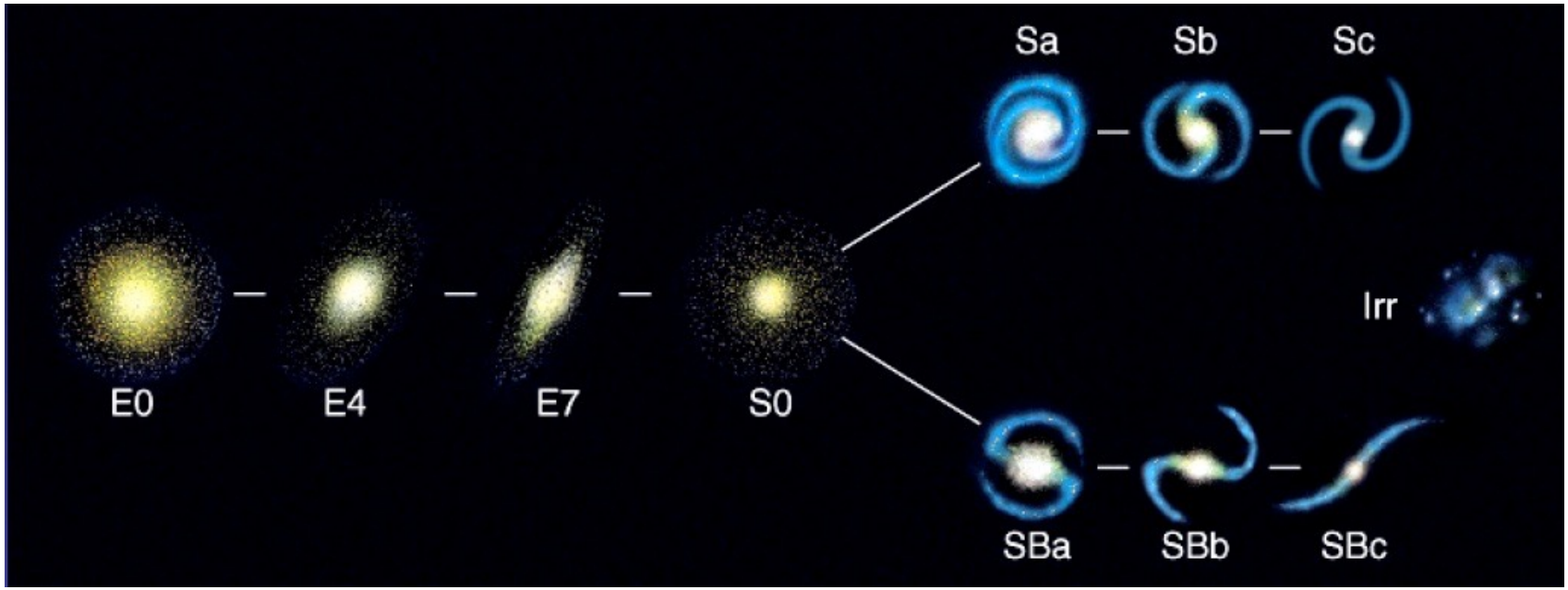
Galaxy Formation and Evolution
Lecture 09:
The evolution of early-type galaxies

Course contents

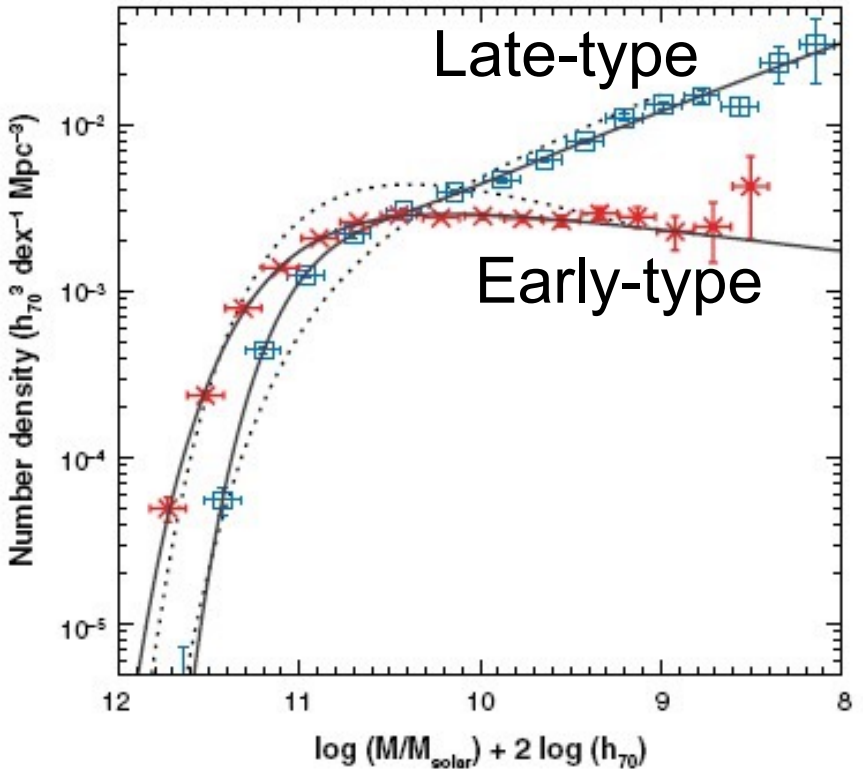
1. Historical introduction
2. Challenges and recent advances
3. Galaxy formation in theory
4. Spectral synthesis and star formation indicators
5. The fossil record for local galaxies
6. Survey astronomy
7. The Madau Diagram and Lyman Break galaxies
8. Studying galaxy evolution in the IR/sub-mm
9. The evolution of early-type galaxies
10. Morphological evolution and spiral galaxies
11. AGN discovery and observed properties
12. AGNs and supermassive black holes
13. Black hole growth and formation
14. The triggering of AGN
15. AGN feedback and outflows
16. The link between star formation and AGN activity
17. The far frontier and outstanding challenges
18. The future of the Universe



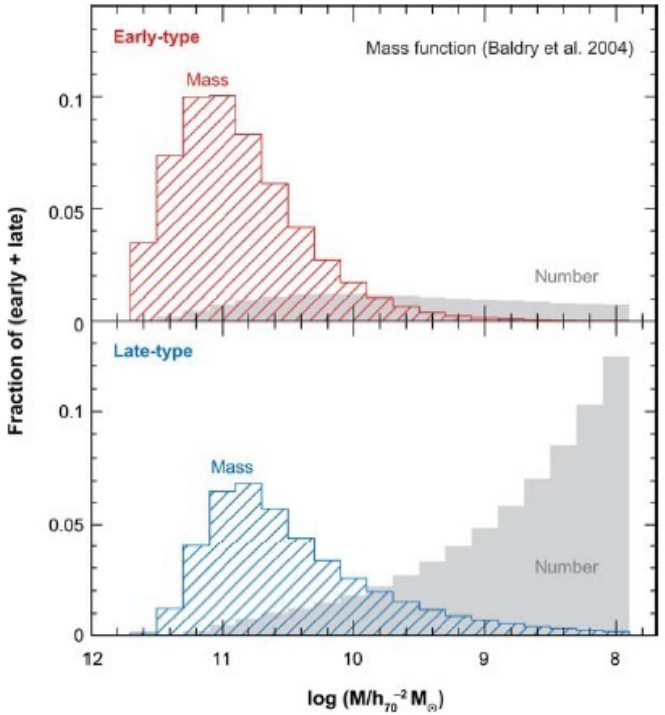
Consider early-type galaxies galaxies (E/SO) together (it's difficult to distinguish between E and S0 types at

Mass contribution of early-type galaxies

Volume number density of early- and late- type galaxies in local Universe



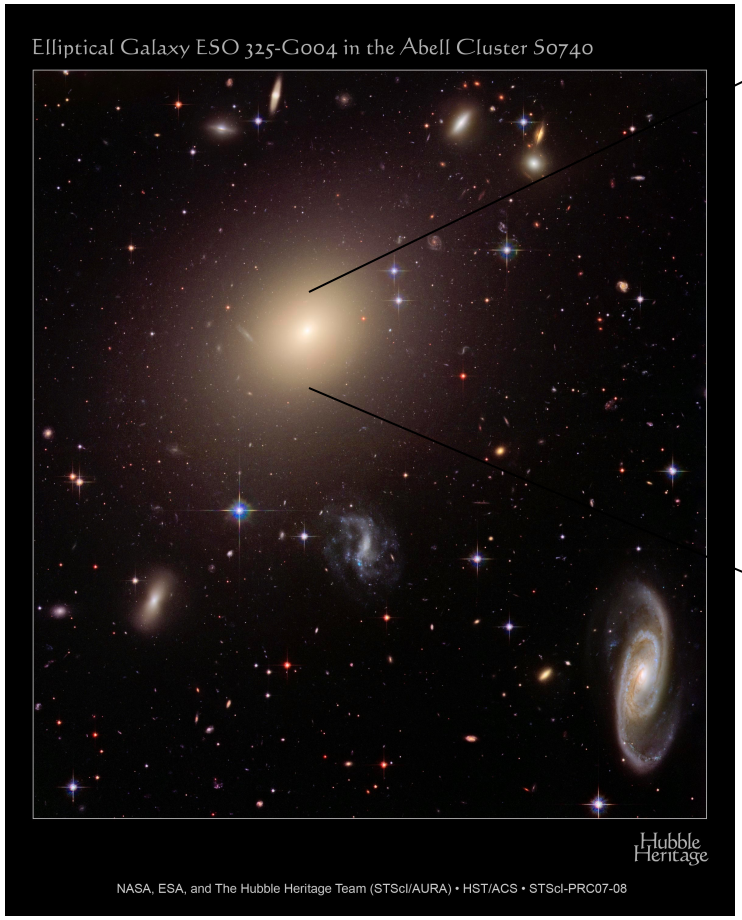
Proportion of total stellar mass in local Universe contributed by galaxies with different individual masses

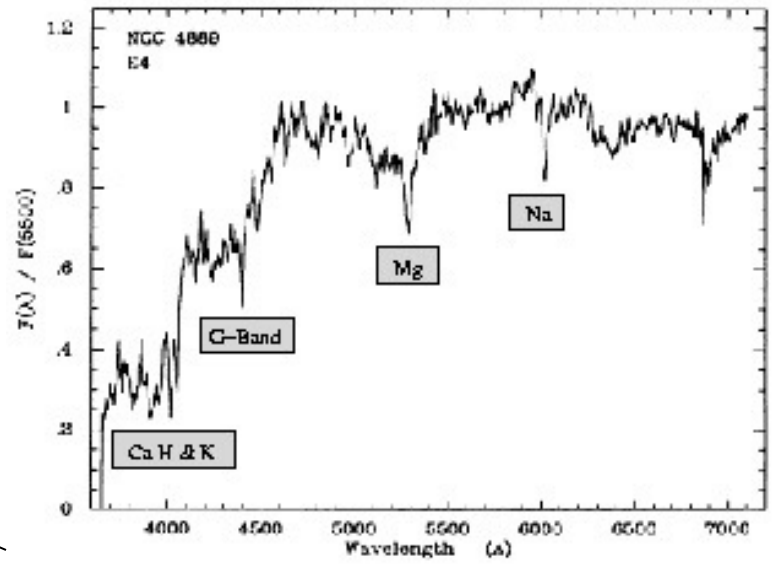


Early-type galaxies contribute ~50%, while spheroids (early-type galaxies+spiral bulges) contribute 50 - 70%, of the total stellar mass in the local Universe.

Elliptical galaxies the fossil record I

Optical spectra: old, red and dead?

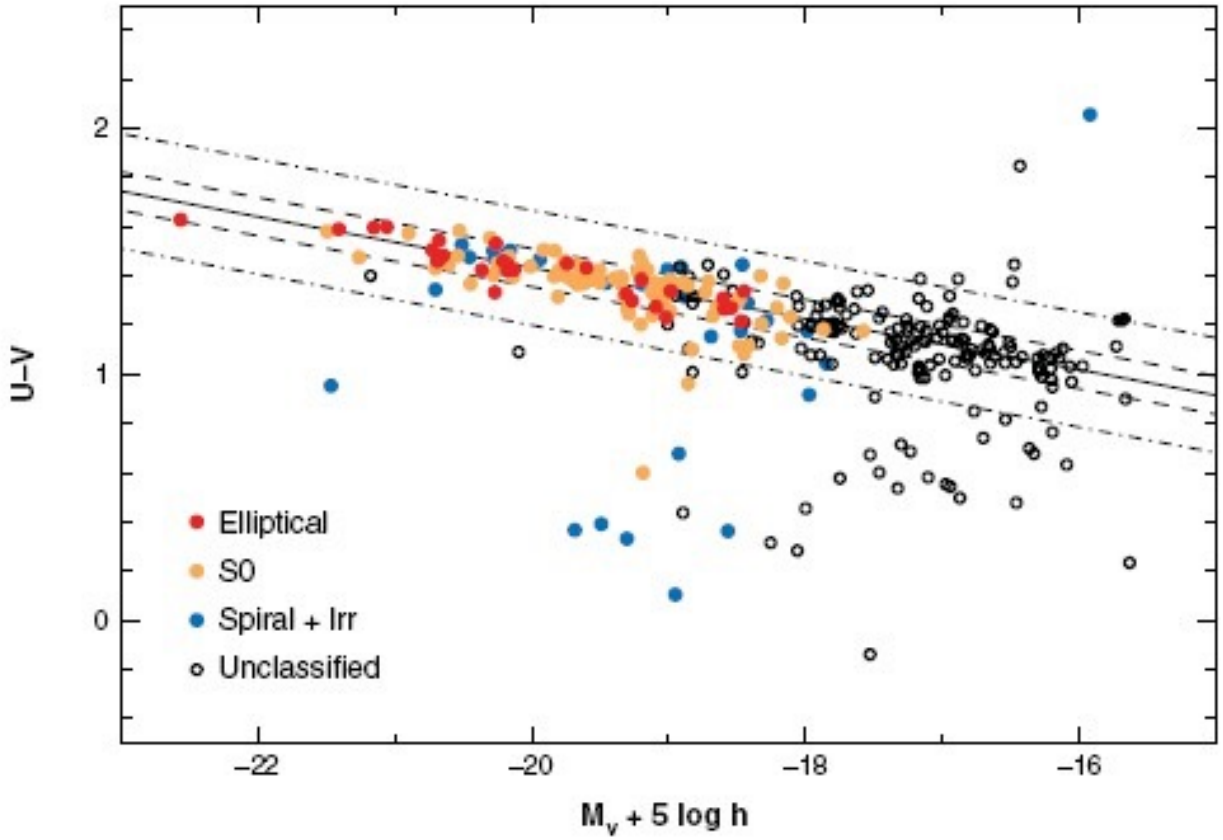




The majority of nearby ellipticals (>70%) have spectra characteristic of old stellar populations: they are red, with strong metal lines. Spectral synthesis fits suggest ages >8Gyr.

Elliptical galaxies: the fossil record II.

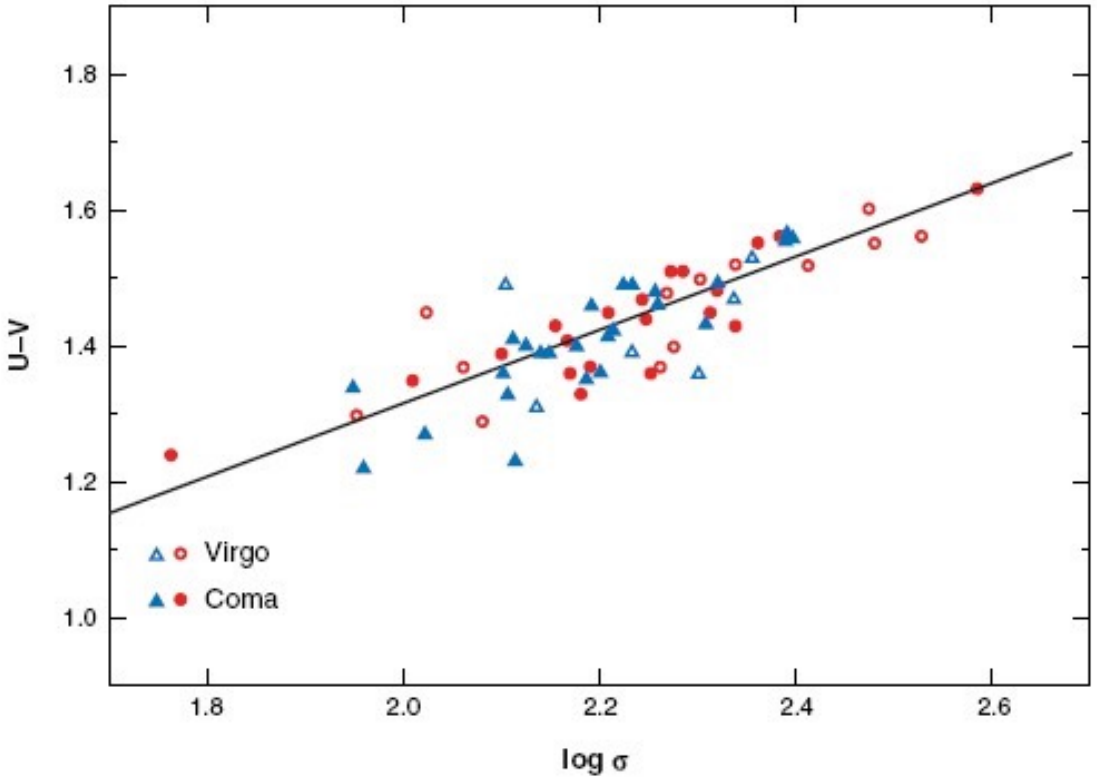
The colour-magnitude diagram for nearby clusters



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

Elliptical galaxies: the fossil record.

The colour-σ diagram for nearby clusters

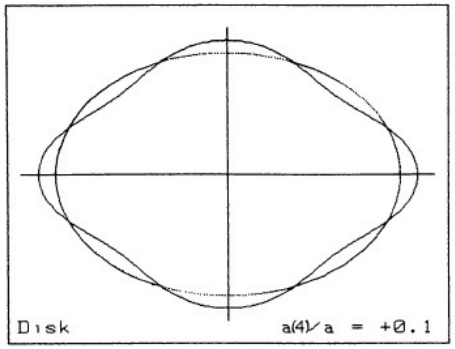


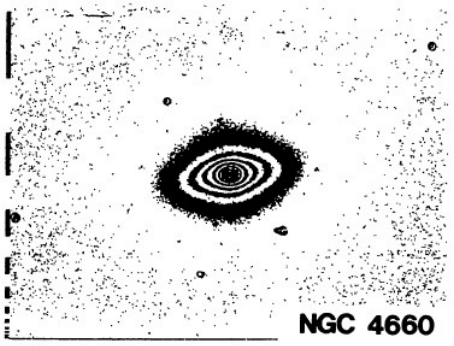
The tightness of the colour-magnitude and colour-σ relationships in clusters suggest an early formation epoch for cluster E/SO galaxies.

Elliptical galaxies: the fossil record IV

Detailed morphologies

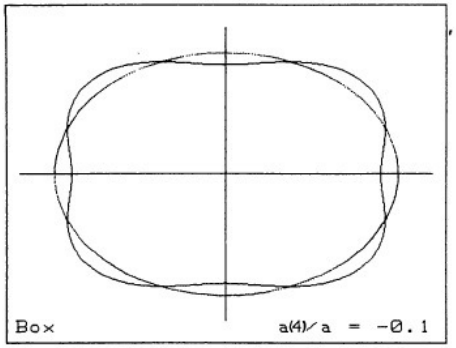
a_4>0.0

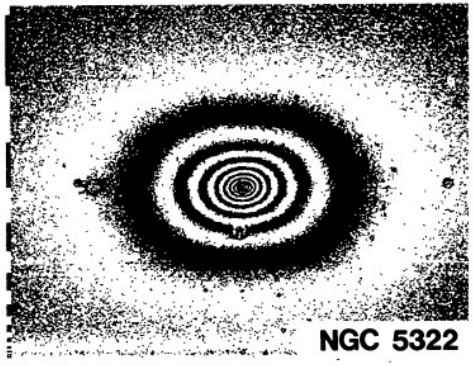




Disky Elliptical

a_4<0.0





Boxy Elliptical

Fit fourier series to departure from purely elliptical isophotes:

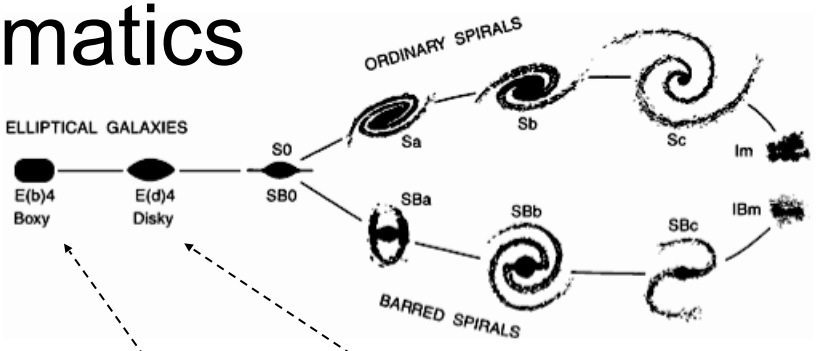
$$\Delta r(\theta) \approx \sum_{k \geq 3} a_k \cos k\theta + b_k \sin k\theta$$

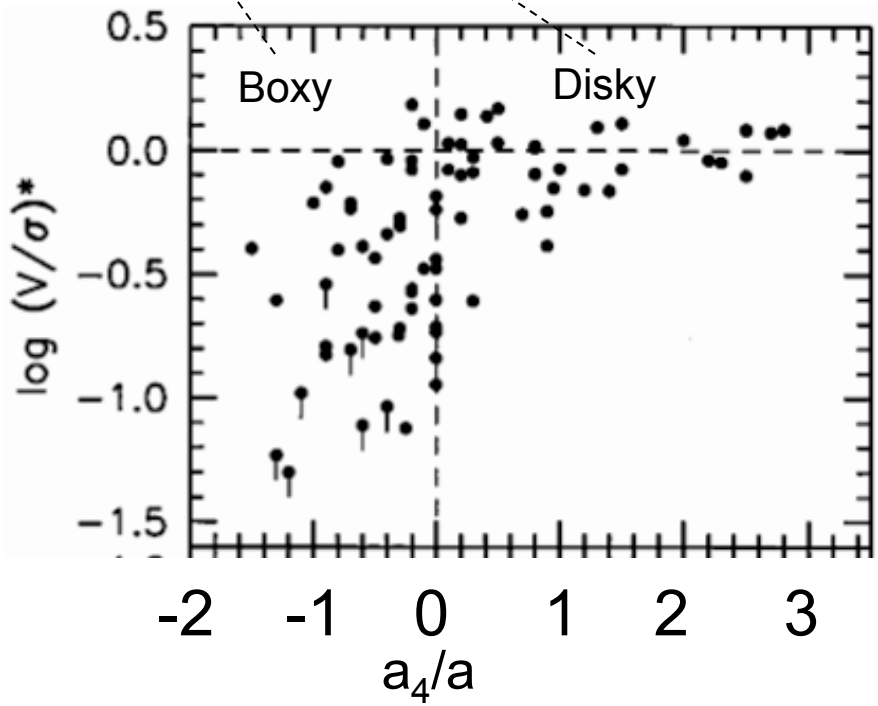
a_4>0.0 → Disky ellipticals

a_4<0.0 → Boxy ellipticals

Elliptical galaxies: the fossil record IV

Morphologies and kinematics





Disky galaxies have a high degree of rotational support (V_{rot}/σ~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).

Kormendy & Bender (1996)

Two families of elliptical galaxies

Disky

- Disky isophotes ($a_4>0$)
- Low luminosity ($M_V>-20.5$)
- Power-law inner profiles
- Significant rotational support ($V_c/\sigma\sim1$)
- Contain little hot, X-ray emitting gas
- Formed in highly dissipative mergers of gas-rich galaxies?

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Boxy

- Boxy isophotes ($a_4<0$)

Two families of elliptical galaxies

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- » Low luminosity ($M_v>-20.5$)
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- » Significant rotational support ($V_c/\sigma\sim1$)
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Boxy

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- High luminosity ($M_v<-20.5$)

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Boxy

- Boxy isophotes ($a_4<0$)
- High luminosity ($M_v<-20.5$)
- Core inner profiles

Two families of elliptical galaxies

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- Low luminosity ($M_v>-20.5$)
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Boxy

- Boxy isophotes ($a_4<0$)
- High luminosity ($M_v<-20.5$)
- Core inner profiles
- Supported mainly by dispersion ($V_c/\sigma<1$)

Two families of elliptical galaxies

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

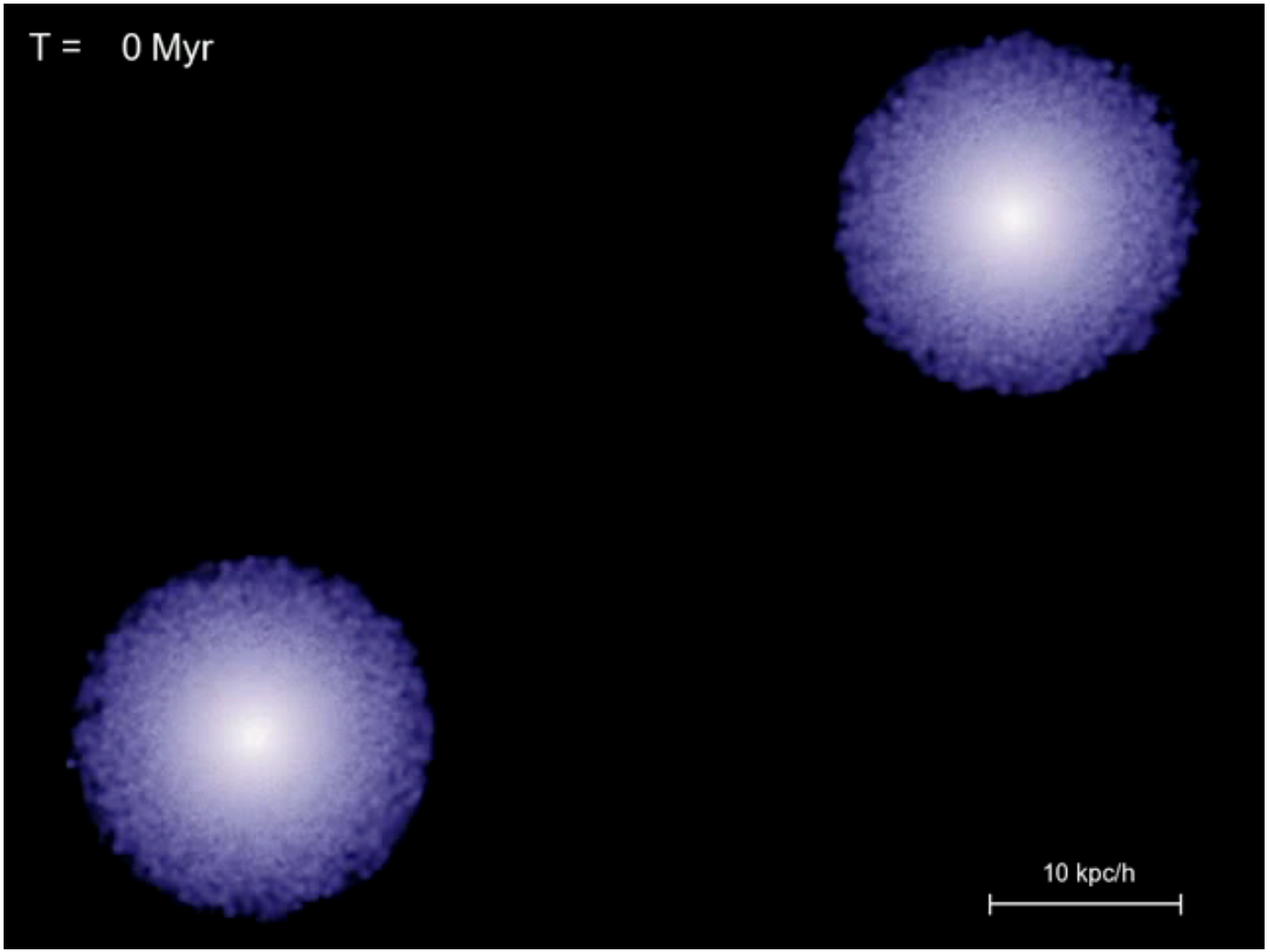
Summary of early-type galaxy fossil record

- 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, luminous (boxy) ETG is suggested by:
  - optical spectral characteristic of old stellar populations;
  - the tightness of the colour-magnitude,colour-σ, and fundamental plane relationships.
- Some disky ETG may have formed by dissipative mergers since z=1.
- But age and metallicity both have a similar effect on the spectra of old stellar populations (*age-metallicity degeneracy*) e.g. a high metallicity/intermediate age stellar population can have a similar spectrum to a lower metallicity/older age stellar population.
- This age-metallicity degeneracy leads to ambiguity in interpreting the fossil record in nearby ETGs.

Early-type galaxies forming locally?

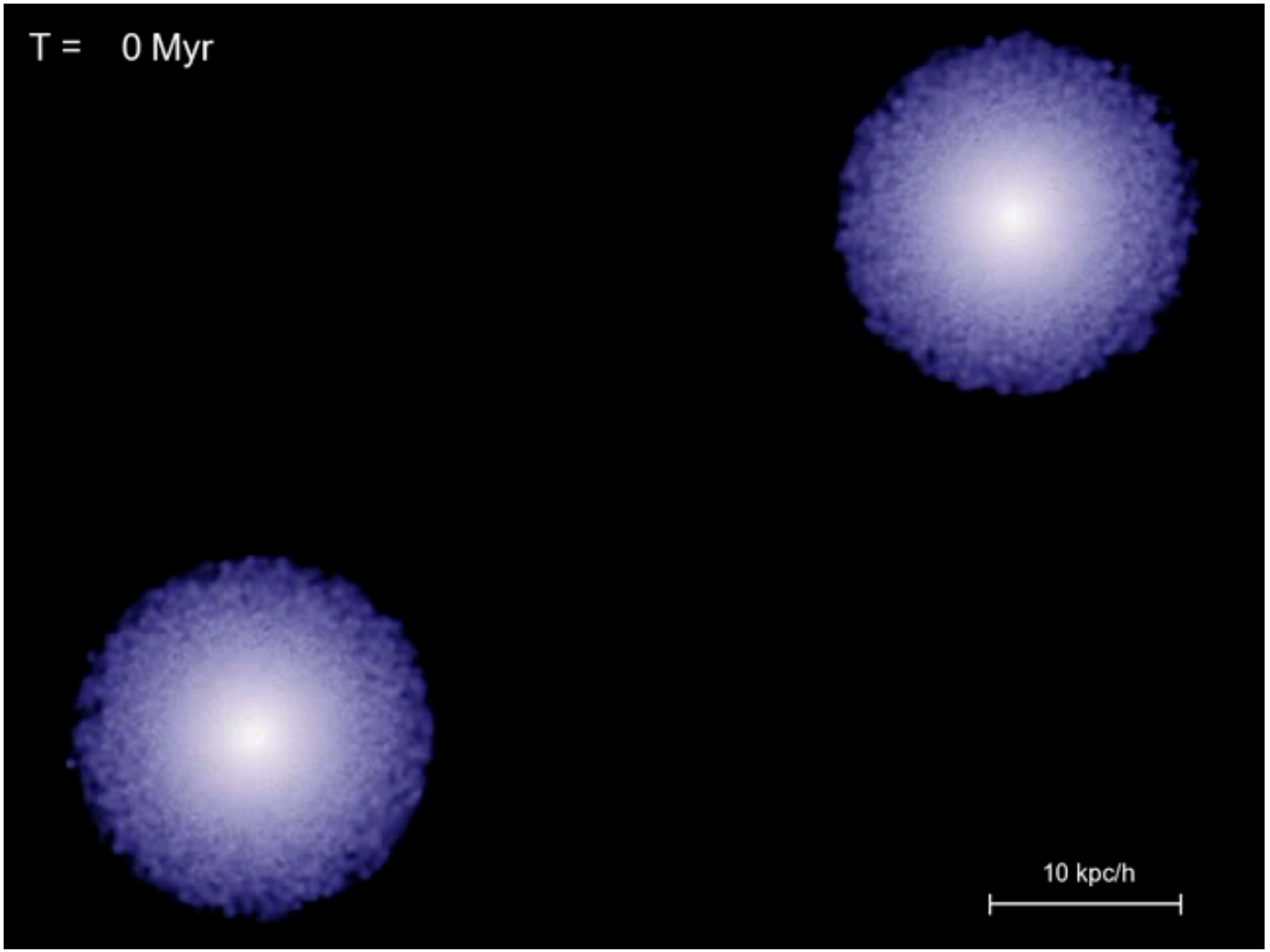
Nearby mergers

Galaxy Mergers



di Matteo et al. (2005)

Galaxy Mergers



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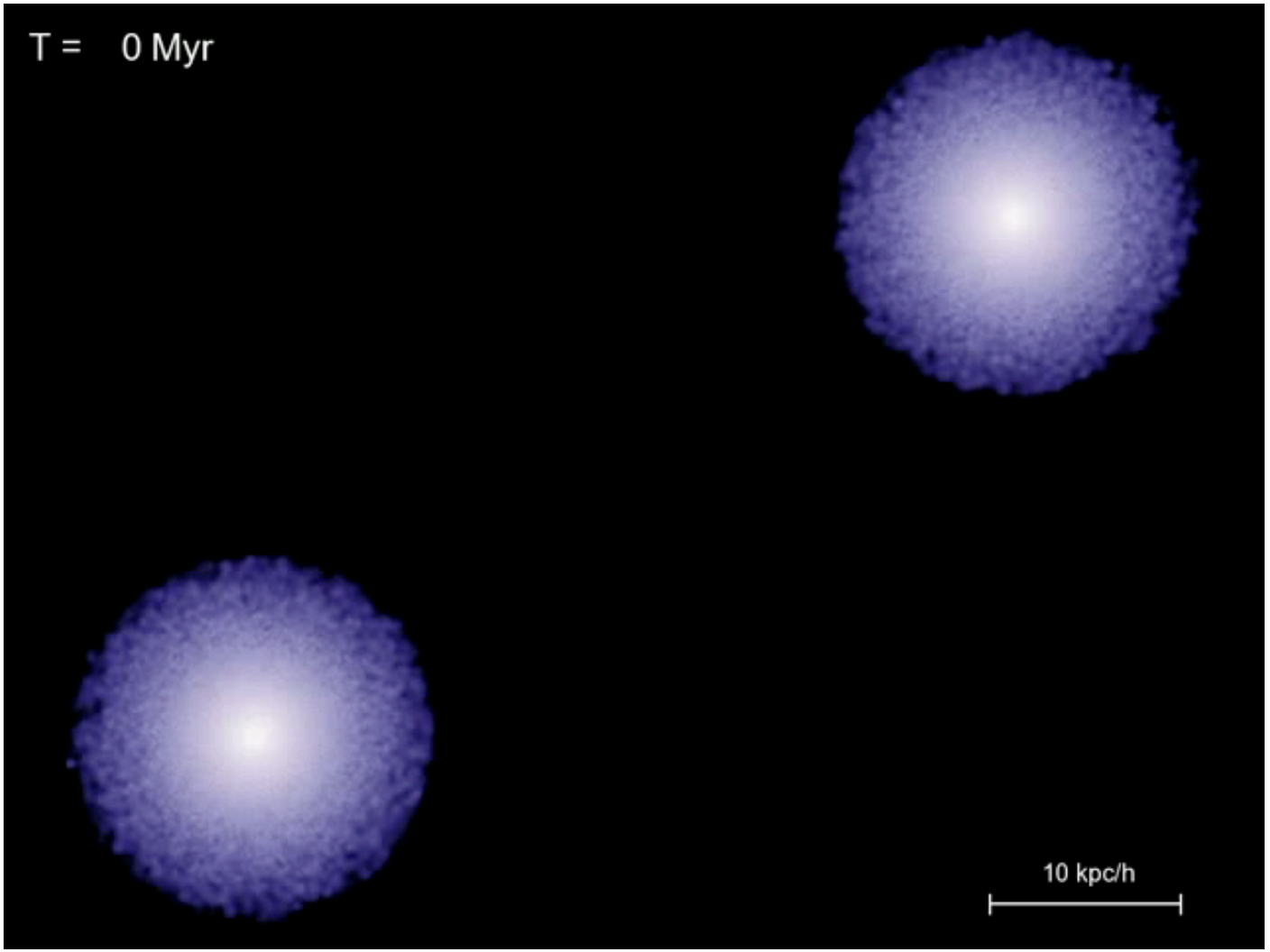
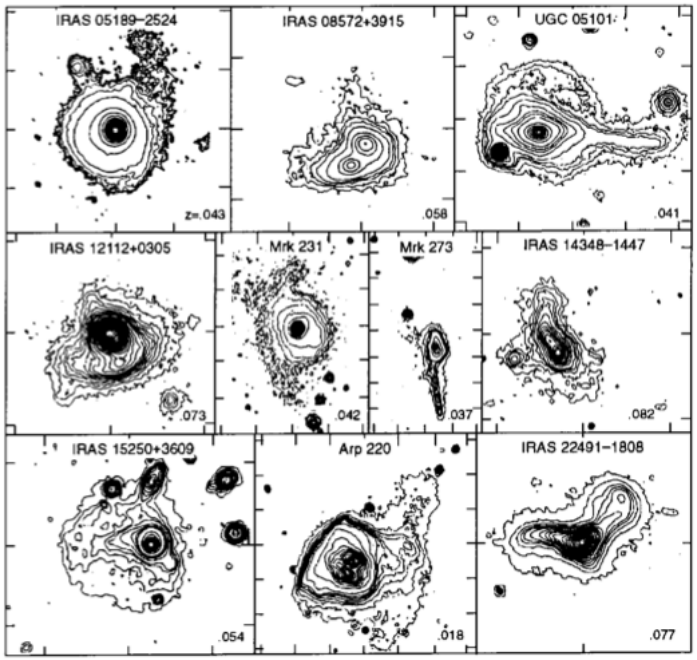
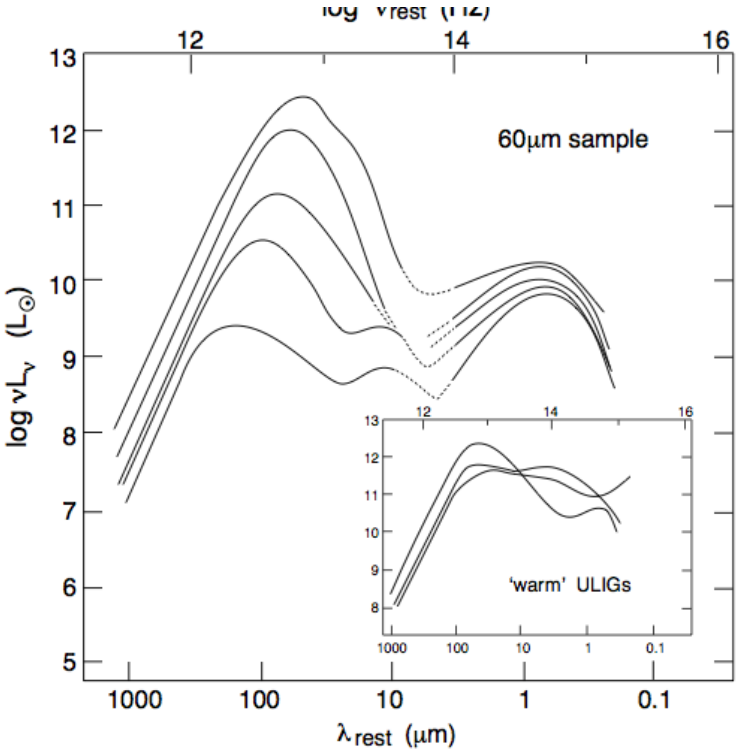
Galaxy Mergers



di Matteo et al. (2005)

Ultra-Luminous Infrared Galaxies (ULIRG)



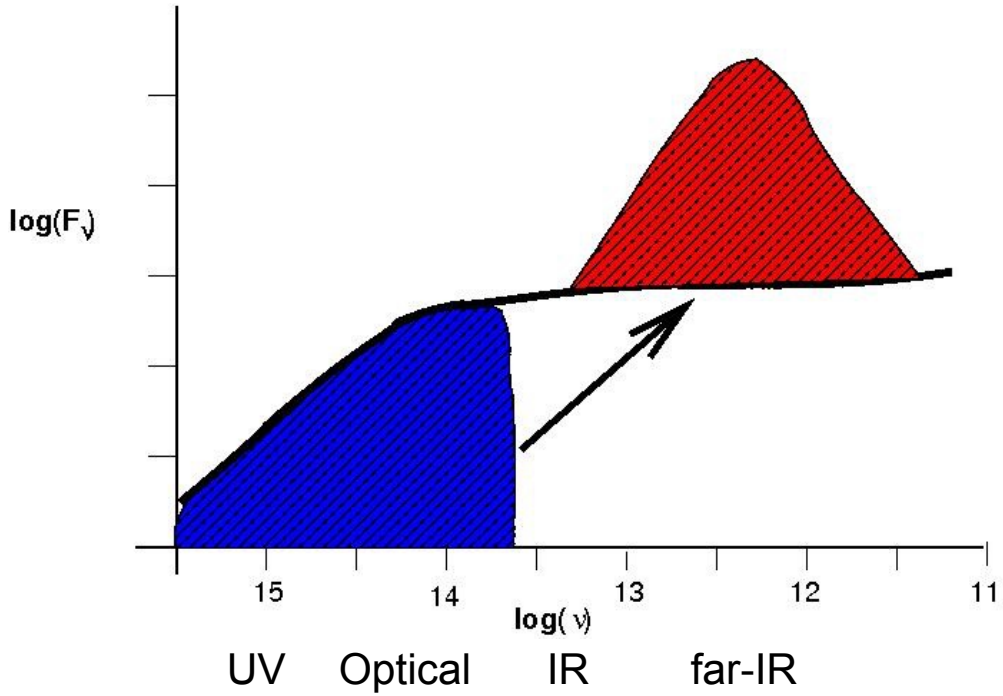


Much of the far-IR emission in ULIRGs is produced by starburst heating of the cool dust in the central regions of the systems.

Dust reprocessing of light from a starburst

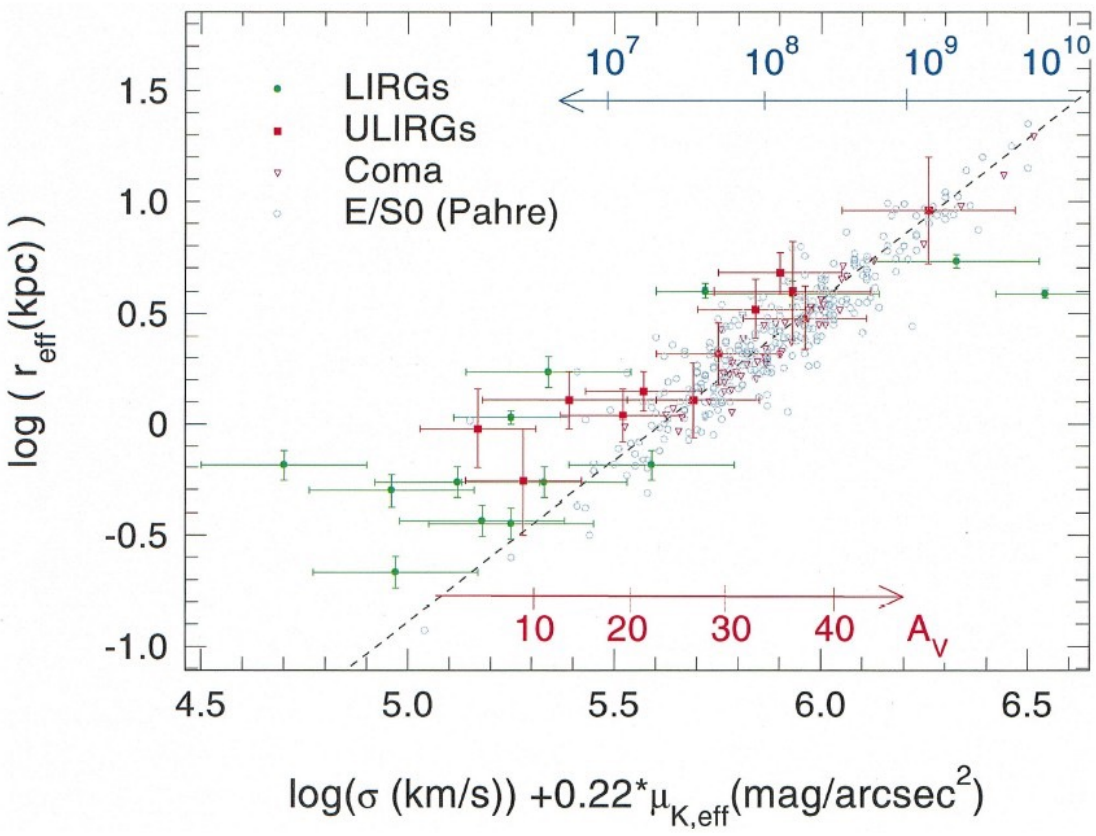
Dust reprocessing of light from a starburst

The Optical/UV light emitted by stars in circum-nuclear starbursts is absorbed by dust, heating it to T_{dust}~20-100K. The energy is re-radiated at far-IR and sub-mm wavelengths (>10μm) as thermal (~black body) radiation. Thus, the far-IR luminosity can be used to measure the star formation rate.



Early-type galaxies forming locally?

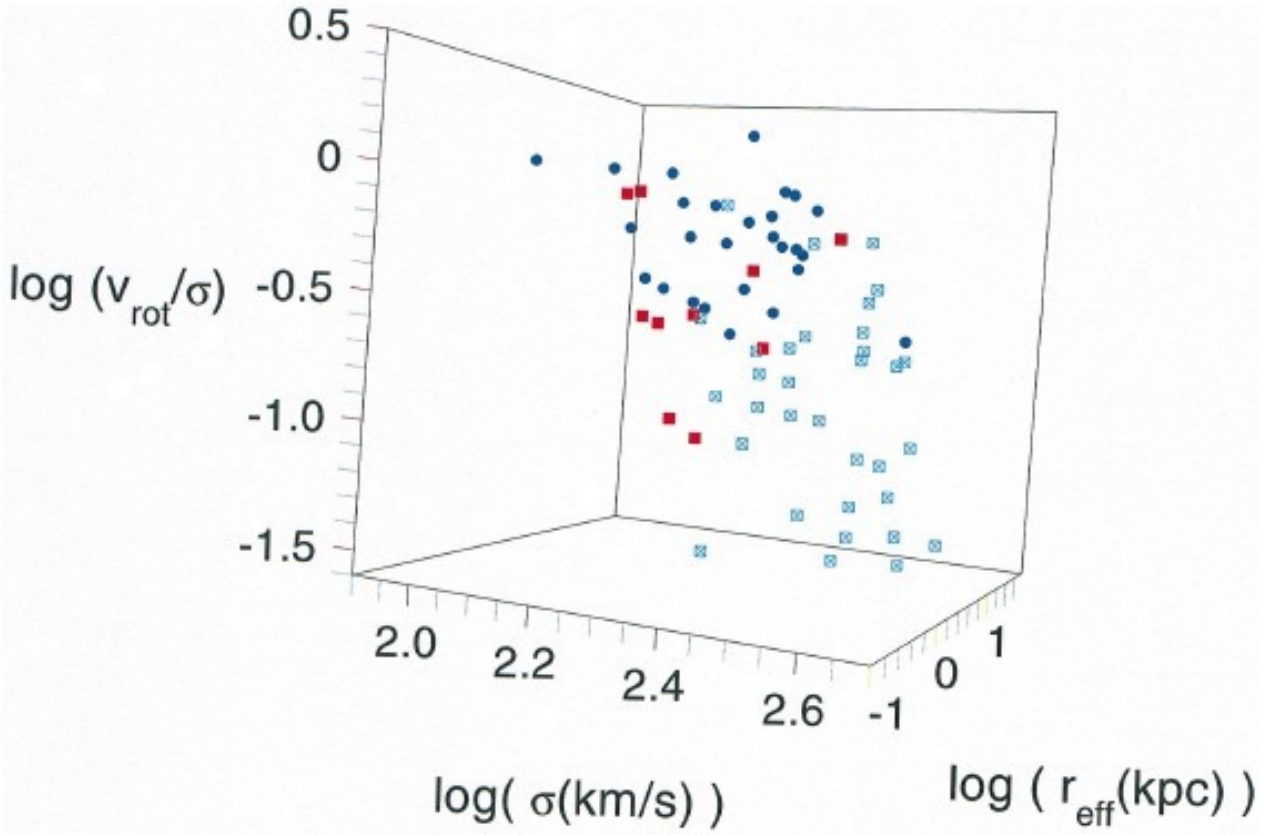
Ultra-Luminous Infrared Galaxies (ULIRG)



Near-IR measurements of the stellar kinematics of ULIRGs can be used to demonstrate that these merger remnants fit onto the scaling. relationships for normal elliptical galaxies

Early-type galaxies forming locally?

Ultra-Luminous Infrared Galaxies (ULIRG)



The stellar kinematics of ULIRG (red squares), are more similar to those of disky ellipticals (black dots) than to boxy ellipticals (blue squares), and indicate a relatively high degree of rotational support.

Early-type galaxies forming locally?

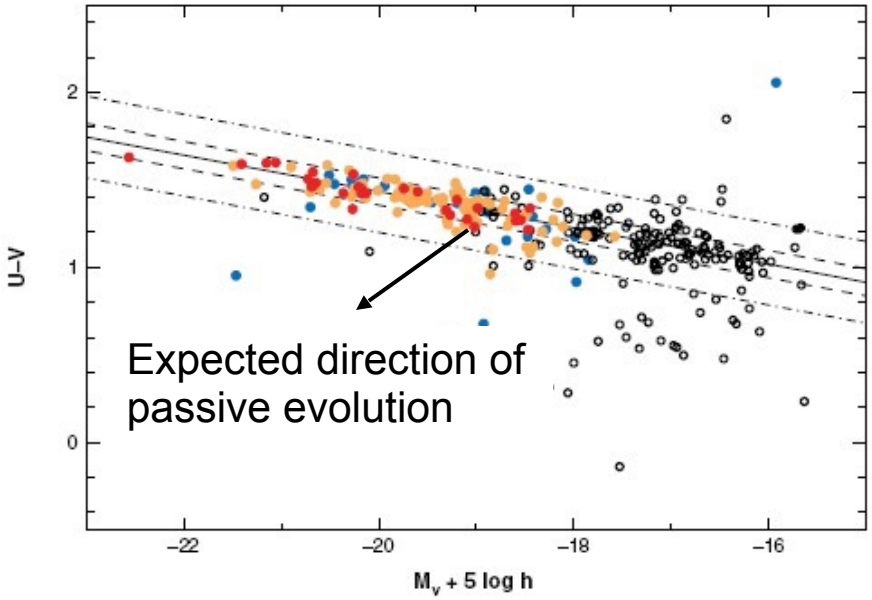
ULIRG summary

- The morphologies of ULIRGs suggest that they represent the final stages of major, gas-rich galaxy mergers.
- Near-IR observations have been used to measure the stellar kinematics of ULIRGs, demonstrating that they are similar to low/moderate luminosity disky eilliptical galaxies in the local universe.
- ULIRGs also appear to fall on the scaling relationships for early-type galaxies.

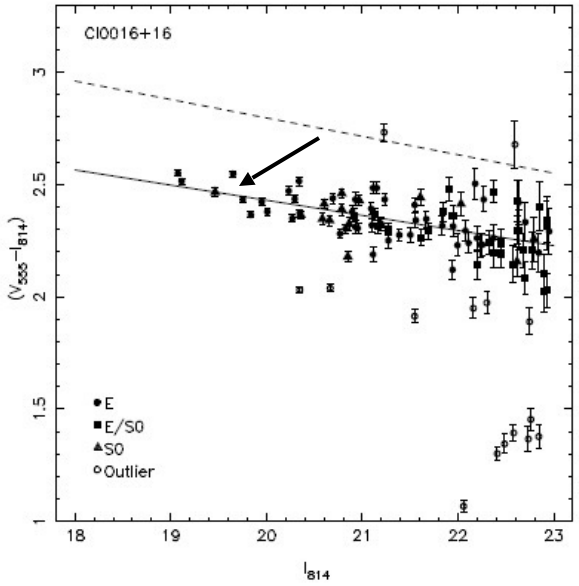
  ➔ All the evidence suggests that ULIRGs represent the transformation of gas-rich spirals into *disky* ellipticals via mergers in the local Universe (galaxy evolution is not confined to high redshifts!)

Evolution of the colour-magnitude diagram - I.

Local C-M diagram



C-M diagram for z=0.55 Cluster



Due to the *passive evolution* of their stellar populations, early-type galaxies are expected to appear bluer and more luminous as the redshift increases.

The *red sequence* (colour-magnitude relationship) has now been detected in clusters up to z~1, and shows the expected degree of passive evolution.

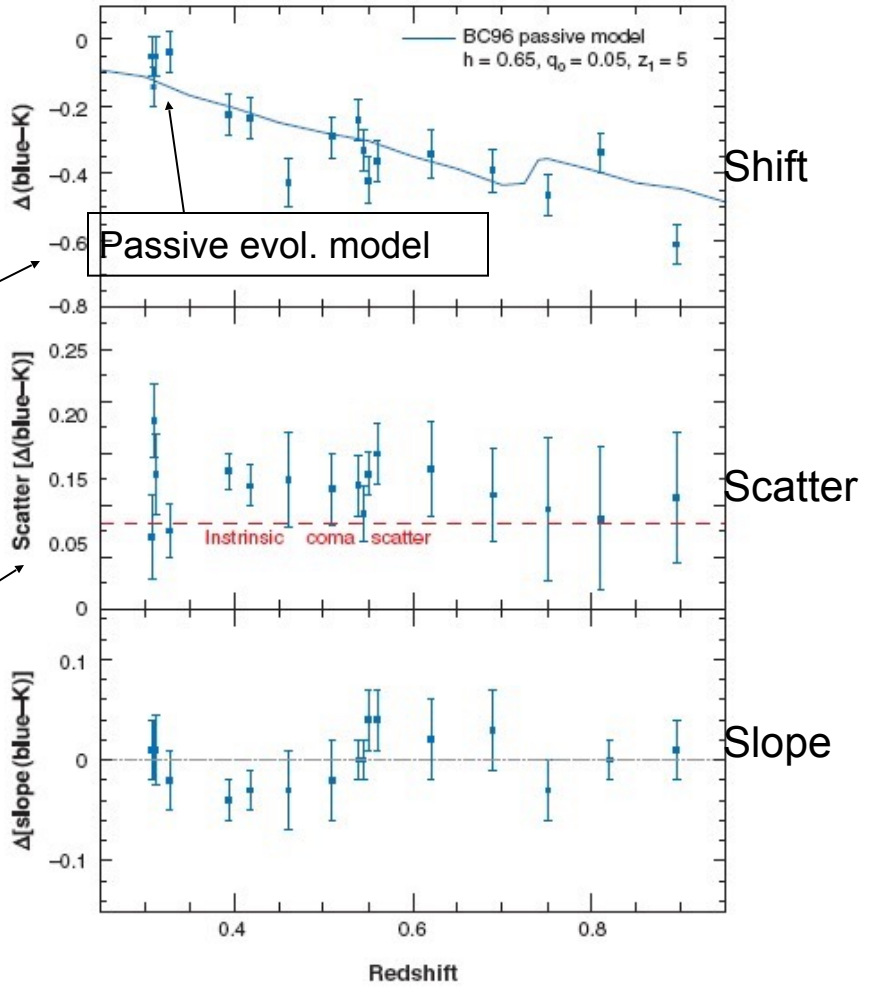
Evolution of the colour-magnitude diagram -II.

With deep imaging observations it has become possible to measure the red sequence colour-magnitude relationship in distant clusters of galaxies up to z~1.

The *vertical shift* in the colour of the C-M relationship with redshift is consistent with passive evolution of the old stellar populations

The scatter and slope of the C-M diagram shows no strong evolution with redshift.

There is little evidence for evolution in the C-M diagram of red sequence up to z~1 (beyond passive)



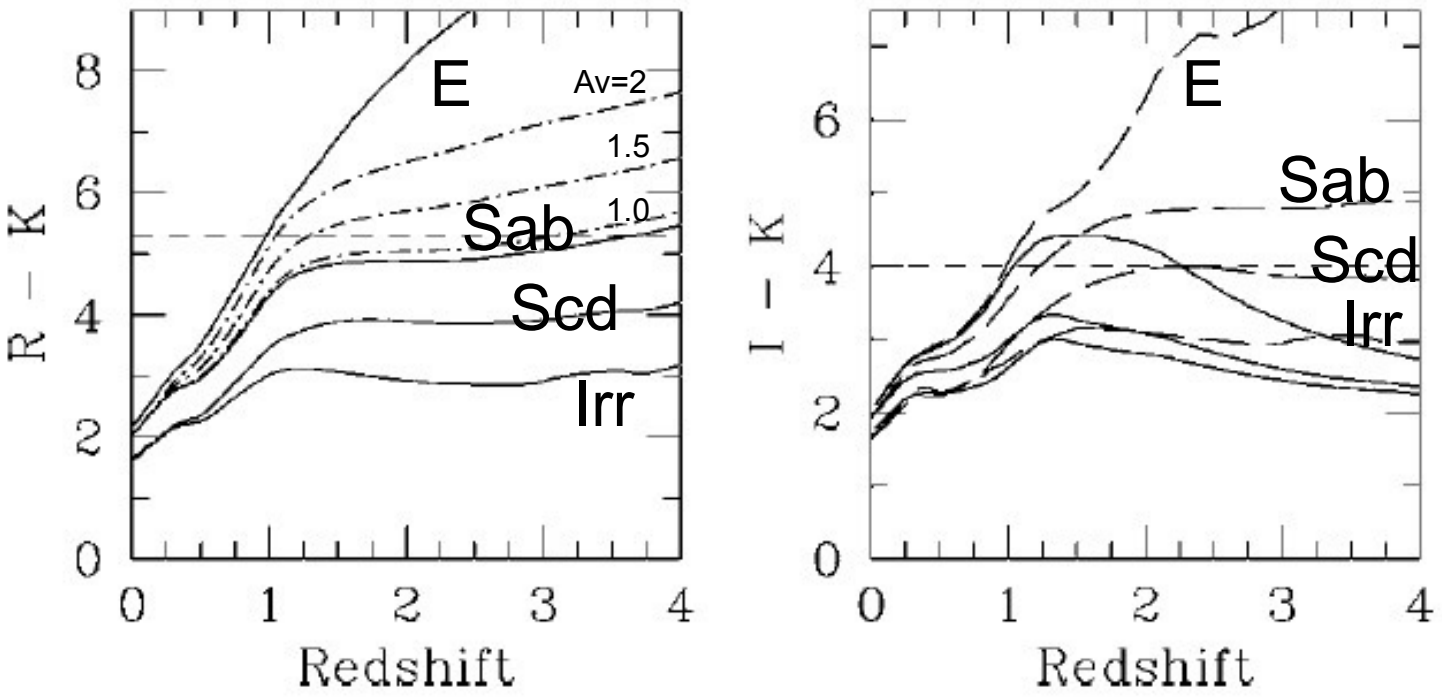
Redshift

Recognising early-type galaxies at high-z

- Early-type galaxies have continuum spectra that drop rapidly to the UV. Therefore it's not possible to use the Lyman break technique to detect them at z>2 (there's little UV flux to absorb the make a break at the Lyman limit!).
- Two main methods are used: optical-IR colour selection (passively evolving elliptical galaxies are predicted to be very red); and K-band selection (the near-IR K-band (2.2μm) is particularly sensitive to old stellar populations.
- These are generally backed up with spectroscopic and morphological classification if the objects are sufficiently bright and nearby.

Colour selection of high-z early-type galaxies

McCarthy (2004)



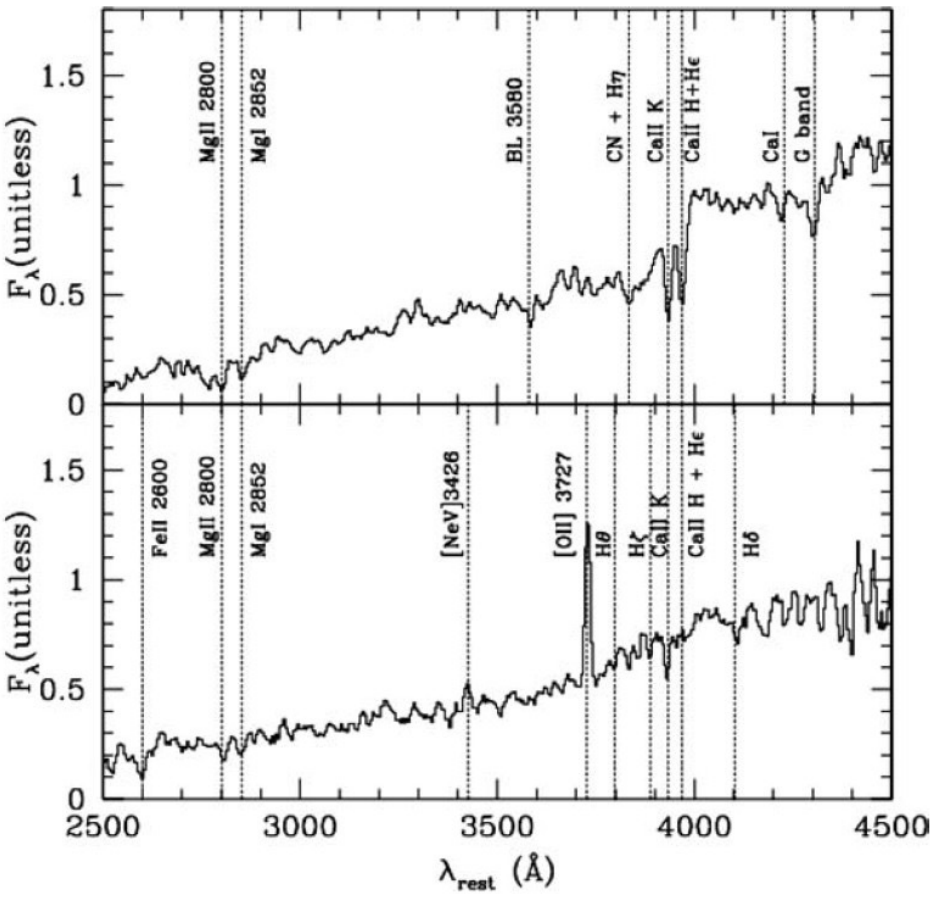
(R-K)>5 and (I-K)>4 efficiently select non-evolving early-type galaxies at high redshifts. Objects with such colours are often known as *Extremely Red Objects* (EROs). However, objects that are highly reddened by dust may also be selected...

Two types of EROs at z~1

Passively evolving objects with relatively old stellar populations

Highly reddened starburst objects

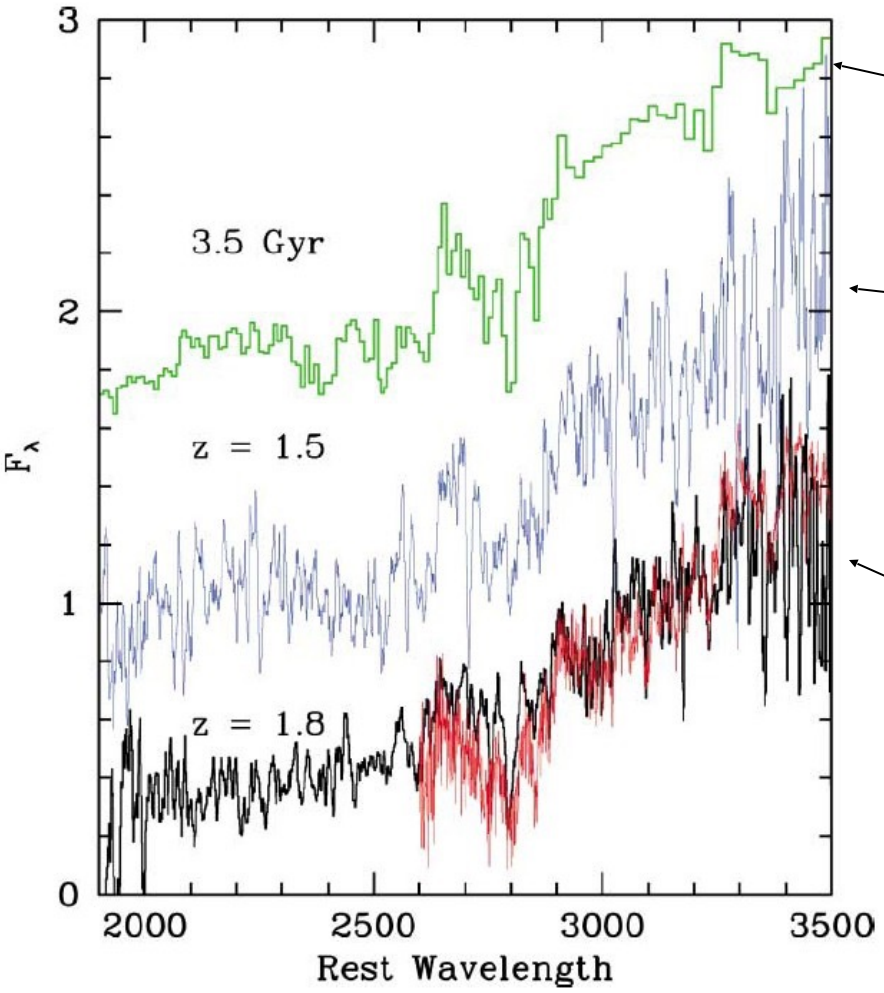
Cimatti et al. (2000)



EROs are roughly evenly divided between reddened starbursts and passively evolving objects with old stellar populations.

Old early-type galaxies at high redshifts - I

The fact that the stellar populations in these z~1.5-1.8 early-type galaxies are already 3.5 Gyr old suggests high formation redshifts (z_f>5).

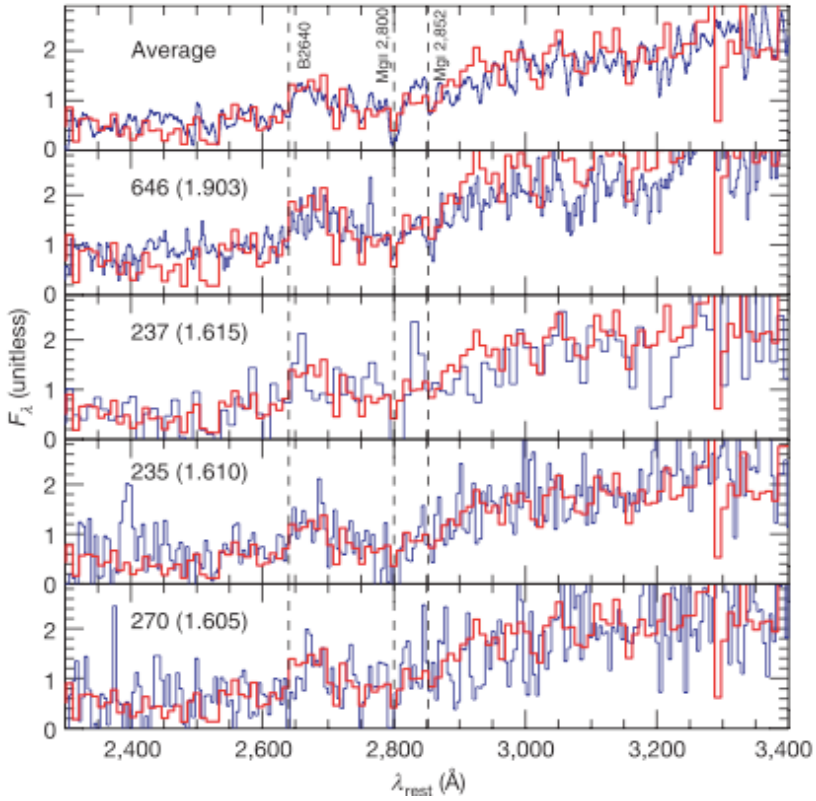


3.5Gyr instantaneous burst model

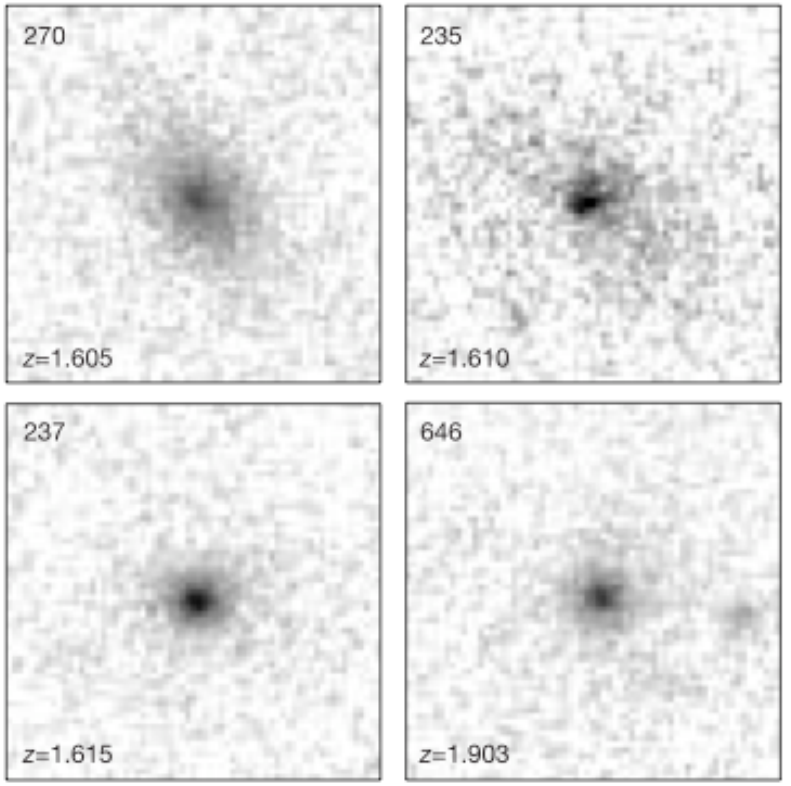
Radio galaxy 53W091

Average of four high-z early-type galaxy spectra

Old early-type galaxies at high redshifts - II



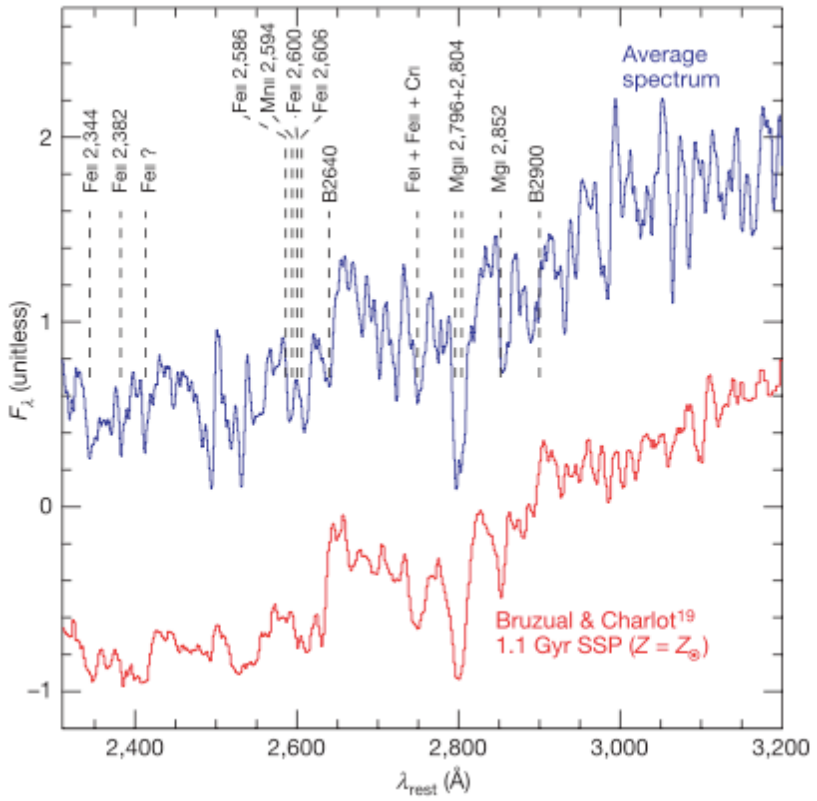
Spectra of 5 early-type galaxies with $1.6 < z < 2$



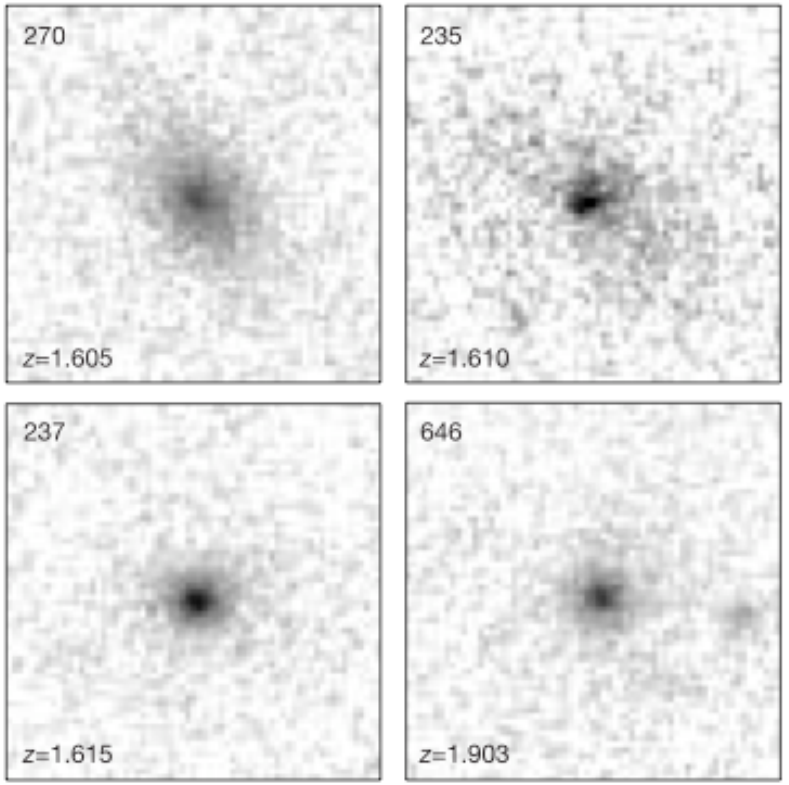
Deep HST images of the high-z early-type galaxies

The detection of these early-type galaxies at $1.6 < z < 2$ with stellar ages >1Gyr suggests that they were formed at $z_f > 3$

Old early-type galaxies at high redshifts - II



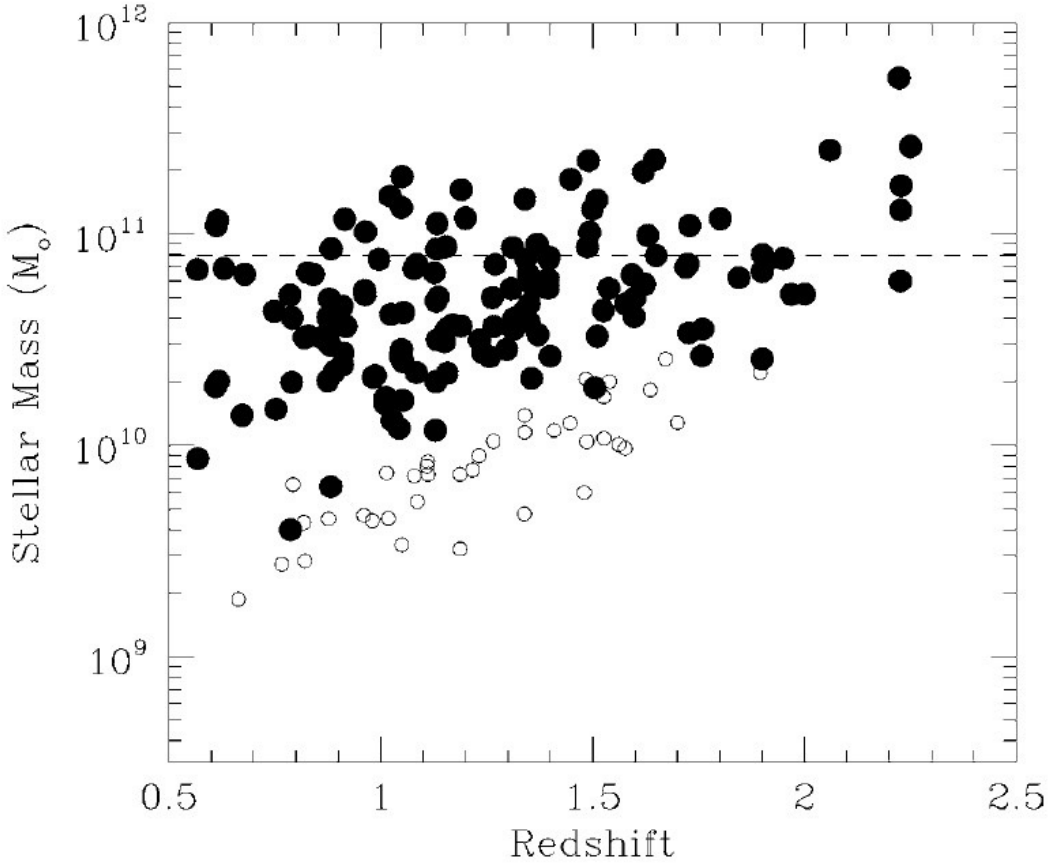
Spectra of 5 early-type galaxies with $1.6 < z < 2$



Deep HST images of the high-z early-type galaxies

The detection of these early-type galaxies at $1.6 < z < 2$ with stellar ages >1Gyr suggests that they were formed at $z_f > 3$

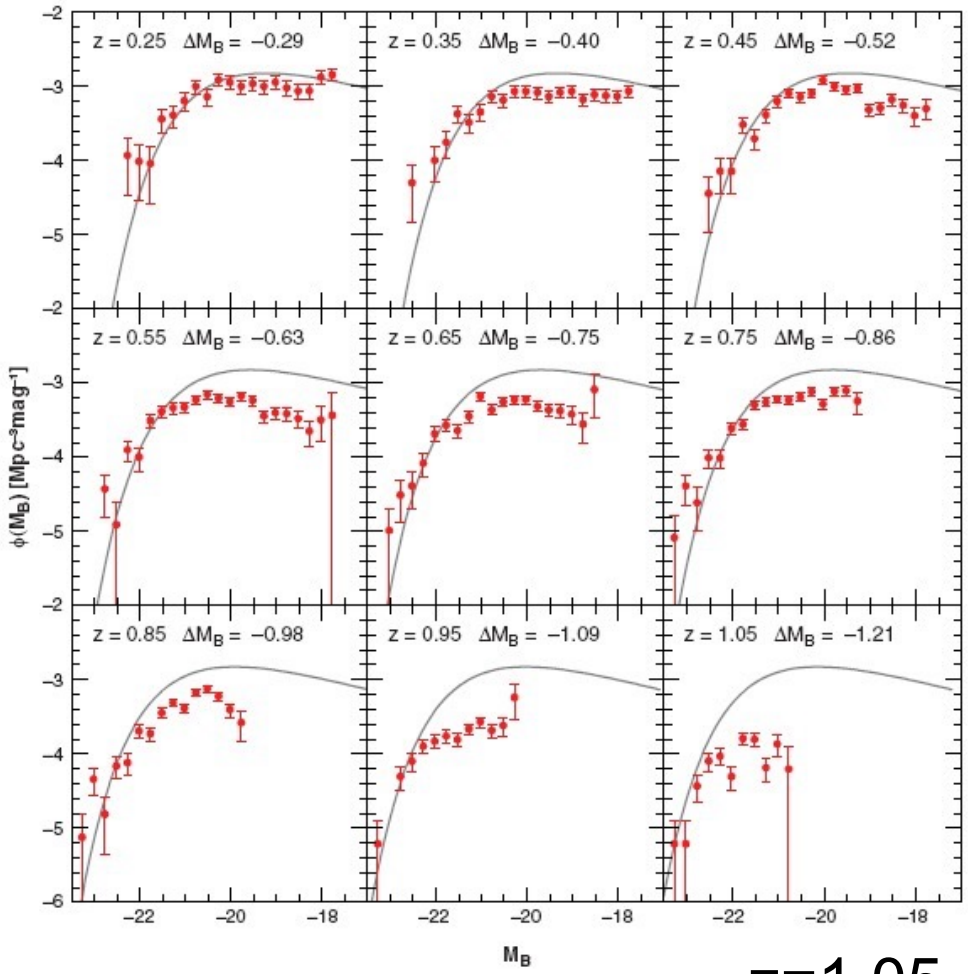
Massive galaxies detected at high redshift



Stellar mass measurements of galaxies in the Gemini Deep Deep Survey (GDDS) suggest that massive (L>L*, M>10^{11} M_{sun}) galaxies were already in place at high redshifts (z>2) -- Glazebrook et al. (2004)

Evolving luminosity function of early-types

z=0.25



Cimatti et al. (2006)

z=1.05

Results from recent deep redshift surveys indicate that, compared with the local E galaxy luminosity function (black line), the space density of the most luminous early-type galaxies (M_B<-22) has remained roughly constant since z~1. However, over the same redshift range, there has been considerable (factor x10) evolution in the luminosity function at the lower luminosity end (M_B>-22).

Summary of evidence

- The fossil record (z~0): spectra, morphologies, kinematics, colour-magnitude and colour-σ relationships, ULIRGs.
- Moderate redshifts ($z < 1$): the evolution of the colour-magnitude diagram and luminosity function.
- High redshifts ($1 < z < 2$): spectra, masses, number density as a function of redshift.

The evolution of early-type galaxies: summary

- The most luminous and massive ($M>10^{11}$ M_{sun}) early-type galaxies have shown little evolution since $z\sim1$; a significant fraction must have been formed at $z>3$. These objects are likely to make up the population of massive, boxy elliptical galaxies in the local Universe (mainly in clusters?).
- Less massive early-type galaxies have shown substantial evolution since $z\sim1$; it's plausible that they are being formed by mergers of spiral galaxies (c.f. ULIRGs), and make up the population of disky elliptical galaxies in the local Universe (mainly in the field?).
- This apparently *anti-hierarchical behaviour* is often termed *cosmic downsizing*.