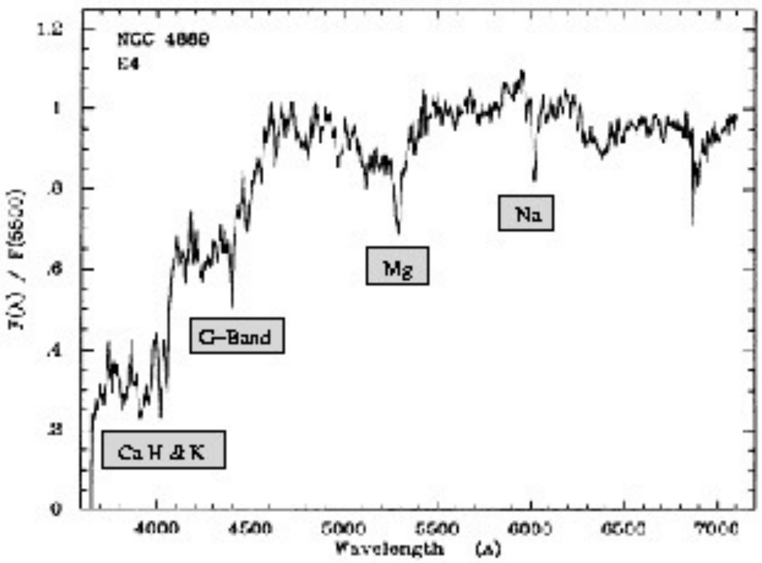
Galaxy morphologies: Hubble sequence



Early-type galaxies

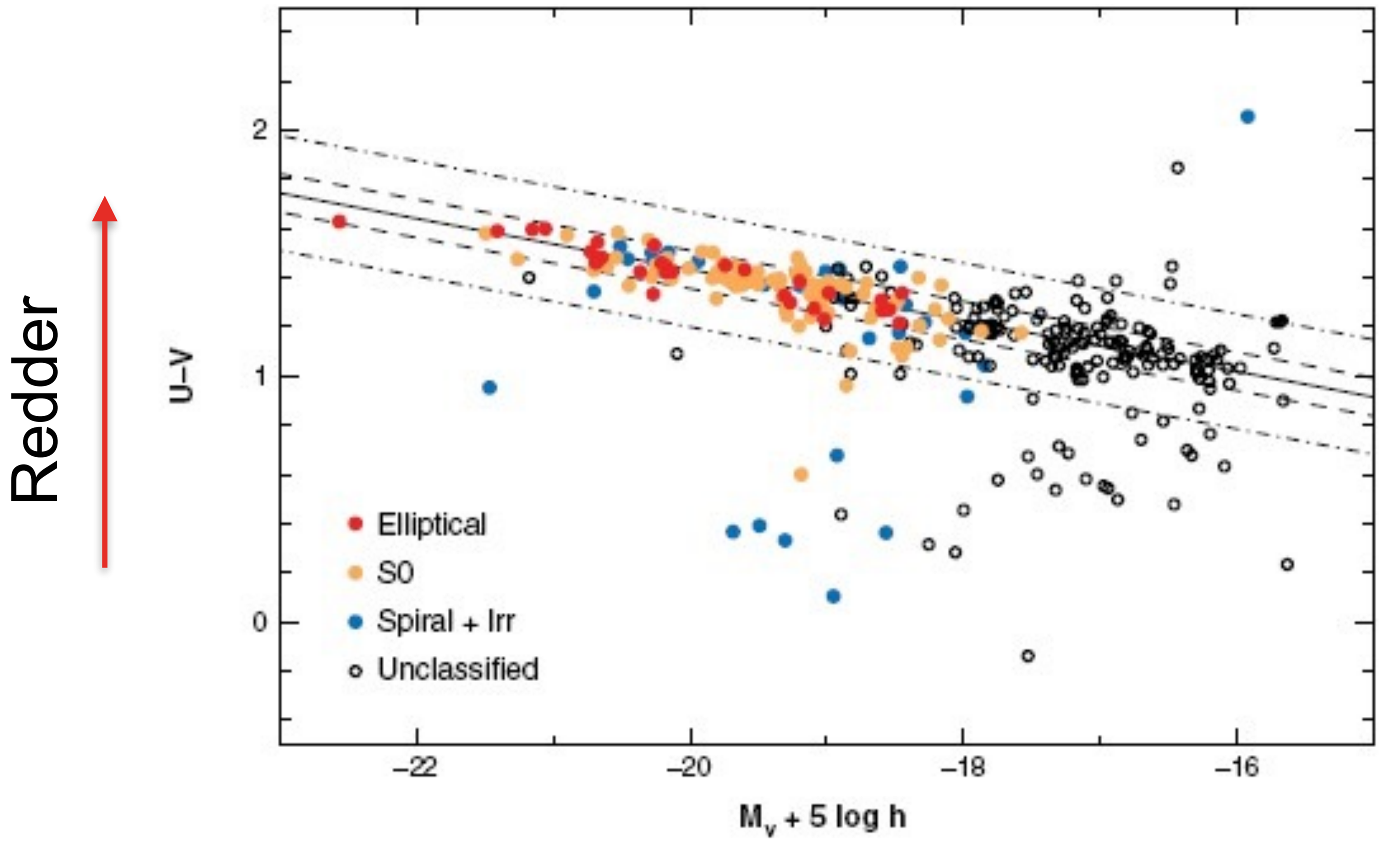
Elliptical galaxies I. Optical spectra: old, red and dead?





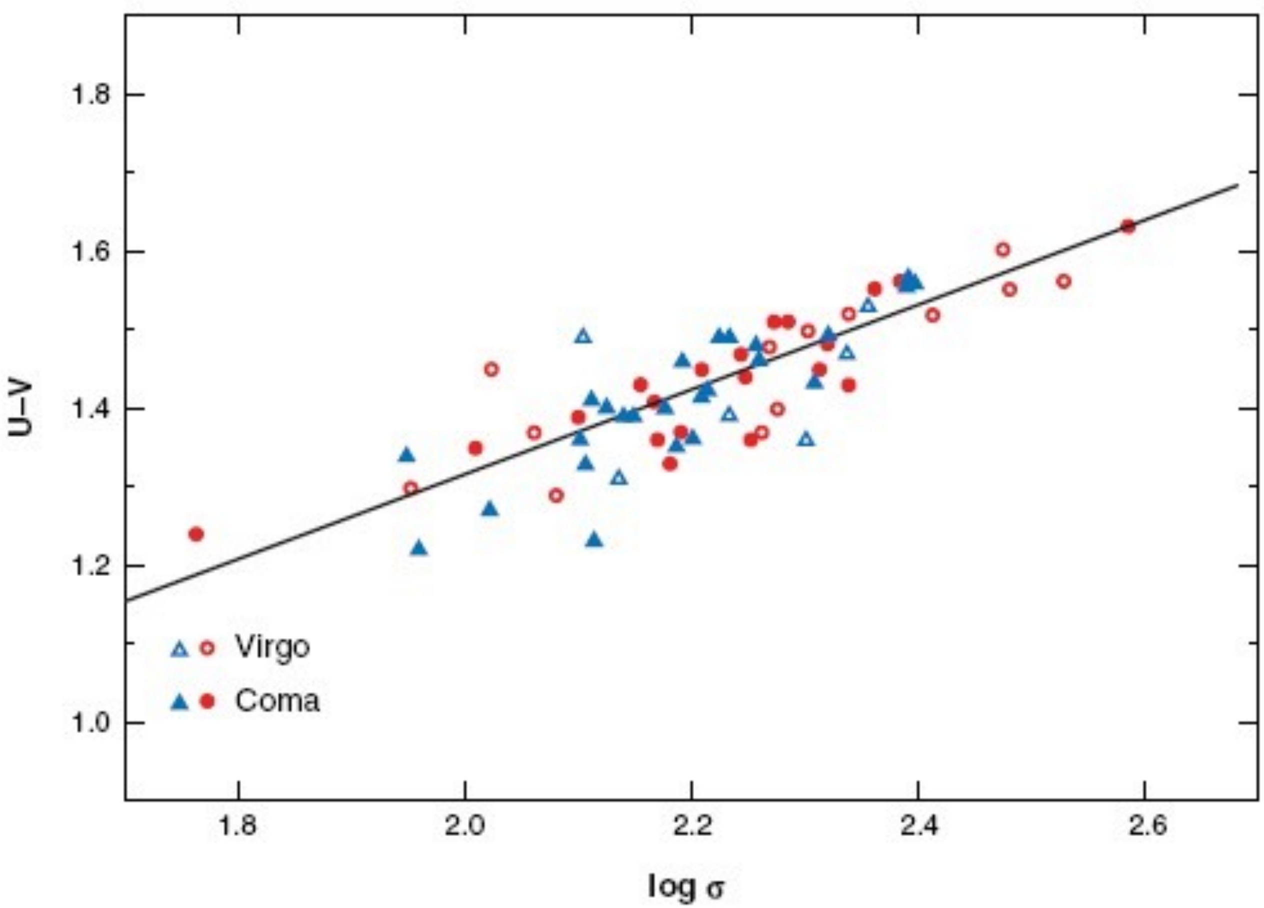
The majority of nearby ellipticals (>70%) have spectra characteristic of old stellar populations: they are red, with strong metal lines. Spectral synthesis fits suggest ages >8Gyr.

Elliptical galaxies II. Colour-magnitude for nearby clusters



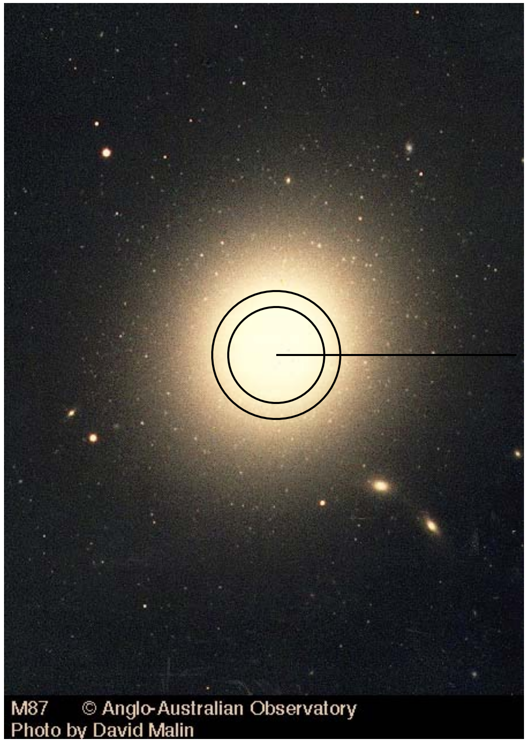
Early-type galaxies in nearby galaxies show a tight colour-magnitude relationship

Elliptical galaxies III: Colour-σ for nearby clusters

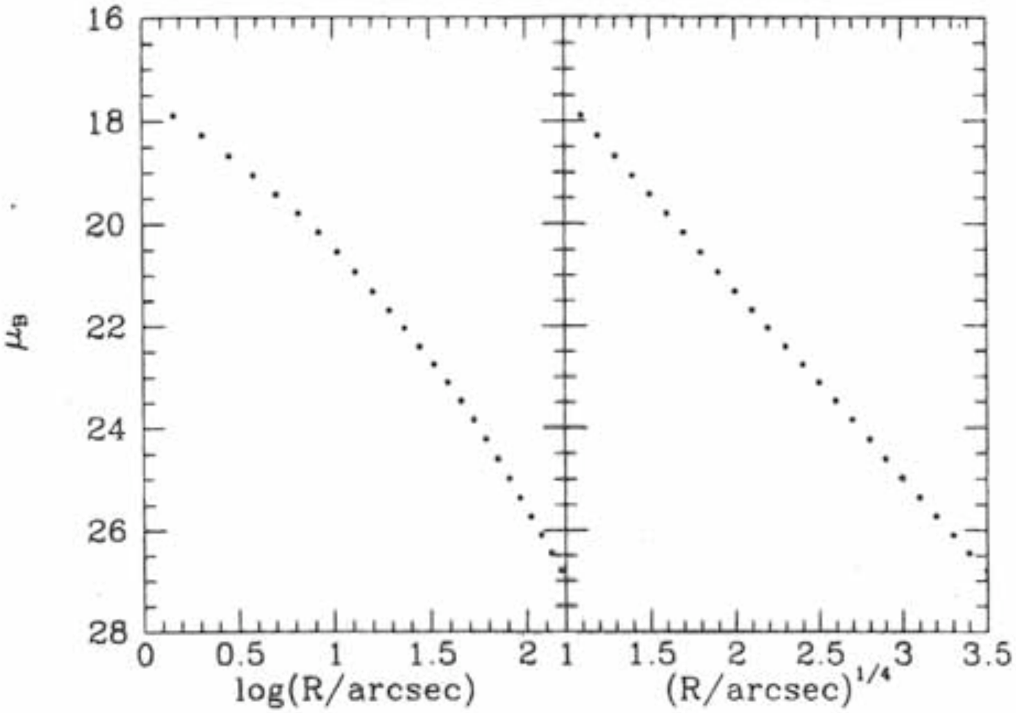


The tightness of the colour-magnitude and colour-σ relationships in clusters suggest cluster E/SO galaxies all formed at roughly the same time.

Normal elliptical galaxy light profiles



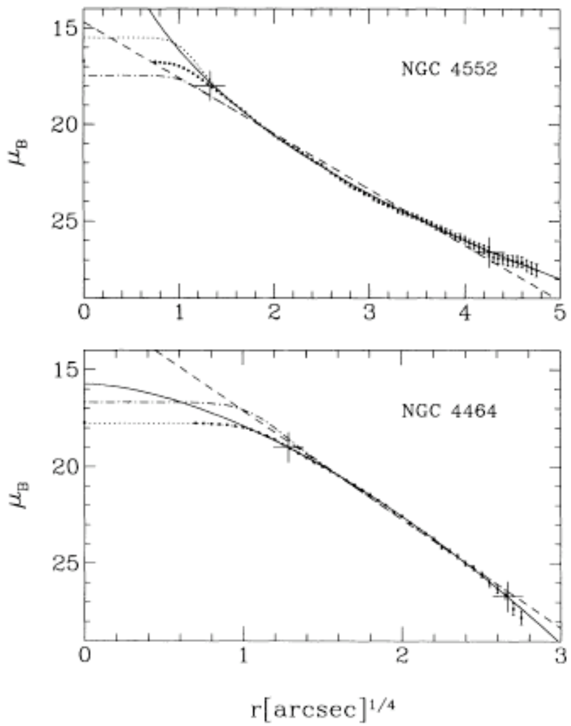
Measure the mean surface brightness (mag arcsec^{-2}) as a function of radius in a series of concentric rings (or ellipses)



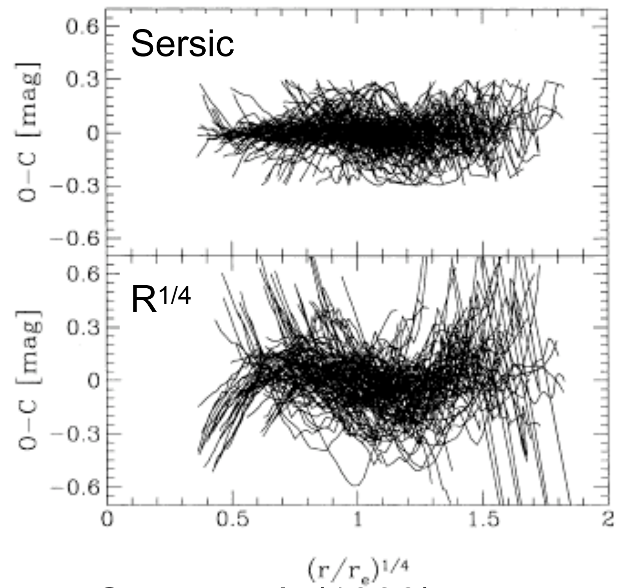
Outside the core regions the light profiles well-fitted by an $R^{1/4}$ law:

$$I(R) = I_e \exp(-7.67[(R/R_e)^{1/4} - 1])$$

Sersic profiles: a better fit?



Residuals from fit



Caon et al. (1993)

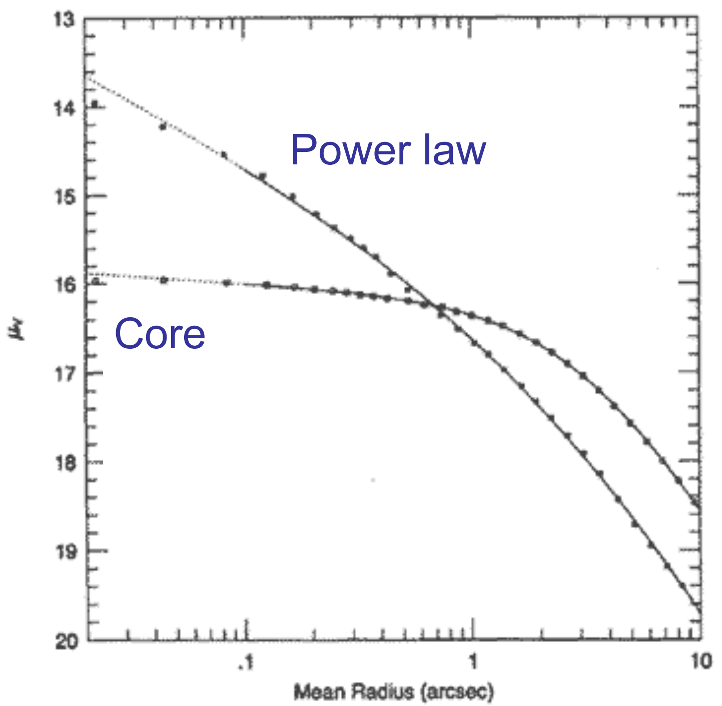
N.B. Lower residuals from Sersic fit.

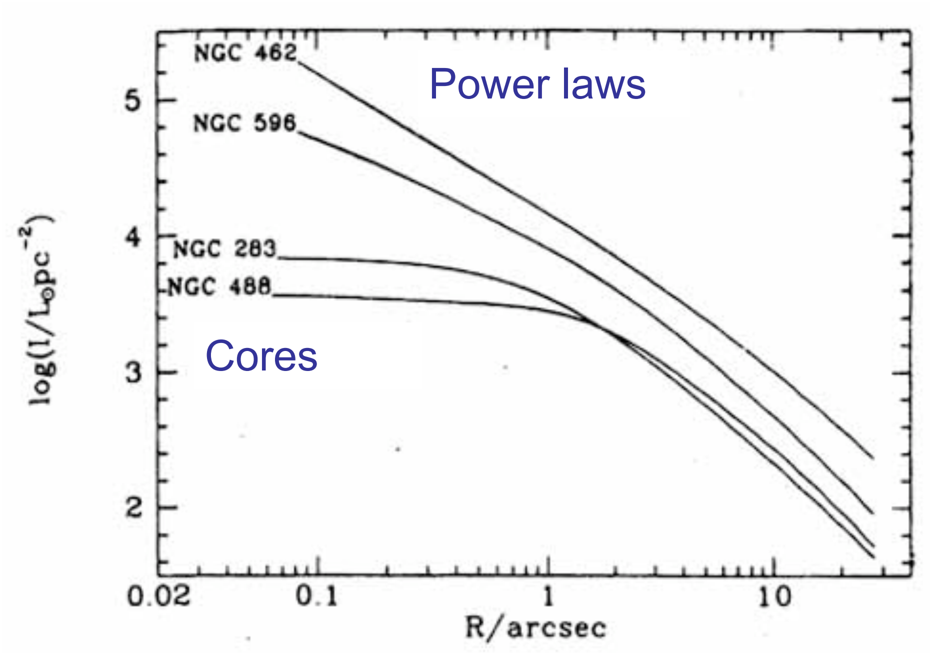
Looking closer at the elliptical galaxy light profiles it was found that a *Sersic law* provides a better fit to the data that $R^{1/4}$:

$$I(R) = I_e \exp\left(-b\left[(R/R_e)^{1/n} - 1\right]\right)$$

where (n) is the *Sersic index* (N.B. n=4 for $R^{1/4}$ law); typical fitted vales fall in the range n=4 to 6.

Elliptical galaxy inner light profiles - I

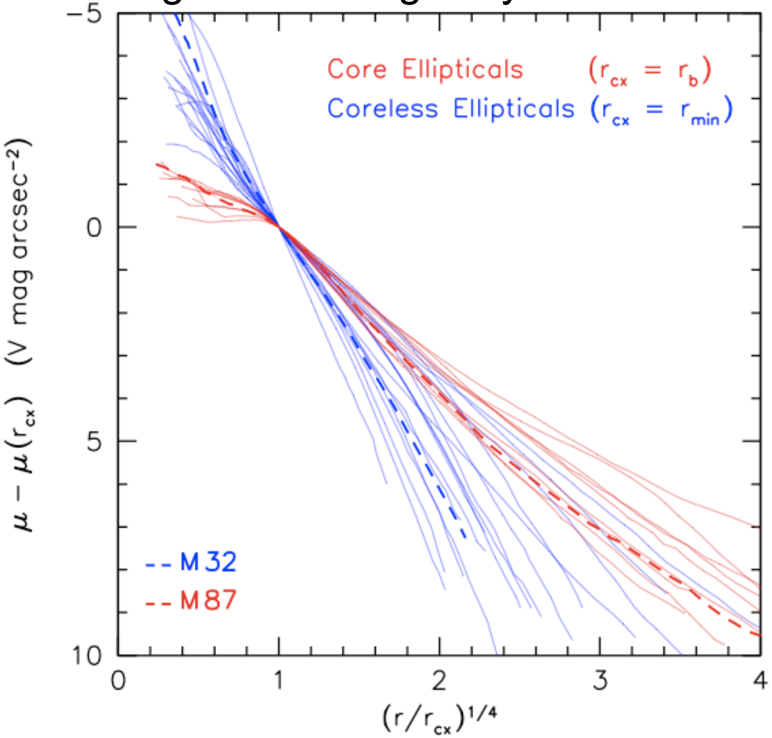




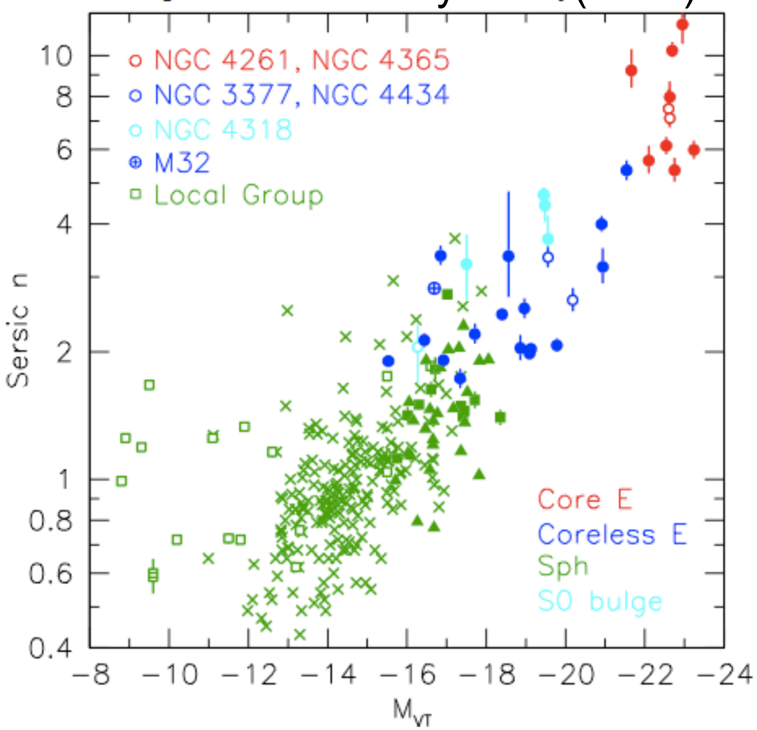
High resolution imaging observations with the HST have revealed that some E-galaxies show large departures from a $R^{1/4}$ law in their central regions (r < 1 arcsec). Some show shallow profiles with a deficit of light at small radii (“cores”), while others show steeply rising power laws (“power laws”).

Elliptical galaxy inner light profiles - II

Virgo cluster E galaxy results



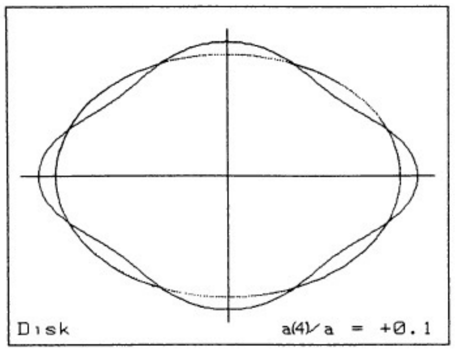
Kormendy et al. (2009)

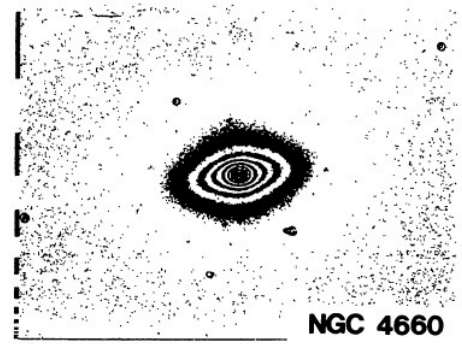


Elliptical galaxies fall into two groups: those with cores, and those without. The core galaxies have high luminosities (Mv <-20.5) whereas the power law galaxies (coreless) have lower luminosities (Mv >-20.5).

Detailed shapes of ellipticals: boxy vs. disky

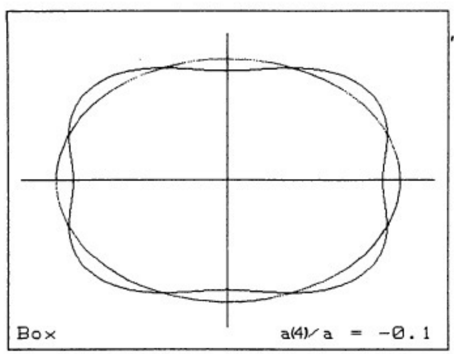
$a_4 > 0.0$

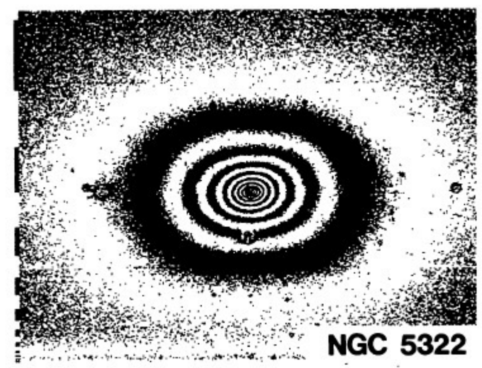




Disky Elliptical

$a_4 < 0.0$





Boxy Elliptical

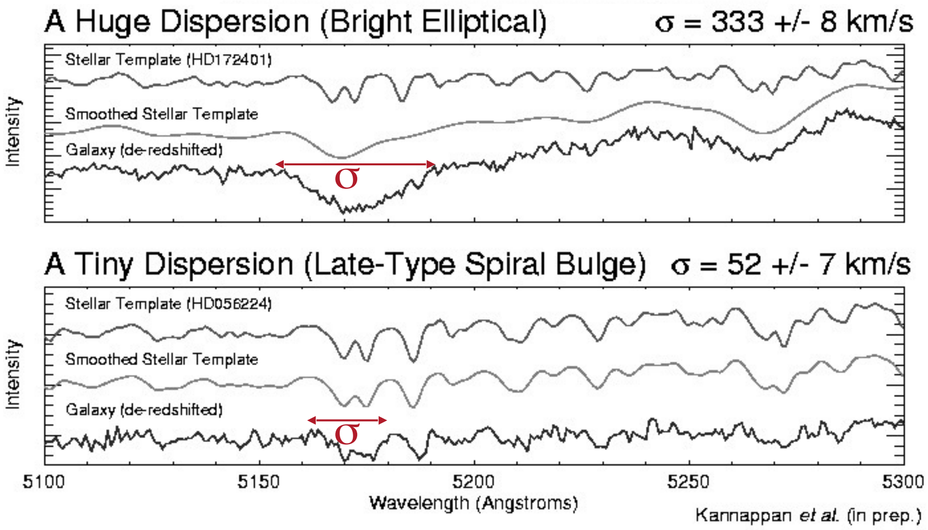
Fit fourier series to departures from elliptical isophotes:

$$\Delta r(\theta) \approx \sum_{k \geq 3} a_k \cos k\theta + b_k \sin k\theta$$

$a_4 > 0.0 \rightarrow$ Disky ellipticals

$a_4 < 0.0 \rightarrow$ Boxy ellipticals

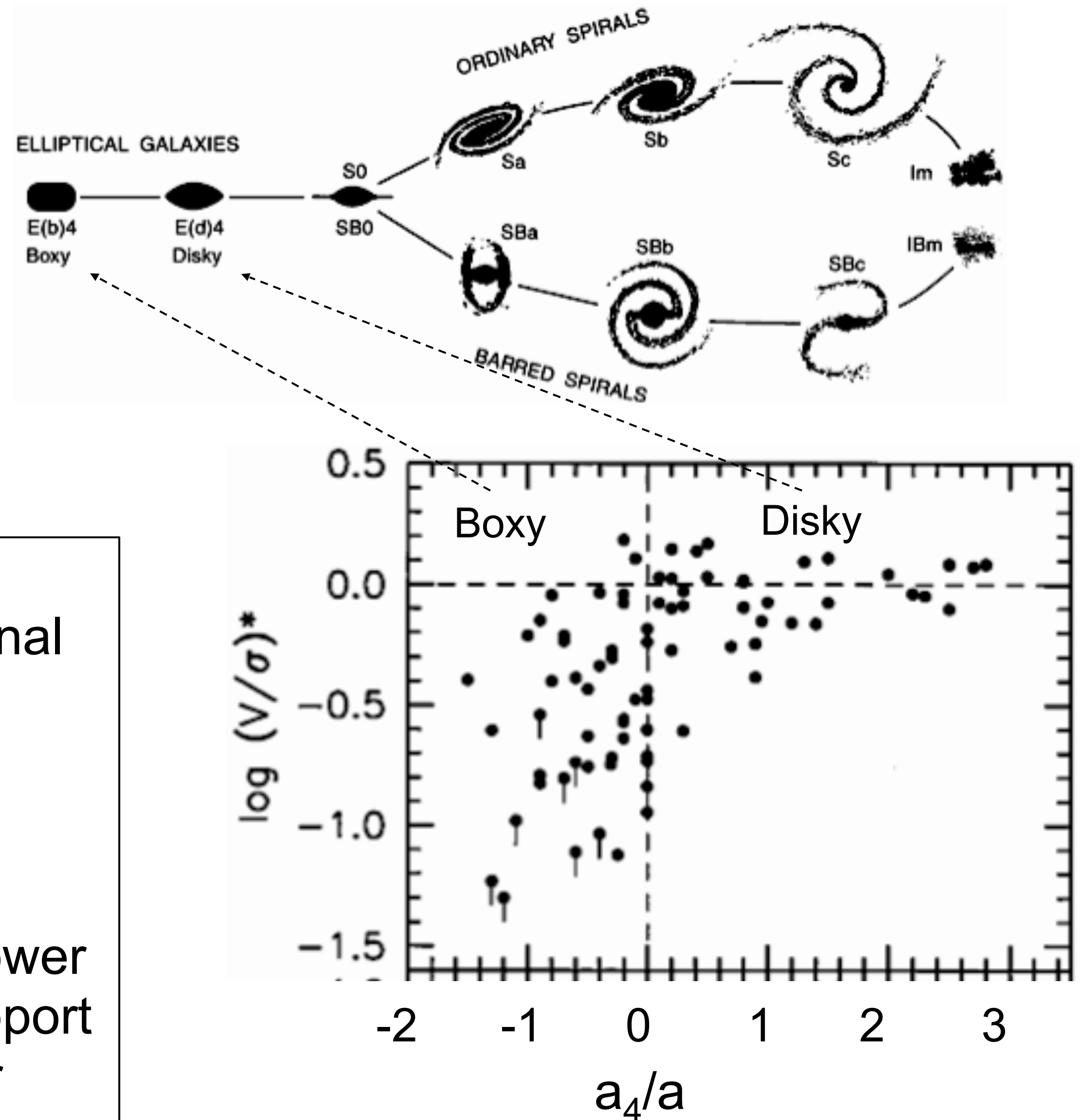
Stellar kinematics in elliptical galaxies



There is little evidence for rapid rotation in most elliptical galaxies. They are supported against collapse mainly by the random (dispersive) motions of their stars. These motions are quantified in terms of the velocity dispersion (σ).

Some rotation can be measured in some E galaxies, but in general they have $V_c/\sigma \leq 1$, compared with $V_c/\sigma > 5$ for stars in spiral galaxy disks.

Links between the shapes and kinematics of E galaxies



Kormendy & Bender (1996)

Disky galaxies have a higher degree of rotational support ($V_{rot}/\sigma \sim 1$), and tend to have lower luminosities ($M_v > -20.5$).

Boxy galaxies have a lower degree of rotational support and tend to have higher luminosities ($M_v < -20.5$).

Two families of elliptical galaxies

Disky

- Disky isophotes ($a_4>0$)
- Low luminosity ($M_v>-20.5$)
- Power-law inner profiles
- Significant rotational support ($V_c/\sigma\sim1$)
- Formed in highly dissipative mergers of gas-rich galaxies?

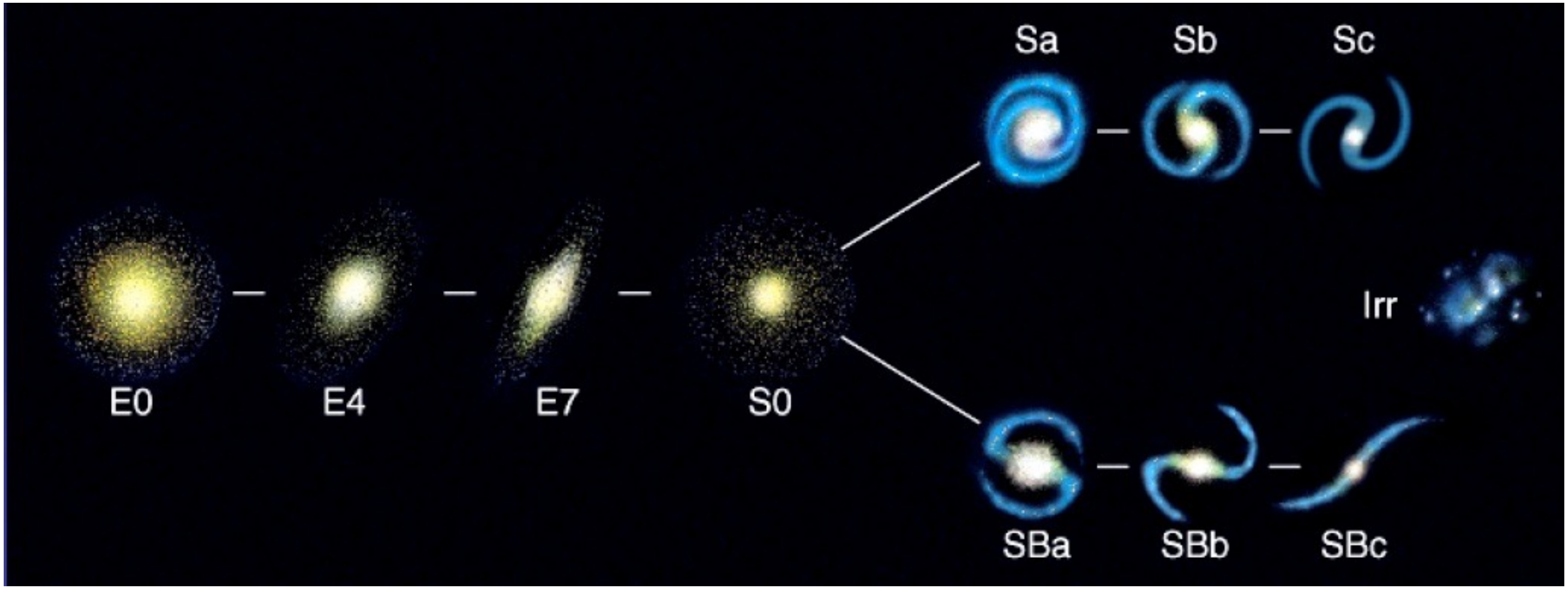
Boxy

- Boxy isophotes ($a_4<0$)
- High luminosity ($M_v<-20.5$)
- Core inner profiles
- Supported mainly by dispersion ($V_c/\sigma<1$)
- Most stars formed in at high redshift ($z>3$), subsequent growth via “dry” mergers of gas-poor (early-type)

Summary of early-type galaxy fossil record

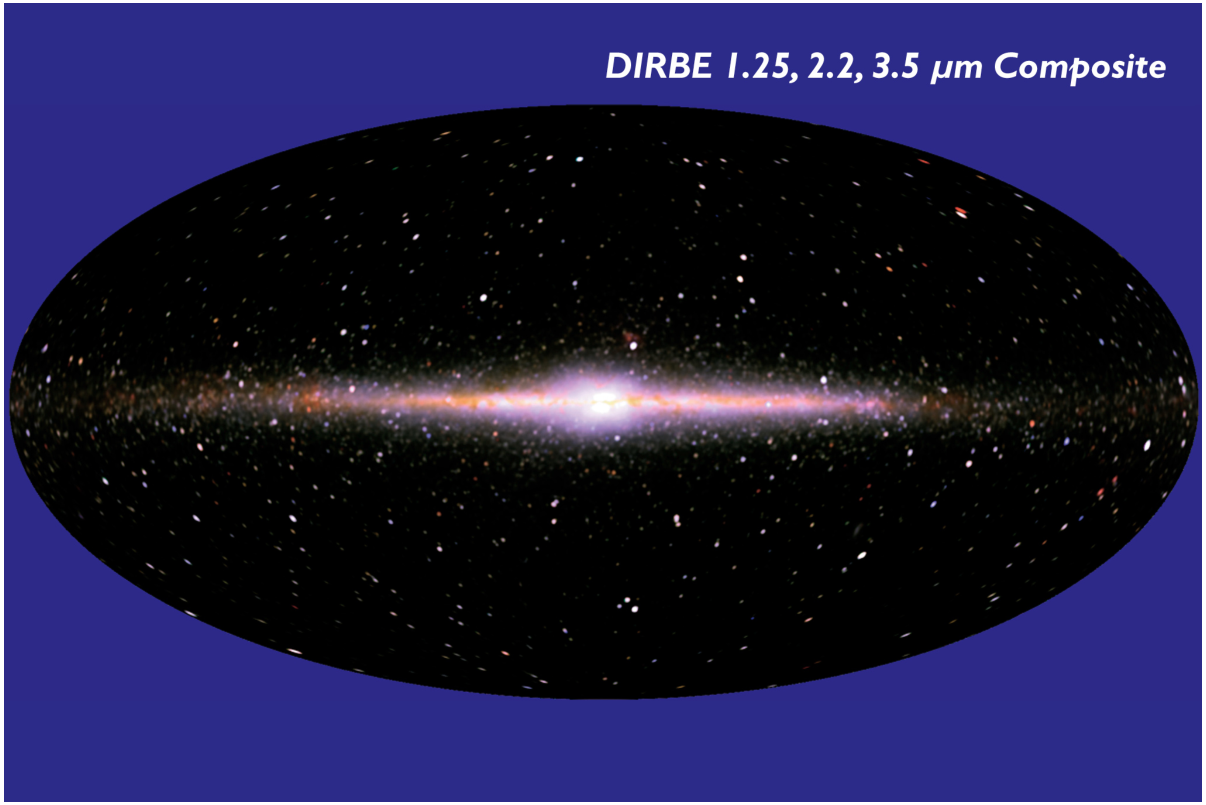
- More massive ellipticals appear redder due to their ability to “hold on” to more metal-rich gas from which later stars form.
- The two main families of elliptical (boxy and disky) have probably evolved in different ways
- An early formation epoch (z>3) for the bulk of the stellar populations in nearby Boxy ETG is suggested by:
    - optical spectral characteristic of old stellar populations;
    - the tightness of the colour-magnitude and colour-σ relationships.
- Disky ETG may have formed by dissipative mergers since z=1.
- “Cores” of Disky Ellipticals are “re-populated” by stars during a gar-rich merger, but not in the gas-poor mergers that form Boxy ellipticals.
-

Galaxy morphologies: Hubble sequence



Late type galaxies

COBE near-IR image of the Milky Way

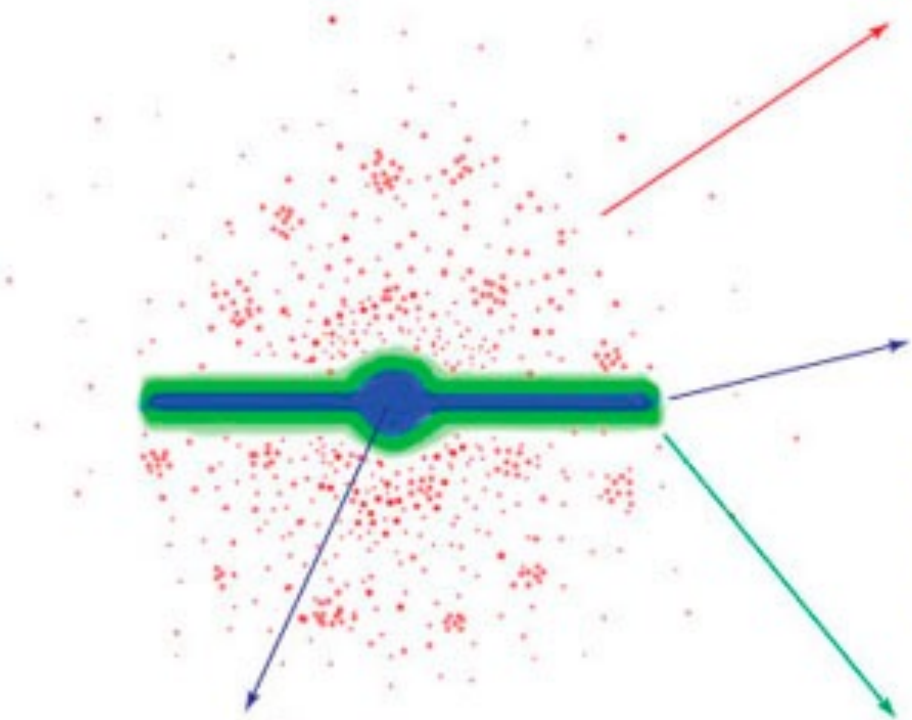


Judging from the relative prominence of its bulge, the Milky Way is likely to be an Sbc or Sc galaxy; it has also been suggested on the basis of the shape and asymmetry of its bulge that the MW has a weak bar.

Tracers of stellar populations

- Space motions (kinematics): the velocities of stars relative to the Sun (e.g. Pop I have low radial velocities relative to Sun, while Pop II have large radial velocities)
- Metal abundances ([Fe/H]): since metals are formed in stars, the relative metal abundances measured in stellar atmospheres depend on age and SF history
- Positions and distances relative to Galactic centre (distances known accurately for nearby stars with parallaxes and for stars in clusters)
- Ages: these are difficult to measure from the spectra of individual stars (though possible in some cases), but can be accurately estimated for stars in clusters

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)

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

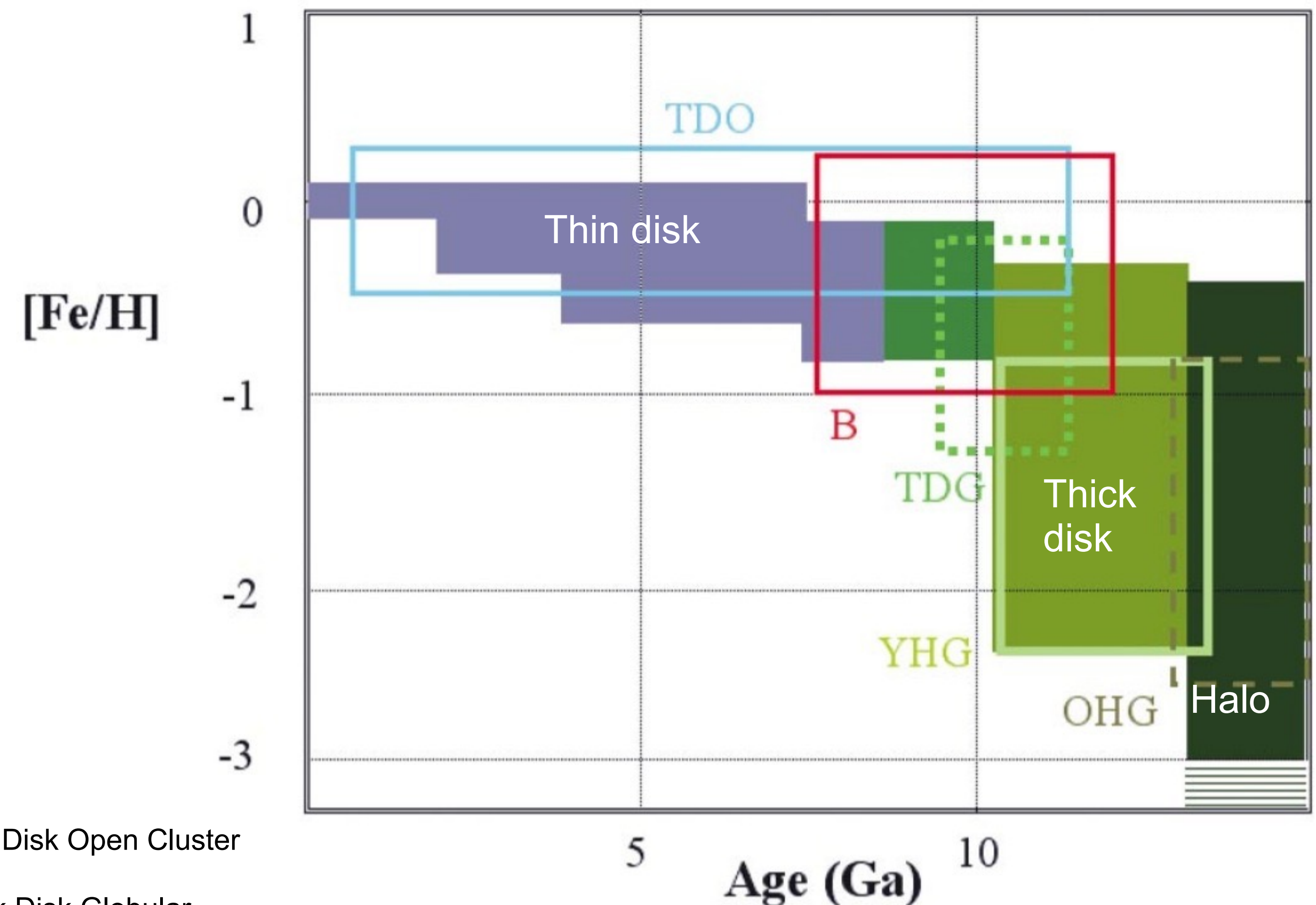
Intermediate Population II or Thick Disk

$\rho(z) \propto e^{-z / 1000\,pc}$
(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

Metallicities and ages of different parts of MW

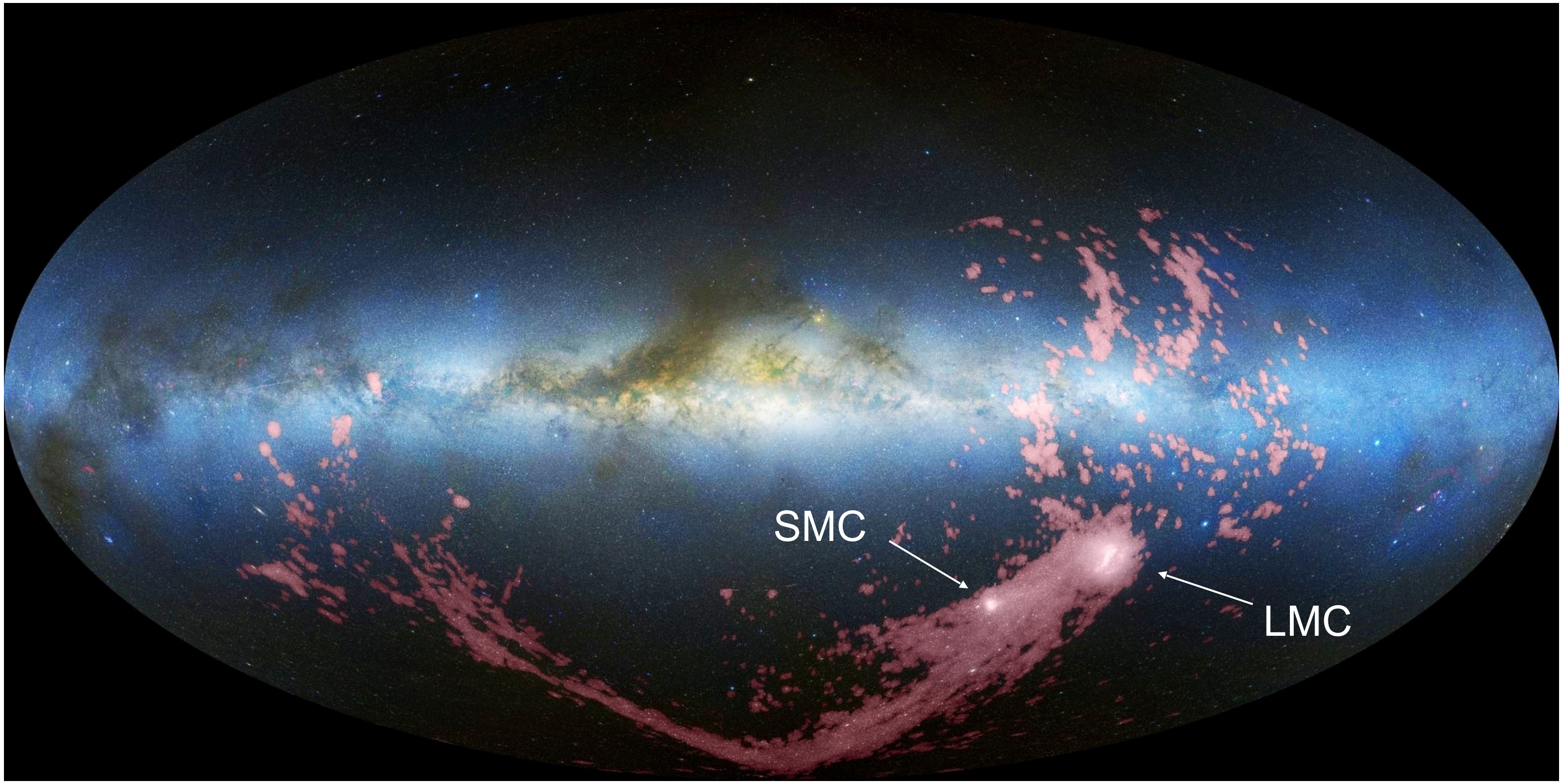


TDO -- Thin Disk Open Cluster
B -- Bulge
TDG -- Thick Disk Globular
YHG -- Young Halo Globular
OHG -- Old Halo Globular

Modern theory for the formation of the Milky Way

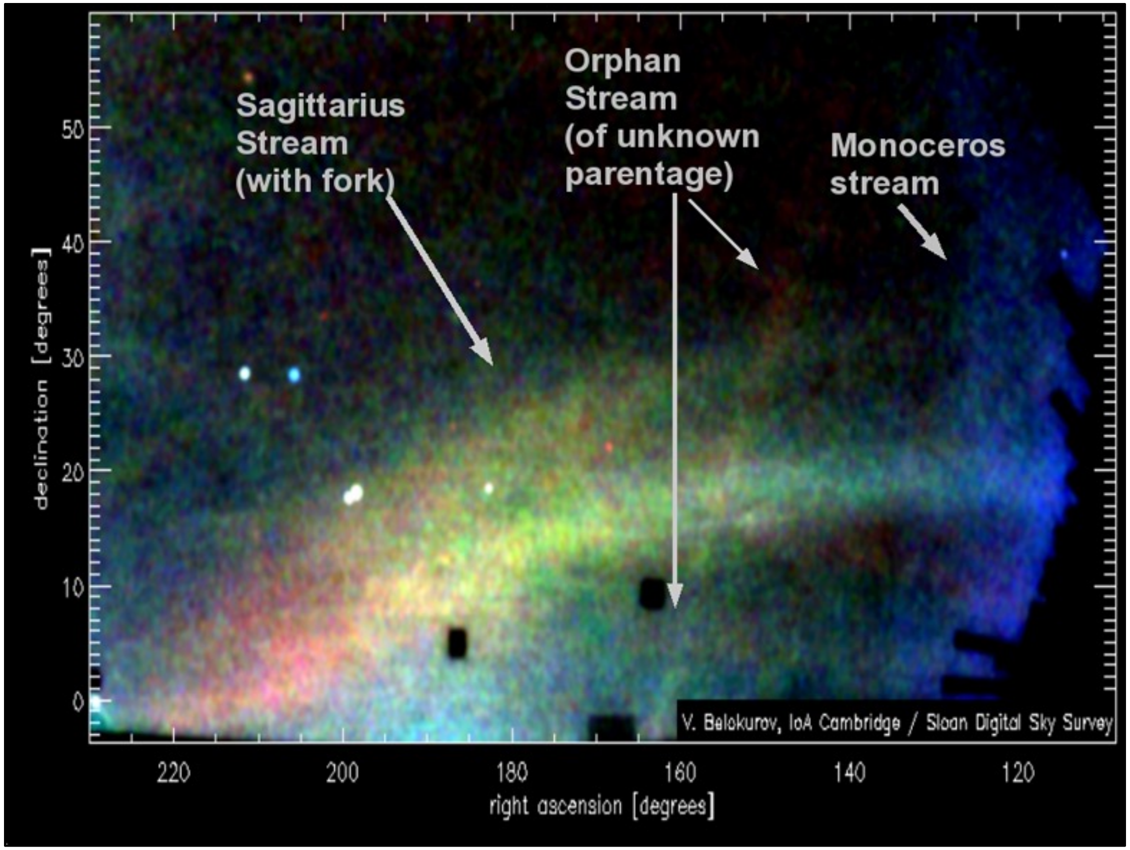
- The Thin Disk. Formed from the *dissipational collapse* of the natal gas cloud. Star formation has continued in the thin disk since it formed > 8 Gyr ago.
- The Thick Disk. Formed from the disruption (heating) of the early thin disk by the accretion of a satellite galaxy ~8 -12 Gyr ago. The thick disk therefore provides a snapshot of conditions in the early thin disk.
- The Bulge. Likely to have a complex formation history: a combination of the early collapse of the natal cloud, and later satellite accretion.
- The Halo. Many of the halo stars may have been formed in satellite galaxies that were then accreted by the MW, but difficult to rule out the idea that some of the halo stars with low abundance formed in the natal cloud before it collapsed.

Milky Way Tidal Streams - The Magellanic Stream

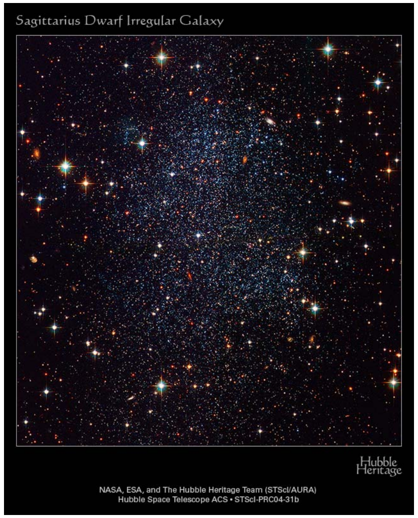


Detected as high velocity gas ($-400 < v_{lsr} < +400$ km/s) in HI 21cm observations, the Magellanic stream is thought to represent the *tidal disruption* of the Magellanic clouds by the gravitational field of the MW.

Milky Way Tidal Streams - The Sagittarius Stream

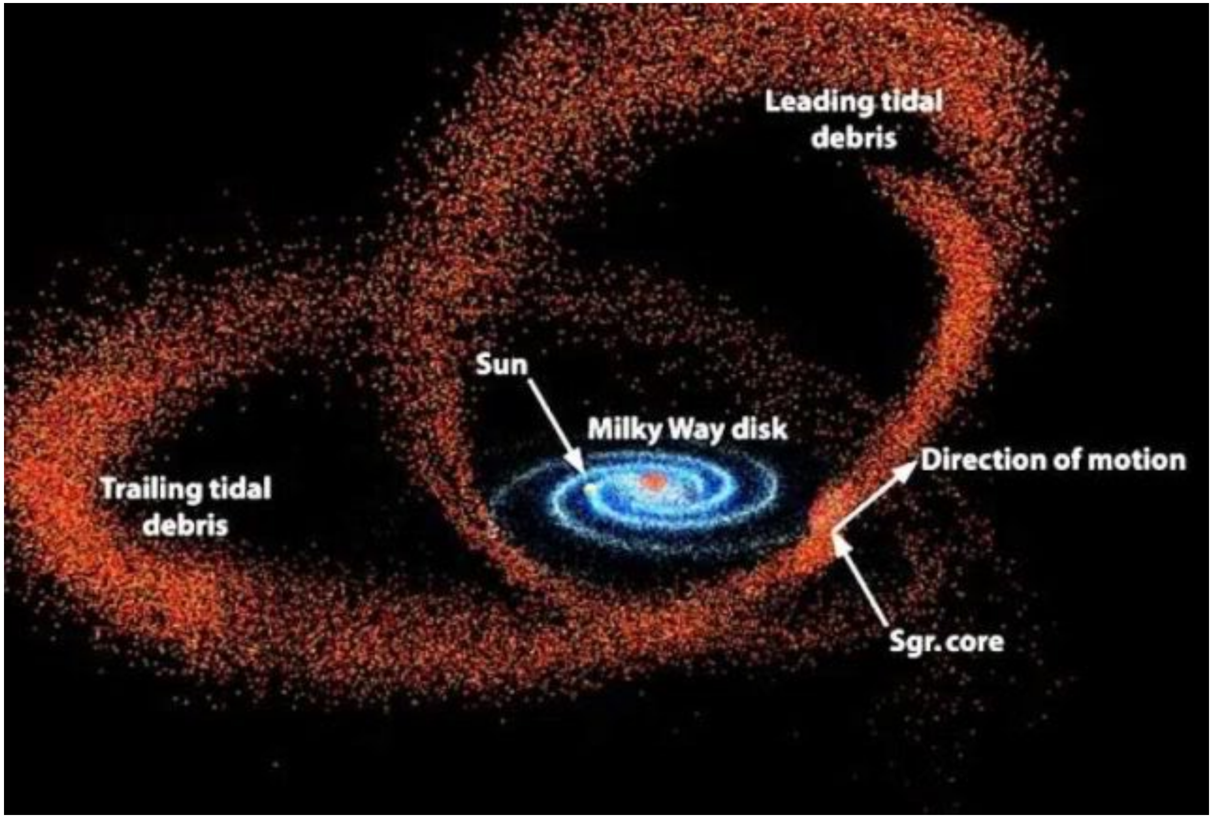


By careful examination of the magnitudes and colours of millions of stars detected in the Sloan Digital Sky Survey (SDSS) it has proved possible to detect streams of stars around the MW.



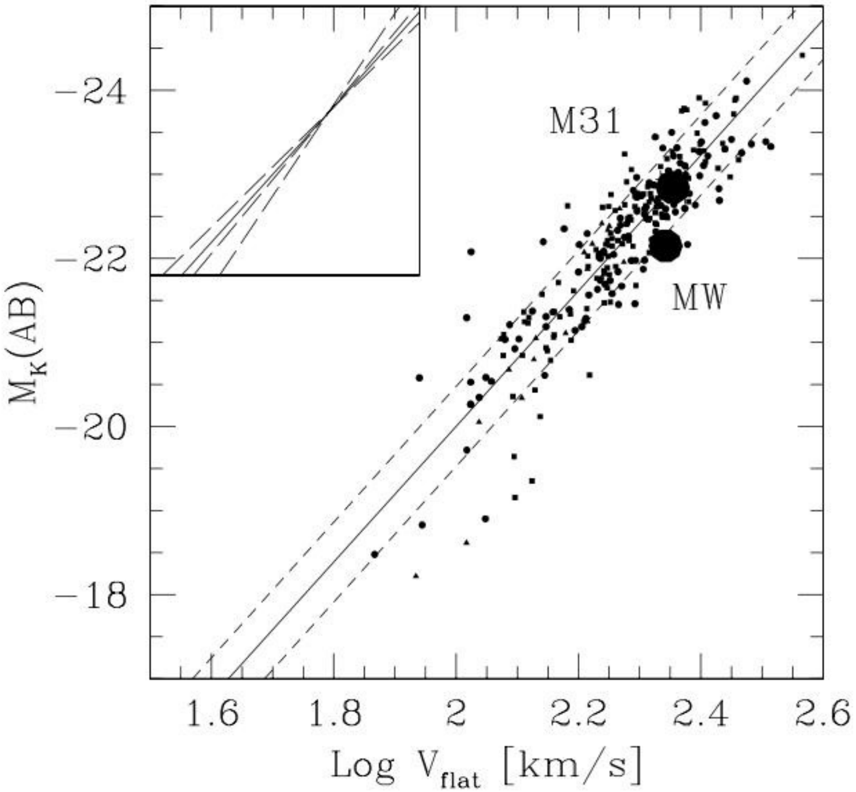
The brightest stream in this “field of streams” connects with the Sagittarius dSph satellite, and is thought to represent the tidal disruption of that galaxy by the MW.

Milky Way Tidal Streams - Significance



The various streams around the MW are formed by tidal disruption of satellite galaxies -- a form of “galactic cannibalism”. Parts of the MW halo and bulge may have formed from such accretion of satellites -- consistent with the Searle & Zinn model for the formation of the MW.

Is the Milky Way a typical spiral galaxy?



Hammer et al. (2007)

The Milky Way falls significantly *below* the Tully Fischer relationship for nearby spiral galaxies.

It has been suggested that this may be because, unlike most spiral galaxies, the MW has undergone relatively few major mergers in the last 10 Gyr.

The Sloan Digital Sky Survey (SDSS)

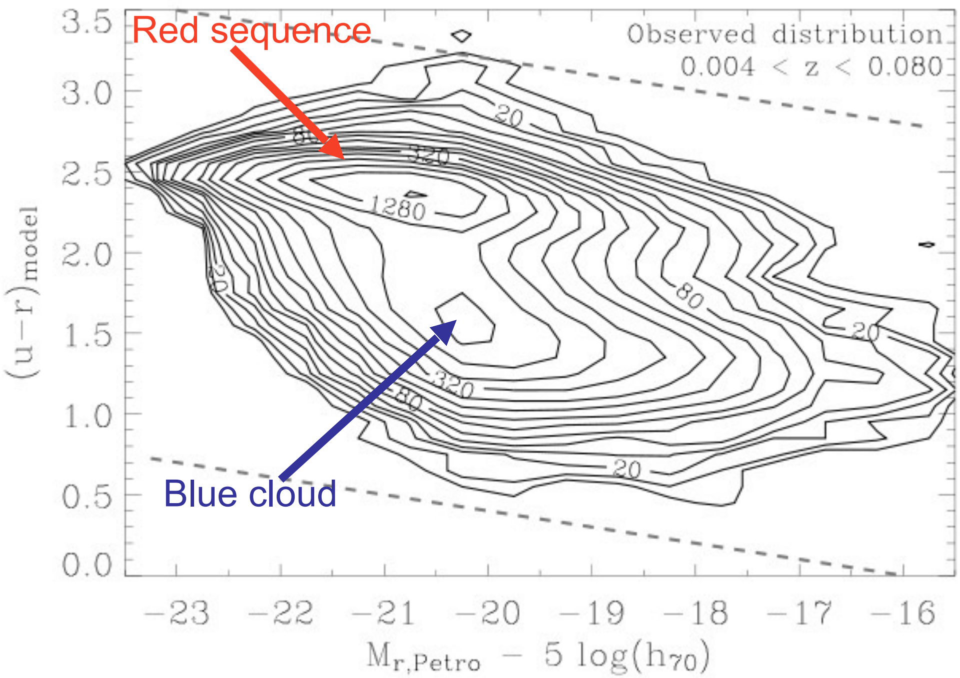
- 2.5m telescope with 1.5 square degree field of view.
- Has covered 14,555 square degrees (~33% of the sky) with deep, multi-colour imaging and spectroscopy observations.
- Fibre-fed multi-object spectrographs capable of observing 600 galaxies in a single observation.
- So far, high quality spectra have been taken for more than 800,000 galaxies, 100,000 quasars and 185,000 stars.

Sloan Telescope, Apache Point, New Mexico

The colour-magnitude diagram for nearby galaxies

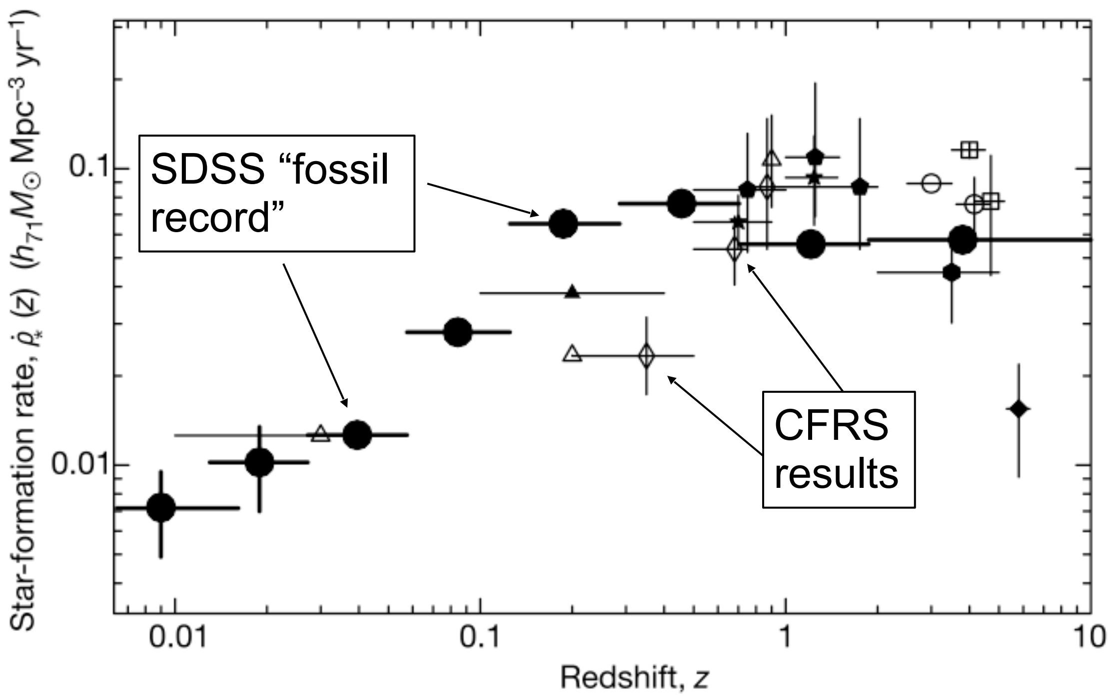
In colour-magnitude diagrams derived using SDSS data, galaxies have a bimodal distribution:

- red sequence (mainly early-type galaxies);
- blue cloud (mainly late-type and star forming galaxies)



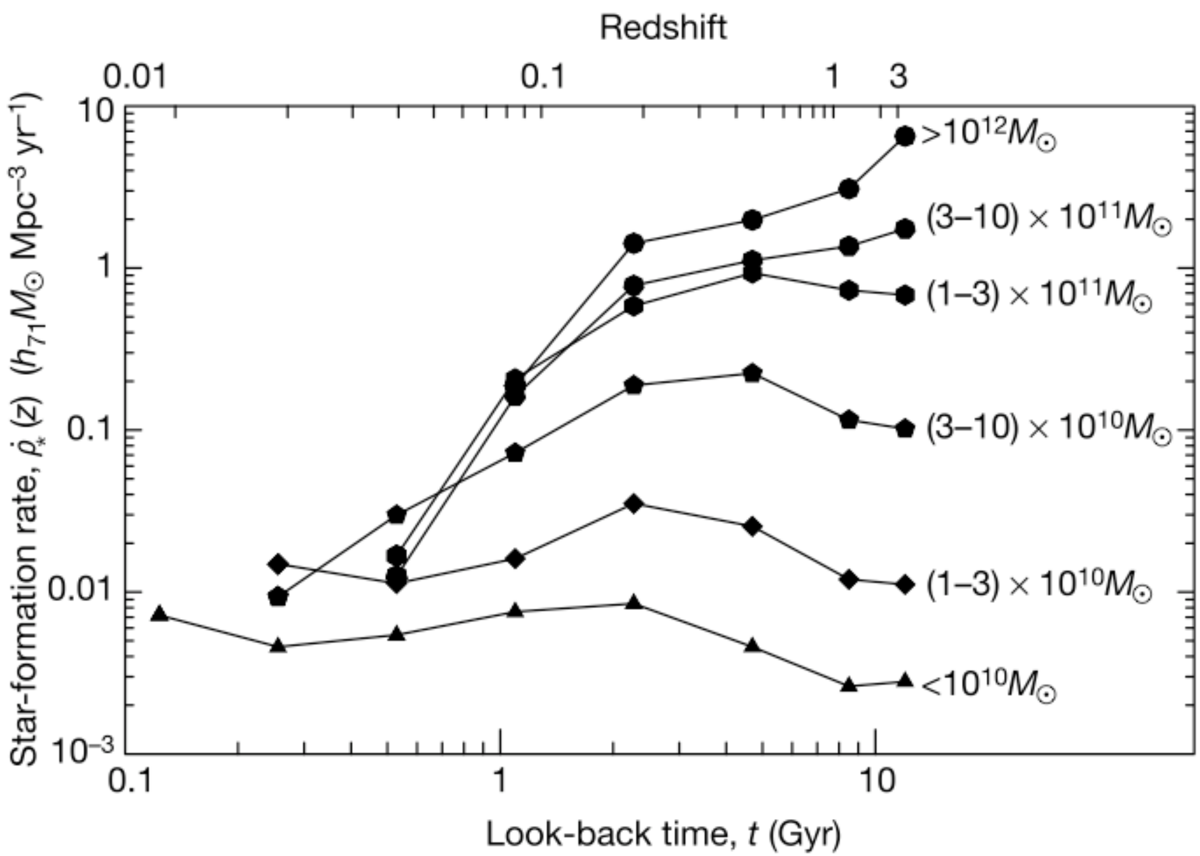
The star formation history of the Universe based on the fossil record

It is possible to gain information about the star formation histories of individual galaxies based on spectral synthesis model fits to their optical spectra. Using fits to the spectra of ~100,000 local galaxies at z < 0.34 from the SDSS survey ("the fossil record"), Heavens et al. (2004) have determined the star formation history of the Universe, by summing together the star formation histories of the individual galaxies.



Mass dependence of the star formation history based on the fossil record

Heavens et al. (2004)



The SDSS fossil record supports the idea that the most massive galaxies formed their stars early, and moderate/low mass galaxies later. However, it is notoriously difficult to obtain unique fits with spectral synthesis models. Therefore the results should be treated with caution.

Lecture 5: learning objectives

- Knowledge of what detailed observations of nearby galaxies (the “fossil record”) tells us about the evolution of both spiral and elliptical galaxies
- An appreciation of how less detailed (statistical) studies of large samples of galaxies in the local Universe aid our understanding of galaxy evolution
- Familiarity with the concept of cosmic downsizing