Galaxy Formation and Evolution

PG lecture course, 2013

Peder Norberg, ICC

(based on Ian Smail's PG slides)

1. Classifying Galaxies: Diversity at z=0
2. Empirical Galaxy Evolution
3. Cosmic Star Formation History
4. Stellar Mass Assembly
5. Theoretical models I (CGL)
6. Theoretical models II (CGL)

What determines properties of galaxies we see today?

Understand how and when galaxies were formed and how they evolved.

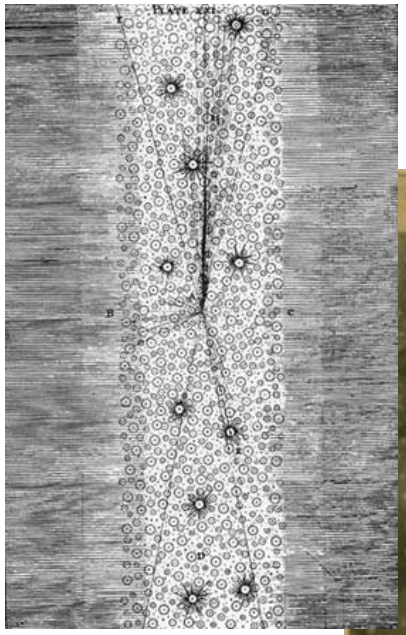
Galaxy formation and evolution

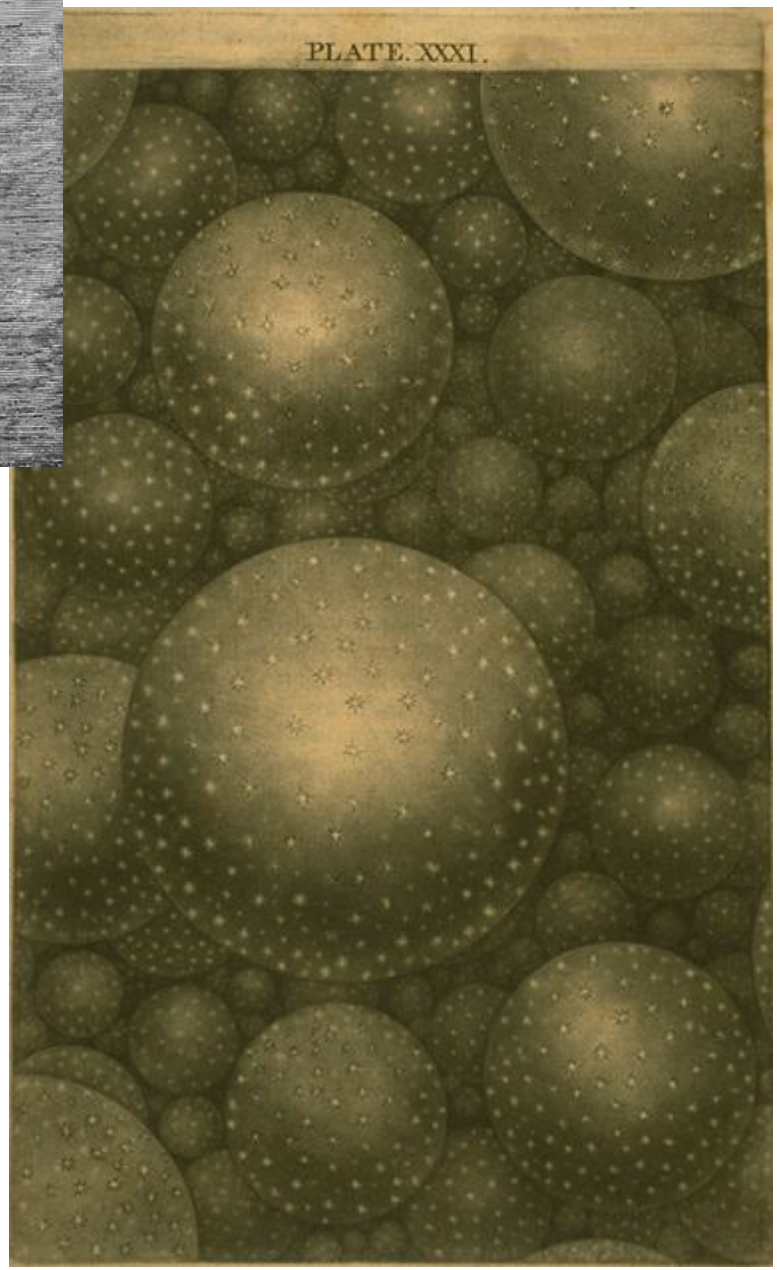
- Durham's early contributions…
- Growth of the field

Basic classification schemes

- Morphology - structure
- Photometric - Mass, SFR, SFH
- Spectroscopic - SFR, SFH

Local Hero





Thomas Wright (1711–1786)

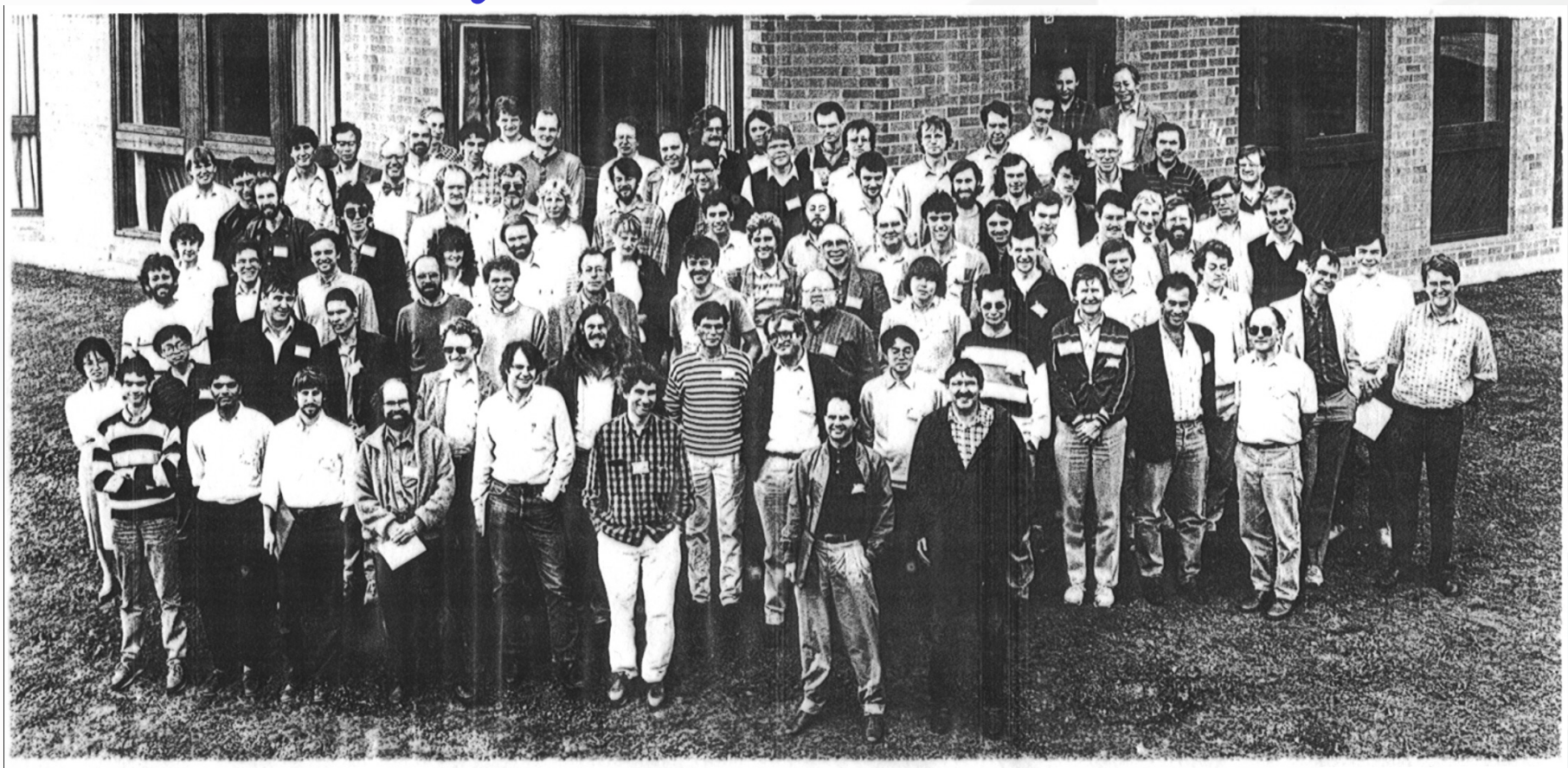
Born in Byers Green

Built an Observatory at Westerton (near Bishop Auckland)

In “A New Theory of the Universe” (1750) he explained the Milky Way as "*an optical effect due to our immersion in what locally approximates to a flat layer of stars.*”

He also proposed that nebulae were external galaxies - picked up by Kant as *“Island Universes”*

Galaxy Formation at Durham



NATO ADVANCED RESEARCH WORKSHOP

"THE EPOCH OF GALAXY FORMATION"

UNIVERSITY OF DURHAM. U.K. JULY 18-22, 1988

Galaxy Formation at Durham

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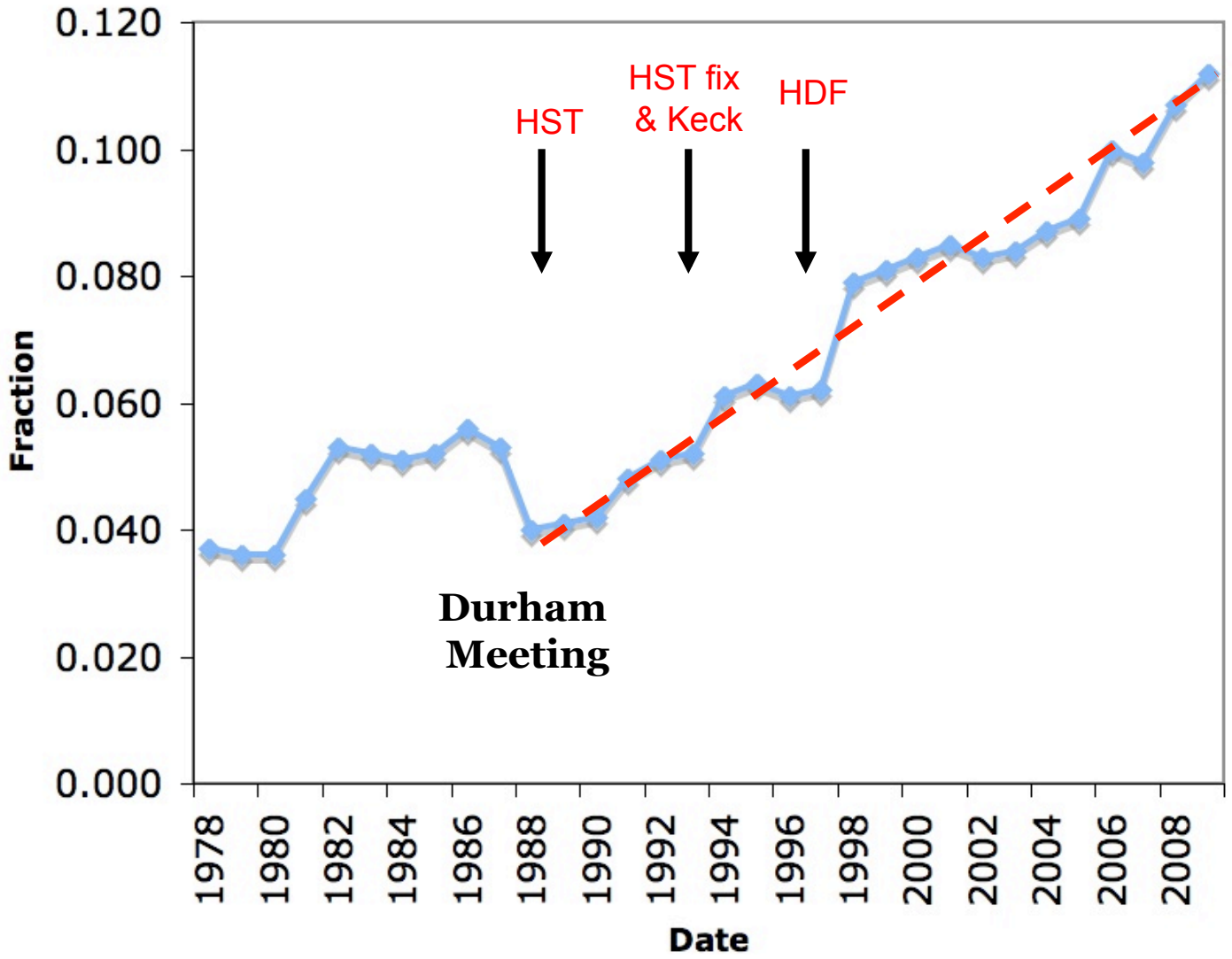
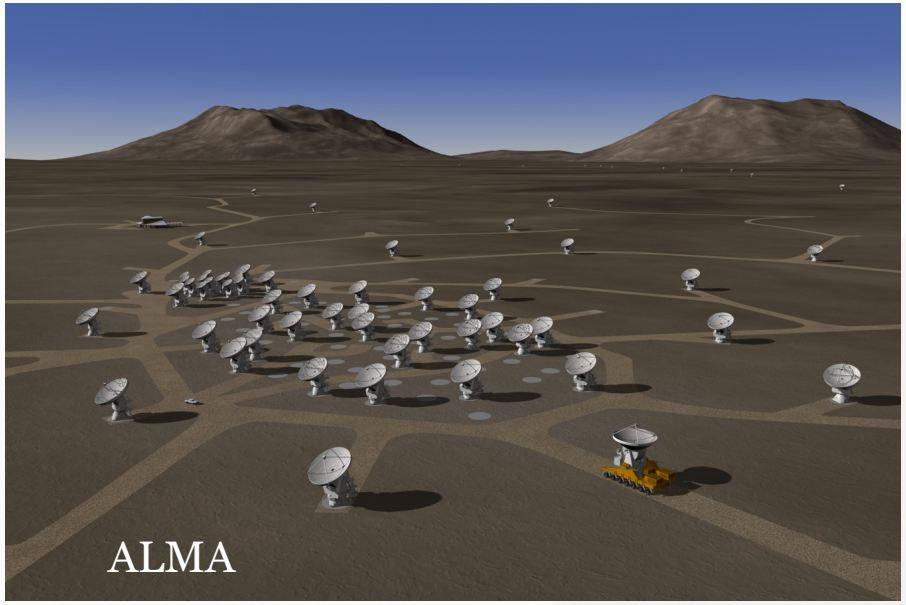
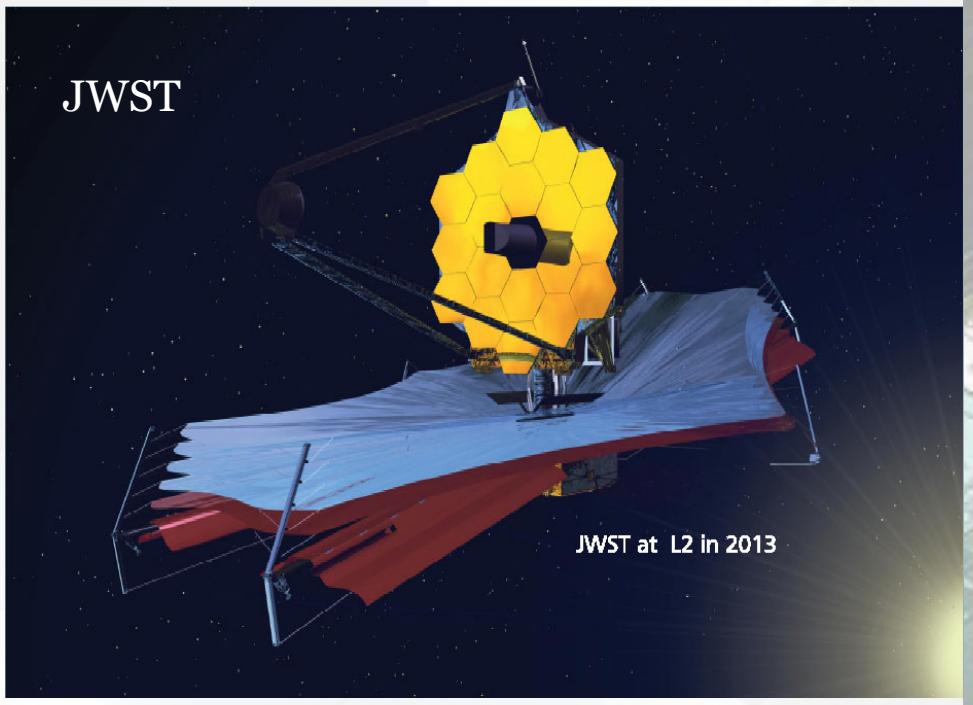
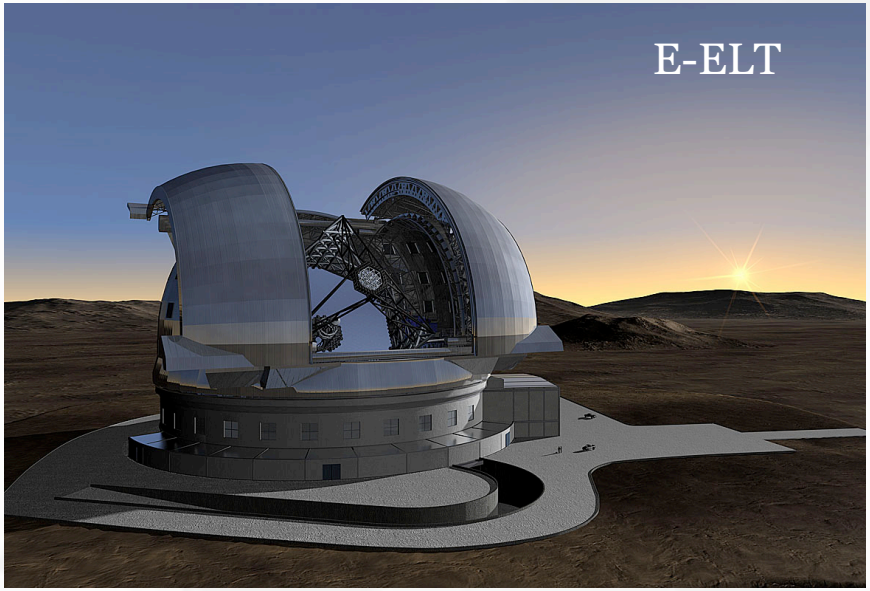
Fraction of Papers related to Galaxy Evolution



New Facilities







All of these facilities have galaxy formation and evolution as a key driver.

Galaxy Formation & Evolution

Understand how and when galaxies (such as the Milky Way) were formed and how they evolved.

To do this start by classifying and grouping galaxies in an attempt to find evolutionary pathways

Look at classification based on:

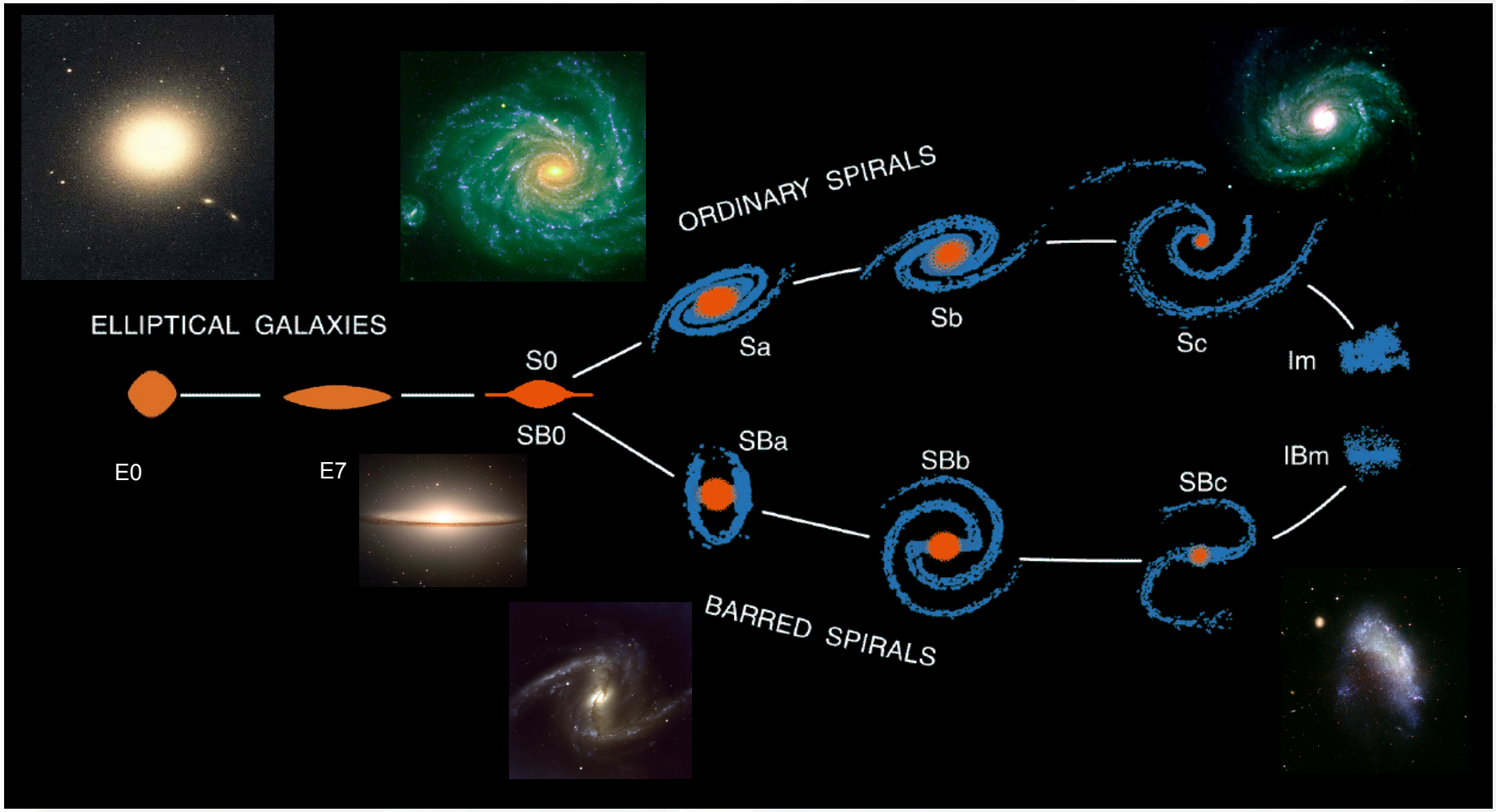
Morphology

Colours

Spectra

Galaxy Morphologies

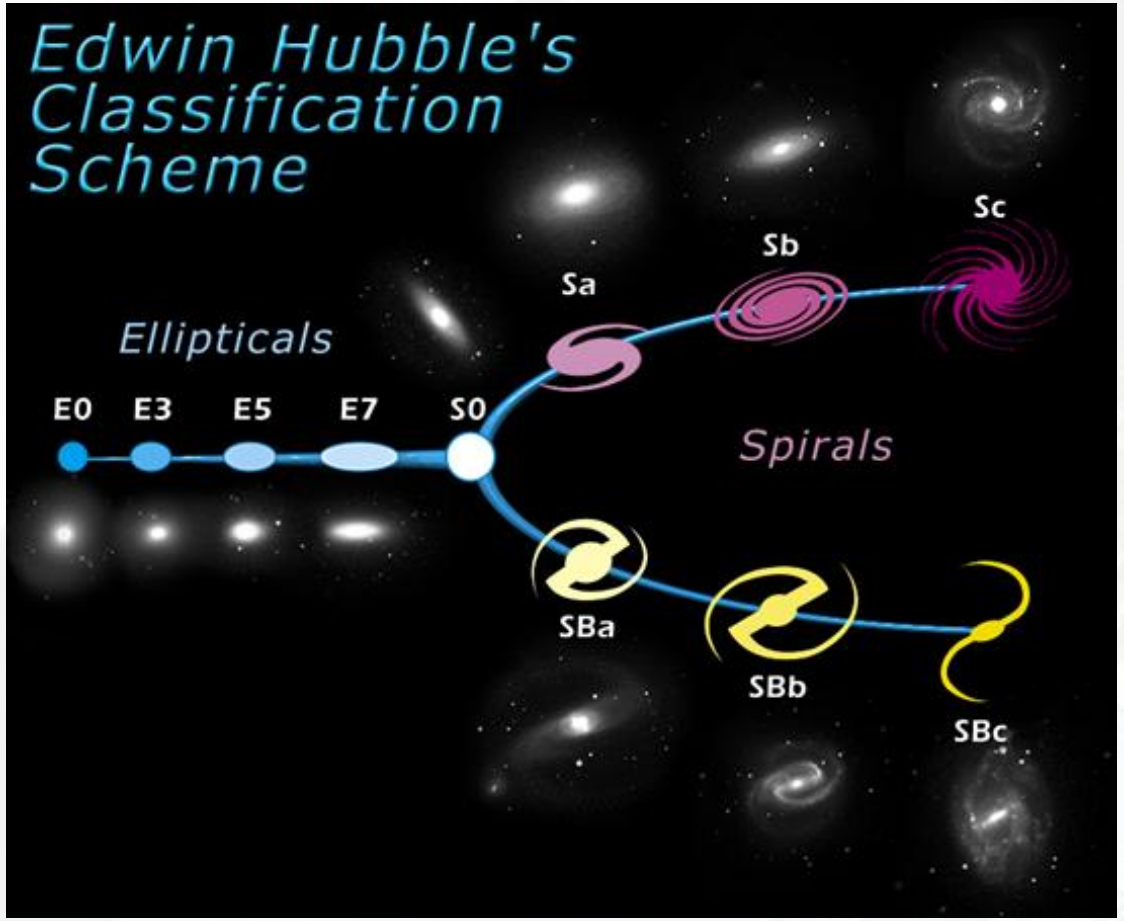
Hubble made a classification scheme based on galaxy morphologies:



E=Elliptical S0=Lenticular S=Spiral SB=Barred spirals Im=Irregular

Early-type Late-type

Hubble's Morphological Sequence



Distinguishes **dynamically distinct** structures:

spirals & S0s – rotating stellar disks

spheroids – ellipsoidal/triaxial systems with anisotropic dispersions

There exist **physical variables** that govern the sequence:

gas content/integrated color → *ratio of current to past average star formation rate*

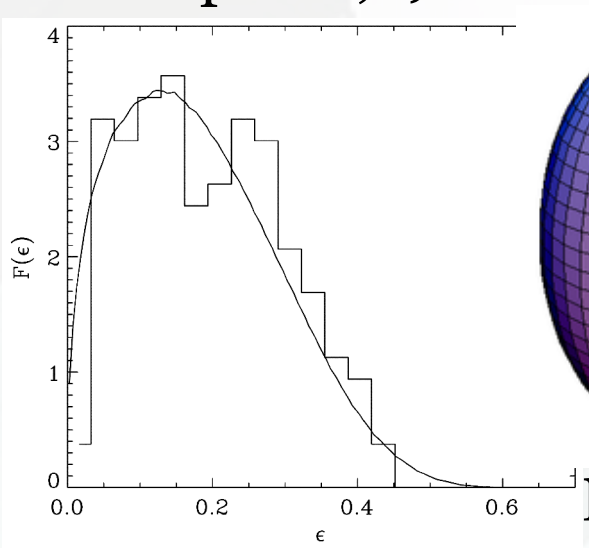
inner structures → *bulge/disk ratio*

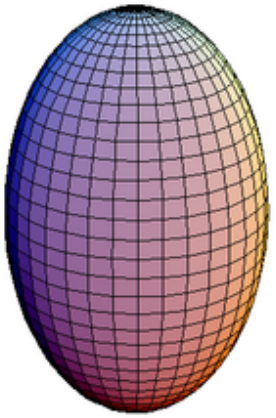
Elliptical Galaxies

Elliptical galaxies have no spiral arms or apparent disk.

Hubble classified ellipticals onto a sequence (E0, E1, E2, E3....E7) based on apparent ellipticity of the light distribution (major/minor axes of the ellipse: a,b):

$$\varepsilon_{app} = 10\frac{(a-b)}{a}$$





prolate

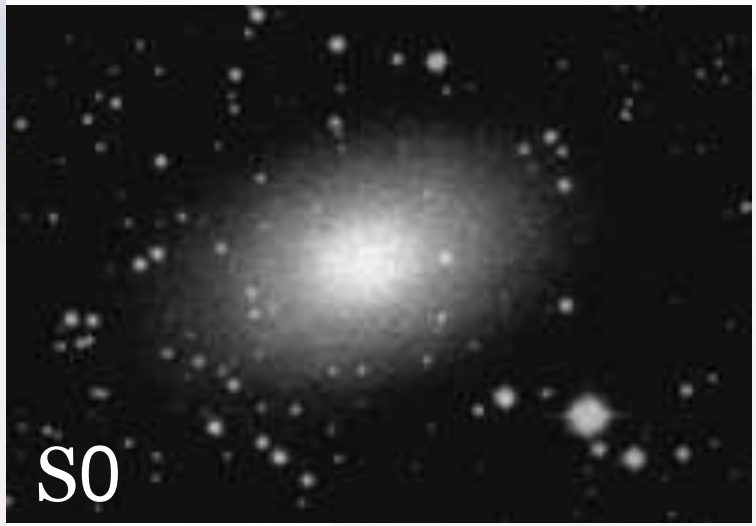
The stars in elliptical galaxies have no axis of rotation, they follow complex/chaotic orbits.

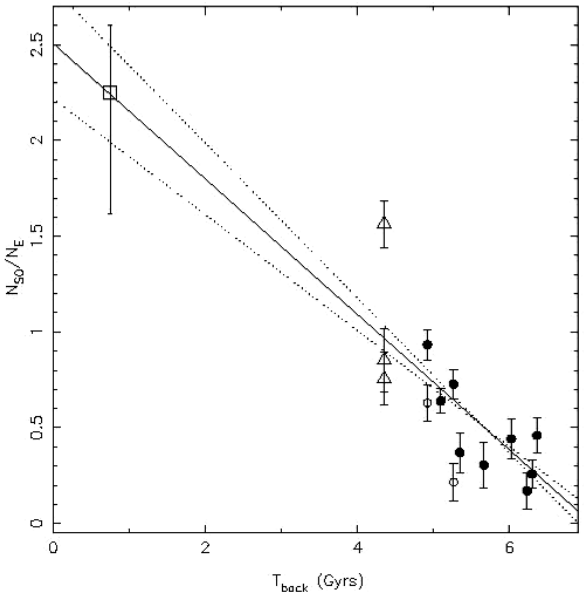
The distribution of light is well-characterised by a decline of surface brightness (SB) with radius as $R^{1/4}$, c.f. spiral galaxies' exponential disks

S0: Lenticulars

Between ellipticals and spirals are the "lenticulars" or S0s.

These are characterised by a bright bulge and a faint disk with no spiral arms. Little on-going star formation:





Important transition population between bulge-dominated and disk-dominated galaxies.

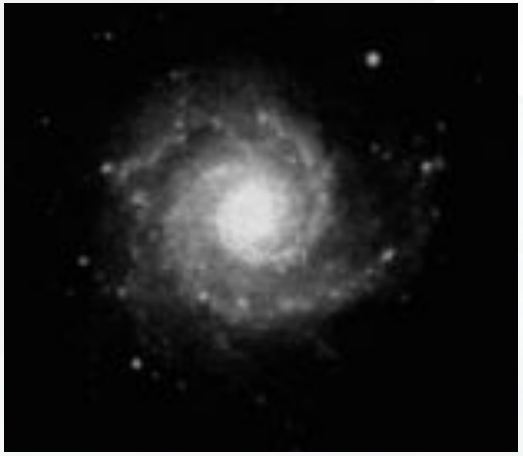
Found in very large numbers in clusters and display strong decline in more distant clusters - formed recently from a morphological transformation?

Spirals: Classification

Spiral galaxies are characterised by a clear disk of stars. They comprise about ~75% of luminosity-limited, local galaxy samples.

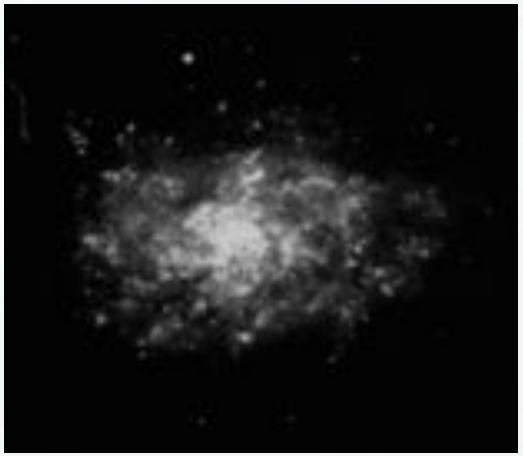
Hubble classified spiral galaxies (Sa/Sb/Sc/Sd) based on the visibility of the spiral arms, the tightness of their winding and the prominence of the central bulge (spheroid):

Sa: obvious disk, but weak or smooth arms and strong bulge



Sc: Arms more loosely wound, weaker bulge

Sb: Arms better defined, weaker bulge



Sd: Very loose arms, most of light in arms not the disk. Almost no bulge

Barred Galaxies

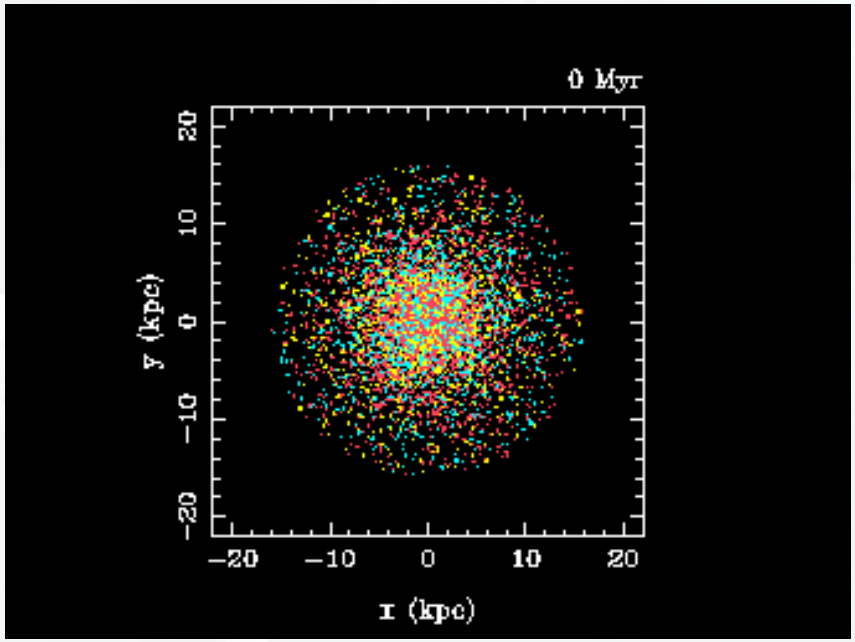
Hubble noted that spirals also show bars.

Parallel classification for these based on same criteria as spirals: SB0, SBa, SBb, SBc, SBd, Ibm.

Around 60% of spiral galaxies show a bar-like feature.

Numerical simulations show that bars frequently form from instabilities in stellar and gas disks.

Models show that bars are suppressed by very massive halos. So fact that ~40% of spirals lack bars is more evidence for massive dark matter halos.



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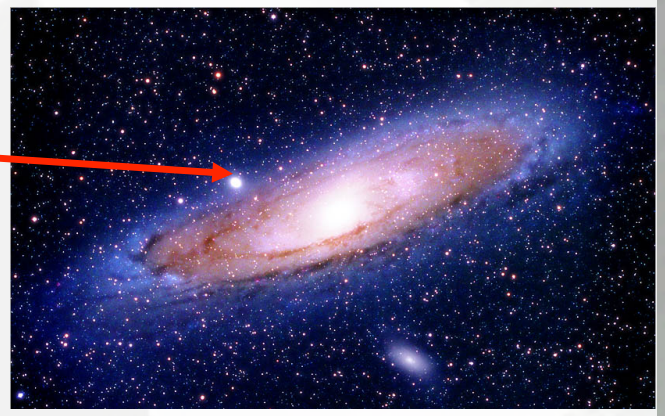
Irregular Galaxies

Lack any regular structure or spiral arms.

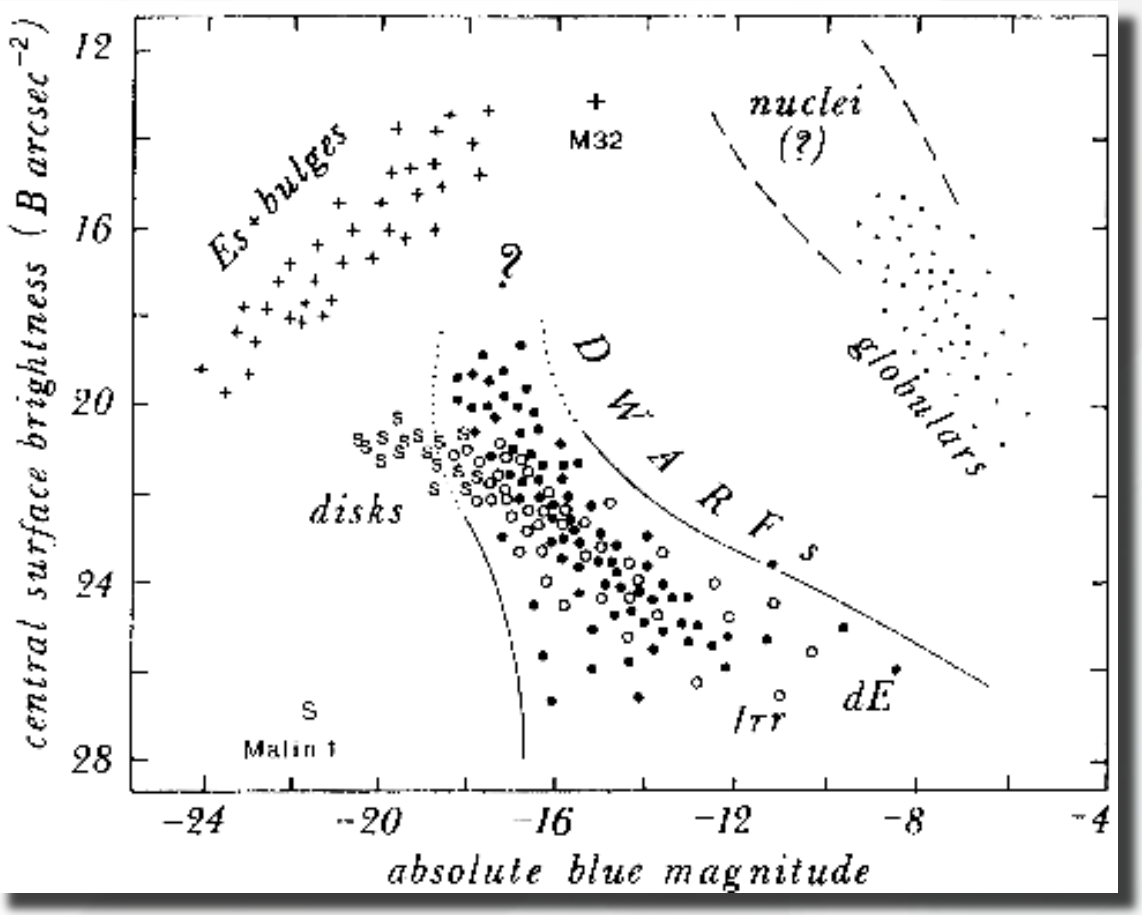
- Im I show resolved OB associations and HII regions.
- Im II are a wider class of “peculiar” galaxies.

The nearest two galaxies in the Milky Way: the Large and Small Magellanic Clouds (LMC and SMC), are the archetypes (LMC is a barred Im).

Dwarf Galaxies



M32 dwarf elliptical



Dwarf galaxies:

Im

dE/dSph

(also LSB galaxies)

Most numerous galaxies in the Universe.

Low-s.b. ones are hard to find…

Physics of Morphology?

But what does the morphology mean physically?

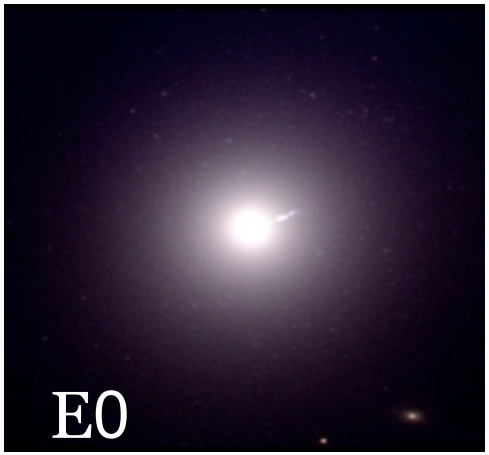
Taxonomy not useful unless you can interpret it.

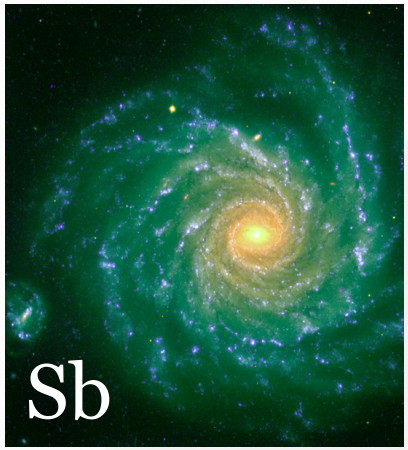
Originally thought to be evolutionary sequence:

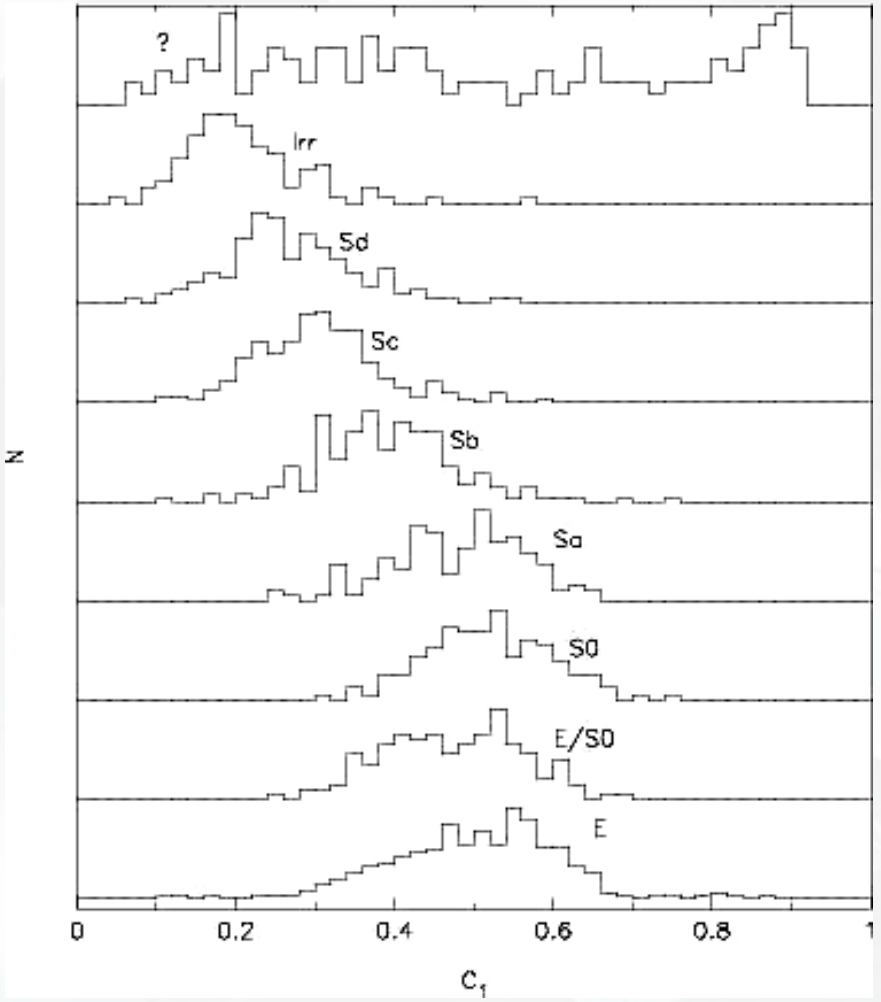
Ellipticals(=early-type) turn into Spirals(=late-type)

Only a few thousand galaxies with reliable morphologies so it is hard to test evolutionary sequences with just morphologies…

Machine-based Morphologies







Difficulty has been quantifying morphologies. Is the detail (Sa-vs-Sc) important or is it just obscuring the real information?

Machine-based morphologies miss much of this detail - basically just Bulge/Disk (or concentration) ratio and perhaps some clumpiness (e.g. CAS - Conselice et al.)

1 Million galaxies classified by the public

www.galaxyzoo.org

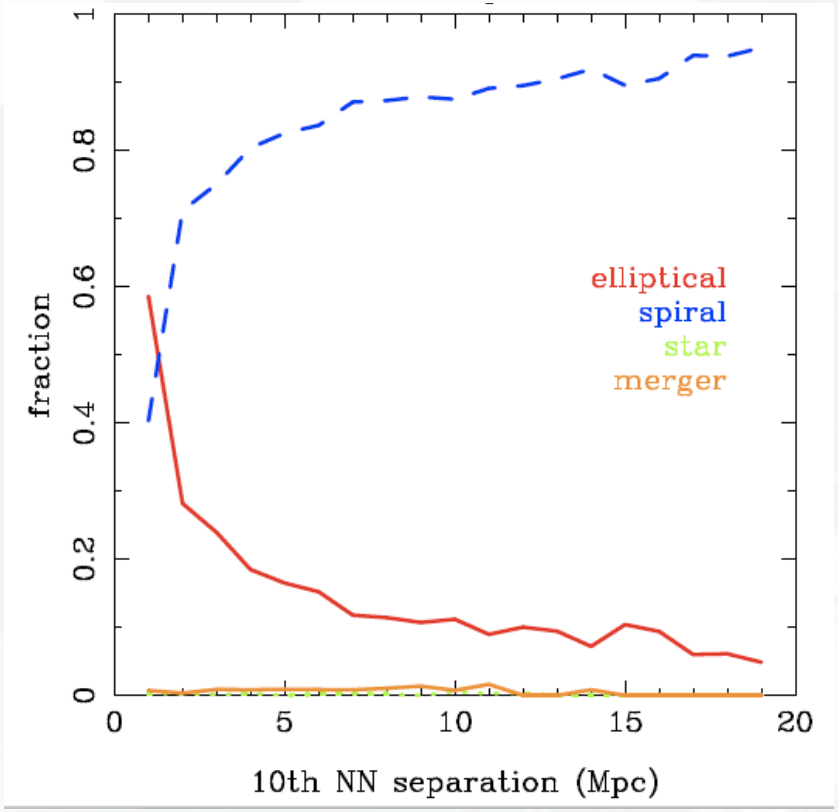
Go and try yourself…

www.galaxyzoo.org

Morphological Correlations

Morphology varies strongly with:

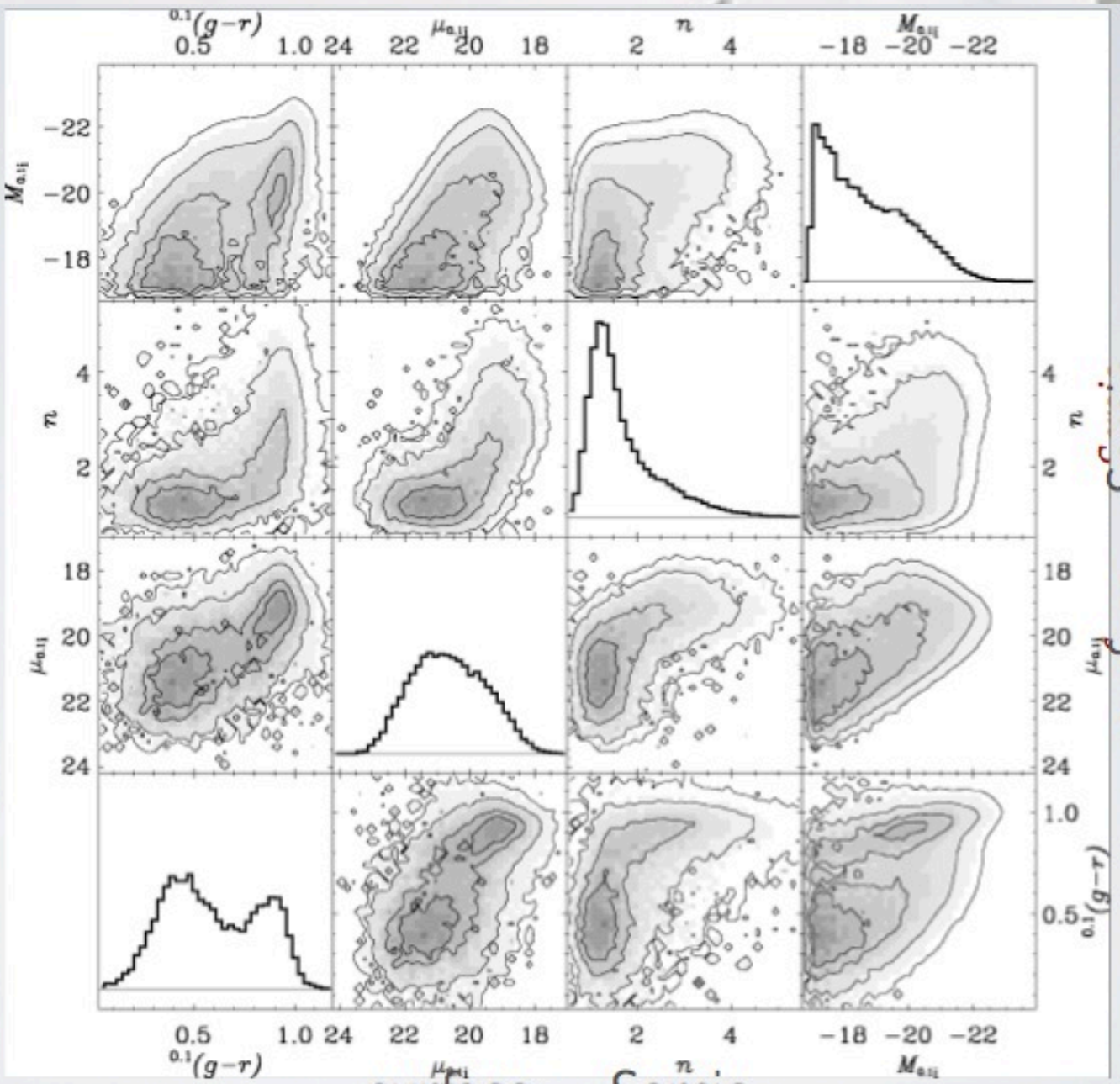
- luminosity/mass: most massive/luminous galaxies are “all” ellipticals
- environment: high-density regions are dominated by E/S0 while low-density “field” is where we find Spirals and Irregulars.



Morphology correlates with:

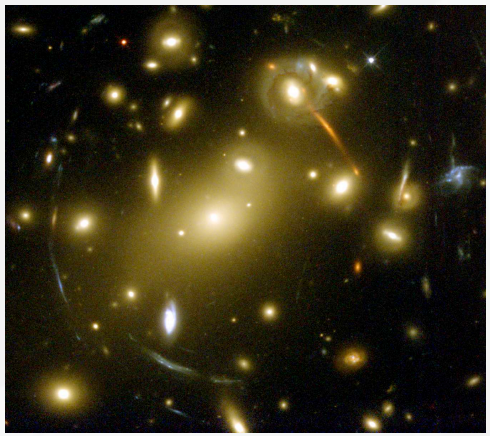
- colour: most E/S0 are red, most spirals/Irr are blue
- spectral type: most spirals/Irr have strong emission lines, while most E/S0 are absorption line systems

Galaxy Correlations

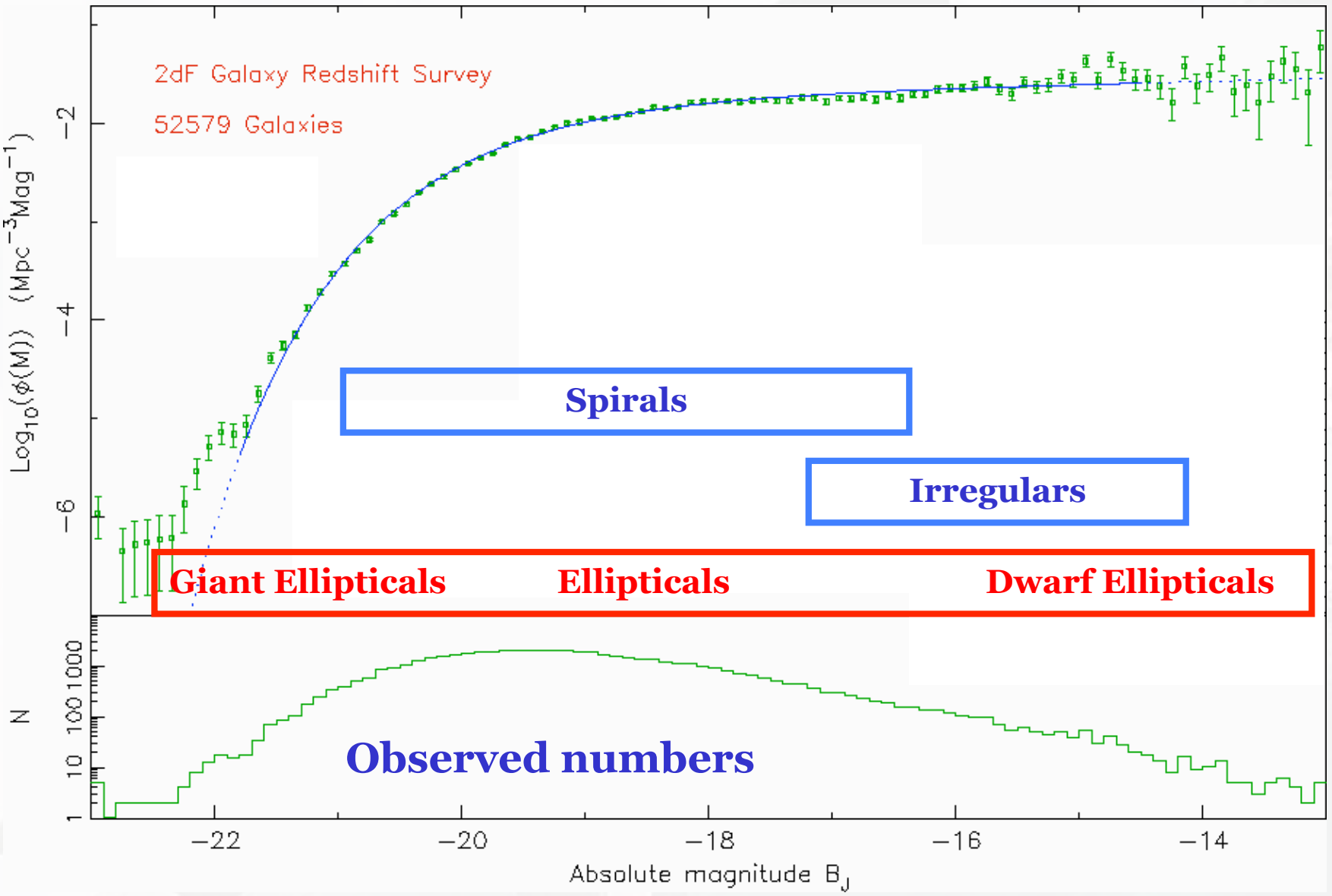


Galaxy Populations @ z~0: typical # & properties

	Elliptical(+S0)	Spiral (inc. Barred)	Irregular
Proportion:	20%	75%	5%
Luminosity:	10^5 to $2x10^{11}L_o$	10^8 to $5x10^{10}L_o$	10^7 to 10^9L_o
Stellar Mass:	10^5 to $10^{13}M_o$	10^9 to $2x10^{12}M_o$	10^8 to $3x10^{10}M_o$
Size:	1 to 100kpc	5 to 50kpc	1-10kpc
Gas fraction:	~0%	4 to 25%	>25%
Colour:	Red (Pop II)	Blue (Pop I+II)	Blue (Pop I)
Environment:	High-density Clusters	Low-density Groups+"Field"	Low-density "Field"
AGN:	QSOs/Radio Gals	QSO/Seyferts	---

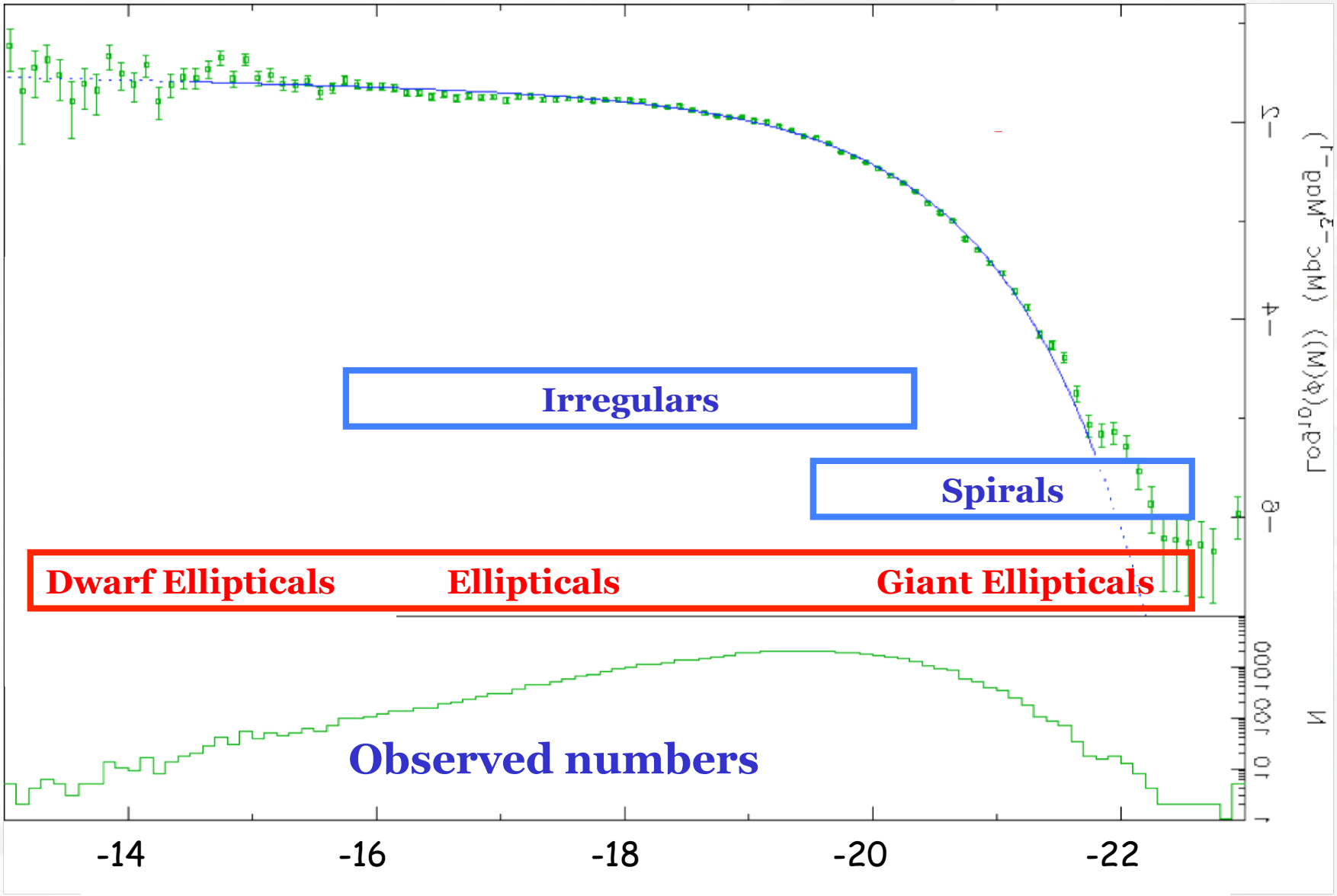


"Observers" Galaxy Luminosity Function

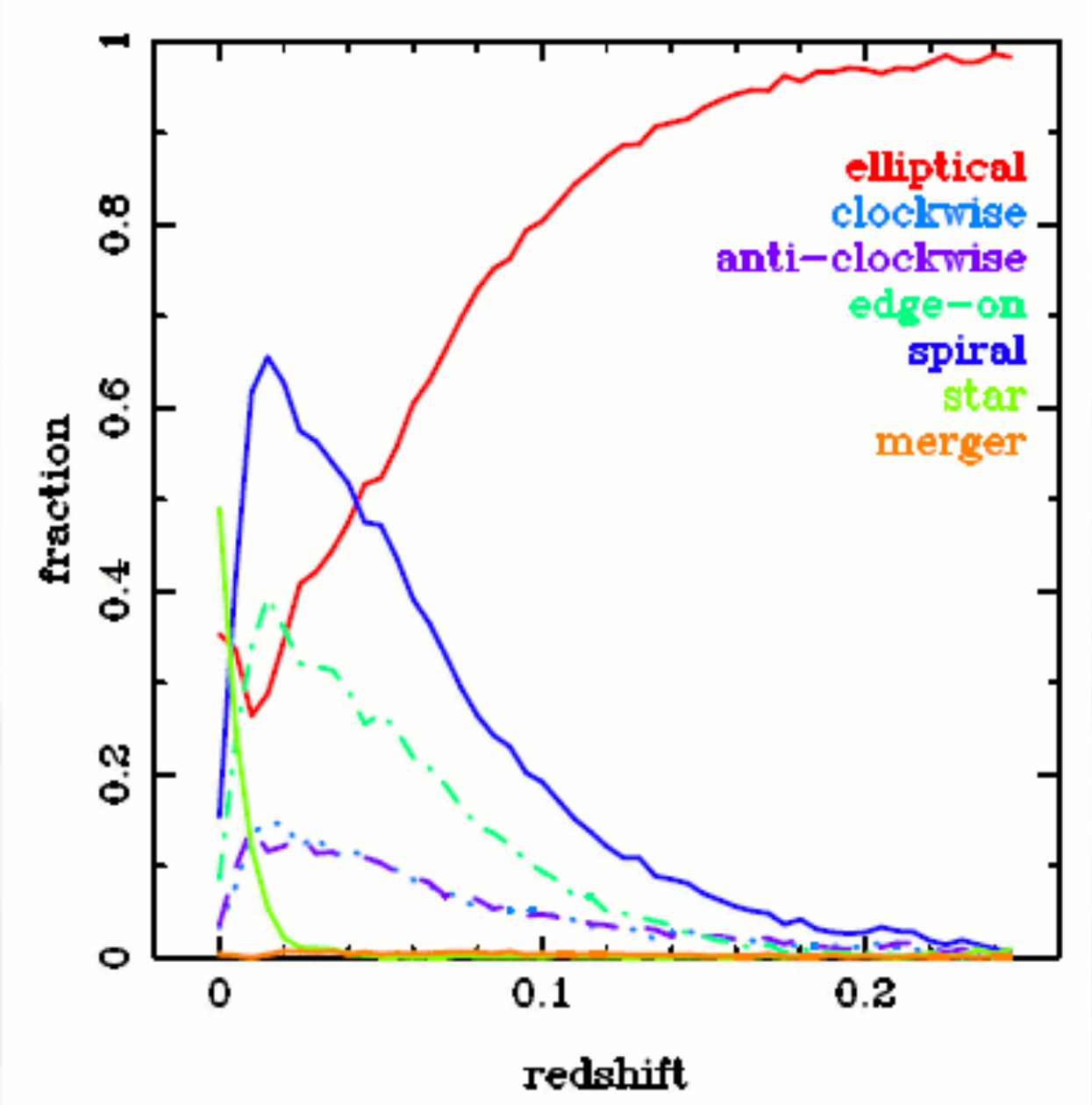


← Luminosity

"Theorist" Galaxy Luminosity Function



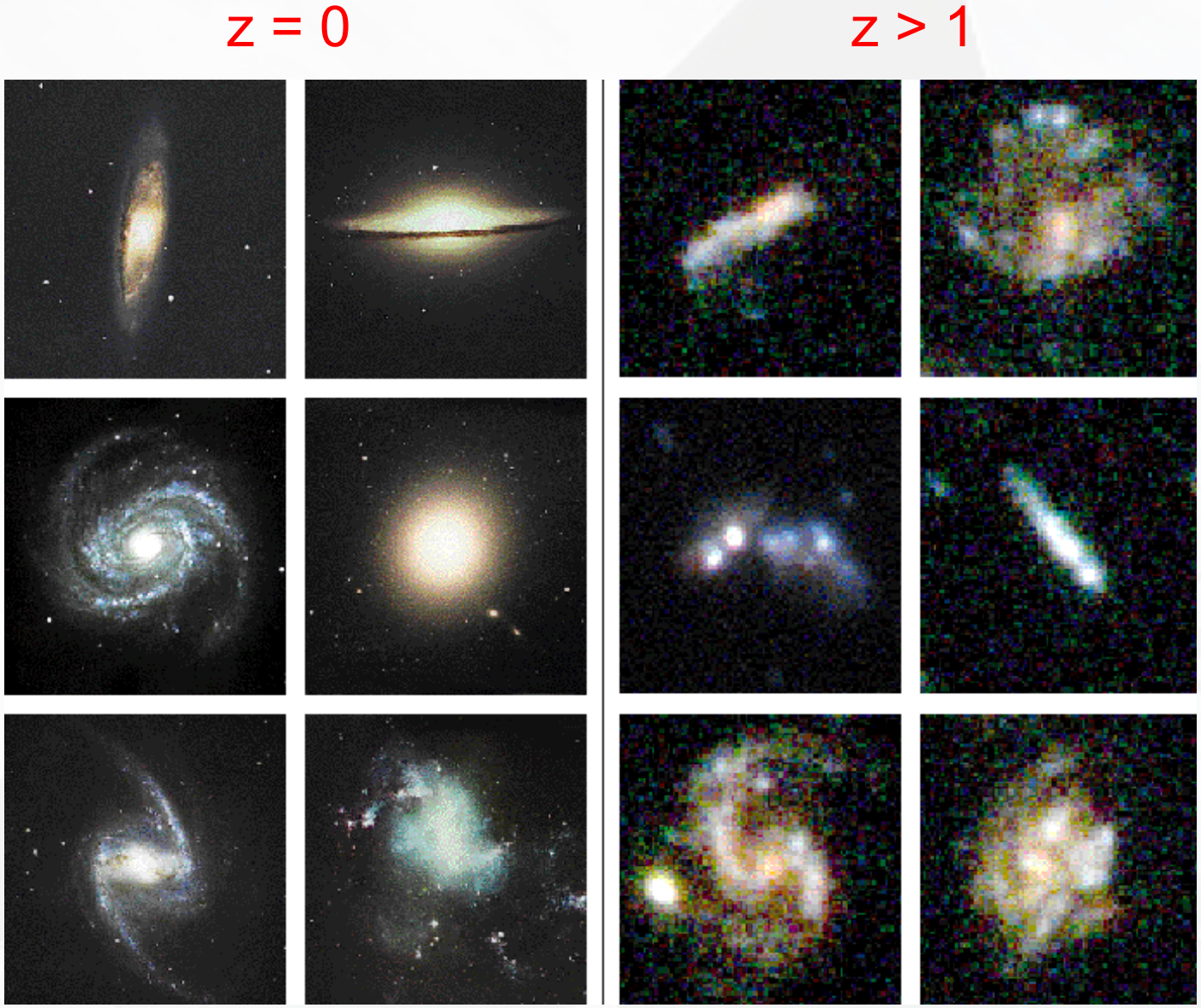
Morphological Evolution?



Do morphologies evolve?

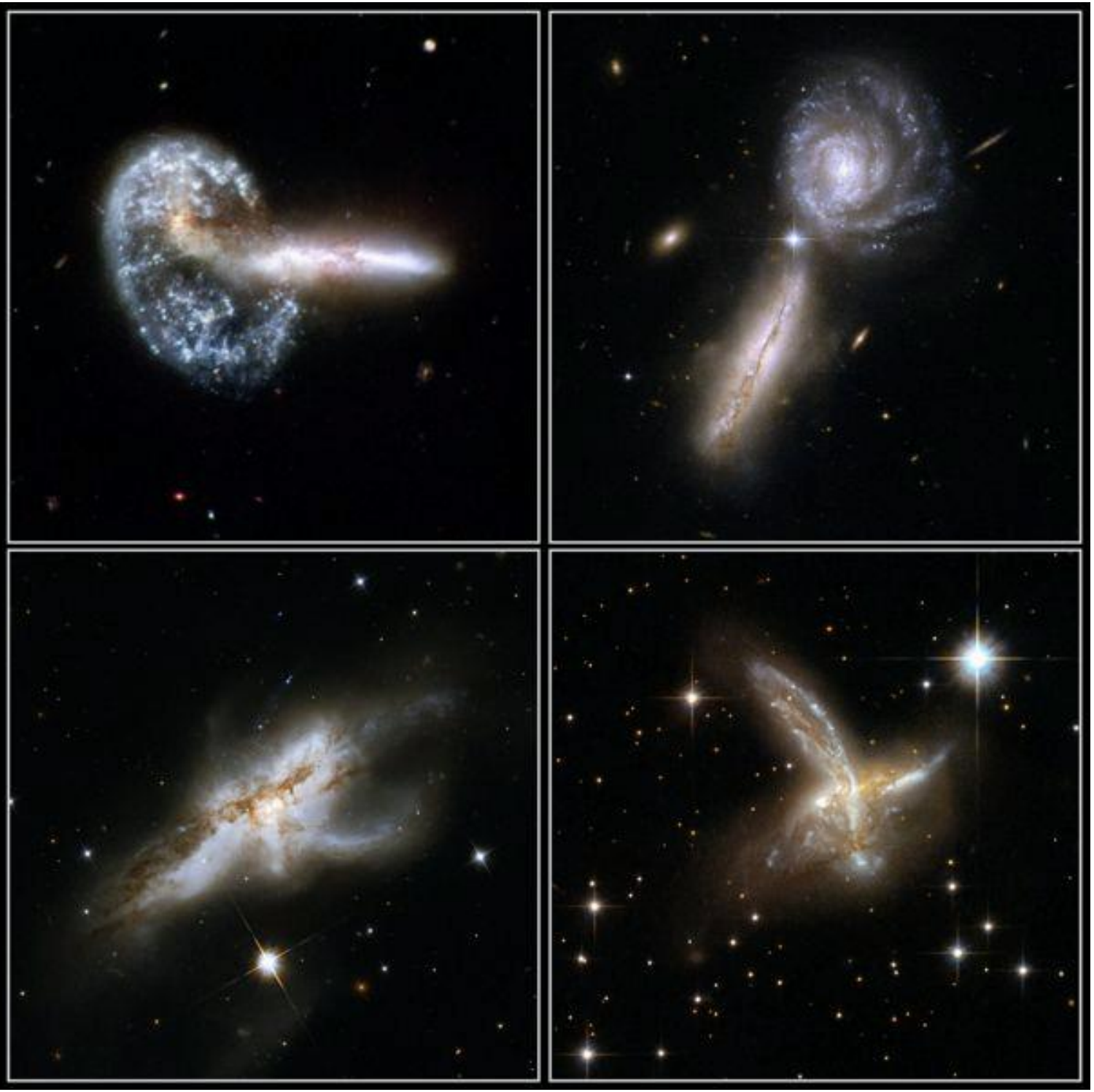
Can galaxies change their morphologies?

Morphological Evolution: HST

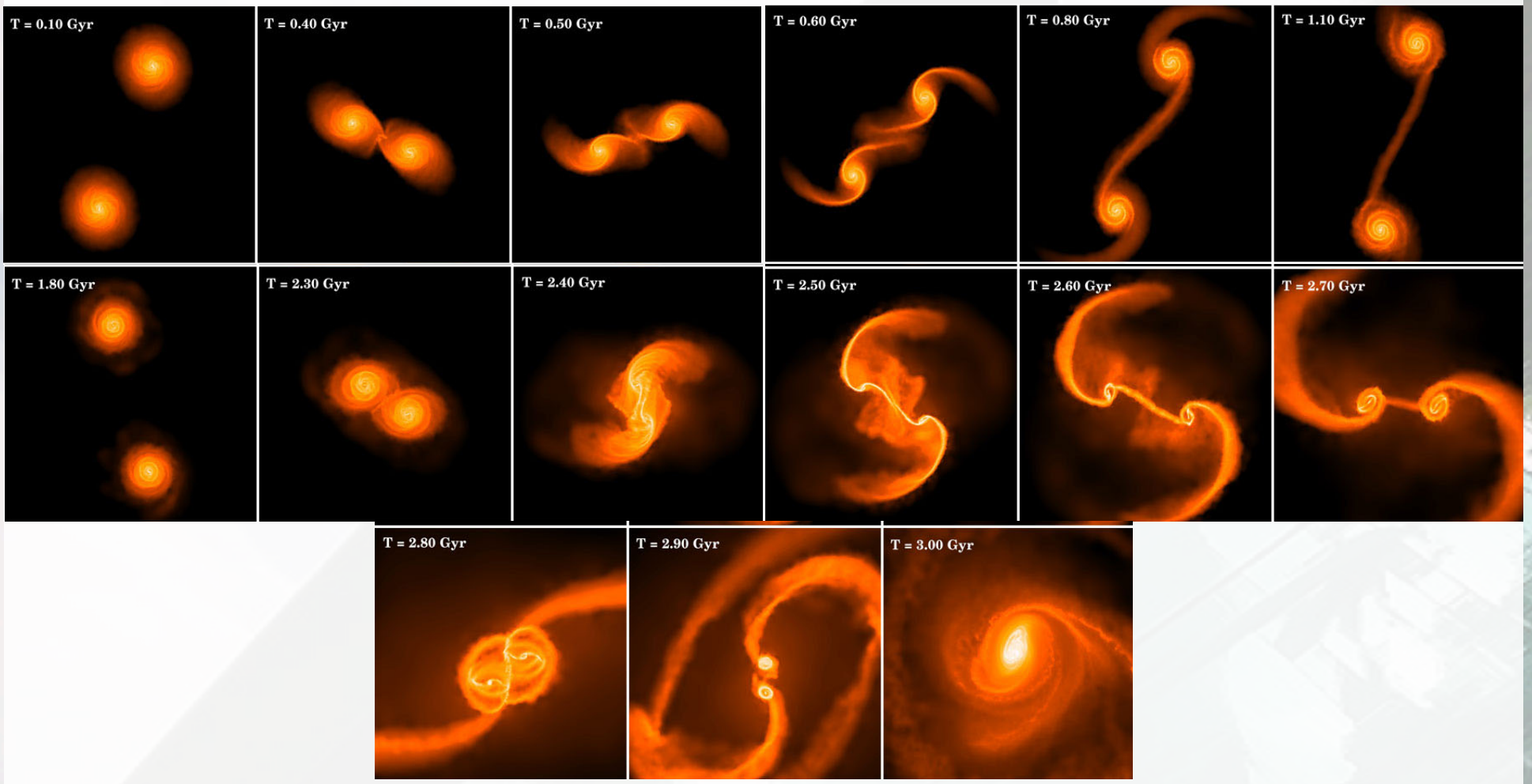


Morphological Transformations

Mergers & Interactions

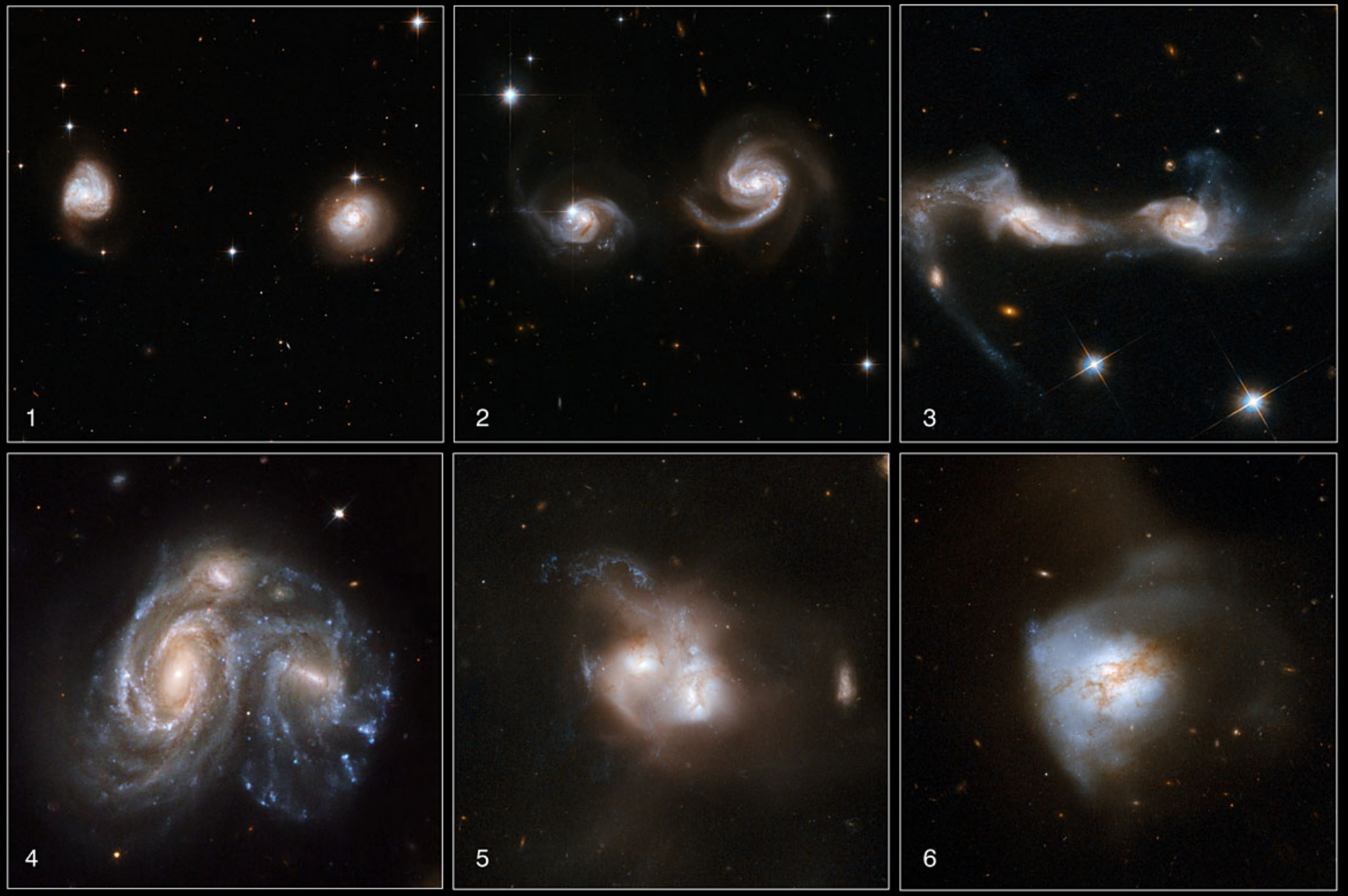


Merger Sequence: Theory

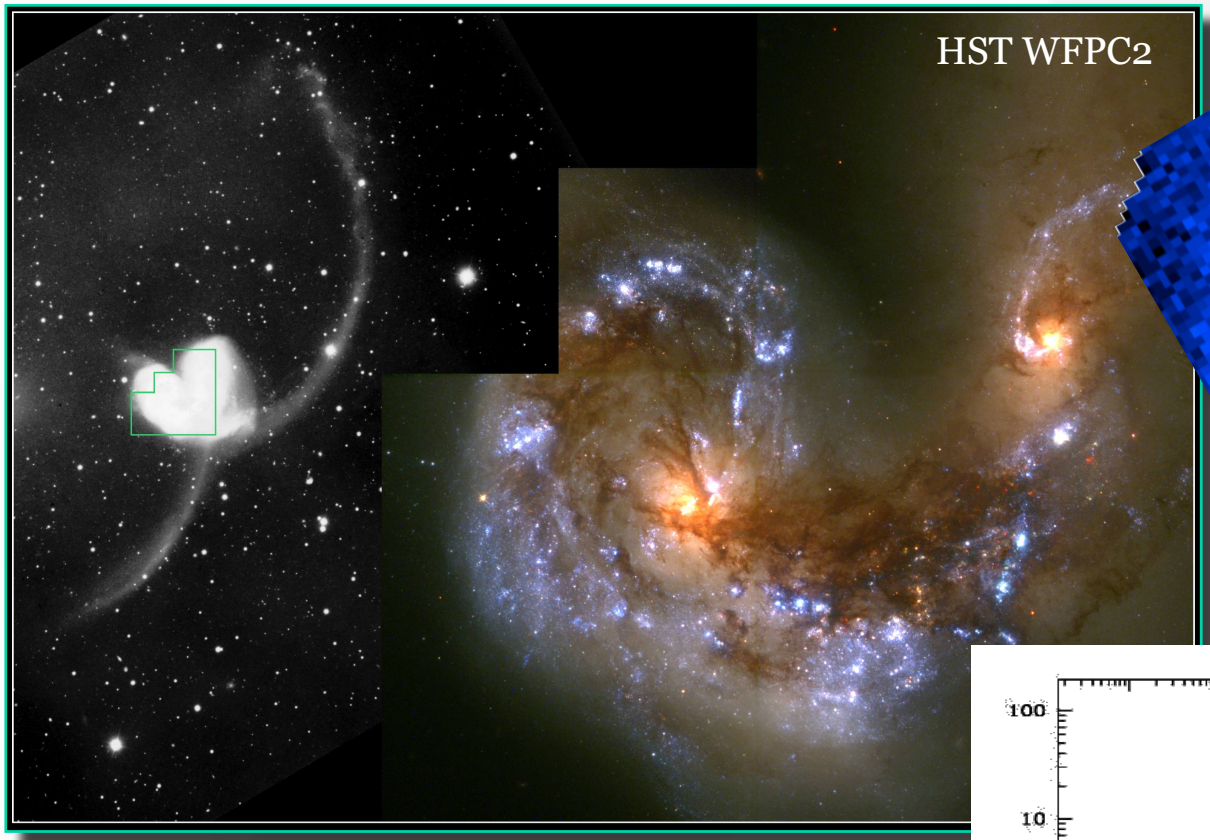


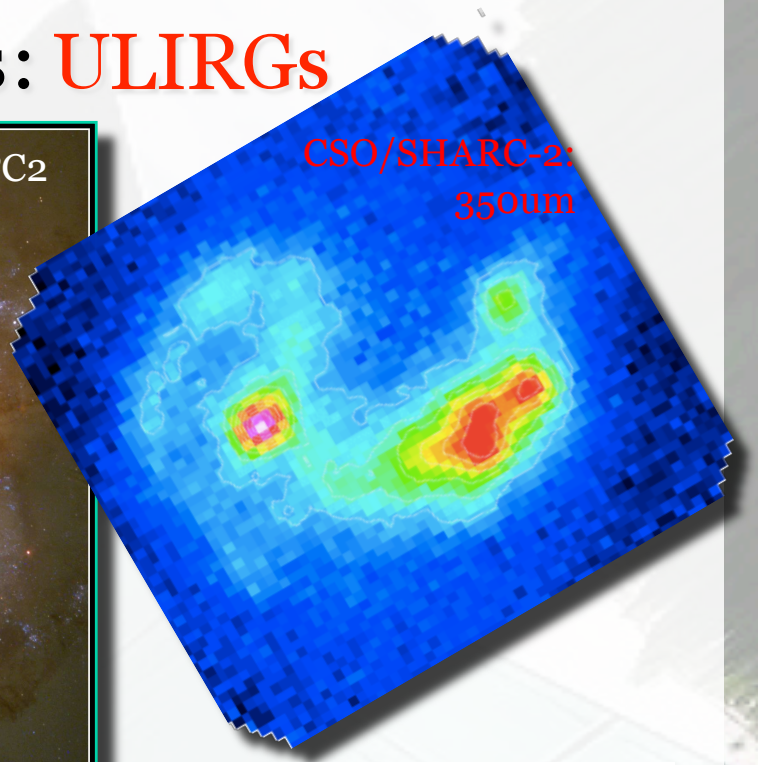
Over ~3Gyrs two bound spiral galaxies merge. In the process they use up all of their gas. The end-product is a gas-poor elliptical-like galaxy. So "late-types" evolve into "early-types".

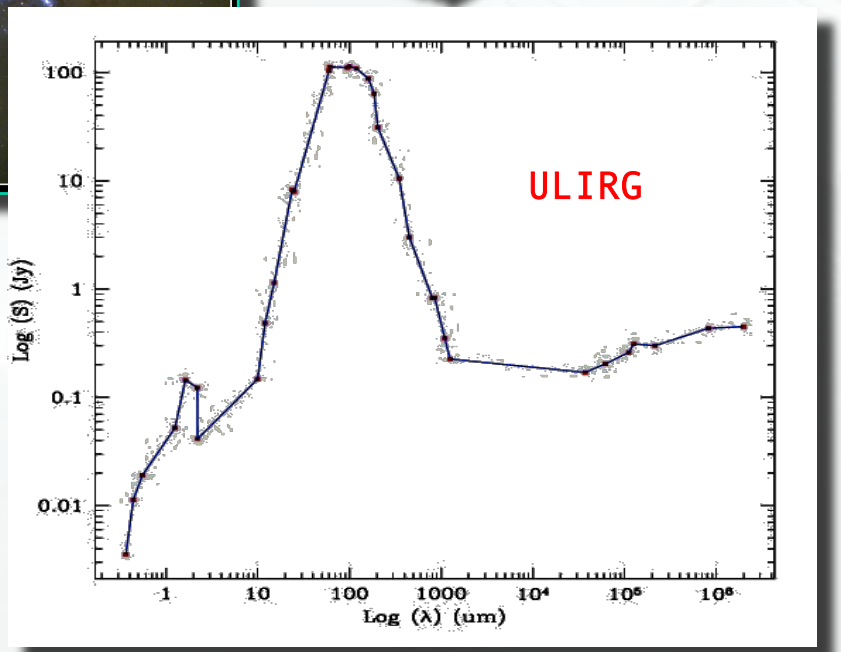
Merger sequence



UltraLuminous InfraRed Galaxies: ULIRGs







Mergers induce flows of gas into galaxy centres, powering intense compact starbursts. These cloak themselves in dust making the galaxies bright FIR sources.

Morphological classification

Morphology varies radically with:

- environment
- star-formation properties
- redshift

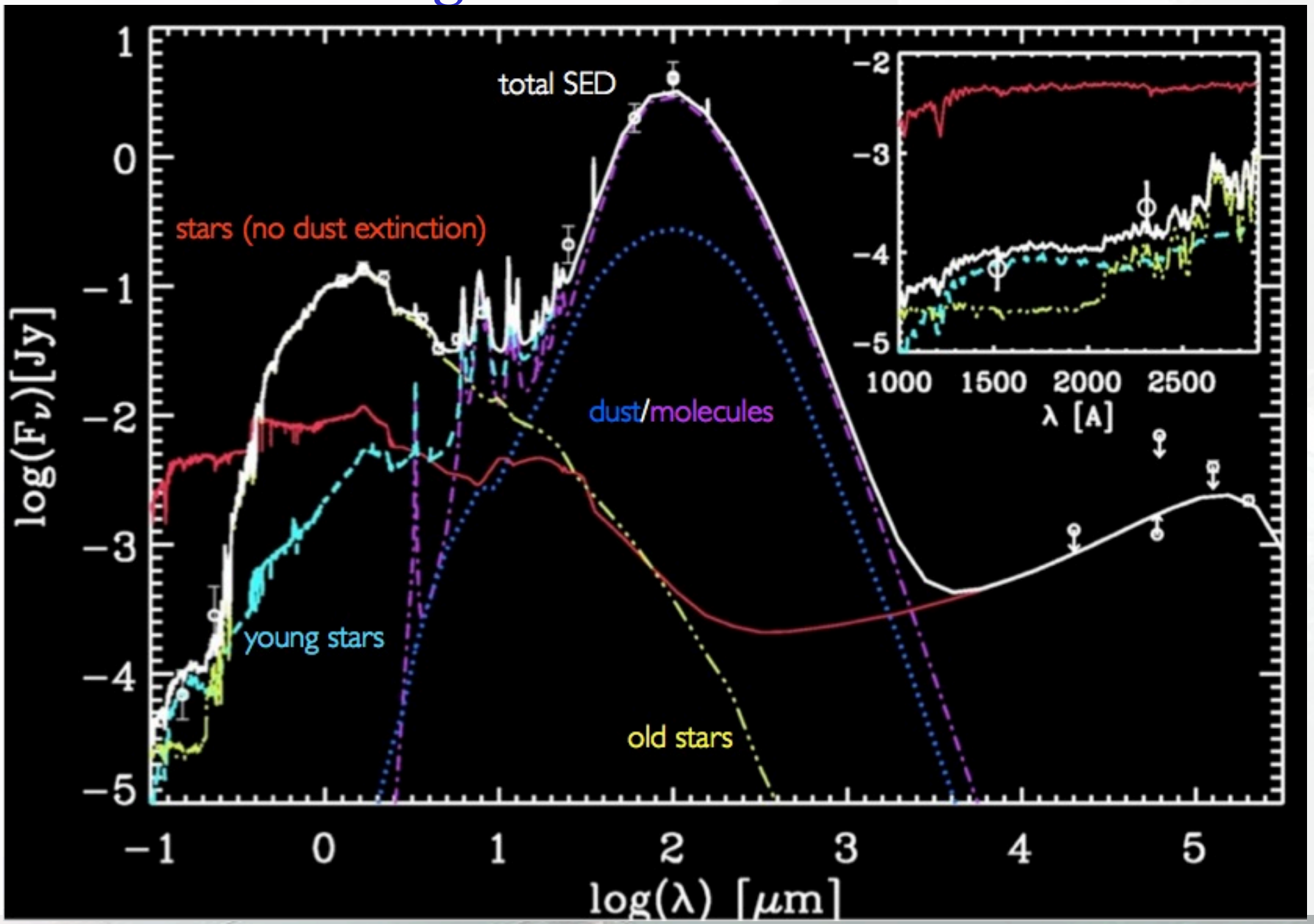
However:

- origin of morphologies poorly understood
- progress limited by lack of more quantitative morphological classifiers

More fundamental tests of galaxy properties focus on the stellar populations within galaxies to distinguish galaxies based on their star formation histories.

Photometric Classification

Light From Galaxies



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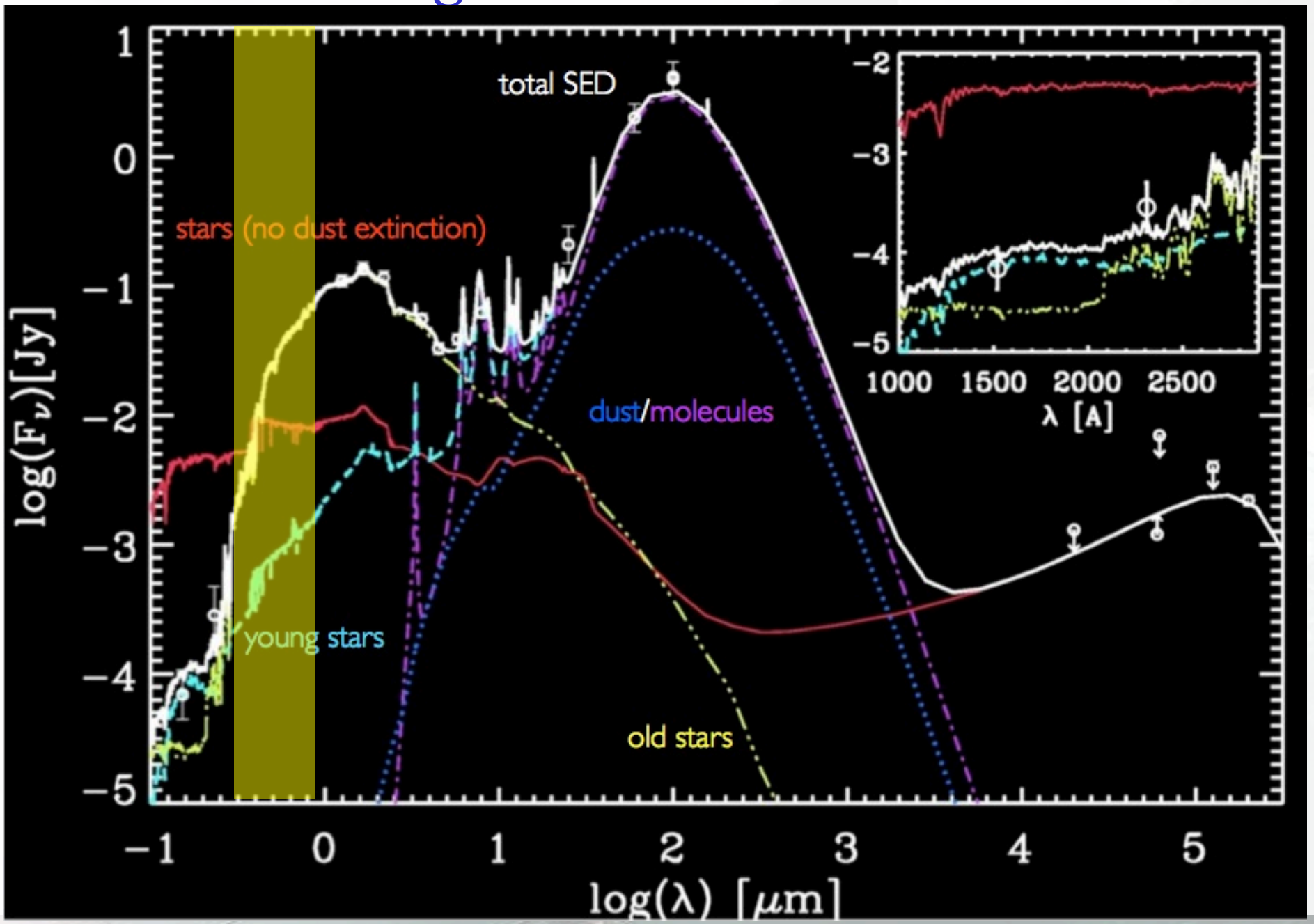


Light From Galaxies

Several processes influence the total observed emission from galaxies including:

1. Stellar light (young and old stars)
2. Hot ionised gas
3. AGN activity (accretion disk and shocks)

} Optical/Near-IR

4. Supernovae — Radio
5. Reprocessed light from gas and dust obscuring stars and AGN — Far-IR

Galactic emission is heavily influenced by levels of star-formation and AGN activity.

So can we use the photometric and spectral properties of galaxies to learn about SFHs and their formation/evolution?

Stellar Populations

For stars: $L \propto M^{3.5}$

So the luminosity of a stellar pop is dominated by most massive stars.

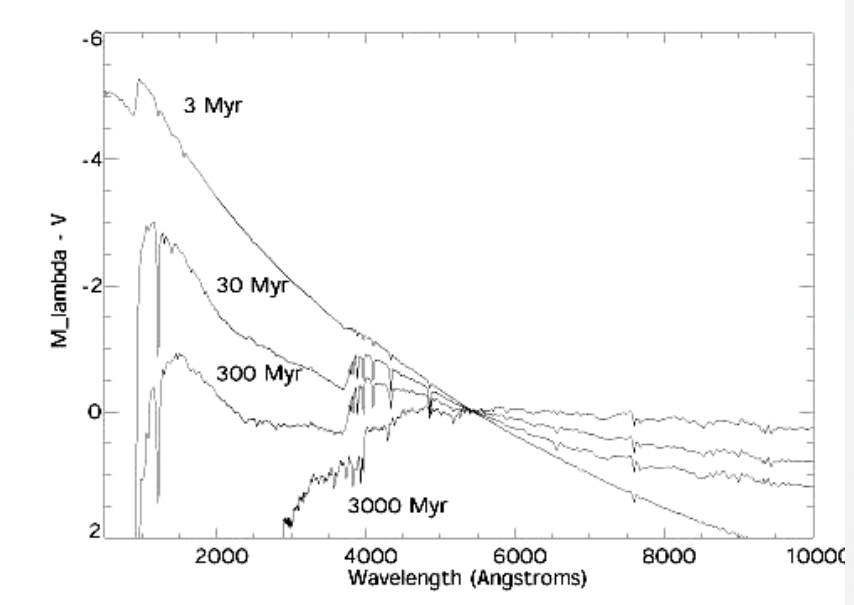
These are shortest lived:

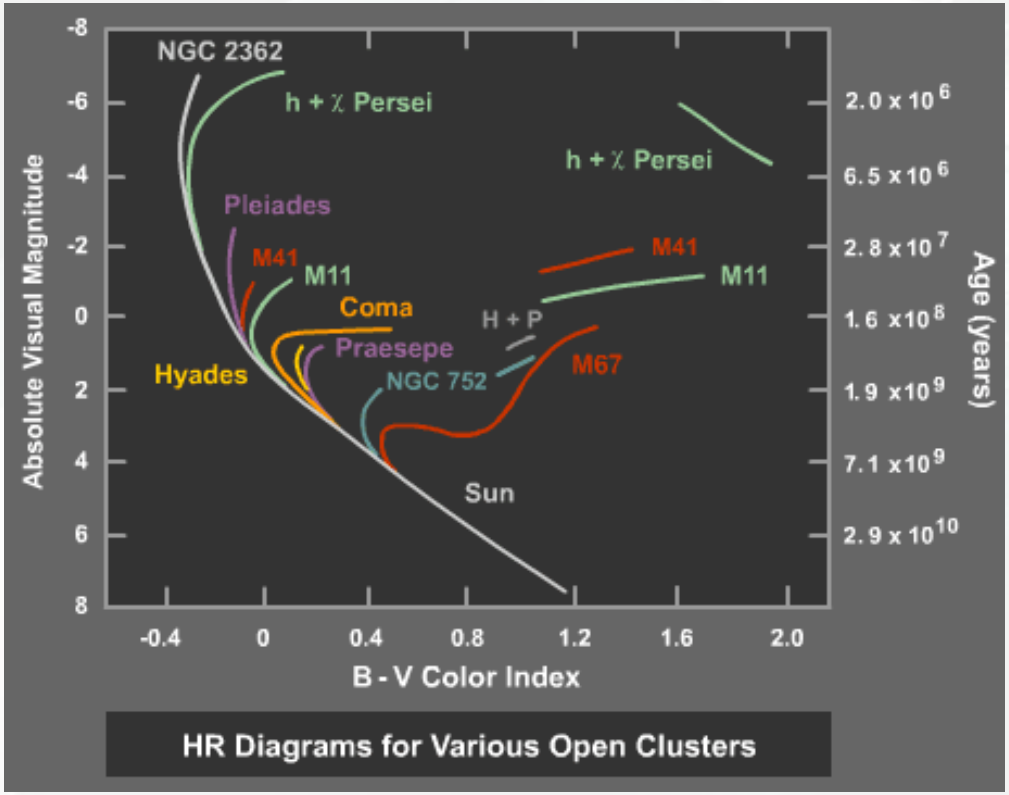
$$T_{MS} \sim M^{-2.5} \times 10\text{Gyrs}$$

and bluest: $T_{eff} \propto R^{-0.5} L^{0.25}$

MS lifetimes

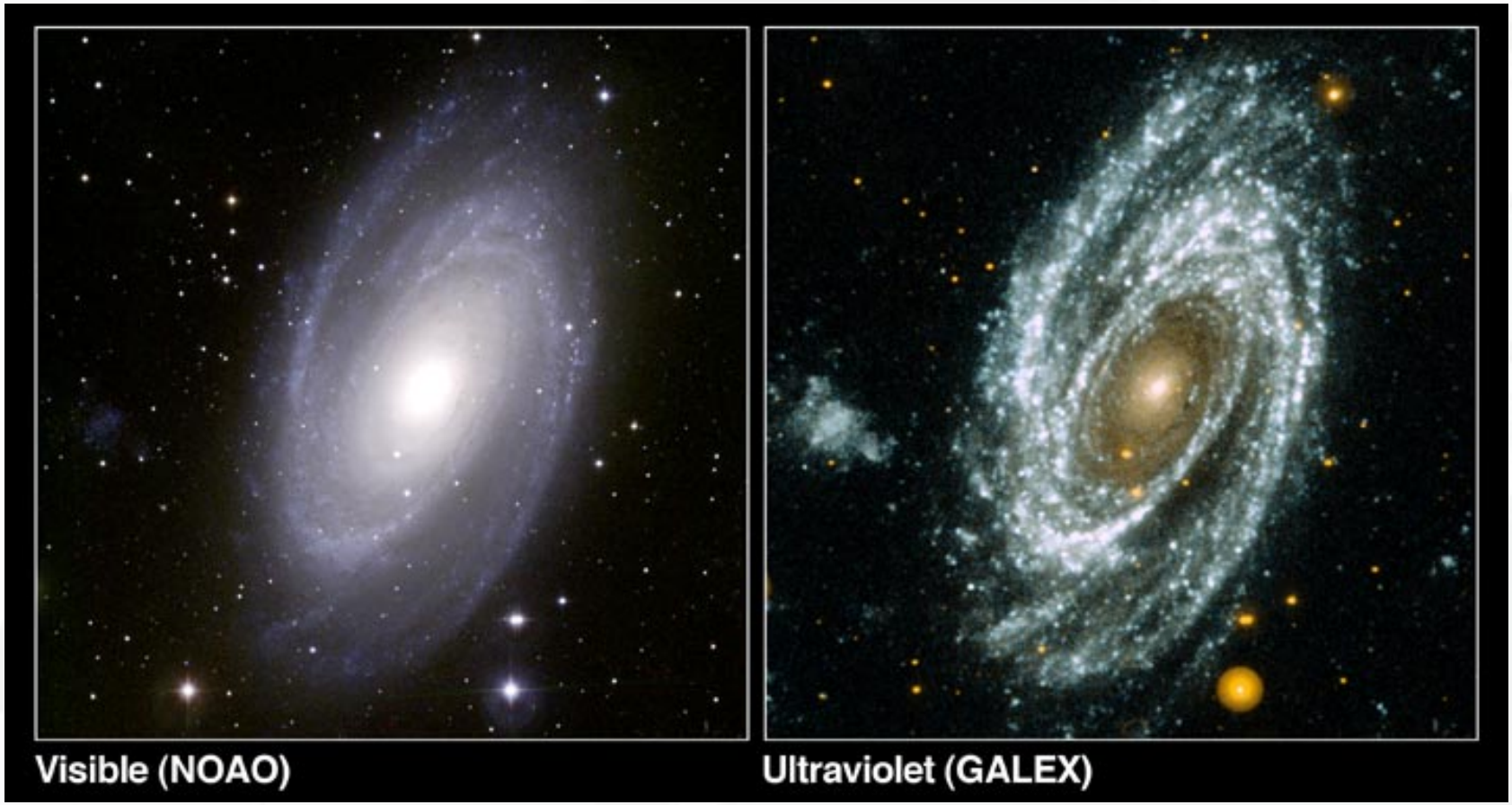
O3	60 $M_\odot \Rightarrow$ 3 Myr
O7	30 $M_\odot \Rightarrow$ 11 Myr
B4	10 $M_\odot \Rightarrow$ 30 Myr
A5	3 $M_\odot \Rightarrow$ 370 Myr
F5	1.5 $M_\odot \Rightarrow$ 3 Gyr
G2	1 $M_\odot \Rightarrow$ 10 Gyr
M7	0.1 $M_\odot \Rightarrow$ 1 Tyr



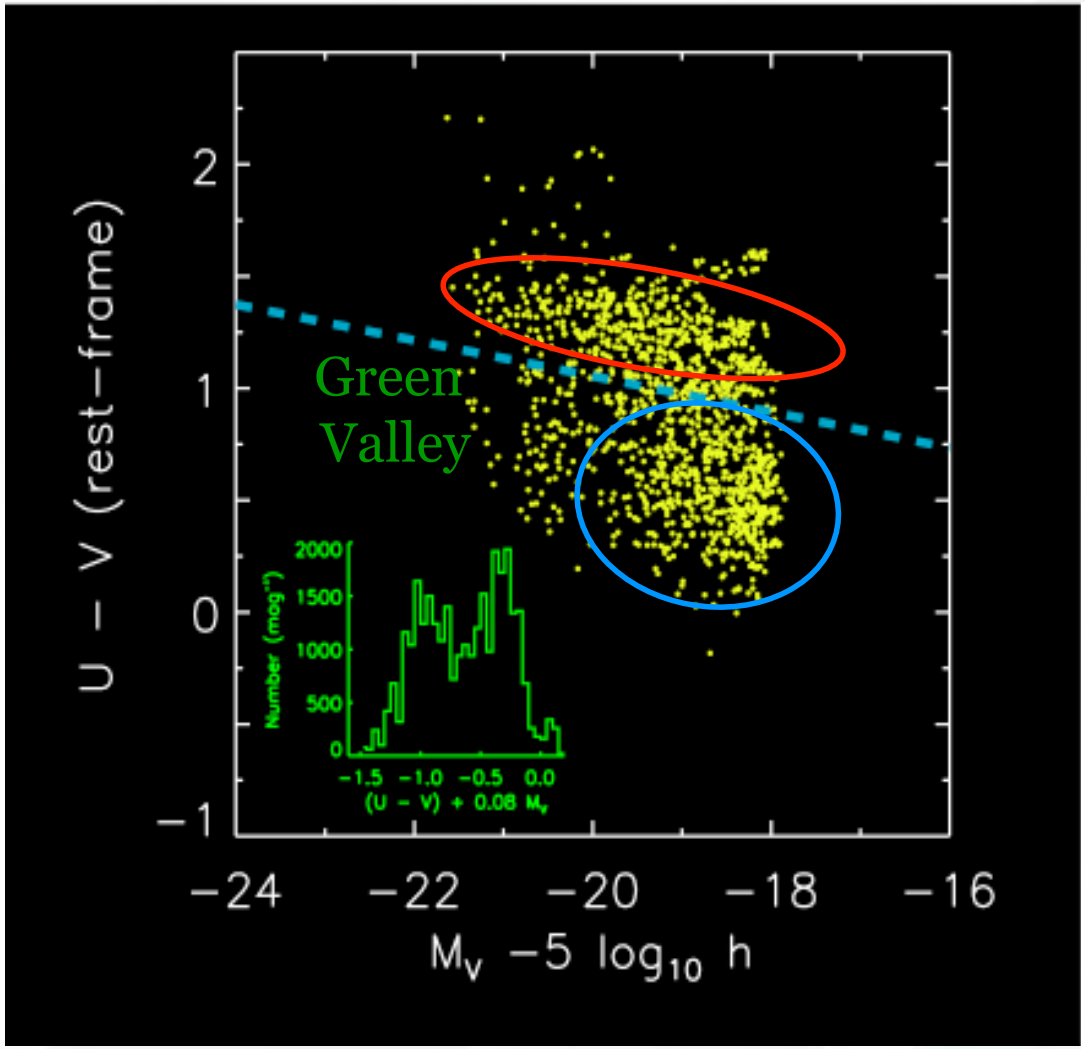


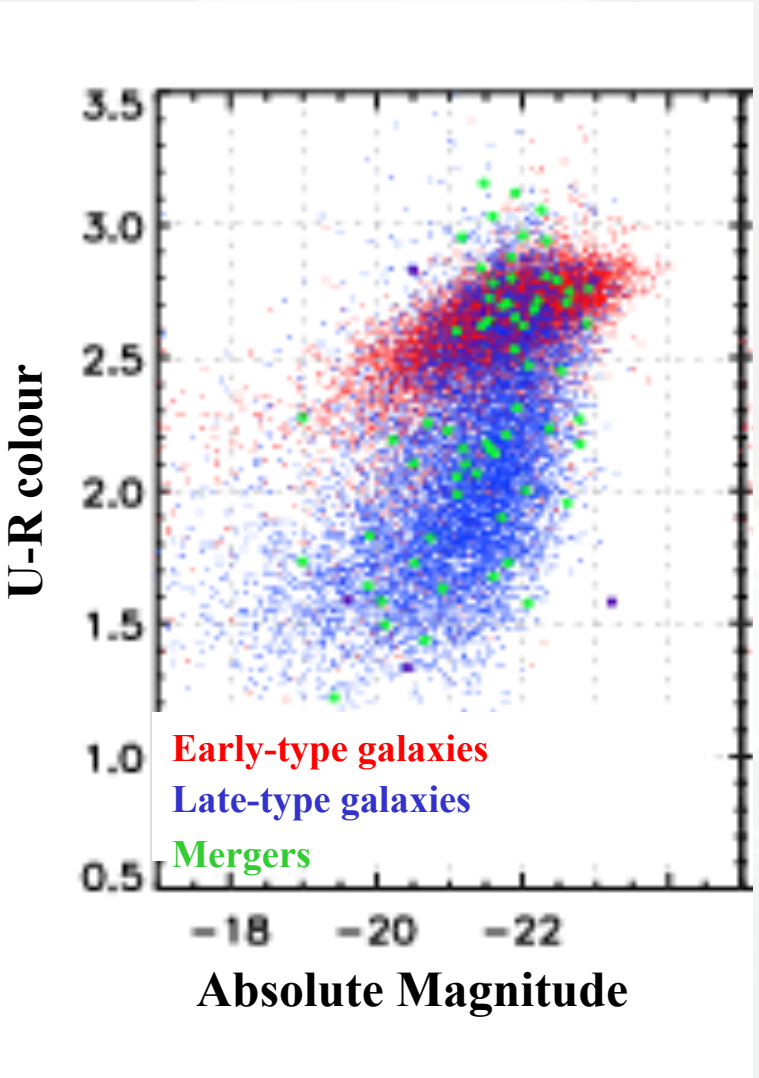
UV Light From Young Stars

Light from young massive stars dominate the stellar light from stellar clusters, emitting large amounts of UV light. The blue stellar light therefore traces regions of recent star formation.



Colour-Luminosity Relation



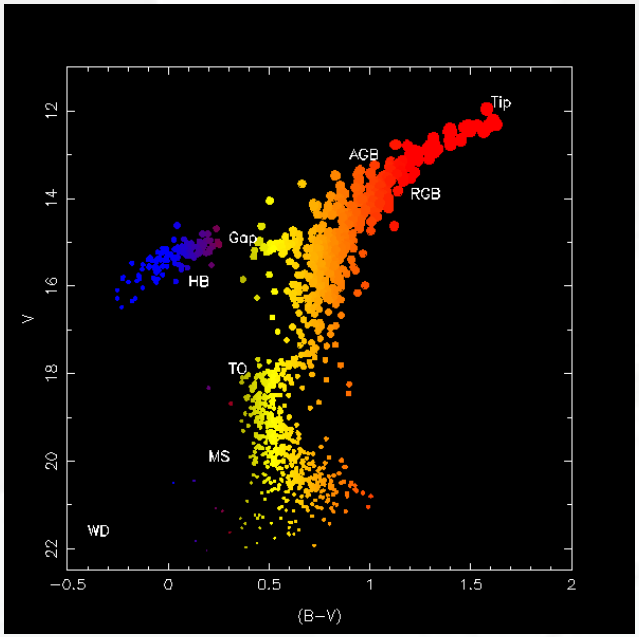


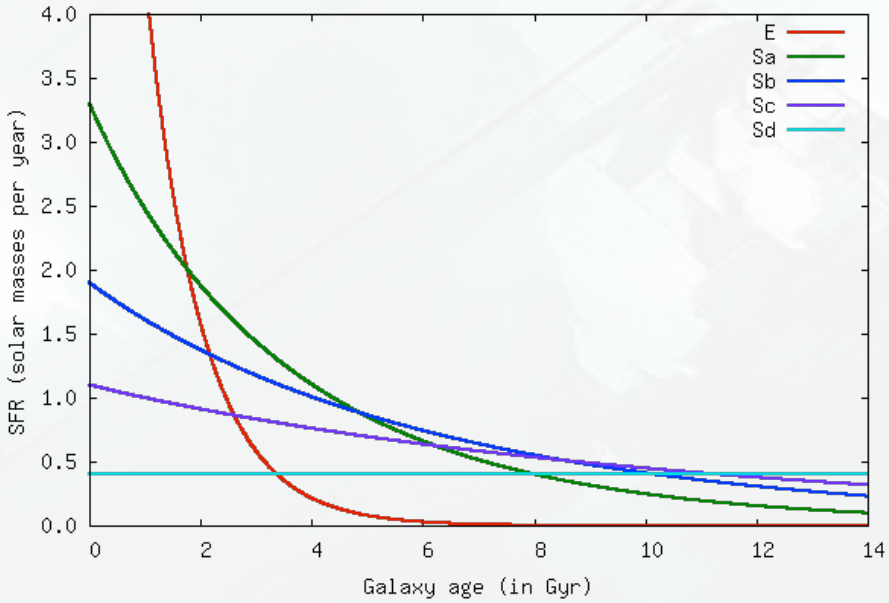
So can we learn more about the formation and evolution of galaxies from their colours/luminosities?

Stellar Pop Synthesis Models

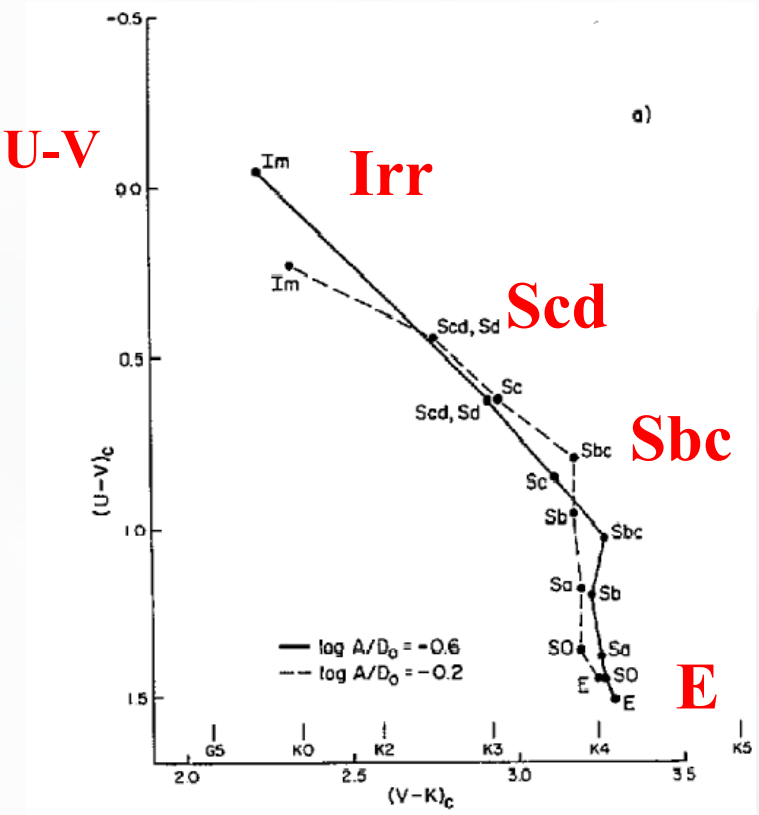
1. A grid of stellar evolution tracks are used to derive spectra of individual stars using stellar atmosphere models.
2. The individual stellar templates are summed together, weighted by an IMF, to give spectra of single-age populations (e.g., star clusters) as a function of age.
3. These populations are added together in linear combination and fit to real galaxy spectra.

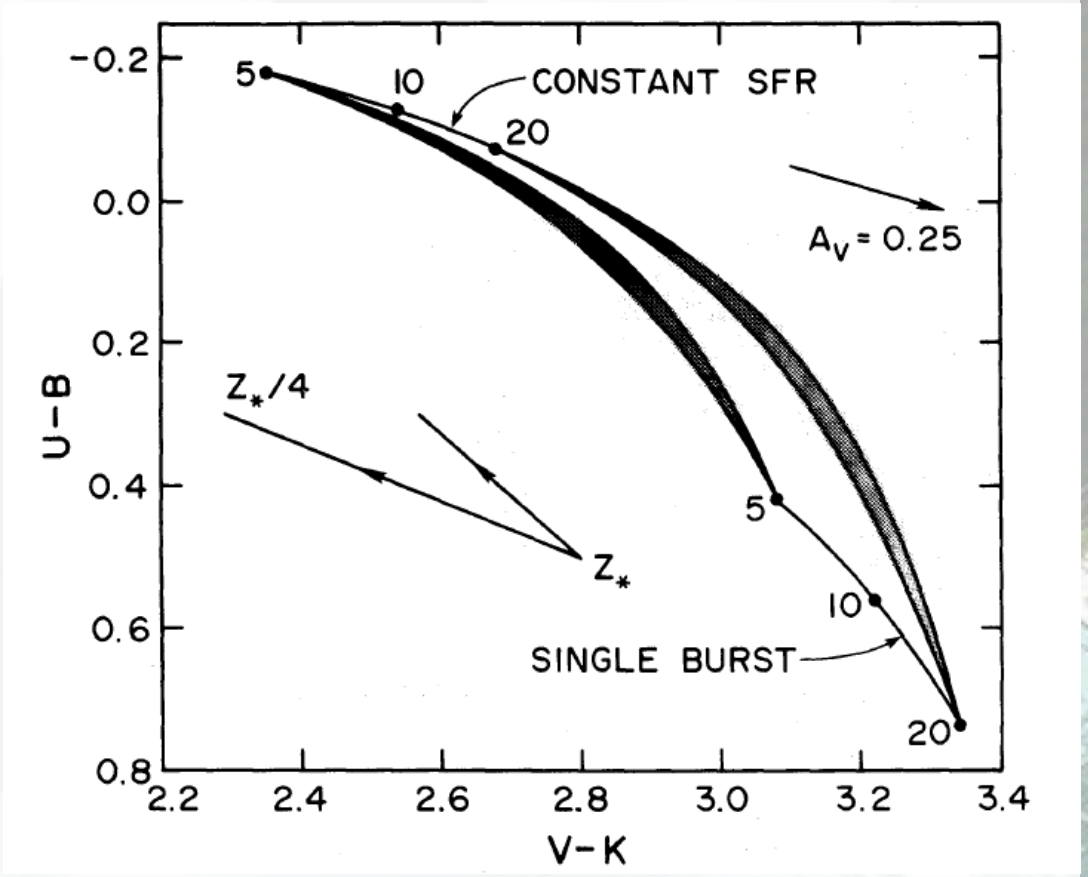
Need to assume a star formation history… (as older stellar pops are easily masked by latest SF)





Colours & Star Formation Histories: Classical View





Ellipticals and bulges – old stellar systems following an initial burst of formation

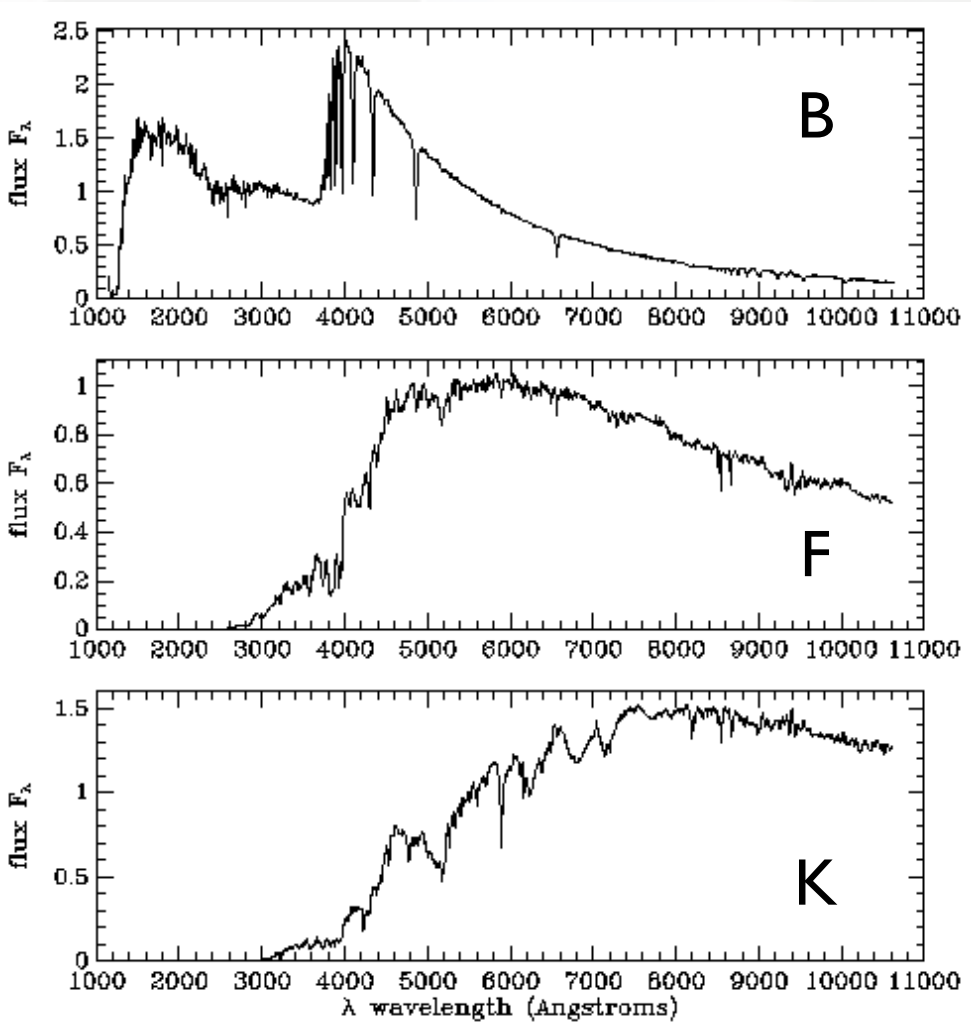
Spiral disks –continuous star formation and younger mean stellar age

Tinsley & Danly Ap J 242, 435 1980

Spectroscopic Classifications

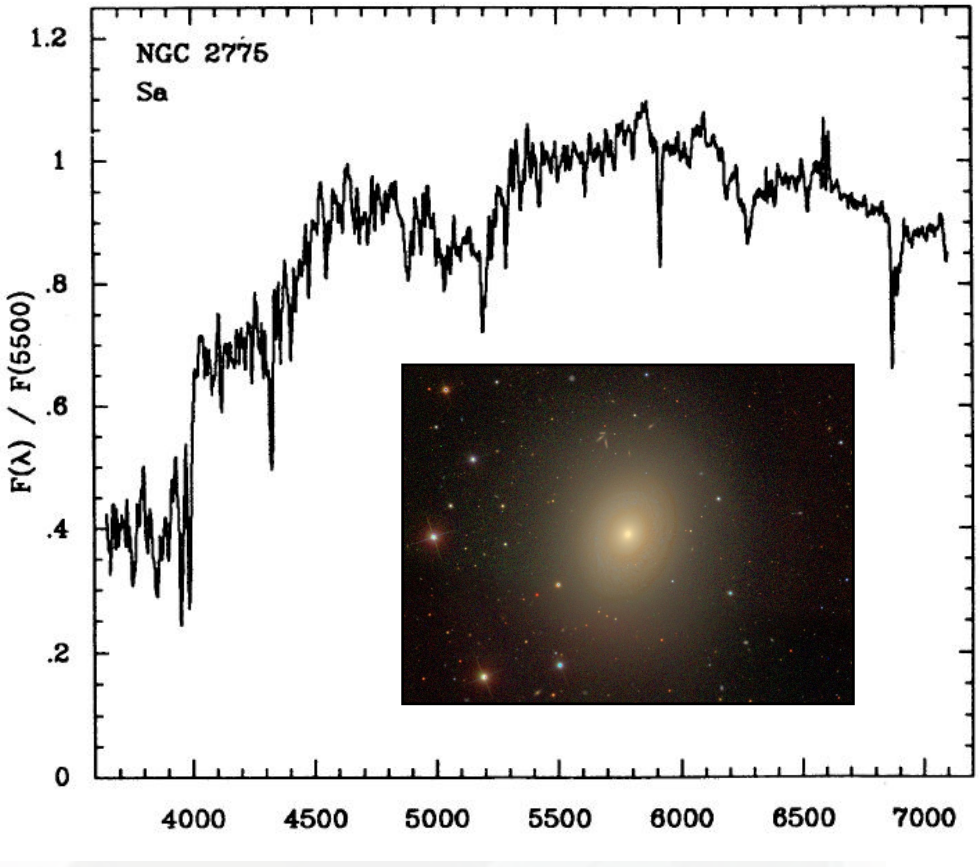
Features of Stellar Spectra

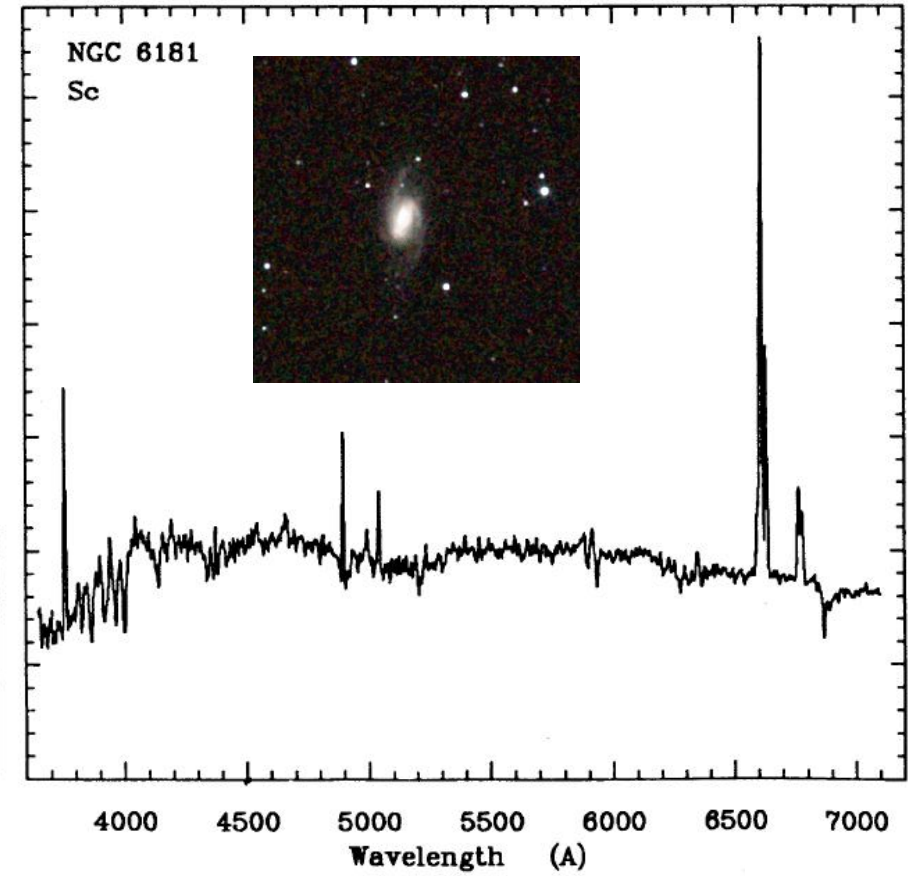
- O/B/A-stars:
  - Lyman break at 912 Å
  - 4000 Å break
  - Helium and Hydrogen absorption lines
- F/G-stars:
  - More prominent 4000 Å break
  - Metallic lines grow in strength
- K/M-stars:
  - Metallic lines and molecular bands provide significant absorption
  - Weak blue continuum



Normal Galaxy Spectra

For normal galaxies, star formation history plays key role in determining the resulting galaxy spectrum.

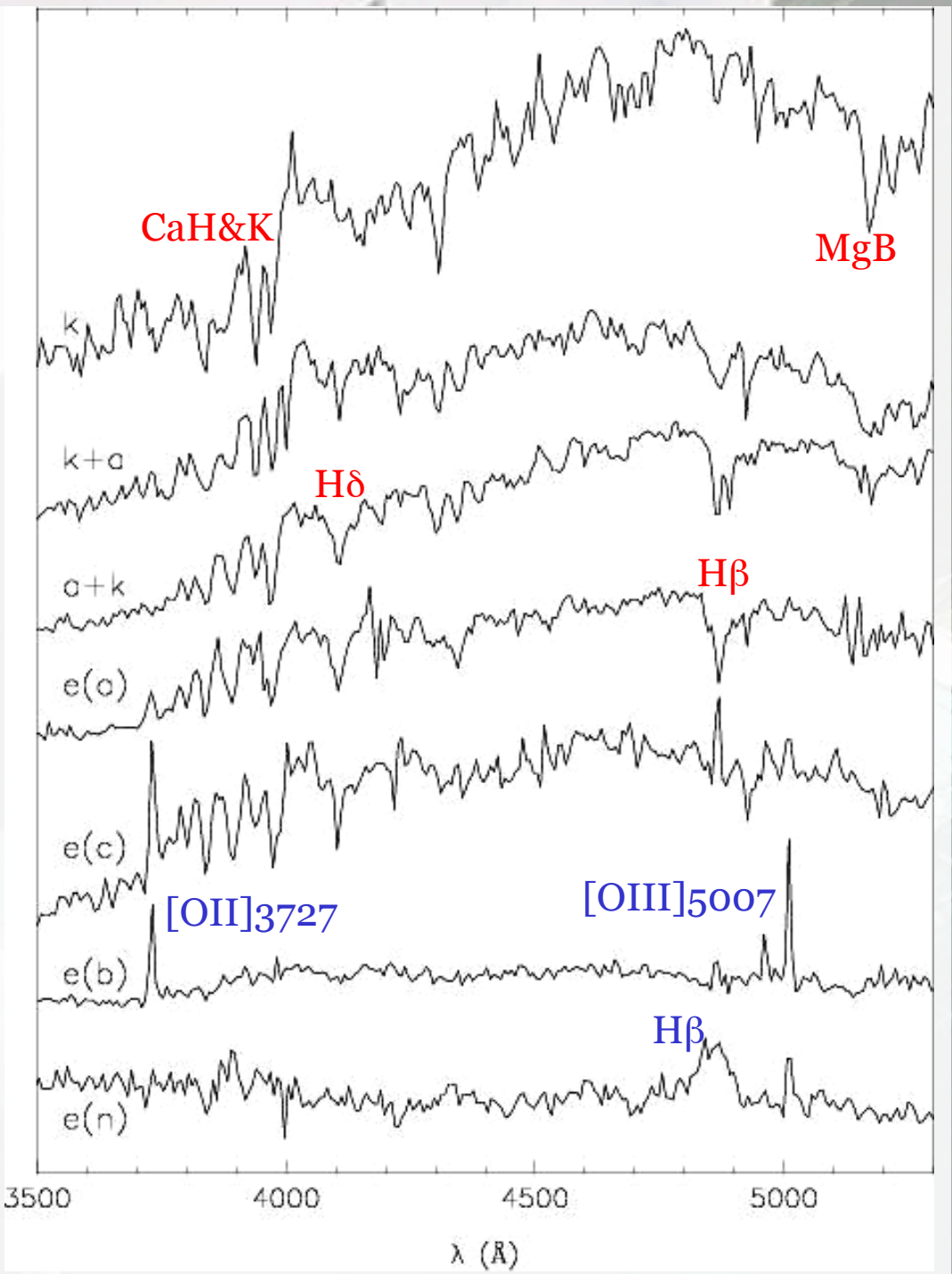




Spectral Classes

A wide variety of spectra depending upon SFH (crudely ratio of current to past SFR)

Classification scheme is based on the presence of emission and absorption lines and shape of continuum: Passive [k], star-forming [e()], and "post-star-forming" [a +k/k+a]

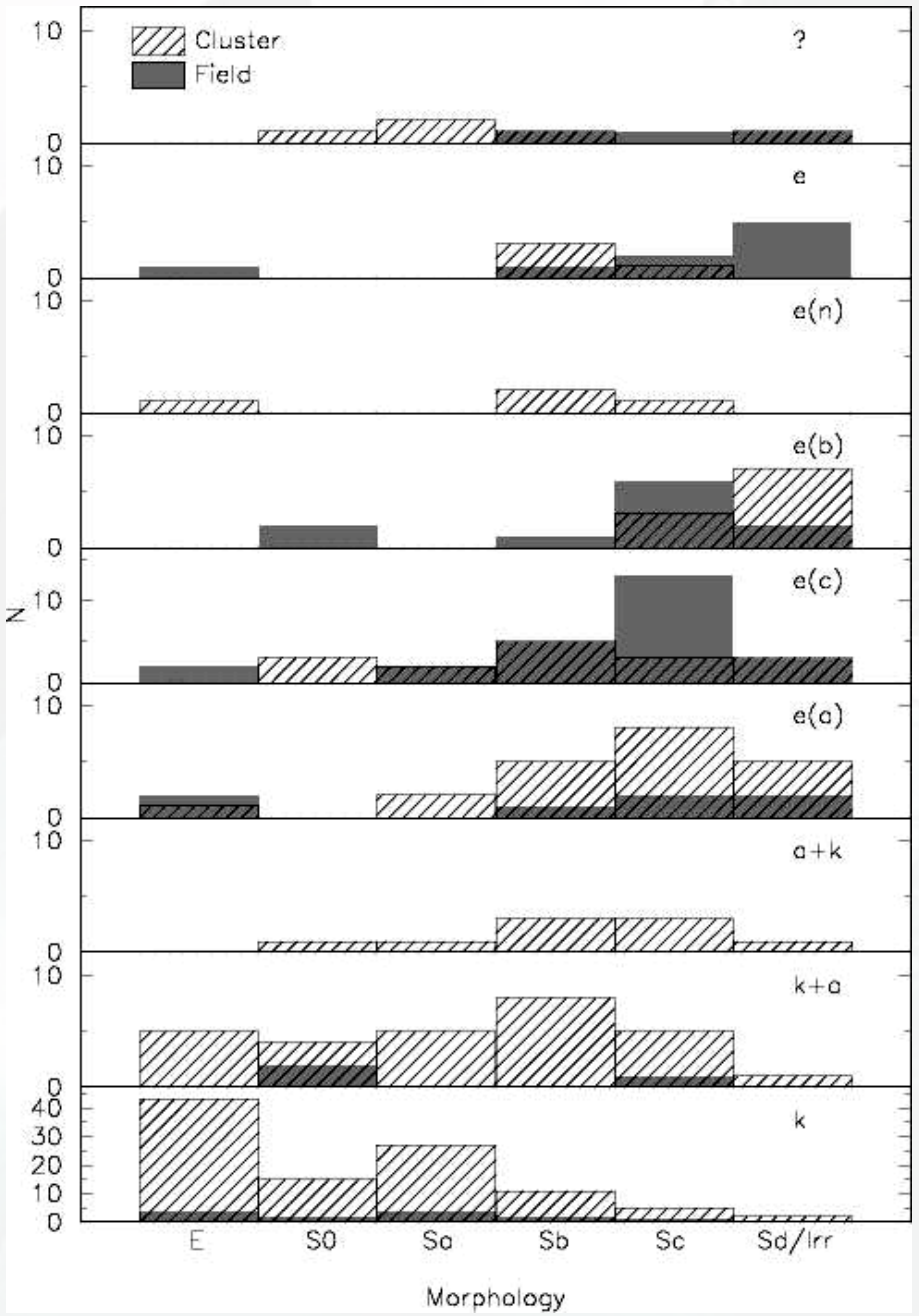


Spectra & Morphologies

Spectral types correlate with morphology (as did colours).

But they can provide a more detailed insight into the star formation histories (and hence evolution) of galaxies.

Also allows us to identify star-forming Ellipticals and passive Spirals, which may be in the process of transformation (e.g. forming S0's?).



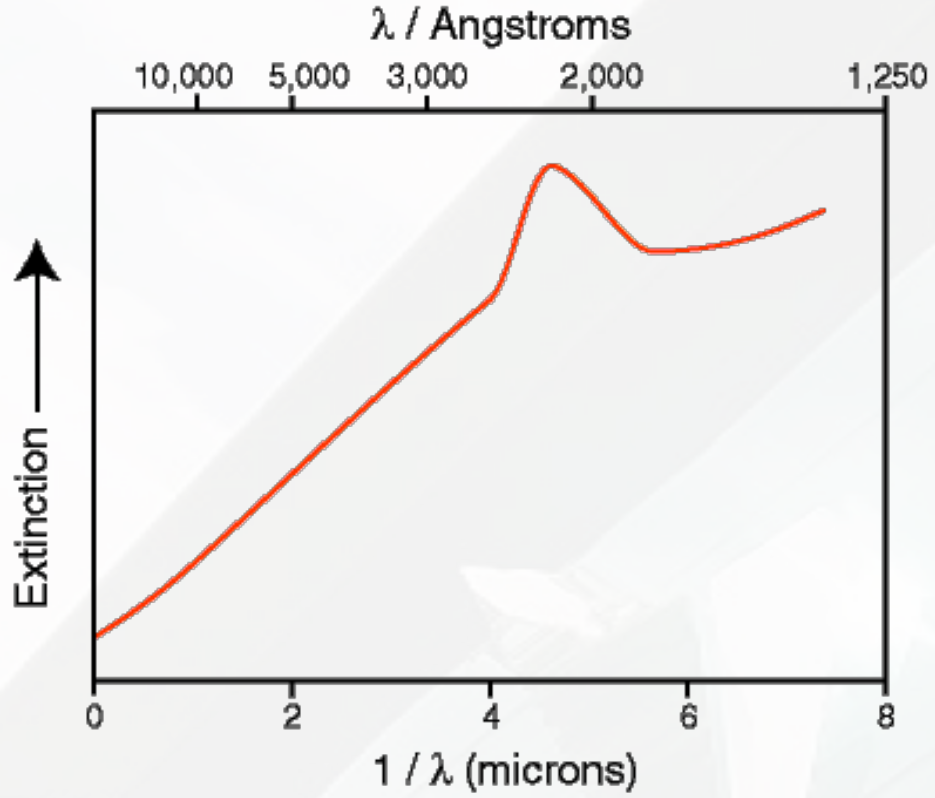
Summary

- Initial classification schemes based on visual morphologies.
- Little advance in morphological classification in ~90 years: humans better than computers at pattern recognition (but not repeatable). GalaxyZoo provides large, statistical samples of morphologies.
- Classification schemes using photometric/spectroscopic properties tell us about galaxy's star formation histories.
- Star formation histories correlate with morphology (as spectral type and colour do):
  - Elliptical galaxies lack current star formation and are dominated by old stellar populations.
  - Spiral galaxies are characterised by on-going star formation, which complicates the analysis of their old fraction.

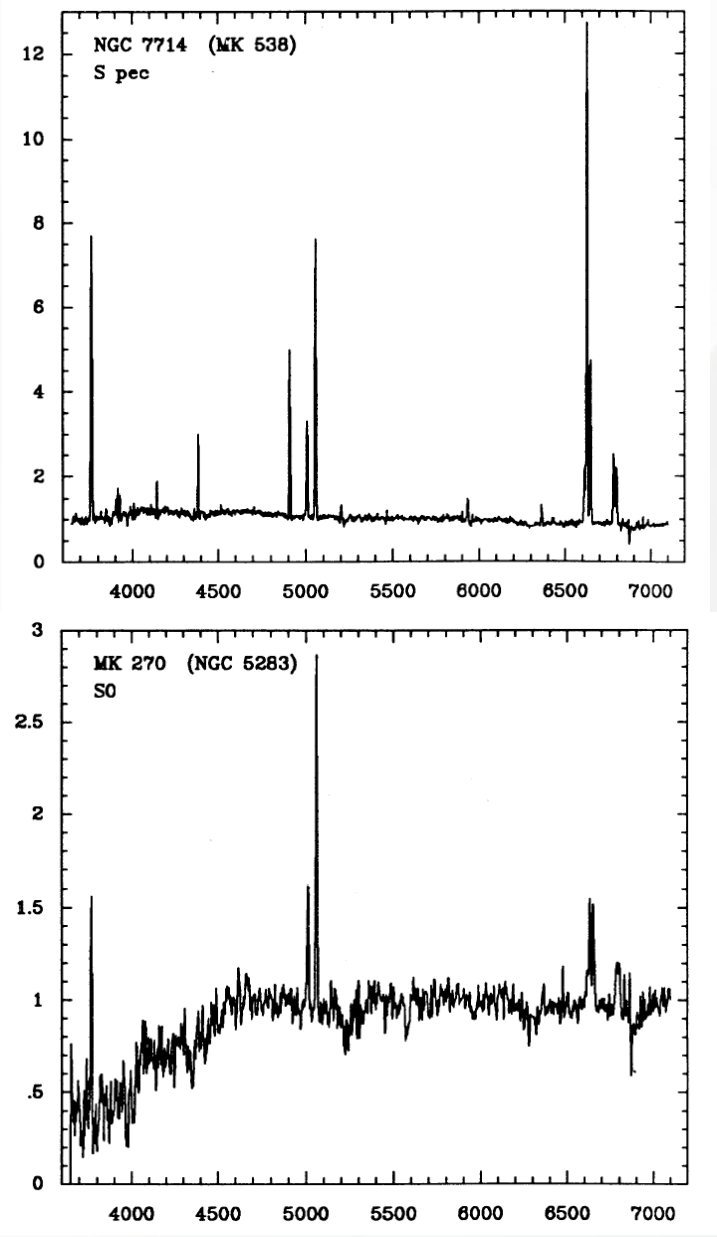
Complicating Factors

Extinction Relation

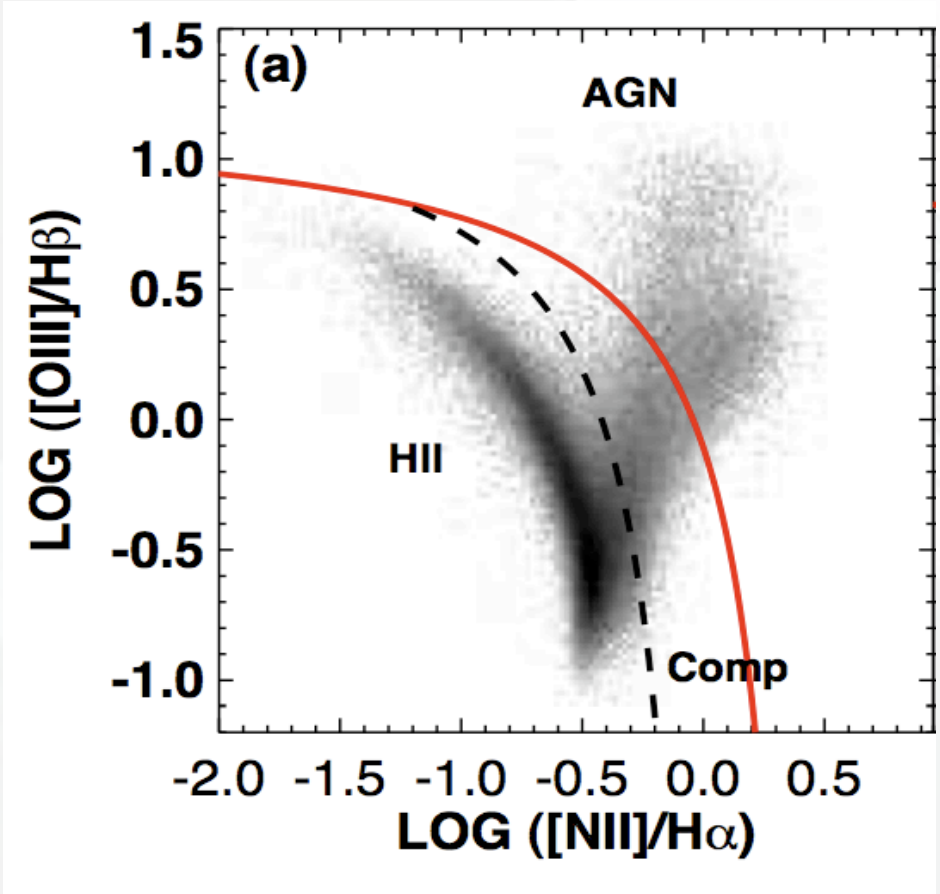
In large clusters the stars are embedded in a cocoon of gas and dust, which significantly obscures our view of the stars. The obscuring material is most affective at UV wavelengths.



AGN or Starburst?



AGNs have similar features to Starbursts, making it difficult to measure the SFRs for such sources.



Summary

SO BEWARE OF THE DETAILS:

- old stars can hide under a small amount of recent Star Formation (SF)
- dust obscuration can be important (& very band specific)
- AGN contamination complicates interpretation
- Unknown complexity due to Star Formation History (SFH)
- Influence of IMF, metallicity, etc.

Galaxy Formation and Evolution

PG lecture course, 2013

Peder Norberg, ICC

(based on Ian Smail's PG slides)

1. Classifying Galaxies: Diversity at z=0
2. Empirical Galaxy Evolution
3. Cosmic Star Formation History
4. Stellar Mass Assembly
5. Theoretical models I (CGL)
6. Theoretical models II (CGL)